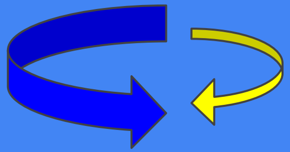


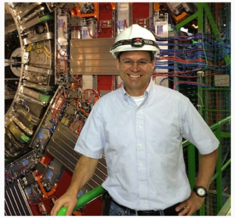
A Muon-Ion Collider at BNL

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)

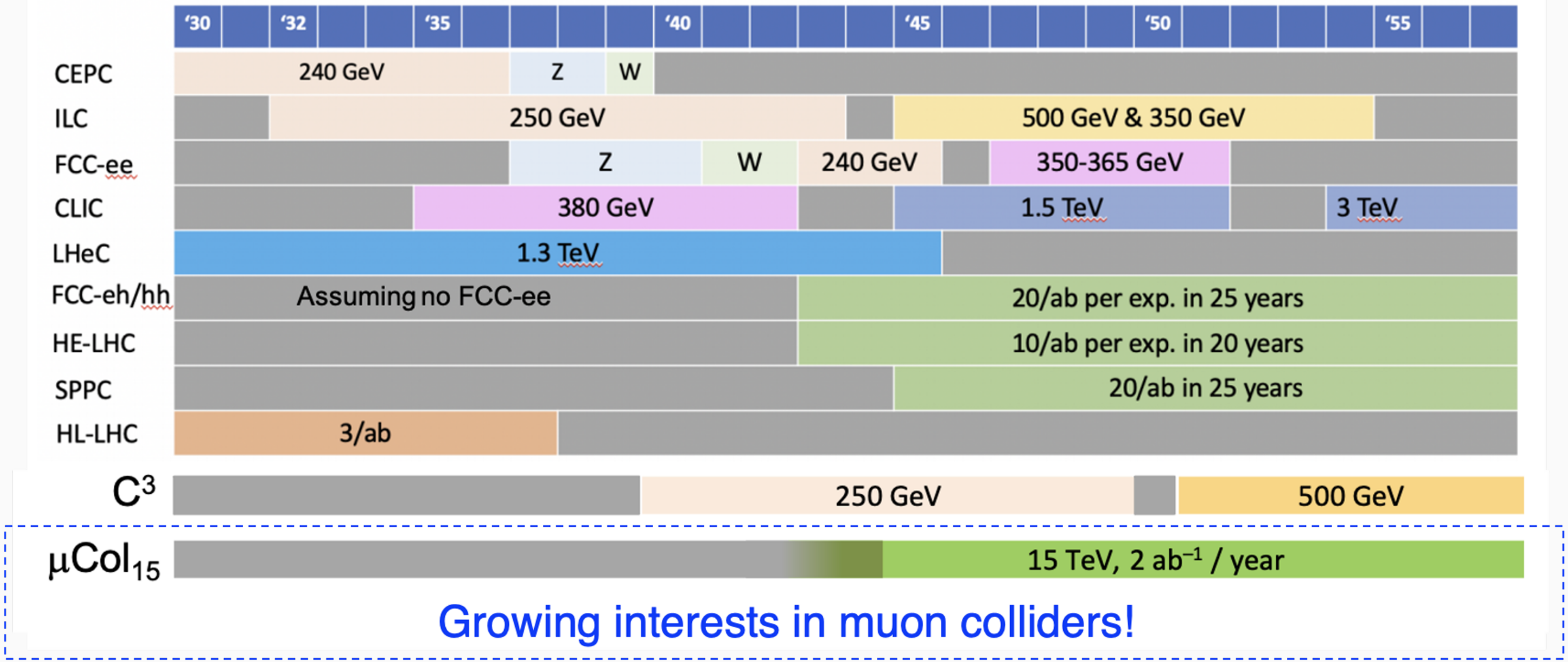
Many examples of successful synergies between HEP and NP in CMS in physics measurements, detector design, operations and upgrades

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...

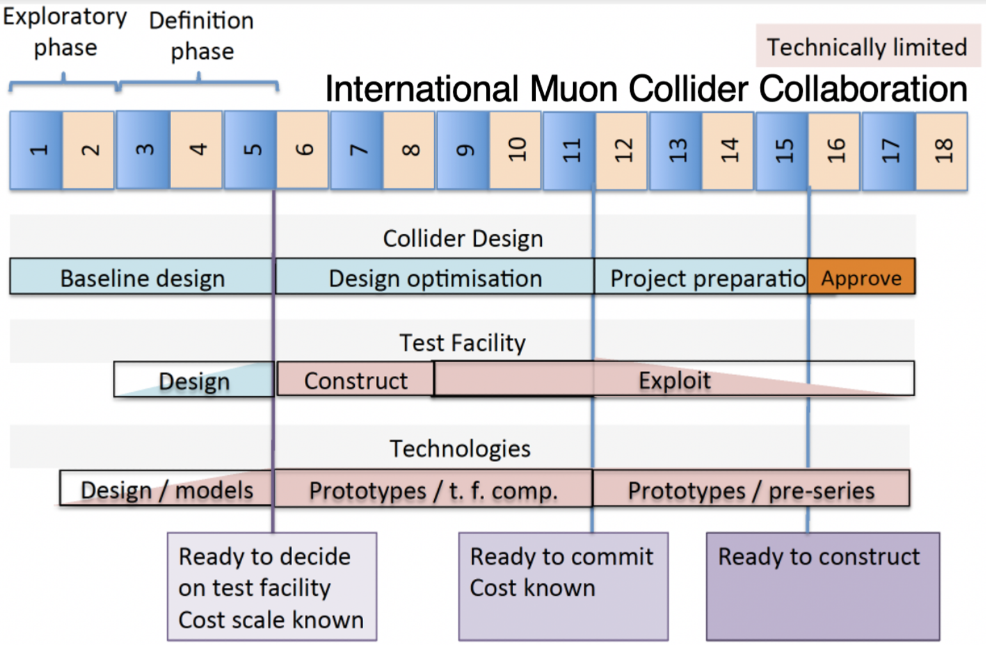
Future of HEP energy frontier

S. Dasu



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

Potential timeline of muon colliders



Physics potential along the way D. Schulte Ultimate Beam Limits, April 6, 2021 arXiv:1901.06150 4

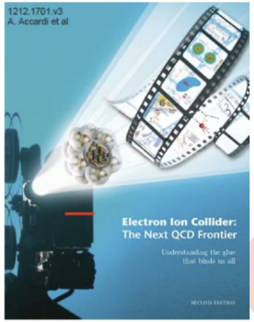
A vigorous and ambitious R&D program is needed to assess the feasibility of a tens-of-TeV's muon collider. Therefore it is important to investigate the physics potential of smaller-scale machines that might be built along the way as technology demonstrators. Starting from medium energy, the first option to be considered is a muon collider operating around the top production threshold ($\sim$ 400 GeV). This

A demonstrator with compelling science is needed before going to O(10+) TeV

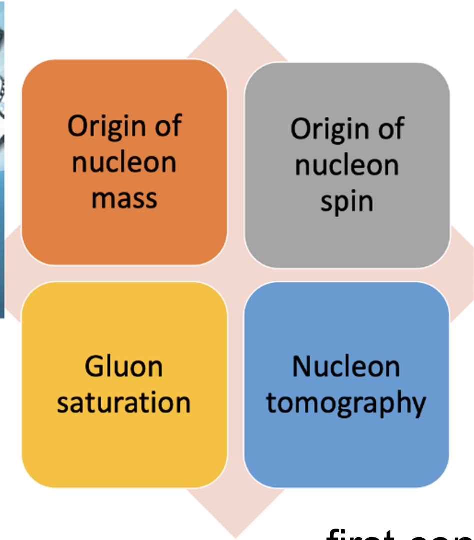
Future of NP in USA

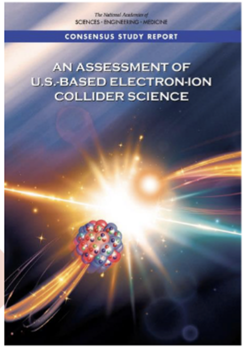
Electron-Ion Collider at BNL (2030-) **– a new QCD frontier**

(CD-1, funded by DOE-NP)

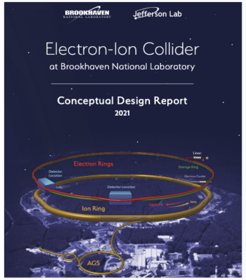


White paper
arXiv:1212.1701

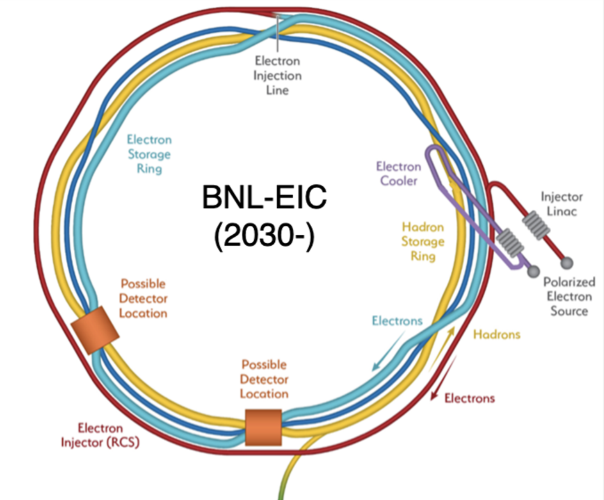


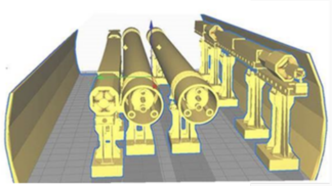


NAS report
July 2018



CDR 2021





first conceived in late 90s

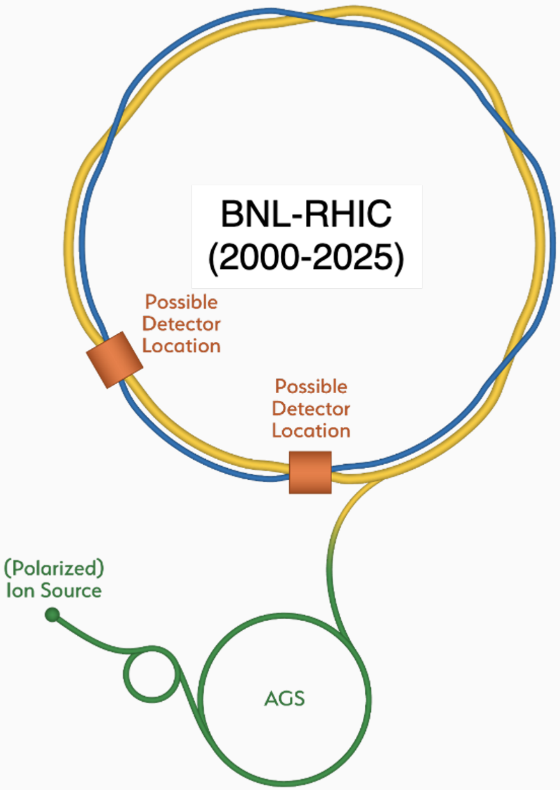
ep, eA (any ion in periodic table) up to 140 GeV;
Polarized e, p, ^{3}He beams (70% polarization)

What's after EIC?

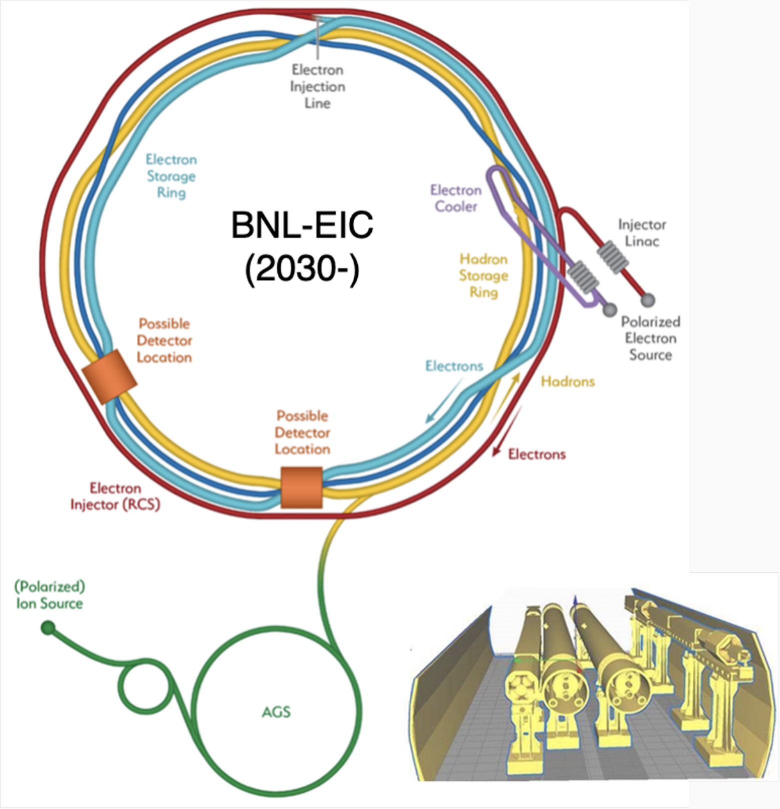
Electron-Ion Collider at BNL

pp, pA, AA up to 500 GeV

ep, eA up to 140 GeV



upgrade



Electron-Ion Collider at BNL

One of hadron storage rings is re-used.

RHIC infrastructure (existing tunnel) is re-used as much as possible.

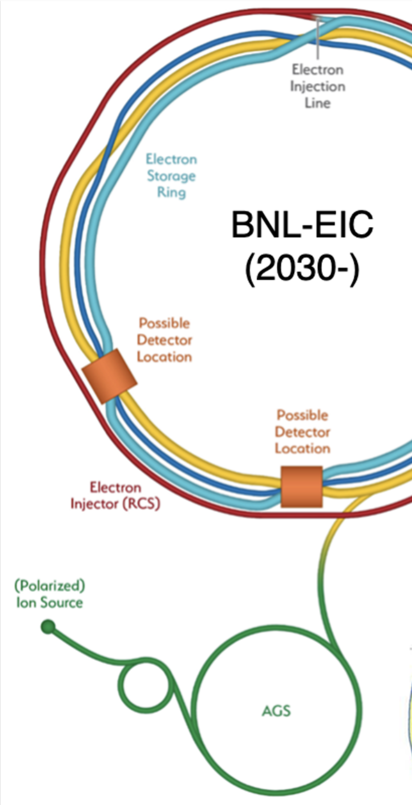
Additions to RHIC:

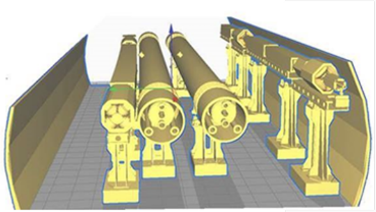
- Polarized electron source
- LINAC
- Rapid-cycling synchrotron (RCS) in the RHIC tunnel.
- A new electron storage ring in the RHIC tunnel.

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

- U.S. accounting, including detectors

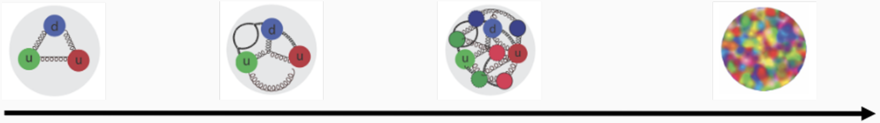
ep, eA up to 140 GeV



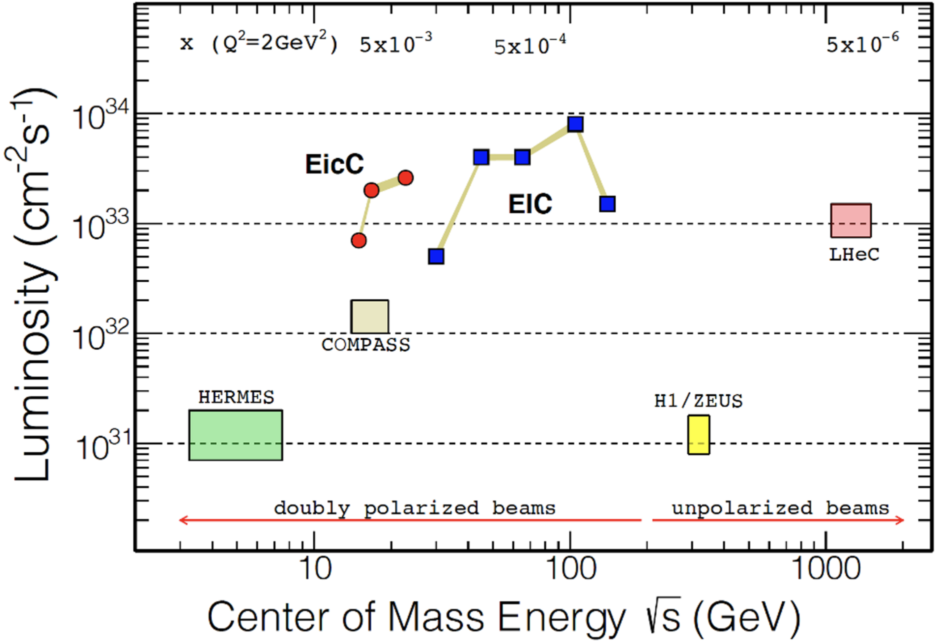


6 straight sections for acceleration

DIS at lepton-hadron colliders



Gluon saturation



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

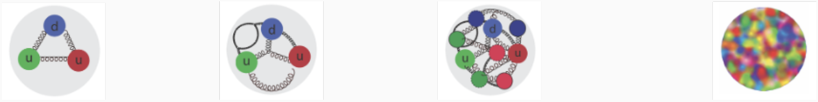
EIC at BNL – lowish energy but high luminosity, doubly polarized, ions

What's after EIC?

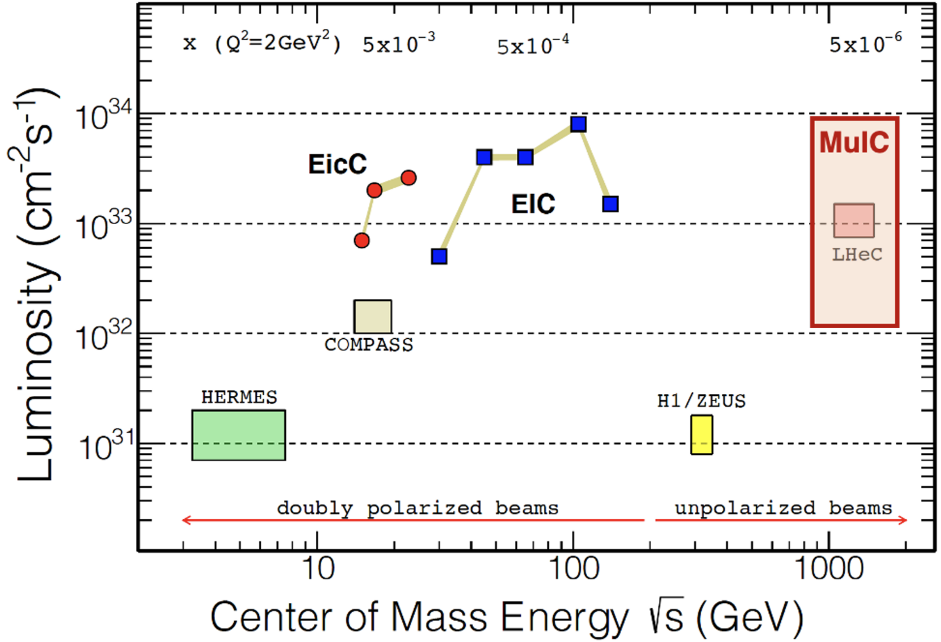
- LHeC (arXiv:2007.14491)?

(*) 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

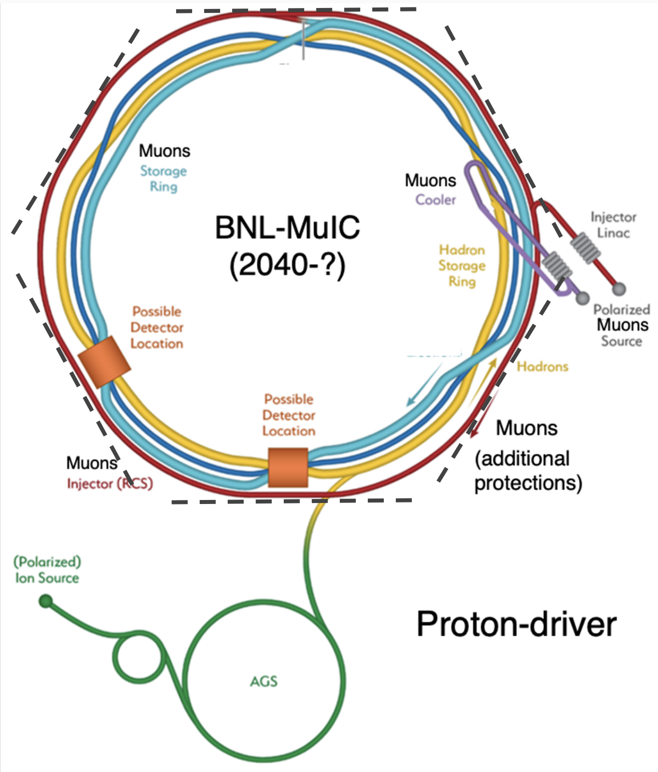
What's after EIC?

- 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

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

The more interaction points,
the better before muons decay …

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

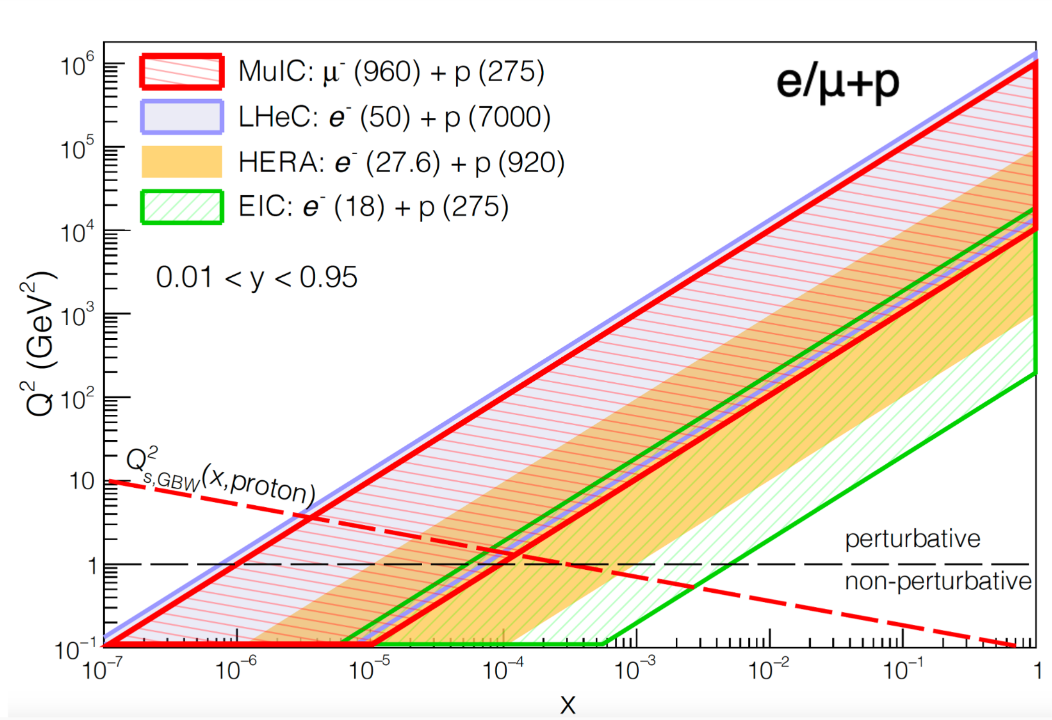
Build a science case for **a TeV muon storage ring** as a demonstrator for a multi-TeV μ+μ- collider

- 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

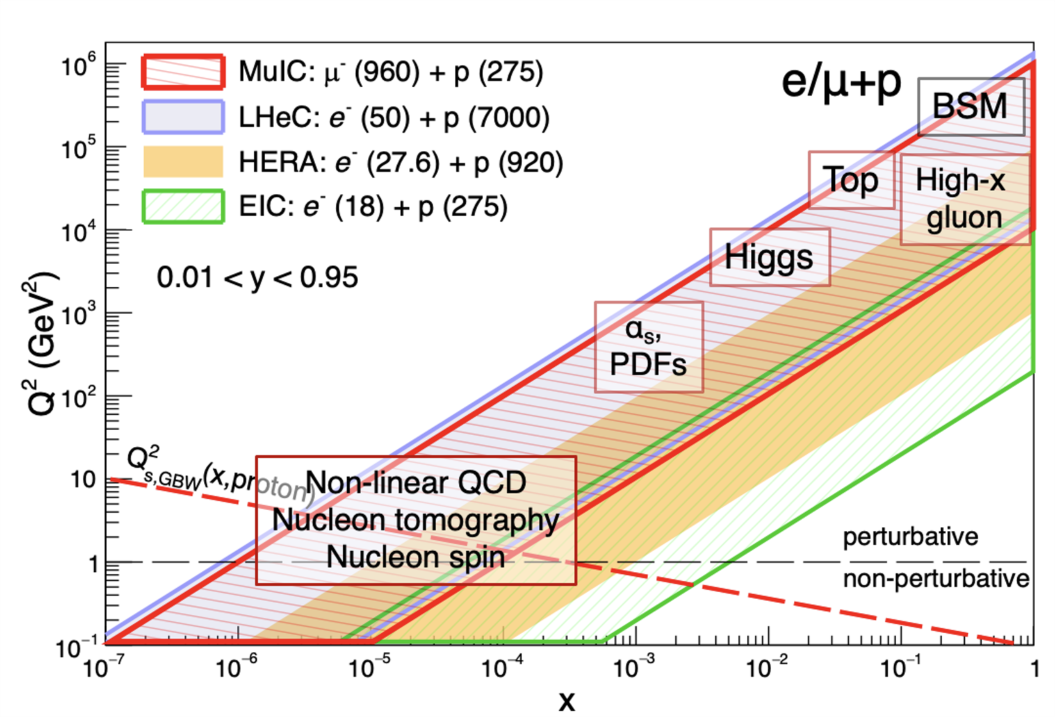


MuIC: μ(960)+p(275), y_{cm} = -0.63 vs. LHeC: e(50)+p(7000), y_{cm} = 2.47

(LHeC physics: arXiv:2007.14491)

Similar √s but very different final-state kinematics

Science potential at the MuIC



Rich physics in NP and HEP!

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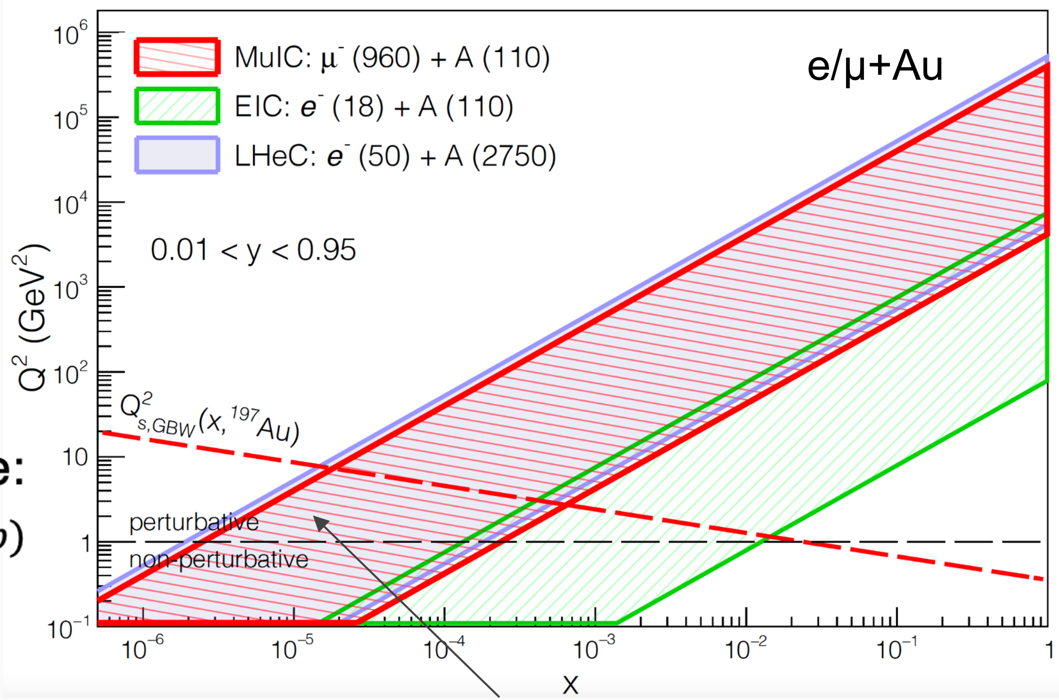


Rich physics in NP and HEP!

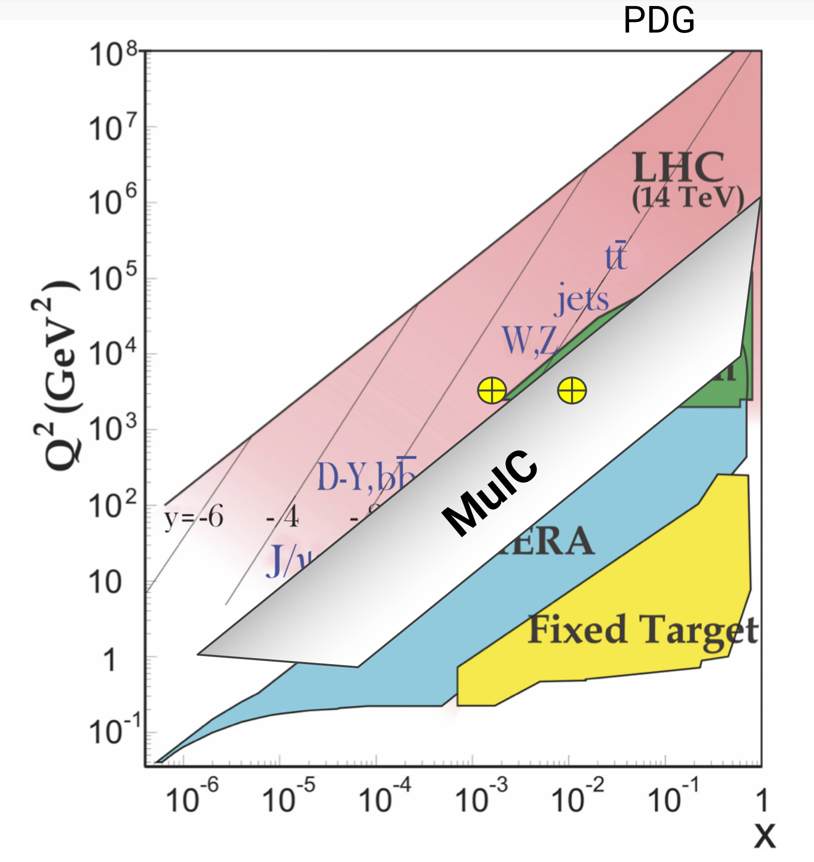
Saturation scale:

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

In eA mode, saturation or non-linear QCD region of extreme parton densities is well within the reach

MuIC can scan a wide range of ion species

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

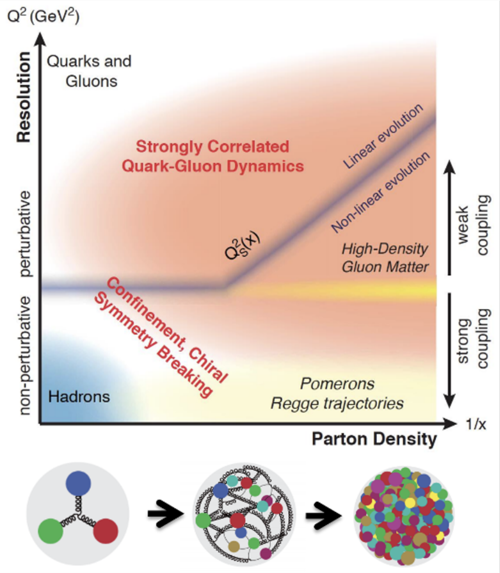
DIS measurements can more cleanly decouple quark flavor and QCD effects

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

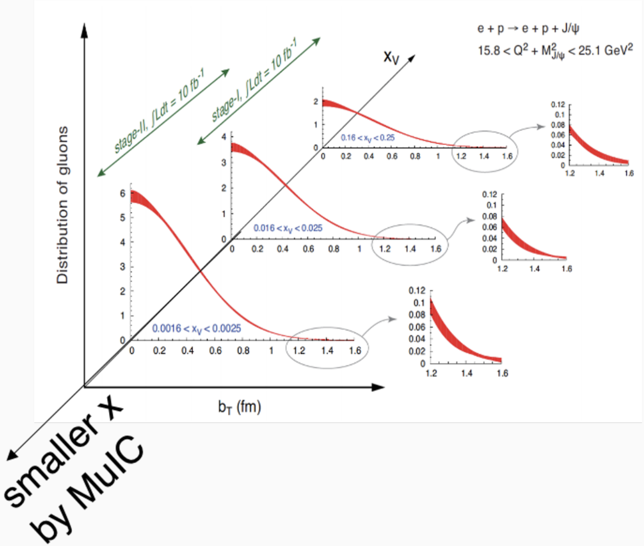
Nuclear Physics at the MuIC

Gluon saturation



What's the property of high-density gluon matter

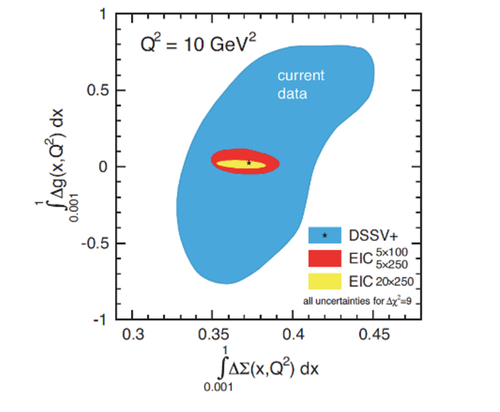
3D Nucleon structure



Nucleon spin puzzle

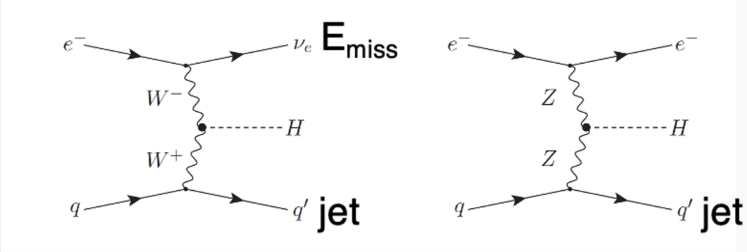
"Helicity sum rule"

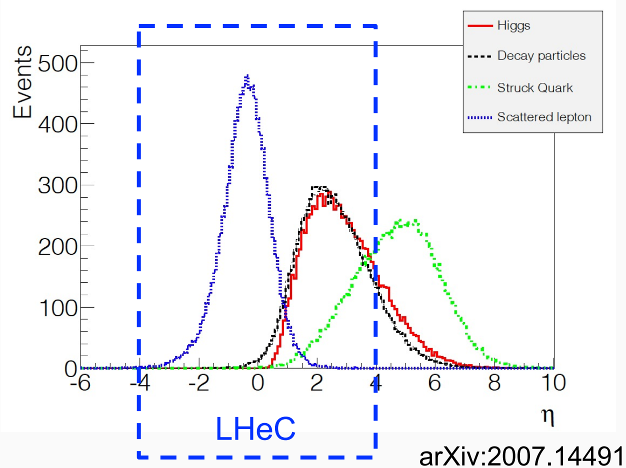
$$\frac{1}{2}\hbar = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quark contribution}} + \underbrace{\Delta G}_{\text{gluon contribution}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{orbital angular momentum}}$$



MuIC to reach $x \sim 10^{-5}$

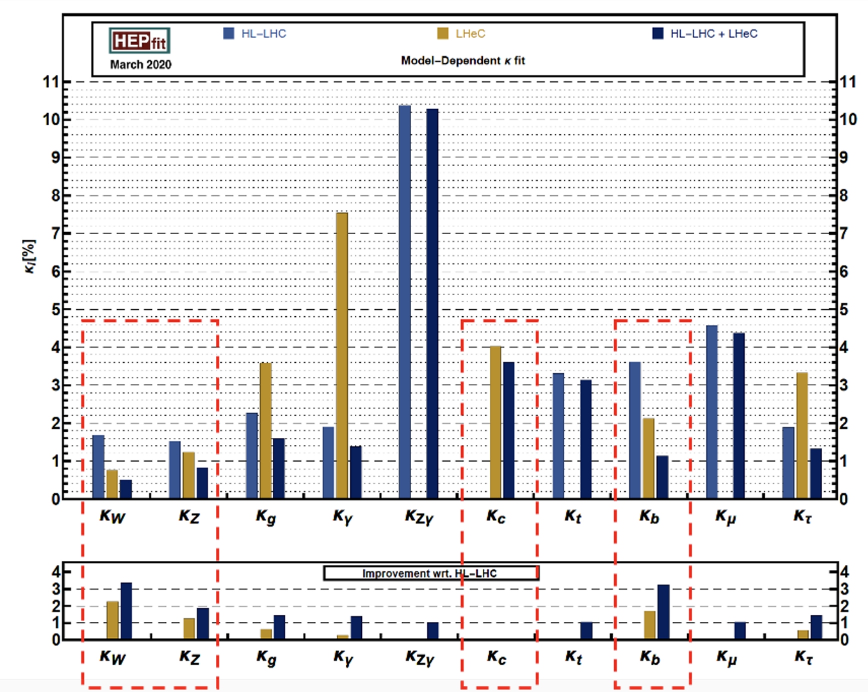
Higgs at the MuIC





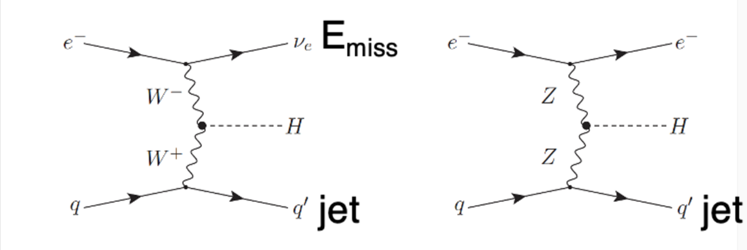
arXiv:2007.14491

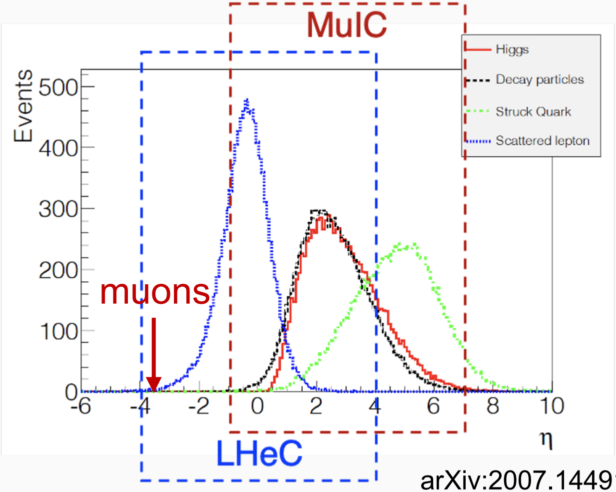
Uncertainties of Higgs couplings



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

Higgs at the MuIC

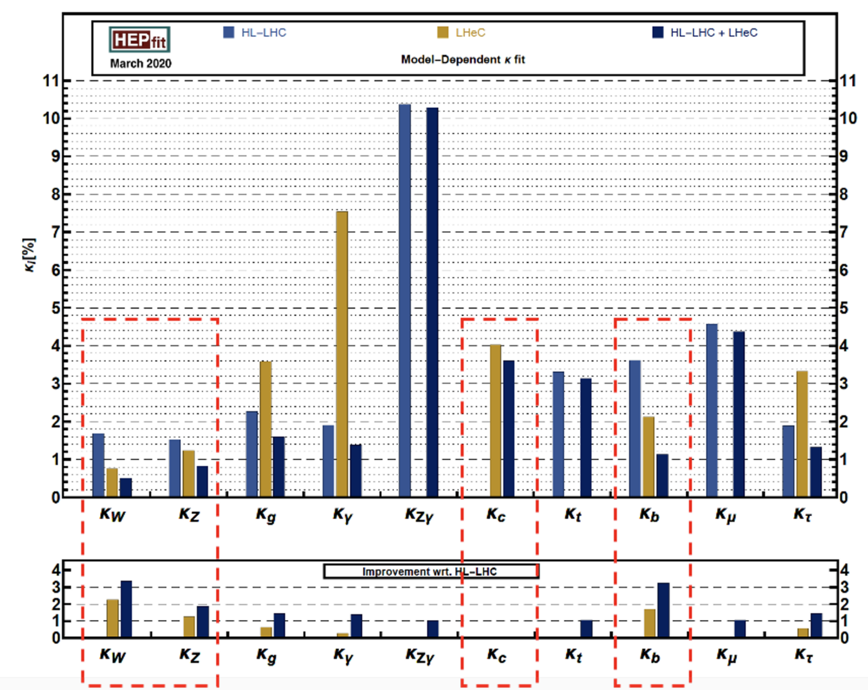




arXiv:2007.14491

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

Uncertainties of Higgs couplings

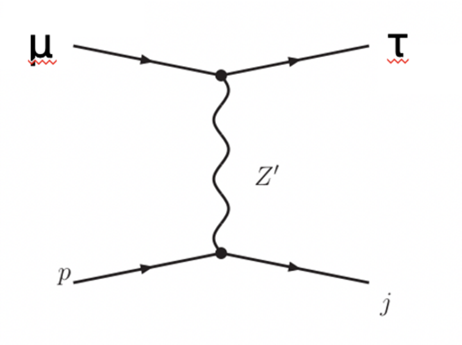


LHeC outperforms HL-LHC with L_{int} = 1/ab in κ_W, κ_Z, κ_b, κ_c

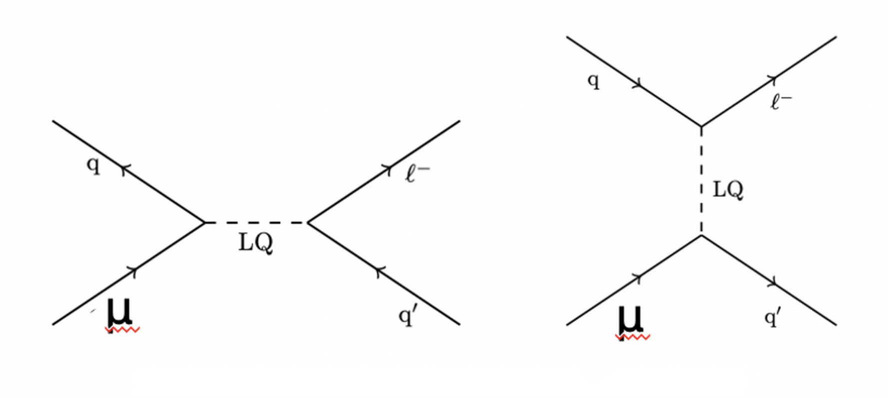
Searches for BSM physics at the MuIC

Searches for charged lepton flavor violation

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

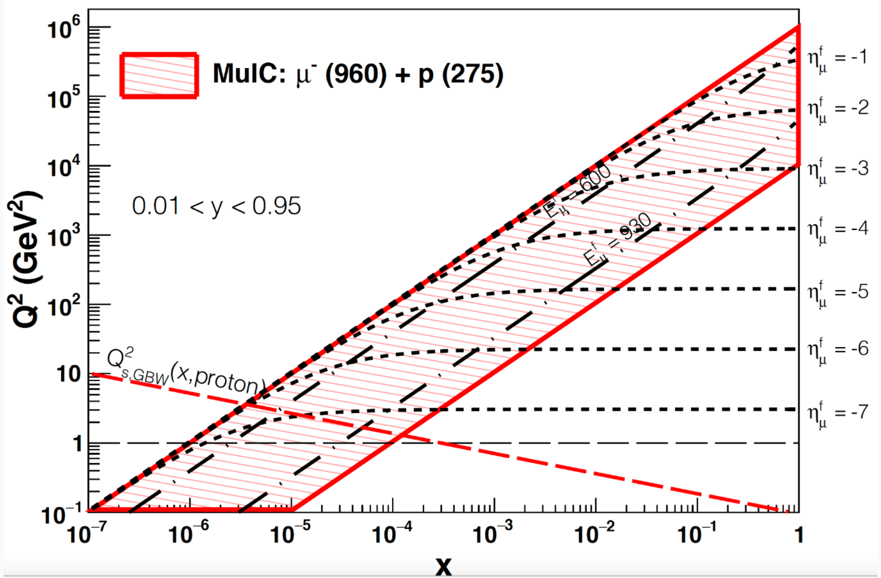


Leptoquarks coupled to μ

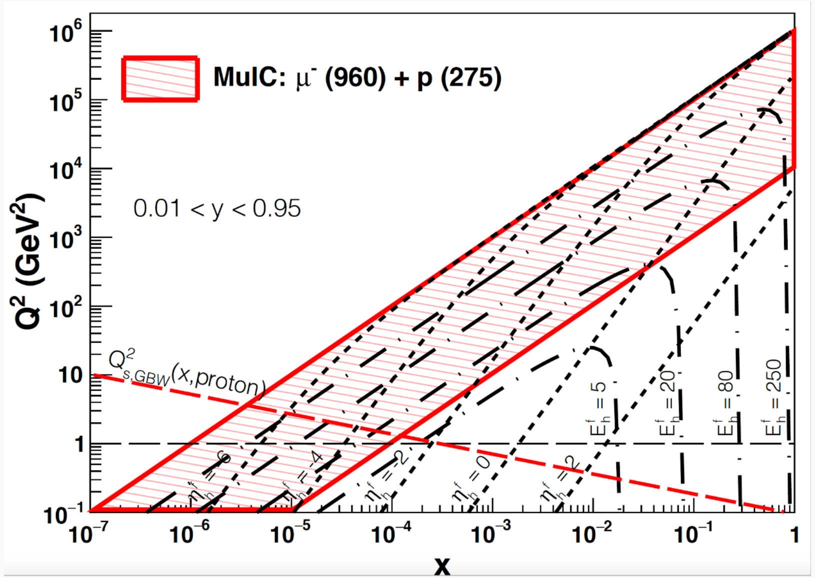


Detector requirements and design

Kinematics for scattered muon



Kinematics for struck quark



Muons very forward ($-7<\eta<-5$) at low Q^2

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

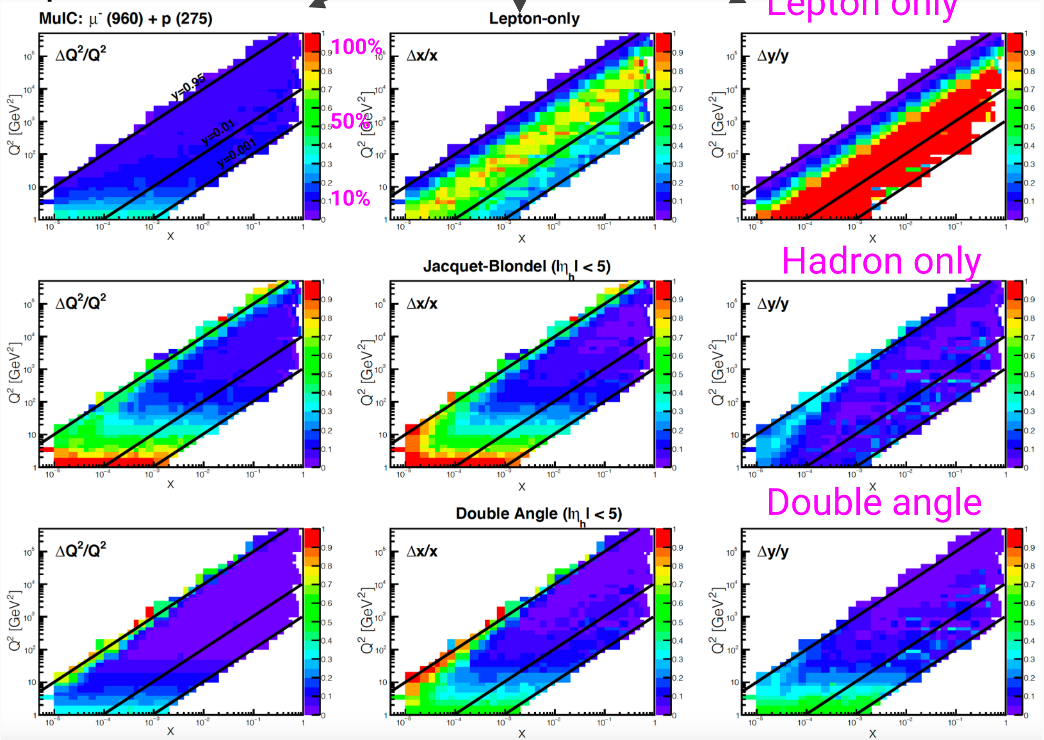
Distinct experimental challenges in tagging very forward muons to address.

(but hundreds of GeV muons will penetrate through anything!)

Detector requirements and design

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

Q^2 vs. x plane:

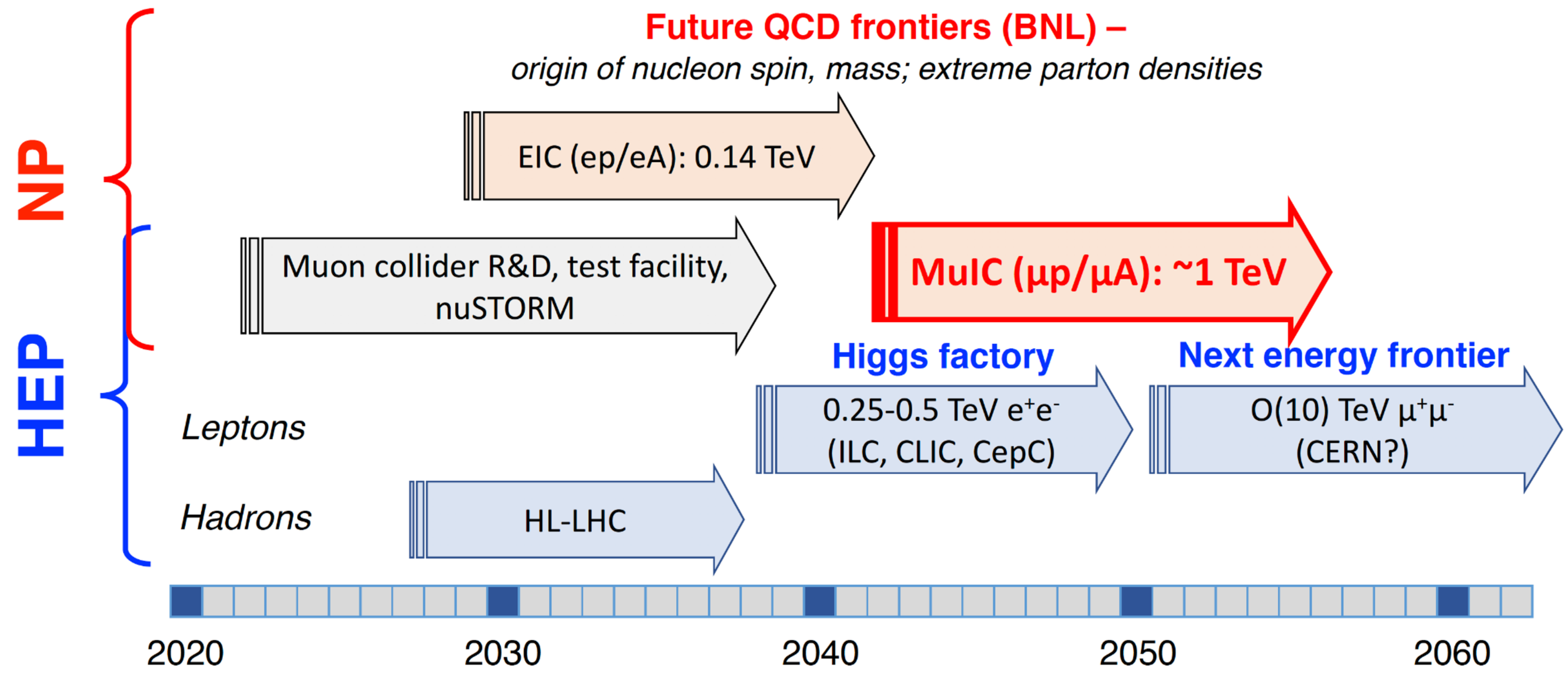


Simple assumptions of detector resolutions to smear particles from PYTHIA 8

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	$\frac{50\%}{\sqrt{E}} \otimes 10\%$	$\frac{0.087}{\sqrt{12}}$

Future work with detailed simulations to fully demonstrate the experimental feasibility

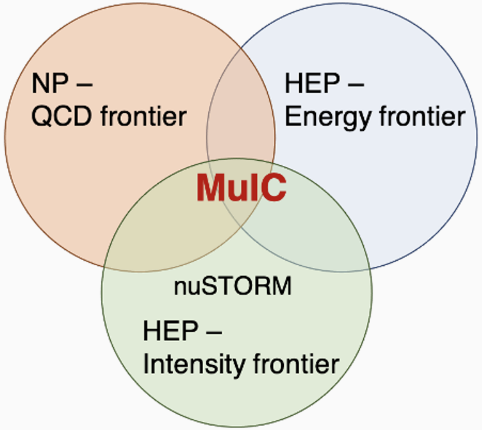
Path forward (in our view)



A possible roadmap to future muon colliders in NP and HEP

Summary and possible 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 $\mu+\mu-$ (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

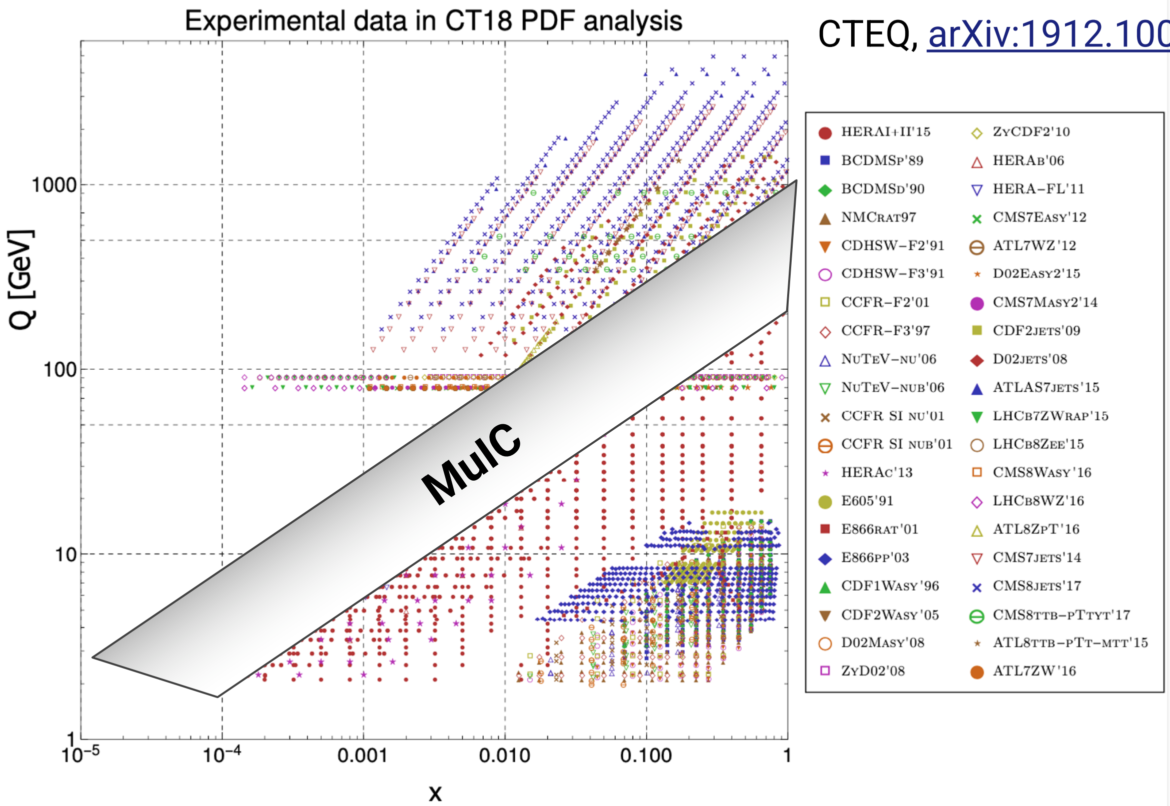
Summary and possible next steps

Next steps:

- Propose MuIC at BNL as one of future muon collider options in US to Snowmass2021, and also plan to propose the idea to the NP community in the upcoming long-range planning process in 2022
- Building on the MuIC concept, seek to establish dedicated R&D program on muon collider technology in US, involving HEP and NP in collaboration with the International Muon Collider Collaboration
- Engage BNL to consider MuIC as a future option of the lab, to start conceiving a possible design and potentially establish test facilities.
- Engage broader theoretical and experimental communities to explore physics potential and address detector design requirements/challenges (workshops, collaboration/working groups)

Extras

Science potential at the MuIC: PDF Measurements



CTEQ, [arXiv:1912.10053](https://arxiv.org/abs/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 …