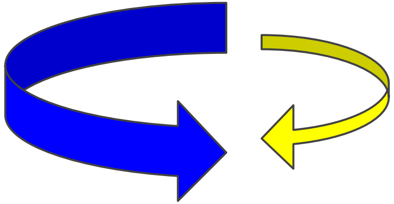


Physics Potential, Accelerator Options, and Experimental Challenges of a TeV-Scale Muon-Ion Collider

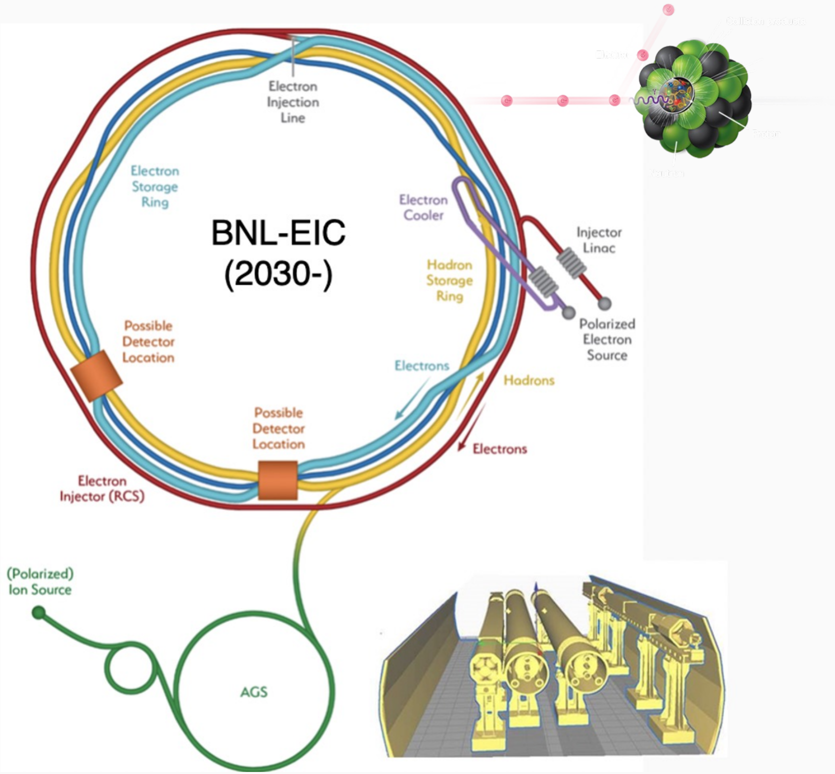
Darin Acosta, Wei Li
Rice University

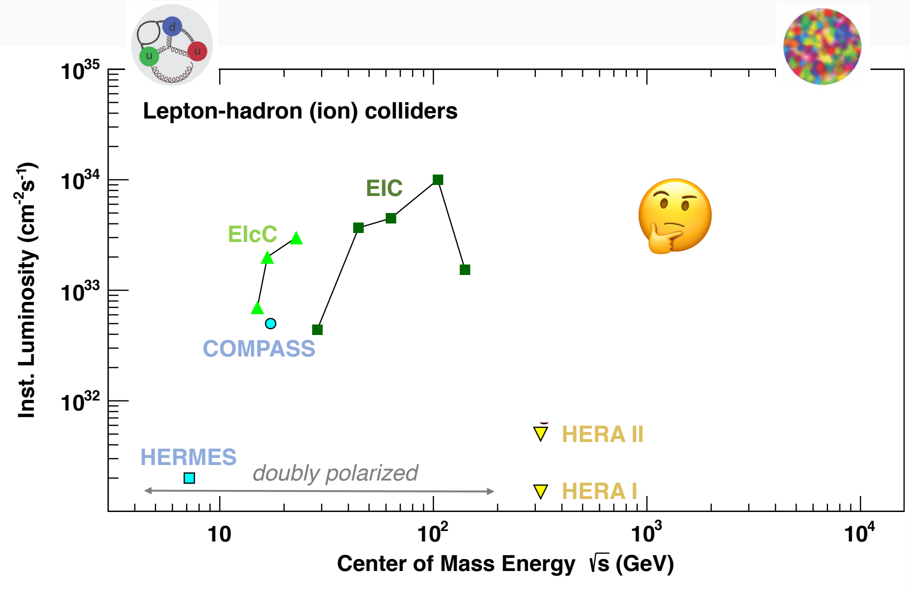
APS GHP workshop
March 14-16, 2025

RICE

The Electron-Ion Collider (EIC) at BNL

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



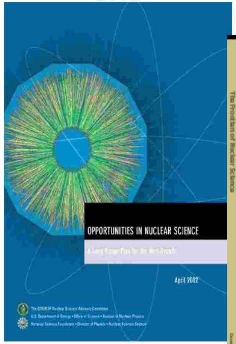


What is after the EIC?

- Can we reach √s of TeV and beyond?

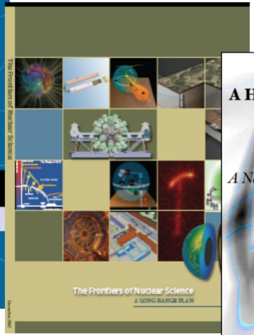
Science for EIC Developed Over Past Two Decades

2002



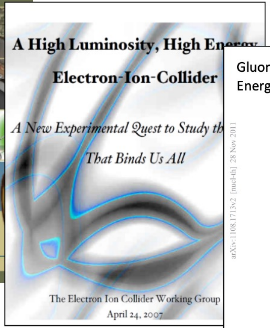
"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

2007



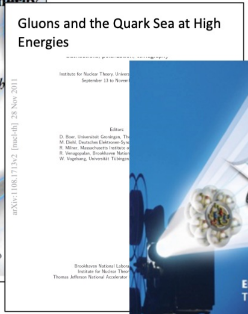
"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

2009



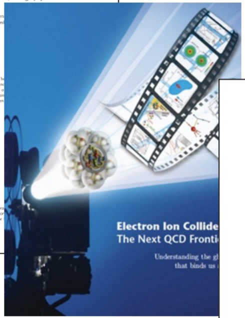
"..a new dedicated facility will be essential for answering some of the most central questions."

2010

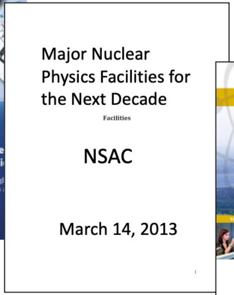


"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

2012

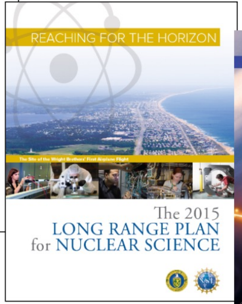


2013



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

2015

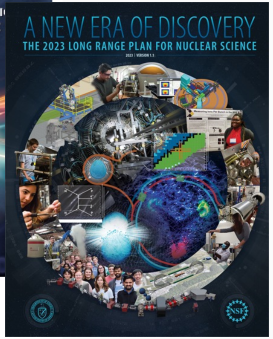


"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

2018

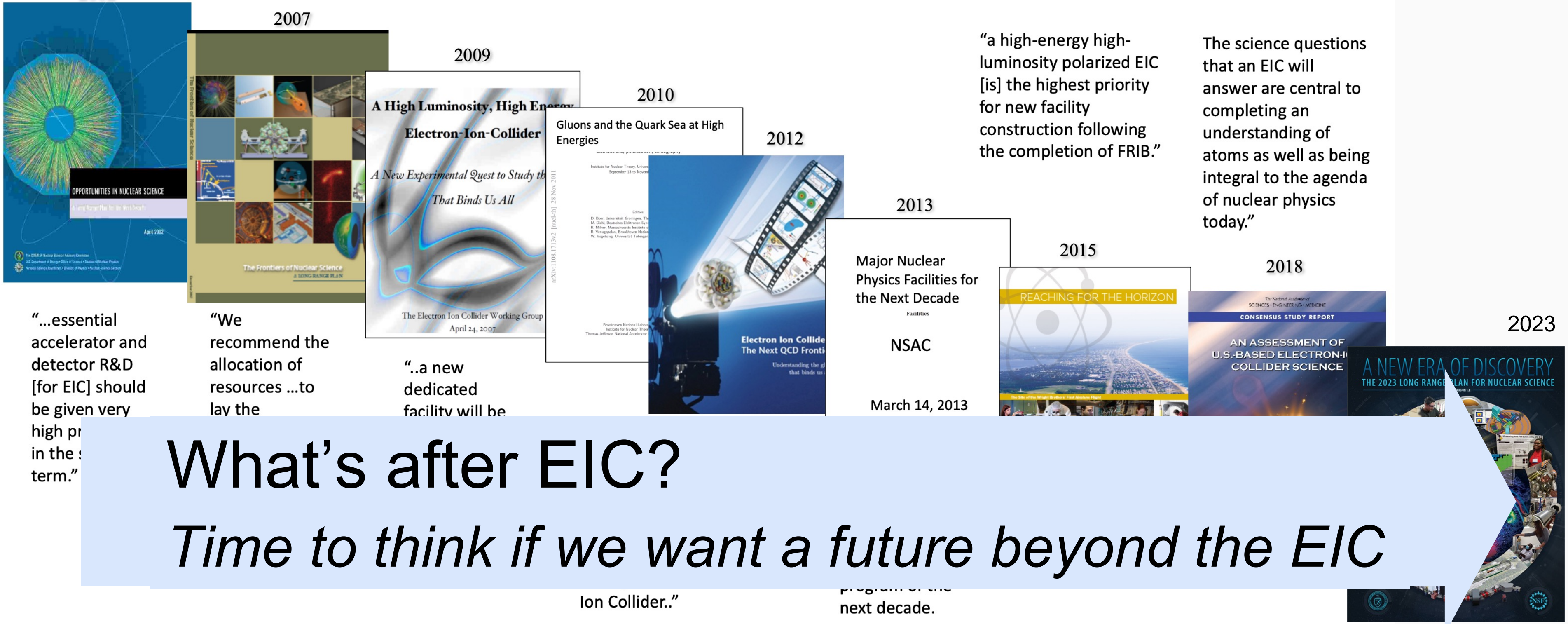
The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

2023



Science for EIC Developed Over Past Two Decades

2002 2007 2009 2010 2012 2013 2015 2018 2023



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

"We recommend the allocation of resources …to lay the

"..a new dedicated facility will be

Ion Collider.."

program of the next decade.

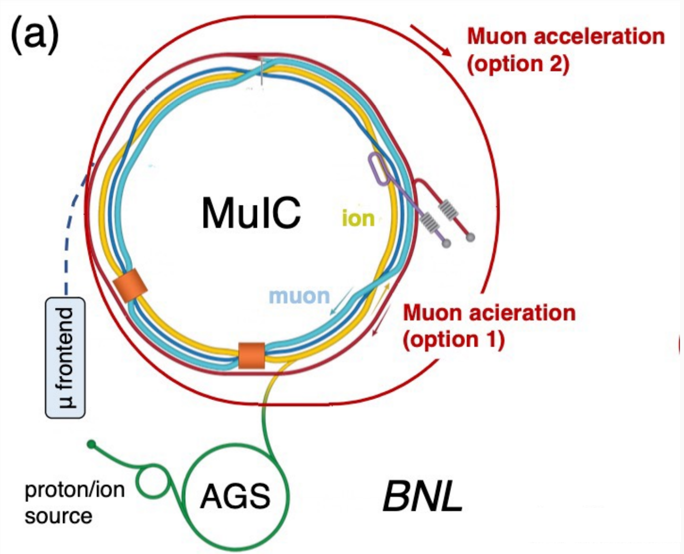
What's after EIC?

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!

μ's do not radiate when bent but they do not live long ...

Bending radius of RHIC tunnel: **r = 290m**

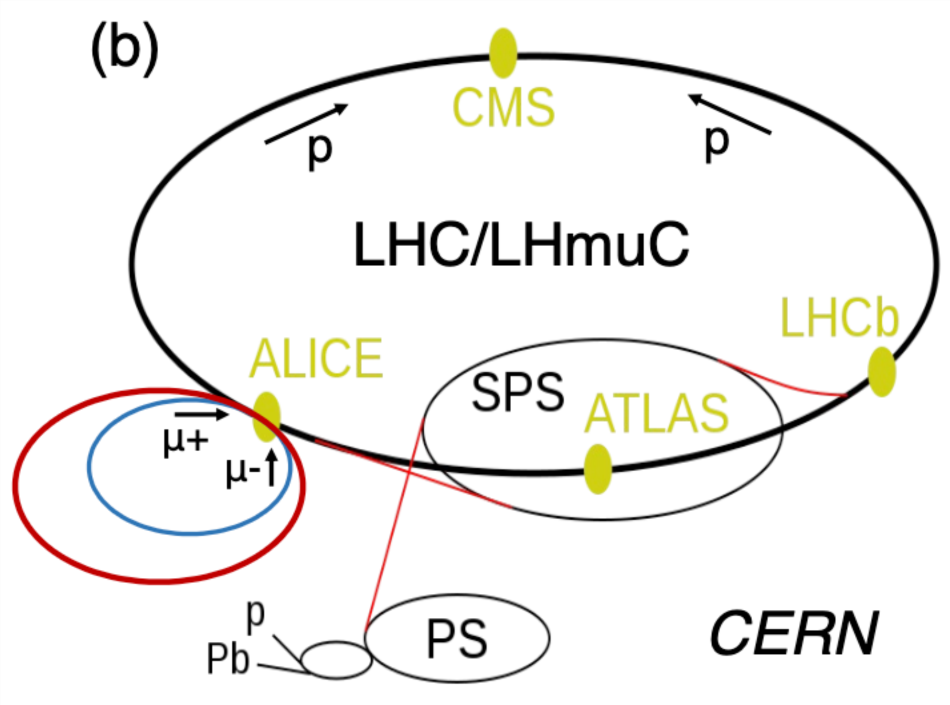
Achievable muon beam energy: **0.3Br**

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

A "LHmuC" option at CERN

Acosta et. al. 2023 JINST 18 P09025

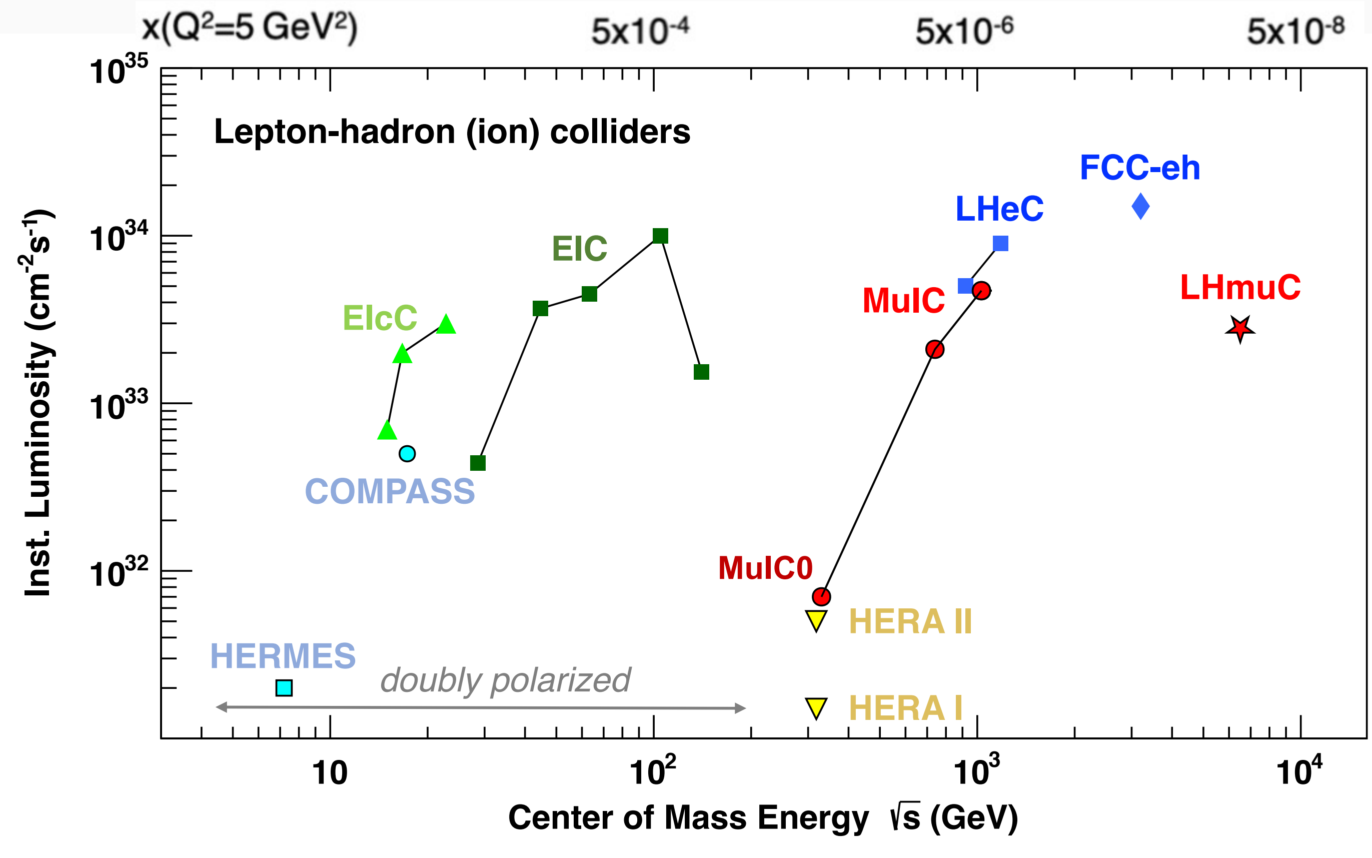


A μp collider option of **$\sqrt{s}$ = 6.5 TeV**,
If an initial 1.5+1.5 TeV $\mu^+\mu^-$ collider is sited at CERN

$\sqrt{s}$ exceeds that of the FCC-eh

Opening new energy frontiers at small footprints

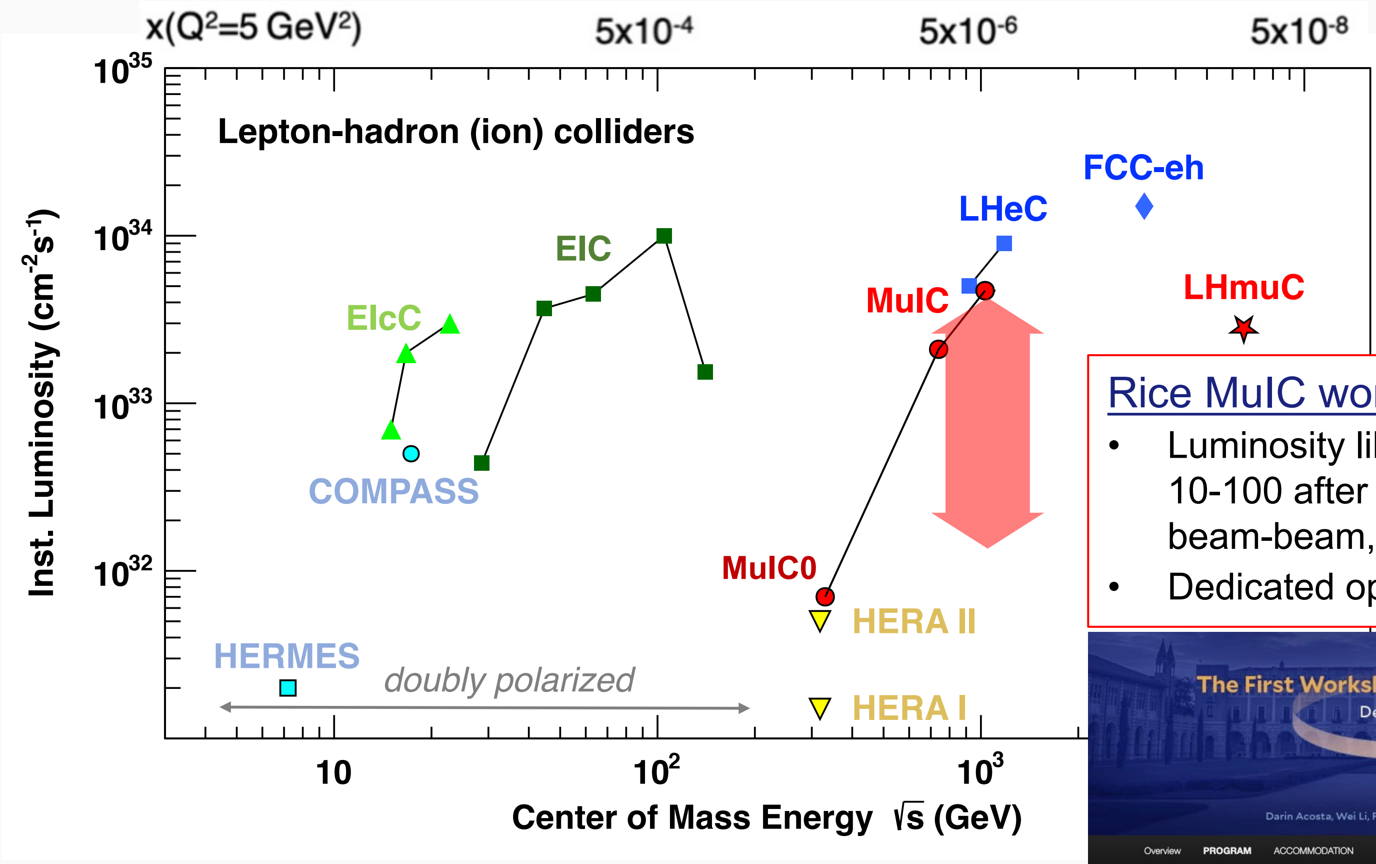
What makes MuIC unique?



Staging options

- *S0: 100 GeV muons*
- *S1: 960 GeV muons*

What makes MuIC unique?



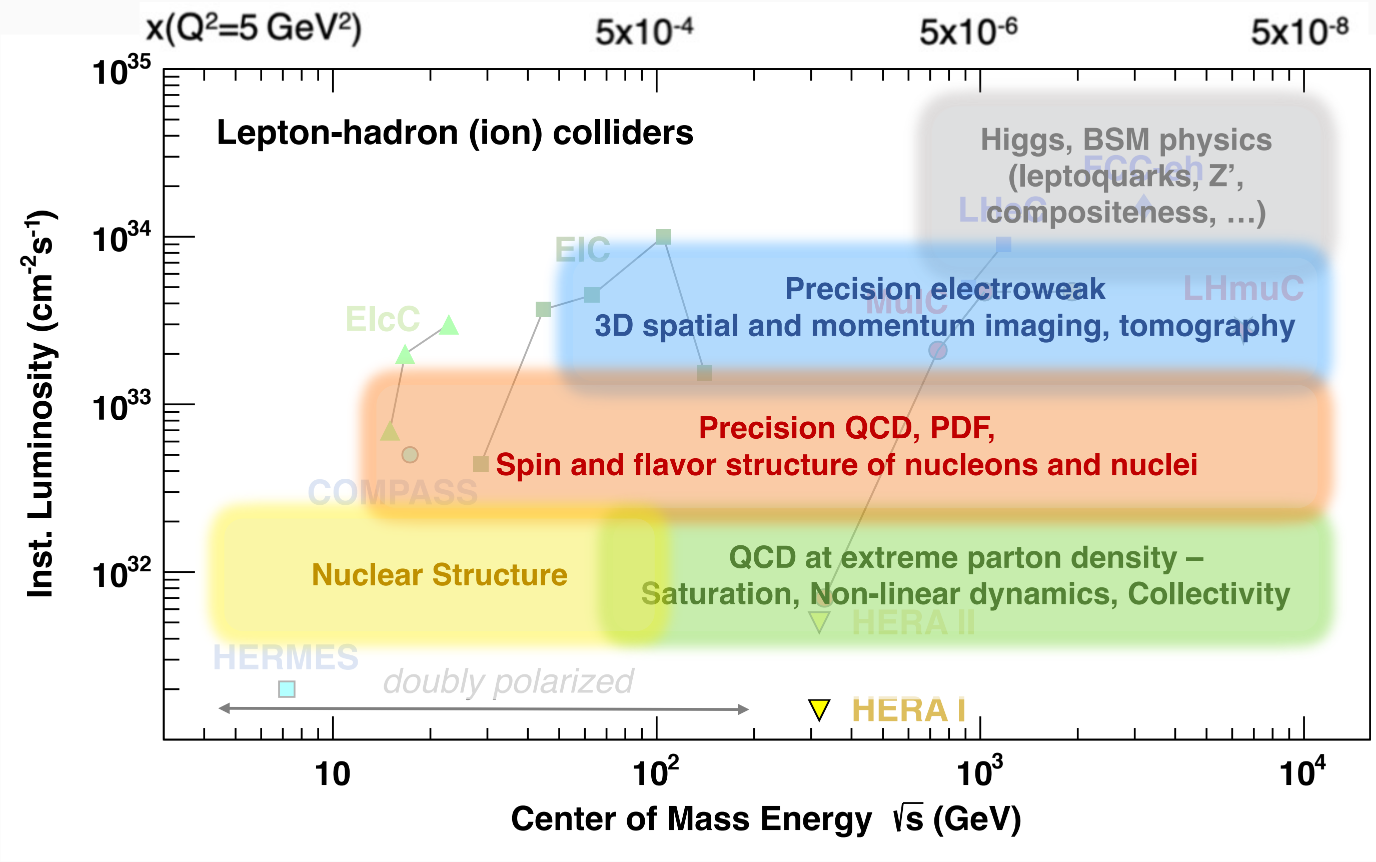
Staging options

- *S0: 100 GeV muons*
- *S1: 960 GeV muons*

Rice MuIC workshop discussion:

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

Why MuIC?



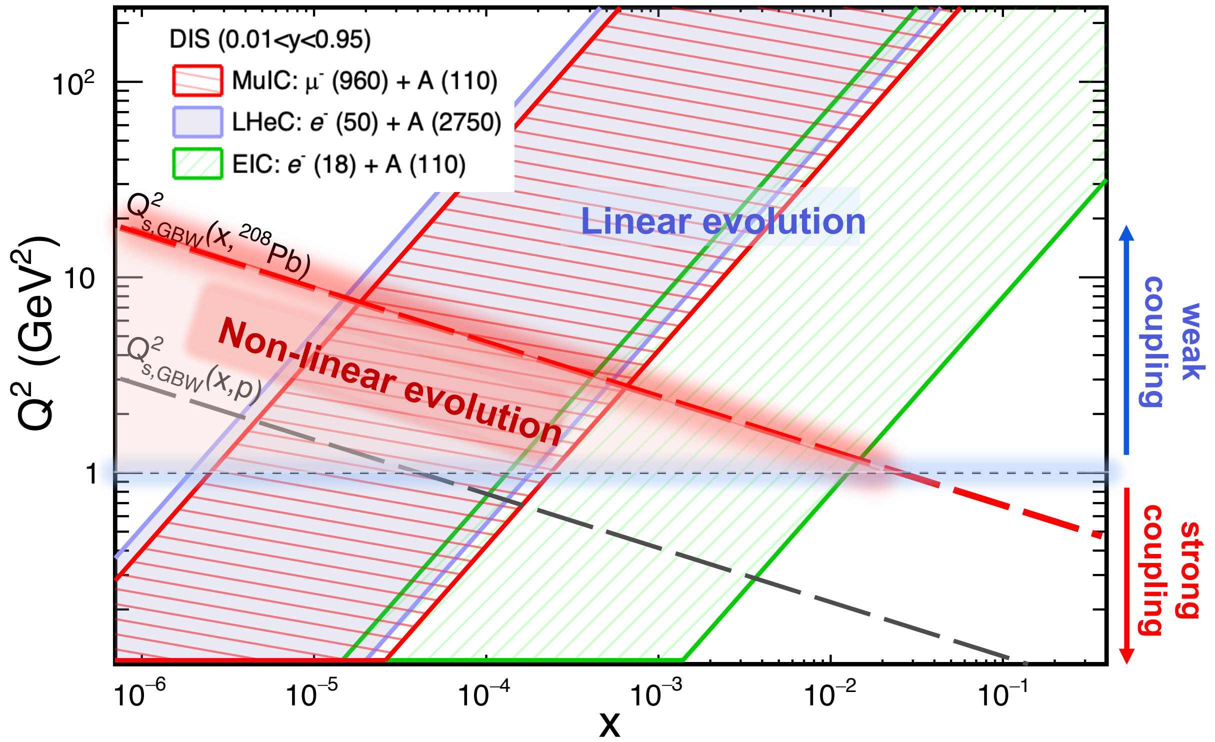
Higgs and BSM searches

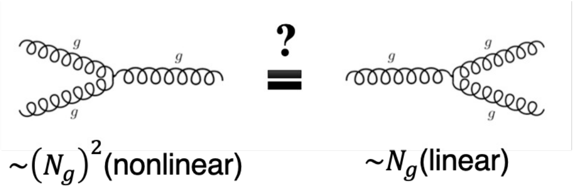
Precision PDF and EWK

Ultimate lab for QCD and nuclei

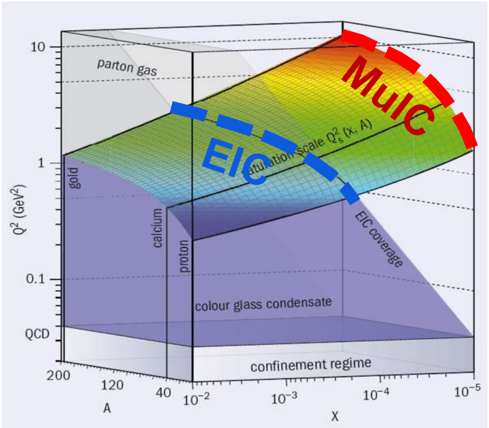
The ultimate lab for QCD and Nuclei

DIS-UPC kinematics coverage



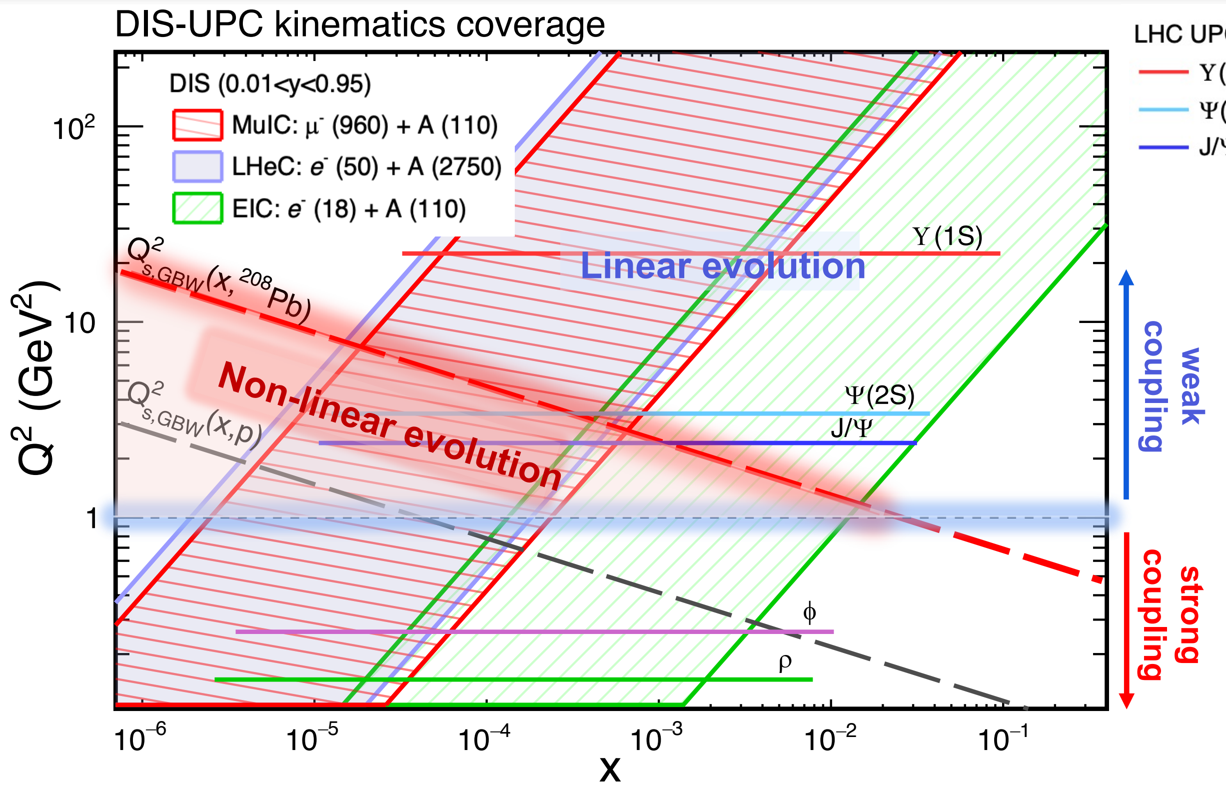


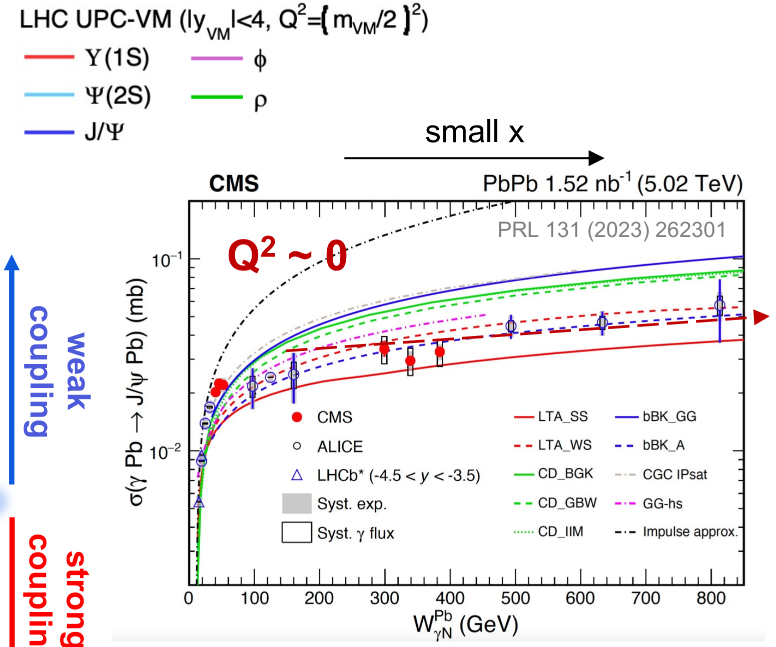
Saturation scale in nuclei



A TeV-scale MuIC will provide unprecedented access to the saturation regime, offering a unique window into non-linear QCD dynamics.

The ultimate lab for QCD and Nuclei

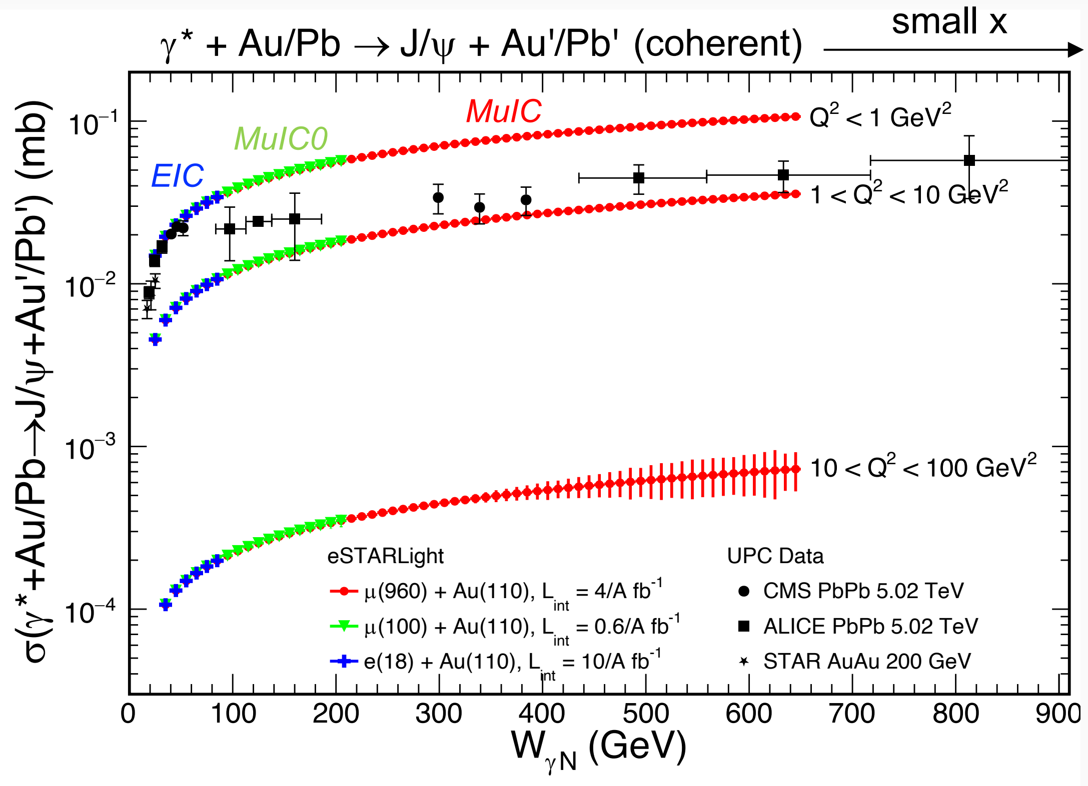




Gluon saturation? But all models fail at the quantitative level.

A TeV-scale MuIC will provide unprecedented access to the saturation regime, offering a unique window into non-linear QCD dynamics.

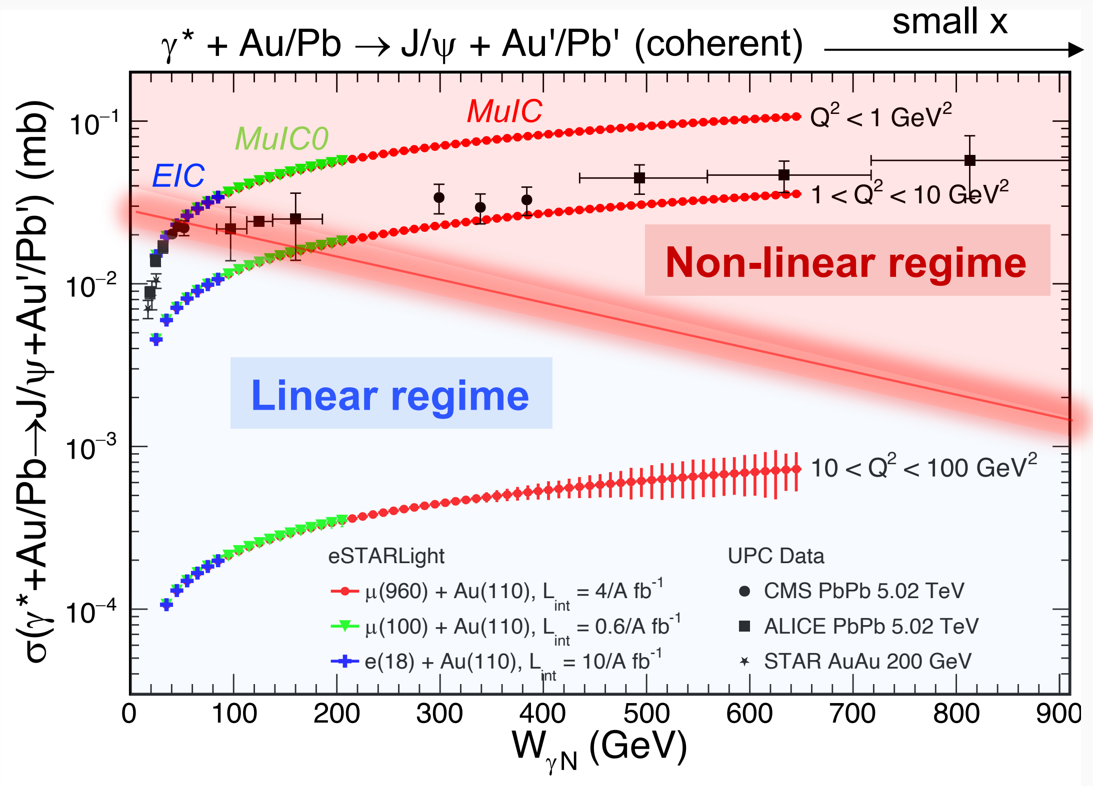
The ultimate lab for QCD and Nuclei



Assume 10% of L_{peak}

A TeV-scale MuIC will provide addition lever arm in Q^2 enabling high-resolution studies to definitively probe saturation/non-linear QCD.

The ultimate lab for QCD and Nuclei



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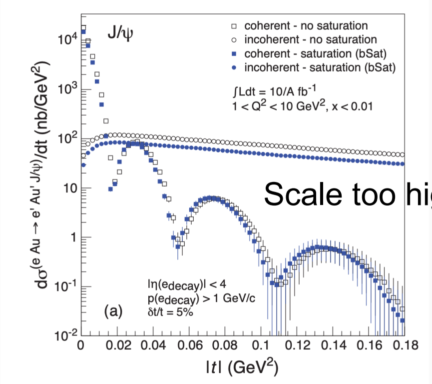
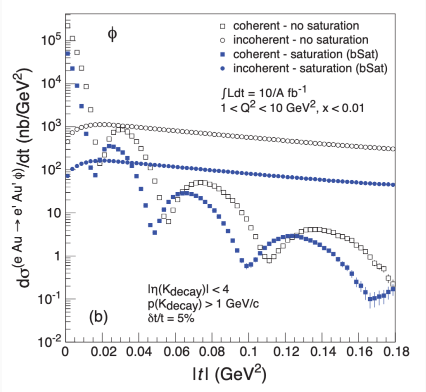
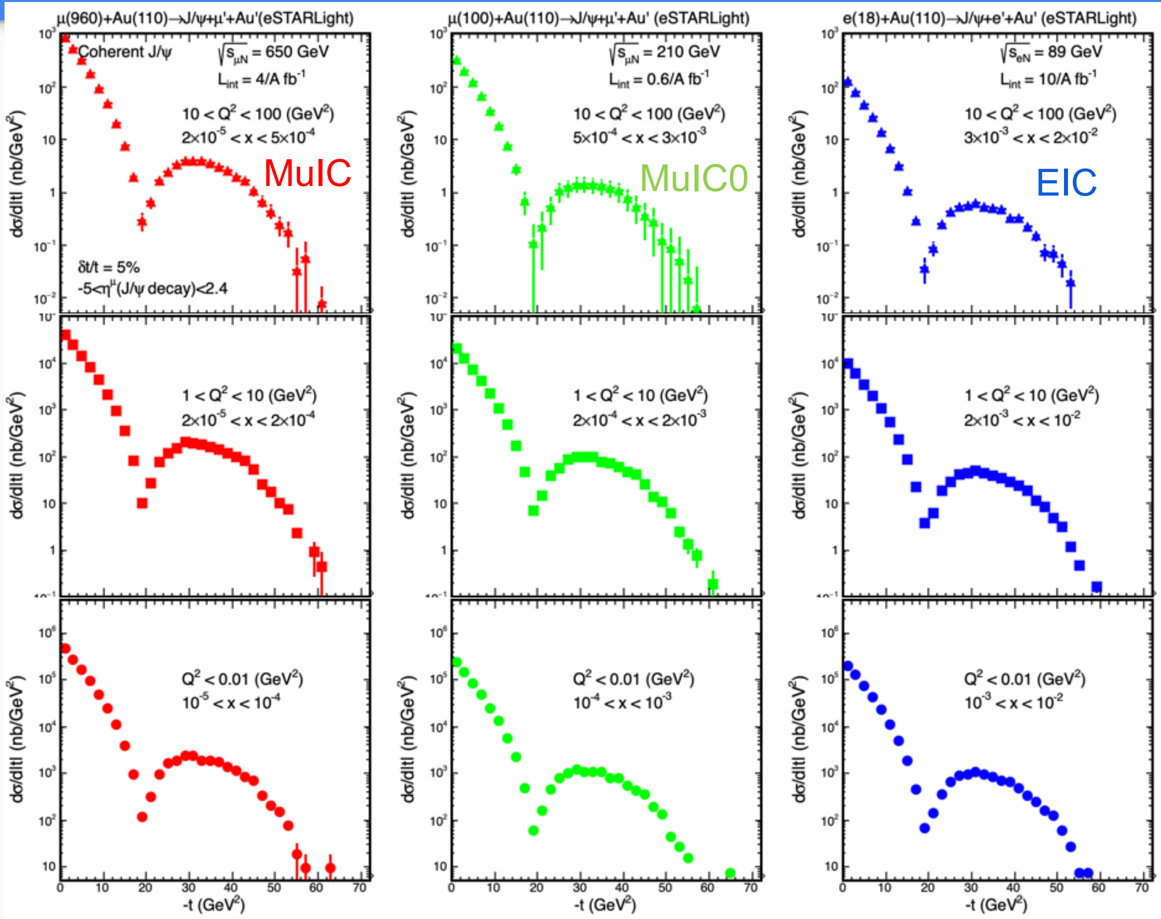
The ultimate lab for QCD and Nuclei

Saturation at EIC



Scale too high?



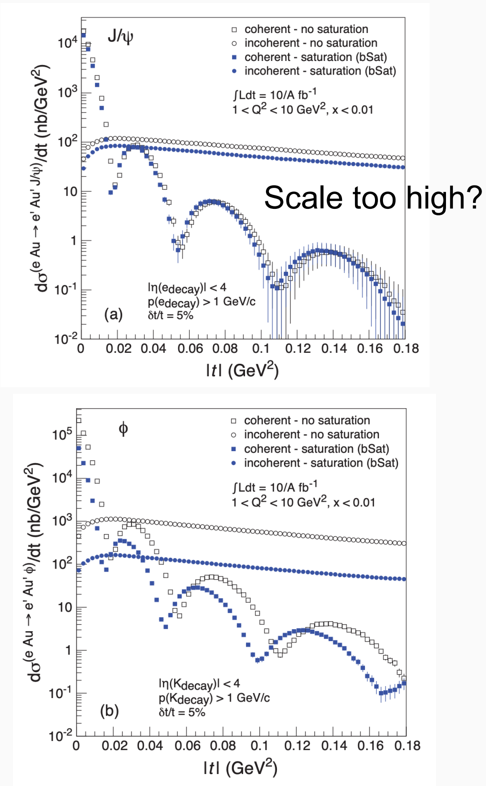


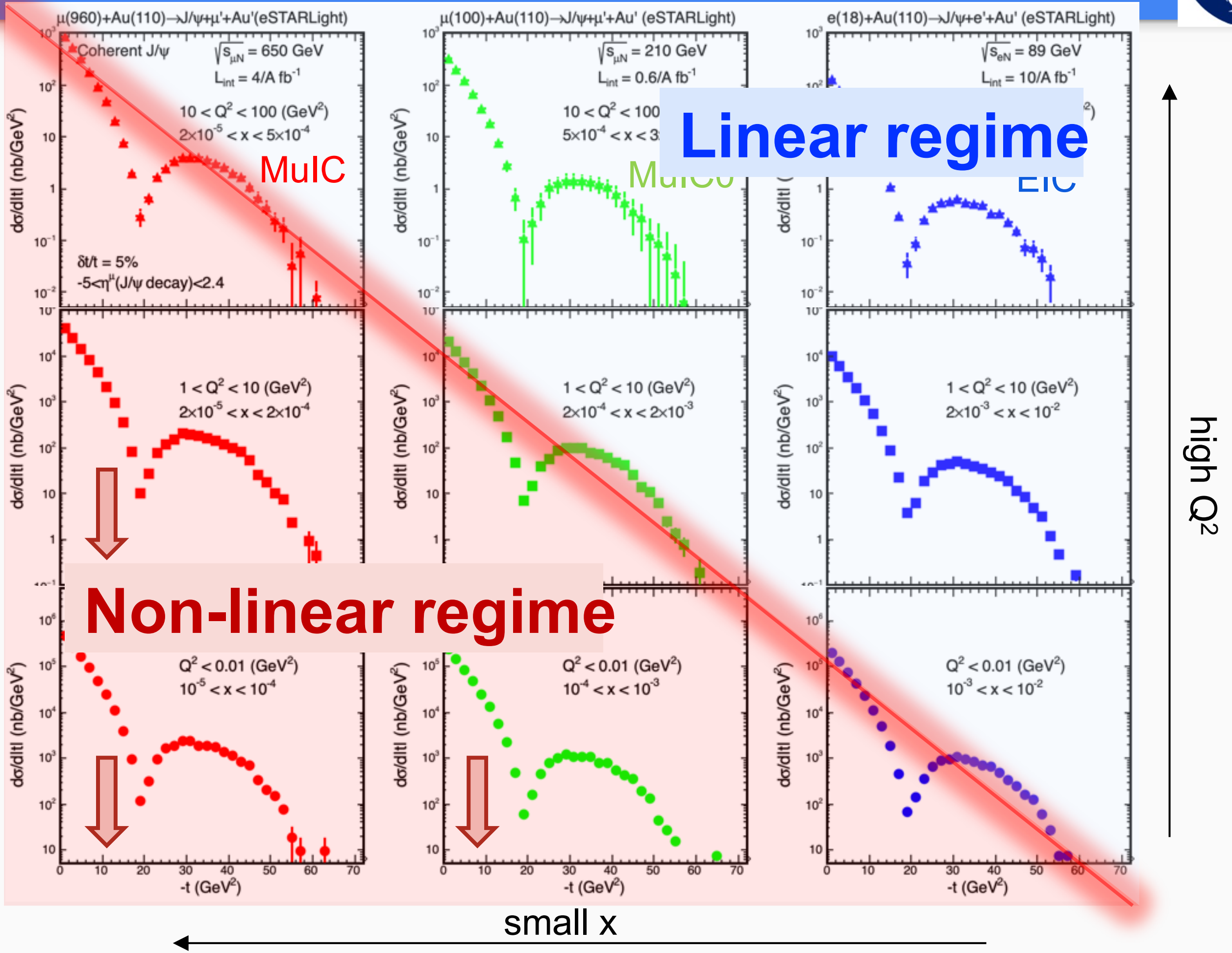
high Q^2

small x

The ultimate lab for QCD and Nuclei

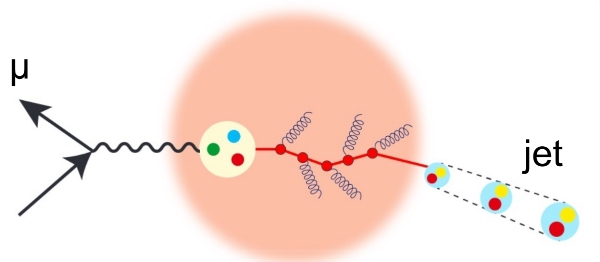
Saturation at EIC

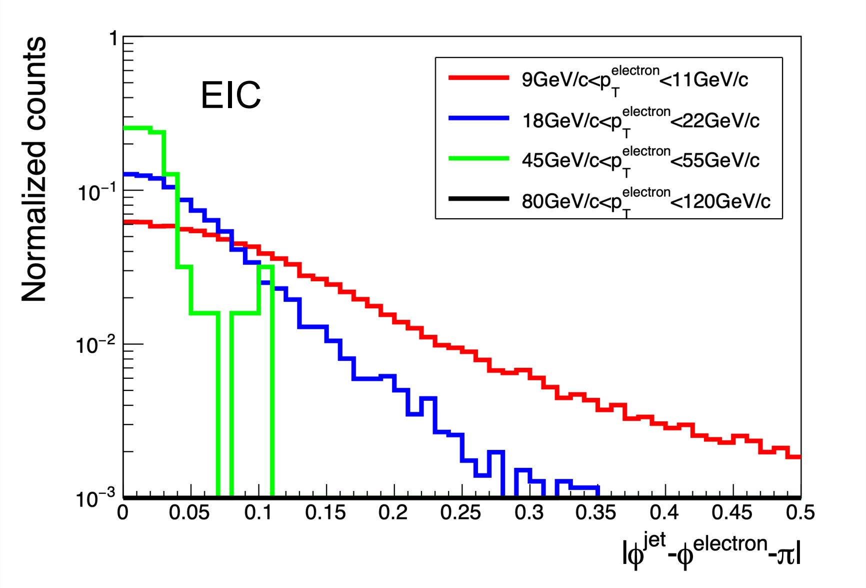


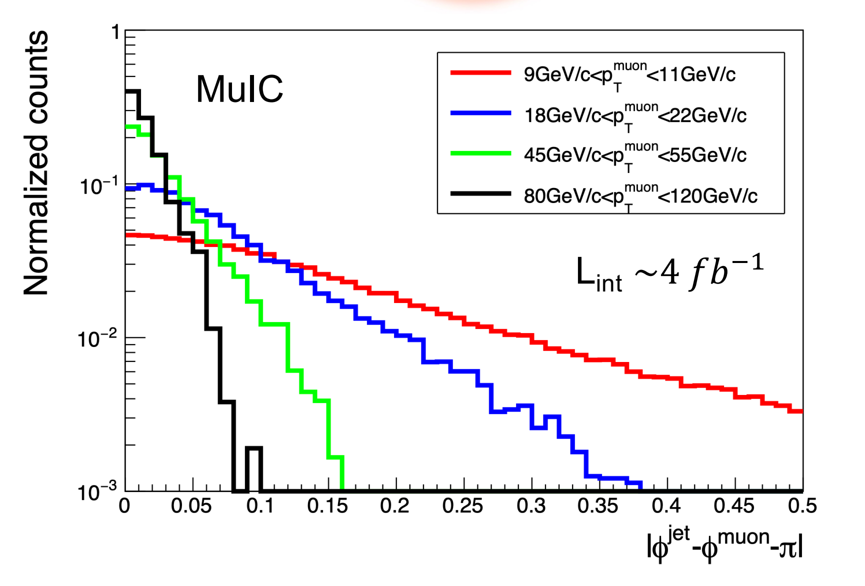


The ultimate lab for QCD and Nuclei

Muon-Jet (de)correlations to probe dense gluonic medium in heavy nuclei



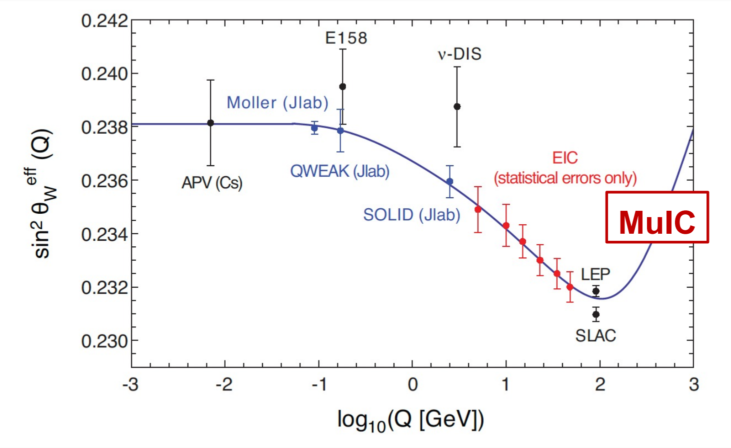




Much wider kinematic lever-arms and precision at TeV DIS machine

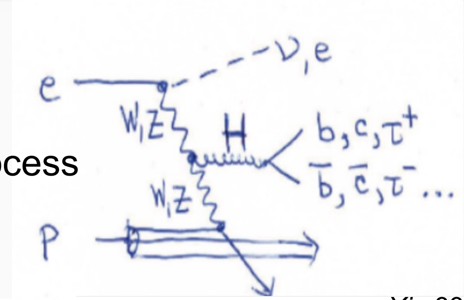
Physics Potentials: EWK, Higgs, BSM

Electroweak:

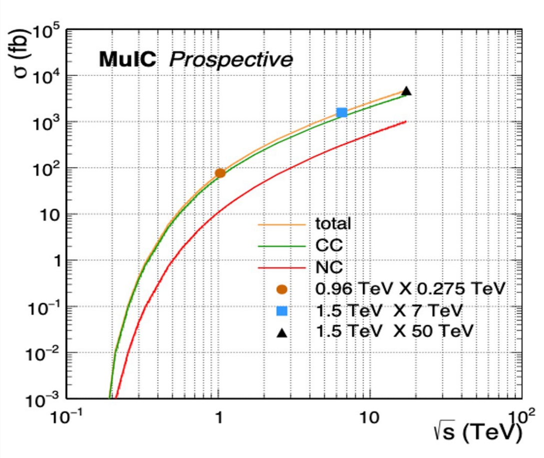


Higgs physics:

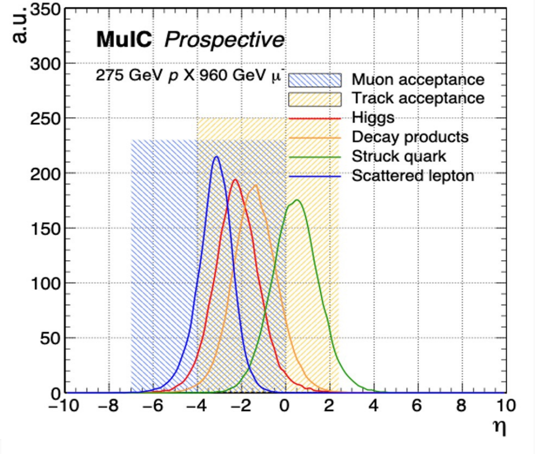
VBF process



arXiv:2203.06258

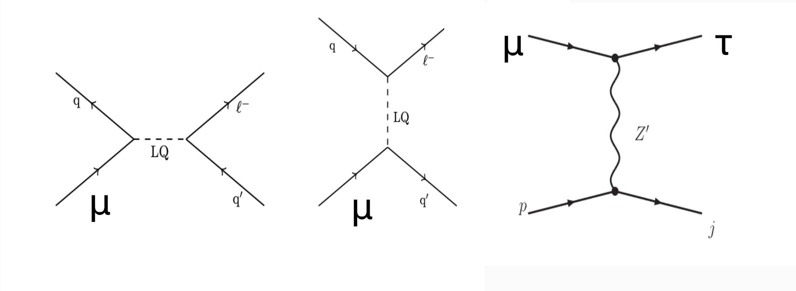


Cross section comparable to LHeC and $\mu^+\mu^-$



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

BSM: Charged lepton flavor violation



How to build a Muon Collider

- International Muon Collider Collaboration (IMCC) led by CERNs since 2021: a design of **10+ TeV $\mu^+\mu^-$** with **3 TeV** as an initial step
- Muon Collider forum in US from Snowmass 21 and P5 (white papers)

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.

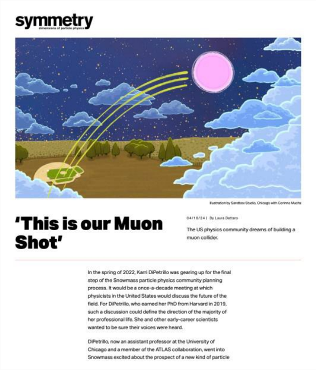
…

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.**

39



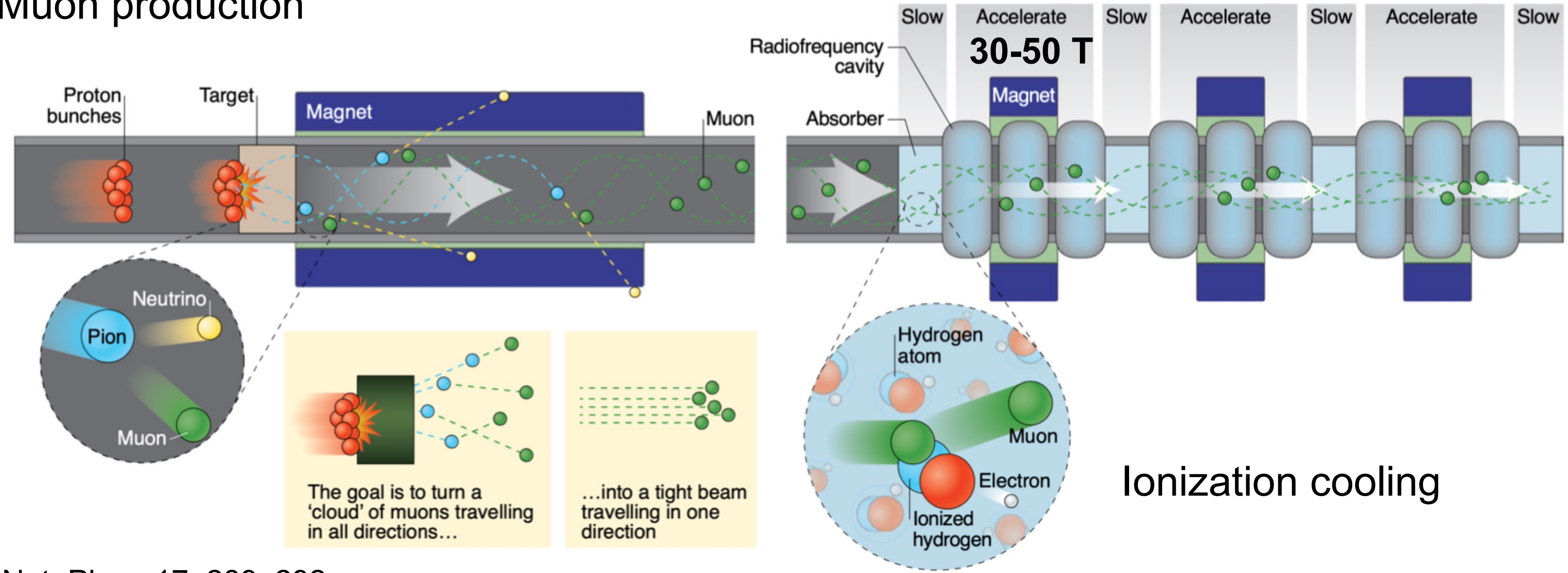
MuIC could be a staging option as a demonstrator

- US Muon Collider Collaboration: https://www.muoncollider.us/

How to build a Muon Collider – proton driver

Muon "cooling": most crucial step to reach high *L*

Muon production



Ionization cooling

Nat. Phys. 17, 289–292

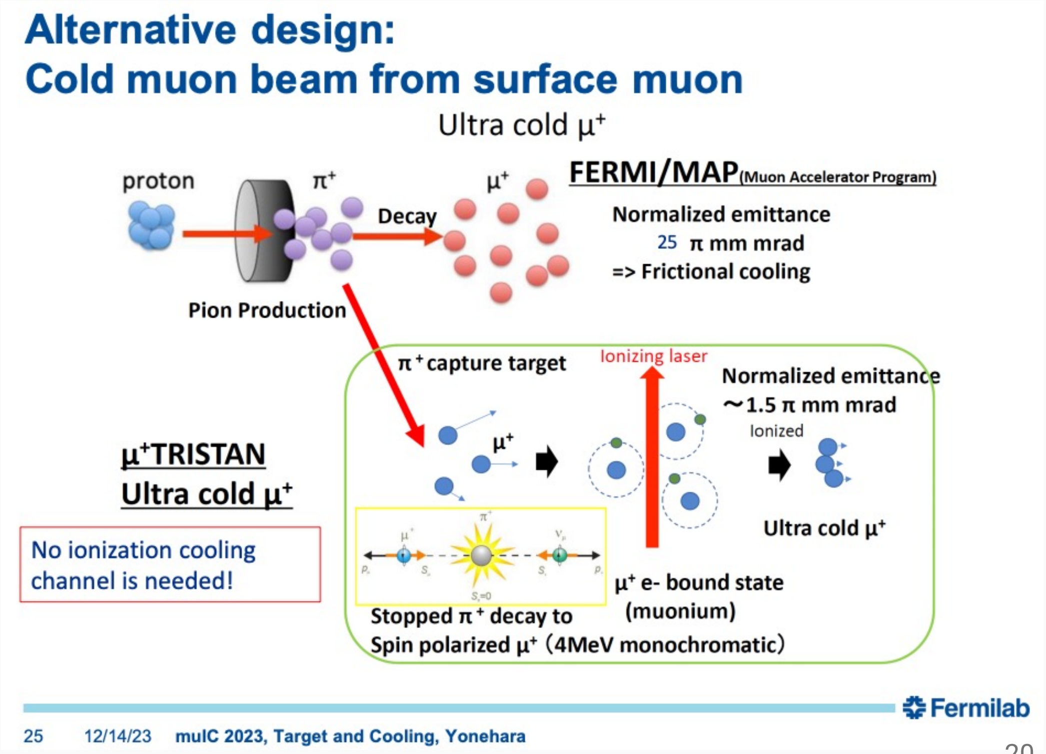
Alternative Cooling Idea for μ+ Only

From Katsuya Yonehara (link)

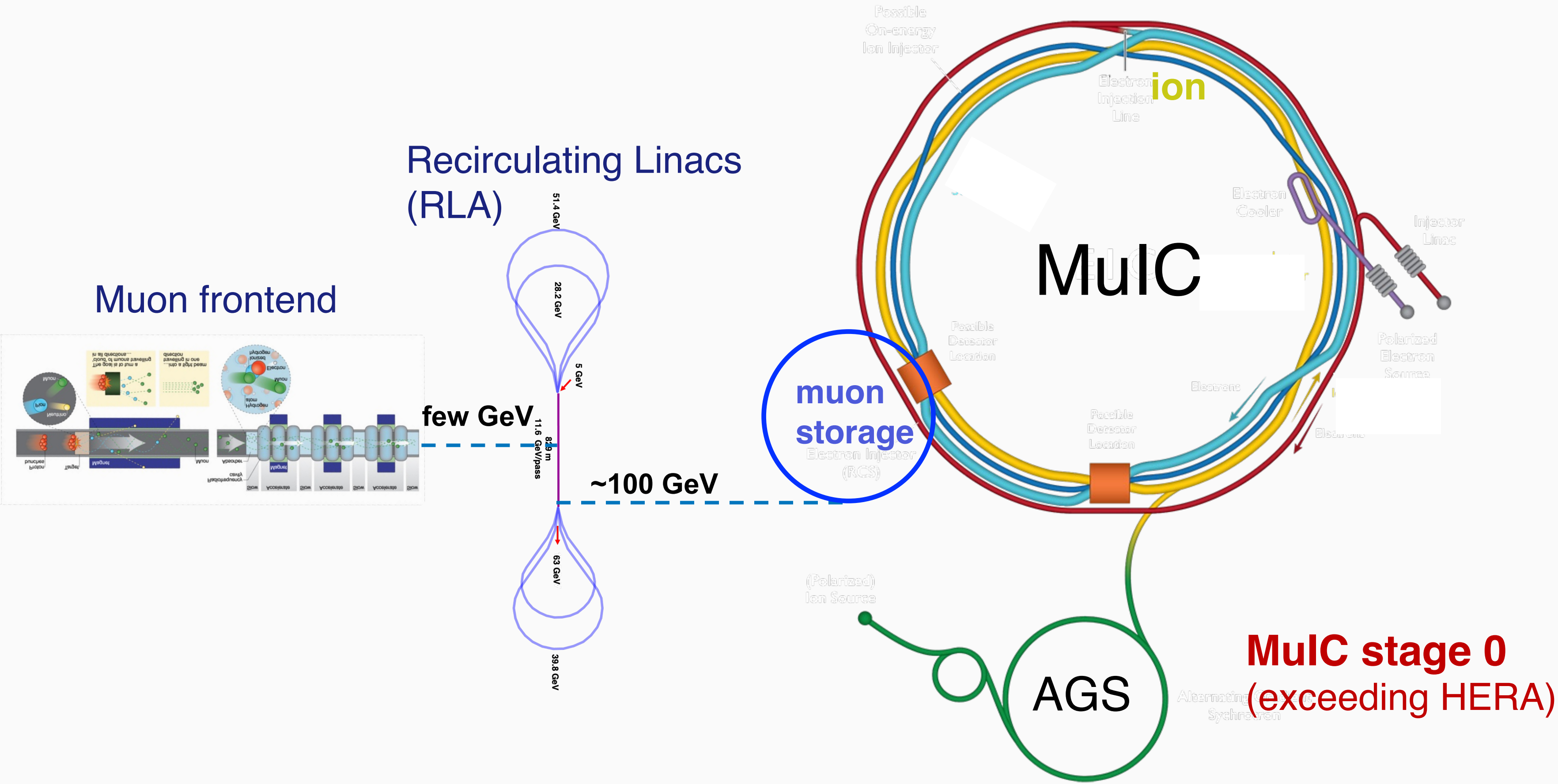
See: https://cerncourier.com/a/muons-cooled-and-accelerated-in-japan/

Capture μ+ with electrons in aerogel (ultracold), and ionize with laser

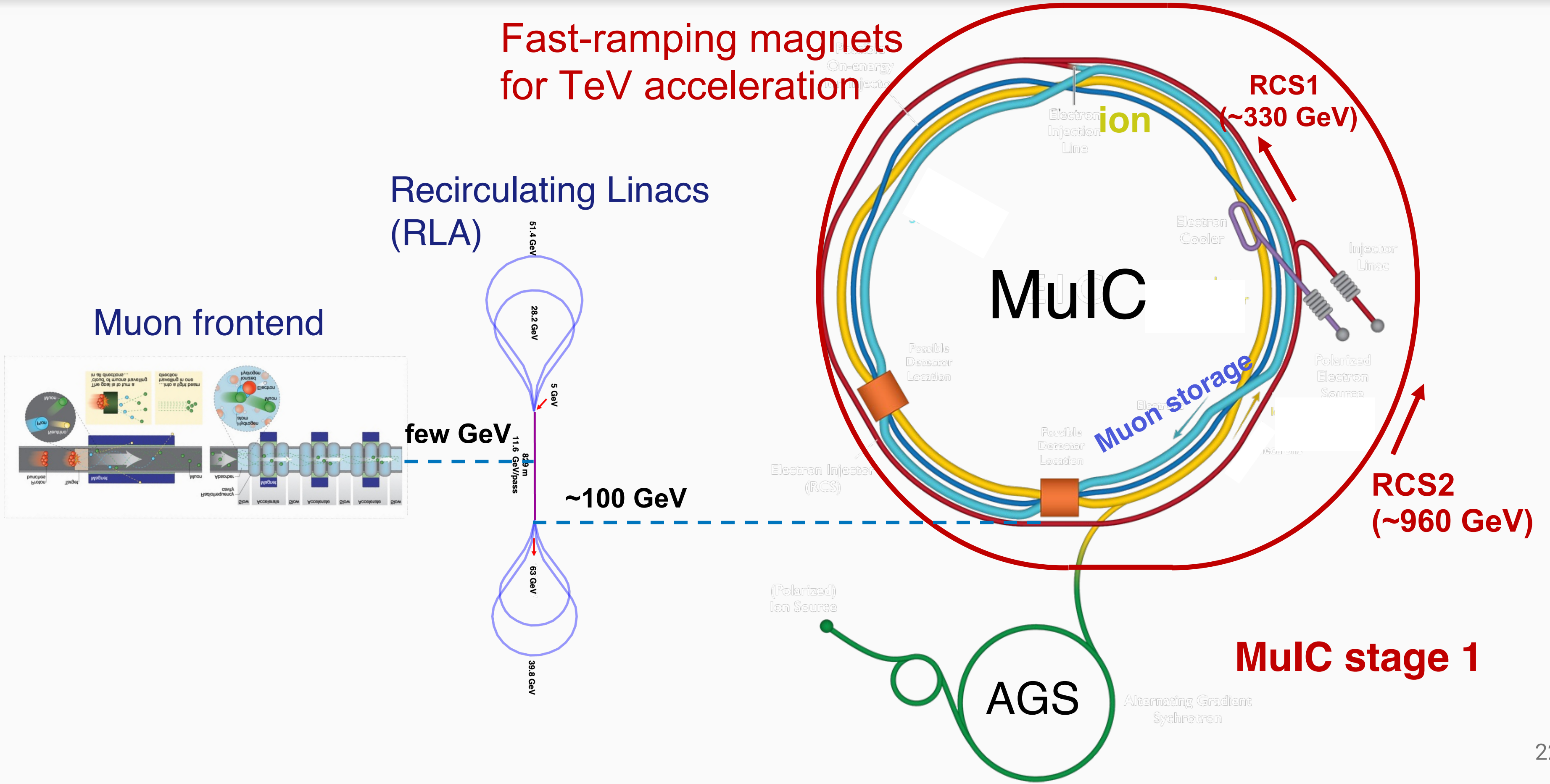
- Very small emittance, 1.5μm – **No ionization cooling needed!**
- Create ~2×10^{10} μ+ – 100x less than desired for MC but a starting point
- Achieve up to **50% polarization**!



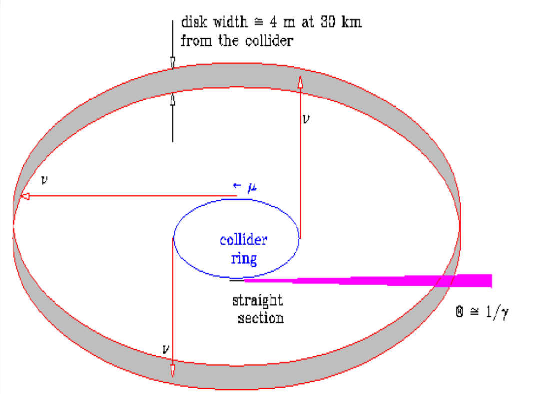
How to build a Muon-ion collider – Stage 0



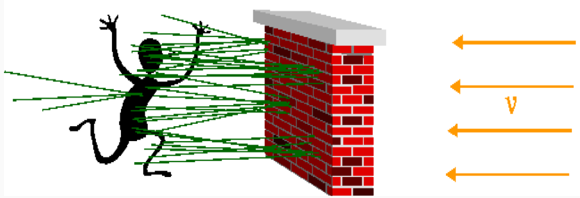
How to build a Muon-ion collider – Stage 1



Neutrino-induced radiation background



Damage by secondary particles induced by neutrinos



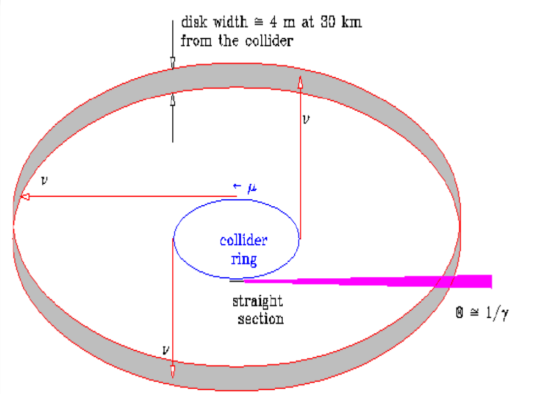
Nikolai Mokhov (FNAL)

→ Deep underground

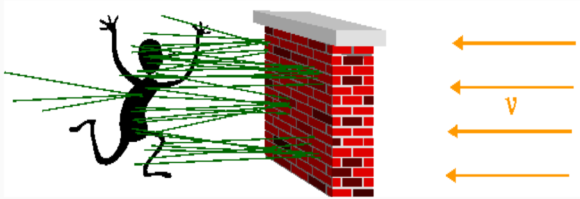
OR

→ Surface of an island

Neutrino-induced radiation background



Damage by secondary particles induced by neutrinos



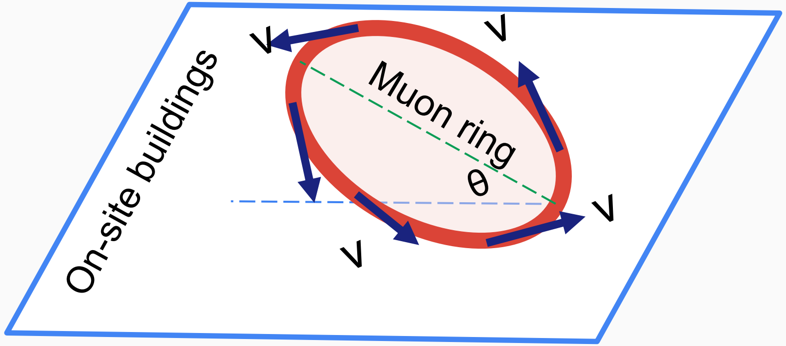
Nikolai Mokhov (FNAL)

→ Deep underground

OR

→ Surface of an island

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

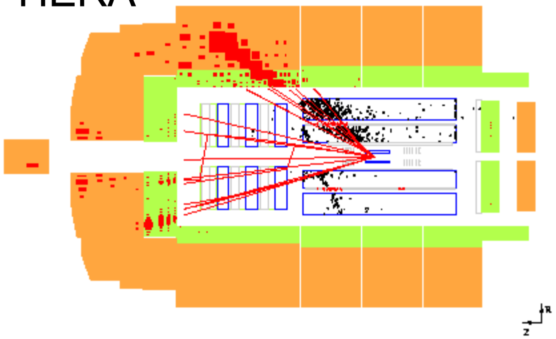


Tilt the disk plane at a small angle?

High-intensity neutrino beams produced are also of significant interest in their own right.

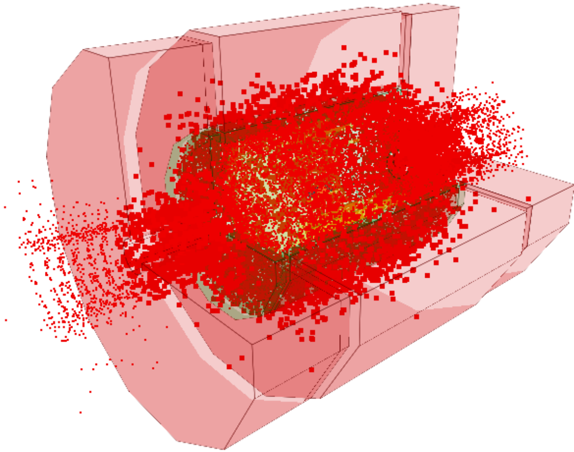
Experimental Challenges & Detector Considerations

HERA

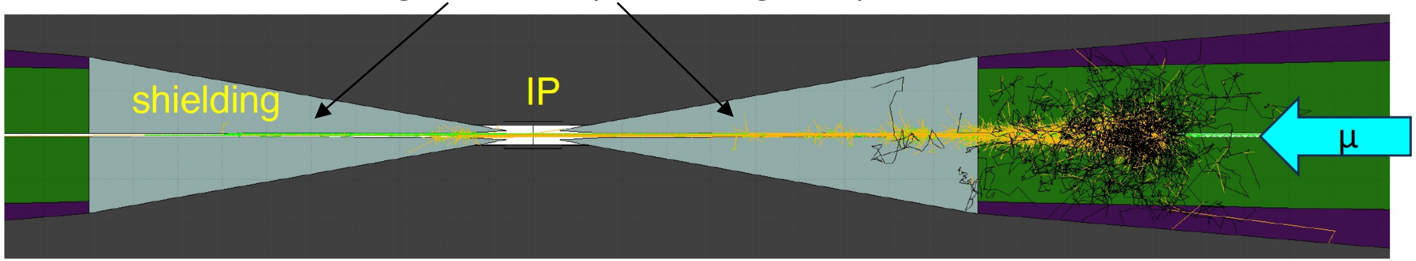


vs.

$\mu^+\mu^-$ collider



Shielding nozzles (lead tungsten)



Single muon decay tracks

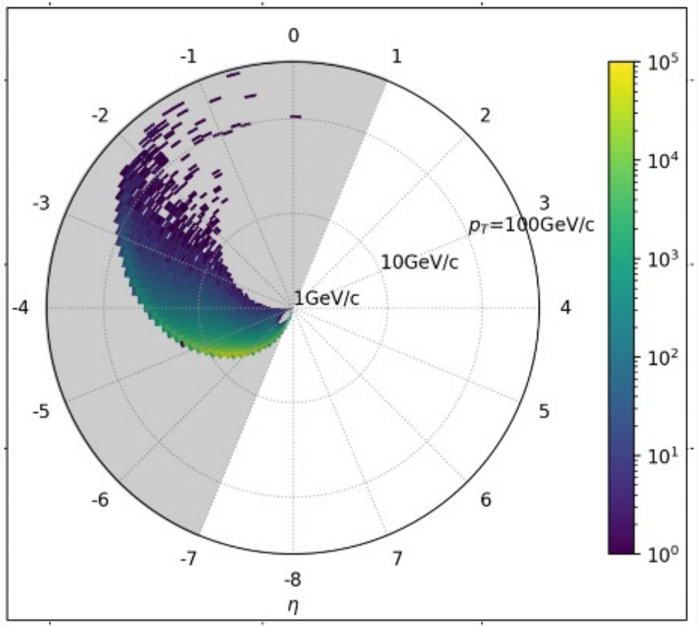
$N_{\mu}^{\pm} \sim 2x10^{12}$/bunch

F. Collamati et al. 2021 JINST 16 P11009

Final-state kinematics at MuIC

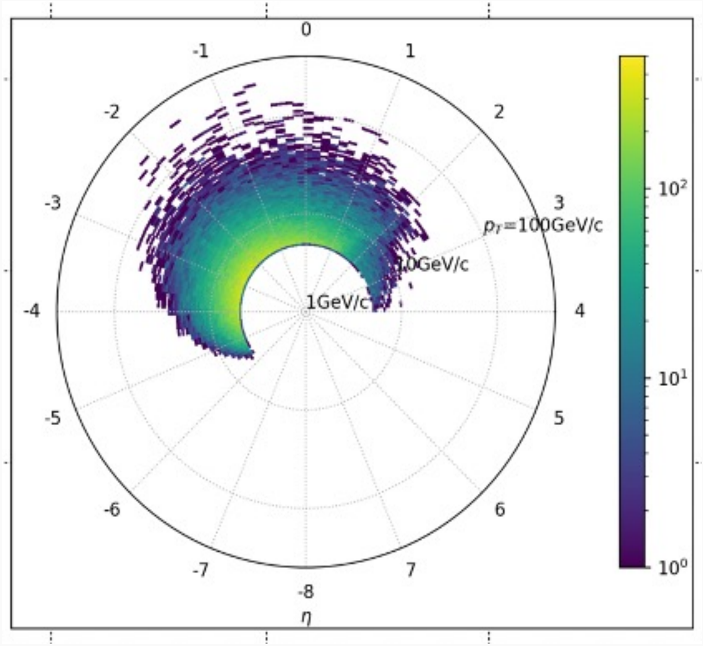
p/A → ← μ

kinematics for scattered **muons**



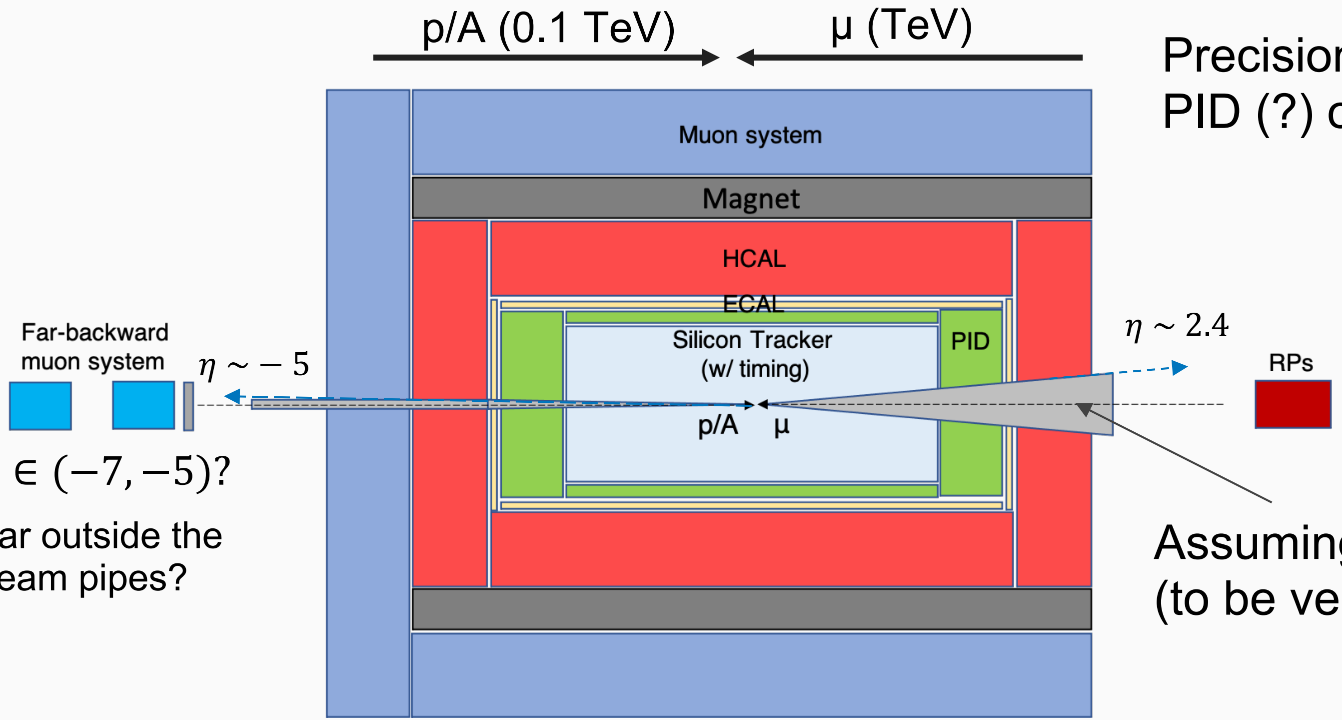
Scattered muons: -7<η<-1

kinematics for struck **quarks**



Jets/hadrons: -4<η<2.4

Detector challenges and R&D needs



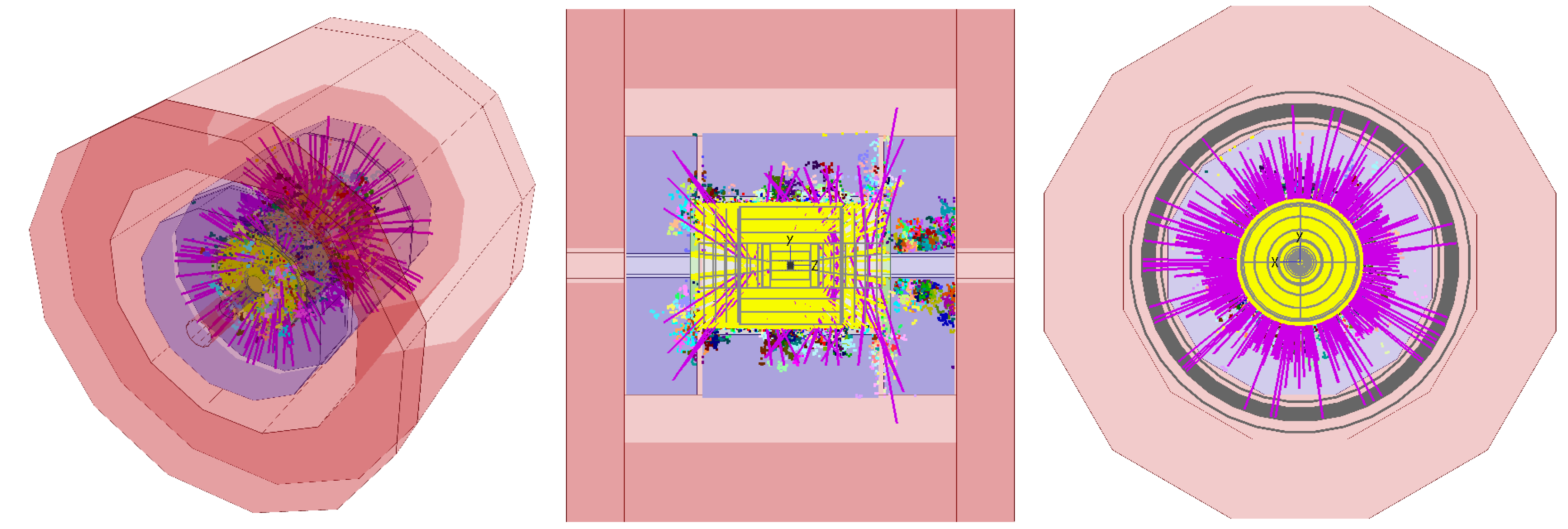
$\eta \in (-7, -5)$?

Far outside the beam pipes?

Precision timing (<50 ps) and PID (?) over $-5 < \eta < 2.4$

Assuming one-sided nozzle (to be verified)

DIS events + BIB simulation (one muon beam)

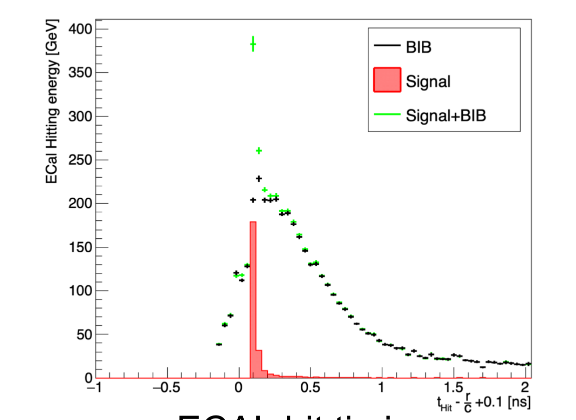


IMCC simulation software

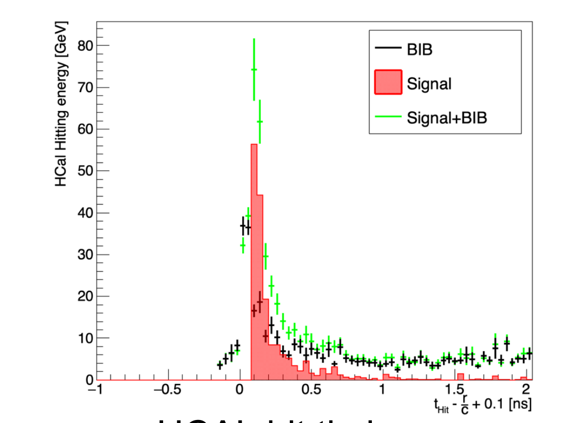
BIBs from one muon beam with IMCC ref. detector (nozzles on both sides)

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

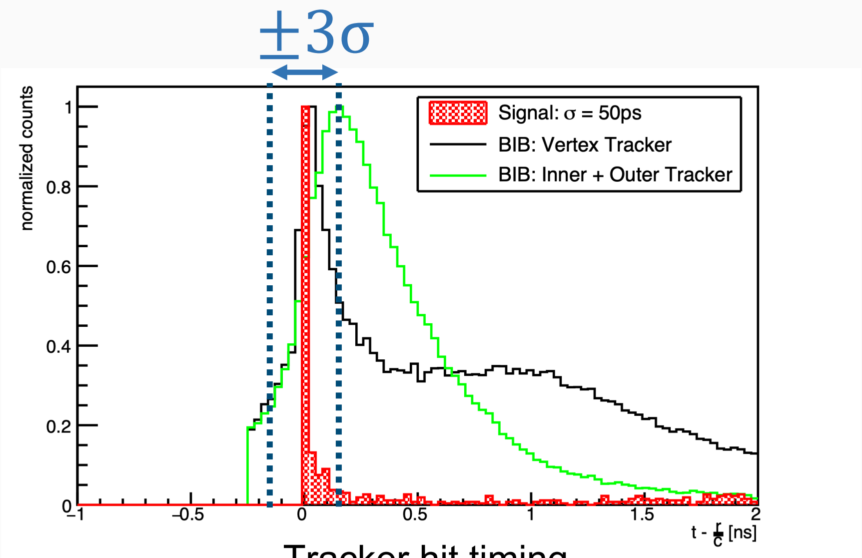
DIS events + BIB simulation (one muon beam)



ECAL hit timing



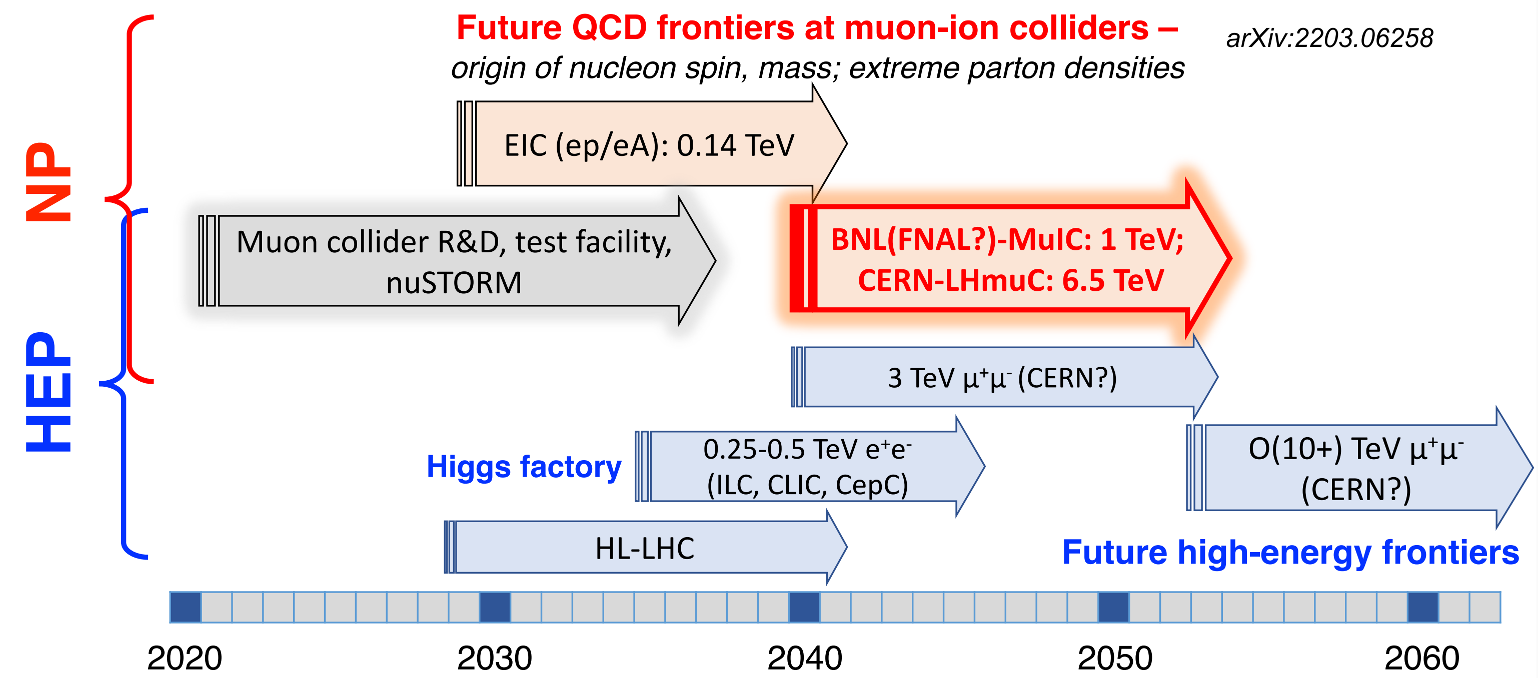
HCAL hit timing



Tracker hit timing

Timing detector (e.g., LGADs) for ECAL and Tracker is crucial for suppressing BIBs

A Roadmap (in our view)



A possible roadmap to future muon colliders in NP and HEP

Summary

A TeV Muon-Ion (proton) Collider:

- **Unprecedented access to small-x & non-linear QCD at TeV scales**
- **Affordable** (e.g., an “upgrade” to the EIC) by re-using the existing facility
- A staging option and **demonstrator** toward the ultimate 10+ TeV $\mu^+\mu^-$
- **Synergy** across nuclear, particle, and intensity frontiers

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To the young generation: Think boldly, and the future is in your hands!

Extras

Outline

- Introduction and motivation of muon-ion collider
- Physics opportunities
- How to realize a muon-based/muon-ion collider
- Detector considerations and experimental challenges

R&D challenges of muon colliders

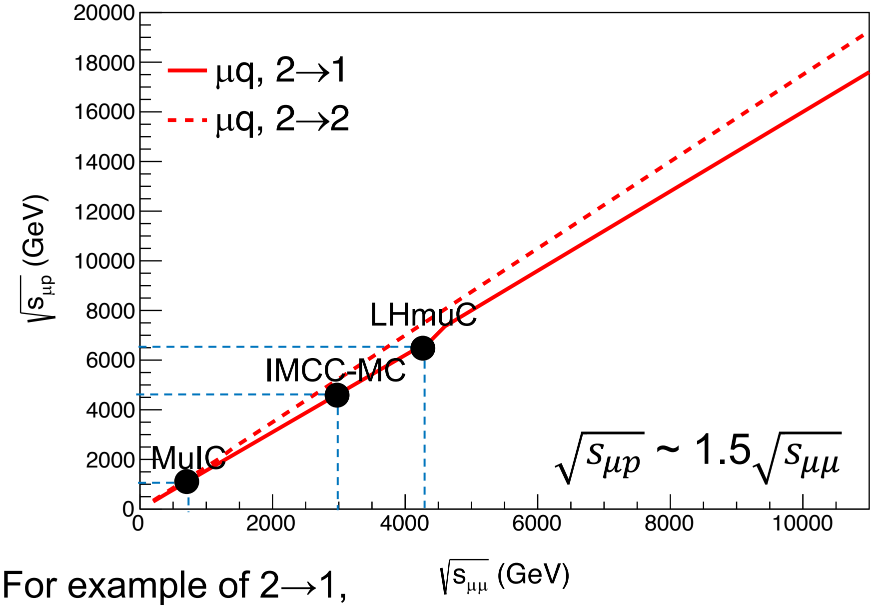
Required key accelerator technologies

- 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

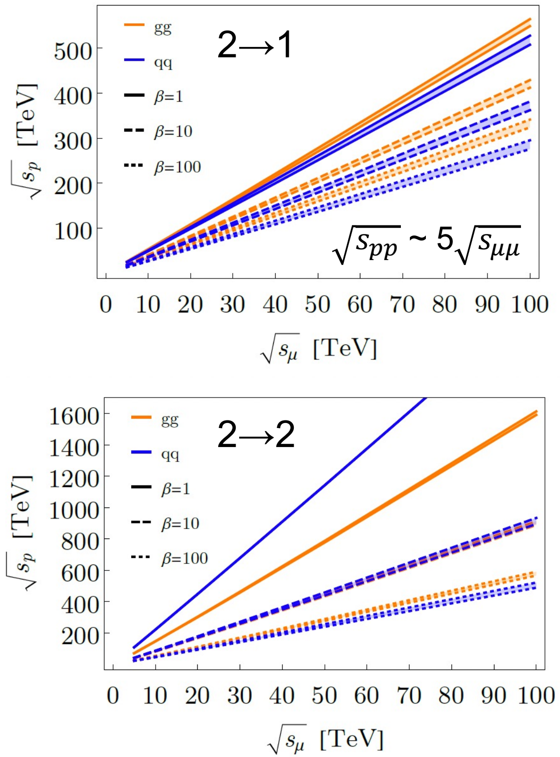
Diktys Stratakis
Snowmass Summer Meeting
19 July 2022

Science potential at the MuIC/LHmuC

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



The muon smasher's guide



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)

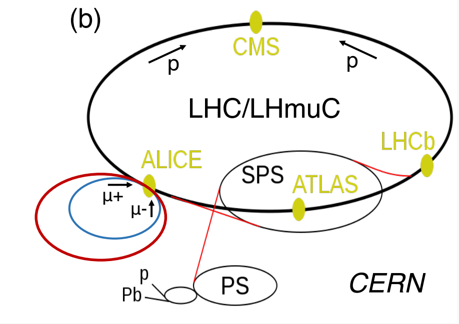
(reproduced in our calculations)

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](CDR))

Similar idea applies to LHC



arXiv:2203.06258

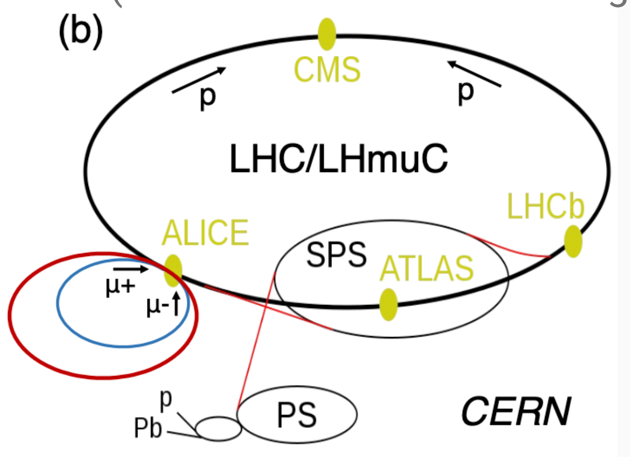
Higher $\sqrt{s}$ than FCC-eh!
(3.5 TeV)

A Muon-Ion Collider at CERN, "LHmuC"

Parameter	LHmuC	
$\sqrt{s_{\mu p}}$ (TeV)	6.5	
$L_{\mu p}$ (10^{33}cm^{-2}s^{-1})	2.8	
Int. Lumi. (fb^{-1}) per 10 yrs	237	
	Muon	Proton
Beam energy (TeV)	1.5	7
N_b (10^{11})	20	2.2
f^{μ}_{rep} (Hz)	12	
Cycles per μ bunch, N^{μ}_{cycle}	3300	
$\varepsilon^*_{x,y}$ (μm)	25	2.5
$\beta^*_{x,y}$ @IP (cm)	0.5	15
Trans. beam size, $\sigma_{x,y}$ (μm)	3	7.1

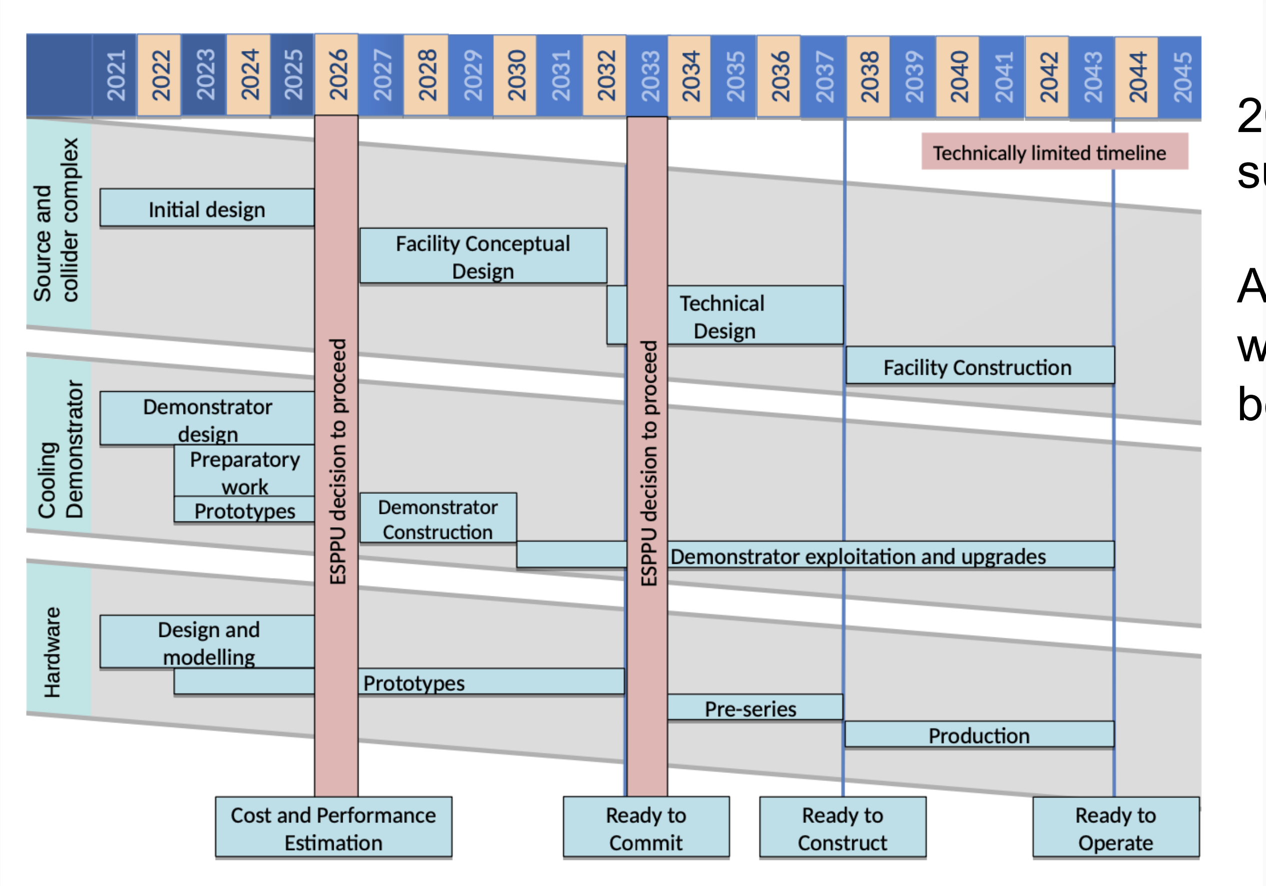
← Likely unrealistic

- Variation of the LHeC concept with a TeV muon beam replacing the 50 GeV electron beam
- Could accommodate a μp collider option if an initial 1.5+1.5 TeV $\mu^+\mu^-$ collider is sited at CERN (Intl. Muon Coll. Collab. design)



- Equivalent √s would actually exceed that of a 3 TeV $\mu^+\mu^-$ collider

IMCC Timeline (technically limited)

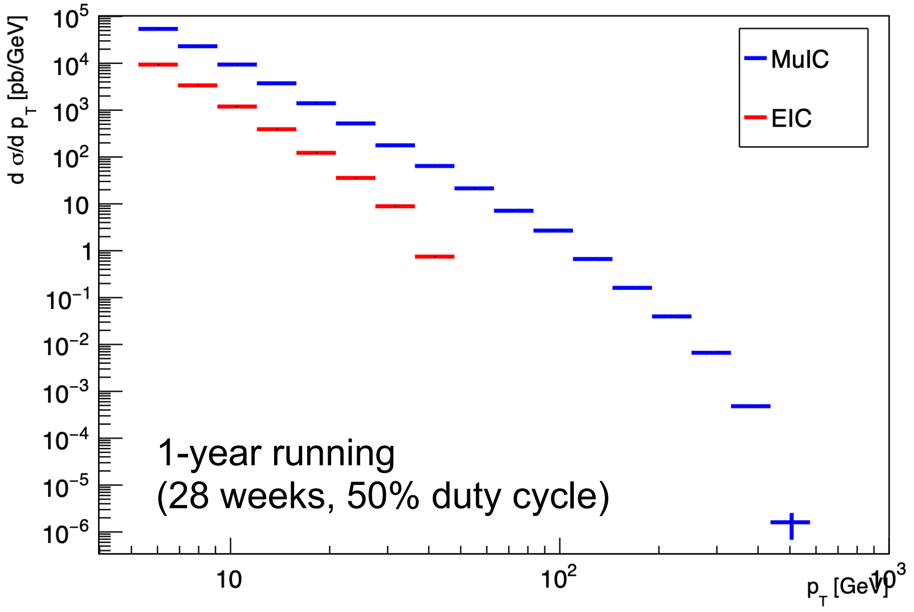


20+ years till the first MC with sustained R&D efforts

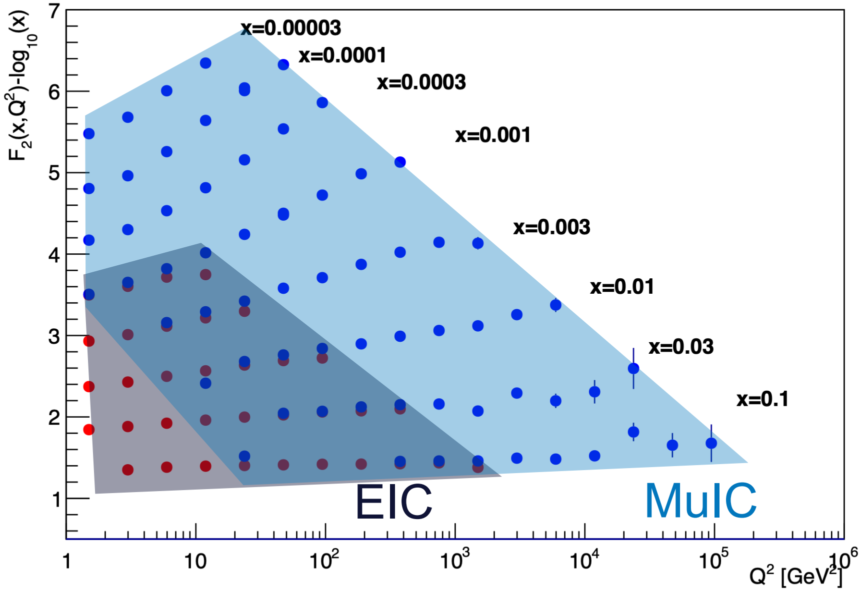
A small-scale **demonstrator** with strong science desired before going to O(10+) TeV

The ultimate lab for QCD and Nuclei

Inclusive jet cross section



Structure function (F_2)



How to build a Muon Collider – proton driver

- 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)

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

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