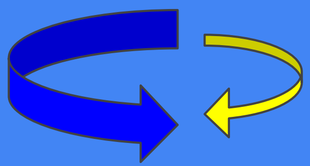


Muon-Ion Collider Overview

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

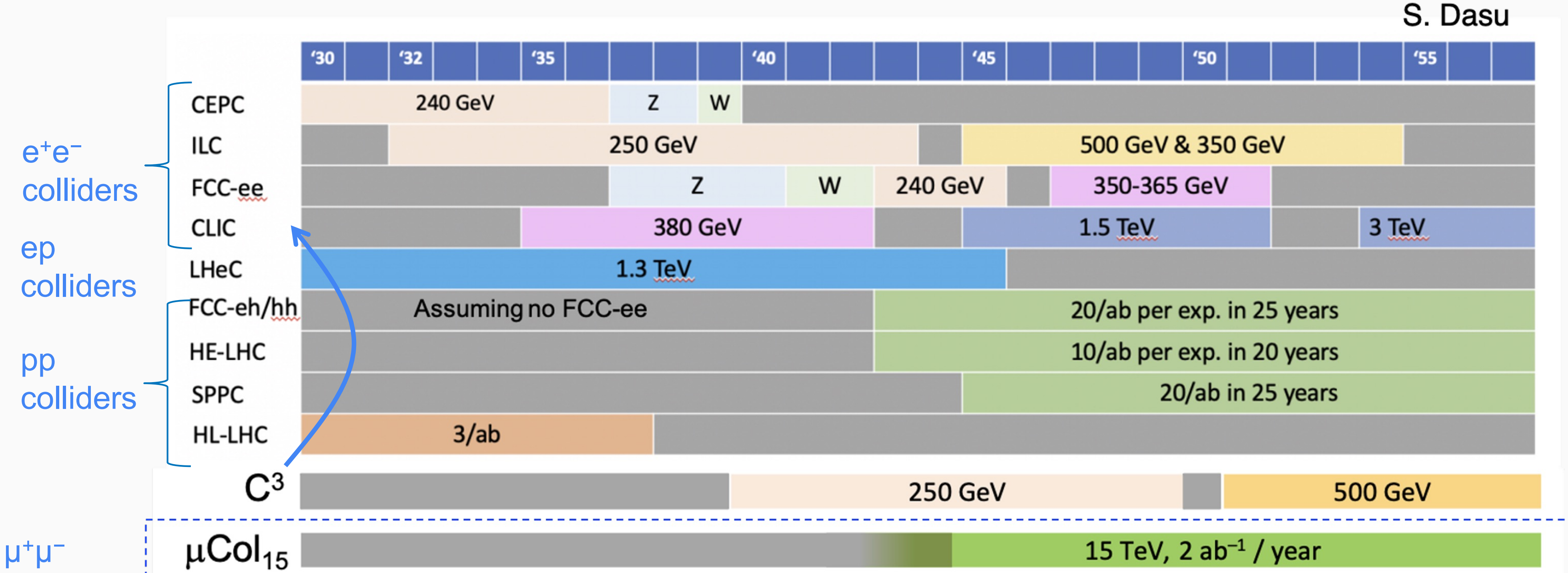
- Future particle collider options, including muon colliders
- Muon-ion collider concept
  - One O(TeV) muon ring as a first step, colliding with a high-energy hadron beam
- Experiment considerations
- Science cases
  - Deep Inelastic Scattering structure measurements of p/ions, and QCD
  - Higgs and SM particle production processes
  - BSM physics (Z’, LQ)

The Future of Particle Physics

- What are the next steps beyond the LHC program to address some of the open questions in particle physics?
  - Higher precision experiments
    - Measure quantities more precisely to test for deviations from theory through higher intensity beams and collisions
    - The indirect, finessed approach
  - Higher energy colliders
    - Pack more energy into collisions to produce more massive particles
    - The brute force, direct approach
  - Or both!
- There is currently an ongoing community exercise in the U.S. to help set the priorities for the future ("Snowmass" process, followed by "P5" report to the Dept. of Energy)
  - In some ways we are at a branch point, with many possible directions
    - "Higgs factories" to study Higgs couplings more precisely
    - Energy frontier machines to produce new particles, probe Higgs potential shape

Future of High Energy Physics Energy Frontier

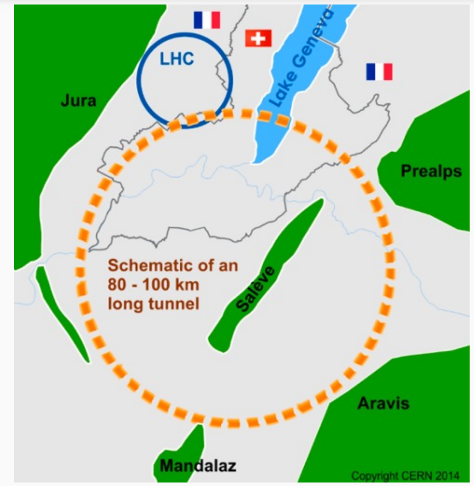
- Many options for Higgs factories and energy frontier machines
- What is an optimal and realistic path forward? Worldwide decision…

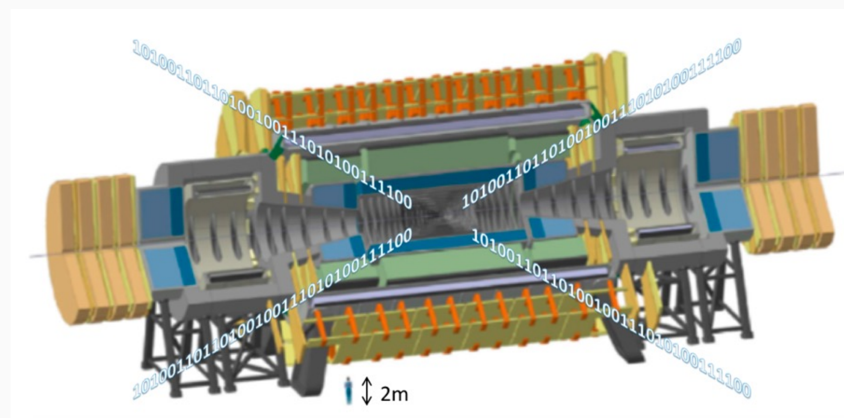


Strong interest in a more exotic collider: a muon collider

A Future Circular Collider? (hadrons)

- Scale up the LHC by about a factor 5 or more
- Goals:
  - Higher energy: ~100 TeV
    - Explore the high energy frontier:
      → heavy new particles
  - Higher luminosity: 5–30 x 10^{34} Hz/cm^2
    - High precision, e.g. Higgs boson couplings
- Challenges:
  - 100 km ring
    - Though the SSC(*) in Texas would have been that size...
  - 1000 pp collisions per beam crossing
  - Higher radiation levels in tracking volume
  - Huge data rates from detectors





The SSC: A Footnote in the Smithsonian

- The Superconducting Super Collider
  - 40 TeV center-of-mass energy
  - Waxahachie, TX
  - R.I.P. 1993

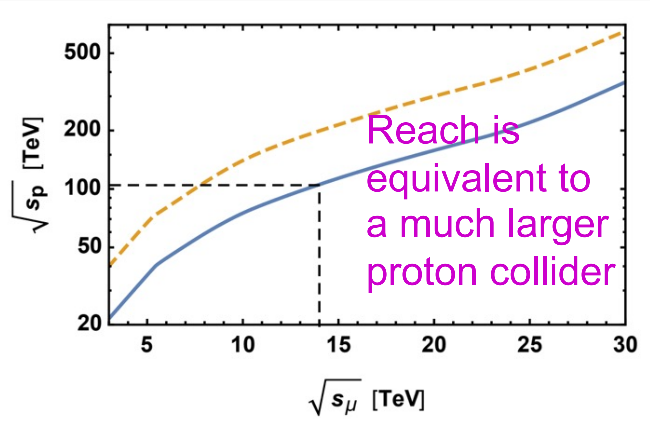
Circa 2005

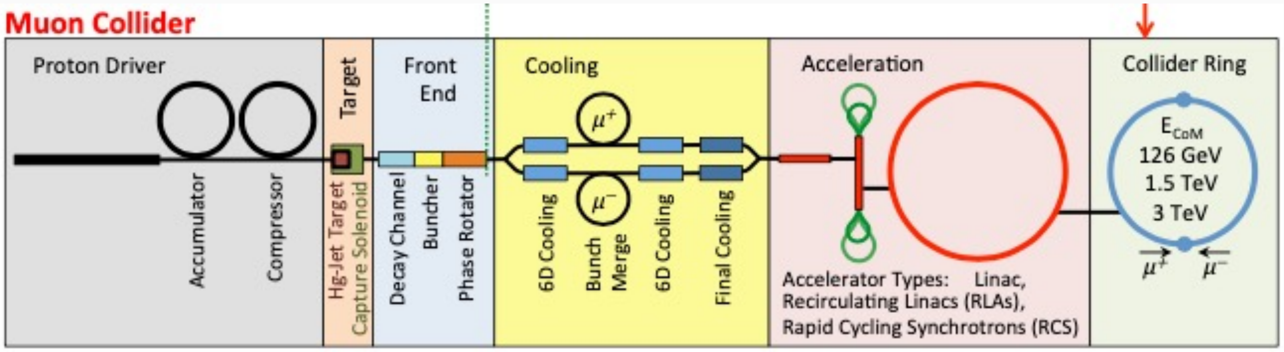
← Texas!

A Muon Collider?

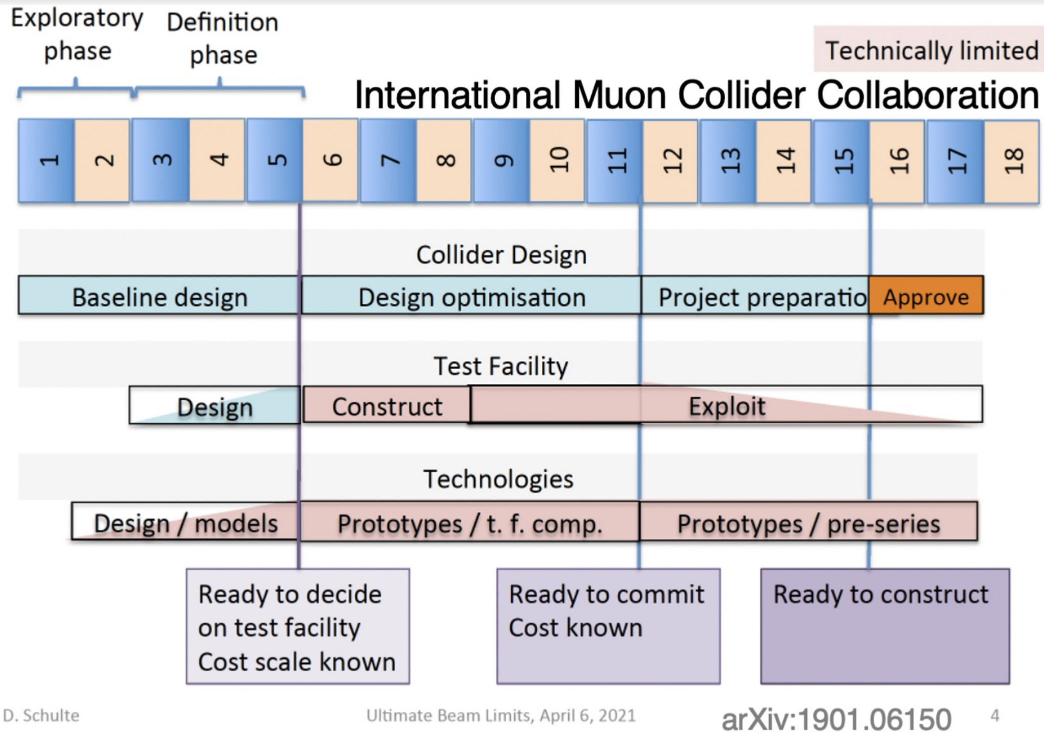
- A more compact and innovative facility to incorporate the advantages of a high precision lepton collider and an energy frontier machine
  - $\mu^+\mu^-$ annihilation uses all of the beam energy in a collision, whereas quark/gluon collisions use only a fraction of the proton beam energies
  - Muons also radiate away much less energy than an e^+e^- collider, and can be smaller than proton colliders for equivalent reach
- But it's a race against time to produce, cool, and accelerate muons !
  - Recall that muons decay in 2.2μs
  - Significant extension to higher energy and intensity than g-2 storage ring

Needs R&D





Potential timeline of muon colliders



arXiv:1901.06150

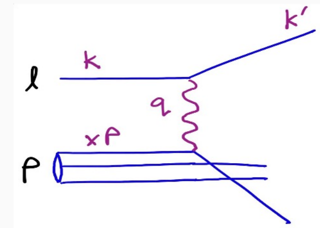
Physics potential along the way

A vigorous and ambitious R&D program is needed to assess the feasibility of a tens-of-TeV's muon collider. Therefore it is important to investigate the physics potential of smaller-scale machines that might be built along the way as technology demonstrators. Starting from medium energy, the first option to be considered is a muon collider operating around the top production threshold ($\sim$ 400 GeV). This

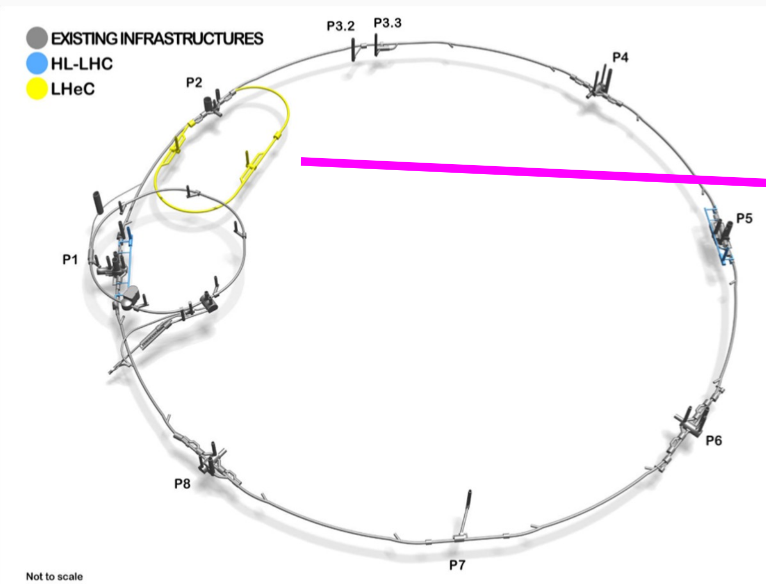
A demonstrator with compelling science is needed before going to O(10+) TeV

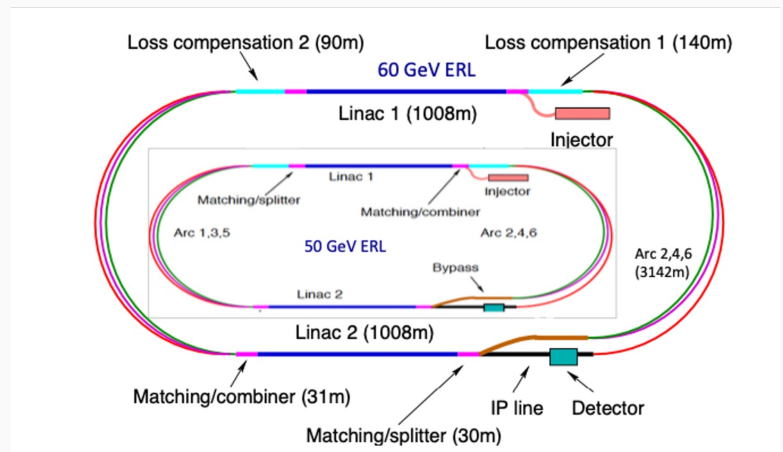
A Hybrid Collider: The Large Hadron-Electron Collider at CERN

LHeC: arXiv:2007.14491

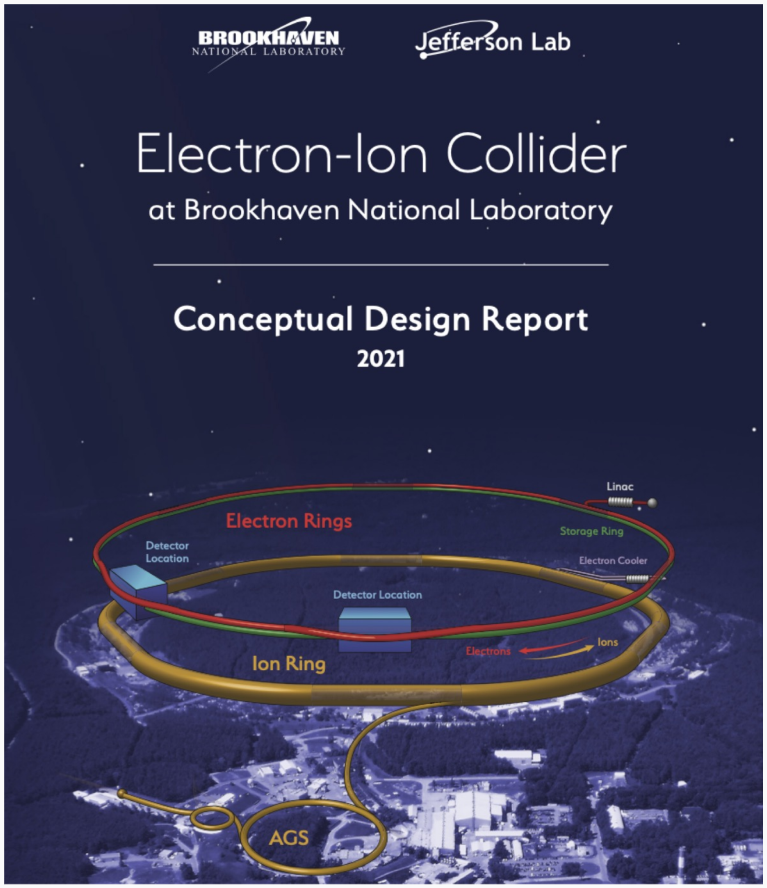


- A proposed next generation Deep Inelastic Scattering experiment to study nuclear structure and more
- LHeC: 50 – 60 GeV e⁻ on 7 TeV p ($\sqrt{s}$ = 1.2−1.3 TeV)
    - Two oppositely directed linacs and 3 arcs, collide with one LHC beam
    - Two design options: 50 GeV (smaller) vs. 60 GeV (larger, more expensive)





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? 🤔

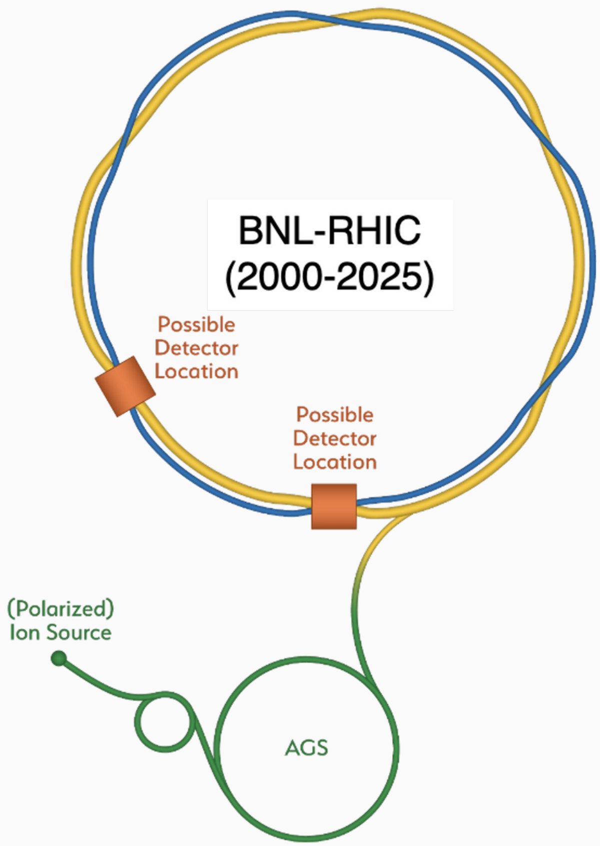
A lot of interest in μμ colliders…

Physics goals:

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

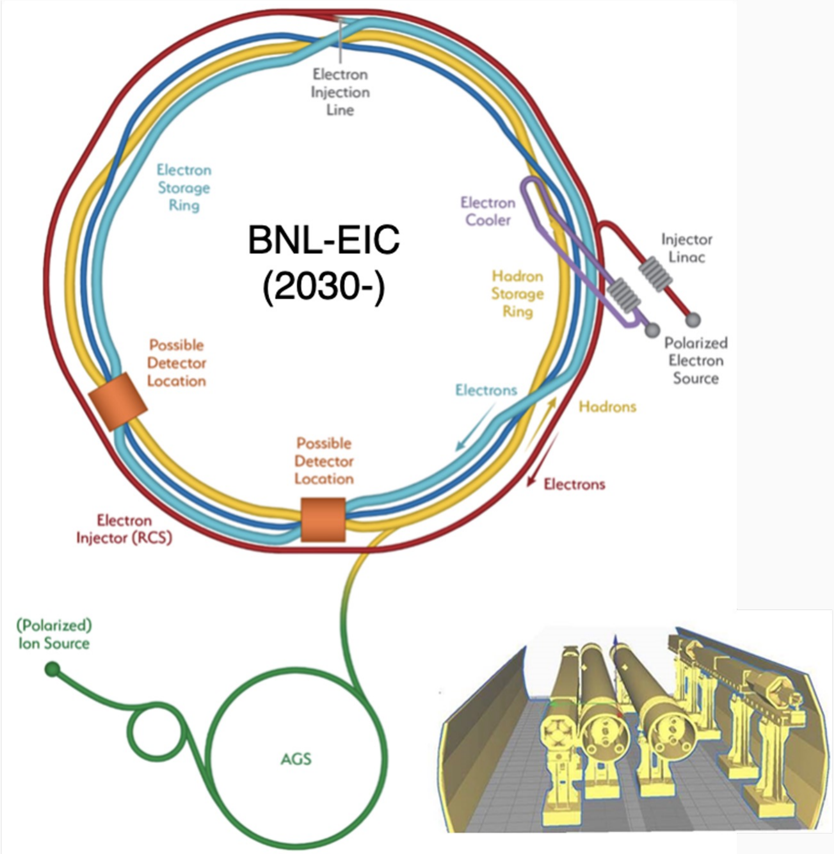
Electron-Ion Collider at BNL

pp, pA, AA up to 500 GeV

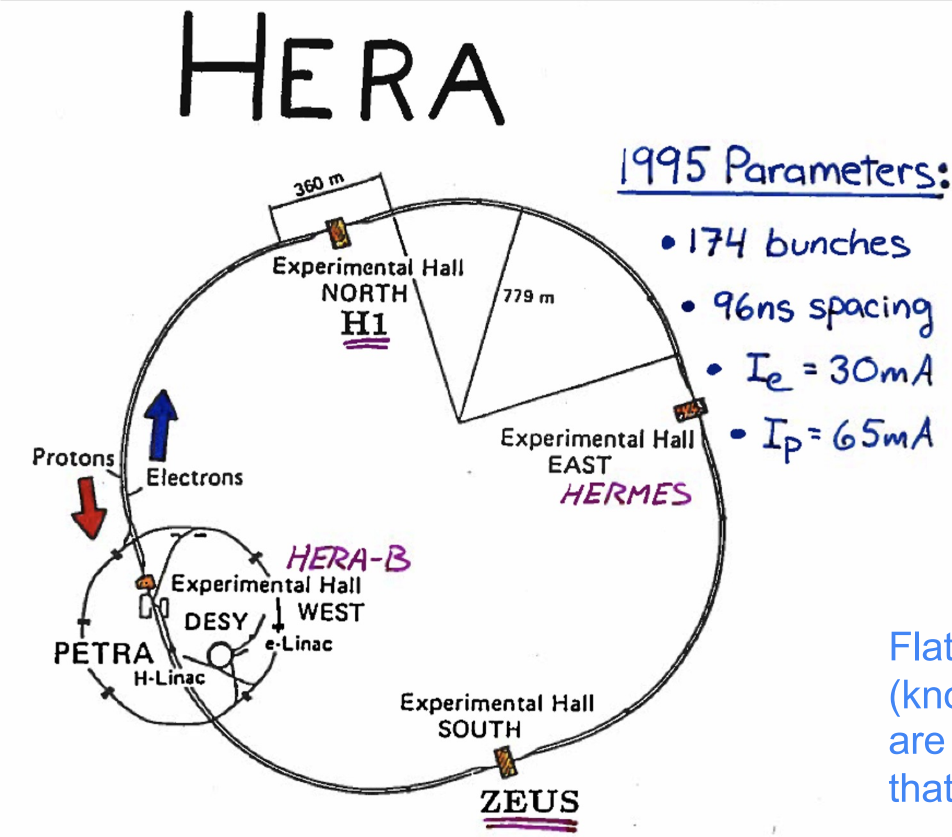


upgrade

ep, eA up to 140 GeV



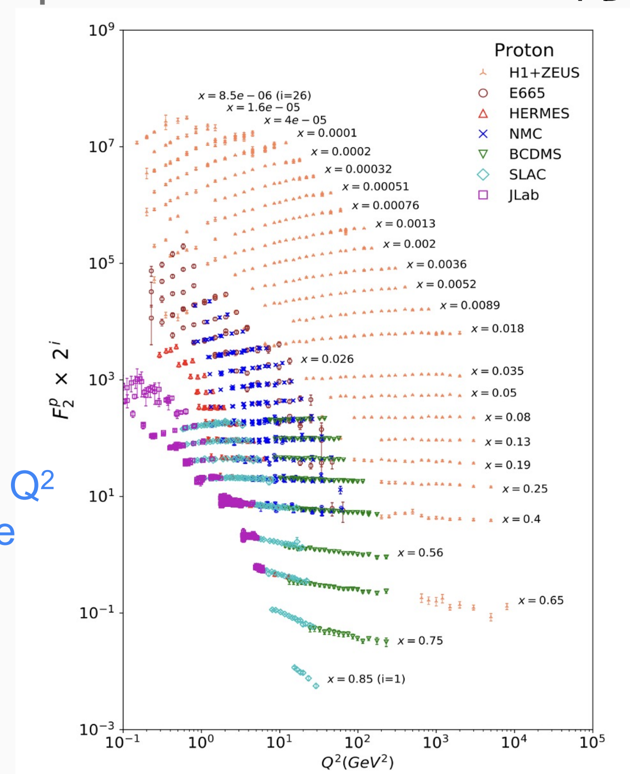
A Successor to HERA



27.5 GeV e± on 820-920 GeV p → √s = 318 GeV

- HERA probed a completely new Deep Inelastic Scattering regime from earlier fixed target experiments

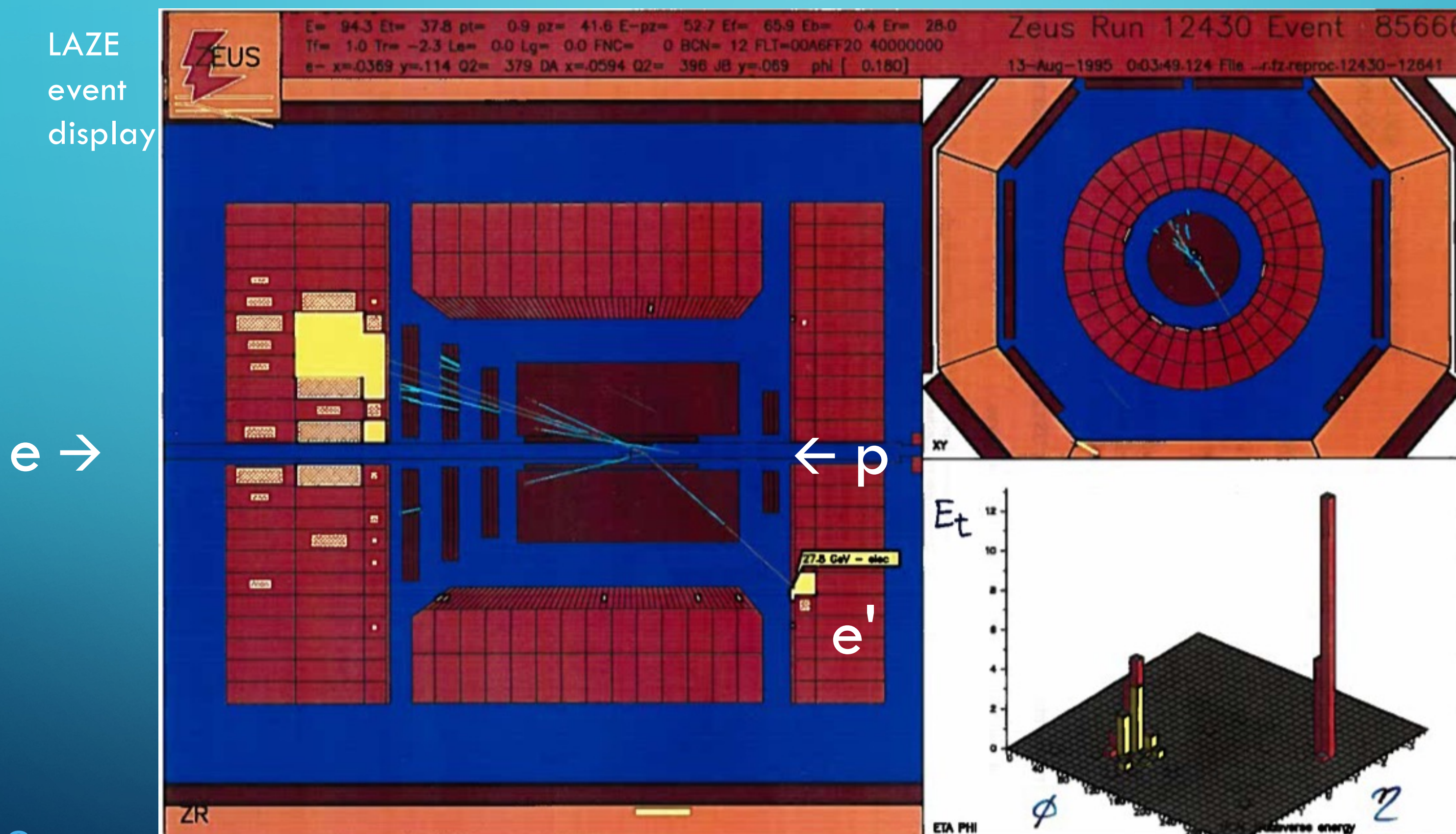
PDG



Flatness of these curves (known as “scaling”) with Q^2 are one piece of evidence that quarks are real

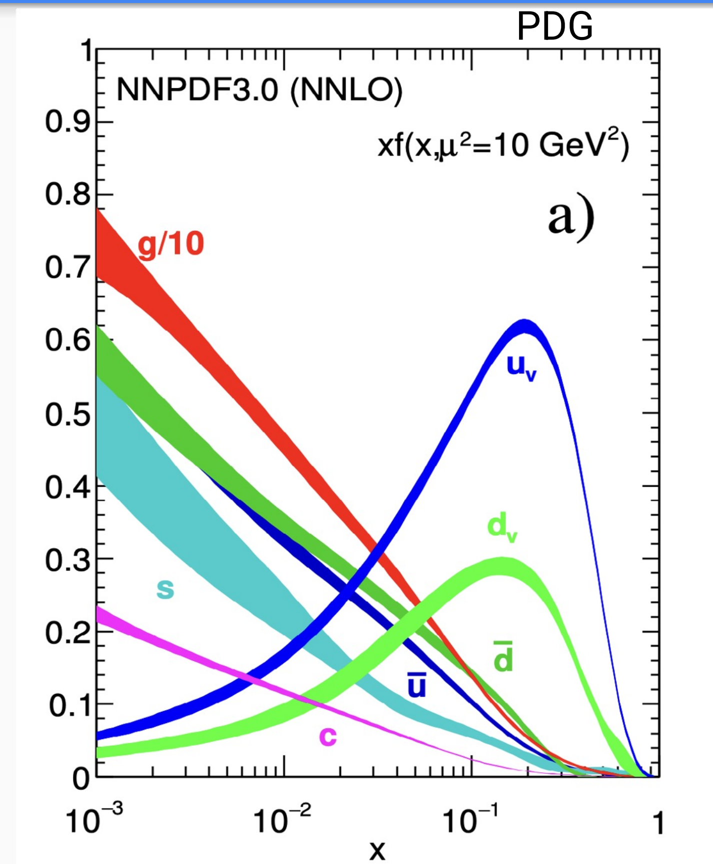
ZEUS DEEP INELASTIC SCATTERING EVENT

LAZE
event
display

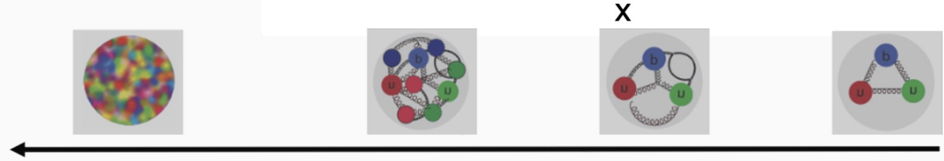


Parton Densities

- HERA paved the way for precision LHC physics through precise structure function measurements, from which the parton densities are extracted through global fits with QCD
- HERA saw the strong rise in the gluon density at low x
    - When do saturation effects come into play?



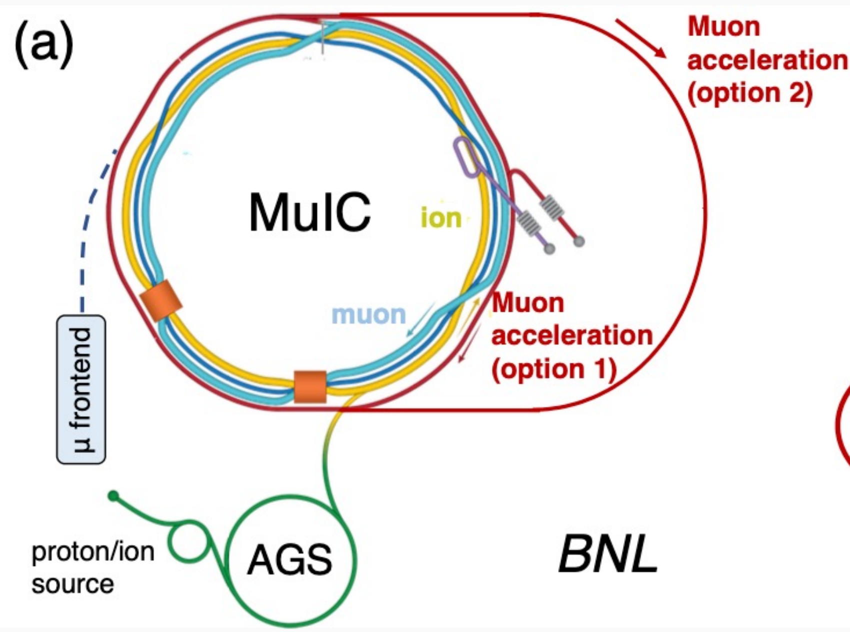
Gluon Saturation



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

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 or more
- Q^2 up to 10^6 GeV^2
- x as low as 10^{-6}

Well beyond the EIC, matches that of the proposed LHeC

Provides a science case for a TeV muon storage ring as a demonstrator toward a multi-TeV $\mu^+\mu^-$ collider

- QCD and hadron/nucleon structure in new regimes
- Higgs, Top, and Beyond Standard Model (particularly with LFV with muons)

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

Re-use existing facilities at BNL (MuIC as an upgrade to the EIC)

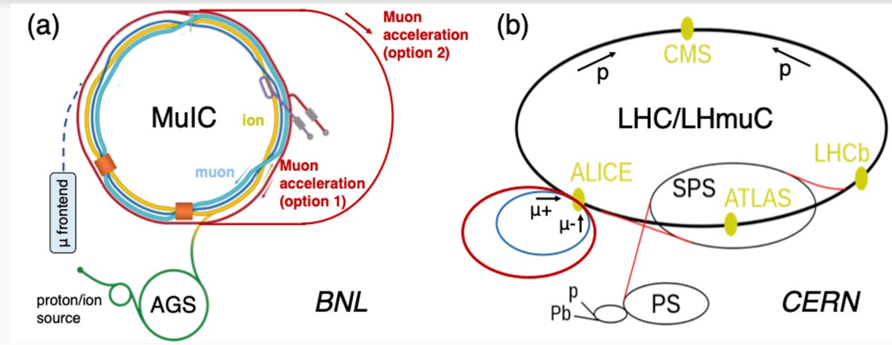
Broad science program helps share costs, and re-use helps economize

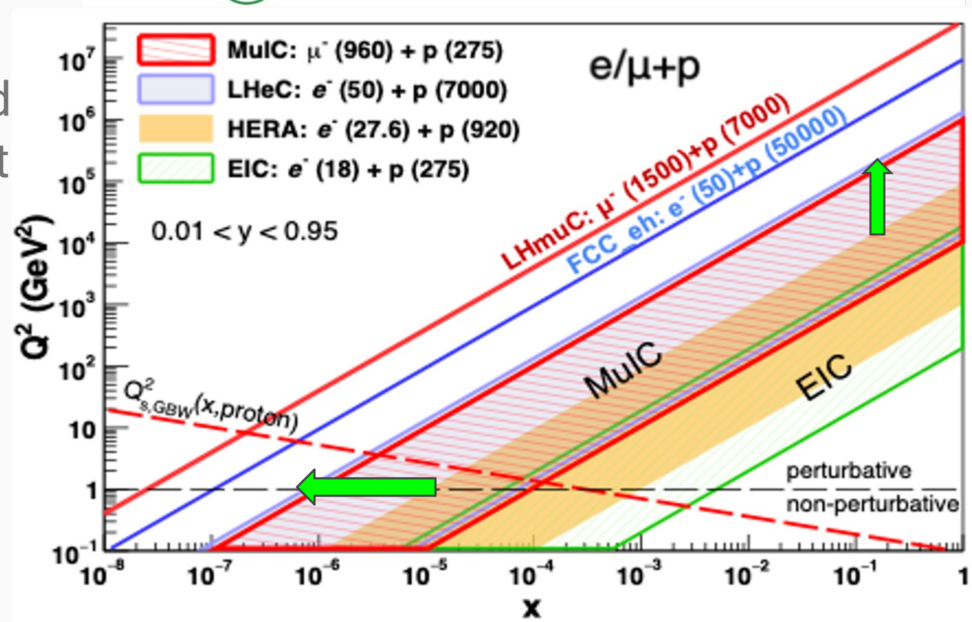
DIS Reach in x and Q^2 for ℓp Collisions

- Expands DIS reach at high Q^2 and low x by 1–3 orders of magnitude over HERA (the only such machine built to date) and the EIC (to be constructed)

- Coverage of MuIC at BNL would be 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



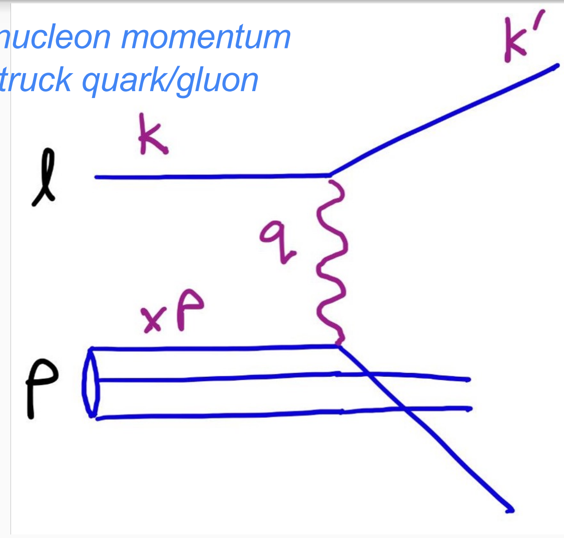


DIS Variables and Kinematics

- $$x = \frac{Q^2}{2P\cdot q}$$ Bjorken x scaling variable

Fraction of nucleon momentum carried by struck quark/gluon

- $$y = \frac{P\cdot q}{P\cdot k}$$ Inelasticity
- $$Q^2 \equiv -q^2 = -(k-k')^2 = sxy$$ 4-mom transfer
- $s = (k + P)^2$ squared c.o.m. energy



θ is the polar angle with respect to the initial hadron direction

From scattered lepton:

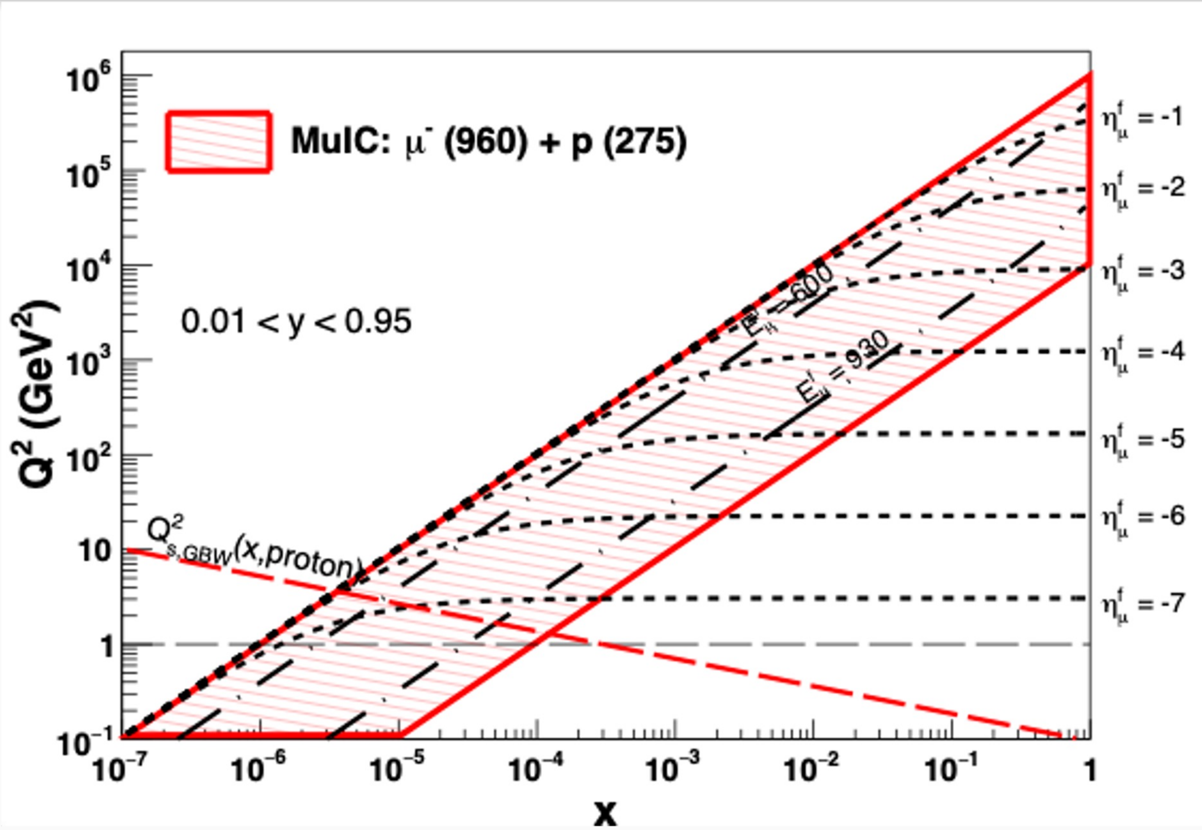
- $$Q^2 = 2E_\ell E'_\ell\,(1+\cos\theta)$$
$$y = 1 - \frac{E'_\ell}{2E_\ell}\,(1-\cos\theta)$$

From scattered hadrons:

$$Q^2(P,\gamma) = \frac{P^2\sin^2\gamma}{1-y(P,\gamma)},$$
$$y(P,\gamma) = \frac{P(1-\cos\gamma)}{2E^i_\mu},$$

$$P^2 = (\Sigma_h P^x_h)^2 + (\Sigma_h P^y_h)^2 + (\Sigma_h P^z_h)^2,$$
$$\cos\gamma = \frac{(\Sigma_h P^x_h)^2 + (\Sigma_h P^y_h)^2 - (\Sigma_h (E_h - P^z_h))^2}{(\Sigma_h P^x_h)^2 + (\Sigma_h P^y_h)^2 + (\Sigma_h (E_h - P^z_h))^2},$$

Scattered Lepton Kinematics - MuIC

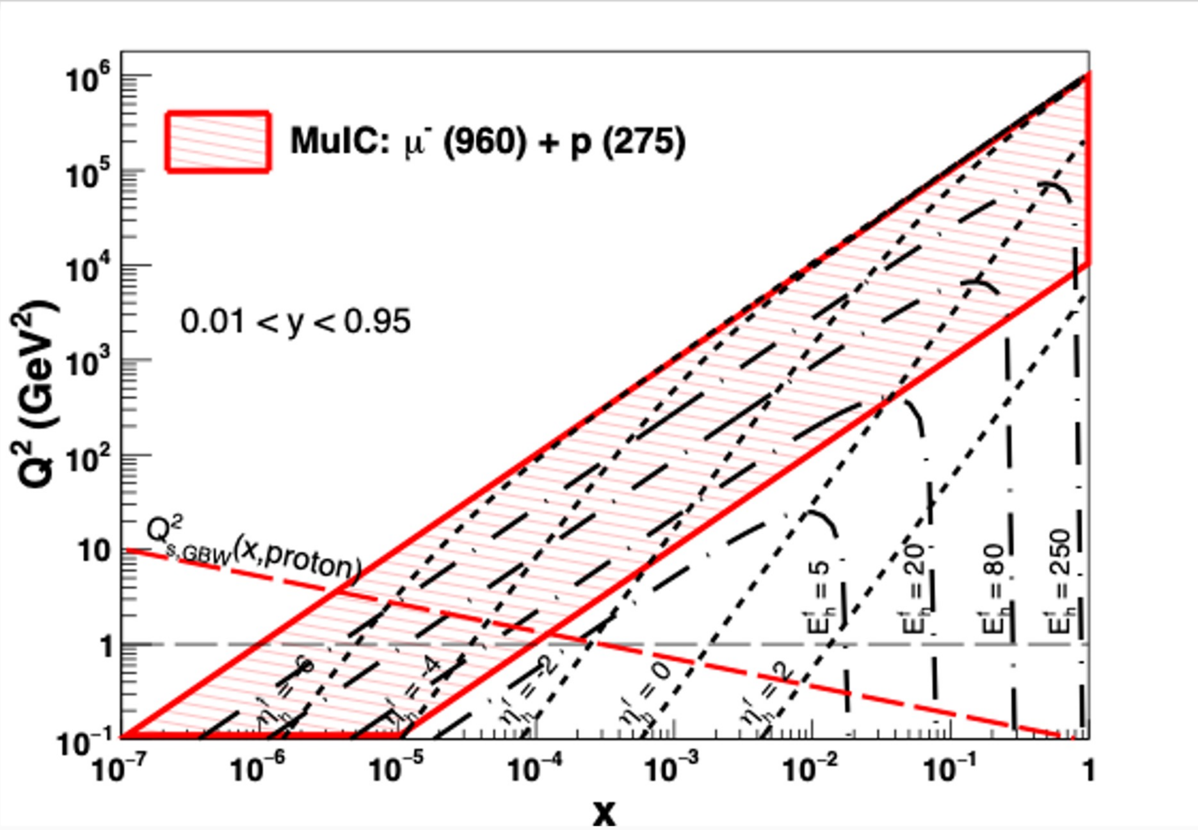


- Scattered muon momentum essentially defines y (decreases with y increasing)
  - **Typically > 500 GeV**
- Scattering angle is in very backward (lepton) direction
  - **−7 < η < −5 at low Q^2**

Only 0.1º to 0.8º from beam line

Distinct experimental challenges in tagging very forward muons to address.
(but hundreds of GeV muons will penetrate through anything, i.e. shielding)

Scattered Hadron Kinematics - MuIC

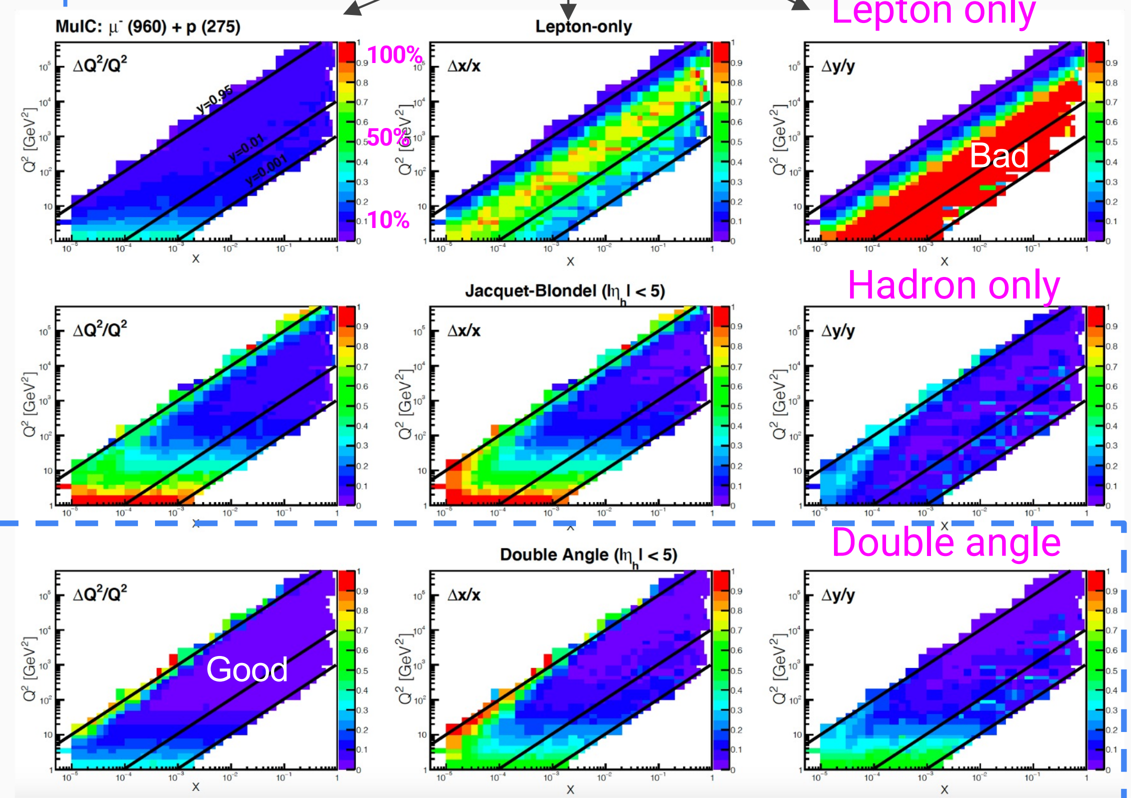


- Scattered energy of hadron system essentially defines y (increases with y)
  - **Typically 20 – 500 GeV**
  - LHeC: < 50 GeV
- Scattering angle is in backward (lepton) direction, less so than muon except at low x
  - **Jet kinematics more central ($-4 < \eta < 2$)**

Detector requirements and design

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: $|\eta| < 5$

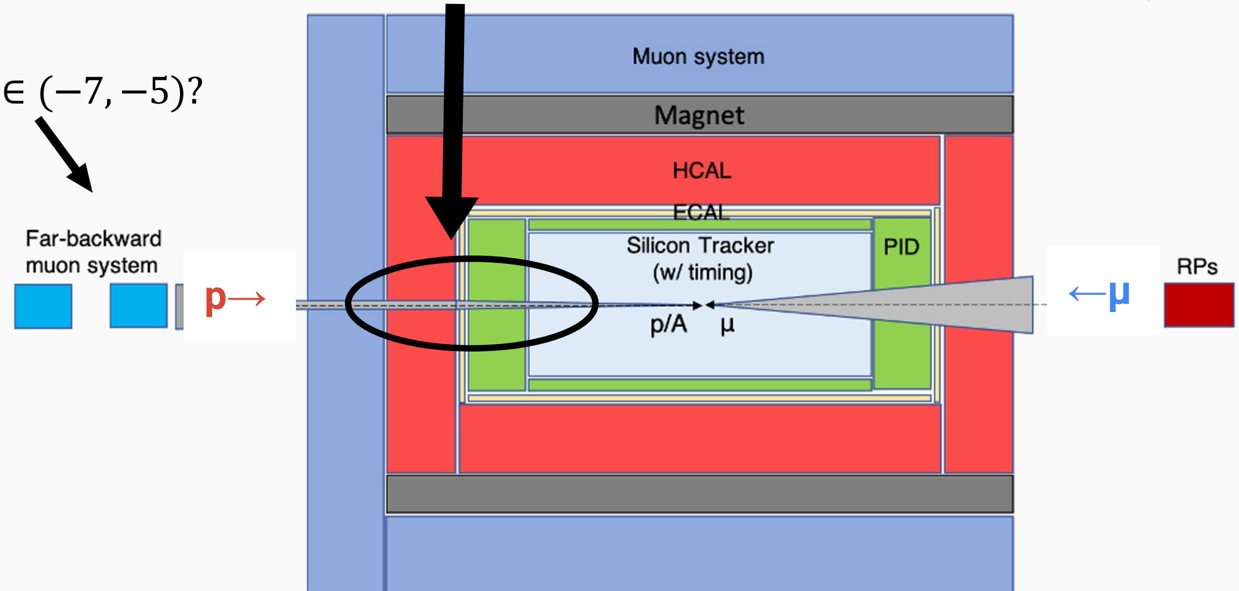
★ Future work: detailed simulations to fully demonstrate the experimental feasibility

Real design may be challenging to achieve goals!

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 an experiment at a $\mu^+\mu^-$ collider to tag/veto NC VBF processes**
- Shielding nozzle **only on incoming muon side** (Needs Beam Induced Background study)

$\eta \in (-7, -5)$?



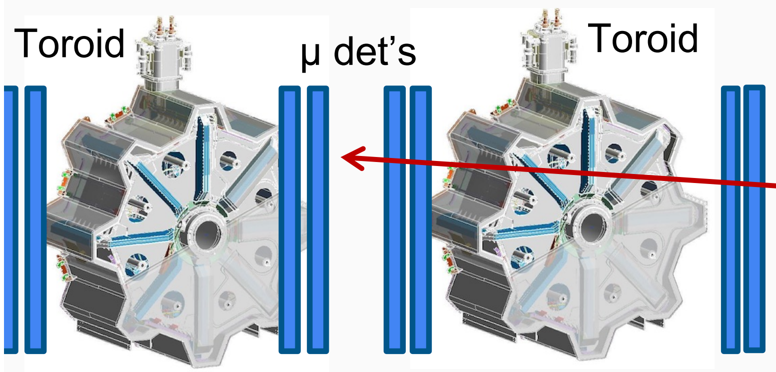
	Main requirements
Muons	**-7<η<0, σ(p)/p < 5%**
Tracking	−5<η<2.4
PID (π/k/p)	**-4<η<2.4, p<100 GeV**
Calorimetry (jets, photons)	-5<η<2.4

A Possible Muon Spectrometer

ATLAS-PHOTO-2022-007-6

Layout adapted from Collamati et al. on $\mu^+\mu^-$ collider: arXiv:2105.09116

ATLAS Endcap Toroids



Option 1:

Z = 400 m
$-6.9 < \eta < -5$

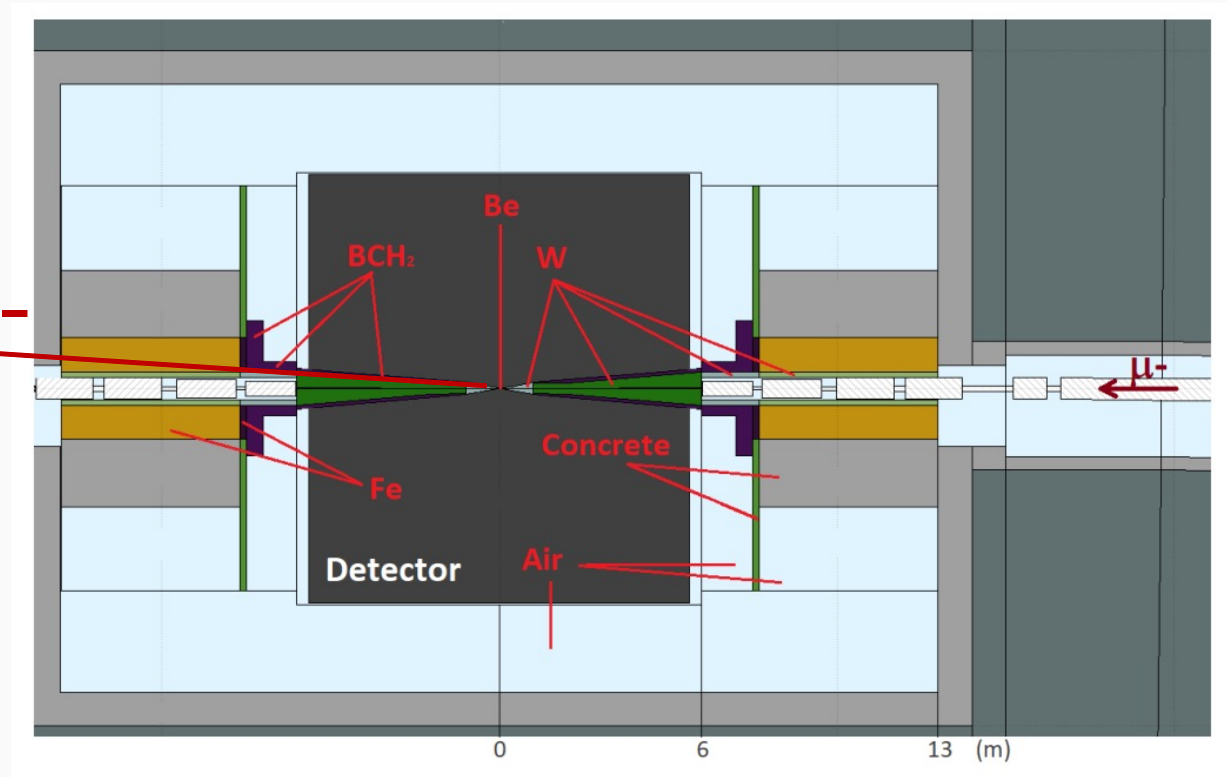
Z = 60 m
$-5 < \eta < -3.1$

Option 2:

Z = 225 m
$-6.3 < \eta < -4.4$

Z = 40 m
$-4.6 < \eta < -2.7$

Distance not to scale



← Option 2 demotes outer radii of toroids which have degraded resolution, and skips high η region covered by dipole

Effect of Shielding Cone on Scattered Muons

V. Di Benedetto et al 2018 JINST 13 P09004

- GEANT-4 detector study initiated by Osvaldo and Mark
- To be extended to its effect on DIS resolution, and muon spectrometer

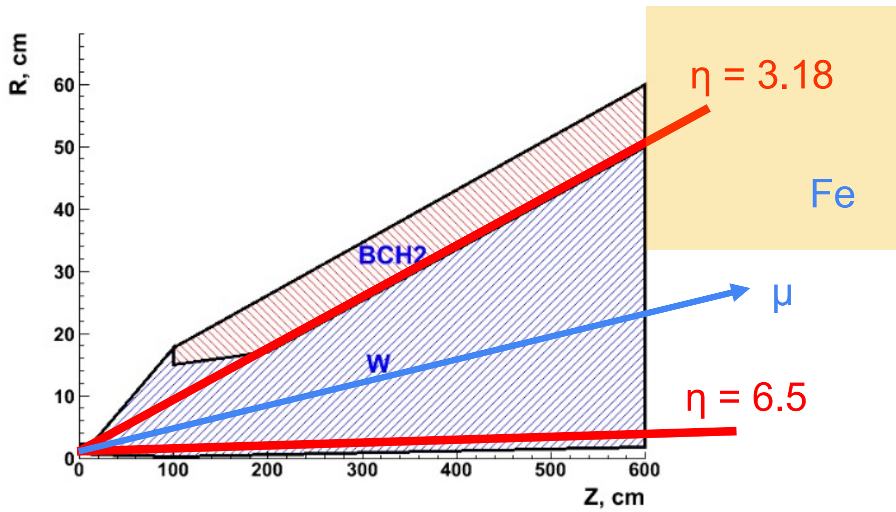


Figure 2. The shielding nozzle, general RZ view (W — tungsten, BCH2– - borated polyethylene).

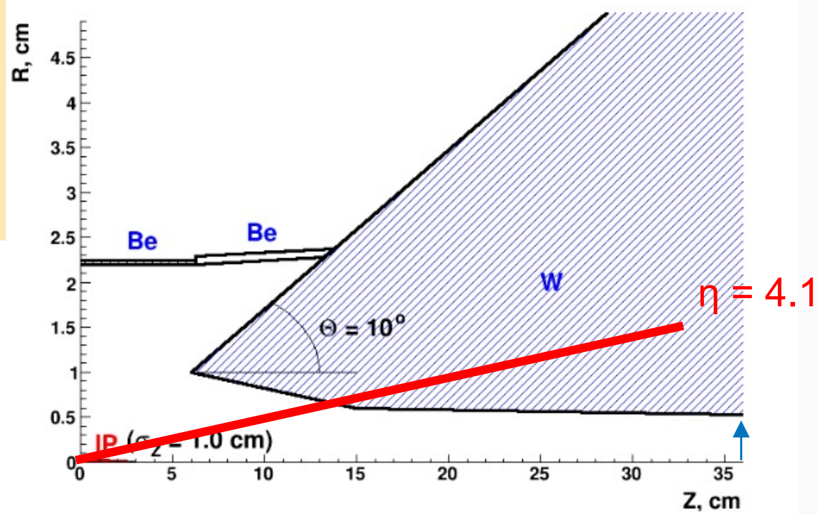
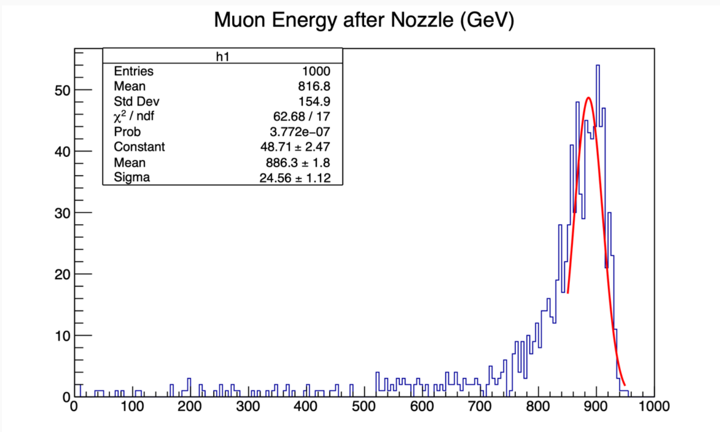


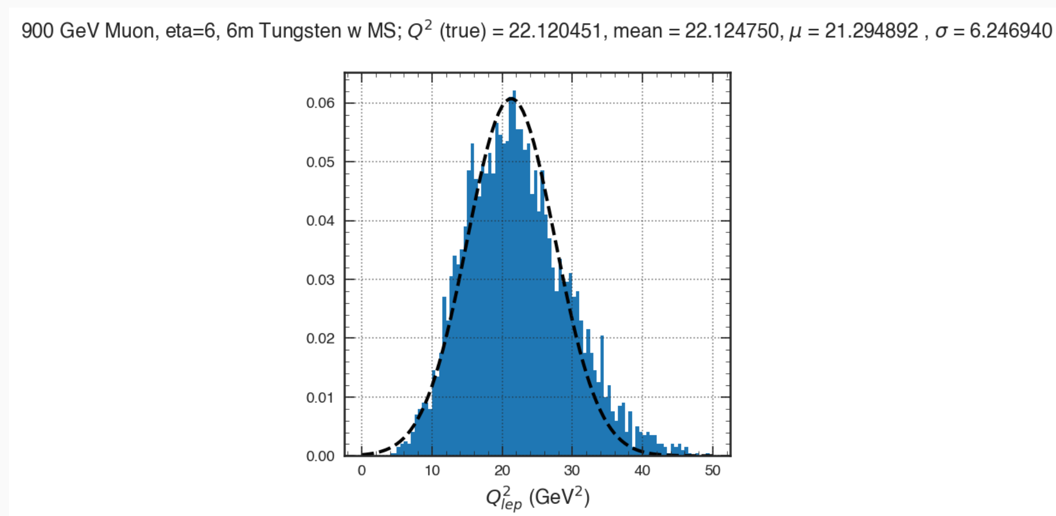
Figure 3. The shielding nozzle, zoom in near IP (Be — beryllium).

Example of Impact on Muon Measurements

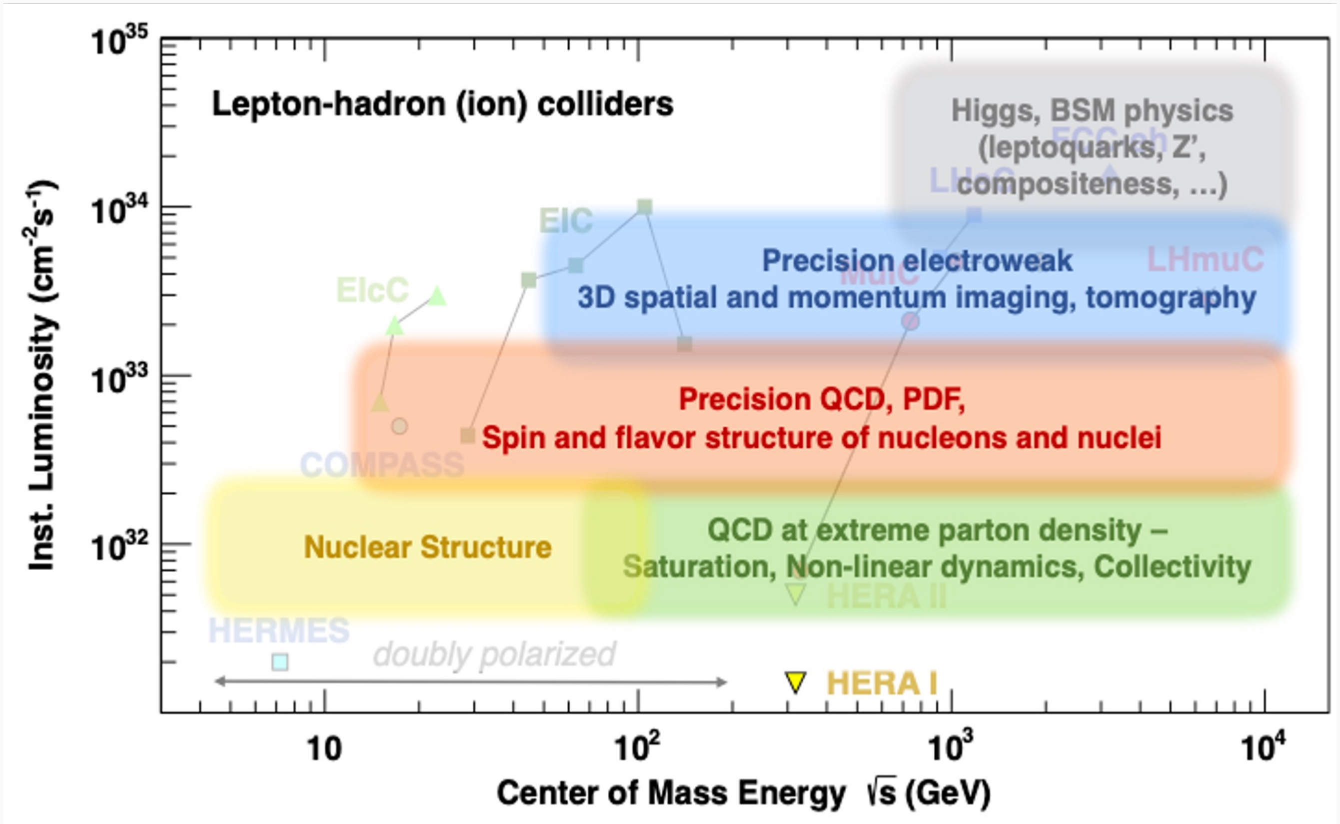
- A 1 TeV muon loses >10% of its energy going through tungsten, with a long tail. Also, multiple scattering smears its outgoing angle.



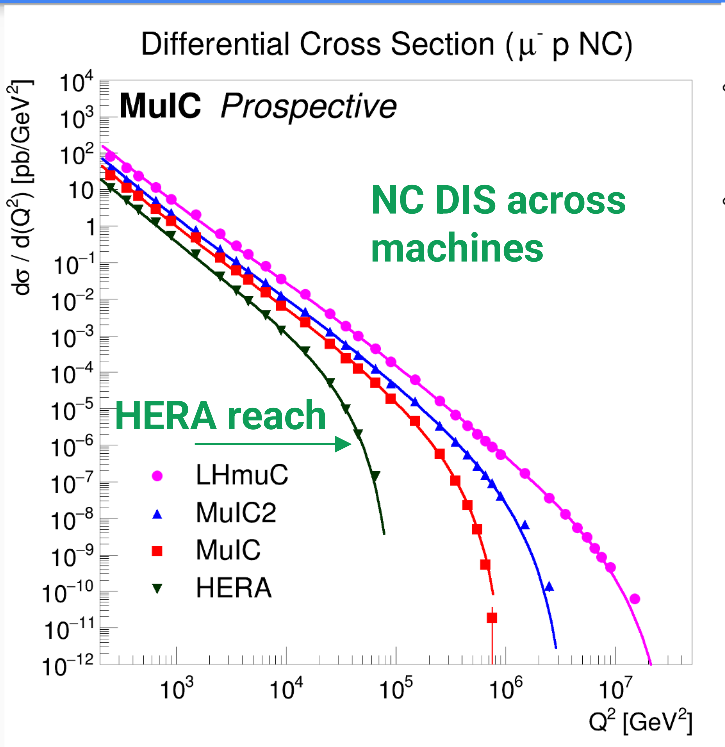
- This affects measurements:
  - e.g. 30% smearing for Q^2 = 20 GeV^2 from reconstructed muon quantities

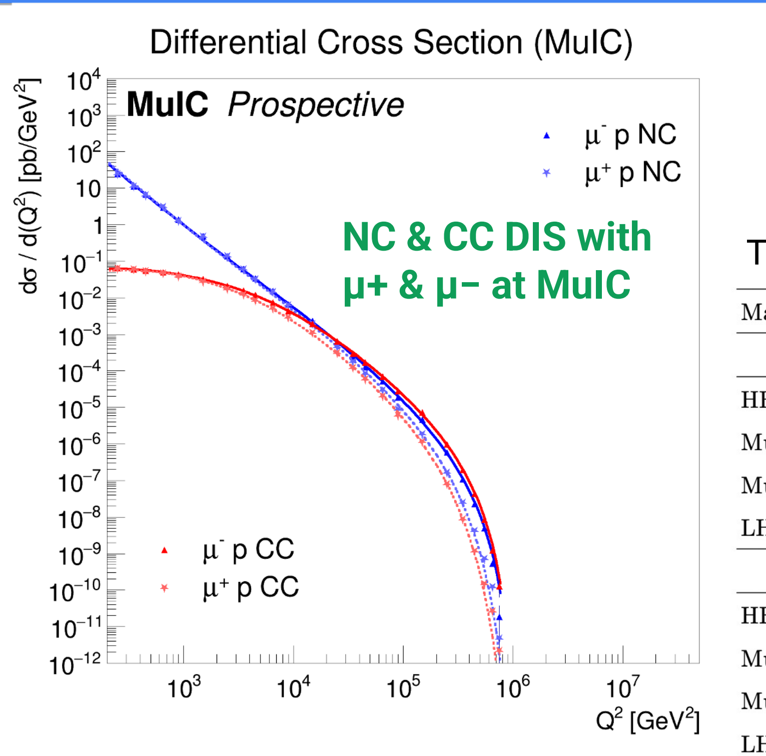


DIS Evolution and Physics Landscape



DIS Differential Cross Sections in Q^2





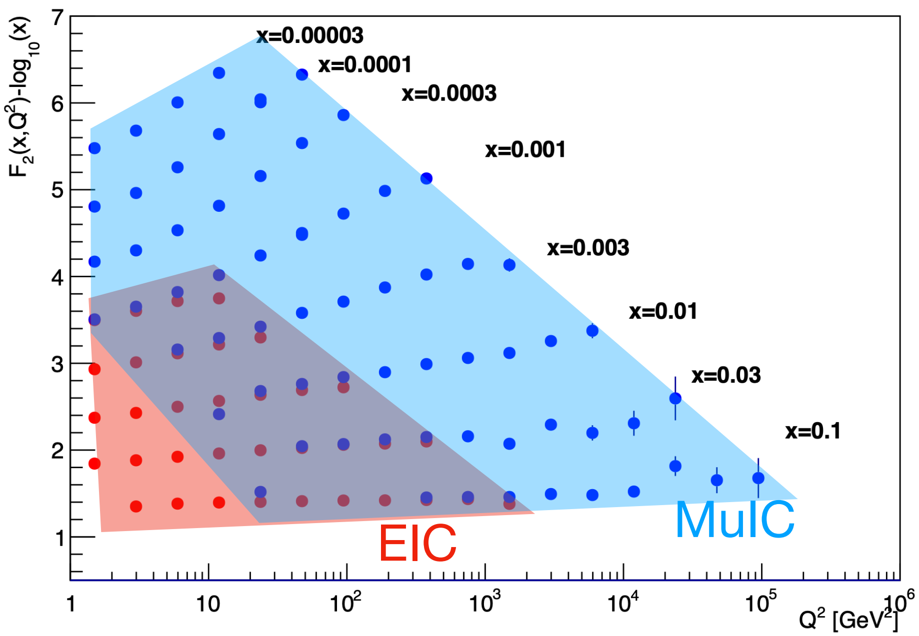
Computed with Pythia8 and NNPDF2.3 PDF set, $0.1 < y < 0.9$

Total integrated CC cross section

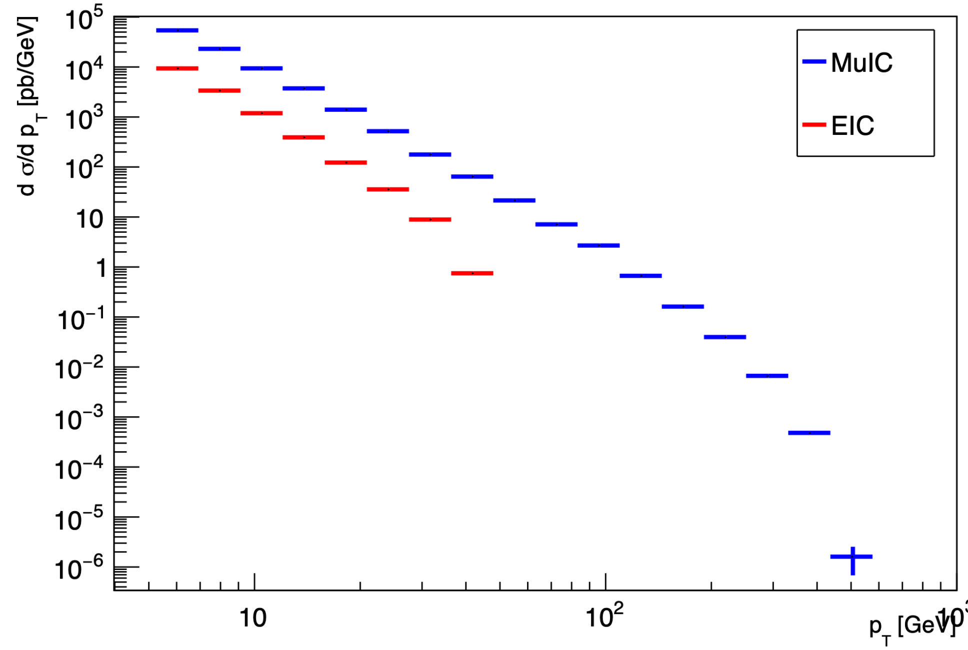
Machine	$Q^2 > 1$	$Q^2 > 3\times10^4$	$Q^2 > 10^5$	$Q^2 > 3\times10^5$
		$\mu^- p \to \nu_\mu X$		
HERA	68	0.038	–	–
MuIC	200	5.2	0.12	0.0053
MuIC2	345	13	0.92	0.20
LHmuC	860	43	4.6	1.6
		$\mu^+ p \to \overline{\nu}_\mu X$		
HERA	37	0.00095	–	–
MuIC	160	1.4	0.0090	–
MuIC2	300	6.5	0.22	0.029
LHmuC	850	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

Physics Potential for Structure Function & QCD Measurements



F_2 Structure function projection of EIC vs MuIC



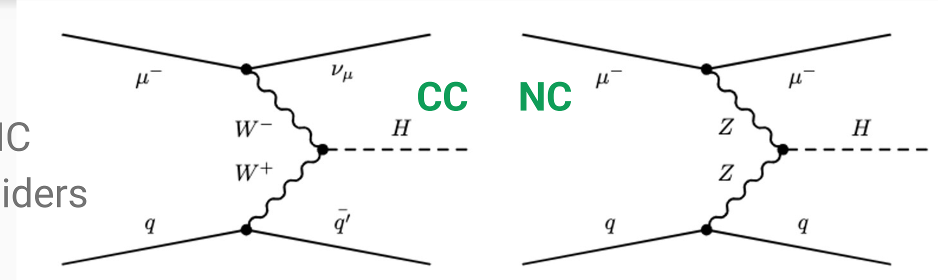
Single jet P_T spectra projection of EIC vs MuIC

Pseudo-data representing one year of running

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

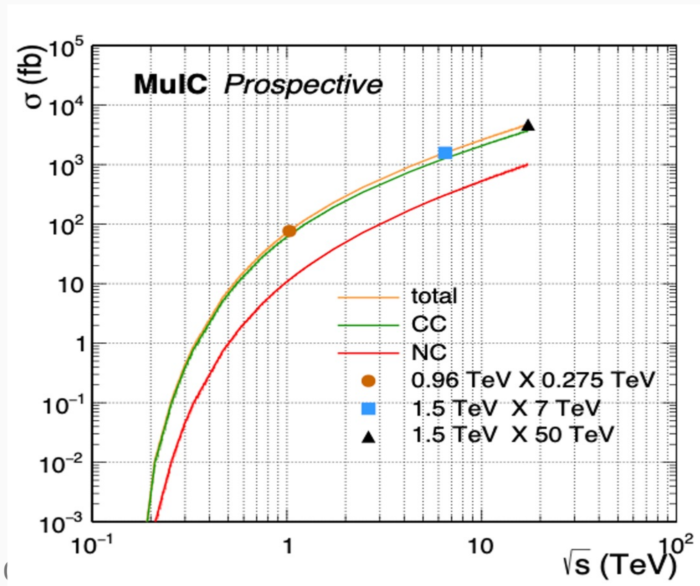
Higgs Physics with MuIC

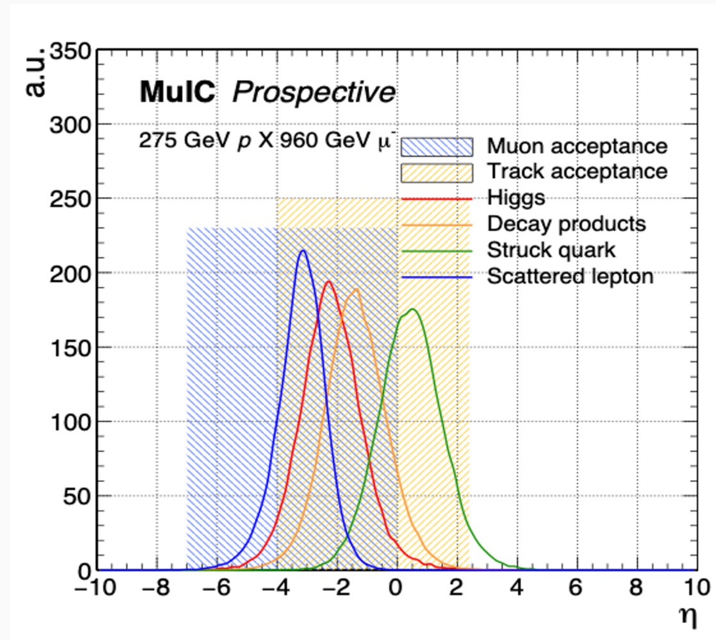
arXiv:2203.06258



- VBF mode
  - σ grows with √s, with 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)

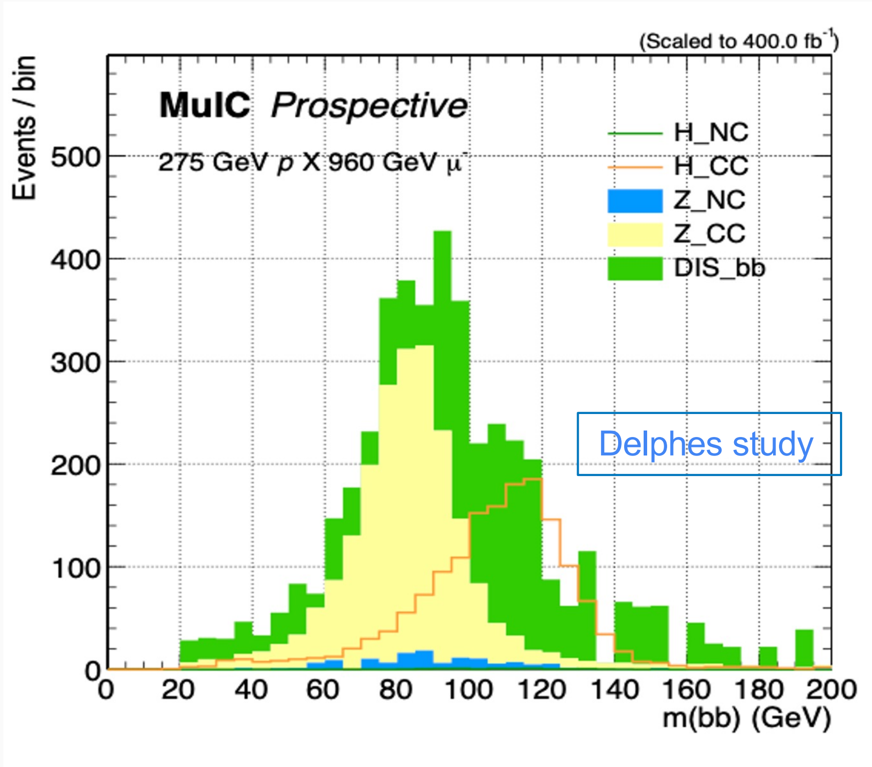
Computed with MadGraph





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

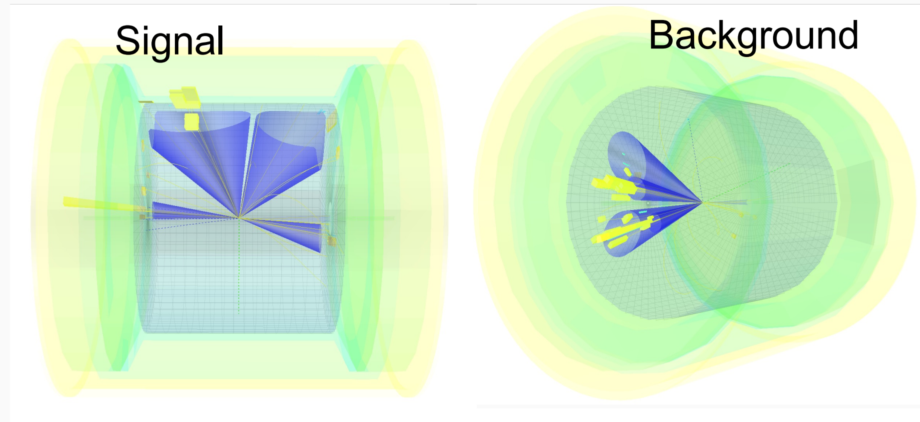


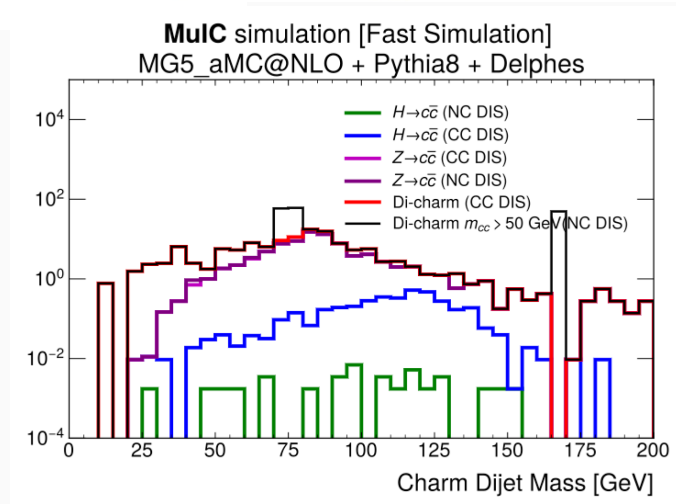
- What about H→cc ?
  - Difficult at LHC
  - See next slide

Higgs → cc   [Independent SMU group study]

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

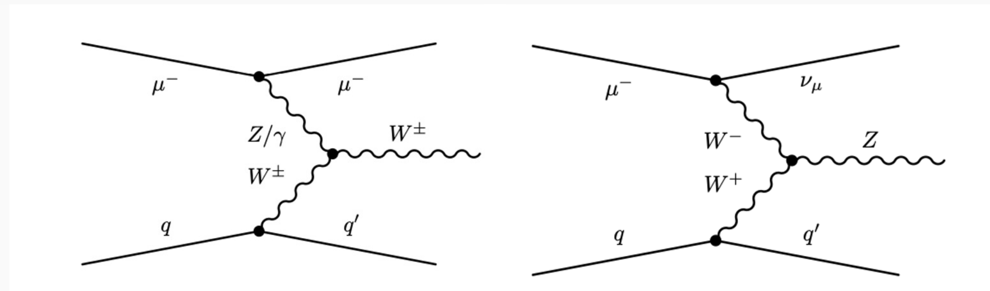
- Similar pseudo-analysis of H →cc at 1 TeV MuIC
  - But smaller BR
  - Smaller c-tagging efficiency (27%), and more bkg…
- Selection:
  - Etmiss > 50 GeV
  - Veto scattered muon (NC)
  - ≥2 charm-tagged jets
- Yields only a handful of events…
- Did not study yet mis-tagged light dijet bkg, whose cross 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… ☹



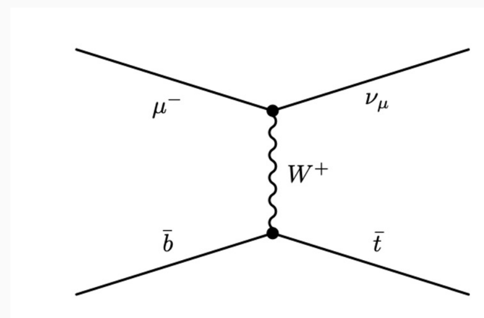


Other SM Particle Production

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



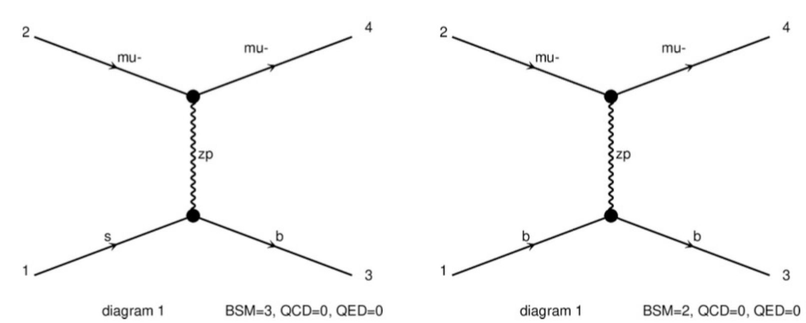
- Single top production
  - Direct measurement of $|V_{tb}|$
  - σ(t) = 1.0 pb for 1 TeV MuIC



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

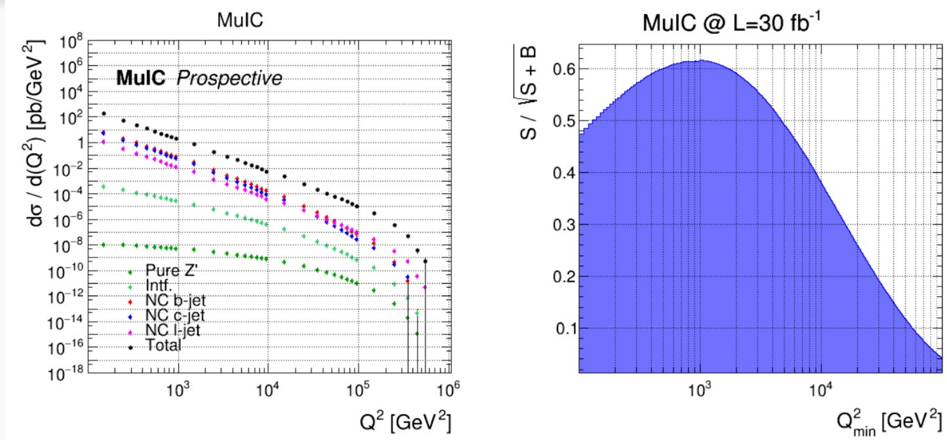
- Consider Z' models and couplings discussed in M.Abdullah et al., Phys. Rev. D 97, 075035 , that couple via O9 operator mostly to 2nd generation leptons (μ) and 2nd and 3rd generation quarks (s, b) to explain anomalies in B meson decays.
  - $$\mathcal{L} \supset Z'^{\mu}\Big[g_\mu \bar{\mu}\gamma^\mu \mu + g_\mu \bar{\nu_\mu}\gamma^\mu P_L \nu_\mu + g_b \sum_{q=t,b} \bar{q}\gamma^\mu P_L q + (g_b \delta_{bs} \bar{s}\gamma^\mu P_L b + \text{h.c.})\Big] \quad (6)$$
  - 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
- Consider interference with NC DIS
  - so flavor conserving coupling dominates



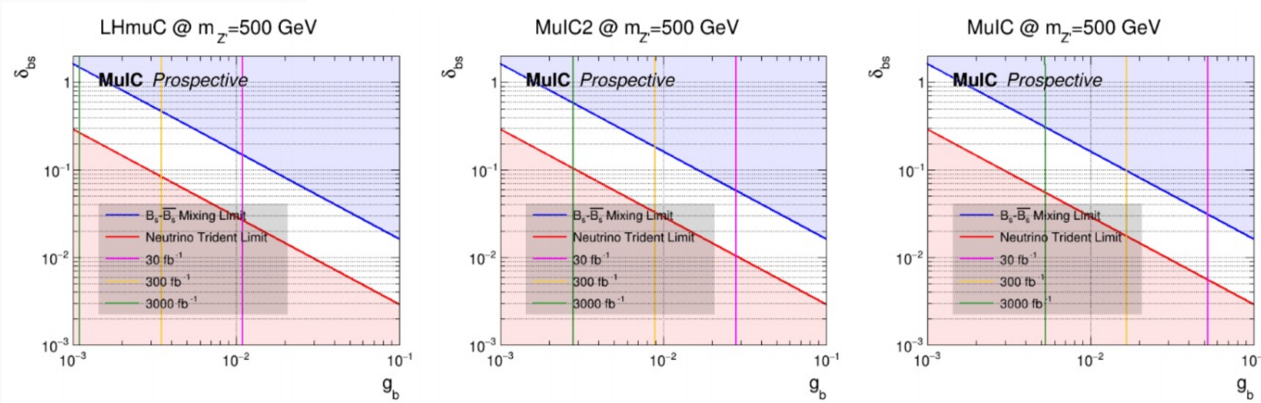
(a) $s\ \mu- \rightarrow b\ \mu-$ (b) $b\ \mu- \rightarrow b\ \mu-$

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 ($120\ \text{fb}^{-1}$) to be competitive with HL-LHC ($3000\ \text{fb}^{-1}$)



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

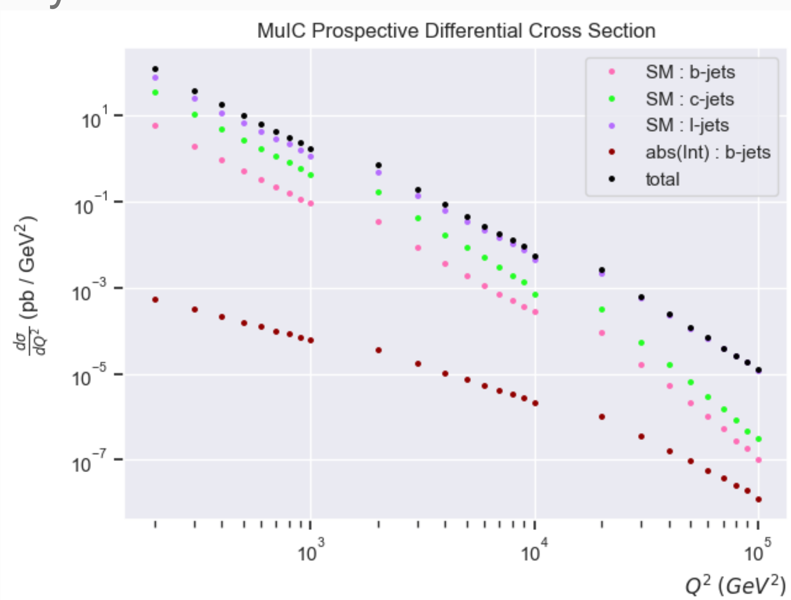


(a) LHmuC (b) MuIC2 (c) MuIC

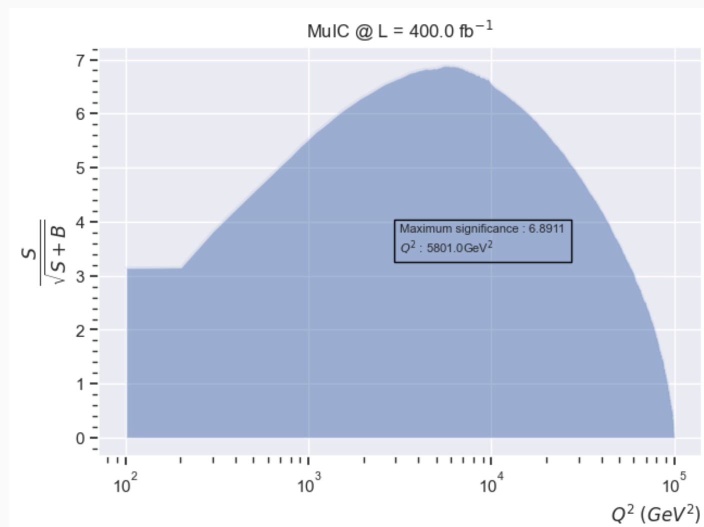
Probing Leptoquarks Relevant to LFU Violations

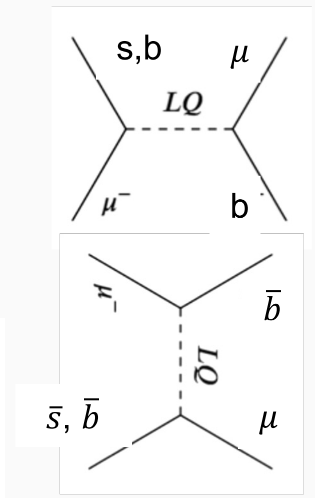
Work in Progress

- Studies focused on LQ models inspired by B and μ anomalies
  - S3 type LQ (F=2, LL coupling, μb), $\lambda = 0.1$, M = 500 GeV shown here
- Consider interference with SM DIS in both s- and t-channel
  - Negative interference term subtracts from SM DIS diff. xsec
- Try Z’ cut-and-count method on reconstructed Q^2 to estimate sensitivity



(On-shell mass peak reconstruction next)





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)

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
  - Leptoquark study performed (Rice undergrad senior thesis)
- Many synergies with muon collider development, nuclear and particle physics programs

Acknowledgements

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

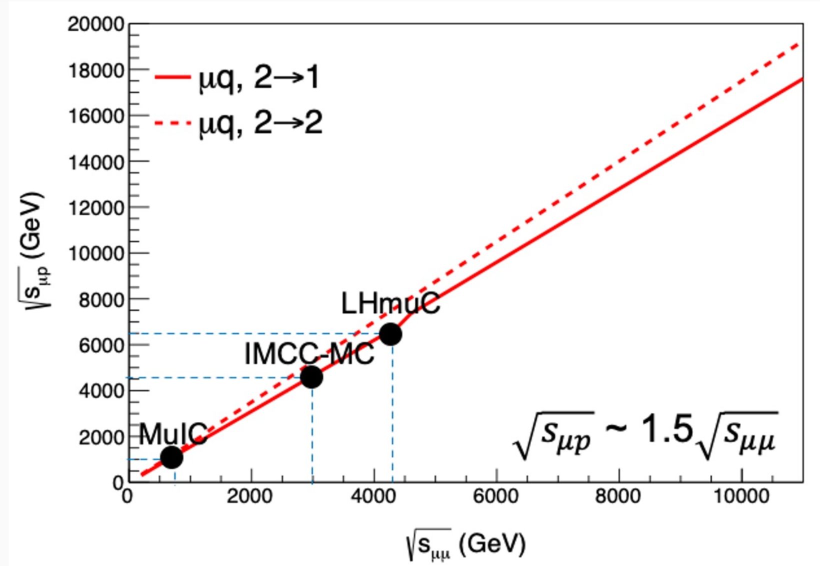
Backup

Equivalent Reach for Production, μp vs. μ⁺μ⁻

- Compute equivalent parton luminosity of a μp collider for 2→1 and 2→2 processes

- We find that **a μ⁺μ⁻ 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 <u>both</u> high energy μ⁺μ⁻ 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?

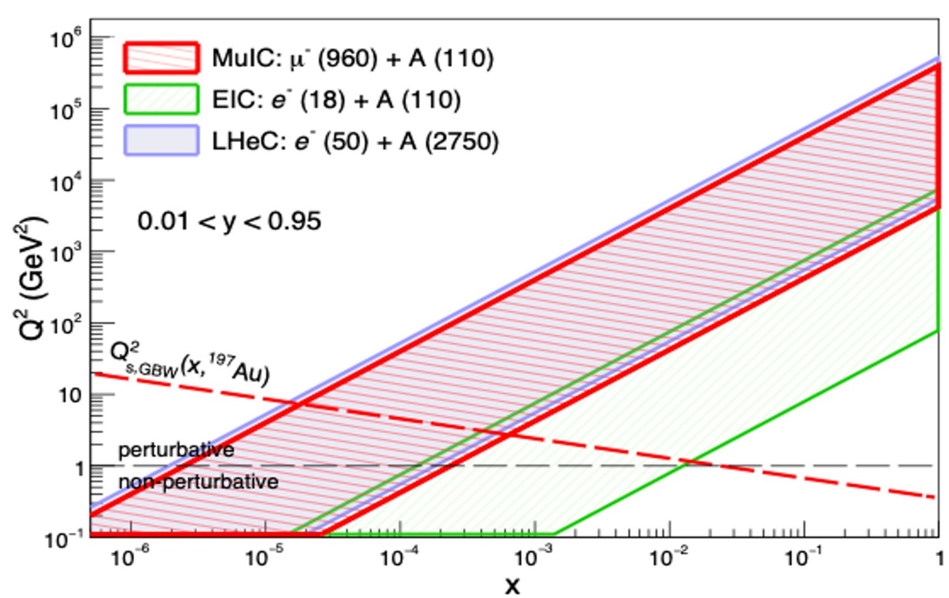
DIS Reach in x and Q^2 for ℓA Collisions

- 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)

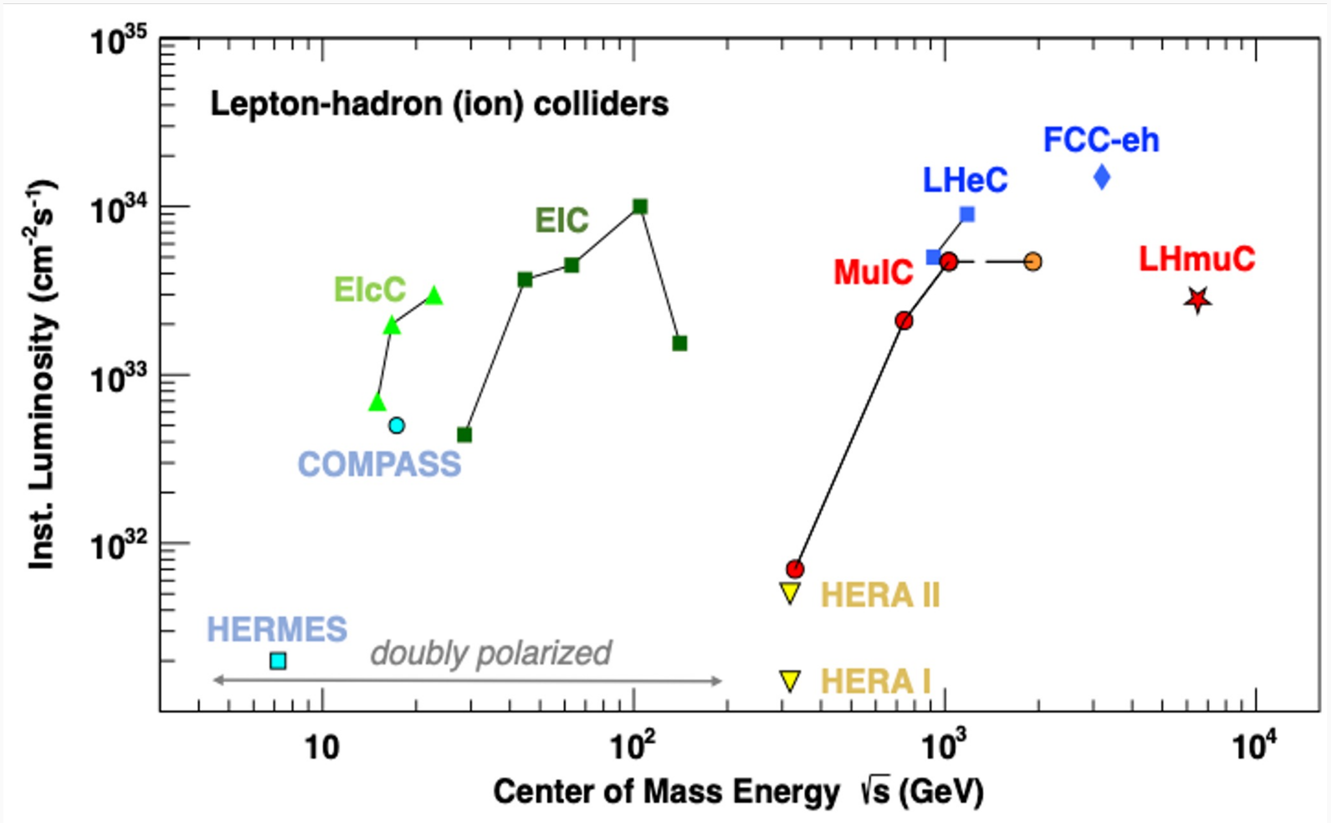
- Also the MuIC at BNL can scan a wide range of ion species, and beam polarization

Saturation scale:

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

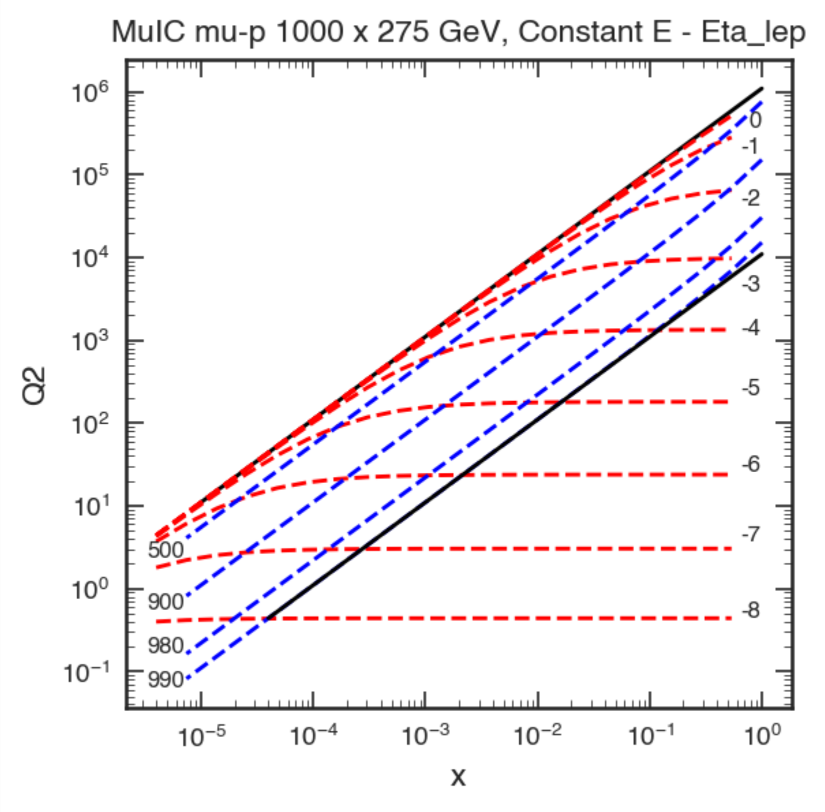


DIS Evolution and Physics Landscape

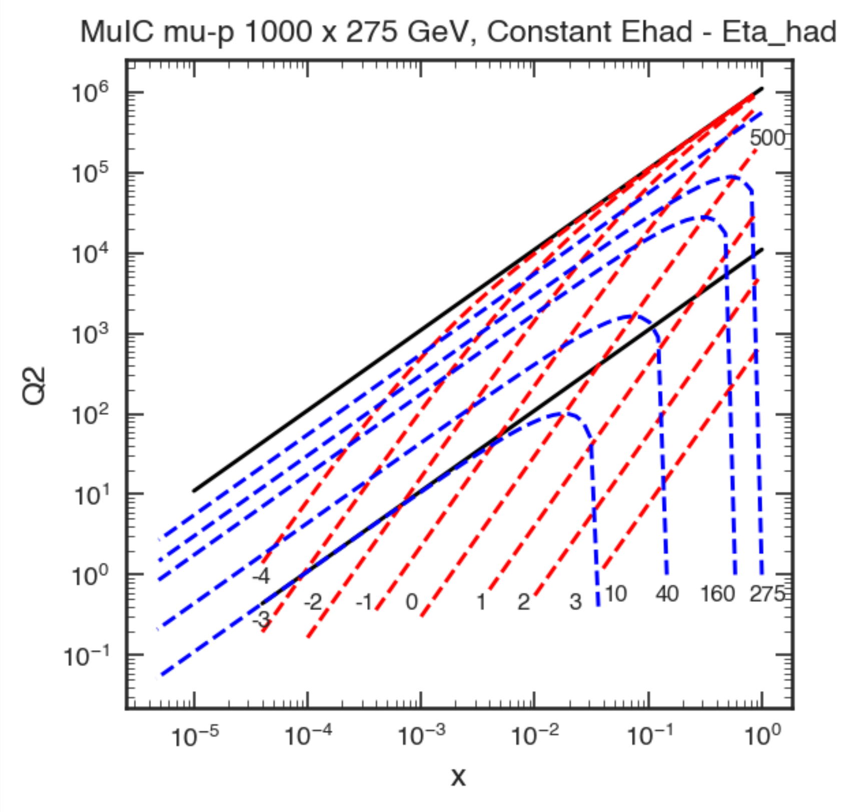


Kinematics

- Scattered muon

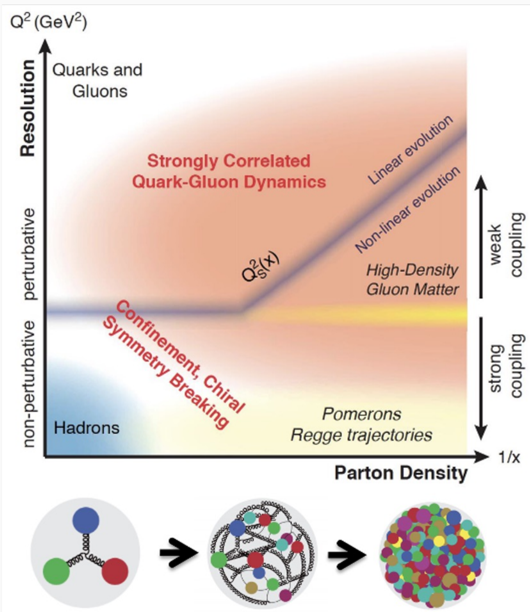


Scattered jet



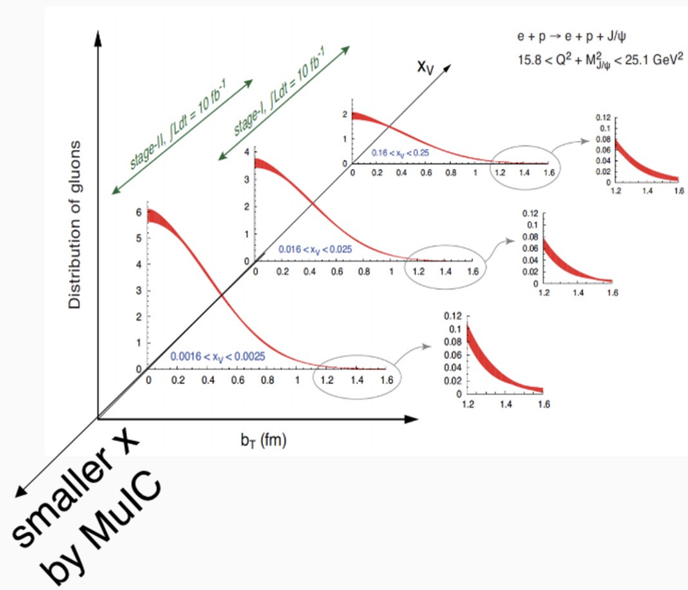
Nuclear Physics at the MuIC

Gluon saturation



What's the property of high-density gluon matter

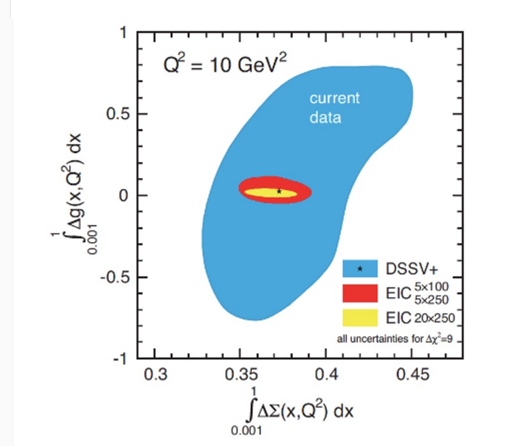
3D Nucleon structure



Nucleon spin puzzle

"Helicity sum rule"

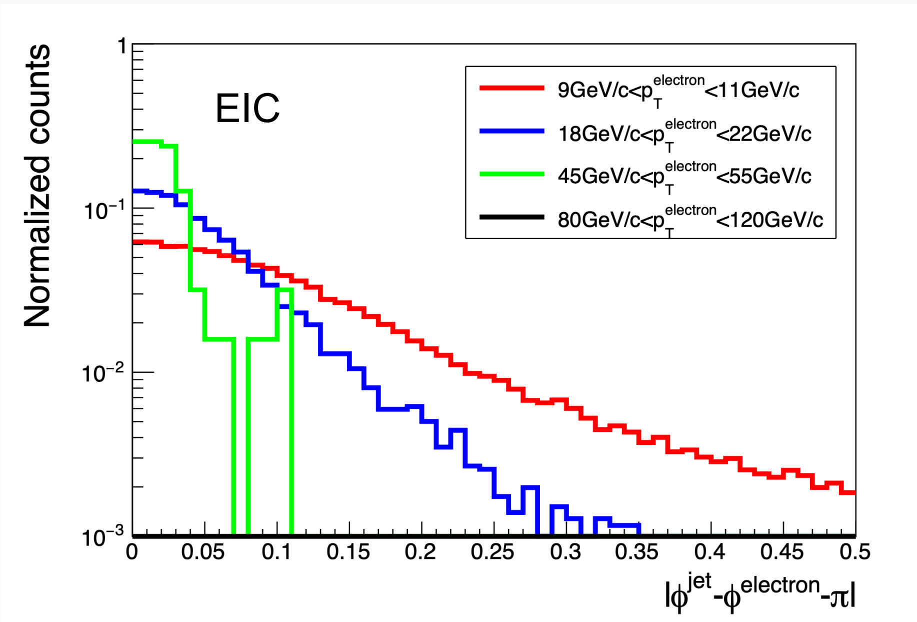
$$\frac{1}{2}\hbar = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quark contribution}} + \underbrace{\Delta G}_{\text{gluon contribution}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{orbital angular momentum}}$$

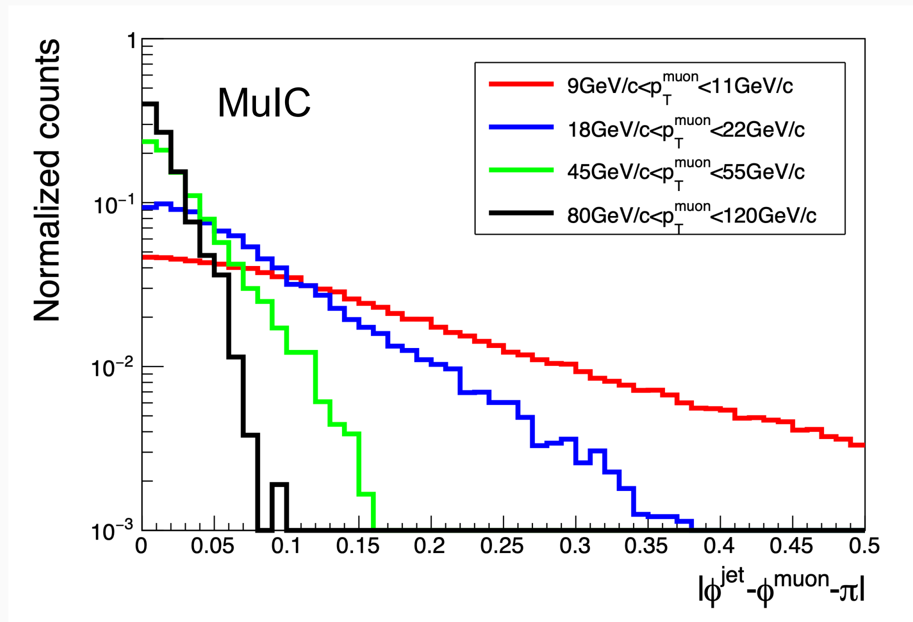


MuIC to reach x ~ 10^{-5}

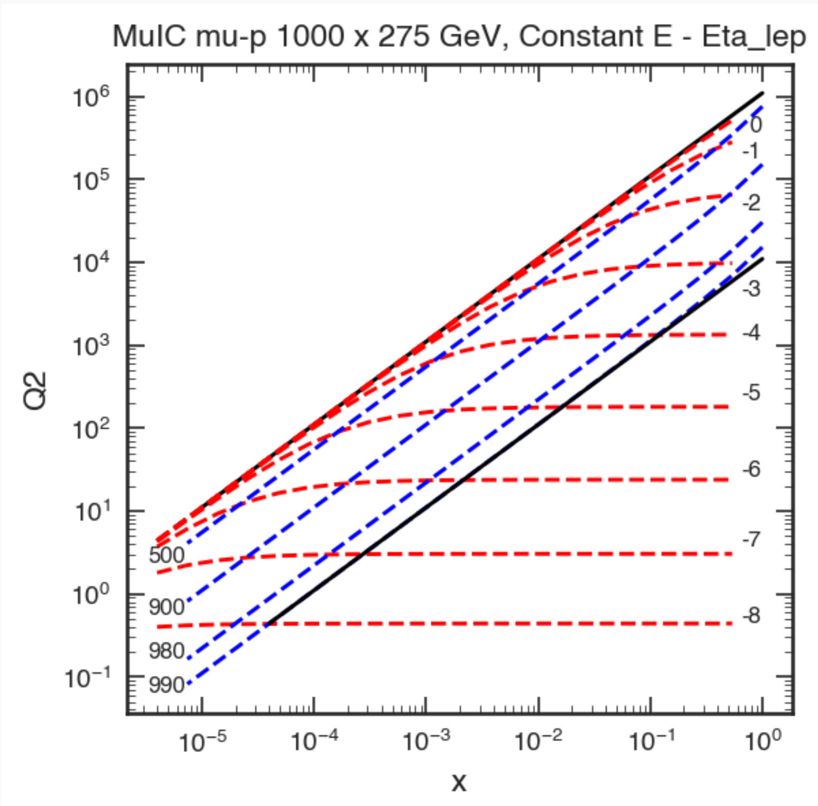
Nuclear Physics: Decorrelation of Mu-Jet Final State

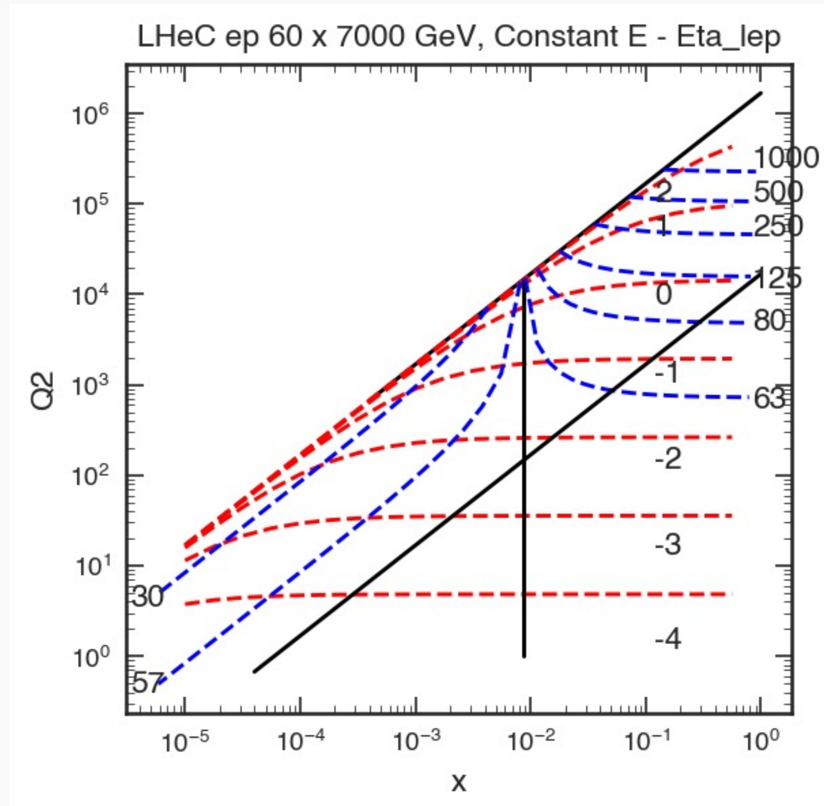
- Promising observable to probe the dense gluonic medium inside a heavy nucleus, and the possible gluon saturation effect is the decorrelation in azimuth from back-to-back of the muon-jet system





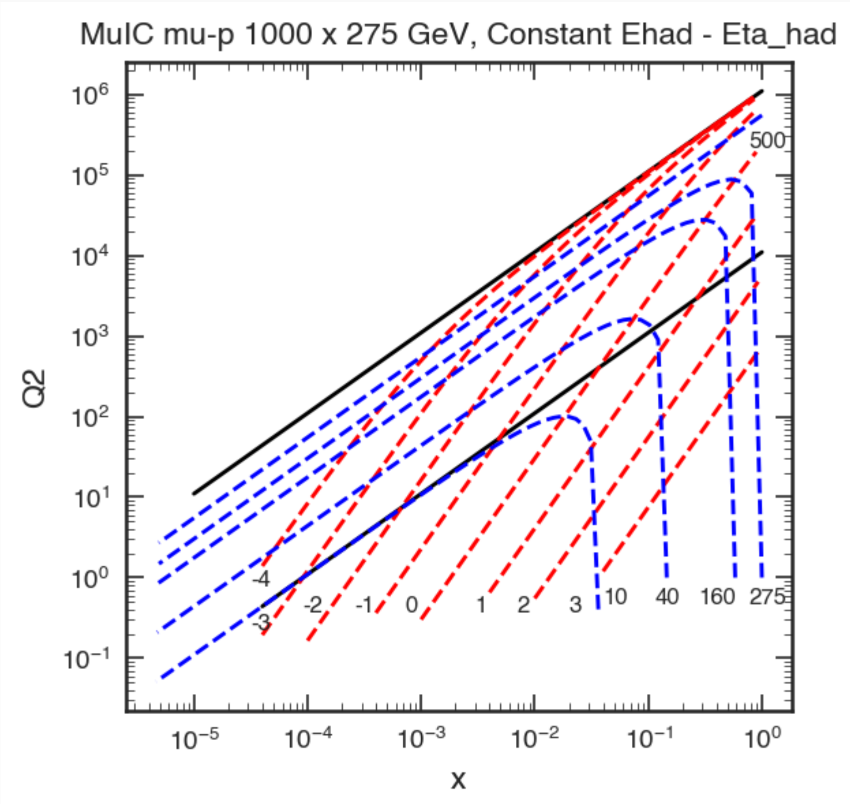
Lepton DIS Kinematics of MuIC Compared to LHeC

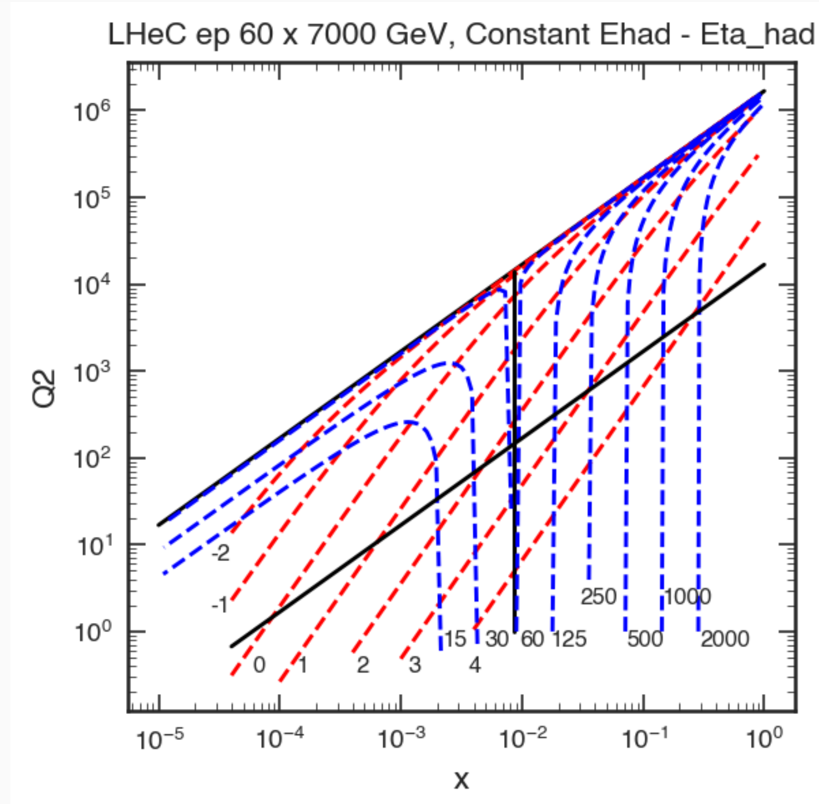




- Much higher scattered muon energy and higher |η| at MuIC

Hadron DIS Kinematics of MuIC Compared to LHeC

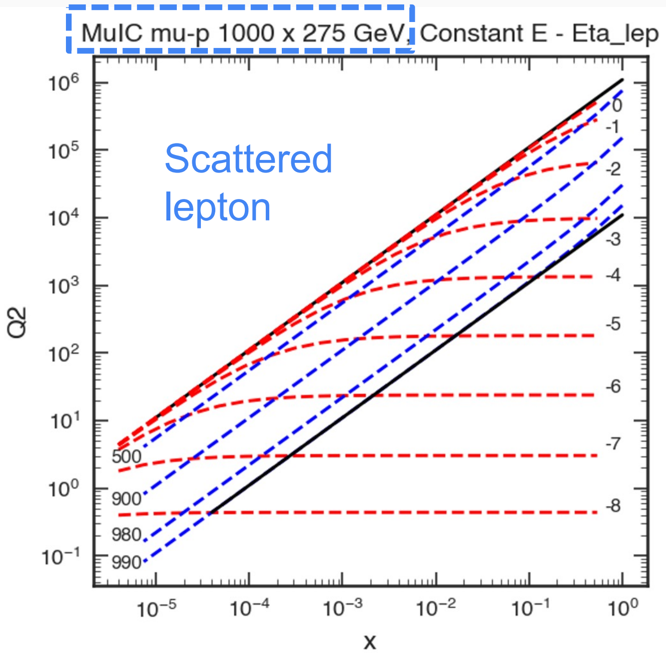


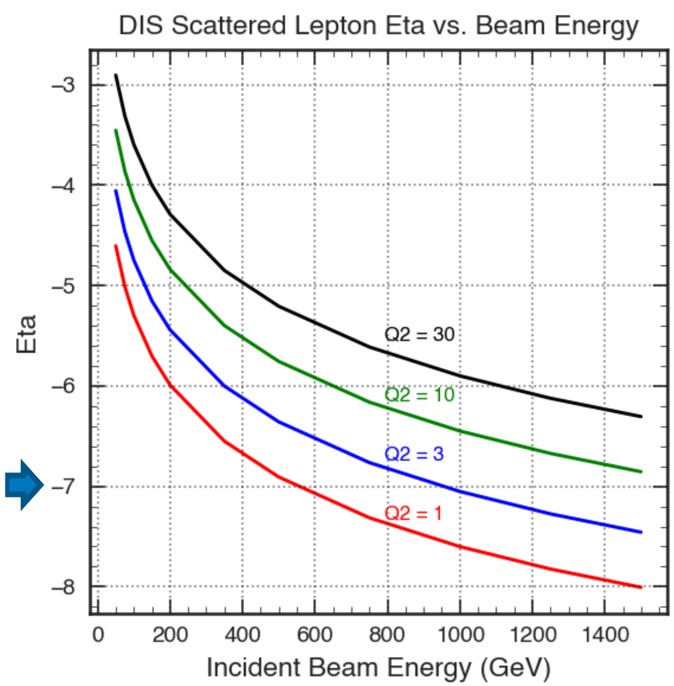


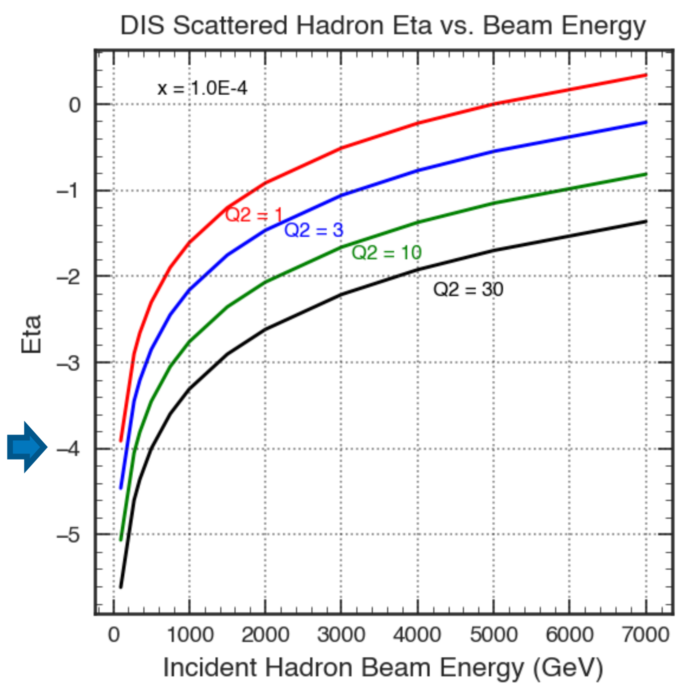
- Hadron system peaks more in proton direction and lower energy at low x for LHeC

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

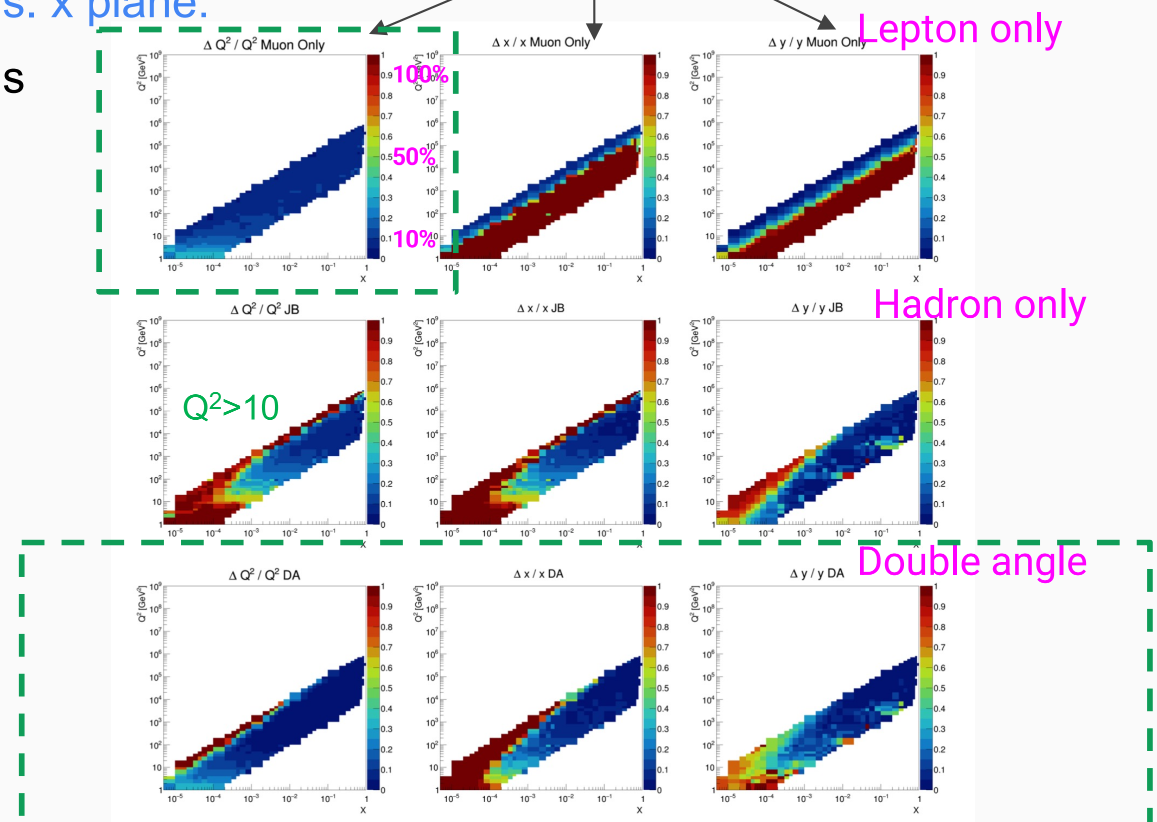
Resolutions of reconstructed Q^2, x and y with 3 methods

Q^2 vs. x plane:

Simple assumptions of detector resolutions to smear particles from PYTHIA 8

Particle	Detector	Resolution: $\frac{\sigma(p)}{p}$ or $\frac{\sigma(E)}{E}$	Resolution: $\sigma(\eta,\varphi)$
(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	$\frac{50\%}{\sqrt{E}} \oplus 10\%$	$\frac{0.087}{\sqrt{12}}$

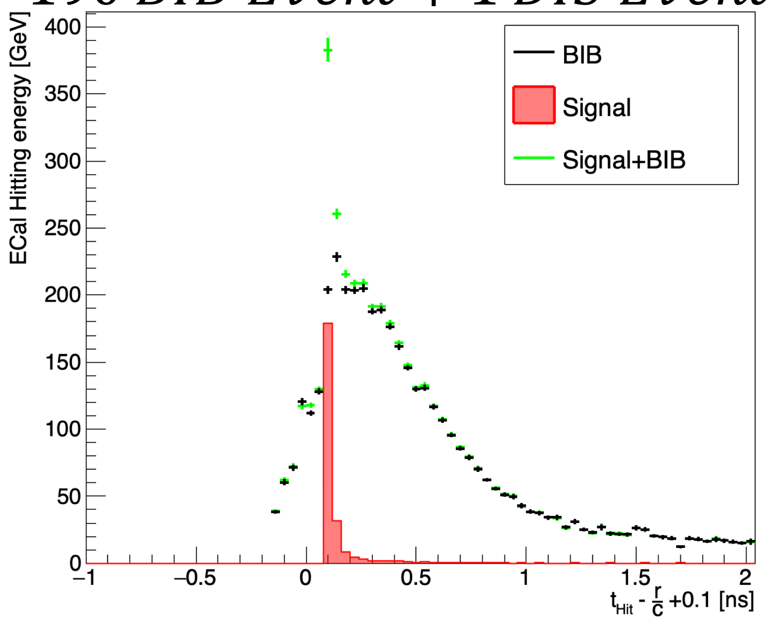
- Muons: 10% at 1 TeV, $\eta > -7$
- Hadrons: $-4 < \eta < 2.4$ (shielding)



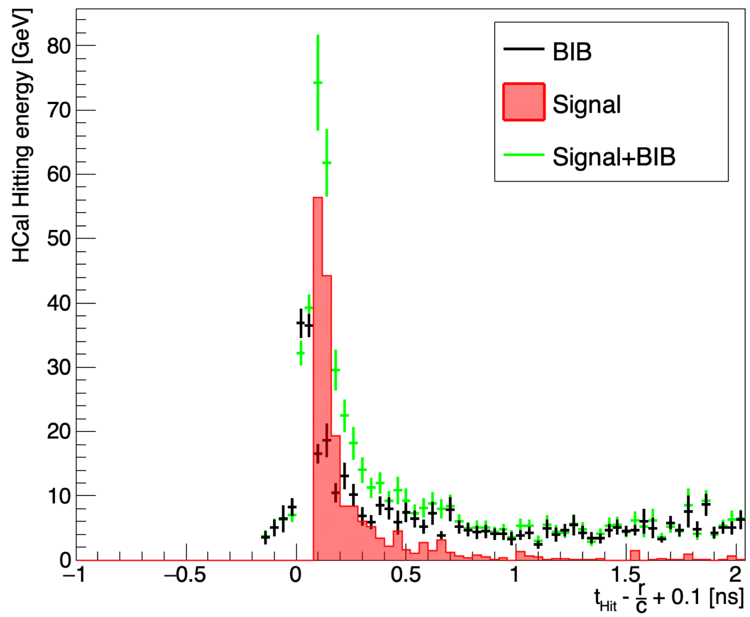
Full Simulation using IMCC Software — Workflow

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

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



ECal Hitting Time

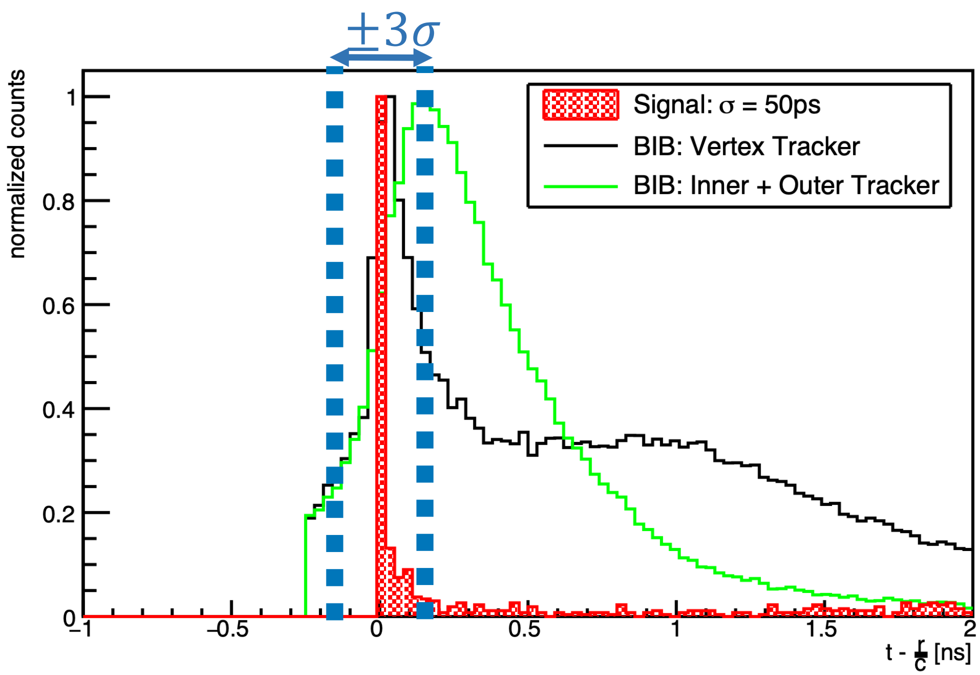


HCal Hitting Time

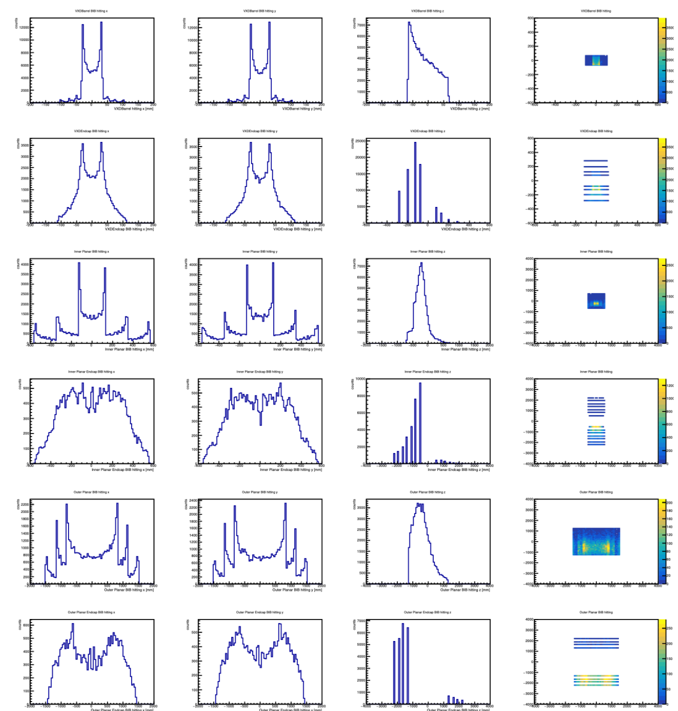
Full Simulation using IMCC Software — Workflow

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

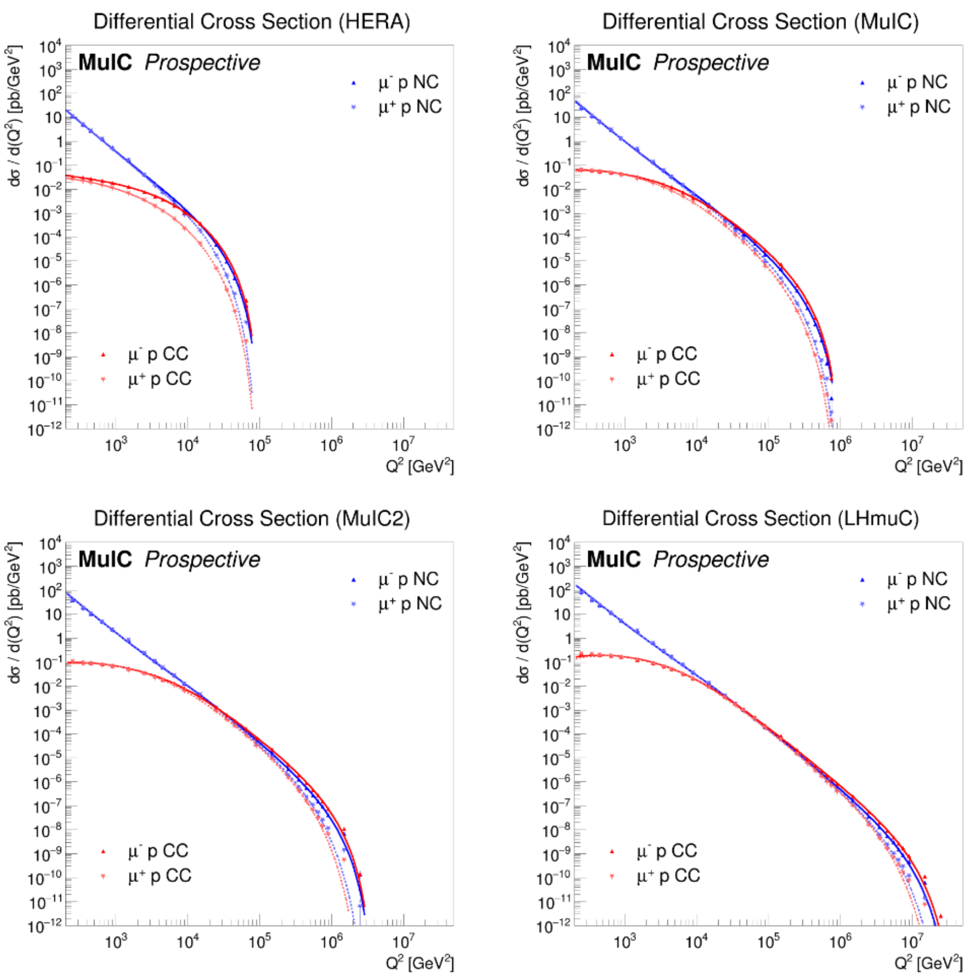
BIB file: sim_mumi-1e3x500-26m-lowth-excl_j1.slcio



Tracker Hitting Time



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 μ^-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⊕α_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 $^{+7.7\%}_{-8.2\%}$ $^{+1.0\%}_{-1.0\%}$

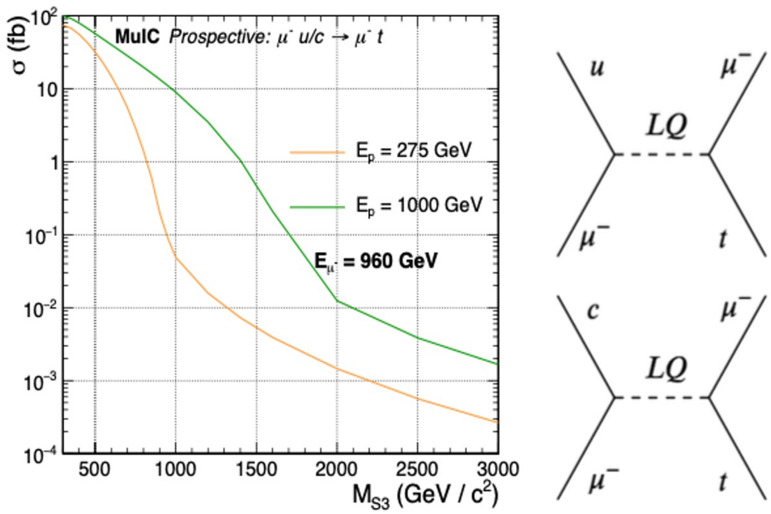
TABLE IX. Cross sections for the $W^-\mu^-$ process in μ^-p collisions for different beam energy configurations and with different cutoffs on the scattered muon p_T. The listed cross sections are in pb, with scale and PDF⊕α_s uncertainties. The μ^- beam energy is unpolarized in all cases.

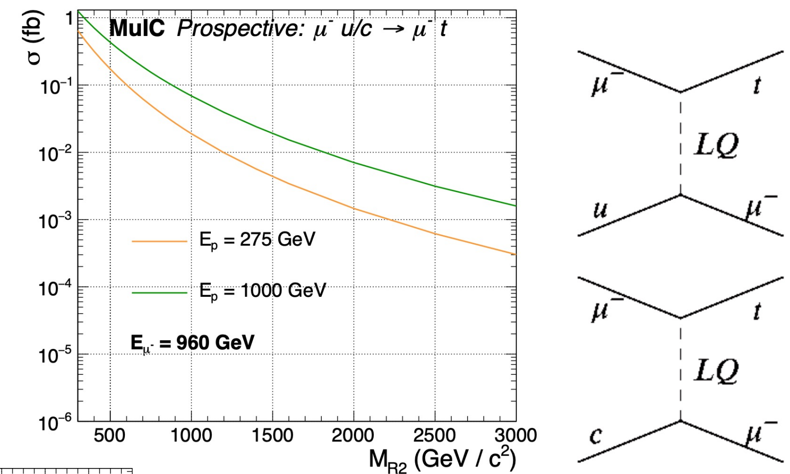
$E_\mu \times E_p$ (TeV^2)	Inclusive	$p_T^\ell > 1$ GeV	$p_T^\ell > 2$ GeV	$p_T^\ell > 5$ GeV
0.96×0.275	8.69 $^{+0.7\%}_{-1.0\%}$ $^{+0.9\%}_{-0.9\%}$	2.10 $^{+1.6\%}_{-2.0\%}$ $^{+0.9\%}_{-0.9\%}$	1.71 $^{+1.8\%}_{-2.1\%}$ $^{+0.9\%}_{-0.9\%}$	1.23 $^{+2.4\%}_{-2.4\%}$ $^{+0.9\%}_{-0.9\%}$
0.96×0.96	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 μ^-p collisions for different beam energy configurat
The μ^- beam energy is unpolarized in all cases.

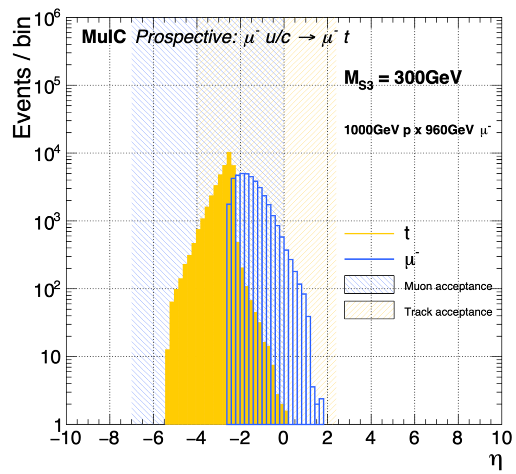
$E_\mu \times E_p$ (TeV^2)	σ (pb)	Scale unc.	PDF⊕α_s unc.
0.96×0.275	1.80	$^{+2.8\%}_{-5.6\%}$	$^{+1.4\%}_{-1.4\%}$
0.96×0.96	7.47	$^{+7.9\%}_{-11\%}$	$^{+1.4\%}_{-1.4\%}$
1.5×7	52.8	$^{+15\%}_{-17\%}$	$^{+1.3\%}_{-1.3\%}$
1.5×13.5	79.8	$^{+16\%}_{-18\%}$	$^{+1.2\%}_{-1.2\%}$
1.5×20	100	$^{+17\%}_{-19\%}$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

Leptoquark Production with 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

Future MuIC Workshop

- We plan to organize a workshop on the topic of MuIC later 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 ?