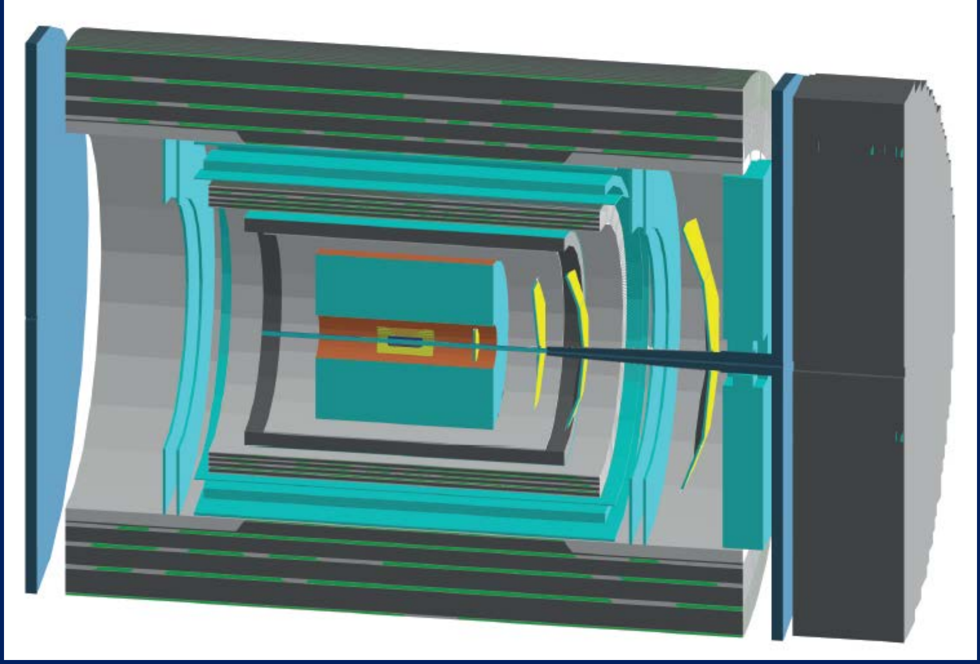
Modest Forward Upgrade Options for sPHENIX



Christine A. Aidala
University of Michigan

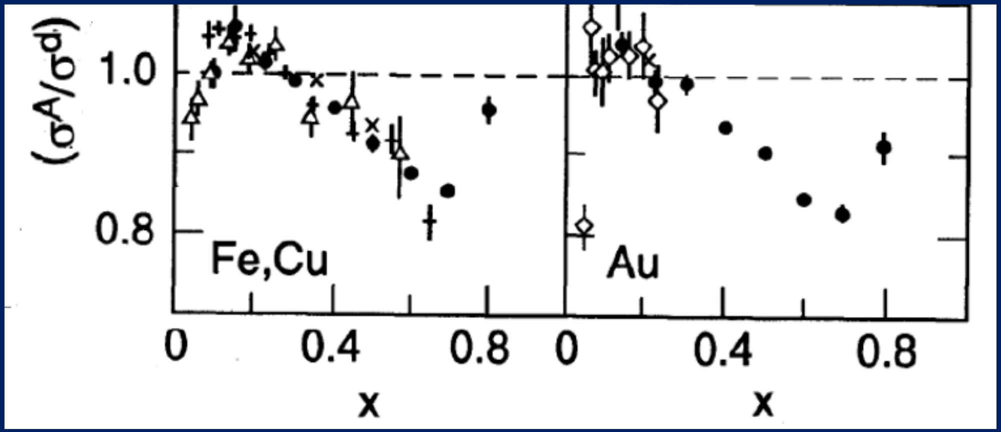
BNL NPP PAC meeting
June 15-16, 2017

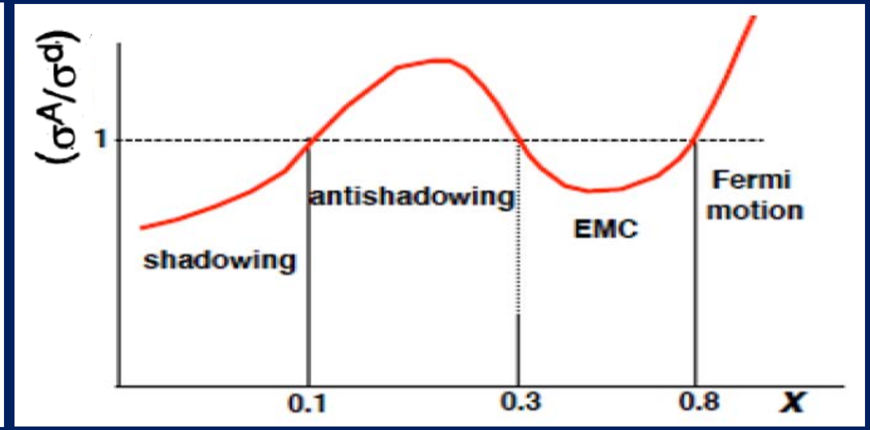
Key physics

R_{pAu} for forward Drell-Yan dielectrons to study how the binding of nucleons into nuclei affects the sea

Transverse single-spin asymmetries for jets and dijets to study parton polarization dynamics and search for non-Abelian effects

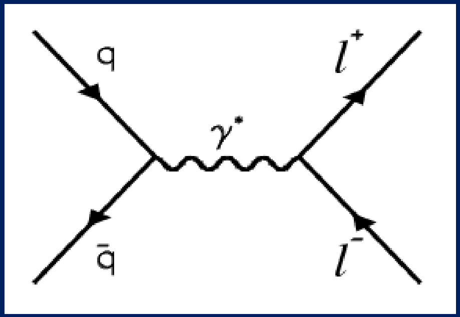
How do partons behave in a nuclear environment?





- DIS data on heavier nuclei compared to deuterium show strong and varying modifications as a function of *x*, not yet well understood
- DIS data don't distinguish between quarks and antiquarks – Does a nuclear environment affect them differently?

Isolating sea quarks in nuclei at sPHENIX

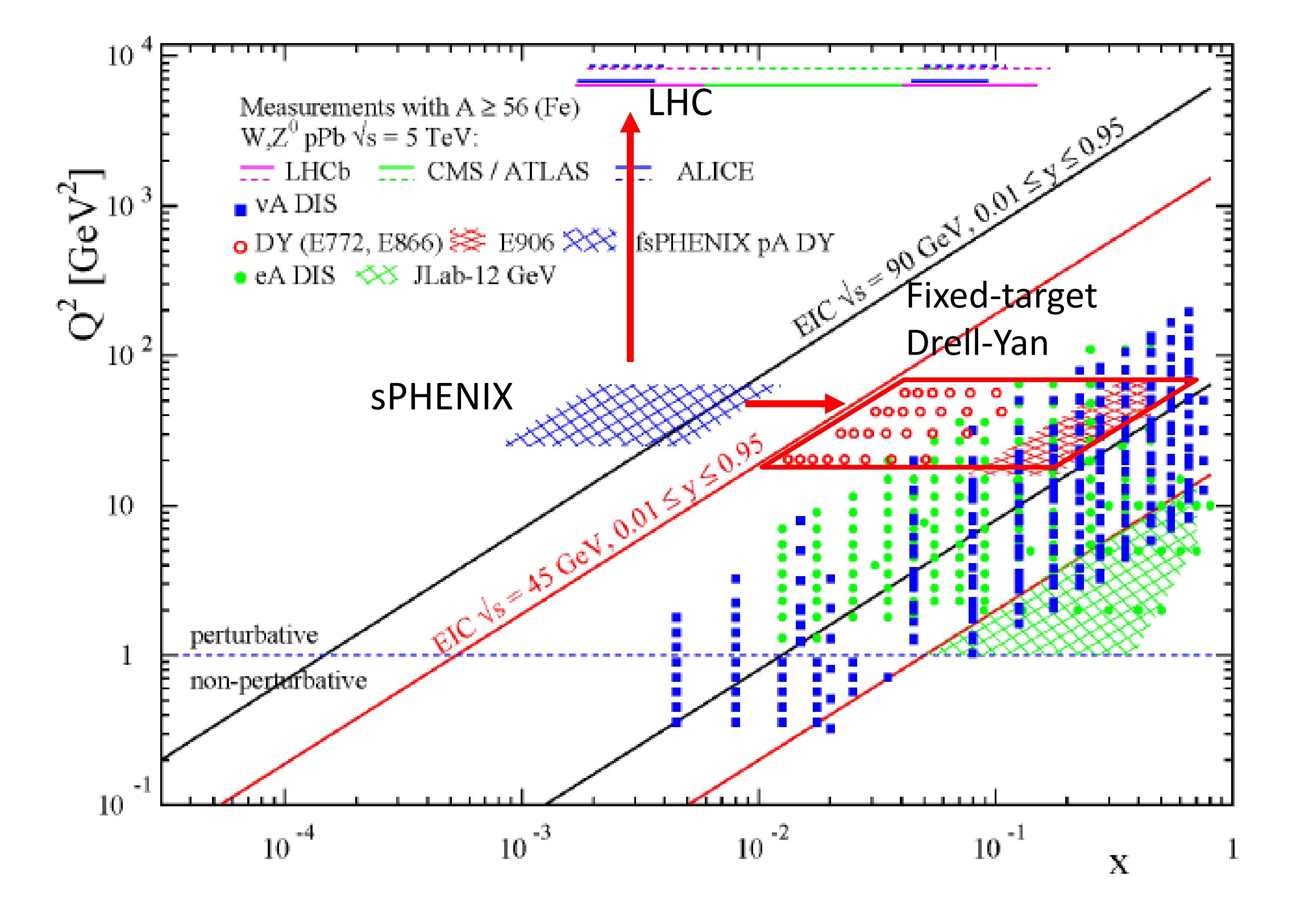


Measure forward Drell-Yan dielectrons in 200 GeV p+A collisions compared to p+p

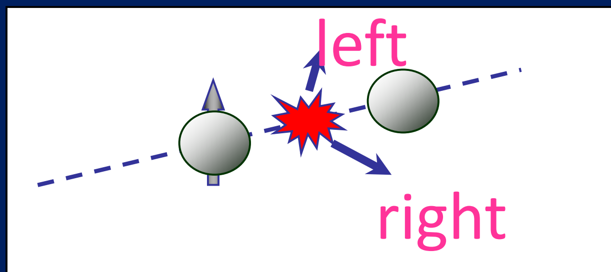
- Forward (proton-going) direction – access sea quarks (low-*x*) in the nucleus
- Drell-Yan process isolates antiquarks, with no dependence on fragmentation functions – to be done before an EIC!

Ultimate goal: Understand the multiple mechanisms that generate the sea, and how binding of nucleons in a nucleus affects these mechanisms

Complementary kinematic coverage to fixed-target p+A Drell-Yan and LHC p+Pb Z/W

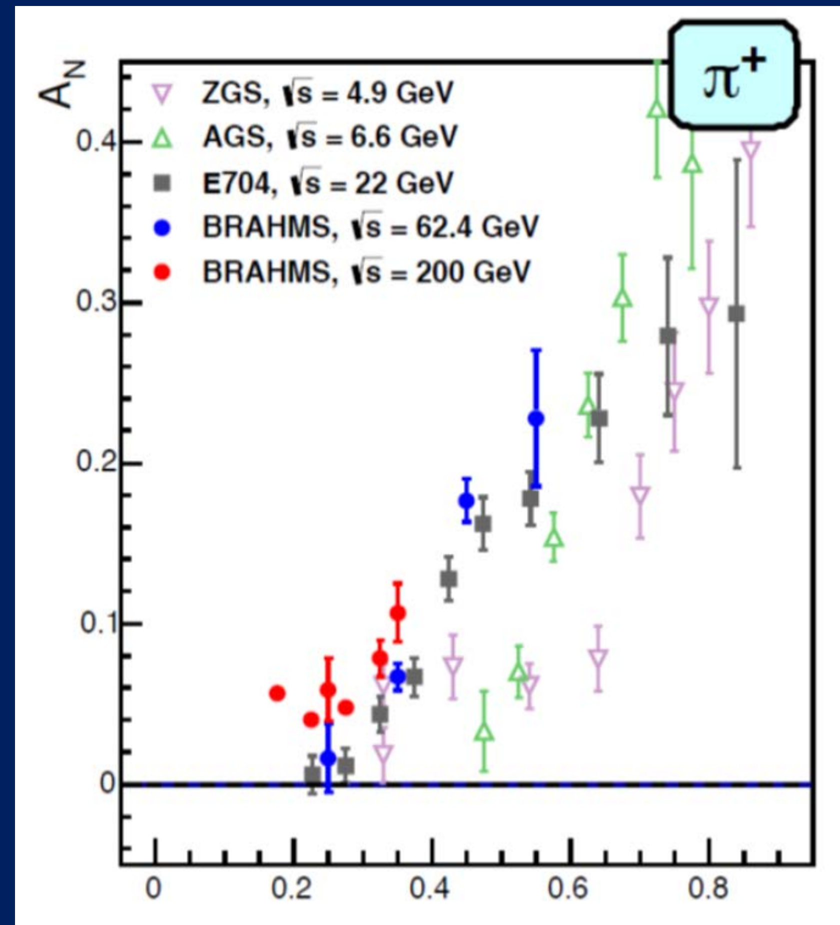


What are the dynamics of partons in a polarized proton?



Huge spin-momentum correlations observed as left-right asymmetries for forward pion production in transversely polarized proton collisions

- Up to 40%, with striking similarity across energies from $\sqrt{s}$ = 5 to 200 GeV!



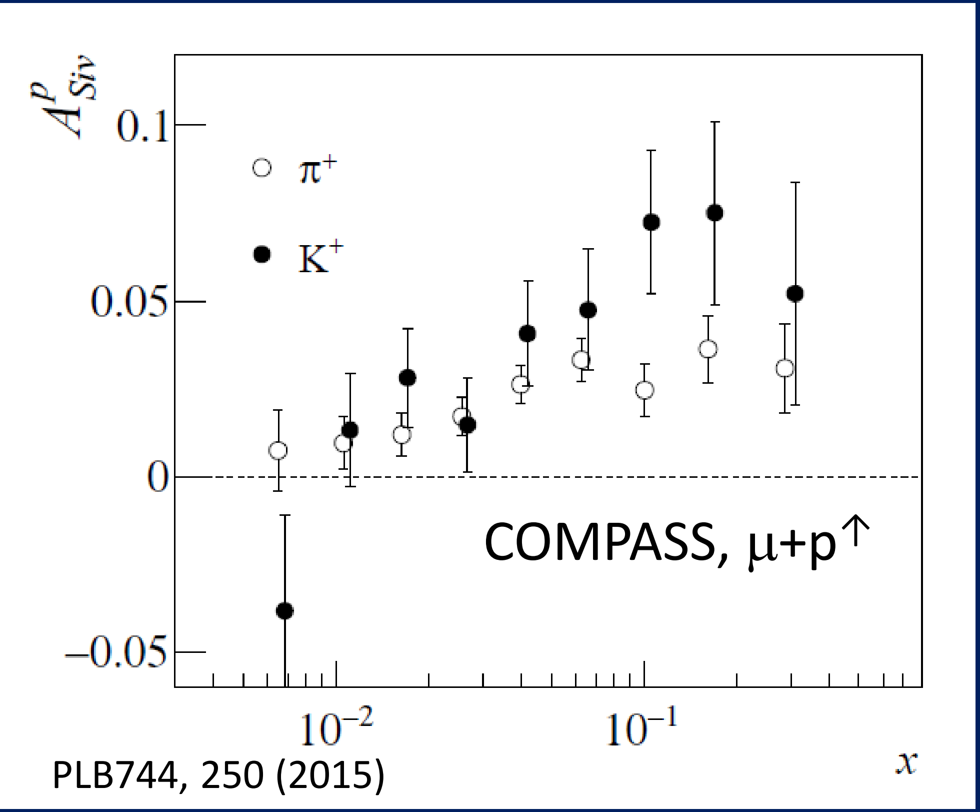
RHIC Cold QCD Plan

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

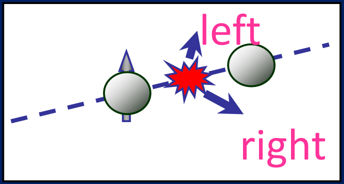
All semi-inclusive DIS transverse single-spin asymmetries more modest

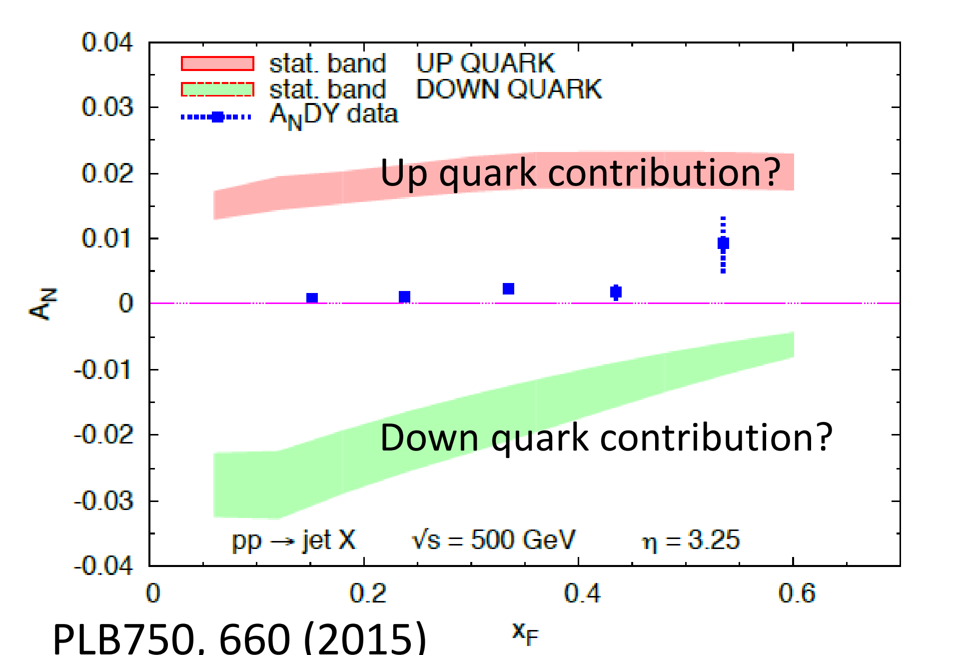
1-10% asymmetries in semi-inclusive DIS

- Could non-Abelian color interactions enhance asymmetries in hadronic collisions?



But even smaller asymmetries in $p^{\uparrow}+p \rightarrow jets$





PLB750, 660 (2015)

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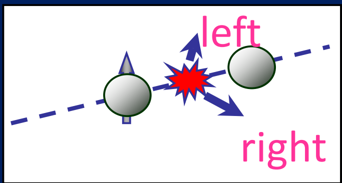

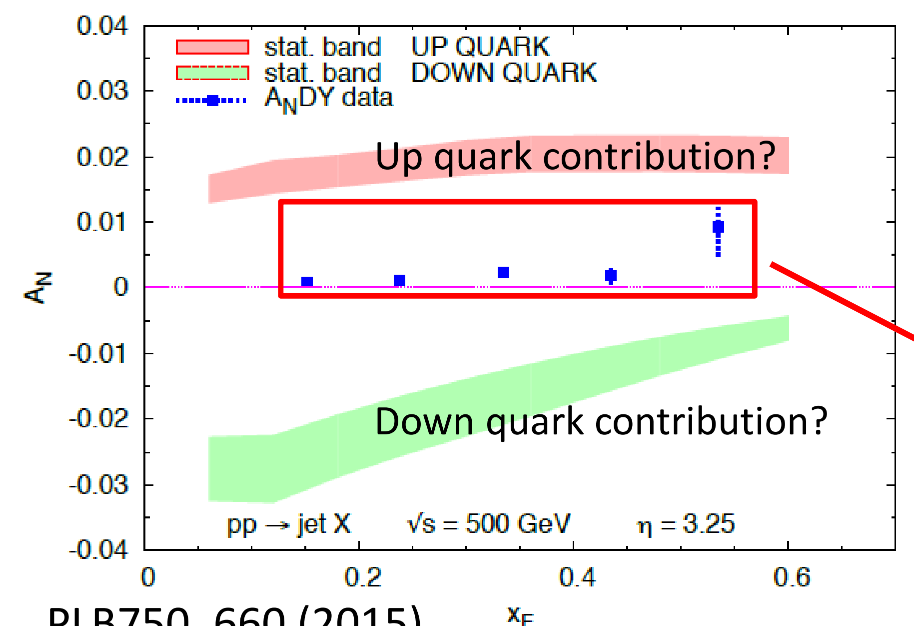

PLB750, 660 (2015)

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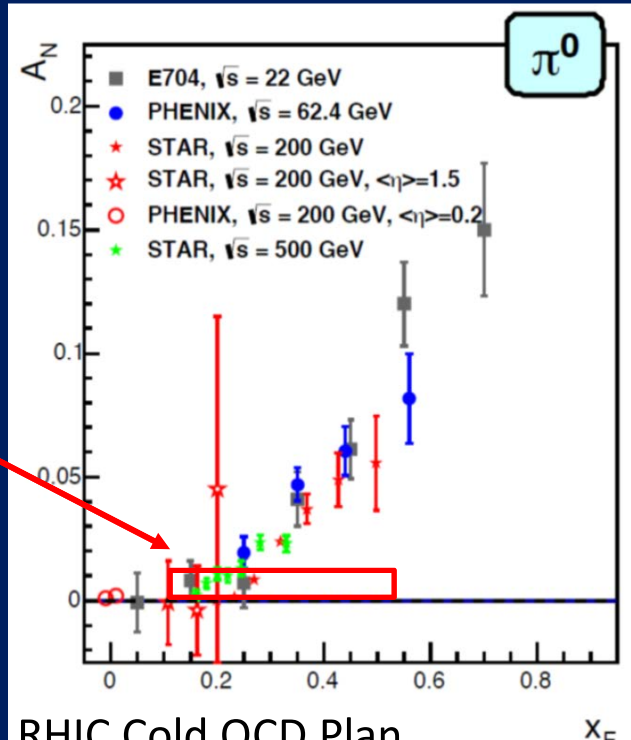


RHIC Cold QCD Plan

- Transverse single-spin asymmetries ≲1% for forward jet production in $p^{\uparrow}+p$, compared to up to 15% measured for forward neutral pion production
  - Up and down flavor cancellations in inclusive jets?
  - If so, why not similar cancellations for π^0? Hadronization effects?

Studying transverse single-spin asymmetries at sPHENIX

Measure transverse single-spin asymmetries in forward jet production in $p^{\uparrow}$+p at 200 and 510 GeV

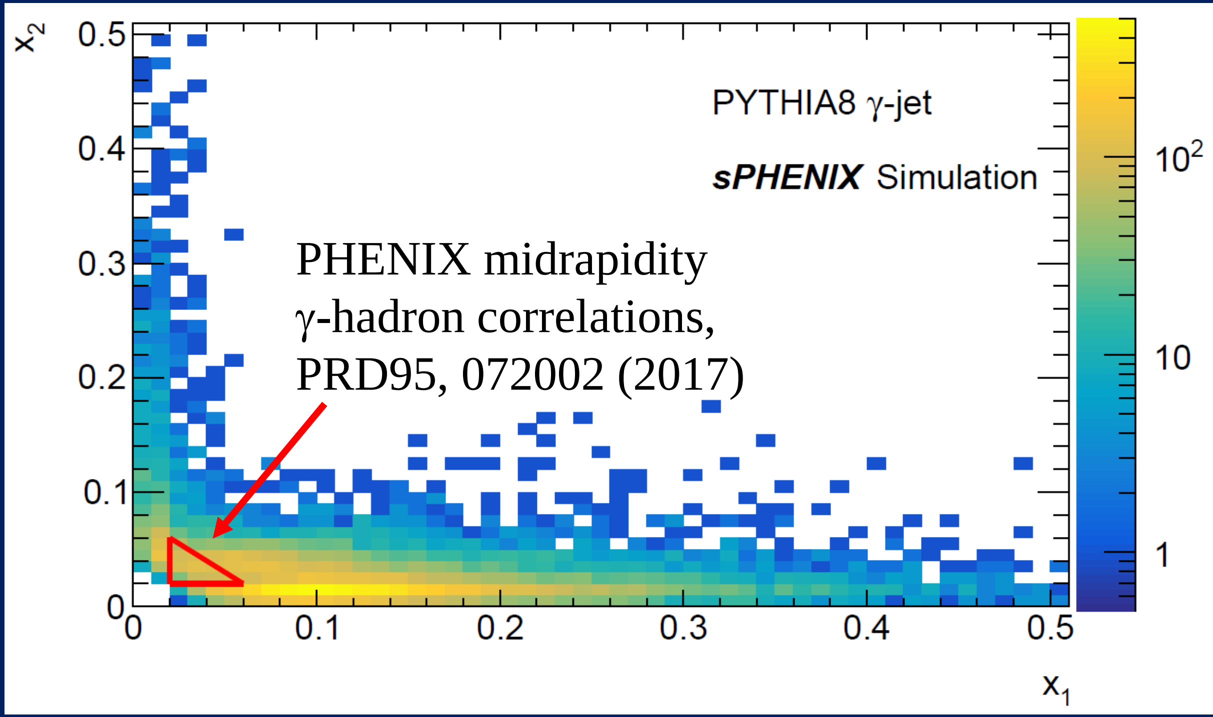
- Forward region – where large effects observed for inclusive pion production in hadronic collisions
  - Potential contributions from initial-state (proton structure), final-state (hadronization), and non-Abelian color interactions not yet disentangled

Suite of measurements with different levels of exclusiveness

- Inclusive jet asymmetries – insensitive to hadronization effects
- Jets with charge tagging of leading hadron – flavor enhancement
- Hadron distributions within jets – proton structure + hadronization effects

- Central-forward photon-jets and dijets – reconstruct leading-order parton kinematics: x_1, x_2, Q^2, z – detailed comparison to single-spin asymmetries in semi-inclusive DIS and e+e- to test universality and search for non-Abelian effects
  - To be done before EIC!

Searching for non-Abelian effects in γ-jet correlations at sPHENIX

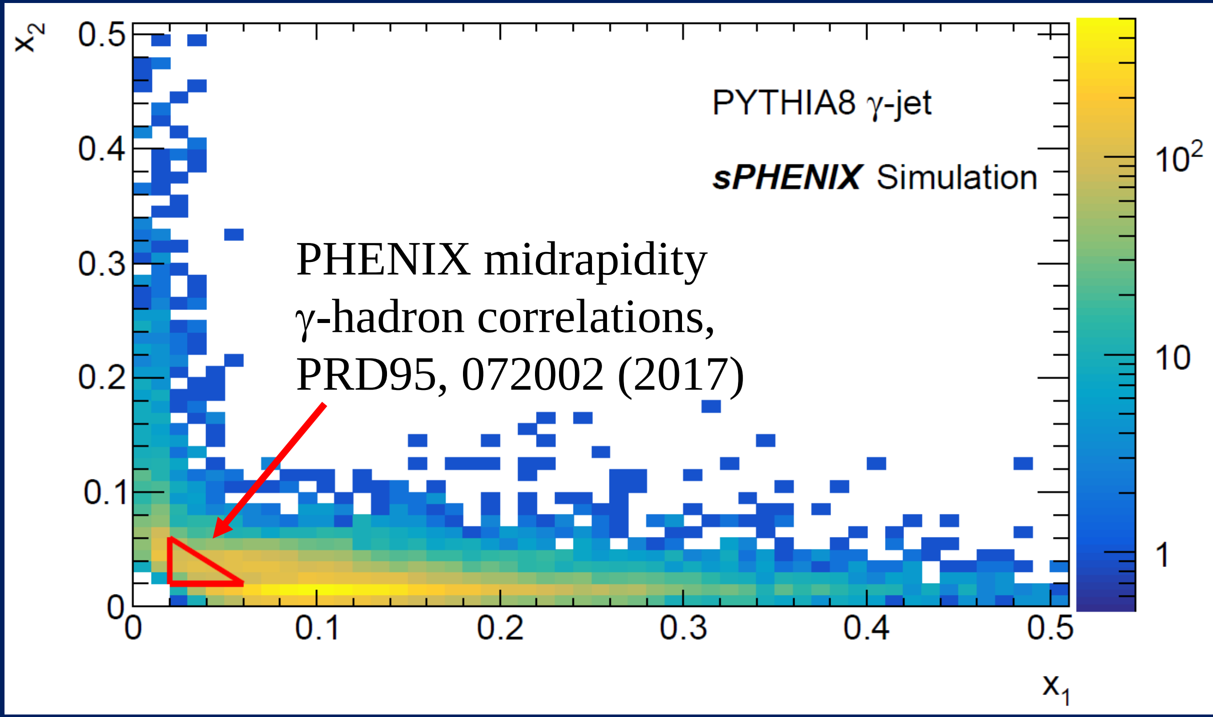


γ-jet: Reconstruct x_1, x_2, Q^2, in contrast to γ-hadron.

Central <u>and</u> forward jet coverage: Vary *x* range.

x_1, x_2 for γ-jet correlations in 510 GeV p+p with $p_T > 7$ GeV γ in sPHENIX barrel and $p_T > 5$ GeV forward jet.

Searching for non-Abelian effects in γ-jet correlations at sPHENIX



γ-jet: Reconstruct x_1, x_2, Q^2, in contrast to γ-hadron.

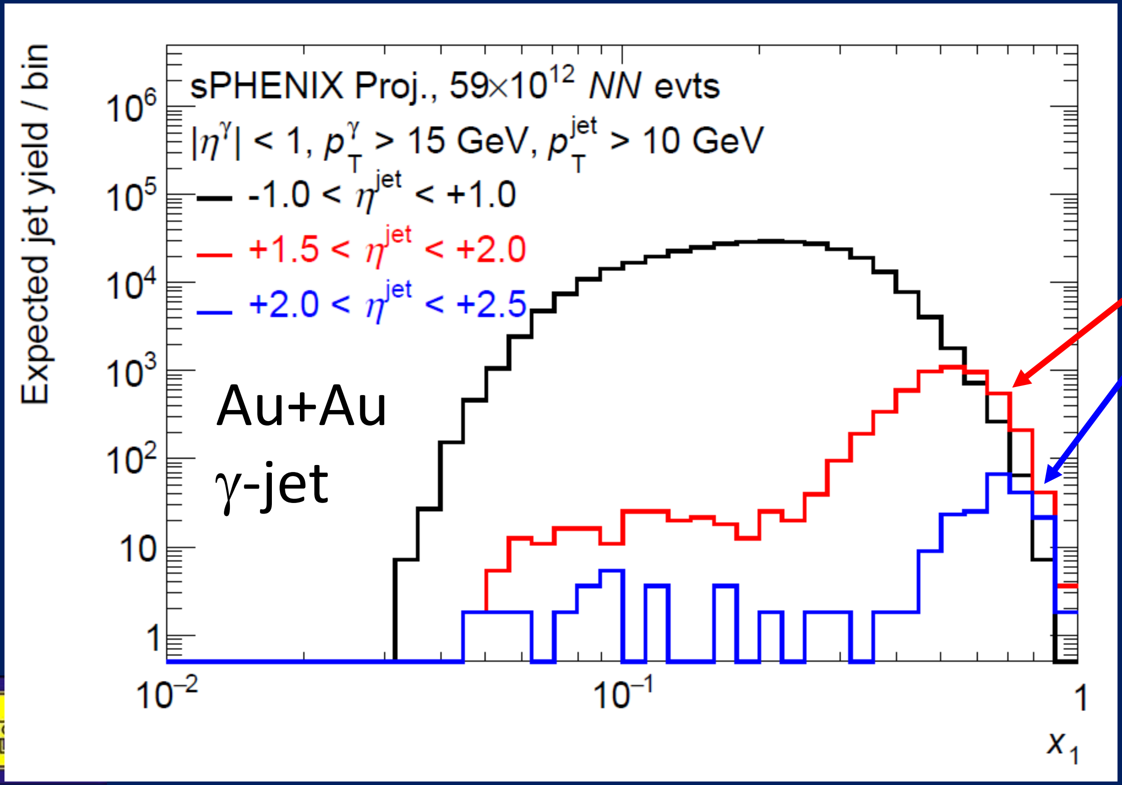
Central and forward jet coverage: Vary *x* range.

Jets at 510 vs. 200 GeV: At 510 GeV, can get further forward (larger asymmetries) for a given p_T

x_1, x_2 for γ-jet correlations in 510 GeV p+p with $p_T > 7$ GeV γ in sPHENIX barrel and $p_T > 5$ GeV forward jet.

Extending midrapidity QGP program

Midrapidity Au+Au jet program furthermore benefits from extending jet and global event characterization capabilities to forward region



Forward jets select higher mean *x*

Will read out barrel <u>and</u> forward arm at full sPHENIX design rate of 15 kHz

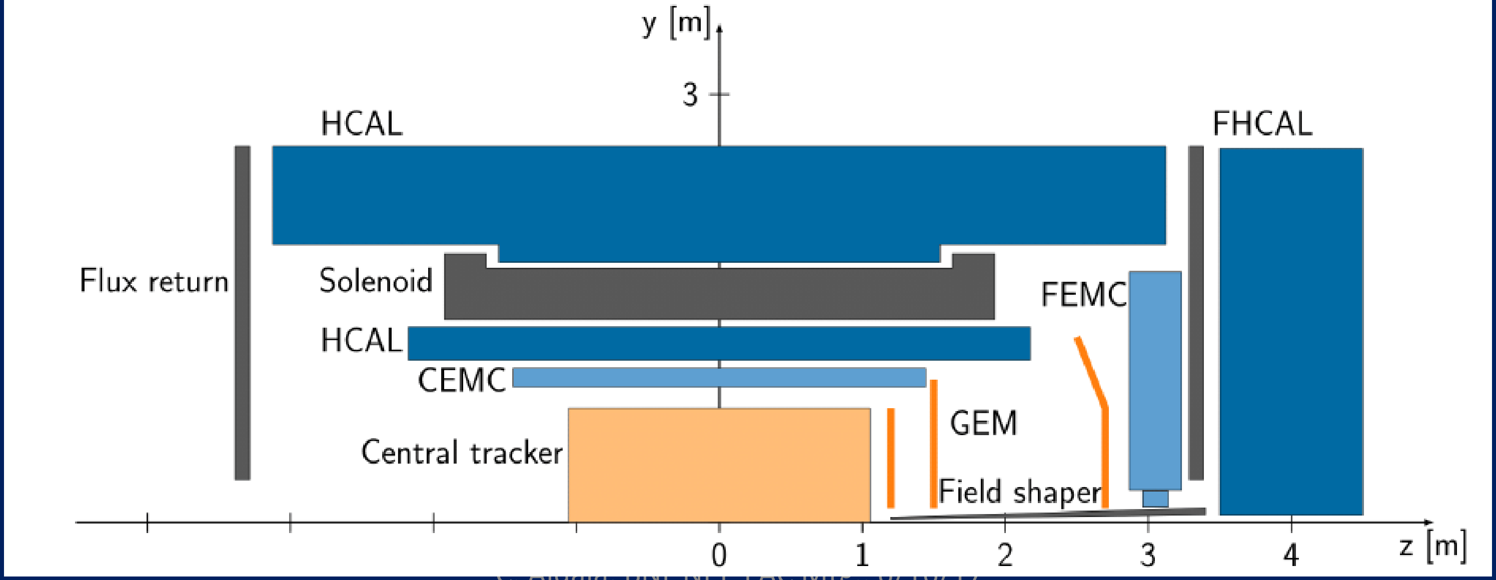
Additional physics opportunities

Wide coverage in η opens up capabilities to study

- High-temperature QGP at varying net baryon densities and opacity by scanning in η, complementary to Beam Energy Scan
- Early times in Au+Au collisions via correlations at wide angular separation
- Multiplicity-dependent behavior observed in p+p and p+A via long-range $\Delta\eta$ correlations

Extend sPHENIX tracking and calorimetry to $\eta = 4$

- Electromagnetic and hadronic calorimetry
  - Jet measurements
  - Drell-Yan dielectron background reduction
  - Triggering
- Forward tracking
  - Drell-Yan dielectrons
  - Hadrons within jets



Forward instrumentation

- EM calorimetry
  - Reuse PHENIX lead-scintillator for $\eta < 3$; MPC $PbWO_4$ crystals for $3 < \eta < 4$
  - SiPM photosensors considered for readout, providing uniformity with sPHENIX barrel
- Hadronic calorimetry
  - Steel- or lead-scintillator
  - Potential interest from RIKEN to develop, test, and construct FHCAL
- Tracking
  - 3 GEM stations out to 3 m
  - $dr\phi \sim 50$ μm for $\eta > 2.5$; $dr\phi \sim 100$ μm for $\eta < 2.5$
  - Outer tracking alternatives: MicroMegas or large-area small-strip Thin Gap Chambers (sTGCs)
  - Saclay a potential participant in developing MicroMegas

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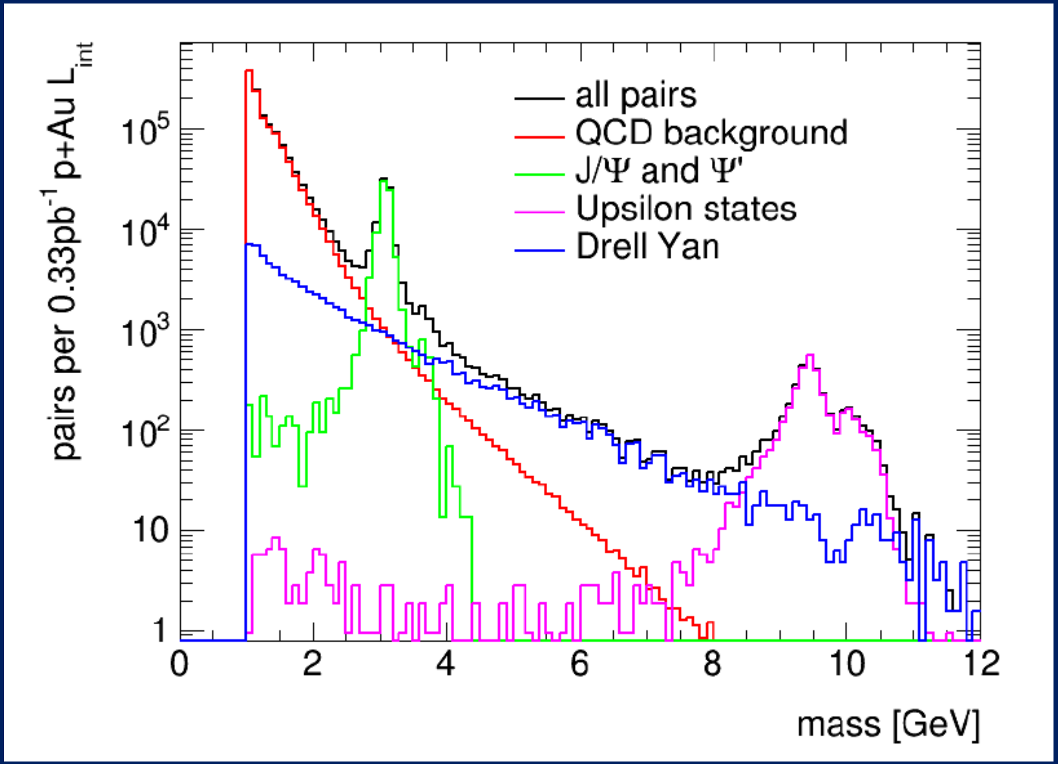
Detector design with future reuse at EIC in mind

Performance study: Dielectron mass spectrum for Drell-Yan



Currently in discussion with Hannu Paukkunen of EPPS16 nuclear PDF global fit to quantify impact of expected sPHENIX data

PYTHIA6 minimum-bias 200 GeV p+p with GEANT4 simulation.

Background suppression such that mass region from 4.5-8 GeV dominated by Drell-Yan dileptons.

Cost estimate

- "Cost" is direct cost only
- Contingency calculated as 40%
- FHCAL and GEM costs based on EIC detector LOI
- Calorimeter electronics costs from sPHENIX project

	Cost	Contingency	Total
FHCAL	2.66	1.06	3.72
FEMC (refurbish PHENIX EMCal)	0.25	0.10	0.35
GEM Tracker	0.74	0.30	1.04
Piston Field Shaper	0.12	0.05	0.17
FHCAL electronics	0.23	0.09	0.32
FEMC electronics	0.39	0.16	0.55
GEM electronics	0.71	0.28	0.99
Total	5.1	2.04	7.14

Summary

System	Scientific Objective	Observable
Au+Au @ 200 GeV	T, μ_B dependence on η	Fourier moments (v_2, etc.) vs. η
	HI initial conditions, early times	rapidity-separated correlations
	energy loss in the QGP	dijets and γ+jet
p↑+Au @ 200 GeV	nuclear PDFs	R_{pAu} for Drell-Yan
		inclusive jets, dijets
		γ + jet
	sea quark dynamics in nuclei	Drell-Yan p_T spectrum
	medium in small systems	rapidity-separated correlations
	quark energy loss	Drell-Yan and inclusive jets
	proton structure at large x	

System	Scientific Objective	Observable
p↑+p↑ @ 200 GeV	nuclear PDF reference data	Drell-Yan
		inclusive jets, dijets
	sea quark dynamics	Drell-Yan p_T spectrum
	spin-momentum correlators	hadron A_N
	factorization breaking	γ + jet, dijets
p↑+p↑ @ 510 GeV	origin of large hadron A_N at high x_F	A_N for flavor-enhanced jets
		γ + jet, dijets with hadron in jet
	transversity at high x, Collins FF	hadron asymmetries in jets
	factorization breaking	γ + jet, dijets

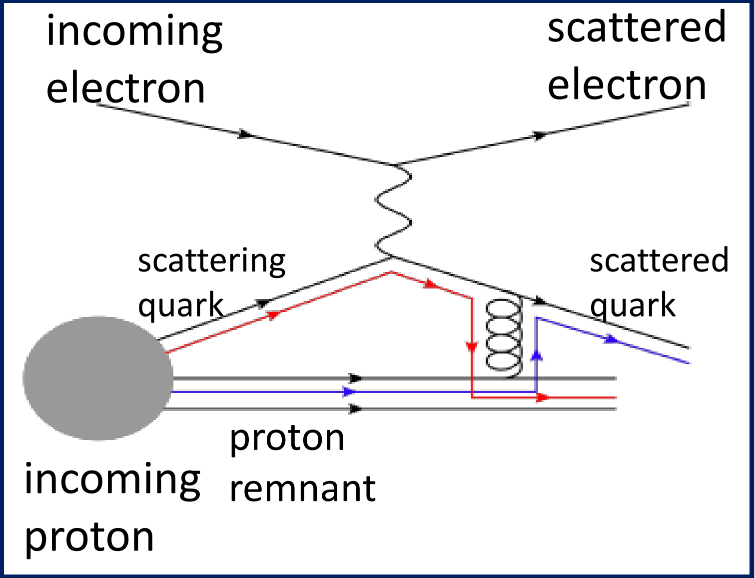
Leveraging the investment in sPHENIX by adding forward instrumentation will

- open up unique physics opportunities
- enhance the existing midrapidity program

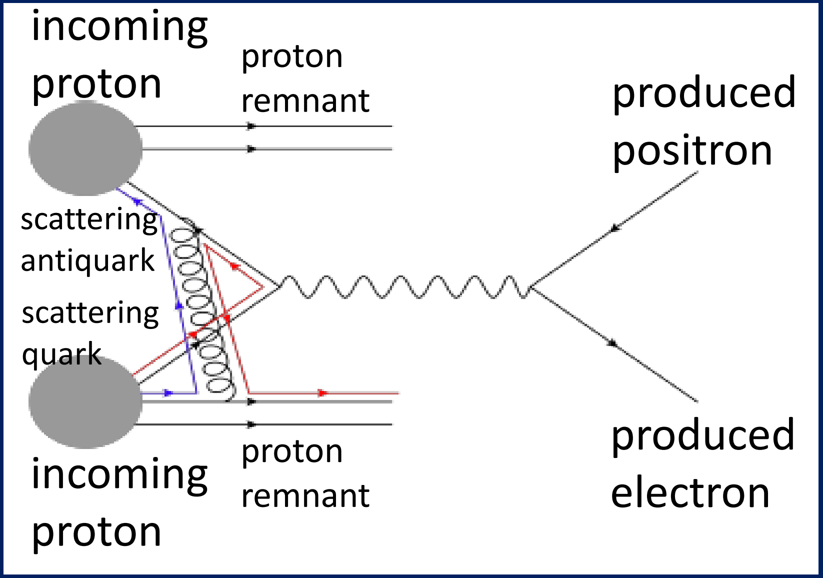
Extra

Modified universality of certain transverse-momentum-dependent distributions: Color in action!

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



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

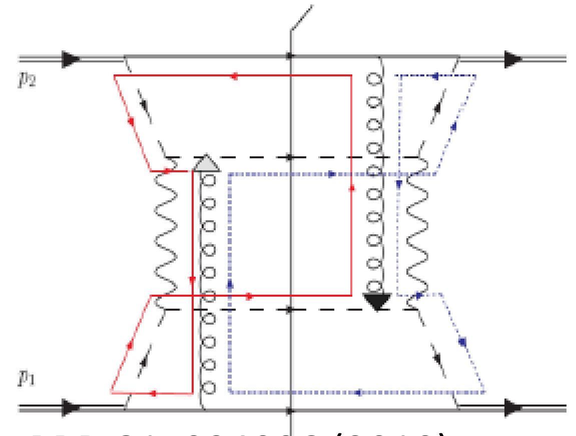


As a result, get *opposite sign* for the Sivers transverse-momentum-dependent pdf when measure in semi-inclusive DIS versus Drell-Yan: *process-dependent* pdf! (Collins 2002)

Figures by J.D. Osborn

QCD Aharonov-Bohm effect: Color entanglement

- 2010: Rogers and Mulders predict *color entanglement* in processes involving p+p production of hadrons 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)

$$p + p \rightarrow h_1 + h_2 + X$$

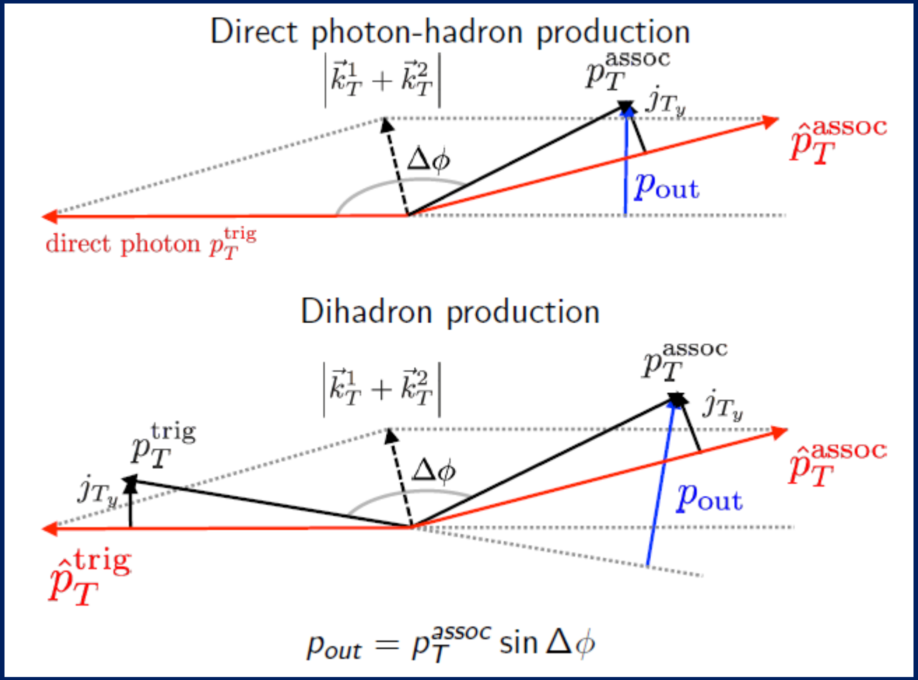
Color flow can't be described as flow in the two gluons separately. Requires simultaneous presence of both.

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

Searching for evidence of color entanglement at RHIC

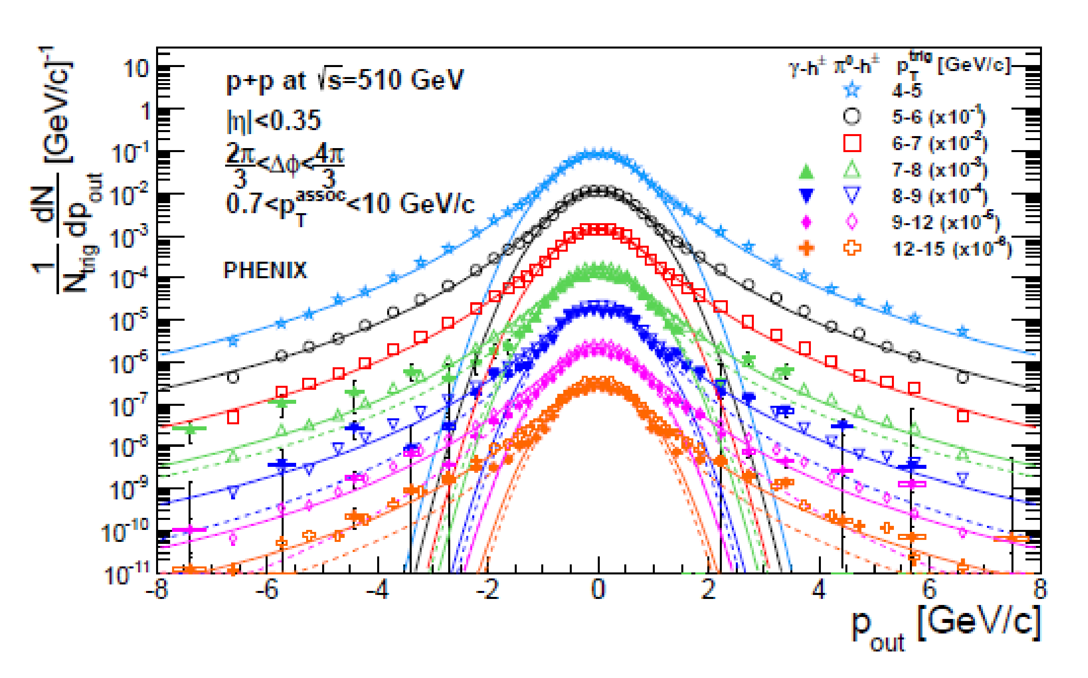
- Need observable sensitive to a nonperturbative momentum scale
  - Nearly back-to-back particle production
- Need 2 initial-state hadrons
  - color exchange between a scattering parton and remnant of other proton
- And at least 1 final-state hadron
  - exchange between scattered parton and either remnant

→ 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

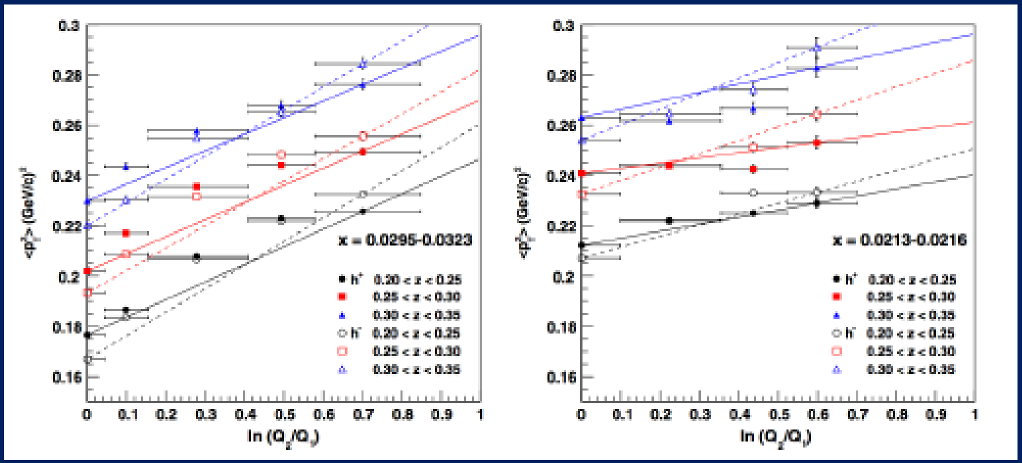
- Clear two-component distribution
  - Gaussian near 0—nonperturbative transverse momentum
  - Power-law at large p_{out}—kicks from hard (perturbative) gluon radiation
- Different colors → different bins in hard interaction scale



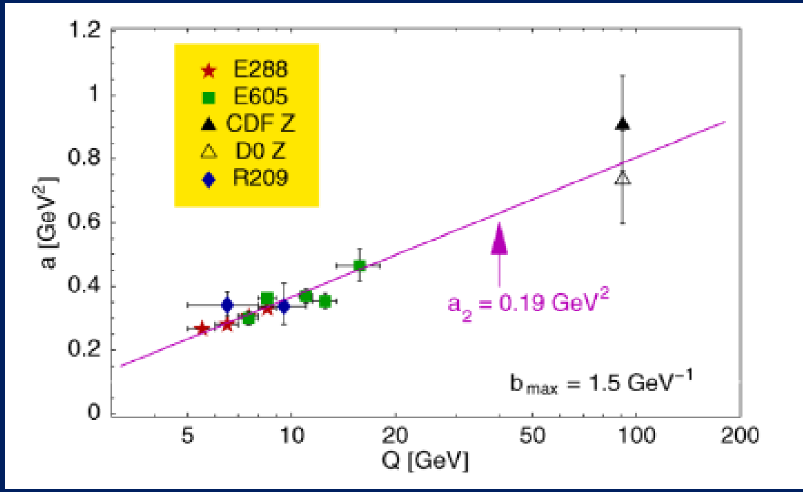
Curves are fits to Gaussian and Kaplan functions, not calculations!

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

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

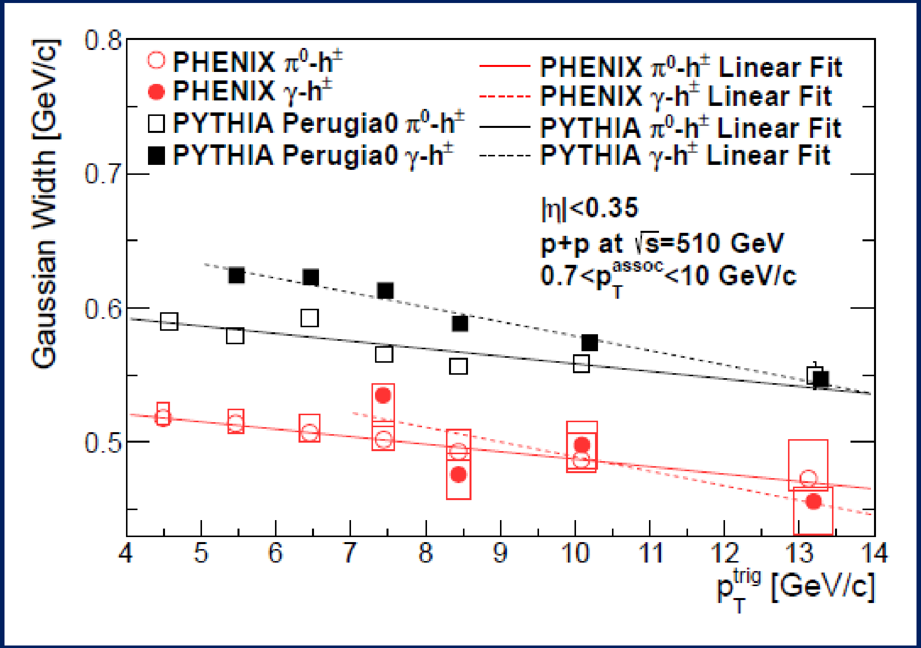


Aidala, Field, Gamberg, Rogers, Phys. Rev. D89, 094002 (2014)



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

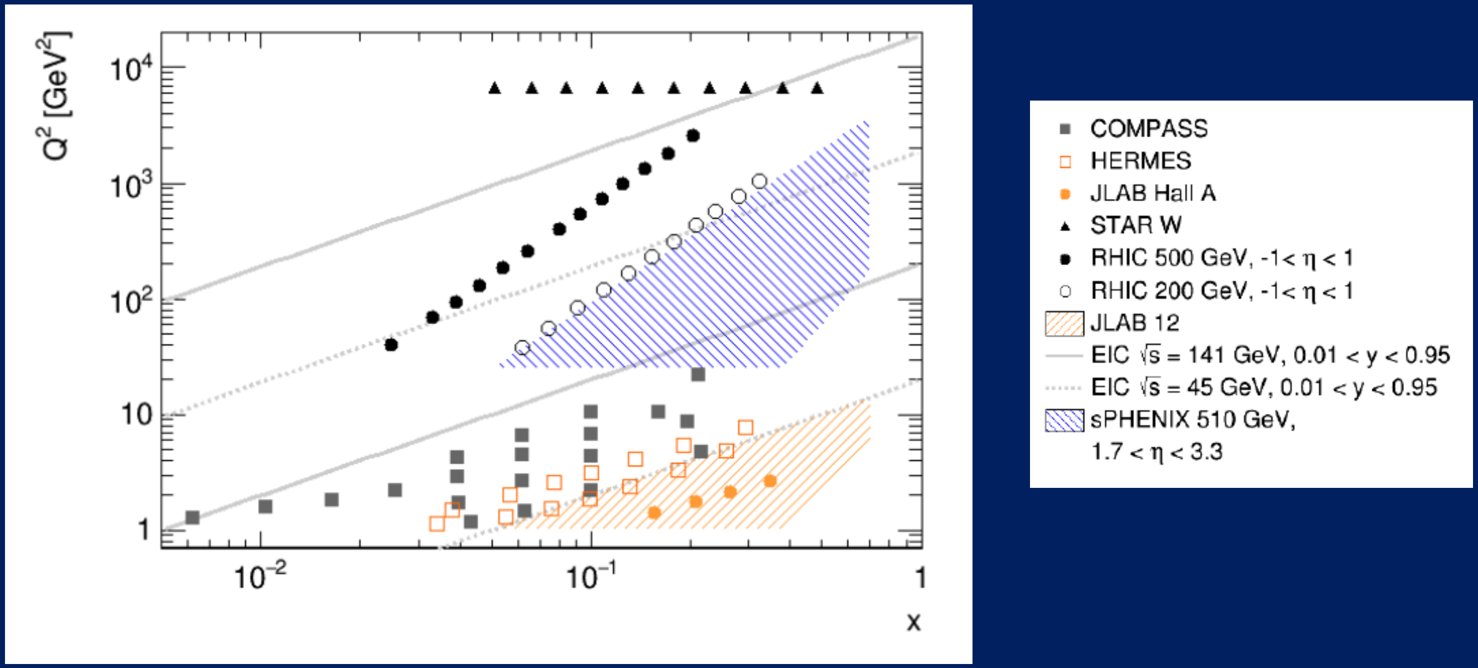
*Nonperturbative momentum widths **decrease** in processes where entanglement predicted*



PHENIX Collab., arXiv:1609.04769, Submitted to PRD

- Suggestive of quantum-correlated partons across colliding protons!
- However, have not yet completely ruled out a "trivial" nonperturbative correlation between partonic longitudinal momentum fraction *x* and partonic transverse momentum k_T
- 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"
- Discussions ongoing, and follow-up studies underway . . .

510 GeV p+p jet kinematics

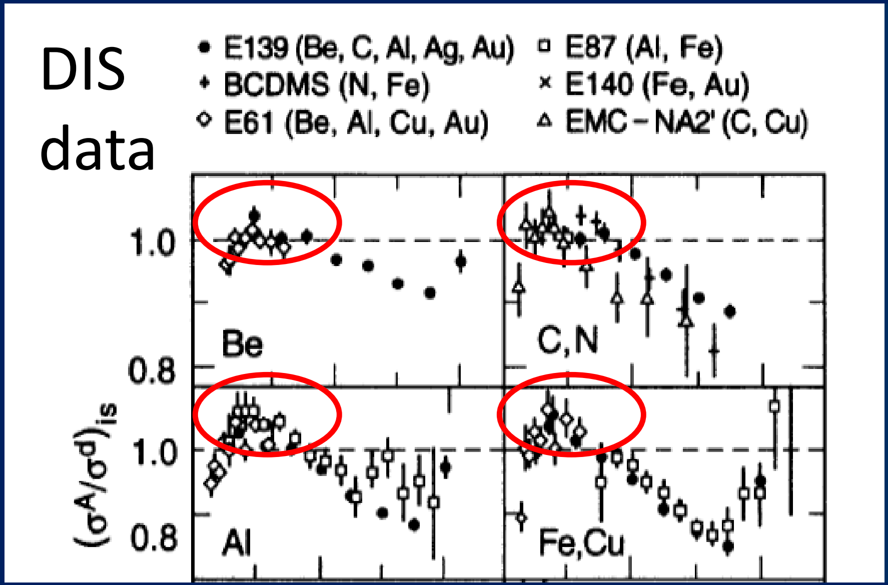


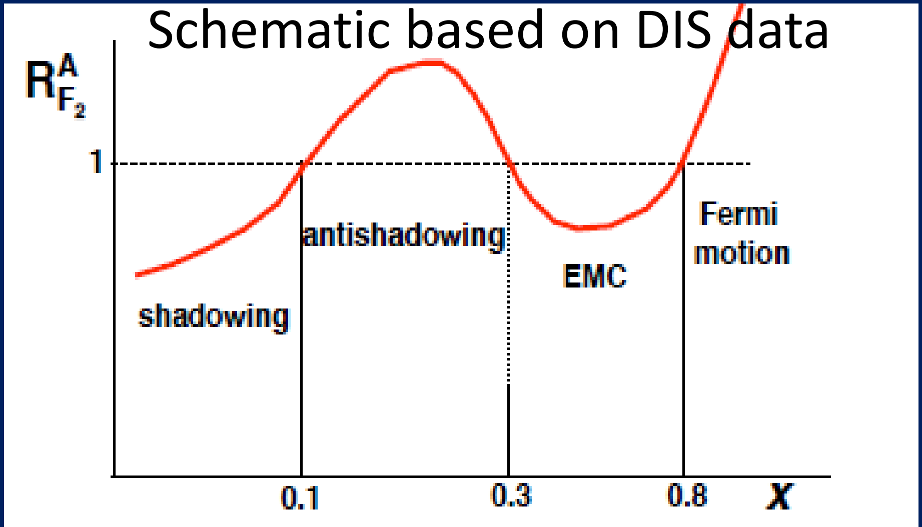
x-Q^2 coverage for sPHENIX forward jets in 510 GeV p+p compared to other experiments

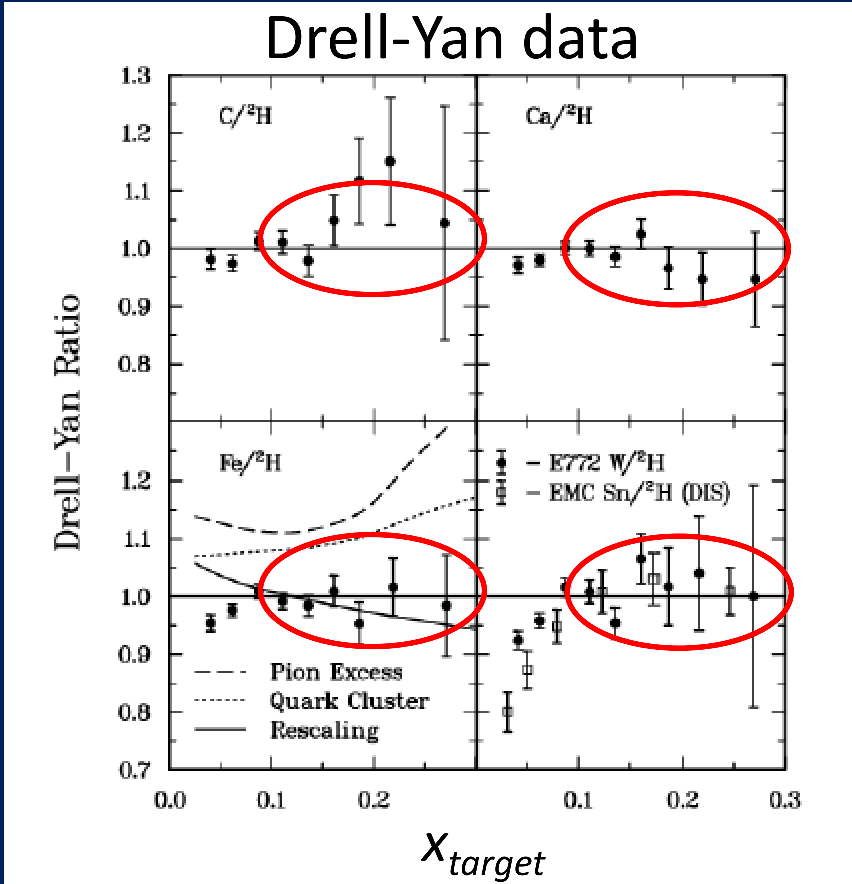
Luminosity estimates

	Recorded Lumi.	Sampled Lumi.
Au+Au 200 GeV	$35.0 nb^{-1}$	$80 nb^{-1}$
p↑+Au 200 GeV	-	$0.33 pb^{-1}$
p↑+p↑ 200 GeV	-	$197 pb^{-1}$
p↑+p↑ 510 GeV	-	$488 pb^{-1}$

Nuclear effects seen in nuclear Drell-Yan that differ from DIS



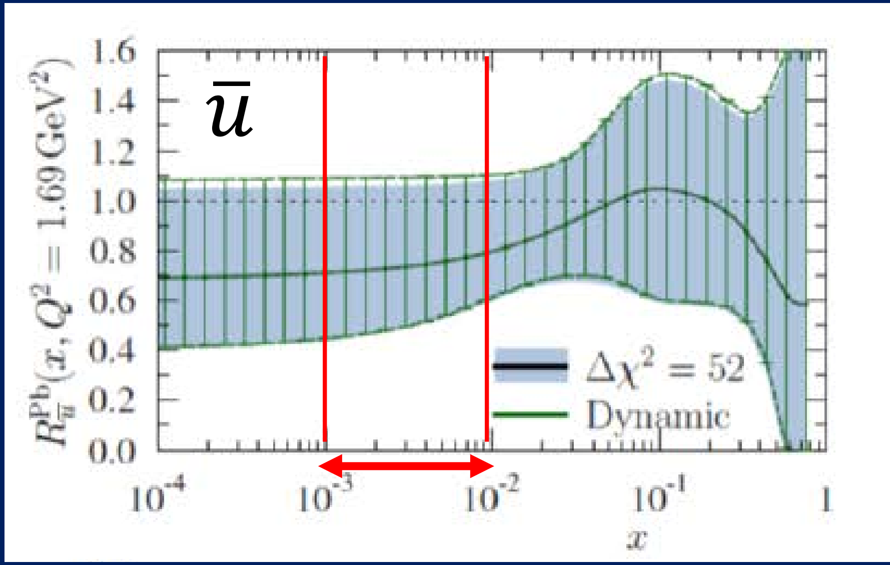


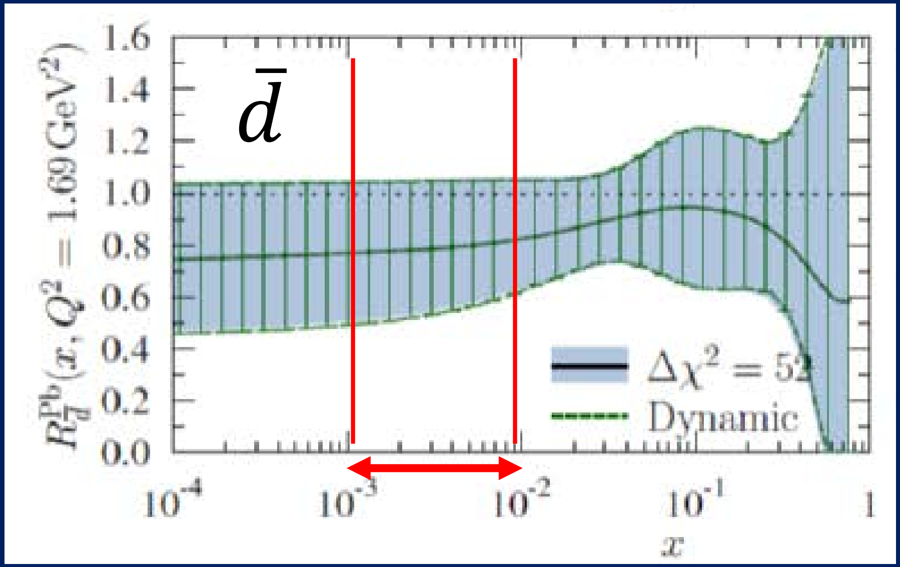


Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

No clear "antishadowing" in Drell-Yan—different nuclear modifications for sea quarks?

Sea quark distributions in nuclei

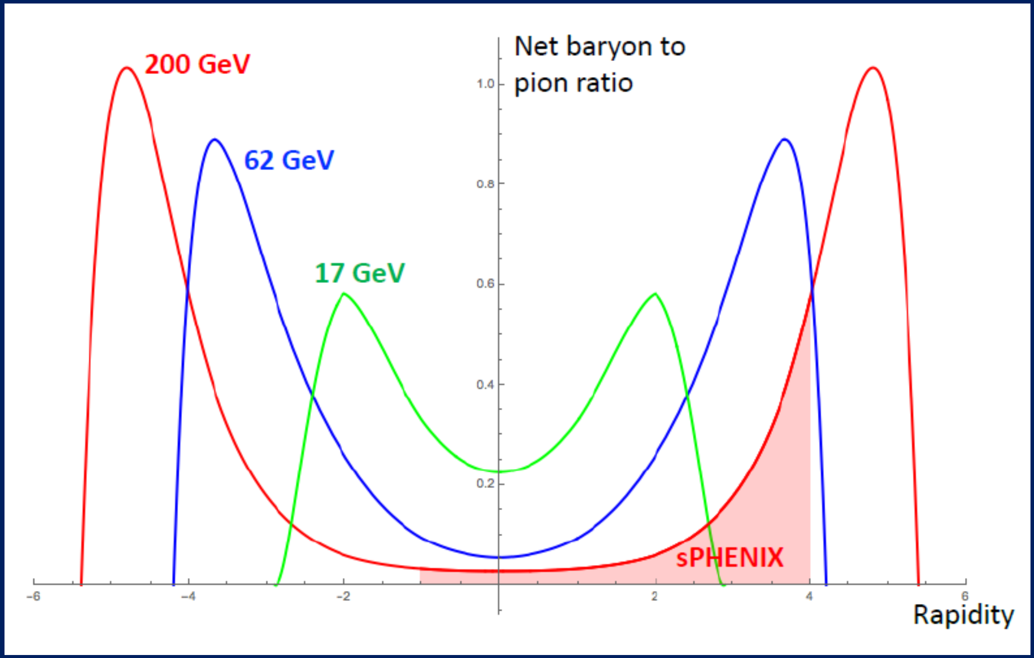




EPPS16 nuclear PDF fits, with sPHENIX *x* range indicated

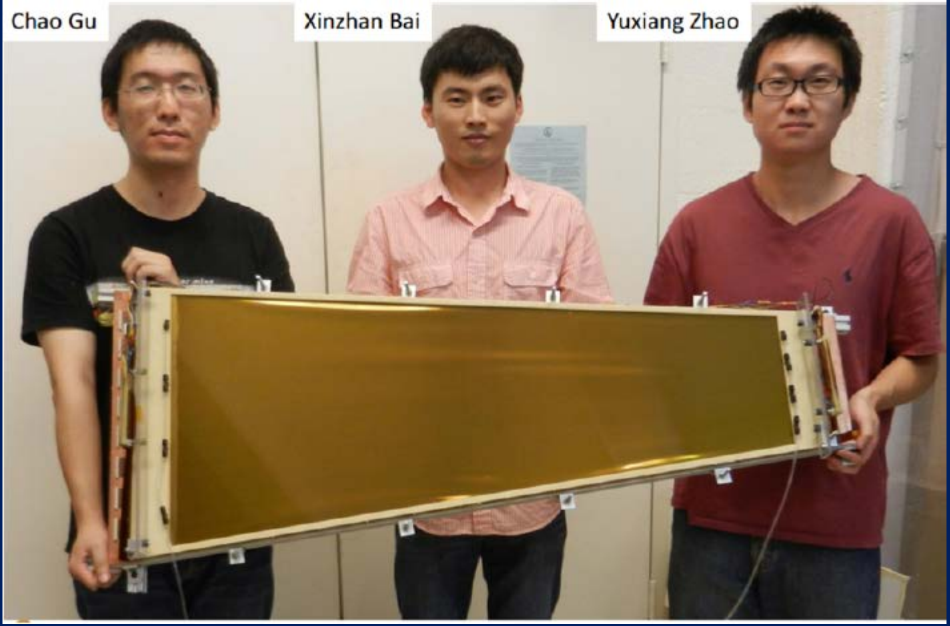
Additional physics: High-temperature sQGP at varying net baryon density

- Probe the high-temperature, strongly interacting QGP formed in high-energy A+A collisions across a region of varying baryo-chemical potential and opacity
  - Flow amplitudes, suppression of high-p_T spectra as a function of η



Tracking

- Take advantage of full lever arm (~3 m) in forward direction for momentum resolution
- drϕ ~ 50 μm for $\eta > 2.5$; drϕ ~ 100 μm for $\eta < 2.5$
- Outer tracking alternatives: MicroMegas or large-area small-strip Thin Gap Chambers (sTGCs)
  - Saclay a potential participant in developing MicroMegas



Electromagnetic calorimetry (FEMC)

- Reuse PHENIX PbSc for η < 3, MPC $PbWO_4$ crystals for 3 < η < 4
- PbSc: 5.5×5.5 cm^2 towers, $\frac{\sigma_E}{E} \sim 8\%/\sqrt{E(GeV)}$
- $PbWO_4$: 2.2×2.2 cm^2 towers, $\frac{\sigma_E}{E} \sim 12\%/\sqrt{E(GeV)}$
- SiPM photosensors considered for readout, providing uniformity with sPHENIX barrel calorimetry
  - APDs as alternative, worked well for PHENIX MPC in forward region

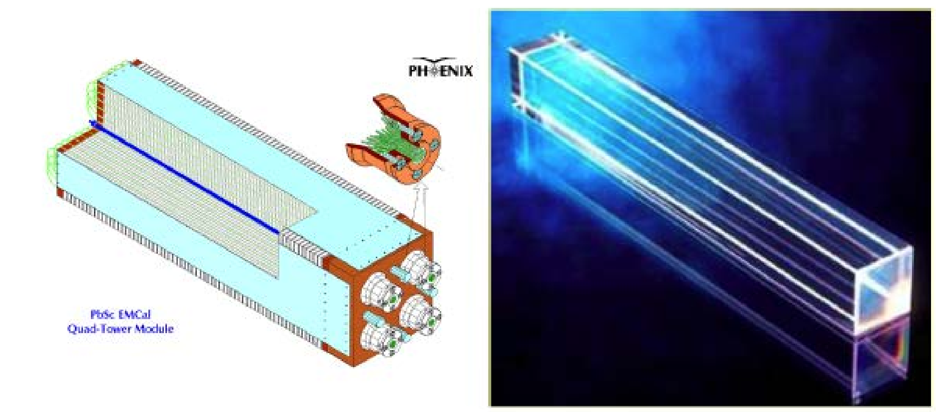
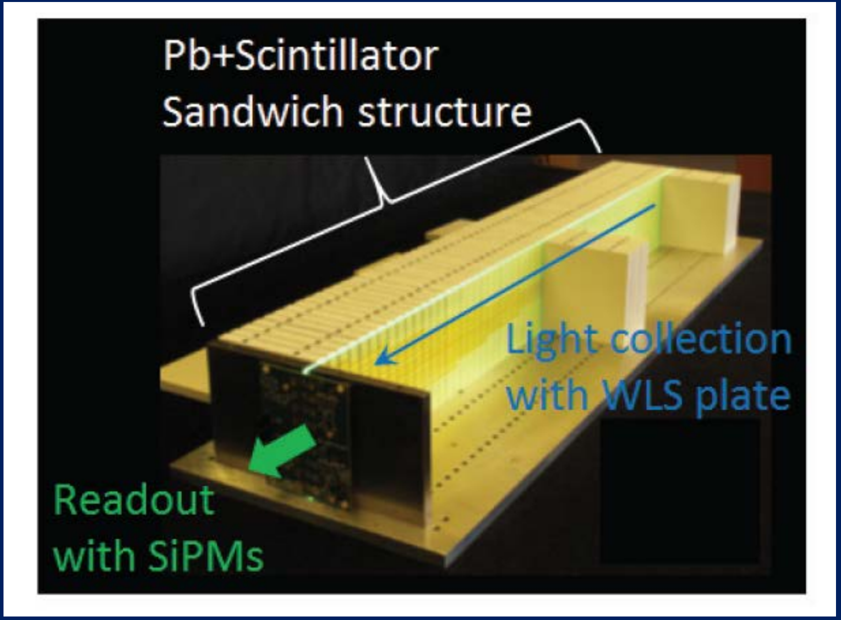


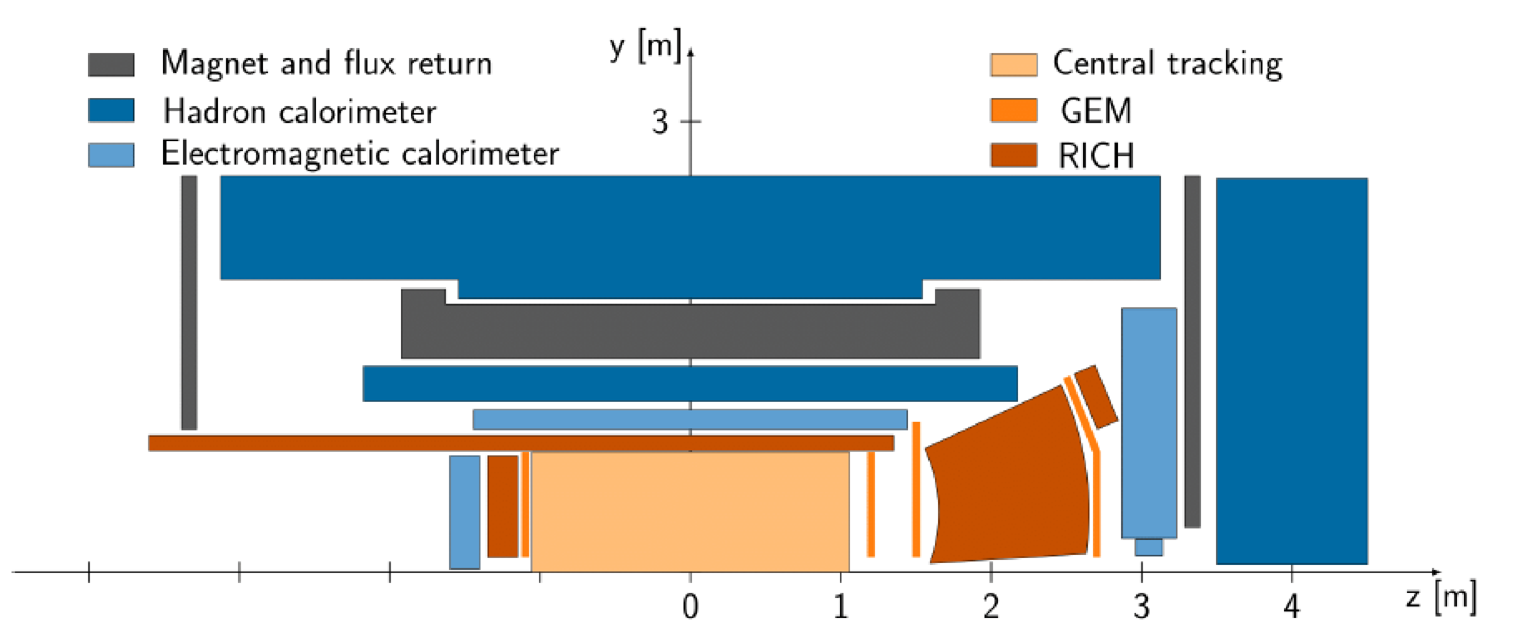
Figure 2.5: (Left) PHENIX PbSc block of four modules. (Right) PHENIX MPC PbWO4 crystal module.

Hadronic calorimetry (FHCAL)

- Steel- or lead-scintillator hadronic calorimeter, $1.2 < \eta < 4$
  - Design and development joint with EIC detector R&D group eRD1 and STAR
- $10 \times 10 \times 81$ cm^3 towers, 4 interaction lengths, $\frac{\sigma_E}{E} \sim 70\%/\sqrt{E(GeV)}$
- Potential interest from RIKEN to develop, test, and construct FHCAL



Evolution to an EIC detector



Instrumentation designed to form a suitable basis for a future EIC detector – add PID, electron-direction tracking and EMCal

Magnetic field

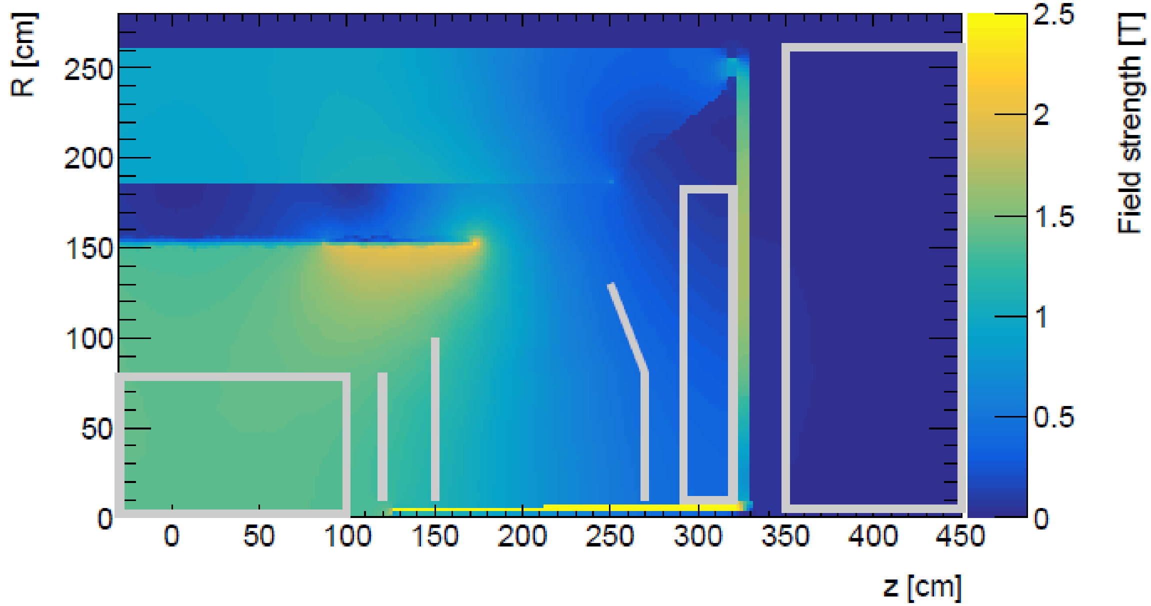


Figure 2.2: Magnetic field configuration, as calculated using the 2D magnetic field solver FEMM 2D and Poisson. Approximate locations for the forward sPHENIX detectors are indicated with gray boxes. From left to right are the central tracking region, GEM trackers, forward EMCal and HCal.

Track momentum resolution for different η values

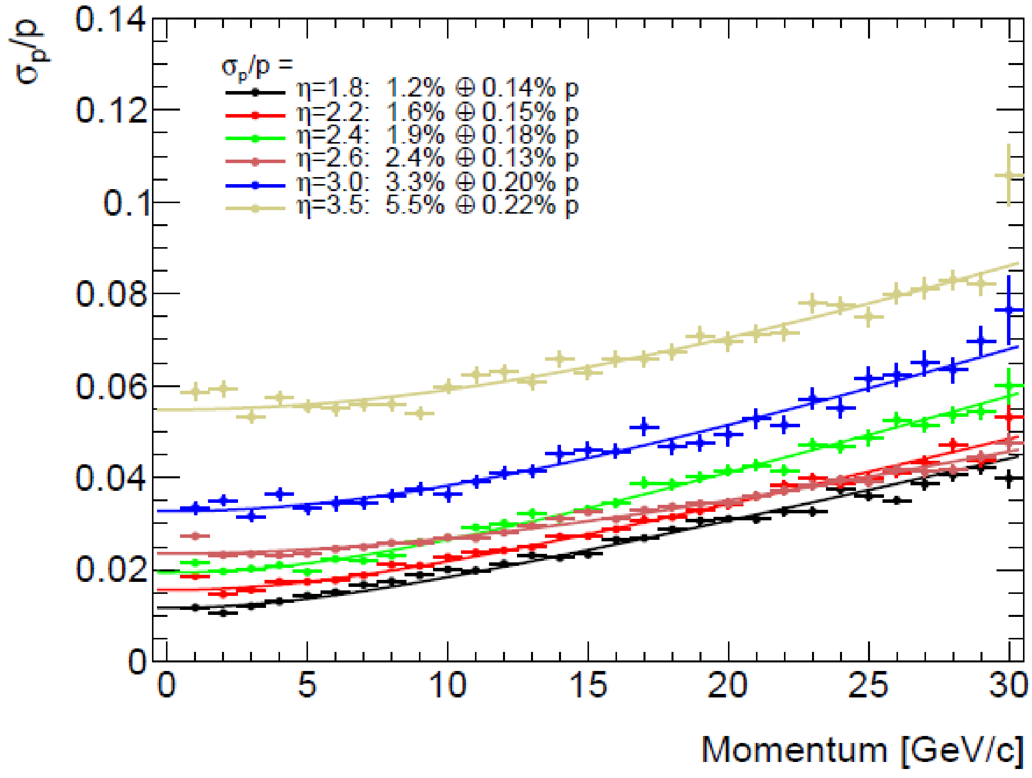


Figure 3.2: The relative momentum resolution for the tracking system as a function of total particle momentum. The values are obtained from a full GEANT4 simulation and a GenFit2-based Kalman filter fit.

Effect of magnet flux return thickness on hadron energy reconstruction

- Nominal thickness of 10.2 cm has minor impact
  - Adds ~12% constant term to energy resolution of 70%/√E

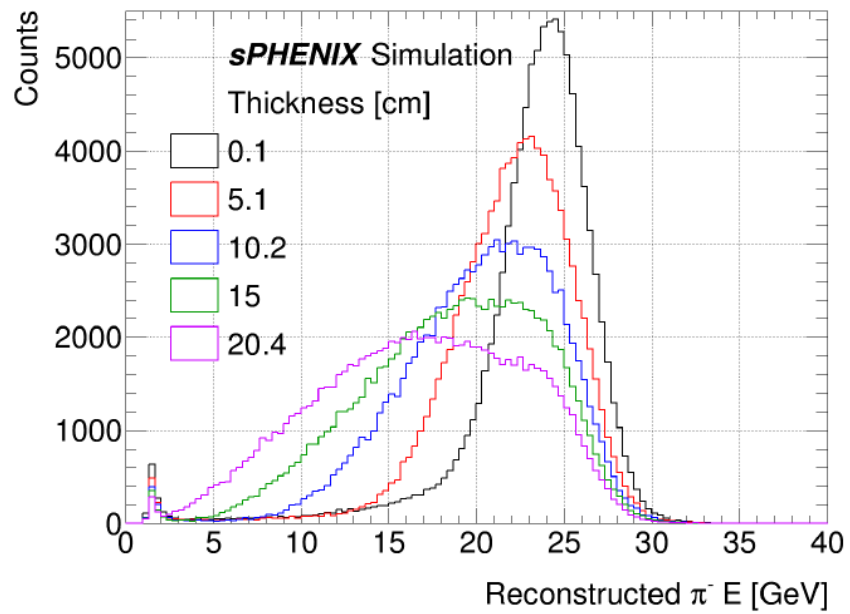


Figure 3.3: The total energy E measured in GEANT4 with the sPHENIX forward electromagnetic and hadron calorimeter for single 30 GeV charged pion events generated with pseudorapidity $\eta = 2$ for various plug door thicknesses d_z.

Jet resolution

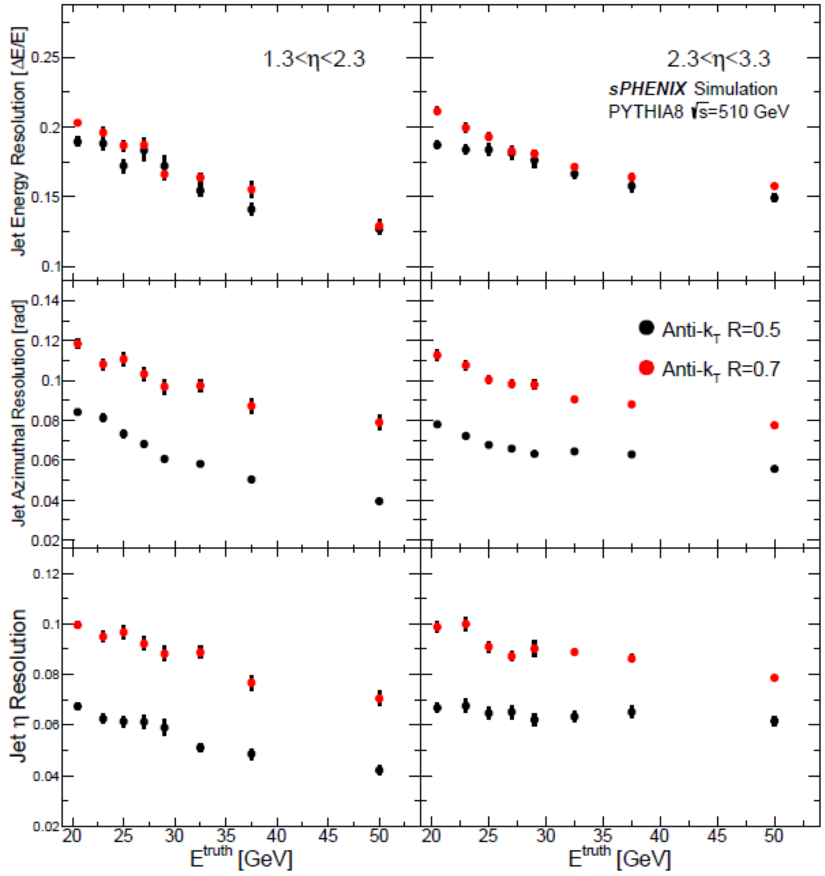
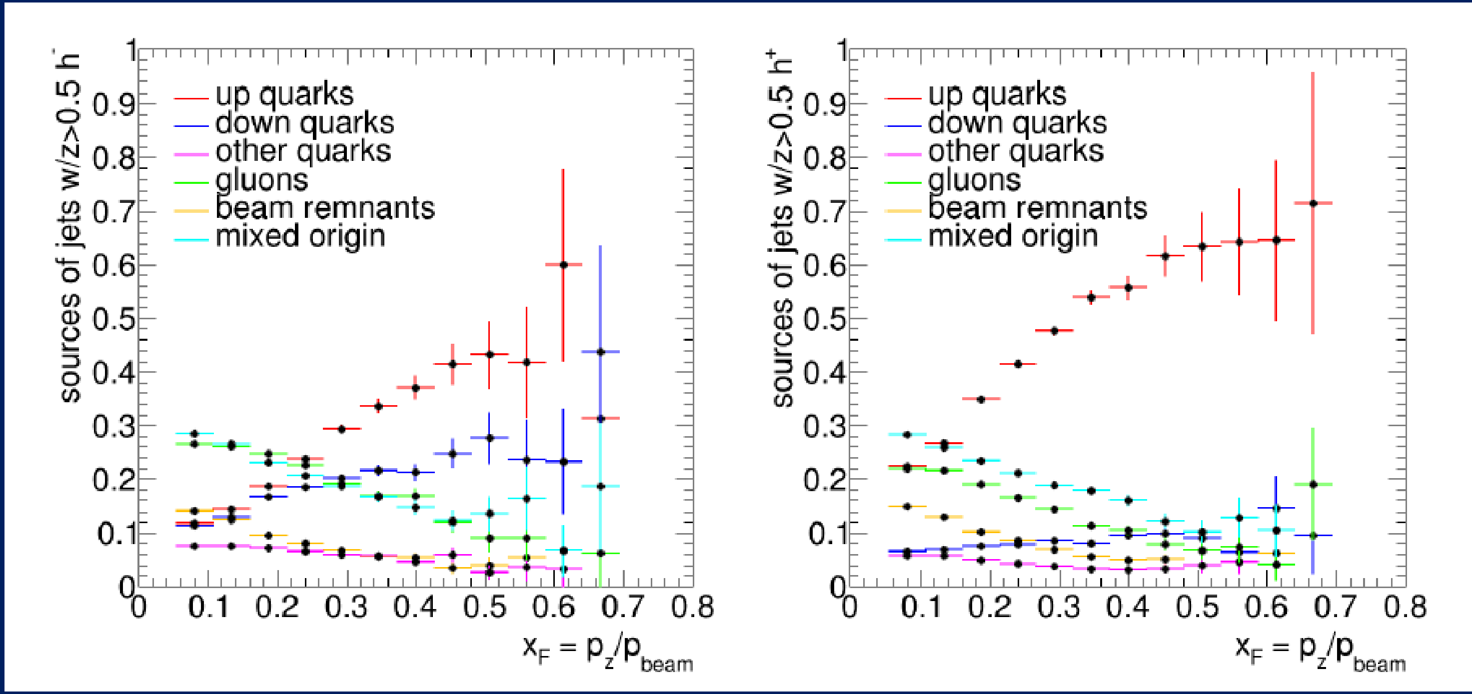


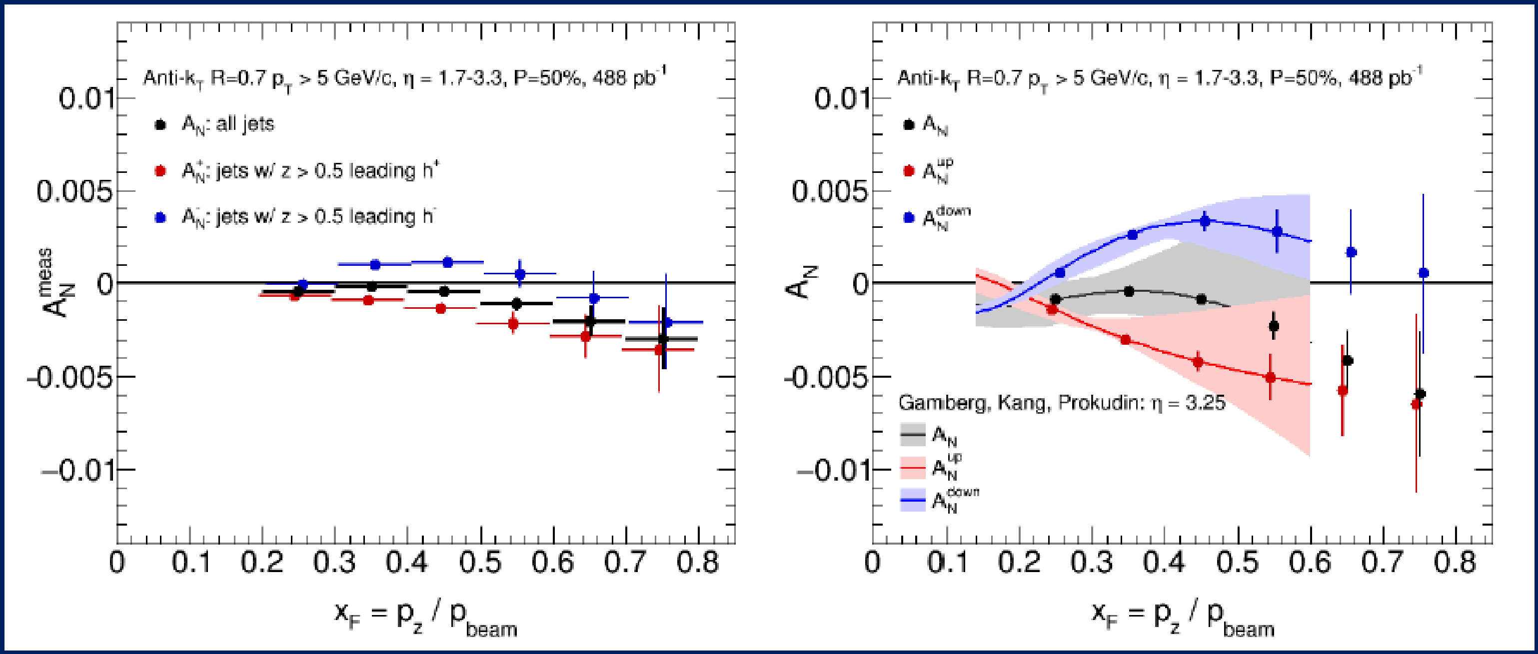
Figure 3.5: The GEANT4 simulated jet resolution of single jets for energy (top row), ϕ (middle row), and η (bottom row) in minimum bias 510 GeV $p+p$ collisions from PYTHIA8. Jets are reconstructed using the FASTJET package anti-k_T algorithm with R=0.5 (black) and R=0.7 (red).

Flavor-enhancement via charge-tagged jets



- Selecting a z > 0.5 hadron with positive or negative charge enhances up vs. down contributions
- 510 GeV p+p, $p_T^{jet} > 5$ GeV

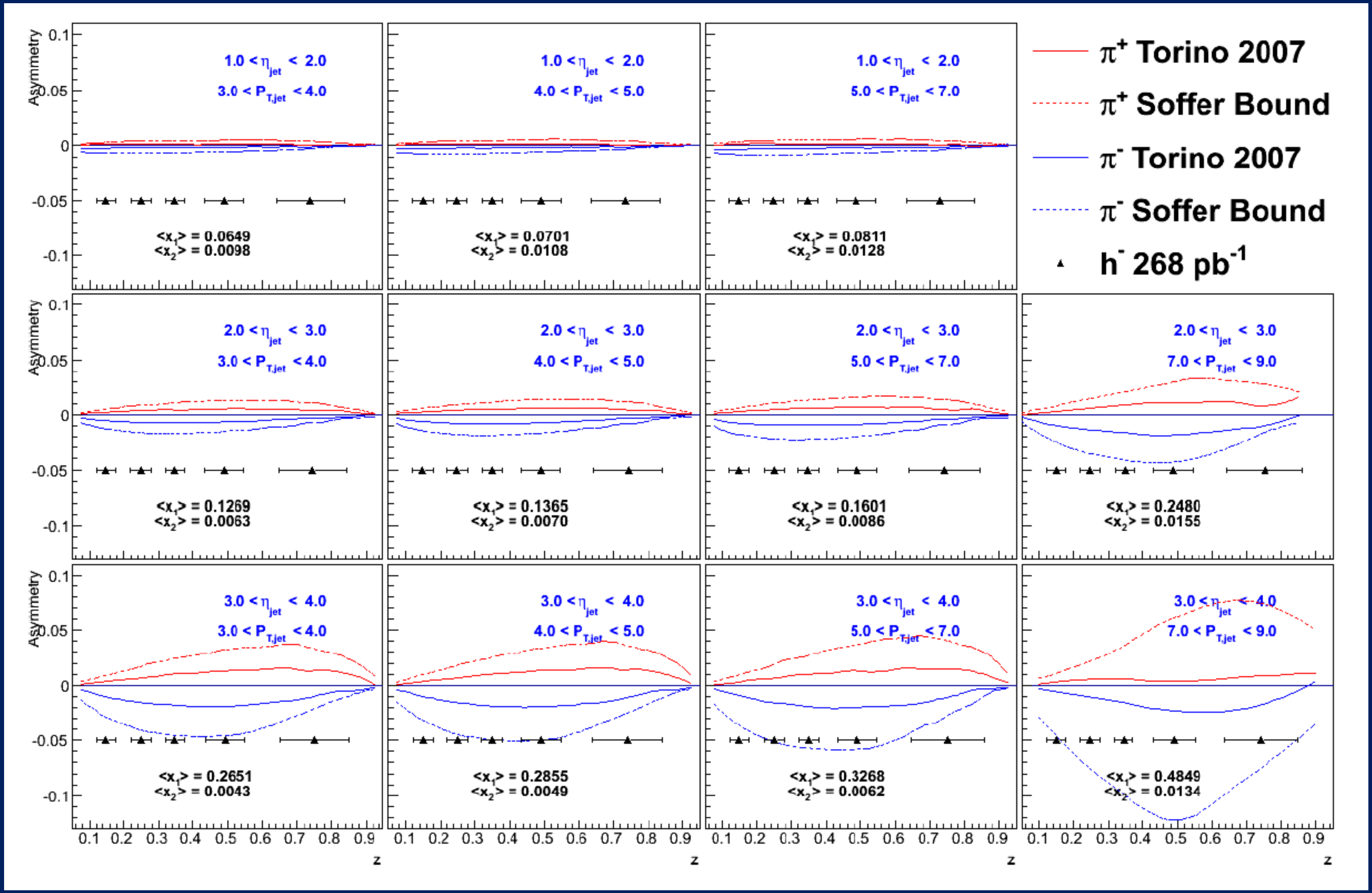
Performance study: Flavor enhancement via charge-tagged jets



- Left: Projected asymmetry measurements for inclusive, positive-, and negative-charge-tagged jets

- Right: Expected uncertainties on an extraction of u and d quark asymmetries from the measured asymmetries

Measuring hadron asymmetries within jets



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