

Nucleon Spin Structure

Ernst Sichtermann - LBNL



W. Pauli

N. Bohr

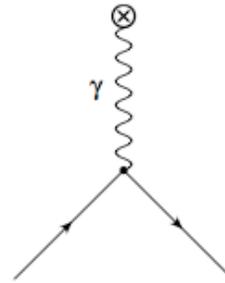


- History, Motivation, and Open Questions
- Experiments and Facilities
- Helicity Structure
 - Gluon Polarization
 - Flavor Decomposition of Quark Spins
- Transverse Spin Phenomena
 - Transversity
 - Orbital Angular Momenta
- Concluding Remarks

History - Magnetic Moment

- The magnetic moment $\vec{\mu}$ of a particle is related to its spin \vec{S} according to:

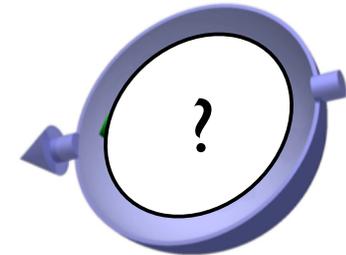
$$\vec{\mu} = g \frac{e}{2mc} \vec{S}$$



$g = 2$ for Dirac particles

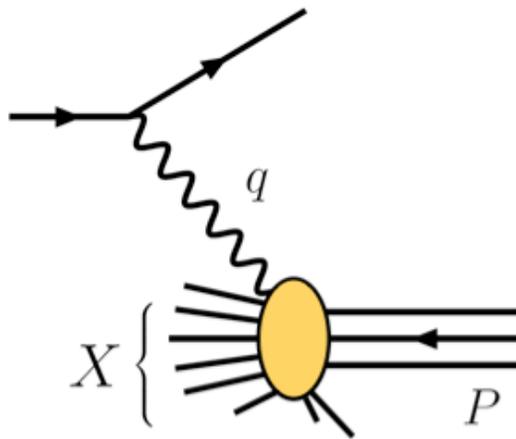
- 1933 - Frisch and Stern:

$$\vec{\mu}_p = 5.8 \frac{e}{2mc} \vec{S}_p - \textit{Proton has (spin-)substructure}$$

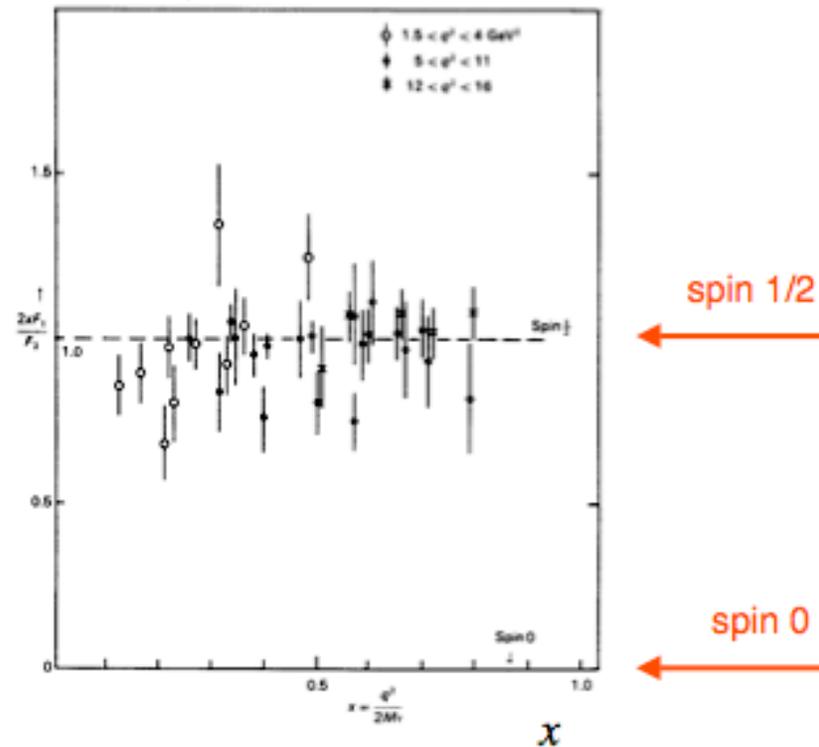


History - early DIS

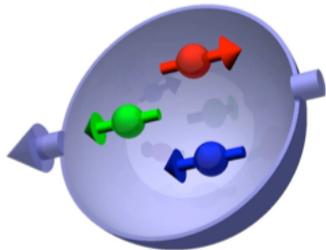
Circa 1970 - Scaling and the Callan-Gross relation:



$$\frac{2xF_1}{F_2}$$



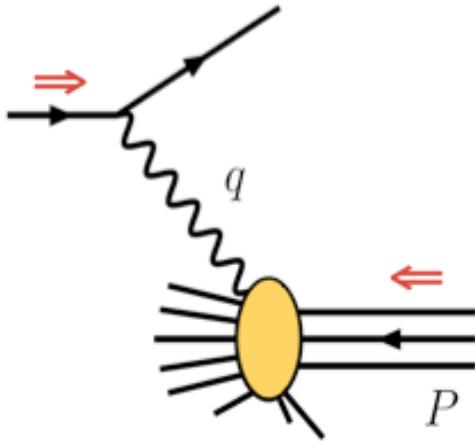
$$\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4 x} \left[xy^2 F_1(x, Q^2) + (1-y) F_2(x, Q^2) \right]$$



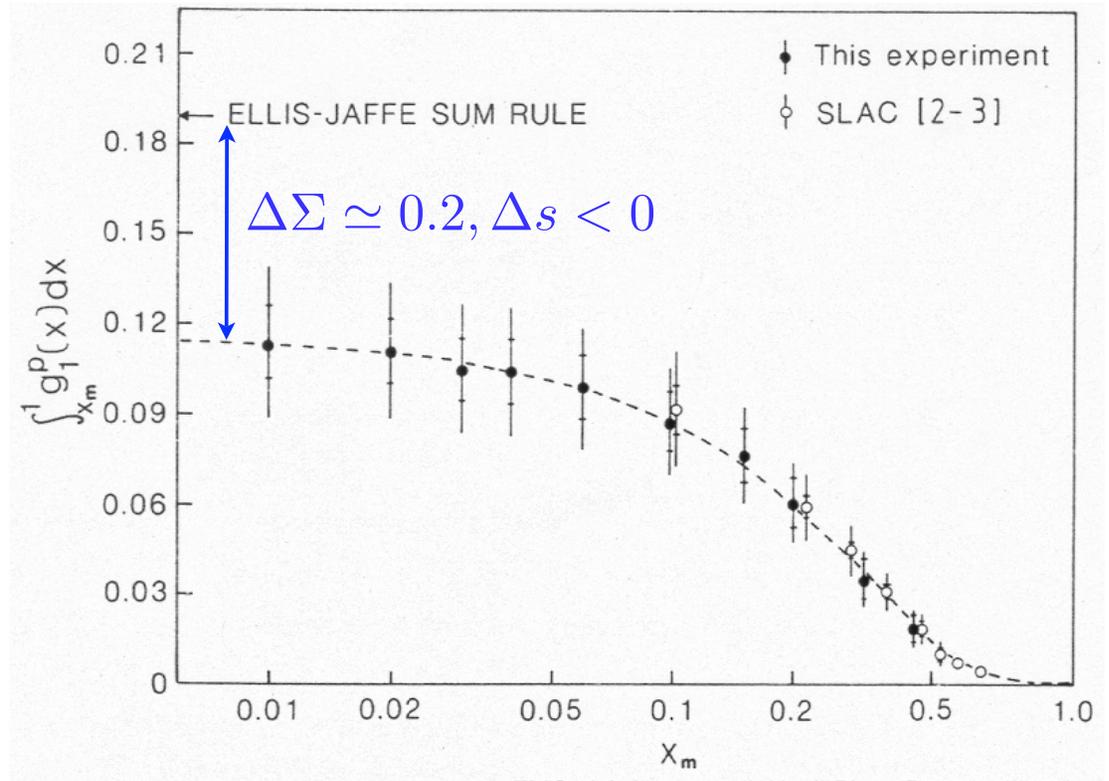
Quarks are spin-1/2

History - polarized DIS

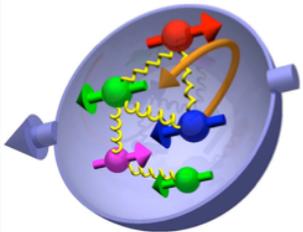
Circa 1985 - European Muon Collaboration:



$$\sigma(\Rightarrow, \Leftarrow) - \sigma(\Rightarrow, \Rightarrow) \sim g_1(x, Q^2)$$

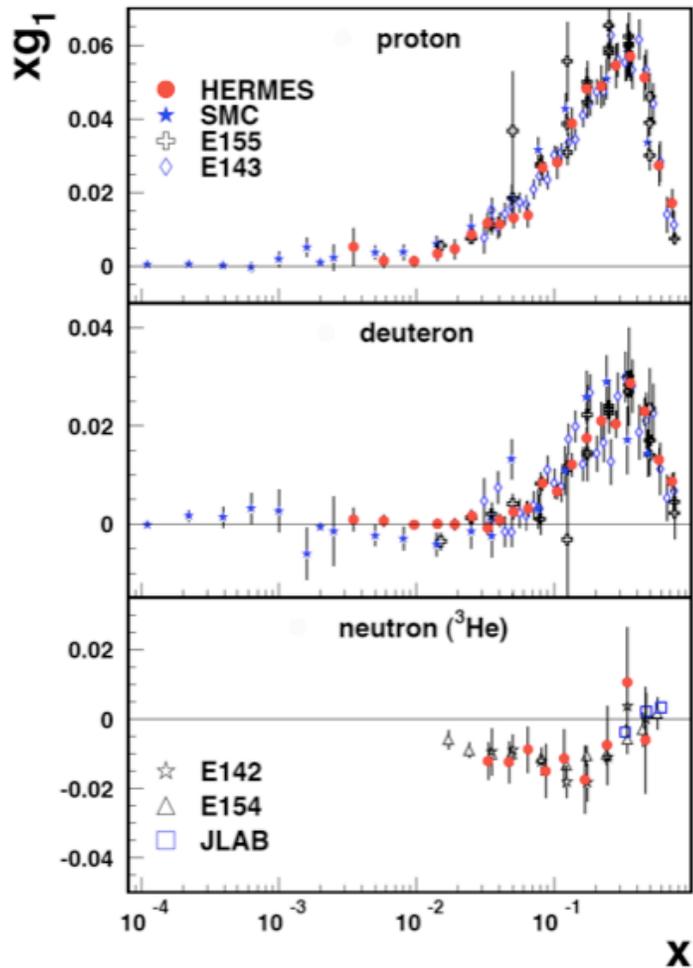


EMC: J.Ashman et al, Nucl. Phys. B328, 1 (1989)

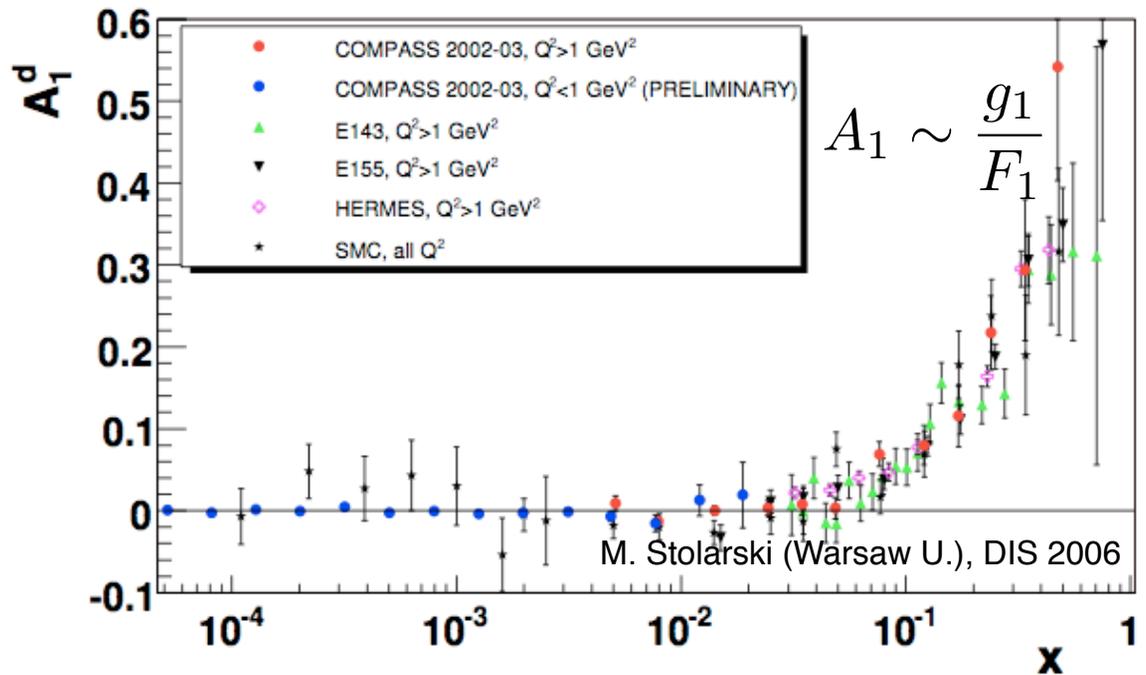


*The sum of Quark Spins contribute little to the proton spin,
Strange quarks are negatively polarized,*

Polarized DIS - Present Data

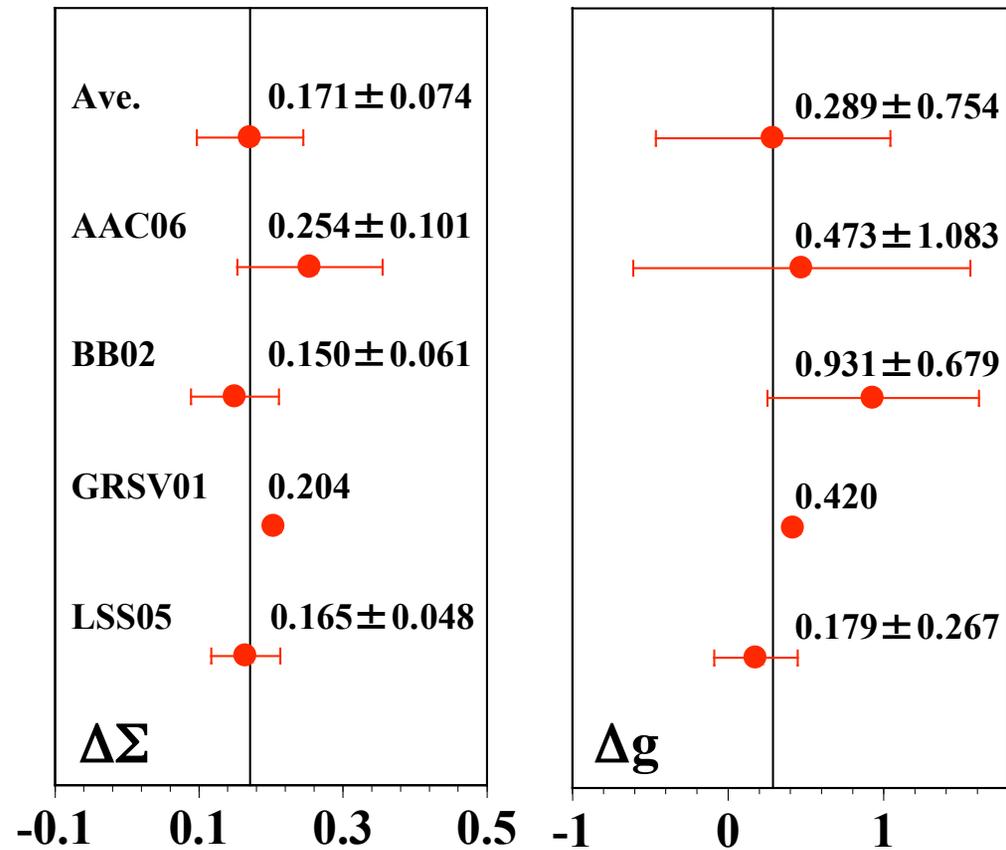
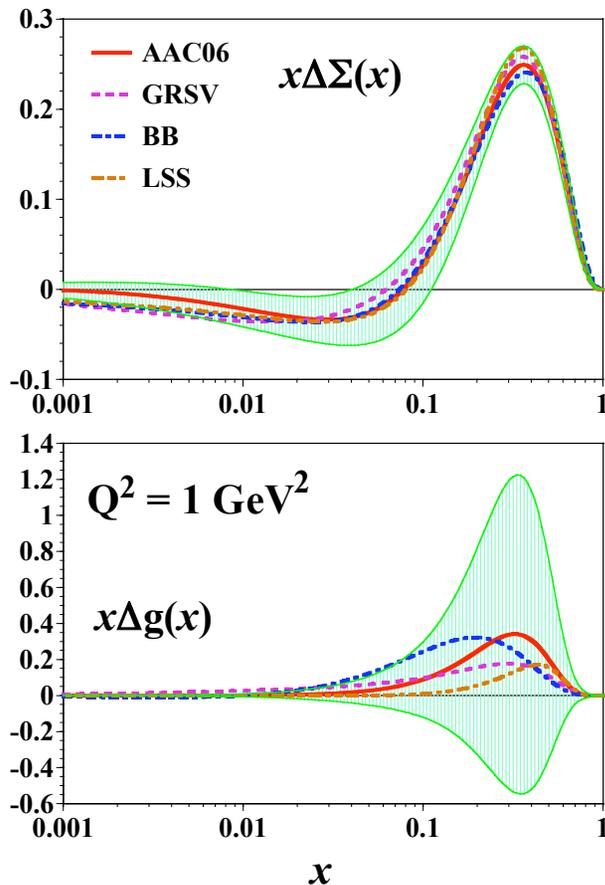


New low- Q^2 Deuteron data from COMPASS at DIS 2006:



Polarized DIS - pQCD Fits

M. Hirai (Asymmetry Analysis Collaboration), DIS 2006:

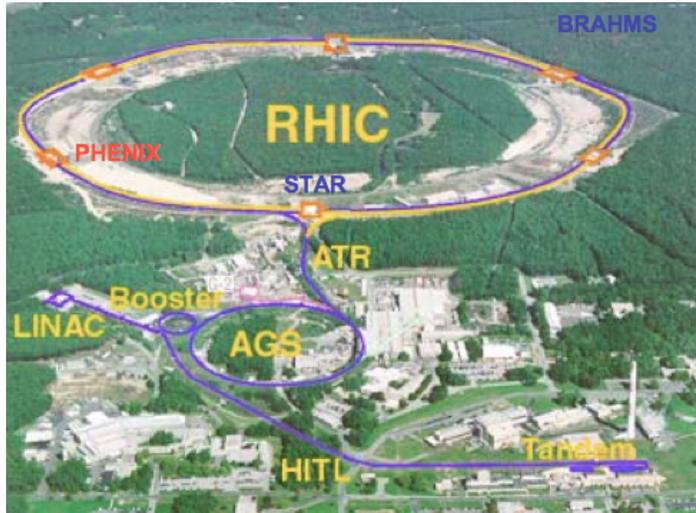


The sum of Quark Spins is well determined by inclusive polarized DIS data, and found small. The polarization of Gluons in the polarized nucleon is poorly constrained.

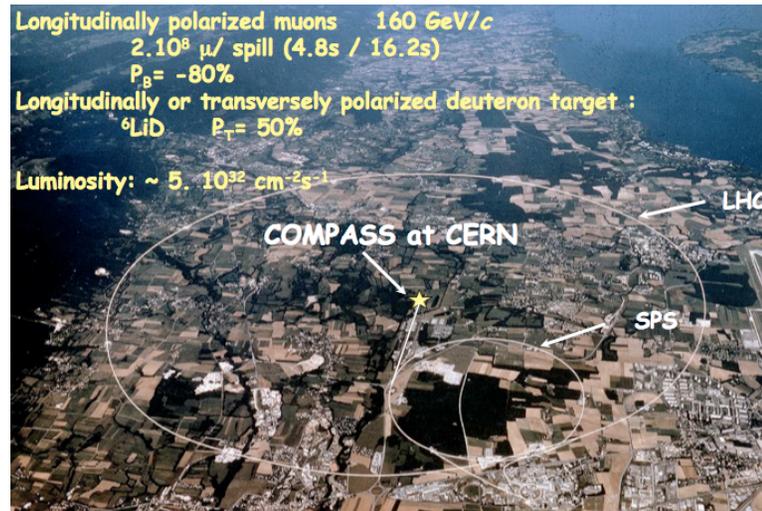
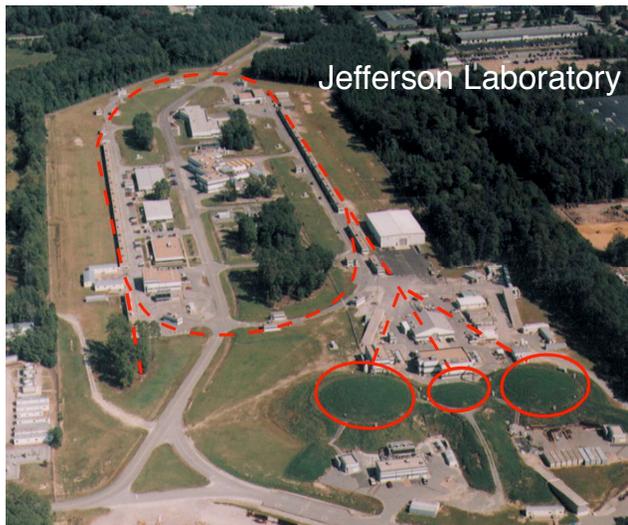
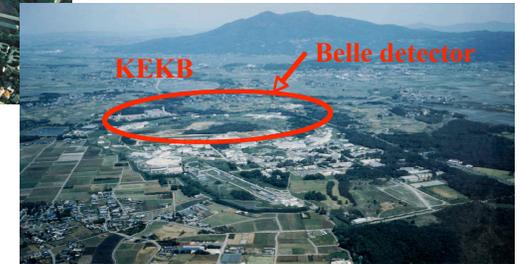
Some Open Questions

- How does gluon polarization contribute to the proton spin?
- What are the quark and anti-quark polarization by flavor?
- What orbital angular momenta do quarks and gluons carry?
- What is the role of transverse spins?

World-wide Quest

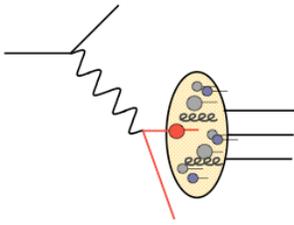


27 GeV e⁺/e⁻ beam of HERA ep collider

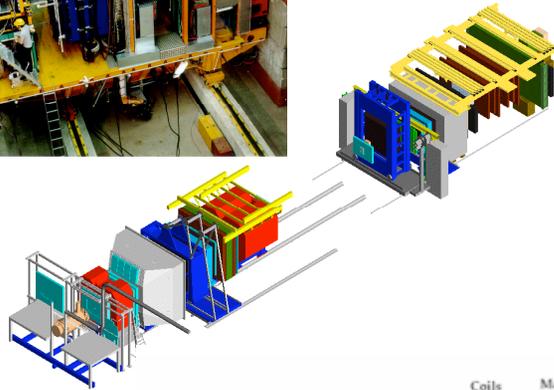


World-wide Quest

DIS

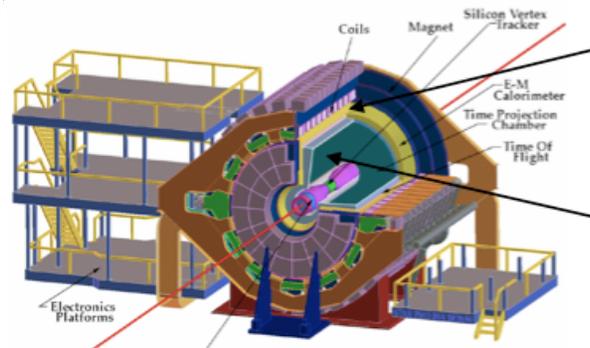
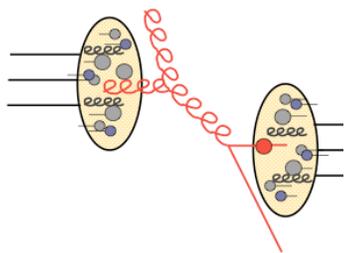


HERMES at DESY:
27 GeV electron beam,
fixed target,
PID

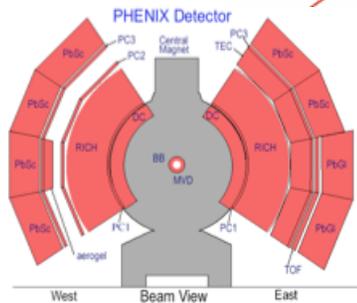


COMPASS at CERN:
160 GeV muon beam,
fixed target,
open spectrometer

pp



STAR at RHIC:
200-500 GeV E_{cms} ,
large acceptance



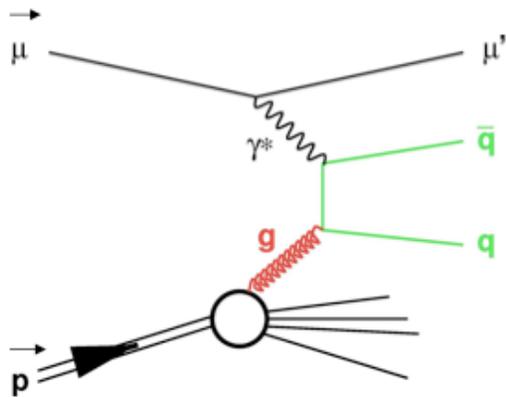
PHENIX at RHIC:
high resolution,
high rate

BRAHMS at RHIC:
spectrometer + PID

Helicity Structure

Gluon Polarization - COMPASS

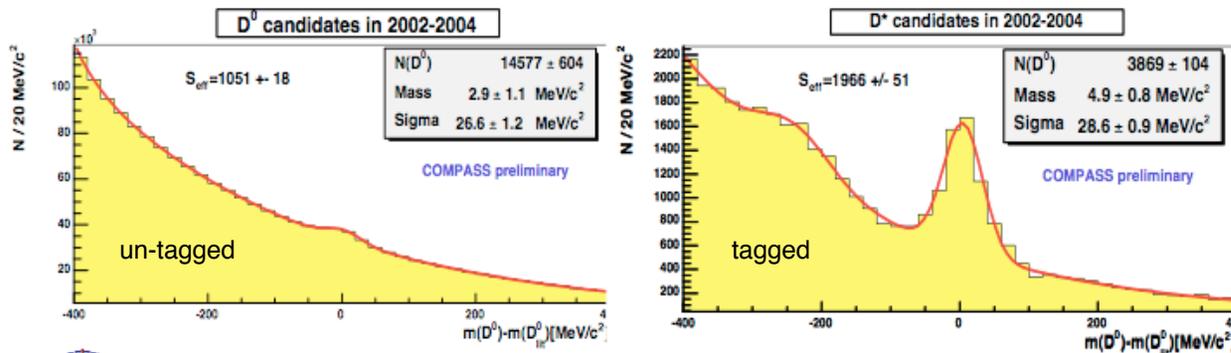
Direct sensitivity to Gluon polarization via photon-gluon fusion,



Measurements of:

- open charm, and
- high- p_T hadron pairs (high and low Q^2)

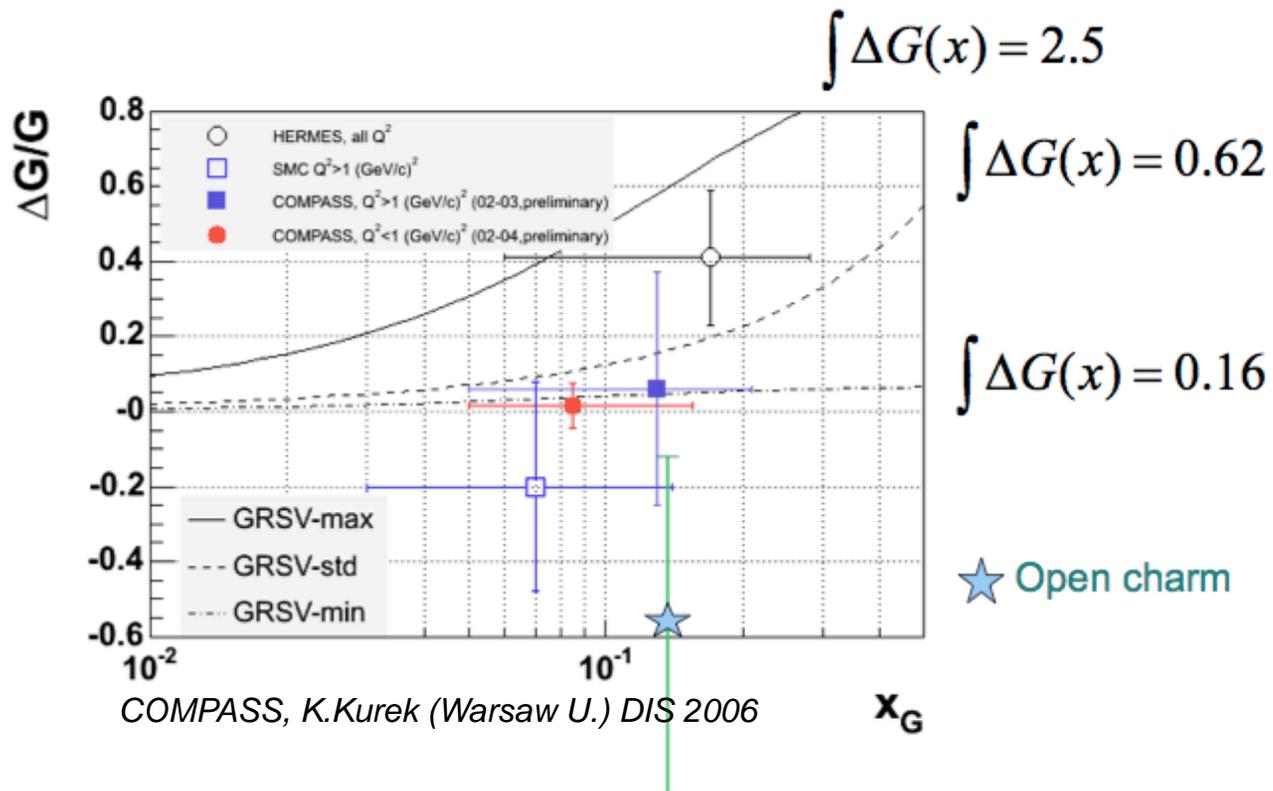
New data on open charm at DIS 2006:



$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \propto \frac{S}{S+B} \tilde{a}_{LL} \frac{\Delta G}{G}$$

and improved statistics on low Q^2 hadron pair analysis,

Glueon Polarization - COMPASS



Improbable that gluon polarization is saturated,

Prospects:

- larger statistics on high- Q^2 hadron pair analysis from 2004,
- increased acceptance from upgraded target magnet, RHIC, and ECAL for 2006.

Gluon Polarization - STAR

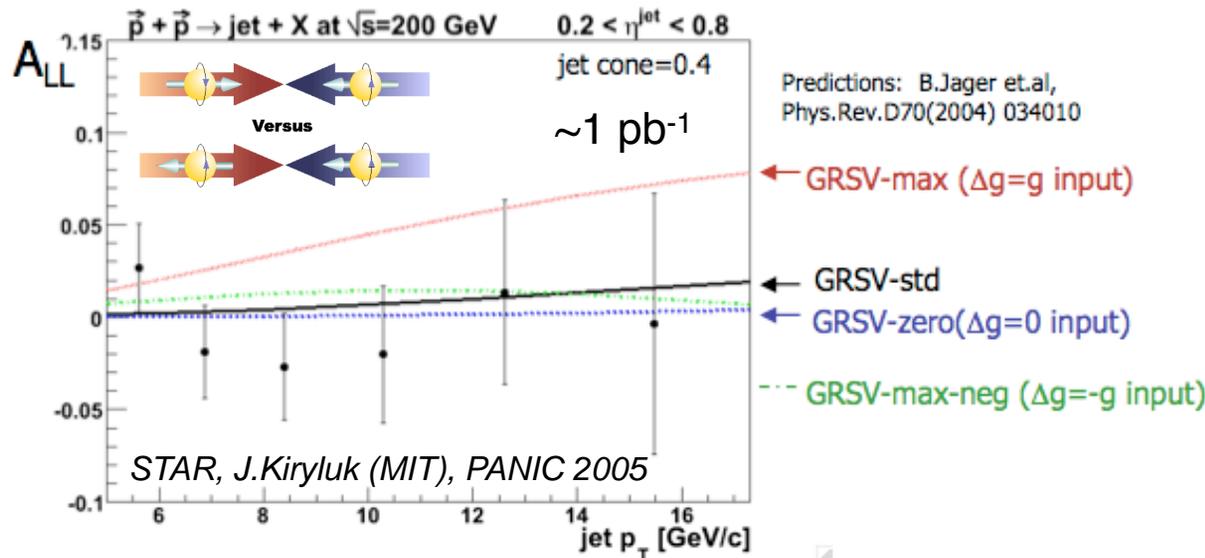
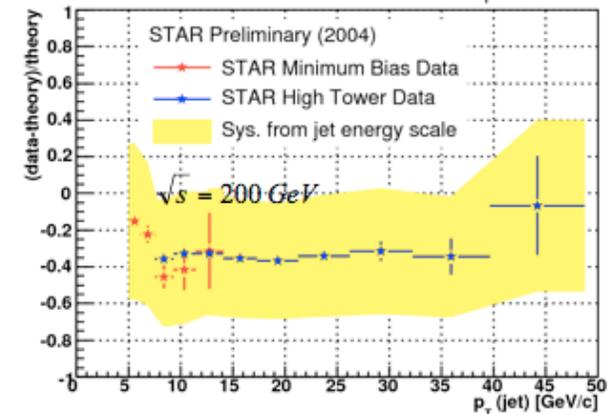
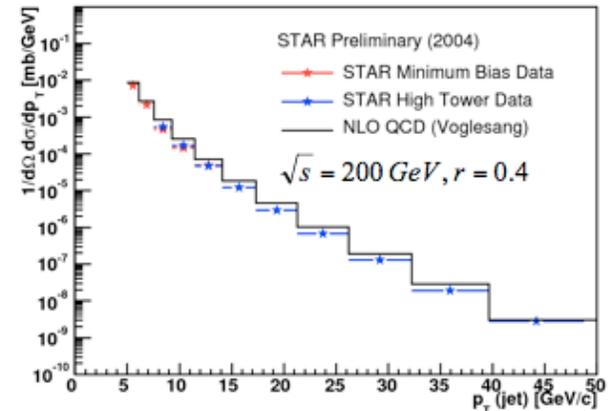
STAR, M. Miller (MIT) PANIC 2005

Direct sensitivity to gluon polarization via inclusive jets,

$$\vec{p} + \vec{p} \rightarrow \text{jet}(s) + X$$

$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \propto$$

Unpolarized cross-section well described by NLO pQCD:



Consistent with DIS,

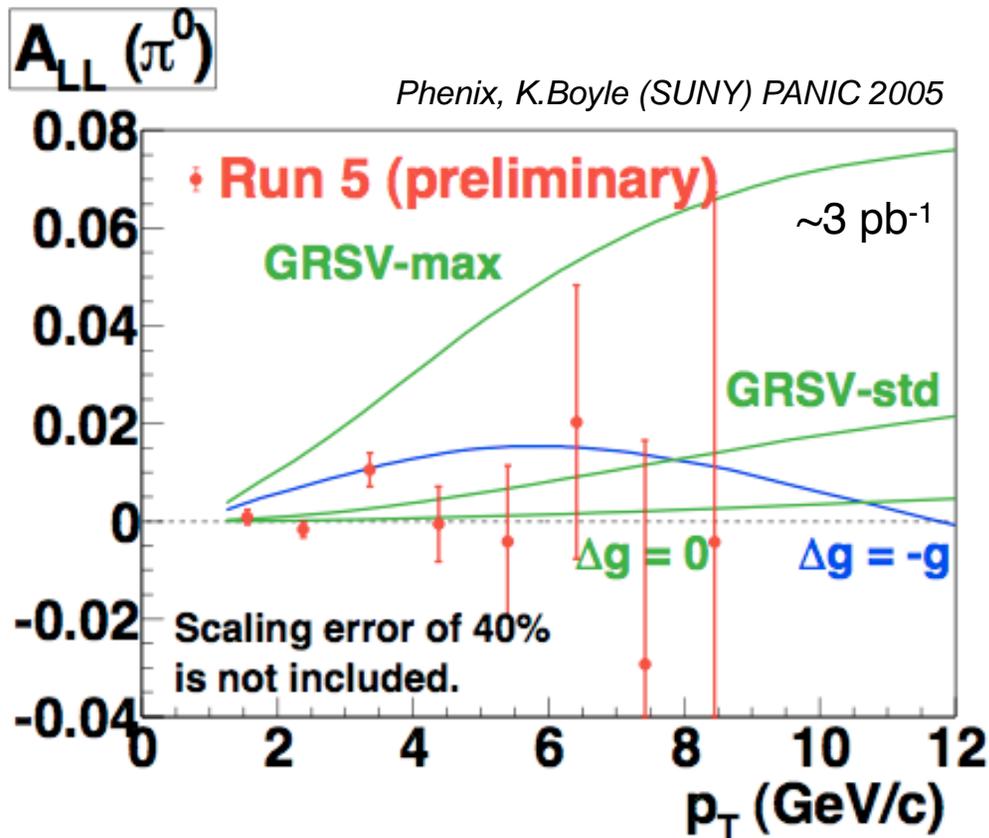
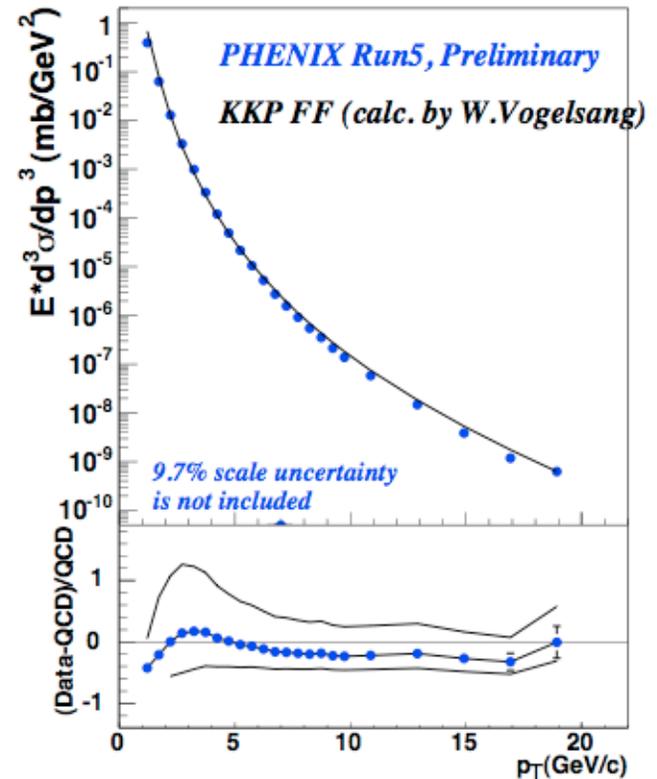
Saturated gluon polarization is improbable.

Gluon Polarization - Phenix

Inclusive neutral pions give sensitivity to gluons,

Unpolarized cross-section is well described with NLO pQCD over 8 orders of magnitude.

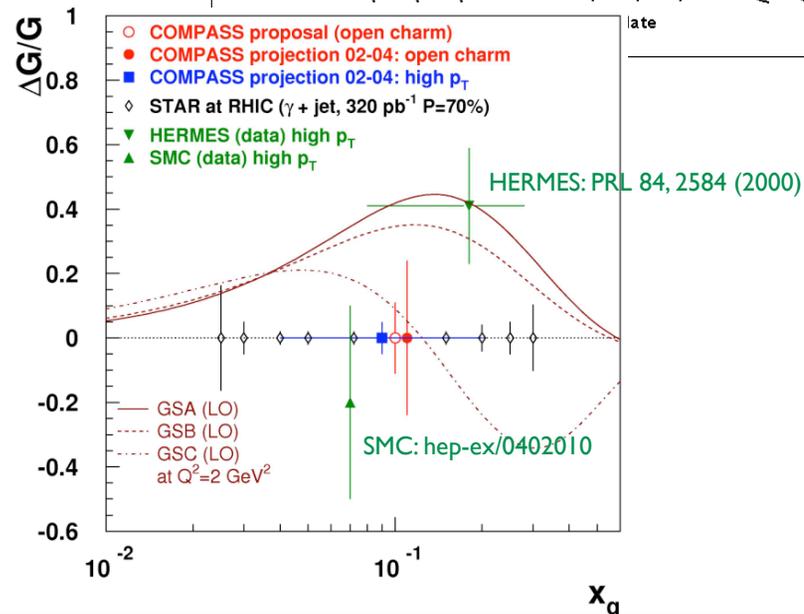
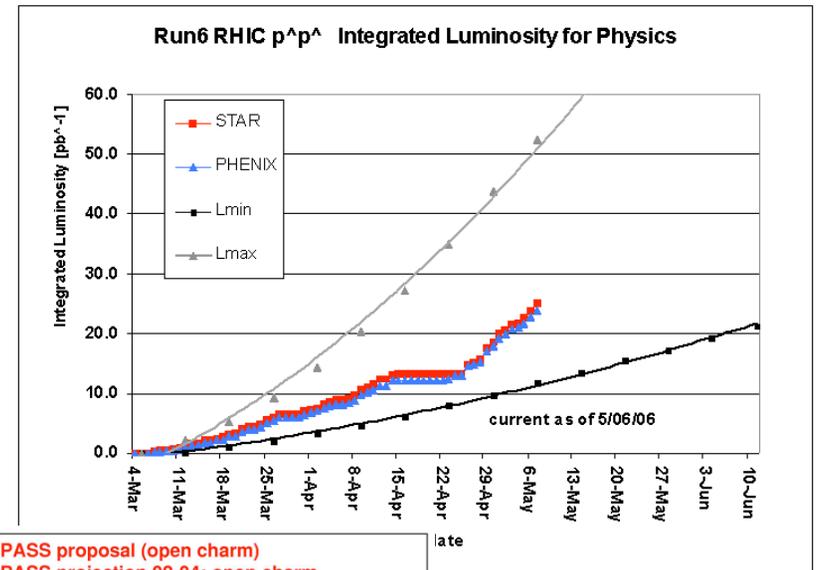
Phenix, Y.Fukao (RIKEN), DIS 2006



GRSV-Max conclusively excluded.

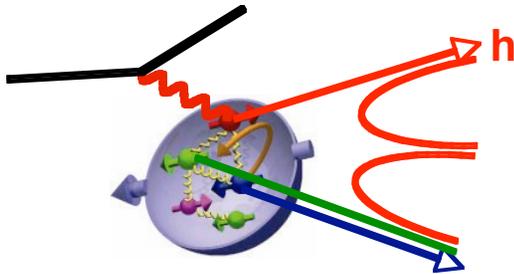
Gluon Polarization - Prospects at RHIC

- run-5 was the *first spin-physics* run at RHIC, $\sim 3 \text{ pb}^{-1}$ sampled at Phenix and STAR
- run-6 is ongoing,
- look forward to:
 - factors in statistics,
 - start of di-jet analysis (STAR),
 - selective channels, e.g. prompt photon
- multi-year goal:
 - $\sim 10^2 \text{ pb}^{-1}$ at E_{cms} 200 and 500 GeV,
 - precise measurements with resolved x_g



Quark Polarization - Semi-Inclusive DIS

Quark-flavor decomposition via fragmentation,

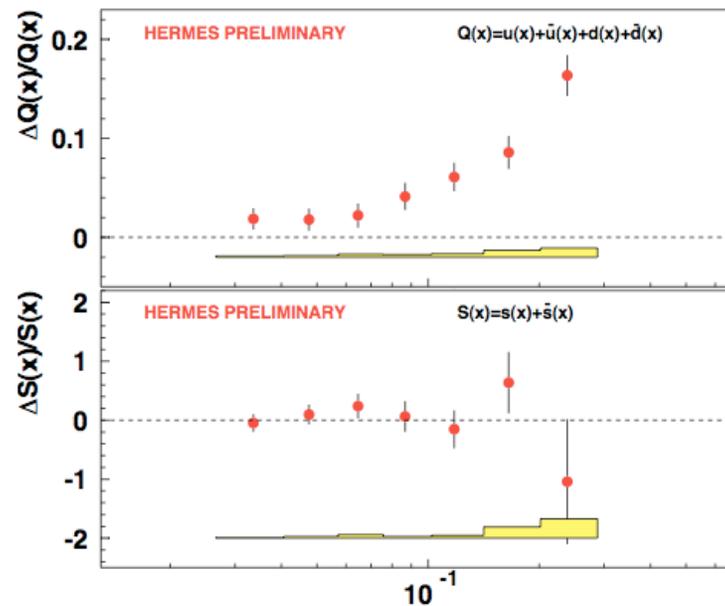


EMC and SMC measured charged hadron asymmetries. HERMES measures *identified* hadron asymmetries.

New Kaon data from HERMES on an iso-scalar target;

No evidence for negative strange quark polarization,

Imminent SIDIS data from:
Compass,
Class,
JLAB E04-113 (~2008)



non-strange quark polarization

$$\int_{0.02}^1 \Delta Q = 0.286 \pm 0.026 \pm 0.011$$

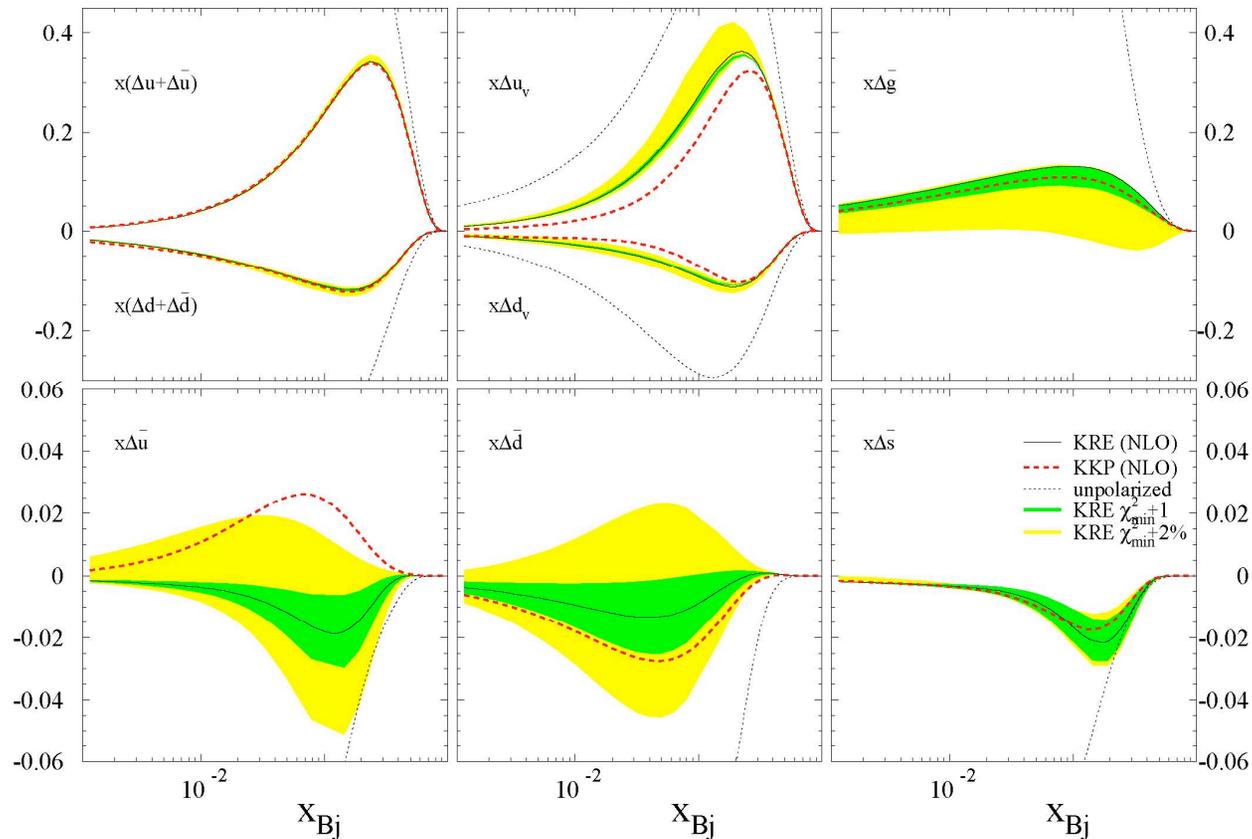
strange quark polarization

$$\int_{0.02}^1 \Delta S = 0.006 \pm 0.029 \pm 0.007$$

HERMES: H.E.Jackson (ANL) PANIC 2005 x_{BJ}

Quark Polarization - Semi-Inclusive DIS

Semi-Inclusive DIS data has been used in pQCD fits to constrain the quark-sea,

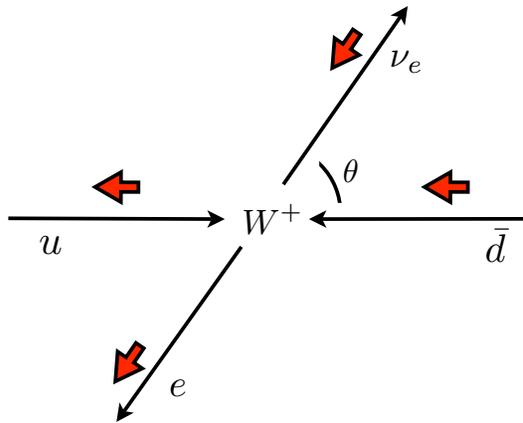


R.Sassot (Buenos Aires) et al., DIS 2006 and hep-ph/0602236

Good consistency with inclusive DIS and early gluon polarization data.
Visible uncertainty from fragmentation in some distributions.

Quark Polarization - RHIC in 2009+

Use W-bosons as polarimeters in measurements,



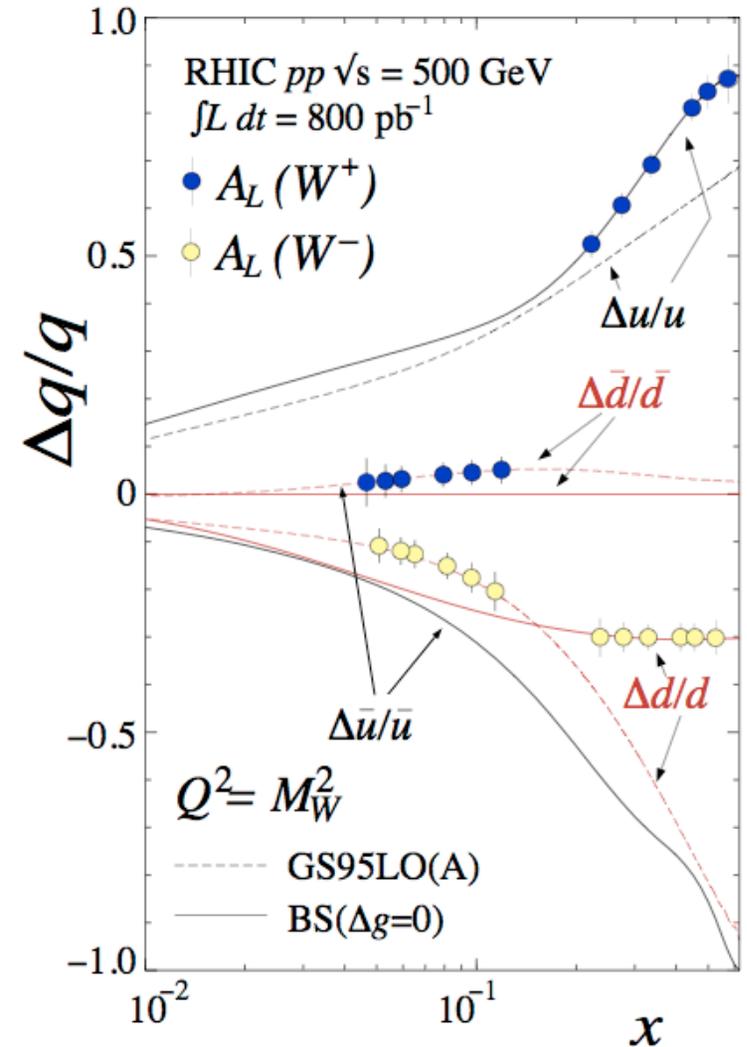
$$\Delta\sigma^{\text{Born}}(\vec{p}p \rightarrow W^+ \rightarrow e^+\nu_e) \propto -\Delta u(x_a)\bar{d}(x_b)(1+\cos\theta)^2 + \Delta\bar{d}(x_a)u(x_b)(1-\cos\theta)^2$$

with one beam polarized.

Observables:

$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\frac{\Delta u(x_a)}{u(x_a)}, & x_a \rightarrow 1 \\ \frac{\Delta\bar{d}(x_a)}{\bar{d}(x_a)}, & x_b \rightarrow 1 \end{cases}$$

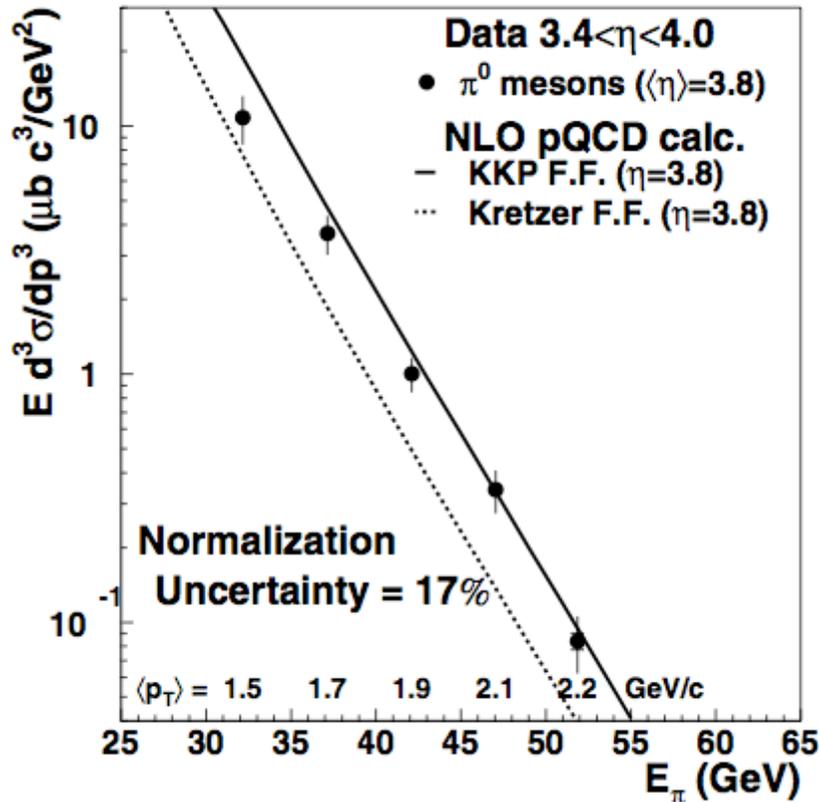
$$A_L(W^-) = \begin{cases} -\frac{\Delta d(x_a)}{d(x_a)}, & x_a \rightarrow 1 \\ \frac{\Delta\bar{u}(x_a)}{\bar{u}(x_a)}, & x_b \rightarrow 1 \end{cases}$$



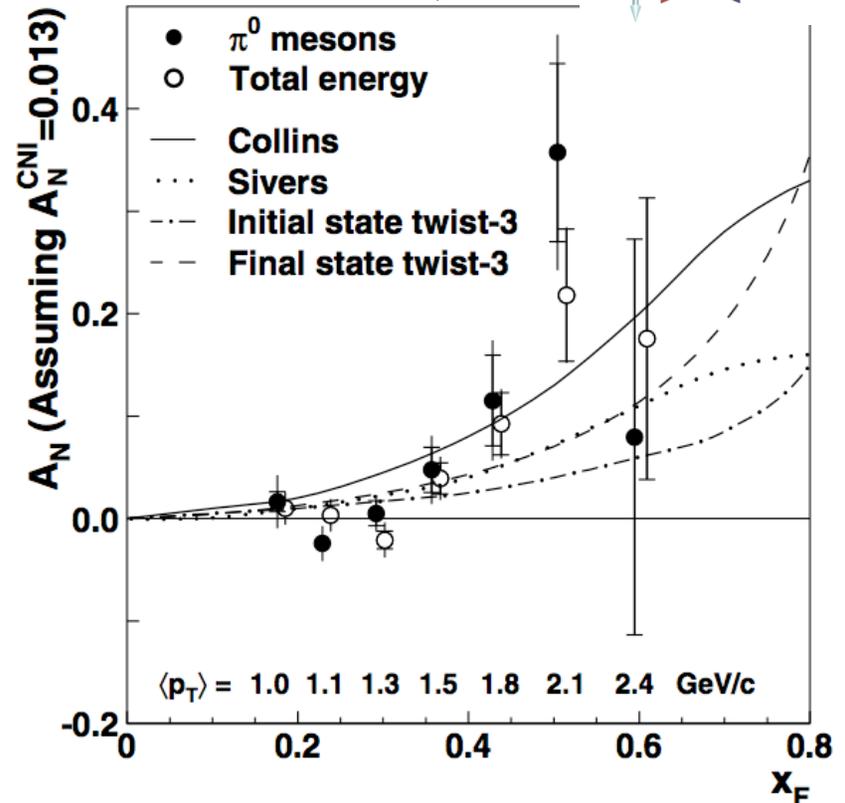
Transverse Spin Phenomena

First Spin Result from RHIC

STAR $\vec{p} + p \rightarrow \pi^0 + X, \eta \simeq 3.8 \quad 0.3 \text{ pb}^{-1}$

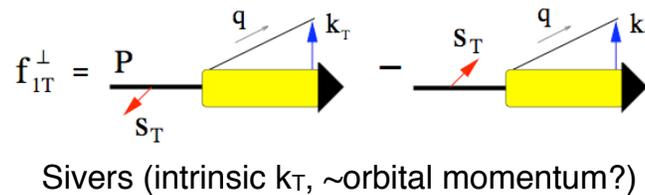
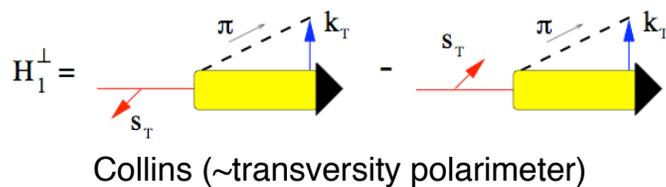


STAR $A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$



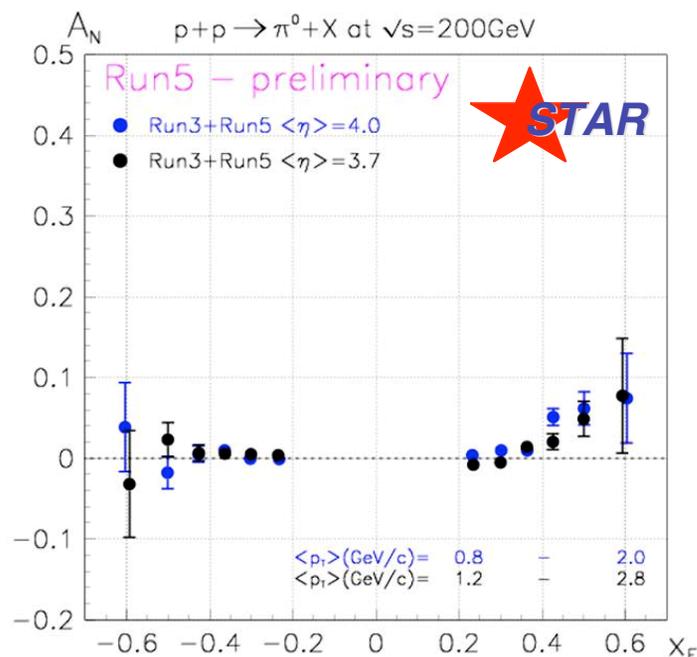
J. Adams et al, PRL 92, 171801 (2004)

Who ordered this?



Other?

New Insights from RHIC



~6 standard deviations from 0 for $x_F > 0.4$,

backwards asymmetries consistent with 0,

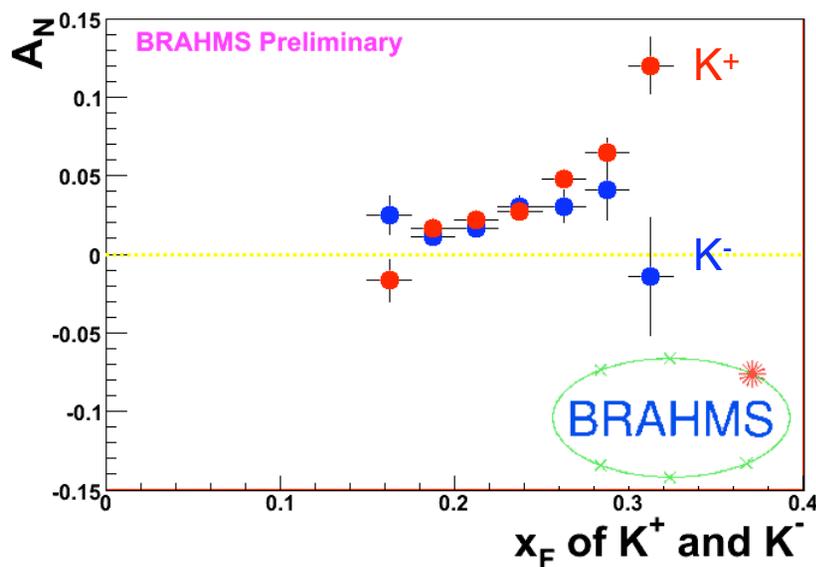
mapping x_F and p_T dependences,

staged upgrade of forward calorimeter to detect photons, and hadron-clusters,

ongoing mid-rapidity dijet measurement.

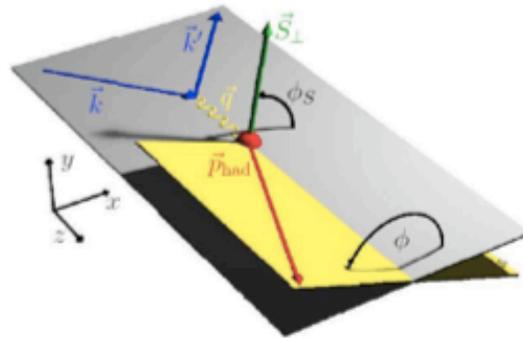
Charged pion asymmetries qualitatively agree with E704 (positive for positive pions, negative for negative pions),

significant and ~equal forward asymmetries for identified charged Kaons.



Transverse Spin - Semi-Inclusive DIS

Semi-inclusive spin measurements with an unpolarized beam and a transversely polarized target can separate the Collins and Sivers effects using angular correlations,



$$d\sigma = d\sigma_{UU}^{(0)} + \cos 2\phi d\sigma_{UU}^{(1)} + S_L \left\{ \sin 2\phi d\sigma_{UL}^{(2)} + \lambda_e d\sigma_{LL}^{(3)} \right\} + \lambda_e \cos(\phi - \phi_S) d\sigma_{LT}^{(4)}$$

$$+ S_T \left\{ \underbrace{\sin(\phi + \phi_S) d\sigma_{UT}^{(5)}}_{\text{Collins}} + \underbrace{\sin(\phi - \phi_S) d\sigma_{UT}^{(6)}}_{\text{Sivers}} + \sin(3\phi - \phi_S) d\sigma_{UT}^{(7)} + \sin \phi_S d\sigma_{UT}^{(8)} \right\}$$

$$d\sigma_{UT}^{\text{Collins}} \propto |S_T| \sin(\phi + \phi_S) \cdot \sum_q e_q^2 I \left[\frac{\vec{k}_T \cdot \hat{P}_{h\perp}}{M_h} \delta q(x, p_T^2) \otimes H_1^{\perp q}(z, k_T^2) \right]$$

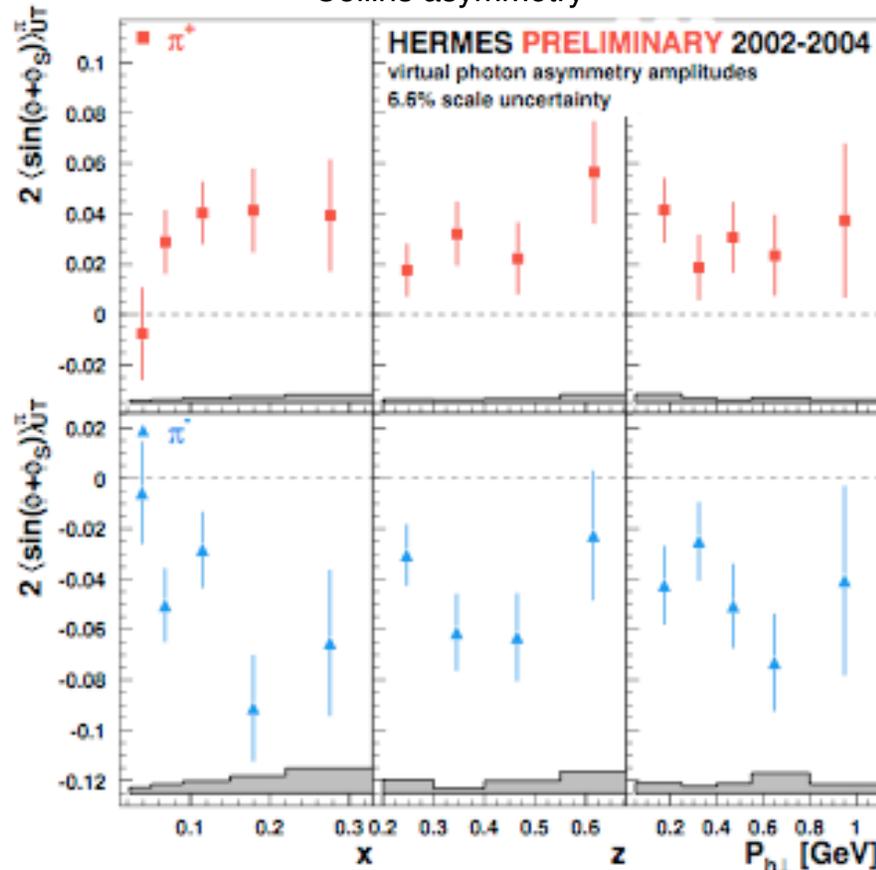
$$d\sigma_{UT}^{\text{Sivers}} \propto |S_T| \sin(\phi - \phi_S) \cdot \sum_q e_q^2 I \left[\frac{\vec{p}_T \cdot \hat{P}_{h\perp}}{M_h} f_{1T}^{\perp q}(x, p_T^2) \otimes D_1^q(z, k_T^2) \right]$$

$I[\dots]$ = convolution integral over initial (\vec{p}_T) and final (\vec{k}_T) quark transverse momenta

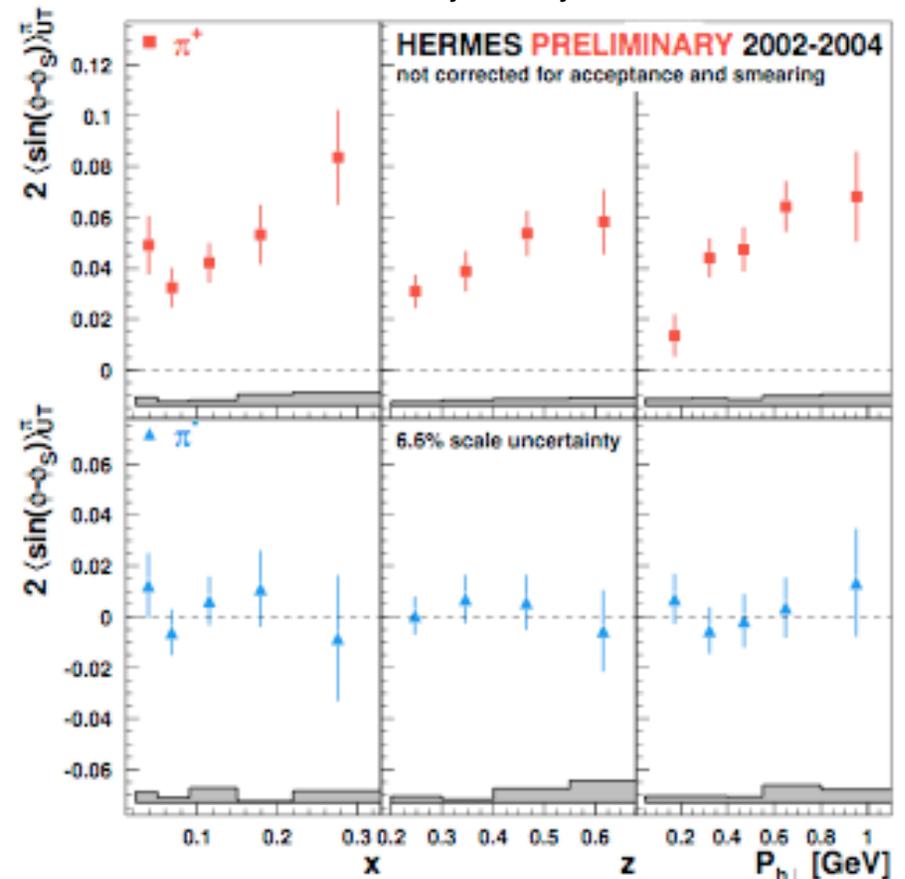
Transverse Spin - Semi-Inclusive DIS



Collins asymmetry



Sivers asymmetry

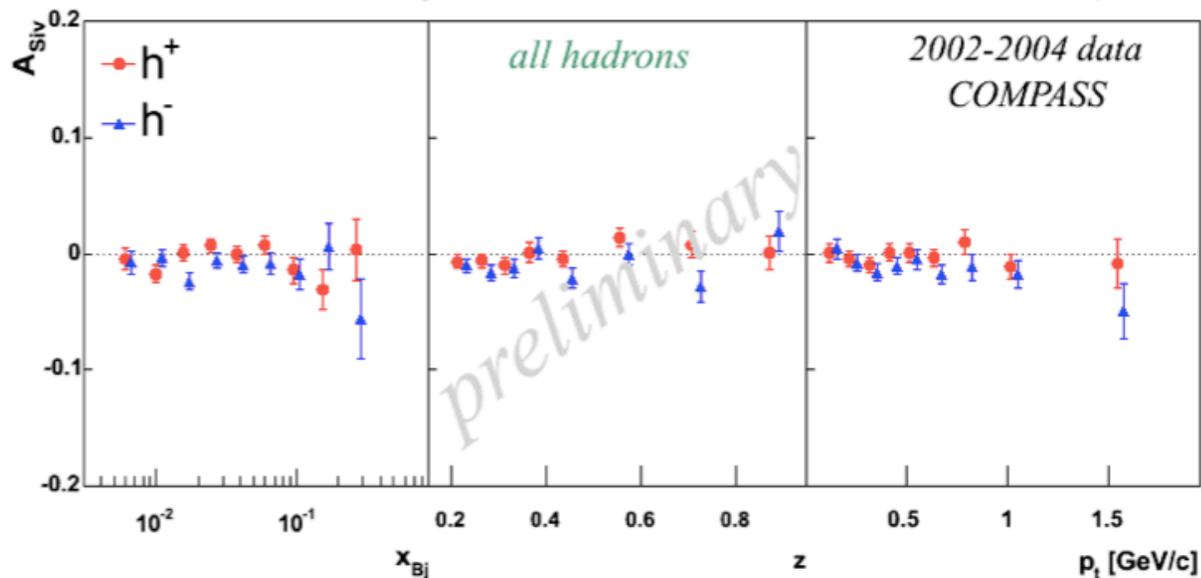
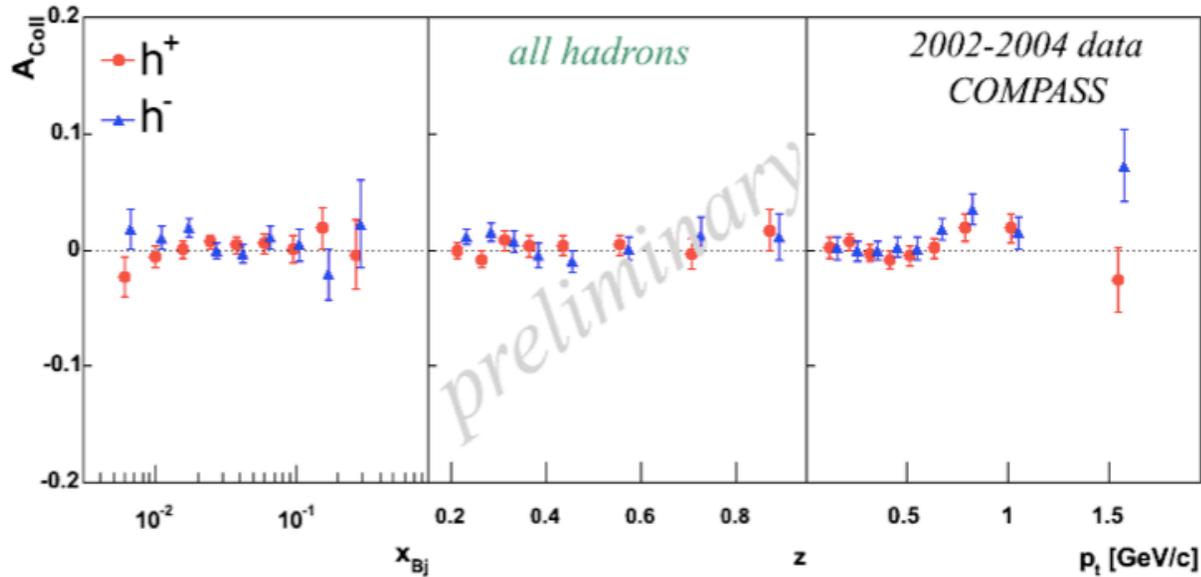


HERMES, S.Pappalardo (Ferrara U.) DIS 2006

Non-zero Collins and Sivers effects on the proton target, indicative of transversity and orbital angular momentum.

Note, BELLE has reported a non-zero Collins fragmentation function.

Transverse Spin - Semi-Inclusive DIS



Small, if any, effect,

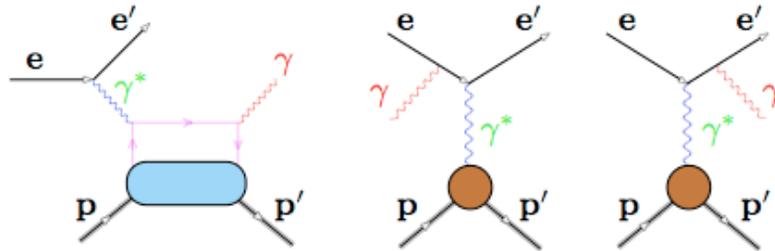
Deuteron target (p and n cancel?),

Proton measurements in 2006

First DVCS Measurements

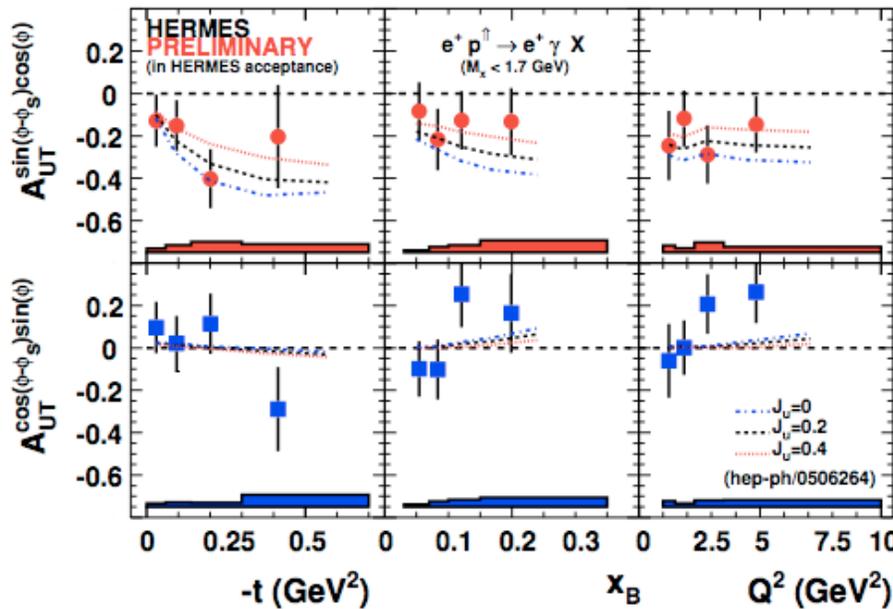
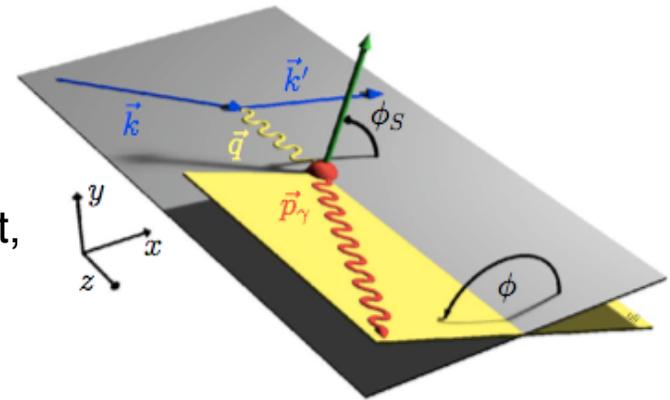


HERMES has measured the DVCS and Bethe-Heitler interference,



for an unpolarized beam and transversely polarized target,

These measurements are sensitive to J_q



Indicative of the role of Quark angular momenta in the polarized nucleon.

- ~20 years after the EMC measurement of the small Quark Spin Contribution to the polarized nucleon,
 - lots of experimental and theoretical activity in nucleon spin structure,
 - some knowns and many unknowns,
- First direct measurements of Gluon polarization are indicative of a smaller contribution than originally conjectured, and conclusive measurements are in the near future,
- Transverse spin phenomena are evolving very rapidly, both experimentally and theoretically. Striking effects observed in the hard-scattering regime.
- Stay Tuned!

Thank you!

