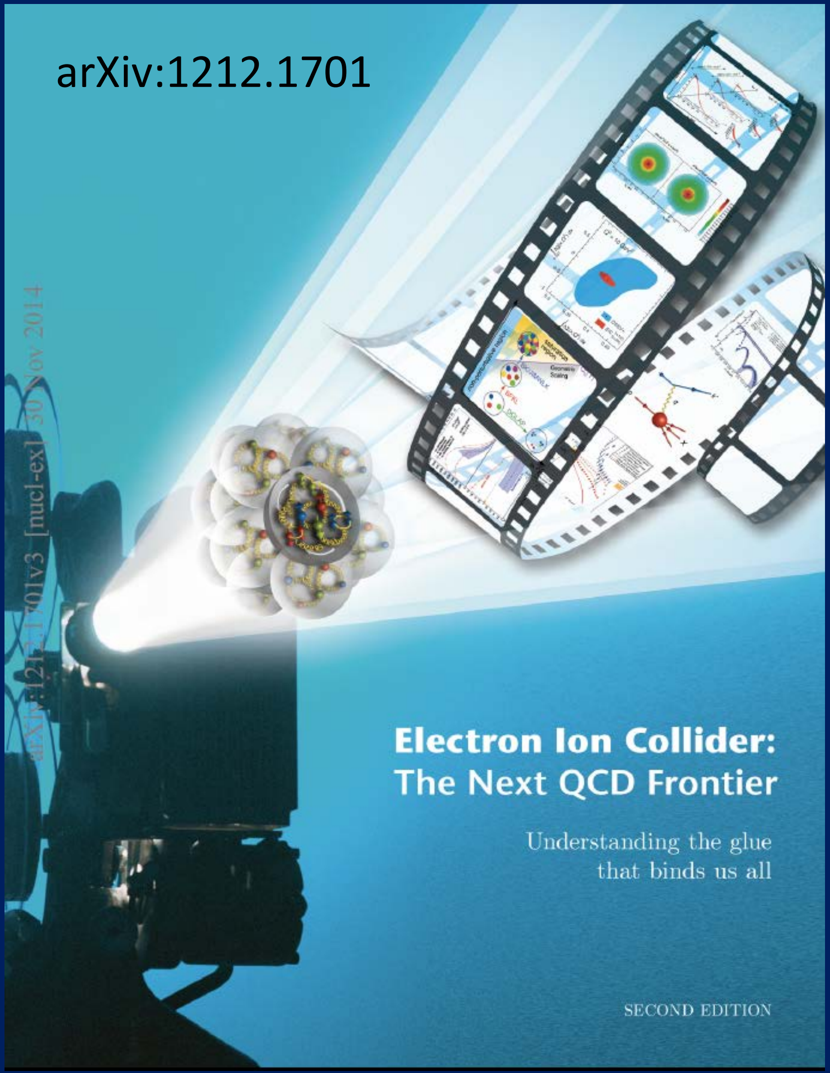
The Electron-Ion Collider: A New Tool for Studying QCD



Christine A. Aidala
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Student Day, Quark Matter 2017
Chicago
February 5, 2017

Areas of study in QCD

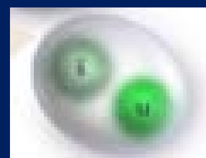
- *Structure/properties* of QCD matter

- *Formation* of states of QCD matter

- *Interactions* within QCD

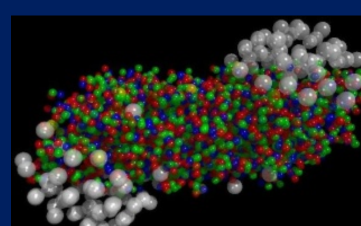
Structure/Properties of QCD matter

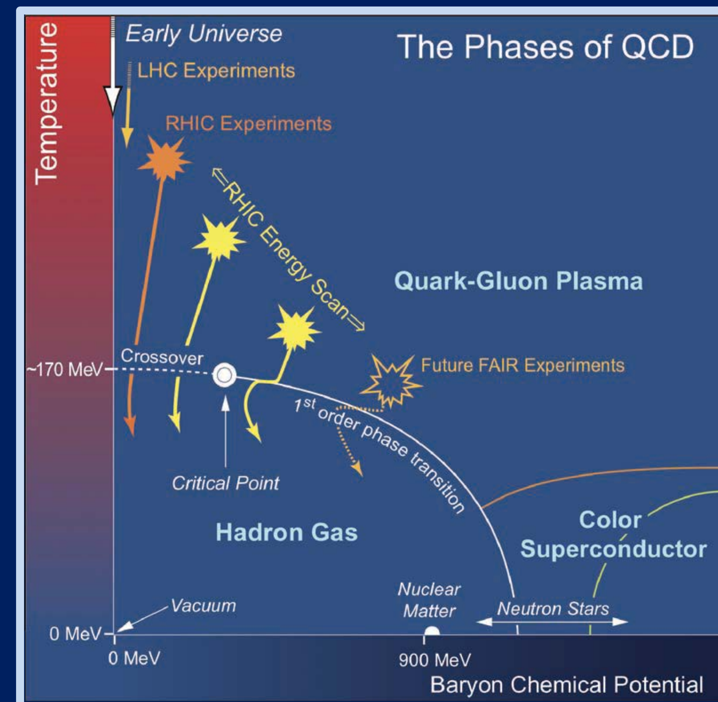
- Bound states: Mesons and baryons



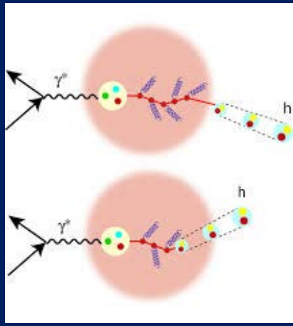

- Bound states of bound states: Nuclei, neutron stars


- Deconfined states: Quark-gluon plasma

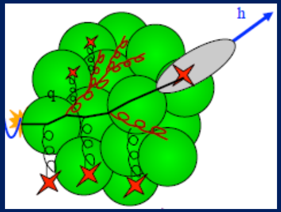




Formation of states of QCD matter

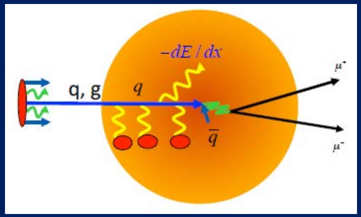


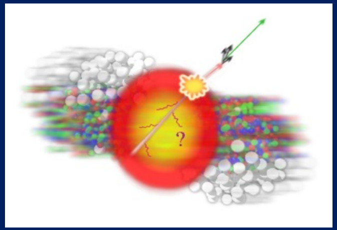
- Hadronization mechanisms
- Formation of bound states of bound states
- Jet structure
- Equilibration of QGP
- Time scales of hadronization/equilibration
- Modification of hadronization in different environments



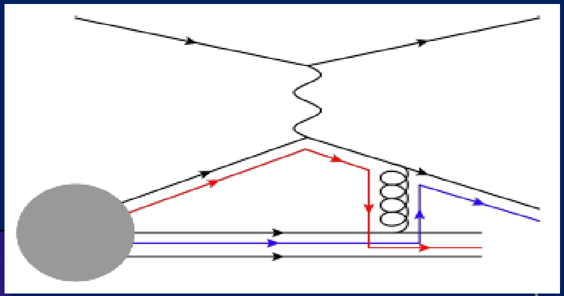
Interactions within QCD

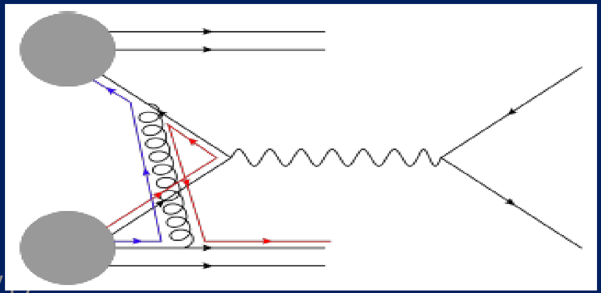
- Parton energy loss in cold and hot QCD matter
- Flow of partons within QGP





- 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: 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

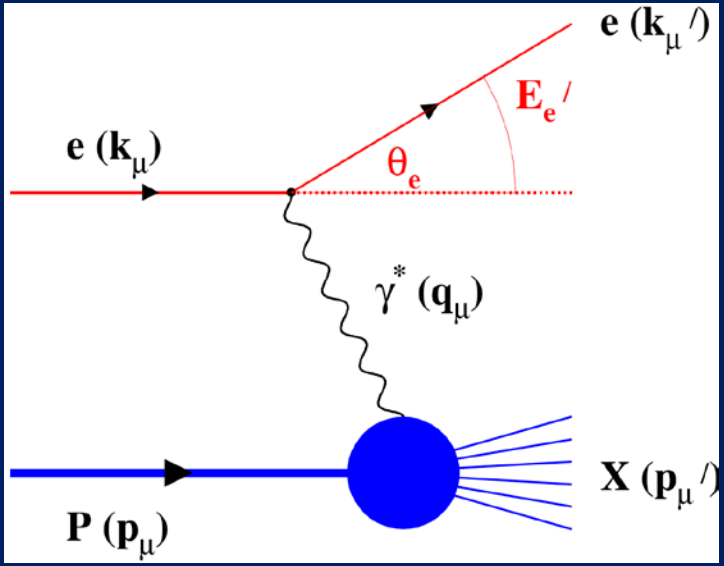
- Centrality, final-state produced particles and their kinematics

Multidifferential measurements even more powerful

- p_T, rapidity, centrality, angular distribution/correlation, PID, . . .

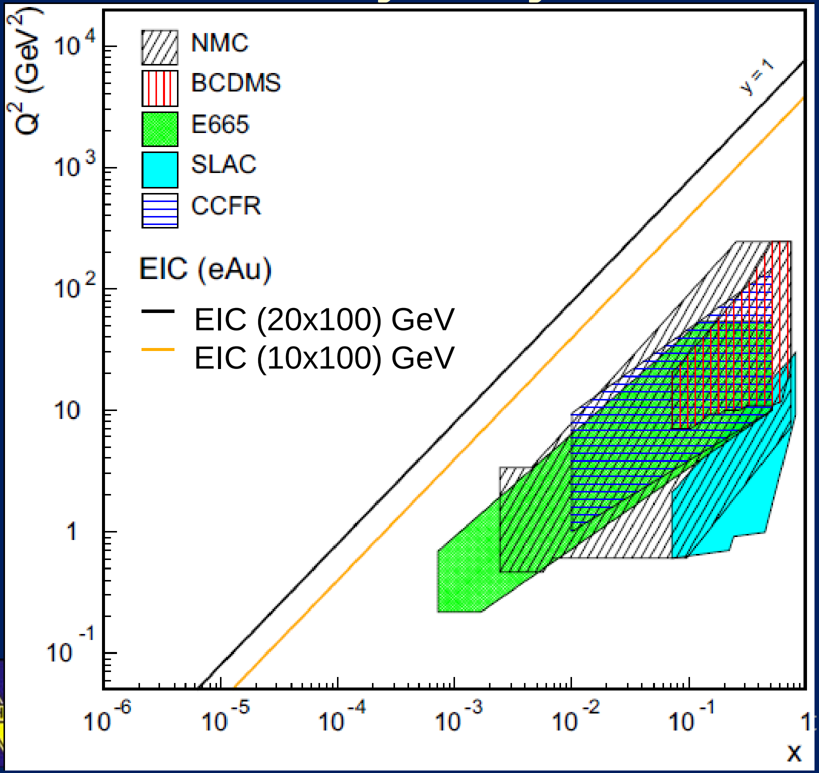
Why an Electron-Ion Collider?

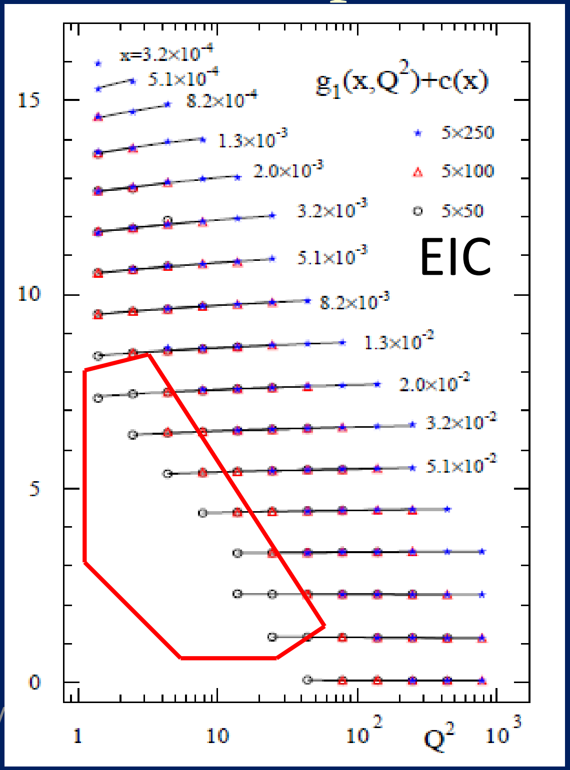
- Electroweak probe
  - "Clean" processes to interpret (QED)
  - Measurement of scattered electron → full kinematic information on partonic scattering
- Collider mode → Higher energies
  - Quarks and gluons relevant d.o.f.
  - Perturbative QCD applicable
  - Heavier probes accessible (e.g. charm, bottom,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



EIC facility concepts

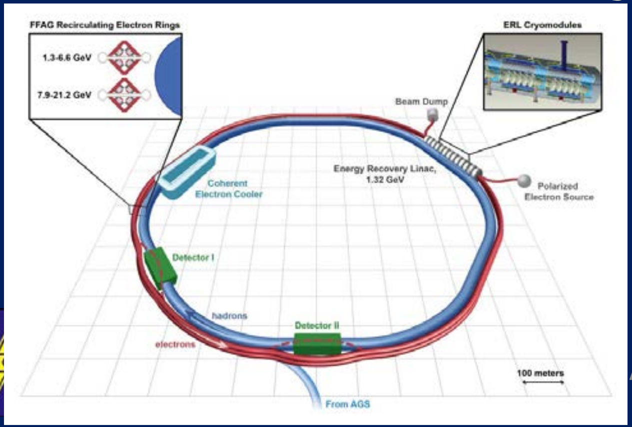
- Beams of light → heavy ions
  - Previously only fixed-target e+A experiments
- *Polarized* beams of p, d/He^3
  - Previously only fixed-target polarized experiments

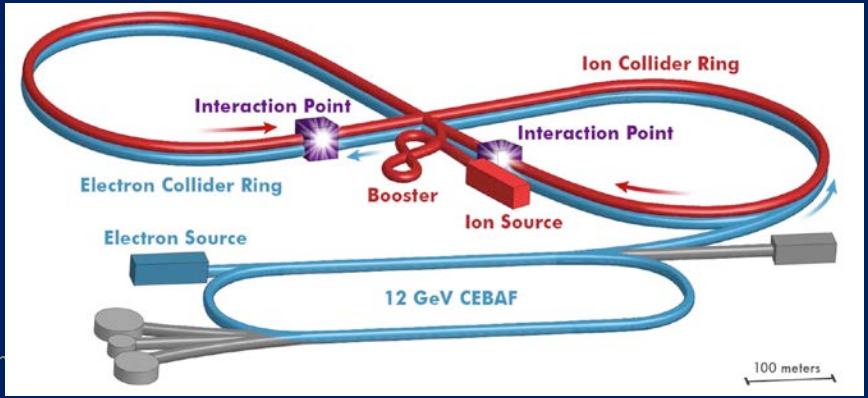




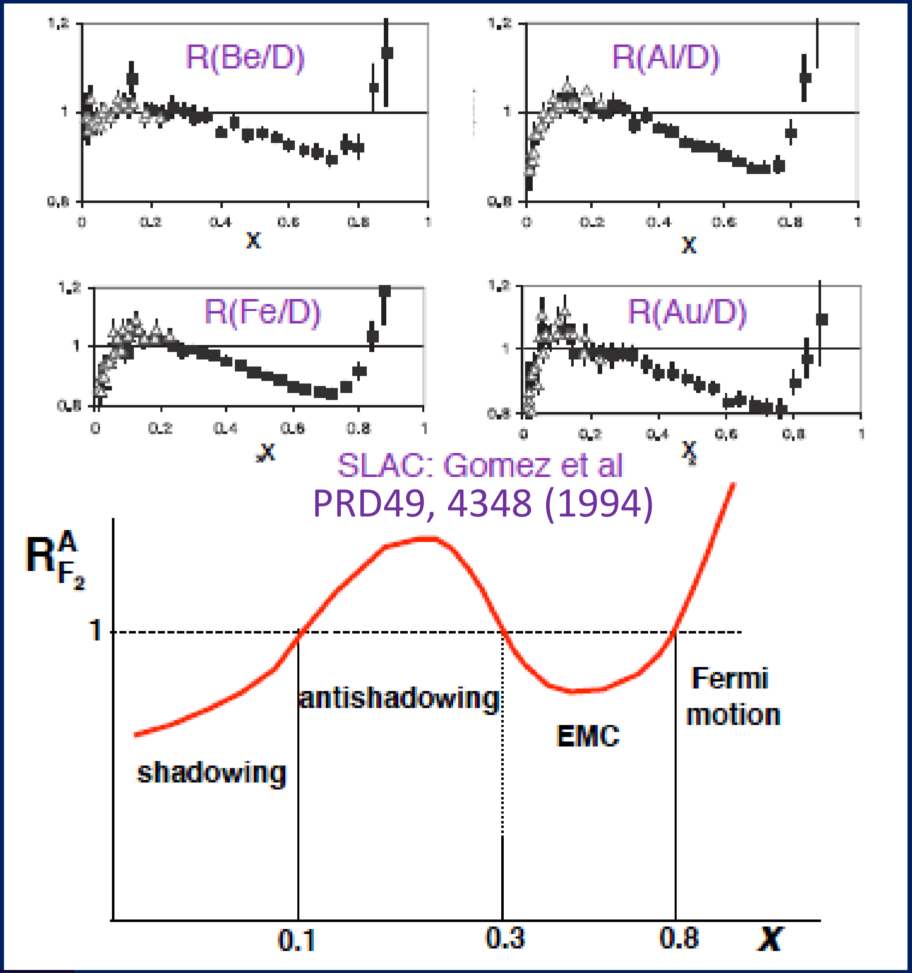
EIC facility concepts

- 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 RHIC at BNL or ion facility to CEBAF at JLab





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

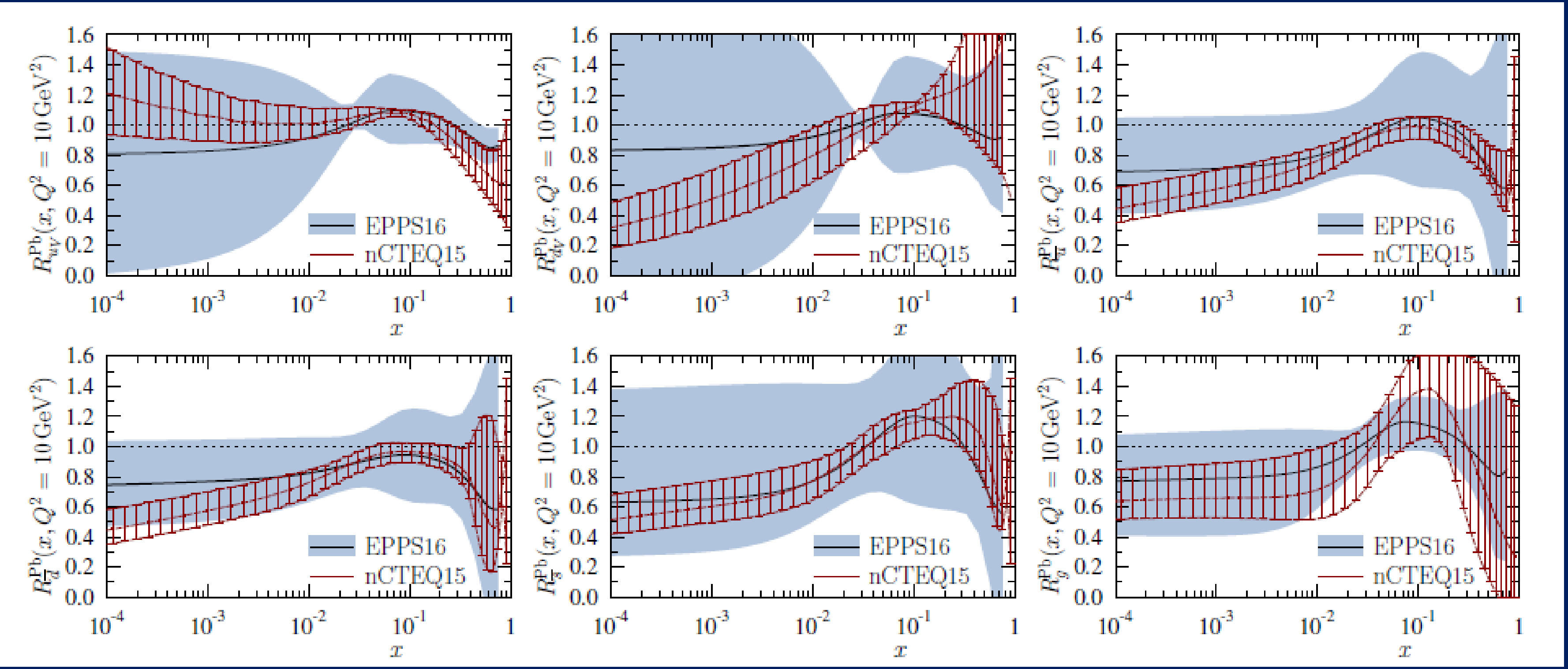


$$R_A \equiv \frac{1}{A}\frac{F_{2A}}{F_{2N}} \neq 1$$

- 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

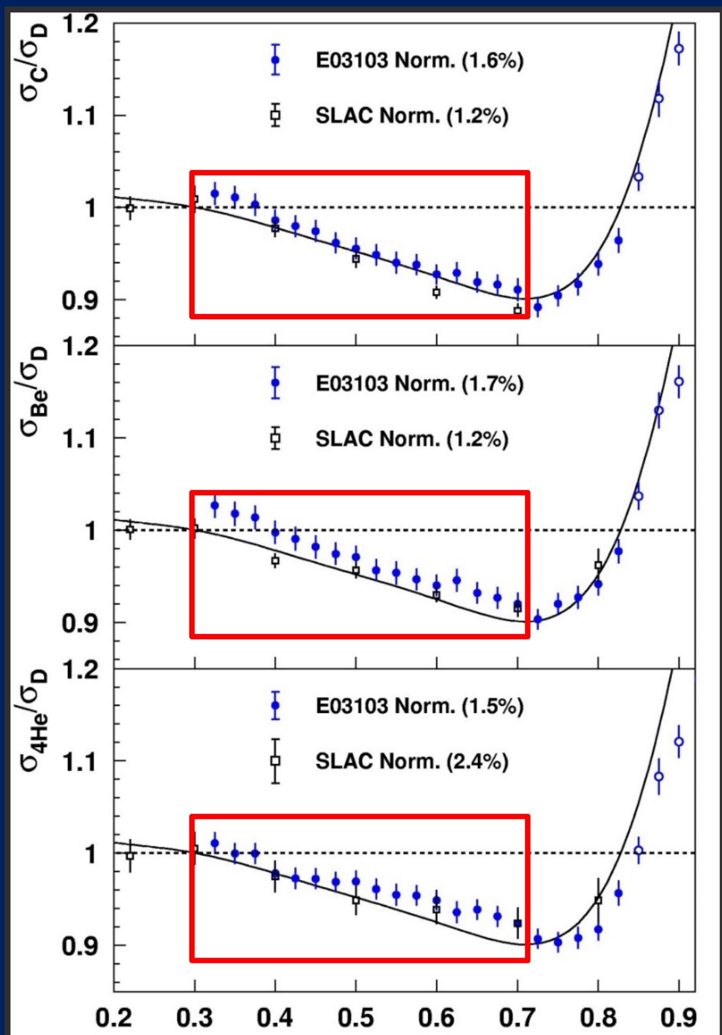
Partonic momentum structure of nuclei: Nuclear parton distribution functions

(Traditional collinear, unpolarized) Nuclear PDFs



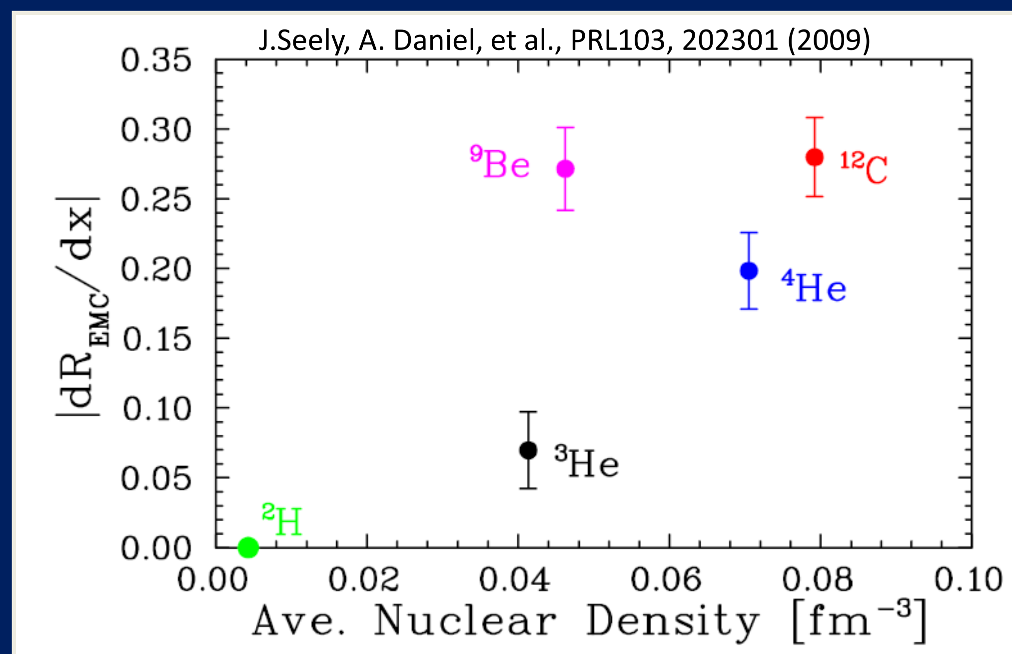
EPPS16 – arXiv:1612.05741

Partonic momentum structure of nuclei: EMC effect and local density



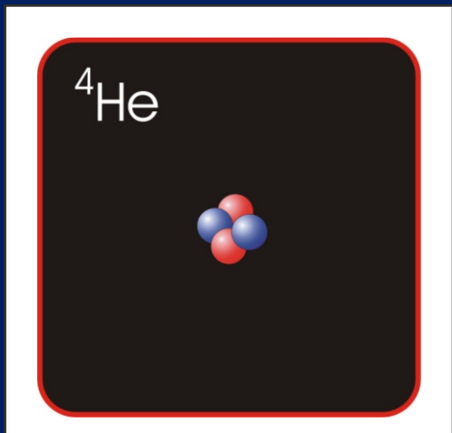
J.Seely, A. Daniel, et al., PRL103, 202301 (2009)

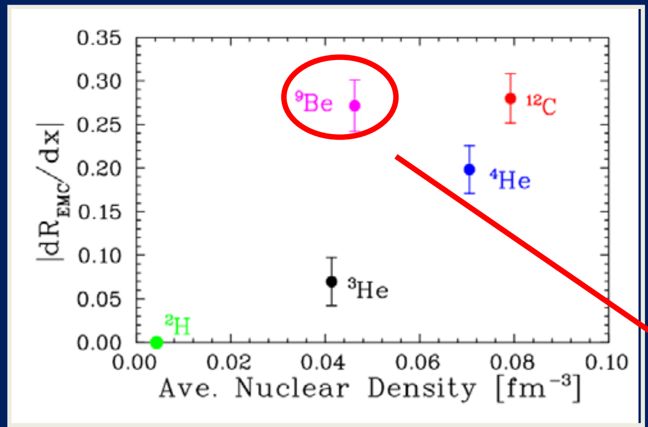
- Fit slope of ratios for 0.3<x<0.7; compare across nuclei
- EMC slope doesn't scale with A or with avg nuclear density…



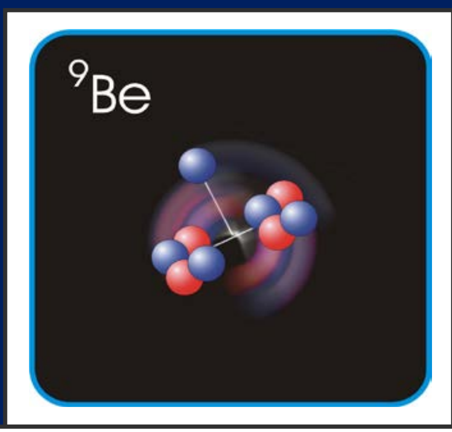
J.Seely, A. Daniel, et al., PRL103, 202301 (2009)

Partonic momentum structure of nuclei: EMC effect and local density

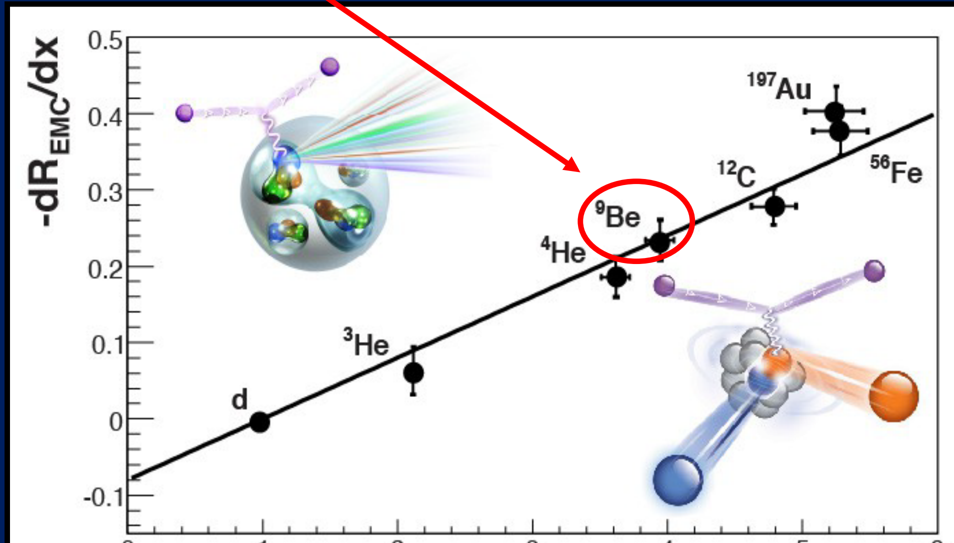




But appears to scale with local density!

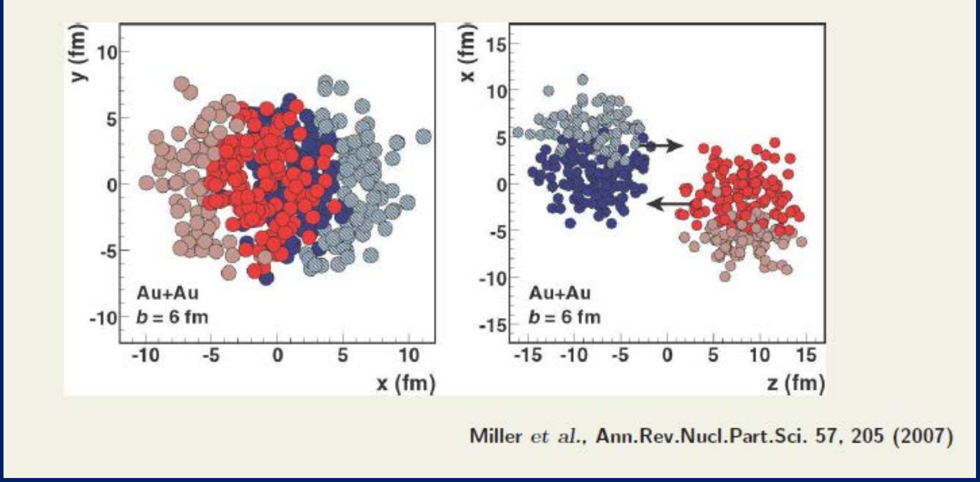


Density determined from *ab initio* few-body calculation
S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)

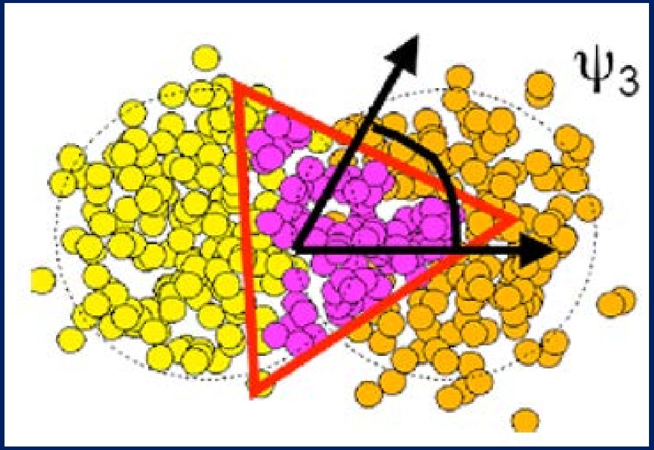


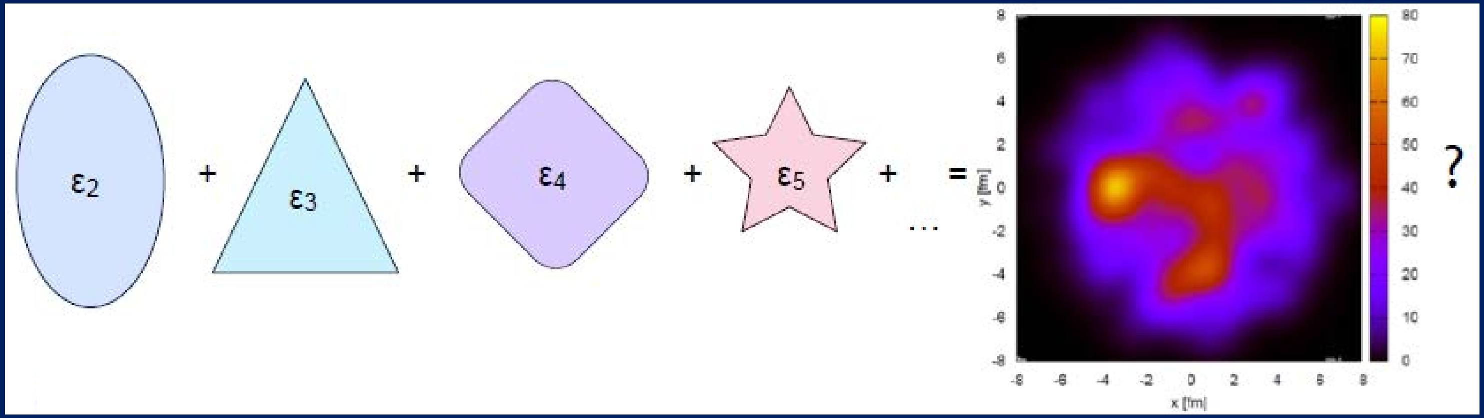
Hen, Piasetzky, Weinstein, Phys. Rev. C85, 047301 (2012)

Local density in nuclei is important!



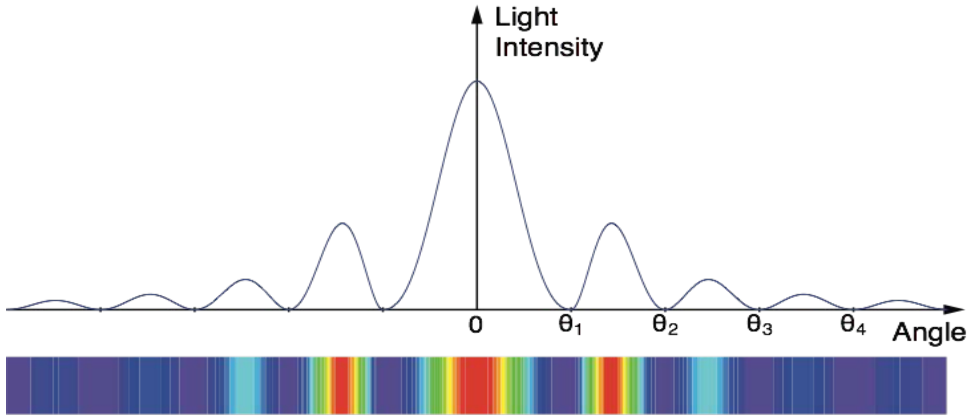
Miller *et al.*, Ann.Rev.Nucl.Part.Sci. 57, 205 (2007)





Partonic spatial structure of nuclei: Diffraction

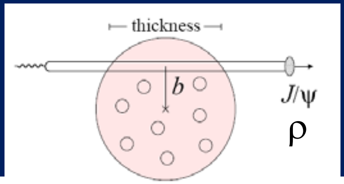
Diffraction pattern from monochromatic plane wave incident on a circular screen of fixed radius



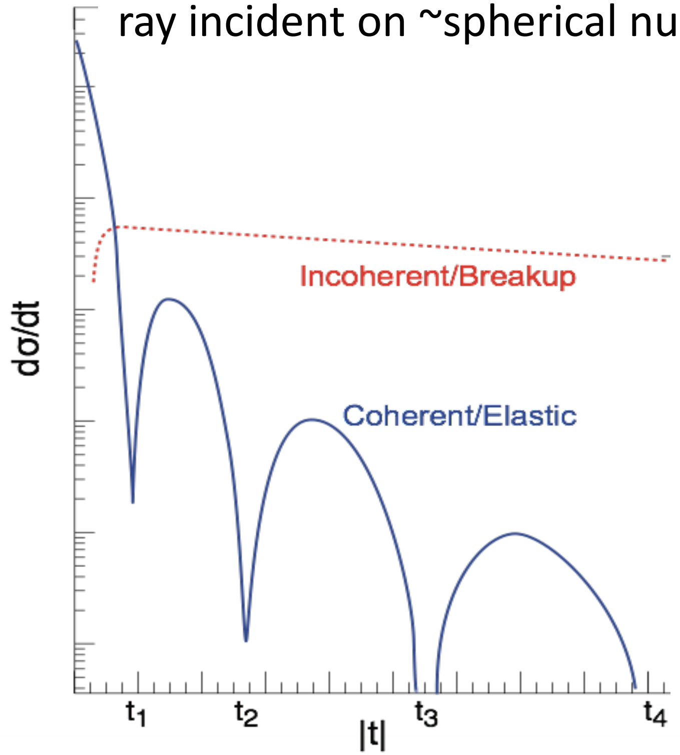
From E. Aschenauer

- 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

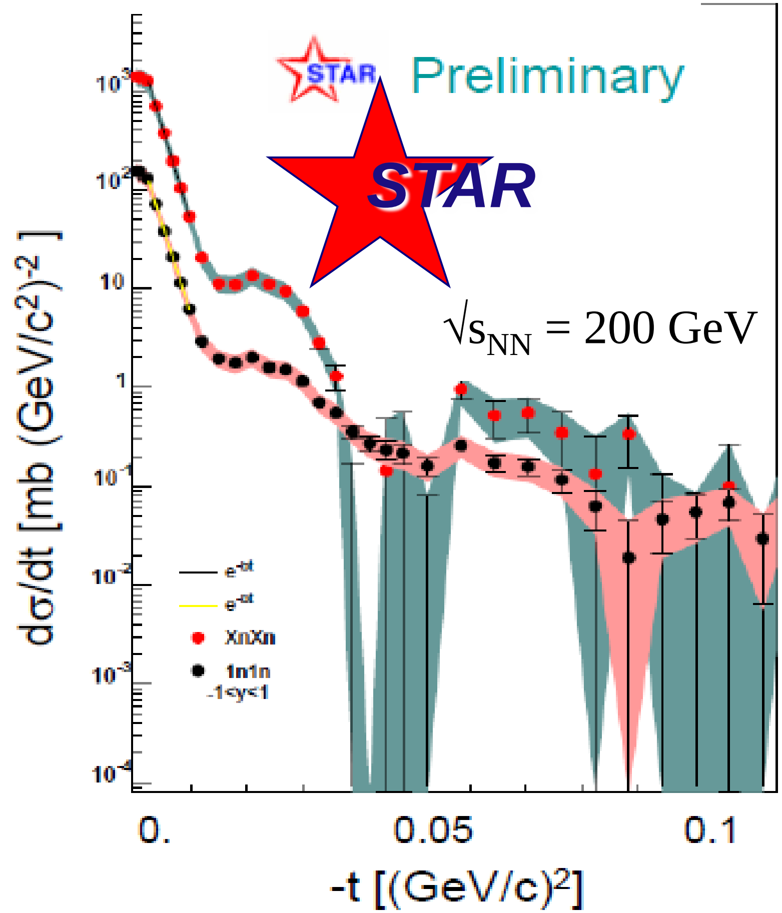


Expected diffraction pattern from gamma ray incident on ~spherical nucleus

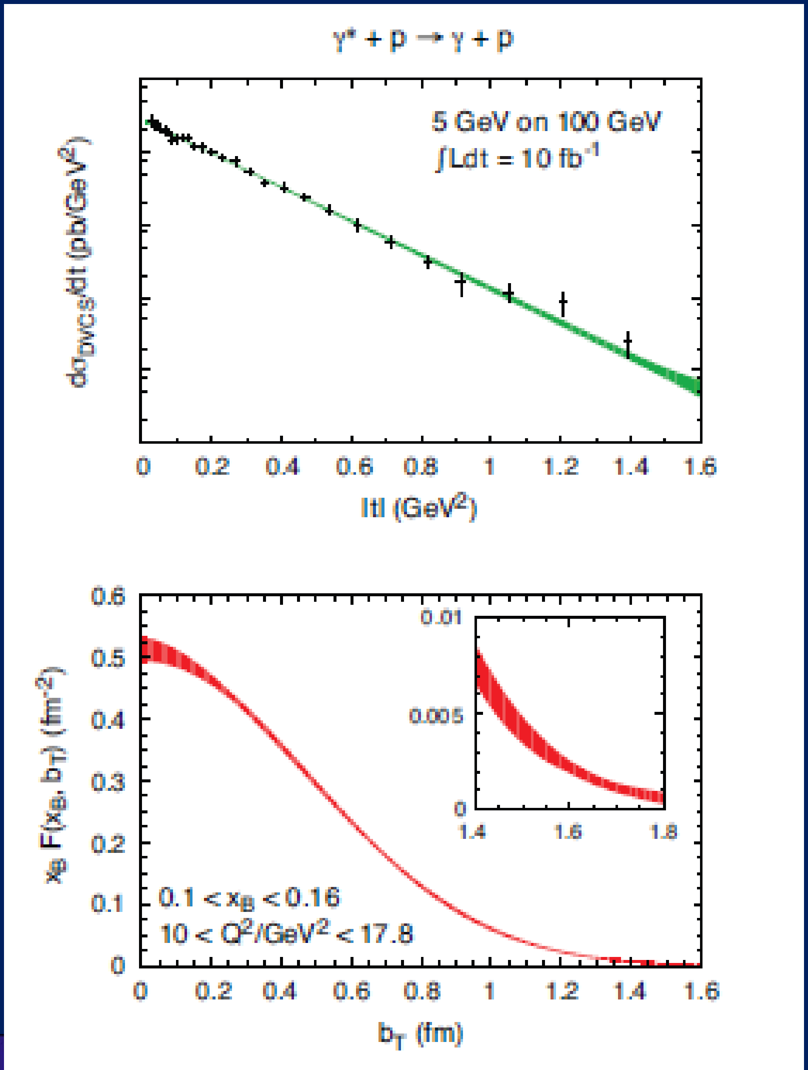


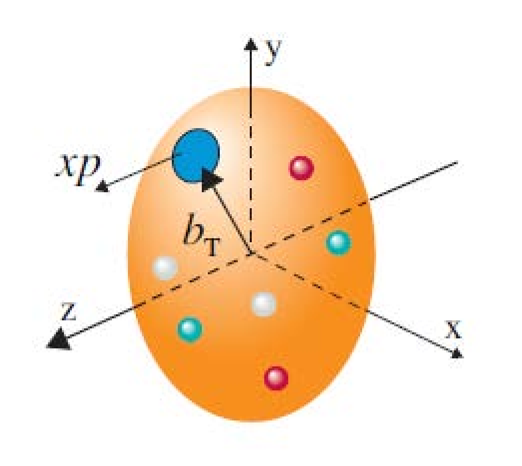
e+A, p+A, or A+A. Probed nucleus in one beam. Gamma emitted by electron or Coulomb-excited proton/nucleus passing nearby in second beam.

Diffractive ρ production in Au+Au ultraperipheral collisions



Partonic spatial structure of nuclei: Diffraction



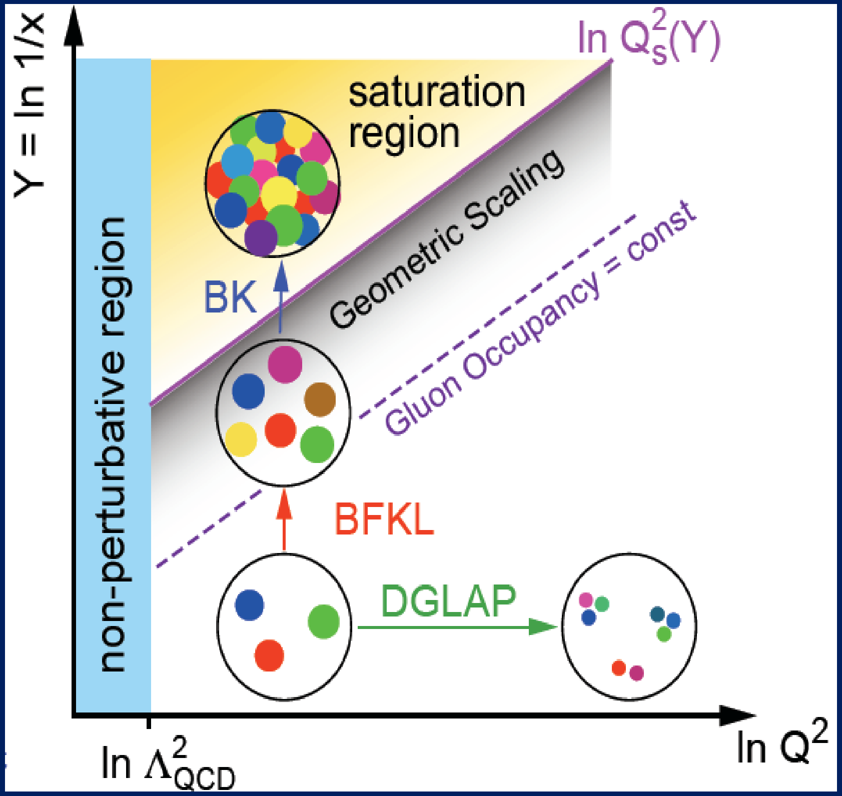


Goal: Cover wide range in *t*.
Fourier transform → impact-parameter-space profiles.
Obtain *b* profile from slope vs. *t*.

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



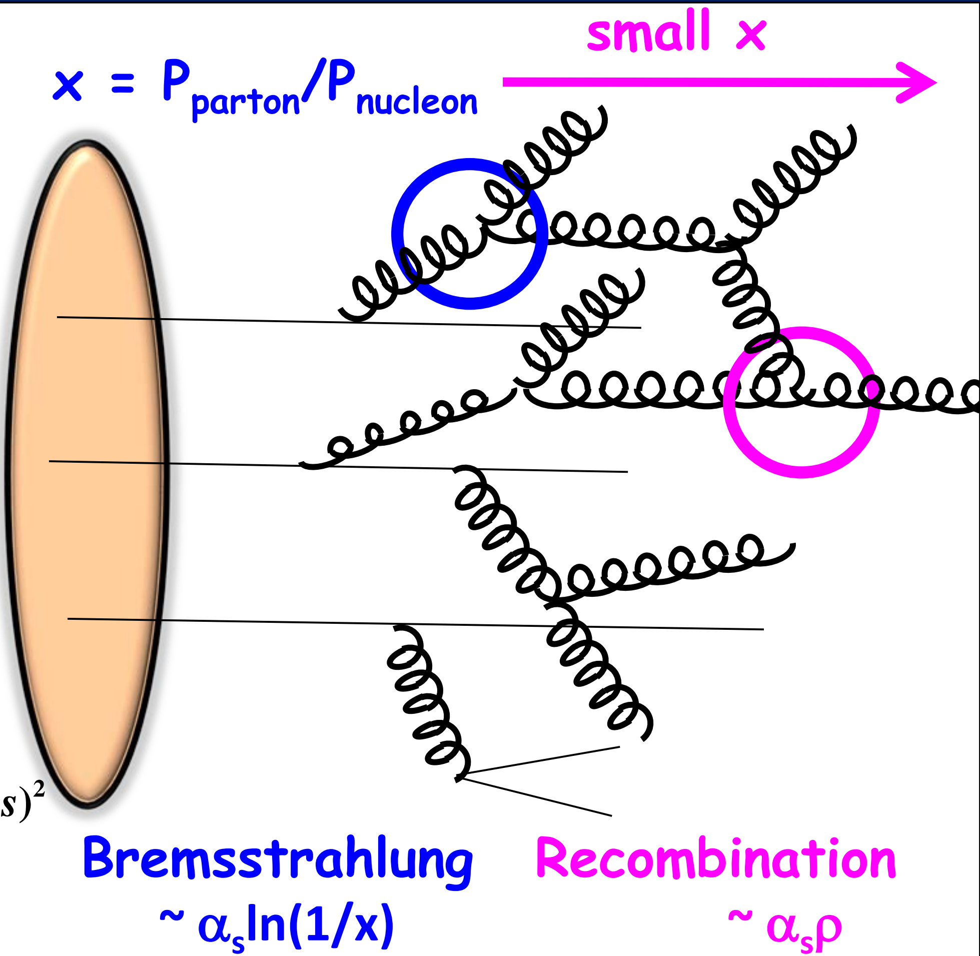
Gluon saturation

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

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

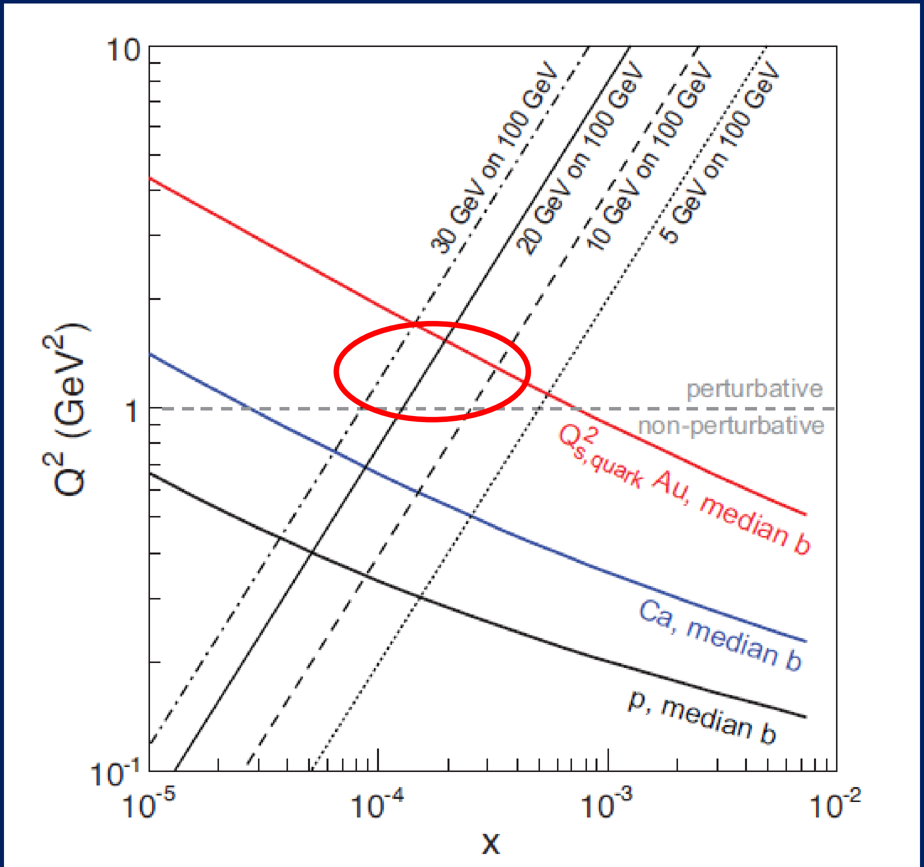
- Dynamically generated scale
  Saturation Scale: $Q^2_s(x)$
  - Increases with energy or decreasing x
- Scale with $Q^2/Q^2_s(x)$ instead of x and Q^2 separately

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



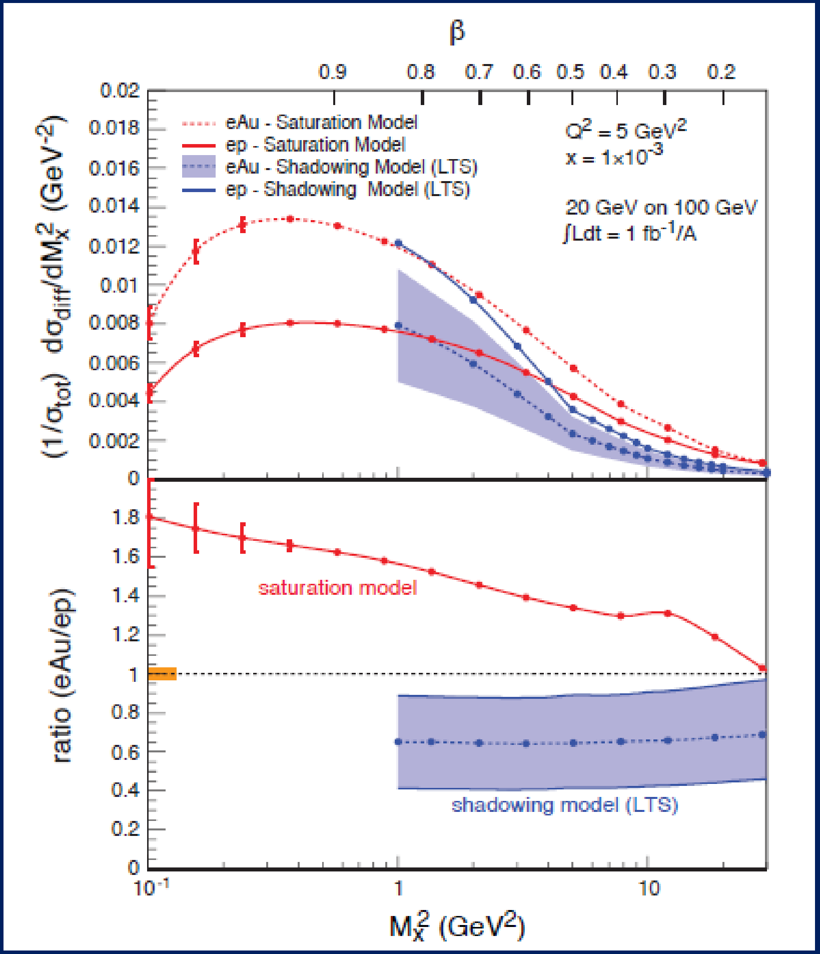
Diffraction in e+A as a probe of gluon saturation

- 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



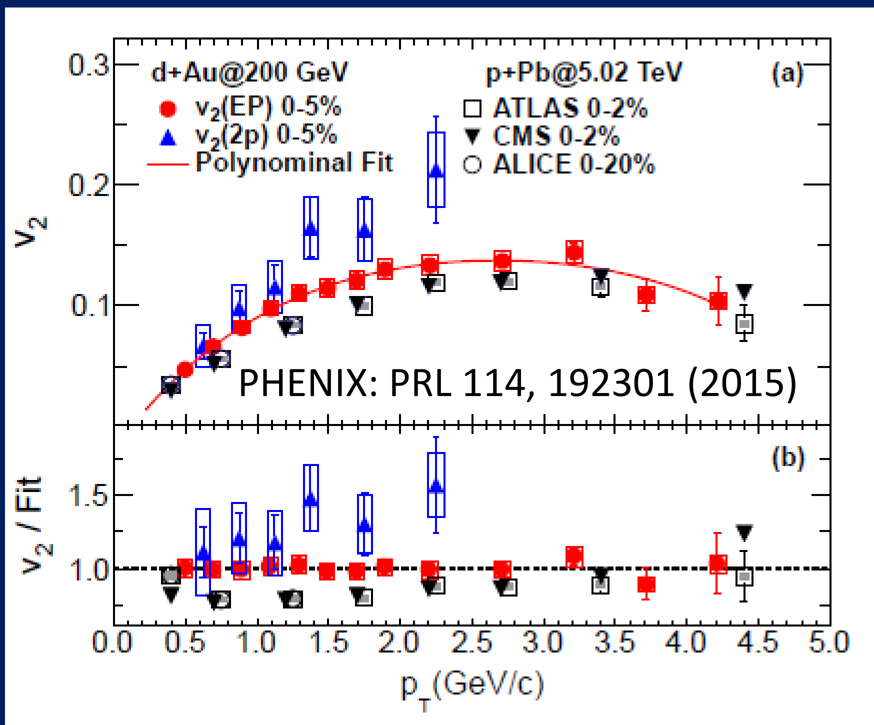
Diffraction in e+A as a probe of gluon saturation

- 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: $(\text{diffractive/total})_{e+A}/(\text{diffractive/total})_{e+p}$
  - 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

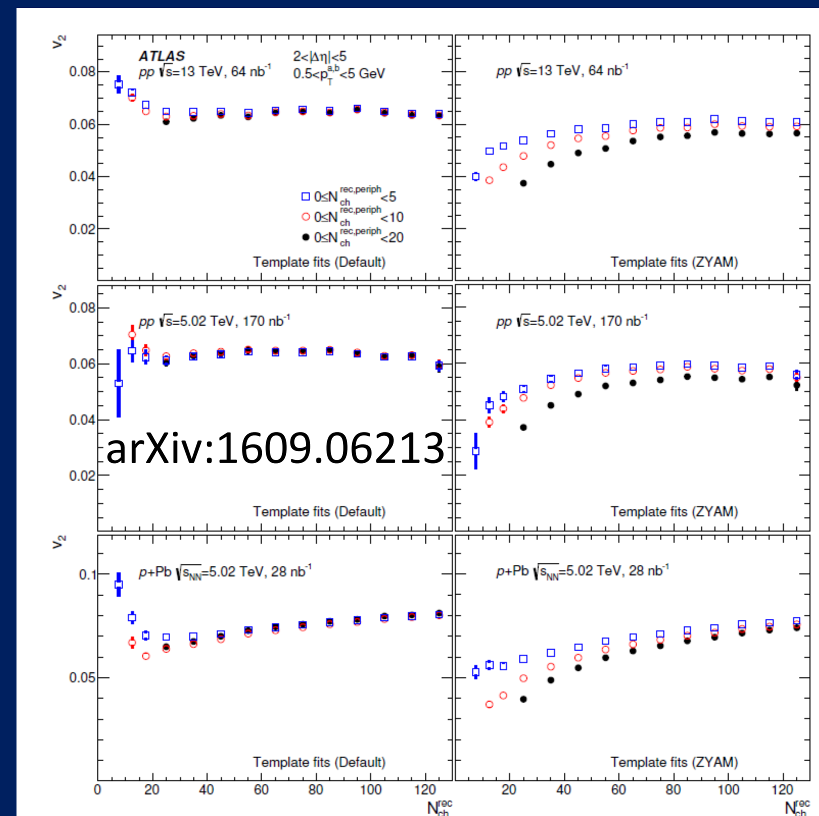


Parton dynamics in QCD systems

- Angular correlations in particle production: one way to probe parton dynamics
- Can look at Fourier amplitudes



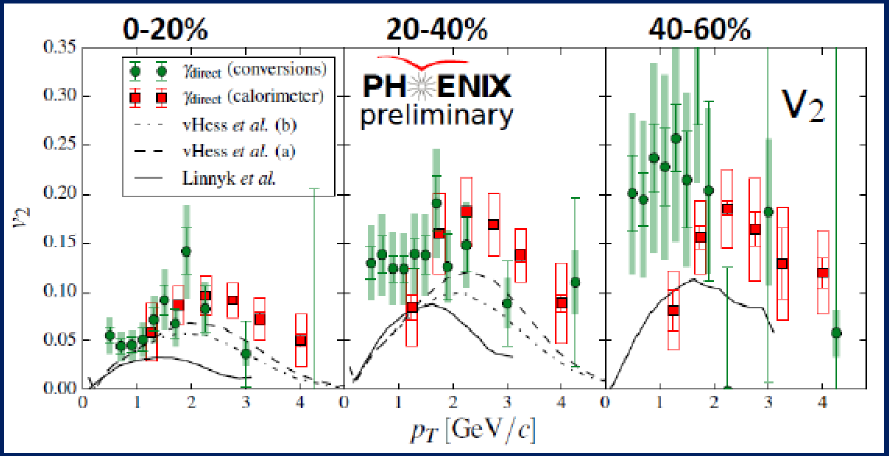
Large cos 2ϕ modulation in d+Au at 200 GeV, p+Pb at 5.02 TeV

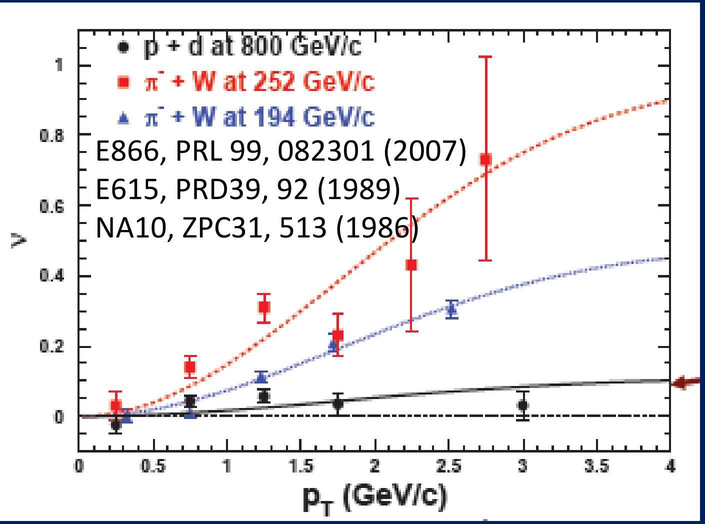


Significant cos 2ϕ modulation also in p+p at 13 TeV

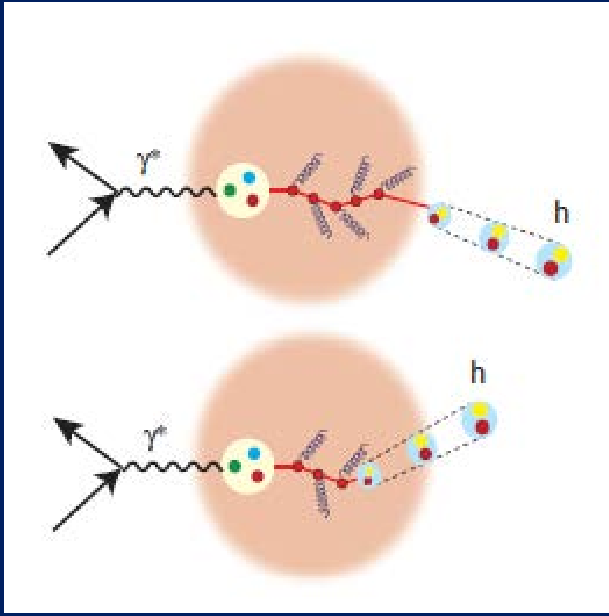
Parton dynamics in QCD systems:
How many ways can a cos 2ϕ modulation be generated in hadronic collisions??

- Large modulation in direct photon production in 200 GeV Au+Au collisions
- *Huge* modulation in pion-induced Drell-Yan
  - Understood as due to *spin-momentum correlations* of partons inside *unpolarized* hadrons
  - These correlations will be studied in detail at EIC





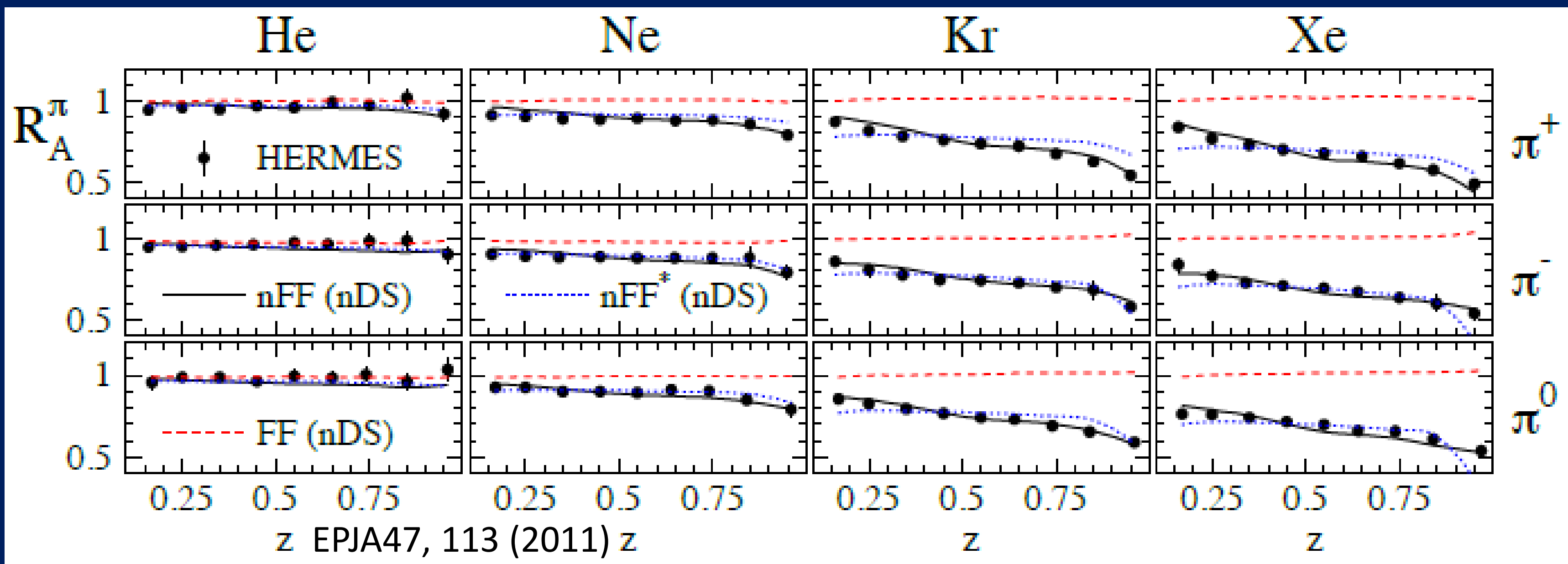
Formation of QCD bound states: Hadronization at EIC



- 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

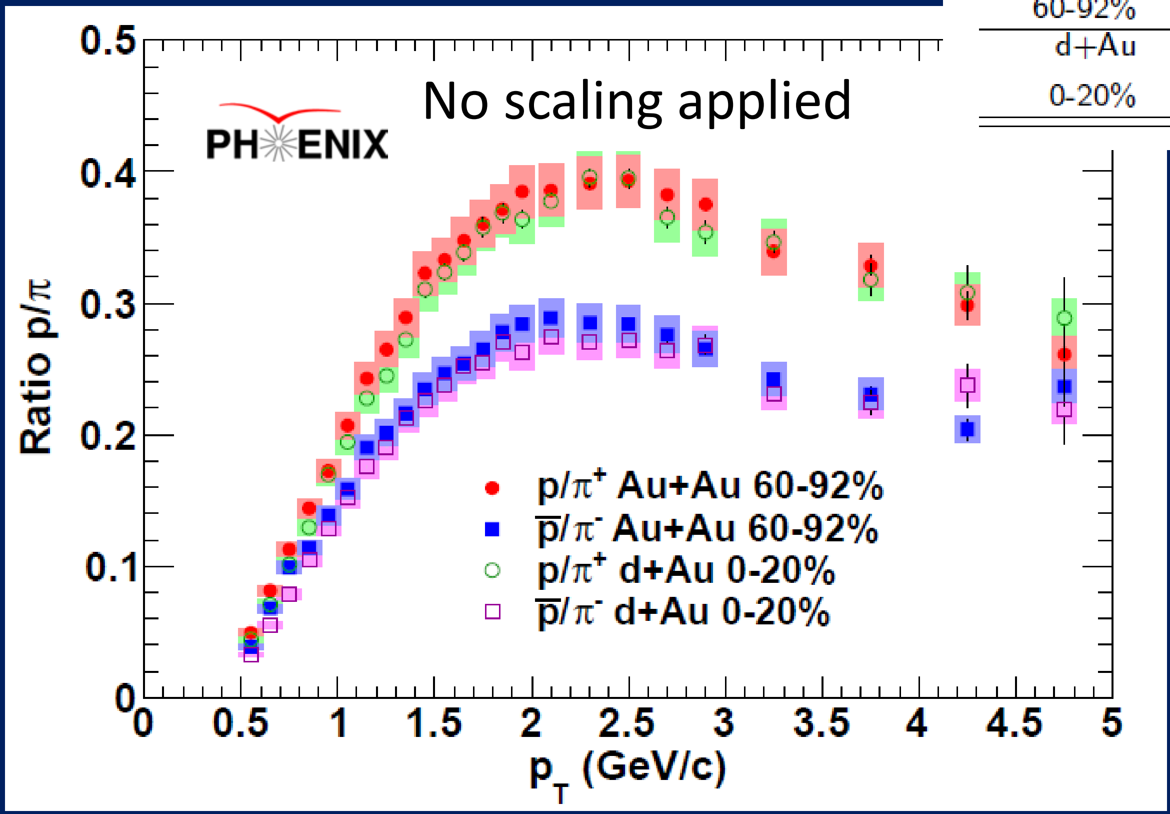
Formation of QCD bound states: Nuclear modification of fragmentation functions



As in A+A and p+A, fragmentation functions are 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)

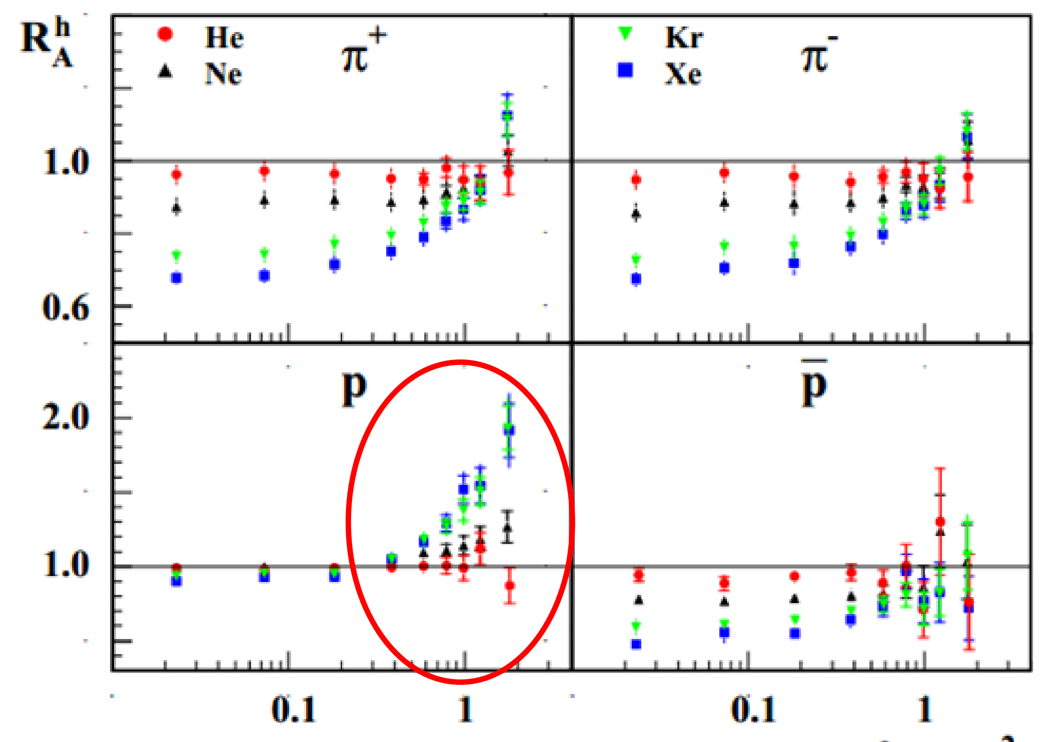
Baryon enhancement observed in central A+A but also peripheral A+A and in p/d+A.

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

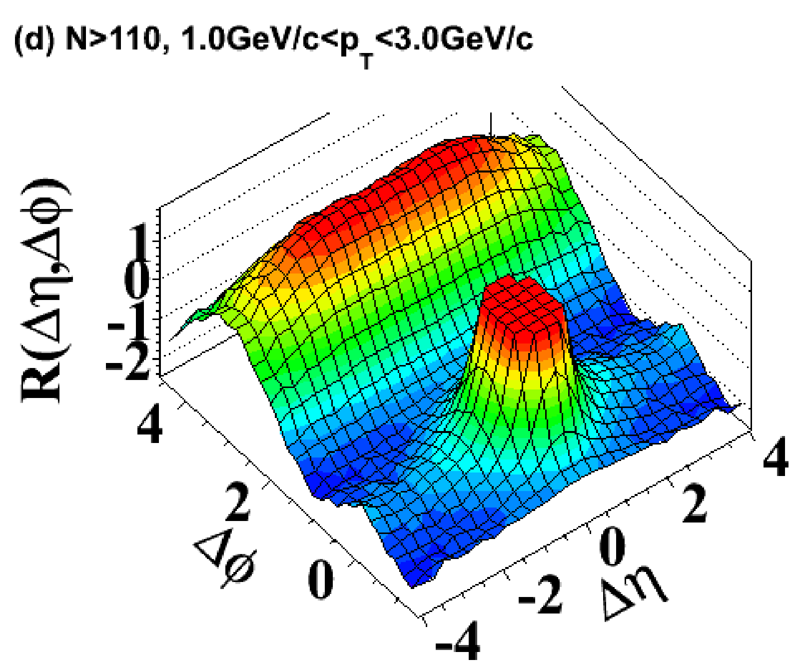
Formation of QCD bound states: Hadronization in higher-density partonic environments

- 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?

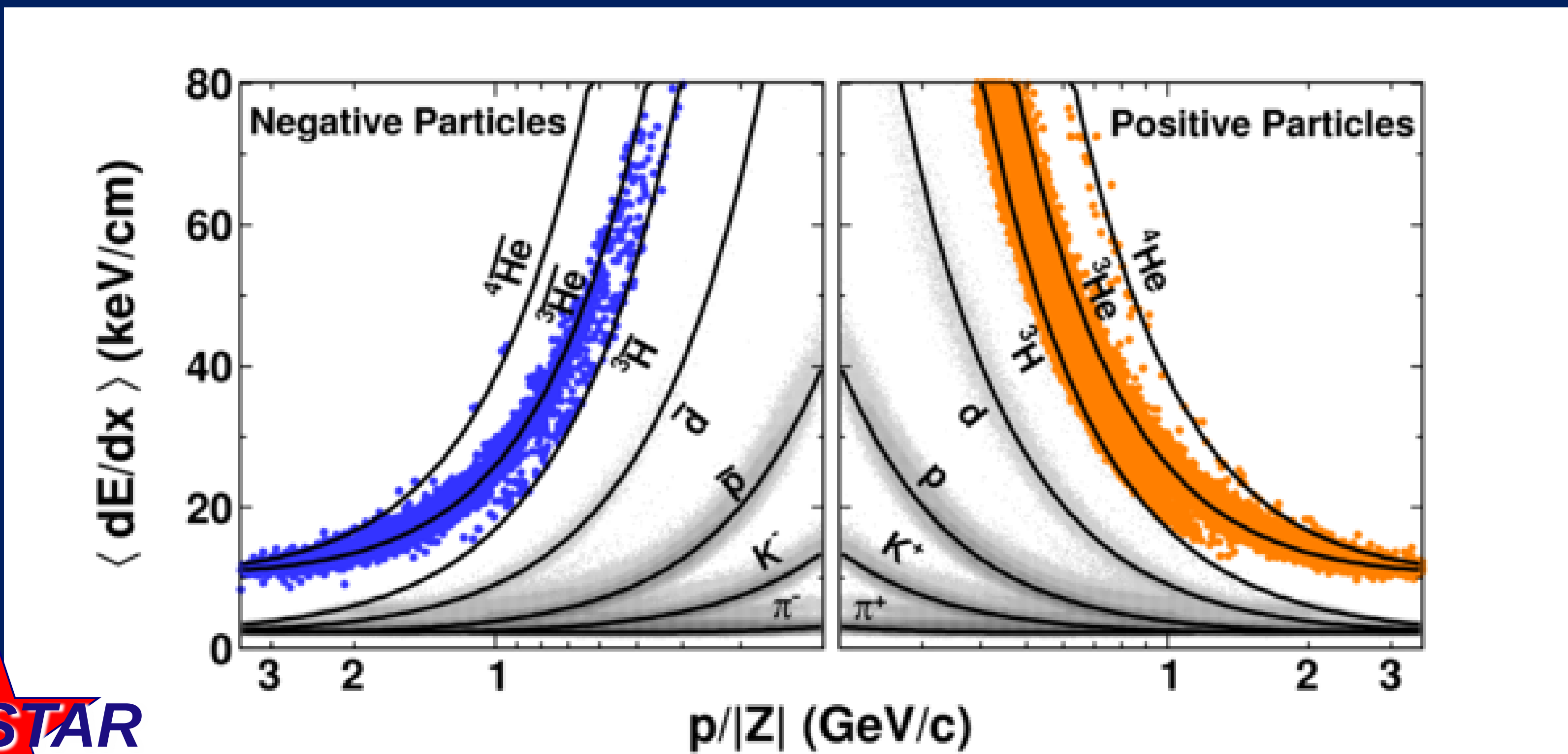


CMS JHEP 09 (2010), 091

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

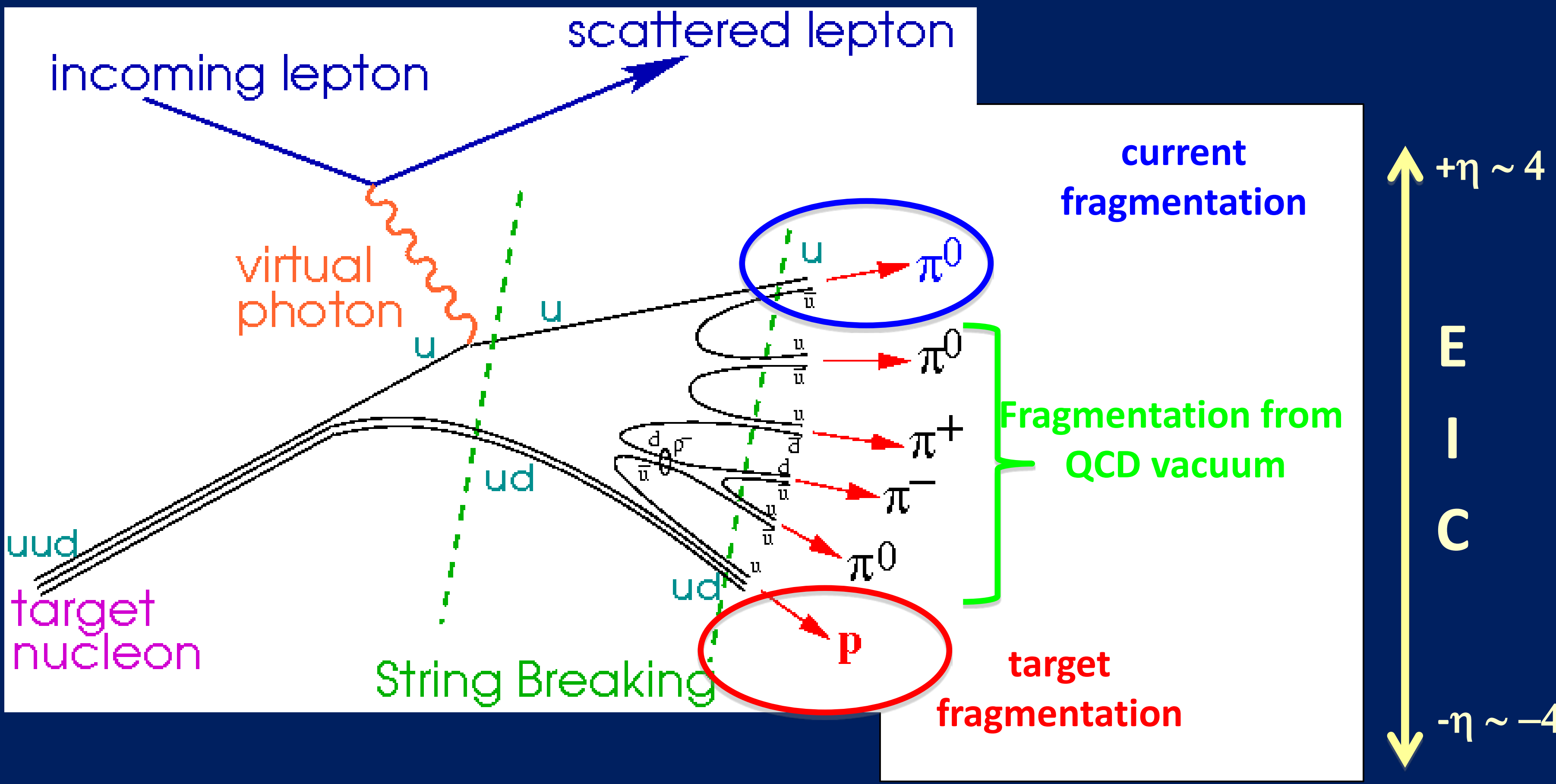
Formation of bound states of bound states: Creating nuclei



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

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

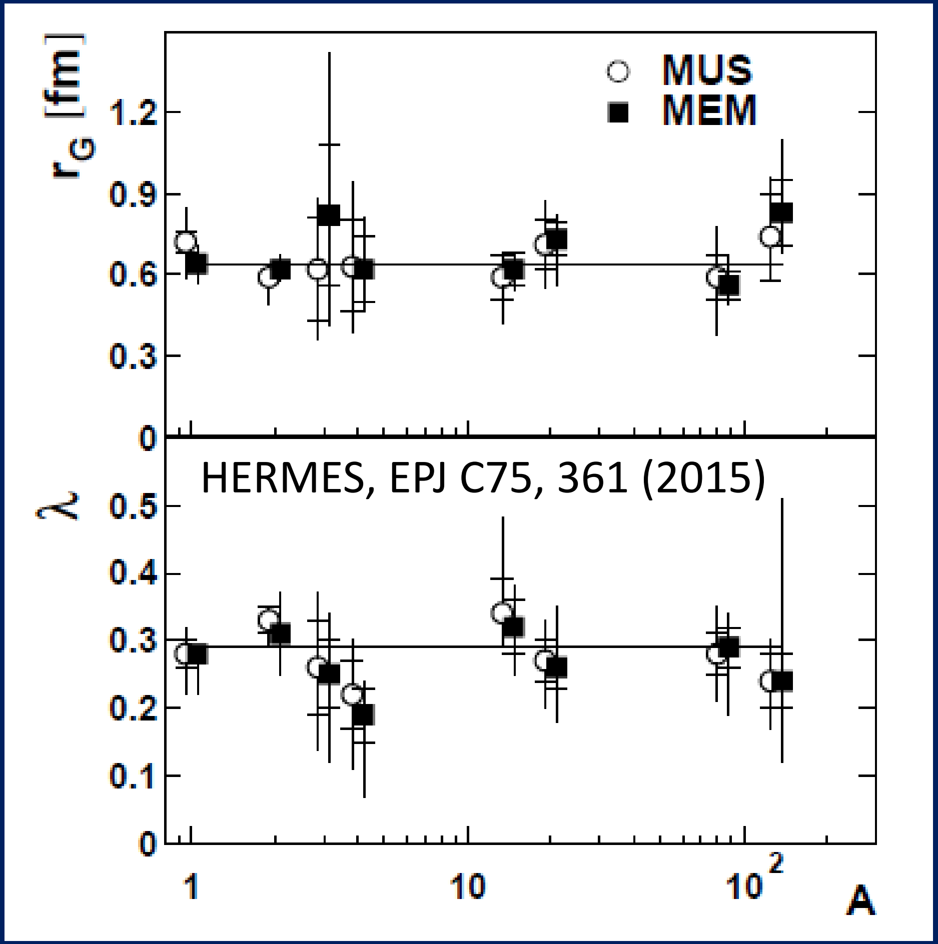
Electron-Ion Collider → next major facility in the ongoing quest to address the fundamental questions of QCD

- 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?

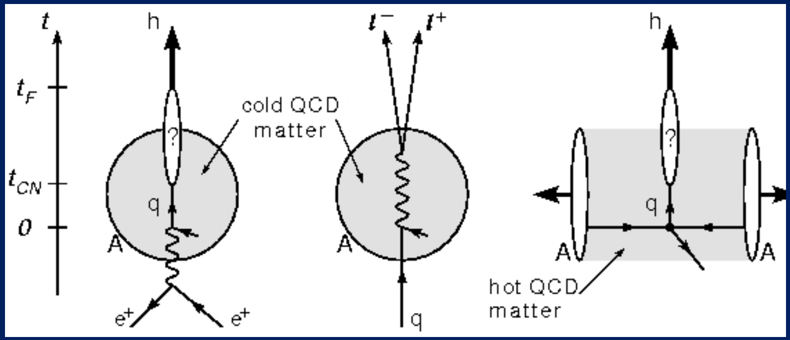
Extra

Bose-Einstein correlations for nuclear semi-inclusive DIS

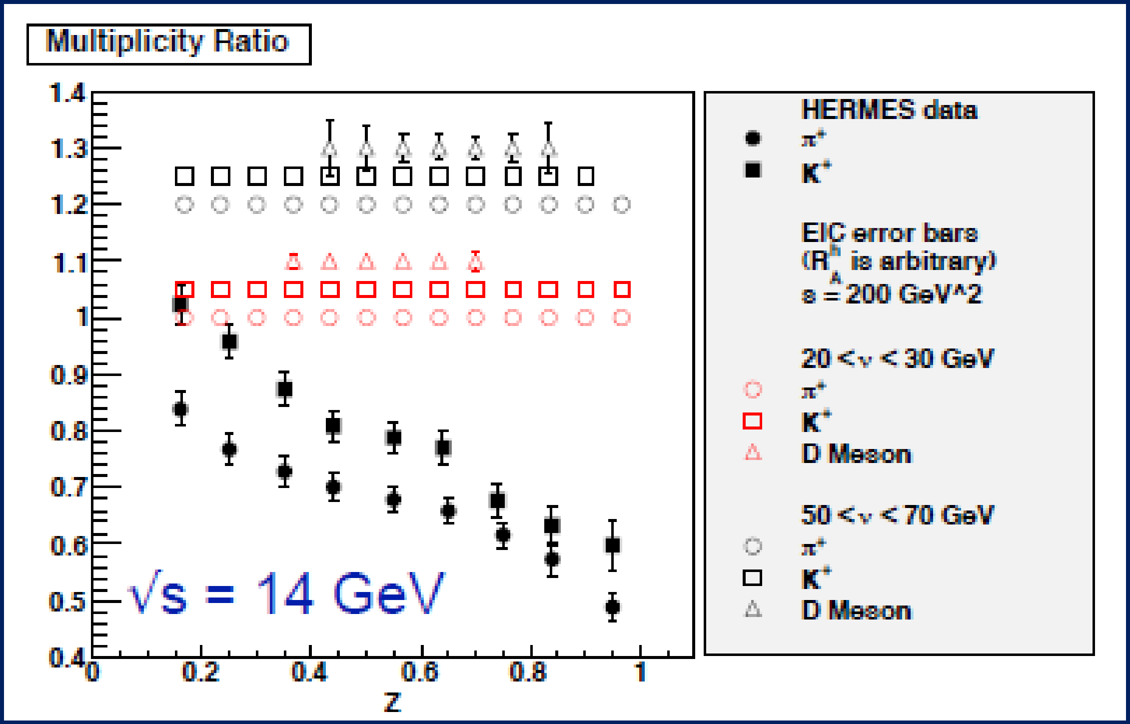
- Sensitive to spatial separation of production of the two particles
- No nuclear dependence found within uncertainties



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!

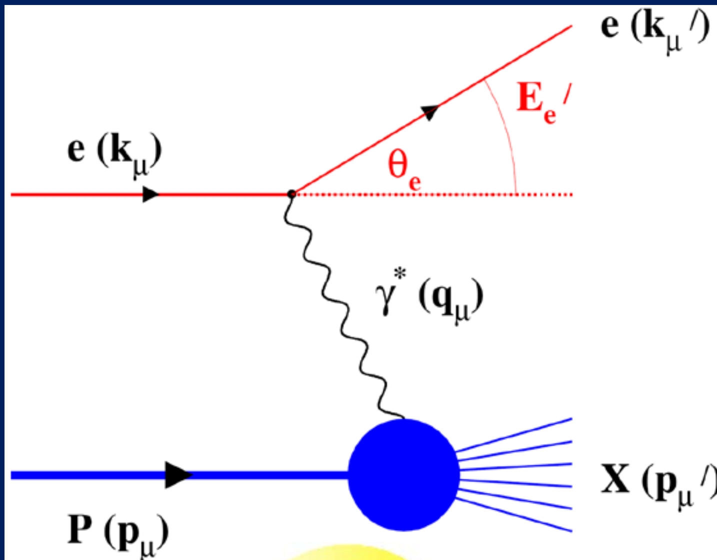
EIC will provide ample statistics and much greater kinematic coverage!

-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:



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

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

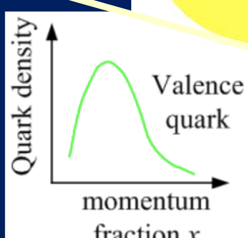
Measure of resolution power

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

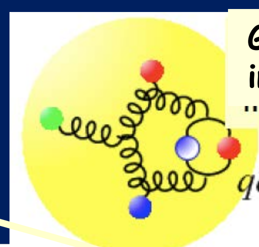
Measure of inelasticity

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

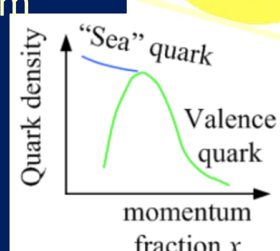
Measure of momentum fraction of struck quark

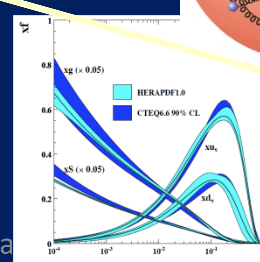


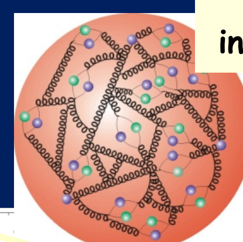
10^{-16}m



Gluon splits into quarks







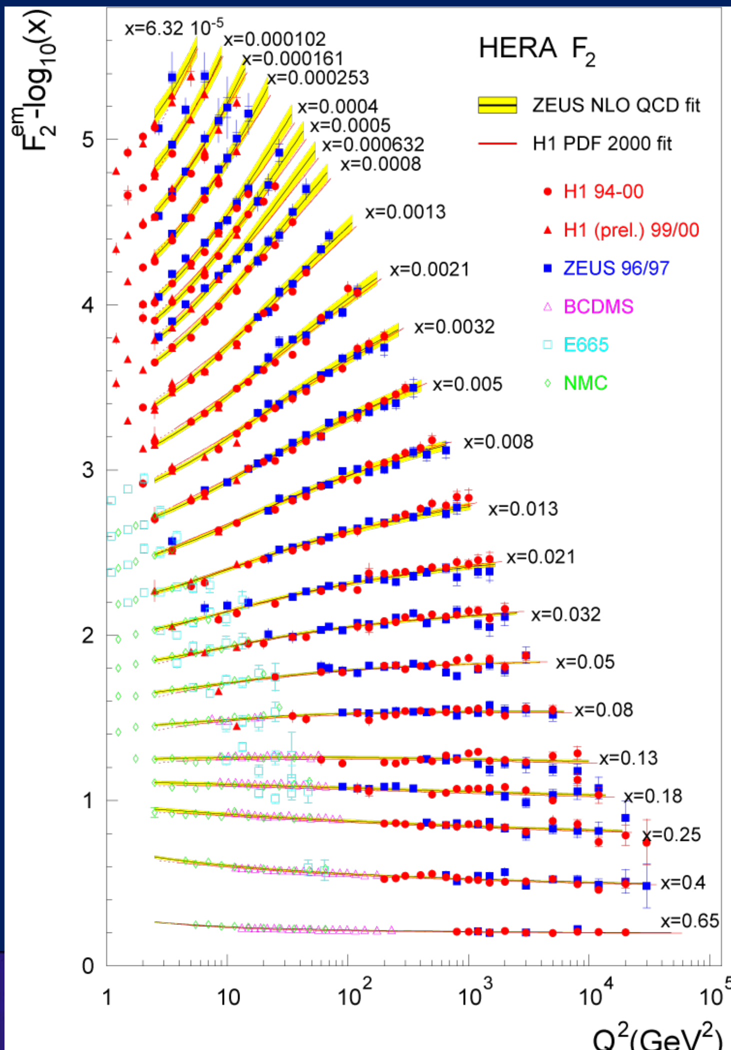
Quark splits into gluon splits into quarks …

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

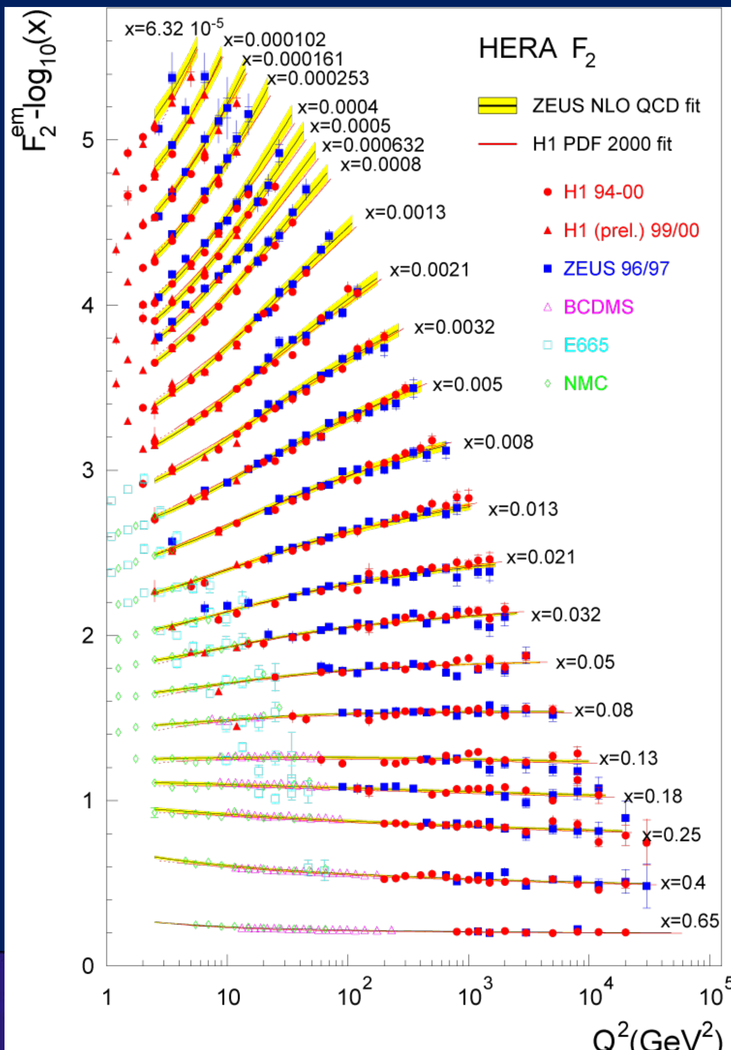
Via dihadron production

OR

Via diffractive scattering

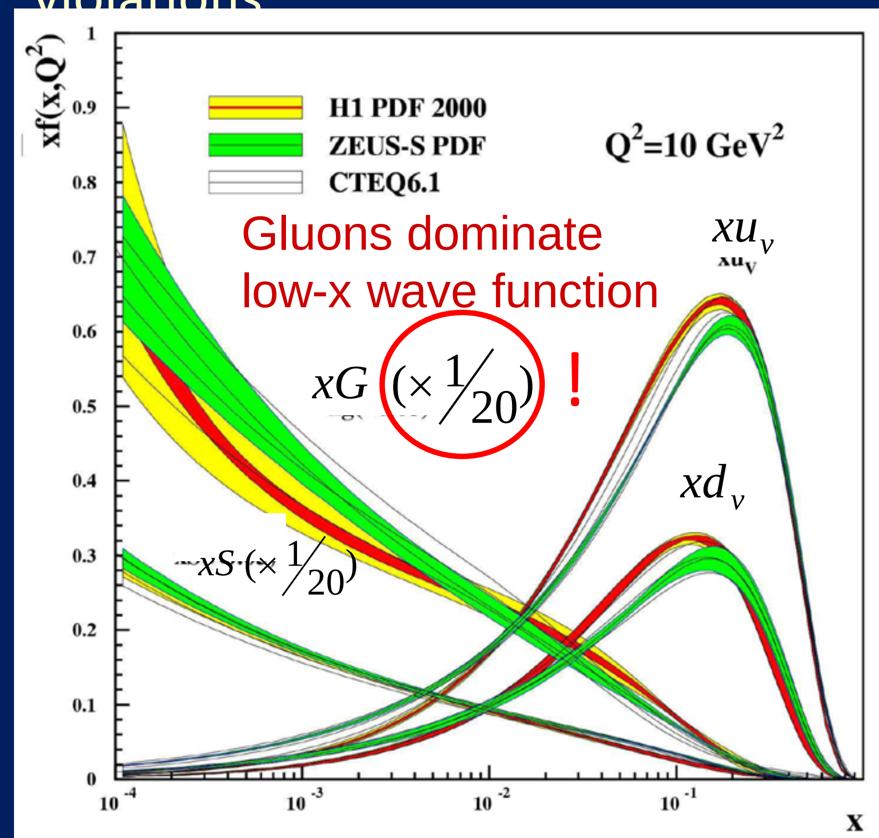
Accessing gluons with an electroweak probe

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



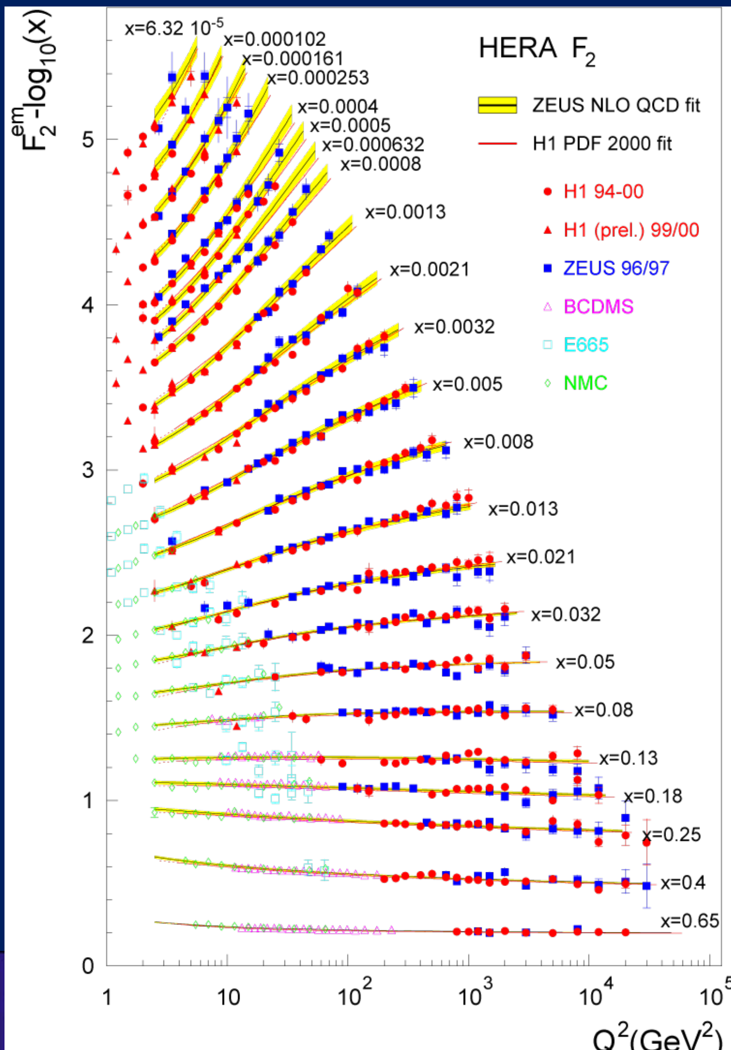
Access the gluons in DIS via scaling violations;

n in

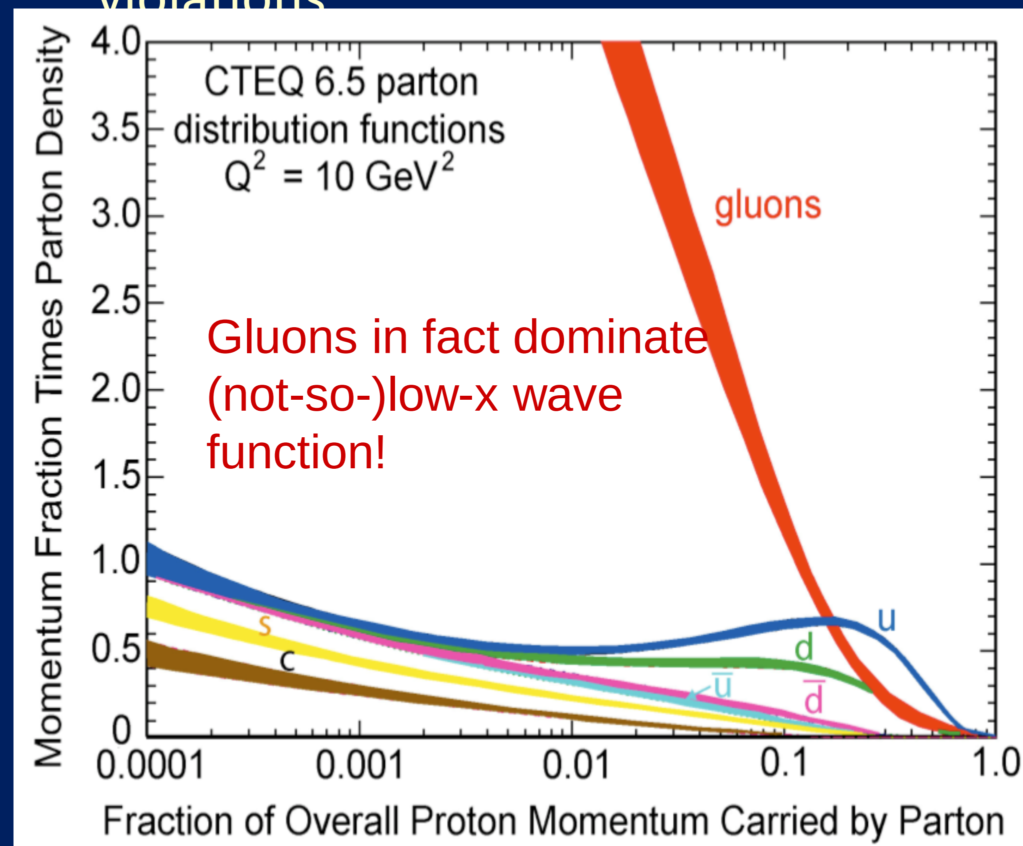


Accessing gluons with an electroweak probe

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



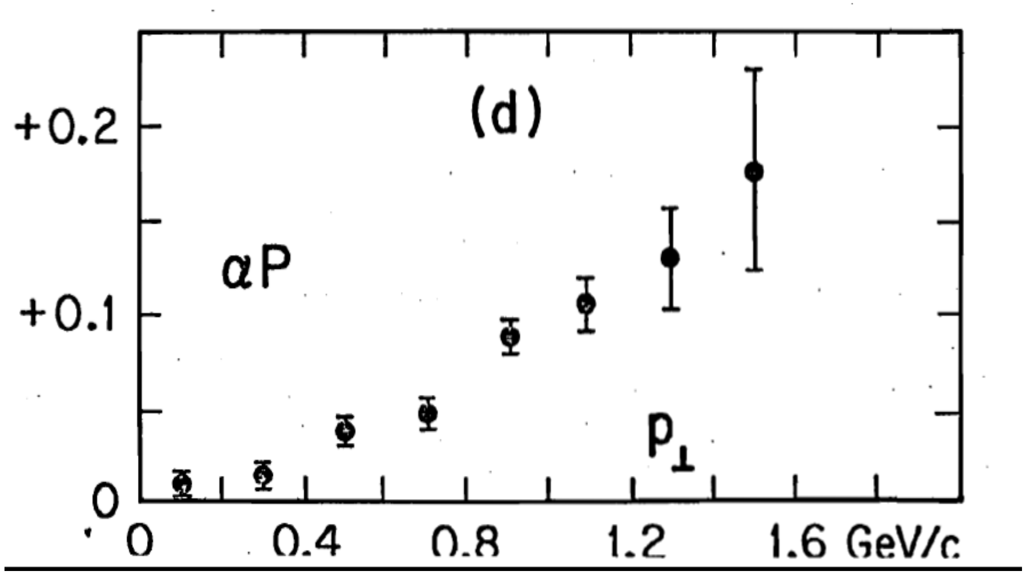
Access the gluons in DIS via scaling violations:



Hyperon polarization from unpolarized collisions

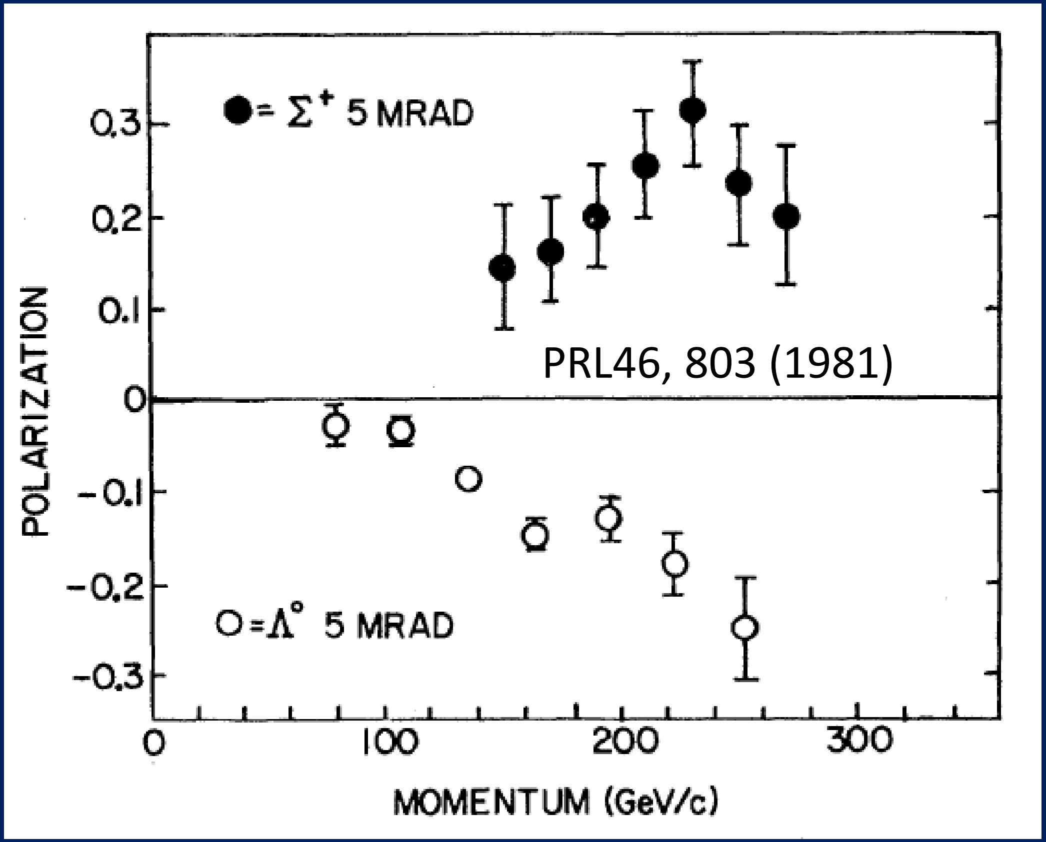
Λ° Hyperon Polarization in Inclusive Production by 300 GeV Protons on Beryllium

PRL36, 1113 (1976)



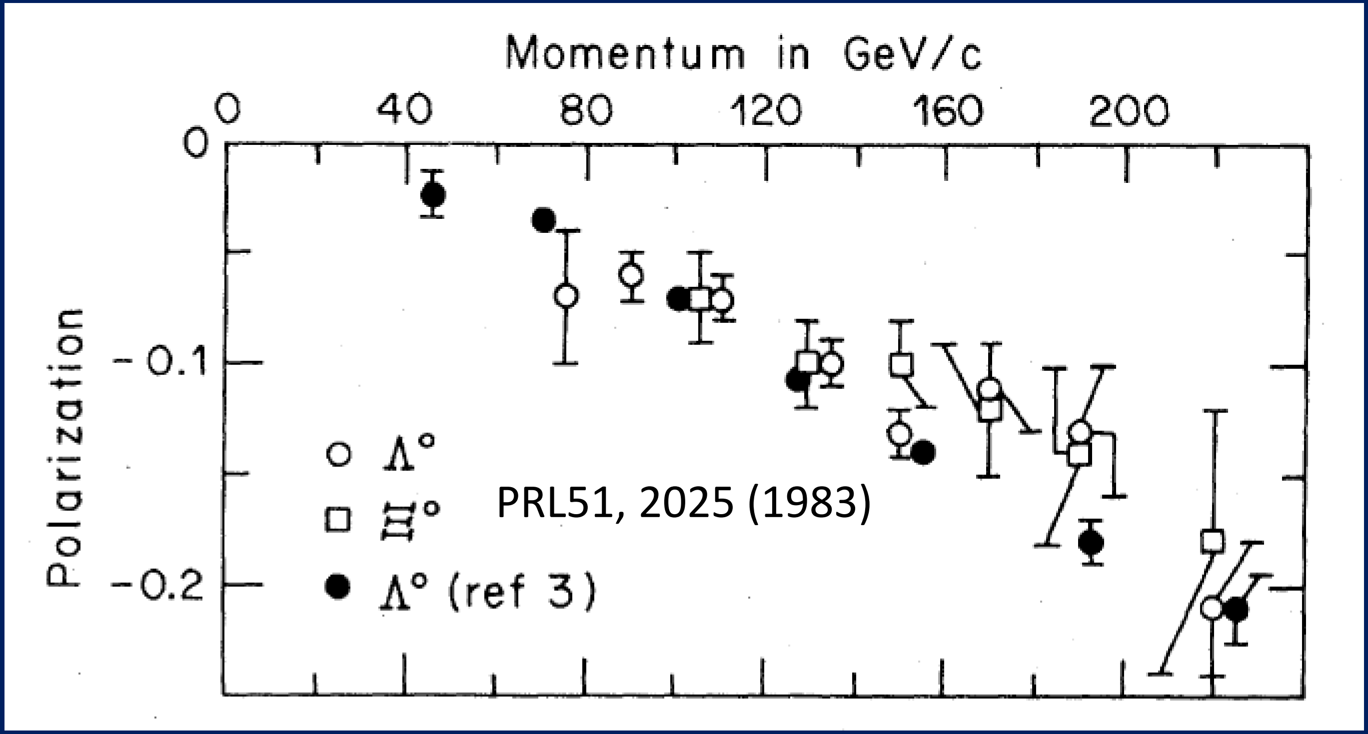
- 1976 lambda polarization discovery: p+Be, 300 GeV beam
- Polarization transverse to production plane up to ~20% for forward-angle lambda production; Polarizing TMD FF?
- Confirmed 1977 at CERN, p+Pt, 24 GeV beam (and by various proton-nucleus and proton-proton experiments afterwards . . .)

Σ^+ polarized with opposite sign



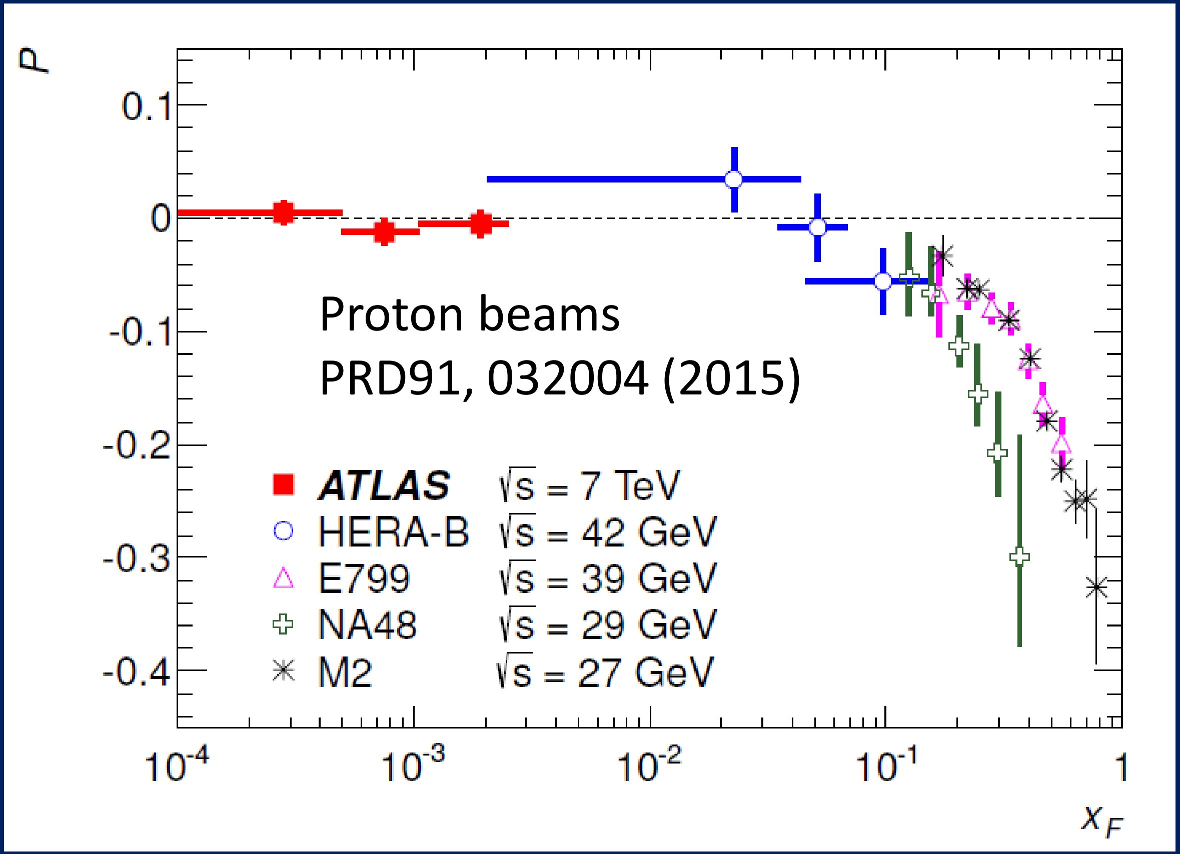
- 1981: p+Be, 400 GeV beam

Ξ^0 polarization similar to Λ^0



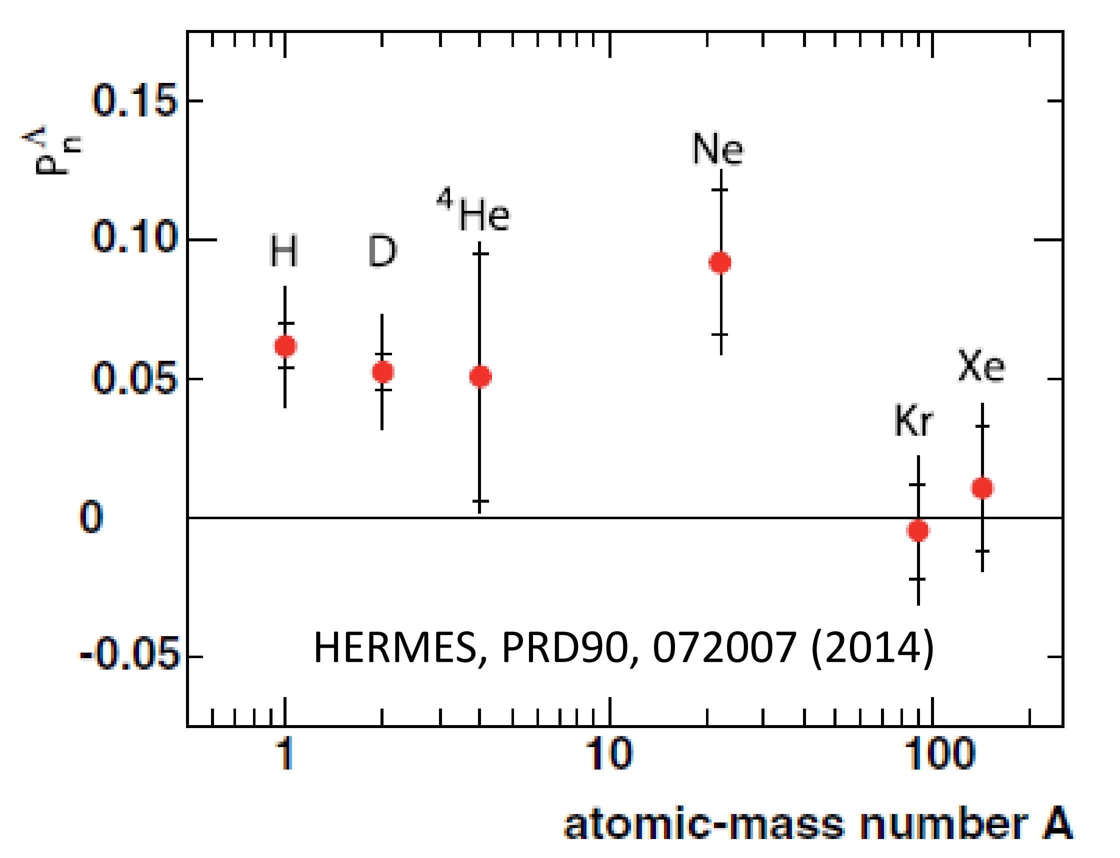
- 1983: p+Be, 400 GeV beam
- Similar results for p+Cu and p+Pb

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



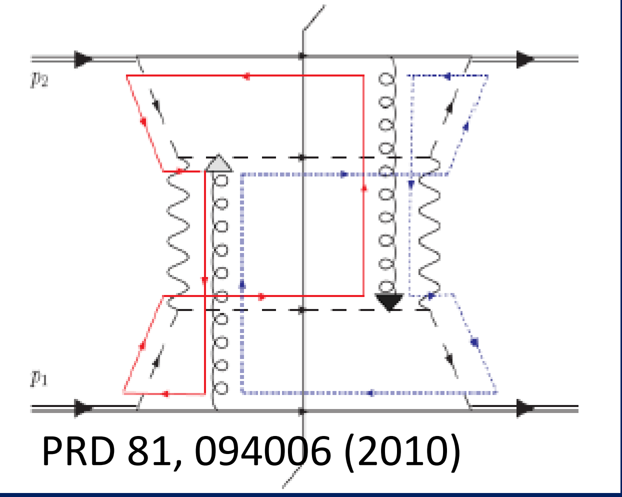
- Nonzero in both forward and backward directions

Formation of QCD bound states: Heavy flavor

- Open heavy flavor—vacuum fragmentation picture
- Heavy quarkonium states—different thinking
  - Handles on production via p_T dependence, polarization, in-medium modification
  - For very high p_T production in hadronic collisions, return to vacuum fragmentation picture? How to handle multiple hard scales in calculations?

Transverse-momentum-dependent (TMD) factorization breaking and color entanglement

- 2010: Rogers and Mulders predict *color entanglement* in processes involving p+p production of hadrons if parton transverse momentum taken into account
- Due to gluon exchange between scattering parton and proton remnant in *both* initial and final state
- Partons become correlated *across* the two colliding protons
  - Can no longer factorize the nonperturbative functions into independent pdfs and fragmentation functions
  - Will need new (unknown) nonperturbative functions describing quantum-correlated partons across bound states
- Consequence of QCD specifically as a ***non-Abelian*** gauge theory!



PRD 81, 094006 (2010)

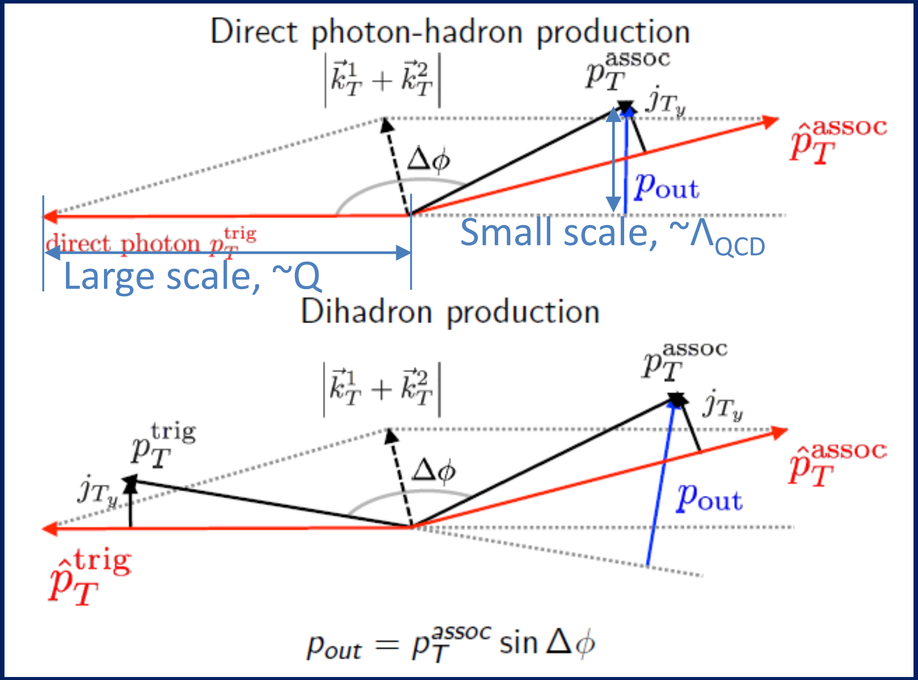
$$p + p \to h_1 + h_2 + X$$

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

Searching for evidence of predicted TMD-factorization breaking at RHIC

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

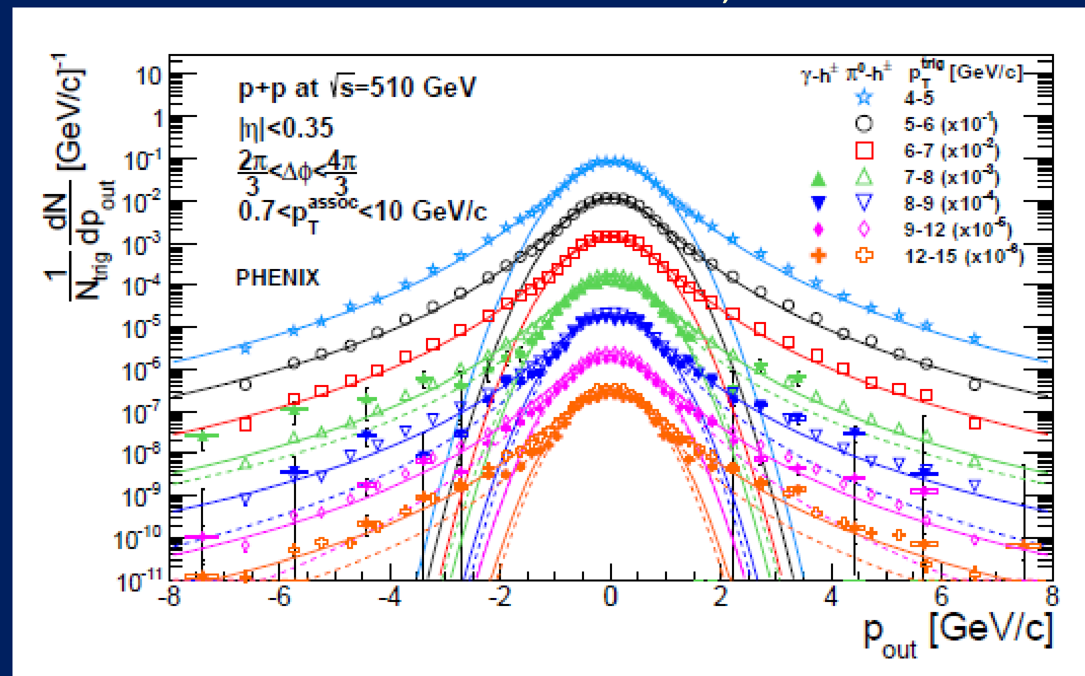
→ In p+p collisions, measure out-of-plane momentum component in nearly back-to-back photon-hadron and hadron-hadron production



Out-of-plane momentum component distributions

- Clear two-component distribution
  - Gaussian near zero—nonperturbative transverse momentum
  - Power-law at large p_{out}—kicks from hard (perturbative) gluon radiation
- Different colors → different bins of trigger particle p_T, proxy for hard interaction scale

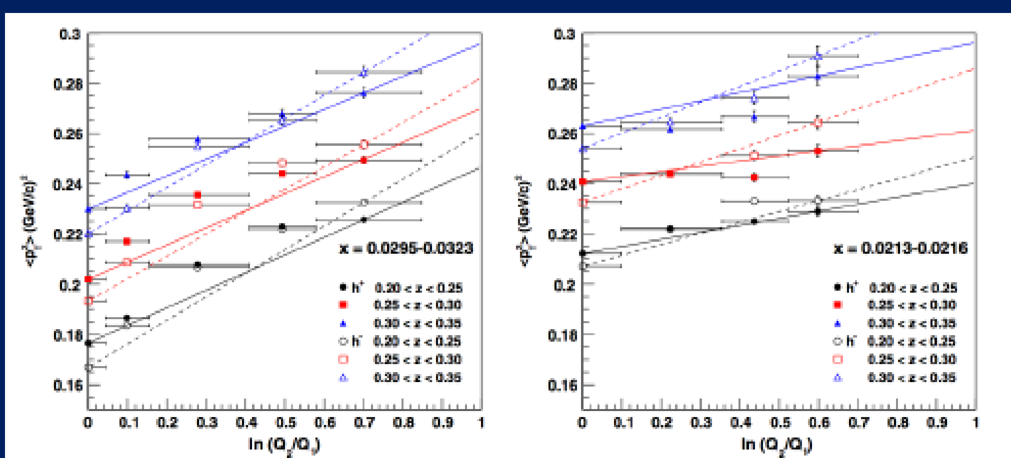
PHENIX Collab., arXiv:1609.04769



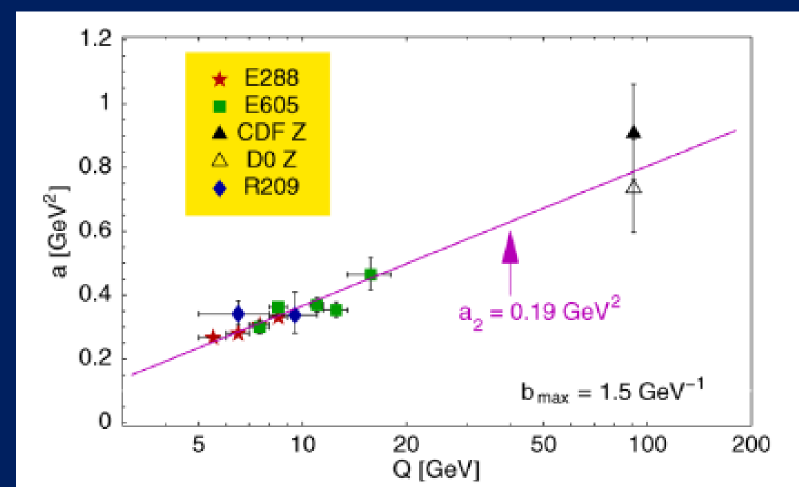
Curves are fits to Gaussian and Kaplan functions, not calculations!

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

- Theoretical proof of factorization within transverse-momentum-dependent framework directly predicts that nonpertubative transverse momentum widths *increase* as a function of the hard scattering energy scale (Collins-Soper-Sterman evolution)
  - Increased phase space for gluon radiation
- Confirmed experimentally in semi-inclusive deep-inelastic lepton-nucleon scattering (left) and quark-antiquark annihilation to leptons (right)

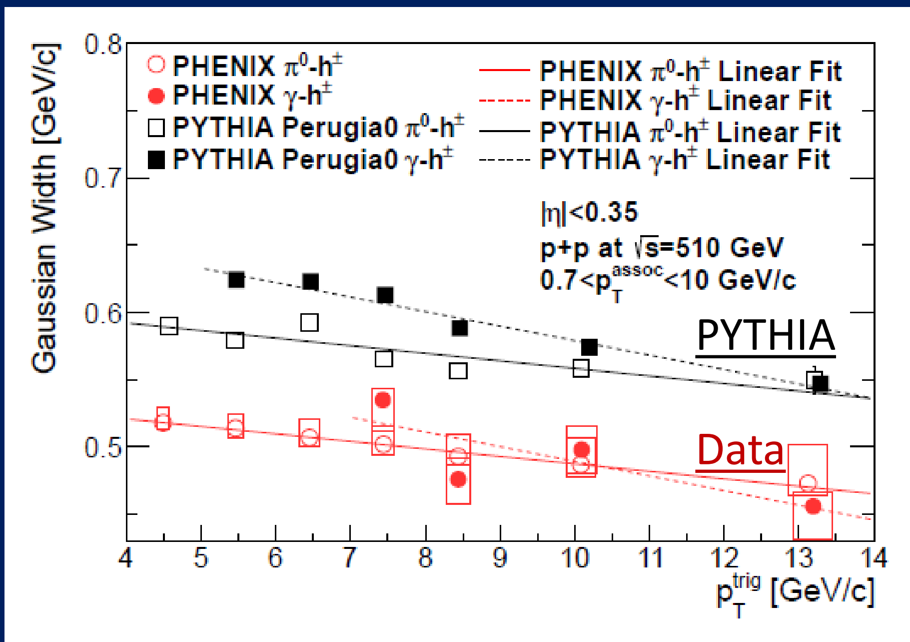


Aidala, Field, Gamberg, Rogers, Phys. Rev. D89, 094002 (2014)



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

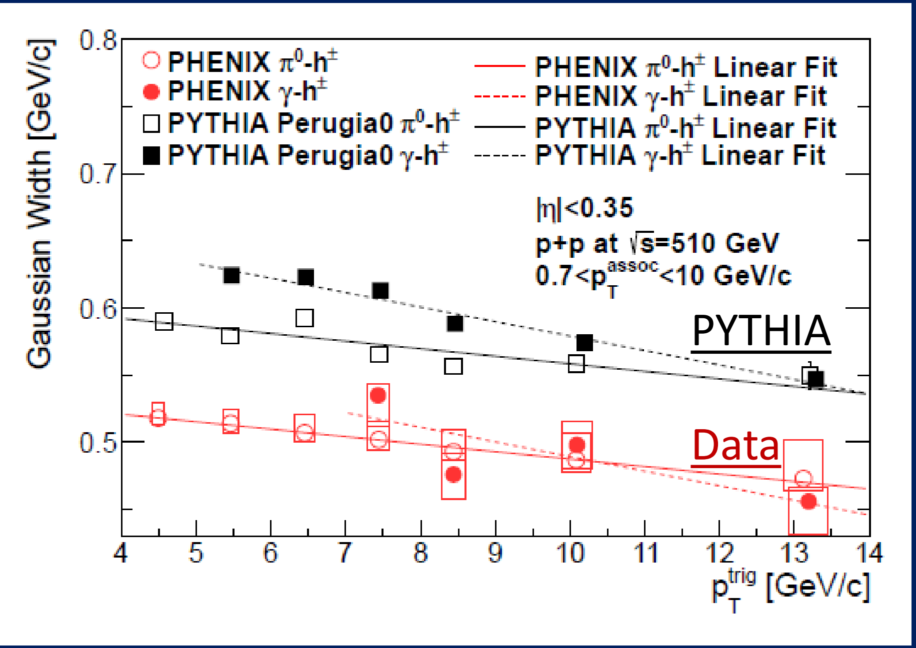
*Nonperturbative momentum widths observed to **decrease** in processes where factorization breaking predicted*



PHENIX Collab., arXiv:1609.04769

- Suggestive of TMD-factorization breaking effects?
- Have not yet completely ruled out a "trivial" nonperturbative correlation between partonic longitudinal momentum fraction *x* and partonic transverse momentum k_T
- Steeper negative slope for photon-hadron than dihadron correlations—counterintuitive?
  - Photon can't exchange gluon with remnant—might expect weaker effects than dihadron case

Nonperturbative momentum widths observed to ***decrease*** *in processes where factorization breaking predicted*



PHENIX Collab., arXiv:1609.04769

- Slope of decrease for both photon-hadron and dihadron correlations reproduced ~exactly in PYTHIA p+p event generator—could this effect be in PYTHIA??
  - Effectively yes! Unlike analytic pQCD calculations, PYTHIA forces *entire event including remnants* to color neutralize, implemented via something they call "color reconnection"