RHIC Spin

Accomplishments, Plans and Issues

OUTLINE

- Spin at RHIC: how its done, why its done, and who does it
- Status of A_{LL} measurements at RHIC: sensitivity to ΔG
- Status of transverse single-spin asymmetries at RHIC
- Future plans

BROOKHAVEN NATIONAL LABORATORY

L.C. Bland, BNL
DOE Science and Technology Review
18 July 2007

RHIC Spin Collaboration

Confederation of Groups Involved in the Effort

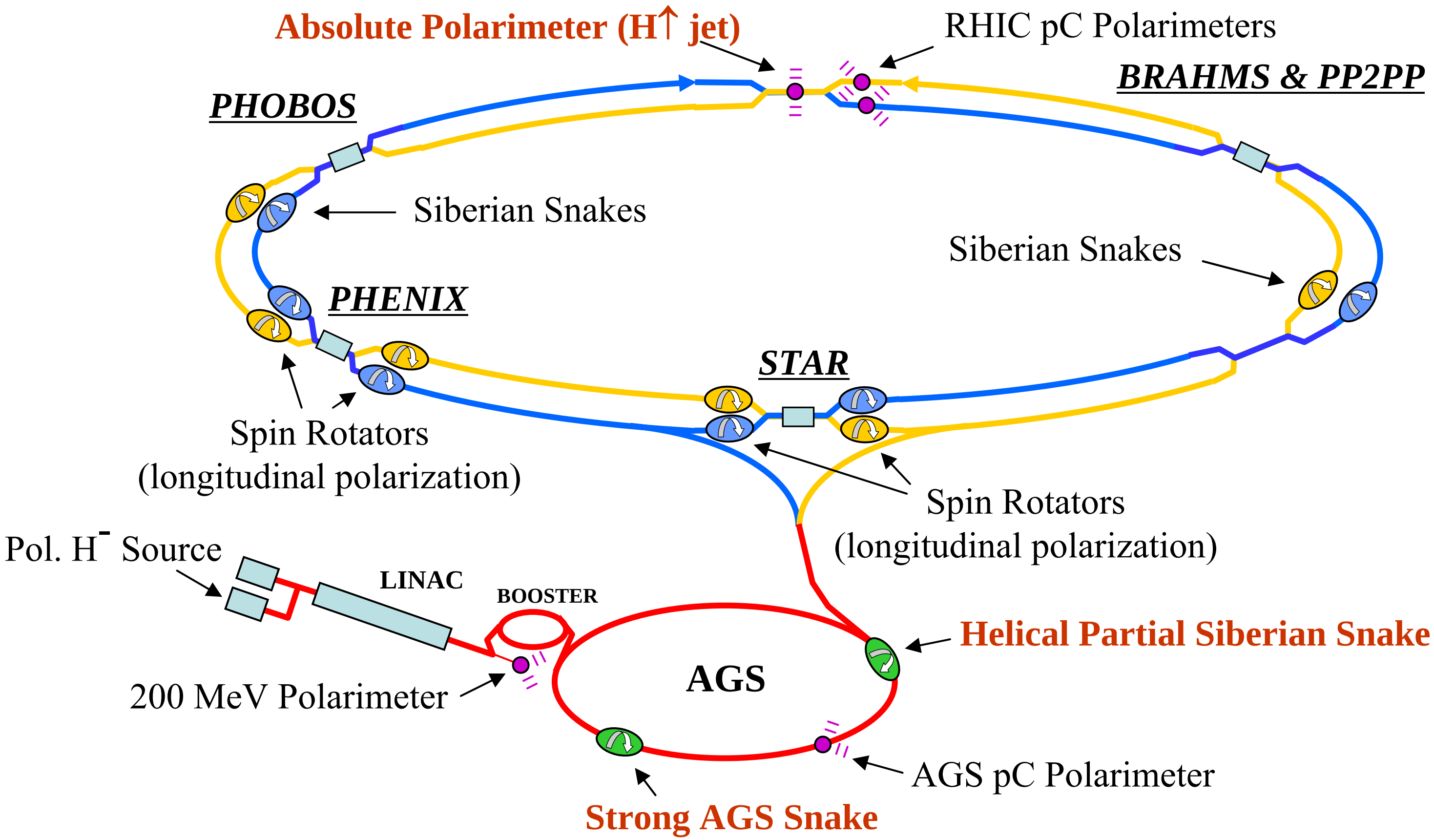
- **Accelerator Physicists / see review talks by Lowenstein,Roser,Bai**
  - Primarily BNL Collider-Accelerator Department
  - RHIC spin is a successful accelerator physics experiment
  - Essential contributions from RIKEN for spin at RHIC
- **RHIC Experiments (PHENIX,STAR,BRAHMS) / see review talks by Jacak,Hallman**
  - RIKEN / RBRC, University and National Laboratory groups
  - RHIC spin planning fully integrated in experiment collaborations
- **Polarimetry / see review talk by Bunce**
  - Primarily BNL effort, with “detailees” from RHIC experiments
  - Essential measurements required for RHIC spin results
- **Theory / see review talk by Kharzeev**
  - RIKEN / RBRC, University and National Laboratory groups
  - RHIC spin results require QCD global analyses to extract physics

RHIC Spin Group at BNL

	FY2006	FY2007
STAR Physics	Les Bland Akio Ogawa (SBU + Zagreb students)	+ Andrew Gordon (7/07) + Hiromi Okada (12/06)
	FPD++: jet-like A_N; $\sigma(\gamma)$	FMS: $A_{LL}(\gamma)$; $A_N(\gamma)$; $g_{Au}(x)$
PHENIX Physics	Gerry Bunce Sasha Bazilevsky	
	$A_{LL}(\pi^0)$	$A_{LL}(\gamma)$
Polarimetry	Ron Gill (0.5)	
	Sandro Bravar	Sasha Bazilevsky Boris Morozov
	Gas-jet target; carbon polarimeters	

RHIC

As a Polarized Collider



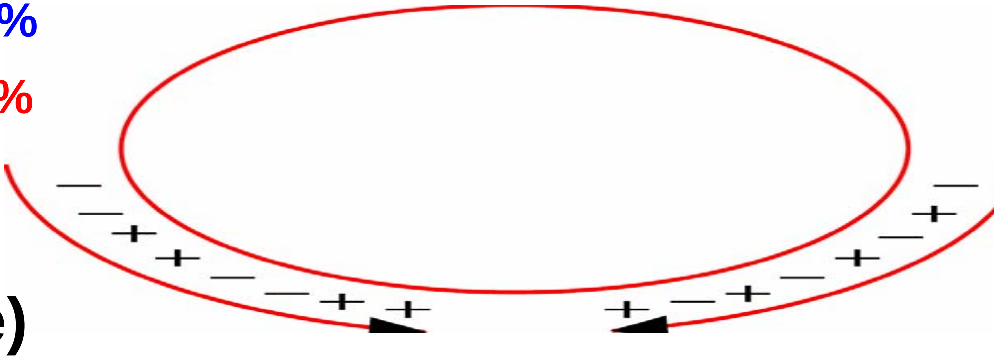
2005: P_{blue} = 49.3% +/- 1.5% +/- 1.4%

P_{yellow} = 44.3% +/- 1.3% +/- 1.3%

$\Delta P/P$ = 4.2% (goal=5%)

2006: 1 MHz collision rate;

Polarization=0.6 (online)



RHIC Spin Goals - I

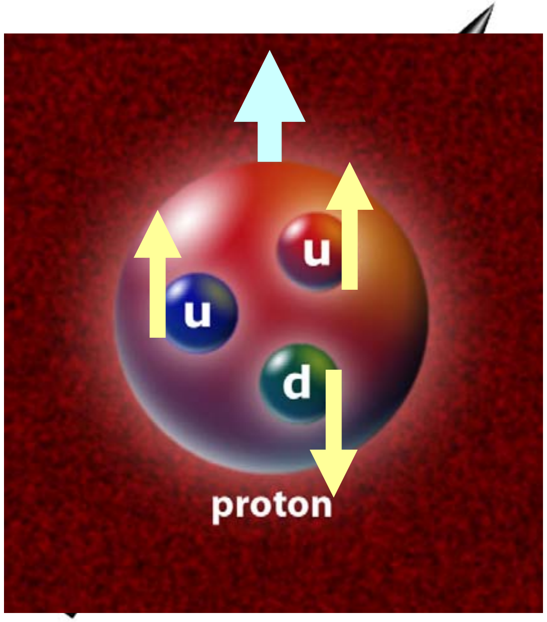
How is the proton built from its known quark and gluon constituents?

As with atomic and nuclear structure, this is an evolving understanding

In QCD: proton is not just 3 quarks !

Recall:
simple quark model

Rich structure of quarks anti-quarks, gluons



It was not sufficient to just know that neutral atoms had positively and negatively charged constituents. Real understanding was gained from knowing how the neutral atom was built from its charged constituents.

RHIC Spin Goals - II

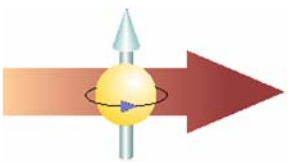
Understanding the Origin of Proton Spin

Spin Sum Rules

Longitudinal Spin

$$S_z = \tfrac{1}{2} = \tfrac{1}{2}\,\Delta\Sigma + \Delta G + L_{z,q} + L_{z,g}$$

Transverse Spin



PRD 70 (2004) 114001

$$S_y = \tfrac{1}{2} = \tfrac{1}{2}\,\delta\Sigma + L_{y,q} + L_{y,g}$$

Understanding the origin of proton spin helps to understand its structure

RHIC Spin Goals - III

Milestones and Other Objectives

- *Direct measurement* of polarized gluon distribution (ΔG) *using multiple probes*

  NSAC Milestone for 2008

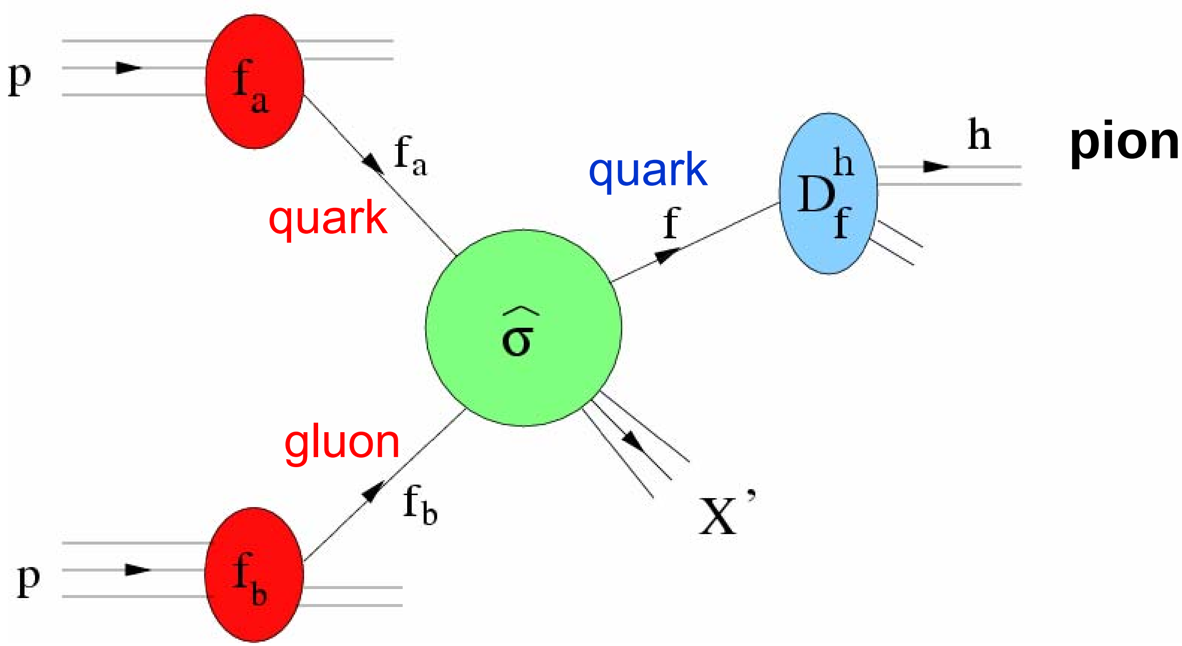
- Direct measurement of flavor identified *anti-quark polarization* using *parity violating production of* $W^{\pm}$

  NSAC Milestone for 2013

- *Transverse spin:* connections to partonic orbital angular momentum (L_y) and transversity ($\delta\Sigma$)

RHIC Spin Probes - I

Polarized proton collisions / hard scattering probes of ΔG



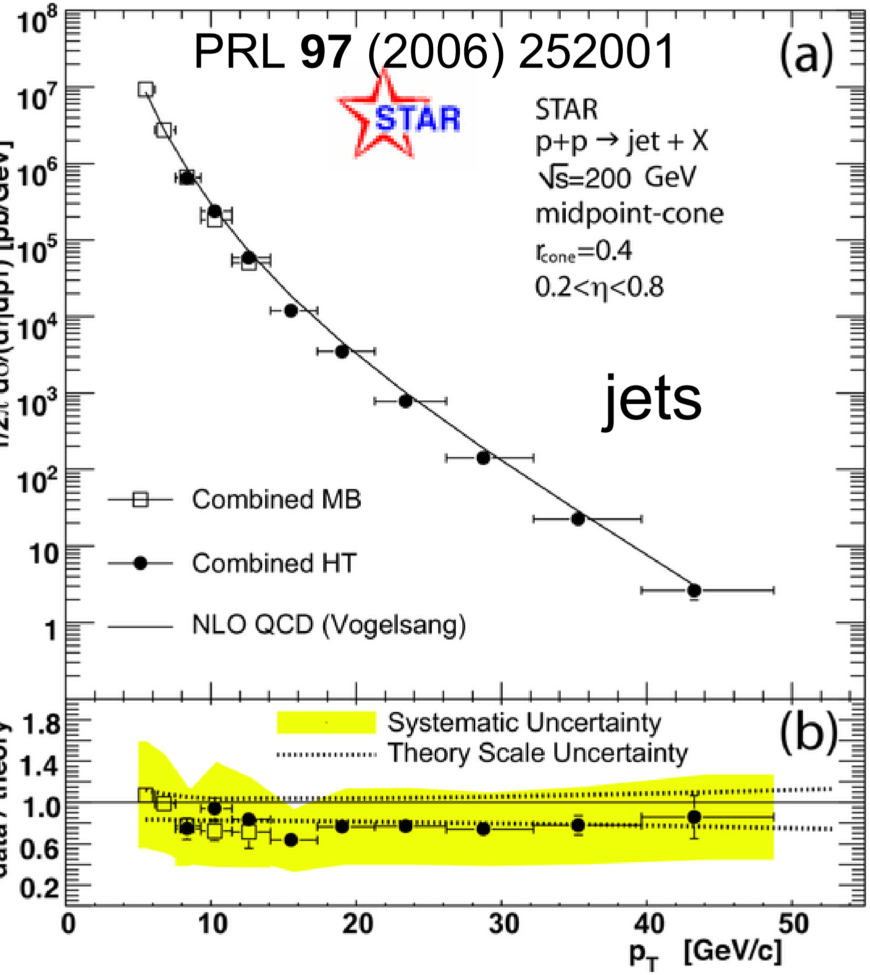
$$d\sigma_\pi = \sum_{a,b,c} \int dx_a \int dx_b \int dz_c \; f_a(x_a) f_b(x_b) D_c^\pi(z_c) d\hat{\sigma}_{ab}^c$$

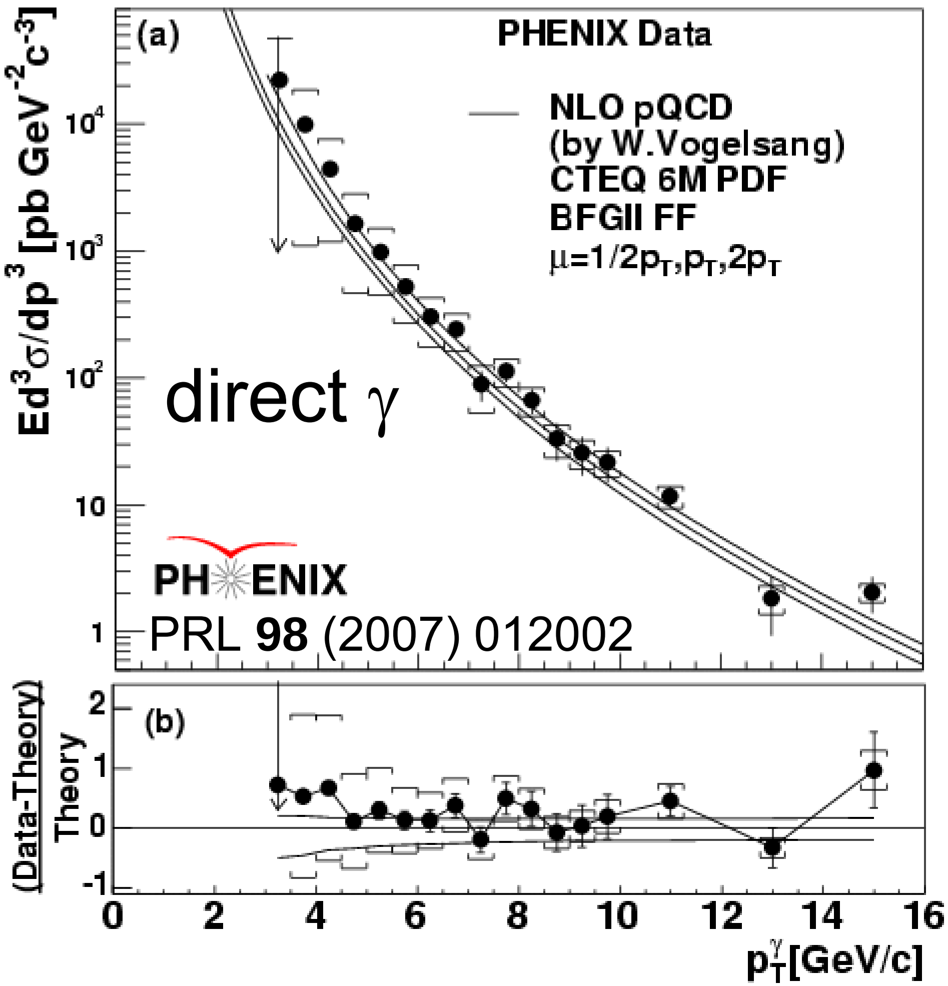
Describe p+p particle production at RHIC energies ($\sqrt{s} \geq 62$ GeV) using perturbative QCD at Next to Leading Order, relying on universal parton distribution functions and fragmentation functions

RHIC Spin Probes - II

Unpolarized cross sections as benchmarks and heavy-ion references

p + p, $\sqrt{s}$ = 200 GeV

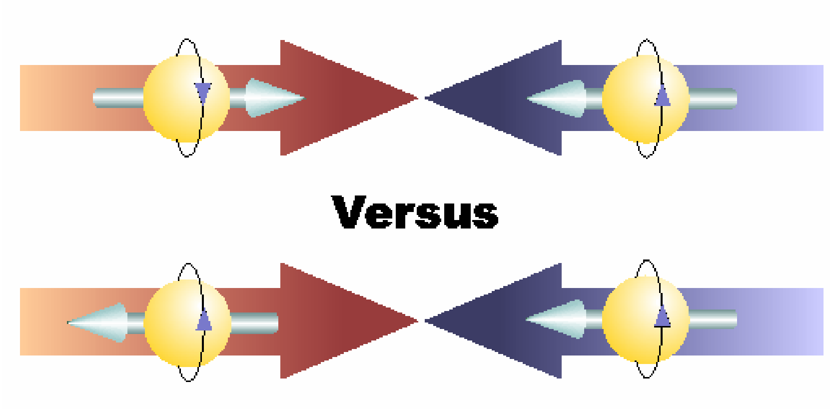




Good agreement between experiment and theory

⇒ calibrated hard scattering probes of proton spin

Longitudinal Two-Spin (A_{LL})

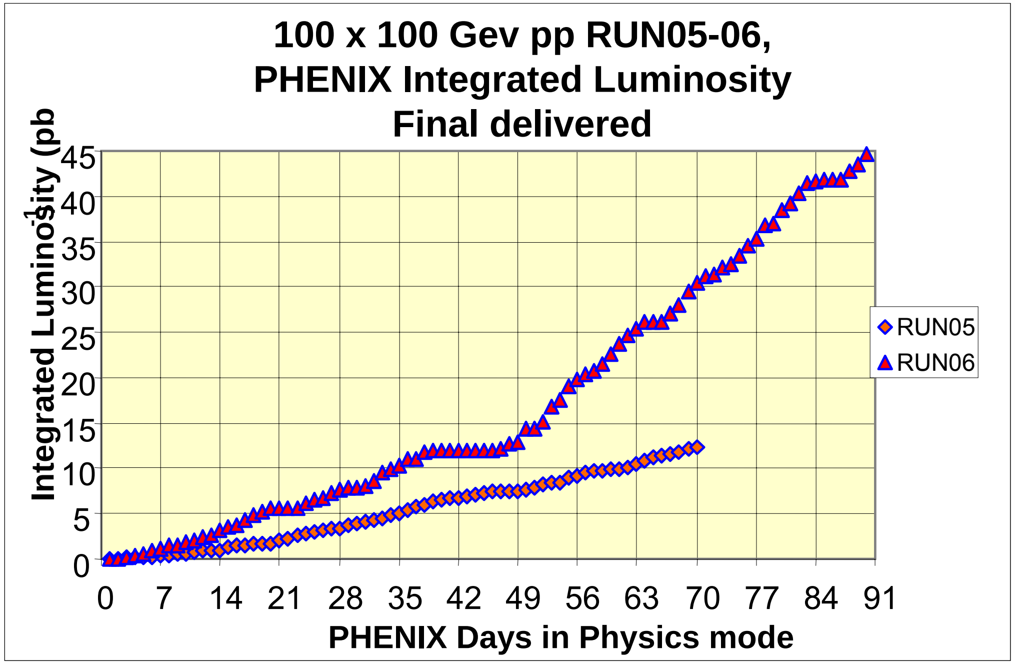


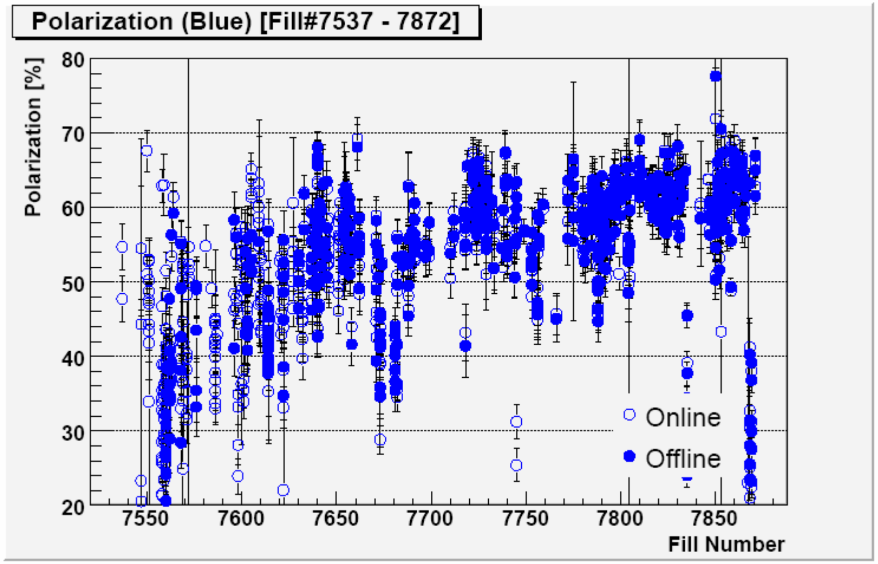
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

Status of probing for gluon polarization via measurements of A_{LL} for midrapidity jet, π^0 production

RHIC Run-6

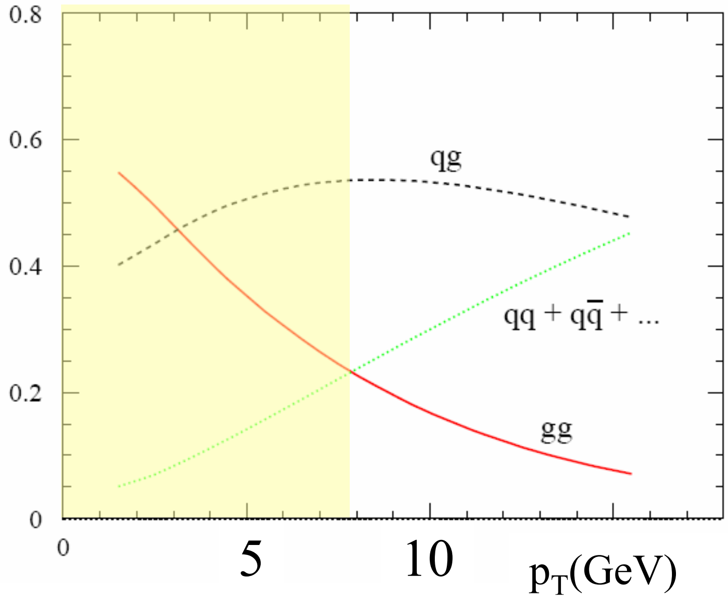
Plot by Phil Pile



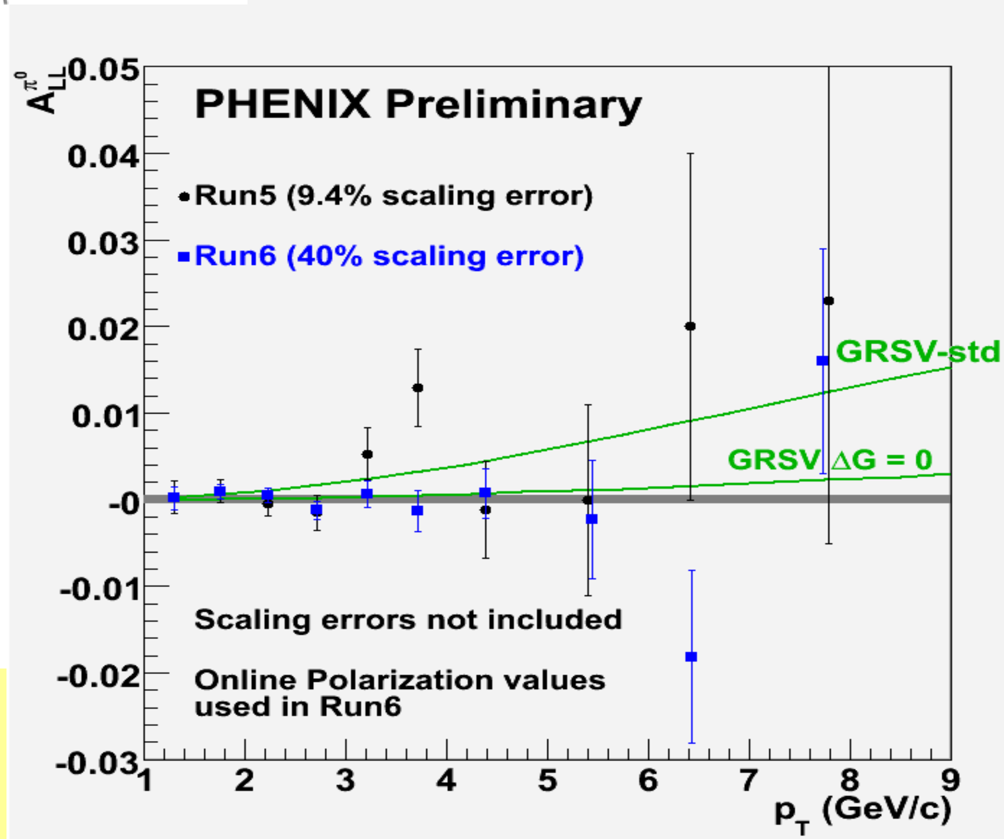


Outstanding luminosity and polarization performance from RHIC for polarized proton collisions at $\sqrt{s}$ = 200 GeV

A_{LL}: π^0



Preliminary Run6 ($\sqrt{s}$=200 GeV)



GRSV model:

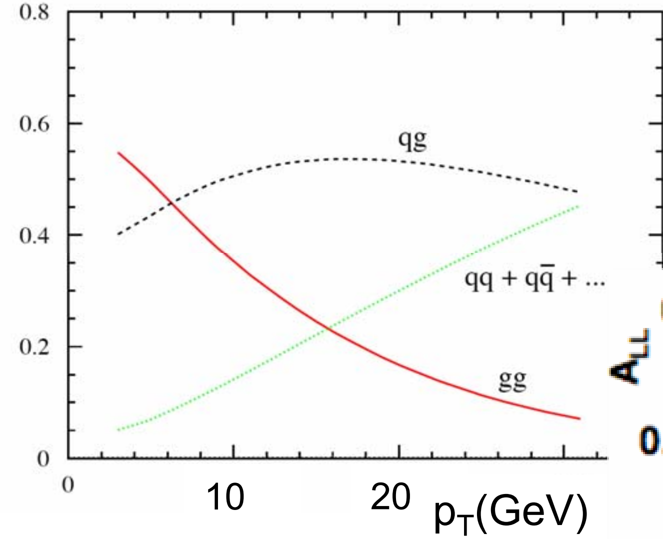
"$\Delta G = 0$": $\Delta G(Q^2=1\text{GeV}^2)=0.1$

"ΔG = std": $\Delta G(Q^2=1\text{GeV}^2)=0.4$

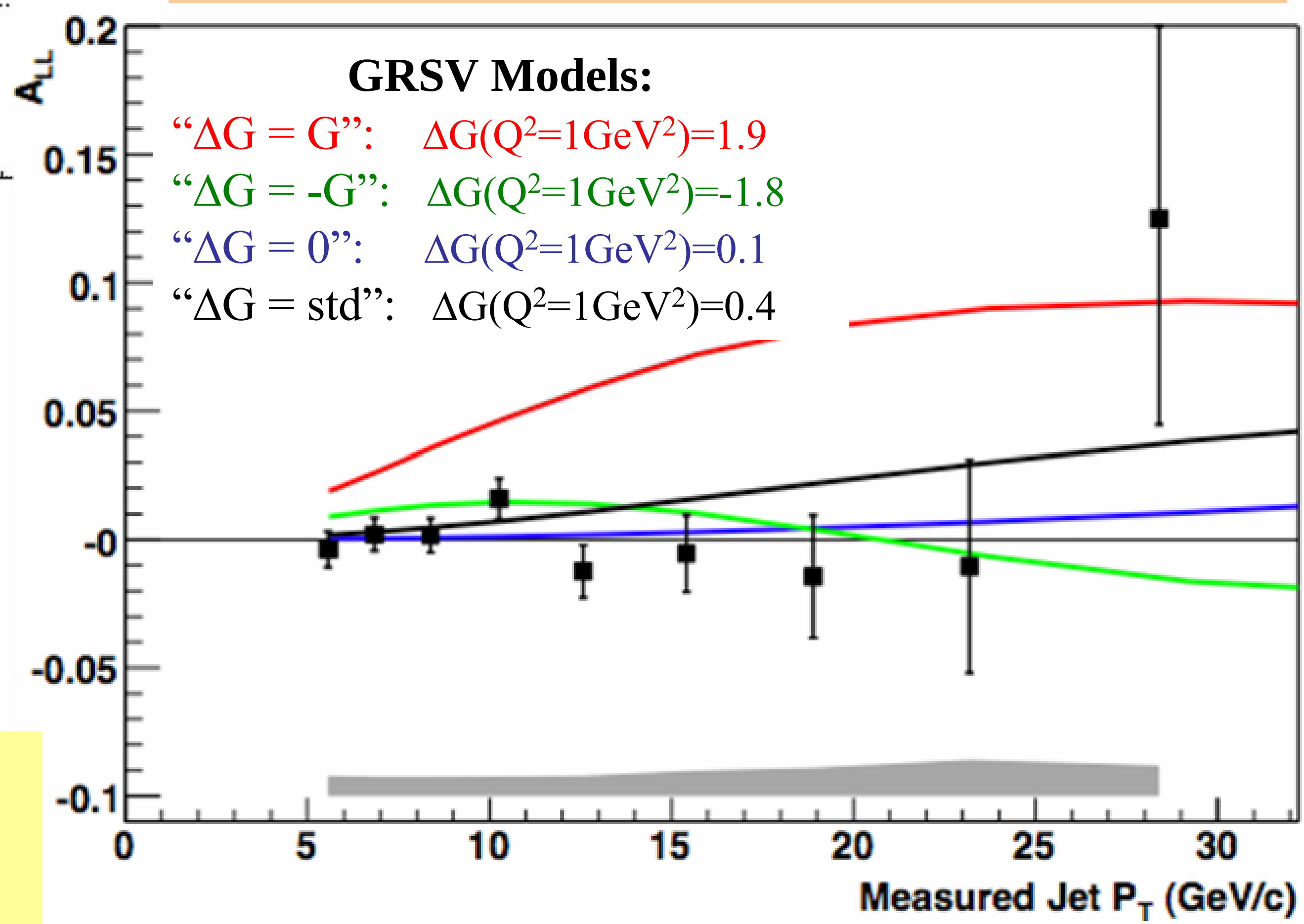
Statistical uncertainties now to the point of distinguishing "std" and "0" scenarios?

Run3,4,5: PRL 93, 202002; PRD 73, 091102; hep-ex-0704.3599

A_{LL}: jets



STAR Preliminary Run5 ($\sqrt{s}$=200 GeV)

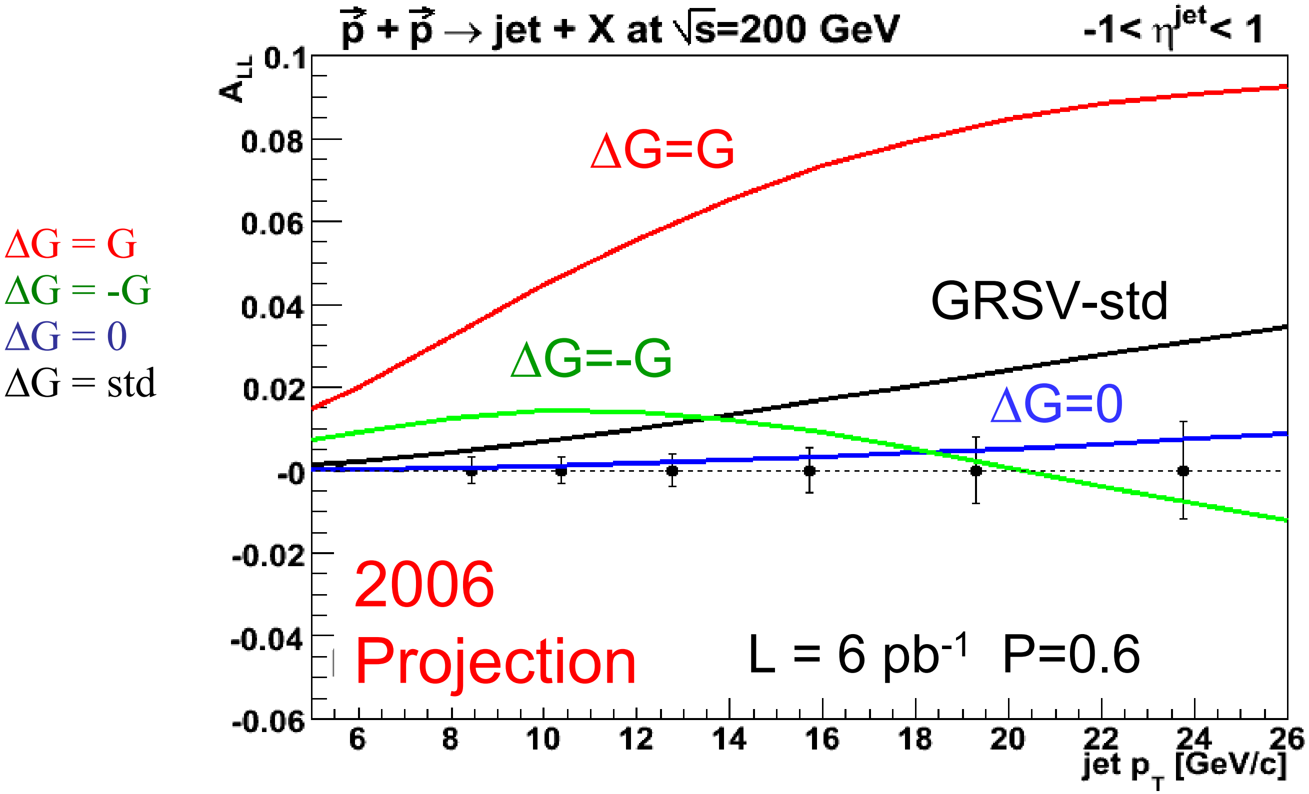


Large ΔG scenario is not consistent with data

Run3&4: PRL 97, 252001

Projected Accuracy for Run-6 Jet Results

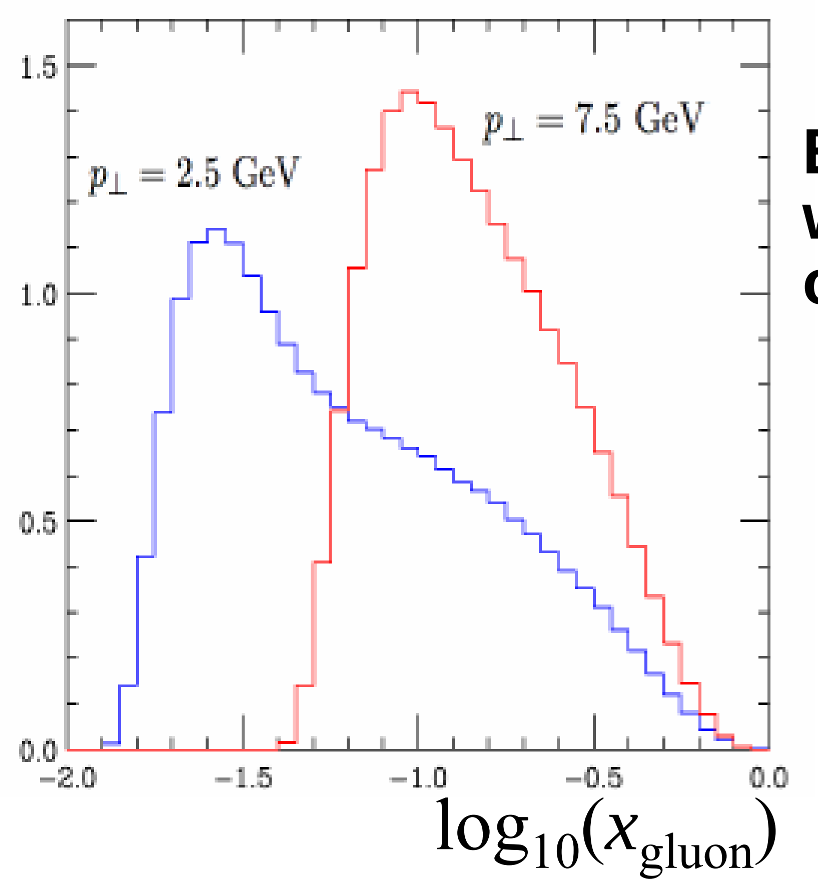
STAR Jets: expectations from Run 6
(√s=200 GeV)



Reconstructions already available
Results expected this fall

From p_T to x_{gluon}

midrapidity neutral pion A_{LL}



Each p_T bin corresponds to a wide range in x_{gluon}, heavily overlapping with other p_T bins

- Data are not sensitive to variation of $\Delta G(x_{gluon})$ within our x range
- Quantitative analysis needs to assume some $\Delta G(x_{gluon})$ shape

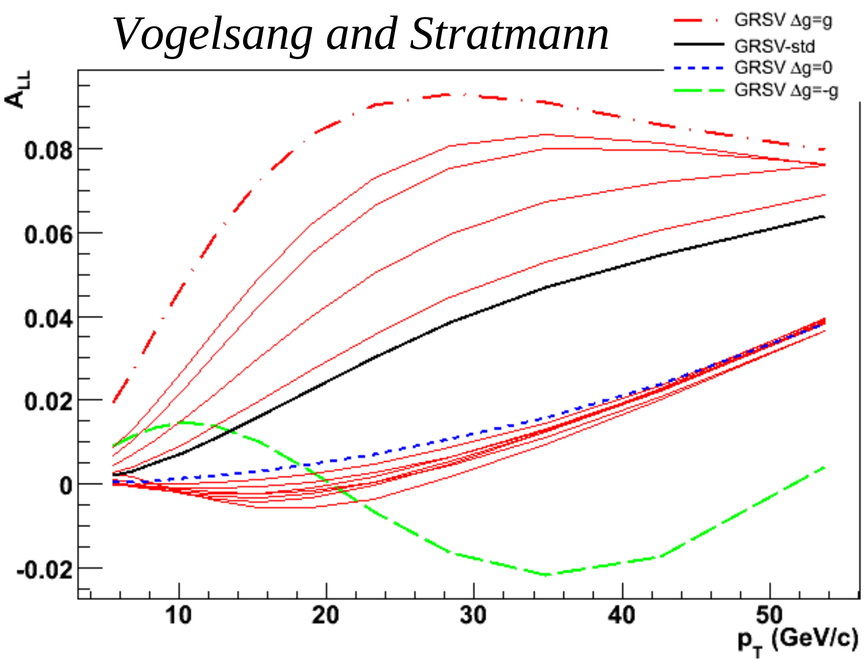
NLO pQCD: for π^0, $2 < p_T < 9$ GeV/c $\Rightarrow 0.02 < x_{gluon} < 0.3$

GRSV model: $\Delta G(0.02 < x_{gluon} < 0.3) \sim 0.6 \Delta G(0 < x_{gluon} < 1)$

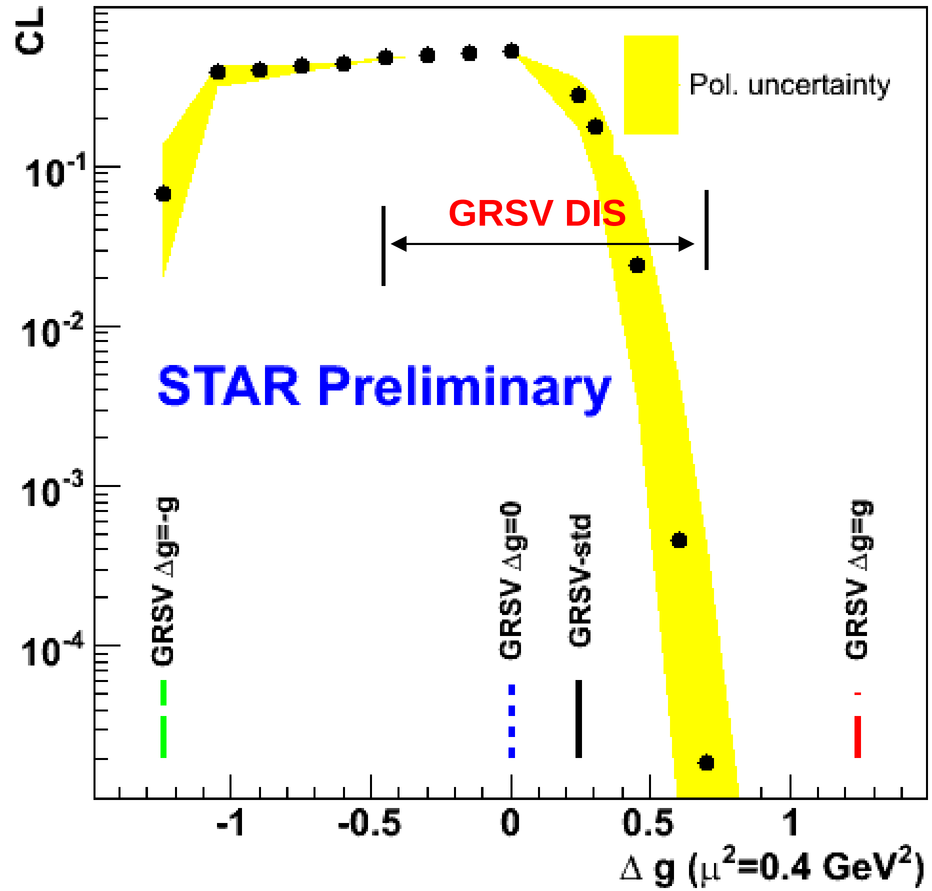
Constraining ΔG from jet production A_{LL}

Before global analyses…

- Compute A_{LL} in NLO pQCD varying integral ΔG, but maintaining GRSV shape
- Perform χ^2 analysis between calculations and measured jet A_{LL}



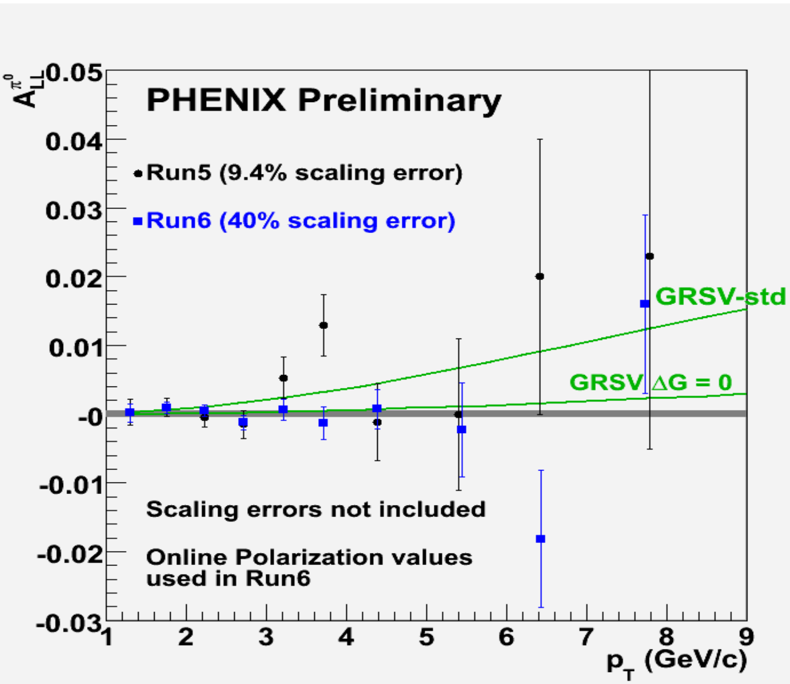
GRSV DIS best fit=0.24
1σ ΔG varies from -0.45 to 0.7
PRD 63, 094005 (2001)



Data not consistent with ΔG larger than GRSV-std in the measured range, $0.03 < x < 0.3$

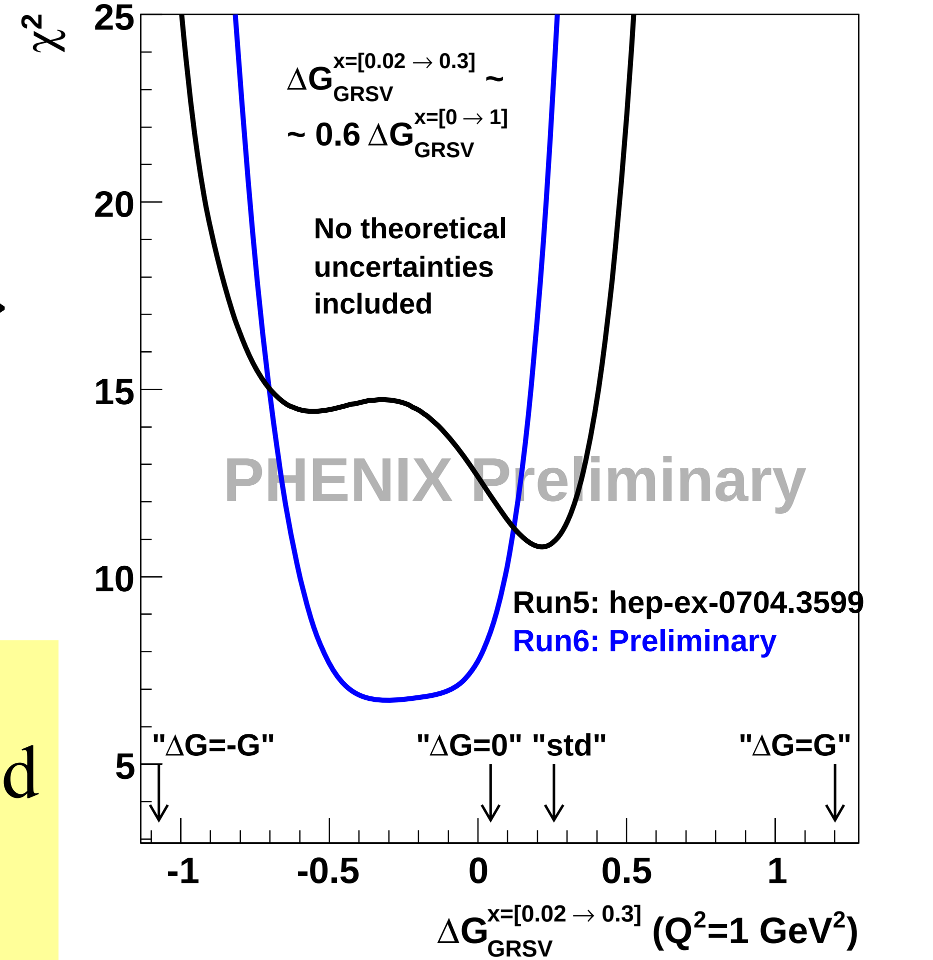
Constraining ΔG from π^0 A_{LL}

Similar approach as used for jets



⇒

Calculations by W.Vogelsang and M.Stratmann



"GRSV-std" scenario, $\Delta G(Q^2=1\text{GeV}^2)=0.4$, is excluded by data on $>3\sigma$ level

- Only exp. stat. uncertainties are included (the effect of syst. uncertainties is expected to be small in the final results)
- Theoretical uncertainties are not included

Summary of A_{LL} Measurements

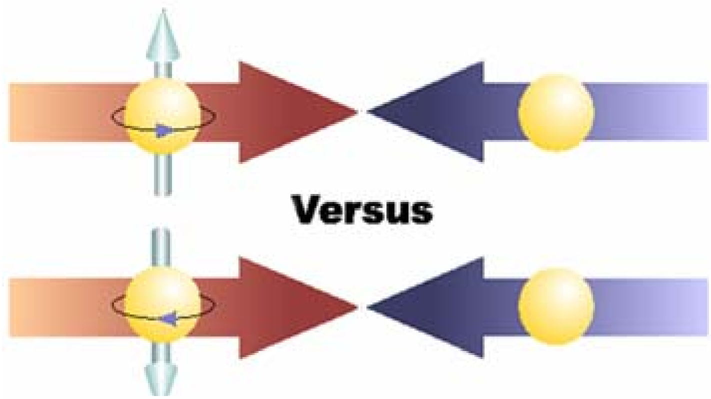
- Data accumulated through RHIC run 6 for inclusive π^0 and jet A_{LL} has reached high statistical significance to constrain ΔG in the limited x range (~0.02–0.3)
    - ❑ ΔG is found to be consistent with zero, to date
    - ❑ Theoretical uncertainties (x dependence) are significant

Future Plans for Probing ΔG

RHIC run 8 and beyond

- Improve statistical precision of midrapidity π^0,jet A_{LL} measurements and extend measurements to higher p_T
- Determine x-dependence of ΔG via correlation measurements: jet_1+jet_2 and γ+jet
- Extend gluon-x range probed to lower x via measurements of A_{LL} at larger rapidity and higher $\sqrt{s}$
- Global analysis in NLO pQCD of RHIC data and HERMES,COMPASS data

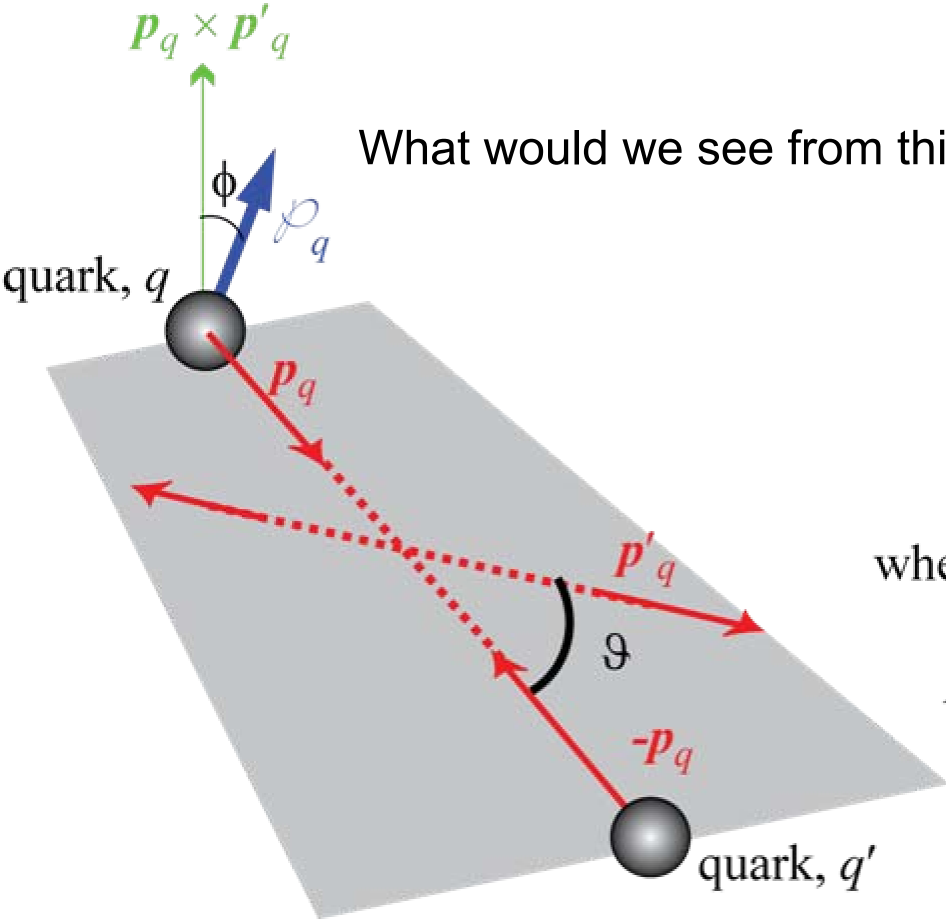
Transverse Single-Spin Asymmetries (A_N)



$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

Probing for orbital motion within transversely polarized protons

Expectations from Theory



What would we see from this gedanken experiment?

$$N(\vartheta,\phi) = N_0(\vartheta)\,[1 + \wp_q A_N \cos\phi]$$

$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

where, $\wp_q$ is quark transverse polarization;
$A_N \propto \mathrm{Im}(NF^*)$;
N is the non-*helicity*-flip amplitude;
and F is the *helicity*-flip amplitude

$F \rightarrow 0$ as $m_q \rightarrow 0$ in vector gauge theories, so $A_N \sim m_q/p_T$

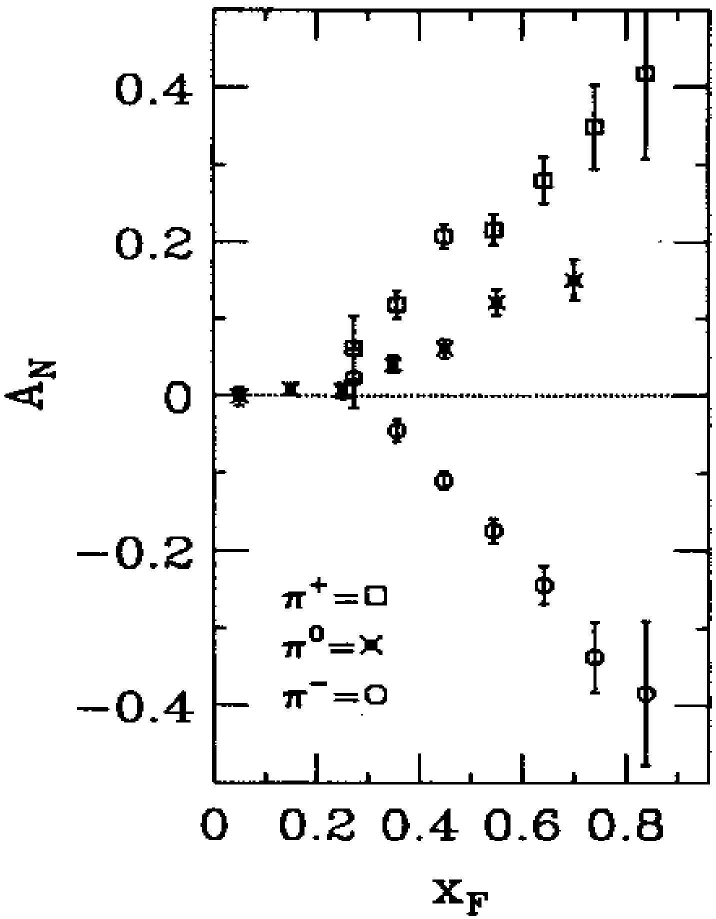
or, $A_N \sim 0.001$ for $p_T \sim 2$ GeV/c

Kane, Pumplin and Repko PRL **41** (1978) 1689

A Brief History…

$$p_{\uparrow} + p \rightarrow \pi + X$$

√s=20 GeV, p_T=0.5-2.0 GeV/c



π^0 – E704, PLB261 (1991) 201.

$\pi^{+/-}$ - E704, PLB264 (1991) 462.

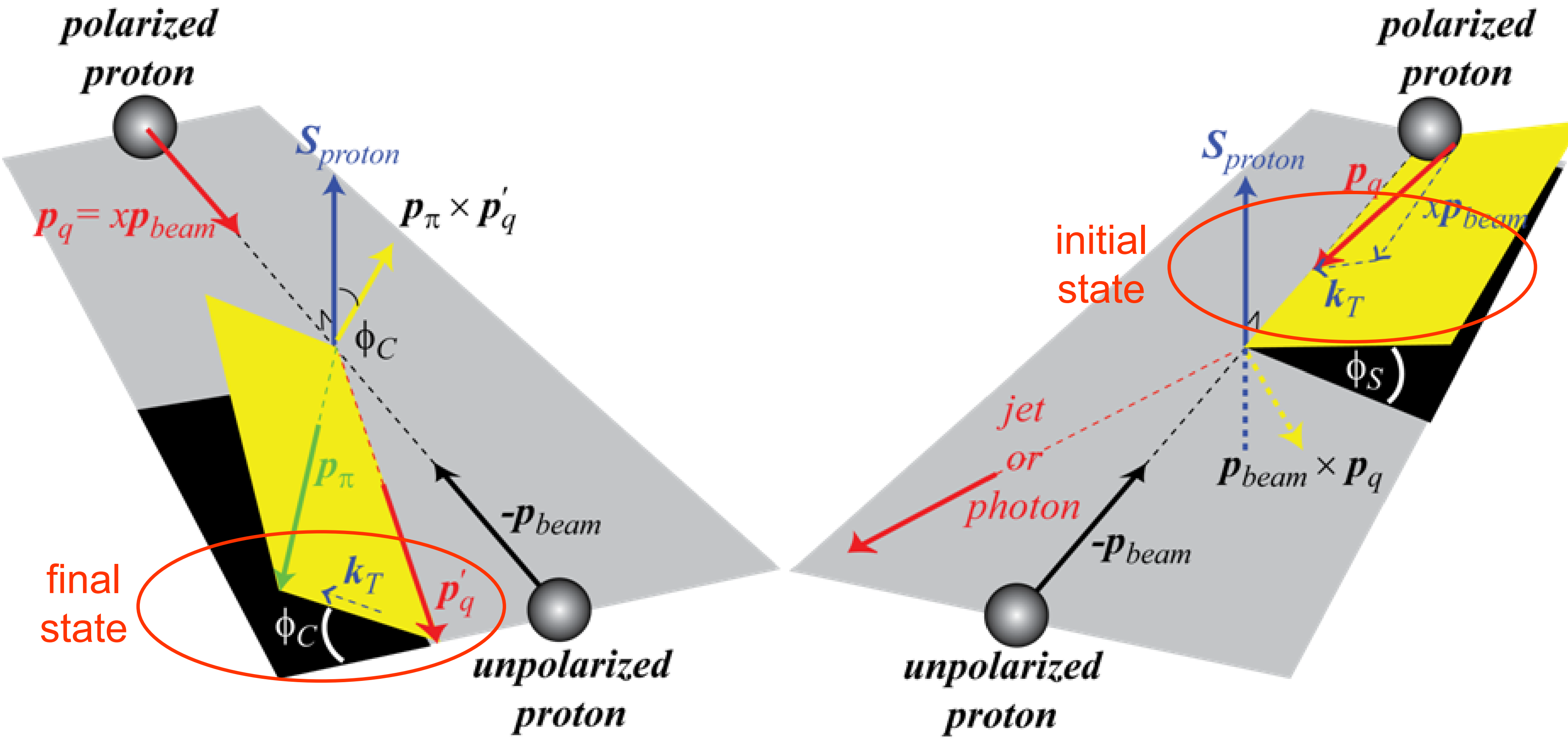
- QCD theory expects very small (A_N~10^{-3}) transverse SSA for particles produced by hard scattering.
- The FermiLab E-704 experiment found strikingly large transverse single-spin effects in $p_{\uparrow}$+p fixed-target collisions with 200 GeV polarized proton beam (⇒√s = 20 GeV).

Two of the Explanations for Large Transverse SSA

Spin-correlated k_T

Collins/Heppelmann mechanism
requires *transverse quark polarization* and *spin-dependent fragmentation*

Sivers mechanism
requires *spin-correlated transverse momentum* in the proton (orbital motion).
SSA is present for jet or γ



Require experimental separation of Collins and Sivers contributions

Transverse Single-Spin Asymmetries

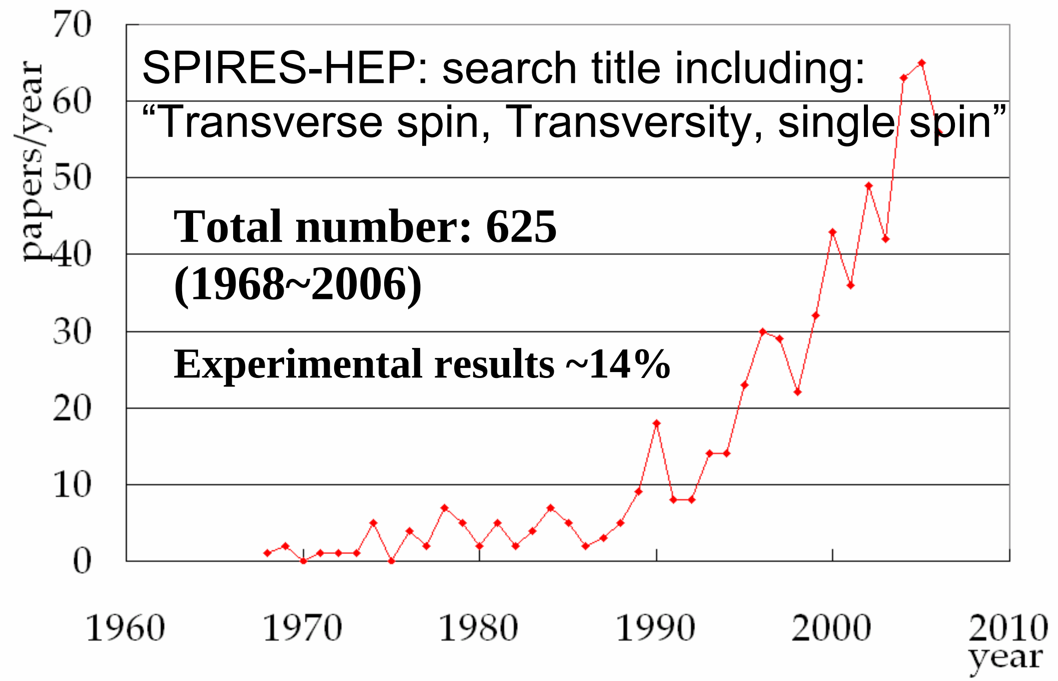
World-wide experimental and theoretical efforts

- Transverse single-spin asymmetries are observed in semi-inclusive deep inelastic scattering with transversely polarized proton targets

  $\Rightarrow$ HERMES (e); COMPASS (μ); and planned at JLab

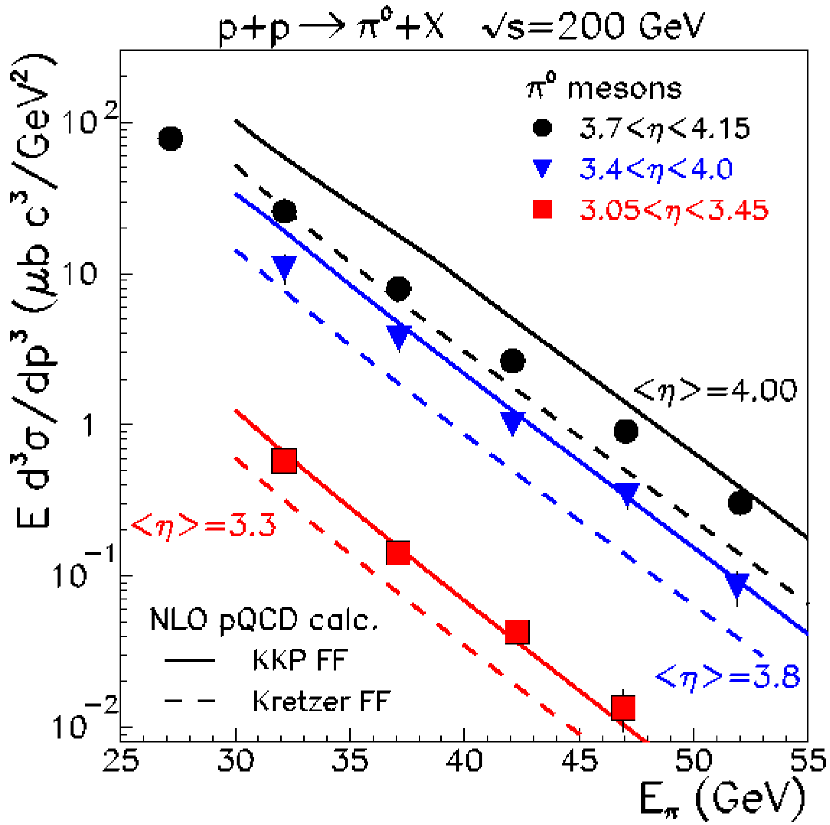
- Collins fragmentation function is observed in hadron-pair production in e^+e^- collisions (BELLE)

- Intense theory activity underway

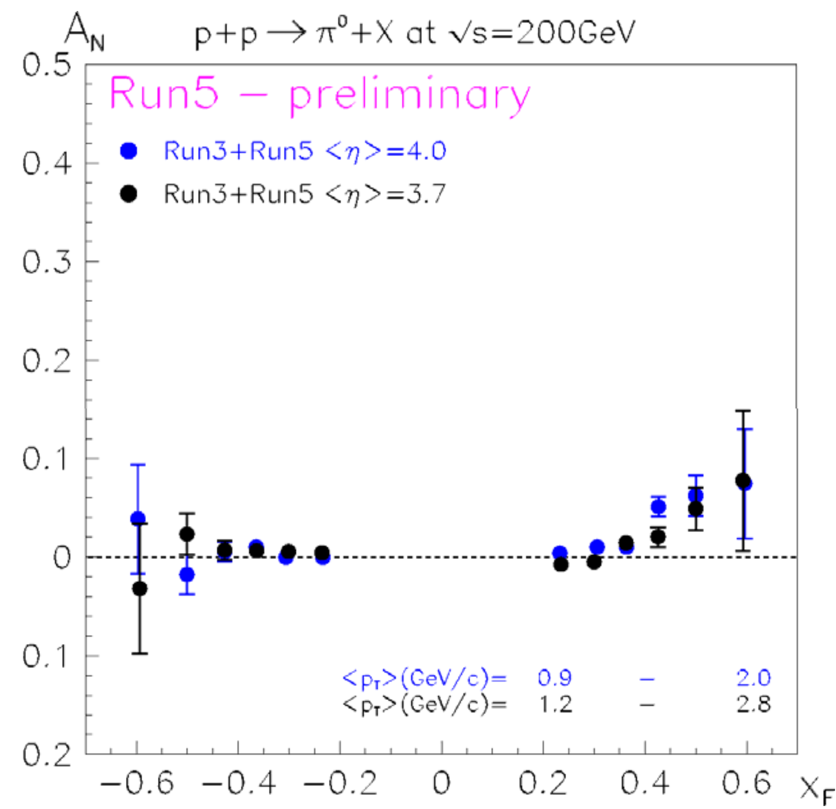


Spin Effects in the Forward Direction

Status prior to RHIC run 6



J. Adams *et al.* (STAR), PRL **92** (2004) 171801; and PRL **97** (2006) 152302



D. Morozov, for STAR [hep-ex/0512013]

⇒ Transverse SSA persist at large x_F at RHIC energies where unpolarized cross sections are calculable

STAR Results vs. Di-Jet Pseudorapidity Sum

Run-6 Result

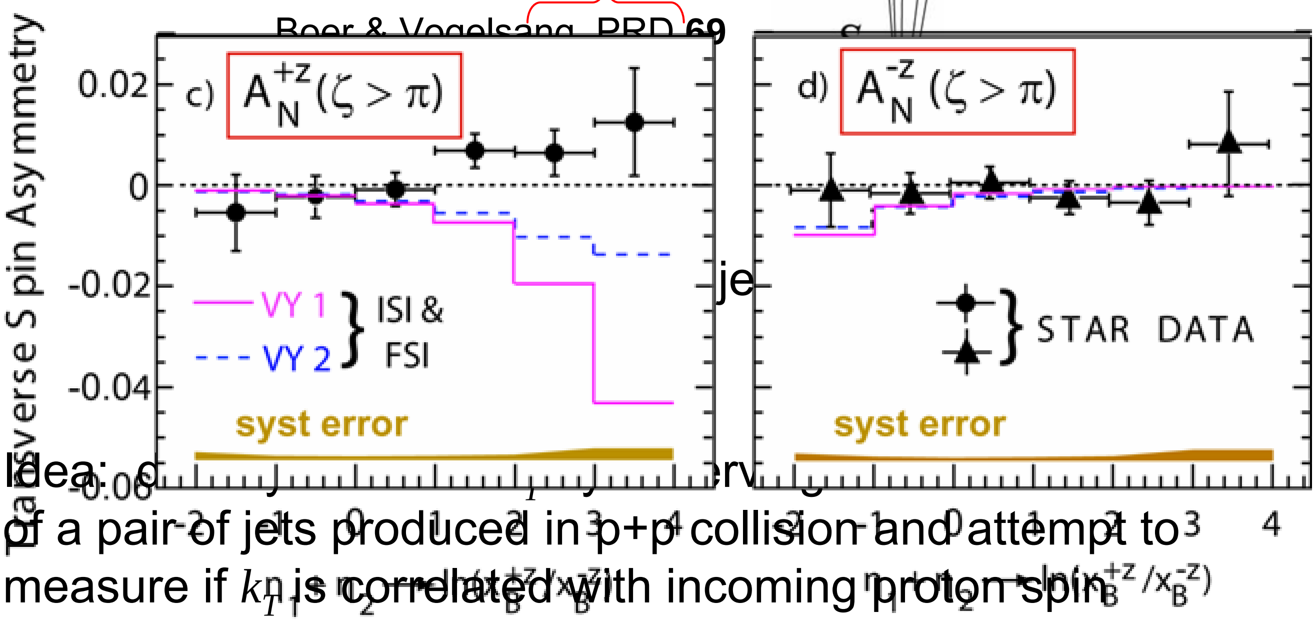
VY 1, VY 2 are calculations by
Vogelsang & Yuan, PRD **72** (2005) 054028

$$A_N \propto p_{beam} \bullet (k_T \times S_T)$$

Emphasizes (50%+) **quark** Sivers

jet

Boer & Vogelsang, PRD **69**



Idea: d... of a pair of jets produced in p+p collision and attempt to measure if k_T is correlated with incoming proton spin

A_N consistent with zero

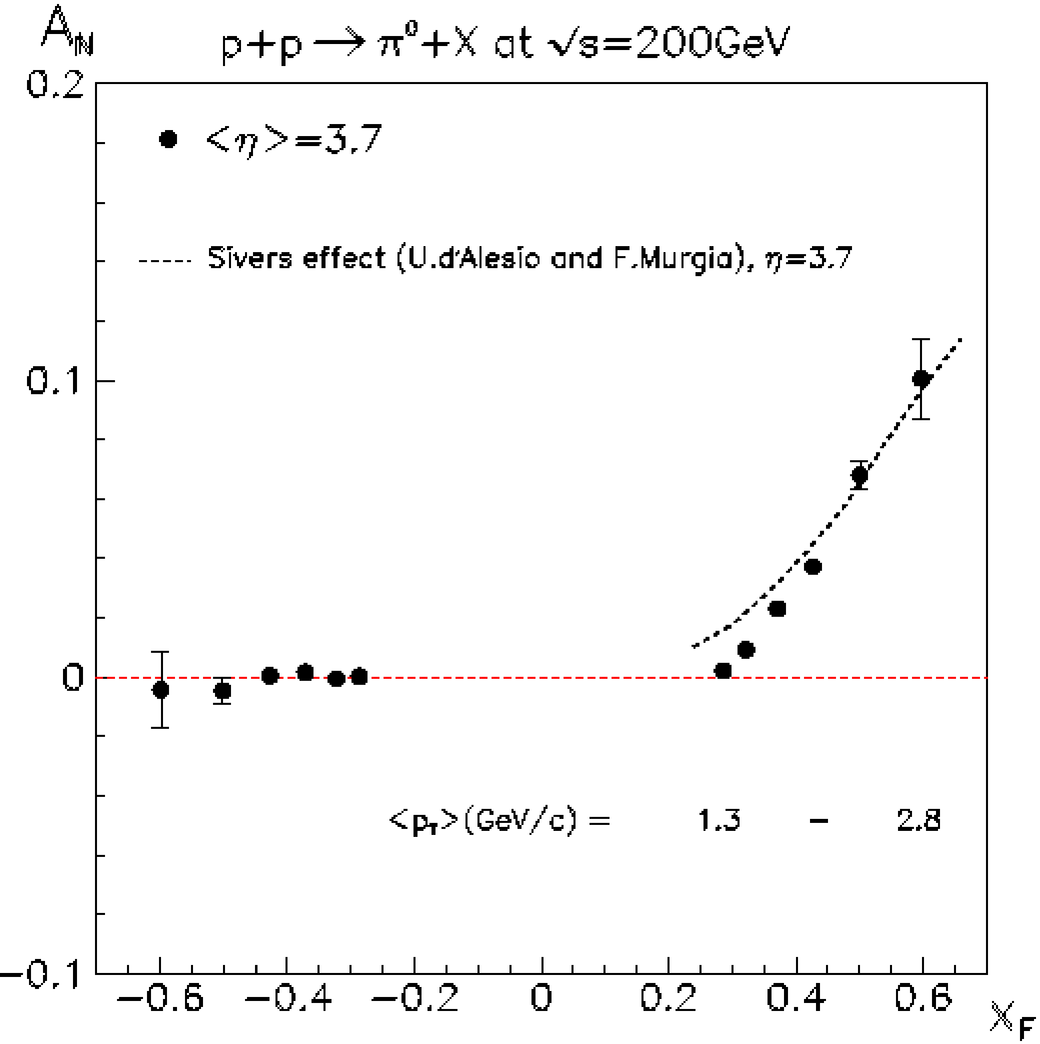
⇒~order of magnitude smaller in pp → di-jets than in semi-inclusive DIS quark Sivers asymmetry!

arXiv:0705.4629v1, submitted to PRL

STAR

π^0 A_N at $\sqrt{s}$=200 GeV – x_F-dependence

Run 6 result



- A_N at positive x_F grows with increasing x_F
- A_N at negative x_F is consistent with zero
- Run 6 data at <η>=3.7 are consistent with the existing measurements and theory
- Precise data allows for quantitative comparison with theory predictions

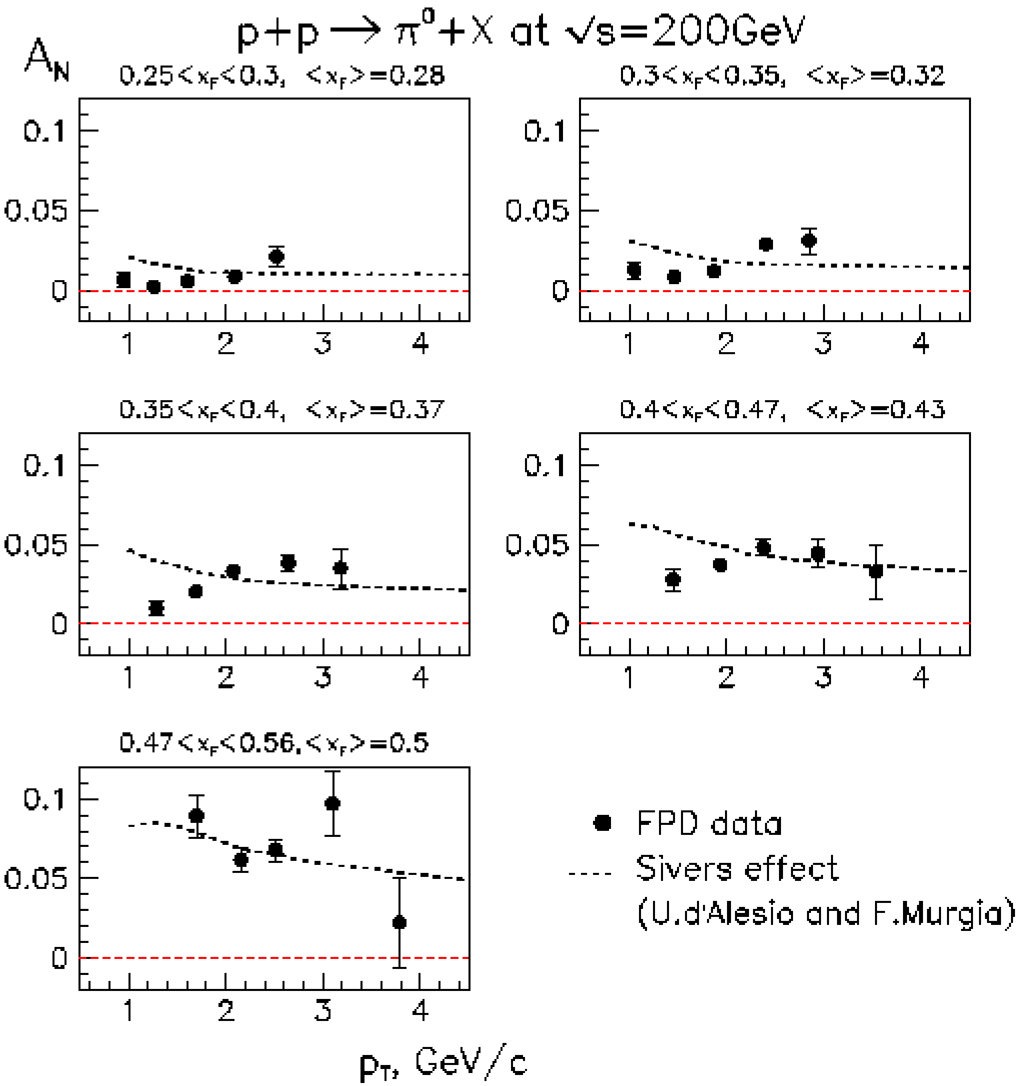
STAR

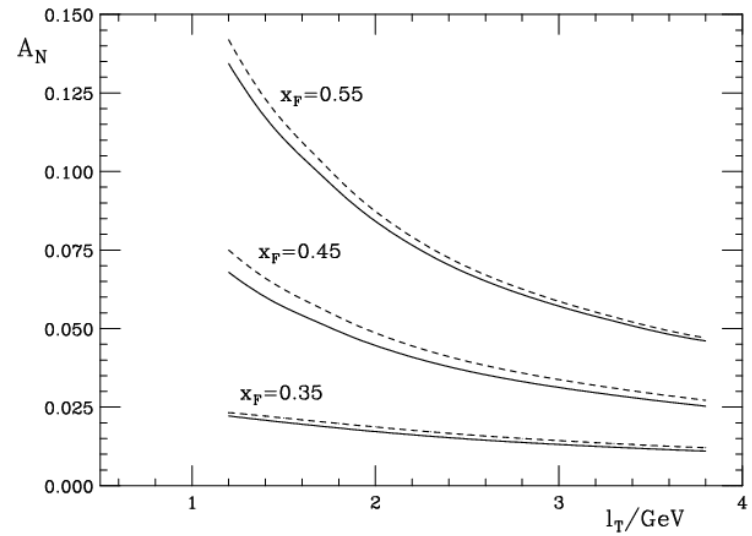
hep-ex/0612030

p_T Dependence of A_N in x_F-Bins

STAR

Run-6 Result





Theory calculations

Sivers effect - D'Alesio & Murgia PRD **70** (2004) 074009

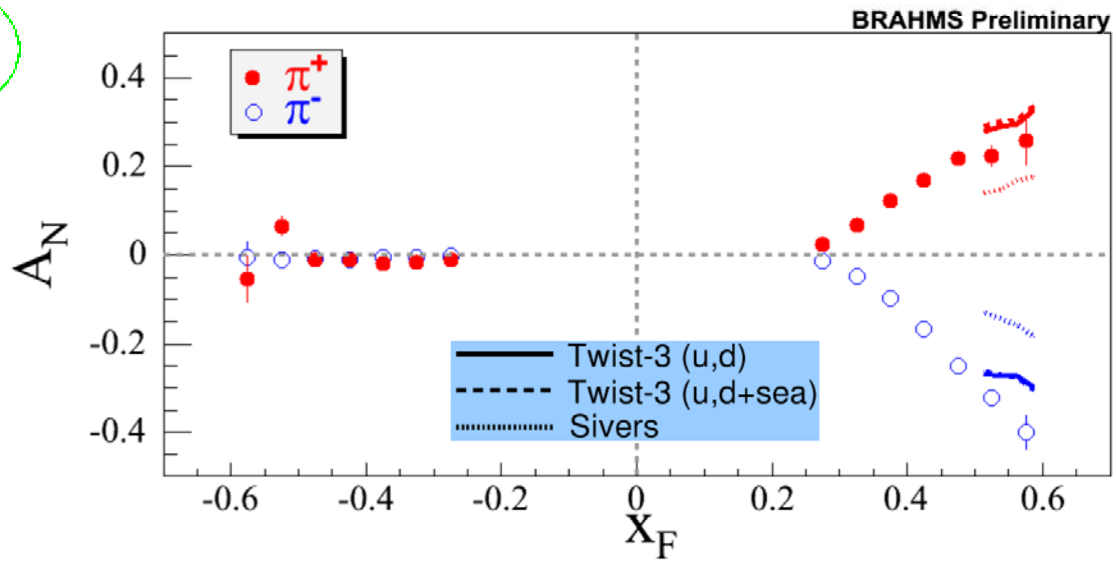
Twist-3 - Kouvaris, Qiu, Vogelsang, Yuan PRD **74** (2006) 114013

p_T dependence of data more complex than simple $1/p_T$ expectation from theory

$\Rightarrow$ Additional challenge to theory

SSA of $\pi^{\pm}$ at $\sqrt{s} = 62.4$ GeV

BRAHMS

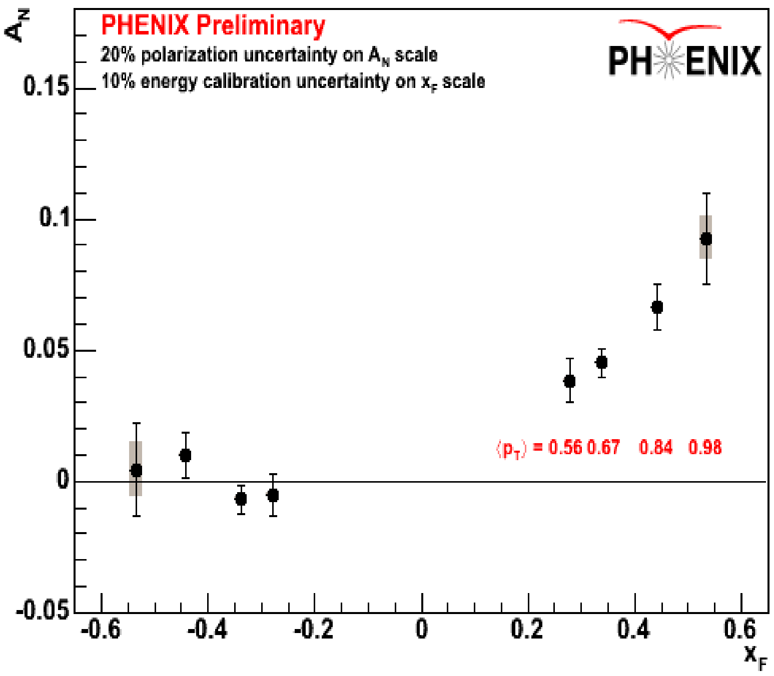


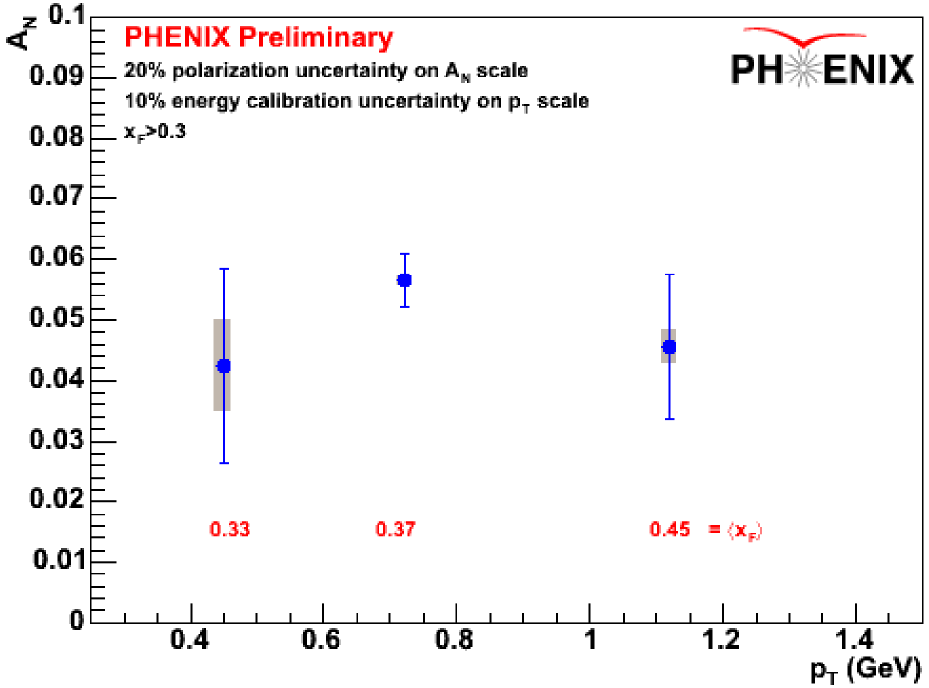
- Large $A_N(\pi^-)$: 40% at $x_F \sim 0.6$, $p_T \sim 1.3$ GeV$/c$, $A_N(-x_F) \sim 0$.
- Strong x_F-dependence
- $|A_N(\pi^+)/A_N(\pi^-)|$ decreases with x_F
- Sivers and Twist-3 calculations are compared with the data: Twist-3 calculations are in a better agreement with data.

PHENIX Goes Forward

First results with muon piston calorimeter from run 6

$p_{\uparrow}+p \rightarrow \pi^0+X$, $\sqrt{s}$ = 62 GeV





Transverse SSA persists with similar characteristics over a broad range of collision energy (20 < $\sqrt{s}$ < 200 GeV)

Summary

Transverse Single Spin Asymmetry (SSA) Measurements

- Feynman-x dependence of large-rapidity pion production shows large transverse SSA at RHIC energies, where cross sections are described by NLO pQCD
- Feynman-x dependence of large-rapidity transverse SSA are consistent with theoretical models (Sivers effect $\Rightarrow$ orbital motion / twist-3 calculations)
- The p_T dependence of large-rapidity π^0 transverse SSA does not follow theoretical expectations
- Direct measurement of spin-correlated k_T (Sivers effect) via midrapidity di-jet spin asymmetries completed in RHIC run 6 and found consistent with zero.
- Cancellations found in theory calculations subsequent to measurements also expect small di-jet spin asymmetries at midrapidity.

Plans for Transverse Polarization Measurements

RHIC run 8 and beyond

- Experimental separation of Collins and Sivers effects via transverse single-spin asymmetry measurements for large rapidity $\pi-\pi$ production

- Extend measurements of transverse single spin asymmetries from hadron production to prompt photon production, including away-side correlations

- Develop RHIC experiments for a future measurement of transverse single spin asymmetries for Drell-Yan production of dilepton pairs

Transverse-Spin Drell-Yan Physics at RHIC

L. Bland, S.J. Brodsky, G. Bunce, M. Liu, M. Grosse-Perdekamp,
A. Ogawa, W. Vogelsang, F. Yuan

http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf

Future RHIC Spin Plans

- Measure parity violation for W± production to determine flavor dependence of quark and antiquark polarization.

- Requires completion of PHENIX muon trigger upgrade and STAR forward tracking for charge sign discrimination.