LUMINOSITY REQUIREMENTS FOR HIGGS RESONANCE STUDIES
AT THE FIRST MUON COLLIDER*

Zohreh Parsa
Department of Physics
Brookhaven National Laboratory
Upton, NY 11973

*This work was performed under the auspices of the U.S. Department
of Energy under Contract No. DE-AC02-76CH00016.
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency, contractor or subcontractor thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency, contractor or subcontractor thereof.
Luminosity Requirement for Higgs Resonance studies
At The First Muon Collider*

Zohreh Parsa

Physics Department, Brookhaven National Laboratory, Upton, New York 11973

For the "2nd Mini - Workshop on Higgs Factory"
UCLA Faculty Center, Los Angeles, California
February 12-13, 1997

Abstract. The results of our Higgs resonance studies at the first Muon collider for the on-resonance goal of \( \mathcal{L}_{\text{ave}} \simeq 5 \times 10^{30}\text{cm}^{-2} \) and \( \mathcal{L}_{\text{ave}} \simeq 5 \times 10^{31}\text{cm}^{-2} \) is given. Our analysis indicates that \( \mathcal{L}_{\text{ave}} \simeq 5 \times 10^{30}\text{cm}^{-2} \) is too low and at least an additional order of magnitude increase in luminosity is needed. We investigated [4,7] the effect of beam polarization on Higgs resonance signals and backgrounds (\( b\bar{b}, \tau\bar{\tau}, c\bar{c} \)), angular distributions (forward-backward charge asymmetries) and the resulting effective enhancement of the Higgs signal relative to the background, as well as the reduction in scan time required for Higgs “discovery”.

- If the Higgs boson has a mass \( \lesssim 160 \text{ GeV} \) (i.e. below the \( W^+W^- \) decay threshold), it will have a very narrow width and can be resonantly studied in the \( s \)-channel via \( \mu^-\mu^+ \rightarrow H \) production at the First Muon Collider (FMC) [1,2]. A strategy for “light” Higgs physics studies would be to first find the Higgs particle at LEPII, the Tevatron, or the LHC and then thoroughly scrutinize

*) Supported by U.S. Department of Energy contract number DE-AC02-76CH00016.
its properties on resonance at the FMC. There, one would hope to precisely determine the Higgs mass, width, and primary decay rates [3].

- The FMC Higgs resonance program would entail two stages: 1) “Discovery” via an energy scan which pinpoints the precise resonance position and (perhaps) determines its width. Since pre-FMC efforts may only determine the Higgs mass to $\pm 0.2-1$ GeV and its width is expected to be narrow $\mathcal{O}(1 \sim 30$ MeV) for $m_H \lesssim 160$ GeV, the resonance scan may be very time consuming [3]. 2) Precision measurements of the primary Higgs decay modes. Deviations from standard model expectations could point to additional Higgs structure or elucidate the framework of supersymmetry [3].

- The Higgs resonance “discovery” capability and scan time will depend on $N_S/\sqrt{N_B}$ (the scan time is proportional to $N_B/N_S^2$), where $N_S$ is the Higgs signal and $N_B$ is the expected background. The precision measurement sensitivity will be determined by $N_S/\sqrt{N_B + N_S}$. For both, it will be extremely important to enhance the signal and suppress backgrounds as much as possible. To that end, one should employ highly resolved $\mu^+\mu^-$ beams with a very small energy spread. The proposed $\Delta E/E \simeq 3 \times 10^{-5}$ is well matched to the narrow Higgs width. It allows $N_S/N_B \sim \mathcal{O}(1)$ for the primary $H \to b\bar{b}$ mode (see Table 1 and 2). Unfortunately, high resolution is accompanied by luminosity loss. The original on-resonance goal of $\mathcal{L}_{\text{ave}} \simeq 5 \times 10^{30}$cm$^{-2}$s$^{-1}$ is too low. Hence, we have assumed in Table 2 and throughout this paper that an additional order of magnitude increase in luminosity to $5 \times 10^{31}$cm$^{-2}$s$^{-1}$ is attainable while maintaining outstanding beam resolution.

- For example, a factor of 10 increase in Luminosity (Table 2) reduces the running (scan) time by factor 10 less. Thus instead of a “3 year” running time, it will be reduced to $(\frac{3}{10}$ year) over “3 months”.
• Expectations for \( m_H = 110 \) GeV are illustrated in Table 1 for luminosity \( \mathcal{L}_{\text{ave}} \simeq 5 \times 10^{30} \text{cm}^{-2} \text{s}^{-1} \) and in Table 2 for luminosity \( \mathcal{L}_{\text{ave}} \simeq 5 \times 10^{31} \text{cm}^{-2} \text{s}^{-1} \).

**TABLE 1.** Expected signals and backgrounds (fully integrated) for a standard model Higgs with \( m_H = 110 \) GeV, \( \Gamma_H \simeq 3 \) MeV. Muon collider resonance conditions with no polarization, \( \Delta E/E \simeq 3 \times 10^{-5} \), and \( L = 0.05 \) fb\(^{-1} \) are assumed. The total number of Higgs scalars produced is \( \sim 3000 \). Realistic efficiency and acceptance cuts are likely to dilute signal and backgrounds for \( b\bar{b} \) and \( c\bar{c} \) by a 0.5 factor.

<table>
<thead>
<tr>
<th>( H \to b\bar{b} )</th>
<th>( c\bar{c} )</th>
<th>( \tau\tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_S ) (events)</td>
<td>2400</td>
<td>120</td>
</tr>
<tr>
<td>( N_B ) (events)</td>
<td>2520</td>
<td>2416</td>
</tr>
<tr>
<td>( \pm \sqrt{N_S + N_B}/N_S )</td>
<td>±0.03</td>
<td>±0.42</td>
</tr>
</tbody>
</table>

**TABLE 2.** Expected signals and backgrounds (fully integrated) for a standard model Higgs with \( m_H = 110 \) GeV, \( \Gamma_H \simeq 3 \) MeV. Muon collider resonance conditions with no polarization, \( \Delta E/E \simeq 3 \times 10^{-5} \), and \( L = 0.5 \) fb\(^{-1} \) are assumed. The total number of Higgs scalars produced is \( \sim 30,000 \). Realistic efficiency and acceptance cuts are likely to dilute signal and backgrounds for \( b\bar{b} \) and \( c\bar{c} \) by a 0.5 factor.

<table>
<thead>
<tr>
<th>( H \to b\bar{b} )</th>
<th>( c\bar{c} )</th>
<th>( \tau\tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_S ) (events)</td>
<td>24,000</td>
<td>1,200</td>
</tr>
<tr>
<td>( N_B ) (events)</td>
<td>25,200</td>
<td>24,160</td>
</tr>
<tr>
<td>( \pm \sqrt{N_S + N_B}/N_S )</td>
<td>±0.009</td>
<td>±0.13</td>
</tr>
</tbody>
</table>

• In these tables \( c\bar{c} \) branching ratios have been reduced compared to those given previously [4,7]. The values given here assume smaller charm quark mass. The prediction is quite sensitive to the mass value assumed.

The selection of the energy and luminosity depends on 1) the reduced scan time to normal time needed, and 2) to improve precision to do physics. For example, to measure \( c\bar{c} \), a factor of 10 increase in luminosity results in the improvement from 42%,
Other decays such as $WW^*$ and $ZZ^*$ are very small for this mass regions and to measure them need to improve precision. The parameter $\pm \sqrt{N_S + N_B}/N_S$ in Tables 1 and 2 was included for convenient. Further note, the values listed in Tables 1 and 2 should be reduced by $\frac{1}{\sqrt{2}}$ to include the effect of acceptance.

- Here we describe additional ways of potentially enhancing the Higgs signal to background ratio. The Higgs signal $\mu^- \mu^+ \rightarrow H \rightarrow f\bar{f}$ results from left-left (LL) or right-right (RR) beam polarizations and leads to an isotropic (i.e. constant) $f\bar{f}$ signal in $\cos\theta$ (the angle between the $\mu^-$ and $f$). Standard model backgrounds $\mu^- \mu^+ \rightarrow \gamma^*$ or $Z^* \rightarrow f\bar{f}$ result from LR or RL initial state polarizations and give rise to $(1 + \cos^2 \theta + \frac{8}{3}A_{FB} \cos \theta)$ angular distributions. Similar statements apply to $WW^*$ and $ZZ^*$ final states, but those modes will not be discussed here.

- To illustrate the difference between signal, $\mu^- \mu^+ \rightarrow H \rightarrow f\bar{f}$,
and background, $\mu^-\mu^+ \rightarrow \gamma^* \text{ or } Z^* \rightarrow f\bar{f}$, we give the combined differential production rate with respect to $x \equiv \cos \theta = 4p_{\mu^-} \cdot p_f / s$ for polarized muon beams and fixed luminosity

$$\frac{dN(\mu^-\mu^+ \rightarrow f\bar{f})}{dx} = \frac{1}{2} N_S(1 + P_+P_-) + \frac{3}{8} N_B[1 - P_+P_- + (P_+ - P_-)A_{LR}](1 + x^2 + \frac{8}{3}xA_{eff}).$$

$P_+(P_-)$ is the $\mu^+(\mu^-)$ polarization with $P = -1$ pure left-handed, $P = +1$ pure right handed, and $P = 0$ unpolarized. $N_S$ is the fully integrated ($-1 < x < 1$) Higgs signal and $N_B$ the integrated background for the case of unpolarized beams, $P_+ = P_- = 0$. In that general expression,

$$A_{LR} = \frac{\sigma_{LR\rightarrow LR} + \sigma_{LR\rightarrow RL} - \sigma_{RL\rightarrow RL} - \sigma_{RL\rightarrow LR}}{\sigma_{LR\rightarrow LR} + \sigma_{LR\rightarrow RL} + \sigma_{RL\rightarrow RL} + \sigma_{RL\rightarrow LR}},$$

where, for example, $LR \rightarrow LR$ stands for $\mu_L^-\mu_R^+ \rightarrow f_L\bar{f}_R$. The effective forward-backward asymmetry is given by

$$A_{eff} = \frac{A_{FB} + P_{eff}A_{FB}^{FLR}}{1 + P_{eff}A_{LR}},$$

with

$$P_{eff} = \frac{P_+ - P_-}{1 - P_+P_-},$$

$$A_{FB} = \frac{3\sigma_{LR\rightarrow LR} + \sigma_{RL\rightarrow RL} - \sigma_{LR\rightarrow RL} - \sigma_{RL\rightarrow LR}}{4\sigma_{LR\rightarrow LR} + \sigma_{RL\rightarrow RL} + \sigma_{RL\rightarrow RL} + \sigma_{RL\rightarrow RL}},$$

$$A_{FB}^{FLR} = \frac{3\sigma_{LR\rightarrow LR} + \sigma_{RL\rightarrow RL} - \sigma_{LR\rightarrow RL} - \sigma_{RL\rightarrow RL}}{4\sigma_{LR\rightarrow LR} + \sigma_{RL\rightarrow RL} + \sigma_{RL\rightarrow RL} + \sigma_{RL\rightarrow RL}}.$$
Realistic cuts, efficiencies, systematic errors etc, will not be considered. They are likely to dilute the $b\bar{b}$ and $c\bar{c}$ event rates by a factor of 0.5. In addition, we ignore the radiative $Z$ production tail under the assumption such events are vetoed.

• The (unpolarized) forward-backward asymmetries are illustrated in Fig. 1. Note that $A_{FB}$ is large (near maximal) for $\tau\bar{\tau}$ and $c\bar{c}$ in the region of interest. As we shall see, that feature can help in discriminating signal from background.

• In principle, large polarization in both beams can be important for enhancing “discovery” and precision measurement sensitivity for the Higgs. From Eq. (1), we find for fixed luminosity that $N_S/\sqrt{N_B}$ is enhanced (for integrated signal and background) by the factor

$$\kappa_{pol} = \frac{1 + P_+P_-}{\sqrt{1 - P_+P_- + (P_+ - P_-)A_{LR}}} ,$$

where the $A_{LR}$ are shown in Fig. 2. That result generalizes the
For natural beam polarization [1], $P_+ = P_- = 0.2$ (assuming spin rotation of one beam), the enhancement factor is only 1.06. For larger polarization, $P_+ = P_- = 0.5$, one obtains a 1.44 enhancement factor (statistically equivalent to about a factor of 2 luminosity increase). Similarly, $P_+ = P_- = 0.7$ leads to a factor of 2 enhancement or equivalently a factor of 4 scan time reduction. Unfortunately, obtaining even 0.5 polarization simply by muon energy cuts reduces each beam intensity [1] by a factor of 1/4, resulting in a luminosity reduction by 1/16. Such a trade-off is clearly unacceptable. Polarization will be a useful tool in Higgs resonance "discovery" and studies only if high polarization is achievable with little luminosity loss. Ideas for increasing the polarization are still being explored [1,6]. Tau final state polarizations can also be used to help improve the $H \to \tau\bar{\tau}$ measurement.

Some "discovery" or sensitivity enhancement can also be obtained from angular discrimination. A proper study would include detector acceptance cuts and maximum likelihood fits. Here, we wish to only approximate the gain. For that purpose, we assume perfect (infinitesimal) binning and obtain a (maximal) measurement sensitivity enhancement factor

$$\frac{1}{2} (1 + P_+ P_-) \sqrt{N_S + N_B} \left[ \int \frac{dx}{dN/dx} \right]^{1/2}$$

which becomes, from Equations (1) and (8),

$$\kappa_{\text{pol}} \left[ \frac{2}{3} \sqrt{\frac{N_S + N_B}{N_B}} \left( \frac{\tan^{-1} \left( \frac{2}{\zeta} \sqrt{1 - \frac{16}{9} A_{\text{eff}}^2 + \zeta} \right)}{\sqrt{1 - \frac{16}{9} A_{\text{eff}}^2 + \zeta}} \right) \right]^{1/2}, \quad \zeta \equiv \frac{4 N_S}{3 N_B} \frac{\kappa_{\text{pol}}^2}{1 + P_+ P_-}$$

In the case of "discovery", high polarization and/or a near maximal forward-backward asymmetry can significantly reduce the scan time. Additional analysis and detail will be given in [7].
Conclusion

We conclude that $L_{\text{ave}} \approx 5 \times 10^{30}\text{cm}^{-2}$ is too low and at least an additional order of magnitude increase in luminosity is needed for the Higgs resonance studies at the First Muon Collider. A factor of 10 in luminosity reduces the scan time by a factor of 10 and increases the resolution by about a factor of 3. The choice of energy and luminosity depends on 1) the scan time needed and 2) how precise a measurement is needed to do physics. For example, to measure $c \bar{c}$, a factor of 10 increase in luminosity provides the improvement from 42% (Table 1) to about 13% (Table 2), and reduces the scan time from 3 years to over 3 months. Other decays such as $WW^*$ and $ZZ^*$ are very small for this mass regions and to measure them need to improve precision, thus the need for increase in Luminosity, etc.

We have shown that polarization is potentially useful for Higgs resonance studies, but only if the accompanying luminosity reduction is not significant. Large forward-backward asymmetries can also be used to enhance the Higgs “discovery” signal or improve precision measurements, particularly for $\tau\bar{\tau}$. However, to make the s-channel Higgs “factory” a compelling facility, we must attain a very good beam resolution and the highest luminosity possible. An additional “discovery” or sensitivity enhancement can be obtained from angular discrimination. For additional discussion see [7].

REFERENCES

Z. Parsa - Luminosity Requirement for Higgs Resonance studies at the FMC
