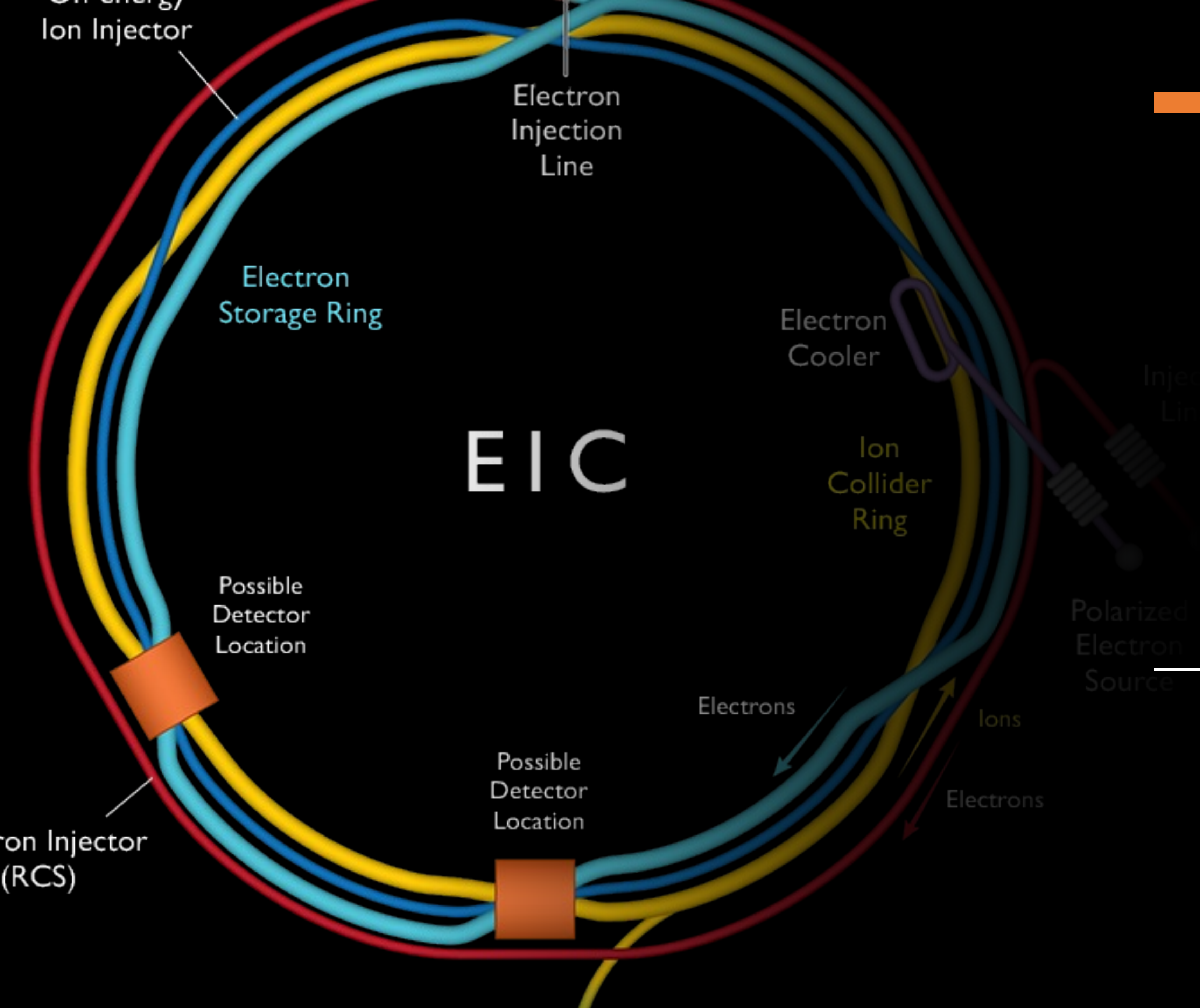
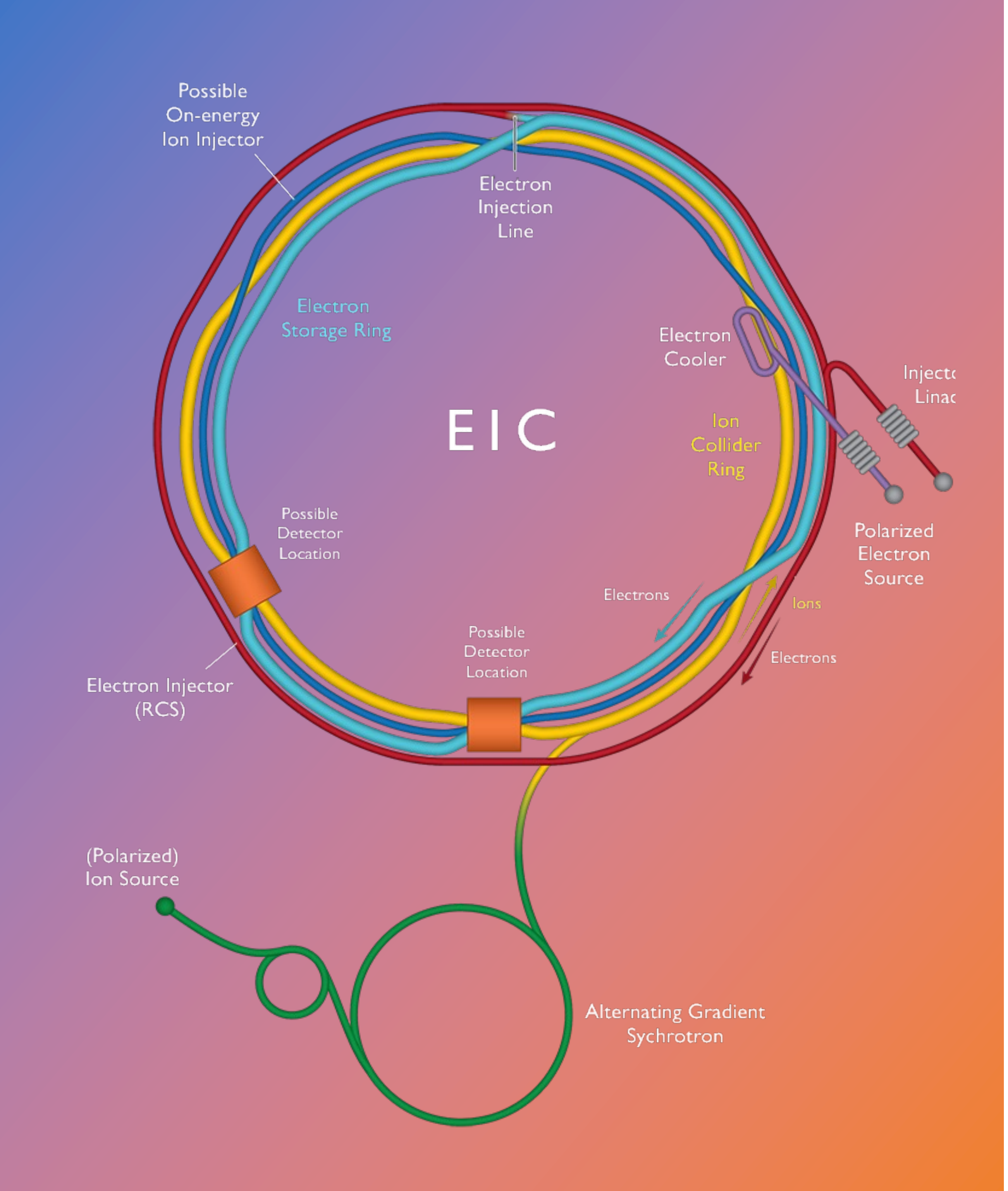


Initial Experiments with the Electron Ion Collider

Renee Fatemi

University of Kentucky

June 15, 2022



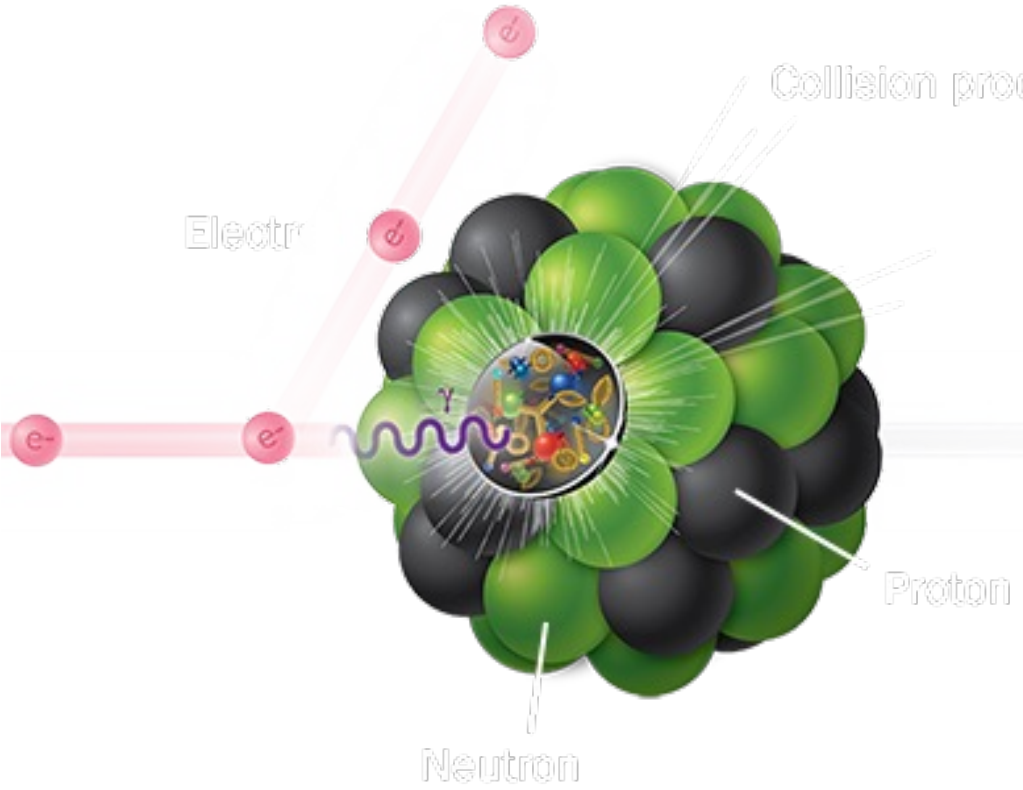
What is the EIC?

A new, innovative, large-scale collider 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

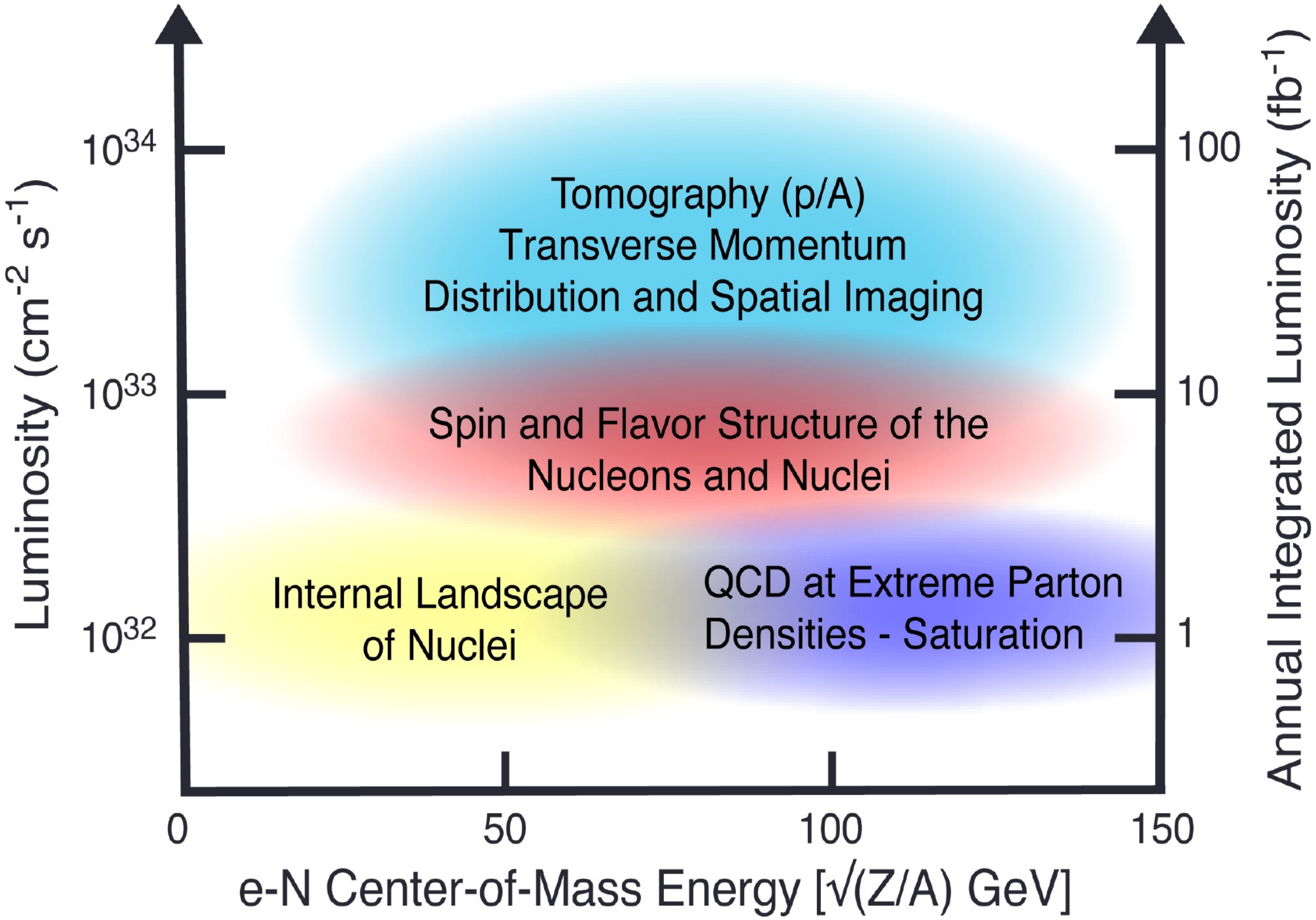
What questions is the EIC designed to answer?



- 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**?

What are the DAY-1 measurements we can make at an EIC?

What beams and detectors do we need to make them?



What are the DAY-1 measurements we can make at an EIC?

What beams and detectors do we need to make them?

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?

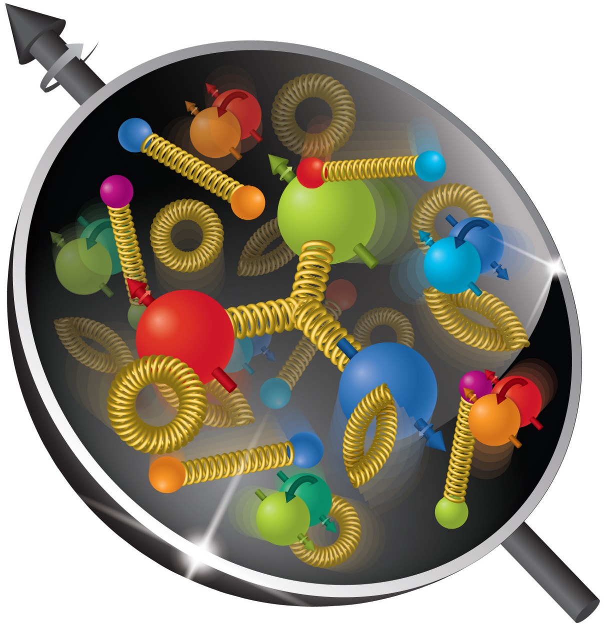
Gluon Helicity

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

QUARK Helicity

GLUON Helicity

QUARK+GLUON Angular Momentum



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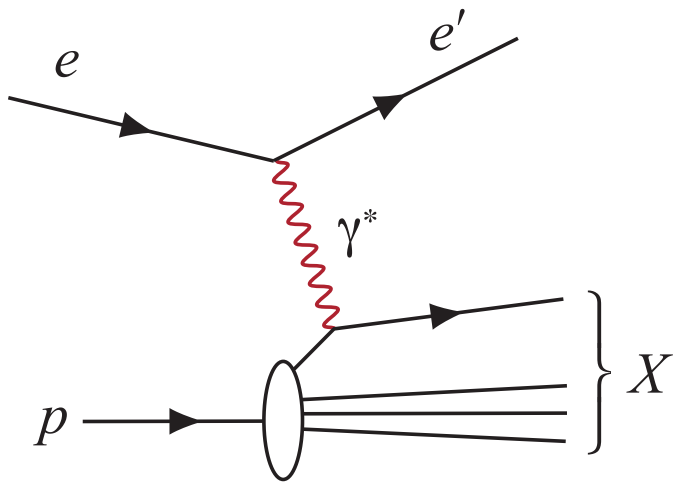

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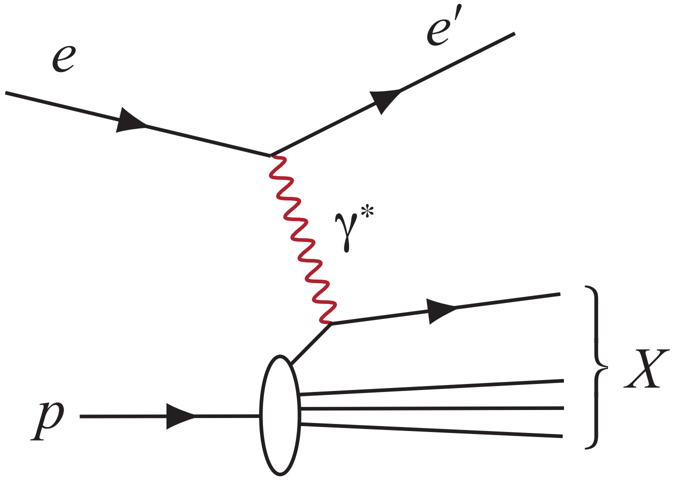
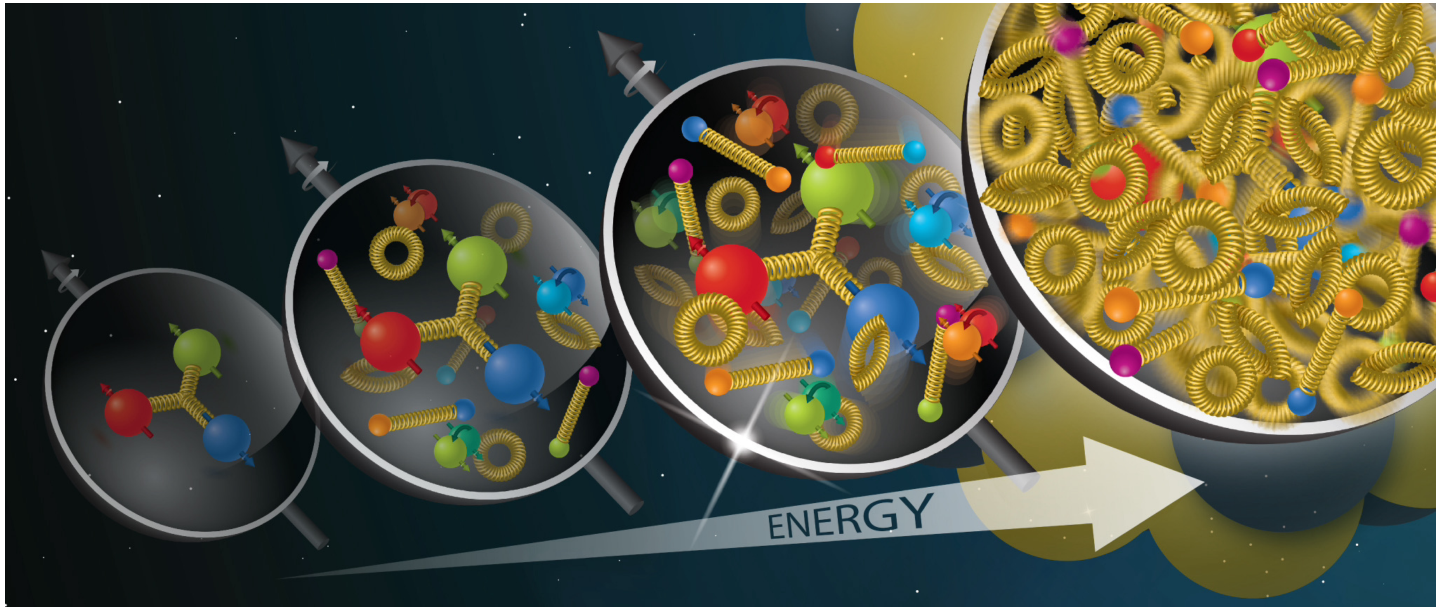
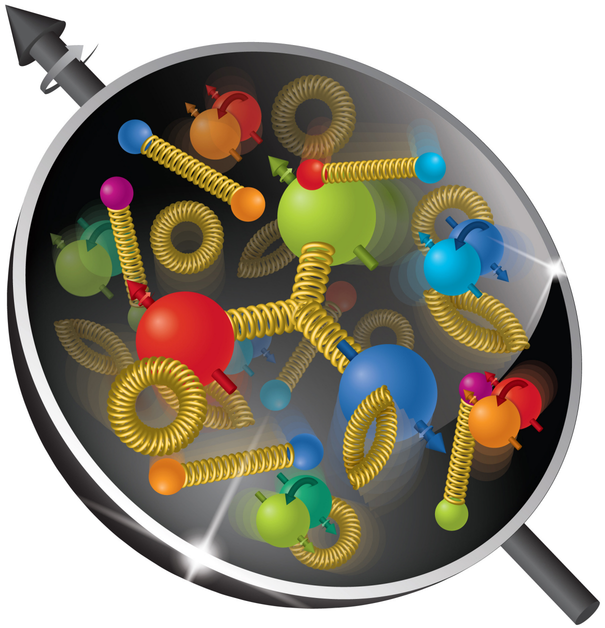




All distributions are defined at renormalization scale **μ** which sets the effective resolution at which the proton is being probed. In this talk $\mathbf{Q^2}$ is the resolution parameter.

Gluon Helicity



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

QUARK Helicity

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

GLUON Helicity

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

QUARK+GLUON Angular Momentum

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

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

Gluon Helicity

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

Fixed Target lepton+p

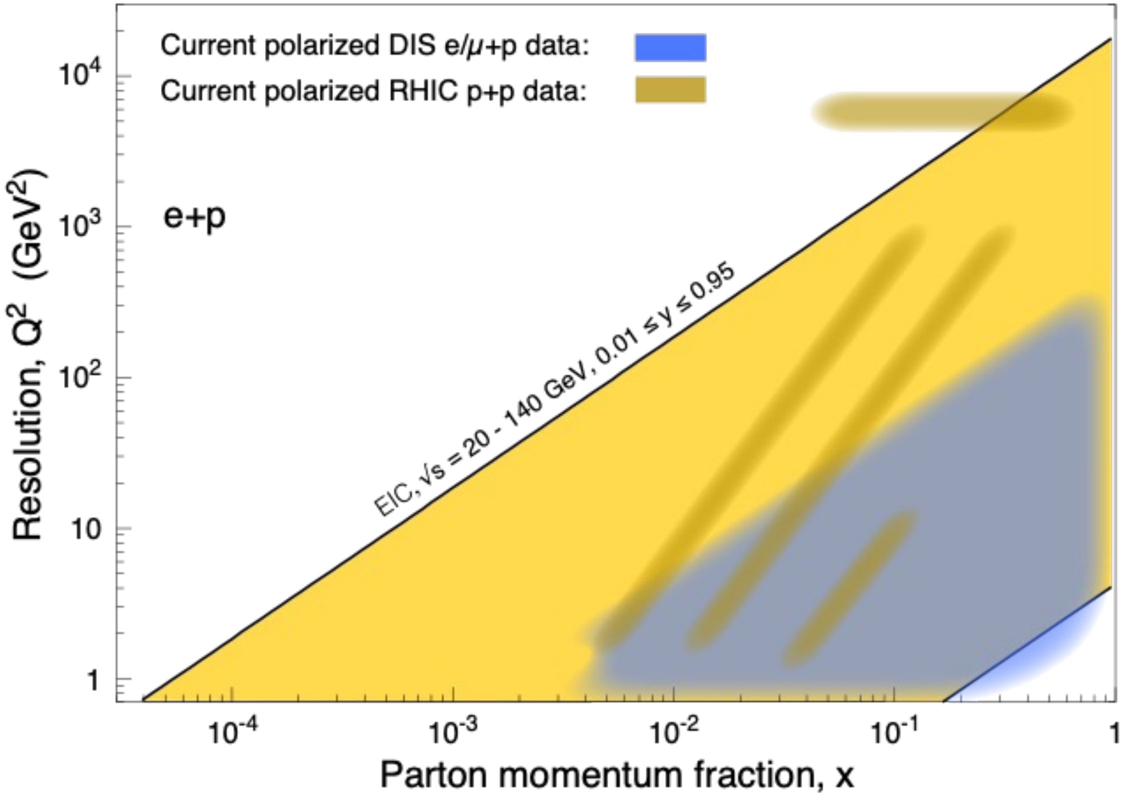
- Allows reconstruction of x and Q^2 on an event-by-event basis
- Fixed target limits x and Q^2 coverage.

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

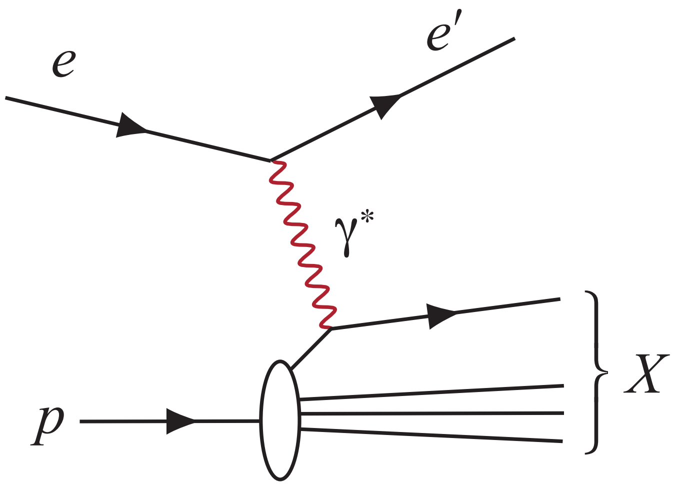


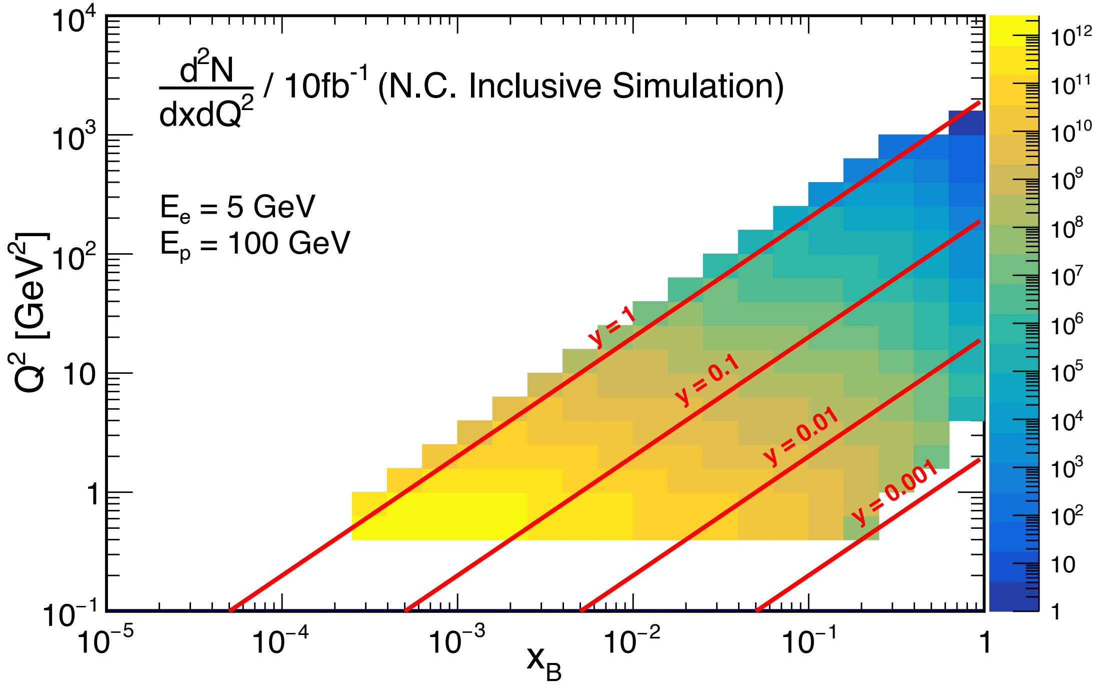
Gluon Helicity

Experimental Signatures at the EIC

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

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





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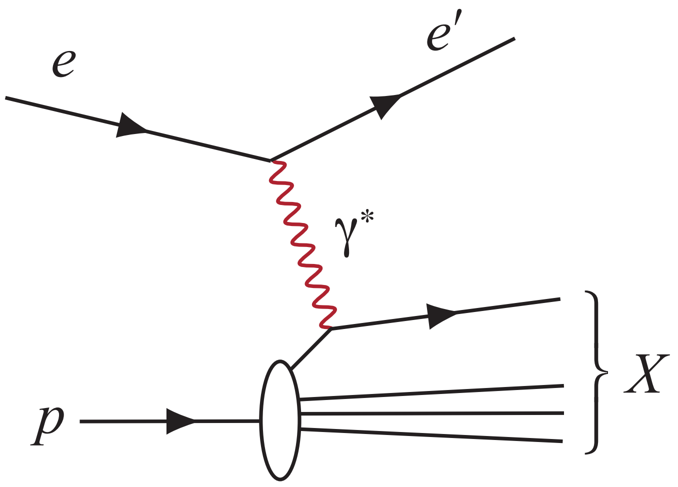

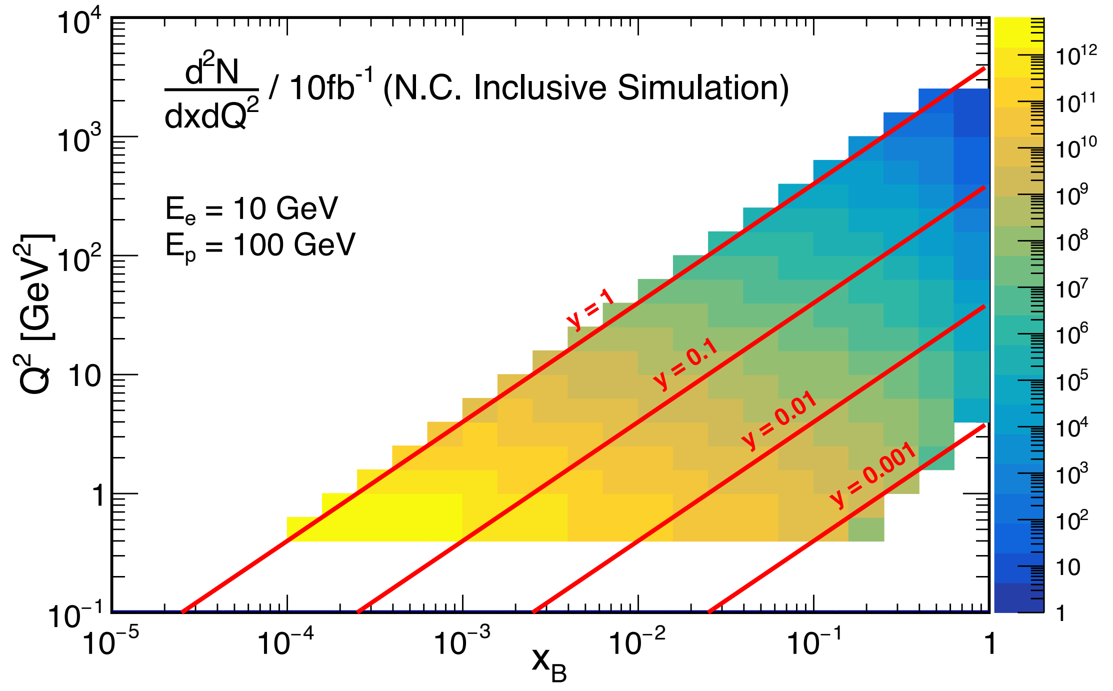

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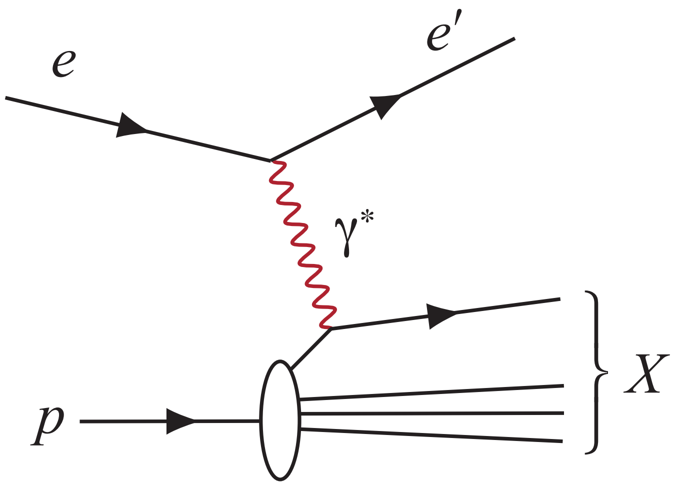
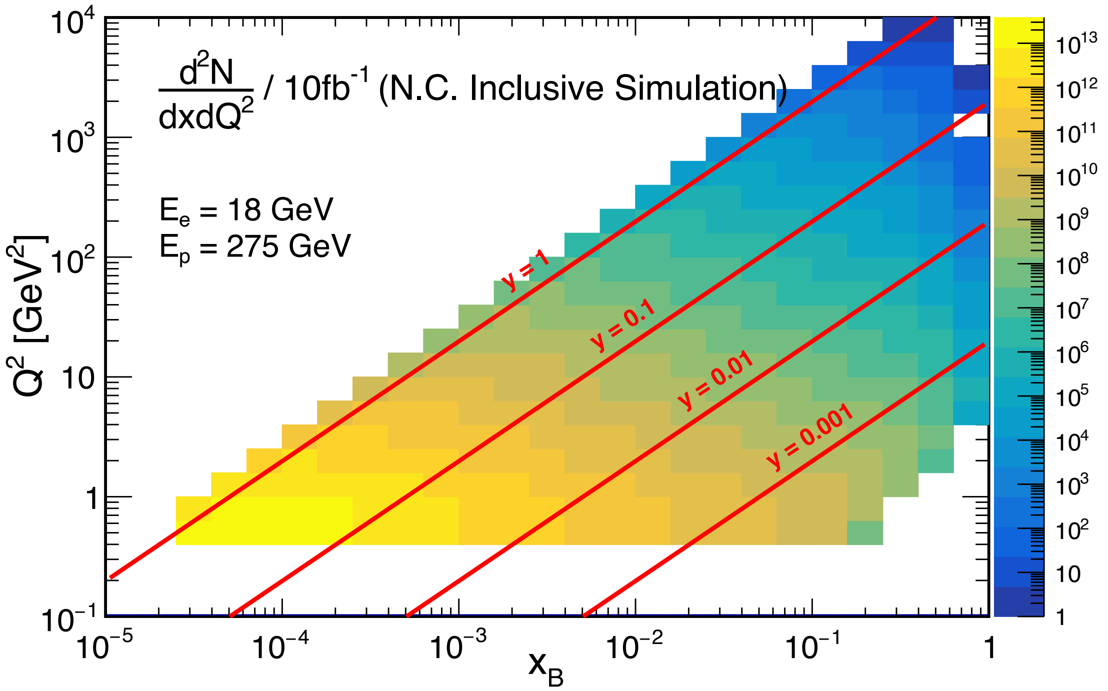


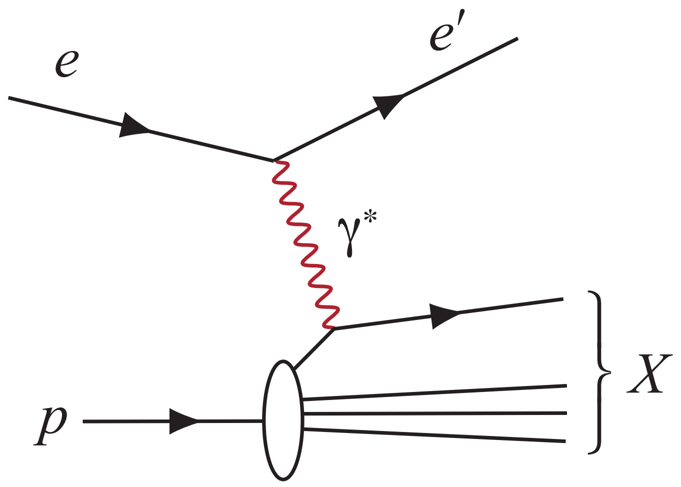


Gluon Helicity

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 :

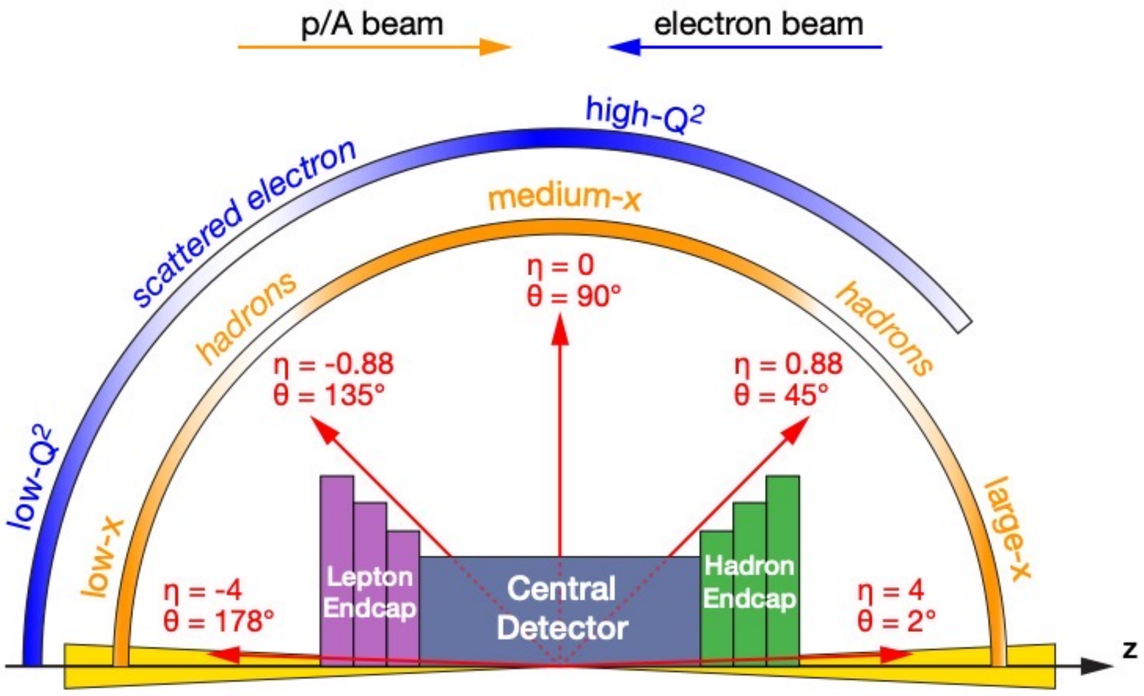
Precise reconstruction of scattered e kinematics via tracking and electromagnetic calorimeters.

BACKWARD

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

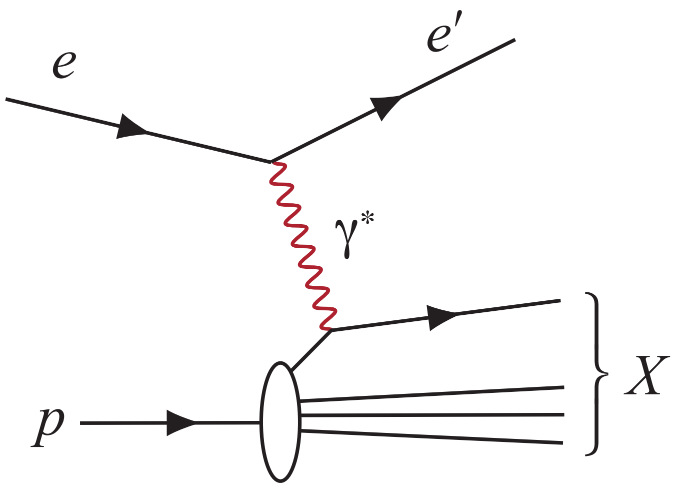
CENTRAL

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



Gluon Helicity

Experimental Signatures at the EIC

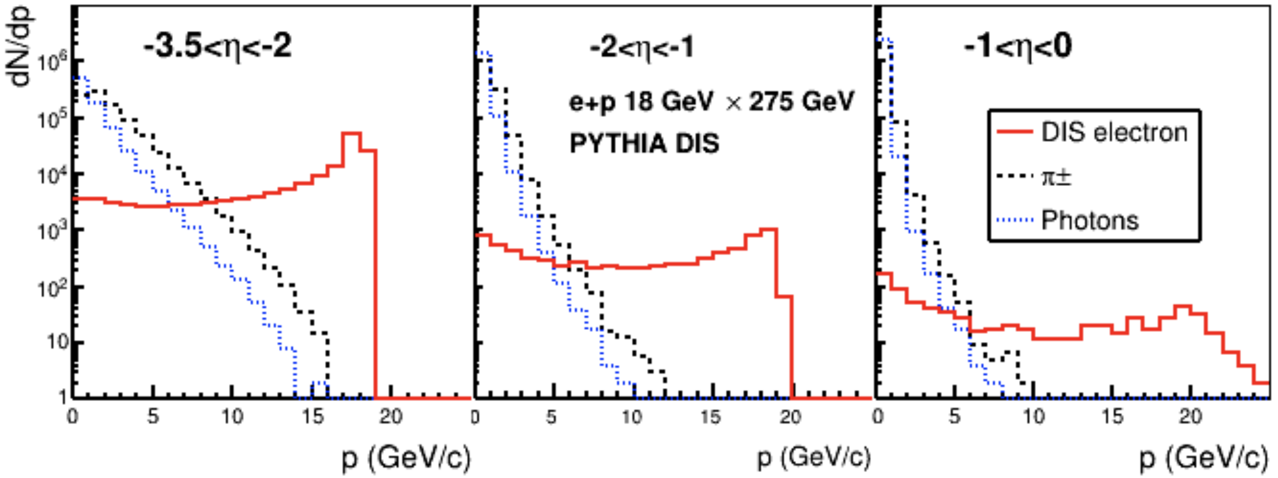


Inclusive Double Spin Asymmetry - requires longitudinally polarized electron and proton beams over a large range of $\sqrt{s}$

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

Detector Requirements :

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

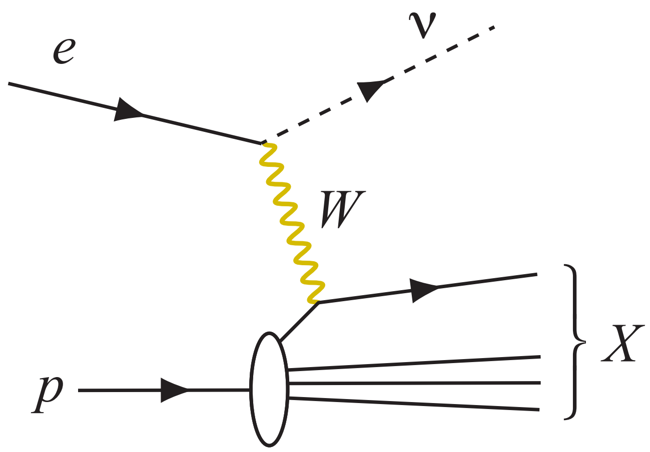


Gluon Helicity

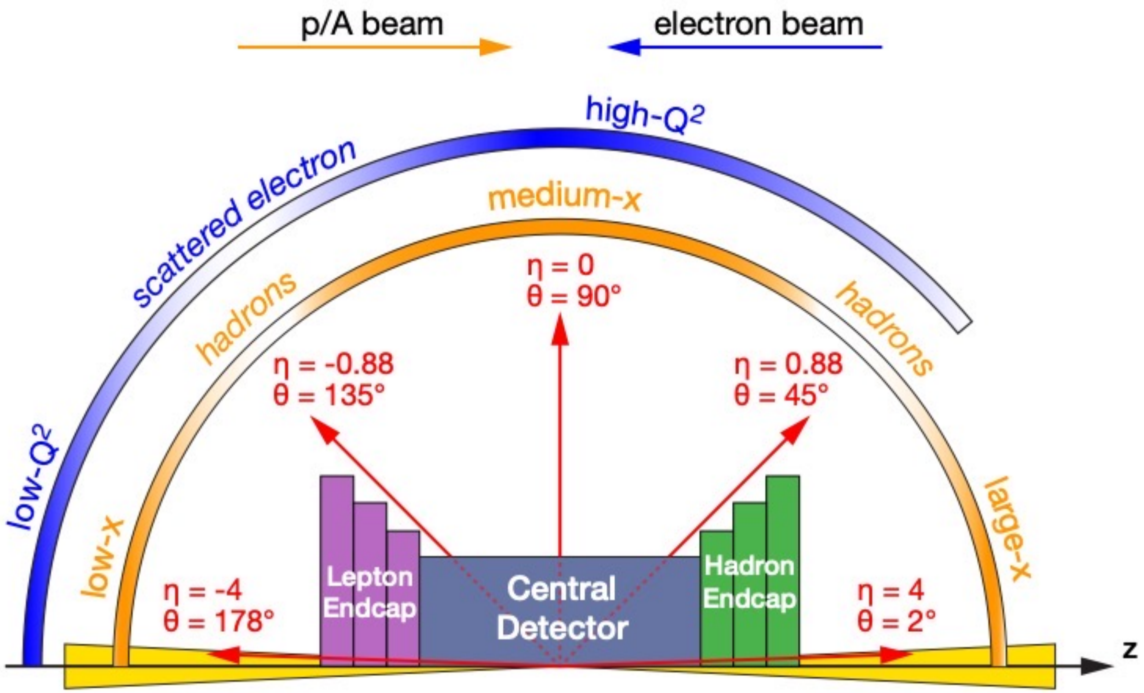
Experimental Signatures at the EIC

Charged Current Channels probe flavor separated helicity distributions.

Only proton beam needs to be polarized but needs both e+ and e- at highest $\sqrt{s}$.

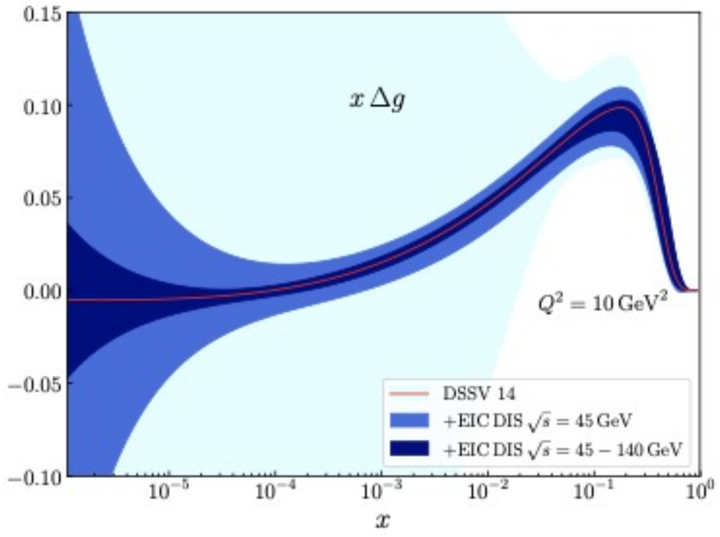


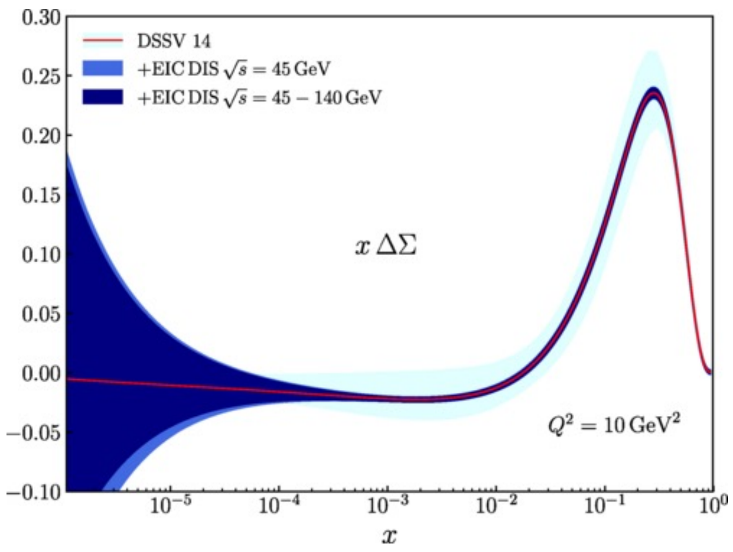
$$A_L = \frac{1}{P_P}\frac{N^+ - RN^+}{N^+ + RN^+}$$

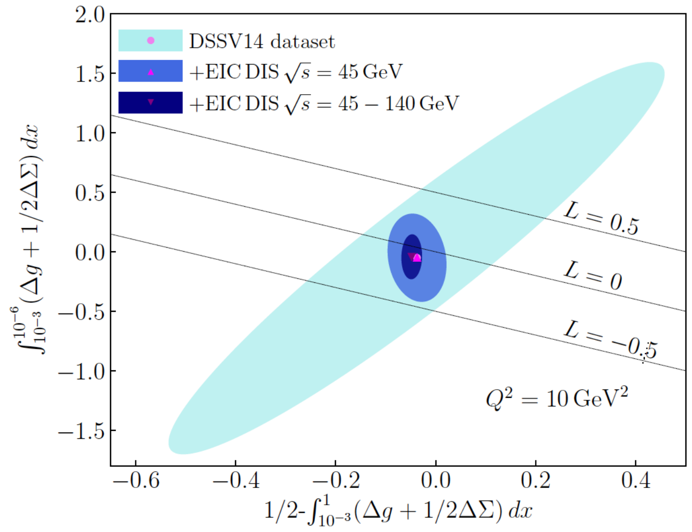


Detector Requirements :

- As much reconstruction of the recoil as possible- calorimetry and tracking needed in forward region.





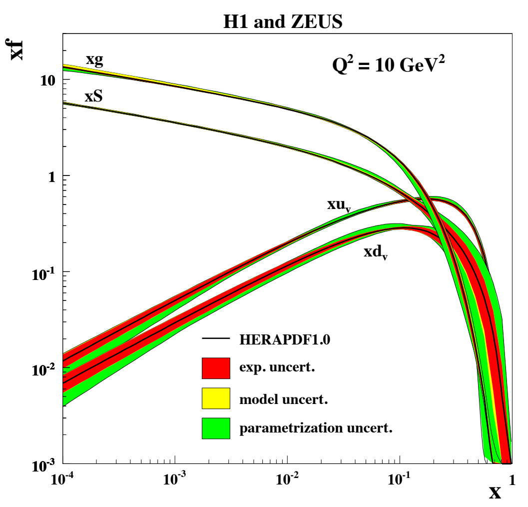


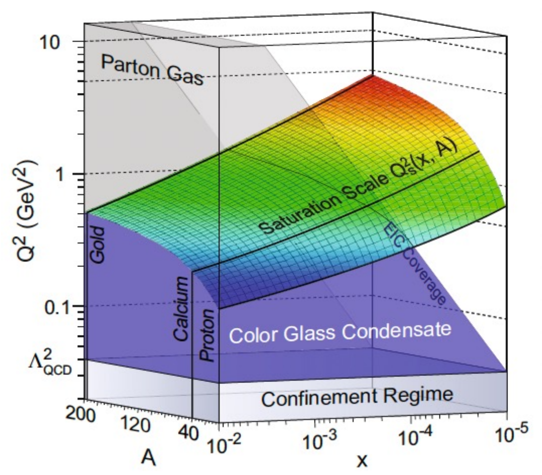
Gluon Helicity Constrains at an EIC

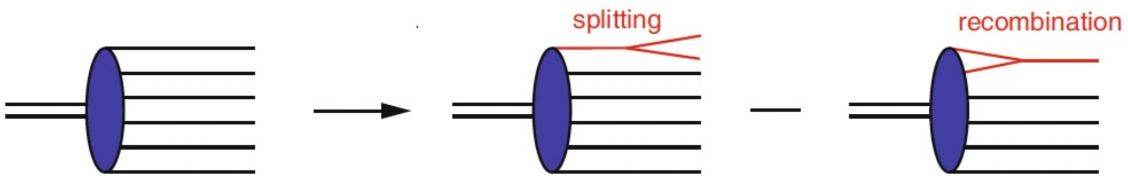
Phys. Rev. D **102**, 094018

Gluon Saturation

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







Gluon Saturation

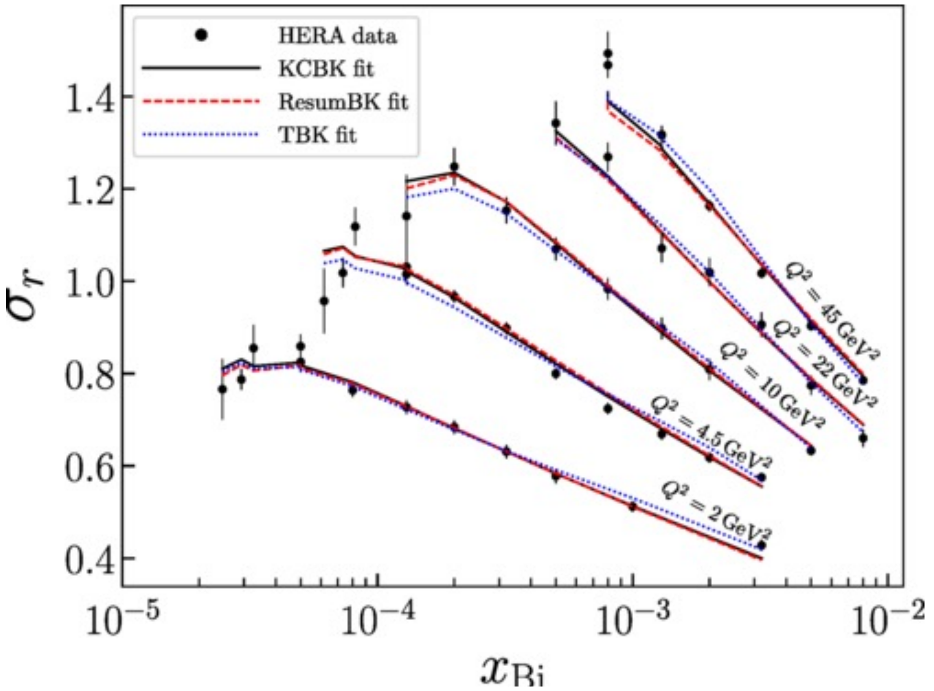
First indications of BFKL evolution at low x came from inclusive e-p Xsec data at HERA.

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

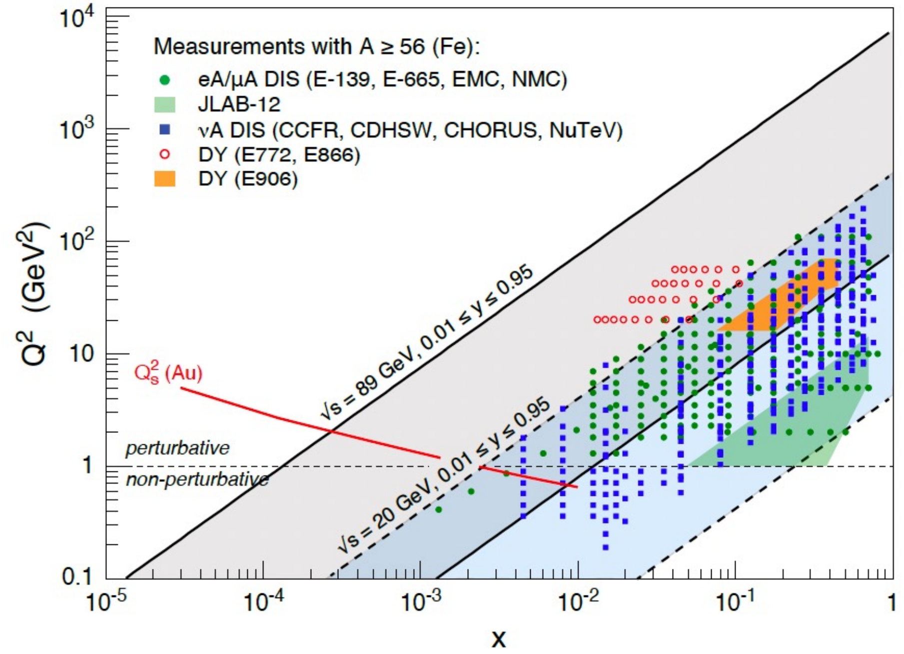
Theory can now reproduce low-x HERA data at NLO within the CGC framework.

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

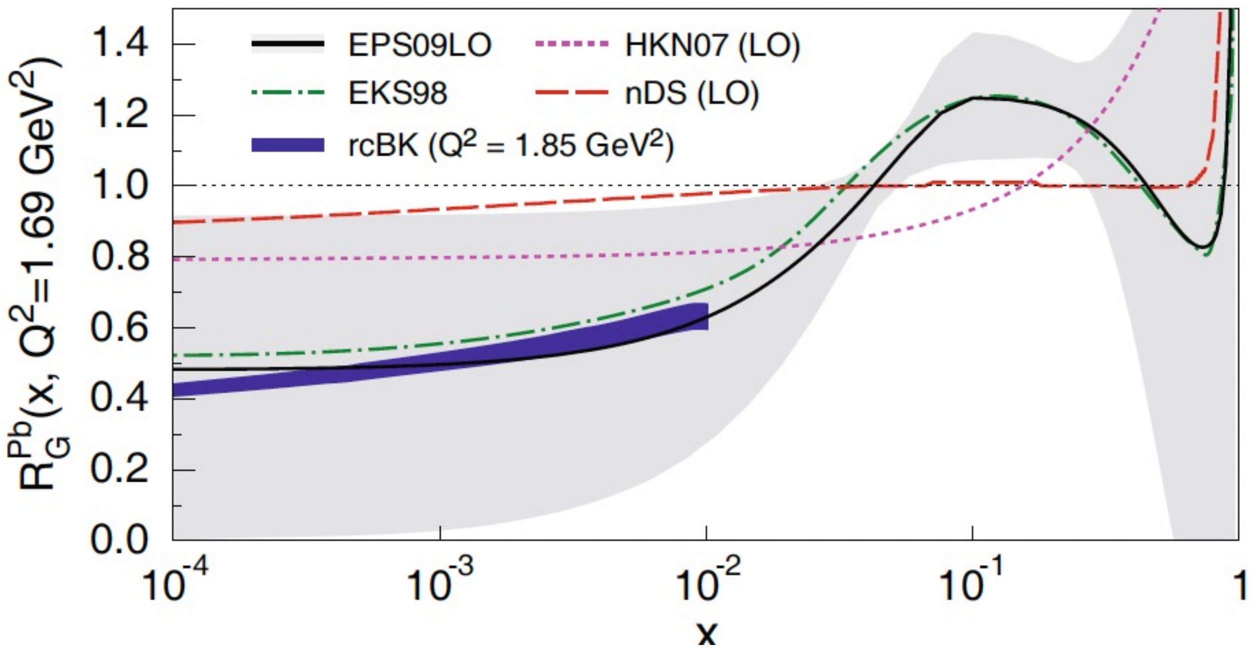
Experimental Signatures at the EIC

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 ΔG measurements.
- Require tracking and high-resolution calorimetry in the backward region to access low x
- Excellent electron PID.

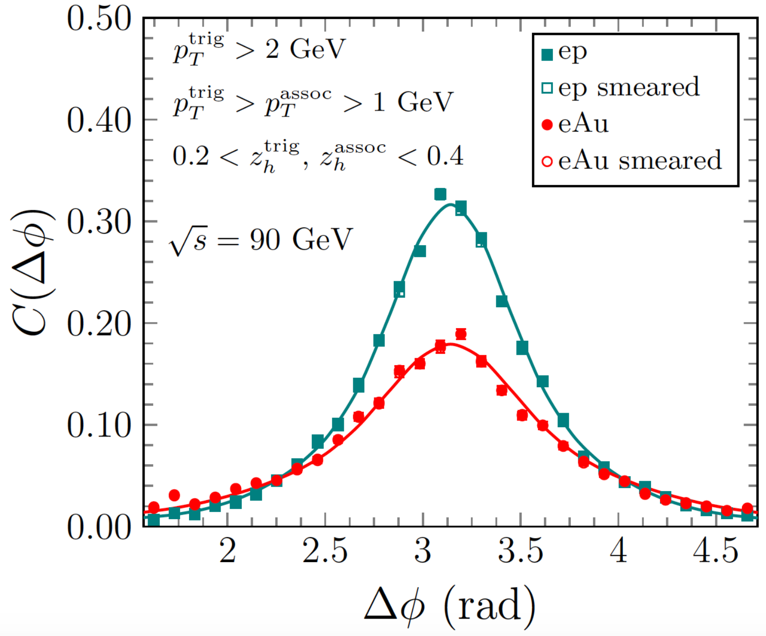


Gluon Saturation

Experimental Signatures at the EIC

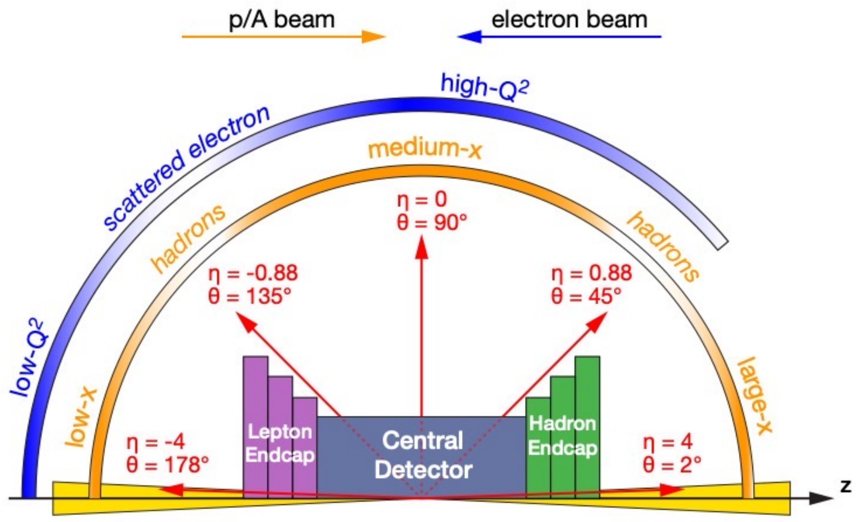
I. Di-hadron and di-jet correlations

- Deviation of opening angle Δϕ = 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

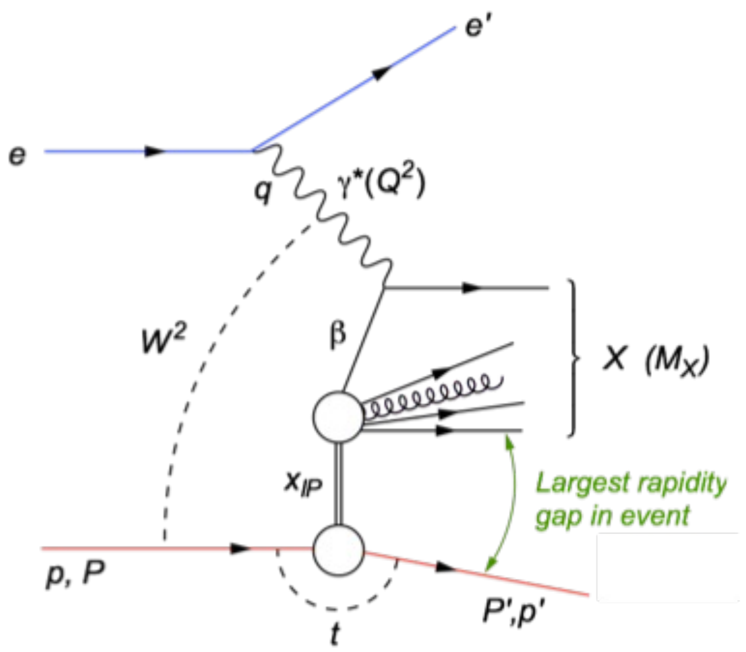


Gluon Saturation

Experimental Signatures at the EIC

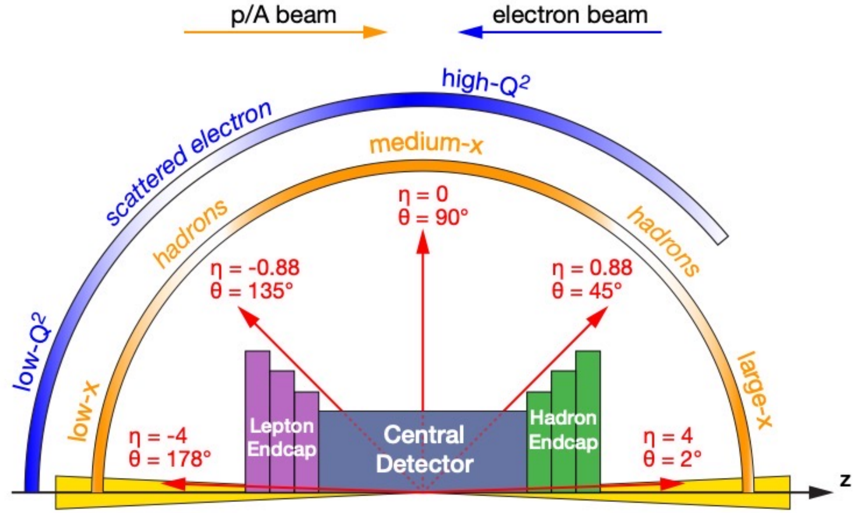
III. Measurement of TOTAL Diffractive cross-section.

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.



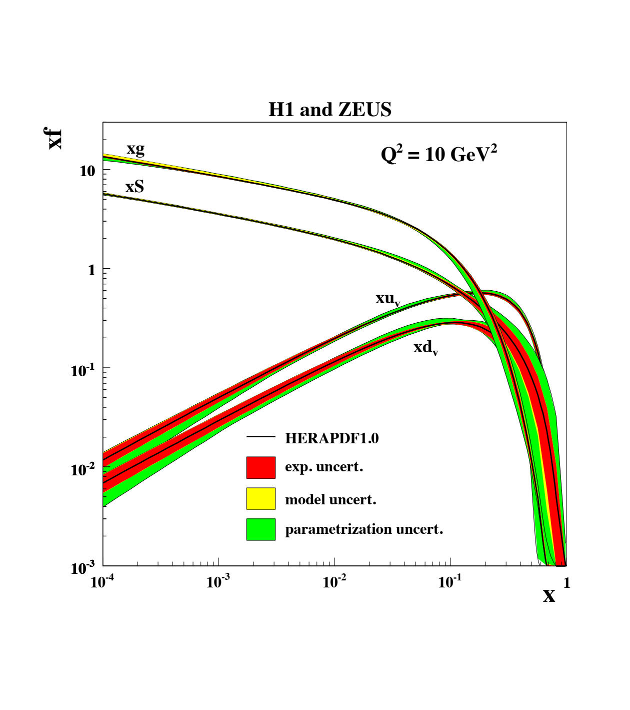
Detector Requirements :

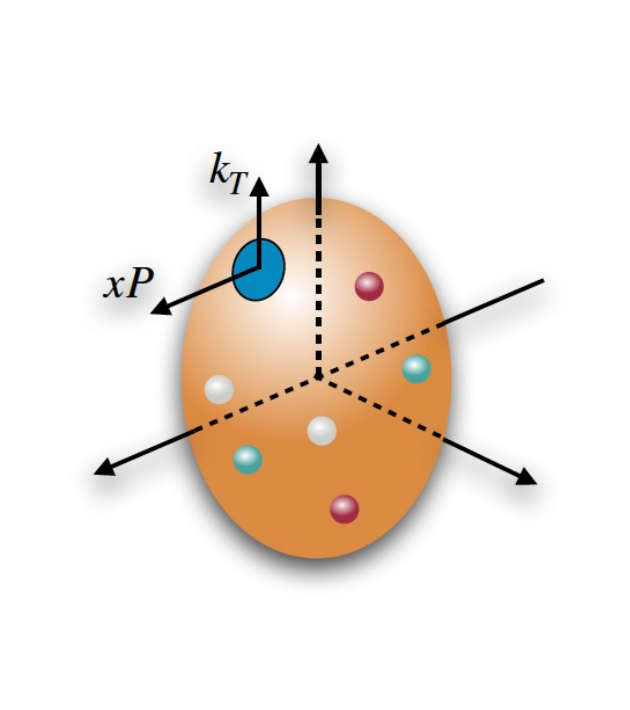
- Far forward detectors to see scattered proton, ie Roman Pots
- For eA need to reconstruct a ''no activity'' rapidity gap
- Electron detection requirements same as inclusive
- Central and forward tracking requirements same as for di-hadrons and jets.

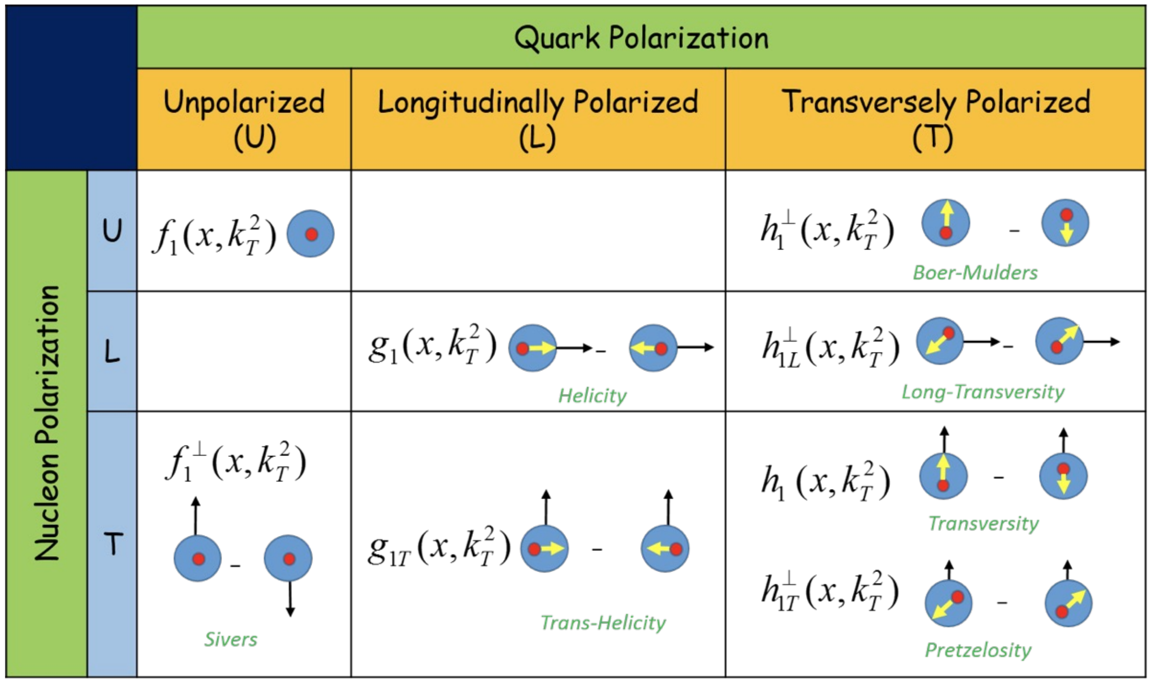


Multi-Dimensional Imaging of the Nucleon

- 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.







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.

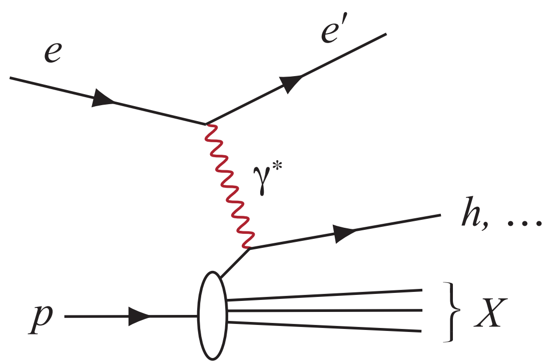
Detector Requirements:

- 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

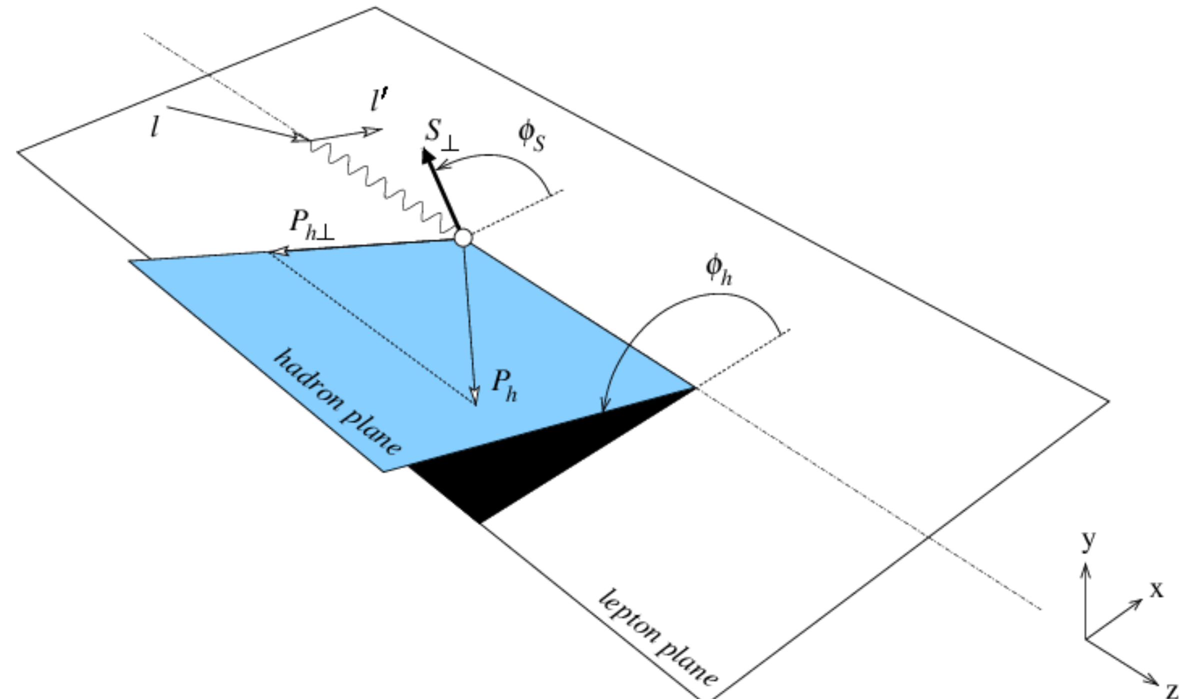
  P < 7 GeV in the backward region



$P_{h\perp}$ 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

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Detector Requirements:

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  P < 50 GeV in the forward region

  P < 10 GeV in the central region

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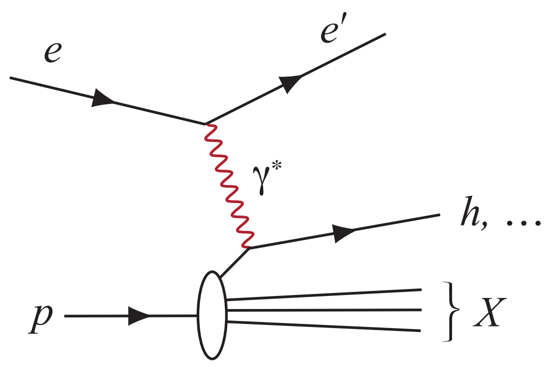

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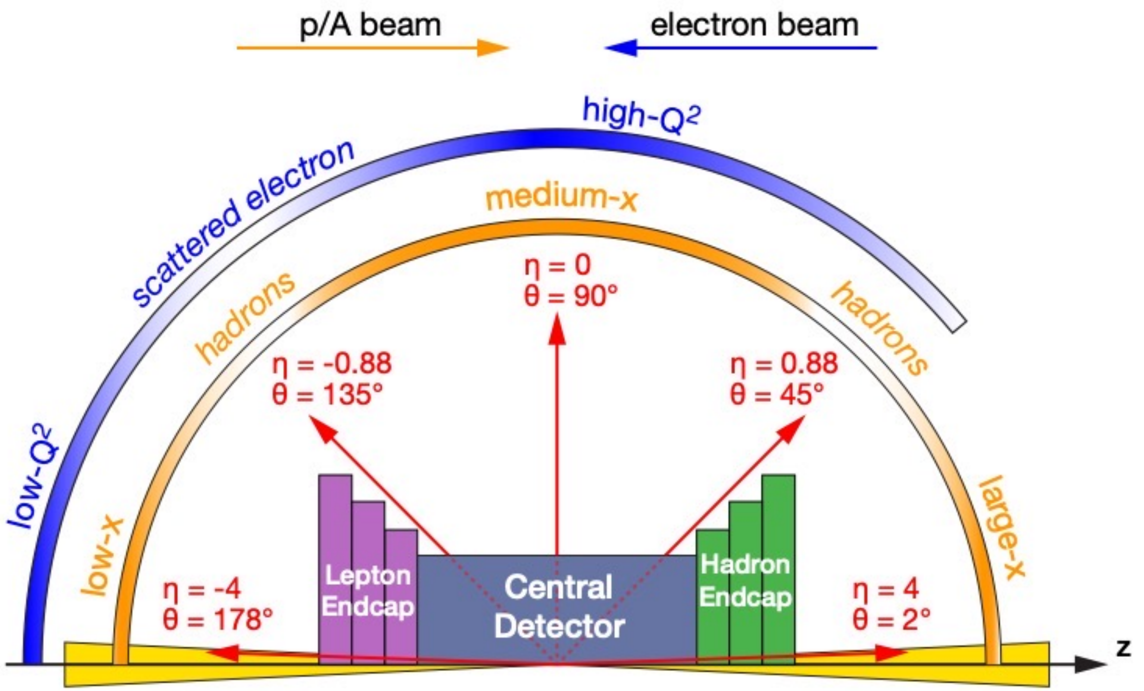


EIC Impact on TMDs

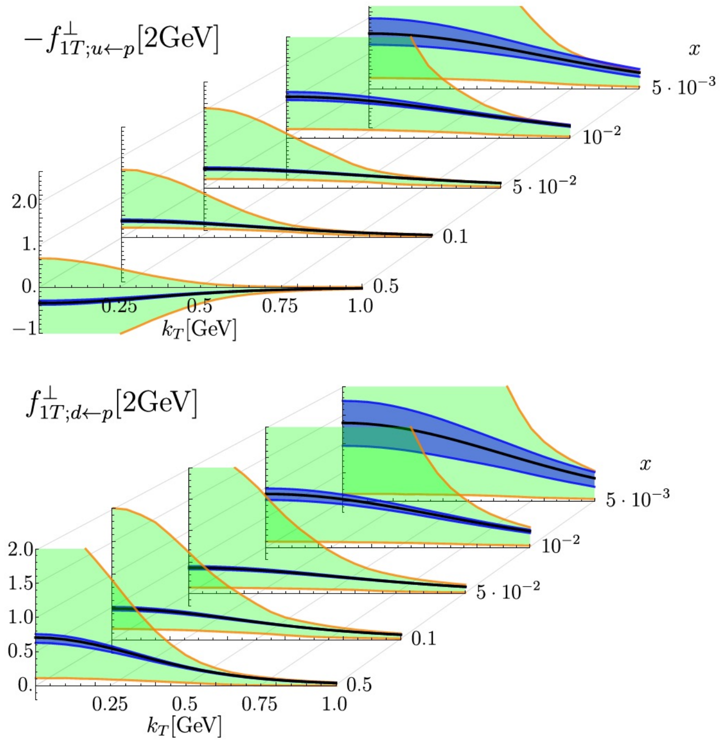
Sivers Function x FF

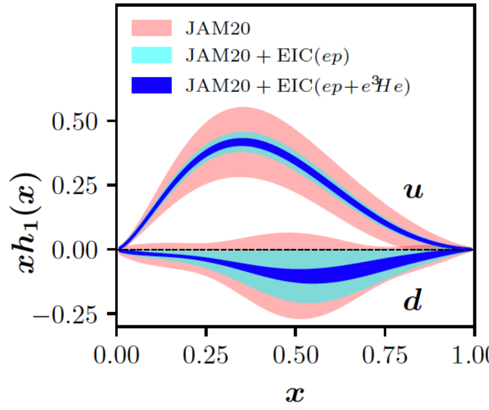
- Parton k_T correlation with proton spin
- Current (green) and EIC (blue) constraints on u/d
- Limited subset of existing data that satisfies factorization conditions.
- Uncertainties reduced by > x10 for all flavors.
- Wide range of hadron p_T facilitates k_T mapping

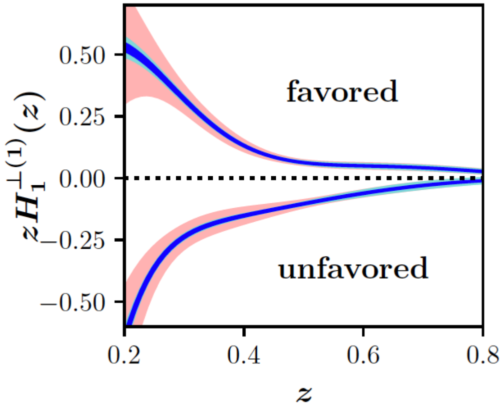
Transversity x Collins FF

- 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





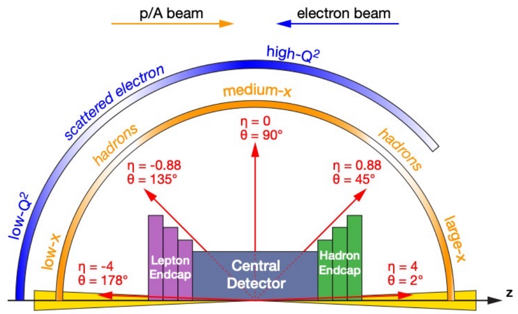


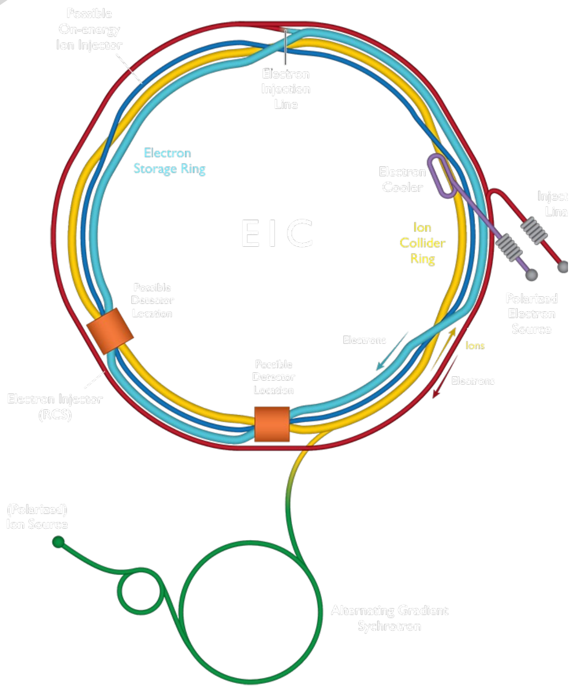
Phys.Lett.B 816 (2021) Phys.Rev.D 102 (2020)

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.



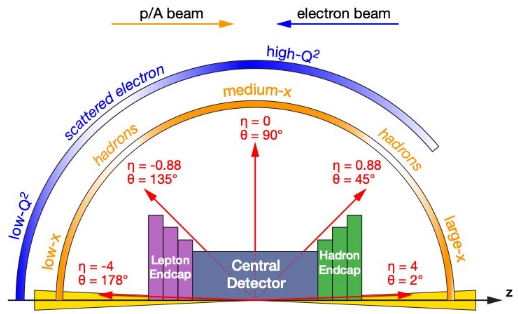


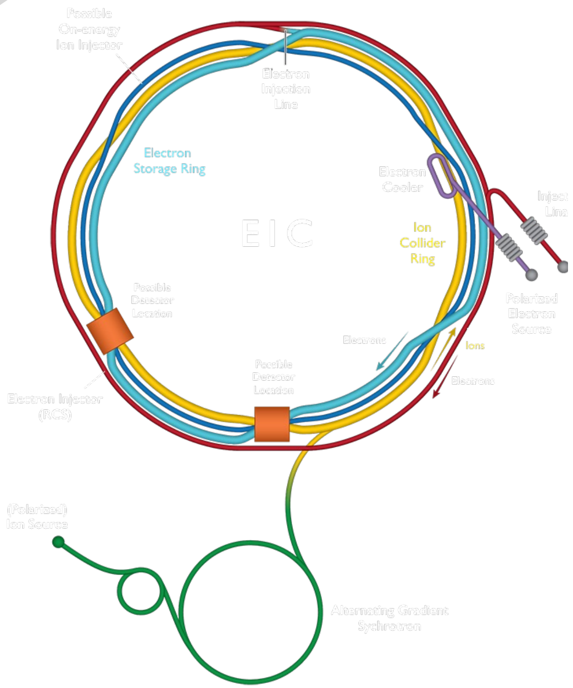
The most pressing questions at the QCD Frontier need:

- 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.

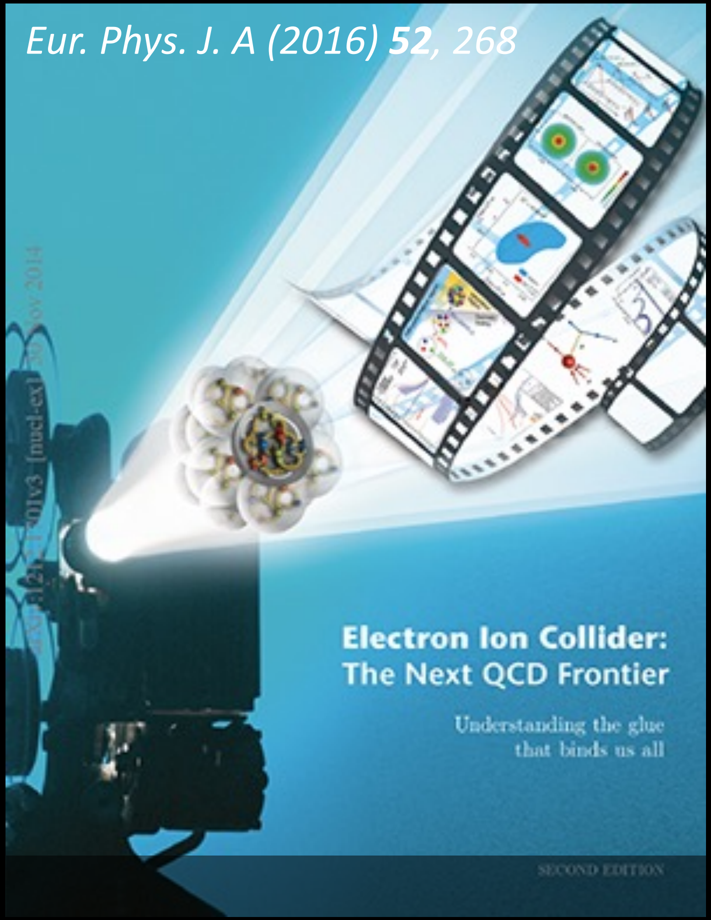
- At least one general purpose reference detector that has broad coverage in tracking, calorimetry and PID.

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

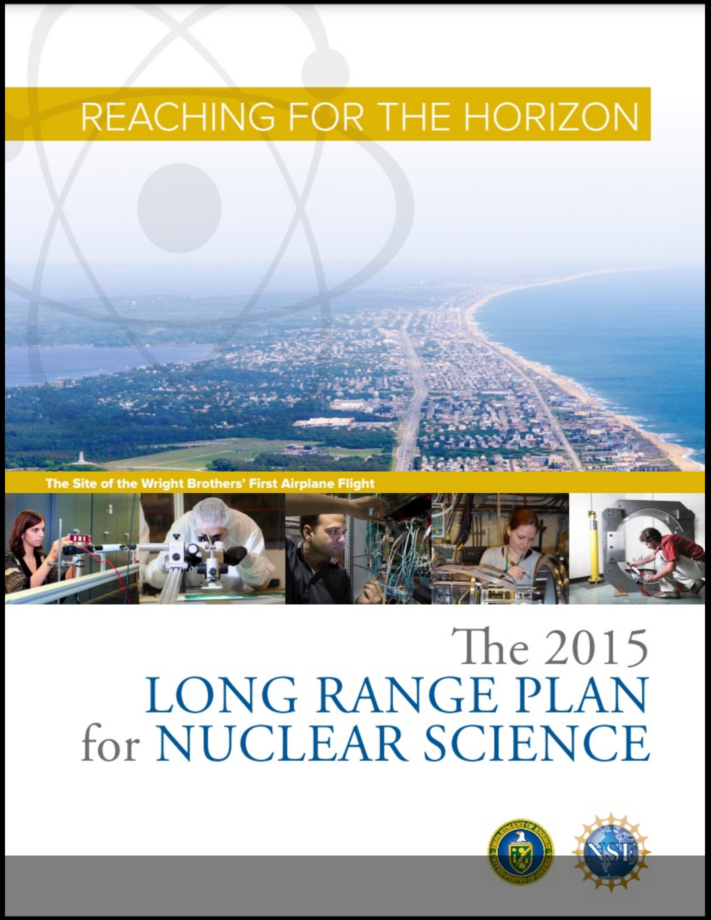




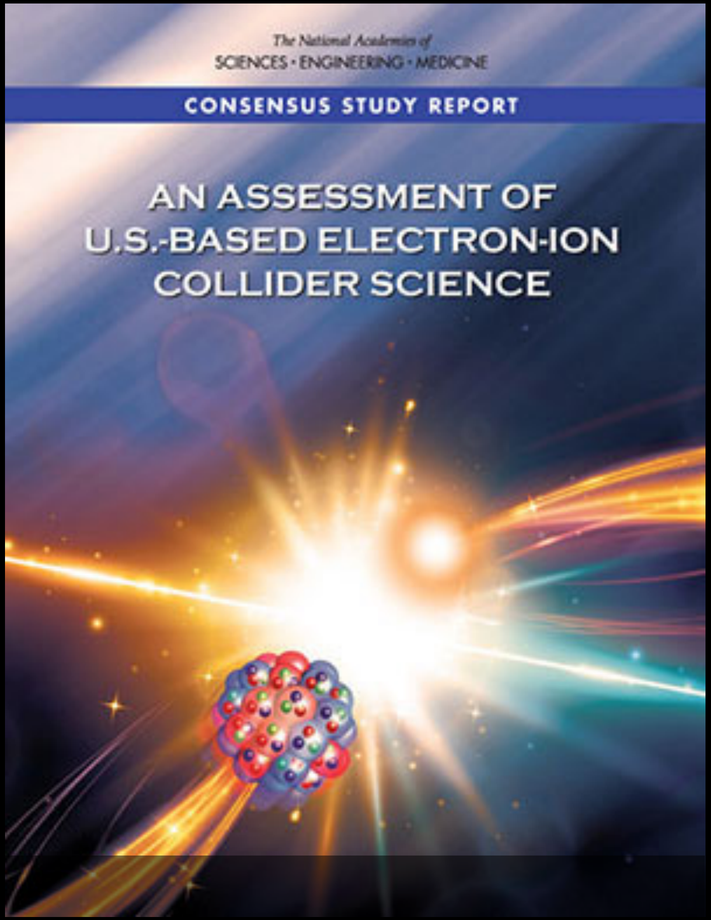
Path to the EIC - Historical Milestones



2014



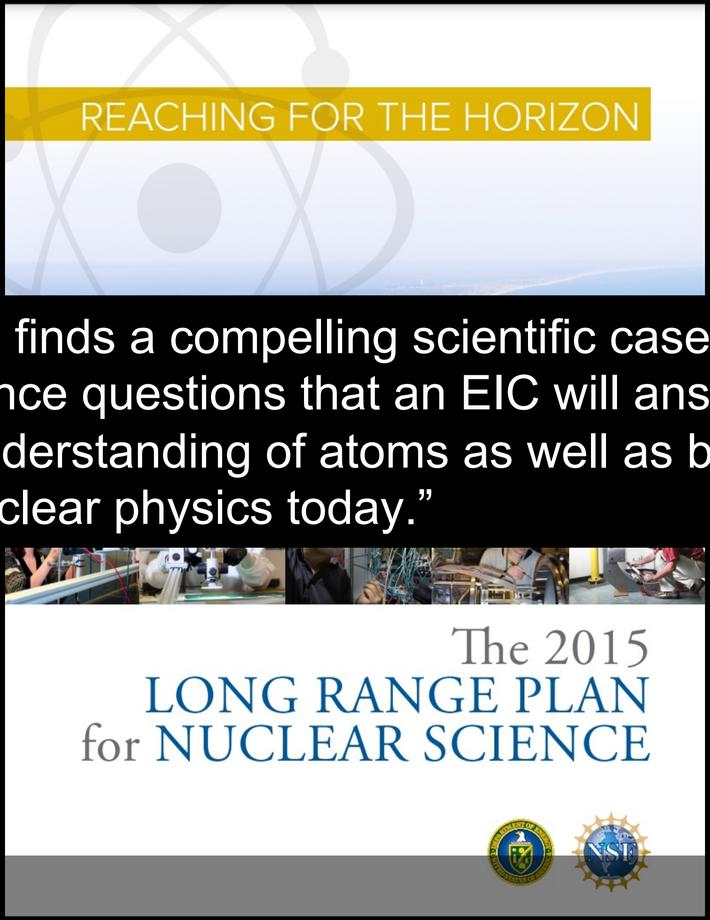
2015



2018

Path to the EIC - Historical Milestones

2014

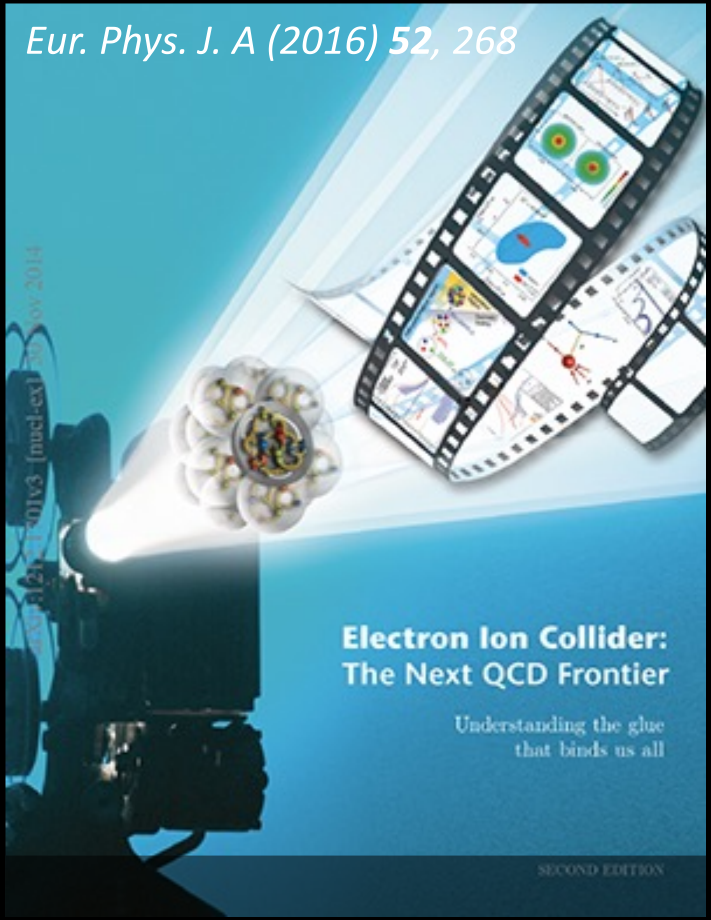


2015

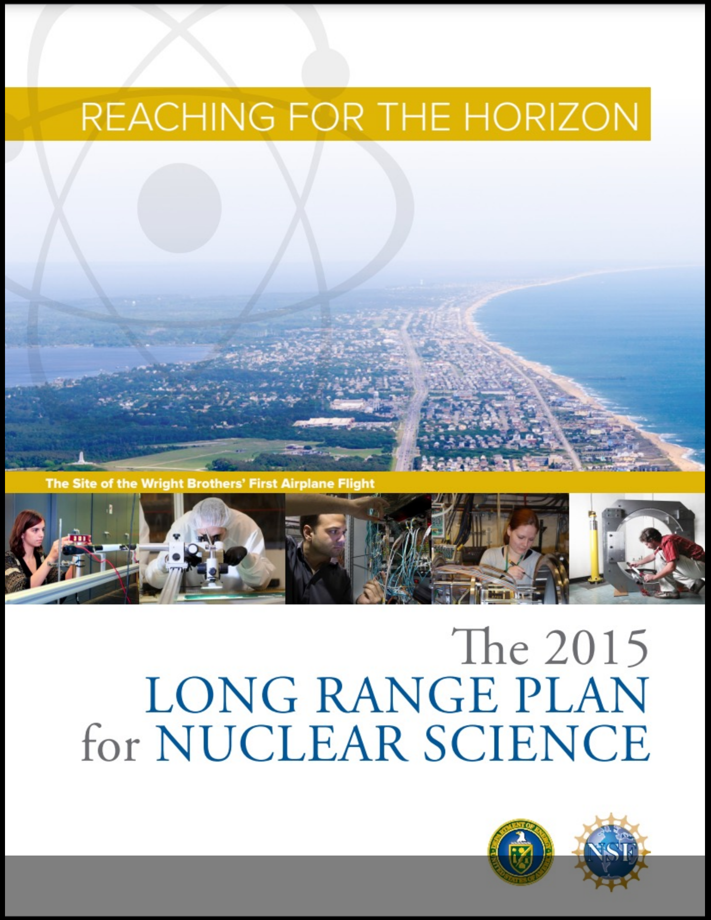
2018

"…the committee finds a compelling scientific case for such a facility. The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

December 2019 – CD0 Mission Need from DOE
January 2020 – Site selection announced



2014



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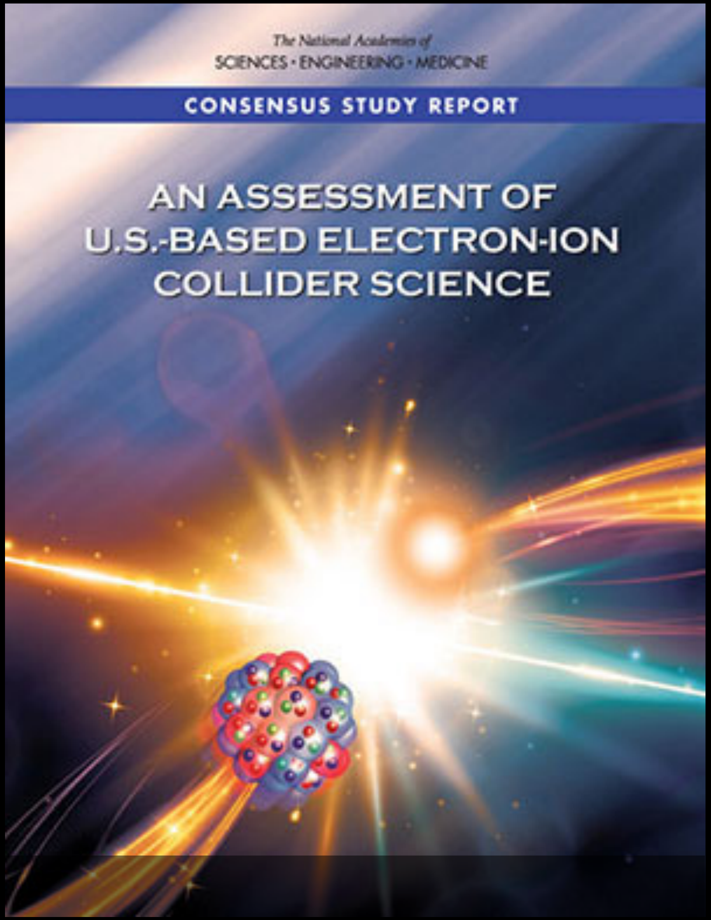
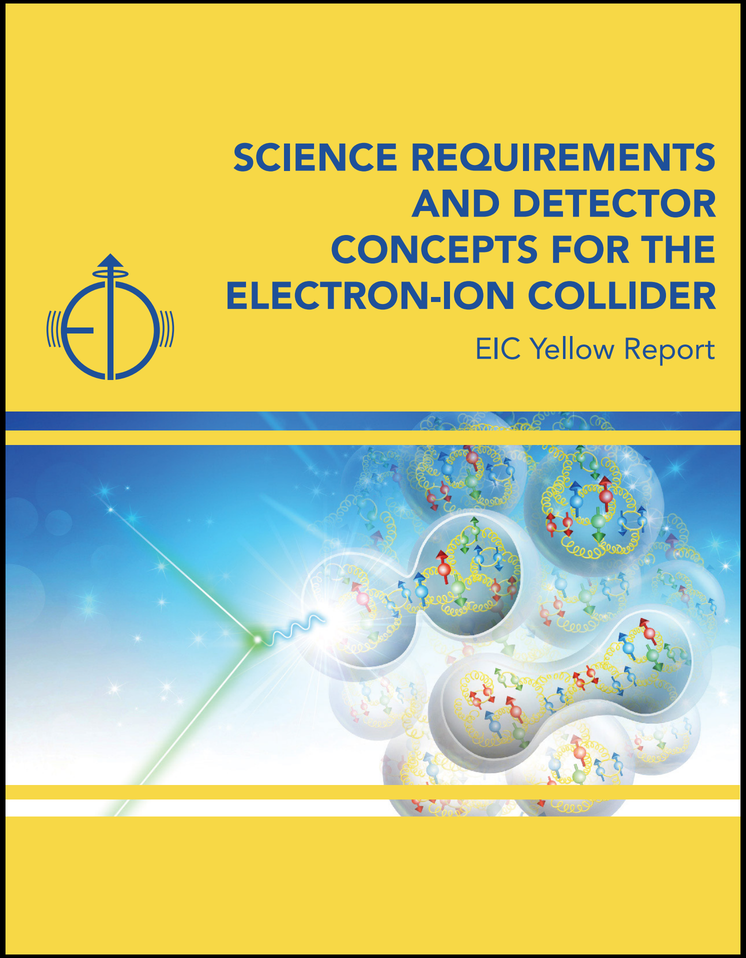


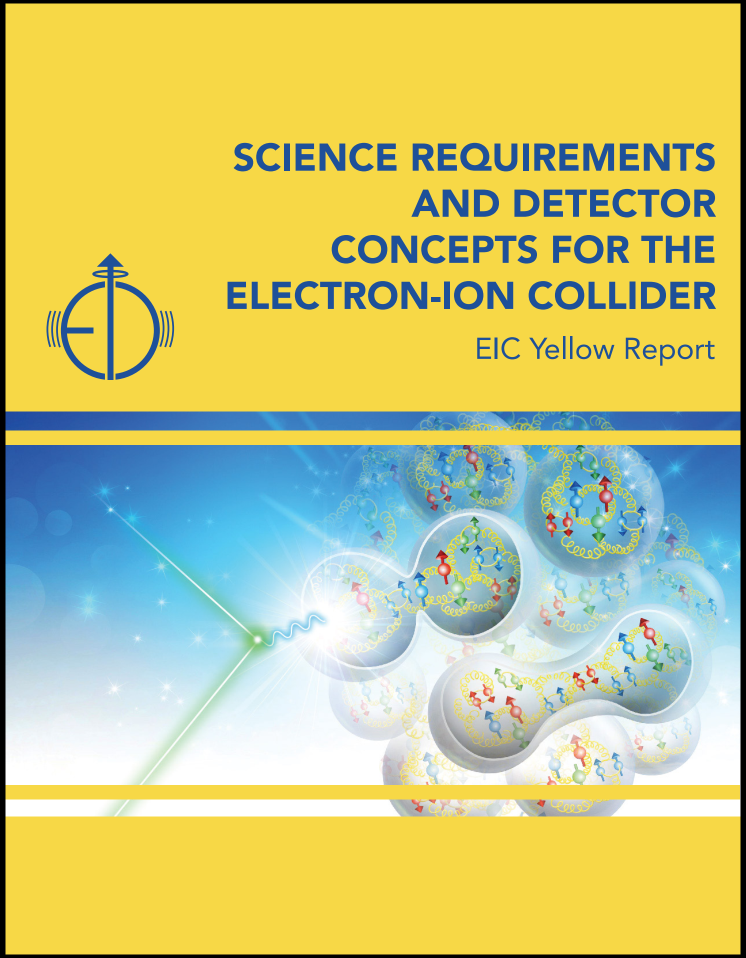
2018

2020 The Yellow Report

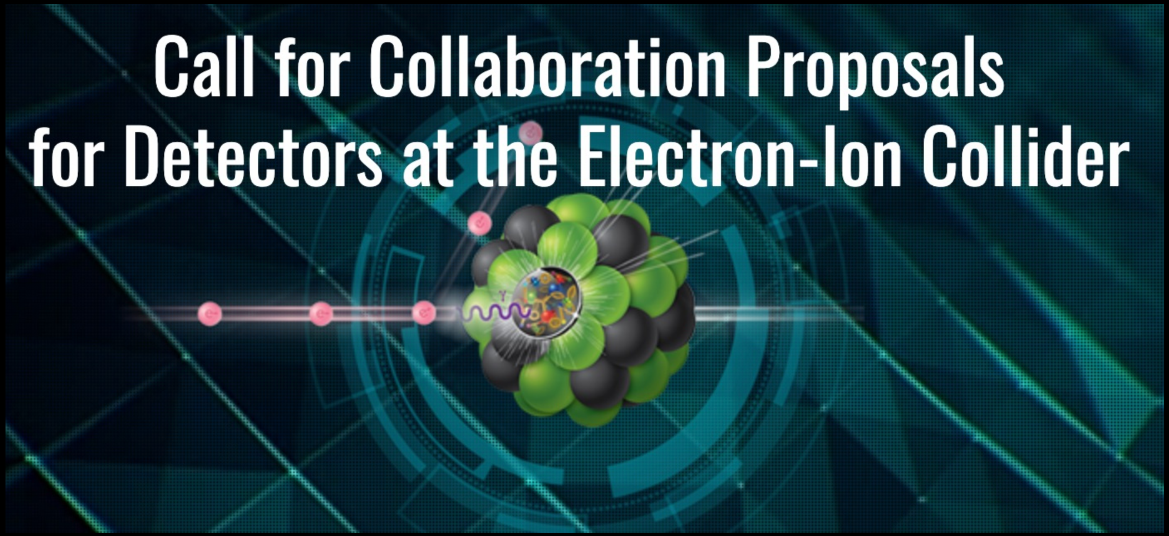


- Update, where necessary, the EIC physics case
- Specify the detector requirements for primary channels
    - Inclusive Deep Inelastic Scattering (DIS)
    - Semi-inclusive DIS
    - Exclusive DIS
    - Jet and Heavy-Flavor Reconstruction
    - Diffractive scattering
- Discuss current state-of-the-art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

2020 The Yellow Report



March 2021



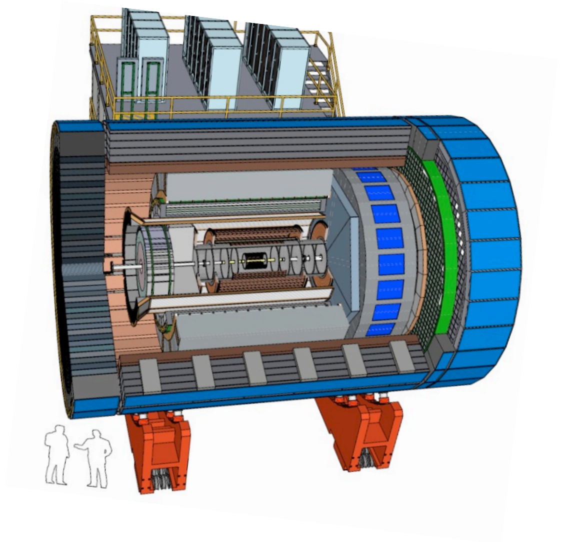
DETECTOR I
Must address EIC White Paper and NAS science case and satisfy the detector requirements for the reference detector as discussed in the Yellow Report.

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

EIC Proto-Collaborations

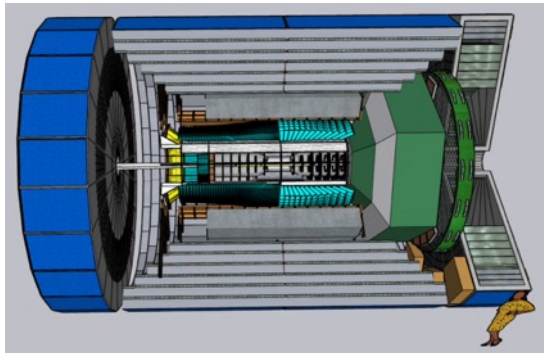
ATHENA (https://sites.temple.edu/eicatip6/)

- Focus on becoming the “project detector”@IP6
- New 3 T magnet and the YR Reference Detector
- Leadership: S. Dalla Torre (INFN Trieste), B. Surrow (Temple)
- 117 collaborating institutions



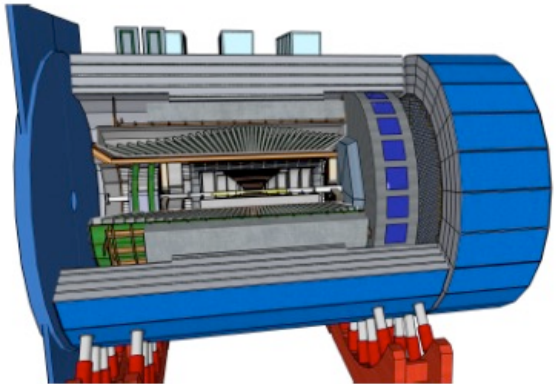
CORE (https://eic.jlab.org/core/)

- An EIC Detector proposal based on a new 3 T compact magnet for the 2nd EIC detector @ IP8
- Contacts: Ch. Hyde (ODU) and P. Nadel-Turonski (SBU)
- Smaller-scale effort, ~20-30 active collaborators

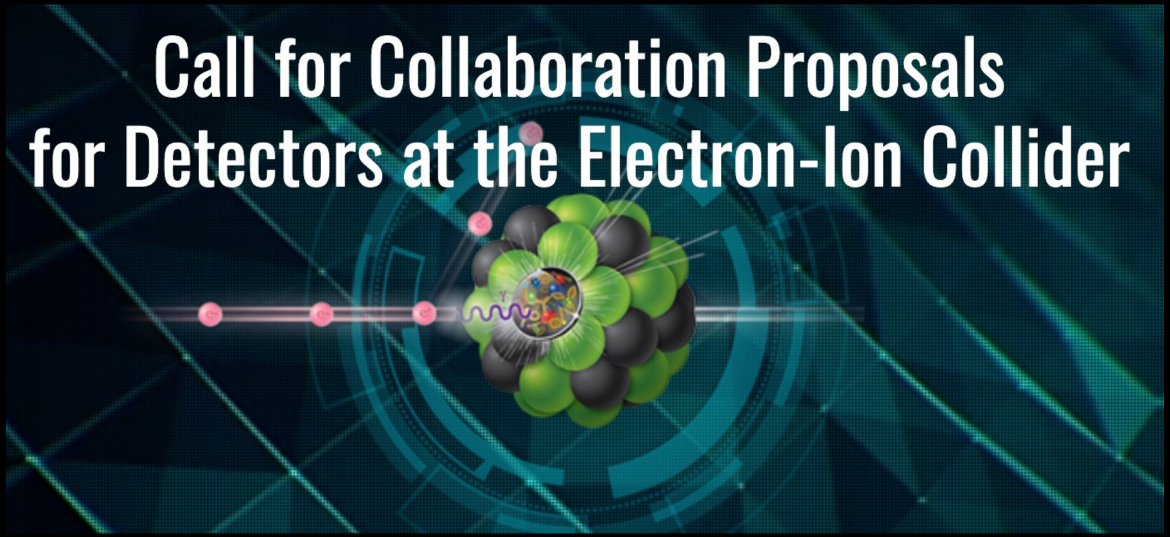


ECCE (https://www.ecce-eic.org)

- Project detector @IP6 using existing 1.5T “Babar” solenoid
- Leadership: O. Hen (MIT), T. Horn (CUA), J. Lajoie (Iowa State)
- 98 collaborating institutions



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.

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

In the summer of 2021 Detector Proposal Advisory Panel was convened

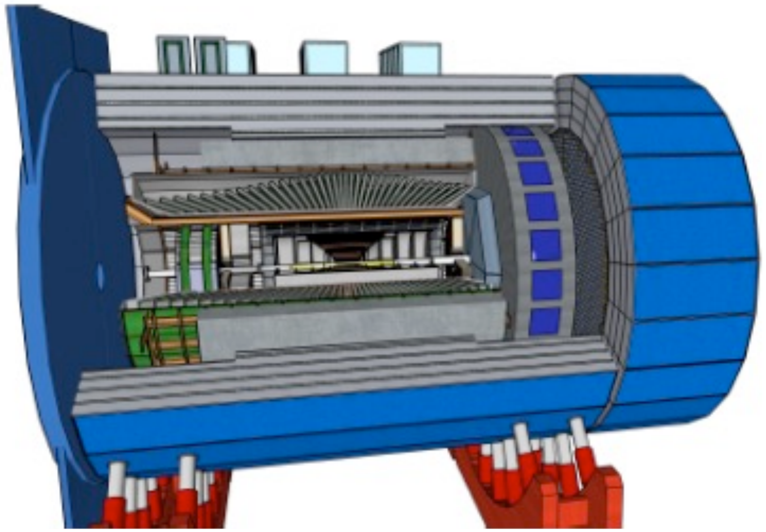
- Co-chair Rolf Heuer (CERN)
- Patty McBride (FNAL)

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

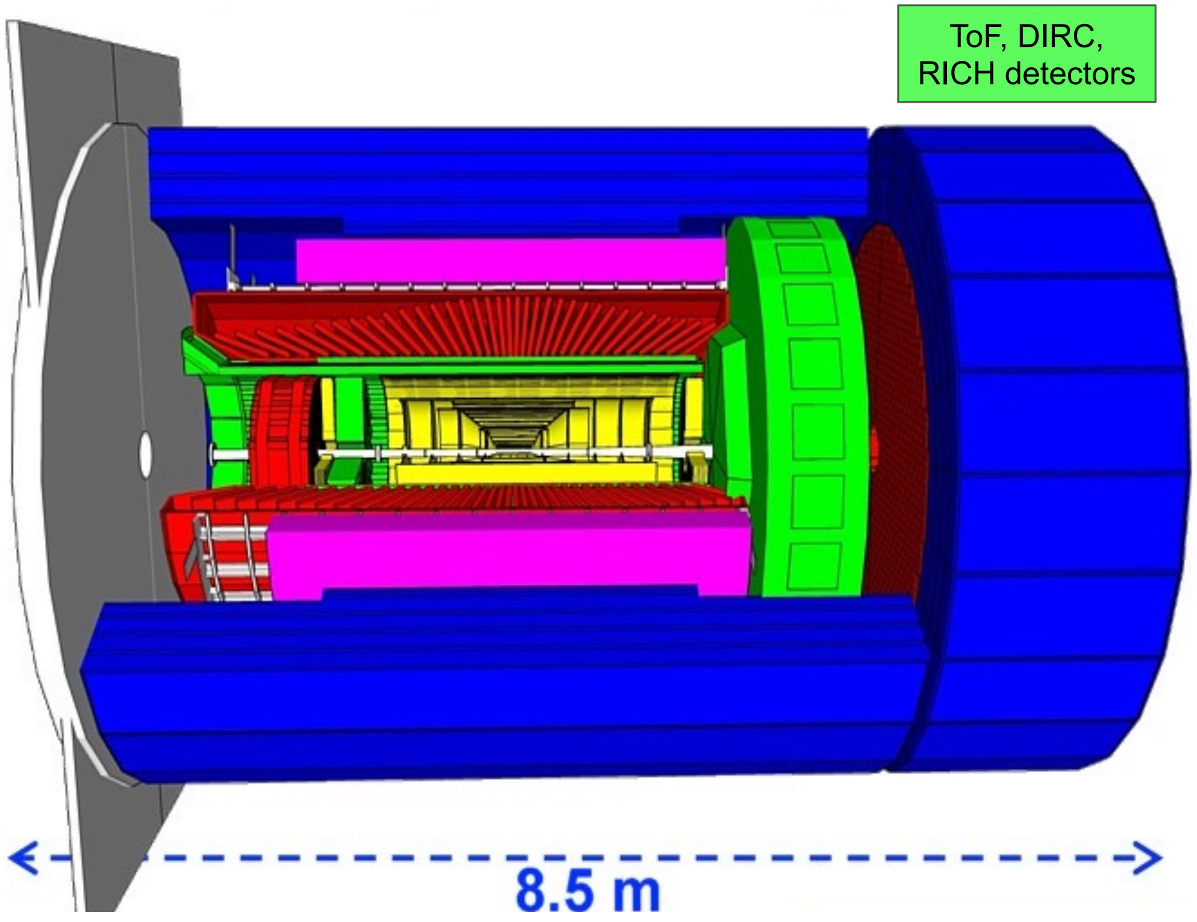


DETECTOR I

DPAP Review Summary

- All three proposals received high marks
- Both ATHENA and ECCE satisfied the requirements for the reference detector
- Noted that many collaborators are involved in multiple proposals and none of the proto-collaborations are currently strong enough to build the project detector
- Strongly encouraged the three proto-collaborations to move forward together based on ECCE as the reference design for the project detector
- Expects the integration of new collaborators and new experimental concepts and technologies to improve physics capabilities, and to prepare the detector as part of the EIC project baseline, the next major DOE schedule milestone
- Enthusiastically supported a second detector as needed to take full advantage of the unique capabilities of EIC facility
- Expects the EIC User Community to come together in support of the project detector as well as a second detector

General Design of Project Detector

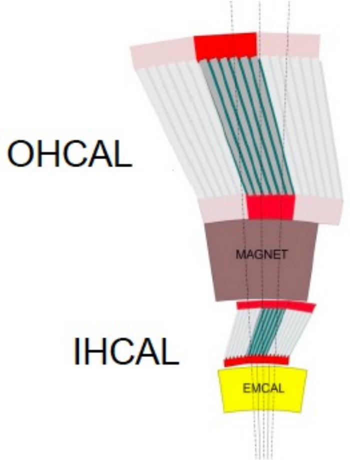


solenoid coils

- Reuse Babar 1.5 T Magnet already installed for sPHENIX at RHIC.
- Detector size/configuration fixed by magnet

hadronic calorimeters

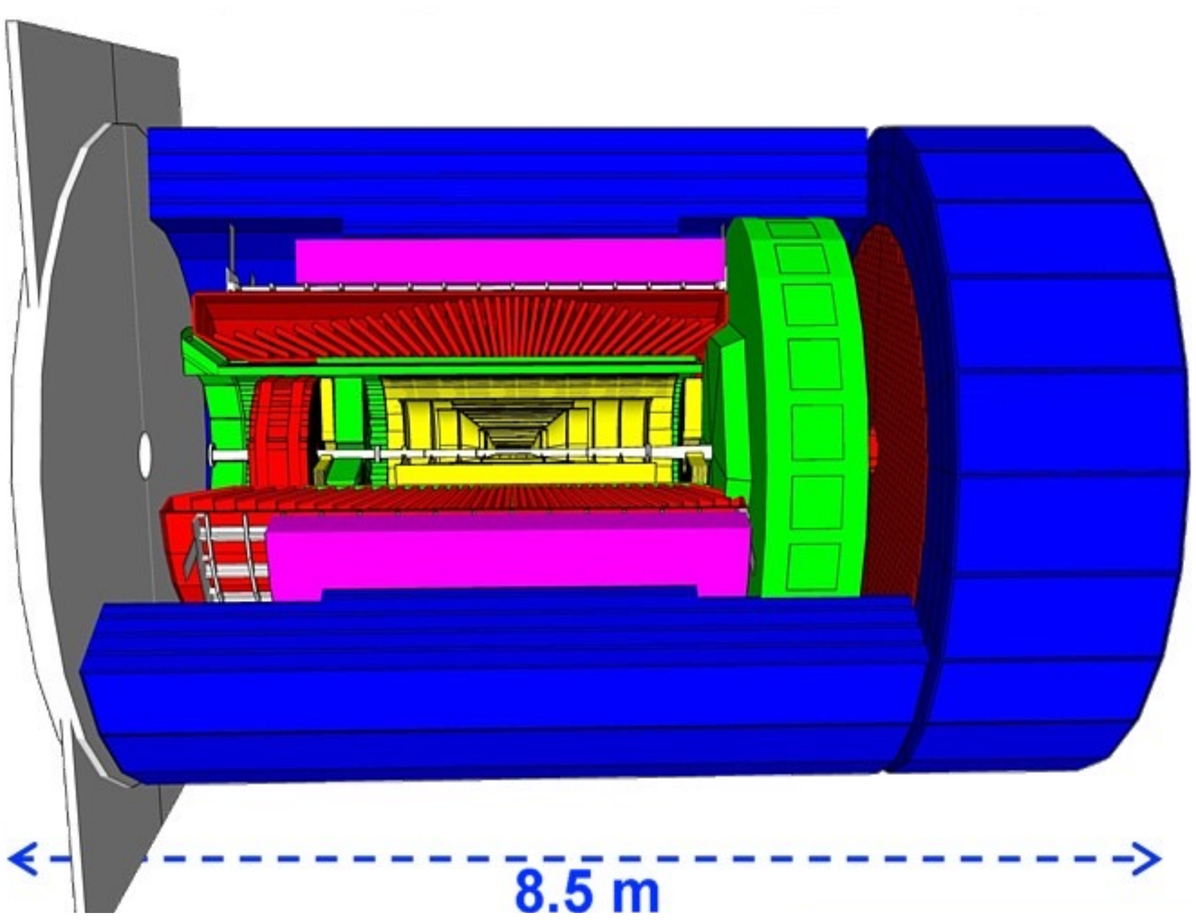
- Central – Fe/Sc HCAL
- Forward – Longitudinally separated HCAL



e/m calorimeters

- Backward – homogenous, high resolution PbWO4 crystals
- Central – Projective SciGlass
- Forward – Pb/Sc Shashilik Sampling

General Design of Project Detector



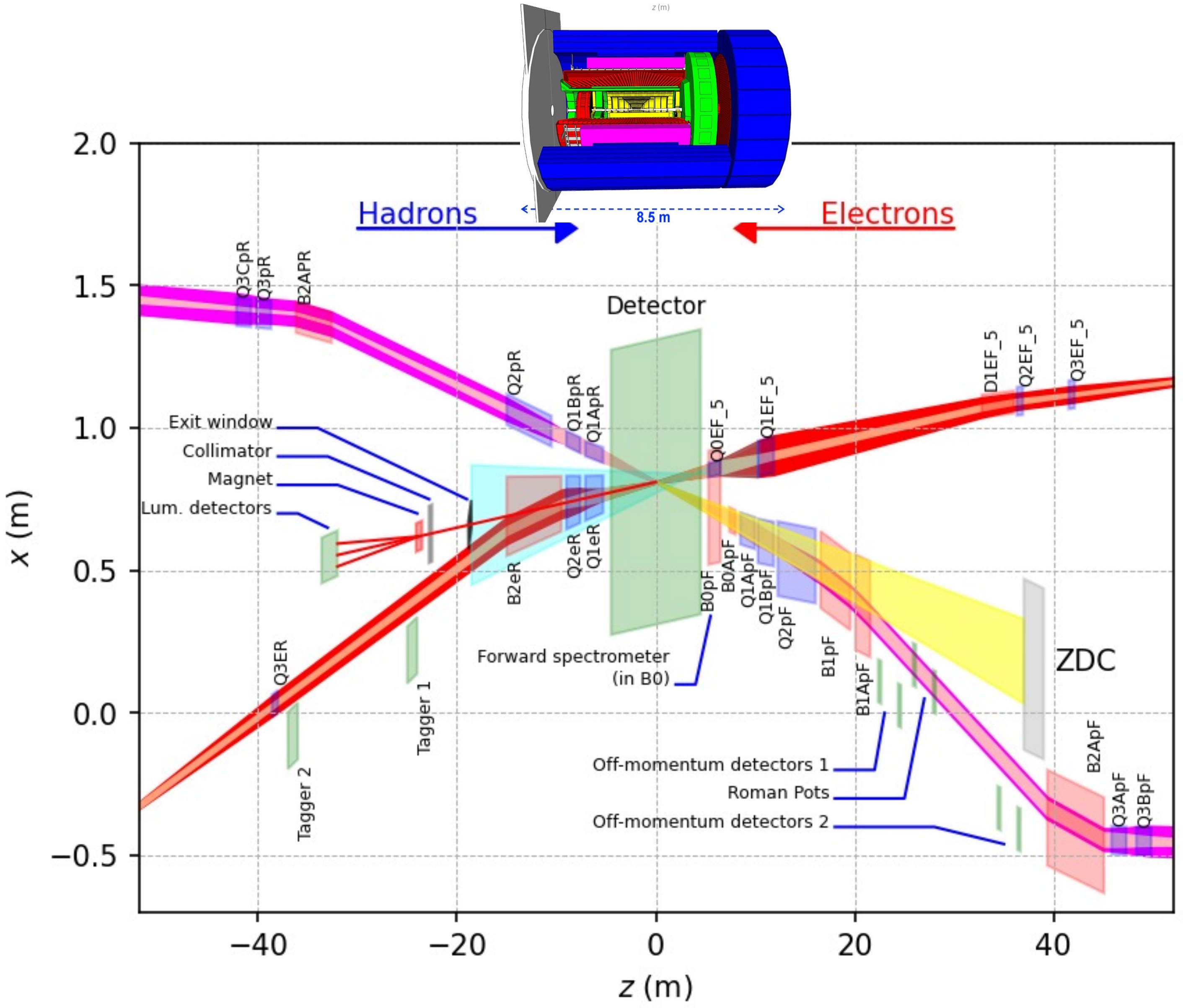
MPG & MAPS trackers

- Backward – 4 MAPs based silicon disks and AC-LGAD TOF
- Central – Silicon vertex tracker + muRWELL subtracker and AC-LGAD TOF
- Forward – 5 MAPs based silicon disks and AC-LGAD TOF

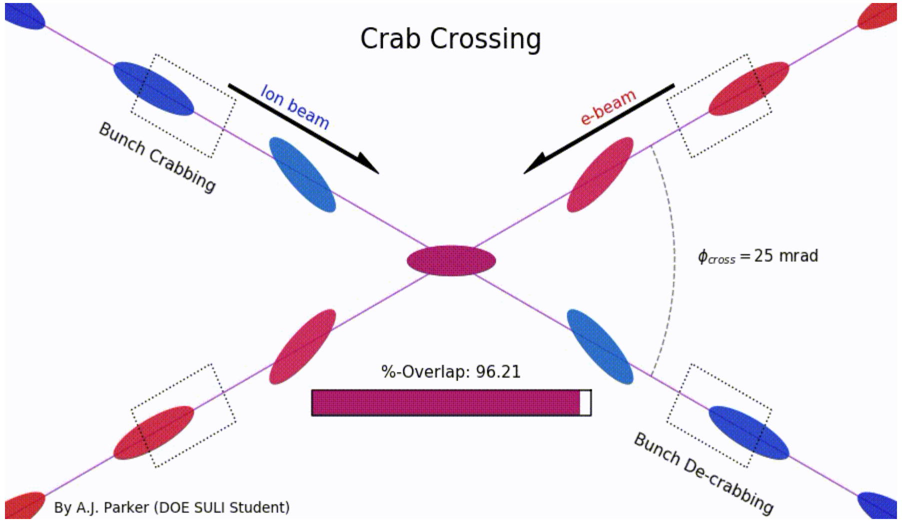
ToF, DIRC, RICH detectors

- Backward – short modular aerogel mDIRC
- Central – radially compact high performance DIRC
- Forward – double radiator gas/aerogel dRICH
- Full coverage – TOF for low momentum hadrons that Cherenkovs cannot cover.

General Design of Project Detector



- 25 mrad crossing angle at IP6
- Crab crossing maximizes luminosity
- Detector rotated by 8 mrad to accommodate e- beam angle
- Auxilary detectors include :
  - Zero degree calorimeters
  - Roman Pots
  - low Q2 taggers
  - B0 system



Moving Forward - Next Steps for the Project

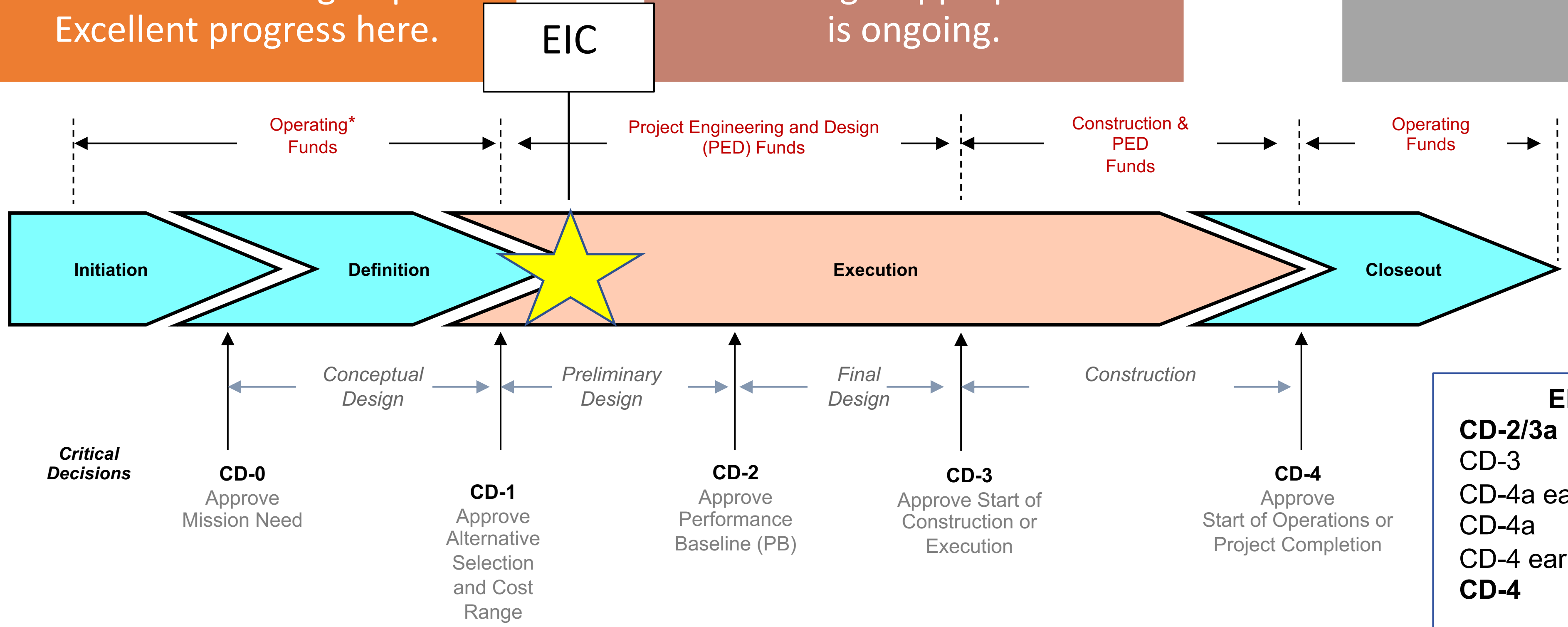
Joint ECCE+ATHENA leadership team is facilitating the merging and integration of new and existing institutions and groups. Excellent progress here.

→

Discussion of integrating new experimental concepts and technologies that improve physics capabilities without introducing inappropriate risk is ongoing.

→

Goal is to advance to CD 2/3 in a timely fashion



EIC Critical Decision Plan

CD-2/3a	**January 2024**
CD-3	April 2025
CD-4a early finish	April 2031
CD-4a	April 2032
CD-4 early finish	April 2032
CD-4	**April 2034**

Moving Forward - Next Steps for the Project

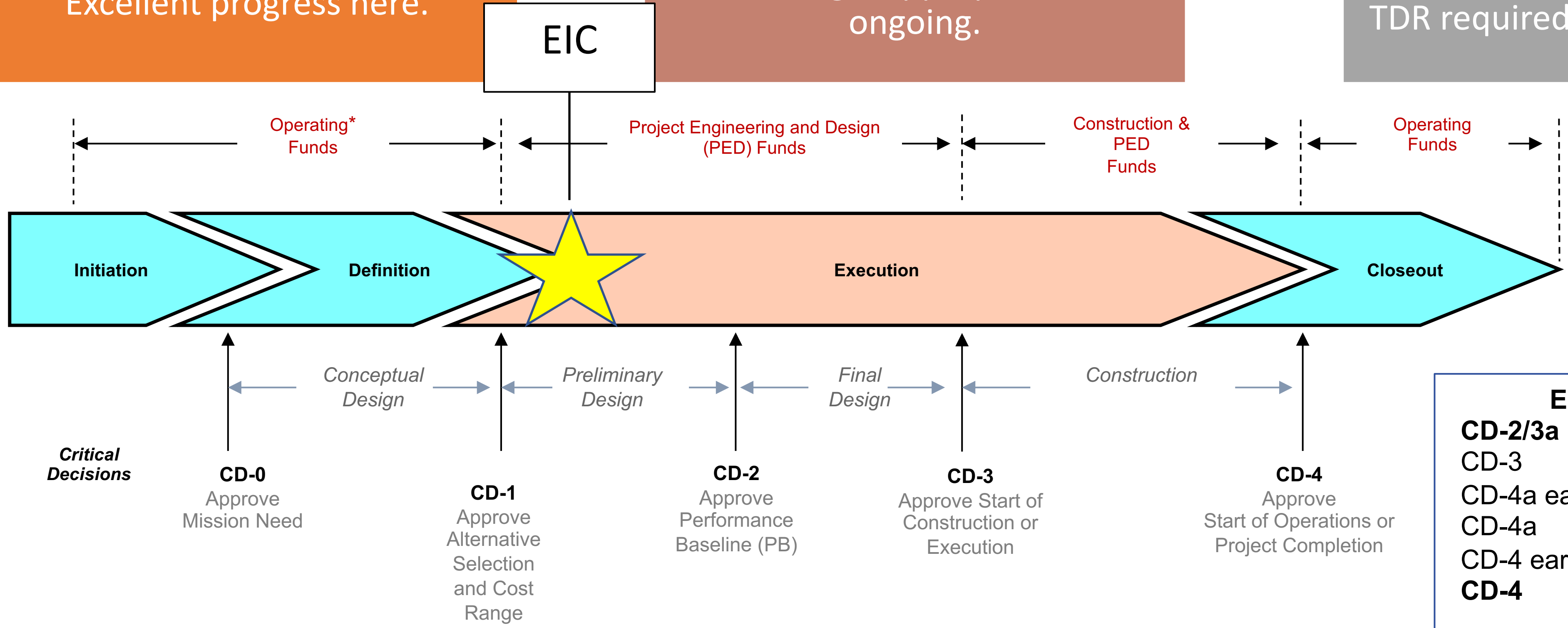
Joint ECCE+ATHENA leadership team is facilitating the merging and integration of new and existing institutions and groups. Excellent progress here.

Discussion of integrating new experimental concepts and technologies that improve physics capabilities without introducing inappropriate risk is ongoing.

CD2 - approval of preliminary design, pre-TDR required

CD3a - long lead procurement

CD3 – approval of final design, TDR required



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CD-2/3a	**January 2024**
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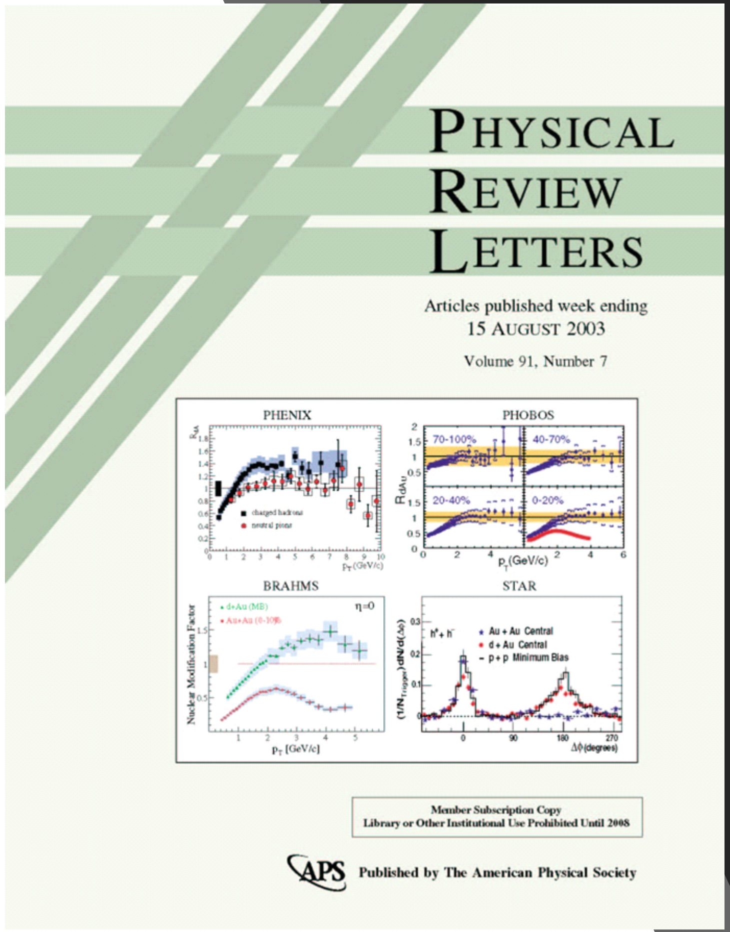
CD-4	**April 2034**

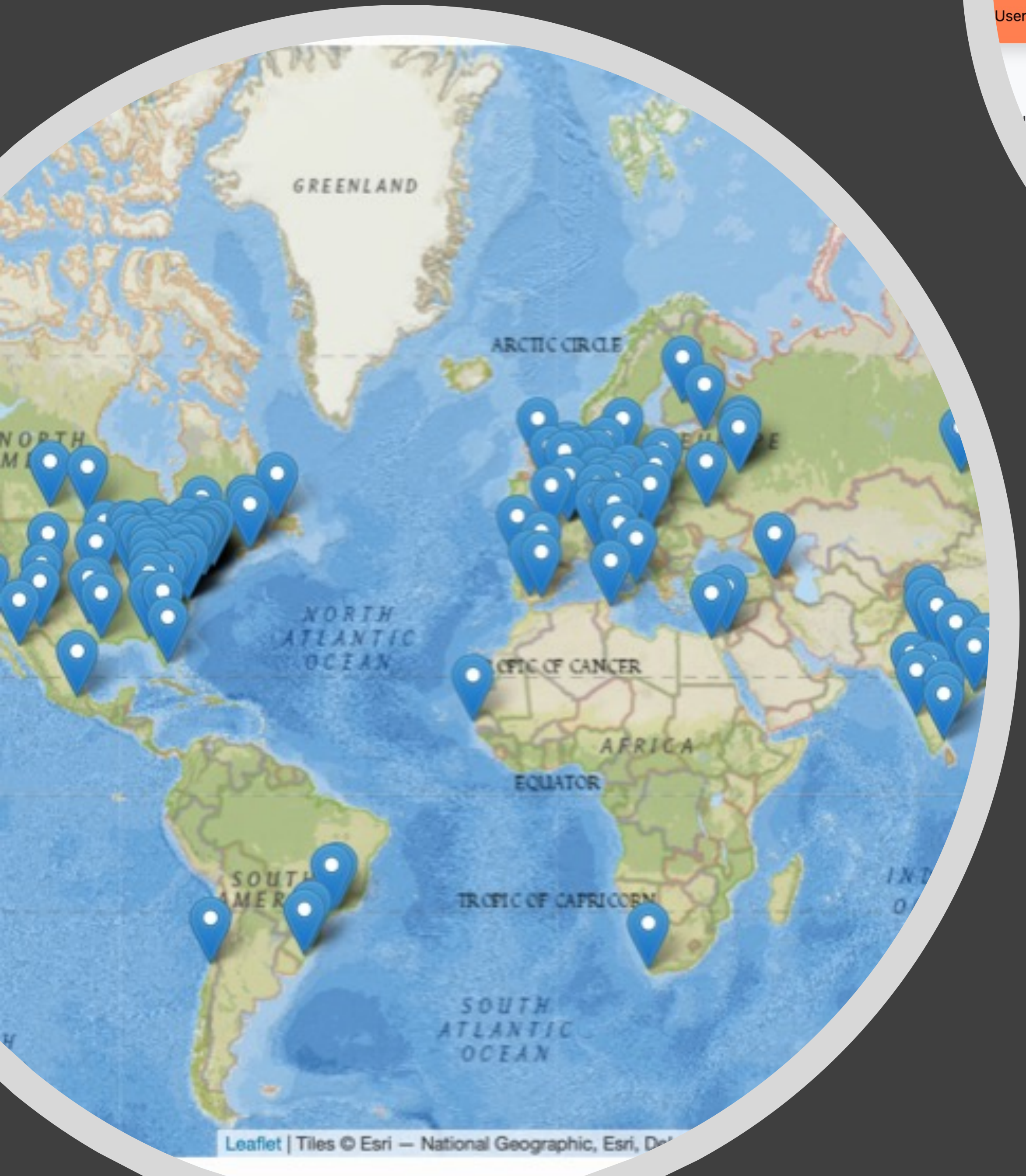
Detector II: The Case for Complementarity

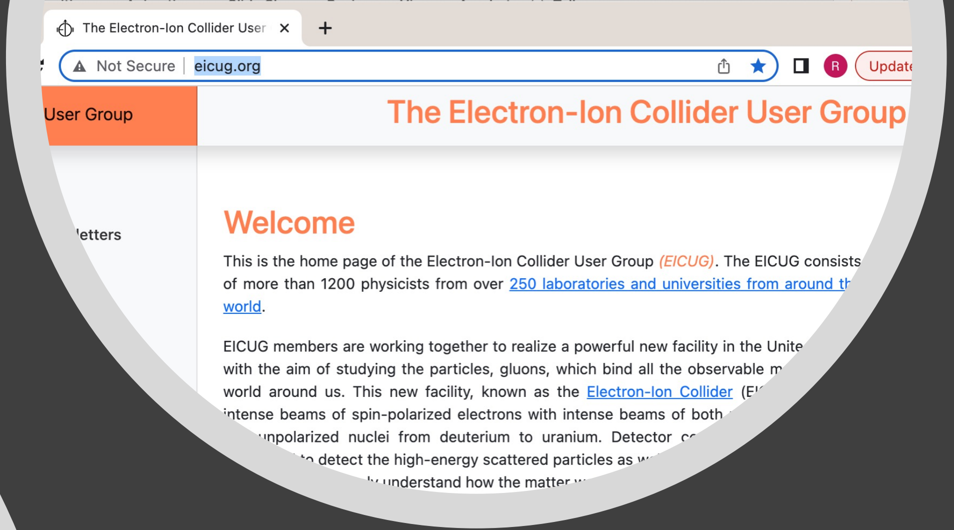


- Community supports a second detector at IP8.
- DPAP Review endorsed this view.
- Important for many reasons
  - Cross-check on discovery results. Historical examples abound …
  - Different designs and technologies leads to different systematic errors and possible overall reduction a'la Zeus and H1.
  - Complementary technologies mitigates risk
  - Allows for optimization for towards different physics focus
  - Provides additional avenues for leadership and creative input
- Realization is trailing Detector I by ~3 years
- DOE is initiating Detector R&D programs to facilitate developing technologies for Detector II and upgrade for detector I

Take Away from Today

- The Electron Ion Collider is the machine we need to tackle some of the most interesting and pressing questions on the QCD frontier.
- The physics program is deep and broad, has been developed for nearly a decade and endorsed by the National Academy of Sciences.
- This year the community took a huge step forward in the selection of the project detector – Detector I – that will be installed at IP6 at RHIC.
- Collaboration formation for Detector I is happening as we speak and finalized detector design planned for the end of the year.
- The community supports a second Detector at IR8 and this effort will start to ramp up this summer at the annual EIC Users Group Meeting.





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!