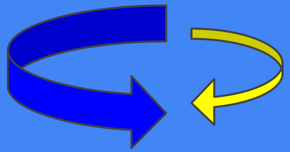


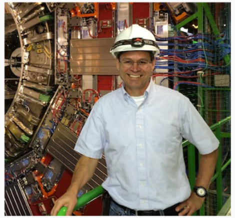
A Muon-Ion Collider at BNL

The future QCD frontier and path to a new energy frontier of $\mu^+\mu^-$ colliders

arXiv:2107.02073

Darin Acosta, Wei Li (Rice U.)

Who we are



Darin Acosta: "Particle Physicist" on CMS (Higgs, standard model physics and BSM searches etc.), funded by DOE-HEP; Previously on ZEUS at HERA (ep collider)

Wei Li: "Nuclear Physicist" on CMS (high-energy nuclear collisions, QCD in extreme densities), funded by DOE-NP; also on STAR (and previously PHOBOS) at RHIC (AA collider) and emerging collaborations at EIC (ep/eA collider)

Many examples of successful synergies between HEP and NP in CMS in physics measurements, detector design, operations and upgrades

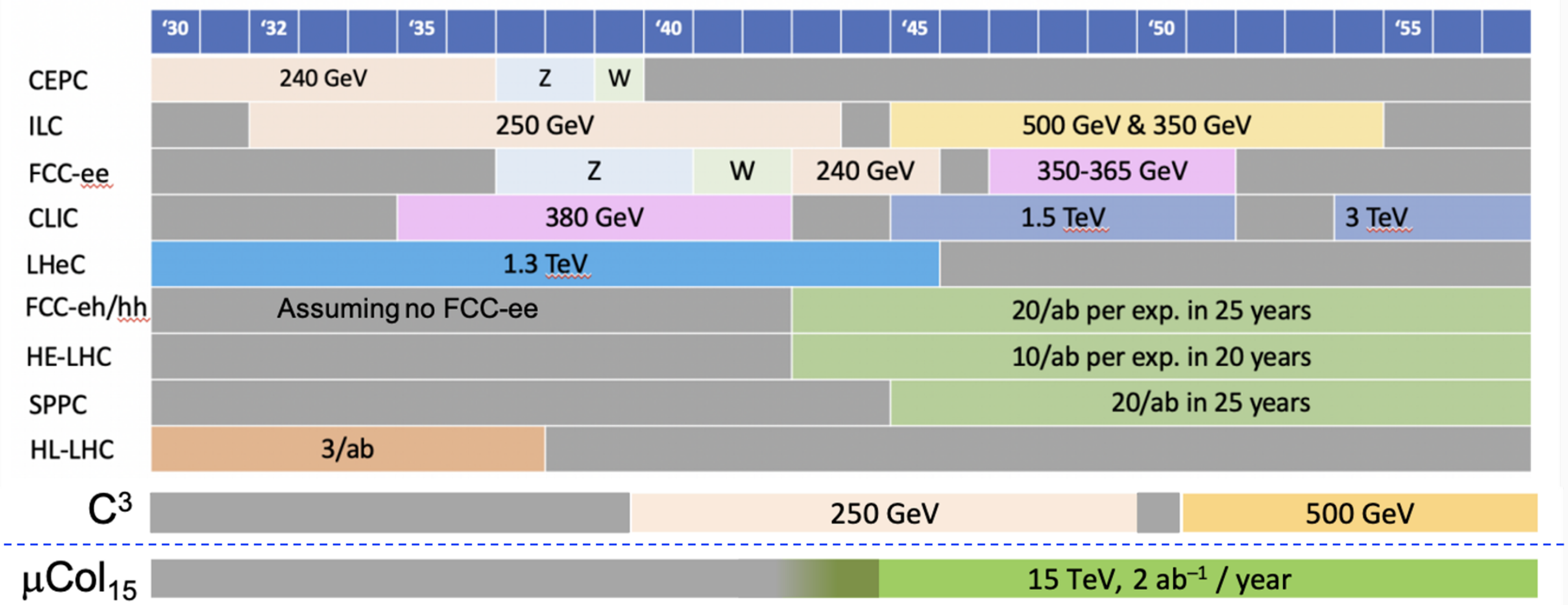
We like chatting about the future of each other's field and looking for opportunities to collaborate

n.b. Neither of us is an accelerator expert, not to mention muon colliders...

Future of HEP energy frontier

- What would be an optimal and realistic path forward?
- Can US play a role in hosting future colliders?

S. Dasu

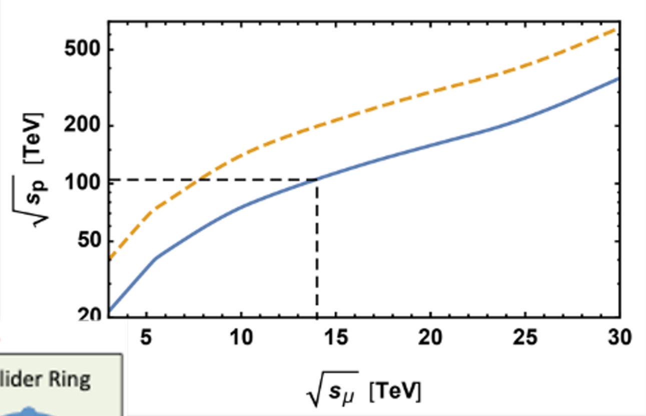


Growing interests in muon colliders!

An Energy Frontier Muon Collider

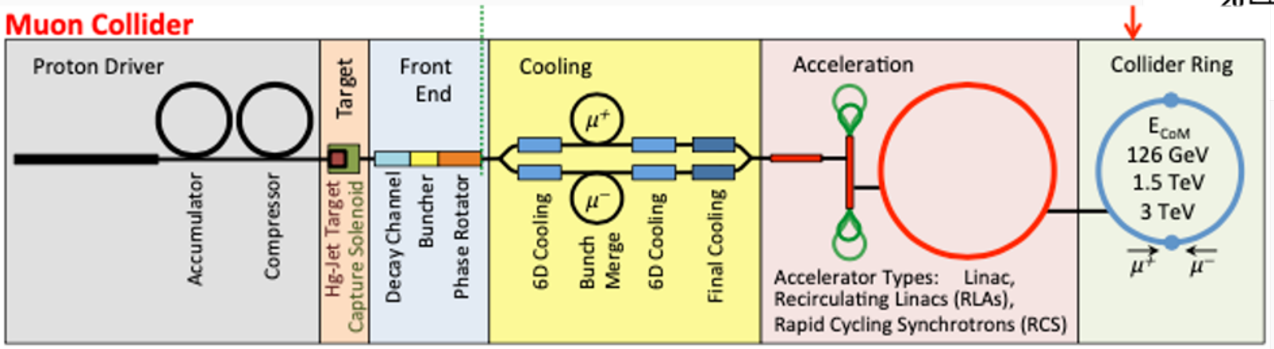
A more compact and innovative facility to incorporate the advantages of a high precision lepton collider and an energy frontier machine

IMC: arXiv:1901.06150



An O(10) TeV muon collider has the equivalent mass reach to an O(100) TeV proton collider

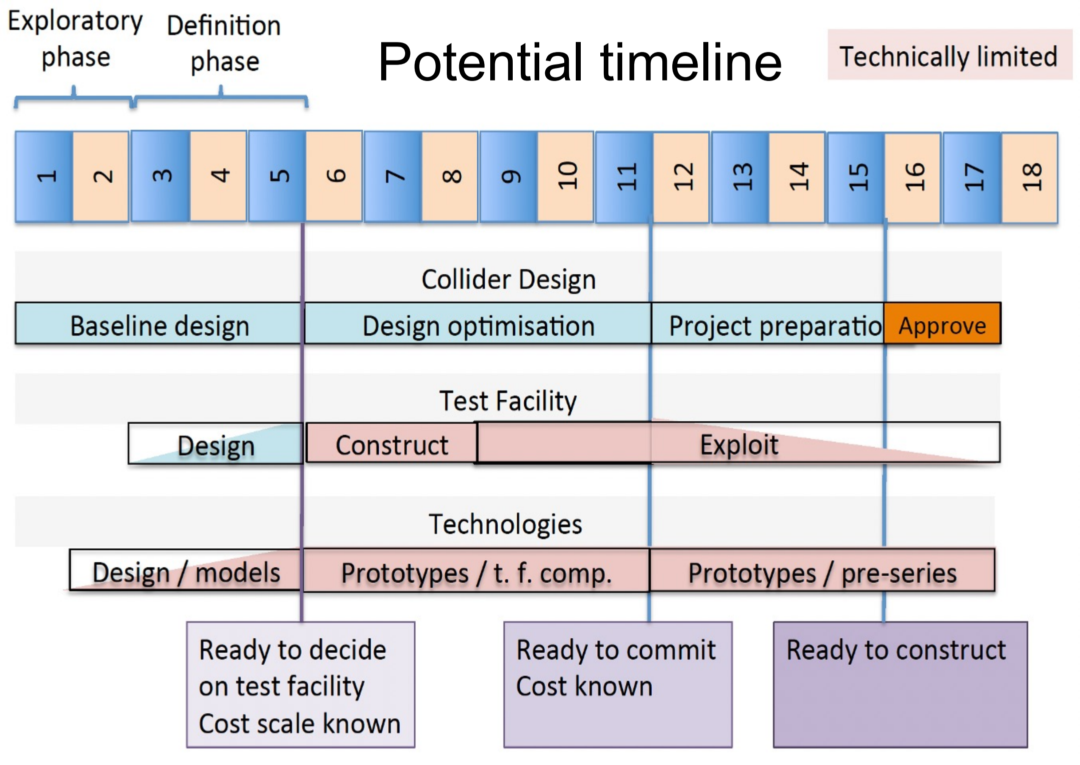
But much R&D still to do...



Muon Accelerator Program (2011-2016)

International Muon Collider Collaboration

https://muoncollider.web.cern.ch/welcome-page-muon-collider-website



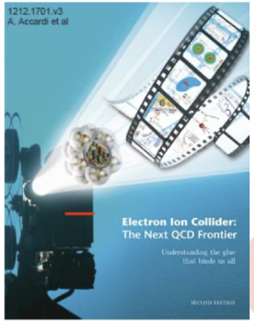
~ 15 years to fully develop the technology

Before reaching O(10+) TeV, a demonstrator is with compelling science program:

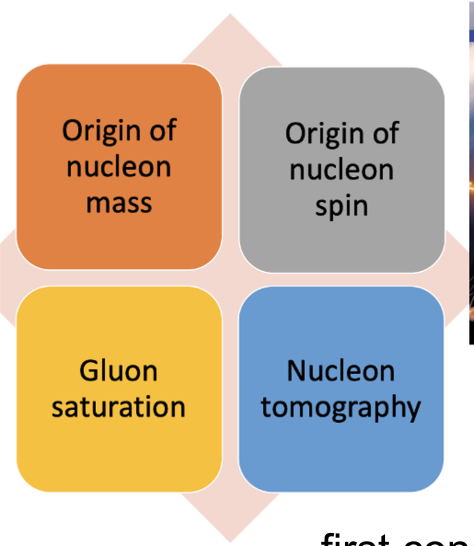
- IMCC is focusing on a design of 3 TeV $\mu^+\mu^-$ as its next step
- Higgs factory?
- Muon-Ion Collider?

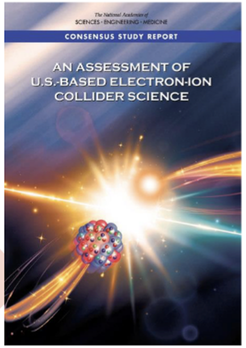
Future of NP in USA

Electron-Ion Collider at BNL (2030-) **– a new QCD frontier**
(CD-1, funded by DOE-NP)

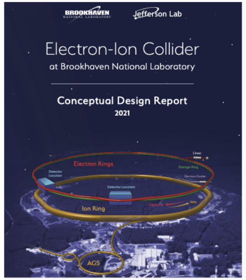


White paper
arXiv:1212.1701

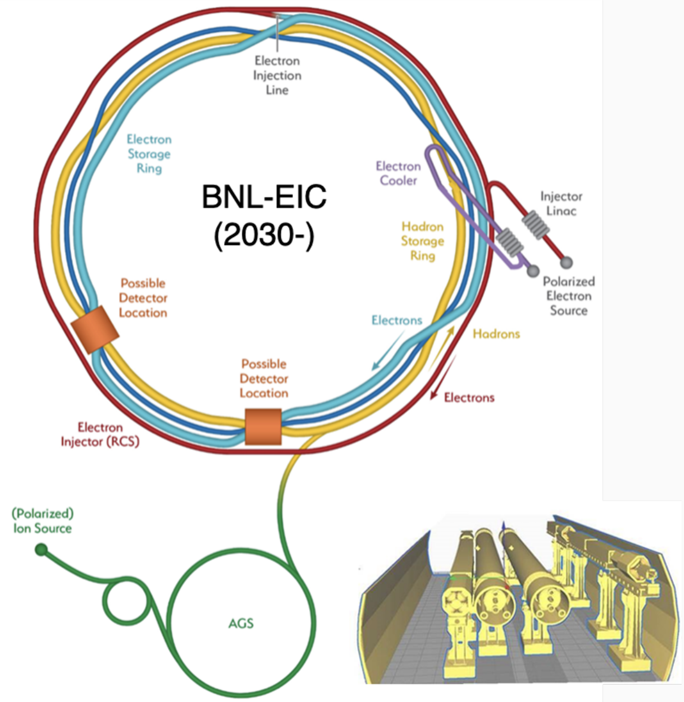




NAS report
July 2018



CDR 2021



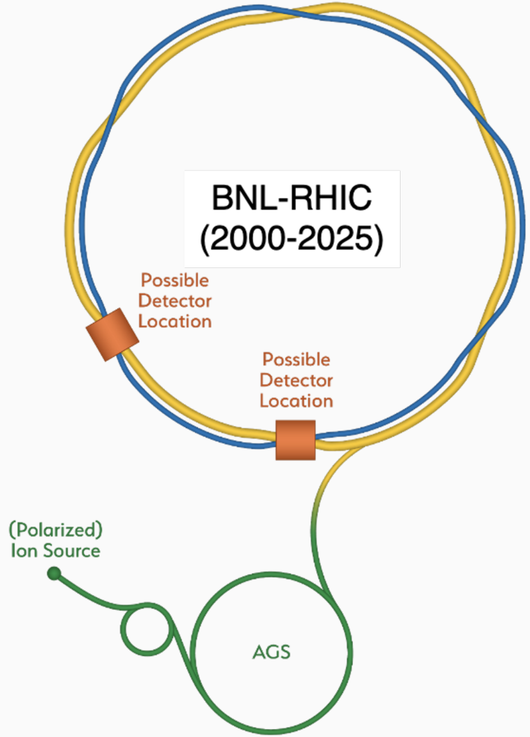
first conceived in late 90s

ep, eA (any ion in periodic table) up to 140 GeV;
Polarized e, p, ^{3}He beams (70% polarization)

Time to think: **What's after EIC?**

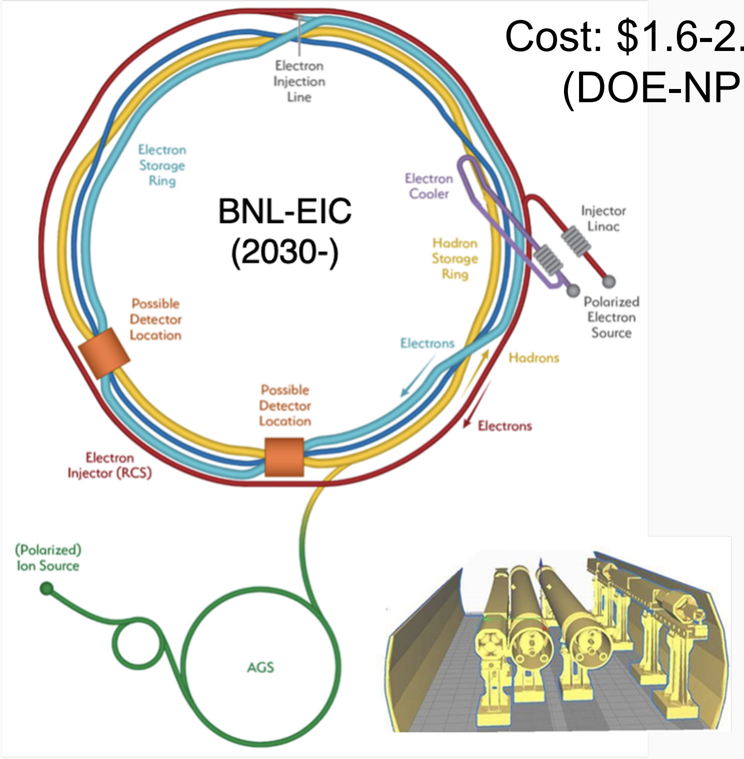
Electron-Ion Collider at BNL

pp, pA, AA up to 500 GeV



upgrade

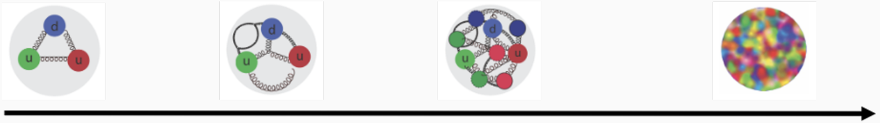
ep, eA up to 140 GeV



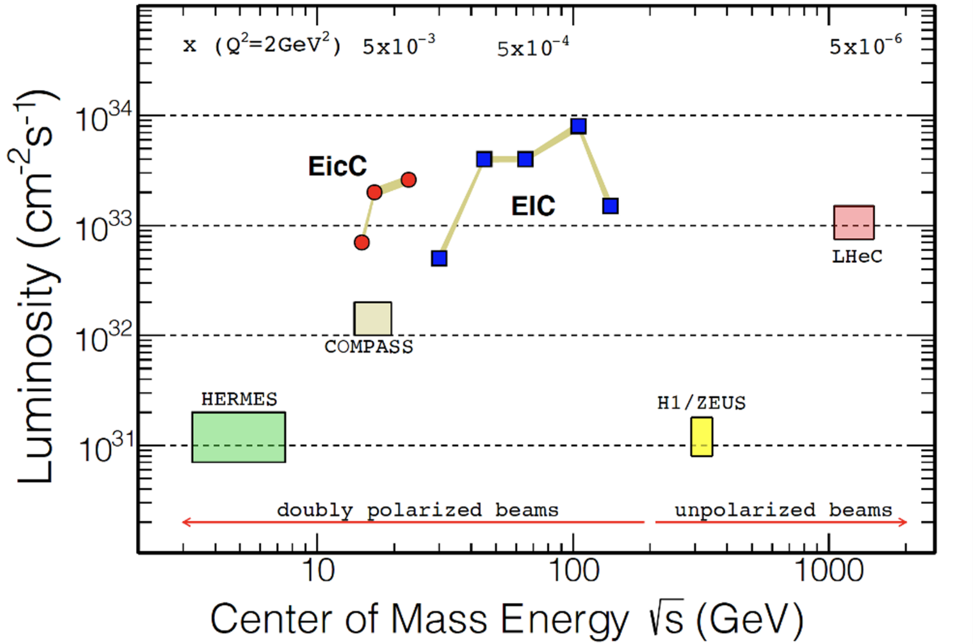
Cost: \$1.6-2.6B (DOE-NP)

Re-using existing facility & infrastructure is key to the realization of EIC

DIS at lepton-hadron colliders



Gluon saturation



HERA at DESY – high energy but low luminosity, unpolarized or singly polarized (*)

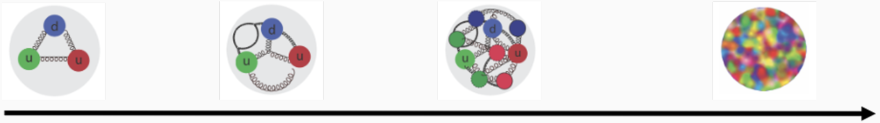
EIC at BNL – lowish energy but high luminosity, doubly polarized, ions

What's after EIC?

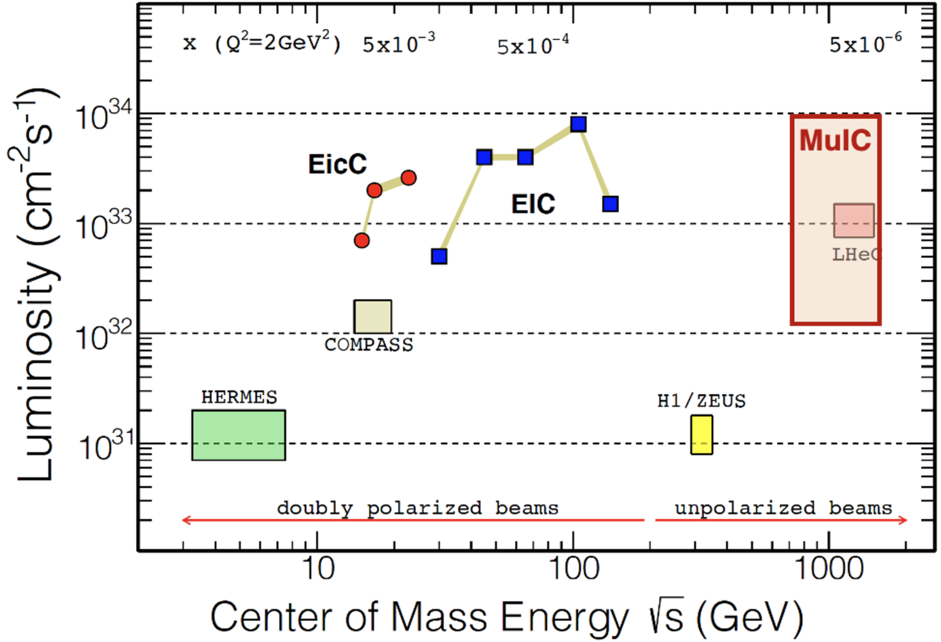
- LHeC (arXiv:2007.14491)?

(*) HERA-II did achieve longitudinally polarized electron beams

DIS at lepton-hadron colliders



Gluon saturation



HERA at DESY – high energy but low luminosity, unpolarized or singly polarized (*)

EIC at BNL – lowish energy but high luminosity, doubly polarized, ions

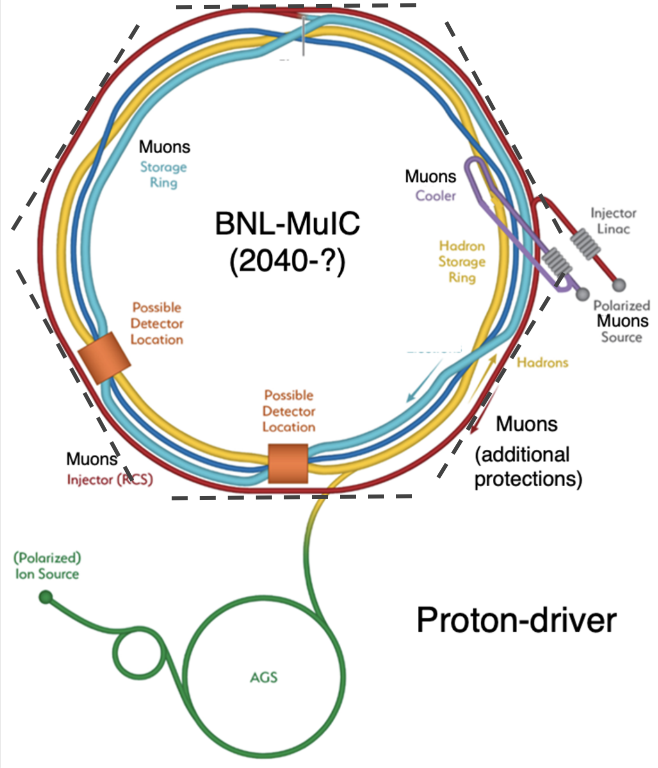
What's after EIC?

- LHeC (arXiv:2007.14491)?
- **Muon-Ion Collider at BNL!**
  (eps. with polarized muons)

(*) HERA-II did achieve longitudinally polarized electron beams

Muon-Ion Collider at BNL

replace e by μ beam



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

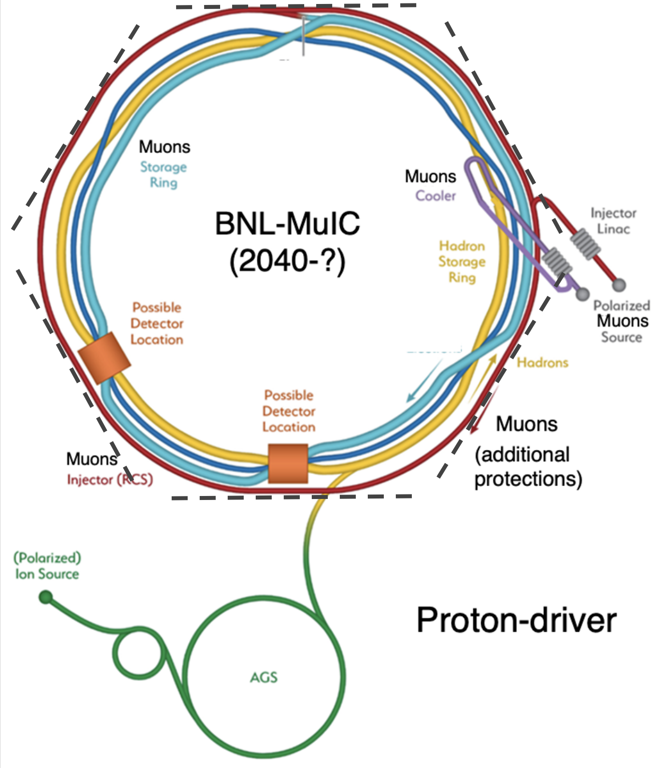
Achievable muon beam energy: **0.3Br**

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)

7-8X increase over top EIC energy

Muon-Ion Collider at BNL

replace e by μ beam



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If $E_p \rightarrow 0.96$ TeV, $\sqrt{s} \rightarrow 1.9$ TeV

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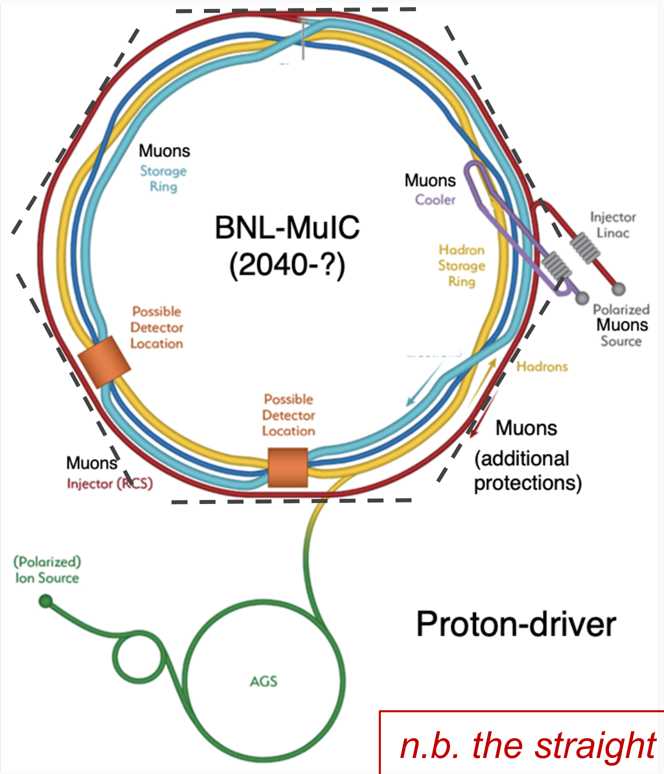
replace e by μ beam



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n.b. the straight sections would provide collimated beams of neutrinos as well

7-8X increase over top EIC energy

If $E_p \to 0.96$ TeV, $\sqrt{s} \to 1.9$ TeV

Muon-Ion Collider at BNL

Luminosity estimate:

$f_c^\mu = f_{rep} * N_c$

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

arXiv:1905.05564

Parameter	Muon	Proton
Energy (TeV)	0.96	0.275
CoM energy (TeV)	1.03	
Bunch intensity (10^{11})	20	3
Norm. emittance, $\varepsilon_{x,y}$ (μm)	25	0.2
$\beta^*_{x,y}$ @IP (cm)	1	5
Trans. RMS beam size, $\sigma_{x,y}$ (μm)	5.2	5.8
Muon repetition rate, f_{rep} (Hz)	15	
Cycles/Collilsions per muon bunch, N_c	3279 (~300B)	
$L_{\mu p}$ (10^{33}cm^{-2}s^{-1})	7	

Muon beam (MAP):

arXiv:1901.06150

Table 1: Main parameters of the proton driver muon facilities

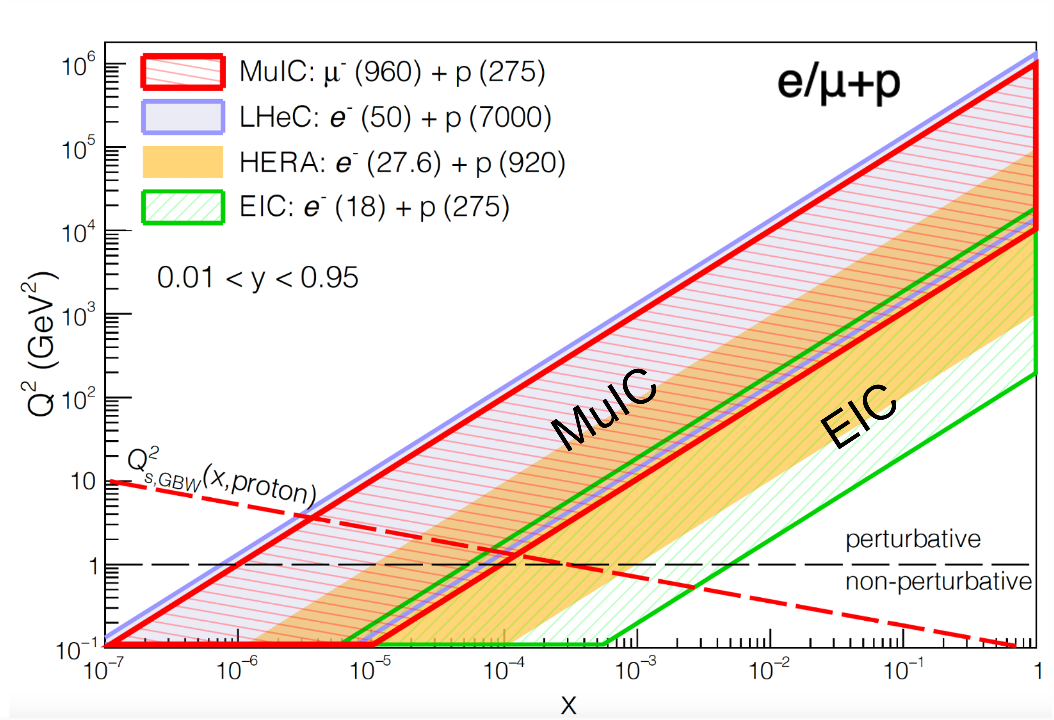
Parameter	Units	Higgs	Multi-TeV		
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7 sec		13'500	37'500	200'000	820'000
Circumference	km	0.3	2.5	4.5	6
No. of IP's		1	2	2	2
Repetition Rate	Hz	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1	0.5	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	μm-rad	200	25	25	25
Norm. Long. Emittance, ε_{LN}	μm-rad	1.5	70	70	70
Bunch Length, σ_S	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Polarized proton beam from eRHIC/EIC

arXiv:1409.1633

Peak possible luminosity: ~7x10^{33}cm^{-2}s^{-1}, but staging from lower luminosity and energy is still compelling and typical for a new collider.

Science potential at the MuIC



EIC → MuIC:
up to two orders of magnitude extension in Q^2 and x

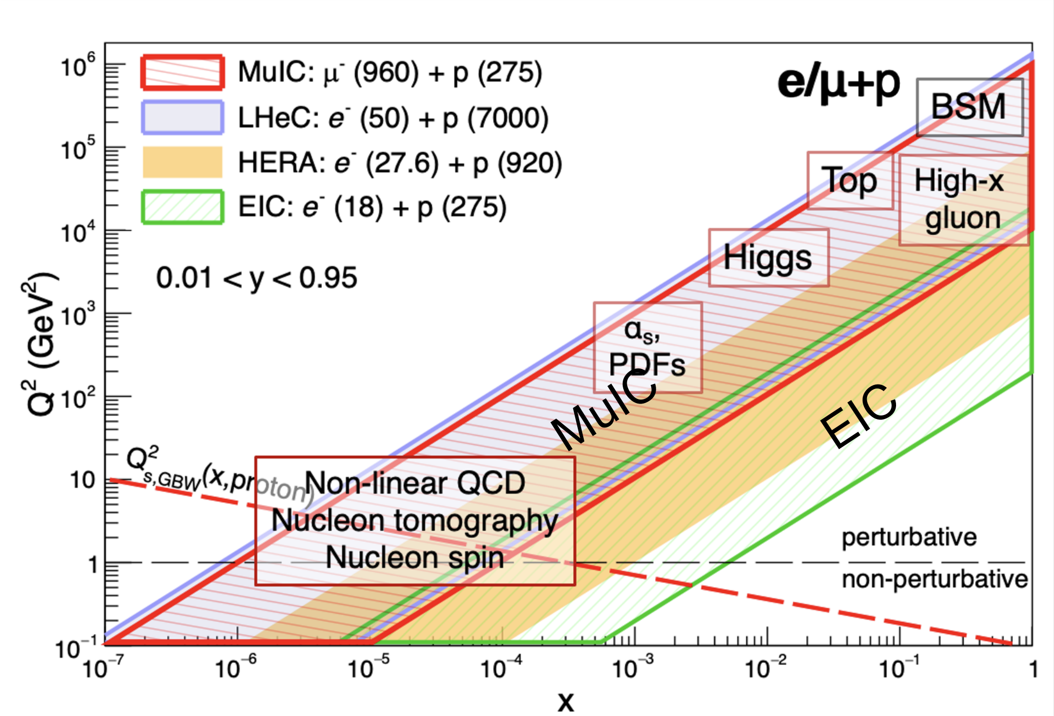
Similar to LHeC in √s but very different final-state kinematics

MuIC: μ(960)+p(275), y_{cm} = -0.63 vs. LHeC: e(50)+p(7000), y_{cm} = 2.47

(with beam polarization)

(LHeC physics: arXiv:2007.14491)

Science potential at the MuIC



EIC → MuIC:
up to two orders of magnitude extension in Q^2 and x

Rich physics in NP and HEP!

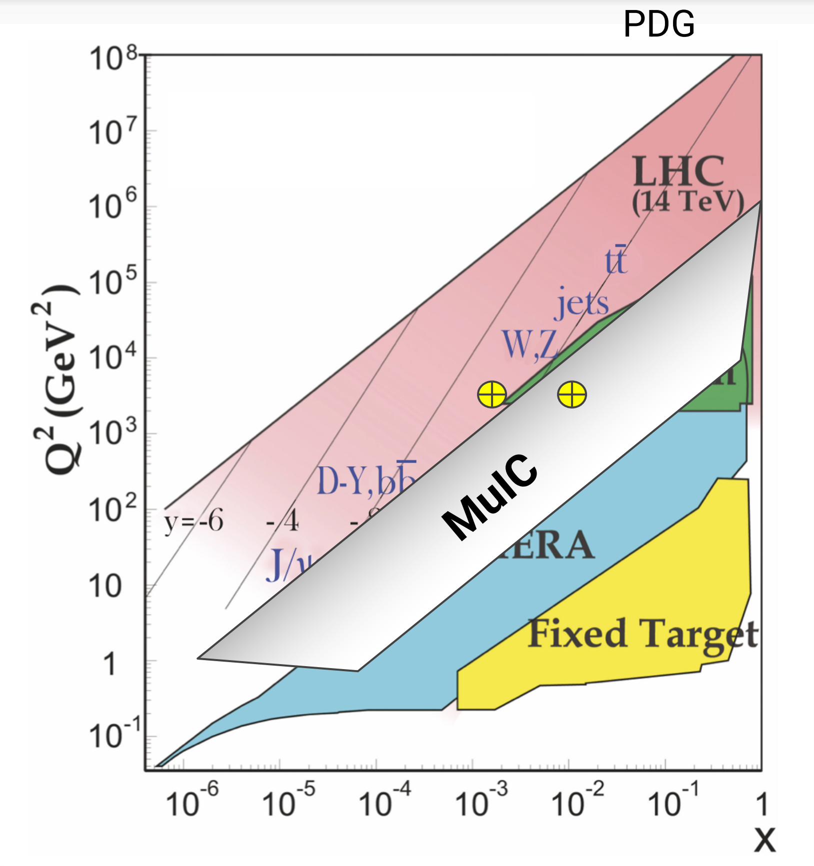
Similar to LHeC in √s but very different final-state kinematics

MuIC: μ(960)+p(275), y_{cm} = -0.63 vs. LHeC: e(50)+p(7000), y_{cm} = 2.47

(with beam polarization)

(LHeC physics: arXiv:2007.14491)

PDF: Complementarity to Hadron Colliders



LHC data also can be used to extract parton densities from Drell-Yan, W, jet, and top production measurements

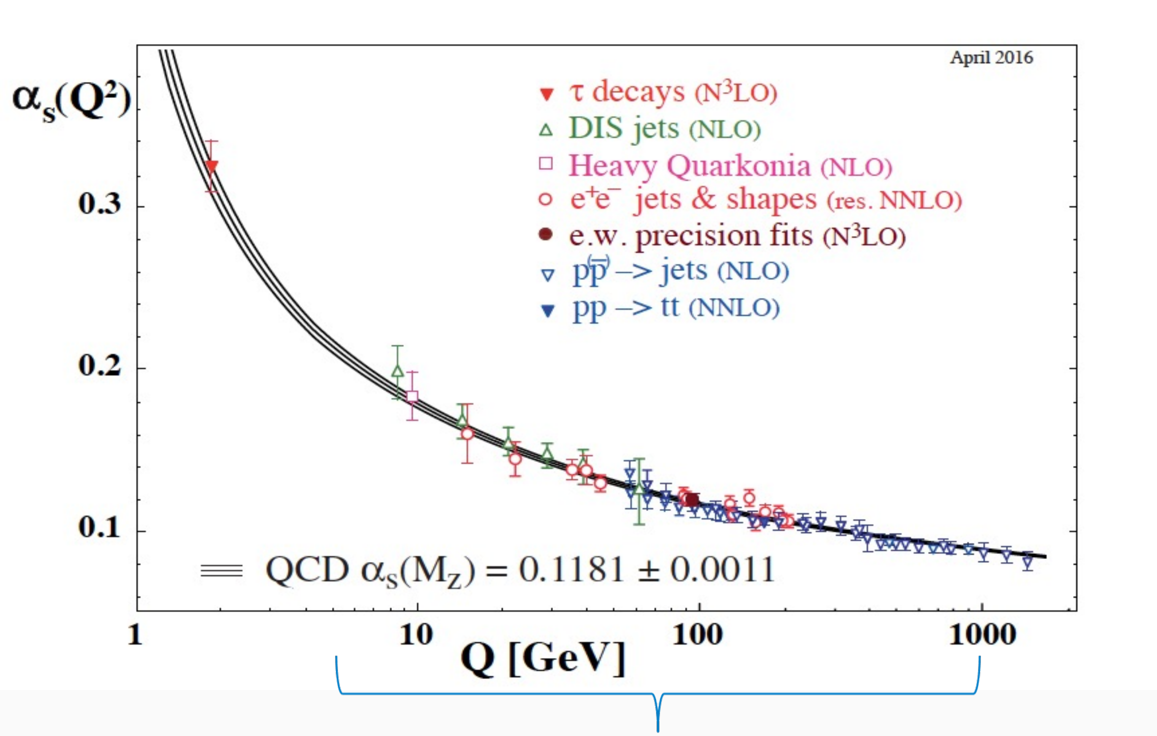
- But it's a bit circular when also trying to measure those cross sections...
- Also convoluted with QCD effects and quark flavor

DIS measurements can more cleanly decouple quark flavor and QCD effects

The MuIC also can directly probe parton densities at the scale for Higgs production at the (HL)LHC and for a future 100 TeV FCChh

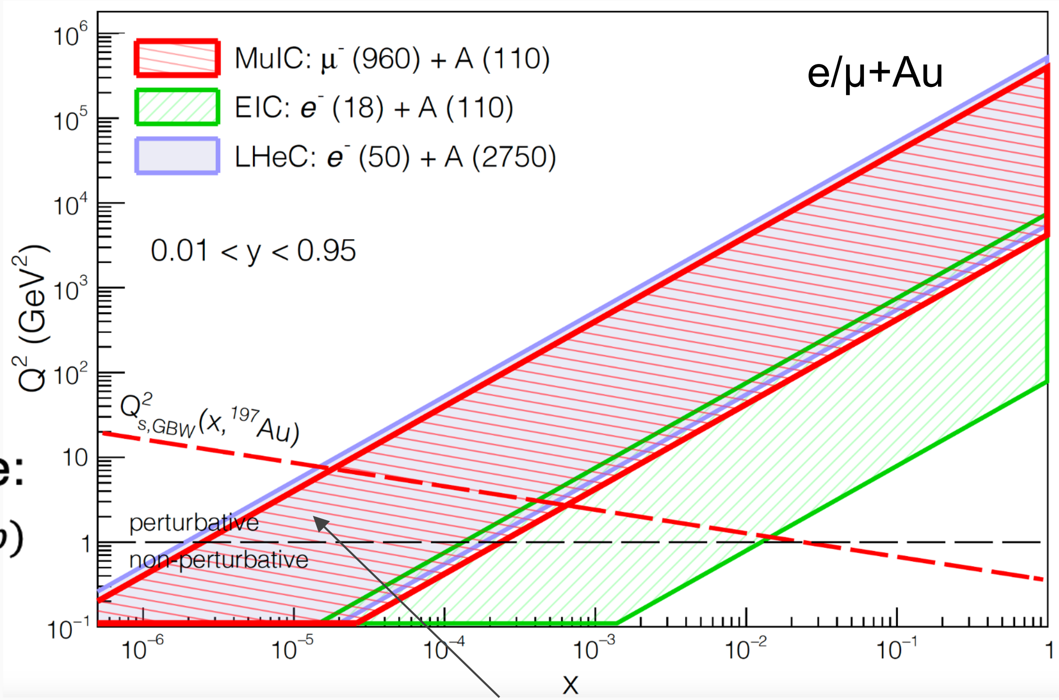
- Less reliant on fit extrapolation → smaller uncertainties on cross sections (<~ 1%)
- Useful input for an FCChh program
  - As HERA was for the LHC

QCD and the Running of α_S

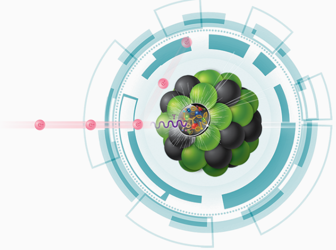


- Measurements can span an even broader range to measure $\alpha_S(Q^2)$ in a **single experiment**
  - Both from QCD evolution fits to structure function data, and from DIS multijet rate measurements
  - Removes some inter-experiment systematics

Science potential at the MuIC



Lepton-ion mode



Saturation scale:

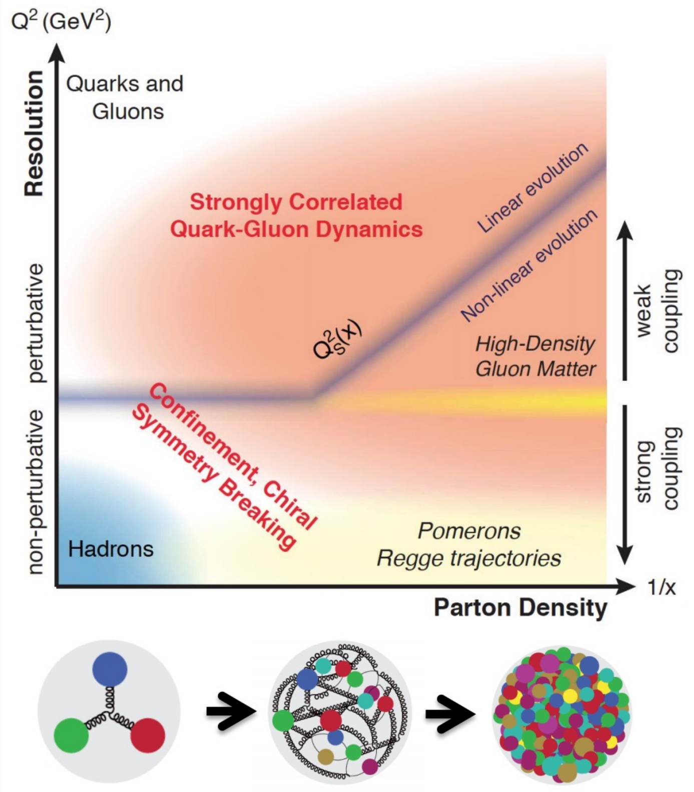
$$Q_s^2(A) = A^{1/3} Q_s^2(p)$$

While the EIC approaches the saturation regime, the MuIC will bring us well into the it to fully explore the non-linear QCD, saturation phenomena

In particular, MuIC can scan a wide range of ion species

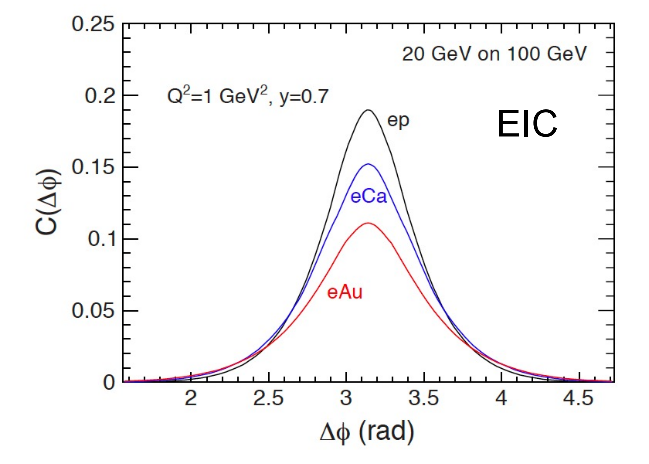
Nuclear Physics at the MuIC

The nucleus: a lab for QCD many-body systems



- Collective behavior of dense gluonic matter
- Propagation of color charges in a nuclear medium

Suppression of back-to-back correlations

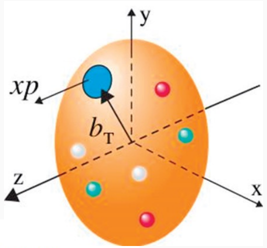


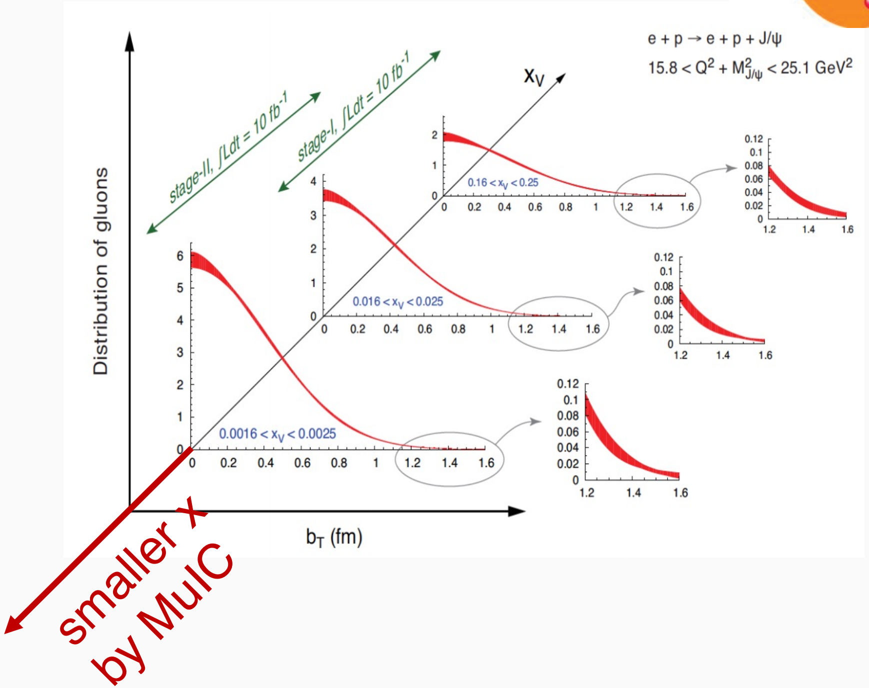
MuIC will unambiguously discover saturation at x ~ 10^{-5}

Nuclear Physics at the MuIC

Origin of nucleon mass

3D Nucleon structure

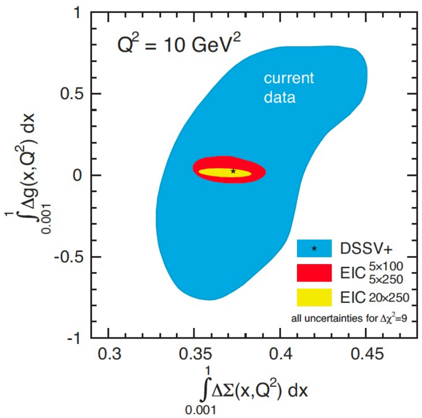




Nucleon spin puzzle

"Helicity sum rule"

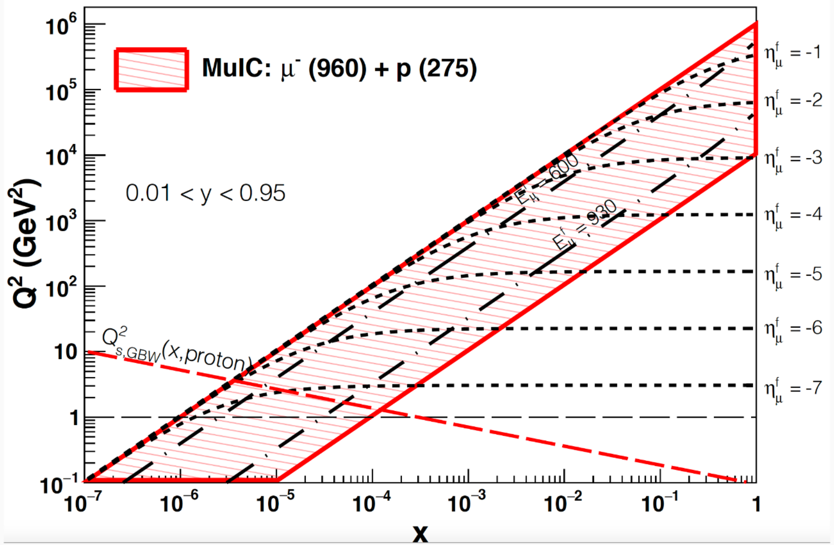
$$\frac{1}{2}\hbar = \frac{1}{2}\underbrace{\Delta\Sigma}_{\text{quark contribution}} + \underbrace{\Delta G}_{\text{gluon contribution}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{orbital angular momentum}}$$



MuIC to reach x ~ 10^{-5}

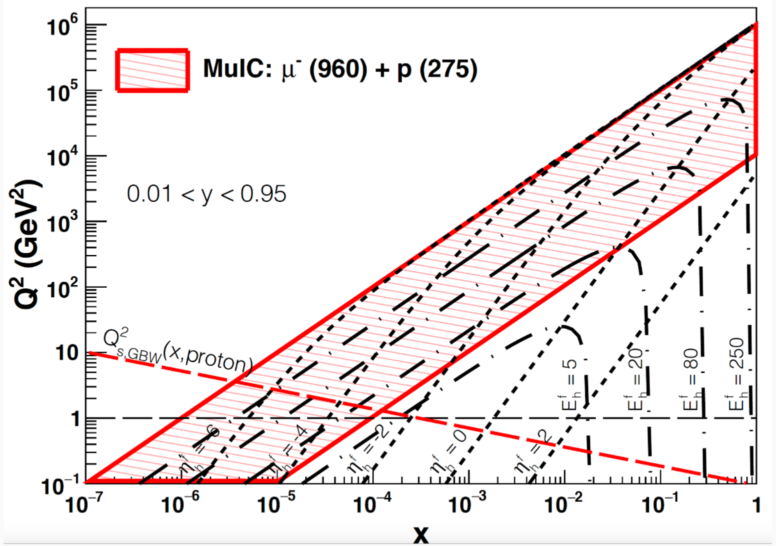
Detector requirements and design

Kinematics for scattered muon



High-energy muons very backward ($-7<\eta<-1$)

Kinematics for struck quark (jets)

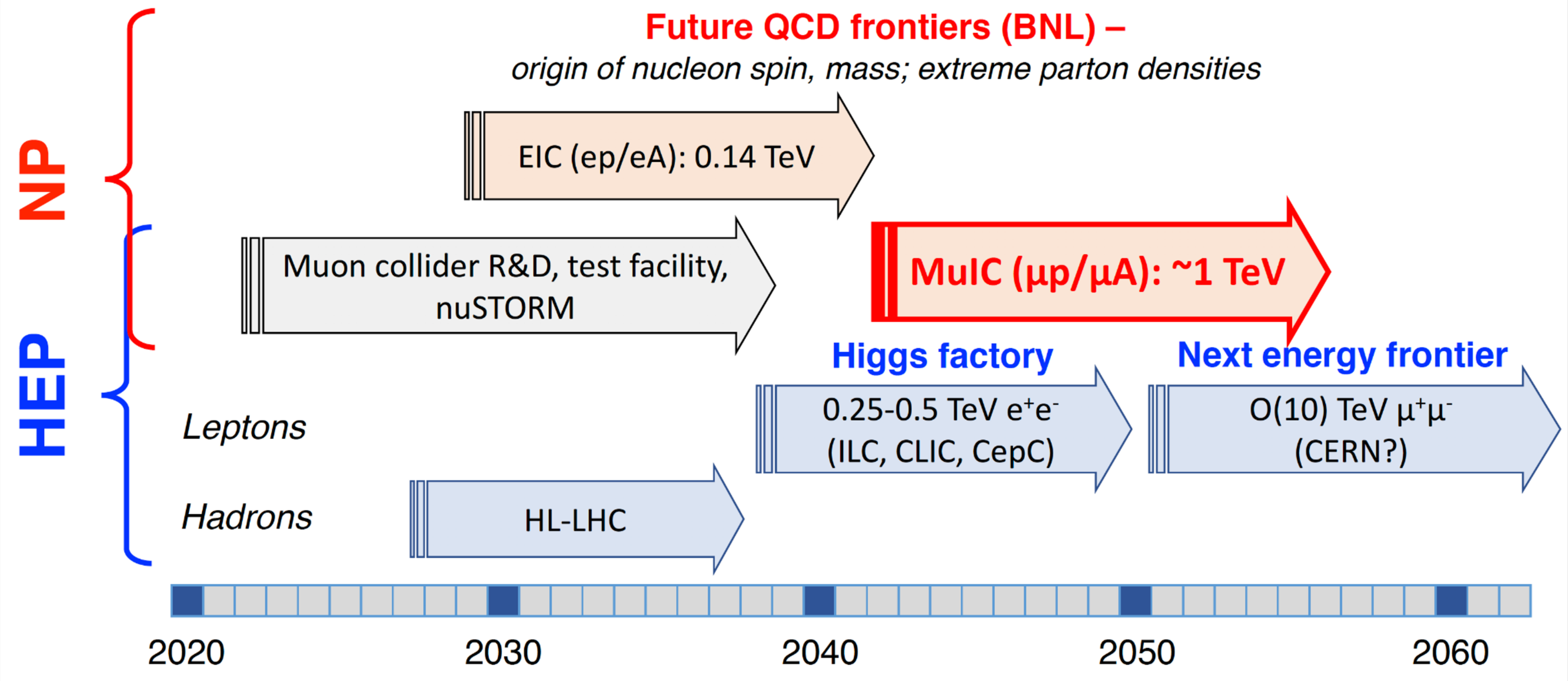


Jet largely central and backward ($-4<\eta<2$)

Distinct experimental challenges from EIC:

- muon detection crucial – far-backward muon spectrometer
- muon beam induced backgrounds – high granularity, timing detectors

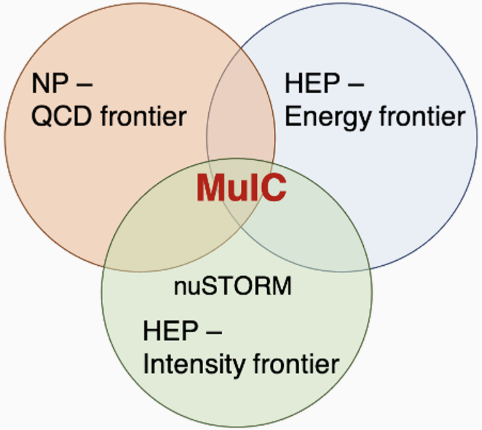
Path forward (in our view)



A possible roadmap to future muon colliders in NP and HEP

Summary and next steps

Key merits of MuIC concept:



- Compelling sciences with synergies across NP, HEP energy and intensity (e.g, nuSTORM) frontiers
- Serves as a demonstrator or staging option to establish the muon collider technology toward the ultimate O(10+) TeV μ+μ- (CERN?)
- Affordable as an "upgrade" to the EIC by re-using the existing facility, infrastructure, accelerator expertise
- A unique muon collider sited in US with a clear design goal by join efforts of HEP and NP communities, and even attracting worldwide interests

Summary and possible next steps

Next steps:

- In discussion with accelerator experts in AF4 and muon collider forum and preparing a white paper on muon-ion collider (ideas, suggestions from EF06 very welcome!). Also bring up the idea to the next NP LRP (possiblely in 2022).
- Try to engage BNL to consider MuIC as a future option of the lab, to start conceiving a possible design, revive muon collider R&Ds in US, and establish test facilities in collaboration with US HEP, IMCC.
- Engage broader theoretical and experimental communities to fully explore physics potential and study detector design requirements/challenges (workshops, collaboration/working groups)

Extras

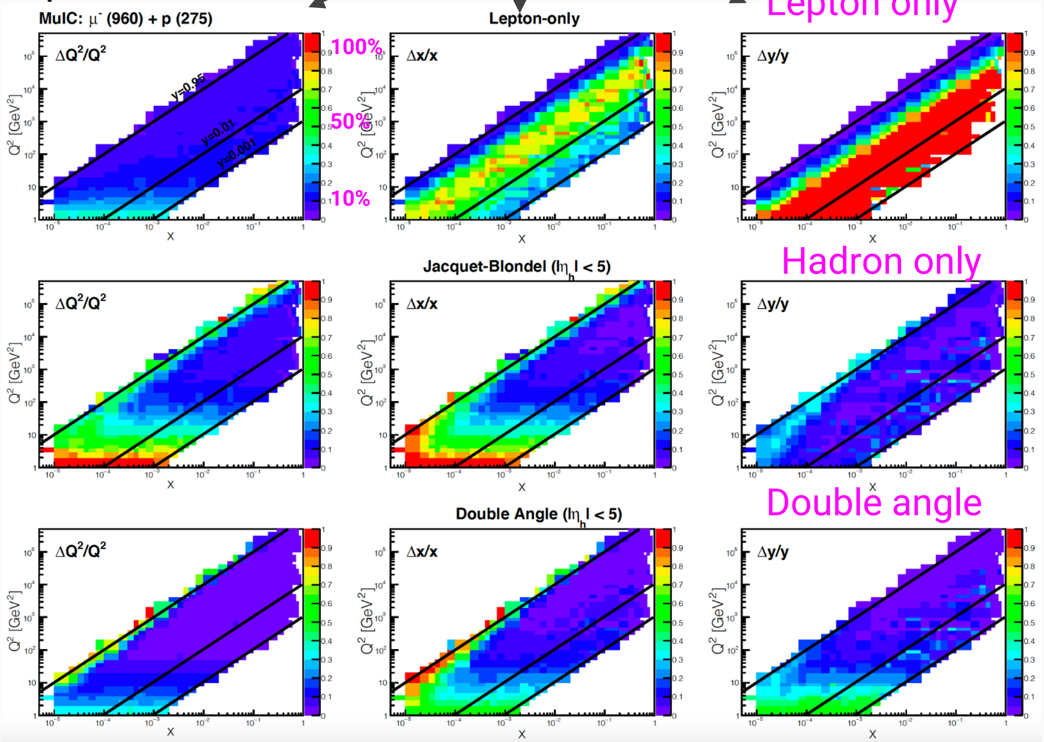
Detector requirements and design

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	$0.01\%\, p \otimes 1\%$	0.2×10^{-3}
Charged particles ($\pi^\pm, K^\pm, p/\bar{p}, e^\pm$)	Tracker + PID	$0.1\%\, p \otimes 1\%$	$\left(\frac{2}{p}\otimes 0.2\right)\times10^{-3}$
Photons	EM Calorimeter	$\frac{10\%}{\sqrt{E}} \otimes 2\%$	$\frac{0.087}{\sqrt{12}}$
Neutral hadrons (n, K_L^0)	Hadronic Calorimeter	$\frac{50\%}{\sqrt{E}} \otimes 10\%$	$\frac{0.087}{\sqrt{12}}$

Resolutions of reconstructed Q^2, *x* and *y* with 3 methods

Q^2 vs. x plane:



Future work with detailed simulations to fully demonstrate the experimental feasibility

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}

An order of magnitude beyond the HERA ep collider

Build a science case for **a TeV muon storage ring** as a demonstrator for a multi-TeV $\mu+\mu-$ collider

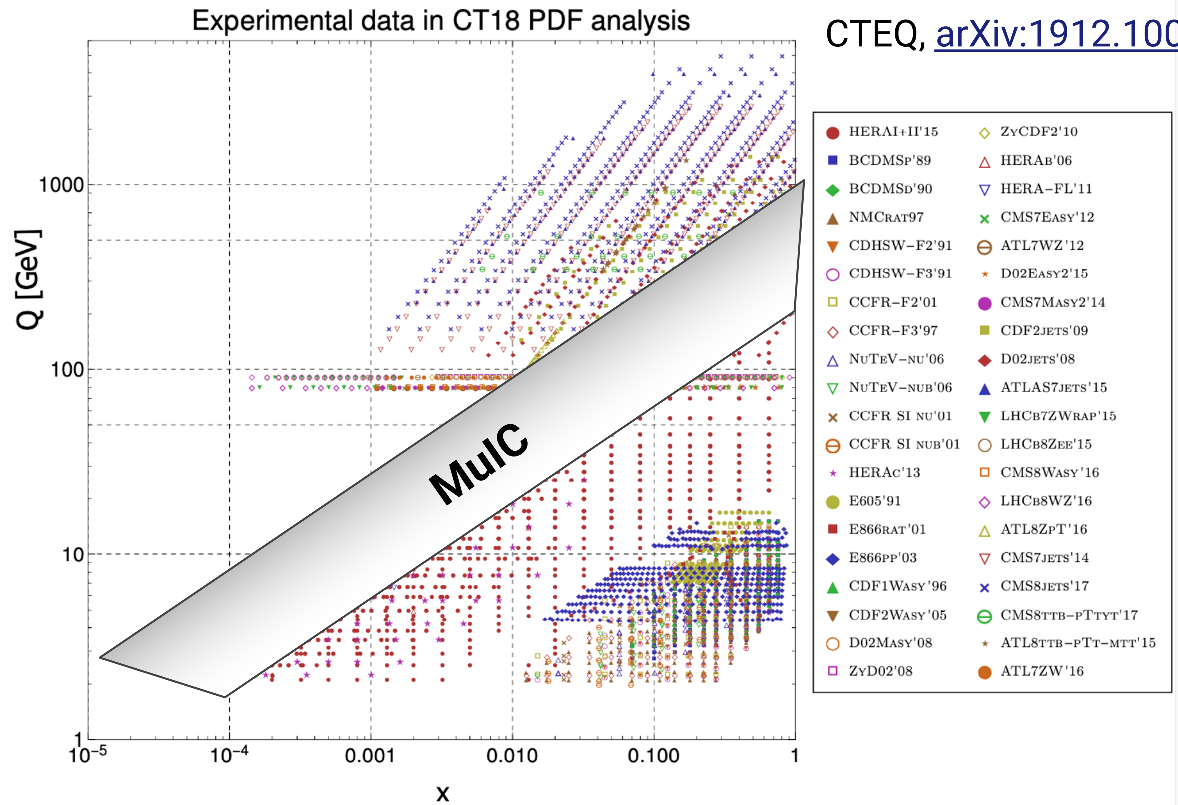
- QCD and hadron/nucleon structure in new regimes
- Higgs, Top, BSM

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)

Science potential at the MuIC: PDF Measurements

CTEQ, [arXiv:1912.10053]



← Data used for global CTEQ fits

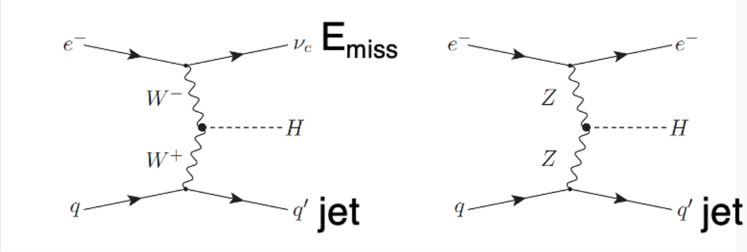
The MuIC would definitely probe new territory

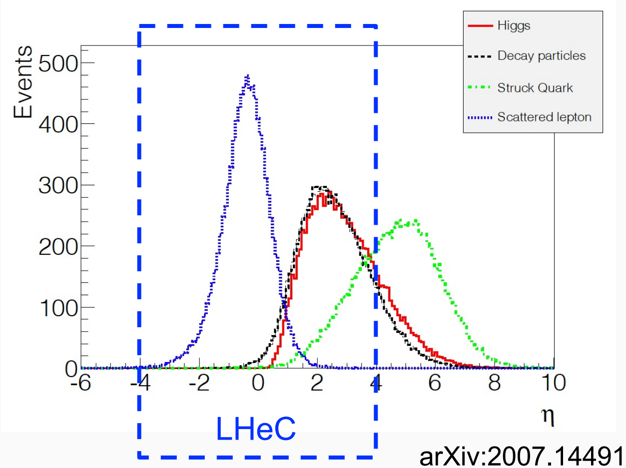
Muon-Ion Collider at BNL

Some specific questions/challenges to address :

- Can we preserve muon beam polarization during acceleration? Muons can be extracted with 20-50% polarization.
- Is neutrino radiation a concern, for a single muon beam of ~ 1 TeV? RHIC/EIC is on the surface.
- To what extent, parts of EIC can be re-used? Can MuIC be fit into the EIC tunnel? Financial implications …

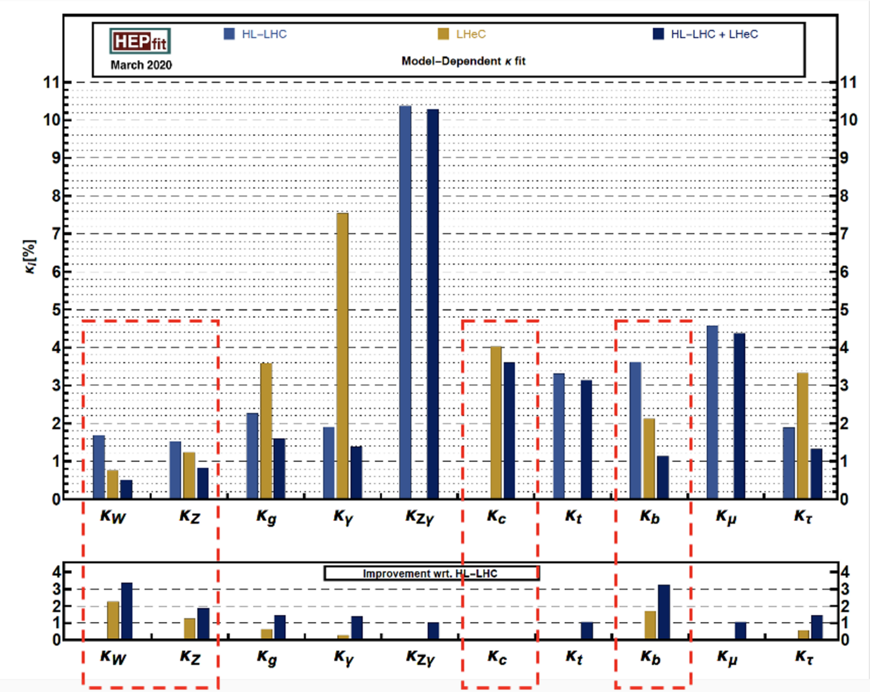
Higgs at the MuIC





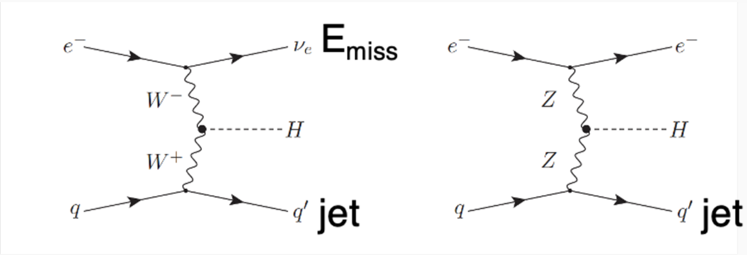
arXiv:2007.14491

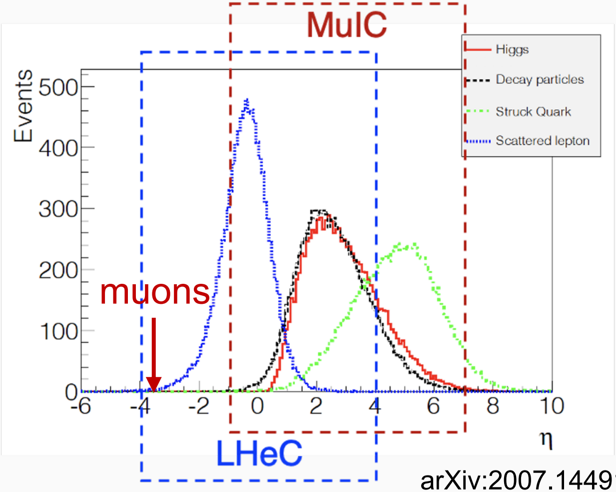
Uncertainties of Higgs couplings



LHeC outperforms HL-LHC with L_{int} = 1/ab in $\kappa_W, \kappa_Z, \kappa_b, \kappa_c$

Higgs at the MuIC





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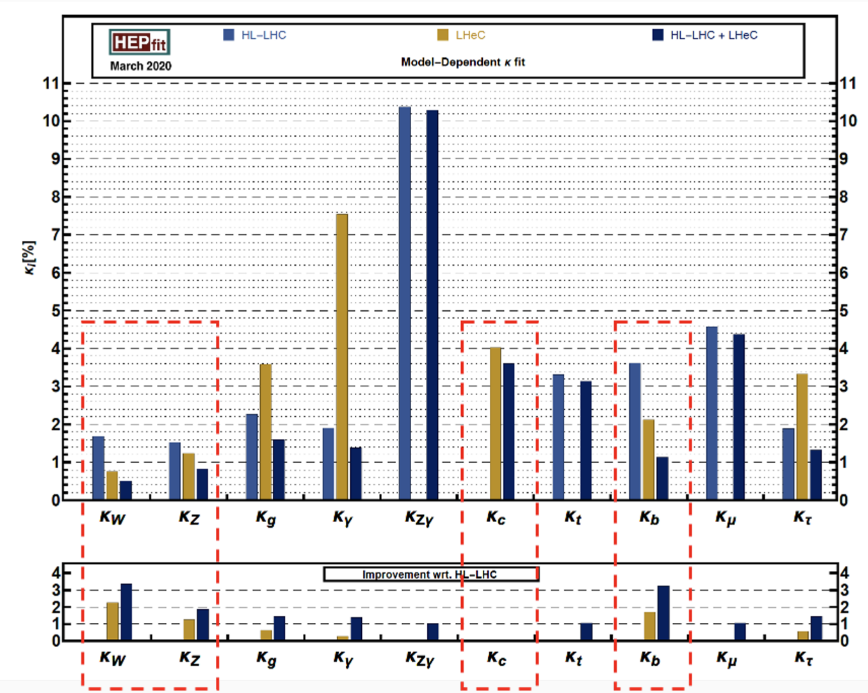
At MuIC, kinematics for Higgs, jets more favorable but scattered muon is very forward.

Uncertainties of Higgs couplings

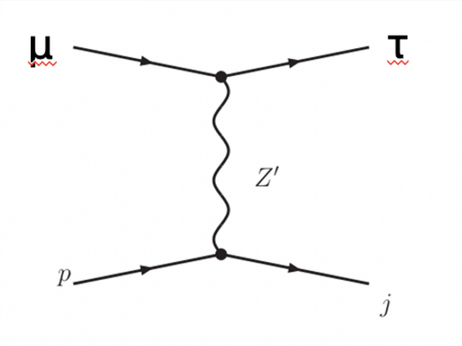


LHeC outperforms HL-LHC with L_{int} = 1/ab in κ_W, κ_Z, κ_b, κ_c

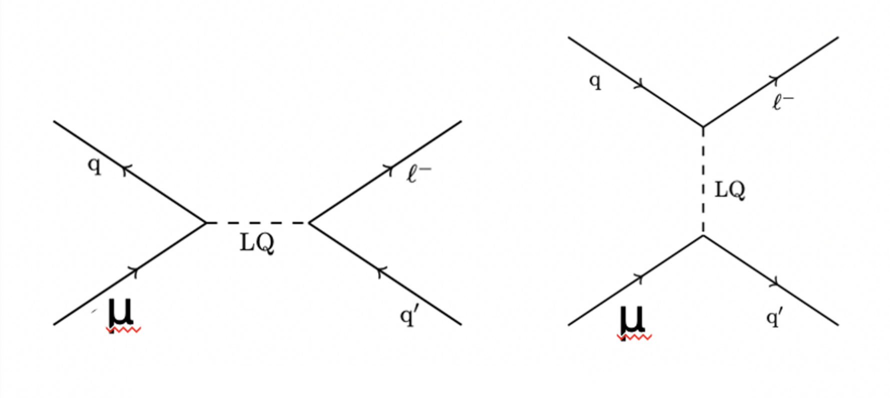
Searches for BSM physics at the MuIC

Searches for charged lepton flavor violation

$\mu + N \rightarrow \tau + N$



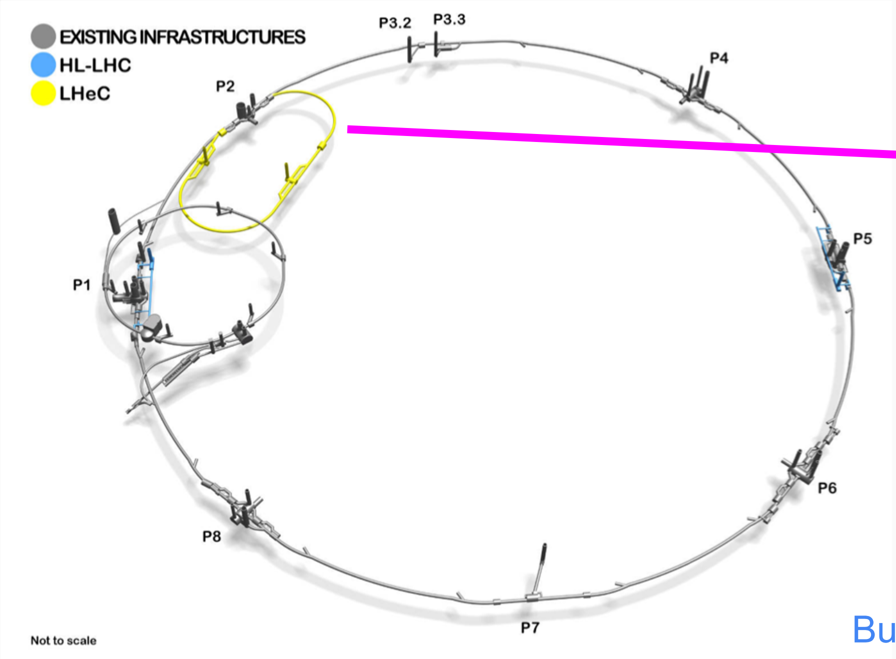
Leptoquarks coupled to μ

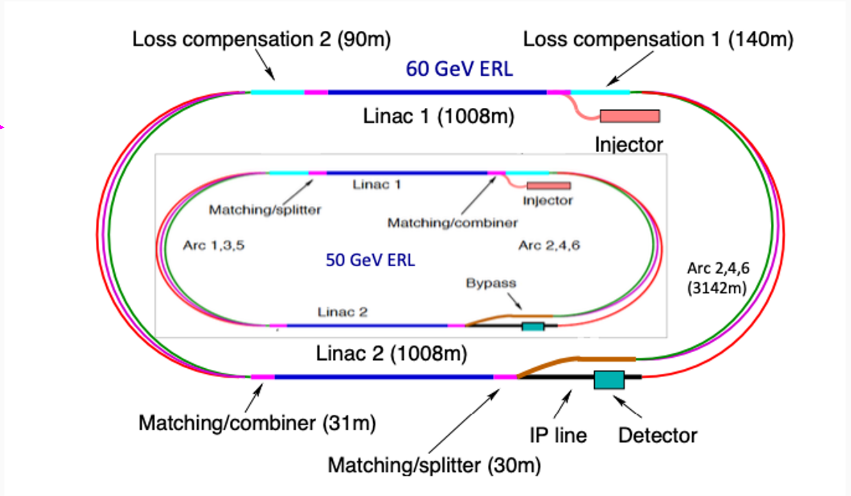


One Approach: the Large Hadron Electron Collider

LHeC: arXiv:2007.14491

- LHeC: **50 – 60 GeV e^- on 7 TeV p** ($\sqrt{s}$ = 1.2–1.3 TeV)
  - Two oppositely directed linacs and 3 arcs
  - Two design options: 50 GeV (smaller) vs. 60 GeV (larger, more expensive)





But how realistic is this option for the HL-LHC timescale?