Physics Potential of a TeV Muon-Ion Collider

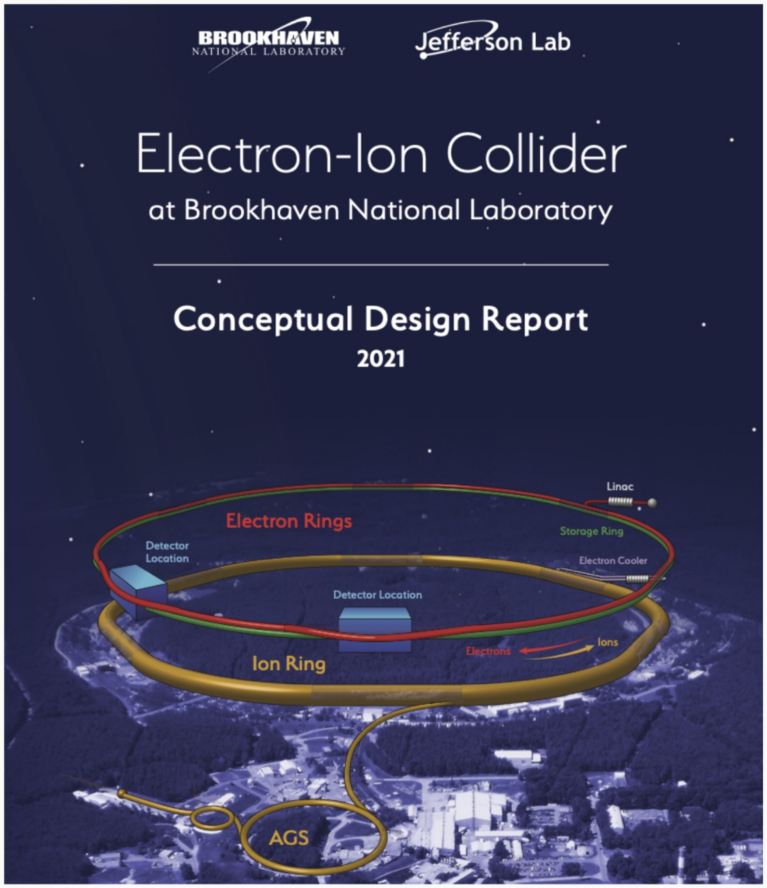
Based on Snowmass '21 whitepaper: arXiv:2203.06258 ,
Initial BNL MuIC paper: NIM A1027 (2022) ,
And some works in progress…

D. Acosta, P.Boyella, W. Li, O. Miguel Colin, Y. Wang, *X. Zuo* (Rice U.)
E. Barberis, N. Hurley, D. Wood (Northeastern U.)

Outline

- Brief review of concept
  - One O(TeV) muon ring as a first step, colliding with a high-energy hadron beam
    - i.e. it is also a Vector Boson Collider along with a DIS machine
- Science case
  - Included in our Snowmass contribution:
    - Covers DIS structure measurements of p/ions, QCD, but focus here on Energy Frontier:
  - Higgs and SM particle production processes
  - BSM physics (Z', LQ)
- Experiment considerations
  - Initial BIB studies
- Future workshop

Inspiration: The Electron-Ion Collider (EIC) at BNL



International facility approved by the U.S. nuclear physics program. Science to begin in 2030s

EIC Conceptual Design Report recently released and project approved. Initial detector design selected and collaboration formed (EPIC)

Salient points:

- Electron beam energy up to 18 GeV
- Hadron beam energy up to 275 GeV
- $\sqrt{s}$ = 20 -- 140 GeV
- Luminosity 10^{33} -- 10^{34} Hz/cm^2
- Polarized electron, proton and ion beams (any)

But what if we changed leptons? 🤔

A lot of interest in μμ colliders

Physics goals:

- ep and eN deep inelastic scattering
- Nucleon spin structure
- Gluon saturation scale (Q_S)

A Muon-Ion Collider – Who Ordered That?

Probe a **new energy scale** and nucleon momentum fraction in Deep Inelastic Scattering using a relatively compact machine

- $\sqrt{s} \sim 1$ TeV
- Q^2 up to 10^6 GeV^2
- x as low as 10^{-6}

Well beyond the EIC, matches that of the proposed LHeC. Further beyond if collided with the LHC

Provides a science case for a (single) TeV muon storage ring demonstrator toward a multi-TeV μ+μ- collider

- Precision PDFs in new regimes (incl. spin at BNL)
- QCD at extreme parton density
- Precision EWK and QCD measurements
- Higgs and other SM particle production
- BSM / LFV sensitivity with an initial muon (e.g. Z', LQ)

Facilitate the **collaboration of the nuclear and particle physics communities** around an innovative and forward-looking machine

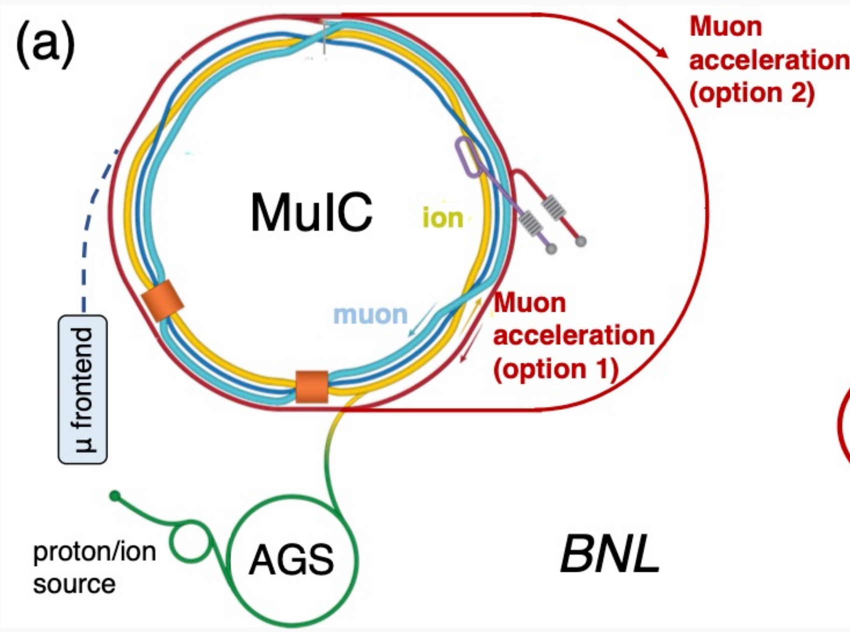
Re-use existing facilities (e.g. MuIC at BNL upgrading EIC, FNAL? CERN?)

Broad science program helps share costs, and re-use helps economize

A Muon-Ion Collider at BNL?

Acosta and Li, NIM A 1027 (2022) 166334

→ Replace e by μ beam at EIC



Bending radius of RHIC tunnel: **r = 290m**

Achievable muon beam energy: **0.3Br**

Parameter	1 (aggressive)	2 (realistic)	3 (conservative)
Muon energy (TeV)	1.39	0.96	0.73
Muon bending magnets (T)	16 (FCC)	11 (HL-LHC)	8.4 (LHC)
Muon bending radius (m)		290	
Proton (Au) energy (TeV)		0.275 (0.11/nucleon)	
CoM energy (TeV)	1.24 (0.78)	1.03 (0.65)	0.9 (0.57)

$\sqrt{s}$ = 1 TeV !

7-8X increase over EIC energy

Energy Configurations and Luminosity

Parameter	MuIC			MuIC2	LHmuC	
$\sqrt{s_{\mu p}}$ (TeV)	0.33	0.74	1.0	→ 2.0	6.5	
$L_{\mu p}$ (10^{33}cm^{-2}s^{-1})	0.07	2.1	4.7 (*)		2.8	
Int. Lumi. (fb^{-1}) per 10 yrs	6	178	400		237	
Staging options	Muon			Proton	Muon	Proton
Beam energy (TeV)	0.1	0.5	0.96	0.275 → 1.0	1.5	7
N_b (10^{11})	40	20	20	3	20	2.2
f^{μ}_{rep} (Hz)	15					
Cycles per μ bunch, N^{μ}_{cycle}	1134					
$\varepsilon^*_{x,y}$ (μm)	200					
$\beta^*_{x,y}$ @IP (cm)	1.7					
Trans. beam size, $\sigma_{x,y}$ (μm)	48	7.6	4.7	7.1	3	7.1

BNL options → MuIC

LHC option

← √s

← Estimate of lumi

← Beam energies

Of 3 TeV μ+μ−

*But note that arXiv:2211.07513 discusses beam-beam tune-shifts that limit luminosity by factor 100.
Need to optimize: decrease particles/bunch, increase number of bunches, etc.

$$\mathcal{L}_{\mu p} = \frac{N^{\mu} N^{p}}{4\pi \max[\sigma^{\mu}_{x}, \sigma^{p}_{x}] \max[\sigma^{\mu}_{y}, \sigma^{p}_{y}]} \min[f^{\mu}_{c}, f^{p}_{c}] H_{hg},$$

$$\sigma^{\mu,p}_{x,y} = \sqrt{\varepsilon^{*}_{x,y} \beta^{*}_{x,y} m^{\mu,p} / E^{\mu,p}}$$

Upgrade hadron ring

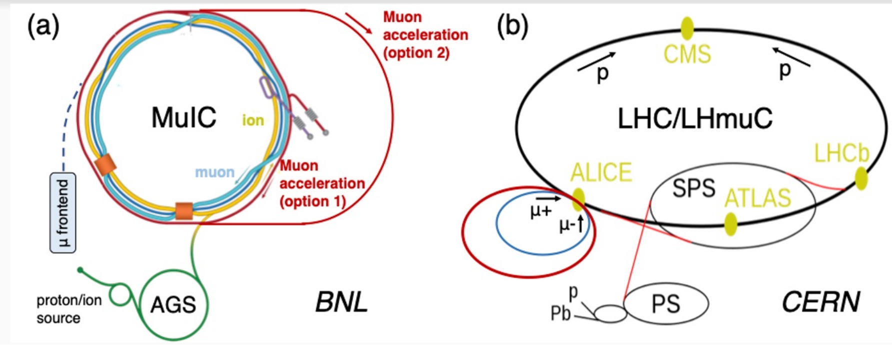
Muon Collider parameters + BNL/EIC and LHC proton beam parameters

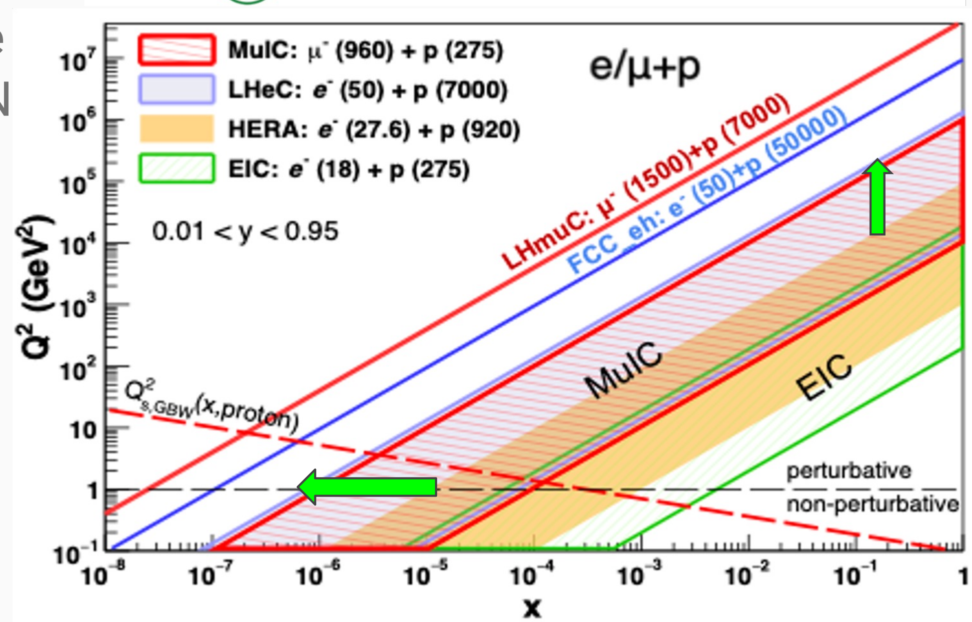
DIS Reach in x and Q^2 for ℓp Collisions

- Expands DIS reach at high Q^2 and low x by 1–3 orders of magnitude over HERA and the EIC

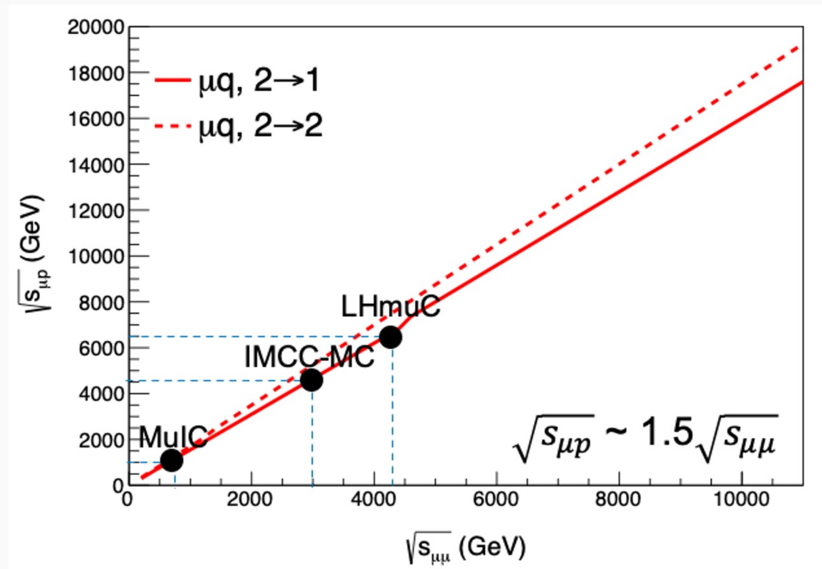
- Coverage of MuIC at BNL is nearly identical with that of the proposed Large Hadron electron Collider (LHeC) at CERN with 50 GeV e⁻ beam
  - With complementary kinematics

- Coverage of a mu-LHC collider at CERN (LHmuC) would significantly exceed even that of the FCC-eh option of a 50 TeV proton beam with 50 GeV e⁻ beam





Equivalent Reach for Production, μp vs. $\mu^+\mu^-$



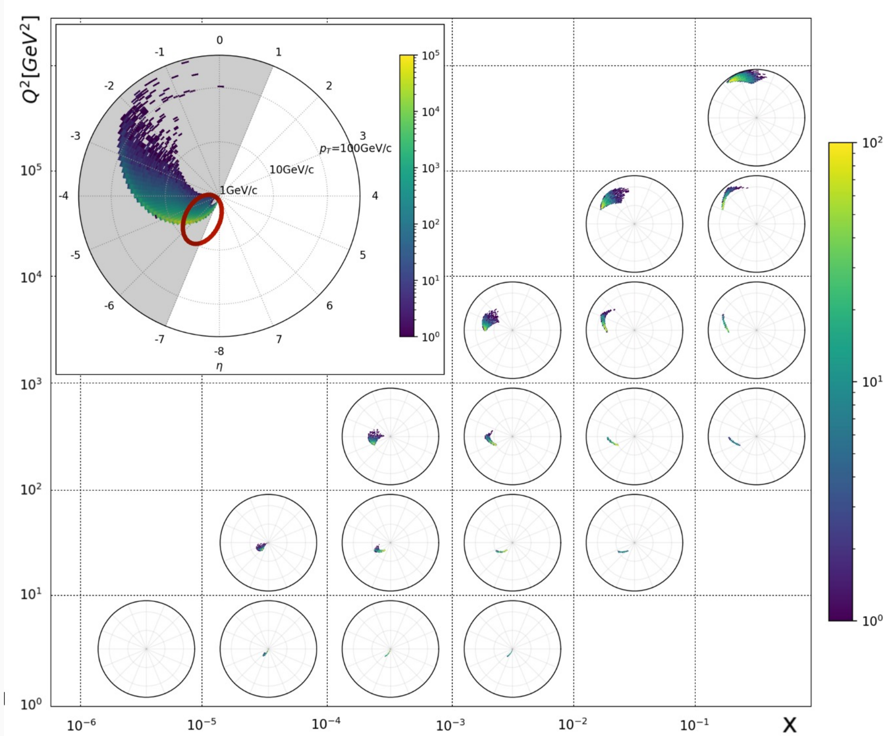
- Compute equivalent parton luminosity of a μp collider for 2→1 and 2→2 processes
- We find that **a $\mu^+\mu^-$ collider is equivalent to a μp collider with 1.5× higher √s** in terms of its discovery potential.
- Put another way, colliding just one muon beam with a well understood (existing?) high energy proton beam can explore interesting EWK phase space
  - Higgs production is via Vector Boson Fusion in both high energy $\mu^+\mu^-$ and μp collisions
  - Swapping 50 GeV e− beam with >50 GeV μ beam exceeds 1.3 TeV LHeC energy scale at CERN, but with potential to go to higher energy!

Perhaps an interesting first step for a non-US muon accelerator?

Acosta et al. -- Potential of a TeV Scale Muon-Ion Collider

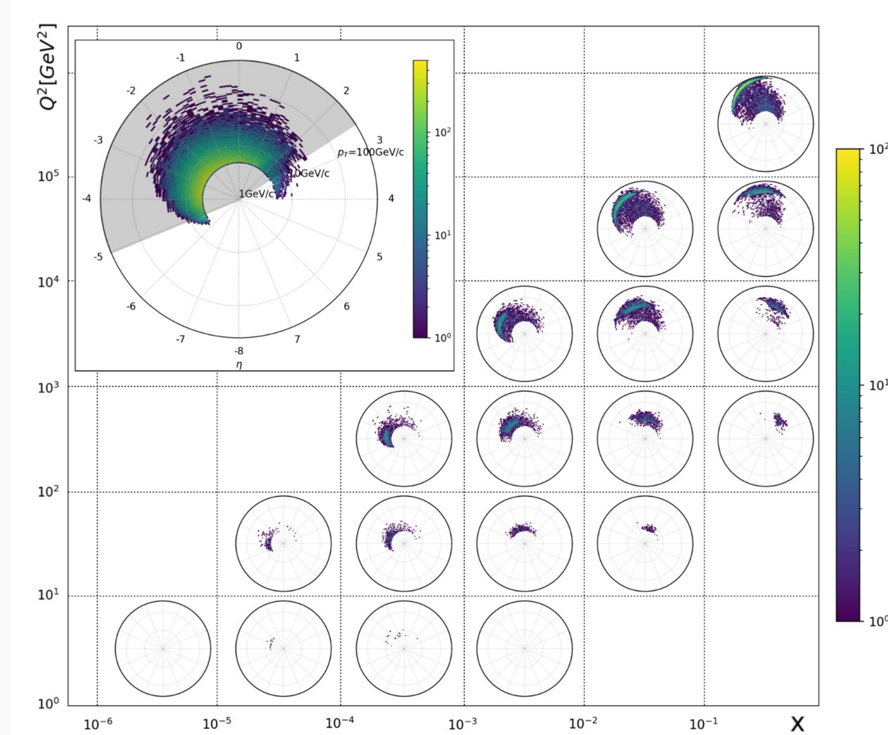
Kinematics

- Scattered muon



Distribution of Scattering Muon

Scattered jet



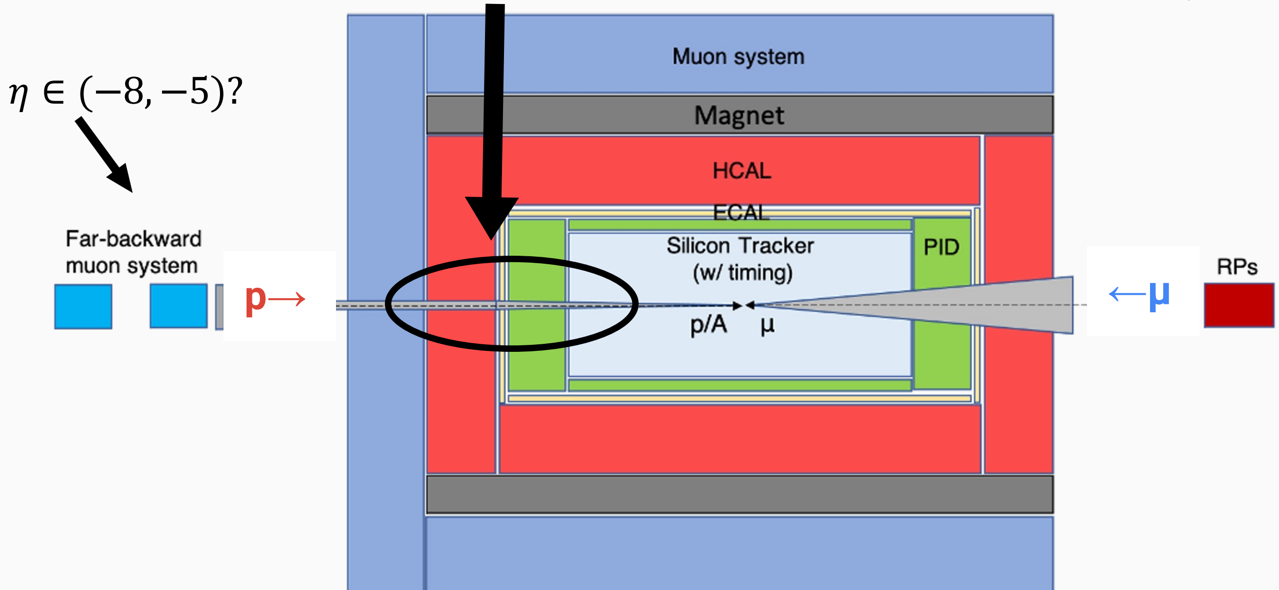
Distribution of Jets

- Backward tagging of muons to η= −7

Hadronic system −5 < η < 2.4

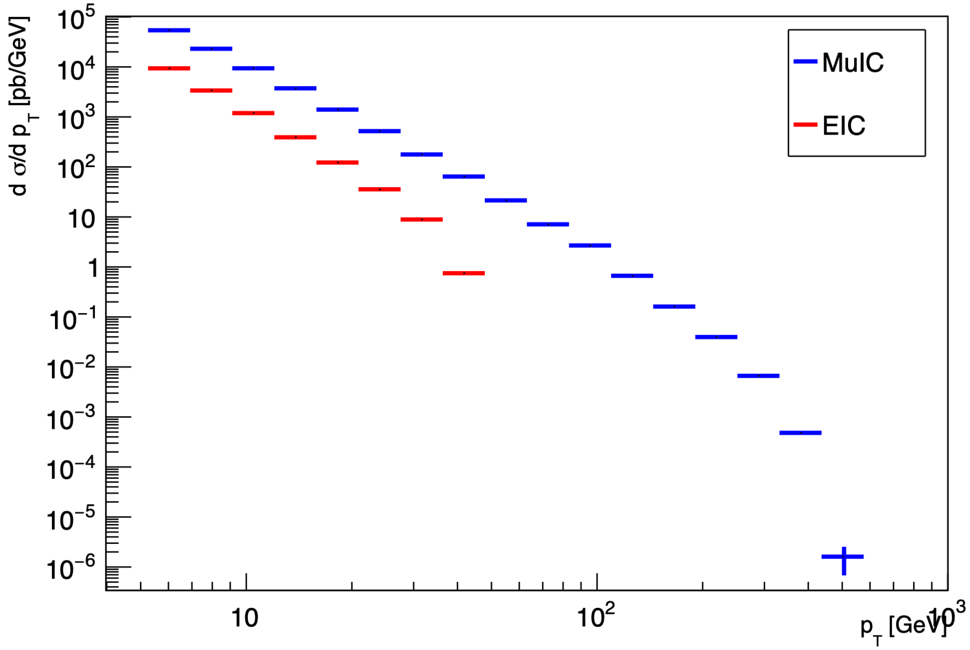
Detector Considerations and Challenges

- Modified $\mu^+\mu^-$ conceptual detector design
- Hadron PID over wide phase space
- Detection of scattered muons is important, mostly at high η (far-backward), with good resolution up to TeV scale
  - **Useful also for a $\mu^+\mu^-$ experiment to tag/veto NC VBF processes**
- Shielding nozzle **only on incoming muon side** (Needs BIB study)

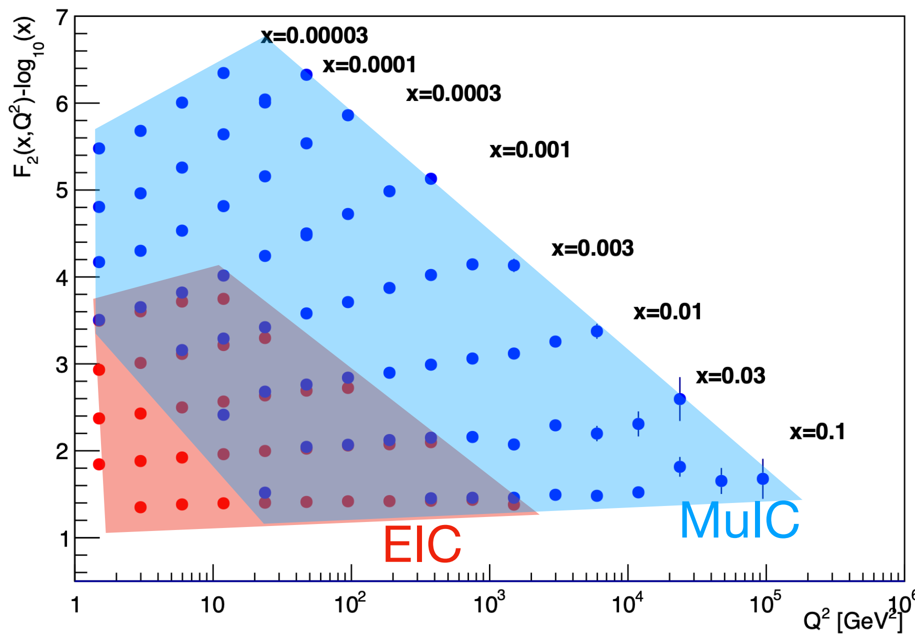


	Main requirements
Muons	**-7<η<0, σ(p)/p < 5%**
Tracking	-4<η<2.4
PID (π/k/p)	**-4<η<2.4, p<100 GeV**
Calorimetry (jets, photons)	-5<η<2.4

Physics Potential in QCD and Nuclear Physics



Single jet spectra projection of EIC vs MuIC



Structure function projection of EIC vs MuIC

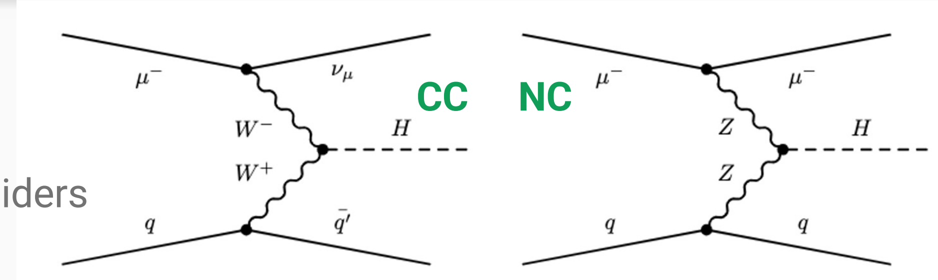
$$pseudo - data\ of\ one\ year\ of\ running$$

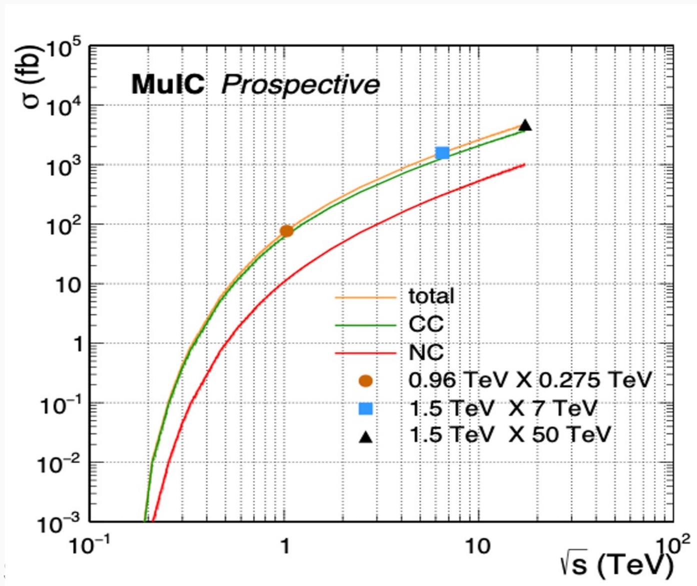
$$(28\ weeks\ and\ 50\%\ duty\ cycle \rightarrow \sim 40\ fb^{-1})$$

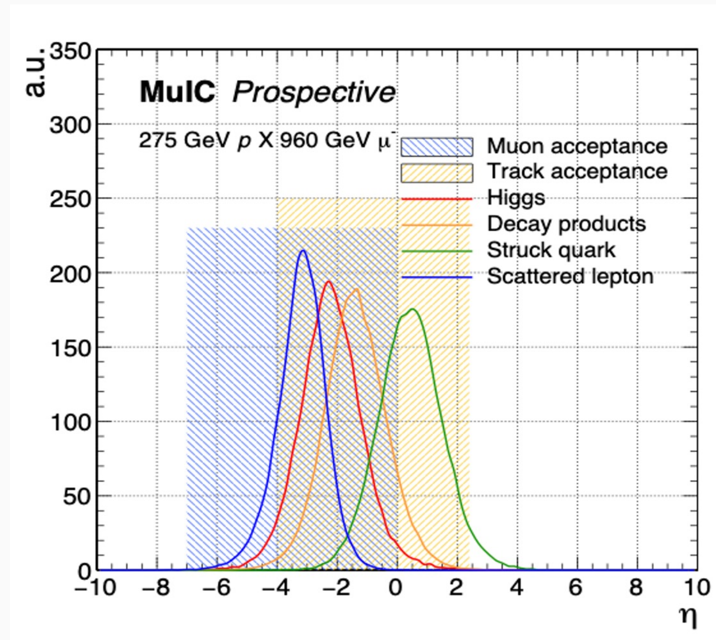
Higgs Physics with MuIC

arXiv:2203.06258

- VBF mode
  - σ grows with √s, CC exchange larger than NC
  - Cross section comparable to LHeC and $\mu^+\mu^-$ colliders
- Acceptance
  - All final state objects, other than the muon, are **in central region of detector** (in contrast to LHeC)



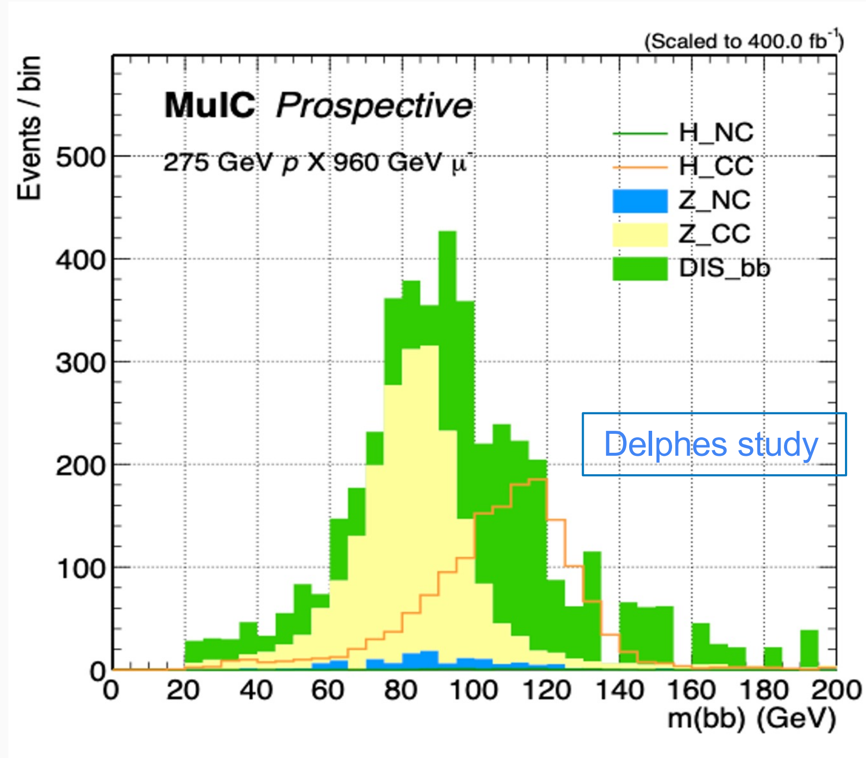




Computed with MadGraph

Higgs →bb with MuIC

- Pseudo-analysis for H→bb
  - Requirements that enhance CC VBF process over NC DIS bb background:
    - 3 jets in final state (2 b-tagged)
    - muon veto, MET
    - Higgs p_T
  - S/B ~ 1 for H→bb
  - **Expect ~900 selected H→bb in 400 fb^{-1} (10y) @ 1TeV MuIC**
    - Increases by factor 10 at LHmuC

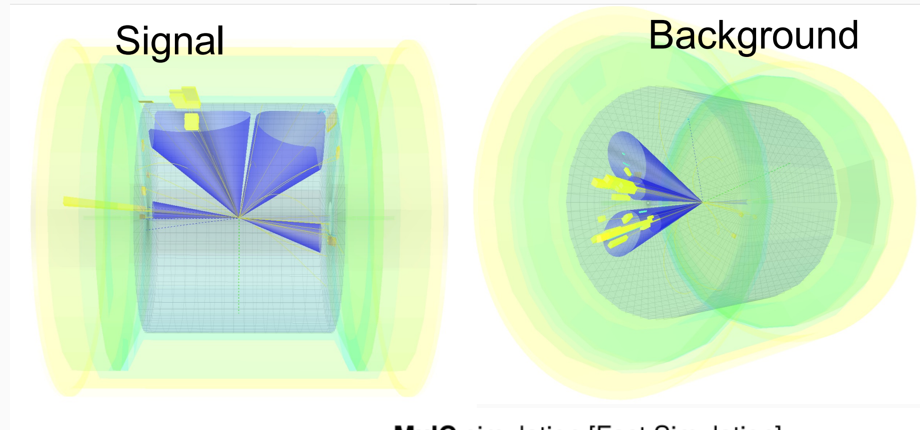


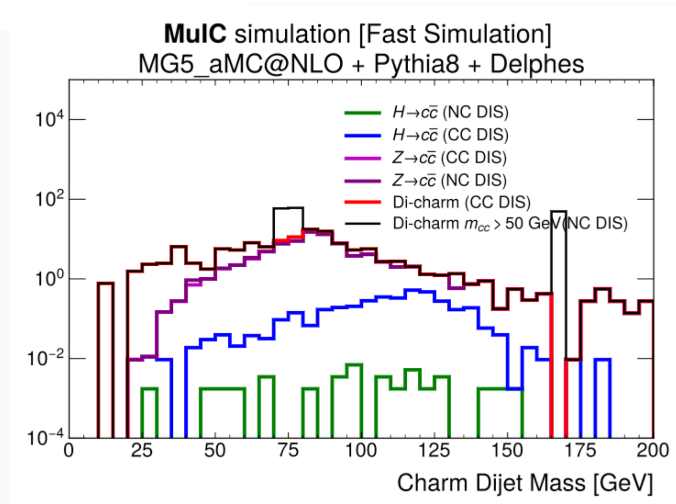
- What about H→cc ?
  - Difficult at LHC
  - See next slide

Higgs → cc [Independent SMU group study]

P.Ahluwalia, S.Sekula, et al. (SMU) arXiv:2211.02615

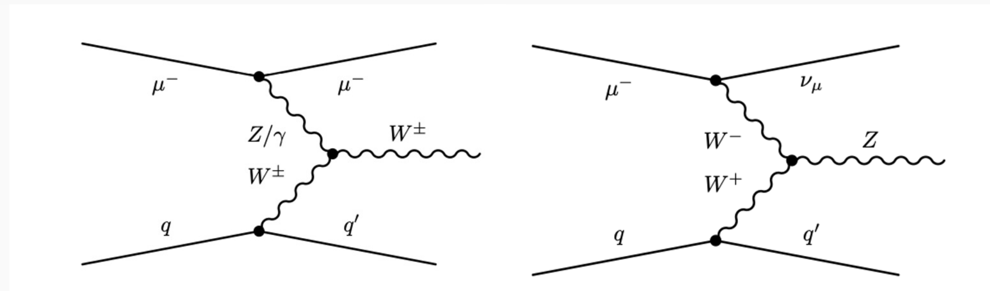
- Similar pseudo-analysis of H →cc at 1 TeV MuIC
  - But smaller BR
  - Smaller c-tagging efficiency (27%), and more bkg…
- Selection:
  - Etmiss > 50 GeV
  - Veto scattered muon (NC)
  - ≥2 charm-tagged jets
- Yields only a handful of events…
- Did not study yet mis-tagged light dijet bkg, whose cross section is much larger
- However, there may be topological features useful to discriminate signal (as seen in event displays)
- Also Higgs cross section grows with √s
- But fair to caution using H →cc as a motivation for MuIC… ☹



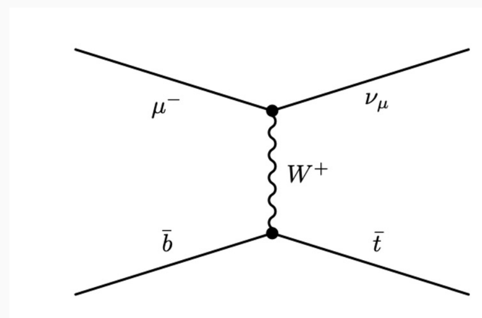


Other SM Particle Production

- Vector boson production, e.g.
  - Sensitive to **triple gauge couplings**
  - σ(W) = 19 pb for 1 TeV MuIC
    - 2.1×10^4 leptonic $W \rightarrow l\nu$ decays into each lepton flavor for 10 fb^{-1}



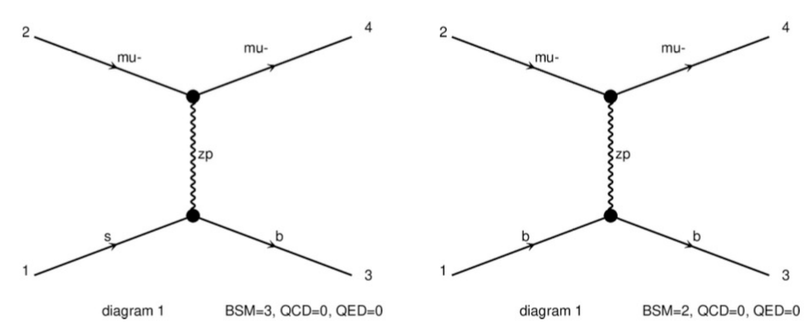
- Single top production
  - Direct measurement of $|V_{tb}|$
  - σ(t) = 1.0 pb for 1 TeV MuIC



Potential for precision coupling measurements (and maybe mass measurements, with larger σ at higher √s and higher luminosity)

Probing Z’ Models Relevant to LFU Violations

- Consider Z’ models and couplings discussed in M.Abdullah et al., Phys. Rev. D 97, 075035 , that couple via O9 operator mostly to 2nd generation leptons (μ) and 2nd and 3rd generation quarks (s, b) to explain anomalies in B meson decays.
  - $$\mathcal{L} \supset Z'^{\mu}\Big[g_\mu \bar{\mu}\gamma^\mu \mu + g_\mu \bar{\nu_\mu}\gamma^\mu P_L \nu_\mu + g_b \sum_{q=t,b} \bar{q}\,\gamma^\mu P_L q + (g_b \delta_{bs} \bar{s}\gamma^\mu P_L b + \text{h.c.})\Big] \quad (6)$$
  - g_μ and g_s are flavor conserving couplings
  - δ_{bs} parameterizes non-flavor conserving couplings
  - $$g_b \delta_{bs} g_\mu (100\ \text{GeV}/m_{Z'})^2 \simeq 1.3 \times 10^{-5} \quad (5)$$
    to fit lepton flavor universality violations

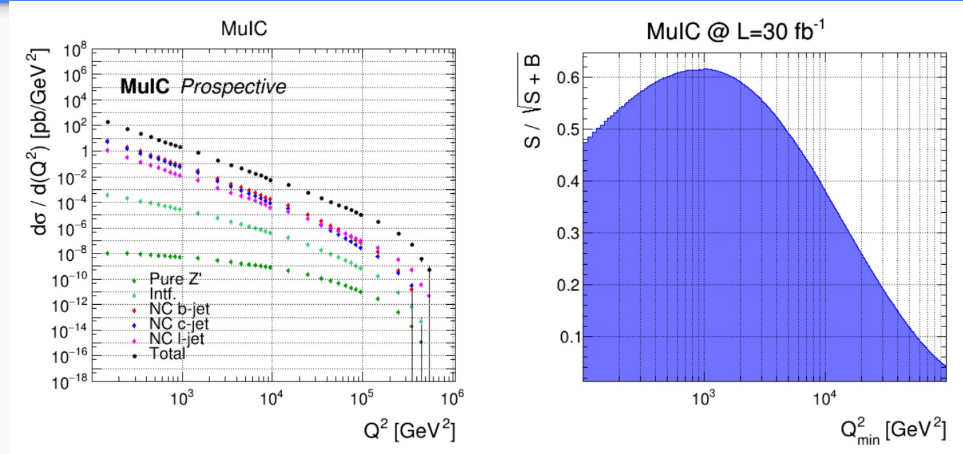


(a) $s\ \mu- \rightarrow b\ \mu-$ (b) $b\ \mu- \rightarrow b\ \mu-$

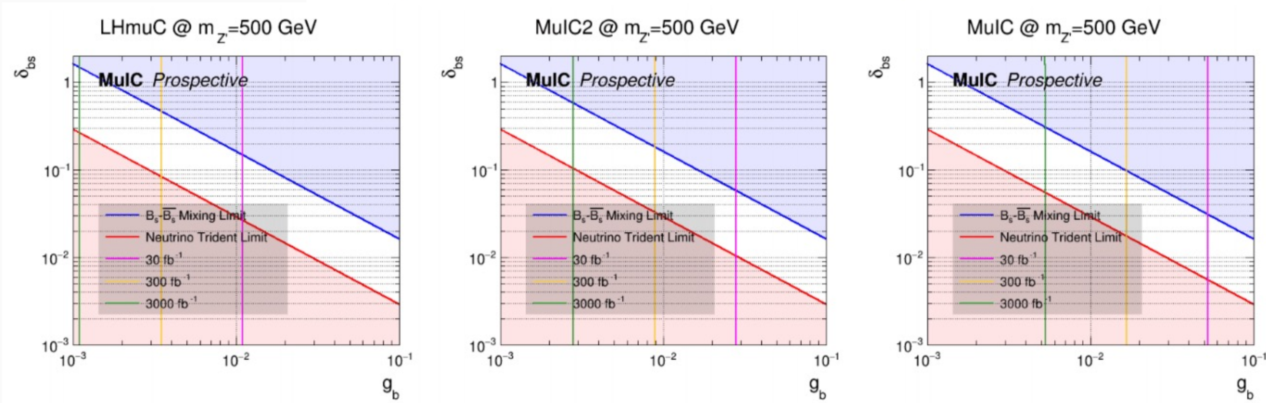
- Consider interference with NC DIS
  - so flavor conserving coupling dominates

Probing Z’ Models Relevant to LFU Violations

- Perform pseudo-analysis using a cut-and-count approach on the reconstructed Q^2 from the muon, optimized for sensitivity
- Apply b-tagging and mis-tagging efficiencies to final state jet
  - b, c, light: 70%, 10%, 1%
- Derive expected limits
- Generally need LHmuC (120 fb^{-1}) to be competitive with HL-LHC (3000 fb^{-1})

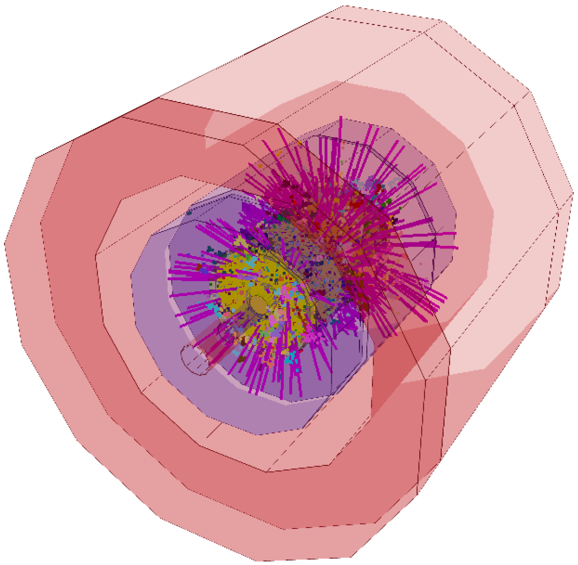


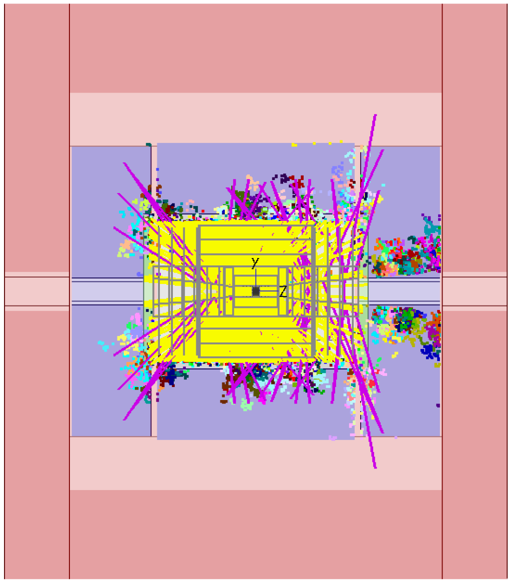
(a) $m_{Z'} = 500$ GeV (b) $m_{Z'} = 500$ GeV

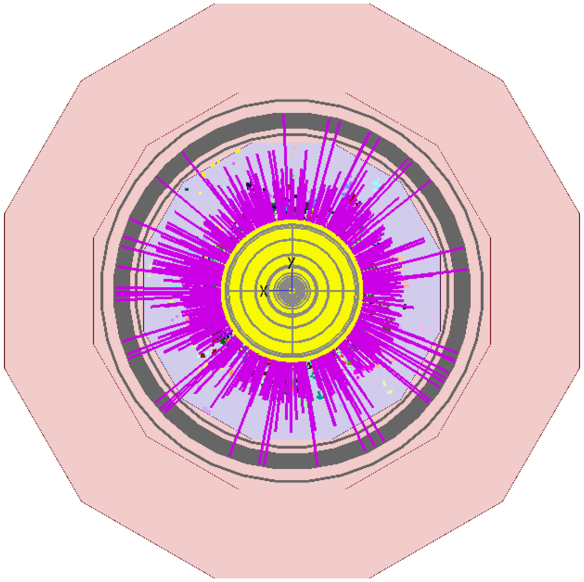


(a) LHmuC (b) MuIC2 (c) MuIC

Full Simulation using IMCC Software







Only one side BIB is turned on

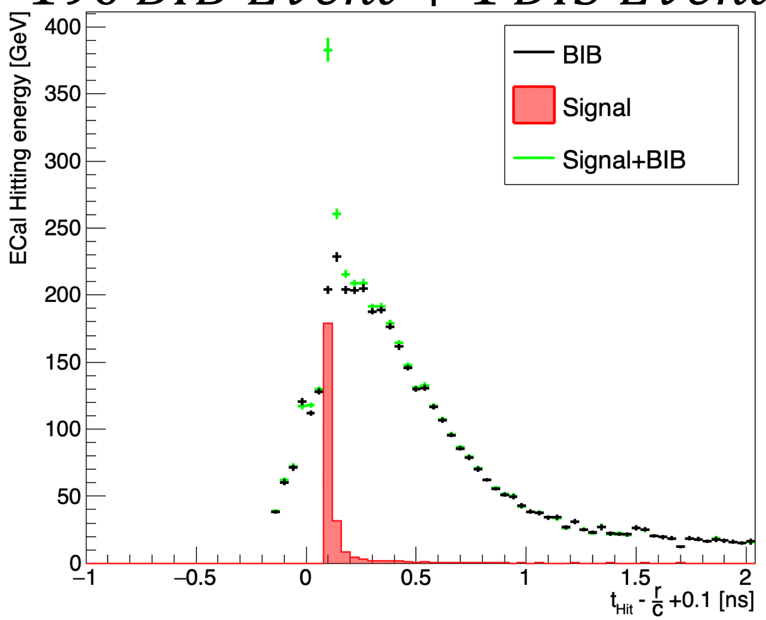
Our next step: Study the feasibility of experimental measurement with BIBs and detector requirements

Would need to also redo BIB simulation with one nozzle missing

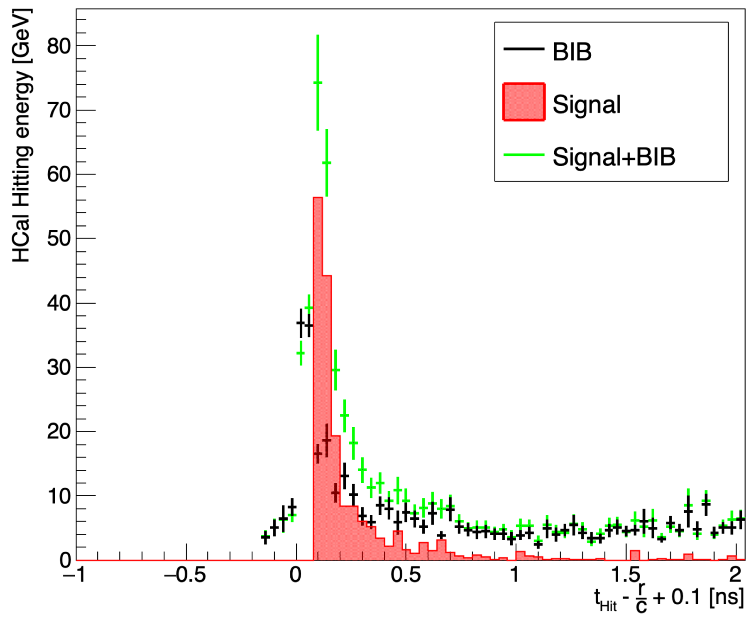
Full Simulation using IMCC Software — Workflow

$190\ BIB\ Event + 1\ DIS\ Event$

BIB file: sim_mumi-1e3x500-26m-lowth-excl_j1.slcio



ECal Hitting Time

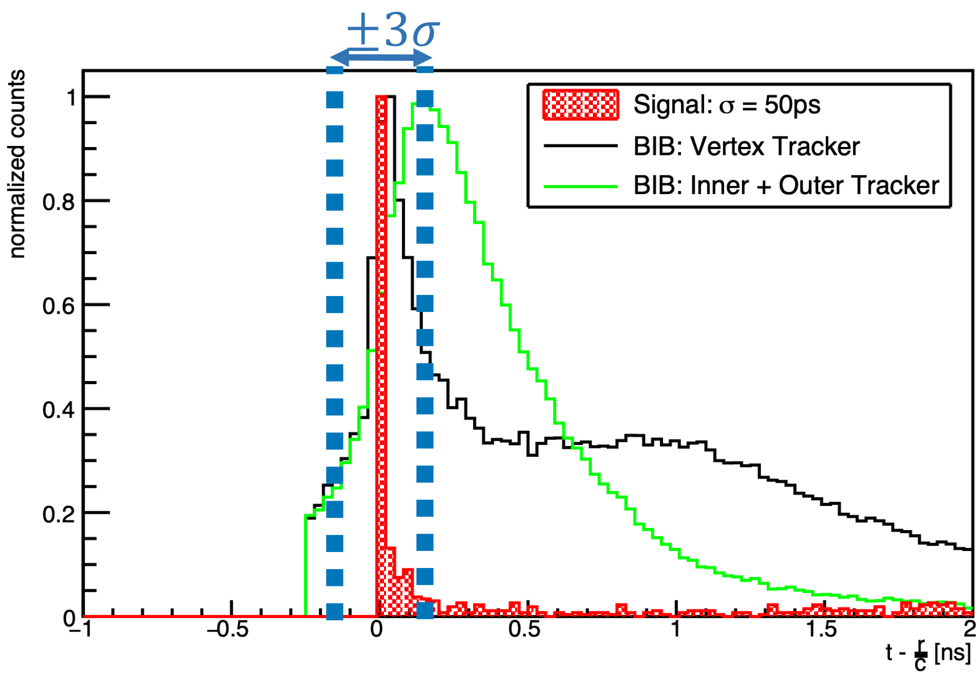


HCal Hitting Time

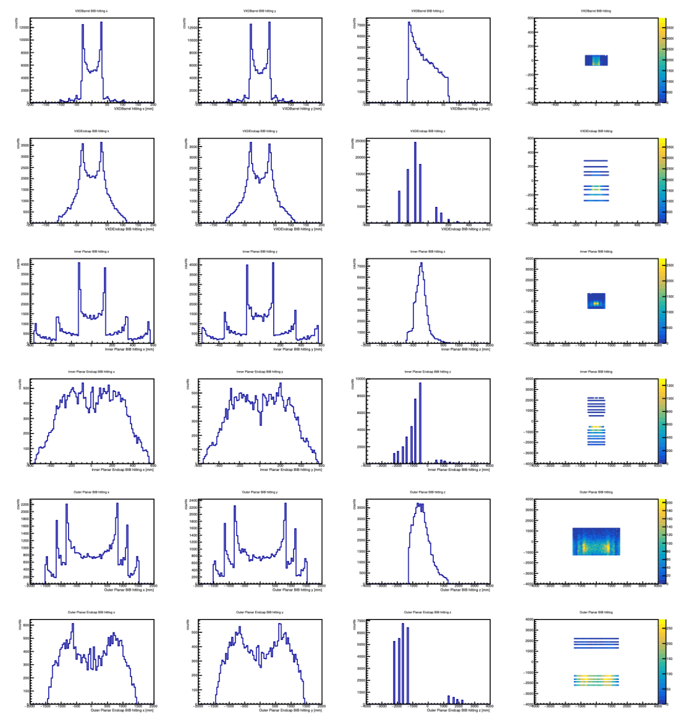
Full Simulation using IMCC Software — Workflow

$190\ BIB\ Event + 1\ DIS\ Event$

BIB file: sim_mumi-1e3x500-26m-lowth-excl_j1.slcio



Tracker Hitting Time



MuIC Synergies with a Muon Collider

- Siting a muon collider at a facility with a high energy hadron ring opens up an interesting additional, complementary science program
  - DIS and QCD, but also electroweak cross sections are comparable to those in $\mu^+\mu^-$ collisions (Need 1.5X larger $\sqrt{s}$)
- Re-use of existing hadron ring infrastructure helps allay some of the cost
  - Also simplifies the design to some degree
  - Can still benefit from a lower initial muon beam energy if collided with TeV scale hadron beam
- A MuIC provides a science case for an initial muon collider demonstrator
  - Luminosity demands for proton/nuclear structure measurements at extreme parton density (low x) are much less stringent than the ultimate needs for Higgs studies, etc.
  - Interesting DIS measurements even for staged muon energies from ~100 GeV
- A MuIC would have both particle physics and nuclear physics interests
  - Two communities to join in detector development and construction
  - Joint funding from particle and nuclear physics programs?
- Similar detector needs
  - Particularly interest in high eta muon spectrometer(s)

Future MuIC Workshop

- We plan to organize a workshop on the topic of MuIC in 2023 at Rice University (secured some funding from the university)
- Aim to bring experimentalists, theorists, accelerator physicists from the HEP and NP communities together to discuss key issues in developing the muon-ion collider concept, as well as associated technologies
  - Synergistic with further muon collider discussions ?

Summary

- Collisions of a TeV-scale muon beam with a high-energy proton/ion beam provides a novel way to explore new a regime in DIS at high Q^2 and low x
  - Two proposed options are at BNL/EIC ($\sqrt{s}$ = 1-2 TeV) and CERN/LHC ($\sqrt{s}$ = 6.5 TeV)
- Luminosity could be a challenge, and needs accelerator study
  - However, there is a science program to do even at low luminosity (new DIS regime)
- Precision electroweak, QCD, and SM particle production measurements (including Higgs) can be performed with sufficient integrated luminosity.
  - $H \rightarrow cc$ would be very challenging, however
- May be an interesting collider to study some BSM physics models
  - Z' study performed
  - Leptoquarks currently under study by an undergrad doing a senior thesis
- Many synergies with muon collider development, nuclear and particle physics programs
- One ring ("to rule them all") easier and cheaper than two?

Acknowledgements

- This work is in part supported by the Department of Energy, United States grant numbers DE-SC0010266 (D.A.), DE-SC0005131 (W.L.)

Backup

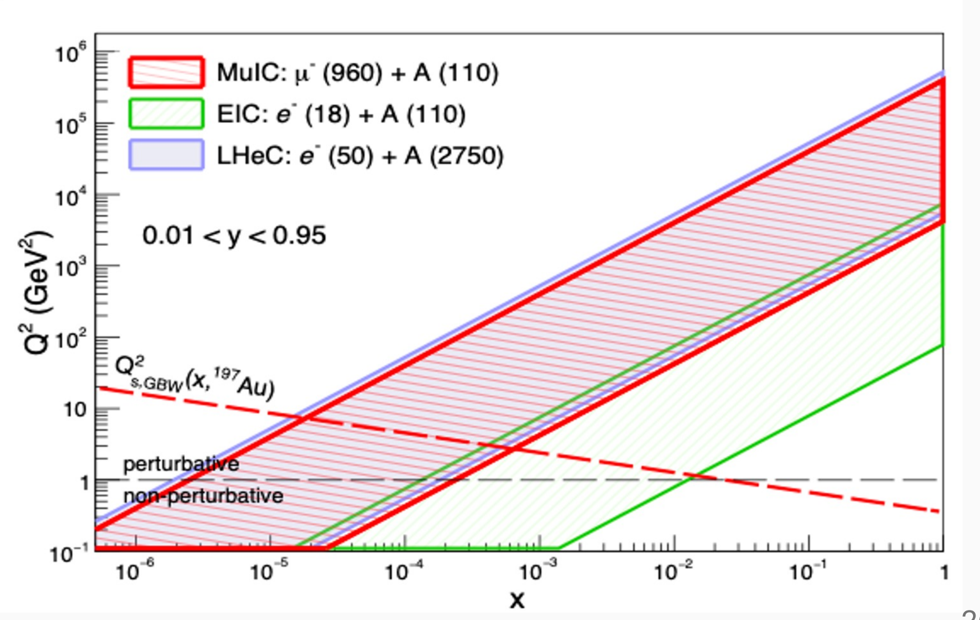
DIS Reach in x and Q^2 for ℓA Collisions

- Can explore well the predicted region of gluon saturation regime in ions at low x in the GBW model [Phys. Rev. D 59, 014017 (1998)] (and in protons, prev. slide)

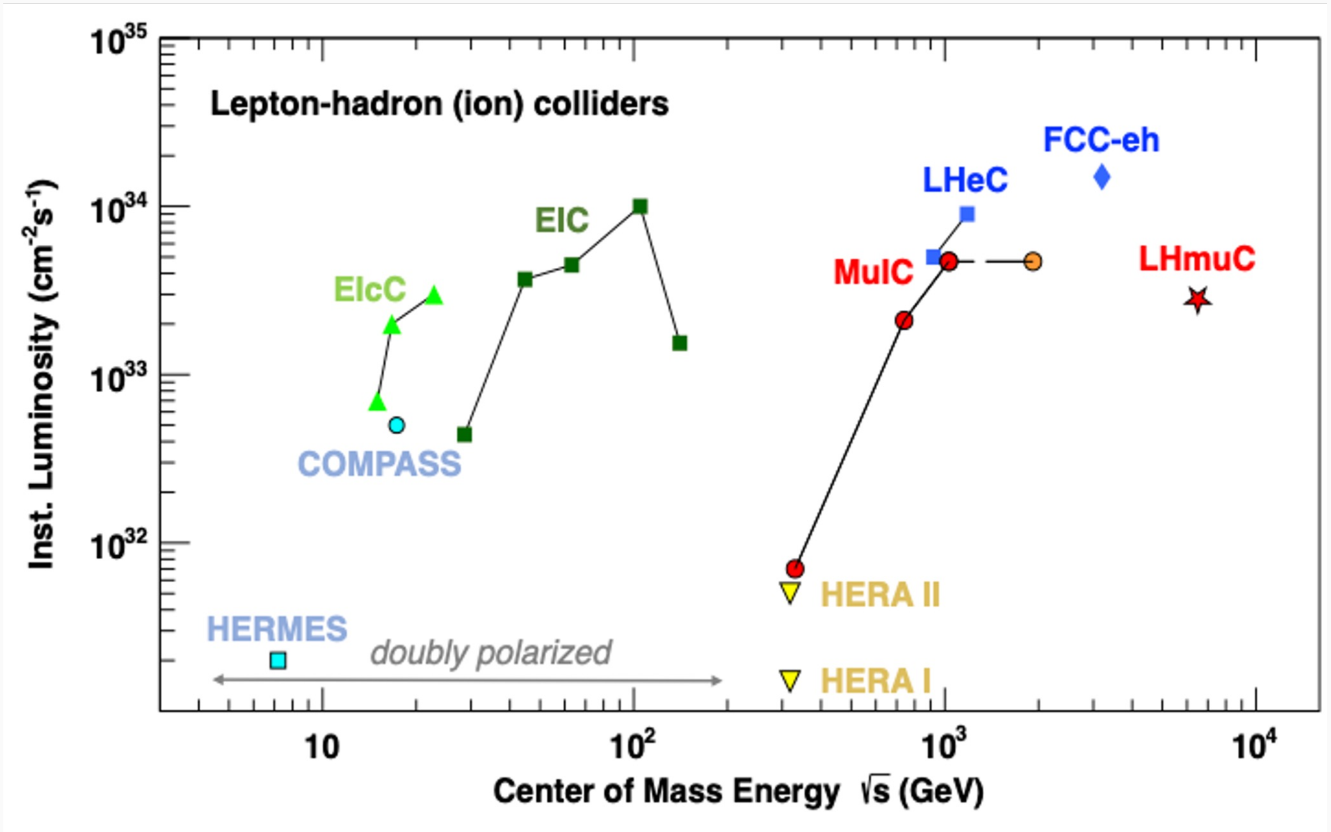
- Also the MuIC at BNL can scan a wide range of ion species, and beam polarization

Saturation scale:

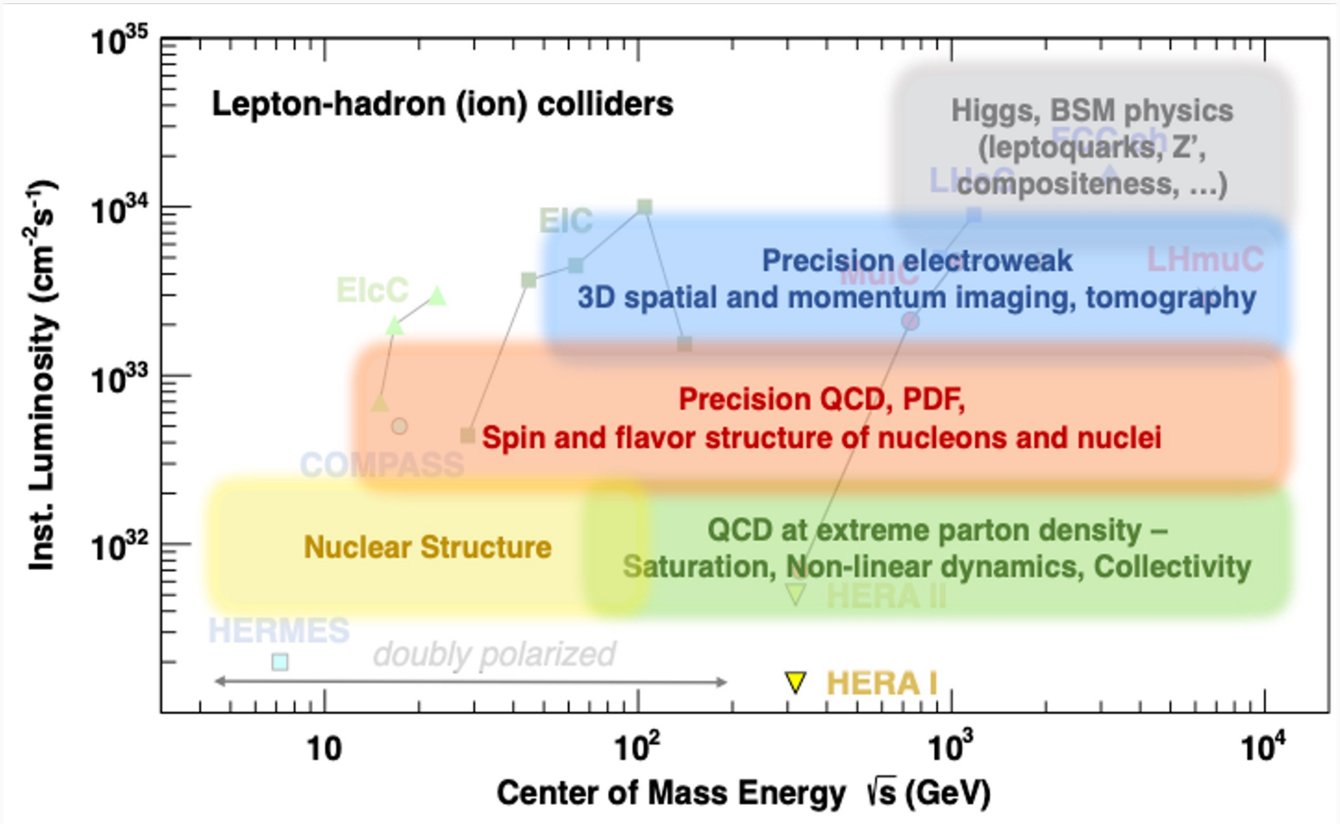
$$Q_s^2(A) = A^{1/3} Q_s^2(p)$$



DIS Evolution and Physics Landscape



DIS Evolution and Physics Landscape



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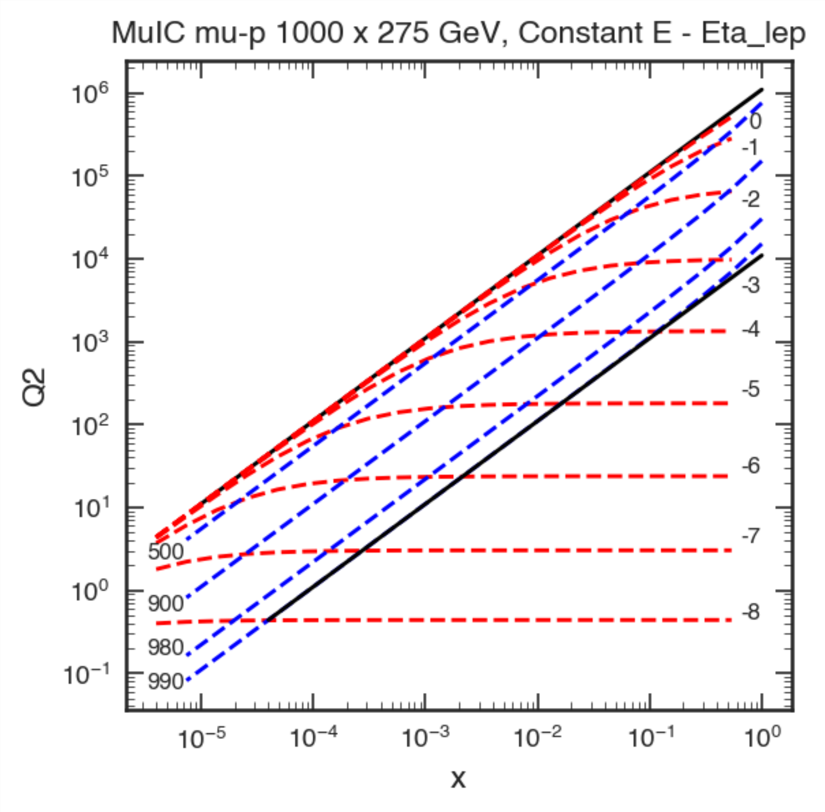
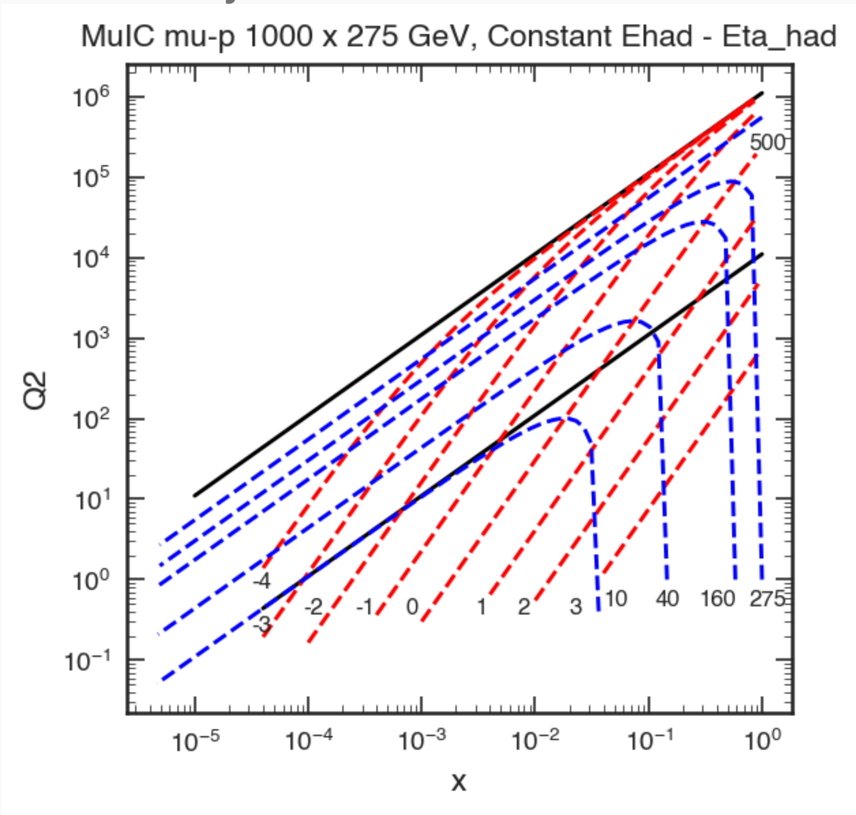
Kinematics

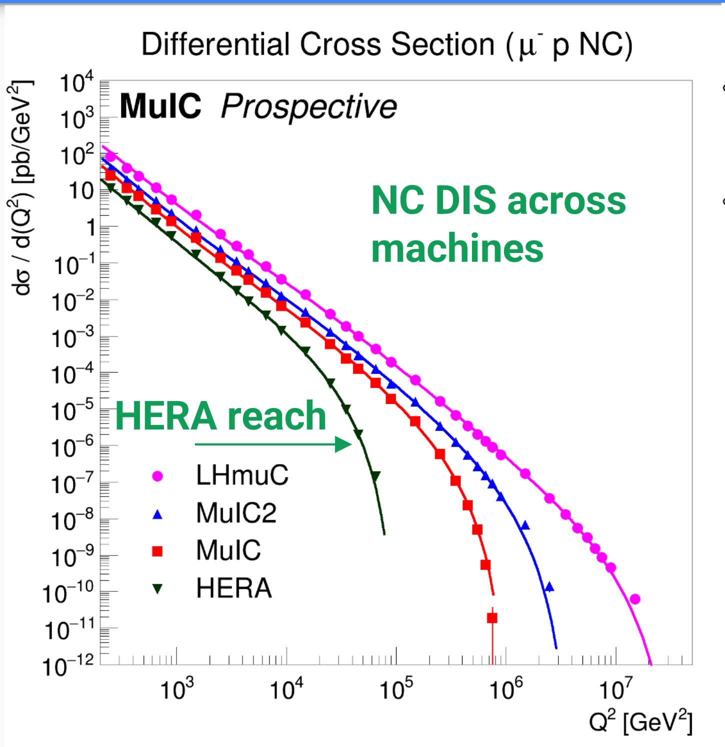
- Scattered muon

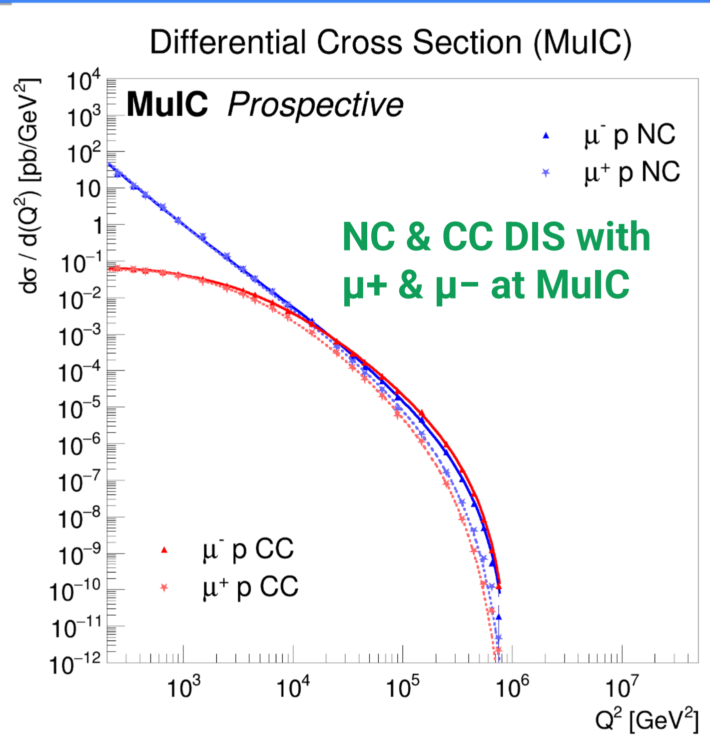


Scattered jet



DIS Differential Cross Sections in Q^2





Computed with Pythia8 and NNPDF2.3 PDF set, $0.1 < y < 0.9$

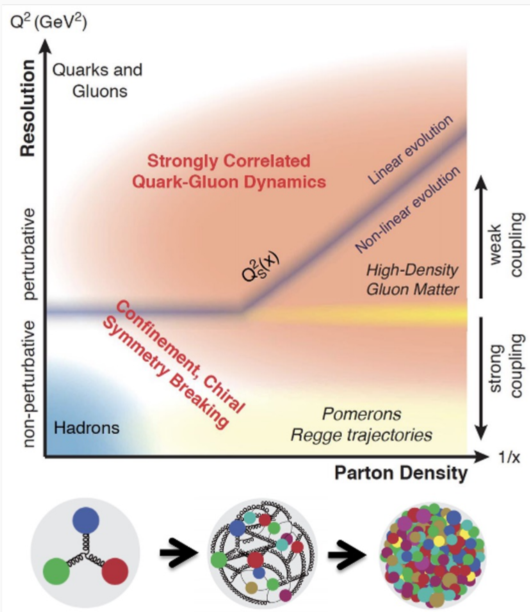
Total integrated CC cross section

Machine	$Q^2 > 1$	$Q^2 > 3 \times 10^4$	$Q^2 > 10^5$	$Q^2 > 3 \times 10^5$
		$\mu^- p \to \nu_\mu X$		
HERA	68	0.038	–	–
MuIC	200	5.2	0.12	0.0053
MuIC2	345	13	0.92	0.20
LHmuC	860	43	4.6	1.6
		$\mu^+ p \to \overline{\nu}_\mu X$		
HERA	37	0.00095	–	–
MuIC	160	1.4	0.0090	–
MuIC2	300	6.5	0.22	0.029
LHmuC	850	36	3.0	0.83

- Probes well beyond HERA and the electroweak scale
- Highest Q^2 requires largest integrated lumi (10^{33}–10^{34} Hz/cm^2)
    - But measurements low Q^2 and x can benefit from relatively low lumi orders of magnitude smaller

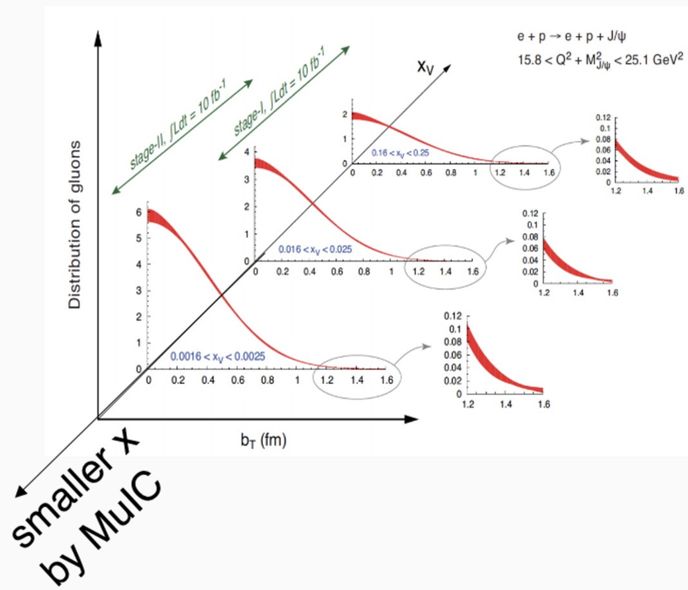
Nuclear Physics at the MuIC

Gluon saturation



What's the property of high-density gluon matter

3D Nucleon structure

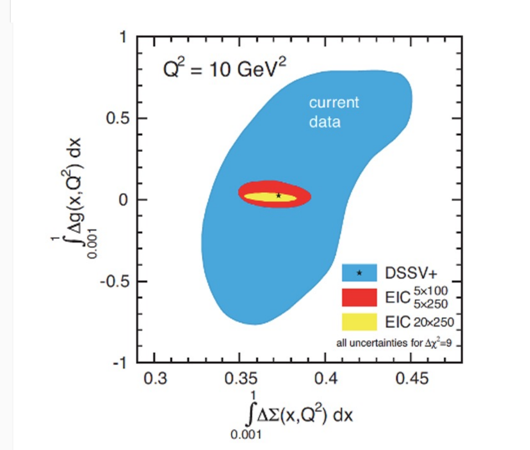


Nucleon spin puzzle

"Helicity sum rule"

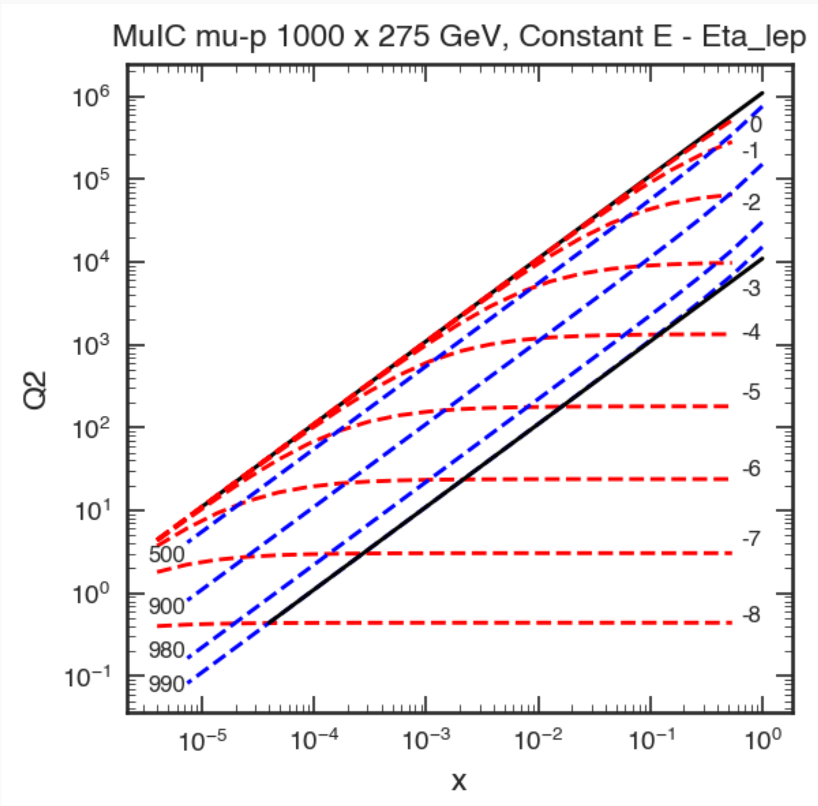
$$\frac{1}{2}\hbar = \frac{1}{2}\Delta\Sigma + \Delta G + \sum_q L_q^z + L_g^z$$

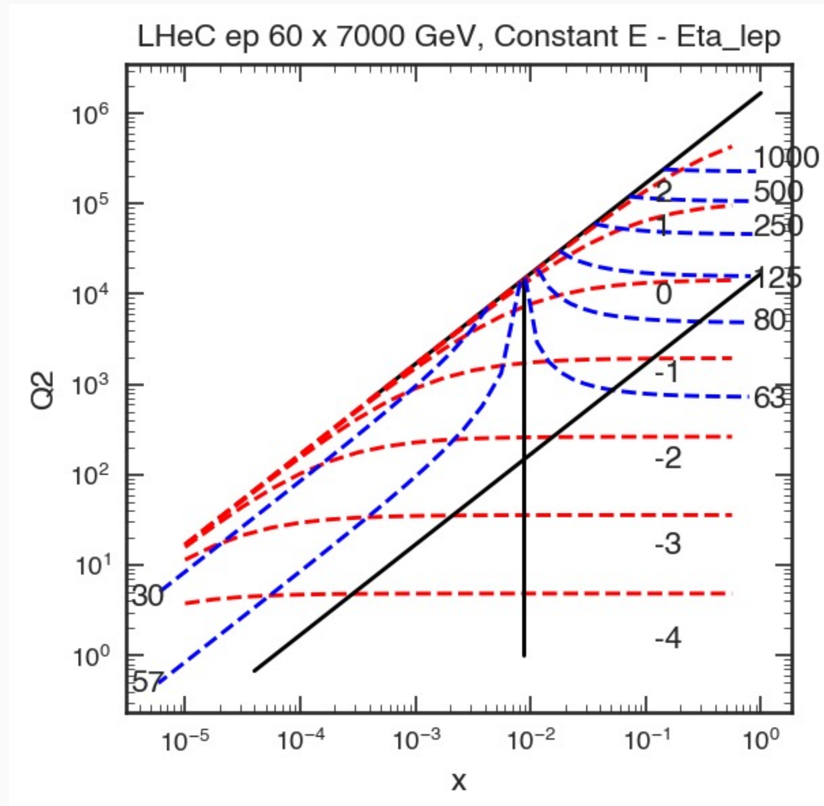
quark contribution | gluon contribution | orbital angular momentum



MuIC to reach x ~ 10^{-5}

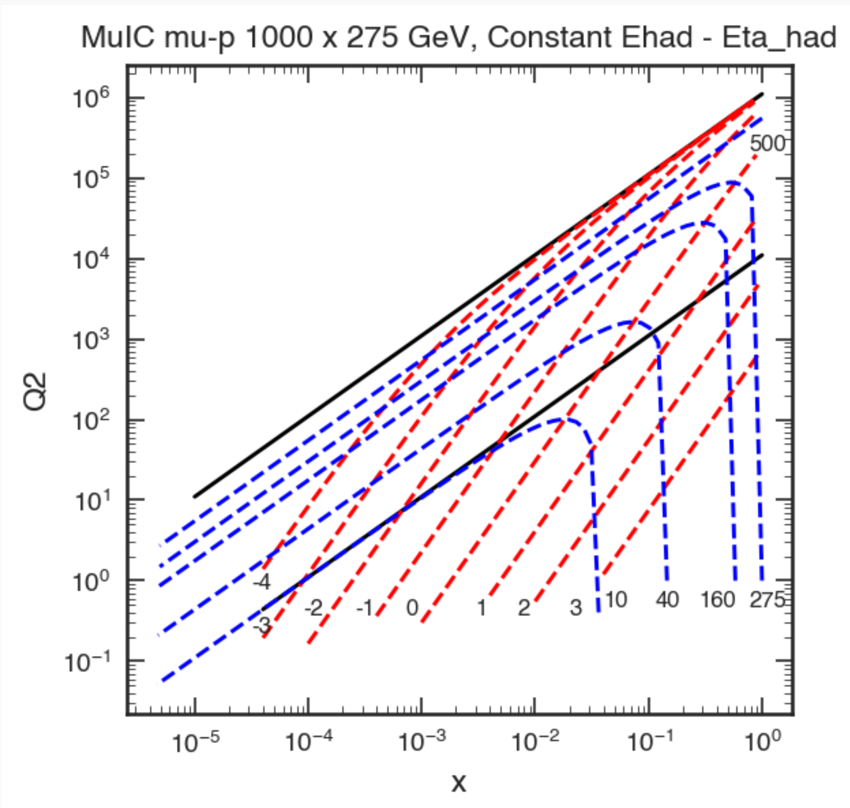
Lepton DIS Kinematics of MuIC Compared to LHeC

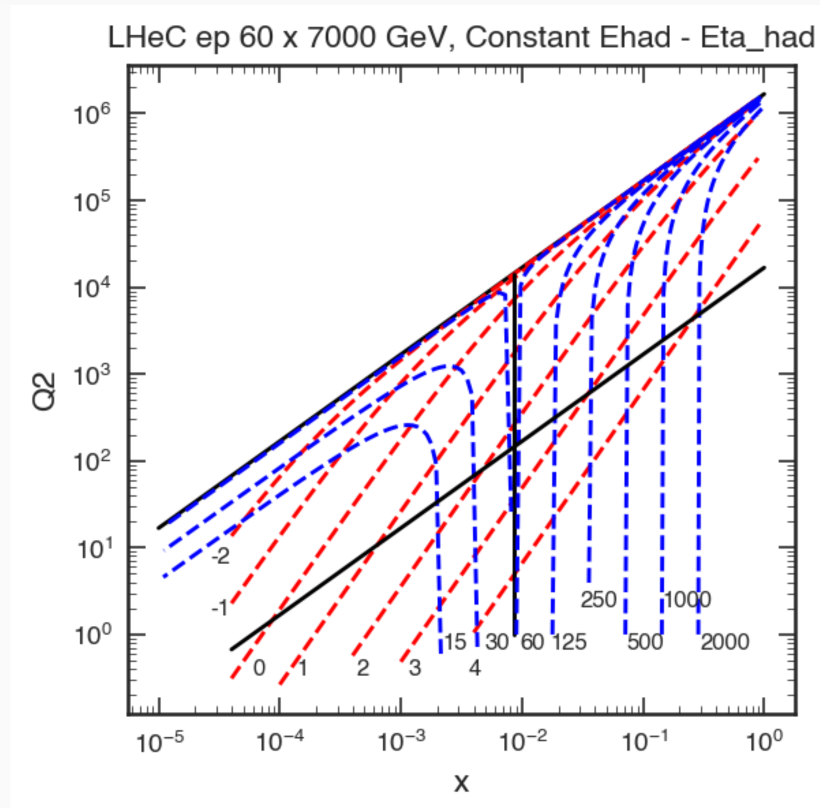




- Much higher scattered muon energy and higher |η| at MuIC

Hadron DIS Kinematics of MuIC Compared to LHeC

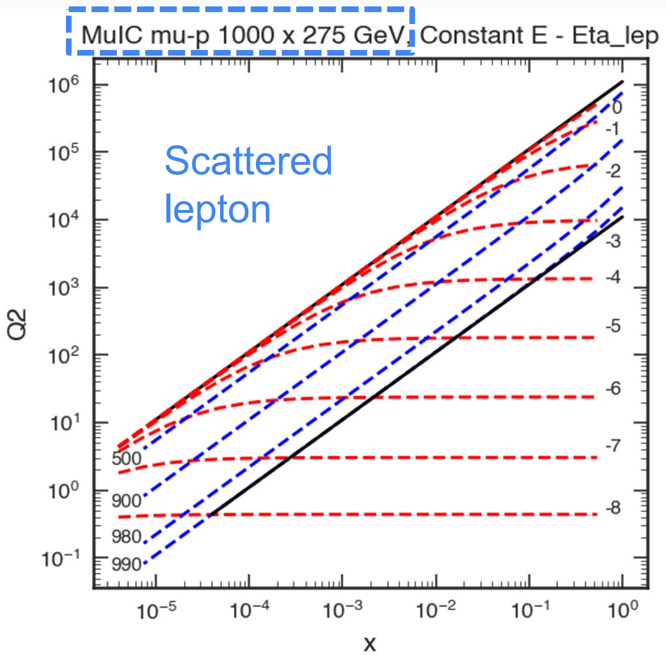


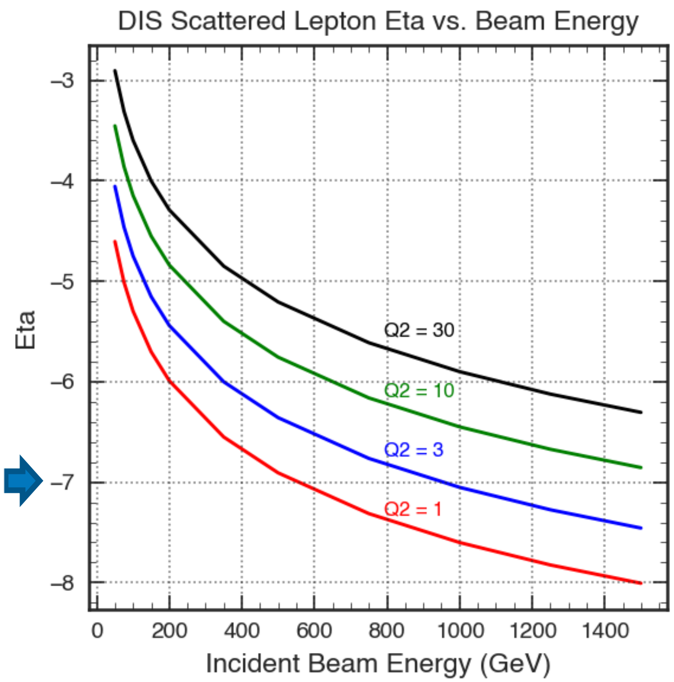


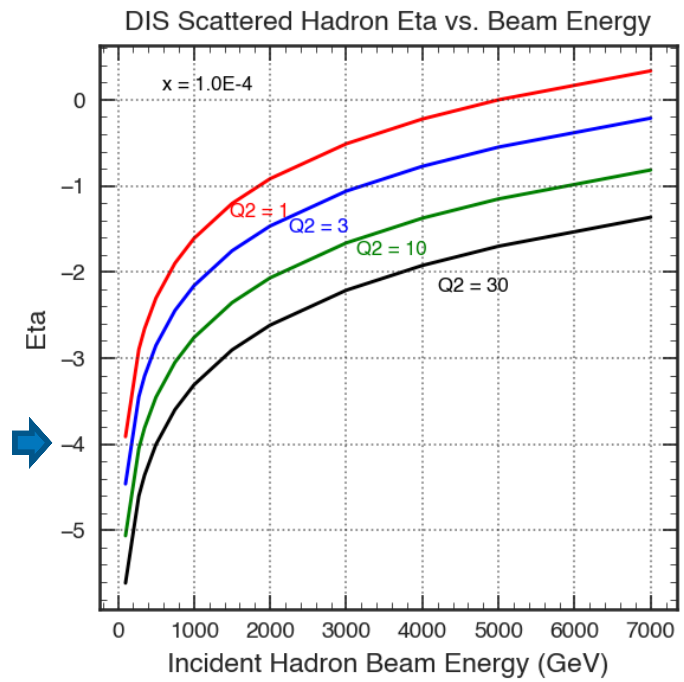
- Hadron system peaks more in proton direction and lower energy at low x for LHeC

DIS Scattering Kinematics at a μp Collider

- The scattered muon is in the far backward (downstream muon) direction
- Hadronic system is more central, but toward muon beam direction



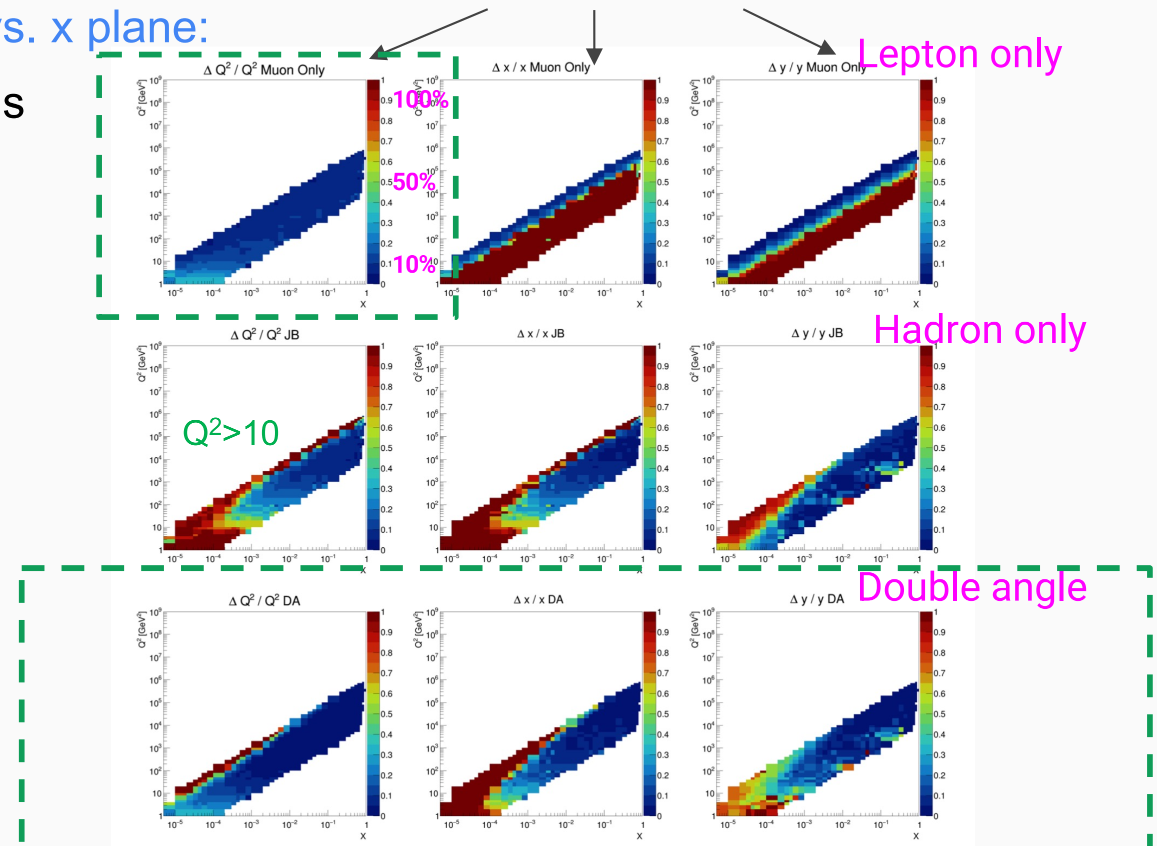




DIS Resolution Studies

Resolutions of reconstructed Q^2, *x* and *y* with 3 methods

Q^2 vs. x plane:

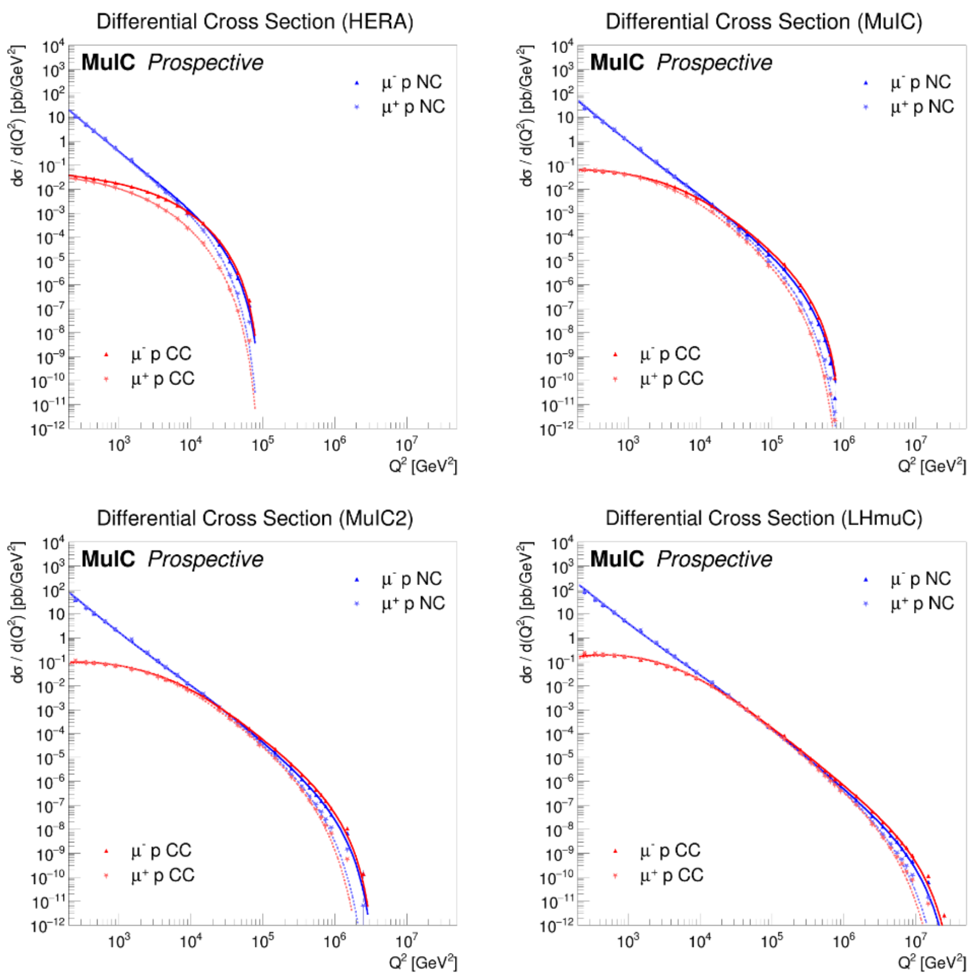


Simple assumptions of detector resolutions to smear particles from PYTHIA 8

Particle	Detector	Resolution	
		$\frac{\sigma(p)}{p}$ or $\frac{\sigma(E)}{E}$	$\sigma(\eta,\varphi)$
(Forward) Muons	e.g., MPGD	$0.01\%\, p \oplus 1\%$	0.2×10^{-3}
Charged particles ($\pi^\pm, K^\pm, p/\bar{p}, e^\pm$)	Tracker + PID	$0.1\%\, p \oplus 1\%$	$\left(\frac{2}{p} \oplus 0.2\right)\times10^{-3}$
Photons	EM Calorimeter	$\frac{10\%}{\sqrt{E}} \oplus 2\%$	$\frac{0.087}{\sqrt{12}}$
Neutral hadrons (n, K_L^0)	Hadronic Calorimeter	$\frac{50\%}{\sqrt{E}} \oplus 10\%$	$\frac{0.087}{\sqrt{12}}$

- Muons: 10% at 1 TeV, $\eta > -7$
- Hadrons: $-4 < \eta < 2.4$ (shielding)

DIS Differential Cross Sections in Q^2



Higgs Boson Cross Sections at MuIC

TABLE XII. Cross sections, in fb, for 125 GeV Higgs boson production in $\mu^- p$ scattering. The μ^- beam energy is 960 GeV and the proton beam energy is 275 GeV. P is the polarization of the muon beam.

	P = −40%	P = −20%	P = −10%	P = 0 %	P = 10%	P = 20%	P = 40%	P = 100%
σ_{CC}	91.1	78.2	71.7	65.1	58.8	52.1	39.0	0
σ_{NC}	12.6	12.1	11.9	11.6	11.4	11.1	10.5	8.9
σ_{tH}	0.0224	0.0187	0.0174	0.0158	0.0139	0.0128	0.0096	0
total	103.7	90.3	83.6	76.7	70.2	63.2	49.5	8.9

TABLE XIII. Cross sections, in fb, for 125 GeV Higgs boson production in $\mu^+ p$ scattering. The μ^+ beam energy is 960 GeV and the proton beam energy is 275 GeV. P is the polarization of the muon beam.

	P = 40%	P = 20%	P = 10%	P = 0 %	P = −10%	P = −20%	P = −40%	P = −100%
σ_{CC}	45.0	38.2	35.6	32.1	28.9	25.6	19.2	0
σ_{NC}	12.4	12.0	11.7	11.6	11.3	11.0	10.6	9.1
σ_{tH}	0.0220	0.0190	0.0173	0.0157	0.0142	0.0127	0.0093	0
total	57.4	50.2	47.3	43.7	40.2	36.6	29.8	9.1

W Boson Cross Sections at MuIC

TABLE VIII. Cross sections for the $W^+\mu^-$ process in $\mu^- p$ collisions for different beam energy configurations and with different cutoffs on the scattered muon p_T. The listed cross sections are in pb, with scale uncertainties and PDF$\oplus\alpha_s$ uncertainties. The μ^- beam energy is unpolarized in all cases.

$E_\mu \times E_p$ (TeV^2)	Inclusive	$p_T^\ell > 1$ GeV	$p_T^\ell > 2$ GeV	$p_T^\ell > 5$ GeV
0.96×0.275	8.93 $^{+1.0\%}_{-1.2\%}$ $^{+0.7\%}_{-0.7\%}$	2.29 $^{+2.4\%}_{-2.5\%}$ $^{+0.8\%}_{-0.8\%}$	1.86 $^{+2.6\%}_{-2.7\%}$ $^{+0.8\%}_{-0.8\%}$	1.32 $^{+3.2\%}_{-3.1\%}$ $^{+0.8\%}_{-0.8\%}$
0.96×0.96	22.4 $^{+1.2\%}_{-1.7\%}$ $^{+0.7\%}_{-0.7\%}$	6.19 $^{+0\%}_{-0.4\%}$ $^{+0.7\%}_{-0.7\%}$	5.13 $^{+0\%}_{-0.3\%}$ $^{+0.7\%}_{-0.7\%}$	3.77 $^{+0.4\%}_{-0.7\%}$ $^{+0.7\%}_{-0.7\%}$
1.5×7	90.1 $^{+6.0\%}_{-6.7\%}$ $^{+1.0\%}_{-1.0\%}$	27.4 $^{+4.6\%}_{-5.3\%}$ $^{+0.8\%}_{-0.8\%}$	23.1 $^{+4.3\%}_{-5.0\%}$ $^{+0.8\%}_{-0.8\%}$	17.6 $^{+4.0\%}_{-4.6\%}$ $^{+0.8\%}_{-0.8\%}$
1.5×13.5	124 $^{+7.4\%}_{-8.0\%}$ $^{+1.1\%}_{-1.1\%}$	38.7 $^{+5.9\%}_{-6.5\%}$ $^{+0.9\%}_{-0.9\%}$	32.6 $^{+5.6\%}_{-6.3\%}$ $^{+0.9\%}_{-0.9\%}$	25.0 $^{+5.2\%}_{-5.9\%}$ $^{+0.8\%}_{-0.8\%}$
1.5×20	150 $^{+8.1\%}_{-8.8\%}$ $^{+1.1\%}_{-1.1\%}$	47.0 $^{+6.6\%}_{-7.3\%}$ $^{+0.9\%}_{-0.9\%}$	40.0 $^{+6.4\%}_{-7.0\%}$ $^{+0.9\%}_{-0.9\%}$	30.6 $^{+5.9\%}_{-6.5\%}$ $^{+0.9\%}_{-0.9\%}$
1.5×50	225 $^{+9.9\%}_{-10\%}$ $^{+1.3\%}_{-1.3\%}$	72.8 $^{+8.4\%}_{-8.9\%}$ $^{+1.0\%}_{-1.0\%}$	61.7 $^{+8.2\%}_{-8.7\%}$ $^{+1.0\%}_{-1.0\%}$	47.8 $^{+7.7\%}_{-8.2\%}$ $^{+1.0\%}_{-1.0\%}$

TABLE IX. Cross sections for the $W^-\mu^-$ process in $\mu^- p$ collisions for different beam energy configurations and with different cutoffs on the scattered muon p_T. The listed cross sections are in pb, with scale and PDF$\oplus\alpha_s$ uncertainties. The μ^- beam energy is unpolarized in all cases.

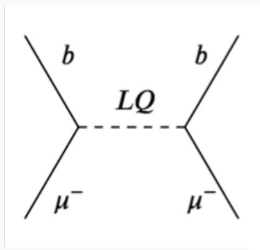
$E_\mu \times E_p$ (TeV^2)	Inclusive	$p_T^\ell > 1$ GeV	$p_T^\ell > 2$ GeV	$p_T^\ell > 5$ GeV
0.96×0.275	8.69 $^{+0.7\%}_{-1.0\%}$ $^{+0.9\%}_{-0.9\%}$	2.10 $^{+1.6\%}_{-2.0\%}$ $^{+0.9\%}_{-0.9\%}$	1.71 $^{+1.8\%}_{-2.1\%}$ $^{+0.9\%}_{-0.9\%}$	1.23 $^{+2.4\%}_{-2.4\%}$ $^{+0.9\%}_{-0.9\%}$
0.96×0.96	21.2 $^{+1.7\%}_{-2.3\%}$ $^{+0.8\%}_{-0.8\%}$	5.76 $^{+0.7\%}_{-1.4\%}$ $^{+0.8\%}_{-0.8\%}$	4.79 $^{+0.6\%}_{-1.2\%}$ $^{+0.8\%}_{-0.8\%}$	3.57 $^{+0.2\%}_{-0.7\%}$ $^{+0.8\%}_{-0.8\%}$
1.5×7	86.7 $^{+6.7\%}_{-7.4\%}$ $^{+1.0\%}_{-1.0\%}$	26.8 $^{+5.5\%}_{-6.3\%}$ $^{+0.9\%}_{-0.9\%}$	22.8 $^{+5.4\%}_{-6.1\%}$ $^{+0.9\%}_{-0.9\%}$	17.8 $^{+5.0\%}_{-5.7\%}$ $^{+0.8\%}_{-0.8\%}$
1.5×13.5	121 $^{+7.9\%}_{-8.6\%}$ $^{+1.1\%}_{-1.1\%}$	38.3 $^{+6.8\%}_{-7.6\%}$ $^{+1.0\%}_{-1.0\%}$	32.6 $^{+6.6\%}_{-7.4\%}$ $^{+0.9\%}_{-0.9\%}$	25.6 $^{+6.2\%}_{-6.9\%}$ $^{+0.9\%}_{-0.9\%}$
1.5×20	145 $^{+8.6\%}_{-9.3\%}$ $^{+1.2\%}_{-1.2\%}$	47.0 $^{+7.4\%}_{-8.2\%}$ $^{+1.0\%}_{-1.0\%}$	40.1 $^{+7.4\%}_{-8.1\%}$ $^{+1.0\%}_{-1.0\%}$	31.6 $^{+7.0\%}_{-7.7\%}$ $^{+0.9\%}_{-0.9\%}$
1.5×50	221 $^{+11\%}_{-11\%}$ $^{+1.4\%}_{-1.4\%}$	73.6 $^{+9.3\%}_{-9.9\%}$ $^{+1.1\%}_{-1.1\%}$	63.3 $^{+9.0\%}_{-9.7\%}$ $^{+1.1\%}_{-1.1\%}$	50.3 $^{+8.6\%}_{-9.3\%}$ $^{+1.2\%}_{-1.1\%}$

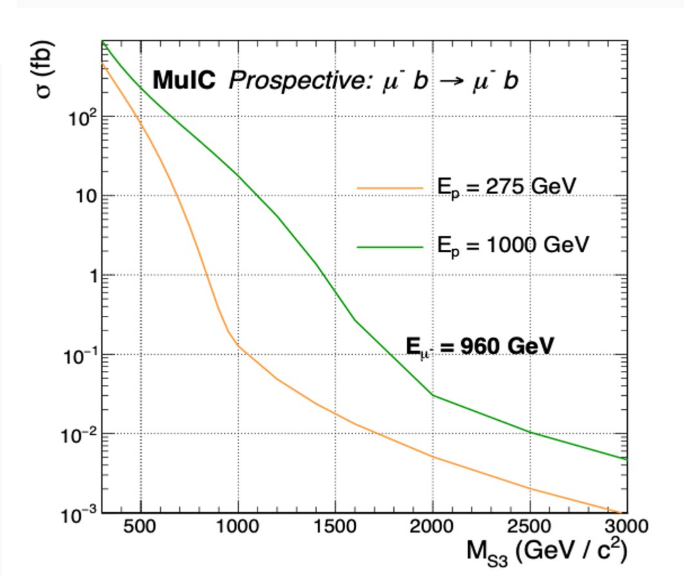
TABLE VI. Cross sections for the $W^-\nu_\mu$ process in $\mu^- p$ collisions for different beam energy configurat
The μ^- beam energy is unpolarized in all cases.

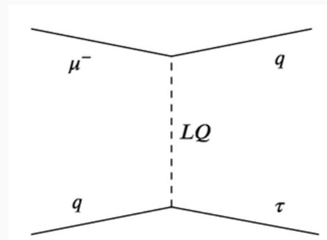
$E_\mu \times E_p$ (TeV^2)	σ (pb)	Scale unc.	PDF$\oplus\alpha_s$ unc.
0.96×0.275	1.80	$^{+2.8\%}_{-5.6\%}$	$^{+1.4\%}_{-1.4\%}$
0.96×0.96	7.47	$^{+7.9\%}_{-11\%}$	$^{+1.4\%}_{-1.4\%}$
1.5×7	52.8	$^{+15\%}_{-17\%}$	$^{+1.3\%}_{-1.3\%}$
1.5×13.5	79.8	$^{+16\%}_{-18\%}$	$^{+1.2\%}_{-1.2\%}$
1.5×20	100	$^{+17\%}_{-19\%}$	$^{+1.2\%}_{-1.2\%}$
1.5×50	167	$^{+19\%}_{-20\%}$	$^{+1.2\%}_{-1.2\%}$

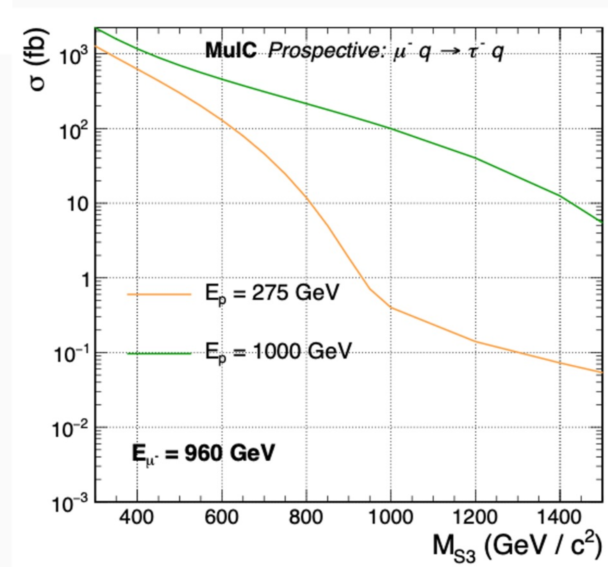
Leptoquark Production with Bottom, Tau

- Studies focused on LQ models inspired by B and μ anomalies and LFV
- s-channel S3 LQ(b) production
- t-channel S3 LQ(τ) production

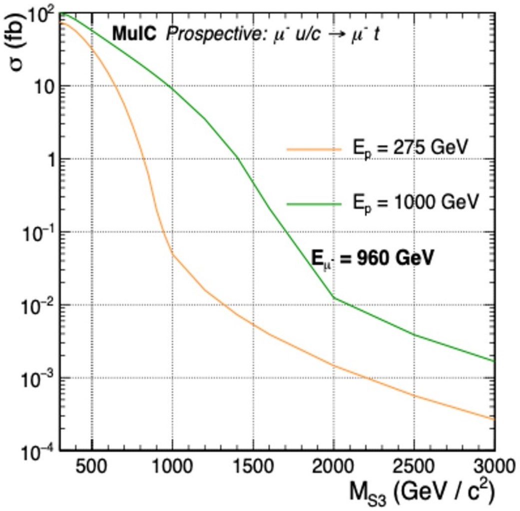


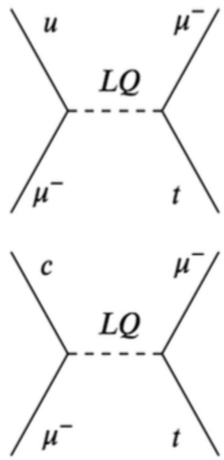


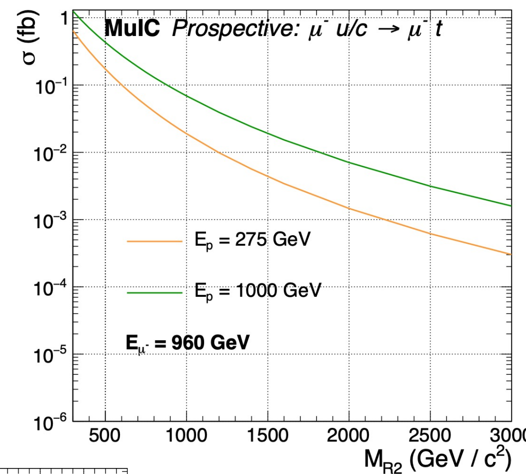


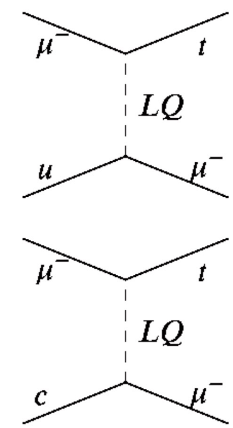


Leptoquark Production with Top

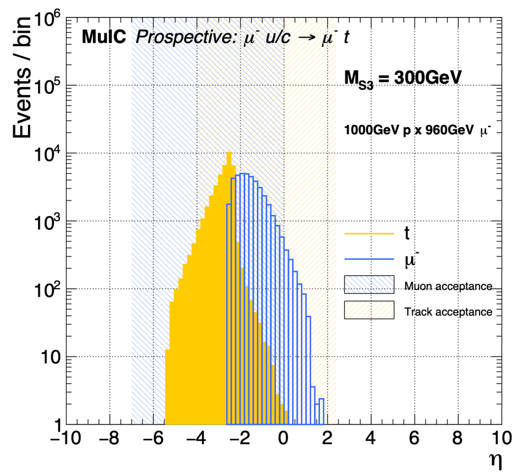








- s-channel S3 LQ production to μ+t
  - Final state muon in central region of detector



- t-channel R2 LQ production to μ+t

Potential limits still to be worked out