

# Muon-Ion Collider Physics Perspectives

Based on Snowmass '21 whitepaper: [arXiv:2203.06258](https://arxiv.org/abs/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.)



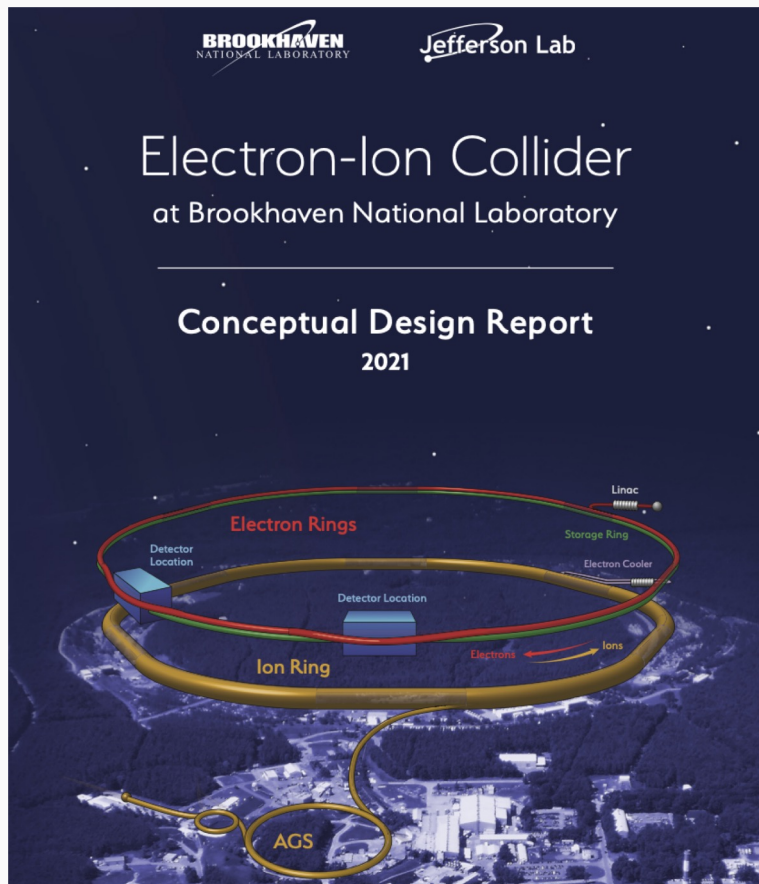
# Outline



- Brief review of concept
  - One O(TeV) muon ring as a first step, colliding with a high-energy hadron beam
    - i.e. a DIS machine, but also a Vector Boson Collider like lepton and hadron colliders
- Experiment considerations
- Science case
  - Included in our Snowmass contribution:
    - Covers [DIS structure measurements](#) of p/ions, QCD
  - Higgs and SM particle production processes
  - [BSM physics \(Z', LQ\)](#)
- Future workshop



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



Acosta et al. -- Muon-Ion Collider Physics Perspectives

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
- $\sqrt{s} = 20 - 140 \text{ GeV}$
- Luminosity  $10^{33} - 10^{34} \text{ Hz/cm}^2$
- Polarized electron, proton and ion beams (any)

But what if we changed leptons?



A lot of interest in  $\mu\mu$  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

- $\sqrt{s} \sim 1 \text{ TeV}$
- $Q^2$  up to  $10^6 \text{ GeV}^2$
- $x$  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  $\mu^+\mu^-$  collider

- Precision PDFs in new regimes (incl. spin at BNL)
- QCD, including 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?)

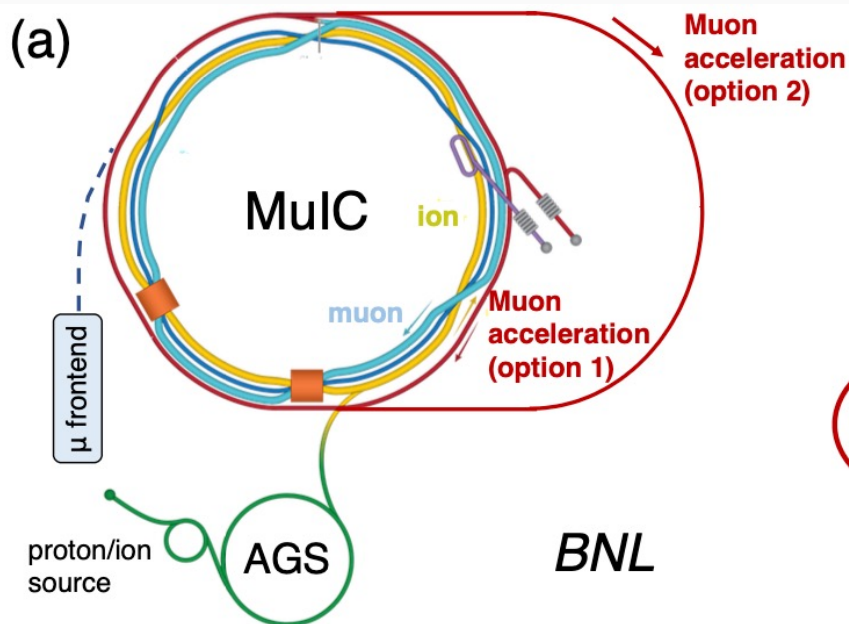
Broad science program helps share costs, and re-use helps economize



# A Muon-Ion Collider at BNL?

Acosta and Li, NIM A 1027 (2022) 166334

→ Replace e by  $\mu$  beam at EIC



Bending radius of RHIC tunnel:  $r = 290\text{m}$

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)

$\sqrt{s} = 1 \text{ TeV} !$

7-8X increase over EIC energy



# Energy Configurations and Luminosity



Parameter	BNL options → MuIC			MuIC2	LHmuC ←	
$\sqrt{s_{\mu p}}$ (TeV)	0.33	0.74	1.0	→ 2.0	6.5	
$L_{\mu p}$ ( $10^{33}\text{cm}^{-2}\text{s}^{-1}$ )	0.07	2.1	4.7 (*)		2.8	
Int. Lumi. ( $\text{fb}^{-1}$ ) 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
$f_{\text{rep}}^{\mu}$ (Hz)	15	<div>*But note that <a href="#">arXiv:2211.07513</a> discusses beam-beam tune-shifts that limit luminosity by factor 100. Need to optimize: decrease particles/bunch, increase number of bunches, etc.</div>				
Cycles per $\mu$ bunch, $N_{\text{cycle}}^{\mu}$	1134					
$\epsilon_{x,y}^*$ ( $\mu\text{m}$ )	200					
$\beta_{x,y}^*$ @IP (cm)	1.7					
Trans. beam size, $\sigma_{x,y}$ ( $\mu\text{m}$ )	48	7.6	4.7	7.1	3	7.1

LHC option

←  $\sqrt{s}$

← Estimate of lumi

← Beam energies

Of 3 TeV  $\mu+\mu^-$

$$\mathcal{L}_{\mu p} = \frac{N^{\mu} N^p}{4\pi \max[\sigma_x^{\mu}, \sigma_x^p] \max[\sigma_y^{\mu}, \sigma_y^p]} \min[f_c^{\mu}, f_c^p] H_{hg},$$

$$\sigma_{x,y}^{\mu,p} = \sqrt{\epsilon_{x,y}^* \beta_{x,y}^* m^{\mu,p} / E^{\mu,p}}$$

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

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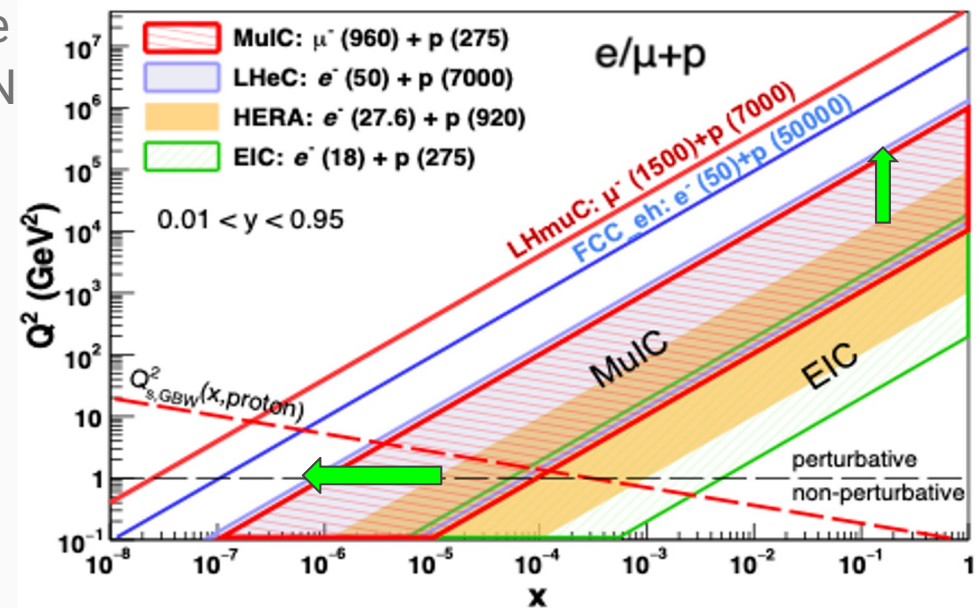
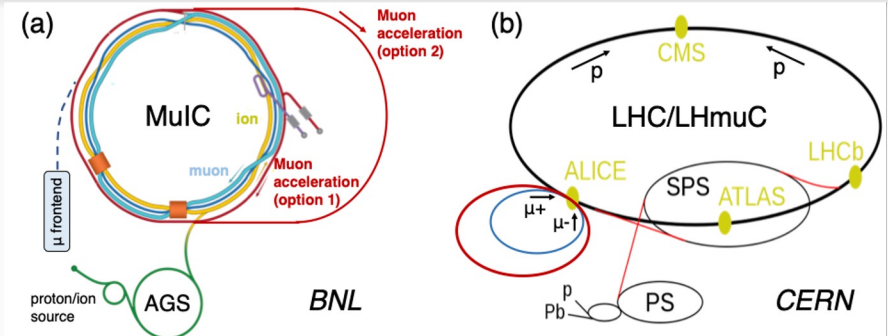
Upgrade  
hadron ring



# DIS Reach in $x$ and $Q^2$ for $\ell p$ 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

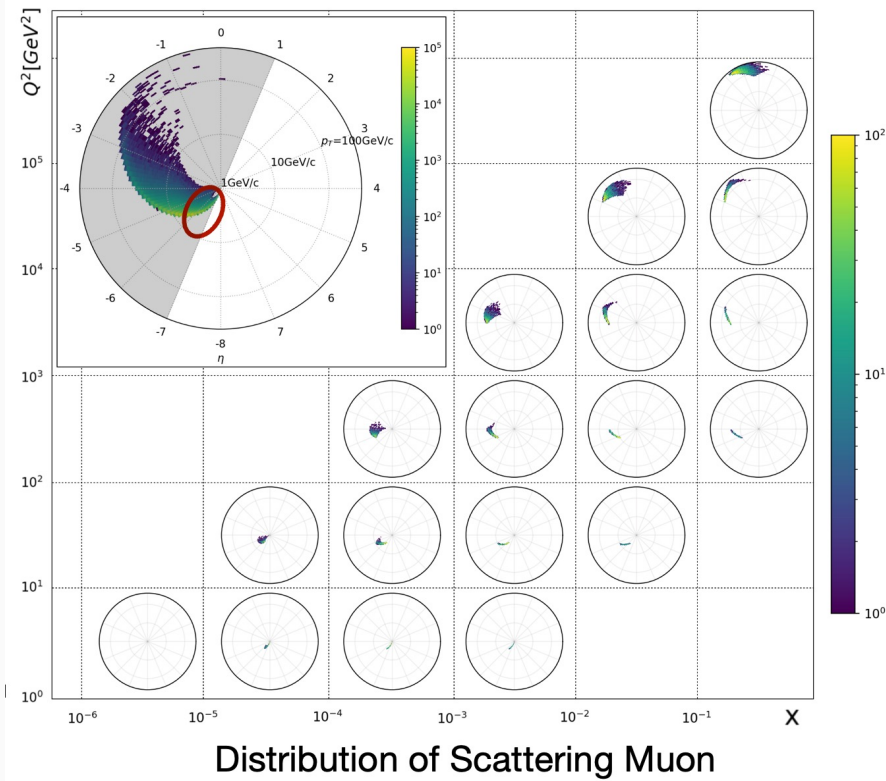




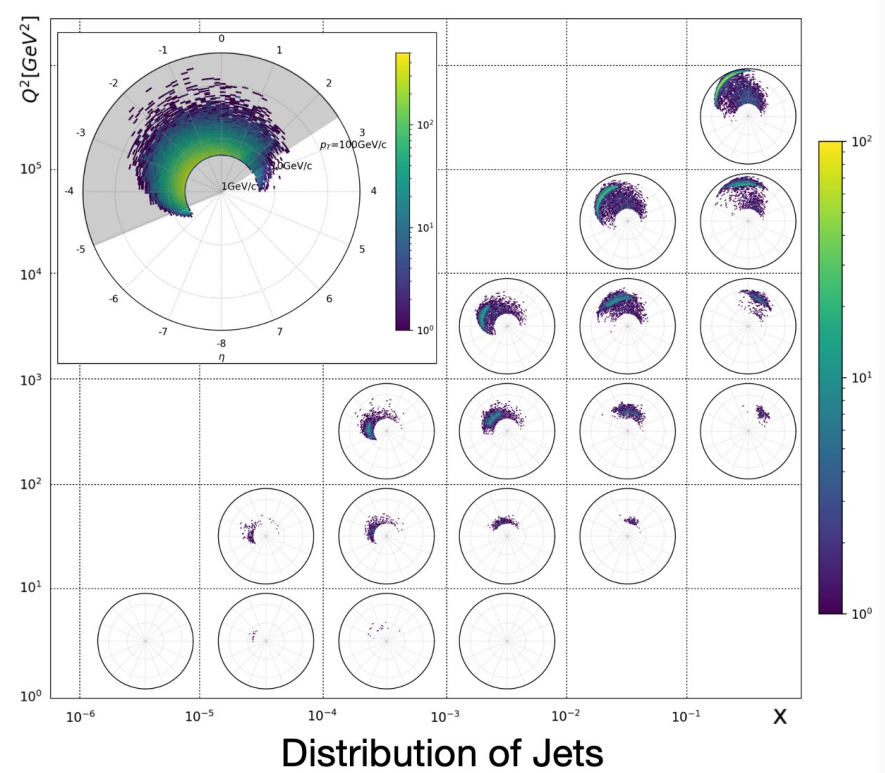
# Kinematics



- Scattered muon ( $\eta$  increases with  $Q^2$ )



- Scattered jet ( $\eta$  decreases with  $y$ )



- Backward tagging of muons to  $\eta = -7$

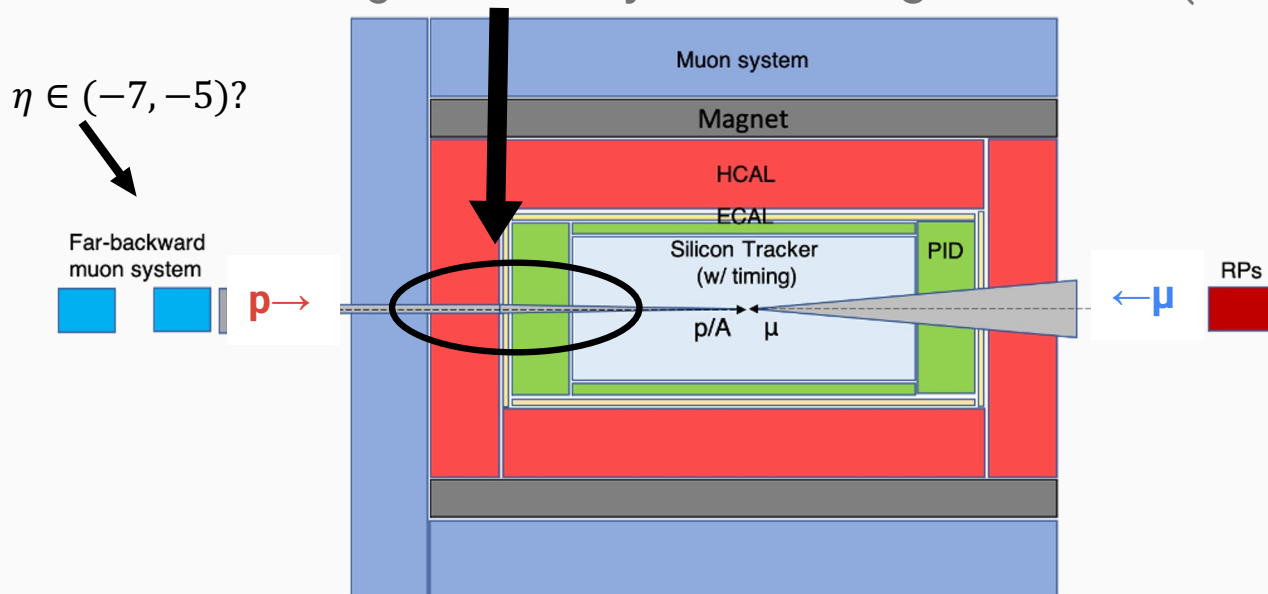
Hadronic system  $-5 < \eta < 2.4$



# Detector Considerations and Challenges



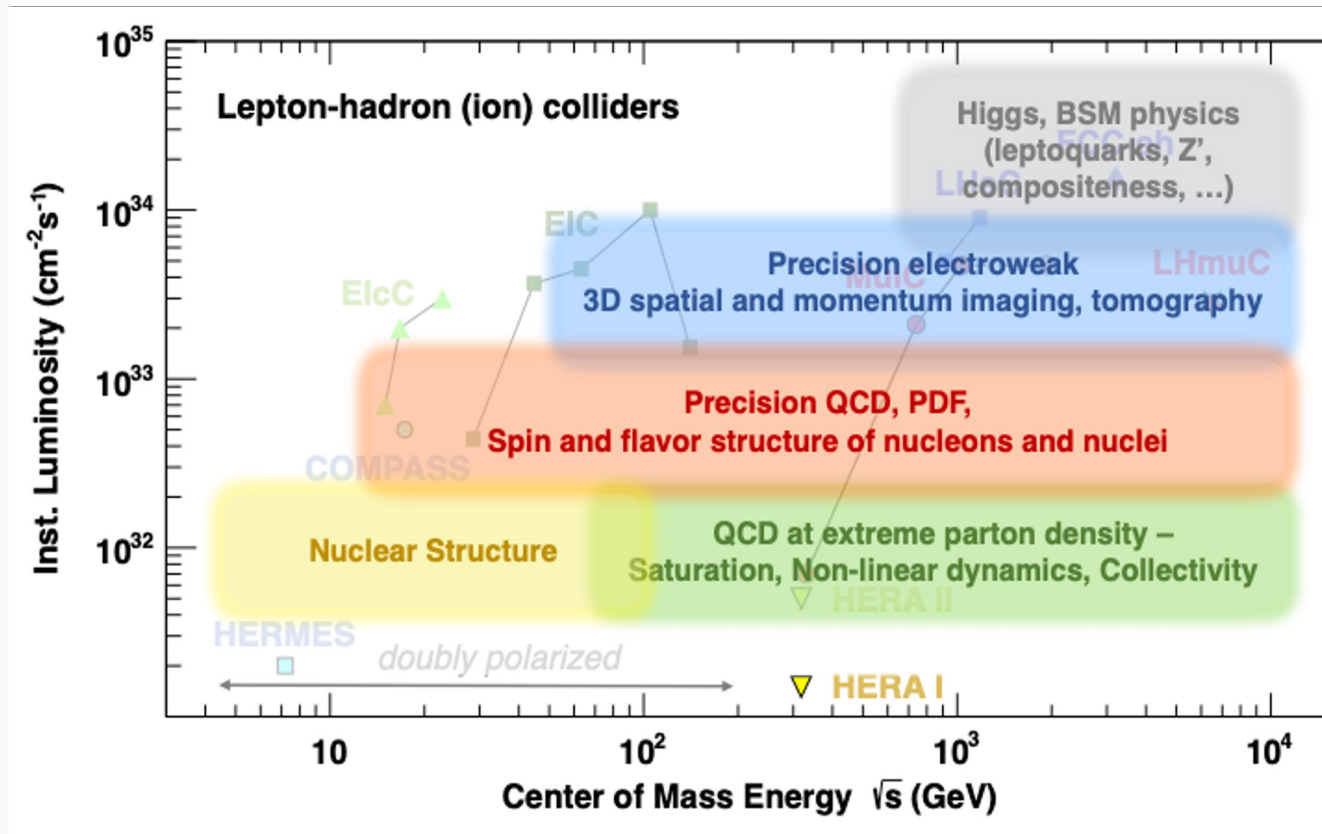
- Modified  $\mu^+\mu^-$  conceptual detector design
- Hadron PID over wide phase space
- Detection of scattered muons is important, mostly at high  $\eta$  (far-backward), with good resolution up to TeV scale
  - Useful also for an experiment at a  $\mu^+\mu^-$  collider to tag/veto NC VBF processes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



	Main requirements
<b>Muons</b>	$-7 < \eta < 0$ , $\sigma(p)/p < 5\%$
Tracking	$-5 < \eta < 2.4$
<b>PID (<math>\pi/k/p</math>)</b>	$-4 < \eta < 2.4$ , $p < 100 \text{ GeV}$
Calorimetry (jets, photons)	$-5 < \eta < 2.4$

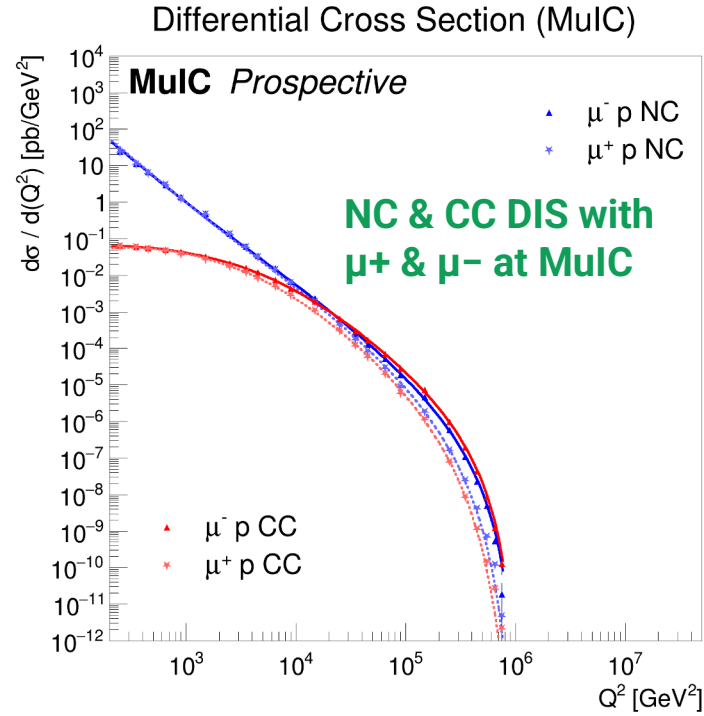
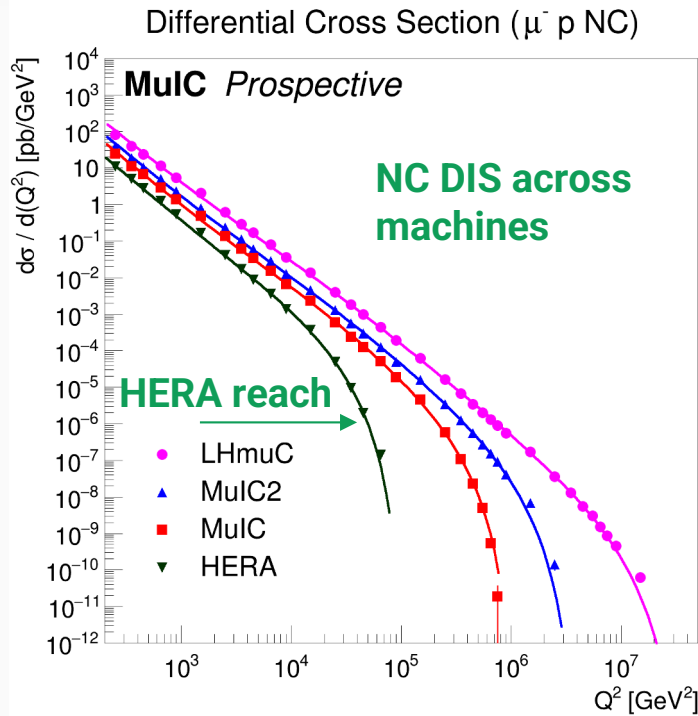


# DIS Evolution and Physics Landscape





# DIS Differential Cross Sections in $Q^2$



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

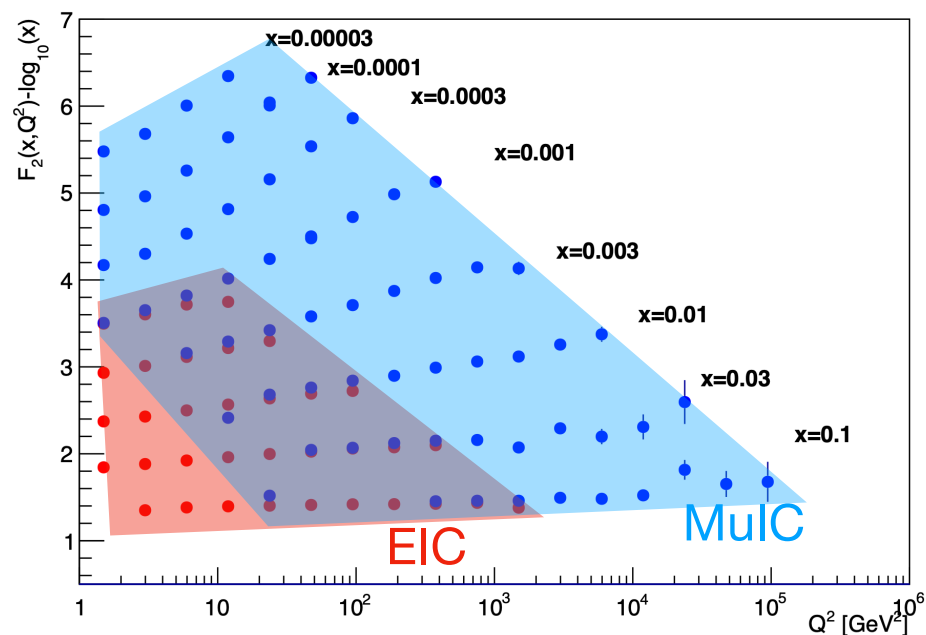
Total integrated CC cross section

Machine	$Q^2 > 1$	$Q^2 > 3 \times 10^4$	$Q^2 > 10^5$	$Q^2 > 3 \times 10^5$
$\mu^- p \rightarrow \nu_\mu X$				
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
$\mu^+ p \rightarrow \bar{\nu}_\mu X$				
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

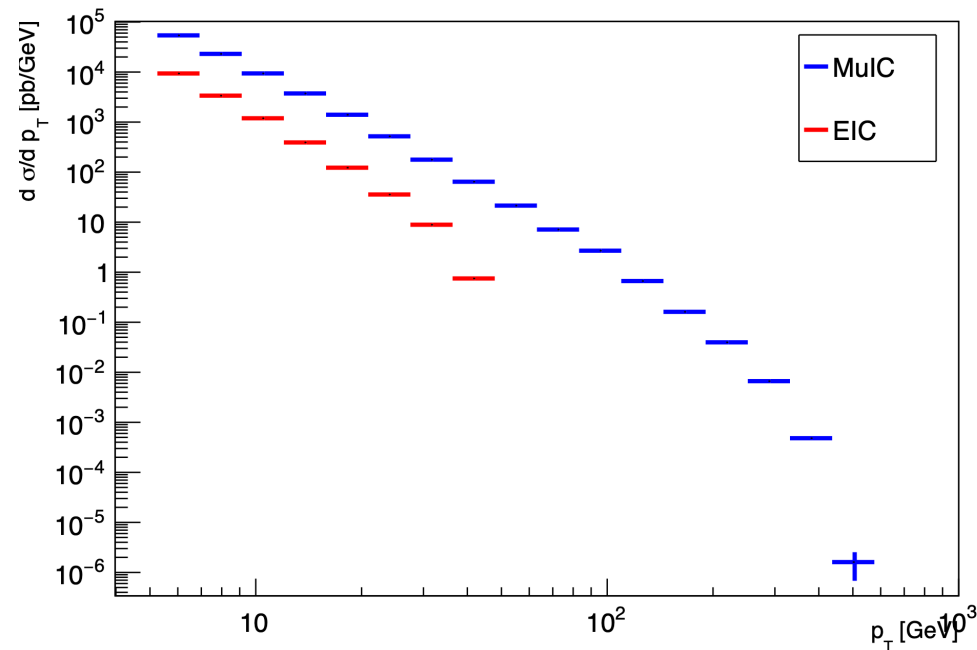
- Probes well beyond HERA and the electroweak scale
- Highest  $Q^2$  requires largest integrated lumi ( $10^{33}$ – $10^{34}$  Hz/cm<sup>2</sup>)
  - But measurements low  $Q^2$  and  $x$  can benefit from relatively low lumi orders of magnitude smaller



# 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

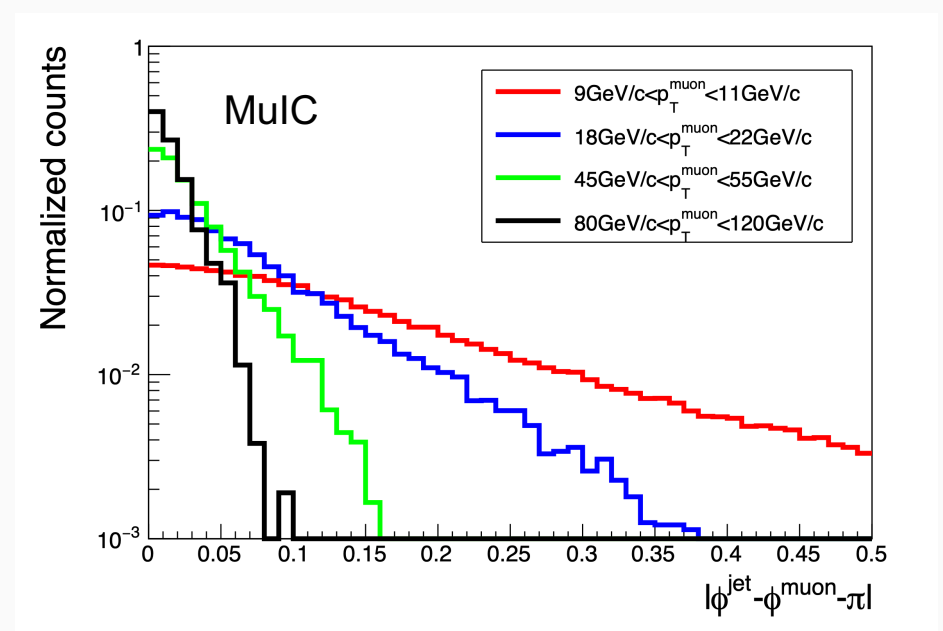
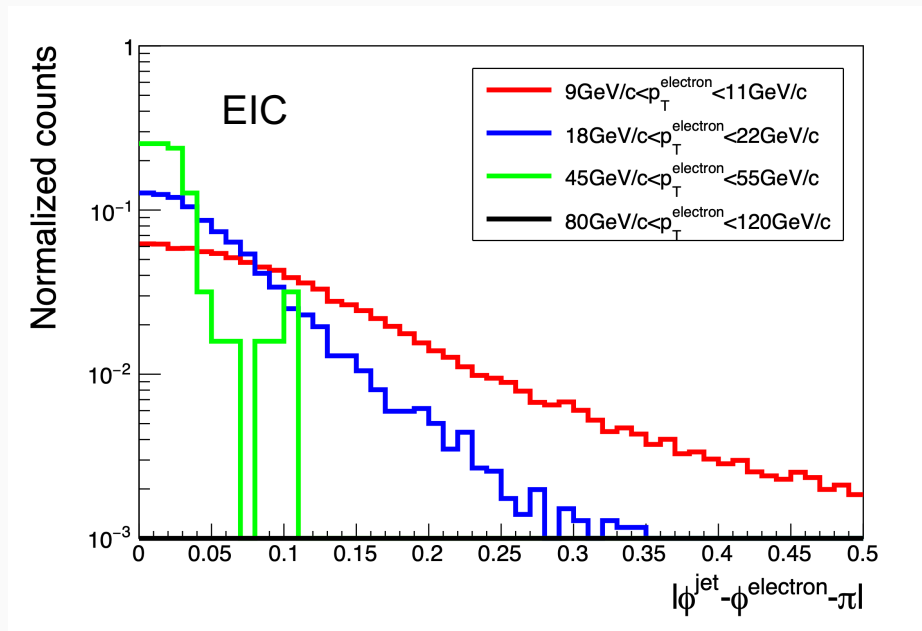
Pseudo-data representing one year of running  
(28 weeks and 50% duty cycle  $\rightarrow \sim 40 \text{ fb}^{-1}$ )



# 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**



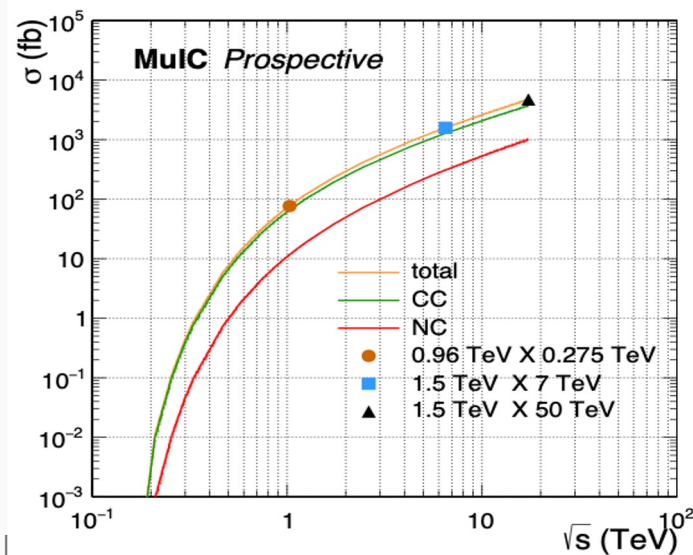
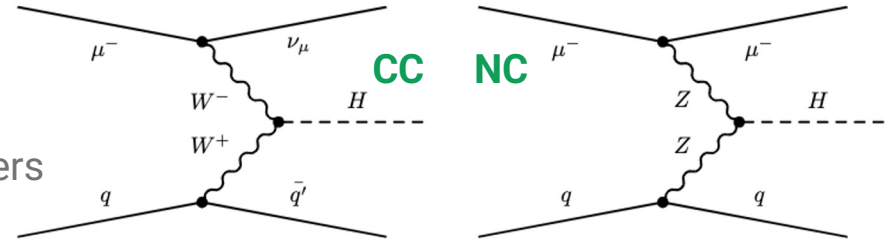


# Higgs Physics with MuIC

arXiv:2203.06258

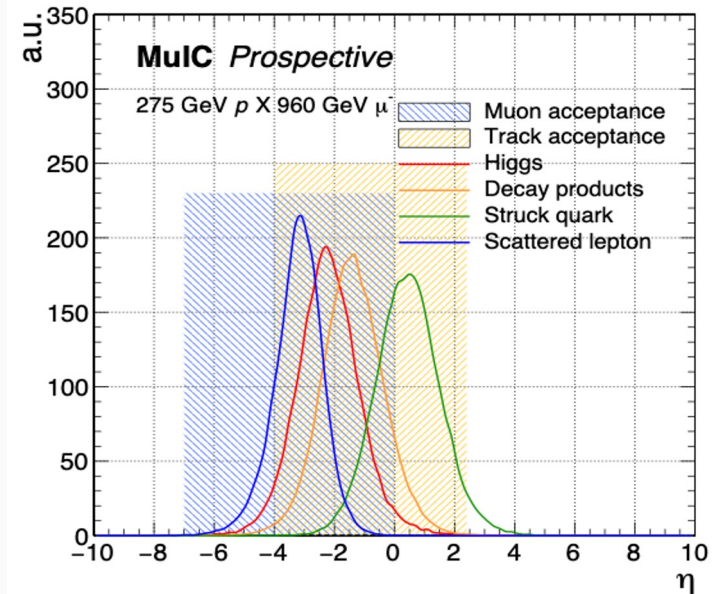


- VBF mode
  - $\sigma$  grows with  $\sqrt{s}$ , with CC exchange larger than NC
  - Cross section comparable to LHeC and  $\mu^+\mu^-$  colliders
- Acceptance
  - All final state objects, other than the muon, are **in central region of detector** (in contrast to LHeC)



Computed with MadGraph

Acosta et al. -- Muon-Ion Collider I

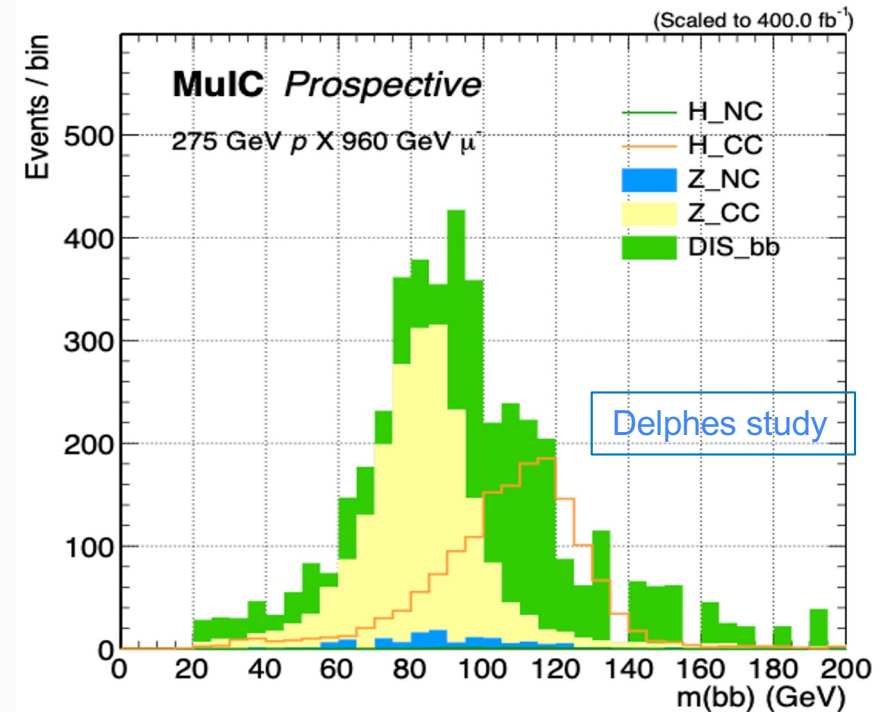




# Higgs $\rightarrow$ bb with MuIC



- Pseudo-analysis for  $H \rightarrow bb$ 
  - Requirements that enhance CC VBF process over NC DIS bb background:
    - 3 jets in final state (2 b-tagged)
    - muon veto, MET
    - Higgs  $p_T$
  - $S/B \sim 1$  for  $H \rightarrow bb$
  - Expect  $\sim 900$  selected  $H \rightarrow bb$  in  $400 \text{ fb}^{-1}$  (10y) @ 1TeV MuIC
    - Increases by factor 10 at LHmuC
- What about  $H \rightarrow cc$  ?
  - Difficult at LHC
  - See next slide



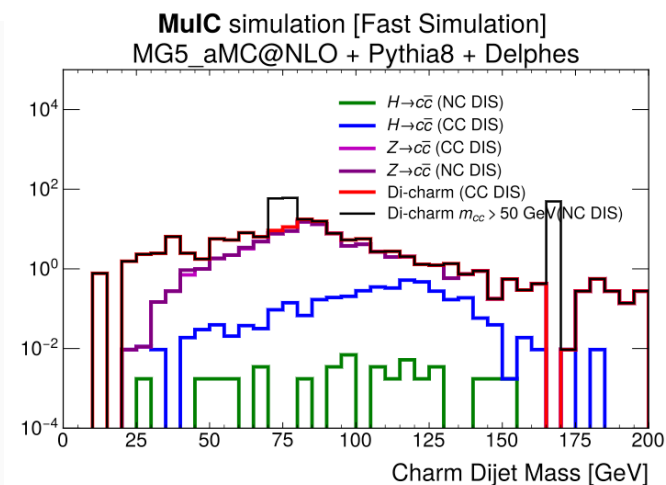
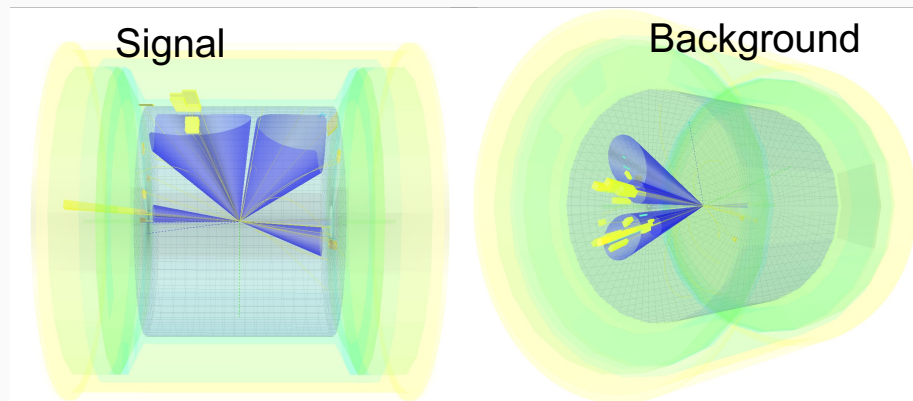


# Higgs $\rightarrow$ cc [Independent SMU group study]



P.Ahluwalia, S.Sekula, et al. (SMU) [arXiv:2211.02615](https://arxiv.org/abs/2211.02615)

- Similar pseudo-analysis of  $H \rightarrow cc$  at 1 TeV MuIC
  - But smaller BR
  - Smaller c-tagging efficiency (27%), and more bkg...
- Selection:
  - $E_{\text{miss}} > 50$  GeV
  - Veto scattered muon (NC)
  - $\geq 2$  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  $\sqrt{s}$
- But fair to caution using  $H \rightarrow cc$  as a motivation for MuIC... ☹

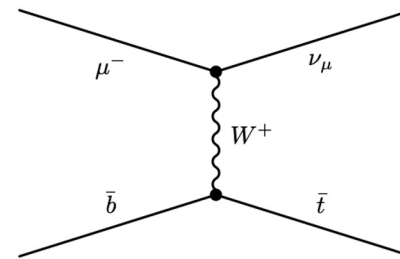
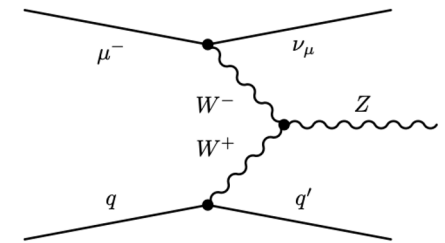
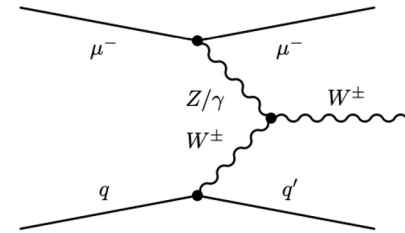




# Other SM Particle Production



- Vector boson production, e.g.
  - Sensitive to **triple gauge couplings**
  - $\sigma(W) = 19 \text{ pb}$  for 1 TeV MuIC
    - $2.1 \times 10^4$  leptonic  $W \rightarrow l\nu$  decays into each lepton flavor for  $10 \text{ fb}^{-1}$
- Single top production
  - Direct measurement of  $|V_{tb}|$
  - $\sigma(t) = 1.0 \text{ pb}$  for 1 TeV MuIC



Potential for precision coupling measurements (and maybe mass measurements, with larger  $\sigma$  at higher  $\sqrt{s}$  and higher luminosity)



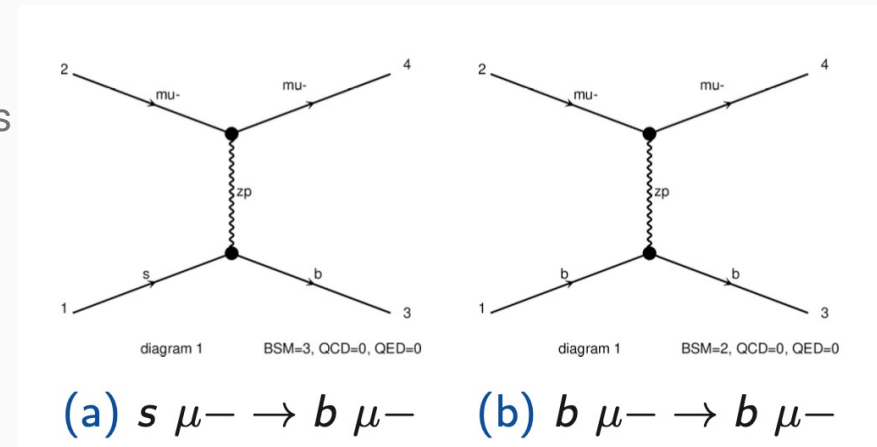
# Probing Z' Models Relevant to LFU Violations



- Consider **Z' models** and couplings discussed in M. Abdullah et al., [Phys. Rev. D 97, 075035](#), that couple via O9 operator mostly to 2<sup>nd</sup> generation leptons ( $\mu$ ) and 2<sup>nd</sup> and 3<sup>rd</sup> generation quarks (s, b) **to explain anomalies in B meson decays**.

$$\mathcal{L} \supset Z'^\mu \left[ g_\mu \bar{\mu} \gamma^\mu \mu + g_\mu \bar{\nu}_\mu \gamma^\mu P_L \nu_\mu + g_b \sum_{q=t,b} \bar{q} \gamma^\mu P_L q + (g_b \delta_{bs} \bar{s} \gamma^\mu P_L b + \text{h.c.}) \right] \quad (6)$$

- $g_\mu$  and  $g_s$  are flavor conserving couplings
- $\delta_{bs}$  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**

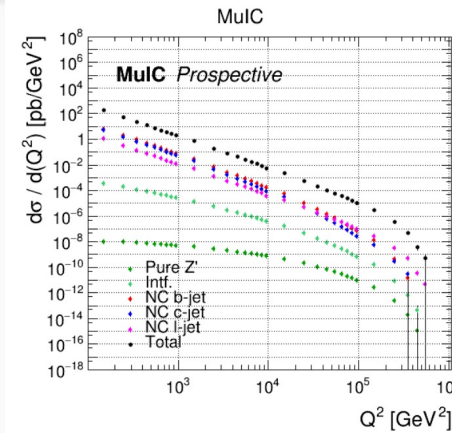




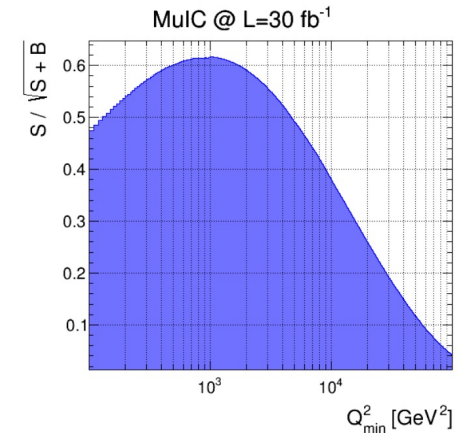
# Probing $Z'$ Models Relevant to LFU Violations



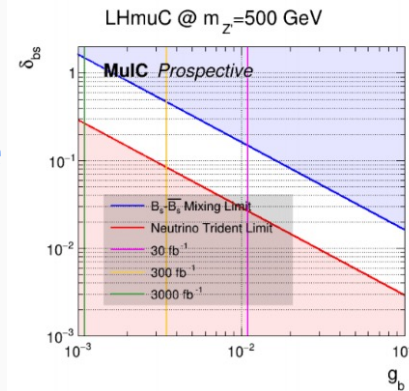
- Perform pseudo-analysis using a cut-and-count approach on the reconstructed  $Q^2$  from the muon, optimized for sensitivity
- Apply b-tagging and mis-tagging efficiencies to final state jet
  - b, c, light: 70%, 10%, 1%
- Derive expected limits
- Generally need LHmuC (120 fb<sup>-1</sup>) to be competitive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



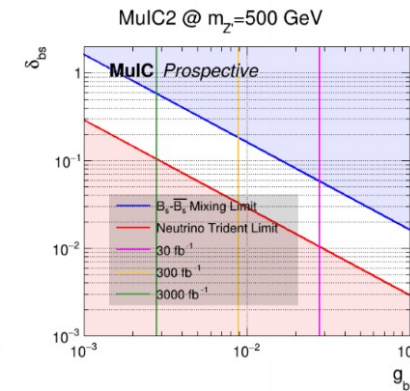
(a)  $m_{Z'} = 500$  GeV



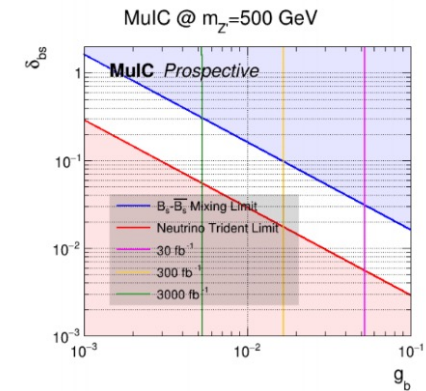
(b)  $m_{Z'} = 500$  GeV



(a) LHmuC



(b) MuIC2



(c) MuIC

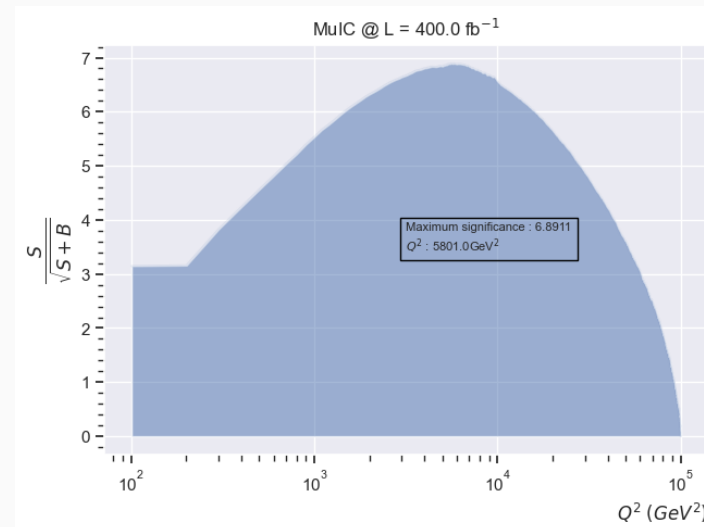
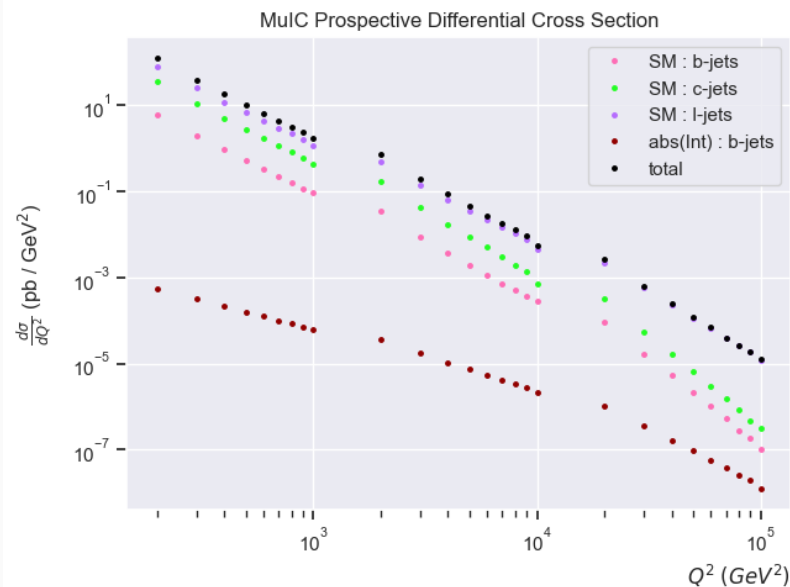
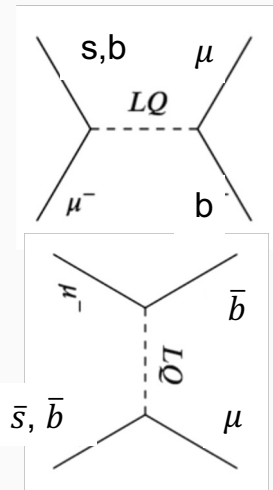


# Probing Leptoquarks Relevant to LFU Violations



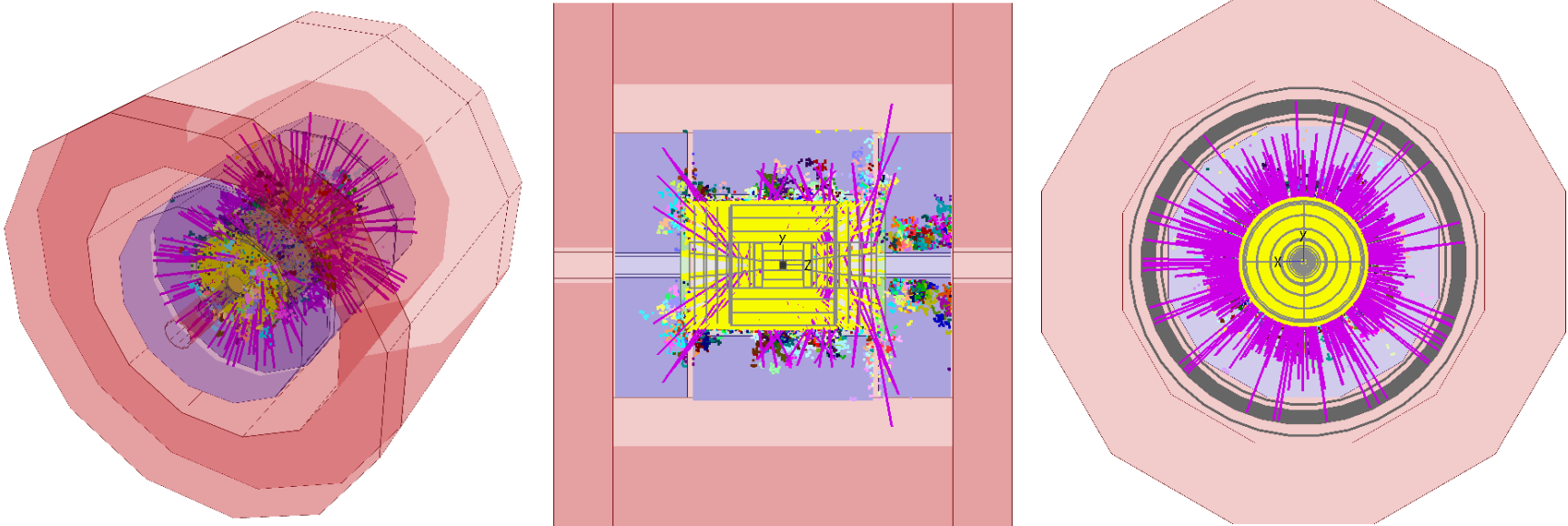
Work in Progress

- Studies focused on LQ models inspired by B and  $\mu$  anomalies
  - S3 type LQ (F=2, LL coupling,  $\mu\text{b}$ ),  $\lambda = 0.1$ ,  $M = 500$  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





## Future Work: Full Simulation Studies with BIB using IMCC Software



*Only one side BIB is turned on*

Our next step: Study the feasibility of experimental measurement with BIBs and detector requirements ([e.g. on forward muon spectrometer](#))

Would need to also redo BIB simulation with one nozzle missing



# 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  $\sim 100$  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 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 ?



# 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 ( $\sqrt{s} = 1\text{-}2$  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.
  - $H \rightarrow c\bar{c}$  would be very challenging, however
- May be an interesting collider to study some BSM physics models
  - $Z'$  study performed
  - Leptoquark study in progress (Rice undergrad doing a 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.)



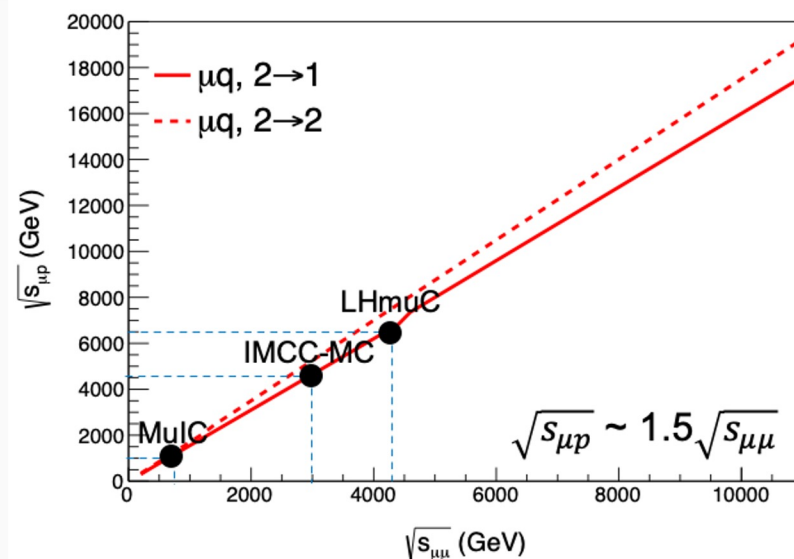
# Backup



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



- Compute equivalent parton luminosity of a  $\mu p$  collider for  $2 \rightarrow 1$  and  $2 \rightarrow 2$  processes
- We find that **a  $\mu^+\mu^-$  collider is equivalent to a  $\mu p$  collider with  $1.5\times$  higher  $\sqrt{s}$**  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  $\mu p$  collisions
  - Swapping 50 GeV  $e^-$  beam with  $>50$  GeV  $\mu$  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?



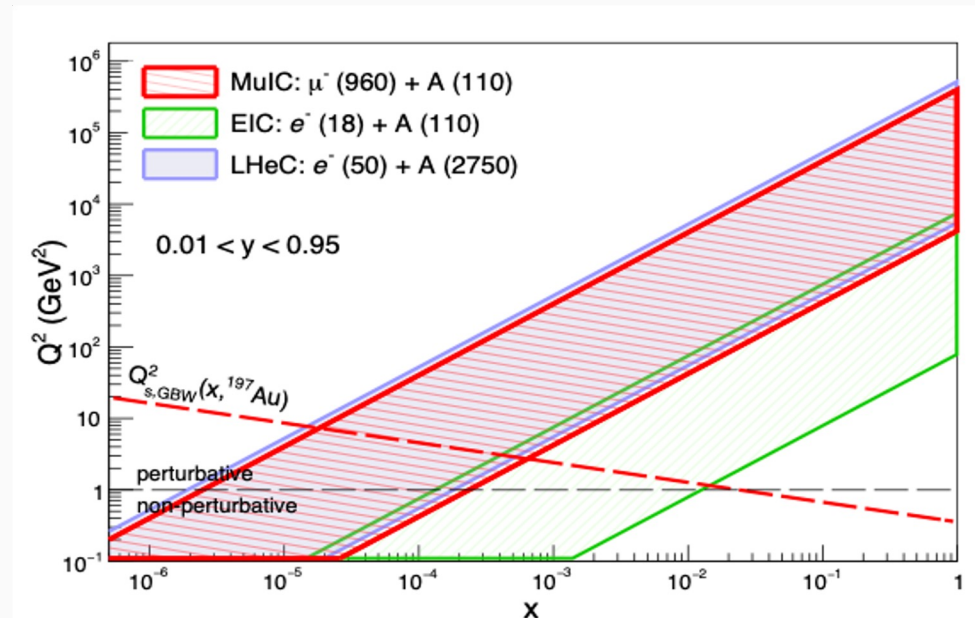
# DIS Reach in $x$ and $Q^2$ for $\ell A$ Collisions



- 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

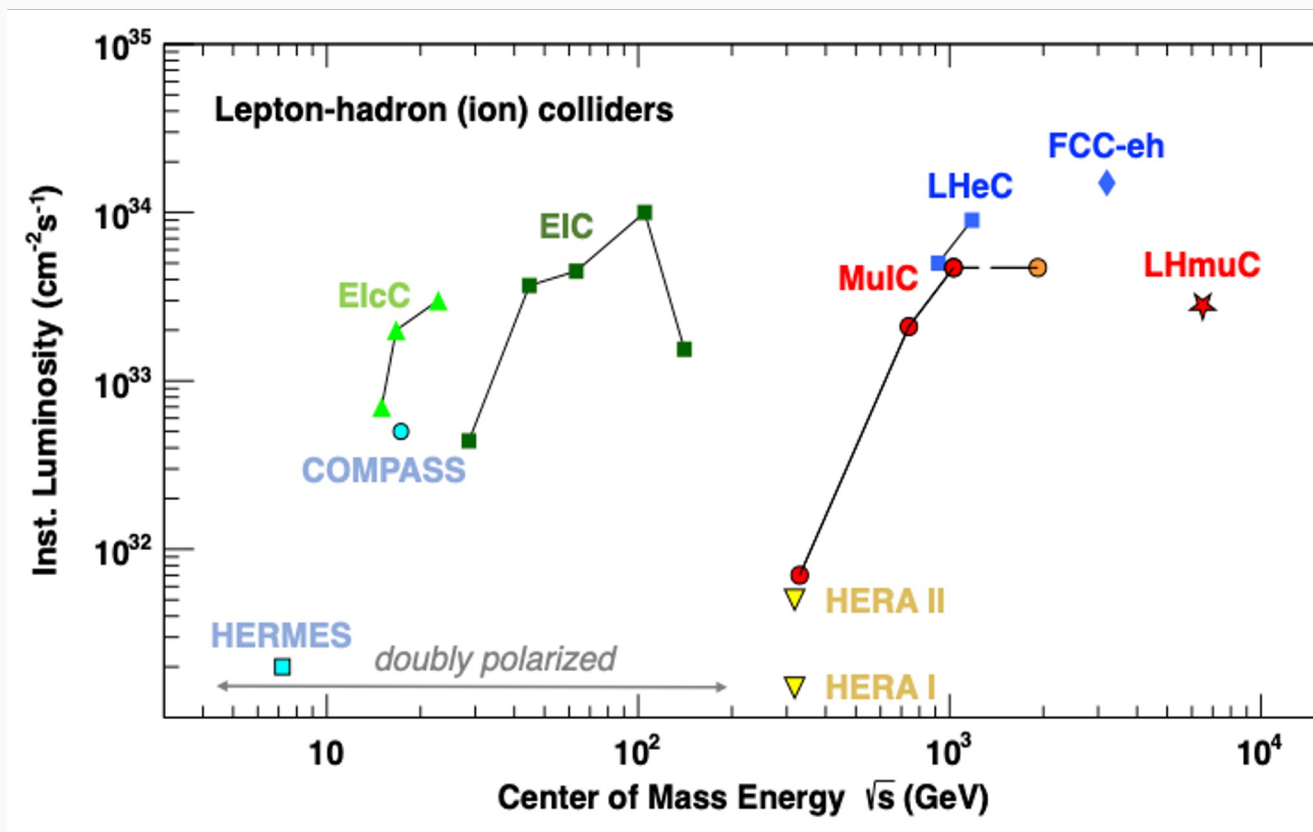
Saturation scale:

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





# DIS Evolution and Physics Landscape

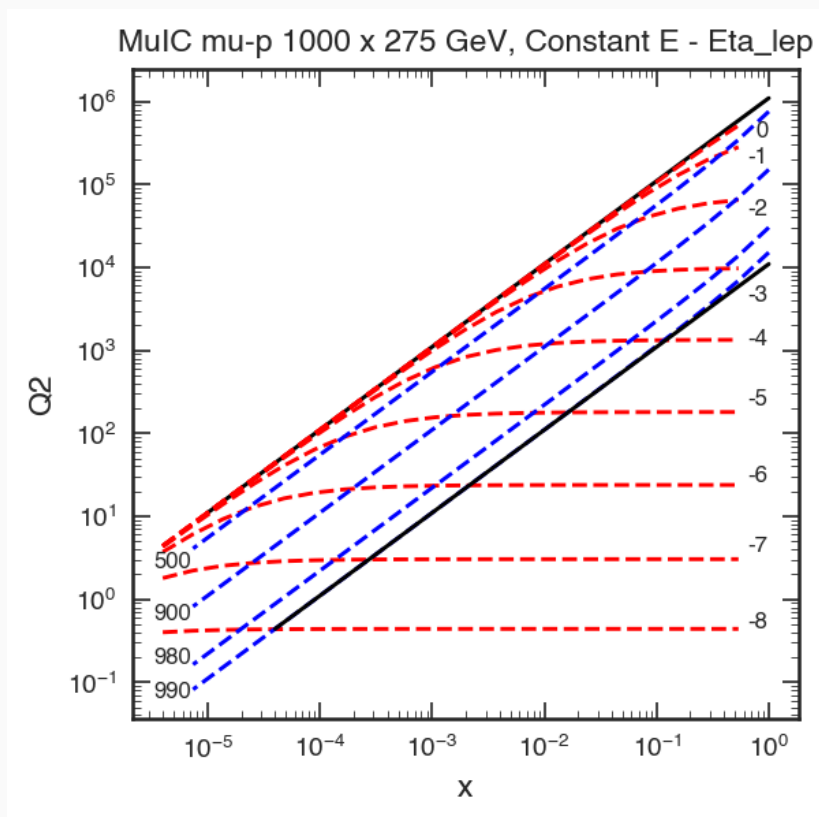




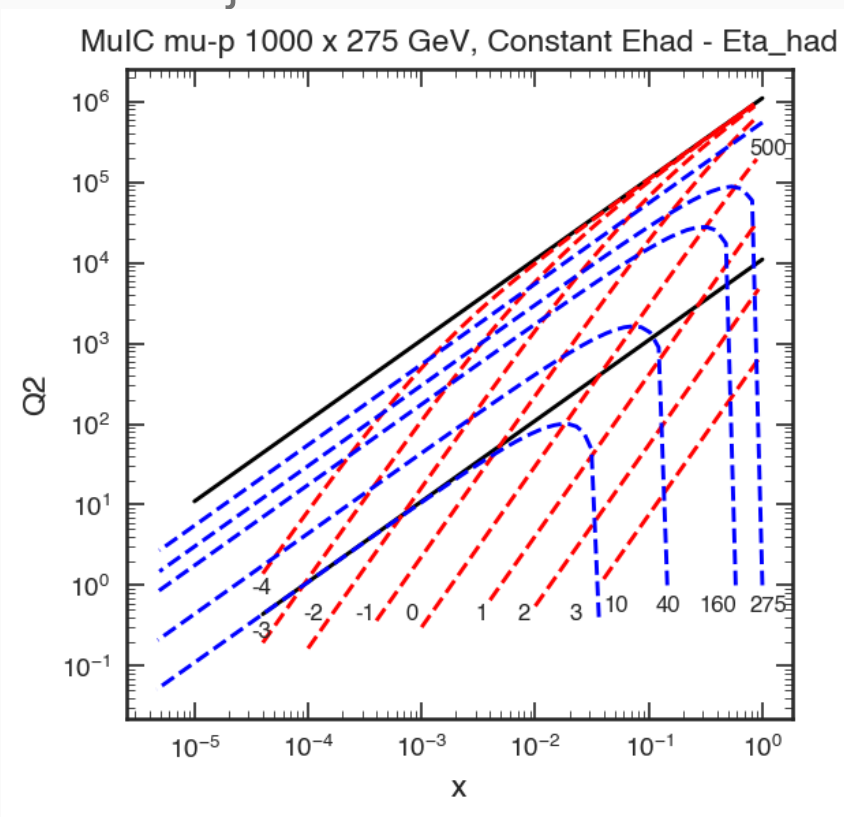
# Kinematics



- Scattered muon



## Scattered jet

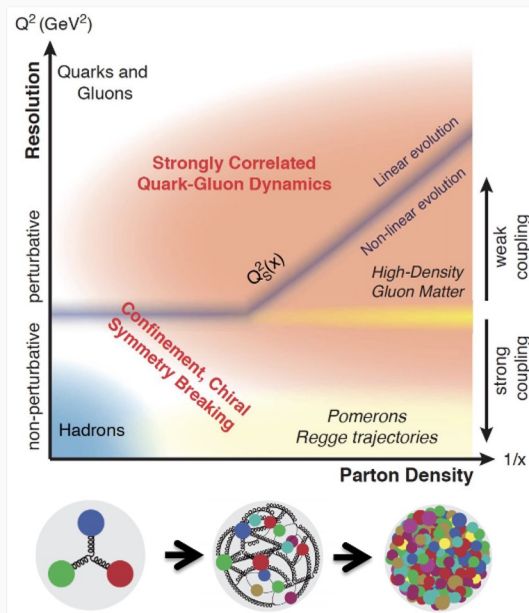




# Nuclear Physics at the MuIC

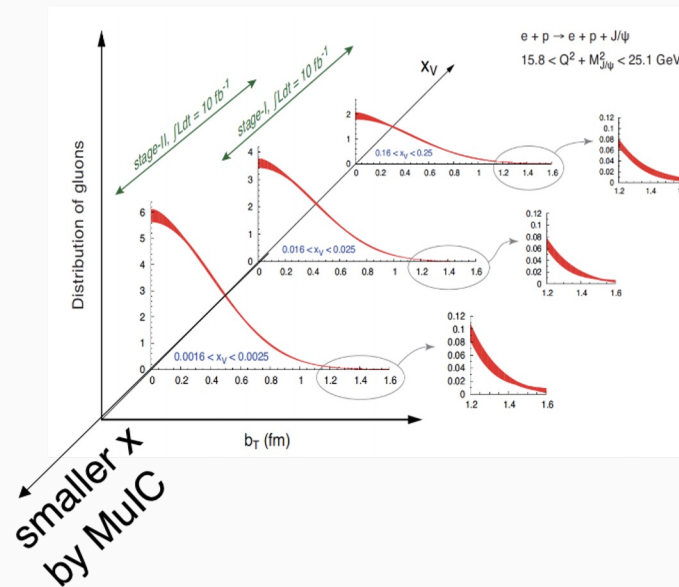


## Gluon saturation



What's the property of high-density gluon matter

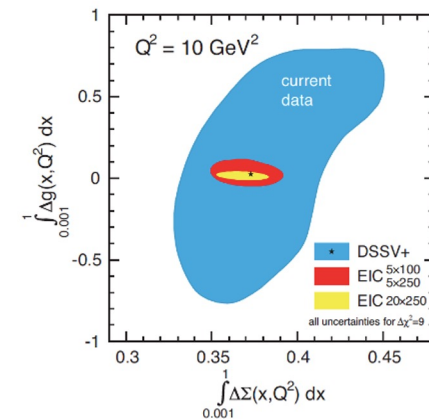
## 3D Nucleon structure



## Nucleon spin puzzle

"Helicity sum rule"

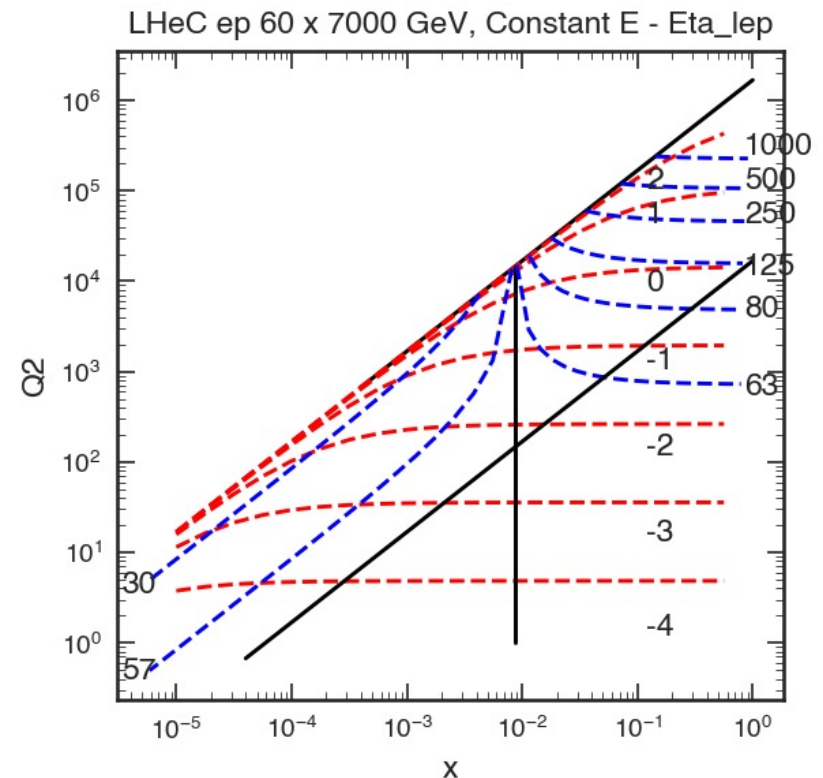
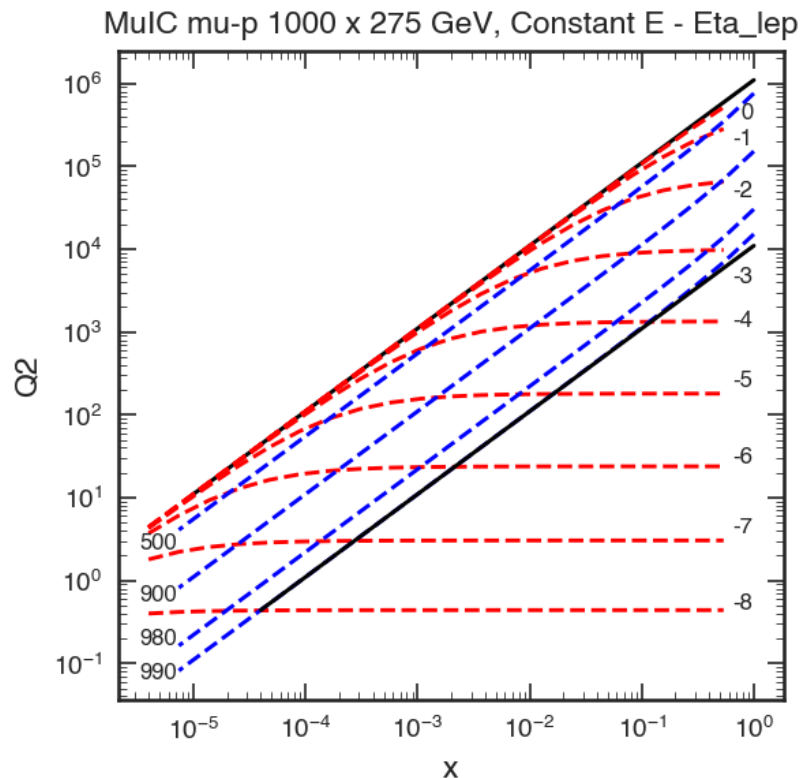
$$\frac{1}{2}\hbar = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quark contribution}} + \underbrace{\Delta G}_{\text{gluon contribution}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{orbital angular momentum}}$$



MuIC to reach  $x \sim 10^{-5}$



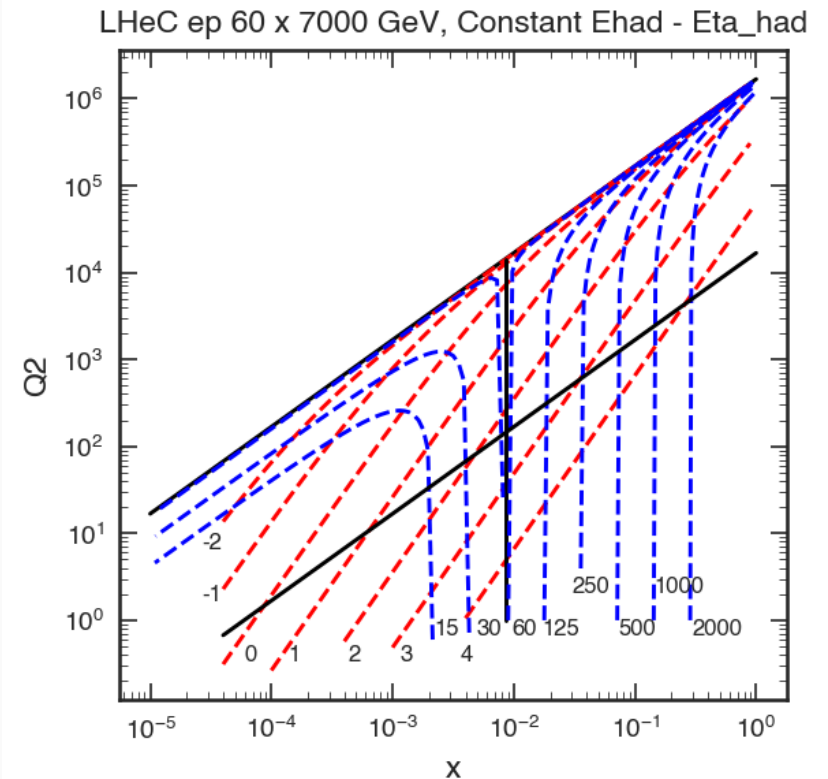
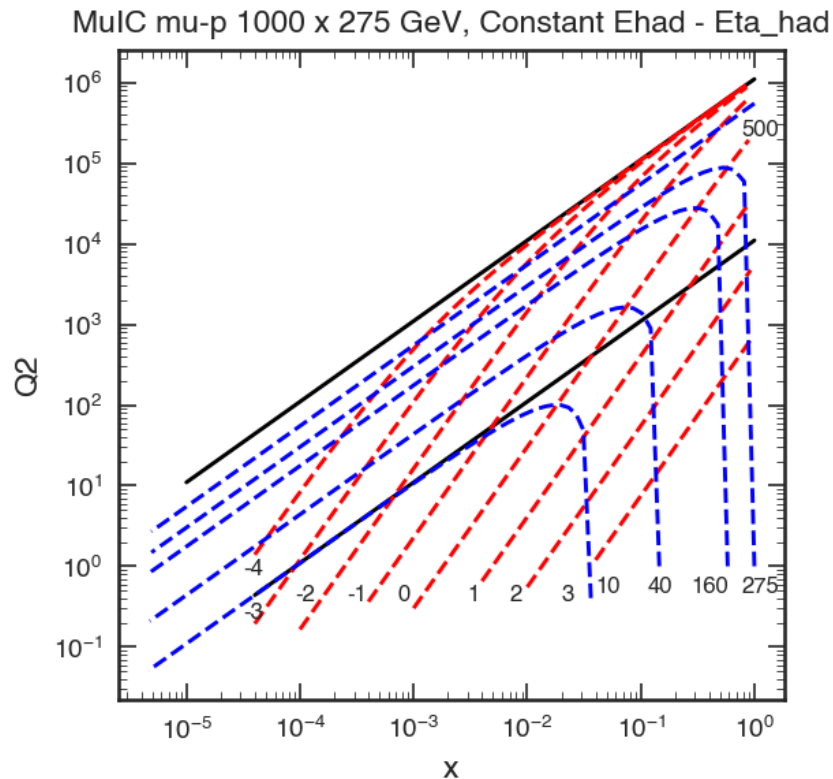
# Lepton DIS Kinematics of MuIC Compared to LHeC



- Much higher scattered muon energy and higher  $|\eta|$  at MuIC



# Hadron DIS Kinematics of MuIC Compared to LHeC



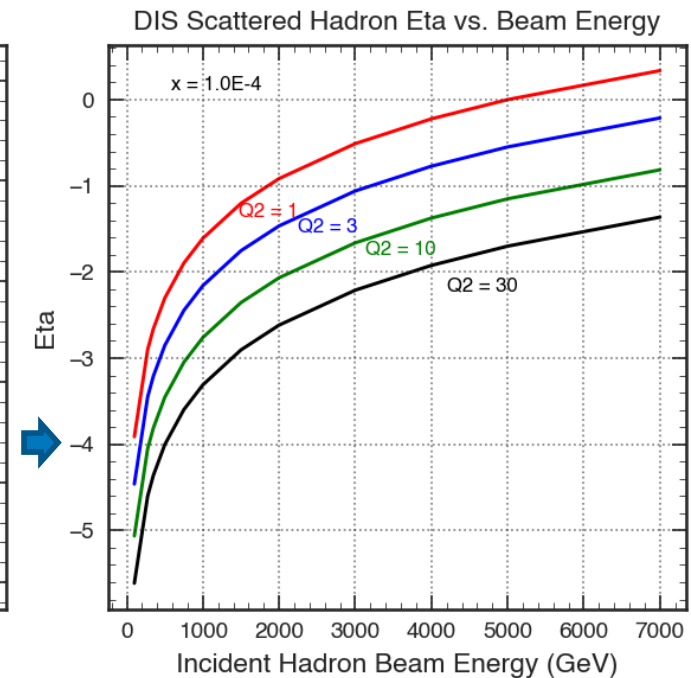
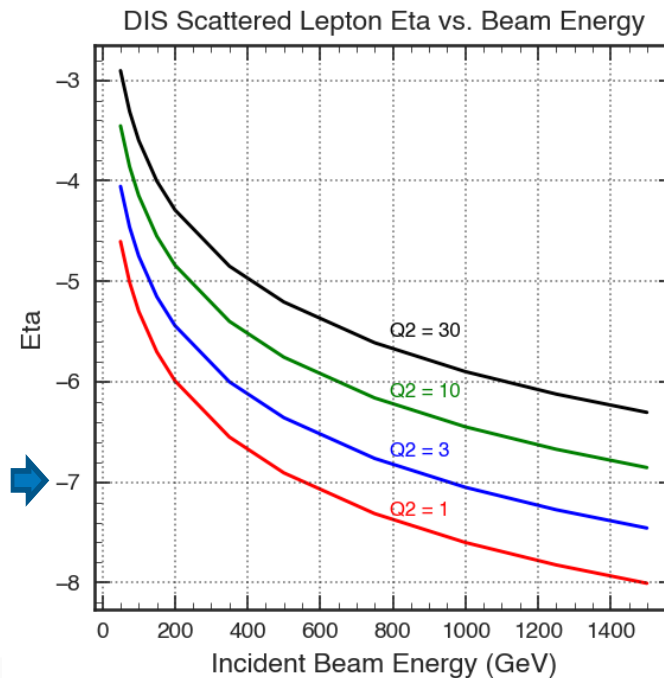
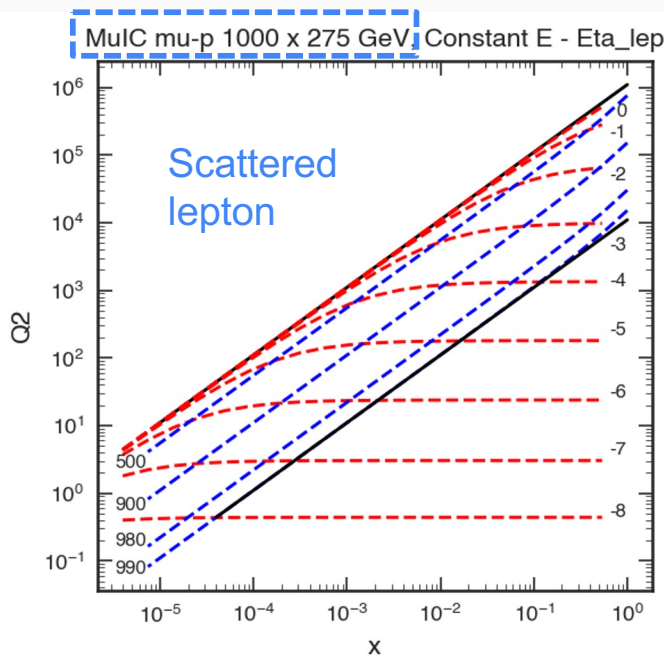
- Hadron system peaks more in proton direction and lower energy at low  $x$  for LHeC



# DIS Scattering Kinematics at a $\mu p$ 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



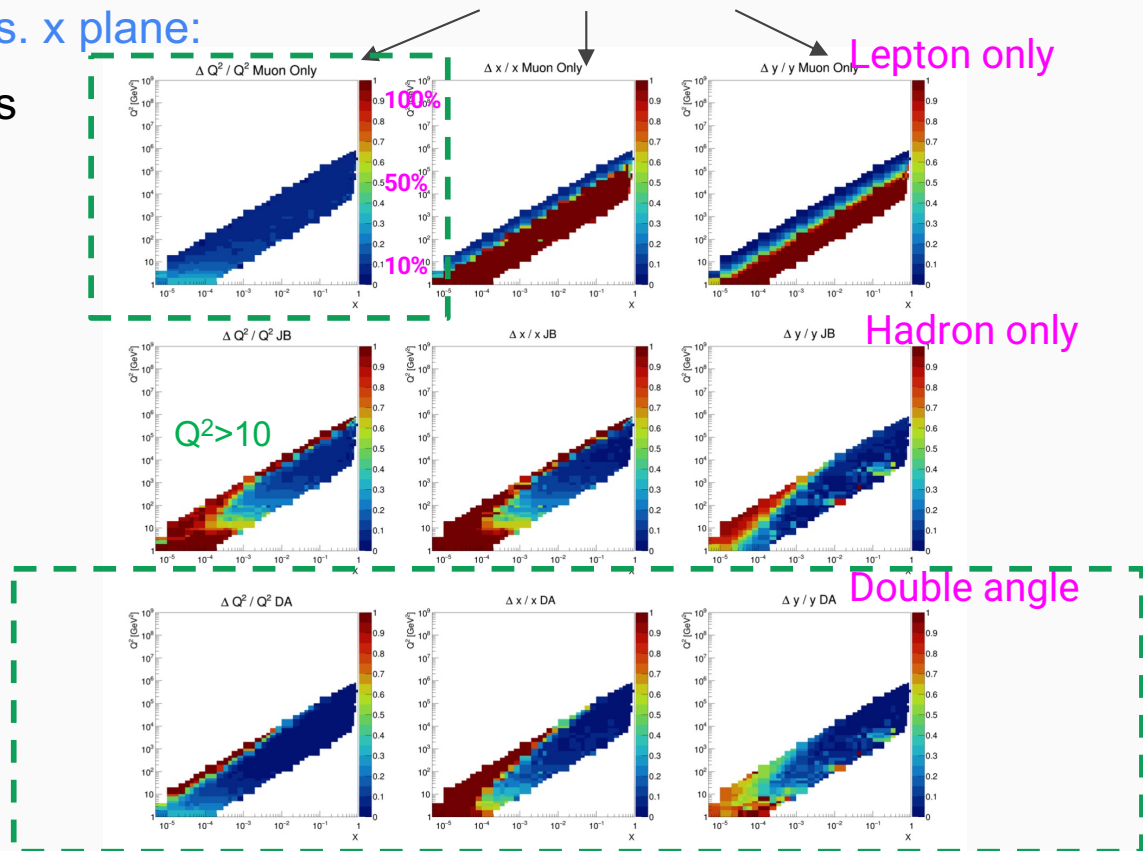
Resolutions of reconstructed  $Q^2$ ,  $x$  and  $y$  with 3 methods

$Q^2$  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	$0.01\% p \oplus 1\%$	$0.2 \times 10^{-3}$
Charged particles ( $\pi^\pm, K^\pm, p/\bar{p}, e^\pm$ )	Tracker + PID	$0.1\% p \oplus 1\%$	$\left(\frac{2}{p} \oplus 0.2\right) \times 10^{-3}$
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)

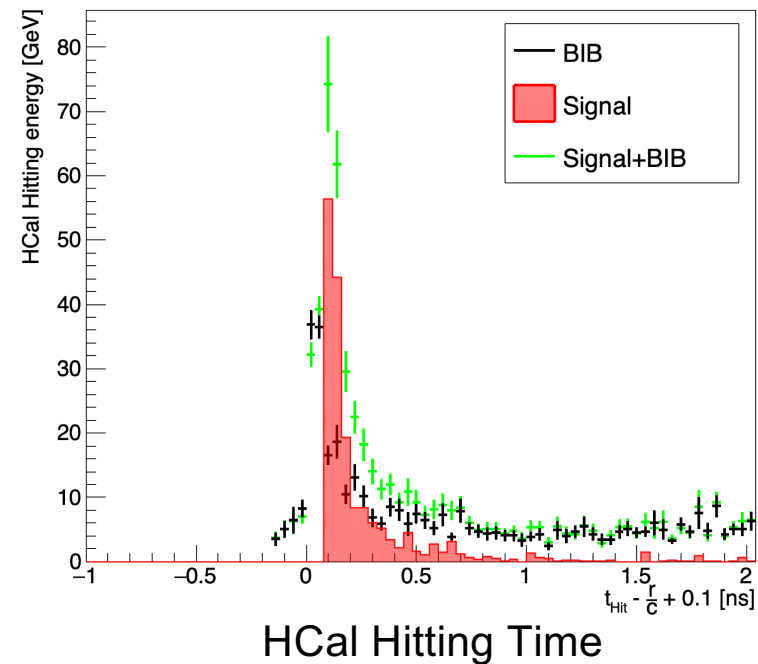
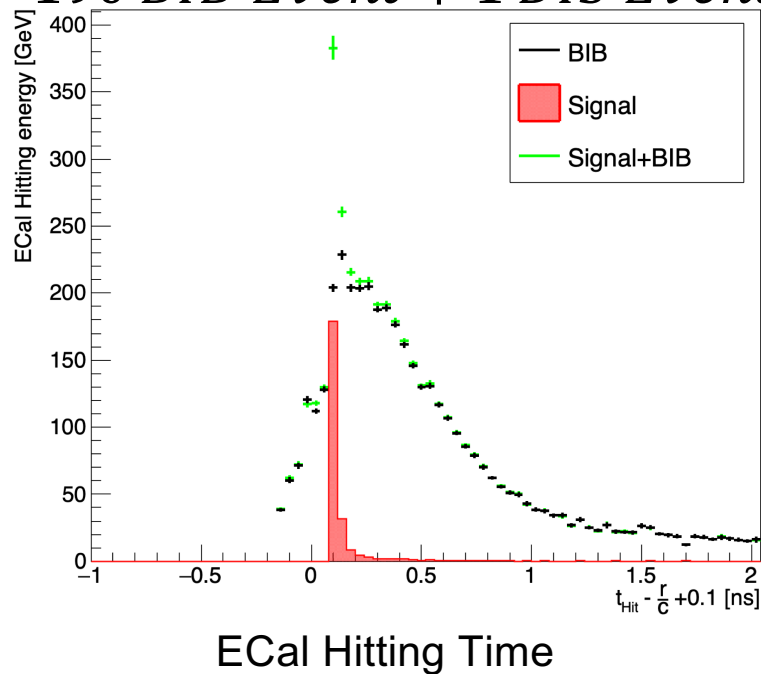




# Full Simulation using IMCC Software — Workflow

190 *BIB* Event + 1 *DIS* Event

BIB file: sim\_mumi-1e3x500-26m-lowth-excl\_j1.slcio

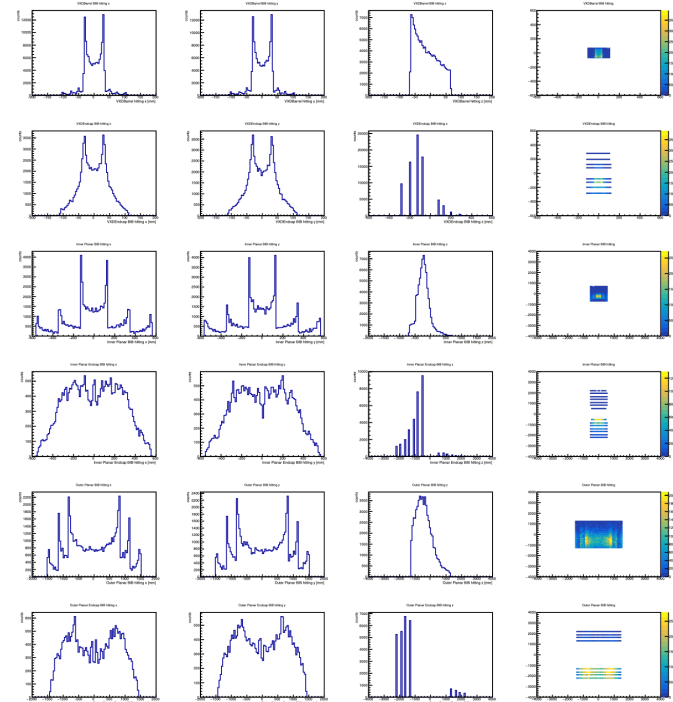
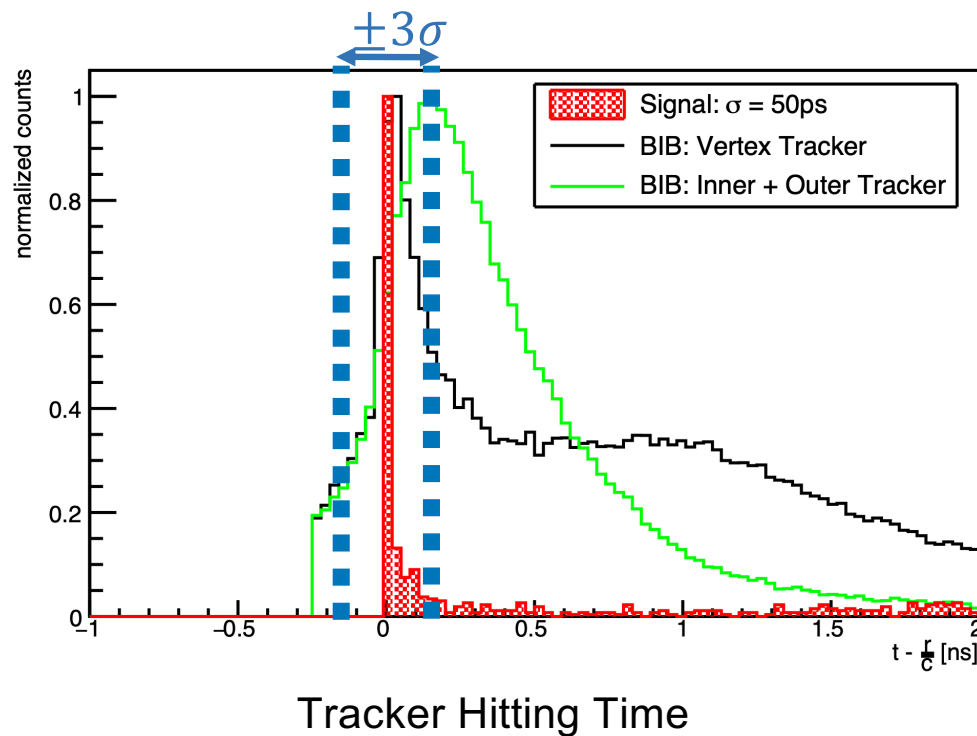




# Full Simulation using IMCC Software — Workflow

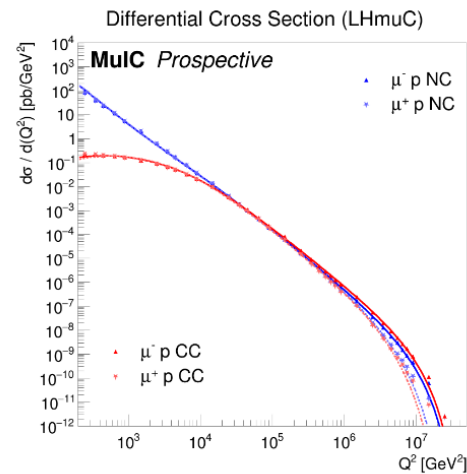
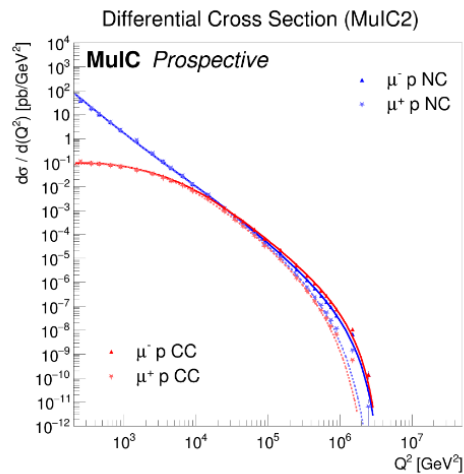
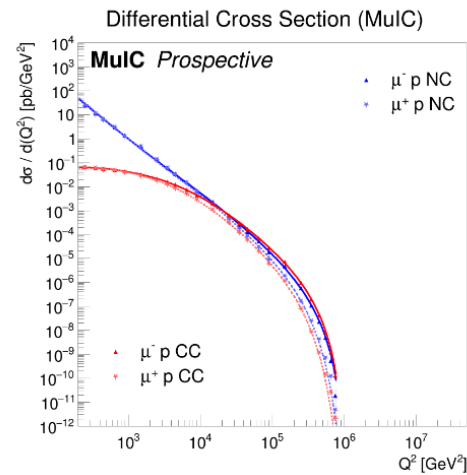
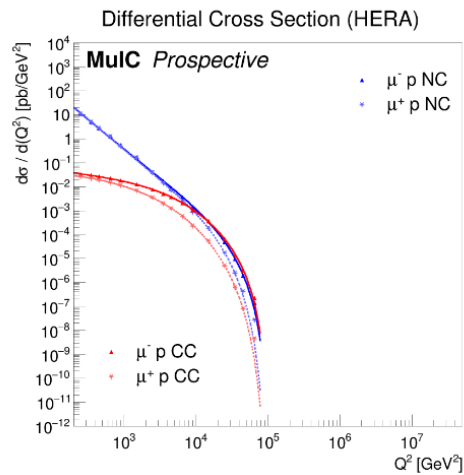
190 *BIB* Event + 1 *DIS* Event

BIB file: sim\_mumi-1e3x500-26m-lowth-excl\_j1.slcio





# 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  $\mu^-$  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%
$\sigma_{CC}$	91.1	78.2	71.7	65.1	58.8	52.1	39.0	0
$\sigma_{NC}$	12.6	12.1	11.9	11.6	11.4	11.1	10.5	8.9
$\sigma_{tH}$	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  $\mu^+$  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%
$\sigma_{CC}$	45.0	38.2	35.6	32.1	28.9	25.6	19.2	0
$\sigma_{NC}$	12.4	12.0	11.7	11.6	11.3	11.0	10.6	9.1
$\sigma_{tH}$	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  $\text{PDF}\oplus\alpha_s$  uncertainties. The  $\mu^-$  beam energy is unpolarized in all cases.

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

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  $\text{PDF}\oplus\alpha_s$  uncertainties. The  $\mu^-$  beam energy is unpolarized in all cases.

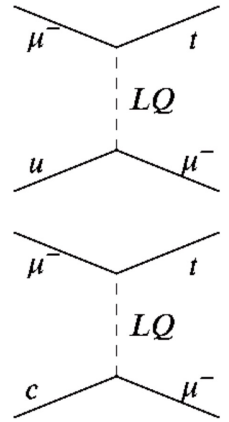
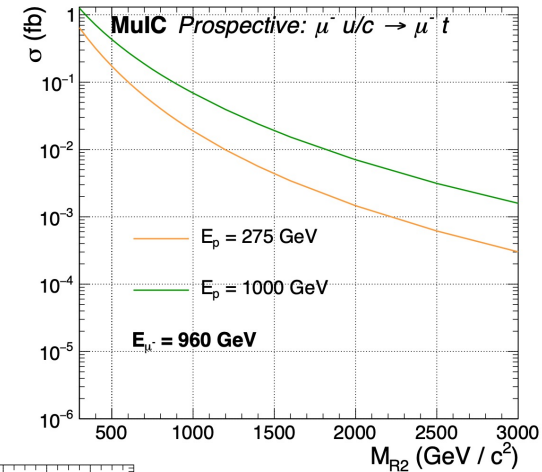
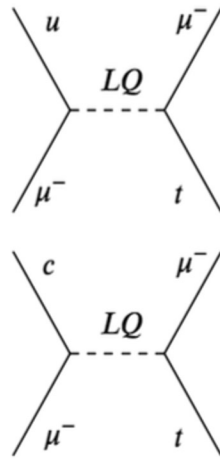
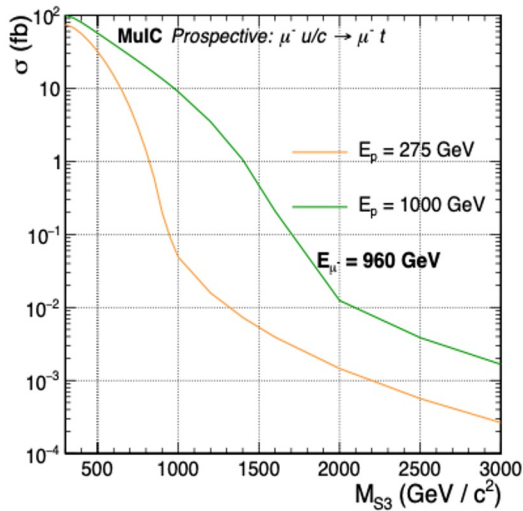
$E_\mu \times E_p$ (TeV <sup>2</sup> )	Inclusive	$p_T^\ell > 1$ GeV	$p_T^\ell > 2$ GeV	$p_T^\ell > 5$ GeV
$0.96 \times 0.275$	8.69 <sup>+0.7%</sup> <sub>-1.0%</sub> <sup>+0.9%</sup> <sub>-0.9%</sub>	2.10 <sup>+1.6%</sup> <sub>-2.0%</sub> <sup>+0.9%</sup> <sub>-0.9%</sub>	1.71 <sup>+1.8%</sup> <sub>-2.1%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

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

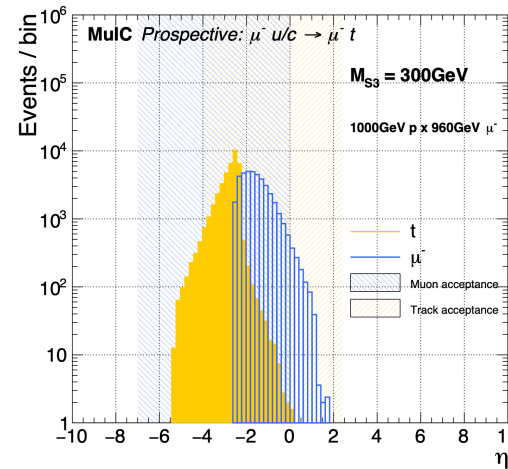
$E_\mu \times E_p$ (TeV <sup>2</sup> )	$\sigma$ (pb)	Scale unc.	$\text{PDF}\oplus\alpha_s$ unc.
$0.96 \times 0.275$	1.80	<sup>+2.8%</sup> <sub>-5.6%</sub>	<sup>+1.4%</sup> <sub>-1.4%</sub>
$0.96 \times 0.96$	7.47	<sup>+7.9%</sup> <sub>-11%</sub>	<sup>+1.4%</sup> <sub>-1.4%</sub>
$1.5 \times 7$	52.8	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



# Leptoquark Production with Top



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



- t-channel R2 LQ production to  $\mu+t$

Potential limits still to be worked out