STAR Transverse Spin

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RHIC-AGS Users' Meeting
June 25, 2013

OUTLINE

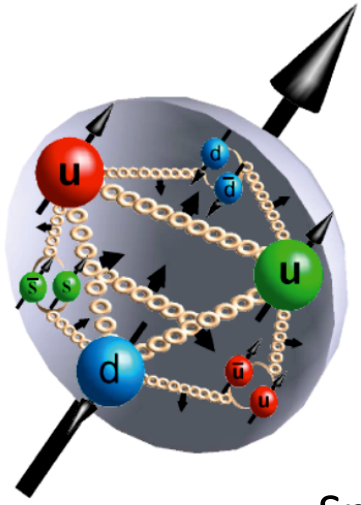
- Introduction
- Inclusive hadrons at forward η
- Jets and di-hadrons at central η
- Future measurements
- Summary

STAR

Valparaiso University

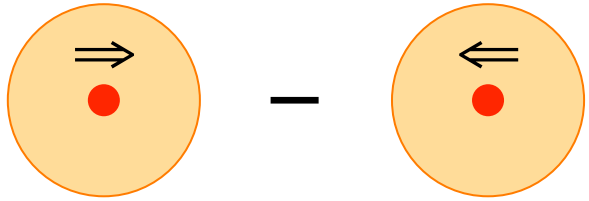
Contributions to Proton Spin Structure

Consider proton moving right



Proton spin ⇒

$\Delta q(x)$
$\Delta g(x)$



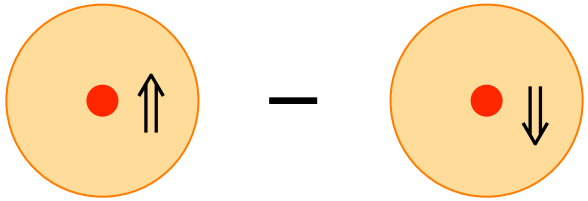
Polarized DIS: ~0.3

Both are poorly constrained

Spin sum rule: $\left\langle S_z^p \right\rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \left\langle L_z \right\rangle$

Proton spin ⇑

$\delta q(x)$

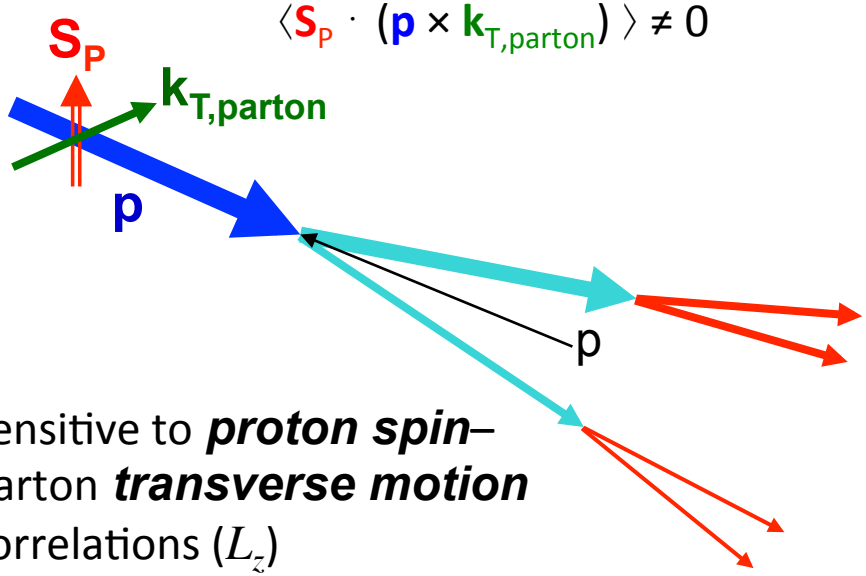


Transversity – data over limited kinematic range

Access to Orbital Motion and Transversity?

Sivers mechanism: asymmetry in the forward jet or γ *production*

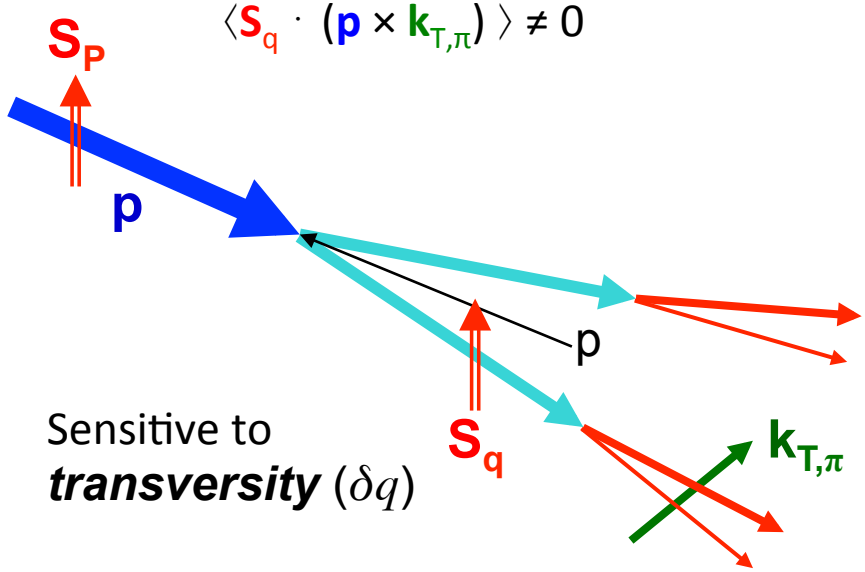
$\langle S_P \cdot (p \times k_{T,parton}) \rangle \neq 0$



Sensitive to ***proton spin***–parton ***transverse motion*** correlations (L_z)

Collins mechanism: asymmetry in the forward jet *fragmentation*

$\langle S_q \cdot (p \times k_{T,\pi}) \rangle \neq 0$



Sensitive to ***transversity*** (δq)

Inclusive hadrons:

Observed transverse single-spin asymmetries could arise from the **Sivers effect** or **Collins effect**, or from a **linear combination of the two**

Sivers or Collins ~ $\sin(\phi_S)$

ϕ_S—*angle between spin and event plane*

Access to Orbital Motion and Transversity?

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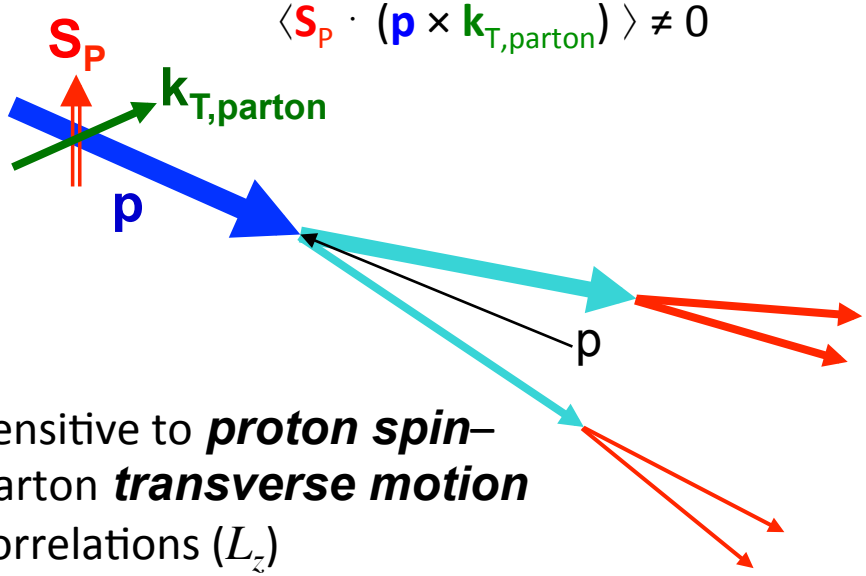

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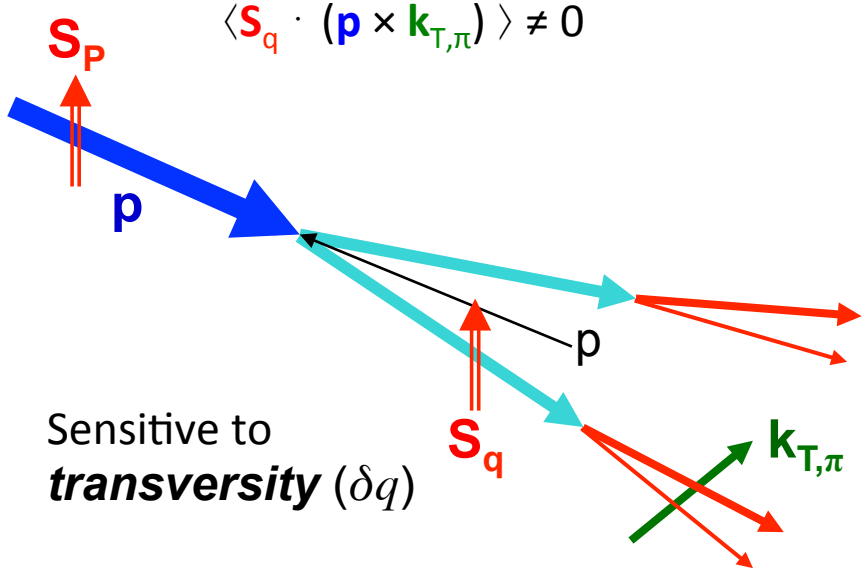


Sensitive to ***transversity*** (δq)

Separate Sivers and Collins:

Go beyond inclusive production - *e.g. Jets, correlations, direct photons*

Sivers ~ $\sin(\phi_S)$

ϕ_S—*angle between spin and event plane*

Collins ~ $\sin(\phi_S - \phi_h)$

ϕ_h—*angle of hadron around jet axis*

STAR as a Detector for Transverse Spin Effects

Higher-twist and Transverse Momentum Dependent Distribution and F.F. Functions (TMD's):

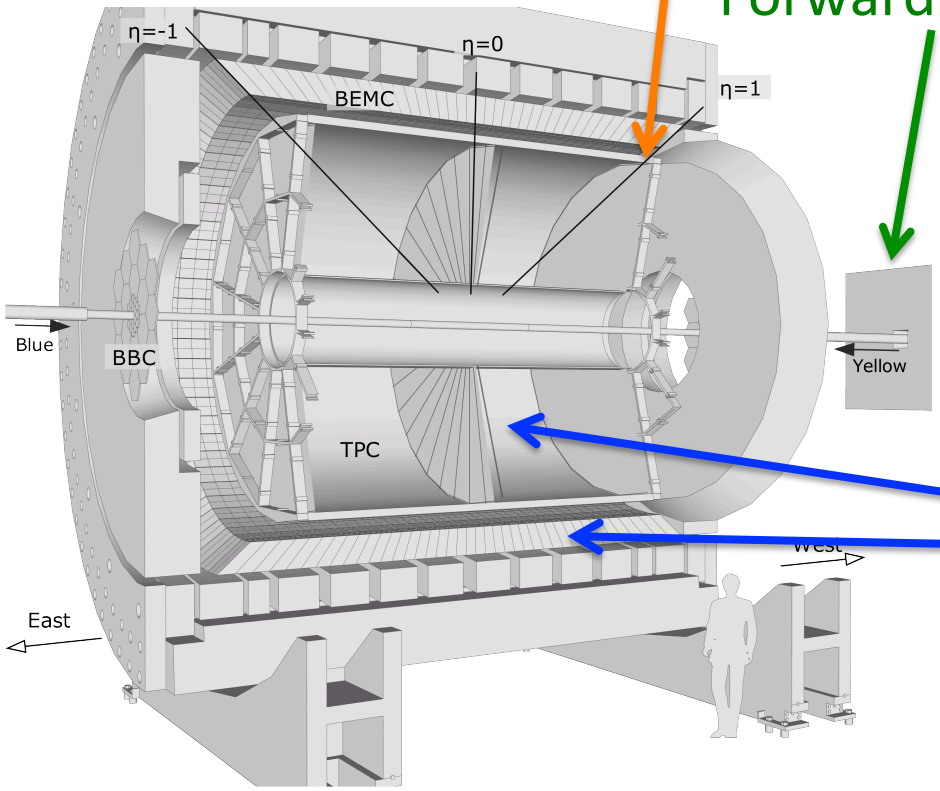
Inclusive hadron asymmetries from

Endcap ElectroMagnetic Calorimeter (EEMC)

and

Forward Meson Spectrometer (FMS)

FPD (east) not shown



Transversity:

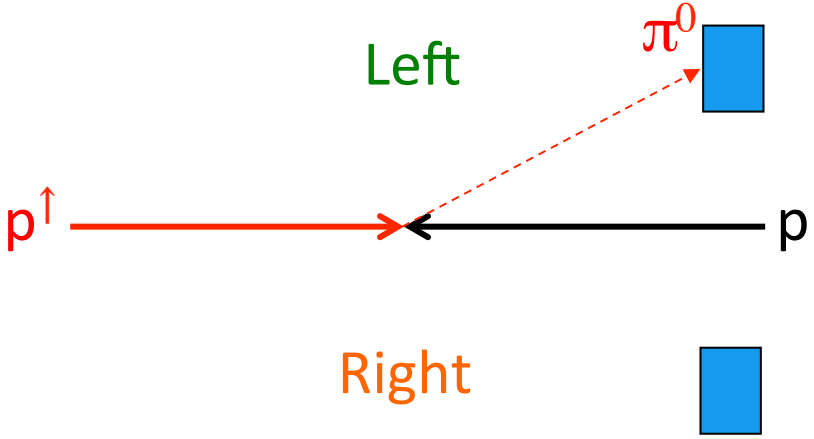
Jet and di-hadron asymmetries from

TPC + Barrel EMC

Transverse Single-spin Asymmetries

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$d\sigma^{\uparrow(\downarrow)}$ – cross section for leftward scattering when beam polarization is spin-up(down)



Positive A_N – more π^0 to ***left*** of (up) polarized beam

Two options to measure A_N

Single-arm:

$$A_N = \frac{1}{P}\frac{N^{\uparrow} - RN^{\downarrow}}{N^{\uparrow} + RN^{\downarrow}} \qquad R = \frac{L^{\uparrow}}{L^{\downarrow}}$$

R = relative luminosity

P = beam polarization normal to π^0

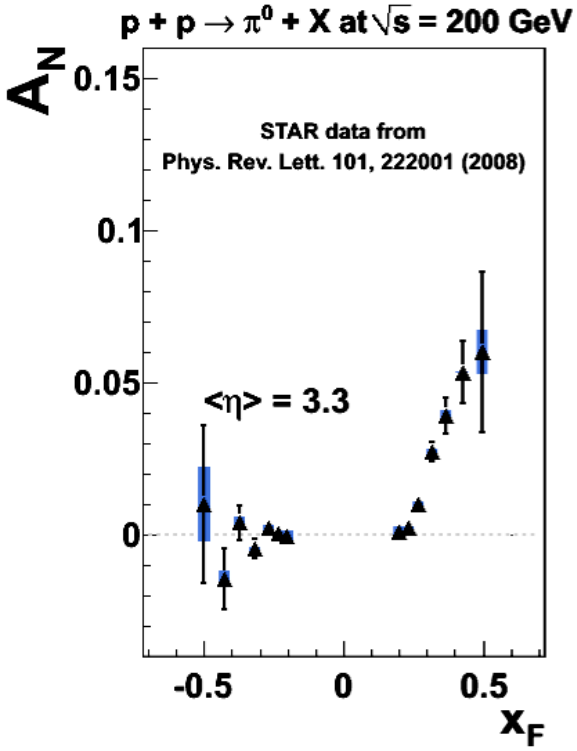
Left-right symmetric detector

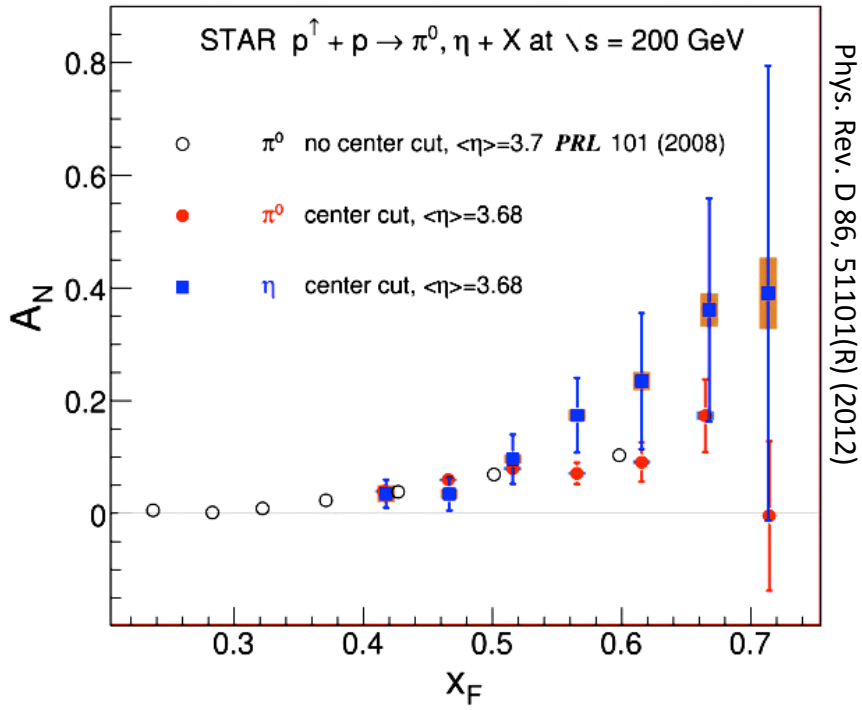
→ Cross-ratio Method:

$$A_N = \frac{1}{P}\frac{\sqrt{N_L^{\uparrow}N_R^{\downarrow}} - \sqrt{N_L^{\downarrow}N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow}N_R^{\downarrow}} + \sqrt{N_L^{\downarrow}N_R^{\uparrow}}}$$

- Less sensitive to instrumental effects
- Factor out relative luminosity

STAR Transverse Asymmetries at Forward Pseudorapidity





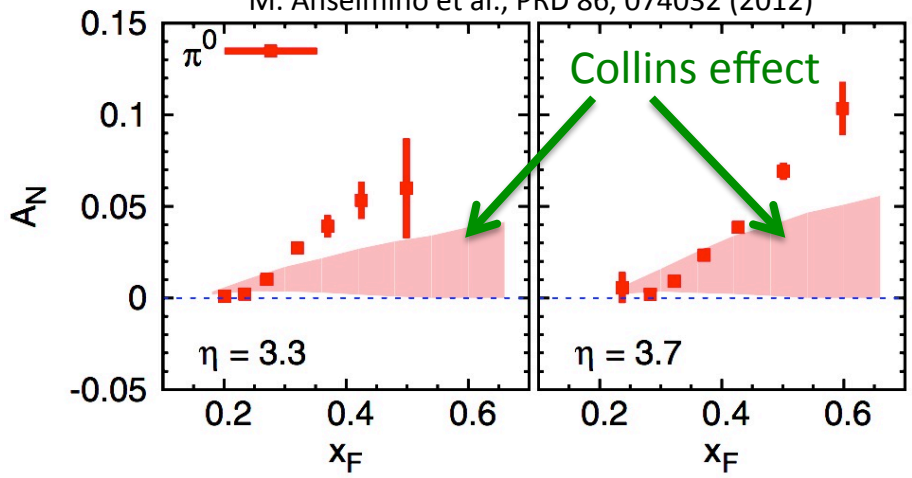
STAR has measured sizeable transverse single-spin asymmetries for forward π^0 and η production

At high-x_F, η asymmetry may be larger than that of π^0

Above results mostly from Run-6 (6.8 pb^{-1} at 55% polarization)

STAR Transverse Asymmetries at Forward Pseudorapidity

M. Anselmino et al., PRD 86, 074032 (2012)



STAR data from PRL 101, 222001 (2008)

Current models based on fits to SIDIS and e^+e^-:

- *"The Collins effect…is not sufficient for the medium-large x_F range of STAR data, $x_F \gtrsim 0.3$"*

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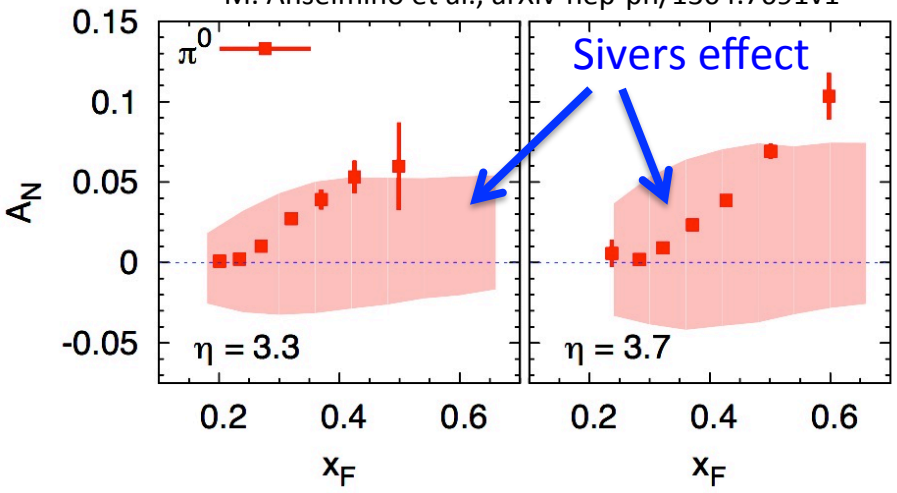
M. Anselmino et al., arXiv-hep-ph/1304.7691v1



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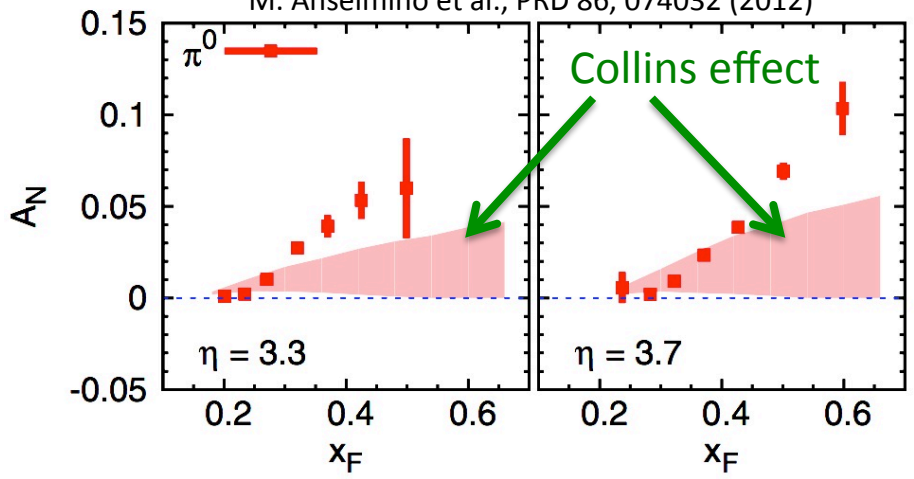

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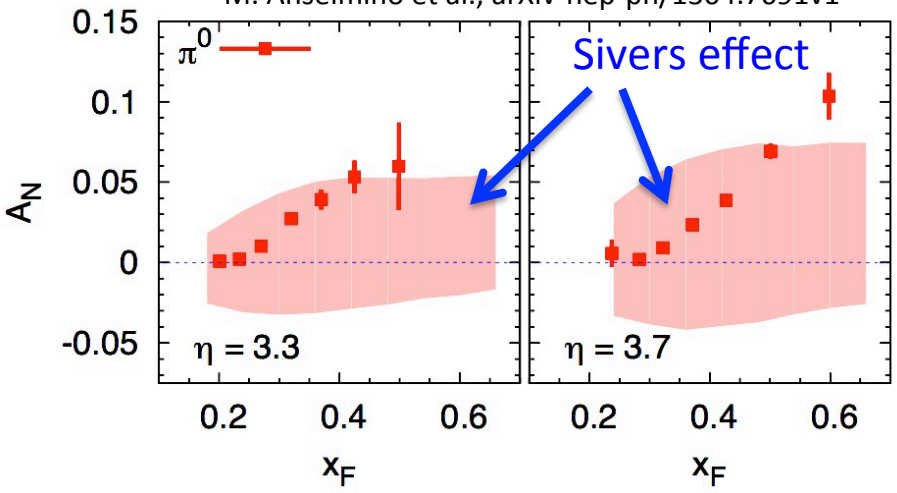

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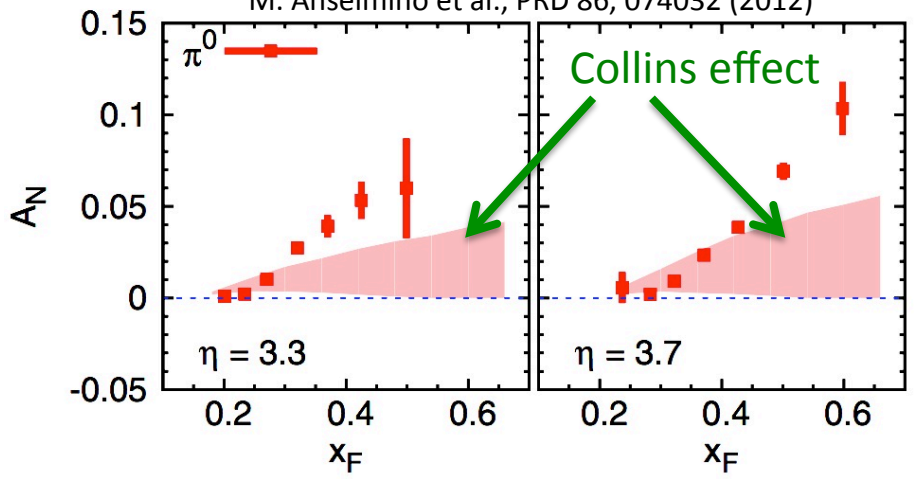

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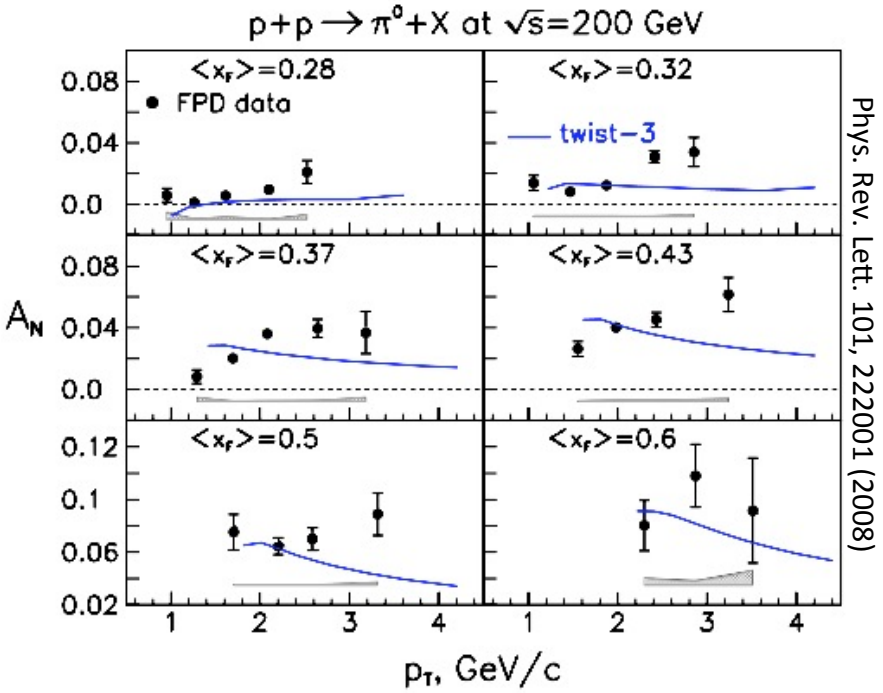
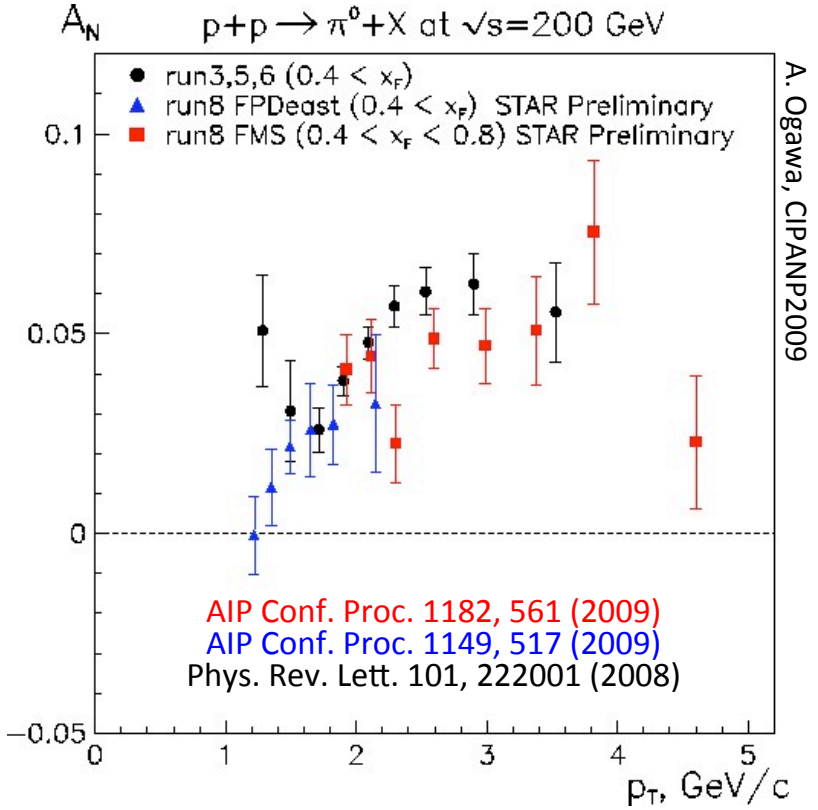
Theoretical questions remain about applicability to p+p data of Sivers extractions from SIDIS

(*e.g. Kang et al., PRD 83, 094001 (2011)*)

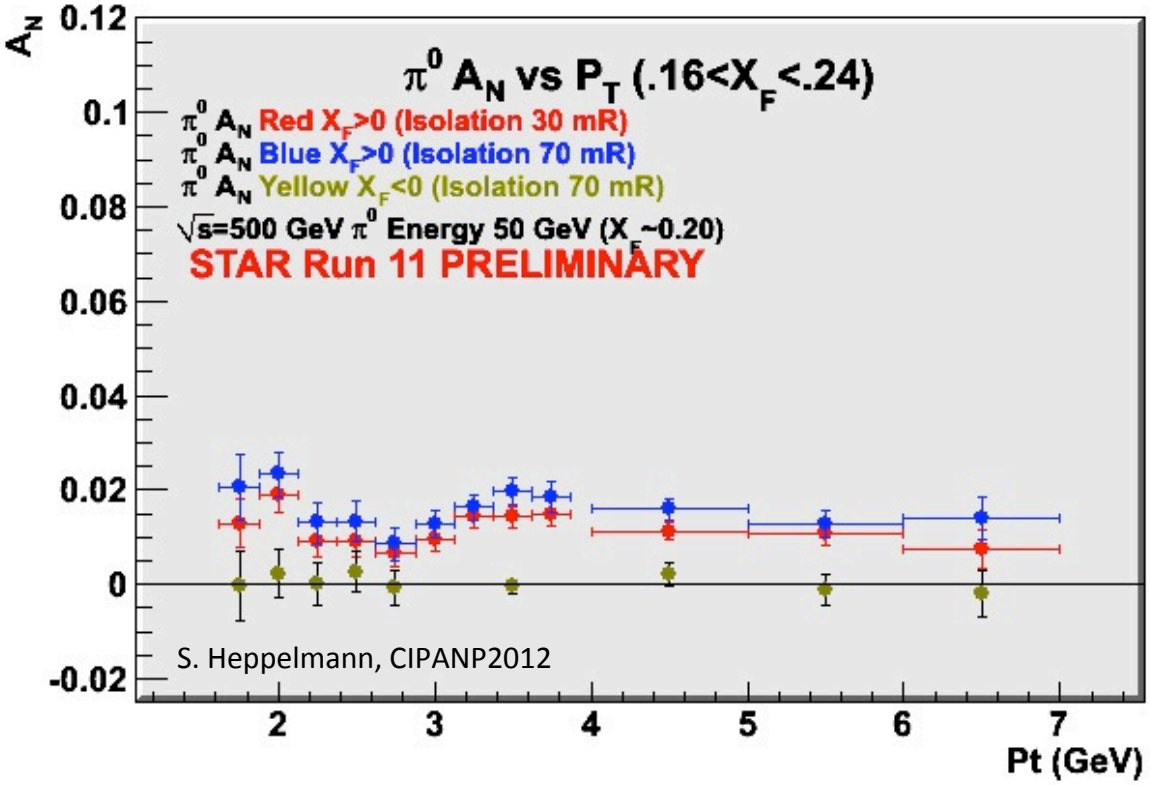
STAR Transverse Asymmetries at Forward Pseudorapidity





Despite expectation of $1/p_T$ scaling, STAR data from Run-3 to Run-8 show ***no sign of $1/p_T$ fall-off out to $p_T \sim 5$ GeV/c***

STAR Transverse Asymmetries at Forward Pseudorapidity



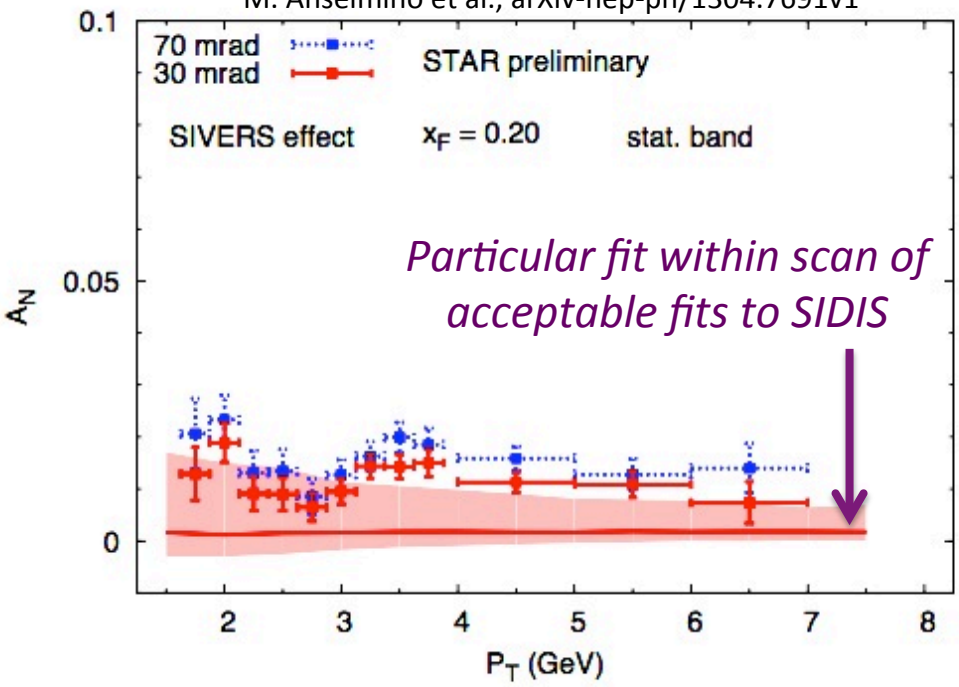
Recent measurements at √s = 500 GeV show

no sign of $1/p_T$ fall-off out to $p_T \sim 10$ GeV/c

(*consistent across multiple x_F-bins*)

STAR Transverse Asymmetries at Forward Pseudorapidity

M. Anselmino et al., arXiv-hep-ph/1304.7691v1



Recent models based on SIDIS fits suggest flat p_T-dependence for **Sivers effect** out to $p_T \sim 7$ GeV/c but at ***lower magnitude than data***

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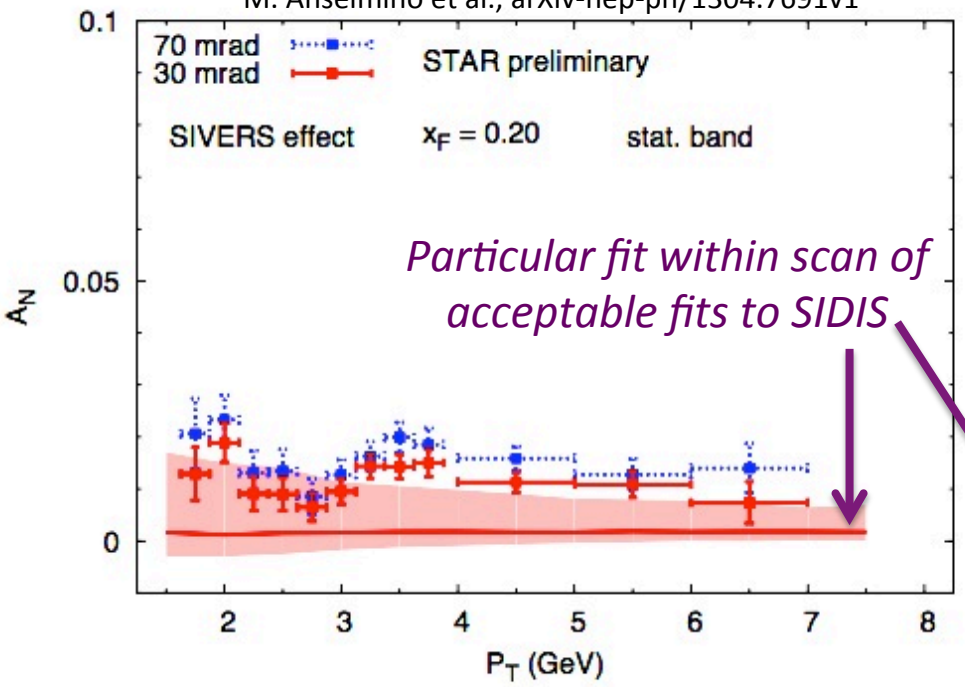
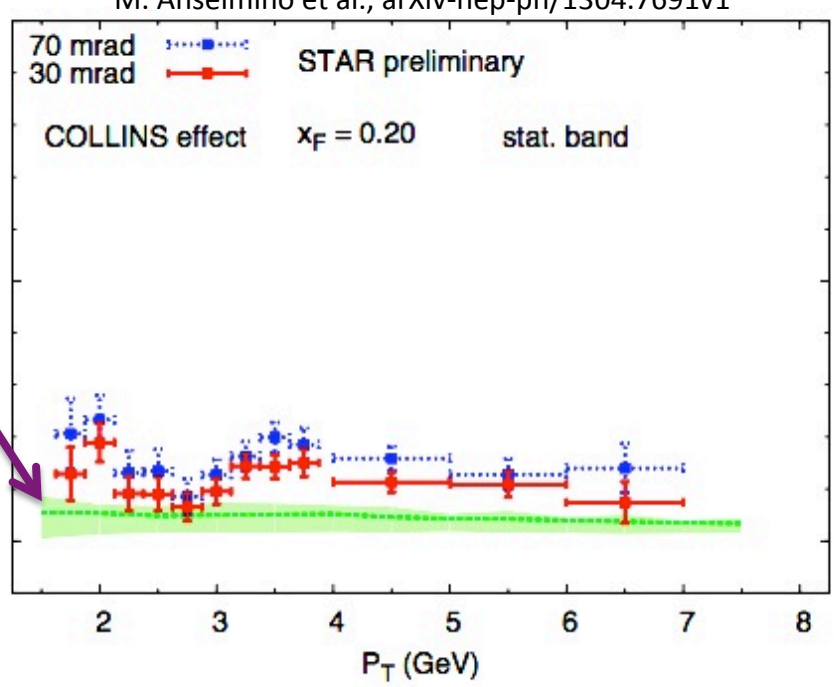


Particular fit within scan of acceptable fits to SIDIS

M. Anselmino et al., arXiv-hep-ph/1304.7691v1



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Similar behavior for **Collins effect** in some parameterizations

→ possible hint of Collins+Sivers effect?

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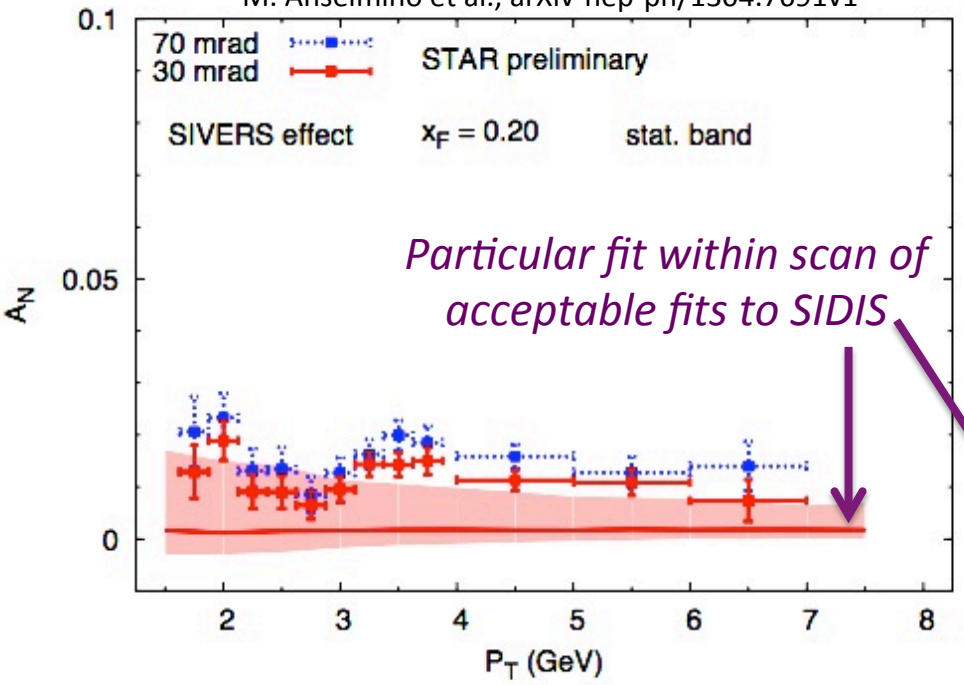

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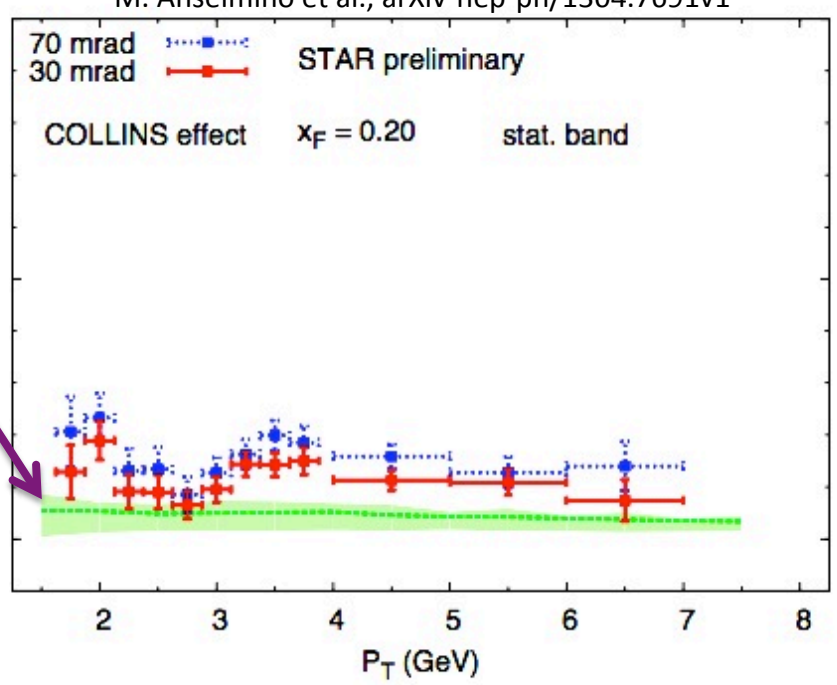

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lower magnitude than data

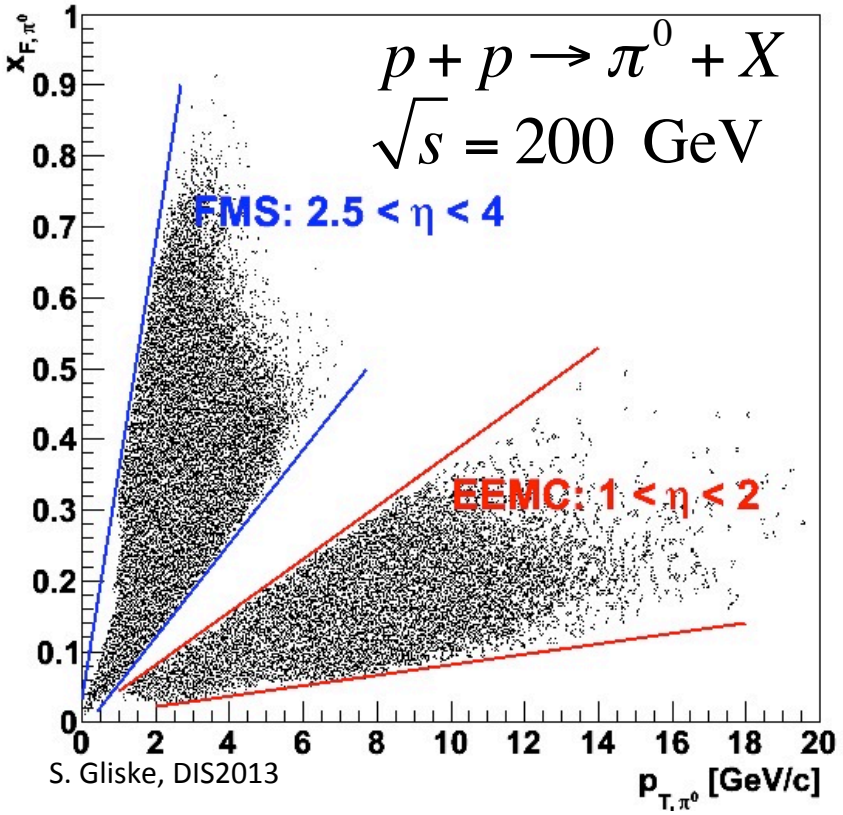
Similar behavior for **Collins effect** in some parameterizations

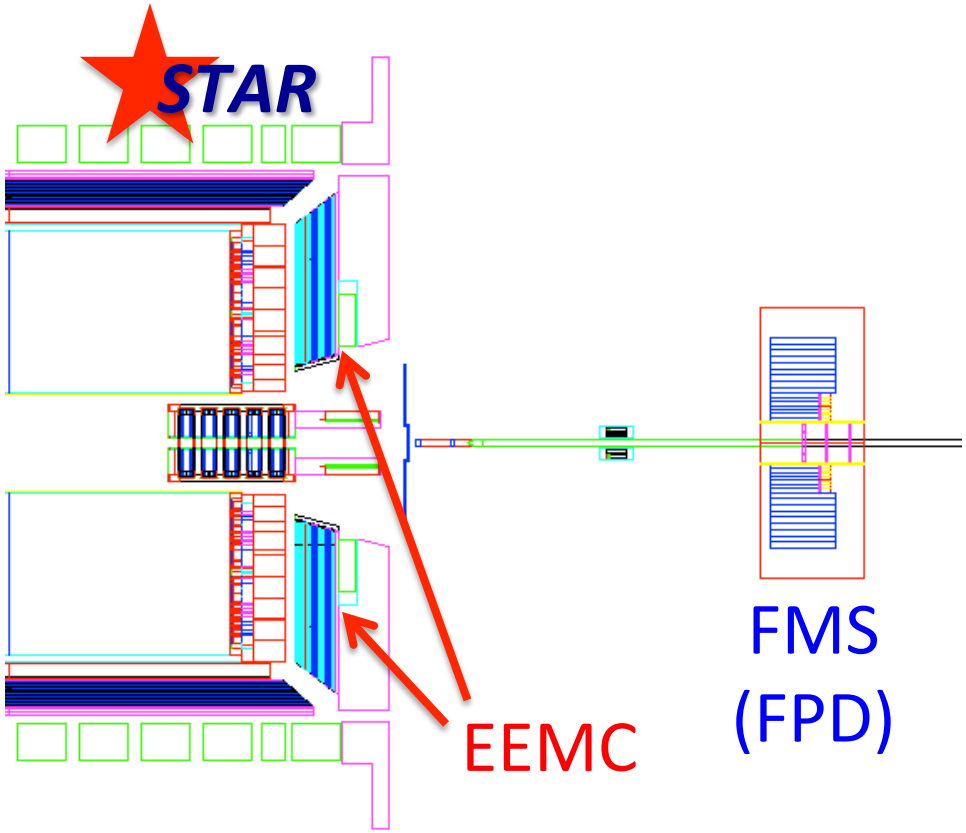
→ ***possible hint of Collins+Sivers effect?***

Twist-3 models also see flat p_T dependence out to $p_T \sim 15$ GeV/c

[*e.g. Kanazawa and Koike, PRD 83, 114024 (2011)*]

A_N: The Kinematic Picture





Map A_N as a function of x_F and p_T

EEMC provides access to lower x_F and higher p_T

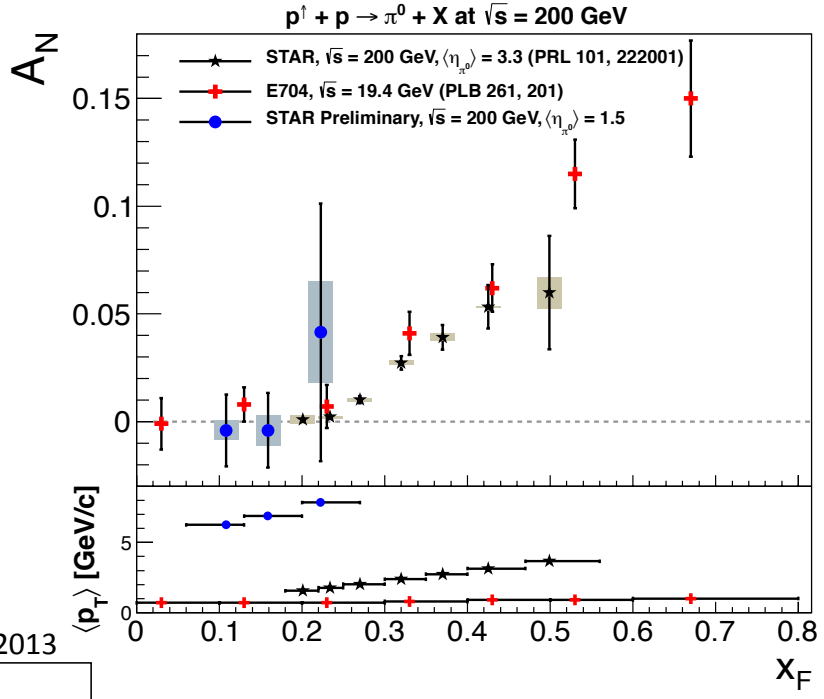
→ *Expect small A_N at small x_F*

Inclusive Neutral Pions at Intermediate Pseudorapidity

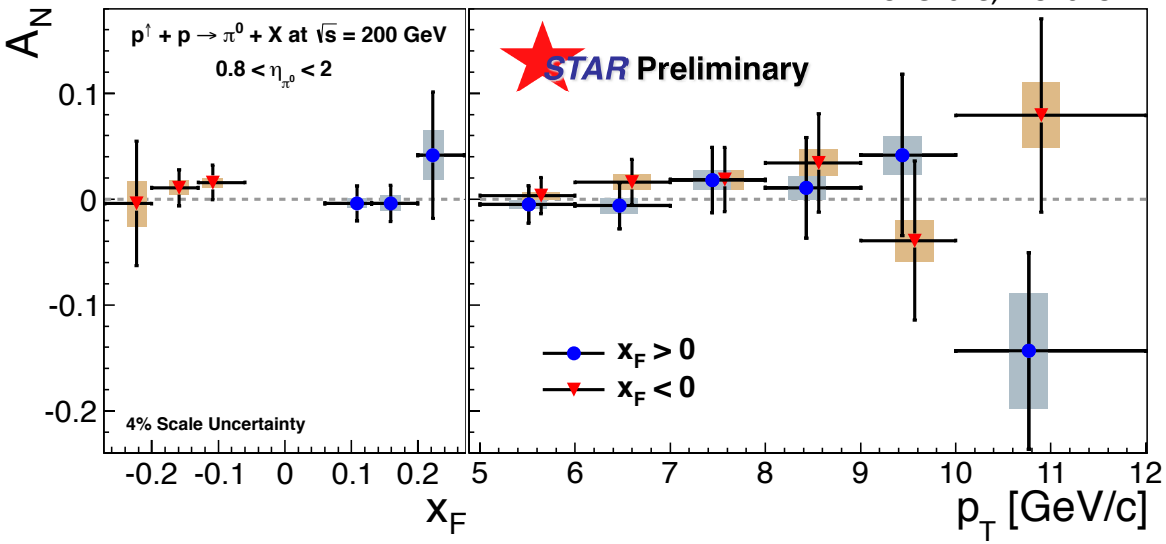
Mapping kinematic topology may help elucidate underlying mechanisms

Intermediate pseudorapidity ($1 \lesssim \eta \lesssim 2$) maps a lower range of x_F for higher p_T than previously measured

Results shown for Run-6 (2.8 pb^{-1} at 56% polarization)
Higher statistics available with recent datasets

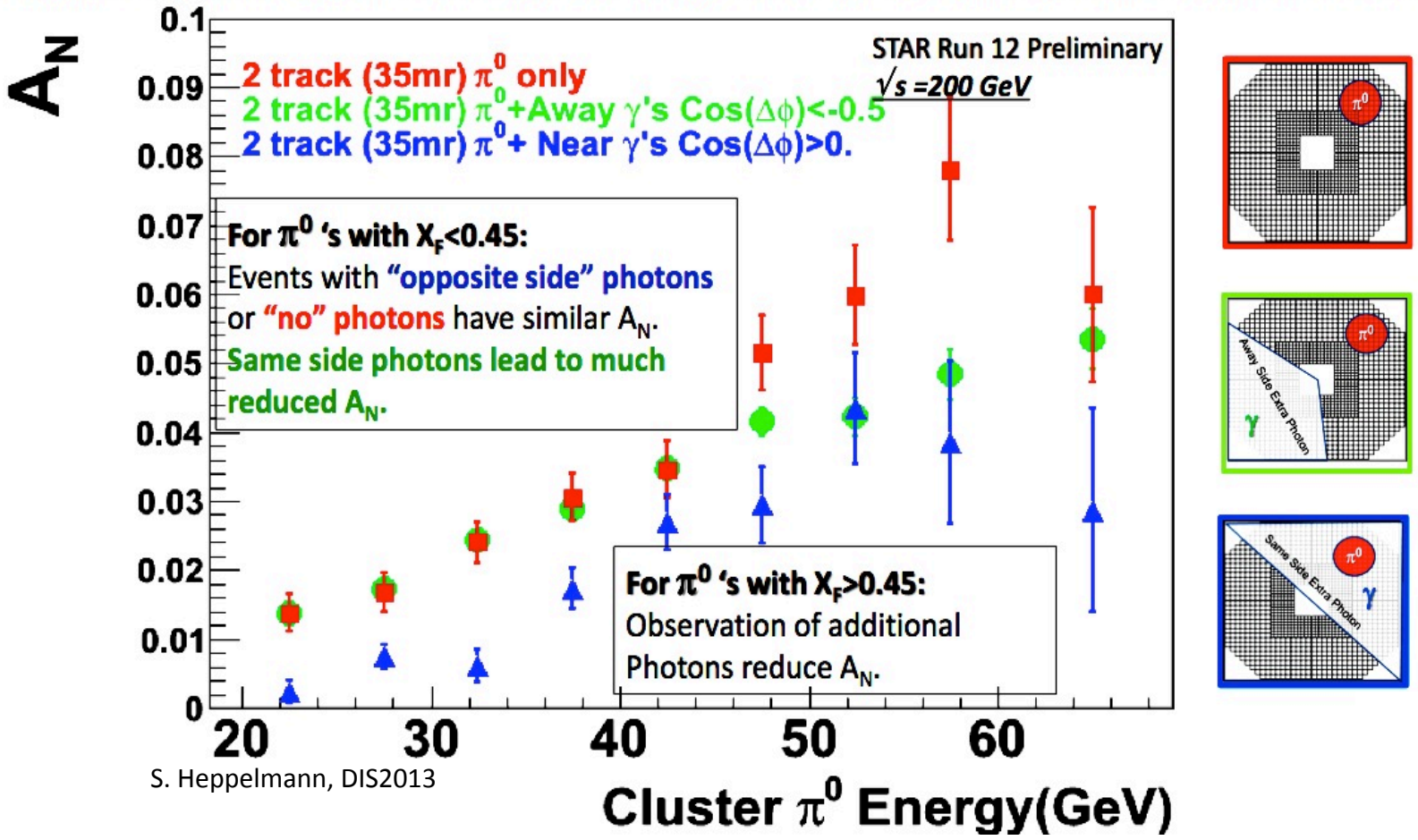


S. Gliske, DIS2013



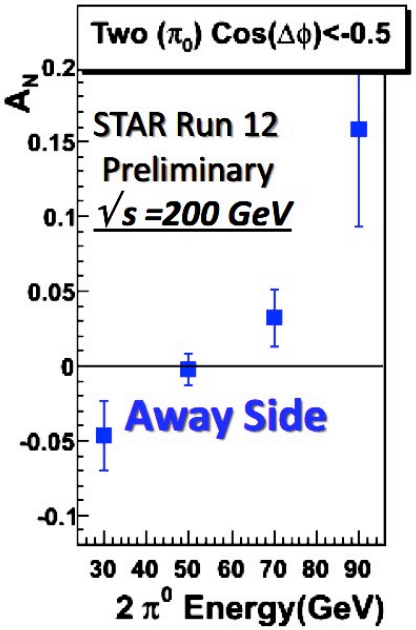
Models predict ***very small*** asymmetries for intermediate pseudorapidity
(e.g. *twist-3 prediction from Kanazawa and Koike*)

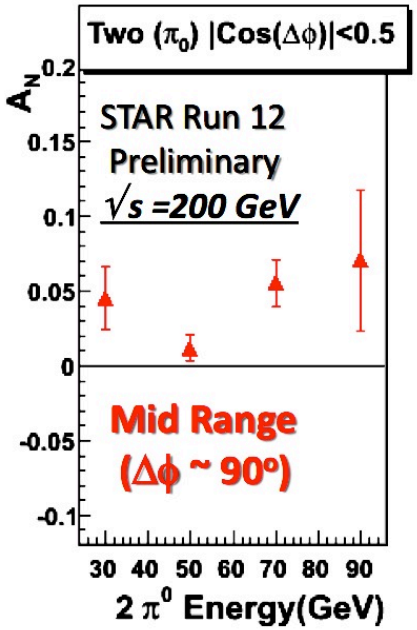
Forward Inclusive Neutral Pions at 200 GeV

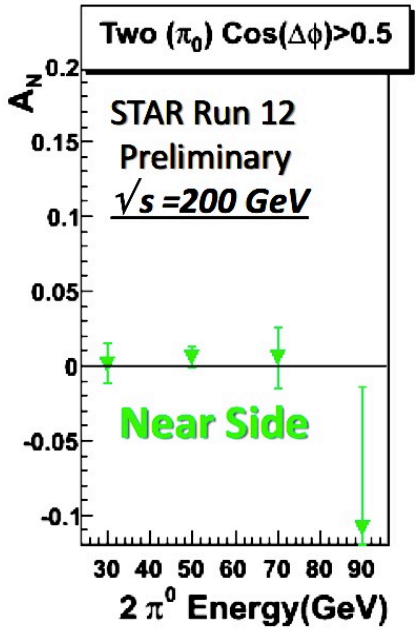


Recent data from Run-12 suggest that asymmetries for pions with additional near-side energy deposit have *lower asymmetries than those of more isolated pions*

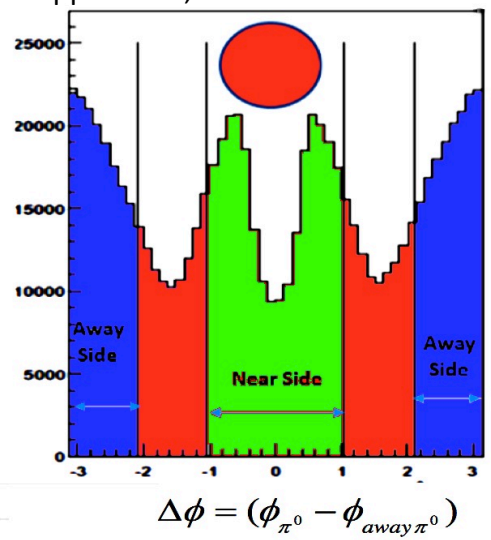
Forward Inclusive Neutral Pions at 200 GeV







S. Heppelmann, DIS2013



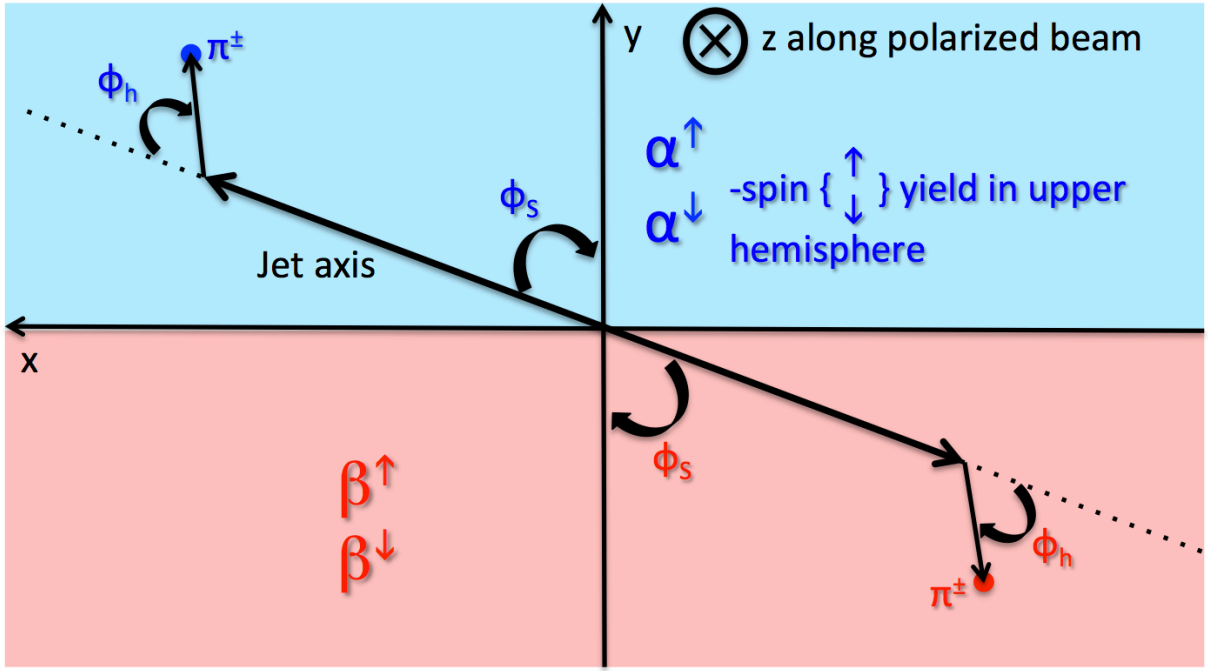
Recent data from Run-12 further suggest that asymmetries for pions with additional near-side pion have

lower asymmetries than those with away-side or mid-range pion

→ In both √s = 200 and 500 GeV isolated pions show higher asymmetry than jet-like pions

Forward neutral-energy jet analysis of Run-11 ongoing (M. Mondal, GHP2013)

Opportunities with Jet Measurements

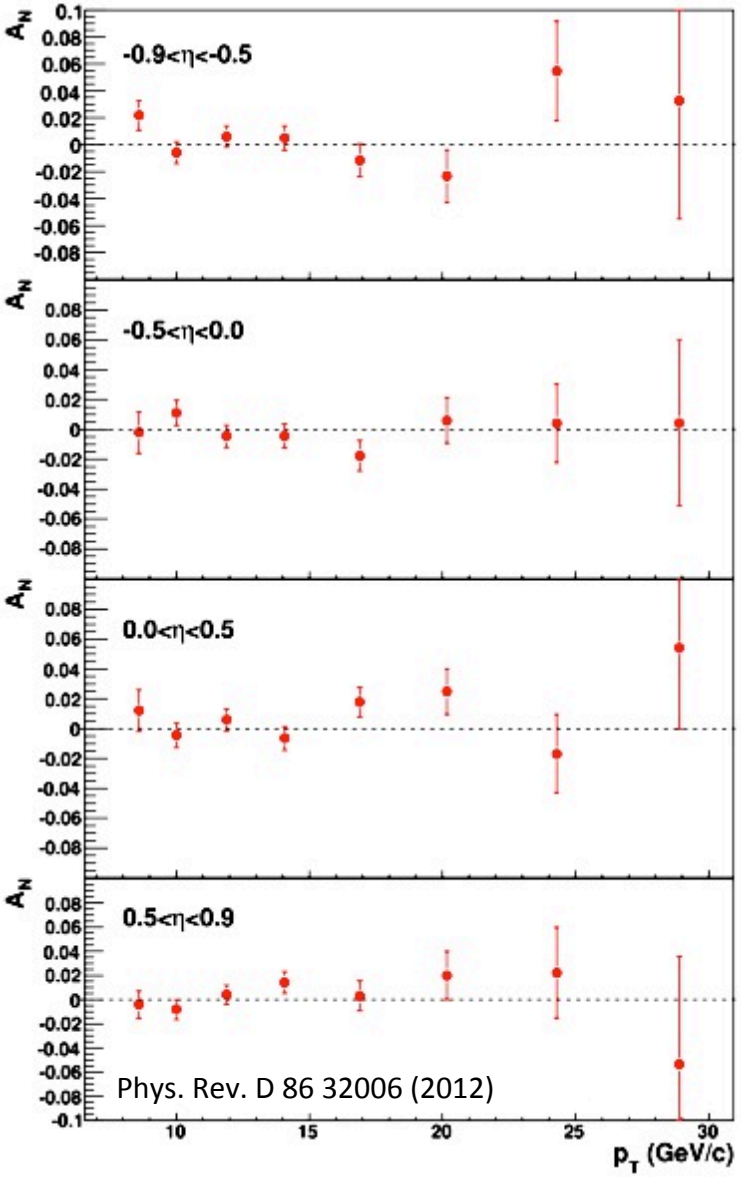


α and β yields are functions of $\left\{ \begin{array}{c} \Delta\phi = \phi_S - \phi_h \\ \phi_S \end{array} \right\}$ integrated over $\left\{ \begin{array}{c} \phi_S \\ \Delta\phi \end{array} \right\}$

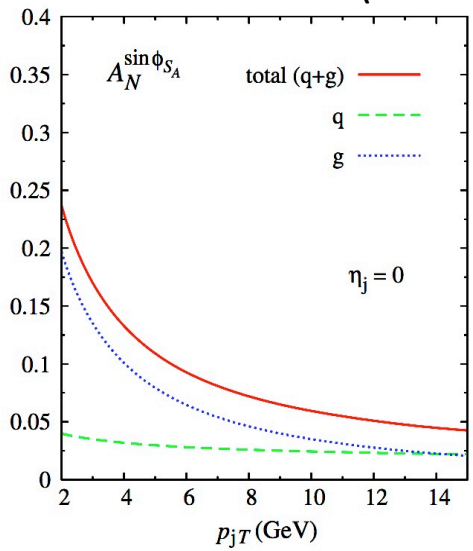
$$A_N = \frac{1}{P} \frac{\sqrt{\alpha^{\uparrow}\beta^{\downarrow}} - \sqrt{\alpha^{\downarrow}\beta^{\downarrow}}}{\sqrt{\alpha^{\uparrow}\beta^{\downarrow}} + \sqrt{\alpha^{\downarrow}\beta^{\downarrow}}}$$

For uniform acceptance: $A_N \left\{ \begin{array}{c} \Delta\phi \\ \phi_S \end{array} \right\} = \left\{ \begin{array}{c} A_{Collins} \sin(\Delta\phi) \\ A_{Sivers} \sin(\phi_S) \end{array} \right\}$

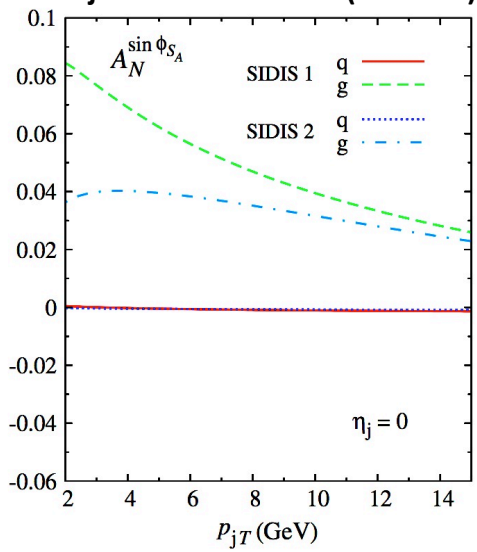
STAR Transverse Asymmetries at Central Pseudorapidity



Maximized Contributions (200 GeV)



Projections from SIDIS (200 GeV)



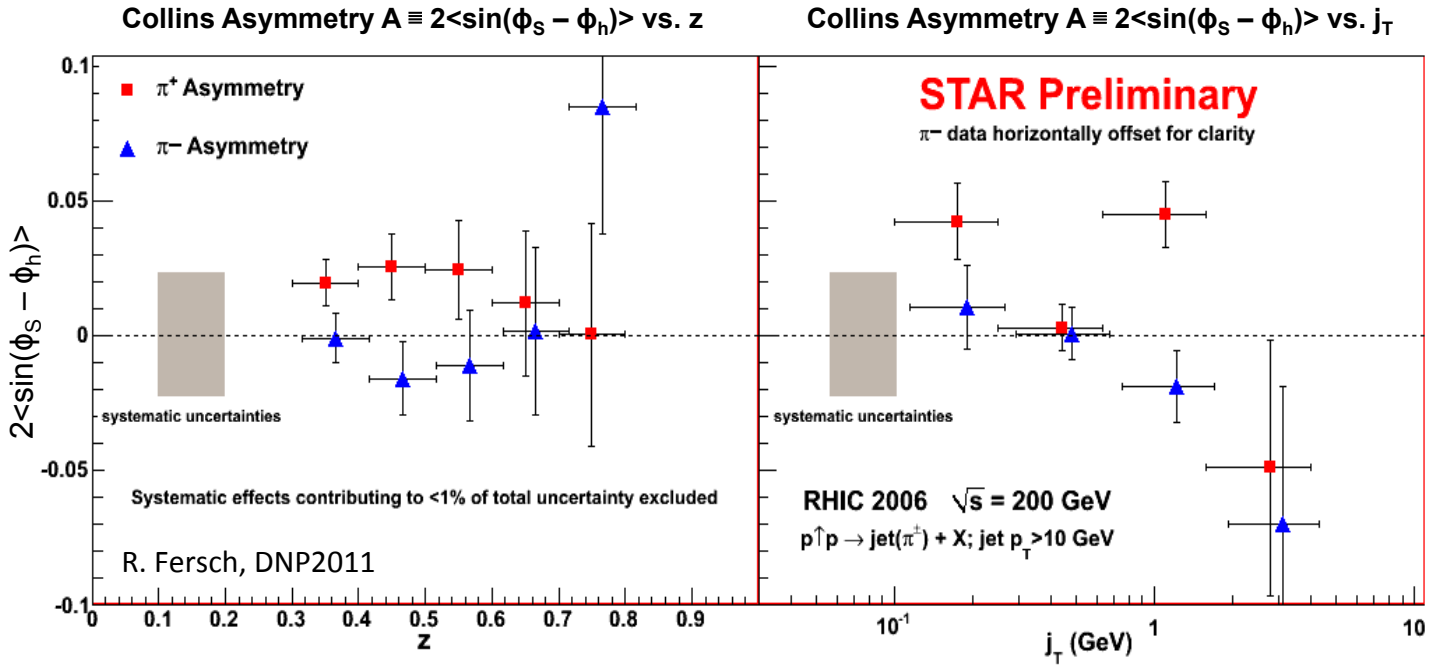
D' Alesio et al., PRD 83, 034021 (2011)

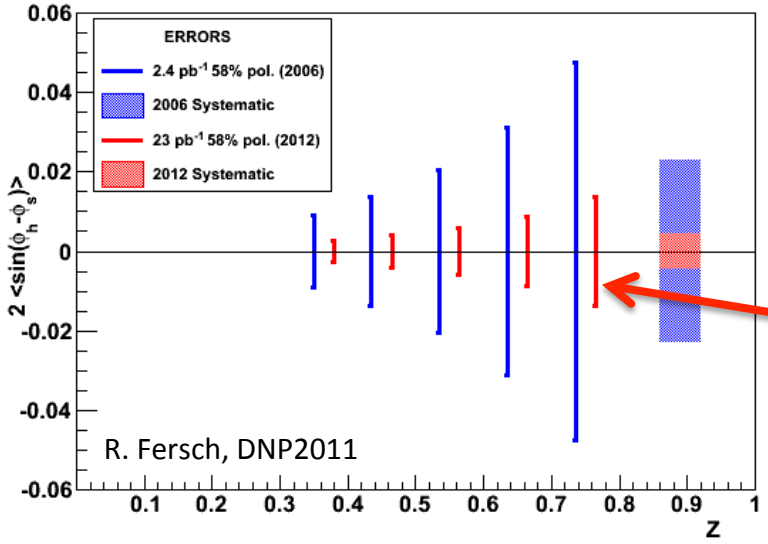
Current measurements of inclusive jet A_N at $-0.9 < \eta < 0.9$ and √s = 200 GeV (Run-6) consistent with zero

→ ***Well below model-based upper limits***

Similarly, Run-6 di-jet A_N consistent with zero [PRL 99, 142003 (2007)]

STAR Transverse Asymmetries at Central Pseudorapidity



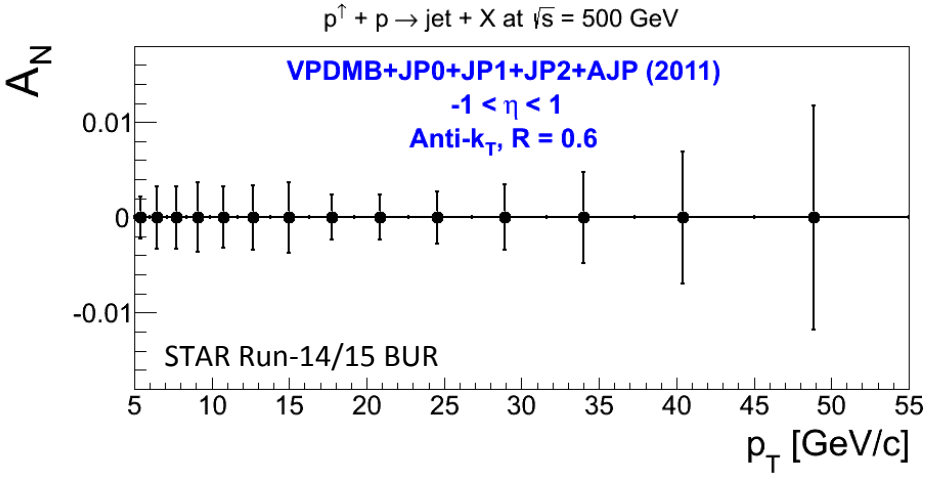


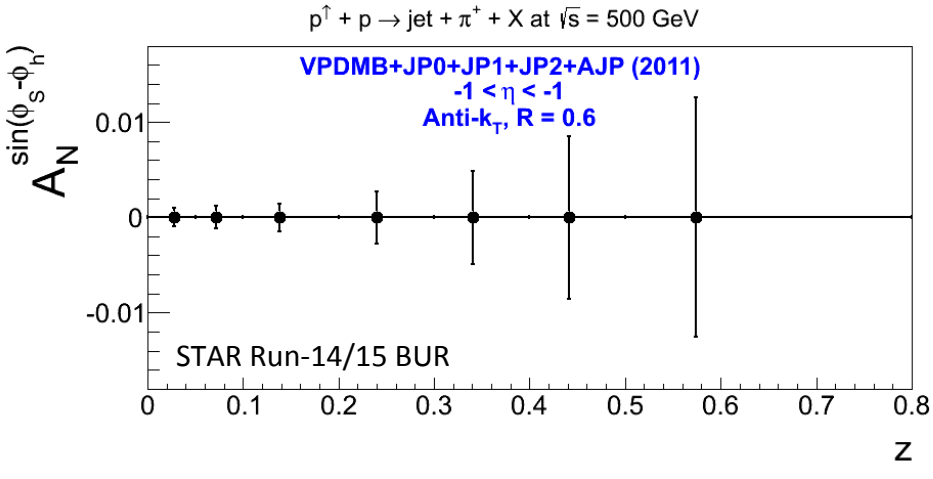
Hints of non-zero signal in Collins asymmetries from Run-6

→ ***Constrain transversity at higher x?***

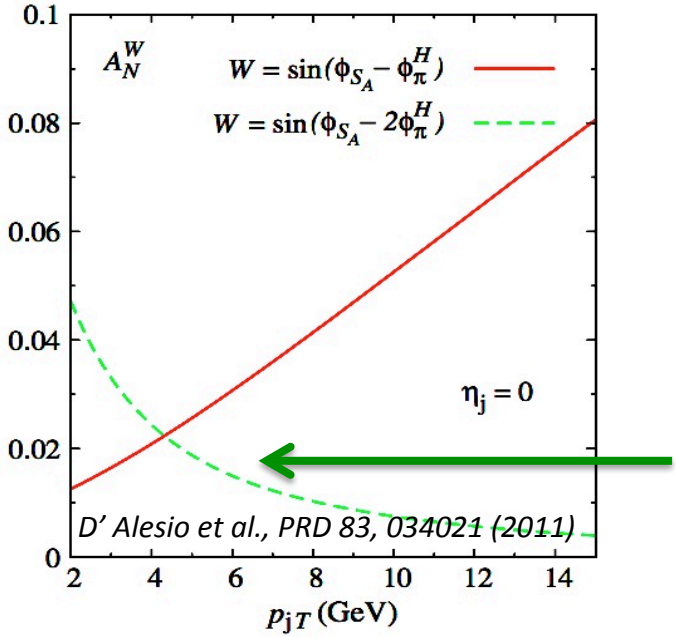
Run-12 provides opportunity for ***higher precision*** *and* ***greatly reduced systematic uncertainties***

STAR Transverse Asymmetries at Central Pseudorapidity





Maximized Contributions (*200 GeV*)



Run-11 provides first look at transverse-spin inclusive jets at central pseudorapidity range with √s = 500 GeV

Collins asymmetries expected to be small at √s = 500 GeV

Higher gluon participation at √s = 500 GeV allows unique sensitivity to gluon Collins-like asymmetry

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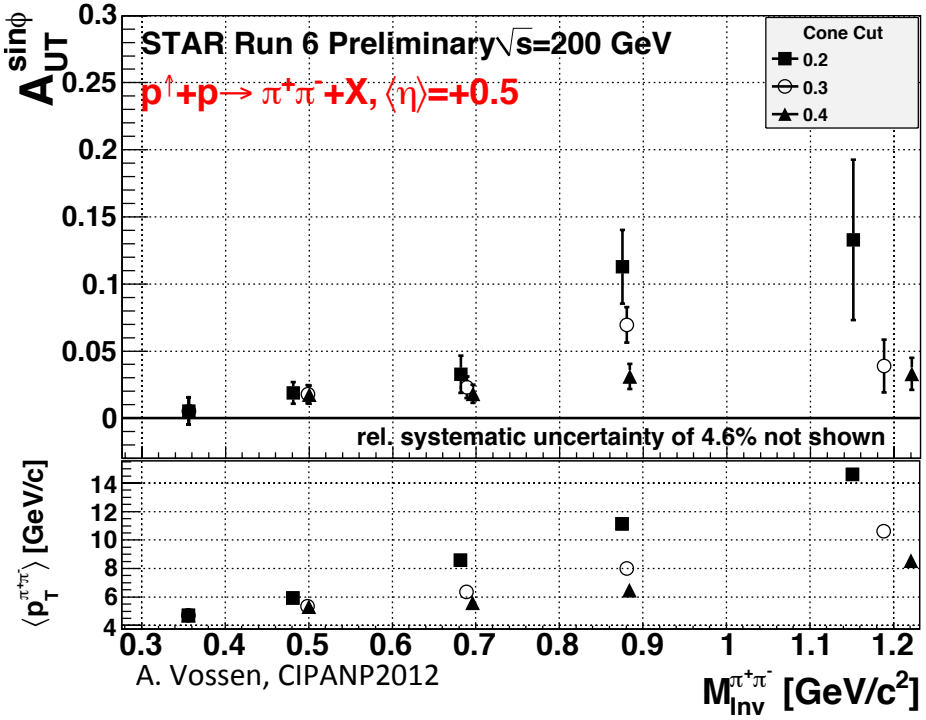
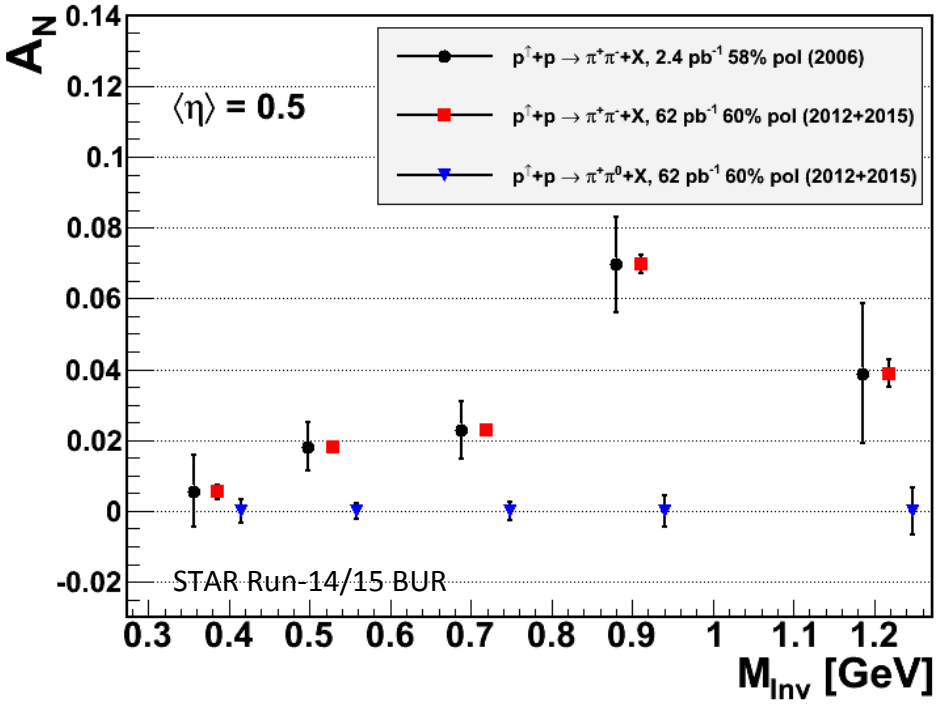




Sign of non-zero signal for di-hadron transverse single-spin asymmetries in Run-6 data

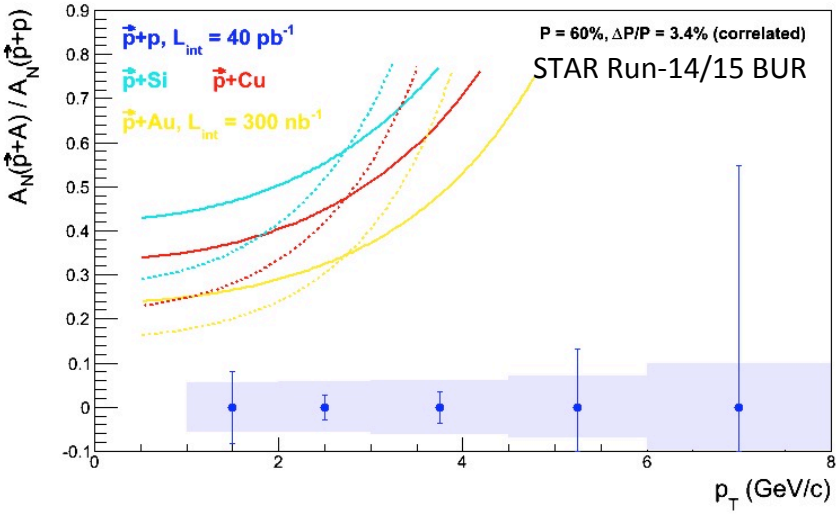
→ ***Constrain transversity at higher x?***

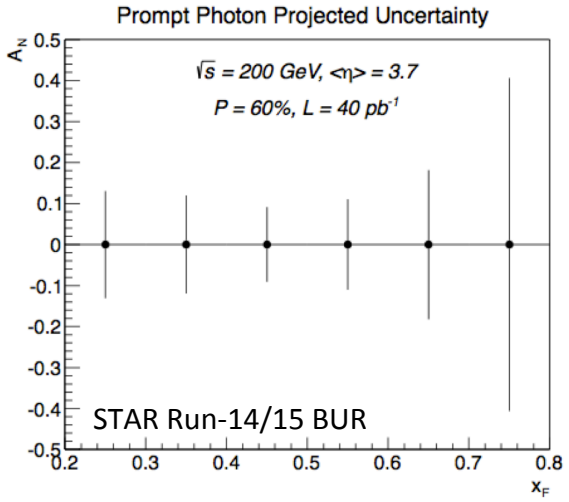
Run-12+15: opportunity for much higher precision

Measurements for Future Datasets

- **Single Transverse Spin Asymmetry in Polarized Proton-Proton Collisions**
  - Reduce statistical uncertainty by 1.4 over Run-12 of for Collins analysis
  - Increased precision for IFF's with addition of $\pi^{\pm}$-π^{0} measurement
  - Utilize forward upgrade for direct-photon Sivers measurement
- **Single Transverse Spin Asymmetry in Polarized Proton-Nucleus Collisions**
  - How does parton saturation enlighten our understanding of TMD's?
  - Can A_N get us to Weizsäcker-Williams gluon distribution?
  - What can direct-photon from pA teach us?
  - Studies of generalized parton distributions, e.g., exclusive J/ψ in ultra-peripheral collisions

See Session I Talk by L. Eun for more details





Summary

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- STAR investigation of large transverse asymmetries at forward-η:
  - Persistence of sizable asymmetries at forward pseudorapidity to $p_T \sim 10$ GeV/c
  - Precise investigation of A_N dependence of on event topology

    → ***asymmetries in jet-like π^0 are smaller than asymmetries in isolated π^0***
  - Investigation of forward calorimeter jets at $\sqrt{s}$ = 500 GeV underway
  - Measurement of π^0 A_N for the first time at intermediate pseudorapidity ($1 < \eta < 2$)

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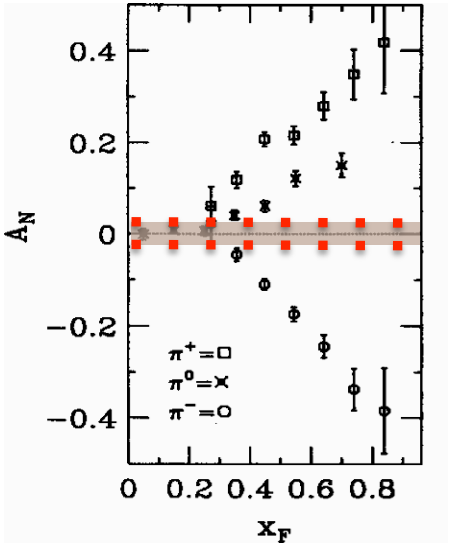
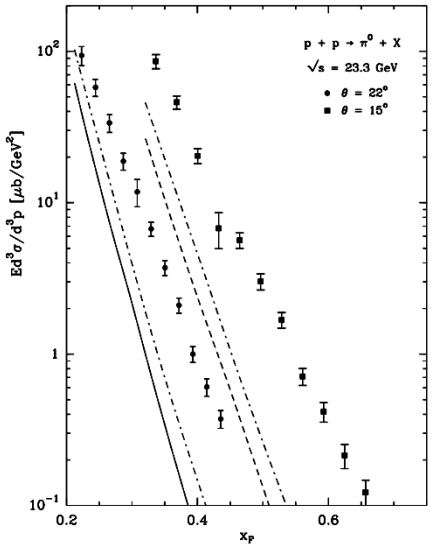
  - Extension of existing Collins and IFF analyses to higher statistical precision and reduced systematics (Run-12)
- Future endeavors include direct photons at forward-η and investigation of transverse-spin phenomena in p+Au collisions

Back-up Slides

Setting the Stage: Inclusive Asymmetries





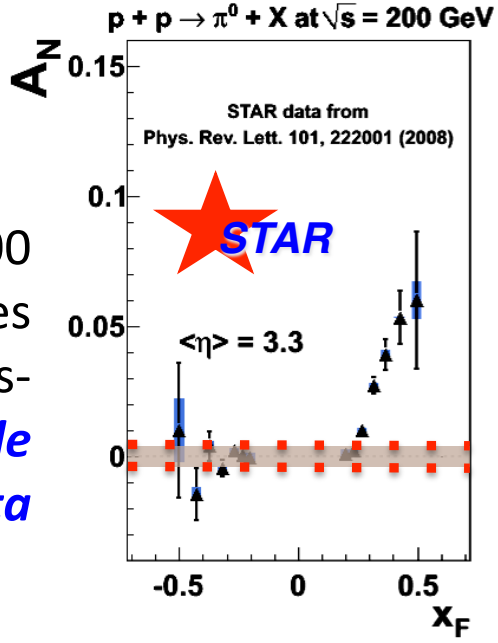
E704 showed *large* A_N for large x_F pion production at $\sqrt{s} \approx 20$ GeV.

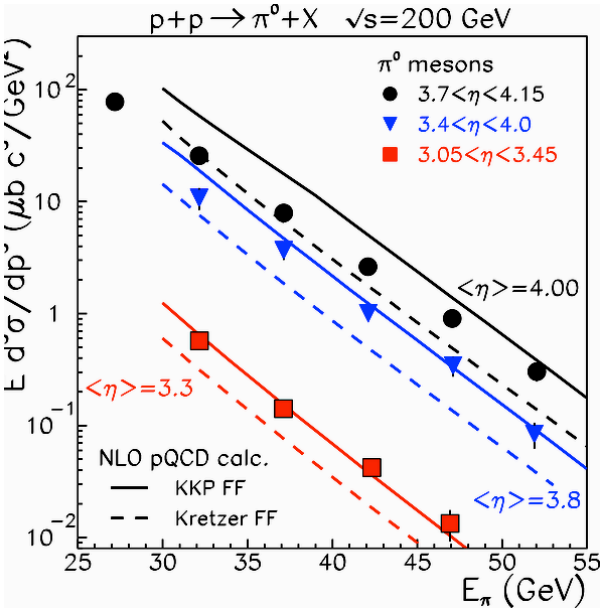
Observed cross-sections *large* compared to pQCD predictions

Phys. Lett. B 261, 201; 264, 462 (1991)

Eur. Phys. Journ. C36, 371 (2004)

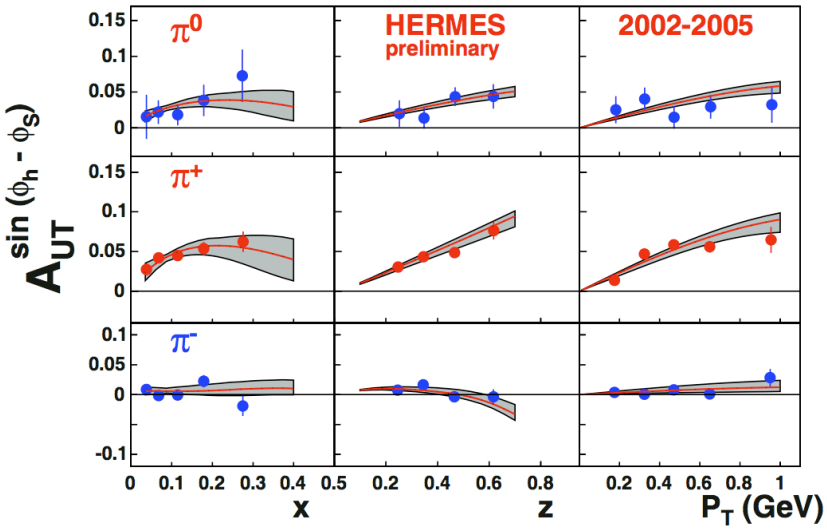
STAR observed *large* A_N for $\sqrt{s}$ = 200 GeV $p + p \rightarrow \pi^0 + X$ at forward angles in region where the pQCD cross-section provides a ***reasonable description of the data***





Phys. Rev. Lett. **97**, *152302 (2006)*

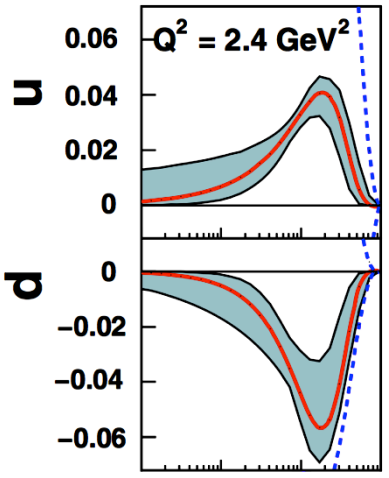
SIDIS Results: Sivers and Collins Asymmetries

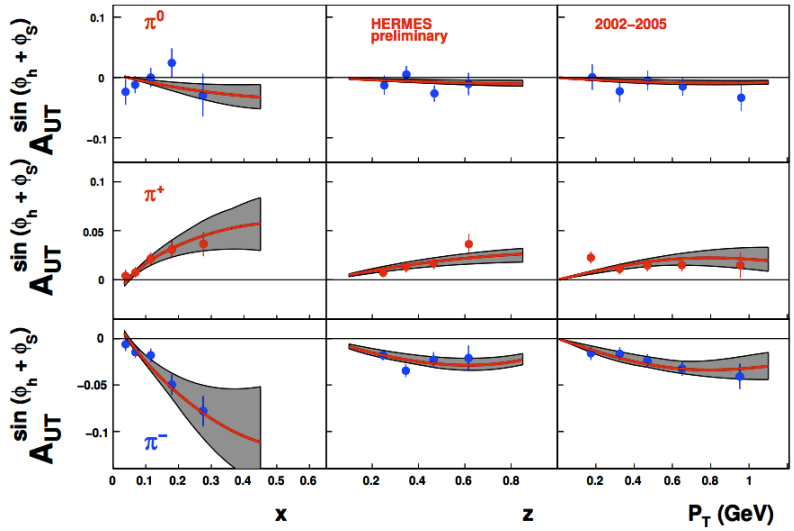


Assume:

- factorized functional form for Sivers function
- tune to SIDIS to parameterize

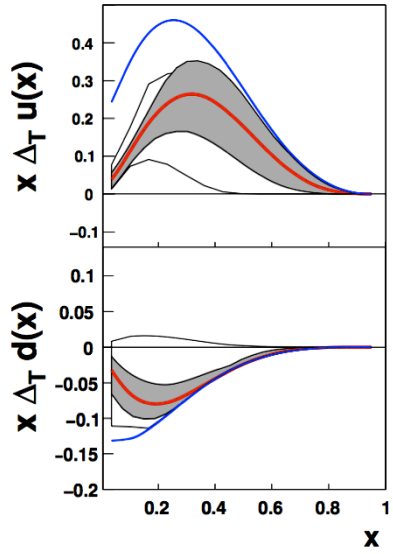
$x\Delta^N f^{(1)}(x)$





Assume:

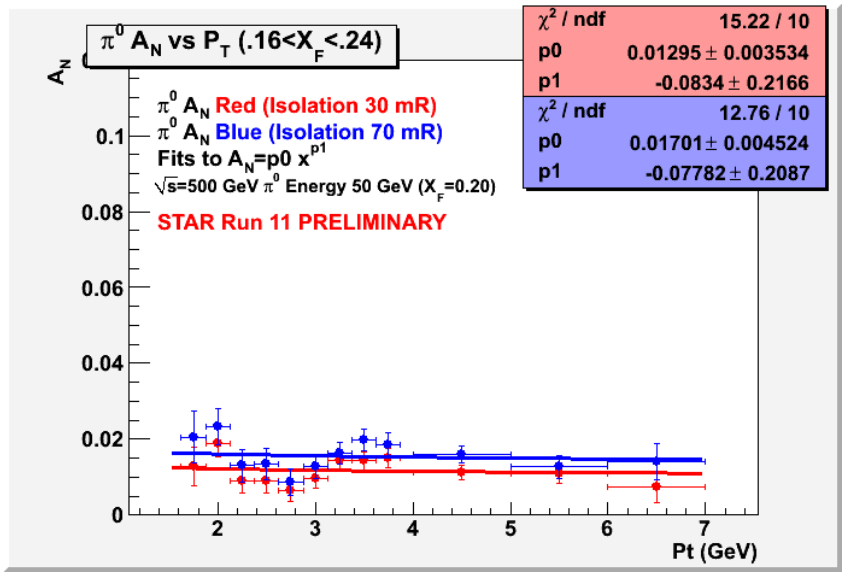
- factorized functional form for Collins and transversity function
- tune to *SIDIS and e^+e^-* to parameterize

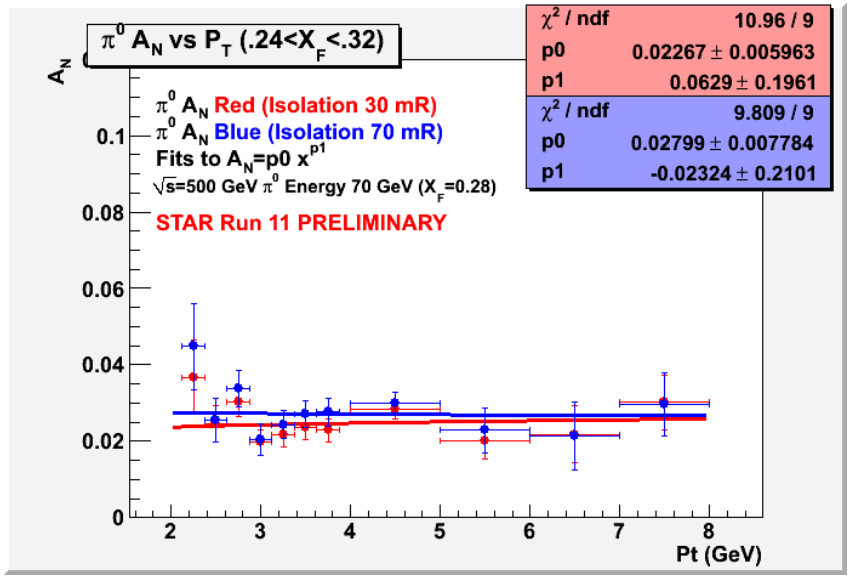


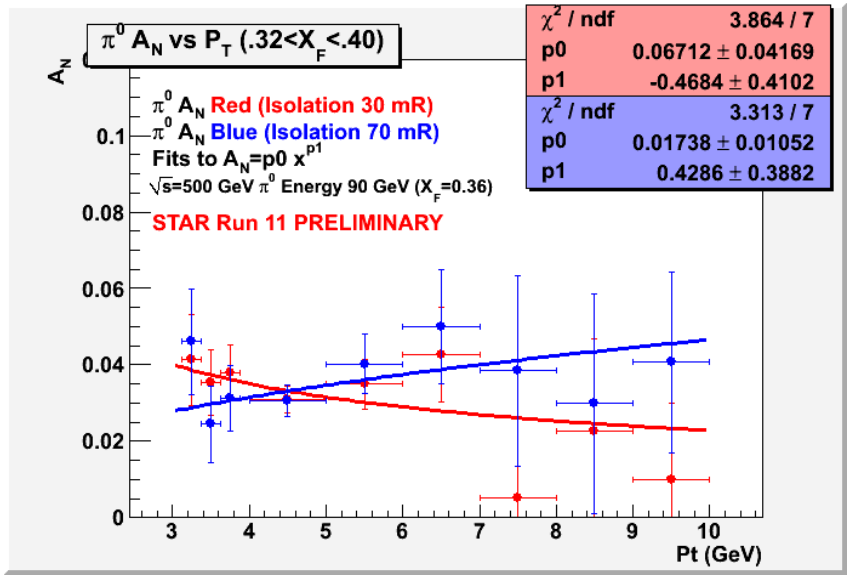
Eur. Phys. J. A 39, 89 (2009);
Nucl. Phys. B (Proc. Suppl.) 191, 98 (2009)

STAR Transverse Asymmetries at Forward Psuedorapidity

Despite expectation of $1/p_T$ scaling, STAR data from Run-3 to Run-8 show ***no sign of $1/p_T$ fall-off out to $p_T \sim 5$ GeV/c***





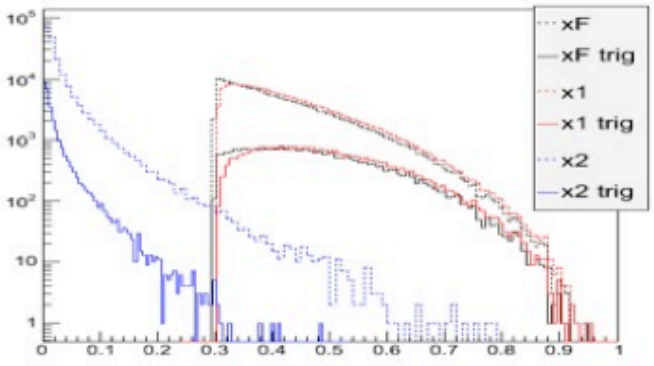


Forward Neutral-energy Jets

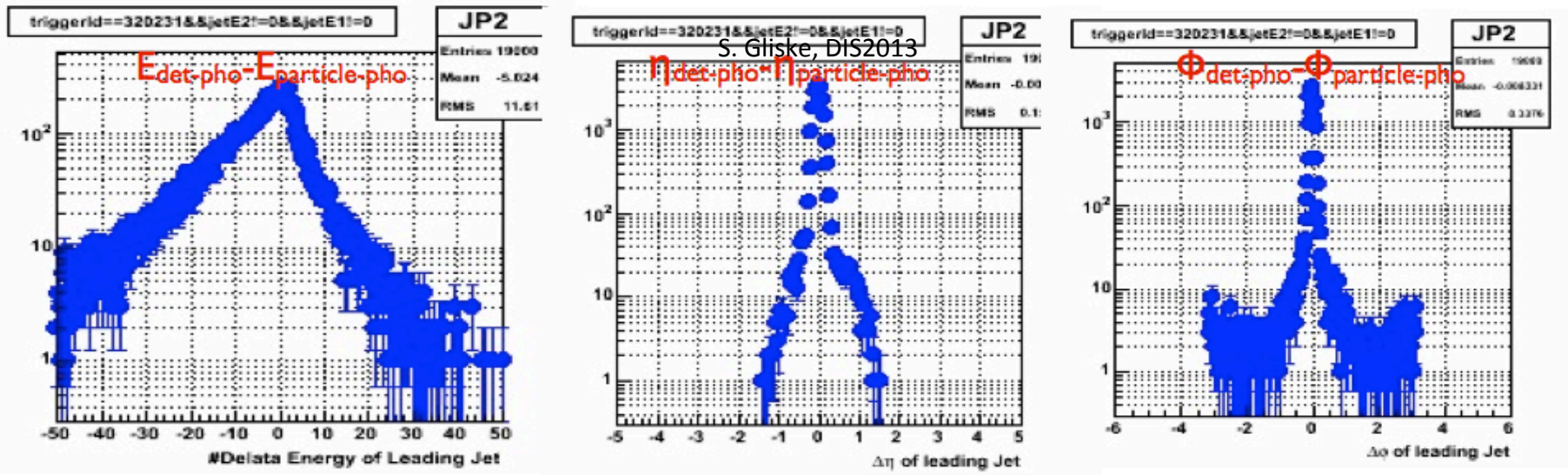
Goals: to correlate jets with neutral energy in the FMS with that of EEMC+BEMC ($-1 < \eta < 2$) and find A_N for jets and inclusive pions for various event topologies

simulation study on PYTHIA events with FMS only

PYTHIA is used for p+p at $\sqrt{s}$ = 500 GeV
Larger fraction of jets in FMS:
$x_F > 0.3$
p_T-hard > 7 GeV/c



After associating a detector-photon jet with a particle-photon jet in FMS

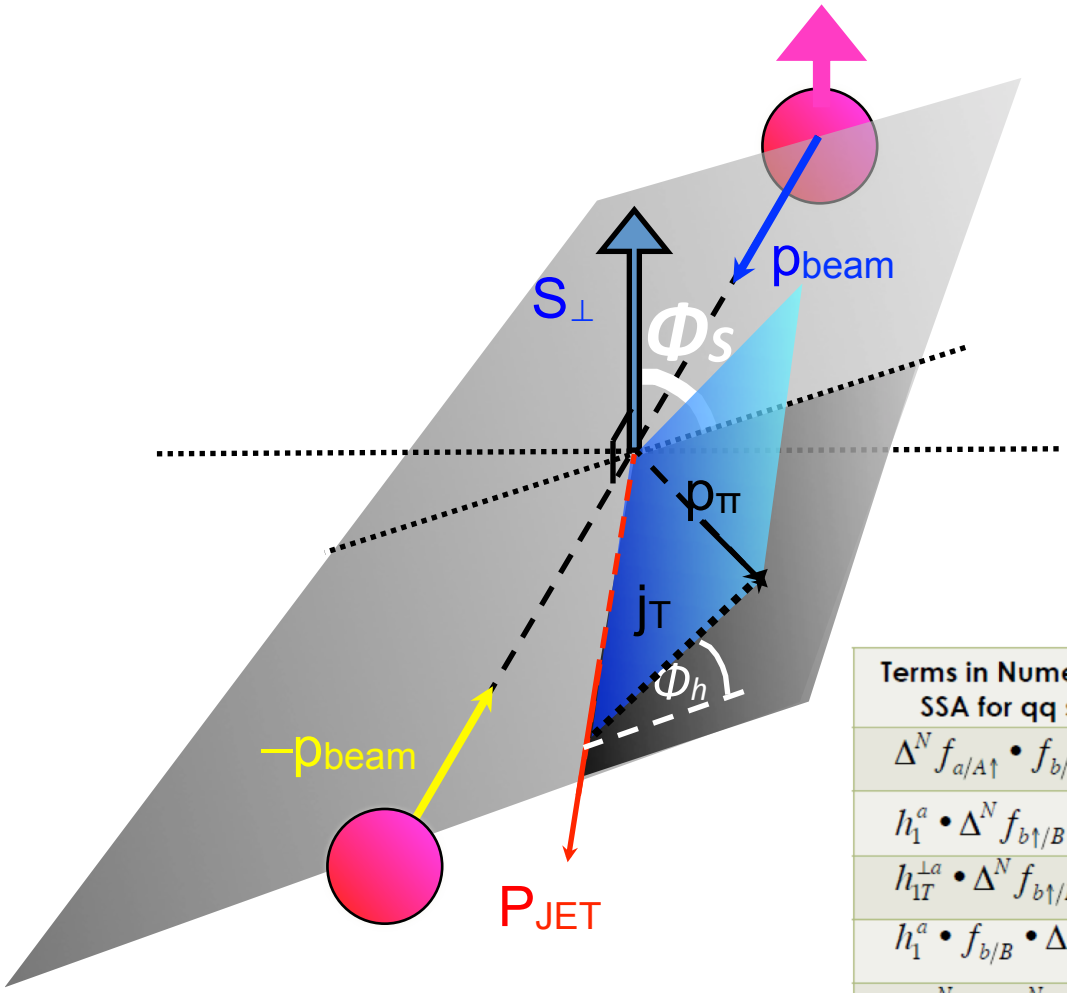


S. Gliske, DIS2013

M. Mondal, GHP2013

analysis of pp 500 transverse data is ongoing…

STAR Transverse Asymmetries at Central Pseudorapidity

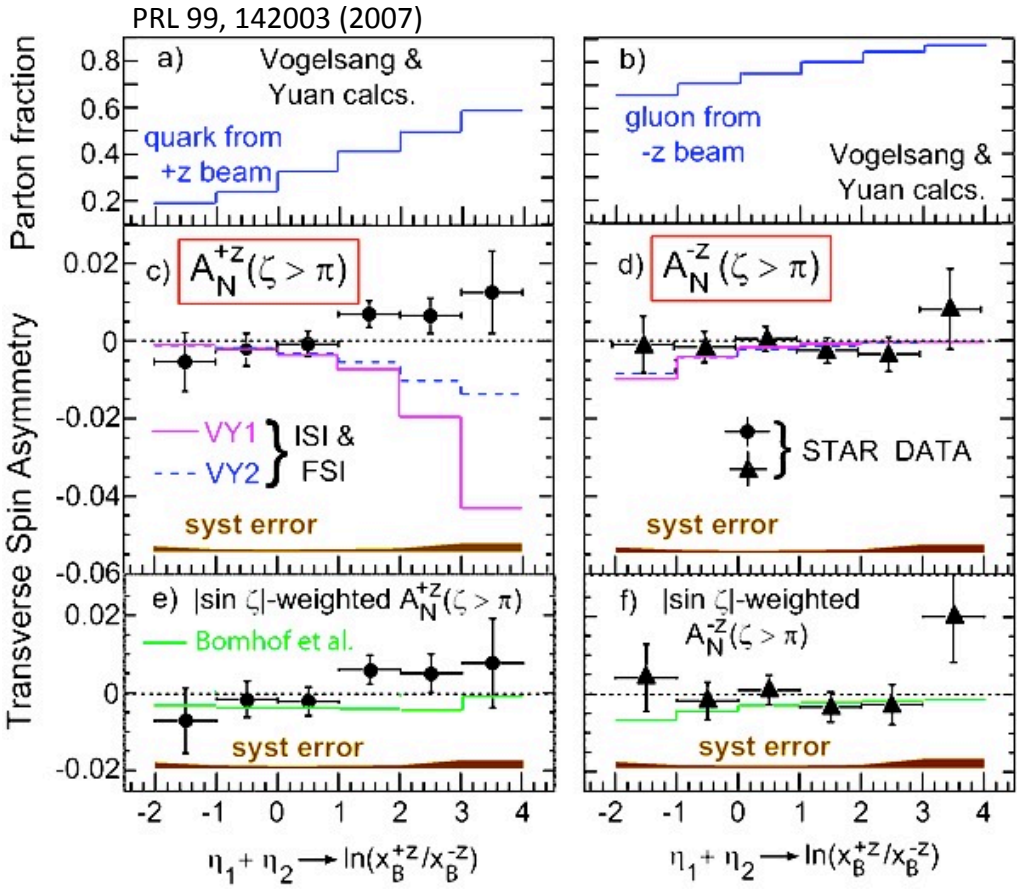


Asymmetry moments sensitive to various contributions (similar moments sensitive to gluon scattering)

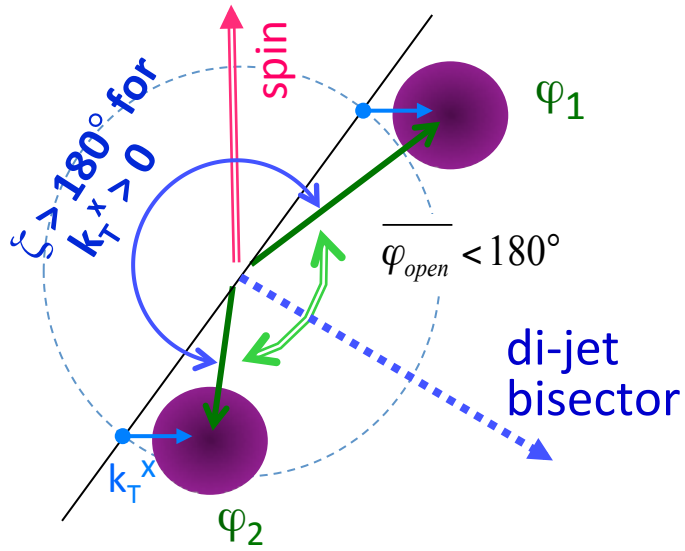
Terms in Numerator of TMD SSA for qq scattering	English Names	Modulate
$\Delta^N f_{a/A\uparrow} \bullet f_{b/B} \bullet D_{\pi/q}$	Sivers • PDF • FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Transversity•Boer-Mulder•FF	$\sin(\varphi_{S_A})$
$h_{1T}^{\perp a} \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Pretzelocity•Boer-Mulder•FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Transversity•PDF •Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulder•Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$h_{1T}^{\perp a} \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Pretzelocity•PDF•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulders•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$

F. Yuan, PRL 100, 032003 (2008)
D'Alesio et al., PRD 83, 034021 (2011)

STAR Transverse Asymmetries at Central Pseudorapidity



Sivers effect in di-jet production

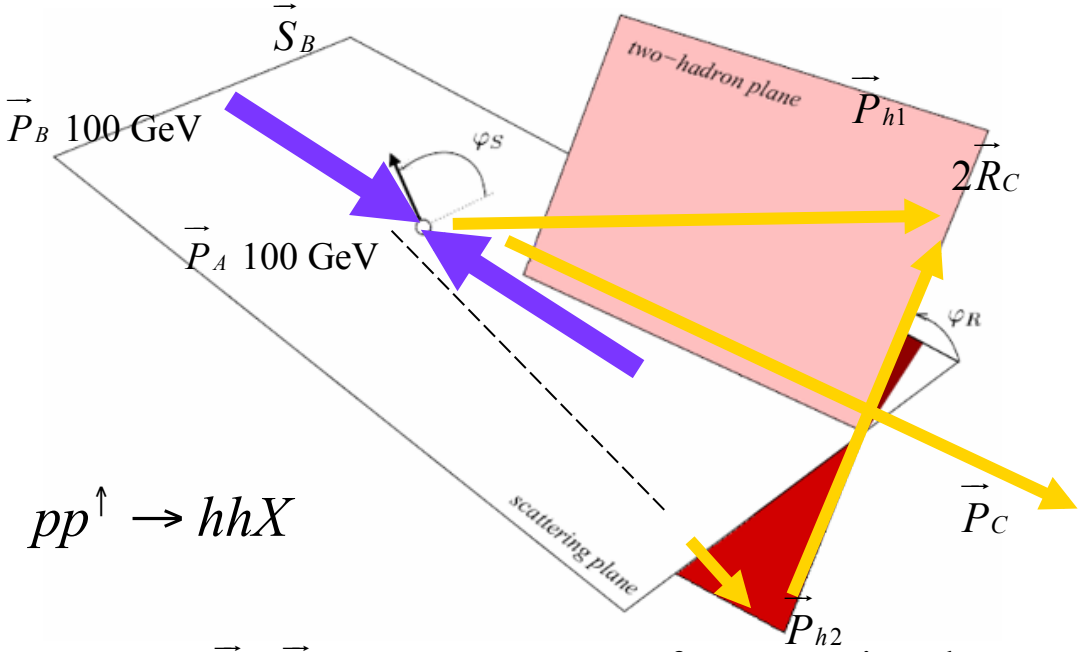


- Spin-dependent sideways boost to di-jets
- Measure di-jet opening angle as function of proton spin
- *Requires parton orbital angular momentum*

Observed di-jet asymmetries much smaller than observed at SIDIS

→ ***Cancellation of initial vs. final state interactions, u vs. d quark effects, and small gluon Sivers effect?***

IFF's: Definition of Vectors and Angles



p+p c.m.s. = lab frame

$\vec{P}_A, \vec{P}_B$: momenta of protons

$\vec{P}_{h1}, \vec{P}_{h2}$: momenta of hadrons

$\vec{P}_C = \vec{P}_{h1} + \vec{P}_{h2}$

$\vec{R}_C = (\vec{P}_{h1} - \vec{P}_{h2})/2$

$\vec{S}_B$: proton spin orientation

hadron plane: $\vec{P}_{h1}, \vec{P}_{h2}$

scattering plane: $\vec{P}_C, \vec{P}_B$

ϕ_R : from scattering plane to hadron plane

ϕ_S : from polarization vector to scattering plane

$$\cos\phi_{S_A} = \frac{(\hat{\mathbf{P}}_A \times \mathbf{P}_C)}{|\hat{\mathbf{P}}_A \times \mathbf{P}_C|} \cdot \frac{(\hat{\mathbf{P}}_A \times \mathbf{S}_A)}{|\hat{\mathbf{P}}_A \times \mathbf{S}_A|}, \qquad \sin\phi_{S_A} = \frac{(\mathbf{P}_C \times \mathbf{S}_A) \cdot \hat{\mathbf{P}}_A}{|\hat{\mathbf{P}}_A \times \mathbf{P}_C|\,|\hat{\mathbf{P}}_A \times \mathbf{S}_A|},$$

$$\cos\phi_{S_B} = \frac{(\hat{\mathbf{P}}_B \times \mathbf{P}_C)}{|\hat{\mathbf{P}}_B \times \mathbf{P}_C|} \cdot \frac{(\hat{\mathbf{P}}_B \times \mathbf{S}_B)}{|\hat{\mathbf{P}}_B \times \mathbf{S}_B|}, \qquad \sin\phi_{S_B} = \frac{(\mathbf{P}_C \times \mathbf{S}_B) \cdot \hat{\mathbf{P}}_B}{|\hat{\mathbf{P}}_B \times \mathbf{P}_C|\,|\hat{\mathbf{P}}_B \times \mathbf{S}_B|},$$

$$\cos\phi_{R_C} = \frac{(\hat{\mathbf{P}}_C \times \mathbf{P}_A)}{|\hat{\mathbf{P}}_C \times \mathbf{P}_A|} \cdot \frac{(\hat{\mathbf{P}}_C \times \mathbf{R}_C)}{|\hat{\mathbf{P}}_C \times \mathbf{R}_C|}, \qquad \sin\phi_{R_C} = \frac{(\mathbf{P}_A \times \mathbf{R}_C) \cdot \hat{\mathbf{P}}_C}{|\hat{\mathbf{P}}_C \times \mathbf{P}_A|\,|\hat{\mathbf{P}}_C \times \mathbf{R}_C|},$$

Bacchetta and Radici, PRD70, 094032 (2004)

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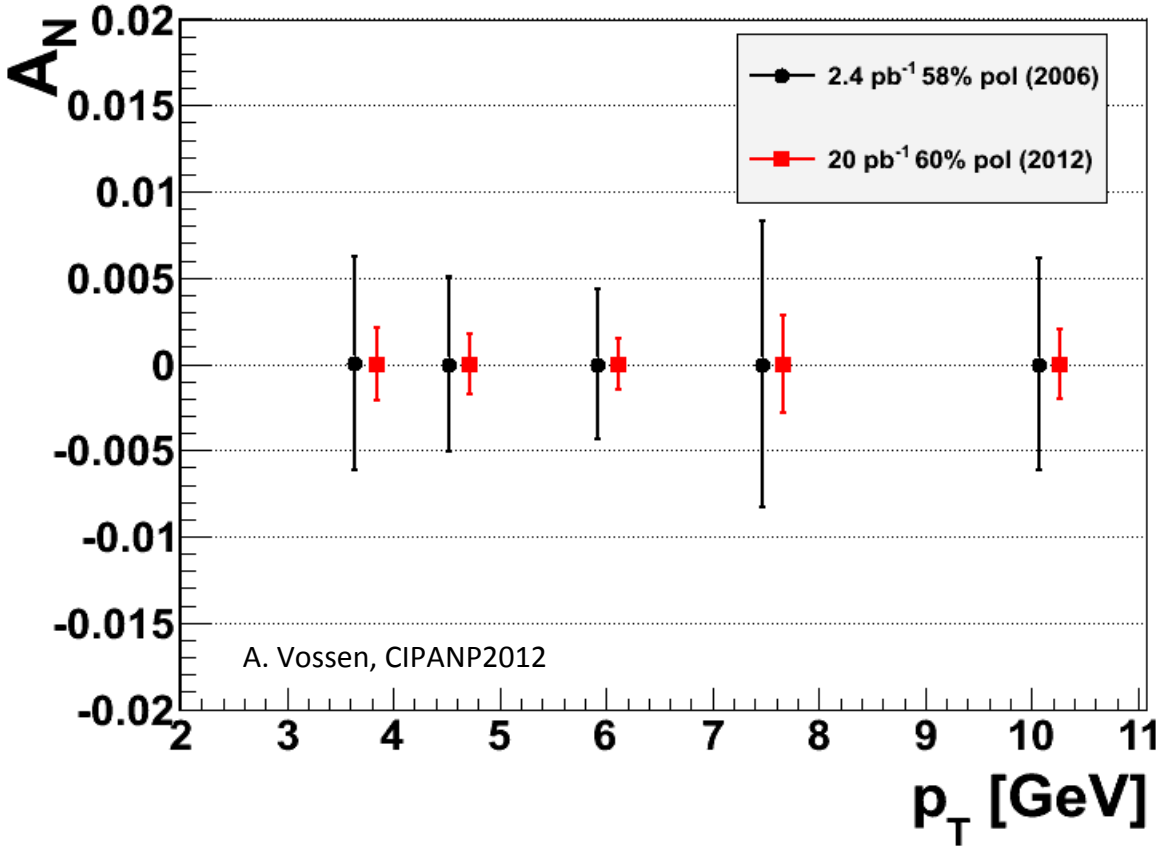
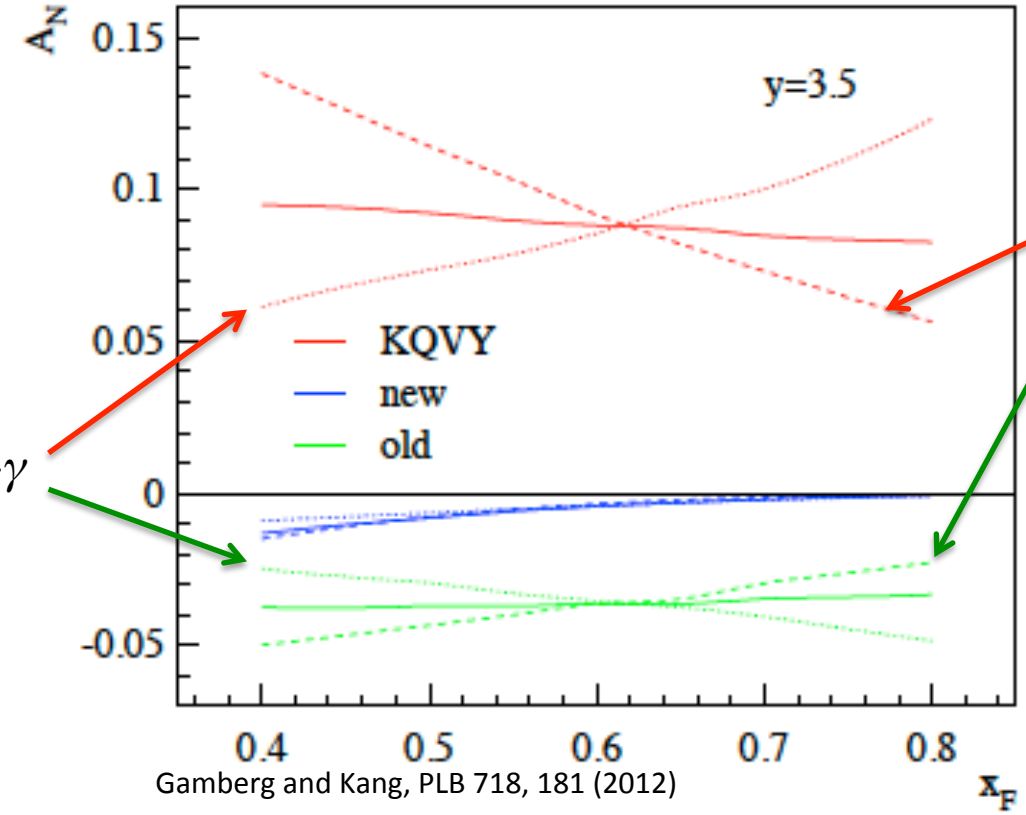


Forward Direct Photons



direct-γ

fragmentation-γ

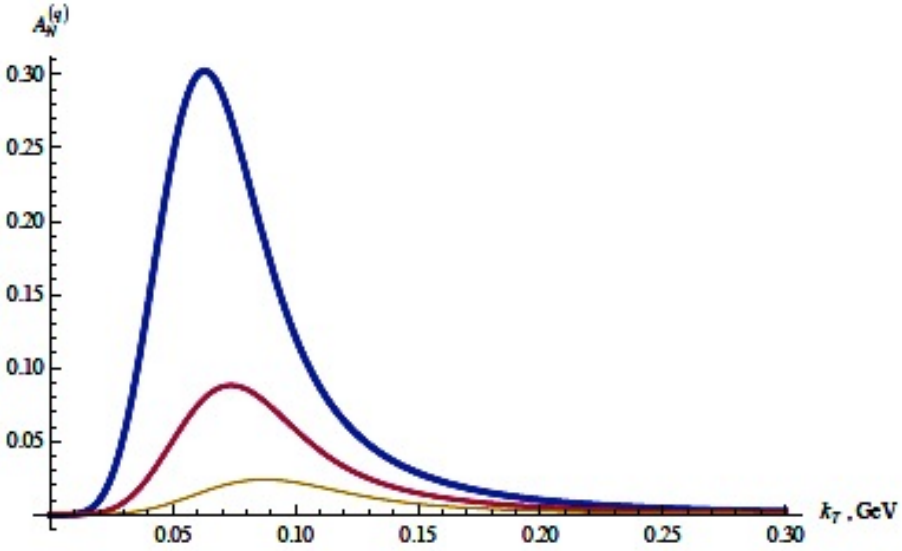
Gamberg and Kang, PLB 718, 181 (2012)

FMS preshower will aid the investigation of forward pseudorapidity direct photon asymmetries

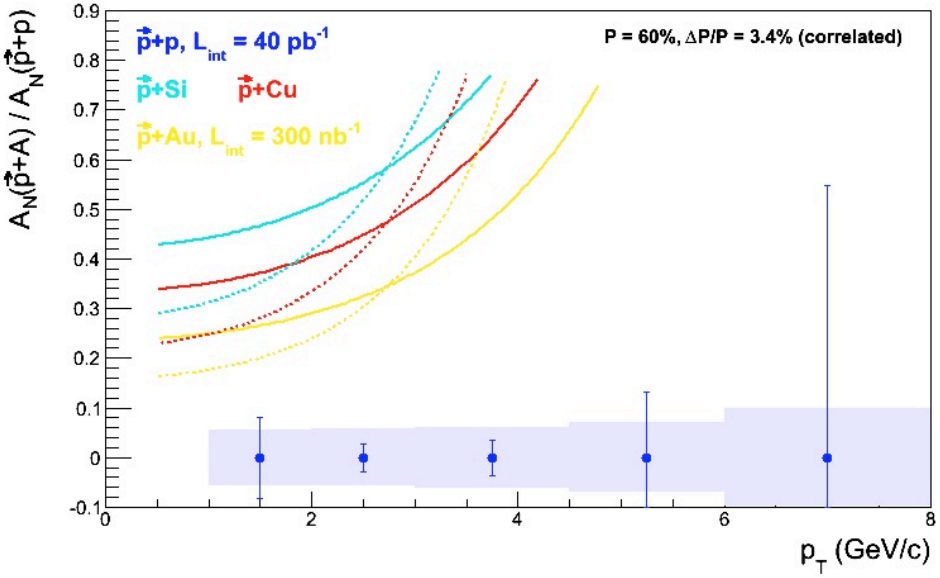
→ **direct access to Sivers effect**

40 pb^{-1} sufficient to distinguish between model assumptions

A_N from p+Au Collisions



Predicted quark SSA for different values of target radius (1, 1.4, and 2 fm)



40 pb^{-1} p+p and 300 nb^{-1} p+Au are sufficient to measure transverse spin observables in pA