Recent Spin Results from RHIC

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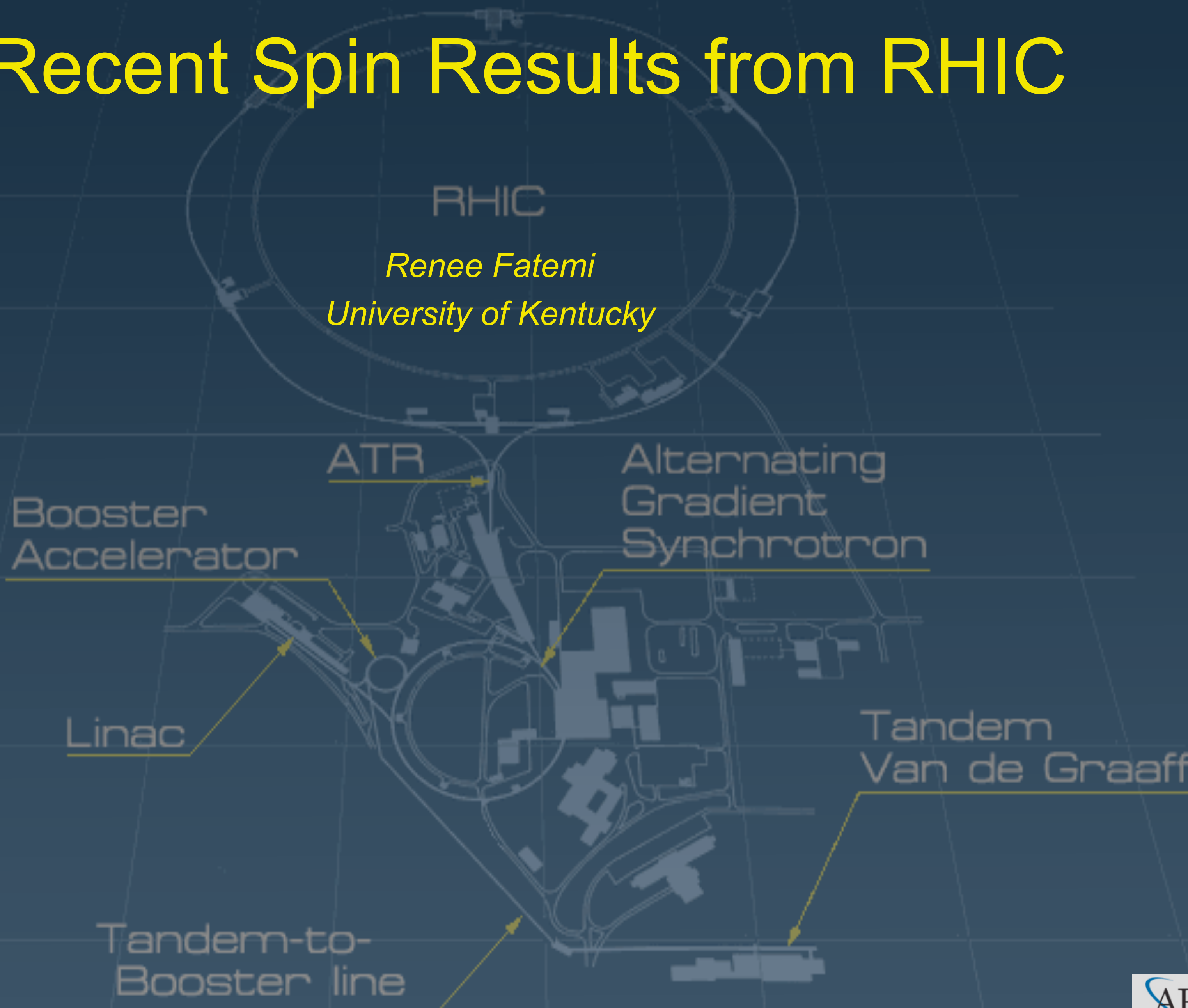


APS April Meeting, Denver CO *May 4th, 2009*

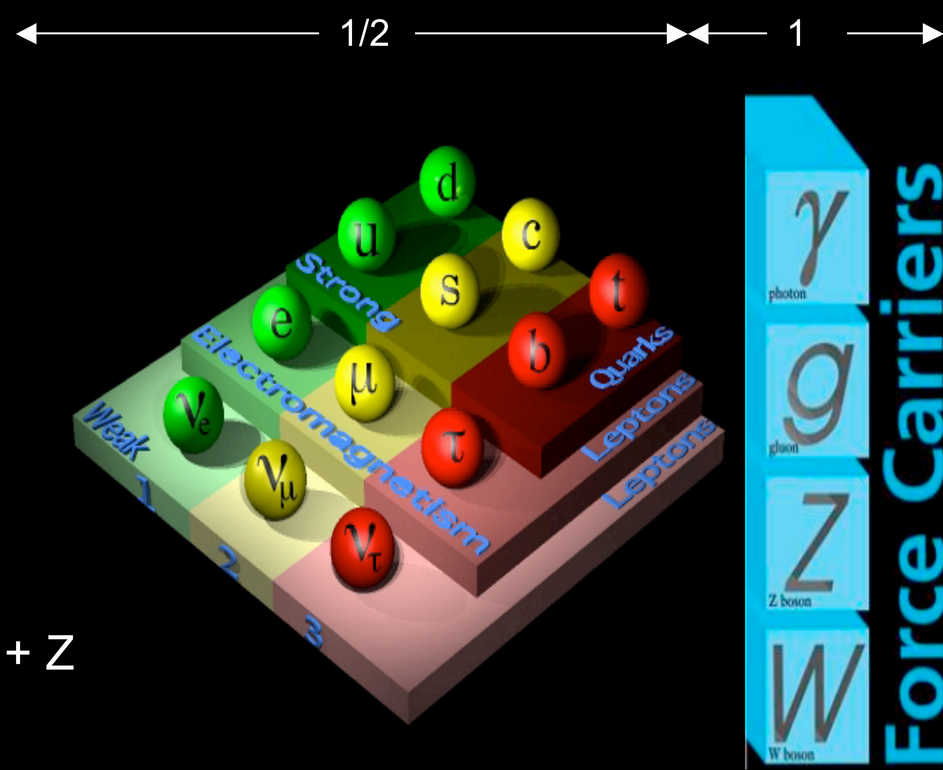
The Agenda

- What insights are gained by studying spin effects in QCD?
- What are the pressing issues in high energy SPIN physics today?
- How has RHIC contributed?
- How will RHIC contribute in the future?

The STANDARD Model

- 3 fundamental forces
  - electromagnetic
  - weak
  - strong

- 16 fundamental particles
  - neutrinos $\rightarrow$ W + Z
  - leptons $\rightarrow$ photon + Z + W
  - quarks $\rightarrow$ gluon + photon + W + Z

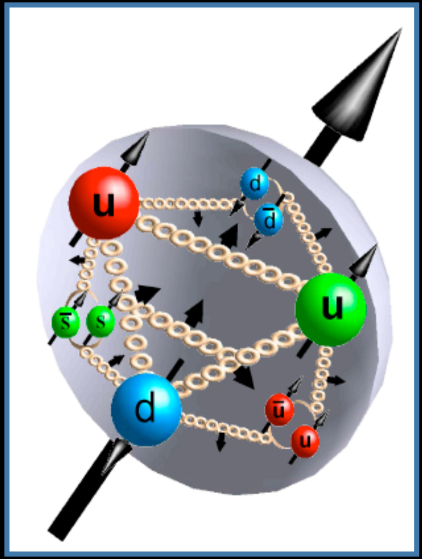


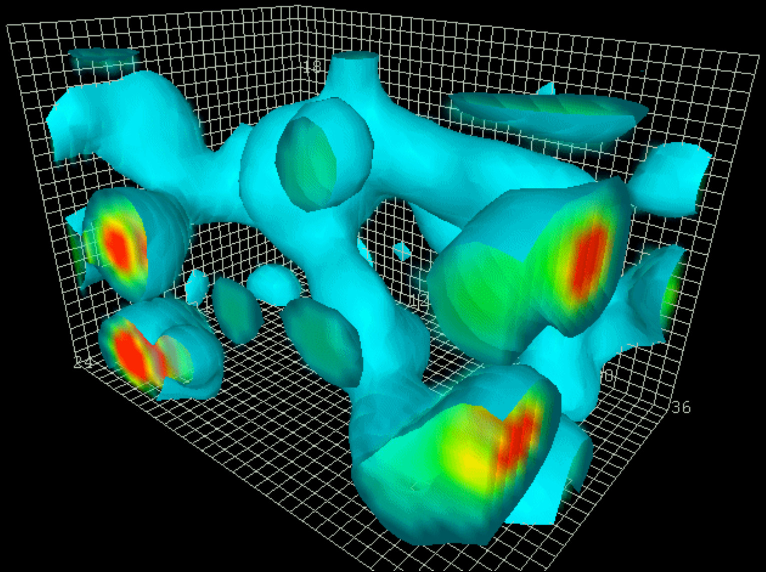
- Quarks and Gluons participate in the strong interaction by exchanging color

- Quantum Chromodynamics (QCD) is the theory of strong interactions

The Proton - A QCD Laboratory

- We want to study QCD via quark-gluon interactions
- Where to find quarks and gluons?
- Confined inside composite particles!
- Need a stable, abundant and easily manipulated particle … the proton!





Simulation from
D. B. Leinweber, hep-lat/0004025
gluon action density: 2.4 x 2.4 x 3.6 fm

- Protons are excellent QCD laboratories
- Bag of quarks held together by a fluctuating gluon field.
- Mapping out the characteristics of the gluon field is integral to our understanding of QCD

From Partons to Protons?

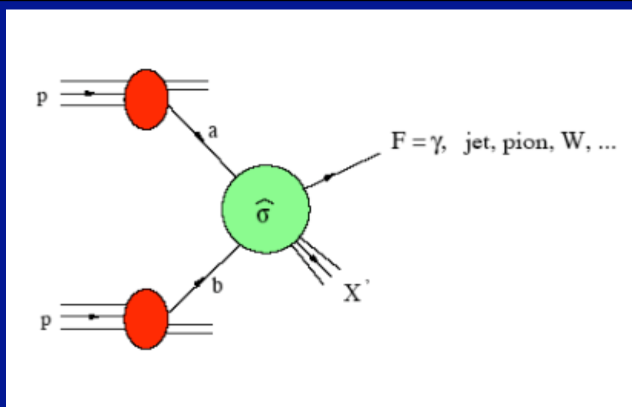
How does the proton emerge from quark-gluon interactions?

- Charge distribution?
- Color distribution ?
- Momentum distribution?
- Spin distribution ?

Must Reproduce Proton Quantum #s:

Electric Charge = +1	2/3	2/3	-1/3
Color Charge = White	u	u	d
Mass = 938 MeV	<1%	<1%	<1%
Spin = 1/2	+1/2	+1/2	-1/2

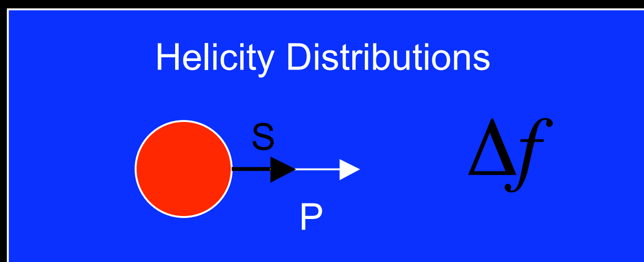
Spin is purely a quantum mechanical dynamic → sensitive probe of QCD theory.

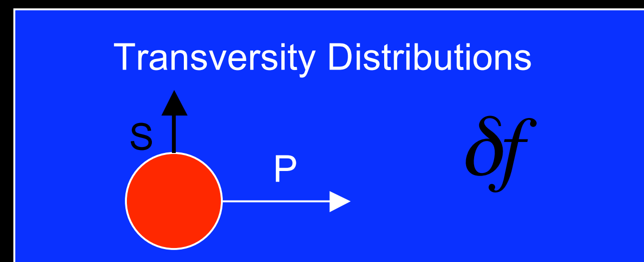


- QCD is a difficult theory
- Calculations limited to short range/high energy interactions (except for lattice!)
- Long range/low energy pieces must be measured experimentally
- Close collaboration between theory and experiment is necessary to unravel this problem.

What are the questions?

1. What is the probability for the spin of a parton (s) to be aligned with the spin of the proton (S)? May depend on momentum (SxP) of the proton.



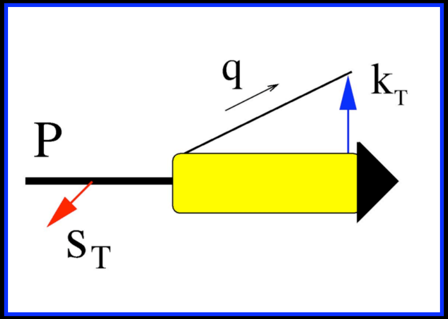


2. What is the contribution from partonic orbital angular momentum?

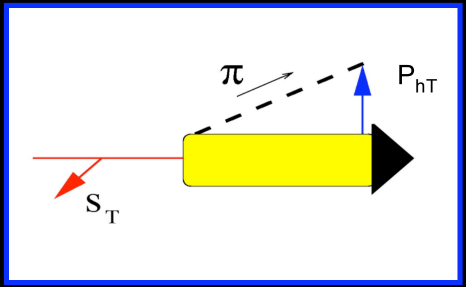
$$J_{PROTON} = \frac{1}{2} = \langle S_q \rangle + \langle S_G \rangle + \langle L_q \rangle + \langle L_g \rangle$$

What are the questions?

3. Does the transverse momentum (k_T) of the parton correlate with the spin of the proton?
   Sivers distributions → Sensitive to Orbital Angular Momentum

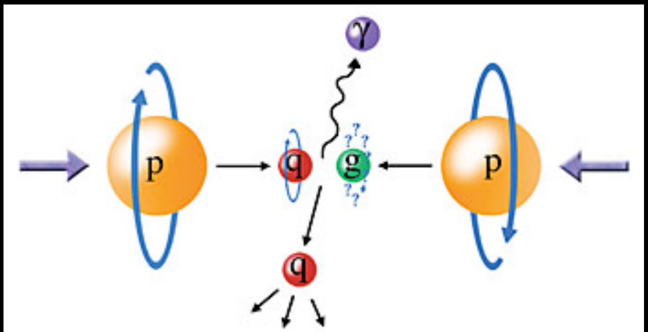


4. Is quark fragmentation (P_{hT}) correlated with the spin of the quark?
   Collins Function → requires Transversity



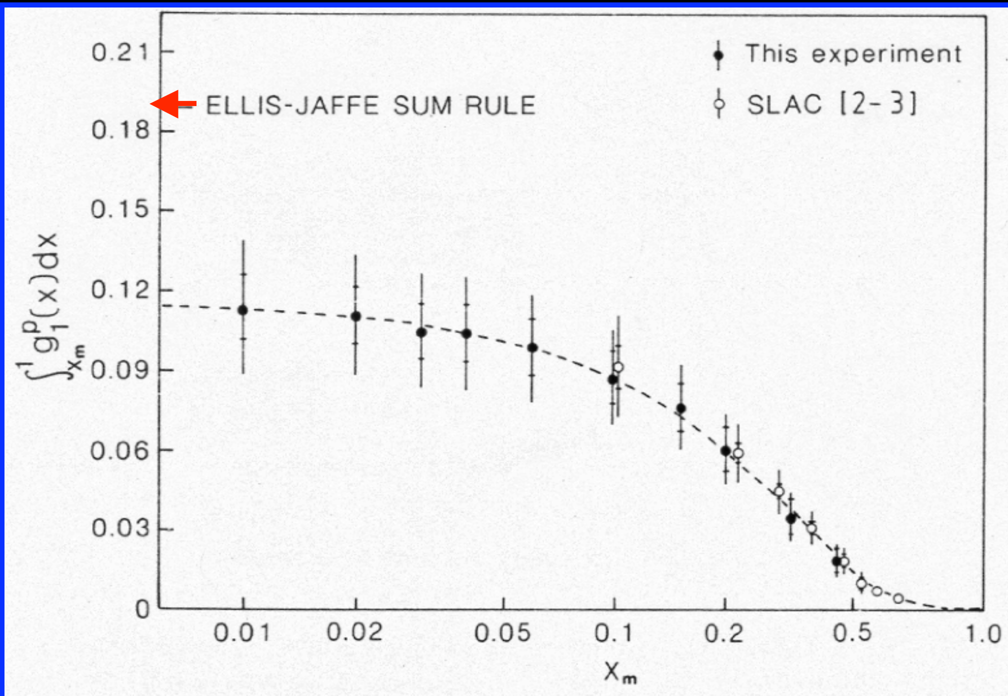
DISCLAIMER: This list is not comprehensive, but serves to illustrate the current landscape of spin observables being discussed in the Spin Community.

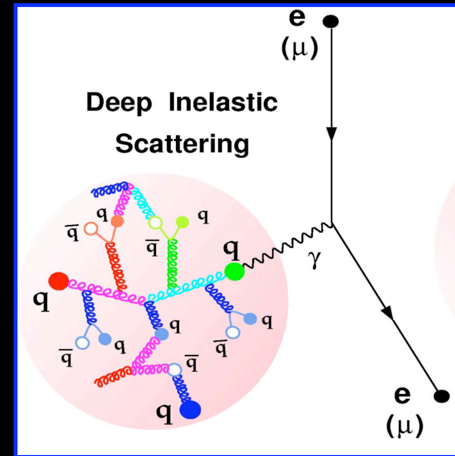
Helicity Distributions



Early Measurements of $\Delta\Sigma = \Delta u + \Delta d + \Delta s$

EMC Collaboration Nucl. Phys. B328, 1 (1989)





- EMC → Deep Inelastic Scattering
- Requires Integration over all X
- Measurement is over a finite X
- Integral is saturating around 0.12
- Ellis-Jaffe prediction = 0.1867
- Ellis-Jaffe assumes no strange or gluon contributions.

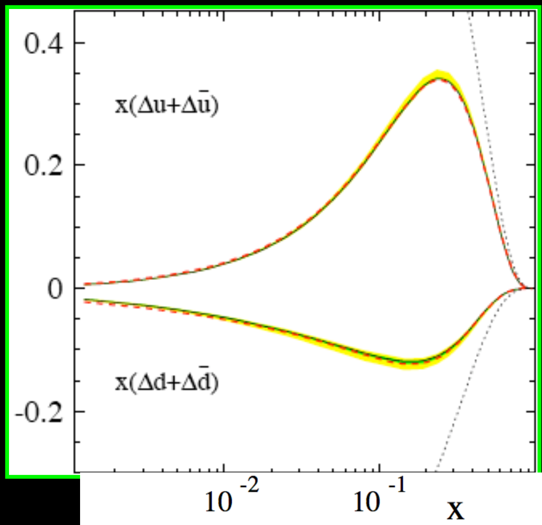
Measured quark distributions ≠ spin of the proton!

1) Could the missing spin be in the gluon? Afterall it contributes half total momentum/mass!

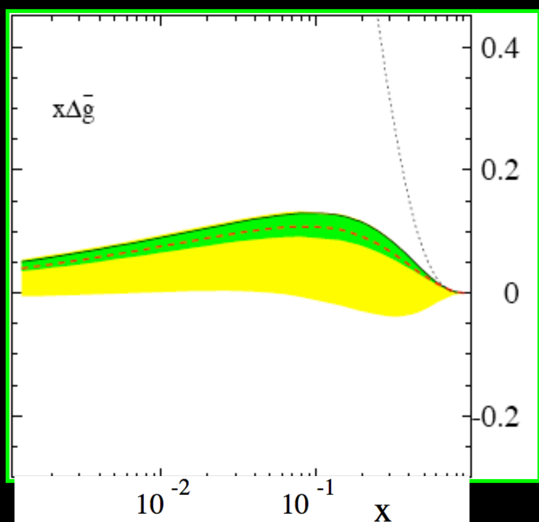
2) Could a large negative strange contribution - not included in theory but measured in data - cause discrepancy between EJ and data?

$$\Delta\Sigma_{EJ} = 0.58 \pm 0.03$$
$$\Delta\Sigma_{EMC} = 0.12 \pm 0.10 \pm 0.14$$

"Pre-RHIC" ΔΣ

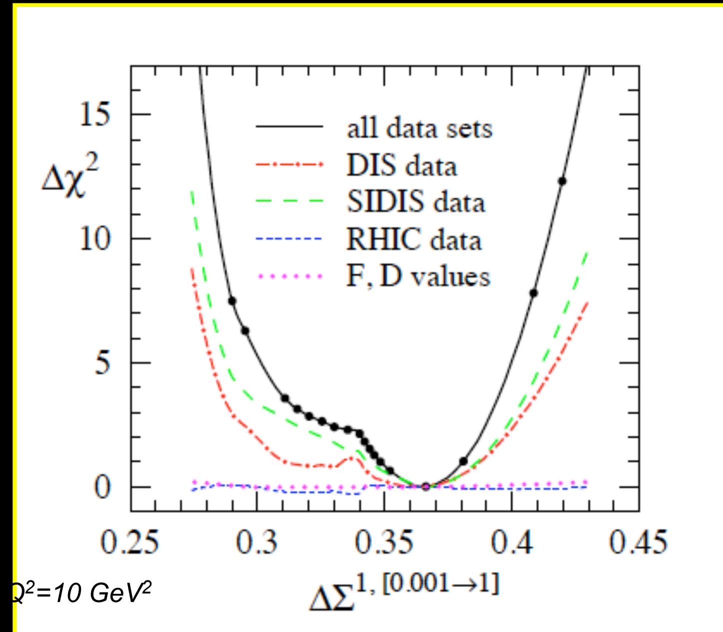


ΔΣ is well constrained by DIS+SIDIS. Quarks contribute ~25% of proton spin at Q^2=10 GeV^2. The truncated integral is ~35% due to the neg. strange contribution at low x.



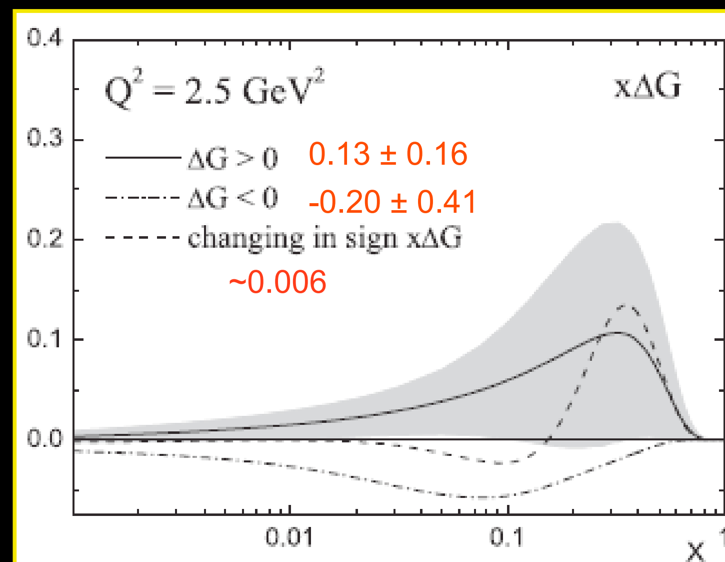
Neither sign or magnitude of ΔG are well constrained by DIS + SIDIS!

de Florian et al., Phys. Rev. D71 094018 (2005)



de Florian et al. arXiv:0904.3821

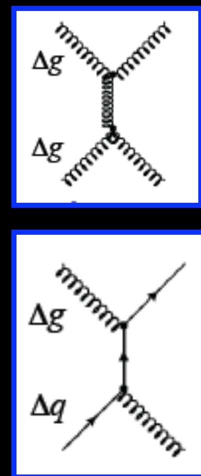
Three recent fits at Q^2 = 1 GeV^2

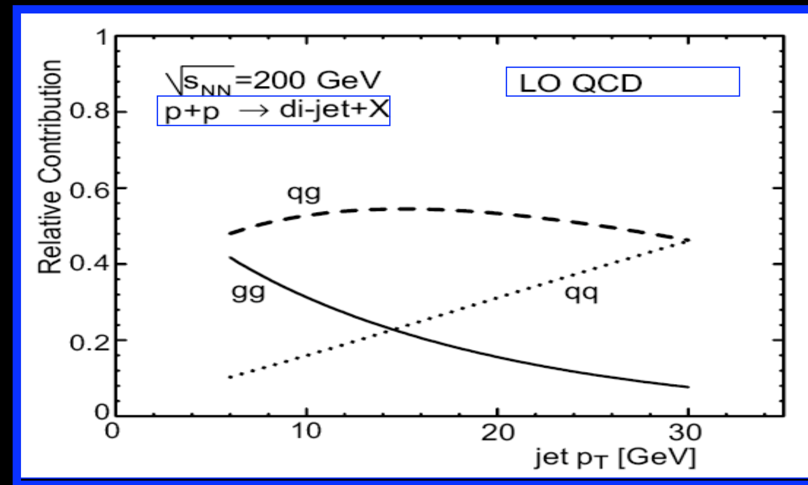


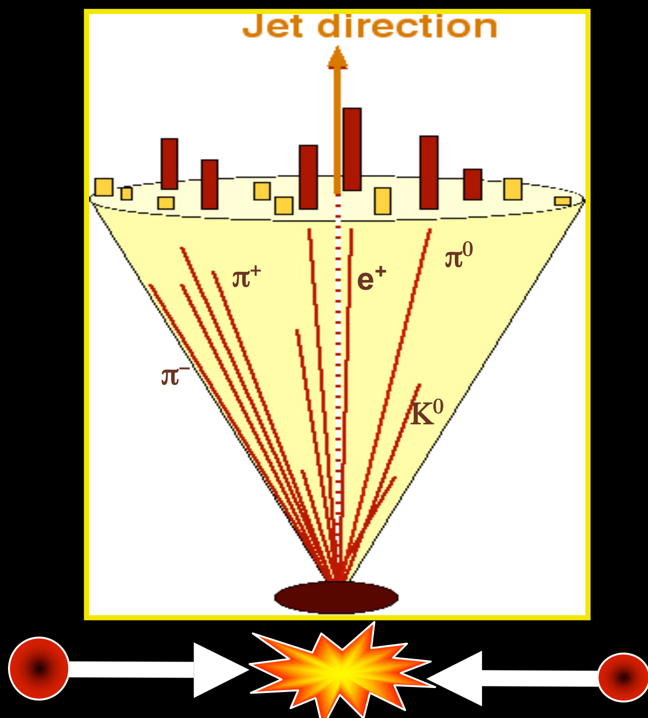
Leader et al, PRD 75, 074027 (2007)

Measure ΔG directly at $\vec{p}\vec{p}$ collider

- ✓ At leading order via g+g and q+g scattering
- ✓ Inclusive signals are diluted by q-q scattering, but these are relatively well studied in DIS.







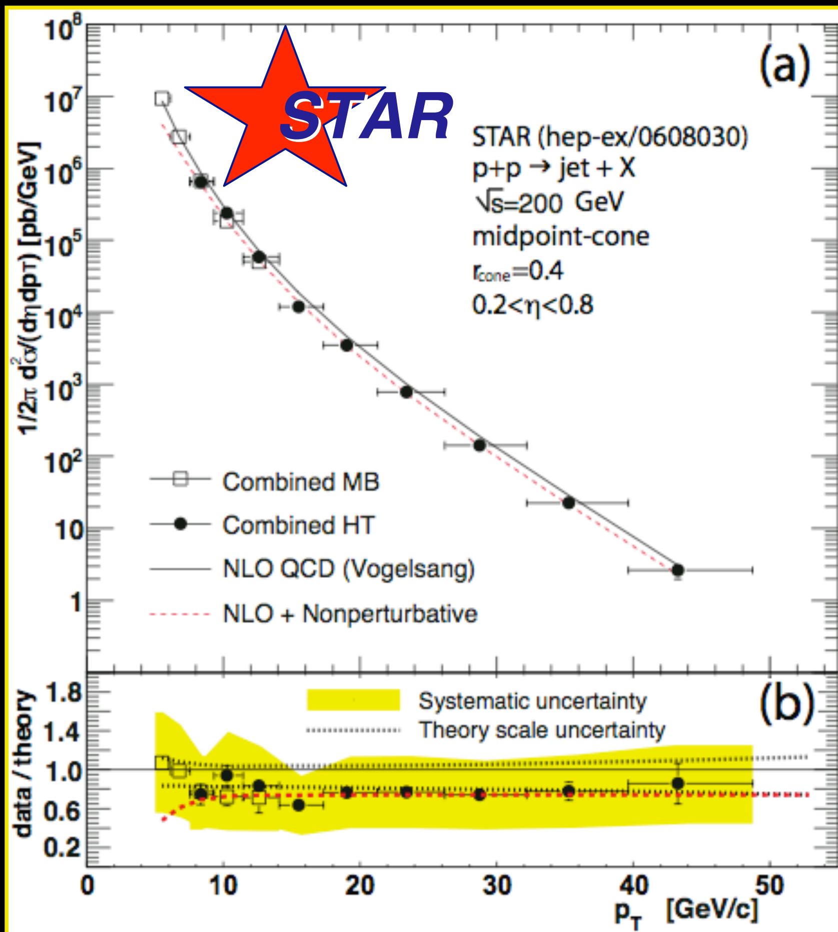
- ✓ Start with inclusive measurements
- ✓ PHENIX uses high resolution calorimeter to detect neutral pions inside jets
- ✓ STAR uses wide angle detector to reconstruct jets
- ✓ Both use asymmetries to access gluon distribution

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \sum_{f_A f_B f_C} \frac{\Delta f_A \Delta f_B \times \Delta\sigma_{AB\to CX} \times D_C}{f_A f_B \times \sigma_{AB\to CX} \times D_C}$$

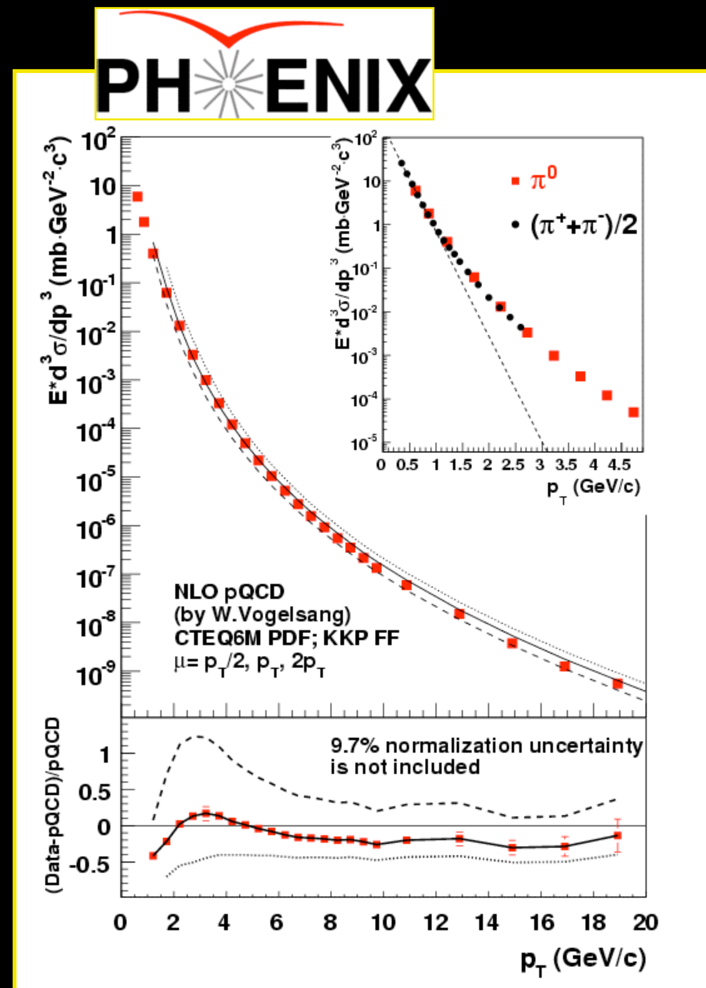
Before we get too far … verify NLO framework is valid!

Afterall we said we understood our Δq dilution. That is only true if PDF's are universal. And ΔG can only be extracted if factorization applies!

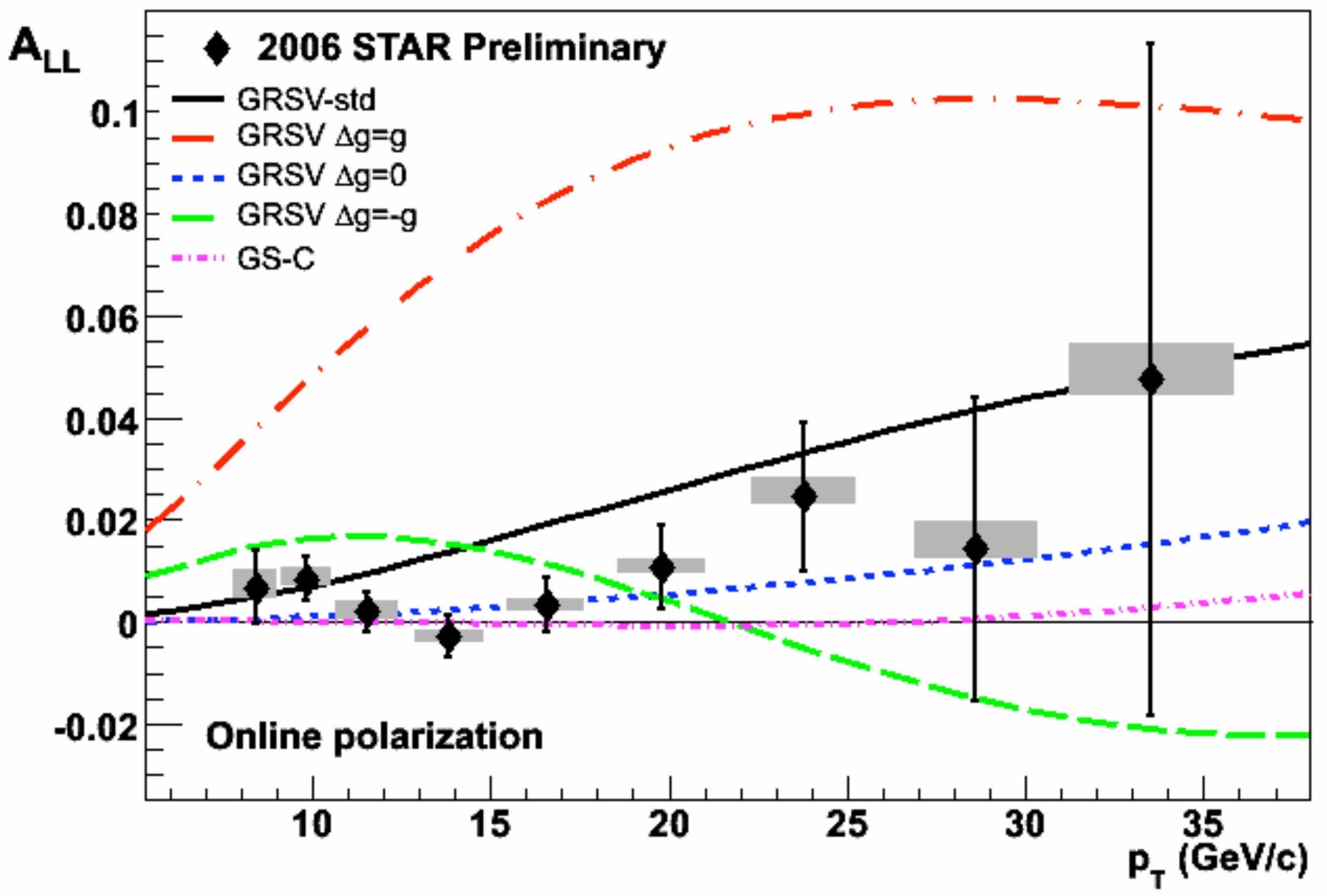
Phys. Rev. Lett. 97 252001 (2006)



arXiv:0704.3599



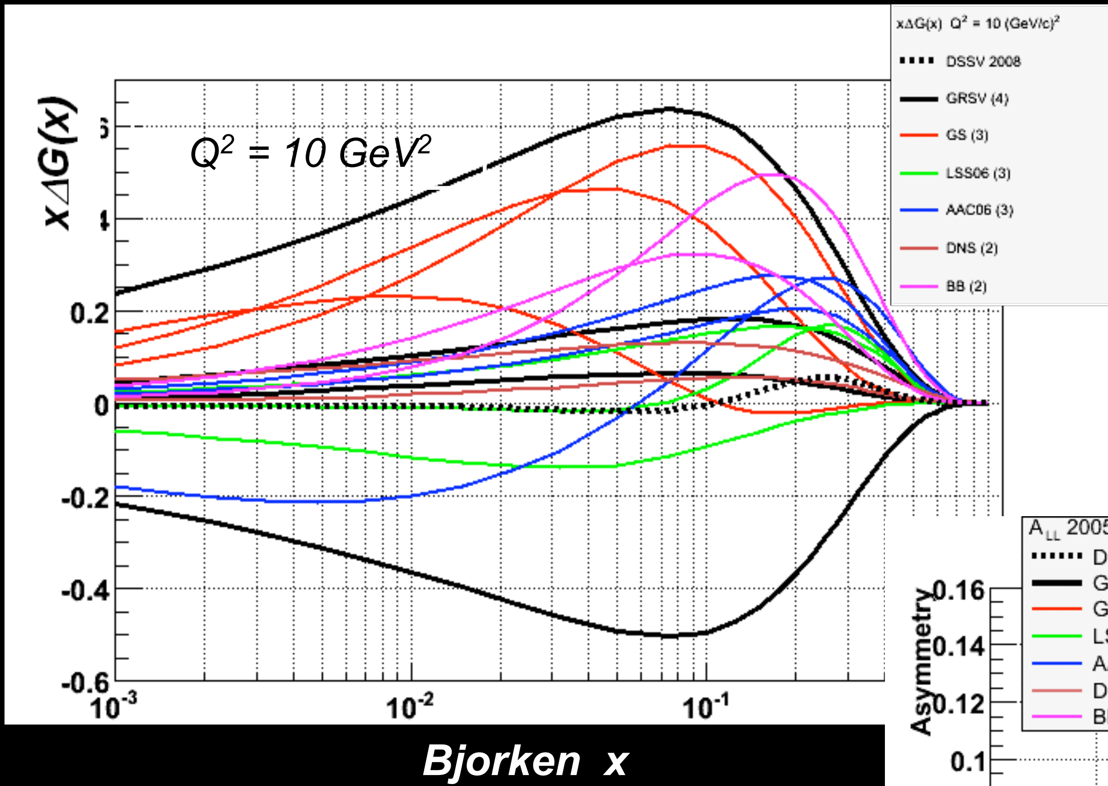
2006 Inclusive Jet A_{LL}



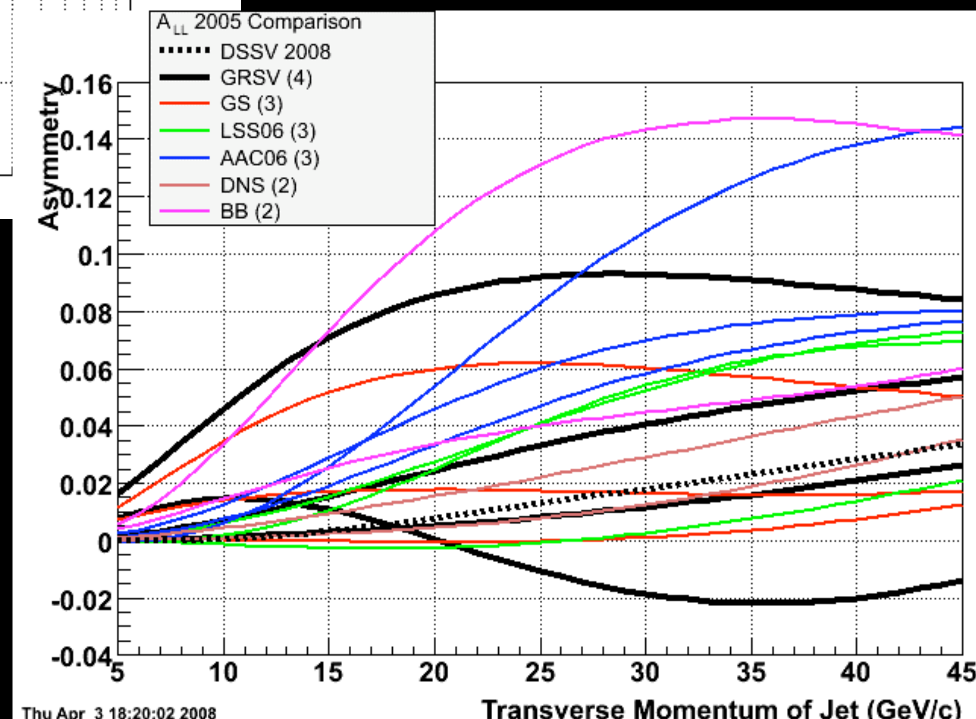
A_{LL} systematics	(x 10^{-3})
Reconstruction + Trigger Bias	[−1,+3] (p_T dep)
Non-longitudinal Polarization	~ 0.03 (p_T dep)
Relative Luminosity	0.94
Backgrounds	1st bin ~ 0.5 Else ~ 0.1

p_T systematic	±6.7%

GRSV curves and data with cone radius R= 0.7 and $-0.7 < \eta < 0.9$

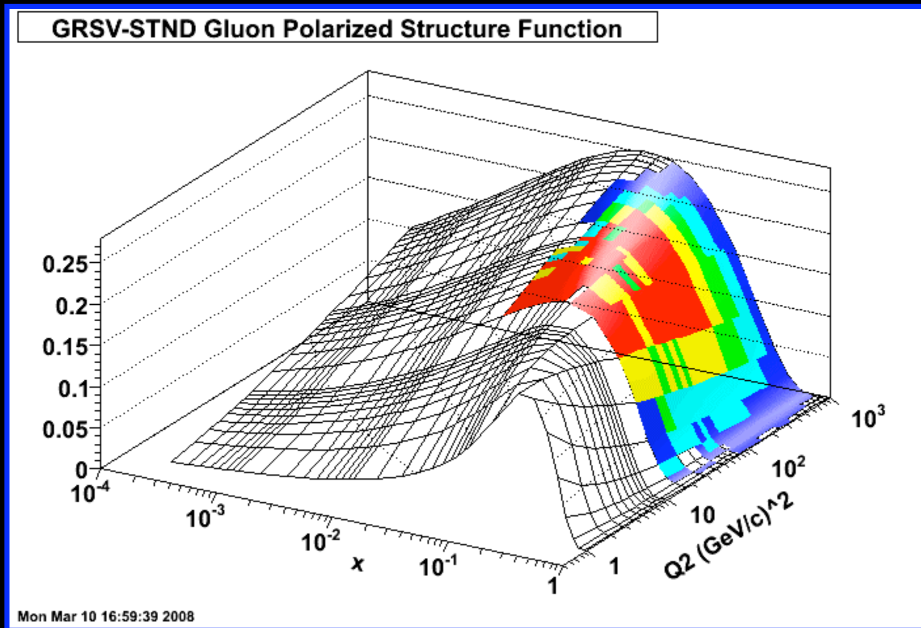


There are many predictions for $\Delta g(x)$ vs x which can be translated into predictions for A_{LL} vs. jet p_T and compared with RHIC data.



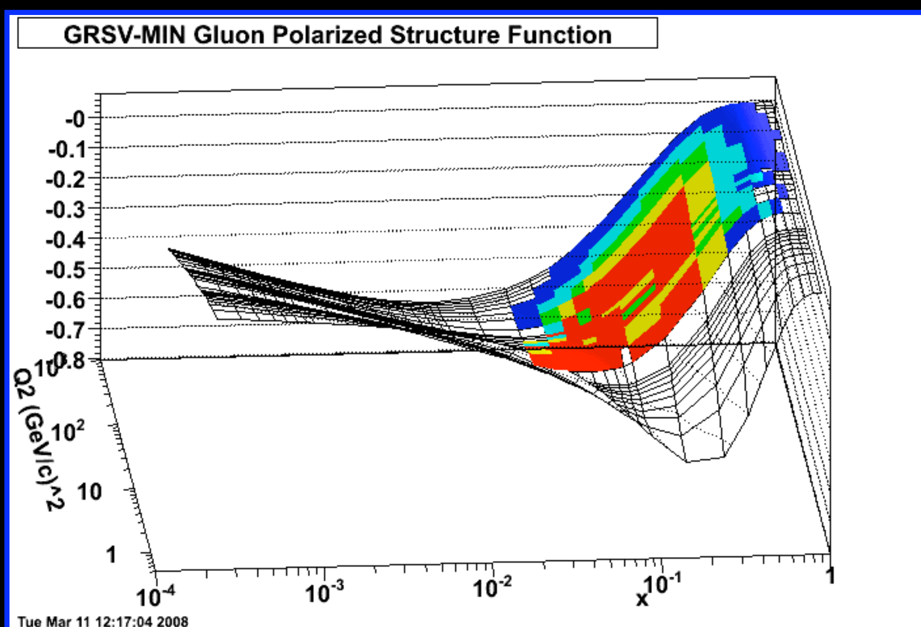
Sensitivity to GRSV is not unique! The STAR data constrain several predictions.

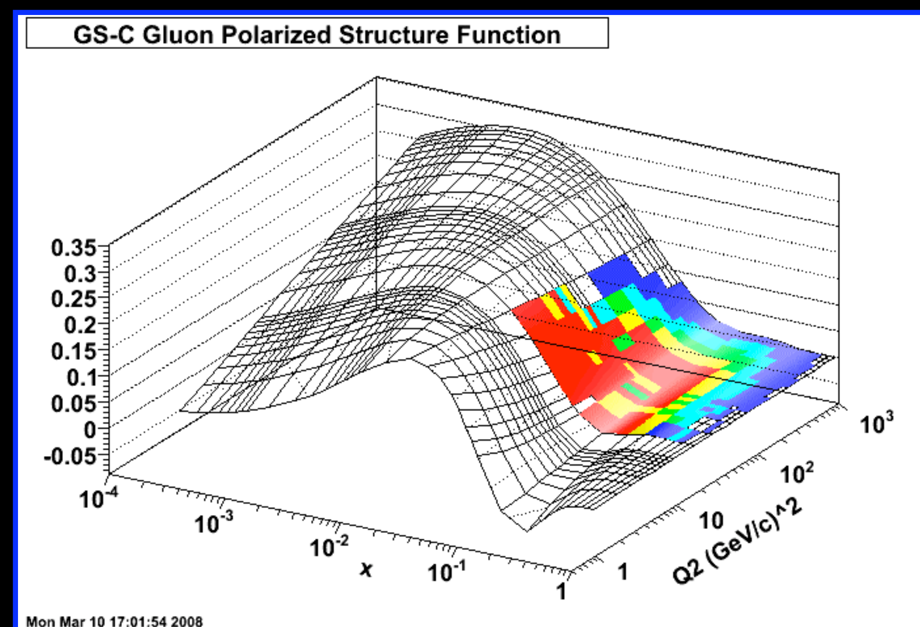
Sampling the integral at STAR



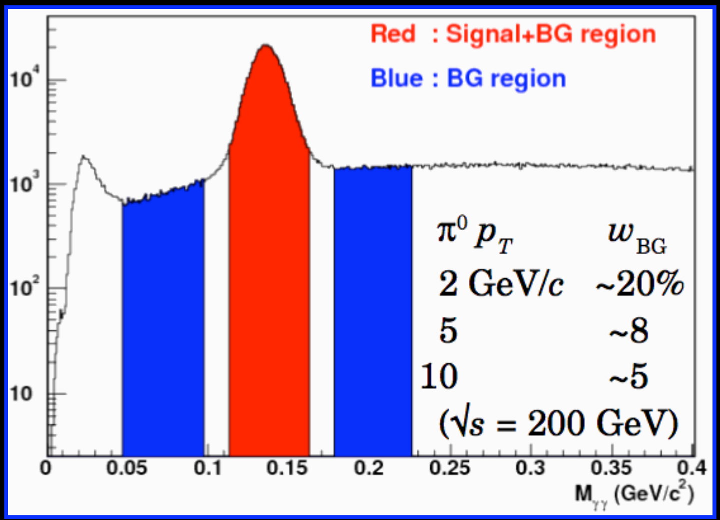
Large fraction of integral sampled.

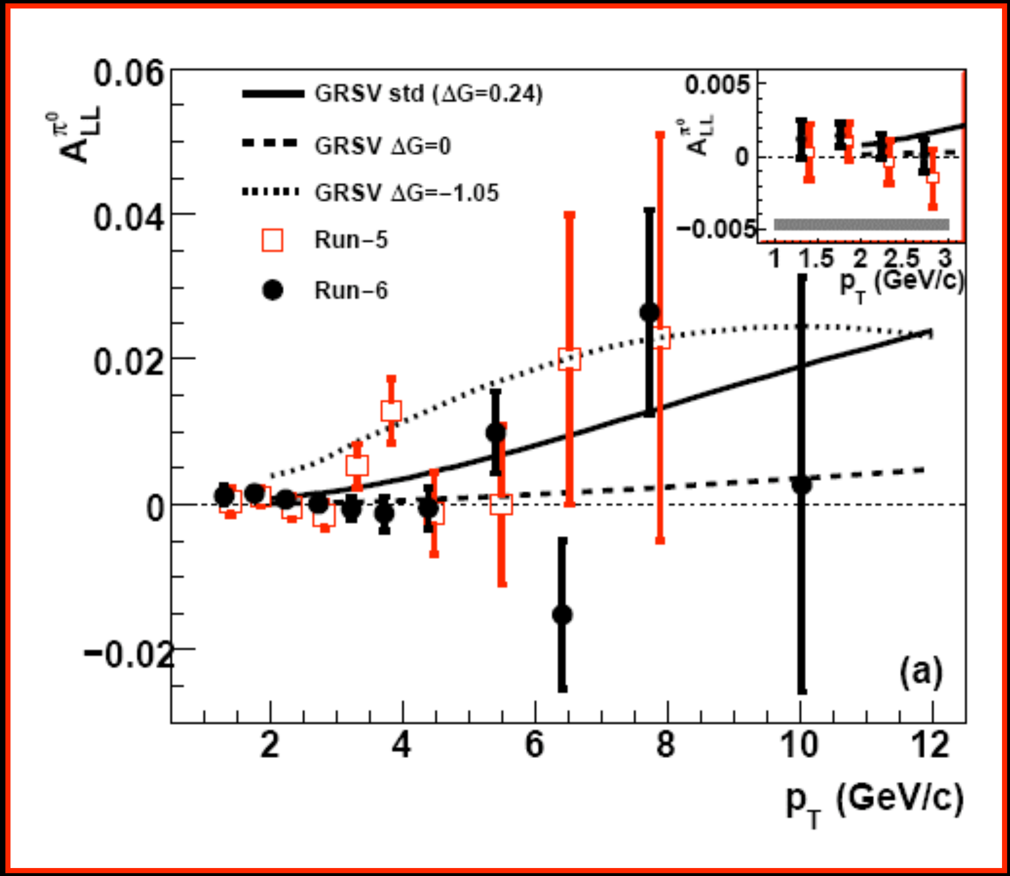
Total integral is sizeable but large fraction lives at lower x !





2006 Inclusive π^0





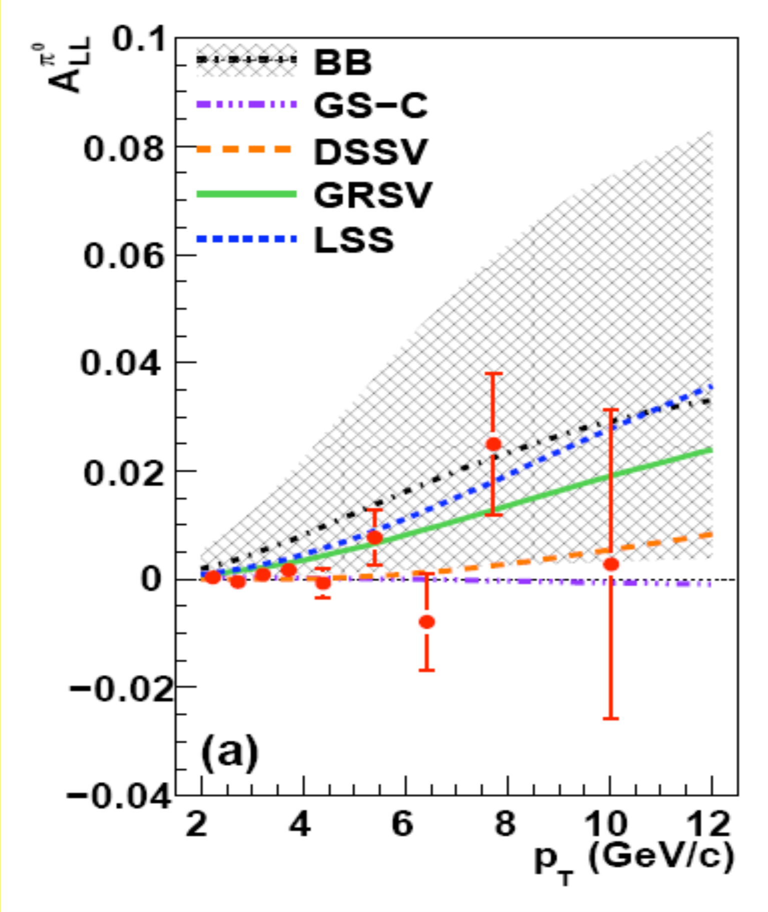
2005: PRD76, 051106

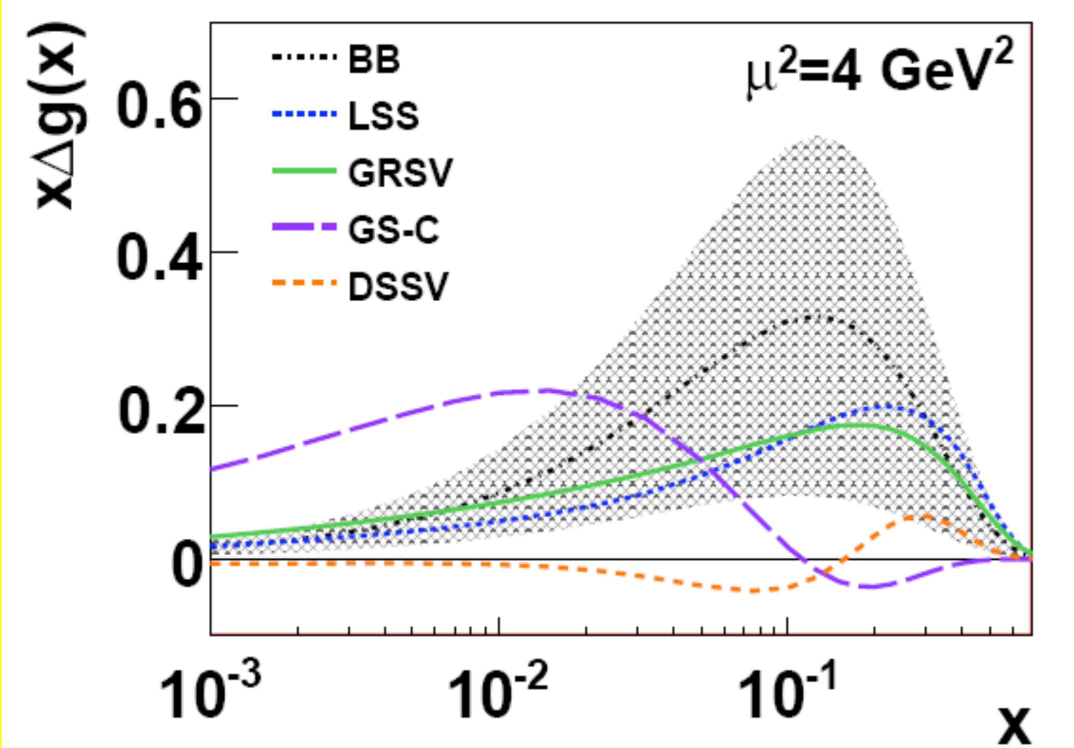
2006: arXiv:0810.0694

π^0 A_{LL}: Agreement with different parametrizations

arXiv:0810.0694

Group	$\Delta G^{[0,1]}$	$\Delta G^{[0.02,0.3]}$	χ^2
	Published best fit		
GS-C	0.95	0.18	8.3
DSSV	-0.05	-0.03	7.5
LSS	0.60	0.37	22.4
GRSV	0.67	0.38	14.8
BB	0.93	0.67	69.0

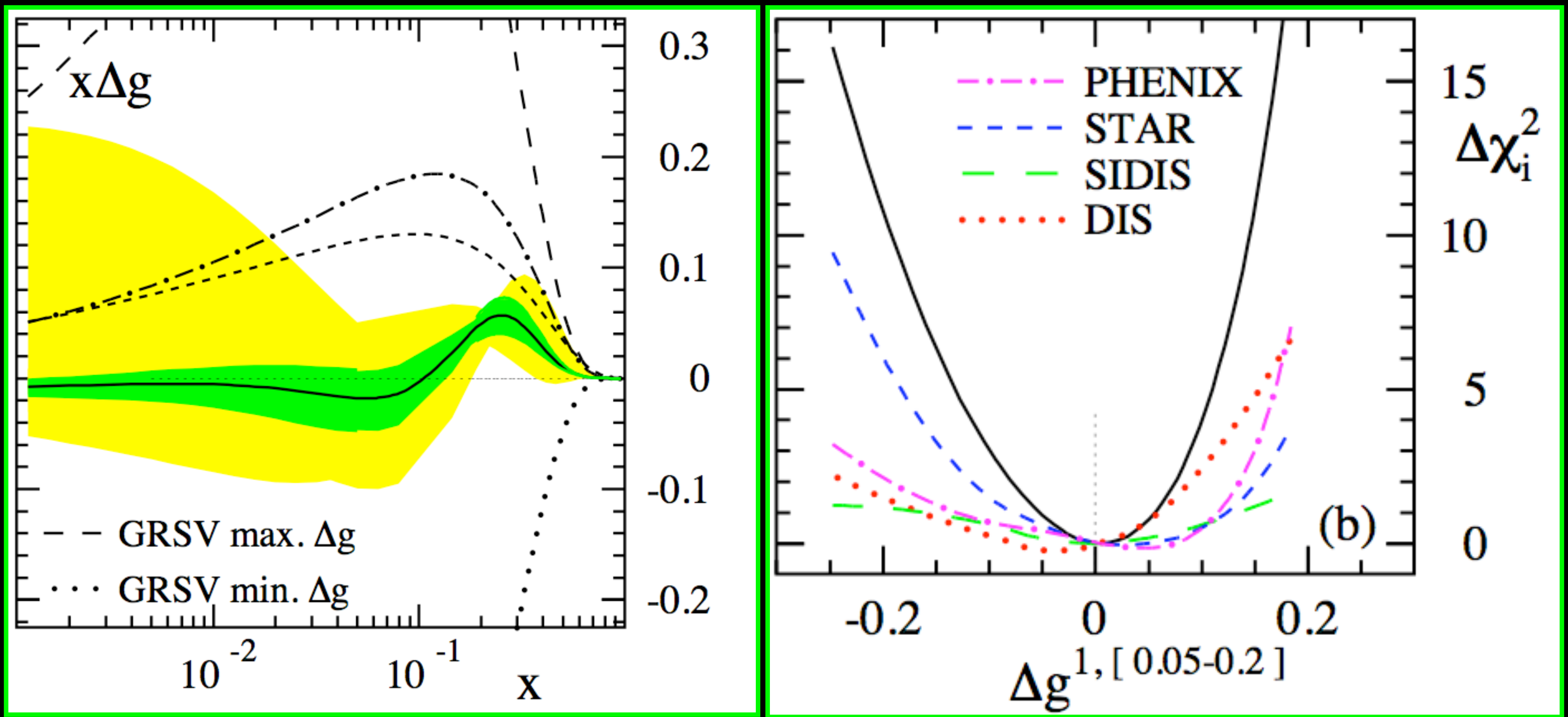




Small ΔG in measured *x* region 0.02 to 0.3 gives small A_{LL} (DSSV and GS-C). Large ΔG gives comparatively larger A_{LL} .

New Global Analysis of World Data - including RHIC Results!

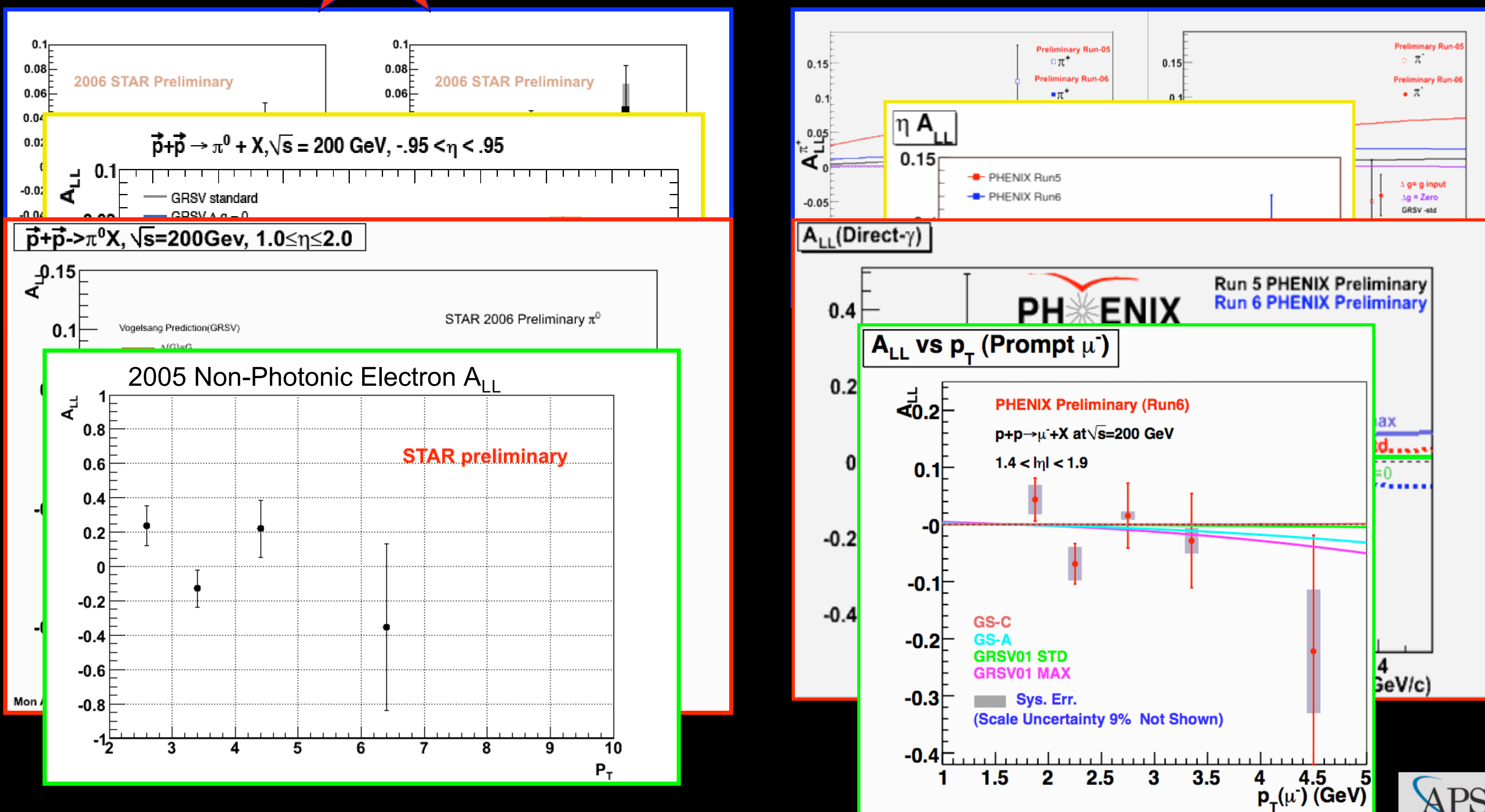
DeFlorian, Sassot, Stratmann and Vogelsang, Phys.Rev.Lett. 101:072001, 2008



Additional Inclusive A_{LL} at 200 GeV

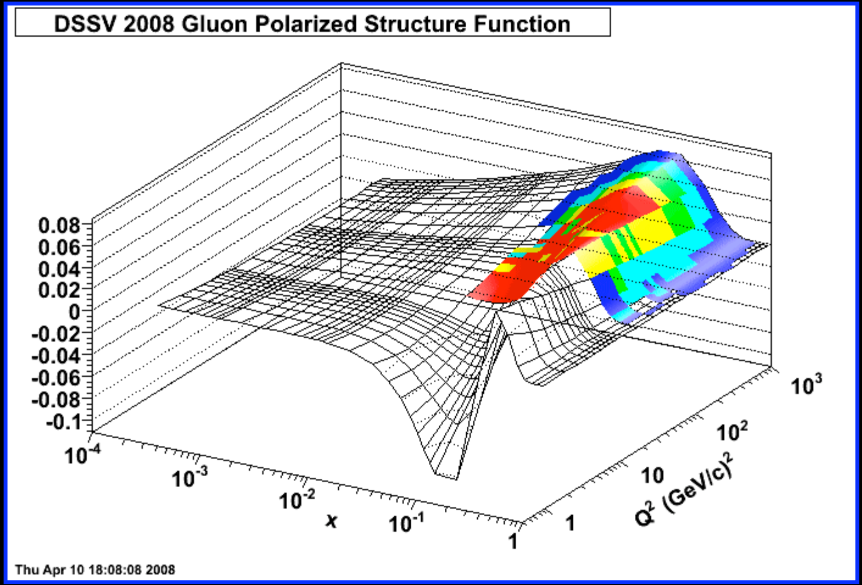
STAR

PHENIX

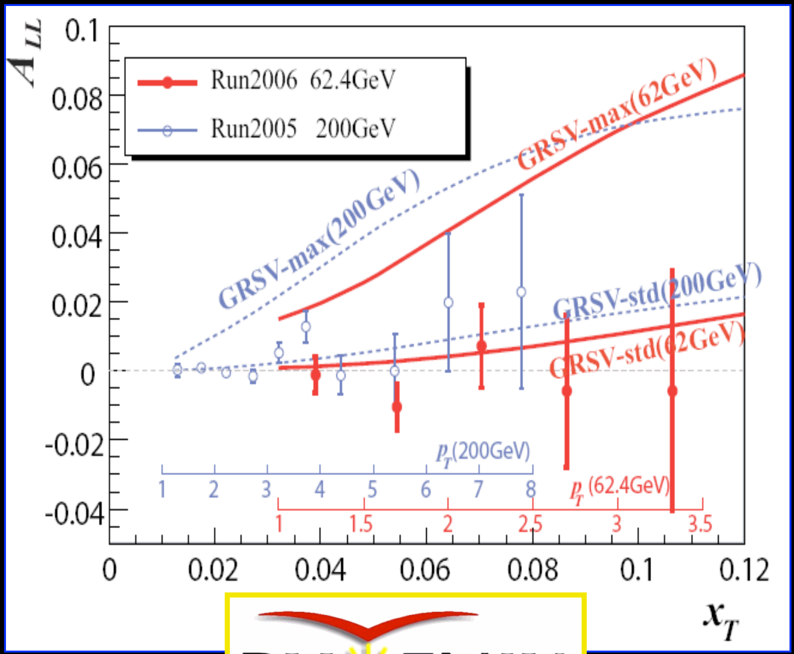


So ΔG is small? Are we done?

NO! ΔG appears to be small at initial scales in the kinematic regions integrated over by current experimental data.



arXiv:0810.0701

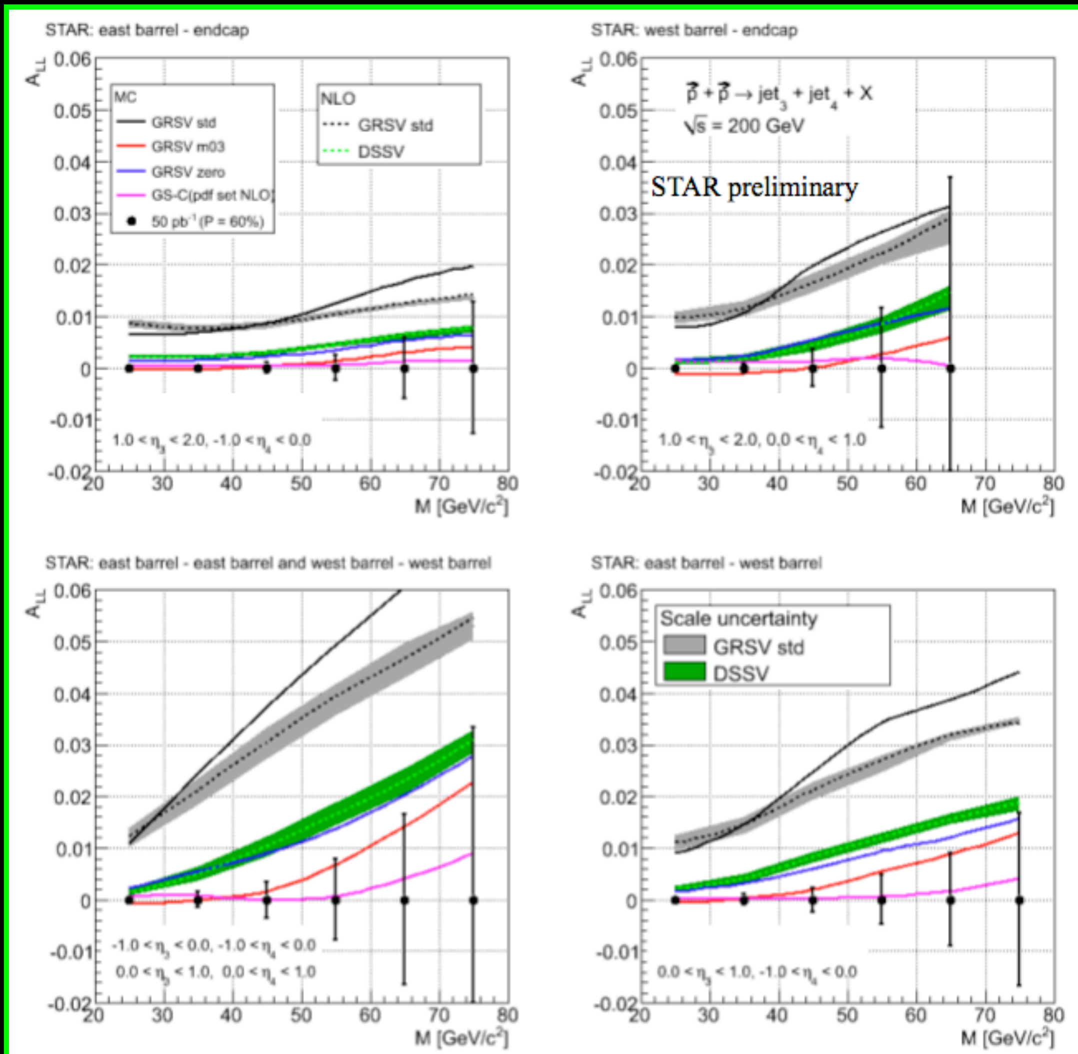


Extend x reach upward/downward by extending inclusive program to lower/higher beam energies.

$$0.02 < x_{gluon} < 0.3 \quad (\sqrt{s} = 200 \text{ GeV})$$

$$0.06 < x_{gluon} < 0.4 \quad (\sqrt{s} = 62.4 \text{ GeV})$$

Reduce Integration Bins: Correlation Measurements



Di-Jet and Photon-Jet Asymmetries allows reconstruction of partonic x1 and x2 at leading order.

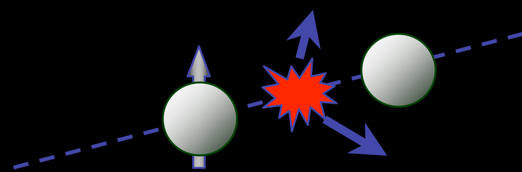
$$x_1 = \frac{x_T}{2}\left(e^{\eta_1} + e^{\eta_2}\right)$$

$$x_2 = \frac{x_T}{2}\left(e^{-\eta_1} + e^{-\eta_2}\right)$$

$$\cos\theta^* = \tanh\left[\pm\frac{1}{2}\left(\eta_1 - \eta_2\right)\right]$$

$$with \quad x_T \equiv \frac{2p_T}{\sqrt{s_{pp}}}.$$

Transverse Single Spin Asymmetries

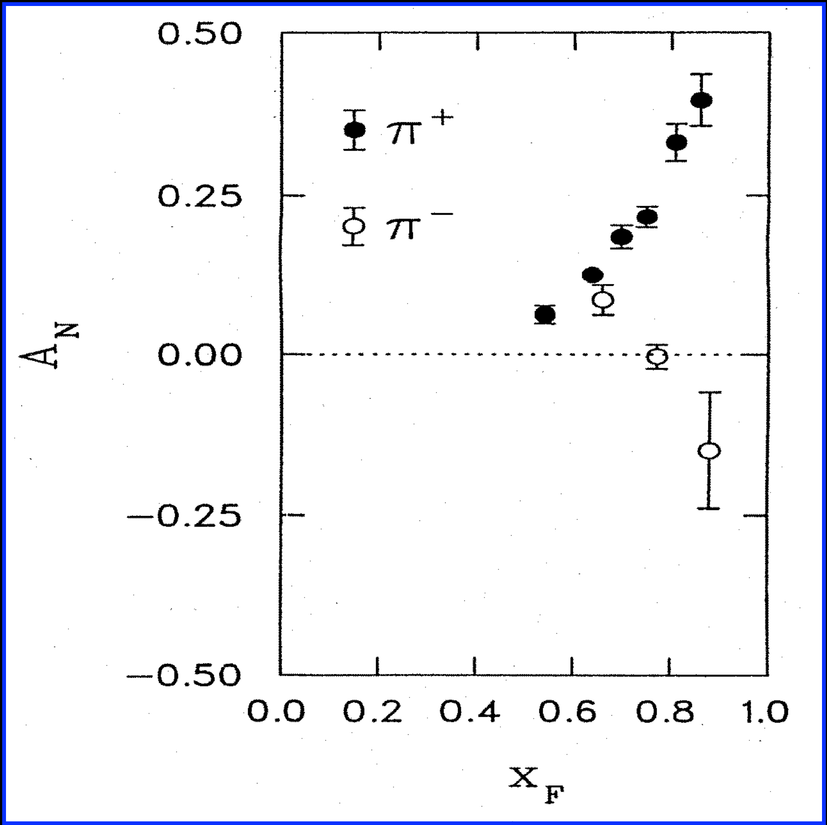


Sensitive to the Transversity + Collins FF and Sivers distributions!

Early Measurement of Single Spin Asymmetries

Argonne ZGS, p_{beam} = 12 GeV/c

W.H. Dragoset et al., PRL36, 929 (1976)



Supposed to be ZERO or at least very very small! Suppressed by

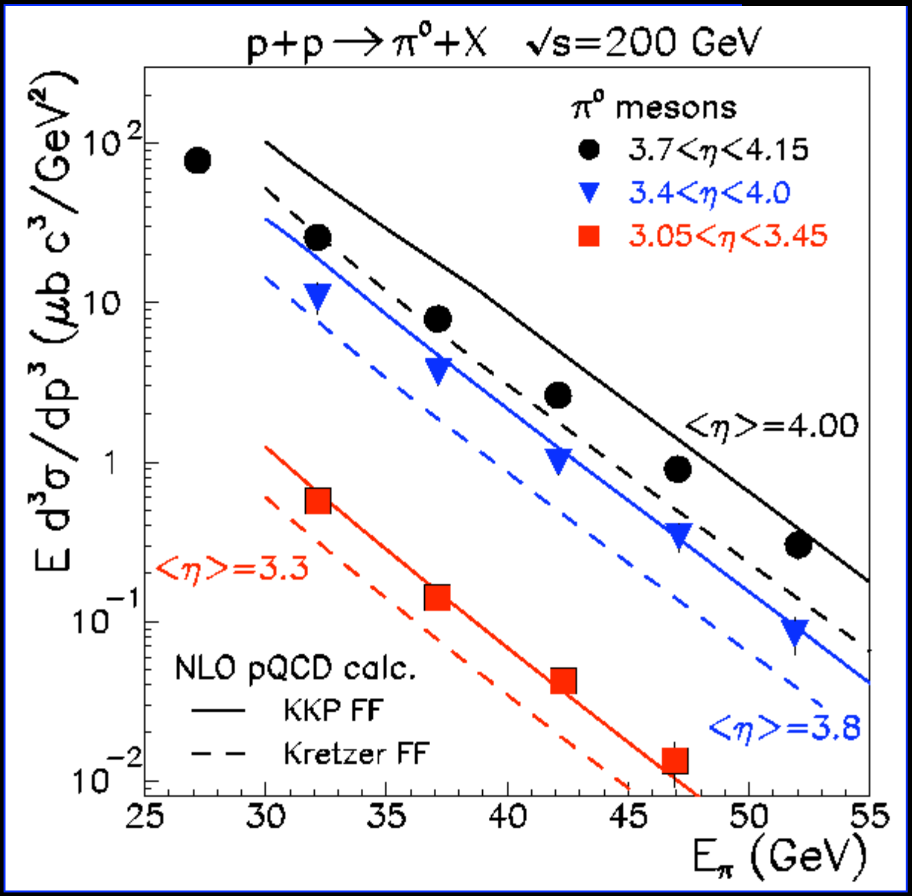
$$m_q \alpha_s / Q$$

Non-zero charged and neutral pion asymmetries seen at the ZGS, AGS and FNL for beam energy from 12 - 200 GeV.

Asymmetries increase with xF

What causes these large asymmetries?

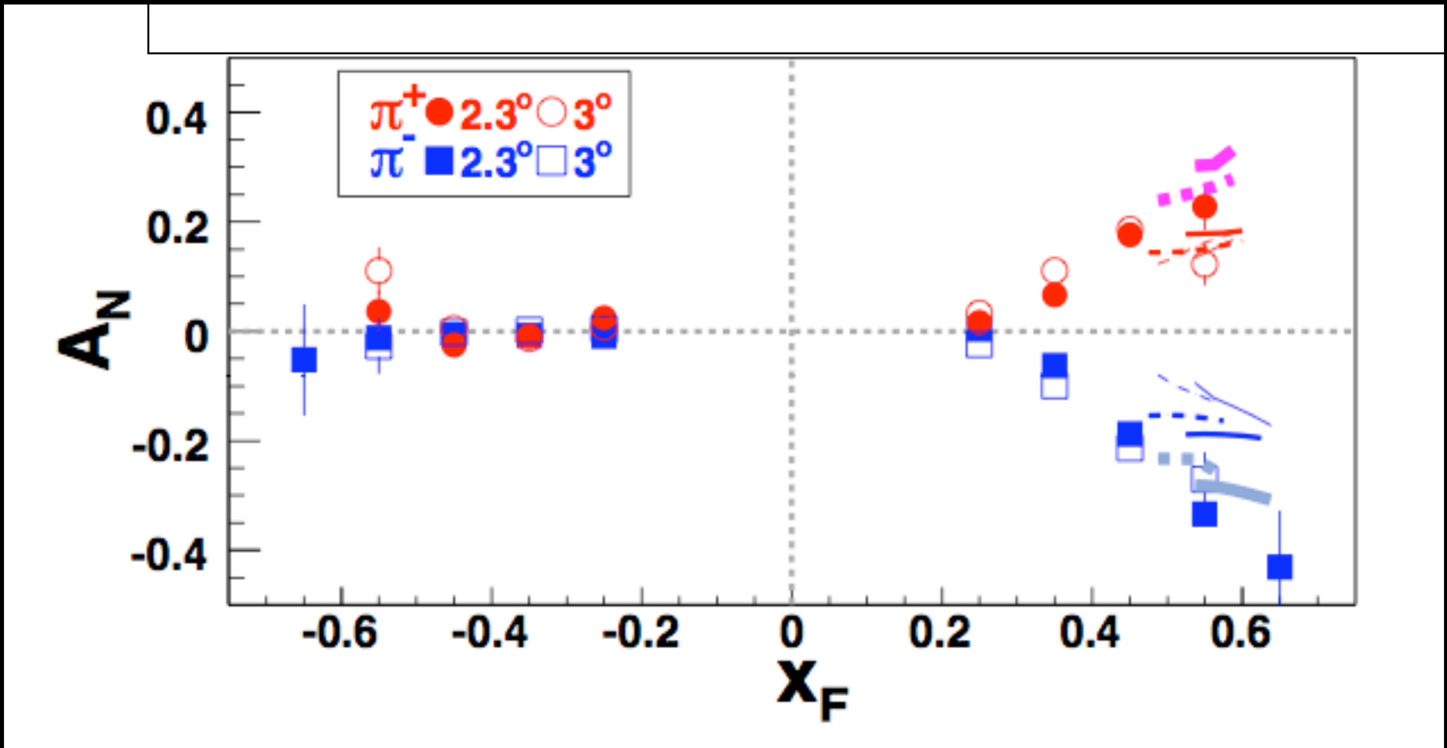
1) Transverse Momentum (TMD) partonic effects - Sivers, Collins, Boer Mulders
2) Twist 3 Effects - gluon correlations
3) Both TMD's and Twist-3 effects are described within pQCD framework.
4) pQCD has been shown to apply at RHIC energies via cross-section measurements.
5) Also interesting to test universality of these TMDs! Compare with Sivers and Collins measured in SIDIS.



PRL 97 (2006) 152302

Transverse SSA's at √s = 64.2 GeV

PRL 101, 042001 (2008)



THICK - Twist 3 initial state

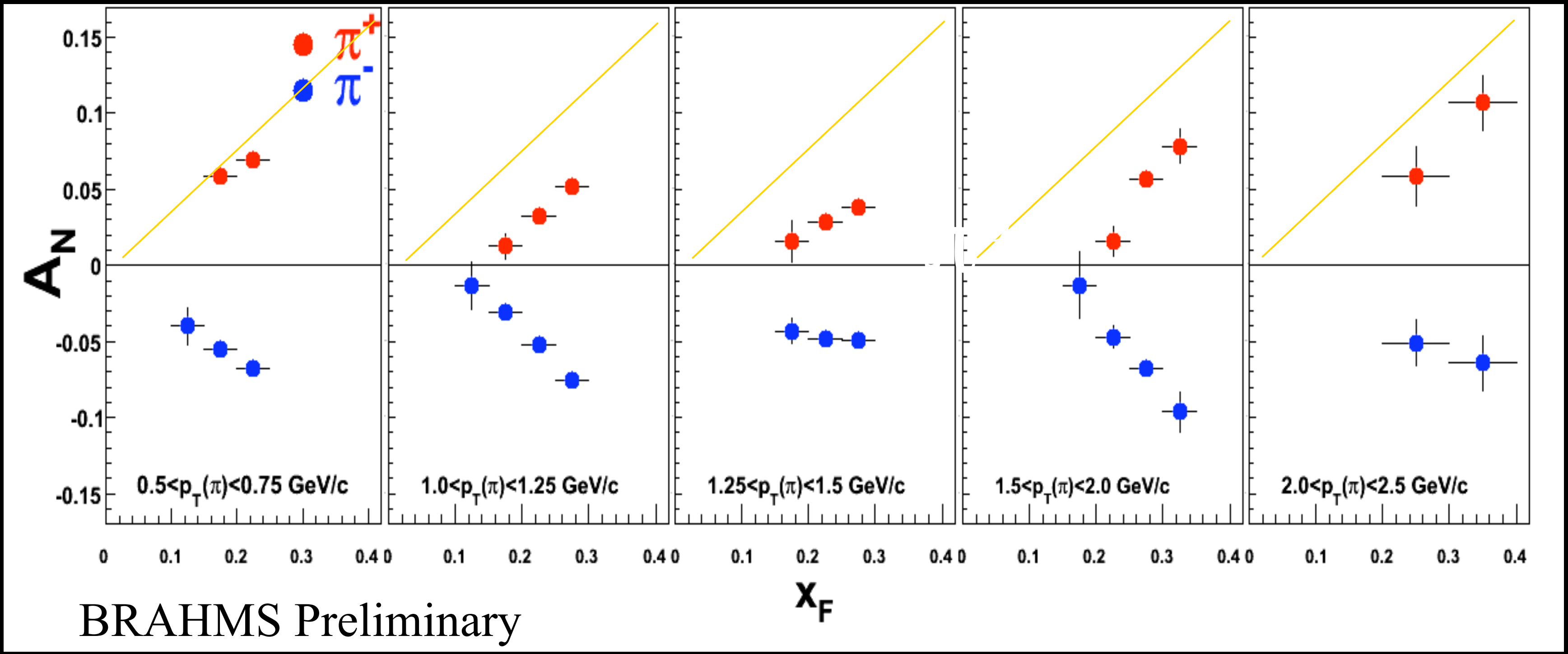
MEDIUM - Twist 3 final state

THIN - Sivers

Solid/Dashed = 2.3/3 degree detectors

Results support "valence quark dominance" interpretation of SSA. If "sea" Sivers is small then π+/π- SSA are largely (favored vs unfavored) determined by u/d distributions. Also based on idea that sea quarks don't often produce high xF mesons.

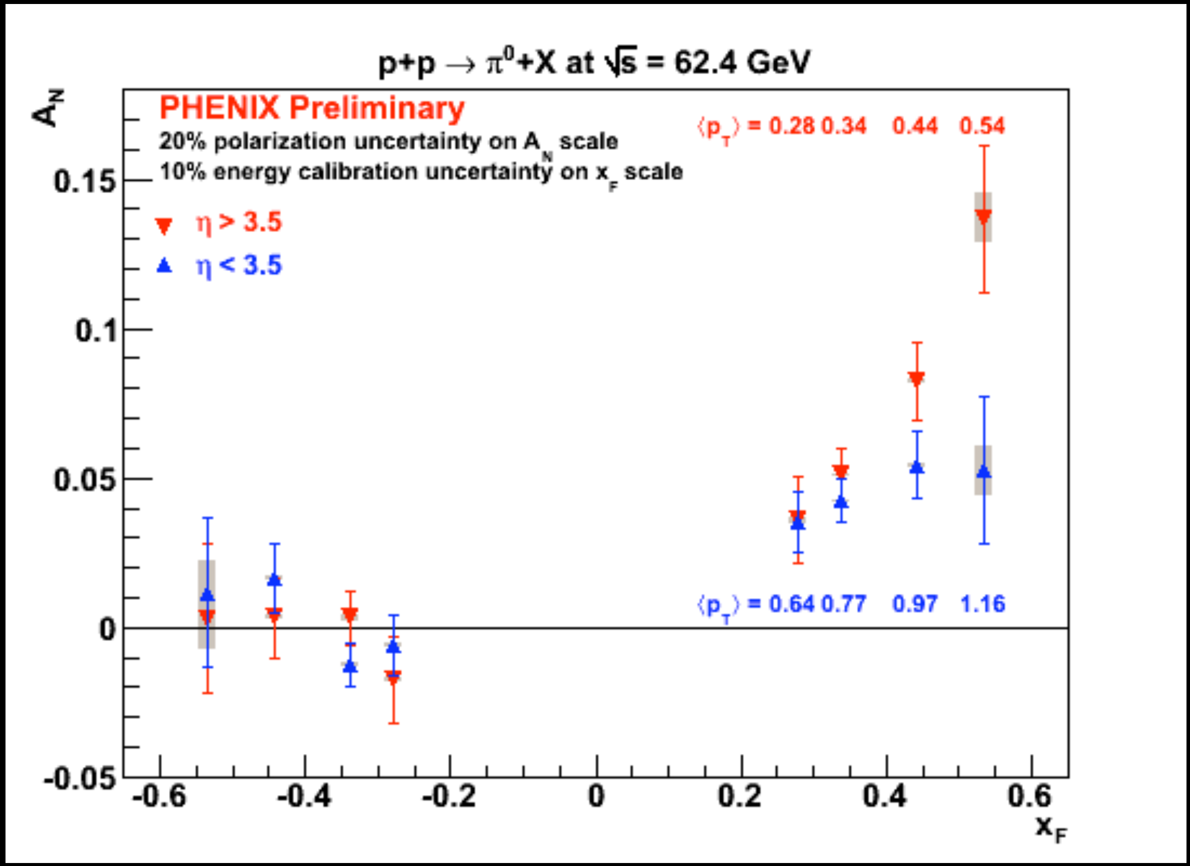
Transverse SSA's continue for $\sqrt{s}$ = 200 GeV



Transverse SSA at $\sqrt{s}$ = 64.2 GeV

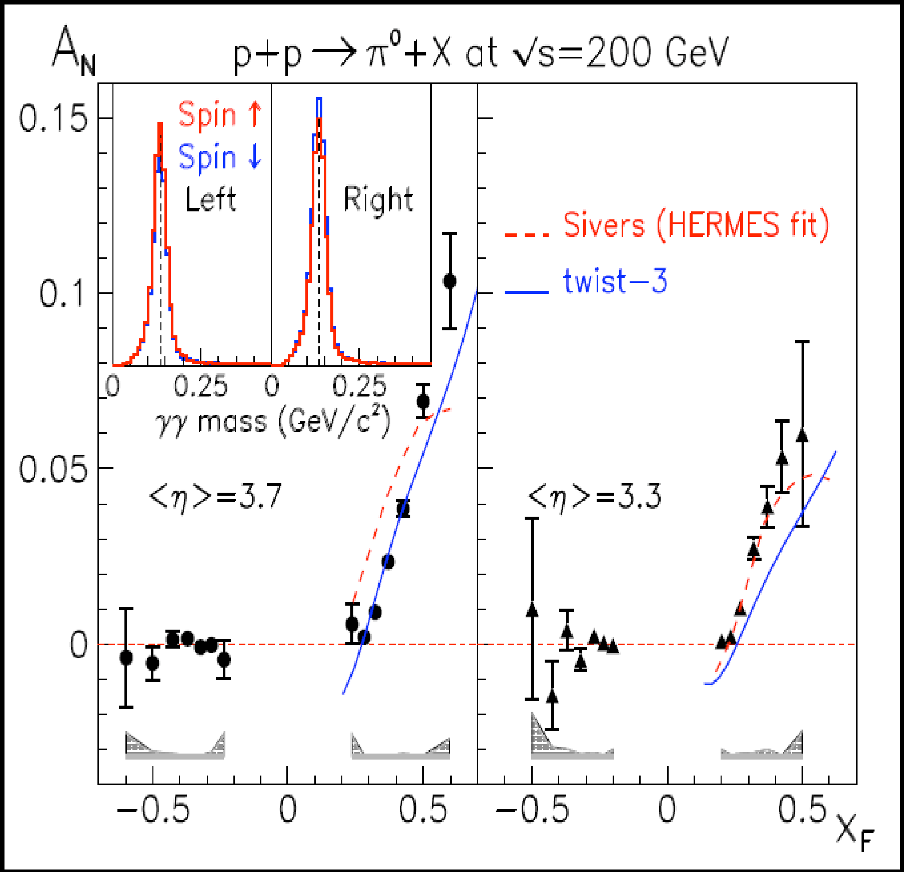
Forward π^0

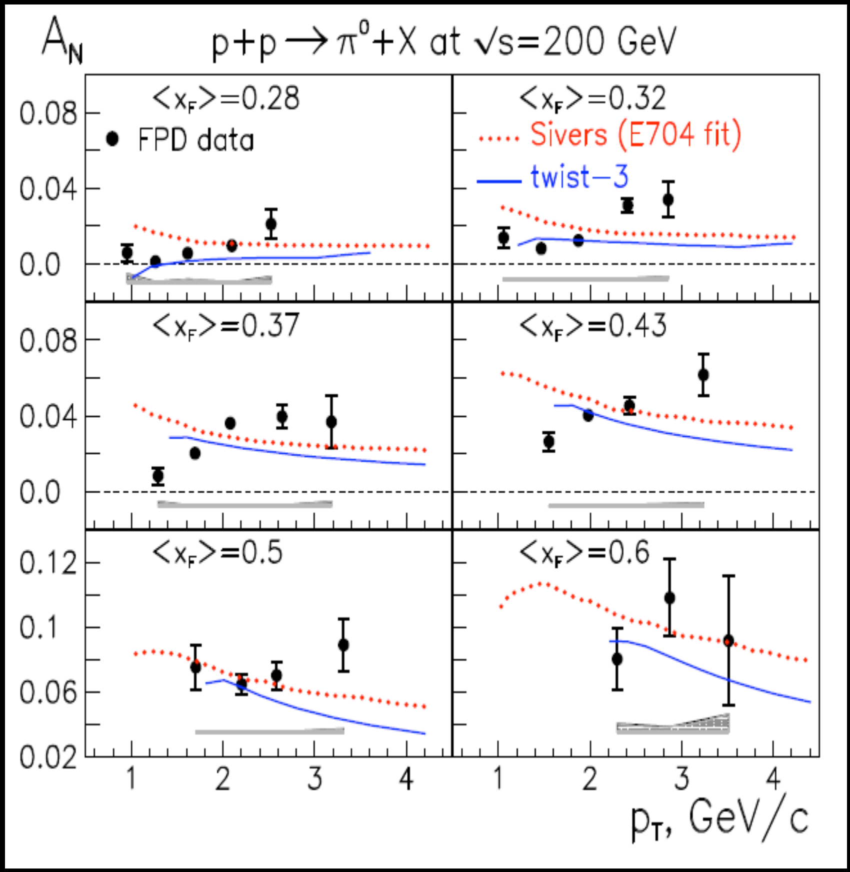
- Forward calorimeter (MPC) added in 2006
- Clear asymmetry in forward π^0 production @ $\sqrt{s}$=62 GeV
- Fully implemented for 2008
- Run8 data is being processed currently.



Transverse SSA's at $\sqrt{s}$ = 200 GeV at STAR

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

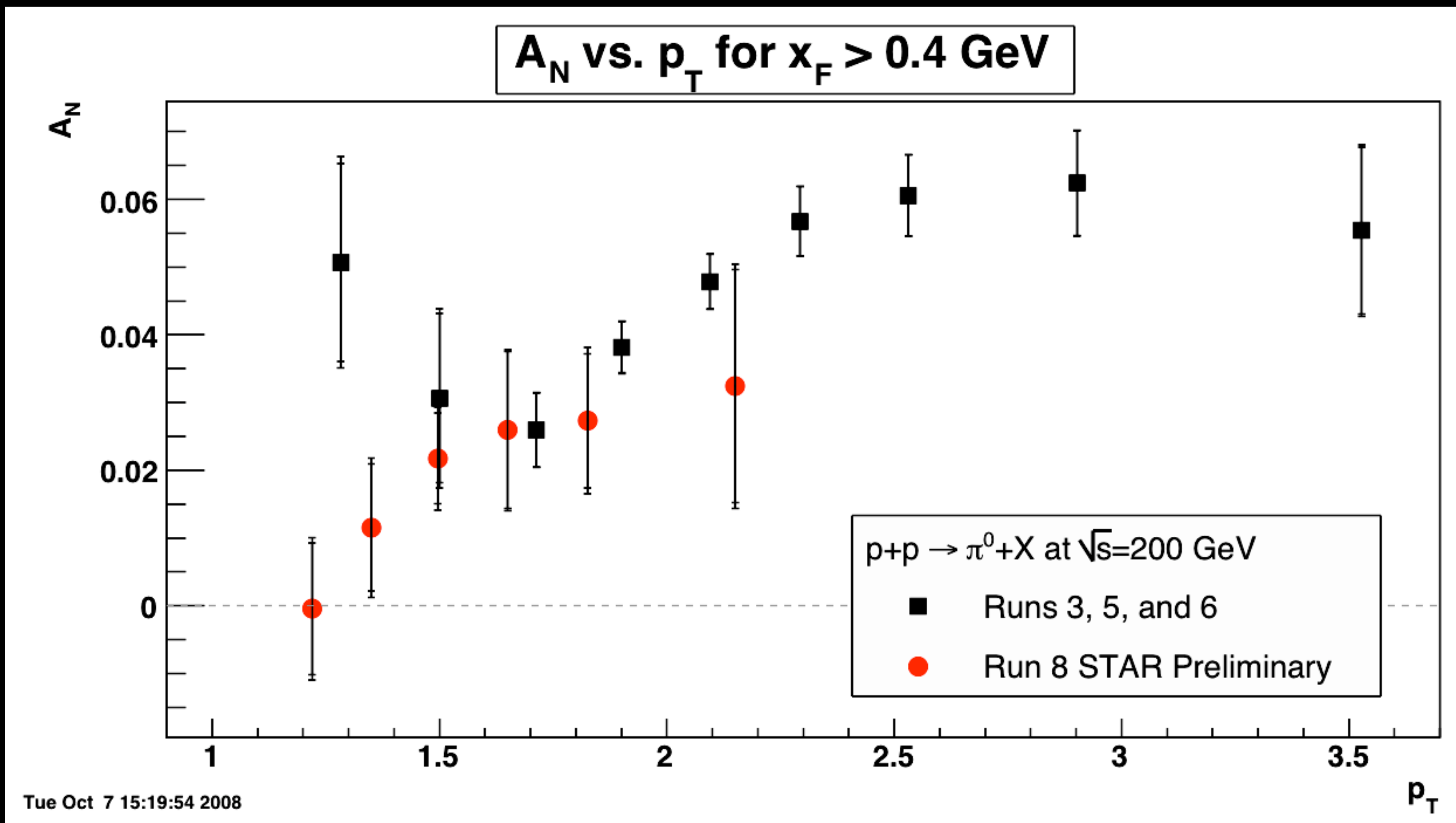




Both Sivers and twist-3 fit the data reasonably well.
Sivers requires a decreasing signal with increasing pT.

No indication of decrease with pT!

Run-8 data does show expected decrease at low pT



Black points: Phys. Rev. Lett. 101, 222001 (2008)

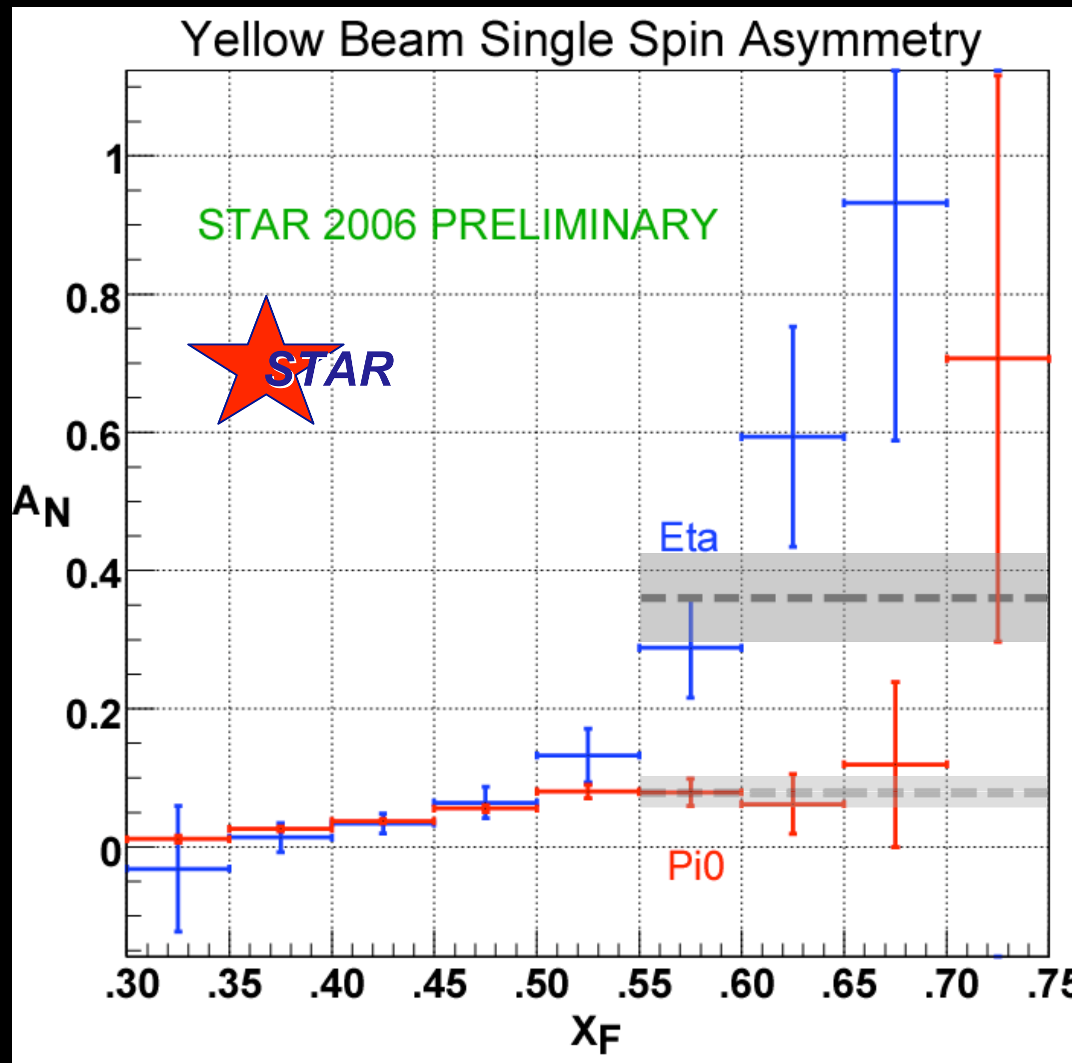
$$p^{\uparrow} + p \rightarrow M + X \qquad \sqrt{s} = 200\,GeV$$
$$M \rightarrow \gamma + \gamma$$

And just when you thought the A_N couldn't get any bigger… along came the η!

$$.55 < X_F < .75$$

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

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



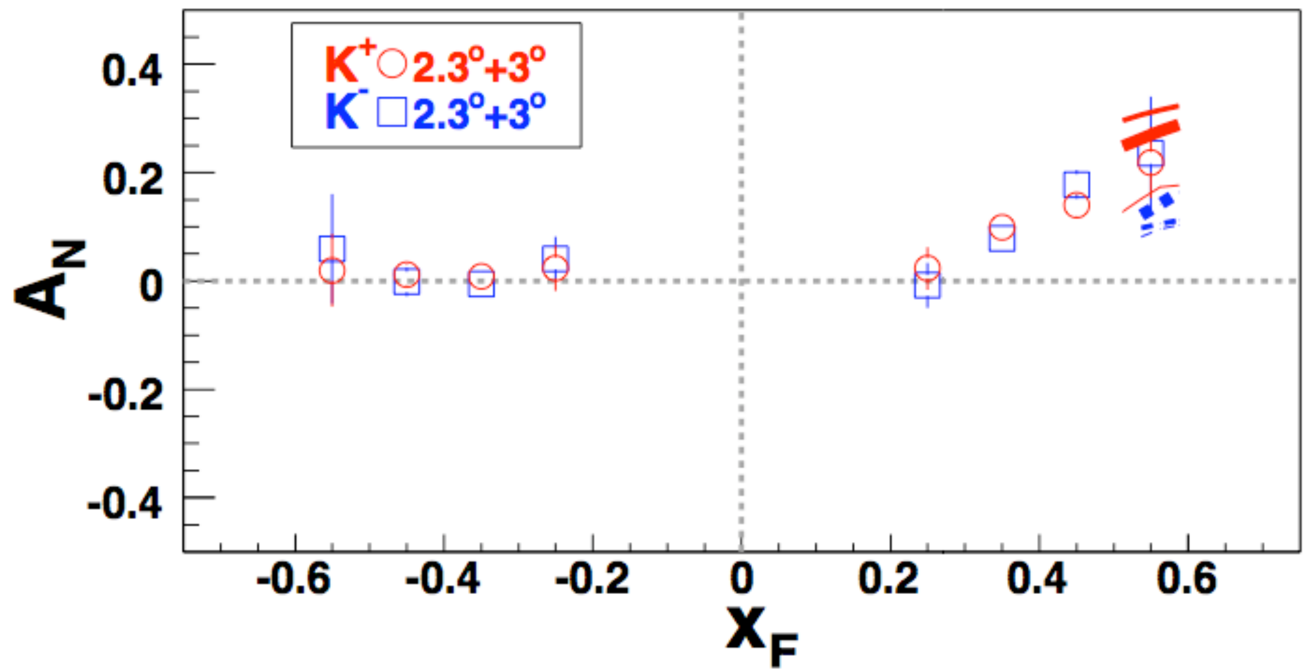
η is like the BRAHMS K+/K- SSA. They do not support the valence dominance interpretation.

$$K^+ \equiv u\bar{s}$$

$$K^- \equiv s\bar{u}$$

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

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



The K- SSA same sign and magnitude of K+! Perhaps sea contribution is not small?

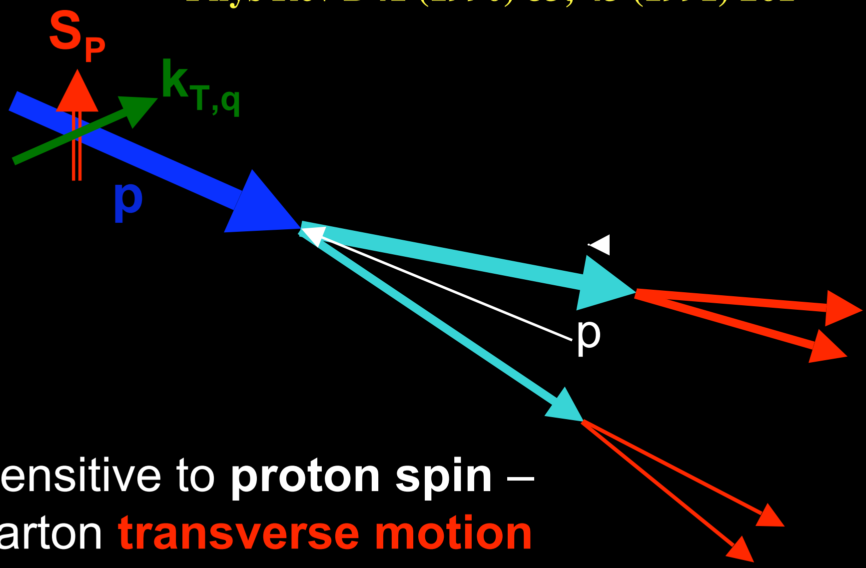
Separating Sivers and Collins effects

Sivers mechanism: asymmetry in the forward jet or γ production

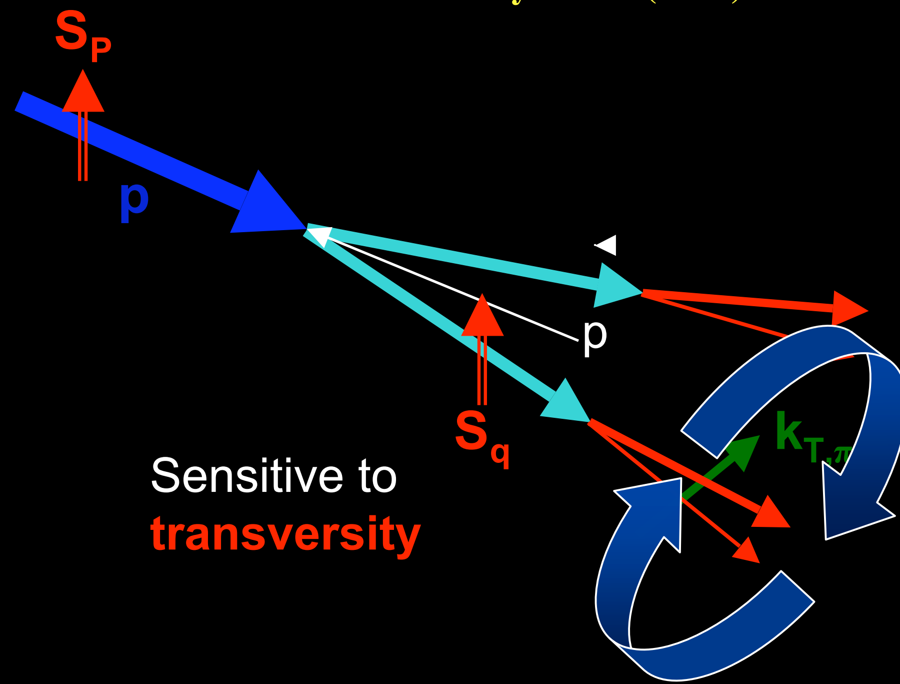
Phys Rev D41 (1990) 83; 43 (1991) 261

Collins mechanism: asymmetry in the forward jet fragmentation

Nucl Phys B396 (1993) 161



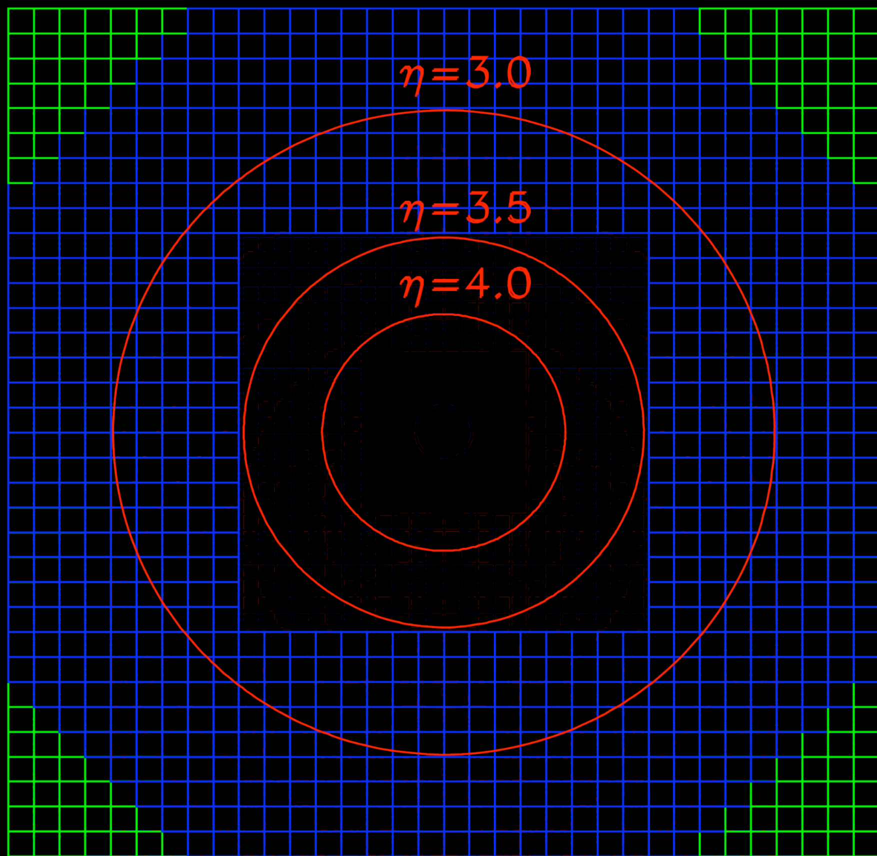
Sensitive to **proton spin** – parton **transverse motion** correlations



Sensitive to **transversity**

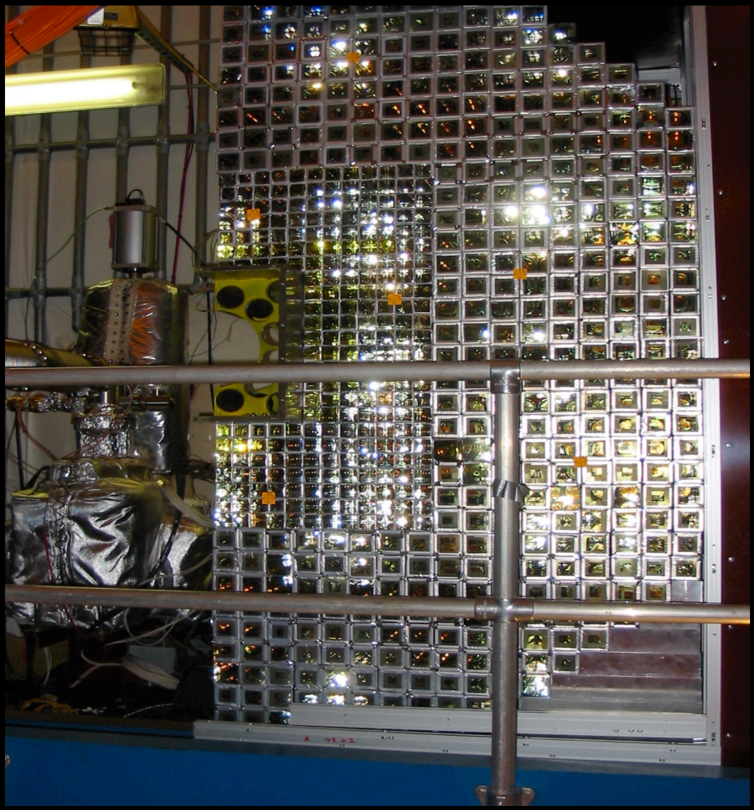
To discriminate between the two effects we need to go beyond π^0 detection to **jet reconstruction**

Forward Meson Spectrometer (FMS) provides nearly 20x the coverage of previous forward detectors



Run 8 FMS

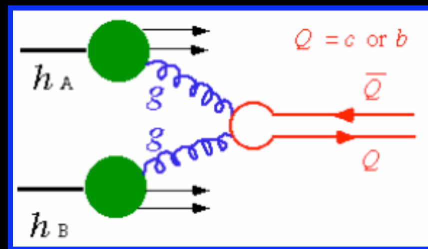
North-half, view from the hall



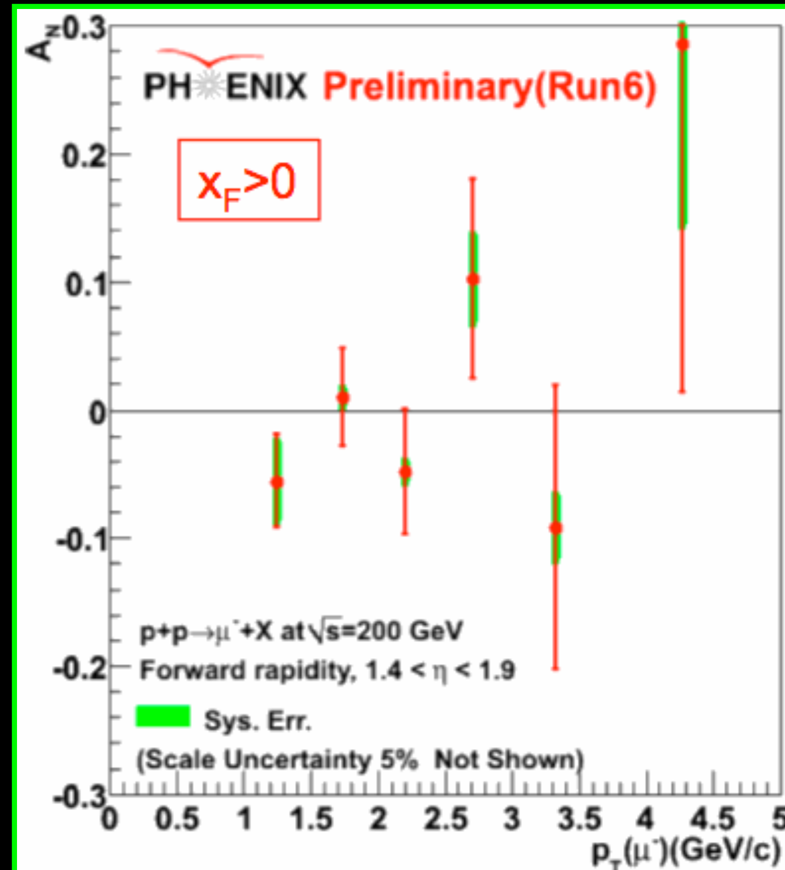
Nearly contiguous coverage for 2.5<η<4.0.

Transverse SSA at $\sqrt{s}$ = 200 GeV

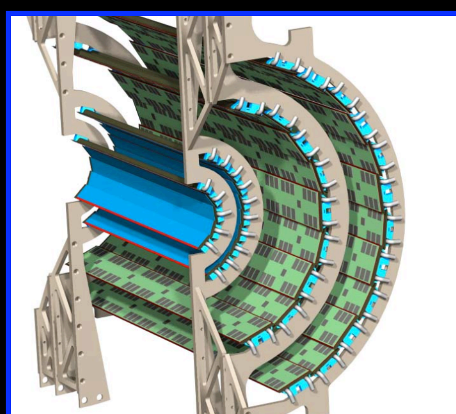
Heavy flavor



- Gluon gluon fusion dominates heavy flavor production
- Gluon transversity = 0
- Isolate's Sivers effect from Collins via single muon measurement



Vertex Tracking upgrade 2010-2011 will increase the power of this measurement



Wrap Up

1) RHIC has been colliding longitudinally and transversely polarized protons since 2002.
2) The seven years following have been very productive.
3) Significant constraints placed on the gluon helicity distribution for 0.02 < x <0.3. ΔG appears to be small in the measured kinematic region.
4) Plans to increase sensitivity to the total integral. Mapping out lower x region is important.
5) Transverse Spin Effects have been verified at both 200 and 64.2 GeV at RHIC.
6) These results have spurred a great deal of theoretical work and experimental interest.
7) Plans to dis-entangle Siver's and Collins are important and on the horizon.

Backup

Polarized Collider Development

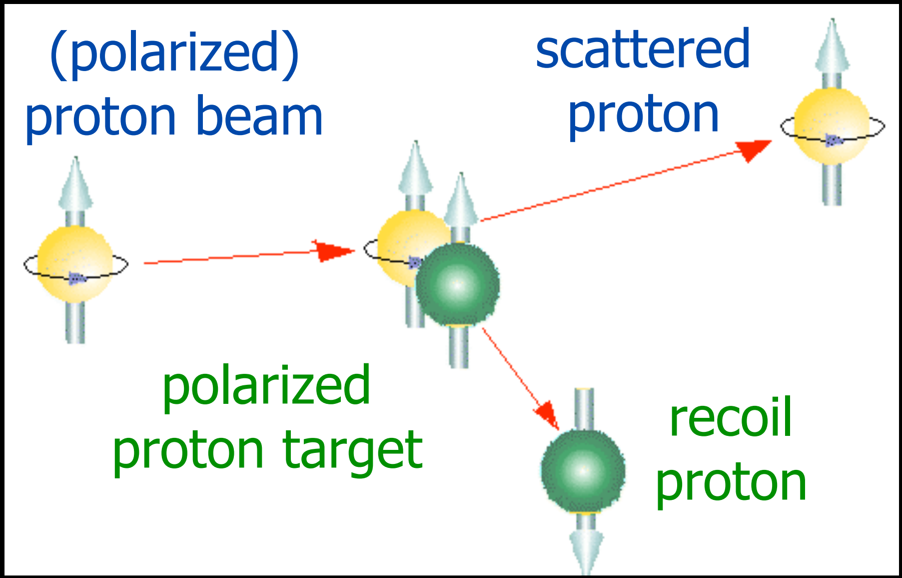
Parameter	Unit	2002	2003	2004	2005	**2006**
No. of bunches	--	55	55	56	106	**111**
bunch intensity	10^{11}	0.7	0.7	0.7	0.9	**1.4**
store energy	GeV	100	100	100	100	**100**
β^*	m	3	1	1	1	**1**
peak luminosity	$10^{30} cm^{-2} s^{-1}$	2	6	6	10	**35**
average luminosity	$10^{30} cm^{-2} s^{-1}$	1	4	4	6	**20**
Collision points	--	4	4	4	3	**2**
average polarization, store	%	15	27	46	50	**57**

Hydrogen-Jet Polarimeter for Beams at Full Energy

- Use transversely polarized hydrogen target and take advantage of transverse *single*-spin asymmetry in elastic proton-proton scattering

$$A_N = \frac{1}{P_{\text{target}}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

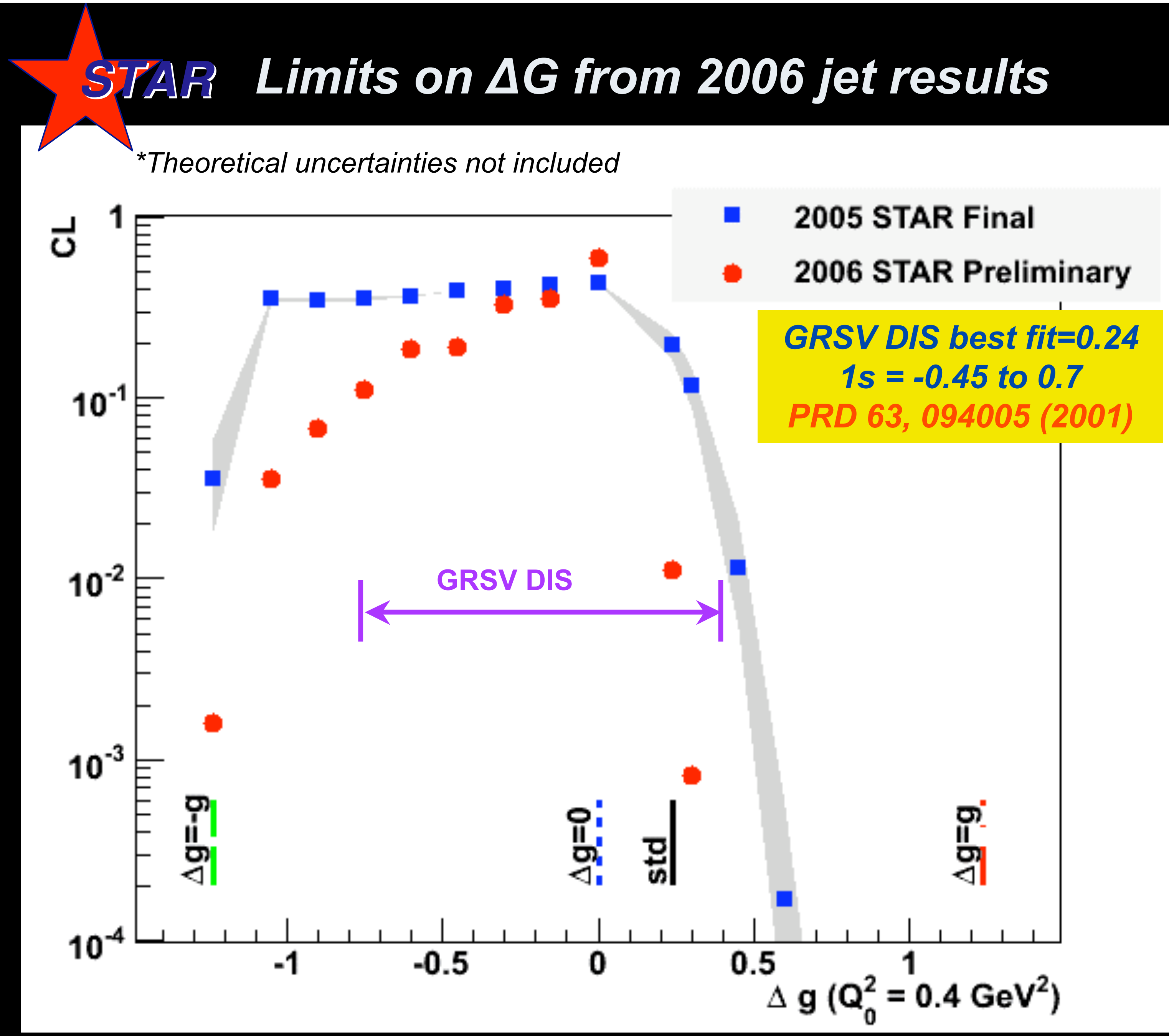
$$P_{\text{beam}} = \frac{1}{A_N} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$



Only consider single polarization at a time. Symmetric process!

- –Know polarization of your target
- –Measure analyzing power in scattering
- –Then use analyzing power to measure polarization of beam

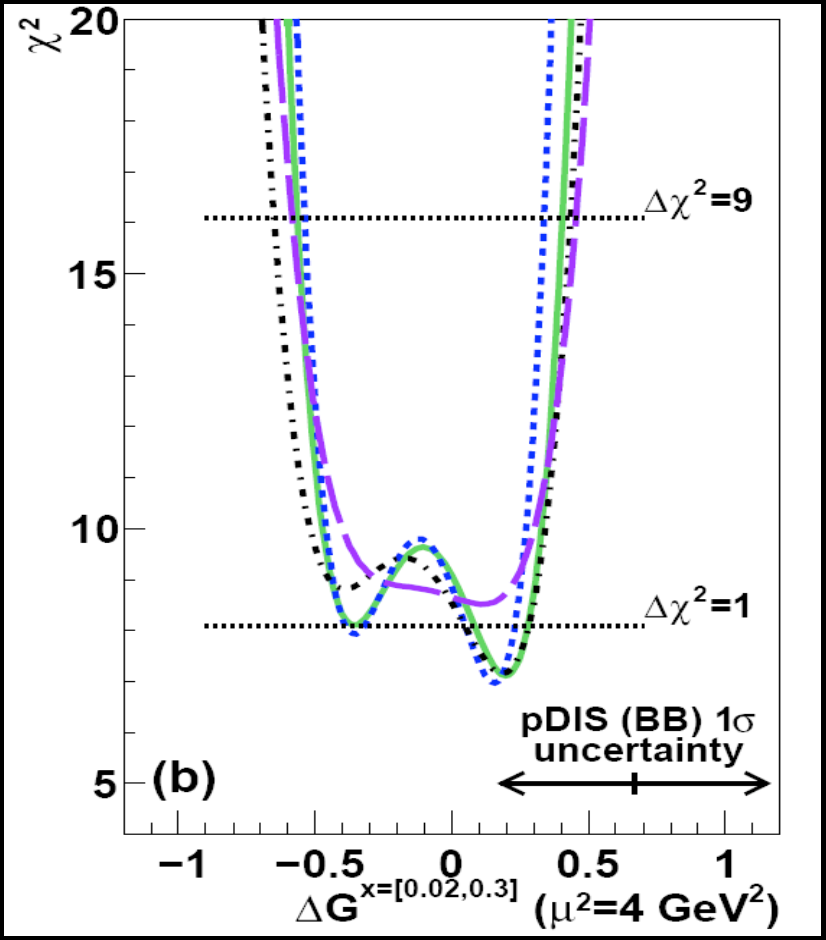
Limits on ΔG from 2006 jet results



π^0 A_{LL}: Agreement with different parametrizations

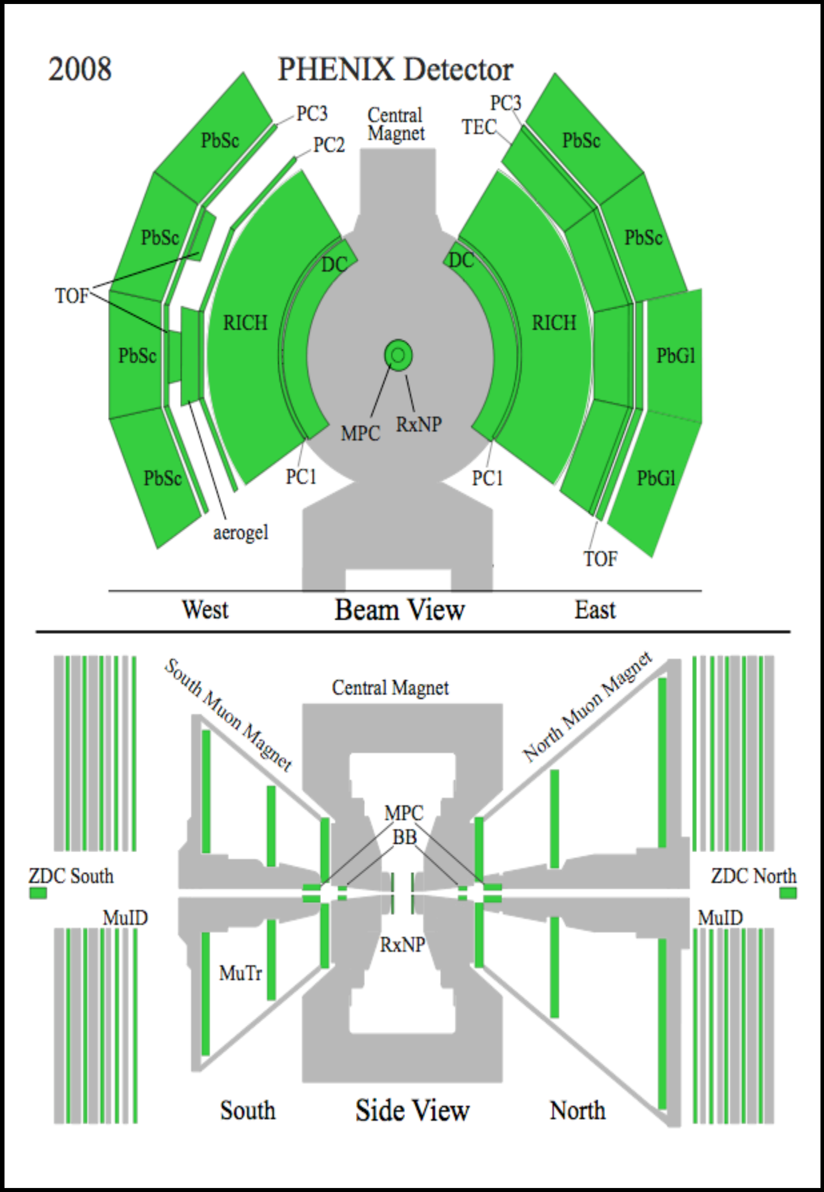
For each parametrization, vary $\Delta G^{[0,1]}$ at the input scale while fixing $\Delta q(x)$ and the shape of $\Delta g(x)$, i.e. no refit to DIS data.

For range of shapes studied, current data relatively insensitive to shape in *x* region covered.



arXiv:0810.0694

PHENIX Detector



π^0, η, γ detection

- Electromagnetic Calorimeter (PbSc/PbGl):
  - High p_T photon trigger to collect trigger to collect π^0's, η's, γ's
  - Acceptance: $|\eta|<0.35$, $\phi = 2 \times \pi/2$
  - High granularity (~10*10mrad^2)

π^+/π^-

- Drift Chamber (DC) for Charged Tracks
- Ring Imaging Cherenkov Detector (RICH)
  - High p_T charged pions (p_T>4.7 GeV).

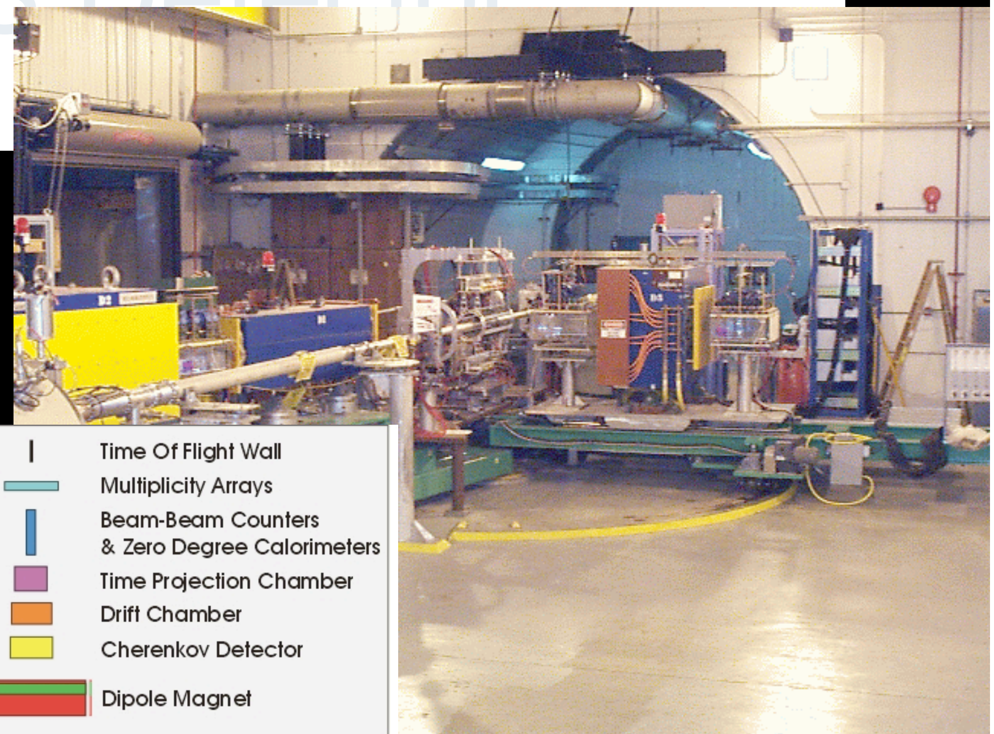
μ^+/μ^-

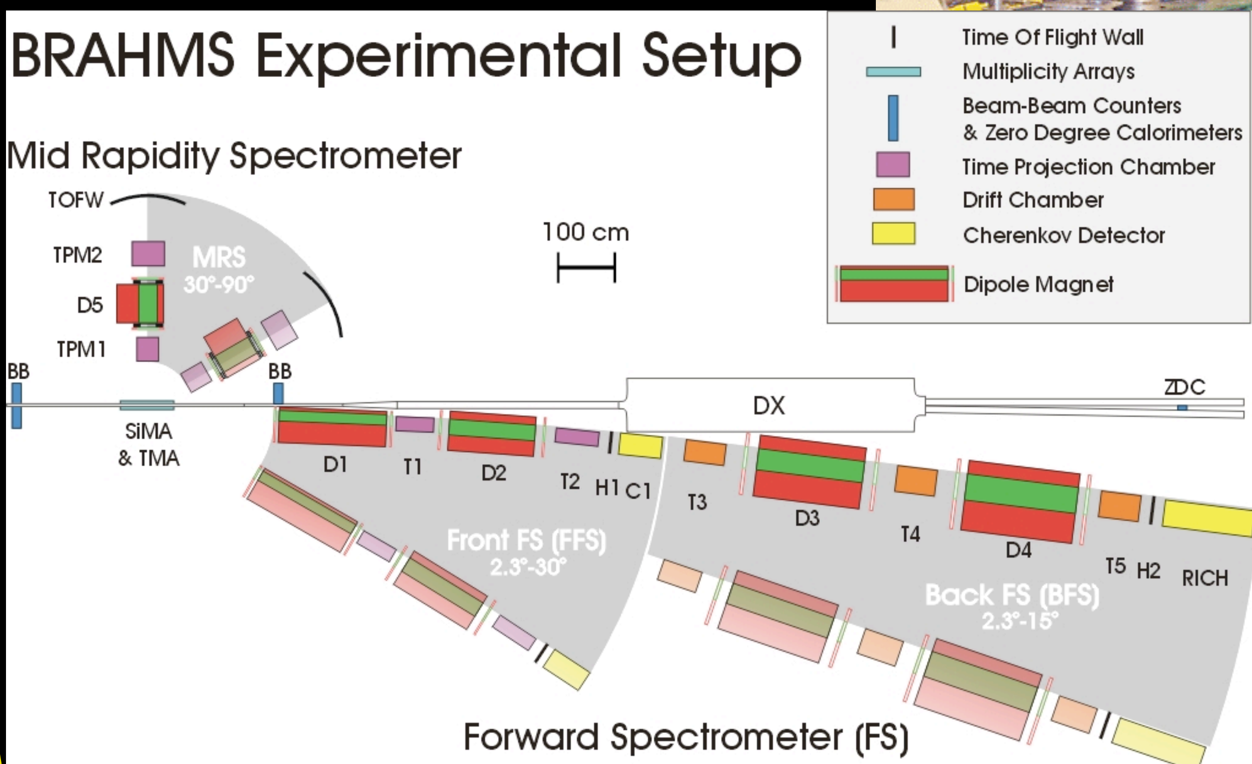
- Muon Tracking (MuTr) and Identification (MuId)

Luminosity (Global) Detectors

- Beam Beam Counter (BBC)
  - Acceptance: $3.0< \eta<3.9$
- Zero Degree Calorimeter (ZDC)
  - Acceptance: ±2 mrad about beam axis

BRAHMS Detector





RHIC and JLAB → Diverging Paths?

Ji:

Measured in DVCS

$$\frac{1}{2} = L_q + \frac{1}{2}\Delta\Sigma + J_g$$

Jaffe:

Measured in DIS+RHIC

$$\frac{1}{2} = l_q + l_g \frac{1}{2}\Delta\Sigma + \Delta G$$

L_q, 1/2 $\Delta\Sigma$ and J_g terms are each gauge invariant. But the separate gluon spin and OAM terms are NOT gauge invariant.

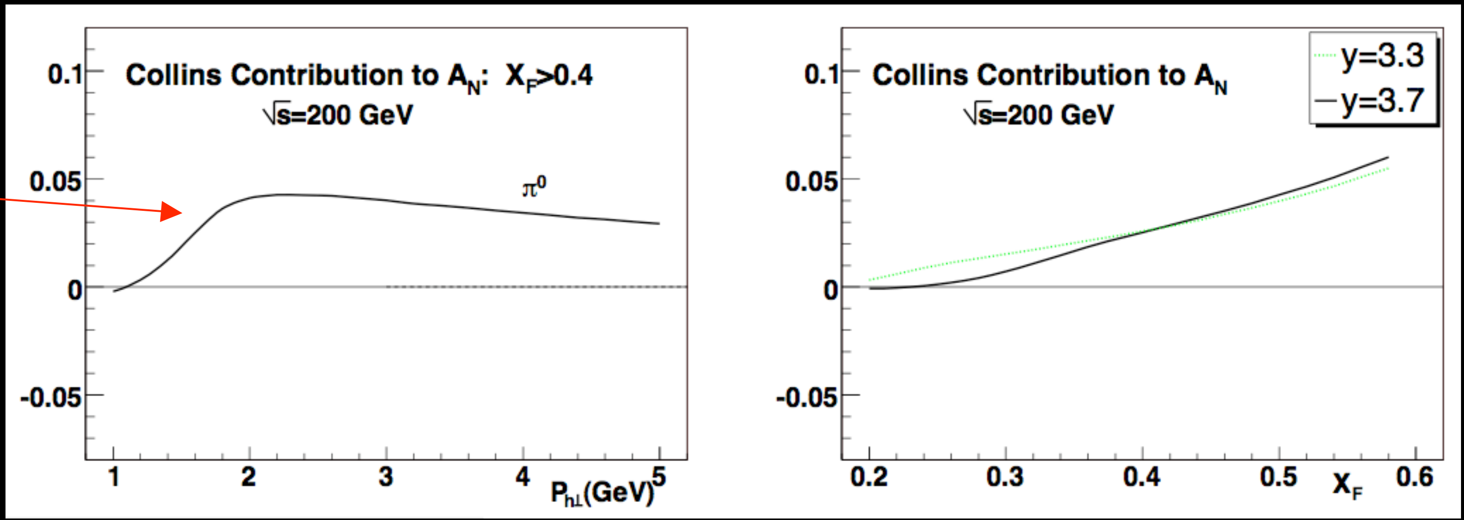
$$J_g \neq l_g + \Delta G$$

l_g, l_q, 1/2 $\Delta\Sigma$, ΔG terms are gauge invariant. But no clear experimental way to measure l_g or l_q yet!

Explanations: Collins Effect

Recent investigation revealed a sign error in the previous limits. It now appears that the Collins effect could indeed explain the full behavior.

Arbitrary cut-off



F. Yuan *arXiv:0804.3047v2 [hep-ph]*

Collins effect would provide a means to constrain the quark transversity.