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DIS Prospects at the Future Muon Collider Facility

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We discuss prospects of deep inelastic scattering physics capabilities at the future muon collider facility. In addition to $\mu^+\mu^-$ collider itself, the facility provides other possibilities. Among the possibilities, we present muon-proton collider and neutrino fixed target programs at the muon collider facility. This $\mu - p$ collider program extends kinematic reach and luminosity by an order of magnitude, increasing the possibility of search for new exotic particles. Perhaps most intriguing DIS prospects come from utilizing high intensity neutrino beam resulting from continuous decays of muons in various sections of the muon collider facility. One of the most interesting findings is a precision measurement of electroweak mixing angle, $sin^2\theta_W$, which can be achieved to the precision equivalent to $\delta M_W \sim 30$MeV.

1 Introduction

Lepton colliders have been used, in general, for precision measurements. High Energy physics field has been performing precision measurements using electron-position (e^-e^+) colliders due to the fact that electrons do not decay in the acceleration process. However, e^-e^+ colliders have difficulties in increasing center of mass energy, $\sqrt{s}$, due to synchrotron radiation energy losses of electrons (positrons) which is proportional to $\frac{1}{m_e^4}$. Thus in order to increase the center of mass energy of an e^-e^+ collider one needs a larger physical size of the collider ring. Since muons, on the other hand, have mass of 200 times bigger than electrons, the synchrotron radiation in a $\mu^+\mu^-$ collider is 10^{-10} less than an e^-e^+ collider, enabling higher $\sqrt{s}$ with the same ring size.

Less radiation energy loss reduces beam momentum spreads and allows precision measurements of any possible resonance states at the given $\sqrt{s}$. In addition, since the Higgs coupling is a Yukawa coupling that is proportional to the square of the mass of the initial state particles [1], the Higgs production cross section at the muon collider is a factor 10^4 bigger than that from e^+e^- colliders at the same $\sqrt{s}$, above the Higgs mass threshold.

The baseline strategy for the muon collider complex is as follows : 1) Start out with intense 16GeV proton sources with the beam intensity of 6×10^{20} protons/year eventually increasing to 1.5×10^{22} protons/year [2]. 2) These high intensity protons produce extremely intense low energy muons and provide

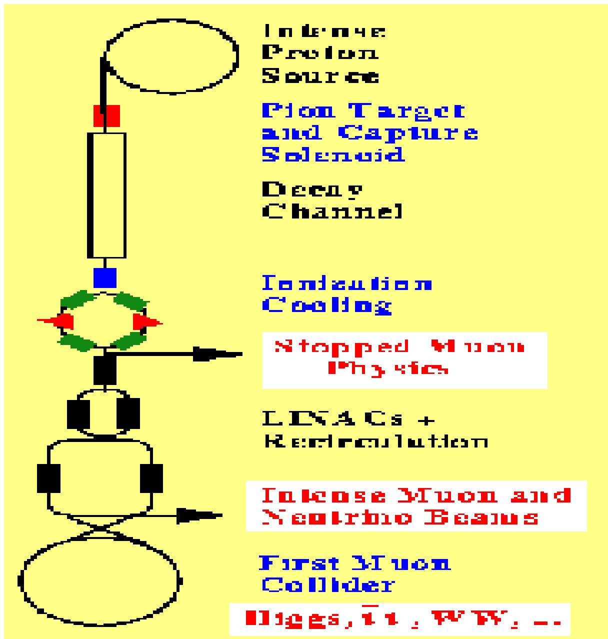

Figure 1: A schematic view of a muon collider facility.

8×10^{19} muons/year, reaching up to 2×10^{21} muons/year.

Figure 1 shows a schematic view of a muon collider facility. The discussions presented in this paper consider the following two options : 1) $\mu - p$ collider program with 200GeV muon beam from the muon collider on 1TeV protons from Tevatron. 2) neutrino fixed target program using extremely intense neutrino beam resulting from the decays of 250GeV muons.

2 Muon-Proton ($\mu - p$) Collider Option

Charged lepton-proton colliders have been used for classical deep inelastic scattering experiments, providing ideal means of probing nucleon structure. Thus one of the options in the $\mu^+\mu^-$ collider complex is the $\mu - p$ collider program using 200GeV μ extracted from the muon collider on 1000GeV protons from the Tevatron. Table 1 compares this $\mu - p$ collider machine parameters [3] to those

Table 1: Comparison of μp collider machine parameters to HERA.

	FMC	HERA
E_l	200GeV μ	27.5 GeV $e^-(e^+)$
E_p	1000GeV	800GeV
Q^2	$\sim 8 \times 10^5$GeV^2	$\sim 9 \times 10^4$GeV^2
$\int \mathcal{L}dt$	$10fb^{-1}/yr$	$1fb^{-1}$/lifetime

of HERA's, including the HERA II. As can be seen in the table, significant improvements can be obtained in kinematic reach and integrated luminosity, increasing both by a factor of 10.

3 DIS in $\mu - p$ Collider

Most significant improvement one would expect in $\mu - p$ collider option comes from increased kinematic reach and the integrated luminosity. Figure 2 shows the kinematic reach in $log_{10}(Q^2)$ vs $log_{10}(x)$ plane, demonstrating the increased Q^2 and x reach by about a factor of 10 relative to HERA. This extended kinematic reach in x would enable probing gluon saturation regions, indicated as a shaded area in the figure, in $x < 10^{-5}$ where the BFKL dynamics would play a role. However, reaching to this very low-x would require a detector coverage down to a very small angle ($\theta = 179^o$). This extreme small angle

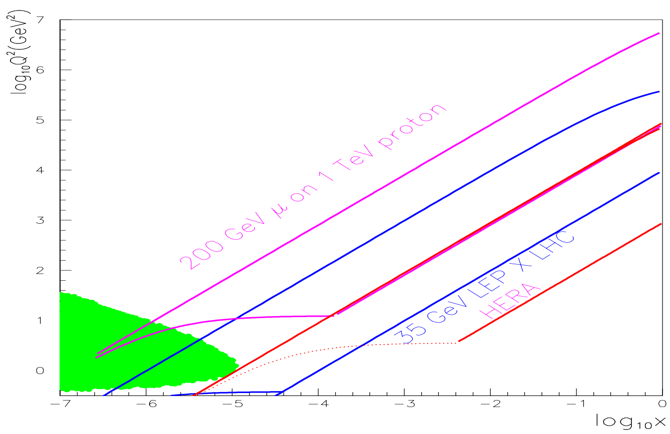

Figure 2: The kinematic reach for an asymmetric $\mu - p$ machine. No μ collider specific backgrounds have been considered. The nominal y and θ_μ cuts which correspond to HERA have been applied.

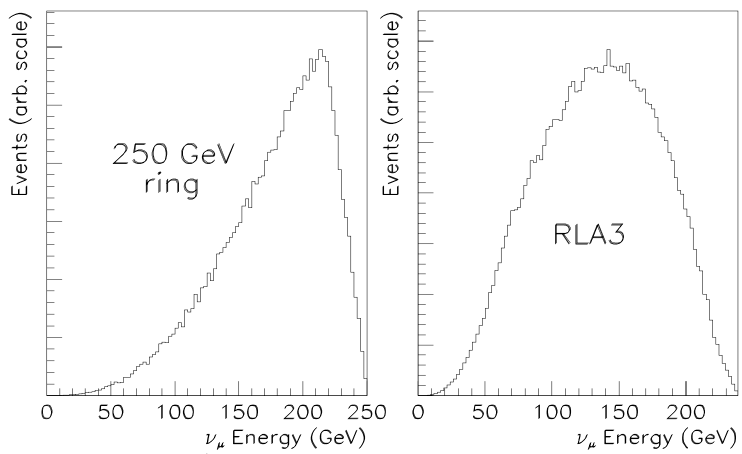

Figure 3: Energy spectra of neutrino beam from 10m straight section of 250GeV ring (left) and RLA3 (right).

coverage is the biggest hurdle in the μp collider due to the electron background from the constant decay of muons in the ring and the finite physical size of the beam pipe.

The extended reach in Q^2, due to higher $\sqrt{s}$ and a factor of 10 increase in luminosity, would result in higher statistics up to $Q^2 = 10^5$ regions, allowing improved sensitivity in exotic particle searches. The configuration given in Table 1 results in ~1 million events per year with $Q^2 > 5000\text{GeV}^2$, compared to 326 events from ZEUS experiment[4] in this region with $\int \mathcal{L}dt = 34pb^{-1}$. This high Q^2 reach also increases the sensitivity for scalar lepto-quark to $M_{LQ} =$ 800GeV to 3×10^{-2}, assuming $\sqrt{s} = 1$TeV and $\int \mathcal{L}dt = 10fb^{-1}$.

4 Neutrino Beam From Muon Colliders

Perhaps, most intriguing byproduct of the muon collider is very intense neutrino beam (ν_μ and $\overline{\nu}_e$) from the continuous decays of muons in the straight sections of the muon collider facility [5]. One can expect the neutrino beam in a small straight sections in two components of the muon collider complex that can be seen in Fig. 1. The two are recirculating linac (RLA3) and the storage ring.

Figure 3 shows the neutrino energy spectra from these two sections of the muon collider [6], assuming 10m straight sections. Since the angular dispersion

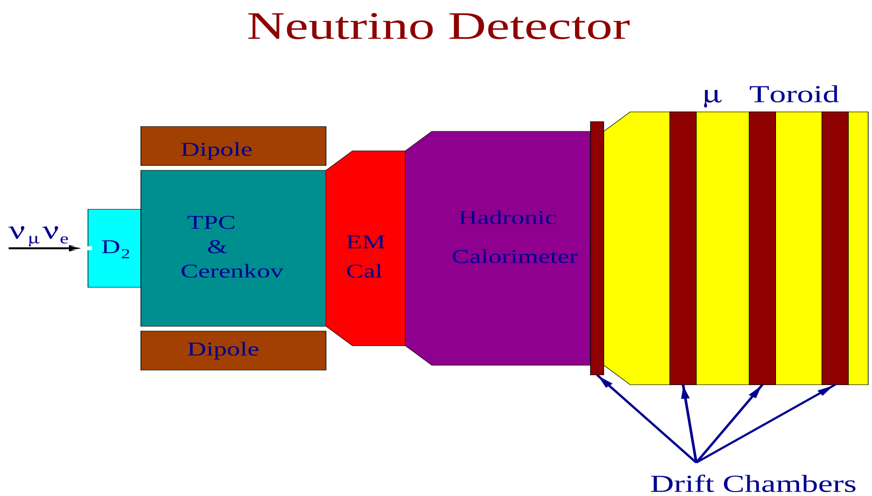

Figure 4: A light target experiment with a generic neutrino detector. The target in this figure is a 1m thick D_2 with a few layers of silicon vertex detector sandwiched inside.

of the neutrinos is inversely proportional to the Lorentz γ factor of muons, the neutrino beam resulting from the two straight sections with $E_\mu = 250$GeV are very well collimated. Expected neutrino fluxes from these two sections are approximately 1000 time that of currently most intense neutrino beam seen at the NuTeV experiment. Due to the high neutrino flux many DIS possibilities lie in the facility.

4.1 Current Neutrino Experiments

In order to compare the muon collider neutrino program prospects with the current experiments, it is beneficial to review current neutrino experiments. The most common characteristics of the current neutrino experiments is the use of heavy target detectors in order to increase statistics, given relatively low neutrino flux. However, using heavy target introduces undesirable features to physical measurements such as: 1) nuclear effects up to $\sim 30\%$ with respect to bare proton target, 2) target dependent isovector corrections, 3) coarse grain calorimetric detectors introduces poor analysis resolution, and 4) fine grain detectors, in general, have poor energy resolution. Despite the fact that the neutrino experiments have the above disadvantages, the neutrino DIS is the only source of measuring $q - \overline{q}$ and V_{dc}, and provides precision measurement of $sin^2\theta_W$.

4.2 A Neutrino Experiment at the Muon Collider Facility

Unlike the current massive target neutrino experiments, one can imagine an experiment with a light target (H_2 or D_2) followed by a generic detector that can distinguish electrons from muons resulting from charged-current (CC) interactions of ν_μ or $\overline{\nu}_e$. Since the neutrino flux expected from the muon collider is 1000 times higher than current beam, one can obtain sufficient statistics even with light neutrino targets. Figure 4 shows a schematic view of such an experiment.

5 DIS Physics at the Neutrino Beam

Due to the intensity of the neutrino beam from the decays of muons in the straight sections of the muon collider, one would expect large improvements in the current neutrino physics programs. The first and most immediate measurement one can think of is a precision measurement of nucleon structure function xF_3 which is the only source of $q-\overline{q}$ and is currently statistics limited. Precise measurement of xF_3 would provide accurate information on valence quarks as well as strange and charm sea quarks.

Heavy quark production measurement is currently statistics limited. Only di-muon final state is used for heavy quark production in present measurements, due to immediate showering of electrons resulting from decays of charmed mesons. On the other hand, the experiment shown in Fig. 4 would allow measurements using more, if not all, di-lepton ($\mu\mu$, ee, and $e\mu$) final states resulting in a total of $\sim 400,000$ di-lepton events per year compared to current level of $\sim$ 5000 events per entire experiment. This large increase in statistics would allow accurate measurements of CKM matrix elements, $\mid V_{cs} \mid^2$ and $\mid V_{dc} \mid^2$.

Using a silicon target that is equivalent to $\sim$ 3m H_2 would result in about 20 events/year of $\mu(e) + b(\overline{b})$ final state assuming 10m straight section of the collider. One would be able to increase statistics by lengthening the straight section from 10m to 100m, using thicker target, or running longer. This increased statistics would allow precision measurement of $\mid V_{ub} \mid^2$. One can also measure neutrino and proton spins, using expected 1million events on 200kg target resulting in a 2% measurement of Δs.

6 Measurement of $sin^2\theta_W$

Measurements of $sin^2\theta_W$ at the heavy target experiments suffer from large statistical uncertainty as well as experimental systematic uncertainties in distinguishing CC from neutral current (NC) interactions [7]. Since the target detectors are heavy materials, the existence of ν_e in the beam causes the current algorithms of distinguishing CC from NC using an event length variables to fail, because the CC interaction from ν_e looks identical as the NC events from ν_μ due to immediate showering of electrons. However, using the experiment shown in Fig. 4, in principle, completely eliminates the experimental uncertainties resulting from the definitions of CC and NC events.

In addition, since the beam is always a mixture of ν_e and ν_μ, CC interactions from both types of neutrinos can be used for $sin^2\theta_W$ measurement, resulting in 20million neutrino events in a year from 1m thick H_2 target. A preliminary result from NuTeV experiment suffers from statistical uncertainty of the order 1% based on $\sim$ 1.5 million neutrino events and major experimental systematic uncertainties from the use of length variable of the order 0.2% [8]. Comparatively, one can expect a dramatic reduction in experimental systematic and statistical uncertainties in neutrino experiments in the muon collider facility, resulting in a measurement equivalent to $\delta M_W = 30$ MeV [9] which is comparable to that expected from the TeV33 in the year 2010, using a traditional M_T fit.

7 Technical Challenges

The most important challenge in the muon collider is a fast and effective cooling of the low energy muon beam produced from 8GeV proton interactions on a production target, because the mean life time of muons is 2.2μsec. Efficiency of capturing as many muons as possible and of transporting them into acceleration is the most crucial factor in determining the success of a muon collider. Currently many ideas, including an ionization cooling, have been suggested and the muon collider collaboration has recently proposed an ionization cooling experiment [10] at Fermilab.

In addition, there are other challenges to overcome, such as : efficient focusing, effective shielding of background from μ decays, possible health hazards due to extreme intensity of neutrinos, extensive and effective beam monitoring, etc.

8 Conclusions

Despite many technical challenges listed in the previous section, the muon collider facility provides exciting possibilities in DIS physics. The $\mu - p$ collider option would open up a maximal reach in Q^2, extending the searches of exotic particles. Reaching to very low x ($x \sim 10^{-5}$) to probe gluon saturation region and to study BFKL dynamics is limited due to electron background in the beam resulting from muon decays as well as an angle limitations of the detectors. While this 200GeV μ on 1000GeV proton is the option from the first muon collider, in a longer term future, it is feasible to build a $\mu - p$ collider with 2 TeV μ on 1 TeV protons with a next generation $\mu^+\mu^-$ collider with $\sqrt{s} = 4$TeV.

What is most interesting byproduct of the muon collider is fixed target programs using well understood high flux neutrino beam. A factor of 1000 increase in neutrino flux relative to present neutrino experiments provides wide range of DIS physics possibilities in addition to the $\mu^+\mu^-$ collider itself.

In conclusion, the muon collider is the facility for High-Energy community to open up rich physics capabilities in 10 to 15 years down the road. In order to realize this exciting facility, it is important to have constant interest and support within the High-Energy community for the program.

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