DIS PROSPECTS AT THE FUTURE MUON COLLIDER FACILITY

JAEOHOON YU
(for the Muon Collider Collaboration & DIS working group at the FMC workshop)
MS309, FNAL, P.O. Box 500, Batavia, IL 60510, USA
E-mail: yu@fnal.gov

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 $\delta M_W \sim 30\text{MeV}$.

1 Introduction

Lepton colliders have been used, in general, for precision measurements. High Energy physics field has been performing precision measurements using electron-positron ($e^-e^+$) 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 $\frac{1}{m_e}$. 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, 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 $6 \times 10^{20}$ protons/year eventually increasing to $1.5 \times 10^{22}$ protons/year. 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} \text{muons/year}, reaching up to 2 × 10^{21} \text{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 \(\mu\) extracted from the muon collider on 1000GeV protons from the Tevatron. Table 1 compares this \(\mu^-p\) collider machine parameters to those
Table 1: Comparison of $\mu p$ collider machine parameters to HERA.

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

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 ($\theta = 179^\circ$). This extreme small angle

Figure 2: The kinematic reach for an asymmetric $\mu - p$ machine. No $\mu$ collider specific backgrounds have been considered. The nominal $y$ and $\theta_\mu$ cuts which correspond to HERA have been applied.
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 $\sim$1 million events per year with $Q^2 > 5000GeV^2$, compared
to 326 events from ZEUS experiment in this region with $\int Ldt = 34pb^{-1}$. This
high $Q^2$ reach also increases the sensitivity for scalar lepto-quark to $M_{LQ} =
800GeV$ to $3 \times 10^{-2}$, assuming $\sqrt{s} = 1TeV$ and $\int Ldt = 10fb^{-1}$.

4 Neutrino Beam From Muon Colliders

Perhaps, most intriguing byproduct of the muon collider is very intense neu-
trino beam ($\nu_\mu$ and $\nu_e$) from the continuous decays of muons in the straight
sections of the muon collider facility. 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 assuming 10m straight sections. Since the angular dispersion

Figure 3: Energy spectra of neutrino beam from 10m straight section of 250GeV ring (left)
and RLA3 (right).
of the neutrinos is inversely proportional to the Lorentz $\gamma$ factor of muons, the neutrino beam resulting from the two straight sections with $E_\mu = 250\text{GeV}$ 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 $\sin^2 \theta_W$. 

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.
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 (H₂ or D₂) followed by a generic detector that can distinguish electrons from muons resulting from charged-current (CC) interactions of $\nu_\mu$ or $\nu_e$. 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 $x F_3$ which is the only source of $q^- q$ and is currently statistics limited. Precise measurement of $x F_3$ 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 ~400,000 di-lepton events per year compared to current level of ~5000 events per entire experiment. This large increase in statistics would allow accurate measurements of CKM matrix elements, $|V_{cs}|^2$ and $|V_{dc}|^2$. Using a silicon target that is equivalent to ~3m H₂ would result in about 20 events/year of $\mu(e) + b(\bar{b})$ 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 $|V_{ub}|^2$. One can also measure neutrino and proton spins, using expected 1million events on 200kg target resulting in a 2% measurement of $\Delta s$.

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. Since the target detectors are heavy materials, the existence of $\nu_e$ in the beam causes the cur-
rent algorithms of distinguishing CC from NC using an event length variables to fail, because the CC interaction from $\nu_e$ looks identical as the NC events from $\nu_\mu$ 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 $\nu_e$ and $\nu_\mu$, CC interactions from both types of neutrinos can be used for $\sin^2\theta_W$ measurement, resulting in 20 million 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%. 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 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 8 GeV proton interactions on a production target, because the mean life time of muons is 2.2 $\mu$sec. 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 at Fermilab.

In addition, there are other challenges to overcome, such as: efficient focusing, effective shielding of background from $\mu$ 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 200 GeV $\mu$ on 1000 GeV 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 $\mu$ 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.

References

1. A. Abbasabaddi, D. Bowser-Chao, D.A. Dicus, and W.W. Repko, UICHEP-TH-97-17, to be published in the proceedings of the Workshop on Physics at the First Muon Collider, Fermilab, Batavia, IL, USA, Nov. 1997
2. C. Ankenbarndt and S. Geer., “Acelerator Scenario and Parameters for the First Muon Collider and Front-end of a Muon Collider,” FERMI LAB-Conf-98/086, March (1998)
3. V.D. Shiltsev, FERMI LAB-Conf-97/114 (1997)
4. G. Howell and D. Williams, in these proceedings.
5. S. Geer, Phys. Rev. D57, 1 (1998)
6. D.A.Harris & K.S. McFarland, MIT-LNS-98-276, to be published in the proceedings of the Workshop on Physics at the First Muon Collider, Fermilab, Batavia, IL, USA, Nov. 1997
7. K.S. McFarland et al., CCtF/NuTeV Collaboration, Eur. Phys. J. C1, 509 (1998)
8. J. Yu, NuTeV collaboration, in these proceedings.
9. J. Yu & A. Kotwal, Fermilab-Conf-98/027, to be published in the proceedings of the Workshop on Physics at the First Muon Collider, Fermilab, Batavia, IL, USA, Nov. 1997
10. S. Geer, Muon Collider Collaboration, “Ionization Cooling Research and Development Program for a High Luminosity Muon Collider,” Fermilab-Conf-98/136, presented at the Workshop on Physics at the JHF (JHF98), KEK, Tsukuba, Ibaraki, Japan, March 4-7 (1998); Refer to the Web site, http://www.fnal.gov/projects/muonCollider/cool/cool.html for cooling experiment proposal