Muon Colliders: The Machine and The Physics *

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Abstract. A review of muon colliders is presented. Basic features of the accelerator and detector are outlined, and the very exciting physics prospects are reviewed.

I INTRODUCTION

This review is divided into two sections. In the first, we outline basics of the muon accelerator complex and the detector, noting critical requirements for optimal physics and the points of greatest current concern and focus for future R&D. In the second section, the physics of the muon collider will be highlighted. On occasion, I will note advantages, disadvantages and complementarity relative to an $e^+e^-$ collider. One finds that there are important physics issues that require both types of collider for the fullest and/or most precise results.

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II THE MACHINE AND DETECTOR

The designs of the muon collider and associated detector have been rapidly evolving in the last few years [1–6]. A muon collider (MC) facility can be developed in stages, each successive stage building upon the previous one. Three stages are currently envisioned.

- Low-energy Higgs factory collider: $\sqrt{s} \sim 100$ GeV.
- Intermediate-energy collider: $\sqrt{s} \lesssim 500$ GeV.
- High-energy collider: $\sqrt{s} \sim 3 - 4$ TeV.

The instantaneous luminosity, $L$, that can be achieved at each stage is still somewhat uncertain. For rather conservative designs of relatively low cost, current minimal expectations are:

- $L \sim 1, 2, 10 \times 10^{31}$ cm$^{-2}$s$^{-1}$ at $\sqrt{s} = 100$ GeV for beam energy resolutions of $R = 0.003\%, 0.01\%, 0.1\%$, respectively;
- $L \sim 1 \times 10^{33}$ cm$^{-2}$s$^{-1}$, at $\sqrt{s} = 300 - 500$ GeV for $R \sim 0.14\%$;
- $L \sim 1 \times 10^{35}$ cm$^{-2}$s$^{-1}$, at $\sqrt{s} = 3 - 4$ TeV with $R \sim 0.16\%$.

(For yearly integrated luminosities, we use the standard convention of $L = 1 \times 10^{32}$ cm$^{-2}$s$^{-1}$ $\Rightarrow L = 1$ fb$^{-1}$/yr.) It is believed that a combination of money and clever ideas may allow the ultimate $L$ values to be as much as a factor of 5 to 10 larger than listed above. We shall occasionally discuss the extent to which such higher luminosity is important for different types of physics.

The basic components of the collider are the following (see Fig. 1).

- **Proton Source:** One begins with a $\sim 600$ MeV Linac, feeding into a $\sim 3.6$ GeV Booster (much like at BNL or SNS), which in turn feeds a $15 - 30$ GeV driver (much as envisioned for JHP & Kaon). At lower (higher) energies, two (four) bunches of $5 \times 10^{13}$ ($2.5 \times 10^{13}$) protons would be employed.

- **Target:** The goal is a large number of pions. A good choice of target might be liquid Ga. (It must be possible to cool the target at these high intensities.)

- **Solenoid(s):** A high percentage of the produced low-energy pions must be captured. A $B = 20$ T solenoid would be employed. This would be followed by a 5 T solenoidal decay channel in which the muons would emerge and be retained.

- **Ionization Cooling:** The muons must next be cooled very rapidly (given the finite muon lifetime) and with minimal losses. The following strategy is envisioned.
Overview of a 4 TeV Muon Collider

**FIGURE 1.** Muon Collider Schematic.
– One reduces both $p_T$ and $p_z$ using $dE/dz$ losses in, e.g., Li.
– Next, the muons are accelerated to increase $p_z$, leaving $p_T$ unchanged. In this way, you are effectively cooling in $p_T$.
– To cool in $p_z$, one introduces dispersion, i.e. separates muons with different $p_z$, and then uses a Be or Li wedge oriented so as to slow down large-$p_z$ muons relative to small-$p_z$ muons, thereby cooling in $p_z$. The different muon ‘streams’ are then brought back together.
– This process is repeated many ($>20$) times.

**Acceleration:** At higher energy, one possible (and possibly the cheapest) approach is to employ synchrotrons with fast pulsed magnets and long SC linacs. For 250 GeV beams, one would employ 4 T pulsed magnets ($t = 1$ msec). For 2 TeV beams, it would be necessary to interlace fixed 8T SC dipole magnets with $\pm 2$ T pulsed magnets. At Higgs factory energies, pulsed magnets would not be required and recycling could be employed.

**Collider Ring:** In order to maximize the luminosity, the number of turns the muons make in the ring before they decay should be as large as possible. The current plan is for about 1000 turns, requiring a high field for the bending magnets. Lattice designs involving octopole and quadrupole magnets have been developed.

One critical issue for a muon collider is the nature of the physics backgrounds. There are three major sources:

**The muon halo:** Muons lost from the main bunches can still make it to the detector with full energy. These can pass through the calorimeter and undergo deep-inelastic scattering. It is found that this background can be adequately controlled by careful injection and collimation.

**Muon decay:** $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ and $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ leads to roughly $2 \times 10^{12} \times 2$ muon decays during the roughly 1000 turns during which a typical muon is stored in the final ring. These decays give rise to two important effects: (a) heating of the beam pipe, which must then be cooled, perhaps by a water-cooled tungsten liner inside the magnets; (b) background at the detector, which can be tamed by careful design of the (Tungsten) nose cone at the detector entrance.

**Beam-beam interactions:** Incoherent $e^+e^-$ pair creation arises from beam-beam interactions at each crossing. The large cross section ($\sigma \sim 10$ mb) yields about $3 \times 10^4 e^+e^-$ pairs per crossing. Most of these soft $e^+e^-$ pairs are curled up by the detector solenoid magnetic field and collimated along the beam pipe. The rest of the soft pairs are taken care of by a careful design for the nose cone. Coherent pair creation has also been shown not to create a problem for the detector.
The current conclusion is that present state-of-the-art technologies will be sufficient to build a detector able to handle the remaining background, consisting primarily of a large number of soft particles, while achieving normal standards for physics capabilities. The major current uncertainty is whether or not the first layer of the vertex detector can be placed close enough to the beam pipe to allow separation of charm from bottom quarks.

An issue currently being explored is whether or not the large number of neutrinos that emanate from the storage ring pose a radiation hazard as they interact over a period of time with the surrounding earth and build up a low-level source of radiation. The latest calculations indicate that if the machine is built at a reasonable depth, then this is not a problem for center-of-mass energies up to about $3 - 4$ TeV. For higher energies, wobbling of the beam orbit or some similar technique could be employed.

At the time of this talk, the primary technical R&D technical developments that are needed in order to make a muon collider a reality are:

- demonstration of a working cooling system with small losses;
- demonstration of the viability of low frequency linacs for phase rotation and cooling;
- development of the pulsed magnets, shielding and SC r.f. cavities required for the accelerator at higher energies.
- demonstrated ability to construct the quadrupole magnets required for the interaction region (expected to be easily achieved for Higgs factory energies).

I now list some of the important +’s and −’s, as well as critical requirements and benchmarks for the muon collider. First, there are some important advantages as compared to an electron collider.

- There is less bremsstrahlung and no beamstrahlung.
- Beam energy resolution can be substantially better — in particular, with beam compression techniques $R = 0.003\%$ can be achieved at the low-energy Higgs factory so that the Gaussian spread in $\sqrt{s}$, given by
  \[ \sigma_{\sqrt{s}} \sim 2 \text{ MeV} \left( \frac{R}{0.003\%} \right) \left( \frac{\sqrt{s}}{100 \text{ GeV}} \right), \]  \[ (1) \]
can be as small as the natural width of a light SM-like Higgs boson.
- The beam energy can be very precisely tuned: $\Delta E_{\text{beam}} \sim 10^{-5} E_{\text{beam}}$ is ‘easy’; $10^{-6}$ is achievable and very important for scanning a narrow Higgs boson and precision $m_W$ and $m_t$ measurements. (To achieve such precision, power supplies stable at the $10^{-6}$ level are required and one must plan to monitor the beam energy continuously via spin rotation measurements.)
• Multiple interaction regions in the final storage ring, allowing full luminosity for several detectors, might not be impossible.

Other positive features of the muon collider include the following. It can be built in stages. The proton driver, intense muon source, cooled low-energy muon beam, and so forth, that will sequentially become available as the machine is constructed would all have important uses of their own. The energy can be increased by additions that are modest in physical size and don’t involve substantial new technology. Particularly noteworthy are the following points.

• If constructed at Fermilab, the $\sim 50$ GeV $\mu^+$ and $\mu^-$ beams needed for the Higgs factory could be collided with the 1 TeV proton beam of the Tevatron, yielding a $\mu p$ analogue of HERA with roughly $\sqrt{2}$ times as large center of mass energy and larger luminosity. Eventual higher energy, higher luminosity muon beams would result in a $\mu p$ collider with physics reach vastly exceeding that of HERA.

• Since the cost of a final storage ring is modest, several would be built as the energy of the machine is increased, each designed to optimize luminosity at specific energies designed for specific physics goals (to be discussed in more detail later). An incomplete list is the following.

  − If a light ($m_h \lesssim 2m_W$) SM-like Higgs boson has been observed (e.g. at the LHC), the first energy goal and ring constructed would be for factory-like s-channel production and study at $\sqrt{s} \sim m_h$ [9,10].

  − A second energy goal and ring would be for operation at high $\mathcal{L}$ near the $Zh$ threshold. (This would actually be the first goal if a SM-like Higgs has been observed and has $m_h > 2m_W$.) One would choose $\sqrt{s}$ so that the $Zh$ cross section is maximal, thereby allowing precise measurement of many Higgs boson properties. (Even if $m_h < 2m_W$, there are important Higgs properties that are not easily measured in s-channel production.) A fairly precise determination of $m_h$ from the $\sigma(Zh)$ threshold rise would also be possible [8].

  − Exceptionally precise measurements of $m_W$ and of $m_t$, $\alpha_s$, $\Gamma_t$, are possible [7] with rings that achieve full luminosity at $\sqrt{s} \sim 2m_W$ and/or $\sqrt{s} \sim 2m_t$, respectively. If no Higgs boson is seen at the LHC, then this would constitute an important first goal for the muon collider.

  − Factories for s-channel production of any new particle with $\mu^+\mu^-$ couplings would be possible. Possibilities include a new $Z'$ and a sneutrino with R-parity-violating coupling to $\mu^+\mu^-$. Once the accelerator is operating at high energy, beams of different energy appropriate to the different rings could be extracted and the luminosity
could be shared among the various rings (and with the $\mu p$ collider). This would allow simultaneous pursuit of many different types of physics at different detectors, as possibly desirable from both a physics and a sociological point of view.

There are two clear disadvantages of a muon collider:

- A $\gamma\gamma$ collider is not possible at a muon collider facility.
- Some polarization is automatic, but large polarization implies sacrifice in luminosity at a muon collider. This is because large polarization is achieved by keeping only the larger $p_z$ muons emerging from the target, rather than collecting nearly all the muons.

### III THE PHYSICS

Early studies [11,12] made it clear that a muon collider would be an extremely valuable tool for exploring the physics of any conceivable extension of the Standard Model (SM). Fully detailed studies are now available for most types of new physics. To illustrate the results, I shall briefly discuss:

- Higgs physics.
- Strong $WW$ sector physics.
- A new $Z'$.
- Precision $m_W$ and $m_t$ measurements.
- Standard supersymmetry.
- R-parity violation phenomena in supersymmetry.
- Leptoquarks.

#### A Higgs Physics

If the $\mu^+\mu^-$ collider is operated by running at the highest energy or at the maximum in the $Zh$ cross section, then it will have similar capabilities to an $e^+e^-$ collider operating at the same $\sqrt{s}$ and $\mathcal{L}$ (barring unexpected detector backgrounds at the muon collider). The totally unique feature of a muon collider is the possibility of $s$-channel Higgs production, $\mu^+\mu^- \rightarrow h$, which can have a very high rate if the total Higgs width, $\Gamma_h^{\text{tot}}$, and the beam energy resolution, $R$, are both small. The importance of small $R$ and small $\Gamma_h^{\text{tot}}$ is evident from the result, $\sigma_h$, of convoluting a Gaussian $\sqrt{s}$ distribution of width $\sigma_{\sqrt{s}}$ with the standard $s$-channel Breit Wigner Higgs resonance cross section. For $\sqrt{s} = m_h$, one obtains
$$\sigma_h \simeq \frac{\pi \sqrt{2\pi} \Gamma(h \rightarrow \mu\mu) BF(h \rightarrow X)}{m_h^2 \sigma_{\sqrt{s}}} \times \left(1 + \frac{\pi}{8} \left[\frac{\Gamma_{h \rightarrow X}}{\sigma_{\sqrt{s}}}\right]^2\right)^{-1/2}.$$  \hspace{1cm} (2)

Eq. (2) shows that the smaller $\Gamma_{h \rightarrow X}$ is, and the more nearly $\sigma_{\sqrt{s}}$ can be made comparable to $\Gamma_{h \rightarrow X}$, the larger will be $\sigma_h$. Although smaller $R$ implies smaller $L$, one finds that for a Higgs boson with a very narrow width, e.g. a SM-like Higgs boson with $m_h \lesssim 2m_W$, it is advantageous to use the smallest $R$ that can be achieved. A Higgs boson with a large width will only be visible at a muon collider if its $\mu^+\mu^-$ coupling (and, hence, partial width) is enhanced relative to that of a SM Higgs boson.

Below, we update results obtained (assuming $R = 0.01\%$ and $L \sim 50 \text{ fb}^{-1}/\text{yr}$) in Refs. [9], [10] and [13] to account for the preliminary Higgs-factory design parameters resulting from the recent detailed study of the low-energy machine — we employ $R = 0.003\%$ and compare luminosities of $L = 0.1 \text{ fb}^{-1}/\text{yr}$ and $1 \text{ fb}^{-1}/\text{yr}$, the former being conservative and the latter optimistic. With regard to the statistical accuracy for various measurements, compared to the earlier studies the lower expected $L$ is only partially offset by the smaller $R$. However, since $\sigma_{\sqrt{s}} \sim \Gamma_{h,SM}^{\text{tot}}$ for $R = 0.003\%$, systematics in measuring $\Gamma_{h}^{\text{tot}}$ (via scanning) associated with imperfect knowledge of the exact shape of the $\sqrt{s}$ spectrum (in particular its wings) are much less of a concern than for $R = 0.01\%$.

1 A Standard Model-Like Higgs Boson

In all likelihood, the $h$ will already have been discovered at either the LHC or NLC, if not at LEP or the Tevatron, by the time the muon collider is built, and its mass will have been accurately measured: $\Delta m_h \sim 100 \text{ MeV}$ for $L = 300 \text{ fb}^{-1}$ at the LHC; $\Delta m_h \sim 50 \text{ MeV}$ for $L = 200 \text{ fb}^{-1}$ in $\sqrt{s} = 500 \text{ GeV}$ running at the NLC [13]. If $m_h > 2m_W$, $\Gamma_{h}^{\text{tot}}$ will be large, leading to tiny $BF(h \rightarrow \mu^+\mu^-)$; the resulting $\sigma_h$ is too small to be seen above background in $s$-channel production at a muon collider. If $m_h < 2m_W$, $\sigma_h$ will be large and a Higgs-factory muon collider ring with optimal luminosity at $\sqrt{s} \sim m_h$ will be a high priority. At the muon collider, the first task will be to scan over the $\Delta m_h$ interval so as to center on $\sqrt{s} \simeq m_h$ within a fraction of $\sigma_{\sqrt{s}}$. A “typical case” is $m_h \sim 110 \text{ GeV}, \sigma_{\sqrt{s}} \sim 2 \text{ MeV}, \Delta m_h \sim 100 \text{ MeV}$. About 50 scan points are needed to center on $\sqrt{s} \simeq m_h$ within $0.3\sigma_{\sqrt{s}}$. Each point requires $L \sim 0.0015 \text{ fb}^{-1}$ to observe or eliminate the $h$ at the $3\sigma$ level. A total of up to $L = 0.075 \text{ fb}^{-1}$ would then be needed for the centering process. Thus, for $L = 0.1 \text{ fb}^{-1}/\text{yr}$ centering might take the better part of a year. The worst case is $m_h \sim m_Z$ — with $\sigma_{\sqrt{s}} \sim 2 \text{ MeV}$ and $\Delta m_h \sim 100 \text{ MeV}$, up to a factor of 50 more $L$ would have to be devoted to the centering process; even for $L = 1 \text{ fb}^{-1}/\text{yr}$ the nearly four years required would be unacceptable.
Once we are able to center on the Higgs peak, the measurements of primary importance are the Higgs total width and the cross sections $\sigma(\mu^+\mu^- \rightarrow h \rightarrow X)$ for $X = b\bar{b}, WW^*, ZZ^*$. To measure all of these simultaneously, it is best to employ an optimized three-point scan of the Higgs peak [10]. The accuracies of the measurements for total luminosities of $L = 4 \text{ fb}^{-1}$ and $0.4 \text{ fb}^{-1}$ (four year’s of running at $L = 1 \text{ fb}^{-1}/\text{yr}$ and $0.1 \text{ fb}^{-1}/\text{yr}$, respectively) are tabulated in Table 1. Note that at $L = 0.4 \text{ fb}^{-1}$ the errors for $\sigma BF(h_{SM} \rightarrow b\bar{b})$ are still generally small but that those for $\Gamma_{h_{SM}}$ are uncomfortably large. In fact, errors for $\Gamma_{h_{SM}}$ obtained indirectly using a combination of $L = 600 \text{ fb}^{-1}$ LHC data, $L = 200 \text{ fb}^{-1}$ NLC data, and $L = 50 \text{ fb}^{-1}$ $\gamma\gamma$-collider data are often better: $\sim 19\%$ for $m_{h_{SM}} \lesssim 120 \text{ GeV}$ and $\sim 10\% - 13\%$ for $130 \text{ GeV} < m_{h_{SM}} \lesssim 180 \text{ GeV}$.

**TABLE 1.** Percentage errors ($1\sigma$) for $\sigma BF(h_{SM} \rightarrow b\bar{b}, WW^*, ZZ^*)$ (extracted from channel rates) and $\Gamma_{h_{SM}}$ for $s$-channel Higgs production at the MC assuming beam energy resolution of $R = 0.003\%$. Results are presented for two integrated four-year luminosities: $L = 4 \text{ fb}^{-1}$ ($L = 0.4 \text{ fb}^{-1}$). An optimized three-point scan is employed [which, for the cross section measurements, is equivalent to $L \sim 2 \text{ fb}^{-1}$ ($L = 0.2 \text{ fb}^{-1}$) at the $\sqrt{s} = m_{h_{SM}}$ peak]. It is useful to compare this table to the $L = 200 \text{ fb}^{-1}$, $R = 0.01\%$ table of Ref. [13].

| Quantity | Errors |
|----------|--------|
| Mass (GeV) | 80 | $m_Z$ | 100 | 110 |
| $\sigma BF(b\bar{b})$ | 0.8(2.4\%) | 7(21\%) | 1.3(4\%) | 1(3\%) |
| $\sigma BF(WW^*)$ | – | – | 10(32\%) | 5(15\%) |
| $\sigma BF(ZZ^*)$ | – | – | – | 62(190\%) |
| $\Gamma_{h_{SM}}^\text{tot}$ | 3\%(10\%) | 25\%(78\%) | 10\%(30\%) | 5\%(16\%) |

| Quantity | Errors |
|----------|--------|
| Mass (GeV) | 120 | 130 | 140 | 150 |
| $\sigma BF(b\bar{b})$ | 1\%(3\%) | 1.5\%(5\%) | 3\%(9\%) | 9\%(28\%) |
| $\sigma BF(WW^*)$ | 3\%(10\%) | 2.5\%(8\%) | 2.3\%(7\%) | 3\%(9\%) |
| $\sigma BF(ZZ^*)$ | 16\%(50\%) | 10\%(30\%) | 8\%(26\%) | 11\%(34\%) |
| $\Gamma_{h_{SM}}^\text{tot}$ | 5\%(16\%) | 6\%(18\%) | 9\%(29\%) | 34\%(105\%) |

The $s$-channel measurements can then be combined with LHC data and data from NLC (or MC) running at $\sqrt{s} > m_Z + m_h$ in order to determine all the properties of the $h$ in a model-independent way. For example, there will be four ways to determine $\Gamma(h \rightarrow \mu^+\mu^-)$:

$^1$ Note from Eq. (2) that $\sigma(\mu^+\mu^- \rightarrow h \rightarrow X)$ provides a determination of $\Gamma(h \rightarrow \mu^+\mu^-)BF(h \rightarrow X)$ unless $\sigma_{\sqrt{s}} \ll \Gamma_{h}^\text{tot}$.
1) \[ \Gamma(h \to \mu^+\mu^-) = \frac{\left[ \Gamma(h \to \mu^+\mu^-)BF(h \to b\bar{b}) \right]_{\text{NLC}}}{BF(h \to b\bar{b})_{\text{NLC}}} ; \]

2) \[ \Gamma(h \to \mu^+\mu^-) = \frac{\left[ \Gamma(h \to \mu^+\mu^-)BF(h \to WW^*) \right]_{\text{NLC}}}{BF(h \to WW^*)_{\text{NLC}}} ; \]

3) \[ \Gamma(h \to \mu^+\mu^-) = \frac{\left[ \Gamma(h \to \mu^+\mu^-)BF(h \to ZZ^*) \right]_{\text{NLC}}}{\Gamma(h \to ZZ^*)_{\text{NLC}}} \Gamma_{\text{tot}}(h) ; \]

4) \[ \Gamma(h \to \mu^+\mu^-) = \frac{\left[ \Gamma(h \to \mu^+\mu^-)BF(h \to WW^*) \Gamma_{\text{tot}}(h) \right]_{\text{NLC}}}{BF(h \to WW^*)_{\text{NLC}}} . \]

The associated errors for the SM Higgs are labelled \((\mu^+\mu^- h_{SM})^2|_{\text{NLC+MC}}\) in Table 2 below.

### Table 2.

Percentage errors (1σ) for combining \(L = 200 \text{ fb}^{-1}\) - \(\sqrt{s} = 500 \text{ GeV} \) NLC, \(L = 600 \text{ fb}^{-1}\) LHC, \(L = 50 \text{ fb}^{-1}\) \(\gamma\gamma\)-collider and MC \(R = 0.003\%\) \(s\)-channel data, with errors for the latter as quoted in Table 1. Results are presented for two total four-year integrated MC luminosities: \(L = 4 \text{ fb}^{-1}\) \((L = 0.4 \text{ fb}^{-1})\) Comparison to the similar table of Ref. [13], which assumed \(L = 200 \text{ fb}^{-1}\) for \(R = 0.01\%\) at the MC, is useful.

| Quantity (GeV)     | Mass (GeV) | Errors          |
|--------------------|------------|-----------------|
|                    | 80         | 100             | 110             | 120             |
| \((b\bar{b} h_{SM})^2|_{\text{NLC+MC}}\) | 6(10%)     | 10(16%)         | 7(13%)          | 7(13%)          |
| \((c\bar{c} h_{SM})^2|_{\text{NLC+MC}}\) | 9(13%)     | 12(18%)         | 10(15%)         | 10(15%)         |
| \((\mu^+\mu^- h_{SM})^2|_{\text{NLC+MC}}\) | 5(5%)      | 5(5%)           | 4(5%)           | 4(4%)           |
| \((\gamma\gamma h_{SM})^2|_{\text{MC}}\)   | 15(18%)    | 17(33%)         | 14(21%)         | 14(20%)         |
| \((\gamma\gamma h_{SM})^2|_{\text{NLC+MC}}\) | 9(10%)     | 10(11%)         | 9(10%)          | 9(10%)          |
|                    | 130        | 140             | 150             | 170             |
| \((b\bar{b} h_{SM})^2|_{\text{NLC+MC}}\) | 8(12%)     | 9(10%)          | 13(13%)         | 23(23%)         |
| \((c\bar{c} h_{SM})^2|_{\text{NLC+MC}}\) | 10(14%)    |                 |                 |                 |
| \((\mu^+\mu^- h_{SM})^2|_{\text{NLC+MC}}\) | 4(5%)      | 4%              | 4(5%)           | 13(14%)         |
| \((WW^* h_{SM})^2|_{\text{MC}}\)   | 17(24%)    | 12(30%)         | 33(104%)        |                 |
| \((WW^* h_{SM})^2|_{\text{NLC+MC}}\) | 5%         | 5%              | 6(8%)           | 10%             |
| \((\gamma\gamma h_{SM})^2|_{\text{MC}}\)   | 14(22%)    | 20(34%)         | 48(110%)        |                 |
| \((\gamma\gamma h_{SM})^2|_{\text{NLC+MC}}\) | 10(12%)    | 13(15%)         | 25(29%)         |                 |

Errors as small as given in Table 2 may make it possible to distinguish between the SM \(h_{SM}\) and the \(h^0\) of the MSSM [13]. If deviations from SM predictions are apparent, then an approximate determination of the crucial MSSM CP-odd Higgs boson mass \(m_{A^0}\) can be made. (The \(h^0\) becomes indistinguishable from the \(h_{SM}\) if \(m_{A^0}\) is large — the decoupling limit.)
most useful quantity for this purpose if only s-channel Higgs factory MC data are available (i.e. no Zh NLC or MC data) is the coupling-squared ratio $(WW^* h_{SM})^2 / (bbh_{SM})^2 \propto \sigma BF(WW^*)/\sigma BF(bb)$. If $110 \lesssim m_{h_{SM}} \lesssim 140$ GeV (a very likely region in the MSSM) then this ratio will be measured with a statistical accuracy of $\lesssim \pm 5\%$ for $L = 4$ fb$^{-1}$ (see Table 1). Systematic errors of order $\pm 5\% - \pm 10\%$ from uncertainty in the b quark mass will also enter the interpretation of this ratio. A $> 2 - 3\sigma$ deviation will be observed if $m_{A^0} < 450$ GeV. For $L = 0.4$ fb$^{-1}$, one would observe a $> 1.5 - 2\sigma$ deviation for $m_{A^0} < 450$ GeV. If Zh data from the NLC (or MC) is available then the best quantity for discriminating between the $h^0$ and $h_{SM}$ is the fundamental coupling $\Gamma(h \rightarrow \mu^+\mu^-)$. For all $m_h \lesssim 2m_W$, the error in $\Gamma(h \rightarrow \mu^+\mu^-)$ obtained after combining NLC and MC data as sketched in the equations above is dominated by the NLC denominators and (for $L = 200$ fb$^{-1}$ at the NLC) is $\lesssim 5\%$, even for $L = 0.4$ fb$^{-1}$ (see Table 2). This will allow detection of a $> 3\sigma$ deviation from the SM value if $m_{A^0} < 600$ GeV. Systematic errors from theoretical uncertainties in the interpretation of this measurement are small. Note that $\Gamma_{h}^{\text{tot}}$ alone cannot be used to distinguish between the MSSM and SM in a model-independent way. This is because $\Gamma_{h}^{\text{tot}}$ depends on many things, including (in the MSSM) the squark-mixing model.

2 MSSM $H^0$ and $A^0$

One of the potentially most important features of a muon collider is that the s-channel processes $\mu^+\mu^- \rightarrow H^0, A^0$ allow production and study of $H^0, A^0$ up to $m_{A^0} \sim m_{H^0} \lesssim \sqrt{s}$ [10]. Discovery possibilities at other colliders are more limited (a more detailed summary and references appear in [13]): (a) at the LHC, discovery of $H^0, A^0$ is not possible for $m_{A^0} \gtrsim 200$ GeV at moderate $\tan \beta \gtrsim 3$; (b) at $\sqrt{s} = 500$ GeV, $e^+e^- \rightarrow H^0 A^0$ pair production probes only to $m_{A^0} \sim m_{H^0} \lesssim 230 - 240$ GeV; (c) a $\gamma\gamma$ collider could potentially probe up to $m_{A^0} \sim m_{H^0} \sim 0.8\sqrt{s} \sim 400$ GeV with $L \gtrsim 150 - 200$ fb$^{-1}$. The reach of the muon collider depends very much on the $\tan \beta$ parameter of the MSSM and the luminosity achievable at intermediate energies. A total of $L = 200$ fb$^{-1}$ must be used in scanning the $200 \lesssim \sqrt{s} \lesssim 500$ GeV interval to guarantee discovery of the $H^0, A^0$ for the $\tan \beta \geq 3$ portion of parameter space such that the $H^0, A^0$ cannot be discovered at the LHC in this same mass interval. The conservative intermediate-energy-collider luminosity corresponds to $L \sim 40$ fb$^{-1}$ over four years, for which one can only reach down to $\tan \beta \geq 5 - 6$. (If $\tan \beta$ is still larger and the MC is run at $\sqrt{s} = 500$ GeV, the $H^0, A^0$ can also be discovered in the bremsstrahlung tail if the $bb$ mass resolution is good enough.) Once discovered, the $H^0, A^0$ can be studied with precision at the $\mu^+\mu^-$ collider. In particular, only a direct s-channel scan may allow separation of the $H^0$ from the $A^0$ when they are approximately degenerate (as predicted for large $\tan \beta$).

Even masses as large as $m_{A^0} \sim m_{H^0} \sim m_{H^\pm} > 1$ TeV cannot be ruled
out simply on the basis of hierarchy/naturalness, although the model would be fine-tuned. Discovery of the $H^0, A^0, H^\pm$ via $e^+e^- \rightarrow H^0A^0, H^+H^-$ would require $\sqrt{s}_{e^+e^-} > 2$ TeV, currently thought difficult to achieve. In contrast, it is currently expected that a muon collider with $\sqrt{s} \sim 3 - 4$ TeV is feasible, in which case $\mu^+\mu^- \rightarrow H^0A^0, H^+H^-$ observation would be straightforward. Studies [14,15] show that the $H^0, A^0$ could be detected in their $b\bar{b}$ or $t\bar{t}$ decay modes and $H^\pm$ in $t\bar{b}$ and $b\bar{t}$ decays, even if SUSY decays are present. Measurements of relative branching ratios for $H^0, A^0, H^\pm$ decays to different final states (including SUSY channels) can also be performed with good accuracy. The branching ratio results, together with the determination of $m_{A^0} \sim m_{H^0} \sim m_{H^\pm}$ and, say, $m_{\tilde{\chi}^\pm_1}$ (the light chargino mass), allow one to discriminate with incredible statistical significance between different closely similar GUT scenarios [14].

3 Exotic Higgs Bosons

A muon collider could play a very important role in probing an exotic Higgs sector, even if the exotic Higgs bosons have already been detected at another accelerator. To give one example, consider a Higgs sector containing a doubly-charged Higgs boson, $\Delta^{--}$, that is a member of a SU(2)×U(1) representation that either has no neutral member or a neutral member with zero vacuum expectation value (as required for $\rho \equiv m_W/[m_Z \cos \theta_W] = 1$ to be natural). For many choices of representation, $e^- e^- \rightarrow \Delta^{--}$ and $\mu^- \mu^- \rightarrow \Delta^{--}$ couplings are allowed. (We denote the Majorana-like coupling strengths by $\lambda_{ee,\mu\mu}$.) A $\Delta^{--}$ with $m_{\Delta^{--}} < 500 - 900$ GeV (depending upon dominant decay) will be seen previously at the LHC, if not TeV33 [16]. Once $m_{\Delta^{--}}$ is known, observation of the s-channel processes $e^- e^- \rightarrow \Delta^{--}$ and $\mu^- \mu^- \rightarrow \Delta^{--}$ will be possible and probably would be the only means of directly measuring $\lambda_{ee,\mu\mu}$ [17]. For couplings not too far below current bounds, factory-like production rates are predicted for the $\Delta^{--}$. For very small couplings (such as those that might be associated with left-right symmetric models) the very excellent $R = 0.003\%$ beam energy resolution that can be achieved at a $\mu^- \mu^-$ collider implies that it can probe $\lambda_{\mu\mu}$ magnitudes that are significantly smaller than the $\lambda_{ee}$ values that can be probed in $e^- e^-$ collisions.

B Strong WW Interactions and Related Models

If no light SM-like Higgs is found at the LHC, NLC or MC, then signals of the concomitant strongly-interacting WW sector will be found [18,19]. However, as detailed in Ref. [20], to fully explore strong WW interactions requires quark, electron or muon collision energies of $\sqrt{s} \geq 3 - 4$ TeV, with appropriately matched luminosity. Such energies may be most easily achievable at
a muon collider. A muon collider with this energy could study (using both $\mu^+\mu^-$ and $\mu^-\mu^-$ collisions) all isospin channels. In close analogy to $\pi\pi$ scattering studies, different models could be distinguished from one another by the detailed $WW$ mass spectra in the different isospin channels. After several years of running at design luminosity, statistics would be such that one could separately project out the cross sections for different final state polarizations, $W_LW_L$, $W_RW_T$ and $W_TW_T$. Only by such precision studies would it be possible to determine in detail the effective 'chiral' Lagrangian for the strong $WW$ sector.

C A New $Z'$

At a high energy $\mu^+\mu^-$ collider, a new $Z'$ with $m_{Z'} \leq \sqrt{s}$ is easily discovered in the bremsstrahlung tail of the $\mu^+\mu^-$ energy spectrum. Once found, a typical $Z'$ would be produced with factory-like rates if a specialized storage ring for $\sqrt{s} \simeq m_{Z'}$ is built. (See Ref. [21] for details.) The machine energy could either be set to this $\sqrt{s}$, or muons of appropriate energy could be extracted early in the acceleration process if the machine is run at higher energy.

D Precision Measurements of $m_W$ and $m_t$

The comparison of electron and muon colliders for such measurements has been studied in Ref. [7] (see also [25]). At the NLC, $m_W$ is best determined via $q\bar{q}$ mass reconstruction at $\sqrt{s} = 500$ GeV [23] (see also [22]) and $m_t$ via $t\bar{t}$ threshold measurements [24]. The resulting precisions are

$$\Delta m_W = 20 \text{ MeV}, \quad \Delta m_t = 0.2 \text{ GeV} \quad (50 \text{ fb}^{-1}, \text{NLC}).$$  \hspace{1cm} (3)

Systematic effects deriving from beam energy spread and beam energy uncertainty are such that the $m_W$ precision could not be improved by running at the $WW$ threshold. At the MC, the one part per million accuracy for the beam energy and the small beam energy spread imply greater precision for the $WW$ threshold and $t\bar{t}$ threshold measurements. For $R \lesssim 0.1\%$,

$$\Delta m_W = 9 \text{ MeV}, \quad \Delta m_t = 0.1 \text{ GeV} \quad (50 \text{ fb}^{-1}, \text{MC}).$$  \hspace{1cm} (4)

where systematic effects have been included. To achieve the indicated $m_W$ precision, the relative luminosity for $\sqrt{s} = 161$ GeV and $\sqrt{s} = 150$ GeV measurements would need to be well measured. Even for $L = 100 \text{ fb}^{-1}$, errors would probably still be statistics dominated at a $\mu^+\mu^-$ collider, in which case one could achieve

$$\Delta m_W = 6 \text{ MeV}, \quad \Delta m_t = 0.07 \text{ GeV} \quad (100 \text{ fb}^{-1}, \text{MC}).$$  \hspace{1cm} (5)
Relatively modest improvements in the conservative \( \mathcal{L} \) expectations for \( R \sim 0.1\% \) muon collider designs (see introduction) would allow \( L = 50 - 100 \text{ fb}^{-1} \) to be accumulated after \( \lesssim 5 \) years at \( \sqrt{s} \sim 2m_t \); more substantial improvements in \( \mathcal{L} \) expectations at \( \sqrt{s} \sim 2m_W \) would be needed.

\[ \text{E Standard SUSY Studies} \]

If R-parity is conserved, supersymmetric particles must be produced in pairs at a lepton collider, requiring center-of-mass energy greater than the sum of the masses. Although fine-tuning considerations suggest that the lightest gauginos should have \( m_{\tilde{\chi}} \lesssim 200 - 400 \text{ GeV} \), it is entirely possible for sfermions, especially the squarks of the first and second generation, to have masses \( \gtrsim 1 \text{ TeV} \) without violating either fine-tuning or considerations of naturalness/hierarchy. Further, gauge unification is most successful if there are SUSY particles above 1 TeV. The LHC will set the mass scale of the squarks, but will not be able to determine their masses and decays in much detail if they are heavy (due to limited event rates after cuts required to control backgrounds). To study sfermions with mass of order 1 TeV, an \( e^+e^- \) or \( \mu^+\mu^- \) collider would need \( \sqrt{s} \gtrsim 2.5 \text{ GeV} \) — the \( \beta^3 \) p-wave threshold behavior for scalar pair production implying a slow rise in the pair cross section above threshold. The \( \sqrt{s} = 3 - 4 \text{ TeV} \) option discussed as a possibility for a \( \mu^+\mu^- \) collider would imply pair production rates (for planned luminosity) adequate for detailed studies of the sfermions [26].

\[ \text{F Leptoquarks and R-parity Violating SUSY Scenarios} \]

The HERA event excess at high-\( Q^2 \) with a possible resonance component at \( M_{e+q} \sim 200 \text{ GeV} \) has led to a resurgence of popularity for models with leptoquarks, including SUSY models in which squarks play the role of leptoquarks. In the latter case, the \( \ell q \to \bar{q} \) coupling derives from R-parity violating Yukawa-like superpotential terms. If the resonance signal holds up with increased statistics, then it will be of great importance to search for a large variety of closely related signals. Of particular importance will be the question of the flavor structure of leptoquarks, in particular whether there are \( \mu q \) leptoquarks as well as \( e q \) leptoquarks. A natural way to explore for the former is via \( \mu^\pm p \) collisions at high luminosity, as possible at a muon collider facility by colliding one of the muon beams with protons of sufficient energy.

Let us [27] compare \( ep \) collisions at HERA (\( \sqrt{s} \sim 314 \text{ GeV} \)) to \( \mu p \) collisions of the Higgs-factory 50 GeV muon beams with the 1 TeV Fermilab Tevatron beam at the Main Injector (\( \sqrt{s} \sim 447 \text{ GeV} \)). If the muon beam is extracted
with $R \sim 0.1\%$ (i.e. before compression to $R = 0.003\%$ or with compression turned off), then yearly luminosity of $L \sim 1$ fb$^{-1}$/yr would be possible, as compared to the $L \sim 0.1$ fb$^{-1}$/yr luminosity for HERA. At HERA the ‘observed’ leptoquark resonance probably contains the proton valence quarks, i.e. is of either the $LQ = ed$ or $eu$ type. To avoid flavor-changing neutral currents, the muon-type leptoquarks are most naturally chosen to be the 2nd family $\mu s$ and $\mu c$ analogues. Let us denote the $LQ \rightarrow \ell q$ coupling as $\lambda^j_{\ell q}$, where $J$ is the spin of the leptoquark. For scalar and vector leptoquarks with mass $M_{LQ} = 200$ GeV, and assuming $BF(LQ \rightarrow \ell q) = 1$, 5 LQ events are predicted at HERA with $L = 0.1$ fb$^{-1}$ for: $\lambda^{0}_{eu} = 0.006$, $\lambda^{0}_{ed} = 0.012$, $\lambda^{1}_{eu} = 0.004$, and $\lambda^{1}_{ed} = 0.008$. To normalize, the observed HERA excess corresponds to $\lambda^{0}_{e+d} = 0.025$. At this same $M_{LQ} = 200$ GeV, the Higgs-factory/MI $\mu \nu$ collider with $L = 1$ fb$^{-1}$ yields 5 LQ events for: $\lambda^{0}_{\mu \nu} = 0.007$, $\lambda^{0}_{\mu s} = 0.006$, $\lambda^{1}_{\mu s} = 0.005$, and $\lambda^{1}_{\mu s} = 0.004$. Given that 2nd family leptoquark couplings will probably be larger than 1st family couplings, the Higgs-factory/MI $\mu \nu$ collider would be a very important facility if leptoquarks exist.

If the leptoquarks turn out to be squarks, then it will be important to ascertain the complete structure of the R-parity violating superpotential. The most general superpotential that violates lepton number while conserving baryon number (in order to ensure proton stability) takes the form

$$ W = \lambda_{ijk} \tilde{L}_i^j \tilde{L}_L^k \tilde{E}_R^k + \lambda'_{ijk} \tilde{L}_i^j \tilde{Q}_L^k \tilde{D}_R^k. $$

The $\lambda'$ type interactions would lead to squark production in $e^+d$ collisions at HERA. If a non-zero value for some of the $\lambda'$s is confirmed, it is very possible that one or more of the $\lambda$’s is also non-zero. Resonant $s$-channel sneutrino production $e^+e^- \rightarrow \tilde{\nu}_\ell (\lambda_{311}), e^+e^- \rightarrow \tilde{\nu}_\mu (\lambda_{121}), \mu^+\mu^- \rightarrow \tilde{\nu}_\tau (\lambda_{232})$, and $\mu^+\mu^- \rightarrow \tilde{\nu}_e (\lambda_{212})$ — would provide a particularly sensitive probe. To give one sample number, suppose $\lambda = 0.01$, $m_{\tilde{\nu}_\tau} = 100$ GeV, and $m_{\tilde{\chi}^0_1} = 90$ GeV. For these choices, $\Gamma^{tot}_{\tilde{\nu}_\tau} = 0.52$ GeV, including $\tilde{\nu}_\ell \rightarrow \nu_\ell \tilde{\chi}^0_1$ decays. The $\mu^+\mu^- \rightarrow \tilde{\nu}_\tau \rightarrow \tilde{\nu}_\tau \tilde{\chi}^0_1$ rate, $S$, for the resonance signal is computed by convoluting a standard $s$-channel resonance form with the luminosity distribution as a function of $\sqrt{s}$. The latter is obtained by assuming a Gaussian distribution in $\sqrt{s}$, modified by the effects of initial state bremsstrahlung from the incoming muons. The maximum $S$ is obtained when the Gaussian distribution is centered at $\sqrt{s} = m_{\tilde{\nu}_\tau}$. The same $\sqrt{s}$ distribution is used to compute the continuum background, $B$. The resulting statistical significance of the signal is defined as $N_{SD} = S/\sqrt{B}$. Assuming a beam energy resolution of $R = 0.1\%$ and adopting the associated (conservative) integrated luminosity at $\sqrt{s} \sim 100$ GeV of $L = 1$ fb$^{-1}$, one finds $S = 1.7 \cdot 10^3$ and $N_{SD} \sim 8$. At fixed $L$, $N_{SD}$ decreases for larger $R$, and for the same underlying $R$, is smaller for the equivalent $e^+e^- \rightarrow \tilde{\nu} \rightarrow e^+e^-$ situation because of the increased bremsstrahlung and non-negligible beamstrahlung. The typical $S$-band $e^+e^-$ collider design has significant beamstrahlung and underlying beam energy resolution of $R \sim 1\%$. 


In combination, the result is roughly the same as a beam energy resolution of \( R \sim 3\% \). For the above parameter choices, one obtains \( S = 70 \) and \( N_{SD} = 0.3 \). Thus, higher luminosity is required to probe the same coupling level in the \( e^+e^- \) case. The most important point is that both a muon collider and an electron collider would be required in order to explore the flavor structure of the \( \lambda \)'s as fully as possible.

\[ \text{IV CONCLUSION} \]

The physics motivation for a muon collider is very strong. Different types of physics would be probed, both as the collider complex is constructed, and, once fully operational, as the energy of the muon beams is increased. Complementarity to other planned and existing facilities would be enormous:

- If the \( ep \) HERA leptoquark signal persists, the \( \mu p \) collider that would be a natural spin-off at a muon collider facility would be mandatory.
- Both a muon collider and an electron collider are needed to understand the flavor structure of new physics in lepton-lepton channels.
- An \( e^+e^- \) collider focusing on \( Zh \) production in combination with a \( \mu^+\mu^- \) collider Higgs factory will allow us to fully explore the properties of a light SM-like Higgs boson in the shortest time.

In addition, the muon collider would have unique capabilities. For example:

- It would have the ability to observe the MSSM heavy Higgs bosons up to the maximum \( \sqrt{s} \) available, using \( s \)-channel production.
- If there is new physics at high \( \sqrt{s} \) (supersymmetry, contact interactions, \( \ldots \)) then a muon collider would be critical if the necessary center-of-mass energy can only be economically achieved in muon collisions.

Studies of, and R&D for, a muon collider should be vigorously pursued.

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