Polarization Effects at a Muon Collider

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Abstract

For Muon Colliders, polarization will be a useful tool if high polarization is achievable with little luminosity loss. Formulation and effects of beam polarization and luminosity including polarization effects in Higgs resonance studies are discussed, for improving precision measurements and Higgs resonance "discovery" capability e.g. at the First Muon Collider (FMC).

1 MUON COLLIDER

New ideas for a muon collider envisions as their starting point very intense clean muons with a small momentum spread. Such beams would be accelerated to collider energies and be used to search for new short distance (high energy) phenomena.

A muon collider with center of mass energy less than about 10 TeV can be circular and relative to a Next Linear Collider of the same energy, it could be far smaller. For the same luminosity, because the muons make about 1000 crossings, a far larger spotsize can be employed. And since there is little beamstrahlung, very small energy spread is possible.

In a muon Collider complex (concepts), a high intensity proton source is bunch compressed and focussed on a heavy metal target. The pions generated are captured by a high field solenoid and transferred to a solenoidal decay channel within a low frequency linac. The linac reduces, by phase rotation the momentum spread of the pions and of the muons into which they decay. Subsequently, the muons are cooled by a sequence of ionization cooling stages. Each stage consists of energy loss, acceleration, and emittance exchange by energy absorbing wedges in the presence of dispersion. Once they are cooled the muons must be rapidly accelerated to avoid decay. This can be done in recirculating accelerators (as at CEBAF) or in fast pulsed synchrotrons. Muon collisions occur in a separate high field collider storage ring with a single very low beta insertion. Figure 1, shows a schematic of a Muon collider.

It is expected that the first stage, proton driver would be 20 to 30 GeV (e.g., AGS at Brookhaven); but would be much faster pulsed, keeping the number of protons per pulse the same or smaller than the AGS. Which is about /7/6 protons per pulse in a year or so. Roughly one expect to get 1 muon/proton on target which would give Luminosity between /7/5 to /7/3 for the 4-TeV envisioned muon collider.

In recent studies a 50 GeV × 50 GeV Muon Collider is being considered as the First Muon Collider (FMC) which could serve as a test of the technology for muon colliders. Some of the parameters [1-2] of the collider rings under study are given in Table 1, for 0.1 TeV, 0.5 TeV and 4 TeV center of mass (C.M.) energy μ+μ− colliders.

Although muon colliders remain a promising complement, to e+e− colliders, much work is still needed, including demonstration of μ production and cooling, detector, and radiation.

2 POLARIZATION

Muons are produced fully polarized in the center of mass of the decaying pions. In the lab system the polarization depends on the pions initial kinetic energy and the decay angle. The neutral polarization of the captured muons is about 20 % after the phase rotation.

If the Higgs boson has a mass ≤ 160 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 μ⁺μ⁻ → H production at the First Muon Collider [1-3]. 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 its properties on resonance at the FMC. There, one would hope to precisely determine...
the Higgs mass, width, and primary decay rates [3].

Since signal and background predominantly come from different polarization states, polarization of the muon beams is more advantageous over the case of unpolarized muons. In this paper, we describe ways of potentially enhancing the Higgs signal to background ratio: beam polarization and final state angular distributions. 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 \( \bar{f} \)). Standard model backgrounds \( \mu^+\mu^- \rightarrow \gamma^* + Z^* \rightarrow f\bar{f} \) result from LR or RL initial state polarizations and give rise to \( (1 + \cos^2\theta + \frac{8}{5}A_{FB} \cos\theta) \) angular distributions. Similar statements apply to \( WW \) and \( ZZ \) final states, but those modes will not be discussed here [5].

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

\[
\frac{dN(\mu^-\mu^+ \rightarrow f\bar{f})}{dx} = \frac{1}{2N_0(1 + P_+ P_-)}A_{LR}(1 + x^2 + \frac{8}{3}A_{eff}).
\]

\( P_+ = P_\mu^\text{left-handed} \) and \( P_- = P_\mu^\text{right-handed} \) are the pure left-handed, \( P = 1 \) pure right handed, and \( P = 0 \) unpolarized. \( N_0 \) is the fully integrated \((-1 < x \leq 1)\) Higgs signal and \( N_0 \) the integrated background for the case of unpolarized beams, \( P_+ = P_- = 0 \). In that expression,

\[
A_{LR} \equiv \frac{\sigma_{LR\rightarrow LR} + \sigma_{LR\rightarrow RL} - \sigma_{RL\rightarrow RL} - \sigma_{RL\rightarrow LR}}{\sigma_{LR\rightarrow LR} + \sigma_{LR\rightarrow RL} + \sigma_{RL\rightarrow RL} + \sigma_{RL\rightarrow LR}}
\]

Table 1: Parameters of \( \mu^+\mu^- \) collider Rings.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (C.M.) TeV</td>
<td>4</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Beam Energy TeV</td>
<td>2</td>
<td>0.25</td>
<td>0.05</td>
</tr>
<tr>
<td>Rep. rate Hz</td>
<td>15</td>
<td>2.5</td>
<td>15</td>
</tr>
<tr>
<td>p Energy GeV</td>
<td>30</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>( \mu^\text{bunch} )</td>
<td>10^{-14}</td>
<td>10^{-14}</td>
<td>5 \times 10^{-14}</td>
</tr>
<tr>
<td>Bunch/signature</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Beam Power MW</td>
<td>38</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>( \epsilon_N ) ( \pi ) mm-mrad</td>
<td>50</td>
<td>90</td>
<td>195</td>
</tr>
<tr>
<td>Circumference km</td>
<td>8</td>
<td>1.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Ave. ring field B T</td>
<td>6</td>
<td>5</td>
<td>3.5</td>
</tr>
<tr>
<td>Effective turns</td>
<td>900</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>IP beam size ( \mu m )</td>
<td>2.8</td>
<td>17</td>
<td>187</td>
</tr>
<tr>
<td>Chromaticity</td>
<td>2000-4000</td>
<td>40-80</td>
<td></td>
</tr>
<tr>
<td>( \beta_{\text{max}} ) km</td>
<td>200-400</td>
<td>10-20</td>
<td>1.5</td>
</tr>
<tr>
<td>Lumin. ( \text{cm}^{-2}\text{s}^{-1} )</td>
<td>10^{-10}</td>
<td>10^{-11}</td>
<td>2 \times 10^{-11}</td>
</tr>
</tbody>
</table>

The effective forward-backward asymmetry is given by

\[
A_{eff} = \frac{A_{FB} + 3P_{eff}A_{LR}}{1 + 3P_{eff}A_{LR}}.
\]

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

\[
P_{eff} = \frac{P_+ - P_-}{1 - P_+ P_-}.
\]

\[
A_{FB} = \frac{3}{4} \frac{\sigma_{LR\rightarrow LR} + \sigma_{RL\rightarrow RL} - \sigma_{LR\rightarrow RL} - \sigma_{RL\rightarrow LR}}{\sigma_{LR\rightarrow LR} + \sigma_{RL\rightarrow RL} + \sigma_{LR\rightarrow RL} + \sigma_{RL\rightarrow RL}}
\]

The (unpolarized) forward-backward asymmetries are illustrated in Fig. 2. 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 $\frac{dN_{+}(\mu^{+}\mu^{-} \rightarrow f \bar{f})}{d\vec{s}}$ we find for fixed luminosity that $N_{S}/\sqrt{N_{B}}$ is enhanced (for integrated signal and background) by the factor

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

(5)

where the $A_{LR}$ are shown in Fig. 3. That result generalizes the $P_{+} = P_{-}$ case [6]. 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 tradeoff 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 [1,7]. Tau final state polarizations can also be used to help improve the $H \rightarrow \tau\bar{\tau}$ measurement.

In summary, we have shown that polarization is potentially useful for Higgs resonance studies, but only if the accompanying luminosity reduction is not significant.

3 REFERENCES


