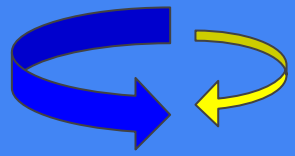


Muon-Ion (proton) Colliders

The future QCD frontier and path to a new energy frontier of μ+μ− colliders
arXiv:2107.02073 (to appear in NIM A)

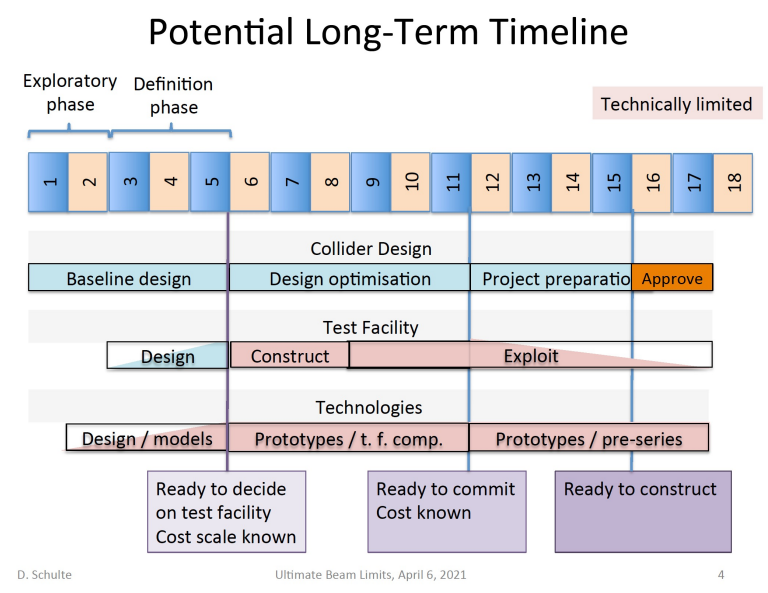
Darin Acosta, Wei Li (Rice U.)

Muon-Ion Collider concept

We share the vision of this community that MC is the best option that will bring us farthest to the future high-energy frontier!

However, MC is hard to build and funding is always constrained. We need to be innovative in exploring viable paths forward

We must establish sustained R&D efforts.



The Muon-Ion Collider concept supports that vison!

Muon-Ion Collider concept

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 μ+μ- collider

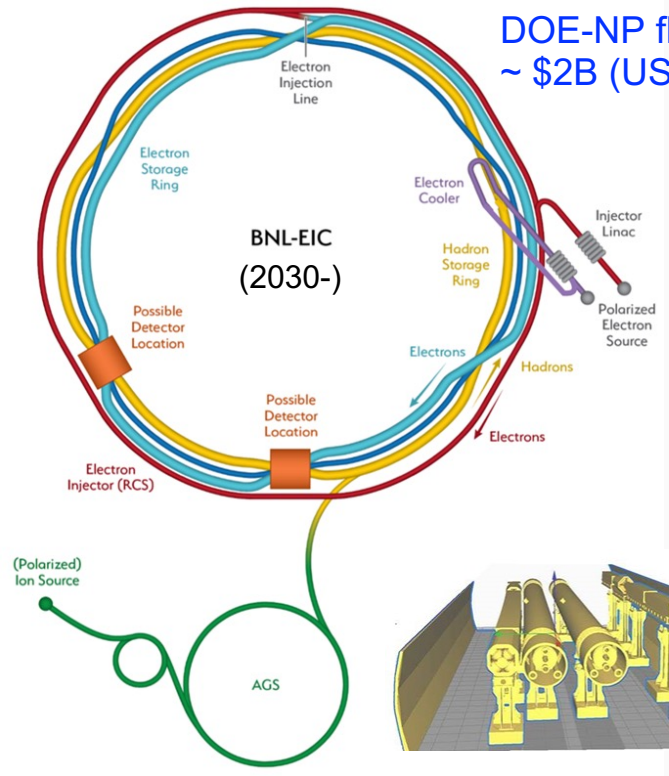
Affordable: one muon beam and leverage resources from HEP and NP to realize a (the first?) muon-based collider in US in 20-25 years!

We look forward to discussion with experts about this proposal.

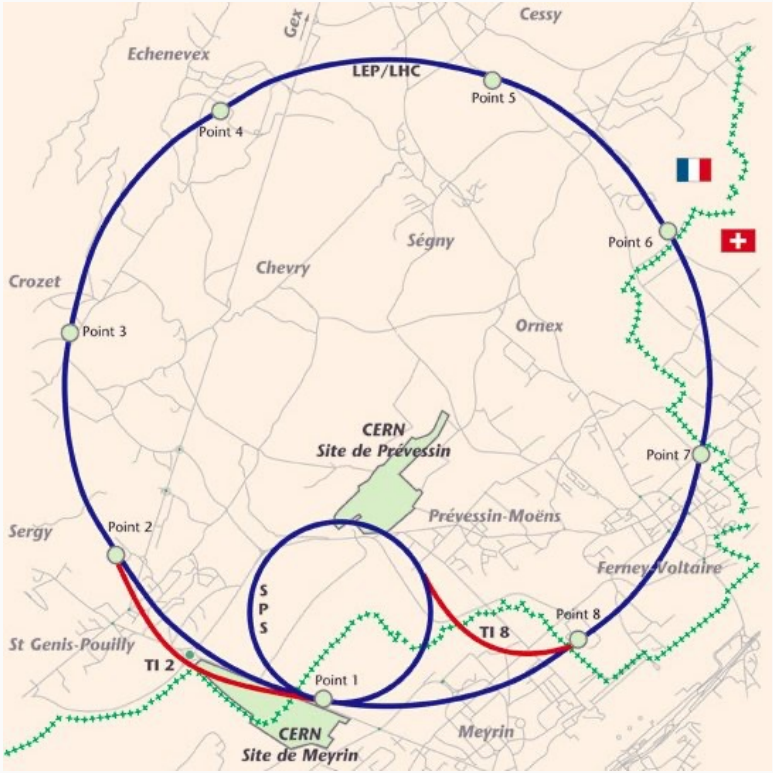
Major colliders in operation worldwide

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

DOE-NP flagship project
~ $2B (US accounting)



CERN-LHC: p(7000)+p(7000) GeV (till ~2040)



primarily HEP plus a small NP component

Design Parameters

	MuIC (BNL, or FNAL?)				LHmuC (CERN)
E_p (GeV)	0.275			0.96 (upgrade)	7
E_μ (GeV)	0.1	0.5	0.96	0.96	1.5 (IMCC)
	(staged muon energy)				
$\sqrt{s_{\mu p}}$ (GeV)	0.33	0.74	**1.0**	1.92	**6.5**
L_{int} ($x10^{33}$ $cm^{-2}s^{-1}$)	0.63	3.1	6	6	4.3

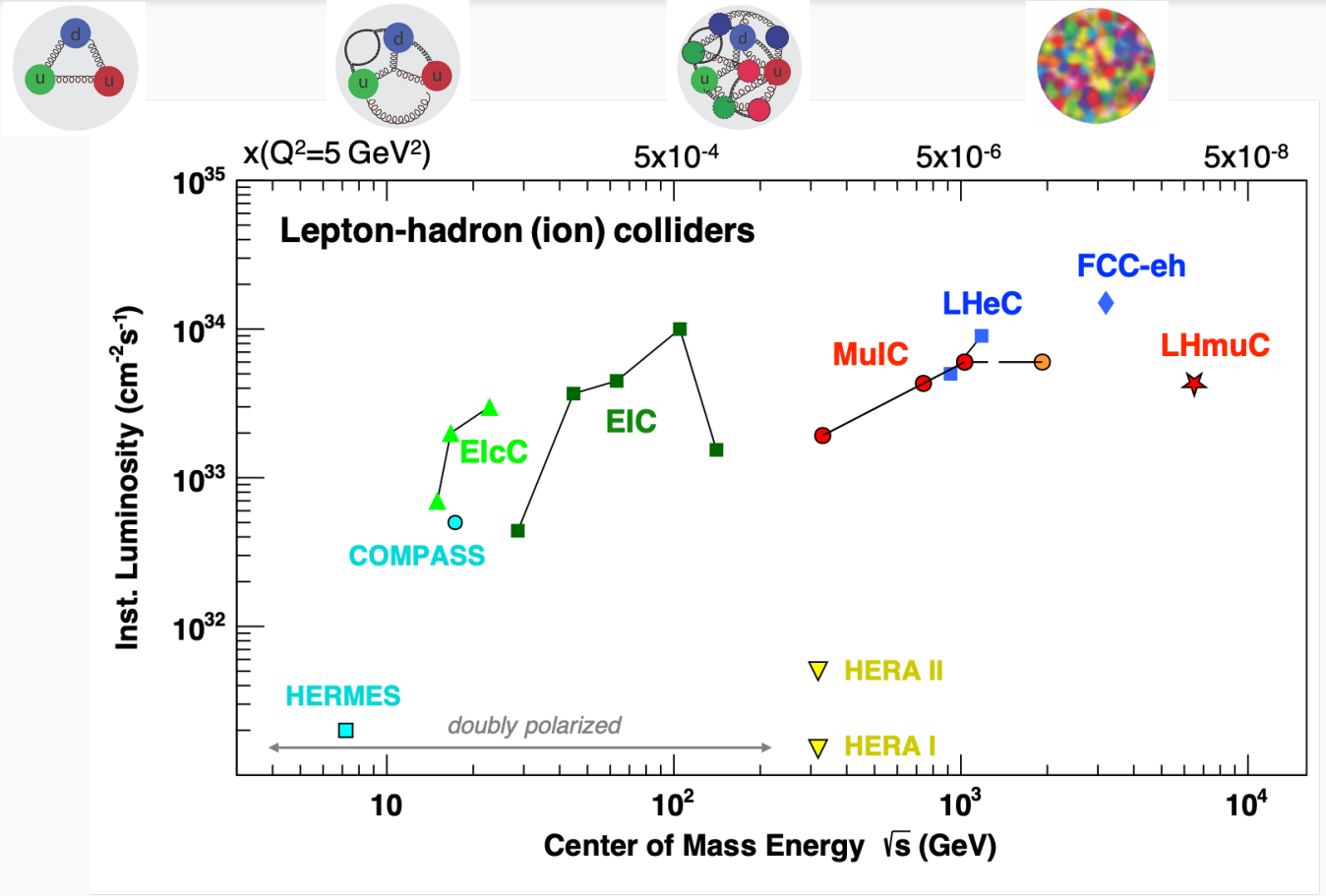
MuIC: re-use EIC (polarized) hadron/ion ring at BNL (or FNAL?)

- **~8x EIC energy**: a new frontier of QCD, EWK and nuclear physics
- Another **2x** if upgrading the hadron ring

LHmuC: re-use LHC ring at CERN and run concurrently with 3 TeV $\mu^+\mu^-$ (IMCC)

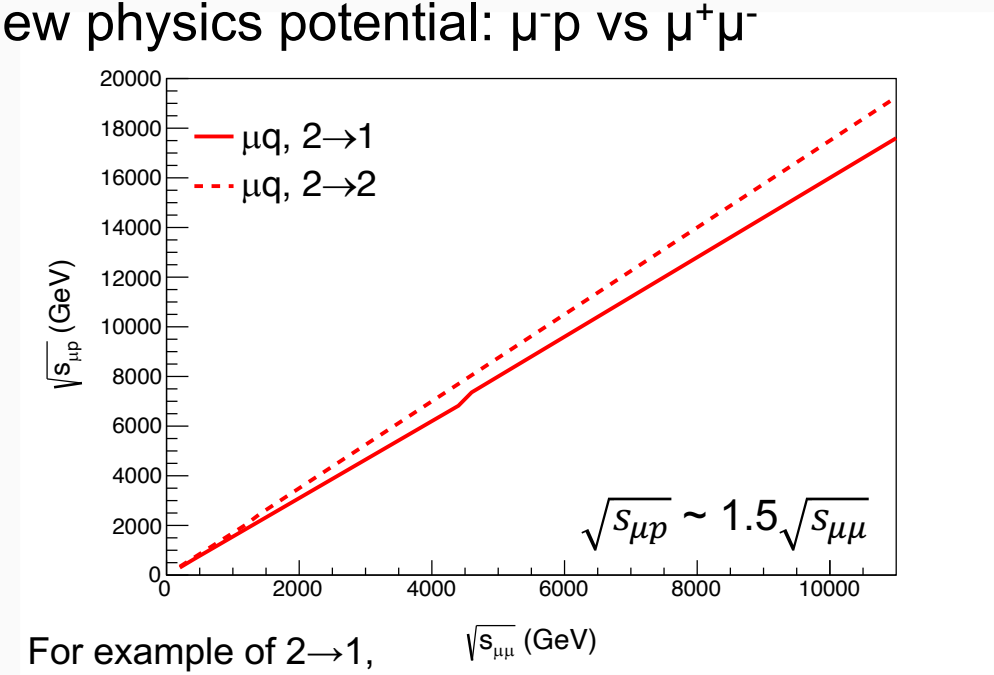
– exceeding FCC-eh energy (100km tunnel)!

MuIC/LHmuC in the worldwide context



Science potential at the MuIC/LHmuC

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

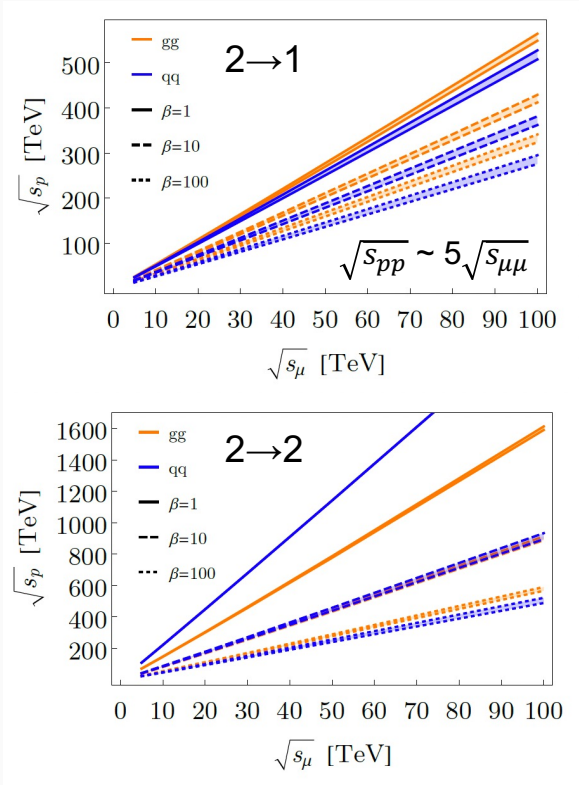


For example of 2→1,

- 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)

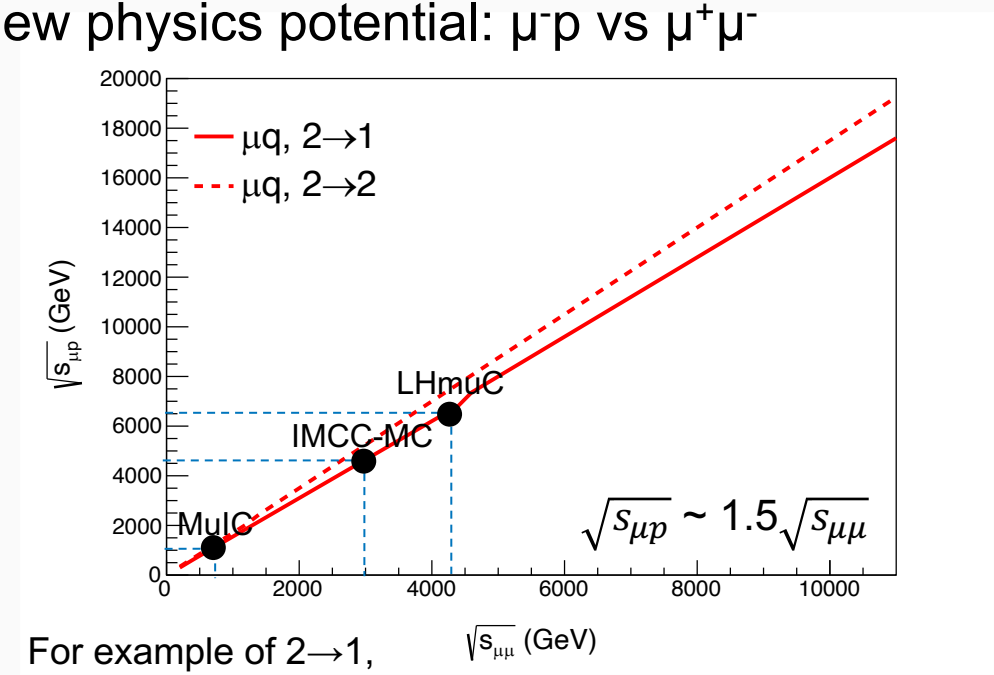
The muon smasher's guide



(reproduced in our calculations)

Science potential at the MuIC/LHmuC

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



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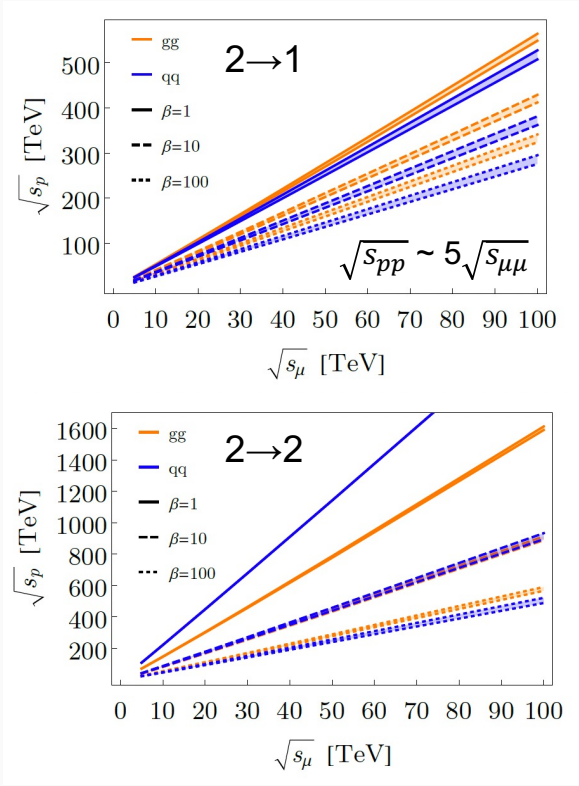
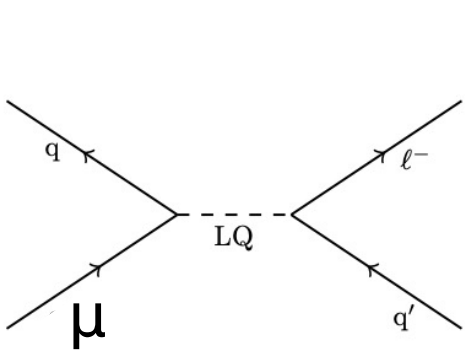


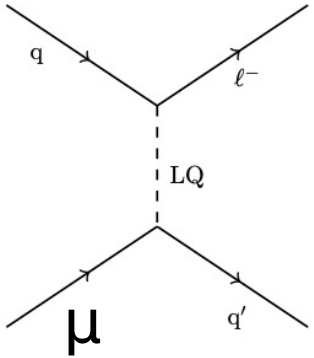
(reproduced in our calculations)

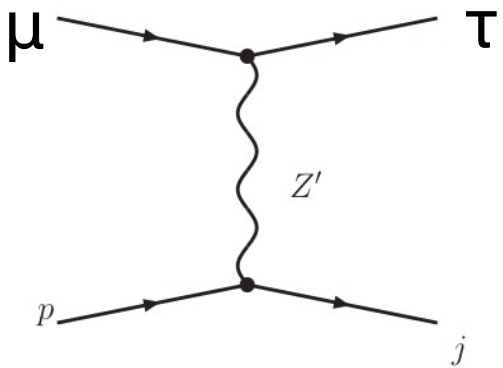
Science potential at the MuIC/LHmuC

Examples:

- Leptoquarks
- Charge lepton flavor violation

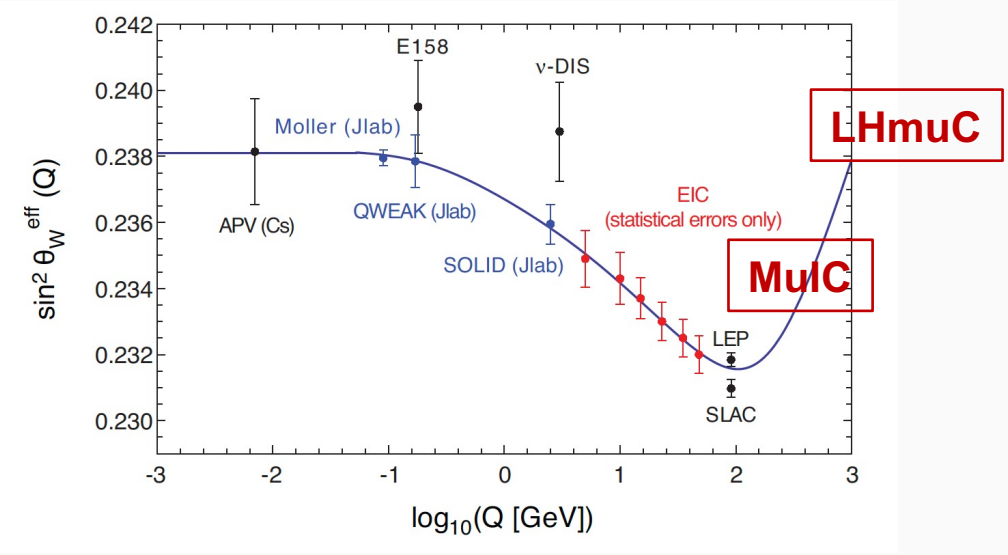






Science potential at the MuIC/LHmuC

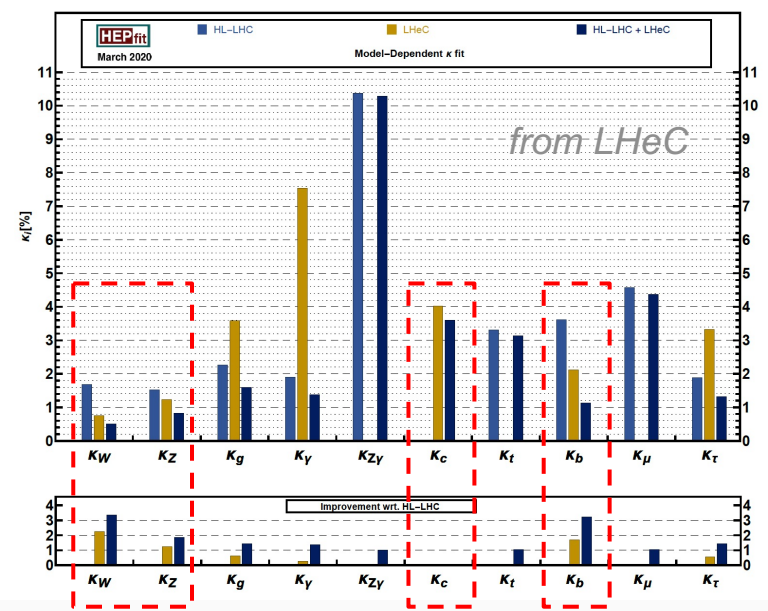
Electroweak physics:



No theoretical uncertainties

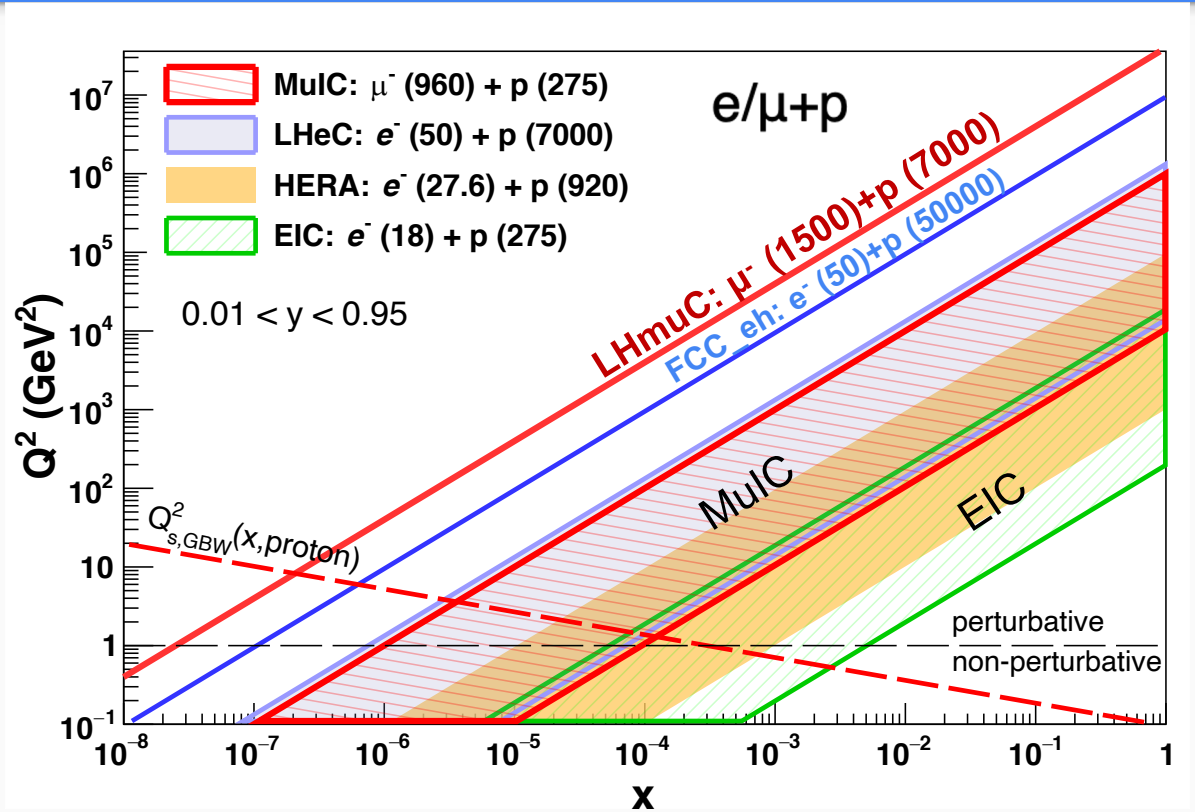
Higgs physics:

Uncertainties of Higgs couplings



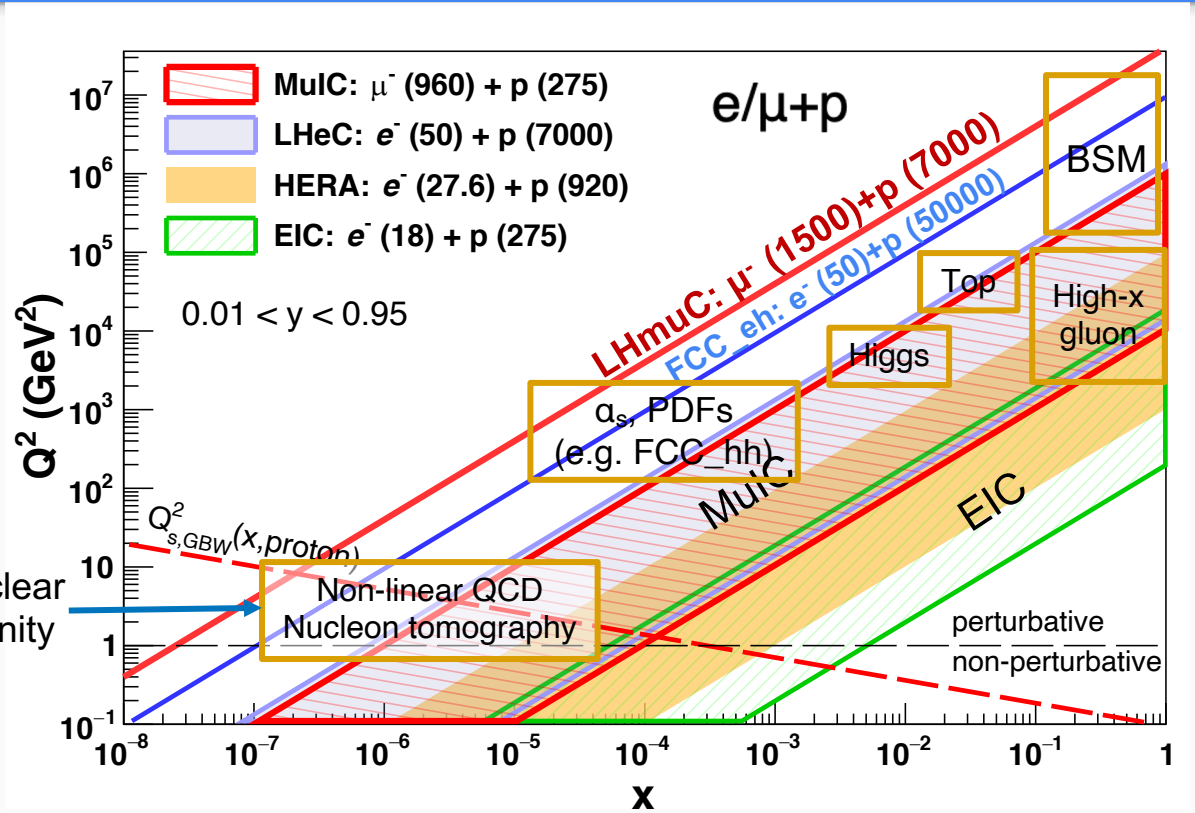
LHeC/MuIC outperforms HL-LHC for certain Higgs decay channels

Science potential at the MuIC/LHmuC



- MuIC ~ LHeC but enables a new technology (and can be sited in US)
- LHmuC exceeds FCC_eh potential

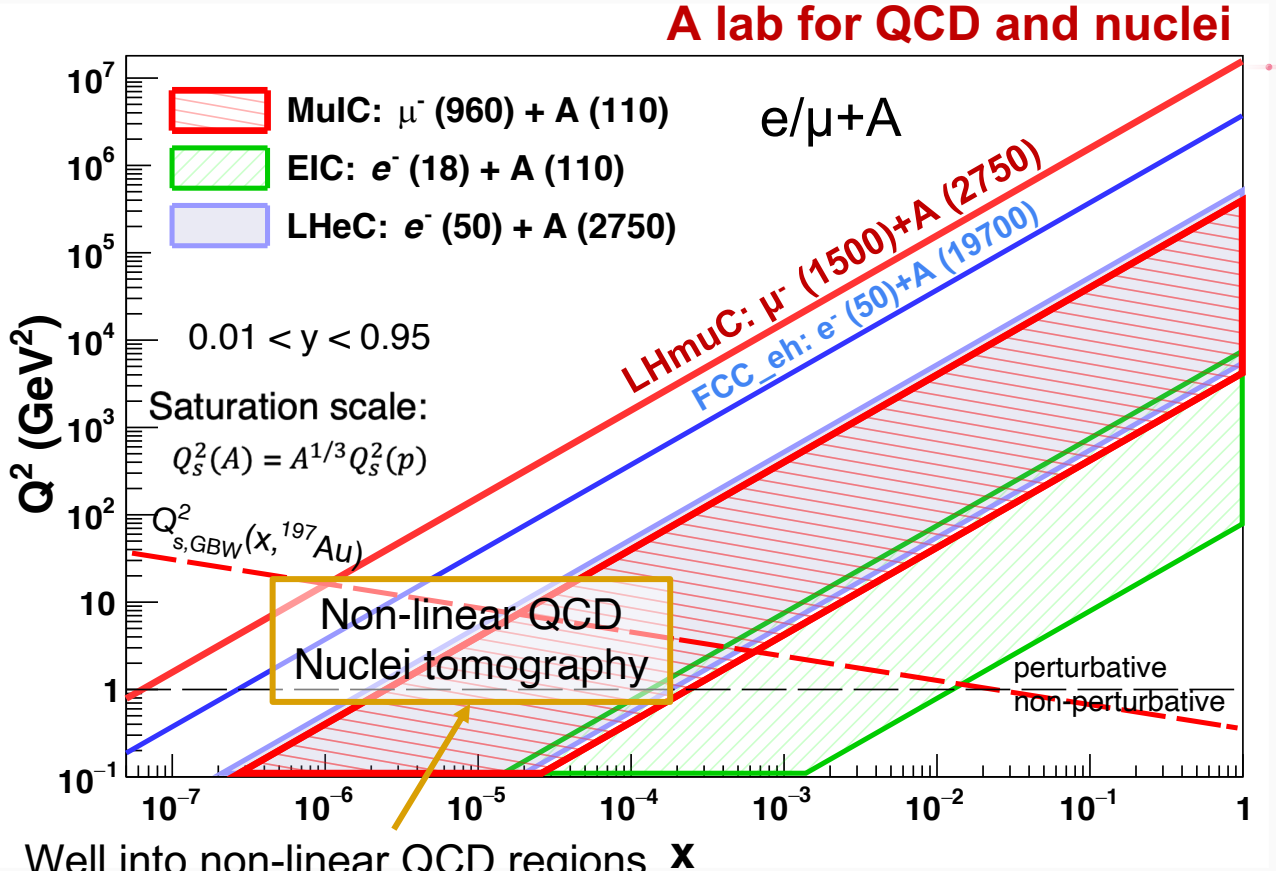
Science potential at the MuIC/LHmuC

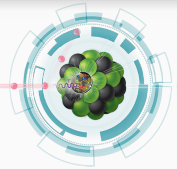


Interests by nuclear physics community

- MuIC ~ LHeC but enables a new technology (and can be sited in US)
- LHmuC exceeds FCC_eh potential

Science potential at the MuIC/LHmuC



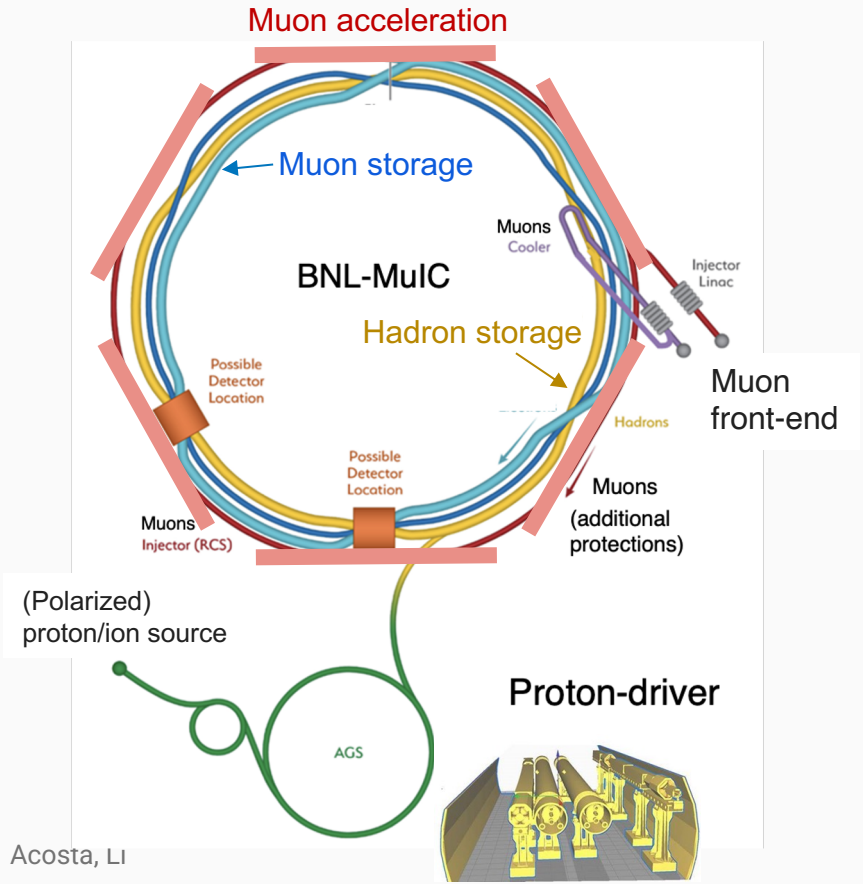


Key science drivers

- The Origin of Mass
- The Origin of Spin
- Gluons in Nuclei
- Multihadron QCD collectivity (connection to AA/pA/pp)

EIC whitepaper, NAS report

MuIC at BNL



- Circumference: 3.86 km
- Bending radius: 290 m
- Bending dipole magnets: 11 T (assumed)

Can muon accelerator and storage rings be fit to the same existing tunnel to replace electrons of EIC for E_μ<1TeV?

- ➢ If not, what would be main limitations? Depending on fast ramping magnets?
- ➢ Six straight sectors for acceleration?

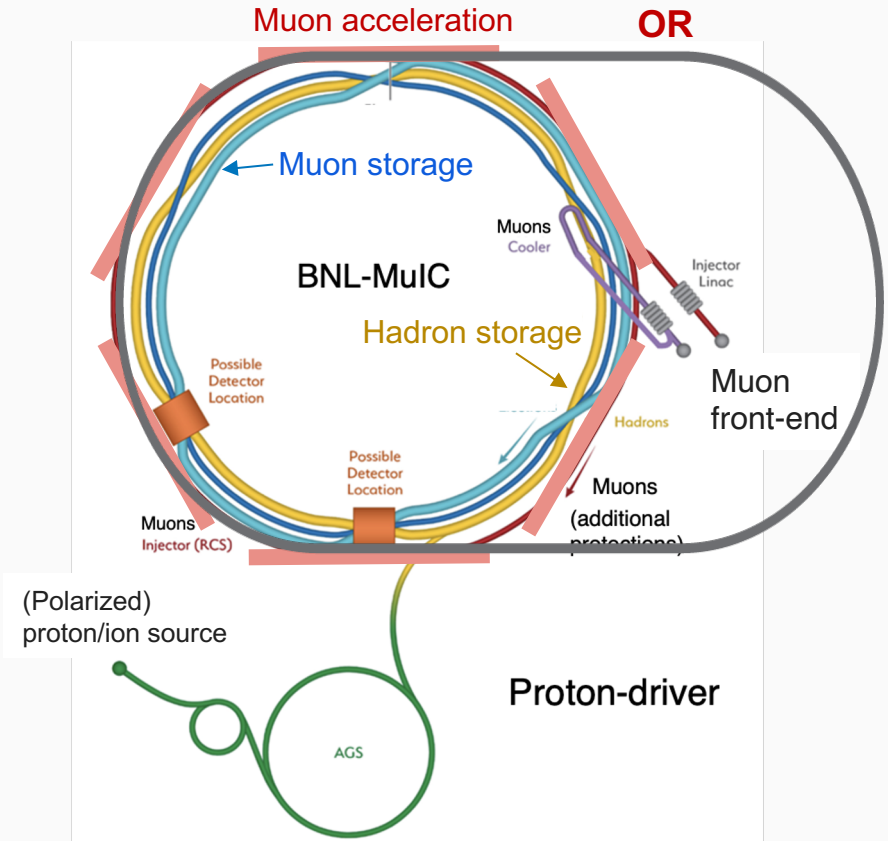
Proton source sufficient to provide muons?

What does it take to maintain the polarization?

- ➢ Muons are produced with P ~ 20% and can be enhanced to P ~ 50% with compromise of luminosity

Issues with radiation protection (next slide)

MuIC at BNL



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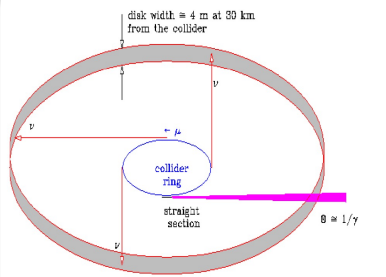
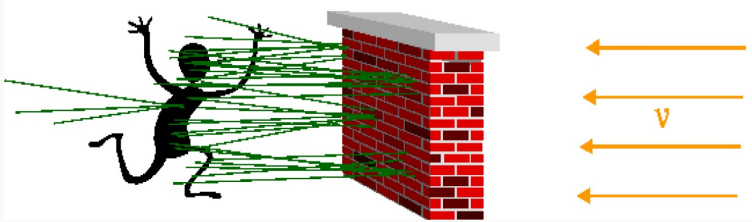
Issues with radiation protection (next slide)

Neutrino-induced radiations



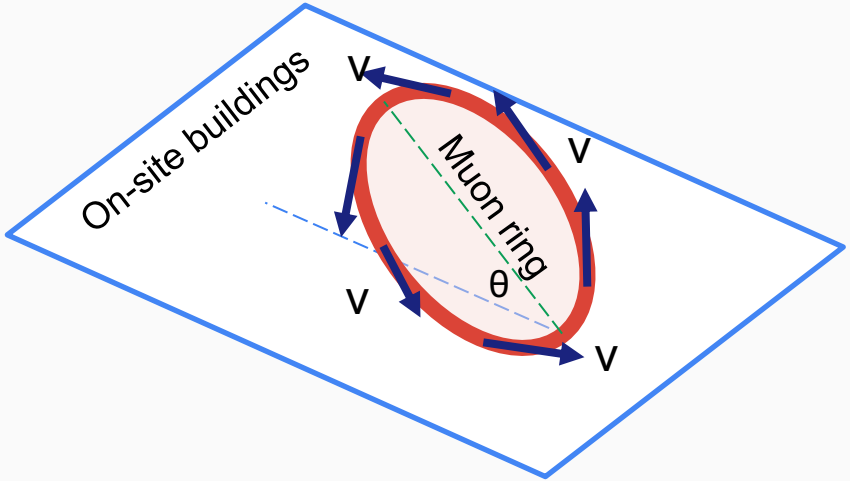
Damage by secondary particles induced by neutrinos



Nikolai Mokhov (FNAL)

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

Is it OK for muon energy < 1 TeV?



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

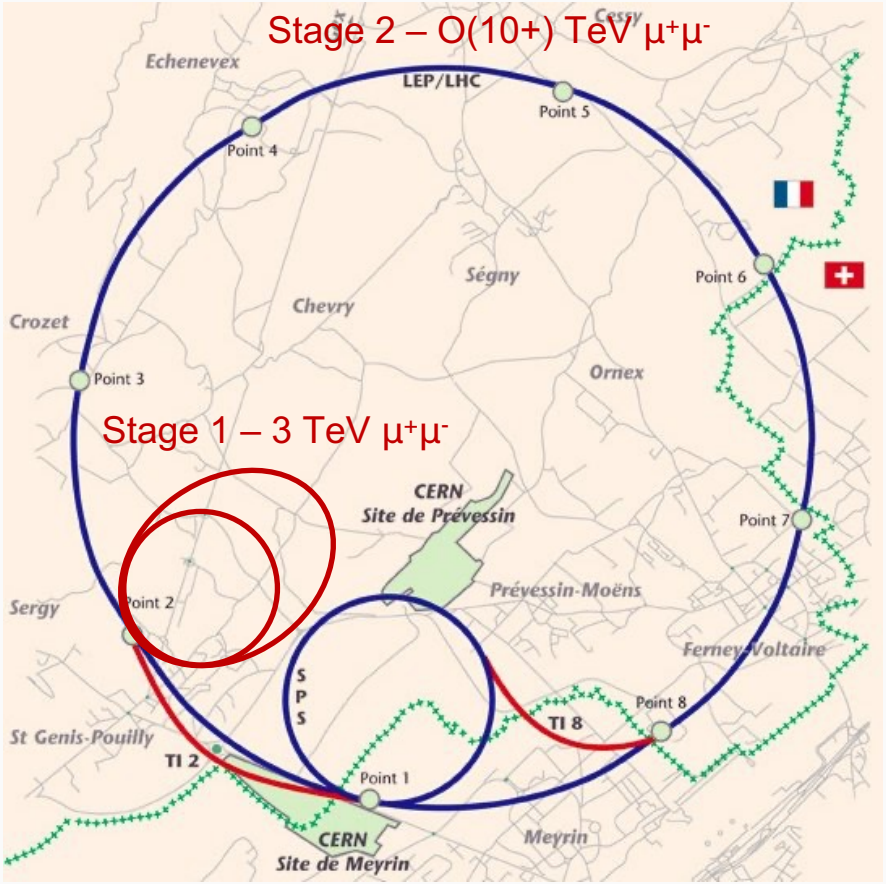
LHmuC at CERN

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.

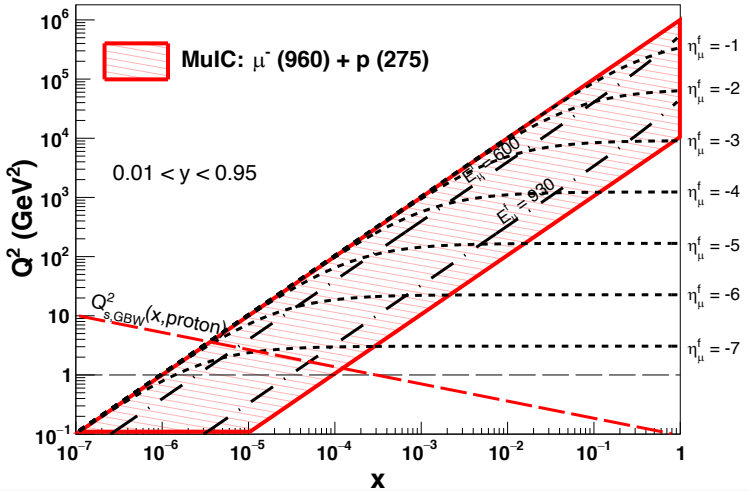
Stage 3: if a large tunnel is built in farther future, a O(100) TeV $\mu^+\mu^-$ may be realized



Final-state kinematics at MuIC/LHmuC

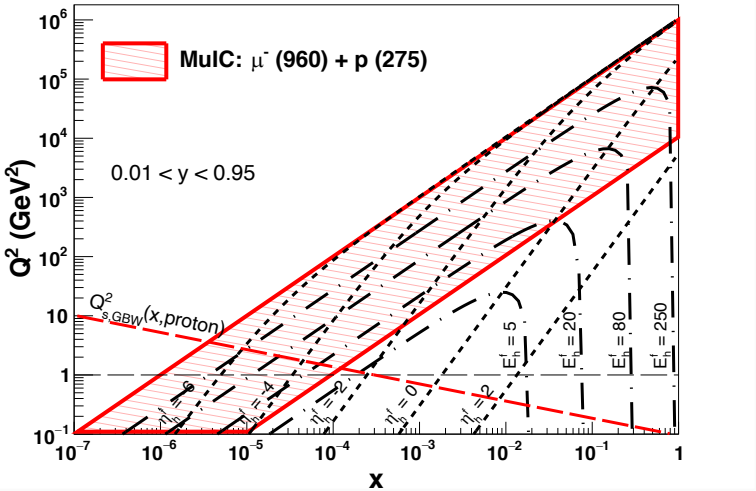
p/A ⟵ μ

kinematics for scattered **muons**

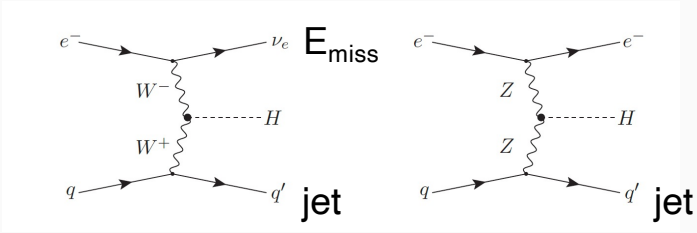


Muons very forward: -7<η<0

kinematics for struck **quarks**



Jets fairly central: -4<η<2

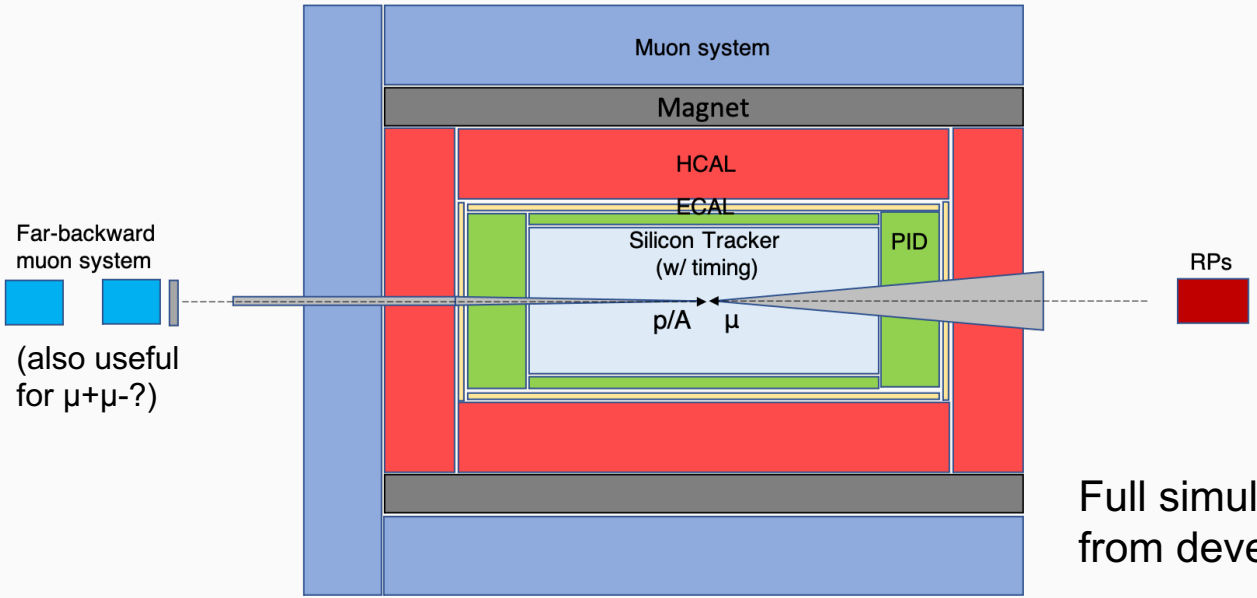


Higgs: <η> ~ -2

Detector considerations and challenges

Unique challenges:

- Detection of scattered muons important, mostly at high η (far-backward)
- Hadron PID over wide phase space

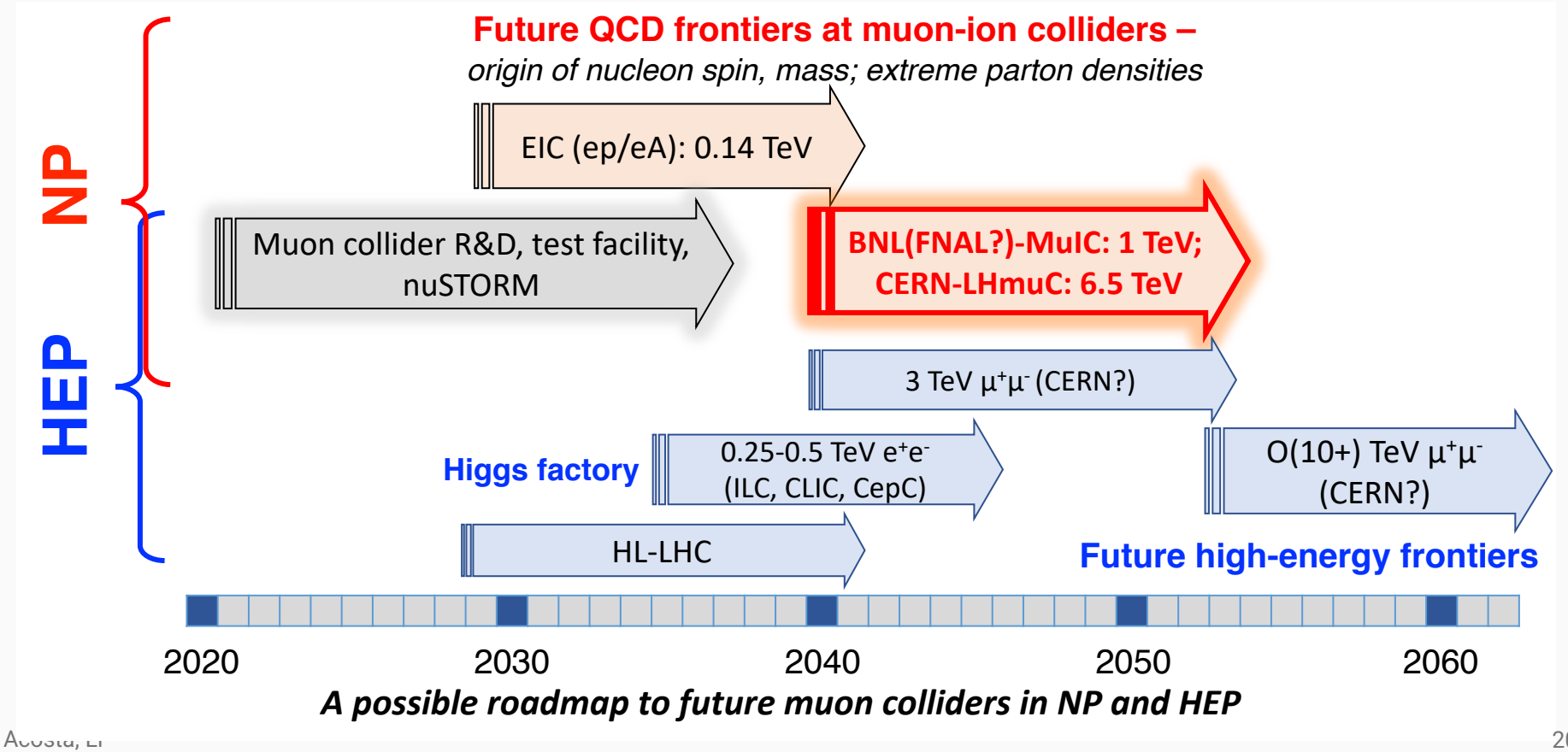


	Main requirements
Muons	**-7<η<0, σ(p)/p < 5%**
Tracking	-4<η<2.4
PID (π/k/p)	**-4<η<2.4, p<100 GeV**
Calorimetry (jets, photons)	-5<η<2.4

Full simulations needed, which can benefit from development in the muon community

Nozzle tungsten only on the incoming μ direction?

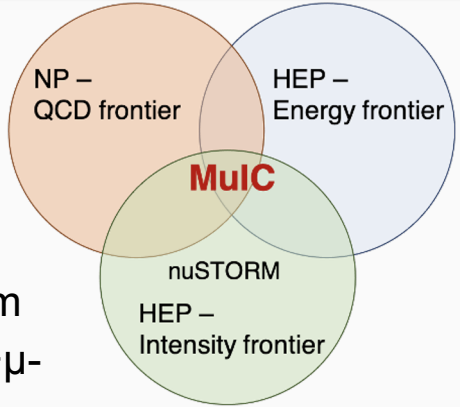
Roadmap (in our view)



A possible roadmap to future muon colliders in NP and HEP

Summary

Muon-Ion (proton) Collider:

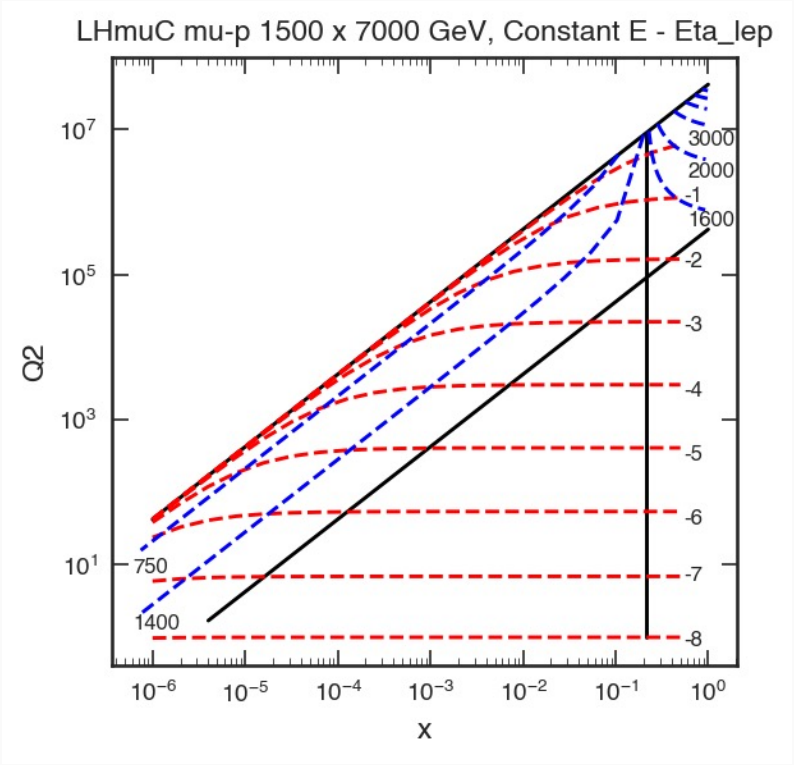


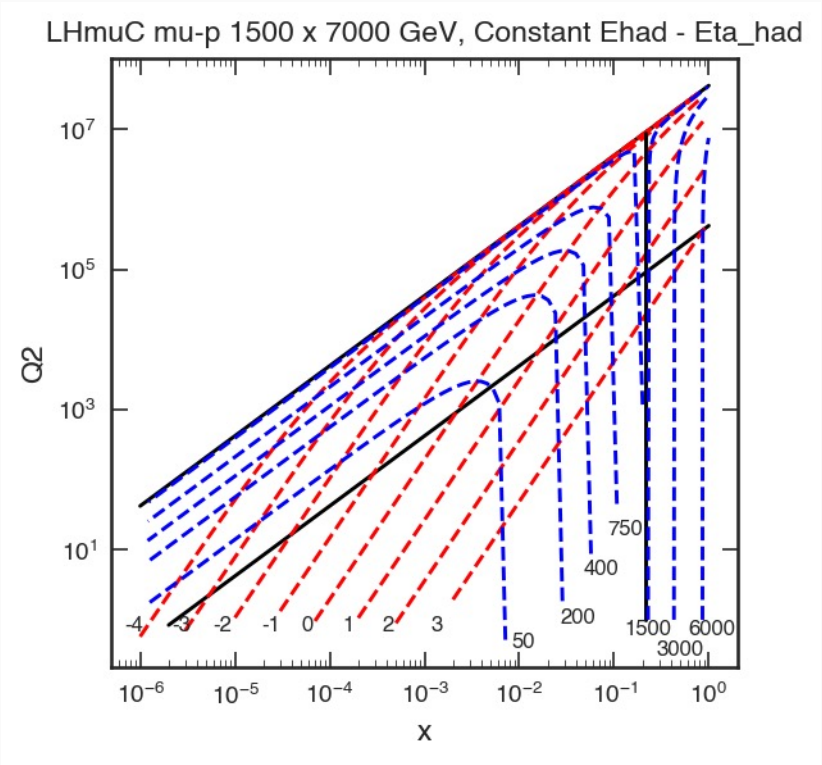
- Compelling sciences with synergies across NP, HEP energy and intensity (e.g., nuSTORM) frontiers
- Providing a path forward: a clear target to establish R&D program and serve as a demonstrator toward the ultimate O(10+) TeV μ+μ-
- Affordable (e.g., an “upgrade” to the EIC) by re-using the existing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

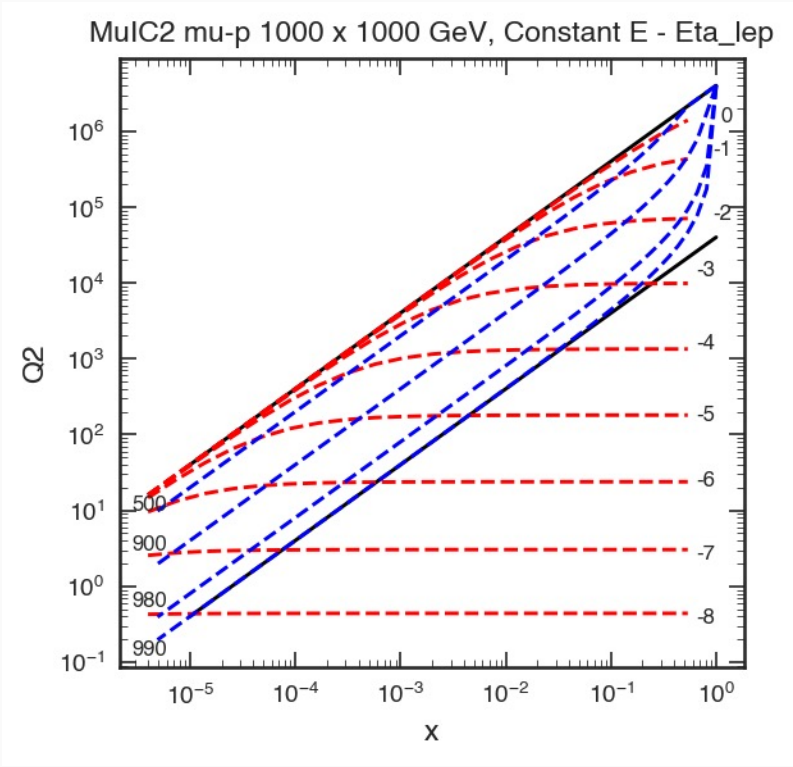
MuIC and MC can be even pursued together if strong interests are drawn from the NP community (NP long-range planning coming in 2022)

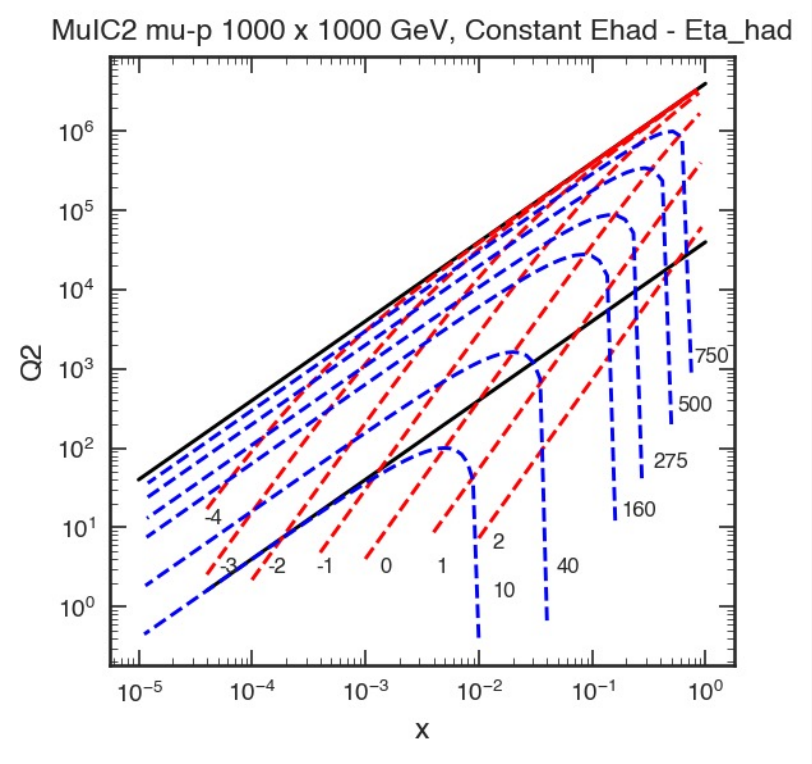
MuIC could be an opportunity for US to become a front runner in muon collider technology so we recommend it be considered as a possible option.

Extras


LHmuC mu-p 1500 x 7000 GeV, Constant E - Eta_lep
Q2
x
10^7
10^5
10^3
10^1
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
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
10^7
10^5
10^3
10^1
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
750
400
-4
-3
-2
-1
0
1
2
3
200
50
1500
6000
3000


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


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