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 ionzation 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 6×10^{13} protons per pulse and would go to about 10^{14} protons per pulse in a year or so. Roughly one expect to get 1 muon/proton on target which would give Luminosity between 10^{34} to 10^{35} for the 4-TeV envisioned muon collider.

In recent studies a 50 GeV $\times$ 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 $\mu^+\mu^-$ colliders.

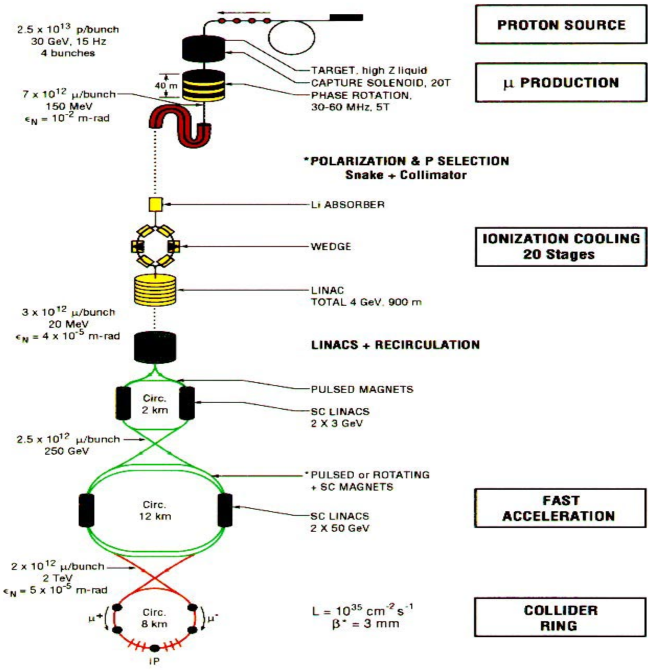

Figure 1: Schematic of a Muon Collider.

Although muon colliders remain a promissing 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 $\lesssim 160$ 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 $\mu^-\mu^+ \to H$ 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

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

Energy (C.M.) TeV	4	0.5	0.1
Beam Energy TeV	2	0.25	0.05
Beam γ	19,000	2,400	473
Rep. rate Hz	15	2.5	15
p Energy GeV	30	24	16
p/pulse	10^{14}	10^{14}	5×10^{13}
μ/bunch	2×10^{12}	4×10^{12}	4×10^{12}
Bunches/sign	2	1	1
Beam Power MW	38	0.7	1.0
ϵ_N π mm-mrad	50	90	195
Bending Field T	9	9	
Circumference km	8	1.3	0.3
Ave. ring field B T	6	5	3.5
Effective turns	900	800	
β^* mm	3	8	9
IP beam size μm	2.8	17	187
Chromaticity	2000-4000	40-80	
β_{max} km	200-400	10-20	1.5
Lumin. $cm^{-2}s^{-1}$	10^{35}	10^{33}	2×10^{31}

the Higgs mass, width, and primary decay rates [3].

Since signal and background predomonantly 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 $\mu^-\mu^+ \to H \to f\bar{f}$ 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 μ^- and f). Standard model backgrounds $\mu^-\mu^+ \to \gamma^*$ or $Z^* \to f\bar{f}$ 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 [5].

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

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

$P_+(P_-)$ 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 ($-1 < x \leq 1$) Higgs signal and N_B the integrated background for the case of unpolarized beams, $P_+ = P_- = 0$. In that expression,

$$A_{LR} \equiv \frac{\sigma_{LR\to LR} + \sigma_{LR\to RL} - \sigma_{RL\to RL} - \sigma_{RL\to LR}}{\sigma_{LR\to LR} + \sigma_{LR\to RL} + \sigma_{RL\to RL} + \sigma_{RL\to LR}}, \tag{1}$$

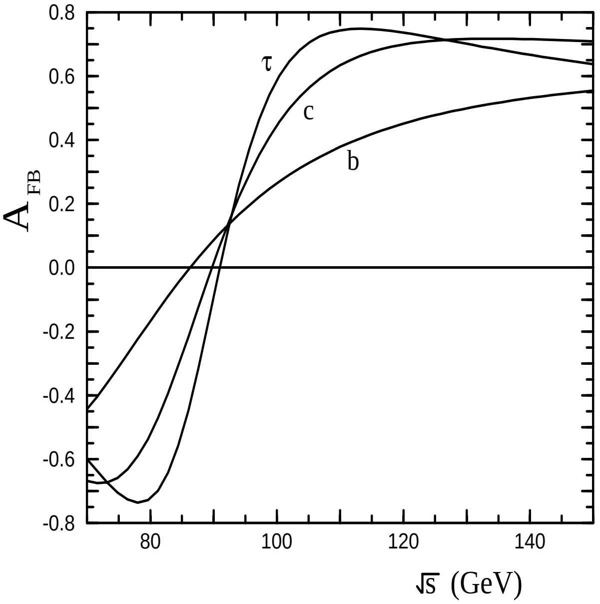

Figure 2: Forward-backward asymmetry for $\mu^-\mu^+ \to f\bar{f}$.

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

$$A_{eff} = \frac{A_{FB} + P_{eff}A_{LR}^{FB}}{1 + P_{eff}A_{LR}}, \tag{2}$$

with

$$\begin{aligned} P_{eff} &= \frac{P_+ - P_-}{1 - P_+P_-}, \qquad (3)\\ A_{FB} &= \frac{3}{4}\frac{\sigma_{LR\to LR} + \sigma_{RL\to RL} - \sigma_{LR\to RL} - \sigma_{RL\to LR}}{\sigma_{LR\to LR} + \sigma_{RL\to RL} + \sigma_{LR\to RL} + \sigma_{RL\to LR}},\\ A_{LR}^{FB} &= \frac{3}{4}\frac{\sigma_{LR\to LR} + \sigma_{RL\to LR} - \sigma_{LR\to RL} - \sigma_{RL\to RL}}{\sigma_{LR\to LR} + \sigma_{RL\to LR} + \sigma_{LR\to RL} + \sigma_{RL\to RL}}. \end{aligned}$$

and the $\mu_i^-\mu_j^+ \to f_{i'}\bar{f}_{j'}$, cross sections ($i \neq j$) are to lowest order

$$\begin{aligned} \sigma_{ij\to i'j'} &= (N_C)\sigma_0\left[1 - \frac{s}{m_Z^2}(1 + F)\right]^2,\\ F &\equiv \frac{(T_{3\mu_i} - Q_\mu\sin^2\theta_W)(T_{3f_{i'}} - Q_f\sin^2\theta_W)}{Q_\mu Q_f\sin^2\theta_W\cos^2\theta_W}\\ T_{3\mu_L} &= T_{3\tau_L} = T_{3b_L} = -T_{3c_L} = -1/2, \qquad (4)\\ T_{3f_R} &= 0, \quad Q_\mu = Q_\tau = 3Q_b = -\frac{3}{2}Q_c = -1 \end{aligned}$$

where $N_C = 3$ for $f = b, c$. 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. 2. Note that A_{FB} is large (near maximal)

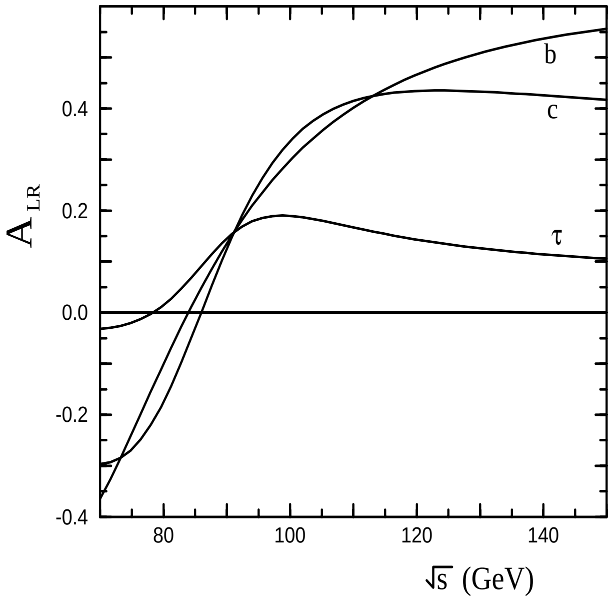

Figure 3: Left-right asymmetry for $\mu^-\mu^+ \to f\bar{f}$.

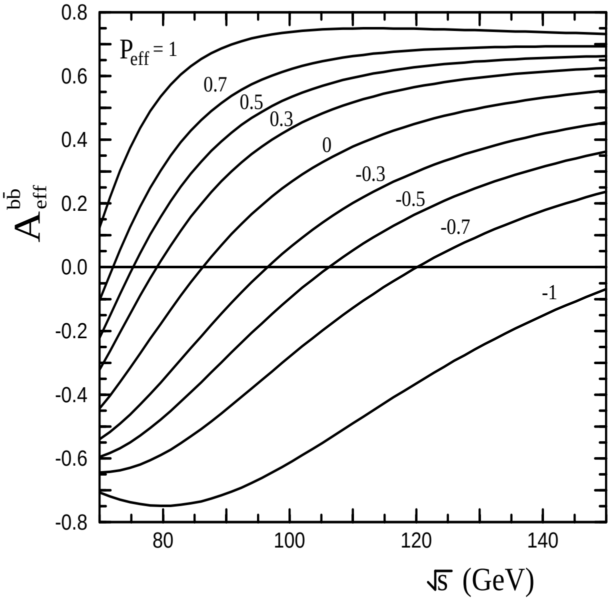

Figure 4: Effective forward-backward asymmetry for $\mu^-\mu^+ \to b\bar{b}$.

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 $\frac{dN(\mu^-\mu^+\to f\bar{f})}{dx}$ we find for fixed luminosity that $N_S/\sqrt{N_B}$ is enhanced (for integrated signal and background) by the factor

$$\kappa_{\rm pol} = \frac{1 + P_+P_-}{\sqrt{1 - P_+P_- + (P_+ - P_-)A_{LR}}} \;, \qquad (5)$$

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 $H \to \tau\bar{\tau}$ 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

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