GaP PROJECT: $\gamma p, \gamma e, \gamma\gamma$ COLLIDERS PHYSICAL PROGRAMS AND CompHEP COMPUTER SYSTEM

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ABSTRACT

We propose the program of physical phenomena investigation on γp, γe and $\gamma\gamma$ colliders at TeV energies. The program contains specialized software (CompHEP system) created for automation of particle interaction processes calculations in the framework of various gauge models.

I. Introduction. $\gamma\gamma, \gamma e, \gamma p$ colliders

Among the TeV energy range colliders under development distinguished place is occupied by e^+e^- and ep colliders with linear electron accelerators. It is well-known that large synchrotron radiation losses of electrons in the ring put limitations on the growth of the electron beam energy. For this reason the transition to the TeV energy scale in e^+e^- collisions is possible only with the implication of linear accelerators. It is natural to expect that the future of ep colliders is connected with electron beams from linacs. Such type of TeV energy ep colliders can be realized on the basis of UNK+VLEPP, HERA+linac, LHC+CLIC, SSC+NLC projects [1,2,3].

Great advantage of linear electron accelerator projects is the possibility of real γ beam generation. It becomes possible to construct $\gamma\gamma$, γe and γp colliders [2,3] with almost the same c.m.s. energy and luminosity as in original e^+e^- and ep machines. The realization of idea how to obtain real γ-beam through inverse

Compton scattering of laser photons on high energy electrons [4,5] has already been demonstrated at SLAC accelerator where 20 GeV photon beam was generated from 30 GeV electron beam. Practical realization of γe colliders based on corresponding e^+e^- linear colliders is under consideration in the framework of VLEPP, JLC and SLAC projects.

Various schemes of e(γ) linear beam collisions with circle p beam were discussed in [2,3] (collisions in proton ring or extracted proton beam version). It was shown [3] that the achievement of physically interesting luminosity ($L>10^{31}cm^{-2}s^{-1}$) is quite possible.

The distinguished status of γ beam colliders is defined by the following circumstances.

For investigations of some physical phenomena γe and γp colliders are more effective then ordinary type colliders. As an example let us mention unique possibilities to search for exotic resonances in s-channel (excited leptons and quarks, color excitations of Z boson) appearing in the framework of various compositeness models.

ep and γp colliders let us to obtain information about proton structure functions of extremely low x (down to kinematical limits x $\simeq 10^{-4}-10^{-5}$).

γe and γp machines introduce new interesting possibilities for detection of higgs bosons (see chapter Y).

γe and γp colliders give unique possibilities to investigate polarization phenomena.

Many other possibilities connected with γ-beam physics exists. Preliminary analysis of various collider types opportunities can be found in [2].

At present time there are practically no explicit calculations for physical processes on colliders with γ beams. So in comparison with e^+e^-,ep and pp colliders projects physical programs of γe and especially γp colliders are practically not worked out.

It is worth noticing that there is some time (about 5 years) for creation of γ beam colliders physical programs because their practical realization will be held after construction of corresponding e beam machines.

Finally it can be emphasized that technical realization of γ-beams on linear electron accelerators is not so expensive.

II. GaP project

The abovementioned features of γ beam physics inspired us to propose the GaP (Gamma Physics) project.

In order to obtain the detailed picture of physical processes with γ beams accurate calculations are necessary. Such calculations can be roughly divided by the following steps:

1) physically meaningful processes calculation in the lowest order of perturbation theory in Standard Model and beyond Standard Model. Such calculation shows us collider detection opportunities;

2) background processes calculation;

3) polarization phenomena calculations;

4) radiative corrections calculation for precise tests of theoretical models.

GaP project includes two main directions - investigation of physical phenomena and computer support of this research.Very large volume of calculations to be performed for any collider project and GaP project in particular is defined by complicated structure of gauge field theory models (Standard Model has 72 vertices and number of diagrams for $2\longrightarrow4$ process can be close to 1000) and also by the variety of models proposed for TeV physics (Standard Model and its various string theory motivated extensions, SUSY, compositeness, etc.). There are many unknown physical parameters (m_t, m_{susy}, ...). Especially tedious calculations are required for background processes (on tree level) and loop corrections to basic processes.

From the theoretical point of view perturbative calculations in gauge theories are done with the help of standard methods with well defined algorithms. Furthermore one can restrict oneself by the limited number of exclusive procrsses types: $2\longrightarrow2$, $2\longrightarrow3$, $2\longrightarrow4$, $1\longrightarrow2$, $1\longrightarrow3$, $1\longrightarrow4$ and a limited number of final characteristics types (cross-sections, asymmetries, decay rates in formulas and plots and some others) needed for the process under consideration. One finds large field for computer applications here (analytical and numerical calculations, graphic routines for representation of results). Nevertheless at present time it is possible and it is necessary to automize theoretical calculations for collision and decay processes to a very large extent creating specialized software. Specialized software allows one to calculate a large number of processes quickly and to avoid mistakes usual for tedious computations done by hand. Features of calculations mentioned above give us good opportunity to specialize software for efficiency and service.

Specialized software must satisfy the following requirements:

- high level of service (application of software by physicists without special computer education must be possible);
- high speed of calculation;
- common (universal) software environment beginning from the choice of lagrangian and ending the graphical result representation;
- hardware portability (for software implementation by different groups of physicists for results exchange and testing).

The first step of the GaP project is under realization now. Preliminary estimates for some physical phenomena were obtained [2]. We shall give brief report on them in the next chapter. The problem of specialized symbolic software creation is practically solved for collision and decay processes in the tree approximation (CompHEP system , see chapter IY). The unification of symbolic calculations and standard numerical and graphical packages in the frame of interactive "user-friendly" shell is under elaboration now (see chapter IY). At the same time we are performing calculations for the GaP project with the help of CompHEP system. The example of such calculation will be presented in the last chapter (higgs boson production in γe collisions).

III. Preliminary physical results for γp collider

Let us describe several production processes of basic interest. Our consideration corresponds to Refs.[2,3].

1) Heavy quark production.

The leading elementary subprocess for heavy quark production in γp collisions is the photon-gluon fusion ($\gamma g \to b\bar{b}, t\bar{t}, \ldots$). The b quark production cross section is approximately 0.1 μb for $\sqrt{s_{\gamma p}}$ = 1 TeV (if mass of the b quark is equal to 5 GeV). For the run with integral luminosity of 100 pb^{-1} this corresponds to the production of 10^7 b quarks. For sufficiently monochromatic photon beam obtained by conversion b quark production takes place at characteristic $x_g \simeq 4m_b^2/s$, corresponding to $x_g \simeq 10^{-4} - 10^{-5}$ for $\sqrt{s}_{\gamma p}$ of several TeV. Hence investigation of b quark production processes allows us to study gluon distributions at extremely small $x_g \simeq 10^{-4} - 10^{-5}$ not accessible on the other types of colliders. It is expected that in this kinematical region the phenomenon of inverse evolution of parton distributions could manifest itself very clearly.

The t-quark masses that can be achieved at different energies and luminosities of γp collider are given in Table 1. As usual, the discovery limit was taken of 100 $t\bar{t}$ pairs production per year. For example, m_t masses up to 450 GeV are achievable for UNK+VLEPP (3 TeV protons on 1 TeV electrons).

2) W,Z production.

Characteristic cross section for W and Z production processes $\gamma p \longrightarrow W(Z)+X$ for instance at UNK+VLEPP energies is equal to 100 pb. At the integral luminosity of 100 pb^{-1} such cross section corresponds to 10^4 W's and Z's. This makes possible to measure the anomalous magnetic moment of W boson with a high accuracy of order 10^{-2} comparable with LHC and SSC. It is possible to obtain higher accuracy on γe collider and we are going to consider this question in the nearest future with the help of CompHEP system.

3) Supersymmetry.

A great number of new processes appear in the framework of supersymmetric models. It is straightforward to consider processes of superparticle production typical for γp

$$\gamma p \longrightarrow \tilde{q} + \tilde{q} + X, \quad \tilde{\gamma}(\tilde{Z},\tilde{W}) + \tilde{q} + X, \quad \tilde{g} + \tilde{q} + X.$$

Discovery limits for SUSY at UNK+VLEPP for example are shown in Table 1. The numerical values correspond to the assumption $m_{\tilde{\gamma}} = 0$, $m_{W,Z} = m_{\tilde{W},\tilde{Z}}$ and 100 events per year. We are going to perform numerous calculations for the main processes with corresponding background processes in different SUSY models.

4) Compositeness.

The composite models of leptons, quarks and intermediate vector bosons predict the existence of excited quarks or excited vector bosons. From the dimensionality considerations one may expect that these particles would have masses of the order of the compositeness scale Λ. The most clear signal in this case would be a single resonance production of excited states in the s-channel fusion reactions γq or γg.

The quark excited state decay into qg will be the main decay mode and experimentally the excited quark will manifest itself as a peak in the distribution versus invariant mass of two-jet events with a large transverse momentum. It is easy to calculate the integrated cross-section of this process according to resonance Breit-Wigner formula. We present the discovery limits on the excited quarks mass at different luminosities in Table 1. We assume as usual that 100 events per year is sufficient to establish the signal.

In some models the intermediate vector bosons are considered as bound states of colored preons. In this case one can predict the existence of color excited intermediate vector bosons W_c, Z_c (octet in color) with masses of order of compositeness scale Λ. In γp collisions the Z_c boson may be produced via photon-gluon fusion. The main decay mode for the color vector boson will be the decay into Zg with a further decay of Z into lepton-antilepton pair or two jets. An indication to the Z_c production would be the observation of a peak in the invariant mass distribution of the three jet events (with the invariant mass of two jets being equal to the to the mass of Z resonance), or of the one jet event with the peak in the transverse momentum distribution at transverse momentum $(1/2\ M_{Z_c})$, or the events containing a jet and a pair of charged leptons.

The detailed analysis of excited quark production process was carried out in [6]. However in the case of color vector boson production the detailed analysis of the background conditions is much more complicated and special consideration is necessary here.

IY. CompHEP system and further software development

1. CompHEP v.2.0 facilities

In March 1990 we presented [7] the interactive system CompHEP.

With the help of CompHEP one can work out second direction of the above stated problem referring to symbolic calculations of the particle interaction processes in gauge models. The following options are realized now (CompHEP version 2.0, see structure of the system in Table 2):

- choice, modifications and creation of new physical model. Four build-in models are available (QED, QCD, SM, QED + QCD + effective 4-fermion interaction);
- selection of the process or subprocess. Tree diagrams (no more than 6 legs) calculations are possible for any process;
- definition of the helicity states for massless fermions;
- definition of the composite objects (for instance hadron in-states)
- consideration of the inclisive processes;
- Feynman diagrams generation for the chosen process and their graphical representation;
- generation of symbolic expressions (in REDUCE codes) corresponding to diagrams according to Feynman rules;
- symbolic calculation of the matrix element squared;
- symbolic results output in REDUCE codes;
- generation of optimized FORTRAN code for cross-sections.
- numerical calculation for 2⟶2 processes with graphical representation of the results.

In order to be sure that physical models built in have the correct form for lepton, quark, gauge boson and higgs sectors we calculated the basic processes with the help of CompHEP and compared our results with the results obtained by others [8]. One can see in Table 3 the list of basic processes used for our system testing on all steps of software development.

In the nearest future we are planning to realize the following possibilities for CompHEP:

- calculation of polarization phenomena (with spin 1 and massive spin 1/2 particles);
- representation of the final result as a function of standard kinematical variables (s, t - 2⟶2, Dalitz vars for 1⟶3 etc.);
-substitution of functional form factors to the CompHEP lagrangians for applications of improved Born approximation (furthermore insertion of any loop boxes);
- applications of various gauges (unitary and Feynman ones);

- build in package for approximation over small parametres in symbolic results obtained for squared matrix elements.

CompHEP v.2.0 is realized on IBM compatible computers in MS DOS environment. Programming language used is TurboPascal. The whole size of source codes is about 12000 lines. EXE+OVR modules size is approximately 250 Kbytes.

2. Inner parts of CompHEP v.2.0

In this chapter we point out some specific features of algorithms realization in CompHEP.

Error diagnostics in "View/Edit Physical Model module" is necessary because information input to various files of Physical Database must be in hard relationship. For instance if one introduces a particle with spin 1 the corresponding vertices must include this particle as a (pseudo)vector one.

Feynman diagrams are generated as trees of decays with one "in" particle as a root and second "in" particle plus all "out" ones as "branches". Tree evolution is performed in a canonical form to exclude equivalent trees. Then some type of crossing is done for the second "in" particle to consider it as second "root". Some procedures are done finally to exclude equivalent diagrams. The runtime to generate 500 diagrams is about 10 s. (IBM PS/2-50, 10 MHz).

Specialized symbolic calculation package has been developed for our system. Color factors are calculated with the help of Kennedy-Cvitanovich algorithm [13]. γ-matrices traces are calculated with the help of Kahane algorithm [14]. Some optimization procedures with Lorentz vector and tensor algebra are performed before symbolic calculations to make them faster and less memory keeping. This package allows us to use 400 Kbyte RAM directly for symbolic calculations. The memory is used with higher efficiency in comparison with REDUCE [15]. For example it is possible to calculate some test using 20 Kb but the same is not possible using PC version of REDUCE [16] addressing 128 Kbytes. Symbolic calculations by our package are performed 10 times faster in comparison with REDUCE [16]. We use special form for algebraic expressions representation. Maximal power in the polynomial is restricted by 64000, coefficients in monoms are restricted by limits $\pm 2048 \cdot 10^6$. Only polynomials over γ-matrix traces or over Lorentz vectors are permitted. Such restrictions let us create symbolic package with excellent memory and runtime characteristics sufficient for our purposes.

The symbolic calculation runtime is about 10÷30s per one $2 \longrightarrow 3$ diagram and up to 1 min for one $2 \longrightarrow 3$ diagram with rather large number of intermidiate bosons or with ghosts (IBM PS/2-50, 10 MHz).

Fortran code optimization is necessary because a very large polynomials arise for real tasks. Hence the optimization of symbolic results for cross-sections could decrease greatly the runtime of correspomding numeric simulations. We use the same optimization idea as in [17]. First we generate Fortran codes for separate diagrams by some modified Gorner scheme. Constants are evaluated before this generating. We eliminate powers of variables by introducing new variables (this step decreases considerably the number of powers and multipliations). This optimization procedure gives simulations about two (sometimes ten) times faster . It may be interesting to use the program COMPACT by Hearn [18] for minimization of number of terms in symbolic expressions by using the energy-momentum conservation law (in real test this gives up to two times decrease).

3. Estimates of numeric simulations

In Table 4 we give upper estimates for numeric simulations of symbolic results produced by CompHEP. We use IBM PS/2-50 (80286 /287, 10 MHz) machine. We take typical SM processes and restrict ourselves to 10 points per one degree of freedom in integration over phase space.

So we conclude that the problem under consideration on the first stage of GaP project could be solved with the help of CompHEP (even on PC) in appropriate time expenses because majority of calculations is $2 \longrightarrow 3$ type with 10 as average quantity of diagrams per process.

However processes $2 \longrightarrow 4$ are very important for the problem under consideration because they represent background processes for physically interesting processes. We see that our estimates for machines used give too much time needed for real calculation. If we pass to next class of machine, workstation with 10÷30 Mips productivity, it becomes more realistic. Notice that average quantity of diagrams per process 2⟶4 is less than 100. Furthermore one can decrease the number of points for integration because estimates of backgrounds can be rather rough.

Nevertheless we feel that hardware must compose of workstation and powerful mainframe (may be with parallel or vector processor). The first item could ensure the work with physical models, task formation, symbolic calculations and FORTRAN codes output. The majority of numeric simulations could be performed by using powerful workstation. Then the tedious part of numeric simulations (for 2⟶4 tasks) could be done on mainframe.

4. Further software development and problems

In the framrwork of GaP project we started the elaboration of interactive "user-friendly" system unifying various aspects of activity. This work is organized on the following principles:

- UNIX environment (we use Interactive System Co. 386/ix UNIX system Y.);
- XWindows graphical standard (XII package in 386/ix);
- standard event generators (PYTHIA, BASES [19]);
- CompHEP system (DOS facilities, VPix package in 386/ix);
- specialized (for estimates, approximations,...) symbolic utilities (UNIX version of REDUCE for 386/ix, probably MATHEMATICA);
- data base for improved Born approximation and 1-loop (may be 2-loop) boxes functional formfactors;
- data base for physical results.

Let us emphasize some problems arising here:

1) Optimization of polynomial output after symbolic calculations on the principally new basis (some partial factorization procedure, symbolic integration over one or two (or three?) kinematical variables). This is necessary to make background processes calculations and radiative corrections calculations more reliable.

2) Rewriting CompHEP source codes (all or some parts) on C programming language (for more portability). Our choice of Turbo Pascal had some historical reasons.

3) Organization of 1-loop (2-loop) boxes database and their

management. Contents of database and the implementation in real calculation process. For instanse, it is a question what to store: exact symbolic results, or/and (numerical?) estimates, or/and approximations, etc.

Specialized programs for automation of theoretical calculations in high energy physics are developed also by two groups: [20] and [21]. The first one elaborated numerical (and symbolic) software intended for precise calculations in Standard Model. The second one developes general purpose packages for symbolic calculations of many loop diagrams.

Y. Higgs production in γe collisions

As we already mentioned in part 1 γe colliders introduce new interesting possibility for higgs boson detection. The following results illustrate the possibilities of CompHEP application to the calculation of new 2$\rightarrow$3 processes.

Search for higgs boson is one of the most important problems for the new generation colliders. Higgs discovery is crucial for physics in the framework of the Standard Model and beyond. For this reason any new possibilities of higgs production and detection are very significant.

Higgs production in γe collisions is possible only via 3-particle final states. There are two basic processes for higgs production

1) $\gamma e \longrightarrow W-, \nu_e, H$

2) $\gamma e \longrightarrow Z, e, H$

We have considered both processes (see CompHEP generated diagrams in fig.1-4). One can notice that W-fusion contribution exists for process 1) and there is no such contribution for process 2). For this reason one can expect that first process cross section is larger then the second one. Our calculations confirm this estimate and the results for total cross section versus higgs mass are represented on fig.5,6 at several c.m.s. energies. At collider luminosity $10^{33}cm^{-2}s^{-1}$ the minimal level of 100 events per year can be observed for the cross section of order 10^{-2} pb. We conclude that for 0.5 TeV c.m.s. energy it is possible to observe higgs masses up to 120 GeV, for 1 TeV c.m.s. energy up to 400 GeV and for 2 TeV c.m.s. energy up to 950 GeV. For the process 2) as one can see at fig.6, the total cross section is always smaller then 10^{-2} pb even for relatively small higgs masses (of order 50 GeV). It follows that the second process is not interesting from the physical point of view for realistic higgs detection.

We compared our results with the results for higgs production at e^+e^- colliders. The processes $e^+e^- \to ZH$, $e^+e^- \to \nu\bar{\nu}H$, $e^+e^- \to e^+e^-H$ were calculated several years ago by various groups (see for example [22]). Our results (fig.7,8) for these processes obtained with the help of CompHEP system are the same. The cross section of $e^+e^- \to ZH$ process decreases with energy while the cross sections for $e^+e^- \to \nu\bar{\nu}H$, $e^+e^- \to e^+e^-H$ grow as energy increases and the dominant process at high energy is $e^+e^- \to \nu\bar{\nu}H$. Let us notice that we checked the well-known fact that the main contribution to $e^+e^- \to \nu\bar{\nu}H$ (about 95%, see fig.7) is given by fusion diagram. The contribution of the fusion diagram grows with energy and gives almost 100% of the cross section at 2 TeV c.m.s. energy.

Our results show that $e^+e^- \to \nu\bar{\nu}H$ total cross section is several times larger then $\gamma e \to W\nu H$ cross section. However in the case of $e^+e^- \to \nu\bar{\nu}H$ large background is given by $e^+e^- \to W^+W^-$ because in the case of $\nu\bar{\nu}H$ final state hardly detectable missing energy is taken by neutrino. But in the case of $W\nu H$ final state the background effect is defined by production of WWW massive vector boson states and it is much smaller. For this reason the ratio of the signal to the background in the case of $\gamma e \to W\nu H$ is several orders of magnitude better then in the case of $e^+e^- \to \nu\bar{\nu}H$. We conclude that γe collider could give us good opportunities to investigate higgs particle production.

YI. Conclusion

Our discussion of the GaP project was rather brief but it is clear that rich opportunities to describe standard physics and discover new physical phenomena appear.

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Table 1.

Discovery limits for new physics at UNK+VLEPP (γp collisions)

E_e, TeV	0.1		0.5		1.0		2.0	
$\sqrt{s}$, TeV	1.1		2.4		3.5		4.9	
$L, cm^{-2}s^{-1}$	10^{30}	10^{31}	10^{30}	10^{31}	10^{30}	10^{31}	10^{30}	10^{31}
M_t, TeV	0.15	0.2	0.25	0.3	0.3	0.45	0.35	0.6
M_{q^*}, TeV	0.7	0.8	1.4	1.7	1.7	2.2	2.2	3.0
$M_{Z^*_\theta}$, TeV	0.5	0.6	0.9	1.1	1.1	1.5	1.5	1.9
$m_{\tilde q} + m_{\tilde g}$, TeV	0.2	0.3	0.25	0.5	0.3	0.55	0.3	0.6

Table 2.
CompHEP version 2.0 STRUCTURE

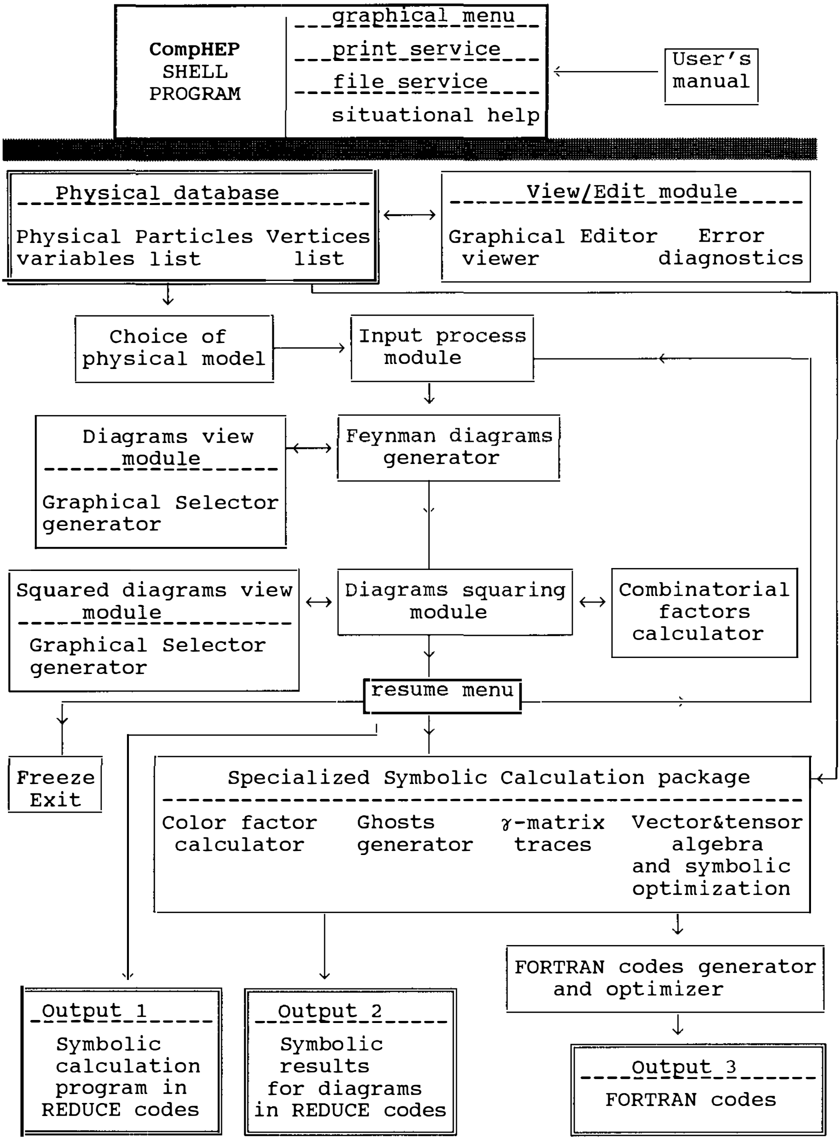

Table 3.
List of basic tests of ComHEP System

QED	ee->ee γe->γe ee->$\gamma\gamma$	electron scattering and e^-e^+ annihilation Compton effect two photon annihilation
QCD 2->2 processes, massless quarks[9]	$q\bar{q}$->gg, gg->$q\bar{q}$, gq->gq, gg->gg;	
QCD 2->2 and 2->3 processes, heavy quarks[10]	$q\bar{q}$->$Q\bar{Q}$, gg->$Q\bar{Q}$, qQ->qQ $q\bar{q}$->$Q\bar{Q}$g, gg->$Q\bar{Q}$q, gg->$Q\bar{Q}$g;	heavy quark excitation
Effective 4-fermion model	μ->e$\upsilon\upsilon$	β-decay
Standard Model[11]	ee->$\mu\mu$ H->$\mu\mu$, H->WW, H->Z$\mu\mu$, H->$W^+\bar{u}$d e^+e^-->ZZ, e^+e^-->W^+W^- e^+e^-->ZH, tt^-->Hg u$\bar{d}$->$W^+\gamma$, W^-->$\gamma\bar{u}$d, t->Wbγ	effects of parity violation by neutral currents higgs decays gauge boson production higgs production radiative amplitude zeroes[12]

Table 4.
Estimates on numeric simulations (IBM PS/2-50, 10 MHz) for typical SM processes with 10 points per one degree of freedom in integration over phase space

Process type	max quantity of terms in polynomials	max quantity of diagrams	quantity of independent simulated variables	quantity of cross-section function calls	typical runtime for process
$2\to2$	6	10	1	10	$2\cdot10^{-2}$s
$2\to3$	35	100	4	10^4	10^3s ≈ 20min
$2\to4$	227	1000	7	10^7	10^8s

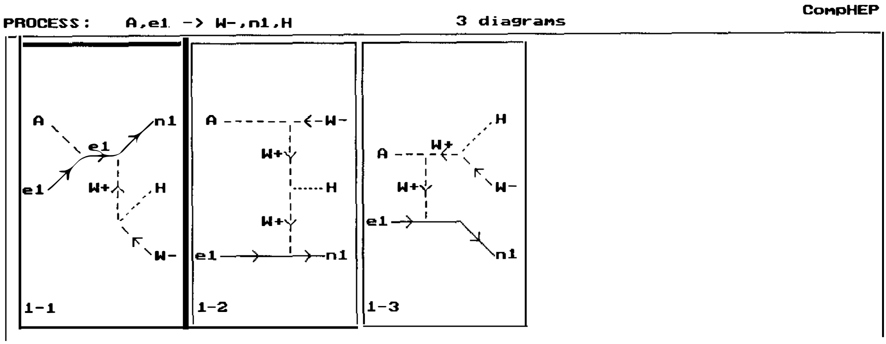

FIG. 1 CompHEP session print screen for $\gamma e^- \to W^- \nu_e H$

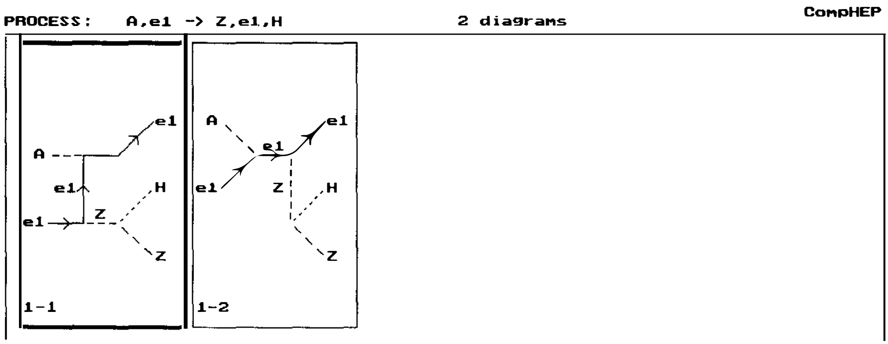

FIG. 2 CompHEP session print screen for $\gamma e^- \to Z e^- H$

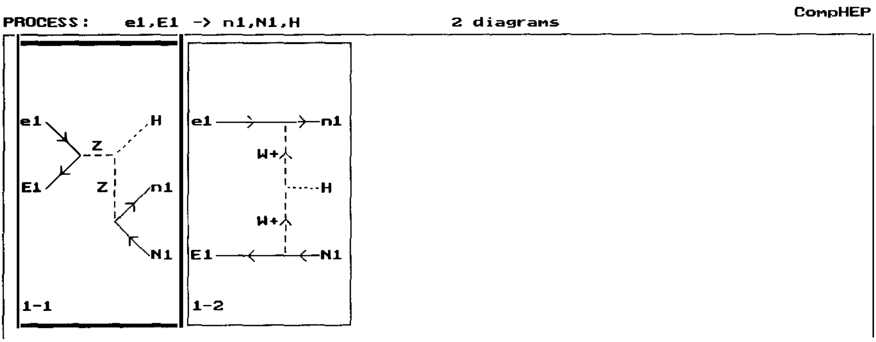

FIG. 3 CompHEP session print screen for $e^+e^- \longrightarrow \nu_e \bar{\nu}_e H$

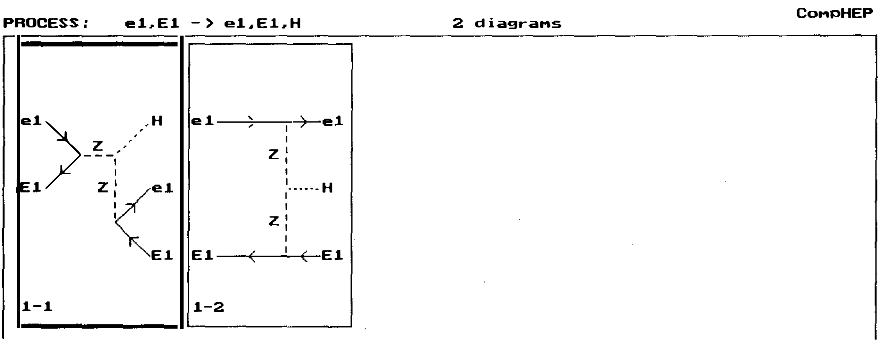

FIG. 4 CompHEP session print screen for $e^+e^- \longrightarrow e^+e^- H$

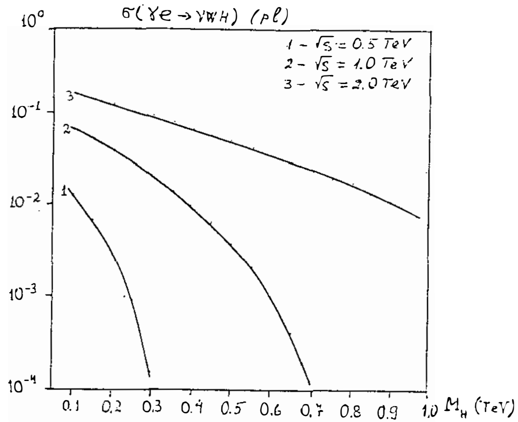

Fig.

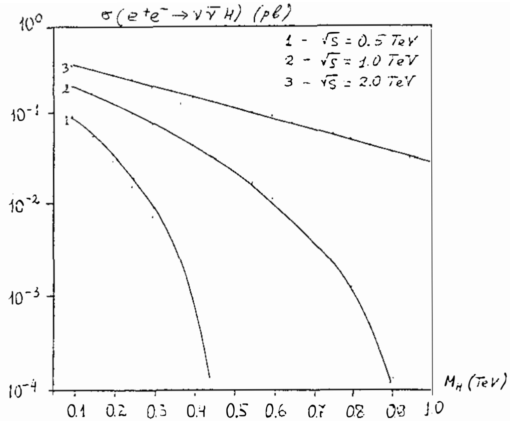

Fig.

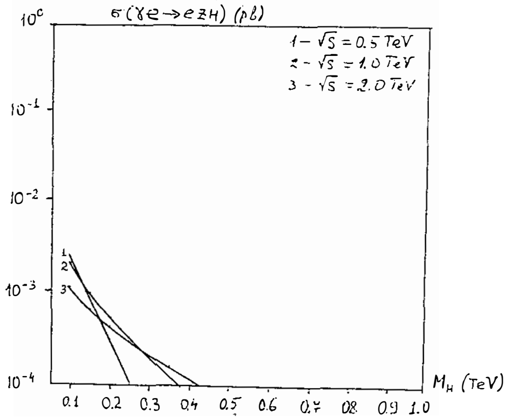

Fig.

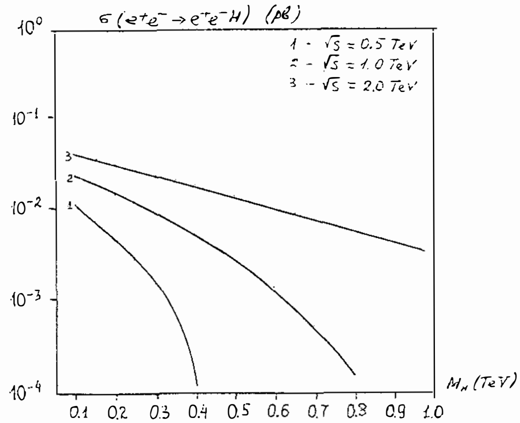

Fig.