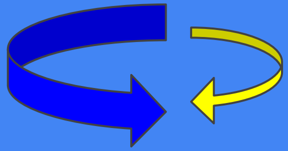


Potential of A TeV Muon-Ion Collider at BNL

– The ultimate QCD frontier and a path toward a new energy frontier

Based on

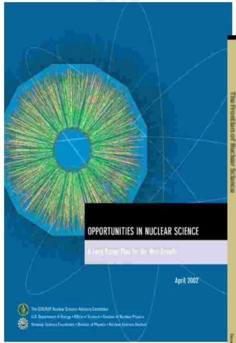
- *Nucl. Instrum. Meth. A* 1027 (2022) 166334
- *arXiv:2203.06258, a whitepaper submitted to Snowmass 2021*

D. Acosta, Wei Li, O. Miguel Colin, X. Zuo (Rice U.)
E. Barberis, N. Hurley, D. Wood (Northeastern U.)

14th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2022)

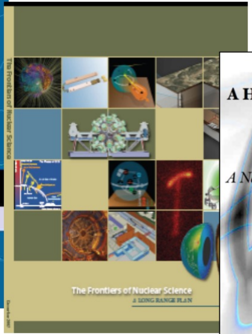
Science for EIC Developed Over Past Two Decades

2002



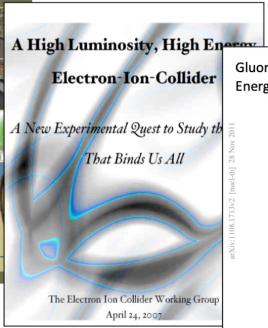
"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

2007



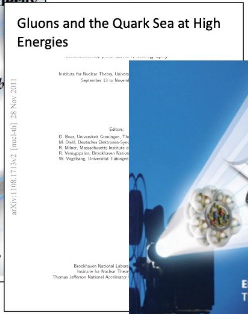
"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

2009

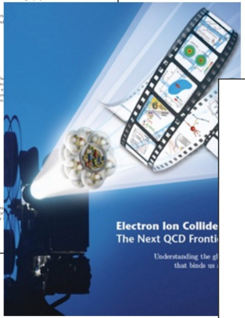


"..a new dedicated facility will be essential for answering some of the most central questions."

2010

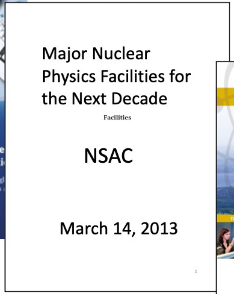


2012



"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

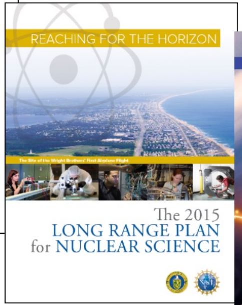
2013



Electron-Ion Collider..absolutely central to the nuclear science program of the next decade.

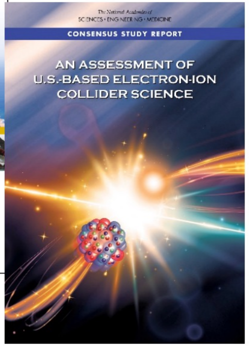
"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

2015



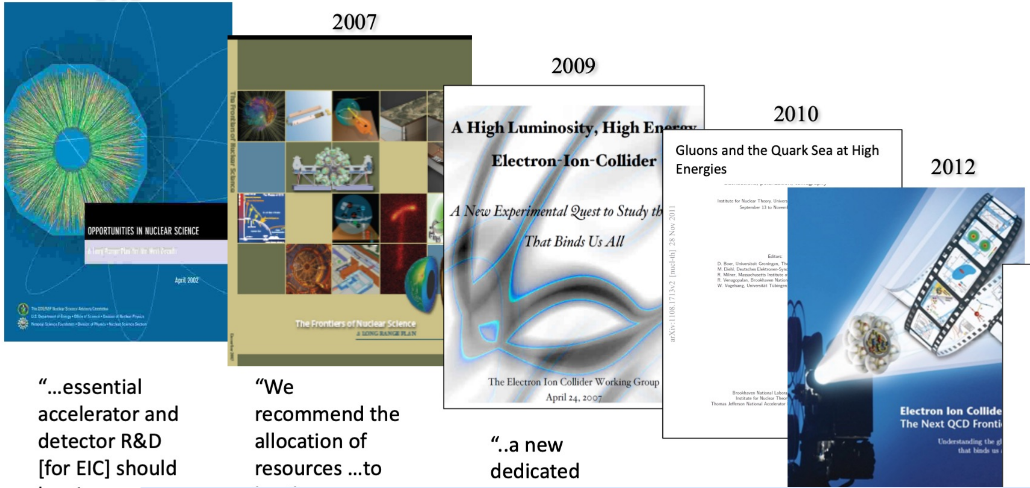
The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

2018

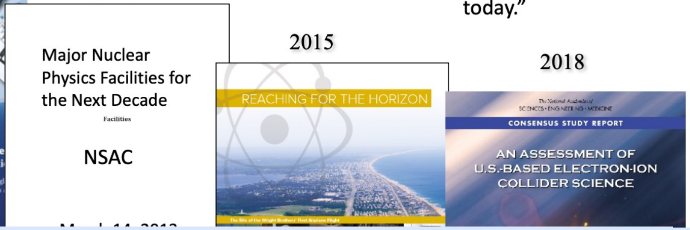


Science for EIC Developed Over Past Two Decades

2002 2007 2009 2010 2012



2013 2015 2018



"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

"...essential accelerator and detector R&D [for EIC] should be ... hi... in... te...

"We recommend the allocation of resources ...to ...

"..a new dedicated ... facility: an Electron Ion Collider.."

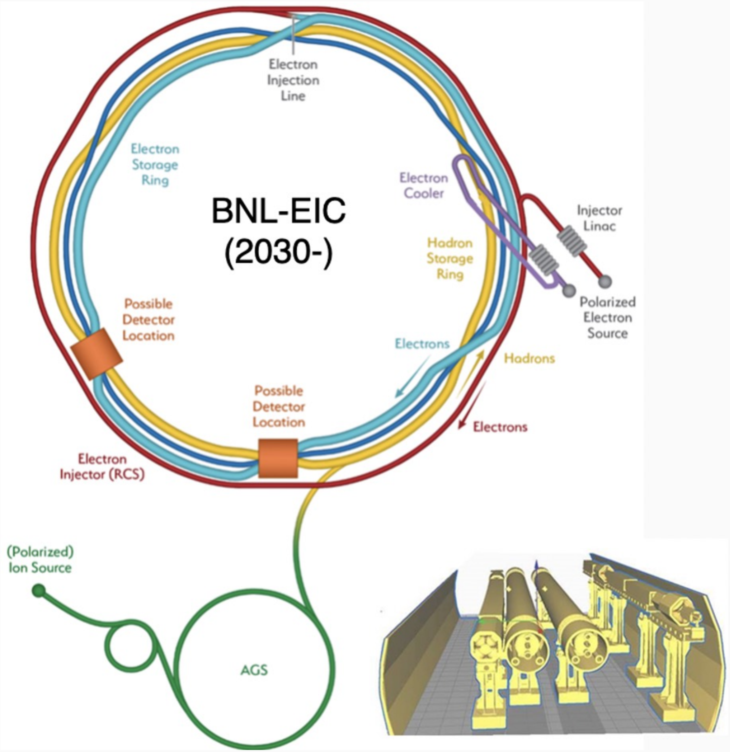
... program of the next decade.

What's after EIC?

Time to think if we want a future beyond the EIC

The Electron-Ion Collider (EIC) at BNL

BNL (US): RHIC → EIC e↑(18)+p↑(275) GeV

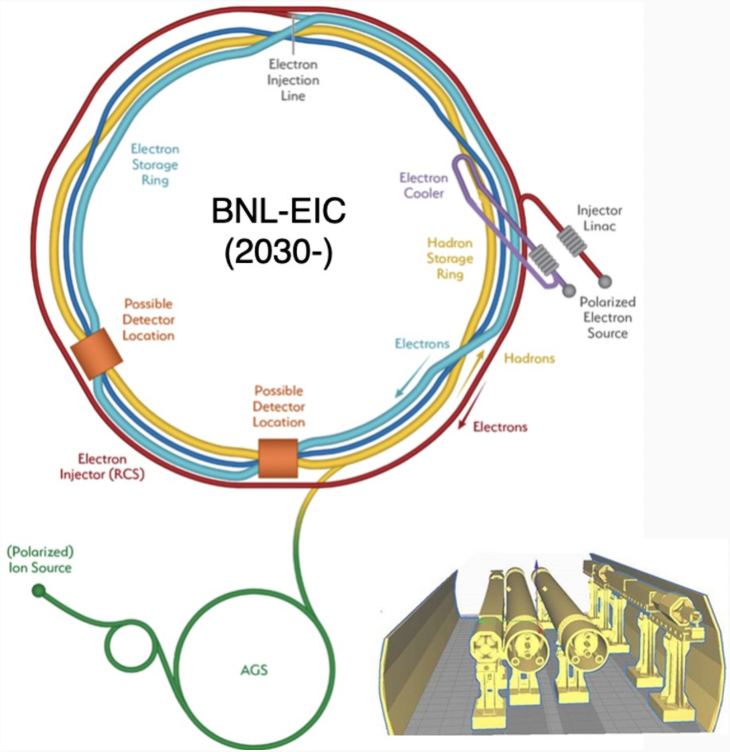


Salient points:

- 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)

The Electron-Ion Collider (EIC) at BNL

BNL (US): RHIC → EIC e↑(18)+p↑(275) GeV



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)

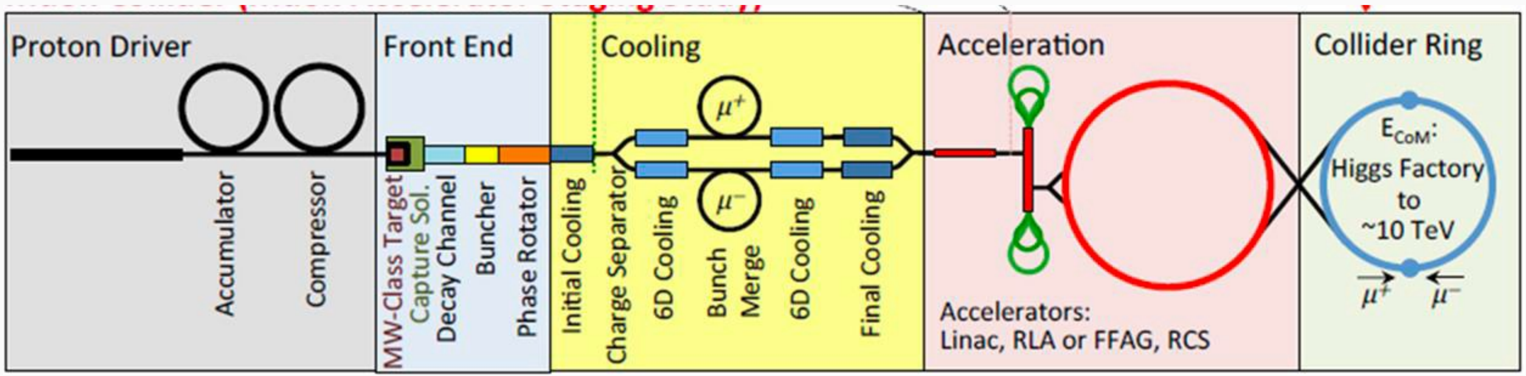
But what if we changed leptons? – **μ!?**

- μ's do not radiate when bent
  → much easier acceler'n in rings
- Unfortunately, μ's do not live long

Muon Colliders

Early mentions of MC date back to 1960s and early designs in 1990s

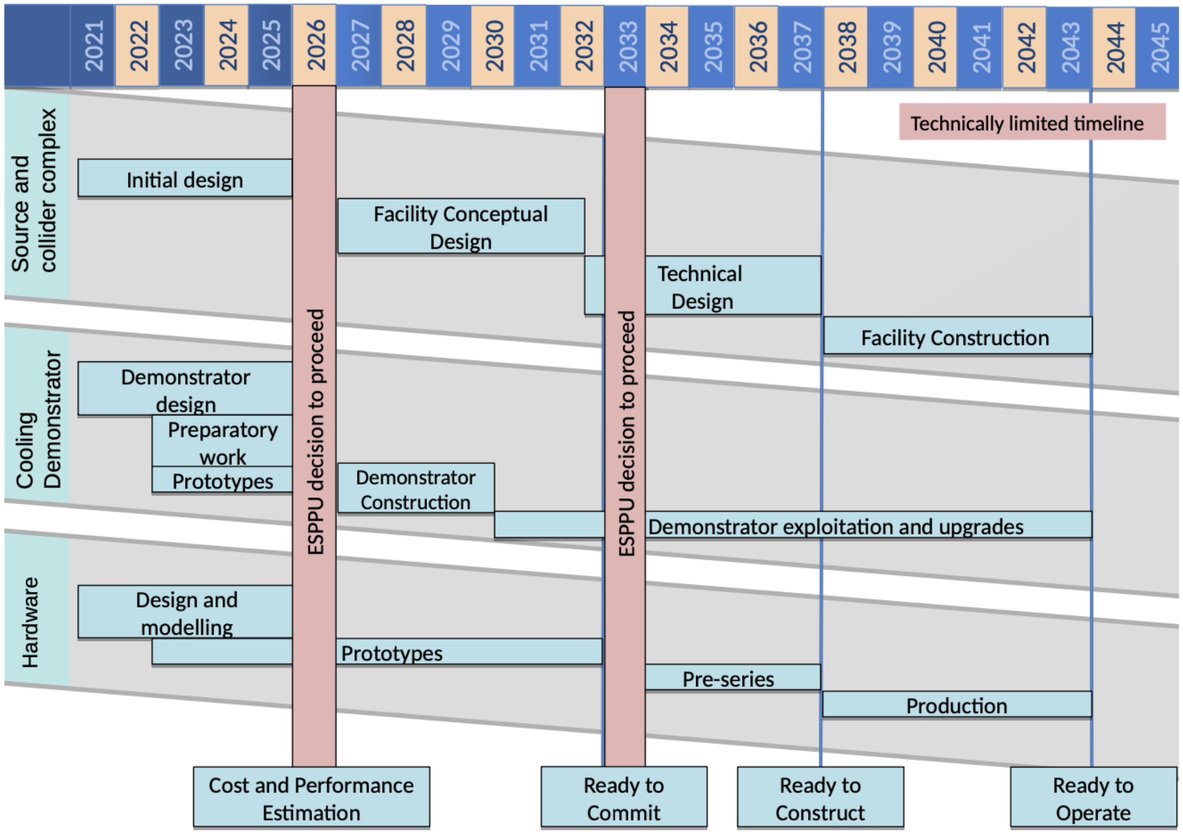
Muon Accelerator Program (MAP, 2011-2016) for feasibility studies



Reviving interests in muon colliders in HEP community recently:

- Formation of International Muon Collider Collaboration (IMCC) by CERN in 2021: consider **10+ TeV $\mu^+\mu^-$** with **3 TeV** as an initial step
- Muon Collider forum in US from Snowmass 21 (white papers)

IMCC Timeline (technically limited)



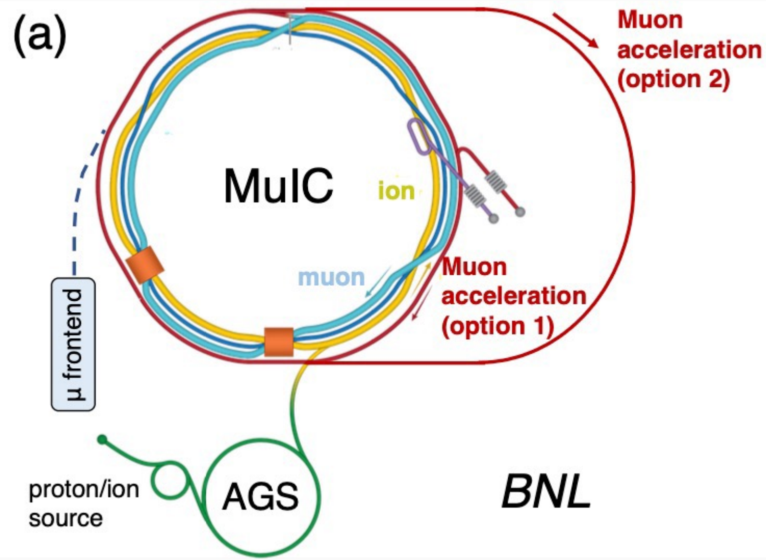
20+ years till the first MC with sustained R&D efforts

A small-scale **demonstrator** with strong science desired before going to O(10+) TeV

A Muon-Ion Collider at BNL

Acosta, Li, NIM A 1027 (2022) 166334

→Re-use EIC facility by replacing e by μ beam



Cost effective and affordable!

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)

$\sqrt{s}$ ~ 1TeV, 7-8x increase over EIC

Design Parameters – MuIC

Parameter	MuIC (BNL)			
$\sqrt{s_{\mu p}}$ (TeV)	0.33	0.74	1.0	
$L_{\mu p}$ (10^{33}cm^{-2}s^{-1})	0.07	2.1	4.7	
Int. Lumi. (fb^{-1}) per 10 yrs	6	178	400	
Staging options		Muon		Proton
Beam energy (TeV)	0.1	0.5	0.96	0.275
N_b (10^{11})	40	20	20	3
f^{μ}_{rep} (Hz)	15	15	15	
Cycles per μ bunch, N^{μ}_{cycle}	1134	1719	3300	
$\varepsilon^*_{x,y}$ (μm)	200	25	25	0.3
$\beta^*_{x,y}$ @IP (cm)	1.7	1	0.75	5
Trans. beam size, $\sigma_{x,y}$ (μm)	48	7.6	4.7	7.1

← $\sqrt{s}$

← Peak lumi.

← Beam energy

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

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

Muon Collider parameters (arXiv:1901.06150)
+ BNL/EIC proton beam parameters (CDR)

Unique challenges for MuIC

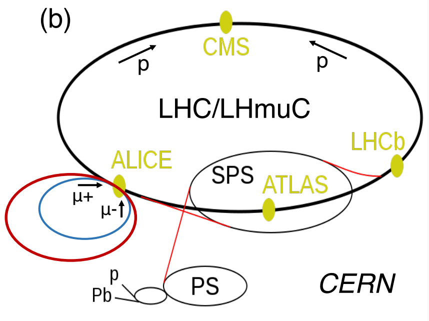
- IP design
- Machine-Detector Interface
- Neutrino radiation mitigation

Design Parameters – MuIC and LHmuC

Parameter	**MuIC** (BNL)				**LHmuC** (CERN)	
$\sqrt{s_{\mu p}}$ (TeV)	0.33	0.74	1.0		6.5	
$L_{\mu p}$ (10^{33}cm^{-2}s^{-1})	0.07	2.1	4.7		2.8	
Int. Lumi. (fb^{-1}) per 10 yrs	6	178	400		237	
Staging options	Muon			Proton	Muon	Proton
Beam energy (TeV)	0.1	0.5	0.96	0.275	1.5	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 (arXiv:1901.06150)
+ BNL/EIC proton beam parameters (CDR)

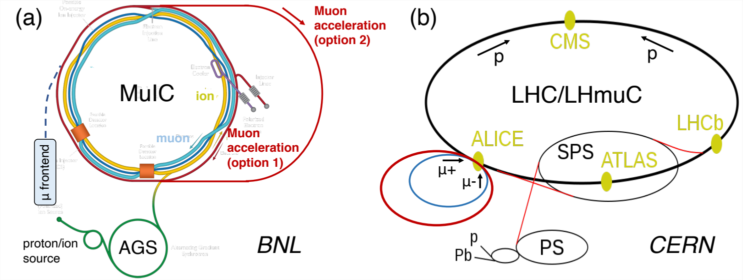
Similar idea applies to LHC

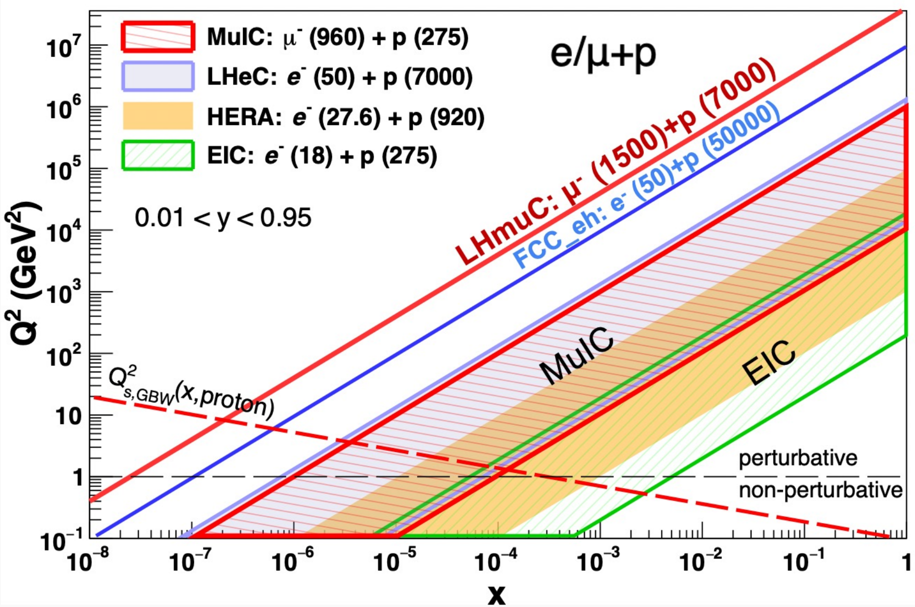


arXiv:2203.06258

Higher $\sqrt{s}$ than FCC-eh!
(3.5 TeV)

Science Potential and Synergy at the MuIC





Probes a **new energy scale** and **Bjorken-x** in DIS using a relatively compact machine

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

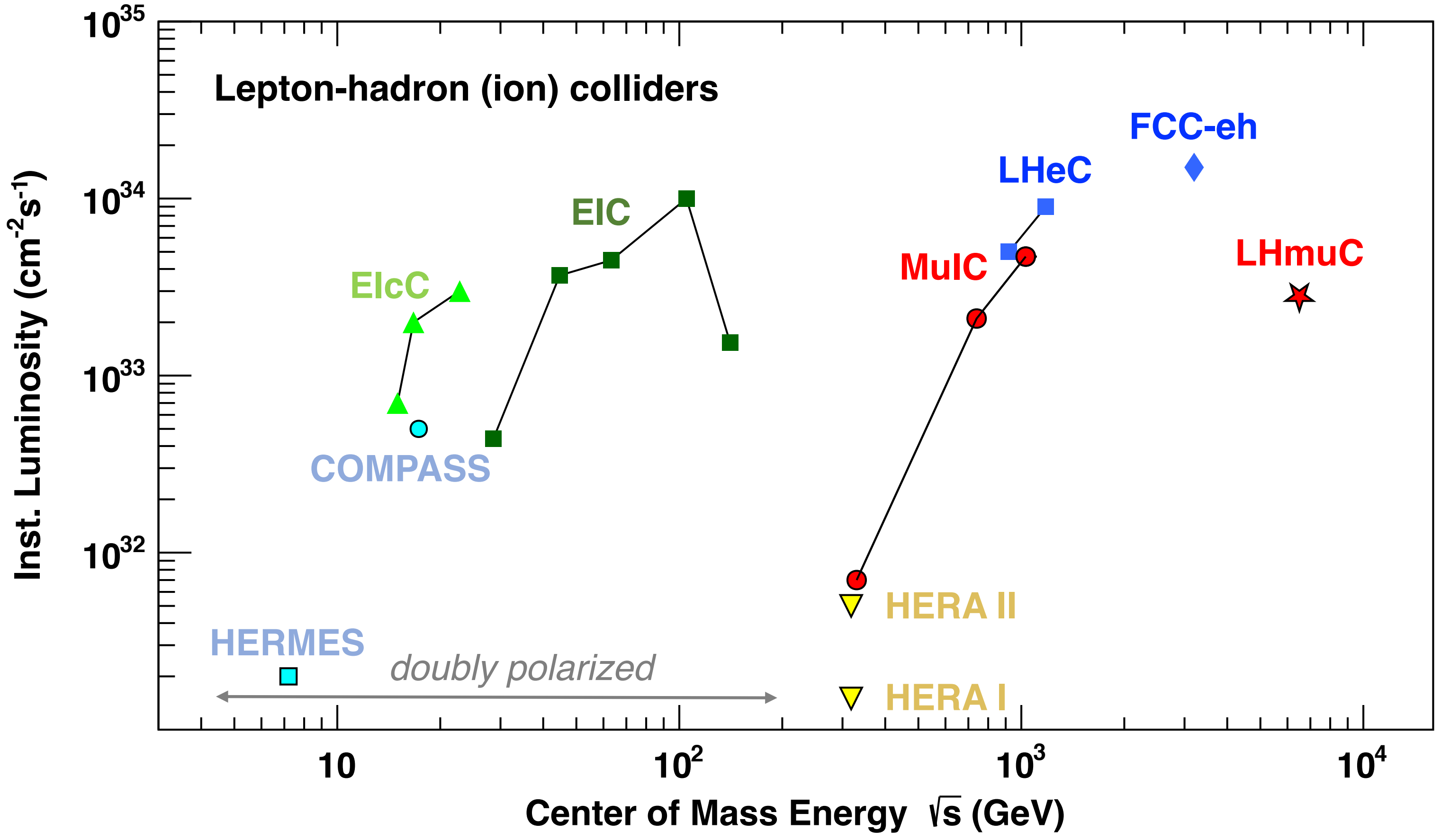
– well beyond EIC

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

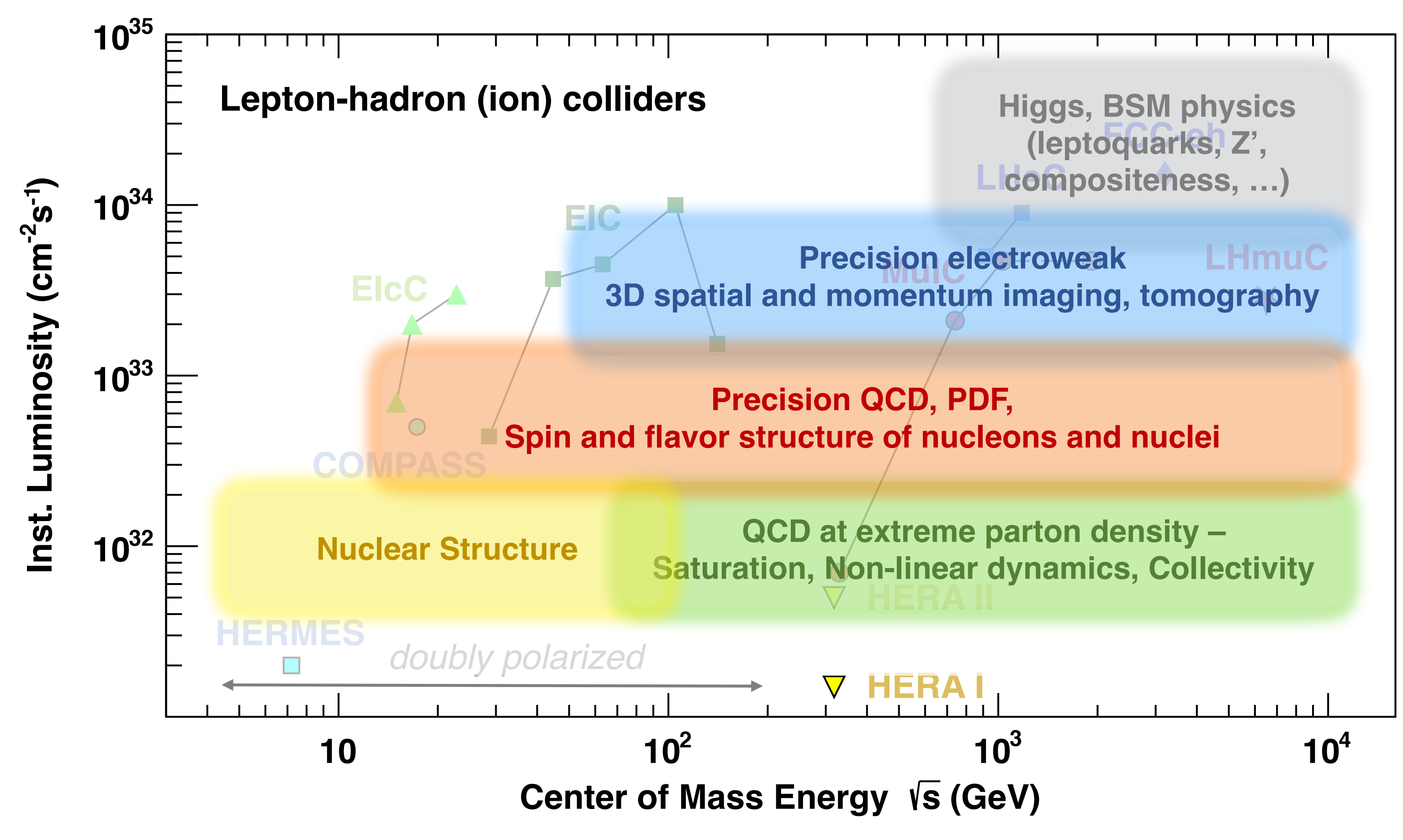
Facilitate the collaboration of the NP and HEP communities around an innovative and forward-looking machine

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

DIS Evolution and Physics Landscape

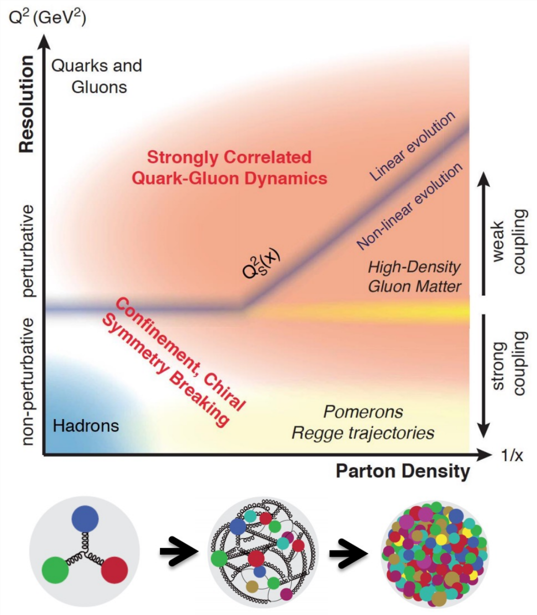


DIS Evolution and Physics Landscape



Nuclear Physics at the MuIC

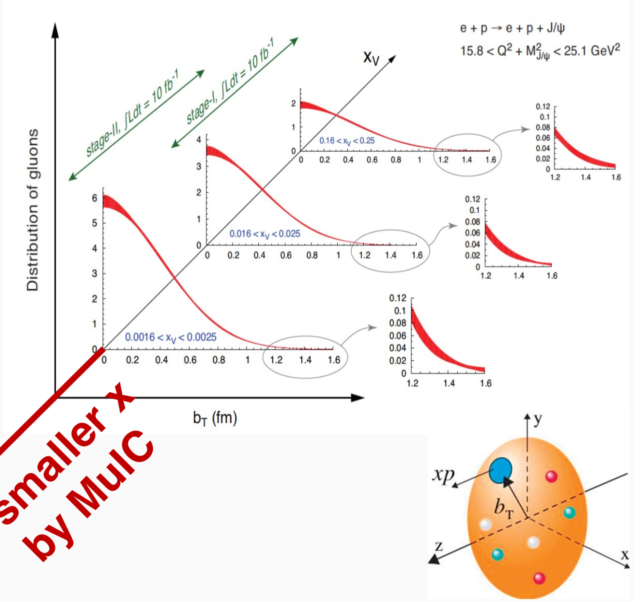
Non-linear QCD effects



Properties of gluonic matter at extreme densities

Origin of nucleon mass

3D Nucleon structure

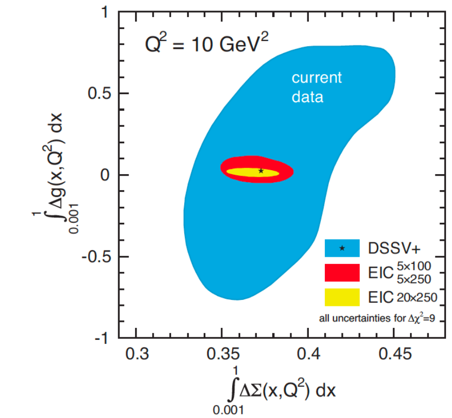


Nucleon spin puzzle

"Helicity sum rule"

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

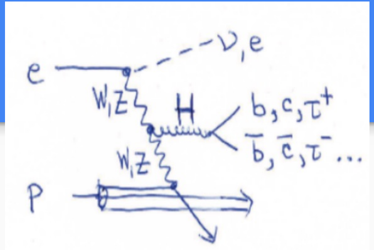
quark contribution; gluon contribution; orbital angular momentum



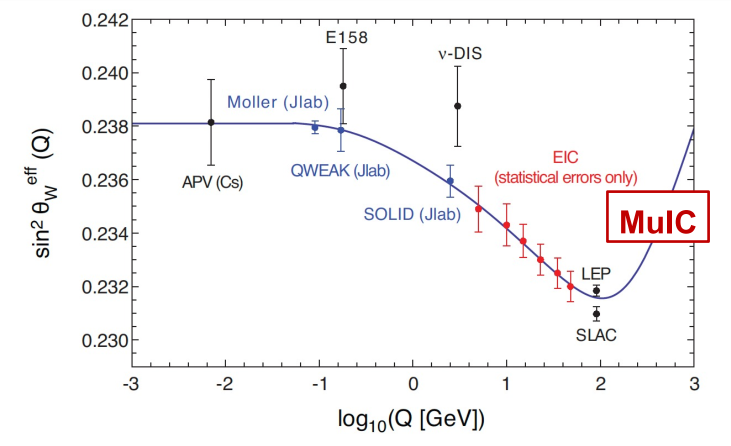
MuIC to reach x ~ 10^{-5}

Building on the EIC science foundation!

Particle Physics at the MuIC

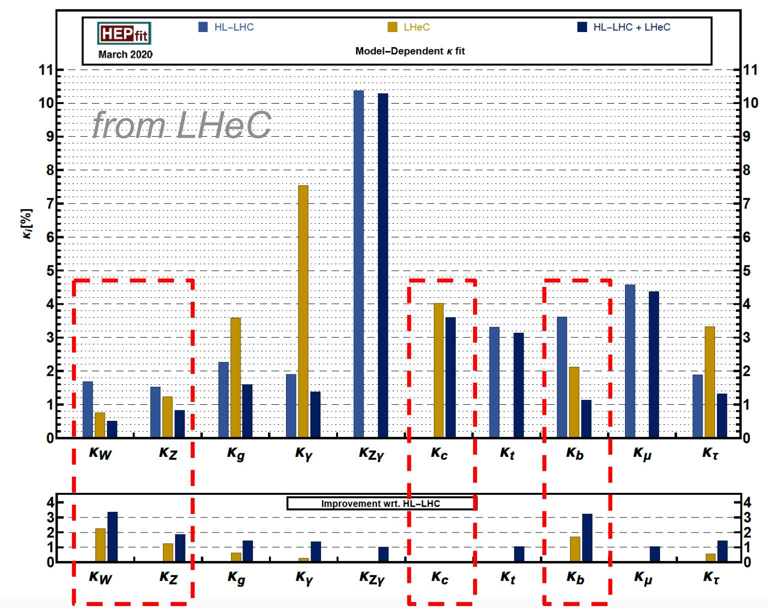


Electroweak:



Higgs physics:

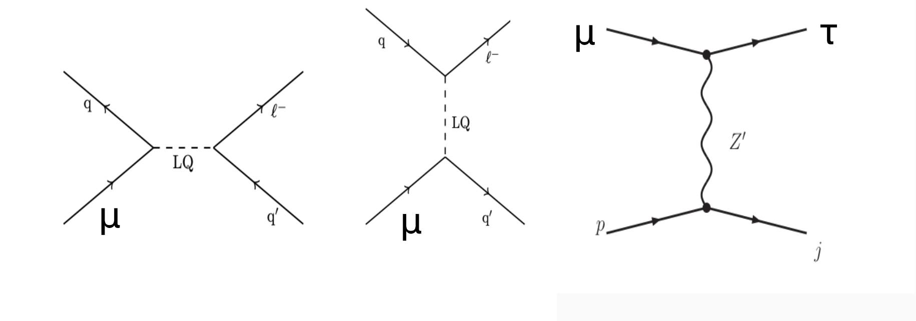
Uncertainties of Higgs couplings



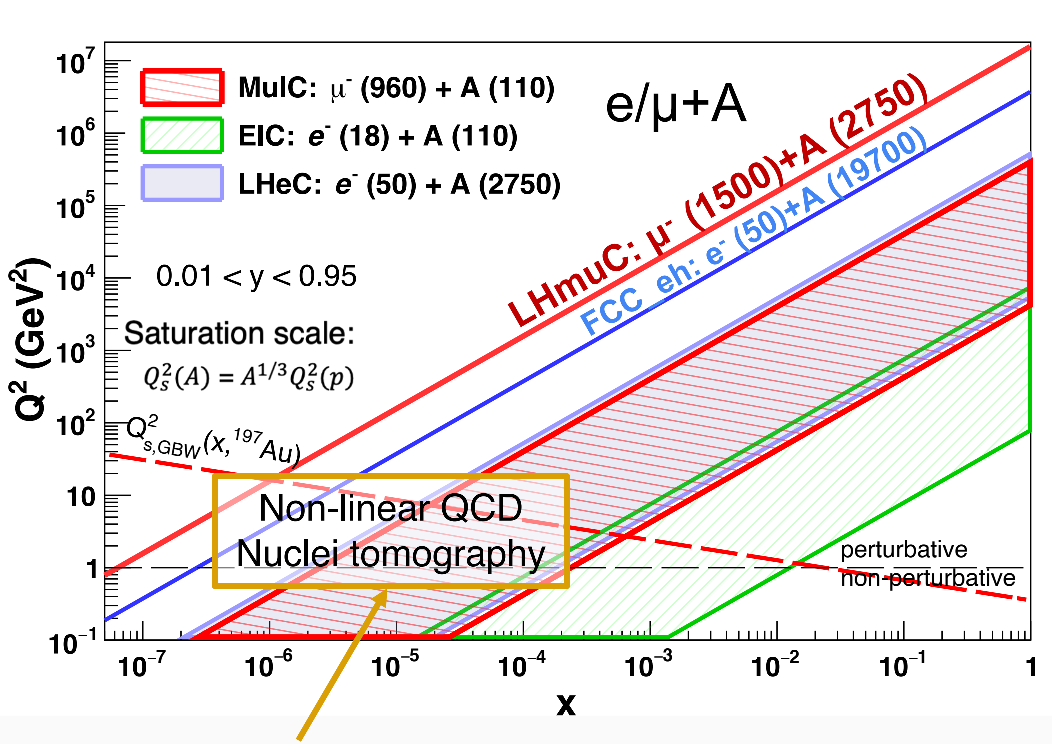
LHeC/MuIC outperforms HL-LHC for certain Higgs decay channels

BSM:

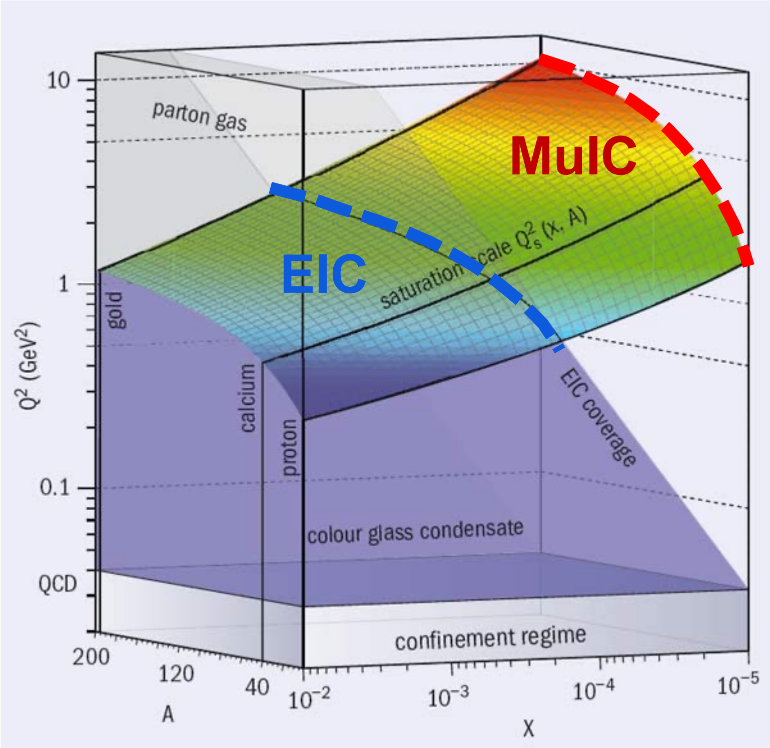
Charged lepton flavor violation



A lab for QCD and Nuclei at the MuIC



Saturation scale in nuclei

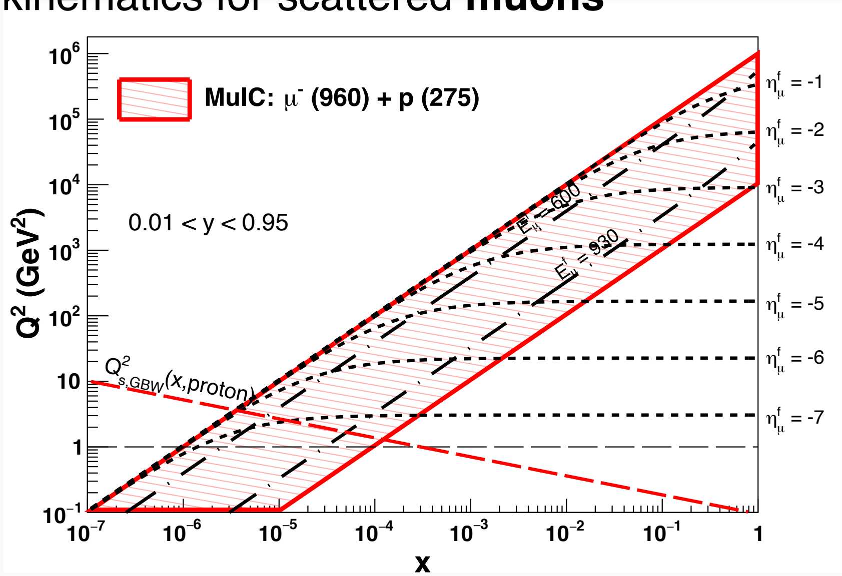


MuIC will bring us well into the nonlinear regime and unambiguously discover saturation at $x \sim 10^{-5}$

Final-state kinematics at MuIC

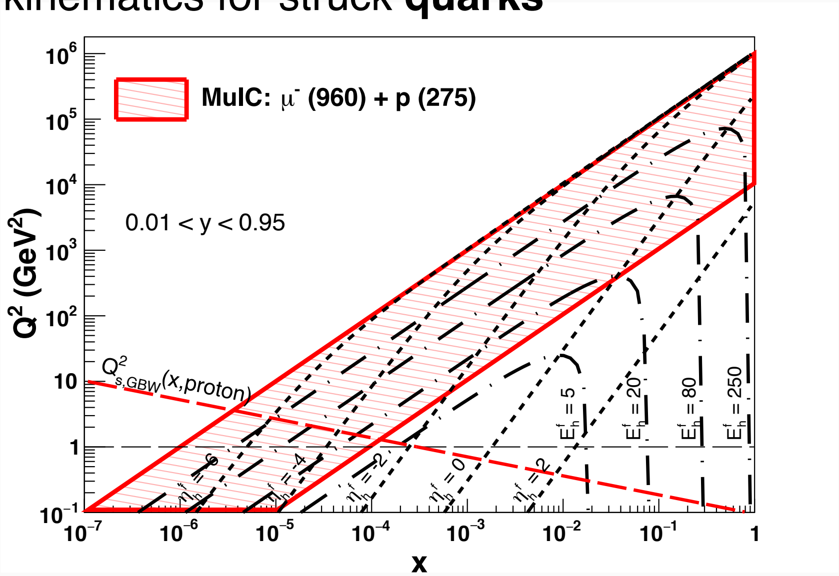
p/A → ← μ

kinematics for scattered **muons**



Muons very forward: -7<η<-1

kinematics for struck **quarks**



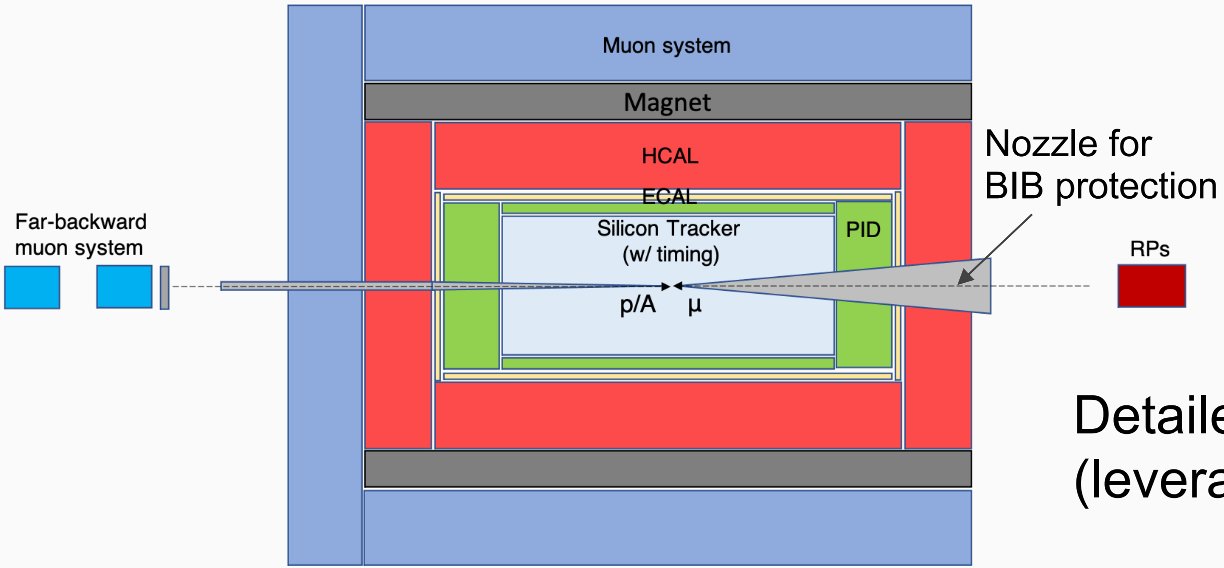
Jets/hadrons fairly central: -4<η<2

Detector challenges and R&D needs

Unique challenges:

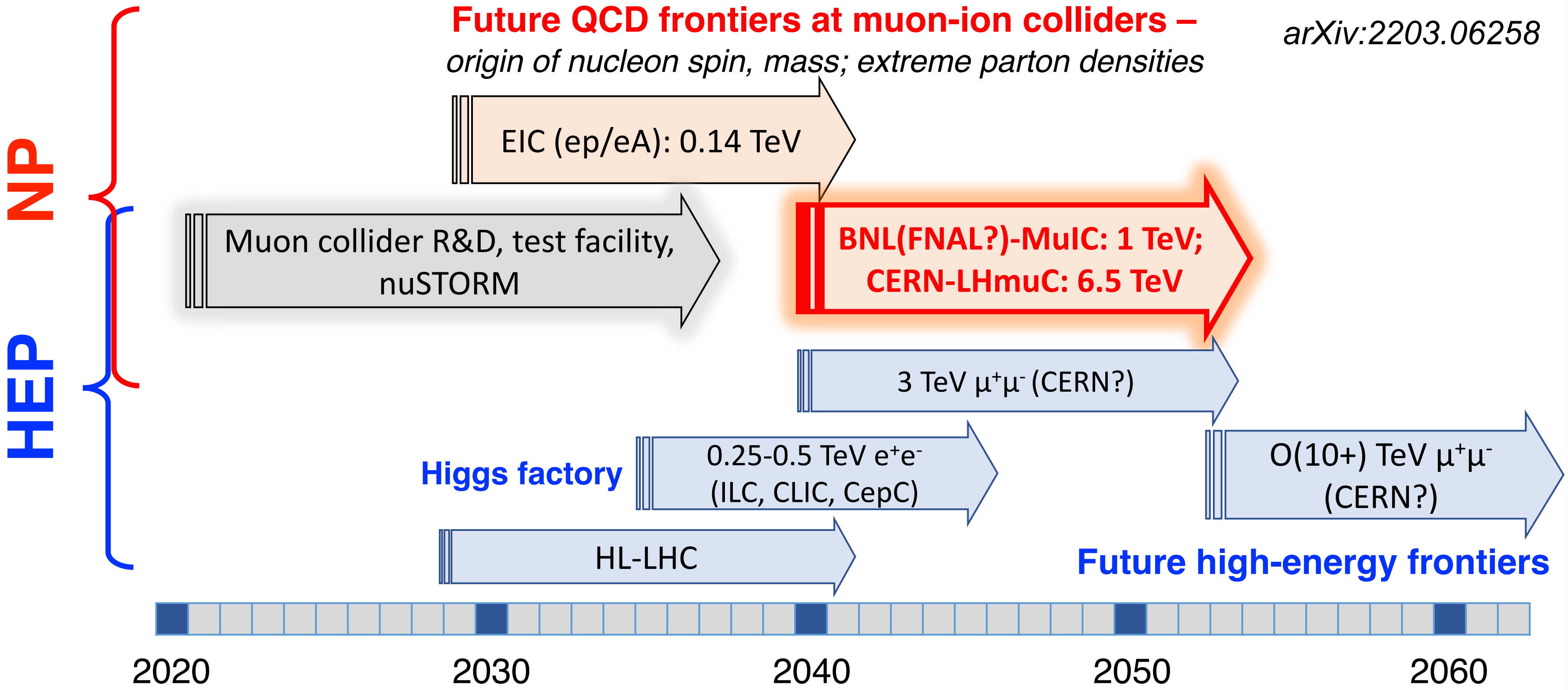
- Asymmetric beam-induced background (BIB)
- Detection of far-backward scattered muons
- Hadron PID at high p over wide coverage

	Main requirements
Muons	**$-7<\eta<-1$, $\sigma(p)/p < 5\%$**
Tracking	$-4<\eta<2.4$
PID (π/k/p)	**$-4<\eta<2.4$, $p<100$ GeV**
Calorimetry (jets, photons)	$-5<\eta<2.4$



Detailed simulations in progress
(leveraging EIC Detector R&Ds)

A Roadmap (in our view)

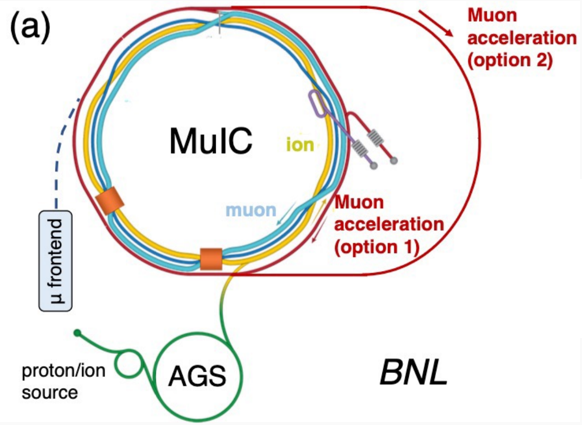


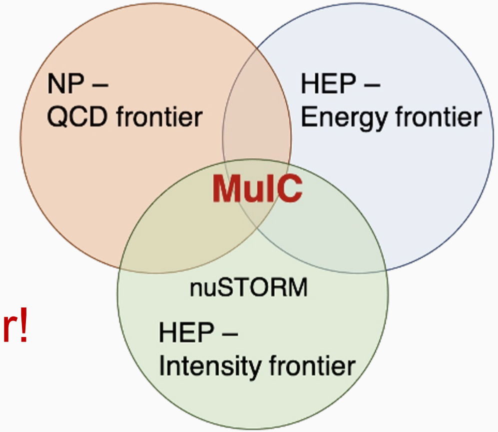
A possible roadmap to future muon colliders in NP and HEP

Summary

A Muon-Ion (proton) Collider:

- Compelling sciences with synergies across NP, HEP energy and intensity (e.g., nuSTORM) frontiers
- Provides a clear target to establish MC R&D program and serves as a demonstrator toward the ultimate 10+ TeV μ+μ-
- Affordable (e.g., an "upgrade" to the EIC) by re-using the existing facility, infrastructure, accelerator expertise, potentially with funding resources from both HEP and NP





MuIC is an opportunity to realize the first muon-based collider!

Extras

Synergy

The key concept is to **re-use an existing hadron collider facility** and add one muon beam – μp and μA.

The motivation is two-fold:

- establish a unique science program in HEP and Nuclear Physics
- serves as a demonstrator to support MC R&Ds and a stepping stone toward the ultimate O(10+) TeV $\mu^+\mu^-$ collider

Affordable: one muon beam and leverage resources from HEP and NP to realize a (the first?) muon-based collider in US in 20-25 years!

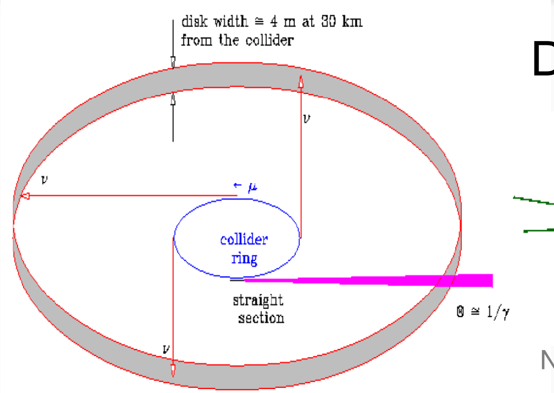
R&D challenges of muon colliders

Required key accelerator technologies

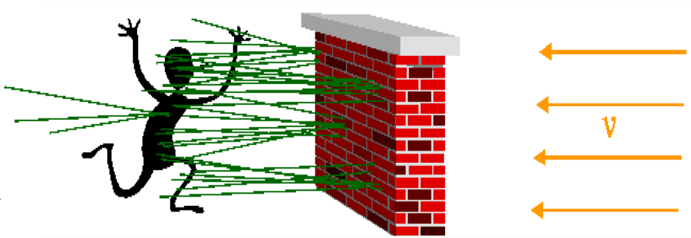
- High power proton driver development
  - 2ns, 8 GeV bunches up to 4 MW with a 15 Hz rep. rate
- Target system capable of managing large instant power
  - 20 T capture solenoid with large bore that can withstand radiation
- Cooling system to reduce 6D emittance by 6 orders of magnitude
  - Demand for high B-fields @ 30-40 T range
  - Placement of NC RF cavities within multi-T B-fields
- Acceleration scheme towards TeV scale energy before decay
  - Fast ramping magnets to deliver ramp times of several T on a ms timescale
- Collider ring
  - 12-16 T dipole magnets with a 150 mm aperture
  - Neutrino flux mitigation system

Diktys Stratakis
Snowmass Summer Meeting
19 July 2022

Neutrino-induced radiation background



Damage by secondary particles induced by neutrinos



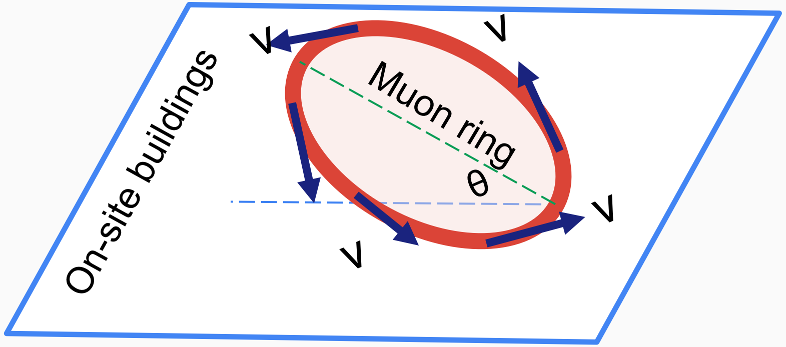
Nikolai Mokhov (FNAL)

→ Very deep underground

OR

→ Surface of an island

RHIC-BNL tunnel is essentially **on the surface**, in a “remote island”



Tilt the disk plane at a small angle to direct straight sectors toward land/sea and sky?

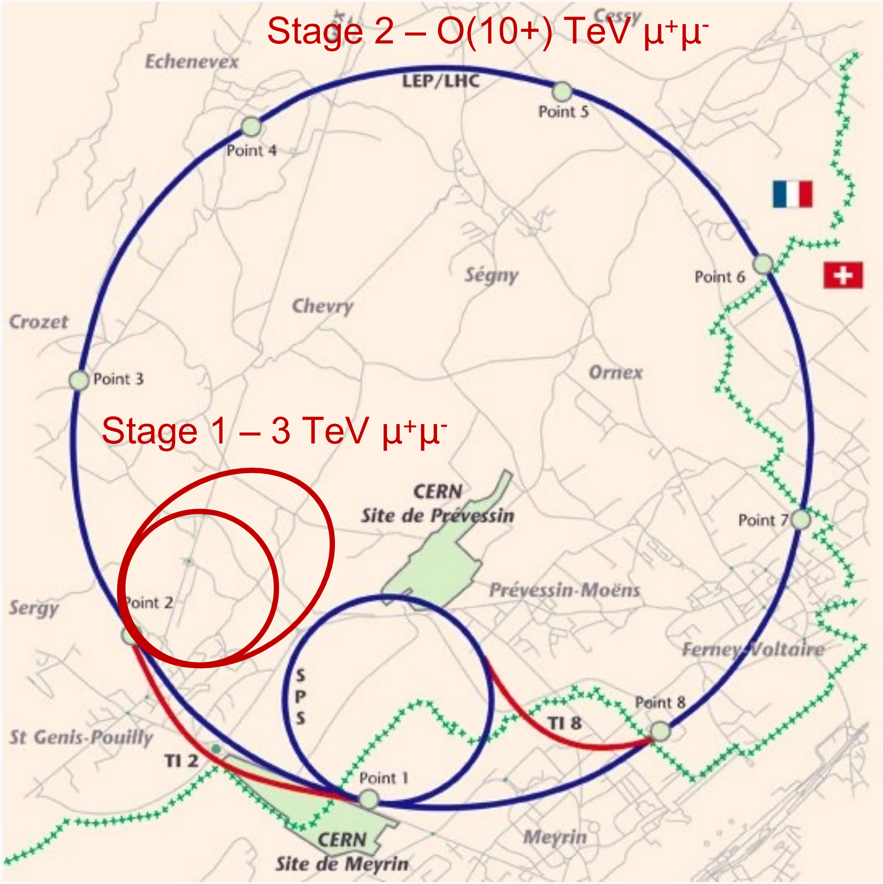
LHmuC at CERN

Stage 1: assuming a 3 TeV $\mu^+\mu^-$ is designed by IMCC and built at CERN, a μ-p/A mode can be operated concurrently with the LHC.

- ➢ **May be even easier to start in μ-p/A mode with one muon beam?**

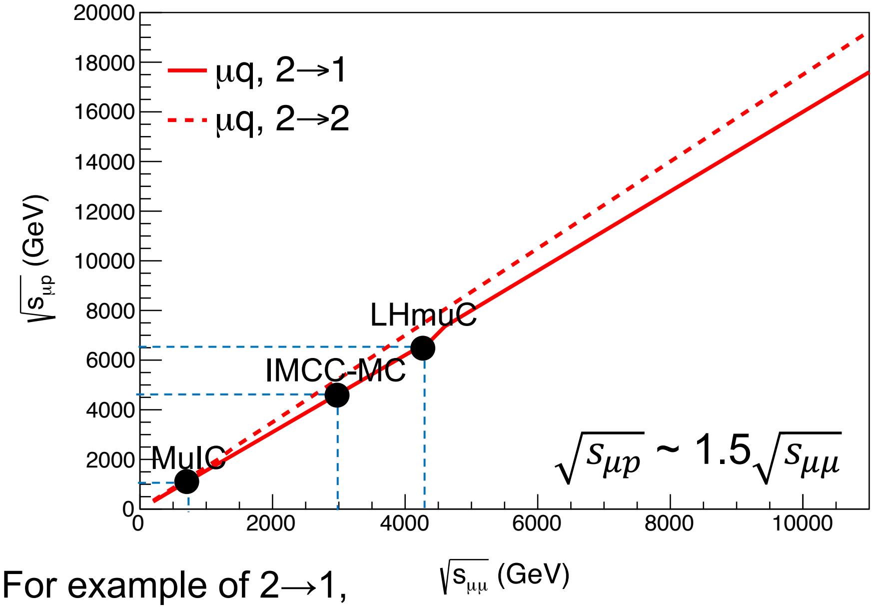
Stage 2: Once O(10+) TeV $\mu^+\mu^-$ design is mature, it can be hosted in the LHC tunnel.

Stage 3: if a large tunnel is built in farther future, a O(100) TeV $\mu^+\mu^-$ may be realized



Science potential at the MuIC/LHmuC

New physics potential: $\mu^- p$ vs $\mu^+\mu^-$

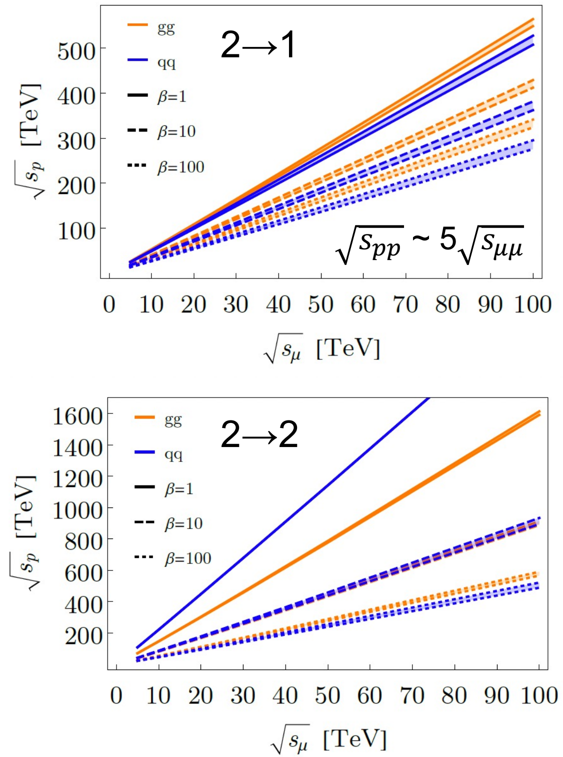


For example of 2→1,

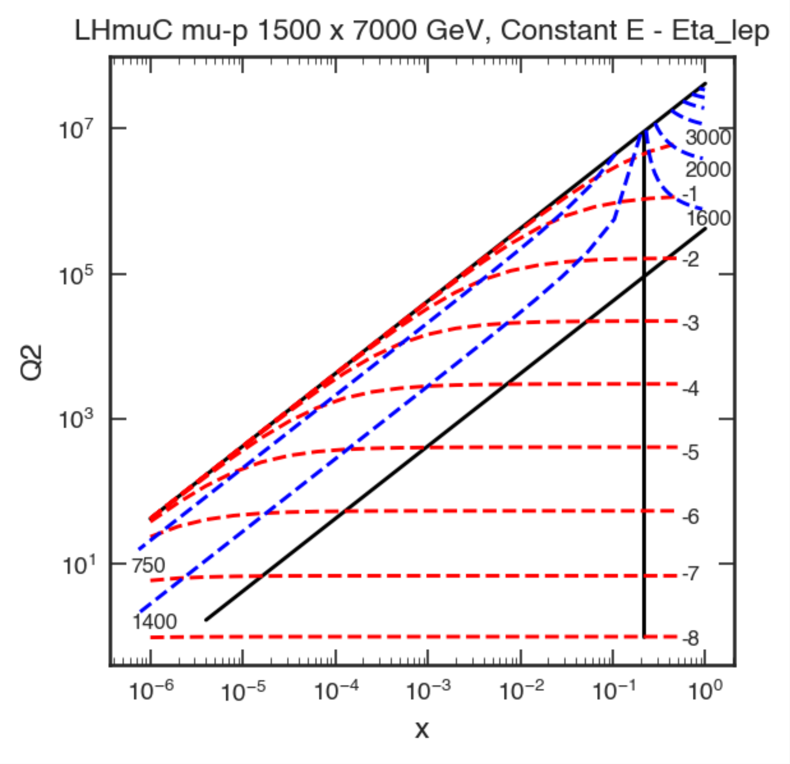
- 3 TeV $\mu^+\mu^-$ (IMCC) ~ 4.5 TeV μ^-p ~ 15 TeV pp
- **6.5 TeV μ^-p (LHmuC) ~ 4.3 TeV $\mu^+\mu^-$ ~ 22 TeV pp**
- 1 TeV μ^-p (MuIC) ~ 0.67 TeV $\mu^+\mu^-$ ~ 3.3 TeV pp

(without considering different bkgs levels)

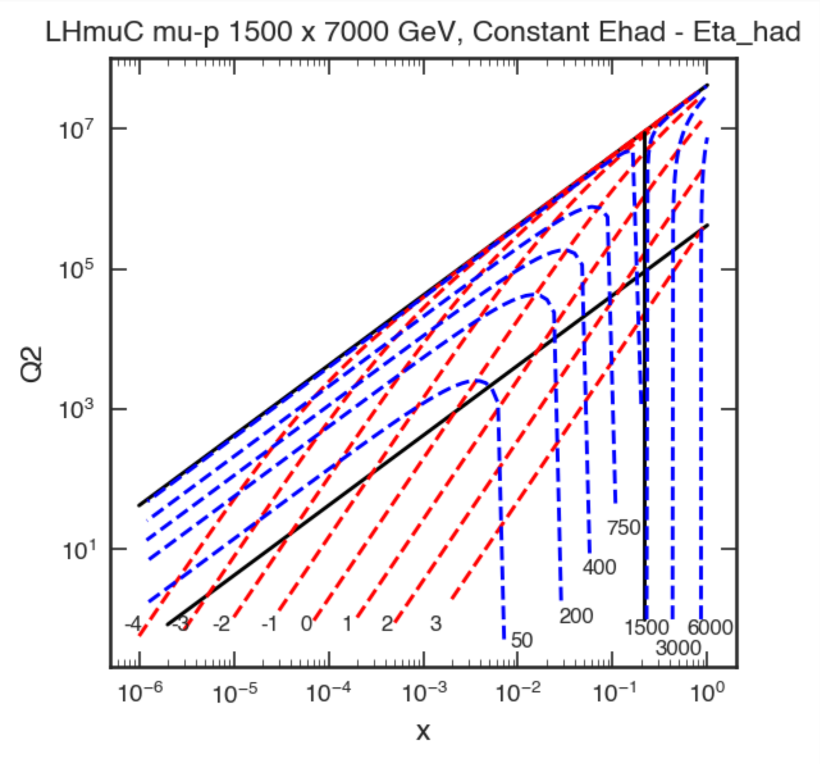
The muon smasher's guide



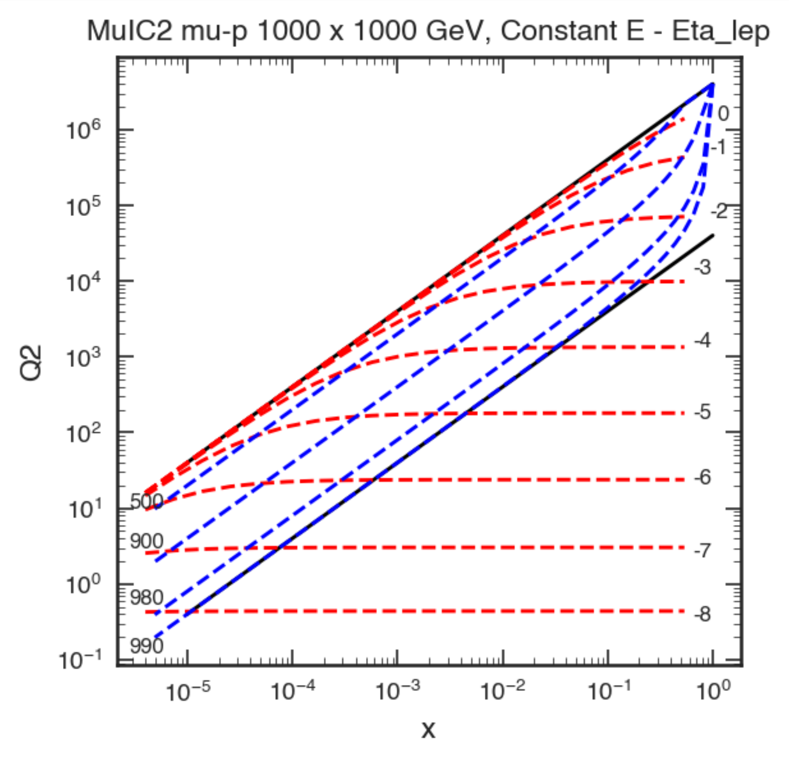
(reproduced in our calculations)

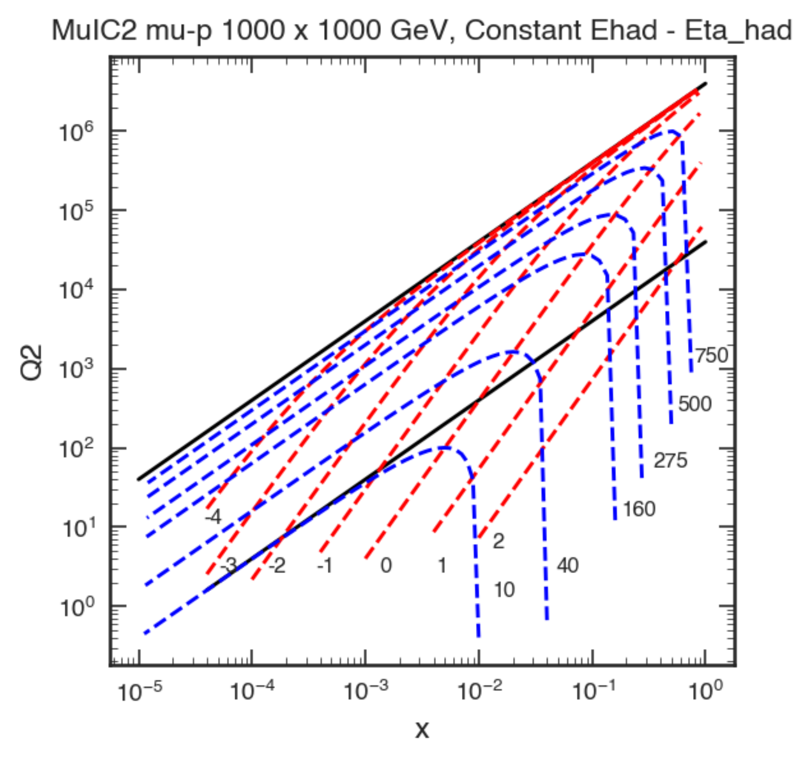


LHmuC mu-p 1500 x 7000 GeV, Constant E - Eta_lep
Q2
x
3000
2000
-1
1600
-2
-3
-4
-5
-6
750
-7
1400
-8



LHmuC mu-p 1500 x 7000 GeV, Constant Ehad - Eta_had
Q2
x
750
400
200
50
1500
6000
3000
-4
-3
-2
-1
0
1
2
3


MuIC2 mu-p 1000 x 1000 GeV, Constant E - Eta_lep
Q2
x
0
-1
-2
-3
-4
-5
-6
-7
-8
500
900
980
990


MuIC2 mu-p 1000 x 1000 GeV, Constant Ehad - Eta_had
Q2
x
750
500
275
160
40
10
2
1
0
-1
-2
-3
-4