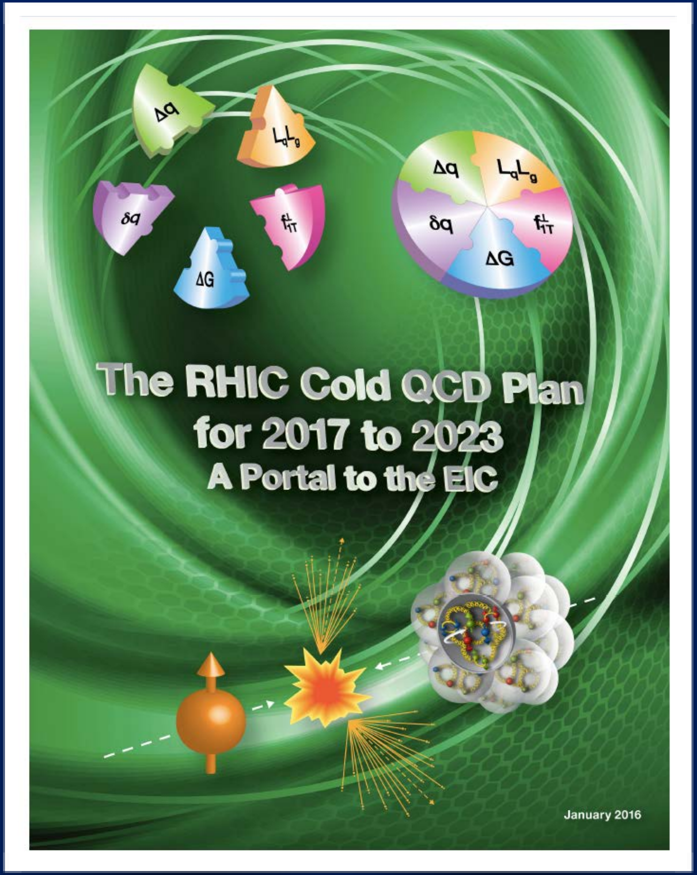
RHIC Cold QCD Plan

Available as arXiv:1602.03922



Christine A. Aidala
University of Michigan

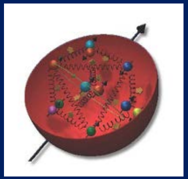
National Academy of Sciences EIC Science Assessment
February 1, 2017

“Cold” QCD

- “Cold” in contrast to “hot” QCD, in which energy densities high enough to form a quark-gluon plasma
- At RHIC
  - proton-proton (p+p)
  - proton-nucleus (p+A)
  - ultraperipheral nucleus-nucleus (A+A) collisions

- Cold QCD focuses on
  - *Structure* – description of QCD bound states in terms of the quarks and gluons within them
  - *Hadronization* – processes by which quarks and gluons form QCD bound states
  - *Interactions* involving hadrons – effects due to color flow in different scattering processes

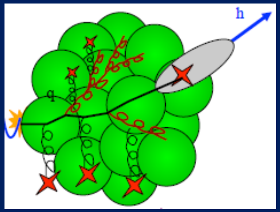
Structure of QCD bound states



Theoretical + experimental progress since late 1990s has permitted increasingly sophisticated pictures of the quark-gluon structure of the nucleon, in terms of:

- *Momentum* – only parton collinear momentum fraction of nucleon momentum considered until 1990s. Considering transverse momentum of partons within nucleon opened up new subfield of parton spin-momentum correlations within nucleon
- *Spin* – Experimental control of nucleon spin enables study of spin-spin correlations and spin-momentum correlations
- *Flavor* – Flavor asymmetry between antidown and antiup quarks in proton discovered in 1990s, still not understood. Evidence for flavor asymmetry in polarized distributions as well
- *Position* – Basic concepts regarding how to access parton radial position within nucleon only in 1990s. Pioneering experimental measurements so far

Knowledge of quark-gluon structure of *nuclei* still relatively primitive



Hadronization

- Not as far along as nucleon structure—much less of a focus in previous decades
  - Phenomenological analyses only incorporated semi-inclusive deep-inelastic scattering and hadronic collision data along with e+e- annihilation data as of 2007

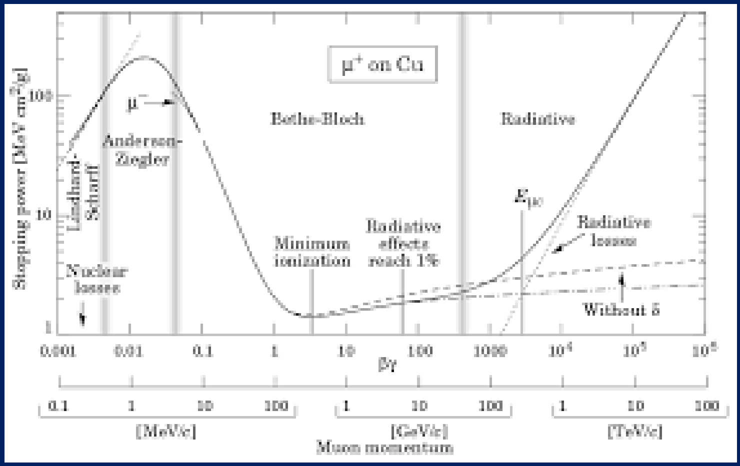
- Recent advances via
  - Spin-momentum and spin-spin correlations in hadronization
  - Multiparton correlations in hadronization—interference effects between hadronization from (q+g) and only a quark, or (g+g) and only a gluon
  - Interference effects of multiple hadrons coming from a single parton
  - Hadronization in nuclear environment

- Topic starting to get more attention → major area of focus at EIC

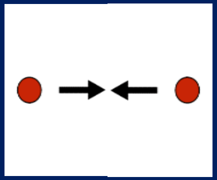
Interactions involving hadrons

- In 2000s, starting to consider color interactions in different scattering processes
  - New interest in the interactions themselves, rather than only hadron structure or hadronization
  - Theoretical breakthroughs in 2002 (Brodsky, Hwang, and Schmidt; Collins) and 2010 (Rogers and Mulders)

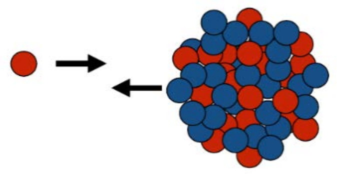
- Another example of interest in interactions: parton energy loss in cold (or hot) QCD matter
  - QCD analog of Bethe-Bloch energy loss



Cold QCD areas of focus at RHIC



(Many linked to one another)



- Partonic structure of the proton
- Partonic structure of nuclei / Nuclear pdfs
- Gluon saturation / Structure at small parton momentum fraction
- Spin-momentum correlations in the nucleon, quantum interference effects and their process dependence
- Diffraction
- Hadronization in different environments

RHIC Cold QCD Plan: Relation to EIC

Focus on measurements *complementary to* or *in support of* future EIC physics program

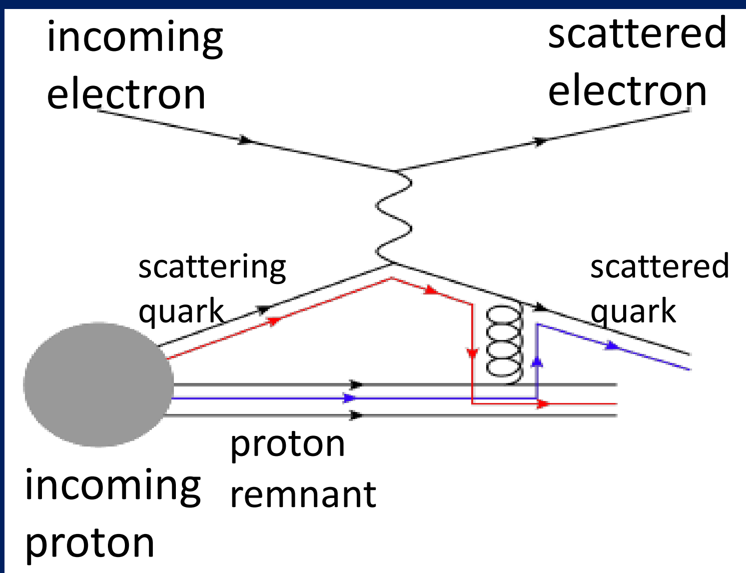
- Unique color interactions in hadronic collisions
  - Comparison to lepton-hadron scattering → universality studies
  - Novel non-Abelian effects not accessible with a lepton beam

- Early measurements of effects/observables to be studied in depth at EIC
  - Investigate scale of effects
  - Push further theoretical development

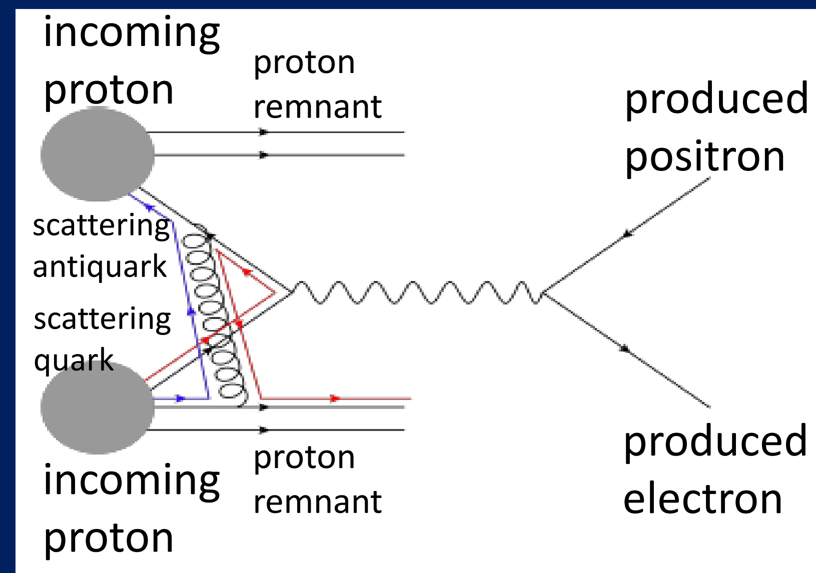
- Draw larger community into EIC physics and observables

Spin-momentum correlations; interactions and color flow

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



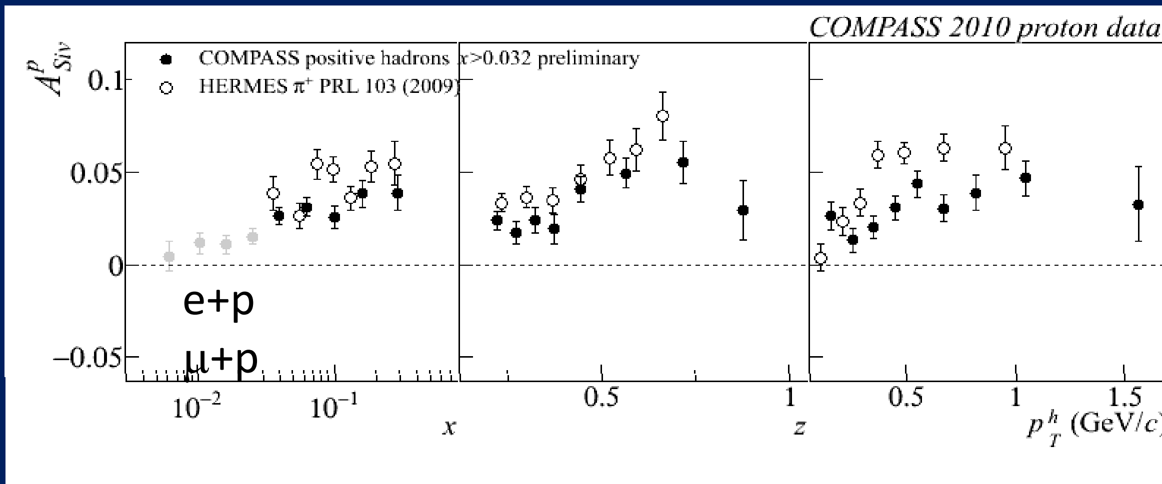
Quark-antiquark annihilation to electrons: Initial-state color exchange



Get *opposite sign* for certain spin-momentum correlations in these two processes, due to phase interference effects and color exchange in the final state vs. initial state (Collins 2002)

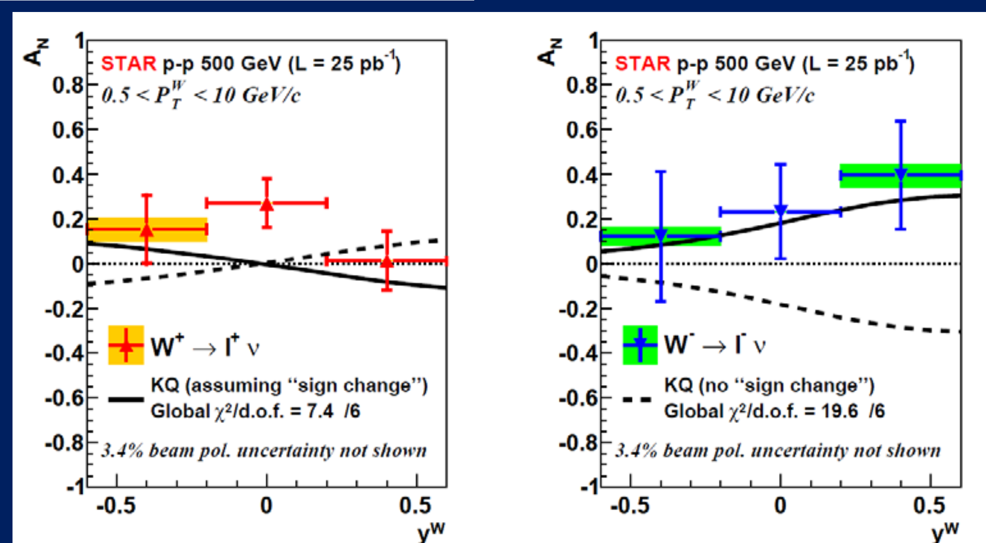
Figures by J.D. Osborn

Spin-momentum correlations; interactions and color flow

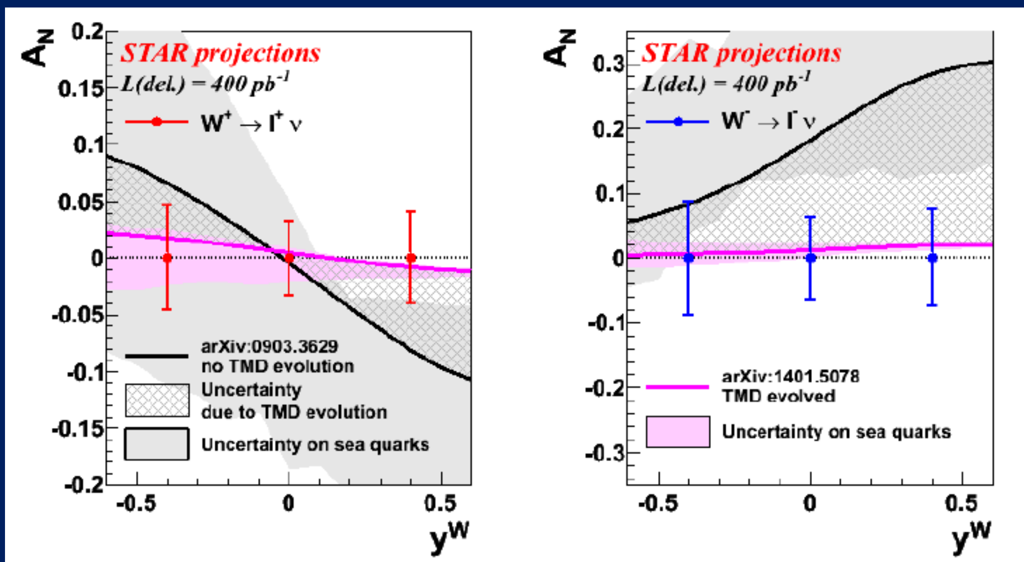


Clear ~5% spin-momentum correlation measured in lepton-proton scattering, only enabled by final-state color exchange

Initial STAR measurement of corresponding spin-momentum correlation in W production suggestive of predicted sign change due to process-dependent color interactions

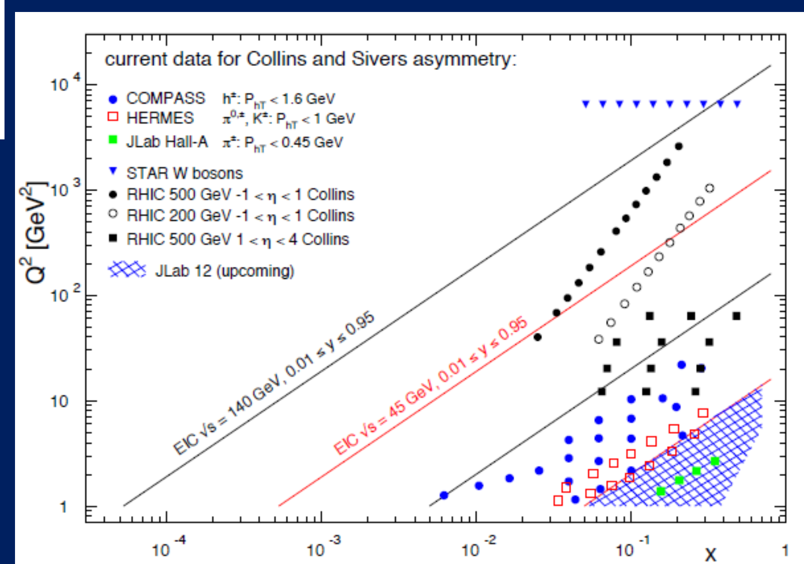


Spin-momentum correlations; interactions and color flow



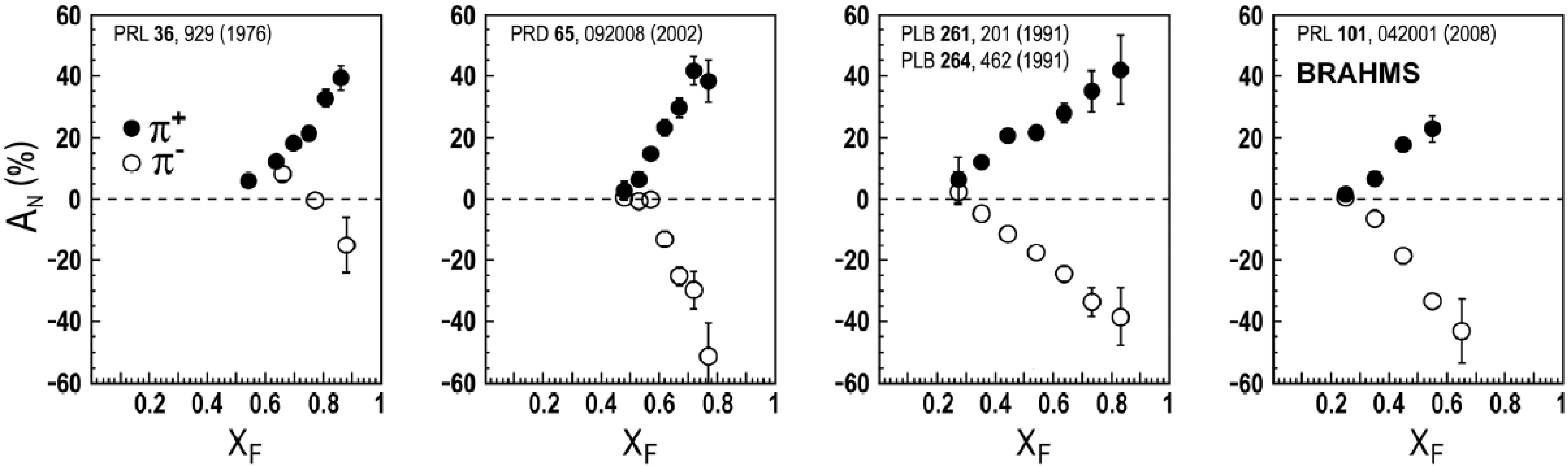
STAR projections for anticipated 2017 data. Stronger check of predicted process dependence, and improved constraints on sea quark spin-momentum correlations, and energy dependence of effects

Comparison of kinematic coverage for similar spin-momentum correlation measurements



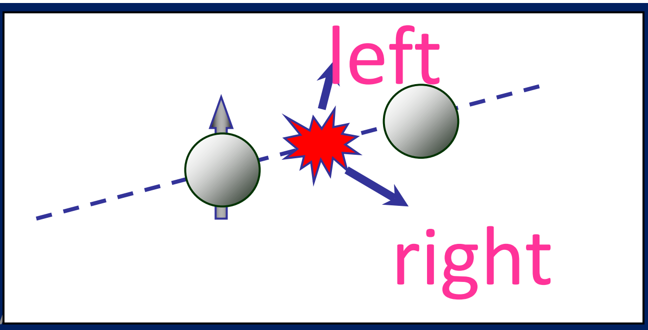
Up to 40% spin-momentum correlations in p+p collisions that persist across energies

ANL	BNL	FNAL	RHIC
√s=4.9 GeV	√s=6.6 GeV	√s=19.4 GeV	√s=62.4 GeV



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

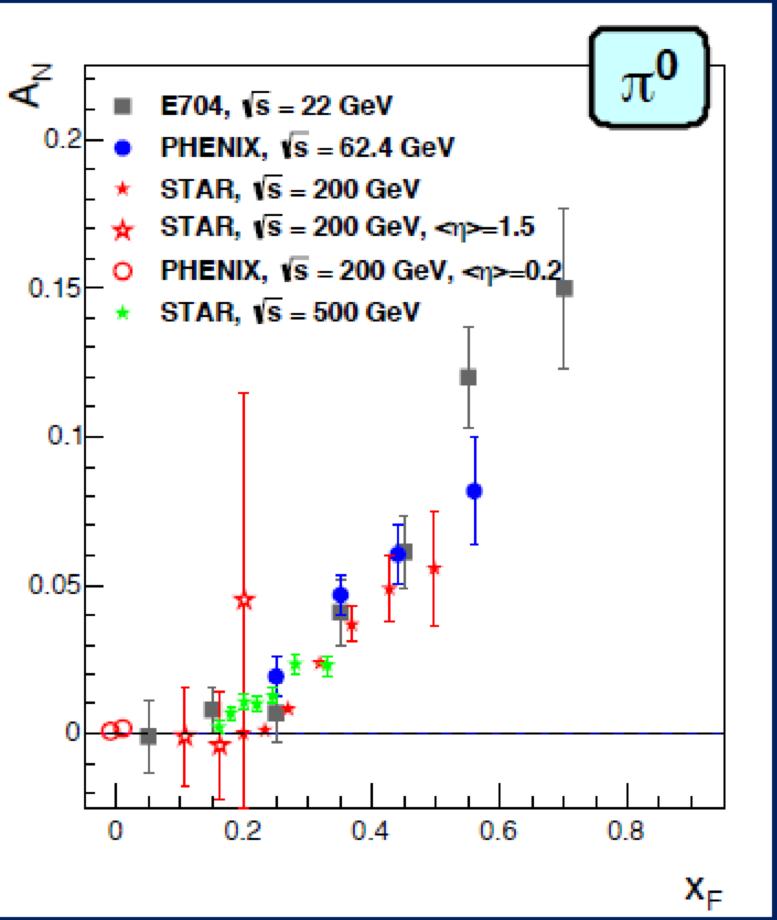
Still not well understood—possible links to diffraction, color interactions, …



Large spin-momentum correlations up to 500 GeV

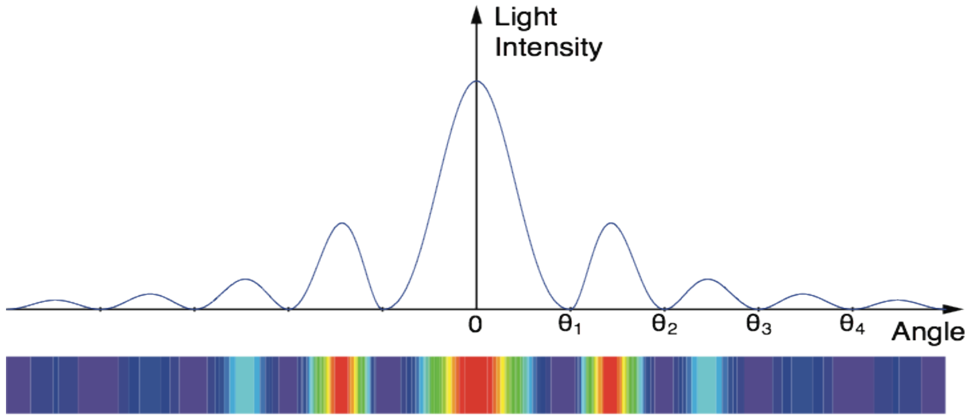
- Neutral pion production asymmetries up to ~10%, with very little dependence on energy up to 500 GeV

- STAR investigating further via *diffractive* measurements …



"Gamma-ray diffraction" to probe spatial structure of nuclei

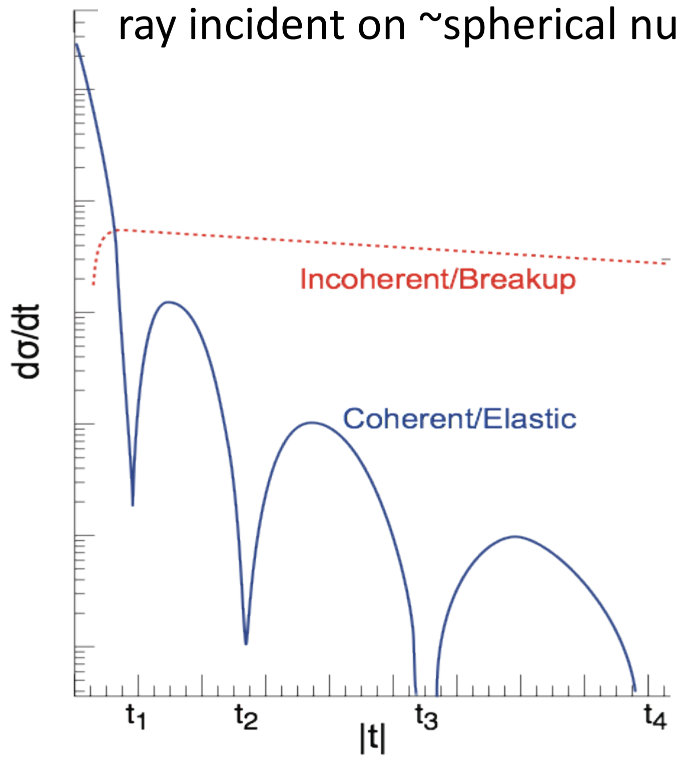
Diffraction pattern from monochromatic plane wave incident on a circular screen of fixed radius



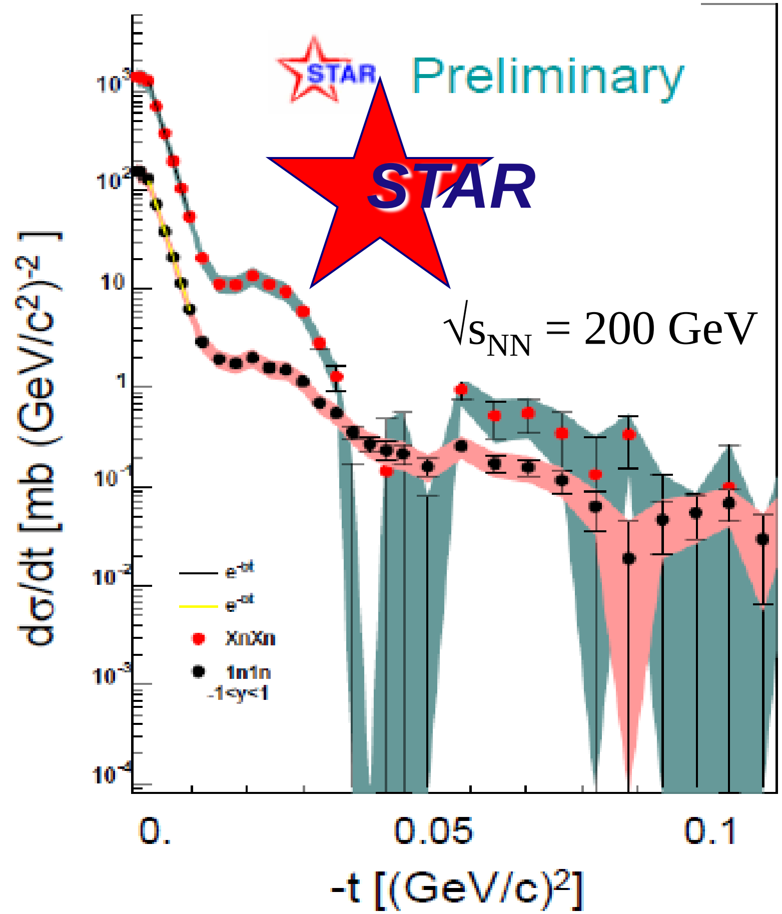
From E. Aschenauer

"Gamma-ray diffraction" to probe spatial structure of nuclei

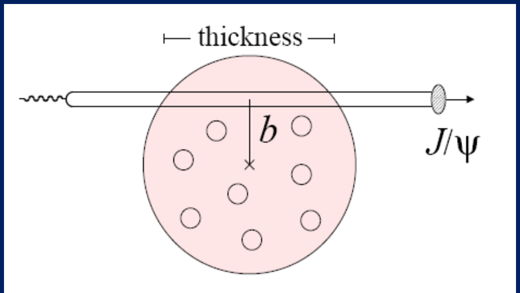
Expected diffraction pattern from gamma ray incident on ~spherical nucleus



Diffractive ρ production in Au+Au ultraperipheral collisions



2 nuclear beams. Probed nucleus in one beam. Gamma emitted by Coulomb-excited nucleus passing nearby in second beam.

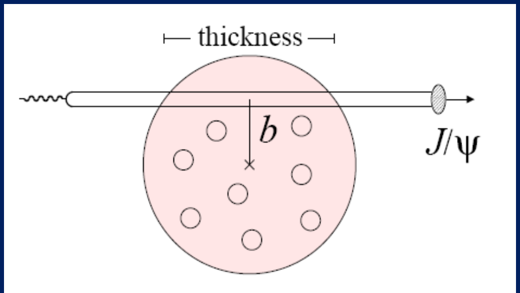


Diffraction at RHIC

- In addition to probing spatial structure, diffraction is one way to probe gluon saturation within nuclei
- Comparing diffraction in hadronic collisions and e+p or e+A is furthermore of interest – study universality

Ongoing measurements by STAR

- Preliminary ρ in Au+Au—clear diffractive peaks
- Measurement of diffractive contribution to huge forward transverse single-spin asymmetries

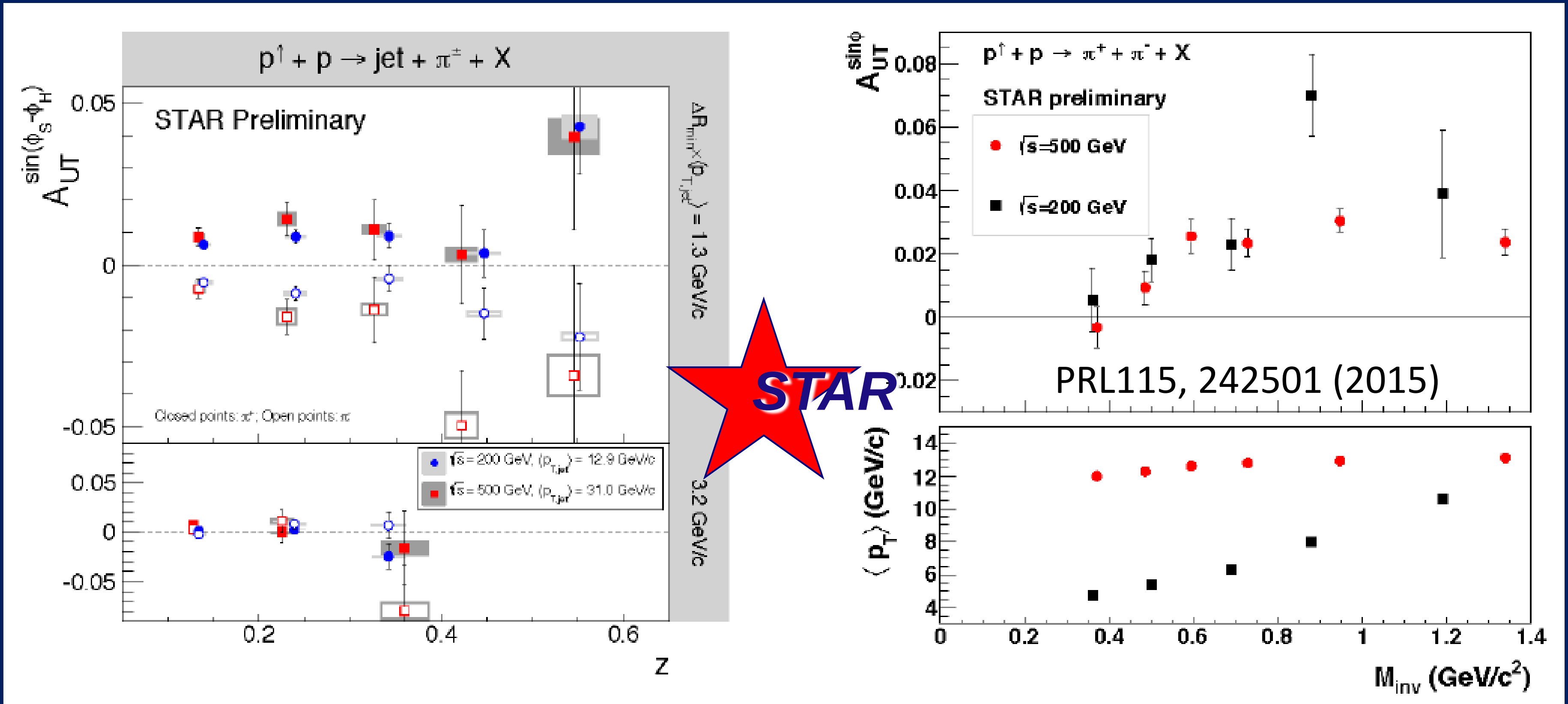


Diffraction at RHIC

- First-ever, early measurement of Generalized Parton Distribution “E” for gluons in 2017 510 GeV p+p via diffractive J/Psi production—sensitive to *gluon orbital angular momentum*

- Diffractive J/Psi production in polarized p+A, for multiple physics measurements
  - *Spatial imaging of gluon distribution in nucleus*
  - Probe gluon orbital angular momentum in polarized proton – Z^2 from heavy nucleus helps

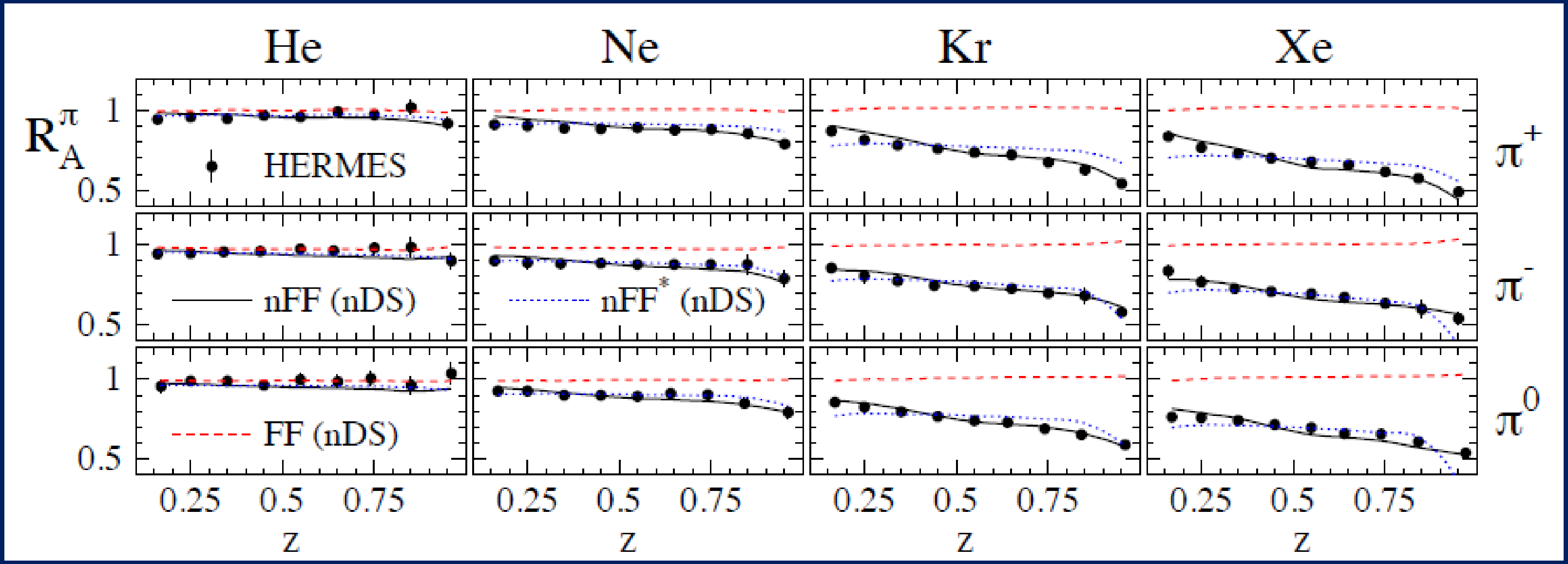
Hadronization: Clear spin-dependent hadronization observed in p+p collisions



Spin-momentum correlation observed for charged pion in a reconstructed jet

Spin-dependent interference between two pions hadronizing from same parton

Hadronization in nuclei: e+A

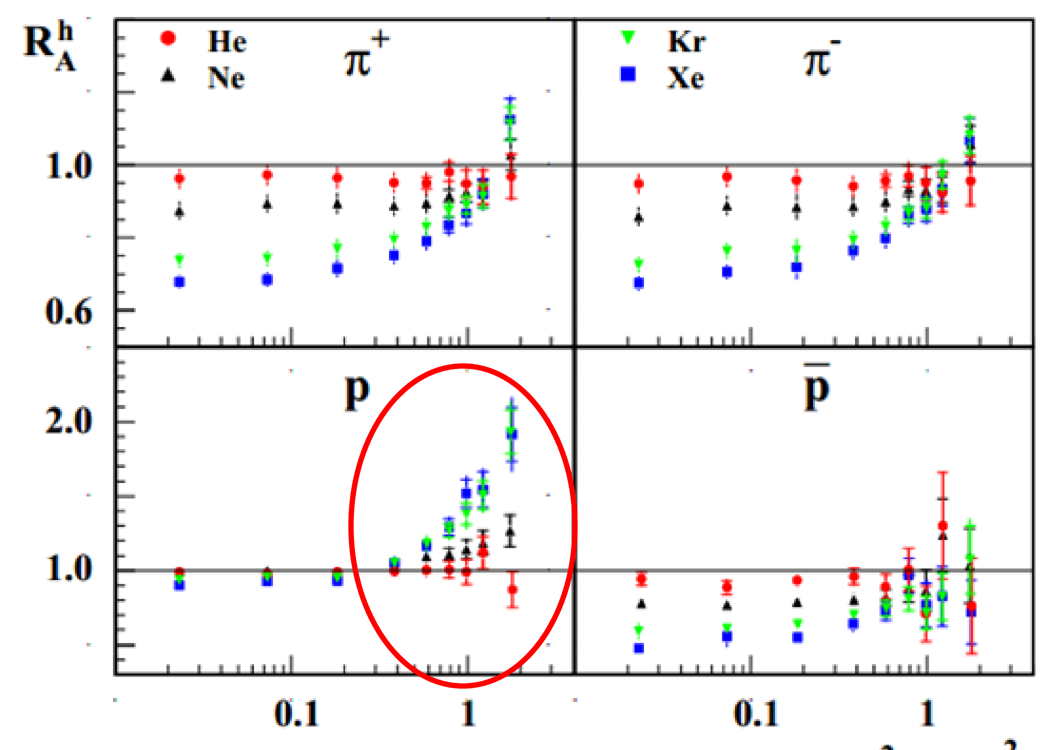


- Modification of pion production in e+A collisions with respect to scaled e+p collisions
- Nuclear mass dependence

Hadronization in nuclei: Effects due to higher-density partonic environments?

- Modification of particle production in e+A compared to e+p
  - Not fully explained by nuclear pdfs

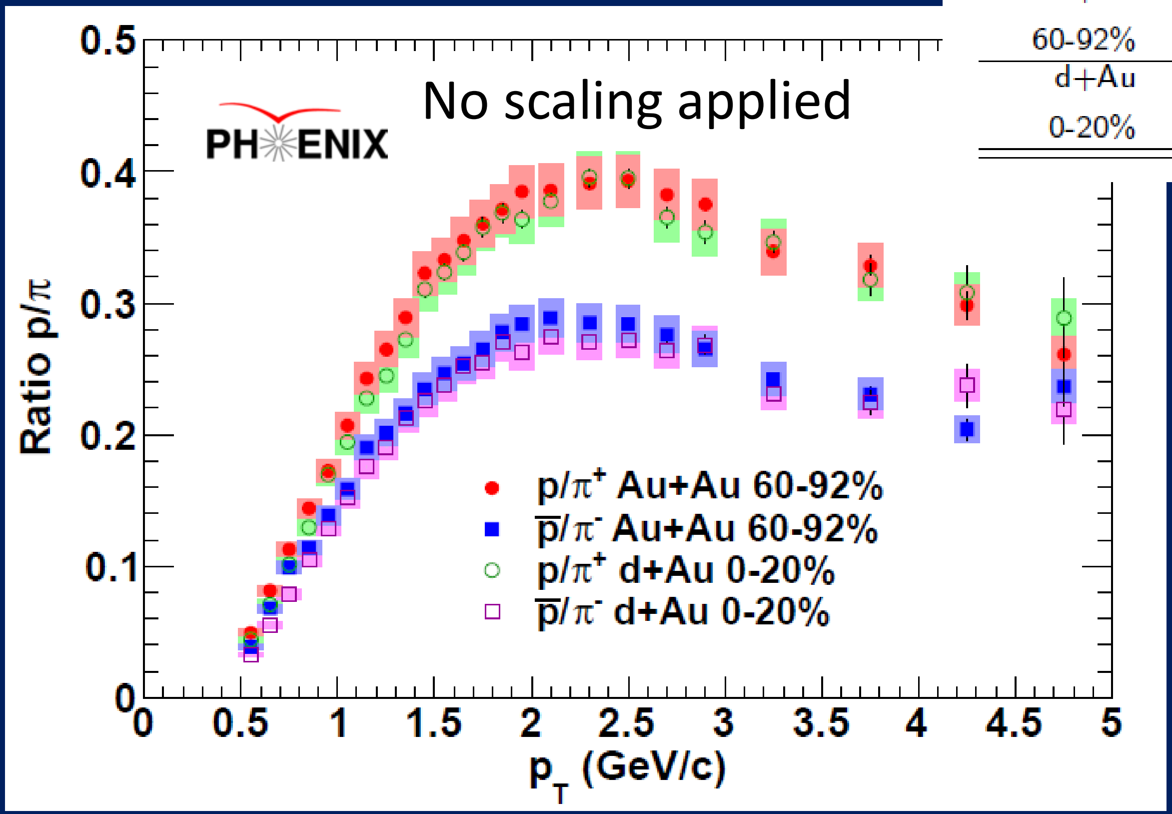
- Enhancement of protons compared to pions in e+A with respect to scaled e+p



HERMES, NPB780, 1 (2007)

Hadronization in nuclei: Effects due to 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

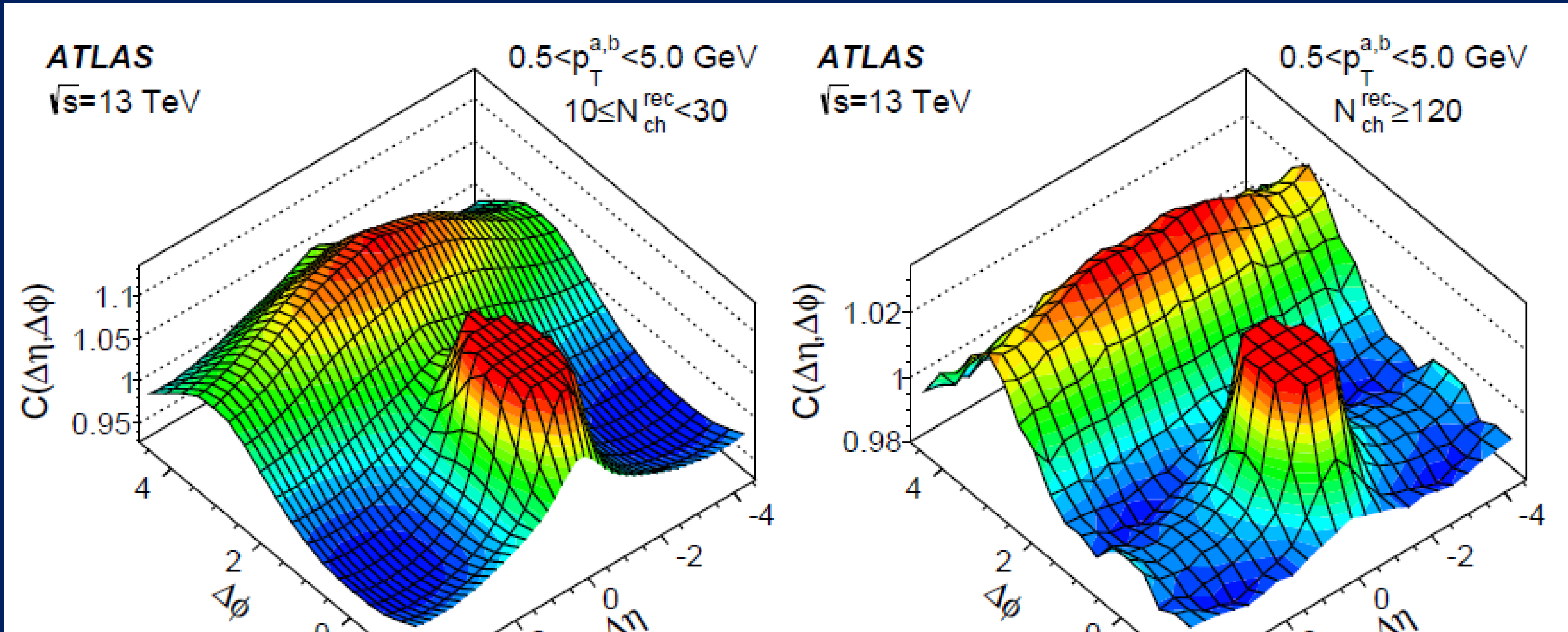


PRC88, 024906 (2013)

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

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



PRL 116, 172301 (2016)

- Long-range correlations in hadron production also observed in deuteron-gold collisions at RHIC
- Unclear so far if "hot" or "cold" QCD effect

Proposed RHIC Cold QCD program

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3 First look at GPD Eg	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR **None** **None**
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η evolution of ETQS fct. properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for γ A_N for diffractive events	Yes Forward instrum. **None** **None**
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY):Yes Forward instrum. **None** Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. **None** Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity observables as in 2017 run	Yes Forward instrum. **None**
	202X	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Yes Forward instrum.

Table 1-2: Summary of the Cold QCD physics program propsed in the years 2017 and 2023 and if an additional 500 GeV run would become possible.

Nominal RHIC timeline

- 2017-21 - only the STAR experiment operating
  - PHENIX experiment completed operations in 2016
  - sPHENIX upgrade detector planned for 2022; received CD0 in Oct 2016
- 2017 - 10-week transversely polarized p+p run at 510 GeV
- 2018-21 – Beam-energy scan to search for QCD critical point
- 2022 – Top-energy nucleus-nucleus collisions
- 2023 – Proton-proton and proton-nucleus running
  - Forward instrumentation in 2022 and 2023 not settled

Generic forward rapidity instrumentation requirements for Cold QCD Plan in 2023

- Coverage approximately $1<\eta<4$
- Calorimetry (electromagnetic and hadronic)
- Tracking
- Roman pots for diffractive measurements
- Hadron PID for hadronization measurements

- Note: Not all proposed measurements require additional forward instrumentation (see table)

Forward rapidity instrumentation for Cold QCD Plan in 2023

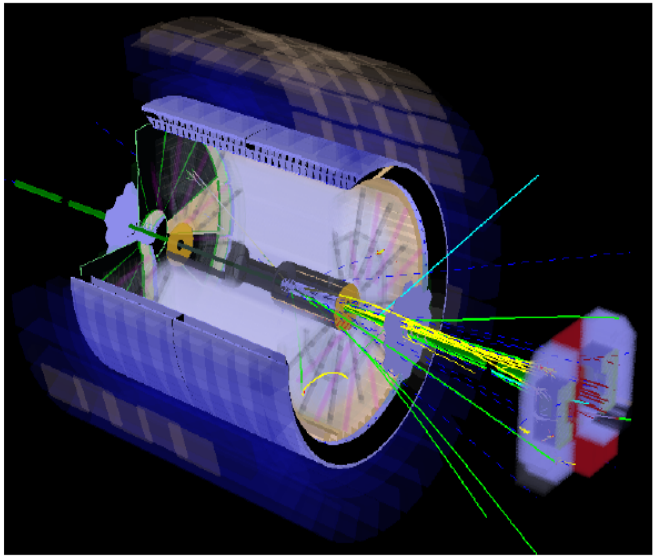
Resources for forward instrumentation not currently clear

- Reconfiguration of previous instrumentation from PHENIX, STAR, or potentially other (non-RHIC) experiments possible, in particular for electromagnetic calorimetry
- Potential new instrumentation should be reusable for EIC
- Detector requirements for forward instrumentation in the hadron beam direction at the EIC are ~identical; possibility of designing a forward spectrometer for the EIC and building it several years early in order to take advantage of hadronic collisions at RHIC under discussion

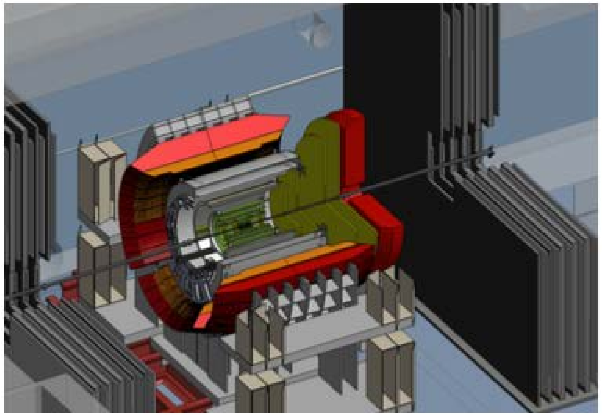
STAR and sPHENIX forward instrumentation ideas

Physics Opportunities with STAR in 2020+

The STAR Collaboration
(Dated: October 19, 2015)



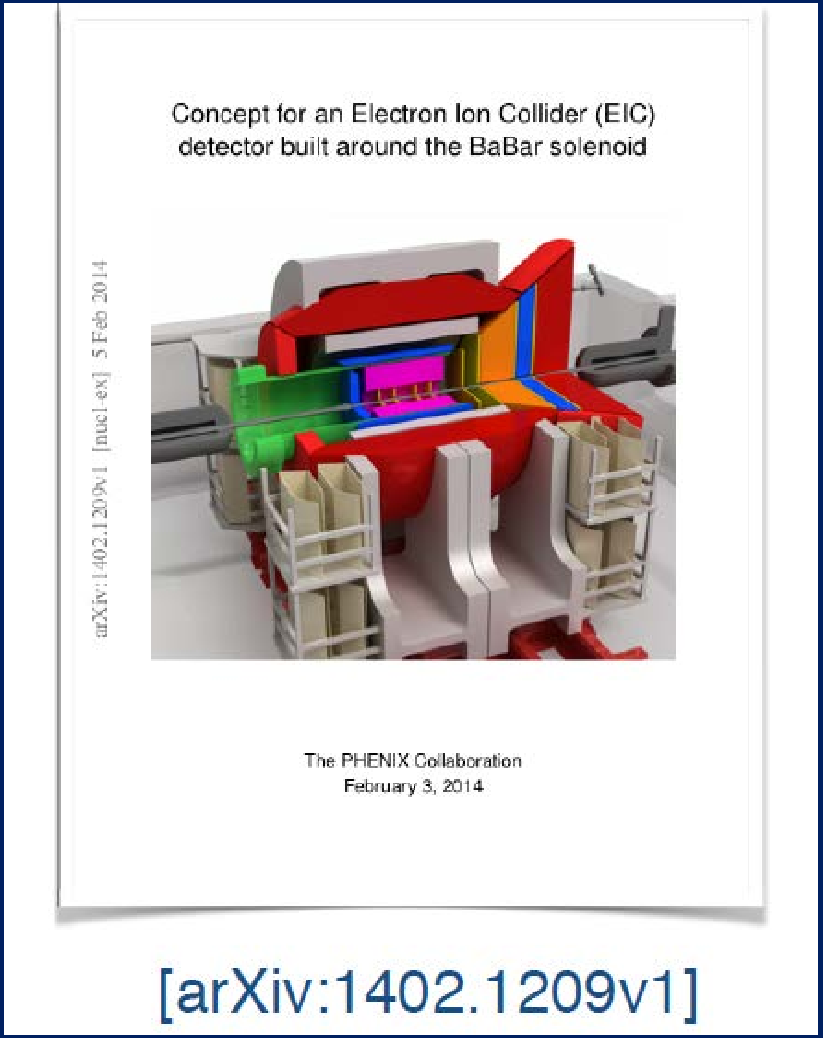
Future Opportunities in p+p and p+A Collisions at RHIC with the Forward sPHENIX Detector



The PHENIX Collaboration
April 29, 2014

LOI for sPHENIX-based EIC detector

Work ongoing to update; new document anticipated for late spring

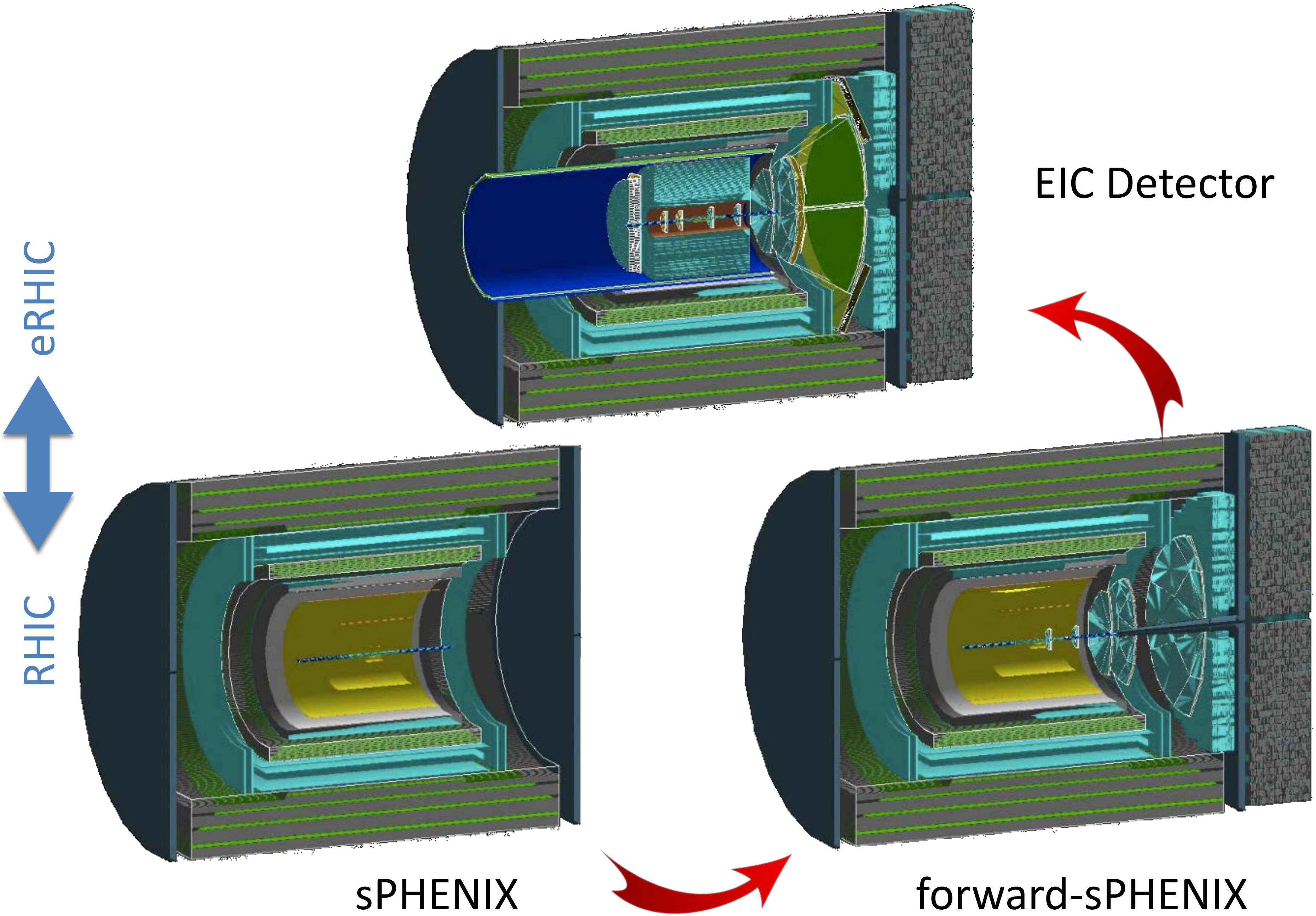


arXiv:1402.1209v1 [nucl-ex] 5 Feb 2014

Concept for an Electron Ion Collider (EIC) detector built around the BaBar solenoid

The PHENIX Collaboration
February 3, 2014

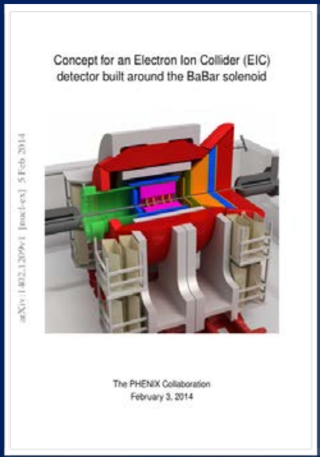
[arXiv:1402.1209v1]


EIC Detector
eRHIC
RHIC
sPHENIX
forward-sPHENIX

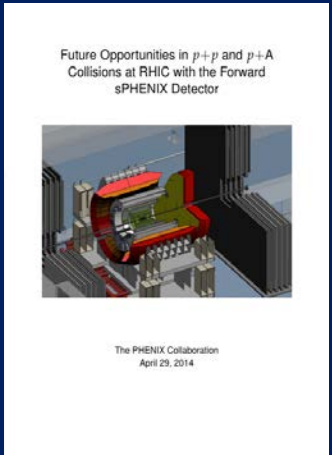
Upcoming meetings

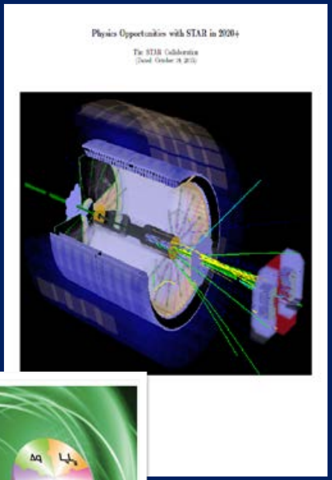
- RHIC Spin Collaboration meeting on hardware for the RHIC Cold QCD Plan – March 9-10 at BNL

- RIKEN-BNL Research Center workshop on p+p and p+A in connection to the EIC – June 26-28 at BNL

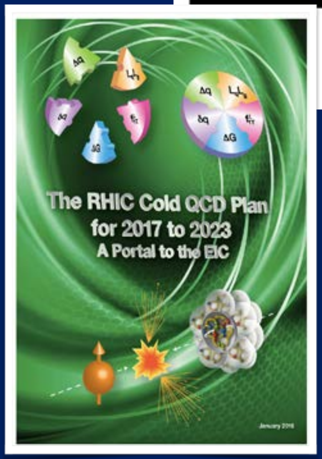


References and resources





- *Concept for an Electron-Ion Collider detector built around the BaBar solenoid*, arXiv:1402.1209
- *Future Opportunities in p+p and p+A Collisions at RHIC with the Forward sPHENIX Detector*, April 2014, http://tinyurl.com/fsphenix2014
- *Physics Opportunities with STAR in 2020+*, Oct 2015
  - https://drupal.star.bnl.gov/STAR/files/STAR-2020-plan.pdf
- *The RHIC Cold QCD Plan for 2017 to 2023: A Portal to the EIC*, arXiv:1602.03922



Conclusions

- RHIC cold QCD program focused on
  - *Hadron structure*
  - *Hadronization*
  - *Interactions involving hadrons*

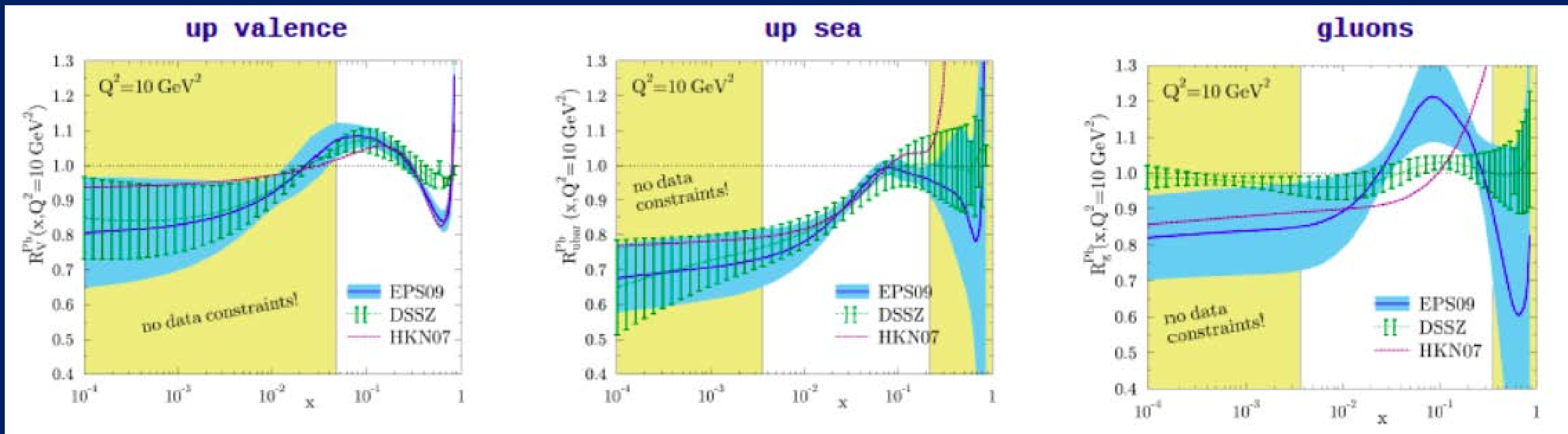
- Planned measurements *complementary to* or *in support of* future EIC physics program

- Broad themes include
  - spin-momentum correlations within the proton and the process of hadronization
  - diffractive measurements as probes of structure and interactions
  - nuclear modification of parton distribution functions and hadronization
  - unique color interactions and tests of universality

- There are a variety of existing and forthcoming measurements based on data already taken
- STAR experiment will take transversely polarized p+p data in 2017
- STAR and sPHENIX have proposals for further cold QCD measurements in 2023

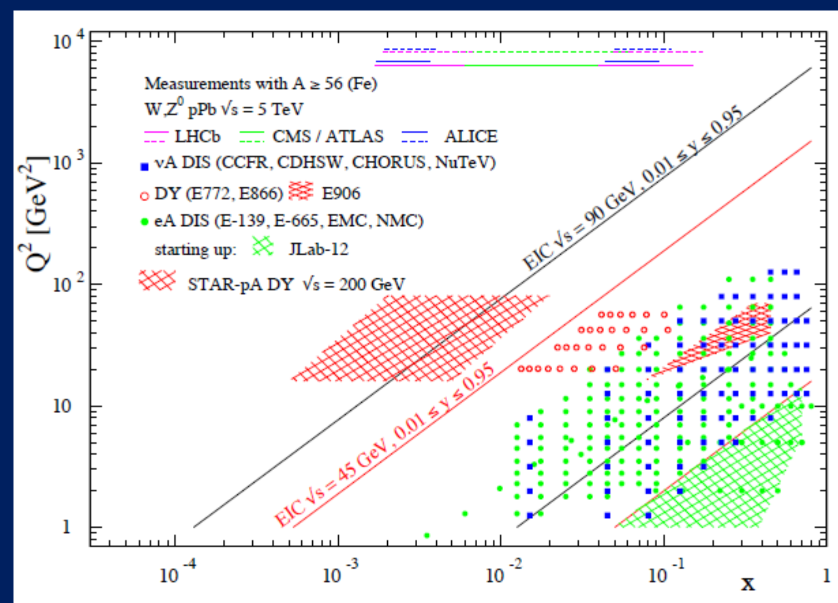
Extra

Nuclear parton distribution functions

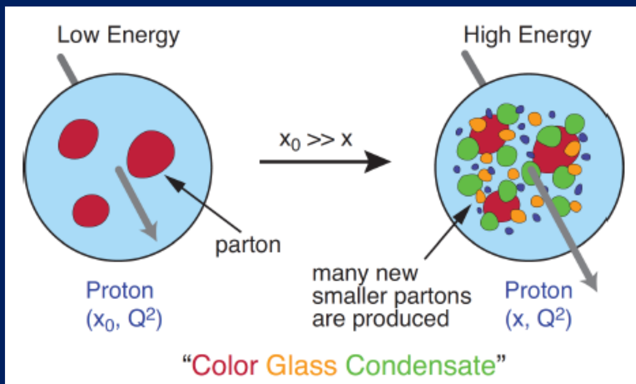


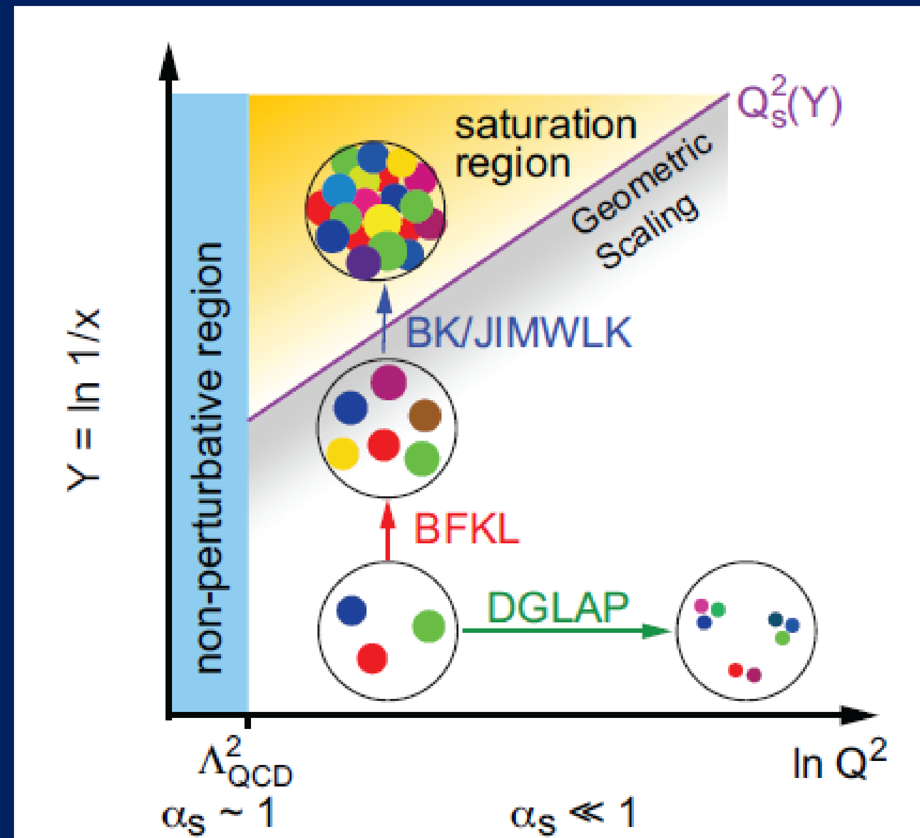
Ratio of parton distribution functions in Pb to those in deuteron

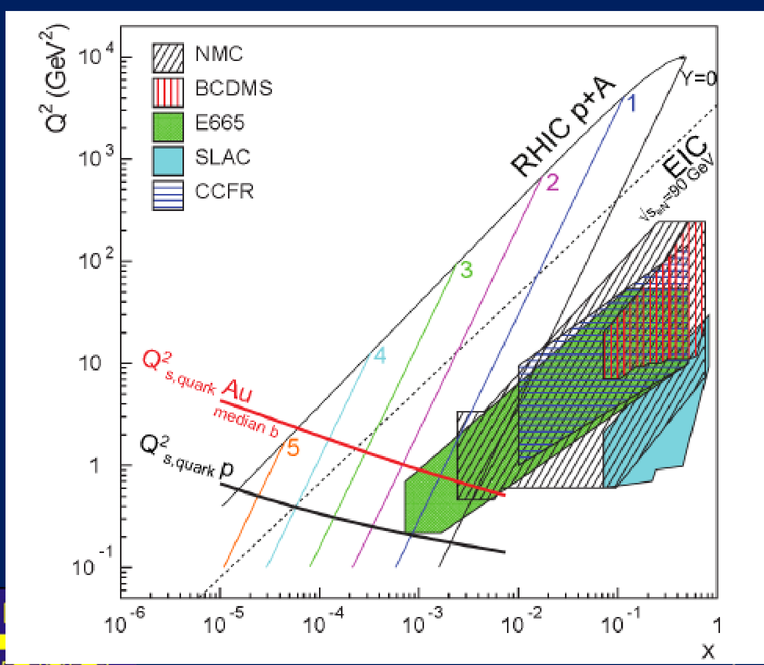
Kinematic coverage for nuclear pdf measurements by different experiments



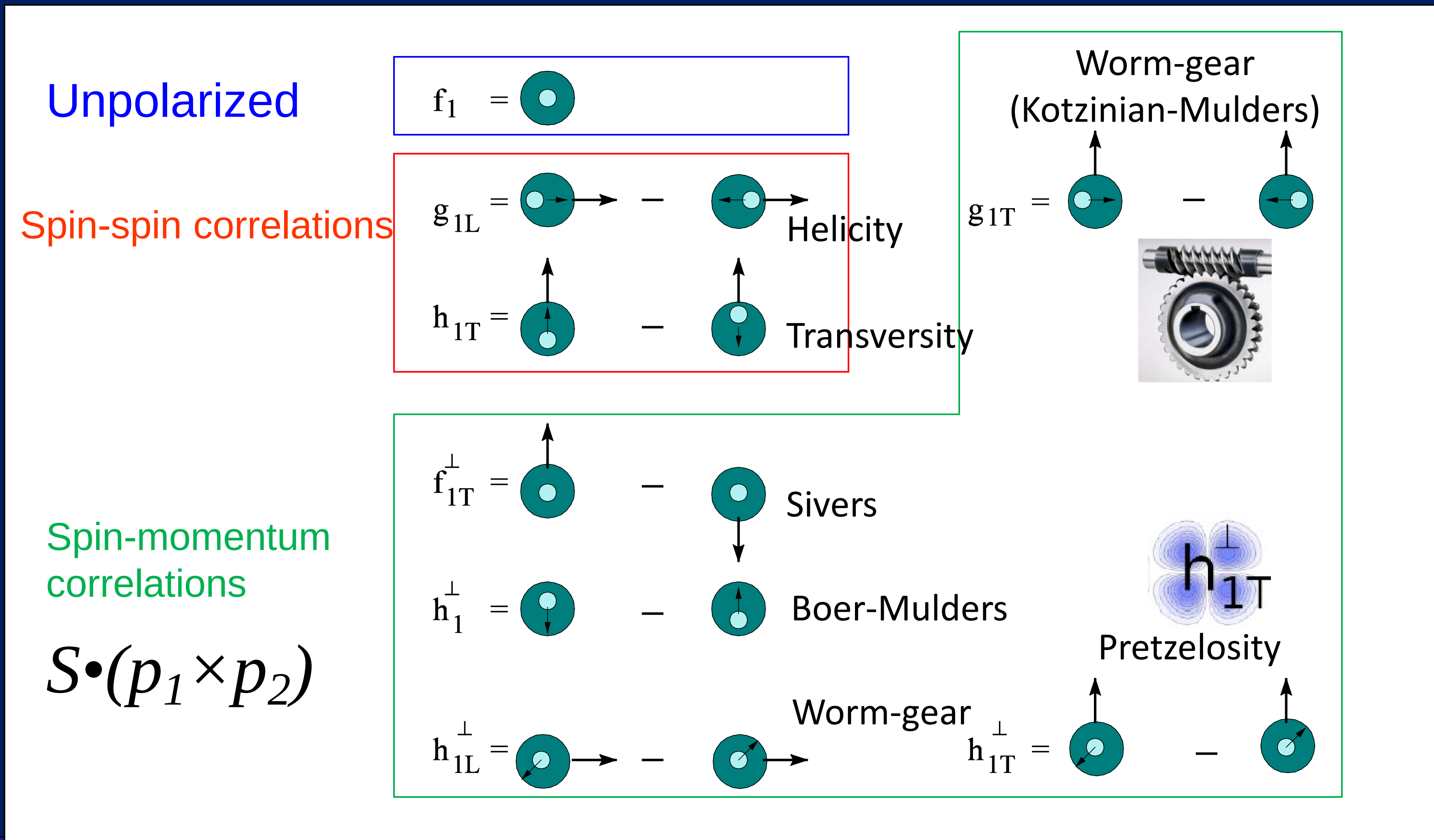
Gluon saturation







Spin-spin and spin-momentum correlations in QCD bound states

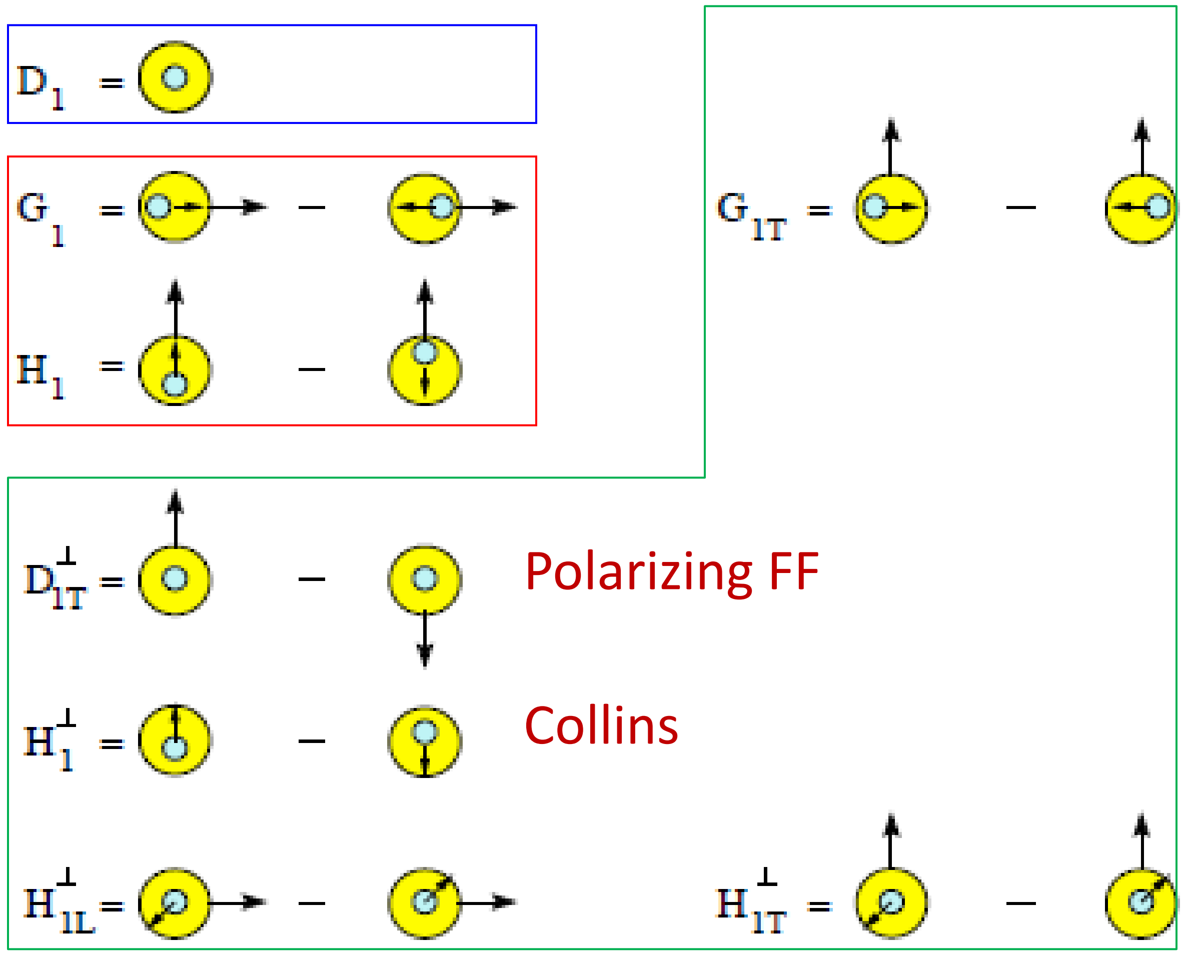


Spin-spin and spin-momentum correlations in hadronization

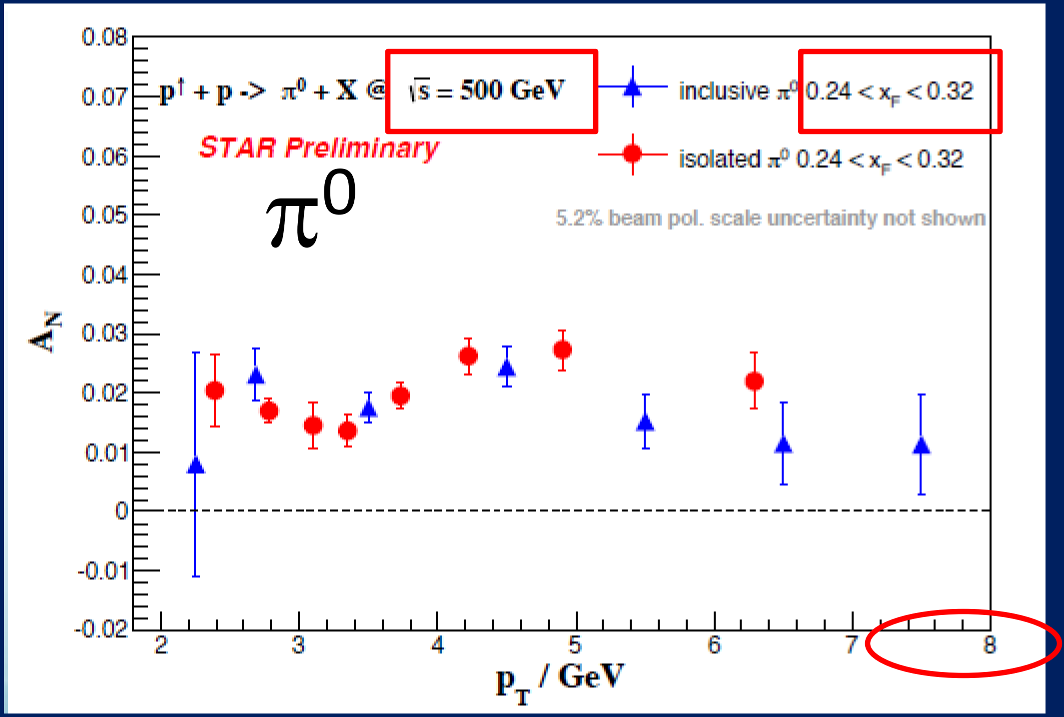
Unpolarized

Spin-spin correlations

Spin-momentum correlations



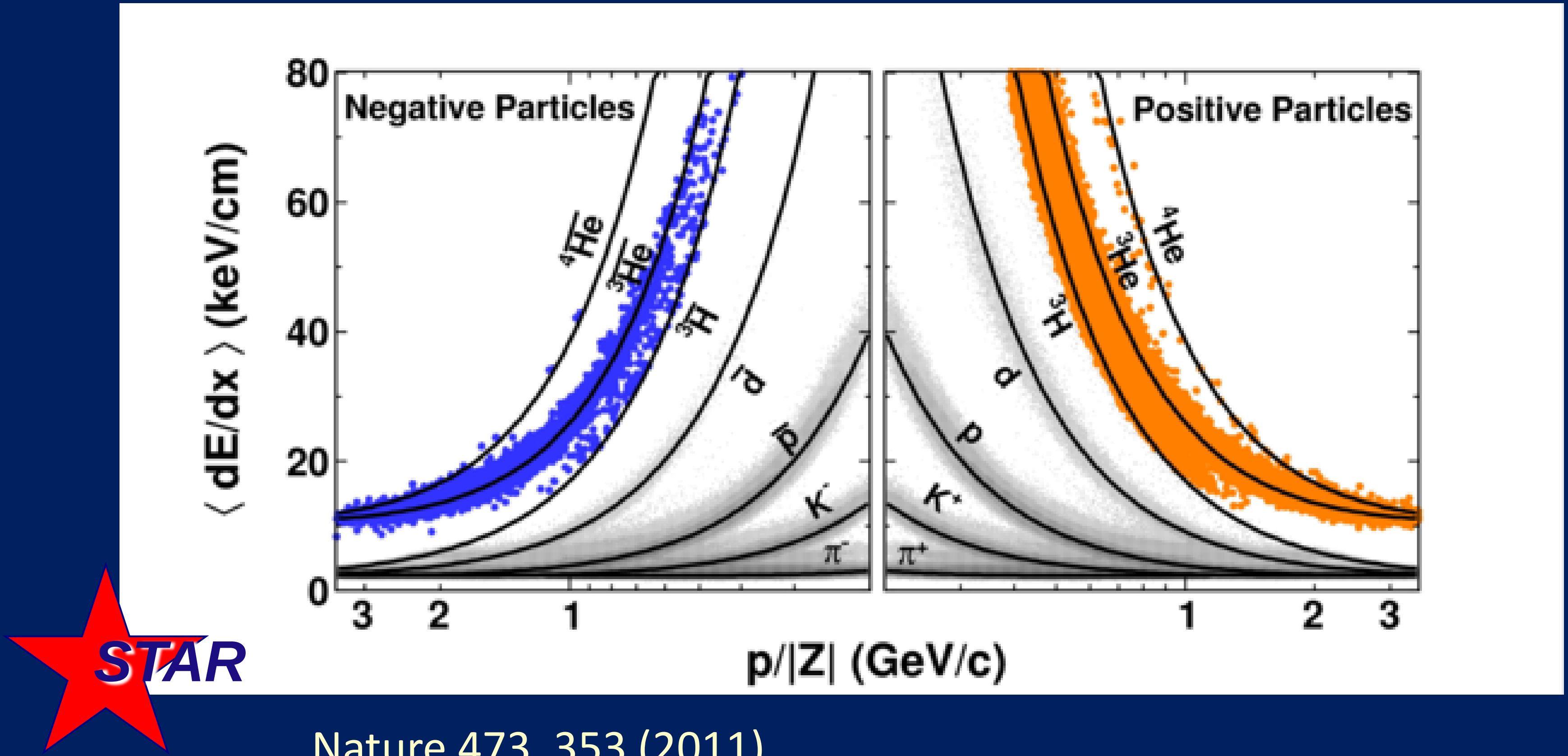
p+p → hadron asymmetries persist up to $\sqrt{s}$=0.5 TeV and p_T = 7 GeV!



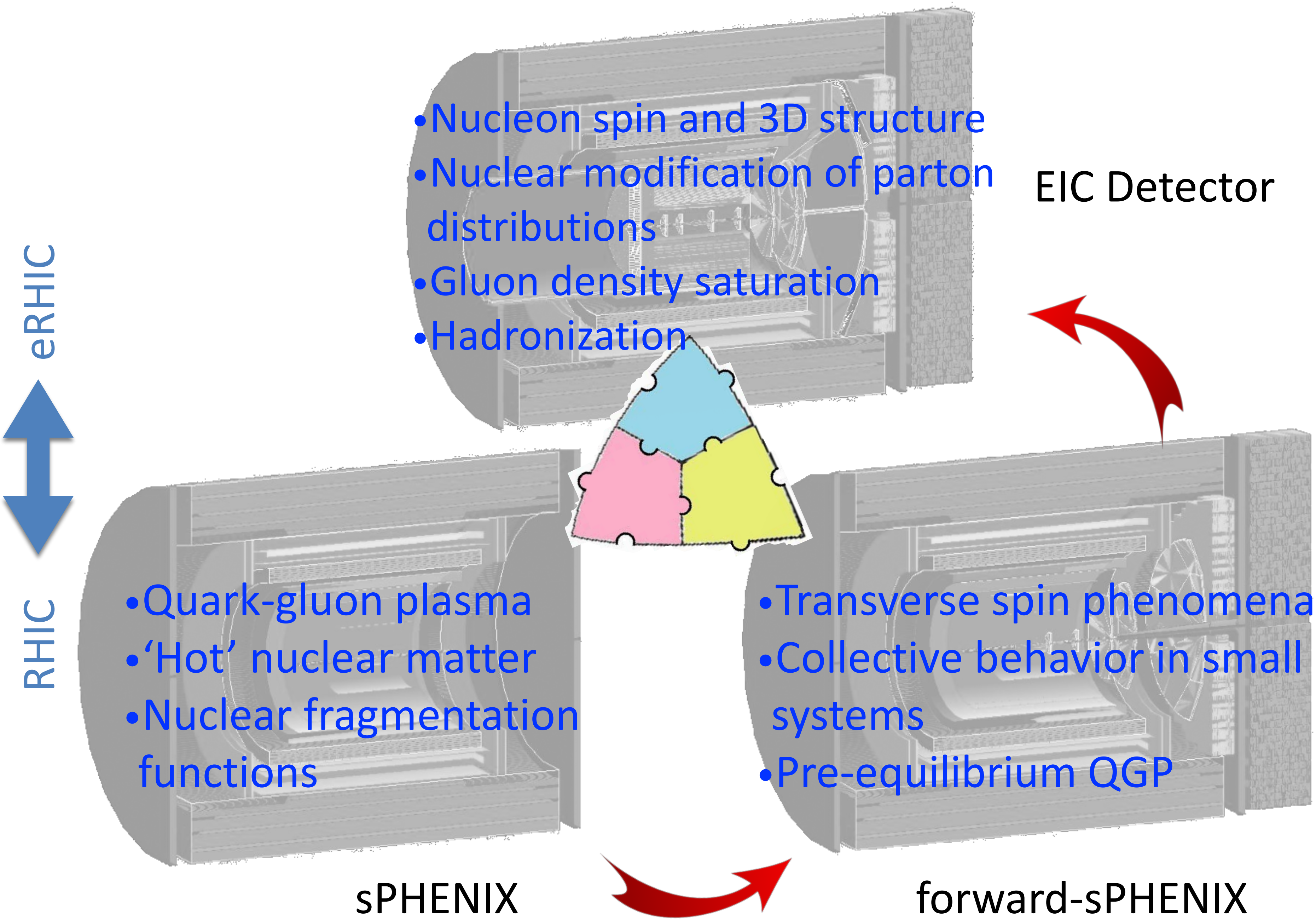
- Effects persist to kinematic regimes where perturbative QCD techniques clearly apply
- p_T = 8 GeV
  → $Q^2 \sim 64$ GeV^2!

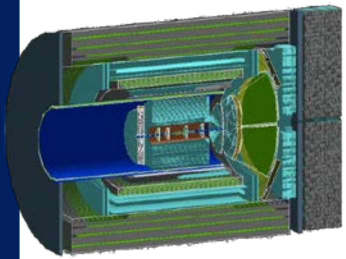
Note x_F = 0.24-0.32 here, where asymmetries approached zero on lower-energy plots—need more-forward measurements at high energies!

Bound states of hadronic bound states: Creating nuclei



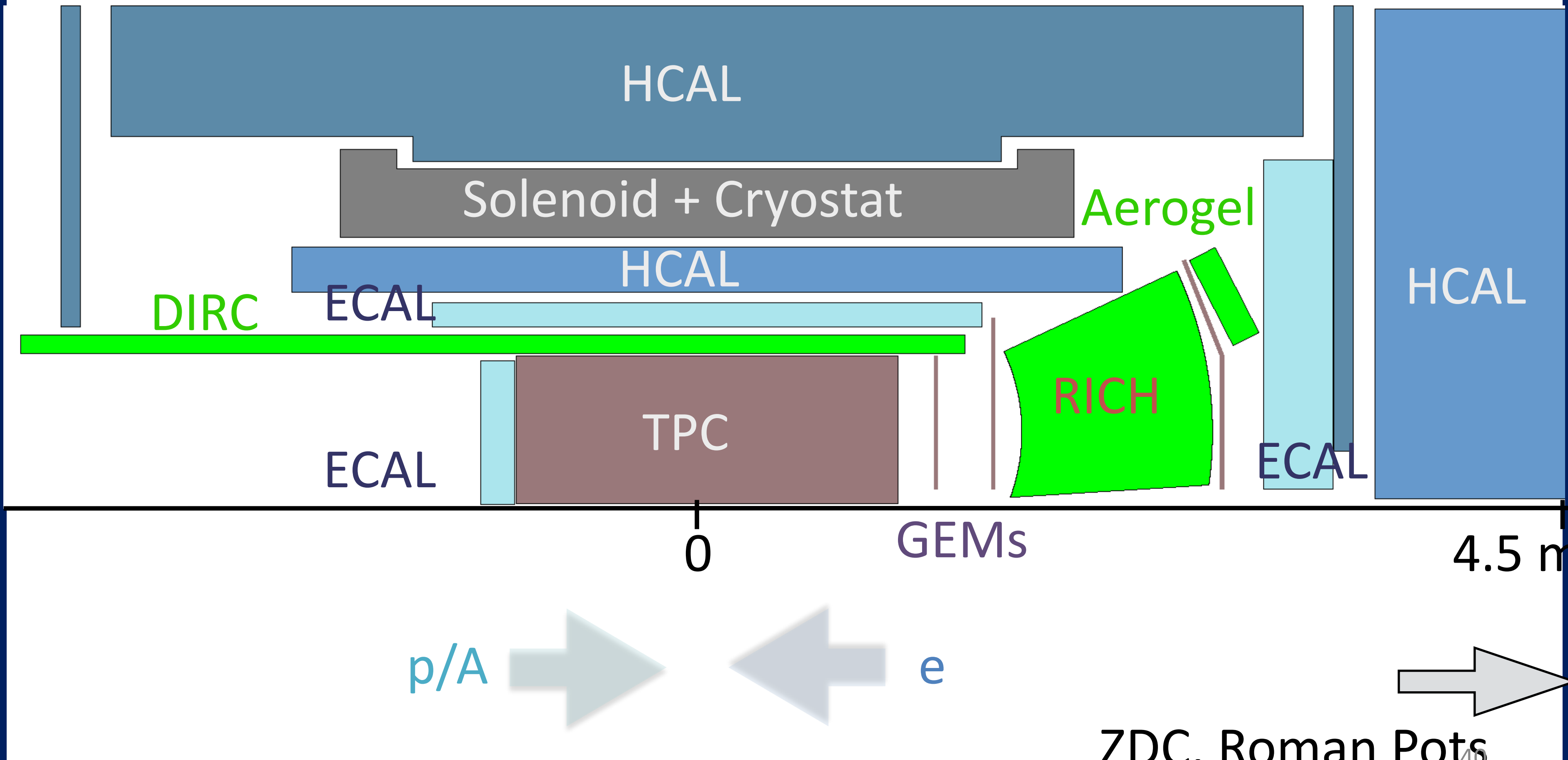
Nature 473, 353 (2011)


•Nucleon spin and 3D structure
•Nuclear modification of parton distributions
•Gluon density saturation
•Hadronization
EIC Detector
eRHIC
RHIC
•Quark-gluon plasma
•'Hot' nuclear matter
•Nuclear fragmentation functions
•Transverse spin phenomena
•Collective behavior in small systems
•Pre-equilibrium QGP
sPHENIX
forward-sPHENIX



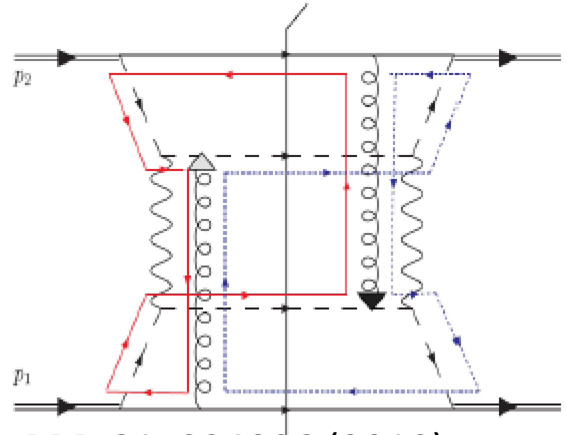
EIC Detector Concept

'2016 revised concept'



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)

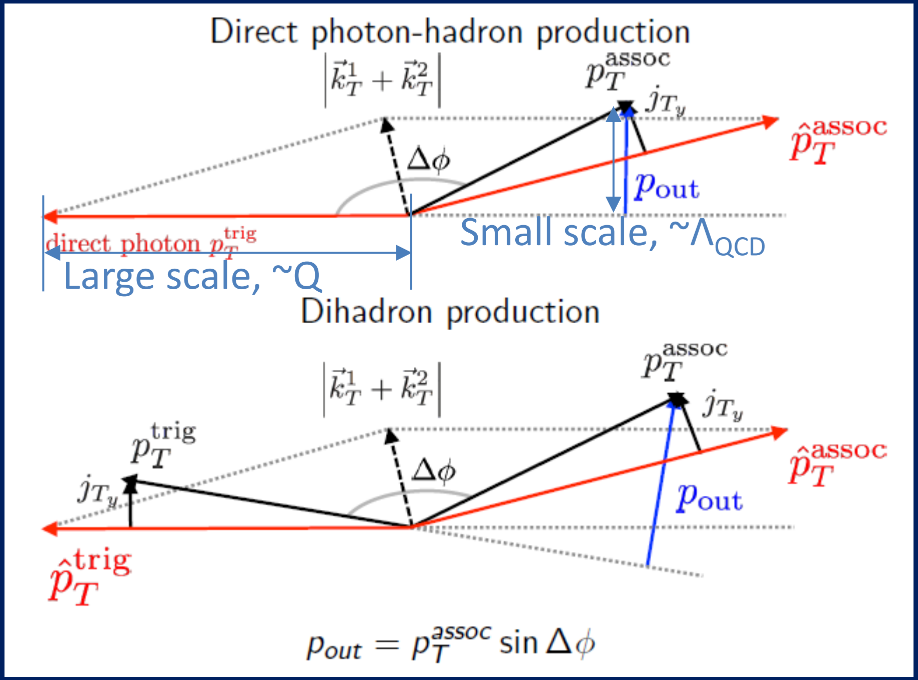
$$p + p \to h_1 + h_2 + X$$

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

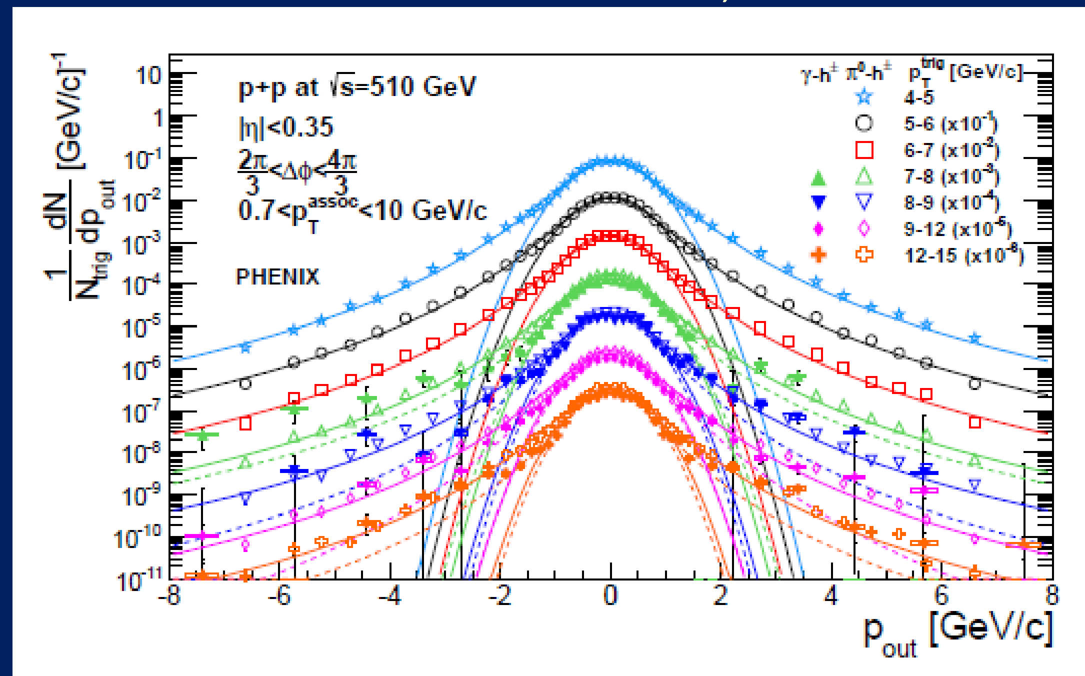
→ In p+p collisions, measure out-of-plane momentum component in nearly back-to-back photon-hadron and hadron-hadron production



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

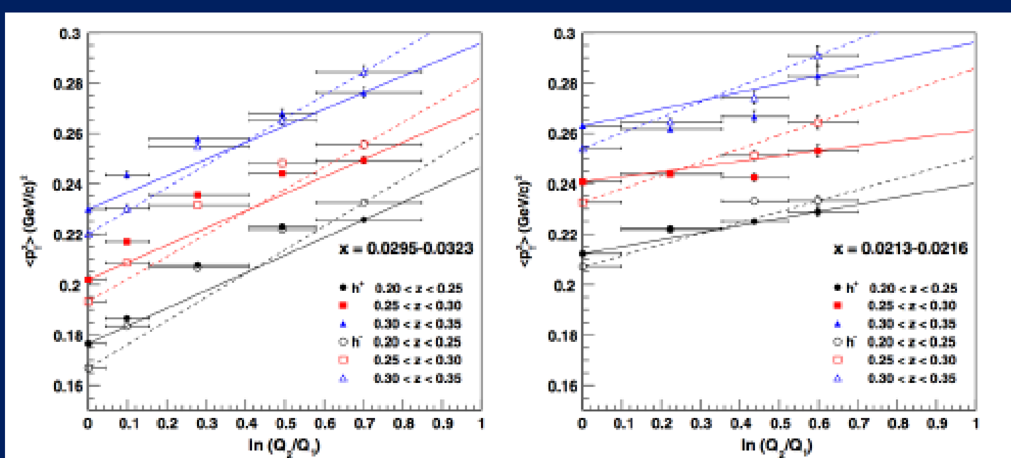
PHENIX Collab., arXiv:1609.04769



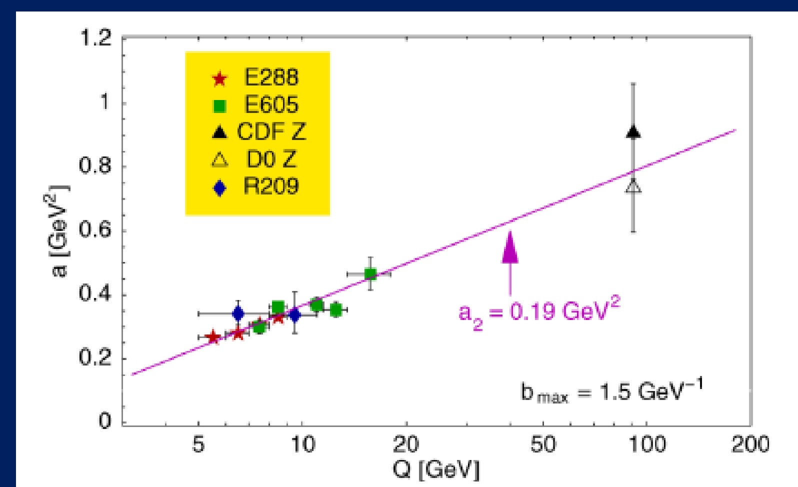
Curves are fits to Gaussian and Kaplan functions, not calculations!

*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)

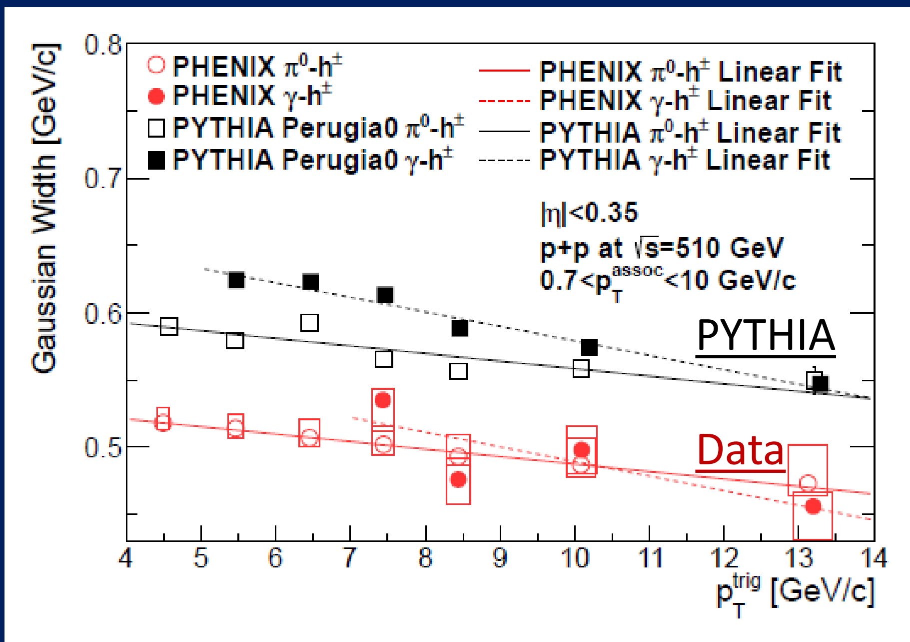


Aidala, Field, Gamberg, Rogers, Phys. Rev. D89, 094002 (2014)



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

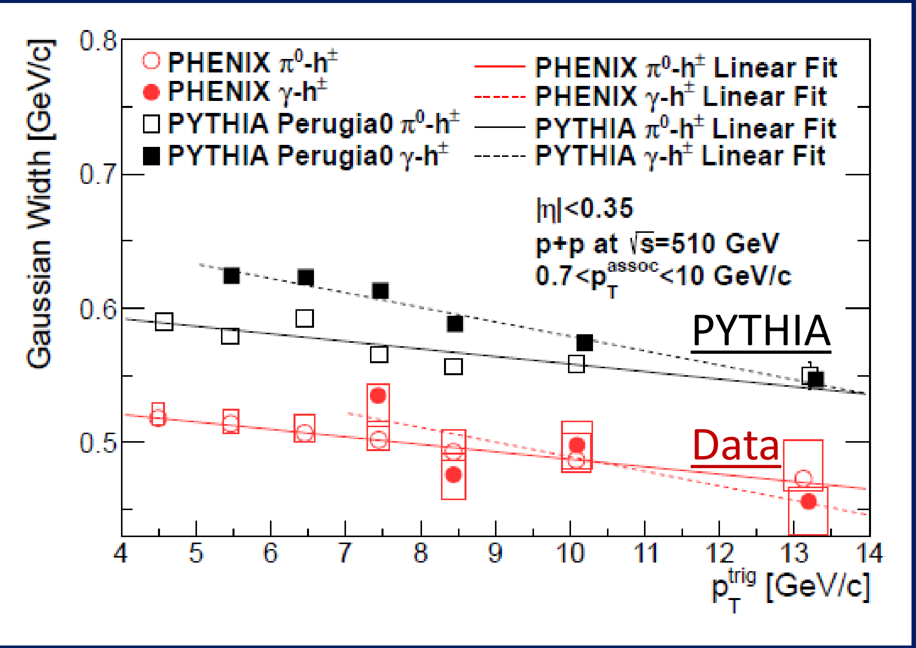
Nonperturbative momentum widths observed to ***decrease*** *in processes where factorization breaking predicted*



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"