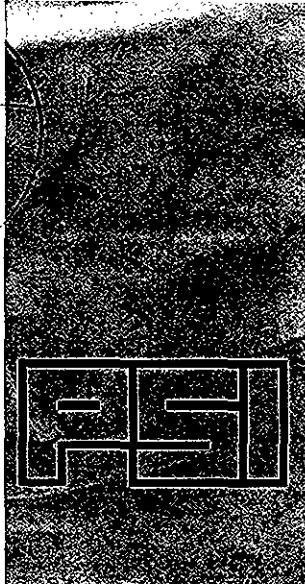


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Paul Scherrer Institut

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F. JEGERLEHNER *

Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland

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Paul Scherrer Institut
Würenlingen und Villigen
CH-5232 Villigen PSI

Telefon 056/99 21 11
Telex 82 74 14 psi ch
Telefax 056/98 23 27 PSI CH

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F. JEGERLEHNER *

Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland

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RENORMALIZING THE STANDARD MODEL

FRED JEGERLEHNER

Paul Scherrer Institute

CH-5232 Villigen PSI, Switzerland

ABSTRACT

We review the renormalization of the Standard Model of electroweak interactions and go into details of calculating and renormalizing parameters and cross sections. The main emphasis is on calculations for precision physics with Z bosons. Theoretical calculations are confronted with recent results from LEP.

I. THE STANDARD MODEL

1. Introduction

The known fundamental interactions of elementary particles (strong, weak and electromagnetic) derive from a *local gauge principle* (Weyl 1932, Yang-Mills 1954) with the gauge group [1,2]

$$G_{loc} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y . \quad (1)$$

The theory is essentially determined once the *matter fields* and their transformation laws under G_{loc} are specified. The real world is built from *massless* spin 1/2 particles, the *leptons and colored quarks*. Massless particles necessarily have fixed helicity (chirality). The relativistic massless Dirac field ψ decomposes into two independent Weyl fields a left-handed field $\psi_L = \frac{1-\gamma_5}{2}\psi$ and a right-handed field $\psi_R = \frac{1+\gamma_5}{2}\psi$:

$$\begin{array}{ccc} \overleftarrow{\tilde{s}} & \circ \overrightarrow{\tilde{s}} & \circ \overleftarrow{\tilde{s}} \\ \psi_L & & \psi_R \end{array}$$

In relativistic quantum field theory locality and causality enforce particle-antiparticle pairing and the spin-statistics theorem to hold. For the chiral fields this implies that a left-handed field ψ_L describes at the same time a left-handed particle and a right-handed antiparticle and a right-handed field ψ_R describes a right-handed particle and a left-handed antiparticle. If we count particles and antiparticles separately, using $\psi_R \simeq \psi_L^c$, we thus

may consider all fields to be left-handed. If we use the labels r=red, g=green and b=blue for the quark colors, the list of particles in the first lepton - quark family reads

$$\nu_{eL}, e_L^-, e_L^+, u_{Lr}, u_{Lg}, u_{Lb}, u_{Lr}^c, u_{Lg}^c, u_{Lb}^c, d_{Lr}, d_{Lg}, d_{Lb}, d_{Lr}^c, d_{Lg}^c, d_{Lb}^c$$

and there are two additional such families. These are 45 degrees of freedom described by the free matter Lagrangian

$$\mathcal{L}_{\text{matter},0} = \sum_a \bar{\psi}_{La} i \gamma^\mu \partial_\mu \psi_{La} . \quad (2)$$

This Lagrangian has a global $U(45)$ symmetry. Nature has chosen the subgroup $G_{loc} \subset U(45)$ to be a *local* symmetry

$$\psi_L \rightarrow U(x) \psi_L, U \in G_{loc}.$$

This requires the existence of a set of gauge fields $V_{\mu i}$ which minimally couple to the fermions

$$\partial_\mu \psi_L \rightarrow D_\mu \psi_L = (\partial_\mu - i \sum_r g_r T_{ri} V_{\mu ri}) \psi_L$$

By T_{ri} we denote the generators of the local group (r labeling the different group factors) and g_r are arbitrary coupling constants. Thus, the matter field interactions are determined to be

$$\mathcal{L}_{\text{matter,int}} = \sum_r g_r j_{ri}^\mu V_{\mu ri} \quad (3)$$

where

$$j_{ri}^\mu = \bar{\psi}_L \gamma^\mu T_{ri} \psi_L$$

are the fermion currents. We observe that fermions talk to each other only via spin 1 gauge bosons.

In the unbroken phase, mass terms for fermions are forbidden, since $\bar{\psi} \psi = \bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L$ is not $SU(2)_L \otimes U(1)_Y$ invariant.

The transformation properties of the fermions under G_{loc} are the simplest possible ones. Only the fundamental (the nontrivial representation of lowest dimension) and the trivial (singlet) representations show up. The weak quantum numbers and multiplets are summarized in the following Tables.

	Doublets				Singlets			
	$(\nu_\ell)_L$	$(\ell^-)_L$	$(u, c, t)_L$	$(\tilde{d}, \tilde{s}, \tilde{b})_L$	$(\nu_\ell)_R$	$(\ell^-)_R$	$(u, c, t)_R$	$(d, s, b)_R$
Q	0	-1	2/3	-1/3	0	-1	2/3	-1/3
T_3	1/2	-1/2	1/2	-1/2	0	0	0	0
Y	-1	-1	1/3	1/3	0	-2	4/3	-2/3

group	multiplet	representation	
$SU(3)_c$:	leptons	1	color singlets
	quarks	3	color triplets
	antiquarks	3^*	anticolor triplets
$SU(2)_L$:	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} u \\ \tilde{d} \end{pmatrix}_L$		
	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} c \\ \tilde{s} \end{pmatrix}_L$	$2 = 2^*$	weak isospin doublets
	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, \begin{pmatrix} t \\ \tilde{b} \end{pmatrix}_L$		
$U(1)_Y$:	$e_R^-, u_R, d_R,$ $\mu_R^-, c_R, s_R,$ τ_R^-, t_R, b_R	1	weak isospin singlets
	$Y = 2(Q - T_3)$		abelian weak hypercharge

By \tilde{q} we denoted the Cabibbo-Kobayashi-Maskawa (CKM) rotated quarks $\tilde{q}_d = U_{KM}q_d$ where $q_d = (d, s, b)$ is a horizontal quark vector (see below) [3].

For the massless spin 1/2 gauge fields and the gauge couplings we will use the following notation,

group	fields		coupling
$SU(3)_c$:	$G_{\mu i}$	$i = 1, \dots, 8$	g_s
$SU(2)_L$:	$W_{\mu a}$	$a = 1, 2, 3$	g
$U(1)_Y$:	B_μ		g'

The pure gauge Yang-Mills Lagrangian is given by a sum of independent pieces from each group factor,

$$\mathcal{L}_{YM} = -\frac{1}{4}G_{\mu\nu i}G^{\mu\nu i} - \frac{1}{4}W_{\mu\nu a}W^{\mu\nu a} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \quad (4)$$

where

$$\begin{aligned} G_{\mu\nu i} &= \partial_\mu G_{\nu i} - \partial_\nu G_{\mu i} + ig_s f_{ijk} G_{\mu j} G_{\nu k} \\ W_{\mu\nu a} &= \partial_\mu W_{\nu a} - \partial_\nu W_{\mu a} + ig \epsilon_{abc} W_{\mu b} W_{\nu c} \\ B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \end{aligned}$$

are the non-abelian and abelian field strength tensors. The crucial consequence of non-abelian gauge invariance is that it requires the non-abelian fields to be self-interacting (they carry themselves non-abelian charge) and that the self-couplings are uniquely fixed once the couplings to the matter fields are determined. Thus one coupling constant determines three topologically different vertices (Fig. 1).

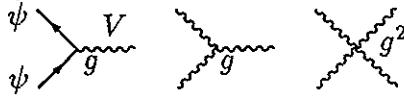


Figure 1: Interrelated interaction vertices of a gauge theory

In the following we will concentrate our considerations to the electroweak subgroup $SU(2)_L \otimes U(1)_Y$ which is broken in the real world to the electromagnetic abelian gauge group $U(1)_{em}$ known from QED.

The eigenstates of charge Q can be found easily. The W 's have $Y = 0$ and hence $Q = T_3$, where T_3 denotes the 3rd component of weak isospin. The charge raising and lowering generators are obtained in the standard way. The shift operators

$$T_{\pm} = T_1 \mp iT_2 ; \quad T_+ = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} , \quad T_- = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

satisfy the commutation relation

$$[T_3, T_{\pm}] = \pm T_{\pm}$$

and correspondingly the fields

$$W_{\mu}^{\pm} = \frac{1}{\sqrt{2}}(W_{\mu 1} \mp iW_{\mu 2}) \quad (5)$$

carry charge ± 1 . The fields $W_{\mu 3}$ and B_{μ} both have $Y = 0$ and $T_3 = 0$ and hence $Q = 0$ and thus can mix. The field which couples to the $Q = 0$ particle ν_{eL} we denote by Z_{μ} and the field orthogonal to it is the photon

$$\begin{aligned} Z_{\mu} &= \cos \Theta_W W_{\mu 3} - \sin \Theta_W B_{\mu} \\ A_{\mu} &= \cos \Theta_W B_{\mu} + \sin \Theta_W W_{\mu 3} . \end{aligned} \quad (6)$$

The weak mixing angle Θ_W is determined by $\tan \Theta_W = g'/g$.¹ In terms of the physical fields we may summarize the structure of the electroweak theory as follows:

¹Historically, the electroweak standard model gauge group has been introduced by Glashow in 1961. At that time only the charge changing weak currents J_{μ}^{+} and $J_{\mu}^{-} = (J_{\mu}^{+})^{\dagger}$ were known. If one argues them to be the Noether currents which derive from a symmetry, $SU(2)$ being the obvious candidate, the algebra of generators must be required to close

$$[T_+, T_-] = -2T_3 .$$

This implies that there must exist a neutral current associated with the 3rd generator T_3 . Since the 3rd current cannot be identified with the electromagnetic current, $W_{\mu 3}$ cannot be identified with the photon and an extra abelian group factor was necessary in order to unify weak and electromagnetic interactions. In this way mixing and the weak mixing parameter $\sin^2 \Theta_W$ was introduced.

The charged current (CC) has the form

$$J_\mu^+ = J_{\mu 1} - i J_{\mu 2} = \bar{\nu}_e \gamma_\mu (1 - \gamma_5) \ell + \bar{q}_u \gamma_\mu (1 - \gamma_5) U_{KM} q_d \quad (7)$$

and exhibits quark flavor changing, through mixing by the unitary Cabibbo- Kobayashi- Maskawa matrix U_{KM} . The neutral current (NC) is strictly flavor conserving [4]

$$J_\mu^Z = J_{\mu 3} - 2 \sin^2 \Theta_W j_\mu^{em} = \sum_f \bar{\psi}_f \gamma_\mu (v_f - a_f \gamma_5) \psi_f \quad (8)$$

with

$$j_\mu^{em} = \sum_f Q_f \bar{\psi}_f \gamma_\mu \psi_f \quad (9)$$

the electromagnetic current. The sums extend over the individual fermion flavors f (and color). In our convention the vector and axial-vector neutral current coefficients are given by

$$v_f = T_{3f} - 2 Q_f \sin^2 \Theta_W, \quad a_f = T_{3f} \quad (10)$$

where T_{3f} is the weak isospin ($\pm \frac{1}{2}$) of the fermion f. The matter field Lagrangian thus takes the form

$$\mathcal{L}_{matter} = \sum_f \bar{\psi}_f i \gamma^\mu \partial_\mu \psi_f + \frac{g}{2\sqrt{2}} (J_\mu^+ W^{\mu-} + h.c.) + \frac{g}{2 \cos \theta_W} J_\mu^Z Z^\mu + e j_\mu^{em} A^\mu \quad (11)$$

where $e = g \sin \Theta_W$ is the charge of the positron (unification condition). The discovery of the W^\pm and Z bosons at the $p\bar{p}$ collider at CERN [5] directly confirmed these weak gauge boson couplings. On the other hand for a direct confirmation of the weak gauge boson self-interactions in the Yang-Mills part of the Lagrangian

$$\mathcal{L}_{YM} = -\frac{1}{4} (\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \frac{1}{4} (\partial_\mu W_{\nu i} - \partial_\nu W_{\mu i} + i g \epsilon_{ikl} W_{\mu k} W_{\nu l})^2 \quad (12)$$

we have to wait for W -pair production at LEP2. Phenomenologically we know that the $SU(2)_L \otimes U(1)_Y$ symmetry is broken by the mass terms

$$\mathcal{L}_{mass} = - \sum_f m_f \bar{\psi}_f \psi_f + \frac{1}{2} M_Z^2 Z_\mu Z^\mu + \frac{1}{2} M_W^2 W_\mu^+ W^{-\mu} \quad (13)$$

of the physical particles. Since the mass terms are not $SU(2)_L \otimes U(1)_Y$ invariant this massive vector boson theory is not renormalizable.

2. The Higgs Mechanism

The minimal renormalizable extension is obtained if we generate the masses by the *Higgs mechanism* (Higgs 1964 [6], Weinberg 1967 [1]). The basic idea comes from

the Landau-Ginsburg theory of superconductivity (see e.g. Landau-Lifschitz, Theoretical Physics, Vol. IX). A massless particle (the photon) moving in a Bose condensate ground state (sea of Cooper-pairs) behaves like a massive particle (Meissner-effect). The Meissner effect is illustrated in the following Figure 2 showing the magnetic field of a magnetic monopole in the normal and in the superconducting phase.

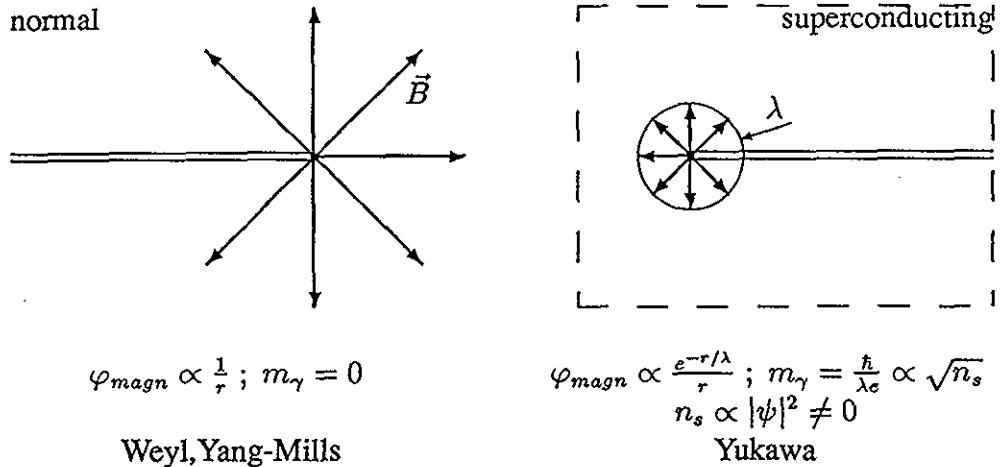


Figure 2: The Meissner effect in superconductivity

One can apply the same principle and couple the “to be massive” fields invariantly to a scalar field which develops a non-vanishing vacuum expectation value. Since we must break the $SU(2)_L$, we need a scalar field which transforms non-trivially under this group. The simplest choice is to take a complex doublet with weak hypercharge $Y = 1$

$$\Phi_b = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} = \frac{1}{\sqrt{2}}(H_s + i\tau_i\phi_i) \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \frac{\rho_H}{\sqrt{2}}e^{i\frac{\tau_3}{2}\theta_i} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (14)$$

and its Y -charge conjugate $\Phi_t = i\tau_2\Phi_b^*$

$$\Phi_t = \begin{pmatrix} \phi_0^* \\ -\phi^- \end{pmatrix} = \frac{1}{\sqrt{2}}(H_s + i\tau_i\phi_i) \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{\rho_H}{\sqrt{2}}e^{i\frac{\tau_3}{2}\theta_i} \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad (15)$$

the charge being determined by $Q = T_3 + Y/2$. In order to write down the gauge invariant Lagrangian for the scalars we need the covariant derivative, which is given by

$$D_\mu \Phi_b = (\partial_\mu - i\frac{g'}{2}B_\mu - i\frac{g}{2}\tau_a W_{\mu a})\Phi_b \quad (16)$$

and the Higgs Lagrangian takes the form (requiring renormalizability)

$$\mathcal{L}_{Higgs} = (D_\mu \Phi_b)^+ (D^\mu \Phi_b) - \lambda (\Phi_b^+ \Phi_b)^2 + \mu^2 (\Phi_b^+ \Phi_b). \quad (17)$$

Since the fermion doublets and the Higgs doublets have identical $SU(2)$ transformation properties, and taking into account the hypercharge assignments, we can write down the following invariant Yukawa type couplings

$$\mathcal{L}_{Yukawa} = - \left(G_{t\ell} \bar{L}_\ell \Phi_t \nu_{\ell R} + h.c. \right) - \left(G_{b\ell} \bar{L}_\ell \Phi_b \ell_R + h.c. \right) - \left(G_{tq} \bar{L}_q \Phi_t u_R + h.c. \right) - \left(G_{bq} \bar{L}_q \Phi_b d_R + h.c. \right) \quad (18)$$

where L_f denote the lepton and quark doublets and $G_{f\ell}$ Yukawa couplings. We choose $\mu^2 > 0$, such that the Higgs potential has a non-trivial minimum at $\langle H_s \rangle = v > 0$ which represents the actual ground state (vacuum) in the broken phase. Here, H_s is the neutral scalar component of the Higgs doublet

$$H_s = \frac{\phi_0 + \phi_0^*}{\sqrt{2}}$$

and $H = H_s - v$ is the physical Higgs field with vanishing vacuum expectation value $\langle H \rangle = 0$.

Exploiting the invariance of all terms in the Lagrangian we notice that we can gauge away the fields θ_i in the polar representation given in Eqs. (14,15), since the exponential is a $SU(2)$ -matrix. This means that three (θ_i) of the four scalar fields (ρ_H, θ_i) are in fact unphysical. They are called Higgs ghosts or “would be Goldstone bosons”. The gauge for which the ghosts are absent is called *unitary* or *physical* gauge. While \mathcal{L}_{matter} and \mathcal{L}_{YM} remain unaffected by a gauge transformation, \mathcal{L}_{Higgs} and \mathcal{L}_{Yukawa} take a special simple form, because

$$\Phi_b = \frac{H + v}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

in this gauge (identifying $\rho_H = H + v$). One gets

$$\begin{aligned} \mathcal{L}_{Higgs} &= \frac{1}{2}(\partial_\mu H \partial^\mu H) + \frac{(H + v)^2}{2v^2} (M_Z^2 Z_\mu Z^\mu + 2M_W^2 W_\mu^+ W^{-\mu}) \\ &\quad - \frac{\lambda}{4} H^4 - \lambda v H^3 - \frac{1}{2} m_H^2 H^2 \\ \mathcal{L}_{Yukawa} &= - \sum_f m_f \bar{\psi}_f \psi_f (1 + \frac{H}{v}) \end{aligned} \quad (19)$$

and thus, $\mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa} = \mathcal{L}_{mass} + \mathcal{L}_H$ with

$$\begin{aligned} \mathcal{L}_H &= \frac{1}{2}(\partial H)^2 - \frac{1}{2} m_H^2 H^2 \\ &\quad - \sum_f \frac{m_f}{v} \bar{\psi}_f \psi_f H + \frac{M_Z^2}{v} Z_\mu Z^\mu H + \frac{2M_W^2}{v} W_\mu^+ W^{-\mu} H + \dots \end{aligned} \quad (20)$$

as an extra piece, which renders the theory renormalizable.

The Higgs sector is completely unverified so far and its confirmation is a big challenge for experimental particle physics. The proof of renormalizability by G. 't Hooft [7]

rejuvenated particle physics about 20 years ago and preceded the first phenomenological success of the SM which was the discovery of the neutral currents [8] in 1973. A basic consequence of the Higgs mechanism is the validity of the following mass-coupling relations. The vector boson masses are given by

$$M_W = \frac{gv}{2}, \quad M_Z = \frac{gv}{2 \cos \Theta_W} . \quad (21)$$

The fermion masses and the Higgs mass are given by similar relations

$$m_f = \frac{G_f}{\sqrt{2}} v, \quad m_H = \sqrt{2\lambda} v . \quad (22)$$

in terms of the Yukawa couplings G_f and of the Higgs coupling λ . In the standard model the μ -decay constant G_μ is given by

$$G_\mu = \frac{g^2}{4\sqrt{2}M_W^2} = \frac{1}{\sqrt{2}v^2} = 1.166389(22) \times 10^{-5} \text{ (GeV)}^{-2} \quad (23)$$

and thus the Higgs vacuum expectation value

$$v = (\sqrt{2}G_\mu)^{-1/2} = 246.2186(16) \text{ GeV}$$

is a very precisely known quantity, frequently called the Fermi scale, which figures as a conversion factor between couplings and masses. One important consequence is that the existence of heavy particles requires strong couplings and for too heavy particles this leads to a breakdown of perturbation theory. With other words, particles with masses large as compared to the Fermi scale are unnatural in the minimal SM. The non-decoupling of heavy particles is a new feature characteristic of a spontaneously broken gauge theory. In contrast, in QED and QCD heavy particles decouple as required by the Appelquist-Carazzone theorem [9].

If we take for granted the SM, we can say that the existence of the Higgs condensate has been established. Like in superconductivity the Higgs could in fact be composite. It is certainly a very interesting question, whether there is an underlying “BCS-theory” for the standard model. In any case, phenomenologically one expects the SM to work as a low energy effective theory at scales below 1 TeV.

On a formal level the role played by the Higgs mechanism is the following: It

- breaks $SU(2)_L \otimes U(1)_Y$ to $U(1)_{em}$,
- generates the masses of the weak gauge bosons W^\pm , Z and the fermions,
- provides a “physical cut-off” to the massive vector boson gauge theory.

The prize we have to pay is that

- a neutral physical particle H must exist.

The mass of the Higgs is a free unknown parameter. At present the limit for m_H from LEP experiments is $m_H > 49$ GeV. At LEP2 the Higgs search can be extended to about $m_H \simeq M_Z$. If the Higgs should be heavier, and this is likely the case, a discovery is possible only at future colliders like SSC or LHC.

3. Yukawa couplings

The most general form for $SU(2)_L \otimes U(1)_Y$ invariant couplings between fermions and scalars follows from the following transformation properties of the fields

$$\begin{aligned}\Psi_{Lf} &\doteq L_f \rightarrow U(x)L_f \text{ fermion doublet} \\ \Phi_{b,t} &\rightarrow U(x)\Phi_{b,t} \text{ Higgs doublet} \\ f_R &\rightarrow f_R \text{ fermion singlet.}\end{aligned}$$

Since we insist in renormalizability, the most general invariant Higgs fermion interaction is a complex linear combination of terms are of the form

$$L_f \Phi_b f_R = (\bar{u}_L^i \phi^+ + \bar{d}_L^i \phi_0) d_R^j, \quad L_f \Phi_t f_R = (\bar{u}_L^i \phi_0^* - \bar{d}_L^i \phi^-) u_R^j$$

and their hermitian conjugates. Here, $i, j = 1, 2, 3$ are family indices and the quantum numbers of the right-handed singlets are fixed by weak hypercharge neutrality. Since each family is made up of fields with identical $SU(2)_L \otimes U(1)_Y$ transformation laws invariant Yukawa couplings are possible for combinations of fields from different families ($i \neq j$).

With the fields having identical $SU(2)_L \otimes U(1)_Y$ quantum numbers one can form *horizontal vectors*. For the quarks there are the 4 horizontal vectors $q_{uL}, q_{dL}, q_{uR}, q_{dR}$ where $q_u = (u, c, t)$ and $q_d = (d, s, b)$.

In order to transform the fermion mass matrix (obtained by replacing $\phi_0^* = \phi_0 = v/\sqrt{2}$, $\phi^+ = \phi^- = 0$) to diagonal form we must perform independent global unitary transformations of the 4 horizontal vectors. Whereas,

- unitary transformations of $(q_u, q_d)_L$ as a doublet, q_{uR} and q_{dR} do *not* change the matter field Lagrangian,
- an independent transformation of q_{dL} leads to “mismatch”

$$\tilde{q}_{dL} = U_{KM} q_{dL}$$

of the quark fields in the charged current.

This leads us to the form of the charged current

$$J_\mu^{CC} = (\bar{u}, \bar{c}, \bar{t}) \gamma_\mu (1 - \gamma_5) U_{KM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad (24)$$

given in Eq. (7) with the unitary 3×3 matrix

$$U_{KM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (25)$$

which may be parametrized in terms of 3 rotation angles and a phase.

This family mixing occurs if 4 independent unitary transformations are required to diagonalize the mass matrix, and this is the case if particles of the same charge all have different masses. This happens to be so for the quarks. If we believe that all neutrinos are massless no mixing in the leptonic current is possible. Indeed all searches for lepton number violation have yielded no signal so far.

Due to unitarity, there is no mixing effect in the neutral current, since

$$\bar{q}_{dL} \tilde{q}_{dL} \equiv \bar{q}_{dL} q_{dL} .$$

This is called the GIM-mechanism explaining the absence of flavor-changing neutral currents (FCNC). In fact, in order to explain the absence of FCNC's, Glashow, Iliopoulos and Maiani had to propose, in 1970, the existence of a fourth quark, the charm quark c as a doublet partner of the s quark. At that time only three quarks were known [4]. The discovery of the J/ψ in 1974 [10] revealed the completeness of the 2nd family with the charm quark c . The first 3rd family member showed up in 1975 with the discovery of the τ [11]. With the observation of the Υ [12] the existence of the b quark could be established. We are still waiting for the direct observation of bottom's doublet partner, the top quark. The direct lower limit for m_t from CDF is [13]

$$m_t > 89 \text{ GeV} . \quad (26)$$

We summarize the following important consequences:

- i) all masses of quarks and leptons are independent
- ii) the coupling of the Higgs boson to the fermions is universally proportional to each fermion mass, for bosons proportional to the square of each boson mass
- iii) there is quark flavor violation in charge exchange weak interactions
- iv) the phases in U_{KM} are CP-violating and thus potentially capable of explaining the observed CP-violation in K-decays. At least 3 families are needed to "explain" CP-violation in this way.
- v) flavor is conserved in neutral currents (GIM mechanism). This is strikingly supported by experiment, at least for the light flavors.

The leptonic CC has some very special properties, which derive from the apparent absence of right-handed neutrinos. If $\nu_{\ell R}$ does not exist $m_{\nu_\ell} = 0$ and lepton number L_ℓ is conserved individually for $\ell = e, \mu, \tau$. Among the neutrino-puzzles we mention: Have neutrinos a mass and if so why are they so small? Do neutrinos have unusual magnetic moments? Are there neutrinos which are their own antiparticles (Majorana neutrinos)?

The properties of the weak currents have been established in a long history which started with Fermi in 1934. Here, we only mention some more recent of the fundamental experimental tests [14]:

- V-A structure of the CC:

μ -decay provides the most sensitive clean direct tests for right-handed currents (e.g. $SU(2)_R \otimes SU(2)_L \otimes U(1)_{B-L}$ extension of the SM). The best limit for the transition amplitude is

$$\frac{A_{V+A}}{A_{V-A}} < 0.029 \quad (90\% CL)$$

- absence of flavor-changing NC at tree level:

$$\begin{aligned} \Gamma(K_L \rightarrow \mu^+ \mu^-)/\Gamma(K_L \rightarrow all) &= (9.5^{+2.4}_{-1.5}) \times 10^{-9} \\ \Gamma(D^0 \rightarrow \mu^+ \mu^-)/\Gamma(D^0 \rightarrow all) &< 1.1 \times 10^{-5} \\ \Gamma(B^0 \rightarrow e^+ e^-)/\Gamma(B^0 \rightarrow all) &< 3 \times 10^{-5} \end{aligned}$$

Flavor-changing NC processes are allowed in higher orders (rare processes).

- special properties of the lepton current:

Present limits on the neutrino masses are:

$$\begin{aligned} m_{\nu_e} &< 9.4 \text{ eV} \quad (\text{from } {}^3H \rightarrow {}^3H_e e^- \bar{\nu}_e) \\ m_{\nu_\mu} &< 250 \text{ keV} \quad (\text{from } \pi \rightarrow \mu \nu_\mu) \\ m_{\nu_\tau} &< 35 \text{ MeV} \quad (\text{from } \tau^- \rightarrow 3\pi \nu_\tau) \end{aligned}$$

L_ℓ conservation is established by the branching fractions:

$$\begin{aligned} R &< 4.9 \times 10^{-11} \quad (\text{from } \mu \rightarrow e\gamma) \\ R &< 1.0 \times 10^{-13} \quad (\text{from } \mu \rightarrow 3e) \end{aligned}$$

Neutrino mixing searches (ν -oscillations $\nu_\ell \leftrightarrow \nu_{\ell'}$) also have been negative so far.

Open problems are the measurements of direct CP-violation (ε') in the K-meson system and CP-violation in the B-meson system [15]. We still do not know whether CP-violation is a phenomenon which has its “origin” in the CKM-phase solely, or if it’s due to a new super-weak interaction outside the SM. Still unsolved is the solar neutrino problem [16]. The observed solar ν_e flux is too low. This could signal flavor mixing (causing conversion of ν_e into $\nu_{\mu,\tau}$ not visible to present detectors) of the neutrinos which is possible only if the neutrinos have different masses. Another possibility would be that the ν_e is unstable. In summary: no deviations from the SM could be established until now.

4. Fixing the parameters of the SM

Besides the fermion masses, the CKM-mixing parameters and the Higgs mass the SM has 3 basic parameters g , g' and v . They are conventionally replaced by parameters which can be measured directly in a physical process. A specific choice of experimental data points as input parameters defines a *renormalization scheme*. Like in QED a natural choice would be the fine structure constant and the physical particle masses (*on-shell scheme*):

$$\alpha, M_W, M_Z, m_f, m_H.$$

Since M_W will not be known accurately at LEP1 we must use the precisely known μ -decay constant G_μ in place of M_W . Thus, we will use the parameter set

$$\alpha, G_\mu, M_Z, m_f, m_H$$

for accurate predictions of measurable quantities. In the pre-LEP era when M_Z was not known or known with rather limited accuracy from the $p\bar{p}$ -collider, instead of M_Z the weak mixing parameter $\sin^2 \Theta_W$ had to be used. For a study of low energy processes this is still the adequate choice

$$\alpha, G_\mu, \sin_{\nu_\mu N(e)}, m_f, m_H$$

The universal fine structure constant $\alpha = e^2/4\pi = 1/137.0359895(61)$ (determined in low momentum transfer Coulomb scattering), the Fermi constant G_μ (from the muon decay rate) and the weak mixing parameter $\sin^2 \Theta_{\nu_\mu N(e)}$ (from low momentum transfer neutrino scattering).

We first discuss the relation between the different parameter sets.

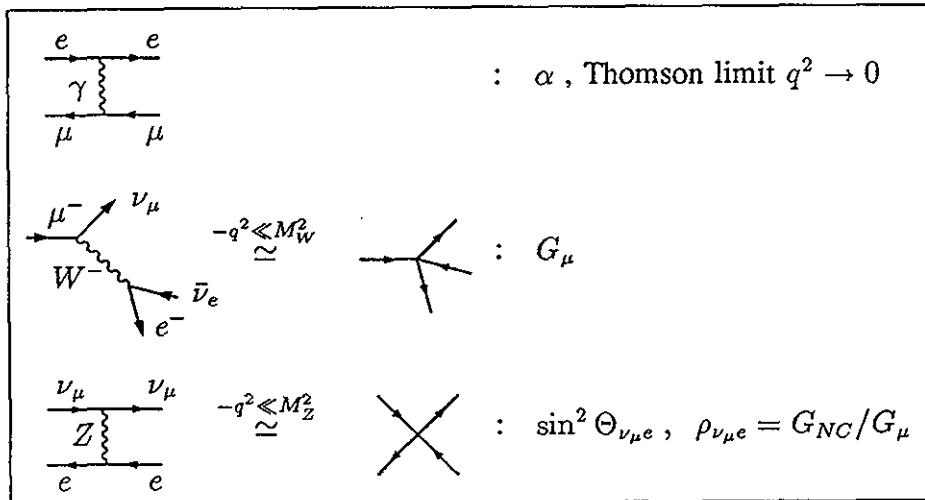


Figure 3: Parameters from low energy four-fermion processes

The low energy four-fermion processes are described by the effective Fermi-type Lagrangian

$$\mathcal{L}_{eff} = -\frac{1}{\sqrt{2}} (G_\mu J_\mu^+ J^{\mu-} + G_{NC} J_\mu^Z J^{\mu Z}) + e j_\mu^{em} A_\mu \quad (27)$$

which is the low energy effective form ($|q^2| \ll M_W^2, M_Z^2$) of

$$\mathcal{L}_{int} = \frac{g}{2\sqrt{2}} (J_\mu^+ W^{\mu-} + h.c.) + \frac{g}{2 \cos \Theta_W} J_\mu^Z Z^\mu + e j_\mu^{em} A_\mu. \quad (28)$$

The electroweak unification condition and the parameter relations deriving from the processes shown in Fig. 3 read

$$\begin{aligned}
i) \quad \sqrt{4\pi\alpha} &= e &= g \sin \Theta_W \\
ii) \quad \sqrt{2}G_\mu &= \frac{g^2}{4M_W^2} &= \frac{1}{v^2} \\
\sqrt{2}G_{NC} &= \frac{g^2}{4M_Z^2 \cos^2 \Theta_W} &= \rho_0 \frac{1}{v^2} \\
iii) \quad \rho_0 &= \frac{G_{NC}}{G_\mu} &= \frac{M_W^2}{M_Z^2 \cos^2 \Theta_W} \equiv \rho_{tree}
\end{aligned} \tag{29}$$

For the moment we have relaxed from the assumption $\rho_0 = 1$ valid in the minimal SM.

From the parameter relations we now obtain the tree level relation

$$\begin{aligned}
\pi\alpha &= \frac{e^2}{4} \stackrel{i)}{=} \frac{g^2 \sin^2 \Theta_W}{4} \\
&\stackrel{ii)}{=} \sqrt{2}G_\mu M_W^2 \sin^2 \Theta_W \\
&\stackrel{iii)}{=} \sqrt{2}G_\mu M_W^2 \left(1 - \frac{M_W^2}{\rho_0 M_Z^2}\right).
\end{aligned}$$

If radiative corrections are included this relation is modified into [17]

$$\sqrt{2}G_\mu M_W^2 \left(1 - \frac{M_W^2}{\rho_0 M_Z^2}\right) = \pi \frac{\alpha}{1 - \Delta r}. \tag{30}$$

which is the defining equation for Δr (with ρ_0 kept fixed at its tree level value!). In the following we take $\rho_0 = 1$, as appropriate for doublet Higgses, such that by the last relation of Eq. (29)

$$\sin^2 \Theta_W = 1 - \frac{M_W^2}{M_Z^2}. \tag{31}$$

The definition of Δr by Eq. (30) is conceptually very simple, all quantities involved have been measured and can be found in the particle data booklet.

Later, we will often use α and the physical particle masses as a convenient set of independent parameters. The Fermi constant is then a calculable quantity (μ -decay amplitude). Originally, the μ life-time τ_μ has been calculated within the framework of the effective four-point Fermi interaction. If we include the QED corrections (Fig. 4) we obtain the result

$$\frac{1}{\tau_\mu} = \frac{G_\mu^2 m_\mu^5}{192\pi^3} \left(1 - \frac{8m_e^2}{m_\mu^2}\right) \left[1 + \frac{\alpha}{2\pi} \left(1 + \frac{2\alpha}{3\pi} \log \frac{m_\mu}{m_e}\right) \left(\frac{25}{4} - \pi^2\right)\right]. \tag{32}$$

This formula is used as the defining equation for G_μ in terms of the experimental μ life-time. Present data [14] yield the value given above.

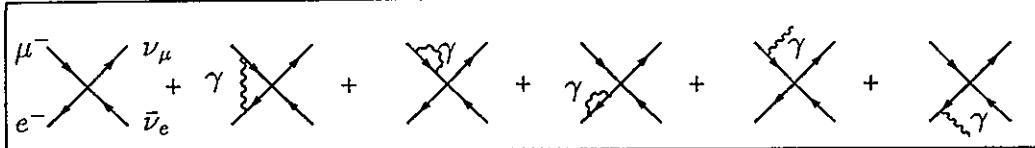


Figure 4: μ decay with QED corrections in the effective Fermi model

The Z -mass has been determined rather accurately now at LEP1 [18]

$$M_Z = 91.176 \pm 0.021 \text{ GeV} \quad (33)$$

while the W mass we know from the collider experiments *UA2* [19] and *CDF* [20]. Using their determination of the mass ratio M_W/M_Z , for which common systematic errors drop out, together with the Z mass from LEP1 we obtain

$$M_W = 80.19 \pm 0.32 \text{ GeV} \quad (34)$$

The various measurements of $\sin^2 \Theta_W$ are collected in Table 1.

Table 1. $\sin^2 \Theta_W$ measurements in NC processes [14,19,20,18]

Measurement	$\sin^2 \Theta_W$		
$\frac{M_W}{M_Z} (p\bar{p})$	0.2265	\pm	0.0062 (ave.)
UA2	0.2202	\pm	0.0084 \pm 0.0045
CDF	0.229	\pm	0.016 \pm 0.002
$\left(\frac{\sigma_{N_G}}{\sigma_{C_C}}\right)_{\nu_\mu N}$	0.232	\pm	0.006 (ave.)
CDHS	0.2275	\pm	0.005 \pm 0.005
CHARM	0.236	\pm	0.005 \pm 0.005
P. V. in Cs	0.215	\pm	0.007 \pm [0.017] th
$e^- D$ (SLAC)	0.217	\pm	0.015 \pm [0.013] th
$R_{\nu_\mu e} = \frac{\sigma_{\nu_\mu e}}{\sigma_{\nu_\mu e}}$ CHARM II	0.240	\pm	0.009 \pm 0.008
assume $m_t = 140 \pm 40 \rightarrow$	0.230	\pm	0.016
Γ_ℓ, A_{FB}^ℓ LEP	0.2302	\pm	0.0025
assume $m_t = 140 \pm 40 \rightarrow$	0.220	\pm	0.006

Assuming $\rho_{tree} = 1$, as required by the minimal SM, recent global fits yield for the weak mixing angle and the top mass (68%*C.L.*)

$$\begin{aligned} \sin^2 \Theta_W &= 0.2273 \pm 0.0033, \quad m_t = 122_{-32}^{+41} \text{ GeV} \quad \text{Ref. [21]} \\ \sin^2 \Theta_W &= 0.2272 \pm 0.0040, \quad m_t = 139_{-39}^{+33} \pm 16 \text{ GeV} \quad \text{Ref. [22]} \\ \sin^2 \Theta_e &= 0.2325 \pm 0.0015, \quad m_t = 127 \pm 34 \pm 17 \text{ GeV} \quad \text{Ref. [18]} \end{aligned} \quad (35)$$

when $40 \text{ GeV} < m_H < 1 \text{ TeV}$.

A very important parameter in electroweak theory is the ρ -parameter, defined by the neutral to charged current ratio at low energy. The νN scattering data yield the most sensitive determination of the ρ -parameter.

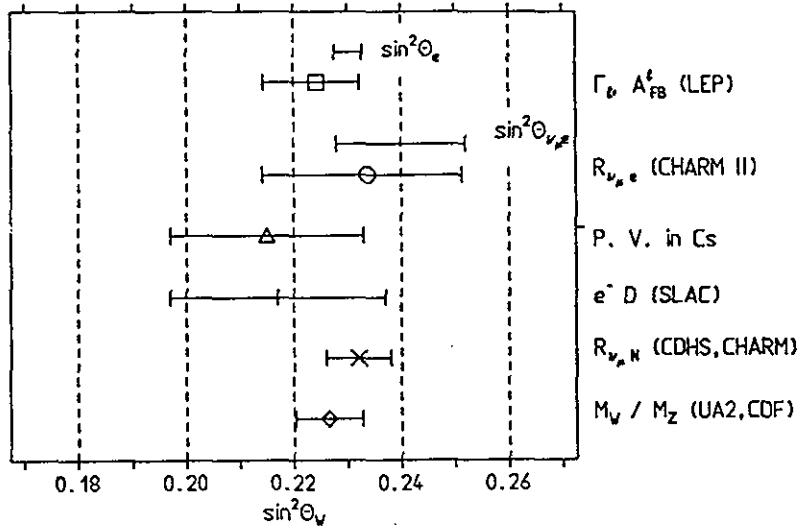


Figure 5: Comparison of various $\sin^2 \Theta$ measurements.

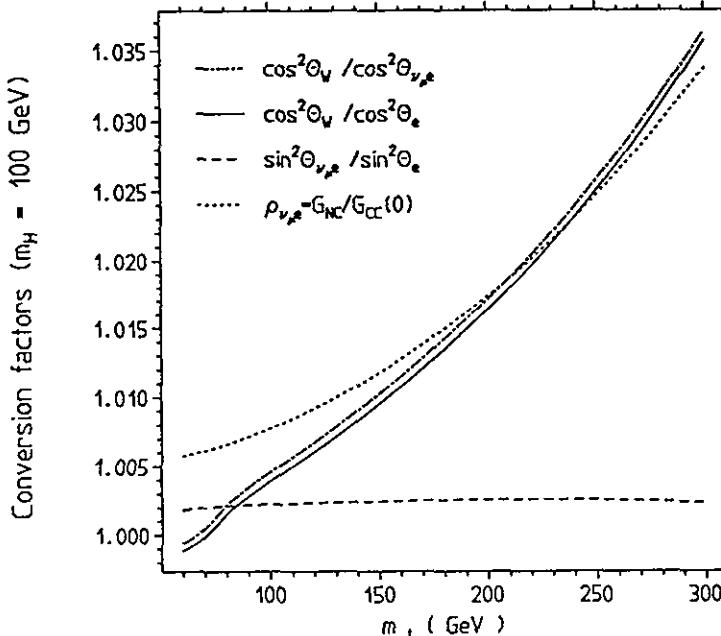


Figure 6: m_t -dependence of various $\sin^2 \Theta$ conversions.

Taking ρ and $\sin^2 \Theta_W$ as independent parameters, a recent global fit to all NC-data [22] yields (the values indicated with an asterisk I have obtained by scaling with the theoretical predictions)

m_t (GeV)	100	140	180	200	
$\sin^2 \Theta_W$	0.2305	0.2260*	0.2207*	0.2215	± 0.0010
$\sin^2 \Theta_W$ (SM)	0.23027	0.22580	0.22048	0.21741	
ρ_0	1.003	0.99996*	0.996*	0.994	± 0.003
ρ (SM)	1.00776	1.01082	1.01492	1.01737	

where the theoretical values (SM) are given for $m_H = 100$ GeV. $\rho_0 = \frac{\rho_{exp}}{\rho_{SM}}$ corresponds to ρ_{tree} if we ignore possible radiative corrections from non-standard physics. Thus ρ_0 is remarkably close to the minimal standard model value $\rho_{tree} = 1$.

These experimental results are extremely important constraints for possible deviations from the SM. For example, the measured value for $\sin^2 \Theta_W$ is clearly in contradiction to the simplest grand unified model, namely, minimal SU(5), which predicts $\sin^2 \Theta_W \simeq 0.211 - 0.218$. Independently, this theory has been ruled out by proton decay experiments. The bounds on the ρ -parameter allow to have additional scalar doublets or singlets which do not affect the minimal SM value $\rho_{tree} = 1$. However, possible Higgs triplet contaminations are limited because they implies $\rho_{tree} < 1$ and a pure triplet would give $\rho_{tree} = 1/2$.

Since the discovery of the weak neutral current, almost two decades ago, the SM has been astonishingly successful and one has to wonder why. In the following we will discuss some important aspect of the SM in more detail with the hope to shed some more light on its unique structure.

Appendix A. Axial Vector Anomaly and Anomaly Cancellation.

Axial vector currents lead to the axial anomaly [23], which is associated with the triangle fermion loop diagram depicted in Figure 7. More generally, anomalies show up in diagrams which exhibit an odd number of axial vector current vertices and which are UV divergent (and hence need regularization at intermediate steps). One can show that all anomalies are related to the triangle anomaly, which we briefly discuss now.

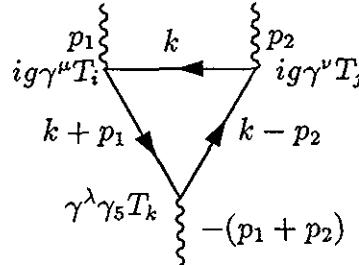


Figure 7: Triangle diagram exhibiting the axial anomaly

The amplitude for the triangle graph is given by the integral

$$\tilde{T}_{ijk}^{\mu\nu\lambda}(p_1, p_2) = -iTr(T_j T_i T_k) \cdot \frac{g^2}{(2\pi)^4} \int d^4 k Tr \left(\frac{1}{k - p_2 + i\epsilon} \gamma^\nu \frac{1}{k + i\epsilon} \gamma^\mu \frac{1}{k + p_1 + i\epsilon} \gamma^\lambda \gamma_5 \right).$$

Adding the diagram we obtain by interchanging the two vector vertices we get an amplitude which is *bose symmetric*

$$T_{ijk}^{\mu\nu\lambda}(p_1, p_2) = \tilde{T}_{ijk}^{\mu\nu\lambda}(p_1, p_2) + \tilde{T}_{jik}^{\nu\mu\lambda}(p_2, p_1)$$

and for which we *impose* vector current conservation (condition on possible renormalization counter term)

$$p_{1\mu} T_{ijk}^{\mu\nu\lambda}(p_1, p_2) = p_{2\nu} T_{ijk}^{\mu\nu\lambda}(p_1, p_2) = 0 .$$

It then turns out that the divergence of the axial vector current is non-vanishing and uniquely determined by the mass independent anomaly

$$-(p_1 + p_2)_\lambda T_{ijk}^{\mu\nu\lambda}(p_1, p_2) = i \frac{g}{16\pi^2} D_{ijk} 4\varepsilon^{\mu\nu\rho\sigma} p_{1\rho} p_{2\sigma} \neq 0 \quad (36)$$

(Adler, Bell and Jackiw 1969). We have introduced the abbreviation $D_{ijk} \equiv \text{Tr}(\{T_i, T_j\} T_k)$ for the representation dependent coefficient of the anomaly. The result can be obtained as a matrix element of the anomalous divergence equation

$$\partial_\lambda j_{5k}^\lambda(x) = \frac{g^2}{16\pi^2} D_{ijk} \tilde{G}_i^{\mu\nu}(x) G_{j\mu\nu}(x) \quad (37)$$

where $G_{i\mu\nu}$ is the (abelian or non-abelian) field strength tensor and $\tilde{G}_i^{\mu\nu} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma} G_{i\rho\sigma}$ its dual tensor. This is a very surprising result because the canonical Ward-Takahashi identities reading

$$\begin{aligned} \partial_\mu (\bar{\psi}_1 \gamma^\mu \psi_2)(x) &= i(m_1 - m_2) (\bar{\psi}_1 \psi_2)(x) \\ \partial_\mu (\bar{\psi}_1 \gamma^\mu \gamma_5 \psi_2)(x) &= i(m_1 + m_2) (\bar{\psi}_1 \gamma_5 \psi_2)(x) \end{aligned}$$

do not exhibit such a term and for massless fields both currents are conserved. The anomaly given above can be shown to be unaltered by higher order effects. Eq. (37) is thus the exact (non-perturbative) form of the axial anomaly (Adler and Bardeen 1969, Gross and Jackiw 1972 and Korthals Altes and Perrottet 1972). The crucial point about the anomaly is the fact that its presence spoils renormalizability of a theory! Only anomaly free theories are viable theories. The appearance of anomalies in a gauge field theory is strongly related to the fermion representations. Which representations are anomaly free?

- Real representations ($R \sim R^*$) are anomaly free, since $D_{ijk} = 0$ for all real representations.
- The groups which have only real representations are: $SO(2\ell + 1)$ for ($\ell > 1$), $Sp(2\ell)$, G_2 , F_4 , E_7 , E_8 . In addition $D_{ijk} = 0$ also holds for $SO(2\ell)$ for ($\ell > 1$) with one exception: $SO(6) \simeq SU(4)$.
- Since for any representation R one has $D_{ijk}(R) = D_{ijk}(R_0) \cdot K(R)$ where R_0 denotes the fundamental representation and $K(R)$ is a representation dependent invariant, all representations are anomaly free if $D_{ijk}(R_0) = 0$. In particular, this is the case for $SU(2)$, for which ($R_0 \sim R_0^*$), and for E_6 .
- The groups $SU(n)$, ($n \geq 3$) have complex representations ($R \not\sim R^*$) and $D_{ijk}(R_0) \neq 0$. These groups are *not anomaly free*!

If we write

$$j_i^\mu = \bar{\psi}_L \gamma^\mu T_{Li} \psi_L + \bar{\psi}_R \gamma^\mu T_{Ri} \psi_R \quad (38)$$

at the γ_5 -vertex and use

$$\gamma_5 \frac{1 \pm \gamma_5}{2} = \pm \frac{1 \pm \gamma_5}{2} \quad (39)$$

we obtain

$$D_{ijk} \equiv Tr(\{T_{Li}, T_{Lj}\}T_{Lk}) - Tr(\{T_{Ri}, T_{Rj}\}T_{Rk}) \quad (40)$$

which tells us that left-handed and right-handed fields give independent contributions to the anomaly. Of particular interest for us is the color group $SU(3)_c$ and the quark representations. The quarks are in the fundamental representation 3, the antiquarks in 3^* . Under charge conjugation we have

$$\psi_L \xrightarrow{C} \psi_L^c = i\gamma^2 \psi_R^*.$$

Therefore it follows that ψ_L and ψ_R are in the same representation and hence $D_{ijk} \equiv 0$. Evidently, renormalizability of QCD requires parity conservation and thus the absence of axial current couplings.

- Finally, anomalies are obtained from abelian axial current couplings. Here we have to worry about the $U(1)_Y$. Per doublet $\Psi = (\psi_1, \psi_2)$, using $Q = T_3 + Y/2$, $Q_1 - Q_2 = 1$ and $Q_{Ri} = Q_{Li}$, we get

$$D = \sum_i (Y_{Li}^3 - Y_{Ri}^3) = -12Q_1 + 6 \quad (41)$$

which yields $D_{lepton} = 6$ and $D_{quark} = -6N_c(2Q_1^q - 1) = -6$.

As a consequence we find that the $U(1)_Y$ subgroup of the standard model is renormalizable if and only if there is the lepton-quark family structure! This lepton-quark duality is one of the most surprising properties of the SM. Nature seems to take very seriously the mathematical consistency of the theory. Although, a direct experimental “proof” for the existence of the top quark is still missing, there is strong indirect evidence for its existence.

Appendix B. How natural is the minimal SM?

We finally try to derive the SM by starting from some general assumptions [24]. Let us make the following assumptions:

- 1) local field theory
- 2) interactions follow from a local gauge principle
- 3) renormalizability
- 4) masses derive from the minimal Higgs system
- 5) ν_R is absent or if it exists it does not carry hypercharge.

We admit that the last assumption looks quite ad hoc, but nevertheless we make it. From the above assumptions the following picture develops:

- For the gauge interactions the simplest non-trivial possibility is that the fundamental massless matter fields group into doublets and triplets which are the fundamental representations of $SU(2)$ and $SU(3)$.
- Since fields are massless all fields can be chosen left-handed. Left-handed particles and left-handed antiparticles at this stage are uncorrelated.
- We must have *pairing* for particles that are going to be massive, since a mass term (we ignore the possibility to have Majorana fields here) has the form $\bar{\psi}\psi = \bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L$. Notice that for massive particles, only, we know which left-handed antiparticle belongs to which left-handed particle to form a Dirac field.
- For $SU(3)_c$ triplets we *must* have pairing in order to avoid axial anomalies. $SU(3)$ is the simplest group having complex representations. This allows to put particles in 3 and antiparticles in the inequivalent 3^* . As a consequence a rich color singlet structure (\equiv hadron spectrum) results. Furthermore, confinement requires $SU(3)_c$ to be unbroken !
- $SU(2)_L$ is anomaly free and hence there is no anomaly condition associated with this group. To generate mass we have to break $SU(2)_L$ by a Higgs mechanism. The simplest and natural possibility is to chose one Higgs field in the fundamental representation of $SU(2)_L$. There is no hypercharge for the moment. The Higgs field may be written in the form

$$\Phi_b = \tilde{\Phi} \chi_b ; \chi_b = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

in terms of a 2×2 matrix field

$$\tilde{\Phi} = \frac{1}{\sqrt{2}}(H_s + i\tau_i\phi_i) .$$

The covariant derivative being given by

$$D_\mu \Phi_b = (\partial_\mu - i\frac{g}{2}\tau_a W_{\mu a})\Phi_b ,$$

the Higgs system Eq. (17) exhibits an extra global $SU(2)_R$ -symmetry $\chi_b \rightarrow V^+ \chi_b$. One easily checks that the transformation

$$\tilde{\Phi} \rightarrow U(x)\tilde{\Phi}V^+$$

with $U(x) \in SU(2)_{L,local}$, $V \in SU(2)_{R,global}$ leaves the Higgs Lagrangian invariant. This implies that the fields (W^+, W_3, W^-) form an isospin triplet with $M_Z = M_{W^\pm}$.

Now consider the fermions (still no hypercharge). Since L_f and Φ_b are doublets R_f *must* be a singlet ! otherwise we would not be able to write down an invariant and renormalizable fermion-Higgs coupling. Therefore $SU(2)_L$ must be parity violating of V-A-type! The Yukawa term has the general form

$$\mathcal{L}_{Yukawa} = -\bar{L}_f \tilde{\Phi} \begin{pmatrix} g_1 g_2 \\ g_3 g_4 \end{pmatrix} R_f + h.c.$$

with 4 complex couplings g_i and R_f a “doublet” having to right-handed singlets as entries. Although we have not used hypercharge to restrict these couplings the existence of a global $SU(2)_R$ -symmetry of the Higgs system allows to transform the Yukawa couplings

$$\tilde{\Phi}(\cdot)R_f \rightarrow \tilde{\Phi}V^+(\cdot)WR_f$$

to standard form, $V^+(\cdot)W$ = real diagonal. Since $V \in SU(2)_R$ has 3 parameters and W is an arbitrary unitary matrix with 4 parameters we end up with one free parameter such that the system exhibits a global $U(1)$ invariance. This is not surprising since in the unitary gauge we always can end up only with \mathcal{L}_{Yukawa} in the simple standard form Eq. (19).

- The global $U(1)$ which is a consequence of the minimal Higgs mechanism may be *interpreted* as a global $U(1)_Y$. We are free to assign to Φ_b $Y = 1$, which means nothing else than that we measure Y in units of the Φ_b -hypercharge. Then

$$\Phi_t = \tilde{\Phi}\chi_t; \chi_t = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

has $Y = -1$, and we may write $\tilde{\Phi} = (\Phi_b, \Phi_t)$. Since we have the global $U(1)_Y$ for free, we may *assume* this symmetry to be *local*. The covariant derivative for $\tilde{\Phi}$ now reads

$$D_\mu \tilde{\Phi} = \partial_\mu \tilde{\Phi} + i \frac{g'}{2} B_\mu \tilde{\Phi} \tau_3 - i \frac{g}{2} \tau_a W_{\mu a} \tilde{\Phi}$$

and we find back the usual Higgs Lagrangian. The 3 real fields ϕ_a $a = 1, 2, 3$ can be gauged away and only 3 out of 4 gauge fields can acquire a mass. Hence there must exist one massless field, the photon! Evidently we obtain the relations $g' = g \tan \Theta_W$ and $\rho = M_W^2 / (M_Z^2 \cos^2 \Theta_W) = 1$! instead of $M_Z = M_{W^\pm}$ when $g' = 0$.

Now, what can we say about the hypercharge of the fermions?:

A left-handed doublet transforms like

$$L \rightarrow e^{i \frac{g'}{2} Y_L} L$$

where Y_L is arbitrary. By inspection of \mathcal{L}_{Yukawa} we find for the hypercharges of the singlets: ψ_{1R} must have $Y_{1R} = Y_L + 1$ and ψ_{2R} must have $Y_{2R} = Y_L - 1$. One consequence is that $U(1)_Y$ *must* violate parity. The astonishing thing is that the fermion current which couples to the photon preserves parity. By inspection we find

$$\begin{aligned} D_\mu L_f &= (\partial_\mu - i \frac{g'}{2} Y_L B - \mu - i \frac{g}{2} \tau_3 W_{\mu 3} - \dots) L_f \\ D_\mu R_f &= (\partial_\mu - i \frac{g'}{2} Y_L B - \mu - i \frac{g}{2} \tau_3 B_\mu - \dots) R_f \end{aligned}$$

and the couplings of L_f and R_f to A_μ read

$$L_f : -i(g \sin \Theta_W \frac{\tau_3}{2} + g' \cos \Theta_W \frac{Y_L}{2}) A_\mu$$

$$R_f : -i(g' \cos \Theta_W \frac{\tau_3}{2} + g' \cos \Theta_W \frac{Y_L}{2}) A_\mu .$$

Because we have $g' \cos \Theta_W = g \sin \Theta_W = e$ we find the Gell-Mann-Nishijima (GMN) relation

$$Q = T_3 + \frac{Y}{2}$$

as a consequence of a minimal Higgs structure! What we find is, that, whatever the hypercharge of L_f is L_f and R_f must couple identically to photons. Thus QED must be parity conserving! Furthermore the charges of the upper (1) and lower (2) components of the doublets satisfy

$$Q_{L1} = Q_{R1} , \quad Q_1 - Q_2 = 1 \text{ and } Q_1 + Q_2 = Y_L .$$

So far we have no charge quantization. Here we need a last assumption.

- If ν_R does not exist we have to set $Y_{\nu R} = 0$ and consequently we must have $Y_{\nu L} = -1 = Y_{\ell L} = 0$ and $Q_\nu = 0, Q_\ell = -1$. For the $U(1)_Y$ anomaly cancellation we need lepton-quark duality and the charges of the quarks must have their known values if they appear in three colors. One thus must have the usual charge quantization.

We finally summarize the consequences of the assumptions stated above:

- Breaking $SU(2)_L$ by a minimal Higgs automatically leads to a global $U(1)_Y$, which can be gauged
- parity violation of $SU(2)_L$
- $\rho = M_W^2 / (M_Z^2 \cos^2 \Theta_W) = 1$
- existence of the photon
- parity conservation of QED
- validity of the Gell-Mann-Nishijima relation
- family structure
- charge quantization

We do not know of course why right-handed neutrinos do not exist or not couple in the real world and it remains a mystery why there exist family replica.

II. QUANTIZATION AND REGULARIZATION

1. Gauge fixing

The quantum field theory associated with the classical gauge invariant Lagrangian

$$\begin{aligned}\mathcal{L}_{inv} &= \mathcal{L}_{matter} + \mathcal{L}_{YM} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa} \\ &= \mathcal{L}_{inv}^{bilinear} + \mathcal{L}_{inv}^{int}\end{aligned}$$

in the broken phase $\Phi_b = \Phi + \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

$$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{e.m.}$$

may be defined by writing down the path-integral representation

$$Z\{J, \bar{\chi}, \chi, \dots\} = \int \mathcal{D}V_\mu \mathcal{D}\psi \mathcal{D}\bar{\psi} e^{i \int (\mathcal{L}_{eff} + JV + \bar{\chi}\psi + \bar{\psi}\chi + \dots)} \quad (42)$$

for the generating functional of the time-ordered Green functions. By $J, \bar{\chi}, \chi, \dots$ we denote the classical source functions. If we would try to choose $\mathcal{L}_{eff} = \mathcal{L}_{inv}$ the functional integral would not exist. The problem is known from QED. Because of the gauge invariance of the action $S_{inv} = i \int d^4x \mathcal{L}_{inv}$ the equations of motion do not determine the gauge fields uniquely. In order to get non-degenerate equations of motion we have to fix a gauge. A convenient choice is the *linear covariant* 't Hooft gauge (R_ξ - gauge). Each gauge field has associated a gauge function

$$\begin{aligned}W_\mu^\pm &: C^\pm = -\partial_\mu W^{\mu\pm} \pm i\xi_W M_W \phi^\pm \quad (= 0) \\ Z_\mu &: C_Z = -\partial_\mu Z^\mu - \xi_Z M_Z \phi \quad (= 0) \\ A_\mu &: C_A = -\partial_\mu A^\mu \quad (= 0)\end{aligned} \quad (43)$$

and one adds to the invariant Lagrangian the bilinear Lorentz-invariant *gauge fixing* part

$$\mathcal{L}_{GF} = -\frac{1}{\xi_W} C^+ C^- - \frac{1}{2\xi_Z} C_Z^2 - \frac{1}{2\xi_A} C_A^2. \quad (44)$$

The ξ 's are independent gauge parameters. For notational convenience we will take them equal, $\xi_W = \xi_Z = \xi_A = \xi$. Of course physics must be independent of ξ ! The extra terms in the gauge functions containing the Higgs ghosts have been chosen such that the non-diagonal (mixed) terms

- $\mathcal{L}_{inv}^{(W,\phi)} = i M_W \partial_\mu W^{\mu+} \phi^- + h.c. + M_Z \partial_\mu Z^\mu \phi$

drop out in the sum $\mathcal{L}_{inv}^{bilinear} + \mathcal{L}_{GF}$. In this way we achieve a diagonalization of the terms bilinear in $\partial_\mu W_a^\mu$ and ϕ_a with the consequence that the Higgs ghosts get a gauge dependent mass. The mass term obtained is

- $\mathcal{L}_{mass}^{(\phi)} = -\xi_W M_W^2 \phi^+ \phi^- - \frac{1}{2} \xi_Z M_Z^2 \phi^2$.

The gauge dependent masses are another direct indication that the Higgs ghosts (“would be Goldstone bosons”) cannot be physical. We now obtain the well-defined gauge boson propagators

$$D_V^{\mu\nu}(p, \xi) \equiv -i \left(g^{\mu\nu} - (1 - \xi_V) \frac{p^\mu p^\nu}{p^2 - \xi_V M_V^2 + i\epsilon} \right) \frac{1}{p^2 - M_V^2 + i\epsilon} \quad (45)$$

for $V = W_\mu^\pm, Z_\mu, A_\mu$ and with $M_A = m_\gamma = 0$. For $\xi = 1$ we have the ‘t Hooft-Feynman gauge where the propagators take the particularly simple form

$$\frac{-ig^{\mu\nu}}{p^2 - M_V^2 + i\epsilon}. \quad (46)$$

The renormalizable R_ξ -gauge (R-gauge) provides a one parameter interpolating family of gauges with the unitary gauge as a limiting case. For $\xi \rightarrow \infty$ we indeed get the physical U-gauge propagator

$$-i \left(g^{\mu\nu} - \frac{p^\mu p^\nu}{M_V^2} \right) \frac{1}{p^2 - M_V^2 + i\epsilon}; \quad V = W, Z$$

which is purely transverse. If we write the R-gauge propagator in the form

$$D_V^{\mu\nu}(p, \xi) = -i \left(g^{\mu\nu} - \frac{p^\mu p^\nu}{M_V^2} \right) \frac{1}{p^2 - M_V^2 + i\epsilon} - i \frac{p^\mu p^\nu}{M_V^2} \frac{1}{p^2 - \xi_V M_V^2 + i\epsilon}$$

we observe that the first term is the unitary piece while the second term is a kind of Pauli-Villars cut-off term. The ghost propagators are given by

$$D_V^\phi(p) = \frac{i}{p^2 - \xi_V M_V^2 + i\epsilon} \quad (47)$$

and freeze out $D_V^\phi(p) \rightarrow 0$ as $\xi \rightarrow \infty$ (unitary gauge). It is rather amusing to see how the “gauging away” of the Higgs ghosts works at the level of the Feynman diagrams.

2. Faddeev-Popov ghosts

Unlike in QED adding \mathcal{L}_{GF} to the invariant Lagrangian spoils gauge invariance, unitarity and renormalizability of S-matrix! If we compare the classical abelian with the non-abelian gauge transformations

$$\begin{aligned} U(1) &: A_\mu \rightarrow A_\mu + \partial_\mu \omega \\ &C_A \rightarrow C_A - \square \omega \\ SU(2) &: W_{\mu a} \rightarrow W_{\mu a} + \partial_\mu \omega_a - g \epsilon_{abc} W_{\mu c} \omega_b \\ &C_a \rightarrow C_a - \square \omega_a + g \epsilon_{abc} \partial^\mu (W_{\mu c} \omega_b) \end{aligned}$$

we observe that the harmless extra term in the abelian gauge function is replaced by a non-trivial and non-harmless extra term in the non-abelian case. Faddeev and Popov [25] have found the way out of the dilemma. The restauration of the gauge symmetry can be achieved by taking into account the functional determinant obtained in the functional integral under a gauge transformation of the fields (integration variables). If we define the functional integral as follows, with a Faddeev-Popov determinant,

$$\int \mathcal{D}W_{\mu a} \text{Det} \left(\frac{\delta C_a}{\delta \omega_b} \right) e^{i \int (\mathcal{L}_{inv} - \frac{1}{2\epsilon} C_a^2) d^4x}$$

one easily checks that now the functional integral is independent on the specific choice of the gauge function C_a . By introducing anticommuting scalars, the FP ghost fields $\bar{\eta}_a$ and η_a , we may represent the FP-determinant as a Berezin integral over Grassmann variables (algebra of anticommuting c-numbers) [26]

$$\text{Det} \left(\frac{\delta C_a}{\delta \omega_b} \right) = \int \mathcal{D}\eta \mathcal{D}\bar{\eta} e^{i \int \mathcal{L}_{FP} d^4x}$$

with

$$\mathcal{L}_{FP} = \bar{\eta}_a M_{ab} \eta_b ; \quad M_{ab} \doteq \frac{\delta C_a}{\delta \omega_b} . \quad (48)$$

As a result we find the proper functional integral quantization

$$\int \mathcal{D}W_{\mu a} \mathcal{D}\eta \mathcal{D}\bar{\eta} e^{i \int \mathcal{L}_{eff} d^4x}$$

with the "quasi invariant" effective Lagrangian

$$\mathcal{L}_{eff} = \mathcal{L}_{inv} + \mathcal{L}_{GF} + \mathcal{L}_{FP} . \quad (49)$$

In the following we will use a somewhat more compact notation. We treat $SU(2)_L \otimes U(1)_Y = G$ as a single gauge group G with generators T_A and structure constants f_{ABC} . The gauge fields and the FP-ghosts are denoted by

$$\begin{aligned} G_{A\mu} &: W_\mu^\pm, Z_\mu, A_\mu & A &: \pm, Z, \gamma . \\ \eta_A &: \eta^\pm, \zeta, \bar{\eta} \end{aligned}$$

Using this notation the FP-Lagrangian reads

$$\mathcal{L}_{FP} = \bar{\eta}^\mp M_{\pm B} \eta_B + \bar{\zeta} M_{ZB} \eta_B + \bar{\eta} M_{\gamma B} \eta_B$$

with

$$M_{AB} \eta_B = \frac{\partial C_A}{\partial G_{C\mu}} \frac{\delta G_{C\mu}}{\delta \omega_B} \eta_B + \frac{\partial C_A}{\partial \Phi_C} \frac{\delta \Phi_C}{\delta \omega_B} \eta_B .$$

Since the quantities associated with a gauge transformation of fields, which appear in the last equation, will be used for a discussion of the Slavnov-Taylor identities later, we list them in detail here:

- The gauge variations are given by:

$$\begin{aligned}
\frac{\delta G_{A\mu}}{\delta \omega_B} \eta_B &\doteq D_{\mu AB} \eta_B \\
D_{\mu \pm B} \eta_B &= \partial_\mu \eta^\pm \pm i \left[e(W_\mu^\pm \aleph - A_\mu \eta^\pm) - g \cos \Theta_W (W_\mu^\pm \zeta - Z_\mu \eta^\pm) \right] \\
D_{\mu ZB} \eta_B &= \partial_\mu \zeta - ig \cos \Theta_W (W_\mu^- \eta^+ - W_\mu^+ \eta^-) \\
D_{\mu \gamma B} \eta_B &= \partial_\mu \aleph + ie (W_\mu^- \eta^+ - W_\mu^+ \eta^-)
\end{aligned} \tag{50}$$

$$\begin{aligned}
\frac{\delta \Phi_A}{\delta \omega_B} \eta_B &\doteq (D\Phi_A)_B \eta_B \\
(D\phi^\pm)_B \eta_B &= \pm \left[e\phi^\pm \aleph + \frac{g(\sin^2 \Theta_W - \cos^2 \Theta_W)}{2 \cos \Theta_W} \phi^\pm \zeta + \frac{g}{2} (H + i\phi) \eta^\pm \right] \\
(D\phi)_B \eta_B &= -i \left[\frac{g}{2 \cos \Theta_W} H \zeta + \frac{g}{2} (\phi^+ \eta^- - \phi^- \eta^+) \right] \\
(DH)_B \eta_B &= i \frac{g}{2 \cos \Theta_W} \phi \zeta + \frac{g}{2} (\phi^+ \eta^- - \phi^- \eta^+)
\end{aligned} \tag{51}$$

$$\begin{aligned}
\frac{\delta \Psi_i}{\delta \omega_B} \eta_B &\doteq (D\Psi_i)_B \eta_B \\
(D\psi_{\nu_\ell})_B \eta_B &= i \left[-\frac{g}{2 \cos \Theta_W} \zeta \psi_{L\nu_\ell} + \frac{g}{\sqrt{2}} \eta^+ \psi_{L\ell} \right] \\
(D\psi_\ell)_B \eta_B &= i \left[\frac{g}{\sqrt{2}} \eta^- \psi_{L\nu_\ell} + \frac{g}{2 \cos \Theta_W} \zeta \psi_{L\ell} - e \aleph \psi_\ell - e \tan \Theta_W \zeta \psi_\ell \right]
\end{aligned} \tag{52}$$

- For $M_{AB} \eta_B$ we obtain:

$$\begin{aligned}
M_{\pm B} \eta_B &= -\square \eta^\pm - \xi M_W^2 \eta^\pm - \xi \frac{M_W^2}{v} (H \pm i\phi) \eta^\pm \\
&\quad + \frac{1}{2} \xi M_W g \cos \Theta_W ((1 - \tan^2 \Theta_W) \zeta - 2 \tan \Theta_W \aleph) \phi^\pm \\
&\quad \pm ig \cos \Theta_W \partial^\mu (W_\mu^\pm (\zeta - \tan \Theta_W \aleph) - (Z_\mu - \tan \Theta_W A_\mu) \eta^\pm) \\
M_{ZB} \eta_B &= -\square \zeta - \xi M_Z^2 \zeta - \xi \frac{M_Z^2}{v} H \zeta \\
&\quad - \xi \frac{M_Z M_W}{v} (\phi^+ \eta^- + \phi^- \eta^+) \\
&\quad + ig \cos \Theta_W \partial^\mu (W_\mu^- \eta^+ - W_\mu^+ \eta^-) \\
M_{\gamma B} \eta_B &= -\square \aleph - ie \partial^\mu (W_\mu^- \eta^+ - W_\mu^+ \eta^-)
\end{aligned} \tag{53}$$

Now, the FP-Lagrangian \mathcal{L}_{FP} is explicitly given by the sum of the last three terms multiplied from the left by $\bar{\eta}^\mp$, $\bar{\zeta}$ and $\bar{\chi}$, respectively. A warning should be made here, \mathcal{L}_{FP} is not hermitian ! Thus in contrast to ordinary fermion loops, FP ghosts contribute differently for ghosts running clock wise or counter-clock wise in a diagram.

By the above expressions the FP-ghost propagators read

$$\Delta_V^\eta(p, \xi) = \frac{i}{p^2 - \xi_V M_V^2 + i\epsilon} \quad (54)$$

and thus look the same as the Higgs ghost propagators. However, they obey Fermi statistics such that there is a factor (-1) per FP-ghost loop! in the Feynman rules. Similarly to the Higgs ghosts, the FP-ghosts freeze out ($\Delta_V^\eta \rightarrow 0$) in the unitary gauge limit $\xi \rightarrow \infty$ with one exception. The FP-ghost partner of the photon $\Delta^\chi(p) = \frac{i}{p^2 + i\epsilon}$ remains in the game. In addition, there are two interaction terms $-\xi \frac{M_W^2}{v} \bar{\eta}^\mp \eta^\pm (H \pm i\phi)$ and $-\xi \left[\frac{M_Z^2}{v} \bar{\zeta} \zeta H + \frac{M_Z M_W}{v} \bar{\zeta} (\phi^+ \eta^- + \phi^- \eta^+) \right]$ which have a coupling proportional to ξ which in the U-gauge limit give rise to the so called Lee-Yang terms [27]. Since we are not going to consider calculations in the unitary gauge we need not care further about these terms.

Quantization complete !

3. Becchi-Rouet-Stora (BRS) symmetry

The local gauge invariance of the functional integral

$$\int \mathcal{D}G \mathcal{D}\eta \mathcal{D}\bar{\eta} e^{i \int \mathcal{L}_{eff} d^4x} \quad (55)$$

yields relations between Green functions, the Slavnov-Taylor (ST) [28] identities. They generalize the Ward-Takahashi (WT) [29] identities which derive from global symmetries. The ST-identities provide the tool needed for proofs of

- i) gauge invariance
- ii) unitarity
- iii) renormalizability

of the S-matrix. ST-identities may be obtained from the BRS-symmetry [30] of \mathcal{L}_{eff} . The idea behind BRS-symmetry is to dispose of the as yet undefined transformation properties of the FP-ghost fields $\bar{\eta}$ and η such that

$$\delta^{BRS} \mathcal{L}_{eff} = 0 . \quad (56)$$

In order to achieve this it is natural to demand the following relations to hold:

- i) $\delta\mathcal{L}_{inv} = 0$
- ii) $\delta\mathcal{L}_{GF} = -\frac{1}{\xi}C_A M_{AB} \omega_B$
- iii) $\delta\mathcal{L}_{FP} = \delta\bar{\eta} M_{AB} \eta_B + \bar{\eta}_A \delta(M_{AB} \eta_B)$
 $= -\delta\mathcal{L}_{GF}$
- iv) $DGD\eta D\bar{\eta}$ invariant.

A solution for this set of conditions may be obtained as follows: 1) Introduce anticommuting global c -number variables $\delta\lambda$, $\delta\lambda$ anticommuting with η and $\bar{\eta}$, and identify $\omega_B = \eta_B \delta\lambda$. Thus

- $\delta G_A = D_{AB} \eta_B \delta\lambda$

where G_A can be a gauge field, a scalar or a fermi field with $D_{AB} \eta_B$ given in the previous subsection. 2) Assume η to transform according to the regular representation, thus

- $\delta\eta_A = -\frac{1}{2}g f_{ABC} \eta_B \eta_C \delta\lambda$

where a permutation symmetry factor 1/2 (antisymmetry of f_{ABC} and anticommutativity of the η 's) has been taken into account. 1) and 2) imply $\delta(M_{AB} \eta_B) = 0$. We thus take the freedom to choose: 3) The field $\bar{\eta}$ transforms as

- $\delta\bar{\eta}_A = -\frac{1}{\xi}C_A \delta\lambda$

such that conditions i) to iii) are satisfied. One can show iv) to be true for the above set of transformations which define the BRS-transformation.

4. ST-identities

The *BRS* invariance of \mathcal{L}_{eff} allows a simple derivation of the ST-identities. Performing a change of integration variables in the functional integral does not change the value of the integral. If we choose an (infinitesimal) BRS-transformation we get

$$\begin{aligned}
 Z\{J, \bar{\beta}, \beta\} &= \int DGD\eta D\bar{\eta} e^{i \int (\mathcal{L}_{eff} + JG + \bar{\eta}\beta + \bar{\beta}\eta) d^4x} \\
 &= \int DGD\eta D\bar{\eta} e^{i \int (\cdots) e^{i \int (J\delta G + \delta\bar{\eta}\beta + \bar{\beta}\delta\eta) d^4x}} \\
 &= \int DGD\eta D\bar{\eta} e^{i \int (\cdots) [1 + i \int dz (J\delta G + \delta\bar{\eta}\beta + \bar{\beta}\delta\eta)(z)]} . \quad (57)
 \end{aligned}$$

In the second step we have used $\delta\lambda^2 = 0$ which implies that terms higher than linear vanish if we expand the exponential. Using $\delta\lambda\beta = -\beta\delta\lambda$ etc. we can write

$$\begin{aligned}
 &\int DGD\eta D\bar{\eta} i \int dz \left\{ J_A D_{AB} \eta_B + \frac{1}{\xi} C_A \beta_A - \frac{1}{2} \bar{\beta}_A g f_{ABC} \eta_B \eta_C \right\} (z) \\
 &\times e^{i \int d^4y (\mathcal{L}_{eff} + J_A G_A + \bar{\eta}_A \beta_A + \bar{\beta}_A \eta_A)} \equiv 0 .
 \end{aligned}$$

Taking the functional derivative

$$i \frac{\delta}{\delta \beta_C(x)} \cdots |_{\bar{\beta}=\beta=0}$$

we obtain the ST-identities

$$\int \mathcal{D}G \mathcal{D}\eta \mathcal{D}\bar{\eta} \ i \int dz \left\{ \bar{\eta}_C(x) J_A D_{AB} \eta_B + i \frac{1}{\xi} C_A \delta_{CA} \delta(x-z) \right\} (z) \times e^{i \int d^4y (\mathcal{L}_{eff} + J_A G_A)} \equiv 0. \quad (58)$$

For the time-ordered Green functions, by applying

$$(-i)^N \frac{\delta^{(N)}}{\delta J_{A_1}(x_1) \cdots \delta J_{A_N}(x_N)} \cdots |_{J=0}$$

to the functional ST-identity, this implies

$$\begin{aligned}
& \frac{1}{\xi} <0|TC_C(x)G_{A_1}(x_1)\cdots G_{A_N}(x_N)|0> \\
& = \sum_i <0|TG_{A_1}(x_1)\cdots \underbrace{\bar{\eta}_C(x)(D_{A_iB}\eta_B)(x_i)}_{\text{replacing } G_{A_i}(x_i)}\cdots G_{A_N}(x_N)|0> . \quad (59)
\end{aligned}$$

As an example we obtain for the gauge boson propagators

$$\langle 0 | T C_C(x) G_A(y) | 0 \rangle = \xi \langle 0 | T \bar{\eta}_C(x) (D_{AB} \eta_B)(y) | 0 \rangle, \quad (60)$$

or, for the individual fields, (by a \bullet we indicates a derivative of a field)

$$- \langle T\partial_\mu A^\mu(x) A_\nu(y) \rangle = \xi \langle T\bar{N}(x) \partial_\nu N(y) \rangle + ie\xi \langle T\bar{N}(x) (W_\mu^- \eta^+ - W_\mu^+ \eta^-)(y) \rangle$$

$$\begin{array}{c}
 \text{Diagram 1: } \text{a circle with a diagonal line through it} \\
 \text{Diagram 2: } \text{a circle with a diagonal line through it} \\
 \text{Diagram 3: } \text{a circle with a diagonal line through it} \\
 \text{Diagram 4: } \text{a circle with a diagonal line through it} \\
 \text{Diagram 5: } \text{a circle with a diagonal line through it}
 \end{array}$$

$$\begin{aligned}
& - < T\partial_\mu Z^\mu(x)Z_\nu(y) > - \xi M_Z < T\phi(x)Z_\nu(y) > \\
& = \xi < T\bar{\zeta}(x)\partial_\nu\zeta(y) > - ig \cos\Theta_W \xi < T\bar{\zeta}(x)(W_\mu^-\eta^+ - W_\mu^+\eta^-)(y) > \\
& \text{Diagram: } \text{a circle with a dot and a wavy line } Z \text{, followed by } Z \text{, followed by } \phi \text{, followed by } Z \text{, followed by } \zeta \text{, followed by } \zeta \text{, followed by } \eta^+ \text{, followed by } W^\pm \text{, followed by } 0 = 0
\end{aligned}$$

For the mixed cases $\langle T\partial_\mu A^\mu Z_\nu \rangle$ and $\langle T\partial_\nu Z^\mu A_\nu \rangle$ we get similar relations. The ST-identities tell us how the gauge terms like $\partial_\mu Z^\mu$ cancel against Higgs and FP-ghosts!

Before we derive another set of relations for gauge field propagators, we consider the FP-ghost propagator. We have

$$\begin{aligned}
& \int \mathcal{D}G \mathcal{D}\eta \mathcal{D}\bar{\eta} \bar{\eta}_C(x) \frac{\delta}{\delta \bar{\eta}_A(z)} e^{\int (\mathcal{L}_{eff} + JG) dx} \\
&= i \int \mathcal{D}G \mathcal{D}\eta \mathcal{D}\bar{\eta} \bar{\eta}_C(M_{AB}\eta_B)(z) e^{i \int (\dots)} \\
&= - \int \mathcal{D}G \mathcal{D}\eta \mathcal{D}\bar{\eta} \delta_{CA} \delta(x - z) e^{i \int (\dots)} \tag{61}
\end{aligned}$$

where the last step is a partial integration. Taking a functional derivative for vanishing sources, we find

$$\langle 0 | T\bar{\eta}_C(x)(M_{AB}\eta_B)(z)G_{A_1}(x_1) \dots | 0 \rangle = i\delta_{CA}\delta(x - z) \langle 0 | TG_{A_1}(x_1) \dots | 0 \rangle, \tag{62}$$

which is the FP-ghost propagator in the standard form. We may use this result in order to get time-ordered Green functions with multiple insertions of gauge functions C_A . To this end, in the derivation of the ST-identities, we add a source term for C_A by replacing $J_A G_A \rightarrow J_A G_A + L_A C_A$. This implies a substitution $J_A D_{AB}\eta_B \rightarrow J_A D_{AB}\eta_B + L_A M_{AB}\eta_B$ in the above derivation and taking the functional derivative

$$-i \frac{\delta}{\delta L_A(y)} \dots |_{J=L=0}$$

of the modified functional ST-identity, we find

$$\begin{aligned}
\frac{1}{\xi} \langle 0 | T C_C(x) C_A(y) | 0 \rangle &= \langle 0 | T \bar{\eta}_C(x)(M_{AB}\eta_B)(y) | 0 \rangle \tag{63} \\
&= i\delta_{CA}\delta(x - y).
\end{aligned}$$

Inserting the specific forms of the gauge functions we arrive at the equations

$$\begin{aligned}
\langle T\partial_\mu A^\mu(x)\partial_\nu A^\nu(y) \rangle &= -i\xi\delta(x - y) \\
\langle T\partial_\mu A^\mu(x)\partial_\nu Z^\nu(y) \rangle + \xi M_Z \langle T\partial_\mu A^\mu(x)\phi(y) \rangle &= 0 \\
\langle T\partial_\mu Z^\mu(x)\partial_\nu Z^\nu(y) \rangle + \xi M_Z \langle T\partial_\mu Z^\mu(x)\phi(y) \rangle \\
&+ \xi M_Z \langle T\phi(x)\partial_\nu Z^\nu(y) \rangle + \xi^2 M_Z^2 \langle T\phi(x)\phi(y) \rangle = -i\xi\delta(x - y)
\end{aligned}$$

for the longitudinal parts of the gauge field propagators. One can use these ST-identities to prove that longitudinal amplitudes in propagators drop out in physical amplitudes. Of course similar relations are valid for vertex functions and higher Green functions.

5. Dimensional Regularization

So far we have ignored that quantities like the path integral and Green functions etc. are mathematically illdefined. We assume the theory to be defined by its formal power series expansion in \mathcal{L}_{int} . The perturbative definition is acceptable if the expansion is well defined order by order in the perturbative expansion and if this expansion is

renormalizable i.e. it can be made finite by a redefinition of the parameters (parameter renormalization) and the fields (multiplicative wave function renormalization).

Starting with the Feynman rules of the classical quantized Lagrangian, called bare Lagrangian, the formal perturbation expansion is given in terms of ultraviolet (*UV*) divergent Feynman integrals. As an example consider the scalar self-energy diagram

$$\text{Diagram: } \begin{array}{c} \text{---} \xrightarrow{k+p} \text{---} \\ \text{---} \xleftarrow{k} \text{---} \end{array} = \frac{1}{(2\pi)^4} \int d^4 k \frac{1}{k^2 - m_1^2 + i\epsilon} \frac{1}{(k+p)^2 - m_2^2 + i\epsilon} \stackrel{|k| \ll m_1, m_2}{\sim} \int \frac{d^4 k}{k^4}$$

which is divergent because the integral does not fall-off sufficiently fast at large k . In order to get a well-defined perturbation expansion the theory must be regularized. The regularization should respect as much as possible the symmetries (*ST*-identities) of the “classical theory”. Two regularizations are known to respect local gauge symmetries (up to possible violation of chiral properties):

1. Lattice regularization, which makes possible the application of methods known from statistical mechanics. In particular it makes possible a non-perturbative approach (Monte Carlo simulation of lattice gauge theories) [31].
2. Dimensional regularization (*DR*), which is suitable for the perturbative approach [32].

Since we are interested in perturbative calculations we need to discuss dimensional regularization only. The basic observations behind DR are the following:

- i) Feynman rules formally look the same in different space-time dimensions $d = n(\text{integer})$
- ii) Feynman integrals converge the better the lower d is.

5. 1. *Dyson power counting*

The action

$$S = i \int d^d x \mathcal{L}_{eff}$$

measured in units of $\hbar = 1$ is dimensionless and therefore $\dim \mathcal{L}_{eff} = d$ in mass units. The inspection of the individual terms yields the following dimensions for the fields:

$$\begin{array}{lll} \bar{\psi} \gamma^\mu \partial_\mu \psi & : \dim \psi & = \frac{d-1}{2} \\ (\partial_\mu G_{i\nu} - \dots)^2 & : \dim G_{i\nu} & = \frac{d-2}{2} \\ \partial_\mu \Phi + \partial^\mu \Phi & : \dim \Phi & = \frac{d-2}{2} \\ \bar{g}_0 \bar{\psi} \gamma^\mu T_i \psi G_{i\nu} & : \dim \bar{g}_0 & = \frac{4-d}{2} \Rightarrow \bar{g}_0 = g_0 \mu^{d/2} \\ \mathcal{L}_{GF} = -\frac{1}{2\xi} (\partial_\mu G_i^\mu + \dots)^2 & : \dim \xi & = 0 \\ \mathcal{L}_{FP} = -\bar{\eta} \square \eta + \dots & : \dim \eta & = \frac{d-2}{2} \end{array}$$

where $\epsilon = d - 4$, g_0 denotes the dimensionless bare coupling constant ($\dim g_0 = 0$) and μ is an arbitrary mass scale. The dimension of time ordered Green functions in momentum space is then given by (the Fourier transformation $\int d^d q e^{-iqx} \dots$ gives $-d$ for each field):

$$\dim G^{(n_B, 2n_F)} = n_B \frac{d-2}{2} + 2n_F \frac{d-1}{2} - (n_g + 2n_F)d \quad (64)$$

where

$$\begin{aligned} n_B &: \# \text{of boson fields} : G_{i\mu}, \Phi, \eta \\ 2n_F &: \# \text{of Dirac fields (in pairs)} : \psi \dots \bar{\psi} . \end{aligned}$$

It is convenient to split off trivial factors which correspond to external propagators and four-momentum conservation:

- amputation of external legs : $G^{(n_B, 2n_F)} \rightarrow G^{(n_B, 2n_F)amp}$
- $\rightarrow \ell = -i(p - m) \rightsquigarrow \ell : \dim G \rightarrow \dim G + 1$
- $\sim \ell = -i(p^2 - m^2) \rightsquigarrow \ell : \dim G \rightarrow \dim G + 2$
- d - momentum conservation : $: G^{(n_B, 2n_F)} = (2\pi)^d \delta^{(d)}(\sum p_{ext}) \hat{G}^{(n_B, 2n_F)}$

yields for the proper amputated vertex functions

$$\dim \hat{G}^{amp} = d - n_B \frac{d-2}{2} - 2n_F \frac{d-1}{2} . \quad (65)$$

A generic Feynman diagram represents a Feynman integral

$$\text{Diagram} \iff I_\Gamma(p) = \int \frac{d^1 k_1}{(2\pi)^d} \dots \frac{d^d k_m}{(2\pi)^d} J_\Gamma(p, k) .$$

The convergence of the integral can be inspected by looking at the behavior of the integrand for large momenta: For $k_i = \lambda \hat{k}_i$ and $\lambda \rightarrow \infty$ we find

$$\Pi_i d^d k_i J_\Gamma(p, k) \rightarrow \lambda^{d(\Gamma)}$$

where

$$d(\Gamma) = d - n_B \frac{d-2}{2} - 2n_F \frac{d-1}{2} + \sum_{i=1}^n (d_i - d) \quad (66)$$

is called the *superficial divergence* of the 1pi diagram Γ . The sum extends over all (n) vertices of the diagram and d_i denotes the dimension of the vertex i. The convergence criterion then reads:

$$\begin{aligned} I_\Gamma \text{ convergent} &\Leftrightarrow d(\gamma) < 0 \quad \forall \text{ 1pi subdiagrams } \gamma \subset \Gamma \\ I_\Gamma \text{ divergent} &\Leftrightarrow \exists \gamma \subset \Gamma \text{ with } d(\gamma) \geq 0 . \end{aligned}$$

In $d \leq 4$ dimensions, a renormalizable theory has the following types of primitively divergent diagrams (i.e. diagrams with $d(\Gamma) \geq 0$ which may have divergent subintegrals):

$d(\Gamma)$ d	$(d = 4)$	$d(\Gamma)$ d	$(d = 4)$		
	$d - 3$	(1)		$\frac{d-4}{2}$	(0)
	$d - 2$	(2)		$1 + \frac{d-4}{2}$	(1)
	$d - 2$	(2)		$d - 4$	(0)
	$d - 2$	(2)		$1 + \frac{d-4}{2}$	(1)

$+L_\Gamma(\frac{d-4}{2})$ for a diagram with L_Γ loops. Thus the dimensional analysis tells us that convergence improves for $d < 4$. For a renormalizable theory we have

- $d(\Gamma) \leq 2$ for $d = 4$.

In lower dimensions

- $d(\Gamma) < 2$ for $d < 4$

a renormalizable theory becomes super-renormalizable, while in higher dimensions

- $d(\Gamma)$ unbounded! $d > 4$

the theory is non-renormalizable.

5. 2. Dimensional regularization

Dimensional regularization of theories with spin is defined in three steps.

1. Start with Feynman rules formally derived in $d = 4$.
2. Generalize to $d = 2n > 4$! This intermediate step is necessary in order to treat the vector and spinor indices appropriately.

- 1) For fermions we need the $d = 2n$ dimensional Dirac algebra:

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu}\mathbf{1}; \quad \{\gamma^\mu, \gamma_5\} = 0 \quad (67)$$

where γ_5 must satisfy $\gamma_5^2 = \mathbf{1}$ and $\gamma_5^+ = \gamma_5$ such that $\frac{1}{2}(\mathbf{1} \pm \gamma_5)$ are the chiral projection matrices. The metric has dimension d

$$g^{\mu\nu}g_{\mu\nu} = g_\mu^\mu = d; \quad g_{\mu\nu} = \begin{pmatrix} 1 & 0 & \cdots & & \\ 0 & -1 & & & \\ \vdots & & \ddots & & \\ & & & & -1 \end{pmatrix}. \quad (68)$$

By $\mathbf{1}$ we denote the unit matrix in spinor space. In order to have the usual relation for the adjoint spinors we furthermore require

$$\gamma^{\mu+} = \gamma^0 \gamma^\mu \gamma^0$$

Simple consequences of this d-dimensional algebra are:

$$\begin{aligned} \gamma_\alpha \gamma^\alpha &= d \mathbf{1} \\ \gamma_\alpha \gamma^\mu \gamma^\alpha &= (2-d) \gamma^\mu \\ \gamma_\alpha \gamma^\mu \gamma^\nu \gamma^\alpha &= 4g^{\mu\nu} \mathbf{1} + (d-4) \gamma^\mu \gamma^\nu \\ \gamma_\alpha \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\alpha &= -2\gamma^\rho \gamma^\nu \gamma^\mu + (4-d) \gamma^\mu \gamma^\nu \gamma^\rho \text{ etc.} \end{aligned} \quad (69)$$

Traces of strings of γ -matrices are very similar to the ones in 4-dimensions. In $d = 2n$ dimensions one can easily write down $2^{d/2}$ dimensional representations of the Dirac algebra [33]. Then

$$\begin{aligned} \text{Tr} \mathbf{1} &= f(d) = 2^{d/2} \\ \text{Tr} \prod_{i=1}^{2n-1} \gamma^{\mu_i} (\gamma^5) &= 0 \\ \text{Tr} \gamma^\mu \gamma^\nu &= f(d) g^{\mu\nu} \\ \text{Tr} \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma &= f(d) (g^{\mu\nu} g^{\rho\sigma} - g^{\mu\rho} g^{\nu\sigma} + g^{\mu\sigma} g^{\nu\rho}) \text{ etc.} \end{aligned} \quad (70)$$

One can show that for *renormalized quantities* the only relevant property of $f(d)$ is $f(d) \rightarrow 4$ for $d \rightarrow 4$. Very often the convention $f(d) = 4$ (for any d) is adopted. Bare quantities and the related MS or \overline{MS} quantities depend upon this convention (by terms proportional to $\ln 2$).

In anomaly free theories we can assume γ_5 to be fully anticommuting! But then

$$\text{Tr} \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \gamma_5 = 0 \text{ for all } d \neq 4!$$

The 4-dimensional object

$$4i\epsilon^{\mu\nu\rho\sigma} = \text{Tr} \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \gamma_5 \text{ for } d = 4 \quad (71)$$

cannot be obtained by dimensional continuation if we use an anticommuting γ_5 [33].

Since fermions do not have self interactions they only appear as closed fermion loops, which yield a trace of γ -matrices, or as a fermion strings connecting an external $\psi \dots \bar{\psi}$ pair of fermion fields. In a transition amplitude $|T|^2 = \text{Tr}(\dots)$ we again get a trace. Consequently, in principle, we have eliminated all γ 's! Commonly one writes a covariant tensor decomposition into invariant amplitudes, like, for example,

$$\text{Diagram: } \gamma \text{ (wavy line)} \otimes \bar{f} \text{ (fermion line)} = -ie \left\{ \gamma^\mu A_1 + \gamma^\mu \gamma_5 A_2 + i\sigma^{\mu\nu} \frac{q_\nu}{2m} A_3 + \dots \right\}$$

where μ is an external index.

2) External momenta (and external indices) must be taken $d = 4$ dimensional because four functions cannot be analytic continuation of three etc. The following rules apply:

$$\begin{aligned} \text{External momenta : } p^\mu &= (p^0, p^1, p^2, p^3, 0, \dots, 0) & 4 \text{ dimensional} \\ \text{Loop momenta : } k^\mu &= (k^0, \dots, k^{d-1}) & d \text{ dimensional} \\ k^2 &= (k^0)^2 - (k^1)^2 - \dots - (k^{d-1})^2 \\ pk &= p^0 k^0 - \vec{p} \cdot \vec{k} & 4 \text{ dimensional etc.} \end{aligned}$$

3. Interpolation in d to complex values and extrapolation to $d < 4$.

Loop integrals now read

$$\mu^{4-d} \int \frac{d^d k}{(2\pi)^d} \dots$$

with μ an arbitrary scale parameter. The crucial properties valid in DR independent of d are: (F.P. = finite part)

- a) $\int d^d k k_\mu f(k^2) = 0$
- b) $\int d^d k f(k + p) = \int d^d k f(k)$
which is not true with UV cut-off's
- c) If $f(k) = f(|k|)$:

$$\int d^d k f(k) = \frac{2\pi^{d/2}}{\Gamma(\frac{d}{2})} \int_0^\infty dr r^{d-1} f(r)$$
- d) For divergent integrals, by analytic subtraction, :
 $F.P. \int_0^\infty dr r^{d-1+\alpha} \equiv 0$ for arbitrary α
so called minimal subtraction (MS). Consequently

$$F.P. \int d^d k f(k) = F.P. \int d^d k f(k + p) = F.P. \int d^d (\lambda k) f(\lambda k) .$$

This implies that

dimensionally regularized integrals behave like convergent integrals
and formal manipulations are justified. Starting with d sufficiently small, by partial integration, one can always find a representation for the integral which converges for $d = 4 - \varepsilon$, $\varepsilon > 0$ small.

In the following we discuss DR for one-loop integrals in some detail.

One-loop integrals:

An integral of the general form

$$I_\Gamma^{\mu_1 \dots \mu_m}(p_1, \dots, p_n) = \int d^d k \frac{\prod_{j=1}^m k^{\mu_j}}{\prod_{i=1}^n ((k + p_i)^2 - m_i^2 + i\varepsilon)} \quad (72)$$

has superficial degree of divergence

$$d(\Gamma) = d + m - 2n \leq d - 2$$

where the bound holds for renormalizable theories and $d \leq 4$. I_Γ is convergent for $d(\Gamma) < 0$ in $d = 4$. If $d(\Gamma) \geq 0$ in $d = 4$, consider $d = n$ integer ≥ 4 because of vectors k^{μ_i} . We split the objects into:

Vectors in physical subspace ($\mu = 0, 1, 2, 3$): \hat{p}, \hat{k}, \dots

Vectors in the $d - 4$ dimensional complement ($\mu = 4, \dots, d - 4$): \bar{p}, \bar{k}, \dots

Correspondingly, the notation is as follows:

$$\begin{aligned} \text{External momenta} &: p_i = \hat{p}_i; \bar{p}_i = 0 \\ \text{Loop momenta} &: k = \hat{k} + \bar{k}; \hat{k} \cdot \bar{k} = 0 \\ & p_i \cdot k = \hat{p}_i \cdot \hat{k} \\ & k^2 = \hat{k}^2 + \bar{k}^2 = \hat{k}^2 - \omega^2; \omega = |\bar{k}| \\ \text{Metric tensor} &: g^{\mu\nu} = \hat{g}^{\mu\nu} + \bar{g}^{\mu\nu}; \hat{g} \cdot \bar{g} = 0 \\ & g_\mu^\mu = d, \hat{g}_\mu^\mu = 4, \bar{g}_\mu^\mu = d - 4. \end{aligned}$$

In physical amplitudes the indices of the integral $I_\Gamma^{\mu_1 \dots \mu_m}$ are either external (if we resort to a covariant decomposition e.g.) or contracted. The possibilities are:

1. contraction with an external momentum $p_i^{\mu_j} : k^{\mu_j} \rightarrow \hat{k}^{\mu_j}$ ($p_k = \hat{p}_k$)
2. the index is external (e.g. γ matrix) $\hat{g}^{\mu_j \alpha} : \hat{g}_\alpha^{\mu_j} k^\alpha = \hat{k}^{\mu_j}$
3. an index pair is contracted (with $g_{\mu\nu}$): $g_{\mu\nu} k^\mu k^\nu = k^2$.

In the first two cases the k^{μ_i} 's can be taken four dimensional, in the last case we obtain an integral of the form

$$\int d^d k \frac{k^2}{(k + p)^2 - m^2 + i\varepsilon} \frac{k^{\mu_1} \dots k^{\mu_{m-2}}}{\prod_{i=1}^{n-1} ((k + p_i')^2 - m_i^2 + i\varepsilon)}.$$

We write

$$k^2 = (k + p)^2 - m^2 - (2\hat{p}\hat{k} + \hat{p}^2 - m^2)$$

such that

$$\frac{k^2}{(k + p)^2 - m^2 + i\varepsilon} = 1 - \frac{(2\hat{p}\hat{k} + \hat{p}^2 - m^2)}{(k + p)^2 - m^2 + i\varepsilon}.$$

In this way all the one-loop integrals reduce to

$$I_\Gamma^{\hat{\mu}_1 \dots \hat{\mu}_m}(\hat{p}_1, \dots, \hat{p}_n) = \int d^d k \frac{\prod_{j=1}^m \hat{k}^{\mu_j}}{\prod_{j=1}^n ((k + \hat{p}_j)^2 - m_j^2 + i\varepsilon)}$$

with

$$d^d k = d^4 \hat{k} d^{d-4} \bar{k} = d^4 \hat{k} \omega^{d-5} d\omega d\Omega_{d-4}.$$

In the $d - 4$ dimensional complement the integrand depends on ω only! The angular integration over $d\Omega_{d-4}$ yields

$$\int d\Omega_{d-4} = S_{d-4} = \frac{2\pi^{\varepsilon/2}}{\Gamma(\varepsilon/2)} ; \quad \varepsilon = d - 4 .$$

which is the surface of the $d - 4$ dimensional sphere. Using this result we get (discarding 4-dimensional indices)

$$I_\Gamma(p_i) = \int d^4 \hat{k} J_\Gamma(d, \hat{p}, \hat{k})$$

where

$$J_\Gamma(d, \hat{p}, \hat{k}) = S_{d-4} \int_0^\infty d\omega \omega^{d-5} f(\hat{p}, \hat{k}, \omega) .$$

Now this integral can be analytically continued to complex values of d . For the ω -integration we have

$$d^\omega(\Gamma) = d - 4 - 2n$$

i.e. the ω -integral converges if

$$d < 4 + 2n \quad (*) .$$

On the other hand the condition for convergence of I_Γ is

$$d(\Gamma) = d + m - 2n < 0$$

i.e. $d < 2n - m$ but then $(*)$ is also true. As a result we find that

- for a renormalizable theory $d(\Gamma) \leq 2$ in $d \leq 4$ and hence all integrals converge for $Re d < 2$. However:

$$\int_0^\infty d\omega \omega^{d-5} f(\hat{p}, \hat{k}, \omega)$$

is infrared divergent for $Re d < 4$. The integral has

$$\text{domain of convergence : } 4 < d < 4 + 2n$$

and is

$$\text{analytic in a strip : } 4 < Re d < 4 + 2n .$$

Therefore it can be defined by analytic continuation in the complex d -plane. The analytic continuation can be obtained by partial integration:

$$\int_0^\infty d\omega \omega^{d-5} f(\hat{p}, \hat{k}, \omega) = \frac{\omega^{d-4}}{d-4} f(\hat{p}, \hat{k}, \omega) \Big|_0^\infty - \int_0^\infty d\omega \frac{\omega^{d-4}}{d-4} \frac{\partial}{\partial \omega} f(\hat{p}, \hat{k}, \omega)$$

The first term vanishes in $4 < \text{Re } d < 4 + 2n$ the second term (integral) is convergent for $3 < \text{Re } d < 4 + 2n$ with a pole at $d = 4$! Using

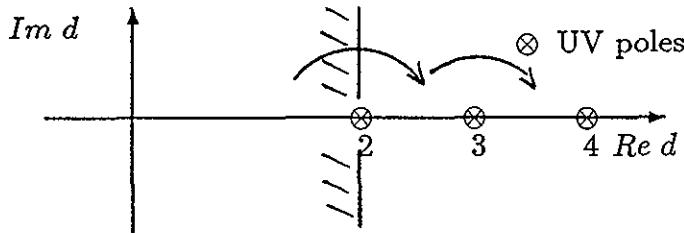
$$\frac{S_{d-4}}{d-4} = \frac{2\pi^{\frac{d-4}{2}}}{\Gamma(\frac{d-4}{2} + 1)} ; \quad (d-4)\Gamma(\frac{d-4}{2}) = 2\Gamma(\frac{d-4}{2} + 1)$$

p -fold partial integration yields

$$I_{\Gamma}^d = \frac{2\pi^{\frac{d-4}{2}}}{\Gamma(\frac{d-4}{2} + p)} \int d^4 \hat{k} \int_0^{\infty} d\omega \omega^{d-5+2p} \left(-\frac{\partial}{\partial \omega^2} \right)^p f(\hat{p}, \hat{k}, \omega) \quad (73)$$

where the integral is convergent in $4 - 2p < \text{Re } d < 2n - m = 4 - d^{(4)}(\Gamma) \geq 2$.

For a renormalizable theory at most 2 partial integrations are necessary to define the theory.



One problem case remains. For $n = 1$ the integral $\int d^d k \frac{1}{k^2}$ diverges for any d ! and hence must be regularized differently

1. either by an *IR* regulator i.e. finite mass or
2. by an *UV* cut off.

In the first case we obtain

$$\begin{aligned} \frac{1}{(2\pi)^d} \int d^d k \frac{1}{k^2 + m^2} &= m^2 (4\pi)^{-2} \left\{ \frac{2}{\varepsilon} - \gamma + \ln 4\pi - \ln m^2 \right\} \\ &\stackrel{\varepsilon=4-d\rightarrow 0}{=} 0 \text{ for } m = 0. \end{aligned}$$

In the second case we find

$$\begin{aligned} \frac{1}{(2\pi)^d} \int_{|k| < \Lambda} d^d k \frac{1}{k^2} &= \frac{S_d}{(2\pi)^d} \int_0^{\Lambda} d\omega \omega^{d-3} \text{ convergent for } \text{Re } d > 2 \\ &= \frac{S_d}{(2\pi)^d} \frac{1}{d-2} \Lambda^{d-2} \text{ analytical in } d. \end{aligned}$$

For $\text{Re } d < 2$ the limit $\lim_{\Lambda \rightarrow \infty} \equiv 0$ exists and thus as an analytical function:

$$\int d^d k \frac{1}{k^2} \equiv 0 \quad \forall d.$$

Notice that 1. and 2. yield the same unambiguous result!

In a similar way we find

$$\int d^d k (k^2)^m \equiv 0 ; \quad \int d^d k \frac{1}{(k^2)^n} \equiv 0$$

$$\int d^d k k^{\mu_1} \dots k^{\mu_m} \equiv 0 \quad (74)$$

This proves the rule:

$$F.P. \int_0^\infty d\omega \omega^\alpha = 0 \text{ any } \alpha \quad (75)$$

or, equivalently,

perform partial integrations until the integral converges for $d \leq 4 - \varepsilon$; $\varepsilon > 0$ infinitesimal, and ignore boundary terms.

We may summarize the results as follows:

- In DR divergent Feynman integrals can be represented by integrals converging in the strip $3 < \text{Re } d < 4$.
- The analytic continuation to this strip is obtained by partial integration and ignoring the boundary terms.
- The integrals are meromorphic functions in d with poles at certain $d = n$ integer.
- The poles at $d = 4$ can only be removed by renormalization.

We add two remarks concerning higher orders and infrared problems.

Higher orders: The order of the poles is given by the order of the perturbation expansion (number of loops)

$$\text{---} \bigcirc \bigcirc \bigcirc \dots \bigcirc \text{---} \quad \propto \varepsilon^{-n} \quad \text{since} \quad \text{---} \times \text{---} \propto \varepsilon^{-1}$$

Infrared problems: $m_i = 0$ integrals

a) One-Loop: the worst case is $I_\Gamma^{\mu_1 \dots \mu_m}$ for $m = 0$. For off-shell momenta (i.e. p_i generic) the integral

$$\int d^d k \frac{1}{\prod_{i=1}^n ((k + p_i)^2 + i\varepsilon)} = \int d^d k \frac{1}{k^2 + i\varepsilon} \frac{1}{(k + p'_1)^2 + i\varepsilon} \dots$$

has the domain of convergence

$$\begin{array}{ccc} 2 & < & d & < & 2n \\ \uparrow & & \uparrow & & \\ \text{for} & & \text{for} & & \\ \text{IR} & & \text{UV} & & \text{convergence} \\ \Rightarrow & \text{no problem for } n > 1! & & & \end{array}$$

The only problem case ($n=1$) has been discussed already before.

b) Higher orders:

1) 1-loop :

$$\text{Diagram: } \text{a loop} \quad \propto \int \frac{d^d k}{(2\pi)^d} \frac{1}{k^2} \frac{1}{(k+p)^2} \propto (p^2)^{\frac{d-4}{2}}$$

2) n -loop :

$$\text{Diagram: } n \text{ loops in a row} \quad \propto (p^2)^{n \frac{d-4}{2}}$$

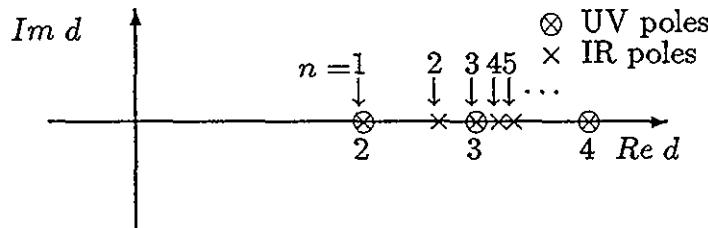
3)

$$\text{Diagram: } n \text{ loops with a bubble on top} \quad \propto \int \frac{d^d k}{(2\pi)^d} (k^2)^{n \frac{d-4}{2}} \frac{1}{(k+p)^2}$$

This integral is UV convergent for $d < 4$ and IR convergent for $d > \frac{4n}{n+1} \xrightarrow{n \rightarrow \infty} 4$! Thus, in $n+1$ -loop order the convergence domain is

$$\frac{4n}{n+1} < d < 4$$

and shrinks to zero as $n \rightarrow \infty$.



Result: For generic off-shell momenta time ordered Green functions exist in DR also for the massless case (on-shell is another story!).

5. 3. Tools for evaluation of Feynman integrals

1. $\varepsilon = 4 - d$ expansion, $\varepsilon \rightarrow +0$.

For the expansion of integrals near $d = 4$ we need some asymptotic expansions of Γ -functions:

$$\Gamma(x) = \frac{\Gamma(x+1)}{x}; \quad \Gamma\left(\frac{1}{2}\right) = \sqrt{\pi}; \quad \Gamma\left(\frac{3}{2}\right) = \frac{1}{2}\sqrt{\pi} \quad (76)$$

$$\psi(1+x) = \frac{d}{dx} \ln \Gamma(1+x) = \frac{\Gamma'(1+x)}{\Gamma(1+x)} \stackrel{|x|<1}{=} -\gamma + \sum_{n=2}^{\infty} (-1)^n \zeta(n) x^{n-1}$$

where $\zeta(n)$ denotes Riemann's Zeta function.

$$\begin{aligned}\Gamma'(1) &= -\gamma; \quad \gamma = 0.577215\cdots \text{ Euler's constant} \\ \Gamma''(1) &= \gamma^2 + \zeta(2); \quad \zeta(2) = \frac{\pi^2}{6} = 1.64493\cdots\end{aligned}$$

As a result

$$\Gamma(1 + \frac{\varepsilon}{2}) = 1 - \frac{\varepsilon}{2}\gamma + (\frac{\varepsilon}{2})^2 \frac{1}{2}(\gamma^2 + \zeta(2)) + \cdots \quad (77)$$

2. Bogolubov-Schwinger parametrization.

Suppose we choose for each propagator an independent momentum and take into account momentum conservation at the vertices by δ -functions. Then, for $d = n$ integer, we use

i)

$$\frac{i}{p^2 - m^2 + i\varepsilon} = \int_0^\infty d\alpha e^{-i\alpha(m^2 - p^2 + i\varepsilon)}$$

ii)

$$\delta^{(d)}(k) = \frac{1}{(2\pi)^d} \int_{-\infty}^{+\infty} d^d x e^{ikx}$$

and find that all momentum integrations are of Gaussian type. The Gaussian integrals yield

$$\int d^d k P(k) e^{ia(k^2 + 2b(k \cdot p))} = P \left(\frac{-i}{2ab} \frac{\partial}{\partial p} \right) \left(\frac{\pi}{ia} \right)^{d/2} e^{-iab^2 p^2}$$

for any polynomial P . The resulting form of the Feynman integral is the so called Bogolubov-Schwinger representation.

3. Feynman parametric representation.

Transforming pairs of α -variables in the above Bogolubov-Schwinger parametrization according to (l is denoting the pair (i, k))

$$(\alpha_i, \alpha_k) \rightarrow (\xi_l, \alpha_l) : (\alpha_i, \alpha_k) = (\xi_l \alpha_l, (1 - \xi_l) \alpha_l)$$

$$\int_0^\infty \int_0^\infty d\alpha_i d\alpha_k \cdots = \int_0^\infty d\alpha_l \alpha_l \int_0^1 d\xi_l \cdots ,$$

the integrals are successively transformed into $\int_0^1 d\xi \dots$ integrals and at the end there remains one α -integration only which can be performed using

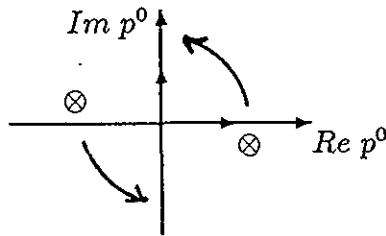
$$\int_0^\infty d\alpha \alpha^a e^{-\alpha x} = \Gamma(a+1) x^{-(a+1)}.$$

The result is the Feynman parametric representation. If L is the number of lines of a diagram, the Feynman integral is $L-1$ dimensional (all other integrations being “trivial”).

4. Euclidean region, Wick rotations.

Time ordered Green functions may be continued analytically in the complex p^0 (x^0) plane. Crucial is the $i\varepsilon$ -prescription in the propagators:

$$\frac{1}{p^2 - m^2 + i\varepsilon} = \frac{1}{p^0 - \sqrt{\vec{p}^2 + m^2 - i\varepsilon}} \frac{1}{p^0 + \sqrt{\vec{p}^2 + m^2 - i\varepsilon}}$$



We can thus perform a rotation by $\pi/2$

$$p \rightarrow \underline{p}; \quad p^0 \rightarrow i p^0 = p^4; \quad p^2 \rightarrow -\underline{p}$$

without crossing any pole. The euclidean propagators

$$\frac{1}{p^2 - m^2 + i\varepsilon} \rightarrow -\frac{1}{p^2 + m^2}$$

are positive (discarding the overall sign) and any integral in Minkowski space may be obtained via

$$I_M(p) = (-i)^a (i)^b I_E(\underline{p}) |_{p^4 = i p^0; \quad m^2 \rightarrow m^2 - i\varepsilon}$$

from its euclidean version. Here, a denotes the number of internal lines (propagators) and b the number of loop integrations if we use the substitutions

$$\frac{1}{p^2 - m^2 + i\varepsilon} \rightarrow \frac{1}{p^2 + m^2}; \quad \int d^d k \rightarrow \int d^d \underline{k}$$

to define the euclidean integrals.

Scalar one-loop integrals (euclidean).

Here we apply our tools to the simplest scalar one-loop integrals (p.i.=partial integration).

$$\begin{aligned}
 \frac{m}{p} &= \frac{\mu^{4-d}}{(2\pi)^d} \int d^d k \frac{1}{k^2 + m^2} = \mu^{4-d} (4\pi)^{-d/2} \int_0^\infty d\alpha \alpha^{-d/2} e^{-\alpha m^2} \\
 &\quad \text{convergent for } d < 2 \\
 &\stackrel{p.i.}{=} -\frac{2m^2}{d-2} \mu^{4-d} (4\pi)^{-d/2} \int_0^\infty d\alpha^{1-d/2} e^{-\alpha m^2} \\
 &\quad \text{convergent for } d < 4 \\
 &= -2m^2 (4\pi)^{-d/2} \frac{\Gamma(2-d/2)}{d-2} \left(\frac{m^2}{\mu^2}\right)^{d/2-2} \\
 &= -2m^2 (4\pi)^{-2} \frac{2}{\epsilon} \Gamma\left(1 + \frac{\epsilon}{2}\right) \frac{1}{2-\epsilon} e^{\frac{\epsilon}{2}(\ln 4\pi - \ln \frac{m^2}{\mu^2})} \\
 &\stackrel{\epsilon \rightarrow +0}{\approx} m^2 (4\pi)^{-2} \left\{ \frac{2}{\epsilon} - \gamma + 1 + \ln 4\pi - \ln \frac{m^2}{\mu^2} \right\} + O(\epsilon)
 \end{aligned}$$

$$\begin{aligned}
 \text{Diagram: } & \text{A loop diagram with two external lines. The top line is labeled } p \text{ and the bottom line is labeled } m_1 \text{ and } m_2. \\
 & = \frac{\mu^{4-d}}{(2\pi)^d} \int d^d k \frac{1}{k^2 + m_1^2} \frac{1}{(k+p)^2 + m_2^2} \\
 & = \mu^{4-d} (4\pi)^{-d/2} \int_0^\infty d\alpha_1 d\alpha_2 (\alpha_1 + \alpha_2)^{-d/2} e^{-(\alpha_1 m_1^2 + \alpha_2 m_2^2 + \frac{\alpha_1 \alpha_2}{\alpha_1 + \alpha_2} p^2)} \\
 & \quad \alpha_1 = x\lambda; \quad \alpha_2 = (1-x)\lambda \\
 & = \mu^{4-d} (4\pi)^{-d/2} \Gamma(2 - \frac{d}{2}) \int_0^1 dx (x m_1^2 + (1-x) m_2^2 + x(1-x) p^2))^{d/2-2} \\
 & \quad \text{convergent for } d < 4 \\
 & = (4\pi)^{-2} \frac{2}{\epsilon} \Gamma(1 + \frac{\epsilon}{2}) e^{\frac{\epsilon}{2} \ln 4\pi} \int_0^1 dx e^{-\frac{\epsilon}{2} \ln \frac{x m_1^2 + (1-x) m_2^2 + x(1-x) p^2}{\mu^2}} \\
 & \underset{\epsilon \rightarrow 0^+}{\approx} (4\pi)^{-2} \left\{ \frac{2}{\epsilon} - \gamma + \ln 4\pi - \int_0^1 dx \ln \frac{x m_1^2 + (1-x) m_2^2 + x(1-x) p^2}{\mu^2} \right\} + O(\epsilon)
 \end{aligned}$$

$$\begin{aligned}
 & \text{Diagram: } \begin{array}{c} p_1 \\ \diagup \quad \diagdown \\ m_1 \quad m_2 \\ \diagup \quad \diagdown \\ p_3 \quad m_3 \\ \diagup \quad \diagdown \\ p_2 \end{array} = \frac{\mu^{4-d}}{(2\pi)^d} \int d^d k \frac{1}{k^2 + m_1^2} \frac{1}{(k+p_1)^2 + m_2^2} \frac{1}{(k+p_1+p_2)^2 + m_3^2} \\
 & \quad \text{convergent for } d = 4 \\
 & \stackrel{\epsilon \rightarrow +0}{\simeq} (4\pi)^{-2} \int_0^\infty d\alpha_1 d\alpha_2 d\alpha_3 \frac{1}{(\alpha_1 + \alpha_2 + \alpha_3)^2} e^{-(\alpha_1 m_1^2 + \alpha_2 m_2^2 + \alpha_3 m_3^2)} \\
 & \quad \times e^{-\frac{\alpha_1 \alpha_2 p_1^2 + \alpha_2 \alpha_3 p_2^2 + \alpha_3 \alpha_1 p_3^2}{\alpha_1 + \alpha_2 + \alpha_3}} \\
 & \quad \alpha_1 = xy\lambda; \quad \alpha_2 = x(1-y)\lambda; \quad \alpha_3 = (1-x)\lambda; \quad \alpha_1 + \alpha_2 + \alpha_3 = \lambda \\
 & = (4\pi)^{-2} \int_0^1 dy dx \frac{1}{N}
 \end{aligned}$$

where

$$N = x^2 y (1-y) \underline{p}_1^2 + x (1-x)(1-y) \underline{p}_2^2 + x (1-x) y \underline{p}_3^2 + x y m_1^2 + x (1-y) m_2^2 + (1-x) m_3^2$$

We summarize these results by listing the

Standard scalar one-loop integrals ($m^2 \hat{=} m^2 - i\varepsilon$).

$$\frac{m}{p} \text{ (loop)} = \mu_0^\varepsilon \int \frac{d^d k}{(2\pi)^d} \frac{1}{k^2 - m^2} \hat{=} -\frac{i}{16\pi^2} A_0(m) \quad (78)$$

where

$$A_0(m) = -m^2(Reg + 1 - \ln m^2). \quad (79)$$

By Reg we denote the UV regulator

$$Reg = \frac{2}{\varepsilon} - \gamma + \ln 4\pi + \ln \mu_0^2 \equiv \ln \mu^2 \quad (80)$$

where the last identification defines the \overline{MS} scheme of minimal subtraction.

$$\frac{m_1}{p} \text{ (loop)} = \mu_0^\varepsilon \int \frac{d^d k}{(2\pi)^d} \frac{1}{(k^2 - m_1^2)((k+p)^2 - m_2^2)} \hat{=} \frac{i}{16\pi^2} B_0(m_1, m_2; p^2) \quad (81)$$

where

$$B_0(m_1, m_2; s) = Reg - \int_0^1 dz \ln(-sz(1-z) + m_1^2(1-z) + m_2^2 z - i\varepsilon). \quad (82)$$

$$\begin{aligned} \frac{p_1}{m_1} \text{ (triangle)} &= \mu_0^\varepsilon \int \frac{d^d k}{(2\pi)^d} \frac{1}{(k^2 - m_1^2)((k+p_1)^2 - m_2^2)((k+p_1+p_2)^2 - m_3^2)} \\ &= -\frac{i}{16\pi^2} C_0(m_1, m_2, m_3; p_1^2, p_2^2, p_3^2) \end{aligned} \quad (83)$$

where

$$C_0(m_1, m_2, m_3; s_1, s_2, s_3) = \int_0^1 dx \int_0^x dy \frac{1}{ax^2 + by^2 + cxy + dx + ey + f} \quad (84)$$

with

$$\begin{aligned} a &= s_2 & d &= m_2^2 - m_3^2 - s_2 \\ b &= s_1 & e &= m_1^2 - m_2^2 + s_2 - s_3 \\ c &= s_3 - s_1 - s_2 & f &= m_3^2 - i\varepsilon. \end{aligned}$$

The UV-singularities (poles in ε at $d=4$) give raise to *finite extra contributions* when they are multiplied with d (or functions of d) which arise from contractions like $g_\mu^\mu = d$, $\gamma^\mu \gamma_\mu = d$ etc. For $d \rightarrow 4$ we obtain:

$$dA_0(m) = 4A_0(m) + 2m^2, \quad dB_0 = 4B_0 - 2. \quad (85)$$

The explicit evaluation of the scalar integrals (up to the scalar four-point function) is discussed in Ref. [35].

5. 4. Tensor integrals (one-loop)

Integrals of the form

$$I^{\mu_1 \dots \mu_m}(p_1, \dots) = \int \frac{d^d k}{(2\pi)^d} \frac{k^{\mu_1} \dots k^{\mu_m}}{(k^2 - m_1^2)((k + p_1)^2 - m_2^2)((k + p_1 + p_2)^2 - m_3^2) \dots}$$

can be reduced to scalar one-loop integrals. In DR transformation of variables and partial fraction decomposition hold true independent of the convergence of the integral. The reduction of tensor integrals to scalar integrals may be achieved by the following steps:

i) Covariant decomposition:

$$I^{\mu_1 \dots \mu_m}(p_1, p_2, \dots) = p_1^{\mu_1} \dots p_1^{\mu_m} I_{m1}(p_1^2, p_1 p_2, p_2^2, \dots) + \dots$$

in terms of an appropriately symmetrized tensor basis formed with the linearly independent momenta and $g_{\mu\nu}$.

ii) Contraction with $g_{\mu\nu}$:

$$\frac{k^2}{k^2 - m^2} = \frac{(k^2 - m^2) + m^2}{k^2 - m^2} = 1 + \frac{m^2}{k^2 - m^2}$$

iii) Contraction with $p_{i\mu}$:

$$2kp_1 = ((k + p_1)^2 - m_2^2) - (k^2 - m_1^2) - (p_1^2 - m_2^2 + m_1^2)$$

$$\frac{2kp_1}{(1)(2)} = \frac{1}{(1)} - \frac{1}{(2)} - (p_1^2 - m_2^2 + m_1^2) \frac{1}{(1)(2)}$$

etc., until all I_{mi} 's are given as linear combination of scalar integrals. By 1/(i) we denote the scalar propagator with mass m_i . In the following we work out

Some basic tensor integrals

A factor $\frac{i}{16\pi^2}$ is taken out for simplicity of notation, i.e.

$$\int_k \dots = \frac{16\pi^2}{i} \int \frac{d^d k}{(2\pi)^d} \dots$$

In order to conform with the Passarino-Veltman convention in Ref. [34], we define the invariant functions I_{m1}, \dots using a factor $(-1)^n$ in front of the integrals, where n is the number of propagators, and a factor (-1) in front of the $g^{\mu_i \mu_k}$'s appearing in the kinematical tensors of the covariant decomposition. Accordingly, we consider integrals of the form

$$\int_k \frac{k^{\mu_1} \dots k^{\mu_m}}{(k^2 - m_1^2) \dots ((k + p_1 + p_2 + \dots + p_{n-1})^2 - m_n^2)} = (-1)^n (p_1^{\mu_1} \dots p_1^{\mu_m} I_{m1} + \dots)$$

in the following, and calculate the I_m 's in terms of scalar functions. We now discuss tadpoles, self-energies and form-factors in turn.

1. Tadpoles

By performing a shift $k \rightarrow k + p$ of the integration variable we easily find the following results:

$$\int_k \frac{1}{(k+p)^2 - m^2} = \int_k \frac{1}{k^2 - m^2} = -A_0(m) \quad (86)$$

$$\int_k \frac{k^\mu}{(k+p)^2 - m^2} = \int_k \frac{k^\mu - p^\mu}{k^2 - m^2} = \underbrace{\int_k \frac{k^\mu}{k^2 - m^2}}_0 - p^\mu \underbrace{\int_k \frac{1}{k^2 - m^2}}_{-A_0(m)} = p^\mu A_0(m) \quad (87)$$

$$\begin{aligned} \int_k \frac{k^\mu k^\nu}{(k+p)^2 - m^2} &= -p^\mu p^\nu A_{21} + g^{\mu\nu} A_{22} \\ &= \int_k \frac{(k-p)^\mu (k-p)^\nu}{k^2 - m^2} = -p^\mu p^\nu A_0(m) + \int_k \frac{k^\mu k^\nu}{k^2 - m^2} \end{aligned} \quad (88)$$

Using

$$g_{\mu\nu} \int_k \frac{k^\mu k^\nu}{k^2 - m^2} = dA_{22} = \int_k \frac{k^2}{k^2 - m^2} = \underbrace{\int_k 1}_{0} + m^2 \underbrace{\int_k \frac{1}{k^2 - m^2}}_{-A_0}$$

we find

$$dA_{22} = -m^2 A_0(m); \quad A_{21} = A_0(m)$$

and expanding in $d = 4 - \varepsilon$, $\varepsilon \rightarrow 0$ we get

$$\begin{aligned} 4A_{22} &= -m^2 A_0(m) + \varepsilon A_{22} \\ &\simeq m^4 \cdot \frac{2}{\varepsilon} + \text{finite} \end{aligned}$$

which implies

$$\varepsilon A_{22} \simeq \frac{2m^4}{4} + 0(\varepsilon)$$

and thus as a final answer

$$\begin{aligned} A_{21} &= A_0(m) \\ A_{22} &= -\frac{m^2}{4} A_0(m) + \frac{m^4}{8} \end{aligned} \quad (89)$$

2. Self-energies

$$\int_k \frac{1}{k^2 - m_1^2} \frac{1}{(k+p)^2 - m_2^2} = B_0(m_1, m_2; p^2) \quad (90)$$

$$\int_k \frac{k^\mu}{(1)(2)} = p^\mu B_1(m_1, m_2; p^2) \quad (91)$$

where contraction with p_μ and using

$$2pk = (p+k)^2 - m_2^2 - (k^2 - m_1^2) - (p^2 + m_1^2 - m_2^2)$$

yields

$$\begin{aligned} 2p^2 B_1 &= \int_k \frac{2pk}{(1)(2)} = \int_k \frac{1}{(1)} - \int_k \frac{1}{(2)} - (p^2 + m_1^2 - m_2^2) \int_k \frac{1}{(1)(2)} \\ &= -A_0(m_1) + A_0(m_2) - (p^2 + m_1^2 - m_2^2) B_0 \end{aligned}$$

$$\parallel B_1(m_2, m_2; p^2) = \frac{1}{2p^2} \{-A_0(m_1) + A_0(m_2) - (p^2 + m_1^2 - m_2^2) B_0\} \quad (92)$$

$$\int_k \frac{k^\mu k^\nu}{(1)(2)} = p^\mu p^\nu B_{21} - g^{\mu\nu} B_{22} \quad (93)$$

Contraction with p_ν gives

$$\begin{aligned} 2p^\mu (p^2 B_{21} - B_{22}) &= \int_k \frac{k^\mu (2pk)}{(1)(2)} \\ &= \int_k \frac{k^\mu}{(1)} - \int_k \frac{k^\mu}{(2)} - (p^2 + m_1^2 - m_2^2) \int_k \frac{k^\mu}{(1)(2)} \\ &= -p^\mu A_0(m_2) - p^\mu (p^2 + m_1^2 - m_2^2) B_1(m_1, m_2; p^2) \\ \triangleright \quad 2(p^2 B_{21} - B_{22}) &= -A_0(m_2) - (p^2 + m_1^2 - m_2^2) B_1 \end{aligned}$$

while contraction with $g_{\mu\nu}$ yields

$$p^2 B_{21} - dB_{22} = \int_k \frac{k^2}{(1)(2)} = \int_k \frac{1}{(2)} + m_1^2 \int_k \frac{1}{(1)(2)}$$

$$\triangleright \quad p^2 B_{21} - dB_{22} = -A_0(m_2) + m_1^2 B_0(m_1, m_2; p^2)$$

Now we have to expand in $d = 4 - \varepsilon, \varepsilon \rightarrow 0$: From

$$\begin{aligned} 2p^2 B_{21} - 2B_{22} &= -A_0(m_2) - (p^2 + m_1^2 - m_2^2) B_1 \\ p^2 B_{21} - 4B_{22} &= -A_0(m_2) + m_1^2 B_0 - \varepsilon B_{22} \end{aligned}$$

we obtain

$$B_{22} = \frac{1}{6} \left\{ A_0(m_2) - 2m_1^2 B_0 - (p^2 + m_1^2 - m_2^2) B_1 - 2\epsilon B_{22} \right\}$$

where the UV singular part (ϵ pole term) is

$$B_{22}^{sing} = -\frac{1}{4} (m_1^2 + m_2^2 - p^2/3) \frac{2}{\epsilon}$$

and hence

$$2\epsilon B_{22} = -(m_1^2 + m_2^2 - p^2/3) + O(\epsilon) .$$

This result also determines

$$B_{21} = \frac{1}{3p^2} \left\{ -A_0(m_2) - 2(p^2 + m_1^2 - m_2^2) B_1 - m_1^2 B_0 + \epsilon B_{22} \right\}$$

and leads us to the final answer

$$\begin{aligned} B_{21} &= \frac{1}{3p^2} \left\{ -A_0(m_2) - 2(p^2 + m_1^2 - m_2^2) B_1 - m_1^2 B_0 - 1/2(m_1^2 + m_2^2 - p^2/3) \right\} \\ B_{22} &= \frac{1}{6} \left\{ +A_0(m_2) - (p^2 + m_1^2 - m_2^2) B_1 - 2m_1^2 B_0 - (m_1^2 + m_2^2 - p^2/3) \right\} \end{aligned} \quad (94)$$

where the arguments of the B -functions are obvious.

3. Form factors

In the simplest cases we define the following invariant amplitudes

$$\int_k \frac{1}{k^2 - m_1^2} \frac{1}{(k + p_1)^2 - m_2^2} \frac{1}{(k + p_1 + p_2)^2 - m_3^2} \doteq -C_0(m_1, m_2, m_3; p_1^2, p_2^2, p_3^2) \quad (95)$$

$$\int_k \frac{k^\mu}{(1)(2)(3)} \doteq -p_1^\mu C_{11} - p_2^\mu C_{12} \quad (96)$$

$$\int_k \frac{k^\mu k^\nu}{(1)(2)(3)} \doteq -p_1^\mu p_1^\nu C_{21} - p_2^\mu p_2^\nu C_{22} - (p_1^\mu p_2^\nu + p_2^\mu p_1^\nu) C_{23} + g^{\mu\nu} C_{24} \quad (97)$$

where $p_3 \doteq -(p_1 + p_2)$.

The C_{1i} 's can be found using all possible independent contractions. This leads to the equations

$$\underbrace{\begin{pmatrix} p_1^2 & p_1 p_2 \\ p_1 p_2 & p_2^2 \end{pmatrix}}_X \begin{pmatrix} C_{11} \\ C_{21} \end{pmatrix} = \begin{pmatrix} R_1 \\ R_2 \end{pmatrix}$$

with

$$\begin{aligned} R_1 &= \frac{1}{2}(B_0(m_2, m_3; p_2^2) - B_0(m_1, m_3; p_3^2) \\ &\quad - (p_1^2 + m_1^2 - m_2^2)C_0) \\ R_2 &= \frac{1}{2}(B_0(m_1, m_3; p_3^2) - B_0(m_1, m_2; p_1^2) \\ &\quad + (p_1^2 - p_3^2 - m_2^2 + m_3^2)C_0) . \end{aligned}$$

The inverse of the kinematical matrix of the equation to be solved is

$$X^{-1} = \frac{1}{\text{Det}X} \begin{pmatrix} p_2^2 & -p_1p_2 \\ -p_1p_2 & p_1^2 \end{pmatrix}, \quad \text{Det}X \doteq p_1^2p_2^2 - (p_1p_2)^2$$

and the solution reads

$$\begin{aligned} C_{11} &= \frac{1}{\text{Det}X} \{p_2^2R_1 - (p_1p_2)R_2\} \\ C_{12} &= \frac{1}{\text{Det}X} \{-(p_1p_2)R_1 + p_1^2R_2\} . \end{aligned} \quad (98)$$

The same procedure applies to the more elaborate case of the C_{2i} 's where the solution may be written in the form

$$C_{24} = -\frac{m_1^2}{2}C_0 + \frac{1}{4}B_0(2, 3) - \frac{1}{4}(f_1C_{11} + f_2C_{12}) + \frac{1}{4} \quad (99)$$

$$\begin{pmatrix} C_{21} \\ C_{23} \end{pmatrix} = X^{-1} \begin{pmatrix} R_3 \\ R_5 \end{pmatrix}; \quad \begin{pmatrix} C_{23} \\ C_{22} \end{pmatrix} = X^{-1} \begin{pmatrix} R_4 \\ R_6 \end{pmatrix} \quad (100)$$

with

$$\begin{aligned} R_3 &= C_{24} - \frac{1}{2}(f_1C_{11} + B_1(1, 3) + B_0(2, 3)) \\ R_5 &= -\frac{1}{2}(f_2C_{11} + B_1(1, 2) - B_1(1, 3)) \\ R_4 &= -\frac{1}{2}(f_1C_{12} + B_1(1, 3) - B_1(2, 3)) \\ R_6 &= C_{24} - \frac{1}{2}(f_2C_{12} - B_1(1, 3)) \end{aligned}$$

and

$$f_1 = p_1^2 + m_1^2 - m_2^2; \quad f_2 = p_3^2 - p_1^2 + m_2^2 - m_3^2 .$$

The notation used for the B -functions is as follows: $B_0(1, 2)$ denotes the two point function obtained by dropping propagator $\frac{1}{(3)}$ from the form factor i.e. $\int_k \frac{1}{(1)(2)}$ and correspondingly for the other cases.

6. Applications

1. Virtual fermion contributions to gauge boson self-energies

$$-i\Pi^{\mu\nu}(p) \doteq \begin{array}{c} f_2, k+p \\ \nearrow V_\nu \\ \text{---} \\ \text{---} \\ \text{---} \\ \searrow V_\mu \\ B \qquad \qquad \qquad A \\ \text{---} \\ f_1, k \end{array}$$

$$= -g_A g_B \int \frac{d^4 k}{(2\pi)^4} \text{Tr} \left\{ \frac{k + m_1}{k^2 - m_1^2} \gamma^\nu (a_B + b_B \gamma_5) \frac{p + k + m_2}{(p + k)^2 - m_2^2} \gamma^\mu (a_A + b_A \gamma_5) \right\}$$

For the different self-energies the couplings are given by:

1. $W^+ W^-$: $g_A = g_B = \frac{M_W}{2v}$; $a_A = a_B = a = 1$
 $b_A = b_B = b = -1$
 $\begin{pmatrix} f_1 \\ f_2 \end{pmatrix}$ doublet $m_1 \neq m_2$; V_{12} assumed
2. ZZ : $g_A = g_B = \frac{M_Z}{2v}$; $a_A = a_B = a = 4Q_f \sin^2 \Theta_W - 2I_{3f}$
 $b_A = b_B = b = -2I_{3f}$
 $f_2 = f_1 = f$ single fermion ; $2I_{3f} = \pm 1$, $m_1 = m_2 = m_f$
3. $Z\gamma$: $g_A = eQ_f$, $g_B = \frac{M_Z}{2v}$; $a_A = 1$, $a_B = a = 4Q_f \sin^2 \Theta_W - 2I_{3f}$
 $b_A = 0$; $b_B = b = -2I_{3f}$
 $f_2 = f_1 = f$; $m_1 = m_2 = m_f$
4. $\gamma\gamma$: $g_A = g_B = eQ_f$; $a_A = a_B = 1$
 $b_A = b_B = 0$
 $f_2 = f_1 = f$; $m_1 = m_2 = m_f$

Calculation of the trace of Dirac matrices:

$$\begin{aligned}
& (k + m_1) \gamma^\nu (a + b\gamma_5)_B (p + k + m_2) \gamma^\mu (a + b\gamma_5)_A \\
= & k \gamma^\nu (a + b\gamma_5)_B (p + k) \gamma^\mu (a + b\gamma_5)_A \\
& + m_1 m_2 \gamma^\nu (a + b\gamma_5)_B \gamma^\mu (a + b\gamma_5)_A \\
& + \text{terms with odd number of } \gamma \text{'s (have } \text{Tr}(\text{)} = 0\text{)} \\
= & k \gamma^\nu (p + k) \gamma^\mu (a_A a_B + b_A b_B + (a_A b_B + a_B b_A) \gamma_5) \\
& + m_1 m_2 \gamma^\nu \gamma^\mu (a_A a_B - b_A b_B - (a_A b_B - a_B b_A) \gamma_5) \\
& + \dots
\end{aligned}$$

Now, $\text{Tr}\gamma^\nu\gamma^\mu\gamma_5 = 0$ and $\text{Tr}k\gamma^\nu(p+k)\gamma^\mu\gamma_5 = 4i\epsilon^{\alpha\nu\beta\mu}k_\alpha(p+k)_\beta$ after integration $\int_k k_\alpha \dots = p_\alpha \dots$ cannot contribute since $\epsilon^{\alpha\beta\nu\mu}p_\alpha p_\beta \equiv 0$.

The trace of the remaining terms is given by:

$$\begin{aligned}\text{Tr}(\dots) &= 4(g^{\alpha\nu}g^{\beta\mu} + g^{\alpha\mu}g^{\beta\nu} - g^{\alpha\beta}g^{\mu\nu})k_\alpha(p+k)_\beta(a_Aa_B + b_Ab_B) \\ &+ 4m_1m_2g^{\mu\nu}(a_Aa_B - b_Ab_B) \\ &= 4(a_Ab_B + b_Ab_B)\{k^\nu(p+k)^\mu + k^\mu(p+k)^\nu - g^{\mu\nu}(k^2 + kp)\} \\ &+ 4(a_Aa_B - b_Ab_B)m_2m_2g^{\mu\nu}\end{aligned}$$

We now may evaluate the integrals. We use the notations (1) = $k^2 - m_1^2 + i\epsilon$, (2) = $(p+k)^2 - m_2^2 + i\epsilon$ and $\int_k \dots \doteq \frac{16\pi^2}{i} \int \frac{d^d k}{(2\pi)^d} \dots$ and use the definitions

$$\begin{aligned}\int_k \frac{k^\mu k^\nu}{(1)(2)} &\doteq p^\mu p^\nu B_{21} - g^{\mu\nu}B_{22} \\ \int_k \frac{k^\mu}{(1)(2)} &\doteq p^\mu B_1 \\ \int_k \frac{1}{(1)(2)} &= B_0 = B_0(m_1, m_2; p^2) \\ \int_k \frac{1}{(1)} &= -A_0(m_1); \quad \int_k \frac{1}{(2)} = -A_0(m_2).\end{aligned}$$

We write $\Pi^{\mu\nu}$ in the form

$$\begin{aligned}\Pi^{\mu\nu}(p) &= g^{\mu\nu}\Pi_1(p^2) + p^\mu p^\nu\Pi_2(p^2) \\ &= (g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2})\Pi_1 + \frac{p^\mu p^\nu}{p^2}(p^2\Pi_2 + \Pi_1).\end{aligned}$$

Only the transverse amplitude Π_1 contributes to S -matrix elements, e.g. if contracted with a polarization vector the Π_2 amplitude drops out due to $\epsilon_\mu(p, \lambda)p^\mu = 0$. In general Π_2 cancels against ghost amplitudes.

The relevant integrals we need are given by:

$$\begin{aligned}2\int_k \frac{k^\mu k^\nu}{(1)(2)} &= p^\mu p^\nu 2B_{21} - g^{\mu\nu}2B_{22} \\ 2\int_k \frac{p^\mu k^\nu}{(1)(2)} &= p^\mu p^\nu 2B_1 \\ \int_k \frac{k^2 + pk}{(1)(2)} &= \frac{1}{2} \left(\int_k \frac{1}{(2)} + \int_k \frac{1}{(1)} + (m_1^2 + m_2^2 - p^2) \int_k \frac{1}{(1)(2)} \right) \\ &= \frac{1}{2}(-A_0(m_1) - A_0(m_2) + (m_1^2 + m_2^2 - p^2)B_0)\end{aligned}$$

where, for the last integral, we have used the decomposition

$$k^2 + pk = \frac{1}{2}(2k^2 + 2pk) = \frac{1}{2}(\underbrace{k^2 - m_1^2}_{(1)} + \underbrace{(k+p)^2 - m_2^2}_{(2)} - (p^2 - m_1^2 - m_2^2))$$

We then obtain the result

$$\begin{aligned}\Pi_1 &= (-i)\frac{i}{16\pi^2}4g_Ag_B \cdot \\ &\quad \{ (a_Aa_B + b_Ab_B) \left(-2B_{22} + \frac{1}{2}A_0(m_1) + \frac{1}{2}A_0(m_2) + \frac{1}{2}(p^2 - m_1^2 - m_2^2)B_0 \right) \\ &\quad + (a_Aa_B - b_Ab_B)m_1m_2B_0 \} \\ \Pi_2 &= (-i)\frac{i}{16\pi^2}4g_Ag_B \cdot \\ &\quad (a_Aa_B + b_Ab_B)(2B_{21} + 2B_1)\end{aligned}$$

with

$$\begin{aligned}
 B_1 &= \frac{1}{2p^2} (-A_0(m_1) + A_0(m_2) - (p^2 + m_1^2 - m_2^2)B_0) \\
 B_{21} &= \frac{1}{3p^2} (-A_0(m_2) - 2(p^2 + m_1^2 - m_2^2)B_1 - m_1^2 B_0 \\
 &\quad - 1/2(m_1^2 + m_2^2 - p^2/3)) \\
 B_{22} &= \frac{1}{6} (A_0(m_2) - (p^2 + m_1^2 - m_2^2)B_1 - 2m_1^2 B_0 \\
 &\quad - (m_1^2 + m_2^2 - p^2/3)) .
 \end{aligned}$$

Inserting the latter expressions yields the final result:

$$\begin{aligned}
 \Pi_1 &= \frac{1}{16\pi^2} 4g_A g_B \cdot \left\{ \frac{1}{3} (a_A a_B + b_A b_B) [(m_1^2 + m_2^2 - p^2/3) \right. \\
 &\quad + A_0(m_1) + A_0(m_2) - \frac{m_1^2 - m_2^2}{2p^2} (A_0(m_1) - A_0(m_2)) \\
 &\quad + \frac{2p^4 - p^2(m_1^2 + m_2^2) - (m_1^2 - m_2^2)^2}{2p^2} B_0(m_1, m_2; p^2)] \\
 &\quad \left. + (a_A a_B - b_A b_B) m_1 m_2 B_0(m_1, m_2; p^2) \right\}
 \end{aligned} \tag{101}$$

We now specialize the result for the different self-energy functions:

1. W-self energy (contribution of a fermion doublet)

$$\begin{aligned}
 \Pi_1^{WW} &= \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \cdot \frac{4}{3} \left\{ m_1^2 + m_2^2 - p^2/3 + A_0(m_1) + A_0(m_2) \right. \\
 &\quad - \frac{m_1^2 - m_2^2}{2p^2} (A_0(m_1) - A_0(m_2)) \\
 &\quad \left. + \frac{2p^4 - p^2(m_1^2 + m_2^2) - (m_1^2 - m_2^2)^2}{2p^2} B_0(m_1, m_2; p^2) \right\}
 \end{aligned} \tag{102}$$

For the evaluation of $\Pi_1^{WW}(0)$ we use the following relations:

$$\begin{aligned}
 B_0(m_1, m_2; p^2) &= B_0(m_1, m_2; 0) + p^2 \dot{B}_0(m_1, m_2; 0) + \dots \\
 B_0(m_1, m_2; 0) &= -\frac{A_0(m_1) - A_0(m_2)}{m_1^2 - m_2^2} \\
 2(m_1^2 - m_2^2)^2 \dot{B}_0(m_1, m_2; 0) &= A_0(m_1) + A_0(m_2) + (m_1^2 + m_2^2)[1 + B_0(m_1, m_2; 0)] \\
 A_0(m) &= -m^2 + m^2 \ln \frac{m^2}{\mu^2}
 \end{aligned}$$

where, writing the bare quantities in the \overline{MS} -scheme, $\ln \mu^2 = \frac{2}{\epsilon} - \gamma + \ln 4\pi$. We find

$$\begin{aligned}
 \Pi_1^{WW}(0) &= \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \left\{ m_1^2 + m_2^2 + A_0(m_1) + A_0(m_2) \right. \\
 &\quad \left. + \frac{(m_1^2 + m_2^2)}{(m_1^2 - m_2^2)} (A_0(m_1) - A_0(m_2)) \right\} \\
 &= \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \left\{ 2 \frac{m_1^4 \ln \frac{m_1^2}{\mu^2} - m_2^4 \ln \frac{m_2^2}{\mu^2}}{m_1^2 - m_2^2} - (m_1^2 + m_2^2) \right\}
 \end{aligned} \tag{103}$$

2. Z -self energy (contribution of a single fermion)

$$\begin{aligned}\Pi_1^{ZZ} = & \frac{\sqrt{2}G_\mu M_Z^2}{16\pi^2} \frac{1}{3} \left\{ (a_f^2 + b_f^2) \left[2m_f^2 - p^2/3 + 2A_0(m_f) \right. \right. \\ & + (p^2 - m_f^2) B_0(m_f, m_f; p^2) \left. \right] \\ & \left. + (a_f^2 - b_f^2) 3m_f^2 B_0(m_f, m_f; p^2) \right\}\end{aligned}\quad (104)$$

For the evaluation of $\Pi_1^{ZZ}(0)$ we use:

$$\begin{aligned}B_0(m_f, m_f; 0) &= -1 - \frac{A_0(m_f)}{m_f^2} \\ A_0(m_f) &= -m_f^2 + m_f^2 \ln \frac{m_f^2}{\mu^2}\end{aligned}$$

and find

$$\begin{aligned}\Pi_1^{ZZ}(0) &= \frac{\sqrt{2}G_\mu M_Z^2}{16\pi^2} \left\{ 2b_f^2(m_f^2 + A_0(m_f)) \right\} \\ &= \frac{\sqrt{2}G_\mu M_Z^2}{16\pi^2} \left\{ 2m_f^2 \ln \frac{m_f^2}{\mu^2} \right\}\end{aligned}\quad (105)$$

a contribution which is purely axial (proportional to b_f).

3. $Z\gamma$ -mixing ($b_A b_B = 0$ pure vector contribution)

$$\begin{aligned}\Pi_1^{Z\gamma} &= \frac{eQ_f(\sqrt{2}G_\mu)^{1/2}M_Z}{16\pi^2} \cdot a_f \cdot \frac{2}{3} \left\{ 2m_f^2 - p^2/3 + 2A_0(m_f) \right. \\ &+ (p^2 + 2m_f^2) B_0(m_f, m_f; p^2) \left. \right\} \\ \Pi_1^{Z\gamma}(0) &= 0 \\ \Pi_1^{Z\gamma} &\simeq -\frac{eQ_f a_f (\sqrt{2}G_\mu)^{1/2} M_Z}{16\pi^2} \frac{2}{3} p^2 \left\{ \ln \frac{p^2}{\mu^2} - \frac{5}{3} \right\} \\ m_f^2 &\ll |p^2|\end{aligned}\quad (106)$$

4. γ -self energy (photon vacuum polarization)

$$\begin{aligned}\Pi_1^{\gamma\gamma} &= \frac{e^2 Q_f^2}{16\pi^2} \frac{4}{3} \left\{ 2m_f^2 - p^2/3 + 2A_0(m_f) + (p^2 + 2m_f^2) B_0(m_f, m_f; p^2) \right\} \\ &= -\frac{e^2 Q_f^2}{16\pi^2} \frac{4}{3} p^2 \left[\ln \frac{m_f^2}{\mu^2} - \frac{5}{3} - y_f - 2(1 + \frac{y_f}{2})(y_f - 1)G(y_f) \right]\end{aligned}\quad (107)$$

where we defined $y_f = \frac{4m_f^2}{p^2}$ and $G(y_f) = \frac{1}{2\beta_f} \ln \frac{\beta_f + 1}{\beta_f - 1}$ with $\beta_f = \sqrt{1 - y_f}$.

As it should be, we find $\Pi_1^{\gamma\gamma}(0) = 0$ i.e. the photon remains massless (unrenormalized). This remains true also at higher orders in the perturbation expansion.

For $\Pi_1^{\gamma\gamma}(p^2) = \frac{\Pi_1^{\gamma\gamma}}{p^2}$ we find the following asymptotic values

$$\begin{aligned}
\Pi_1^{'\gamma\gamma}(0) &= -\frac{e^2}{16\pi^2} \frac{4}{3} Q_f^2 \ln \frac{m_f^2}{\mu^2} \\
\Pi_1^{'\gamma\gamma}(p^2) &\simeq -\frac{e^2}{16\pi^2} \frac{4}{3} Q_f^2 \left(\ln \frac{p^2}{\mu^2} - \frac{5}{3} \right) \\
m_f^2 &\ll |p^2|
\end{aligned} \quad (108)$$

We may apply these results to calculate quantities which show up in the calculation of electroweak parameter shifts to be discussed in Sections IV and V.

1. ρ -parameter

The ρ -parameter is defined as the neutral to charged current ratio, which within the SM is a finite gauge invariant calculable quantity. For the fermion contributions we obtain

$$\begin{aligned}
\rho &= \frac{G_{NC}}{G_\mu} = 1 + \Delta\rho \\
\Delta\rho &= \frac{\Pi_1^Z(0)}{M_Z^2} - \frac{\Pi_1^{WW}(0)}{M_W^2} \\
&= \frac{\sqrt{2}G_\mu}{16\pi^2} N_{cf} \left(m_1^2 + m_2^2 + \frac{2m_1^2 m_2^2}{m_1^2 - m_2^2} \ln \frac{m_2^2}{m_1^2} \right) \\
&\simeq \frac{\sqrt{2}G_\mu}{16\pi^2} N_{cf} \cdot \left\{ \begin{array}{ll} m_{heavy}^2 &; m_{heavy} \gg m_{light} \\ 0 &; m_1 = m_2 \end{array} \right\}
\end{aligned}$$

(Veltman 1977). For the known fermion doublets only the top-bottom doublet has a large mass splitting. A very heavy top yields a contribution

$$\Delta\rho^{top} \simeq \frac{\sqrt{2}G_\mu}{16\pi^2} 3m_t^2; \quad m_t \gg m_b.$$

2. Δr

Within the SM the Fermi constant G_μ can be calculated in terms of α , M_W and M_Z . It thus appears as a correction to the μ -decay amplitude

$$\sqrt{2}G_\mu = \frac{\pi\alpha}{M_W^2(1 - \frac{M_W^2}{M_Z^2})} (1 + \Delta r).$$

One may write Δr in the form

$$\Delta r = \Delta\alpha - \frac{\cos^2\Theta_W}{\sin^2\Theta_W} \Delta\rho + \Delta r_{rem}$$

where Δr_{rem} collects the numerically small terms ($\sim 0.6\%$). The large term $\Delta\alpha$ is due to the photon vacuum polarization

$$\begin{aligned}
\Delta\alpha &= \Pi_1^{'\gamma\gamma}(0) - \Pi_1^{'\gamma\gamma}(M_Z^2) \\
&= \frac{\alpha}{3\pi} \sum_f Q_f^2 N_{cf} \left(\ln \frac{M_Z^2}{m_f^2} - \frac{5}{3} \right) \simeq 0.06.
\end{aligned}$$

The numerical value is given for the sum of the contributions from the light fermions e, μ , τ , u, d, c, s, b (see Sec. IV). Since the W-mass is not yet very precisely known we may use this result to predict M_W in terms of α , G_μ and M_Z . By solving the defining equation for M_W we obtain

$$M_W^2 = \frac{\rho M_Z^2}{2} \left(1 + \sqrt{1 - \frac{4A_0^2}{\rho M_Z^2} \frac{1}{1 - \Delta\alpha} (1 + \Delta r_{rem})} \right)$$

where $\rho = \frac{1}{1 - \Delta\rho}$ and

$$A_0^2 = \frac{\pi\alpha}{\sqrt{2}G_\mu} .$$

3. NC couplings near the Z peak

The $Z f\bar{f}$ -vertex to lowest order is given by

$$(\sqrt{2}G_\mu)^{1/2} 2M_Z \gamma^\mu (-Q_f \sin^2 \Theta_W + (1 - \gamma_5) \frac{I_{3f}}{2})$$

and higher order effects (radiative corrections) may be included by using renormalized effective couplings:

$$\begin{aligned} G_\mu &\rightarrow \rho_f G_\mu = G_{NCf}(M_Z^2) \\ \sin^2 \Theta_W &\rightarrow \kappa_f \sin^2 \Theta_W = \sin^2 \Theta_f \end{aligned}$$

Since α , G_μ and M_Z are given, we may calculate $\sin^2 \Theta_f$ using

$$\sqrt{2}G_\mu M_Z^2 \cos^2 \Theta_f \sin^2 \Theta_f = \frac{\pi\alpha}{1 - \Delta r_f}$$

where Δr_f has the form

$$\Delta r_f = \Delta\alpha - \Delta\rho + \Delta_{f,rem} ,$$

a relation similar to the expression given for Δr , however with a $\Delta\rho$ contribution which is by a factor $\sin^2 \Theta_W / \cos^2 \Theta_W$ smaller.

We finally calculate another interesting type of diagrams, namely, those exhibiting a virtual Higgs particle.

2. Virtual Higgs contributions to gauge boson self-energies

$$-i\Pi^{\mu\nu}(p) = \text{Diagram } 1 + \text{Diagram } 2 + \text{Diagram } 3$$

Diagram 1: A loop with a Higgs boson line (H) and a gauge boson line (V) entering and leaving the loop. The loop is shaded.

Diagram 2: A loop with a Higgs boson line (H) and a gauge boson line (V) entering and leaving the loop. The loop is shaded.

Diagram 3: A loop with a Higgs boson line (H) and a gauge boson line (phi) entering and leaving the loop. The loop is shaded.

$$W: \quad \left(\frac{v^2 g^2}{2}\right)^2 \int_k \left(\frac{(1-\xi)k^\mu k^\nu}{k^2 - \xi M_W^2 + i\epsilon} - g^{\mu\nu} \right) \frac{1}{k^2 - M_W^2 + i\epsilon} \frac{1}{(k+p)^2 - m_H^2 + i\epsilon}$$

$$+ \left(\frac{g}{2}\right)^2 \int_k \frac{1}{k^2 - \xi M_W^2 + i\epsilon} \frac{1}{(p+k)^2 - m_H^2 + i\epsilon} (2k+p)^\mu (2k+p)^\nu$$

$$- \frac{g^2}{2} \frac{1}{2} \int_k \frac{g^{\mu\nu}}{k^2 - m_H^2 + i\epsilon}$$

$$Z: \quad g \rightarrow \frac{g}{\cos \Theta_W}, \quad M_W \rightarrow M_Z$$

We take the 't Hooft-Feynman gauge $\xi = 1$ and use $\frac{g^2}{4} = \frac{M_W^2}{v^2} = \sqrt{2}G_\mu M_W^2$ obtaining

$$= \frac{i}{16\pi^2} \sqrt{2}G_\mu M_W^2 \cdot$$

$$\{ p^\mu p^\nu [B_0(M_W, m_H; p^2) + 4B_1 + 4B_{21}] - g^{\mu\nu} [4M_W^2 B_0 + 4B_{22} + A_0(m_H)] \}$$

Thus we get the amplitudes

$$\Pi_1^{WW}(p^2) = \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \{ 4B_{22} + 4M_W^2 B_0 + A_0(m_H) \}$$

$$\Pi_2^{WW}(p^2) = -\frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \{ 4B_{21} + 4B_1 + B_0 \} .$$

In terms of the scalar one-loop integrals we then find for the physical transverse part ($V = W, Z$):

$$\Pi_1^{VV}(p^2) = \frac{\sqrt{2}G_\mu M_V^2}{3 \cdot 16\pi^2} \left\{ A_0(M_V) + 4A_0(m_H) + \frac{M_V^2 - m_H^2}{p^2} (A_0(M_V) - A_0(m_H)) \right.$$

$$+ (p^2 + 10M_V^2 - 2m_H^2 + \frac{(M_V^2 - m_H^2)^2}{p^2}) B_0(M_V, m_H; p^2)$$

$$\left. - 2(M_V^2 + m_H^2 - p^2/3) \right\} \quad (109)$$

Proceeding as we did for the fermions we get

$$\Pi_1^{VV}(0) = \frac{\sqrt{2}G_\mu M_V^2}{2 \cdot 16\pi^2} \left\{ 4A_0(m_H) - M_V^2 - m_H^2 - 6 \frac{M_V^2}{M_V^2 - m_H^2} (A_0(M_V) - A_0(m_H)) \right\}$$

$$= \frac{\sqrt{2}G_\mu M_V^2}{2 \cdot 16\pi^2} \left\{ 5(M_V^2 - m_H^2) + 4m_H^2 \ln \frac{m_H^2}{\mu^2} - 6M_V^2 \ln \frac{M_V^2}{\mu^2} \right.$$

$$\left. + 6 \frac{M_V^2 m_H^2}{M_V^2 - m_H^2} \ln \frac{m_H^2}{M_V^2} \right\} \quad (110)$$

in the 't Hooft-Feynman gauge $\xi = 1$ and the \overline{MS} -scheme.

Using these results we may calculate the Higgs contributions to the parameter shifts.

1. ρ -parameter

$$\begin{aligned}\Delta\rho = \frac{\Pi_1^{ZZ}(0)}{M_Z^2} - \frac{\Pi_1^{WW}(0)}{M_W^2} &= \frac{\sqrt{2}G_\mu}{2\cdot 16\pi^2} \left\{ -6(M_Z^2 \ln \frac{M_Z^2}{\mu^2} - M_W^2 \ln \frac{M_W^2}{\mu^2}) \right. \\ &\quad \left. + 5(M_Z^2 - M_W^2) + 6 \left(\frac{M_Z^2 m_H^2}{M_Z^2 - m_H^2} \ln \frac{m_H^2}{M_Z^2} - \frac{M_W^2 m_H^2}{M_W^2 - m_H^2} \ln \frac{m_H^2}{M_W^2} \right) \right\}.\end{aligned}$$

In contrast to the fermion contributions, the Higgs contribution alone is neither gauge invariant nor UV-finite! Only the sum with the remaining (non-fermionic) contribution is finite and gauge independent. For $\mu = M_W$ and $\xi = 1$ one obtains a possible splitting of terms which exhibits the full m_H -dependence in any case.

We finally consider limiting cases: (setting $\mu = M_W$)

i) $m_H \ll M_V$:

$$\Delta\rho = \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \cdot 3 \frac{\sin^2 \Theta_W}{\cos^2 \Theta_W} \left(\frac{\ln \cos^2 \Theta_W}{\sin^2 \Theta_W} + \frac{5}{6} \right)$$

ii) $m_H \gg M_V$:

$$\Delta\rho = -\frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \cdot 3 \frac{\sin^2 \Theta_W}{\cos^2 \Theta_W} \left(\ln \frac{m_H^2}{M_W^2} - \frac{5}{6} \right).$$

Notice:

1. For $g' \rightarrow 0$ ($M_Z \rightarrow M_W$, $\sin^2 \Theta_W \rightarrow 0$) we get $\Delta\rho^{\text{Higgs}} \equiv 0$.
 W^\pm, Z would be $SU(2)_R$ triplet of a global $SU(2)_R$ of $\mathcal{L}_{\text{Higgs}}$, i.e. $\Delta\rho^{\text{Higgs}}$ measures breaking of $SU(2)_R$ by the weak hypercharge.
2. The limit $m_H \rightarrow 0$ exists and yields a small finite term.
3. There remain no m_H^2 terms for $m_H \rightarrow \infty$. Instead one observes a logarithmic Higgs mass dependence.

Similarly one finds:

2. $\Delta r, \Delta r_f$

$$\begin{aligned}\Delta r^{\text{Higgs}} &\simeq \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \frac{11}{3} \left(\ln \frac{m_H^2}{M_W^2} - \frac{5}{6} \right) \\ \Delta r_f^{\text{Higgs}} &\simeq \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \frac{1 + 9 \sin^2 \Theta_W}{3 \cos^2 \Theta_W} \left(\ln \frac{m_H^2}{M_W^2} - \frac{5}{6} \right).\end{aligned}$$

III. RENORMALIZATION

So far, we have defined dimensionally regularized Green functions for complex space-time dimensions d with $\text{Re } d < 4$ which have poles in $\varepsilon = d - 4$. These *bare* Green functions have been obtained by the perturbation expansion based on the splitting

$$\mathcal{L}_b = \mathcal{L}_{b\,o} + \mathcal{L}_{b\,int} \quad (111)$$

of the full Lagrangian \mathcal{L}_b into a free and an interaction part. This splitting is not UV-finite, and hence not physical, and makes sense only if we have regularized the theory. The bare perturbation expansion thus is *regularization dependent*. In particular, using dimensional regularization it depends on an arbitrary scale parameter μ ! For the bare Green functions the limit $\varepsilon \rightarrow 0$ does not exist! Green functions which allow to take the limit $\varepsilon \rightarrow 0$ require renormalization, which amounts to a reorganization of the formal perturbation series.

Basic reason for the problem is the following: We have tried to solve the equations of motion of the system without imposing appropriate boundary conditions. Since our goal is to calculate scattering matrix elements, the physical boundary conditions are obvious: We have to introduce renormalized fields which describe, at asymptotic times, free physical scattering states. For the electron field, for example

$$\psi_e^{\text{ren}}(\vec{x}, t) \xrightarrow{t \rightarrow -/+ \infty} \psi_{e\,\text{in/out}}(\vec{x}, t) \quad (112)$$

must describe a free electron of mass m_e . This is the so called LSZ asymptotic condition [36]

Since masses and the normalization of fields are altered by quantum effects (loops) the physical boundary conditions (renormalization conditions) must be enforced by renormalization. These boundary conditions are conditions on the mass-shell $p^2 = m^2$ of the external particles, therefore the corresponding renormalization procedure (renormalization scheme) is called *on-shell scheme*.

The independent parameters are the physical particle masses plus a coupling constant. A natural choice for the coupling is the universal (due to electromagnetic current conservation) fine structure constant α . This defines a QED-like on-shell renormalization scheme with *independent parameters*:

$$\alpha, M_W, M_Z, m_f, m_H. \quad (113)$$

All other couplings are then fixed (*dependent parameters*) by the mass-coupling relations:

$$\begin{aligned} \sin^2 \Theta_W &= 1 - \frac{M_W^2}{M_Z^2} \\ g &= \frac{\sqrt{4\pi\alpha}}{\sin \Theta_W} \quad , \quad g' = \frac{\sqrt{4\pi\alpha}}{\cos \Theta_W} \\ \sqrt{2}G_\mu &= \frac{1}{v^2} = \frac{\pi\alpha}{M_W^2 \sin^2 \Theta_W}. \end{aligned} \quad (114)$$

The renormalization then may be performed in two steps:

1. Parameter renormalization

The parameters in the true bare Lagrangian are the bare parameters α_b, M_{Wb}, \dots . We *reparametrize* the bare Lagrangian in terms of the physical parameters (experimental input) α, M_W, \dots by the following parameter renormalizations:

$$\begin{aligned} M_{Vb}^2 &= M_V^2 + \delta M_V^2 = M_V^2 \left(1 + \frac{\delta M_V^2}{M_V^2}\right); V = W, Z \\ m_{fb} &= m_f + \delta m_f = m_f \left(1 + \frac{\delta m_f}{m_f}\right) \\ m_{Hb}^2 &= m_H^2 + \delta m_H^2 = m_H^2 \left(1 + \frac{\delta m_H^2}{m_H^2}\right) \\ \alpha_b &= \alpha + \delta\alpha = \alpha \left(1 + \frac{\delta\alpha}{\alpha}\right) \end{aligned} \quad (115)$$

which have to be performed for the dependent parameters (which serve as convenient abbreviations only) correspondingly :

$$\begin{aligned} \sin^2 \Theta_{Wb} &= \sin^2 \Theta_W + \delta \sin^2 \Theta_W = \sin^2 \Theta_W \left(1 + \frac{\delta \sin^2 \Theta_W}{\sin^2 \Theta_W}\right) \\ G_{\mu b} &= G_\mu + \delta G_\mu = G_\mu \left(1 + \frac{\delta G_\mu}{G_\mu}\right) \end{aligned} \quad (116)$$

where, to *linear* order (suitable for one-loop calculations):

$$\begin{aligned} \frac{\delta \sin^2 \Theta_W}{\sin^2 \Theta_W} &= \cot^2 \Theta_W \left(\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2}\right) \\ \frac{\delta G_\mu}{G_\mu} &= 2 \frac{\delta v^{-1}}{v^{-1}} = \frac{\delta\alpha}{\alpha} - \frac{\delta M_W^2}{M_W^2} - \frac{\delta \sin^2 \Theta_W}{\sin^2 \Theta_W}. \end{aligned} \quad (117)$$

It is important to notice that these parameter shifts do not alter the invariance properties of the Lagrangian. The ST-identities thus keep their *bare* form. Since the bare parameters and the renormalized parameters (determined by S-matrix elements) are gauge invariant also the parameter counter terms are *gauge invariant* ! This statement is true only if the tadpoles are treated properly. Since (momentum independent) tadpoles drop out from physical quantities we will not discuss them further (see e. g. [37]).

2. Field renormalization (wave function renormalization)

In order that the fields describe properly normalized scattering states we must renormalize them such that the residue of the propagator pole is *unity*.

For simplicity we ignore the *infrared problem* caused by soft photon effects. This problem has to be treated in the same way as in pure QED and we assume the reader to

be familiar with it. We shall use an infinitesimal photon mass m_γ as an infrared regulator at intermediate steps. For observable quantities the limit $m_\gamma \rightarrow 0$ must exist.

We then write for the physical fields:

$$\begin{aligned} V_{\mu b} &= \sqrt{Z_V} V_{\mu ren} ; V = A, Z, W^\pm \\ \psi_{f b} &= \sqrt{Z_f} \psi_{f ren} \\ H_b &= \sqrt{Z_H} H_{ren} \end{aligned} \quad (118)$$

and the Z-factors are fixed by the condition that propagators of the renormalized fields have residue *one* at the pole.

For unstable particles, like the vector bosons, the location and residue of the pole are complex. Unitarity requires the counter terms to be real. Therefore the counter terms are determined by the real parts of the location and residue of the pole, in this case.

It may be questioned whether independent field renormalizations are compatible with the local non-abelian gauge structure. In fact the canonical (= bare) form of the ST-identities only admits a renormalization factor for each field multiplet ! The following remarks are important here:

- The Z-factors are *gauge dependent* and in order to get gauge invariant S-matrix elements there is no freedom in the choice of the wave function renormalization factors. Only the Z-factors fixed by the LSZ-conditions for the individual fields lead to the physical S-matrix [38] [39].
- The apparent conflict with the ST-identities is not as serious as it looks at first. From the path-integral representation of the generating functional

$$Z\{J, \bar{\chi}, \chi, \dots\} = \int DV_{\mu i} \mathcal{D}\psi \mathcal{D}\bar{\psi} e^{i \int (L_{eff} + JV + \bar{\chi}\psi + \bar{\psi}\chi + \dots)} \quad (119)$$

we learn that a change of the integration variables, for example,

$$V_{\mu i b} \rightarrow \sqrt{Z_i} V_{\mu i ren}$$

does not change the value of the integral ! This means that if the fields $V_{\mu i}$ do not appear as external fields, all the Z-factors drop out completely in the interior of the Feynman diagrams. The Z-factors only affect the external legs (source terms in Eq. (119)) of a diagram, i.e. only external fields carry a normalization factor

$$V_{\mu i b} \rightarrow V_{\mu i ren} = \frac{1}{\sqrt{Z_i}} V_{\mu i b} . \quad (120)$$

Consequently: If we perform individual field renormalizations in the bare ST-identities their renormalized forms are not altered by higher order corrections, although, now, they have no longer a simple canonical form. Notice that, when written in terms of the physical

fields, the ST-identities do not look very symmetric anyhow. If one insists in preserving the bare form of the ST-identities one has to renormalize away only the singular ϵ -pole terms. These of course satisfy the bare ST-identities. This latter procedure is called *minimal subtraction MS* or \overline{MS} - *scheme*, defined by the substitutions

$$\begin{aligned} MS: \quad & \frac{2}{\epsilon} + \ln \mu_0^2 = \ln \mu_{MS}^2 \\ \overline{MS}: \quad & \frac{2}{\epsilon} - \gamma + \ln 4\pi + \ln \mu_0^2 = \ln \mu_{\overline{MS}}^2, \end{aligned} \quad (121)$$

respectively. These subtractions correspond to a choice of counter-terms

$$\begin{aligned} (\delta M_V^2)_{\overline{MS}} &= (\delta M_V^2)_{OS,UV} \\ &\vdots & \vdots \\ (\delta\alpha)_{\overline{MS}} &= (\delta\alpha)_{OS,UV} \\ (\delta Z_i)_{\overline{MS}} &= (\delta Z_i)_{OS,UV} \end{aligned} \quad (122)$$

as compared to the on-shell scheme (OS). By the index UV we indicated the ϵ -pole terms related to the UV-divergences. *All the renormalization schemes used by different authors range from pure \overline{MS} to pure OS and mixtures of them!*

The irreducible vertices are obtained by amputation of the external legs (amputated legs correspond to scattering states!). Amputation means multiplication with the inverse propagator which carries a factor Z_i . Thus, field renormalization for the irreducible vertices amounts to multiplication of an external (amputated) field by $\sqrt{Z_i}$. To leading order $Z_i = 1$ and we may write

$$Z_i = 1 + \delta Z_i; \sqrt{Z_i} \simeq 1 + \frac{1}{2}\delta Z_i + \dots \quad (123)$$

The renormalization procedure for physical amplitudes may be summarized by the following simple rules: Performing the parameter shifts and the field renormalizations and expanding to linear order (appropriate for one-loop calculations) we get the simple substitutions (we abbreviate $\sin^2 \Theta_W = s_W^2$)

$$\begin{aligned} eQ_f \gamma^\mu &\rightarrow eQ_f \gamma^\mu \cdot \left(1 + \frac{1}{2}\delta Z_\gamma + \delta Z_f + \frac{\delta e}{e}\right) \\ \frac{M_Z}{v} \gamma^\mu (T_{3f}(1 - \gamma_5) - 2Q_f s_W^2) &\rightarrow \frac{M_Z}{v} \gamma^\mu \left(T_{3f}(1 - \gamma_5) - 2Q_f s_W^2 \left(1 + \frac{\delta s_W^2}{s_W^2}\right) \right) \\ &\quad \cdot \left(1 + \frac{1}{2}\delta Z_Z + \delta Z_f + \frac{1}{2}\frac{\delta M_Z^2}{M_Z^2} + \frac{1}{2}\frac{\delta G_\mu}{G_\mu}\right) \\ \frac{M_W}{\sqrt{2}v} \gamma^\mu (1 - \gamma_5) &\rightarrow \frac{M_W}{\sqrt{2}v} \gamma^\mu (1 - \gamma_5) \\ &\quad \cdot \left(1 + \frac{1}{2}\delta Z_W + \frac{1}{2}\delta Z_{f_1} + \frac{1}{2}\delta Z_{f_2} + \frac{1}{2}\frac{\delta M_W^2}{M_W^2} + \frac{1}{2}\frac{\delta G_\mu}{G_\mu}\right) \end{aligned}$$

and analogously for the other vertices.

3. Renormalization schemes

The notion “renormalization scheme” is used in two different senses of the word. Often the term is used in a more technical sense as

- a specific way of performing renormalization at intermediate steps. This includes the choice of the regularization, the way field renormalizations and/or parameter renormalizations are organised. Some authors emphasize the use of renormalized Green-functions at intermediate steps others are interested in on-shell matrix-elements only. If the same physical quantity is calculated in terms of the same parameters to the same order in perturbation theory the result does not depend on the choice of the scheme. This first kind of distinction of different schemes is therefore not relevant for the physics.

The second possible distinction of renormalization schemes is more physical, namely as characterizing

- a specific choice of input parameters. Perturbative predictions in terms of different input parameter sets are scheme dependent as we shall see below.

We will use the term in general in this second sense. Before we are going to discuss the scheme dependence of physical predictions we briefly give an incomplete survey of different schemes used for one-loop calculations in electroweak theory by different groups:

1. $\overline{\text{MS}}$: [41]	
2. semi OS	: [42, 43]	parameter counter-terms OS <i>one</i> OS Z-factor per gauge multiplet
3. full OS	: [44]	leads to S-matrix elements in one step!
4. *	: [45]	emphasize VB propagator effects and running parameters (bubble summation)

The relation between the OS-scheme and the \star -scheme is briefly discussed in an Appendix at the end of this Section.

Notice: If a physical transition matrix element is calculated in terms of a given set of physical input parameters the answer does not depend on the scheme used at intermediate steps (the schemes differ by the bookkeeping only). Evidently in all schemes the starting quantities are the bare or the equivalent $\overline{\text{MS}}$ quantities. If a particular value for μ is chosen one may give numerical values for $\overline{\text{MS}}$ quantities e. g. for $\alpha_{\overline{\text{MS}}}$, $\sin^2\Theta_{\overline{\text{MS}}}(\mu = M_Z)$.

A *scheme dependence* of physical predictions shows up if different input parameters are used in a calculation. A specific choice of experimental data points used as an input parameter set defines a renormalization scheme (RS). Parametrizations frequently used are the following:

1) A natural choice of "basic" parameters is the QED-like parametrization in terms of the fine structure constant α and the physical particle masses

$$\alpha, M_W, M_Z, m_f, m_H \quad (I)$$

often referred to as the "on-shell scheme". We shall refer to it as the α -scheme. It allows for a natural separation of the QED part of the electroweak radiative corrections which is dominated often by large soft photon effects accompanying external charged particles.

2) In the Standard Model, which unifies weak and electromagnetic interactions, we can use as a coupling parameter as well the Fermi constant G_μ instead of α . We then have

$$G_\mu, M_W, M_Z, m_f, m_H \quad (II)$$

as an independent set of parameters. This set is suitable for processes which are dominated by neutral (NC) or charged (CC) current transitions. An important property of G_μ is that it is not running from low energy up to the vector boson mass scale $M_W(M_Z)$. This G_μ -scheme thus is a genuine high energy scheme in the sense that no large logarithms show up in the calculation of vector boson processes in the LEP energy region (Z and W-pair production).

We know that the parameters of the two schemes are related by [17]

$$\sqrt{2}G_\mu = \frac{\pi\alpha}{M_W^2 \sin^2 \Theta_W} \frac{1}{1 - \Delta r}, \quad (124)$$

where Δr is the non-QED correction to μ -decay calculated in the α -scheme. If not stated otherwise, we use the definition

$$\sin^2 \Theta_W = s_W^2 = 1 - \frac{M_W^2}{M_Z^2} \quad (125)$$

for the weak mixing angle.

A disadvantage of the parametrizations (I) and (II) is that they require a precise knowledge of M_W which will be measured precisely at LEP2 only. In order to keep the input parameter errors as small as possible we have to replace M_W by G_μ in (I).

3) The scheme to be used as a starting point for precise calculations of radiative corrections uses

$$\alpha, G_\mu, M_Z, m_f, m_H \quad (III)$$

as input parameters, with M_Z measured from the Z line-shape at LEP1.

4) A similar parameter set using the W -mass instead of the Z -mass

$$\alpha, G_\mu, M_W, m_f, m_H \quad (IV)$$

seems not particularly interesting, since the W -mass will never be known more accurately than the Z -mass.

5) Another interesting possibility would be to predict quantities in terms of the low energy parameters

$$\alpha, G_\mu, \sin^2 \Theta_{\nu_\mu e}, m_f, m_H \quad (V)$$

where $\sin^2 \Theta_{\nu_\mu e}$ is determined from neutrino-electron scattering (by CHARM II for example).

Scheme-dependence can be investigated by predicting an observable in terms of different input parameter sets. Since not all the parameters are known to the same precision we proceed as follows: We first predict M_W and $\sin^2 \Theta_{\nu_\mu e}$ in the scheme (III) and then take any 3 parameters which are independent at tree level to calculate quantities like the vector boson widths $\Gamma_{Z f \bar{f}}$, $\Gamma_{W f \bar{f}'}$, or the cross-sections $\sigma(e^+ e^- \rightarrow f \bar{f})$, $\sigma(e^+ e^- \rightarrow W^+ W^-)$ e.t.c.

Predictions of physical quantities of course should not depend on the specific choice of the input parameters and they in fact do not if we include all orders of the perturbation expansion. Actually, the reparametrization invariance is inferred by renormalization group invariance. However, practical perturbative calculations are *approximations* obtained by truncation of the perturbation series. The accuracy of the finite order approximations depends on the choice of the input parameters i.e. finite order results are scheme dependent [46].

Let us illustrate this point by an example: Suppose we compute a matrix element M in the α -scheme (I) to one-loop order yielding a result

$$M^{(1)} = \alpha^n C [1 + b\alpha].$$

Now, suppose we calculate the same quantity in the G_μ -scheme (II) which amounts to a replacement of $\alpha \simeq 137^{-1}$ by $\alpha' = \frac{\alpha}{1 - \Delta r} \simeq 128^{-1}$ i.e. to one-loop order $\alpha' = \alpha[1 + a\alpha]$ and

$$M'^{(1)} = \alpha'^n C [1 + b'\alpha'].$$

Inserting α' we get

$$M'^{(1)} = M^{(1)} + \delta M$$

with $b' = b - na$ and

$$\delta M = \alpha^n C \left[\left(\frac{n(n-1)}{2} a^2 + (n+1)ab'\right) \alpha^2 + \cdots + a^{n+1}b'\alpha^{n+2} \right].$$

Thus the result differs by δM . If we do not actually calculate the higher orders

$$\delta M = M'^{(1)} - M^{(1)}$$

must be considered as an uncertainty due to unknown higher order effects.

For LEP experiments one-loop calculations are insufficient to get the precision of 0.1% and one has to go to resummation improved calculations by including leading higher order effects. The study of the scheme dependence of resummation improved results is a way to estimate missing higher order contributions (*educated guess*). Of course only an actual n-loop calculation can tell us what the full n-loop answer is.

Let us summarize the content of this subsection by the following conclusions:

- If a physical quantity is calculated with different input parameters the answer is the same if we calculate it to arbitrary high orders.

However:

- Calculating a quantity to a given order the omitted higher order terms differ for different parametrizations. This leads to a *scheme dependence* of the result (approximate) due to different truncation errors.
- Differences can also be due to different resummation prescriptions (see below).

After these general considerations we now discuss one-loop renormalization in details.

4. One-loop renormalization

4.1. Feynman rules

Starting point is the classical gauge invariant Lagrangian

$$\mathcal{L}_{inv} = \mathcal{L}_{Yang-Mills} + \mathcal{L}_{matter} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa} .$$

The quantization is obtained by adding the gauge-fixing (GF) and Faddeev-Popov (FP) terms in order to get the quasi-invariant effective action suitable for the path-integral quantization:

$$\mathcal{L}_{eff} = \mathcal{L}_{inv} + \mathcal{L}_{GF} + \mathcal{L}_{FP} .$$

The correct Feynman rules for non-abelian Gauge theories have first been obtained by 't Hooft [7]. Here we restrict ourselves to write down, in Figure 8, the Feynman rules in the Feynman - 't Hooft gauge for the physical fields. The gauge self-couplings are given in terms of the tensors (momenta incoming)

$$\begin{aligned} V^{\rho\sigma,\mu}(p) &= g^{\rho\sigma} (p_2 - p_1)^\mu + g^{\rho\mu} (p_1 - p_3)^\sigma + g^{\sigma\mu} (p_3 - p_2)^\rho \\ T^{\mu\nu,\rho\sigma} &= 2 g^{\mu\nu} g^{\rho\sigma} - g^{\mu\rho} g^{\nu\sigma} - g^{\mu\sigma} g^{\nu\rho} \end{aligned}$$

These Feynman rules are “complete” only in the unitary gauge. In this gauge

$$\begin{array}{ccc}
 -ig_{\mu\nu} \frac{1}{k^2 - M^2} & \rightarrow & -i \left(g_{\mu\nu} - \frac{k_\mu k_\nu}{M^2} \right) \frac{1}{k^2 - M^2} \\
 \text{Feynman-t Hooft} & & \text{unitary (non-renormalizable)}
 \end{array}$$

such that $\partial_\mu W_i^\mu = 0$ on the mass-shell (i.e. $k^\mu (\dots) = 0$ for $k^2 = M^2$).

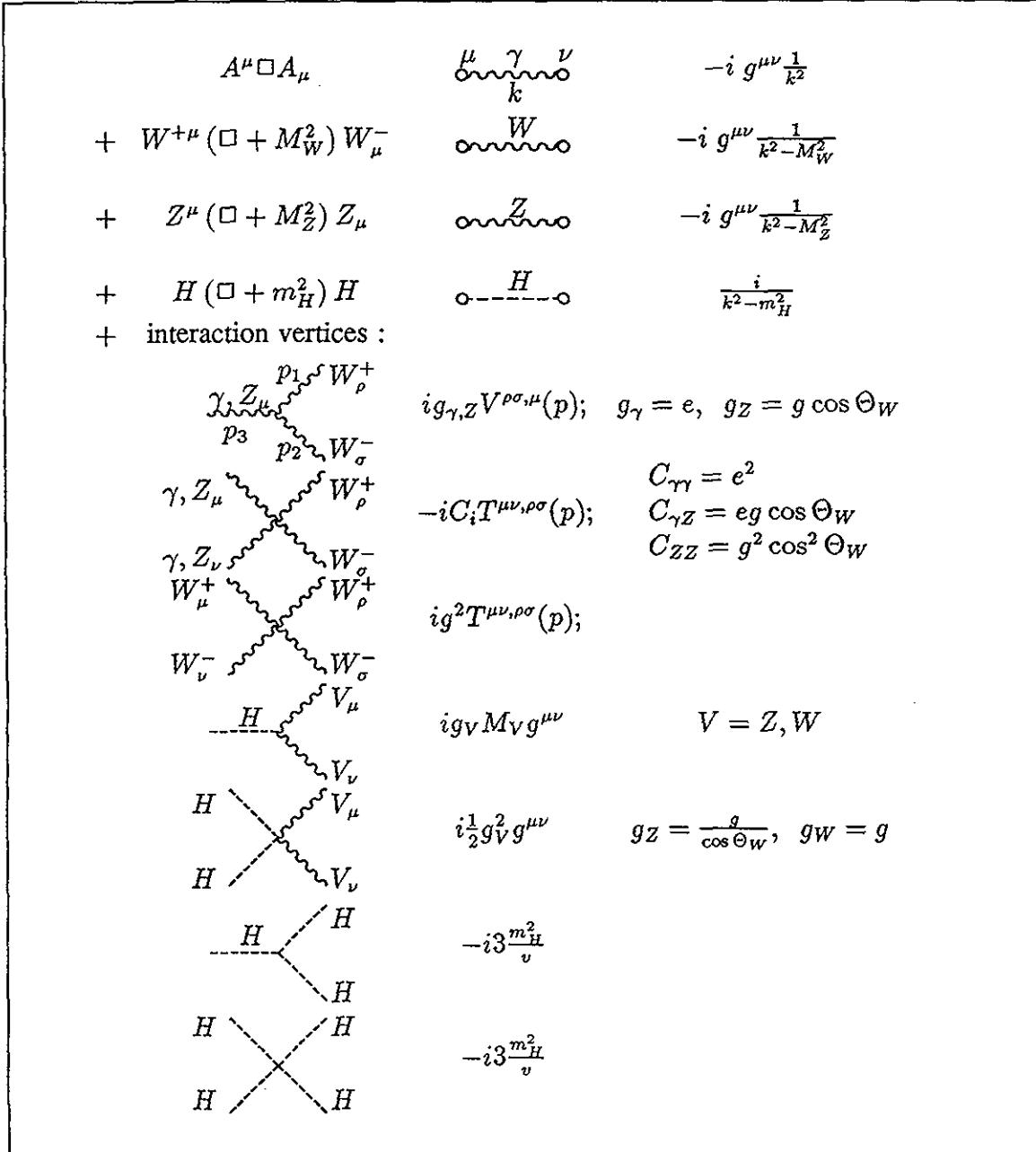


Figure 8a: Feynman rules for $\mathcal{L}_{YM} + \mathcal{L}_{Higgs}$

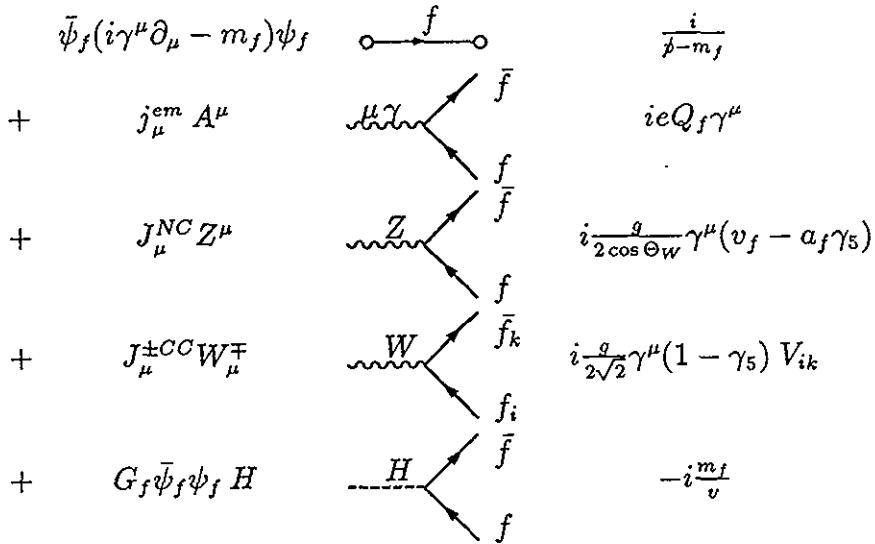


Figure 8b: Feynman rules for $\mathcal{L}_{\text{matter}} + \mathcal{L}_{\text{Yukawa}}$

Here and in the following we do not explicitly write the $i\epsilon$ -prescription for the Feynman propagators and include it in the mass. Thus M^2 always stands for $M^2 - i\epsilon$.

As discussed in Sec. II the gauge boson propagators are only defined after fixing a gauge, because the 4-component field $W_{\mu i}$ describes only 3 physical degrees of freedom (2 transverse and 1 longitudinal). A convenient gauge is the general covariant and linear 't Hooft gauge also called "R_ξ" gauge" for which the massive vector boson propagators take the form

$$-i \left(g_{\mu\nu} - (1 - \xi) \frac{k_\mu k_\nu}{k^2 - \xi M^2} \right) \frac{1}{k^2 - M^2} \quad (126)$$

The price we have to pay in going from the physical non-renormalizable unitary gauge to a renormalizable gauge is that we have to take into account ghosts: the 3 Higgs ghosts ϕ^\pm and ϕ and 4 Faddeev-Popov ghosts ζ^\pm , ζ and η , which have 39 additional interaction vertices. The existence of the 't Hooft gauge is conceptually very important because it allows to interpolate in a continuous way between a renormalizable gauge like the *Feynman-t Hooft* gauge with $\xi = 1$ (simple propagators, unphysical polarization, ghosts) and the unitary gauge reached as $\xi \rightarrow \infty$ (no ghosts, Lee-Yang terms, UV-behavior of off-shell quantities bad). For the gauge invariant (ξ -independent) physical quantities this infers at the same time renormalizability *and* unitarity.

After these introductory remarks we are going to discuss renormalization in more detail. In order to be able to control the UV-divergences, we have to use a renormalizable gauge (validity of power counting arguments). In order to keep notation as handy as possible we use the Feynman-t Hooft gauge. We have to inspect those Green functions which are superficially divergent, propagators, form-factors and four-point functions.

4.2 VB propagator corrections

Since, in physical matrix elements (on-shell quantities), the longitudinal parts of the VB propagators cancel against ghost amplitudes, as a consequence of the Slavnov-Taylor identities, we need consider only the transverse part in the following. In order to see how the splitting into transverse and longitudinal parts works, we introduce the projectors

$$T_{\mu\nu} = g_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} \quad , \quad L_{\mu\nu} = \frac{k_\mu k_\nu}{k^2}$$

transverse projector longitudinal projector

which satisfy

$$\begin{aligned} T_\nu^\mu + L_\nu^\mu &= \delta_\nu^\mu \\ T_\rho^\mu T_\nu^\rho &= T_\nu^\mu \quad , \quad L_\rho^\mu L_\nu^\rho = L_\nu^\mu \\ T_\rho^\mu L_\nu^\rho &= 0 \quad , \quad L_\rho^\mu T_\nu^\rho = 0 \end{aligned}$$

and write a VB-propagator in the form

$$\begin{aligned} D_{\mu\nu}(k) &= -i \left(T_{\mu\nu} \cdot \Pi_1(k^2) + L_{\mu\nu} \cdot \Pi_2(k^2) \right) \\ &= -i \left(g_{\mu\nu} \cdot \Pi_1(k^2) + k_\mu k_\nu \cdot \hat{\Pi}_2(k^2) \right) \end{aligned} \quad (127)$$

with $\Pi_2 = k^2 \hat{\Pi}_2 + \Pi_1$. Thus the transverse amplitude Π_1 is uniquely given by the $g_{\mu\nu}$ -term in the propagator and Π_2 does not mix with the transverse part. The index 1 will be omitted in the following

4.2.1 The W -propagator

Diagrammatically the W -propagator is given in Figure 9a. Since the $g_{\mu\nu}$ -tensor in front of the transverse self-energy acts as a unit tensor, we may omit it for notational convenience. Thus $-i/(k^2 - M_W^2)$ represents the free transverse VB-propagator and

$$-i g_{\mu\nu} \Pi_W(k^2) \equiv \text{wavy line with cross-hatch} + \text{wavy line with tadpole} \quad (128)$$

defines the self-energy function as the propagator with amputated legs, given by the sum of one-particle irreducible (1pi) diagrams. These are the graphs which cannot be cut into two disjoint parts by cutting one line. The tadpole graphs (2nd group in the figure above) play a special role. They must be included if one wants to have gauge invariant

mass counter-terms. They cancel however in physical quantities and will be omitted henceforth. At one loop order the propagator is then given by

$$-i D_W(k^2) = \frac{-i}{k^2 - M_W^2} (-i \Pi_W(k^2)) \frac{-i}{k^2 - M_W^2}$$

The full or dressed propagator is given by the geometrical progression (Dyson summation)

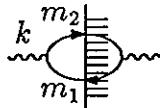
$$\begin{aligned}
 \text{Diagram: } & \text{W} \text{ (wavy line)} \text{---} \text{W} \text{ (wavy line)} = \text{W} \text{ (wavy line)} + \text{W} \text{ (wavy line)} \text{---} \text{W} \text{ (wavy line)} + \text{W} \text{ (wavy line)} \text{---} \text{W} \text{ (wavy line)} \text{---} \dots \\
 & = \frac{-i}{k^2 - M_W^2} + \frac{-i}{k^2 - M_W^2} (-i \Pi_W) \frac{-i}{k^2 - M_W^2} + \\
 & \quad \frac{-i}{k^2 - M_W^2} (-i \Pi_W) \frac{-i}{k^2 - M_W^2} (-i \Pi_W) \frac{-i}{k^2 - M_W^2} + \dots \\
 & = \frac{-i}{k^2 - M_W^2} \left\{ 1 + \left(\frac{-\Pi_W}{k^2 - M_W^2} \right) + \left(\frac{-\Pi_W}{k^2 - M_W^2} \right)^2 + \dots \right\} \\
 & = \frac{-i}{k^2 - M_W^2} \left\{ \frac{1}{1 + \frac{\Pi_W}{k^2 - M_W^2}} \right\} = \frac{-i}{k^2 - M_W^2 + \Pi_W(k^2)} \equiv -i D_W(k^2)
 \end{aligned} \tag{129}$$

Let us briefly discuss some important properties of Π_W :

1) $\Pi_W(k^2)$ is complex, when $k^2 > (m_1 + m_2)^2$

$$\Pi_W = \text{Re } \Pi_W + i \text{Im } \Pi_W$$

m_1 and m_2 are the masses of the particles into which the W can decay. For example W^- can decay into $\bar{\nu}_e e^-$ and we have $m_1 = m_{\nu_e} = 0$ and $m_2 = m_e$ so $\text{Im } \Pi_W \neq 0$ if $k^2 > m_e^2$. As a rule, a cut diagram



contributes to the imaginary part if the cut diagram kinematically allows physical intermediate states. The W is an unstable particle and on the mass-shell $k^2 = M_W^2$ of the W we have

$$\text{Im } \Pi_W(k^2 = M_W^2) = M_W \Gamma_W \neq 0 \tag{130}$$

defining the finite width Γ_W of the W -particle. The real part $\text{Re } \Pi_W$ is UV-divergent and requires renormalization: At lowest order the propagator is

$$D_W = \frac{1}{k^2 - M_W^2}$$

which has a pole $k^2 = M_W^2$ with residue one. In higher orders we define the mass (and the width) from the location of the pole of the propagator, which for *unstable particles* lies in the complex k^2 -plane. We define the pole to lie at

$$(k^2)_{pole} = M_W^2 - i M_W \Gamma_W \equiv \tilde{M}_W^2 \quad (131)$$

thus we have the correspondence

$$\begin{aligned} \text{physical mass} &\iff \text{real part of location of propagator pole} \\ \text{width} &\iff \text{imaginary part of the location of the pole} . \end{aligned}$$

By our derivation above we obtained

$$D_W = \frac{1}{k^2 - M_W^2 + \Pi_W(k^2)}$$

with $Re \Pi_W(M_W^2) \neq 0$, which tells us that the location of the pole gets shifted by radiative corrections. Consequently, M_W in the previous equation cannot be the physical mass of the W but it is the *bare* mass. Thus

$$M_W^2 \rightarrow M_{Wb}^2 = M_W^2 + \delta M_W^2$$

where δM_W^2 is the mass counter-term fixed by the condition:

$$\begin{aligned} Re [k^2 - M_W^2 - \delta M_W^2 + \Pi_W(k^2)] \Big|_{k^2=\tilde{M}_W^2} &= 0 \\ \uparrow \\ \delta M_W^2 &= Re \Pi_W(\tilde{M}_W^2) \simeq Re \Pi_W(M_W^2) \end{aligned} \quad (132)$$

this removes the quadratically divergent term from the W self-energy. Since $\Gamma_W/M_W = O(\alpha)$, we may use $\tilde{M}_W^2 \simeq M_W^2$ in the one-loop approximation. Now, after *one* subtraction,

$$D_W = \frac{1}{k^2 - M_W^2 + (\Pi_W(k^2) - Re \Pi_W(\tilde{M}_W^2))}$$

is logarithmically divergent, only. Thus it still has poles in $\varepsilon = d - 4$. If the W is not an external particle (describing a scattering state) we may use minimal subtraction here by applying the substitution Eq. (121). This procedure preserves the bare form of the Slavnov-Taylor identities. For an external W we have to proceed differently and perform on-shell wave function renormalization: It is fixed by the condition

- the real part of the residue of the propagator pole must be normalized to one.

Because the W is a charged particle the on-shell residue of the pole does not exist for massless photons (QED infrared problem). As mentioned earlier we use an infinitesimal

photon mass in this case in order to be able to proceed in the canonical way which, in a strict sense, applies to neutral particles only. After these remarks we go on with the determination of the residue of the pole. If we expand the self-energy at the pole

$$\Pi_W(k^2) \simeq \Pi_W(\tilde{M}_W^2) + (k^2 - \tilde{M}_W^2) \frac{d\Pi_W}{dk^2}(\tilde{M}_W^2) + \dots ; k^2 \rightarrow \tilde{M}_W^2$$

we obtain, using $\delta M_W^2 = \text{Re}\Pi(\tilde{M}_W^2)$, $M_W \Gamma_W = \text{Im}\Pi(\tilde{M}_W^2)$,

$$\begin{aligned} D_W &= \frac{1}{k^2 - M_W^2 + (\Pi_W(k^2) - \text{Re}\Pi_W(\tilde{M}_W^2))} \\ &= \frac{1}{k^2 - \tilde{M}_W^2} \frac{1}{1 + \frac{d\Pi_W}{dk^2}(\tilde{M}_W^2)} + O(k^2 - \tilde{M}_W^2) \end{aligned}$$

and the residue of the pole can be read off. If we now perform the field renormalization Eq. (118) and consider the propagator of the renormalized field $D_{W\text{ren}} = Z_W^{-1} D_{W\text{bare}}$ i. e.

$$\frac{1}{k^2 - M_W^2 + \Pi_{W\text{ren}}(k^2)} = \frac{1}{Z_W} \cdot \frac{1}{k^2 - M_W^2 + (\Pi_W(k^2) - \text{Re}\Pi_W(\tilde{M}_W^2))} \quad (133)$$

which is required to have residue one and thus

$$Z_W = \text{Re} \left[1 + \frac{d\Pi_W}{dk^2}(\tilde{M}_W^2) \right]^{-1}. \quad (134)$$

If we expand to linear order (suitable for 1-loop calculations)

$$\delta Z_W = Z_W - 1 \simeq -\text{Re} \frac{d\Pi_W}{dk^2}(M_W^2) \quad (135)$$

and the renormalized self-energy function reads

$$\begin{aligned} \Pi_{W\text{ren}}(k^2) &= \Pi_W(k^2) - \text{Re}\Pi_W(M_W^2) - (k^2 - M_W^2) \text{Re} \frac{d\Pi_W}{dk^2}(M_W^2) \\ &\quad + O((k^2 - M_W^2)^2). \end{aligned} \quad (136)$$

The wave function renormalization also affects the imaginary part and hence the width by a next order term. Denoting by $\Delta\Gamma_Z^{(1)}$ the next order corrections not considered here, the corrected width reads

$$\Gamma_Z^{(1)} = \left(\Gamma_Z^{(0)} + \Delta\Gamma_Z^{(1)} \right) / \left(1 + \text{Re} \frac{d\Pi_W}{dk^2}(M_W^2) \right). \quad (137)$$

We finally notice that the inverse bare propagator

$$-i g_{\mu\nu} D_W^{-1} = -i g_{\mu\nu} (k^2 - M_W^2 + \Pi_W(k^2)) = \text{~~~~~}^{-1} + \text{~~~~~} \text{~~~~~}$$

is given by the irreducible self-energy diagrams.

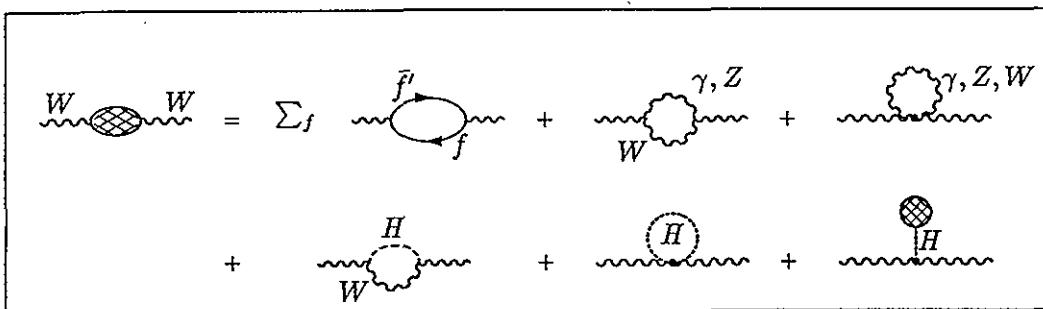


Figure 9a: W self-energy diagrams

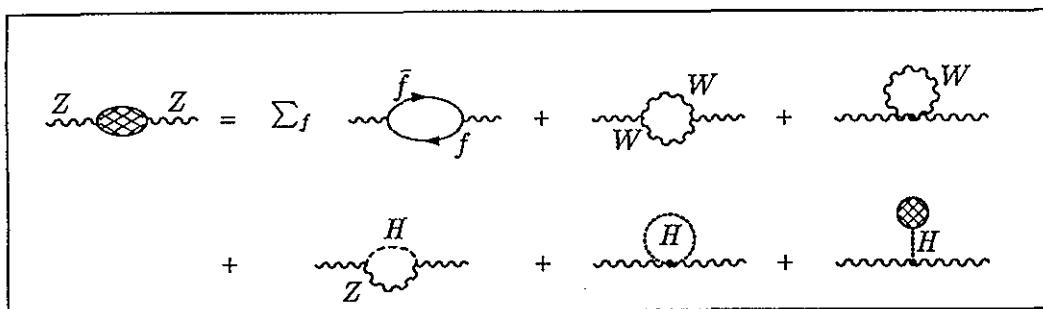


Figure 9b: Z self-energy diagrams

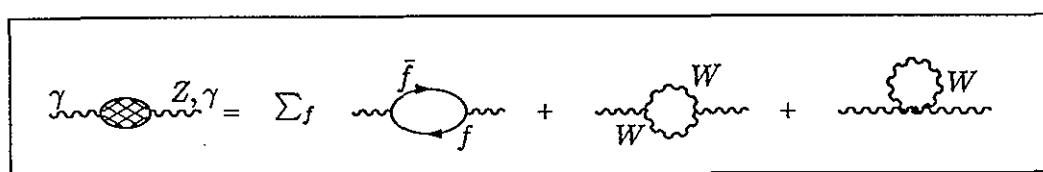


Figure 9c: γ and γZ self-energy diagrams

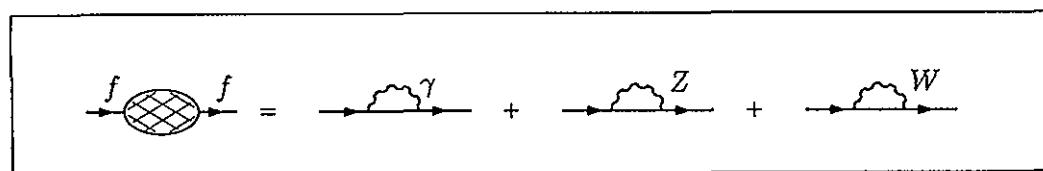


Figure 10: Fermion self-energy diagrams

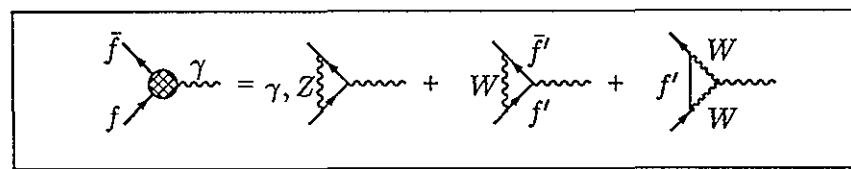


Figure 11: Electromagnetic vertex diagrams

4.2.2 The (Z, γ) -propagator

The renormalization of the Z -propagator

$$\text{---} \overset{Z}{\text{---}} \text{---} = \text{---} \text{---} + \text{---} \text{---} + \text{---} \overset{Z}{\text{---}} \text{---} + \text{---} \overset{\gamma}{\text{---}} \text{---} + \dots ,$$

proceeds similarly to the W -propagator, however, the situation is complicated by $\gamma - Z$ mixing

$$\text{---} \overset{\gamma}{\text{---}} \text{---} \overset{Z}{\text{---}} \neq 0 .$$

Due to mixing one cannot treat the Z and the γ propagators separately. They rather form a 2×2 -matrix propagator. The simplest way to treat this problem is to start from the inverse propagator given by the irreducible self-energies (sum of 1pi diagrams). Again we restrict ourselves to a discussion of the transverse part and we take out a trivial factor $-i g_{\mu\nu}$ in order to keep notation as simple as possible. With this convention we have for the inverse $\gamma - Z$ propagator the symmetric matrix

$$\hat{D}^{-1} = \begin{pmatrix} k^2 + \Pi_{\gamma\gamma}(k^2) & \Pi_{\gamma Z}(k^2) \\ \Pi_{\gamma Z}(k^2) & k^2 - M_Z^2 + \Pi_{ZZ}(k^2) \end{pmatrix} \quad (138)$$

Using 2×2 matrix inversion

$$M = \begin{pmatrix} a & b \\ b & c \end{pmatrix} \Rightarrow M^{-1} = \frac{1}{ac - b^2} \begin{pmatrix} c & -b \\ -b & a \end{pmatrix}$$

we find for the propagators

$$\begin{aligned} D_{\gamma\gamma} &= \frac{1}{k^2 + \Pi_{\gamma\gamma}(k^2) - \frac{\Pi_{\gamma Z}^2(k^2)}{k^2 - M_Z^2 + \Pi_{ZZ}(k^2)}} \simeq \frac{1}{k^2 + \Pi_{\gamma\gamma}(k^2)} \\ D_{\gamma Z} &= \frac{-\Pi_{\gamma Z}(k^2)}{(k^2 + \Pi_{\gamma\gamma}(k^2))(k^2 - M_Z^2 + \Pi_{ZZ}(k^2)) - \Pi_{\gamma Z}^2(k^2)} \simeq \frac{-\Pi_{\gamma Z}(k^2)}{k^2(k^2 - M_Z^2)} \\ D_{ZZ} &= \frac{1}{k^2 - M_Z^2 + \Pi_{ZZ}(k^2) - \frac{\Pi_{\gamma Z}^2(k^2)}{k^2 + \Pi_{\gamma\gamma}(k^2)}} \simeq \frac{1}{k^2 - M_Z^2 + \Pi_{ZZ}(k^2)} . \end{aligned} \quad (139)$$

These expressions sum correctly all the reducible bubbles. The approximations indicated are the one-loop results. The extra terms are higher order contributions. For precision physics at LEP they have to be taken into account because, as we shall see later, one-loop approximations are insufficient. Of course we have to proceed order by order in perturbation theory and we only discuss the one-loop case here. At *one-loop* order the Z propagator is renormalized in the same way as the W propagator. Thus with $M_{Zb}^2 = M_Z^2 + \delta M_Z^2$ and $Z_{\mu b} = \sqrt{Z_Z} Z_{\mu ren}$

$$\delta M_Z^2 = \text{Re } \Pi_{ZZ}(M_Z^2), \quad Z_Z = \text{Re} \left[1 + \frac{d\Pi_{ZZ}}{dk^2}(M_Z^2) \right]^{-1} . \quad (140)$$

¹ Diagrammatically the Z -propagator is given in Figure 9b.

For the photon propagator the unbroken local $U(1)_{em}$ -invariance (conservation of the electromagnetic current) implies

$$\Pi_{\gamma\gamma}(k^2) = k^2 \Pi'_{\gamma\gamma}(k^2) \quad (141)$$

and hence (ignoring the higher order mixing term (see below))

$$\text{Diagram: } \gamma \text{ (in) } \text{blob} \text{ (out)} \gamma = -i g_{\mu\nu} \frac{1}{k^2} \frac{1}{1 + \Pi'_{\gamma\gamma}(k^2)} = -i g_{\mu\nu} D_\gamma(k^2) \quad (142)$$

and thus the pole is strictly at $k^2 = 0$. No photon mass term is generated by higher order effects and there is no photon mass renormalization. Like in QED, the photon wave

¹We should mention that the definition of the physical vector boson masses M_W and M_Z is not unique because of the instability of these particles. Usually they are defined by the real parts of the locations of the poles of the transverse parts of the W and Z propagators:

$$\begin{aligned} D_W(s) &= \frac{1}{s - M_W^2 - \delta M_W^2 + \Pi_W(s)} \\ D_Z(s) &= \frac{1}{s - M_Z^2 - \delta M_Z^2 + \Pi_{ZZ}(s) - (\Pi_{\gamma Z}(s))^2 / (s + \Pi_{\gamma\gamma}(s))} \end{aligned}$$

To the order $O(\alpha)$ (neglecting the mixing term in the Z propagator), M^2 is the physical mass if we fix the mass counter-term δM^2 by $\delta M^2 = \text{Re}\Pi(M^2)$. The total width Γ is determined by the imaginary part of the self-energy function Π according to $M\Gamma = \text{Im}\Pi(M^2)$.

A subtlety comes in, if we want to include higher order effects, because the vector bosons are unstable particles such that the poles of the propagators are located at complex values $s_0 = M^2 - iM\Gamma$ of s . To our knowledge, all LEP physics calculations, which intend to include higher order effects systematically, have been using the "physical" masses defined by the location of the propagator pole in the zero width approximation such that

$$\begin{aligned} \delta M_W^2 &= \text{Re}\Pi_W(M_W^2) \\ \delta M_Z^2 &= \text{Re}(\Pi_{ZZ}(M_Z^2) - (\Pi_{\gamma Z}(M_Z^2))^2 / (M_Z^2 + \Pi_{\gamma\gamma}(M_Z^2))) \end{aligned}$$

are the mass counter-terms. Since, near the resonance, the imaginary part of Π is linear in s to a very good approximation, $\text{Im}\Pi(s) \simeq s\Gamma/M$ [47], the real part of the location of the pole is not M^2 but $M'^2 = M^2 - \Gamma^2$ (by insertion of s_0 given above in $\text{Im}\Pi(s)$) (see Consoli and Sirlin in Ref. [47]). Thus, there is a difference between the two definitions of the mass given by $M - M' = \frac{1}{2}\Gamma^2/M$. The "true" mass M' to the order $O(\alpha^2)$ coincides with the "reduced" mass introduced by Bardin et al. [49], which is obtained if one redefines the mass and the width in such a way, that the s dependence of the width in the propagator disappears near resonance:

$$\sigma_{\text{peak}} \propto \frac{s}{(s - M^2)^2 + s^2 \frac{\Gamma^2}{M^2}} = \frac{1}{1 + \gamma^2} \frac{s}{(s - M'^2)^2 + M'^2 \Gamma'^2}$$

with $\gamma = \Gamma/M$, $M' = M/\sqrt{1 + \gamma^2}$ and $\Gamma' = \Gamma/\sqrt{1 + \gamma^2}$. So $M_Z - M'_Z$ is about 35 MeV and, depending on the top mass, $M_W - M'_W$ is about 30 or 40 MeV.

It should be stressed that this higher order ambiguity in the definition of the vector boson masses does not mean that $O(\alpha^2)$ effects are not taken care off correctly in the standard approach. The two definitions just lead to a different bookkeeping of the higher order effects.

function renormalization is given by

$$Z_\gamma = [1 + \Pi'_{\gamma\gamma}(0)]^{-1} \simeq 1 - \Pi'_{\gamma\gamma}(0). \quad (143)$$

The mixing amplitude has to be renormalized as well. The proper renormalized photon and Z fields must be determined such that the (γ, Z) -propagator has the correct particle pole structure. To this end we have to guarantee that the renormalized propagator matrix is diagonal at the photon pole $k^2 = 0$ and at the Z-pole $k^2 = \tilde{M}_Z^2 \simeq M_Z^2$. This is satisfied precisely if the $\gamma - Z$ mixing amplitude vanishes at both poles (see (139)). Thus the renormalized mixing self-energy must be

$$\Pi_{\gamma Z \text{ ren}}(k^2) = \Pi_{\gamma Z}(k^2) - \Pi_{\gamma Z}(0) - \frac{k^2}{M_Z^2} (Re\Pi_{\gamma Z}(M_Z^2) - \Pi_{\gamma Z}(0)). \quad (144)$$

This can be achieved by two subsequent transformations of the bare fields:

i) Infinitesimal (perturbative) rotation

$$\begin{pmatrix} A_b \\ Z_b \end{pmatrix} = \begin{pmatrix} 1 & -\Delta_0 \\ \Delta_0 & 1 \end{pmatrix} \begin{pmatrix} A' \\ Z' \end{pmatrix}$$

diagonalizing the mass matrix at one-loop (n+1-loop) order given that the mass matrix has been diagonalized at tree (n-loop) level.

ii) Upper diagonal matrix wave function renormalization inducing a kinetic mixing term (this cannot be done by an orthogonal transformation)

$$\begin{pmatrix} A' \\ Z' \end{pmatrix} = \begin{pmatrix} \sqrt{Z_\gamma} & -\Delta_Z \\ 0 & \sqrt{Z_Z} \end{pmatrix} \begin{pmatrix} A_r \\ Z_r \end{pmatrix}$$

which allows to normalize the residues to one for the γ and Z-propagator and to shift to zero the mixing propagator at the Z-pole.

Thus the relationship between the bare and the renormalized (LSZ) fields is (expanded to linear order)

$$\begin{aligned} A_b &= \sqrt{Z_\gamma} A_r - (\Delta_Z + \Delta_0) Z_r \\ Z_b &= \sqrt{Z_Z} Z_r + \Delta_0 A_r, \end{aligned} \quad (145)$$

generalizing (118). The counter-terms Δ_0 and Δ_Z are determined by the condition (144)

$$\begin{aligned} \Delta_0 &= \frac{\Pi_{\gamma Z}(0)}{M_Z^2} \\ \Delta_Z &= \frac{Re\Pi_{\gamma Z}(M_Z^2) - \Pi_{\gamma Z}(0)}{M_Z^2} \end{aligned} \quad (146)$$

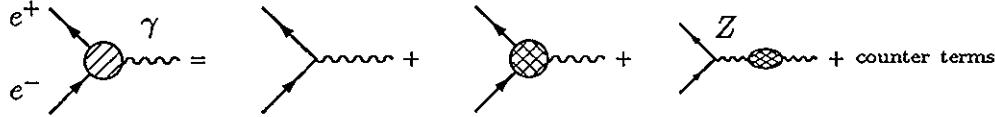
The field transformations of course induce mixing counter terms at the vertices. Again, this non-symmetric transformation only affects the bookkeeping such that the propagator pole structure becomes obvious. It does not change the value of the functional integral i.e. the mixing counter terms cancel in the interior of Feynman diagrams.

4.3 Charge renormalization

In electroweak theory charge renormalization looks formally pretty much the same as in pure QED. There are of course additional Feynman diagrams contributing. In particular there are new γZ mixing contributions. The fermion propagators are renormalized in the same way as the electron propagator in QED. However unlike in QED the right-handed and left-handed fields are renormalized in a different way such that

$$\delta Z_f = z_{vf} + z_{af}\gamma_5. \quad (147)$$

Finally, we have to determine the counter term for the electric charge. The condition is that



evaluated in the Thomson limit ($k^2 = 0, E_\gamma \rightarrow 0$) gives the renormalized charge e . Thus

$$\begin{aligned} & -ie\left\{ \gamma^\mu \left(1 + \frac{\delta e}{e} + \frac{1}{2}\delta Z_\gamma + z_{ve} + A_1^{\gamma ee} - \frac{v_e}{2 \sin \Theta_W \cos \Theta_W} \frac{\Pi_{\gamma Z}}{M_Z^2} \right. \right. \\ & \quad \left. \left. + (z_{ae} + A_2^{\gamma ee} - \frac{a_e}{2 \sin \Theta_W \cos \Theta_W} \frac{\Pi_{\gamma Z}}{M_Z^2}) \gamma_5 \right) - i\sigma^{\mu\alpha} \frac{k_\alpha}{2m_e} A_3^{\gamma ee} \right\} \\ & \rightarrow -ie\gamma^\mu \text{ in the Thomson limit} \end{aligned} \quad (148)$$

where $A_i^{\gamma ee}$ are vertex corrections and $\Pi_{\gamma Z}$ is the $\gamma - Z$ mixing term. By the electromagnetic Ward-Takahashi identity ($\partial_\mu j_{em}^\mu = 0$) some of the diagrams cancel. For example, we have ($V = \gamma, Z$)



The diagrams with the loops sitting on the external legs are contributions to the wave function renormalization and the factor $\frac{1}{2}$ has its origin in Eq. (123).

While in pure QED

$$\frac{\delta e}{e} = -\frac{1}{2}\delta Z_\gamma = \frac{1}{2}\Pi'_\gamma(0)$$

in the Standard Model we find

$$\frac{\delta e}{e} = \frac{1}{2}\Pi'_\gamma(0) - \frac{1 - 4s_W^2}{4s_W c_W} \frac{\Pi_{\gamma Z}(0)}{M_Z^2} - A_1^{\gamma ee}(0) - z_{ve} = \frac{1}{2}\Pi'_\gamma(0) + 2Ks_W^2 L. \quad (149)$$

where $K = \frac{\alpha}{4\pi s_W^2}$, $L = \ln \frac{M_W^2}{\mu^2}$. The last term is the non-abelian contribution from bosonic loops in the \overline{MS} scheme and the Feynman-'t Hooft gauge. Since

$$2 \frac{s_W}{c_W} \frac{\Pi_{\gamma Z}(0)}{M_Z^2} = 4K s_W^2 L$$

we may write

$$\frac{\delta\alpha}{\alpha} = 2 \frac{\delta e}{e} = \Pi'_\gamma(0) + 2 \frac{s_W}{c_W} \frac{\Pi_{\gamma Z}(0)}{M_Z^2} . \quad (150)$$

The fermionic contributions $\Pi_{\gamma Z}^f(0) = 0$ vanish at zero momentum transfer. By the e.m. Ward-Takahashi identity we have

$$A_2^{\gamma ee} + z_{ae} - \frac{1}{4s_W c_W} \frac{\Pi_{\gamma Z}(0)}{M_Z^2} = 0 . \quad (151)$$

With δe , the mass counter-terms and the wave function renormalization factors we have a complete set of counter-terms which allow to renormalize all other divergent quantities. The Feynman diagrams for the vector boson self-energies are depicted in Fig. 9. Since the tadpoles drop out in renormalized quantities we will not consider them. The fermion self-energies are needed for the determination of the wave function renormalization factors only. The diagrams for the fermion self energies and the electromagnetic vertex are shown in Figs. 10 and 11, respectively. Graphs involving ghost fields and graphs which vanish in the limit of vanishing fermion masses are not shown.

Appendix: \star -scheme and \overline{MS} -scheme versus on-shell scheme

The \star -scheme is equivalent to \overline{MS} together with propagator resummation and a particular choice of physical boundary conditions. VB self-energies plus certain universal vertex and box contributions are incorporated in running "bare" parameters

$$\begin{aligned} \frac{1}{e_*^2(q^2)} &= \frac{1}{e_b^2(\mu^2)} - Re\Pi'_{QQ}(q^2, \mu^2) \\ \frac{1}{g_*^2(q^2)} &= \frac{1}{g_b^2(\mu^2)} - Re\Pi'_{3Q}(q^2, \mu^2) \\ \frac{1}{4\sqrt{2}G_{\mu*}(q^2)} &= \frac{1}{4\sqrt{2}G_{\mu b}(\mu^2)} - Re(\Pi_\pm - \Pi_{3Q})(q^2, \mu^2) \\ \frac{1}{4\sqrt{2}G_{\mu*}\rho_*(q^2)} &= \frac{1}{4\sqrt{2}G_{\mu b}\rho_b(\mu^2)} - Re(\Pi_{33} - \Pi_{3Q})(q^2, \mu^2) . \end{aligned}$$

Here, the reduced self-energy amplitudes have been defined by

$$\begin{aligned}
\Pi_{\gamma\gamma} &= e_b^2 \Pi_{QQ} \\
\Pi_{\gamma Z} &= \frac{e_b^2}{s_b c_b} (\Pi_{3Q} - s_b^2 \Pi_{QQ}) \\
\Pi_{ZZ} &= \frac{e_b^2}{s_b^2 c_b^2} (\Pi_{33} - 2s_b^2 \Pi_{3Q} + s_b^4 \Pi_{QQ}) \\
\Pi_{WW} &= \frac{e_b^2}{s_b^2} \Pi_{\pm}
\end{aligned}$$

with $s_b^2 = e_b^2/g_b^2$ and $c_b^2 = 1 - s_b^2$. Such reduced self-energy functions have been used before in Refs. [54, 55]. Notice that at this point the running parameters do not satisfy the appropriate physical boundary conditions. For example, for fixed bare parameters,

$$e_*^2(q^2) \xrightarrow{q^2 \rightarrow 0} e^2 = 4\pi\alpha .$$

In order to fulfill the physical renormalization conditions the bare parameters must be *tuned* appropriately. The \star -scheme uses matching conditions for α , G_μ and M_Z

$$\begin{aligned}
e^2 &= e_*^2(0) = 4\pi\alpha^{exp} \\
G_\mu &= G_{\mu\star}(0) = G_\mu^{exp} \\
\rho &= \rho_\star(0) = \rho_{\nu N}^{exp} \\
M_Z^2 &= \frac{e_*^2}{s_*^2 c_*^2} \frac{1}{4\sqrt{2}G_{\mu\star}\rho_\star} \Big|_{M_Z^2} = M_Z^{exp2}
\end{aligned}$$

With the definition

$$g^2 = g_*^2(M_Z^2) = 2\sqrt{2}G_{\mu\star}\rho_\star M_Z^2 \left\{ 1 + \sqrt{1 - \frac{e_*^2}{\sqrt{2}G_{\mu\star}\rho_\star M_Z^2}} \right\}$$

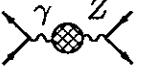
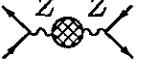
the running of the parameters is determined by

$$\begin{aligned}
e_*^2(q^2) &= \frac{e^2}{1 - e^2 \Delta_Q(q^2)} \\
g_*^2(q^2) &= \frac{g^2}{1 - g^2 \Delta_{3Q}(q^2)} \\
G_{\mu\star}(q^2) &= \frac{G_\mu}{1 - 4\sqrt{2}G_\mu \Delta_{\pm}(q^2)} \\
G_{\mu\star}(q^2)\rho_\star(q^2) &= \frac{G_\mu \rho}{1 - 4\sqrt{2}G_\mu \rho \Delta_3(q^2)}
\end{aligned}$$

where

$$\begin{aligned}
 \Delta_Q(q^2) &= \text{Re} \left\{ \Pi'_{QQ}(0) - \Pi'_{QQ}(q^2) \right\} \\
 \Delta_{3Q}(q^2) &= \text{Re} \left\{ \Pi'_{3Q}(M_Z^2) - \Pi'_{3Q}(q^2) \right\} \\
 \Delta_{\pm}(q^2) &= \text{Re} \left\{ \Pi_{\pm}(q^2) - \Pi_{3Q}(q^2) - \Pi_{\pm}(0) \right\} \\
 \Delta_3(q^2) &= \text{Re} \left\{ \Pi_3(q^2) - \Pi_{3Q}(q^2) - \Pi_{33}(0) \right\} .
 \end{aligned}$$

Evaluated at the vector boson mass scale, these running parameters have been used in Ref. [55], with the exception that G_μ , which does not run up to the vector boson mass scale, was kept fixed. After having imposed the matching conditions for given α , G_μ and M_Z , all quantities in the standard OS-scheme have equivalent representations in the \star -scheme. Let $\hat{\Pi}$ denote the renormalized self-energies expressed in terms of α , G_μ and M_Z . For four-fermion processes with light fermions, suppressing the external fermion current matrix elements, we obtain the following correspondence:

	$= \frac{e^2}{1 + \hat{\Pi}'_{\gamma\gamma}(s)} = e_*^2 = \bar{e}^2$
	$: s_W^2 + s_W c_W \frac{\hat{\Pi}'_{ZZ}(s)}{1 + \hat{\Pi}'_{\gamma\gamma}(s)} = s_*^2 = \bar{s}^2$
	$= \frac{e^2}{s_W^2 c_W^2} \frac{1}{s - M_Z^2 + \hat{\Pi}_Z(s)} = \frac{e_*^2}{s_*^2 c_*^2} \frac{1}{s - \frac{e_*^2}{s_*^2 c_*^2} \frac{1}{4\sqrt{2}G_{\mu*}\rho_*} + i\sqrt{s}\Gamma_{*Z}(s)}$
	$= \frac{e^2}{s_W^2} \frac{1}{s - M_W^2 + \hat{\Pi}_W(s)} = \frac{e_*^2}{s_*^2} \frac{1}{s - \frac{e_*^2}{s_*^2} \frac{1}{4\sqrt{2}G_{\mu*}} + i\sqrt{s}\Gamma_{*W}(s)}$

The weak mixing angles \bar{s}^2 and $s_W^2 = \sin^2 \Theta_W$ are determined from α , G_μ and M_Z using

$$\bar{s}^2 \bar{c}^2 = \frac{\pi \alpha}{\sqrt{2}G_\mu M_Z^2} \frac{1}{1 - \Delta \bar{r}}, \quad s_W^2 c_W^2 = \frac{\pi \alpha}{\sqrt{2}G_\mu M_Z^2} \frac{1}{1 - \Delta r}$$

and the W-mass is given by $M_W^2 = M_Z^2 \cos^2 \Theta_W$. The radiative corrections Δr and $\Delta \bar{r}$ will be given in detail in Sections IV and V, respectively. The renormalized VB self-energies have been defined here as suitable for the study of four-fermion processes. Since there are no external vector bosons involved, the VB wave-function renormalization factors drop out from the matrix-elements (remember the discussion after Eq. (118) at the beginning of this Section). However, in order to get finite (renormalized) self-energy functions a second subtraction (besides mass renormalization) is necessary. The one

chosen here is obtained in a natural way by starting from the bare matrix-elements and rewriting them in terms of the renormalized parameters by means of the shifts (115-117). The parameter counter terms then may be combined with the bare self energies, where they show up in form of wave function factors. One obtains

$$\begin{aligned}\hat{\Pi}_W(s) &= \Pi_W(s) - \Pi_W(M_W^2) - (s - M_W^2) \left(\left(\frac{\delta\alpha}{\alpha} \right)' - \left(\frac{\delta \sin^2 \Theta_W}{\sin^2 \Theta_W} \right)' \right) \\ \hat{\Pi}_Z(s) &= \Pi_Z(s) - \Pi_Z(M_Z^2) - (s - M_Z^2) \left(\left(\frac{\delta\alpha}{\alpha} \right)' - \frac{c_W^2 - s_W^2}{c_W^2} \left(\frac{\delta \sin^2 \Theta_W}{\sin^2 \Theta_W} \right)' \right) \\ \hat{\Pi}_{\gamma Z}(s) &= \Pi_{\gamma Z}(s) - \Pi_{\gamma Z}(0) + s \left(\frac{s_W}{c_W} \left(\frac{\delta \sin^2 \Theta_W}{\sin^2 \Theta_W} \right)' \right) \\ \hat{\Pi}_\gamma(s) &= \Pi_\gamma(s) - s \left(\left(\frac{\delta\alpha}{\alpha} \right)' \right)\end{aligned}$$

with

$$\begin{aligned}\left(\frac{\delta\alpha}{\alpha} \right)' &= \frac{\delta\alpha}{\alpha} - 2 \frac{\sin \Theta_W}{\cos \Theta_W} \frac{\Pi_{\gamma Z}(0)}{M_Z^2} \\ &= \Pi'_\gamma(0) \\ \left(\frac{\delta \sin^2 \Theta_W}{\sin^2 \Theta_W} \right)' &= \frac{\delta \sin^2 \Theta_W}{\sin^2 \Theta_W} + 2 \frac{\cos \Theta_W}{\sin \Theta_W} \frac{\Pi_{\gamma Z}(0)}{M_Z^2} \\ &= \frac{\cos^2 \Theta_W}{\sin^2 \Theta_W} \operatorname{Re} \left\{ \frac{\Pi_Z(M_Z^2)}{M_Z^2} - \frac{\Pi_W(M_W^2)}{M_W^2} + 2 \frac{\sin \Theta_W}{\cos \Theta_W} \frac{\Pi_{\gamma Z}(0)}{M_Z^2} \right\}\end{aligned}$$

for the “renormalized” self-energies. Since the splitting into self-energy and vertex+box contributions is not gauge invariant and finite terms proportional to $\Pi_{\gamma Z}(0)$ have been subtracted from the self-energies and added to the vertex+box contributions such that the two groups of contributions are separately finite. We mention that $\Pi_{\gamma Z}(0)$ vanishes in the unitary gauge as well as in the \overline{MS} scheme for $\mu = M_W$. In the ’t Hooft-Feynman gauge the vertex+box contribution is numerically small, though not negligible.

In the \star -scheme the physical widths of the Z is determined from the imaginary part of the propagator by (see Eq. (137))

$$\Gamma_Z = \frac{\Gamma_{*Z}(M_Z^2) + \Delta\Gamma_Z}{1 + \kappa_{*Z}}$$

where $1 + \kappa_{*Z}$ is determined by the residue of the Z-propagator

$$s - \frac{e_*^2}{s_*^2 c_*^2} \frac{1}{4\sqrt{2} G_{\mu*} \rho_*} = (s - M_Z^2) (1 + \kappa_{*Z})$$

and $\Delta\Gamma_Z$ stands for additional corrections (vertex, QED and possible QCD corrections). For the W width corresponding equations hold.

The effective weak mixing angle parametrizing the NC-couplings at LEP energies has been given different names by different authors. Up to numerically small contributions $(s')^2$ [54], $\sin^2\Theta_{eff}$ [55], s_*^2 [45], $\sin^2\bar{\Theta} = \bar{s}^2$ [56] and $\sin^2\Theta_{\overline{MS}} = \sin^2\hat{\Theta}$ [41] are equivalent, particularly, for what concerns the fermion contributions, the top and Higgs mass dependence.

The special treatment of the self-energies is justified because they include the large non-QED corrections (fermion loops) and can be used to get improved Born approximations, which take into account the numerically most relevant non-photonic corrections. Of course, in order to get fully corrected four-fermion amplitudes form-factor and box-diagram corrections must be added. In general only the full set of corrections is gauge-invariant and finite. Any kind of splitting into effective couplings plus remainders is ambiguous and only a matter of bookkeeping and should not affect physical predictions within the given precision of the perturbative approximation.

The resummation of the reducible blocks involved in the above treatment of the propagator corrections means that some higher order effects have been taken into account while others (e.g. two-loop irreducible contributions) have been omitted. The question is whether this partial resummation of higher order terms leads to a better approximation to the unknown full answer. For the gauge couplings e and g one can show that the propagator resummation is equivalent to solving the renormalization group (RG) for the running gauge couplings, which is a systematic resummation of the leading logarithmic corrections. For the other two parameters G_μ and ρ the summation of the reducible diagrams only does not properly include terms of leading size! i.e. the two-loop irreducible diagrams give contributions of the same order as the square of the one loop result included in the bubble summation. This will be discussed in detail in the next section.

The relationship between the standard OS-scheme and the \overline{MS} scheme is relatively simple. For example, for the weak mixing angle the OS version $\sin^2\Theta_W$ is related to its bare value by (116,117)

$$\begin{aligned}\sin^2\Theta_b &= \left(1 + \frac{\delta\sin^2\Theta_W}{\sin^2\Theta_W}\right) \sin^2\Theta_W \\ \frac{\delta\sin^2\Theta_W}{\sin^2\Theta_W} &= \frac{\cos^2\Theta_W}{\sin^2\Theta_W} \operatorname{Re} \left\{ \frac{\Pi_Z(M_Z^2)}{M_Z^2} - \frac{\Pi_W(M_W^2)}{M_W^2} \right\}\end{aligned}$$

while the \overline{MS} version is defined by

$$\sin^2\Theta_b = \left(1 + \left(\frac{\delta\sin^2\Theta_W}{\sin^2\Theta_W}\right)_{\overline{MS}(\mu=M_W)}\right) \sin^2\hat{\Theta}$$

where $\left(\frac{\delta\sin^2\Theta_W}{\sin^2\Theta_W}\right)_{\overline{MS}(\mu=M_W)}$ only picks the UV singular term from $\frac{\delta\sin^2\Theta_W}{\sin^2\Theta_W}$. The choice $\mu = M_W$ for the scale is made here because we are interested in an effective $\sin^2\Theta$ at LEP energies. The relation between the two mixing angles thus reads, expanded to linear order,

$$\sin^2\hat{\Theta} = \left(1 + \frac{\delta\sin^2\Theta_W}{\sin^2\Theta_W} - \left(\frac{\delta\sin^2\Theta_W}{\sin^2\Theta_W}\right)_{\overline{MS}(\mu=M_W)}\right) \sin^2\Theta_W$$

which is finite, depends however on the particular choice of μ . The finite quantity

$$\Delta\rho = \left\{ \frac{\Pi_Z(0)}{M_Z^2} - \frac{\Pi_W(0)}{M_W^2} + 2 \frac{\sin\Theta_W}{\cos\Theta_W} \frac{\Pi_{\gamma Z}(0)}{M_Z^2} \right\}$$

exhibiting the leading heavy particle effects is present in $\frac{\delta\sin^2\Theta_W}{\sin^2\Theta_W}$ only

$$\frac{\delta\sin^2\Theta_W}{\sin^2\Theta_W} = \frac{\cos^2\Theta_W}{\sin^2\Theta_W} \Delta\rho + \dots$$

but absent in $(\frac{\delta\sin^2\Theta_W}{\sin^2\Theta_W})_{\overline{MS}(\mu=M_W)}$. Hence the main difference is exhibited in

$$\sin^2\hat{\Theta} = \left(1 + \frac{\cos^2\Theta_W}{\sin^2\Theta_W} \Delta\rho \right) \sin^2\Theta_W = \sin^2\Theta_W + \Delta\rho \cos^2\Theta_W$$

and one may calculate $\hat{s}^2 = \sin^2\hat{\Theta}$ from α , G_μ and M_Z by

$$\hat{s}^2\hat{c}^2 = \frac{\pi\alpha}{\sqrt{2}G_\mu M_Z^2} \frac{1}{1 - \Delta\hat{r}},$$

where $\Delta\hat{r}$ is obtained from Δr , discussed in the next section, by replacing the OS counter terms by their \overline{MS} counter parts. Corresponding, considerations apply to other quantities.

A final remark should be made. The advantage of the effective weak mixing parameters, or other running parameters, is that they are flavor independent and take into account the universal large fermion loop effects. The disadvantage is that they are theoretical constructs and do not simply relate to physical quantities, like for example $\sin^2\Theta_W$, which is determined by the physical VB mass ratio and is completely model independent. It is also clear from the many slightly differing definitions that a natural definition accepted by everybody does not exist. Hence a precise comparison of different definitions always needs a lot of explanation, and the members of the radiative corrections community can keep busy by debating for their preferred parametrization. After all a properly done physical prediction to a given accuracy should not depend on such bookkeeping questions.

IV. RENORMALIZATION OF MASS-COUPLING RELATIONS

The title of this Section could read as well: "Calculation of the muon decay constant G_μ in terms of α and the vector boson masses". By the relation (30) the parameters M_W , M_Z , α and G_μ are not independent. Here we calculate G_μ from α , M_W and M_Z (on-shell scheme):

$$G_\mu = \frac{\pi\alpha}{\sqrt{2}} \frac{1}{M_W^2 \sin^2 \Theta_W} \frac{1}{1 - \Delta r}$$

where $\Delta r \neq 0$ due to radiative corrections. Since the QED corrections have been already included in the definition of G_μ , we have to calculate the non-QED part of the μ decay transition amplitude for $k^2 \simeq 0$

$$-4 \frac{G_\mu}{\sqrt{2}} J_\mu^{(\mu)} J_\mu^{(e)\mu}$$

Here, $J_\mu^{(\mu)} = \bar{u}_{\nu_\mu} [\gamma_\mu (1 - \gamma_5)] u_\mu$ and $J_\mu^{(e)} = \bar{u}_e [\gamma_\mu (1 - \gamma_5)] v_{\nu_e}$ denote the muon (μ) and the electron (e) charged current matrix elements, u and v are the external spinors. The different contributions are shown in Fig. 12.

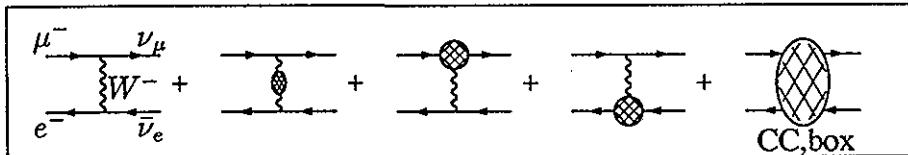


Figure 12a: Radiative corrections to μ -decay

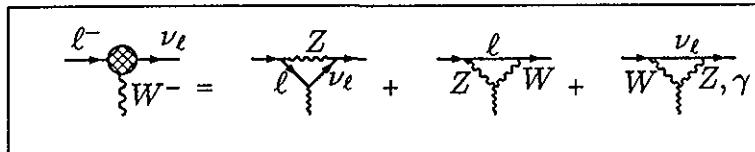


Figure 12b: CC vertex diagrams

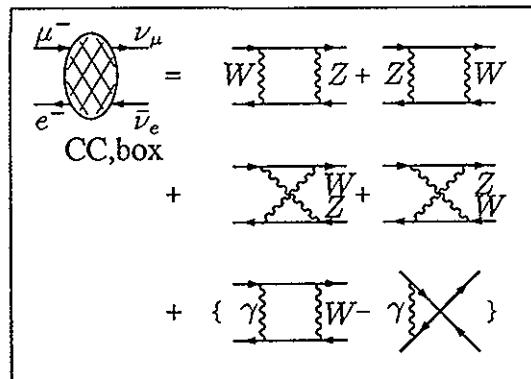


Figure 12c: CC box diagrams

At the tree level we read off

$$\frac{G_\mu}{\sqrt{2}} = \frac{e^2}{8M_W^2 \sin^2 \Theta_W} = \frac{\pi \alpha}{M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)}.$$

We may check the validity of this relation by using the experimental values for α , G_μ and $\sin^2 \Theta_W = 0.231 \pm 0.006$, obtained from deep inelastic $\nu_\mu N$ scattering, for a prediction of the vector boson masses which are given by

$$M_W = \frac{A_0}{\sin \Theta_W}, \quad M_Z = \frac{M_W}{\cos \Theta_W}; \quad A_0 = \left(\frac{\pi \alpha}{\sqrt{2}G_\mu}\right)^{1/2} = 37.2802(3) \text{ GeV}. \quad (152)$$

Comparing the lowest order predictions $M_W = 77.57 \pm 1.01$ and $M_Z = 88.39 \pm 0.81$ with the experimental values $M_W^{exp} = 80.19 \pm 0.32$ and $M_Z^{exp} = 91.176 \pm 0.021$, we see that the numbers are not in agreement with each other. This disagreement illustrates the importance of radiative corrections.

Including the one-loop radiative corrections we distinguish among 1) propagator (self-energy) corrections, 2) vertex corrections and 3) box contributions. We will neglect terms proportional to the light fermion masses, since for $m_f \ll M_W$, they are numerically insignificant. This will lead to rather simple analytical expressions for the vertex and box contributions in the low energy limit.

Using the bare parameter relations (115-117) we get

$$\begin{aligned} \frac{G_\mu}{\sqrt{2}} &= \frac{e_b^2}{8 \sin^2 \Theta_{Wb} M_{Wb}^2} \left\{ 1 + \frac{\Pi_W(0)}{M_W^2} + \delta_{CC,vertex} + \delta_{CC,box} \right\} \\ &= \frac{e^2}{8 \sin^2 \Theta_W M_W^2} \left\{ 1 + 2 \frac{\delta e}{e} - \frac{\cos^2 \Theta_W}{\sin^2 \Theta_W} \left(\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2} \right) \right. \\ &\quad \left. - \frac{\delta M_W^2}{M_W^2} + \frac{\Pi_W(0)}{M_W^2} + \delta_{CC,vertex} + \delta_{CC,box} \right\} \\ &= \frac{\pi \alpha}{2 \sin^2 \Theta_W M_W^2} \{1 + \Delta r\} \end{aligned} \quad (153)$$

The vertex and box diagrams are depicted in Figs. 12b and 12c.

The important quantity Δr has been calculated first by Sirlin [17]. We read off the formal one-loop result from the foregoing expression. Collecting the self-energy terms in Δr_{se} we may write

$$\begin{aligned} \Delta r &= \Delta r(\alpha, M_W, M_Z, m_H, m_f) \\ &= \Delta r_{se} + \Delta r_{vertex+box}. \end{aligned} \quad (154)$$

and denoting $s_W^2 = \sin^2 \Theta_W$ and $c_W^2 = \cos^2 \Theta_W$ we have

$$\Delta r_{vertex+box} = \frac{\alpha}{4\pi s_W^2} \left(6 + \frac{7 - 4s_W^2}{2s_W^2} \ln c_W^2 \right) \quad (155)$$

which is the sum of the vertex, box and lepton wave-function contributions plus a γZ mixing term $2\frac{c_W}{s_W}\frac{\Pi_{\gamma Z}(0)}{M_Z^2}$, rendering the term ultraviolet finite (in the 't Hooft-Feynman gauge)¹. If we insert the expressions for the counter-terms and rewrite the result by splitting off the self-energies at $k^2 = 0$ as

$$\Pi(k^2) \equiv \Pi(0) + k^2 \Pi'(k^2)$$

the self-energy contributions read:

$$\begin{aligned} \Delta r_{se} = & \Pi'_\gamma(0) - Re \Pi'_\gamma(M_Z^2) \\ & - \frac{\cos^2 \Theta_W}{\sin^2 \Theta_W} \left\{ \frac{\Pi_Z(0)}{M_Z^2} - \frac{\Pi_W(0)}{M_W^2} + 2 \frac{\sin \Theta_W}{\cos \Theta_W} \frac{\Pi_{\gamma Z}(0)}{M_Z^2} \right\} \\ & - Re \Pi'_W(M_W^2) + Re \Pi'_\gamma(M_Z^2) + \frac{\cos \Theta_W}{\sin \Theta_W} Re \Pi'_{\gamma Z}(M_Z^2) \\ & - \frac{\cos^2 \Theta_W}{\sin^2 \Theta_W} Re \left\{ \Pi'_Z(M_Z^2) - \Pi'_W(M_W^2) + \frac{\sin \Theta_W}{\cos \Theta_W} \Pi'_{\gamma Z}(M_Z^2) \right\} \end{aligned} \quad (156)$$

This is a representation of Δr_{se} in terms of the unrenormalized gauge boson self-energy functions. The form of this result exhibits the large and potentially large terms in Δr which we may write as

$$\Delta r = \Delta \alpha - \frac{\cos^2 \Theta_W}{\sin^2 \Theta_W} \Delta \rho + \Delta r_{rem} \quad (157)$$

¹Different from the NC processes (at one-loop order), for the CC processes there is no natural separation into QED and "weak" part in the Standard Model. The QED corrections to μ decay are not ultraviolet finite and they do not form a gauge invariant subset. This is in contrast also to the QED corrections for this process if modeled by an effective Fermi interaction, which can be transformed into a NC form via a Fierz transformation. The only trouble is caused by the photonic box diagram. After subtraction of the photonic four-fermion vertex correction, which has been included by convention in the QED correction factor of (32), an ultraviolet divergent and gauge dependent contribution R_w , as indicated in Fig. 12c, is left over which has to be included in (155).

We then have

$$\Delta r_{vertex+box} = 2 \left(\frac{\delta e}{e} \right)_{vertex} + \delta_{CC,vertex} + \delta_{CC,box} + 2 \frac{c_W}{s_W} \frac{\Pi_{\gamma Z}(0)}{M_Z^2}$$

where

$$\begin{aligned} 2 \left(\frac{\delta e}{e} \right)_{vertex} &= -2A_1^{\gamma ee} + \frac{4s_W^2 - 1}{2s_W c_W} \frac{\Pi_{\gamma Z}(0)}{M_Z^2} = K \cdot 4s_W^2 L \\ \delta_{CC,vertex} &= (A_L^{W\mu\nu_\mu} + A_L^{W\bar{\nu}\nu_e}) = -K \cdot 2 \left\{ \left(2 + \frac{s_W^2}{2} \right) L + \left(\frac{1}{2} - \frac{3}{s_W^2} \right) c_W^2 \ln c_W^2 + \left(\frac{s_W^2}{4} - 3 \right) \right\} \\ \delta_{CC,box} &= A_{LCC}^{box} = -K \cdot \frac{1}{2s_W^2} (-3 + 6c_W^2 + 2c_W^4) \ln c_W^2 + R_w \end{aligned}$$

where $K = \frac{\alpha}{4\pi s_W^2}$, $L = \ln \frac{M_W^2}{\mu^2}$ and $R_w = K \cdot \frac{s_W^2}{2} (2L + 1)$. The amplitudes A_i are normalized to the Born terms. We refer the reader to [50] for a more detailed discussion.

where

$$\begin{aligned}\Delta\alpha &= \Pi'_\gamma(0) - \text{Re } \Pi'_\gamma(M_Z^2) \\ \Delta\rho &= \frac{\Pi_Z(0)}{M_Z^2} - \frac{\Pi_W(0)}{M_W^2} + 2 \frac{\sin\Theta_W}{\cos\Theta_W} \frac{\Pi_{\gamma Z}(0)}{M_Z^2}.\end{aligned}\quad (158)$$

are the large (due to fermion loop contributions) terms and Δr_{rem} is the remainder. Though the latter term is numerically smaller by one order of magnitude it is an interesting term which includes contributions from gauge boson self-couplings and Higgs-vector boson interactions. We are now going to discuss the various terms in (156) in some detail.

1. $\Delta\alpha$

$\Delta\alpha$ is the photon vacuum polarization contribution which comes in through

$$\begin{aligned}2\frac{\delta e}{e} &= \Pi'_\gamma(0) + \dots \\ &= \Pi'_\gamma(0) - \text{Re } \Pi'_\gamma(M_Z^2) + \dots + \text{Re } \Pi'_\gamma(M_Z^2) \\ &= \Delta\alpha + \dots\end{aligned}$$

and is large due to the large change in scale going from zero momentum (Thomson limit) to the Z-mass scale $\mu = M_Z$. Here, by zero momentum more precisely we mean the light fermion mass thresholds. The leading light fermion ($m_f \ll M_W$) contribution is given by

$$\begin{aligned}\Delta\alpha &= \sum_f \text{Diagram: a fermion loop with a photon loop attached to one of the fermion lines. The loop is labeled 'f' and the photon lines are labeled 'gamma'.} \\ &= \frac{\alpha}{3\pi} \sum_f Q_f^2 N_{cf} \left(\ln \frac{M_Z^2}{m_f^2} - \frac{5}{3} \right) \\ &= \Delta\alpha_{leptons} + \Delta\alpha_{hadrons}^{(5)} + \Delta\alpha_{top}.\end{aligned}\quad (159)$$

Since the top quark is heavy we cannot use the light fermion approximation for it. A very heavy top in fact gives no contribution since

$$\Delta\alpha_{top} \simeq -\frac{\alpha}{3\pi} \frac{4}{15} \frac{M_Z^2}{m_t^2} \rightarrow 0$$

when $m_t \gg M_Z$.

A serious problem is the low energy contributions of the five light quarks u,d,s,c and b which cannot be reliably calculated using perturbative QCD. Fortunately one can evaluate this hadronic term $\Delta\alpha_{hadrons}^{(5)}$ from hadronic e^+e^- - annihilation data by using a

dispersion relation. The relevant vacuum polarization amplitude satisfies the convergent dispersion relation

$$Re\Pi'_\gamma(s) - \Pi'_\gamma(0) = \frac{s}{\pi} Re \int_{s_0}^{\infty} ds' \frac{Im\Pi'_\gamma(s')}{s'(s' - s - i\varepsilon)}$$

and using the optical theorem (unitarity) one has

$$Im\Pi'_\gamma(s) = \frac{s}{e^2} \sigma_{tot}(e^+e^- \rightarrow \gamma^* \rightarrow hadrons)(s).$$

In terms of the cross-section ratio

$$R(s) = \frac{\sigma_{tot}(e^+e^- \rightarrow \gamma^* \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \gamma^* \rightarrow \mu^+\mu^-)},$$

where $\sigma(e^+e^- \rightarrow \gamma^* \rightarrow \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}$ at tree level, we finally obtain

$$\Delta\alpha_{hadrons}^{(5)}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi} Re \int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s - M_Z^2 - i\varepsilon)}. \quad (160)$$

Using the experimental data for $R(s)$ up to $E_{cut} = 40$ GeV (for larger energies γZ mixing would complicate the analysis) and perturbative QCD for the high energy tail we get (see Appendix to this section)

$$\begin{aligned} \Delta\alpha_{hadrons}^{(5)}(s) &= 0.0282 \pm 0.0009 \\ &+ 0.002980 \cdot \{\ln(s/s_0) + 0.005696 \cdot (s/s_0 - 1)\} \end{aligned} \quad (161)$$

with $\sqrt{s_0} = 91.176$ GeV [51]. In the range $50 \text{ GeV} \leq \sqrt{s} \leq 200 \text{ GeV}$ the above fit is “exact” as compared to the error. Alternatively, this result of the dispersion calculation can be reproduced by using perturbative QCD with the effective “quark masses”

$$\begin{aligned} m_u &= 62 \text{ MeV}, & m_d &= 83 \text{ MeV} \\ m_s &= 215 \text{ MeV}, & m_c &= 1.5 \text{ GeV} \\ m_b &= 4.5 \text{ GeV} \end{aligned}$$

and a QCD correction factor $(1 + \alpha_{s,eff}/\pi)$ with $\alpha_{s,eff} = 0.133$ ².

We should mention that a light fermion not only contributes to $\Delta\alpha$ but also to Δr_{rem} :

$$\Delta r_{rem}^f \simeq \frac{\alpha}{4\pi s_W^2} \left(1 - \frac{c_W^2}{s_W^2}\right) \frac{N_{cf}}{6} K_{QCD} \ln c_W^2.$$

²Warning: Do not use these values for the quark masses for small space-like momenta (as needed in Bhabha scattering). These would give wrong results.

This yields $\Delta r_{rem,leptons} \simeq 0.0015$ and $\Delta r_{rem,hadrons}^{(5)} \simeq 0.0040$.

Perturbative QCD corrections for light quarks (at some high energy scale) are taken care off by the factor $K_{QCD} = 1 + \delta_{QCD}$ given by

$$\delta_{QCD} = \frac{\alpha_s(M_Z^2)}{\pi} + 1.405 \left(\frac{\alpha_s(M_Z^2)}{\pi} \right)^2 \quad (162)$$

using [52]

$$\Lambda_{MS}^{(5)} = 200^{+200}_{-100} \text{ MeV corresponding to } \alpha_s(M_Z^2) = 0.117 \pm 0.01. \quad (163)$$

We first assume the top to be a "normal" not too heavy fermion and will discuss heavy top effects in a second step. If there would not exist heavy unknown particles, Δr would be determined by the following typical contributions ($m_t = 60 \text{ GeV}$, $m_H = 100 \text{ GeV}$):

$$\begin{aligned} \Delta r_{leptons} &\simeq 0.0315 + 0.0015 = 0.0330 \\ \Delta r_{hadrons} &\simeq 0.0282 + 0.0040 = 0.0322 \pm 0.0009 \\ \Delta r_{top} &\simeq 0.0025 \quad (\text{depends on } m_t) \\ \Delta r_{bosons} &\simeq 0.0033 \quad (\text{depends on } m_H). \end{aligned}$$

The term $\Delta r_{vertex+box} \simeq 0.0064$ is included in Δr_{bosons} . For the light fermions the individual contributions from $\Delta\alpha$ and Δr_{rem} are exhibited as a sum of two terms. The full analytic expression for a light top would be

$$\Delta r_{top} = \frac{\alpha}{3\pi} \frac{4}{3} \left(\ln \frac{M_Z^2}{m_t^2} - \frac{5}{3} \right) + \frac{\alpha}{16\pi s_W^2} \left(1 - \frac{c_W^2}{s_W^2} \right) 2 \ln c_W^2 \quad (164)$$

for $m_t \ll M_Z$.

Numerically the fermionic contributions dominate. The bosonic contributions are smaller by one order of magnitude but they are nevertheless non-negligible. The self-energy contributions are large and depend on unknown physics, like the top mass, the Higgs mass, on 4th family fermion masses e.t.c. Next we consider what happens if the top is very heavy.

2. $\Delta\rho$

It has been observed first by Veltman [53] that fermion doublets with large mass splitting give large non-decoupling contributions to $\Delta\rho$ (large weak isospin breaking effects). By now we know that the top quark is unexpectedly heavy, $m_t > 89 \text{ GeV}$, while $m_b \simeq 4.8 \text{ GeV}$ is rather light.

The diagrams yielding leading doublet mass splitting effects are those which exhibit Wtb (CC) transitions and are quadratically divergent. The Ztt and Zbb (NC) vertices do

not mix t and b and thus do not “feel” the mass splitting. In our case we are concerned with the finite part of the W self-energy diagram ³

$$\text{Diagram: } W \text{ loop with } t \text{ and } b \text{ lines.} = -\frac{\alpha}{4\pi} \frac{1}{4s_W^2} N_c \frac{m_t^2}{M_W^2} + \dots$$

It yields a k^2 -independent leading term which is (for dimensional reasons) quadratic in m_t . We thus obtain

$$\Delta\rho = \frac{\Pi_Z(0)}{M_Z^2} - \frac{\Pi_W(0)}{M_W^2} \simeq \frac{\alpha}{16\pi s_W^2} N_c \frac{m_t^2}{M_W^2} + \dots \quad (165)$$

and this large contribution gets further *enhanced* in Δr

$$\Delta r|_{heavy} = -\frac{c_W^2}{s_M^2} \Delta\rho + \dots$$

by an enhancement factor $\simeq 3.34$ for $s_W^2 = 0.23$.

The remainder also contains logarithmic terms which are not negligible numerically. A heavy top would give the contribution

$$\Delta r^{top} = -\frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \left\{ 3 \frac{c_W^2}{s_W^2} \frac{m_t^2}{M_W^2} + 2 \left(\frac{c_W^2}{s_W^2} - \frac{1}{3} \right) \ln \frac{m_t^2}{M_W^2} + \frac{4}{3} \ln c_W^2 + \frac{c_W^2}{s_W^2} - \frac{7}{9} \right\}. \quad (166)$$

Let us mention finally that whereas $\Delta\alpha$ is unchanged by unknown physics, $\Delta\rho$ is sensitive to all kinds of $SU(2)_L$ multiplets which directly couple to the gauge bosons and exhibit large mass-splitting.

3. Higgs contribution

The Higgs contributions deserve our special attention. In the light fermion approximation only the vector-boson self-energy diagrams

$$\text{Diagram: } V \text{ loop with } H \text{ line.} + \text{Diagram: } H \text{ loop with } V \text{ line.} \quad V = Z, W$$

contribute. At one-loop order there is no quadratic Higgs mass dependence in $\Delta\rho$ and in Δr . The leading heavy Higgs contribution is logarithmic:

$$\begin{aligned} \Delta\rho^{Higgs} &\simeq -\frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \frac{s_W^2}{c_W^2} \left\{ 3 \left(\ln \frac{m_H^2}{M_W^2} - \frac{5}{6} \right) \right\} \\ \Delta r^{Higgs} &\simeq \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \left\{ \frac{11}{3} \left(\ln \frac{m_H^2}{M_W^2} - \frac{5}{6} \right) \right\} \quad (m_H \gg M_W). \end{aligned} \quad (167)$$

³The UV singular terms are proportional to m_t^2 also for the Z self-energy and the latter must be taken into account to cancel the UV divergence of the W self-energy.

This is due to the accidental $SU(2)_R$ symmetry of the Higgs sector in the minimal Standard Model, which implies $\rho = 1$ at tree level (Veltman screening) [57]. More precisely, the theorem states that for vanishing fermion masses quadratic terms are absent. Furthermore, in $\Delta\rho$ also the logarithmic term disappears in the limit of vanishing $U(1)_Y$ coupling g' . The logarithmic term in the low energy observable $\Delta\rho$ is a consequence of the weak isospin breaking by hypercharge. On the other hand, in Δr the coefficient of the logarithm does not depend on g' . Next we have to include the leading higher order effects.

4. Summation of leading higher order effects

Our one-loop calculation gave us the $O(\alpha)$ result

$$\sqrt{2}G_\mu = \frac{\pi\alpha}{\sin^2\Theta_W M_W^2} (1 + \Delta r).$$

Typically we get $\Delta r \simeq 0.07$ for $M_Z = 91$ GeV, $m_t = 60$ GeV and $m_H = 100$ GeV. For the next order term we expected a contribution of the order $\Delta r^2 \simeq 0.005$. This would yield a shift in the prediction of the W mass (in terms of α , G_μ and M_Z) of $\delta M_W \simeq 190$ MeV. Since M_W will be measured with an accuracy of $\delta M_W \simeq 70$ MeV at LEP2, the $O(\alpha)$ result is insufficient for LEP experiments and we have to think about how to include the leading higher order terms.

a. Summation of leading logarithms.

The summation of leading logarithms is governed by the renormalization group. Since, in our case, the leading logs showed up in the QED vacuum polarization only, the leading log summation may be understood as the solution of the renormalization group equation for the $U(1)_{em}$ coupling constant (μ = renormalization scale)

$$\mu^2 \frac{\partial}{\partial\mu^2} \alpha(\mu^2) = \frac{\beta(\alpha)}{2} = \frac{\alpha^2(\mu^2)}{3\pi} \sum_{m_f < \mu} N_{cf} Q_f^2$$

yielding the effective fine structure constant at scale M_Z

$$\alpha(M_Z) = \frac{\alpha}{1 - \Delta\alpha} \tag{168}$$

where

$$\Delta r \simeq \Delta\alpha \simeq \frac{\alpha}{3\pi} \sum_{m_f < M_Z} N_{cf} Q_f^2 \ln \frac{M_Z^2}{m_f^2}$$

in this approximation. Thus Eq. (30) obtained from our one-loop result by the substitution

$$1 + \Delta r \rightarrow \frac{1}{1 - \Delta\alpha}$$

represents the resummation of all powers of $(\alpha \ln \frac{M_W^2}{m_f^2})$. It is important to notice that the leading log summation is scheme independent. This can be seen by writing, in leading log approximation,

$$\Delta\alpha^{-1} = \frac{1}{\alpha(0)} - \frac{1}{\alpha(\mu^2)} = \frac{1}{3\pi} \sum_{m_f < \mu} N_{cf} Q_f^2 \ln \frac{\mu^2}{m_f^2} ; \mu \leq M_W$$

exhibiting that the r.h.s is independent of the electroweak couplings and hence of the parametrization used.

Including non-leading log terms we observe that the substitution

$$1 + \Delta r = 1 + \Delta\alpha + \Delta r_w \rightarrow \frac{1}{1 - \Delta\alpha - \Delta r_w} = \frac{1}{1 - \Delta r}$$

in fact only is correct if Δr_w is small. This would be the case only if the top would be light. As a next step we have to investigate what happens if $\Delta\rho$ is large.

b. Summation of large $\Delta\rho$ terms.

A careful analysis of the resummation of large $\Delta\rho$ terms [58] shows that Eq. (30) gets modified into

$$G_\mu = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2 \Theta_W} \left\{ \frac{1}{1 - \Delta\alpha} \frac{1}{1 + \frac{\cos^2 \Theta_W}{\sin^2 \Theta_W} (\Delta\rho)_{irr}} + \Delta r_{rem} \right\} . \quad (169)$$

Here, $(\Delta\rho)_{irr}$ represents the leading irreducible contribution to the ρ parameter defined from the ratio of neutral current to charged current amplitudes at low energy, calculated in Ref. [59], i.e.

$$\frac{G_{NC}(0)}{G_{CC}(0)} = \rho = 1 + (\Delta\rho)_{irr} + (\Delta\rho)_{irr}^2 + \dots = \frac{1}{1 - (\Delta\rho)_{irr}}. \quad (170)$$

It is important to note that, in contrast to $\Delta\alpha$, which is not significantly modified by the inclusion of two loop irreducible contributions,

$$\Delta\alpha_{leptons}^{(1)} \rightarrow (1 + \frac{3\alpha}{4\pi}) \Delta\alpha_{leptons}^{(1)}$$

where $\Delta\alpha_{leptons}^{(1)}$ is the one-loop lepton contribution to $\Delta\alpha$, ρ as defined in Eq. (172), can sizably differ from the one loop result. In fact as shown in Ref. [58], by including the two loop irreducible terms calculated in Ref. [59], one finds

$$(\Delta\rho)_{irr} = N_{cf} x_f [1 - (2\pi^2 - 19)x_f + \dots], \quad x_f = \frac{\Delta m_f^2 G_\mu}{8\pi^2 \sqrt{2}}. \quad (171)$$

This means that low energy physics, is not sensitive to the *bare* mass splitting (Δm_f^2) , but rather to the effective quantity

$$(\Delta m_f^2)_{eff} = \Delta m_f^2 \left\{ 1 - (2\pi^2 - 19) \frac{\Delta m_f^2 G_\mu}{8\pi^2 \sqrt{2}} \right\}.$$

The screening effects, due to the Yukawa coupling with the scalar sector, may become large for a large mass splitting. This phenomenon, if confirmed from a closer inspection of the higher order terms in the perturbative expansion, may have far reaching consequences (possible restoration of decoupling) for our understanding of the Standard Model.

If we take the result of the full one loop calculation and include correctly the $\Delta\alpha$ and $\Delta\rho$ effects, resummed to all orders, we arrive at the final expression

$$M_W^2 = \frac{\rho M_Z^2}{2} \left(1 + \sqrt{1 - \frac{4A_0^2}{\rho M_Z^2} \left(\frac{1}{1 - \Delta\alpha} + \Delta r_{rem} \right)} \right). \quad (172)$$

Nonleading one-loop self-energy effects can be included by using Eq. (172) together with the replacements [58] [60]:

$$\begin{aligned} \Delta\alpha &\rightarrow \Delta e = \Pi'_\gamma(0) - \Pi'_W(M_W^2) + \frac{c_W}{s_W} \Pi'_{\gamma Z}(M_Z^2) \\ \Delta\rho &\rightarrow \Delta\hat{\rho} = \frac{\Pi_Z(M_Z^2)}{M_Z^2} - \frac{\Pi_W(M_W^2)}{M_W^2} + \frac{s_W}{c_W} \frac{\Pi_{\gamma Z}(M_Z^2) + \Pi_{\gamma Z}(0)}{M_Z^2}, \end{aligned} \quad (173)$$

where Π_Z includes γZ mixing terms as given in Eq. (139). We have checked that the above substitution reproduces correctly all self-energy terms up to $O(\alpha^2)$. Such a resummation could make sense for the fermion contributions, which form a gauge invariant subset. However, since terms like the irreducible contribution proportional to $\frac{\alpha}{4\pi}\sqrt{2}G_\mu m_t^2 \ln(m_t^2/M_Z^2)$ are unknown, non leading terms and the vertex and box corrections, (contributing to Eq. (30)) should be added perturbatively i.e. included in Δr_{rem} .

5. Applications

Once Δr is given the W mass can be predicted by using the values of α , G_μ and M_Z from LEP1. According to Eqs. (30) and (31) we obtain

$$M_W^2 = \frac{M_Z^2}{2} \left(1 + \sqrt{1 - \frac{4A_0^2}{M_Z^2} \frac{1}{1 - \Delta r}} \right) \quad (174)$$

and, equivalently,

$$\sin^2 \Theta_W = \frac{1}{2} \left(1 - \sqrt{1 - \frac{4A_0^2}{M_Z^2} \frac{1}{1 - \Delta r}} \right). \quad (175)$$

with A_0 given in Eq. (152). Explicit expressions for the various quantities which have been mentioned in this section can be found in Ref. [48,41], for example. Numerical results are given in Tab. 2. In Fig. 13 the m_t -dependence of Δr is shown for various Higgs masses. The W mass measurement is equivalent to a determination of

$$\Delta r = 1 - \frac{\pi\alpha}{\sqrt{2}G_\mu} \frac{1}{M_Z^2 \frac{M_W^2}{M_Z^2} \left(1 - \frac{M_W^2}{M_Z^2} \right)}. \quad (176)$$

Table 2. Prediction of M_W and related parameters ($M_Z = 91.176$ GeV, $\alpha_s = 0.117$). Masses in GeV. $\sin^2 \Theta_e$, $\sin^2 \Theta_b$ and $\sin^2 \bar{\Theta}$ will be considered below.

m_t	m_H	M_W	Δr	$\sin^2 \Theta_W$	$\sin^2 \Theta_e$	$\sin^2 \Theta_b$	$\sin^2 \bar{\Theta}$
90	100	79.928	0.06032	0.2315	0.2334	0.2335	0.2326
110	100	80.037	0.05430	0.2294	0.2329	0.2333	0.2322
130	50	81.182	0.04607	0.2266	0.2321	0.2328	0.2313
130	100	80.151	0.04786	0.2272	0.2324	0.2330	0.2316
130	1000	80.002	0.05623	0.2301	0.2334	0.2341	0.2327
150	100	80.275	0.04068	0.2248	0.2318	0.2328	0.2310
200	100	80.642	0.01840	0.2177	0.2299	0.2321	0.2292
230	100	80.905	0.00133	0.2126	0.2286	0.2315	0.2278

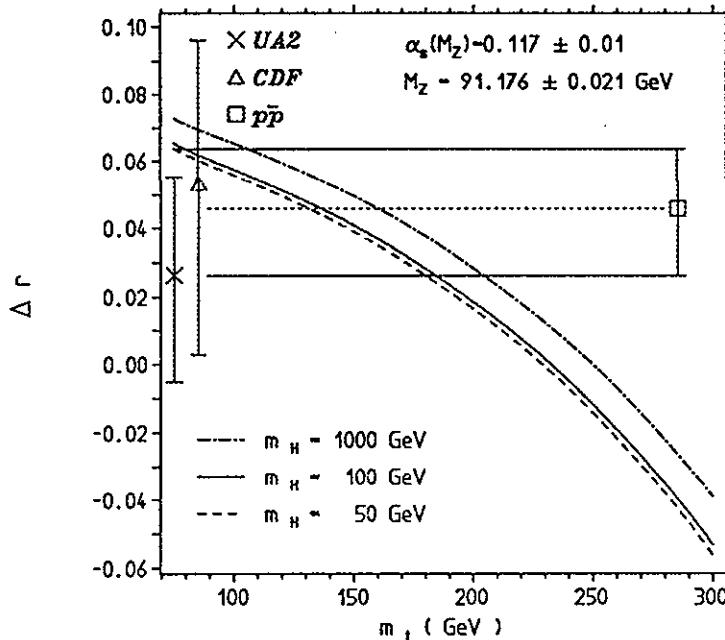


Figure 13: Δr as a function of the top mass for various m_H

Using the experimental values (33-34) for M_Z and M_W , Δr is determined fairly well and since Δr is strongly dependent on the top mass we can use the results to find a

direct constraint on the top mass. Within one standard deviation we read off from Fig. 13 (the second uncertainty in m_t comes from the change of m_H)

$$\Delta r = 0.046^{+0.018}_{-0.019} \Leftrightarrow m_t = 136^{+47+21}_{-57-5} \text{ GeV} \quad (177)$$

assuming $m_H \leq 1$ TeV. We notice that the direct lower limit $m_t > 89$ GeV is stronger than the indirect one obtained here.

In future one expects to be able to achieve a precision of $\delta M_W = 70$ MeV at LEP2. An accuracy $\delta M_W = 100$ MeV possibly may be achieved by combining the hadron collider results from CDF and D0 by the end of 1995 with an integrated luminosity of about $70 pb^{-1}$ [61]. This corresponds to an error in Δr of $\delta \Delta r = 0.0056$, and using $\frac{\delta m_t}{m_t} = -\frac{1}{2} \frac{\delta \Delta r}{\Delta r}$ this would determine m_t to an accuracy better than $\delta m_t = 10$ GeV. Of course we are waiting for the direct discovery of the top which is within reach in the next years at the Tevatron.

Appendix: Hadronic contributions to coupling shifts (update of Ref. [51]).

The Crystal Ball (CB) Collaboration has carefully reanalyzed their old e^+e^- - annihilation data and now obtain $R(s)$ values substantially lower than the Mark I data [62] and in agreement with other experiments (LENA). The results now are in much better agreement with perturbative QCD. The change of the data is mainly due to a up to date treatment of the QED radiative corrections and τ subtraction. If we include the new results from CB and discard the Mark I data, which systematically lie 28% higher, in average, we obtain updated values for the hadronic contributions to the photon vacuum polarization. The results for $\Delta\alpha/e^2 = \Delta\pi_\gamma(M_Z)$ are collected in Table 3.

Table 3a: Contributions to $\Delta\pi_\gamma(M_Z) \times 10^3$

(final state)	(energy range)	(contribution) (stat) (syst)
ρ	(0.28, 1.20)	37.36 (0.15) (1.12)
ω	(0.42, 2.00)	3.74 (0.38) (0.11)
ϕ	(0.42, 2.00)	5.75 (0.26) (0.17)
J/ψ		11.08 (1.46) (1.66)
Υ		1.27 (0.04) (0.08)
hadrons	(0.84, 3.10)	38.59 (0.99) (7.72)
hadrons	(3.10, 3.60)	6.52 (0.34) (1.25)
hadrons	(3.60, 5.20)	19.04 (0.19) (1.27)
hadrons	(5.20, 9.46)	35.78 (0.52) (2.16)
hadrons	(9.46, 40.00)	102.07 (1.36) (3.18)
perturbative	(40.0, ∞)	46.53 (0.32) (0.64)

Table 3b: "Distribution" of errors

	$\Delta\pi_\gamma \times 10^3$	relat. error
Resonances:	59.20 (2.53)	4.3 %
($\rho\omega\phi$:	46.85 (1.24)	2.6 %)
Background:		
$E < M_{J/\psi}$	38.59 (7.78)	20.2 %
$M_{J/\psi} < E$	6.52 (1.30)	19.9 %
$> M_\Upsilon$	19.04 (1.28)	6.7 %
$40\text{GeV} > E > M_\Upsilon$	35.78 (2.22)	6.2 %
	102.07 (3.46)	3.4 %
$E < 40\text{ GeV}$ data	261.12 (9.34)	3.6 %
$E > 40\text{ GeV}$ QCD	46.53 (0.72)	1.5 %
total	307.65 (9.36)	3.0 %
(*)	(6.62)	(2.1 %)

The last line (*) shows the error one would get if the experimental error on $R(s)$ would be reduced to 5% in the regions with larger errors.

$\Delta\alpha_{2\text{had}}^{(5)}$ may be determined using a partial separation of flavors, as explained in Ref. [51]. The following results are obtained:

Partial flavor separation of $\Delta\pi_\gamma(M_Z)$			
	uds	c	b
$E < M(J/\psi)$	85.44		
$M(J/\psi) < E < M(\Upsilon)$	43.94	28.48	
$M(\Upsilon) < E$	55.68	37.12	10.55

Using the approximate relation

$$\Delta\pi_{3\gamma} = \frac{1}{2}\Delta\pi_\gamma^{uds} + \frac{3}{8}\Delta\pi_\gamma^c + \frac{3}{4}\Delta\pi_\gamma^b,$$

which derives from assuming $SU(3)_{\text{flavor}}$ for (u,d,s) and the OZI-rule for the heavy flavors c,b and t, the hadronic contributions to the shift of the $SU(2)$ coupling α_2 is the given by

$$\Delta\alpha_{2\text{had}}^{(5)} = g^2 \Delta\pi_{3\gamma}(M_Z), \quad g^2 = e^2 / \sin^2 \Theta_W.$$

For $\sin^2 \Theta_W = 0.23$ we obtain

$$\begin{aligned} \Delta\alpha_{had}^{(5)} &= 0.0282 \pm 0.0009(6) \\ \Delta\alpha_{2\text{had}}^{(5)} &= 0.0587 \pm 0.0018(12) \end{aligned}$$

where the error in brackets is the (\star) value mentioned above. Since the errors of $\Delta\alpha_{had}^{(5)}$ and $\Delta\alpha_{2\,had}^{(5)}$ are correlated the error in the renormalization of the weak mixing angle from neutrino scattering

$$\sin^2 \bar{\Theta} = \left(\frac{1 - \Delta\alpha_2}{1 - \Delta\alpha} + \dots \right) \sin^2 \Theta_{\nu_\mu N(e)}$$

remains quite small. We get

$$\delta \left(\frac{1 - \Delta\alpha_2}{1 - \Delta\alpha} \right) \simeq 0.0009$$

or

$$\delta \sin^2 \Theta_{\nu_\mu N(e)} \simeq 0.00021$$

which is negligibly small relative to the experimental error 0.006 shown in Tab. 1.

V. LEP/SLC PHYSICS

Radiative corrections play a crucial role in the interpretation of electroweak precision measurements. In this last section, we will concentrate on discussing radiative corrections for LEP1/SLC physics near the Z peak.

The basic processes investigated at LEP1/SLC are fermion pair production $e^+e^- \rightarrow f\bar{f}$ ($f \neq e$) and Bhabha scattering $e^+e^- \rightarrow e^+e^-$. At LEP2 W -pair production $e^+e^- \rightarrow W^+W^-$ will be the main process.

The large cross-section at the Z -peak, $\sigma_{peak}^{f\bar{f}} \simeq 1.45$ (1.95) nb for $f = e, \mu, \tau$ and 30.08 (40.65) nb for hadrons, (in brackets, the value without QED corrections) gives easily a production of 1 million Z 's per year at LEP1. The cross-section is enhanced relative to the pure QED process by a factor $(M_Z/\Gamma_Z)^2 \simeq 10^3$ or about 150 for leptons and 750 for hadrons.

For precision physics the most important aims are

- the detailed investigation of $e^+e^- \rightarrow f\bar{f}$ around the Z resonance which should allow to observe small calculable deviations of the partial and total cross-sections $\sigma_f = \sigma(e^+e^- \rightarrow f\bar{f})$ and $\sigma_{tot} = \sum_f \sigma_f$ and the partial and total widths $\Gamma_f = \Gamma(Z \rightarrow f\bar{f})$ and $\Gamma_Z = \sum_f \Gamma_f$ from their lowest order predictions

$$\Gamma_{Zf\bar{f}} = \frac{\sqrt{2}G_\mu M_Z^3}{12\pi} (v_f^2 + a_f^2) N_{cf} ; \quad \sigma_{peak}^{f\bar{f}} \simeq \frac{12\pi \Gamma_e \Gamma_f}{M_Z^2 \Gamma_Z^2} \quad (179)$$

where $v_f = T_{3f} - 2Q_f \sin^2 \Theta_W$ and $a_f = T_{3f}$ are, respectively, the vector and axial-vector neutral current (NC) couplings for fermions with flavor f . N_{cf} is the color factor which is 1 for leptons and 3 for quarks.

- Additional information will be obtained from the on-resonance asymmetries, the forward-backward asymmetries $A_{FB}^{f\bar{f}}$ and the τ polarization-asymmetry A_{pol}^τ . If longitudinally polarized beams would be realized, the measurement of the left-right asymmetry A_{LR} and the polarized forward-backward asymmetries $A_{FB,pol}^{f\bar{f}}$ would allow to substantially improve the results. All the asymmetries are functions of the specific ratios

$$A_f = \frac{2v_f a_f}{v_f^2 + a_f^2} \quad (180)$$

of the NC couplings, and thus provide accurate determinations of the weak mixing angle $\sin^2 \Theta_W$. At the tree level the on-resonance asymmetries are given by

$$A_{FB}^{f\bar{f}} = \frac{3}{4} A_e A_f, \quad A_{LR} = A_{pol}^\tau = A_e, \quad A_{FB,pol}^{f\bar{f}} = \frac{3}{4} A_f. \quad (181)$$

The "weak" (non-QED) radiative corrections reveal the asymmetries to be very interesting quantities, mainly because the different asymmetries exhibit different sensitivities

to various interesting effects. The measurement of many independent quantities, which depend in their own way on unknown physics, is important in order to be able to disentangle the origin of possible deviations from lowest order predictions.

Since higher order predictions depend on the unknown mass of the Higgs boson, the remnant of the spontaneous symmetry breaking, and the mass of the unknown top quark, the missing member of the 3rd fermion family and other possible unknown physics, as a first step, data mainly constrain the unknown parameters of the SM. At the same time bounds on possible extensions of the SM gradually improve.

While the higher order predictions of physical quantities depend substantially on the unknown top mass the dependence on the unknown Higgs mass is much weaker. The first important goal thus is to restrict the range for the top mass.

1. Effective Couplings at the Z Resonance

Radiative corrections for the NC process $e^+e^- \rightarrow f\bar{f}$ have been calculated by many groups [63]. The diagrams for the “weak” (=non-photonic) one-loop corrections are depicted in the Figure 14. Diagrams involving ghost particles are not shown.

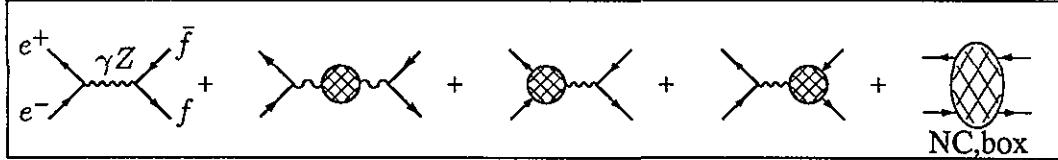


Figure 14a: Radiative corrections to $e^+e^- \rightarrow f\bar{f}$

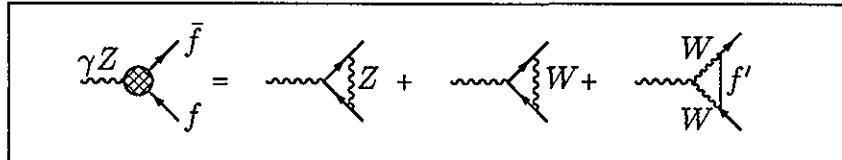


Figure 14b: NC vertex diagrams

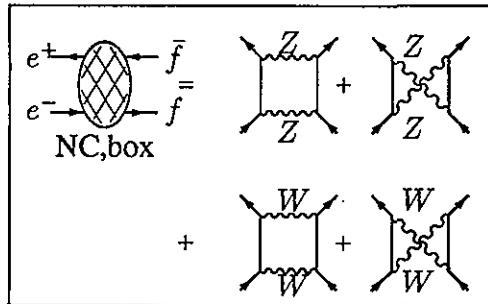
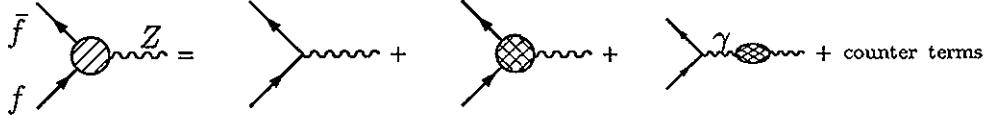


Figure 14c: NC box diagrams

Here we discuss the non-photonic corrections for the observables Eqs. (179,181), measured in resonant production and decay of Z 's in $e^+e^- \rightarrow Z \rightarrow f\bar{f}$. Because of the

factorization of the “weak” corrections at the resonance, we restrict ourselves to consider the Z vertex corrections



They can be cast into an overall renormalization of the $Z f \bar{f}$ vertex

$$(\sqrt{2}G_\mu)^{1/2} M_Z \gamma^\mu (-2Q_f \sin^2 \Theta_W + (1 - \gamma_5) T_{3f})$$

by $\rho_f^{1/2}$ and a renormalization of $\sin^2 \Theta_W$ in the NC vector-coupling [65]:

$$G_\mu \rightarrow \rho_f G_\mu, \quad \sin^2 \Theta_W \rightarrow \kappa_f \sin^2 \Theta_W, \quad (182)$$

where $\rho_f = 1 + \Delta \rho_{se} + \Delta \rho_{f,vertex}$ and $\kappa_f = 1 + \Delta \kappa_{se} + \Delta \kappa_{f,vertex}$. In terms of the corrections δv_f and δa_f of the vector and axial-vector couplings we have

$$\Delta \rho = 2 \frac{\delta a_f}{a_f}, \quad \Delta \kappa = \frac{a_f \delta v_f - v_f \delta a_f}{-Q_f a_f \sin^2 \Theta_W}.$$

Using the counter terms defined in Eqs. (115-117) and (123,147) we find

$$\begin{aligned} \delta v_f &= A_v^{Zff} + \frac{v_f}{2} \left(\delta Z_Z + \frac{\delta M_Z^2}{M_Z^2} + \frac{\delta G_\mu}{G_\mu} \right) - 2Q_f \sin^2 \Theta_W \left(\frac{\delta \sin^2 \Theta_W}{\sin^2 \Theta_W} + \frac{c_W \Pi_{\gamma Z}(M_Z^2)}{s_W M_Z^2} \right) \\ \delta a_f &= A_a^{Zff} + \frac{a_f}{2} \left(\delta Z_Z + \frac{\delta M_Z^2}{M_Z^2} + \frac{\delta G_\mu}{G_\mu} \right) \end{aligned}$$

where the lepton wave function terms (124) have been added to the bare vertex corrections $A_v \rightarrow A_v + v z_v - a z_a$, $A_a \rightarrow A_a + a z_v - v z_a$. Inserting the explicit expressions for the counter terms we may write $\Delta \rho$ and $\Delta \kappa$ in terms of the bare self-energies plus vertex corrections. The potentially large self-energy contributions (se) are universal. The analogues of Eq. (157) for $\Delta \rho$ and $\Delta \kappa$ read

$$\begin{aligned} \Delta \rho_{se} &= \Delta \bar{\rho} = \Delta \rho + \Delta \rho_{se,rem} \\ \Delta \kappa_{se} &= \Delta \bar{\kappa} = \frac{c_W^2}{s_W^2} \Delta \rho + \Delta \kappa_{se,rem} \end{aligned} \quad (183)$$

with $\Delta \rho$ defined in Eq. (158). The self-energy terms are given by

$$\begin{aligned} \Delta \rho_{se,rem} &= \Delta_Z = \frac{\Pi_Z(M_Z^2)}{M_Z^2} - \frac{\Pi_Z(0)}{M_Z^2} - \left(\frac{d\Pi_Z}{dq^2} \right) (M_Z^2) \\ \Delta \kappa_{se} &= \frac{c_W^2}{s_W^2} \Delta \hat{\rho} \end{aligned} \quad (184)$$

where $\Delta\hat{\rho}$ is given in Eq. (173). The vertex contributions are (if $f \neq b$) relatively small (but not negligible) and flavor dependent¹. We may define effective $\sin^2\Theta$'s by

$$\sin^2\Theta_f = \kappa_f \sin^2\Theta_W = \tilde{\kappa}_f \tilde{s}^2 \quad (186)$$

where

$$\tilde{s}^2 = \sin^2\tilde{\Theta} = \frac{1}{2} (1 - \sqrt{1 - 4A_0^2/M_Z^2}) = 0.2122(1) \quad (187)$$

is the lowest order $\sin^2\Theta$ in terms of α , G_μ and M_Z . We have

$$\tilde{\kappa}_f = \kappa_f + \frac{\tilde{c}^2}{\tilde{c}^2 - \tilde{s}^2} \Delta r = \frac{\tilde{c}^2}{\tilde{c}^2 - \tilde{s}^2} \Delta r_f \quad (188)$$

and, generalizing Eq. (176),

$$\sqrt{2}G_\mu M_Z^2 \cos^2\Theta_f \sin^2\Theta_f = \frac{\pi\alpha}{(1 - \Delta r_f)} ; \quad \Delta r_f = \Delta r + \frac{\tilde{c}^2 - \tilde{s}^2}{\tilde{c}^2} \Delta \kappa_f . \quad (189)$$

Using Eqs. (157) and (183) we obtain

$$\Delta r_f = \Delta\alpha - \Delta\rho + \Delta r_{f,rem} . \quad (190)$$

¹The explicit expressions for the light fermion vertex corrections are [42, 64]

$$\begin{aligned} \Delta\rho_{f,vertex} &= \frac{\sqrt{2}G_\mu M_Z^2}{16\pi^2} \{ 2(3v_f^2 + a_f^2)\Lambda_2(s, M_Z) \\ &\quad - 4c_W^2(1 - 2(1 - |Q_f|)s_W^2)\Lambda_2(s, M_W) + 24c_W^4\Lambda_3(s, M_W) \} - \Delta r_{vertex+box} \\ \Delta\kappa_{f,vertex} &= \frac{\sqrt{2}G_\mu M_Z^2}{16\pi^2} \{ -(1 - 4|Q_f|s_W^2)(1 - 2|Q_f|s_W^2)\Lambda_2(s, M_Z) \\ &\quad + 2c_W^2(1 - 2(1 - |Q_f|)s_W^2)\Lambda_2(s, M_W) - 12c_W^4\Lambda_3(s, M_W) \} \end{aligned} \quad (185)$$

where $\Delta r_{vertex+box}$ is given by Eq. (155) and comes in through the $\alpha \rightarrow G_\mu$ replacement used here. The functions $\Lambda_i(s, M)$ are given ($y = M^2/s$ with $M = M_Z$ or M_W , $s > 0$)

$$\begin{aligned} \Lambda_2(s, M) &= -\frac{7}{2} - 2y - (2y + 3)\ln(y) \\ &\quad + 2(1 + y)^2 \left[\ln(y) \ln\left(\frac{1 + y}{y}\right) - Sp\left(-\frac{1}{y}\right) \right] \\ &\quad - i\pi \left[3 + 2y - 2(y + 1)^2 \ln\left(\frac{1 + y}{y}\right) \right] \\ \Lambda_3(s, M) &= \frac{5}{6} - \frac{2y}{3} + \frac{2}{3}(2y + 1) \sqrt{4y - 1} \arctan \frac{1}{\sqrt{4y - 1}} \\ &\quad - \frac{8}{3}y(y + 2) \left(\arctan \frac{1}{\sqrt{4y - 1}} \right)^2 . \end{aligned}$$

where the formula for Λ_3 is valid for $s < 4M^2$ only. The Spence function is defined by $Sp(x) = -\int_0^1 \frac{dt}{t} \ln(1 - xt)$. For $f=b$ the expressions are more complicated and may be found in Ref. [66].

and we may calculate

$$\sin^2 \Theta_f = \kappa_f \sin^2 \Theta_W = \frac{1}{2} \left(1 - \sqrt{1 - \frac{4A_0^2}{M_Z^2} \frac{1}{1 - \Delta r_f}} \right) \quad (191)$$

which compares to Eq. (175). Figs. 15 and 16 exhibit the different behavior as a function of m_t .

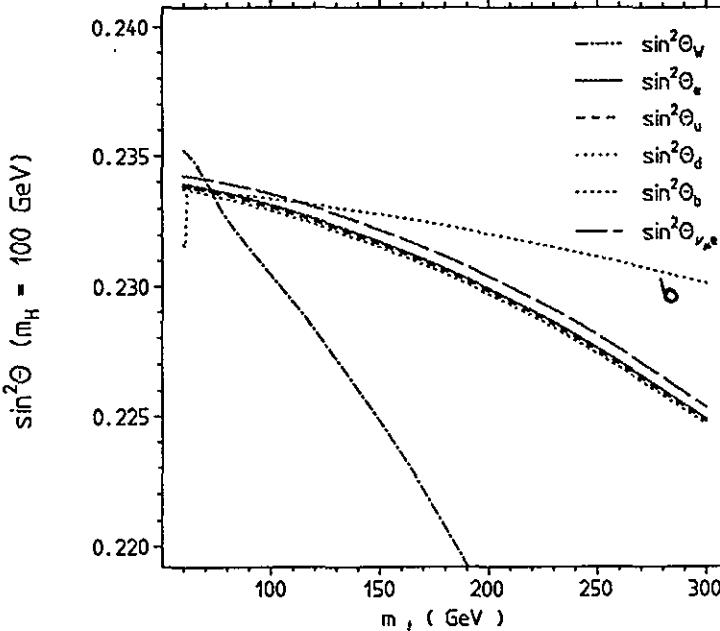


Figure 15: Flavor dependence of effective $\sin^2 \Theta$'s.

Comparing (190) with (157), we notice that the LEP1 versions Δr_f and $\sin^2 \Theta_f$ of Δr and $\sin^2 \Theta_W$ (obtained from the W-mass measurement) are by a factor $c_W^2/s_W^2 \simeq 3.3$ less sensitive to heavy particle effects (see Fig. 15 below). But in both cases it is the same quantity, namely $\Delta \rho$, which is measured. Also, one finds that the sensitivity to a heavy Higgs is lower by a factor $(1 + 9s_W^2)/(11c_W^2) \simeq 2.8$. This does not mean that LEP1 experiments are less suitable to get important information on heavy physics, however. Thanks to the higher statistics of LEP1 experiments, LEP1 observables are measured with higher precision. Furthermore, the relative sensitivity to the Higgs is higher at LEP1, a welcome fact, since the Higgs remains “the big unknown” in the Standard Model.

From the measured effective $\sin^2 \Theta_i$'s we may evaluate

$$\Delta r_i^{exp} = 1 - \frac{\pi \alpha}{\sqrt{2} G_\mu M_Z^2} \frac{1}{\sin^2 \Theta_i^{exp} \cos^2 \Theta_i^{exp}}. \quad (192)$$

The values for $\sin^2 \Theta_f^{exp}$ can be obtained, using the tree level formulae, from the on-resonance asymmetries which have been corrected for QED effects, experimental cuts

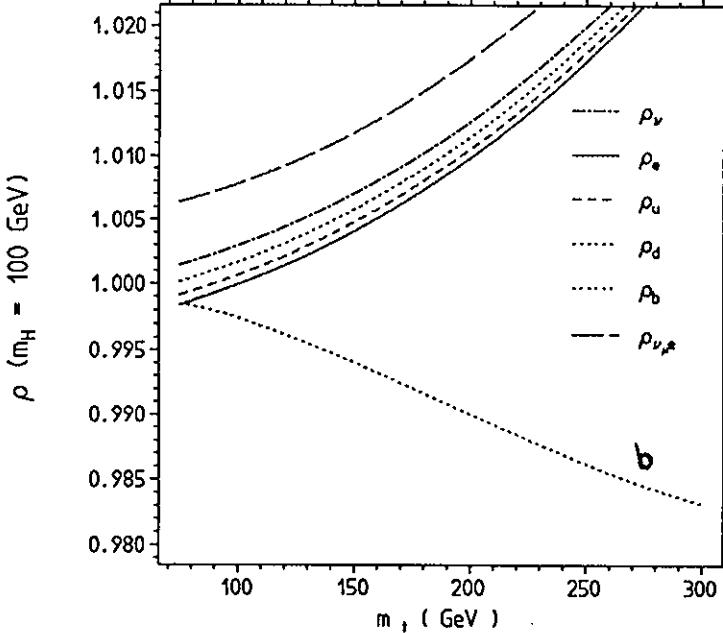


Figure 15: Flavor dependence of effective ρ 's.

and detector efficiencies. For example, from the experimental left-right asymmetry we get

$$\sin^2 \Theta_e^{exp} = \sin^2 \Theta_{LR} = \frac{A_{LR} - 1 + \sqrt{1 - A_{LR}^2}}{4A_{LR}}, \quad (193)$$

which confronts with the theoretical prediction (191). The last equation may also be used to determine $\sin^2 \Theta_e^{exp}$ from the forward-backward asymmetry $A_{FB}^{\mu^+\mu^-}$ if we identify

$$A_{LR} = \sqrt{\frac{4}{3} A_{FB}^{\mu^+\mu^-}}.$$

The weak mixing parameter most precisely measured at LEP is

$$\sin^2 \Theta_e(M_Z^2) = 0.2302 \pm 0.0025 \Leftrightarrow m_t = 196^{+54+24}_{-76-16} \text{ GeV}. \quad (194)$$

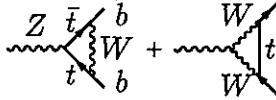
We see that the m_t -bound is weaker than the one obtained from the hadron collider results. The smaller error cannot yet compensate for the weaker m_t -dependence of $\sin^2 \Theta_e$ in comparison to $\sin^2 \Theta_W$. While this measurement does not improve the upper limit, it does improve the lower limit to $m_t > 104$ GeV. LEP has dramatically improved the precision of the leptonic Z couplings

Particle Data 90 [14]	LEP 90 [18]
$g_V^e = -0.045 \pm 0.022$	-0.037 ± 0.005
$g_A^e = -0.513 \pm 0.025$	-0.501 ± 0.003

Since $g_A^e = -\rho_e/2$ and $g_V^e/g_A^e = 1 - 4(1 + \Delta\tilde{\kappa}_e) \tilde{s}^2 1 = 1 - 4\sin^2\Theta_e$ we obtain

$$\Delta\rho_e = 0.002 \pm 0.006, \quad \Delta\tilde{\kappa}_e = 0.126 \pm 0.048, \quad \sin^2\Theta_e = 0.2315 \pm 0.0027.$$

Due to virtual b-t transitions in the $Zb\bar{b}$ vertex



one finds large vertex corrections from a heavy top quark, given by [65, 66]

$$\begin{aligned} \Delta\kappa_{b,vertex} &= \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \left\{ 2\frac{m_t^2}{M_W^2} + \frac{1}{3}(16 + \frac{1}{c_W^2}) \ln \frac{m_t^2}{M_W^2} + \dots \right\} \\ \Delta\rho_{b,vertex} &= -2\Delta\kappa_{b,vertex}. \end{aligned} \quad (195)$$

These corrections lead to a much weaker top mass dependence of quantities (partial width, asymmetries) associated with $b\bar{b}$ final states. Thus, in comparison with other channels the production of $b\bar{b}$ is particularly interesting since

$$\begin{aligned} \sin^2\Theta_b - \sin^2\Theta_e &= \tilde{s}^2(\Delta\kappa_{b,vertex} - \Delta\kappa_{e,vertex}) \\ g_A^b/g_A^e &= 1 + (\Delta\rho_{b,vertex} - \Delta\rho_{e,vertex}) \end{aligned}$$

measure the large top contribution of the Zbb -vertex. They are completely independent of Higgs and other heavy particle effects and hence they are ideal *heavy top meters*. As an example, for $m_t = 200$ GeV we obtain $\sin^2\Theta_b - \sin^2\Theta_e = 0.0020$ and $g_A^b/g_A^e = 0.9821$. For $\sin^2\Theta_b$ an experimental accuracy of 0.0009 is supposed to be achievable.

We may define a flavor independent effective $\sin^2\Theta$ by

$$\sin^2\bar{\Theta} = (1 + \Delta\kappa_{se}) \sin^2\Theta_W \quad (196)$$

and include the small vertex corrections in a second step

$$\sin^2\Theta_f = (1 + \Delta\kappa_{f,vertex}) \sin^2\bar{\Theta} \quad (197)$$

up to negligible higher order terms.

The flavor independent auxiliary quantity $\sin^2\bar{\Theta}$ is used in Ref. [56, 64] and is very similar to s_*^2 introduced in Ref. [45]. The “barred”(or “starred”)-quantities are obtained by ignoring (small) corrections different from the vector boson self-energies.

The leading heavy top and heavy Higgs dependence is given by

$$\begin{aligned} \Delta\bar{r}^{top} &= \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \left\{ -3\frac{m_t^2}{M_W^2} + \frac{2}{3c_W^2} \ln \frac{m_t^2}{M_W^2} + \dots \right\} \\ \Delta\bar{r}_b^{top} &= \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \left\{ -\frac{1+s_W^2}{c_W^2} \frac{m_t^2}{M_W^2} + \frac{16c_W^2(c_W^2-s_W^2)-1}{3c_W^4} \ln \frac{m_t^2}{M_W^2} + \dots \right\} \end{aligned} \quad (198)$$

and

$$\Delta\bar{r}^{Higgs} \simeq \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2} \left\{ \frac{1+9s_W^2}{3c_W^2} \left(\ln \frac{m_H^2}{M_W^2} - \frac{5}{6} \right) \right\} \quad (199)$$

respectively. Except from extra top contributions in the case $f = b$, all heavy particle effects are universal i.e. $\Delta r_{f \neq b}^{top} = \Delta r^{top}$ and $\Delta r_f^{Higgs} = \Delta\bar{r}^{Higgs}$.

What is the proper resummation of the large higher terms in case $\Delta\rho$ is large? Using Eqs. (183), (170) and (172) we have

$$\begin{aligned} \sin^2\Theta_f &= \left(1 + \frac{\cos^2\Theta_W}{\sin^2\Theta_W} \Delta\rho + \dots \right) \sin^2\Theta_W \\ &= 1 - \frac{M_W^2}{\rho M_Z^2} + \dots = \frac{1}{2} \left(1 - \sqrt{1 - \frac{4A_0^2}{\rho M_Z^2} \left(\frac{1}{1 - \Delta\alpha} + \dots \right)} \right) + \dots \end{aligned}$$

where the ellipses stand for the small remainder terms. As a result we obtain

$$\frac{1}{1 - \Delta r_f} = \frac{1}{1 - \Delta\alpha} (1 - (\Delta\rho)_{irr}) + \Delta r_{f,rem} \quad (200)$$

for the proper resummation of the large terms in Eqs. (189) and (191). This leads to the important relation

$$\sqrt{2}G_\mu \bar{\rho} M_Z^2 \cos^2\Theta_f \sin^2\Theta_f = \pi \bar{\alpha} (1 + \Delta r_{f,vertex}) \quad (201)$$

where

$$\bar{\rho} = \frac{1}{1 - \Delta\bar{\rho}} \simeq \frac{1}{1 - \Delta\rho}, \quad \bar{\alpha} = \frac{\alpha}{1 - \Delta\alpha} \simeq \frac{\alpha}{1 - \Delta\alpha} \quad (202)$$

with $\Delta\bar{\rho}$ and $\Delta\alpha$ given in Eqs. (183) and (173), respectively. Ignoring vertex corrections we obtain the universal relation

$$\sqrt{2}G_\mu \bar{\rho} M_Z^2 \cos^2\bar{\Theta} \sin^2\bar{\Theta} = \pi \bar{\alpha}. \quad (203)$$

For completeness we mention that $\sin^2\Theta_e$ measured at the Z peak is the high energy analogue of $\sin^2\Theta_{\nu_\mu e}$ measured in low momentum transfer $\nu_\mu e - scattering$. In fact, the two versions of $\sin^2\Theta$ are related in a way which is practically independent of unknown effects (they differ by γZ mixing and ν_μ charge radius contributions only, which, by accident, largely cancel each other numerically). Formally we have

$$\sin^2\Theta_e = (1 + \Delta_{se} + \Delta_{\nu_\mu e, vertex+box} + \Delta_{\kappa_e, vertex}) \sin^2\Theta_{\nu_\mu e} \quad (204)$$

where

$$\begin{aligned} \Delta_{se} &= \frac{\cos\Theta_W}{\sin\Theta_W} \left\{ \Pi'_{\gamma Z}(M_Z^2) - \frac{d\Pi_{\gamma Z}}{dq^2}(0) \right\} \\ &= \Delta\alpha - \Delta\alpha_2 \\ \Delta_{\nu_\mu e, vertex+box} &= \frac{\alpha}{4\pi s_W^2} \left\{ \frac{2}{3} \left(\ln \frac{M_W^2}{m_\mu^2} + 1 \right) + \frac{24c_W^4 - 14c_W^2 + 9}{4c_W^2} \right\} \end{aligned} \quad (205)$$

and $\Delta\kappa_{e,vertex}$ is the same as in Eq. (182) (see (185)). The shift $\Delta\alpha_2$ in the $SU(2)_L$ coupling $\alpha_2 = \frac{g^2}{4\pi}$ is analogous to $\Delta\alpha$ Eq. (158)

$$\begin{aligned}\Delta\alpha_2 &= \Pi'_{3\gamma}(0) - \Pi'_{3\gamma}(M_Z^2) \\ &= \frac{\alpha_2}{12\pi} \sum_l |Q_l| \left(\ln \frac{M_Z^2}{m_l^2} - \frac{5}{3} \right) + \Delta\alpha_{2,hadrons}^{(5)}\end{aligned}\quad (206)$$

where the sum extends over the light leptons and [51] (see Appendix Sec. IV)

$$\begin{aligned}\Delta\alpha_{2,hadrons}^{(5)}(s) &= 0.0587 \pm 0.0018 \\ &\quad + 0.006184 \cdot \{ \ln(s/s_0) + 0.005513 \cdot (s/s_0 - 1) \}\end{aligned}\quad (207)$$

is the hadronic contribution of the 5 known light quarks u,d,s,c,b ($\sqrt{s_0} = 91.176$ GeV).

The proper summation of the higher order effects in this case reads

$$\sin^2 \Theta_e = \left\{ \frac{1 - \Delta\alpha_2}{1 - \Delta\alpha} + \Delta_{\nu_\mu e, vertex+box} + \Delta\kappa_{e, vertex} \right\} \sin^2 \Theta_{\nu_\mu e} \quad (208)$$

The ratio $\sin^2 \Theta_{\nu_\mu e} / \sin^2 \Theta_e$ is shown in Fig. 6 as a function of m_t . The value of this ratio is close to 1.002. This relation provides a short of “model independent” constraint for the Standard Model. The CHARM II value for 0.240 ± 0.012 [67] is in agreement with the SM. The precise definition of the low energy ρ -parameter is (to linear order)

$$\rho_{\nu_\mu e} = \frac{G_{NC}(0)}{G_{CC}(0)} = 1 + \Delta\rho + \Delta\rho_{vertex+box} \quad (209)$$

with $\Delta\rho$ given in Eq. (158) and

$$\Delta\rho_{vertex+box} = \frac{\sqrt{2}G_\mu M_Z^2}{16\pi^2} \left\{ 24c_W^4 - 44c_W^2 + 15 - 2\frac{c_W^2}{s_W^2}(4c_W^2 + 3) \ln c_W^2 \right\}.$$

Similar to the asymmetries, the corrected partial widths $\Gamma_{Zf\bar{f}} = \frac{\sqrt{2}G_\mu M_Z^3}{3\pi}(v_f^2 + a_f^2)N_{cf}K_{QCD}(1 + \delta_{QED})$ and the peak cross-sections $\sigma_{peak}^{f\bar{f}} \simeq \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_f}{\Gamma_Z^2}$ are given by the Born formulae using the effective parameters Eq. (182). The uncertainty in α_s implies an uncertainty of 12 MeV in $\Gamma_{Z,tot}$. The QED-correction including real photon emission is given by $\delta_{QED} = \frac{3\alpha}{4\pi} Q_f^2$. In Tab. 4 some values are given for the widths and peak cross-sections. Full QCD corrections are taken into account [68]. In contrast to other authors we use a running \overline{MS} top mass. QCD corrections for the heavy top are small in this case, i.e. the results are close to the results which do not include QCD corrections for the heavy top.

Table 4. Z widths and peak cross-sections for $M_Z = 91.176$ GeV and $\alpha_s = 0.117$. Masses are given in GeV, widths in MeV and cross sections in nb.

m_t	m_H	Γ_Z	Γ_h	Γ_ℓ	Γ_{inv}	Γ_c	Γ_b	R_{had}	σ_μ^{peak}	σ_{had}^{peak}
90	100	2482	1733	83.4	499	296	378	20.787	1.9927	41.423
110	100	2485	1735	83.5	499	296	378	20.782	1.9937	41.432
130	50	2490	1739	83.7	500	297	378	20.780	1.9944	41.443
130	100	2489	1738	83.7	500	297	377	20.775	1.9949	41.444
130	1000	2481	1732	83.5	499	296	376	20.755	1.9971	41.449
150	100	2494	1741	83.9	501	298	377	20.767	1.9963	41.456
200	100	2508	1751	84.4	504	301	375	20.745	2.0002	41.494
230	100	2519	1759	84.9	506	303	375	20.731	2.0028	41.521

2. Results from LEP at the Z Resonance

The results from LEP based on 600,000 Z decays (presented at the Aspen Conference January 1991) are collected in Tab. 5.

The central values are given for $m_t = 136$ GeV and $m_H = 100$ GeV. The uncertainties for the SM predictions include variations of the parameters within the one standard deviation bounds $89 \text{ GeV} < m_t < 204 \text{ GeV}$, from the UA2 and CDF data, and $50 \text{ GeV} < m_H < 1 \text{ TeV}$. More precisely, the allowed range for m_t depends on m_H . Since, in the range of interest, all quantities are monotonic functions of m_H and m_t we may inspect the extremal cases simply: For $m_H = 50$ GeV the 1σ range for m_t is $(74, 180)$ GeV or $(89, 180)$ GeV if we take into account the direct bound (26). For $m_H = 1 \text{ TeV}$ we get $(104, 204)$ GeV. The bounds given in Tab. 5 are then the maximum or minimum values from the two extremal cases. Taking an upper bound 1 TeV for the Higgs mass is of course a theoretical prejudice.

The mass and the total width of the Z are determined from the line-shape. The separate analysis of the visible channels $e^+e^- \rightarrow \text{hadrons}$ and $e^+e^- \rightarrow \ell^+\ell^-$ allows to determine Γ_{had} and Γ_ℓ ($\ell = e, \mu, \tau$), respectively. Using that the total Z -width is given by

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_\ell + \Gamma_{invisible} ; \quad \Gamma_{invisible} = N_\nu(\Gamma_\nu)_{SM} \quad (210)$$

in terms of the hadronic, leptonic and neutrino contributions, $\Gamma_{invisible}$ is determined. N_ν is the effective number of SM neutrinos. The most important result established by the LEP experiments is that $N_\nu = 2.95 \pm 0.05$ and hence no additional light ($m_\nu \lesssim 45 \text{ GeV}$)

neutrino (sneutrino, Majoron etc.) exists [18]. This rules out the existence of further family replicas of the known type with (within experimental limits) massless neutrinos.

Table 5. LEP results on the Z peak

	ALEPH	DELPHI	L3	OPAL	LEP	SM	$\sin^2 \bar{\Theta}$
Z decays	195,000	130,000	125,000	156,000	600,000		
M_Z (GeV)	91.182 ± 0.009 ± 0.020	91.175 ± 0.010 ± 0.020	91.180 ± 0.010 ± 0.020	91.160 ± 0.009 ± 0.020	91.176 ± 0.005 ± 0.020		0.2315 $^{+0.0018}_{-0.0019}$
Γ_Z (MeV)	2488 ± 17	2454 ± 21	2500 ± 17	2497 ± 17	2485 ± 10	2490 ± 22	0.2322 $^{+0.0017}_{-0.0024}$
σ_{had}^{peak} (nb)	41.76 ± 0.39	41.98 ± 0.63	40.92 ± 0.47	41.23 ± 0.47	41.45 ± 0.21	41.45 ± 0.12	0.2313
Γ_{had} (MeV)	1756 ± 15	1718 ± 22	1739 ± 19	1747 ± 19	1744 ± 10	1739 ± 18	0.2314 ± 0.0022
Γ_ℓ (MeV)	83.6 ± 0.7	83.4 ± 1.0	83.3 ± 0.8	83.4 ± 0.7	83.4 ± 0.4	83.7 ± 0.5	0.2326 ± 0.0021
R_{had}	21.07 ± 0.19	21.61 ± 0.33	20.88 ± 0.28	20.94 ± 0.24	20.92 ± 0.13	20.77 ± 0.12	
Γ_{inv} (MeV)	487 ± 14	486 ± 21	511 ± 18	499 ± 17	496 ± 9	500 ± 3	
N_ν	2.90 $\pm .08$	2.93 $\pm .13$	3.08 $\pm .10$	3.00 $\pm .10$	2.95 $\pm .05$	3	
$(v_e/a_e)^2$	0.0081 ± 0.0028	0.0028 ± 0.0056	0.0081 ± 0.0051	0.0024 ± 0.0028	0.0056 ± 0.0016	0.0051 ± 0.0013	0.2315 ± 0.0027
A_{FB}^b	0.141 ± 0.044		0.130 ± 0.043	0.080 $\pm ?$	0.117 ± 0.027	0.0962 $^{+0.012}_{-0.006}$	0.2241 ± 0.0077
$A_{FB}^{\mu^+\mu^-}$	0.0239 ± 0.0082	0.0084 ± 0.0168	0.0239 ± 0.0150	0.0072 ± 0.0084	0.0166 ± 0.0047	0.0151 ± 0.004	0.2313 ± 0.0027

Of particular interest is the observable $R_{had} = \Gamma_{had}/\Gamma_\ell$ which is almost independent of m_t , due to an accidental cancellation of the m_t -dependence between the Zbb-vertex and the self-energies. A deviation from the SM would be a direct signal for non-standard physics. The experimental value 20.92 ± 0.13 is slightly higher than the SM prediction 20.77 ± 0.12 . Also the hadronic peak cross-section σ_{had}^{peak} is weakly dependent on m_t

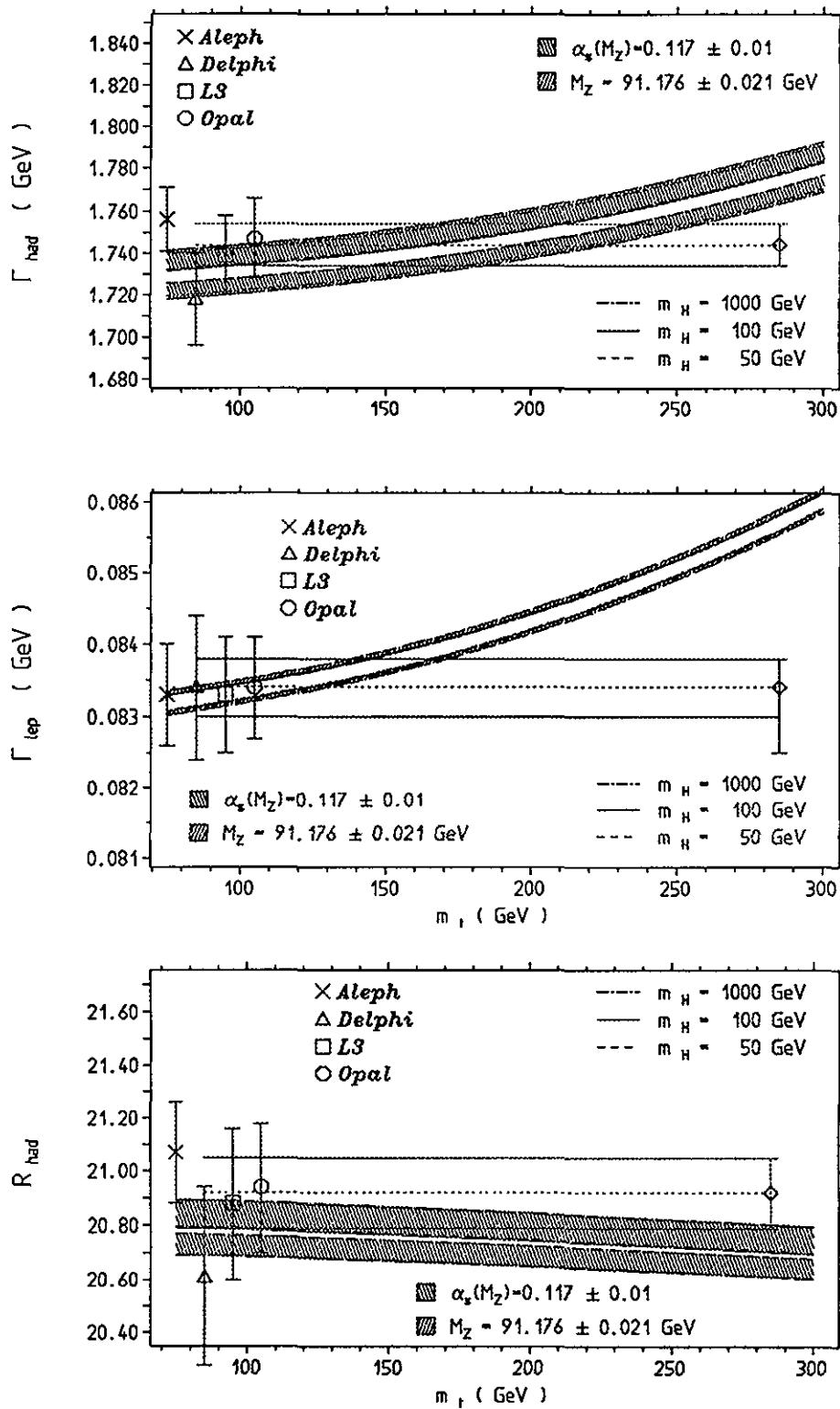


Figure 17: Results for Γ_{had} , Γ_ℓ and R_{had} .

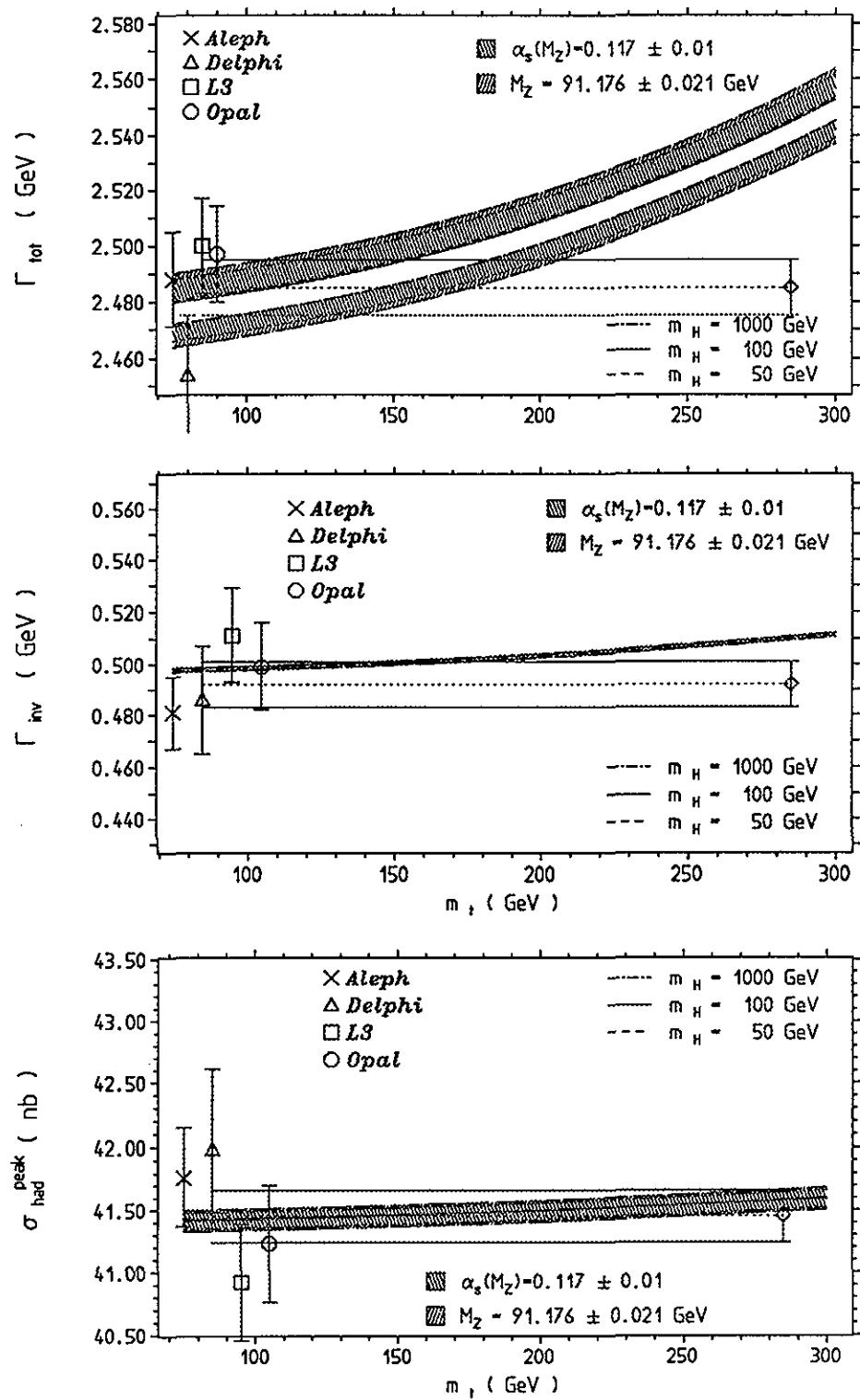


Figure 18: Results for Γ_Z , Γ_{inv} and σ_{had}^{peak} .

only. The experimental value is in perfect agreement with the prediction. Before more stringent tests are possible one has to pin down further the allowed mass ranges for the top and the Higgs. We do not expect that the errors on M_Z and α_s can be substantially improved further.

Some major results obtained in the first year of LEP ($\sim 600\ 000$ Z's) are shown together with theoretical predictions in Figures 17 and 18. All Figures show the data together with the theoretical prediction as a function of the top mass for $m_H = 50, 100$ and 1000 GeV. An uncertainty $\delta\alpha_s = \pm 0.01$ in the strong interaction coupling constant is shown as a inner error band whereas the outer error band shows the uncertainty in the prediction due to the experimental error $\delta M_Z = \pm 0.021$ in the Z-mass. The agreement between the experimental numbers and the theoretical predictions is impressive.

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