OVERVIEW OF PHYSICS AT A MUON COLLIDER

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Historically High Energy Particle physics has always pushed towards the next energy frontier. A muon collider will take physics to that next frontier. The muon's much larger mass than the electron, allow a muon collider to have advantages of a lepton collider without the negative effect of bremstrallung experienced at e^+e^- colliders. The physics potential along the way is vast and varied. It spans the Standard Model (SM), beyond SM, Strong Dynamics in the absence of a SM Higgs and general high mass resonances.

1 Introduction

There are three broad groups of high energy particle colliders; lepton and hadron colliders and those which collide leptons on hadrons. pp hadron colliders are the highest energy machines built to date. Yet protons are composite objects and consequently only a few percent of the center of mass energy ($\sqrt{s}$), on average, is realized per collision. This is not a problem with e^+e^- lepton colliders where the entire $\sqrt{s}$ contributes in each collision. However, electrons lose energy through bremsstrahlung radiation, energy which needs to be put back into the beam through RF power. This bremstrallung radiation also places a limitation on the electron beam resolution. A muon collider would have the advantage of being a point particle as the electron and since it is 200 times the mass of the electron, does not suffer from the beam energy degradation due to the bremstrallung radiation. This sharp beam energy determination is an asset for the muon collider. In addition, the muon collider has the ability to go to very high energies as a result of the little or no bremstrallung radiation.

The difficulties for a muon collider are mainly technical and are not covered within the scope of this overview.

The physics program of a muon collider can be classified into the following main categories.

1. Higgs physics.
2. Electroweak symmetry breaking and beyond the SM.
3. Single muon beam physics.

The First Muon Collider (FMC), a machine with a center of mass energy, $\sqrt{s}$, on the order of $\mathcal{O}(100-500$ GeV), would be ideal to perform the Higgs studies once a light Higgs is discovered. The Next Muon Collider (NMC) with a $\sqrt{s} \approx \mathcal{O}(3-4$ TeV) would be used to search for high mass exotic states and/or a new electroweak symmetry breaking mechanism in the absense of a light Higgs particle. There are other options for muon colliders such as an ultra high energy $\sqrt{s} > \mathcal{O}(10-100$ TeV) or μp colliders but these are likely to be further down the road.

The FMC will be a unique machine for the study of the neutral Higgs boson through its s-channel resonant production. It will also probe physics beyond the Standard Model (SM). Threshold physics, in the measurement of the production cross sections of W^+W-,

$t\bar{t}$ and Zh can also be performed at such a facility. Measurements of pair production cross sections of various supersymmetric (SUSY) particles, $\chi_1^+\chi_1^-$, $\chi_1^0\chi_2^0$, $\tilde{l}^+\tilde{l}^-$ and $\tilde{\nu}\bar{\tilde{\nu}}$, at a FMC will determine the masses of the respective particles to high precision. The FMC will also be pivotal in other precision physics. If operated as a Z factory ($\mu^+\mu^- \to Z^0$) with partial muon beam polarization, significant improvements can be made on the value of $\sin^2\theta_w$. B-mixing and CP-violation studies can also be studied. The cross sections for SM processes versus the center of mass energy at a FMC is shown in figure 1[1].

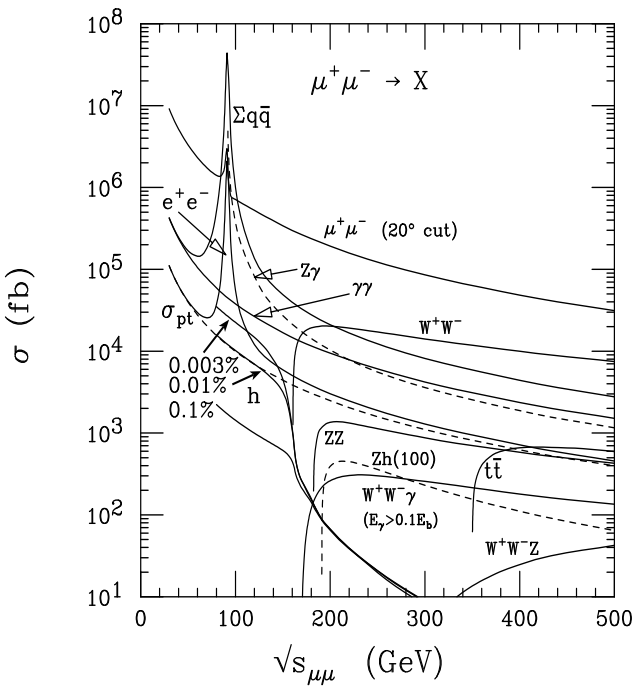

Figure 1. Cross sections for SM processes versus $\sqrt{s}$ at the FMC. $\sigma_{pt} \equiv \sigma(\mu^+\mu^- \to \gamma^* \to e^+e^-)$. For the s-channel Higgs boson production, three different beam energy resolutions (0.003%, 0.01% and 0.1%) are presented.

The NMC will push the energy frontier in order to reconstruct SUSY particles of high mass from their numerous and complicated decay chains. Any other resonances, such as Z', which are within its kinematic reach can also be measured. More importantly, should no Higgs be discovered below 1 TeV, the NMC is ideal to study the strong dynamics of WW scattering, which must exist in the absence of a light Higgs particle.

The high intensity muon source will allow for the search of rare muon processes. In addition the decay muons will provide a high-intensity neutrino beam for a rich field of neutrino physics of precision cross section measurements and longbaseline experiments.

There are numerous other new physics opportunities for muon facilities, such as same

sign muon colliders or μp colliders[2] each providing the chance for valuable measurements to be made.

In the following sections the main physics program at a muon collider facility, consisting of Higgs and precision physics, high mass resonances and single muon beam physics, are outlined.

2 Higgs Boson Physics

One of the greatest physics opportunities and main arguments in support of a muon collider facility is the extensive Higgs physics program which could be undertaken at such a machine. In the absence of any unexpected detector backgrounds at the Muon Collider and away from the s-channel higgs pole, e^+e^- machines have similar capabilities as a muon collider, given the same $\sqrt{\hat{s}}$ and luminosity ($\mathcal{L}$). However, if such a machine is operated at $\sqrt{\hat{s}} = m_h$ then the cross section for the production of a Higgs boson in the s-channel (see figure 2) is over $40,000$ times larger than the corresponding cross section for $e^+e^- \to h$. This raises the possibility of creating a Higgs factory.

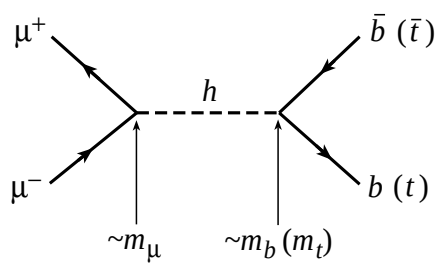

Figure 2. Feynman diagram for s-channel production of a Higgs boson.

The resonance cross section for Higgs boson production at a muon collider is given by:

$$\sigma_{\mu\bar{\mu}\to h\to X}(\sqrt{\hat{s}}) = \frac{4\pi\Gamma(h\to\mu\bar{\mu})\Gamma(h\to X)}{(\hat{s}-m_h^2)^2 + m_h^2(\Gamma_{\rm tot}^h)^2}, \tag{1}$$

where $\hat{s}$ is the square of the center of mass energy, $\Gamma_{\rm tot}^h$ is the total Higgs width and X denotes the final state. Another crucial feature of a muon collider is a small beam energy spread $\sigma_{\sqrt{s}}$. The root mean square spread $\sigma_{\sqrt{s}}$ is given by

$$\sigma_{\sqrt{s}} = (2\ \text{MeV})\left(\frac{R}{0.003\%}\right)\left(\frac{\sqrt{s}}{100\text{GeV}}\right), \tag{2}$$

where a beam resolution, R, as low as 0.003% may be attainable[3] at a muon collider. This R can be compared to values of $R > 1\%$, expected at an e^+e^- linear collider[4]. The effective s-channel cross section convoluted with a Gaussian beam spread is illustrated in figure 2, assuming $m_h = 110$ GeV. Figure 2 shows light Higgs resonance profiles versus the center of mass energy $\sqrt{s}$. The Breit-Wigner line shape of the resonance can be measured along

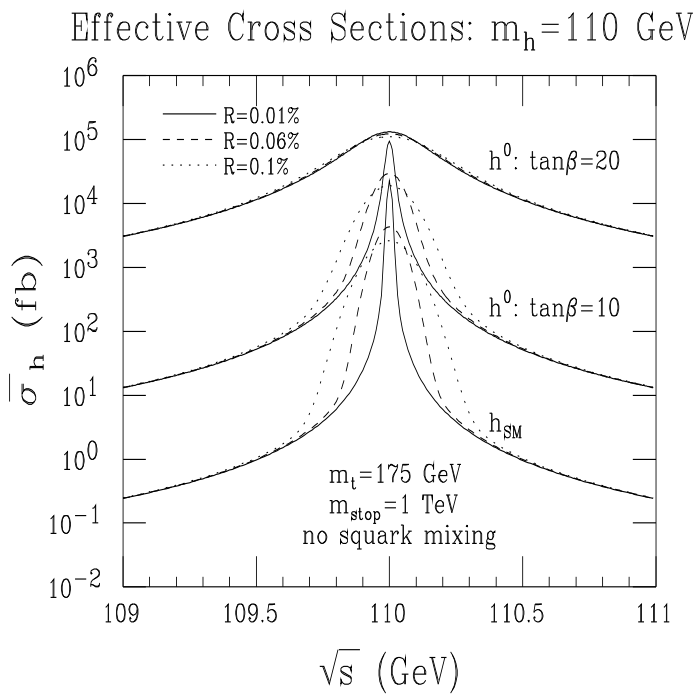

Figure 3. Effective s-channel higgs cross section $\bar{\sigma}_h$ obtained by convoluting the Breit-Wigner resonance formula with a Gaussian distribution for several resolutions (R)[5].

with the width Γ_h, if the resolution $\sigma_{\sqrt{s}}$ is on the order of Γ_h. A resolution $R < 0.01\%$ corresponds to a sensitivity on Γ_h of a few MeV. A SM-like Higgs with a mass $m_h \sim 100$ GeV has a width of a few MeV. The width of the lightest SUSY Higgs may be comparable to that of the SM Higgs for $\tan\beta < 2$ or as large as 500 MeV for $\tan\beta \sim 50$.

At $\sqrt{s} = m_h$, the effective s-channel Higgs cross section is

$$\bar{\sigma}_{\mu\bar{\mu}\to h\to X} = \frac{4\pi}{m_h^2}\frac{\mathrm{BF}(h\to\mu\bar{\mu})\mathrm{BF}(h\to X)}{\left[1+\frac{8}{\pi}\left(\frac{\sigma_{\sqrt{s}}}{\Gamma^h_{\mathrm{tot}}}\right)^2\right]^{1/2}}. \tag{3}$$

BF denotes the branching fraction for the h decay. Note from equation 3 that $\bar{\sigma}_h$ is very large for small R and when h is light. A light Higgs ($m_h < 2M_W$) is expected as fits to existing global analyses of precision electroweak data indicate a strong preference for a light SM-like Higgs [1]. A light Higgs is also relevant in SUSY models where the light SM-like h^0 has a mass of less than 150 GeV.

The important features that make the s-channel Higgs physics so attractive at the FMC are:

1. Energy resolutions $\sigma_{\sqrt{s}}$ of the order of a few MeV.

2. Little bremsstrahlung and no beamstrahlung smearing.

3. Precise tuning of the beam energy to an accuracy of 1 ppm, achieved through continuous spin-rotation measurements [6].

The program of Higgs study at the FMC would begin with the prior discovery of the Higgs boson at the Tevatron, or more likely the LHC[a] or a future electron-positron linear collider , with a precision on the true Higgs mass of $\Delta m_h \sim 100$ MeV. The prospects for observing the SM Higgs at a $\mu\bar{\mu}$ collider are plotted in figure 4 versus the Higgs mass. The

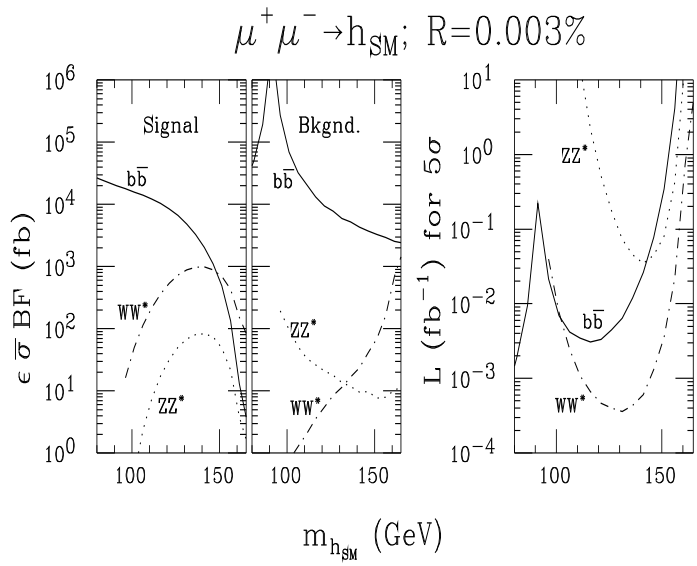

Figure 4. The SM Higgs rates and $\mathcal{L}$ required for 5σ observation as a function of $m_{h_{SM}}$, for $R = 0.003\%$[7].

first two panels show the signal and background expectation for a resolution of $R = 0.003\%$. The right most panel gives the luminosity requirements for a 5σ direct detection of a $m_h =$ 100 GeV Higgs in the $b\bar{b}$ final state. Note the luminosity requirements are very reasonable (~ 100 pb^{-1}), above the region of the Z-boson peak.

A muon collider ring design could be optimized to run at energy $\sqrt{s} = m_h$. A scan covering a 200 MeV region of the resonance peak could then be performed. If one requires 3 standard deviations for detection or rejection of a signal and a resolution ($R \sim 0.003\%$) or $\sigma_{\sqrt{s}} \sim 2$ MeV is employed, then the necessary luminosity per scan point is 0.0015 fb^{-1} for $m_h < 2M_W$ and m_h not near M_Z[8]. Hence the total luminosity needed to reach an accuracy on the Higgs mass of $\Delta m_h \approx \sigma_{\sqrt{s}} \sim 2$ MeV is:

$$\mathcal{L}_{\rm tot} = \frac{\rm ScanRange}{\sigma_{\sqrt{s}}} \times (\mathcal{L}/{\rm point})$$

[a] Large Hadron Collider.

$$= \frac{200 \text{ MeV}}{2 \text{ MeV}} \times (0.0015 \text{ fb}^{-1})$$
$$= 0.15 \text{ fb}^{-1}.$$

Thus a machine delivering $\mathcal{L}_{\text{inst}} = 1.5 \times 10^{31} cm^{-2} s^{-1}$ would complete the scan and measure the Higgs mass to an accuracy of $\Delta m_h \approx \mathcal{O}(\sigma_{\sqrt{s}})$ in one year of running.

Once m_h is determined to such an accuracy, a 3-point fine scan[5] can be performed, with one setting at the peak and two settings on the wings $\pm\sigma_{\sqrt{s}}$ from the peak. The ratios of $\sigma(\text{wing})/\sigma(\text{peak})$ determine m_h and Γ_h. Then with $\mathcal{L}_{\text{tot}} = 0.4$ fb^{-1}, assuming $m_h = 110$ GeV and $\Gamma_h = 3$ MeV, accuracies of $\Delta\Gamma_h/\Gamma_h = 16\%$ and $\Delta m_h \sim 0.1$ MeV are attainable[8]. Concurrently, branching ratios for the dominant decay channels, $\sigma \cdot \text{BF}(b\bar{b})$ and $\sigma \cdot \text{BF}(W^+W^-)$, can also be measured to a precision or 3% and 15% respectively. Such high precision measurements would be significant to electroweak physics in and beyond the SM. For example, an accuracy of 15% on the ratio $\text{BF}(W^+W^-)/\text{BF}(b\bar{b})$, would allow the detection of A^0 effects for $M_{A^0} > 400$ GeV through comparison with MSSM and SM predictions[5].

The heavier neutral MSSM[b] Higgs bosons are also observable in the s-channel. Figure 5 gives the cross sections and significance of the CP-odd state A^0 versus its mass. Discovery and study of the A^0 is possible at all m_{A^0} if $\tan\beta > 2$ and at $m_{A^0} < 2m_t$ if $\tan\beta < 2$. In the limit of large m_{A^0}, which is a natural consequence of a large number of SUGRA

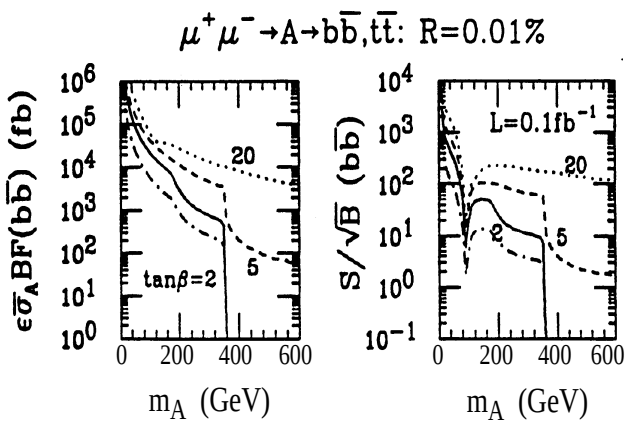

Figure 5. Cross sections and significance for detection of the A^0 Higgs boson with and efficiency[9] $\epsilon = 0.5$ and a $\mathcal{L} = 0.1$ fb^{-1}.

inspired models, the masses of A^0, H^0 and $H^\pm$ are similar. In such a situation the A^0 and H^0 contributions can be separated by an s-channel scan with the good resolution of a muon collider, as illustrated in figure 6.

The CP properties of a neutral Higgs, once discovered, can be studied at a muon collider and would be very instructive. Can it be verified that the SM Higgs is CP-even? If CP

[b]Minimal Supersymmetric extension to the Standard Model.

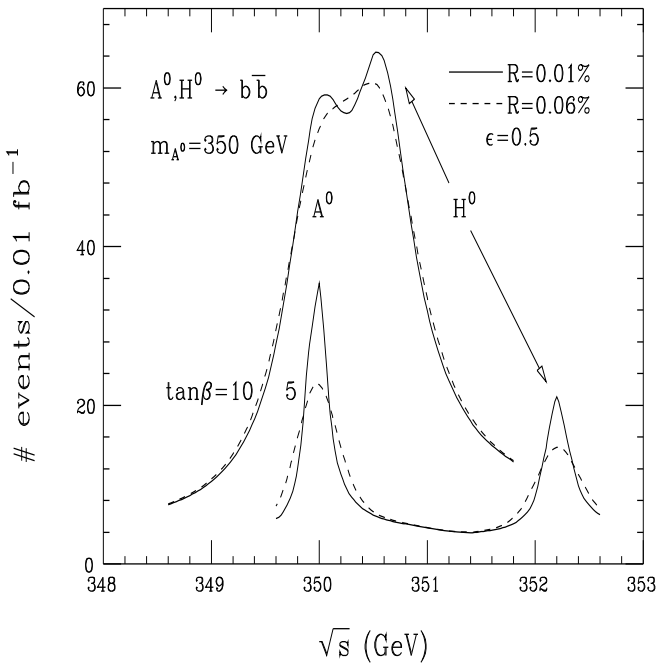

Figure 6. Separation of the A^0 and H^0 signals for $\tan\beta = 10^5$.

violation in the Higgs sector is observed then the profound conclusion is that neither the SM nor the MSSM can be correct. Both models would require a more complicated Higgs sector to be viable. A muon collider may be the ideal machine for directly probing the the CP properties of a Higgs boson[10]. For 100% transverse polarization of the muon beams,

$$\sigma(\phi) \propto 1 - \frac{a^2 - b^2}{a^2 + b^2}\cos\phi + \frac{2ab}{a^2 + b^2}\sin\phi, \tag{4}$$

where ϕ is the angle between μ^+ and μ^- transverse polarization and a and b are the CP-even and CP-odd couplings of the Higgs respectively. In the case that the Higgs is a CP mixture then both a and b are non-zero and the asymmetry

$$A_1 \equiv \frac{\sigma(\pi/2) - \sigma(-\pi/2)}{\sigma(\pi/2) + \sigma(-\pi/2)} = \frac{2ab}{a^2 + b^2} \tag{5}$$

will be large. For a pure CP Higgs, the asymmetry

$$A_2 \equiv \frac{\sigma(\pi) - \sigma(0)}{\sigma(\pi) + \sigma(0)} = \frac{a^2 - b^2}{a^2 + b^2} \tag{6}$$

is $+1$ and -1 for a CP-even or CP-odd Higgs, respectively.

3 Technicolor and more s-channel physics

Technicolor is a possible new strong interaction of fermions and gauge bosons at the TeV scale, which causes the dynamical breaking of electroweak symmetry. In most technicolor models, there will be light (< 500 GeV), neutral and colorless technipion resonances. In all models, such resonances are predicted to have substantial Yukawa couplings to muons and can be produced in the s-channel at a muon collider.

$$\mu^+\mu^- \to \pi_T^0, \rho_T^0, w_T^0 \tag{7}$$

4 Precision, Threshold and Physics at the Z-pole

Beyond Higgs and s-channel physics, a muon collider can provide an ideal environment for the kind of precision measurements which have become the main diet for the high energy physics community in recent years.

A muon collider operated as a Z factory is an interesting option for measurement of polarization asymmetries, $B_s^0 - \bar{B}_s^0$ mixing and for measurements of CP violation in the B-meson system. A sample of 10^8 Z-boson events per year would be required to achieve significant improvements over measurements at existing and future B-facilities in the B-sector. This corresponds to a luminosity of > 0.15 fb^{-1}/year, which is well within the domain of muon collider expectations[3]. A modest resolution of $R \sim 0.1\%$ would be more than adequate in such a study given the large width of the Z ($\Gamma_Z \sim 2.4$ GeV).

Even with partial muon beam polarization, a muon collider would be advantageous for B physics studies because of the long B-decay length for B-mesons. The left-right asymmetry, A_{LR} is the most accurate measure of $\sin^2\theta_W$, since the uncertainty is statistics dominated. The present LEP and SLD polarization measurements show standard deviations of 2.4 in A_{LR}^0, 1.9 in $A_{FB}^{0,b}$ and 1.7 in $A_{FB}^{0,\tau}$ [11]. The CP angle β could be measured from $B^0 \to K_s J/\psi$ decays.

With 10 fb^{-1} integrated luminosity devoted to a measurement of a threshold cross section, the following precisions on particle masses may be achievable[12]:

$\mu^+\mu^- \to W^+W^-$ $\quad \Delta M_W = 20$ MeV,
$\mu^+\mu^- \to t\bar{t}$ $\quad \Delta m_t = 200$ MeV,
$\mu^+\mu^- \to Zh$ $\quad \Delta m_h = 140$ MeV (if $m_h = 100$ GeV).

Electroweak radiative corrections can be thoroughly tested with increasing precision on measurements of M_W and m_t through the relation

$$M_W = M_Z \left[1 - \frac{\pi\alpha}{\sqrt{2}G_\mu M_W^2(1-\delta r)}\right]^{1/2}, \tag{8}$$

where δr represents loop corrections. In the SM, δr depends on m_t^2 and $\log m_h$.

Furthermore, once m_h is known from direct measurements, SUSY loop contributions can be tested.

In top-quark production at a muon collider above the threshold region, modest muon polarization would allow sensitive tests of anomalous top quark couplings[13].

One of the important physics opportunities at a muon collider is the production of the lighter chargino, $\tilde{\chi}_1^+$. Fine-tuning arguments in mSUGRA[c] models suggest that is should be

[c] minimal SUper GRAvity.

lighter than 200 GeV, thereby making it accessible even to a FMC. The two destructively interfering contributing diagrams in the chargino pair production process at a muon collider are shown in figure 7. The $\tilde{\chi}_1^+$ and $\tilde{\nu}_\mu$ masses can be inferred from the shape of the cross

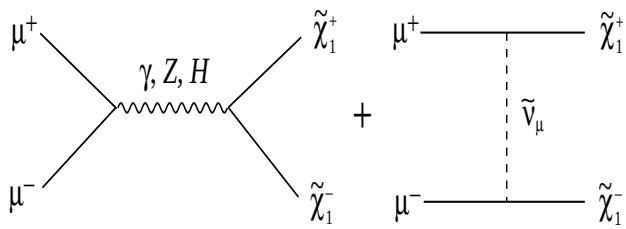

Figure 7. Diagrams for production of the lighter chargino.

section in the threshold region[14].

5 High Mass States

Besides the already mentioned SUSY impact a FMC may have, the muon collider in any incarnation will be a very useful tool in elucidating the heavier SUSY sector.

The requirement of gauge coupling unification predicts a mean SUSY mass of $\mathcal{O}(1\text{ TeV})$. This is derived from the value of the strong coupling at the Z-mass scale[11]. Figure 8 shows the SUSY GUT[d] predictions versus $\alpha_s(M_Z)$. Hence some SUSY particles will likely have masses at the TeV scale.

A muon collider will be useful in illuminating the SUSY particle mass spectrum. The following are examples of further measurements not accessible at the LHC:

1. The determination of the Lightest Supersymmetric Particle (LSP) or NLSP[e] mass, depending on the theory being considered.

2. Sleptons masses > 200 GeV as Drell-Yan production becomes too small at these masses.

3. Study of heavy gauginos $\tilde{\chi}_2^\pm$ and $\tilde{\chi}_{3,4}^0$ which are higgsino like for a large portion of SUSY parameter space and have small direct production rates and small branching fractions to channels useful for detection.

Since spin-0 pair production is p-wave suppressed at lepton colliders[16], energies well above the thresholds are required to have sufficient production rates. (see figure 9.)

A common low-energy SUSY consequence of string models is s-channel contributions of Z' bosons with mass far above the kinematic reach of the collider. Such effects could be revealed as contact interactions [17] at a muon collider.

[d] Grand Unification Theory.
[e] Next Lightest Supersymmetric Particle.

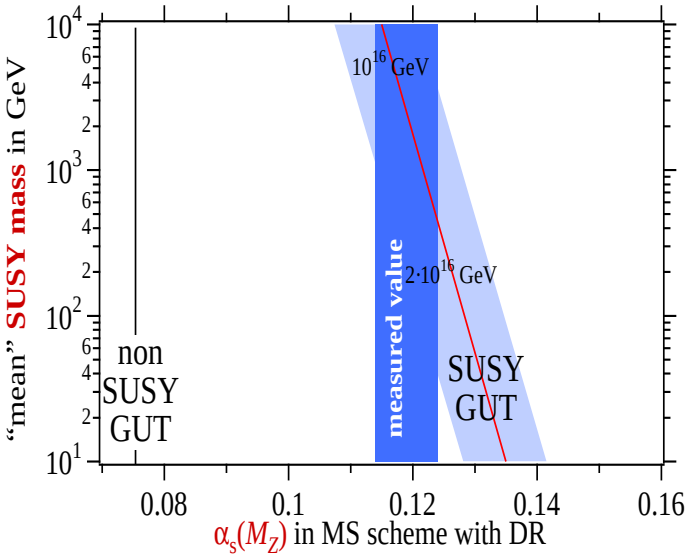

Figure 8. α_s prediction MSSM in the Dimensional Regularization scheme[15].

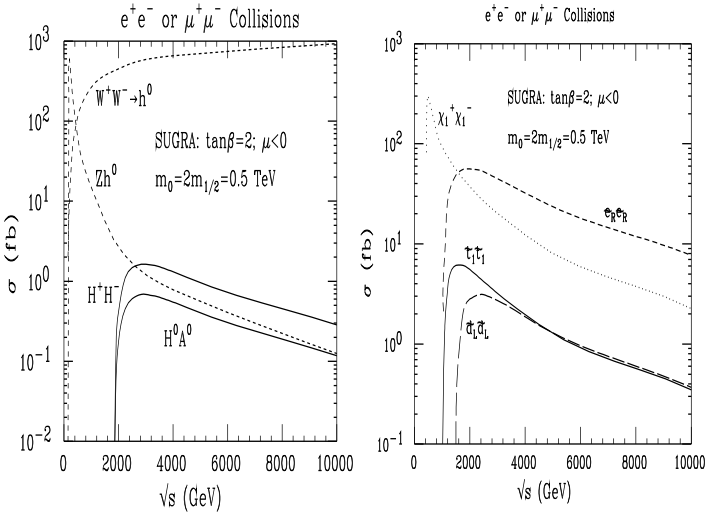

Figure 9. Cross sections for pair production of Higgs bosons and scalar particles at a NMC[16].

If there is R-parity violation of the form $\lambda_{ijk} L_L^i L_L^j \bar{E}_R^k$, lepton flavour is violated and a multitude of new signals arise. Production of a sneutrino through the following interactions, $\mu^+\mu^- \to \tilde{\nu}_\tau$ (λ_{223}) and/or $\tilde{\nu}_e$ (λ_{122}) is an exciting prospect. The $\tilde{\nu}_\tau$ is expected to be the lightest of the sneutrinos and hence the muon collider looks especially interesting for s-channel sneutrino production. Once more, the ability to achieve $R = 0.003\%$ at a muon collider could allow one to resolve a splitting ($\mathcal{O}$(1 MeV)) of the CP-odd and CP-even components of the $\tilde{\nu}_\tau$[7].

Here an NMC could provide the necessary conditions to pursue the topics mentioned. Furthermore, the excellent initial state beam energy resolution of a muon collider is once again advantageous in reconstructing the sparticle mass spectra through their complex and varied decay chains.

6 Strong Dynamics

In the case that no Higgs boson is discovered at previous experiments such as the LHC or a linear collider below 1 TeV, then partial wave unitarity of $W_L W_L \to W_L W_L$ scattering requires that the scattering be strong at the $\mathcal{O}$(TeV) scale[7]. The scattering of weak bosons can be studied at a muon collider through the process illustrated in figure 10. The amplitude

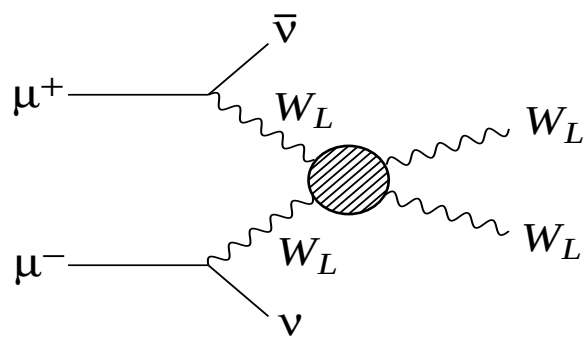

Figure 10. Diagram for strong WW scattering.

for longitudinally polarized W-boson scattering is given by

$$A \sim m_h^2/v^2 \quad \text{if a light Higgs exists,}$$
$$A \sim s_{WW}/v^2 \quad \text{if no light Higgs exists,}$$

where s_{WW} is the square of the WW center of mass energy and $v = 246$ GeV is the SM Higgs vacuum expectation value. In the absence of a Higgs the nature of the underlying dynamics is unknown. Many models for this scattering assume some heavy resonant scalar or vector particle, or a non-resonant amplitude $A_{W_L W_L} \sim s/v^2$ which is an extrapolation of the low energy theorem. In this situation, the energy reach of any potential machine is critical. A $\sqrt{s_{WW}} > 1.5$ TeV is needed to probe the strong dynamics. Hence a 4 TeV muon collider, as in the case of a NMC, would have sufficient energy for a

comprehensive study of strong electroweak symmetry. The cross section at a NMC in all existing models are significant. Signals of strong WW scattering on the order of 50 fb[18] are expected.

7 Front-end Physics

An intense muon source for a muon collider can in itself allow a program of study. The intense muon beam at the front end of a muon collider may provide an excellent source for the study of rare muon processes $\mu \to e\gamma$, $\mu N \to eN$ conversion and the measurement of the muon electric dipole[1]. These can be probed beyond current levels. Lepton flavour mechanisms as a result of SUSY GUT interactions or CP violating processes should occur at significant rates. Such processes can also occur via leptoquarks, Z' boson or heavy neutrinos.

8 Neutrino Physics

As an additional consequence of the muon collider beams, neutrino beams from an energetic μ beam would be excellent for νN fixed target experiments. For such fixed target experiments, a muon collider could provide a thousand times larger flux than at present machines[19]. This would result in $\sim 10^6$ νN and $\bar{\nu} N$ events per year, which could be used to measure charm production and make a $\sin^2\theta_w$ measurement.

A special purpose muon storage ring can produce a very intense beam of neutrinos through muon decays in the straight sections of the ring. Such large neutrino fluxes would be ideal for neutrino oscillation experiments[20]. Neutrino fluxes from $\mu^- \to \nu_\mu \bar{\nu}_e e^-$ or $\mu^+ \to \bar{\nu_\mu} \nu_e e^+$ decays can be calculated with little systematic error. The known neutrino fluxes can then be used for longbaseline oscillation experiments at any detector in the world.

9 Summary and Conclusion

A Muon Collider would be the ideal machine for the study of a light higgs and possible discovery of heavier SUSY higgs bosons. $\mu^+\mu^-$ interactions at such a collider profit from large s-channel resonant cross sections in the search for SUSY, technicolor and Z' bosons. A muon collider would also make a wonderful *smachine* for the measurement of SUSY particle spectra.

The intense muon beams required to make the muon collider feasible can also be used in non-collider modes. The muon beam can provide insight into rare muon decays. The muon decays can also provide a well collimated high energy neutrino beam for fixed target and/or longbaseline neutrino oscillation experiments.

Other incarnations or running options offer further physics opportunities. Same sign muon colliders[21] can be used to search for exotic doubly charged higgs, compositness and heavy majorana neutrinos.

Higgs and s-channel physics at the muon collider are the machine's strength. However, if no higgs is discovered at the LHC or other machines, then the alternative of strongly interacting gauge bosons can be studied at a muone collider. Moreover, in the absence of a higgs discovery, precision physics at the muon collider can test the SM to new levels and give possible hints of new physics.

A $\mu\bar{\mu}$ collider can conceivably be run at higher energies ($\sqrt{s} = 10 - 100$ TeV) thus providing a future energy frontier.

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