Nucleon Structure and the Electron-Ion Collider

Lecture 2: Exploring Color Flow in Hadronic Interactions, and the Electron-Ion Collider

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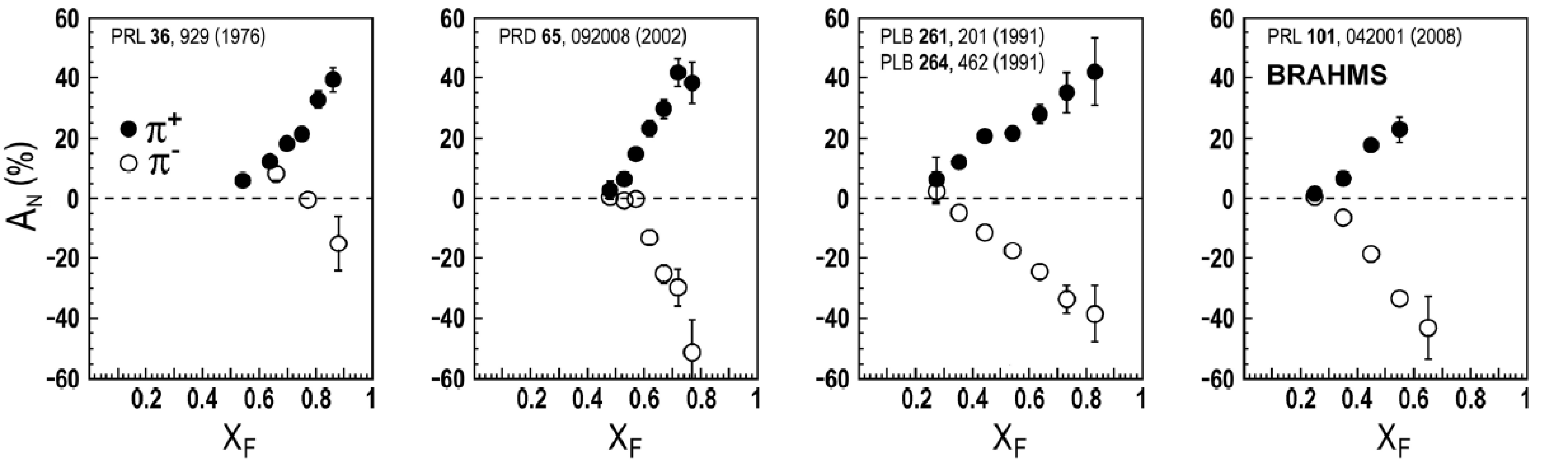
University of Michigan

GRK Retreat
September 11, 2018

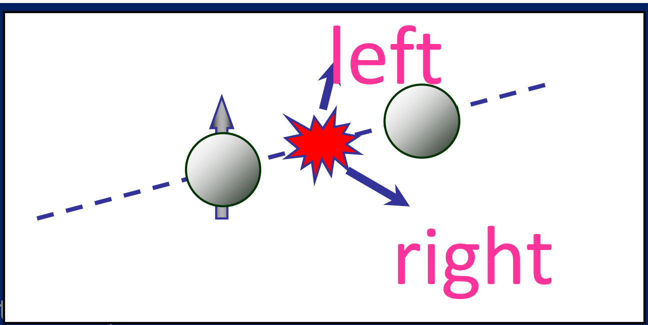
Back to those huge spin-momentum correlations in proton-proton collisions…

ANL	BNL	FNAL	RHIC
$\sqrt{s}$=4.9 GeV	$\sqrt{s}$=6.6 GeV	$\sqrt{s}$=19.4 GeV	$\sqrt{s}$=62.4 GeV



Aidala, Bass, Hasch, Mallot, RMP 85, 655 (2013)

$$x_F = 2p_{long} / \sqrt{s}$$



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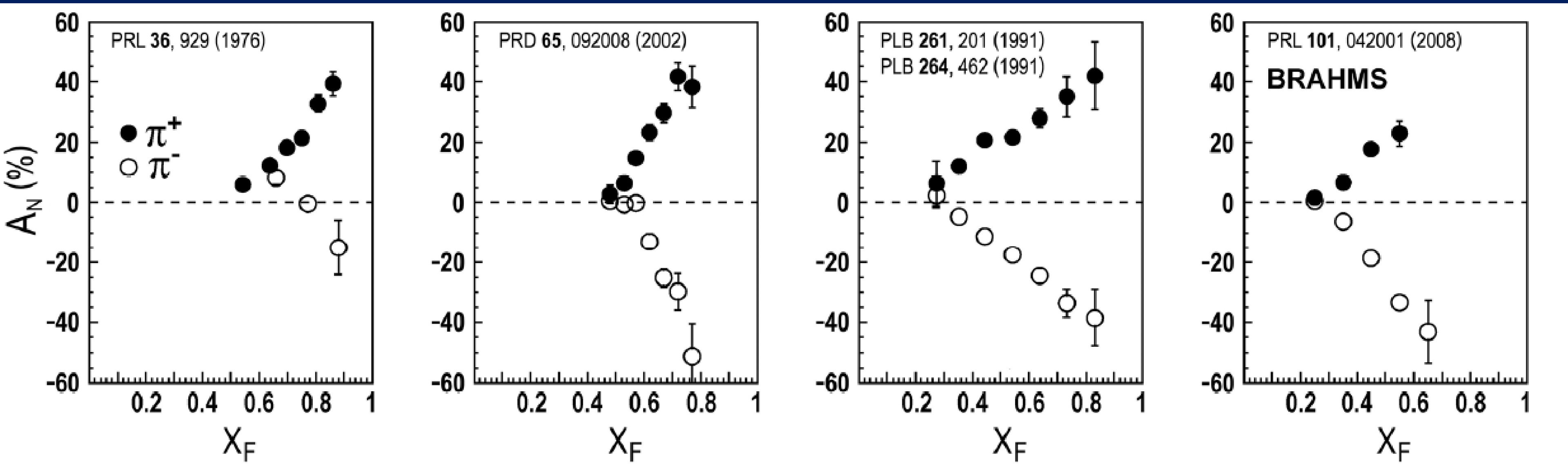
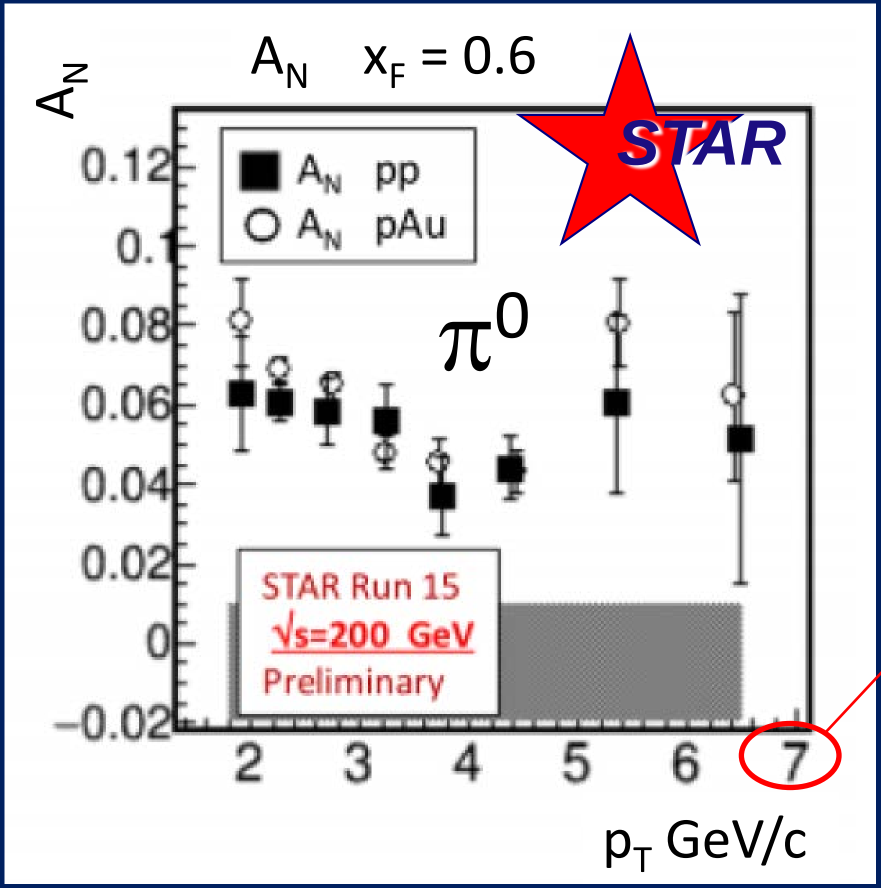
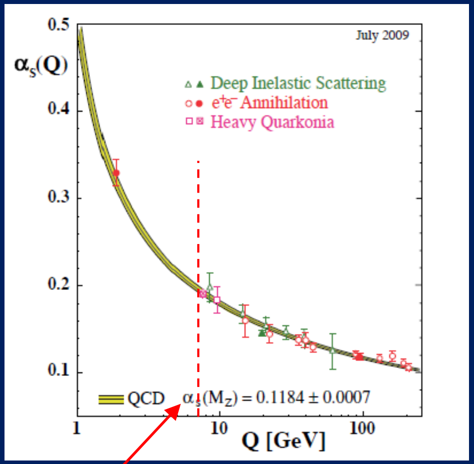


Ai

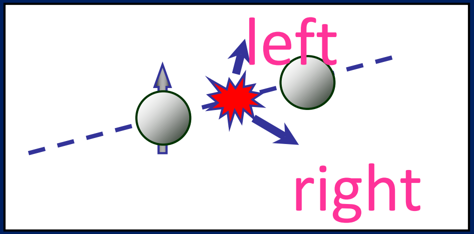
Much larger spin-momentum correlations, and strikingly similar effects across energies!

Single-spin asymmetries in transversely polarized proton-proton collisions





Effects persist to kinematic regimes where perturbative QCD techniques clearly apply



proton-proton → pion + X: Challenging to interpret

- Always huge effects!

- But in p+p → pion +X don’t have enough information to separate initial-state (proton structure) from final-state (pion formation) effects

- Need to think more carefully . . .

Different symmetry properties for different spin-momentum correlations

- Some transverse-momentum-dependent parton distribution functions odd under a parity- and time-reversal (PT) transformation

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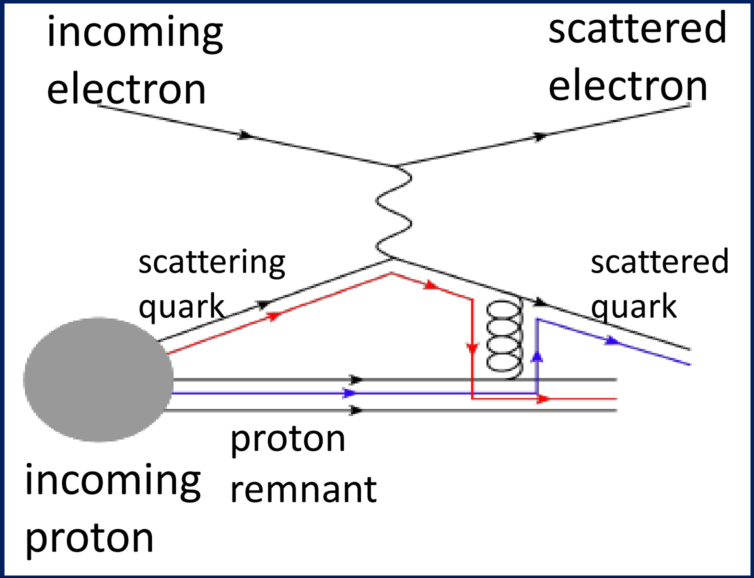
- In 1993, after original 1990 paper by D.W. Sivers, J.C. Collins claimed such functions must vanish

Different symmetry properties for different spin-momentum correlations

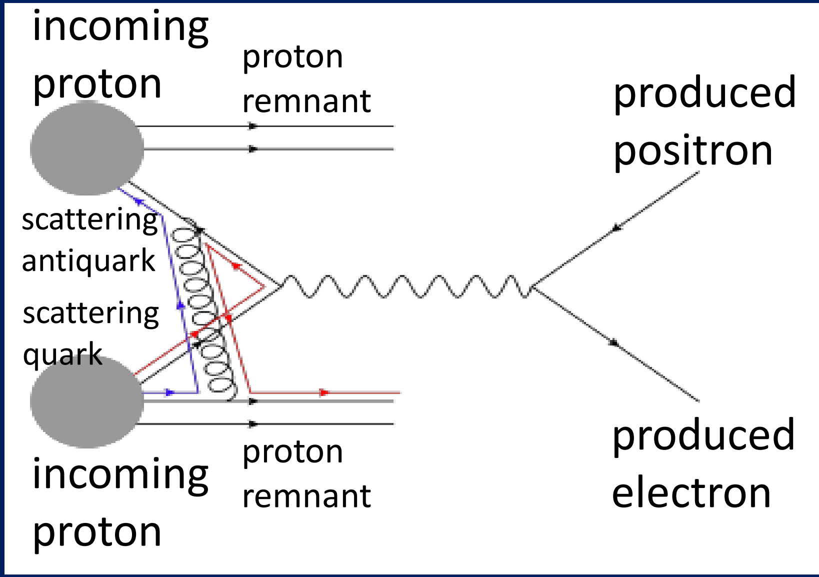
- Some transverse-momentum-dependent parton distribution functions odd under a parity- and time-reversal (PT) transformation
- In 1993, after original 1990 paper by D.W. Sivers, J.C. Collins claimed such functions must vanish
- Only realized in 2002 by Brodsky, Hwang, and Schmidt that could be nonvanishing if *phase interference effects due to color interactions* present

Modified universality of PT-odd correlations: Color in action!

Deep-inelastic lepton-nucleon scattering: Final-state color exchange



Quark-antiquark annihilation to leptons: Initial-state color exchange

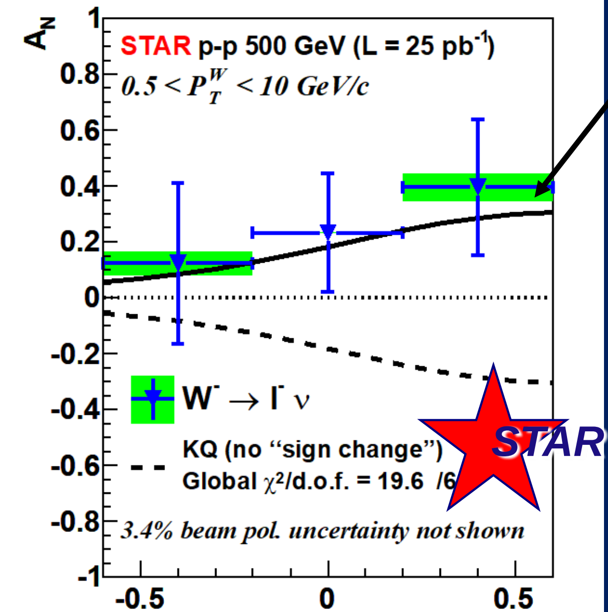


***Opposite sign* for PT-odd transverse-momentum-dependent distributions measured in these two processes: *process-dependent*! (Collins 2002)**

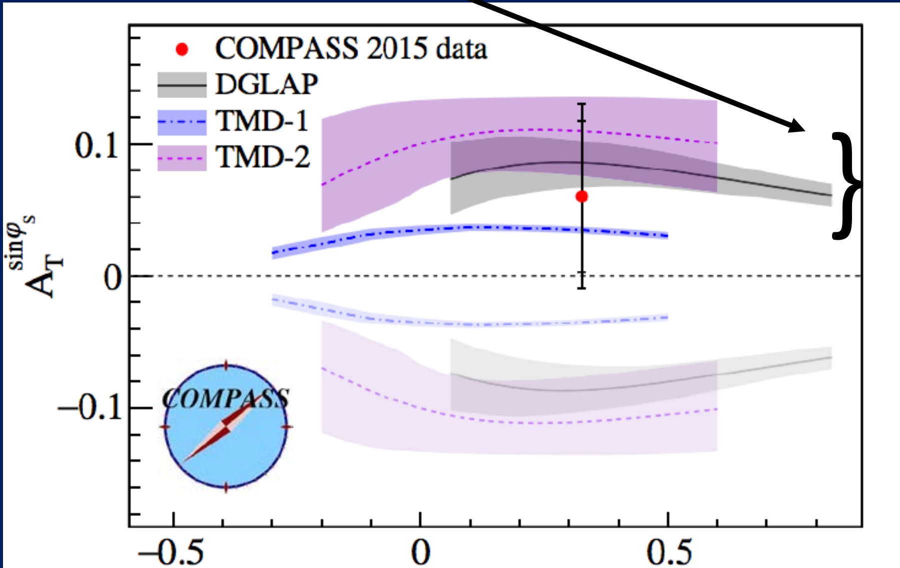
Figures by J.D. Osborn

Modified universality: Initial experimental hints

Predictions including sign change



PRL 116, 132301 (2016)



PRL 119, 112002 (2017)

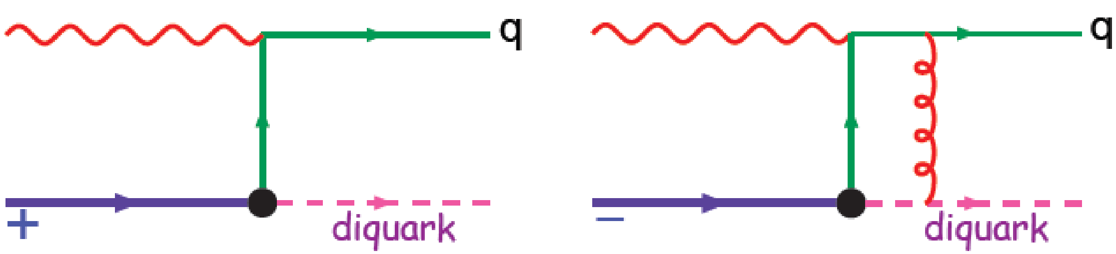
First measurements by STAR at RHIC and COMPASS at CERN suggestive of predicted sign change in color-annihilation processes compared to quark knock-out by an electron.
More statistics forthcoming . . .

Modified universality requires full QCD: Gauge-invariant quantum field theory

We have ignored here the subtleties needed to make this a gauge invariant definition: an appropriate path ordered exponential of the gluon field is needed [18].

gauge links have physical consequences;
quark models for non vanishing Sivers function,

SIDIS final state interactions



Brodsky, Hwang, Schmidt, PL B530 (2002) 99 - Collins, PL B536 (2002) 43

An earlier proof that the Sivers asymmetry vanishes because of time-reversal invariance is invalidated by the path-ordered exponential of the gluon field in the operator definition of parton densities. Instead, the time-reversal argument shows that the Sivers asymmetry is reversed in sign in hadron-induced hard processes (e.g., Drell-Yan), thereby violating naive universality of parton densities. Previous phenomenology with time-reversal-odd parton densities is therefore validated.

$$[f_{1T}^{q\perp}]_{\rm SIDIS} = -[f_{1T}^{q\perp}]_{\rm DY}$$

From 1993 claim by J.C. Collins that such processes must vanish

Slide from M. Anselmino, Transversity 2014

Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm (1959)

Wikipedia:

"The Aharonov–Bohm effect is important conceptually because it bears on three issues apparent in the recasting of (Maxwell's) classical electromagnetic theory as a gauge theory, which before the advent of quantum mechanics could be argued to be a mathematical reformulation with no physical consequences. The Aharonov–Bohm thought experiments and their experimental realization imply that the issues were not just philosophical.

The three issues are:

- whether potentials are "physical" or just a convenient tool for calculating force fields;
- whether action principles are fundamental;
- the principle of locality."

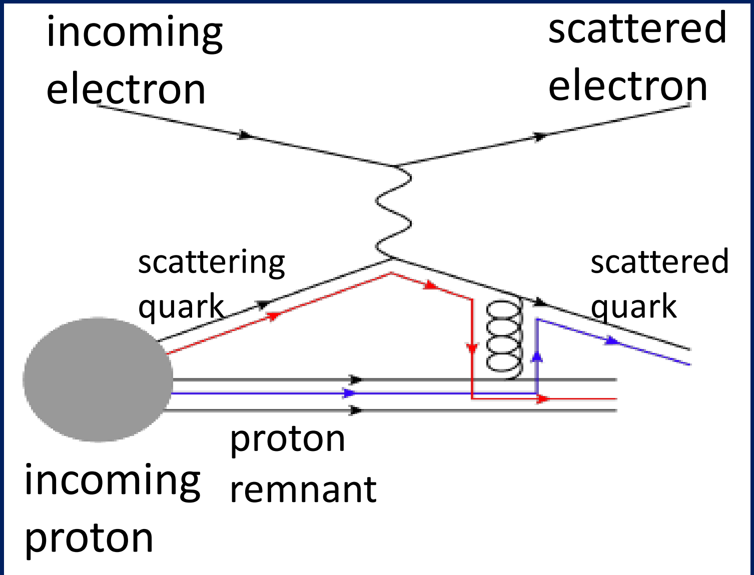
Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm (1959)

Physics Today, September 2009 :
The Aharonov–Bohm effects: Variations on a subtle theme,
by Herman Batelaan and Akira Tonomura.

"Aharonov stresses that the arguments that led to the prediction of the various electromagnetic AB effects apply equally well to any other gauge-invariant quantum theory. In the standard model of particle physics, the strong and weak nuclear interactions are also described by gauge-invariant theories. So one may expect that particle-physics experimenters will be looking for new AB effects in new domains."

Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm effect in QCD!!

Deep-inelastic lepton-nucleon scattering: Final-state color exchange



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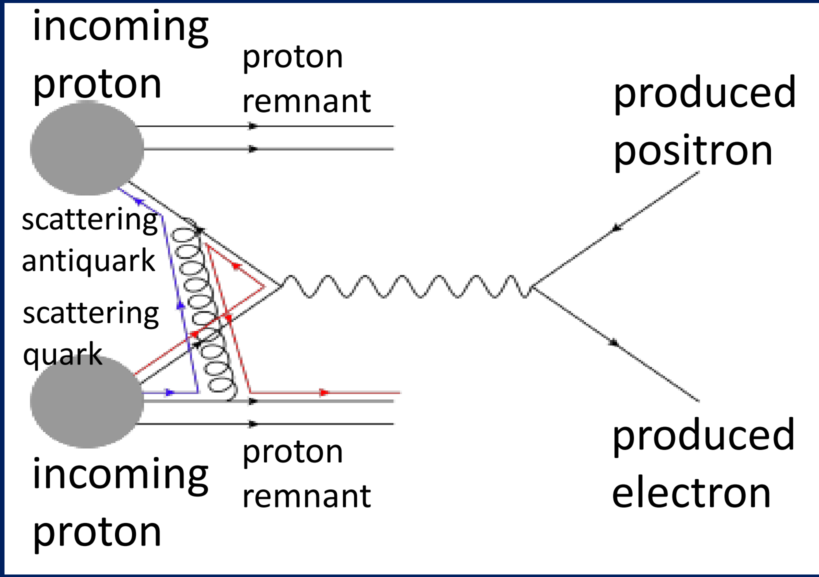

See e.g. Pijlman, hep-ph/0604226
or Sivers, arXiv:1109.2521

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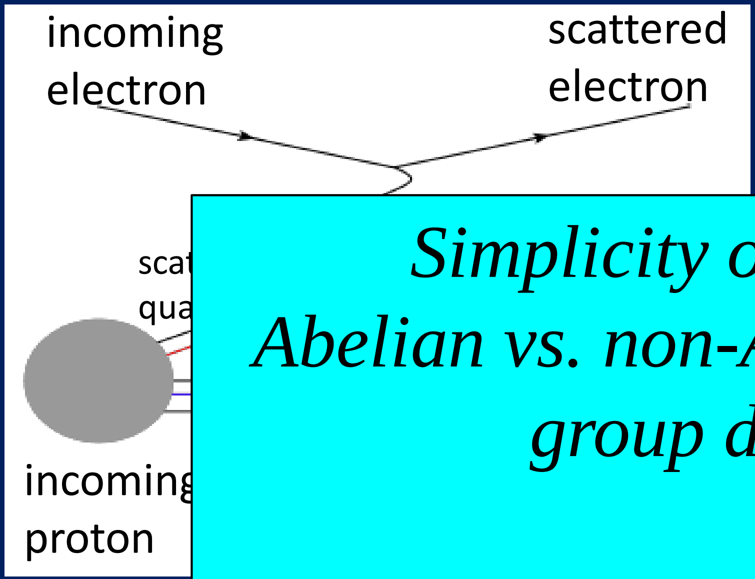

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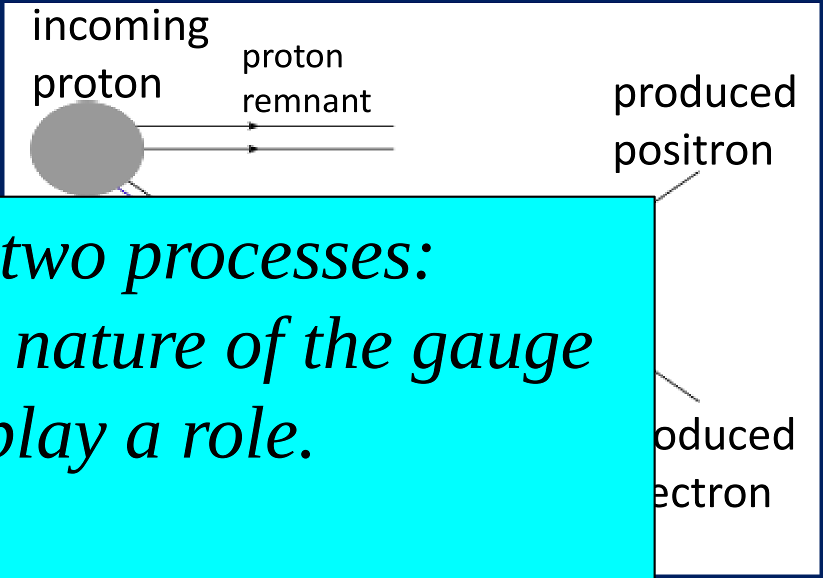
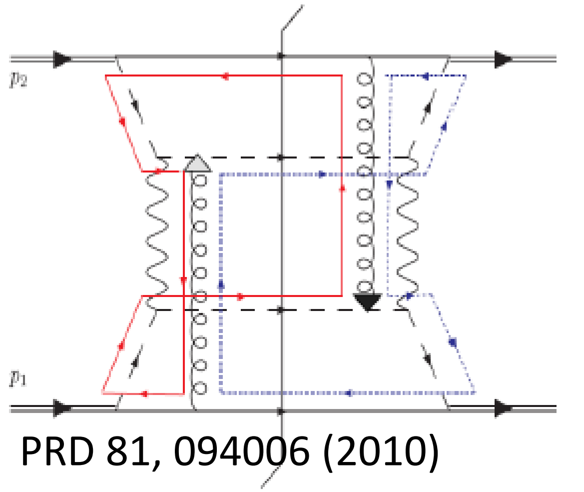


Simplicity of these two processes:
Abelian vs. non-Abelian nature of the gauge group doesn't play a role.

BUT: In QCD expect additional, new effects due to specific <u>non-Abelian</u> nature of the gauge group

QCD Aharonov-Bohm effect: Color entanglement

- 2010: T.C. Rogers and P. Mulders predict *color entanglement* in processes involving proton-proton production of QCD bound states if quark transverse momentum taken into account
- Quarks become correlated *across* the two colliding protons
- Consequence of QCD specifically as a ***non-Abelian*** gauge theory!



PRD 81, 094006 (2010)

$$p + p \to h_1 + h_2 + X$$

Color flow can't be described as flow in the two gluons separately. Requires presence of both.

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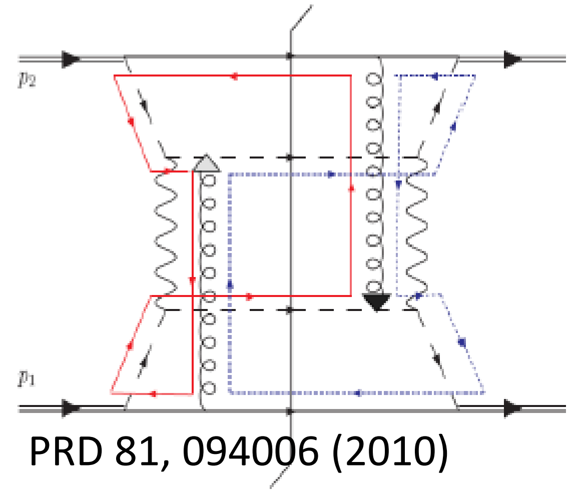

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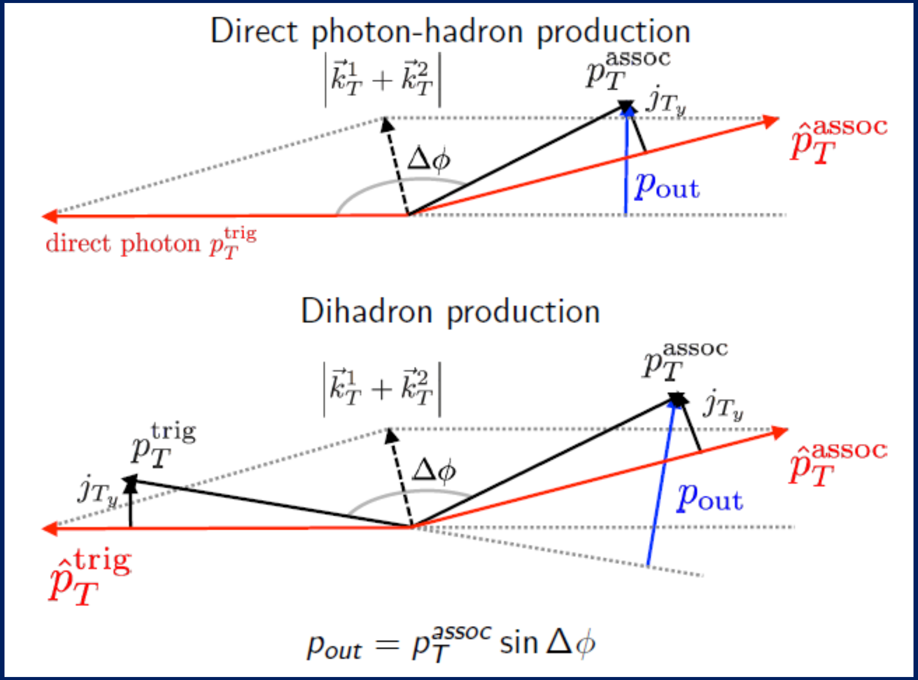
Huge transverse spin asymmetries in p+p a color entanglement effect??

Searching for evidence of color entanglement at RHIC

- Need observable sensitive to a nonperturbative momentum scale
  - Nearly back-to-back particle production
- Need 2 initial QCD bound states
  - color exchange between a scattering quark and remnant of other proton
- And at least 1 final QCD bound state
  - exchange between scattered quark and either remnant

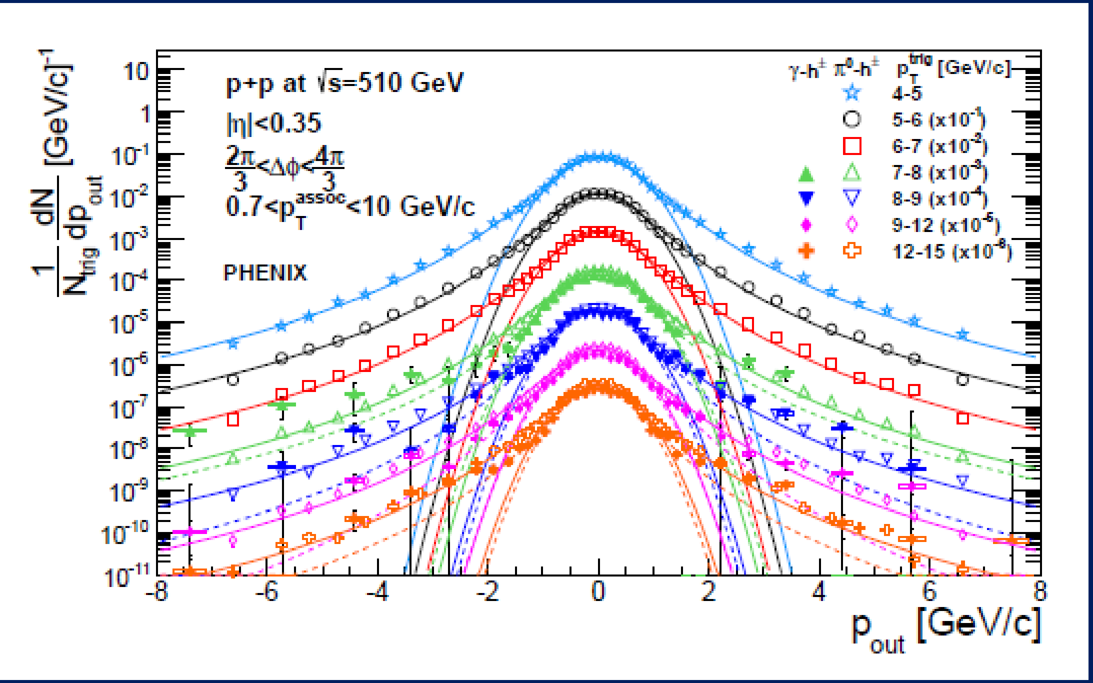


→ In p+p collisions, measure out-of-plane momentum component in nearly back-to-back photon-hadron and hadron-hadron production

Out-of-plane momentum component distributions

- Clear two-component distribution
  - Gaussian near 0—nonperturbative transverse momentum
  - Power-law at large p_{out}—kicks from hard (perturbative) gluon radiation
- Different colors → different bins in hard interaction scale

PRD95, 072002 (2017)



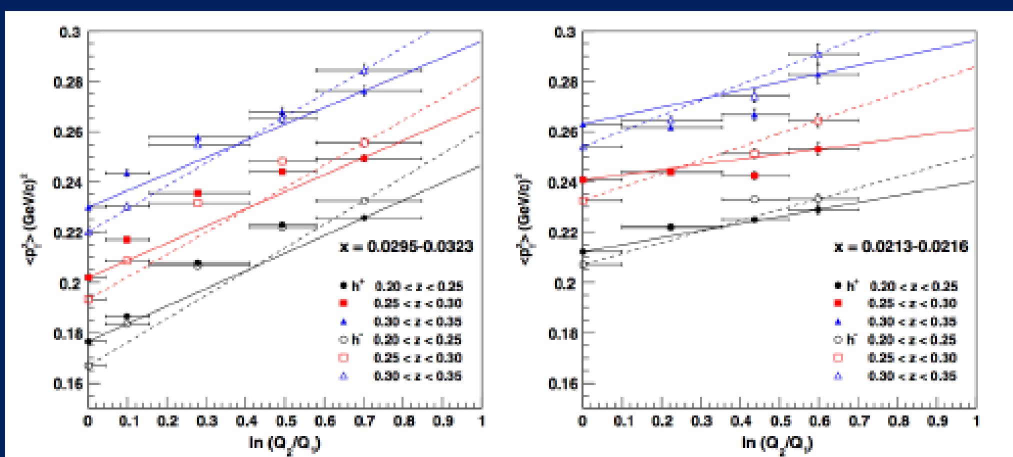
Curves are fits to Gaussian and Kaplan functions, not calculations!

*Look at **evolution** of nonperturbative transverse momentum widths with hard scale (Q^2)*

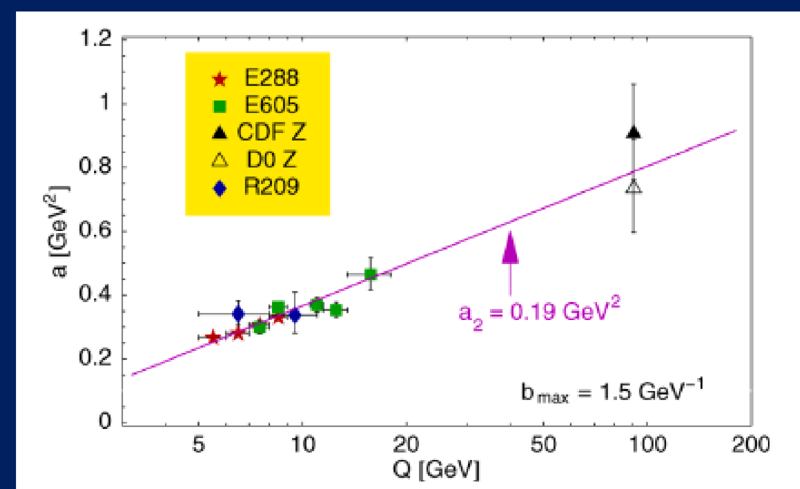
- Proof of factorization (i.e. no entanglement) for processes sensitive to nonperturbative transverse momentum directly predicts that nonperturbative transverse momentum widths *increase* as a function of the hard scattering energy scale
  - Increased phase space for gluon radiation

*Look at **evolution** of nonperturbative transverse momentum widths with hard scale (Q^2)*

- Proof of factorization (i.e. no entanglement) for processes sensitive to nonperturbative transverse momentum directly predicts that nonperturbative transverse momentum widths *increase* as a function of the hard scattering energy scale
  - Increased phase space for gluon radiation
- Confirmed experimentally in deep-inelastic lepton-nucleon scattering (left) and quark-antiquark annihilation to leptons (right)



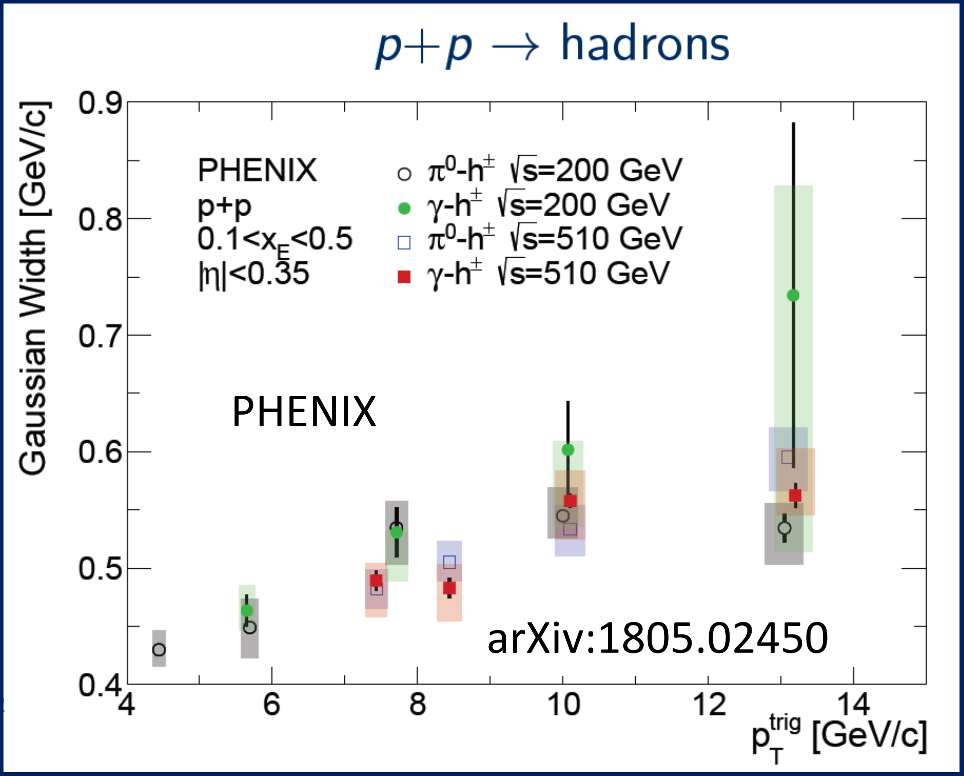
Aidala, Field, Gamberg, Rogers, Phys. Rev. D89, 094002 (2014)



Konychev + Nadolsky, Phys. Lett. B633, 710 (2006)

Evolution of nonperturbative momentum widths in processes where entanglement predicted

- No clear qualitative difference observed. Will need *quantitative* calculations from theorists to draw a conclusion …
  - Perform calculations assuming factorization holds, and look for discrepancies with measurement.
  - Currently no idea how to perform calculations for partons entangled across colliding protons!



Will perform follow-up studies at LHCb, for Z-jets, dijets, and Drell-Yan (as control comparison) in overlapping kinematics

Beyond simple pictures of QCD and hadron structure

- Gradually shifting to think about QCD systems in new ways, focusing on ideas/concepts that have long been familiar to the world of condensed matter and atomic, molecular, and optical physics
  - All sorts of correlations within systems
  - Quantum mechanical phase interference effects
  - Quantum entangled systems

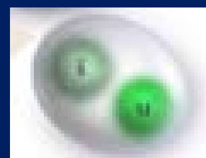
- These new ways of thinking will help deepen our understanding of QCD as a non-Abelian quantum gauge theory

Setting the stage for a next-generation QCD facility: Areas of study

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

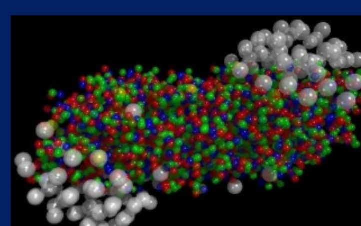
Structure/Properties of QCD matter

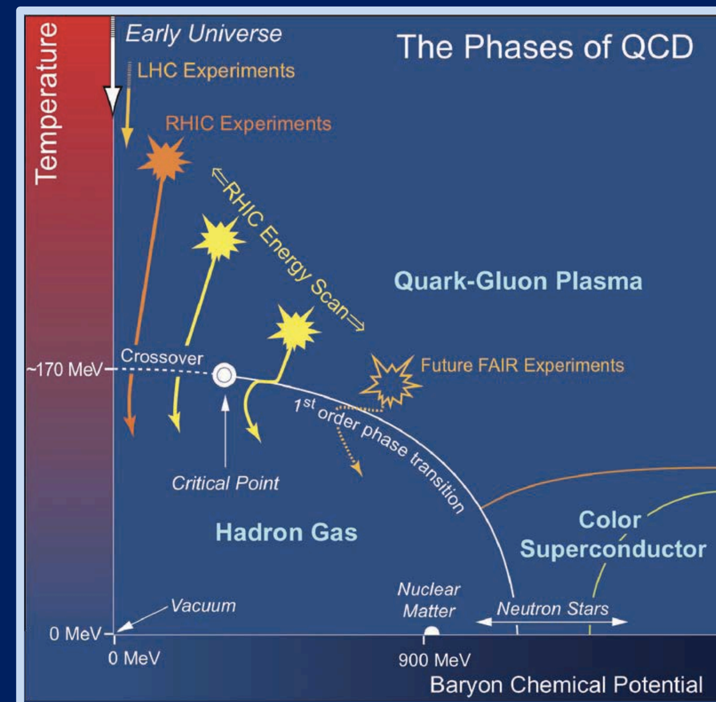
- Bound states: Mesons and baryons



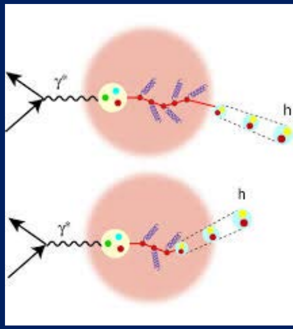

- Bound states of bound states: Nuclei, neutron stars


- Deconfined states: Quark-gluon plasma

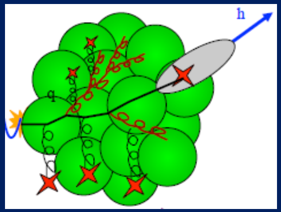




Formation of states of QCD matter

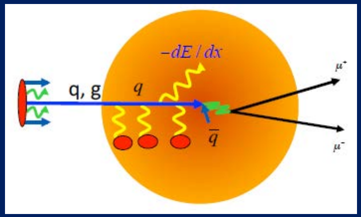


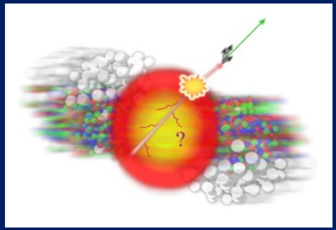
- Hadronization mechanisms
- Formation of bound states of bound states
- Jet structure
- Equilibration of QGP
- Time scales of hadronization/equilibration
- Modification of hadronization in different environments



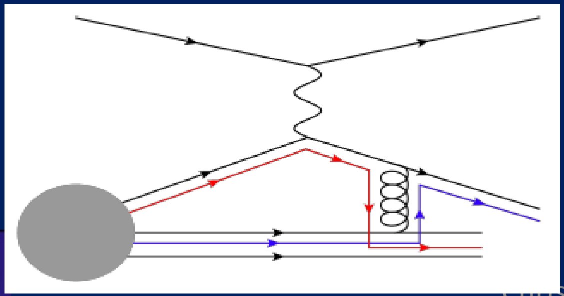
Interactions within QCD

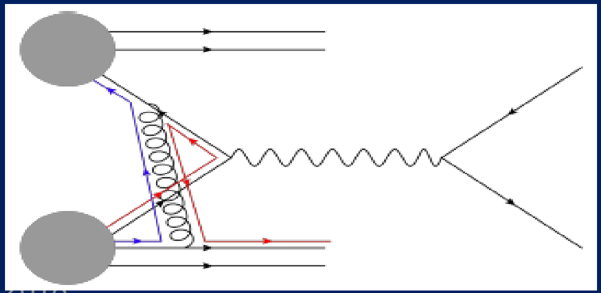
- Parton energy loss in cold and hot QCD matter
- Flow of partons within quark-gluon plasma





- Quantum interference and phase shifts
  - E.g. quantum interference effects in hadronization
    - One parton → multiple hadrons
    - Multiple partons → one hadron
- Color flow effects
  - Process-dependent spin-momentum correlations in hadrons
  - Quantum entanglement of partons across colliding hadrons





Complexity and richness of QCD: Confinement

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

- Always an interplay between partonic/hadronic descriptions, reductionist/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 can also
  - Allow use of perturbative theoretical tools
  - Provide access to new probes, e.g. heavy flavor, Z/W bosons

High-energy collisions: Tools to study QCD

Can study QCD via

- Hadron-hadron collisions: p+p, p+A, A+A, pbar+p/A, π+A
- Lepton-hadron collisions: e/μ+p, e/μ+A, ν+A
- Lepton-lepton collisions: e^+e^- (hadronization)

High-energy collisions to study QCD: 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, 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 (e.g. gluon saturation)

Some aspects we *select* rather than control

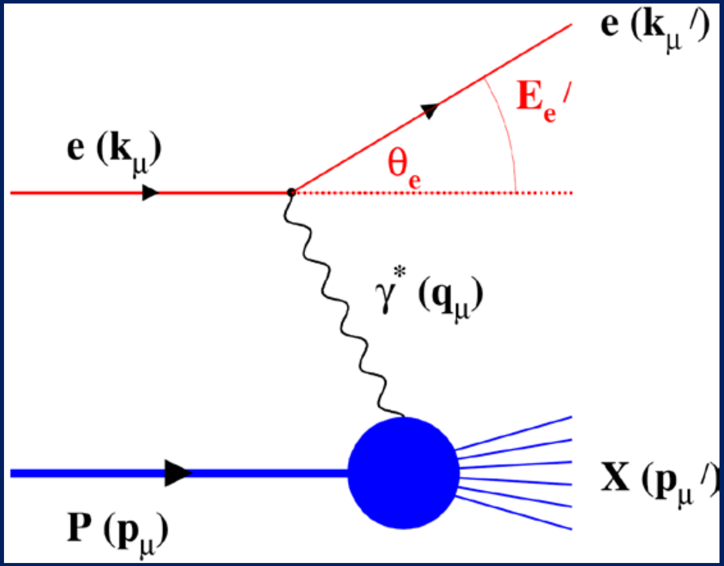
- Final-state produced particles and their kinematics, centrality of a heavy ion collision

Multidifferential measurements even more powerful

- p_T, rapidity, centrality, angular distribution/correlation, particle species, . . .

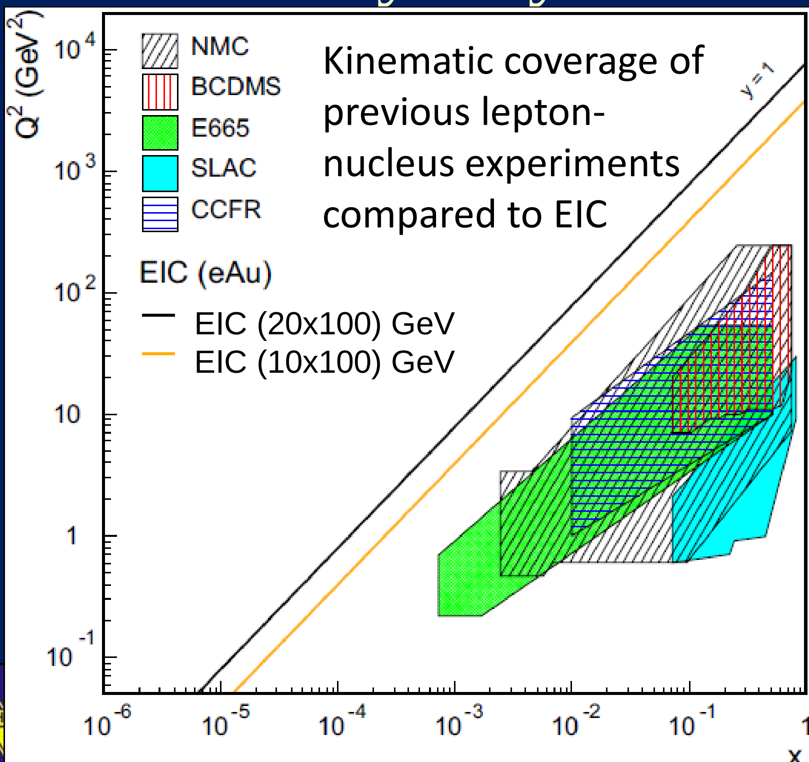
Why an Electron-Ion Collider as a next-generation QCD facility?

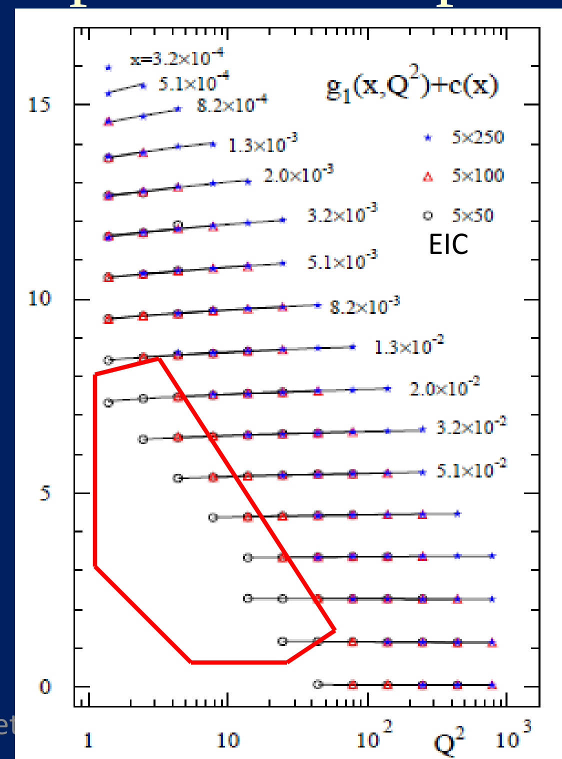
- Electroweak probe
  - "Clean" processes to interpret (QED at leading order)
  - Measurement of scattered electron → full kinematic information on partonic scattering
- Collider mode → Higher energies
  - Quarks and gluons relevant d.o.f.
  - Perturbative QCD applicable
  - Heavier probes accessible (e.g. charm, bottom, W boson exchange)



EIC facility concepts

- 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



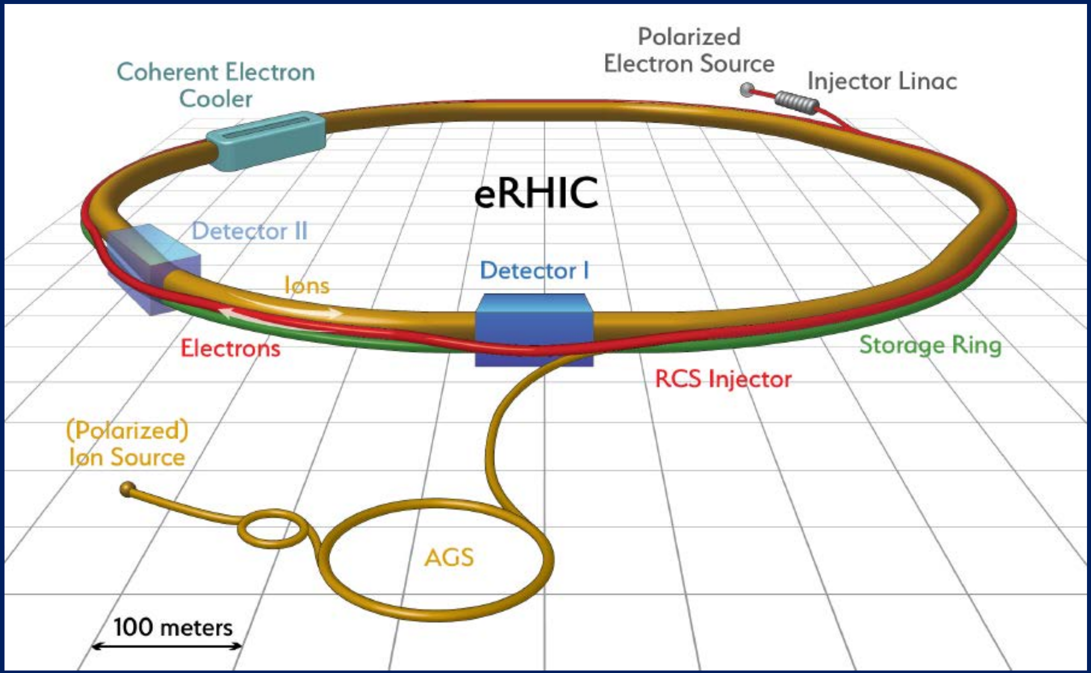


Kinematic coverage of previous polarized lepton-proton experiments compared to EIC projected data points

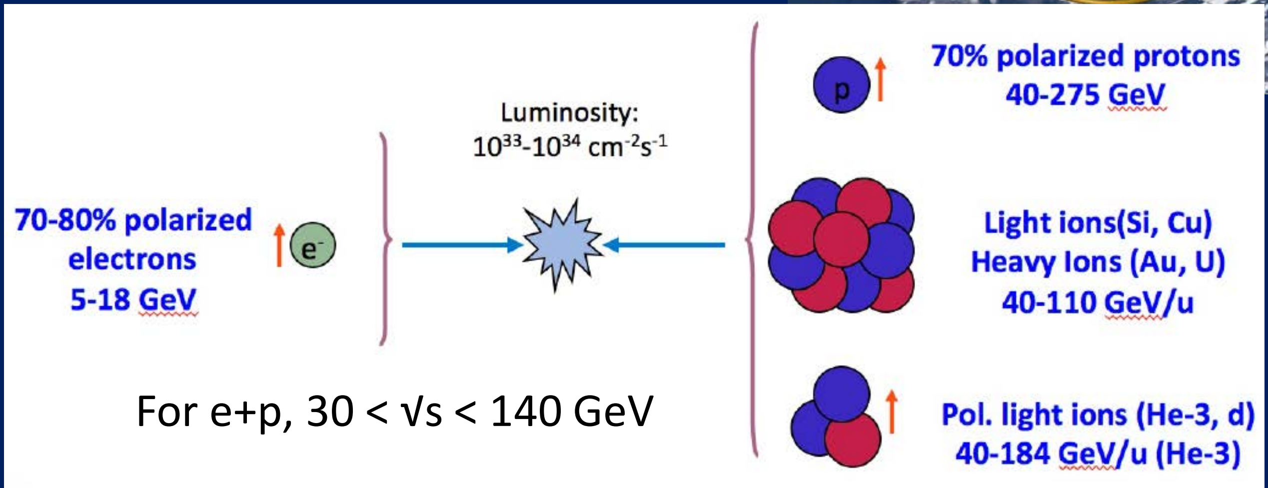
EIC facility concepts

- 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
- Luminosity 100-1000x that of HERA e+p collider
- Two concepts: Add electron facility to the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab or add ion facility to the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab

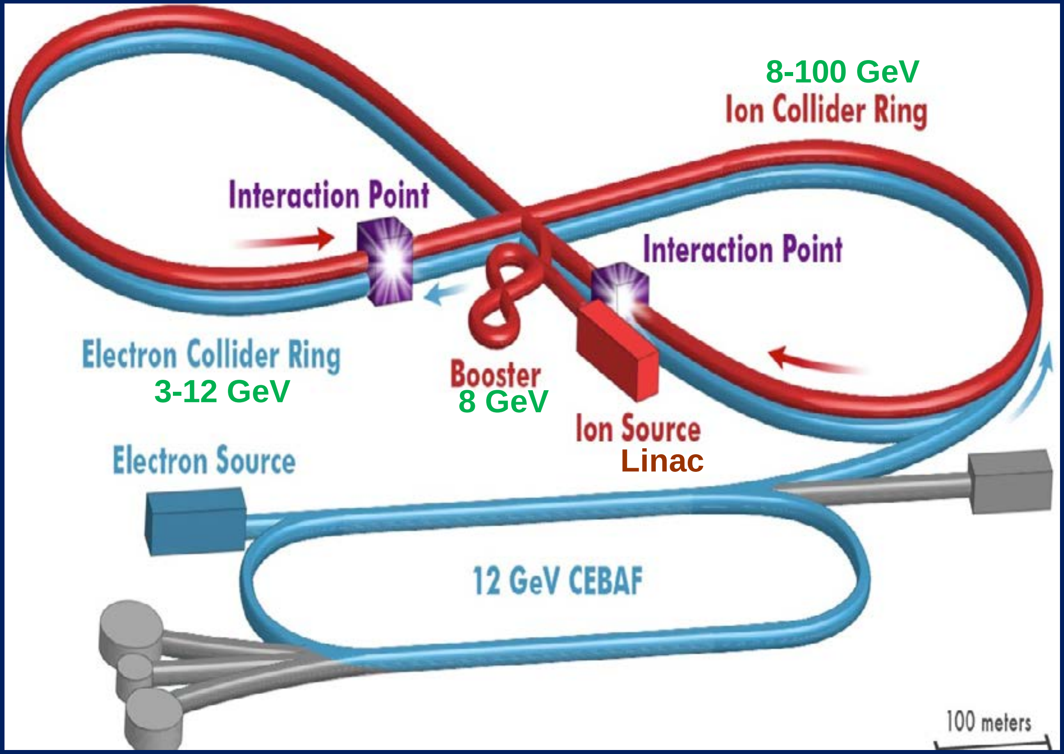
eRHIC at BNL

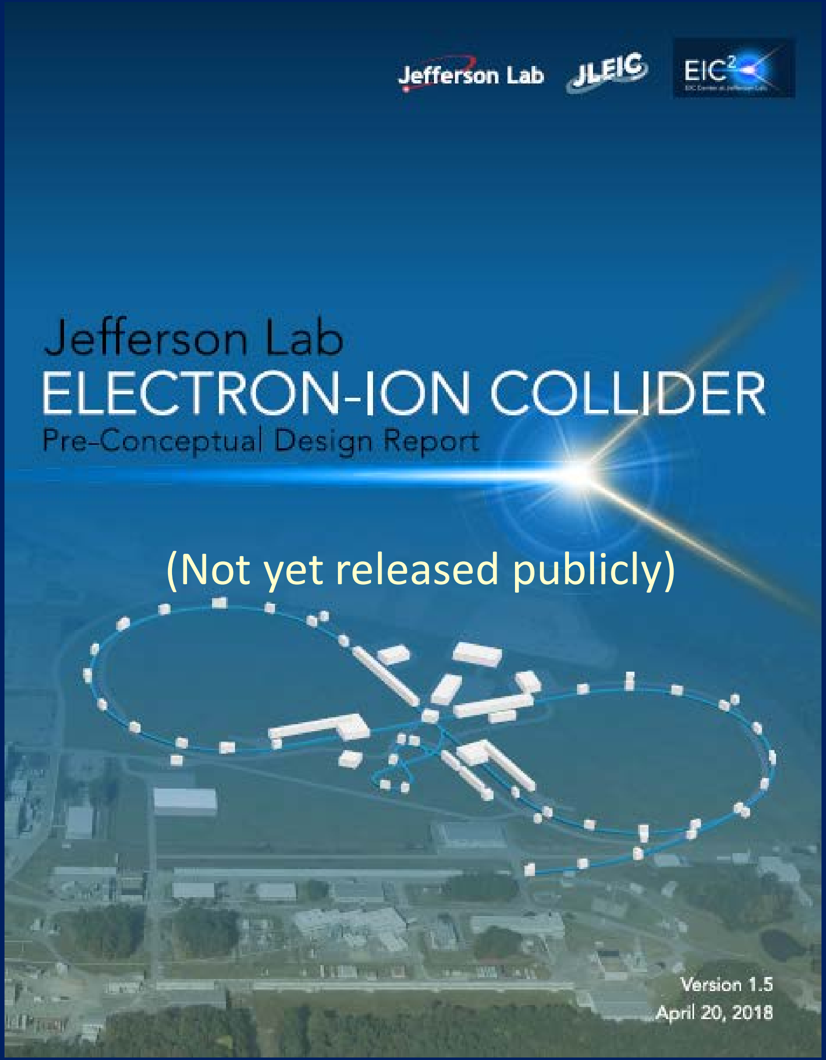

Polarized
Electron Source
Coherent Electron
Cooler
Injector Linac
eRHIC
Detector II
Detector I
Ions
Electrons
Storage Ring
RCS Injector
(Polarized)
Ion Source
AGS
100 meters


BROOKHAVEN
NATIONAL LABORATORY
eRHIC
Electron-Ion Collider
at Brookhaven National Laboratory
Pre-Conceptual Design Report
July 2018
(Not yet released publicly)
eRHIC
RHIC
AGS


70% polarized protons
40-275 GeV
Luminosity:
10^33-10^34 cm^-2s^-1
70-80% polarized
electrons
5-18 GeV
Light ions(Si, Cu)
Heavy Ions (Au, U)
40-110 GeV/u
For e+p, 30 < √s < 140 GeV
Pol. light ions (He-3, d)
40-184 GeV/u (He-3)

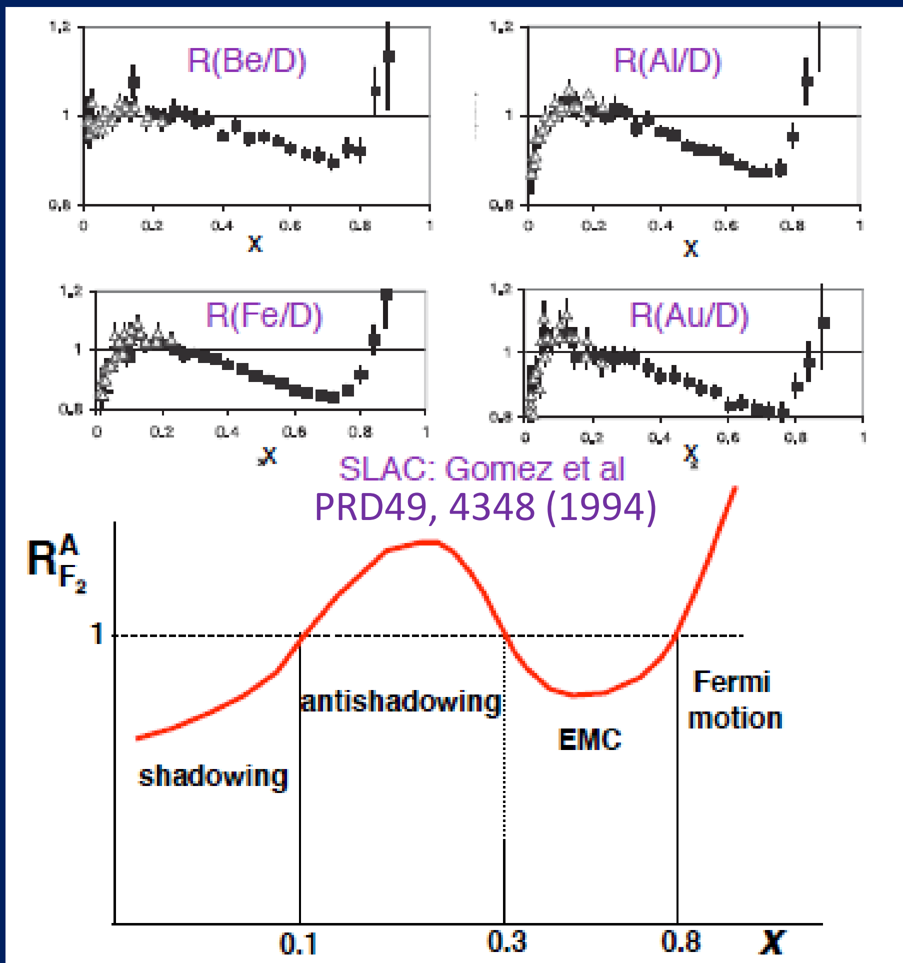
JLEIC at JLab





- 70% polarized electrons, 3-12 GeV
- Protons up to 100 GeV, ions up to 40 GeV/n
- 70% polarized p, d, ^{3}He. Figure-8 design – spin precession in the left and right parts cancels
- Luminosity 10^{33} to 10^{34} cm^{-2}s^{-1}
- For e+p, $15 < \sqrt{s} < 70$ GeV

Partonic momentum structure of nuclei: Not just superposed protons and neutrons

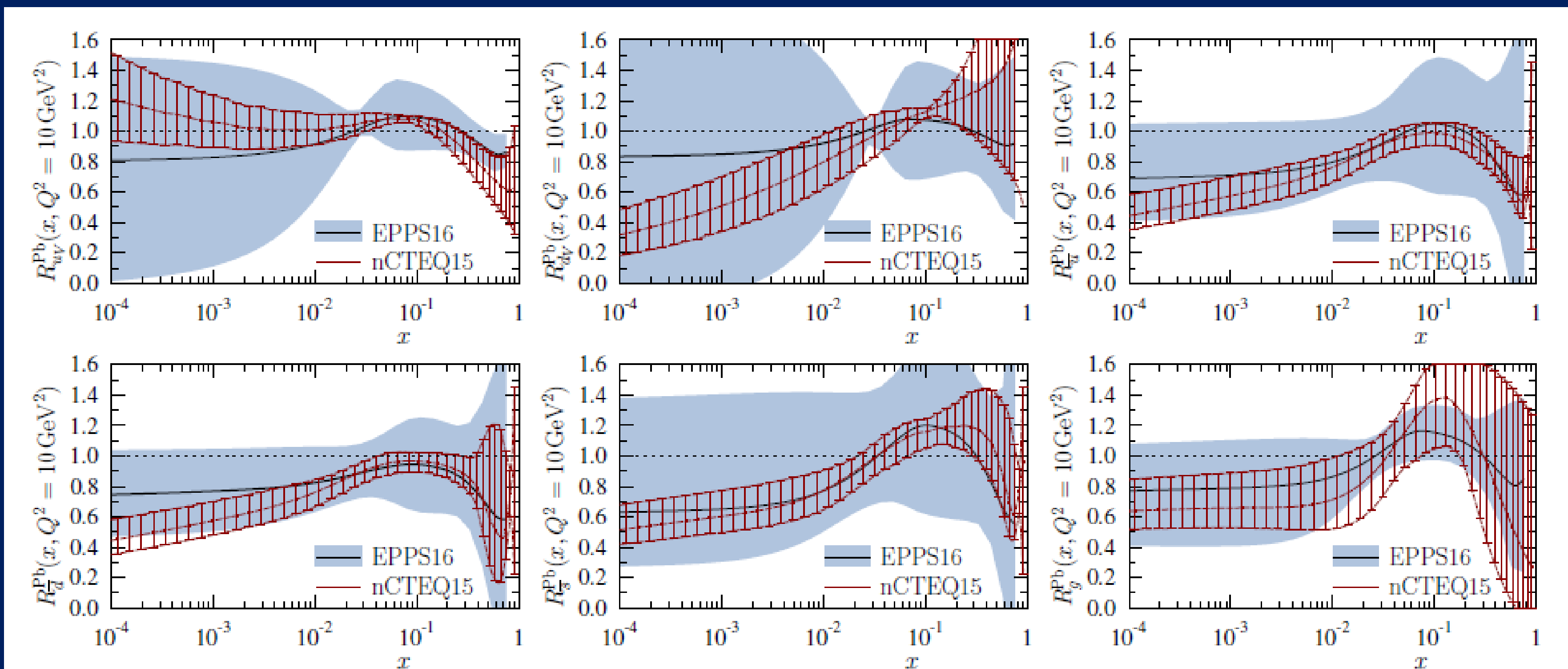


$$R_A \equiv \frac{1}{A}\frac{F_{2A}}{F_{2N}} \neq 1$$

- Ratio of cross section for e+A compared to scaled e+p collisions, shown vs. parton momentum fraction x
- Regions of both enhancement and depletion—only Fermi motion reasonably understood

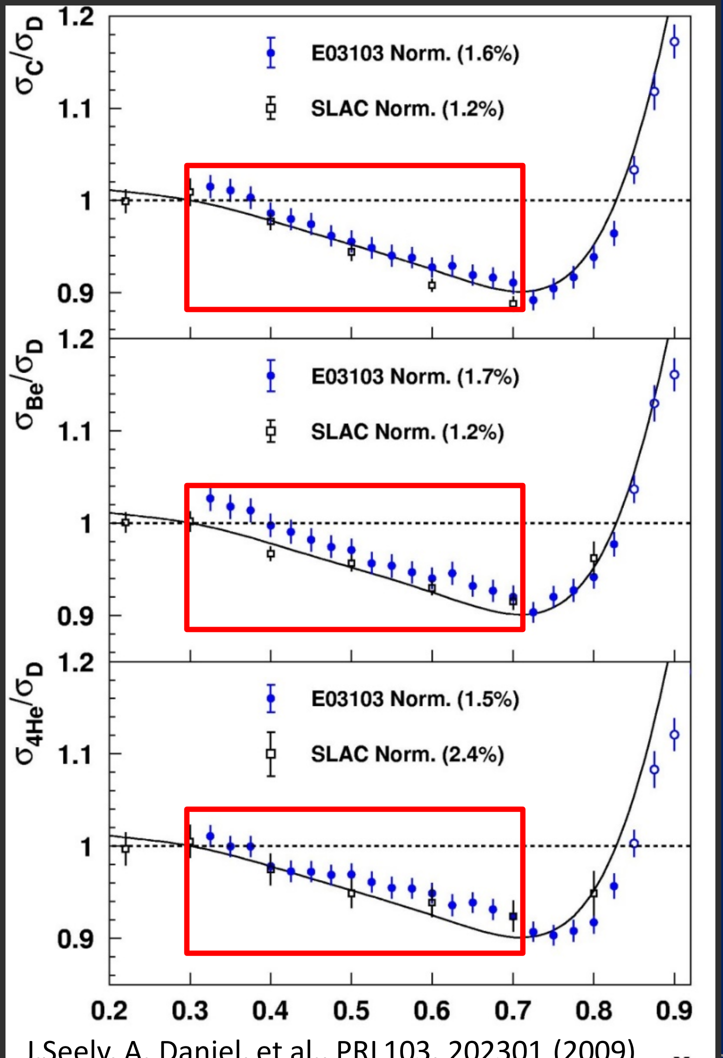
Partonic momentum structure of nuclei: Nuclear parton distribution functions

(Traditional collinear, unpolarized) Nuclear PDFs



EPPS16 – arXiv:1612.05741

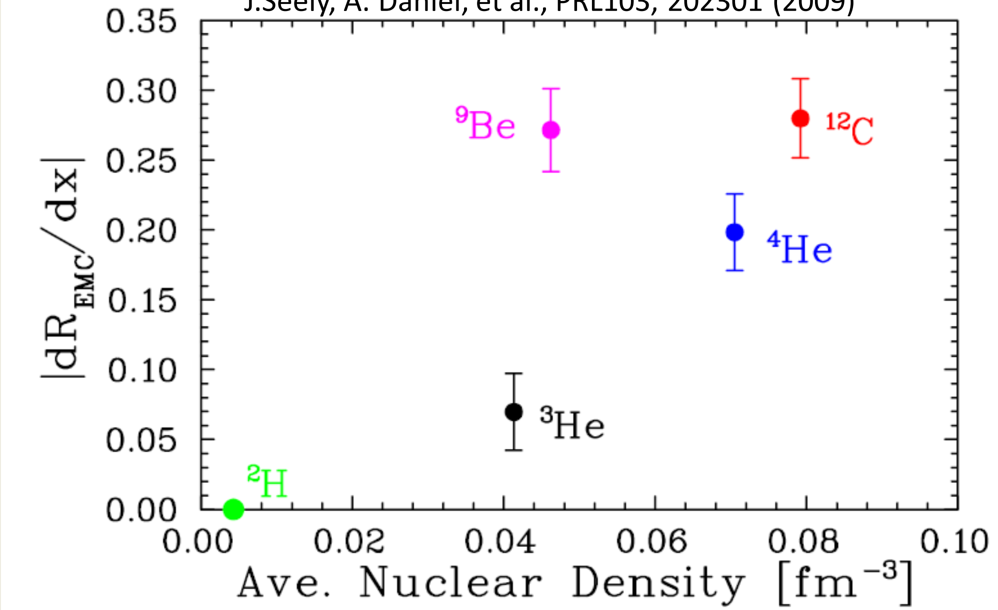
Partonic momentum structure of nuclei: EMC effect and local density



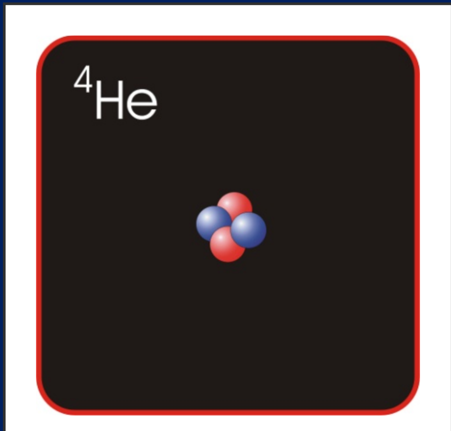
J.Seely, A. Daniel, et al., PRL103, 202301 (2009)

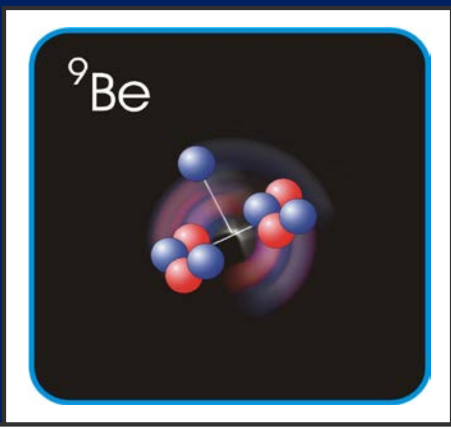
- Fit slope of ratios for 0.3<x<0.7; compare across nuclei
- EMC slope doesn't scale with A or with avg nuclear density…

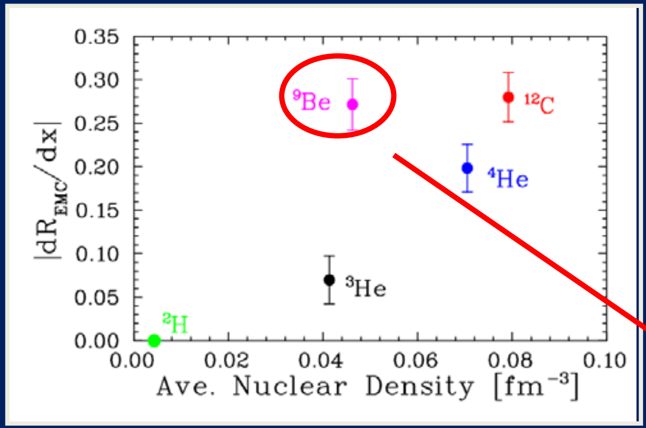
J.Seely, A. Daniel, et al., PRL103, 202301 (2009)



Partonic momentum structure of nuclei: EMC effect and local density

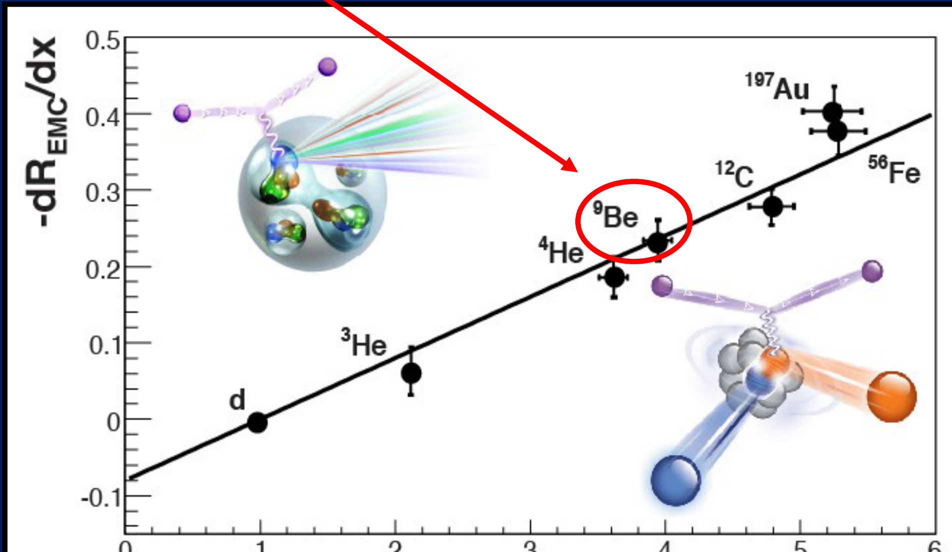






But appears to scale with local density!

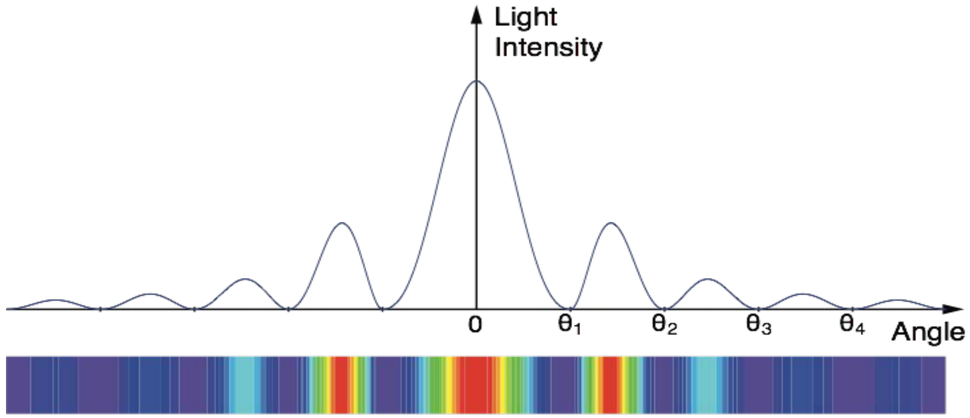
Density determined from *ab initio* few-body calculation
S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)



Hen, Piasetzky, Weinstein,
Phys. Rev. C85, 047301 (2012)

Partonic spatial structure of nuclei: Diffraction

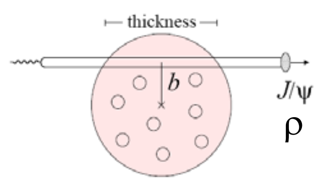
Diffraction pattern from monochromatic plane wave incident on a circular screen of fixed radius



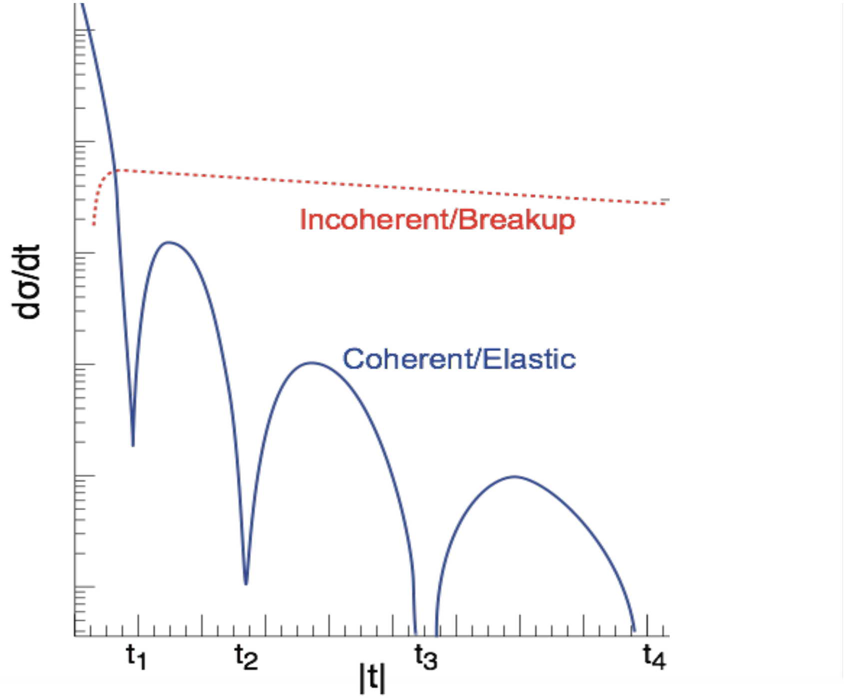
From E. Aschenauer

- 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

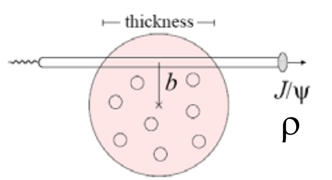


Expected diffraction pattern from gamma ray incident on ~spherical nucleus



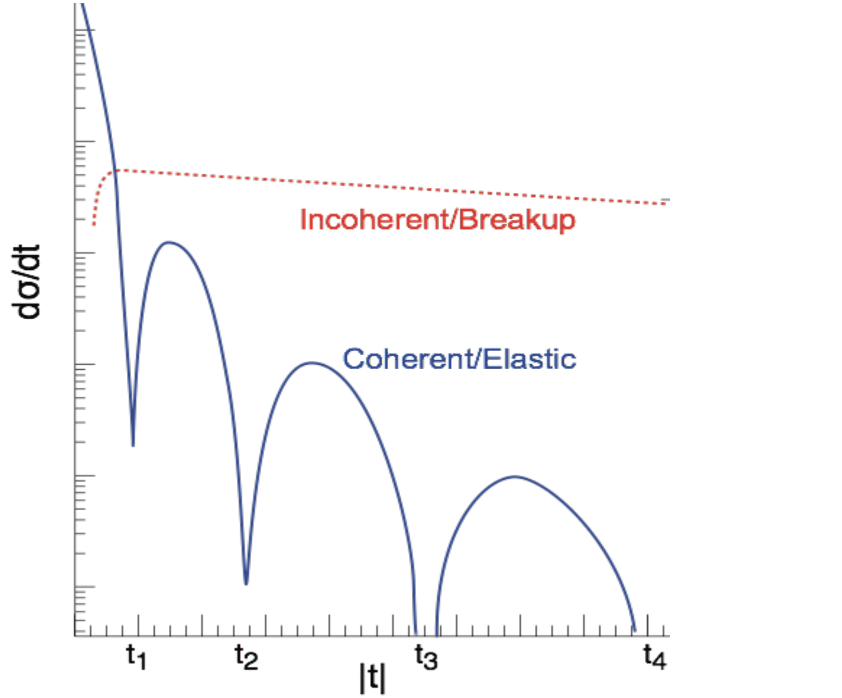
e+A, p+A, or A+A. Probed nucleus in one beam. Gamma emitted by electron or Coulomb-excited proton/nucleus passing nearby in second beam.

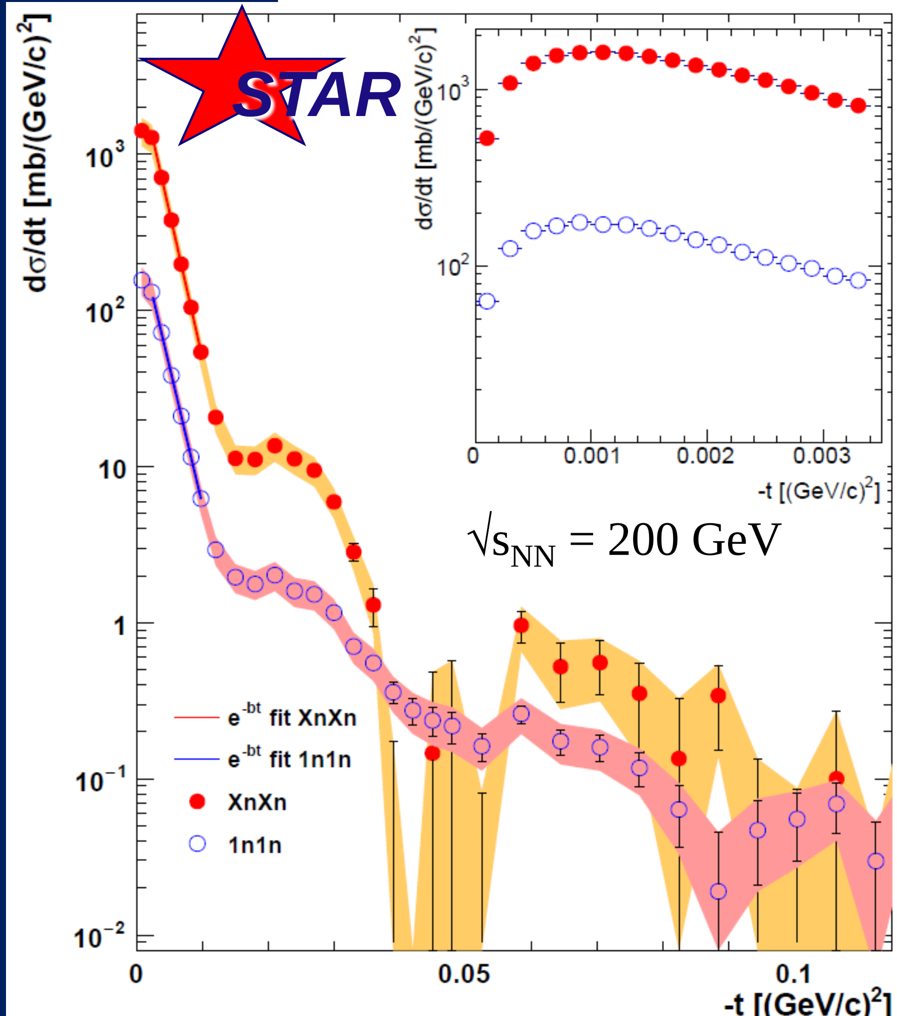
Partonic spatial structure of nuclei: Diffraction



Diffractive ρ production in Au+Au ultraperipheral collisions

Expected diffraction pattern from gamma ray incident on ~spherical nucleus

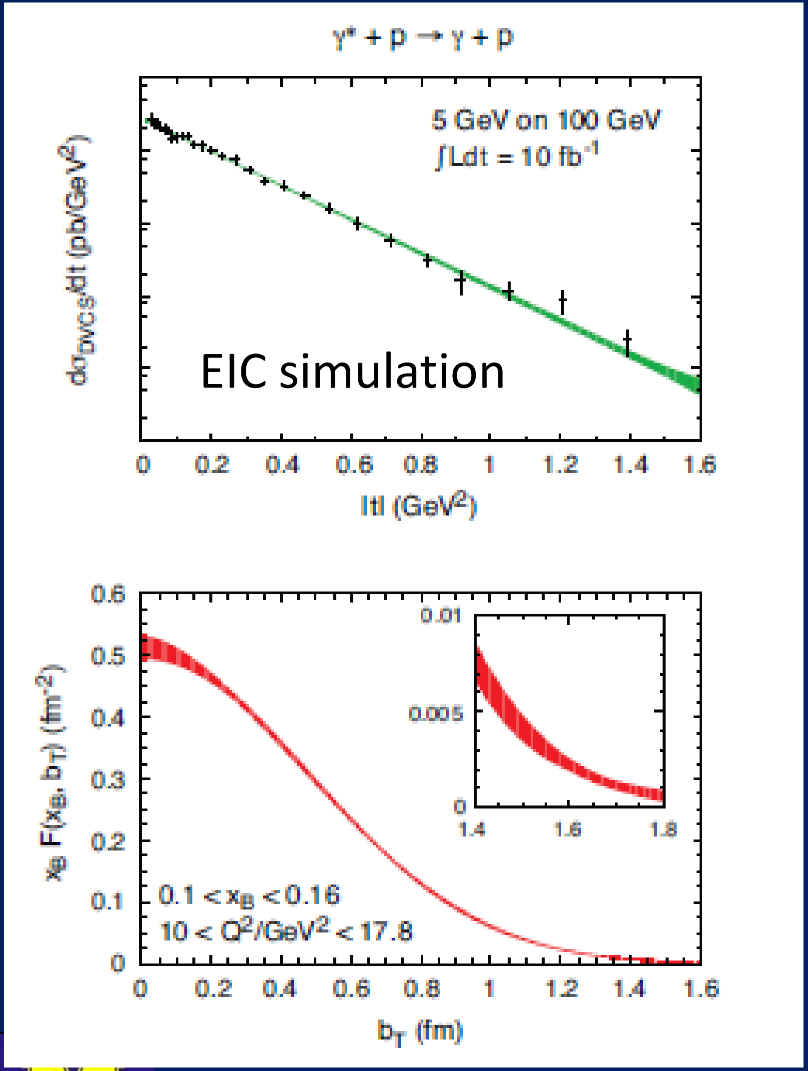


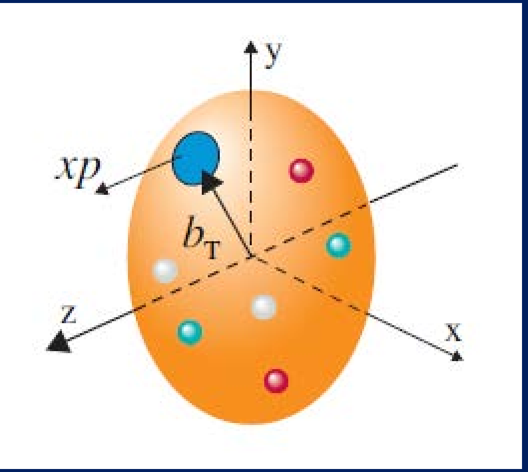


e+A, p+A, or A+A. Probed nucleus in one beam. Gamma emitted by electron or Coulomb-excited proton/nucleus passing nearby in second beam.

PRC96, 054904 (2017)

Partonic spatial structure of nuclei: Diffraction



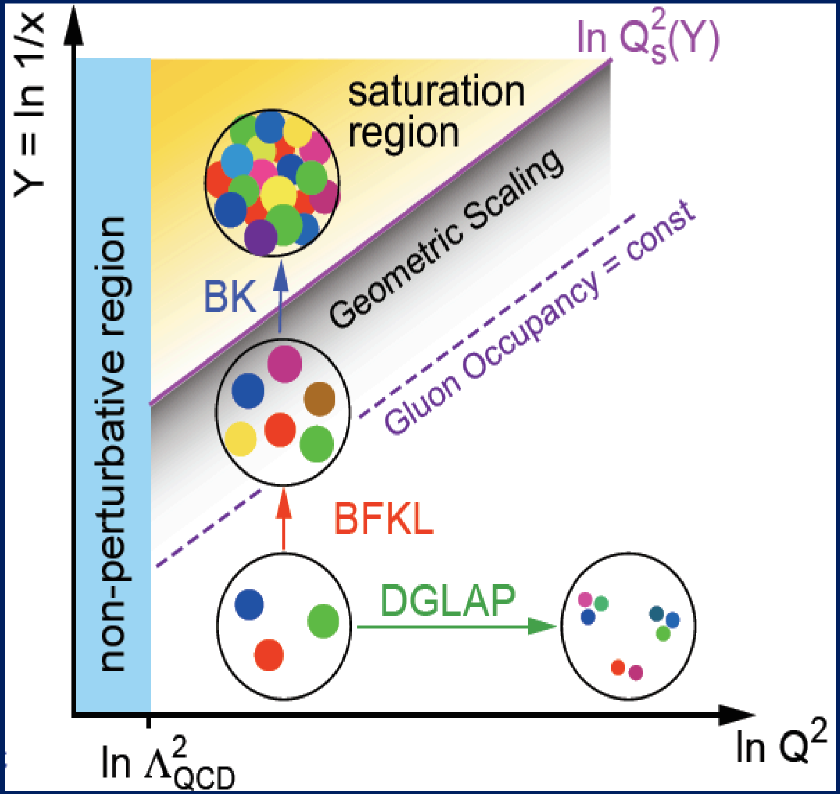


Goal: Cover wide range in *t*.
Fourier transform → impact-parameter-space profiles.
Obtain *b* profile from slope vs. *t*.

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

Diffraction to study universal state of gluonic matter: Gluon saturation

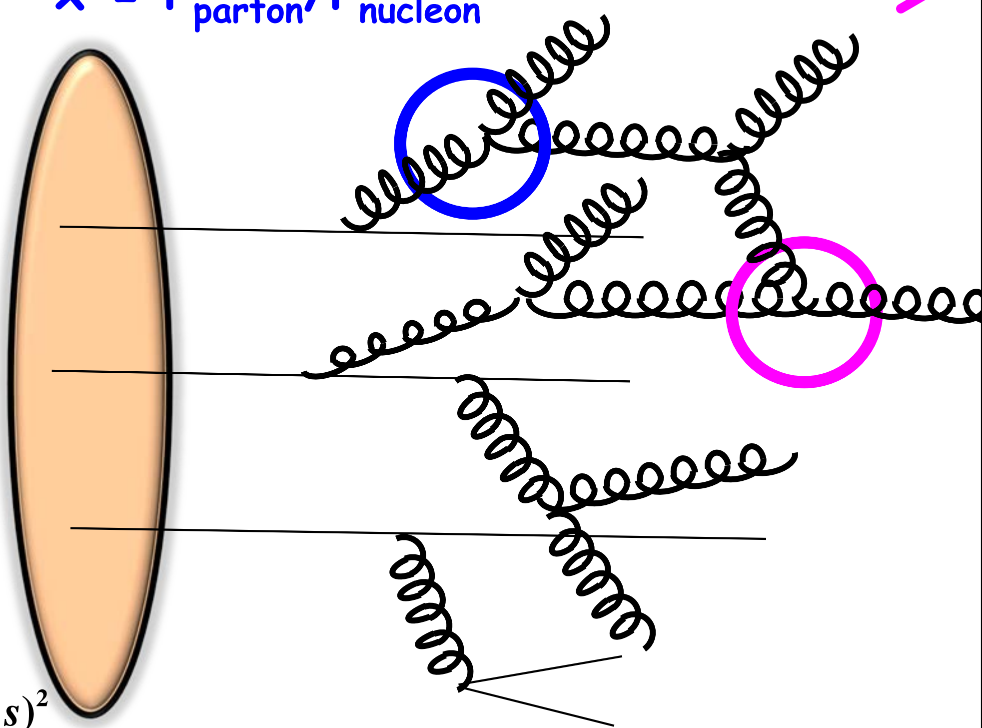
- In addition to probing spatial structure, diffraction is one way to probe gluon saturation within nuclei



Gluon saturation

small x

$x = P_{parton}/P_{nucleon}$



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

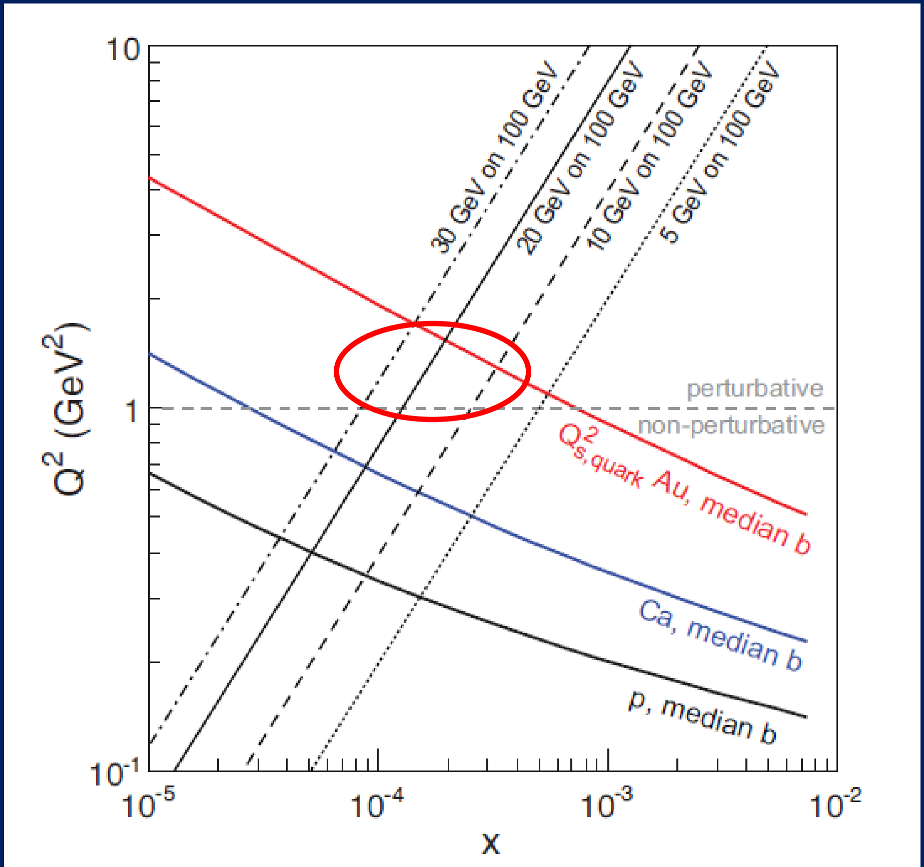
$$\sigma_{tot} = \frac{\pi}{m_\pi^2}(\ln s)^2$$

Bremsstrahlung $\sim \alpha_s \ln(1/x)$

Recombination $\sim \alpha_s \rho$

Diffraction in e+A as a probe of gluon saturation

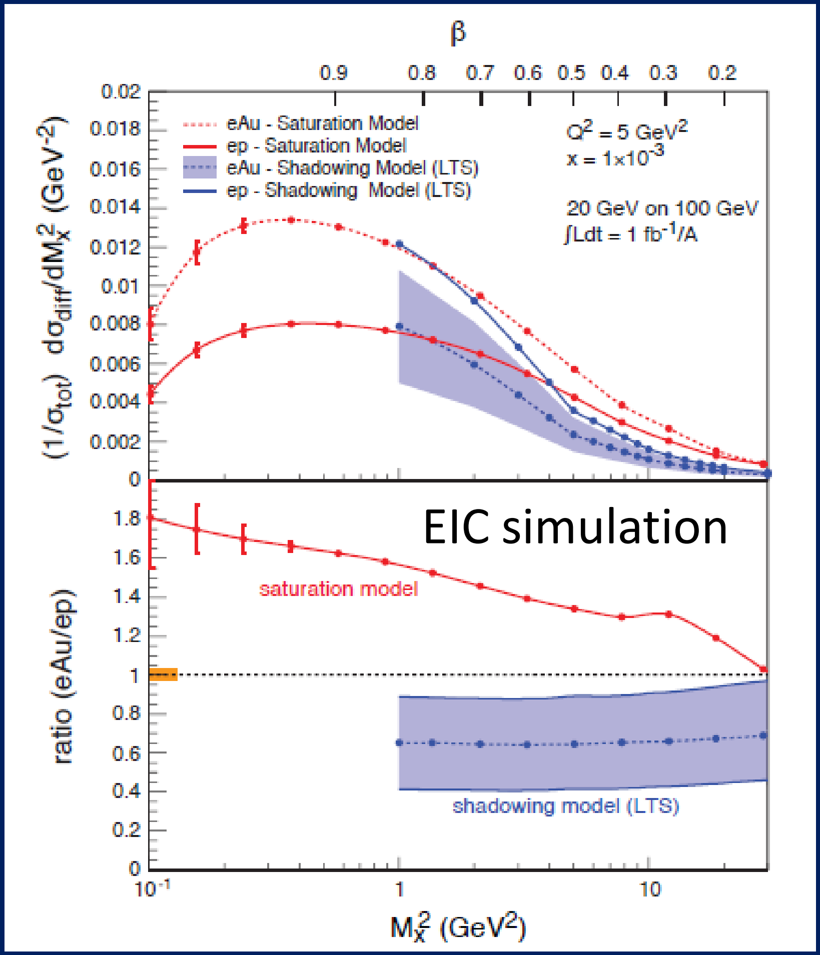
- Fewer potential competing effects in e+p/A than hadron-hadron collisions
- Easier to reach predicted saturation regime with e+A than e+p
- e+Au at higher c.m. energies for EIC will provide window of overlap where both Color-Glass Condensate effective field theory calculations and perturbative QCD calculations can be done and compared



Diffraction in e+A as a probe of gluon saturation

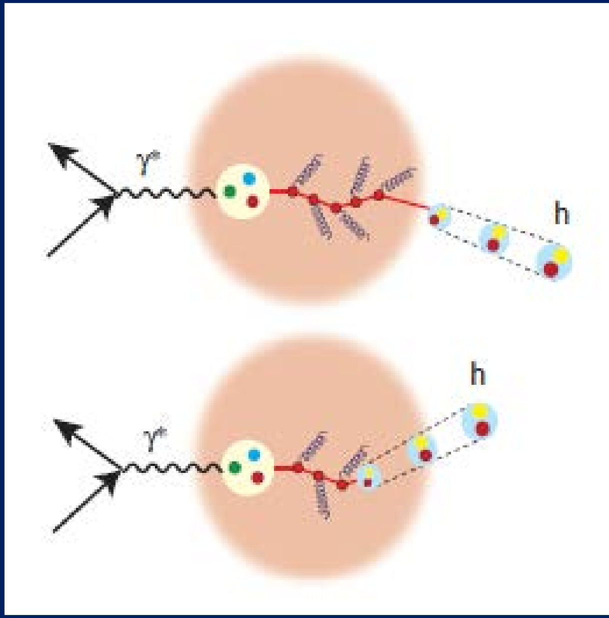
- Top panel: EIC projections for ratio of diffraction cross section to total, along with predictions based on saturation and shadowing models
- Bottom panel: Projections and predictions for *double* ratio: (diffractive/total)$_{e+A}$/(diffractive/total)$_{e+p}$
  - Very strong handle to distinguish saturation from shadowing!

- Note: Saturation can also be probed via 2-particle correlations in e+A, as in p/d+A



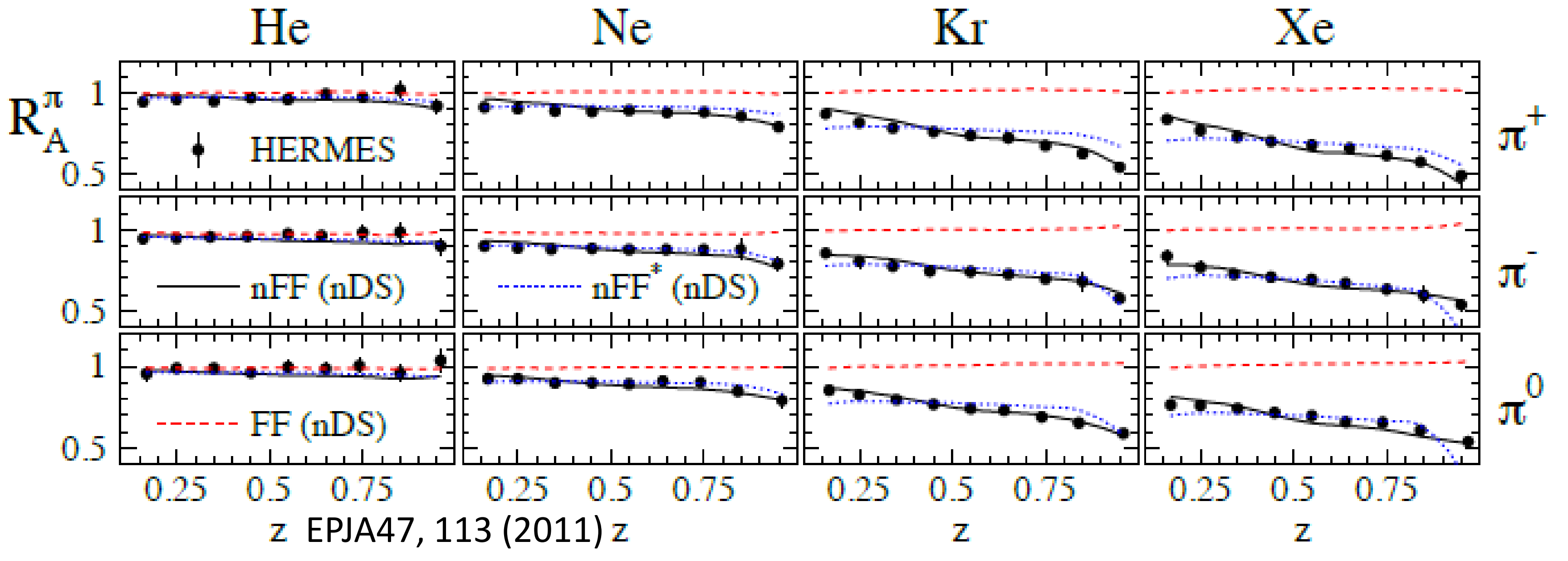
Formation of QCD bound states: Hadronization at EIC

- 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



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

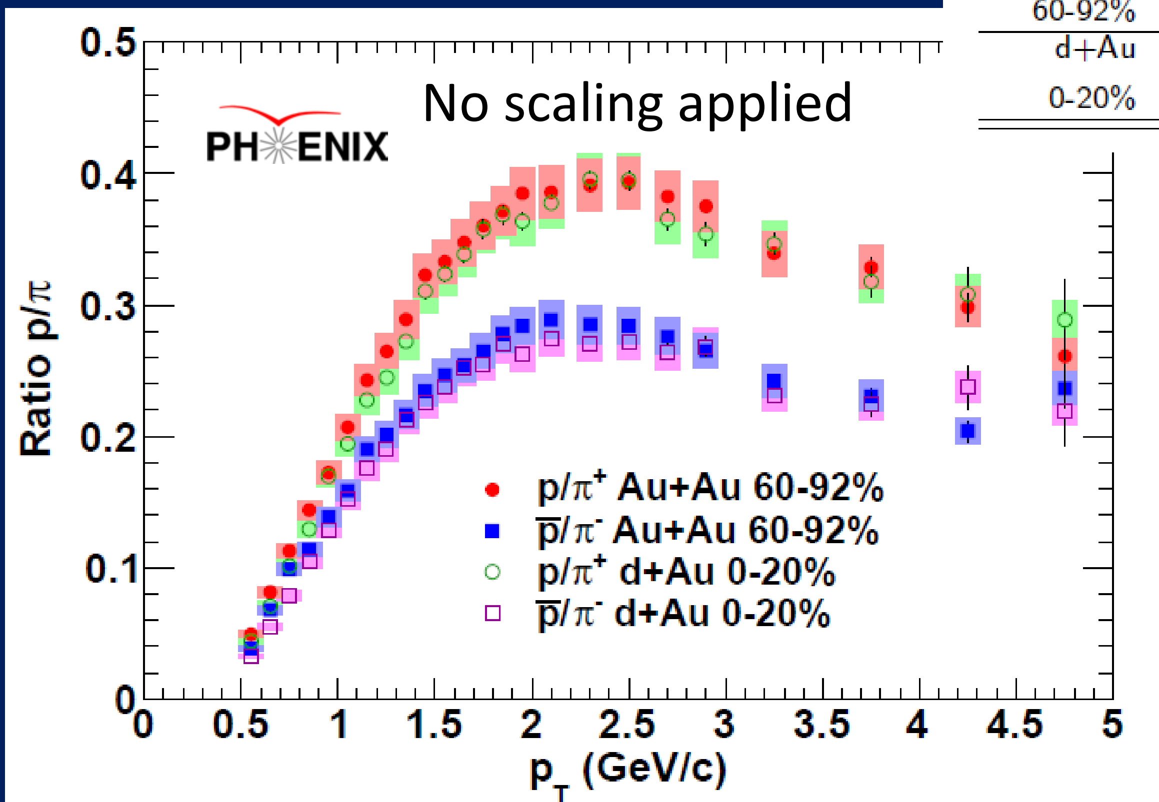
Formation of QCD bound states: Nuclear modification of fragmentation functions



Fragmentation functions have been observed to be modified in e+A, e.g. suppression of pion production

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

Centrality	$\langle N_{coll} \rangle$	$\langle N_{part} \rangle$
Au+Au 60-92%	14.8 ± 3.0	14.7 ± 2.9
d+Au 0-20%	15.1 ± 1.0	15.3 ± 0.8



PRC88, 024906 (2013)

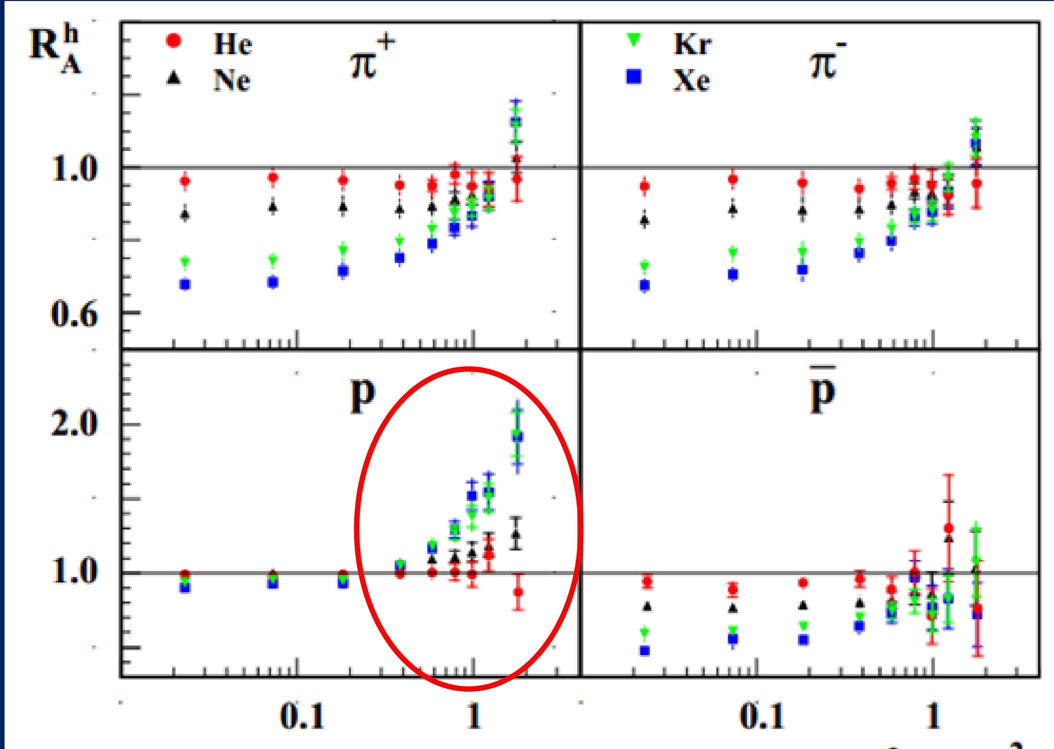
Baryon enhancement observed in central A+A but also peripheral A+A and in p/d+A.

p/π ratio for central d+Au and peripheral Au+Au—shape *and* magnitude identical!

Suggests common mechanism(s) for baryon production in the two systems

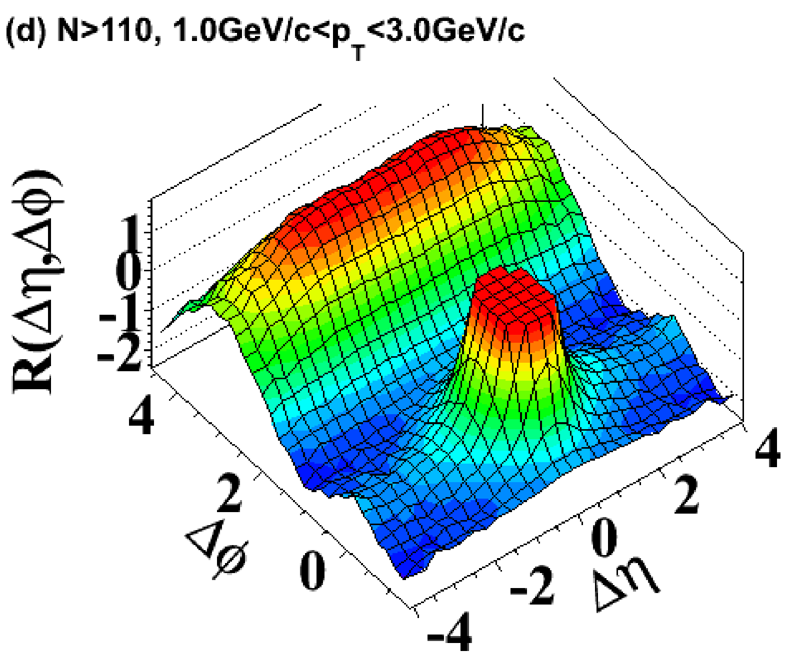
Formation of QCD bound states: Hadronization in higher-density partonic environments

- 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)

Links to collective behavior in high-multiplicity p+p, and in p+A?

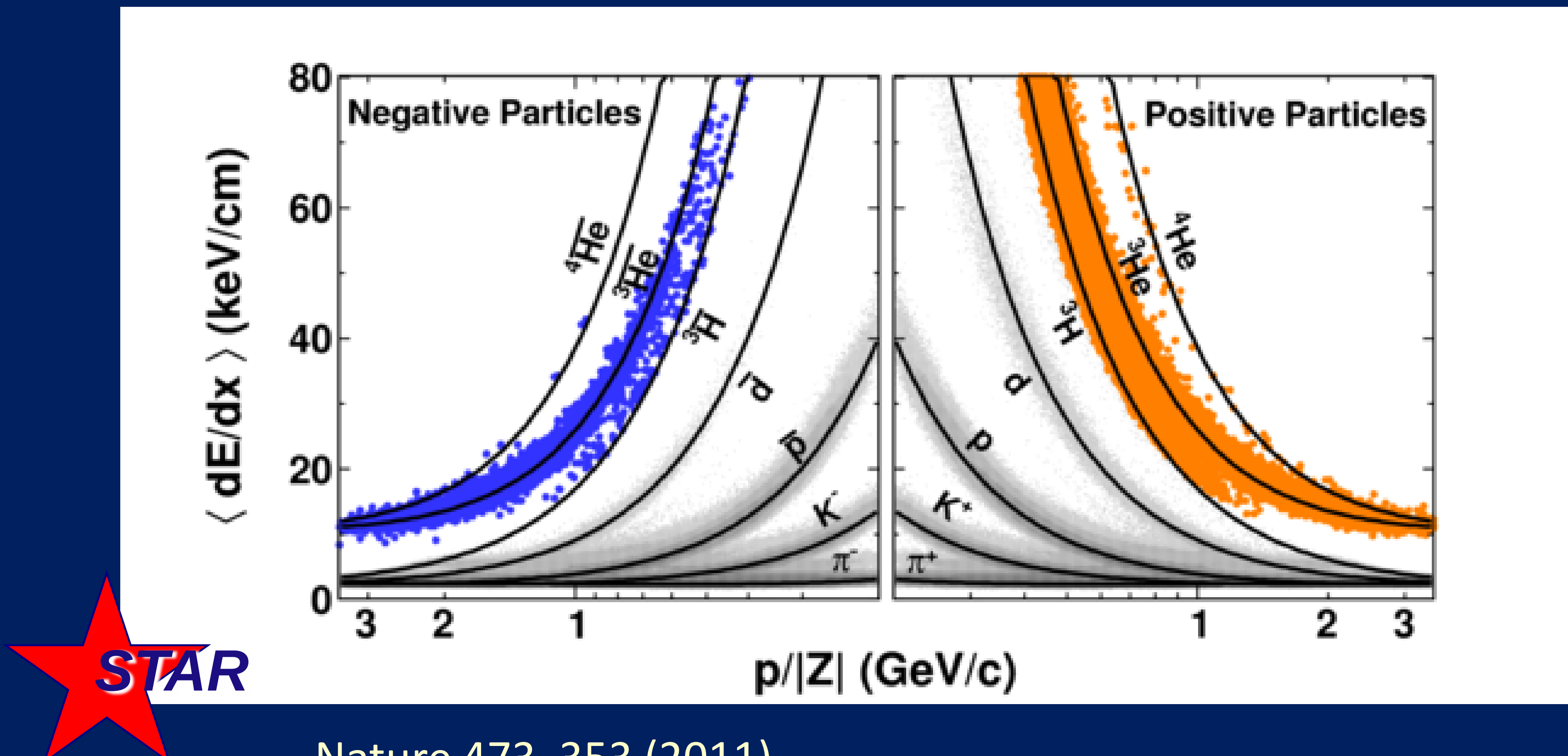


CMS JHEP 09 (2010), 091

Long-range correlations in high-multiplicity p+p at 7 TeV

Lots of interesting behavior when extra partons come into play, whether it's "hot" or "cold" QCD

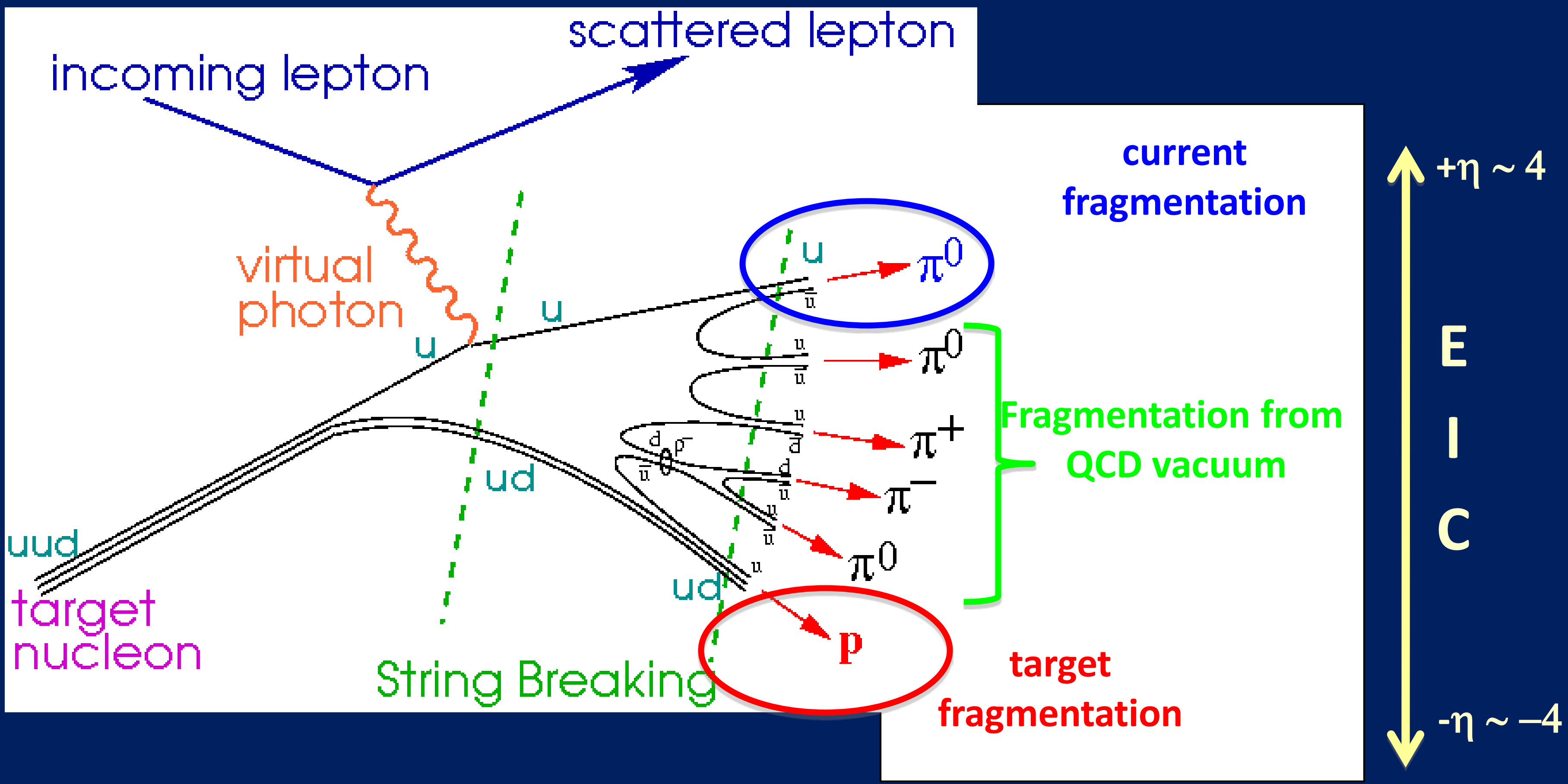
Formation of bound states of bound states: Creating nuclei



Nature 473, 353 (2011)

Will it be possible to create e.g. d, dbar in e+A??

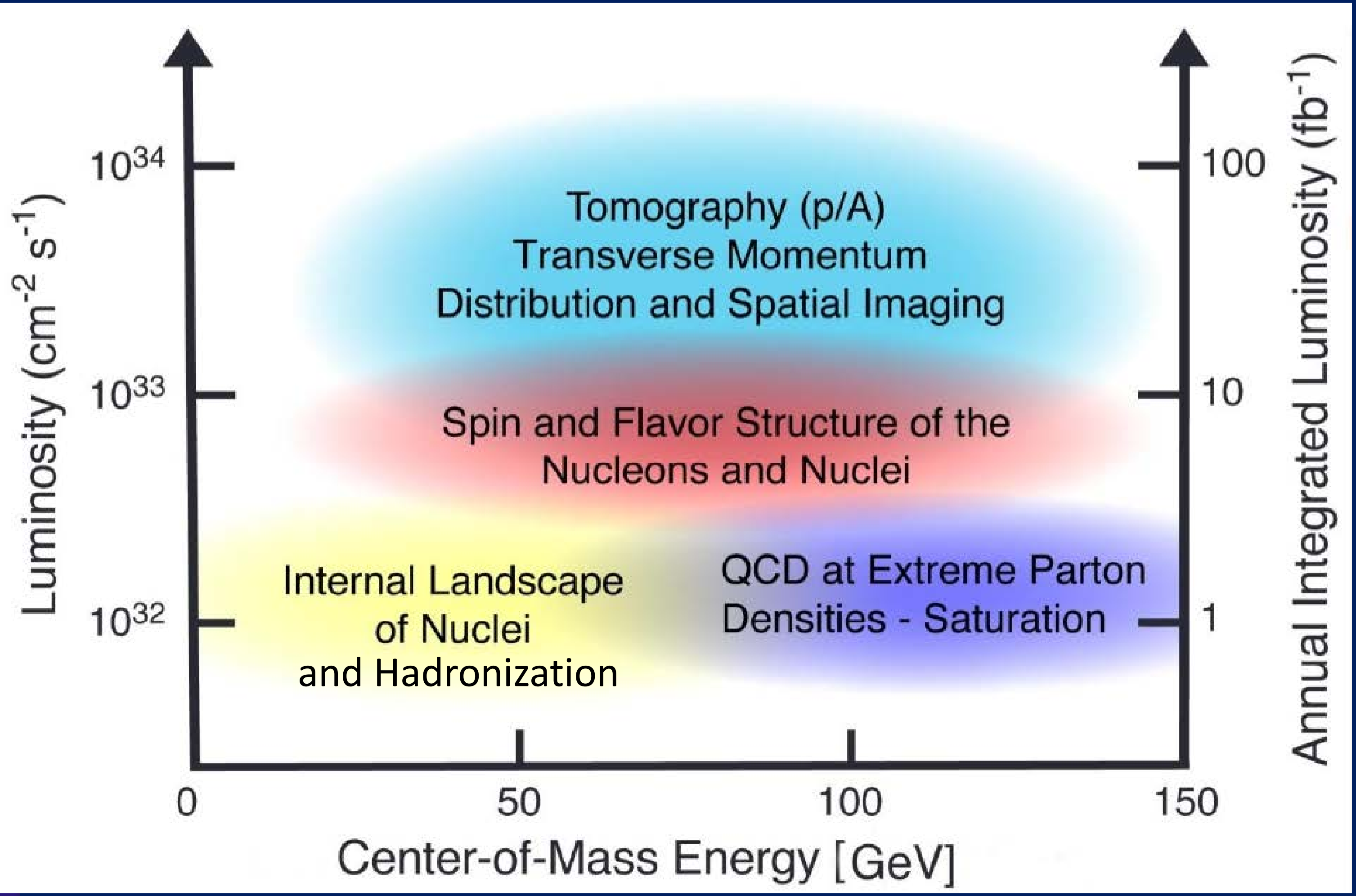
Formation of QCD bound states: Hadronization at EIC



Formation of QCD bound states: "Target fragmentation" region

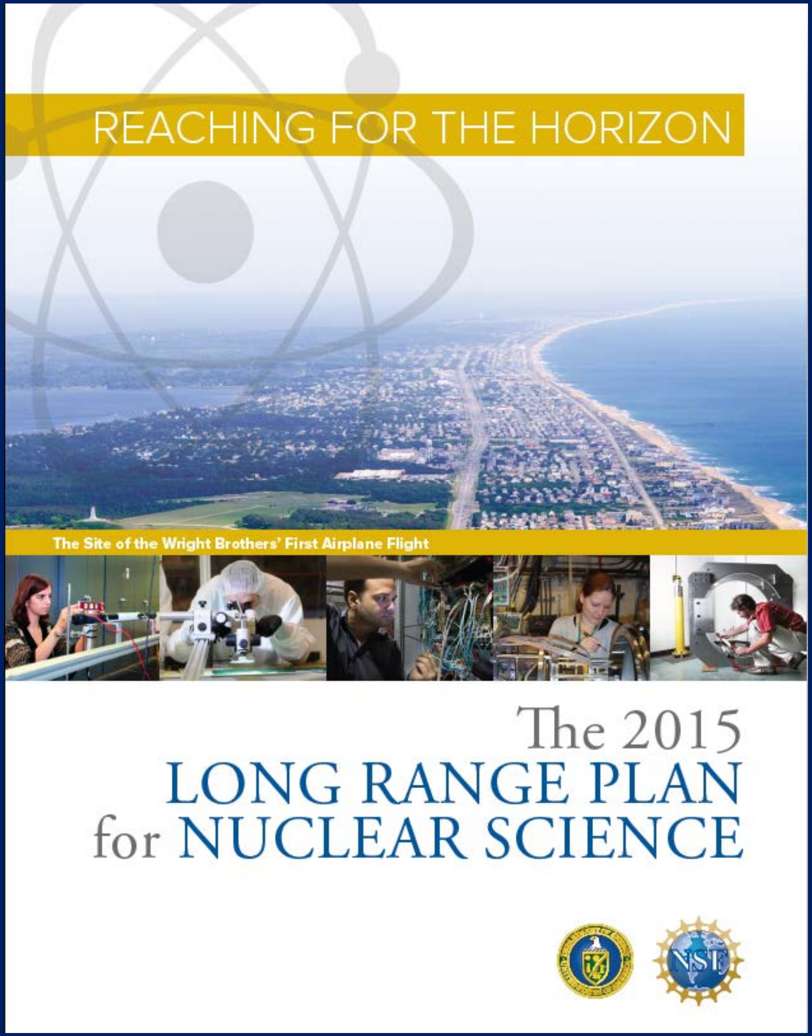
- Related to color neutralization of remnant—soft particle production
- Electron-Ion Collider will map out target fragmentation region well
  - Collider geometry – easier than in fixed-target to separate "current" from "target" fragmentation
- Connections to
  - "Underlying event" in hadron-hadron collisions
  - Forward hadron production in hadron-hadron collisions
  - Cosmic ray physics
- "Fracture functions" – theoretical tools to describe target fragmentation

EIC physics as a function of energy and luminosity



2015 U.S. Nuclear Physics Long-Range Plan

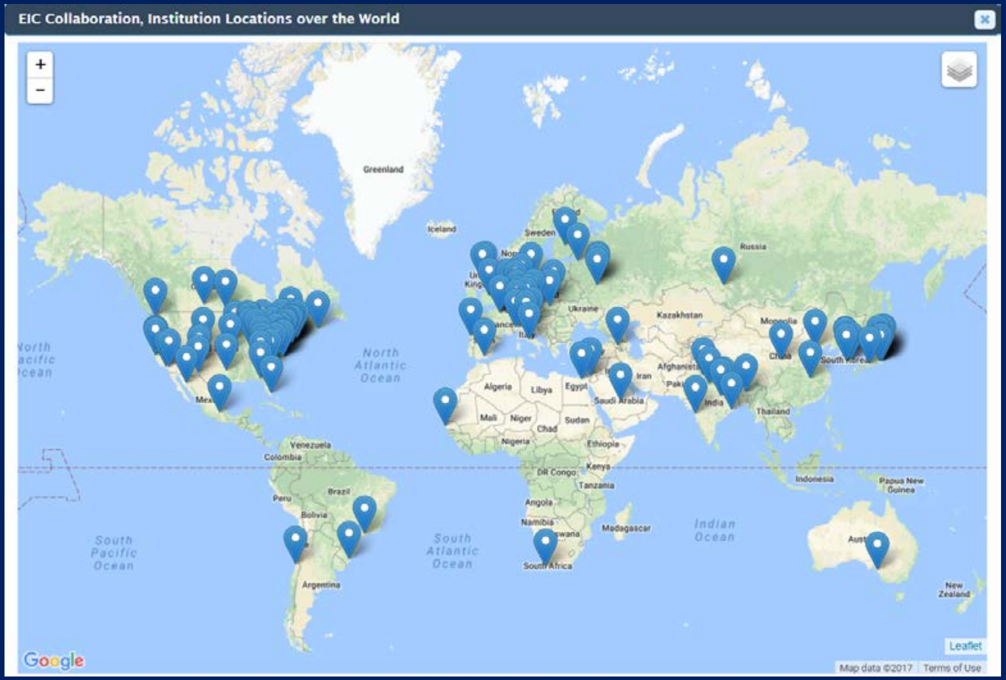
- EIC endorsed by U.S. nuclear community as highest priority facility for new construction after completion of Facility for Rare Isotope Beams (FRIB)



2016: Creation of EIC User Group

www.eicug.org

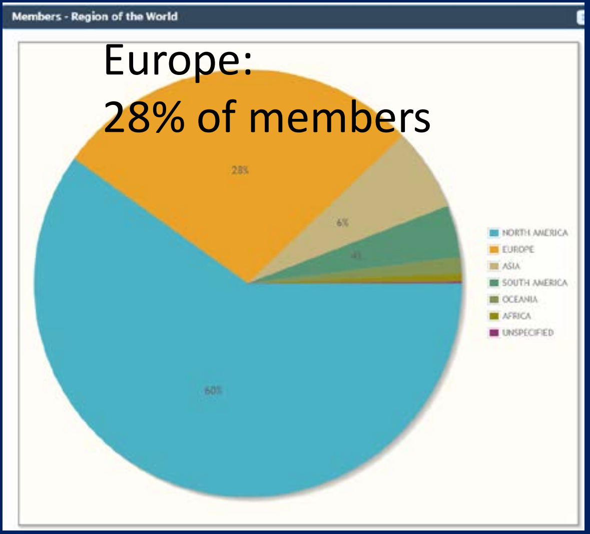
- 2015 Long-Range Plan prompted official formation of EIC User Group, consisting of interested members of the experimental, theoretical, and accelerator communities
- Goal to give community a stronger and more visible role in the process leading to the realization of an EIC
- Currently 816 members from 173 institutions in 30 countries



Strong EIC community within Europe

228 EICUG members from Europe, from 58 institutions

- Currently 8 German institutions, including Muenster



EICUG WEBSITE] PhoneBook: Electron-Ion Collider Users Group [close all tabs]

Intro | Institutions

Search:

Full name of the institution	Institution acronym	Country	Region of the World
Deutsches Elektronen-Synchrotron (DESY)	DESY	GERMANY	EUROPE
GSI		GERMANY	EUROPE
Max-Planck Institute for Physics Munich	MPI Munich	GERMANY	EUROPE
Universitaet Regensburg		GERMANY	EUROPE
University of Hamburg	Hamburg	GERMANY	EUROPE
University of Mainz		GERMANY	EUROPE
University of Muenster		GERMANY	EUROPE
University of Tuebingen		GERMANY	EUROPE

2017-18: U.S. National Academy of Sciences review of EIC science

- National Academy of Sciences: Established in 1863 by an Act of Congress, signed by President Lincoln, as a private, non-governmental institution to advise the nation on issues related to science and technology

- In 2016, Dept. of Energy charged the National Academy of Sciences to assess the science case for a U.S.-based Electron-Ion Collider
- Positive report released July 24, 2018
  - Dept. of Energy has initiated discussions with Congress and the White House Office of Management and Budget
  - Next anticipated step is "Critical Decision 0," formal recognition by the Dept. of Energy of scientific mission need for such a facility

An Assessment of
U.S.-Based Electron-Ion Collider Science

Committee on U.S.-Based Electron-Ion Collider Science Assessment

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

A Consensus Study Report of

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

THE NATIONAL ACADEMIES PRESS
Washington, DC
www.nap.edu

https://www.nap.edu/catalog/25171/an-assessment-of-us-based-electron-ion-collider-science

Conclusions

- These are exciting times in QCD!
- Complementary facilities, as well as theoretical advances, are allowing us to probe QCD's rich complexities in ever-greater detail, with ever-increasing sophistication
  - Part of new era of QCD as a more mature field

Conclusions

- An Electron-Ion Collider with
  - polarized electrons
  - a range of unpolarized nuclear species
  - polarized protons and polarized light nuclei
  - center-of-mass energies from ~30 to ~100 GeV
  - luminosities 10^{33} -10^{34} cm^{-2} s^{-1}

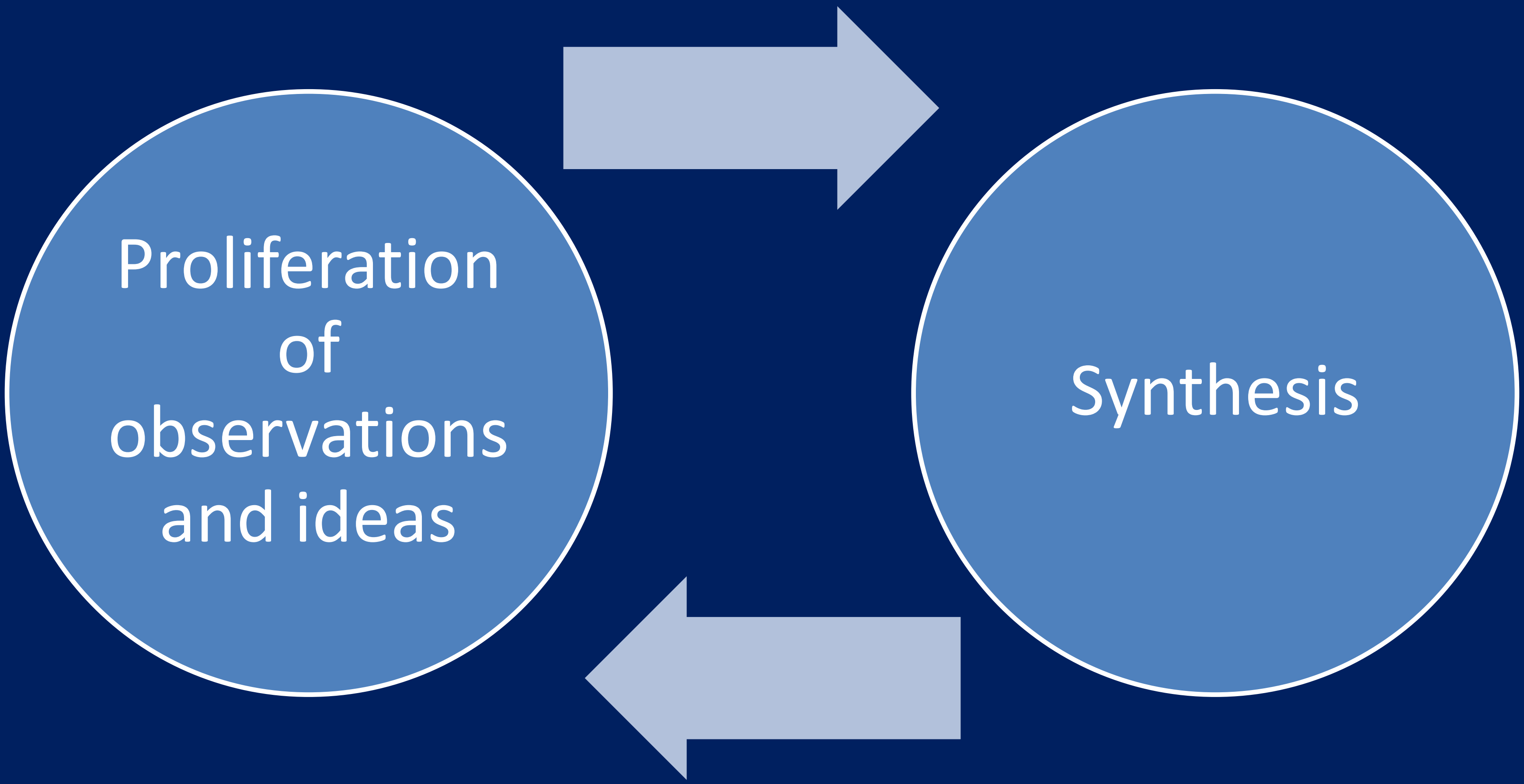
will be the next major facility to bring this new era to fulfillment, addressing fundamental questions in QCD:

- How do we describe different QCD systems in terms of their quark and gluon degrees of freedom?
- In what ways can colored quarks and gluons form colorless QCD bound states?
- What are unique properties of QCD interactions?

After a long road, many developments in the past three years! Look for more to come in the near future …

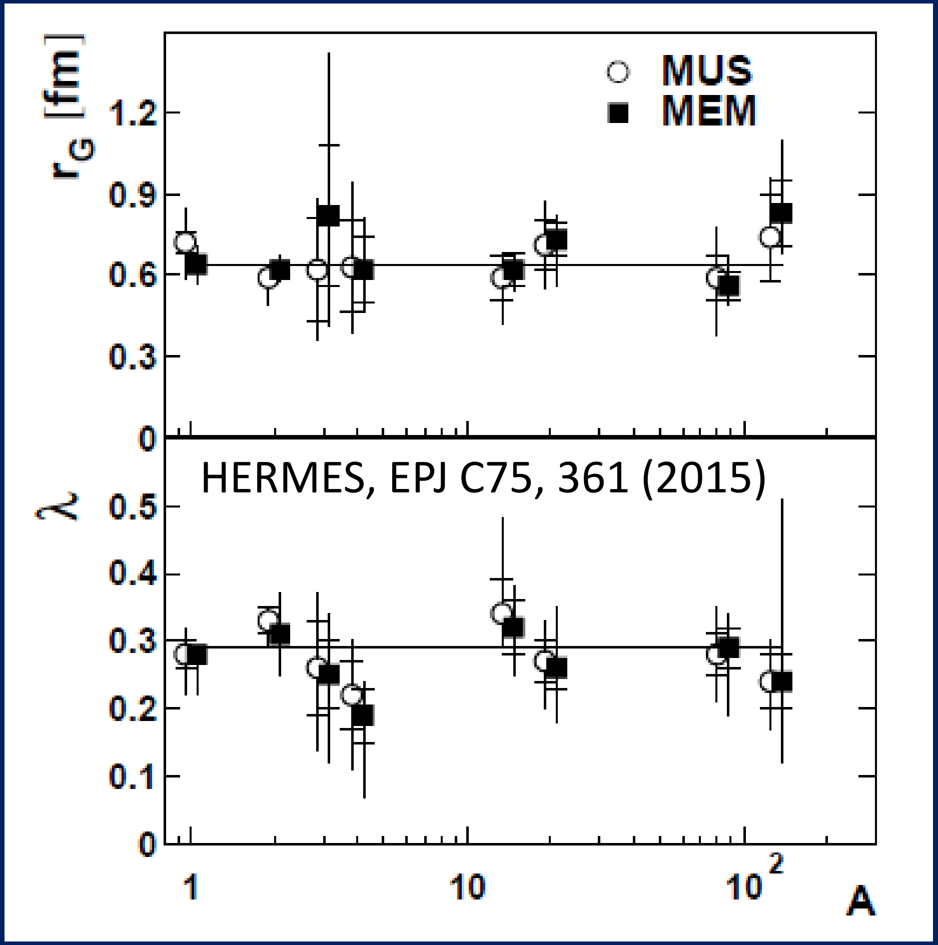
Extra

EIC will bring us through another cycle

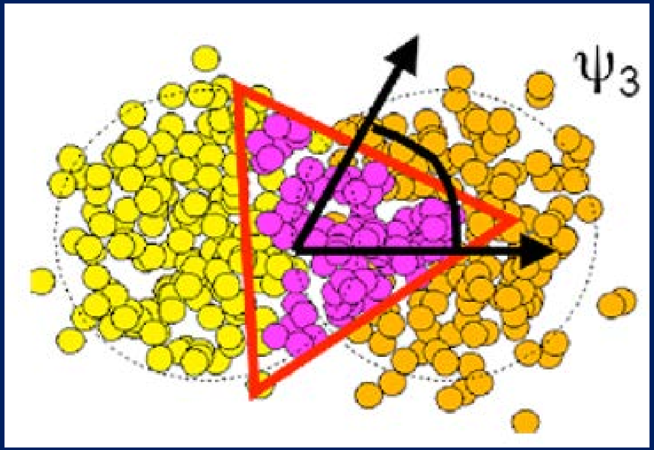


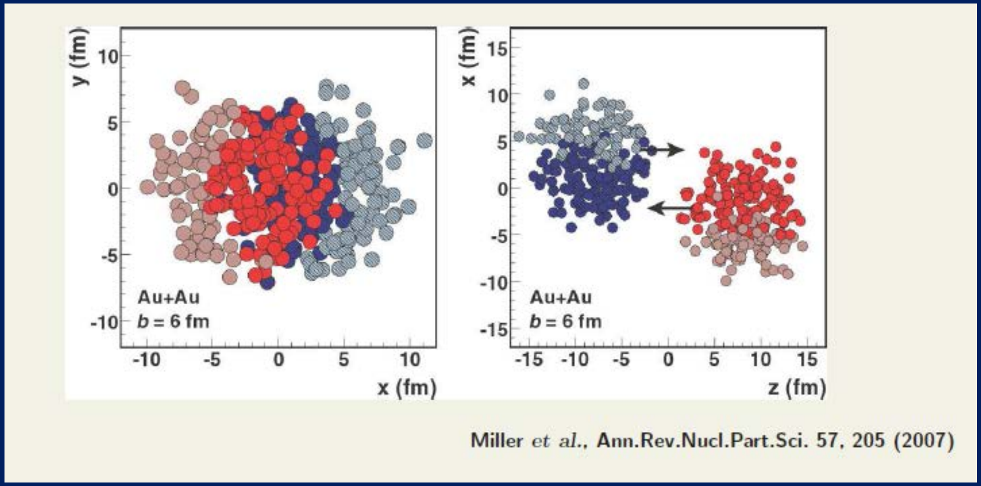
Bose-Einstein correlations for nuclear semi-inclusive DIS

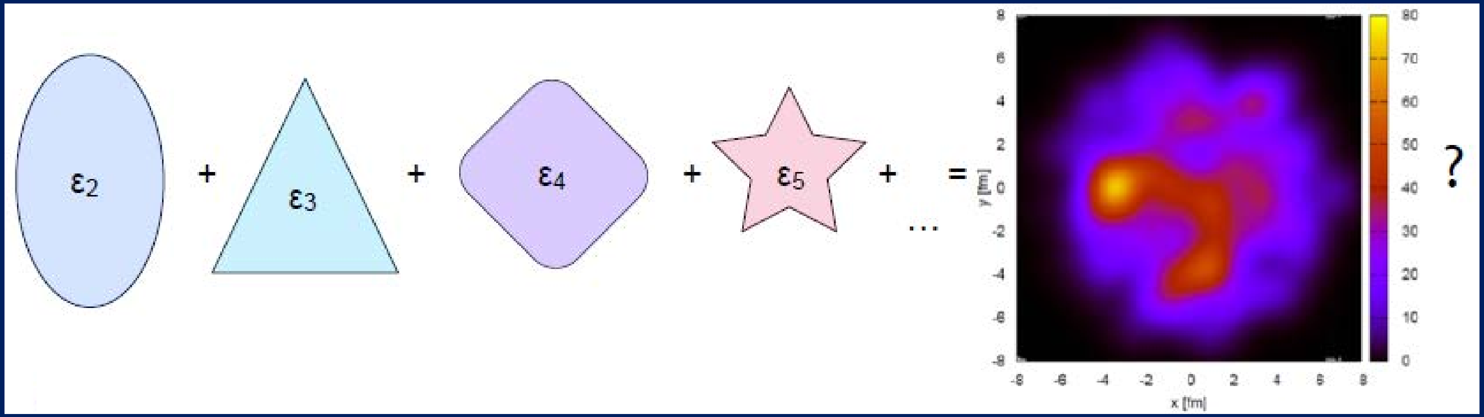
- Sensitive to spatial separation of production of the two particles
- No nuclear dependence found within uncertainties



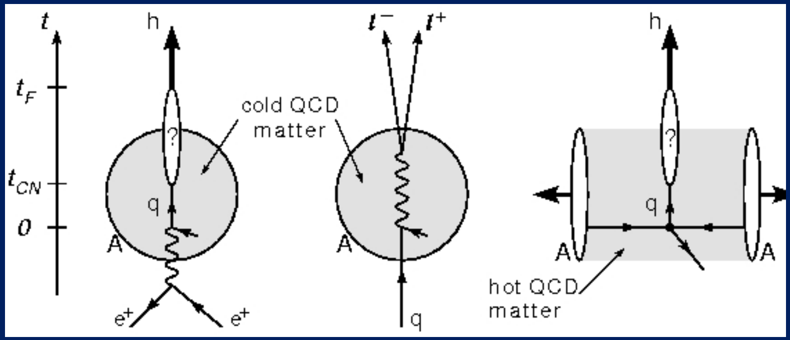
Local density in nuclei is important!



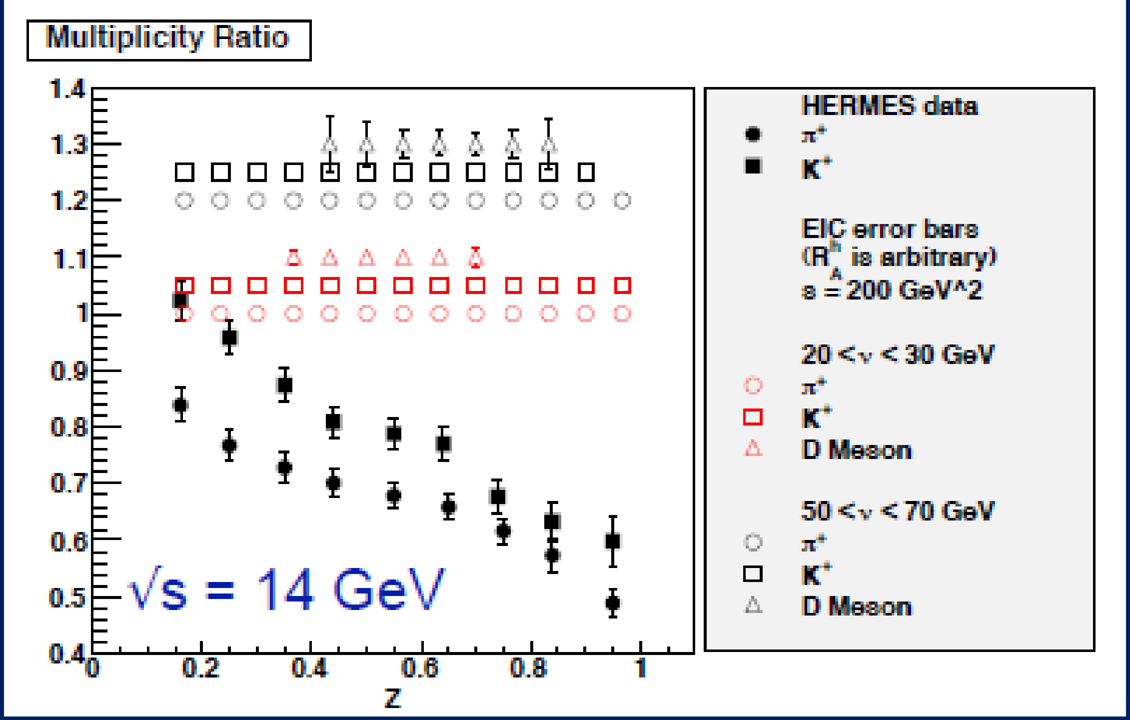




Hadronization: Parton propagation in matter



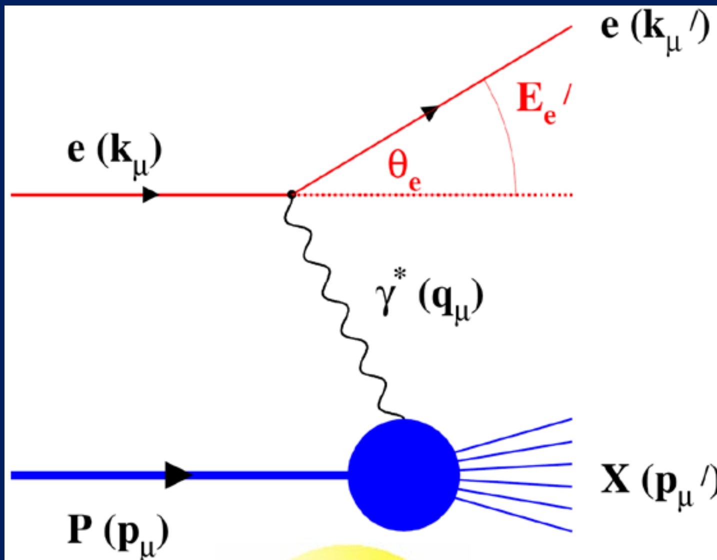
- Interaction of fast color charges with matter?
- Conversion of color charge to hadrons through fragmentation and breakup?



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

Accessing quarks and gluons through DIS

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e (1 - \cos\Theta_{e'})$$

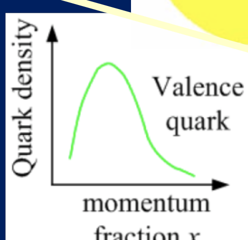
Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

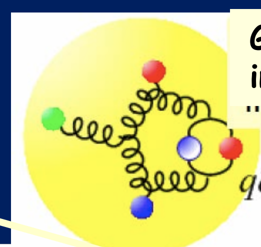
Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

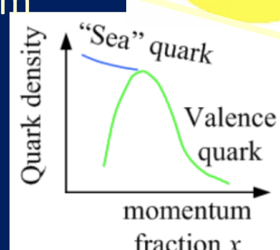
Measure of momentum fraction of struck quark

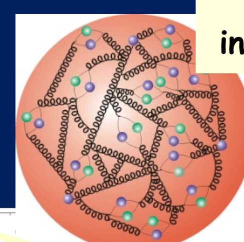


10^{-16}m

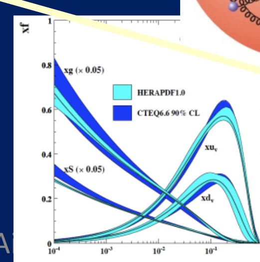


Gluon splits into quarks





Quark splits into gluon splits into quarks …

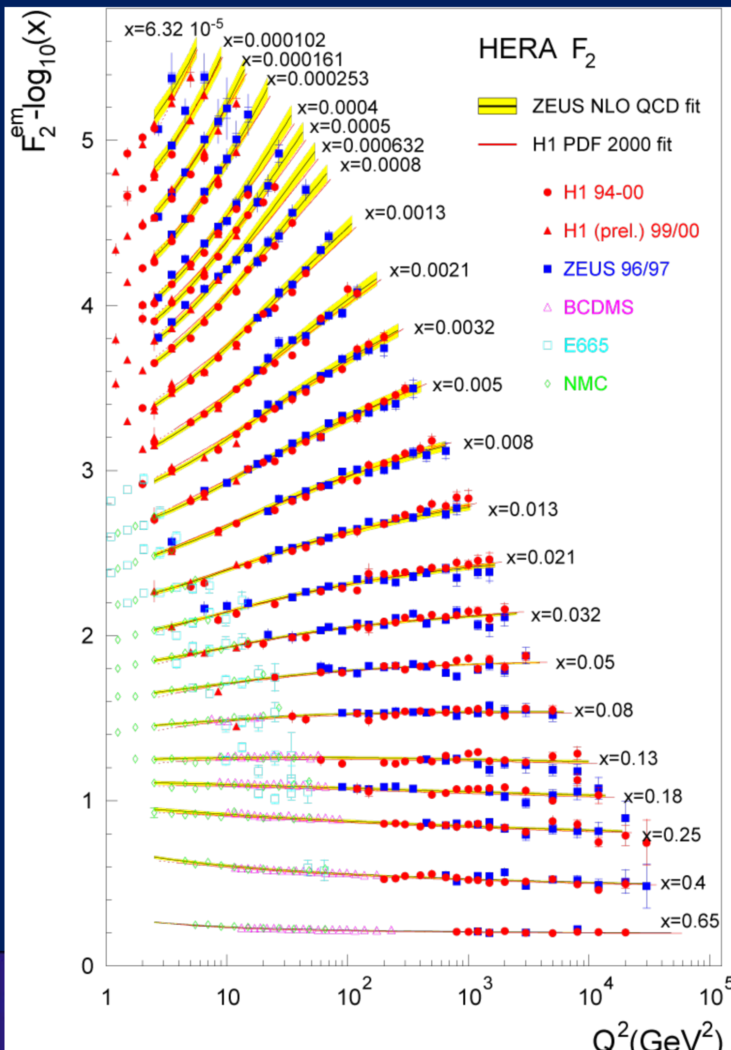


10^{-19}m

higher √s increases resolution

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 $Q^2 \rightarrow G(x,Q^2)$

OR

Via F_L structure function

OR

Via dihadron production

OR

Via diffractive scattering

Accessing gluons with an electroweak probe

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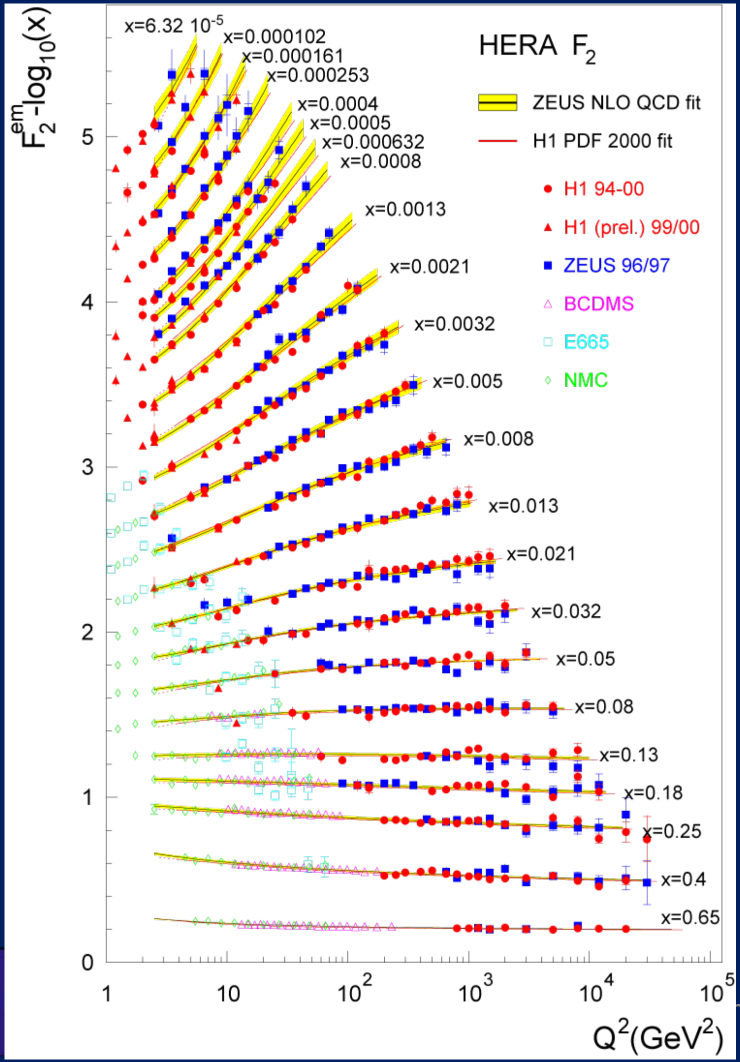
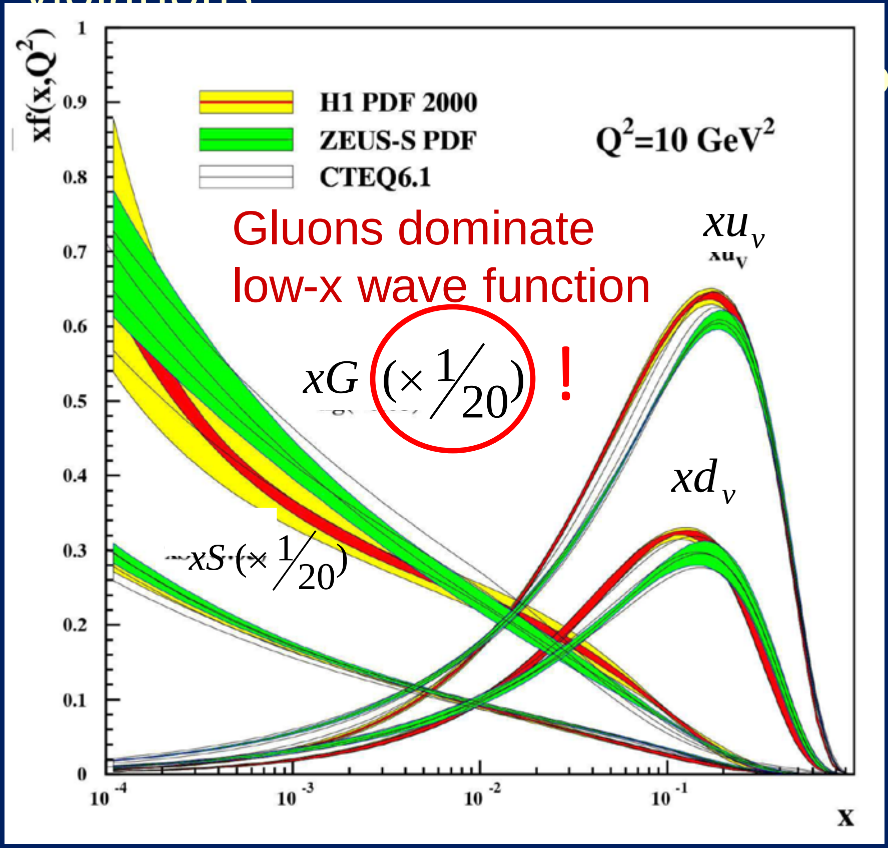


Access the gluons in DIS via scaling violations:

...n in



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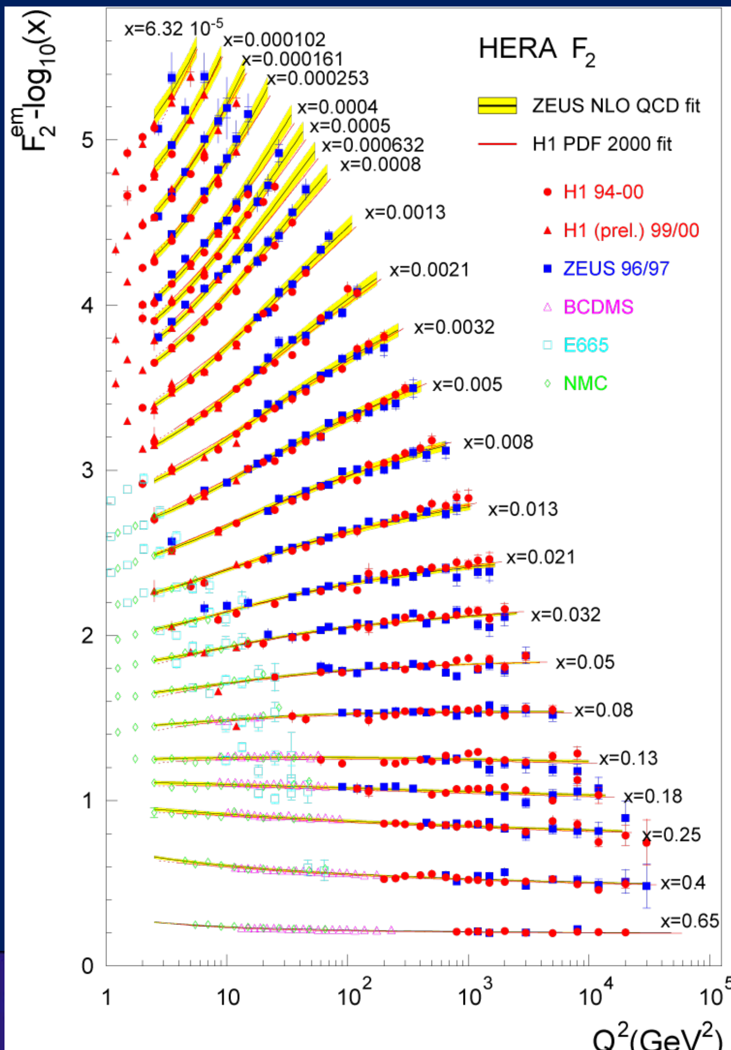
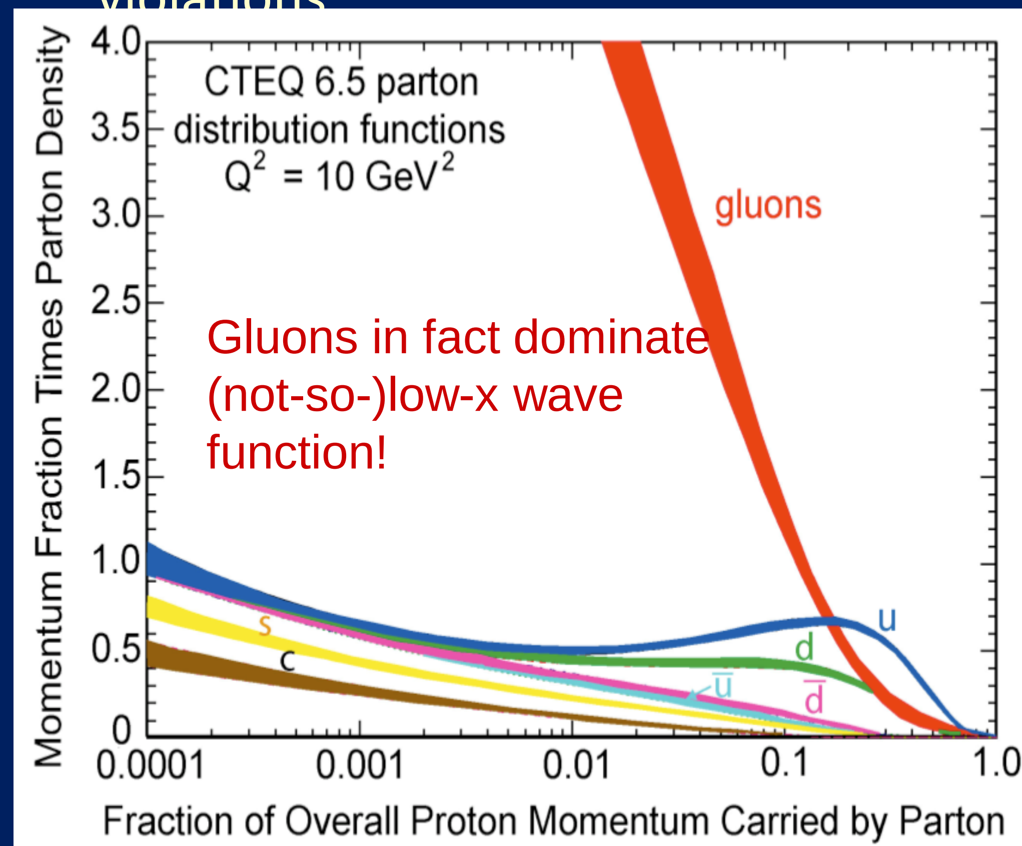
Access the gluons in DIS via scaling violations:

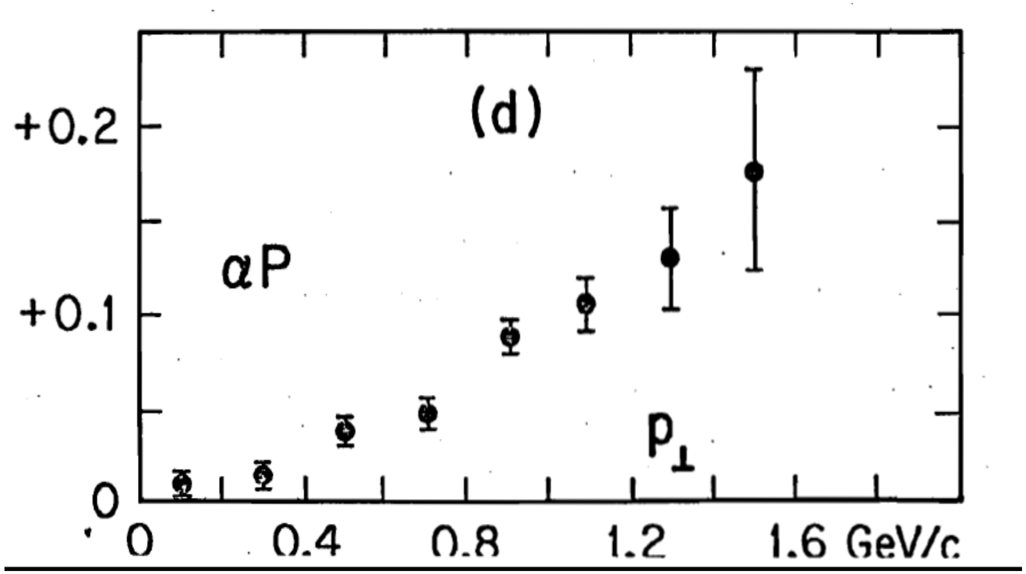




Hyperon polarization from unpolarized collisions

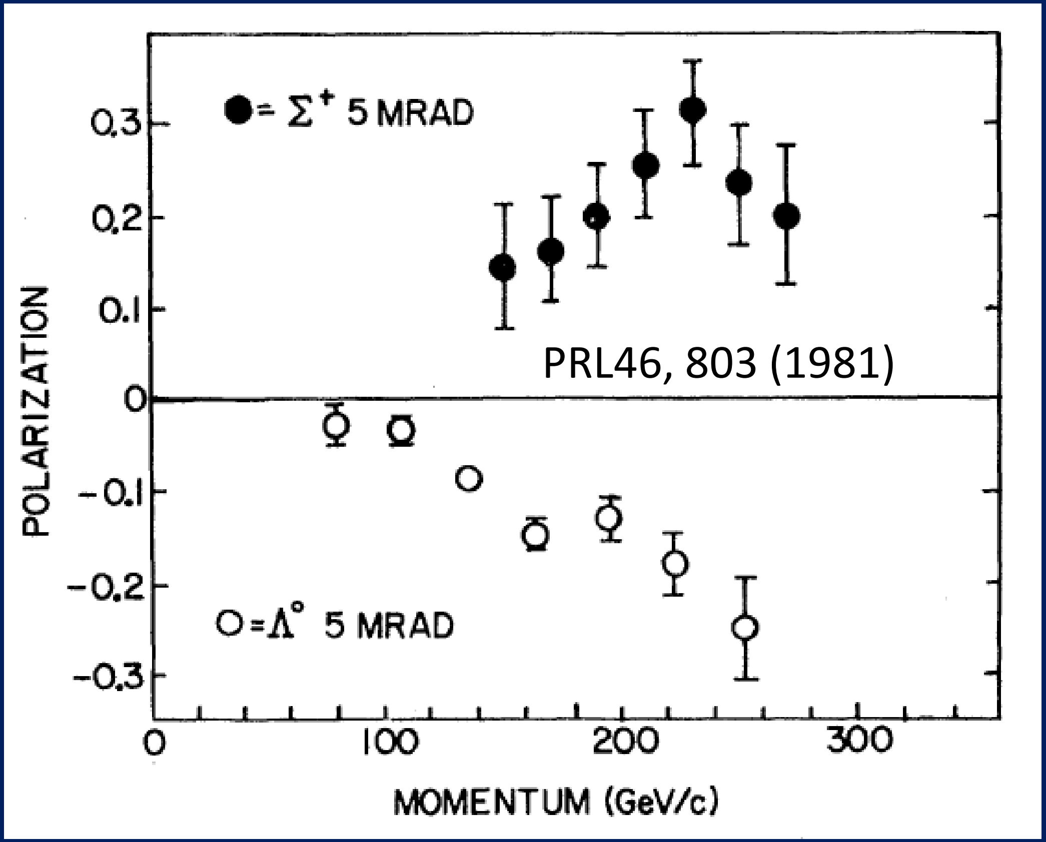
Λ^0 Hyperon Polarization in Inclusive Production by 300 GeV Protons on Beryllium

PRL36, 1113 (1976)



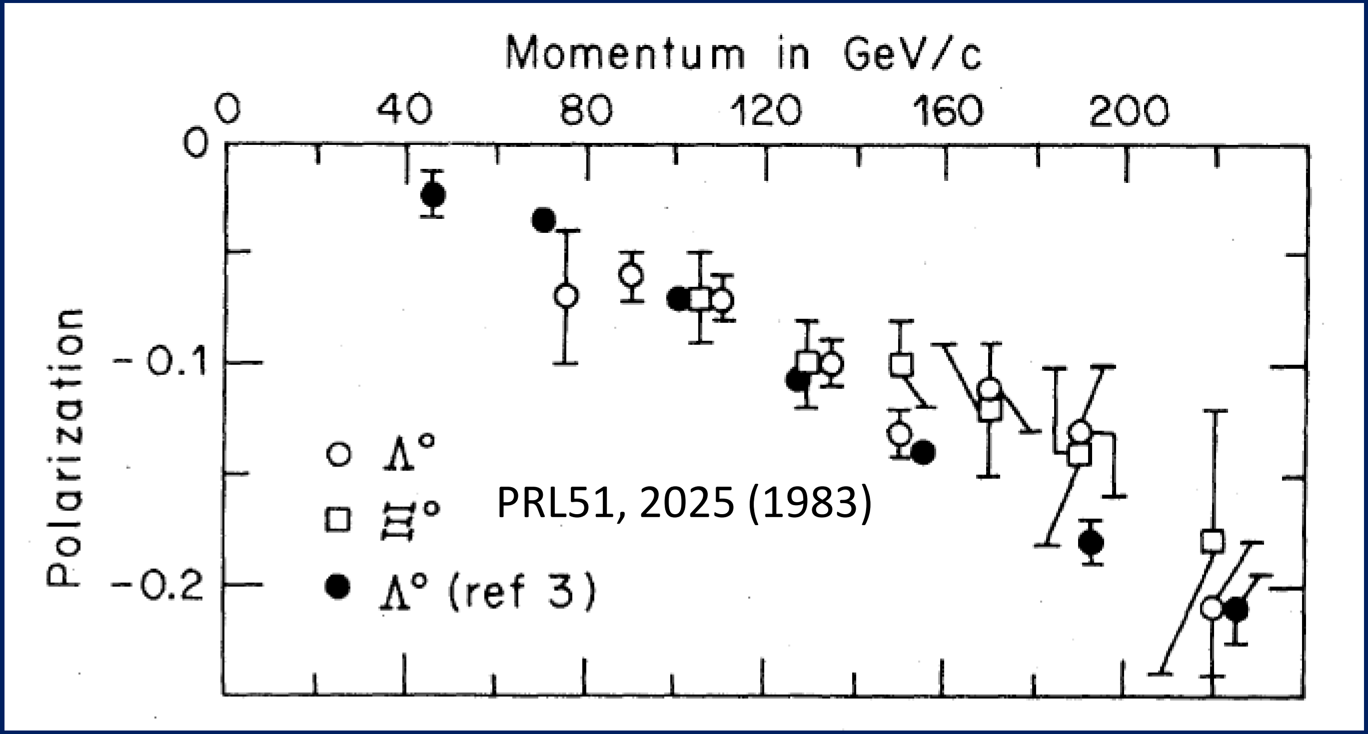
- 1976 lambda polarization discovery: p+Be, 300 GeV beam
- Polarization transverse to production plane up to ~20% for forward-angle lambda production; Polarizing TMD FF?
- Confirmed 1977 at CERN, p+Pt, 24 GeV beam (and by various proton-nucleus and proton-proton experiments afterwards . . .)

Σ^+ polarized with opposite sign



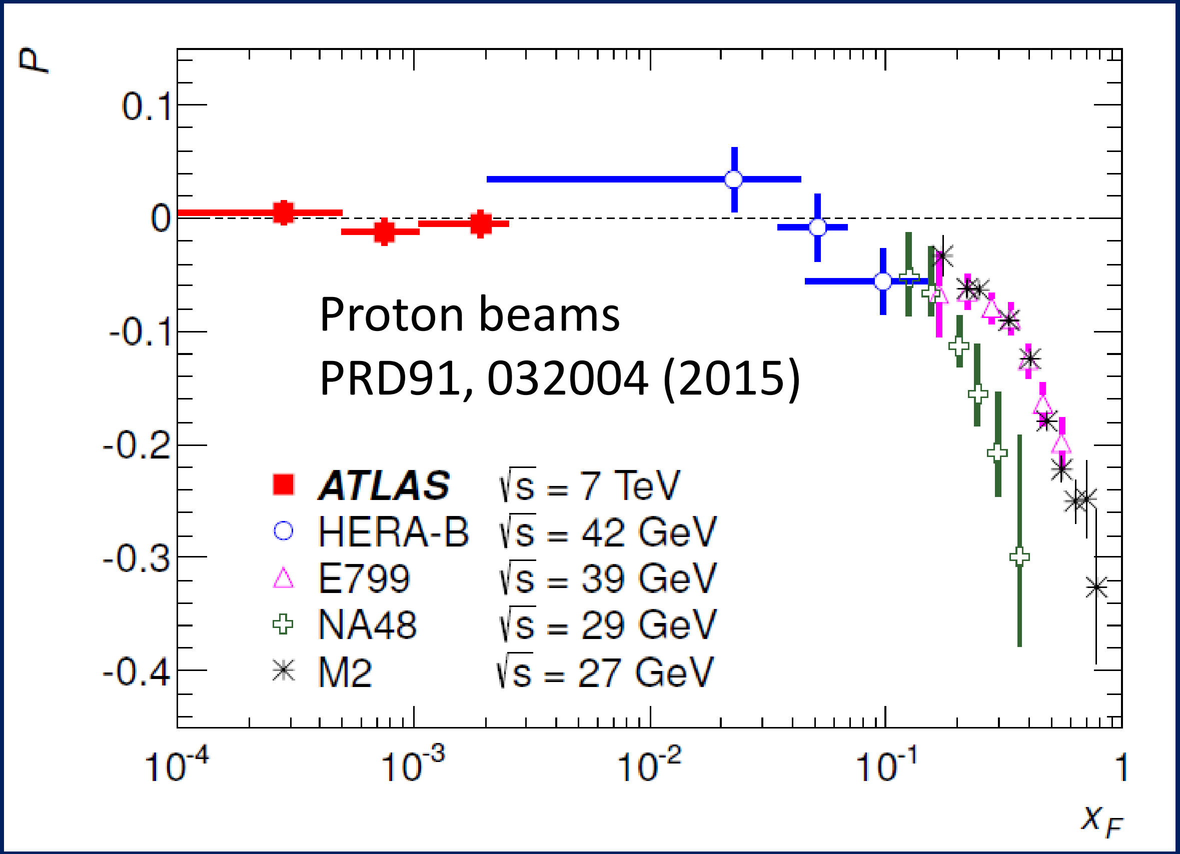
- 1981: p+Be, 400 GeV beam

Ξ^0 polarization similar to Λ^0



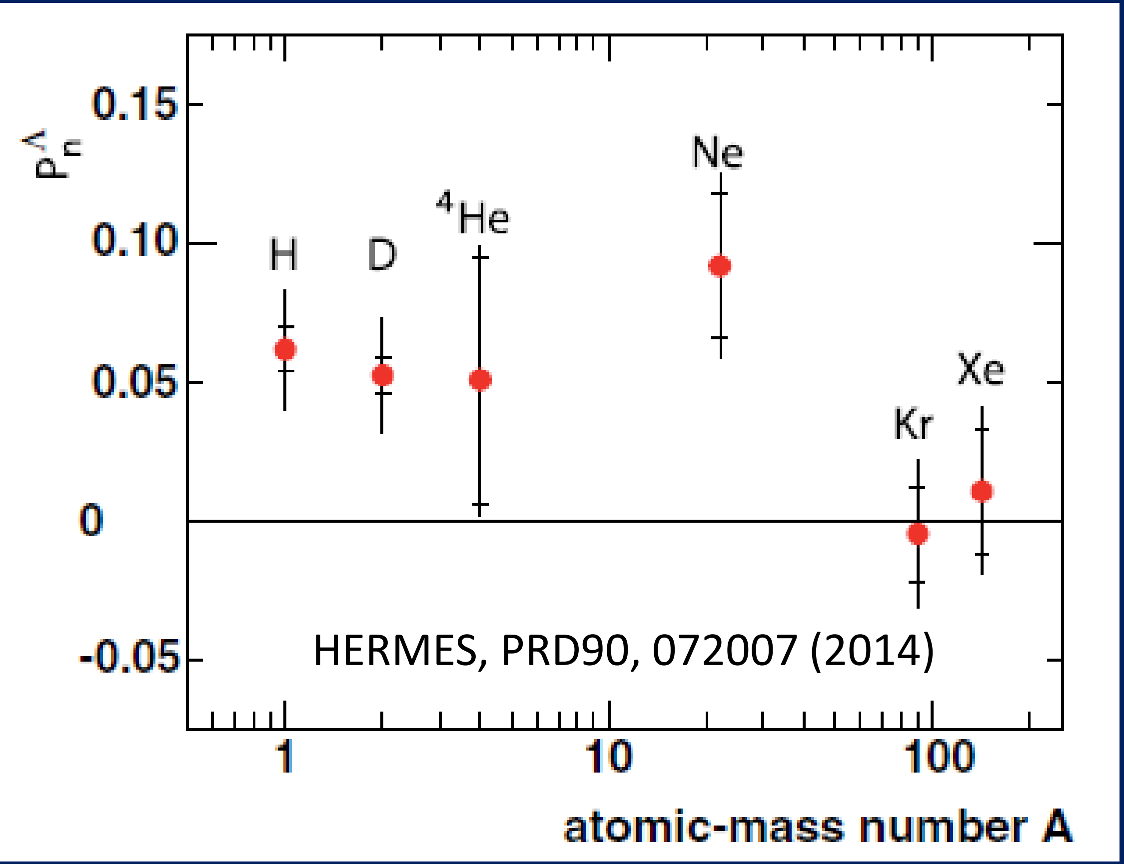
- 1983: p+Be, 400 GeV beam
- Similar results for p+Cu and p+Pb

x_F dependence of lambda polarization in hadronic collisions



- Same sign and general x_F dependence for neutron beams
- But for K- and Σ- beams, positive polarization at positive x_F
- And for π- beam, positive polarization but at negative x_F!
- Consistent with zero for π+ and K+ beams

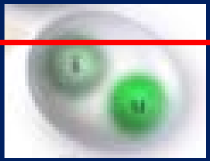
Lambda polarization observed in semi-inclusive DIS

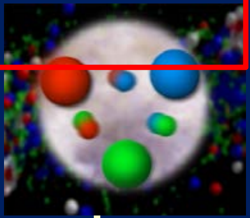


- Nonzero in both forward and backward directions

Structure/Properties of QCD matter

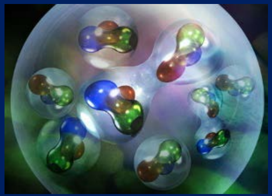
- Bound states: Mesons and baryons

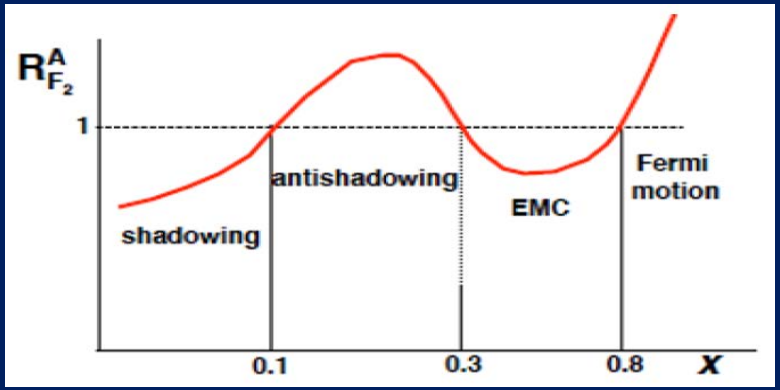




EIC will address!

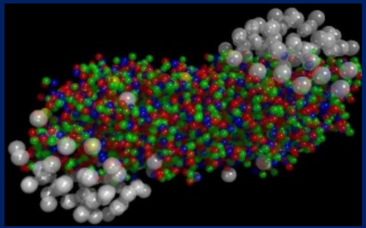
- Bound states of bound states: Nuclei, neutron stars



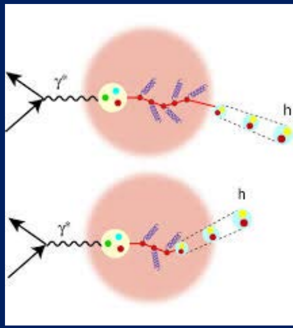


Nuclei aren't just superpositions of free nucleons!

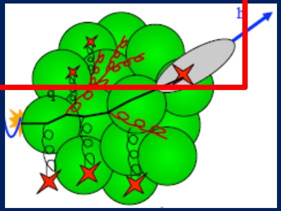
- Deconfined states: Quark-gluon plasma



Formation of states of QCD matter

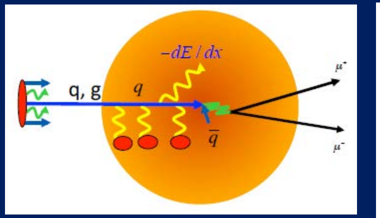


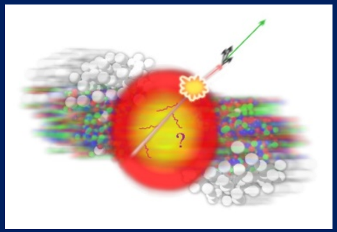
- Hadronization mechanisms
- Formation of bound states of bound states
- Jet structure
- Equilibration of QGP
- Time scales of hadronization/equilibration
- Modification of hadronization in different environments



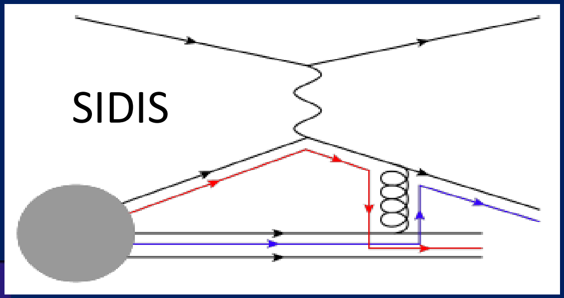
Interactions within QCD

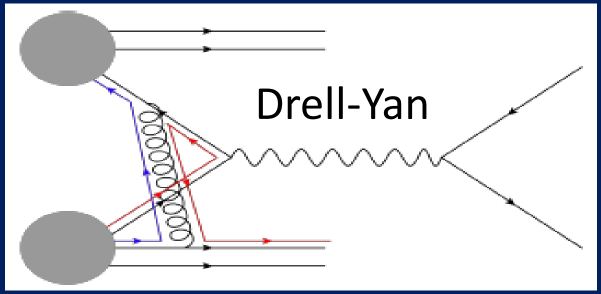
- Parton energy loss in cold and hot QCD matter
- Flow of partons within quark-gluon plasma





- Quantum interference and phase shifts
  - E.g. quantum interference effects in hadronization
    - One parton → multiple hadrons
    - Multiple partons → one hadron
- Color flow effects
  - Process-dependent spin-momentum correlations in hadrons
  - Quantum entanglement of partons across colliding hadrons





eRHIC parameters

TABLE 4.1 Main Parameters of eRHIC for Collisions of Protons, at Their Maximum Energy of 275 GeV, with 10 GeV Electrons

		No Hadron Cooling		Strong Hadron Cooling	
Parameter	**Units**				
Particle		Protons	Electrons	Protons	Electrons
Center of Mass Energy	GeV	105		105	
Beam Energy	GeV	275	10	275	10
Collision Frequency	MHz	56.3		112.6	
Particles/bunch	1.00E+10	10.5	30	6	15.1
Beam Current	A	0.87	2.5	0.99	2.5
Bunch length, RMS	cm	7	1.9	5	1.9
Emittance norm (x,y)	µm	4.1/2.50	391/87.1	2.7/0.36	391/19.0
Luminosity / IP	1.0 E34 cm-2s-1	0.44		1.02	

From U.S. National Academy of Sciences report:
https://www.nap.edu/catalog/25171/an-assessment-of-us-based-electron-ion-collider-science

JLEIC parameters

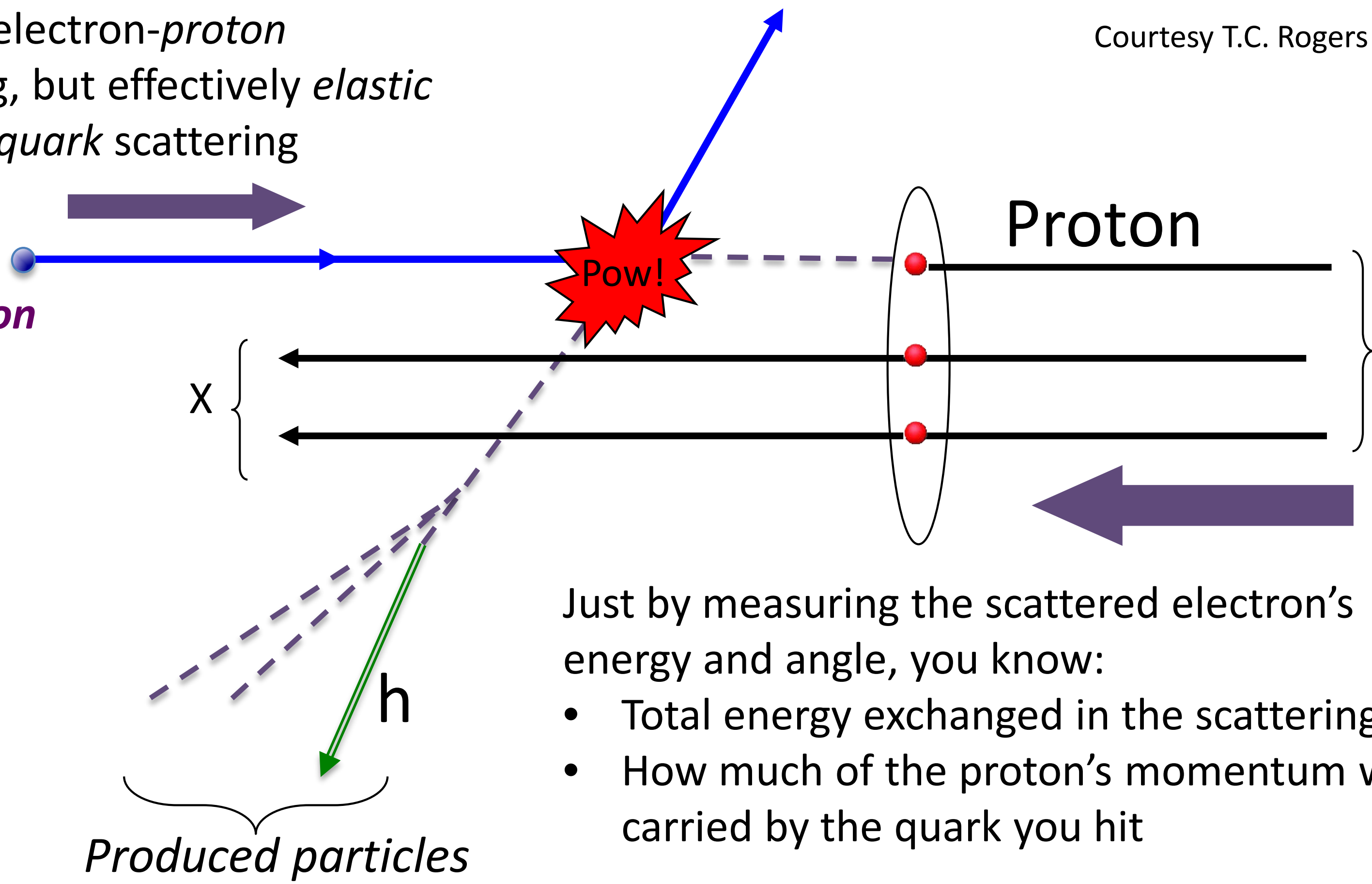
TABLE 4.2 Main Parameters of the Jefferson Laboratory Electron-Ion Collider for Collisions of Protons with Electrons for a Full Acceptance Detector

		Low CM Energy		Medium CM Energy		High CM Energy	
Parameter	**Units**						
Particle		Protons	Electrons	Protons	Electrons	Protons	Electrons
Center of Mass Energy	GeV	21.9		44.7		63.3	
Beam Energy	GeV	40	3	100	5	100	10
Collision Frequency	MHz	476		476		476/4=119	
Particles/bunch	1.00E+10	0.98	3.7	0.98	3.7	3.9	3.9
Beam Current	A	0.75	2.8	0.75	2.8	0.75	0.71
Bunch length, RMS	cm	3	1	1	1	2.2	1
Emittance norm (x,y)	µm	0.3/0.3	24/24	0.5/0.1	54/10.8	0.9/0.18	432/86
Luminosity / IP	1.0 E34 cm-2s-1	0.25		2.14		0.59	

From U.S. National Academy of Sciences report:
https://www.nap.edu/catalog/25171/an-assessment-of-us-based-electron-ion-collider-science

Electron-proton scattering

Inelastic electron-*proton* scattering, but effectively *elastic* electron-*quark* scattering



Just by measuring the scattered electron's energy and angle, you know:

- Total energy exchanged in the scattering
- How much of the proton's momentum was carried by the quark you hit