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PHYSICS AT HIGH LUMINOSITY $\mu^{\pm}$ COLLIDERS AND A FACILITY OVERVIEW

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Physics potentials at future colliders including high luminosity $\mu^+\mu^-$ colliders are discussed. Luminosity requirement estimates for Muon collider energies of interest (0.1 TeV to 100 TeV) are calculated. Schematics and an overview of Muon Collider facility concept are also included.

1 Introduction

Future colliders beyond the e^+e^- colliders and LHC are of great interest to the high enery physics community, e.g. for finding Higgs bosons (thus understanding the origin of electroweak symmetry breaking), supersymmetric (SUSY) particles, and more.

In devising a strategy for technical accelerator possibilities, we note that the experiments over the last two decades have convincingly shown that the strong, electromagnetic, and weak forces are all closely related and are simply described by the "Standard Model." In particular the anticipated sixth quark, top, has been found at Fermilab, and the predicted properties of the Z boson, one of the carriers of the weak force, have been tested to better than 0.1%. Although there is now little doubt that the Standard Model is a very good description of the basic forces responsible for all atomic and nuclear physics, there remain many open questions [2,4,5]. Thus, new physics beyond what has been observed is required. The simplest possibility, the "Higgs Mechanism" predicts the existence of a fundamental Higgs Boson. Finding that elusive particle or whatever new physics is actually responsible for mass generation remains the primary goal of the next generation of colliders.

A number of other interesting and more elaborate models have been proposed, but there is as yet no direct experimental evidence supporting any of them.

Noting that, recently Experiment E821 at Brookhaven National Laboratory announced that, a precision measurement of the anomalous magnetic moment of the muon, – deviates by a 2.6 sigma from the value predicted by the Standard Model (after analysis of their 1999 data). This could indicate that other physical theories that go beyond the assumptions of the Standard Model may now be open to experimental exploration. E.g., that 2.6 sigma difference

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from the Standard Model may be a strong indication of supersymmetry in roughly the $\tan\beta \simeq 4$, $m_{\rm SUSY} \simeq 100$ GeV $-$ $\tan\beta \simeq 40$, $m_{\rm SUSY} \simeq 450$ GeV region or an indication of radiative muon mass generation from "new physics" in the $1-2$ TeV range. Both cases can illustrate exciting prospects with very interesting implications for future experiments.

Obviously, before the assertion of any "new physics" can be taken seriously, one has to wait for completion of the E821 (2000 and 2001 data) analysis, (which has about 7 times the amount of data that was already reported in 1999), and furhter checks on refining the values of $a_\mu^{\rm exp}$ and $a_\mu^{\rm SM}$ [5].

2 Future Colliders

The high energy community is interested in the potential of colliders beyond the (e^+e^-) colliders and LHC. Particle beam colliders are the primary tools for performing high energy physics research. Collisions of high energy particles produce events in which much of the energy of the beams can be converted into the masses of new heavy particles not normally found in nature. By studying the production and decay of these new particles, the underlying structure of the universe and the laws that govern it are unveiled.

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High energy physicists are anxiously waiting for the next dramatic experimental discovery. Fortunately, anticipated future collider facilities offer broad discovery potential. The Fermilab main injector upgrade allows the $p\bar{p}$ Tevatron to operate at $\sqrt{s} \lesssim 2$ TeV and luminosity $\sim 2 \times 10^{32}$, and with additional upgrades would allow even higher luminosities to be attained. Those improvements broaden the discovery potential while allowing precision measurements and searches for rare B and τ decays. The Higgs mass region of $110 \sim 130$ GeV or higher may be explored via $W^{\pm}H$ and ZH associated production if the $H \to b\bar{b}$ mode is resolvable, e.g., [4] - [11].

Asymmetric B factories provide new ways to explore CP violation. LEPII has achieved e^+e^- center-of-mass energy of about $\gtrsim 207 GeV$, (e.g., ALEPH collected 217 pb^{-1} of data at energies 200–209 GeV in 2000) and a mass bound of $\gtrsim$ 113 GeV on Higgs boson mass. Furthermore, the $W^{\pm}$ mass has been measured at LEPII, and Fermilab, providing an interesting constraint on the Higgs mass via quantum loop relations.

In some longer term ($\sim$ 2006), the LHC pp collider with $\sqrt{s} = 14$ TeV should find the Higgs scalar or tell us it doesn't exist. If SUSY exists $\lesssim 1$

TeV, it will be discovered. Hopefully, completely unexpected revelations will also be made.

Beyond the LHC, various collider options are possible. The Next Linear Collider (NLC) may start e^+e^- collisions at $\sqrt{s} = 500$ GeV and be upgradeable to 1–1.5 TeV. It would have high luminosity $> 5 \times 10^{33}$ and polarization. The NLC also offers $\gamma\gamma$, e^-e^-, and $e^-\gamma$ collider options which expand its physics potential. There has been also some discussion of possible future e^+e^- colliders with $\sqrt{s} \simeq 5$ TeV, a major step, if achievable. The NLC will be a superb tool for studying the Higgs, SUSY, Technicolor etc., [12,13].

Other possibilities include a $\mu^+\mu^-$ collider and Very Large Hadron Collider (*pp* with $\sqrt{s} \simeq 100$ TeV or more) which are less advanced.

The muon collider concept is very interesting, but require series studies and technology demonstrations. Various machine energies has been considered previously by our collaboration, Since building a full high energy Muon Collider will take a considerable time to realize, as a first step a Muon storage ring based Neutrino Factory has been considered by our collaboration.

In this new (a smaller group) 6 month feasibility study, the charge is to consider in addition to sub-TeV, and multi-TeV, many-TeV (e.g. 30 TeV) Muon Colliders for possible new Physics processes and precession studies. In the following sections we discuss Luminosity requirements, Physics potentials and present an overview of muon collider concepts.

The Very Large Hadron Collider(VLHC) with $\sqrt{s} \simeq 100$ TeV and $\mathcal{L} \simeq 10^{35}$ looks technically feasible but is very expensive. Does a Very Large Hadron Collider with $\sqrt{s} \simeq 100$ TeV have viability? Our SSC experience suggests a prohibitive cost and difficult construction issues because of its size. However, new ideas about inexpensive magnets and tunnels and/or a new technology could offer hope for the needed significant reduction in cost.

Figure 1 shows a schematic layout of the high energy accelerators to illustrate their relative sizes and energies.[16]

3 Muon Collider

Figure 2 shows a schematic of a high energy muon collider components [16,17]. A high intensity proton source is bunch compressed and focused on a heavy metal target. The pions generated are captured by a high field solenoid and transferred to 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, and 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 2, shows the collider ring and how the accelerator ring may compactly contain the other components.

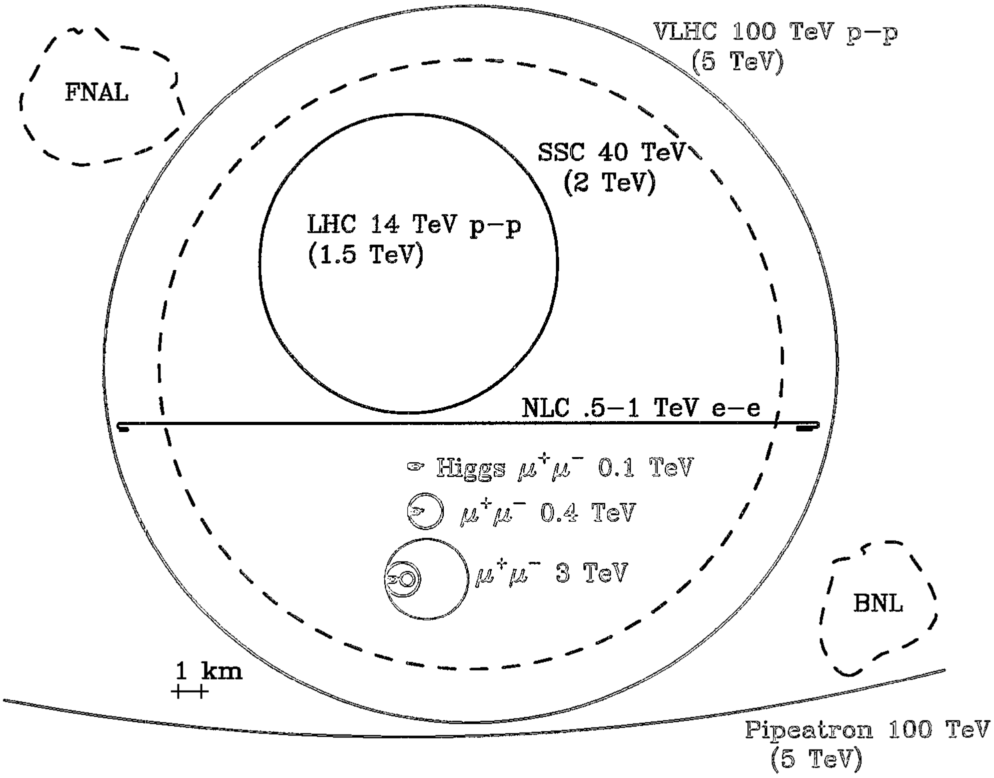

Figure 1. Comparison of relative sizes of Muon Colliders, Large Hadron Collider (LHC), and Next Linear Collider (NLC), relative to the BNL and FNAL sites.

A muon collider with center of mass energy less than about 10 TeV can be circular and relative to NLC (a Next Linear Collider) of the same energy, it could be far smaller in size. For the same luminosity a muon collider can tolerate a far larger spot size than an electron linear collider since the muons make about 1000 crossings. Muon ($m_\mu/m_e = 207$) have the same advantage in energy reach as electron but has little beamstrahlung, thus very small energy spread is obtainable. In addition the direct coupling of lepton-lepton system to Higgs boson has a cross section proportional to the square of the lepton mass. thus the cross section for direct Higgs production from a $\mu^+\mu^-$ collider is about 40,000 times that from an e^+e^- collider system.

A large effort previously was devoted to design and assessing the feasibility of building a high energy muon collider at a 4-3 TeV, .5-.4 TeV and .1 TeV [16,17].

Figure 3 illustrates concept of a 4 TeV muon collider complex. Machines with energies higher than 3 $\sim$ 4 TeV, have a significant beam current con-

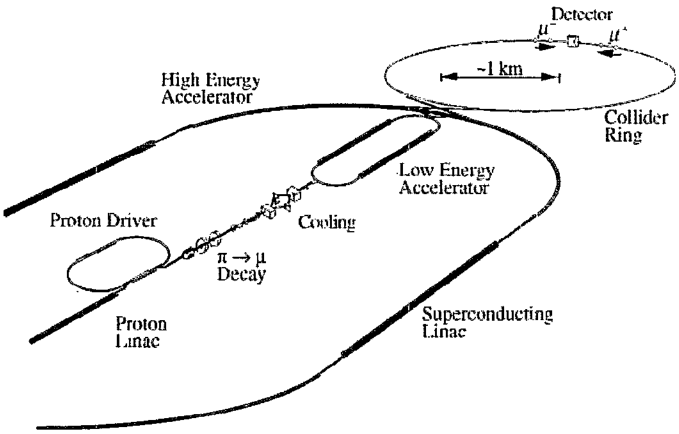

Figure 2. Schematic of How the accelerator ring may compactly contain the other components

straints from the neutrino radiation limits. Thus to reach the required high luminosities without unacceptable radiation hazards, a significant improvements in the muon emittance to the current base-line values are required.

A 100 TeV muon collider provides a unique opportunity for exploring high energy physics, and mysteries of the elementary particles and their role in the universe.

Table 1 [15] illustrates a sample Straw-man parameter sets distributed for the study. These parameters are speculative and may require technical extrapolation much beyond present limits and may not be possible for many decades to come? Unfortunately, the estimates of the size, cost and radition problems seems to prohibit muon colliders at the high energies, without some drastic new developments? For energies below 3 TeV, and for a fixed muon current, the neutrino radiation falls proportional to the energy cubed, which may be less of a problem??

4 New Physics Potentials

Muon Colliders have unique physics and technical advantages and disadvantages as compared to e^+e^- and hadron colliders and are to be considered as complementary. For the same energy and integrated luminosity, anything that can be done at e^+e^-, should be possible at $\mu^+\mu^-$ collider, and more. E.g., possibilities for s-channel Higgs production, and a higher center-of mass energy with reduced backgrounds. Both of which are due to the large muon mass as compared to the electron mass. Higher energy may be crucial e.g., in improving signals for WW scattering, and the kinematical reach for pair production of SUSY particles.

The figure of merit in physics searches at an e^+e^- or $\mu^+\mu^-$ collider, is expressed by the QED point cross section for $e^+e^- \to \mu^+\mu^-$:

$$\sigma_{QED}(\sqrt{s}) = (\frac{100[fb]}{s[TeV^2]}) \times (\frac{\alpha(s)}{\alpha(M_z^2)}) \qquad (1)$$

As before e.g., [19], we will neglect the factor $(\frac{\alpha(s)}{\alpha(M_z^2)})$ as it varies slowly with s.

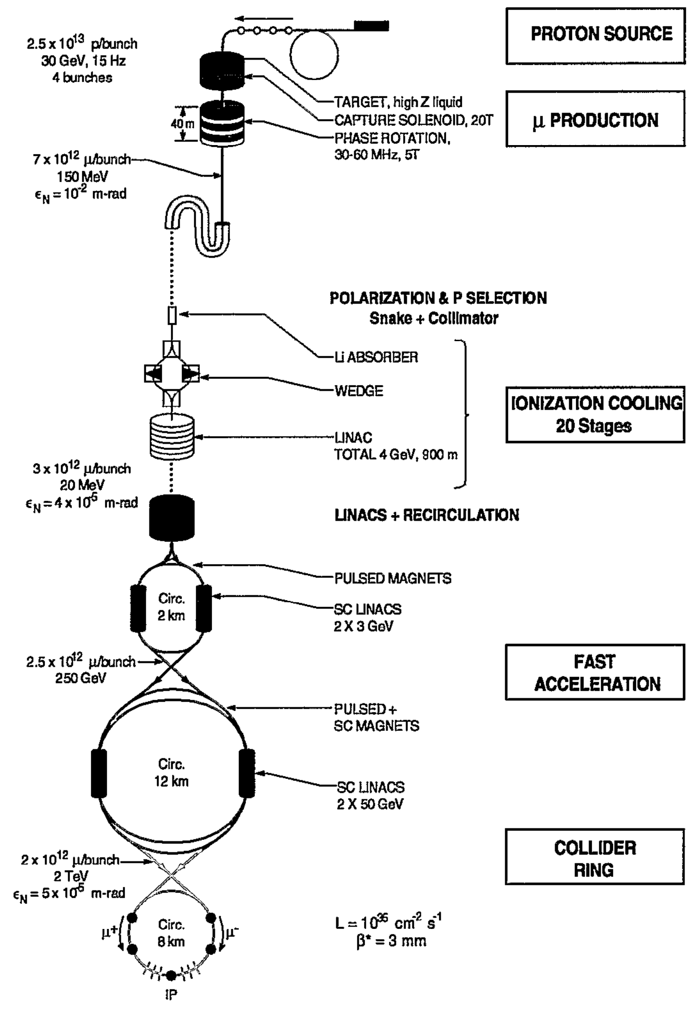

Figure 3. Schematic of a 4 TeV Muon Collider.

4.1 Integrated Luminosity for "New Physics"

If the integrated luminosity needed for studying the new physics signals is:

$$(\int Ldt)\sigma_{QED} \gtrsim 1000\ events, \tag{2}$$

then the $\mu^+\mu^-$ collider design should be able to deliver an integrated luminosity of

$$(\int Ldt) \gtrsim 10s[fb^{-1}]. \tag{3}$$

If this is to be accumulated for one year of running time, the required luminosity estimate is

$$L[fb^{-1}] \gtrsim 10^{33}s[cm^{-2}][sec^{-1}]. \tag{4}$$

The estimates of the luminosity requirements for a 100 TeV and the collider energies of interest for this study are given below:

- For $\sqrt{s} \simeq 100[TeV]$, $L[fb^{-1}] \gtrsim 10^{37}[cm^{-2}][sec^{-1}]$
- For $\sqrt{s} \simeq 30[TeV]$, $L[fb^{-1}] \gtrsim 9 \times 10^{35}[cm^{-2}][sec^{-1}]$
- For $\sqrt{s} \simeq 10[TeV]$, $L[fb^{-1}] \gtrsim 10^{35}[cm^{-2}][sec^{-1}]$
- For $\sqrt{s} \simeq 4[TeV]$, $L[fb^{-1}] \gtrsim 10^{34}[cm^{-2}][sec^{-1}]$
- For $\sqrt{s} \simeq 3[TeV]$, $L[fb^{-1}] \gtrsim 10^{33}[cm^{-2}][sec^{-1}]$
- For $\sqrt{s} \simeq 0.1[TeV]$, $L[fb^{-1}] \gtrsim 10^{31}[cm^{-2}][sec^{-1}]$.

Note that, some of these energies and high luminosities may not be possible in practice?

5 Discussion

A high energy muon collider (100 TeV or a 30 GeV energy of interest at this workshop) would provide a unique opportunity for exploring high energy physics, and mysteries of the elementary particles and their role in the universe. Unfortunately, the estimates of e.g., cost and radiation problems seems to prohibit muon colliders at such energies, for many decades to come, without some drastic new technology developments?

Although a full high energy muon collider may take a considerable time to realize, intermediate steps in its direction, such as high intensity muon experiments, neutrino factories, and other steps toward the muon collider are possible and extremely important. They will greatly expand our abilities and build confidence in the credibility of high energy muon colliders.

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Table 1. Straw-man Parameter Sets For Muon Colliders (Feasibility studies)

center of mass energy, E_{CoM} description	0.1 to 3 TeV MCC status report	400 GeV top threshold	4 TeV frontier	30 TeV many-TeV
collider physics parameters:				
luminosity, $\mathcal{L}$ [$cm^{-2}.s^{-1}$]	$(0.08 \rightarrow 700) \times 10^{32}$	3.0×10^{33}	5.0×10^{33}	3.0×10^{35}
$\int \mathcal{L}dt$ [fb^{-1}/year]	0.08→700	30	50	3000
No. of $\mu\mu \rightarrow$ ee events/det/year	650→13 000	16 000	270	290
No. of (115 GeV) SM Higgs/year	2000→800 000	14 000	55 000	5×10^6
CoM energy spread, σ_E/E [10^{-3}]	0.02→1.1	1.4	1.0	0.14
collider ring parameters:				
circumference, C [km]	0.35→6.0	1.0	8.7	45
ave. bending B field [T]	3.0→5.2	4.2	4.8	7.0
beam parameters:				
(μ^- or) μ^+/bunch, $N_0[10^{12}]$	2.0→4.0	4.0	3.5	2.3
(μ^- or) μ^+ bunch rep. rate, f_b [Hz]	15→30	15	1.0	7.5
6-dim. norm. emit., $\epsilon_{6N}[10^{-12}m^3]$	170→170	170	170	100
$\epsilon_{6N}[10^{-4}m^3.MeV/c^3]$	2.0→2.0	2.0	2.0	1.2
P.S. density, $N_0/\epsilon_{6N}[10^{22}m^{-3}]$	1.2→2.4	2.4	2.2	2.3
x,y emit. (unnorm.) [$\pi.\mu$m.mrad]	3.5→620	41	2.4	0.19
x,y normalized emit. [π.mm.mrad]	50→290	77	46	27
long. emittance [10^{-3}eV.s]	0.81 → 24	10	28	48
fract. mom. spread, δ [10^{-3}]	0.030→1.6	2.0	1.4	0.20
relativistic γ factor, E_μ/m_μ	473→14 200	1890	18 900	142 000
time to beam dump, $t_D[\gamma\tau_\mu]$	no dump	no dump	0.5	no dump
effective turns/bunch	450→780	620	450	1040
ave. current [mA]	17→30	24	0.63	12
beam power [MW]	1.0→29	3.8	2.2	83
synch. rad. critical E [MeV]	$5 \times 10^{-7} \rightarrow 8 \times 10^{-4}$	1.1×10^{-5}	0.0013	0.11
synch. rad. E loss/turn	7 eV → 0.3 MeV	0.6 keV	700 keV	450 MeV
synch. rad. power	0.1 W → 10 kW	15 W	470 W	5.2 MW
beam + synch. power [MW]	1.0→29	3.8	2.2	88
decay power into beam pipe [kW/m]	1.0→2.1	2.1	0.06	0.8
interaction point parameters:				
rms spot size, $\sigma_{x,y}$ [μm]	3.3→290	18	2.7	1.0
rms bunch length, σ_z [mm]	3.0→140	7.5	3.0	4.8
$\beta^*_{x,y}$ [mm]	3.0→140	7.5	3.0	4.8
rms ang. divergence, σ_θ [mrad]	1.1→2.1	2.3	0.90	0.20
beam-beam tune disruption, $\Delta\nu$	0.015→0.051	0.056	0.083	0.092
pinch enhancement factor, H_B	1.00→1.01	1.02	1.08	1.09
beamstrahlung frac. E loss/collision	negligible	negligible	6×10^{-9}	9×10^{-8}
final focus lattice parameters:				
max. poletip field of quads., $B_{5\sigma}$ [T]	6→12	10	12	15
max. full aper. of quad., $A_{\pm 5\sigma}$[cm]	14→24	18	18	18
quad. gradient, $2B_{5\sigma}/A_{\pm 5\sigma}$[T/m]	50→90	110	130	160
approx. β_{max}[km]	1.5→150	8	140	1800
ff demag., $M \equiv \sqrt{\beta_{max}/\beta^*}$	220→7100	100	7000	19 000
chrom. quality factor, $Q \equiv M \cdot \delta$	0.007→11	0.003	10	4
neutrino radiation parameters:				
collider reference depth, D[m]	10→300	20	300	100
ave. rad. dose in plane [mSv/yr]	$2 \times 10^{-5} \rightarrow 0.02$	7×10^{-4}	9×10^{-4}	6
str. sec. len. for 10x ave. rad. [m]	1.3→2.2	1.6	1.1	1.9
ν beam distance to surface [km]	11→62	16	62	36
ν beam radius at surface [m]	4.4→24	8.4	3.3	0.25