The Physics of RHIC

(5) Spin Physics at RHIC

HUGS 2007

Carl A. Gagliardi

Texas A&M University

Origin of the proton spin?

Polarized DIS: 0.2~0.3

Poorly Constrained

$$\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$

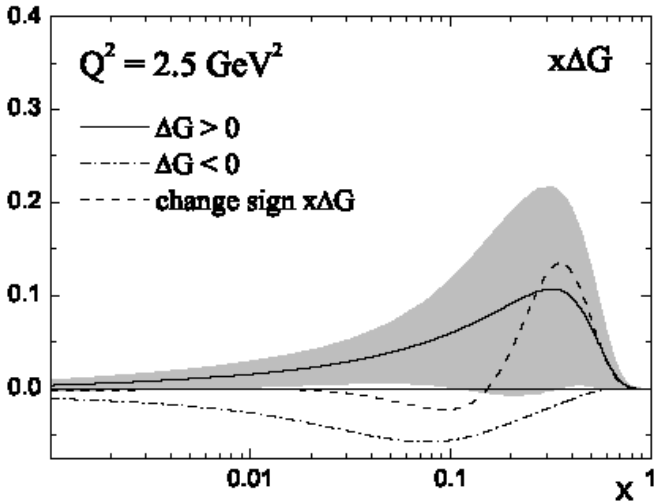
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s}$$

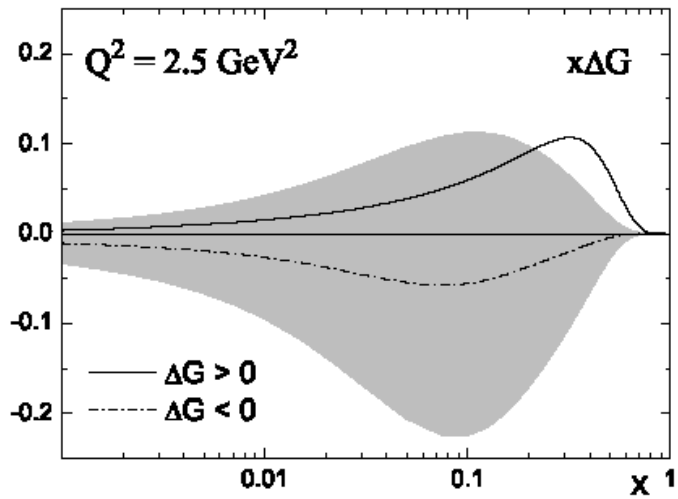
Leader et al, hep-ph/0612360

$\Delta G = 0.13 \pm 0.16$

$\Delta G \sim 0.006$

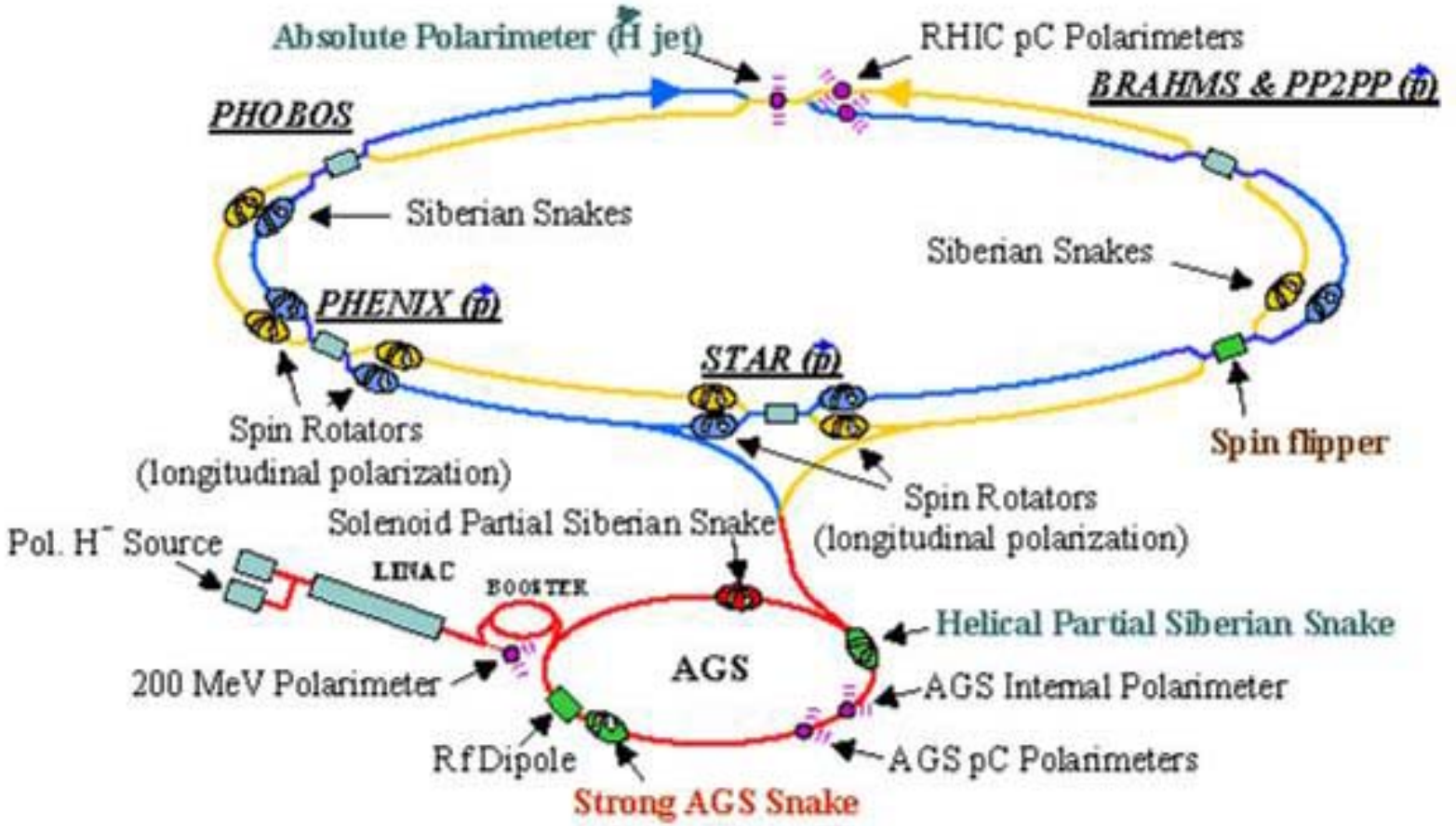
$\Delta G = -0.20 \pm 0.41$





- RHIC Spin program
  - Longitudinal polarization: Gluon polarization distribution
  - Transverse polarization: Parton orbital motion and transversity
  - Down the road: Anti-quark polarization

Polarized protons in RHIC

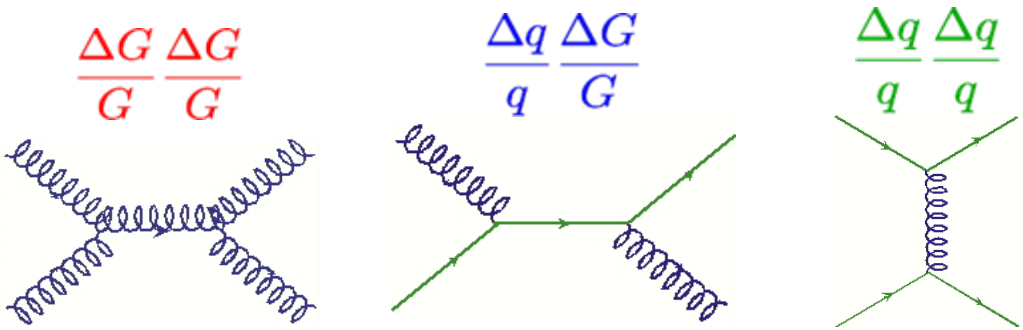


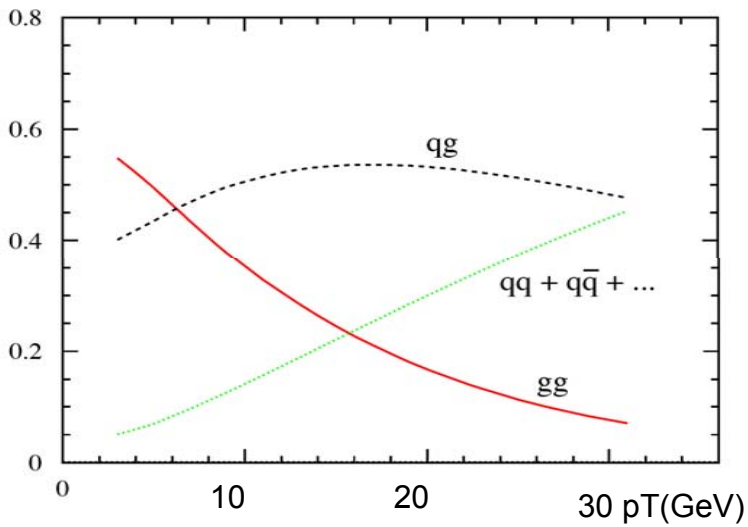
- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide flexibility for STAR and PHENIX measurements
- “Billions” of spin flips during a fill with little if any depolarization

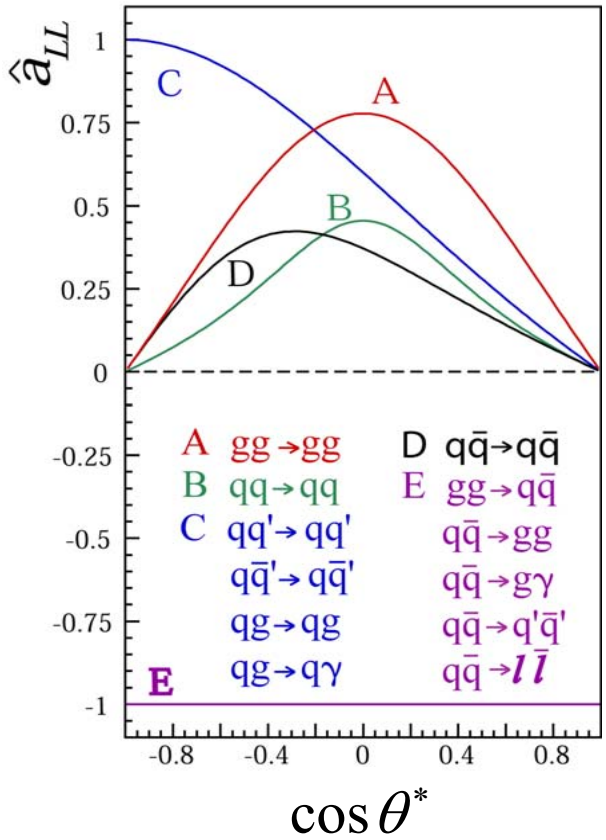
Inclusive A_{LL} measurements (π^o, $\pi^{\pm}$, and jets)

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

Δf: polarized parton distribution functions

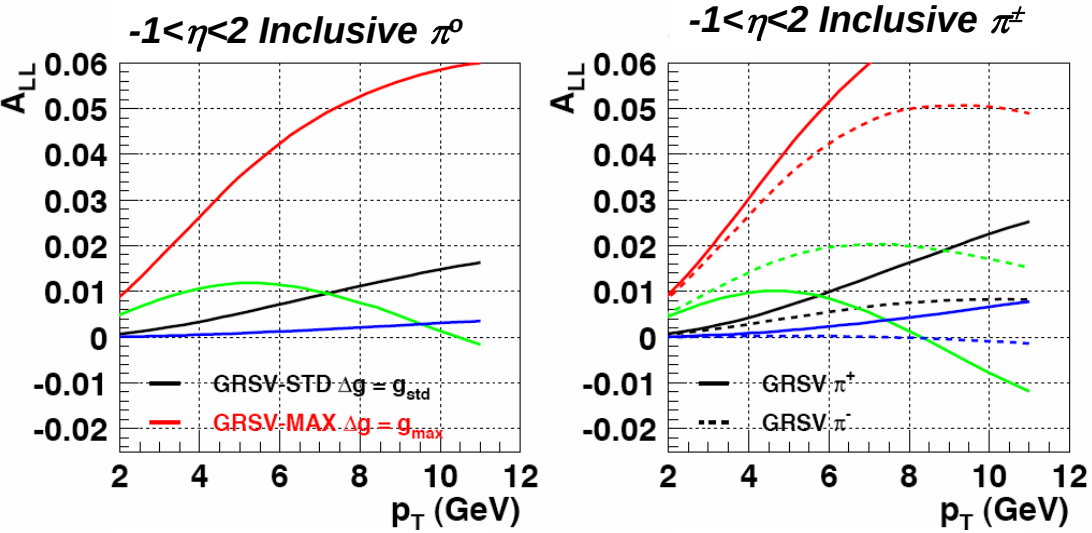


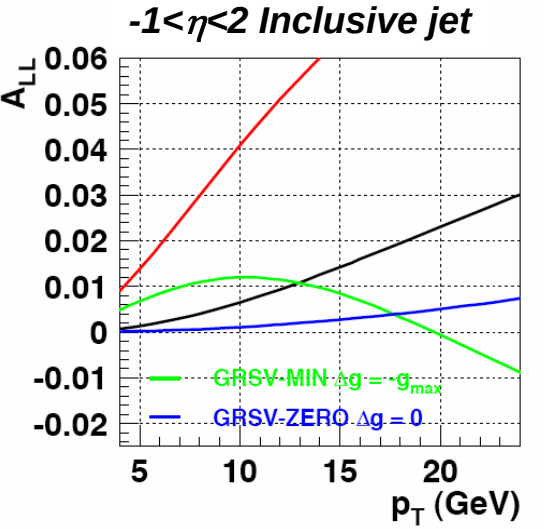


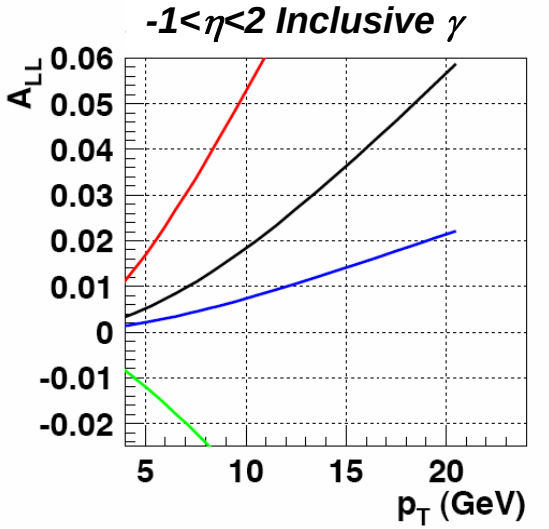


For most RHIC kinematics, *gg* and *qg* dominate, making A_{LL} sensitive to **gluon polarization**.

Predicted sensitivity for different ΔG scenarios

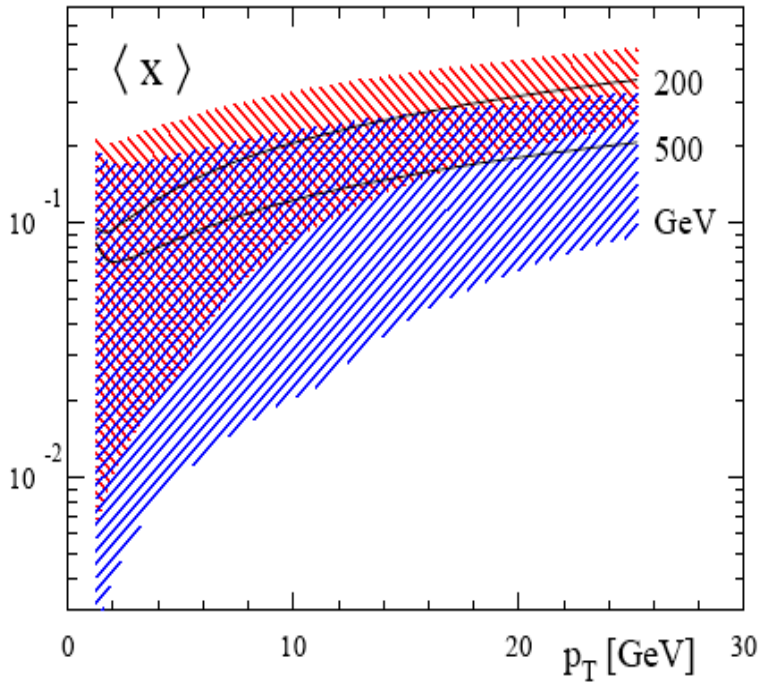






Calculations by
W. Vogelsang

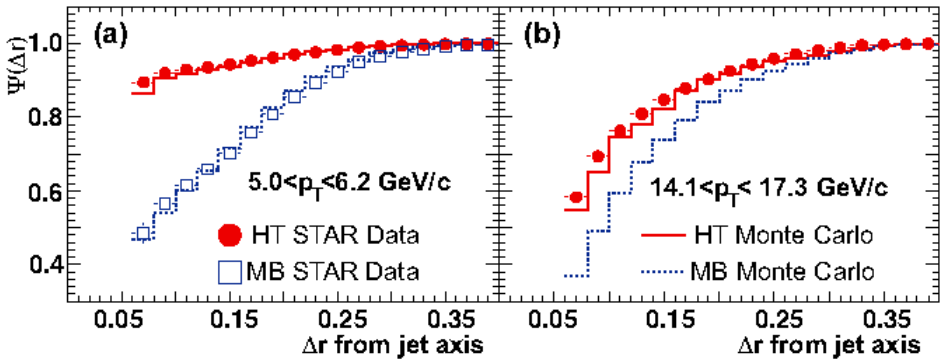
Sampled x range
for inclusive jets



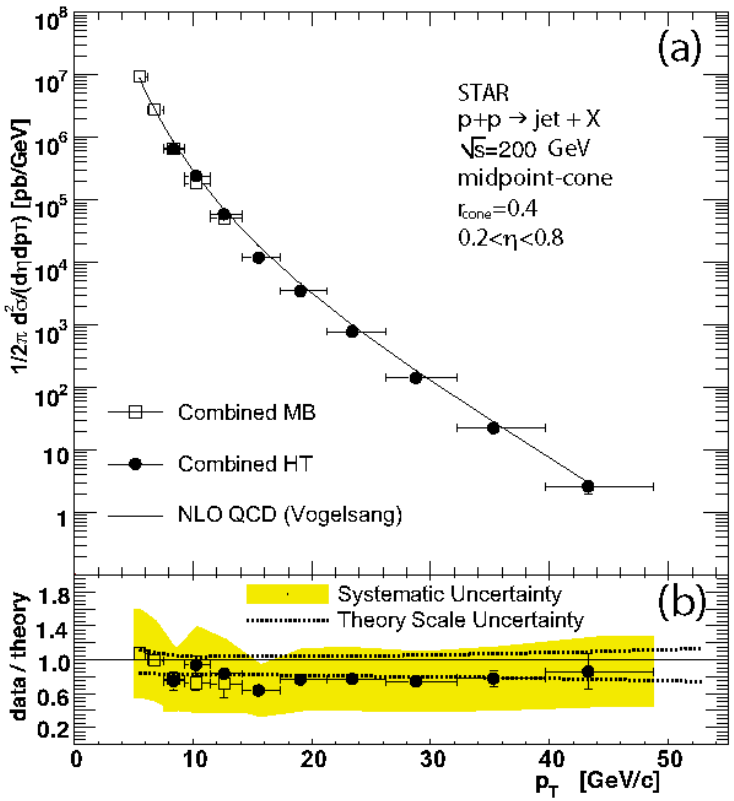
- Jets (STAR) and π^0 (PHENIX and STAR) easier
- γ and $A_{LL}(\pi^+)$ - $A_{LL}(\pi^-)$ sensitive to the sign of ΔG
- Inclusive measurements average over broad *x* ranges

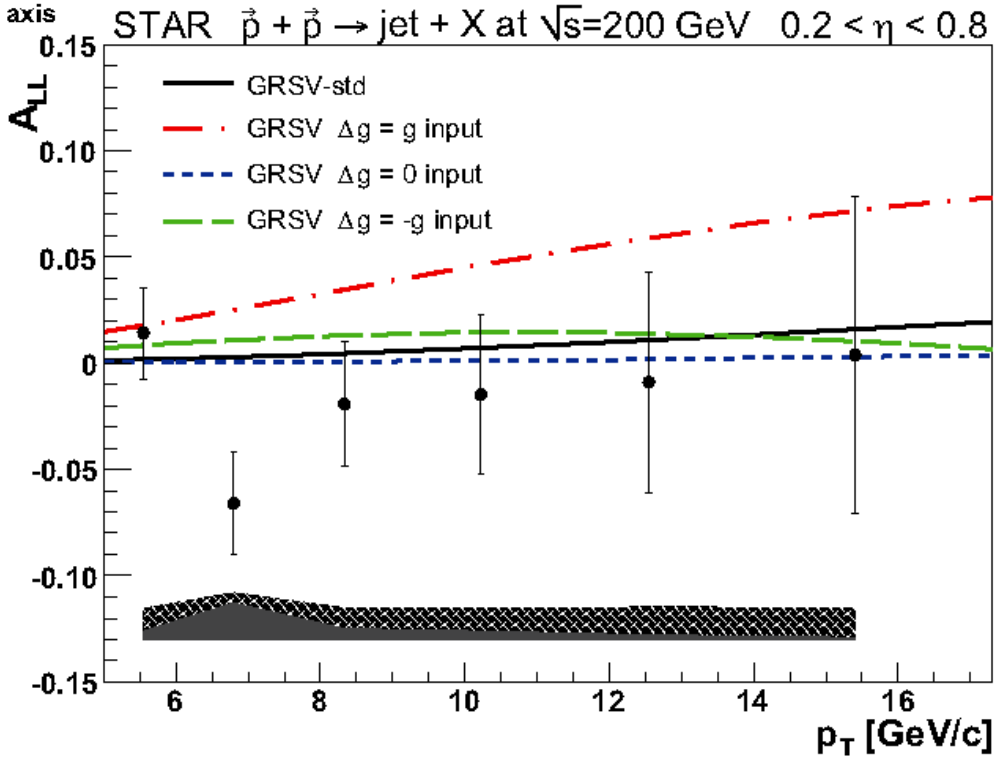
STAR jets from Runs 3+4

PRL 97, 252001



We understand our jets.

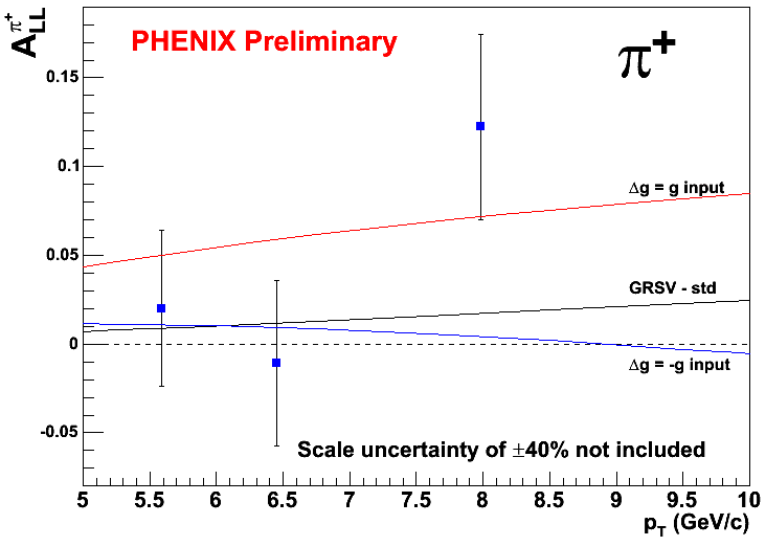


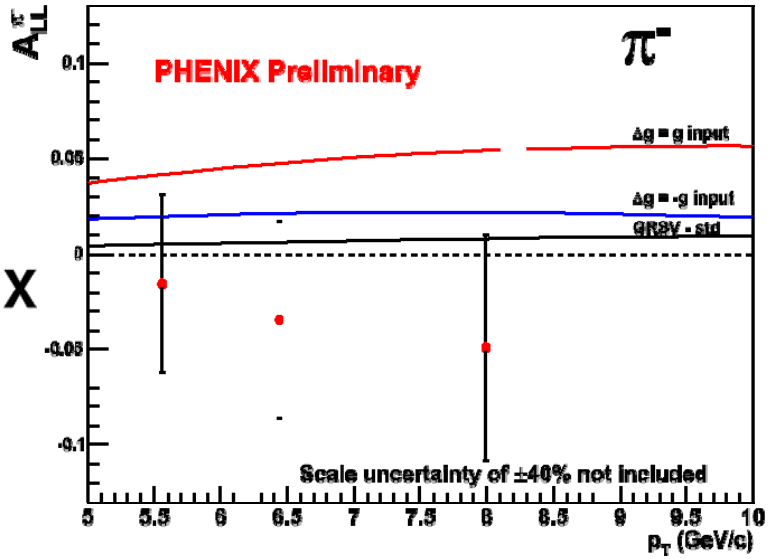


Gluon polarization is not “really big”

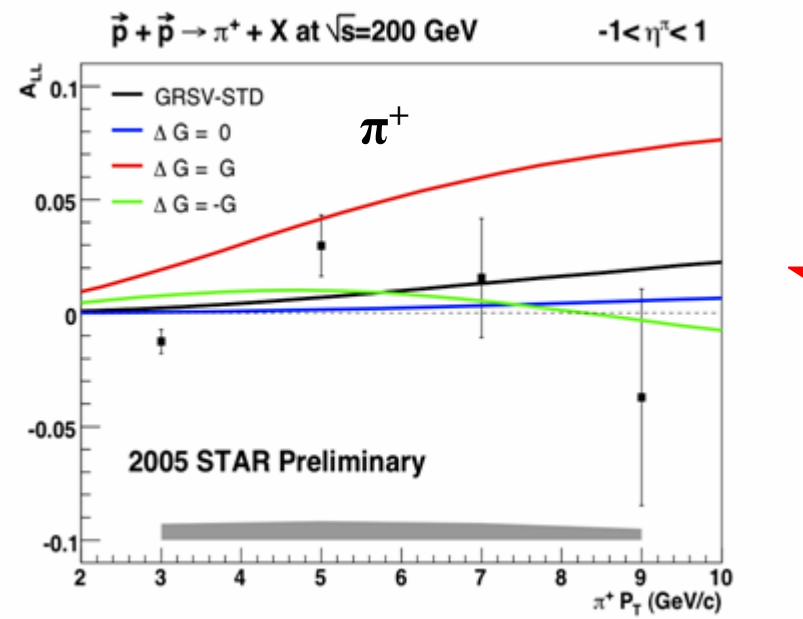
(GRSV-max: CL ~ 0.02)

Charged pions from Run 5

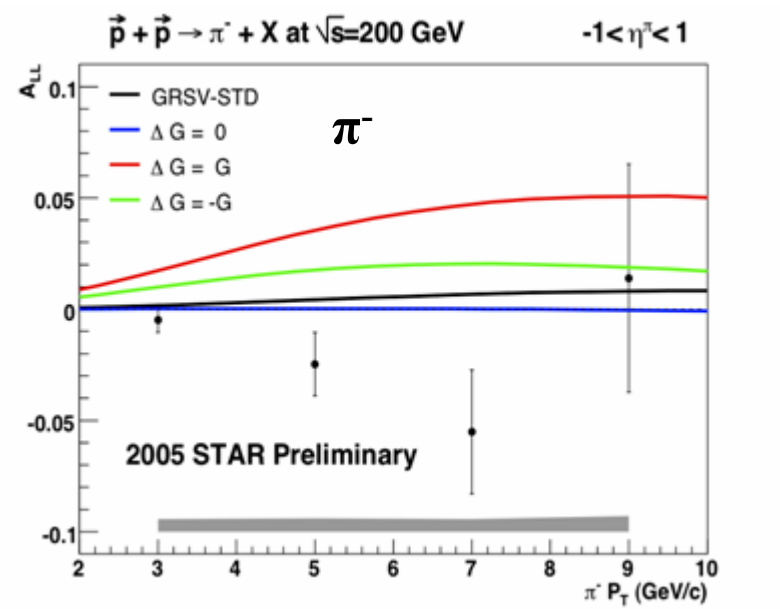




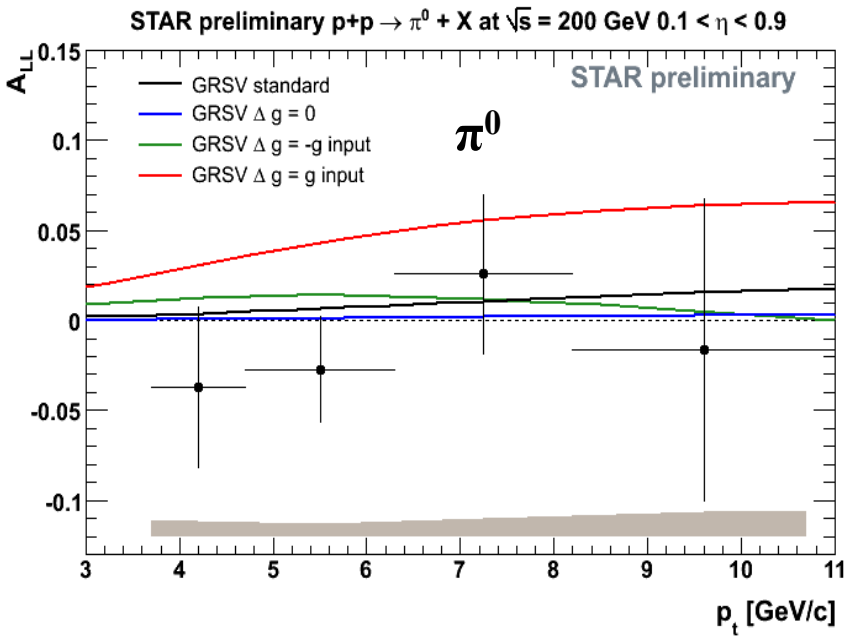
PHENIX



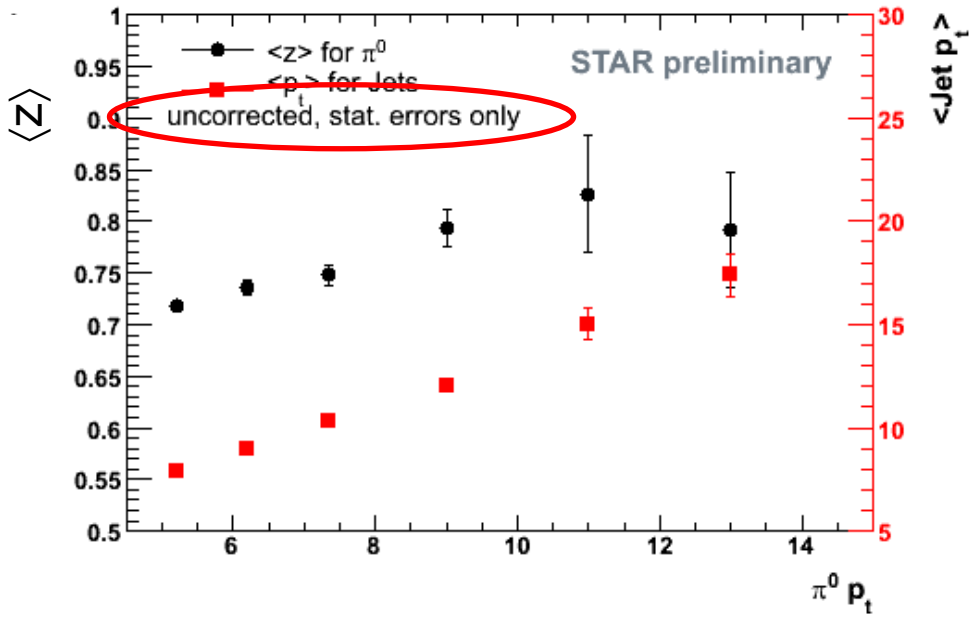
STAR



STAR neutral pions from Run 5



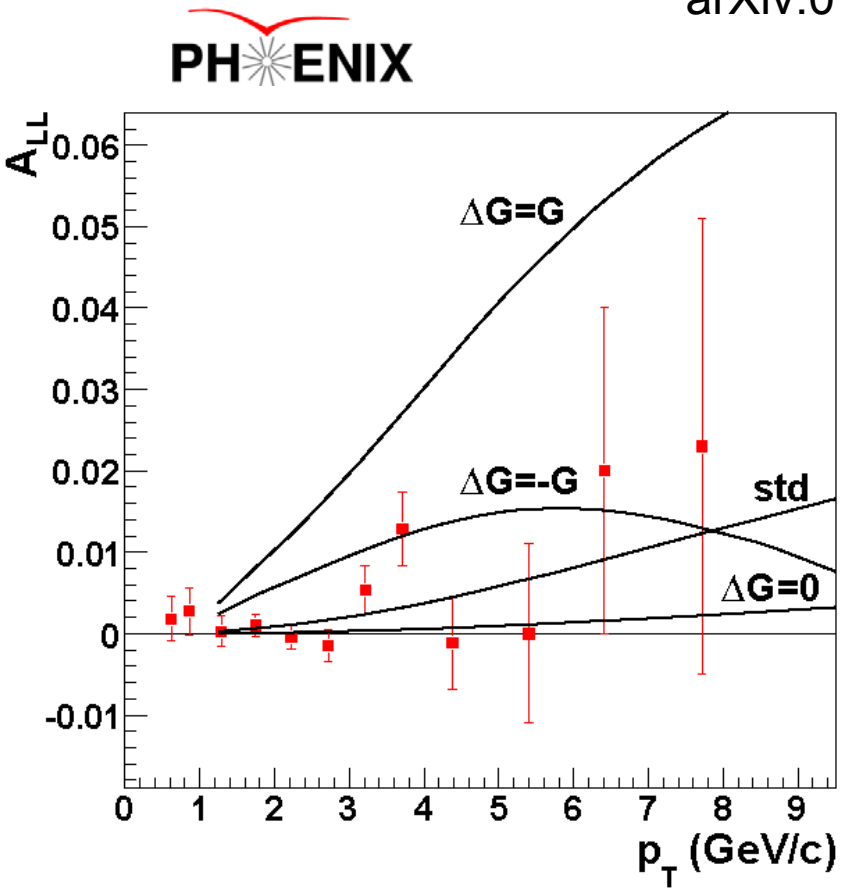
⟨z⟩ ≡ Mean ratio of π^0 p_T to Jet p_T

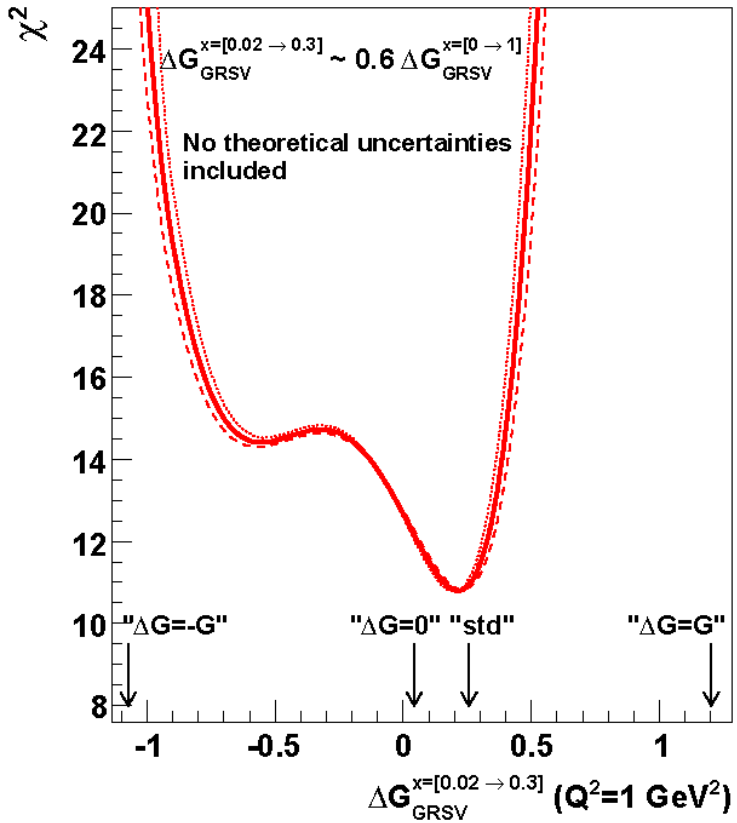


- A_{LL} disfavors large (positive) gluon polarization
- Energetic π^0 carry a significant fraction of the total transverse momentum of their associated jet

PHENIX neutral pions from Run 5

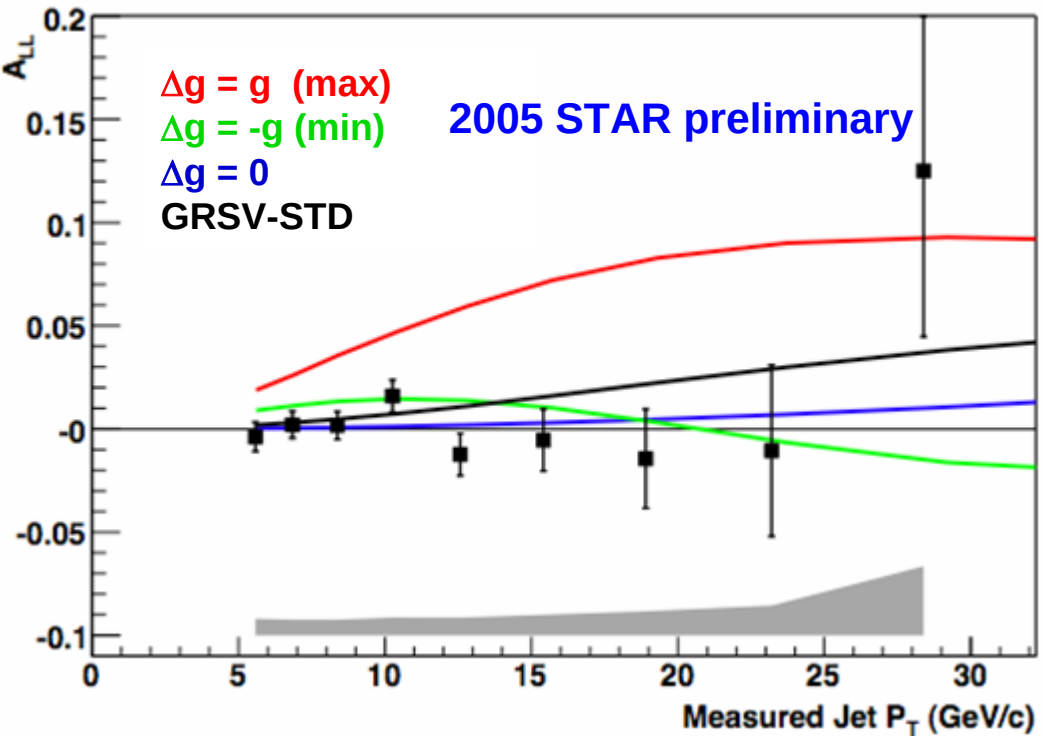
arXiv:0704.3599

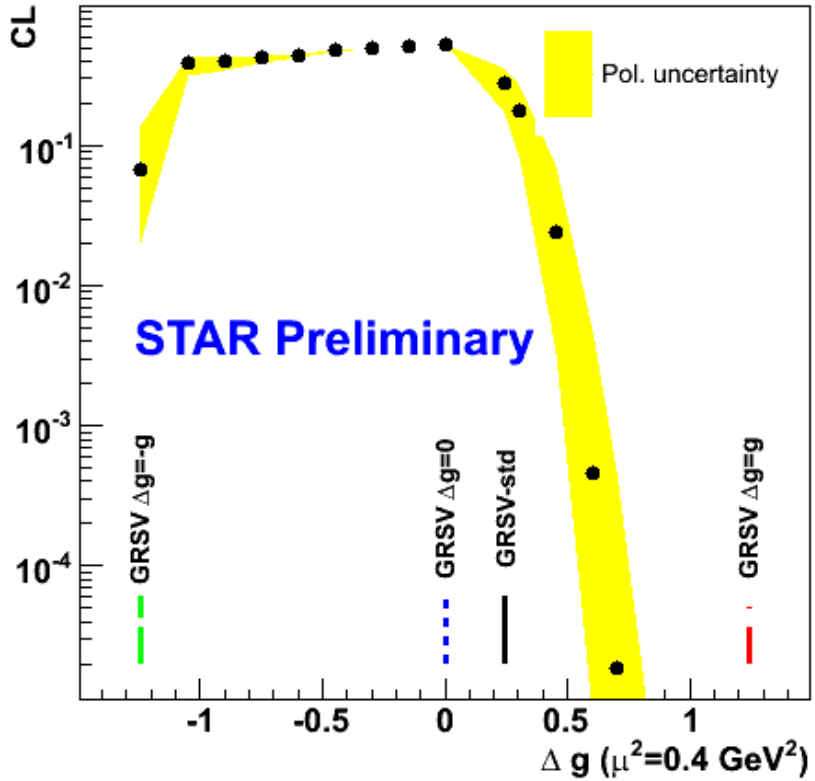




- χ^2 from a comparison to the GRSV polarized parton distributions
- Uncertainties associated with GRSV functional form not included
- Large positive polarizations excluded; large negative polarizations disfavored
- Uncertainties from Run 6 will be a factor of ~2 smaller

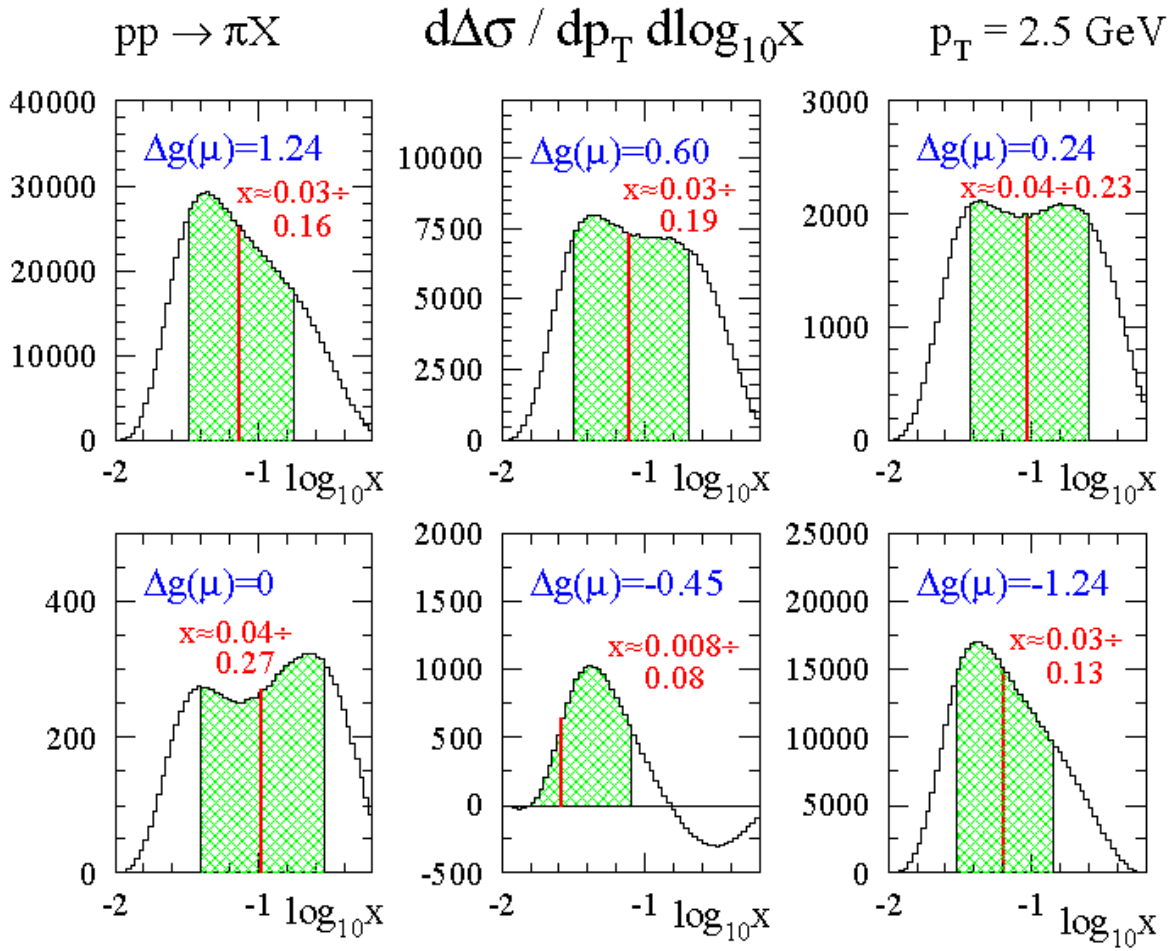
STAR jets from Run 5





- CL from a comparison to the GRSV polarized parton distributions
- Uncertainties associated with GRSV functional form not included
- Large positive polarizations excluded; large negative polarizations disfavored
- Uncertainties from Run 6 will be a factor of ~3 smaller at high p_T

The limitation of inclusive A_{LL} measurements



From Marco Stratmann, DIS'06

- Inclusive A_{LL} measurements at fixed p_T average over a **broad x range**.
- You don't know the range until you know the answer!
- Need a global analysis to determine the implications

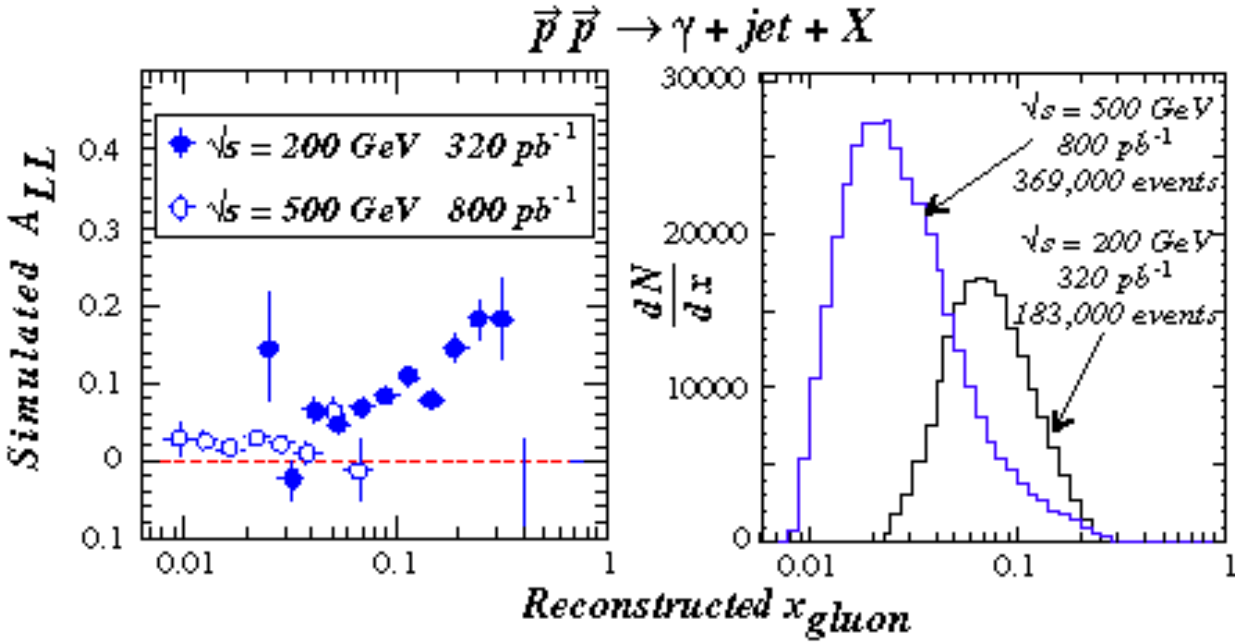
The next few years: $\Delta G(x)$

$$x_1 = \frac{1}{\sqrt{s}}\left(p_3 e^{\eta_3} + p_4 e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_3 e^{-\eta_3} + p_4 e^{-\eta_4}\right)$$

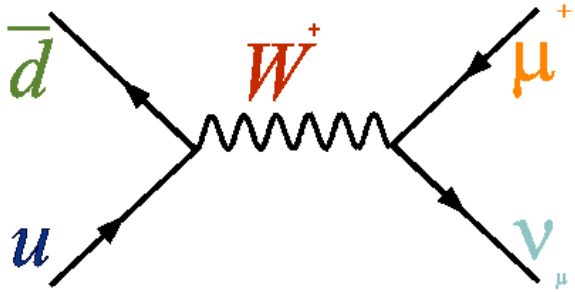
$$\frac{x_1}{x_2} = e^{\eta_3 + \eta_4}$$

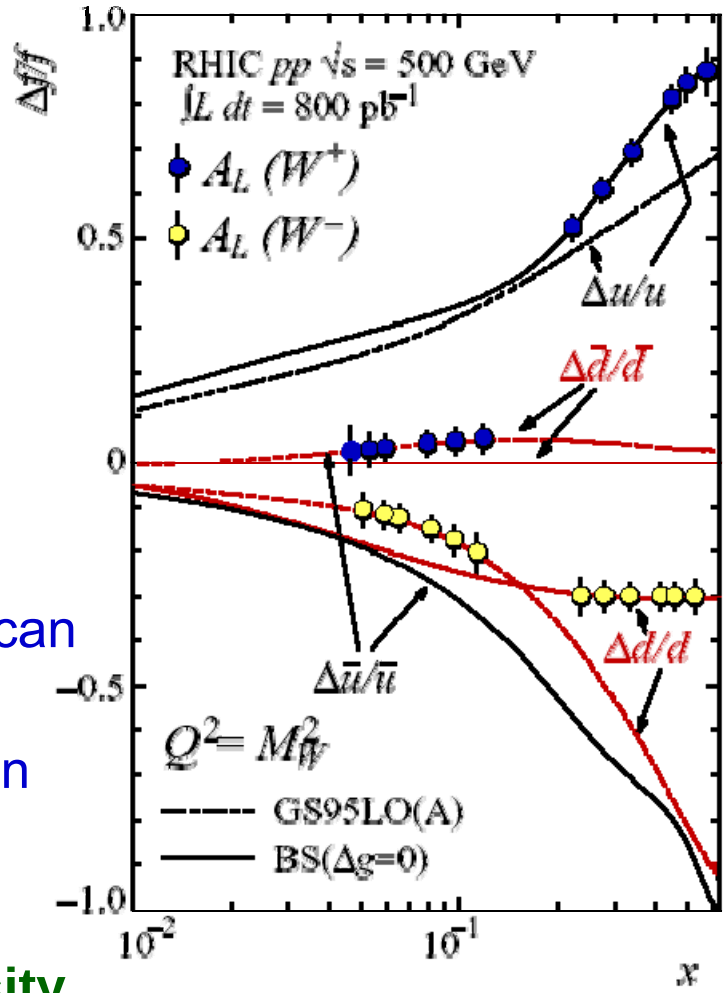
$$|\cos\theta^*| = \tanh\frac{|\eta_3 - \eta_4|}{2}$$



- Di-jets and γ+jet permit LO determination of x_1 and x_2
- Can select those events with maximal sensitivity
- Di-jets are more plentiful
  - Get started with existing Run 6 data
- γ+jet results are easier to interpret
  - Physics in Runs 8+

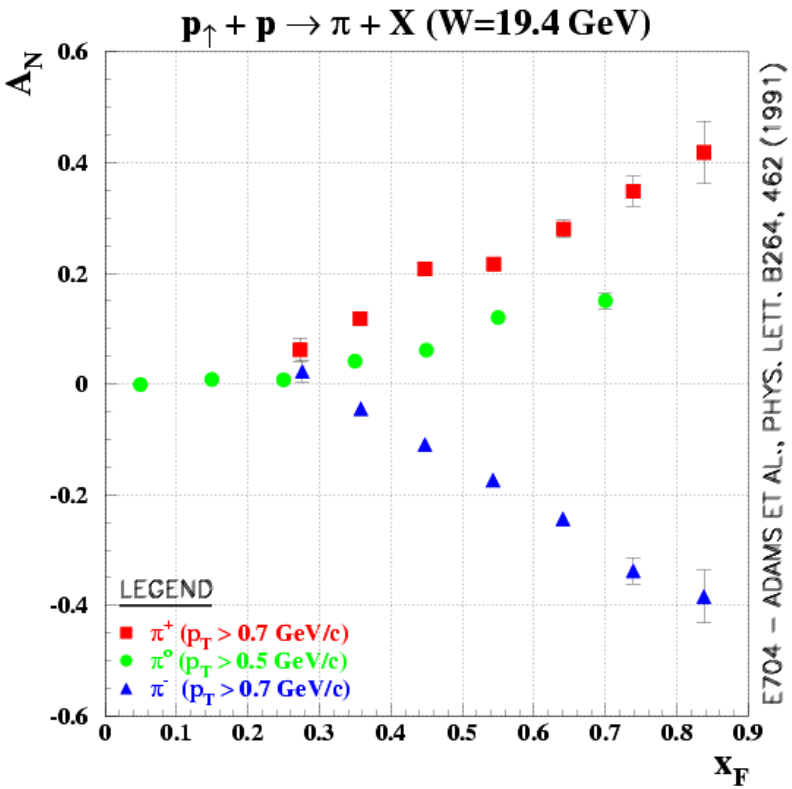
Further future: anti-quark polarization



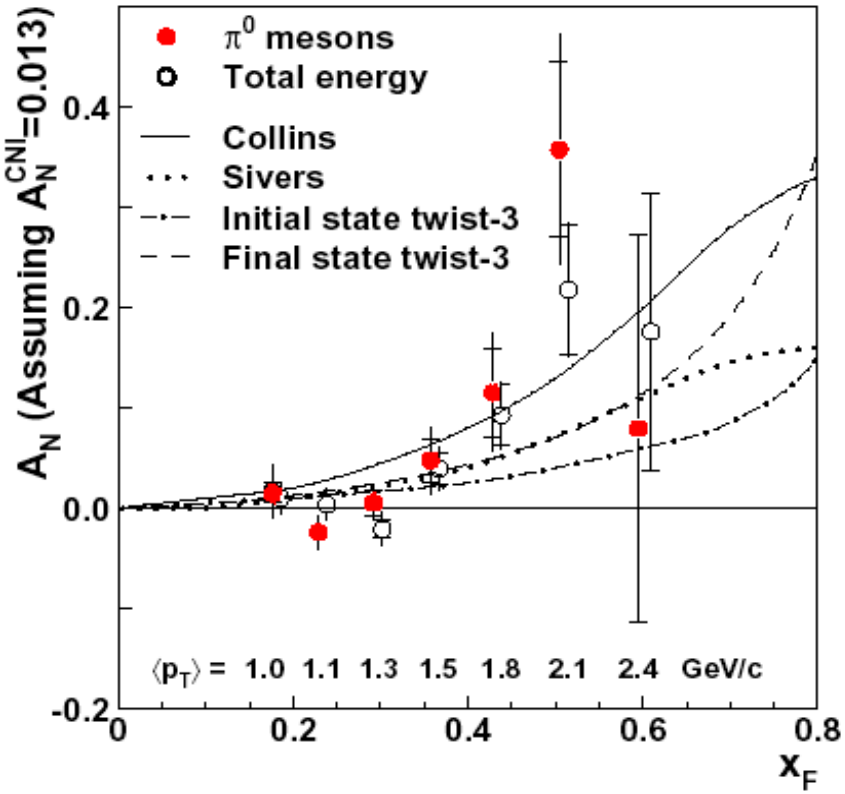


- With two polarized beams and W^+ and W^-, can separate u, d, $\bar{u}$, $\bar{d}$ polarizations
- These simulations are for the PHENIX muon arms
- STAR will do this with electrons
- Need **500 GeV collisions at high luminosity**, and upgrades to both PHENIX and STAR

Single-spin asymmetries at forward rapidity



STAR, PRL 92, 171801

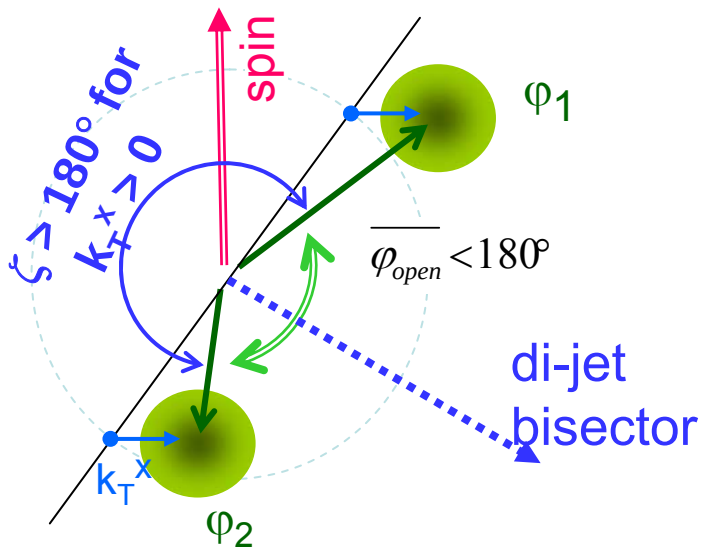


- Large single-spin asymmetries at CM energies of 20 and 200 GeV
- May arise from “Sivers effect”, “Collins effect”, or a combination

Sivers effect in di-jet production

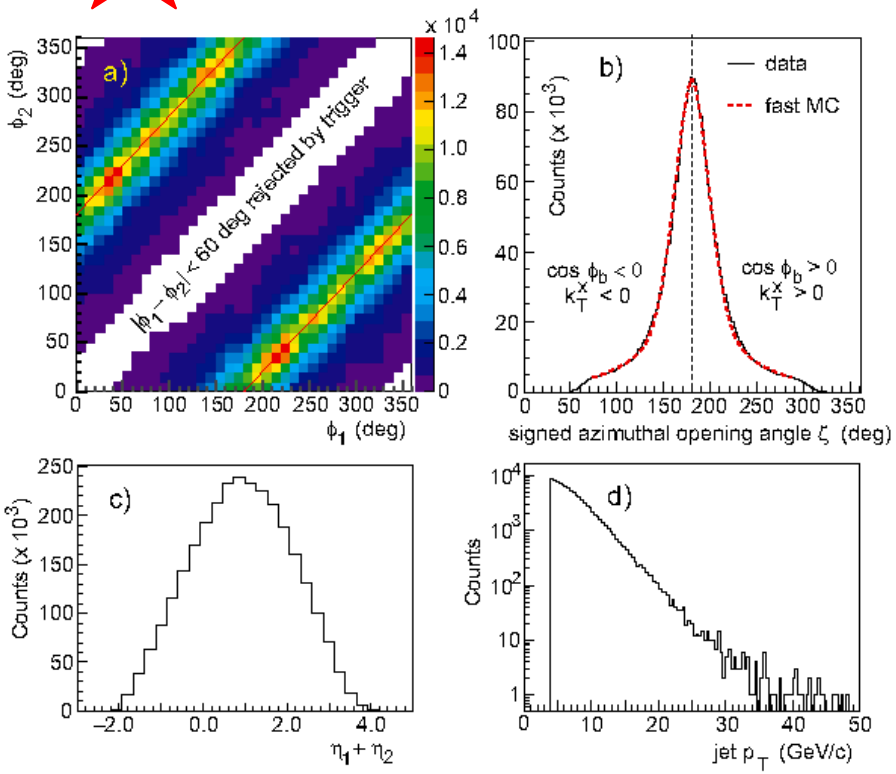
Sivers effect: $\langle k_T^{\text{parton}} \cdot (\vec{s}_{\text{proton}} \times \vec{p}_{\text{proton}}) \rangle \neq 0$

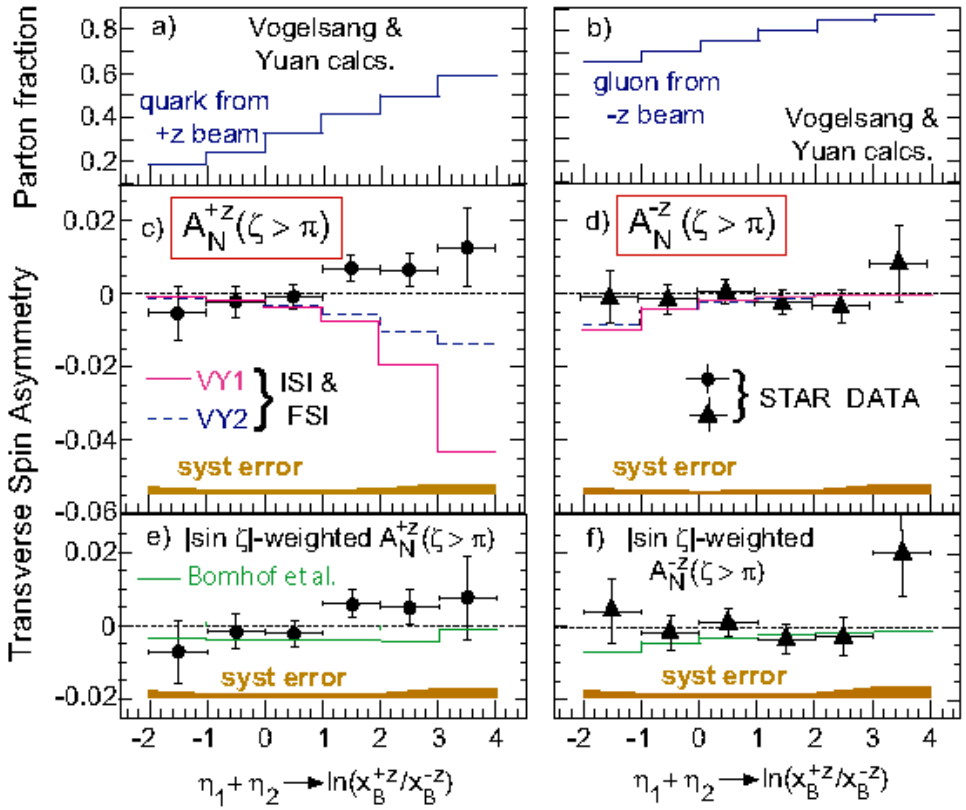
- Left/right asymmetry in the k_T of the partons in a polarized proton
- Spin dependent sideways boost to di-jets
- **Requires parton orbital angular momentum**
- Both beams polarized, $x_a \neq x_b \Rightarrow$ pseudorapidity dependence can distinguish q vs. g Sivers effects.



STAR Sivers di-jet measurement

arXiv:0705.4629 (posted 8 pm yesterday!)



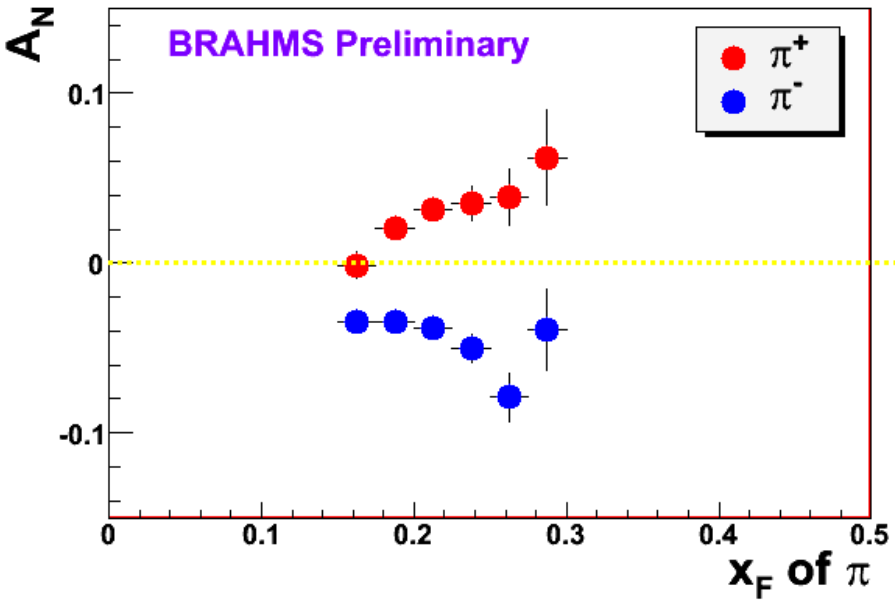


- Allow separation of quark and gluon Sivers functions
- Observed asymmetries are an order of magnitude smaller than seen in semi-inclusive DIS by HERMES
- Detailed cancellations of initial vs. final state effects and *u* vs. *d* quark effects?

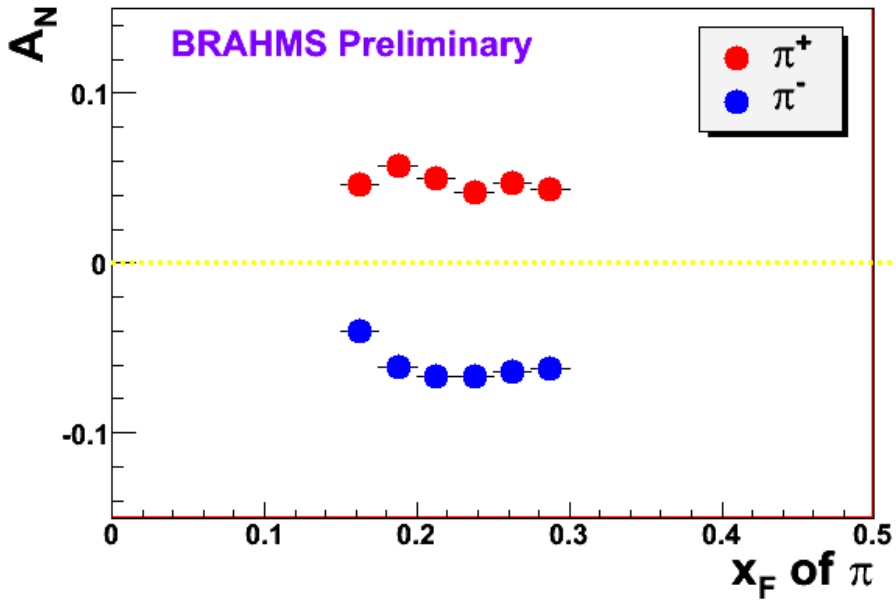
BRAHMS charged pion measurements at 200 GeV

BRAHMS

η = 3.35;
p_T = 2 GeV/c at x_F = 0.29



η = 3.9;
p_T = 1 GeV/c at x_F = 0.25

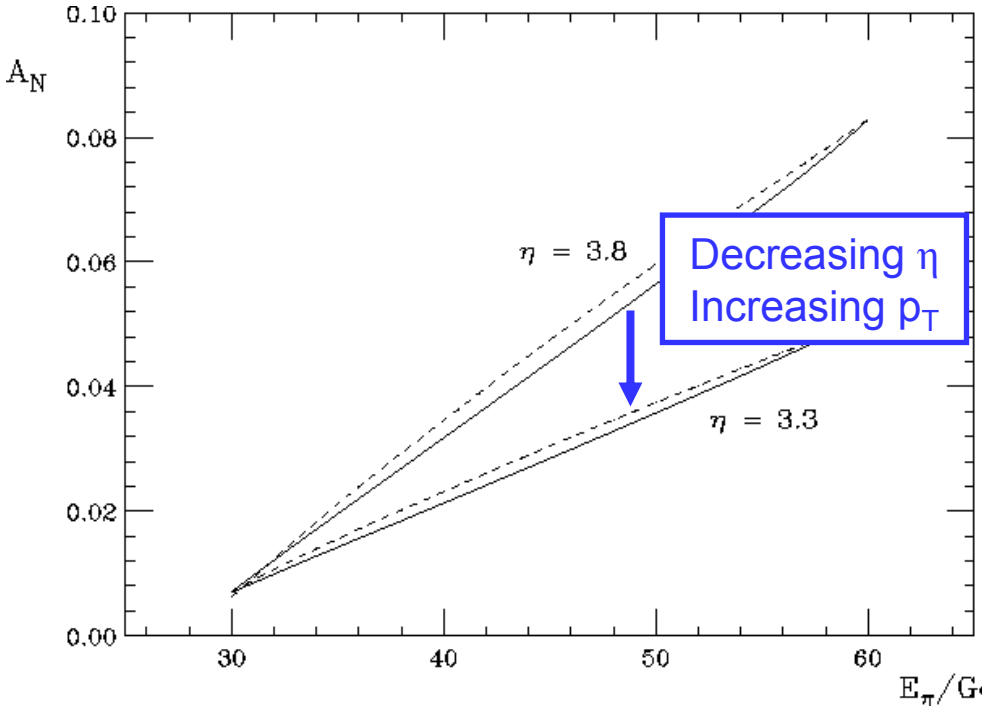


- Sign dependence of charged pion asymmetries persists to 200 GeV
- p_T is linearly proportional to x_F
- Identified K^+, K^-, anti-proton all give positive A_N. Proton $A_N \sim 0$
- 62 GeV results qualitatively similar, but with even larger asymmetries (up to 0.25 at x_F=0.6 for π^+, -0.4 at x_F=0.6 for π^-)

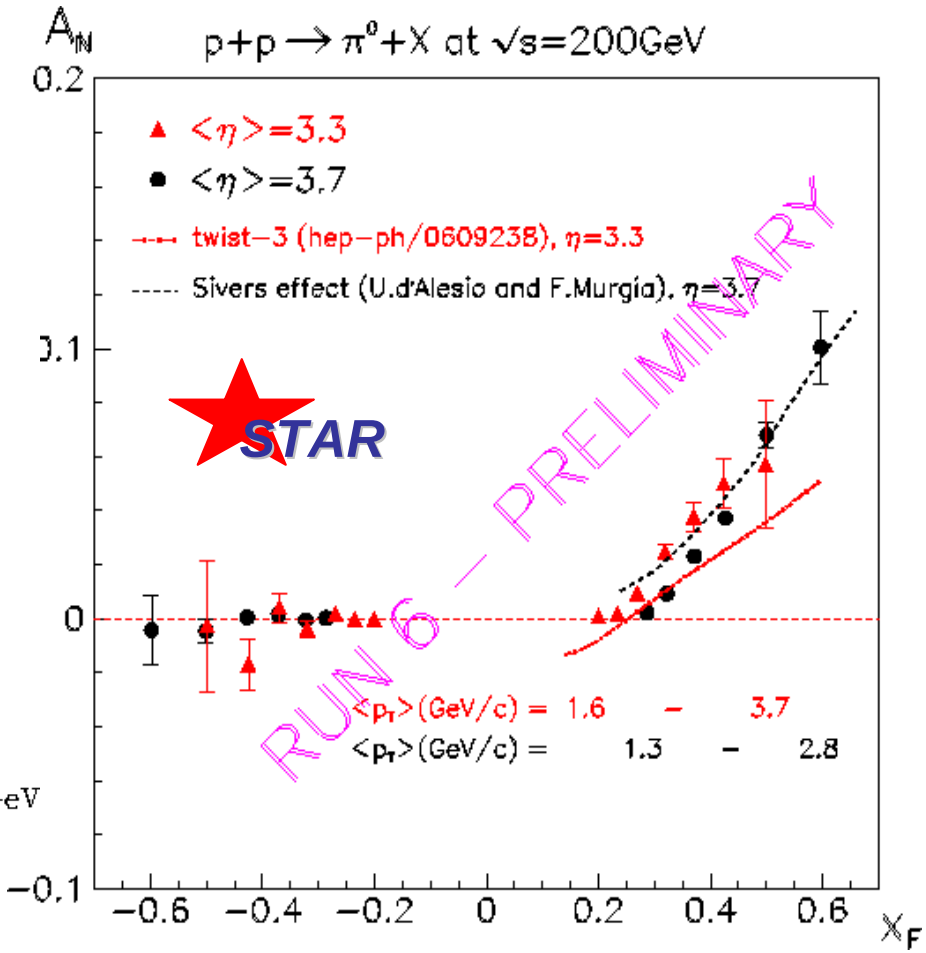
Inclusive forward π^o asymmetry, A_N

Theory

Kouvaris et al, hep-ph/0609238

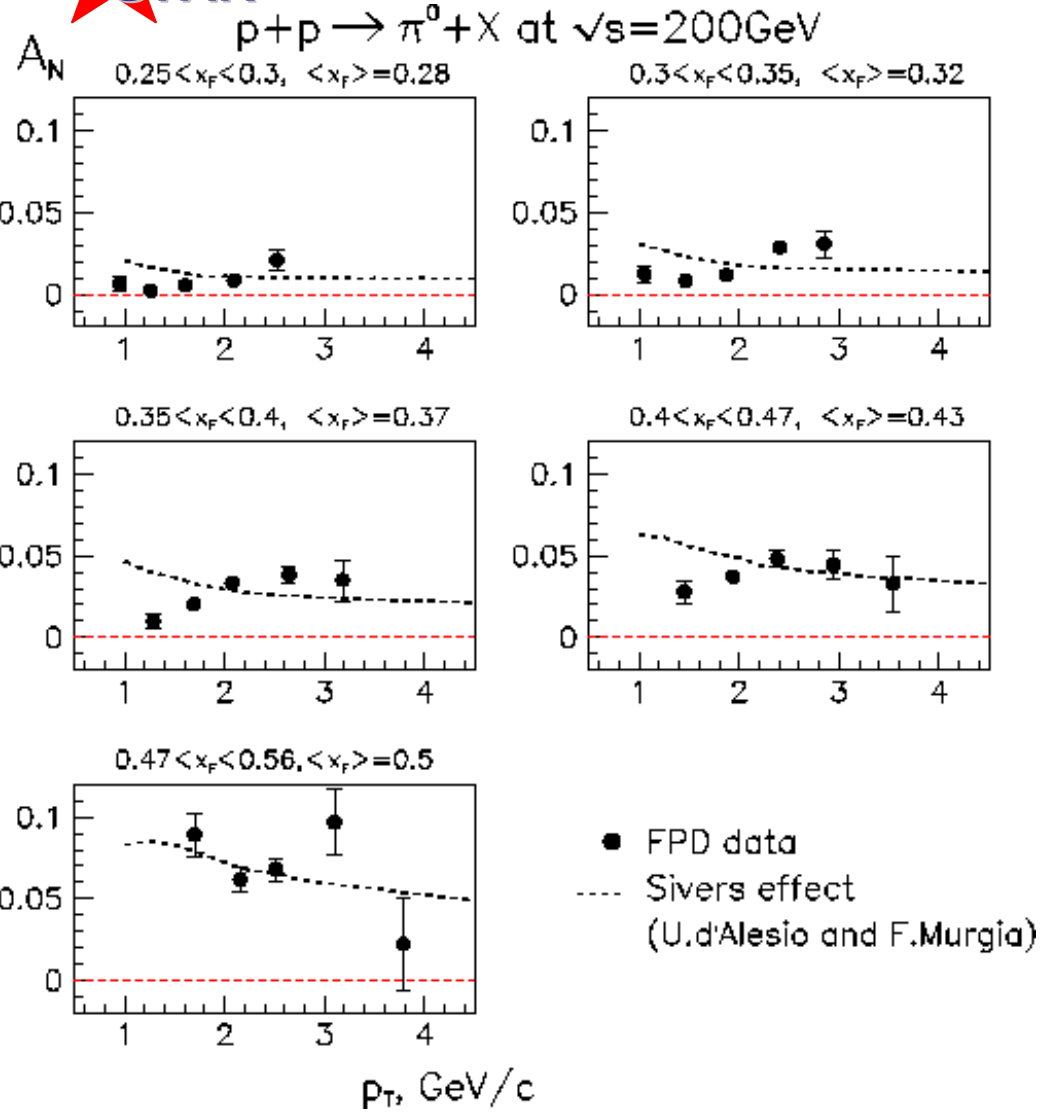


Data

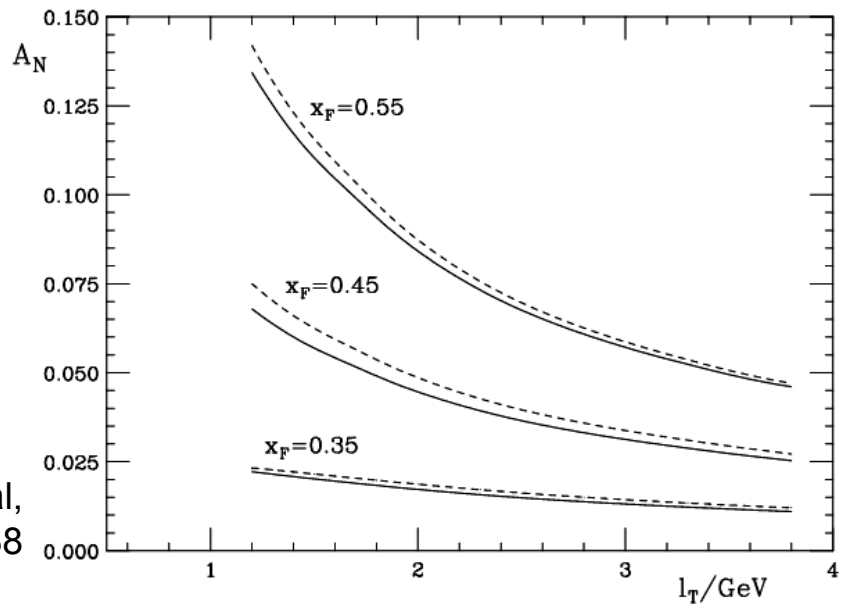


The data show exactly the **opposite** behavior

$A_N(p_T)$ in x_F-bins



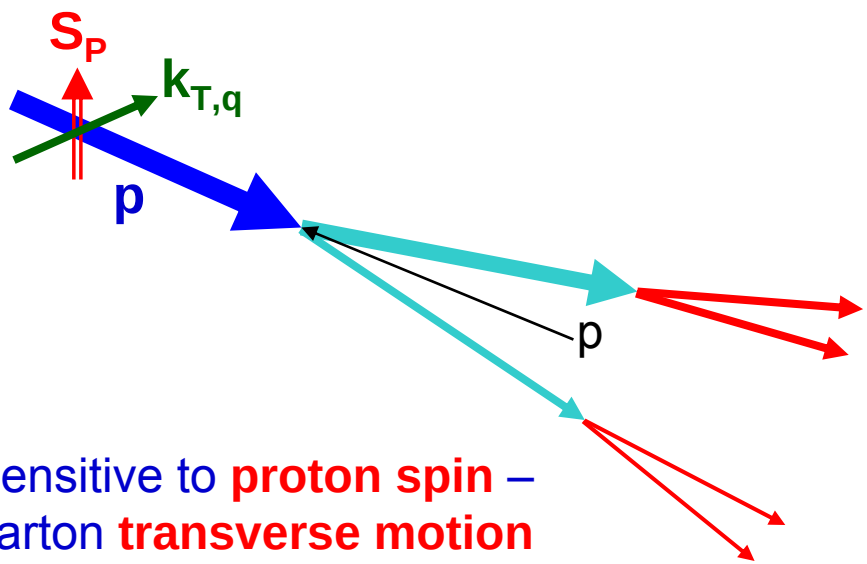
- Combined data from three runs at $\langle\eta\rangle$=3.3, 3.7 and 4.0
- In each x_F bin, $\langle x_F\rangle$ does not significantly changes with p_T
- Measured A_N is not a smooth decreasing function of p_T as predicted by theoretical models



Kouvaris et al, hep-ph/0609238

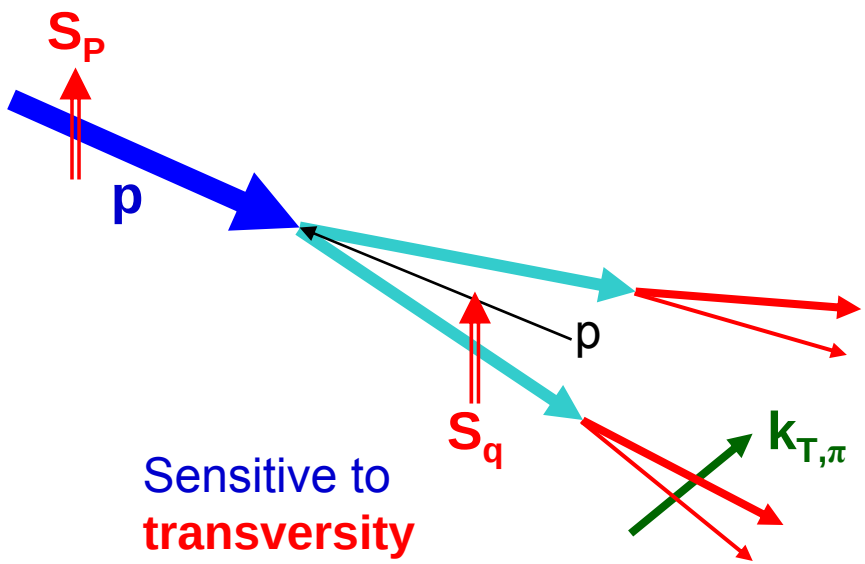
Separating Sivers and Collins effects

Sivers mechanism: asymmetry in the forward jet or γ production



Sensitive to **proton spin** – parton **transverse motion** correlations

Collins mechanism: asymmetry in the forward jet fragmentation



Sensitive to **transversity**

- Need to go beyond inclusive π^0 to measurements of jets or direct γ
- Have some Run 6 data with FPD++
- Will study in Run 8 with the STAR FMS

Conclusion

- The world's first polarized hadron collider is generating a wealth of new data regarding the spin structure of the proton

- **We've only barely started!**