1.1 Towards a Muon Collider

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1.1.1 Physics Landscape

The Standard Model (SM) has been a spectacular success. For more than thirty years all new observations have fit naturally into this framework. But basic questions remain: (1) There is as of now no direct evidence for the Higgs boson or its interactions. Is this the correct mechanism of electroweak symmetry breaking? (2) How do the fermion masses and flavor mixings arise? Furthermore, the Standard Model is incomplete. It does not explain dark matter; neutrino masses and mixings require new particles or interactions; and the observed baryon asymmetry in the universe requires additional sources of CP violation. From a theoretical viewpoint there are also problems with the SM. It has been argued by G. 't Hooft that the SM is not natural at any energy scale Λ much above the Terascale (~1 TeV) because the small dimensionless parameter $\xi(\Lambda) = (m_H/\Lambda)^2$ is not associated with any symmetry in the limit $\xi = 0$ [1]. This is the naturalness problem of the SM. If the SM is valid all the way up to the Planck scale Λ_{Pl} (~ 10^{19} GeV), then the SM has to be fine tuned to a precision of one part in $(m_H/\Lambda_{Pl})^{-2}$! In this decade, the physics of the Terascale will be explored at the LHC. Planned experiments studying neutrino oscillations, quark/lepton flavor physics, and rare processes may also provide insight into new physics at the Terascale and beyond.

Discoveries made at the LHC will elucidate the origin of electroweak symmetry breaking. Is that mechanism the SM Higgs scalars or does it involve new physics? New physics might be new gauge bosons, additional fermion generations or fundamental scalars. It might be SUSY or new dynamics or even extra dimensions. Significant theoretical questions will likely remain even after the full exploitation of the LHC. Most notably, the origin of fermion (quark and lepton) masses, mixings and CP violation; the character of dark matter and detailed questions about spectrum, dynamics, and symmetries of any observed new physics. Thus, it is hard to imagine a scenario in which a multi-TeV lepton collider would not be required to fully explore the new physics.

To prepare for the energy frontier in the post-LHC era, research and development is being pursued on a variety of lepton colliders: A low energy ($E_{c.m.}$ < 1 TeV) linear electron-positron collider (ILC), a second design (CLIC) capable of higher energies ($E_{c.m.}$ = 3 TeV), and a multi-TeV muon collider.

A multi-TeV muon collider provides a very attractive possibility for studying the details of Terascale physics after the LHC. Presently physics and detector studies are under way to understand the required muon collider parameters (in particular luminosity

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and energy) and map out, as a function of these parameters, the associated physics potential. The physics studies will set benchmarks for various new physics scenarios (e.g., SUSY, Extra Dimensions, New Strong Dynamics) as well as Standard Model processes.

1.1.2 Neutrino Factory

The SM has three generations of quarks and leptons. The flavor eigenstates for the left-handed neutrinos are denoted ν_e, ν_μ and ν_τ and the mass eigenstates by ν_i (i =1,2,3). In the simpler case of two flavors the probability (P) of flavor (a,b) mixing over a distance (L) for neutrino energy (E) is given by $P_{(a \to b)} = \sin^2 2\theta \sin^2(\Delta m^2 L/4E)$ where Δm^2 is the mass squared difference of the two mass eigenstates. Flavor mixing implies masses for neutrinos. Flavor mixing has been observed for solar neutrinos and atmospheric neutrinos with very different scales of mass difference, Δm^2 (solar) $<< \Delta m^2$ (atmospheric).

In the SM, the mixing is represented by a 3×3 mixing matrix, the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. This matrix has three angles θ_{12} , θ_{23} , θ_{13} and one phase δ. If there are right-handed neutrinos (sterile under the SM interactions) this is the whole story. If there are no right-handed neutrinos then the mass terms are Majorana, lepton number is broken, and two additional phases appear. There are four important questions about the neutrino sector:

1) Are the neutrinos Majorana or Dirac?
2) Is the mass hierarchy normal (smaller splitting between the two lightest neutrinos) or inverted (the two most massive neutrinos have smaller splitting)?
3) What is the value of θ_{13} ? The other two angles are already measured and large.
4) Is there CP violation, i.e., is δ not equal to 0 (mod π)?

The first question can be addressed in neutrinoless double β decay experiments. The remaining three questions will be addressed with neutrino beams. A neutrino factory (NF) has been proposed that uses a muon storage ring at an energy of 25 GeV with long straight sections to produce beams of neutrinos from the muon decays. This approach requires high intensity muon beams as it assumes 10^{21} muon decays per year. It is very likely that a neutrino factory will be needed to provide detailed measurements of θ_{13}, the mass hierarchy, and the CP violating phase δ.

The comparison of a Neutrino Factory with other neutrino beam facilities is shown in Fig. 1. As can be seen, the approach with the greatest reach is a neutrino factory (NF). This and many other details of the neutrino physics facilities can be found in the reports of the ISS Physics Working Group [2].

One advantage of the Muon Collider is that it lends itself to a staged program with physics at each stage of producing and cooling the muons. An important physics opportunity is the possibility of a neutrino factory as a step to a Muon Collider.

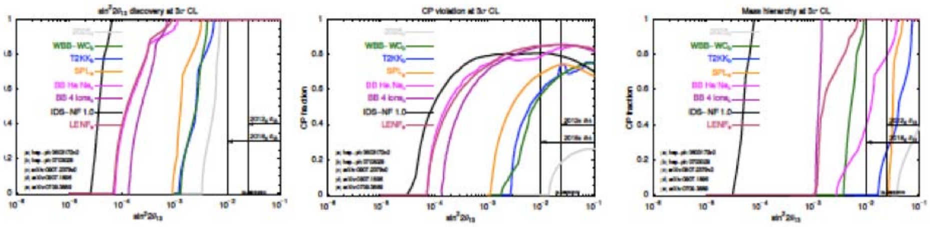

Figure 1: Comparison of physics reach of NF with other potential neutrino facilities [2].

1.1.3 Muon Collider Physics

The Muon Collider is an energy frontier machine. It offers both discovery as well as precision measurement capabilities. The physics goals of a Muon Collider (MC) are for the most part the same as a linear electron collider (CLIC) [3] at the same energy. The main advantages of a MC are the ability of studying the direct (s-channel) production of scalar resonances, a much better energy resolution (because of the lack of significant beamstrahlung), and the possibility of extending operations to very high energies. At CLIC, however, significantly greater polarization of the initial beams is possible [3].

1.1.3.1 Basics

There are basically three kinds of channels of interest for a lepton collider: (1) open pair production, (2) *s*-channel resonance production and (3) fusion processes.

1.1.3.1.1 Pair Production

The kinematic thresholds for pair production of standard model particles ($X + \overline{X}$) are well below $E_{\mathrm{c.m.}} = 500$ GeV. For standard model particles at $E_{\mathrm{c.m.}} > 1$ TeV the typical open channel pair production process is well above its kinematic threshold and the cross section becomes nearly flat in

$$R \equiv \frac{\sigma(\mu^+\mu^- \to X + \bar{X})}{\sigma_{QED}(\mu^+\mu^- \to e^+e^-)} .$$

For the MC a forward/backward angular cut (e.g., 10°) is imposed on the outgoing pair. Closer to the beam direction, a shielding wedge is needed to suppress detector backgrounds arising from the effects of muon decay in the beam.

For a process whose rate is one unit of *R*, an integrated luminosity of 100 fb^{-1} at $E_{\mathrm{c.m.}} =$ 3 TeV yields ~1000 events. As an example, the rate of top quark pair production at 3 TeV is only 1.86 units of *R*. This clearly demonstrates the need for high luminosity in a multi-TeV lepton collider.

1.1.3.1.2 Resonances

Many models beyond the SM predict resonances that may be produced directly in the s-channel at a Muon Collider. Here, the narrow beam energy spread of a Muon Collider,

$\Delta E/E \sim 10^{-3}$ could be an important advantage. The cross section for the production of an s-channel resonance, X, with spin J, mass M and width Γ is given by:

$$\sigma_{\mu^+\mu^-\to X} = \frac{\pi}{4k^2}(2J+1)\frac{\Gamma^2}{(E-M)^2+\Gamma^2/4}B_{\mu^+\mu^-}B_{visible}$$

where k is the momentum of the incoming muon and E is the total energy of the initial system ($E_{c.m.}$). $B_{\mu+\mu-}\Gamma$ is the partial width of $X \to \mu+\mu^-$ and $B_{visible}\Gamma$ is the visible decay width of X. At the peak of the resonance with negligible beam energy spread:

$$R_{peak} = 3(2J+1)\frac{B(\mu^+\mu^-)B(visible)}{\alpha_{EM}^2} \quad .$$

For a sequential standard model Z' gauge boson, the value of R_{peak} is strikingly large, typically $R_{peak} \sim 10^4$. The luminosity, L, for $1.5 < M_{Z'} < 5.0$ TeV required to produce 1000 events on the Z' peak is only $0.5–5.0 \times 10^{30}$ cm^{-2} s^{-1}. Hence, a comprehensive first-order study of the properties of a narrow resonance, such as a Z', in the few-TeV mass range, can be carried out with a low luminosity, $L \sim 10^{30}$ cm^{-2} s^{-1}, Muon Collider.

1.1.3.1.3 Fusion Processes

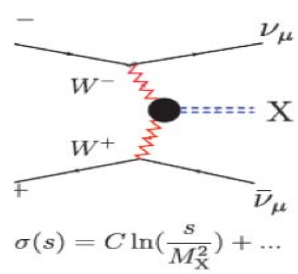

Figure 2: Typical fusion process.

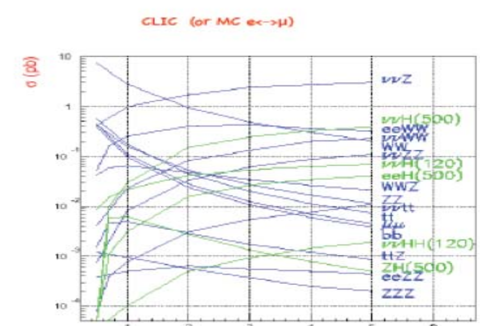

Figure 3: Fusion cross sections versus $\sqrt{s}$ at lepton collider.

A typical fusion process $\mu^+\mu^- \to W^+W^- \nu_\mu \bar{\nu}_\mu \to X \nu_\mu \bar{\nu}_\mu$ is shown in Fig. 2. For $E_{c.m.} >> M_X$ the cross section is typically large and grows logarithmically with $s = E_{c.m.}^2$; while the usual pair-production processes are constant in R and thus dropping like $1/s$. Thus, for asymptotically high energies fusion processes dominate. For lepton colliders, this crossover occurs in the few-TeV region in standard model processes, as shown in Fig. 3. A variety of processes are shown including WW and ZZ inclusive production. The large rates for WW, WZ and ZZ fusion processes imply that the multi-TeV Muon Collider is also effectively an electroweak-boson collider.

Physics studies of fusion processes such as $\mu^+\mu^- \to Z^0 Z^0 \mu^+\mu^- \to X \mu^+\mu^-$ benefit greatly by the tagging of the outgoing $\mu^\pm$ and hence will be sensitive to the required 10° angular cut.

1.1.3.2 Standard Model Higgs Bosons

Studies of the feasibility of direct production of the SM Higgs boson were carried out over a decade ago [4] for a low-energy, high-luminosity MC. It was found that very precise control of the beam energy and energy spread are required.

Higgs bosons can be studied in a number of other ways at a multi-TeV Muon Collider.

1. Associated production: $\mu^+\mu^- \to Z^* \to Z^0 + h^0$ has $R \sim 0.12$. We can measure the b-quark Higgs-Yukawa coupling and look for invisible decay modes of the Higgs boson.

2. Higgstrahlung : $\mu^+\mu^- \to t\bar{t}\ h^0$ has $R \sim 0.01$ (so such a study requires ~ 5 ab^{-1}). This could provide a direct measurement of the top quark Higgs-Yukawa coupling.

3. W*W* fusion into $\nu_\mu\, \nu_{\bar{\mu}}\, h^0$ has R ~ 1.1 s ln(s) (for m_h = 120 GeV). It allows the study of Higgs self-coupling and certain rare decay modes.

1.1.3.3 Extended Higgs Sector

In the two-Higgs doublet scenario there are five scalars: Two charged scalars $H^\pm$, two neutral CP-even scalars h, H^0, and a CP-odd neutral A. For the supersymmetric MSSM models, as the mass of the A is increased, the h becomes closer to the SM Higgs couplings and the other four Higgs become nearly degenerate in mass, as shown in Fig. 4. This makes resolving the two neutral-CP states difficult without the good energy resolution of a Muon Collider.

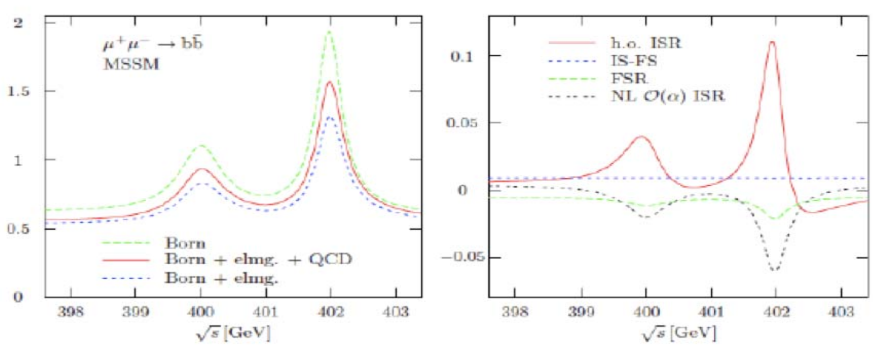

Figure 4: MSSM cross section $\mu^+\mu^- \to b\bar{b}$ near the H and A resonances (with M_A = 400 GeV and tan β = 5 (left), and with some contributions to the radiative corrections (right). From Ref. [5].

1.1.3.4 Supersymmetry

Supersymmetry (SUSY) provides a solution to the naturalness problem of the SM. It is a symmetry that connects scalars with fermions, ordinary particles with superpartners—a symmetry that is missing in the SM.

The simplest SUSY model is the MSSM, with only five parameters determining the masses of all the superpartners. It is now highly constrained by direct limits on the Higgs, mainly from LEP, CDF and DZero. *Z*-pole studies have provided constraints from electroweak precision measurements, and we have no indication of SUSY from flavor physics so far [6]. Recently the LHC has produced strong lower bounds on the masses of squarks and gluinos [7,8]. All this, taken together, makes it almost certain that direct coverage of the remaining MSSM parameter space requires a multi-TeV scale lepton collider such as CLIC or a Muon Collider.

1.1.3.5 New Strong Dynamics

Strong dynamical models of electroweak symmetry breaking have no elementary scalars and thus avoid the naturalness problem of the SM. Chiral symmetry breaking (à la QCD) in the technicolor sector produces technipions that give the proper masses to the W and Z bosons. For details and a discussion of various new strong dynamics models see the review of Hill and Simmons [9].

The "minimal Technicolor model" contains an isospin triplet techni-rho (ρ_T) and singlet techni-omega (ω_T) vector mesons, which can be produced in the *s*-channel in lepton colliders. In addition, it contains a techni-eta' (η_T') which would be produced in association with *Z* bosons in analogy to the Higgs boson.

In less minimal schemes, there are residual techni-pions, $\pi_T^{\pm}$ and π_T^0, that can be produced in lepton colliders. The techni-rho is typically broad if the two–techni-pion channel is open but, as in QCD, the techni-omega is nearly degenerate and narrow. In low-scale Technicolor models, some techni-rho (ρ_T) can be light (~250 GeV) as well as nearly degenerate in mass with a techni-omega, and these can be studied in great detail at a Muon Collider with the appropriate energy [10]. For techni-rho and techni-omega masses in the TeV range, a CLIC study has been done to determine its resolving power. The results for a Muon Collider are essentially the same as the CLIC curve before including the beamstrahlung and ISR effects. For this physics, the Muon Coliider has a distinct advantage over CLIC. The comparison is shown in Fig. 5.

There are other approaches to new strong dynamics: Topcolor, TC2, and Light Higgs models [9]. All of these would provide a rich spectrum of states that can be observed at a multi-TeV Muon Collider.

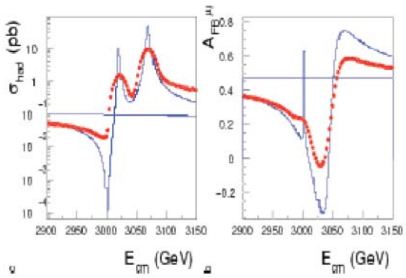

Figure 5: D-BESS model at CLIC. CLIC energy resolution limits ability to disentangle nearby states expected in models with new strong dynamics.

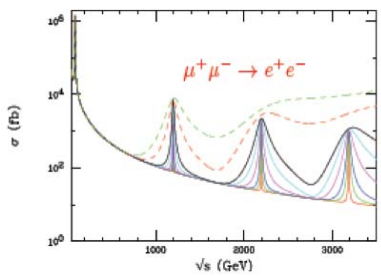

Figure 6: Graviton KK modes in a Randall-Sundrum model.

1.1.3.6 Contact Interactions

New physics can enter through contact interactions, which are higher dimension operators in the effective Lagrangian as:

$$\mathcal{L} = \frac{g^2 \bar{\psi}\Gamma\psi\bar{\psi}\Gamma\psi}{\Lambda^2}$$

The MC is sensitive to $\Lambda \sim 200$ TeV, roughly equivalent to CLIC. Preliminary studies suggest that the forward angle block-out is not an issue here [11]. If polarization is not available at a MC, it may be at a disadvantage compared with CLIC in being able to disentangle the chiral structures of the new operators.

1.1.3.7 Extra Dimensions

These theories have extra dimensions that have a radius of curvature close to the Terascale. For gravity and any other interactions that occur in the bulk (in extra dimensions) one expects an excitation spectrum of standard model particles arising from excited modes in the extra dimensions.

From the perspective of energy frontier colliders, however, only the physics at the first (perhaps second) Kaluza-Klein (KK)-mode will be relevant. All kinematically allowed (KK)-mode resonances are accessible to a multi-TeV Muon Collider. These include the Z' and γ' of the electroweak sector. The precise measurement of the Z' and γ' mass scales will determine the various electroweak symmetry breaking structures, and how these states couple to different fermion generations will determine bulk fermion localization.

In theories such as the Randall-Sundrum warped extra dimensions models [12], the graviton spectrum contains additional resonances (KK-modes) that can be probed by a Muon Collider as shown in Fig. 6.

1.1.4 Summary

A multi TeV Muon Collider is required for the full coverage of Terascale physics. The physics potential for a Muon Collider at ~3 TeV and integrated luminosity of 1 ab^{-1} is outstanding. Particularly strong cases can be made if the new physics is SUSY or new strong dynamics. Furthermore, a staged muon collider can provide a Neutrino Factory to fully disentangle neutrino physics. If a narrow *s*-channel resonance state exists in the multi-TeV region, the physics program at a Muon Collider could begin with less than 10^{31} cm^{-2} s^{-1} luminosity.

Detailed studies of the physics case for a 1.5–4 TeV muon collider are just beginning. The goals of such studies are to: (1) identify benchmark physics processes; (2) study the physics dependence on beam parameters; (3) estimate detector backgrounds; and (4) compare the physics potential of a Muon Collider with those of the ILC, CLIC and upgrades to the LHC.

1.1.5 Acknowledgments

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1.1.6 References

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