PROCEEDINGS OF SCIENCE

Physics Potential, Accelerator Options, and Experimental Challenges of a TeV-Scale Muon-Ion Collider

D. Acosta,[a,*] **E. Barberis,**[b] **N. Hurley,**[b] **W. Li,**[a] **O. Miguel Colin,**[a] **M. Munyi,**[a] **Y. Wang,**[a,c] **D. Wood,**[b] **K. Yang**[a] **and X. Zuo**[a,d]

[a] *Rice University, Physics & Astronomy Department, Rice University, Houston, Texas 77251, USA*
[b] *Northeastern University, Physics Department, Boston, MA 02115, USA*
[c] *University of Science and Technology of China, Department of Modern Physics, University of Science and Technology of China, Hefei, 230052, China*
[d] *Karlsruhe Institute of Technology, Germany*

E-mail: dea6@rice.edu

A TeV muon-ion collider could be established if a high energy muon beam that is appropriately cooled and accelerated to the TeV scale is brought into collision with a high energy hadron beam at facilities such as Brookhaven National Lab, Fermilab, or CERN. Such a collider opens up a new regime for deep inelastic scattering studies as well as facilitates precision QCD and electroweak measurements and searches for beyond Standard Model physics, in an alternative and complementary way to the proposed LHC-electron collider. We discuss the potential physics program of a muon-ion collider and summarize some accelerator options. We also explore some of the associated experimental challenges to be addressed and the requisite detector performance, including initial studies of a forward muon spectrometer design applicable for a muon-ion or muon-muon collider experiment.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

*Speaker

PoS(ICHEP2024)817

1. Overview

We propose the development of a "muon-ion collider" (MuIC), a muon-proton and muon-nucleus collider, that could make use of existing hadron accelerator facilities at Brookhaven National Laboratory (BNL), Fermilab, or CERN and leverage or facilitate the development of a high-energy muon storage ring at the same site. A center-of-mass energy at the TeV scale is achieved when a TeV muon beam is brought into collision with a hadron beam of hundreds of GeV to several TeV. Research and development of the technology for a high energy muon collider, despite the unstable nature of the muon, is under consideration as a path toward reaching the next high energy frontier of particle physics with a relatively compact machine footprint [1].

A MuIC offers the opportunity to explore deep inelastic scattering in protons and nuclei in entirely new regimes at high Q^2 as well as low x. It forms an interesting extension and upgrade, for example, of the physics program of the high-energy and high-luminosity polarized electron-ion collider (EIC) that has recently been endorsed to be built at BNL by the 2030s [2] by nearly an order of magnitude in $\sqrt{s}$, as noted in our initial proposal [3]. A MuIC also would be able to test the standard model of particle physics through vector boson fusion processes, as well as be sensitive to beyond standard model phenomena that may be enhanced for processes with enhanced couplings to second generation leptons as will be discussed briefly here and also in Ref. [4]. If constructed at CERN, a MuIC forms an alternative to the proposed the Large Hadron-electron Collider (LHeC) [5], with very similar kinematic reach and physics programs.

2. Collider Configurations

Some MuIC collider configuration options have been discussed in Refs. [3] and [4], though the luminosity estimates are likely overestimated by a factor 10–100 without further optimization (i.e. $\mathcal{L}_{\text{inst}} \to 10^{31}$–$10^{32}$ cm^{-2}s^{-1}) because of beam effects, as commented in Ref. [6]. Here we concentrate on the options of a MuIC at BNL, with a muon beam energy of 1 TeV and a proton beam energy of 275 GeV ($\sqrt{s}$ = 1.0 TeV), and a MuIC at CERN with a muon beam energy of 1.5 TeV and an LHC proton beam energy of 7 TeV ("LHmuC", $\sqrt{s}$ = 6.5 TeV). These configurations dramatically increase the Deep Inelastic Scattering (DIS) experimental reach in Q^2 to 10^6 and 4×10^7 GeV^2, respectively. In fact the MuIC at BNL option has nearly the same kinematic coverage of the proposed LHeC using a 50 GeV electron beam, and yet could fit on the BNL site as an upgrade to the EIC. The LHmuC option has a $\sqrt{s}$ that would actually exceed that of an "FCC-he", whereby a 50 GeV electron beam would be brought into collision with a 50 TeV proton beam at a future $O(100)$km circular collider.

The muon ionization cooling portion of a muon accelerator complex is expected to be among the most challenging and costly components, and requires R&D investment to demonstrate the cooling and acceleration to specification. However, we note an alternative cooling and acceleration approach applicable to μ^+ beams only, but appropriate for a MuIC, that has recently been demonstrated at the KEK J-PARC complex [7]. Here the μ^+ have been slowed and captured by electrons in an aerogel to form a muonium atom (so ultra cold), which are then ionized with a laser and subsequently accelerated with very small emittance and potentially with polarization.

3. Physics Potential

Many aspects of the science potential of a MuIC have been discussed in Refs. [3, 4], ranging from standard model measurements to beyond standard model searches, depending on the achieved luminosity. The "bread and butter" of lepton-hadron scattering measurements are the structure functions, which provide input to parton density function (PDF) evolution fits at unexplored regions at high Q^2 and low-x. Even at HERA luminosities (10^{31}–10^{32} cm^{-2}s^{-1}), the reach in Q^2 of a 1 TeV MuIC is 4 times greater than that of HERA (up to 200 000 GeV^2), and higher still at higher luminosities or higher $\sqrt{s}$. These measurements could significantly reduce the systematic uncertainty of cross section calculations arising from PDF uncertainties for high-energy processes such as Higgs boson production at the LHC and at future hadron colliders, to the level of $\approx$1% by analogy to the expected precision of measurements that could be made at the LHeC [5]. Additionally, a MuIC at BNL could offer polarization of both beams, which would allow measurements of the spin structure functions.

Extraction of the strong coupling constant α_S can be obtained from PDF evolution fits to MuIC structure function measurements as well as from direct measurements of multi-jet production over a broad range on energy scale Q in a single experiment. Similarly, measurements of the effective weak mixing angle also could be made over a broad range in Q. Both running coupling constant measurements would complement and extend to higher Q the measurements that will be done at the forthcoming EIC [8].

We have shown that the equivalent parton luminosity of a MuIC collider for $2 \to 1$ and $2 \to 2$ processes compared to a $\mu^+\mu^-$ collider can be achieved with a MuIC that has $\sqrt{s}$ only 50% larger than that of a $\mu^+\mu^-$ collider [4]. Thus an LHmuC with a 1.5 TeV muon beam and 7 TeV proton beam, for example, would have an equivalent $\sqrt{s_{\mu\mu}}$ of about 4.3 TeV, which in turn would be roughly equivalent to a 30 TeV proton collider (essentially an LHC energy doubler). Thus much of the same program of standard model particle production measurements and beyond standard model searches at a $\mu^+\mu^-$ collider could be done at a MuIC assuming all other luminosity factors are equal. Both types of colliders can be considered vector boson colliders, which is the dominant mechanism to produce the Higgs and vector bosons. Hence measurements of the Higgs branching fraction to bottom quarks could be made, where the inclusive Higgs boson cross section for a 1 TeV $\mu^- p$ MuIC is 77 fb [4]. Measurements of triple gauge couplings also could be made, as well as measurements of the top-bottom quark CKM matrix element through single top quark production, which has a cross section of 1 pb for a 1 TeV MuIC [4].

4. Experimental Considerations

The detectors for an experiment at a MuIC share many of the same challenges of an experiment at a high-energy $\mu^+\mu^-$ collider experiment. Namely, a large beam-induced background (BIB) caused by muon decays along the beam line will expose detectors to a large flux of particles. However, it is expected that precise timing measurements (precision of tens of picoseconds) provided by the detectors and their associated electronics can alleviate some of this diffuse background, and the overall challenge is not unlike the challenges facing the next generation of hadron colliders with a large pileup of collisions.

PoS(ICHEP2024)817

One of the unique challenges of a MuIC experiment is the detection of high-energy muons very close to the beam line (up to $|\eta| \approx 7$) arising from the DIS kinematics of a TeV-scale MuIC. For a $\mu^+\mu^-$ collider experiment, 6-m-long tungsten shielding cones ($|\eta| > 2.4$) are planned for each end of the experiment to shield the inner detectors from the BIB. Ideally, for a dedicated MuIC experiment, the shielding cone on the downstream side of the experiment could be removed as there is no BIB from the other direction. But this may not be possible if the experiment and collider complex serves both $\mu^+\mu^-$ and MuIC programs. In this case, outgoing high-energy muons will traverse the shielding cone, lose energy, and undergo multiple scattering, which will disturb measurements. We have conducted GEANT4 [9] simulations of the energy loss for TeV muons traversing such a tungsten cone and find that on average the muon loses ≈18% of its energy, with a most probable value of ≈10%, as shown in Fig. 1. While a correction for this most probable loss could be made, the spread around this value will remain. Along with the energy loss, a high energy muon also undergoes multiple scattering as it traverses the tungsten shielding cone. The standard deviation of this angular spread in a plane is of the order 1 mrad and depends on the momentum. While small, this can have a large impact on the resolution of DIS quantities such as Q^2 at large $|\eta|$, where the scattering angle from the beam line is similarly at the mrad level, using only the measured momentum and angle of the outgoing muon. Thus, for measurements at low Q^2, where the muon deflection is small, it would be better to remove the downstream shielding cone or otherwise make use of the scattered hadrons for kinematic reconstruction.

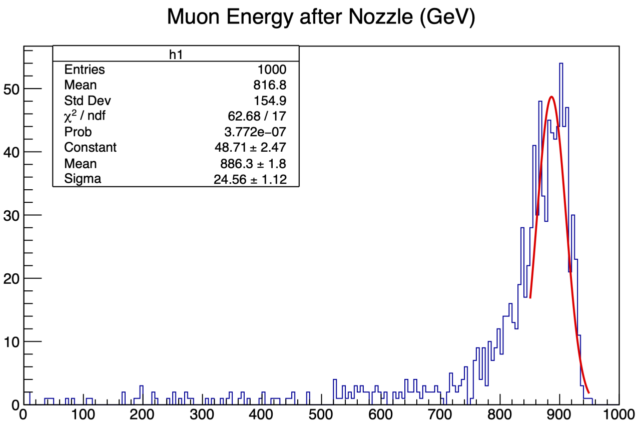

Figure 1: Energy distribution of 1000 GeV muons after passing through a 6 m tungsten shielding cone.

We have begun to explore possible designs for a muon magnet spectrometer able to meet the requirements of a TeV-scale MuIC based around the design of the endcap toroid magnets of the ATLAS experiment [10], as illustrated in Fig. 2. These magnets have a field that varies from roughly 4 to 1 T for radii from about 1 to 5 m, respectively. With a depth of about 4.5 m, such a magnet could provide the necessary bending power to measure the momentum of TeV muons along the beam line. Associated muon detectors in front and behind the toroid with a spatial resolution of the order of 150 μm, achievable with current muon detector technologies such as used by the LHC experiments, could provide a momentum resolution of about 10% or better at 1 TeV. Depending the on the η range to be covered by an experiment, two or three stations of such toroids and muon detectors positioned from tens to hundreds of meters downstream would be necessary (each toroid would cover $\Delta\eta \approx 1.6$), assuming that a solenoid magnet and other muon detectors cover the central region of the experiment.

We note that one station of such a muon spectrometer on each side of a $\mu^+\mu^-$ symmetric collider experiment also could be useful to tag and measure outgoing muons in vector boson fusion processes as well as measure the luminosity from Bhabha scattering.

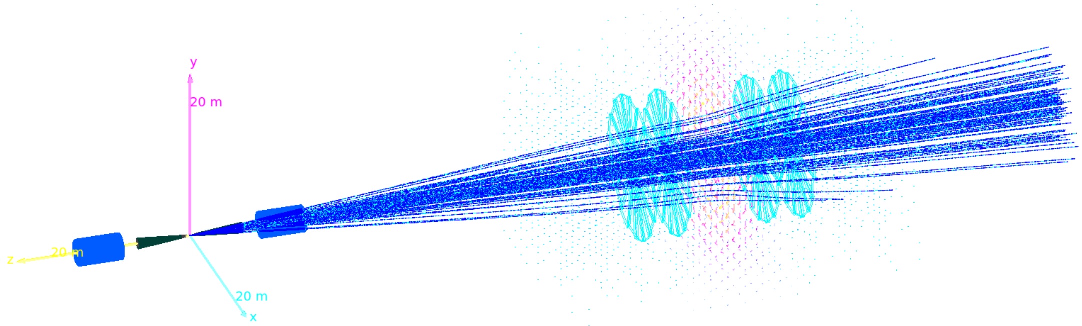

Figure 2: Possible layout of a magnet spectrometer with muon detectors before and after a large toroid, with tungsten shielding cones near the collision point, to measure the momentum of scattered muons. Also shown are the trajectories of TeV muons simulated with GEANT4. The toroid was situated 60 m downstream of the collision point.

5. Summary

In summary, collisions from a TeV-scale muon beam with a high-energy proton/ion beam provide a novel way to explore a new regime in DIS at high Q^2 and at low x. Collider and site options for a MuIC include BNL ($\sqrt{s}$ = 1–2 TeV) as an EIC upgrade, CERN/LHC ($\sqrt{s}$ = 6.5 TeV), or FNAL depending on how the US muon and neutrino programs develop. Such a facility opens a unique new frontier in particle and nuclear physics, ranging from the partonic structure of matter, precision QCD and electroweak interactions, Higgs bosons, and searches for physics beyond the standard model. High luminosity could be a challenge, and needs dedicated accelerator optimization. However, there remains novel measurements to make at lower luminosities such as on nuclear structure and couplings. Thus a MuIC could serve as a scientific target for a muon collider demonstrator, even simply by accelerating and colliding protons in place of μ+, and thus serve as a stepping stone toward an ultimate $O(10+)$ TeV $\mu^+\mu^-$ collider. Unique experimental challenges of a MuIC include the need for a dedicated magnet spectrometer to detect TeV muons at small scattering angles, but this appears possible in principle.

Acknowledgments

This work is in part supported by the Department of Energy grant numbers DE-SC0010103, DE-SC0010266 (D.A.), and DE-SC0005131 (W.L.). D.A. also acknowledges the support from the Rice Office of Undergraduate Research and Inquiry and from the Rice Department of Physics and Astronomy. N.H. acknowledges support from the Office of Undergraduate Research and Fellowships at Northeastern University.

References

[1] *Report of the 2023 Particle Physics Project Prioritization Panel*. https://www.usparticlephysics.org/2023-p5-report/

[2] *An Assessment of U.S.-Based Electron-Ion Collider Science*. The National Academies Press, Washington, DC, 2018.

[3] Darin Acosta and Wei Li. *A muon–ion collider at BNL: The future QCD frontier and path to a new energy frontier of $\mu+\mu-$ colliders*. *Nucl. Instrum. Meth. A*, 1027:166334, 2022.

[4] D. Acosta et al. *The Potential of a TeV-Scale Muon-Ion Collider*. *JINST*, 18:P09025, 2023.

[5] P. Agostini et al. *The Large Hadron-Electron Collider at the HL-LHC*. arXiv:2007.14491 [hep-ex], 2020.

[6] B. Ketenoglu et al. *Review of muon-proton and muon-nucleus collider proposals*. *Mod. Phys. Lett.* 37:2230013, 2022.

[7] *Muons cooled and accelerated in Japan*. *CERN Courier*, 64:8, July/August 2024.

[8] A. Accardi et al. *Electron Ion Collider: The Next QCD Frontier*: Understanding the glue that binds us all. *Eur. Phys. J. A*, 52:268, 2016.

[9] S. Agostinelli et al. *Geant4 - A Simulation Toolkit*. *Nucl. Instrum. Meth. A* 506:250, 2003. J. Allison et al. *Geant4 Developments and Applications*. *IEEE Trans. Nucl. Sci.* 53:270, 2006. J. Allison et al. *Recent Developments in Geant4*. *Nucl. Instrum. Meth. A* 835:186, 2016.

[10] D. Elwyn Baynham et al. *ATLAS End Cap Toroid Magnets Cold Mass Design and Manufacturing Status*. *IEEE Transactions on Applied Superconductivity*, 14:485, 2004.