Physics Potential, Accelerator Options, and Experimental Challenges of a TeV-Scale Muon-Ion Collider

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U.S. DEPARTMENT OF ENERGY
Office of Science

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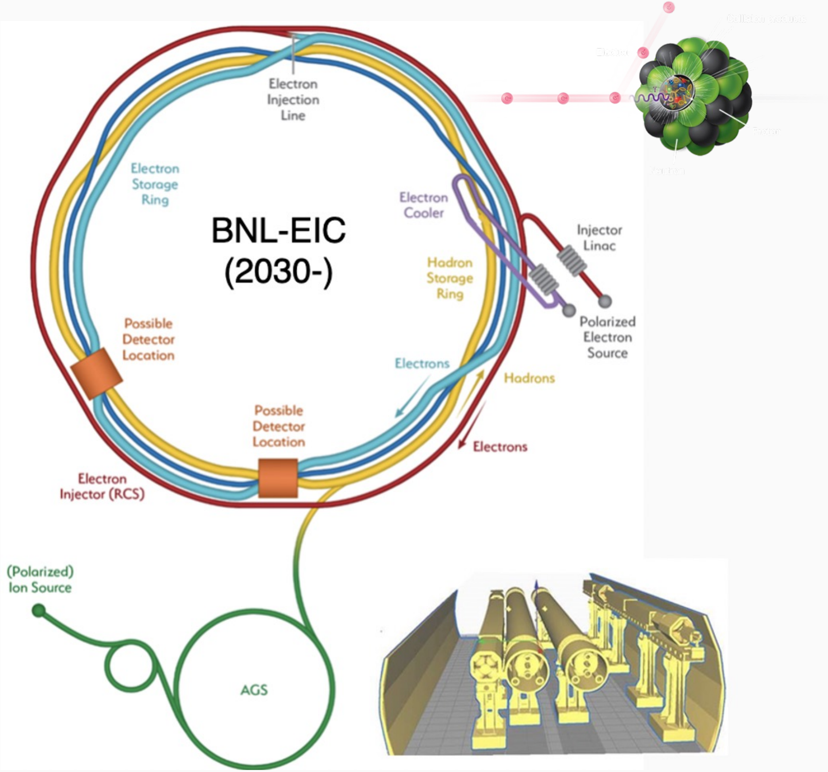
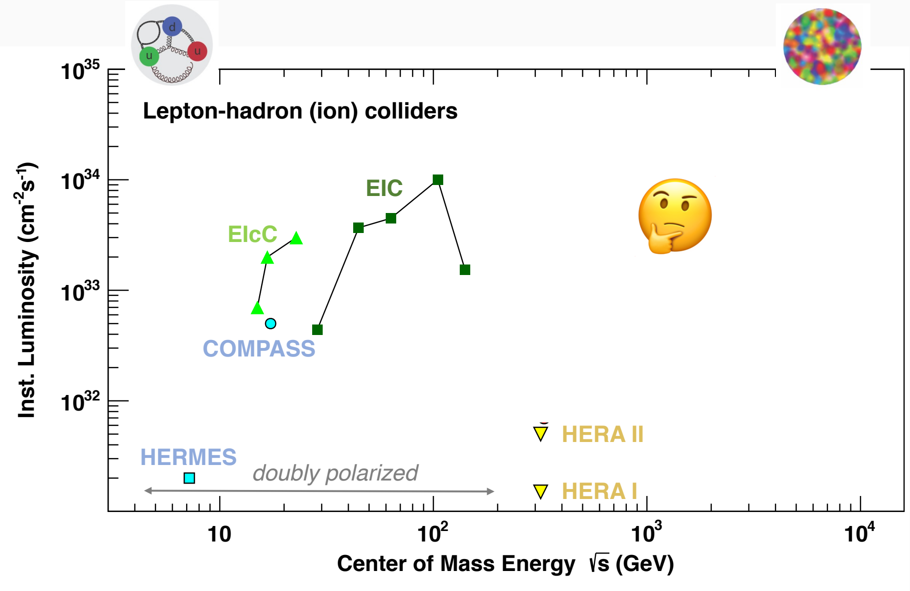
RICE

The Electron-Ion Collider (EIC) at BNL

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



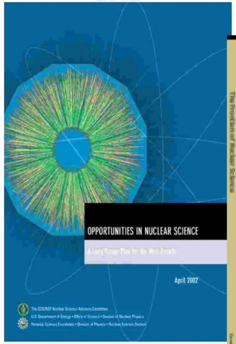


What is after the EIC?

- Can we reach √s of TeV and beyond?

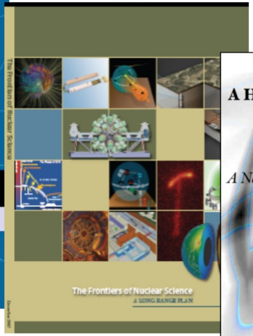
Science for EIC Developed Over Past Two Decades

2002



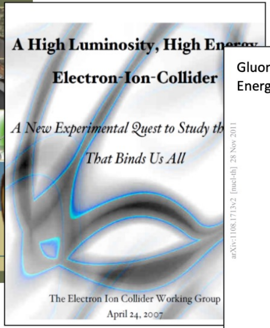
"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

2007



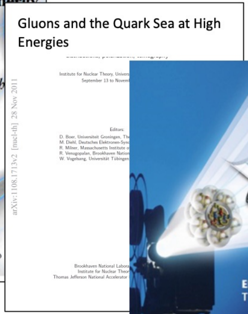
"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

2009



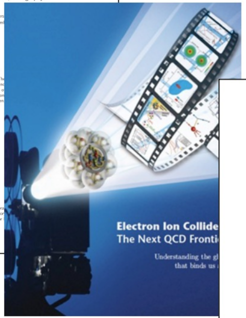
"..a new dedicated facility will be essential for answering some of the most central questions."

2010

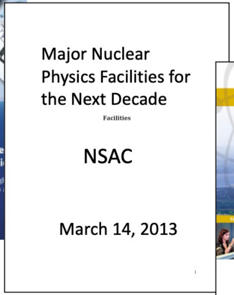


"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

2012



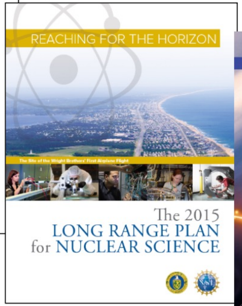
2013



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."

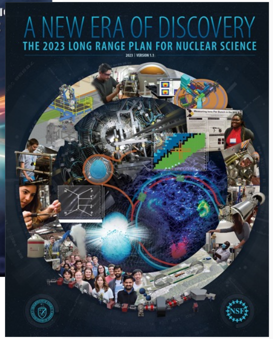
2015



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

2023



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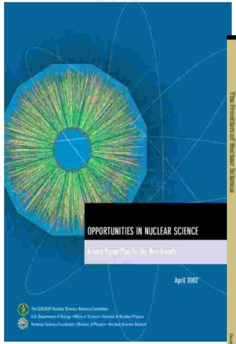

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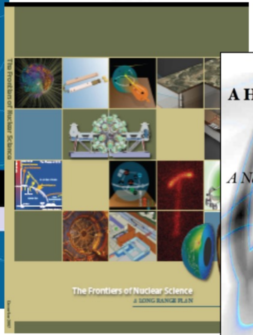

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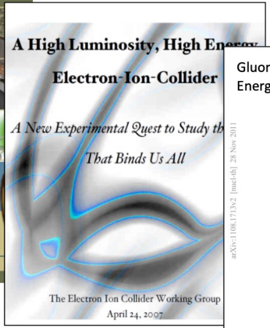

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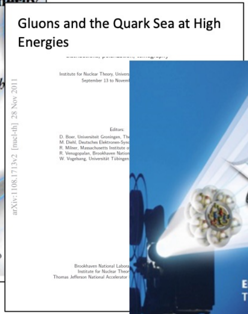
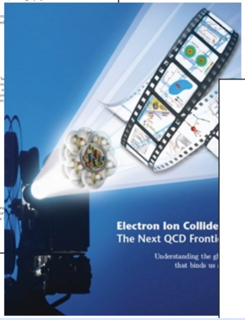


Ion Collider.."

2012



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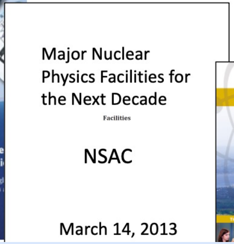
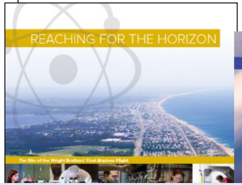


program of the
next decade.

2015



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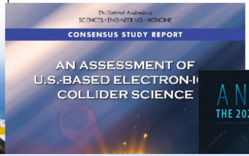

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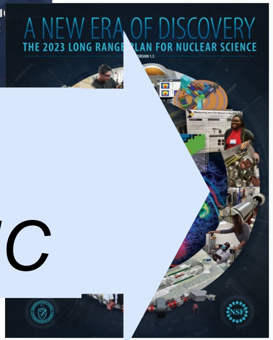


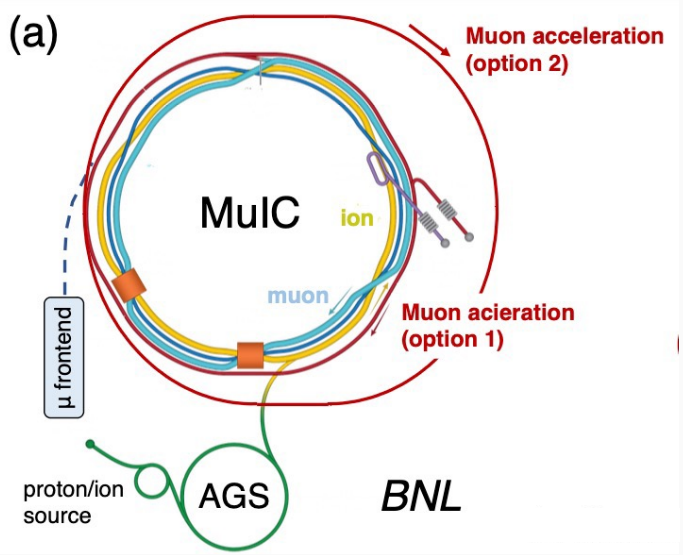
What's after EIC?

Time to think if we want a future beyond the EIC

A Muon-Ion Collider at BNL

Acosta, Li, NIM A 1027 (2022) 166334

An "upgrade" of EIC 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

But muons decay very quickly!

Reviving interests in Muon Colliders

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

Muon Frontend:

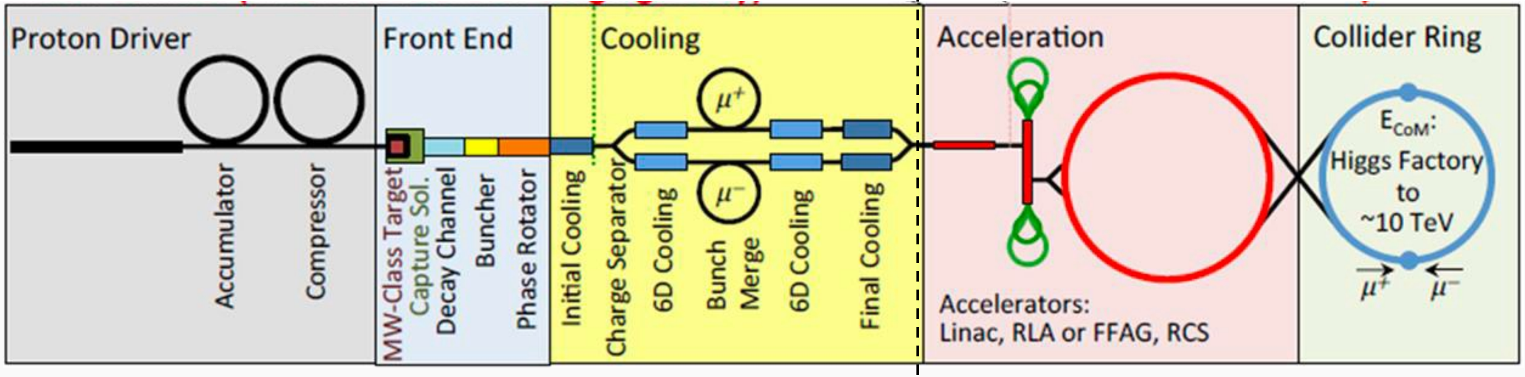
Production

Capture

6-D cooling (ionization)

Fast-ramping acceleration: ***in a few turns***

- Recirculating Linacs (RLA)
- Rapid Cycling Synchrotrons (RCS)



Collider ring:

- Large aperture dipole magnets
- Neutrino radiation mitigation

The Muon Shot!

From the HEPAP P5 Committee report released December 2023:

Exploring the Quantum Universe

2.3 The Path to a 10 TeV pCM

Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where decisions will be taken collectively from the outset by the partners. This differs from current and past international projects in particle physics, where individual laboratories started projects that were later joined by other laboratories. The proposed program aligns with **the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

…

In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

…

Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

MuIC could be a staging option as a demonstrator

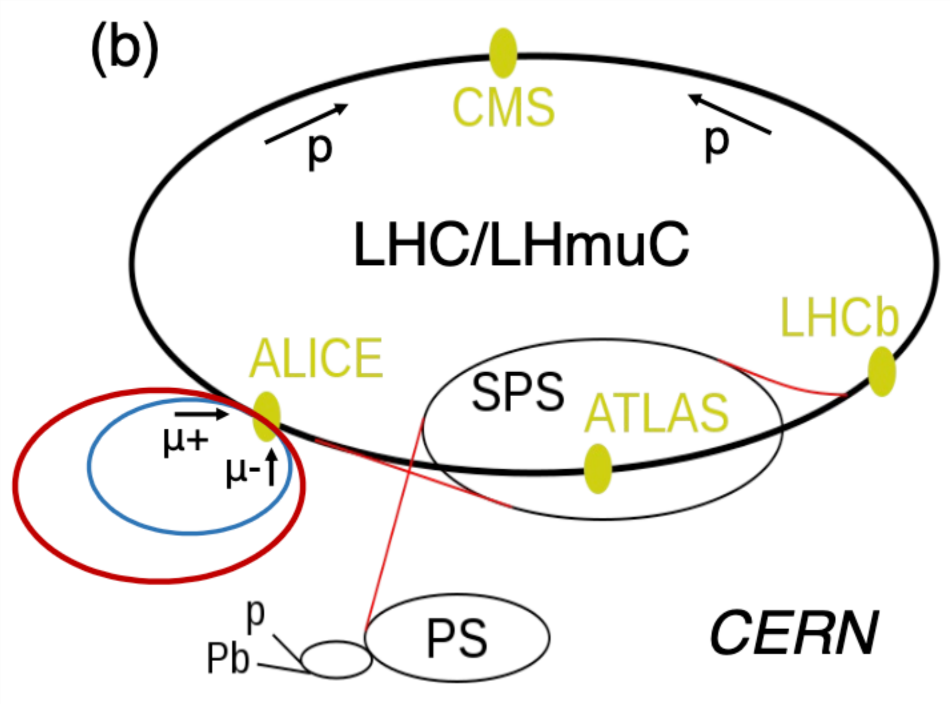
Recent MuIC Workshop @ Rice, December 2023

https://muic2023.rice.edu

Live discussions among physicists from particle physics, nuclear physics, and accelerator science. Check out the program details at indico.

A "LHmuC" option at CERN

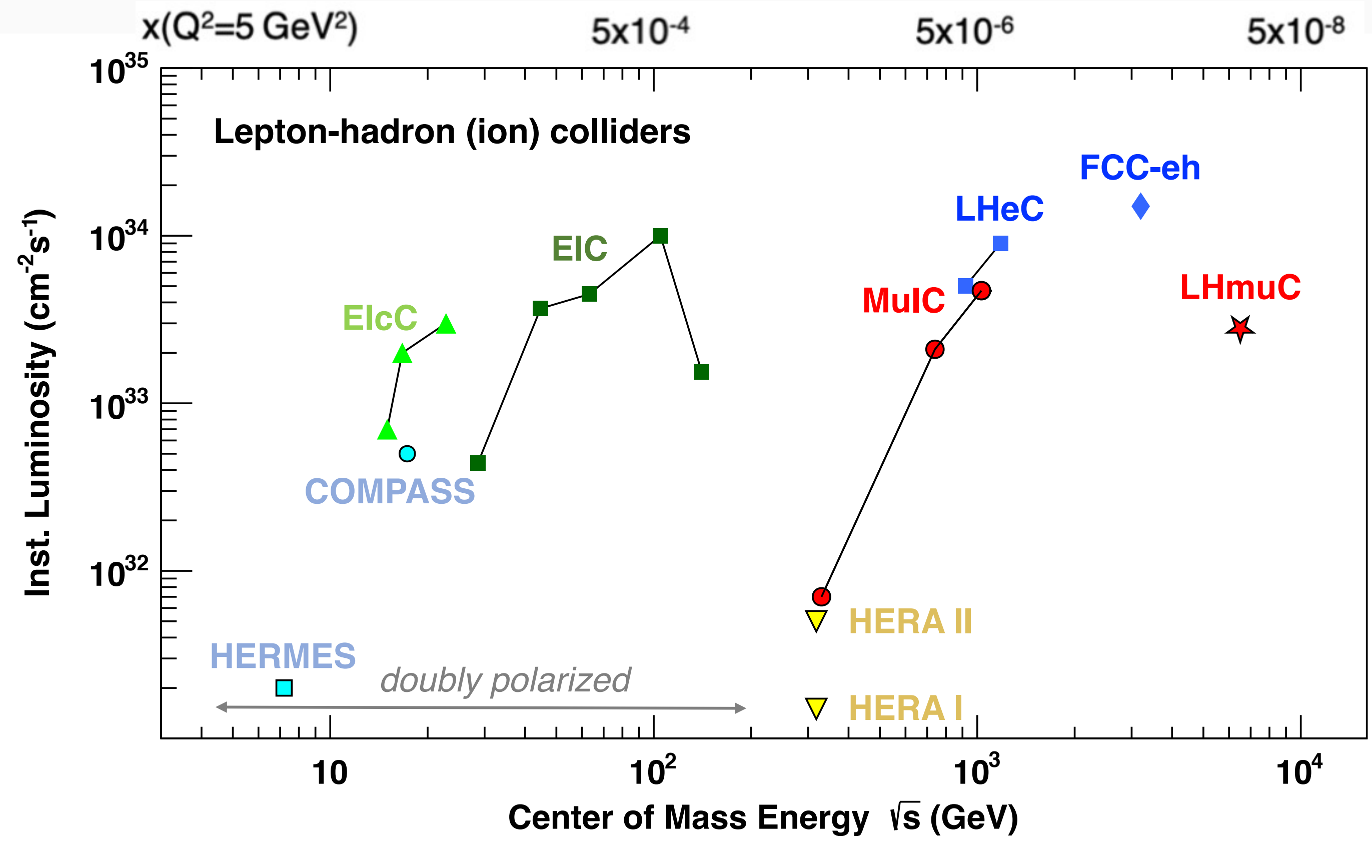
Acosta et. al. 2023 JINST 18 P09025



A μp collider option of **$\sqrt{s}$ = 6.5 TeV**,
If an initial 1.5+1.5 TeV $\mu^+\mu^-$ collider is sited at CERN

Equivalent $\sqrt{s}$ exceeds that of the 3 TeV $\mu^+\mu^-$ collider.

Landscape of DIS physics machines



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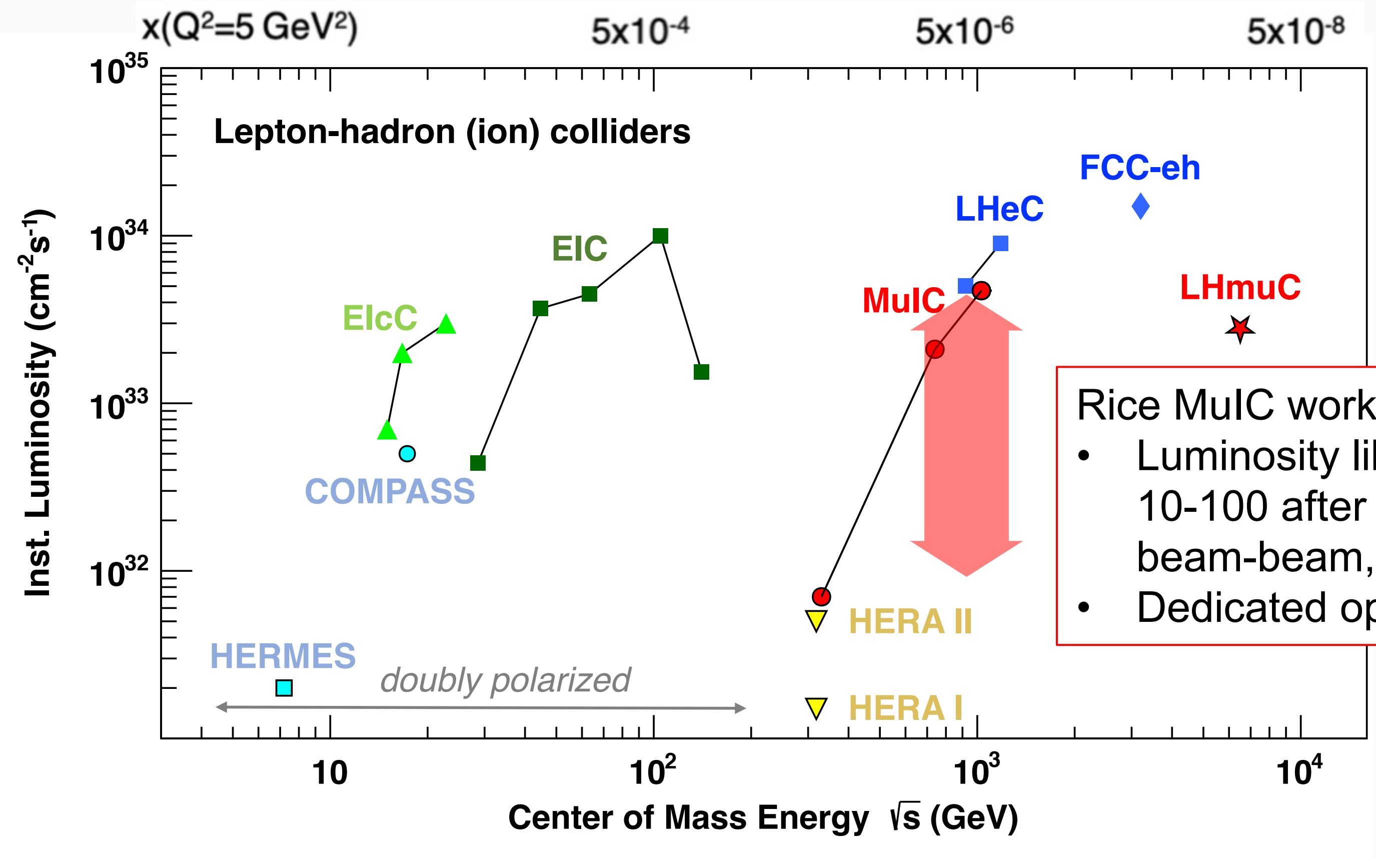

Rice MuIC workshop discussion:

- Luminosity likely overestimated by 10-100 after taking into account beam-beam, space charge effects.
- Dedicated optimization of IR needed

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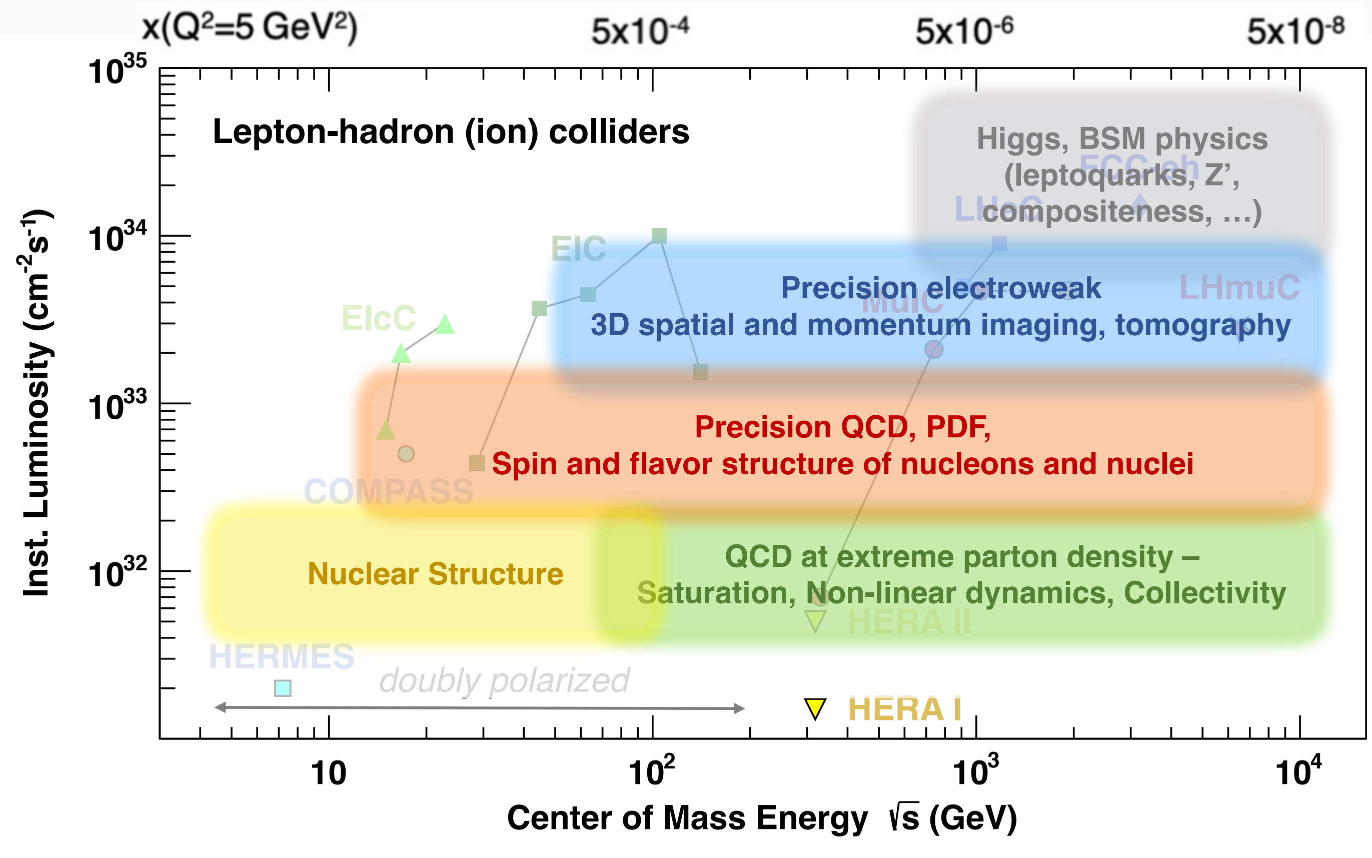
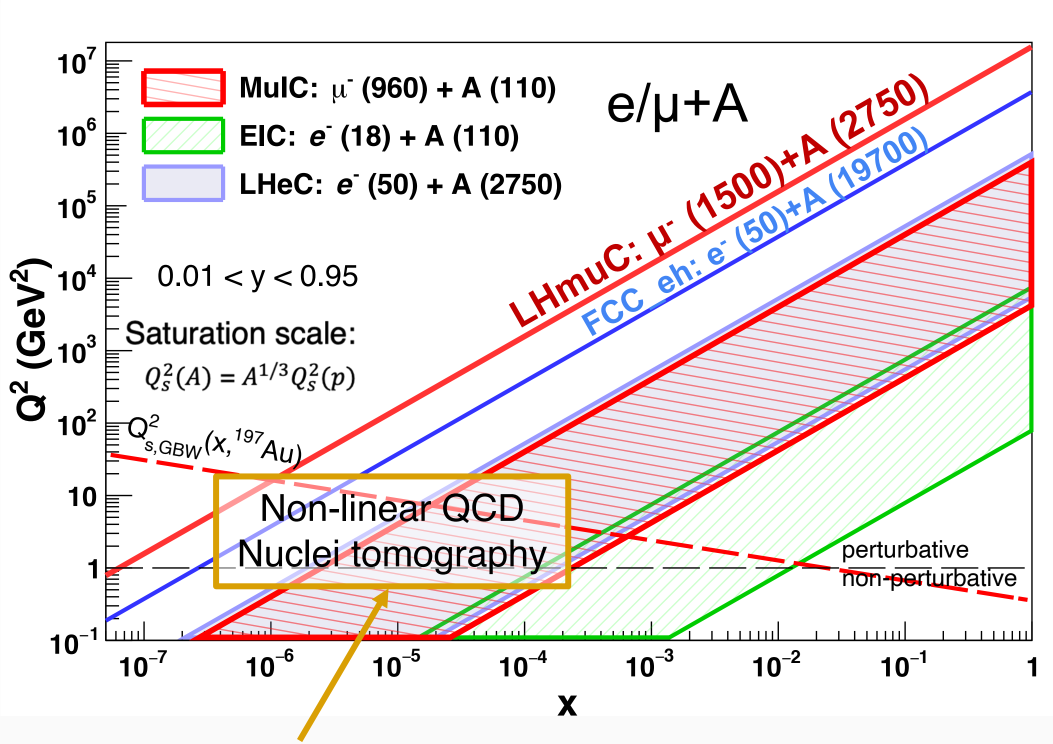
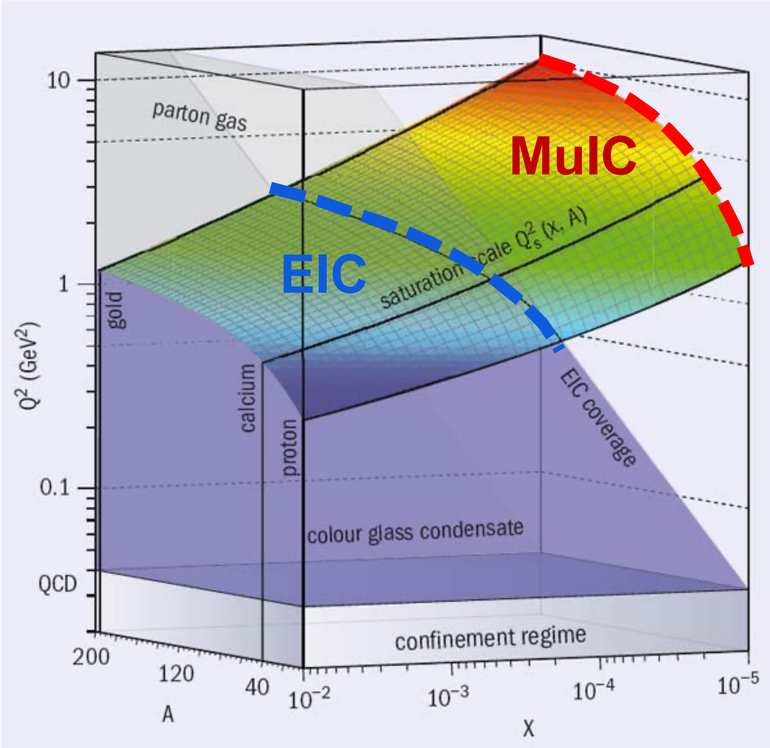


A lab for QCD and Nuclei at the MuIC



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

Saturation scale in nuclei



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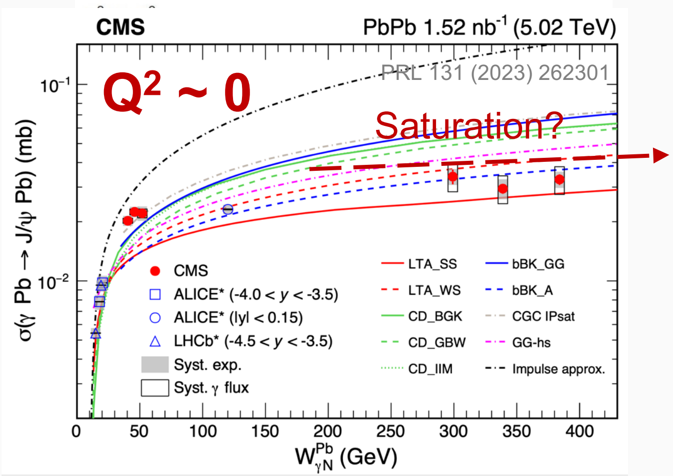
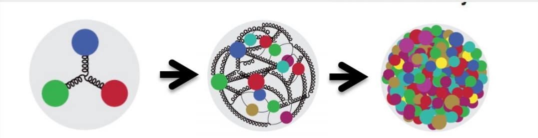
Non-linear QCD effects



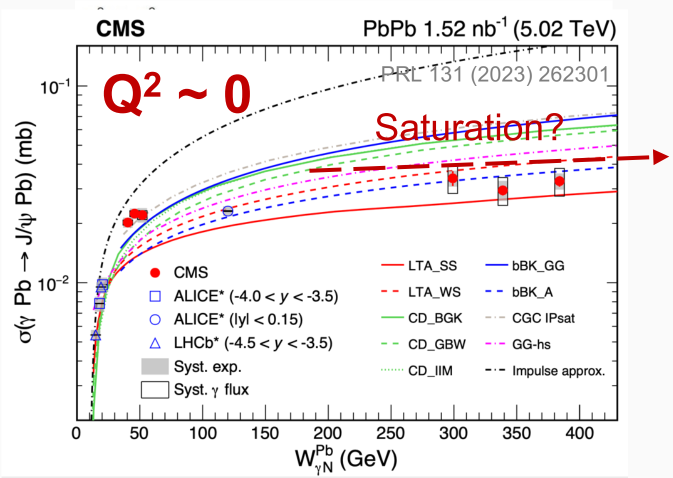


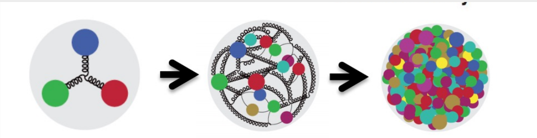
MuIC to access a wide range of both x and Q^2

Building on the EIC (and LHC) science foundation!

A lab for QCD and Nuclei at the MuIC

Non-linear QCD effects

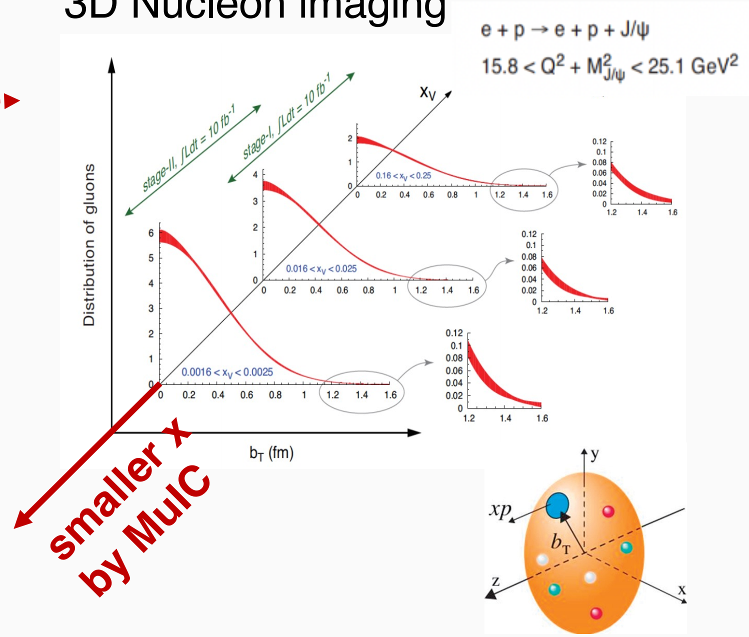




MuIC to access a wide range of both x and Q²

Origin of nucleon mass

3D Nucleon imaging



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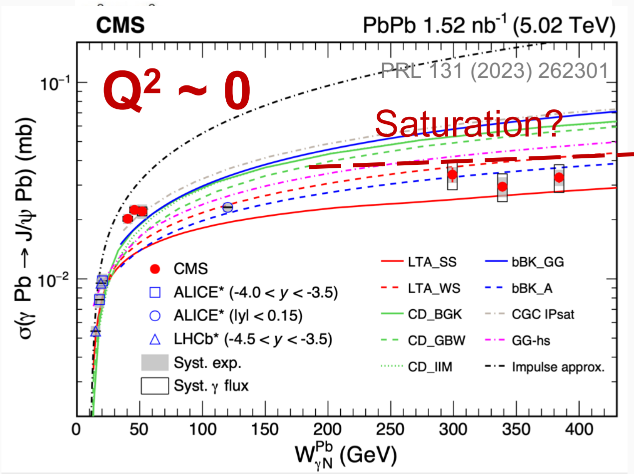

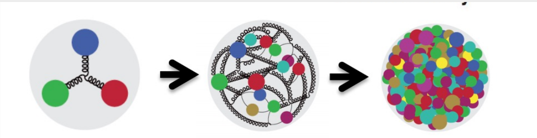

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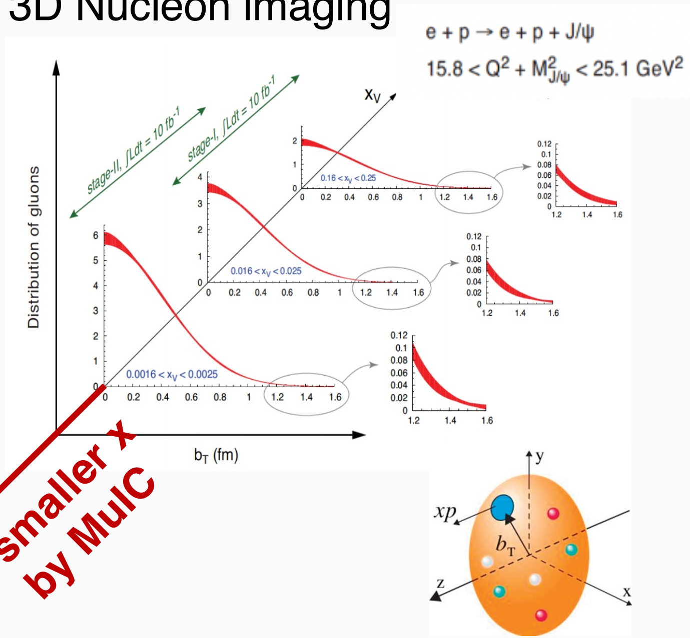
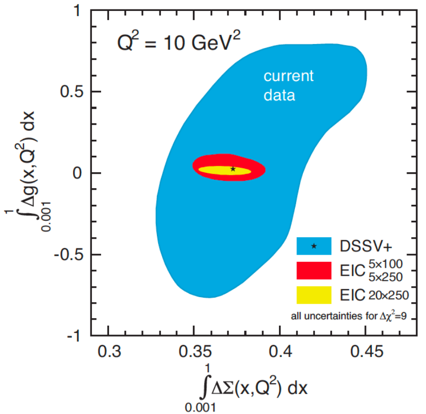


Nucleon spin with polarized beams

"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

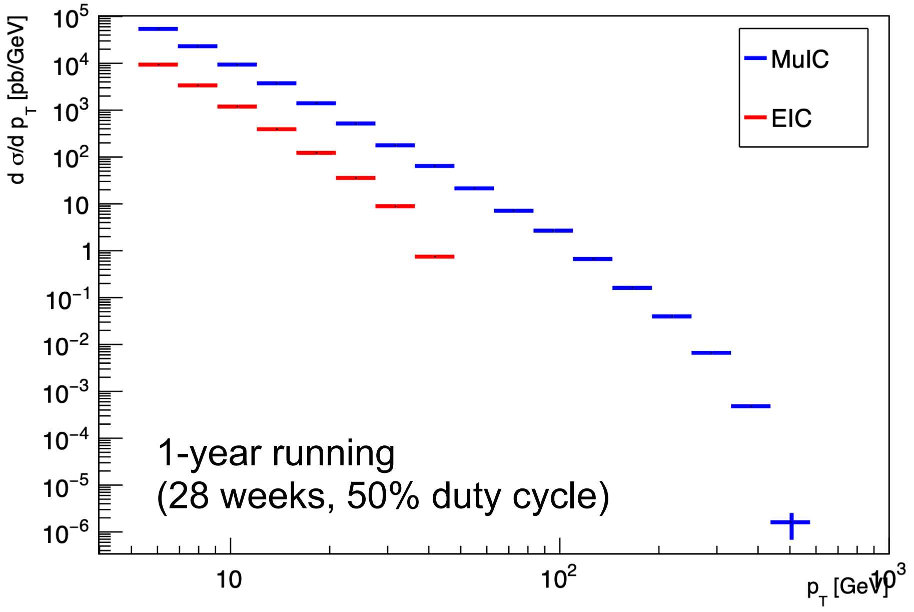


MuIC to reach x ~ 10^{-5}

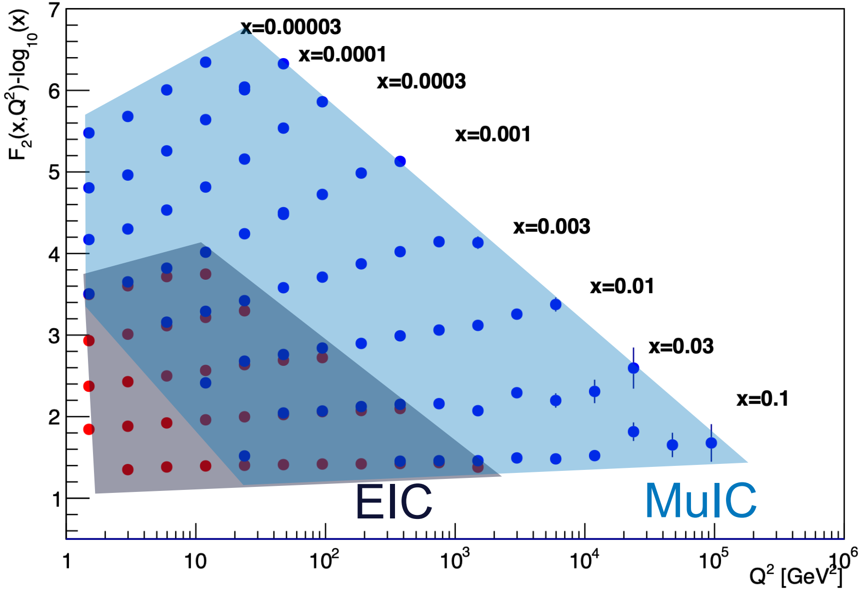
Building on the EIC (and LHC) science foundation!

A lab for QCD and Nuclei at the MuIC

Inclusive jet cross section

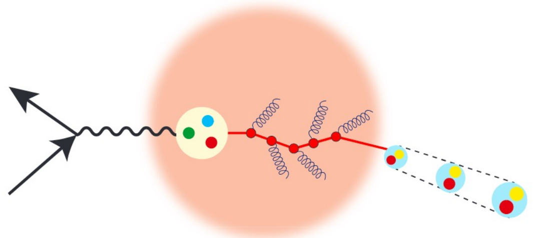


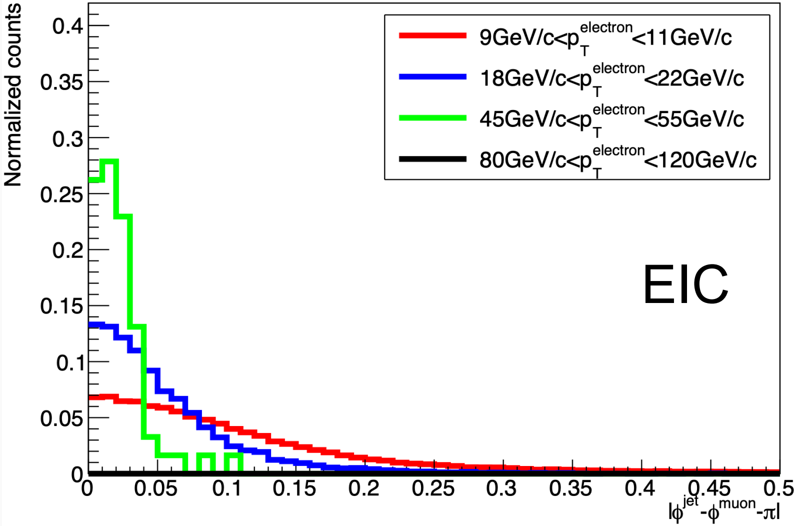
Structure function (F_2)

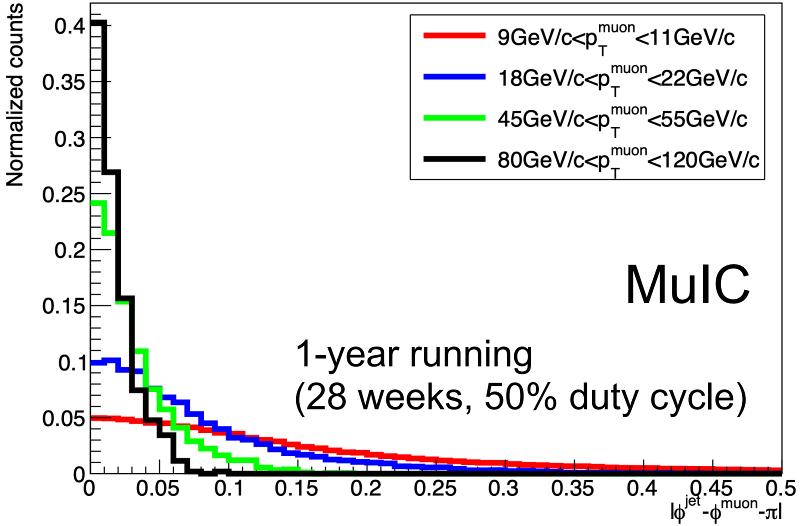


A lab for QCD and Nuclei at the MuIC

Lepton-Jet (de)correlations to probe cold nuclear matters



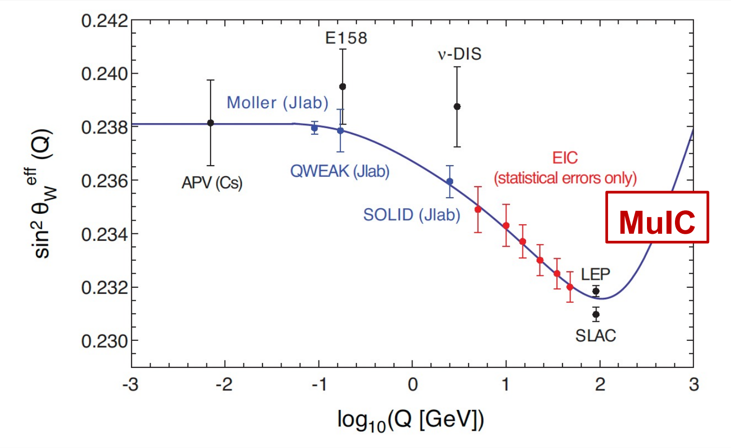




Much wider kinematic lever-arms and precision at TeV DIS machine

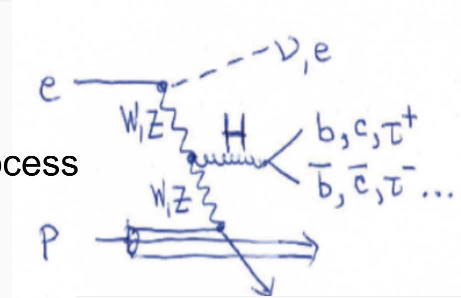
Physics Potentials: EWK, Higgs, BSM

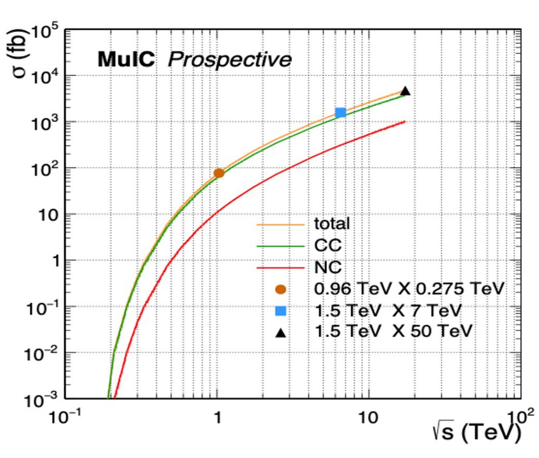
Electroweak:



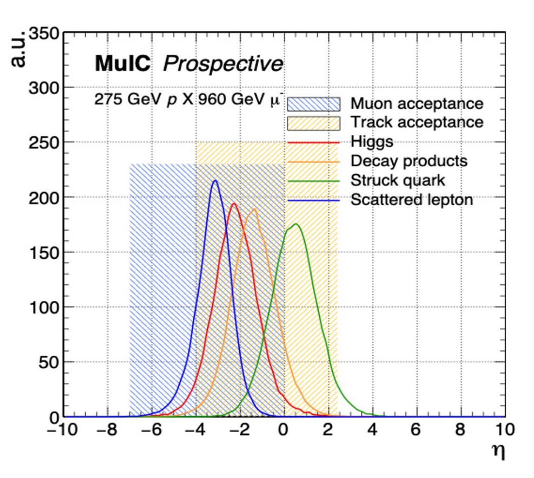
Higgs physics:

VBF process



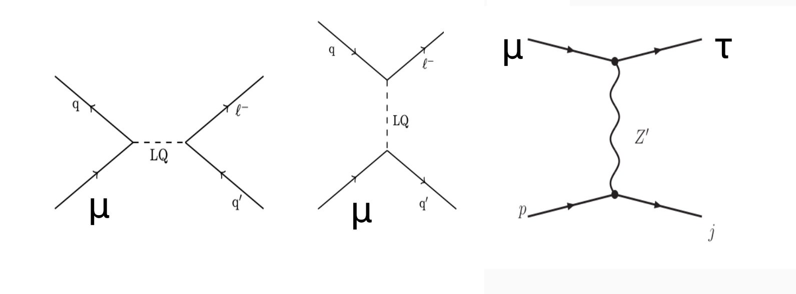


Cross section comparable to LHeC and $\mu^+\mu^-$

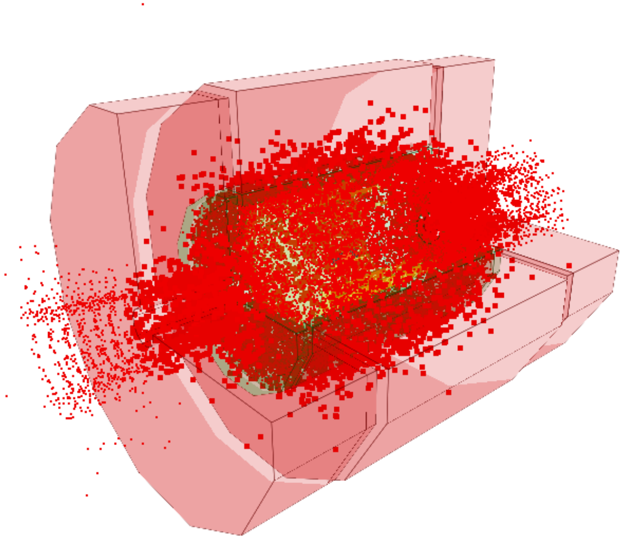


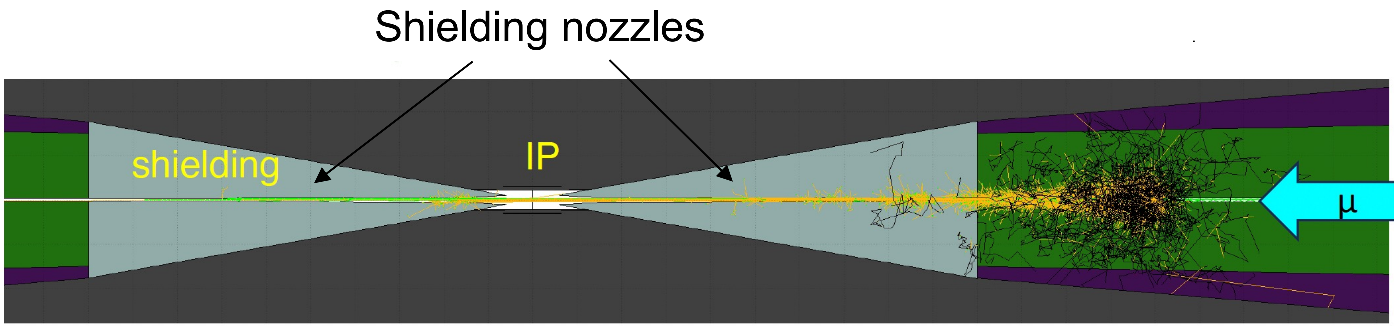
Final-state objects are in central region (in contrast to LHeC)

BSM: Charged lepton flavor violation



Detector Considerations and Challenges





Single muon decay tracks

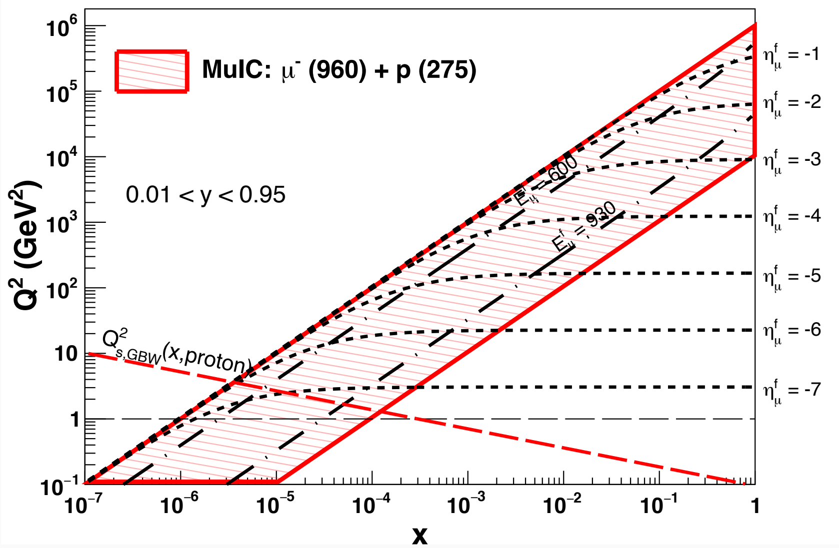
$N_{\mu}^{\pm} \sim 2x10^{12}$/bunch

F. Collamati et al. 2021 JINST 16 P11009

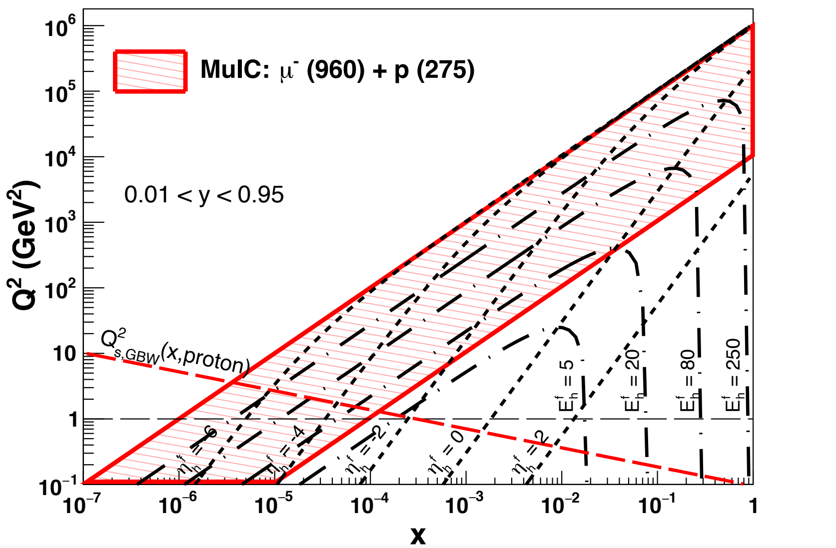
Final-state kinematics at MuIC

p/A → ← μ

kinematics for scattered **muons**



kinematics for struck **quarks**



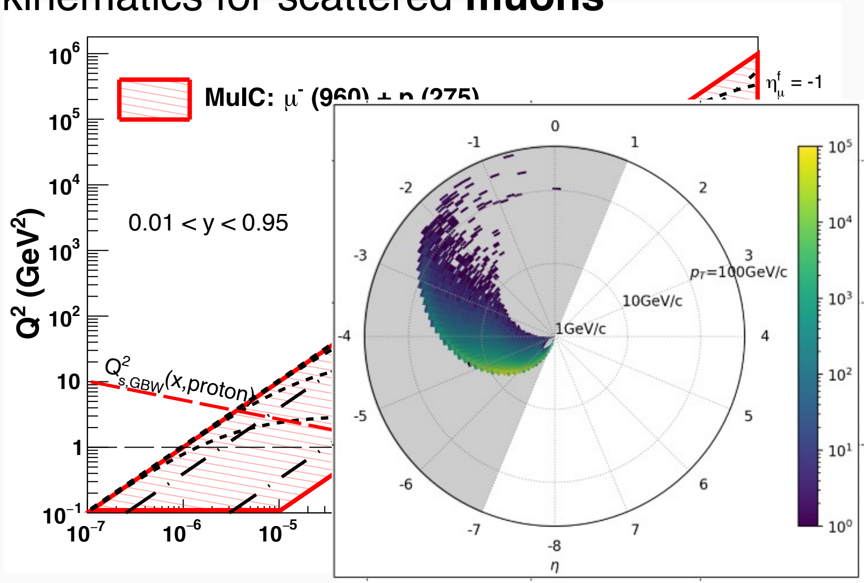
Scattered muons: -7<η<-1

Jets/hadrons: -4<η<2.4

Final-state kinematics at MuIC

p/A → ← μ

kinematics for scattered **muons**



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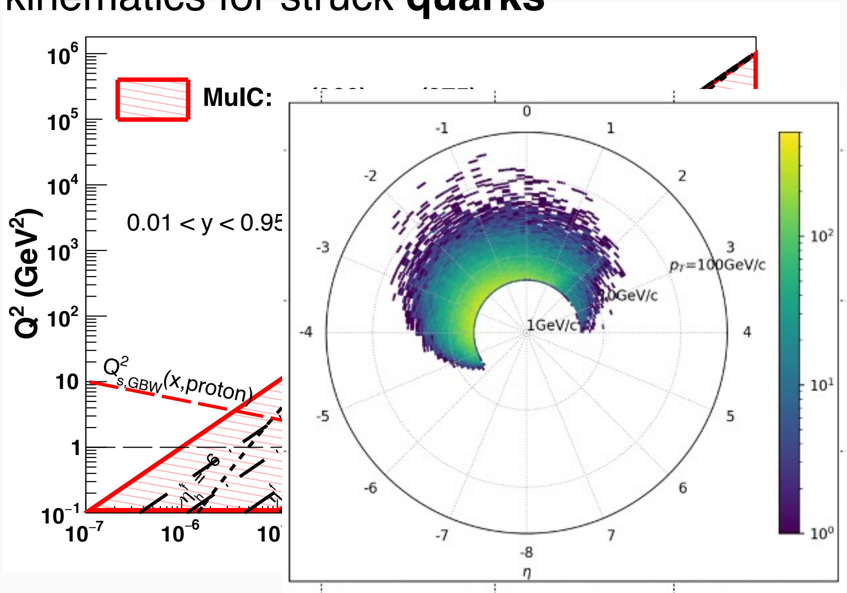

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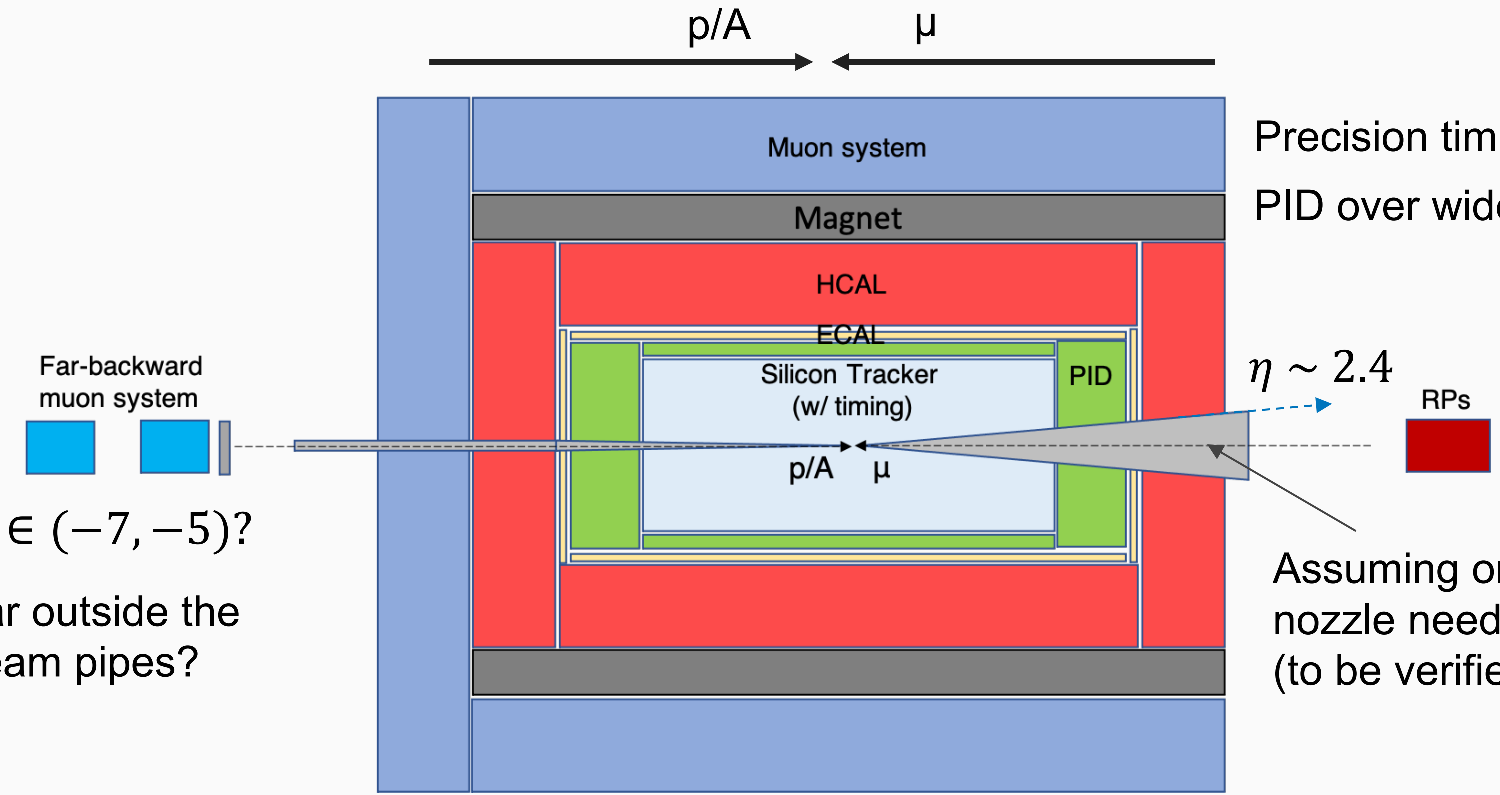
Detector challenges and R&D needs



Precision timing everywhere

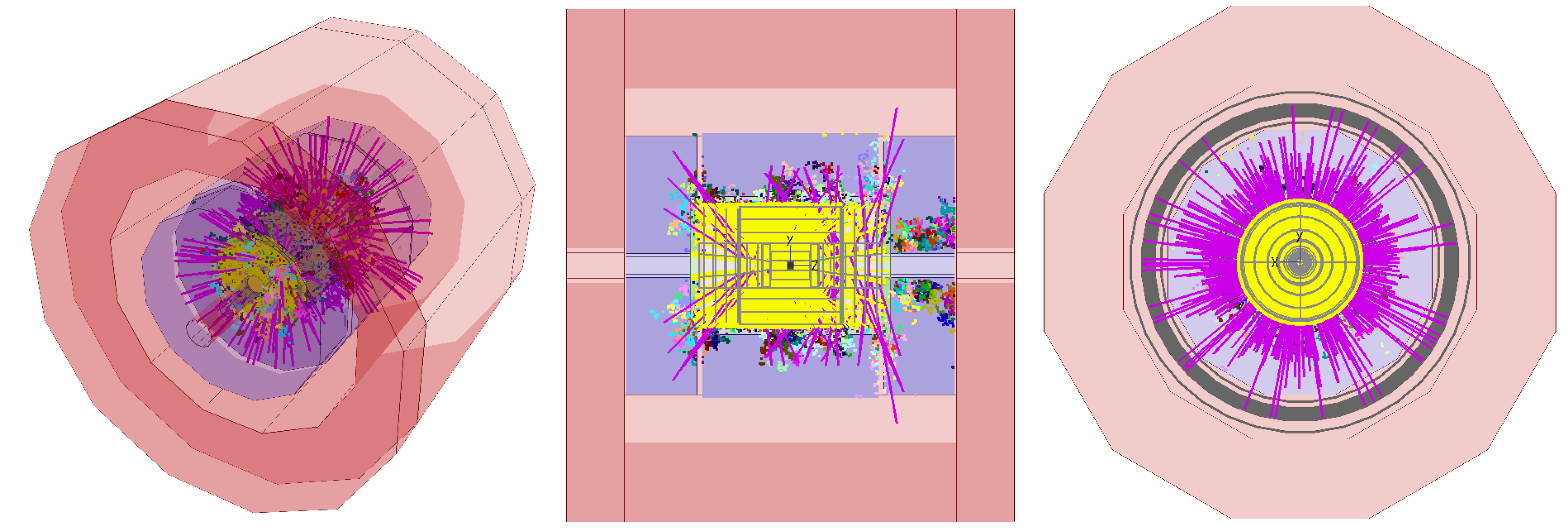
PID over wide p range

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

Far outside the beam pipes?

Assuming only one-side nozzle needed (to be verified)

DIS events + BIB simulation (one muon beam)

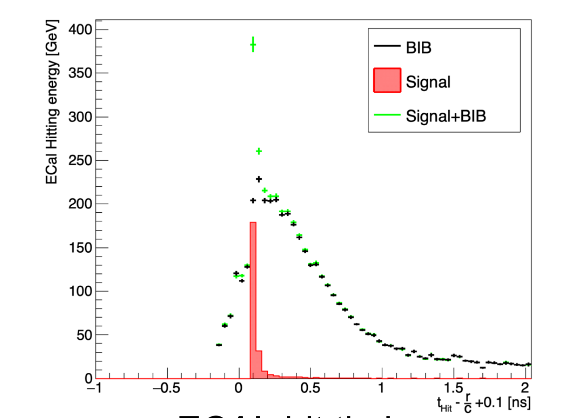


IMCC simulation software

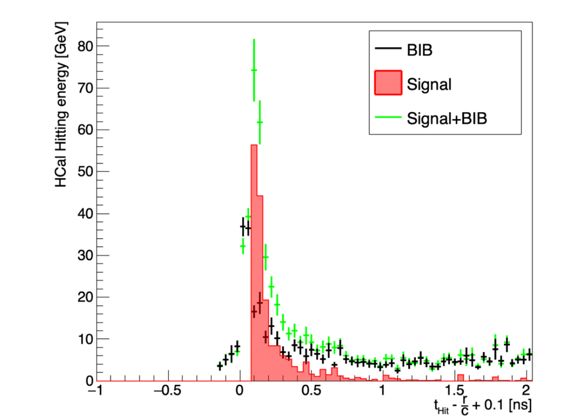
BIBs from one muon beam with IMCC ref. detector (nozzles on both sides)

Next: BIB simulation with single-side nozzle and detector optimized for MuIC

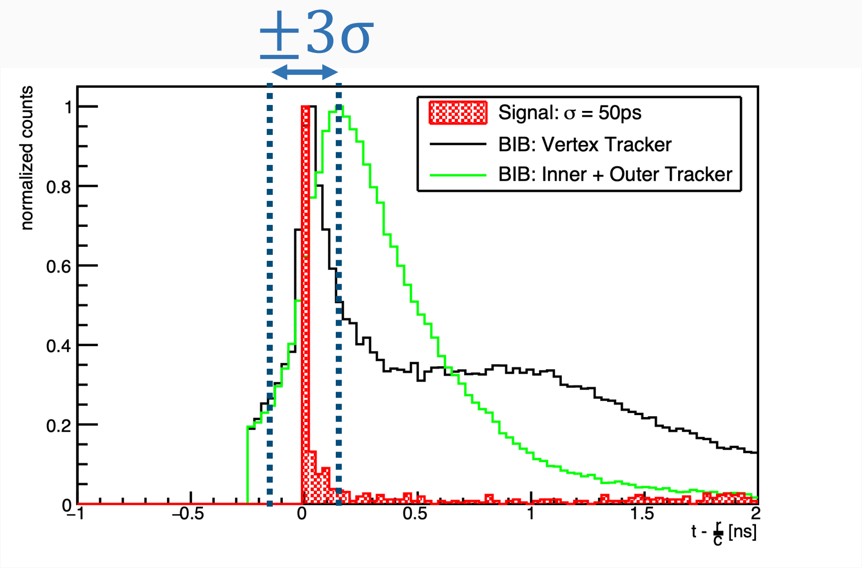
DIS events + BIB simulation (one muon beam)



ECAL hit timing



HCAL hit timing



Timing information for ECAL and Tracker is crucial for suppressing BIBs

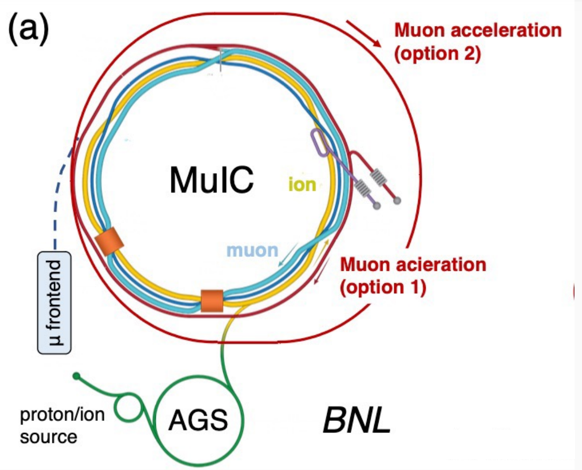
Summary

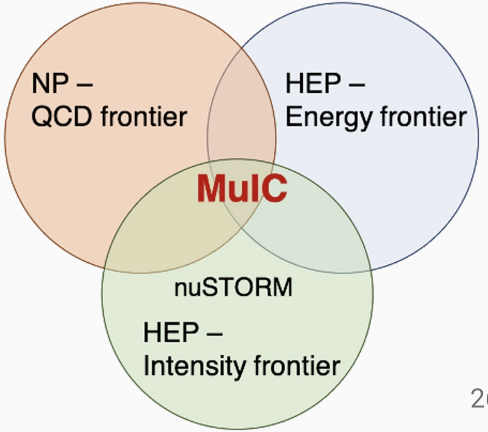
A Muon-Ion (proton) Collider:

- **A TeV DIS machine of rich physics** 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.

Moving forward: strengthen key physics goals, determine R&D needs for detector, MDI, and grow the community interest (more workshops/programs to come!)

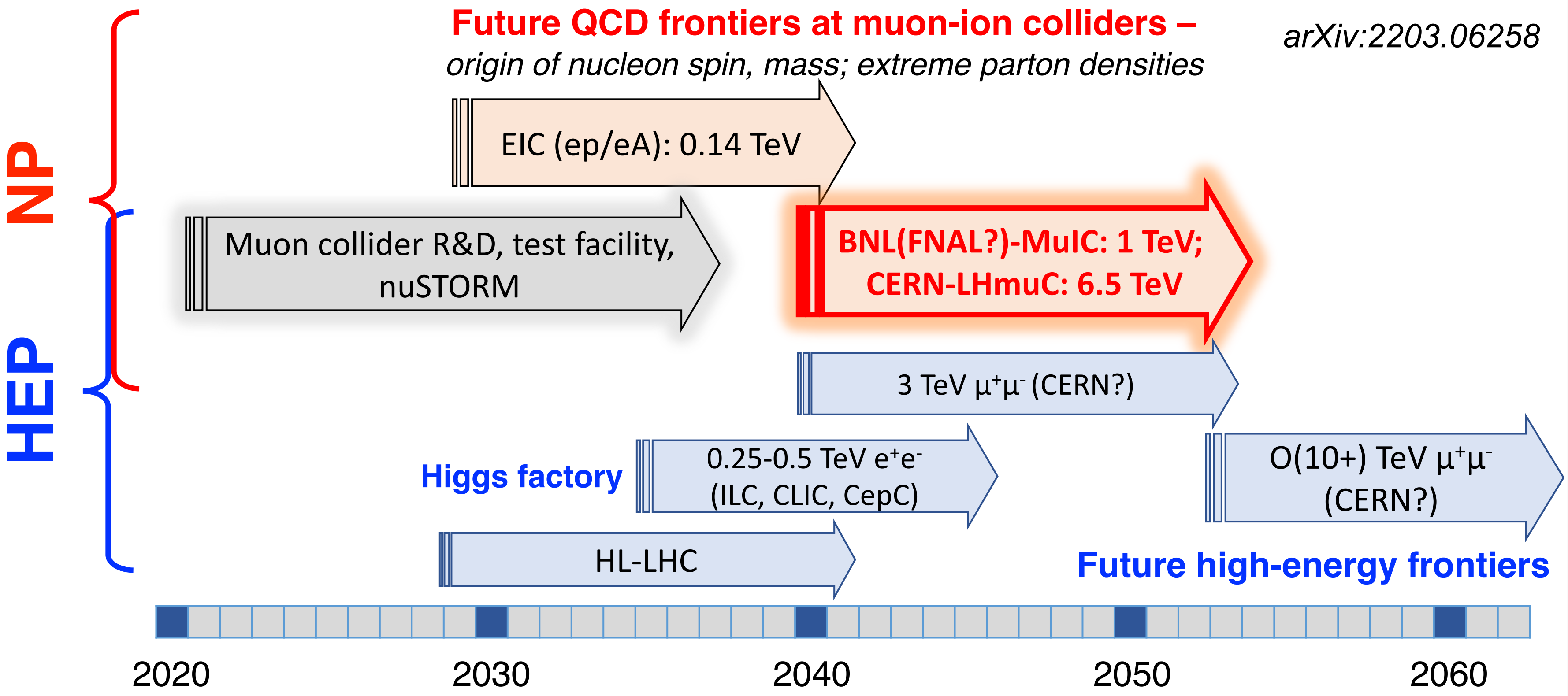
Join us: https://mailman.rice.edu/mailman/listinfo/muic!





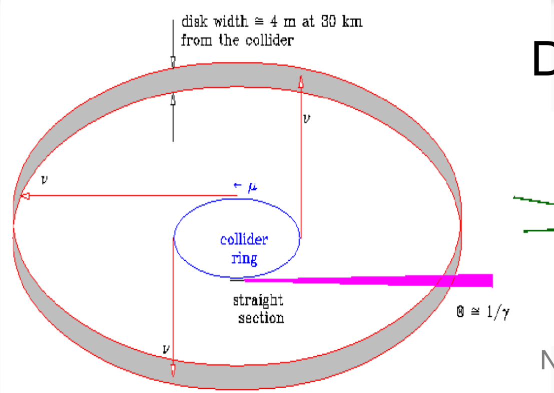
Extras

A Roadmap (in our view)

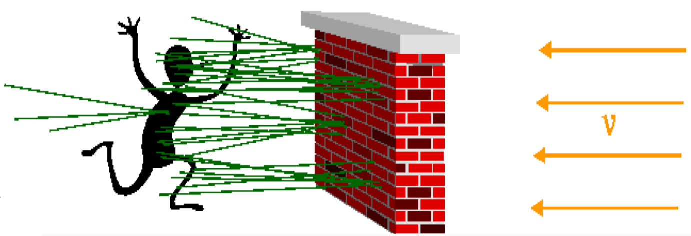


A possible roadmap to future muon colliders in NP and HEP

Neutrino-induced radiation background



Damage by secondary particles induced by neutrinos



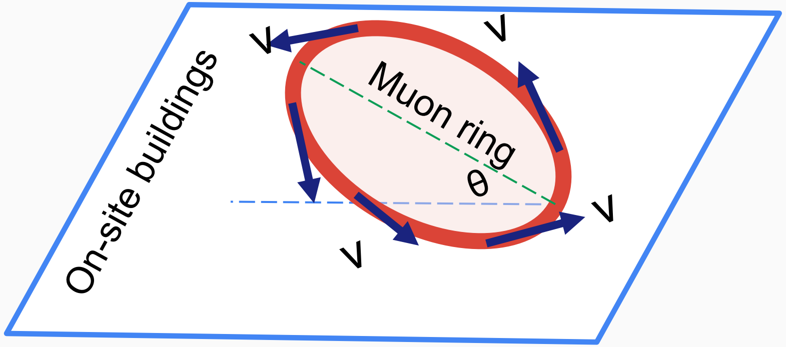
Nikolai Mokhov (FNAL)

→ Very deep underground

OR

→ Surface of an island

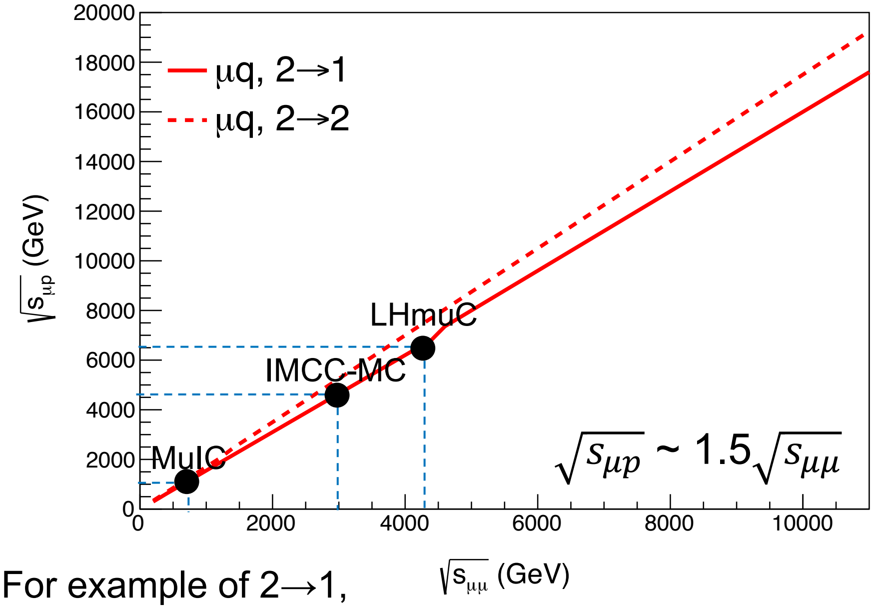
RHIC-BNL tunnel is essentially **on the surface**, in a "remote island"



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

Science potential at the MuIC/LHmuC

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

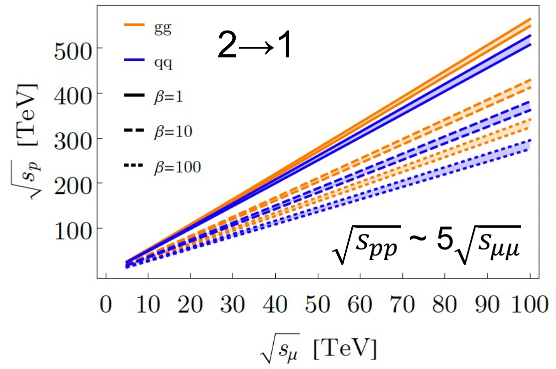


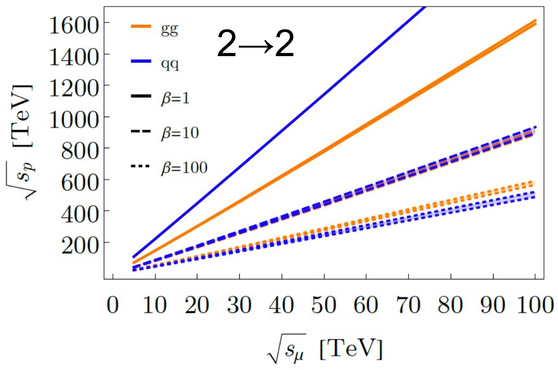
For example of 2→1,

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

(without considering different bkgs levels)

The muon smasher's guide





(reproduced in our calculations)

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

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

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

Unique challenges for MuIC

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

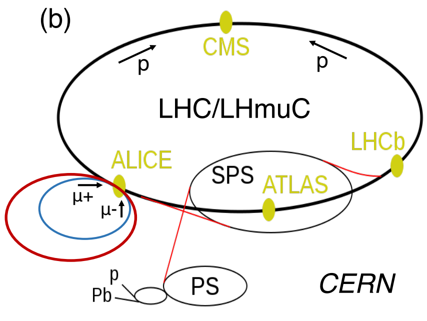
Muon Collider parameters (arXiv:1901.06150)
+ BNL/EIC proton beam parameters (CDR)

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)

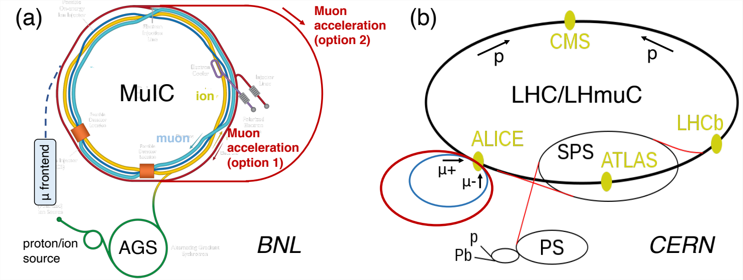
Similar idea applies to LHC

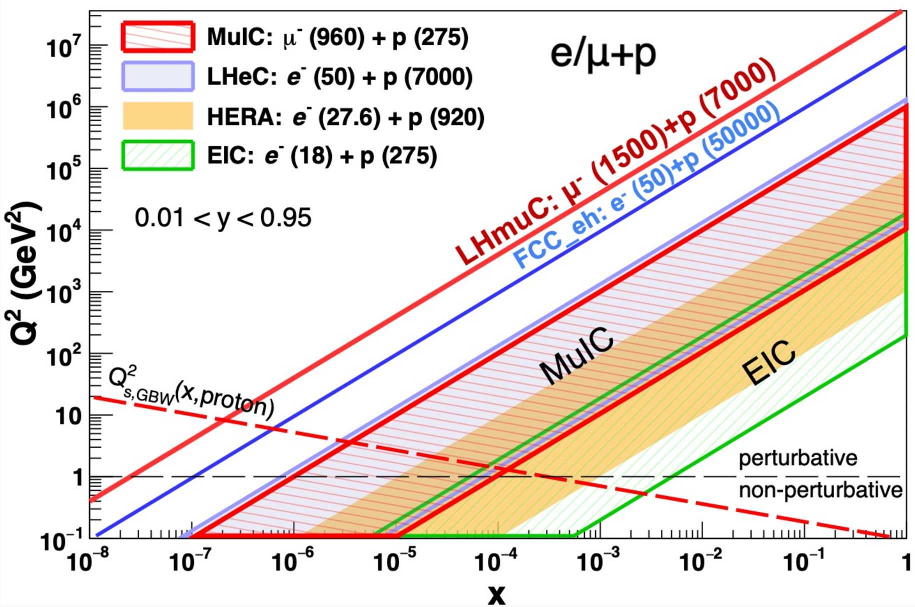


arXiv:2203.06258

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}

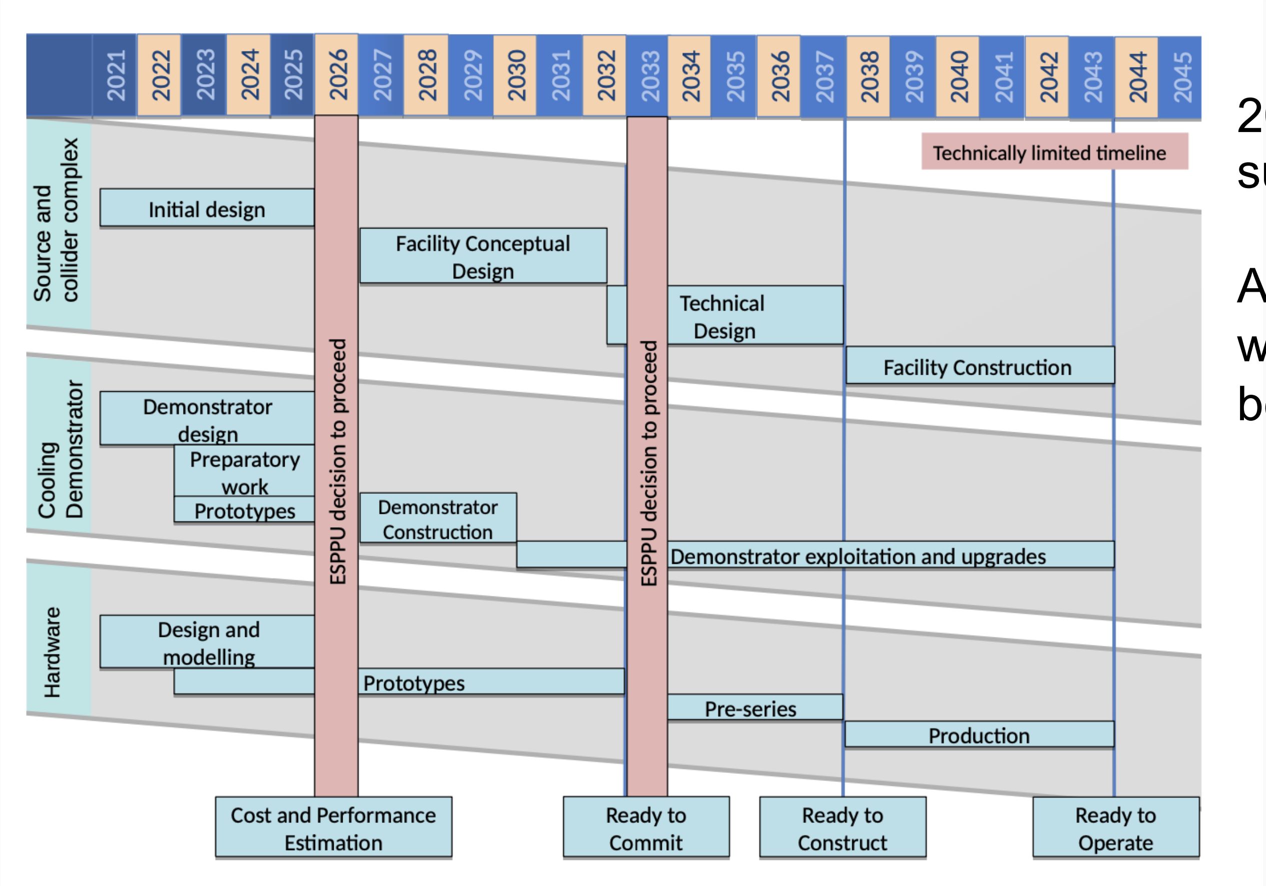
– well beyond EIC

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)

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

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