BNL - 66097
CAP - 244-MUON-98C

POLARIZATION AND LUMINOSITY REQUIREMENTS FOR THE FIRST MUON COLLIDER*

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*This work was performed under the ausices of the U.S. Department of Energy under Contract No. DE-AC02-98CH10886.

November 1998

Submitted to the 8th Workshop on Advanced Accelerator Concepts , Baltimore, MD, July 5-11, 1998.

Polarization and Luminosity Requirement for the First Muon Collider*

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Abstract. Muon Polarization and Luminosity requirement for physics studies at a muon collider are discussed. An overview of a muon collider concepts and design parameters for 0.1, 0.5, and 4 Tev muon colliders are also presented.

I INTRODUCTION

We discuss the effects of beam polarization and luminosity in Higgs resonance studies, for improving precision measurements and Higgs resonance "discovery" capability at a muon collider (e.g. at FMC). In the following, we provide a brief overview of a muon collider concepts and parameters (for 0.1, 0.5 and 4 TeV Center of mass energy muon collider rings), and discuss Higgs physics at the first muon collider.

II MUON COLLIDER

In a muon Collider (concepts) complex, 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. Muon collisions occur in a separate high field collider storage ring with a single very low beta insertion. Fig. 1, shows a schematic of a Muon collider and Fig. 2, illustrates the relative sizes of Muon Collider, Large Hadron Collider (LHC), and Next Linear Collider (NLC), relative to the sizes of the existing laboratory (BNL and FNAL) sites [1].

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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 a 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.

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	450
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}

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

III HIGGS PHYSICS AT THE FIRST MUON COLLIDER

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 (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 its properties on resonance

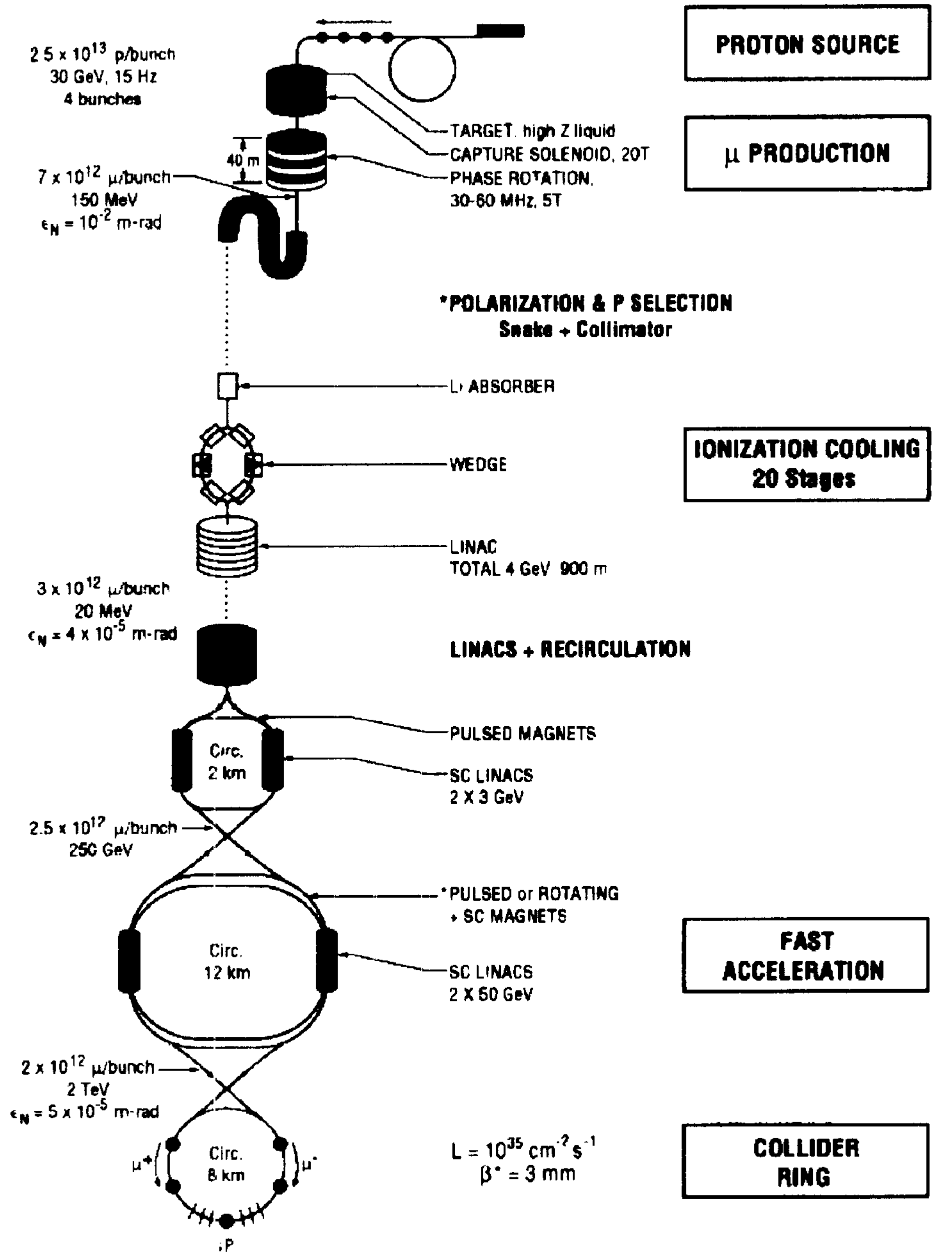

FIGURE 1. Schematic of a Muon Collider [1].

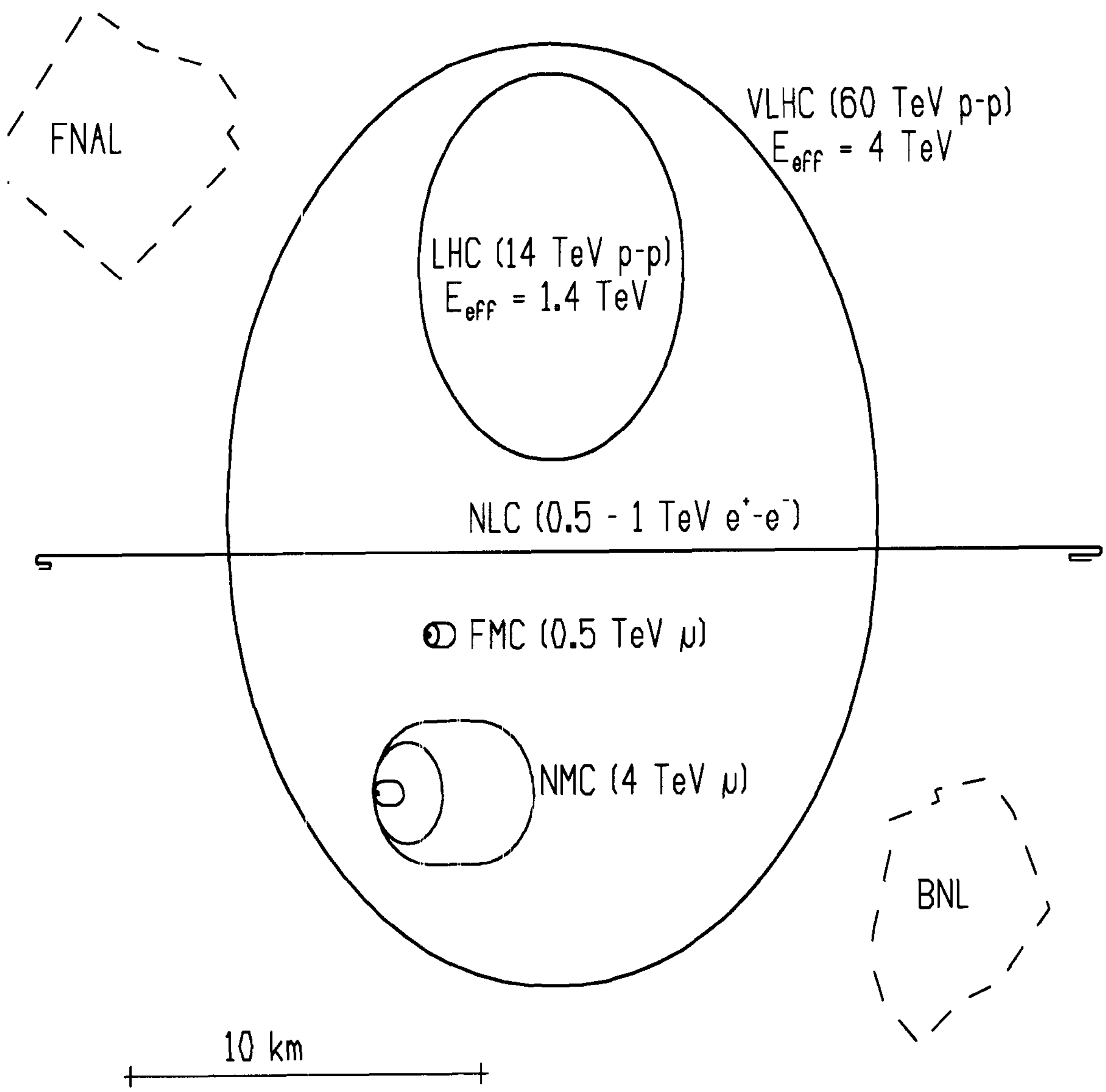

FIGURE 2. Schematics of the relative sizes of Muon Collider (.5 and 4 TeV), Large Hadron Collider (LHC), and Next Linear Collider (NLC) are shown relative to the BNL and FNAL sites [1] for illustration. Noting that, the present studies [1], envisions a 0.1 TeV (not the 0.5 TeV shown, center of mass) energy, for the First Muon Collider (FMC).

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 $\sim \pm 0.2$–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. Unfortunately, high resolution is accompanied by luminosity loss.

Expectations for $m_H = 110$ GeV are illustrated in Table 2 for luminosity $\mathcal{L}_{\text{ave}} \simeq 5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$.

TABLE 2. Expected signals and backgrounds (fully integrated) for a standard model Higgs with $m_H = 110$ GeV, $\Gamma_H \simeq 3$ MeV.

$H \to$	$b\bar{b}$	$c\bar{c}$	$\tau\bar{\tau}$
N_S (events)	24,000	1,200	2,700
N_B (events)	25,200	24,160	9,450
$\pm\sqrt{N_S + N_B}/N_S$	±0.009	±0.13	±0.04

In Table 2, we assumed muon collider resonance conditions with no polarization, $\Delta E/E \simeq 3 \times 10^{-5}$, and $L = 0.5\ \text{fb}^{-1}$. 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. In this table $c\bar{c}$ branching ratios have been reduced compared to those given previously [4,7], since for values given here a smaller charm quark mass was assumed. 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%, (at $5 \times 10^{30}\text{cm}^{-2}\text{s}^{-1}$) to about 13%, (at $5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$, in Table 2). Further, a factor of 10 increase in Luminosity (Table 2, as compared to the example of $5 \times 10^{30}\text{cm}^{-2}\text{s}^{-1}$ Luminosity) reduces the running (scan) time by factor 10 less. Thus instead of a "3 years" running time, it will be reduced to ($\frac{3}{10}$ year) 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. The parameter $\pm\sqrt{N_S + N_B}/N_S$ in Table 2 was included for convenient. Further note, the values listed in Table 2 should be reduced by $\frac{1}{\sqrt{2}}$ to include the effect of acceptance.

IV ENHANCING THE HIGGS SIGNAL TO BACKGROUND RATIO

In the following we discuss additional ways of potentially enhancing the Higgs signal to background ratio. 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.

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

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

$P_+(P_-)$ 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 general expression,

$$A_{LR} \equiv \frac{\sigma_{LR\to LR} + \sigma_{LR\to RL} - \sigma_{RL\to RL} - \sigma_{RL\to LR}}{\sigma_{LR\to LR} + \sigma_{LR\to RL} + \sigma_{RL\to RL} + \sigma_{RL\to LR}}, \tag{2}$$

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

$$A_{eff} = \frac{A_{FB} + P_{eff}A_{LR}^{FB}}{1 + P_{eff}A_{LR}}, with \tag{3}$$

$$P_{eff} = \frac{P_+ - P_-}{1 - P_+P_-}, \tag{4}$$

$$A_{FB} = \frac{3}{4}\frac{\sigma_{LR\to LR} + \sigma_{RL\to RL} - \sigma_{LR\to RL} - \sigma_{RL\to LR}}{\sigma_{LR\to LR} + \sigma_{RL\to RL} + \sigma_{LR\to RL} + \sigma_{RL\to LR}}, \tag{5}$$

$$A_{LR}^{FB} = \frac{3}{4}\frac{\sigma_{LR\to LR} + \sigma_{RL\to LR} - \sigma_{LR\to RL} - \sigma_{RL\to RL}}{\sigma_{LR\to LR} + \sigma_{RL\to LR} + \sigma_{LR\to RL} + \sigma_{RL\to RL}}. \tag{6}$$

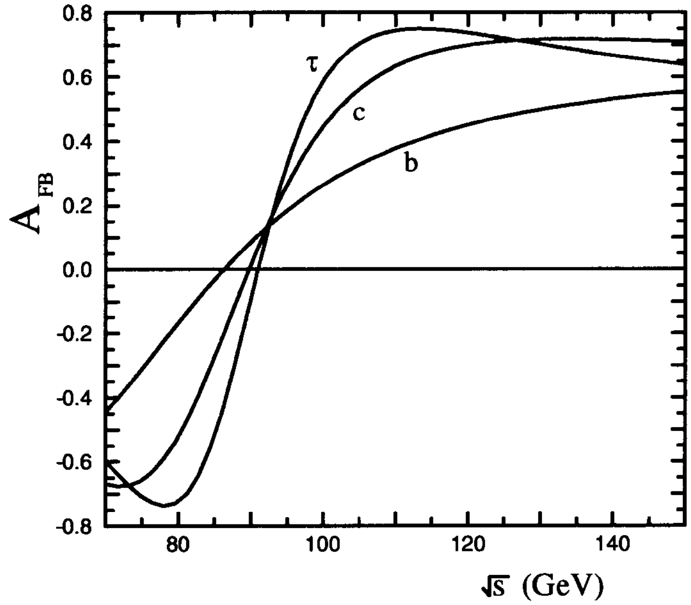

FIGURE 3. Forward-backward asymmetry for $\mu^-\mu^+ \to f\bar{f}$.

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. 3. 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.

V POLARIZATION - ENHANCEMENT FACTOR

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

$$\kappa_{\rm pol} = \frac{1 + P_+P_-}{\sqrt{1 - P_+P_- + (P_+ - P_-)A_{LR}}} \,, \tag{7}$$

where the A_{LR} are shown in Fig. 4. That result generalizes the $P_+ = P_-$ case [5]. 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

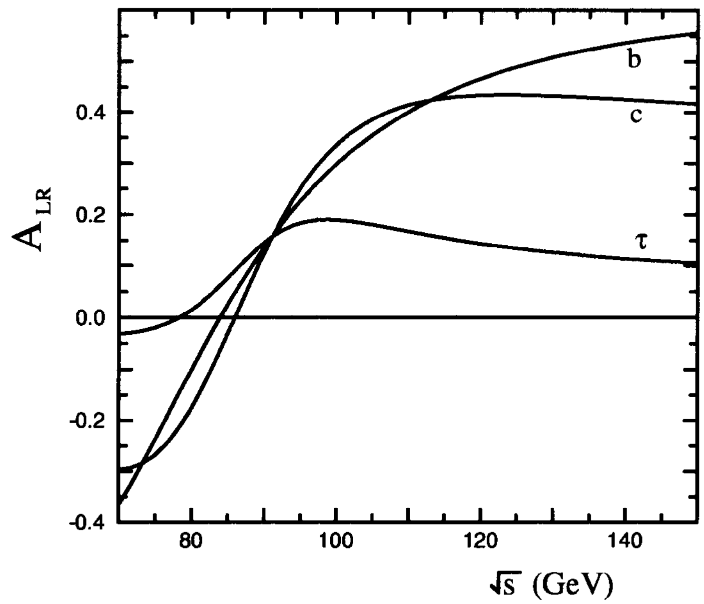

FIGURE 4. Left-right asymmetry for $\mu^-\mu^+ \to f\bar{f}$.

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. If $P_+ = P_- = 1$, you have completely spin 0 state, pure signal (and no background) in which case $\kappa_{\rm pol}$ (formula 8) no longer apply.

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.

VI "DISCOVERY" FROM ANGULAR DISCRIMINATION

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

$$\frac{1}{2}(1+P_+P_-)\sqrt{N_S+N_B}\left[\int \frac{dx}{dN/dx}\right]^{1/2}, \tag{8}$$

which becomes, from Equations (1) and (7),

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

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 [4,7].

VII CONCLUSION

We investigated 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" [4,7,8]. We conclude that $\mathcal{L}_{\rm ave} \simeq 5 \times 10^{31} \rm cm^{-2}$ is (about the minimum Luminosity), needed for the Higgs resonance studies at the First Muon Collider. And that 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 the scan time needed, and how precise a measurement is needed to do physics. 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].

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