Investigating Proton Structure at the Relativistic Heavy Ion Collider

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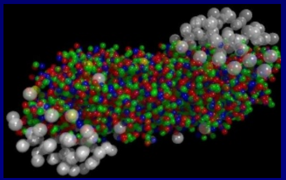
The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

- A collider-based program, but not designed to be at the energy (or intensity) frontier. More closely analogous to many areas of condensed matter research—create a system and study its properties





- What systems are we studying?
  – "Simple" QCD bound states—the proton is the simplest stable bound state in QCD (and conveniently, nature has already created it for us!)
  – Collections of QCD bound states (nuclei, also available out of the box!)
  – QCD deconfined! (quark-gluon plasma, some assembly required!)

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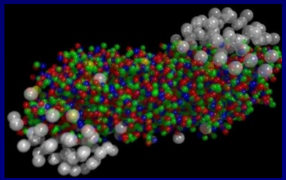
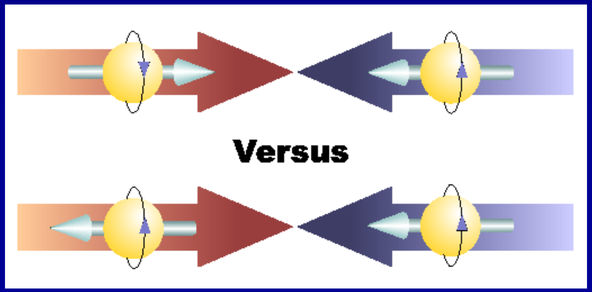


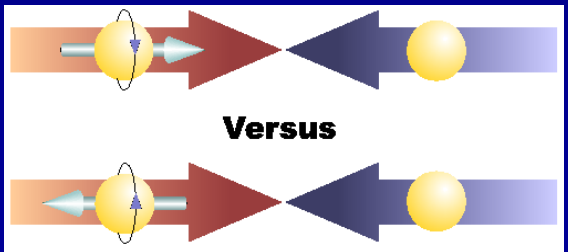
Understand more complex QCD systems within the context of simpler ones

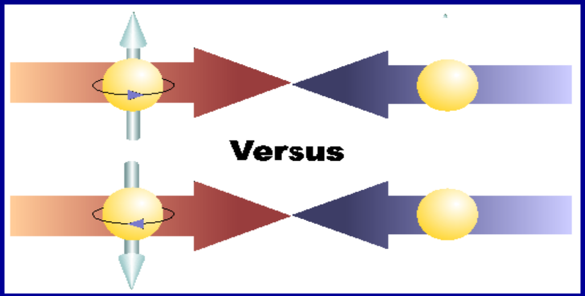
→RHIC designed from the start as a single facility capable of nucleus-nucleus, proton-nucleus, and proton-proton collisions

Proton spin structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse spin and spin-momentum correlations
π, Jets $\quad A_{LL}(gg, gq \to \pi + X)$ Back-to-Back Correlations	**W Production** $A_L(u + \bar{d} \to W^+ \to \ell^+ + \nu_l)$ $A_L(\bar{u} + d \to W^- \to \ell^- + \bar{\nu}_l)$	Transverse-momentum-dependent distributions Single-Spin Asymmetries







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Advantages of a polarized *proton-proton collider*:

- Hadronic collisions → Leading-order access to gluons
- High energies → Applicability of perturbative QCD
- High energies → Production of new probes: W bosons

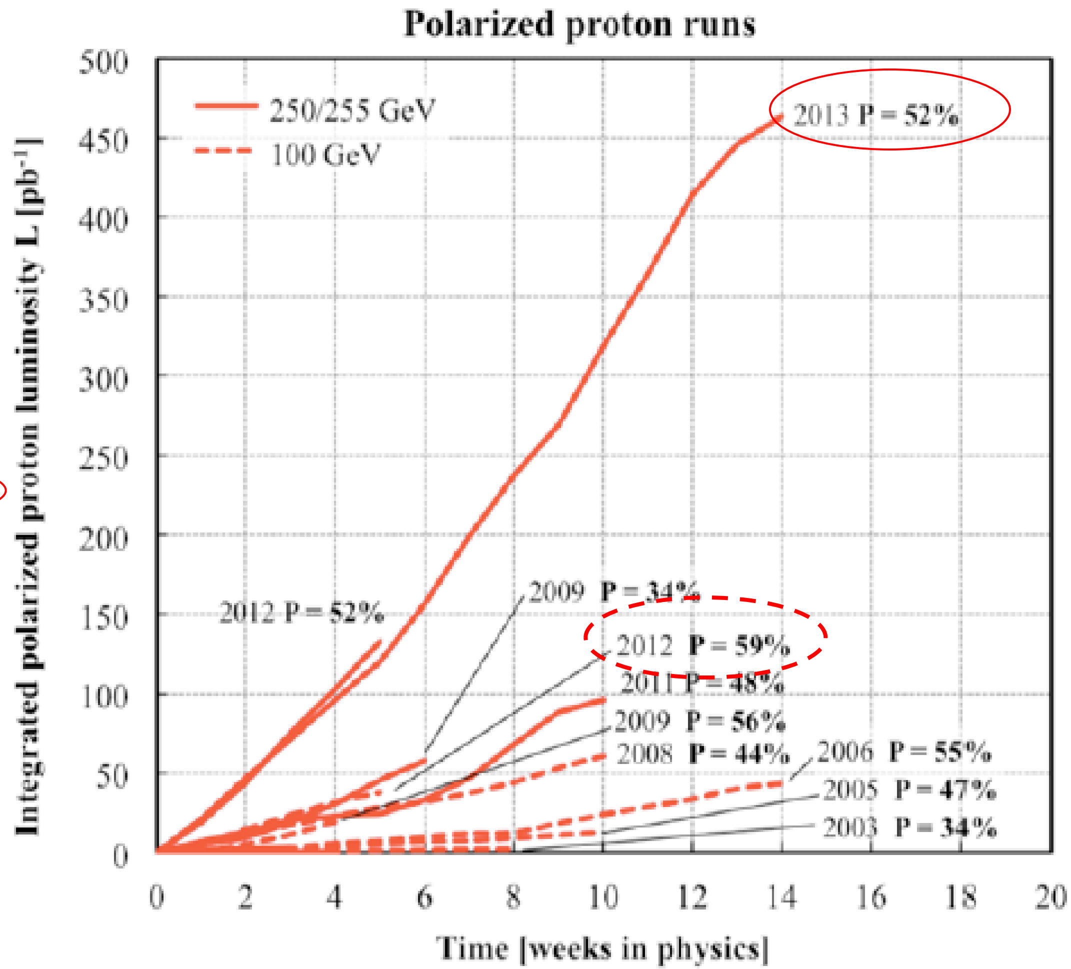
Reliance on input from simpler systems

- Disadvantage of hadronic collisions: much "messier" than deep-inelastic scattering → *Rely on input from simpler systems*
  - Just as the heavy ion program at RHIC relies on information from simpler collision systems

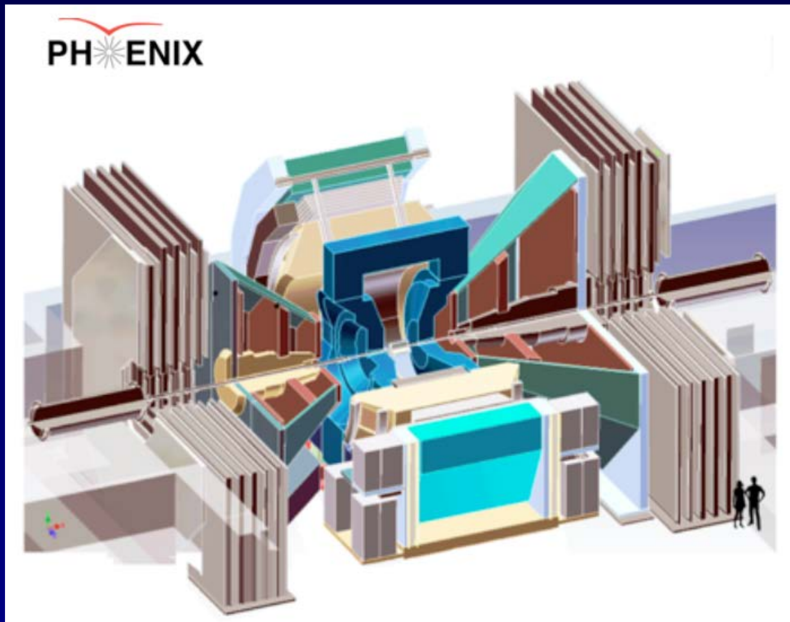
- The more we know from simpler systems such as DIS and e+e- annihilation, the more we can in turn learn from hadronic collisions!

RHIC performance for polarized protons

Longitudinal data	STAR
√s = **200 GeV**	
2005	3 pb^{-1}
2006	7 pb^{-1}
2009 (2015)	35 pb^{-1} (50 pb^{-1})
√s = **500 GeV**	
2009	10 pb^{-1}
2011	12 pb^{-1}
2012	82 pb^{-1}
2013	300 pb^{-1}
Transverse data	
√s = **200 GeV**	
2006	9 pb^{-1}
2008	8 pb^{-1}
2012 (2015)	22 pb^{-1} (50 pb^{-1})
√s = **500 GeV**	
2011 (2016)	25 pb^{-1} (400 pb^{-1})

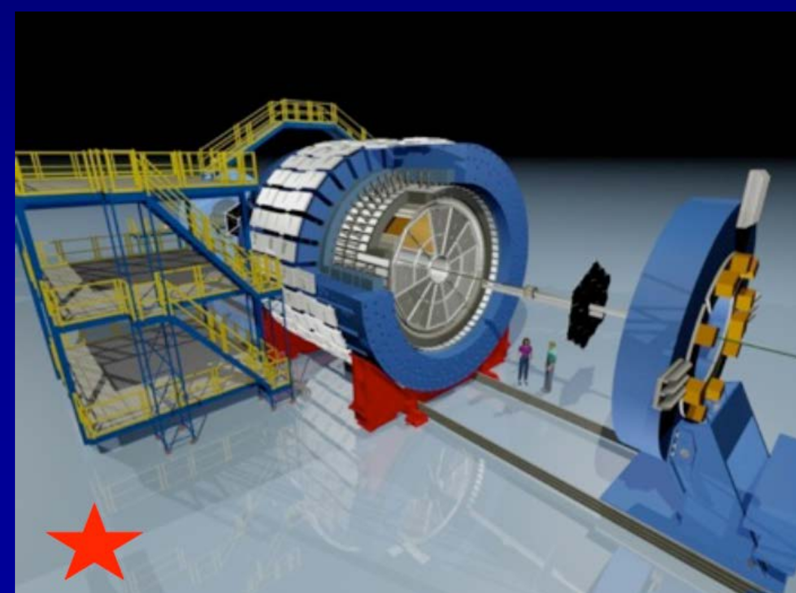


RHIC's current main experiments



PHENIX:

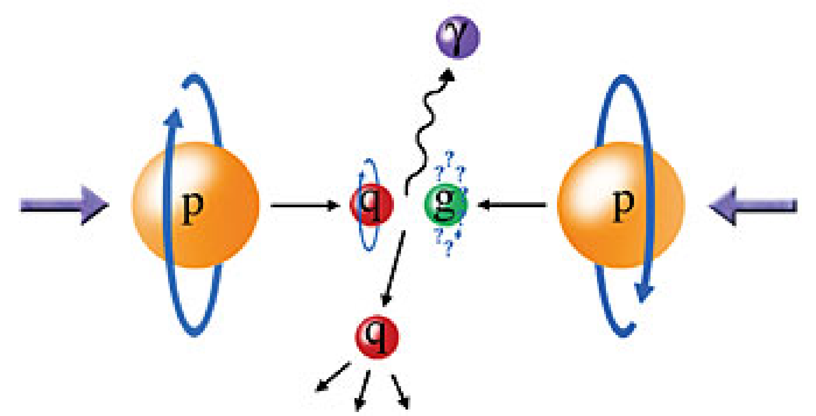
- High resolution; high rate capabilities for rare probes
- Central arms $|\eta|<0.35$, $\Delta\phi\sim2\pi$ with key strength measuring EM probes
- Muon arms $1.2<|\eta|<2.4$
- Forward EM calorimetry



STAR:

- Key strengths jets + correlations
- Full acceptance including PID for $|\eta|< 1$, $\Delta\phi\sim2\pi$
- Forward EM calorimetry

Probing the helicity structure of the nucleon with p+p collisions



$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{1}{|P_1 P_2|} \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

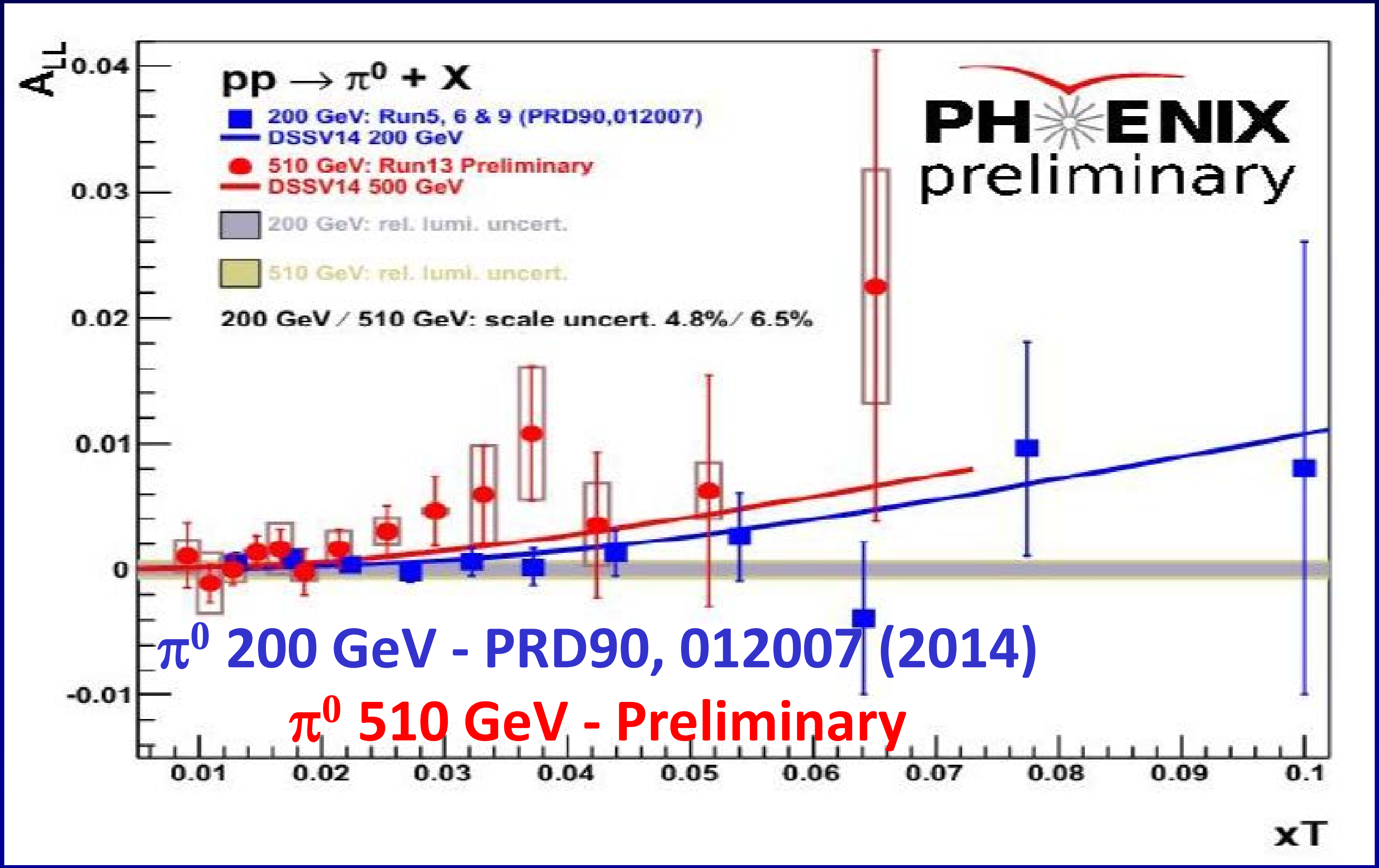
Study difference in particle production rates for same-helicity vs. opposite-helicity proton collisions

$$\Delta\sigma(pp \to \pi^0 X) \propto \Delta q(x_1) \otimes \Delta g(x_2) \otimes \Delta\hat{\sigma}^{qg \to qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

DIS ? pQCD e+e-

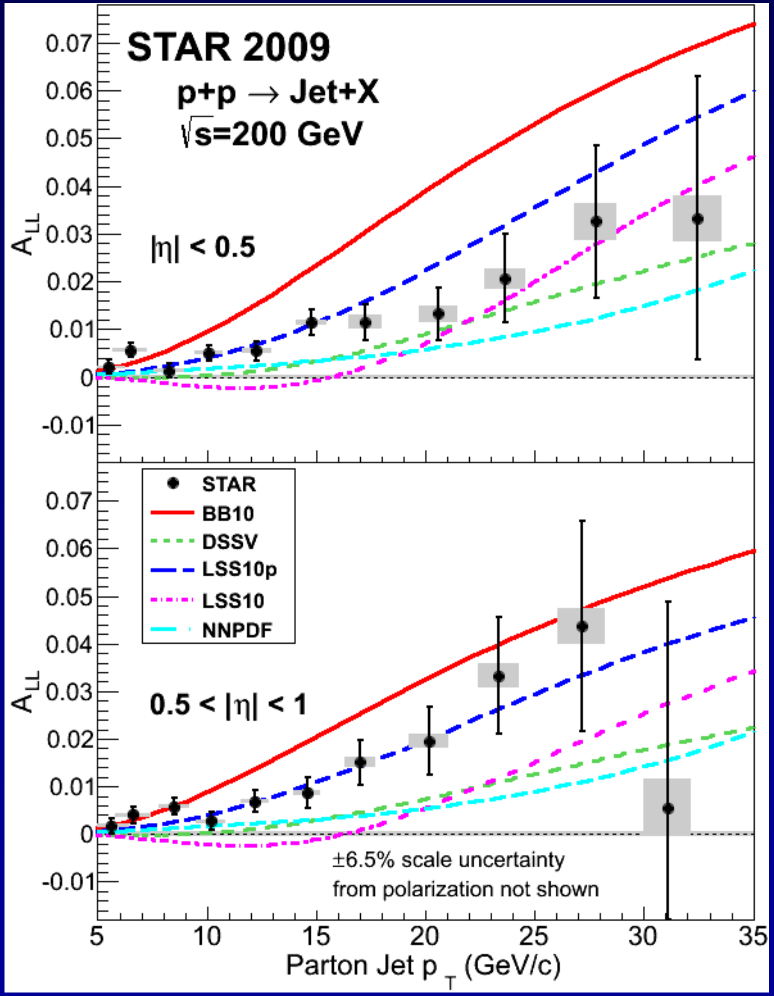
Leading-order access to gluons → ΔG

Neutral pion and jet double-helicity asymmetries



Neutral pion and jet double-helicity asymmetries

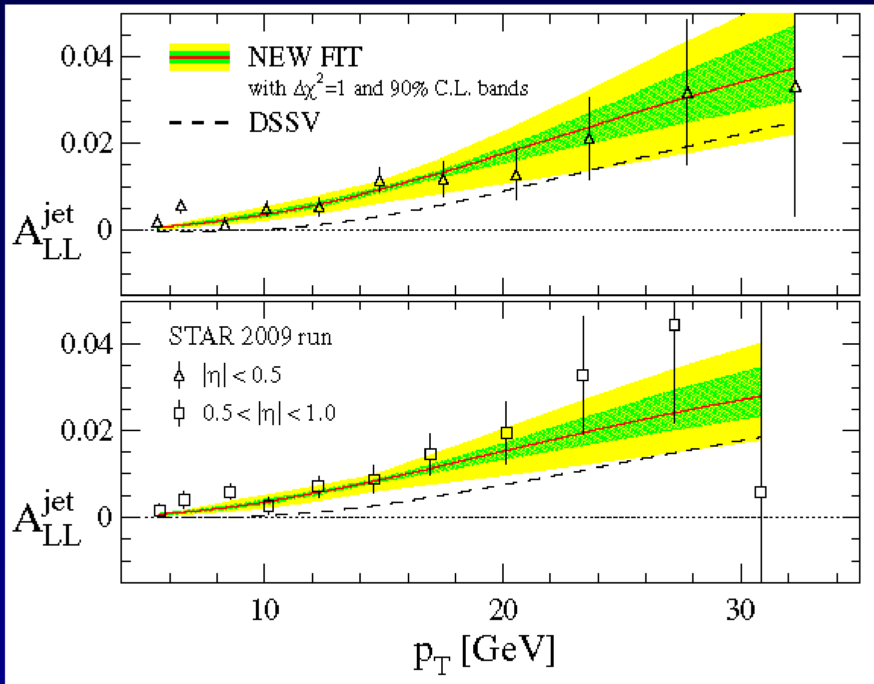
arXiv:1405.5134



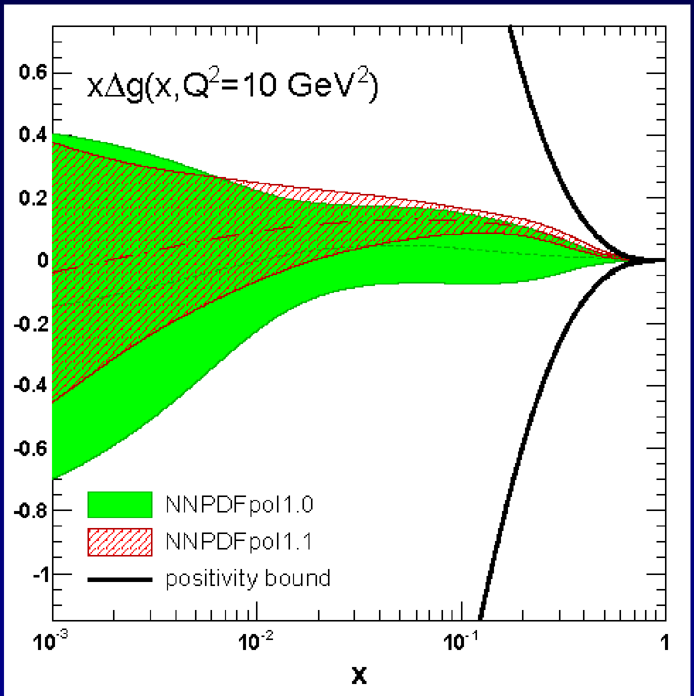
- Clear nonzero asymmetry seen in STAR jet measurements from 2009 data!
- PHENIX π^0 data consistent

Two new helicity pdf fits

DSSV, PRL 113, 012001 (2014)

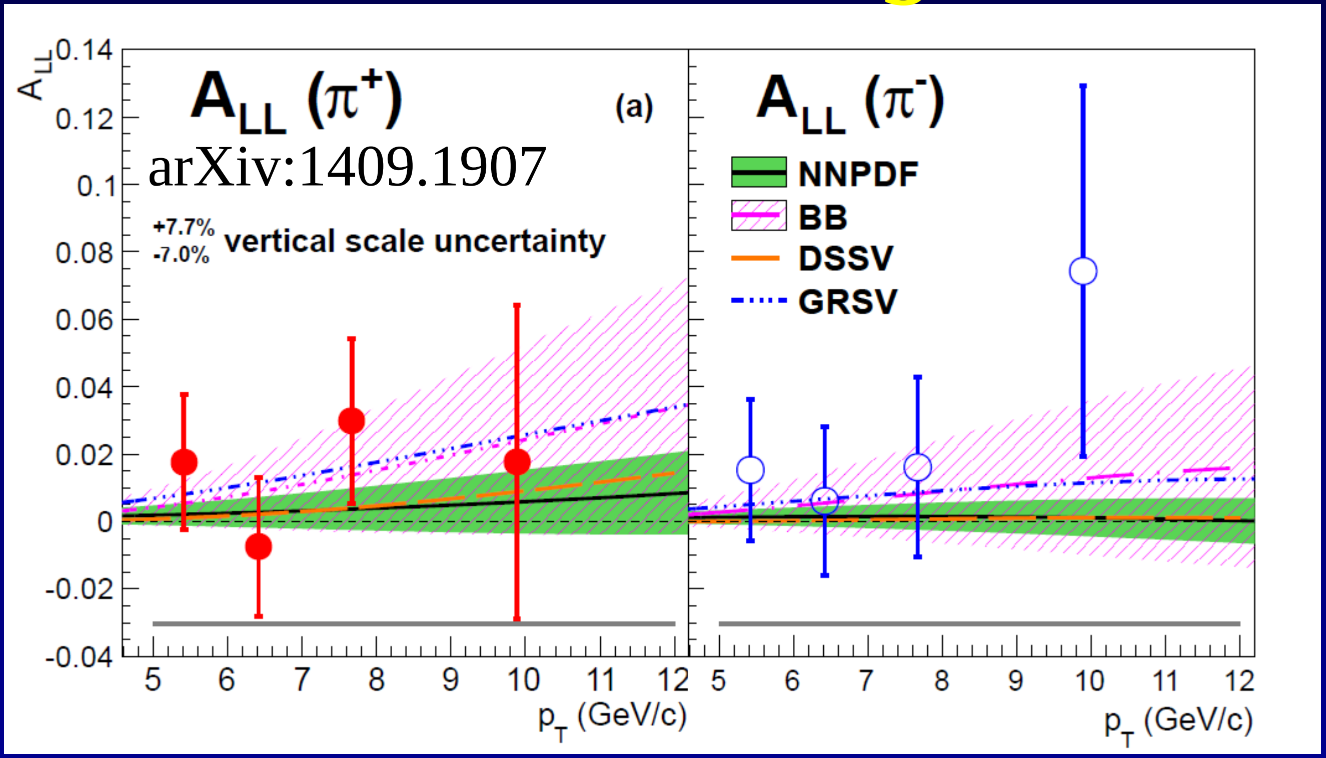


NNPDF, NPB 887.276 (2014)



- DSSV and NNPDF have released new polarized pdf fits including RHIC data
- 2009 STAR jet A_{LL} results in particular provide significantly tighter constraints on gluon polarization than previous measurements
- Both find evidence for positive gluon polarization in the region x > 0.05 – See talks by M. Stratmann and E. Nocera

Other recently measured probes sensitive to gluon helicity



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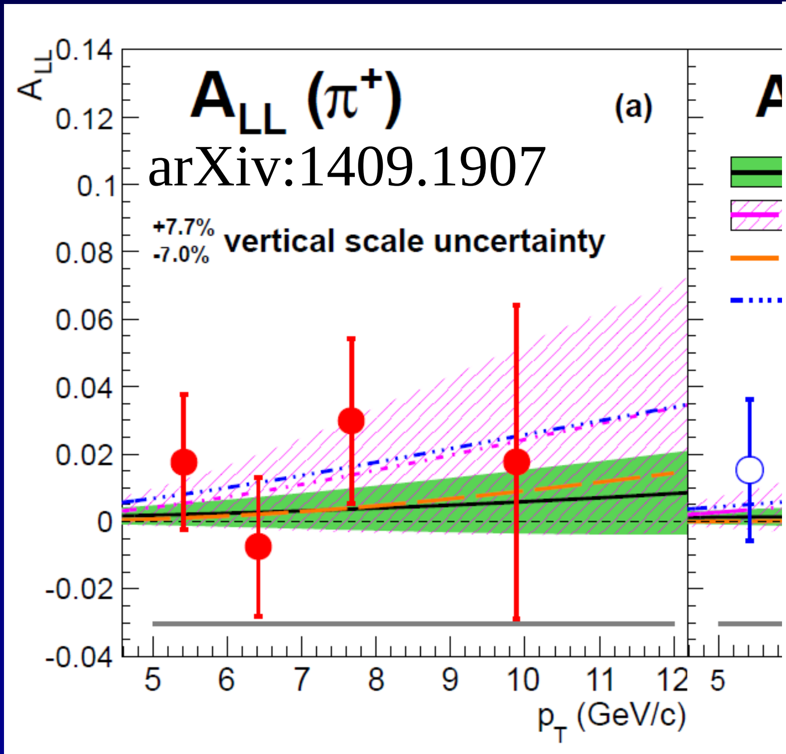

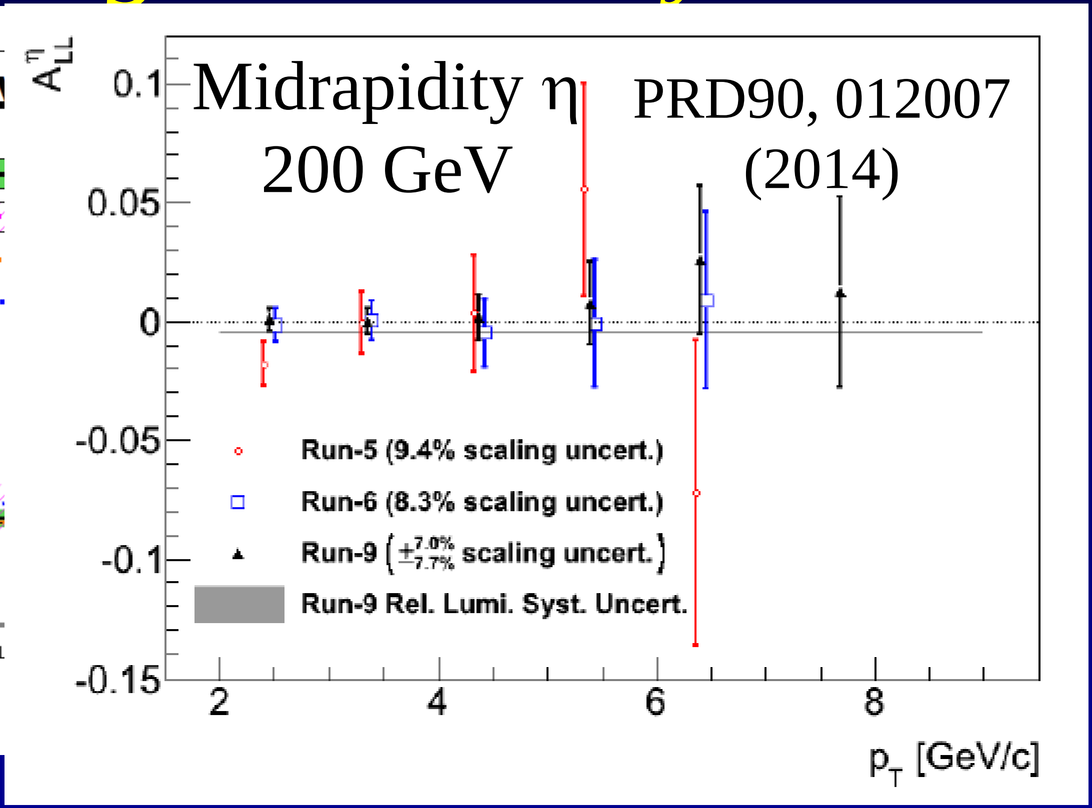

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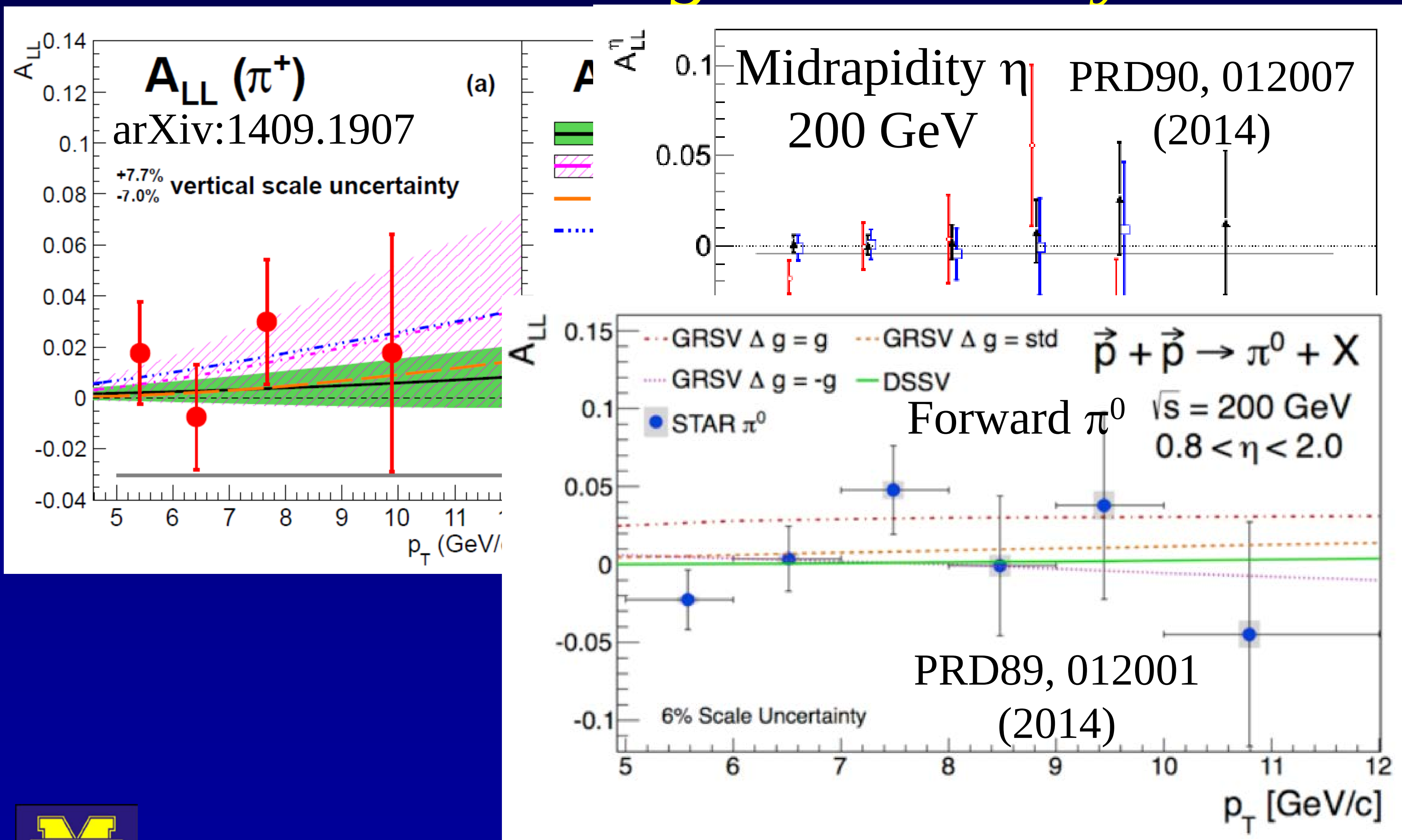

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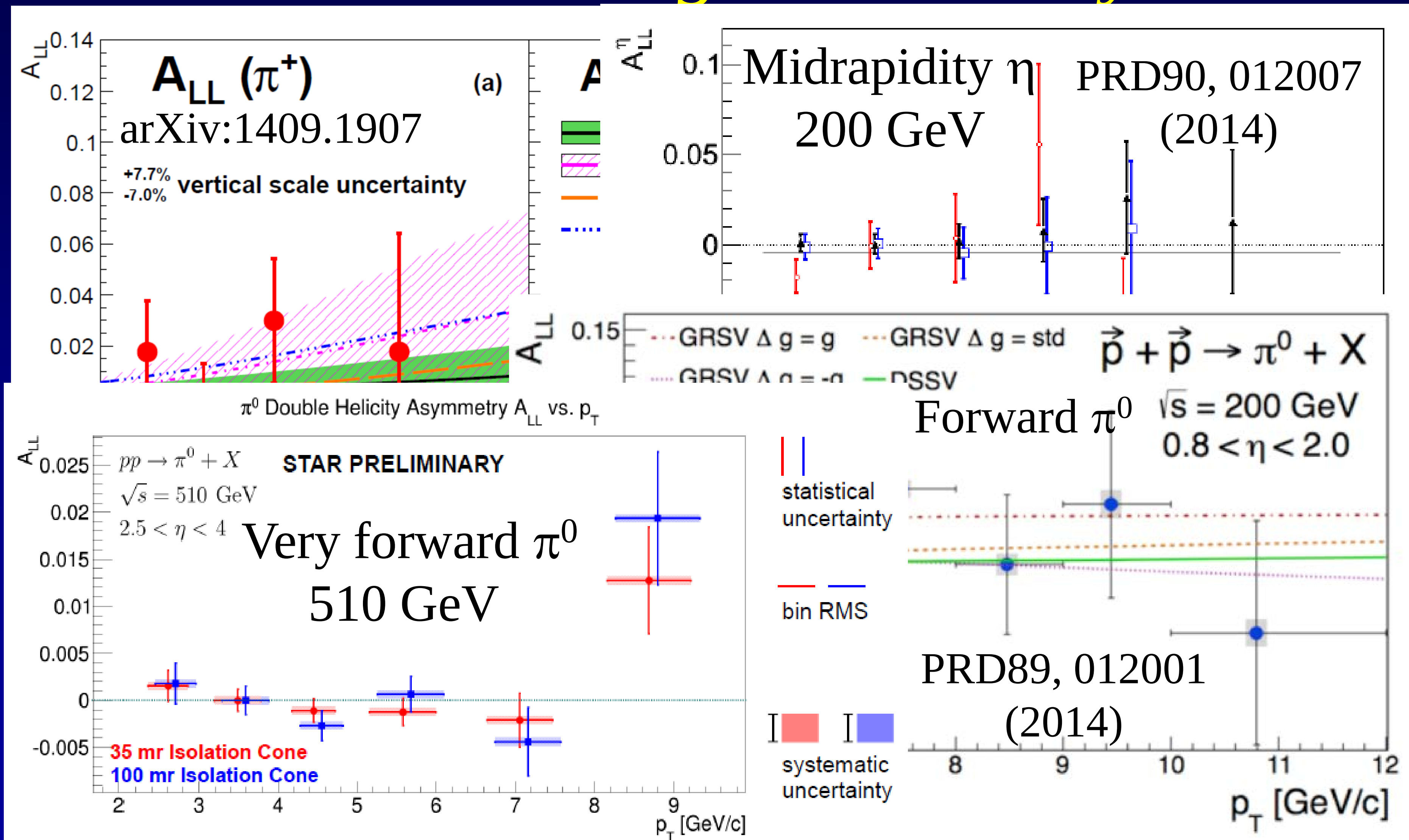

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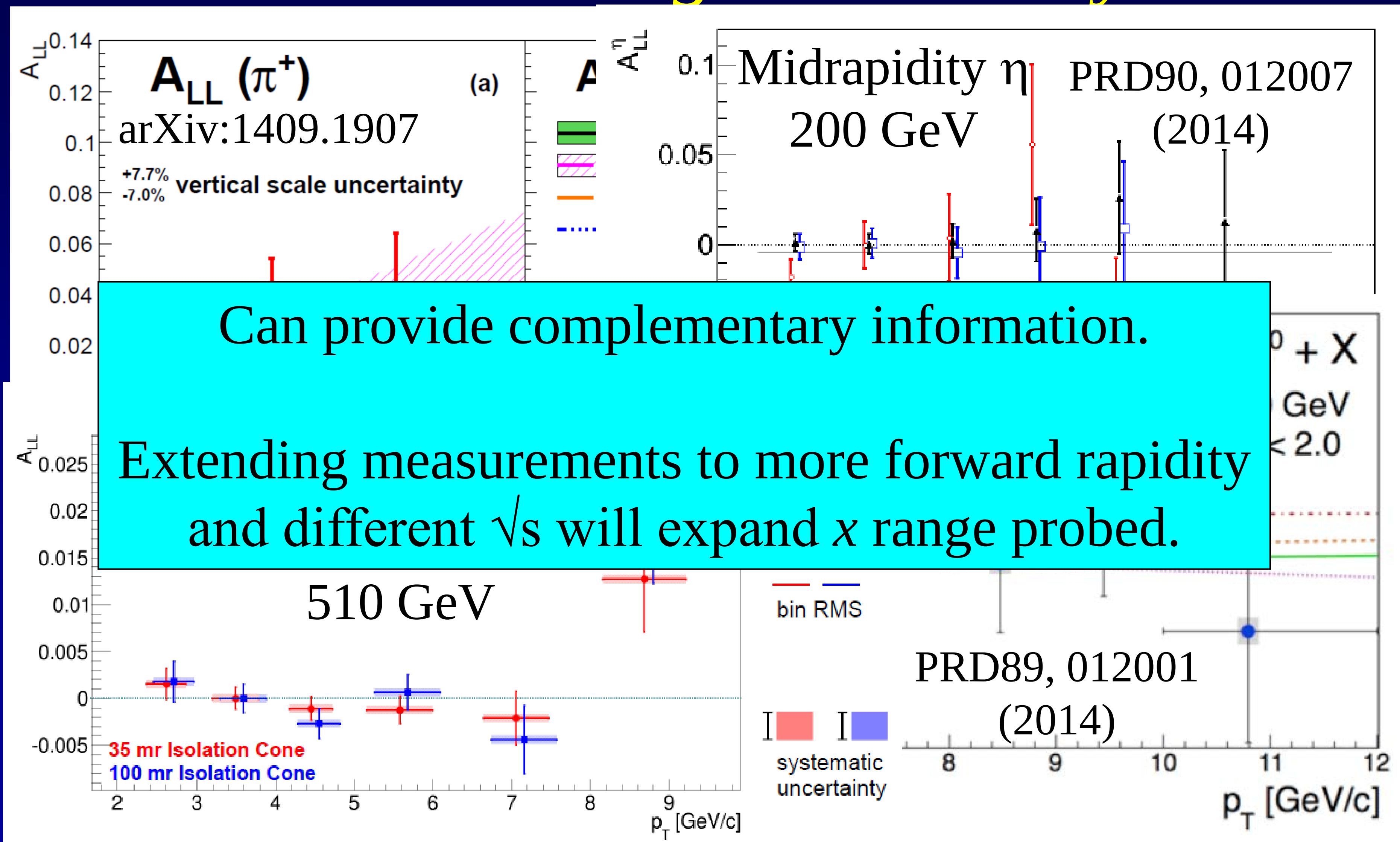
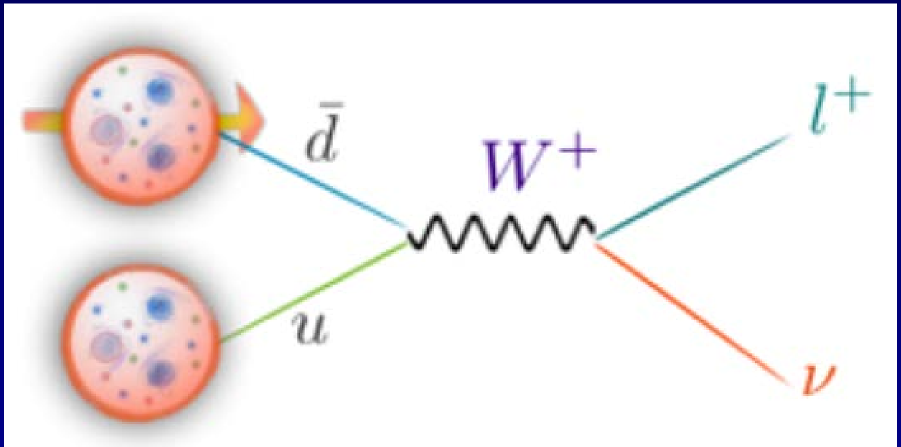


Can provide complementary information.

Extending measurements to more forward rapidity and different √s will expand *x* range probed.

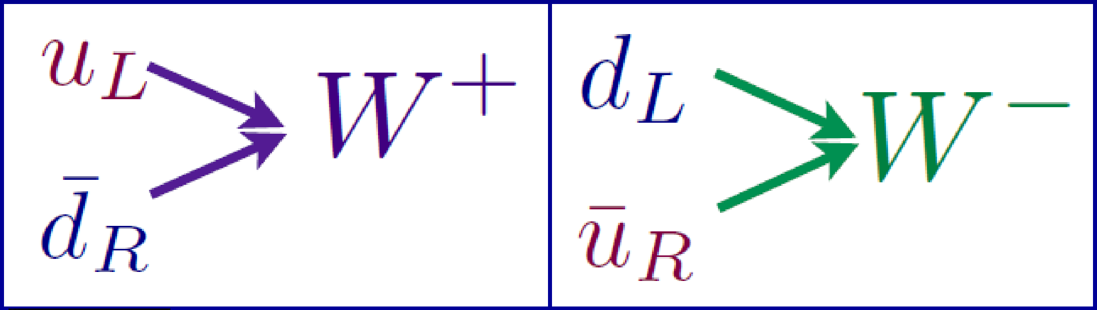
Flavor-separated sea quark helicities through W production

$$\Delta q(x), \Delta \bar{q}(x)$$



$$A_L^{W^+} \approx -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta \bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) - \bar{d}(x_1)u(x_2)}$$

$$A_L^{W^-} \approx -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta \bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) - \bar{u}(x_1)d(x_2)}$$



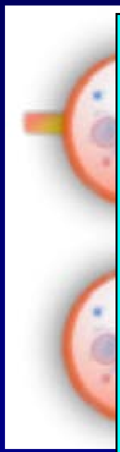
Parity violation of weak interaction + control over proton spin orientation gives access to *flavor*-spin structure of proton

Flavor-separated sea quark helicities through W production

$$\Delta q(x), \Delta\bar{q}(x)$$

$$A_L^{W^+} \approx -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) - \bar{d}(x_1)u(x_2)}$$

$$\ldots)d(x_2) \over \ldots d(x_2)$$



Flavor separation of the polarized sea quarks with ***no reliance on fragmentation functions,*** *and at* ***much higher scale*** *than previous fixed-target experiments.*

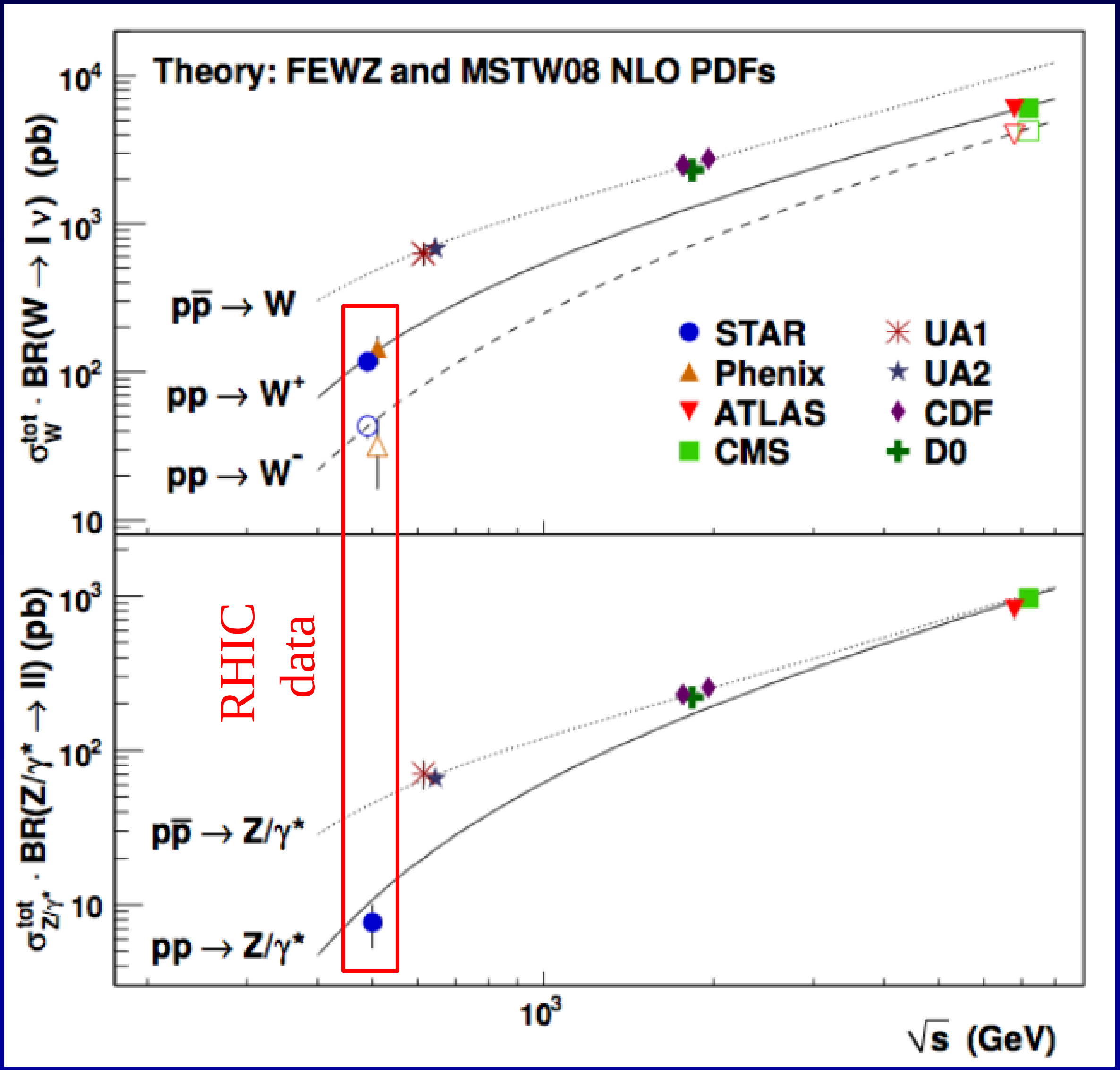
Complementary *to semi-inclusive DIS measurements.*

...eak

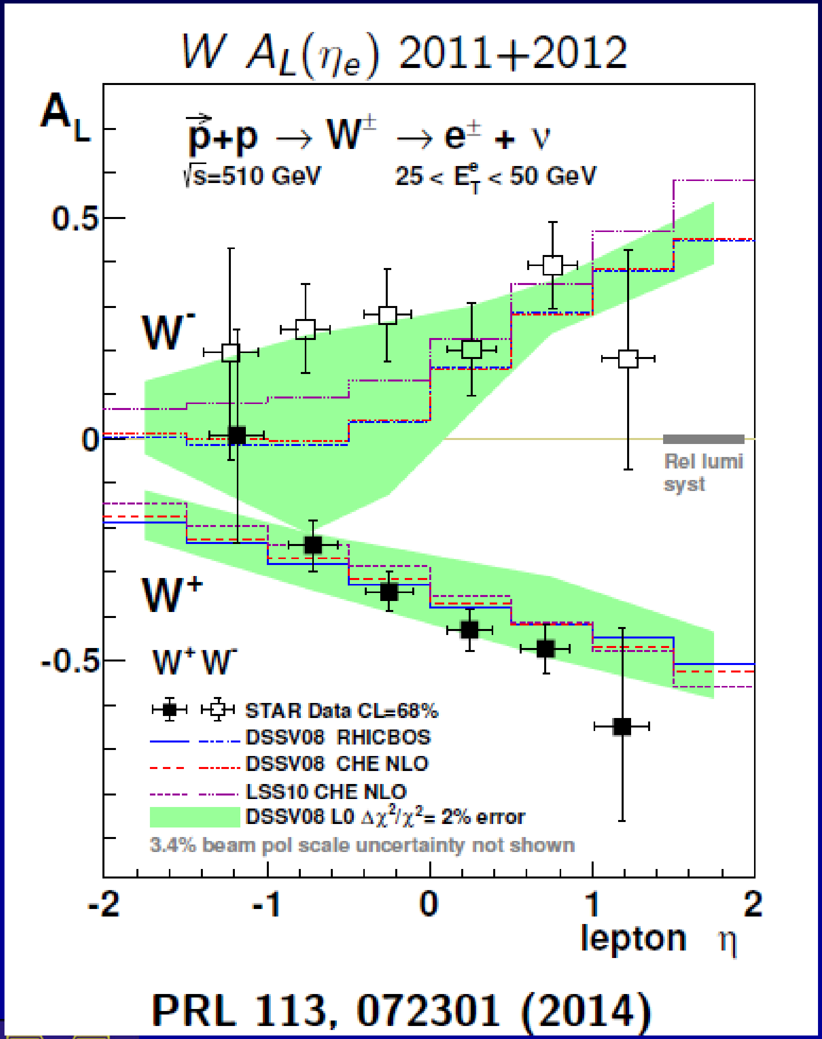
...spin orientation gives access to *flavor*-spin structure of proton

$$u_L,\ \bar{d}_R \rightarrow W^+ \qquad d_L,\ \bar{u}_R \rightarrow W^-$$

World W cross section measurements



Large parity-violating single-helicity asymmetries



- Improve constraints on light antiquark helicity distributions
  - See talks by M. Stratmann, E. Nocera

$$A_L = \frac{1}{P}\frac{N^+/L^+ - N^-/L^-}{N^+/L^+ + N^-/L^-}$$

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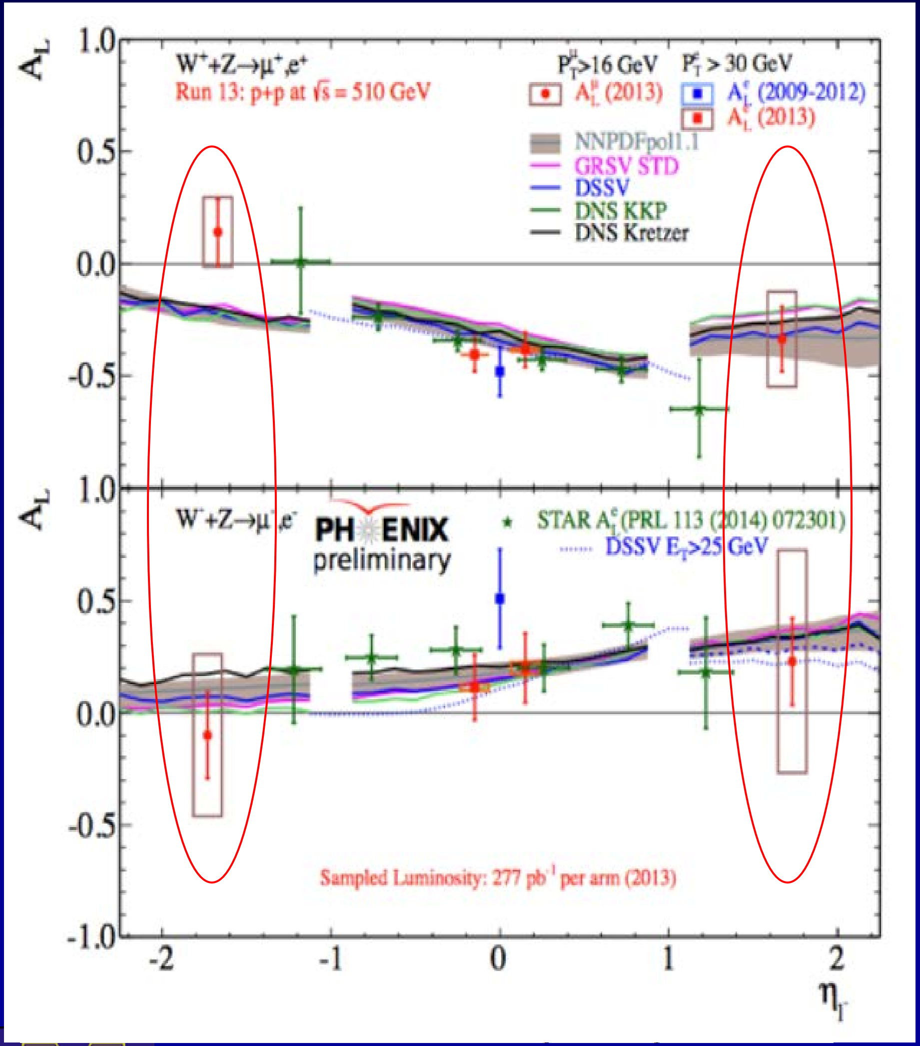
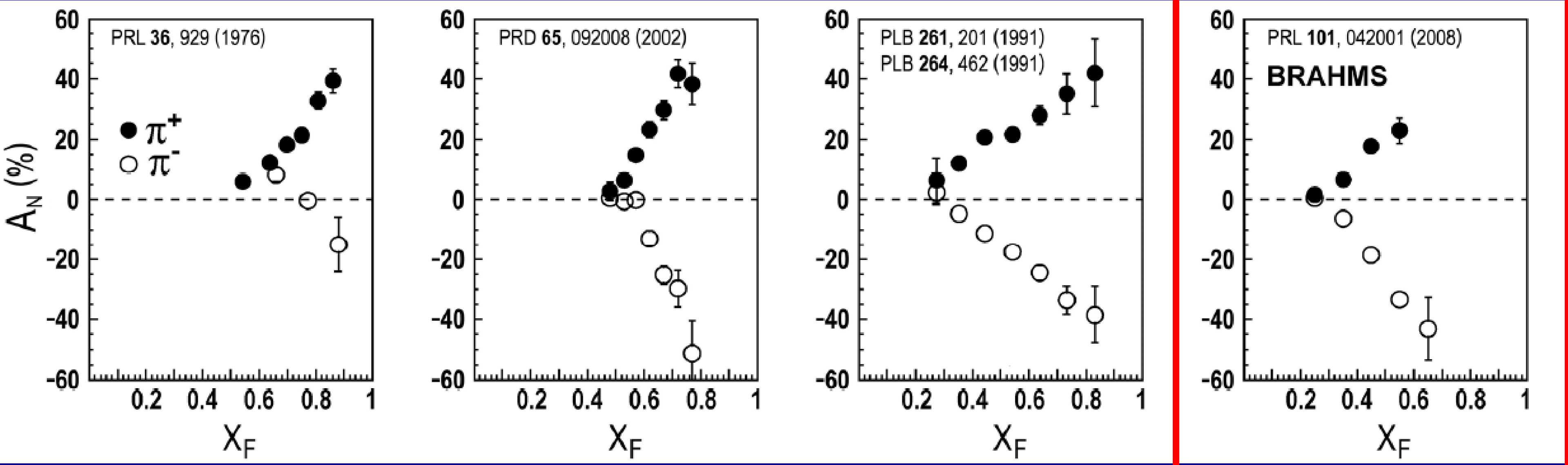


- Improve constraints on light antiquark helicity distributions
  - See talks by M. Stratmann, E. Nocera
- New preliminary PHENIX muon results extend rapidity range

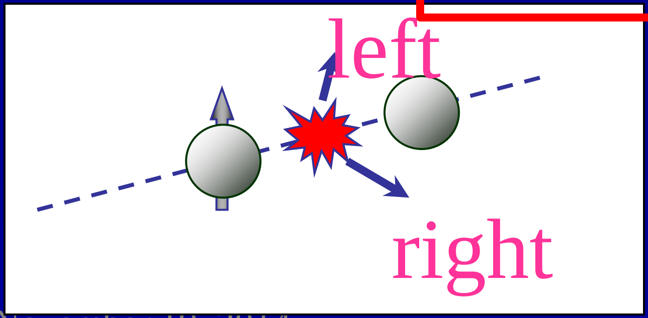
$$A_L = \frac{1}{P}\frac{N^+/L^+ - N^-/L^-}{N^+/L^+ + N^-/L^-}$$

Transverse single-spin asymmetries: From low to high energies!

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



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



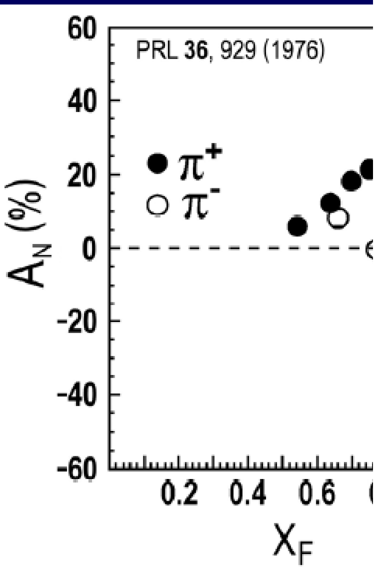
Transverse single-spin asymmetries: From low to high energies!

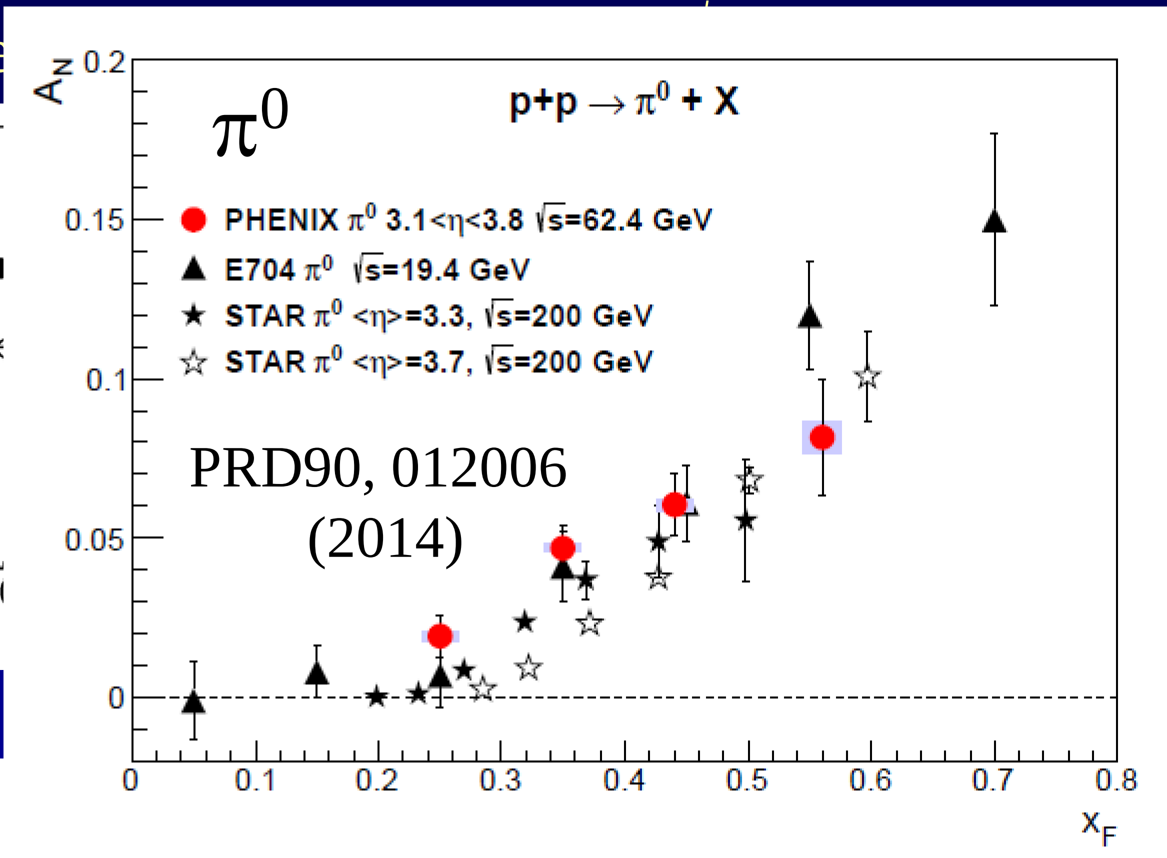
ANL $\sqrt{s}$=4.9 Ge

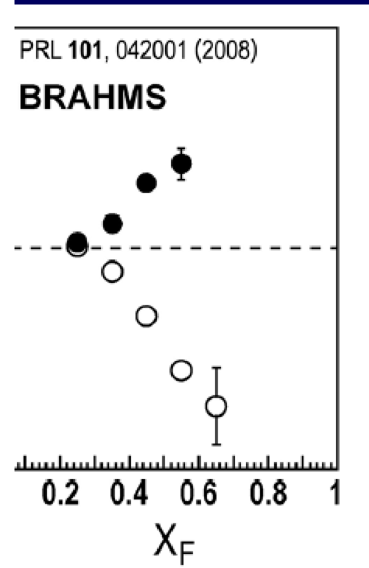
BNL

FNAL

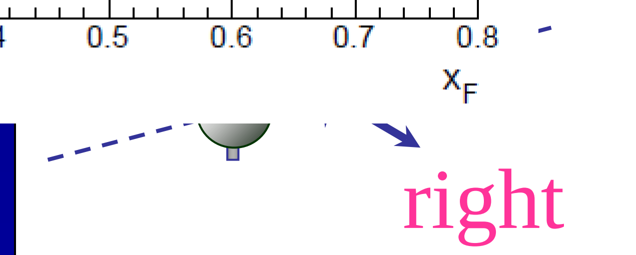
RHIC $\sqrt{s}$=62.4 GeV



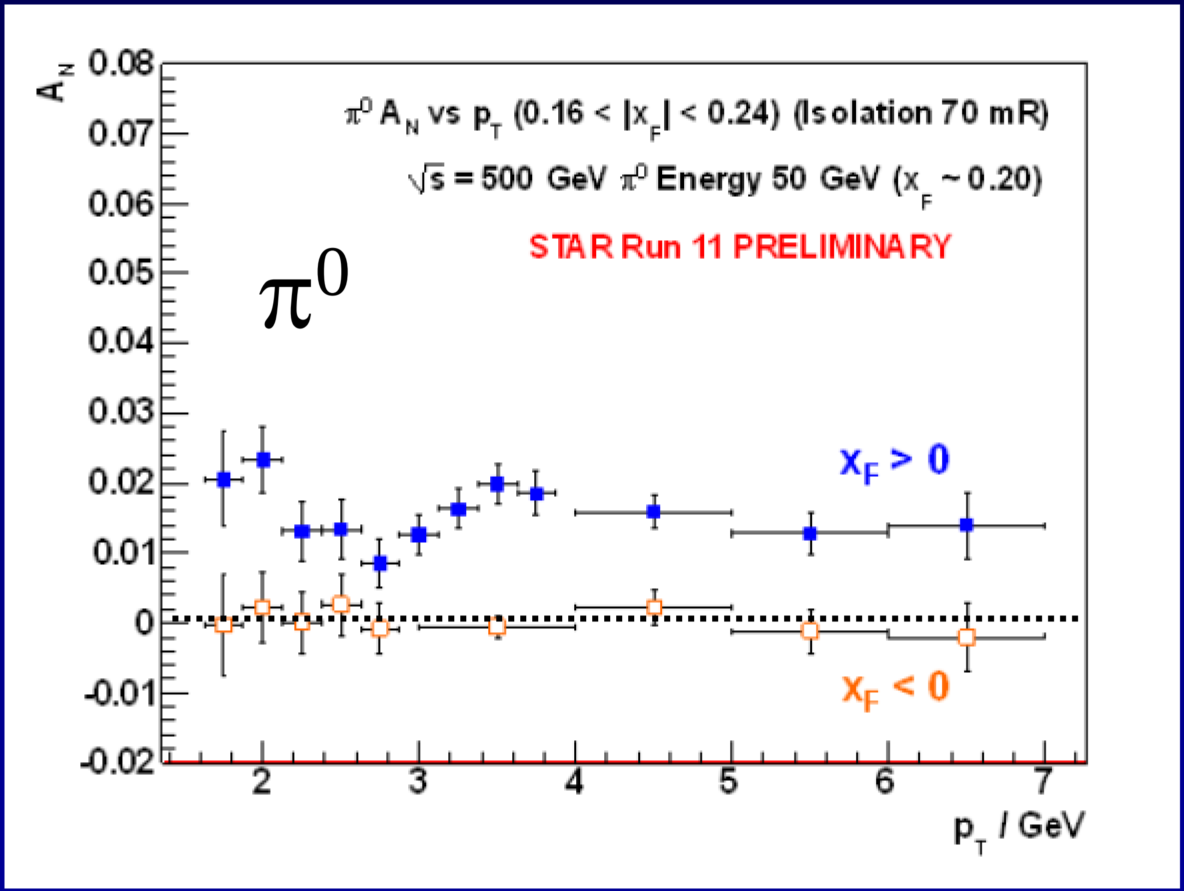




$x_F =$



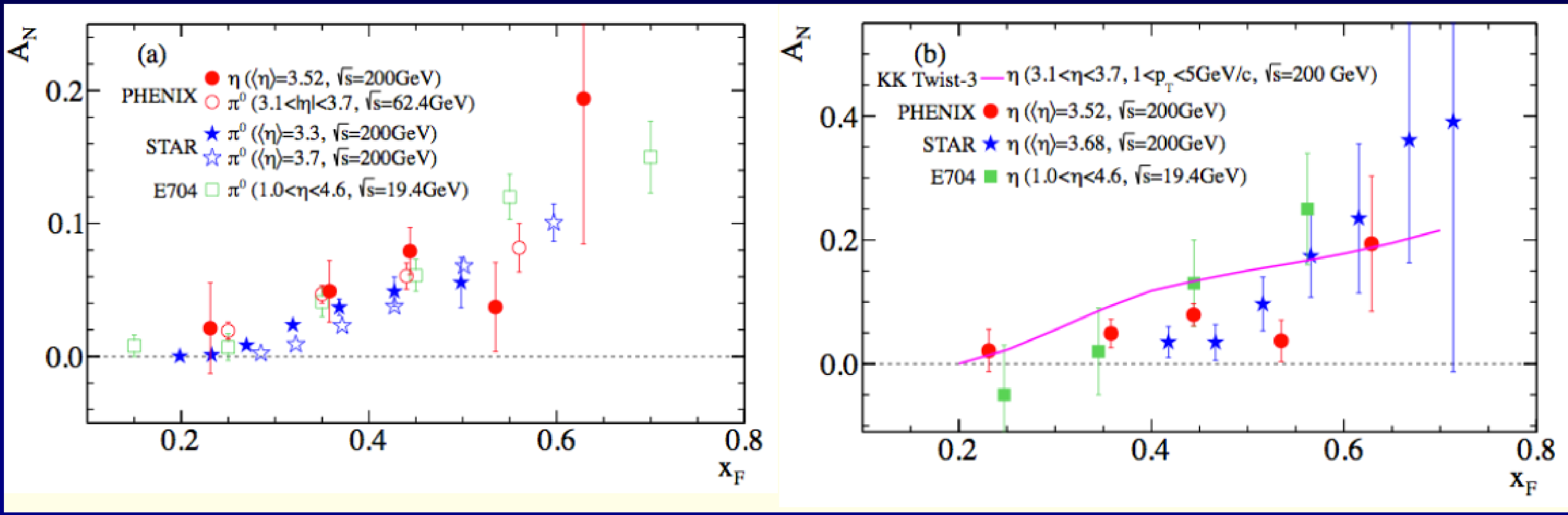
Effects persist up to transverse momenta of 7(!) GeV/c at √s=500 GeV



- Can try to interpret these non-perturbative effects within the framework of perturbative QCD.
- Haven't yet disentangled all the possible contributing effects to the (messy) process of p+p to pions

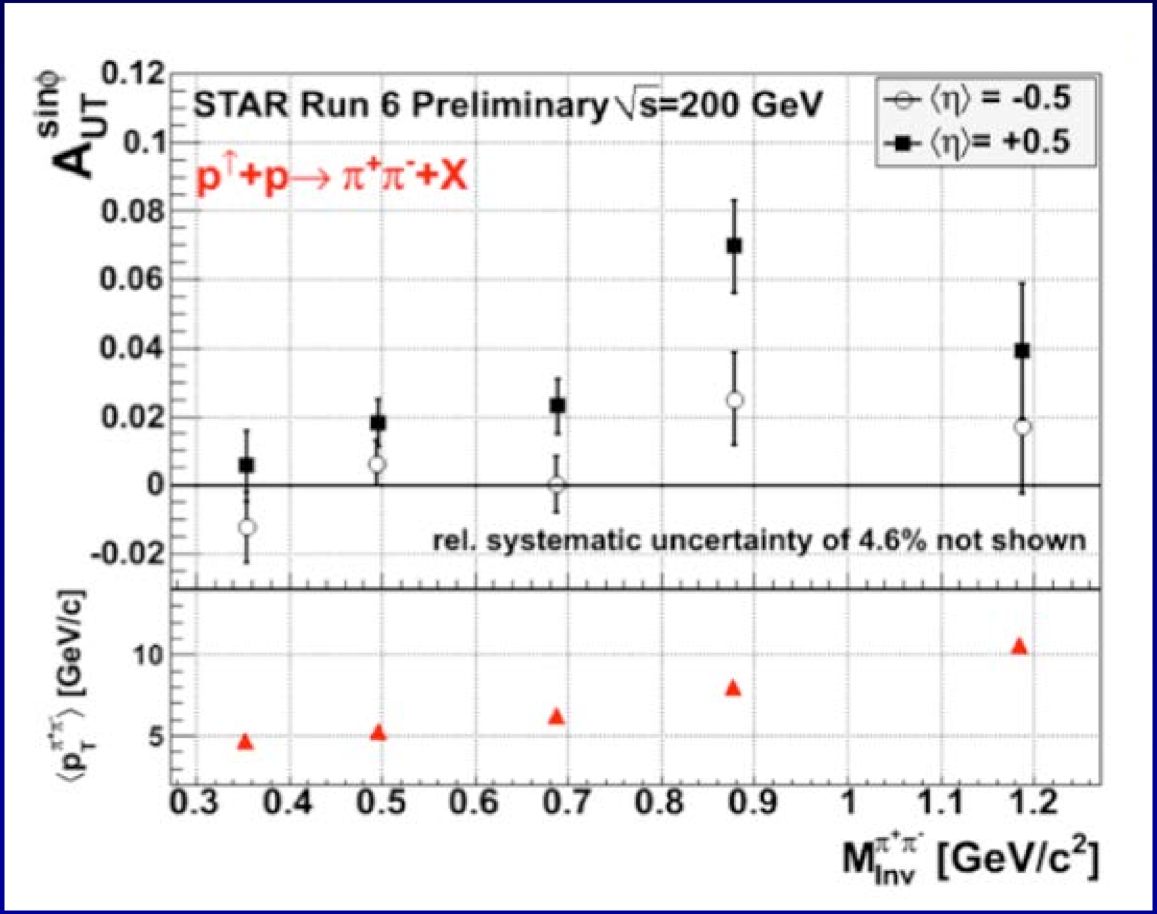
New eta A_N from PHENIX

PRD90, 072008 (2014)



- Large η A_N observed by STAR and PHENIX (and E704), similar in magnitude to π^0
- Expect to measure forward *direct photons* from 2015 data for p+p, p+A with transverse proton polarization—minimal sensitivity to final-state effects
  - PHENIX MPC-EX forward preshower upgrade

Transverse single-spin asymmetry in dihadron production from STAR



- Nonzero result observed in 200 GeV
- Collinear process—should be cleanly sensitive to transversity times dihadron interference FF

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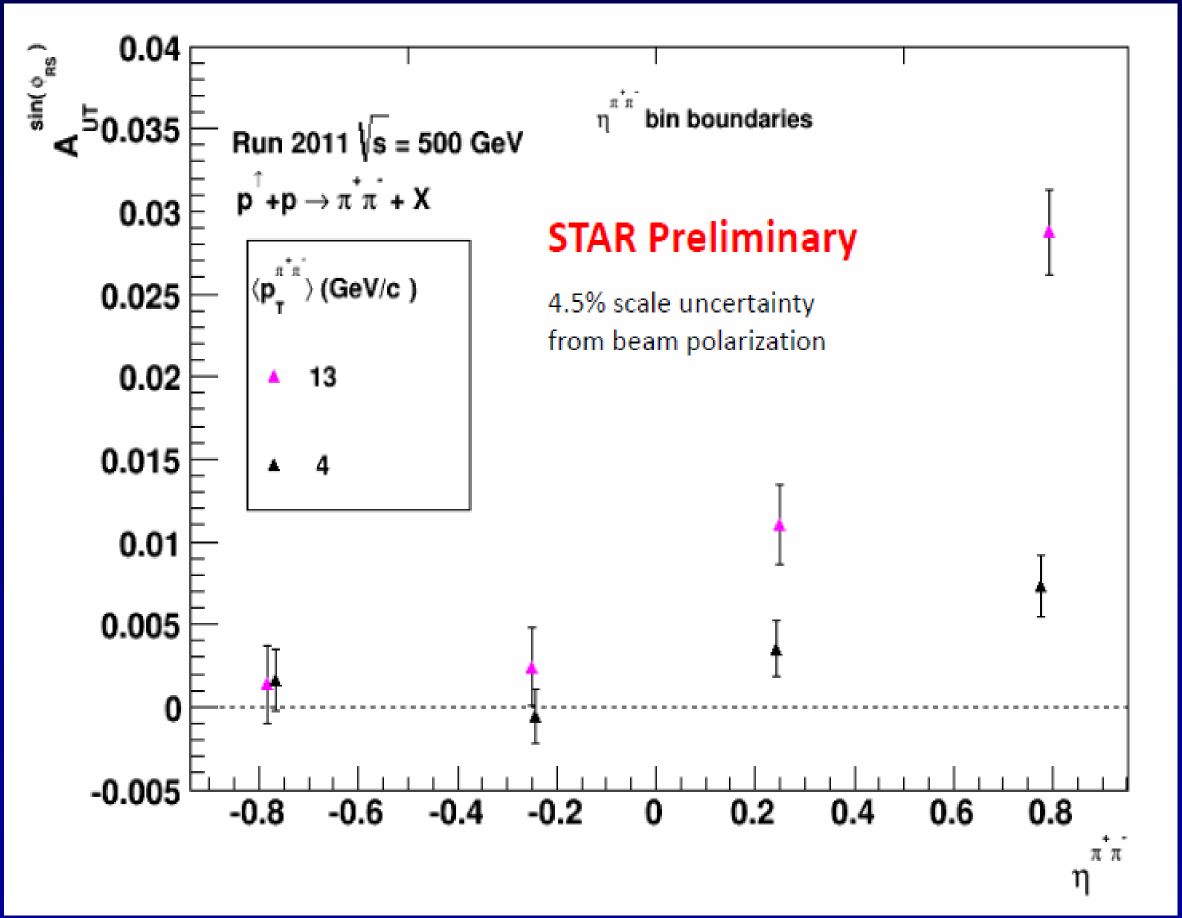

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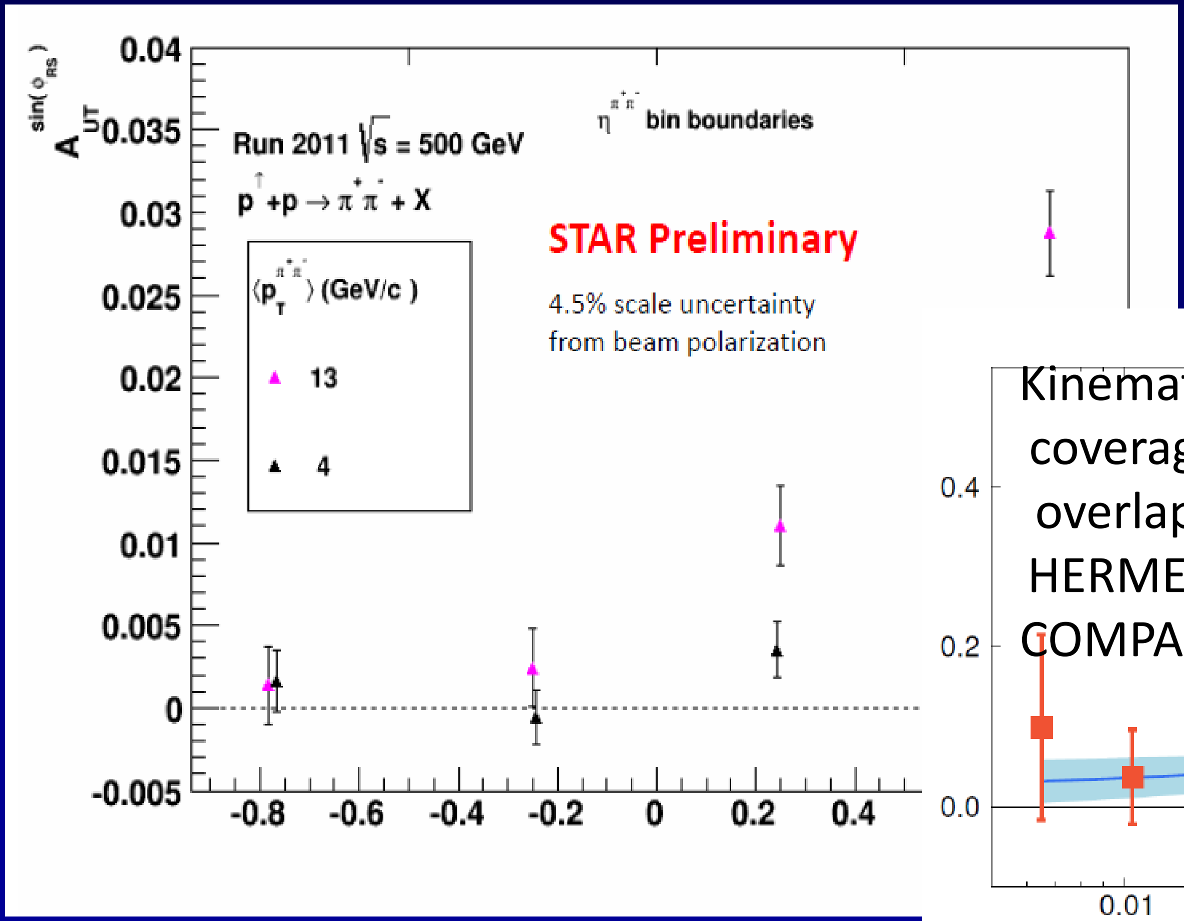
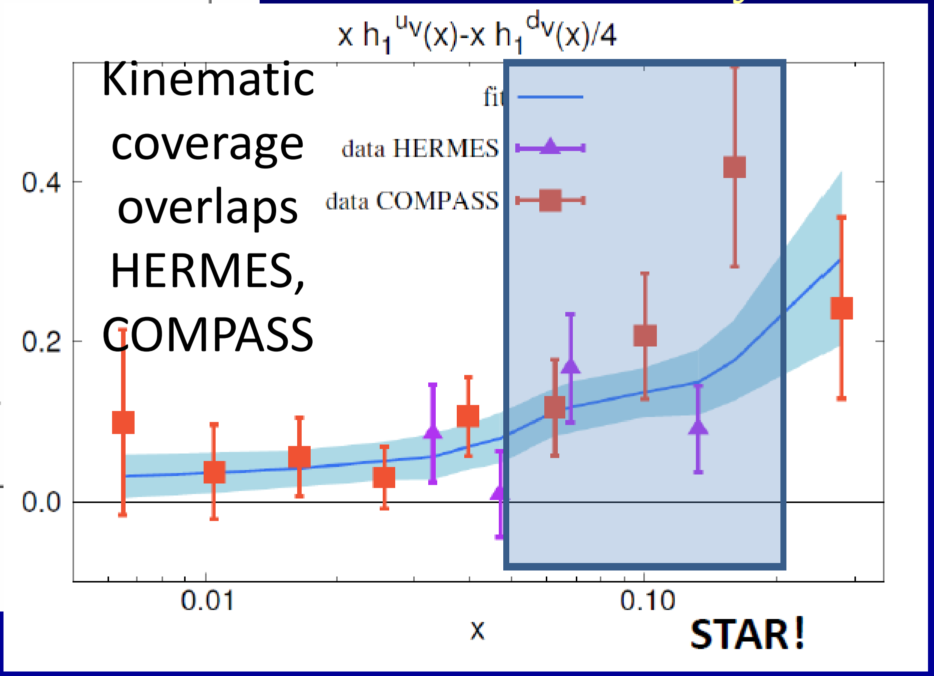
- Collinear process—should be cleanly sensitive to transversity times dihadron interference FF
- Recent results from 500 GeV—also nonzero, and larger for larger pair p_T and larger pseudorapidity

Transverse single-spin asymmetry in dihadron production from STAR

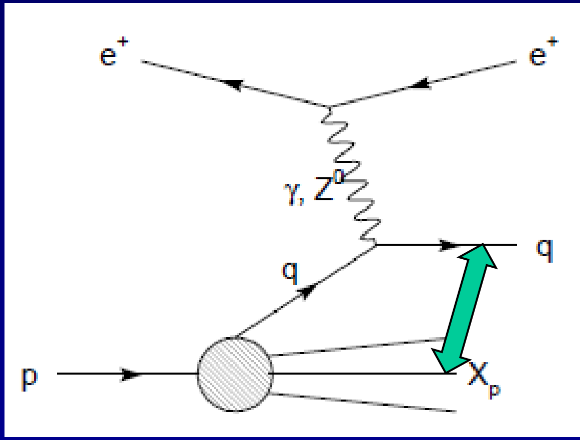


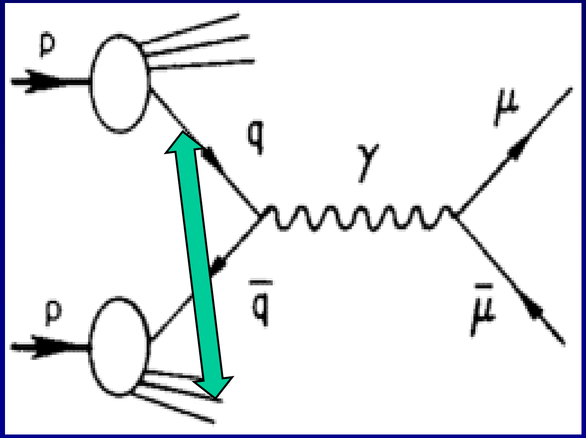
- Nonzero result observed in 200 GeV
- Collinear process—should be cleanly



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

Deep-inelastic lepton-nucleon scattering: **Attractive final-state interactions**	**Quark-antiquark annihilation to leptons:** **Repulsive initial-state interactions**

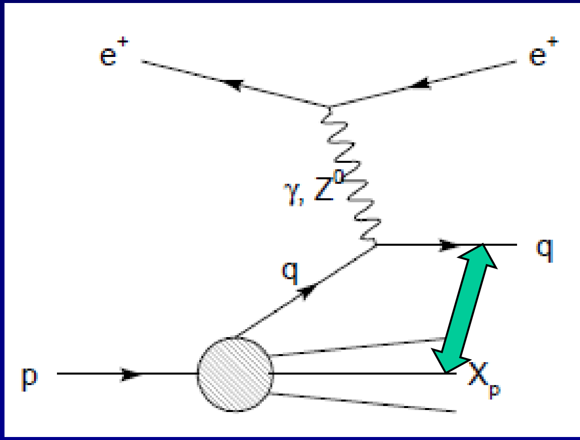




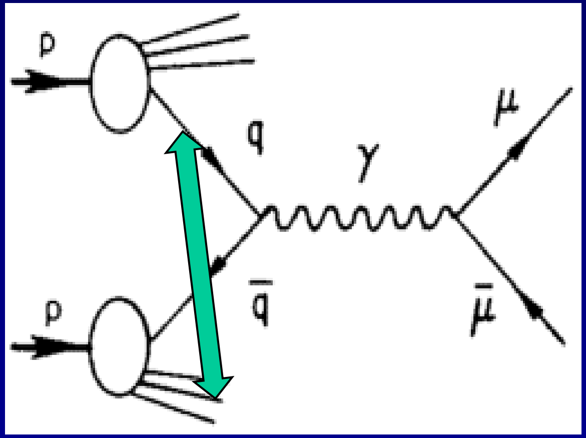
As a result, get *opposite sign* for the Sivers transverse-momentum-dependent pdf when measure in semi-inclusive DIS versus Drell-Yan: *process-dependent* pdf! (Collins 2002)

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

Deep-inelastic lepton-nucleon scattering:
Attractive final-state interactions

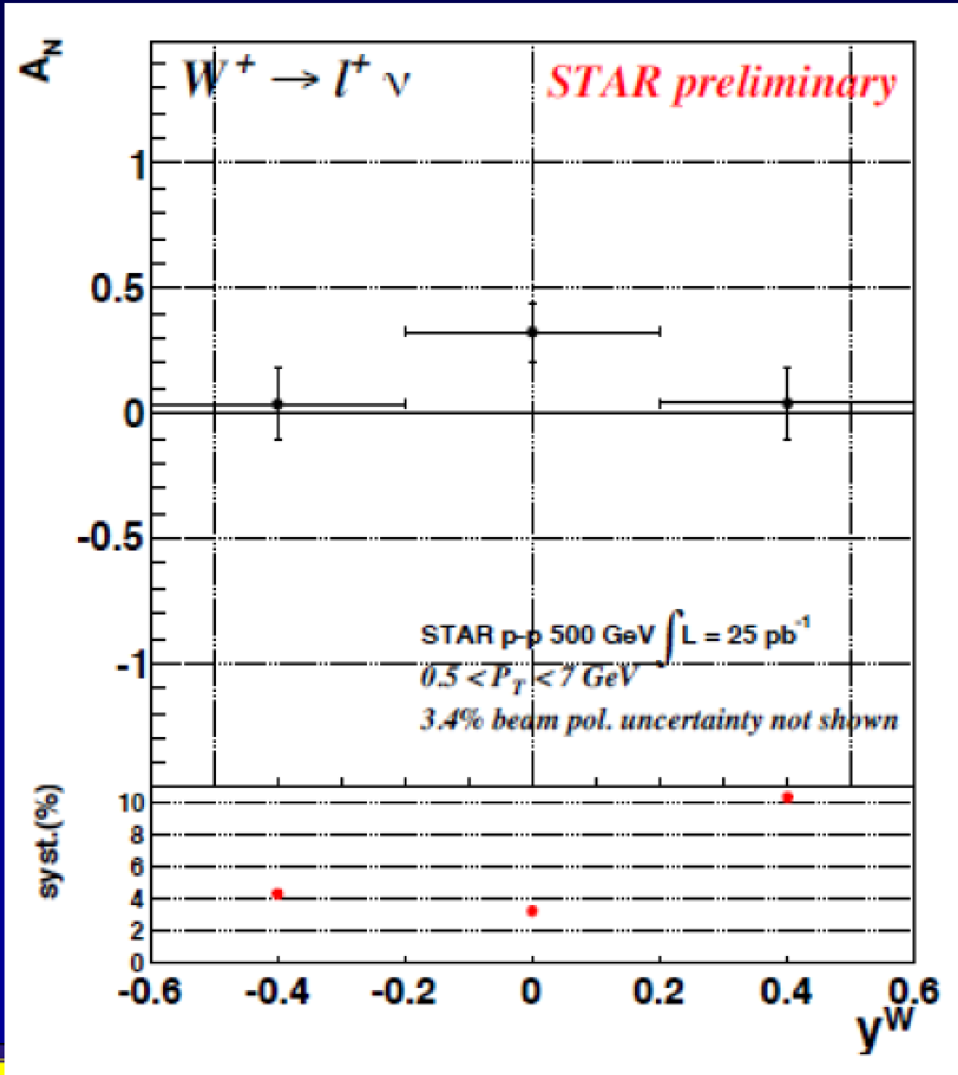


Quark-antiquark annihilation to leptons:
Repulsive initial-state interactions



Still waiting for a polarized quark-antiquark annihilation measurement to compare to existing lepton-nucleon scattering measurements . . .

Probing modified universality via W production at RHIC



- Possible long 510 GeV run in 2016
  - Could measure W A_N with uncertainty ~0.06 at STAR

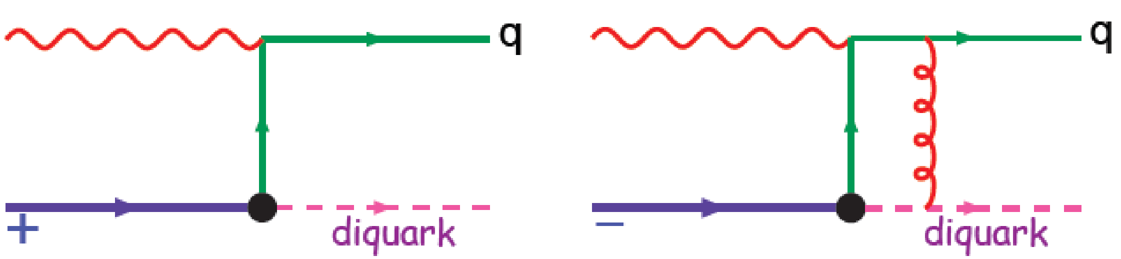
Modified universality requires full QCD: Gauge-invariant quantum field theory

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].

Collins, 1993

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 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)

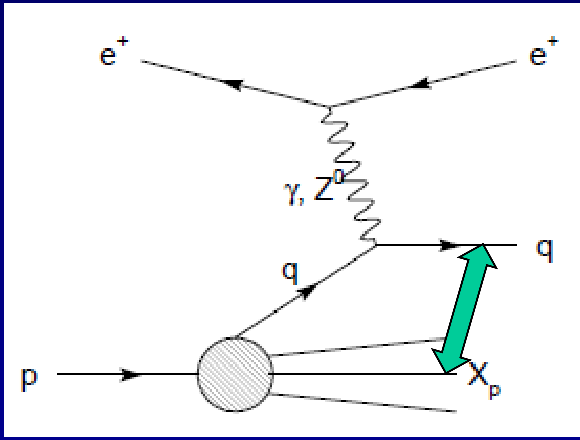
Physics Today, September 2009 :
The Aharonov–Bohm effects: Variations on a subtle theme,
by Herman Batelaan and Akira Tonomura.

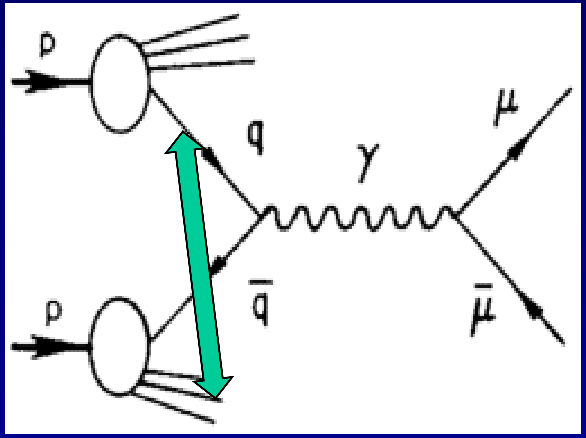
“Aharonov stresses that the arguments that led to the prediction of the various electromagnetic AB effects apply equally well to any other gauge-invariant quantum theory. In the standard model of particle physics, the strong and weak nuclear interactions are also described by gauge-invariant theories. 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:
Attractive final-state interactions

Quark-antiquark annihilation to leptons:
Repulsive initial-state interactions





As a result: $$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

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

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

Deep-inelastic lepton-nucleon scattering:
Attractive final-state interactions

Quark-antiquark annihilation to leptons:
Repulsive initial-state interactions

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

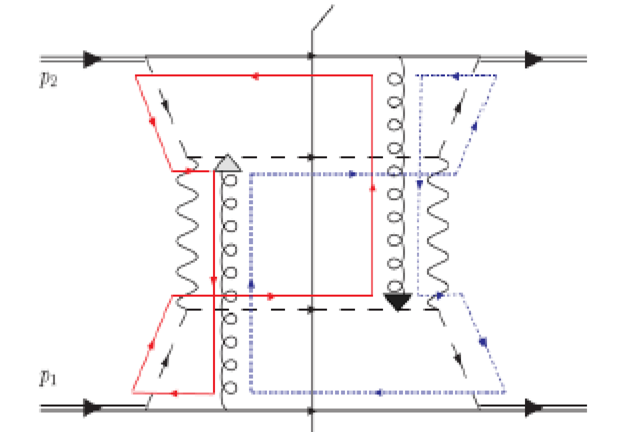
BUT: In QCD expect additional, new effects due to specific non-Abelian nature of the gauge group

As a r

Pijlman,
604226
ers,
arXiv:1109.2521

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 protons
- Consequence of QCD specifically as a ***non-Abelian*** gauge theory!

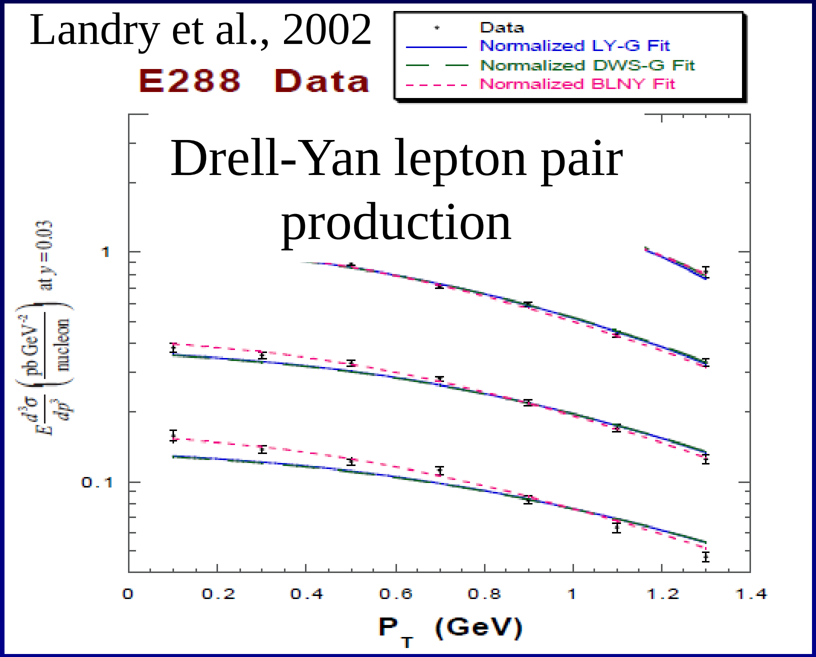


PRD 81:094006 (2010)

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

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

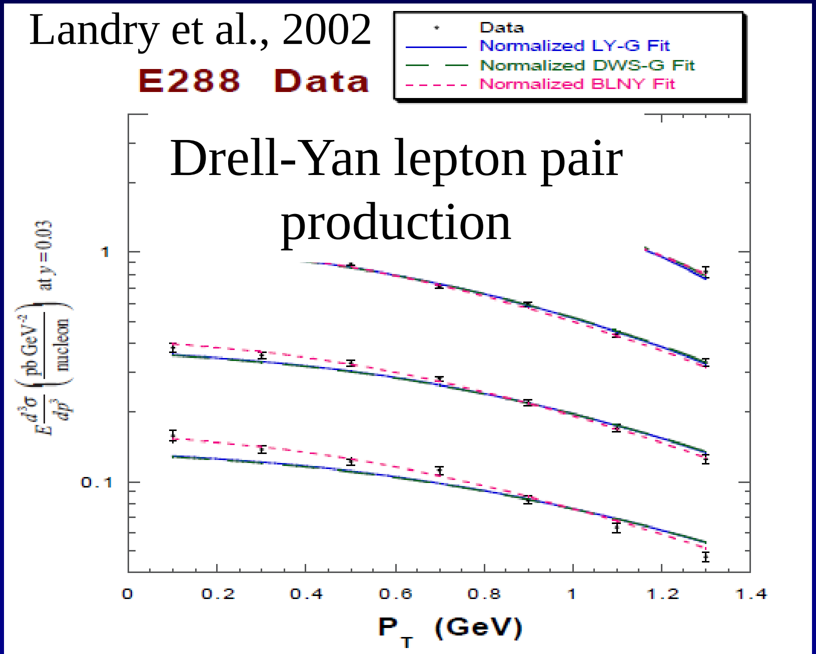
Testing the Aharonov-Bohm effect in QCD as a non-Abelian gauge theory



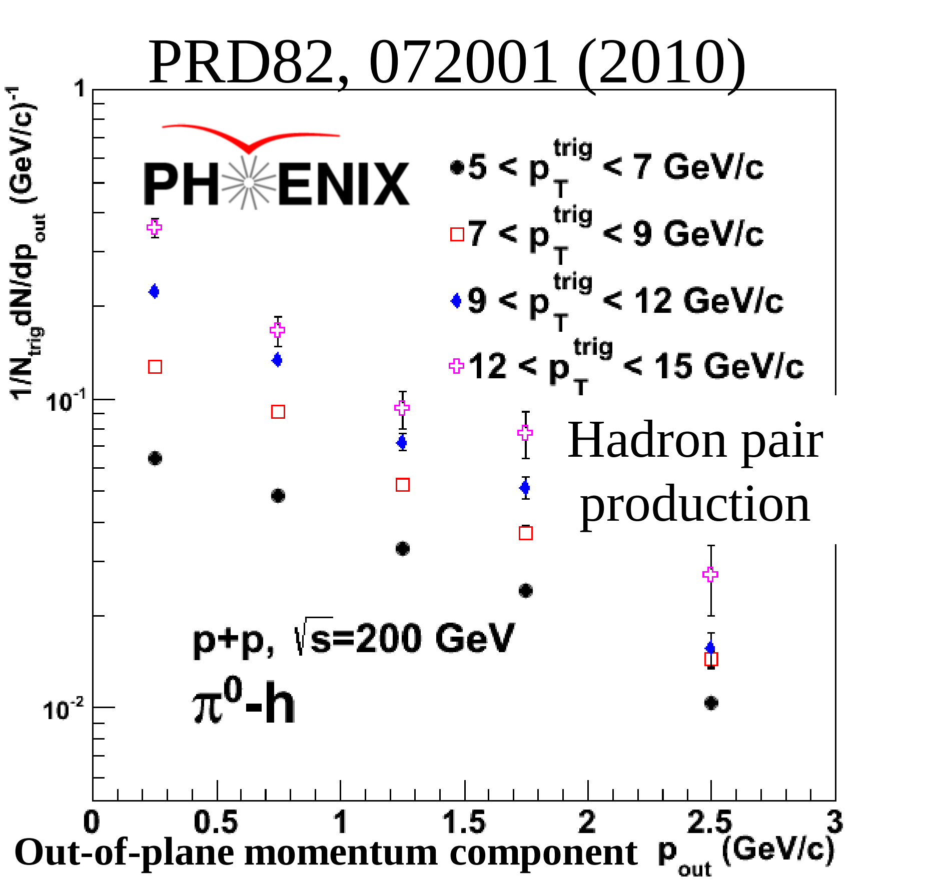
$p+A \rightarrow \mu^{+}+\mu^{-}+X$
for different
invariant masses:
No color
entanglement
expected

Get predictions from fits to data where no entanglement expected

Testing the Aharonov-Bohm effect in QCD as a non-Abelian gauge theory



Get predictions from fits to data where no entanglement expected



Make predictions for processes where entanglement *is* expected; look for deviation

Summary and outlook

- Data from RHIC are helping to constrain the gluon and flavor-separated sea quark helicity distributions
- Lots of interesting effects continue to be observed in transverse single-spin asymmetries in p+p
  - Spin-momentum and spin-spin correlations
- Additional results forthcoming from 2012 and 2013 data sets
- Stay tuned for polarized p+p and p+A running in 2015!

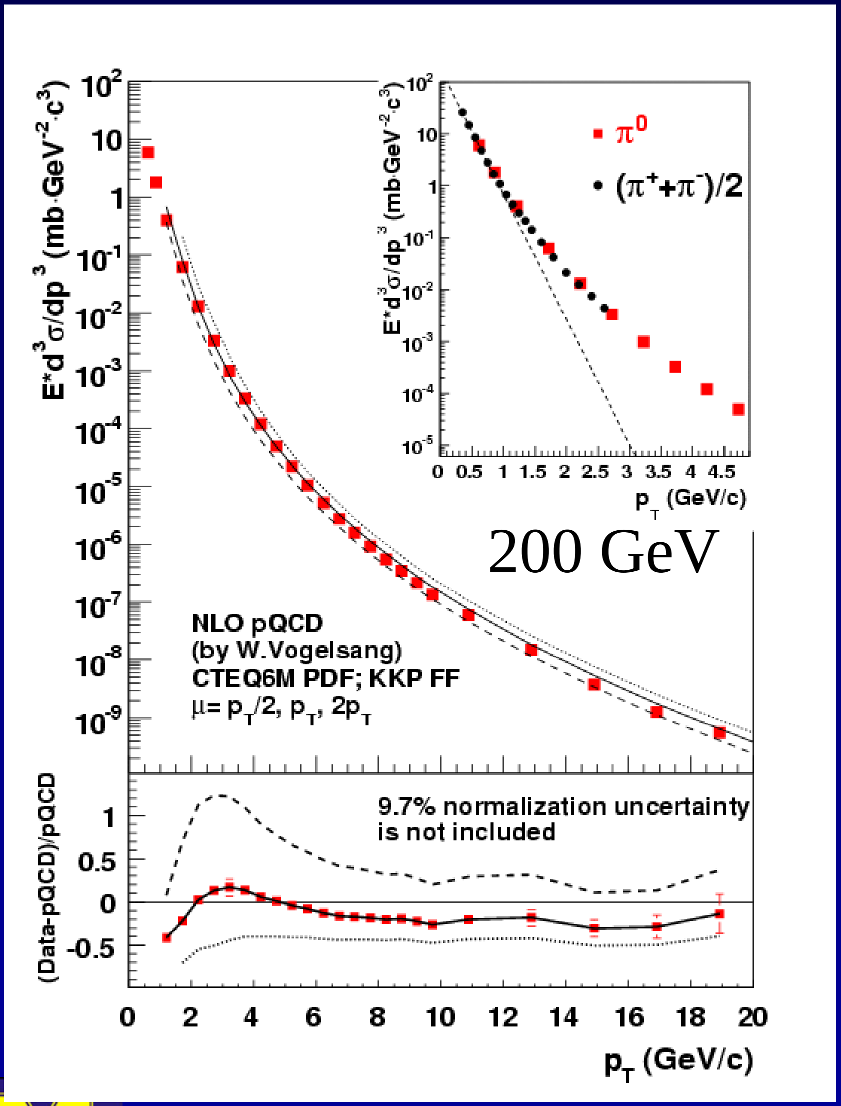
Summary and outlook

- Data from RHIC are helping to constrain the gluon and flavor-separated sea quark helicity distributions
- Lot … erved in t …
  - S …
- Ad … d 2013 data sets
- Stay tuned for polarized p+p and p+A running in 2015!

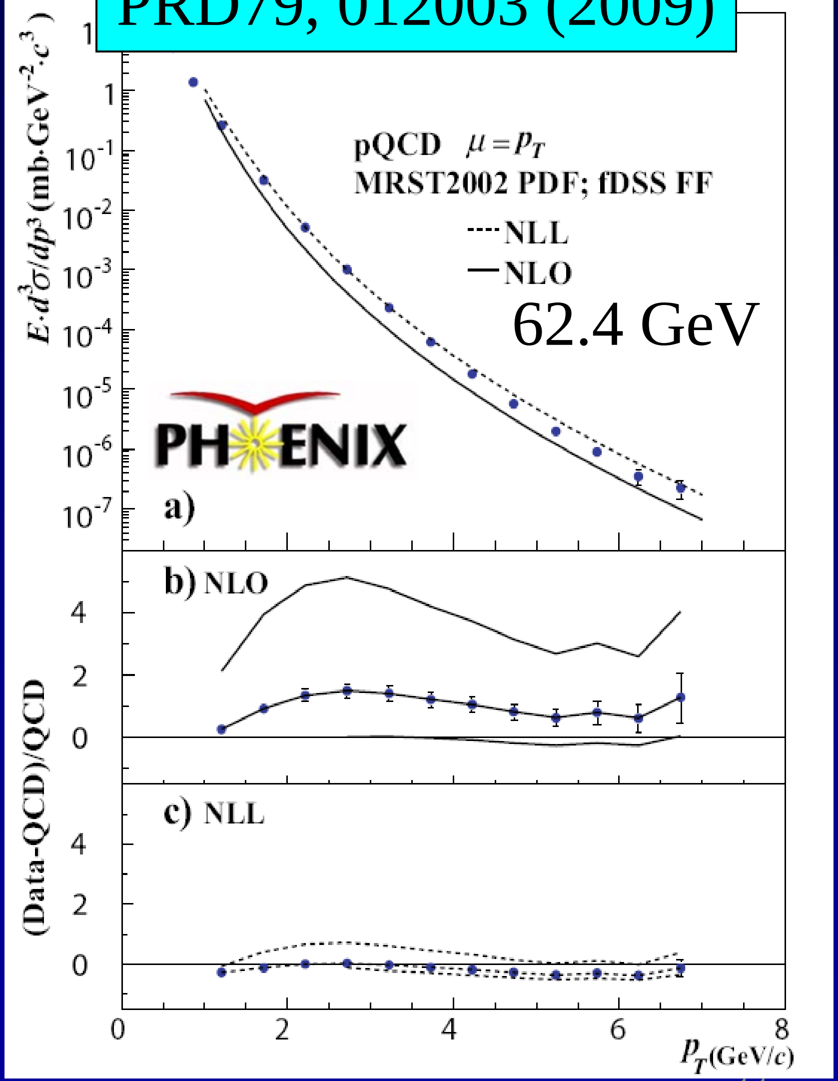
*Hadronic interactions play a complementary role to DIS in the study of nucleon structure, and allow further exploration of **color** effects*

Additional Material

Neutral pion cross sections



PRD79, 012003 (2009)

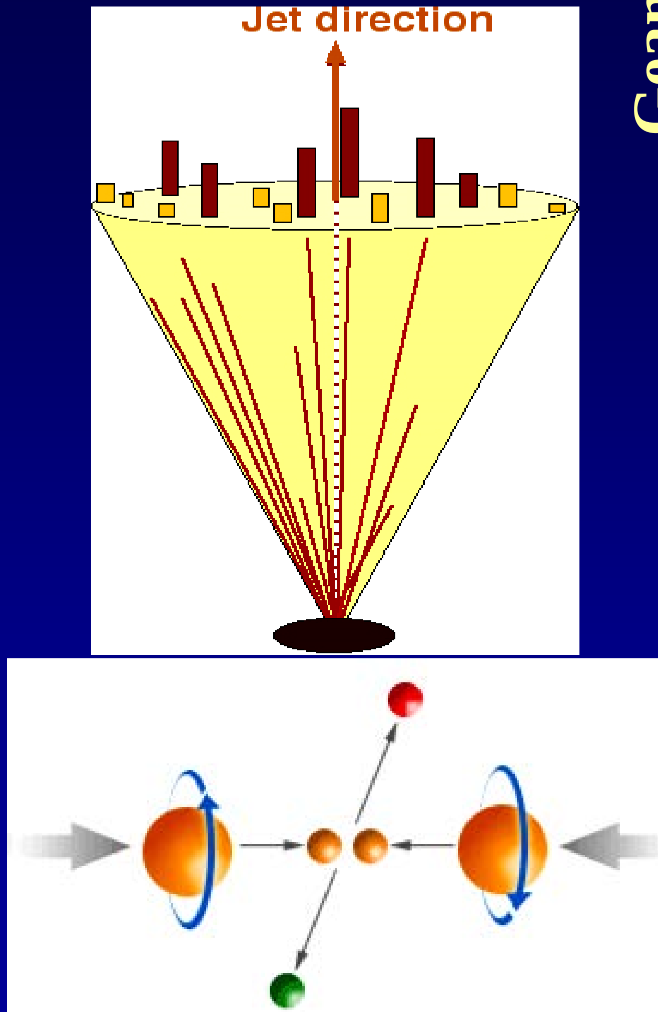


Jet reconstruction at STAR

Detector

Particle

Parton



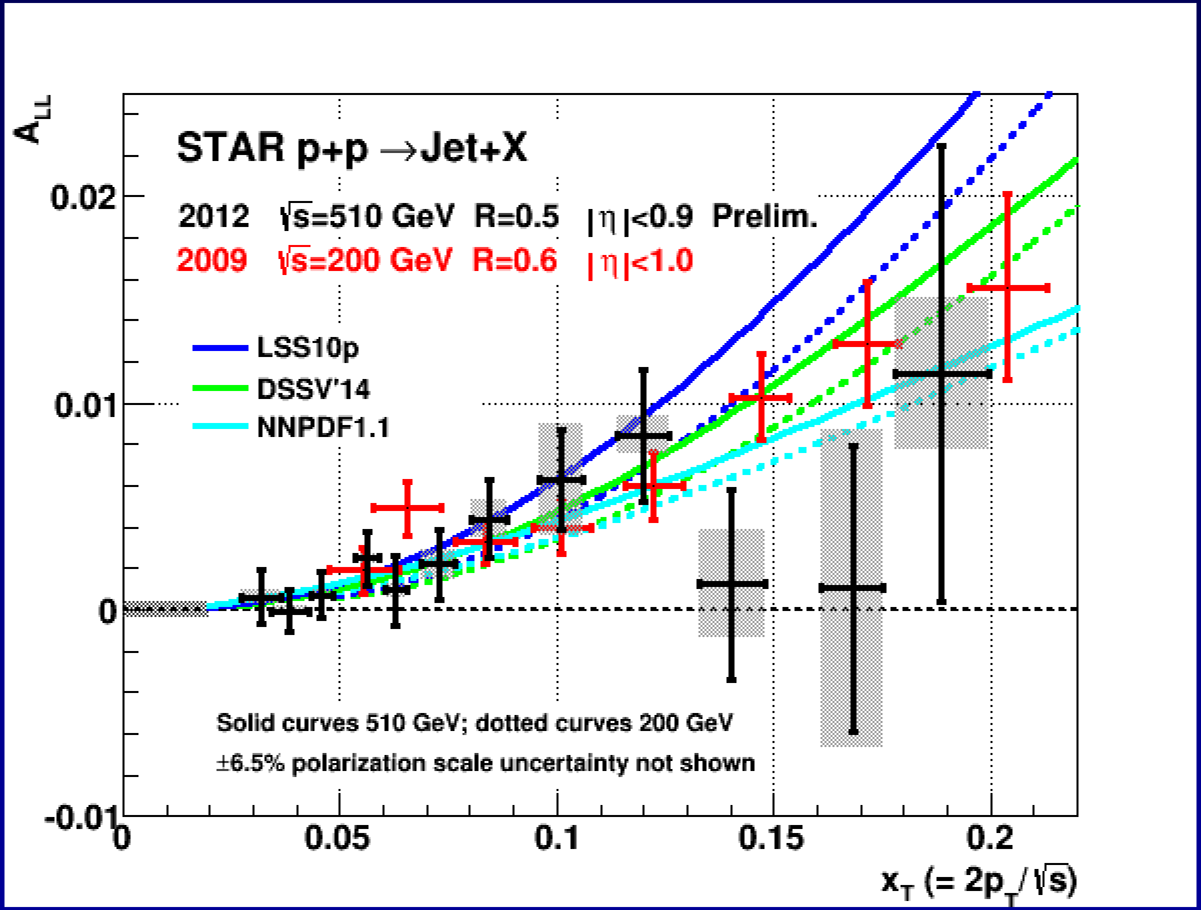
Geant

Pythia

- For 2006 200 GeV data:
  Mid-point cone algorithm
  Adapted from Tevatron II – hep-ex/0005012
  a. Seed energy = 0.5 GeV
  b. Cone radius R = 0.7 in η-φ space
  c. Split/merge fraction f = 0.5
- For 2009 200 GeV data
  Anti-k_T algorithm
  Cacciari, Salam, and Soyez, JHEP 0804, 063
  - Cone radius **R = 0.6**
- For 2012 510 GeV data
  Anti-k_T algorithm
  - Cone radius **R = 0.5**

Use Pythia + Geant to quantify detector response

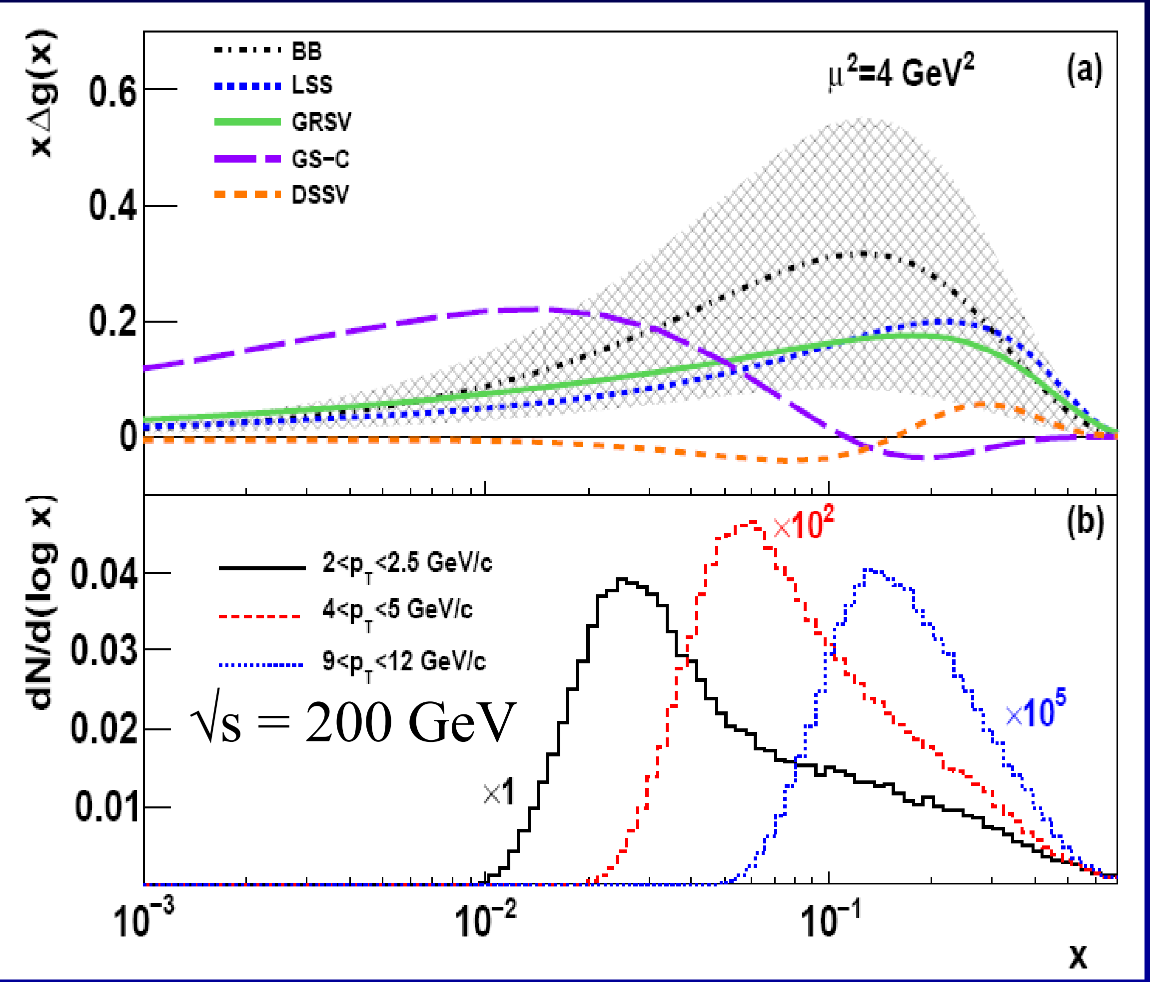
Jet double-helicity asymmetry at 510 GeV



- Also clearly nonzero

Sampling the integral of ΔG: π^0 p_T vs. x_{gluon}

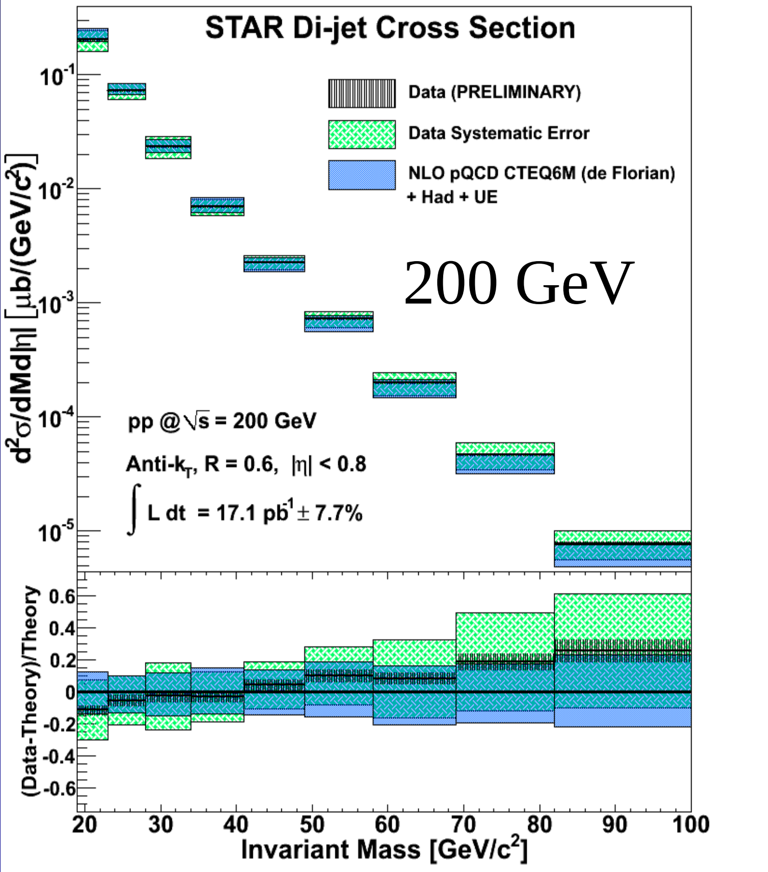
Inclusive asymmetry measurements in p+p collisions sample from wide bins in *x*—sensitive to (truncated) integral of ΔG, not to functional form vs. *x*

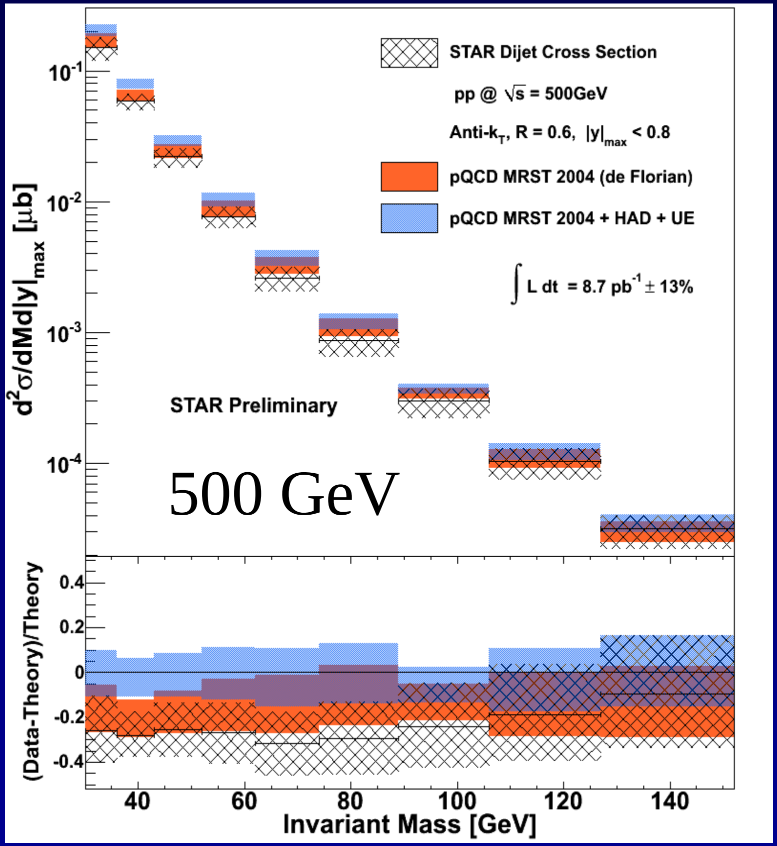


Based on simulation using NLO pQCD as input

PRL 103, 012003 (2009)

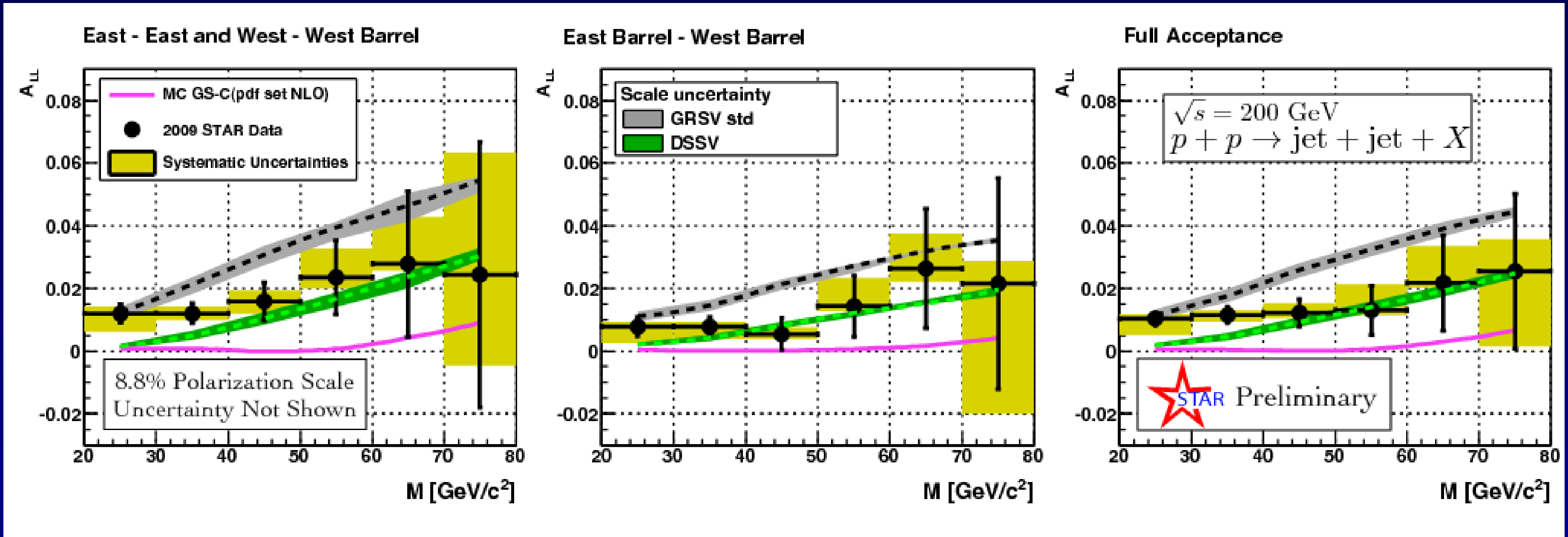
Dijet cross section at 200 GeV and 500 GeV





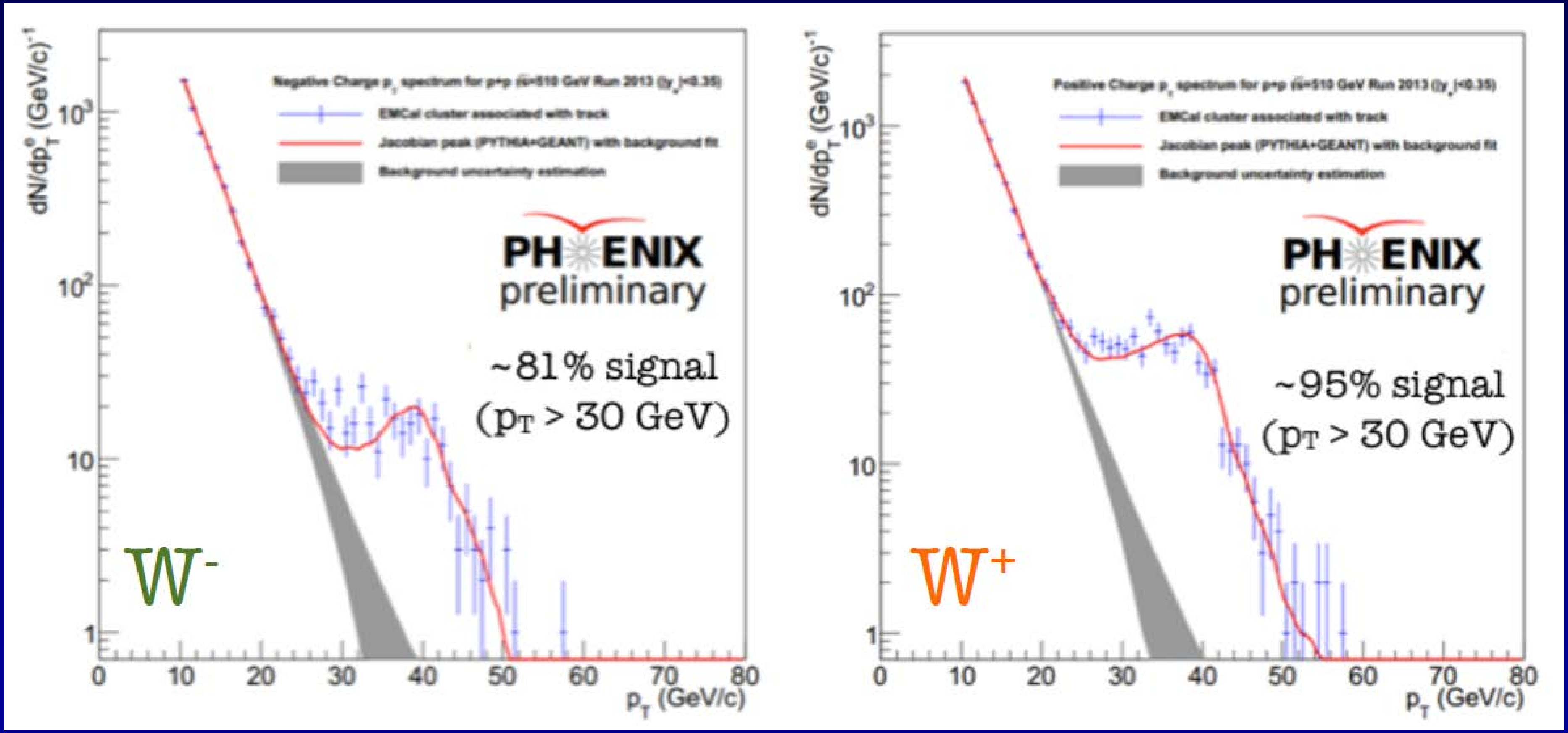
- Di-jet cross section well described by NLO pQCD with corrections for hadronization and underlying event

Dijet double helicity asymmetry

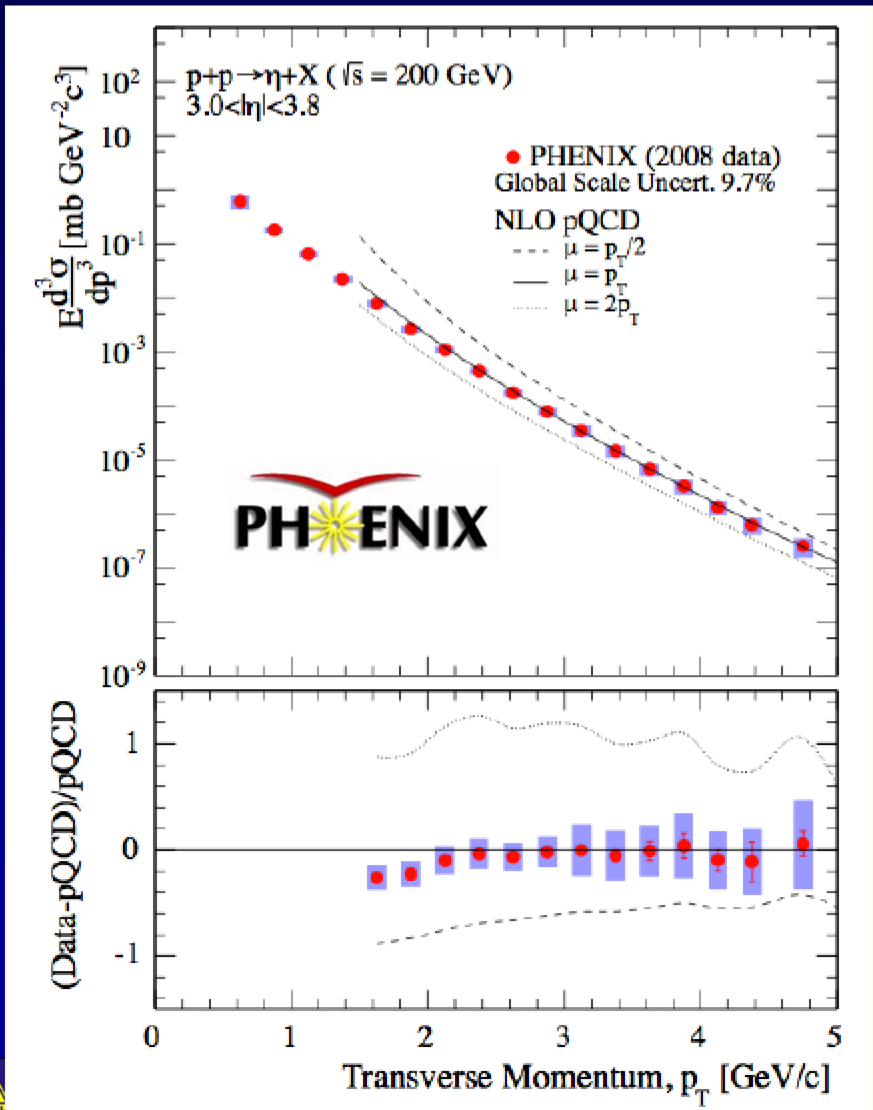


- Clear nonzero asymmetry observed
- Can better reconstruct hard scattering kinematics to pin down x values probed

PHENIX Run-13 preliminary W peaks (midrapidity)



Forward eta cross section at 200 GeV

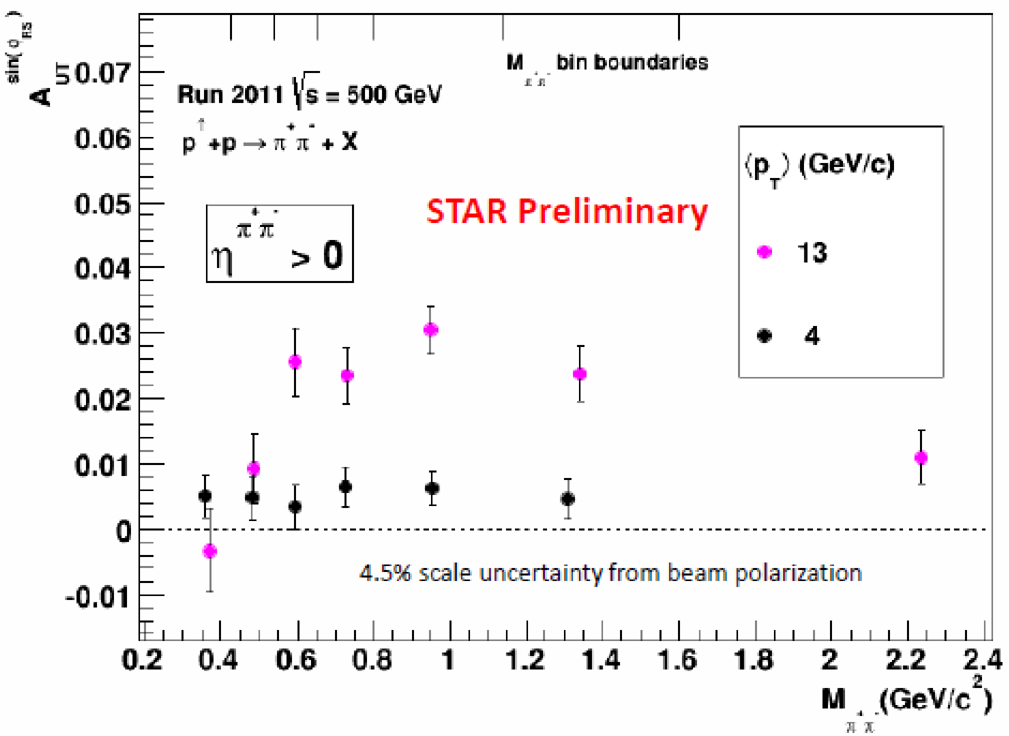


PRD90, 072008 (2014)

Transverse single-spin asymmetry in dihadron production

Asymmetry (M_{Inv} ,p_T)

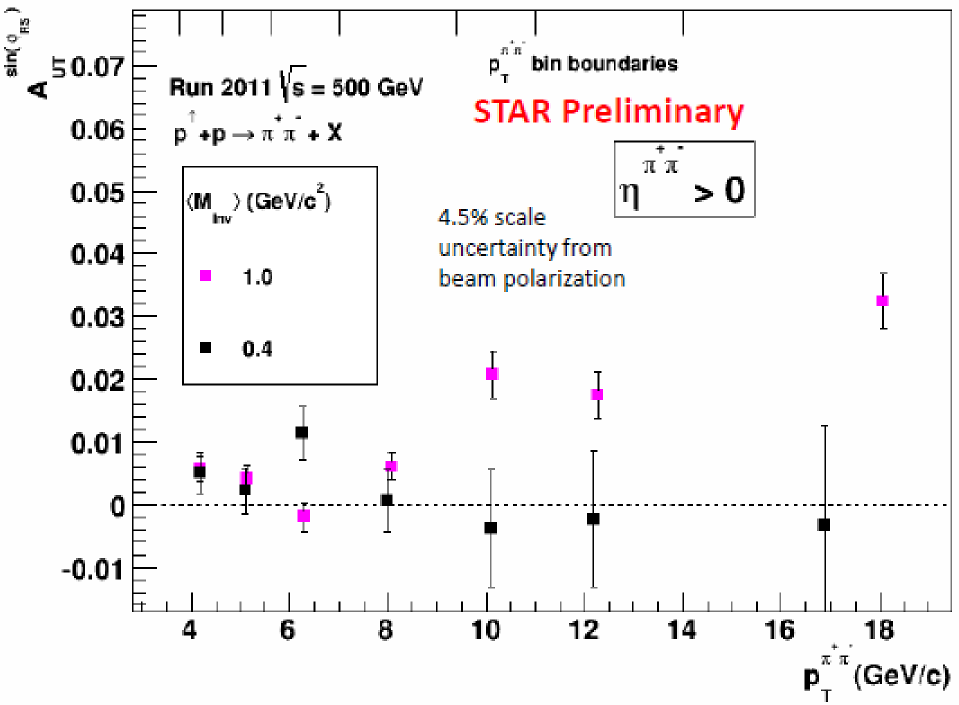
- A_{UT} as a function of M_{Inv} plotted for 5 p_T bins
- Avg M_{Inv} in each M_{Inv} bin decreases with decreasing <p_T>
- Significant asymmetry seen at mid-M_{Inv} and high <p_T>



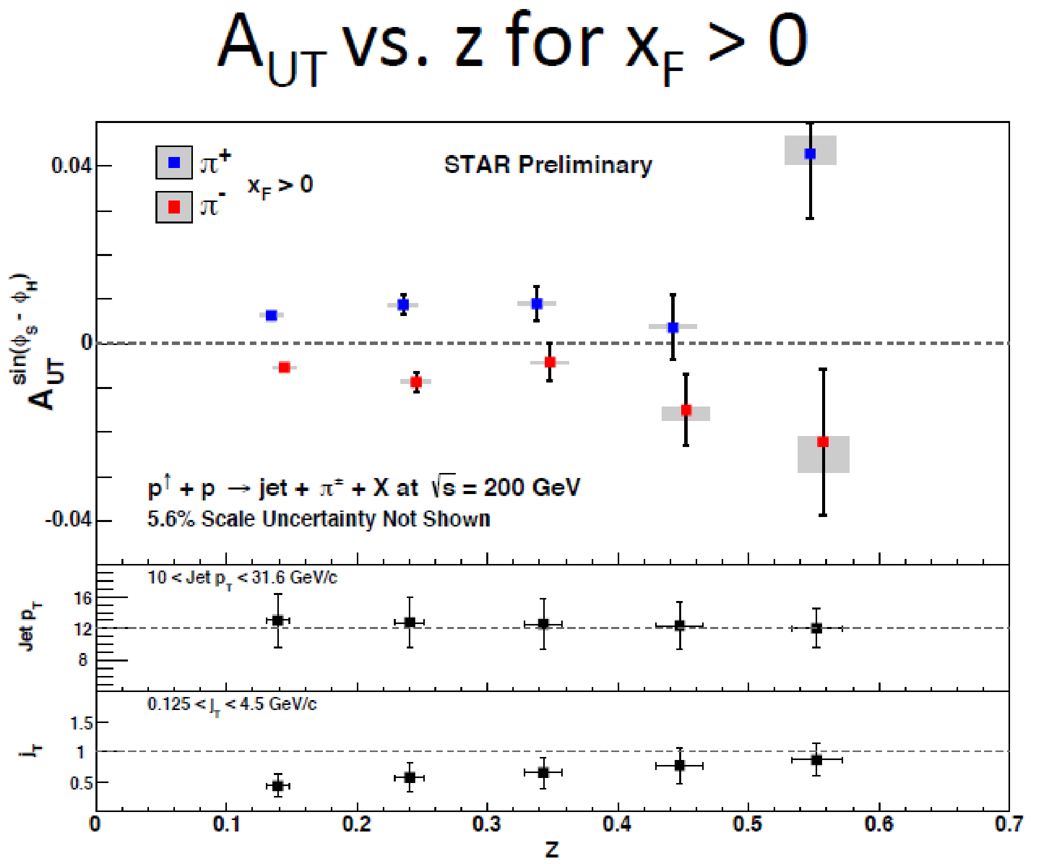
Transverse single-spin asymmetry in dihadron production

Asymmetry (p_T, M_{Inv})

- A_{UT} as a function of p_T plotted for 5 M_{Inv} bins
- Avg p_T in each p_T bin slightly decreases with decreasing $\langle M_{Inv} \rangle$
- Asymmetry rises significantly for high p_T and high M_{Inv}

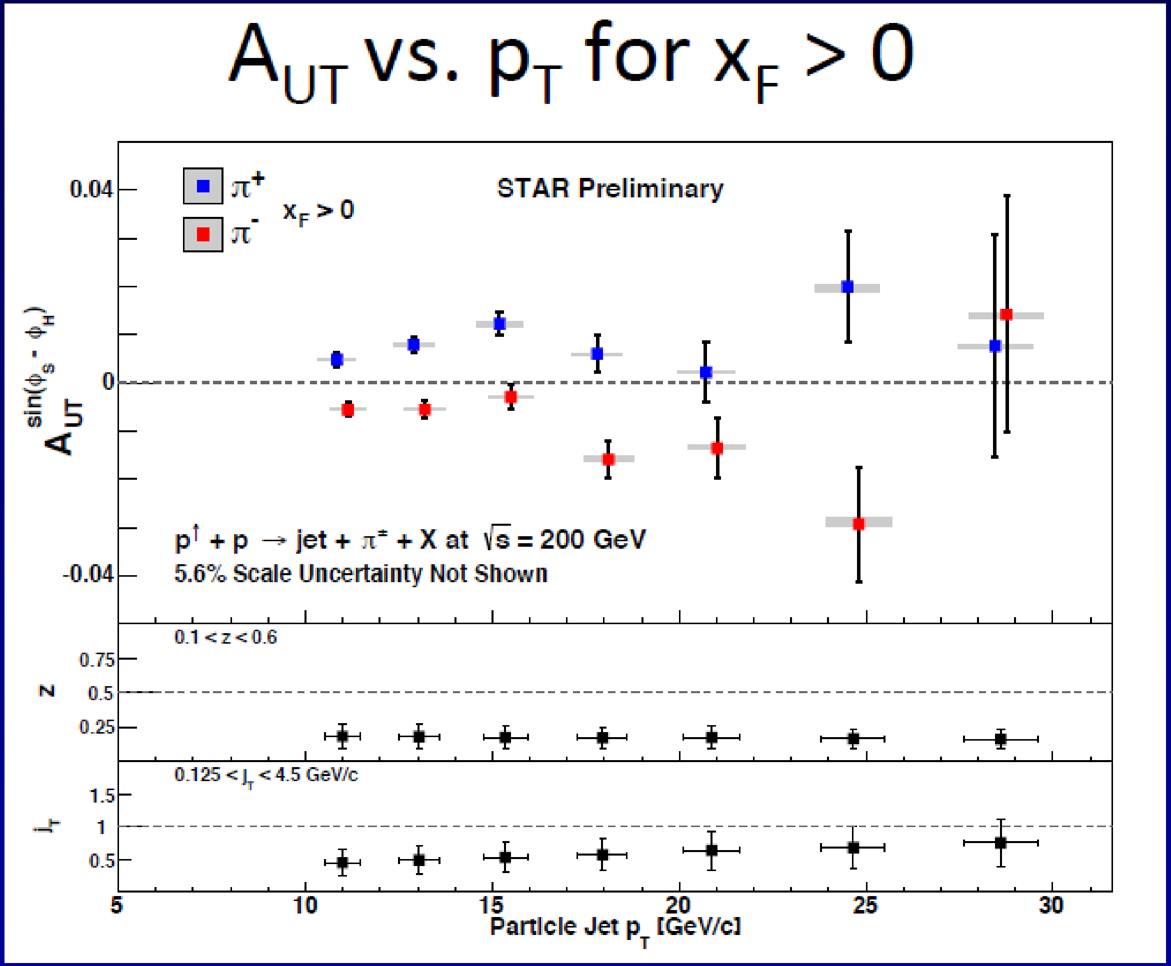


Azimuthal distribution of pions within jets

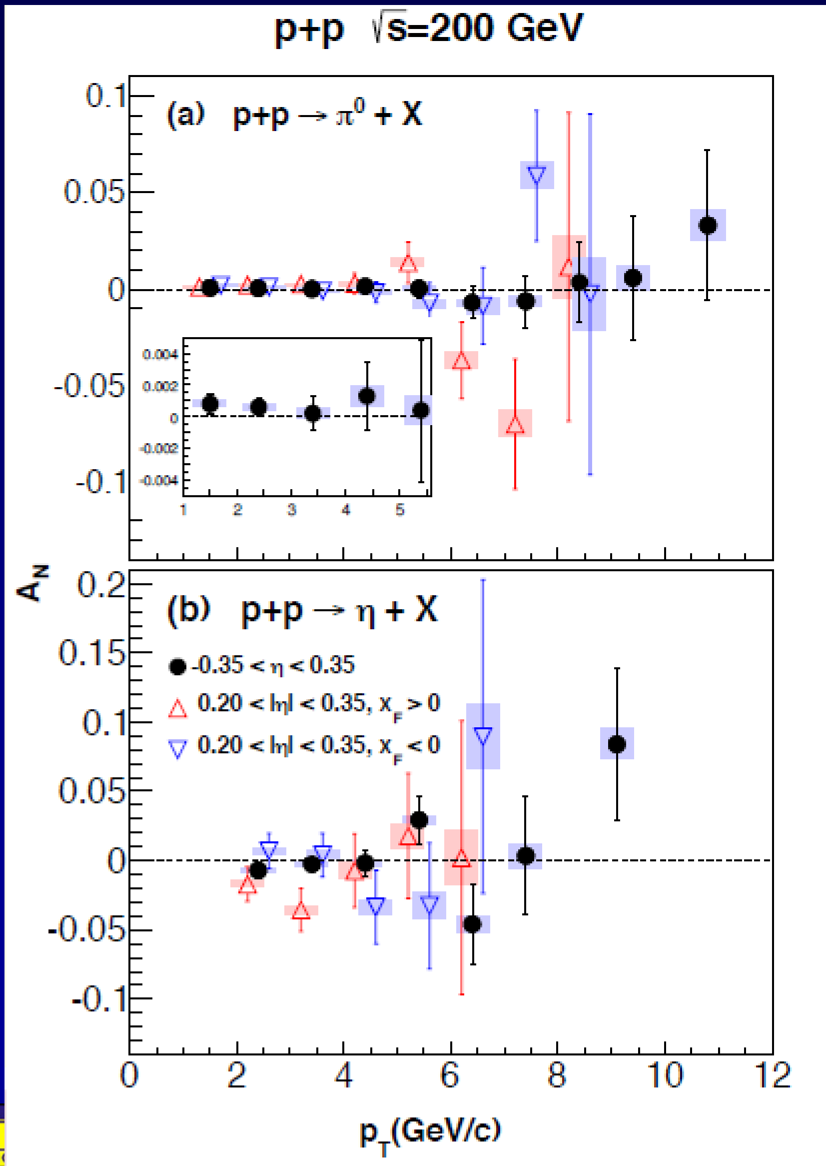


- Collins-like measurement
- Nonzero effect observed

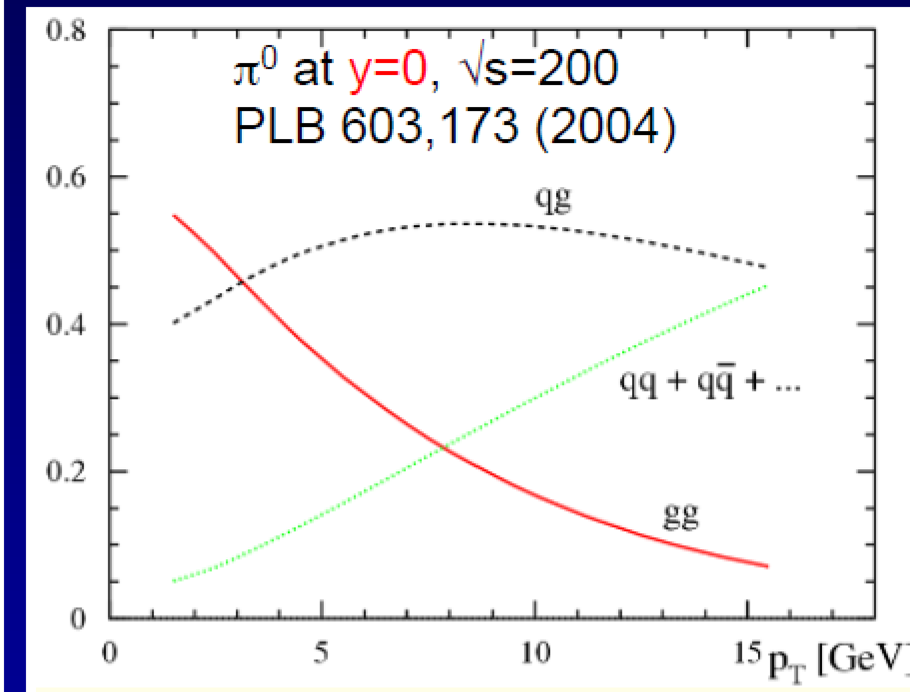
Azimuthal distribution of pions within jets



η and π^0 A_N at midrapidity



PHENIX collaboration: PRD90, 012006 (2014)

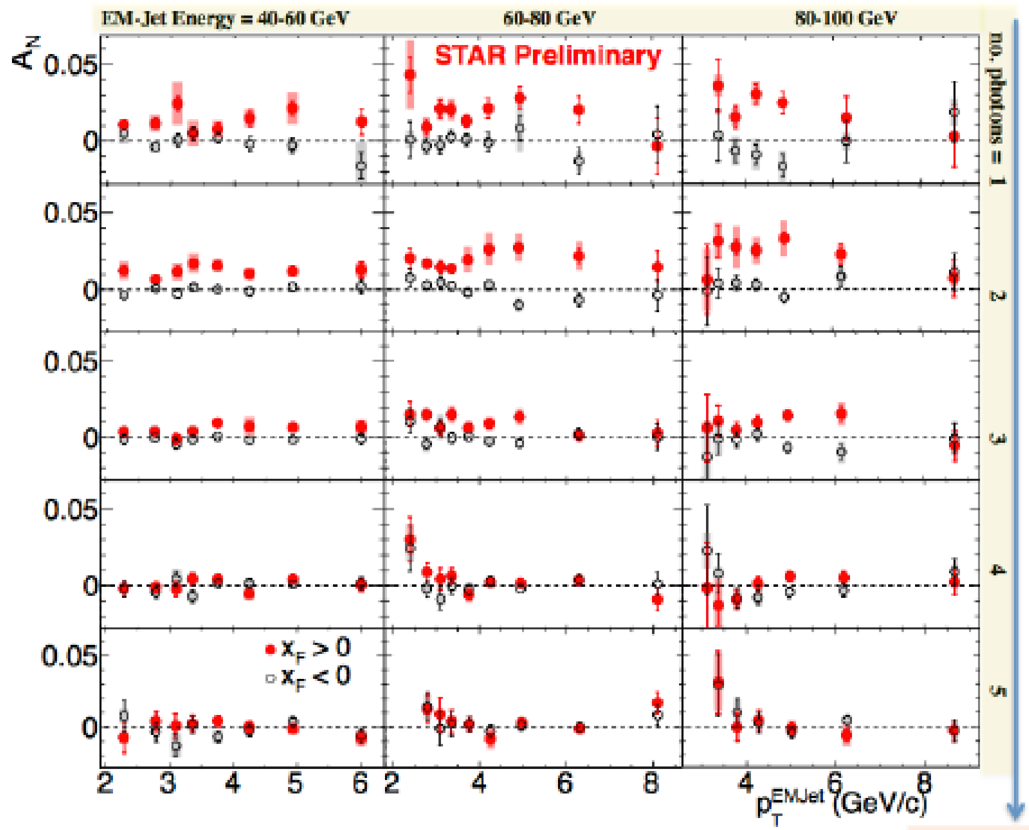


Sensitive to gg, qg scattering
Consistent with zero

Enhanced A_N for isolated forward neutral pions

Transverse Spin Phenomena - Large Forward A_N

The puzzle continues...



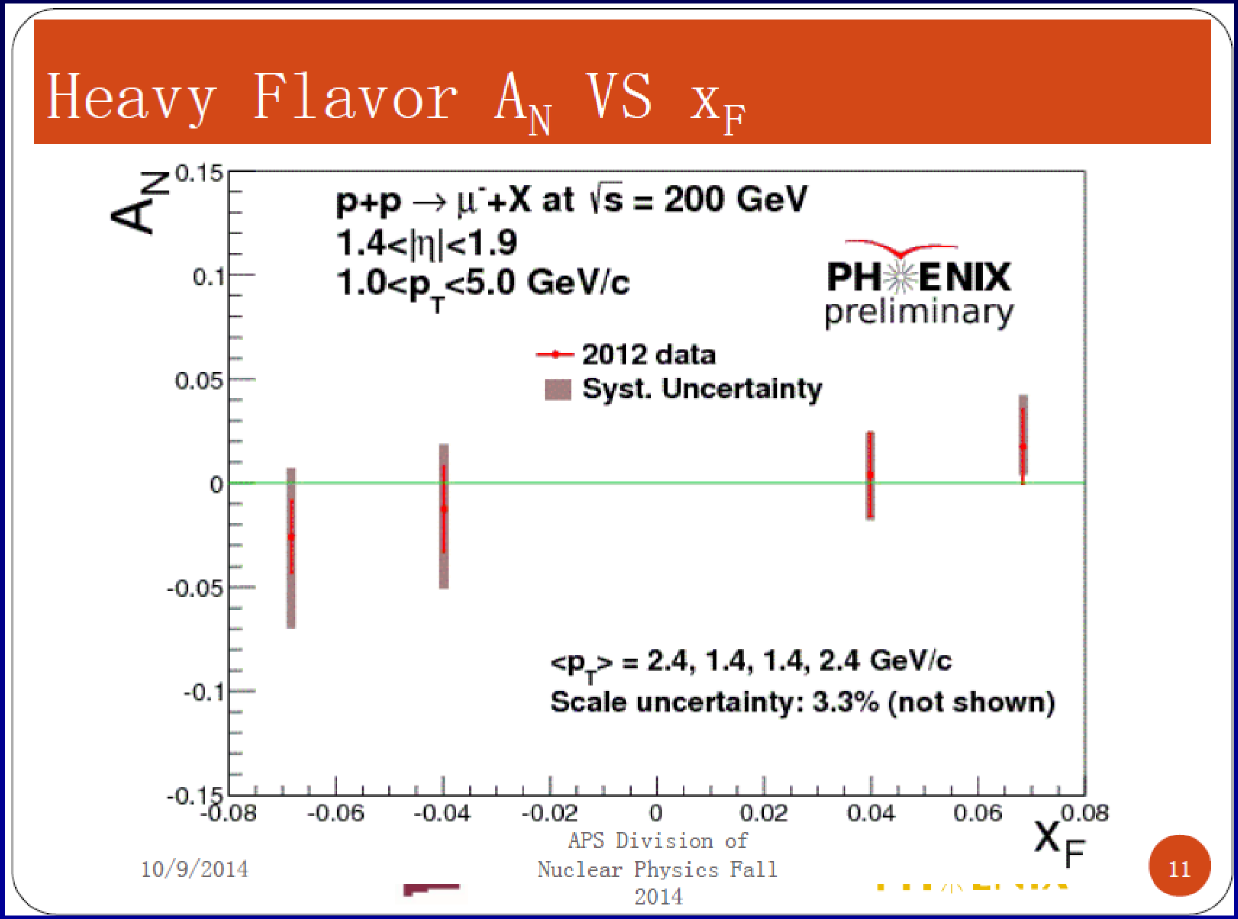
- 1-photon events, which include a large π^0 contribution in this analysis, are similar to 2-photon events
- Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π^0's
- A_N decreases as the event complexity increases (i.e., the "jettiness"
- A_N for #photons >5 is similar to that for #photons = 5

Jettier events

Mriganka Mondal, for the collaboration (DIS 2014)

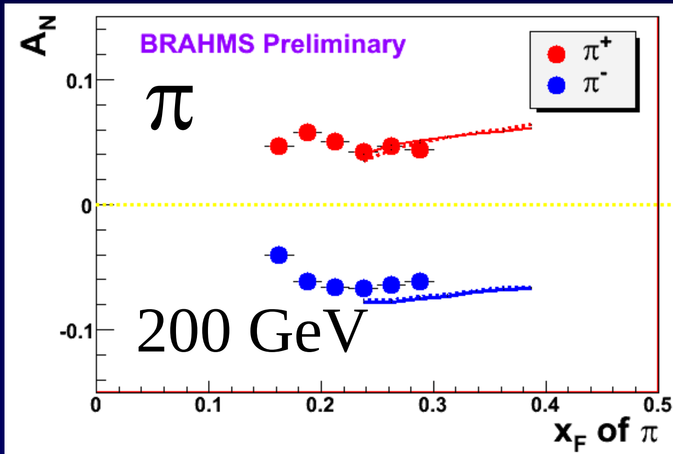
and points to a need for qualitatively new instrumentation and measurements

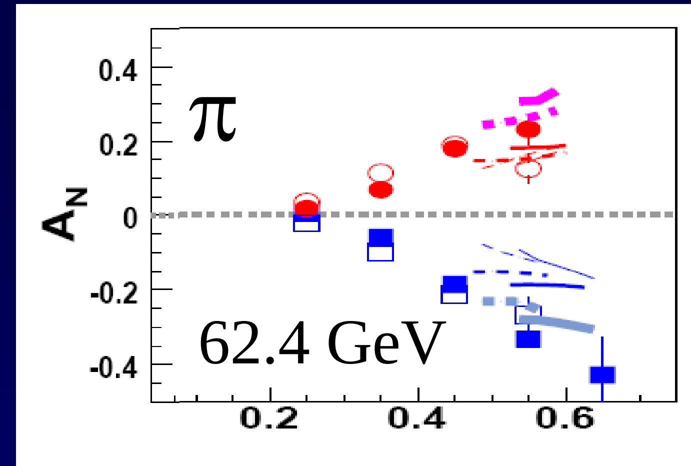
Open heavy flavor A_N to probe twist-3 trigluon correlations



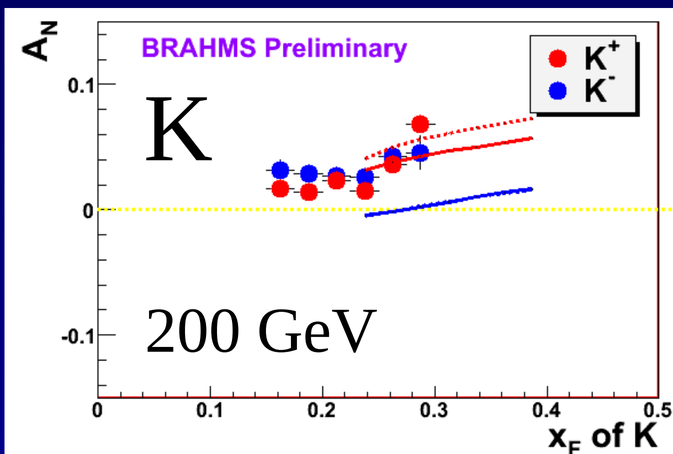
Expect measurement with ~0.01 accuracy from 2015 data, with displaced vertex heavy flavor tagging

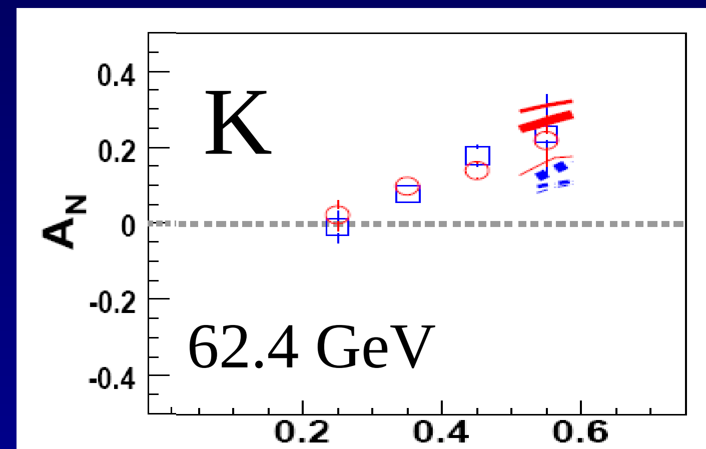
π, K, p at 200 and 62.4 GeV



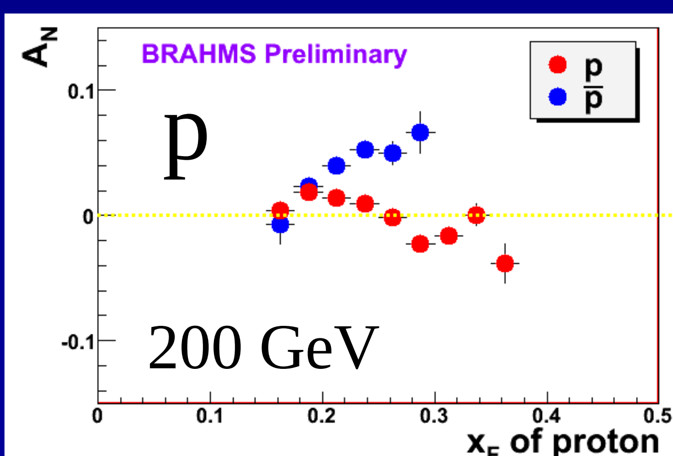


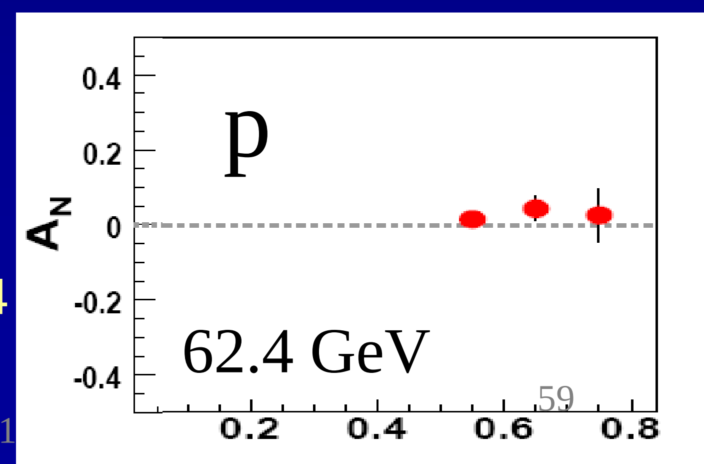
Note different scales



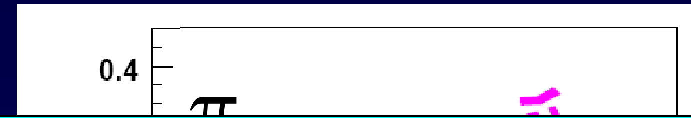


K- asymmetries underpredicted

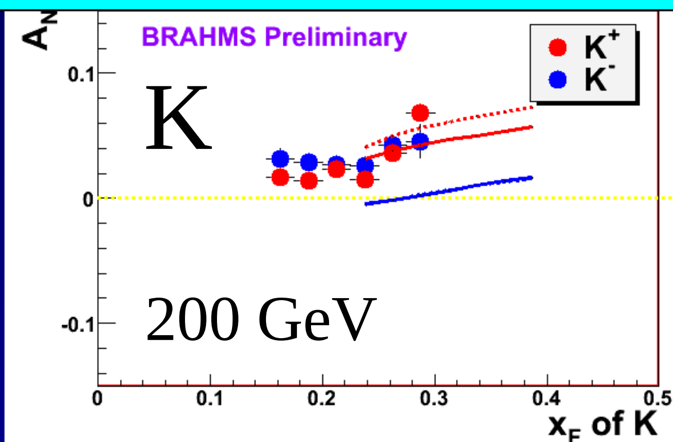




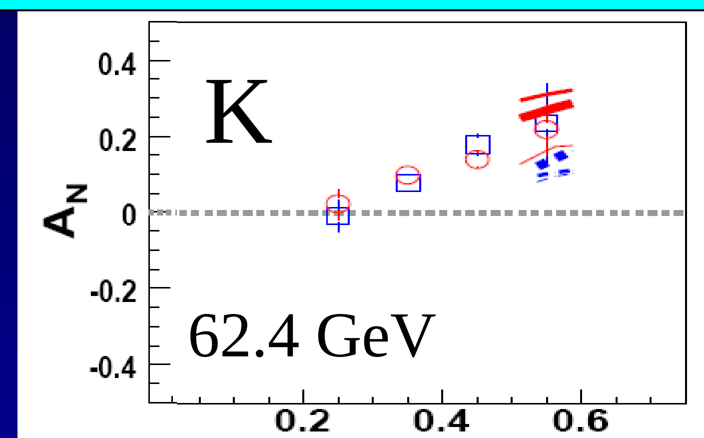
Large antiproton asymmetry?? Unfortunately no 62.4 GeV measurement

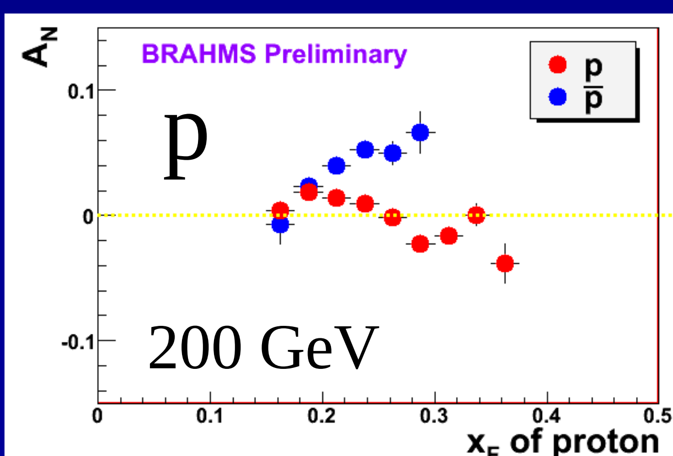


Pattern of pion species asymmetries in the forward direction
→ valence quark effect.
But this conclusion confounded by kaon and antiproton asymmetries!



K- asymmetries underpredicted





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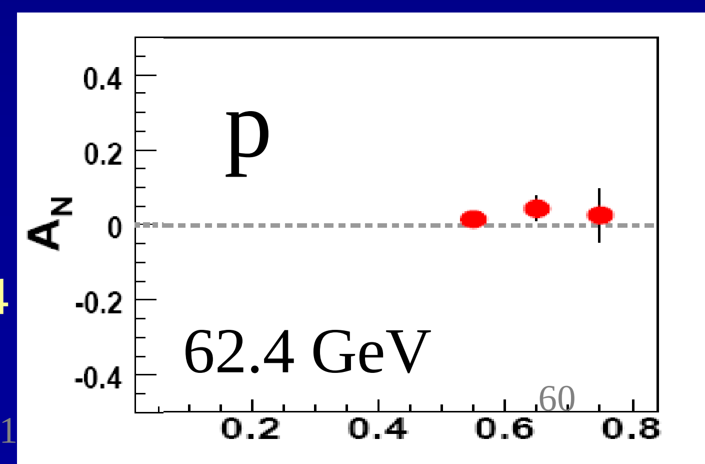


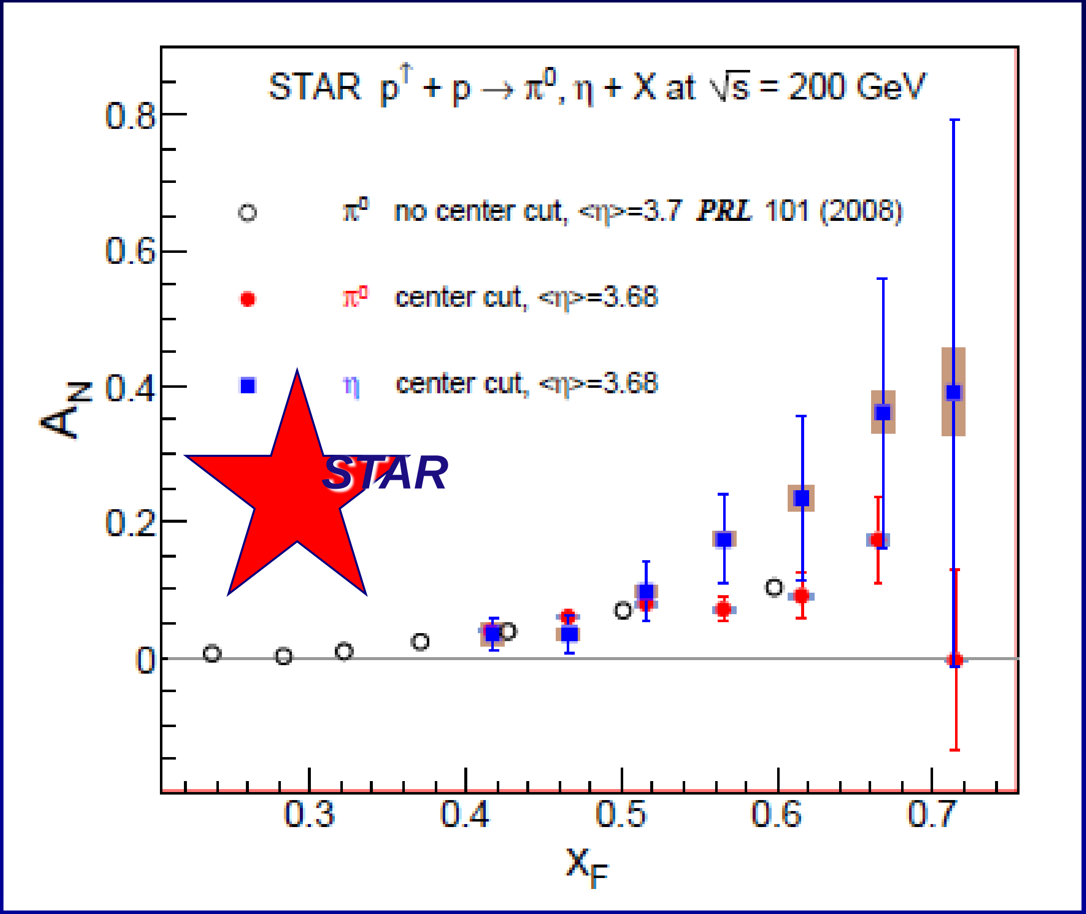
Another surprise: Transverse single-spin asymmetry in eta meson production

$$p^{\uparrow} + p \rightarrow \eta + X \quad \sqrt{s} = 200\,\text{GeV}$$
$$\eta \rightarrow \gamma + \gamma$$

Larger than the neutral pion!

$$.55 < X_F < .75$$
$$\langle A_N \rangle_\eta = 0.361 \pm 0.064$$
$$\langle A_N \rangle_\pi = 0.078 \pm 0.018$$

$$\pi^0 \equiv \frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$$
$$\eta \equiv \frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}$$



PRD 86:051101 (2012)

Another surprise: Transverse single-spin asymmetry in eta meson production

$$p^{\uparrow} + p \rightarrow \eta + X \quad \sqrt{s} = 200\,\text{GeV}$$

$\eta \rightarrow$

Larg

Further evidence against a valence quark effect!
Lots of territory still to explore to understand spin-momentum correlations in QCD!

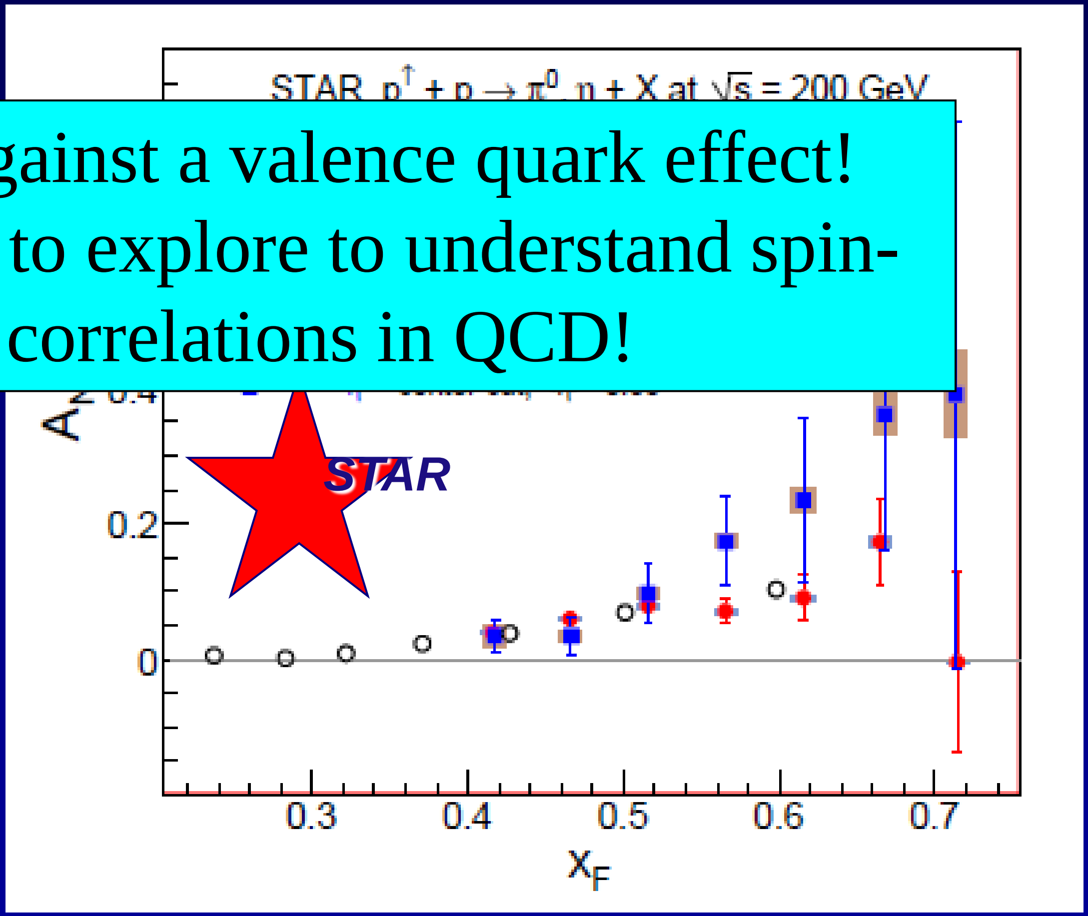
$.55 < x_F < .75$

$$\langle A_N \rangle_\eta = 0.361 \pm 0.064$$

$$\langle A_N \rangle_\pi = 0.078 \pm 0.018$$

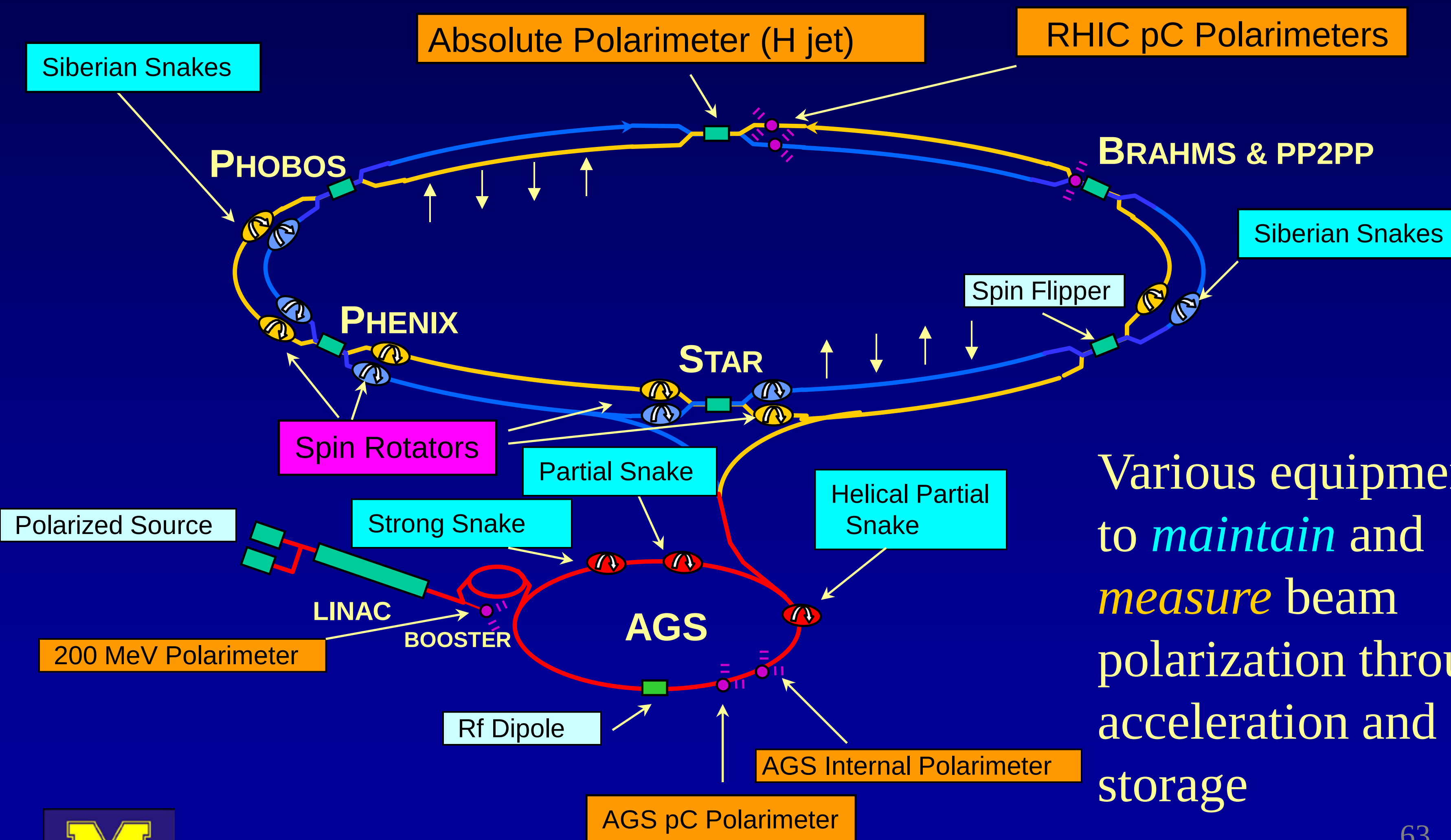
$$\pi^0 \equiv \frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$$

$$\eta \equiv \frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}$$

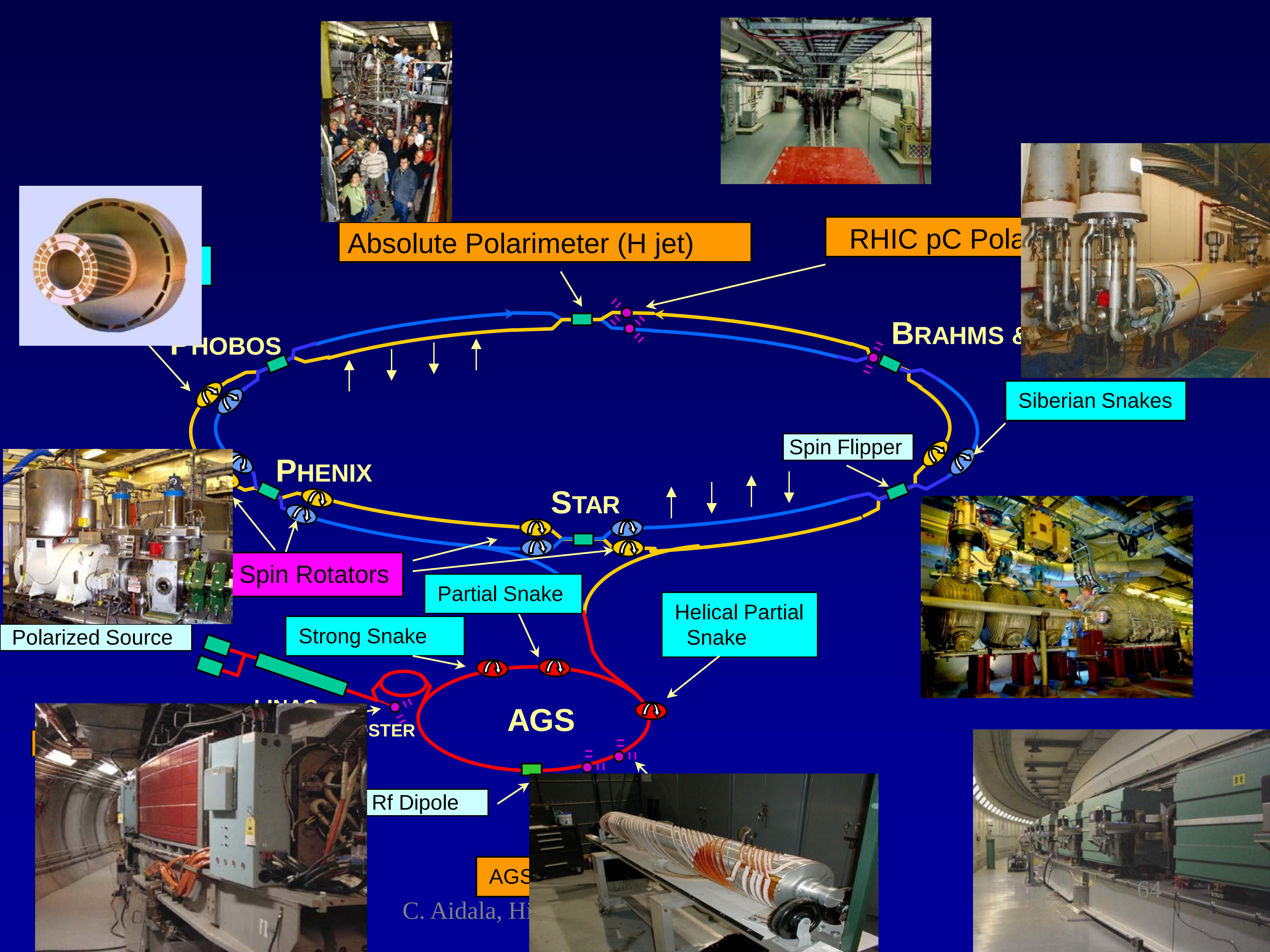


PRD 86:051101 (2012)

RHIC as a polarized p+p collider



Various equipment to *maintain* and *measure* beam polarization through acceleration and storage


Absolute Polarimeter (H jet)
RHIC pC Pola
PHOBOS
BRAHMS &
Siberian Snakes
Spin Flipper
PHENIX
STAR
Spin Rotators
Partial Snake
Helical Partial Snake
Polarized Source
Strong Snake
LINAC
STER
AGS
Rf Dipole
AGS