The Electron-Ion Collider: Tackling QCD from the Inside (of Nucleons and Nuclei) Out

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How do we understand the visible matter in our universe in terms of the quark and gluon degrees of freedom of quantum chromodynamics?

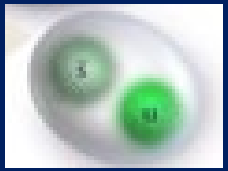
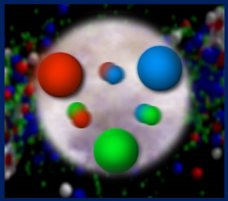
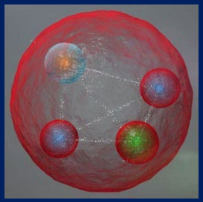
How can studying QCD systems teach us more about fundamental aspects of QCD as a theory?

(One way of dividing up)
Areas of study in QCD

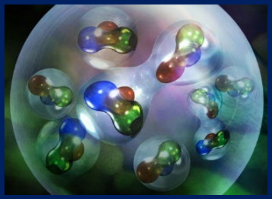
- *Structure/properties* of QCD matter
- *Formation* of states of QCD matter
- *Interactions* within QCD

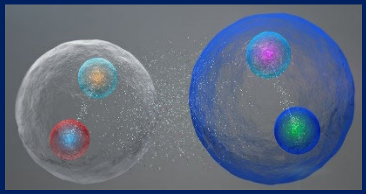
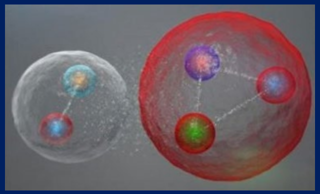
Structure/Properties of QCD matter

- Bound states: Mesons, baryons, also tetraquarks, pentaquarks, sexaquarks?

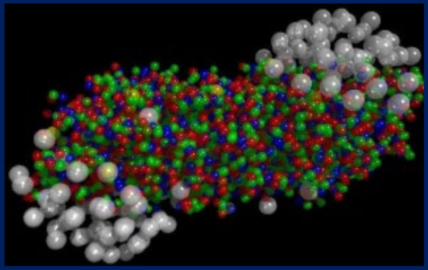





- Bound states of bound states: Nuclei, neutron stars, other hadronic molecules?



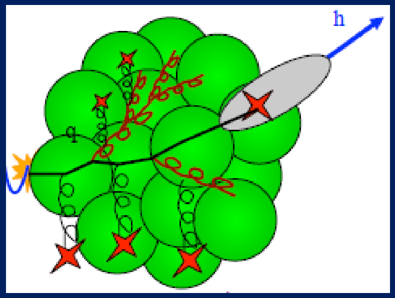



- Deconfined states: Quark-gluon plasma



Formation of states of QCD matter

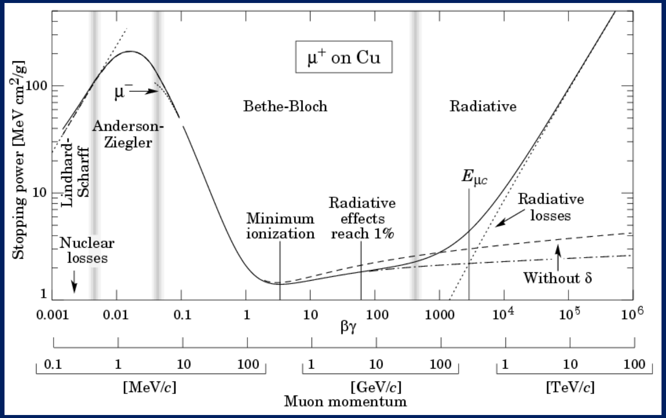
- Bound state formation mechanisms
- Formation of bound states of bound states
- Equilibration of quark-gluon plasma
- Time scales of hadronization/equilibration
- Modification of hadronization in different environments



Knock a quark out of a free proton vs. a nucleus—how is new bound state formation from the scattered quark affected by the presence of the nucleus? Or simply a hadronic environment rather than e+e-?

Interactions within QCD

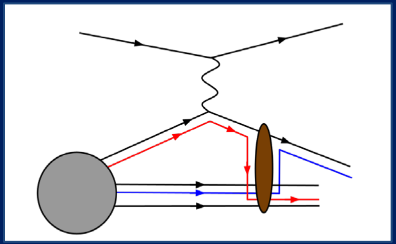
- Quark and gluon energy loss in cold and hot QCD matter
  - What is the analog of the Bethe-Bloch curve for QCD rather than electromagnetism?

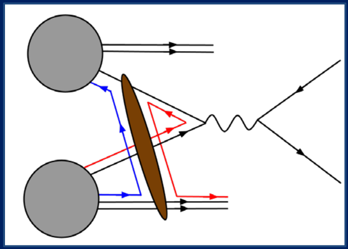


Electromagnetic energy loss of muons passing through copper

- Quantum interference and phase shifts
  - E.g. quantum interference effects in hadronization
    - One quark or gluon → multiple hadrons
    - Multiple quarks or gluons → one hadron

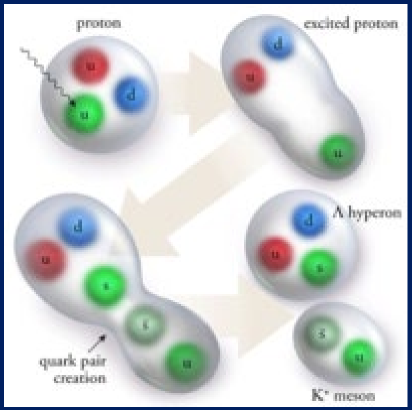
- Color charge flow effects in scattering processes
  - Process-dependent spin-momentum correlations in hadrons
  - Quantum entanglement of quarks across colliding hadrons





Sivers TMD PDF sign change in SIDIS vs. Drell-Yan

Complexity and richness of QCD: Confinement



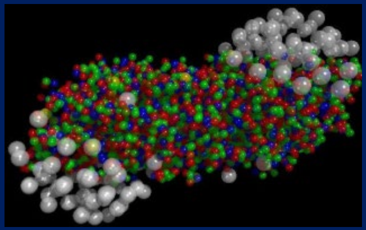
CLAS Collaboration
PRL 113, 152004 (2014)

- QCD theory: Quarks and gluons
- QCD experiment: QCD bound states

- Always an interplay between parton vs. bound-state descriptions, reductionist vs. emergent pictures

High-energy collisions: Tools to study QCD

- Need high (enough) energies to
  - Access subnuclear distance scales
  - Form new states of QCD matter



- High energies also
  - Allow use of perturbative theoretical tools
  - Provide access to new probes, e.g. heavy quarks, Z and W bosons

High-energy collisions: Complementary systems

Can study QCD via

- Hadron-hadron collisions: proton-proton, proton-nucleus, nucleus-nucleus, antiproton-proton, pion-nucleus, …
- Lepton-hadron collisions: e/μ-proton, e/μ-nucleus, ν-nucleus
- Lepton-lepton collisions: e^+-e^- (hadronization)

High-energy collisions: Control

The more aspects of the collisions we can control/manipulate, the more powerful our tools

- Collision species → state of matter to be studied, geometry, path length, quark flavor/isospin, electroweak vs. strong interactions
- Energy → distance/time scales, probes accessible, states of matter
- Polarization → spin-spin and spin-momentum correlations in QCD systems or in hadronization, sensitivity to system properties

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Some aspects we *select* rather than control

- Overlap of colliding nuclei, final-state produced particles and their kinematics, …

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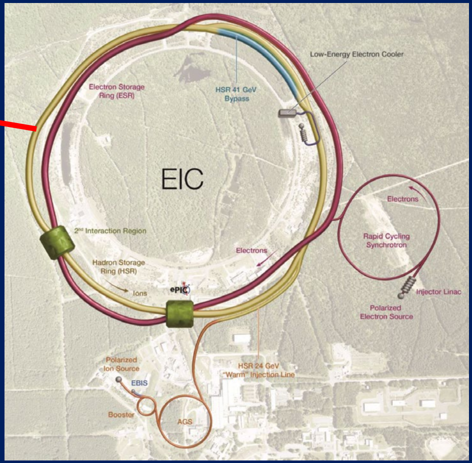
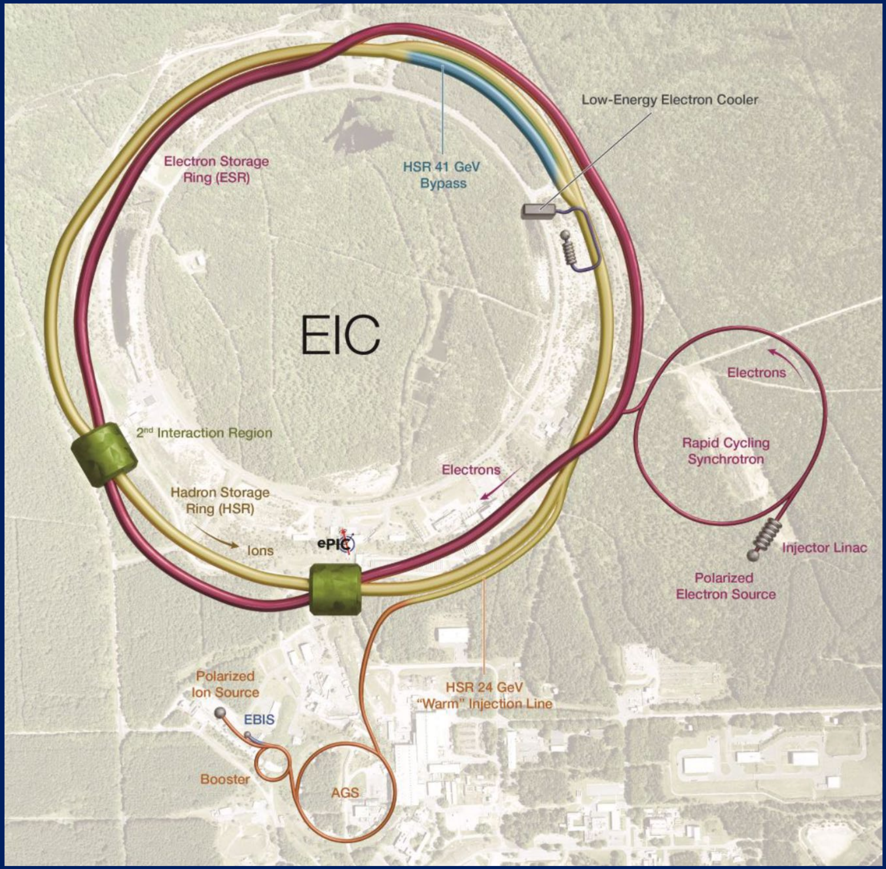
The Electron-Ion Collider

A joint endeavor by Thomas Jefferson National Accelerator Facility and Brookhaven National Lab



The Electron-Ion Collider

- Highly polarized electron (~70%) and proton (~70%) beams
- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium
- Variable $e + p$ center-of-mass energies from 28-140 GeV
- $e + p$ luminosity $10^{33} - 10^{34}$ cm^{-2} s^{-1}



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- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium
  - Including polarized ^{3}He and possibilities for polarized deuterons!
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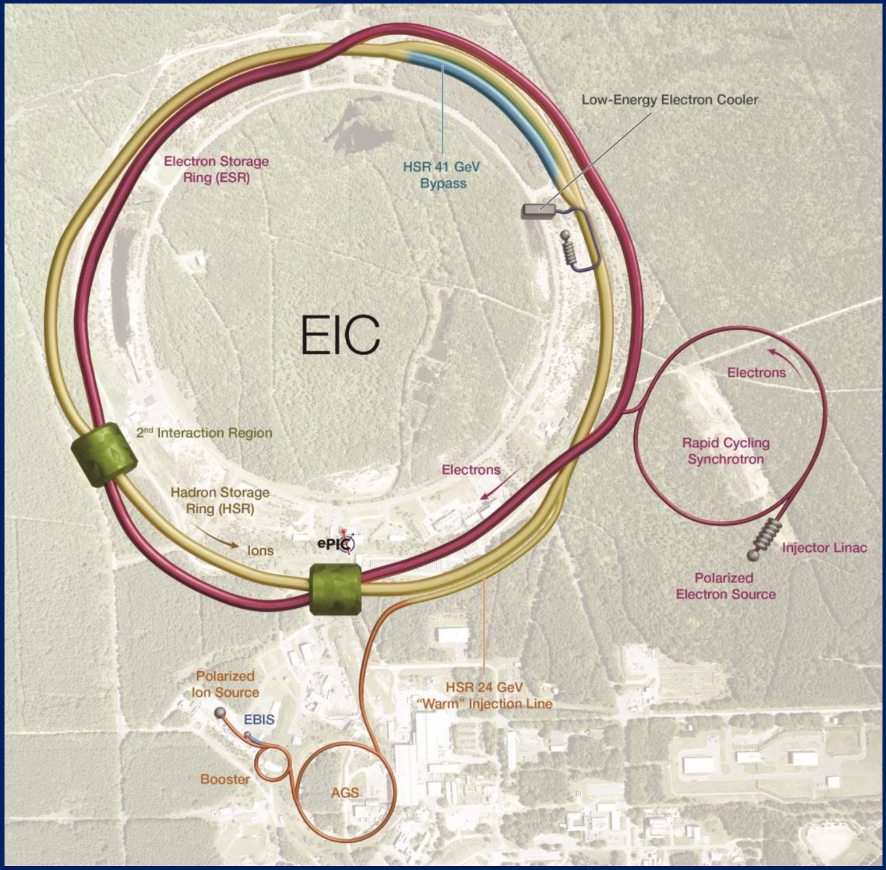


A physics program attracting world-wide interest

www.eicug.org

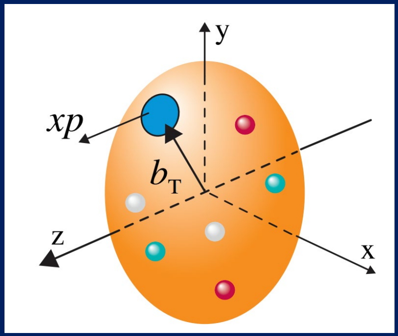
- EIC User Group formed in 2016. Has grown tremendously in recent years.

Electron-Ion Collider User Group:
Currently >1500 members from 303 institutions in 40 countries.
(~25% theorists, ~10% accelerator physicists, ~65% experimentalists)

The EIC science program

- How do the nucleon properties like mass and spin emerge from quarks and their interactions?

- How are the sea quarks and gluons distributed in space and momentum inside the nucleon? How is spin dynamically generated?



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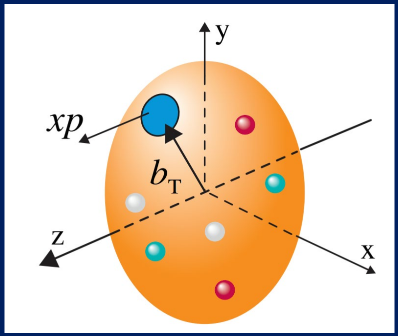

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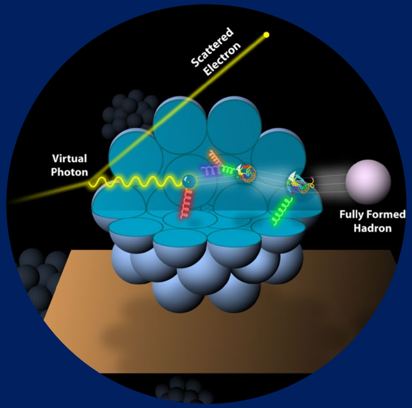

- How do new confined hadronic states emerge after the breakup of a nucleon?
- In what manner do color-charged quarks and gluons, along with colorless jets, interact with the nuclear medium?
- What impact does a high-density nuclear environment have on the interactions, correlations, and behaviors of quarks and gluons?

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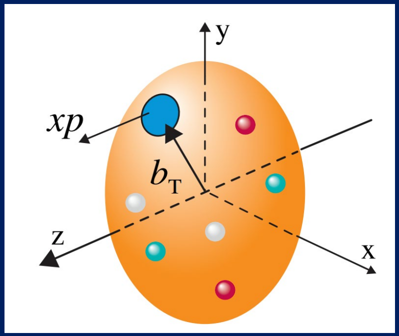

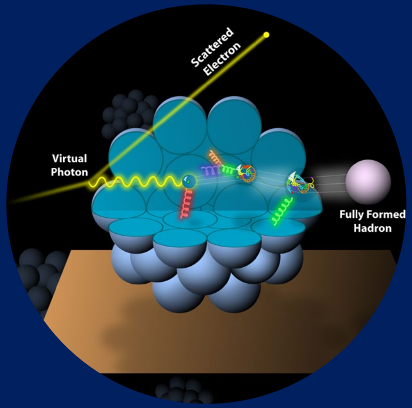

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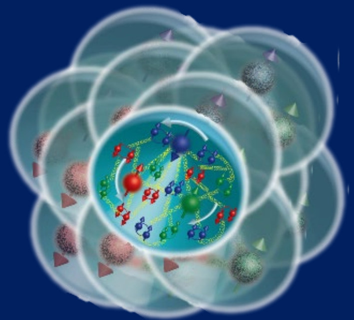
- What impact does a high-density nuclear environment have on the interactions, correlations, and behaviors of quarks and gluons?

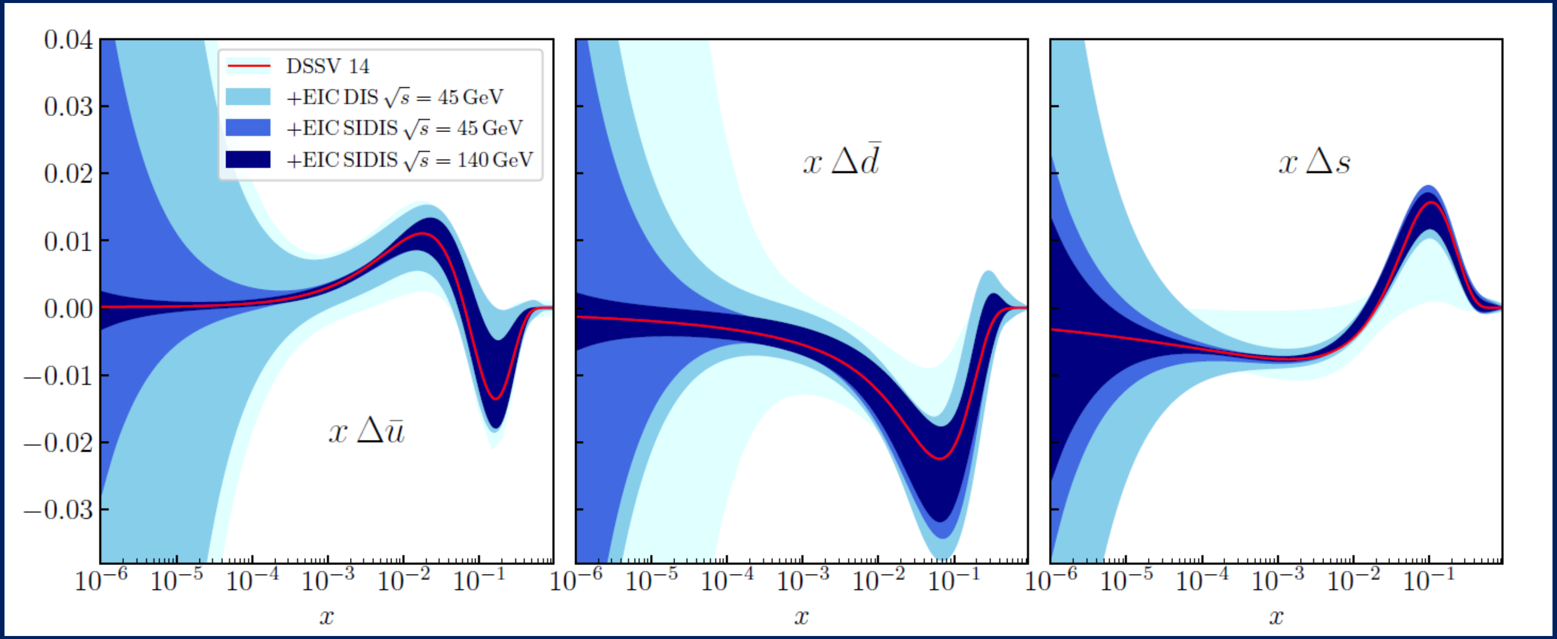
- What is the mechanism through which quark-gluon interactions give rise to nuclear binding?

- Is there a saturation point for the density of gluons in nuclei at high energies, and does this lead to the formation of gluonic matter with universal properties across all nuclei, including the proton?



EIC: Improving the flavor-separated helicity distributions of the proton sea through SIDIS

PRD102, 094018 (2020)
DSSV14: PRL113, 012001 (2014)



Access flavor through SIDIS measurements of identified charged pions and kaons.

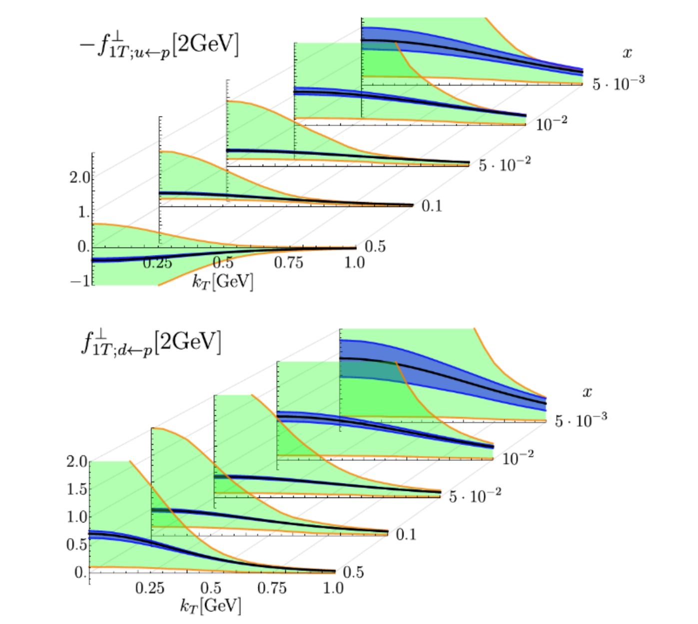
Current treatment of strangeness assumes $\Delta s = \Delta\bar{s}$ and incorporates constraints from hyperon β decay. In the future could use positive and negative kaons to separate Δs and $\Delta\bar{s}$.

EIC: Transverse spin structure of the proton and TMD PDFs and FFs

Yellow Report : 2103.05419

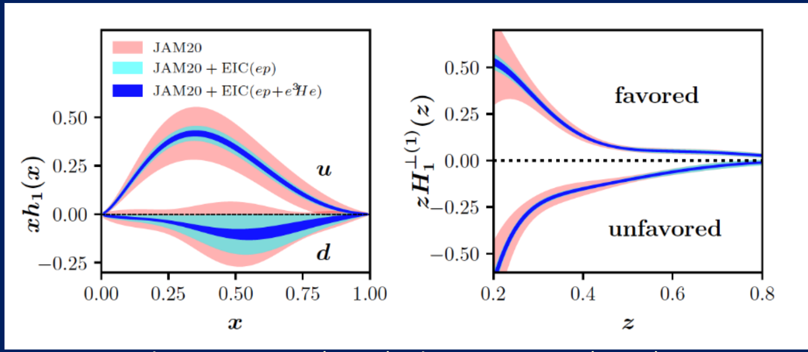
Sivers TMD PDF x unpolarized FF

- 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 > ×10 for all flavors.
- Wide range of hadron p_T facilitates k_T mapping



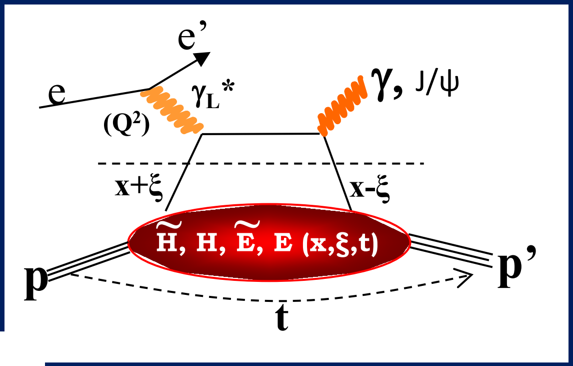
Transversity PDF x Collins TMD FF

- 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 He^3 beams



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

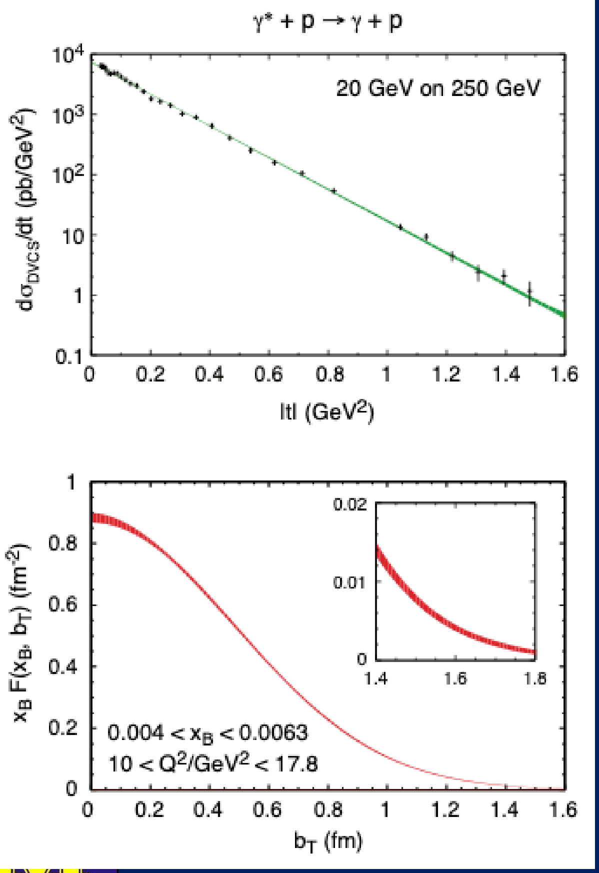
EIC: 2+1D imaging in coordinate space

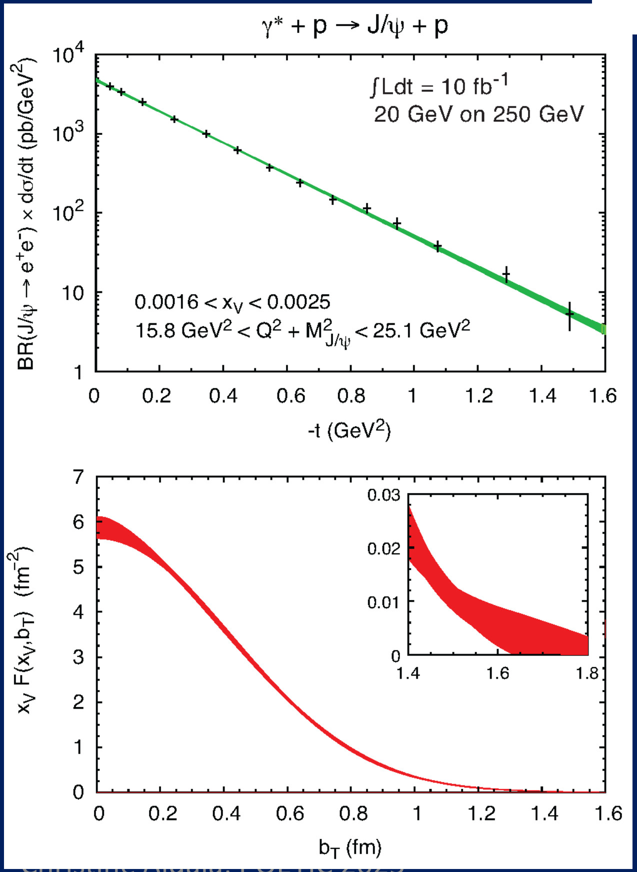


High precision imaging at EIC at low and high *x* to constrain generalized parton distributions (GPDs)

DVCS

J/ψ





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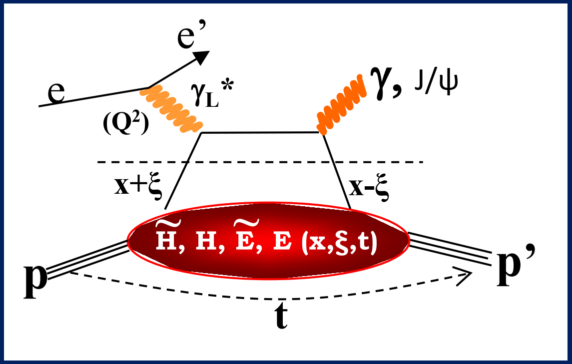

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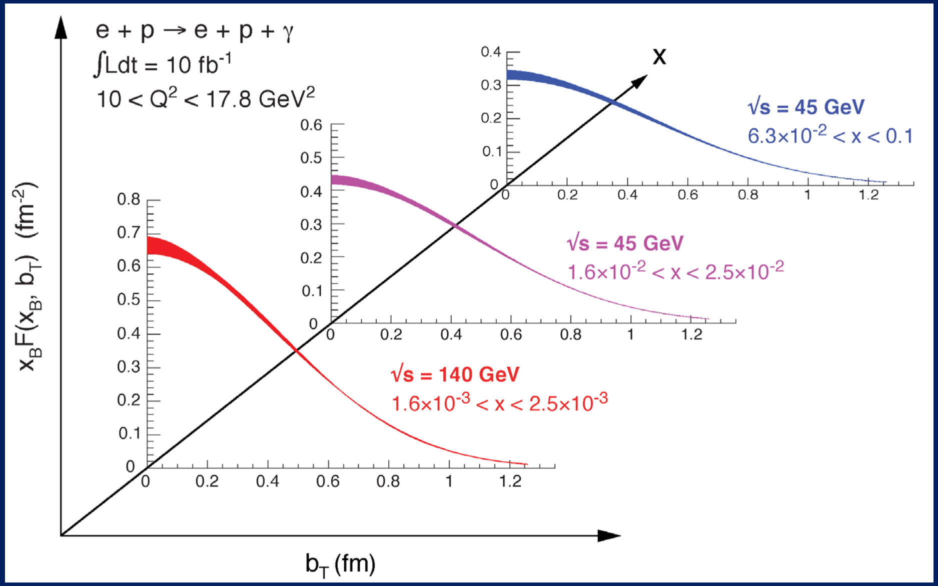

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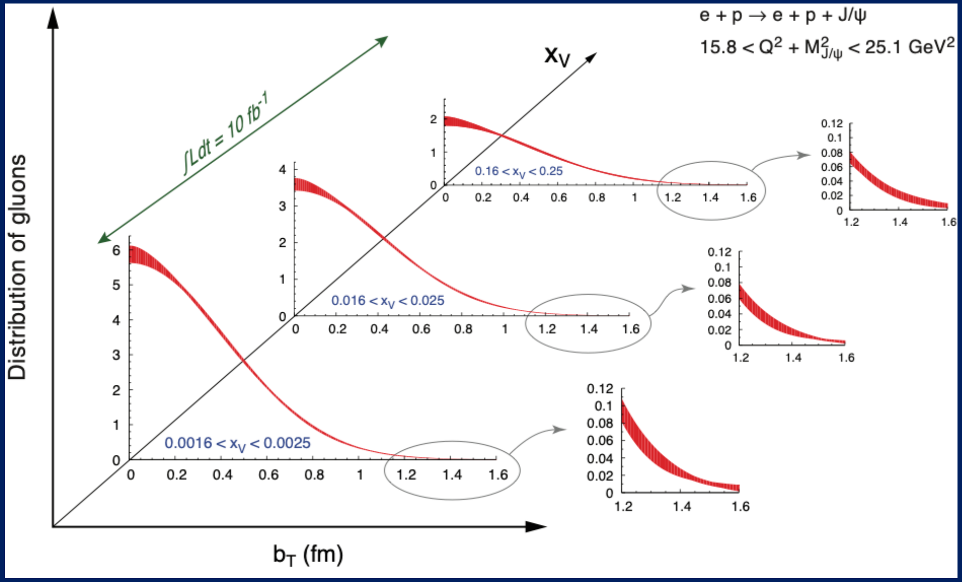
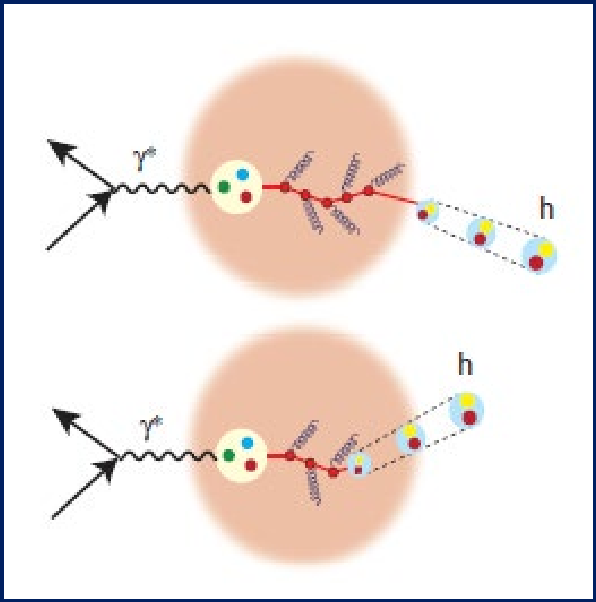


Formation of QCD bound states: Hadronization at EIC

- Use nuclei as femtometer-scale detectors of the hadronization process!
- Wide range of scattered parton energy; small to large nuclei
  - Move hadronization inside/outside nucleus
  - Distinguish energy loss and attenuation



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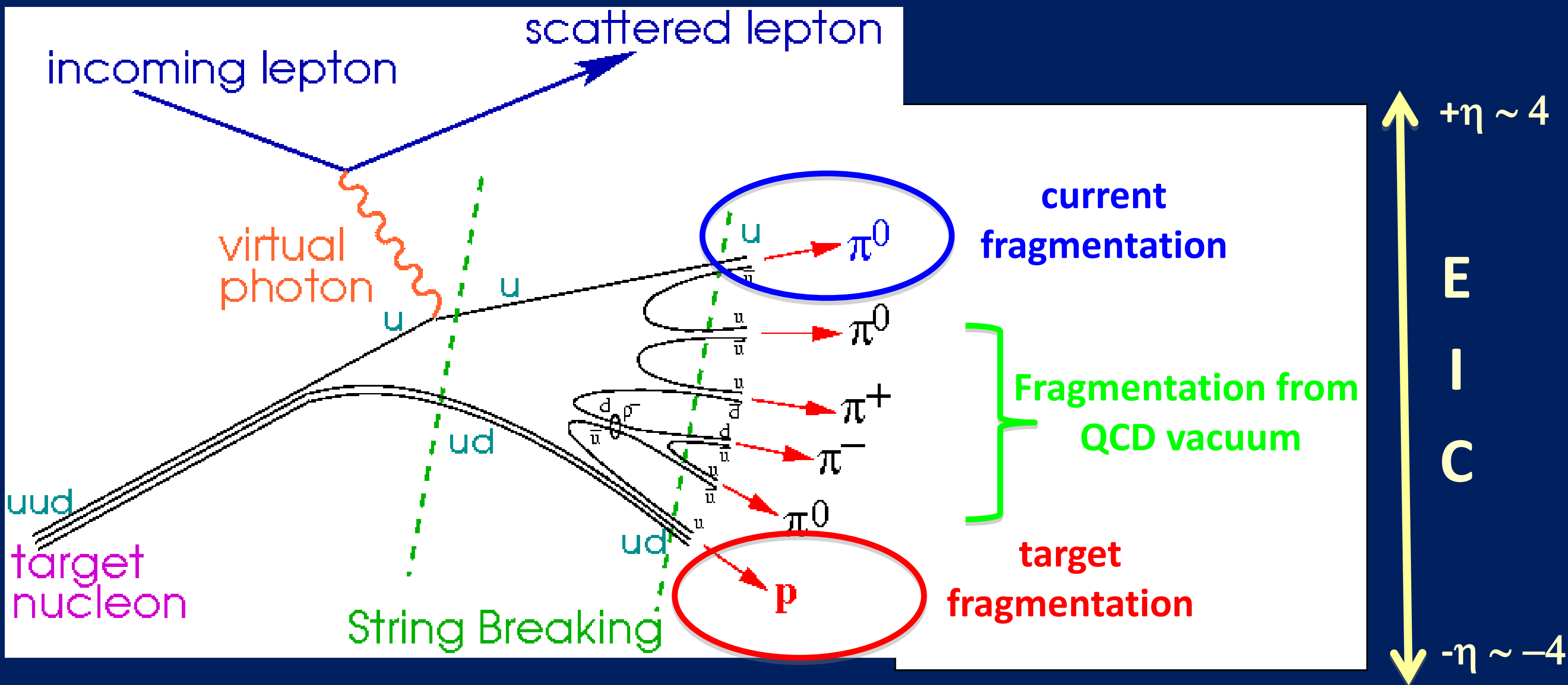
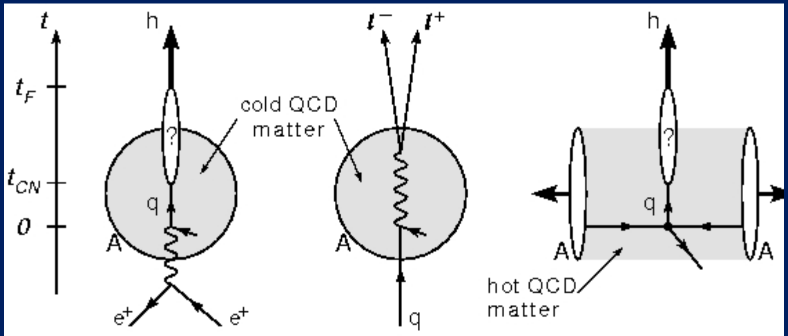
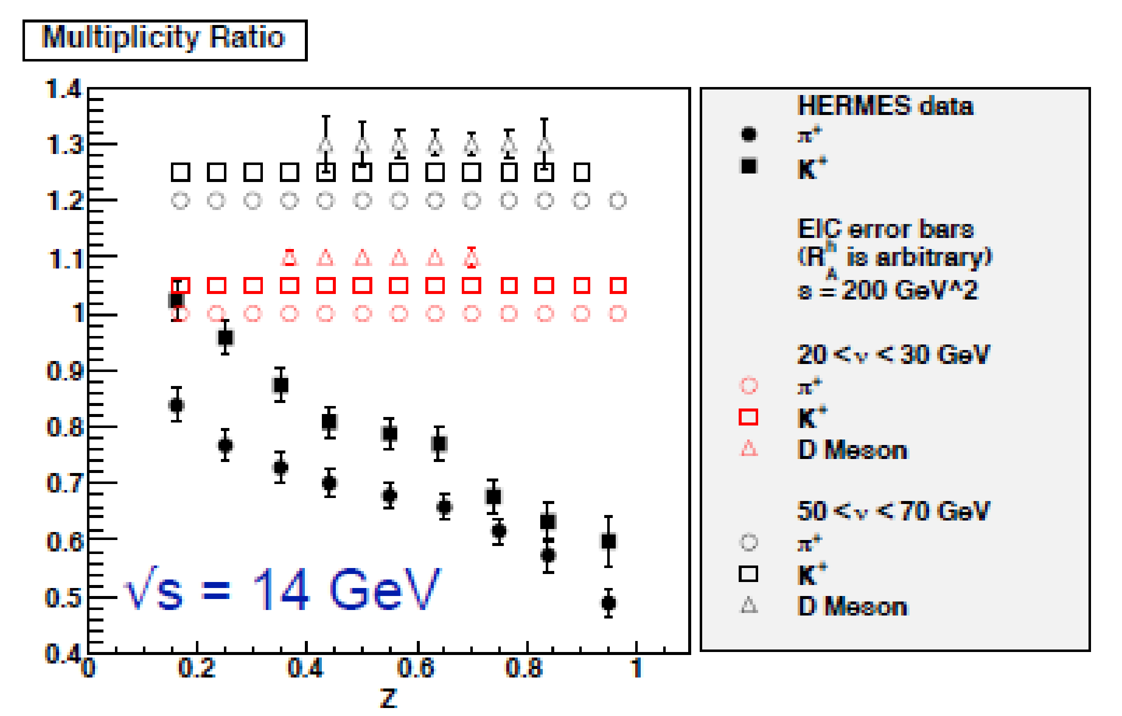


With a leptonic probe and collider geometry, will have unprecedented opportunities to cleanly study the target fragmentation region and correlated hadron production across regions

EIC: Hadronization and parton propagation in matter



- Interaction of fast color charges with matter?
- Conversion of color charge to hadrons?



Existing data → hadron production modified on nuclei compared to the nucleon!

EIC will provide ample statistics and much greater kinematic coverage.

-Study time scales for color neutralization and hadron formation

- e+A complementary to jets in A+A: cold vs. hot matter

Continued theory progress will be critical!

- Theoretical advancements offer new tools and new insights, with the power to shift—drastically or subtly—the way we think about the physics we study

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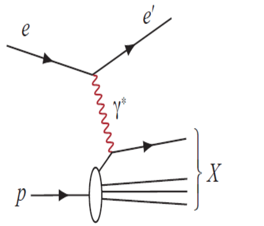
- E.g. recent advances/developments in
  - Lattice QCD
  - Higher-order calculations for different processes (N^nLO, N^nLL', higher-twist,…)
  - Heavy flavor jet tagging algorithms
  - Energy-momentum tensor of the nucleon
  - Techniques for phenomenological extraction of (TMD) PDFs, fragmentation functions, GPDs, . . .
  - Energy correlators
  - Incorporating more first-principles QCD into MC event generators
  - Quantum computing toward quantum simulations of QCD physics
  - …

Translating physics requirements to detector requirements

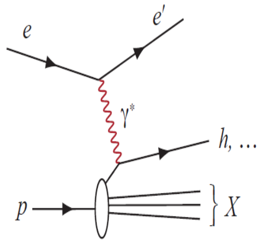
REQUIREMENTS →

ePIC detector

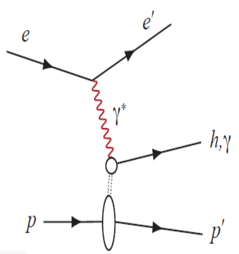
Measurement categories to address EIC physics:



- Inclusive DIS
  - fine multi-dimensional binning in x, Q^2



- Semi-inclusive DIS
  - 5-dimensional binning in x, Q^2, z, p_T, θ



- Exclusive processes
  - 4-dimensional binning in x, Q^2, t, θ to reach |t| > 1 GeV2

- *Large coverage ($-4<\eta<4$) for wide phase-space reach*
- *Excellent EM-calorimetry with PID support for e/π separation*
- *Fine resolution tracking with low mass*

- *Fine p_T resolution*
- *Extended PID systems for hadron identification*
- *H-calorimetry to perform TMD measurements with jets*

- *Extend acceptance at extremely small scattering angles by far forward detectors*
- *Fine vertex resolution by tracking*

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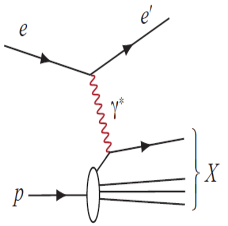

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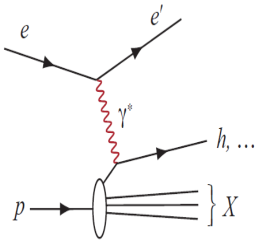

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A 2nd interaction region and detector have long been envisioned as part of a robust program at the EIC facility, enabling complementary opportunities.

Not just QCD!

- While the facility design is driven by QCD, we should exploit all physics opportunities within reach!
  - See talks on Beyond-the-Standard-Model physics Tuesday
  - Interdisciplinary and cross-cutting connections
  - …

Conclusions

- The EIC will be a beautiful and flexible facility for controlled manipulation of QCD systems!

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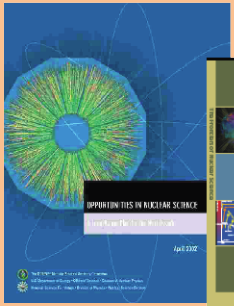
The more we learn in the upcoming years from theoretical developments as well as existing and near-term data from complementary facilities, the more fully we will be able to exploit the EIC's powerful and unique capabilities once it turns on!

Extra

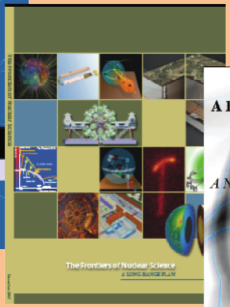
EIC science case developed over more than two decades

2002



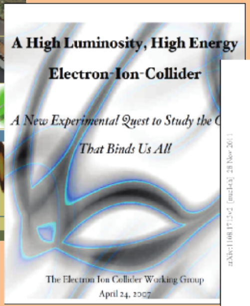
"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

2007



"We recommend the allocation of resources …to lay the foundation for a polarized Eletron-Ion Collider…"

2009

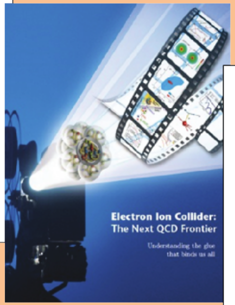


"..a new dedicated facility will be essential for answering some of the most central questions."

2010

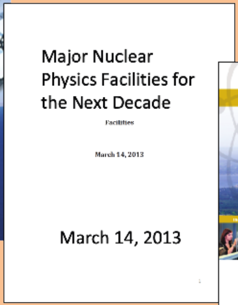
"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

2012



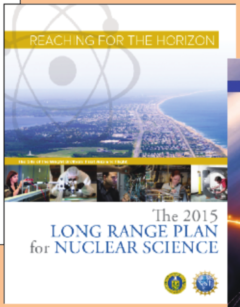
"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

2013



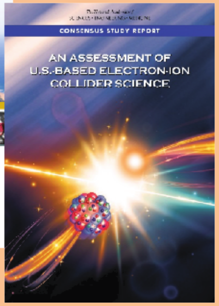
"Electron-Ion Collider..absolutely central to the nuclear science program of the next decade."

2015



"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

2018



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."

Maximizing the scientific output of the EIC: A second detector at IP8

Paradigm shifts require cross-checks and verification!

Historical examples in QCD	
Discovery of the Gluon	TASSO, JADE, Mark J and PLUTO
Gluon dominance at low-x	H1 and ZEUS
Discovery of the Quark-Gluon Plasma	BRAHMS, PHOBOS, PHENIX and STAR
Proton spin puzzle	EMC, SMC and SLAC
First parton imaging measurements	COMPASS, HERMES and JLAB
EMC Effect	EMC, NMC and SLAC

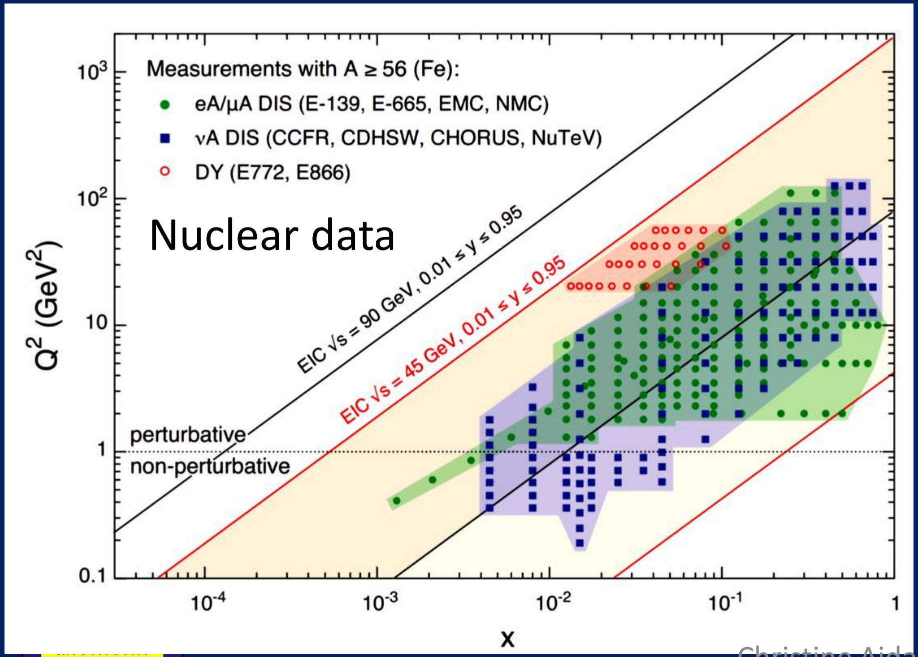
The EIC will be a unique facility, dedicated to *precision* QCD measurements. It will be difficult, to impossible, for other existing or planned facilities to confirm or explore the same physics.

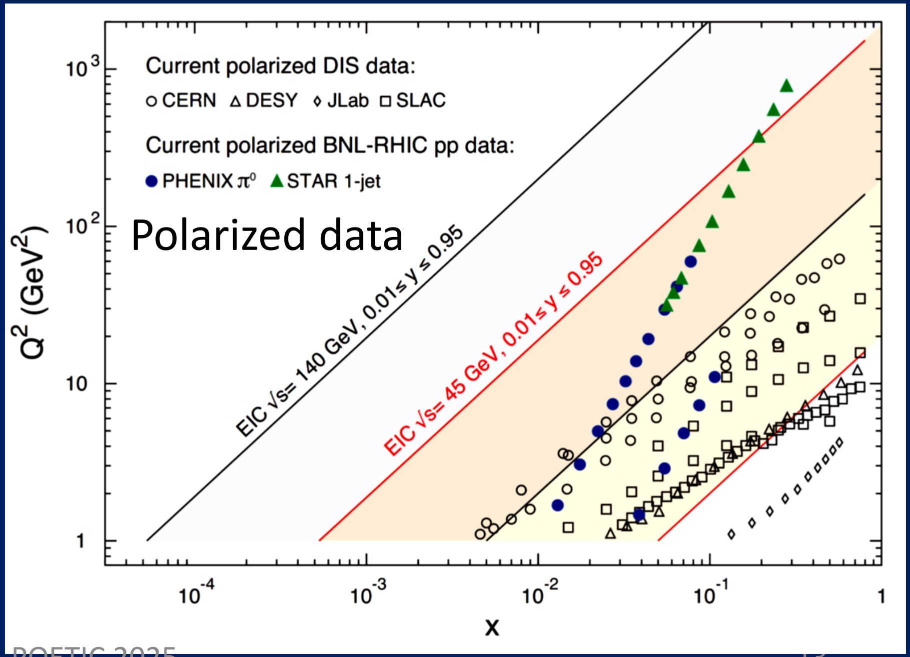
Cross-checks and Verification

A 2nd detector requires a 2nd collaboration that will bring with it independent analysis frameworks and ideas. Healthy competition encourages efficiency and accountability.

Going beyond previous facility capabilities

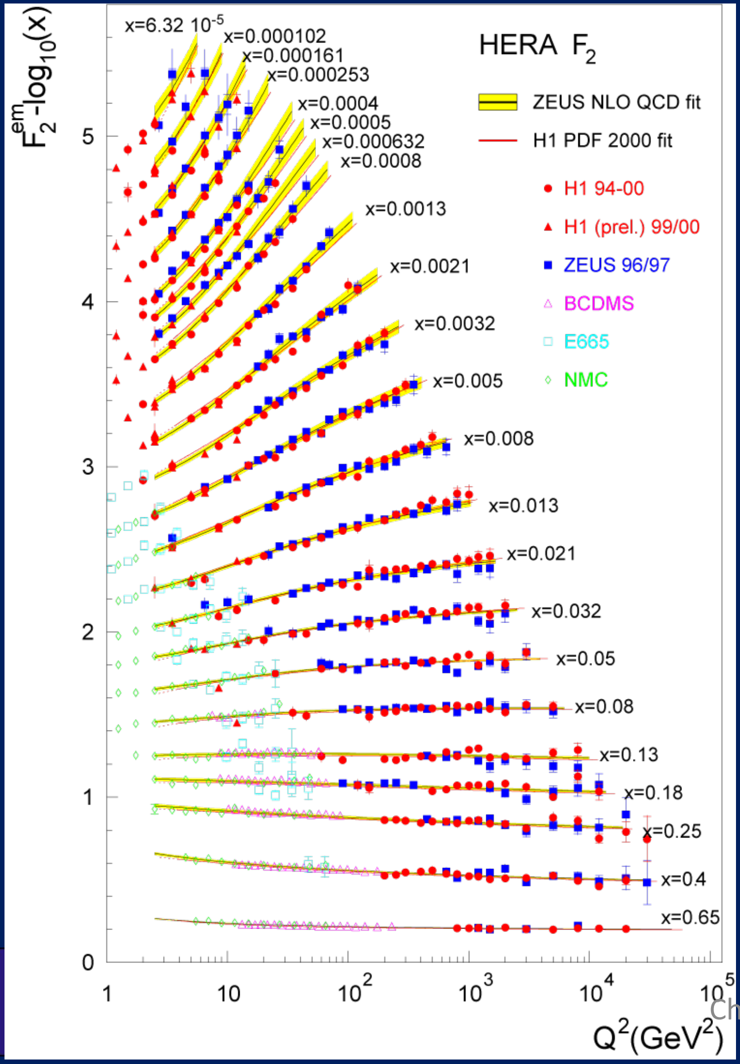
- Beams of light → heavy ions
  - Previously only fixed-target e+A experiments
- *Polarized* beams of p, d/He^3
  - Previously only fixed-target polarized experiments





Accessing gluons with an electroweak probe

$$\text{DIS}: \quad \frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$



Access the gluons in DIS via scaling violations:

$dF_2/d\ln Q^2$ and linear DGLAP evolution in Q^2 → $G(x,Q^2)$

OR

Via F_L structure function

OR

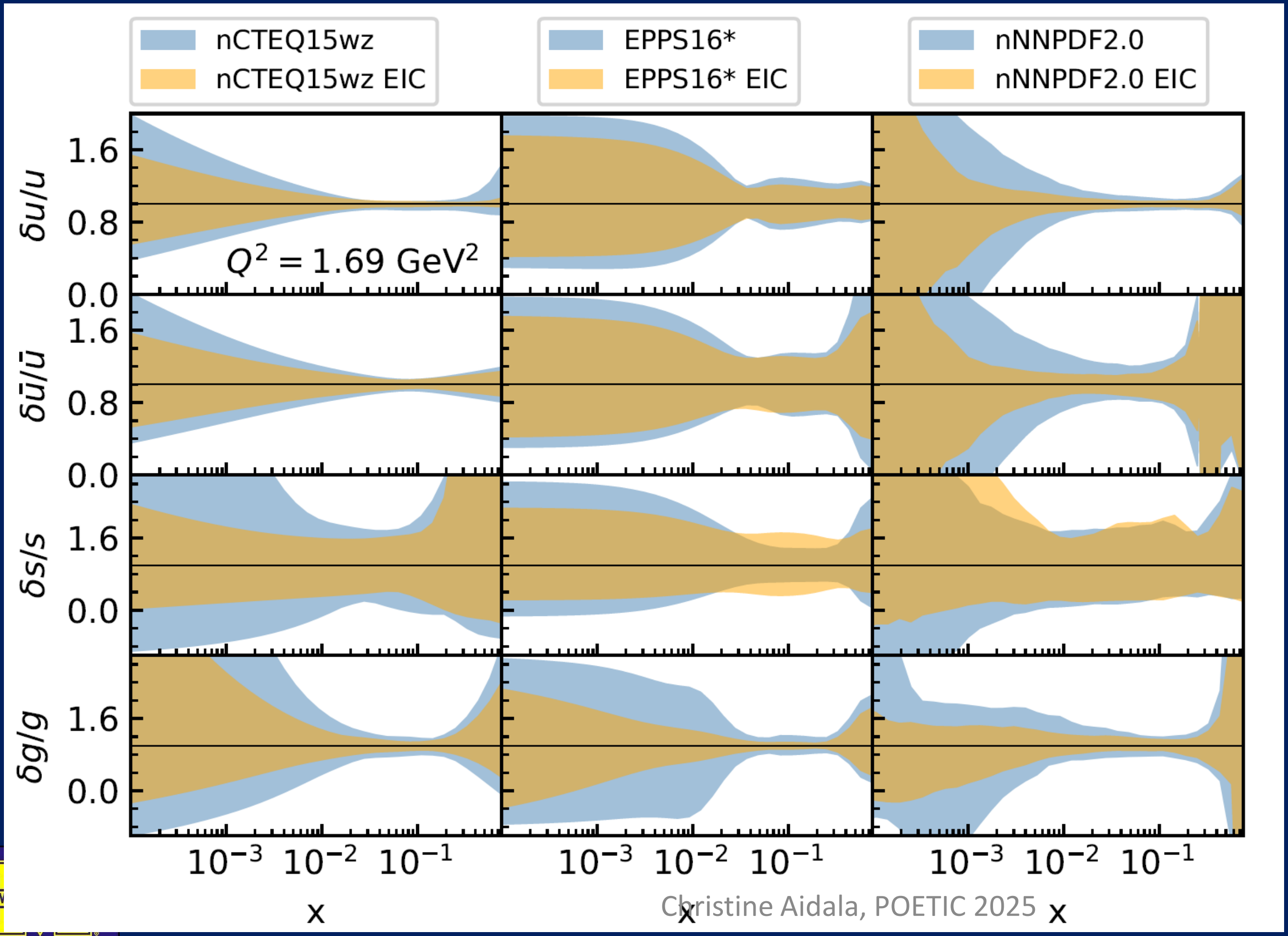
Via dihadron production

OR

Via diffractive scattering

Partonic momentum structure of nuclei: Nuclear parton distribution functions

(Traditional collinear, unpolarized) Nuclear PDFs

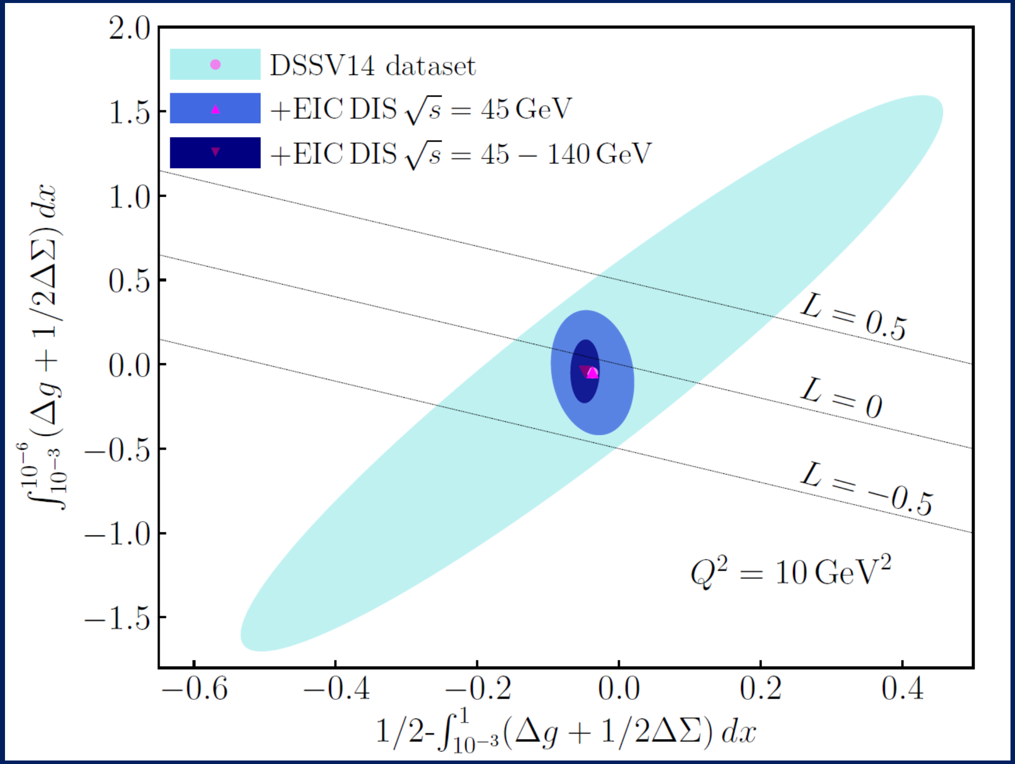


Expected improvement on uncertainty in nuclear PDFs - from Yellow Report

Yellow Report : 2103.05419

EIC: Spin sum rule, low-x contributions, and orbital angular momentum

PRD102, 094018 (2020)
DSSV14: PRL113, 012001 (2014)

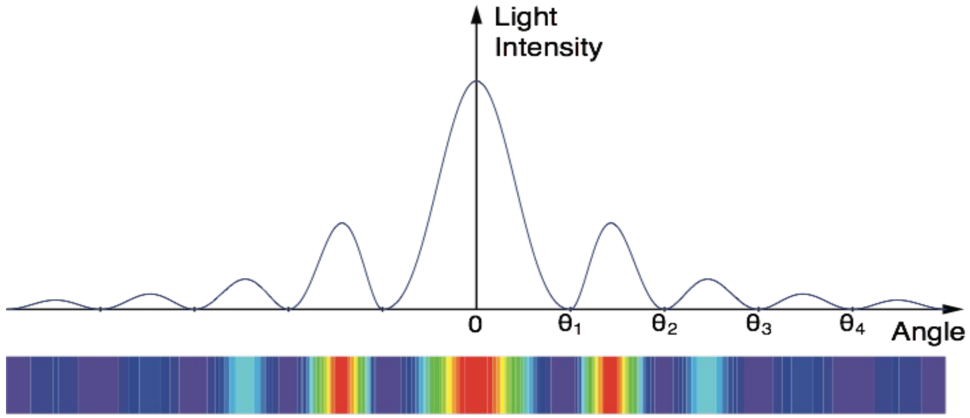


Note different horizontal and vertical axis scales!

- Current polarized data cover $x > \sim 10^{-3}$
- Could there be significant spin contributions for $10^{-6} < x < 10^{-3}$?
- EIC data for Δg at low x will significantly improve uncertainty on the total quark and gluon contributions to proton spin
- Remainder must be orbital angular momentum!

Imaging spatial structure of quarks in nuclei: Diffraction

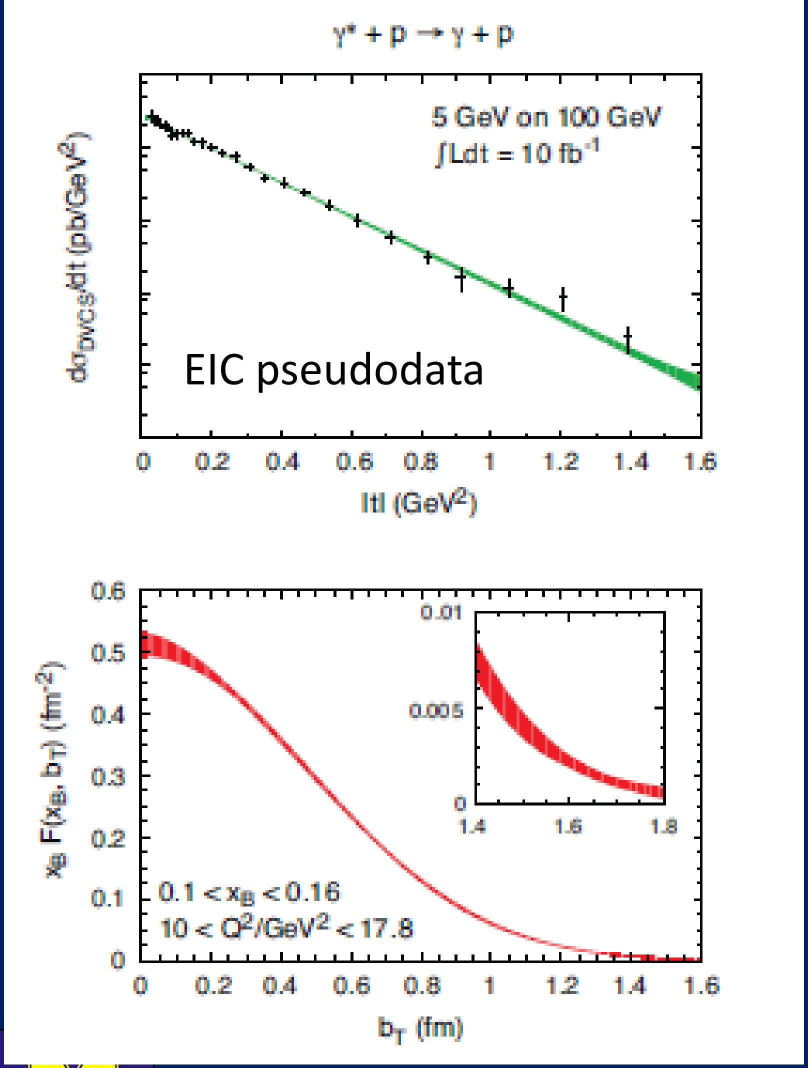
Diffraction pattern from monochromatic plane wave incident on a circular screen of fixed radius

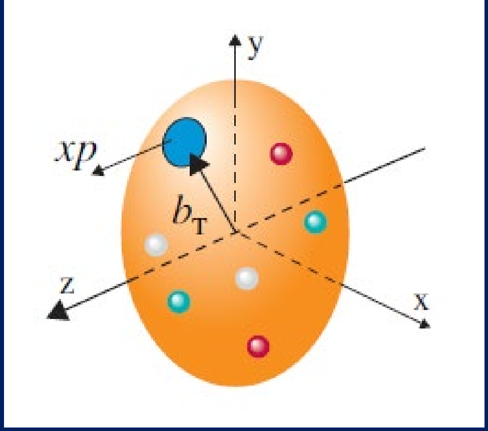


From E. Aschenauer

- X-ray diffraction used to probe spatial structure of atomic crystal lattices
  - Measure in momentum space, Fourier transform to position space
- Nuclear distance scales → Need gamma ray diffraction!
  - Again measure diffractive cross section in momentum space (Mandelstam t), Fourier transform to position space

Partonic spatial structure of nuclei: Diffraction





Goal: Cover wide range in *t*.
Fourier transform → impact-parameter-space profiles.
Obtain *b* profile from slope vs. *t*.

Note: To probe spatial distributions, can also use Bose-Einstein correlations (HBT) in e+A to probe spatial extent of particle production region, as in hadron-hadron collisions

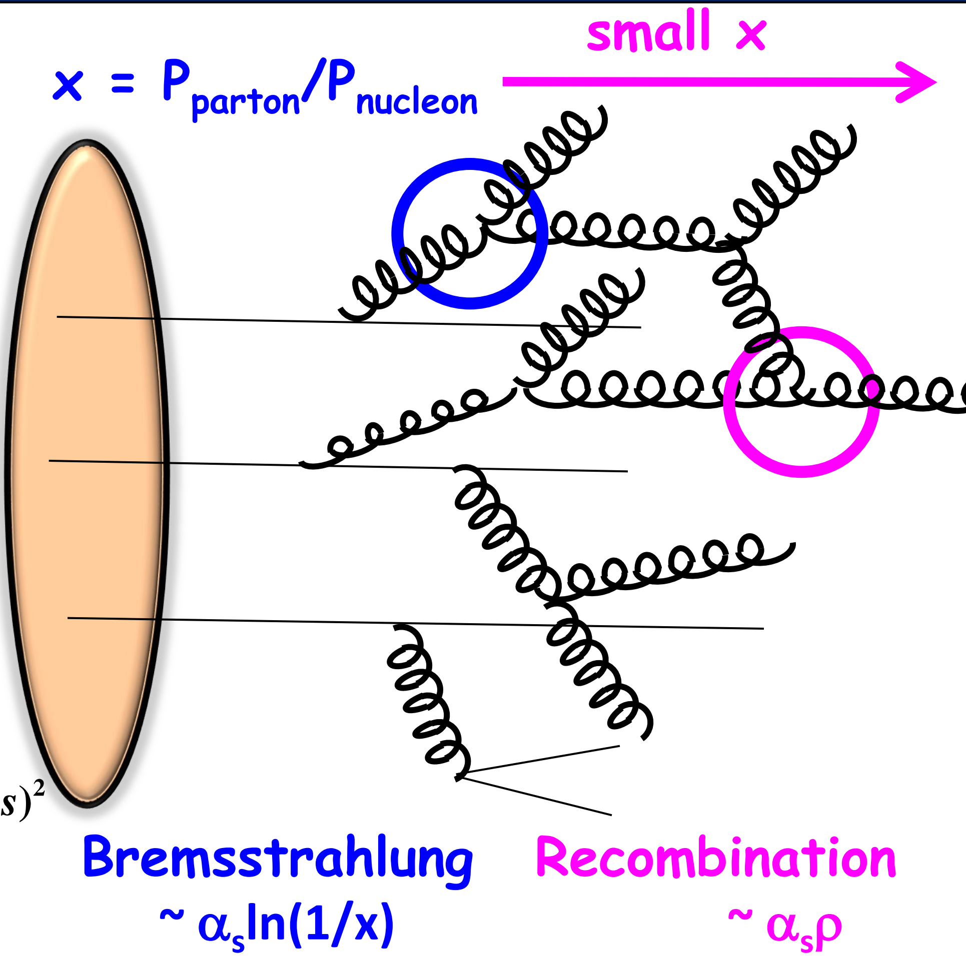
Gluon saturation

At small x linear evolution gives strongly rising g(x) – but must be bounded!

BK/JIMWLK non-linear evolution includes recombination effects → saturation

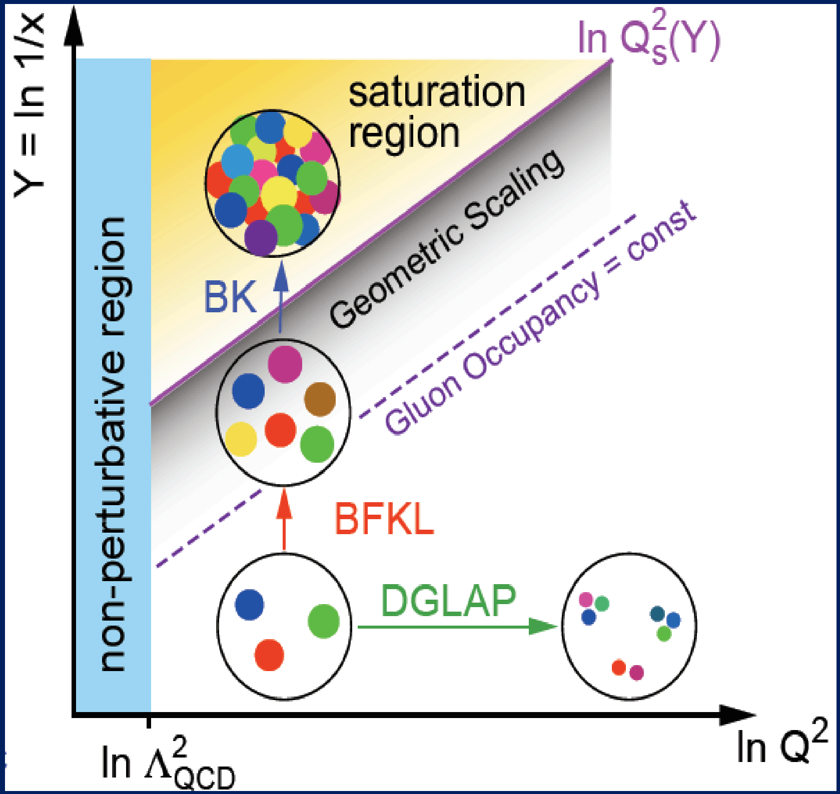
- Dynamically generated scale
  Saturation Scale: $Q^2_s(x)$
  - Increases with energy or decreasing x
- Scale with $Q^2/Q^2_s(x)$ instead of x and Q^2 separately

$$\sigma_{tot} = \frac{\pi}{m_\pi^2}(\ln s)^2$$

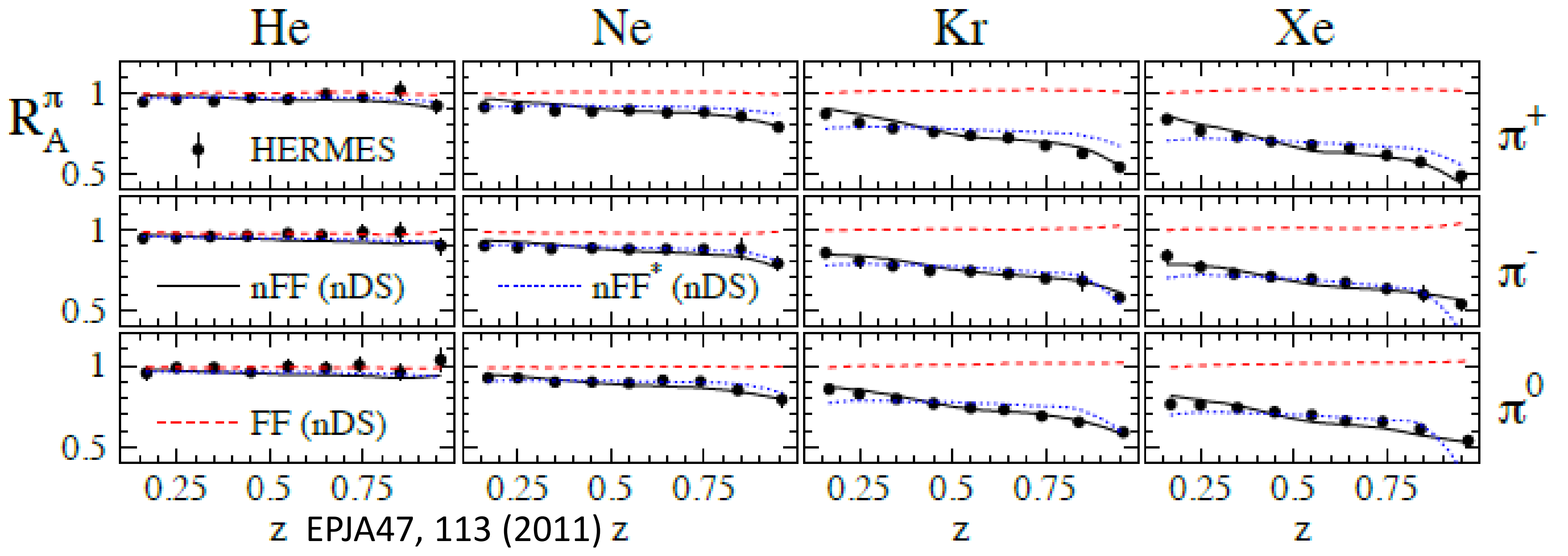


Diffraction to study universal state of gluonic matter: Gluon saturation

- In addition to probing spatial structure, diffraction is one way to probe gluon saturation within nuclei



Formation of QCD bound states: Nuclear modification of fragmentation functions

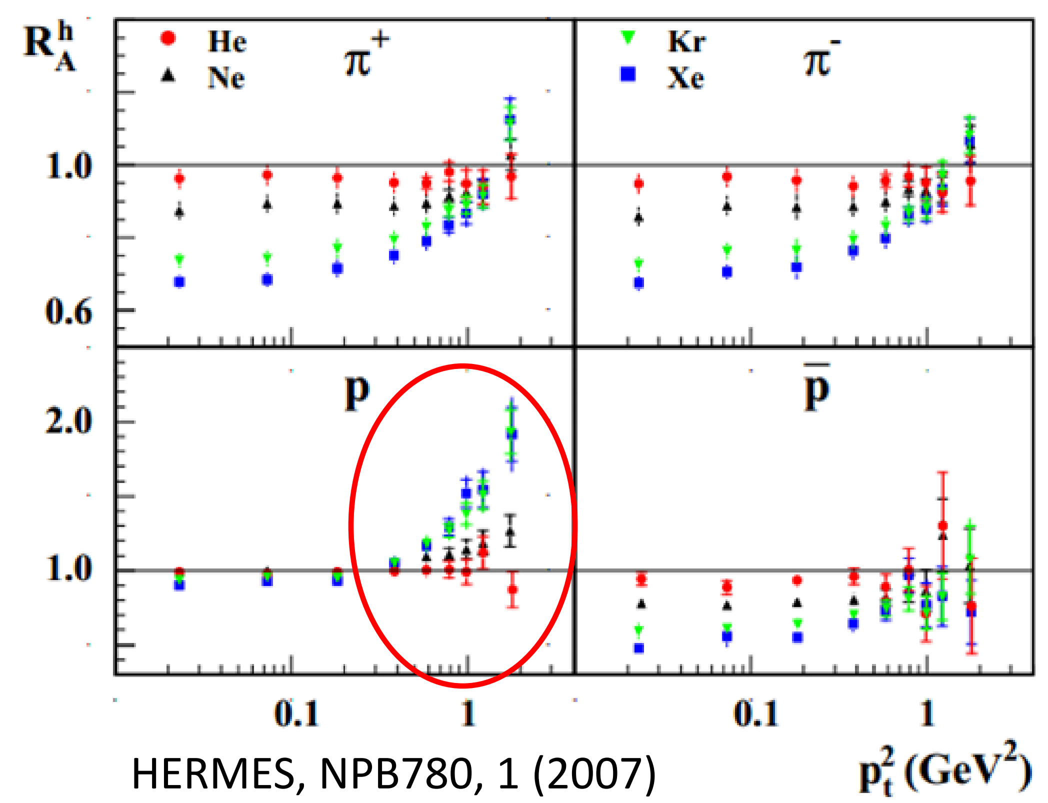


EPJA47, 113 (2011)

As in A+A and p+A, fragmentation functions are modified in e+A with respect to e+p, e.g. suppression of pion production

Formation of QCD bound states: Hadronization in higher-density partonic environments

- Evidence for baryon enhancement also in e+A!
- Baryon enhancement in A+A, p+A, e+A suggests mechanism(s) other than "vacuum fragmentation"
- Binding of nearby partons in phase space?

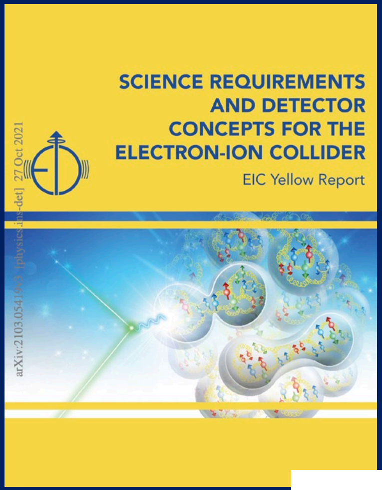


HERMES, NPB780, 1 (2007)

Comprehensive studies of hadronization as well as of propagation of color charges through nuclei possible at EIC

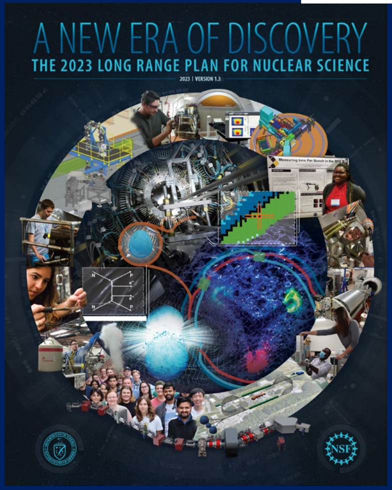
Building the experimental program

- Development of EIC Yellow Report 2020
  - Detector and machine design parameters driven by physics objectives



- Subsequent call for proposals and review process 2021-22 led to establishment of ePIC Collaboration, with charter ratified in Feb 2023

- Oct 2023: EIC/ePIC endorsed as highest priority for new facility construction in the U.S. Long Range Plan for Nuclear Science



Maximizing the scientific output of the EIC: A second detector at IP8

- At this time the EIC project supports only one interaction region (IP6) and one detector (ePIC).
- A deliverable of the EIC project is the *possibility* of a second interaction region and detector at IP8.
- Significant external funding required before Dept. of Energy would consider any additional commitments to a 2nd Detector.
- A 2nd interaction region and detector has long been envisioned as part of a robust program at the EIC facility.