Overview of *STAR* Spin Measurements

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for the STAR Collaboration

OUTLINE

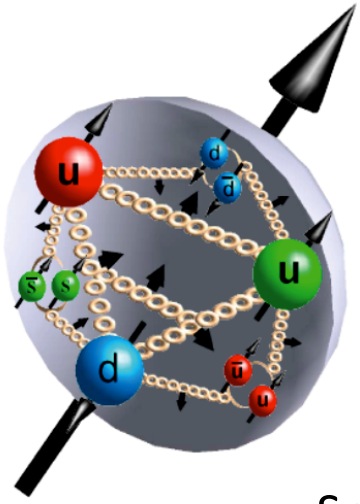
- Introduction
- Inclusive hadron production
- Jet+hadron and di-hadron production
- Summary

STAR

Valparaiso University

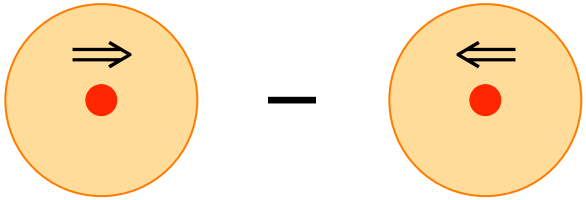
Contributions to Proton Spin Structure

Consider proton moving right



Proton spin ⇒

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



coming into focus:

$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.1 \pm^{0.06}_{0.07}$$

arXiv:nucl-ex/1304.0079

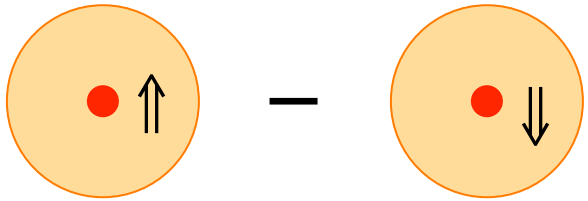
Polarized DIS: ~ 0.3

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

poorly constrained

Proton spin ⇑

$h_1(x)$



Transversity – data over limited kinematic range: $x_{Bj} \leq 0.3$

Contributions to Proton Spin Structure

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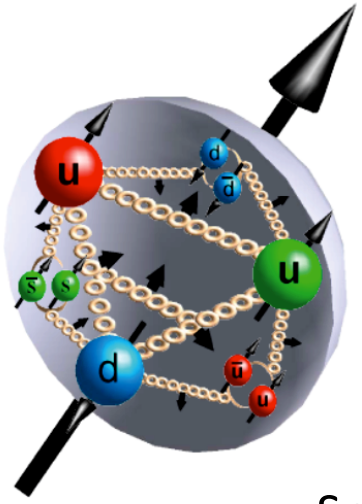

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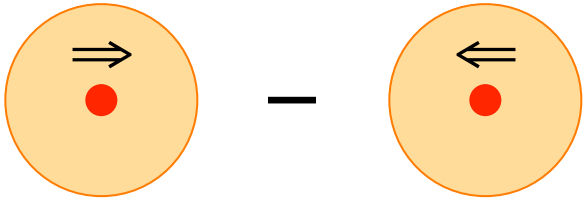

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STAR spin program:
Exploring components of the proton with limited constraints

Proton spin ⇑

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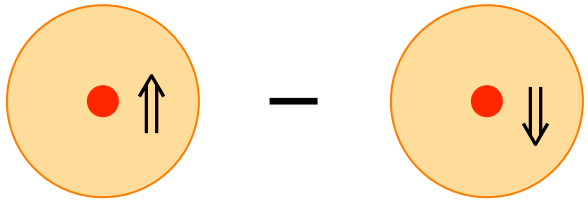

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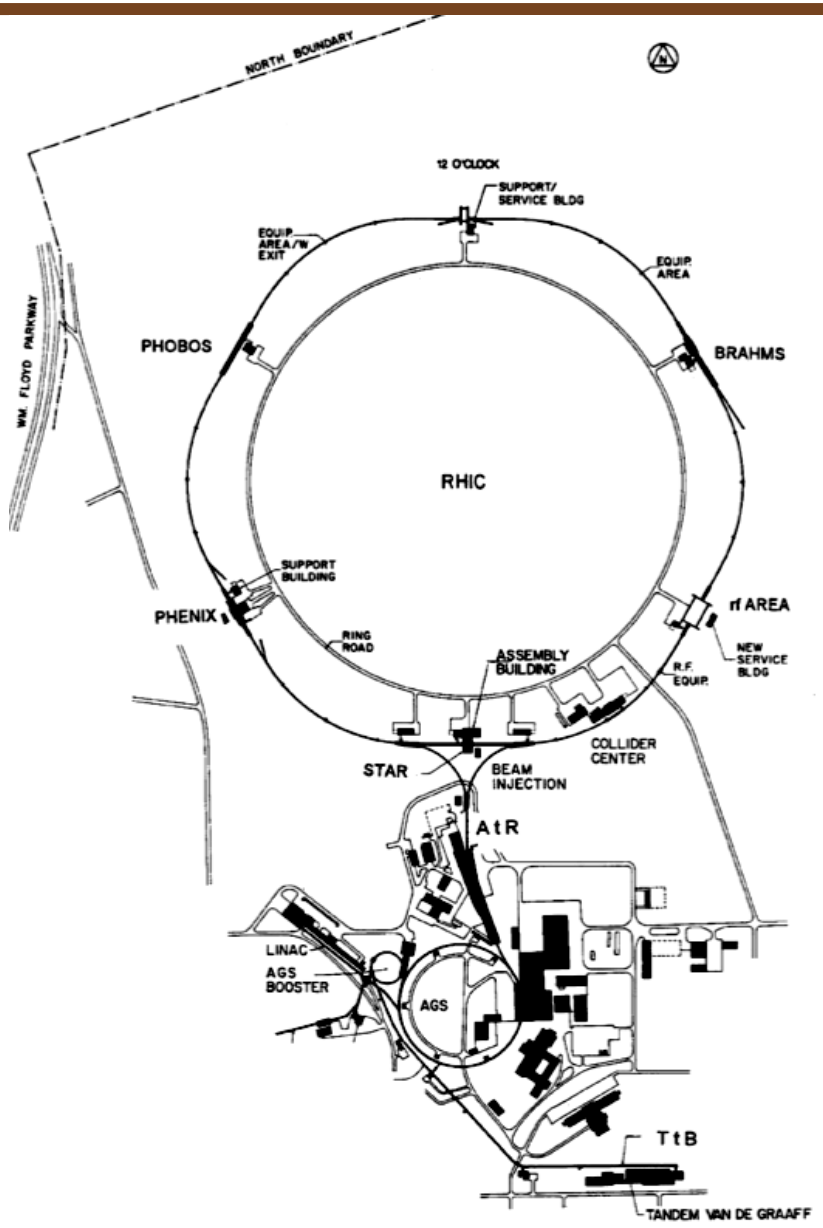
Relativistic Heavy Ion Collider as a Spin Collider



Concert of Facilities

- OPPIS → LINAC → AGS → RHIC

Polarized-proton Collider

- Mitigate effects of depolarization resonances with "Siberian Snakes"
- Polarization measured with CNI polarimeter
- Spin rotators provide choice of spin orientation *independent of experiment*

RHIC Beam Characteristics

- Clockwise beam: "**blue**"; counter-clockwise beam: "**yellow**"
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill

Solenoidal Tracker at RHIC

Inclusive hadron measurements:

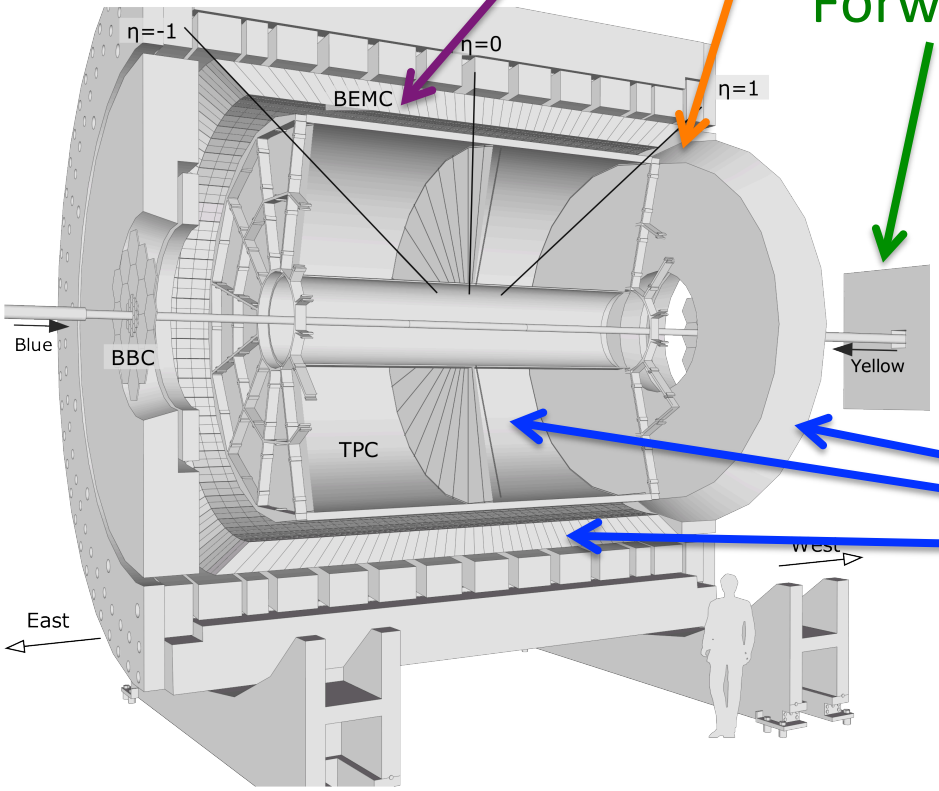
Barrel ElectroMagnetic Calorimeter (BEMC),

Endcap ElectroMagnetic Calorimeter (EEMC),

and

Forward Meson Spectrometer (FMS)

FPD (east) not shown

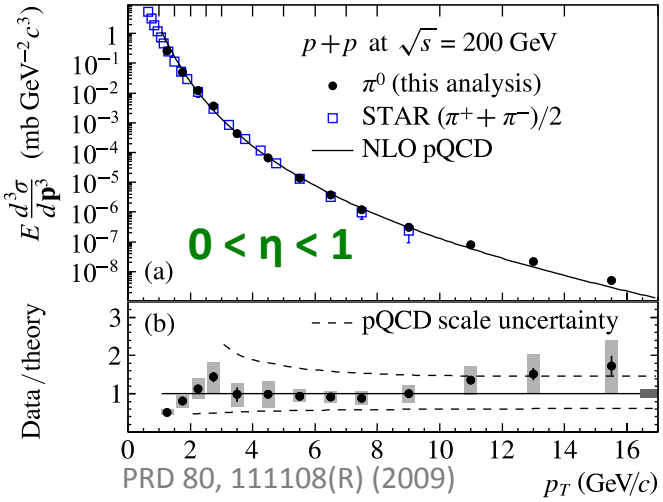


Jet and di-hadron measurements:

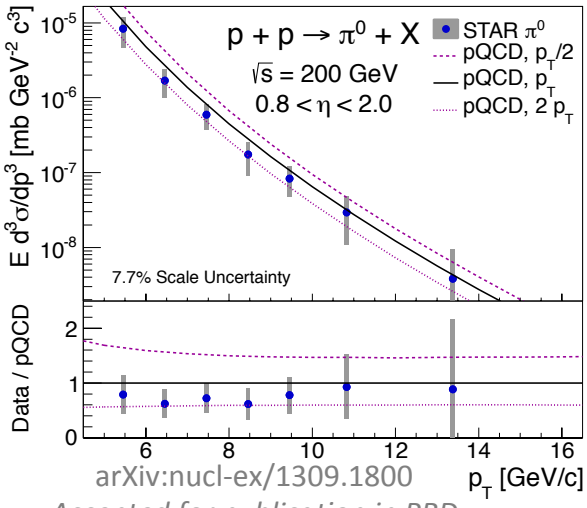
TPC + Barrel + Endcap EMC

For details on STAR hyperons, stay tuned for E. Sichtermann's talk, coming right up!

Inclusive Hadron Production at STAR



PRD 80, 111108(R) (2009)



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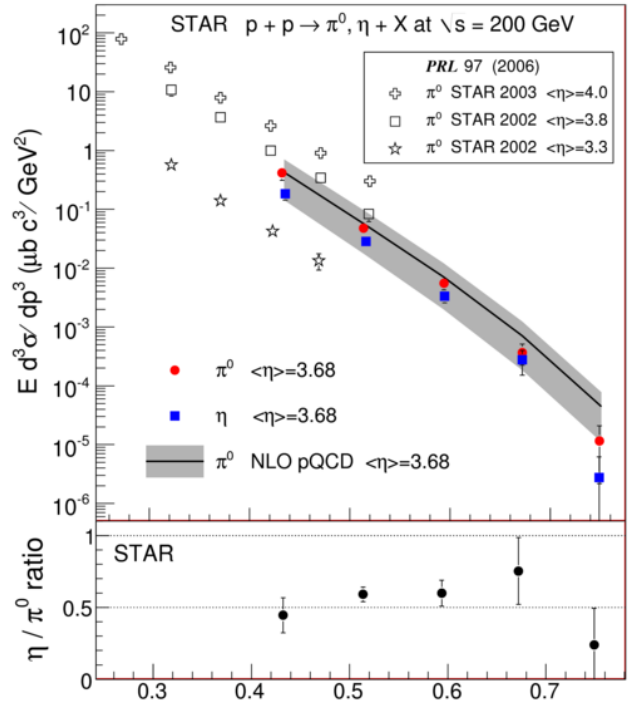
Accepted for publication in PRD



PRD 86, 051101(R) (2012)

Inclusive π^0 production at $\sqrt{s} = 200$ GeV measured over three ranges of pseudorapidity at STAR

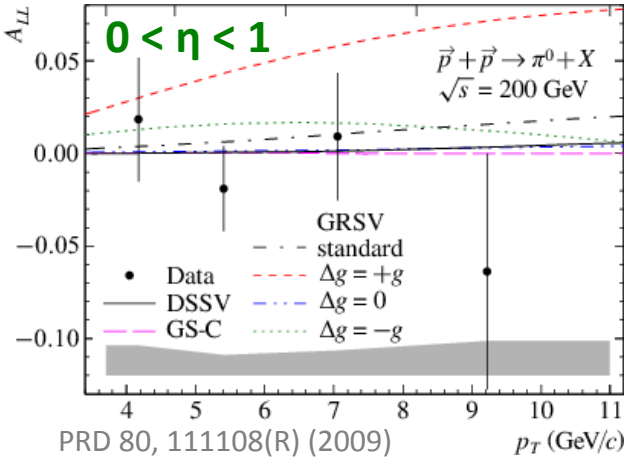
All in agreement with NLO pQCD predictions (DSS Frag. Func.)

→ **Important benchmark for asymmetry studies**

(*Inclusive jet cross section at 200 GeV also found in agreement with NLO pQCD*)

PRL 97, 252001 (2006)

STAR Longitudinal Asymmetries from Inclusive Hadrons



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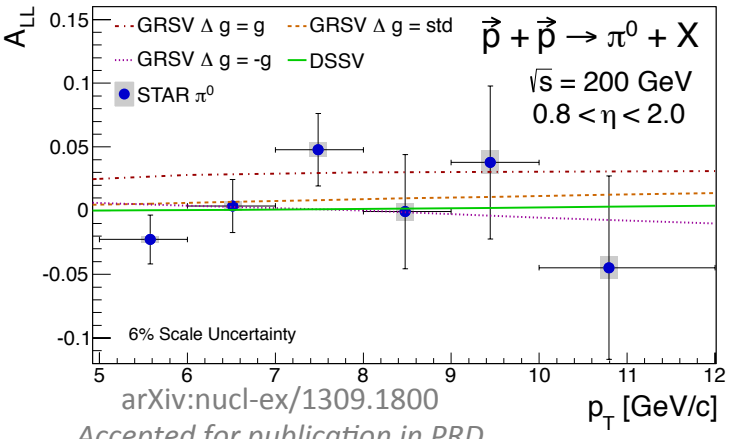

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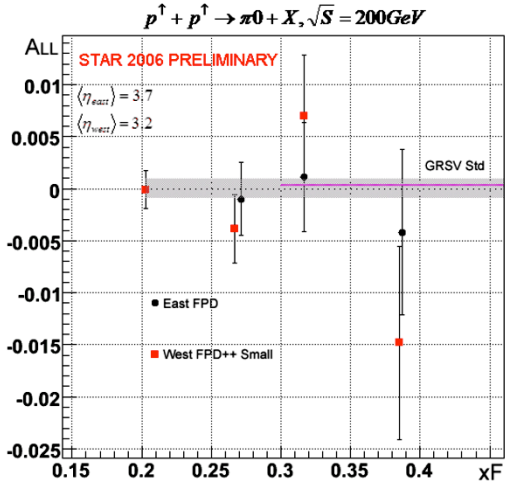
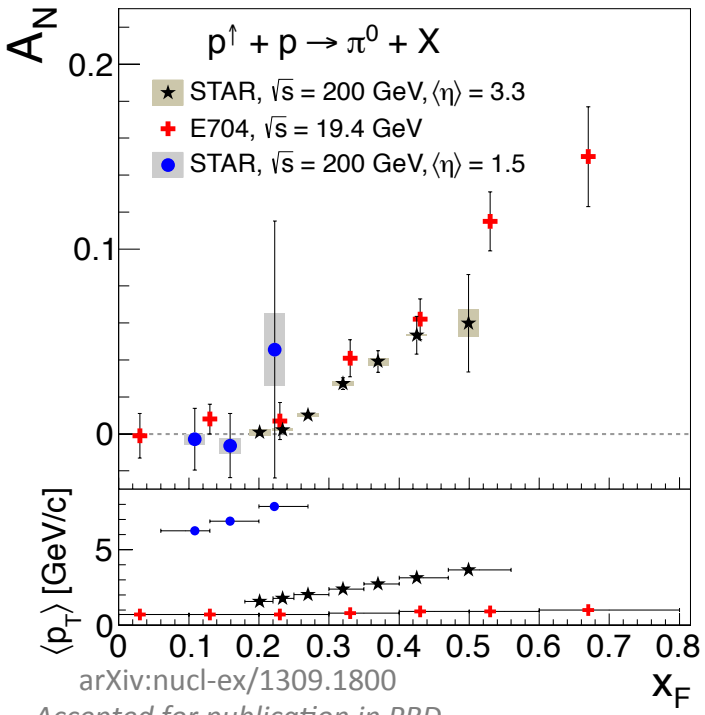


S. Wissink, Spin 2008

A_{LL} for Inclusive π^0 production at $\sqrt{s} = 200$ GeV measured over three ranges of pseudorapidity at STAR

- Complementary to STAR jet measurements
- Expect A_{LL} to decrease with increasing pseudorapididty
- Current statistics dominated by 2005/2006 datasets
- Higher-statistics datasets under investigation

STAR Transverse Asymmetries from Inclusive Hadrons



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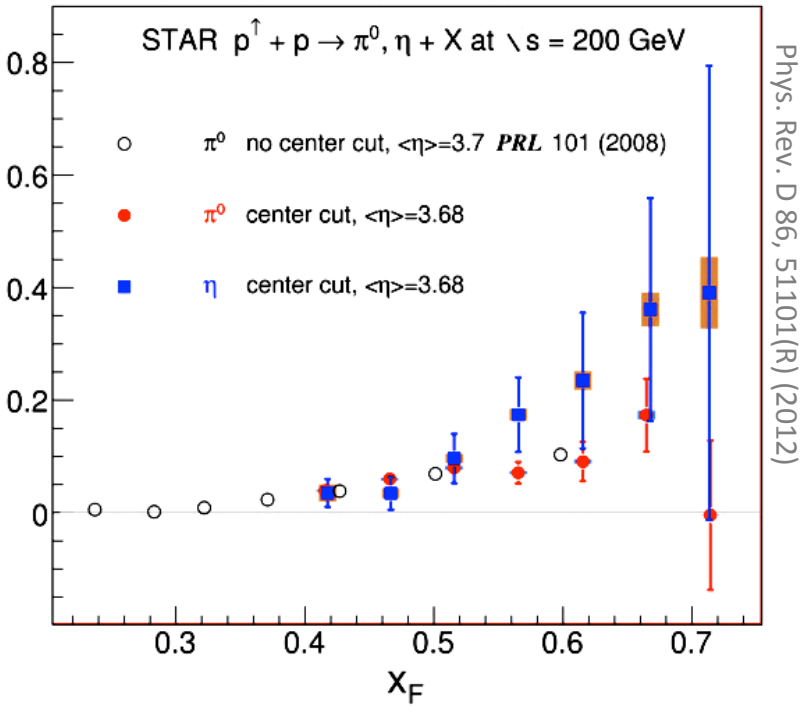


Phys. Rev. D 86, 51101(R) (2012)

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

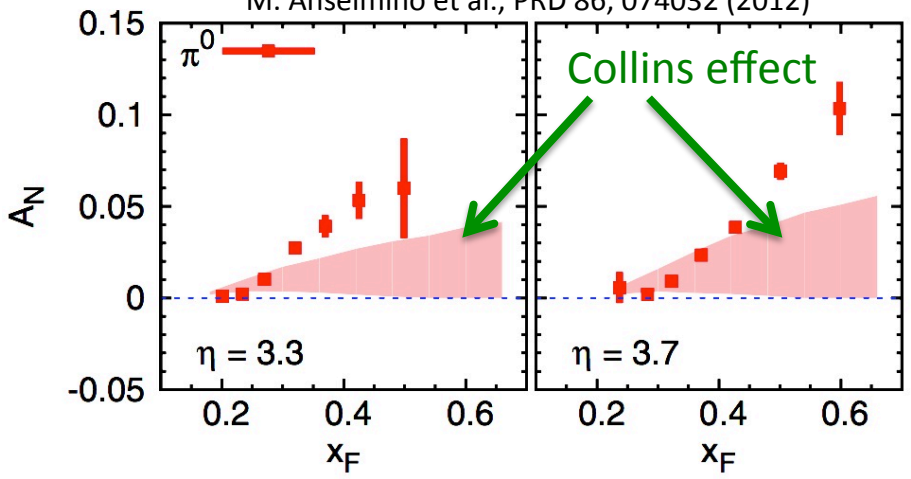
At high-x_F, η asymmetry may be larger than that of π^0

Asymmetries at intermediate pseudorapidity consistent with zero

Above results mostly from 2006 (6.8 pb^{-1} at 55% polarization)

STAR Transverse Asymmetries from Inclusive Hadrons

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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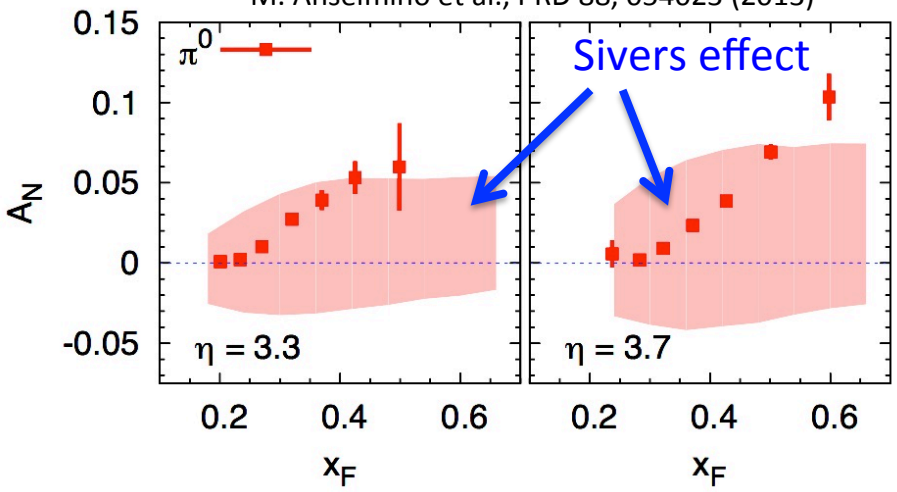

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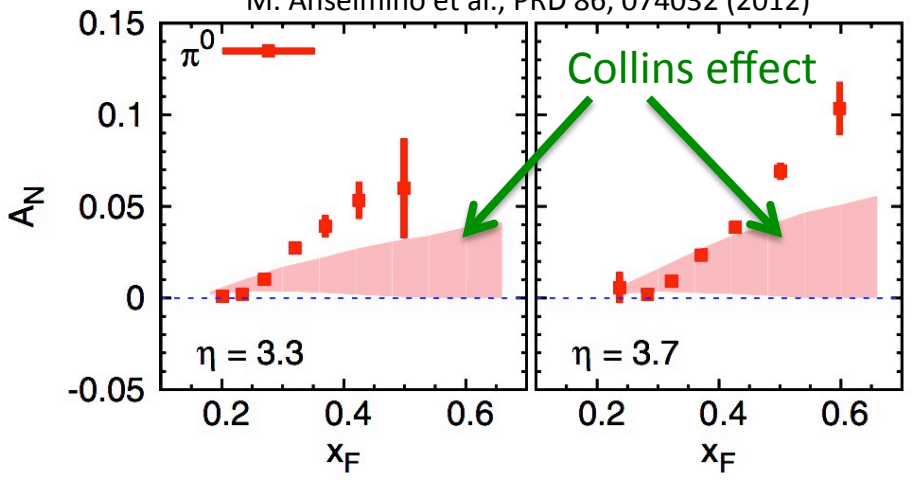

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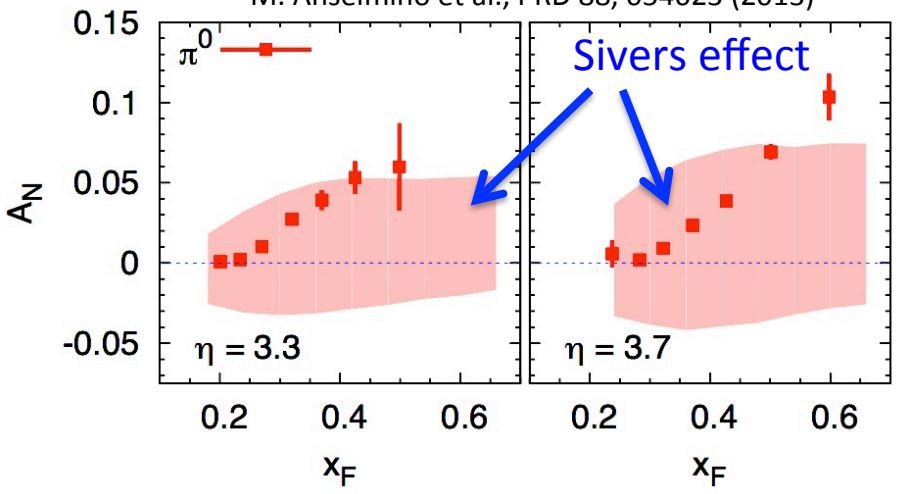

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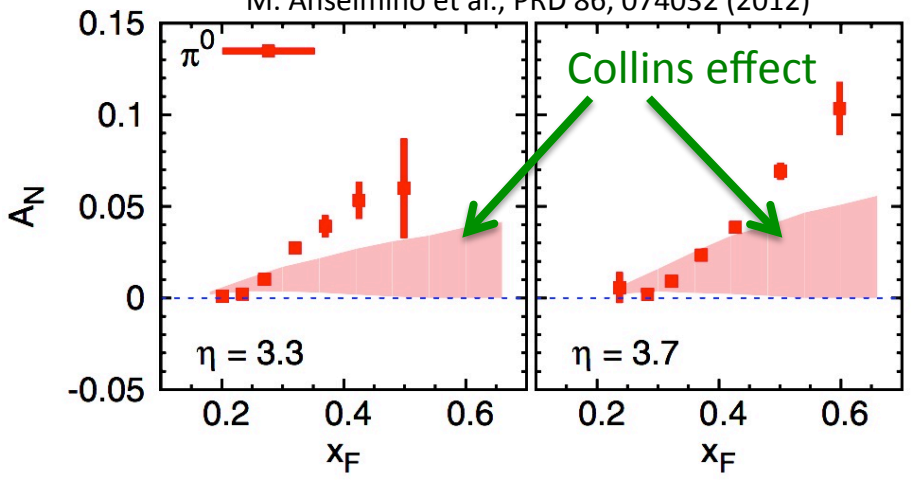

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Theoretical questions remain about applicability to p+p data of Sivers extractions from SIDIS

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

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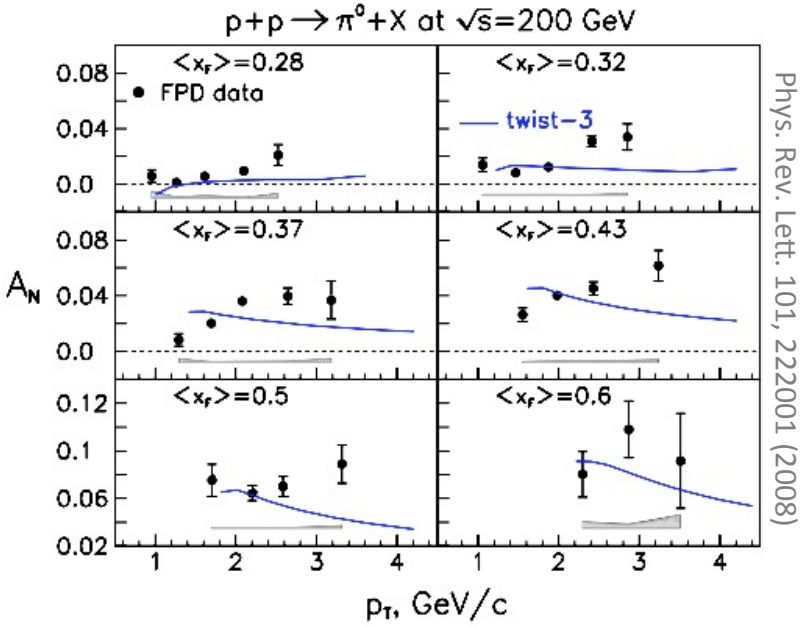
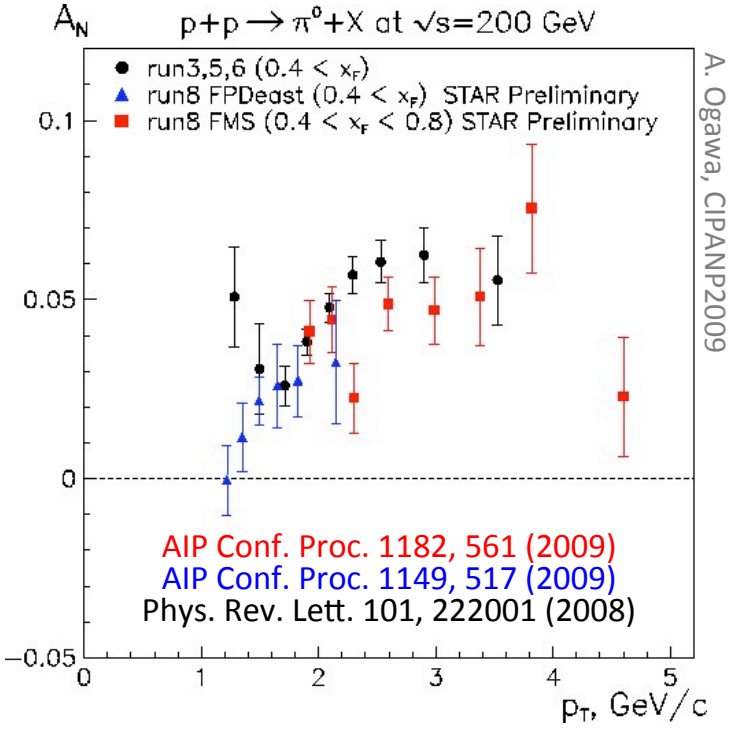
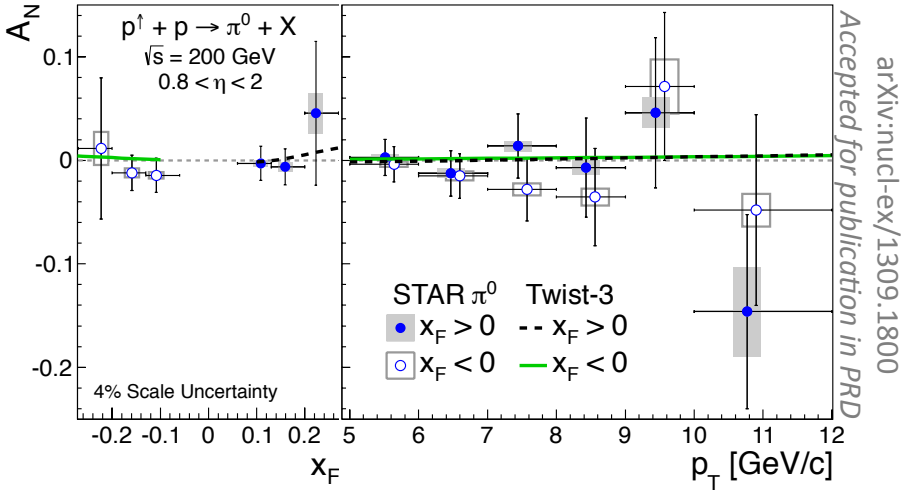


Phys. Rev. Lett. 101, 222001 (2008)



A. Ogawa, CIPANP2009



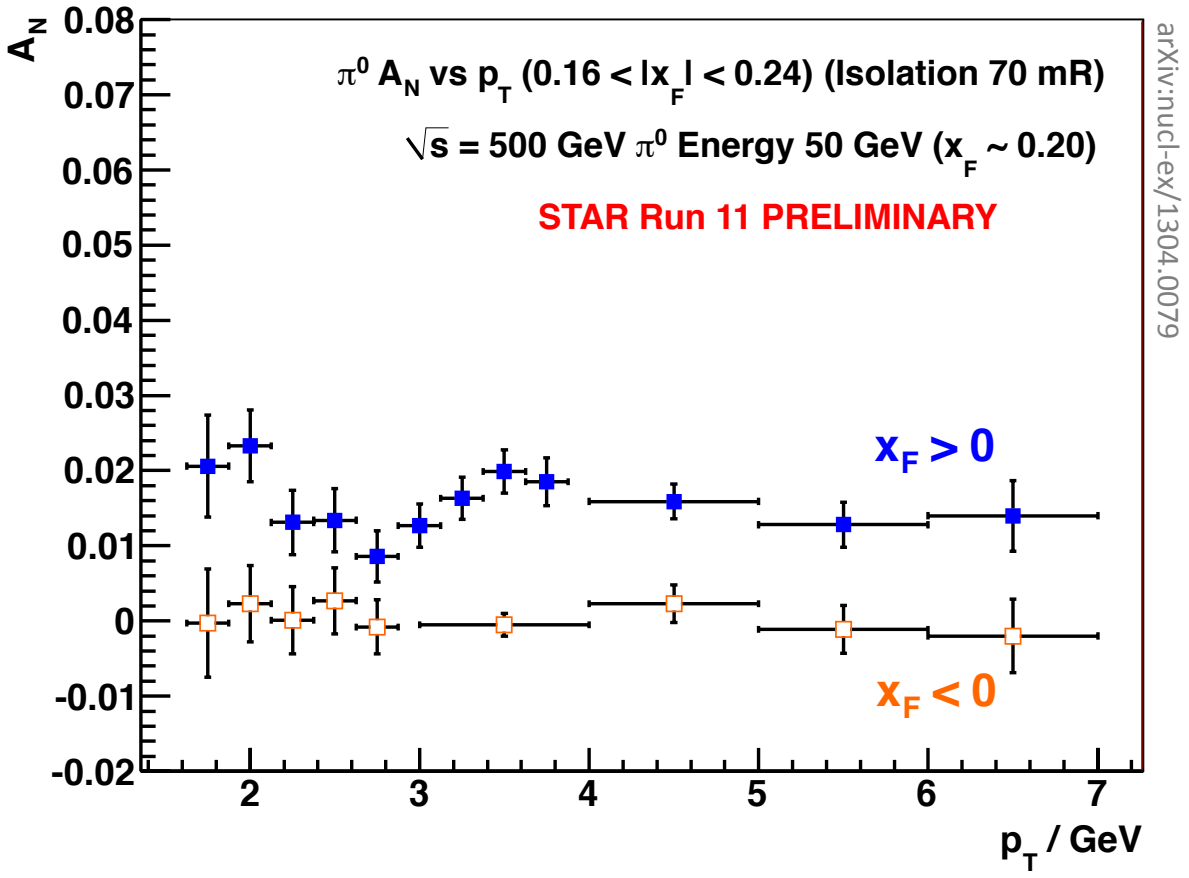
arXiv:nucl-ex/1309.1800

Accepted for publication in PRD

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***

Asymmetries at intermediate-η consistent with zero for $5 < p_T < 12$ GeV/c

STAR Transverse Asymmetries from Inclusive Hadrons



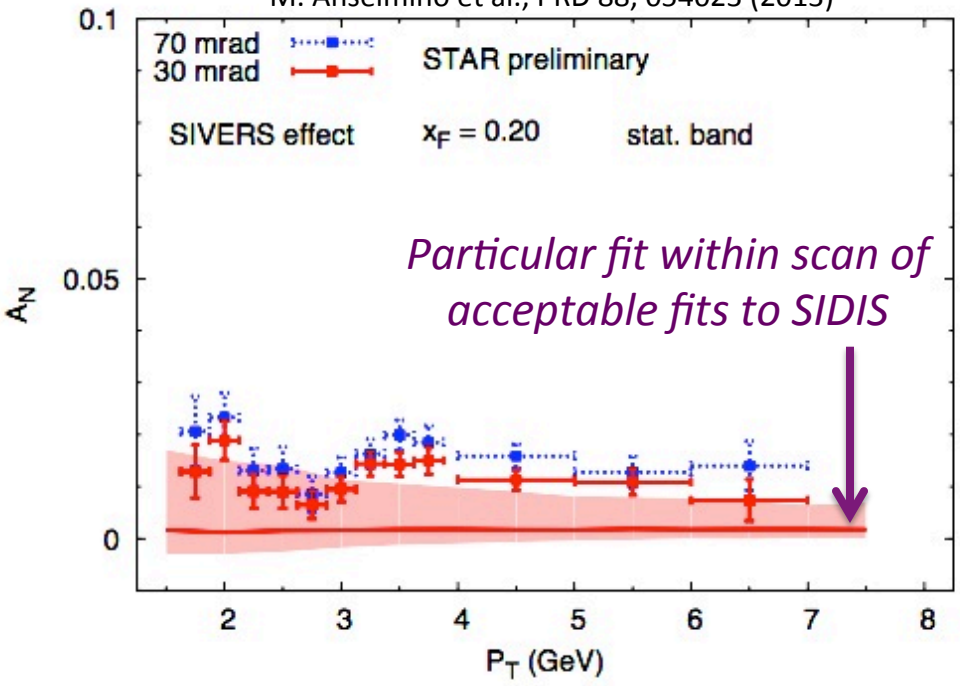
Recent measurements at $\sqrt{s} = 500$ GeV show

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 from Inclusive Hadrons

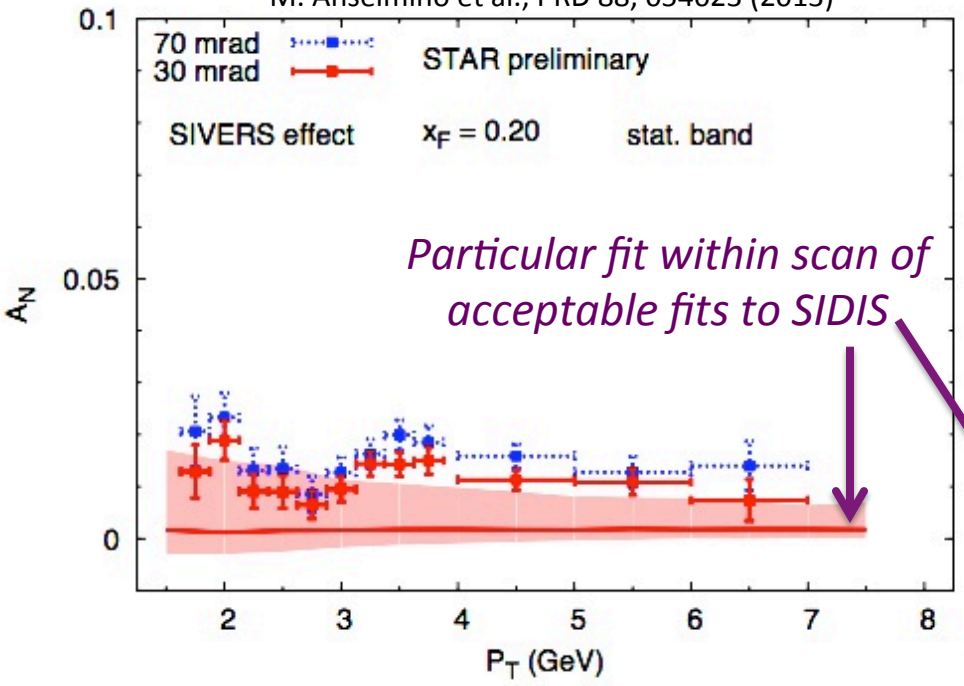
M. Anselmino et al., PRD 88, 054023 (2013)



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***

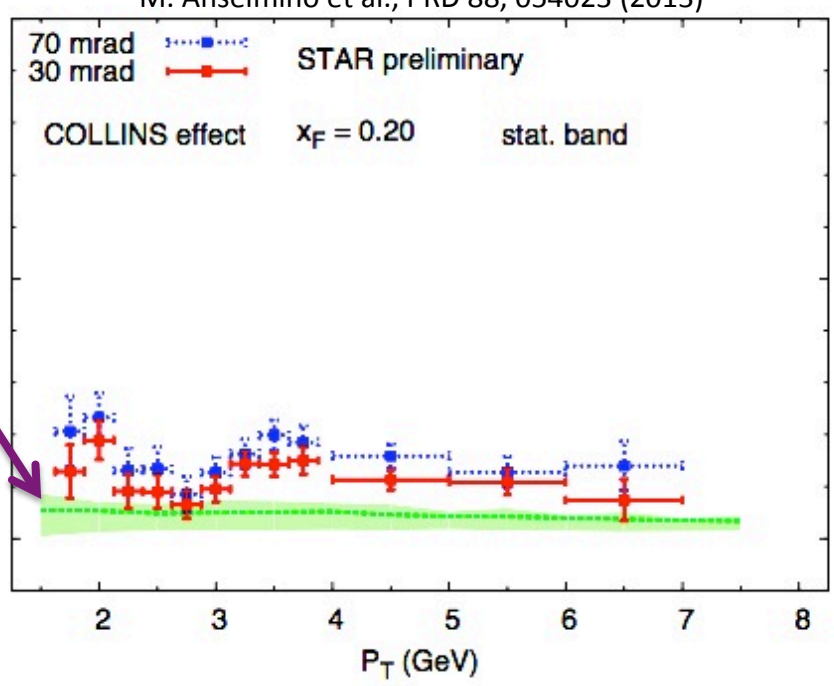
STAR Transverse Asymmetries from Inclusive Hadrons

M. Anselmino et al., PRD 88, 054023 (2013)



Particular fit within scan of acceptable fits to SIDIS

M. Anselmino et al., PRD 88, 054023 (2013)



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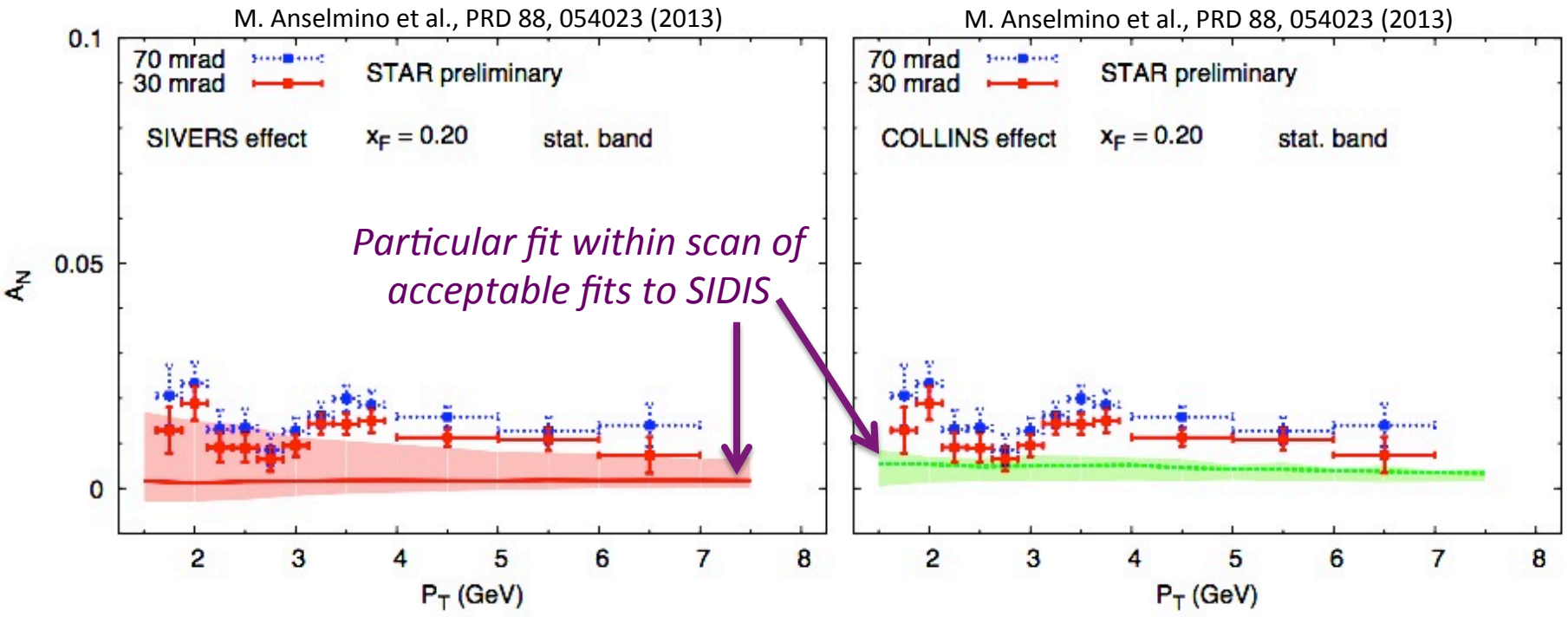
Similar behavior for **Collins effect** in some parameterizations

→ possible hint of Collins+Sivers effect?

STAR Transverse Asymmetries from Inclusive Hadrons



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lower magnitude than data

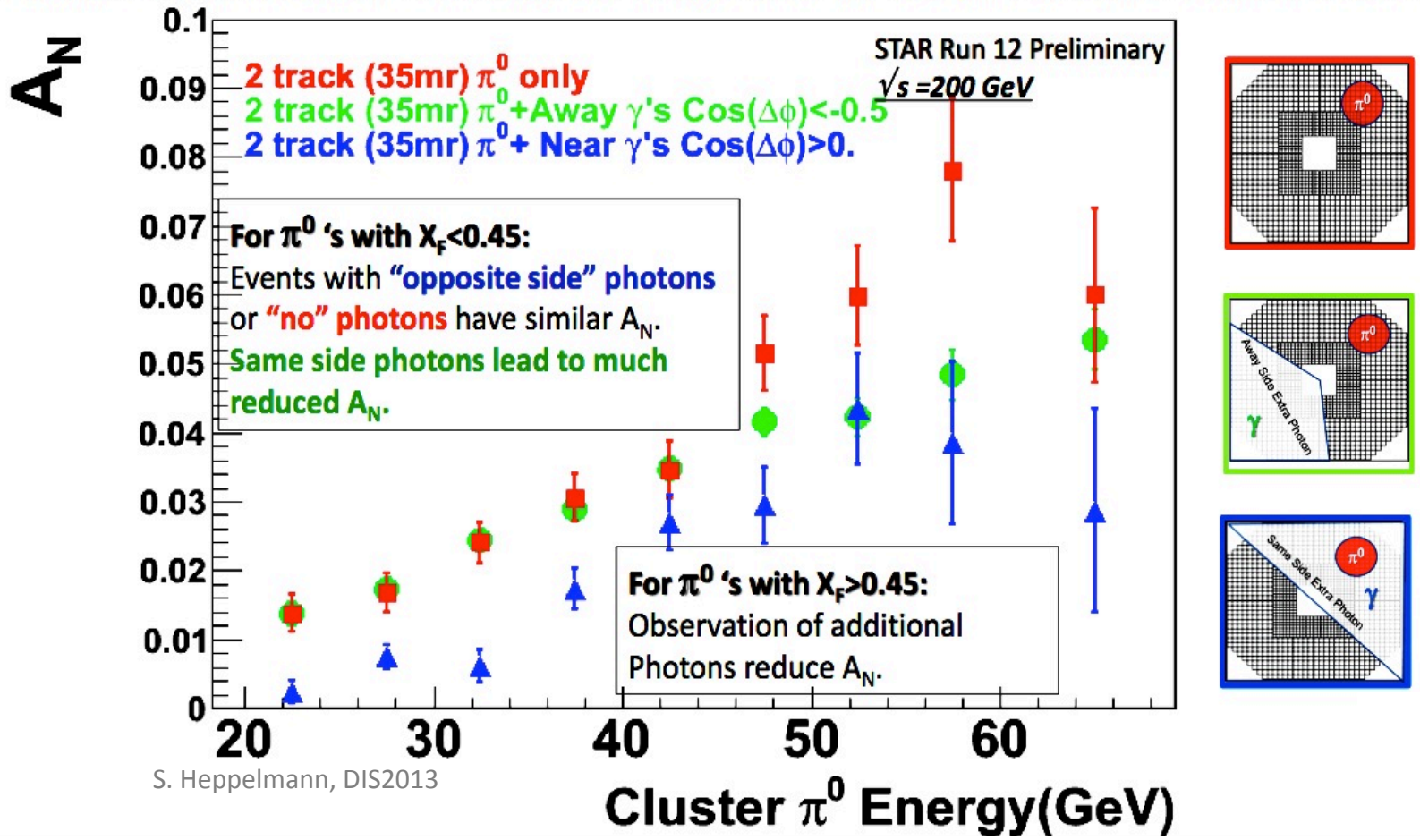
Similar behavior for **Collins effect** in some parameterizations

→ ***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)*]

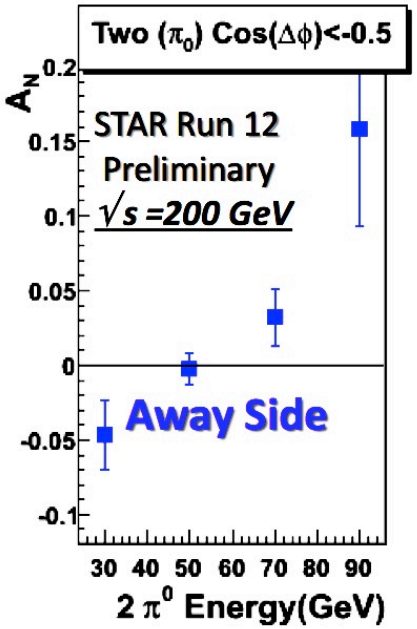
STAR Transverse Asymmetries from Inclusive Hadrons

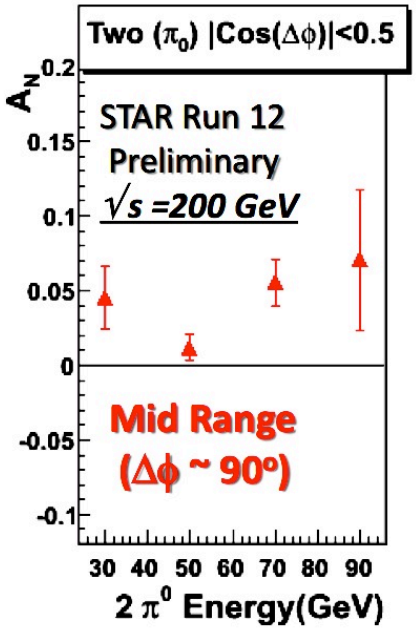


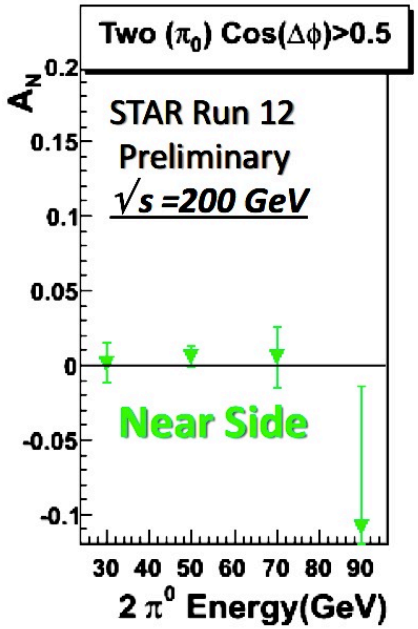
S. Heppelmann, DIS2013

Recent data from 2012 suggest that asymmetries for pions with additional near-side energy deposit have *lower asymmetries than those of more isolated pions*

STAR Transverse Asymmetries from Inclusive Hadrons







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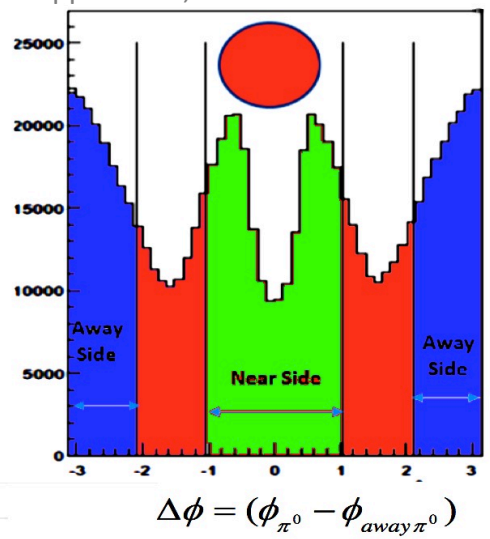


Recent data from 2012 further suggest that asymmetries for pions with additional near-side pion have

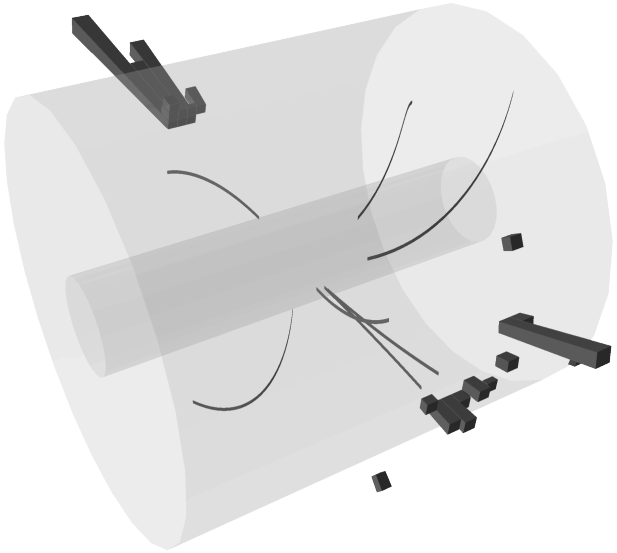
lower asymmetries than those with away-side or mid-range pion

→ In both $\sqrt{s} = 200$ and 500 GeV isolated pions show higher asymmetry than jet-like pions

Forward neutral-energy jet analysis of 2011 ongoing (M. Mondal, GHP2013)

Jet Reconstruction in STAR

STAR Di-jet event at detector-level



e.g. Anti-k_T algorithm (2011 results)

JHEP 0804, 063 (2008)

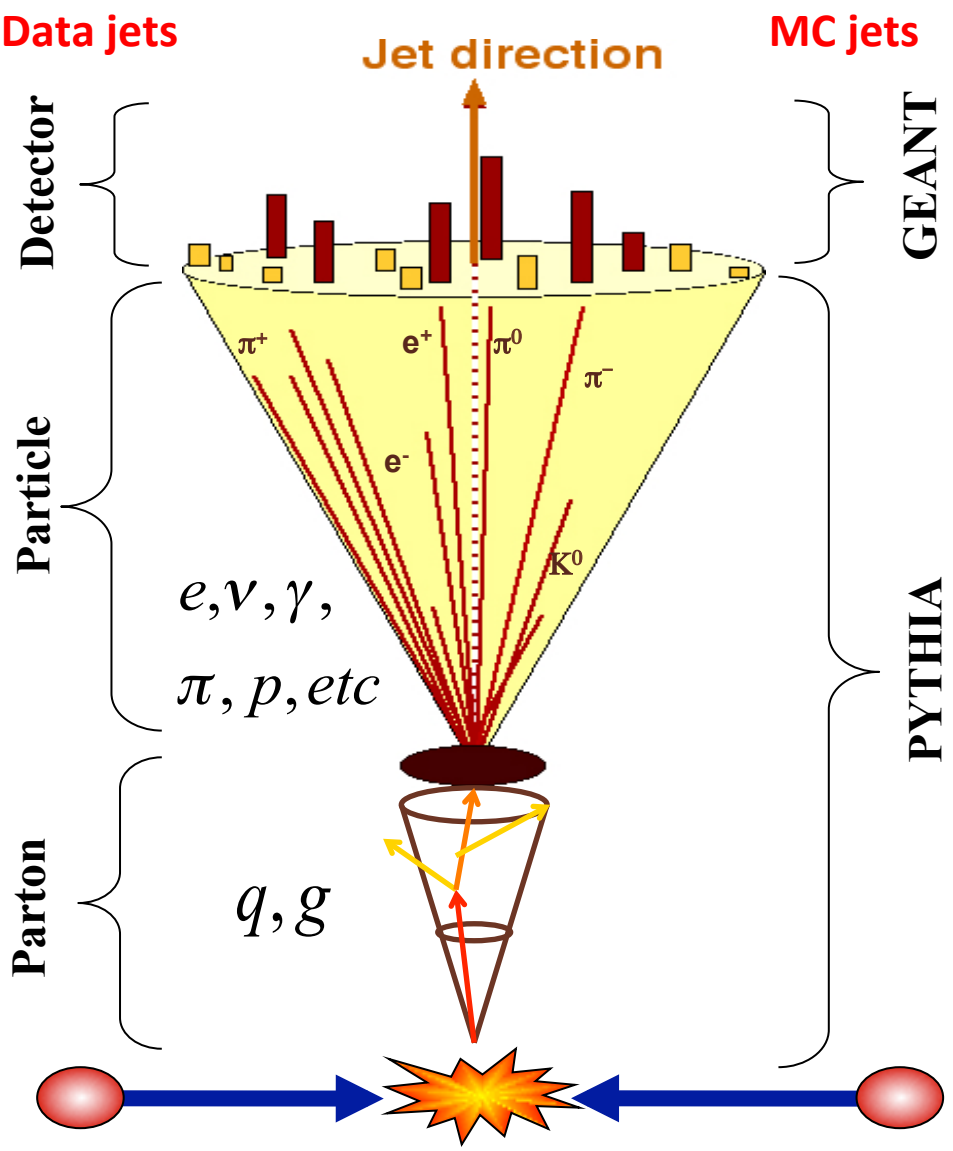
Radius parameter R = 0.6

Use **PYTHIA** + **GEANT** to quantify detector response

$\pi^{\pm}$ Kinematic Variables

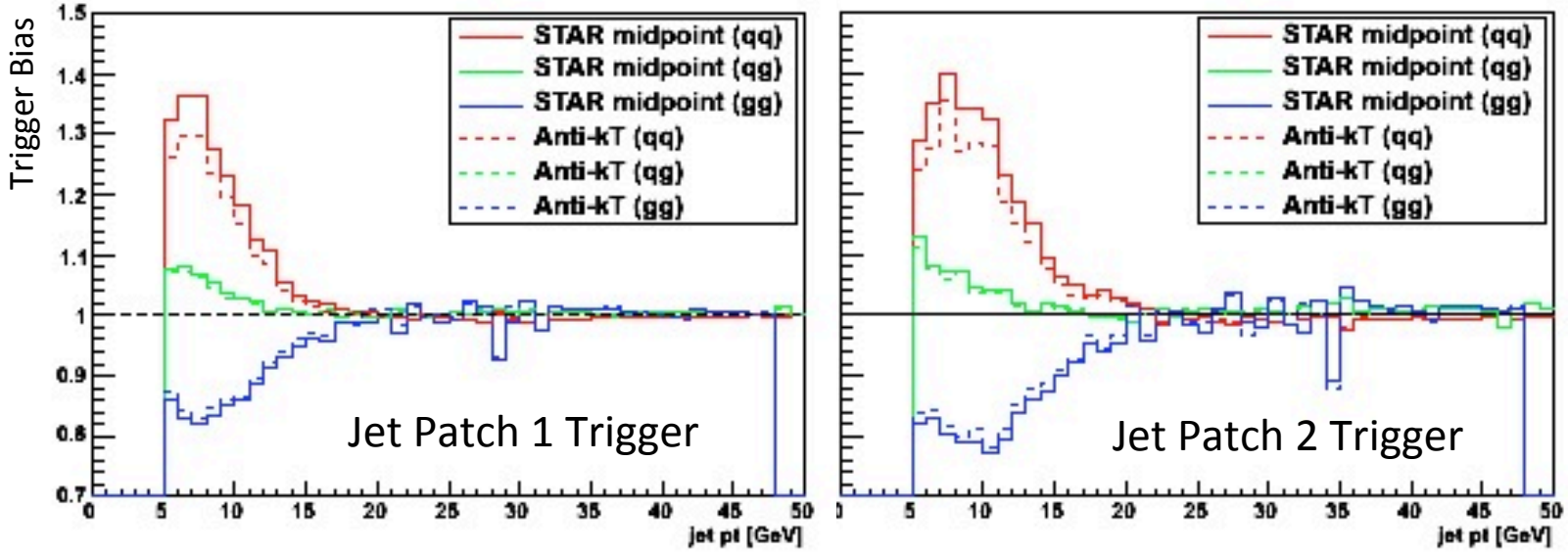
z – π momentum / jet momentum

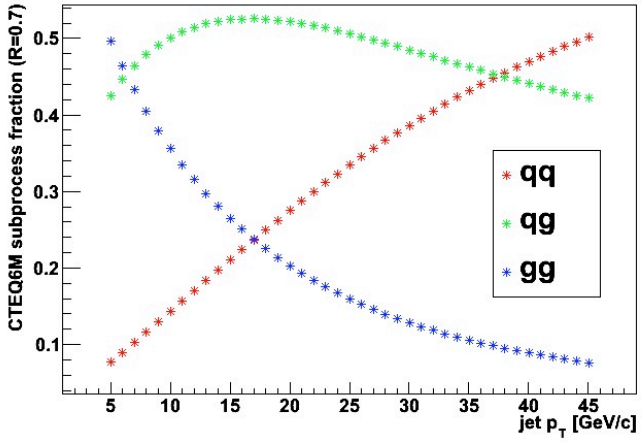
j_T – π p_T relative to jet axis



Fragmentation in STAR Jet Reconstruction

Parton-jet Level Association with Radius = 0.6





$$Trigger\ Bias = \frac{subprocess\ trigger\ efficiency}{average\ trigger\ efficiency}$$

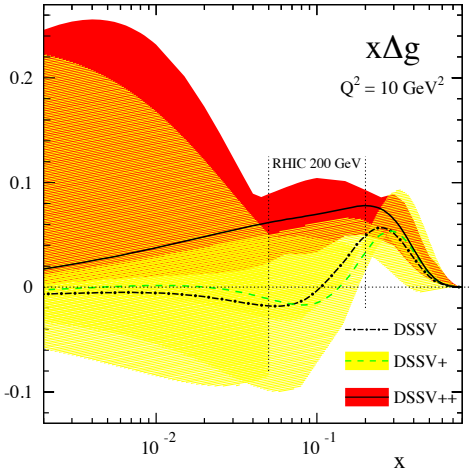
qq subprocess

- more efficient than qg or gg at lower p_T
- *small fraction* of event sample in p_T-range where qq bias is significant

For anti-k_T, particle-jet bias is factor ~2-3 smaller than parton-jet bias

STAR Longitudinal Asymmetries from Inclusive Jets

- 2009 A_{LL} → two pseudorapidity ranges
- **Forward jets (0.5 < η < 1):**
  - Larger fraction of q-g scattering with
    - Higher *x* quarks that are more polarized
    - Lower *x* gluons that are less polarized
  - Larger |cos(θ*)| → reduced $\hat{a}_{LL}$
- A_{LL} falls between the predictions from **DSSV** and **GRSV-STD**
- First experimental evidence of **non-zero Δg(x)** in range 0.05 ≤ x ≤ 0.2

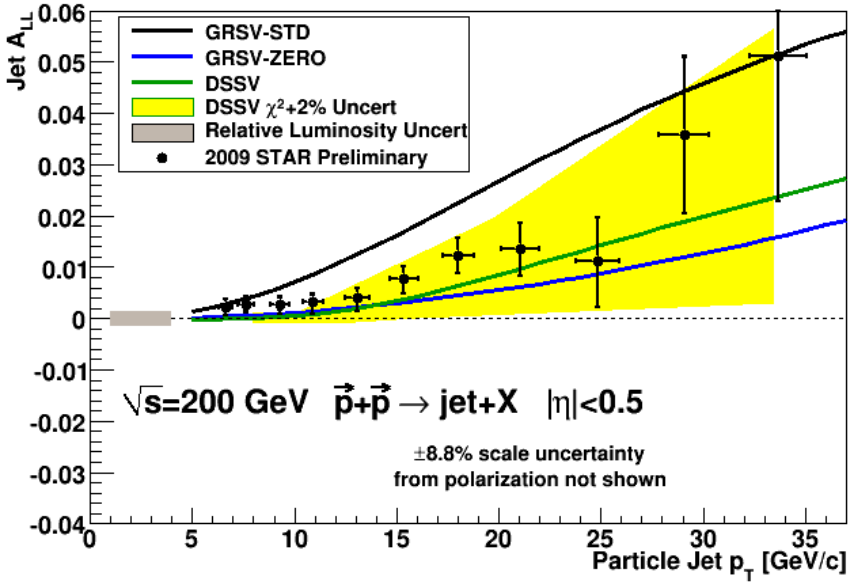


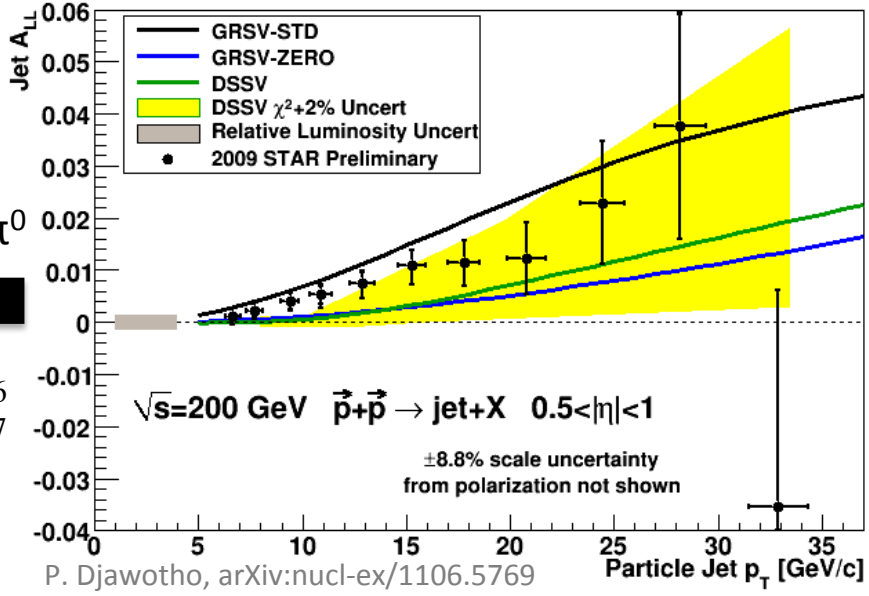
2009 STAR Jets + PHENIX π^0

$$\int_{0.05}^{0.20} \Delta g(x)\,dx = 0.10^{+0.06}_{-0.07}$$

with $Q^2 = 10\ \mathrm{GeV}^2$

arXiv:nucl-ex/1304.0079

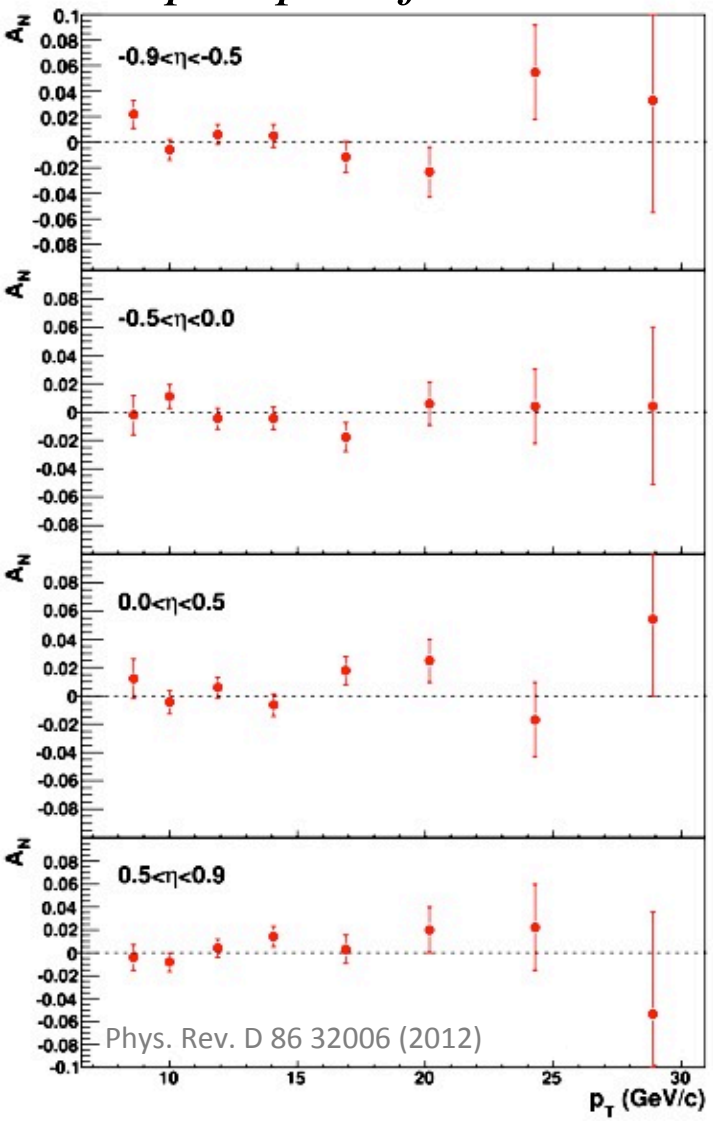




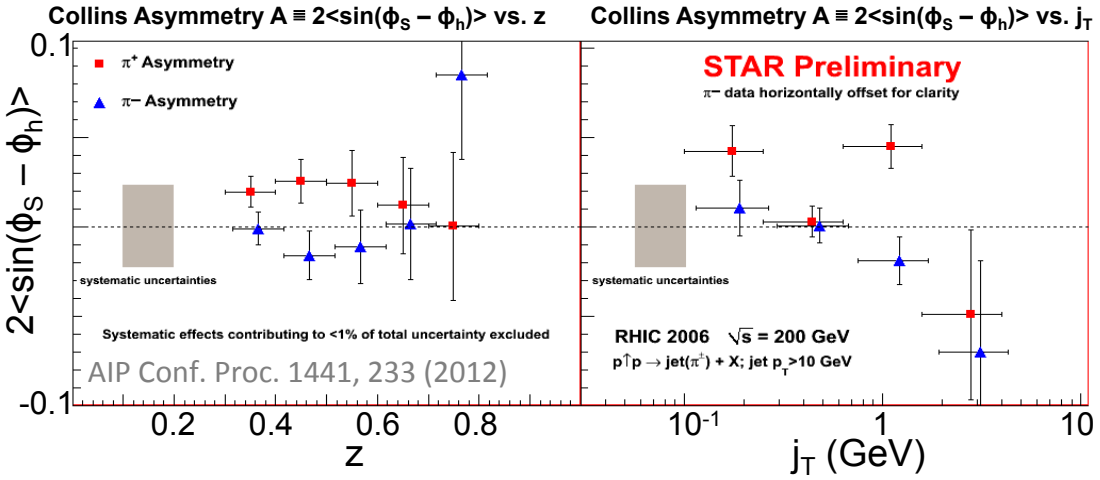
P. Djawotho, arXiv:nucl-ex/1106.5769

STAR Transverse Asymmetries from Inclusive Jets

$$p^{\uparrow} + p \rightarrow jet + X$$



Phys. Rev. D 86 32006 (2012)



AIP Conf. Proc. 1441, 233 (2012)

STAR measured transverse single-spin asymmetries for inclusive jet production at central pseudorapidity and $\sqrt{s} = 200$ GeV (2006)

$A_{UT}^{\sin(\phi_S)}$: consistent with zero

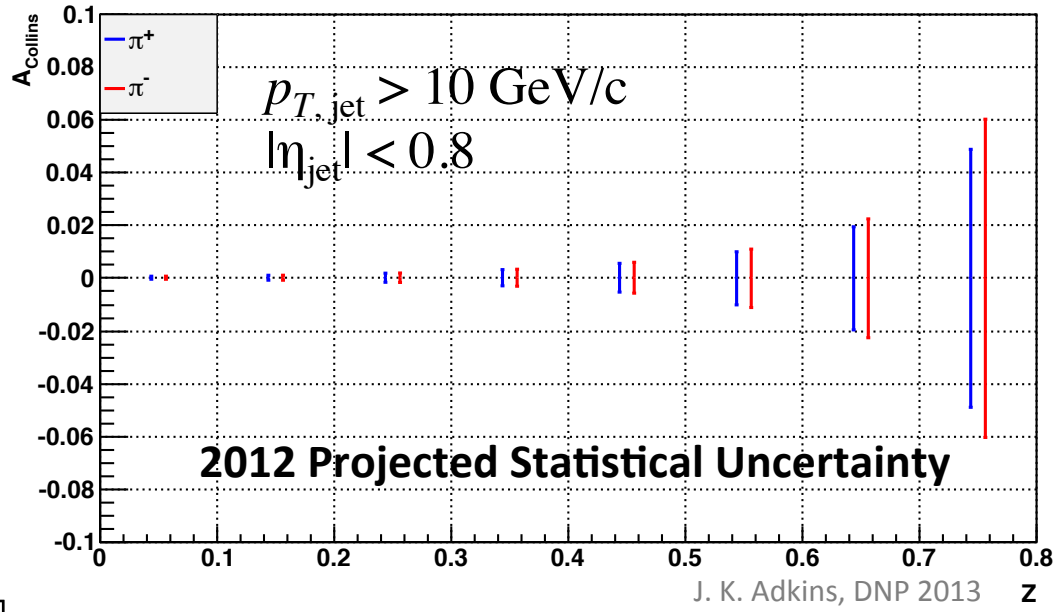
$A_{UT}^{\sin(\phi_S - \phi_h)}$: hints of non-zero asymmetry with charge-sign dependence

Similarly, di-jet at central psuedorapidity and 200 GeV consistent with zero

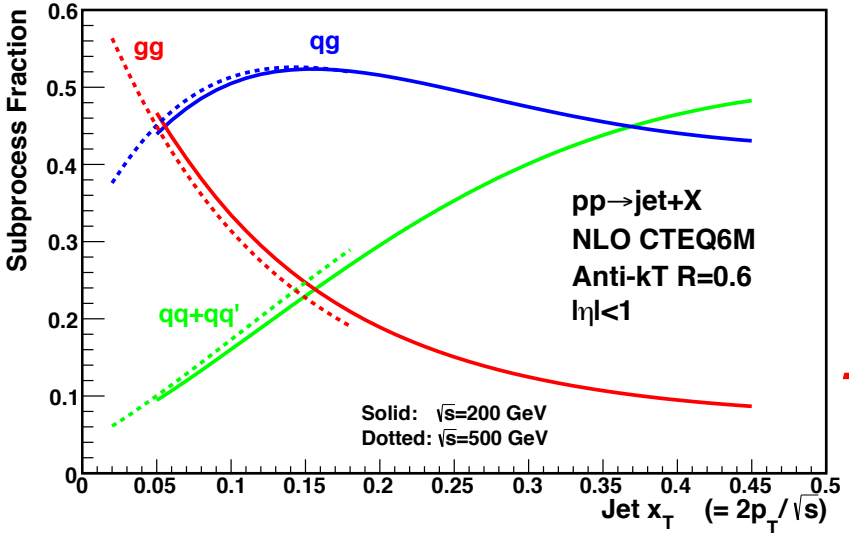
PRL 99, 142003

STAR Transverse Asymmetries from Inclusive Jets

2012 STAR data provide opportunity for ***higher precision*** *and* ***greatly reduced systematic uncertainties*** *at* $\sqrt{s} = 200$ *GeV* ***analysis well underway***



J. K. Adkins, DNP 2013



2011 STAR data provide opportunity for first measurements of **central pseudorapidity inclusive jet asymmetries at** $\sqrt{s} = 500$ **GeV**

→ ***Increased sensitivity to gluonic subprocesses***

Moments of Jet Asymmetries at 500 GeV

Various contributions to polarized jet+π cross section (TMD approach)

$$d\sigma(\phi_S,\phi_h) - d\sigma(\phi_S+\pi,\phi_h) \sim d\Delta\sigma_0 \sin\phi_S$$
$$+d\Delta\sigma_1^- \sin(\phi_S-\phi_h) + d\Delta\sigma_1^+ \sin(\phi_S+\phi_h)$$
$$+d\Delta\sigma_2^- \sin(\phi_S-2\phi_h) + d\Delta\sigma_2^+ \sin(\phi_S+2\phi_h)$$

Phys. Rev. D 83, 034021 (2011)

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Phys. Rev. D 83, 034021 (2011)

Negligible under ***maximized*** scenario!

Moments of Jet Asymmetries at 500 GeV

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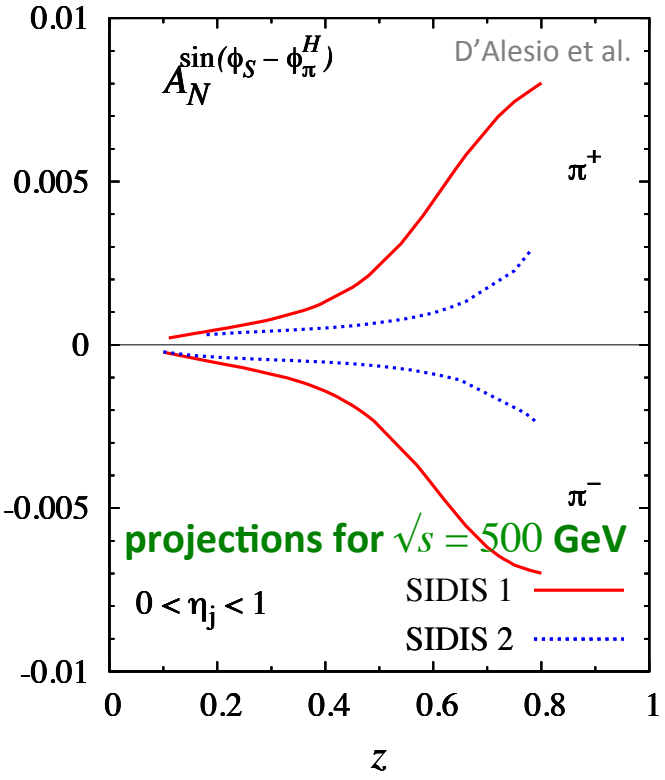
Phys. Rev. D 83, 034021 (2011)



Possible non-zero contributions,

expected to be quite small

e.g. Phys. Rev. Lett 99, 142003 (2007);
Phys. Rev. D 86, 032006 (2012);
Phys. Lett. B 720, 161 (2013)

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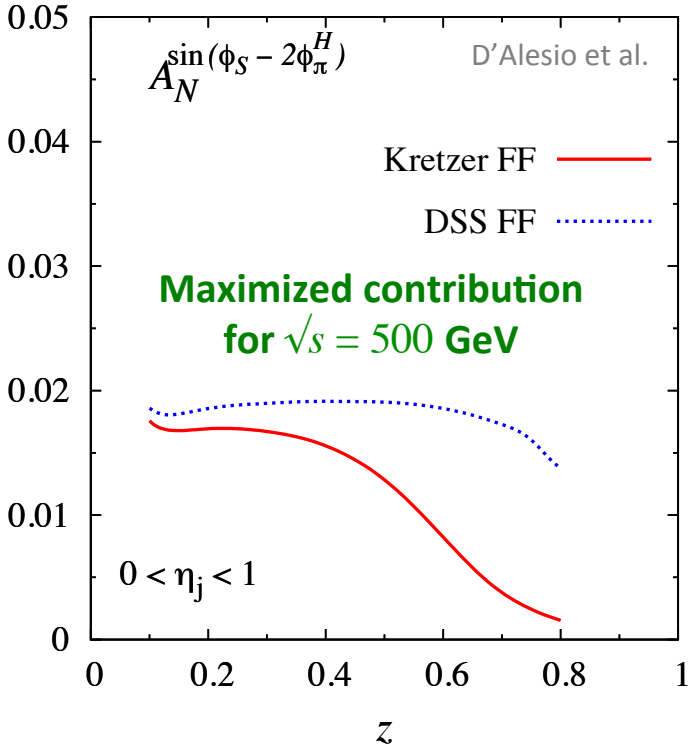
Phys. Rev. D 83, 034021 (2011)



"Collins-like" asymmetry:

Sensitive to linearly polarized gluons

Completely unconstrained!

Gluon helicity density matrix

$$\rho = \frac{1}{2}\begin{pmatrix} 1+P_{circ} & -P_{lin}e^{-2i\phi} \\ -P_{lin}e^{2i\phi} & 1-P_{circ} \end{pmatrix}$$

Off-diagonal terms related to linear polarization in (xy) plane at angle ϕ to x-axis

Phys Rev. D 73, 014020 (2006)

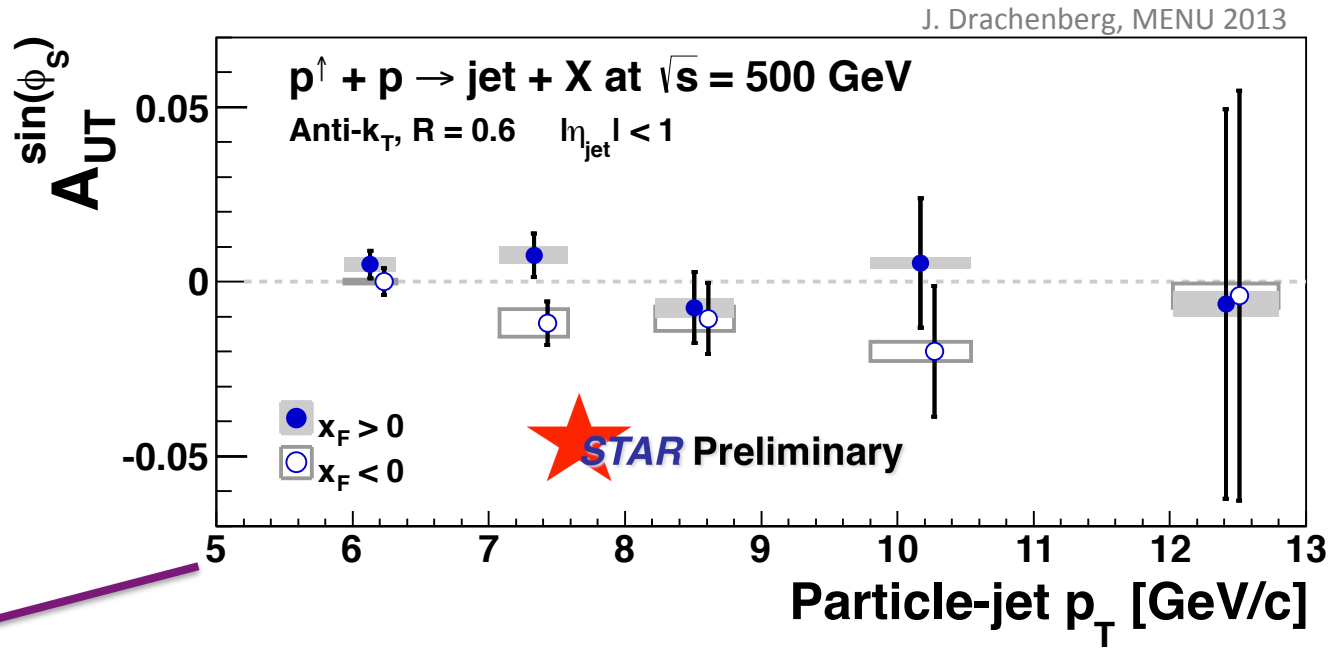
Sivers Asymmetries at 500 GeV

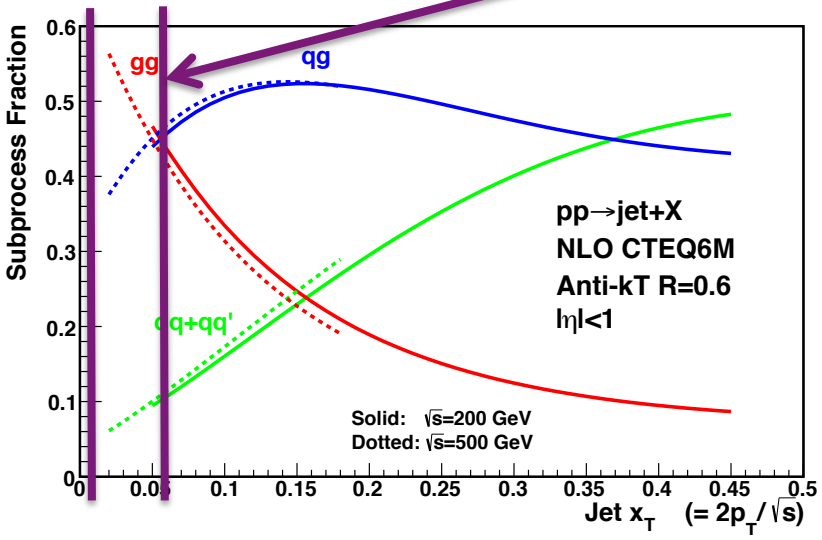
Asymmetries shown as function of particle-jet p_T

Corresponding parton-jet p_T lower by 0.6-1.4 GeV/c

Horizontal errors include uncertainties from statistics, calorimeter gains, efficiencies, track momentum, and tracking efficiency

J. Drachenberg, MENU 2013





No sign of sizable azimuthal asymmetry in jet production at $\sqrt{s} = 500$ GeV

Consistent with expectation from inclusive jets, di-jets, and neutral pions at $\sqrt{s} = 200$ GeV

Sivers Asymmetries at 500 GeV

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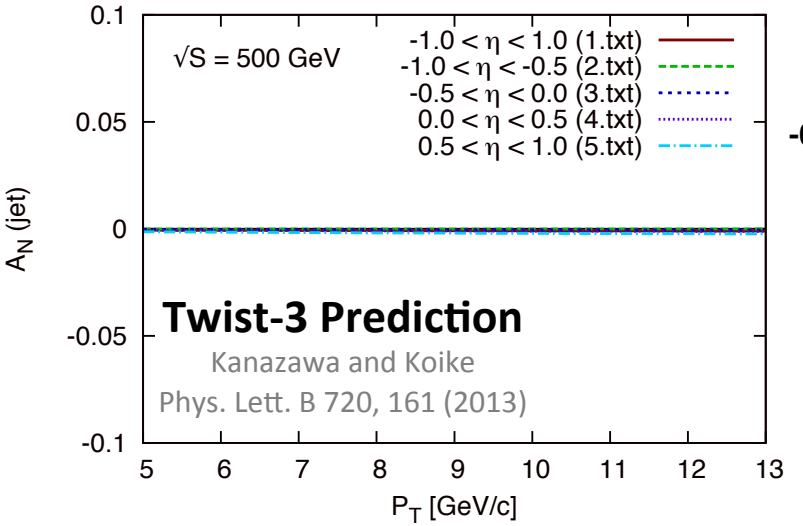
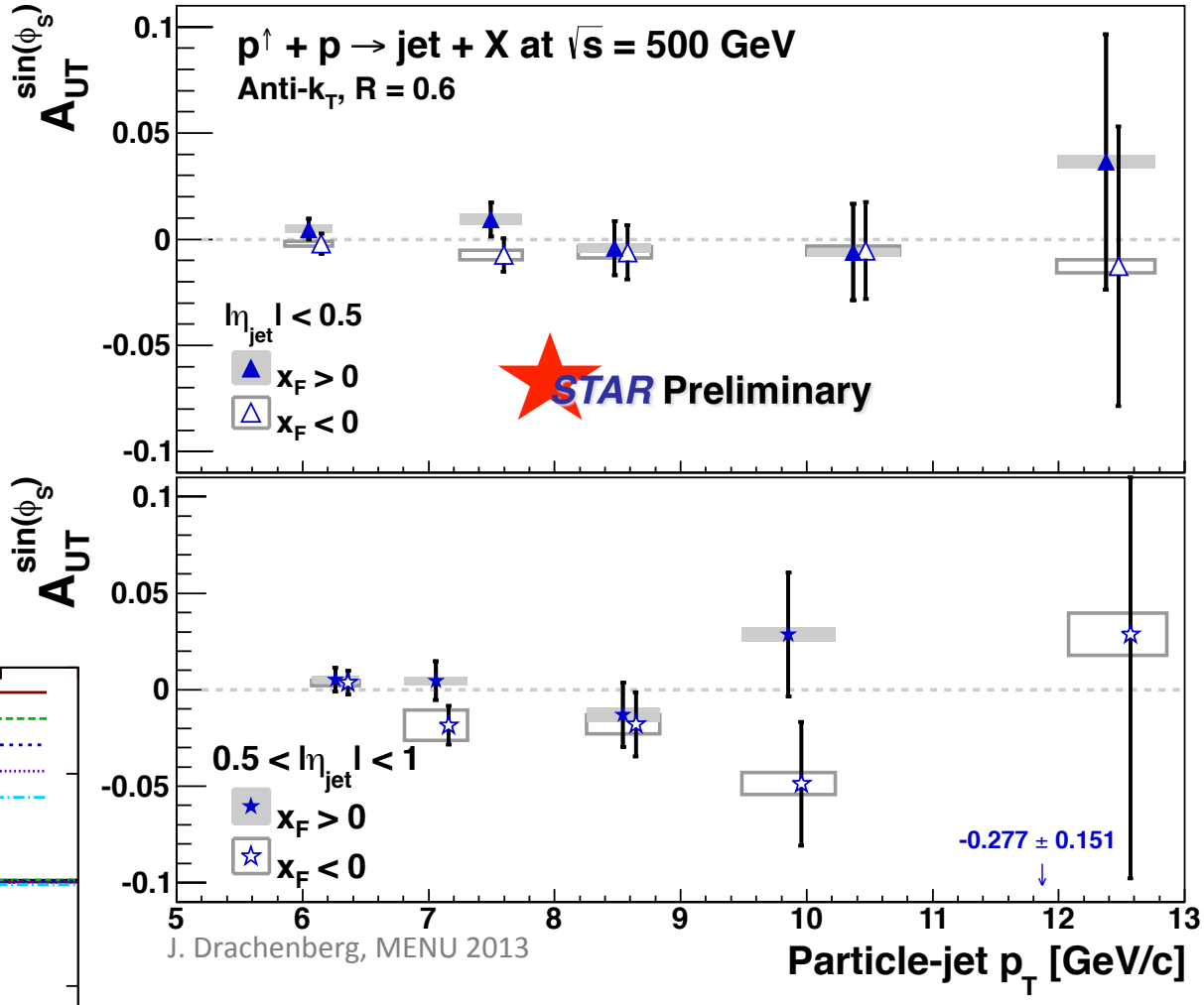


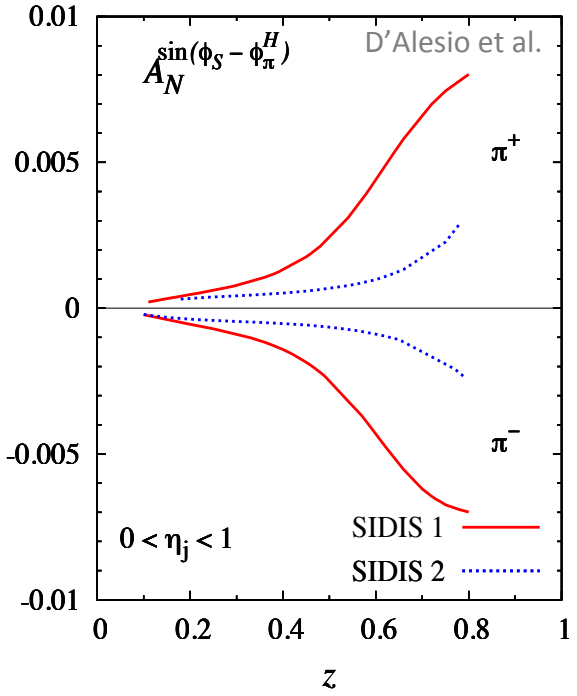


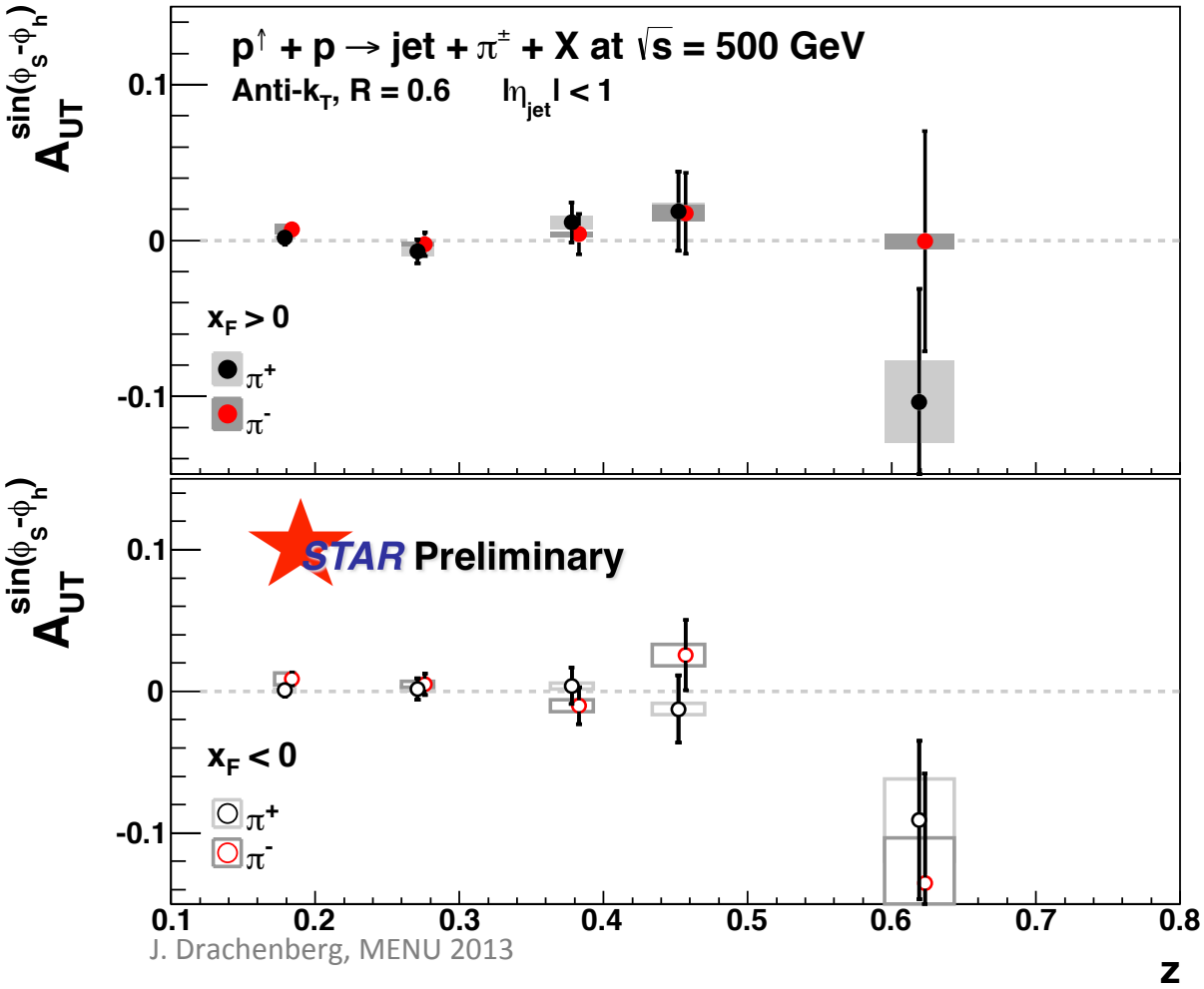
Measured asymmetries shown in η-bins

No sign of sizable asymmetry

Collins Asymmetries at 500 GeV

Increased gluonic subprocesses at $\sqrt{s} = 500$ GeV lead to expectation of ***small Collins asymmetry*** until larger z

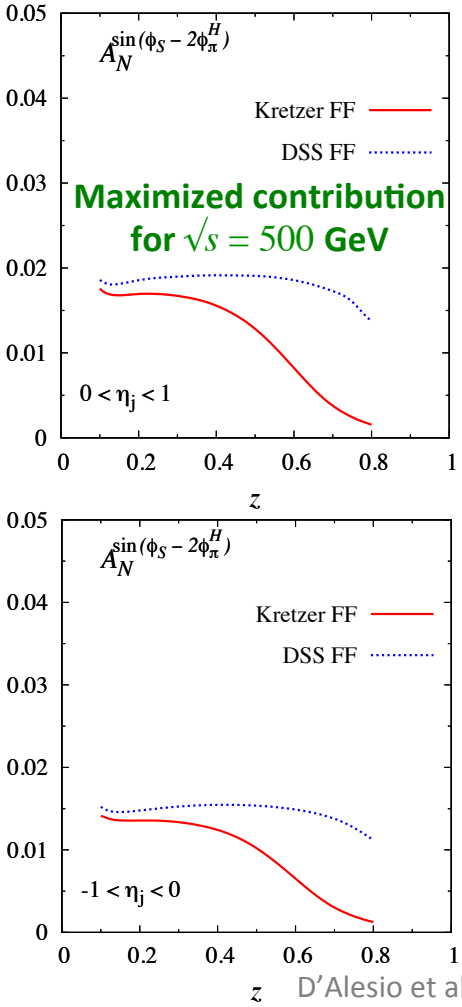


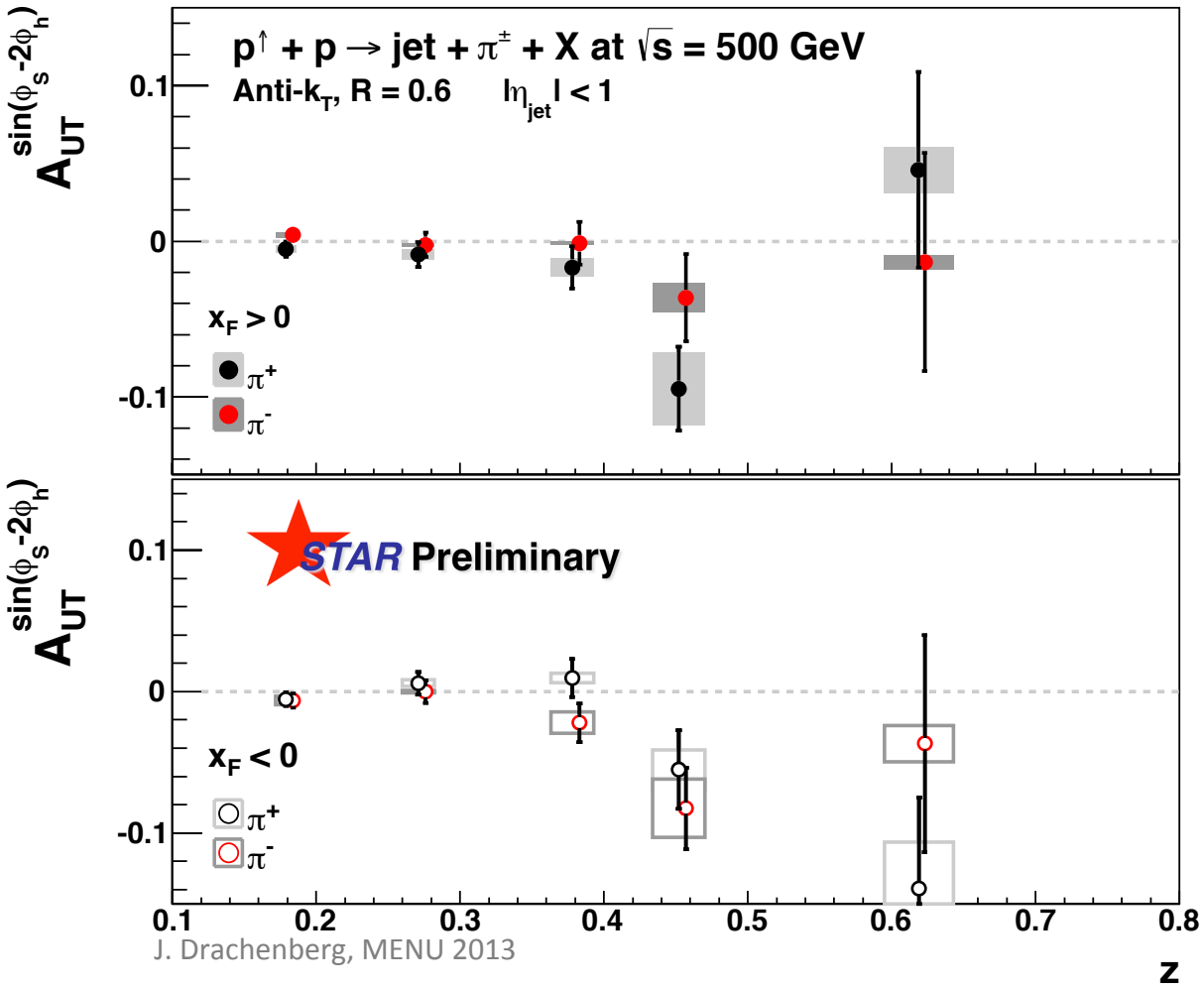


J. Drachenberg, MENU 2013

Present data do not have sufficient statistics at high-z to observe Collins asymmetry of order 1%

Collins-like Asymmetries at 500 GeV



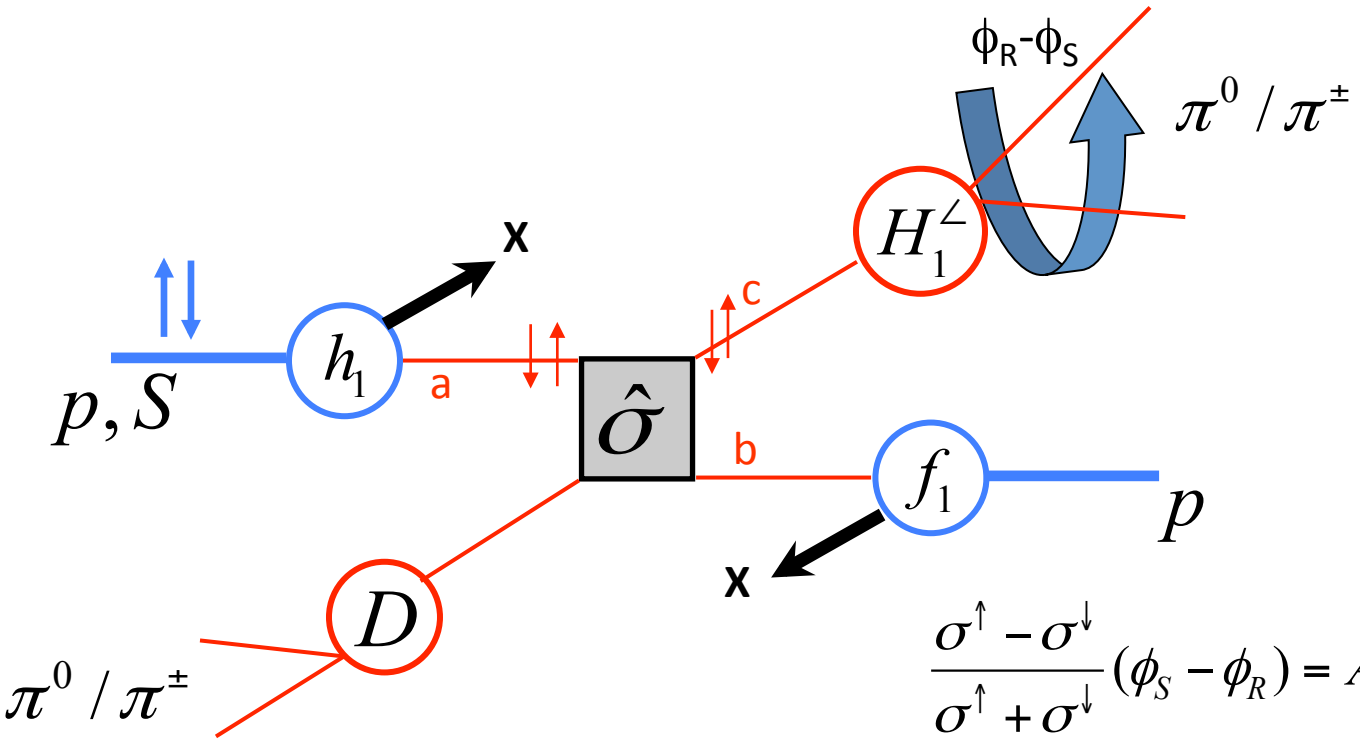


Model predictions shown for "maximized" effect, saturated to positivity bound

Until now, Collins-like asymmetries completely unconstrained

→ ***Sensitive to linearly polarized gluons***

STAR Transverse Asymmetries from Di-hadrons



$$\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}(\phi_S - \phi_R) = A_{UT} \sin(\phi_S - \phi_R)$$

$$A_{UT} \propto h_1 \otimes H_1^{\angle}$$

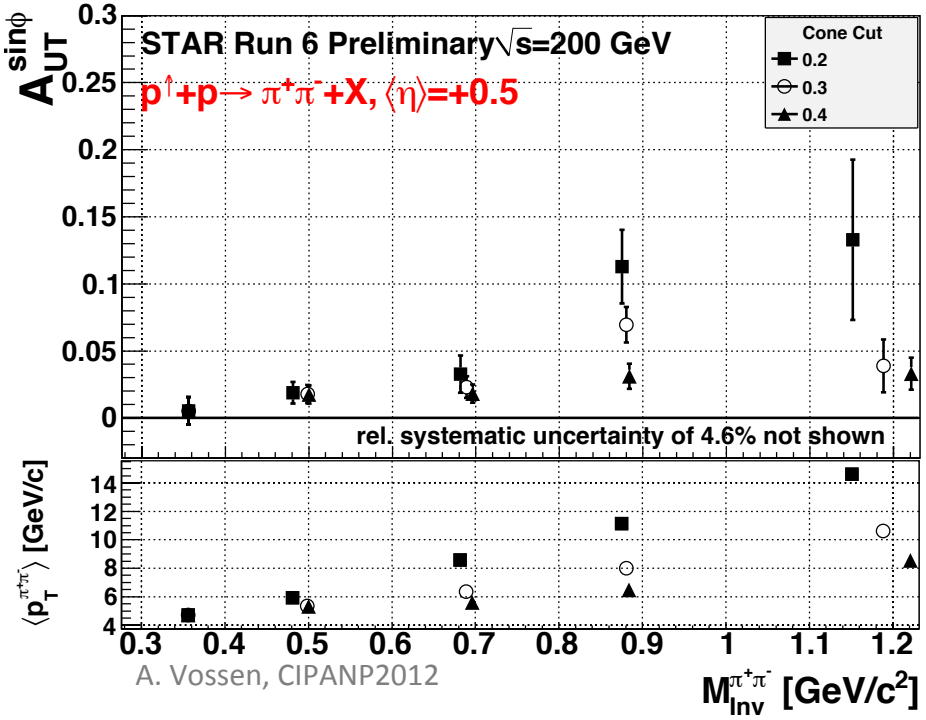
ϕ_S: Angle between polarization vector and event plane

Another path to transversity:

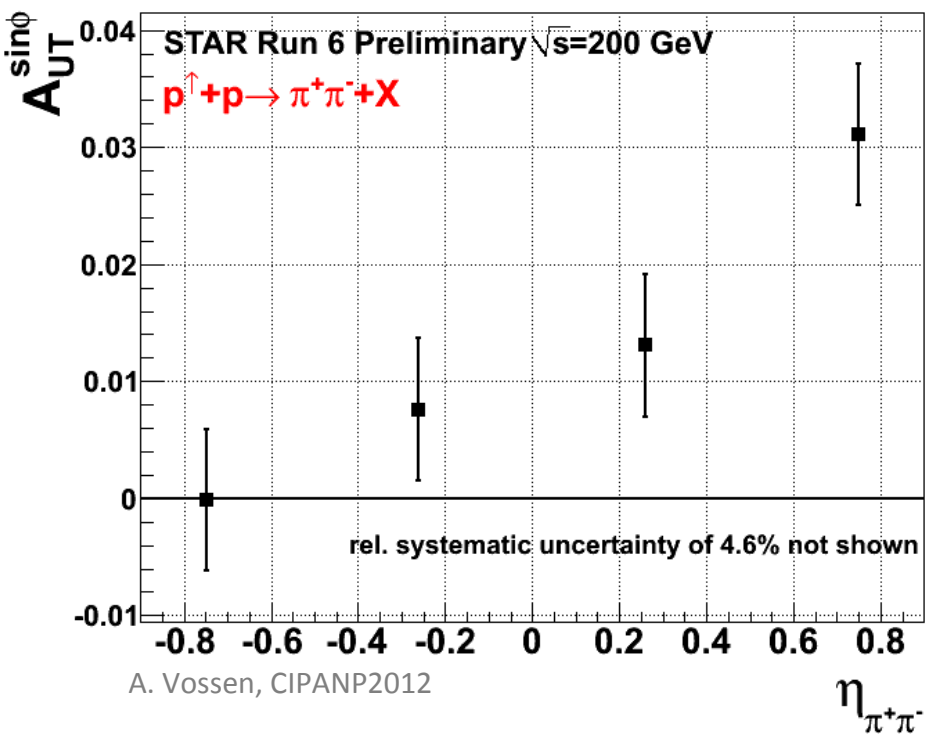
interference fragmentation functions via di-hadron asymmetries

Advantage: *applicable in collinear framework*

STAR Transverse Asymmetries from Di-hadrons



A. Vossen, CIPANP2012

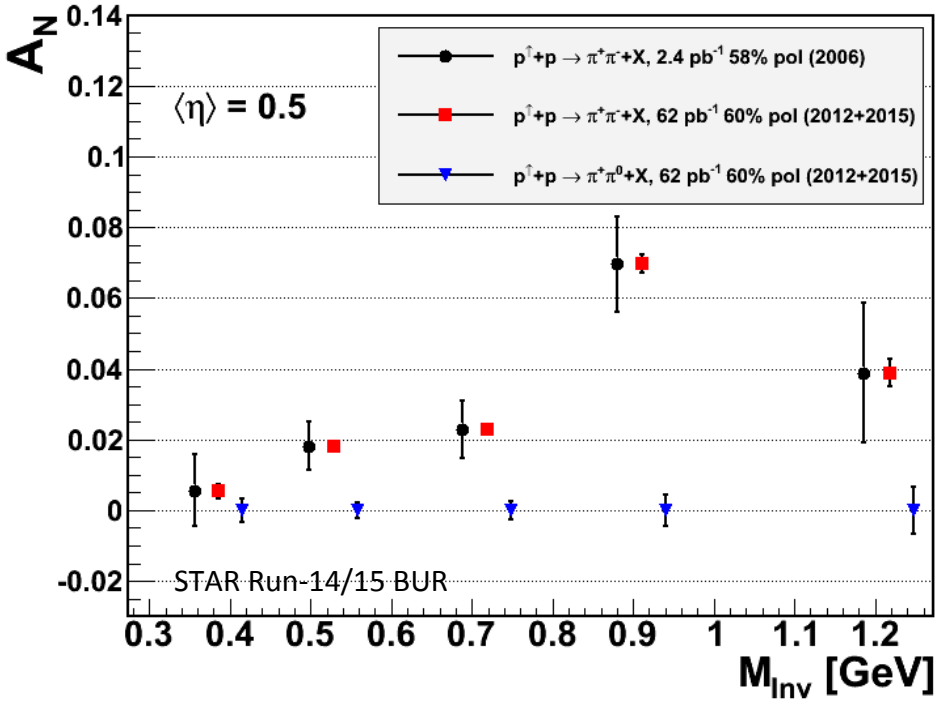


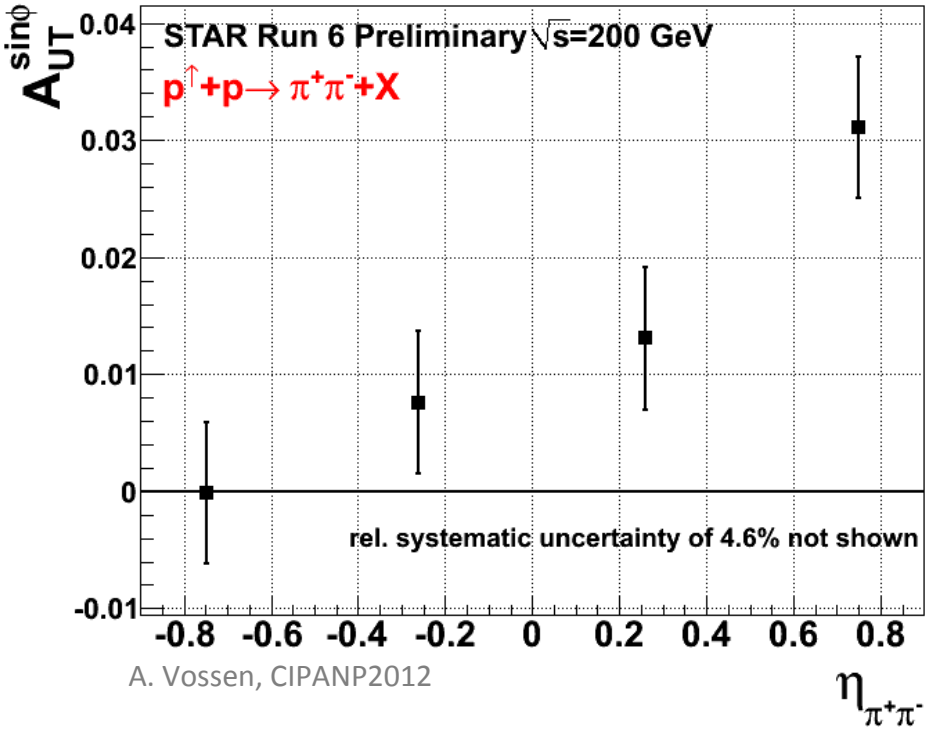
A. Vossen, CIPANP2012

Non-zero signal for di-hadron transverse single-spin asymmetries in 2006 data

→ ***Inform transversity at higher x, Q^2?***

STAR Transverse Asymmetries from Di-hadrons





A. Vossen, CIPANP2012

Non-zero signal for di-hadron transverse single-spin asymmetries in 2006 data

→ ***Inform transversity at higher x, Q^2?***

2012+15: opportunity for much higher precision

Analysis of 2012 data underway

Summary

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  - Persistence of sizable A_N at forward pseudorapidity to $p_T \sim 10$ GeV/c
  - Measurement of π^0 A_N for the first time at intermediate pseudorapidity ($0.8 < \eta < 2$)
    → ***asymmetries consistent with zero***
  - Precise investigation of A_N dependence of on event topology
    → ***asymmetries in jet-like π^0 are smaller than asymmetries in isolated π^0***

Summary

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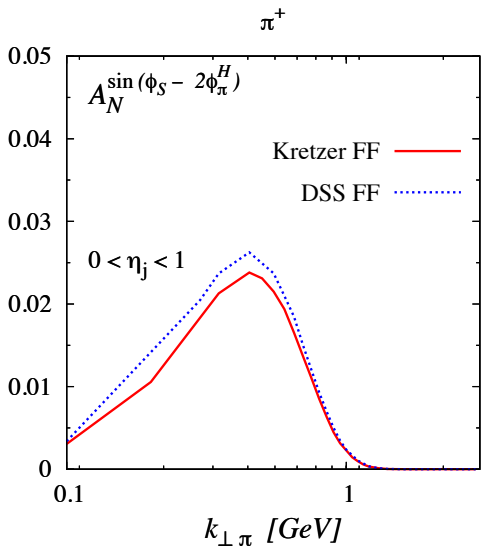
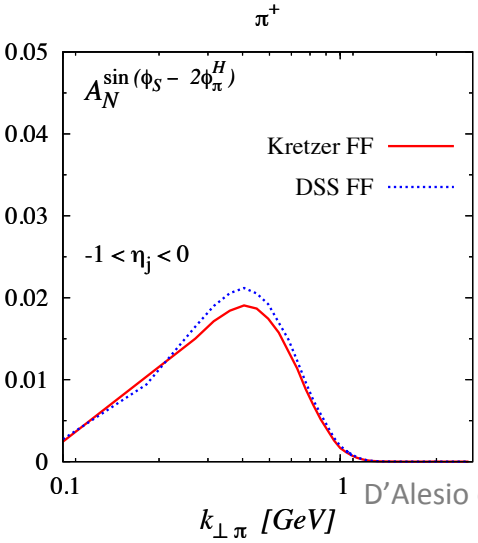
    → ***asymmetries in jet-like π^0 are smaller than asymmetries in isolated π^0***
- STAR inclusive jet and di-hadron production
  - ***Significant constraints*** placed on gluon polarization → between DSSV and GRSV-STD
  - First signs of transversity at RHIC through inclusive jet and di-hadron asymmetries
  - Investigation of transverse single-spin asymmetries for the first time in inclusive jets at central pseudorapidity and $\sqrt{s} = 500$ GeV
    - ***First ever measurement of "Collins-like" effect from linearly polarized gluons***
    - ***Stage set for analysis of A_{UT}-moment evolution from 200 GeV to 500 GeV***
  - Analyses underway of Collins and IFF from 2012 run → ***higher statistical precision and reduced systematics***

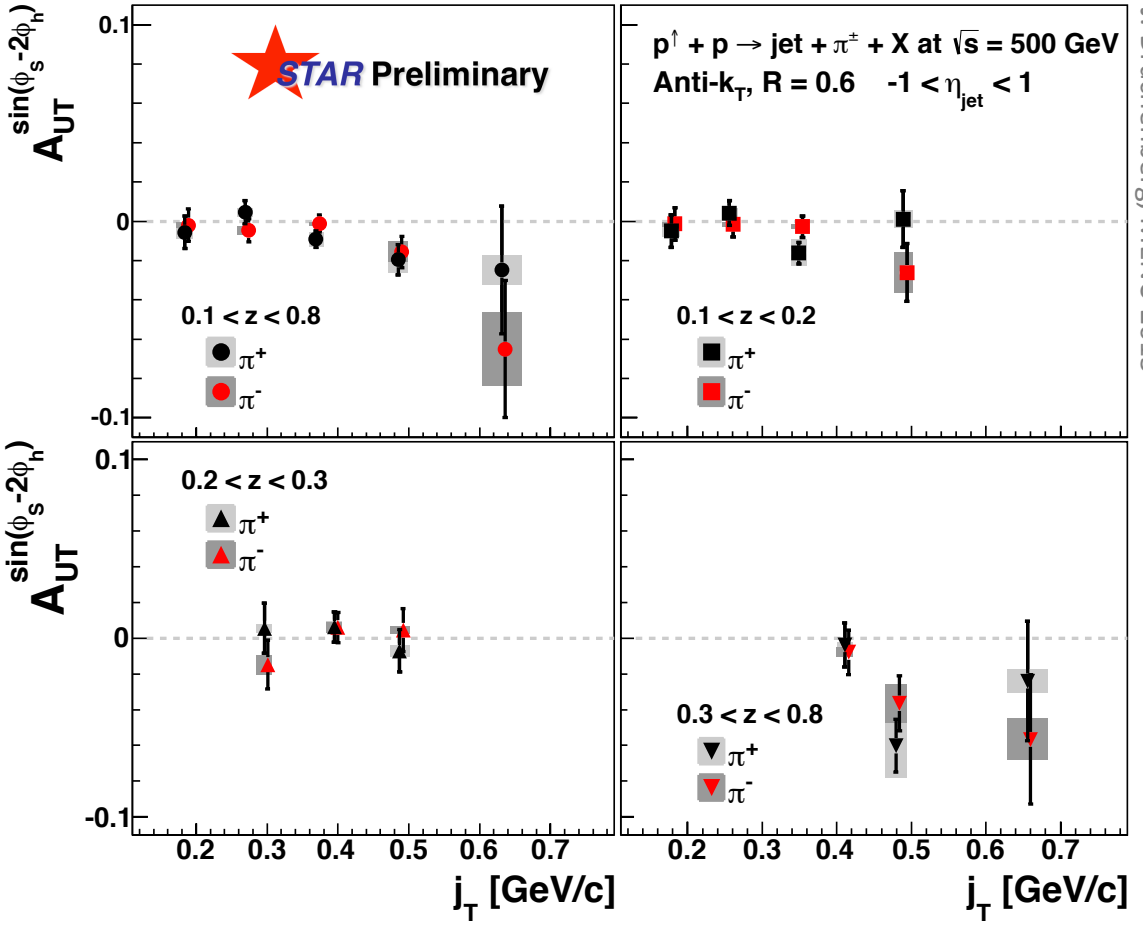
Back-up Slides

Collins-like Asymmetries at 500 GeV





D'Alesio et al.

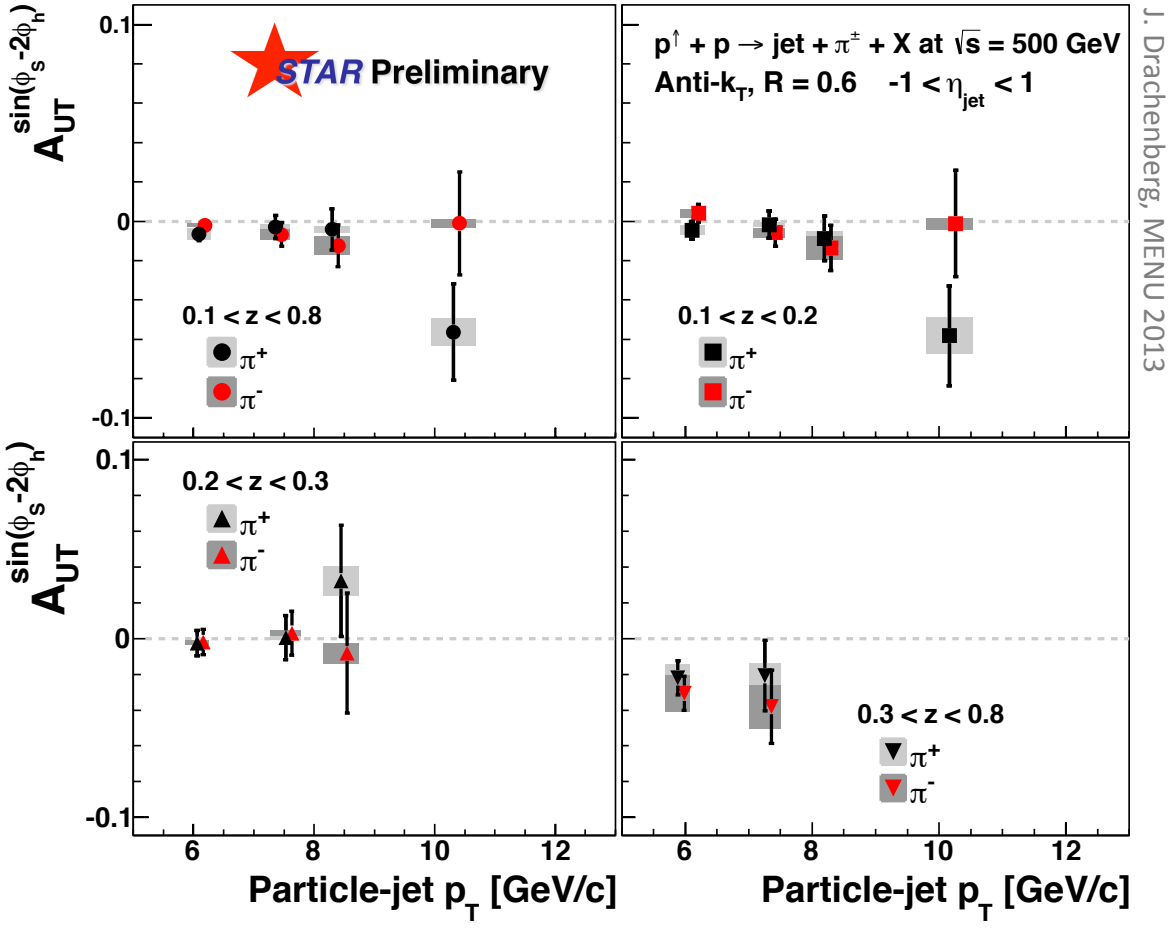


J. Drachenberg, MENU 2013

Measured asymmetries shown for -1 < η < 1 in z-bins

Consistently below 2% maximum from model

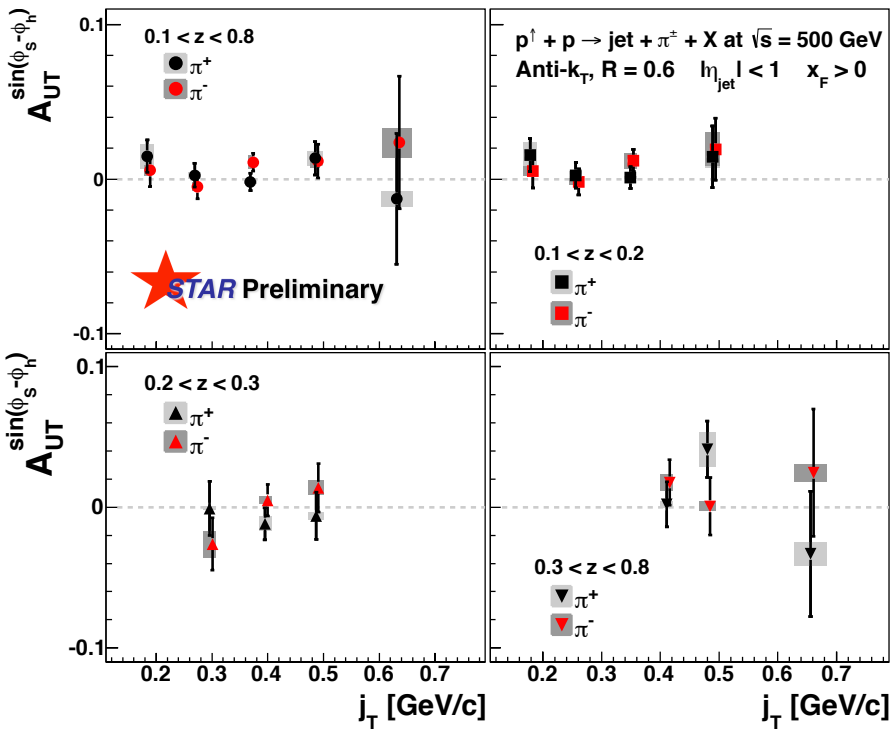
Collins-like Asymmetries at 500 GeV

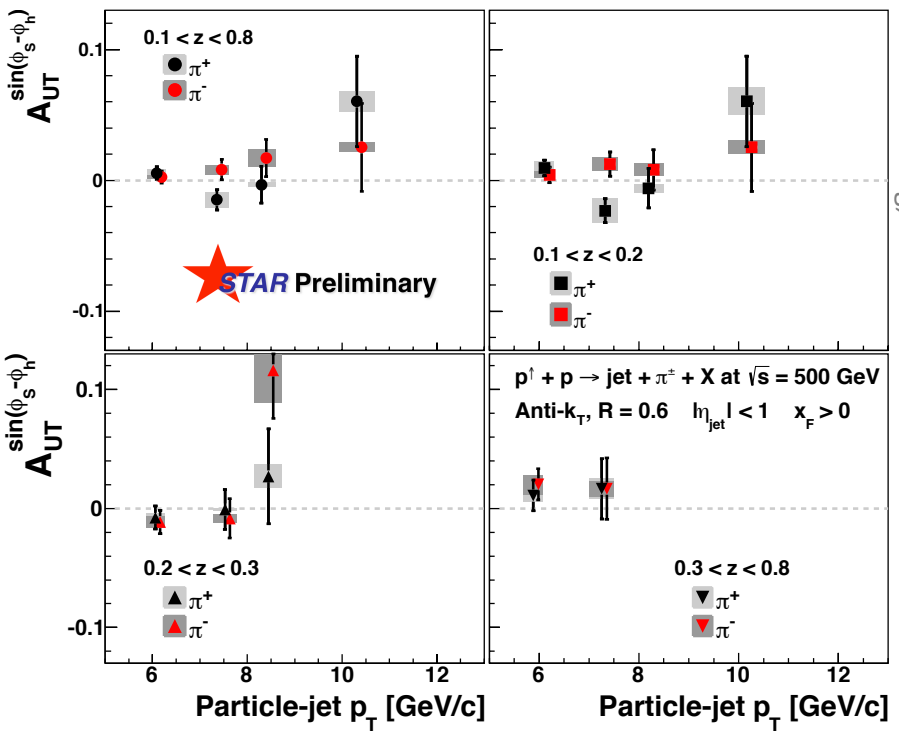


Similarly, no large effect observed as a function of jet p_T

Measured asymmetries shown for $-1 < \eta < 1$ in z-bins

Collins Asymmetries





J. Drachenberg, MENU 2013

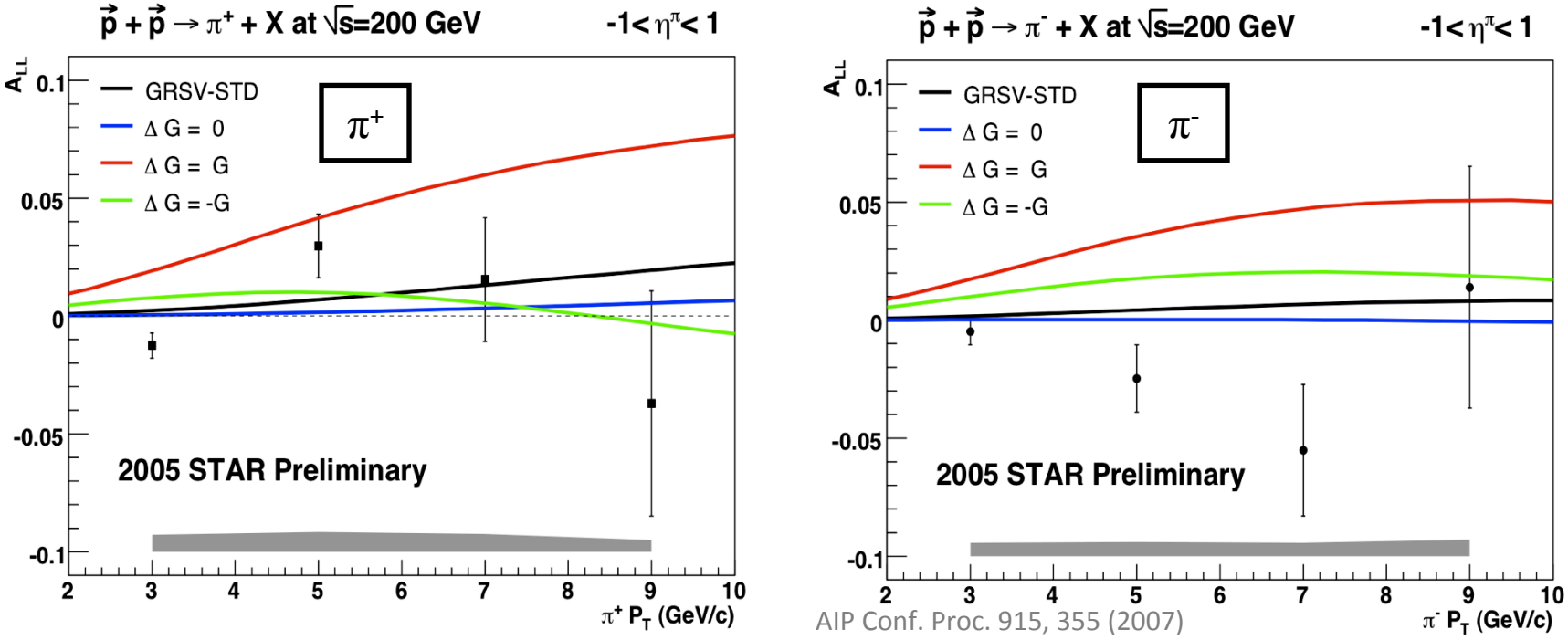
Present model predictions expect negligible effects for A_{UT} vs. j_T integrated over $z > 0.1$

Measured asymmetries shown for $x_F > 0$ (i.e. $0 < \eta_{jet} < 1$) in z-bins

No sign of non-zero asymmetry as a function of j_T or jet p_T

Similarly, no sign of positive effect for backward region ($x_F < 0$), as expected

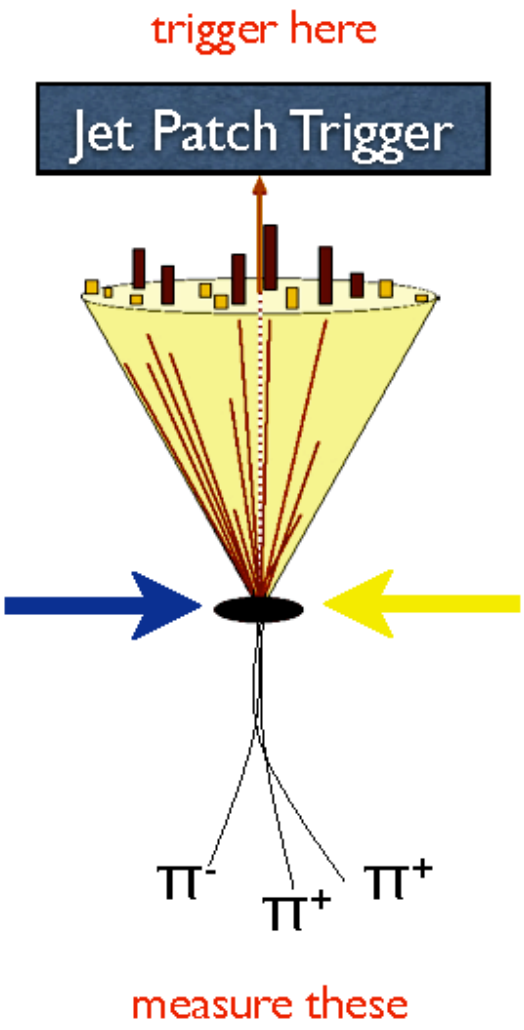
STAR Longitudinal Asymmetries from Inclusive Hadrons

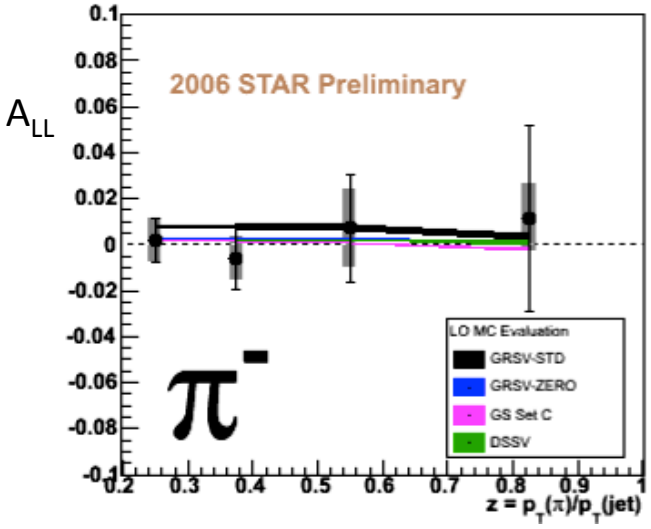


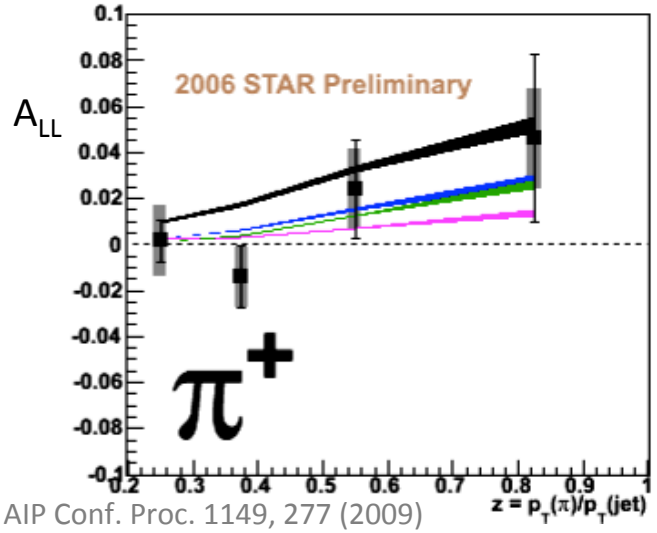
AIP Conf. Proc. 915, 355 (2007)

- STAR measured A_{LL} for inclusive charged pions during 2005
- $A_{LL}(\pi^{+}) - A_{LL}(\pi^{-})$ is sensitive to the sign of ΔG
- **Difficult to trigger on charged pions**
- Used the E/M calorimeter jet patch trigger as a surrogate
  → **significant trigger bias** (*dominates syst. error band*)

STAR Longitudinal Asymmetries from ~~Inclusive~~ Hadrons



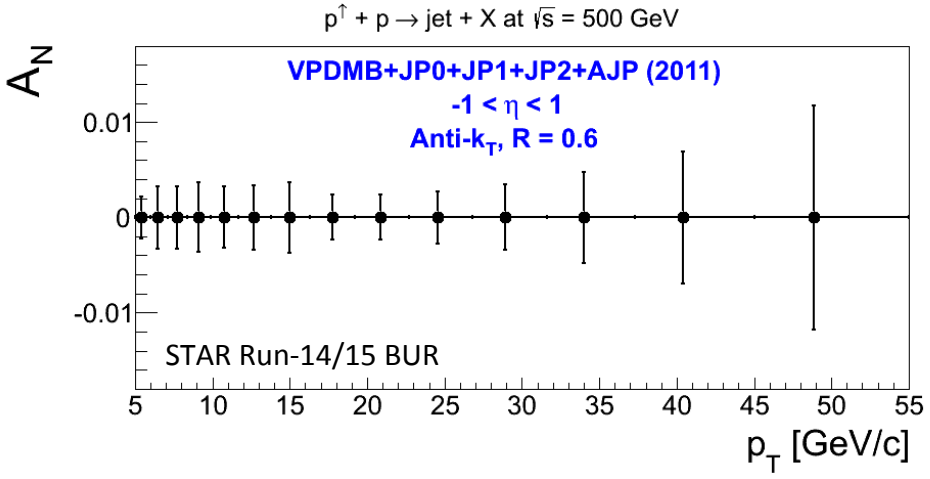


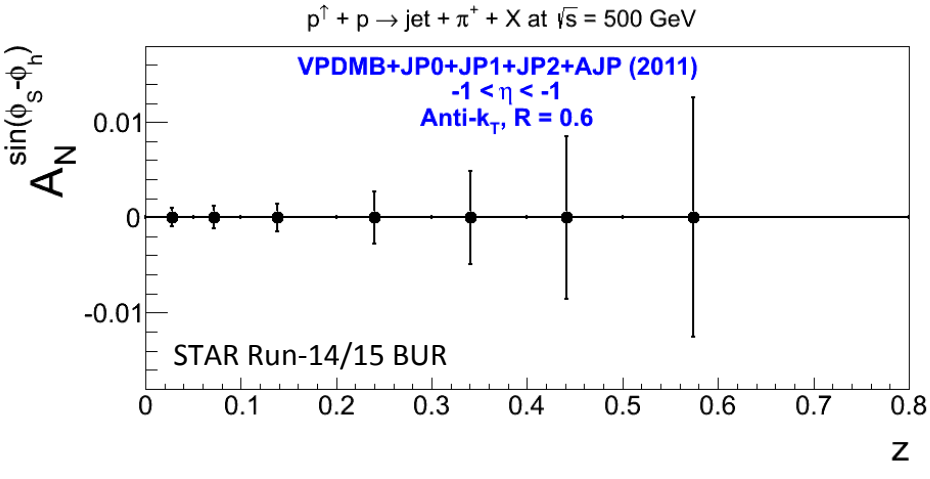


AIP Conf. Proc. 1149, 277 (2009)

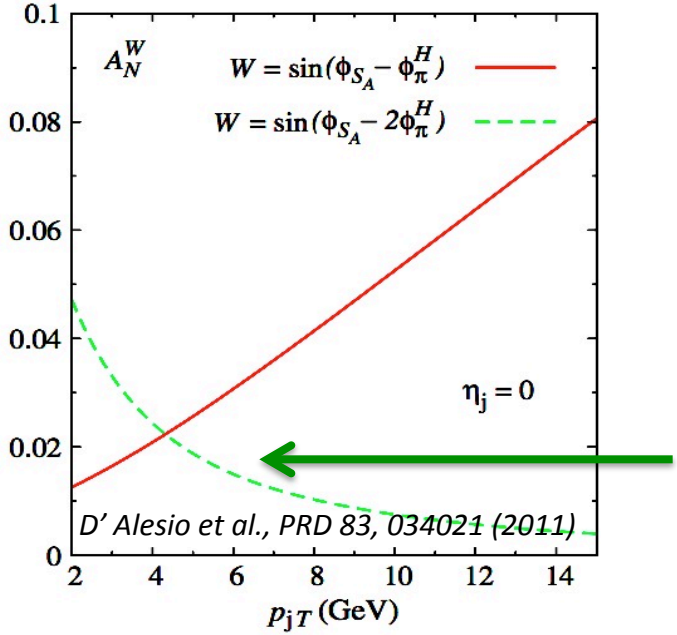
- Making lemons into lemonade
  → *Beat the trigger bias by using it*
- Trigger and reconstruct a jet, then look for a charged pion on the opposite side
- Correlation measurement significantly increases the sensitivity of $A_{LL}(\pi^+)$

STAR Transverse Asymmetries at Central Pseudorapidity





Maximized Contributions (*200 GeV*)



2011 provides first look at transverse-spin inclusive jets at central pseudorapidity range with $\sqrt{s} = 500$ GeV

Collins asymmetries expected to be small at $\sqrt{s} = 500$ GeV

Higher gluon participation at $\sqrt{s} = 500$ GeV allows unique sensitivity to gluon Collins-like asymmetry