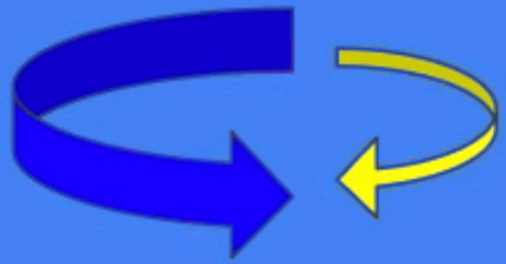


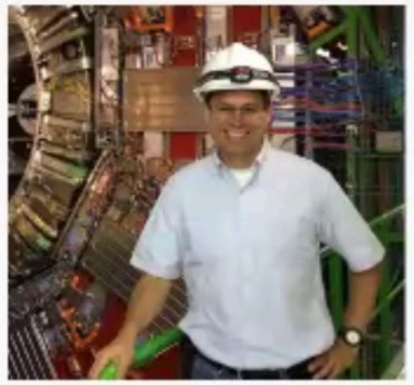
A Muon-Ion Collider (at BNL)

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

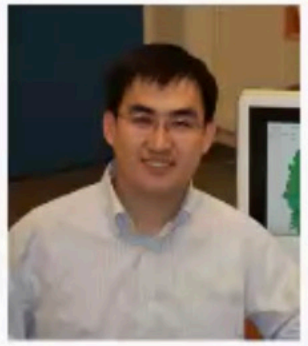
arXiv:2107.02073

Darin Acosta, Wei Li (Rice University)

Who we are



Darin Acosta: Particle Physicist on CMS (Higgs, Standard Model physics and BSM searches etc.), funded by US DOE-HEP; Previously on CDF at the Tevatron, and on ZEUS at HERA (ep collider)



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

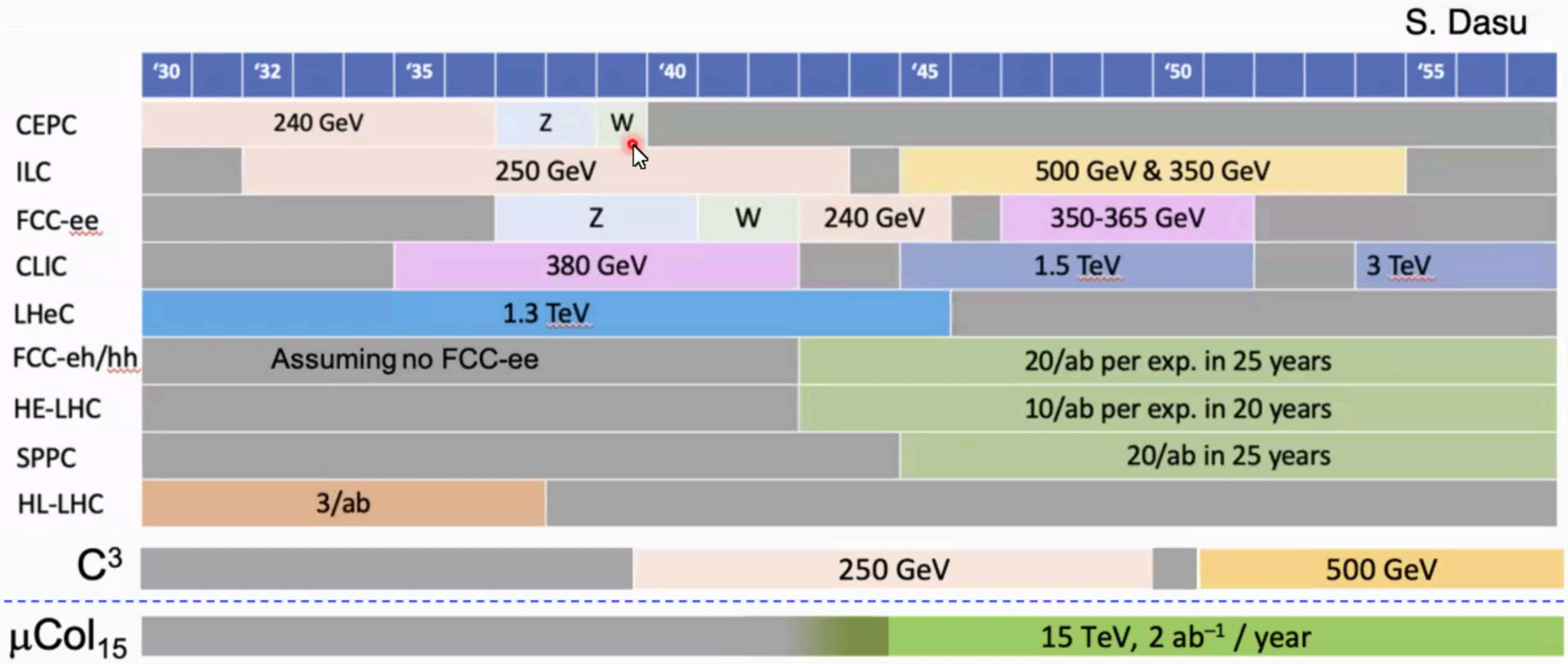
There are many examples of successful synergies between HEP and NP in CMS in physics measurements, detector design, operations and upgrades

In chatting about the future of each other's fields, we recognize further opportunities to collaborate…

n.b. Neither of us is an accelerator expert…

Future of High Energy Physics Energy Frontier

- Many options for Higgs factories and energy frontier machines
- What would be an optimal and realistic path forward?



Growing interests in muon colliders!

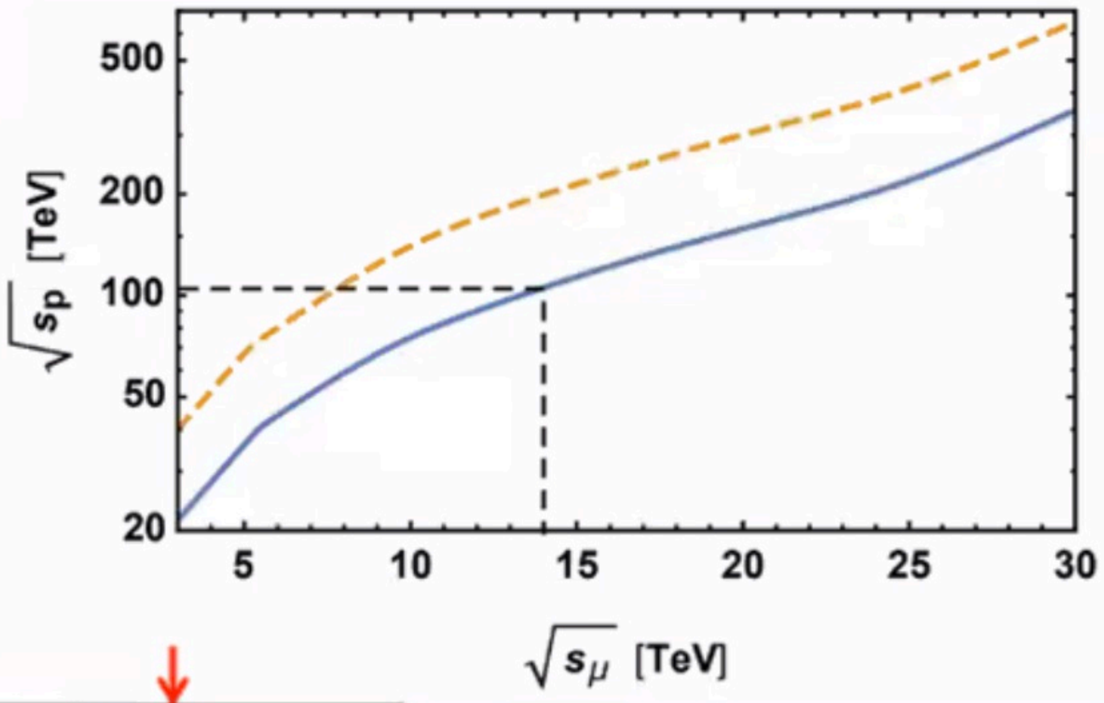
An Energy Frontier Muon Collider

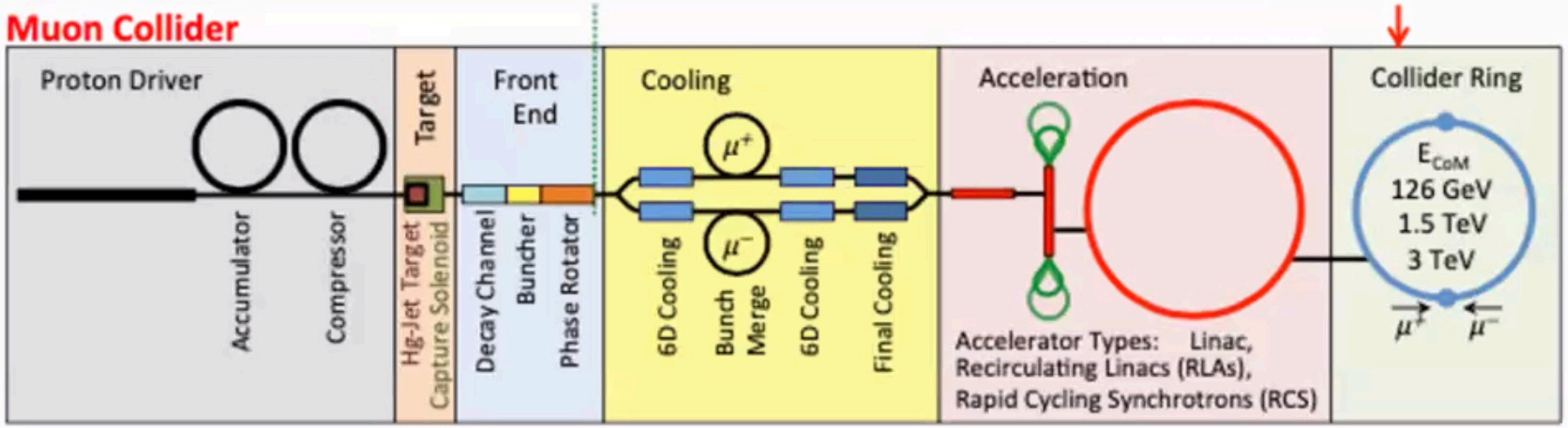
A more compact and innovative facility to incorporate the advantages of a high precision lepton collider and an energy frontier machine

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

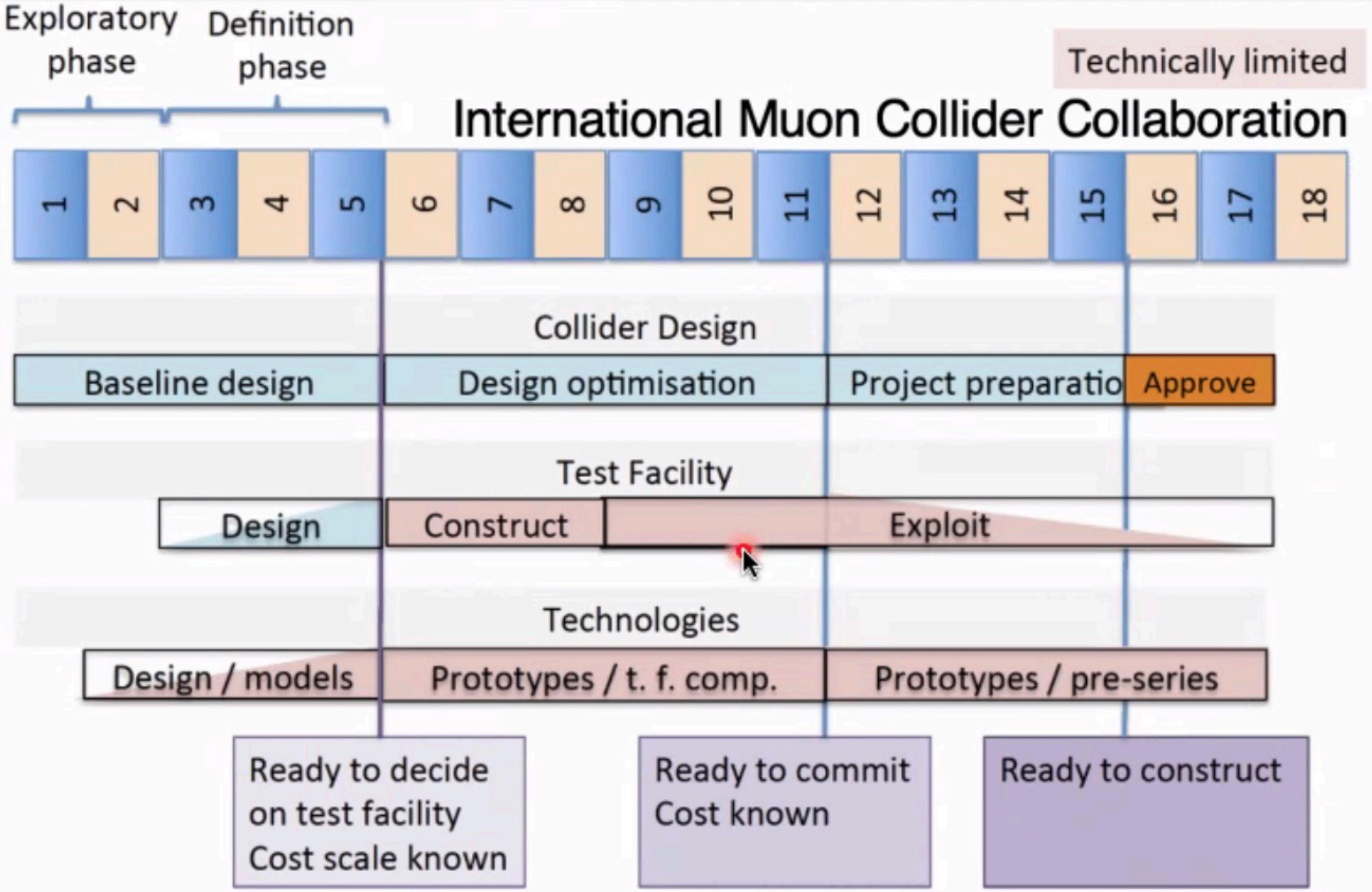
But much R&D still to do...

arXiv:1901.06150





Potential timeline of muon colliders



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

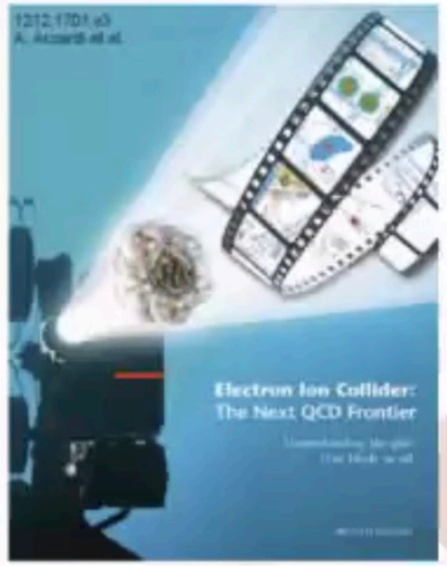
A vigorous and ambitious R&D program is needed to assess the feasibility of a tens-of-TeV's muon collider. Therefore it is important to investigate the physics potential of smaller-scale machines that might be built along the way as technology demonstrators. Starting from medium energy, the first option 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)



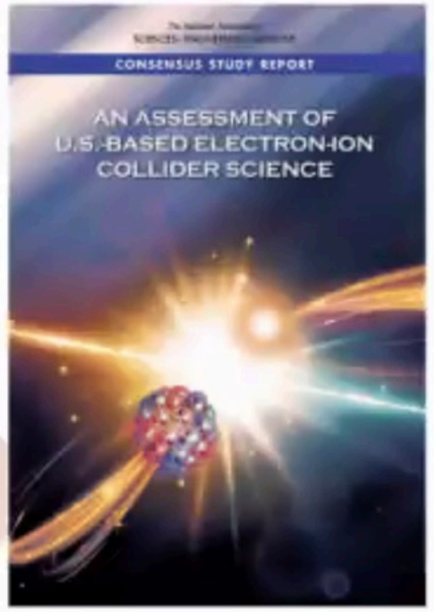
White paper
arXiv:1212.1701

Origin of nucleon mass

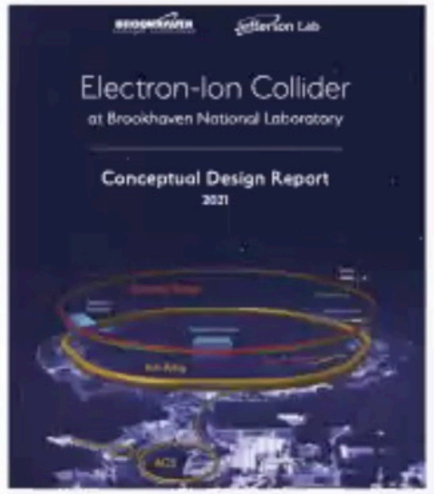
Origin of nucleon spin

Gluon saturation

Nucleon tomography

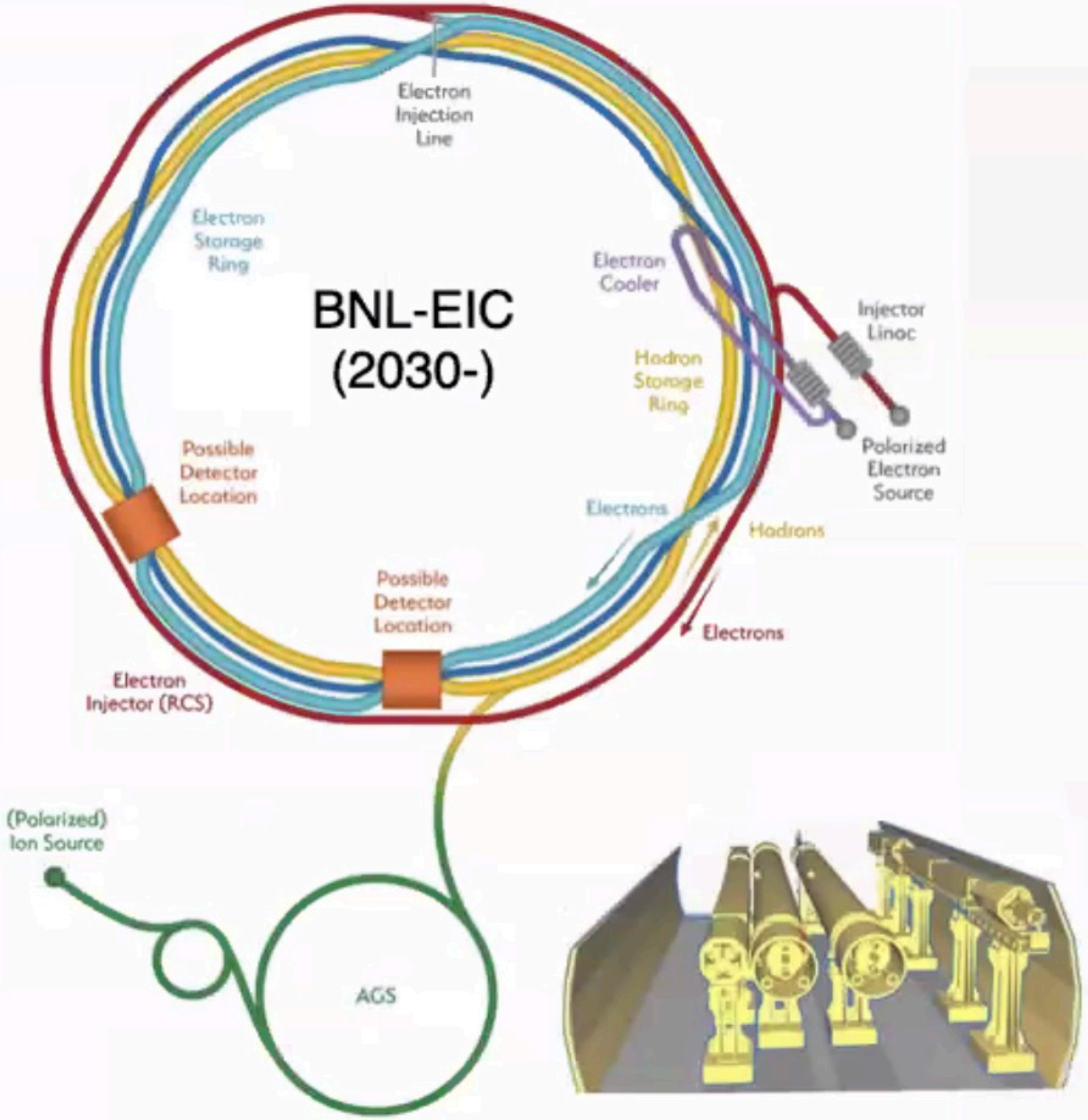


NAS report
July 2018



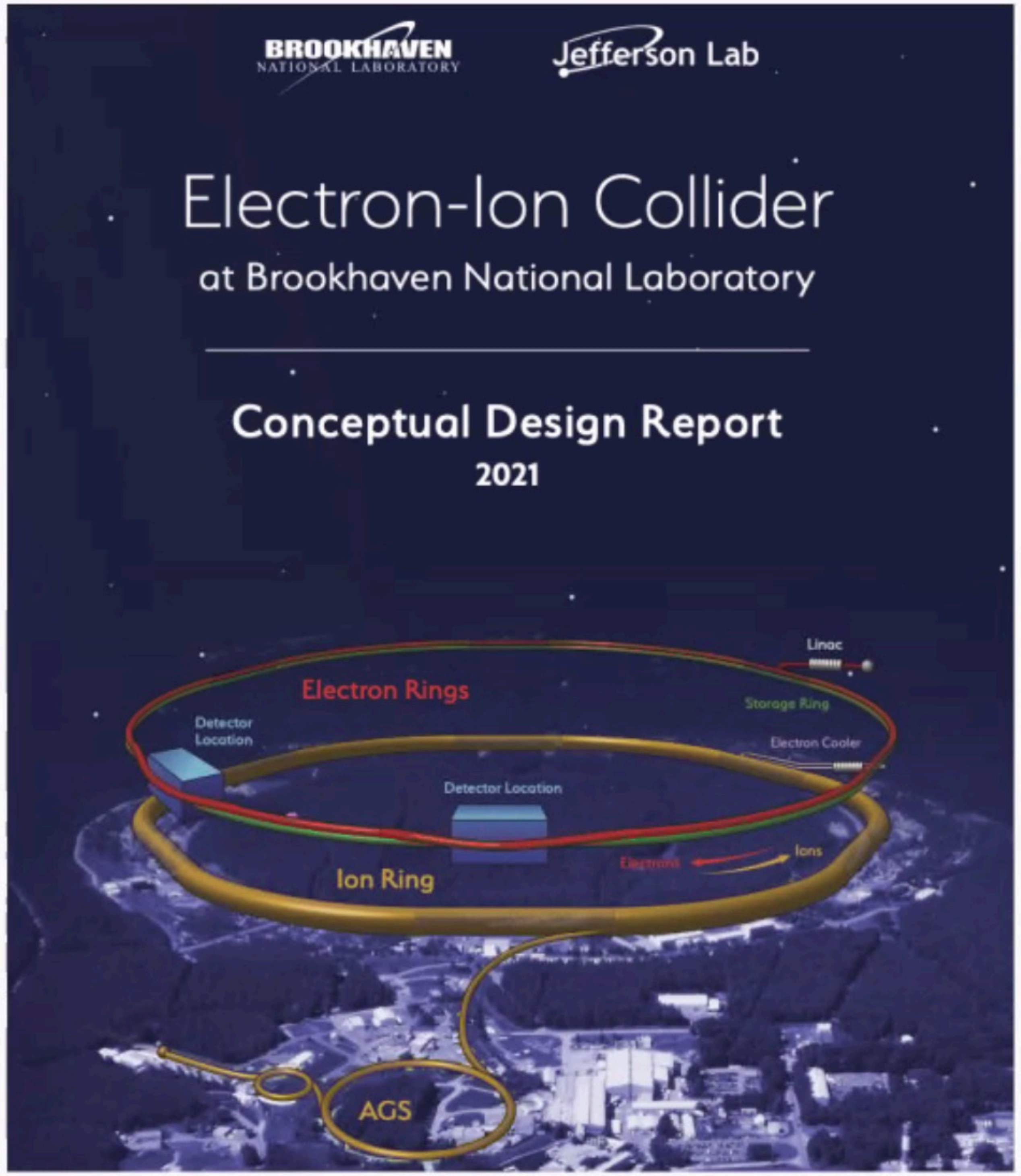
CDR 2021

first conceived in late 90s



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

The Electron-Ion Collider (EIC)



EIC Conceptual Design Report just released and project approved

Salient points:

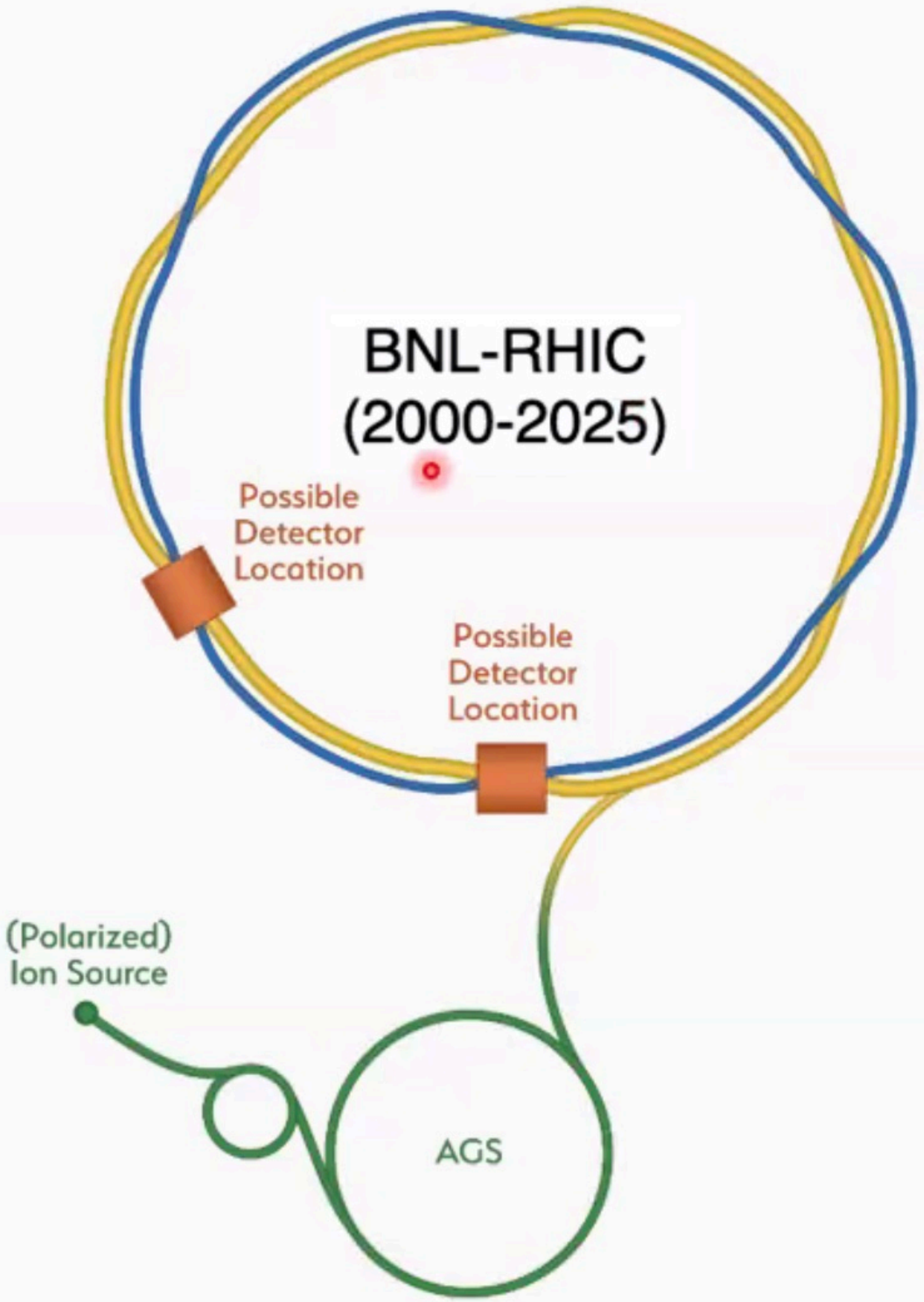
- Hadron beam energy up to 275 GeV (increase from RHIC)
- Electron beam energy up to 18 GeV
- $\sqrt{s}$ = 20 -- 140 GeV
- Luminosity 10^{33} -- 10^{34} Hz/cm^2
- Polarized electron, proton and ion beams (any)
- Design supports 2 detectors, only one in project scope

Physics goals:

- ep and eN deep inelastic scattering
- Nucleon spin structure
- Gluon saturation scale (Q_S)

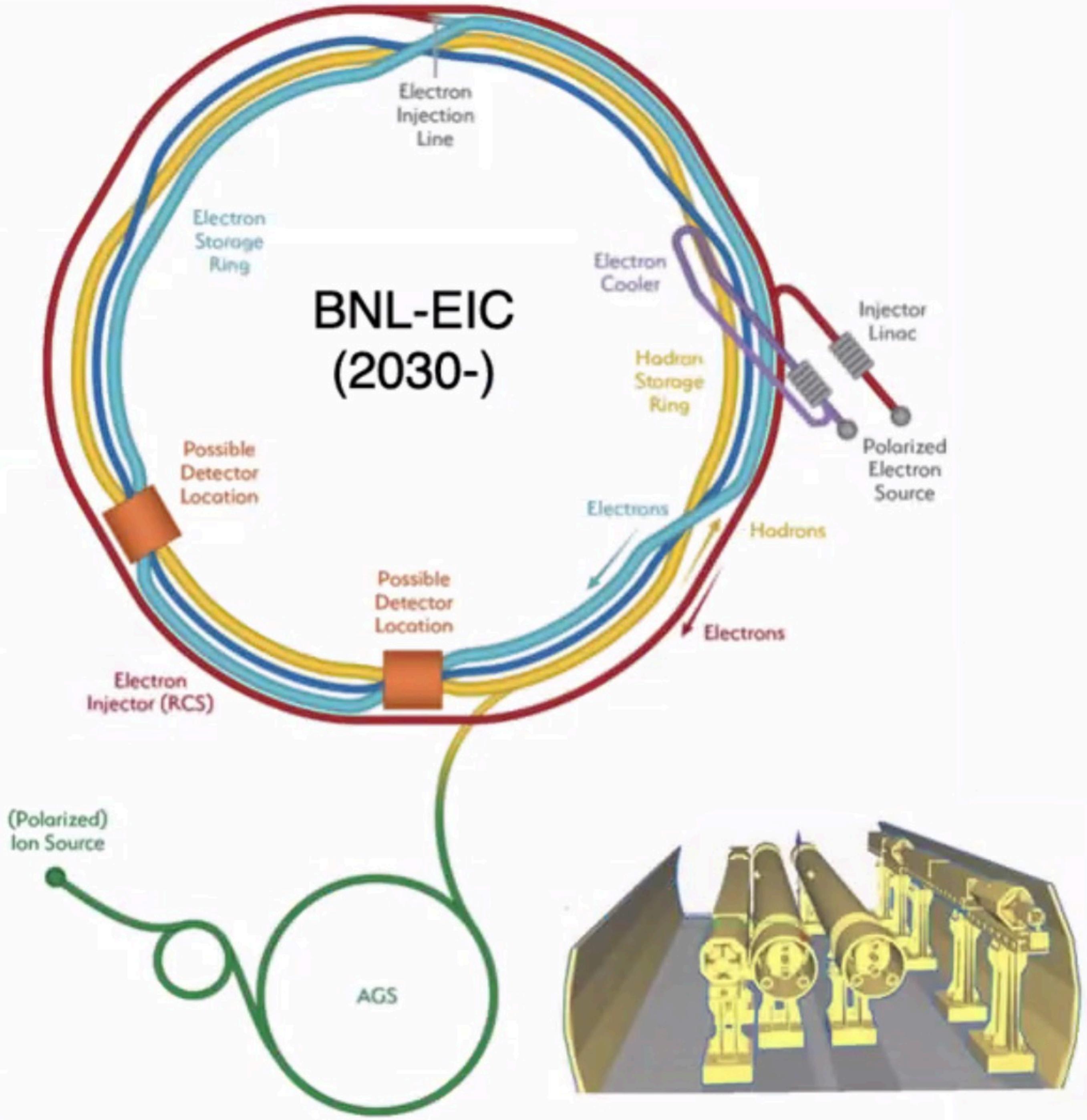
Electron-Ion Collider at BNL

pp, pA, AA up to 500 GeV



upgrade

ep, eA up to 140 GeV



Electron-Ion Collider at BNL

One of hadron storage rings is re-used.

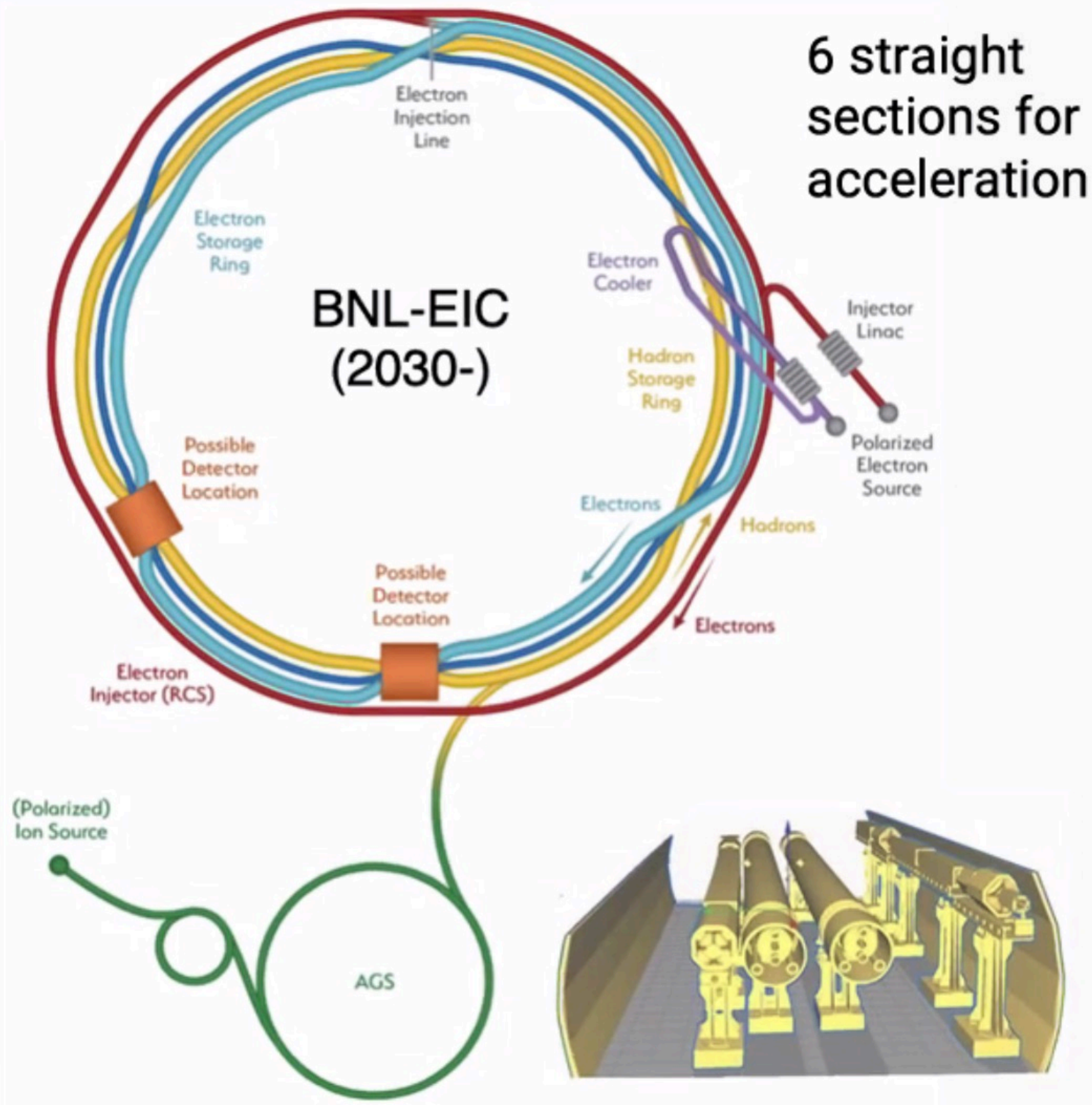
RHIC infrastructure (existing tunnel) is re-used as much as possible.

Additions to RHIC:

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

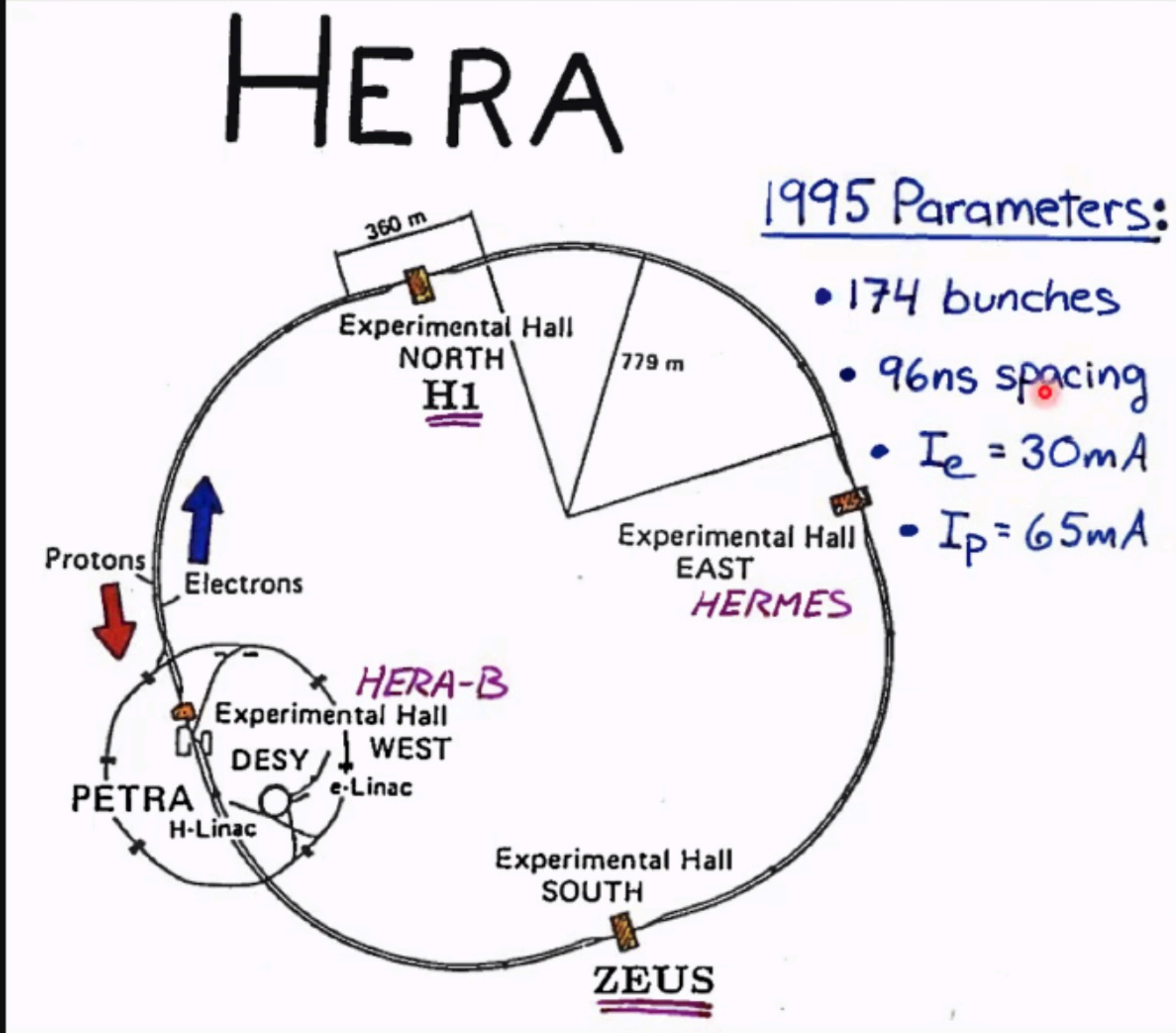
Cost: $1.6-2.6B (DOE-NP).
 - U.S. accounting, including detectors

ep, eA up to 140 GeV



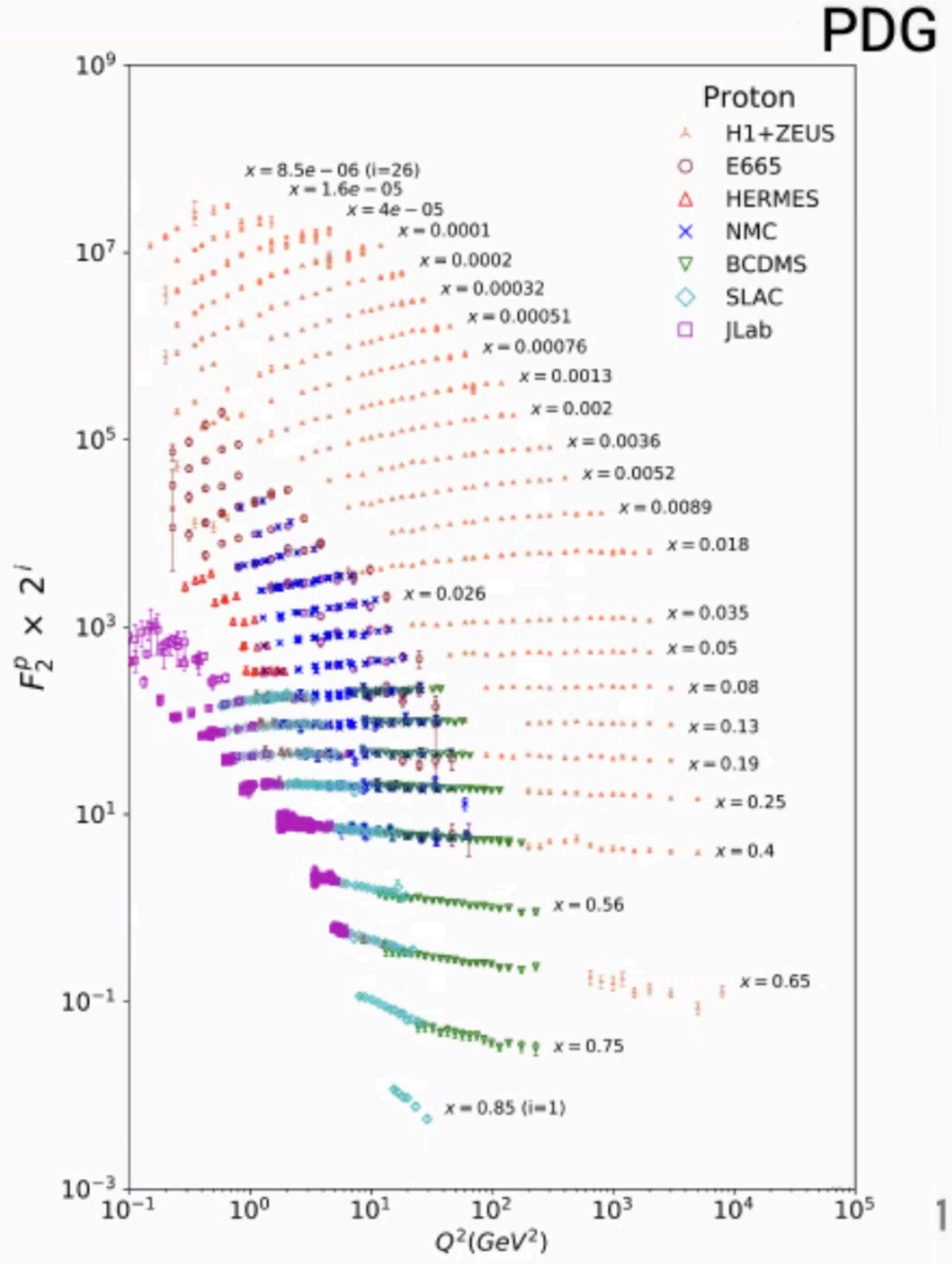
6 straight sections for acceleration

A Successor to HERA



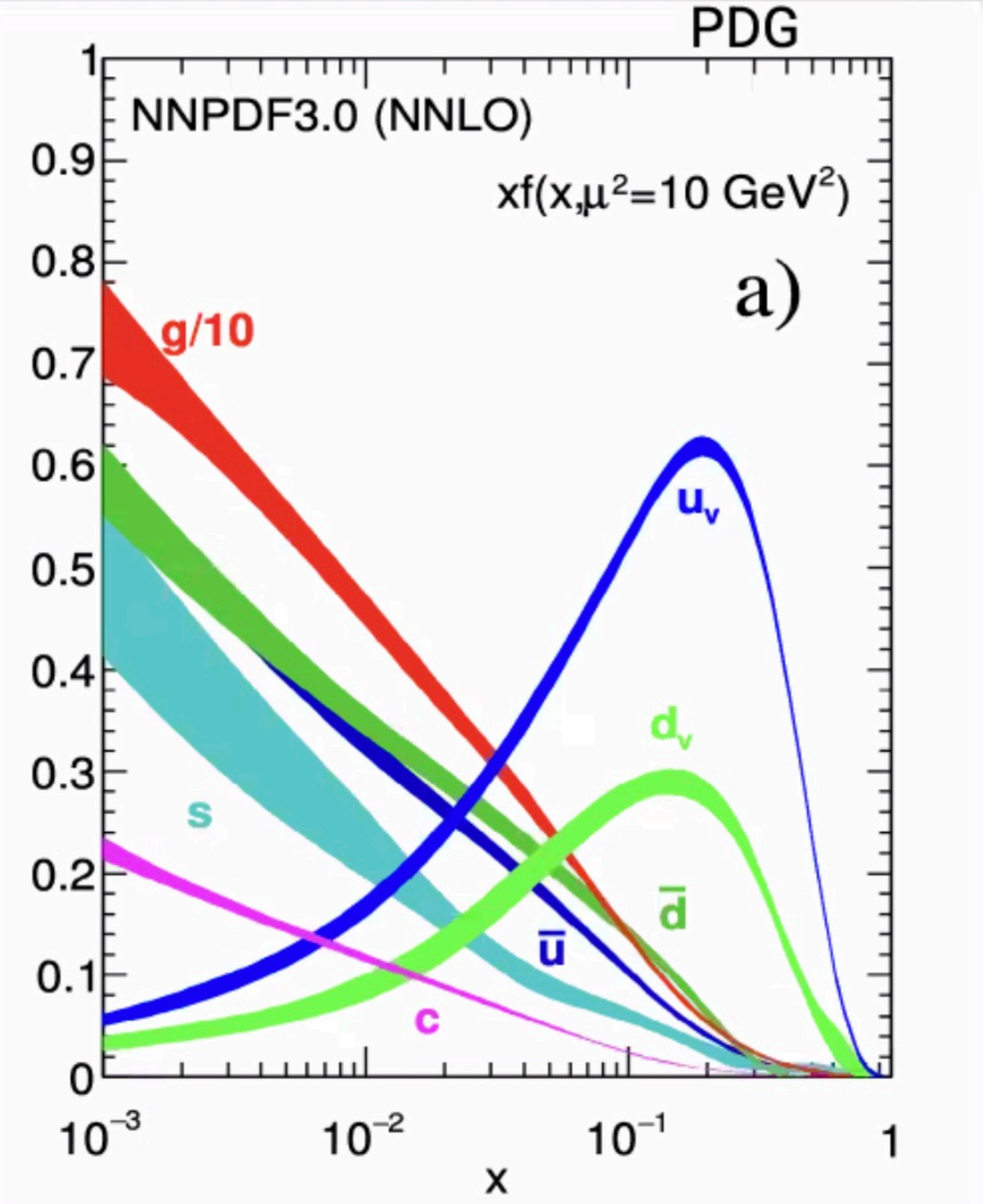
27.5 GeV e± on 920 GeV p → √s = 318 GeV

- HERA probed a completely new DIS regime from earlier fixed target experiments

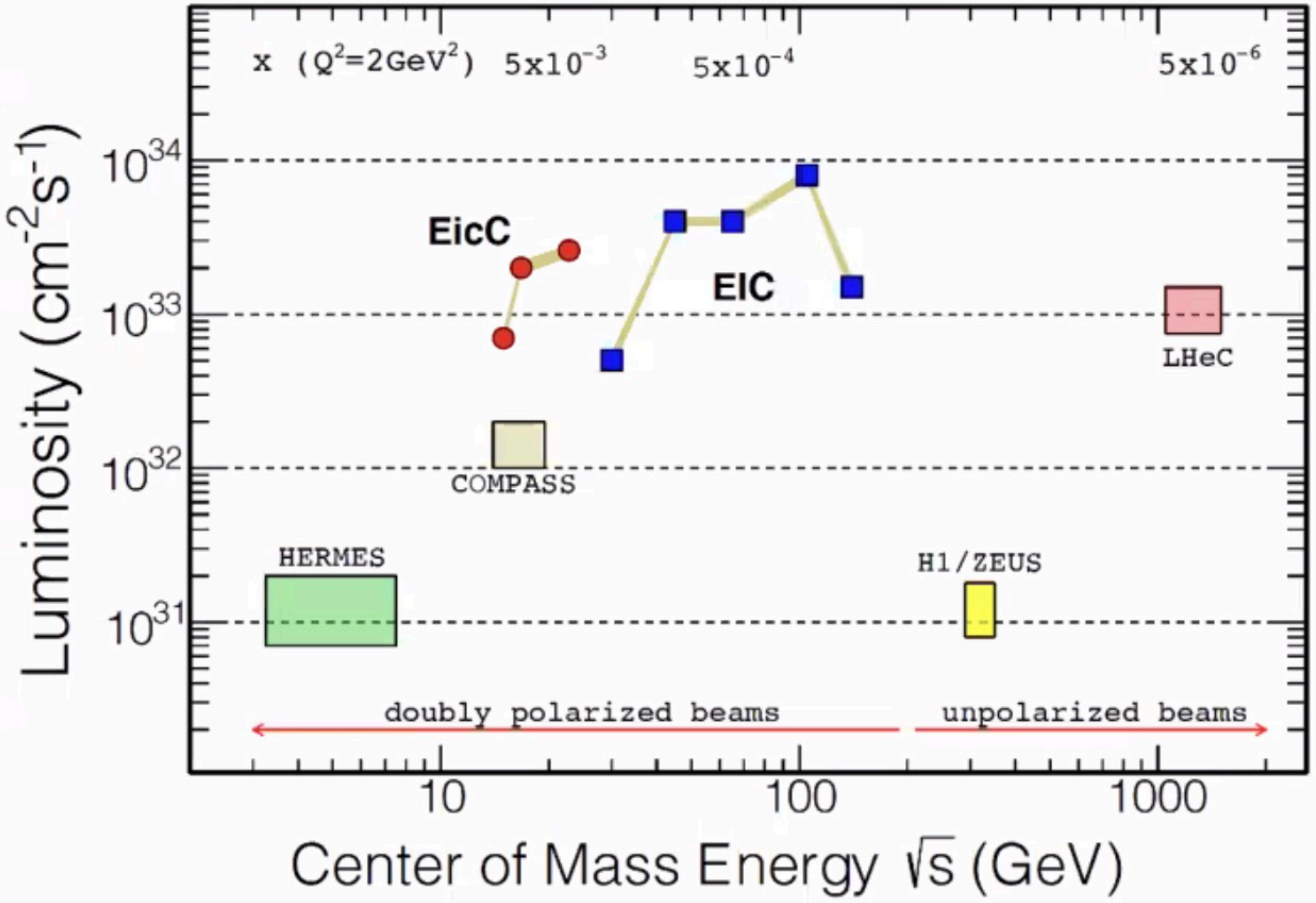


Parton Densities

- HERA paved the way for precision LHC physics through precise structure function measurements, from which the parton densities are extracted through global fits with QCD
- HERA saw the strong rise in the gluon density at low x
    - When do saturation effects come into play?



Lumi vs. √s at lepton-hadron colliders



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

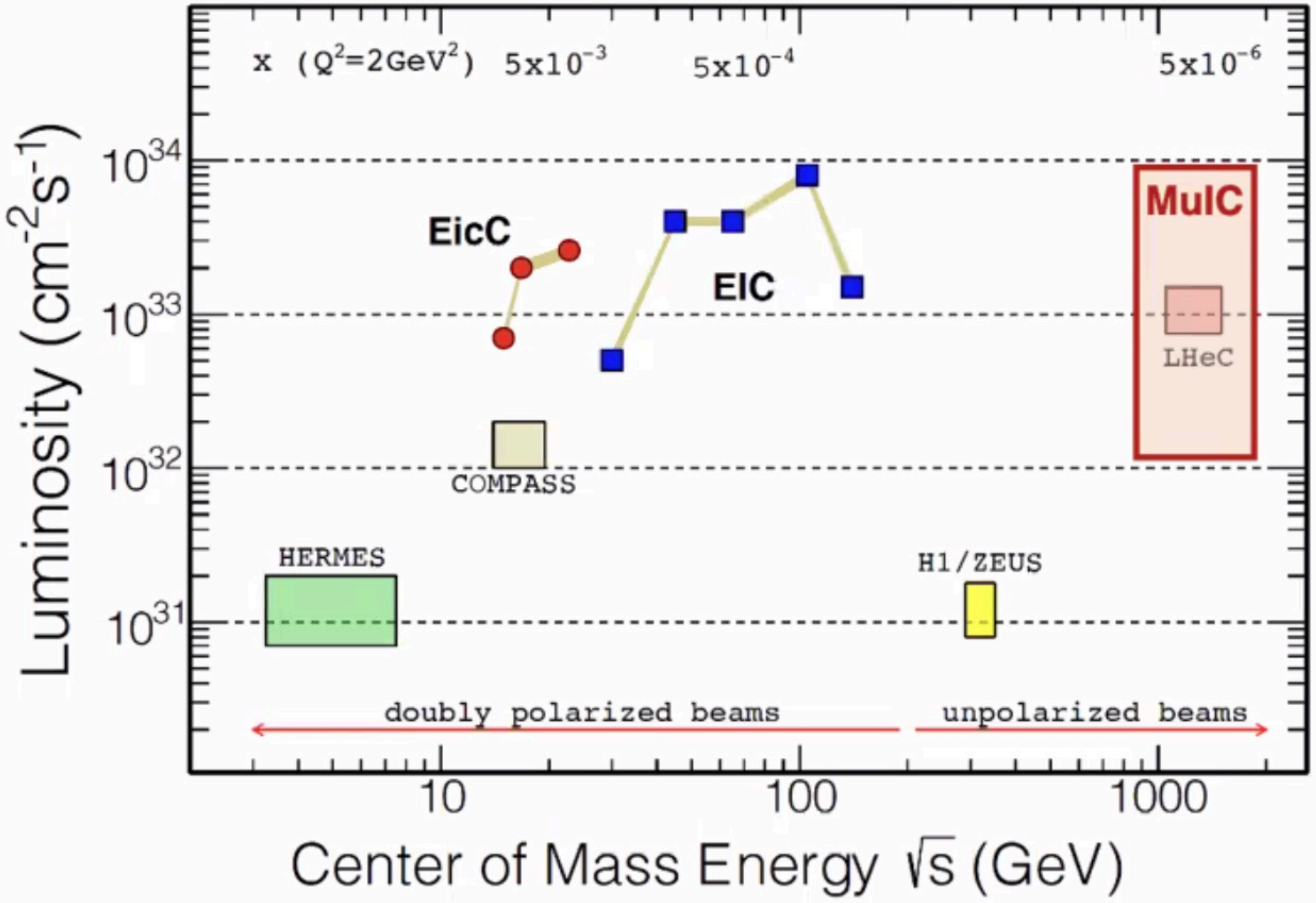
EIC at BNL – lowish energy but high luminosity, doubly polarized, ions

What's after EIC?

- LHeC (arXiv:2007.14491)?

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

DIS at lepton-hadron colliders



HERA at DESY – high energy but low luminosity, unpolarized

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

What's after EIC?

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

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 toward a multi-TeV μ+μ- collider

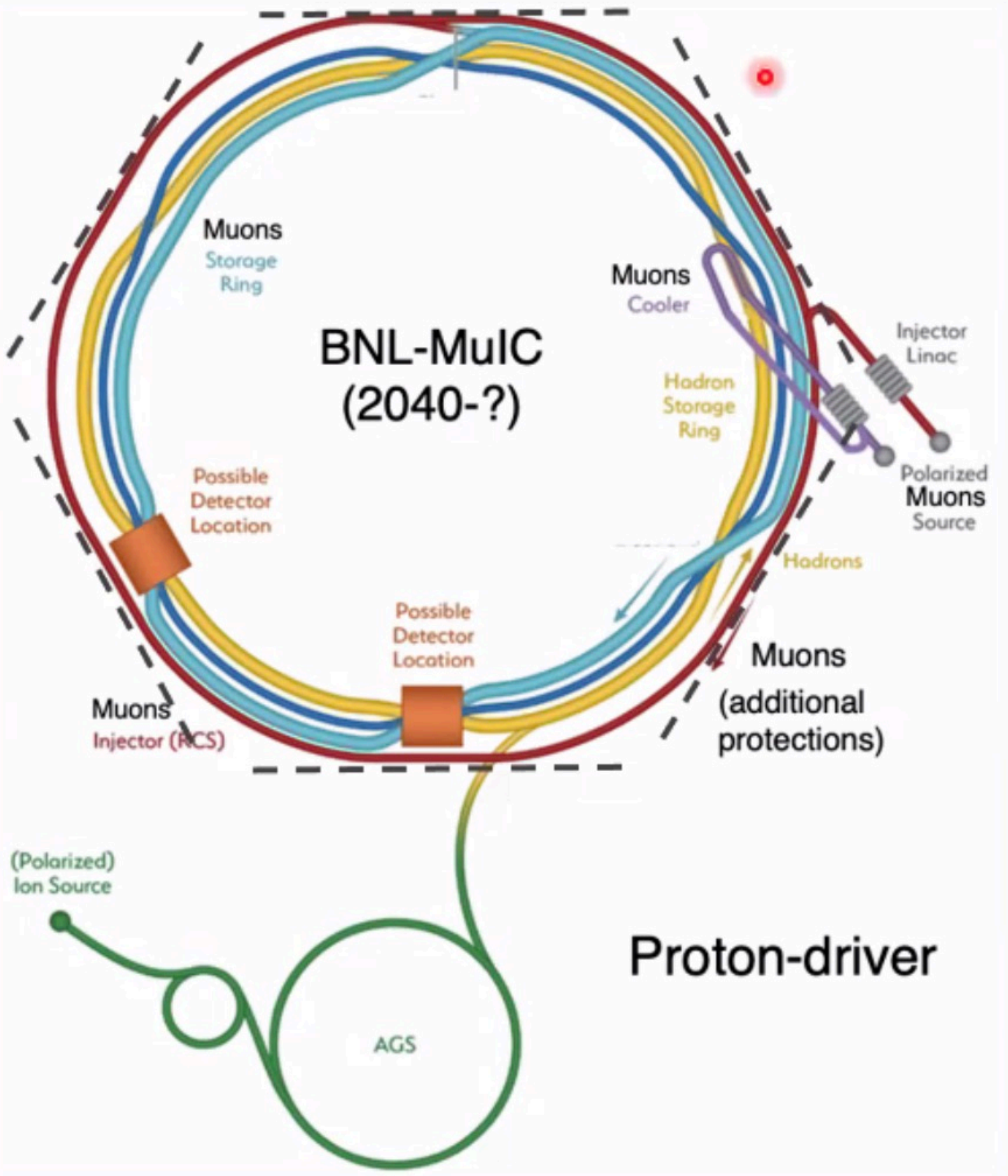
- QCD and hadron/nucleon structure in new regimes
- Higgs, Top, BSM

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)

Muon-Ion Collider at BNL

replace e by μ beam



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

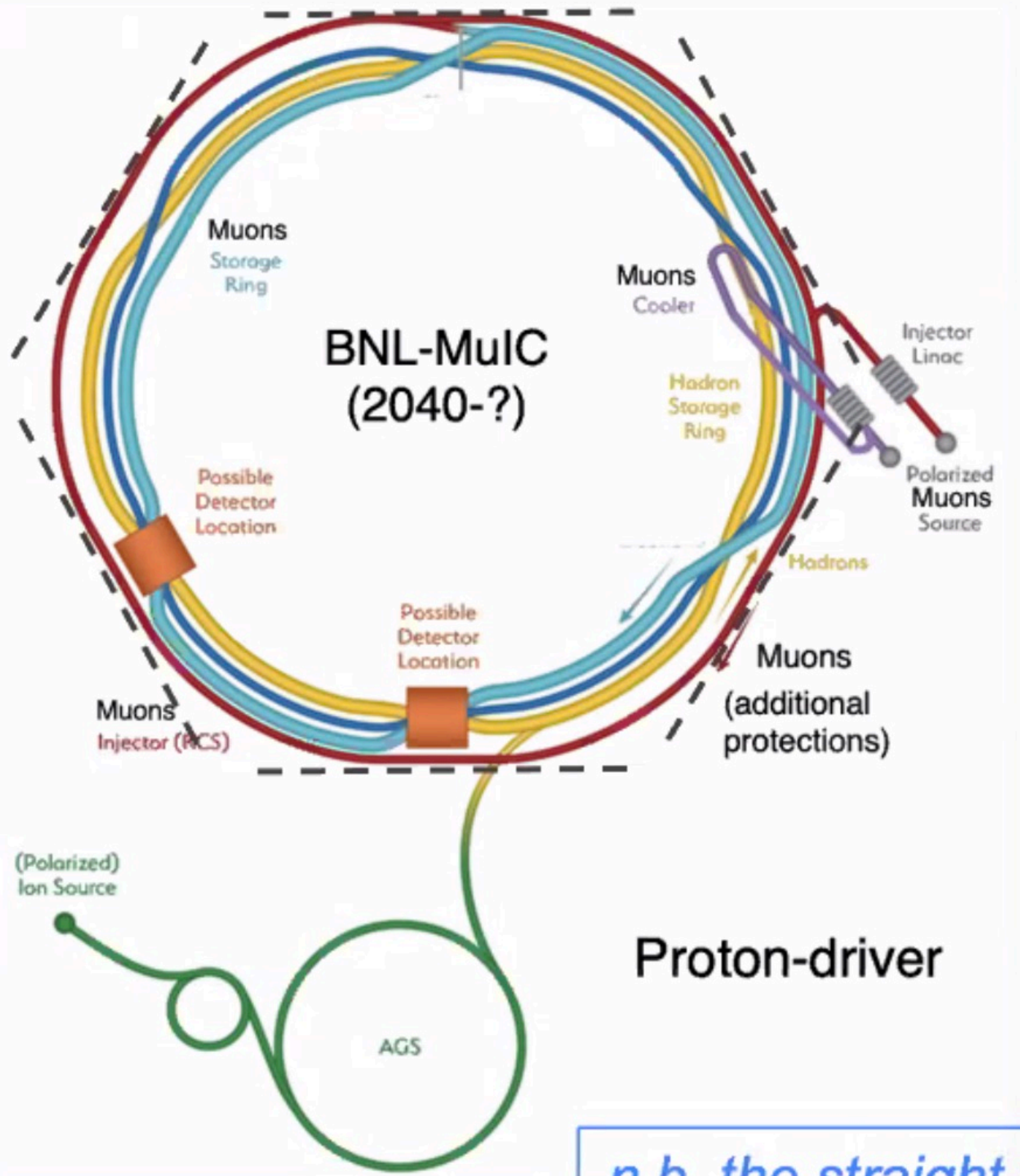
Achievable muon beam energy: **0.3Br**

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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7-8X increase over top EIC energy

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

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

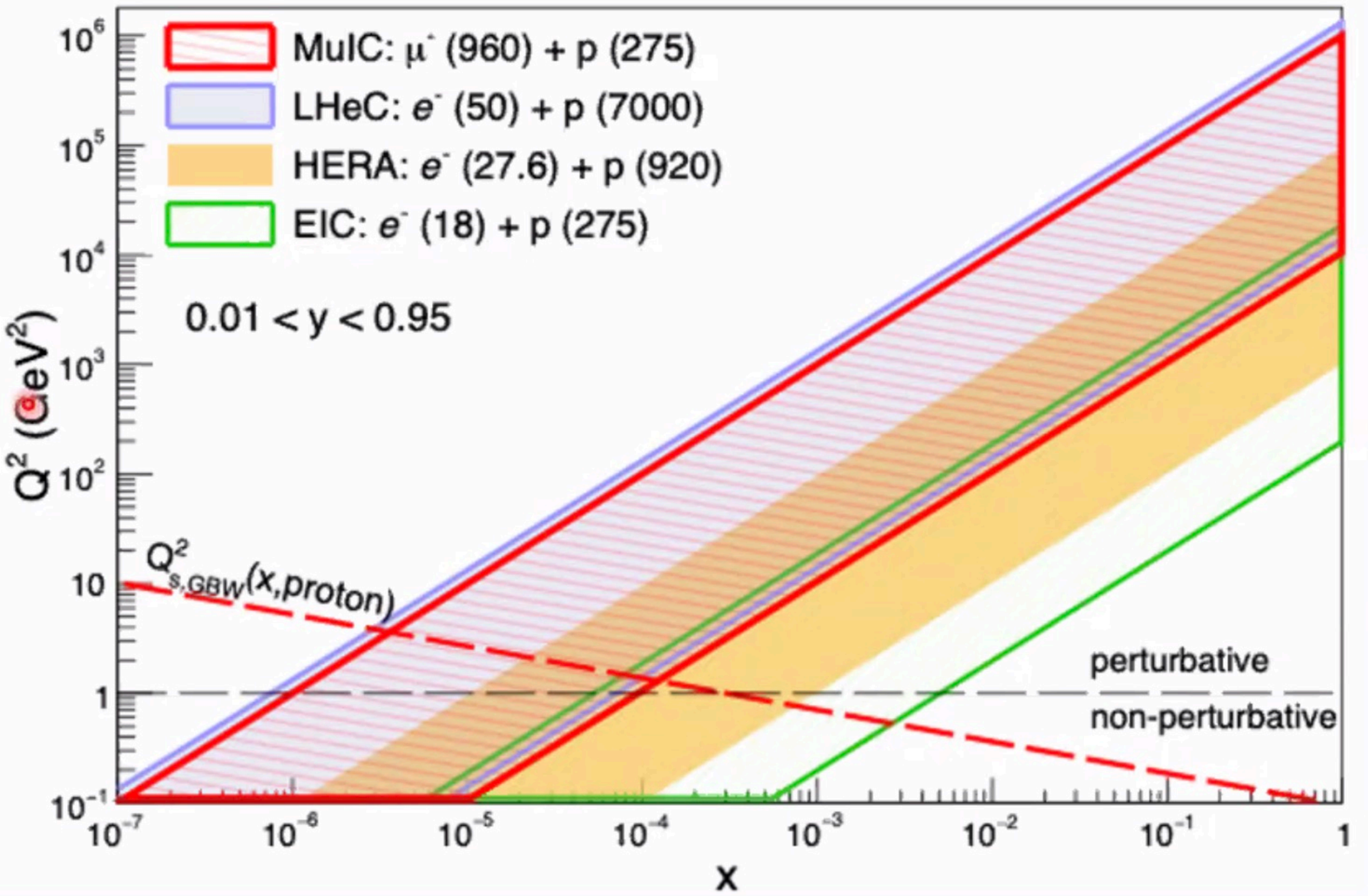
Parameter	Units	Higgs		Multi-TeV	
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7 sec		13'500	37'500	200'000	820'000
Circumference	km	0.3	2.5	4.5	6
No. of IP's		1	2	2	2
Repetition Rate	Hz	15	15	12	6
$\beta^*_{x,y}$	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

And the more experimental interaction points, the better before the muons decay…

Q^2-x Reach Comparison: e(μ)-p Scattering



Well beyond the coverage of the EIC and HERA

Similar coverage to the proposed Large Hadron Electron Collider **LHeC** [1]

Potential to see gluon saturation [2] in the proton

[1] LHeC: arXiv:2007.14491

[2] GBW model: Phys. Rev. D 59, 014017 (1998)

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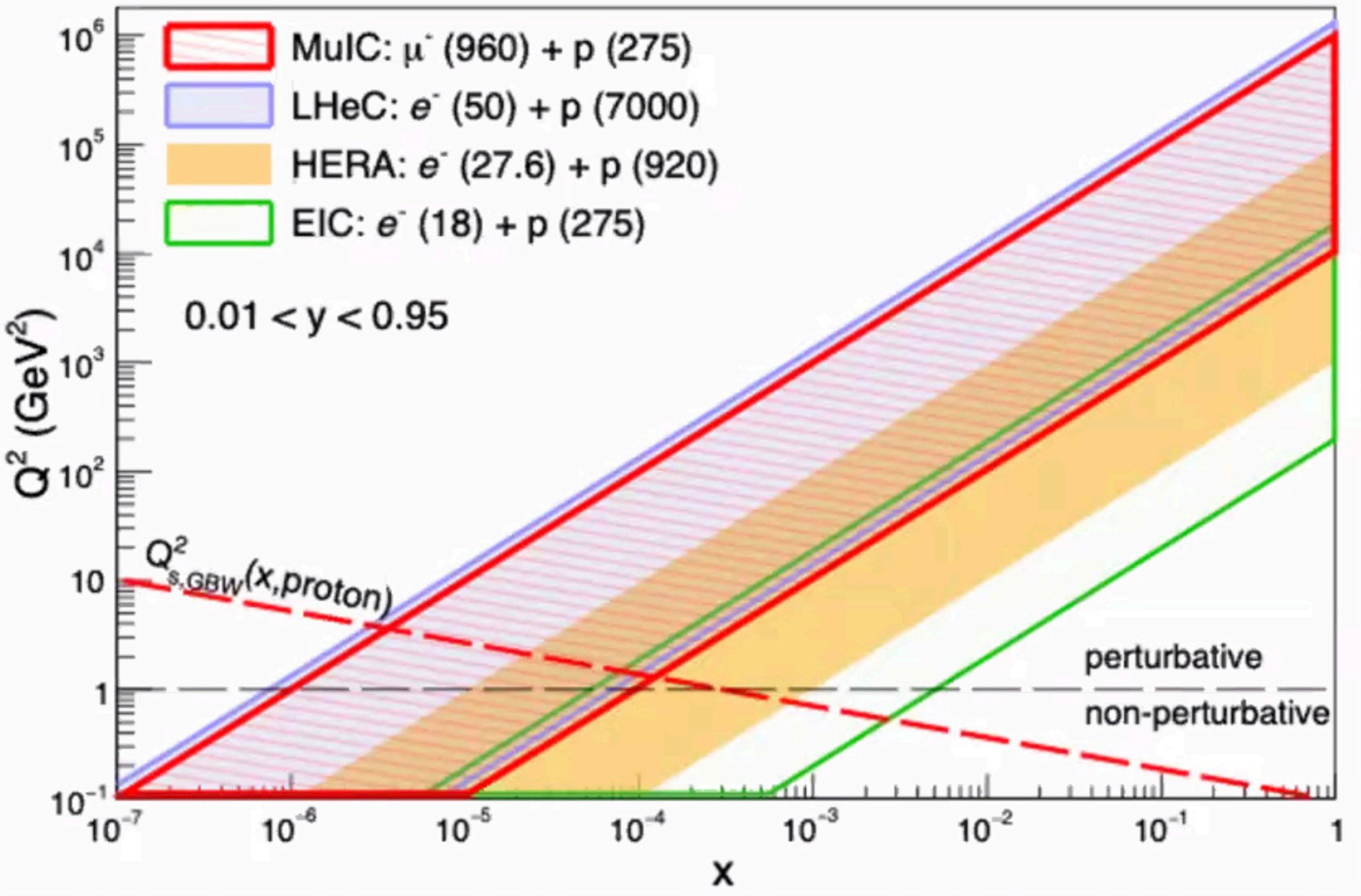

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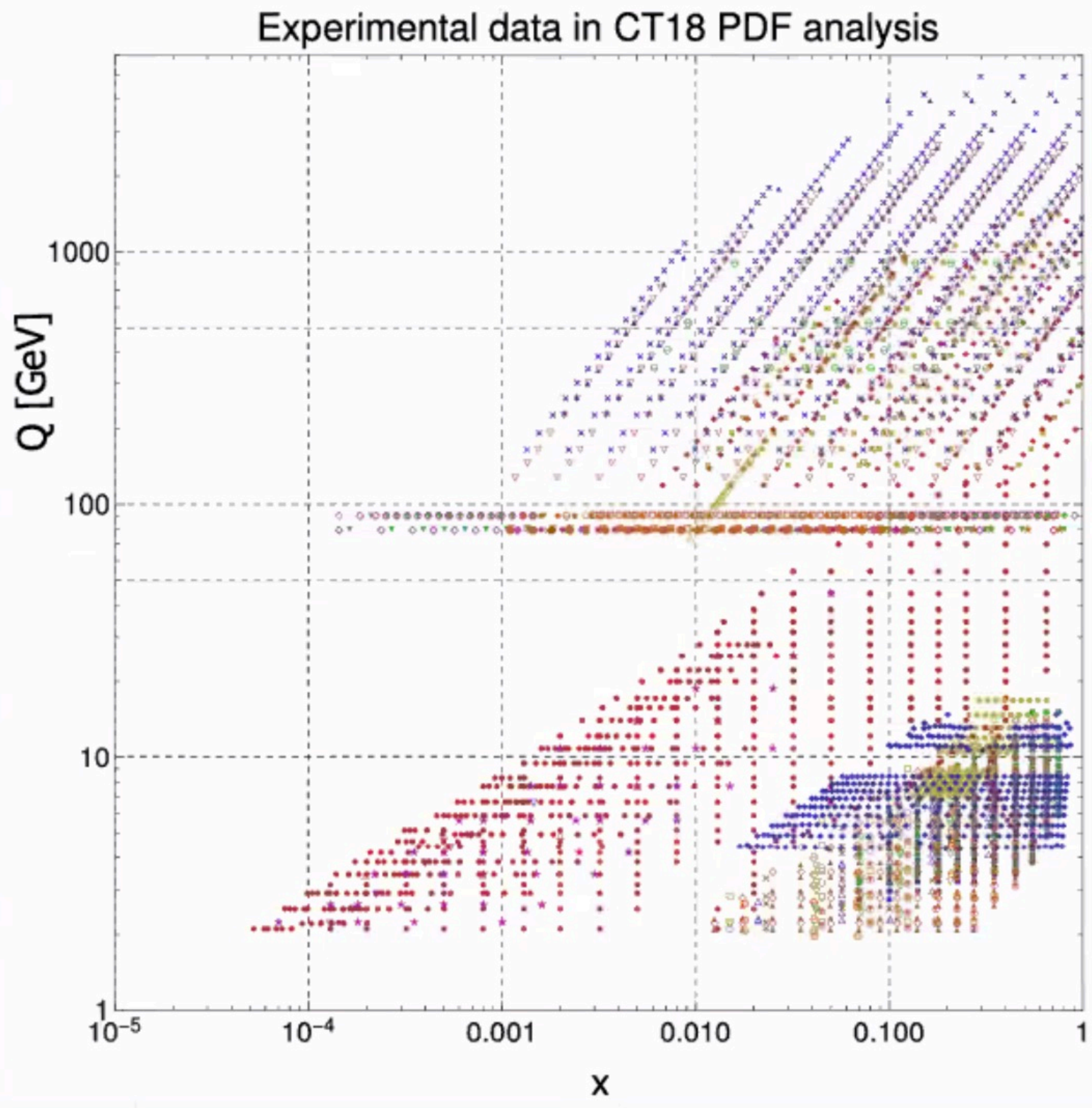
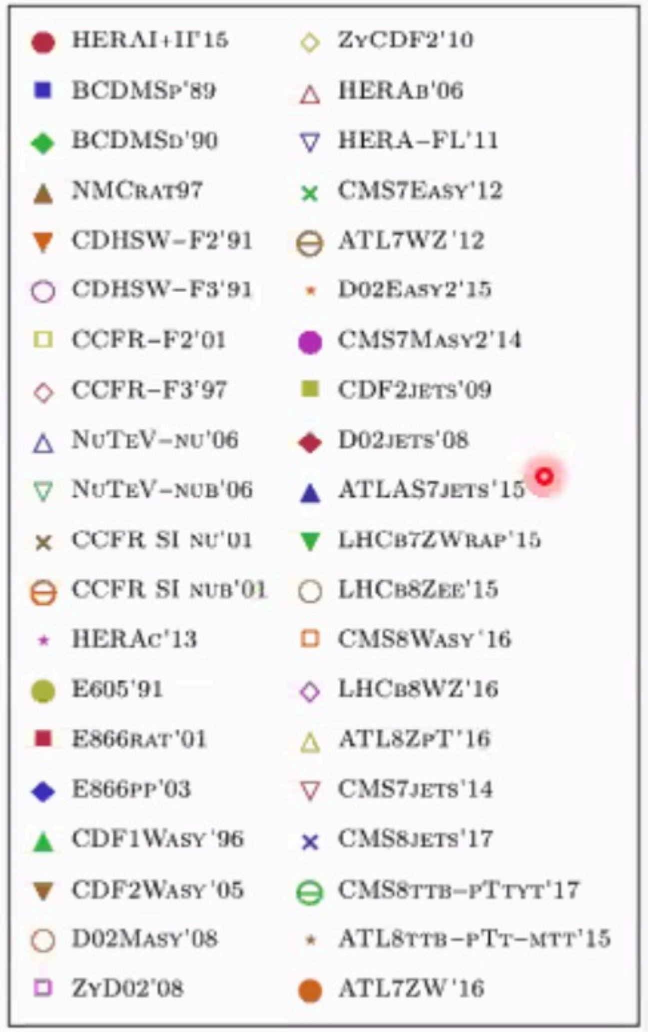
MuIC: μ(960)+p(275), $y_{cm} = -0.63$ vs. LHeC: e(50)+p(7000), $y_{cm} = 2.47$

Similar √s but very different final-state kinematics

Science potential at the MuIC: PDF Measurements



CTEQ, arXiv:1912.10053

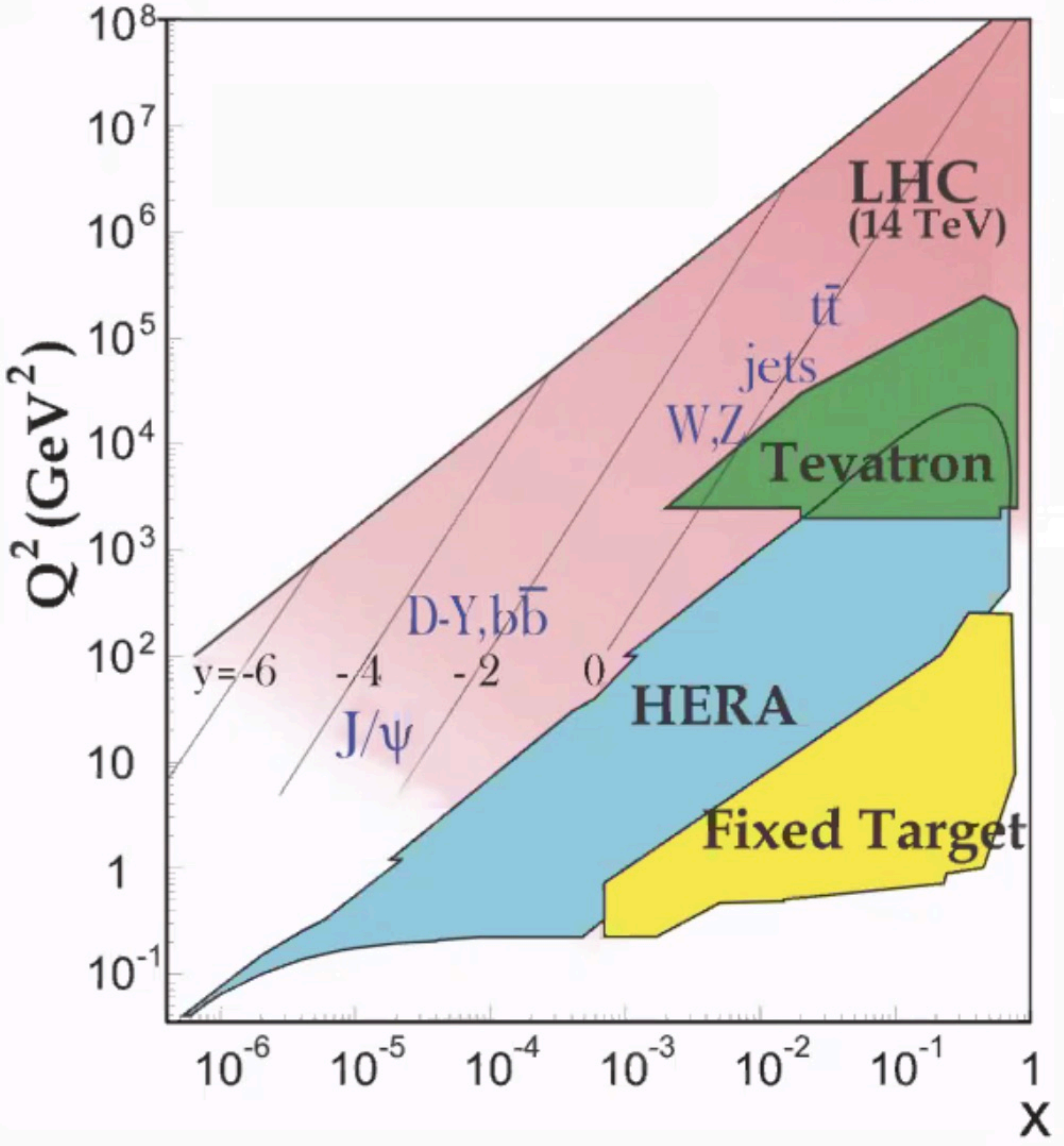


← Data used for global CTEQ fits

The MuIC would definitely probe new territory

PDF Measurement is Complementary to Hadron Colliders

PDG



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 should one be built

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

PDF Measurement is Complementary to Hadron Colliders

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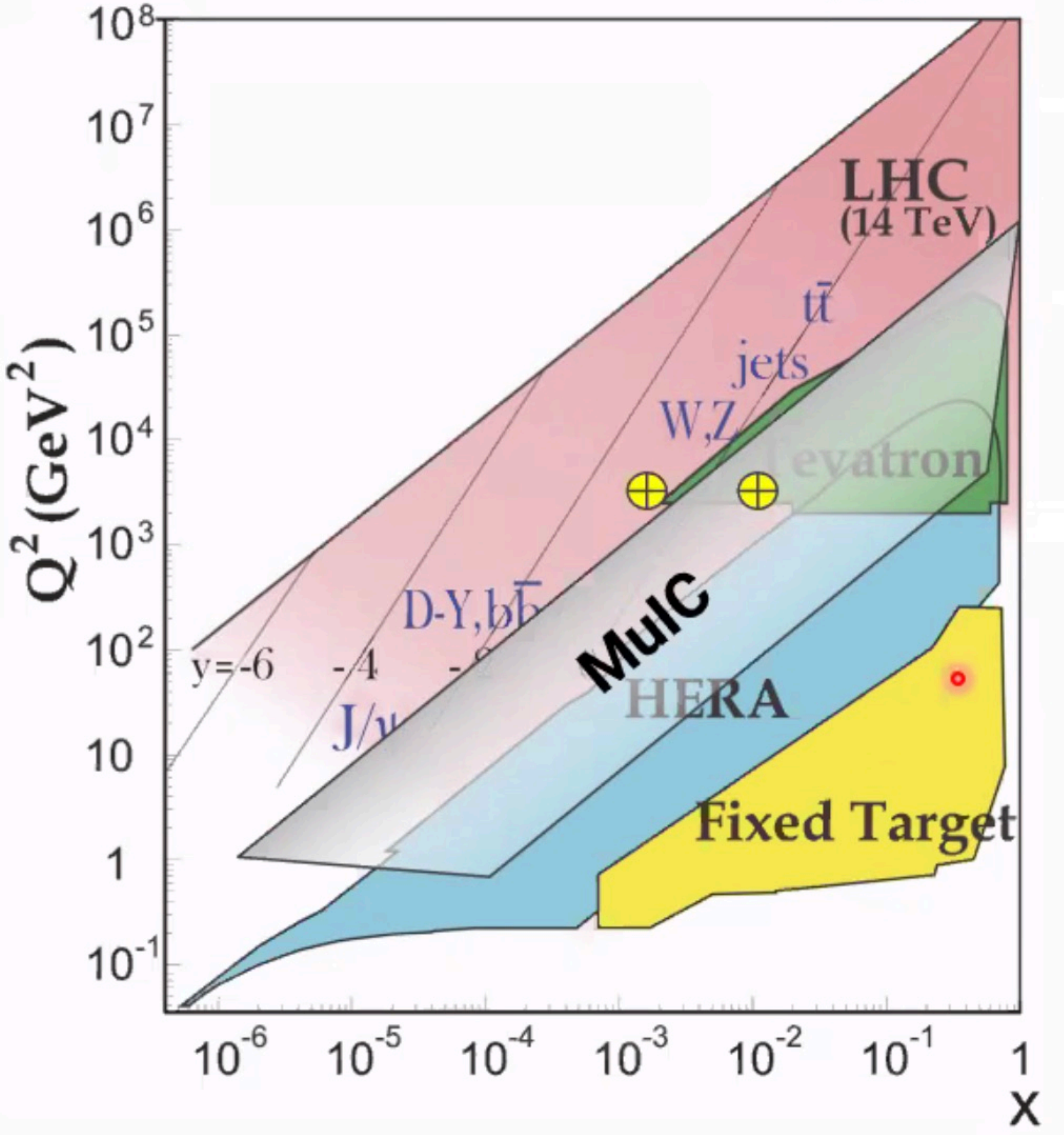

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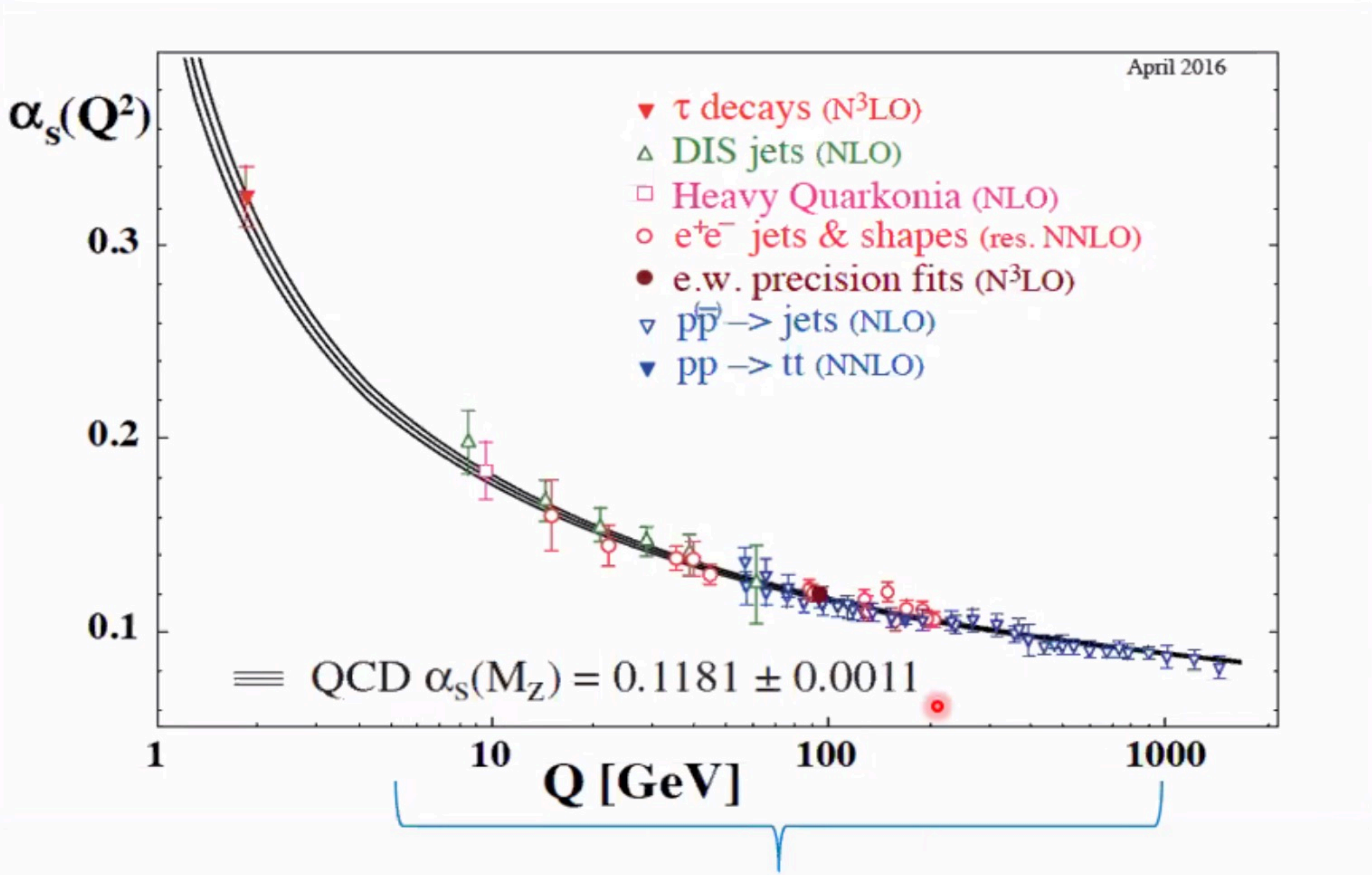
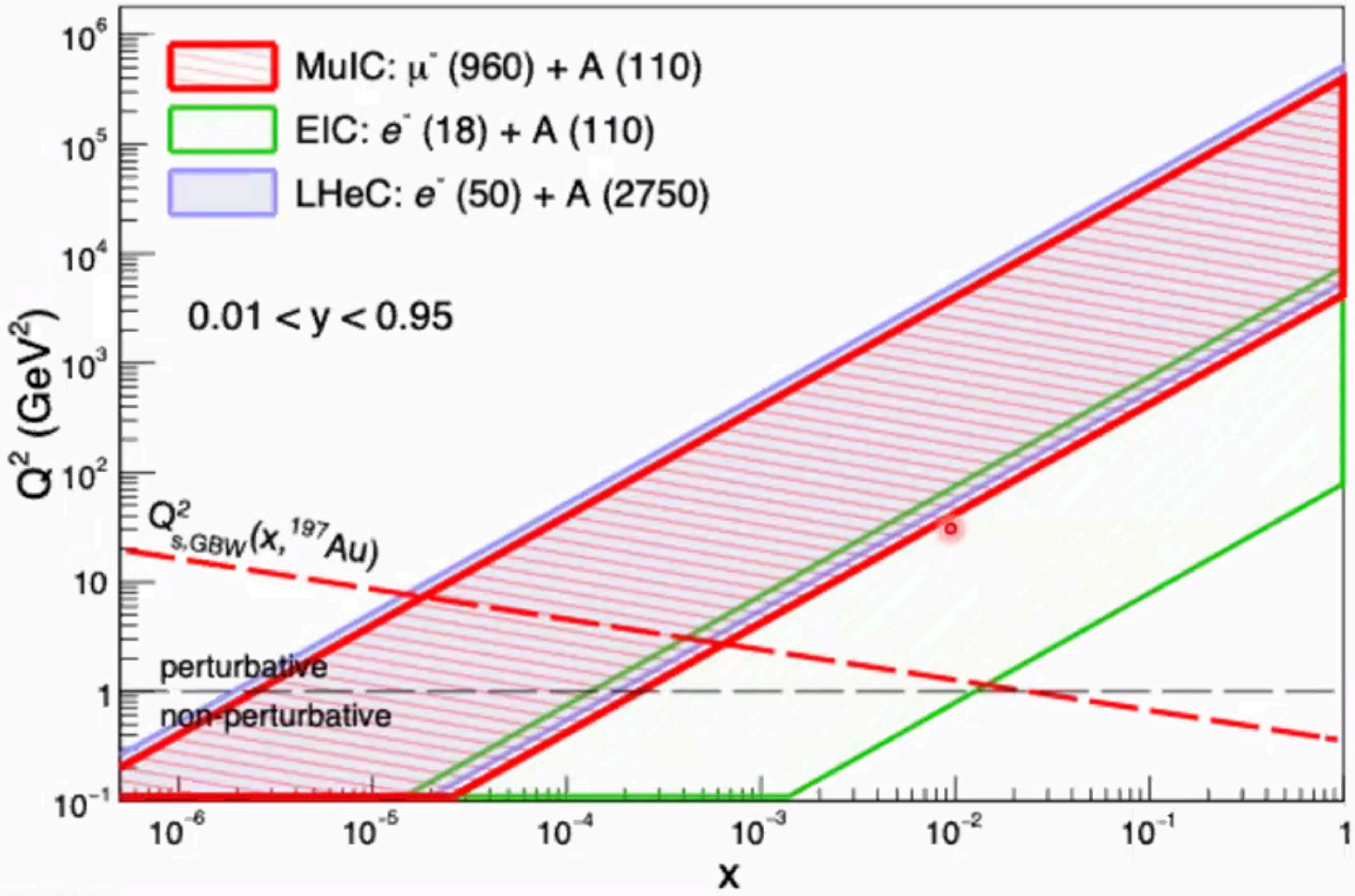
QCD and the Running of α_S



- 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

Q^2-x Reach Comparison: e(μ)-A Scattering

Can explore well the predicted saturation regime [1] in ions



Saturation scale:

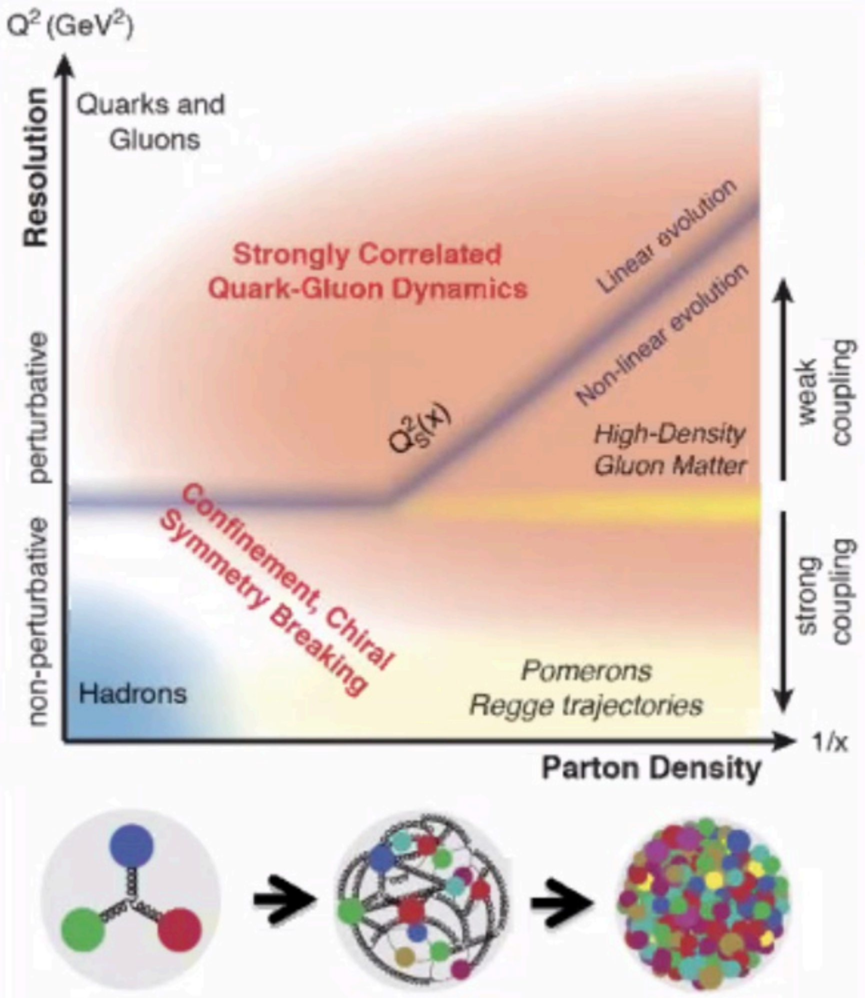
$$Q_s^2(A) = A^{1/3} Q_s^2(p)$$

Also the MuIC can scan a wide range of ion species

[1] GBW model: Phys. Rev. D 59, 014017 (1998)

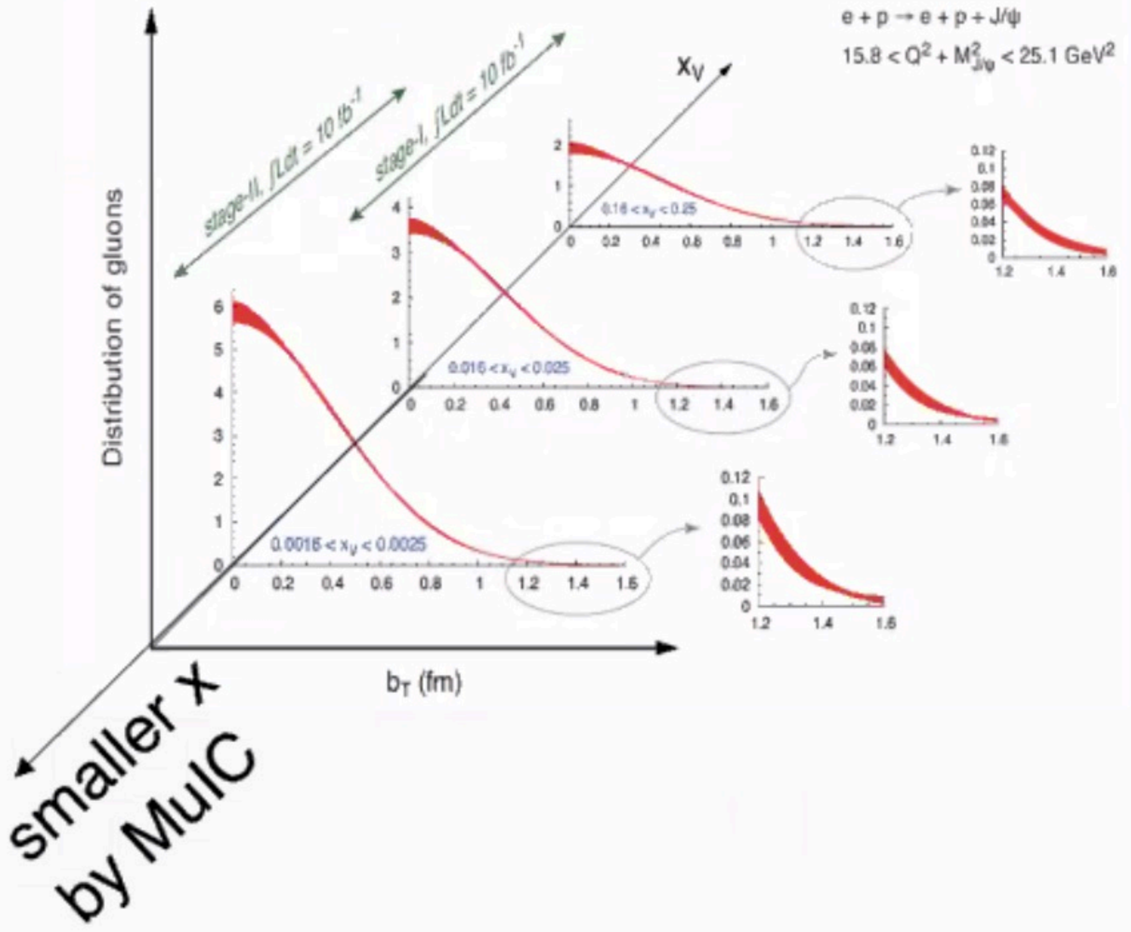
Nuclear Physics at the MuIC

Gluon saturation



What's the property of high-density gluon matter

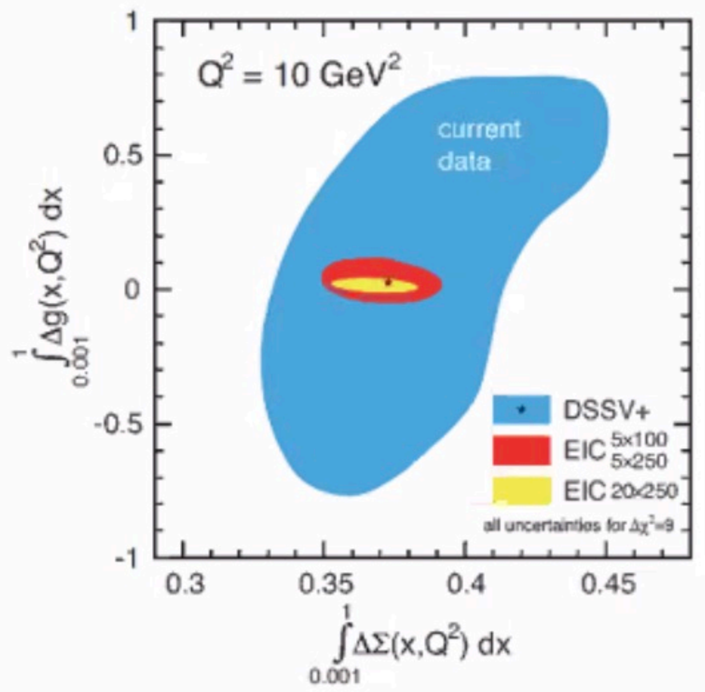
3D Nucleon structure



Nucleon spin puzzle

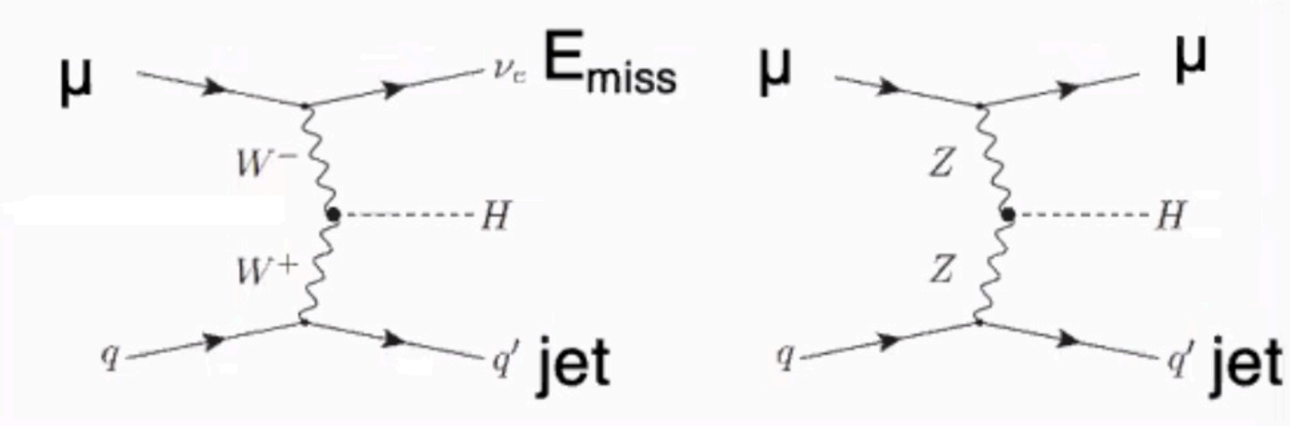
"Helicity sum rule"

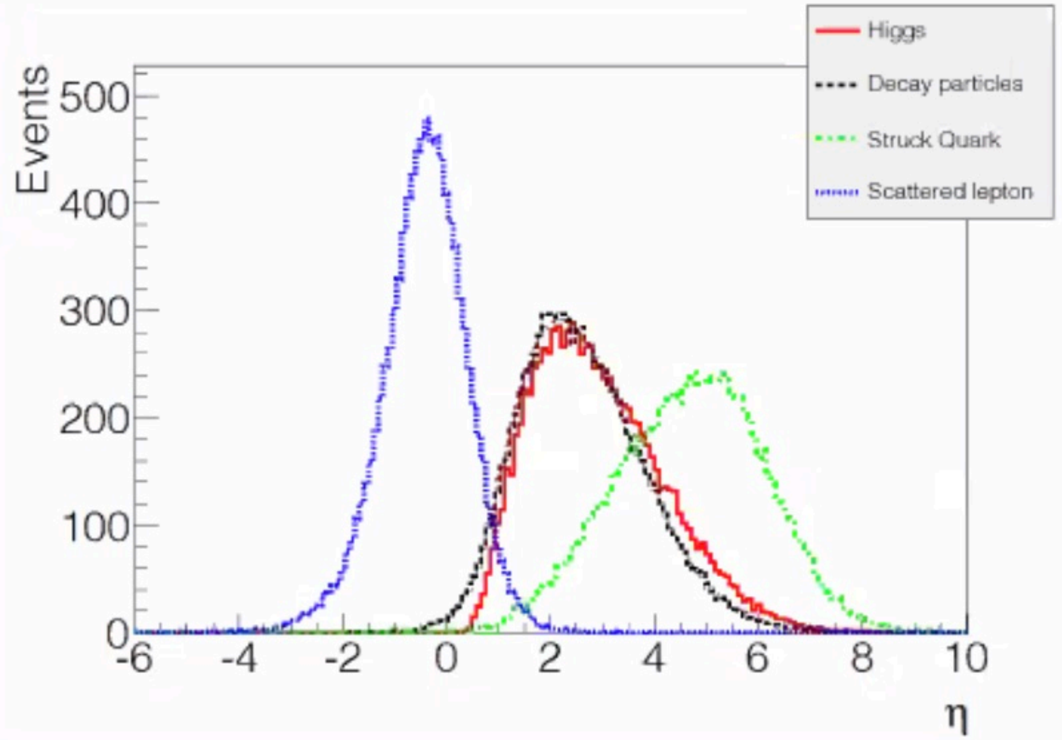
$$\frac{1}{2}\hbar = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quark contribution}} + \underbrace{\Delta G}_{\text{gluon contribution}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{orbital angular momentum}}$$



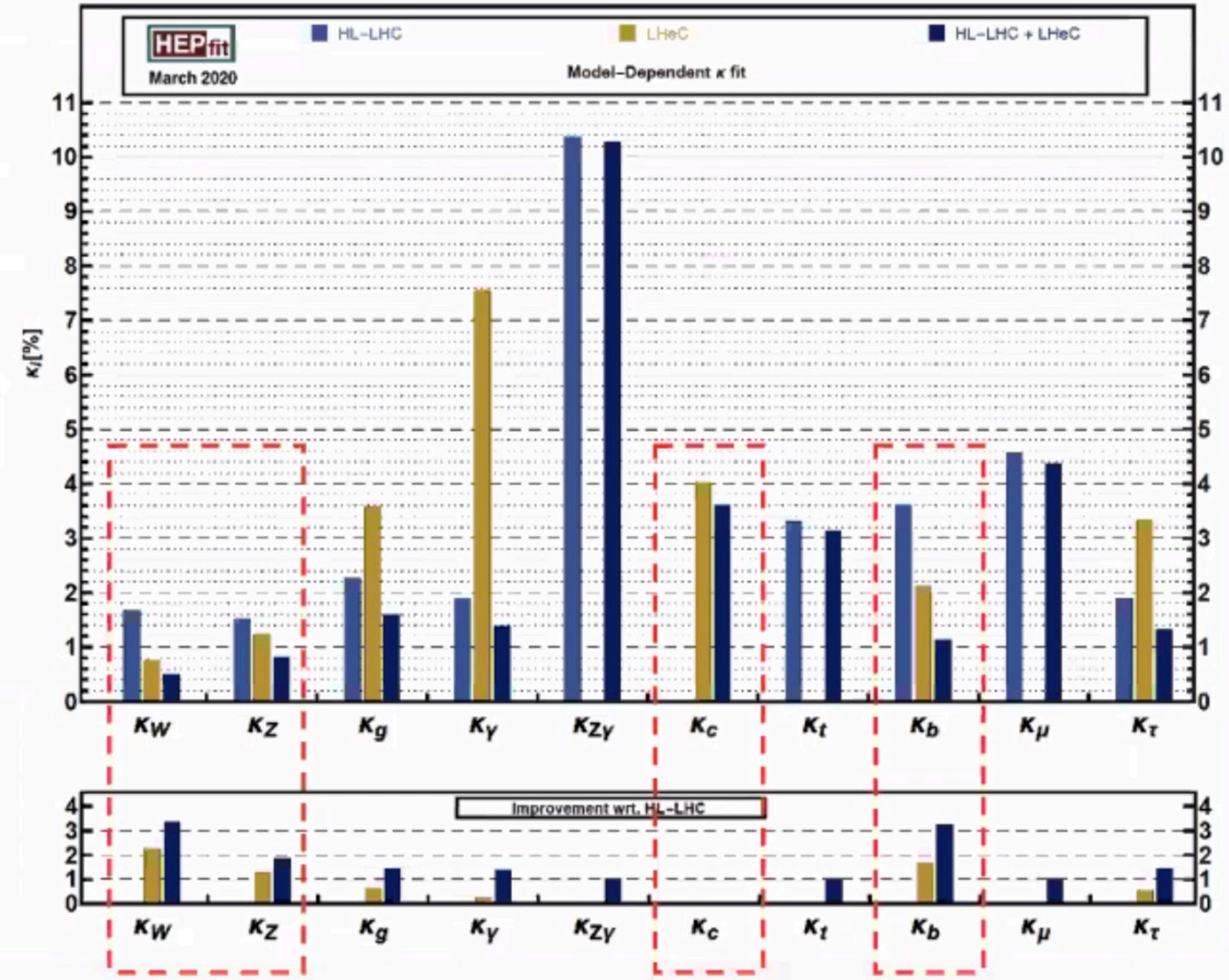
MuIC to reach $x \sim 10^{-5}$

Higgs at the MuIC



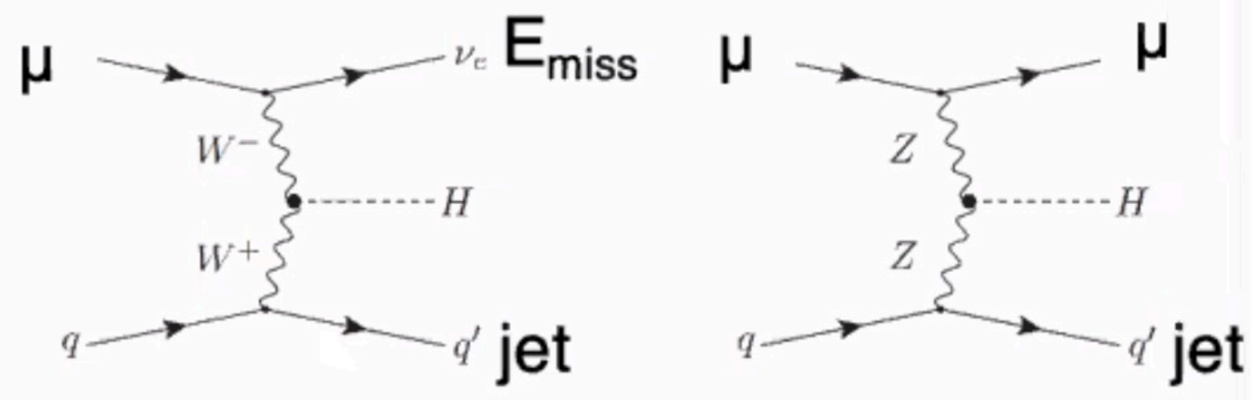


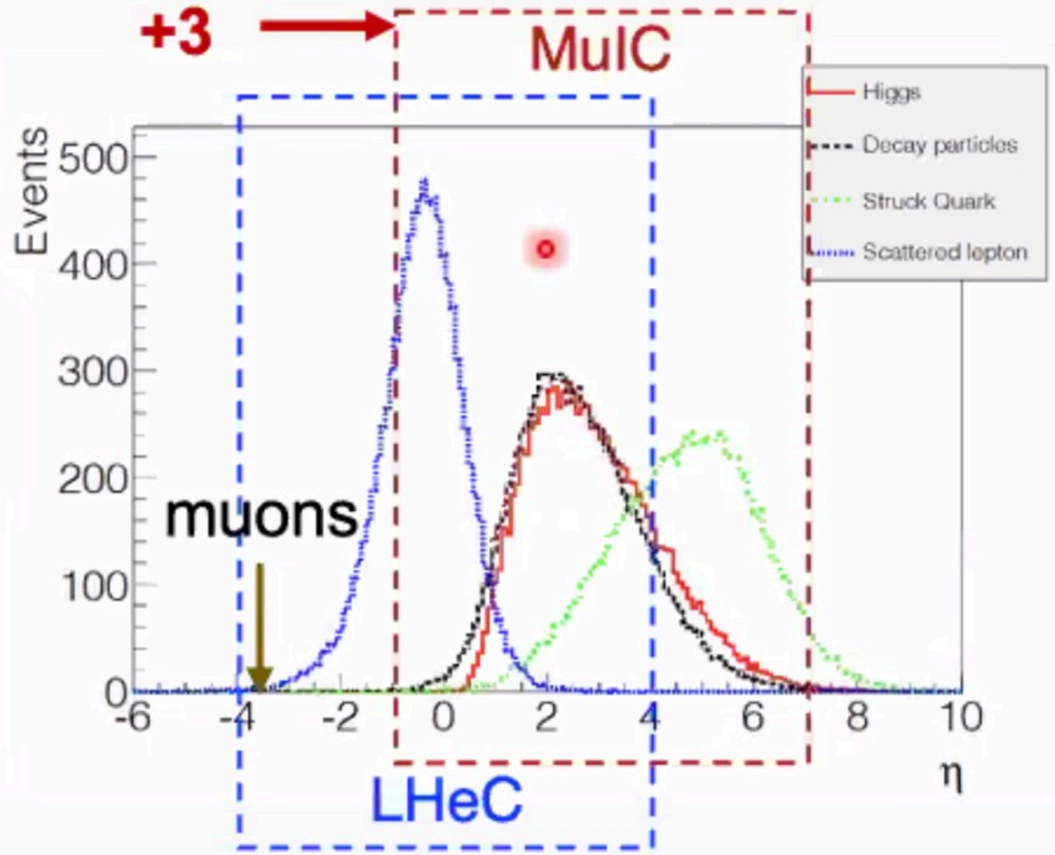
Uncertainties of Higgs couplings



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

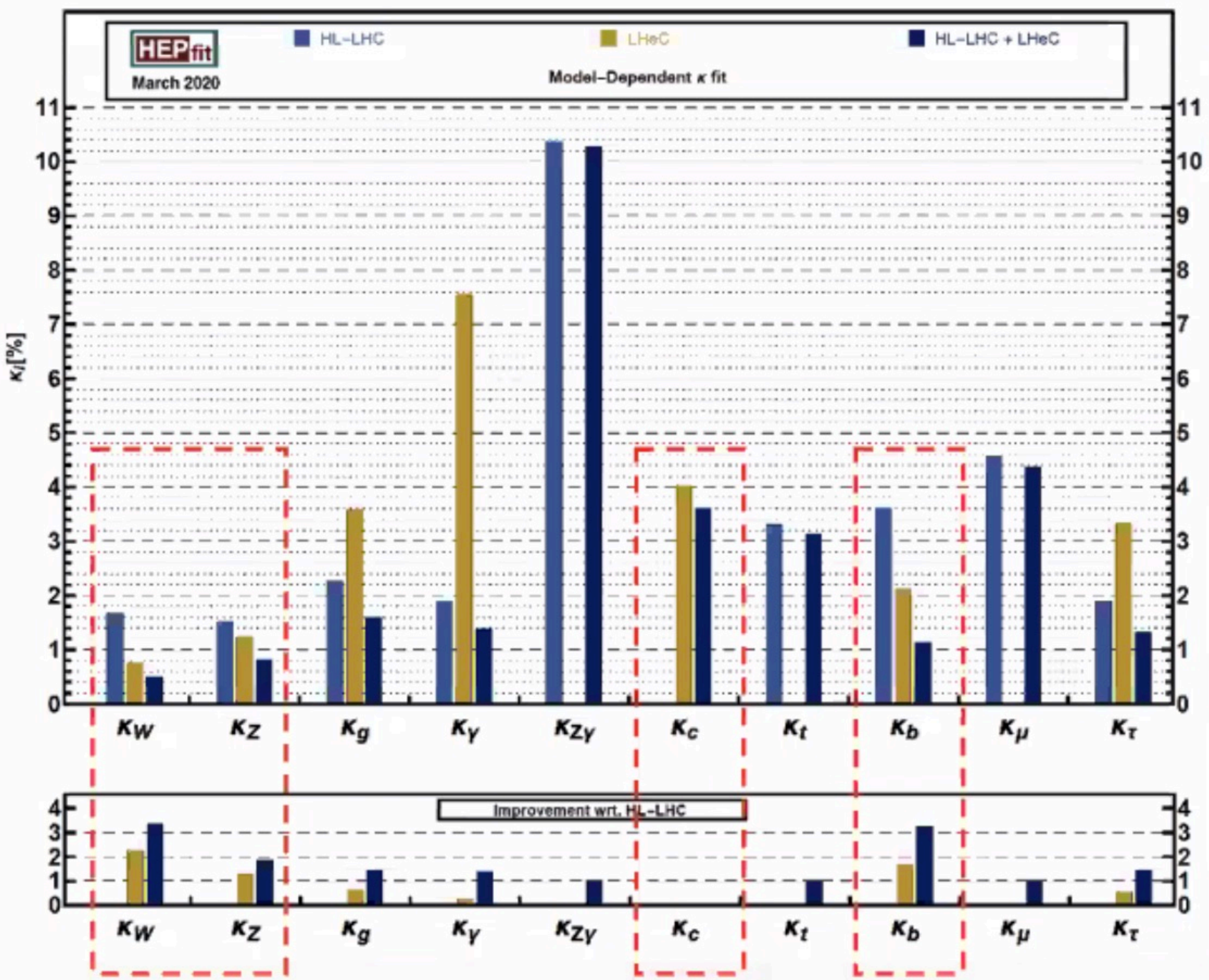
Higgs at the MuIC





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

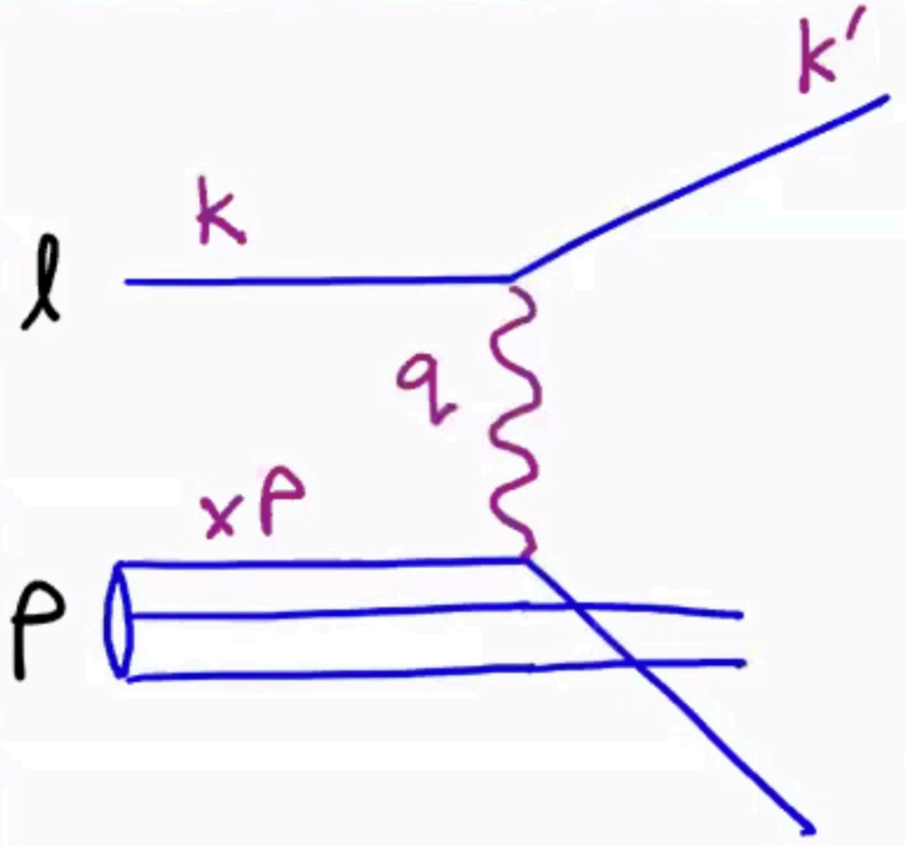
Uncertainties of Higgs couplings



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

DIS Variables and Kinematics

- $$x = \frac{Q^2}{2P \cdot q}$$ Bjorken x scaling variable
- $$y = \frac{P \cdot q}{P \cdot k}$$ Inelasticity
- $$Q^2 \equiv -q^2 = -(k - k')^2 = sxy$$ 4-mom transfer
- $s = (k + P)^2$ squared c.o.m. energy



From scattered lepton:

- $$Q^2 = 2E_\ell E'_\ell (1 + \cos\theta)$$

$$y = 1 - \frac{E'_\ell}{2E_\ell}(1 - \cos\theta)$$

From scattered hadrons:

DIS Variables and Kinematics

- $x = \frac{Q^2}{2P \cdot q}$ Bjorken x scaling variable
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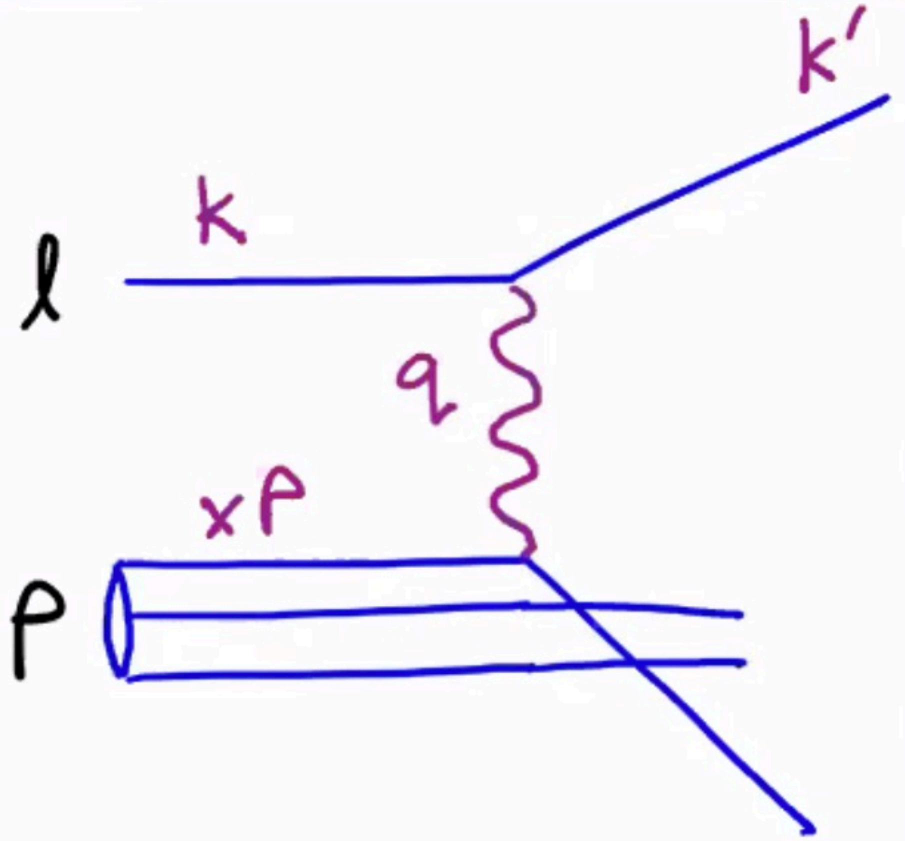
- $Q^2 \equiv -q^2 = -(k - k')^2 = sxy$ 4-mom transfer
- $s = (k + P)^2$ squared c.o.m. energy



θ is the polar angle w.r.t. the initial hadron direction

From scattered lepton:

- $Q^2 = 2E_\ell E'_\ell (1 + \cos\theta)$

$$y = 1 - \frac{E'_\ell}{2E_\ell}(1 - \cos\theta)$$

From scattered hadrons:

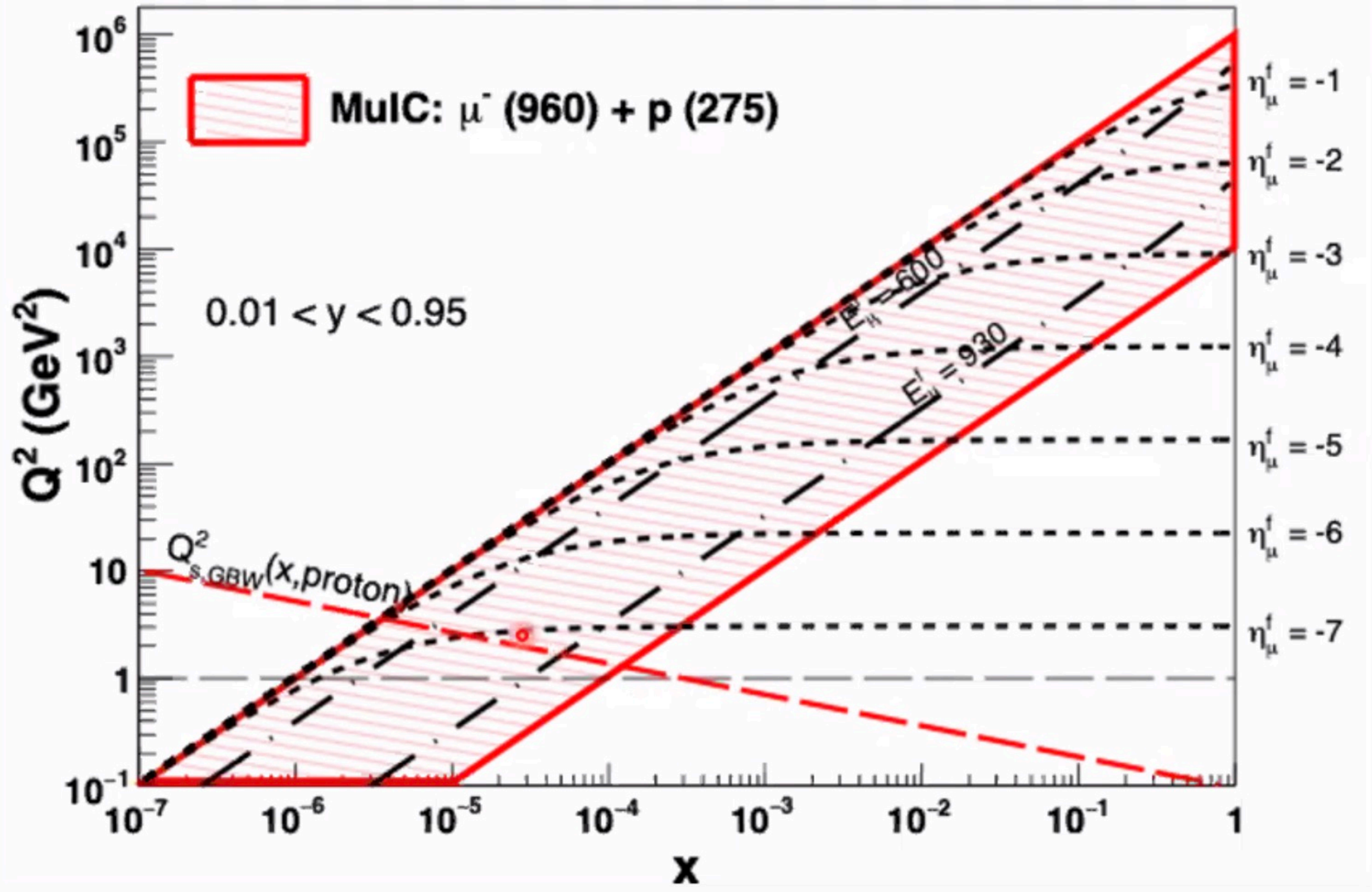
$$Q^2(P,\gamma) = \frac{P^2 \sin^2\gamma}{1 - y(P,\gamma)},$$

$$y(P,\gamma) = \frac{P(1-\cos\gamma)}{2E^i_\mu},$$

$$P^2 = (\Sigma_h P_h^x)^2 + (\Sigma_h P_h^y)^2 + (\Sigma_h P_h^z)^2,$$

$$\cos\gamma = \frac{(\Sigma_h P_h^x)^2 + (\Sigma_h P_h^y)^2 - (\Sigma_h (E_h - P_h^z))^2}{(\Sigma_h P_h^x)^2 + (\Sigma_h P_h^y)^2 + (\Sigma_h (E_h - P_h^z))^2},$$

Scattered Lepton Kinematics - MuIC



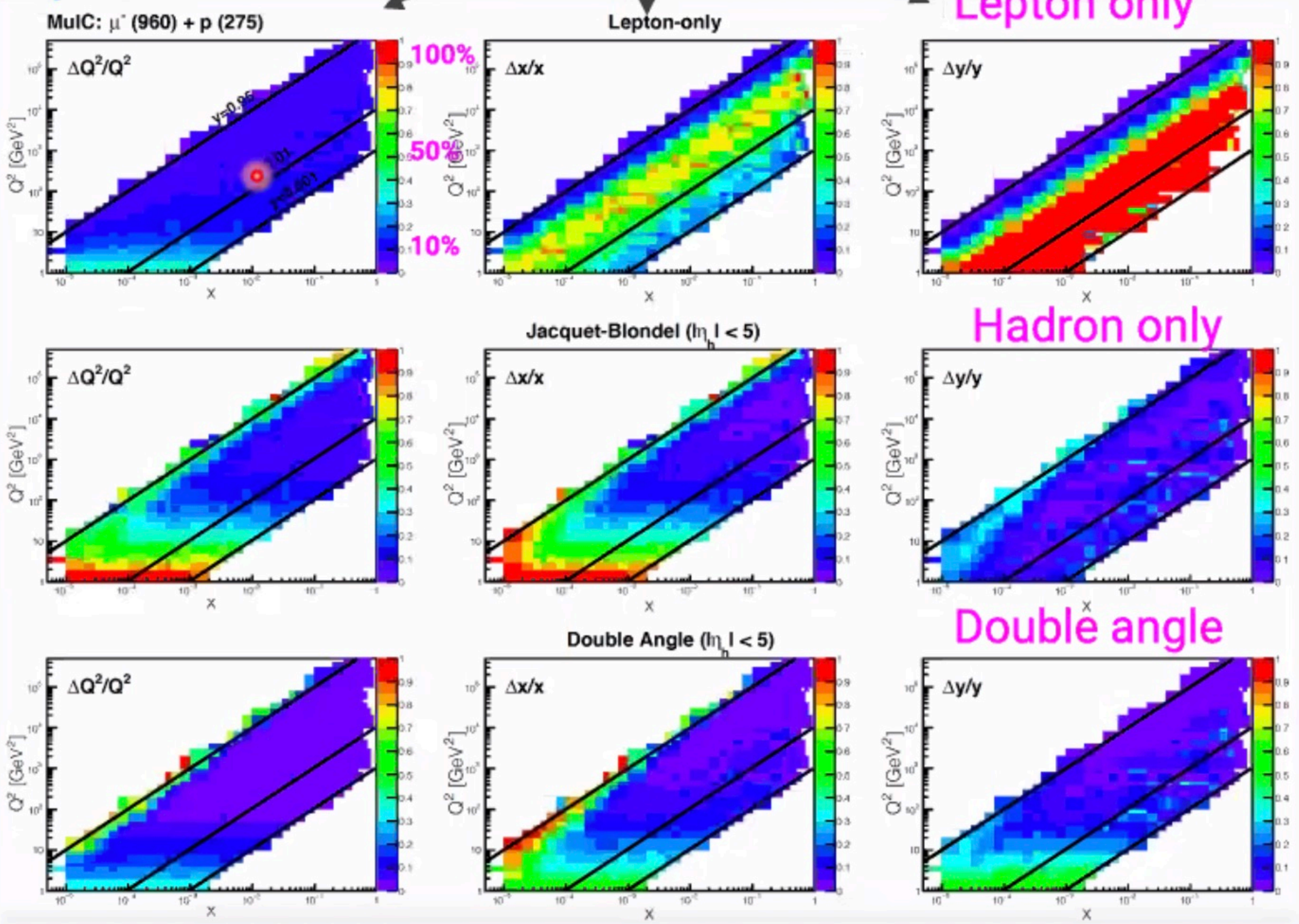
- Scattered muon momentum essentially defines y (decreases with y increasing)
  - Typically > 500 GeV
- Scattering angle is in very backward (lepton) direction
  - $-7 < \eta < -5$ at low Q^2

Distinct experimental challenges in tagging very forward muons to address.
(but hundreds of GeV muons will penetrate through anything, i.e. shielding)

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

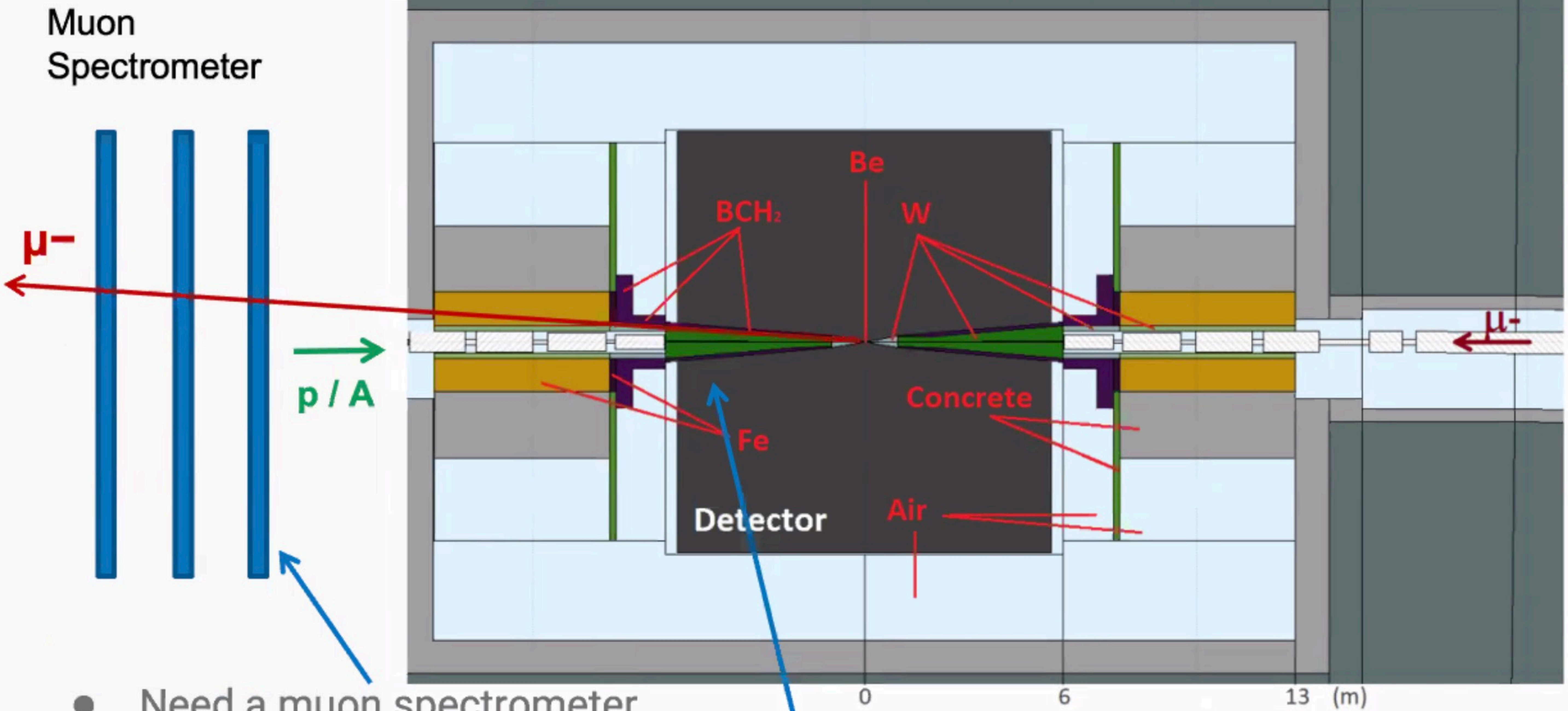
Particle	Detector	Resolution: $\frac{\sigma(p)}{p}$ or $\frac{\sigma(E)}{E}$	Resolution: $\sigma(\eta,\varphi)$
(Forward) Muons	e.g., MPGD	$0.01\%\, p \oplus 1\%$	0.2×10^{-3}
Charged particles ($\pi^\pm, K^\pm, p/\bar{p}, e^\pm$)	Tracker + PID	$0.1\%\, p \oplus 1\%$	$\left(\frac{2}{p} \oplus 0.2\right)\times10^{-3}$
Photons	EM Calorimeter	$\frac{10\%}{\sqrt{E}} \oplus 2\%$	$\frac{0.087}{\sqrt{12}}$
Neutral hadrons (n, K_L^0)	Hadronic Calorimeter	$\frac{50\%}{\sqrt{E}} \oplus 10\%$	$\frac{0.087}{\sqrt{12}}$

- Muons: 10% at 1 TeV, $\eta > -7$
- Hadrons: $|\eta| < 5$

Future work: detailed simulations to fully demonstrate the experimental feasibility

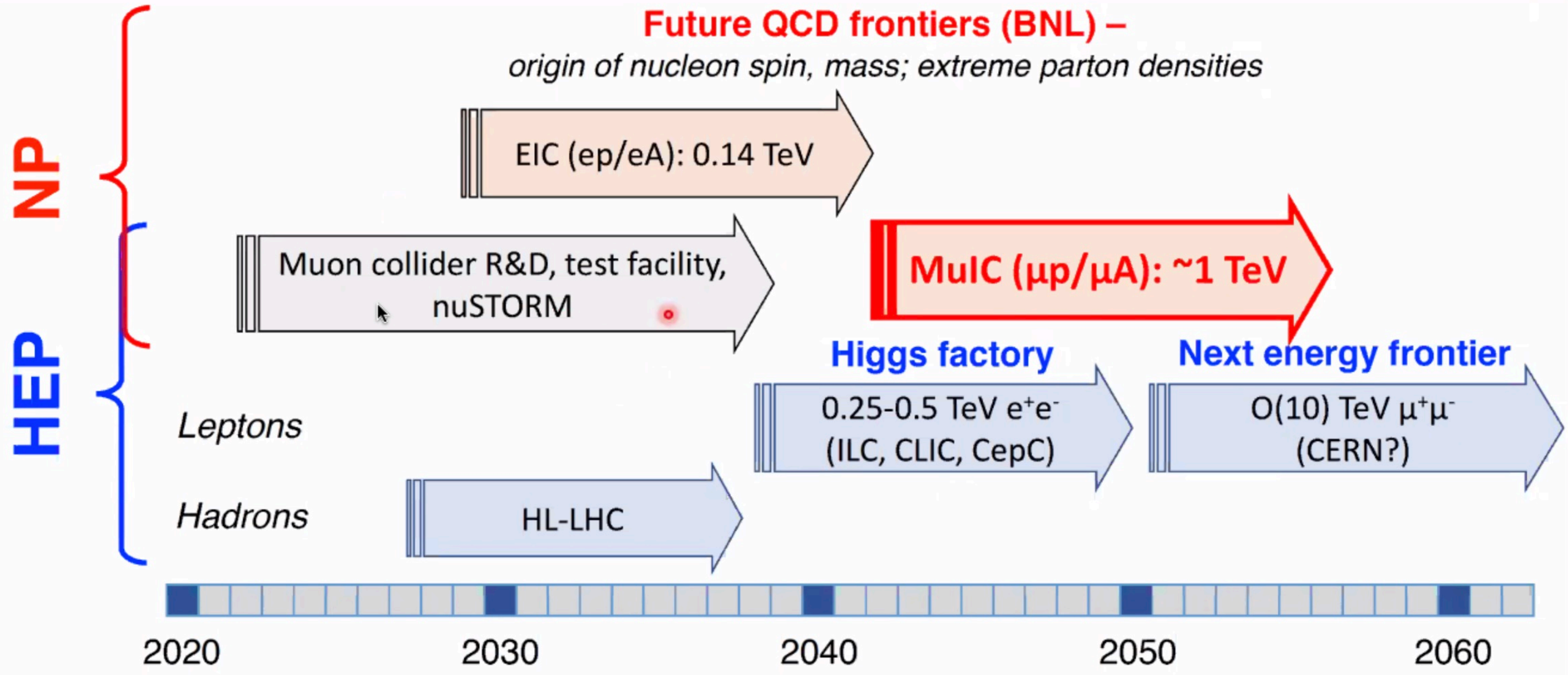
Detector Design Considerations

From Collamati et al. on $\mu^+\mu^-$ collider: arXiv:2105.09116



- Need a muon spectrometer
- Perhaps can reduce downstream shielding to improve hadron acceptance, as shielding nozzle may start at $|\eta|$ ~2.4

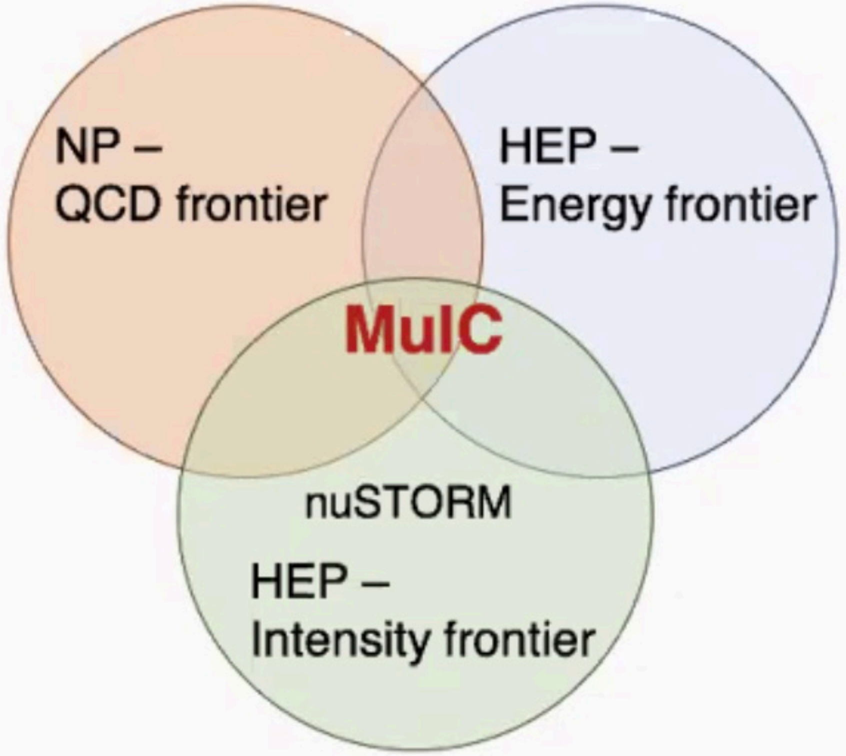
Path forward (in our view)



A possible roadmap to future muon colliders in NP and HEP

Summary

Key merits of MuIC concept:



- Compelling sciences with synergies across NP and 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

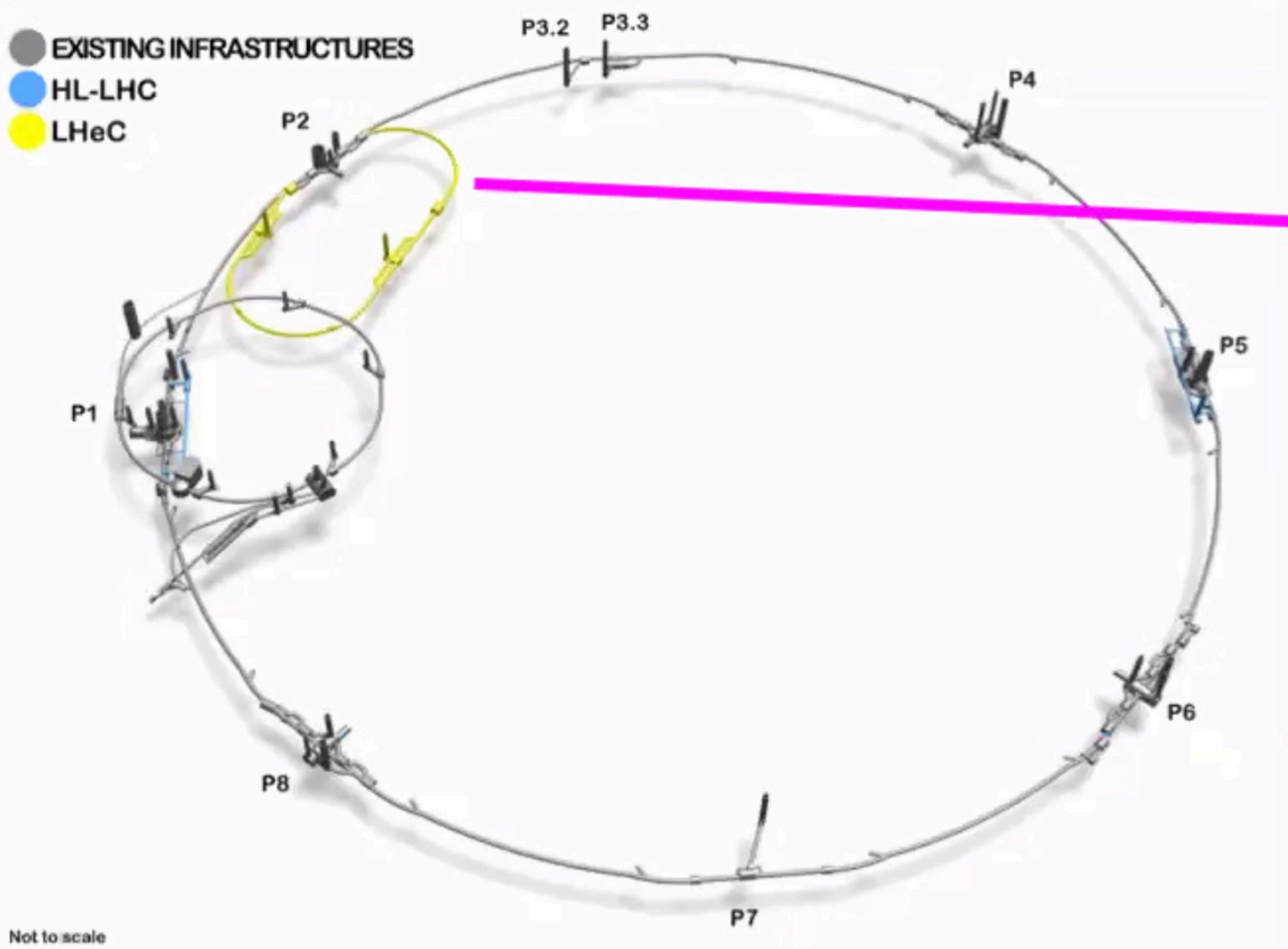
Next steps

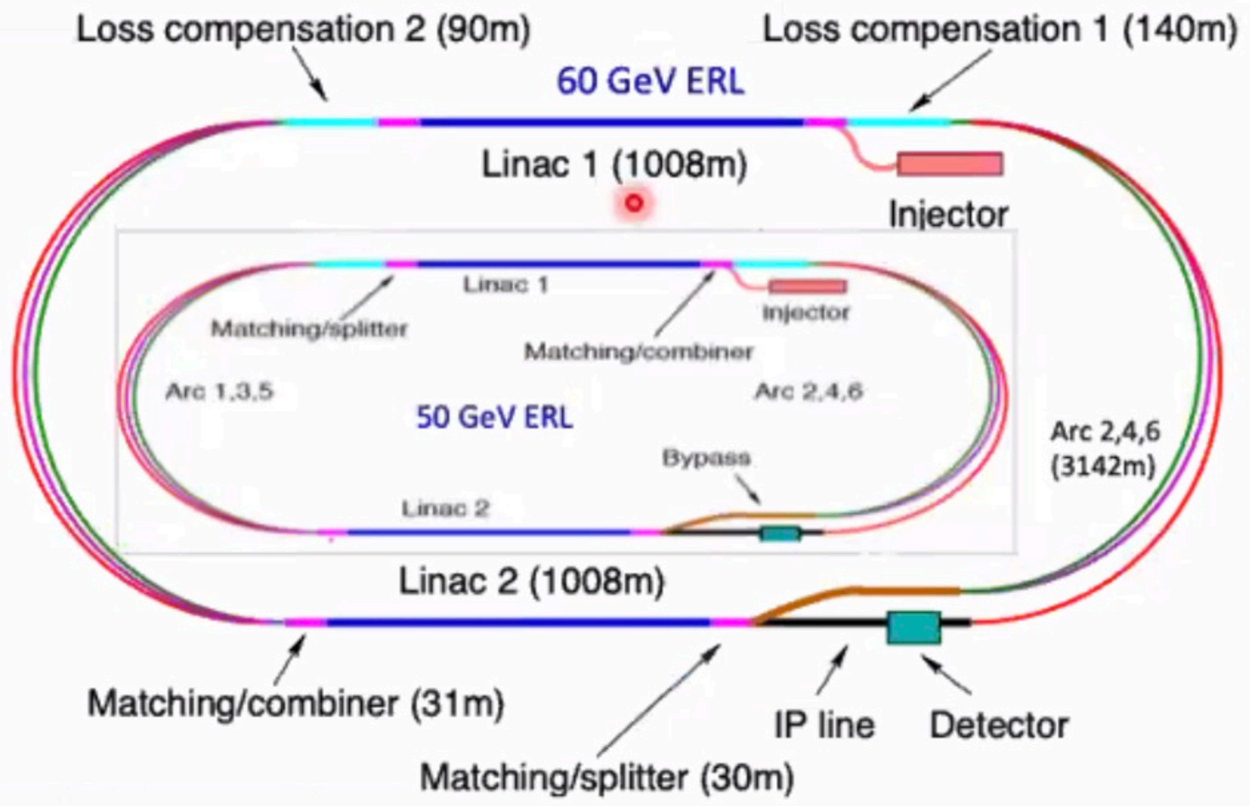
- Propose MuIC at BNL as one of future muon collider options in US to the Snowmass2021 planning exercise, and also propose the idea to the NP community in the upcoming long-range planning process in 2022
- Build on the MuIC concept, seek to establish dedicated R&D program on muon collider technology 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.
    - **Discuss with accelerator design experts on feasibility of muon acceleration at BNL facility**
- Engage broader theoretical and experimental communities to explore the physics potential and to address detector design requirements/challenges (workshops, collaborations, and working groups)

One Approach: 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)





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

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...

arXiv:1901.06150