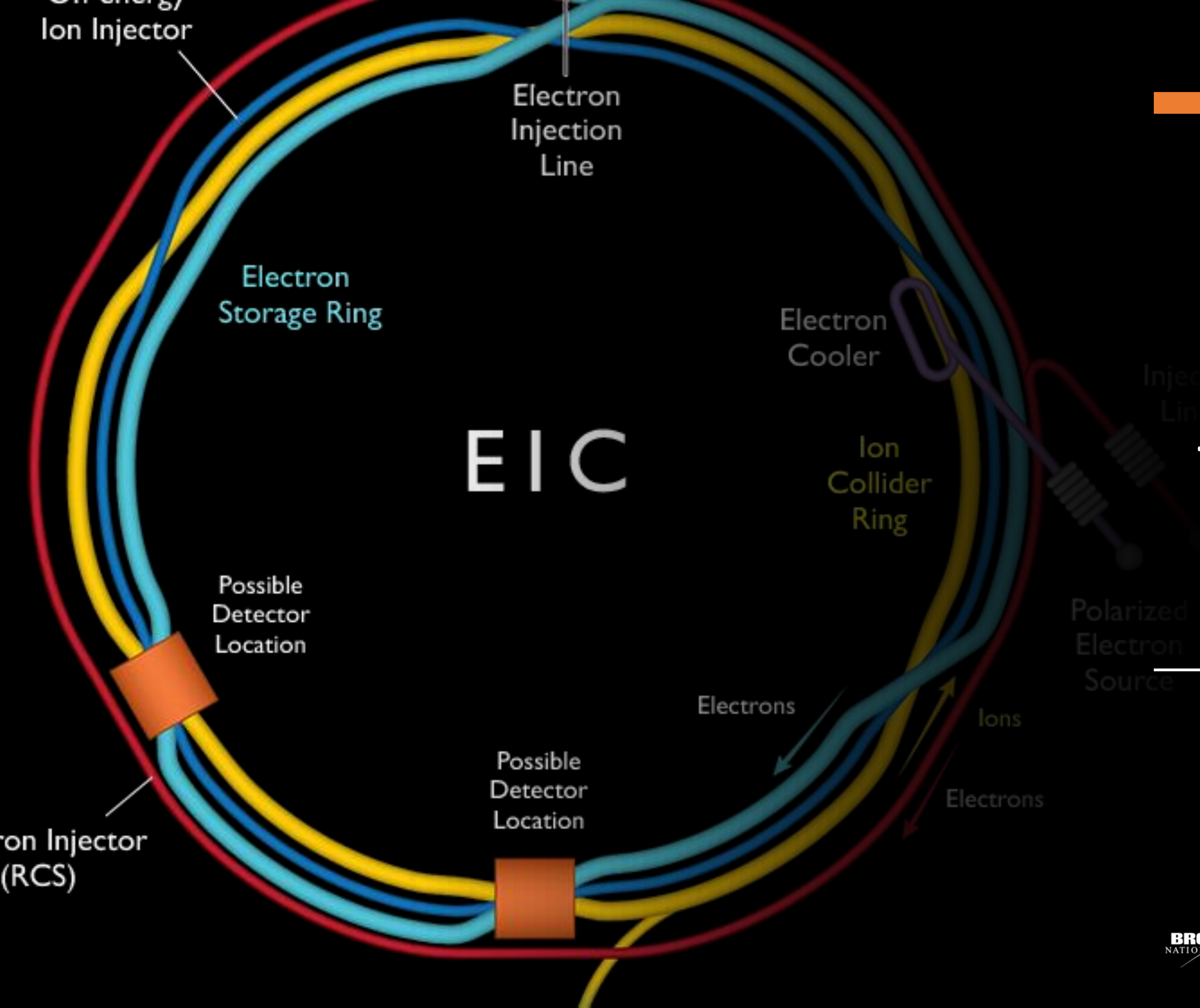
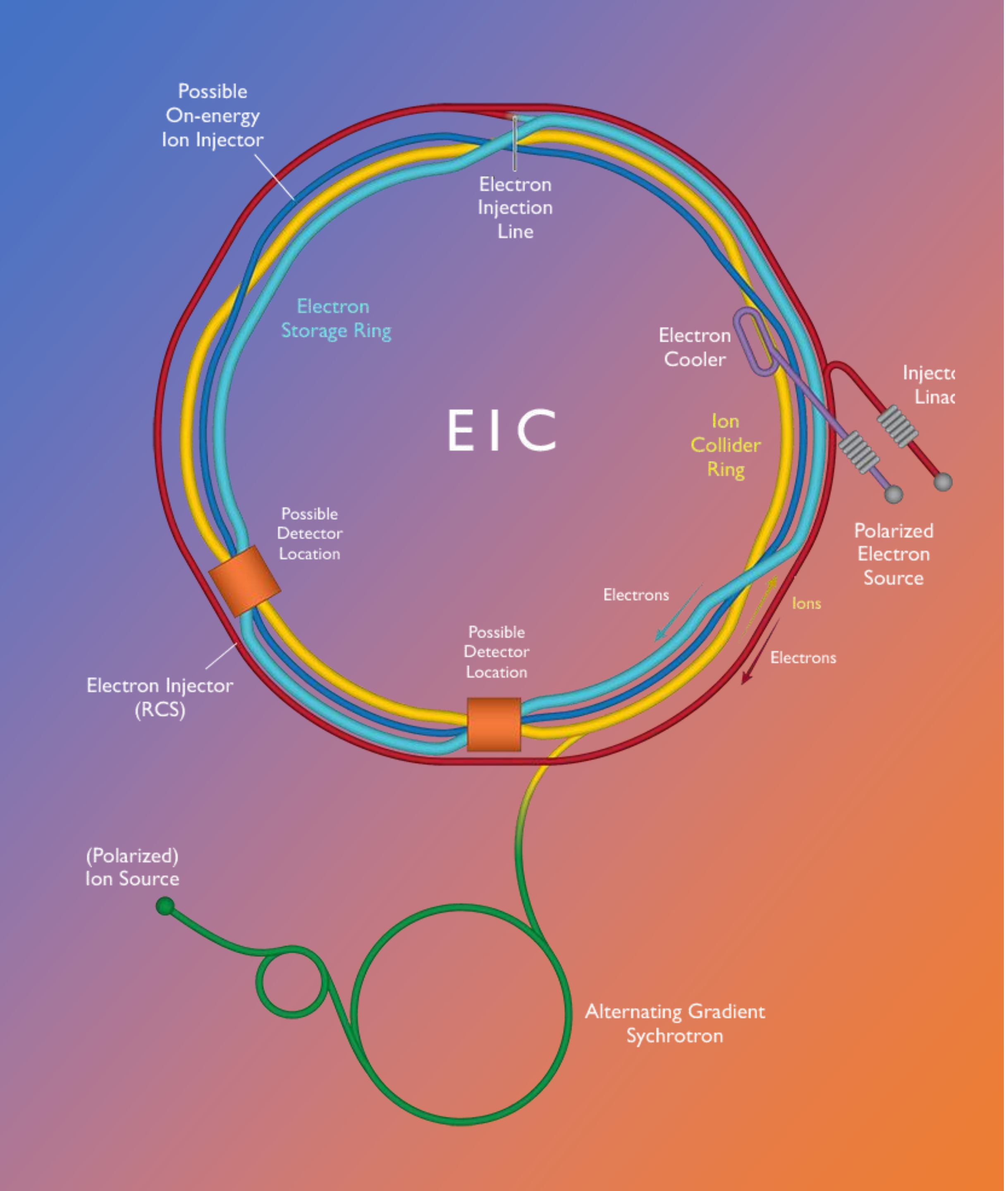


The Electron-Ion Collider : The Next QCD Frontier

Renee Fatemi

June 7, 2022

Brookhaven National Laboratory · Jefferson Lab · U.S. Department of Energy Office of Science



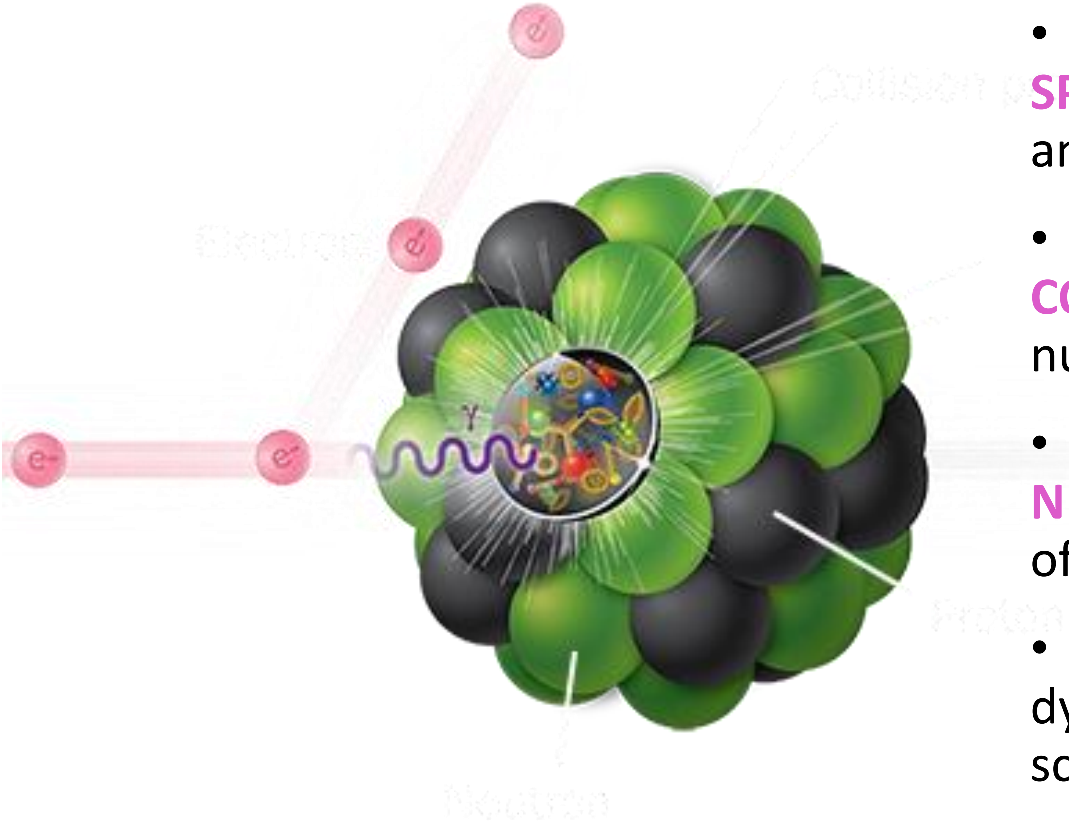
What is the EIC?

A new, innovative, large-scale particle accelerator facility that will enable the study of protons, neutrons and atomic nuclei at unprecedented levels of resolution and precision.

- Highly polarized (~70%) electron and proton beams
- Ion beams ranging from deuterons to heavy nuclei, such as lead, gold and uranium.
- Variable electron-proton center-of-mass energies ranging from 28-140 GeV.
- High collision electron-nucleon luminosities of $10^{33} – 10^{34}$ $cm^{-2}s^{-1}$
- 2nd interaction region possible

Joint endeavor by Thomas Jefferson National Accelerator Facility and Brookhaven National Lab

What questions is the EIC designed to answer?



- How do nucleon properties, like **MASS** and **SPIN**, emerge from the quark and gluon quantum numbers and their underlying interactions?
- How do the quarks and gluons orient themselves in **COORDINATE AND MOMENTUM SPACE**, inside of the nucleon?
- How do fragmenting quarks and gluons **INTERACT WITH NUCLEAR MATTER**? How does this change the characteristics of the colorless hadrons they produce?
- How does a dense nuclear environment affect the dynamics of the quarks and gluons? What is the nature and scale for **GLUON SATURATION**?

Why is the EIC the right facility for the QCD Frontier?

Answer in three case studies:

I. Gluon Helicity Distribution

How much do the gluons contribute to the proton spin?

II. Gluon Saturation

Is there an energy scale where gluon fields in nucleons and nuclei become saturated and are well described by the Color-Glass-Condensate Framework?

III. Multi-Dimensional Imaging of the Nucleon

What is the 3D momentum space structure of the partons inside of nucleons and nuclei?

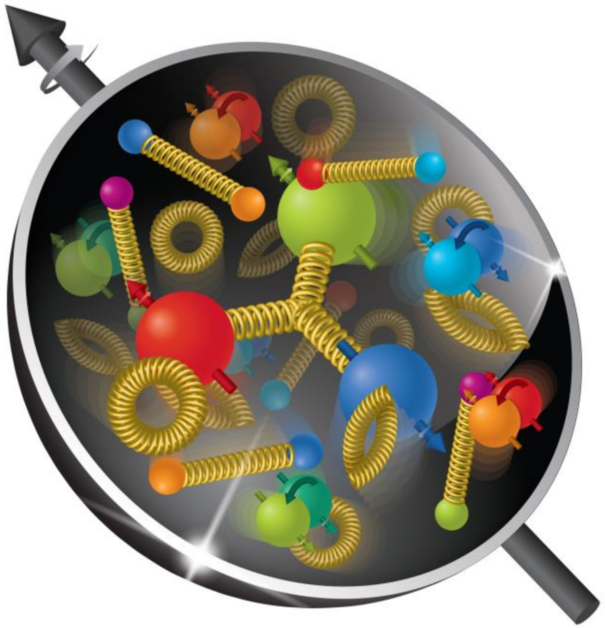
Gluon Helicity

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \boldsymbol{\Delta G(\mu)} + L_{Q+G}(\mu)$$

QUARK Helicity

GLUON Helicity

QUARK+GLUON Angular Momentum



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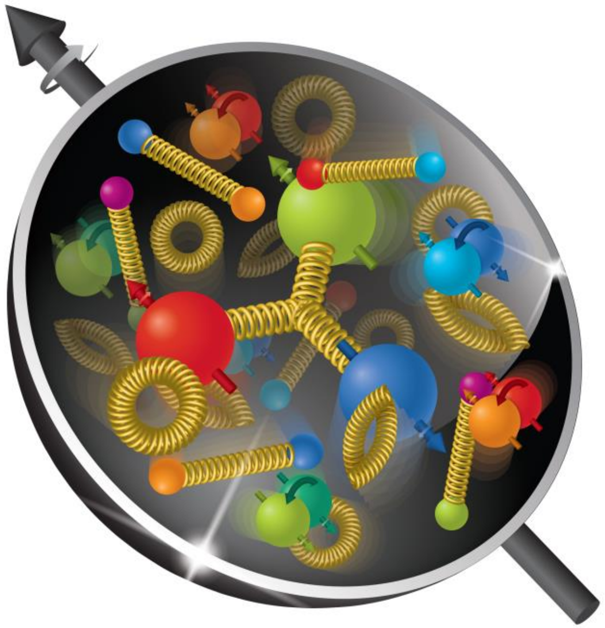
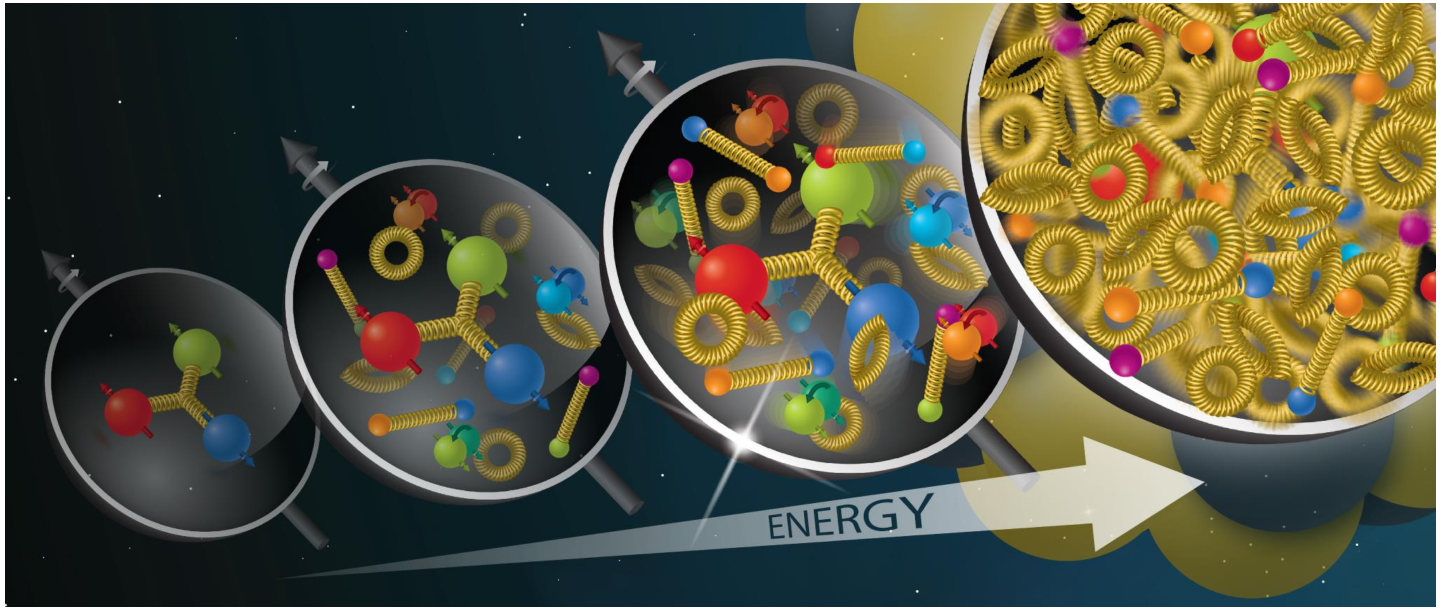




All distributions are defined at renormalization scale **μ** which sets the effective resolution at which the proton is being probed. In this talk **Q^2** is the resolution parameter.

Gluon Helicity

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \boldsymbol{\Delta G(\mu)} + L_{Q+G}(\mu)$$

QUARK Helicity

$$\Delta\Sigma(\mu) = \sum_f \boxed{\int_0^1} \Delta q(x,\mu)dx$$

GLUON Helicity

$$\Delta G(\mu) = \boxed{\int_0^1} \Delta g(x,\mu)dx$$

QUARK+GLUON Angular Momentum

$$L_{Q+G}(\mu) = \boxed{\int_0^1} [l_q(x,\mu) + l_g(x,\mu)]dx$$

Helicity PDFs - probability of a parton, carrying momentum fraction **x**, to have its spin aligned vs. anti-aligned with the spin of a relativistic proton.

Gluon Helicity

$$\Delta G(\mu) = \int_0^1 \Delta g(x,\mu)dx$$

Fixed Target lepton+p

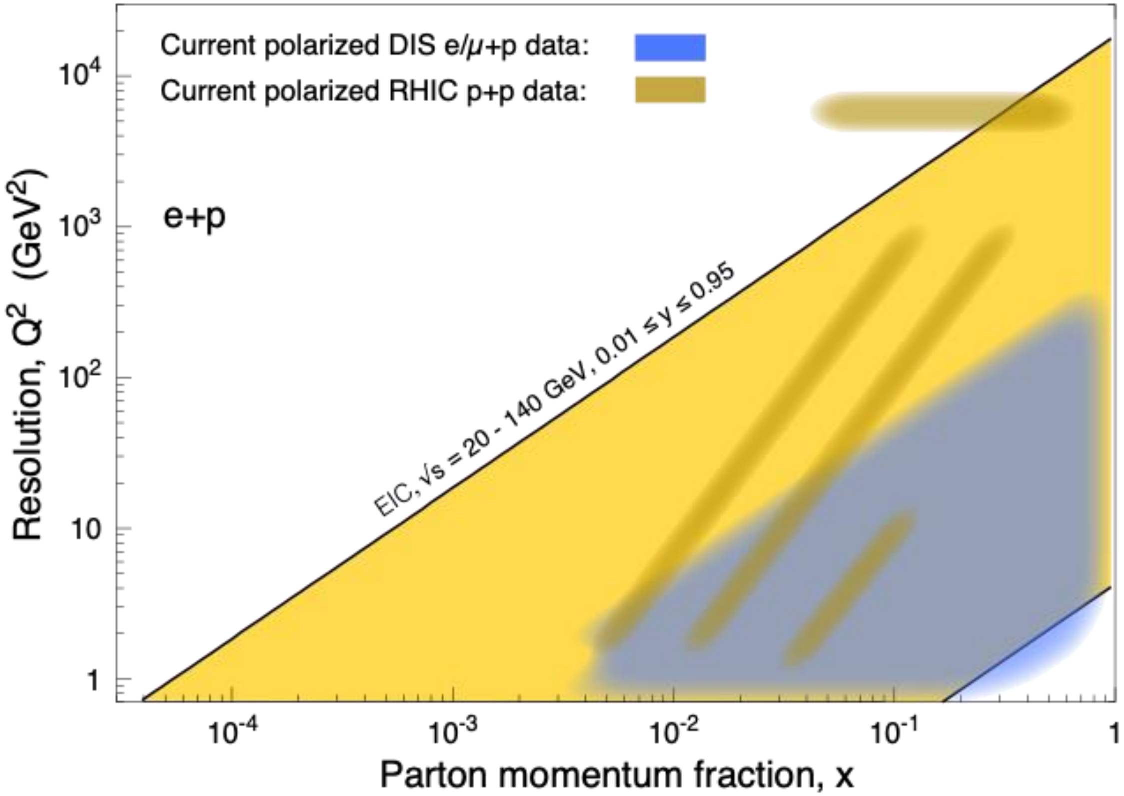
- Allows reconstruction of x and Q^2 on an event-by-event basis
- Fixed target limits x and Q^2 coverage.

Polarized pp collider

- higher Q^2 on average than Fixed Target
- limited x range sensitivity
- Inclusive measurements average over x

EIC

- Combines the best of both!
- Precision probe covers wide range of x and Q^2



Gluon Helicity

Experimental Signatures at the EIC

Inclusive Double Spin Asymmetry -
requires longitudinally polarized electron and proton beams over a large range of $\sqrt{s}$

$$A_{LL} = \frac{1}{P_e P_P} \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}$$

Detector Requirements :

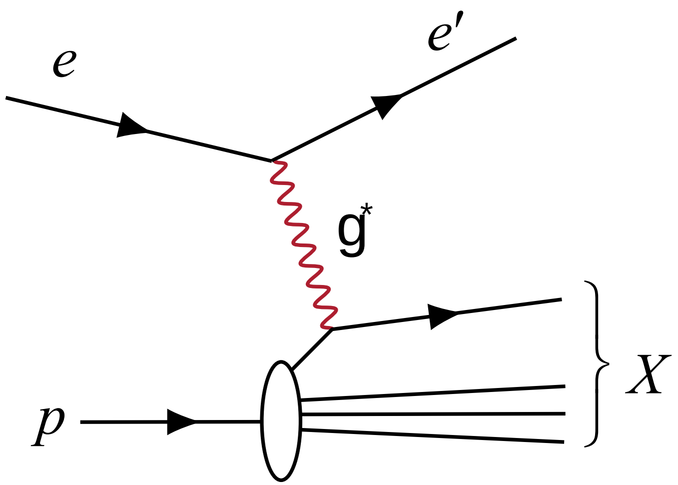
Precise reconstruction of scattered e kinematics via EM calorimeters.

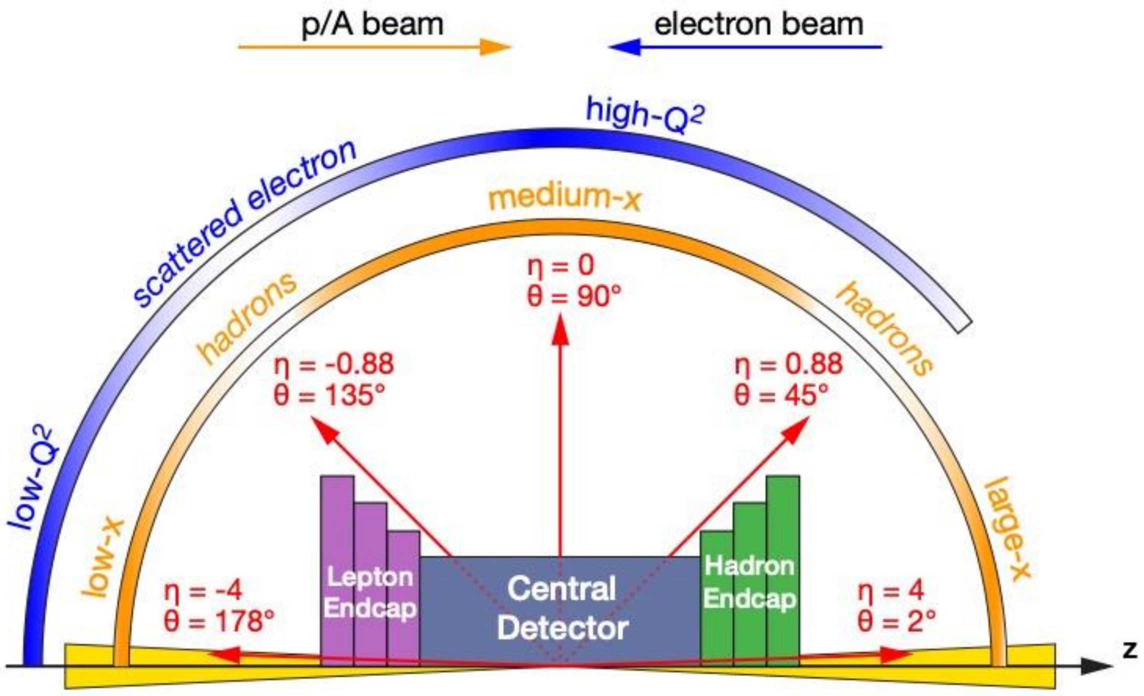
BACKWARD

$$\sigma(E)/_E \approx {}^{2\%}/_{\sqrt{E}} \otimes (1 - 3\%)$$

CENTRAL

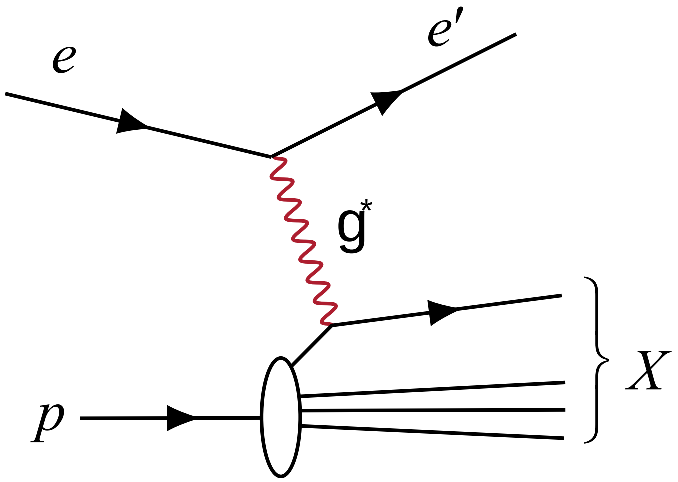
$$\sigma(E)/_E \approx {}^{10\%}/_{\sqrt{E}} \otimes (1 - 3\%)$$





Gluon Helicity

Experimental Signatures at the EIC

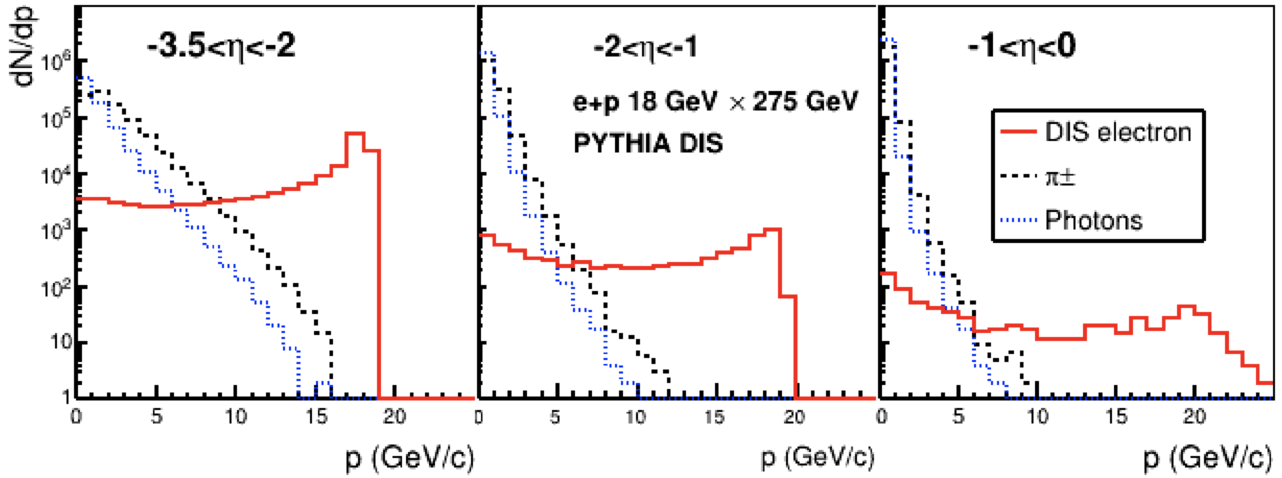


Inclusive Double Spin Asymmetry - requires longitudinally polarized electron and proton beams over a large range of $\sqrt{s}$

$$A_{LL} = \frac{1}{P_e P_P} \frac{N^{++} - R N^{+-}}{N^{++} + R N^{+-}}$$

Detector Requirements :

- Excellent hadron/electron separation. Need < 1% pion contamination to remain statistics limited.



Gluon Helicity

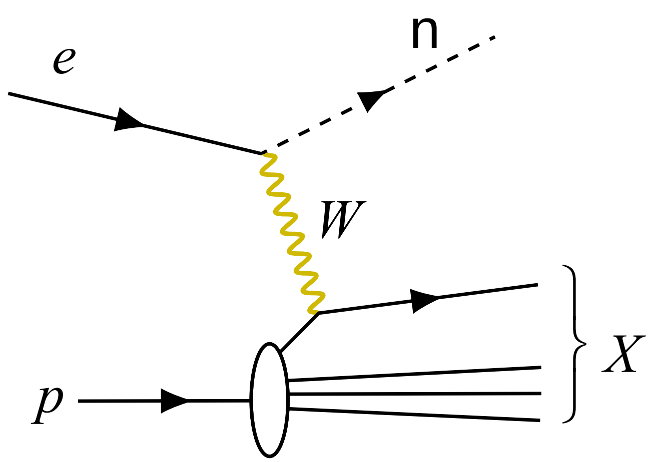
Experimental Signatures at the EIC

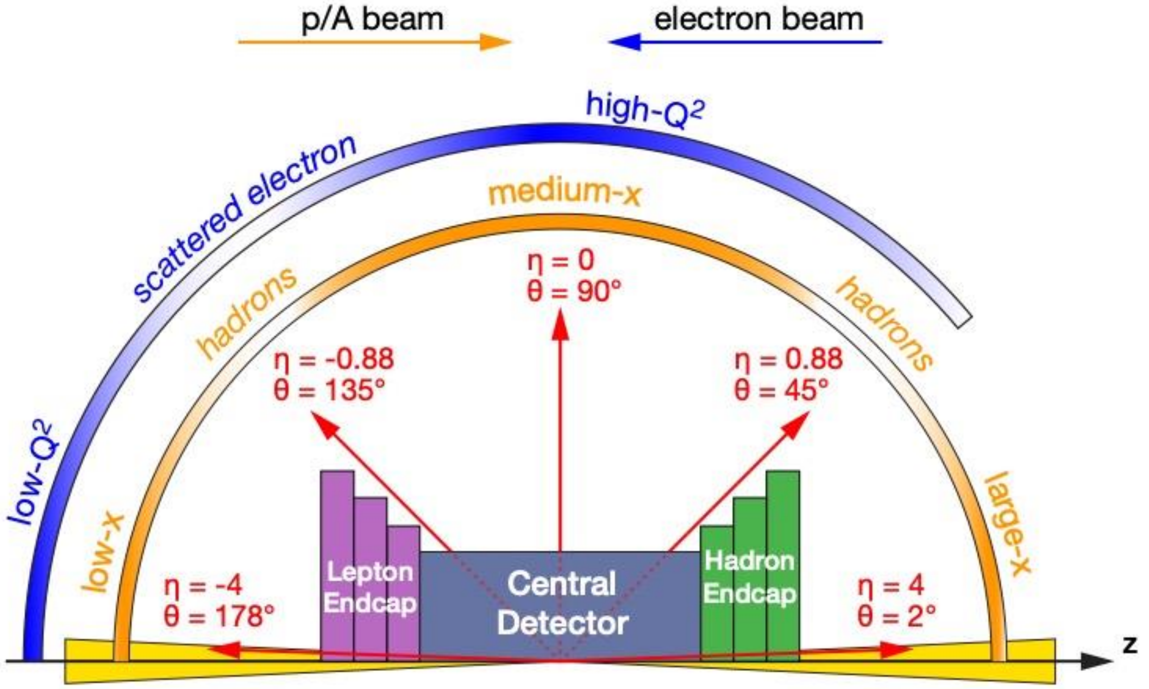
Inclusive Double Spin Asymmetry - requires longitudinally polarized electron and proton beams over a large range of $\sqrt{s}$

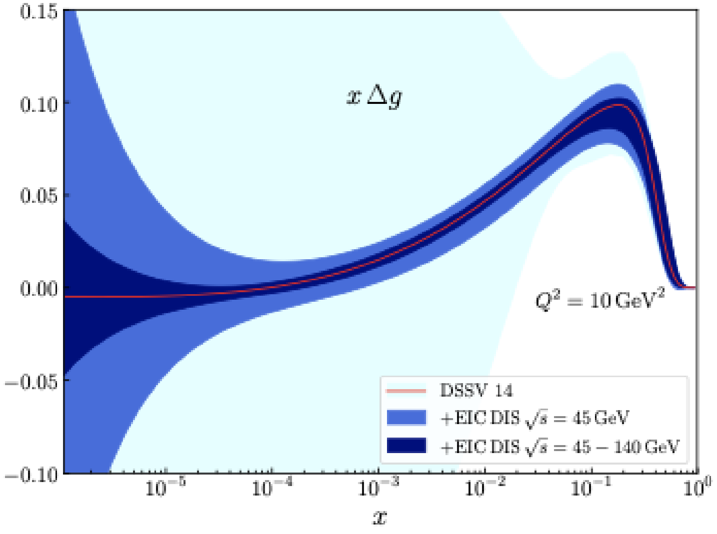
$$A_{LL} = \frac{1}{P_e P_P} \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}$$

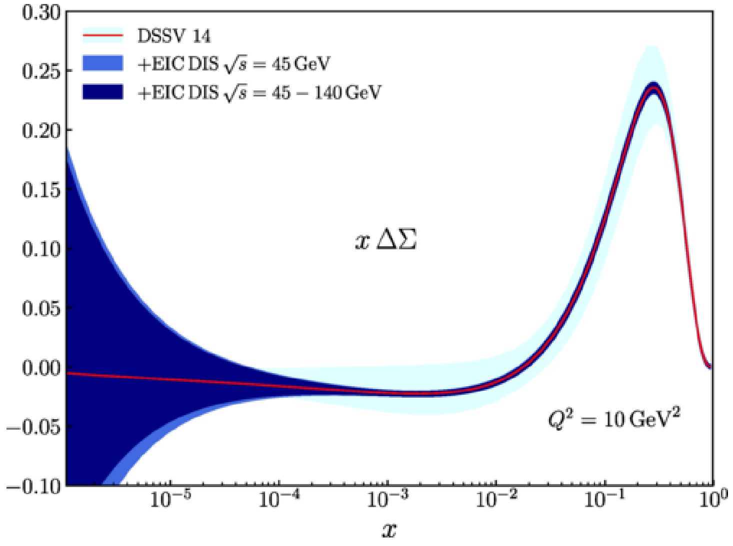
Detector Requirements :

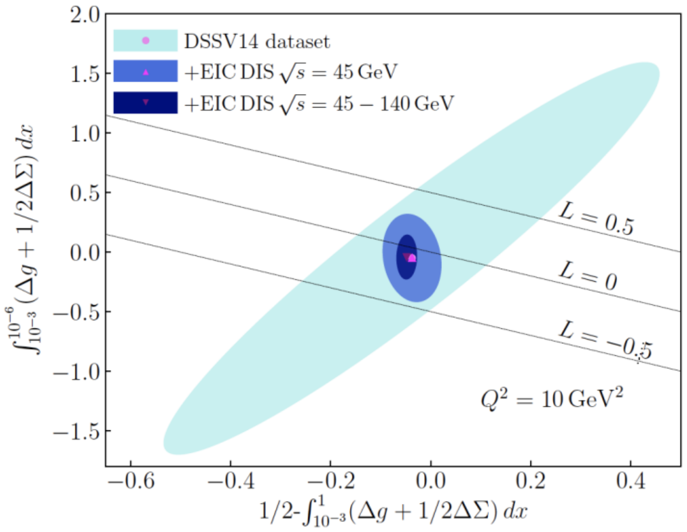
- Excellent hadron/electron separation. Need < 1% pion contamination to remain statistics limited.
- For CC channels calorimetry and tracking needed in forward region.









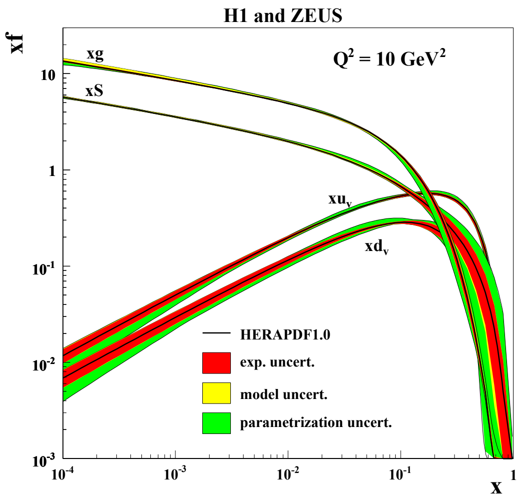


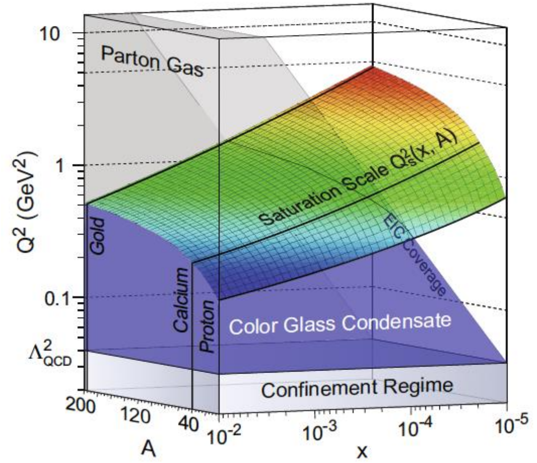
Gluon Helicity Constrains at an EIC

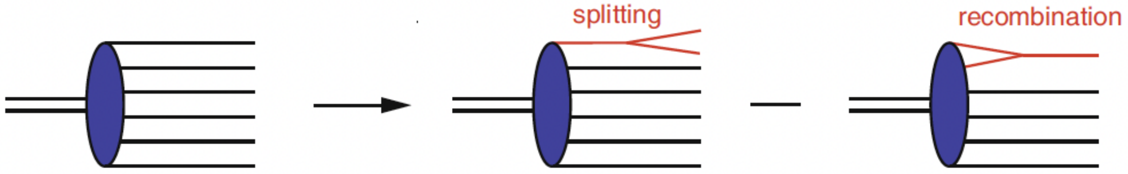
Phys. Rev. D **102**, 094018

Gluon Saturation

- Increasing density of the gluons at low x must level off, or **saturate**, due to gluon recombination.
- Define $Q_s \sim (1/x)^{\lambda}$ when splitting equals recombination.
- In heavy nuclei Q_s is enhanced by $A^{1/3}$!
- Gluons in this high-density regime are described the semi-classical EFT framework - the **Color Glass Condensate** (CGC).
- Goal is to observe the onset of gluon saturation and explore its properties.







Gluon Saturation

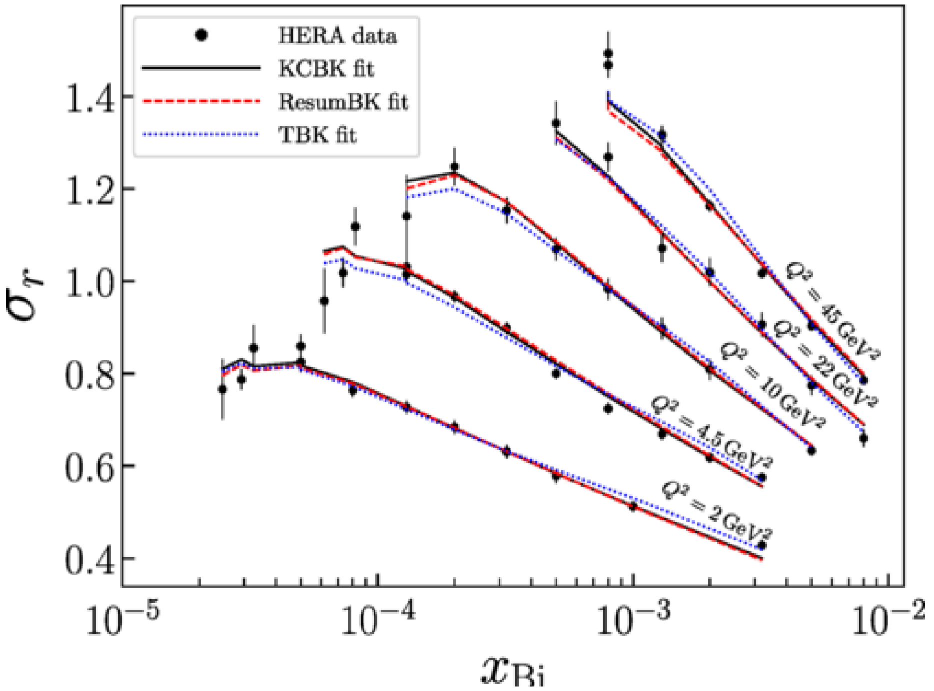
First indications of BFKL evolution at low x came from inclusive e-p Xsec data at HERA.

$$\sigma_r(x,y,Q^2) = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$

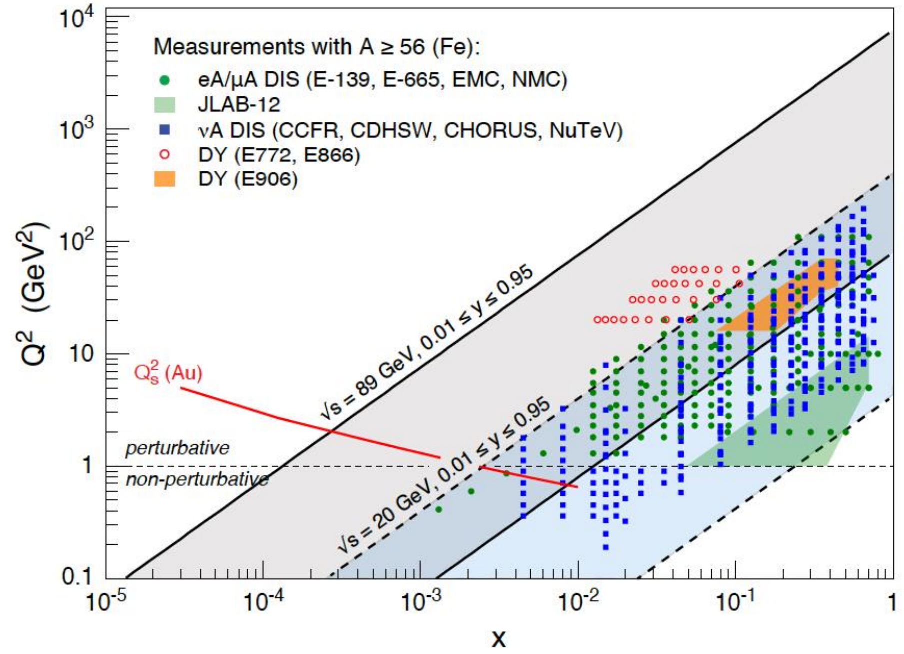
Theory can now reproduce low-x HERA data at NLO within the CGC framework.

High energy – High A beams are critical!

- Saturation effects are enhanced due to $A^{1/3}$
- Saturation scales are higher, facilitating comparisons with linear perturbative calculations.
- Q_s is x4 higher At an EIC @ $\sqrt{s} = 90$ than at HERA.



Phys. Rev. D102, 074028 (2020)



Gluon Saturation

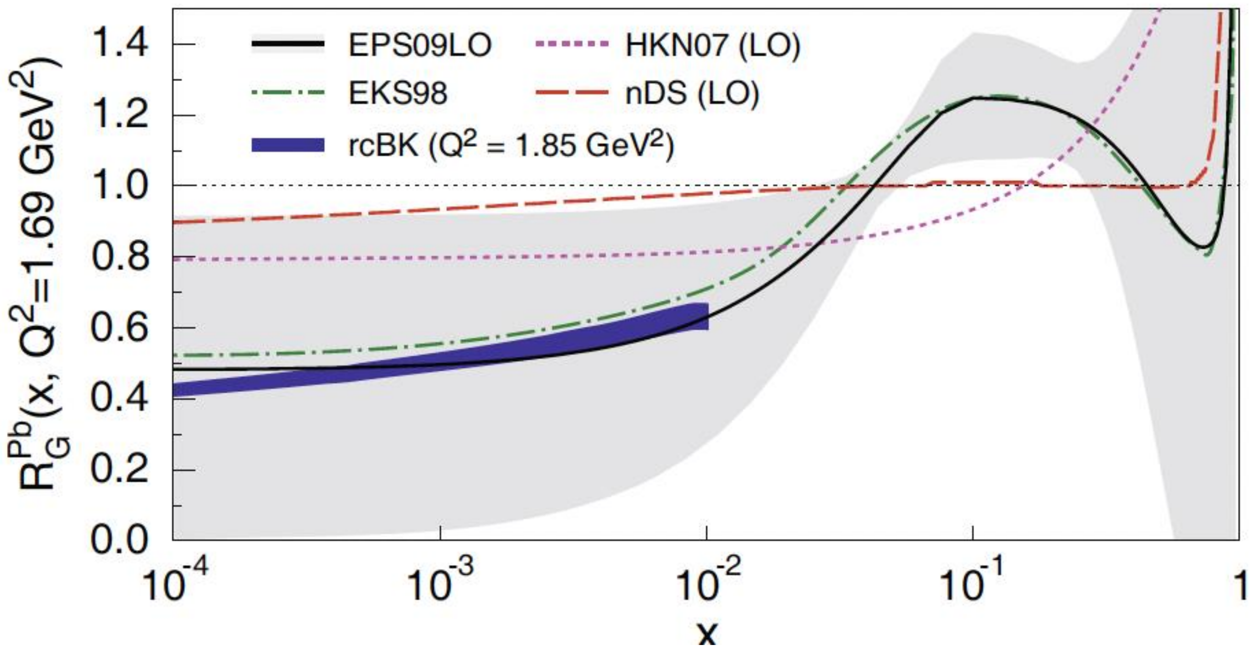
Experimental Signatures at the EIC

I. Reduced cross-section measurements in e+p and e+A at highest possible $\sqrt{s}$.

$$R_G(x,Q^2) \equiv \frac{xG_A(x,Q^2)}{A\,xG_p(x,Q^2)}$$

Detector Requirements :

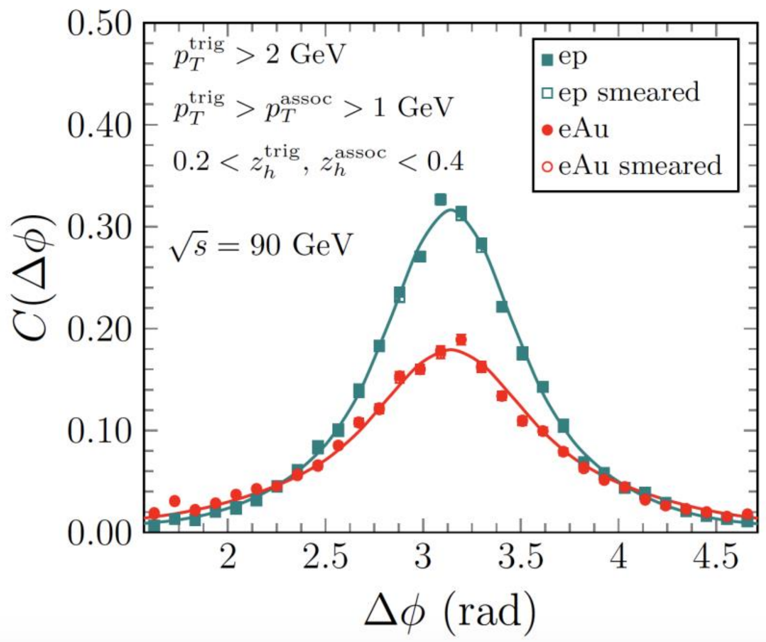
- Identical to inclusive $\triangle$G measurements.
- Require high resolution calorimetry in the backward region to access low x
- Excellent electron PID.



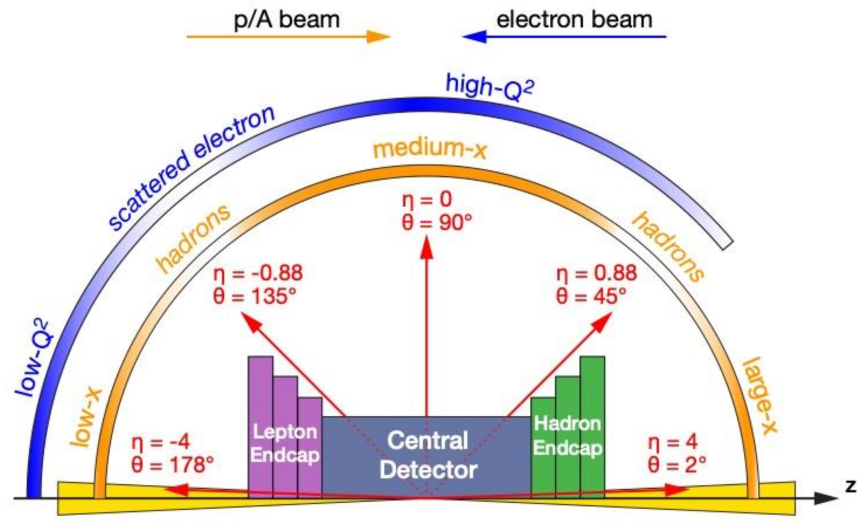
Gluon Saturation

Experimental Signatures at the EIC

I. Di-hadron and di-jet correlations
- Deviation of opening angle △ϕ = 180 degrees is sensitive to the kT dependent gluon distribution.
- The CGC will cause the scattered partons to interact with the dense strongly interacting matter, broadening the opening angle.
- Away-side suppression expected to increase with A, energy and rapidity



Detector Requirements :
- Electron detection as in inclusive case
- Tracker at mid-rapidity and far forward to capture low x partons.
- Resolution of 0.05%xp + 1% for central and 0.1%xp + 2% for forward



Gluon Saturation

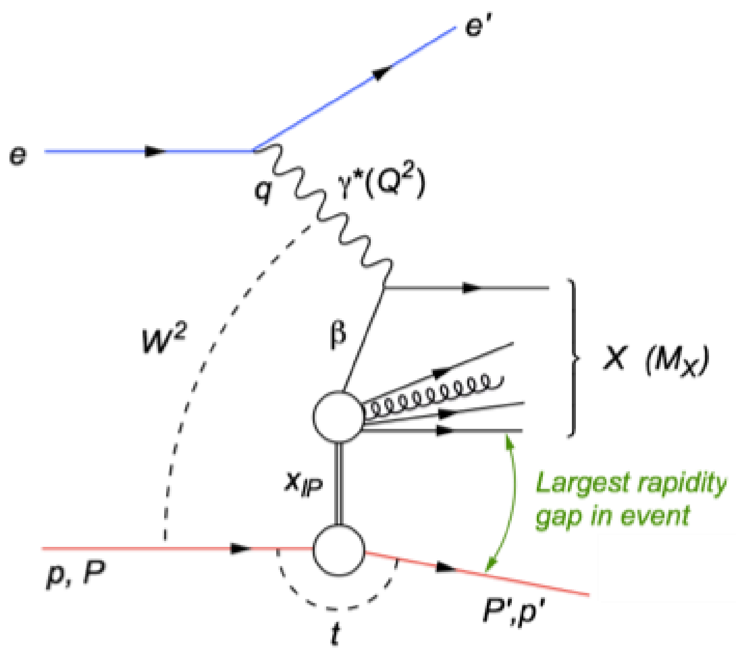
Experimental Signatures at the EIC

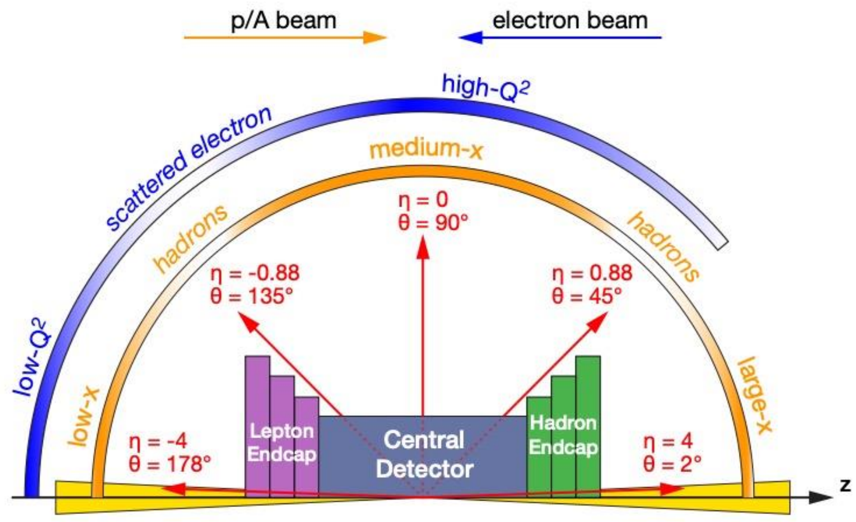
III. Measurement of TOTAL Diffractive cross-section.

Diffraction is very sensitive to the gluon distribution. Some saturation models predict it will comprise 30-40% of the total cross-section in eA, significantly enhanced compared to eP.

Detector Requirements :

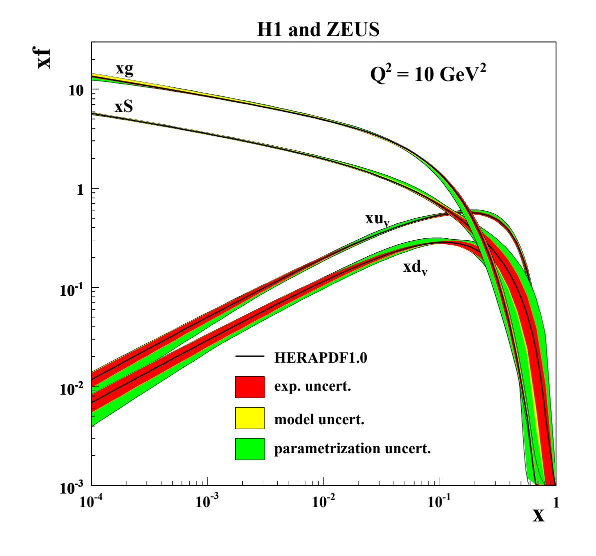
- Far forward detectors to see scattered proton, ie Roman Pots
- For eA need to reconstruct a ”no activity” rapidity gap
- Electron detection requirements same as inclusive
- Central and forward tracking requirements same as for di-hadrons and jets.

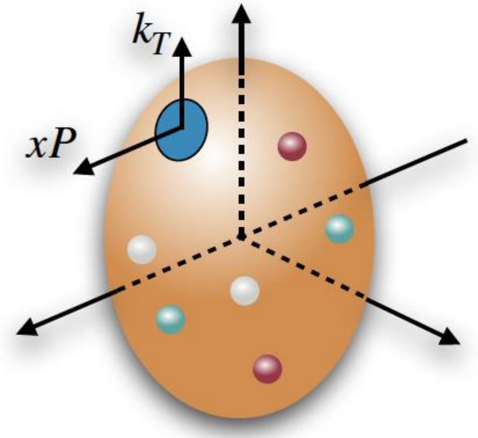




Multi-Dimensional Imaging of the Nucleon

- Collinear PDFs are k_T integrated functions.
- Transverse motion arises from confinement.
- Correlations between kT and parton and/or proton spin result in spin dependent Transverse momentum dependent PDFS (TMDs).
- Existing measurements of these TMDs point to flavor dependence, which would be explored via flavor tagging at an EIC.





		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$		$h_1^{\perp}(x,k_T^2)$ - Boer-Mulders
	L		$g_1(x,k_T^2)$ - Helicity	$h_{1L}^{\perp}(x,k_T^2)$ - Long-Transversity
	T	$f_1^{\perp}(x,k_T^2)$ - Sivers	$g_{1T}(x,k_T^2)$ - Trans-Helicity	$h_1(x,k_T^2)$ - Transversity $h_{1T}^{\perp}(x,k_T^2)$ - Pretzelosity

Transverse Momentum PDFs

Experimental Signatures at the EIC

I. Semi-Inclusive Deep Inelastic Scattering –

Cross-sections and asymmetries used to access quark TMDs. Requires longitudinally and transversely polarized beams over large $\sqrt{s}$ range.

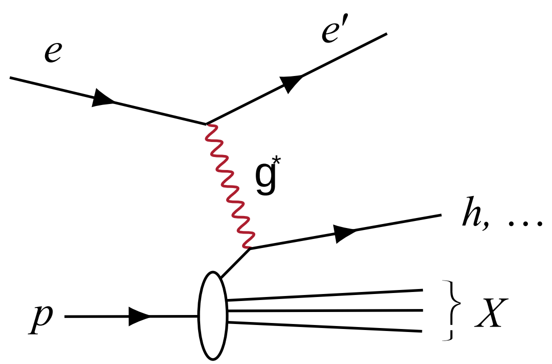
Detector Requirements:

- Electron ID and reconstruction the same as for inclusive channels
- Exceptional particle identification needed to separate pi/K/P at 3σ level for

  P < 50 GeV in the forward region

  P < 10 GeV in the central region

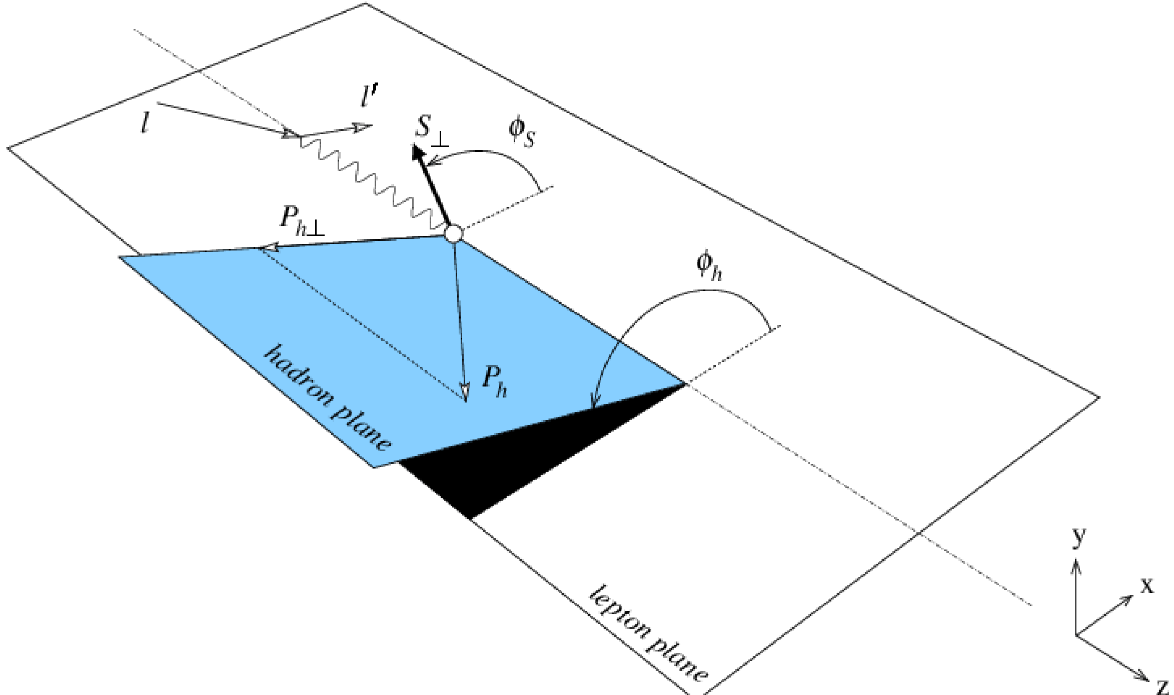
  P < 7 GeV in the backward region



$P_{h\perp}$ the transverse momentum of the reconstructed hadron

ϕ_h the angle between the hadron and scattering plane

ϕ_S the angle between the nucleon spin and the scattering plane.



Transverse Momentum PDFs

Experimental Signatures at the EIC

I. Semi-Inclusive Deep Inelastic Scattering –

Cross-sections and asymmetries used to access quark TMDs. Requires collisions of longitudinally and transversely polarized beams over large $\sqrt{s}$ range. Multi-dimensional binning will require high luminosities and longer running times.

Detector Requirements:

- Electron ID and reconstruction the same as for inclusive channels
- Exceptional particle identification needed to separate pi/K/P at 3σ level for

  P < 50 GeV in the forward region

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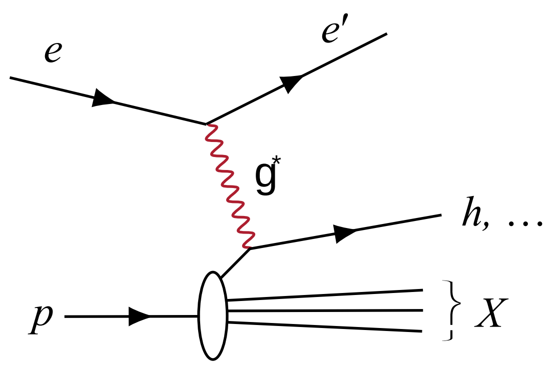

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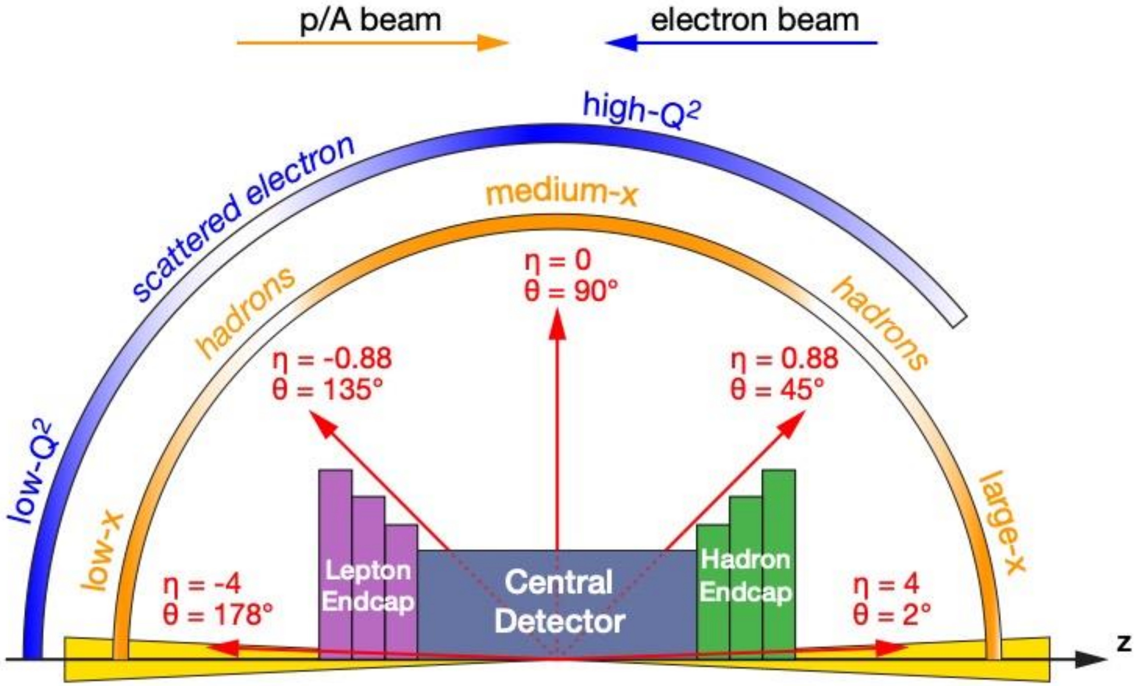


EIC Impact on TMDs

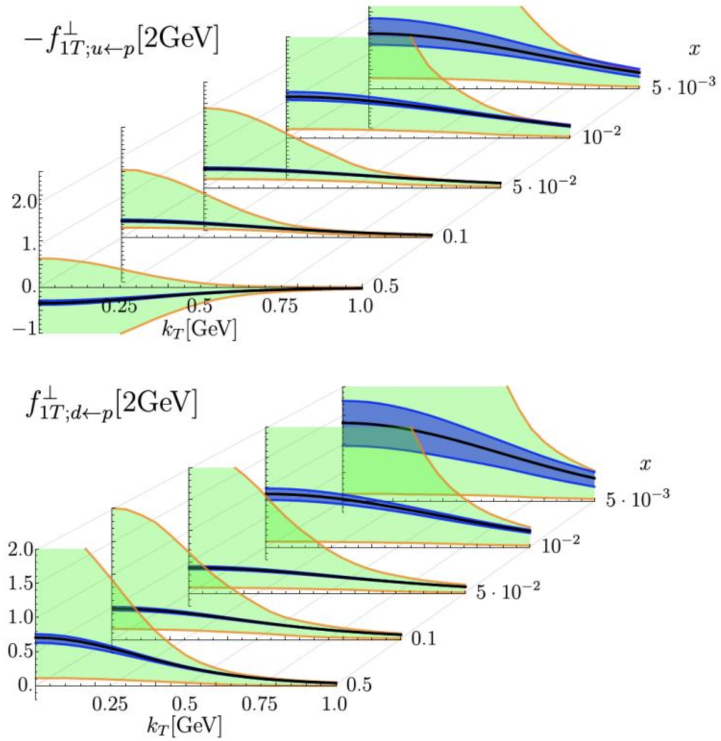
Sivers Function x FF

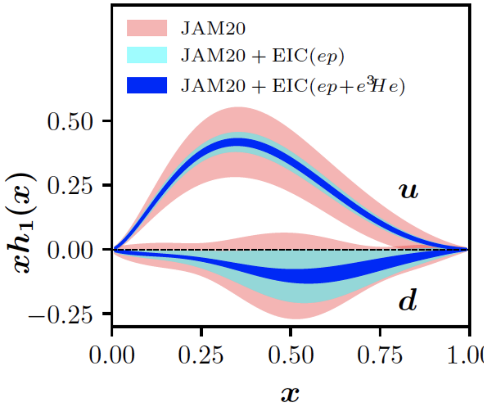
- Parton k_T correlation with proton spin
- Current (green) and EIC (blue) constraints on u/d
- Limited subset of existing data that satisfies factorization conditions.
- Uncertainties reduced by > x10 for all flavors.
- Wide range of hadron p_T facilitates k_T mapping

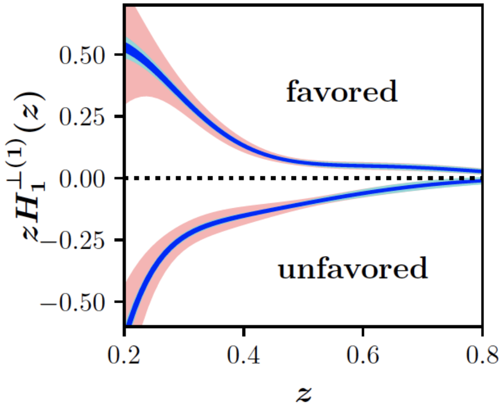
Transversity x Collins FF

- Spin of parton correlated with spin of proton
- Correlation of fragmenting parton k_T and spin
- Current (pink) and EIC (blue) constraints on u/d
- Benefits from polarized D/He^3 beams

Yellow Report : [2103.05419]



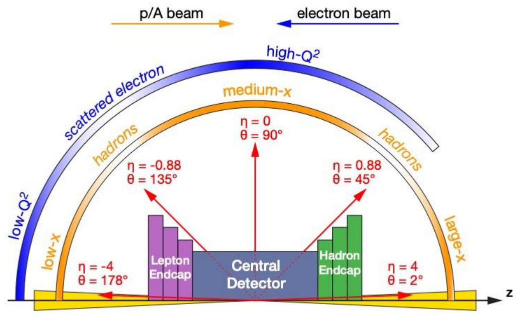


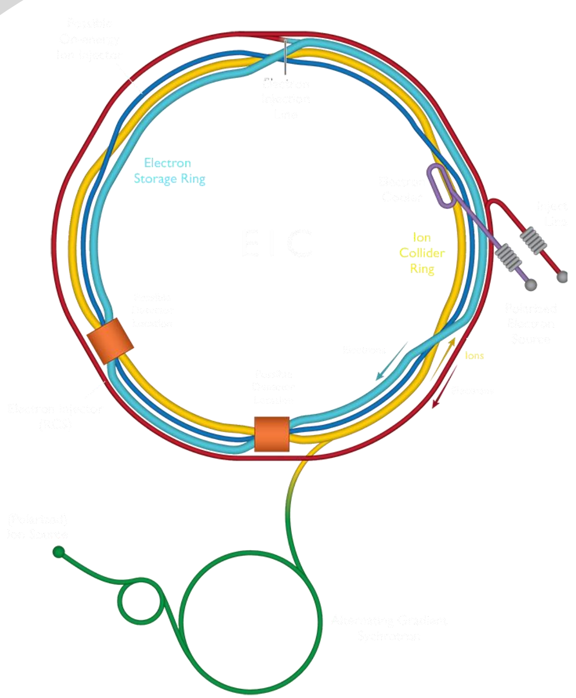


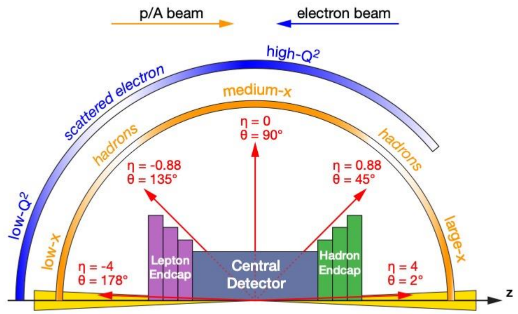
Phys.Lett.B 816 (2021) Phys.Rev.D 102 (2020)

The most pressing questions at the QCD Frontier need:

- A high energy, high luminosity collider, capable of providing polarized electron, proton and “neutron” beams as well as a range of ion beams. The ability to scan in $\sqrt{s}$ is essential both for discovery channel and precision measurements.
- At least one general purpose reference detector that has broad coverage in tracking, calorimetry and PID.







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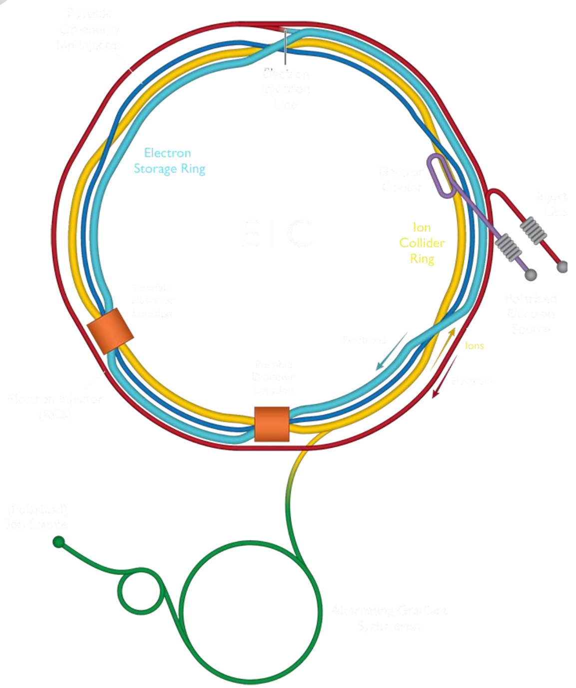
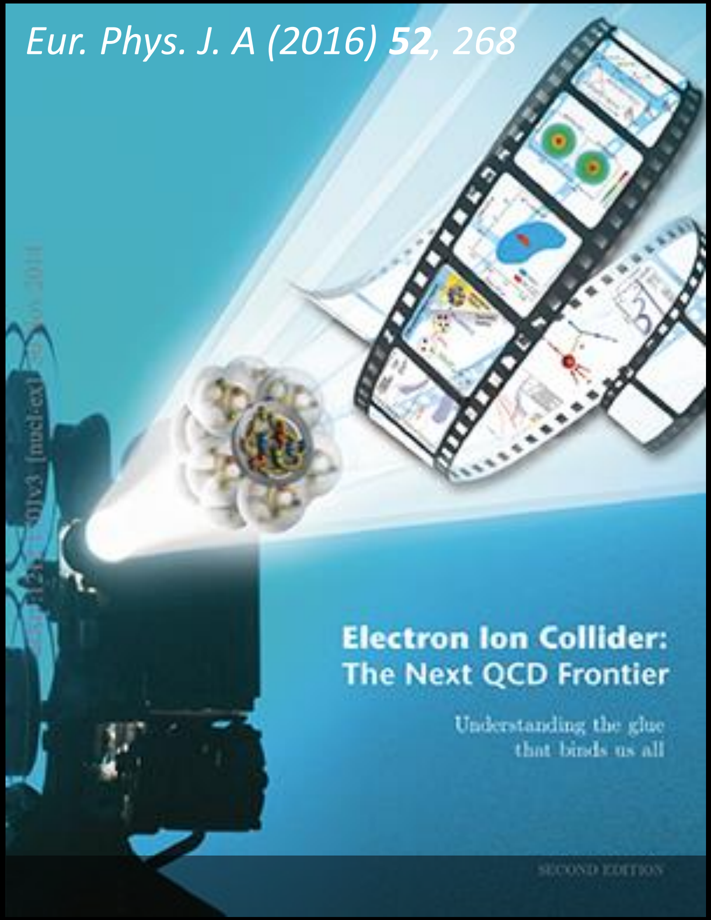
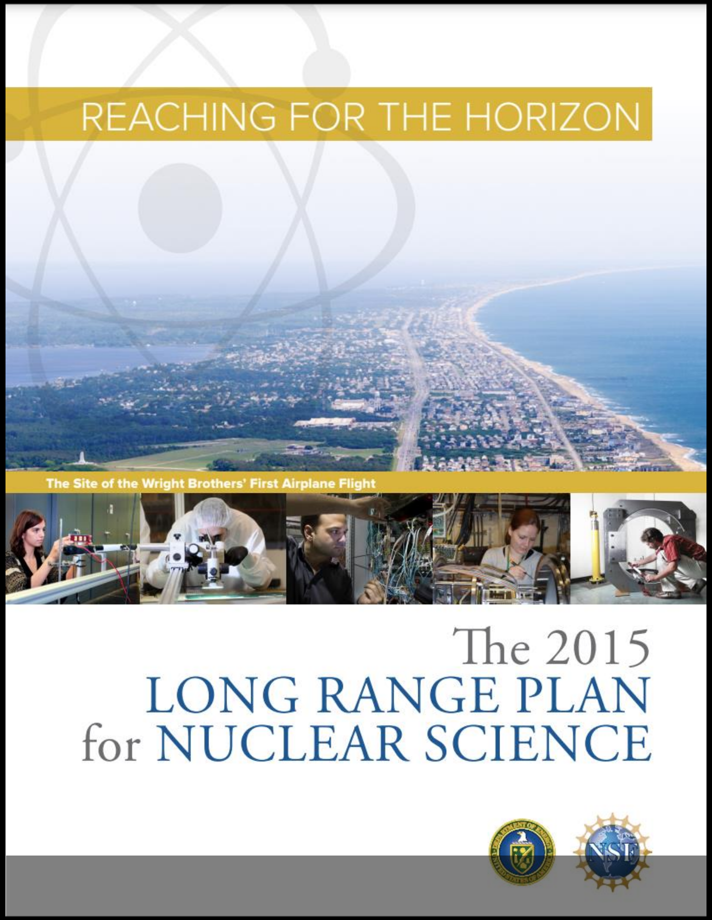


Let me quickly remind you of how we came to this conclusion

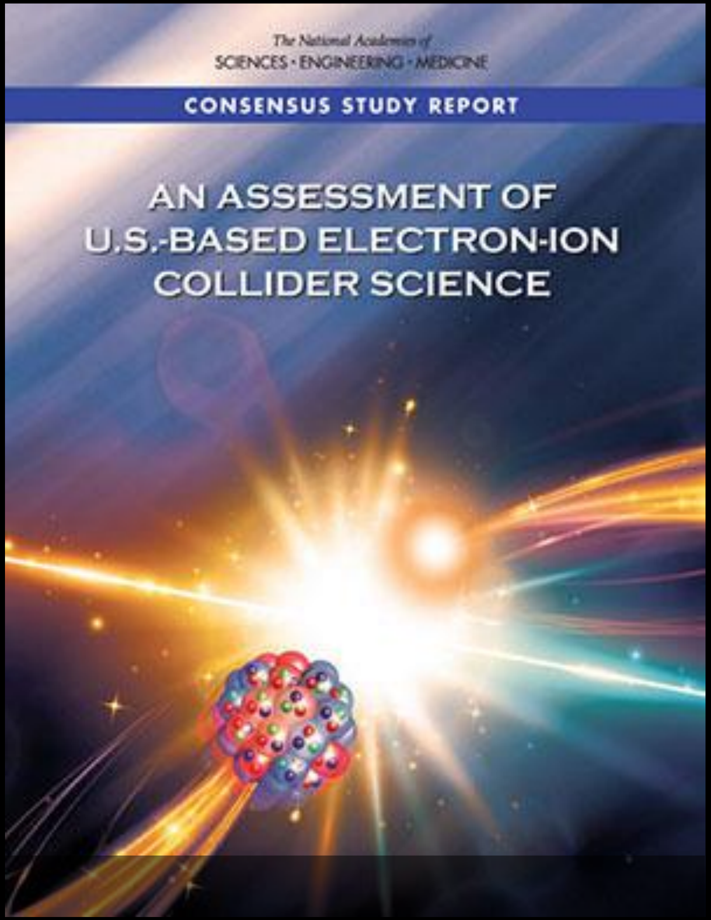
Path to the EIC - Historical Milestones



2014

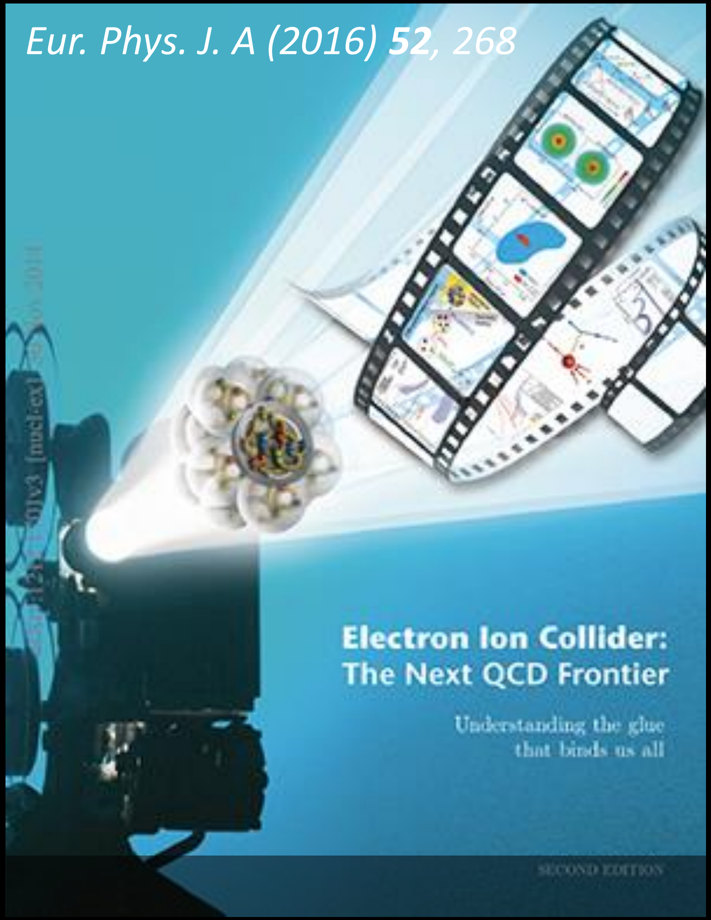


2015

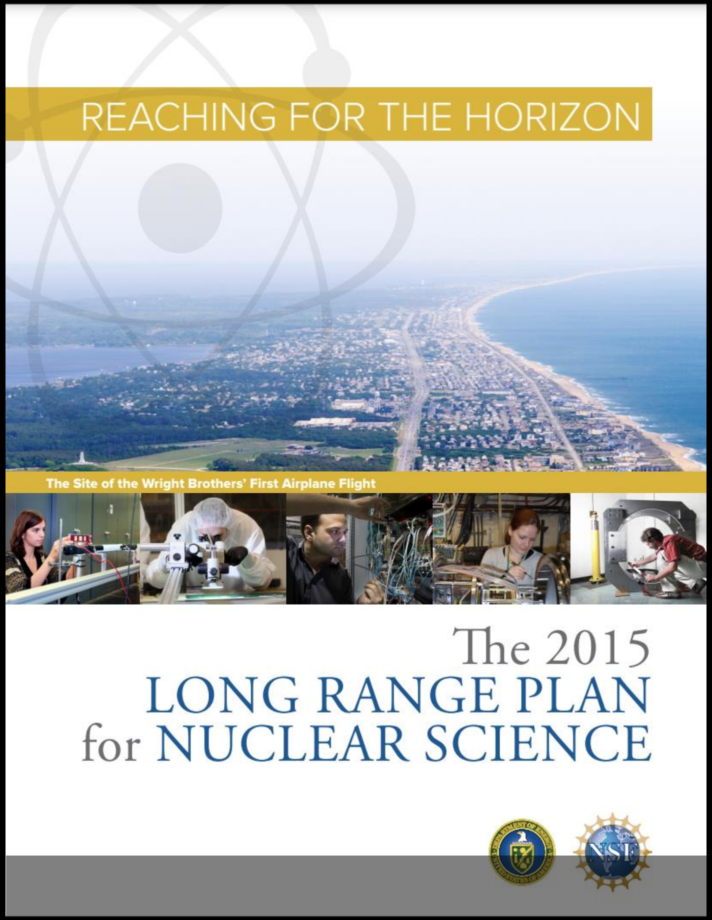


2018

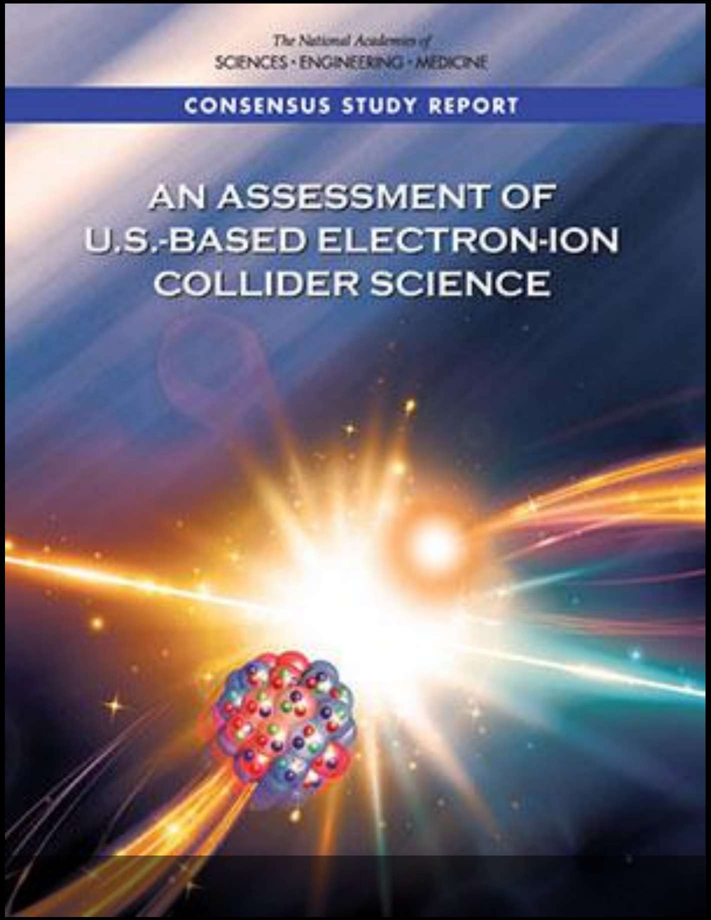
December 2019 – Mission Need (CD0) approved by US Department of Energy



2014



2015

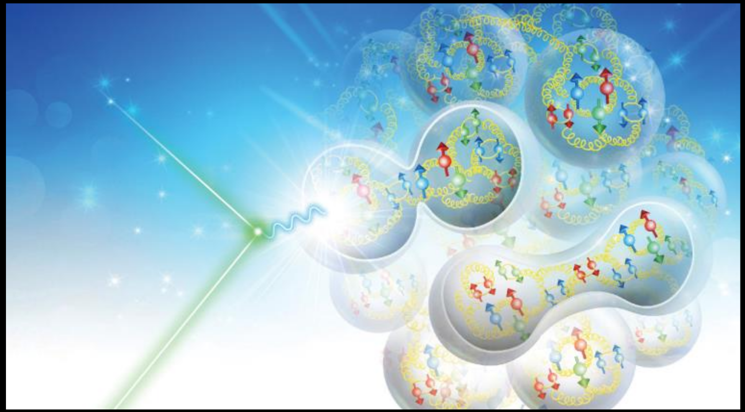


2018

2020 The Yellow Report

SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER

EIC Yellow Report

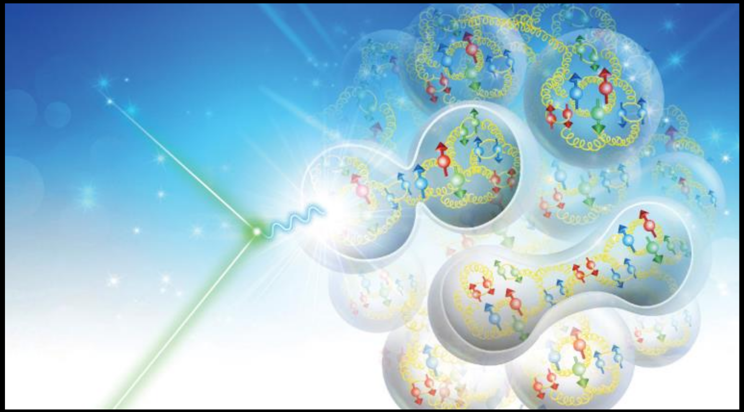


- Update, where necessary, the EIC physics case
- Specify the detector requirements for primary channels
  - Inclusive Deep Inelastic Scattering (DIS)
  - Semi-inclusive DIS
  - Exclusive DIS
  - Jet and Heavy-Flavor Reconstruction
  - Diffractive scattering
- Discuss current state-of-the-art detector technologies needed for reconstruction of each channel.
- Lay out the requirements for a day-1 reference detector.

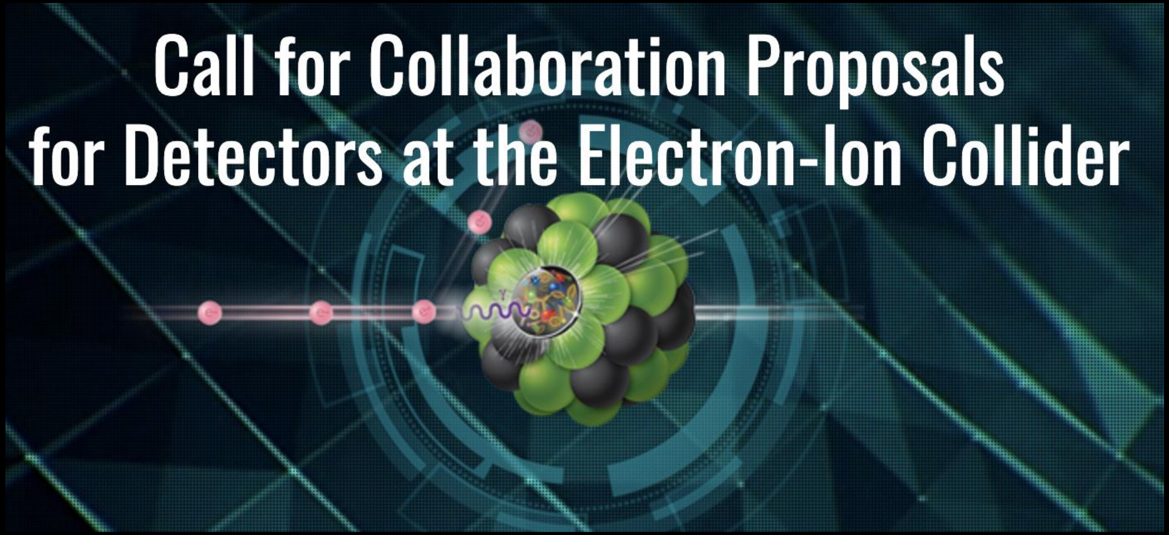
2020 The Yellow Report

SCIENCE REQUIREMENTS
AND DETECTOR
CONCEPTS FOR THE
ELECTRON-ION COLLIDER

EIC Yellow Report



March 2021



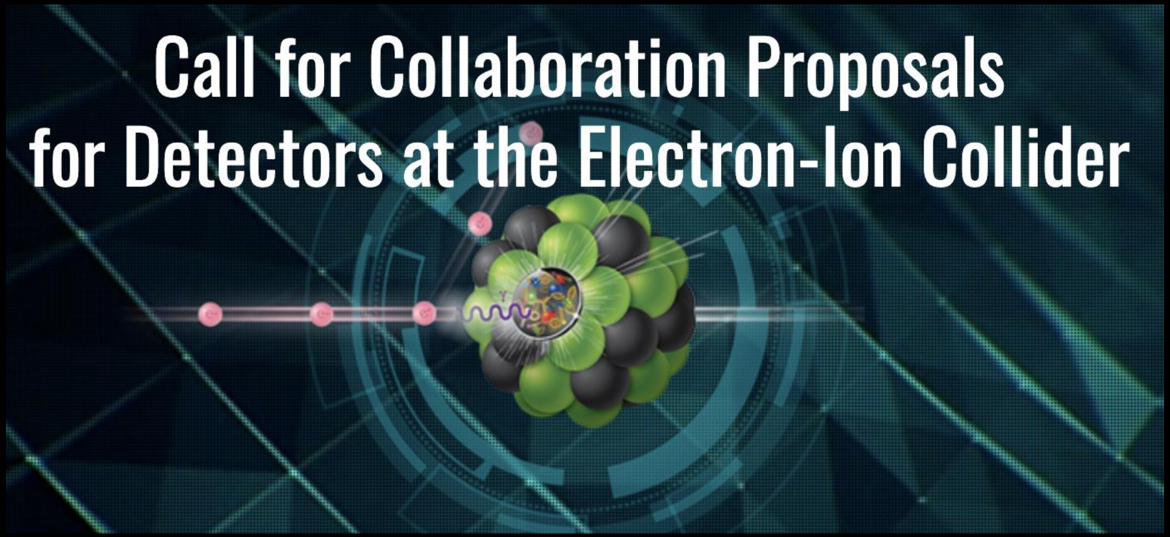
DETECTOR I

Must address EIC White Paper and NAS science case and satisfy the detector requirements for the reference detector as discussed in the Yellow Report.

DETECTOR II

Address EIC White Paper science case and possibly science beyond that and enable complementarity to Detector I

March 2021



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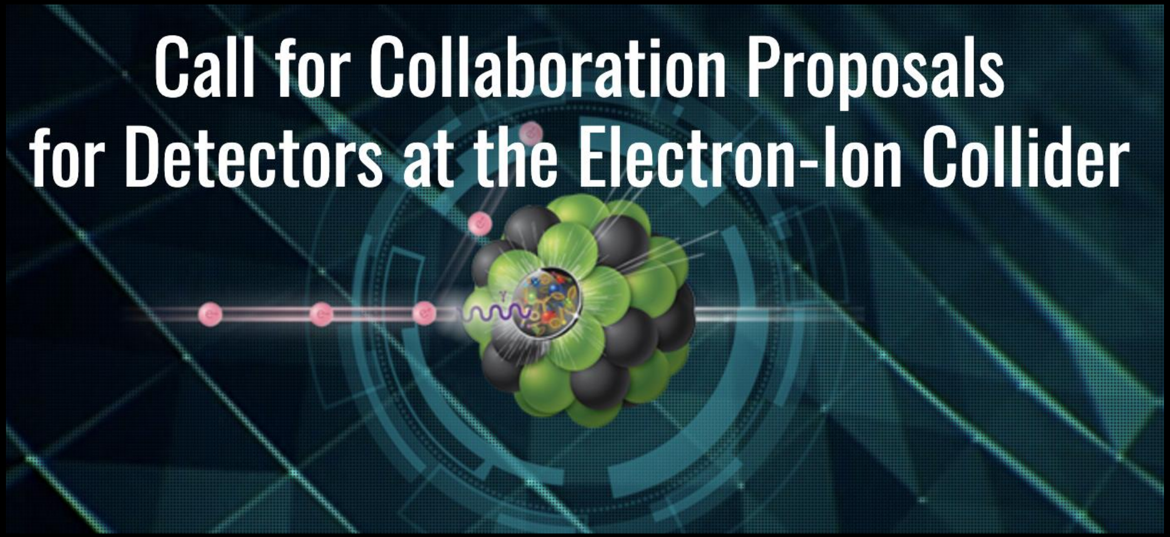
- Co-chair Rolf Heuer (CERN)
- Patty McBride (FNAL)

Proposals Due on December 1, 2021
- ATHENA and ECCE are submitted as Detector I
- CORE submitted at DETECTOR II

Detector Presentations to DPAP
Dec. 13-15 2021

DPAP review to community
March 2022

March 2021



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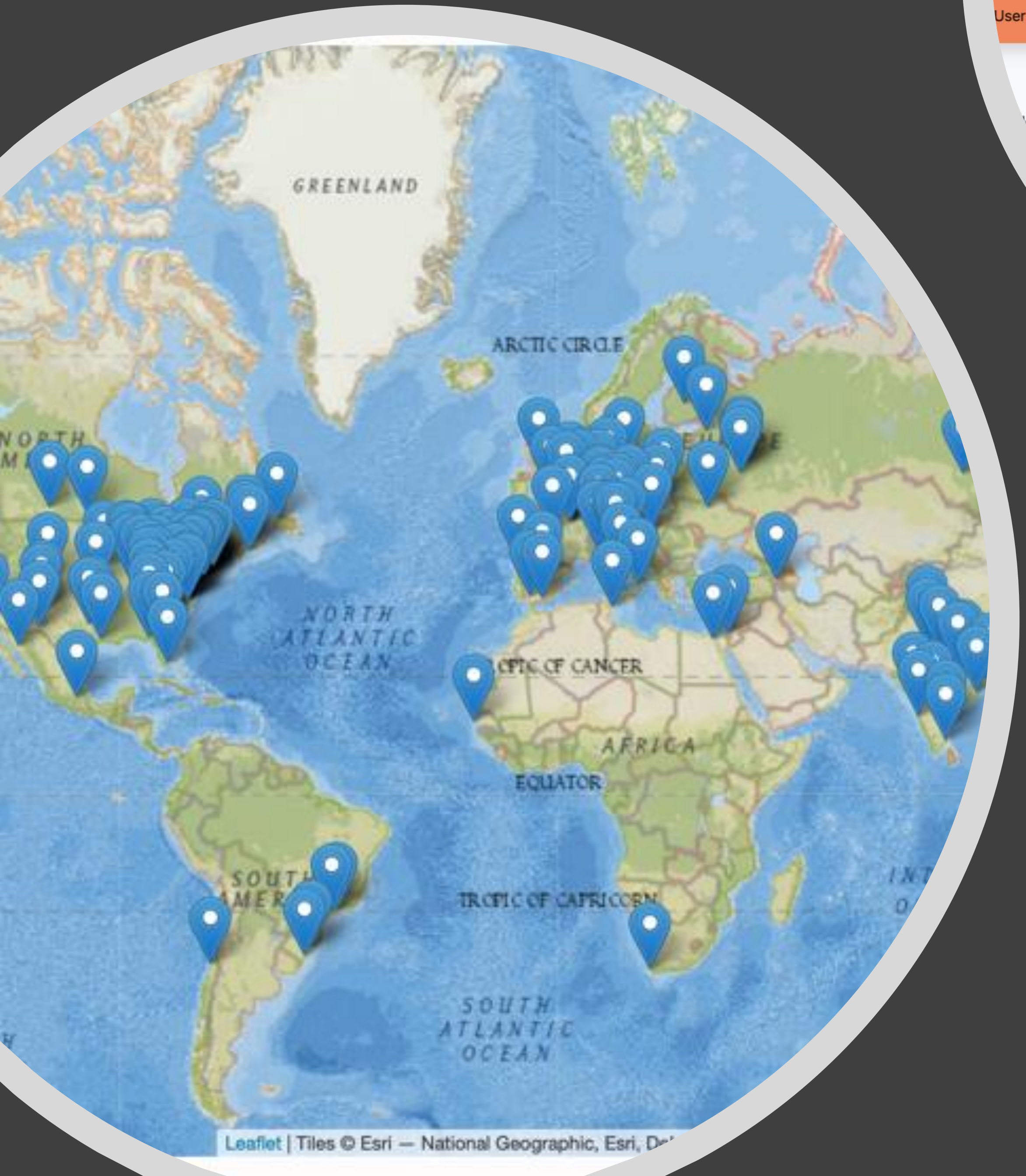
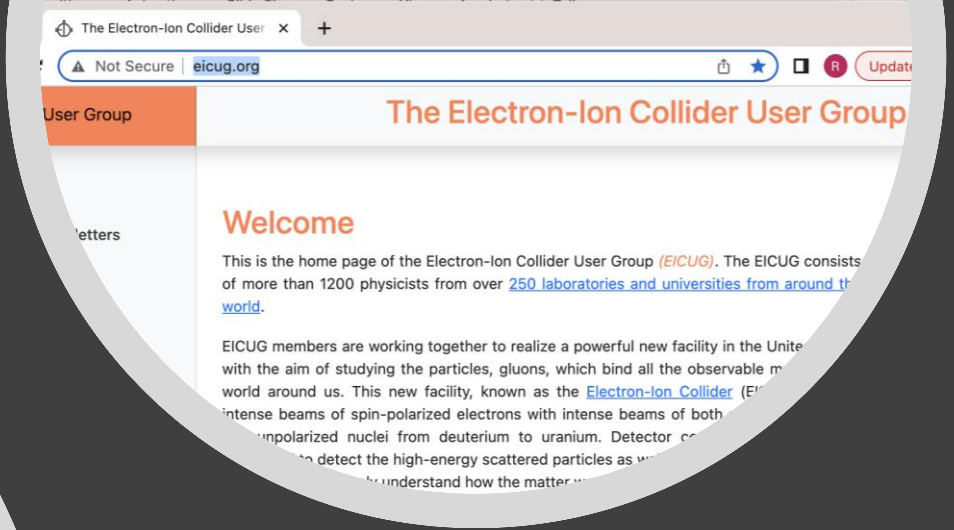
STAY TUNED to NEXT TALK!!



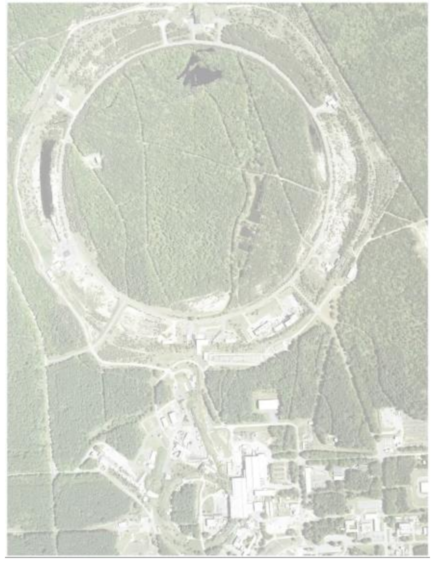


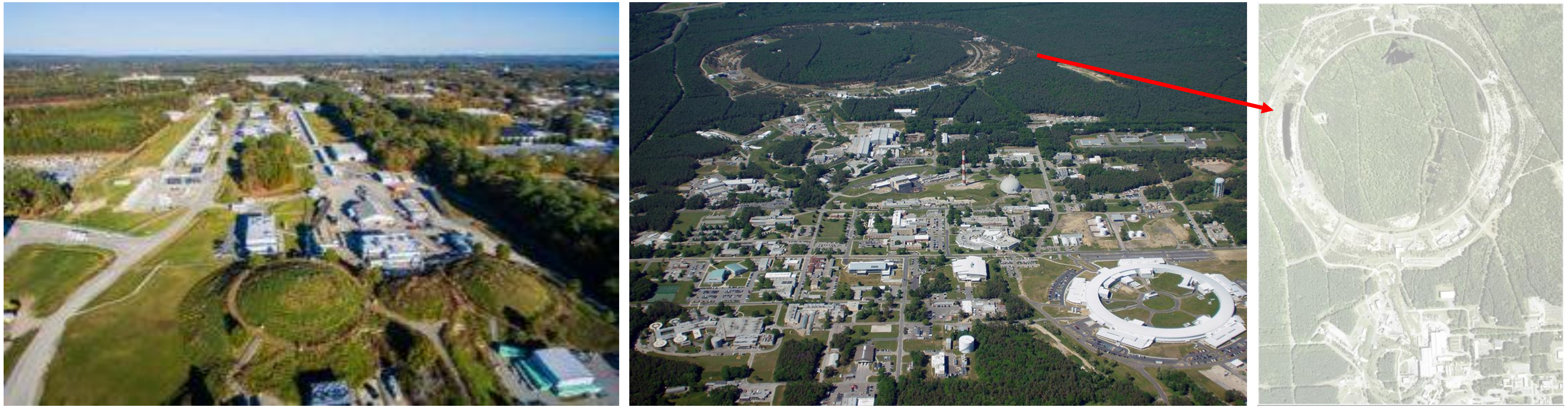
Come Join Us!

We are an international group of over 1300 nuclear, particle and accelerator experimentalist and theorists.

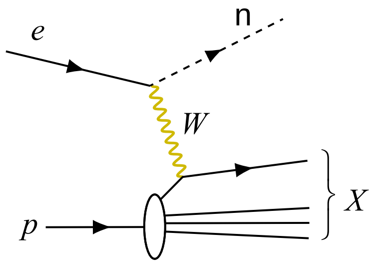
Be a part of building the future of physics in QCD!

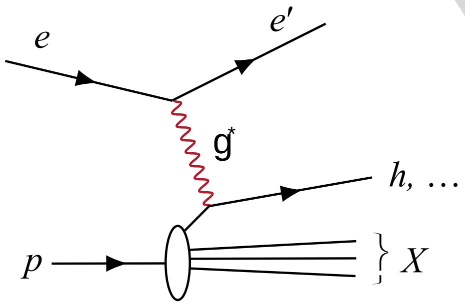
Backup



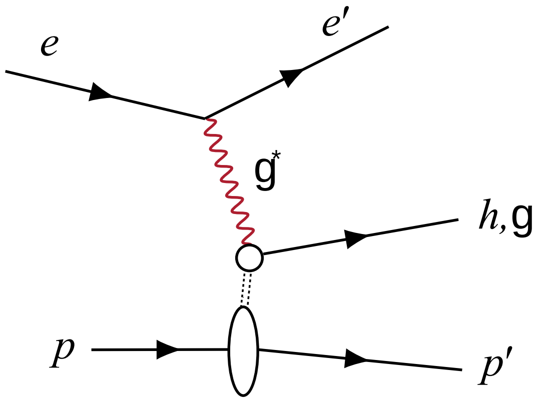


Charged Current DIS

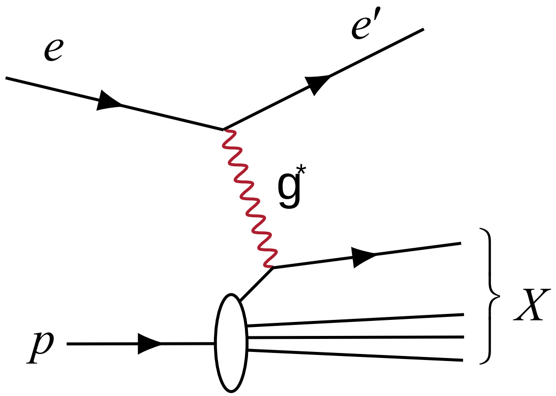




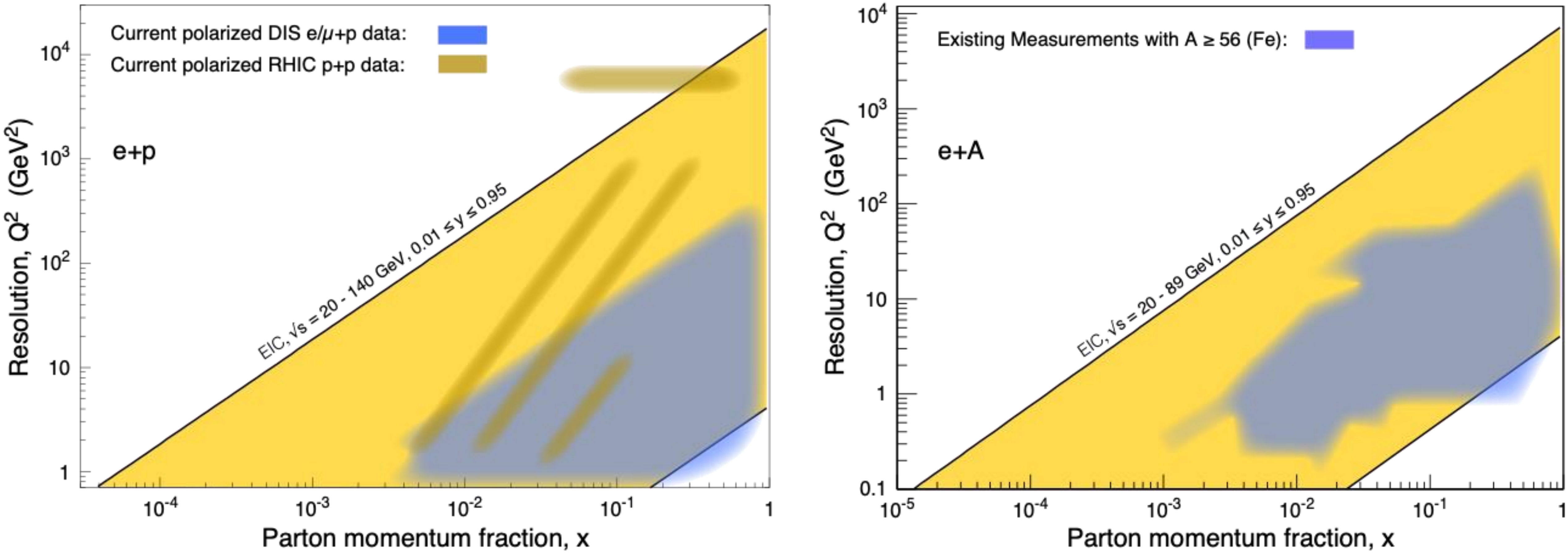
Semi-Inclusive DIS



Exclusive DIS



Neutral Current Inclusive Deep Inelastic Scattering



Current polarized DIS e/μ+p data:
Current polarized RHIC p+p data:
e+p
EIC, √s = 20 - 140 GeV, 0.01 ≤ y ≤ 0.95
Resolution, Q² (GeV²)
10⁴
10³
10²
10
1
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
Parton momentum fraction, x
Existing Measurements with A ≥ 56 (Fe):
e+A
EIC, √s = 20 - 89 GeV, 0.01 ≤ y ≤ 0.95
Resolution, Q² (GeV²)
10⁴
10³
10²
10
1
0.1
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
Parton momentum fraction, x