Physics Potential of a TeV Muon-Ion Collider

Based on Snowmass '21 whitepaper: arXiv:2203.06258

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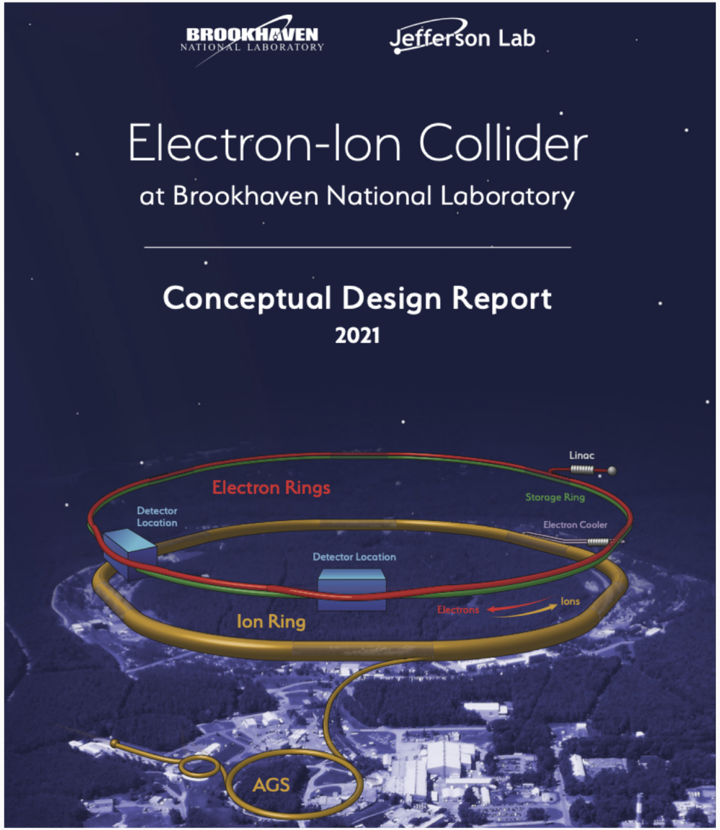
Outline

- Overview of concept
- Potential machines
  - Though not the technical challenges of establishing muon collider technology
- Science program
  - DIS measurements
  - Higgs and other SM particle production processes
  - BSM physics
- Kinematics and resolution
- Experiment considerations

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 (ECCE) also selected.

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

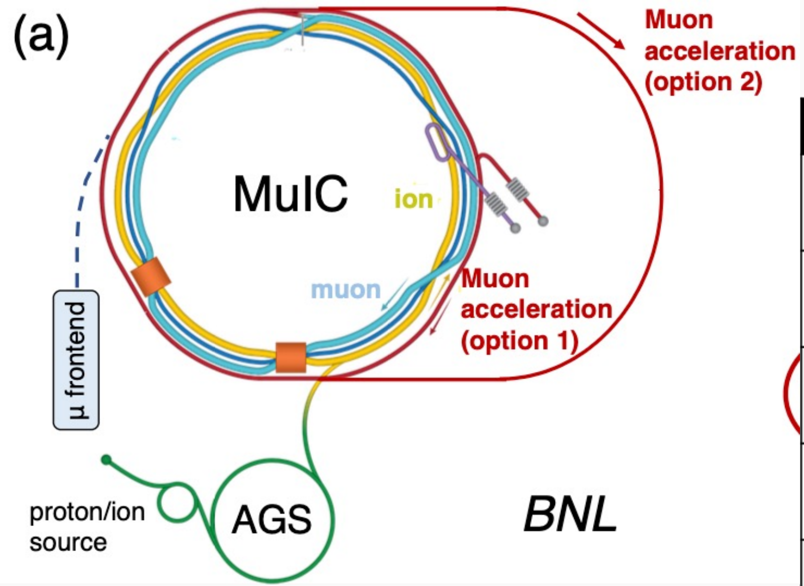
Physics goals:

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

A Muon-Ion Collider 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

See also talk by Ethan Cline in this session

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 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. LQ, Z')

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

Energy Configurations and Luminosity

Parameter	BNL options: MuIC			MuIC2	LHmuC	
$\sqrt{s_{\mu p}}$ (TeV)	0.33	0.74	1.0	$\rightarrow$ 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 $\rightarrow$ 1.0	1.5	7
N_b (10^{11})	40	20	20	3	20	2.2
f^{μ}_{rep} (Hz)	15	15	15		12	
Cycles per μ bunch, N^{μ}_{cycle}	1134	1719	3300		3300	
$\varepsilon^*_{x,y}$ (μm)	200	25	25	0.3	25	2.5
$\beta^*_{x,y}$ @IP (cm)	1.7	1	0.75	5	0.5	15
Trans. beam size, $\sigma_{x,y}$ (μm)	48	7.6	4.7	7.1	3	7.1

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

LHC option

← √s

← Estimate of lumi

← Beam energies

Upgrade hadron ring

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

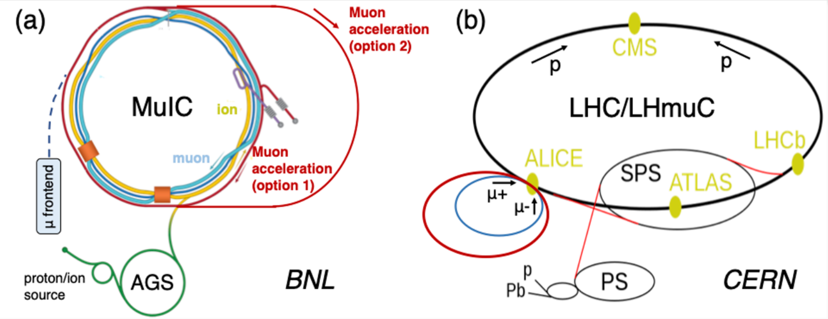
$$\sigma_{x,y}^{\mu,p} = \sqrt{\varepsilon^*_{x,y} \beta^*_{x,y} m^{\mu,p} / E^{\mu,p}}$$

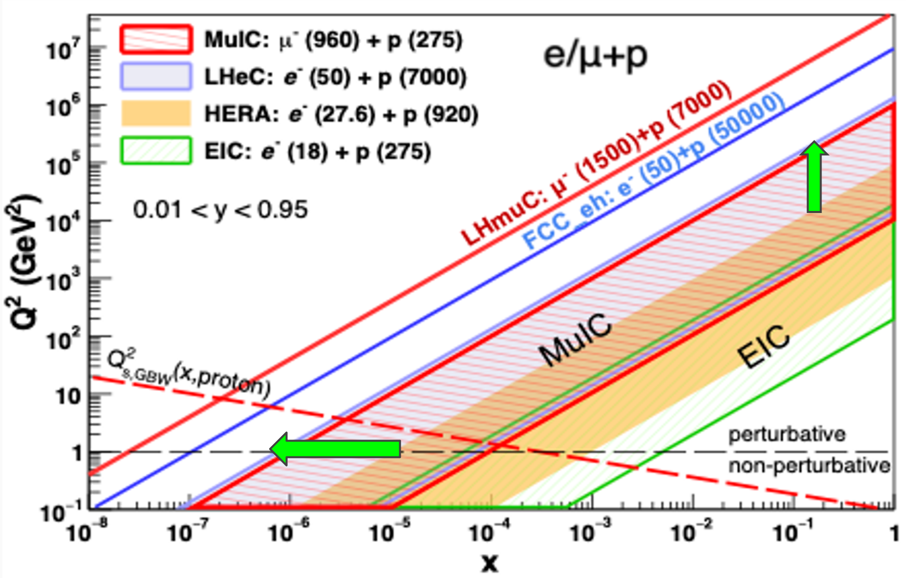
DIS Reach in x and Q^2 for ℓp Collisions

- 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





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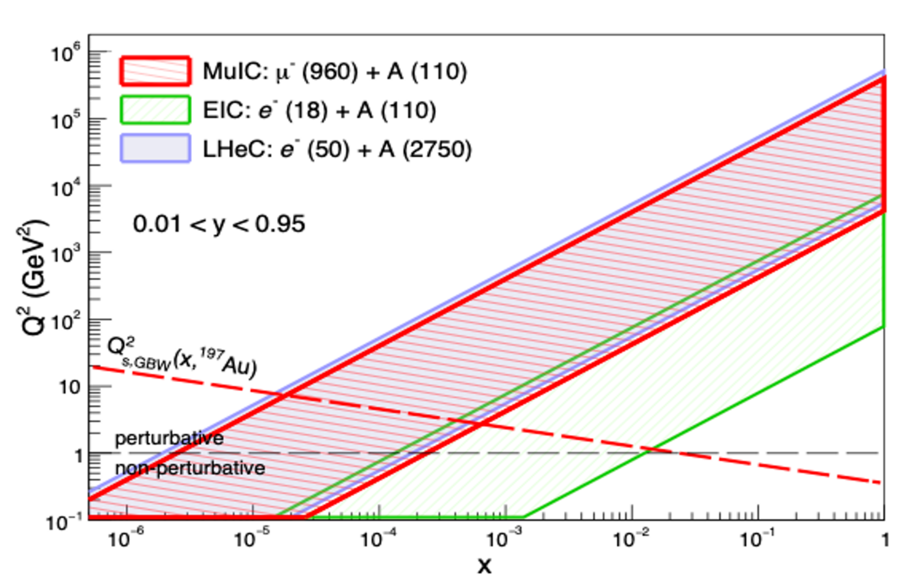
DIS Reach in x and Q^2 for ℓA Collisions

- 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)

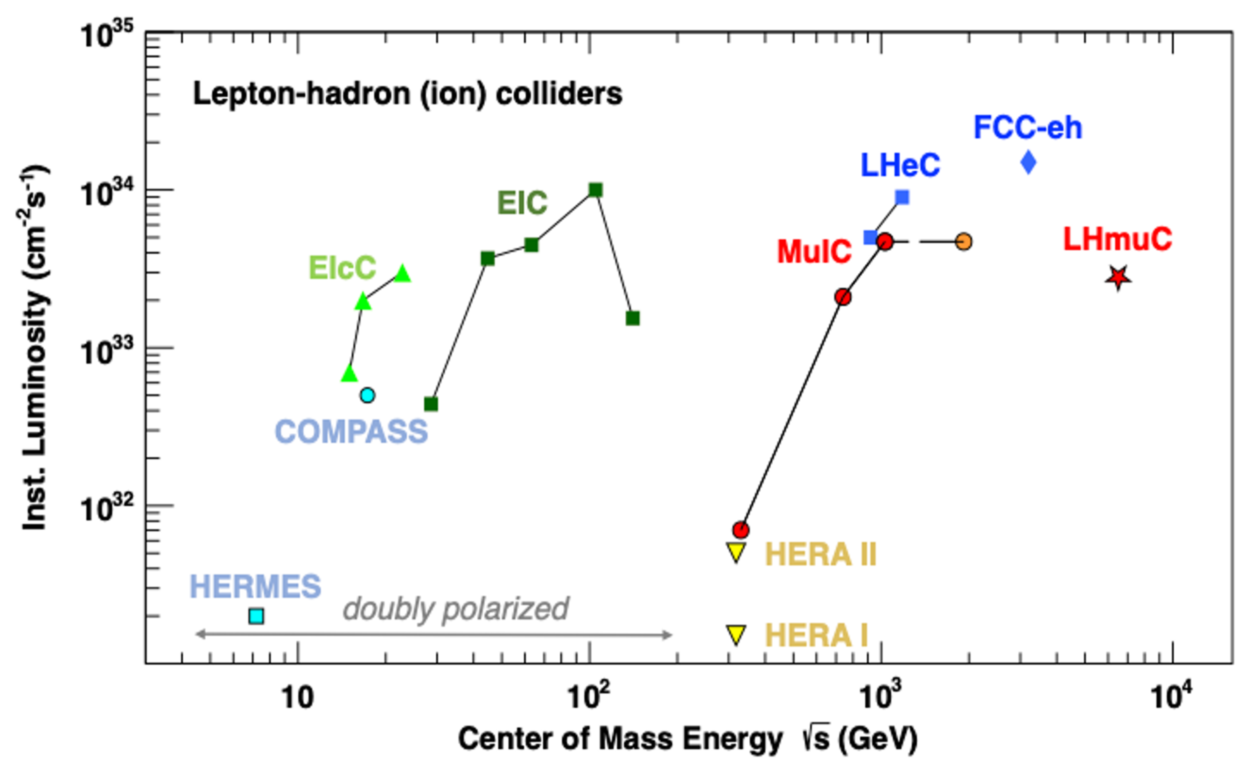
- Also the MuIC at BNL can scan a wide range of ion species, and beam polarization

Saturation scale:

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



DIS Evolution and Physics Landscape



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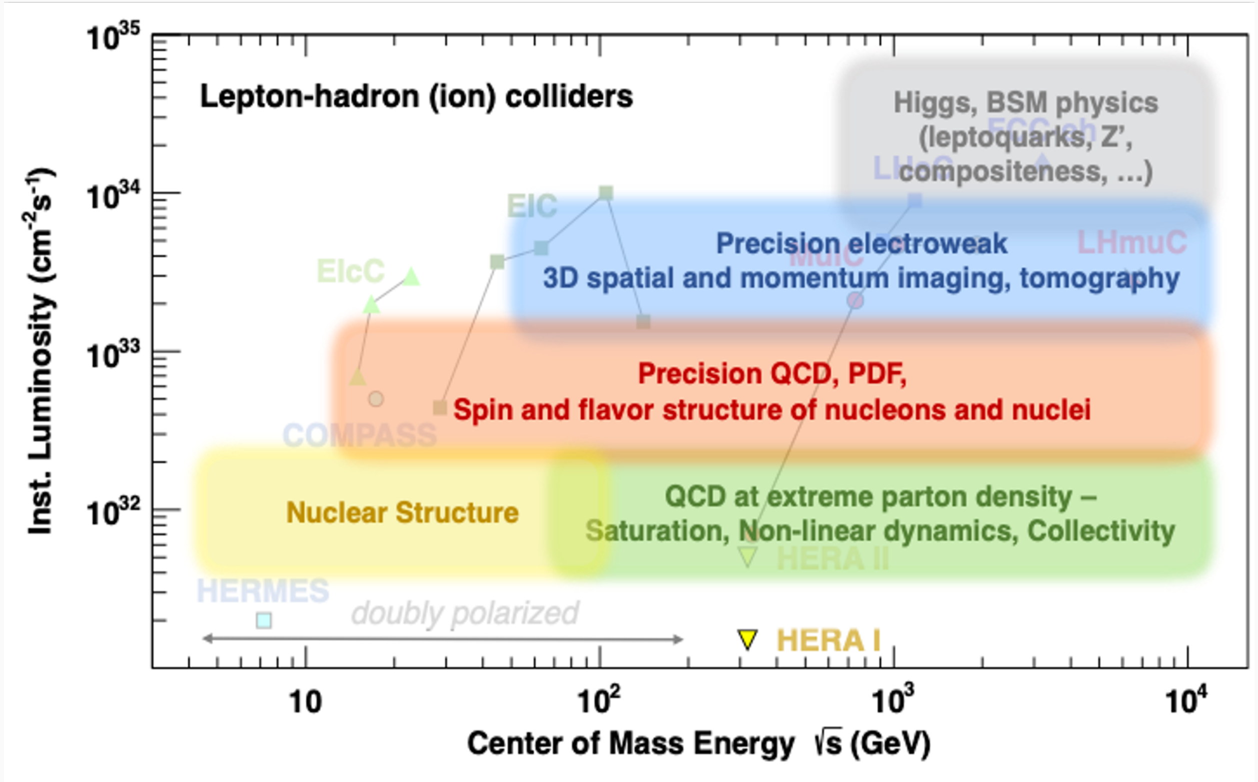
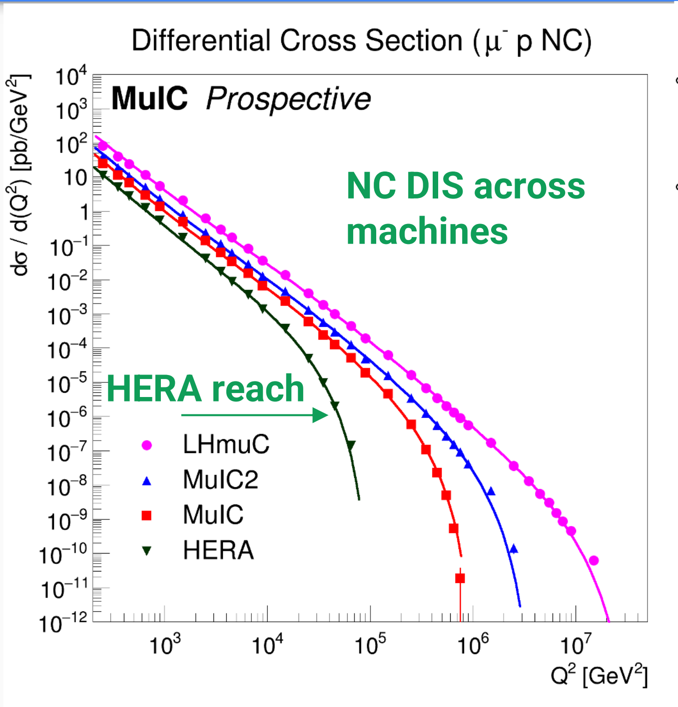
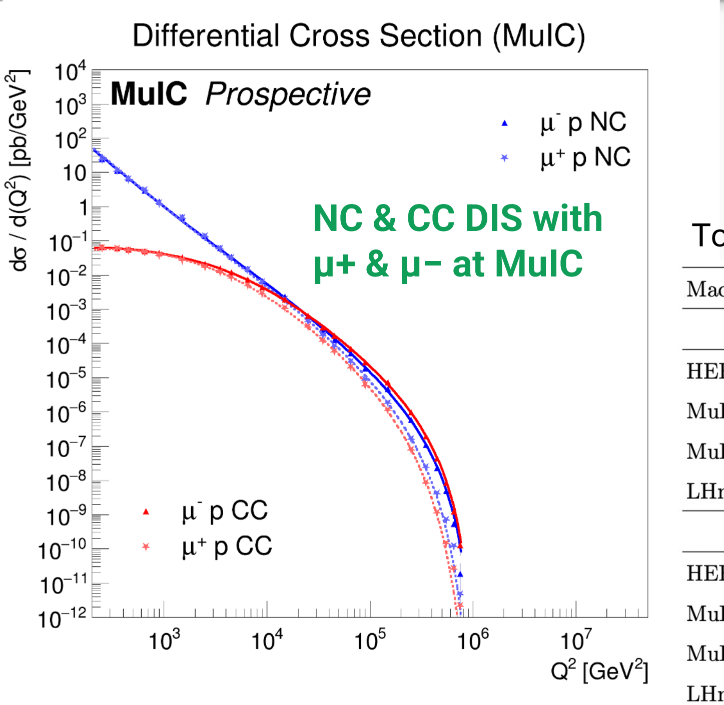


DIS Differential Cross Sections in Q^2





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

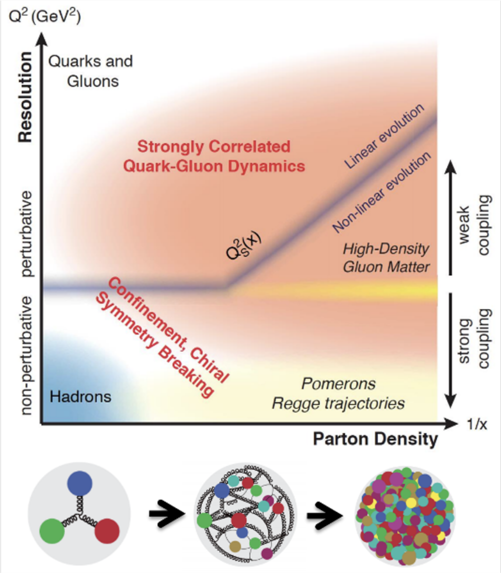
Total integrated CC cross section

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
		$\mu^+ p \to \bar{\nu}_\mu X$		
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^2)
  - But measurements low Q^2 and x can benefit from relatively low lumi orders of magnitude smaller

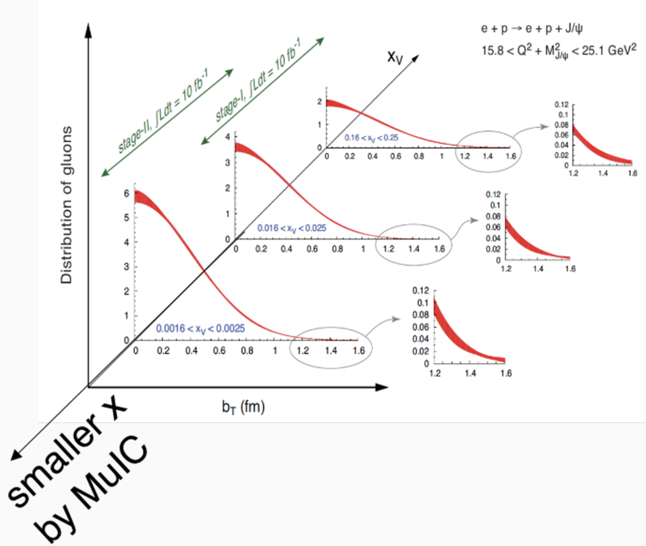
Nuclear Physics at the MuIC

Gluon saturation



What's the property of high-density gluon matter

3D Nucleon structure

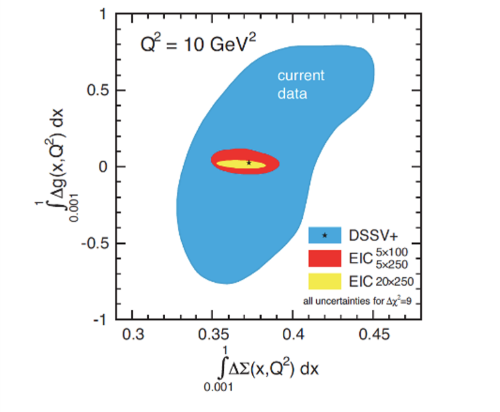


Nucleon spin puzzle

"Helicity sum rule"

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

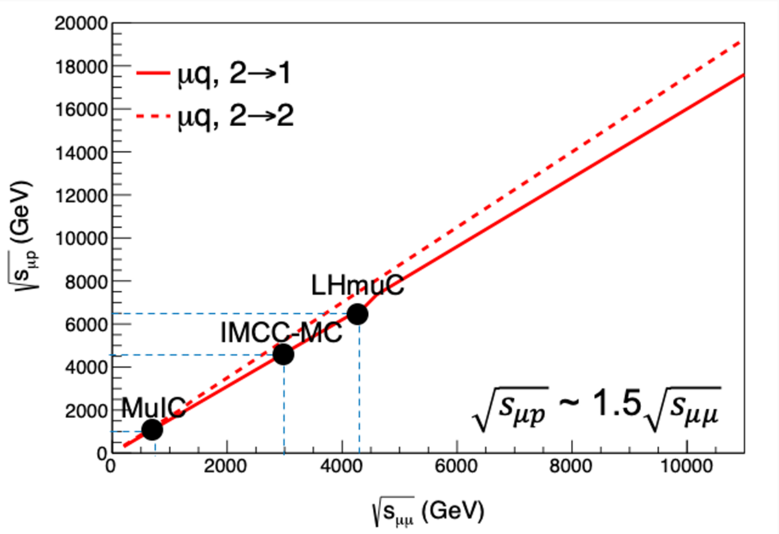
quark contribution, gluon contribution, orbital angular momentum



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

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.
- A 1.5x7 TeV LHmuC with √s = 6.5 TeV exceeds that of a 3 TeV μ+μ− collider as proposed by the IMCC (equiv. to 4.3 TeV).



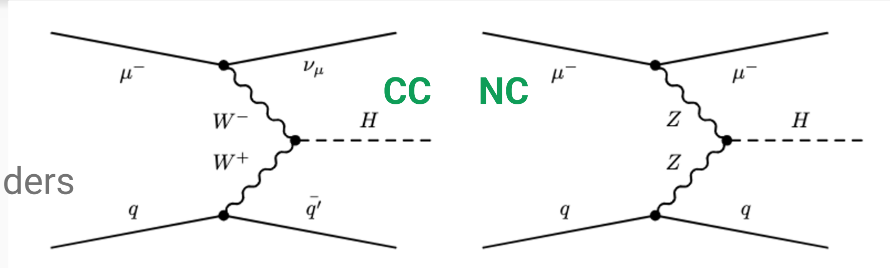
The parton luminosity of a μp collider is expressed as,

$$\frac{dL_i}{d\tau}(\tau,\mu_f) = \int_\tau^1 \frac{dx}{x} f_i(x,\mu_f). \quad (1)$$

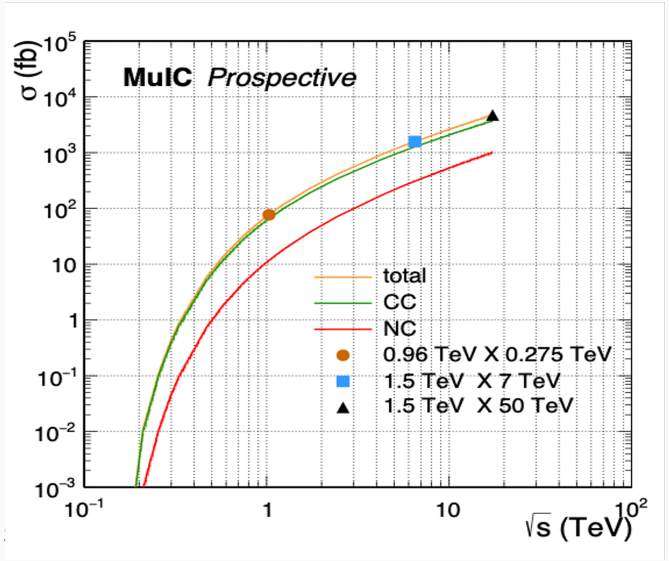
Here the $f_i(x,\mu_f)$ are the parton distribution functions (PDFs) for parton i carrying a fraction x of the longitudinal momentum, at factorization scale $\mu_f = \sqrt{\hat{s}}/2$, where $\hat{s}$ is the partonic center-of-mass energy and $\tau = \hat{s}/s$.

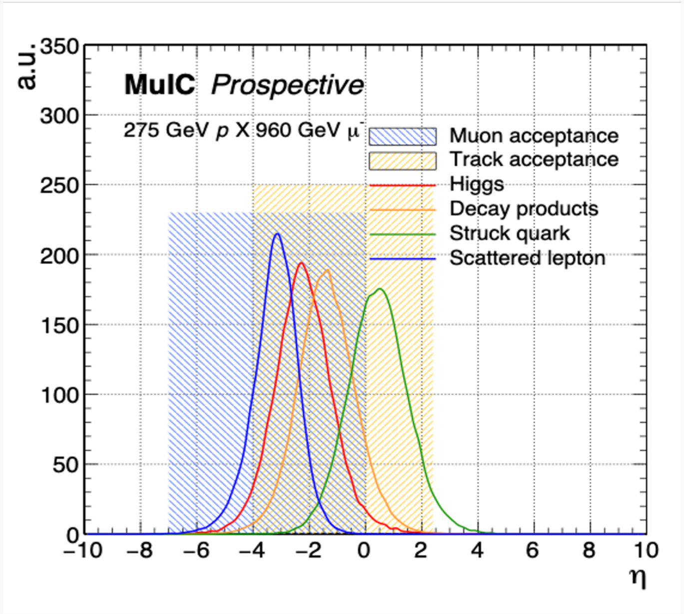
Higgs Physics with MuIC

- 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)



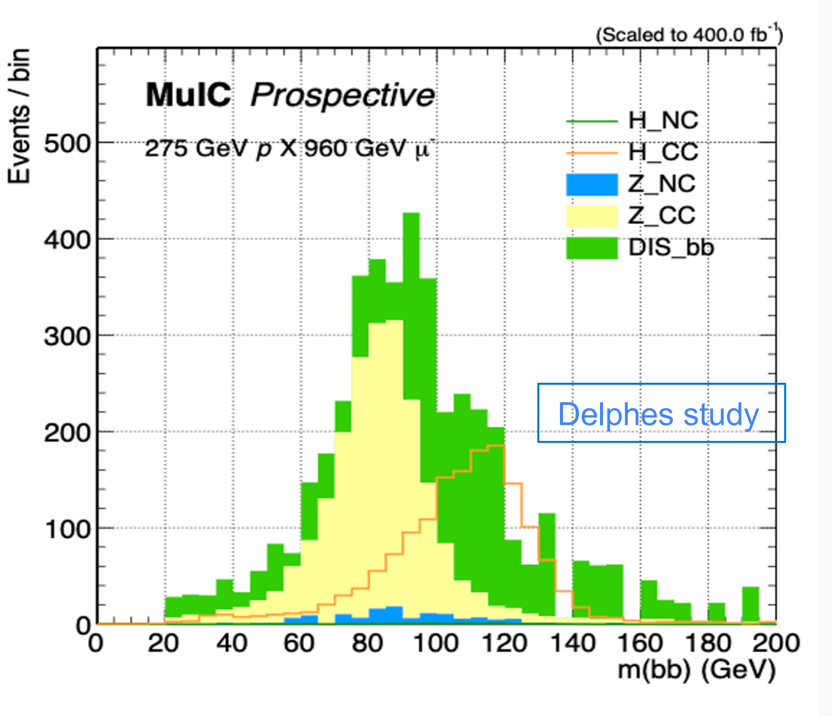
Computed with MadGraph





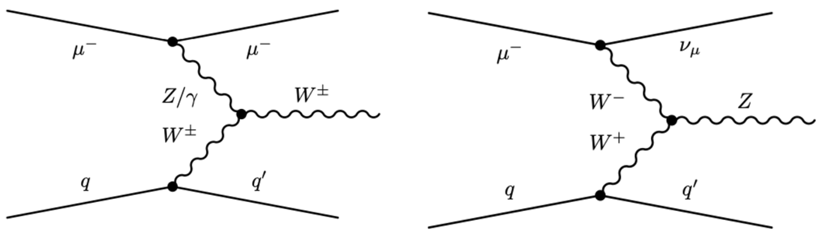
Higgs Physics with MuIC

- 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
- H→cc may become measurable also with higher cross section at LHmuC

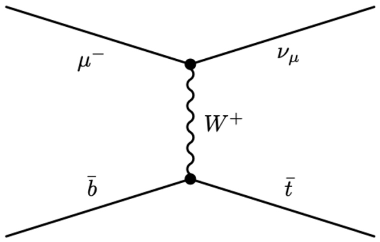


Other SM Particle Production

- Vector boson production, e.g.
  - Sensitive to **triple gauge couplings**
  - $\sigma(W)$ = 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 $|V_{tb}|$
  - $\sigma(t)$ = 5.4 pb for 1 TeV MuIC



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

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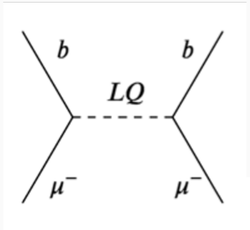
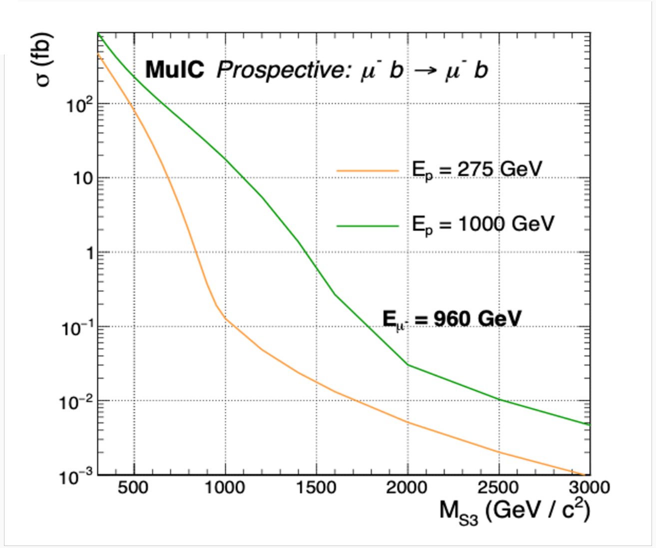
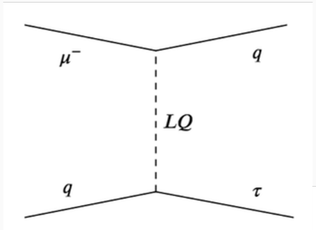
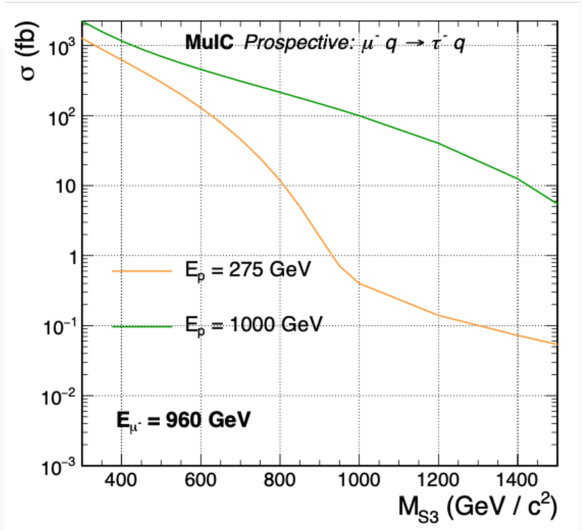
Leptoquark Production with Bottom, Tau

- 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









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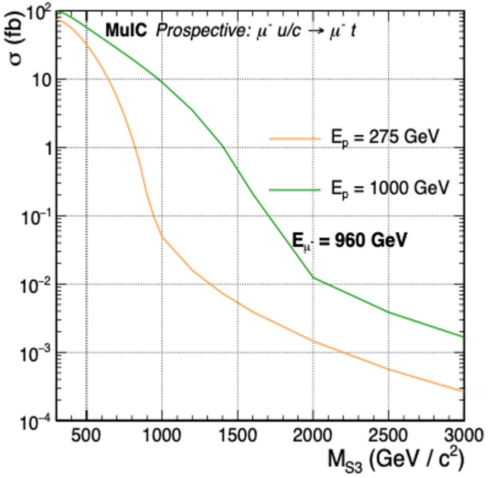
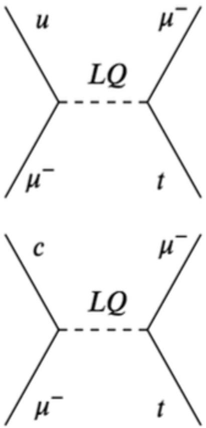
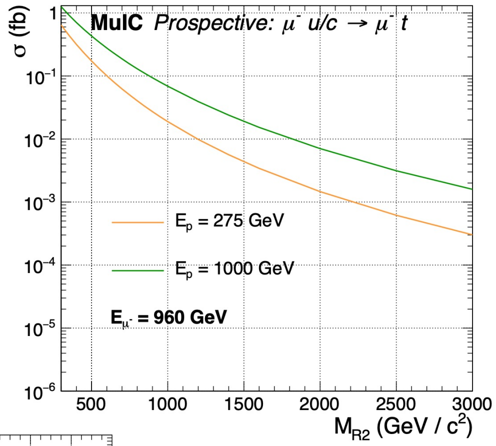
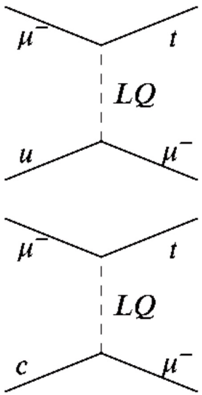
Leptoquark Production with Top

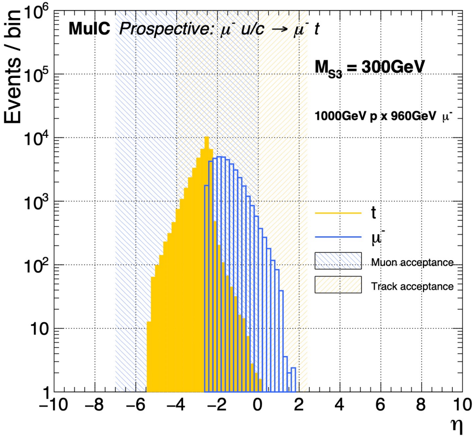








- s-channel S3 LQ production to μ+t
    - Final state muon in central region of detector



- t-channel R2 LQ production to μ+t

Potential limits still to be worked out

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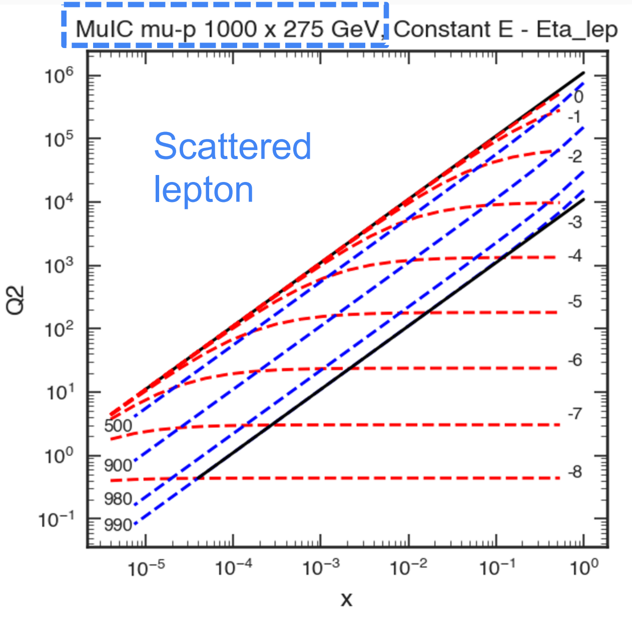
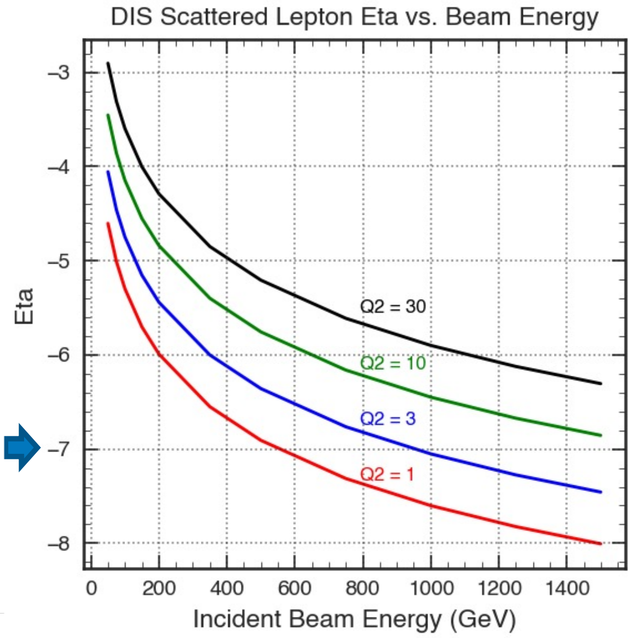
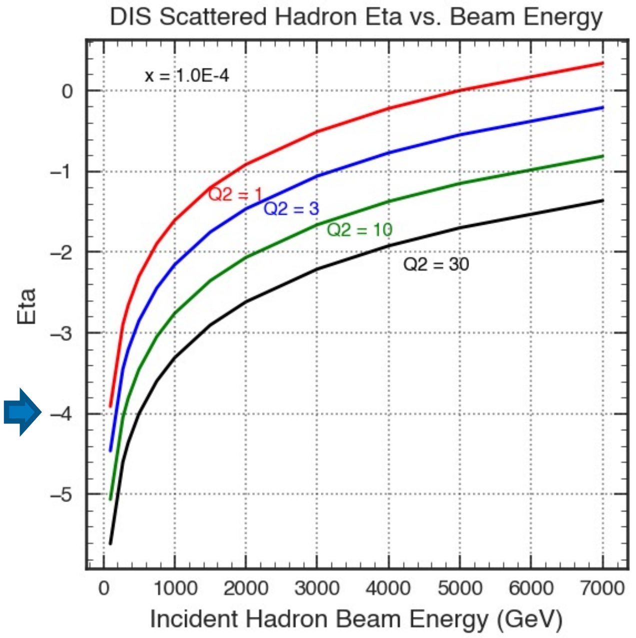
DIS Scattering Kinematics at a μp Collider

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

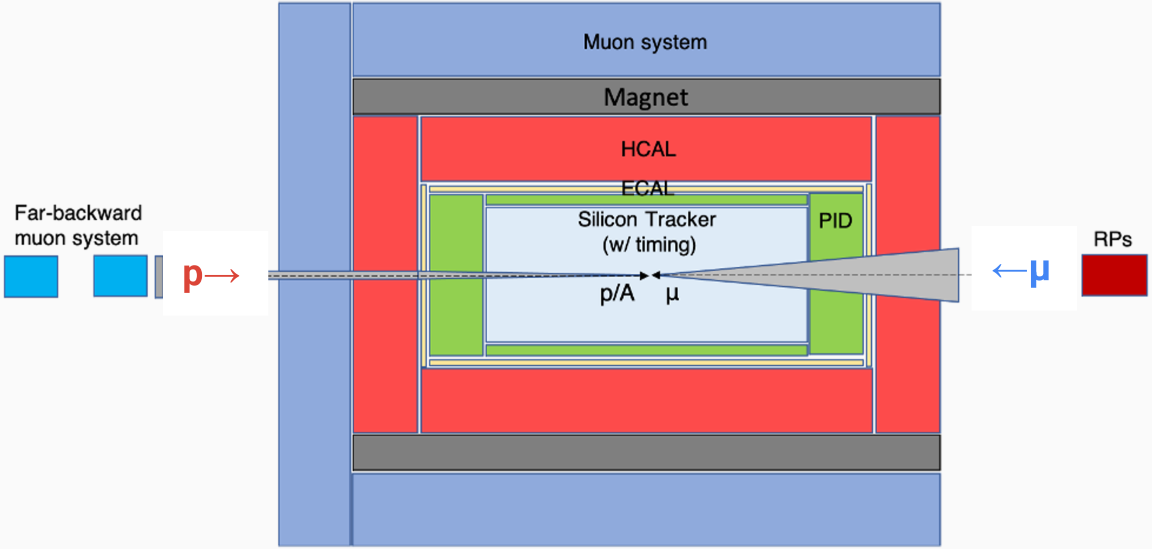






Detector Considerations and Challenges

- 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 NC VBF processes?
- Shielding nozzle **only on incoming muon side** (Needs BIB study)

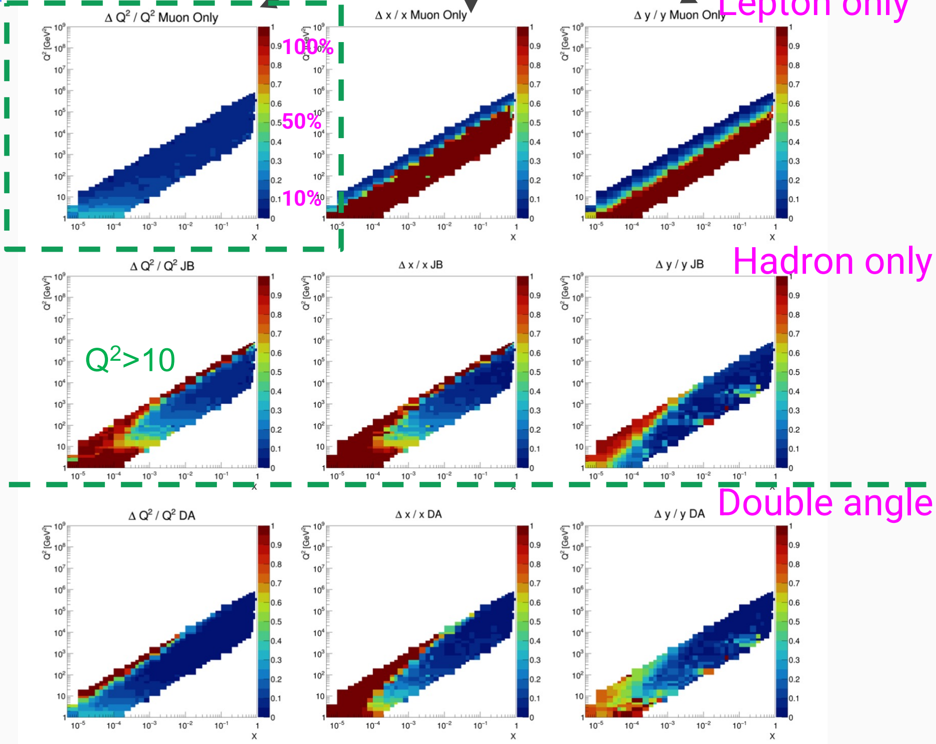


	Main requirements
Muons	**$-7<\eta<0$, $\sigma(p)/p < 5\%$**
Tracking	$-4<\eta<2.4$
PID (π/k/p)	**$-4<\eta<2.4$, $p<100$ GeV**
Calorimetry (jets, photons)	$-5<\eta<2.4$

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)

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
- Re-use of existing hadron ring infrastructure helps allay some of the cost
- 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

Summary

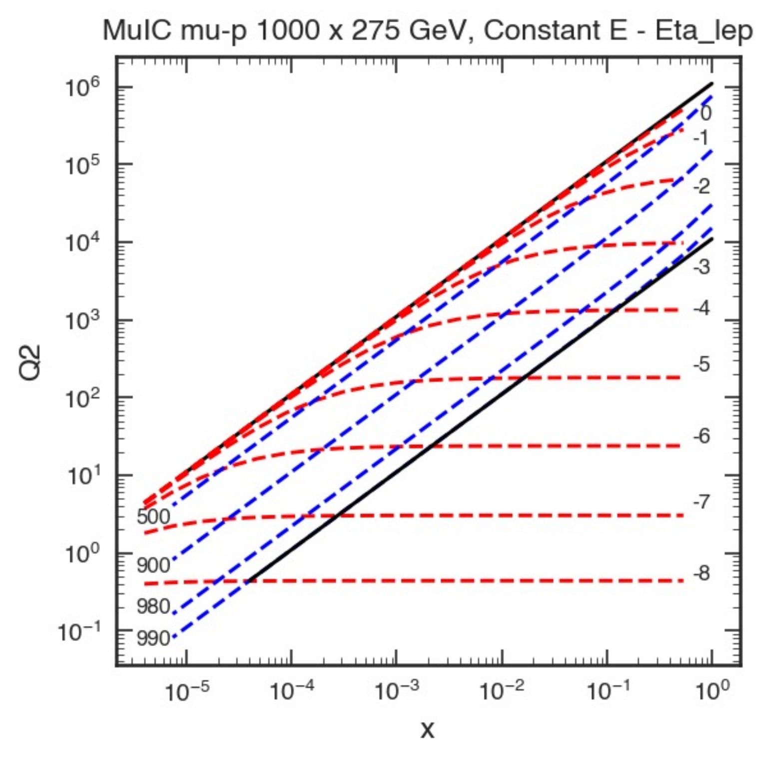
- Collisions of a TeV-scale muon beam with a high-energy proton/ion beam provides a novel way to explore new a regime in DIS at high Q^2 and low x
    - Proposed options at BNL/EIC ($\sqrt{s}$ = 1-2 TeV) and CERN/LHC ($\sqrt{s}$ = 6.5 TeV)
- Luminosity > 10^{33} Hz/cm^2 may be possible
- Precision electroweak, QCD, and SM particle production measurements (including Higgs) can be performed
- Complementary way to probe BSM physics
- Kinematics: small muon scattering angles, more central hadronic systems
- Many synergies with muon collider development, nuclear and particle physics programs
- *In case you are interested to support this concept for the U.S. Snowmass process (or provide any comments):* https://docs.google.com/spreadsheets/d/1Vqz__4DqSt7HFrvpSYs5-e1k7GgQBsypxvYebfR17ic/edit#gid=0

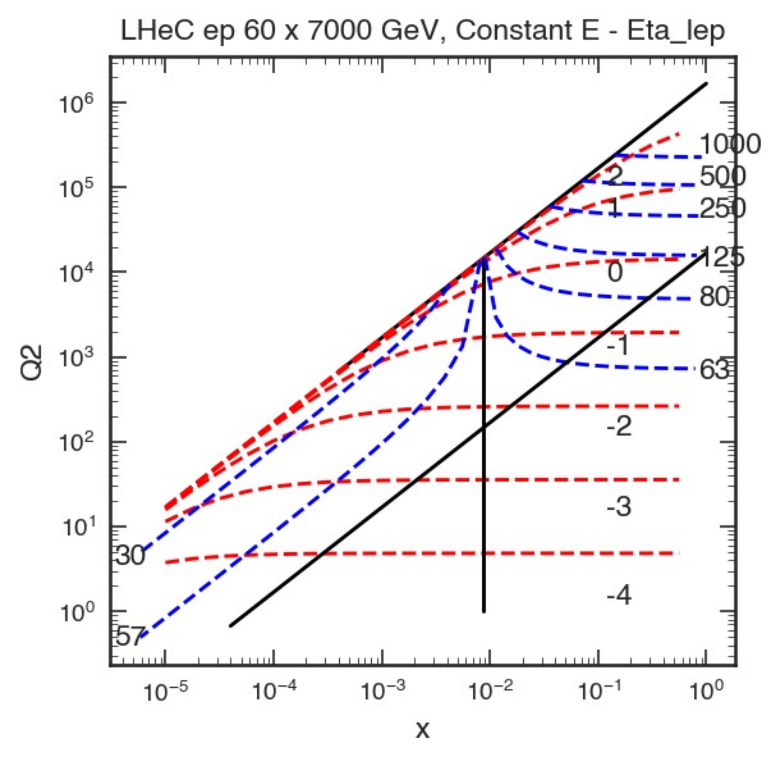
Acknowledgements

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

Backup

Lepton DIS Kinematics of MuIC Compared to LHeC





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

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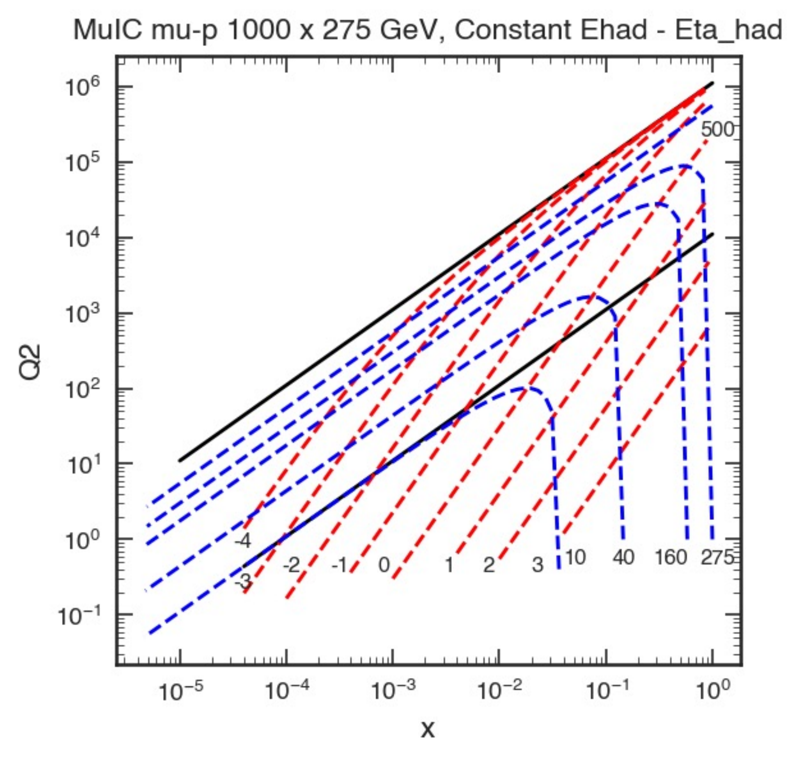
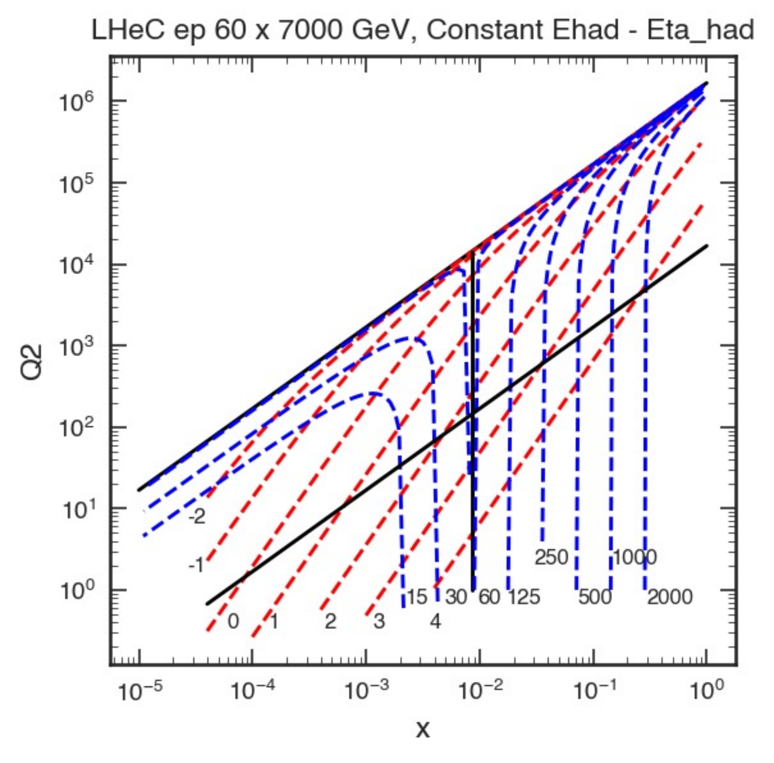
Hadron DIS Kinematics of MuIC Compared to LHeC





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

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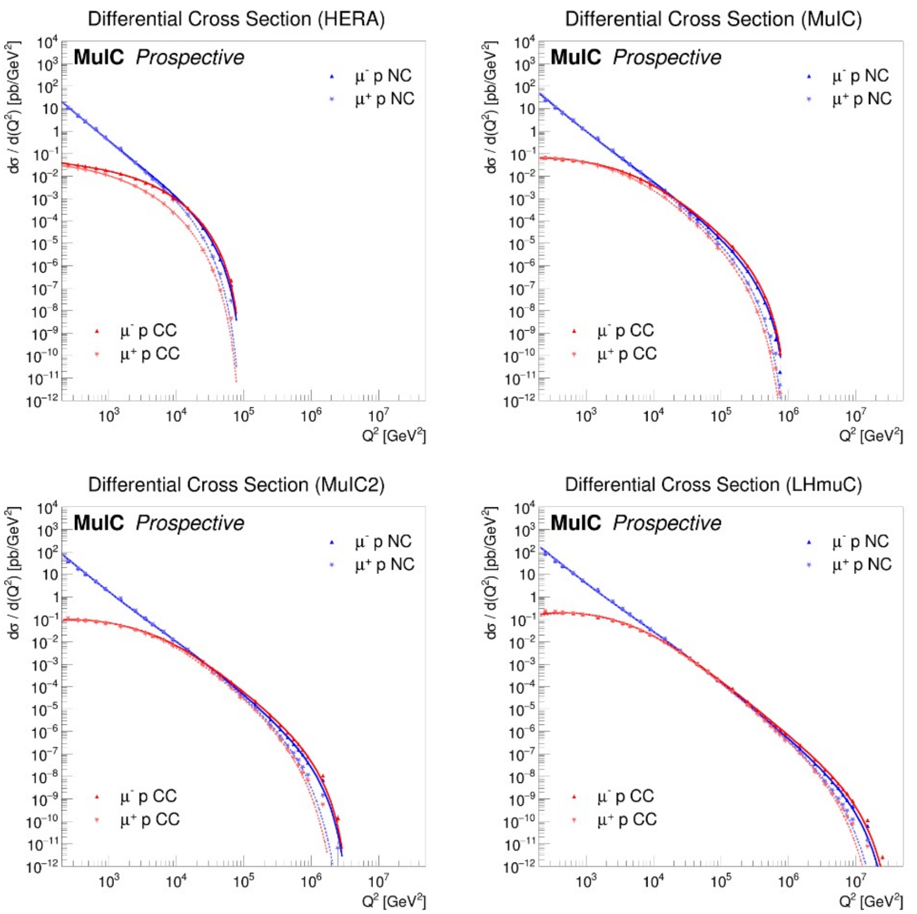
DIS Differential Cross Sections in Q^2



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

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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$\oplus\alpha_s$ 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 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$\oplus\alpha_s$ 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 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$\oplus\alpha_s$ 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	$^{+19\%}_{-20\%}$	$^{+1.2\%}_{-1.2\%}$