Spin Physics with Protons

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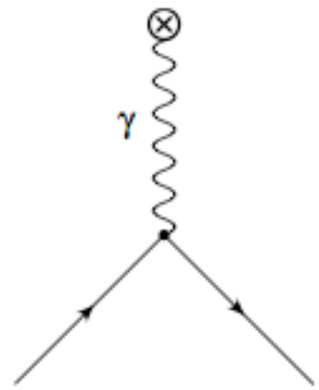
Relativistic Nuclear Collisions Program, NSD

Monday Morning Meeting
June 22, 2009

Proton Magnetic Moment - circa 1935

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

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



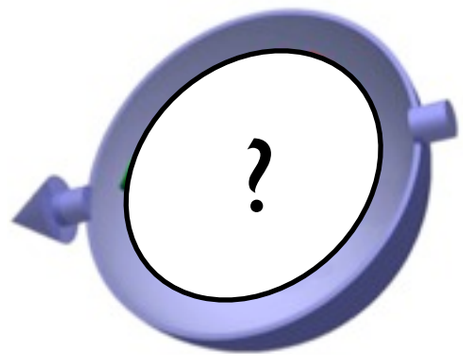
$$g = 2 + \mathcal{O}(\alpha_e)$$

for Dirac particles

- 1933 - Frisch and Stern:

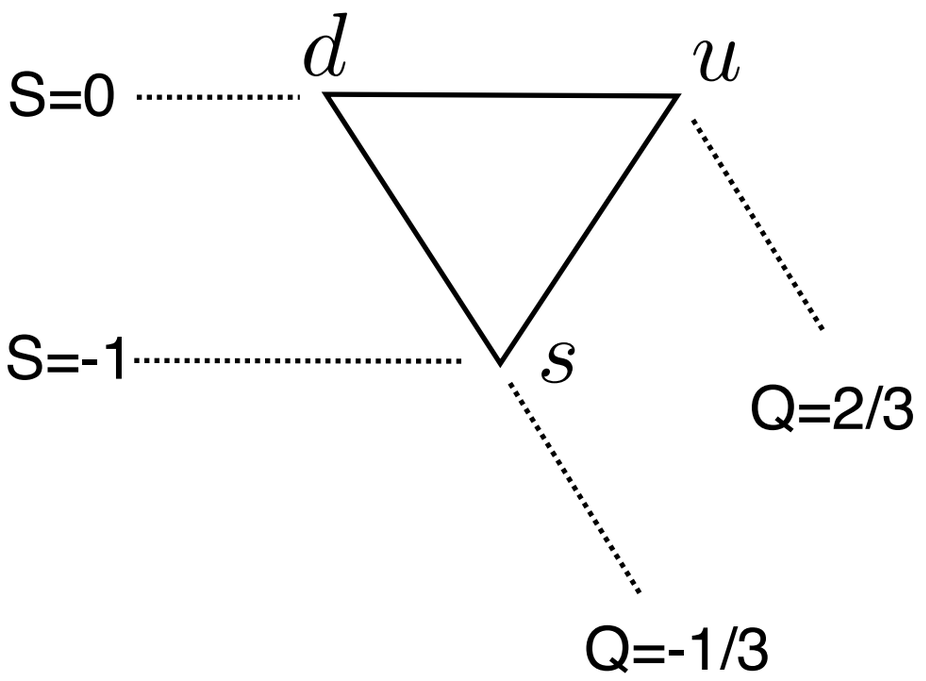
$$\vec{\mu}_p = 5.8\frac{e}{2mc}\vec{S}_p$$ - *Proton has (spin-)substructure*

But, what is it?

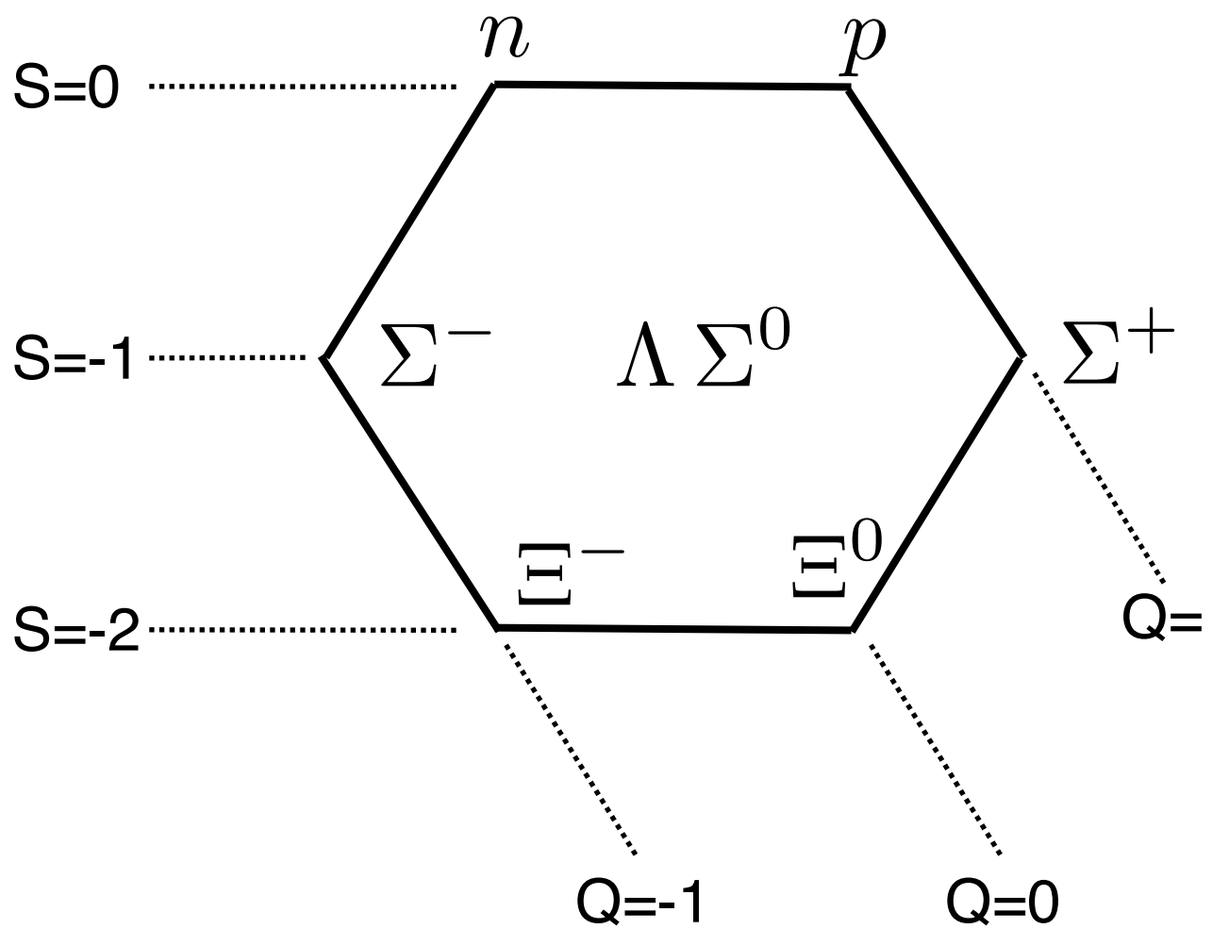


Quark-parton Structure - circa 1960

3 light Quarks



L=0, S=1/2 Baryon Octet

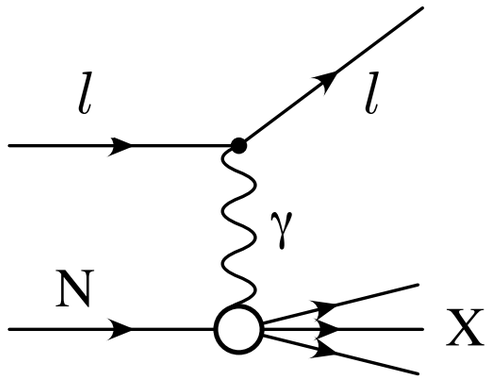


Highly successful in describing spectroscopy, *magnetic moments*, ...

$$|p:\frac{1}{2}\frac{1}{2}>=\frac{2}{3\sqrt{2}}\left(u(\uparrow)u(\uparrow)d(\downarrow)\right)-\frac{1}{3\sqrt{2}}\left(u(\uparrow)u(\downarrow)d(\uparrow)\right)-\frac{1}{3\sqrt{2}}\left(u(\downarrow)u(\uparrow)d(\uparrow)\right)\ +\ \text{permutations}$$

Deep Inelastic Scattering - circa 1970

- SLAC-MIT experiment - start of deep-inelastic scattering,

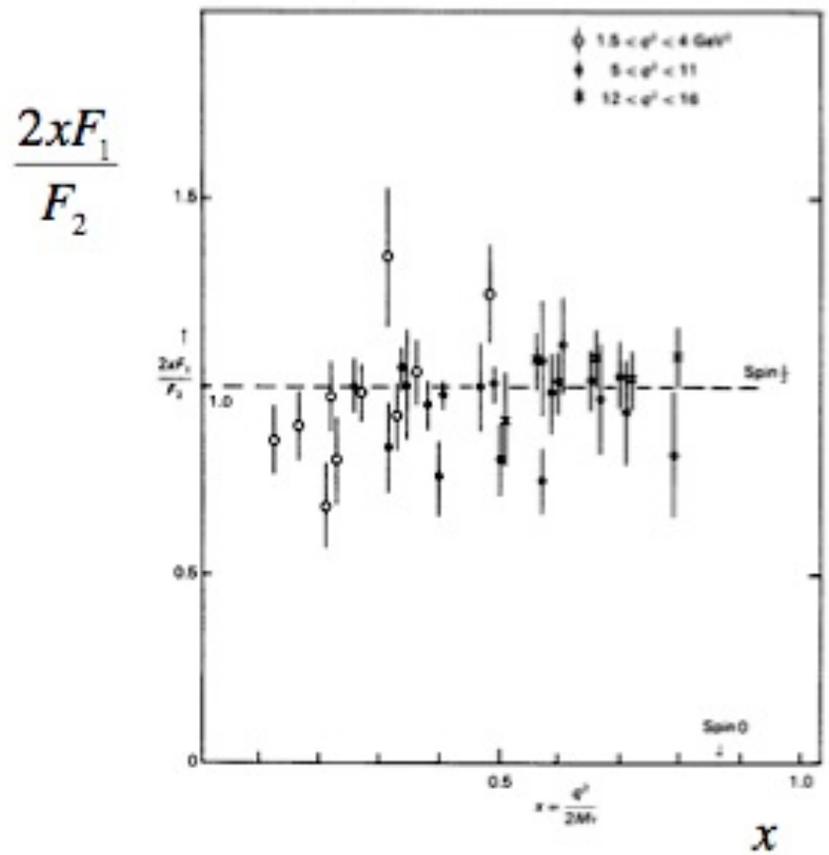


Q^2 ~ wavelength (in Compton sense) of the photon,

x ~ fraction of the proton momentum carried by the struck 'quark' in the proton inf. mom. frame,

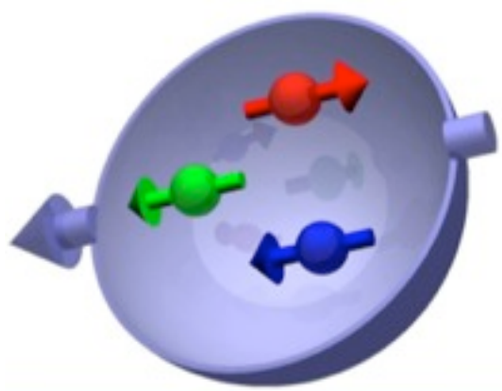
F_1, F_2 structure functions, parametrizations of the (spin-averaged) inclusive cross-section

- among the early results: the partons (quarks) are indeed spin $\frac{1}{2}$



spin 1/2

spin 0



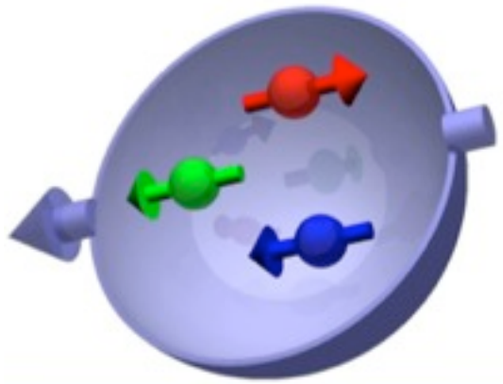
Proton (Spin) Structure - circa 1970

- Development of the quark-parton model,

$$F_1(x) = \frac{1}{2}\sum_q e_q^2 q(x)$$

$$F_2(x) = x\sum_q e_q^2 q(x) \quad +\mathcal{O}(\alpha_s)$$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta q(x)$$



- Polarized beam and target development make (spin) measurements of $g_1(x)$ possible;

- Ellis-Jaffe sum rule relates $\int g_1(x)\mathrm{d}x$ to couplings in weak n and Σ^- decay, for $\Delta(\bar{s}+s) = 0$

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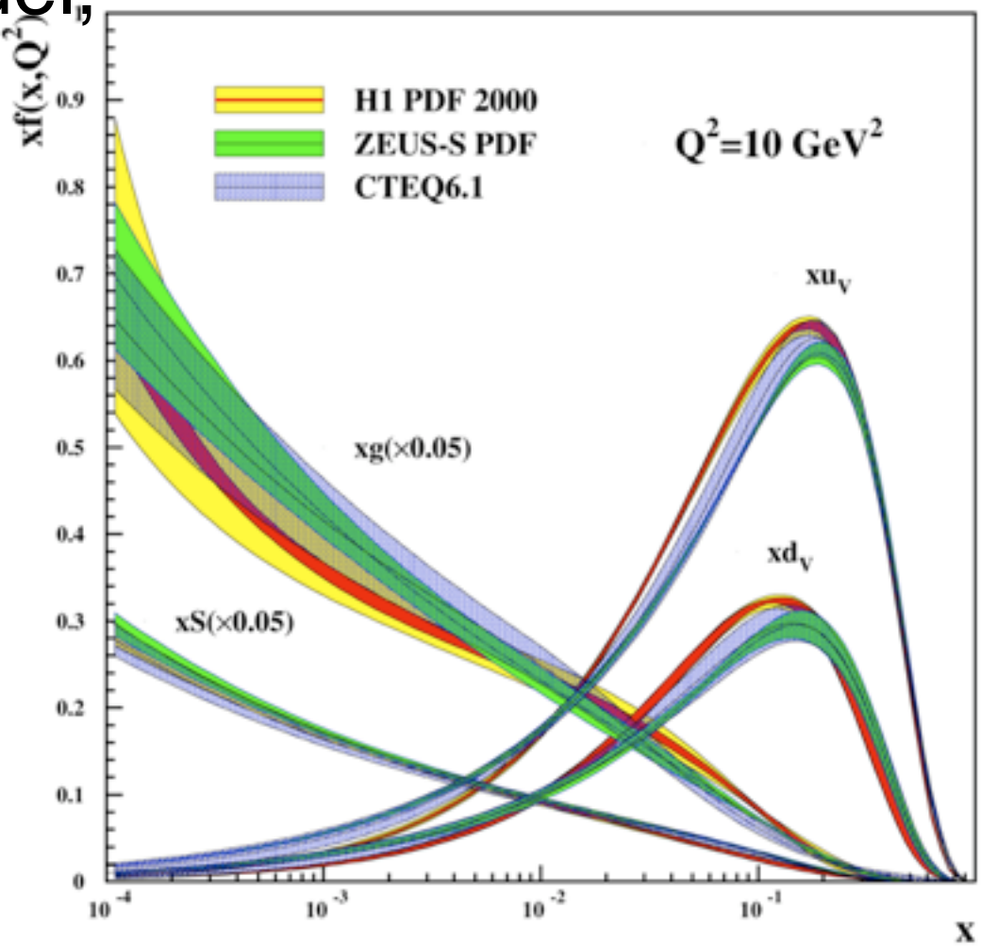

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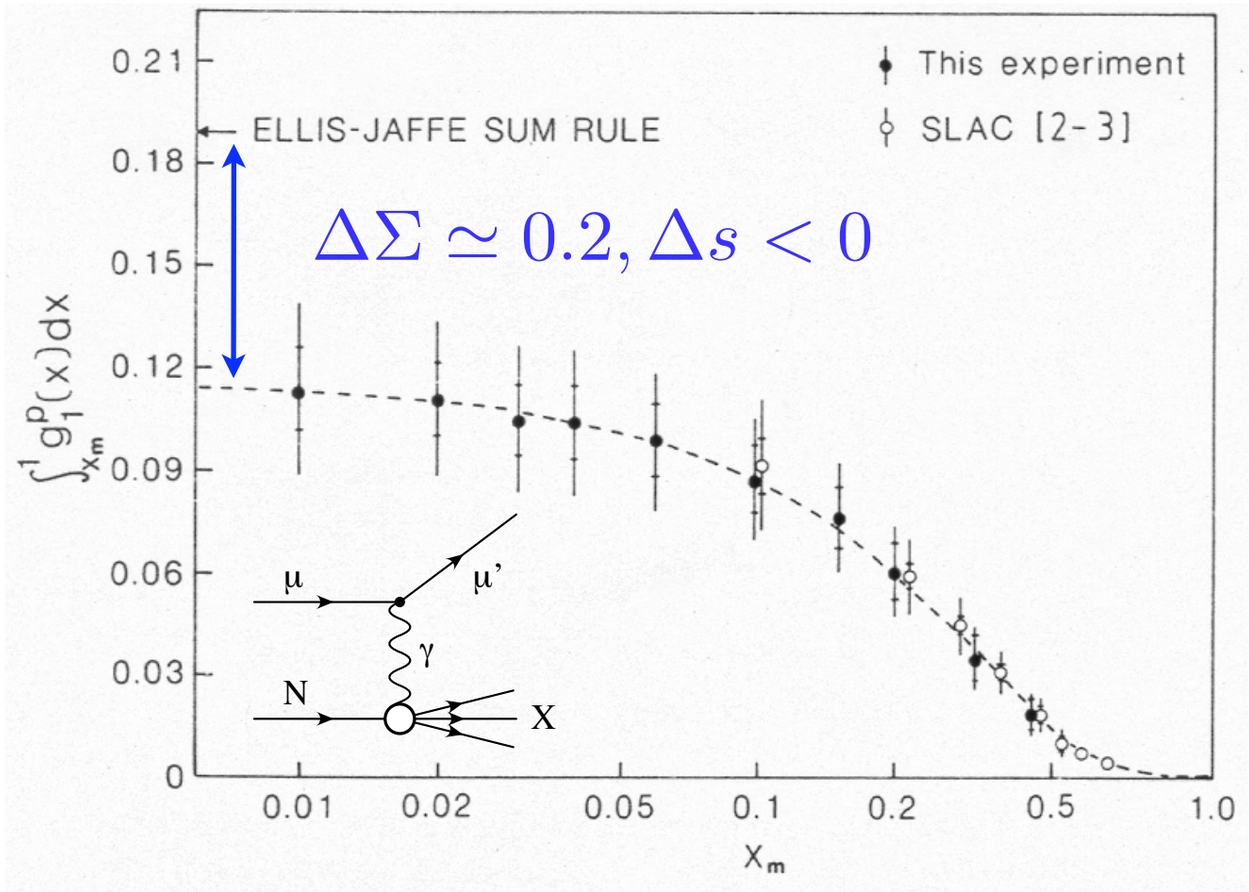
Proton Spin Structure - Renewed Interest

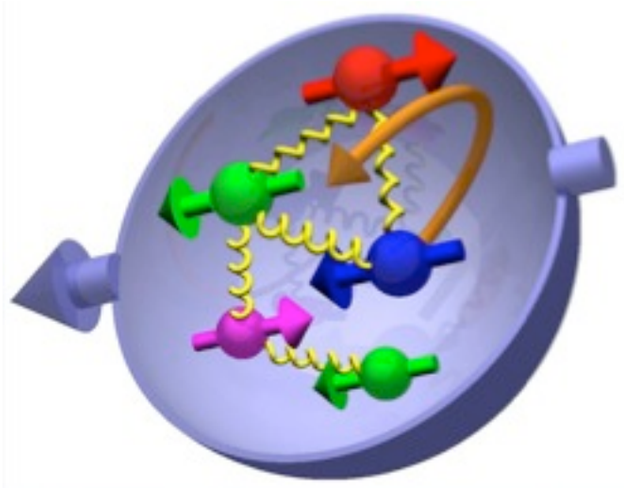
- *Polarized DIS* - European Muon Collaboration:



- *Quark spins carry only a small fraction of the proton spin,*

- *Strange sea is negatively polarized,*

- J. Ashman et al [EMC], Nucl. Phys. B 328:1 (1989), 1000+ citations



- SMC, E142, E143, E155, Hermes, and JLab have since confirmed the EMC data, and

- have tested the Bjorken Sum to ~7% precision.

- *forces to rethink nucleon (spin) structure.*

Nucleon Spin Structure - Present

Frontier *questions* in nucleon spin physics,

- gluon polarization (gluons are numerous, $\alpha_s \Delta G \propto \mathrm{constant}$, ...)

- flavor composition of quark spins ($\Delta s < 0$, cancellation, symmetries, ...),

- angular momenta, $J_q(\infty) : J_g(\infty) \sim 1:1$ as for ordinary momenta, ...

- role of transverse spins,

~30 participants (natl.+intl.), org: F.Yuan, W.Vogelsang, E.S.
http://www-nsdth.lbl.gov/~fyuan/spin09/

Nucleon Spin Structure - Experiments

SLAC

E142, E143,
E154, E155

CERN

EMC, SMC,
COMPASS

DESY

HERMES

JLab

Hall A, CLAS

BNL

PHENIX, STAR

1st pp collisions at
500 GeV recently

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- role of transverse spins,

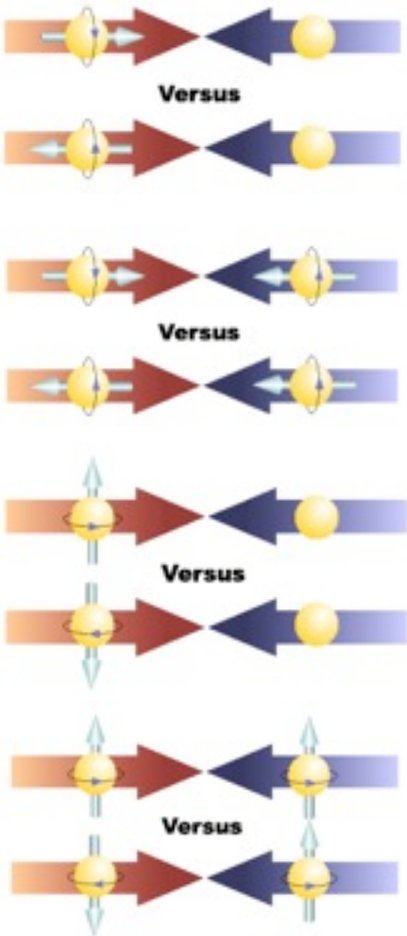
Complementary ways to address several of these questions,

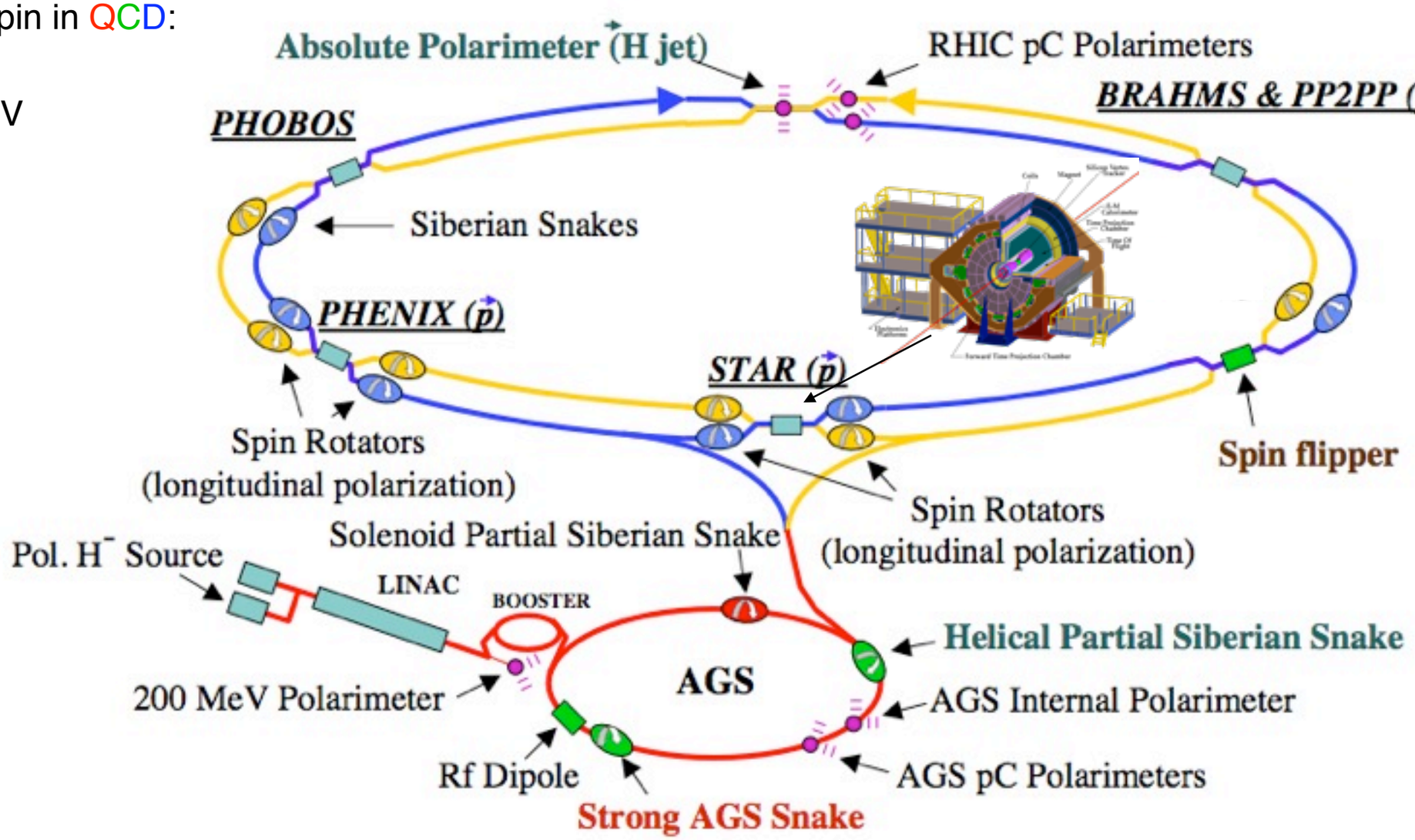
within a common factorized framework.

RHIC - Polarized Proton-Proton Collider

Unique opportunities to study spin in QCD:

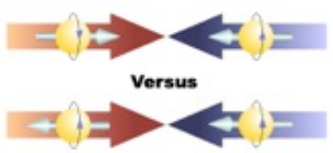
√s = 62, 200, and 500 GeV





at hard (perturbative) scales with good systematic controls, e.g. bunch pattern:

Longitudinal performance (STAR recorded):

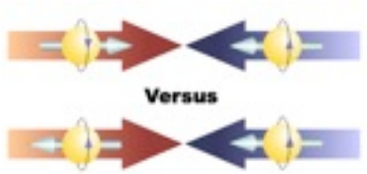


√s = 200 GeV

2003-2004	2005	2006	2009 (ongoing)	
0.3 pb^{-1}	2 pb^{-1}	5 pb^{-1}	50 pb^{-1}	Luminosity
30-45%	50%	~55%	60%	Polarization
0.01 pb^{-1}	0.1 pb^{-1}	0.5 pb^{-1}	6 pb^{-1}	FoM - $L.P^4$

Nucleon Spin Structure - Gluon Polarization

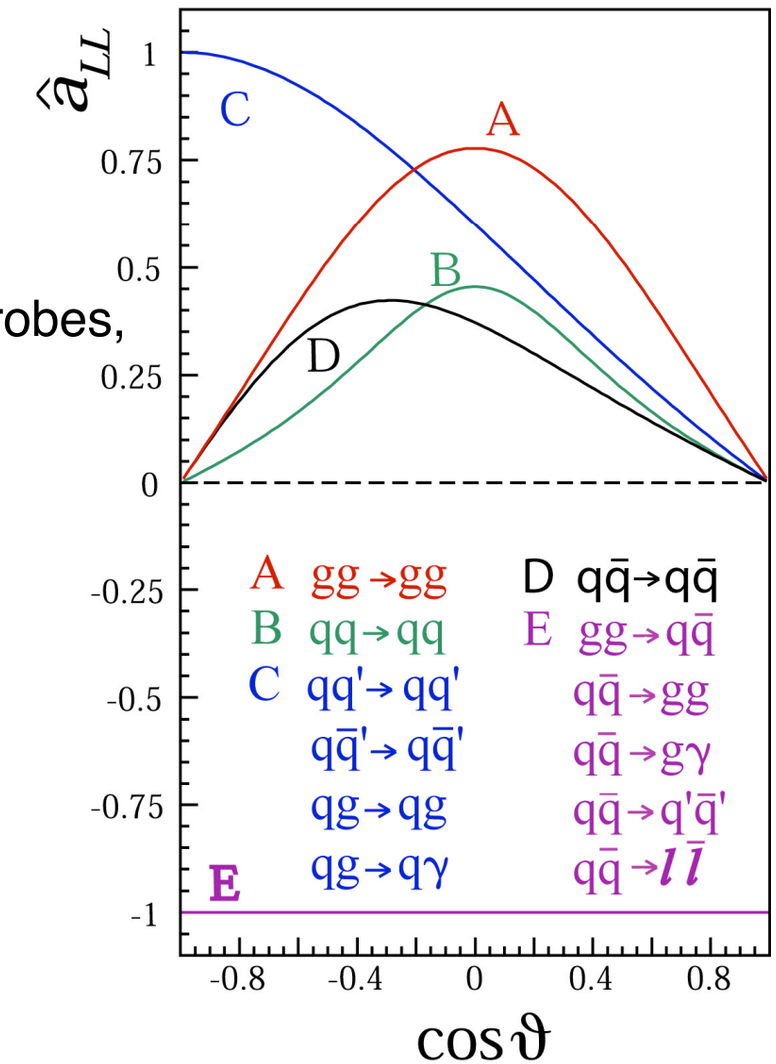
Measure double longitudinal spin asymmetries in an interpretable experiment:



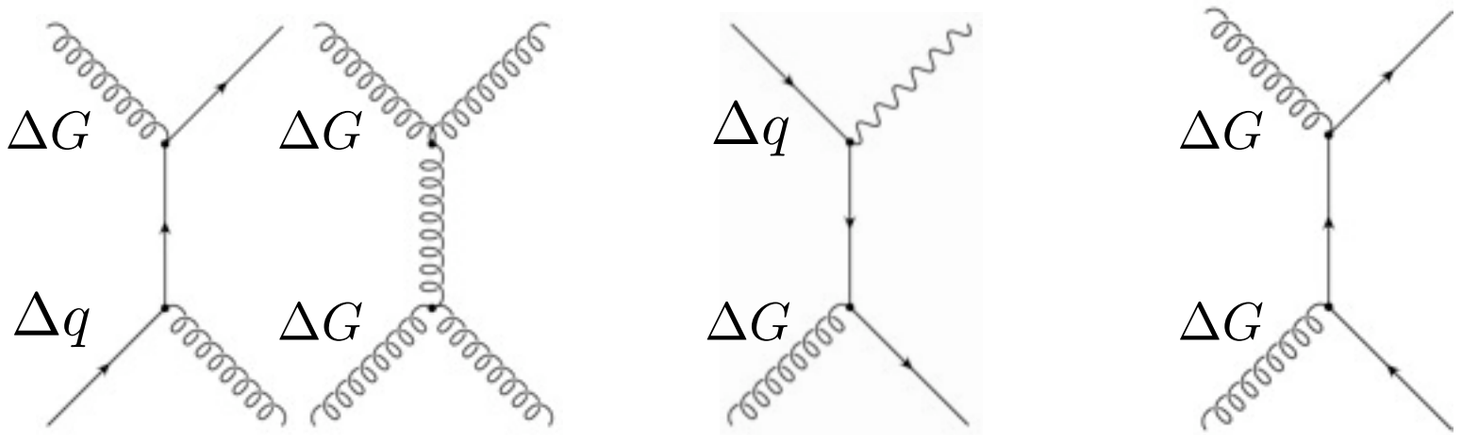
$$A_{LL} \equiv \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \stackrel{?}{=} \sum \frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2} \otimes \hat{a}_{LL} \, (\otimes \text{ fragmentation functions})$$

Start with abundantly produced probes (jets, pions, ...) at mid-rapidity, where the partonic asymmetries are sizable.

Pursue precision, coverage, sensitivity to initial kinematics, and selective probes,



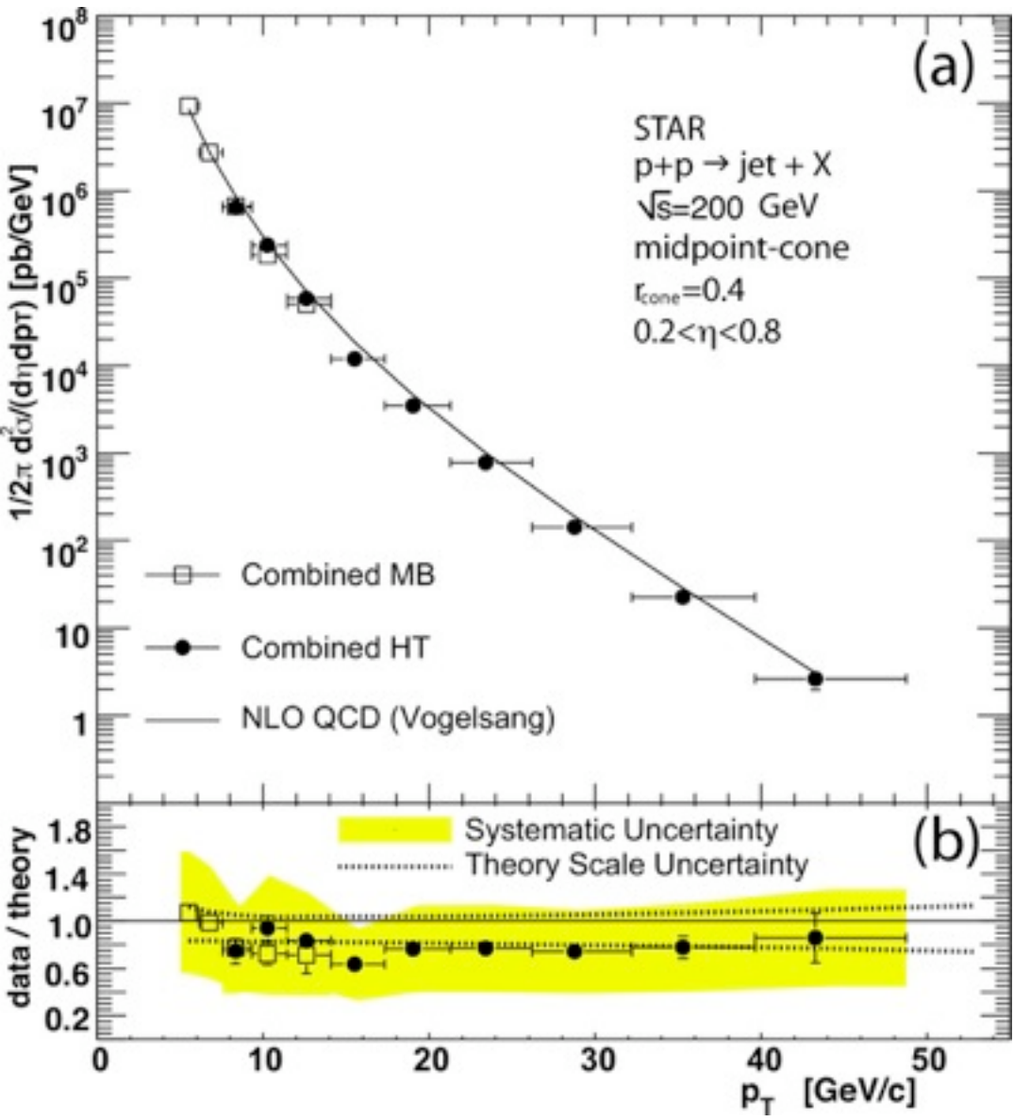
$\vec{p} + \vec{p} \to \text{jet(s)} + X$ $\quad$ $\vec{p} + \vec{p} \to \gamma + \text{jet}$ $\quad$ $\vec{p} + \vec{p} \to c\bar{c}, b\bar{b} + X$

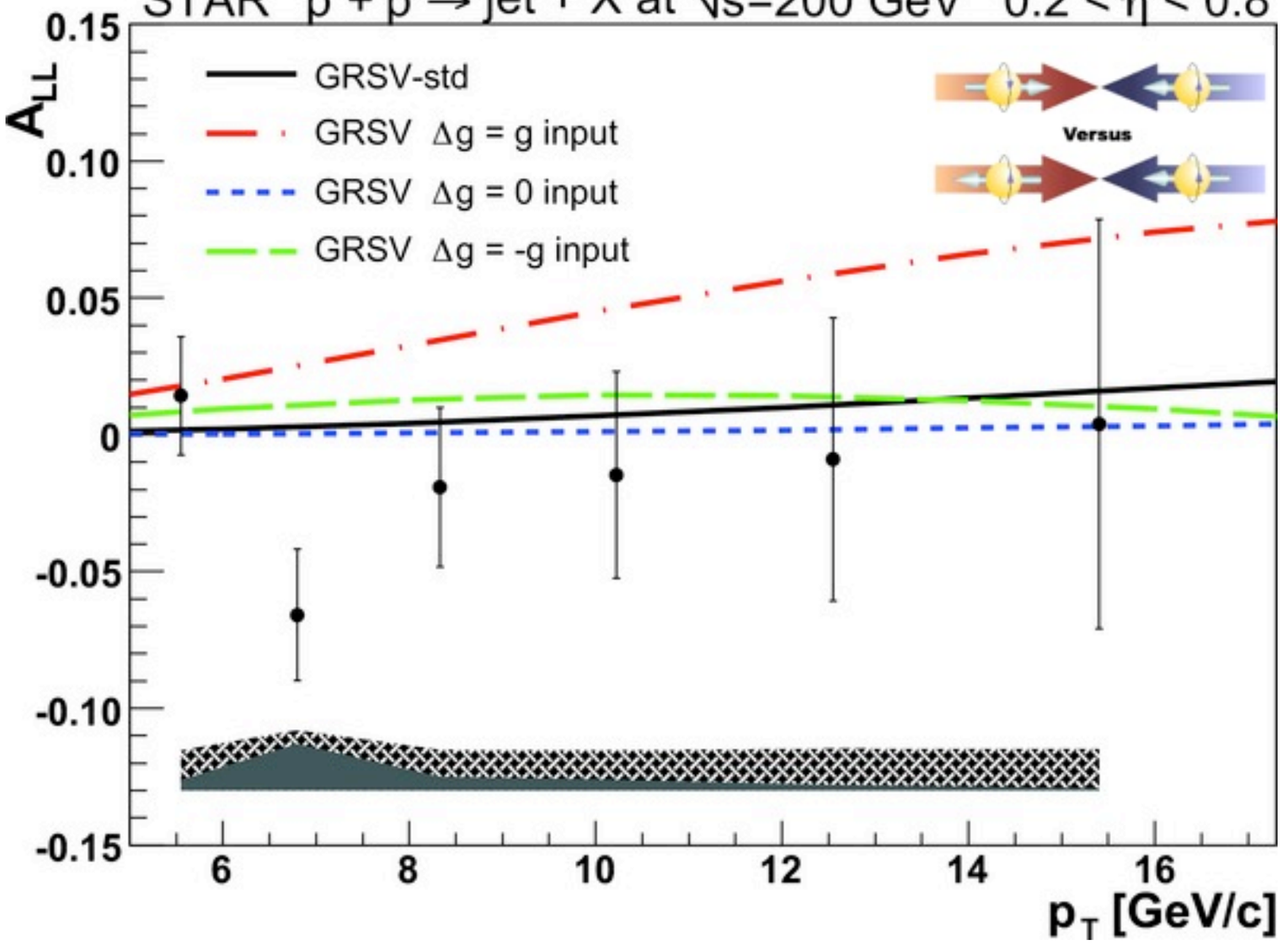


$$\mathcal{L} \simeq 3 - 8 \cdot 10^2 \, \text{pb}^{-1}, \quad P = 0.4 - 0.7, \quad \sqrt{s} = 200 - 500 \, \text{GeV}$$

time

STAR - First Longitudinal Spin Results





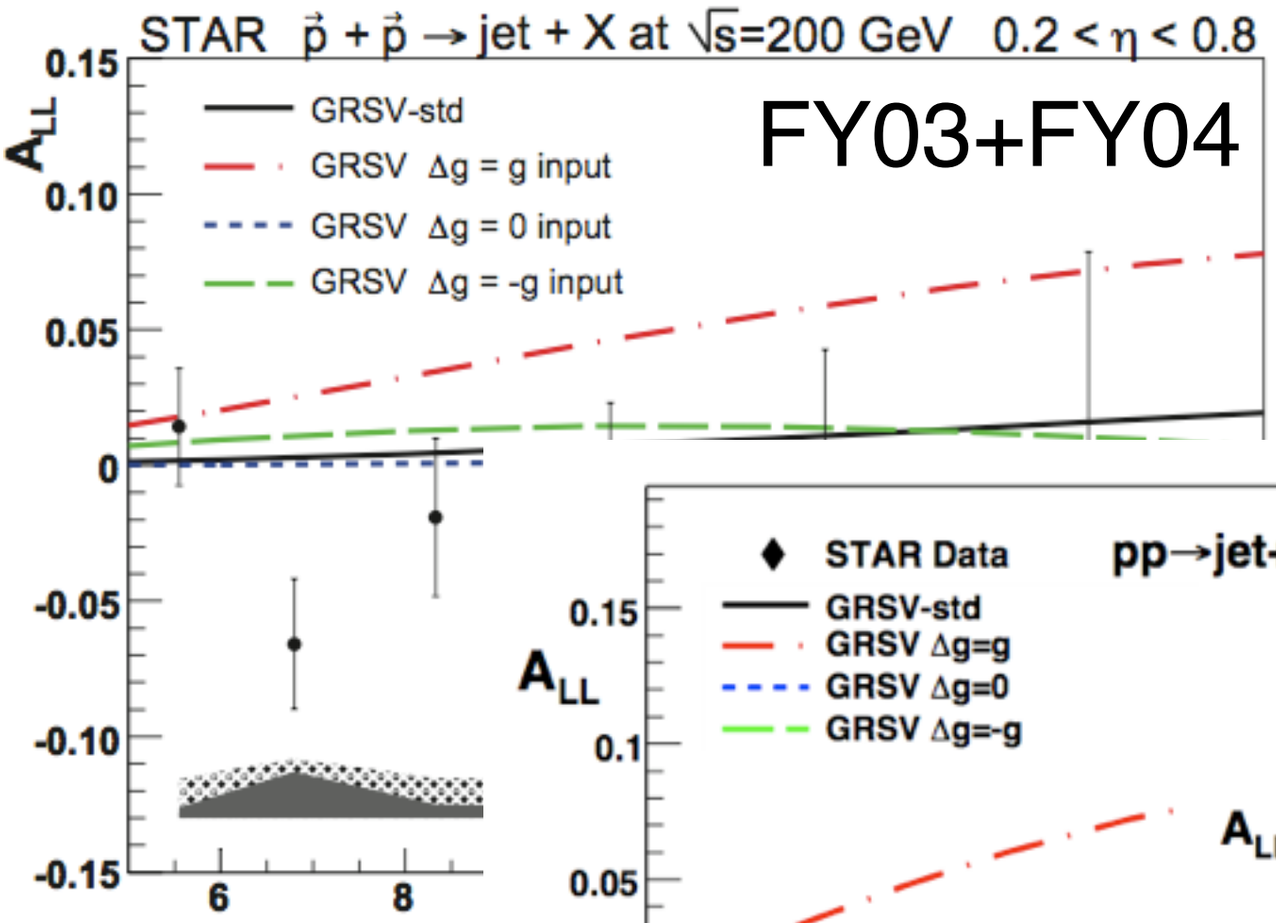
Phys. Rev. Lett. 97, 252001 (2006), 50+ citations.

"The data favor at 98% C.L. maximal positive gluon polarization in the polarized nucleon."

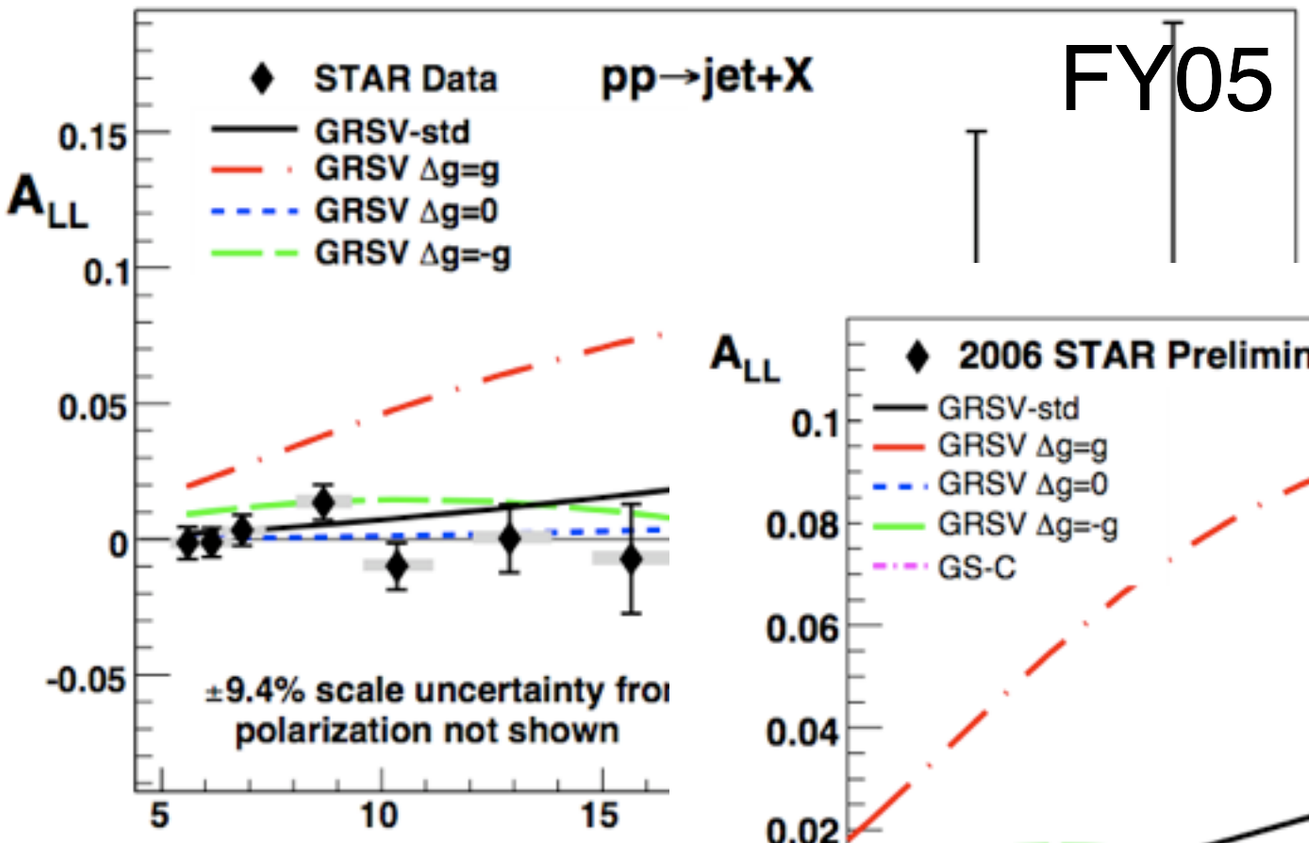
That is,

- the gluon spin contribution is *not* ~3 times larger than the nucleon spin (a contribution which would need to be compensated by similarly *huge* orbital angular momenta),
- there is a very clear *need for better precision.*

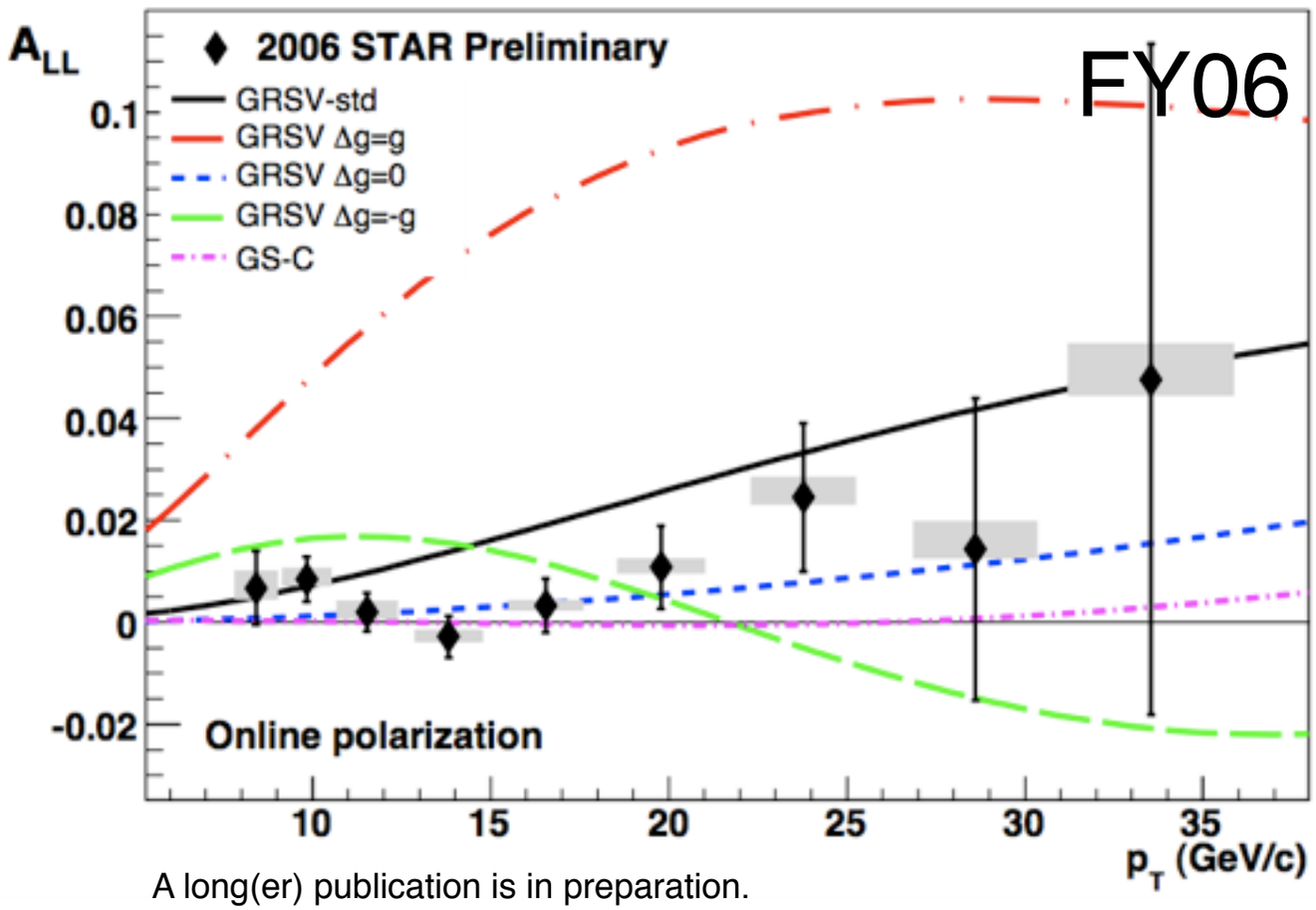
Towards Physics Answers - Improved Precision



Phys. Rev. Lett

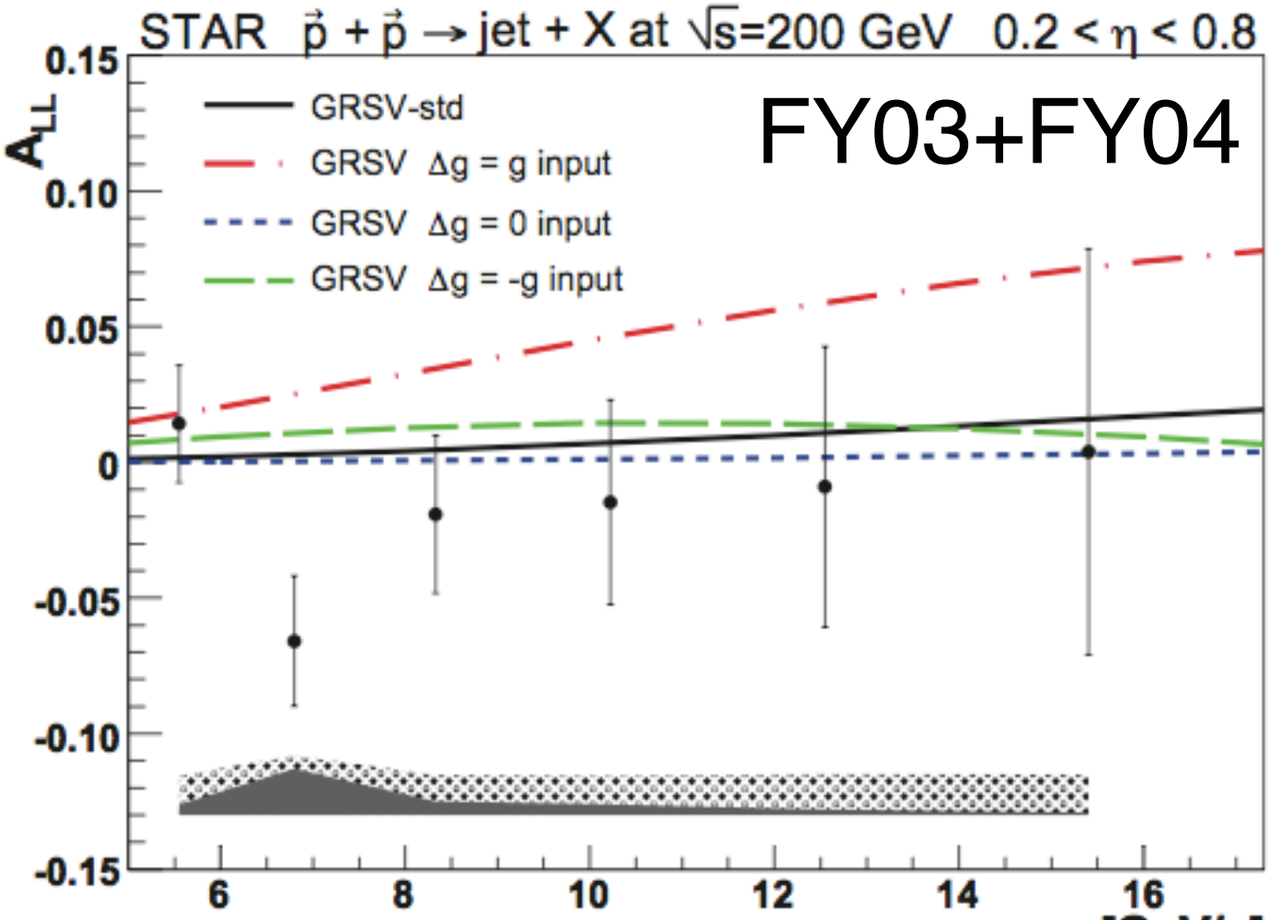


Phys. Rev. Lett. 100, 23 (2008),



A long(er) publication is in preparation.

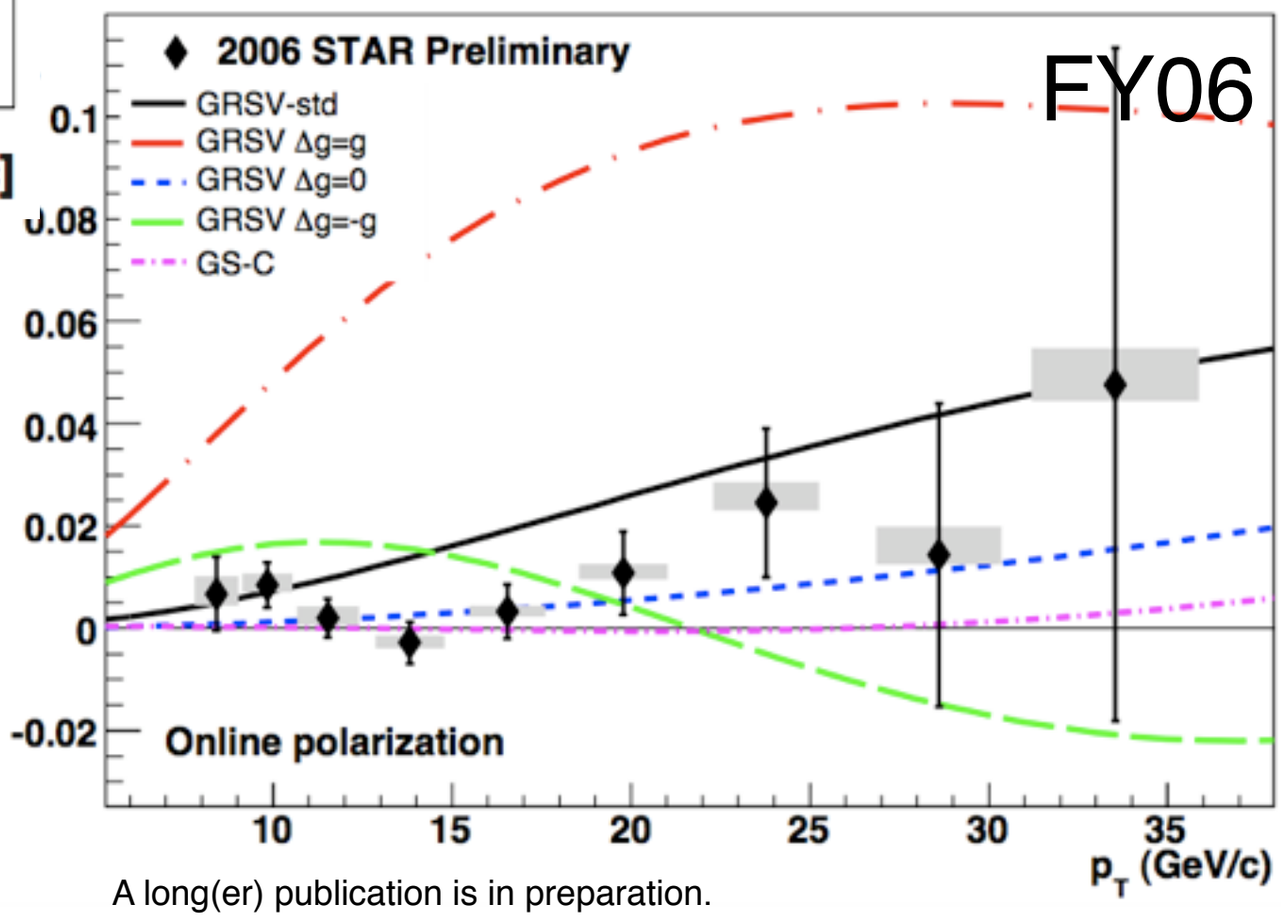
Towards Physics Answers - Improved Precision



Phys. Rev. Lett. 97, 252001 (2006), 50+ citations,

An order of magnitude in precision,

Twice the kinematic range.



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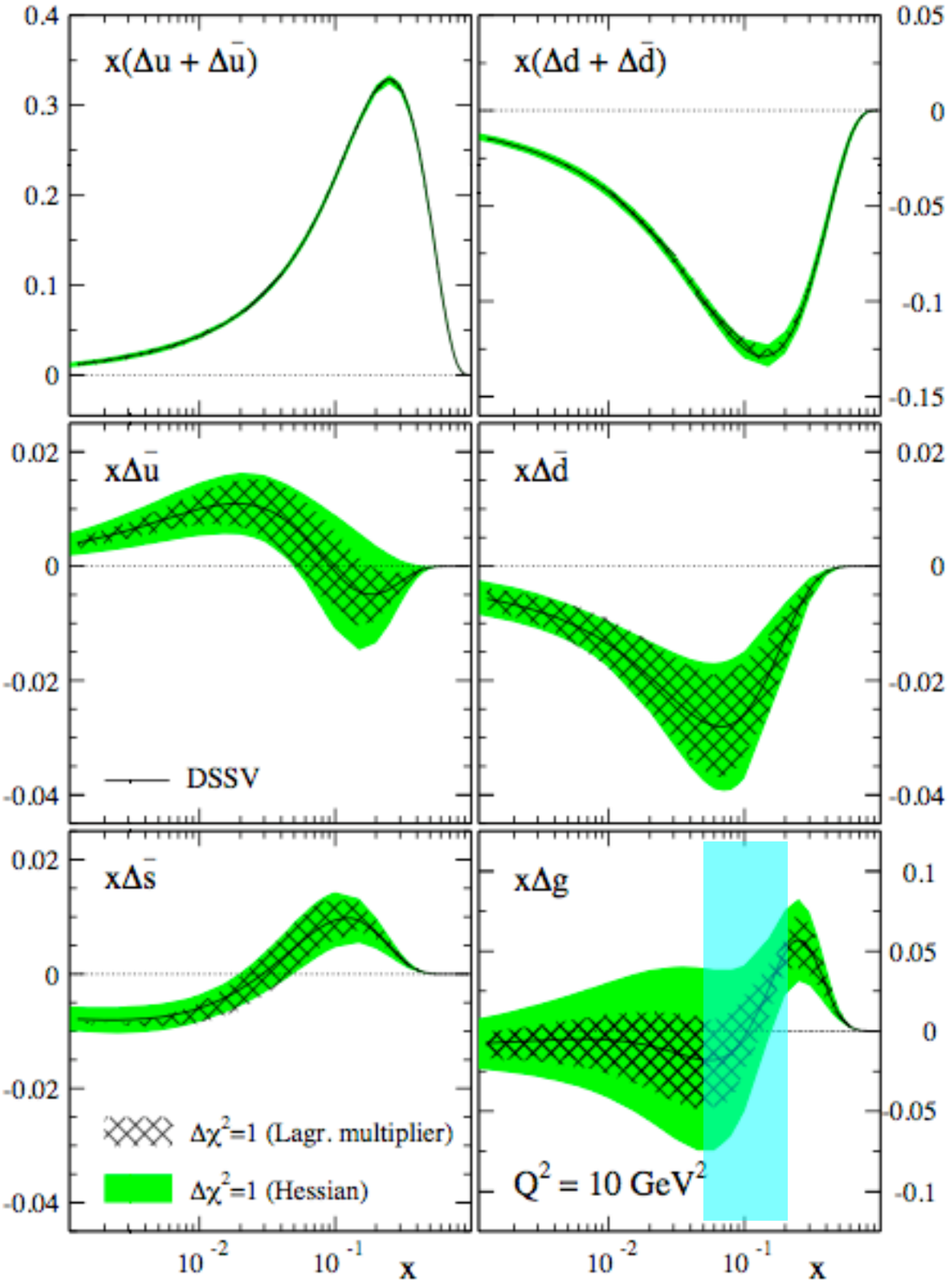
Present Picture of Nucleon Spin



Approximate kinematic range of STAR jet data

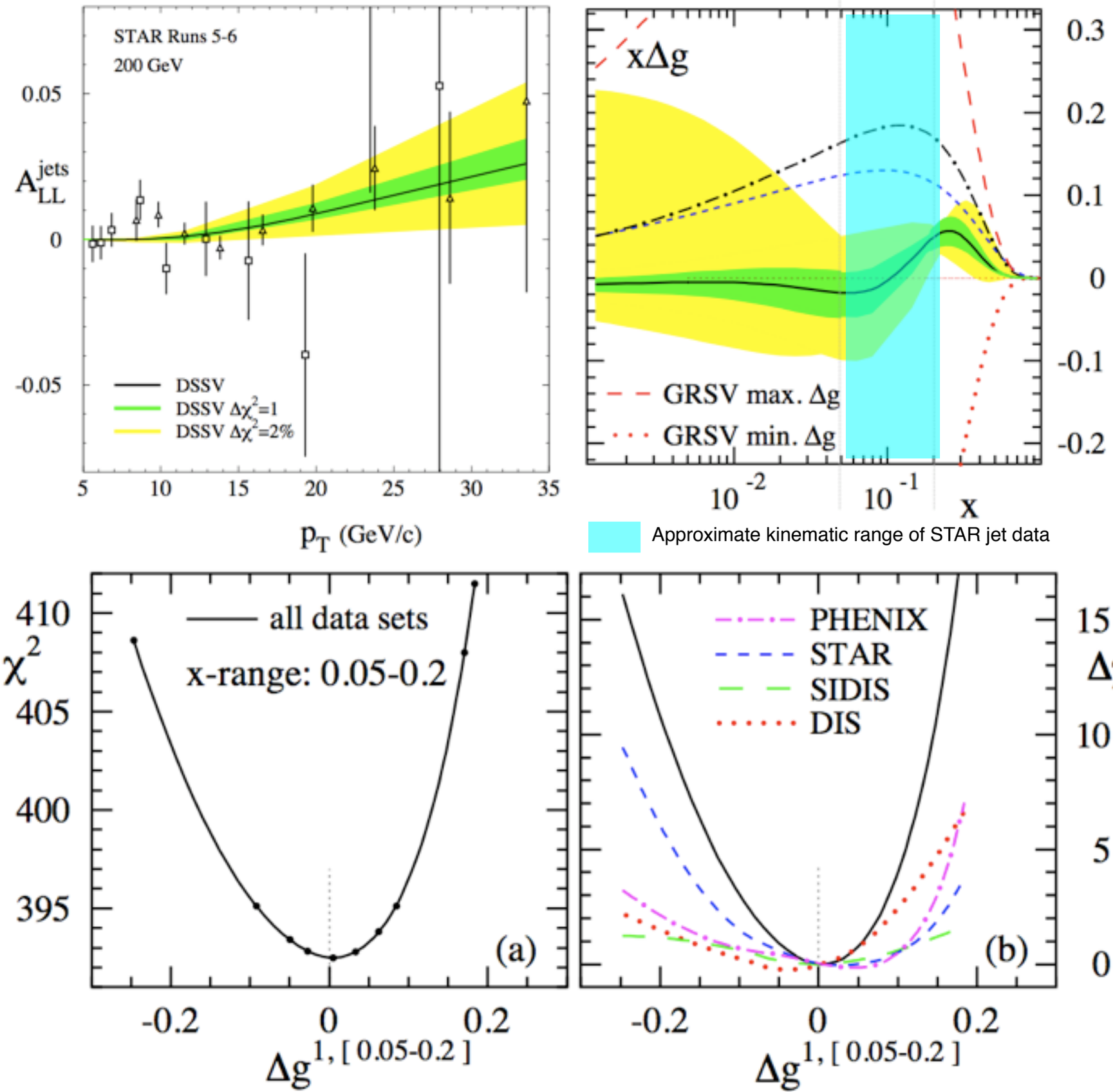
D. de Florian et al, Phys. Rev. Lett. 101:072001 (2008) and arXiv:0904.3821 [hep-ph],

"State-of-the-art": only polarized analysis that incorporates DIS, SIDIS, and RHIC data,

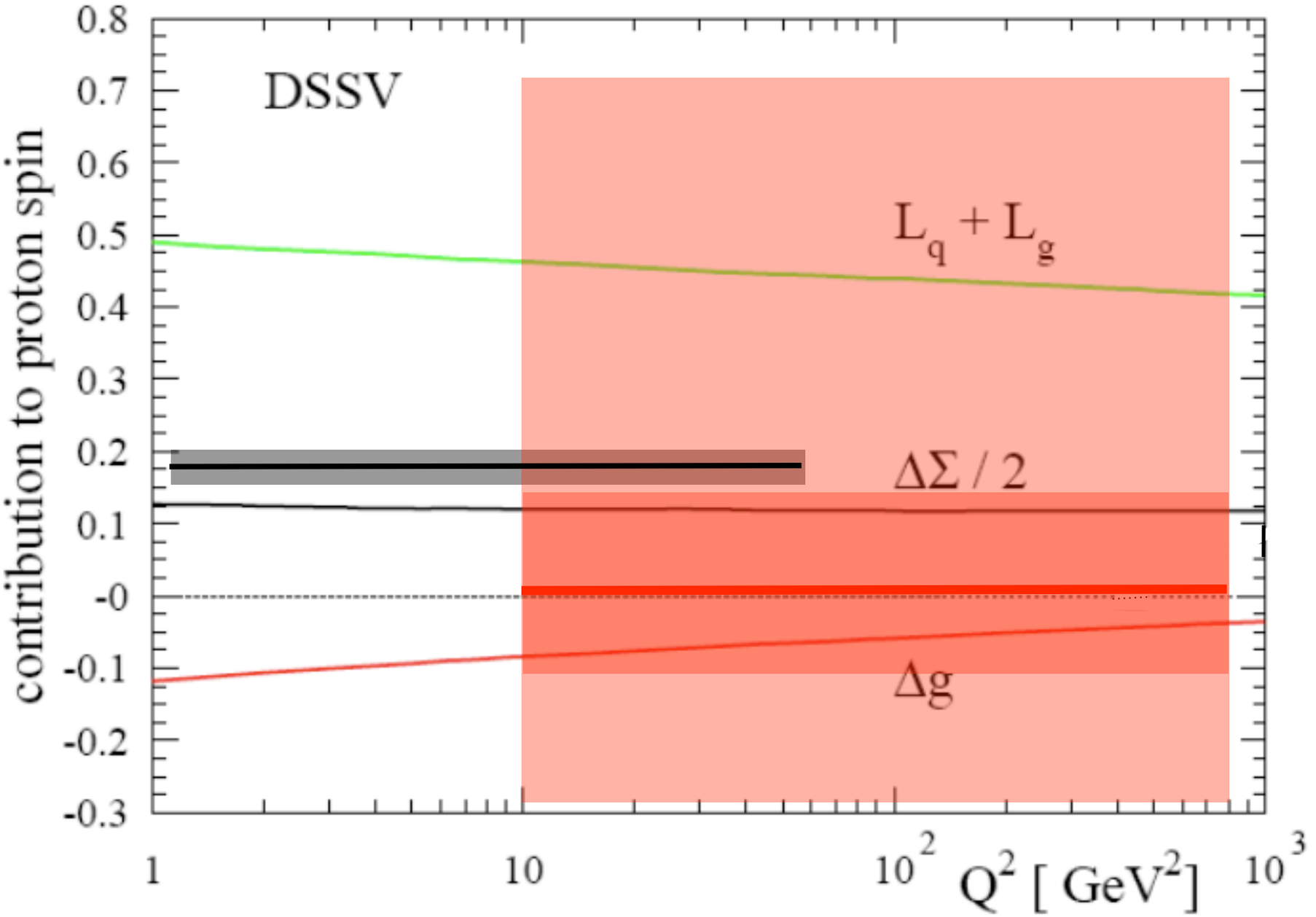
Quark + anti-quark distributions are well determined by DIS data; up quark spins preferentially point along the proton spin, whereas down quarks oppose it,

Focus is on sea quark and gluon polarizations; note in particular the nodes in the light-cone momentum fraction *x*

Impact of STAR (RHIC, DIS) data on ΔG



Picture of Proton Spin

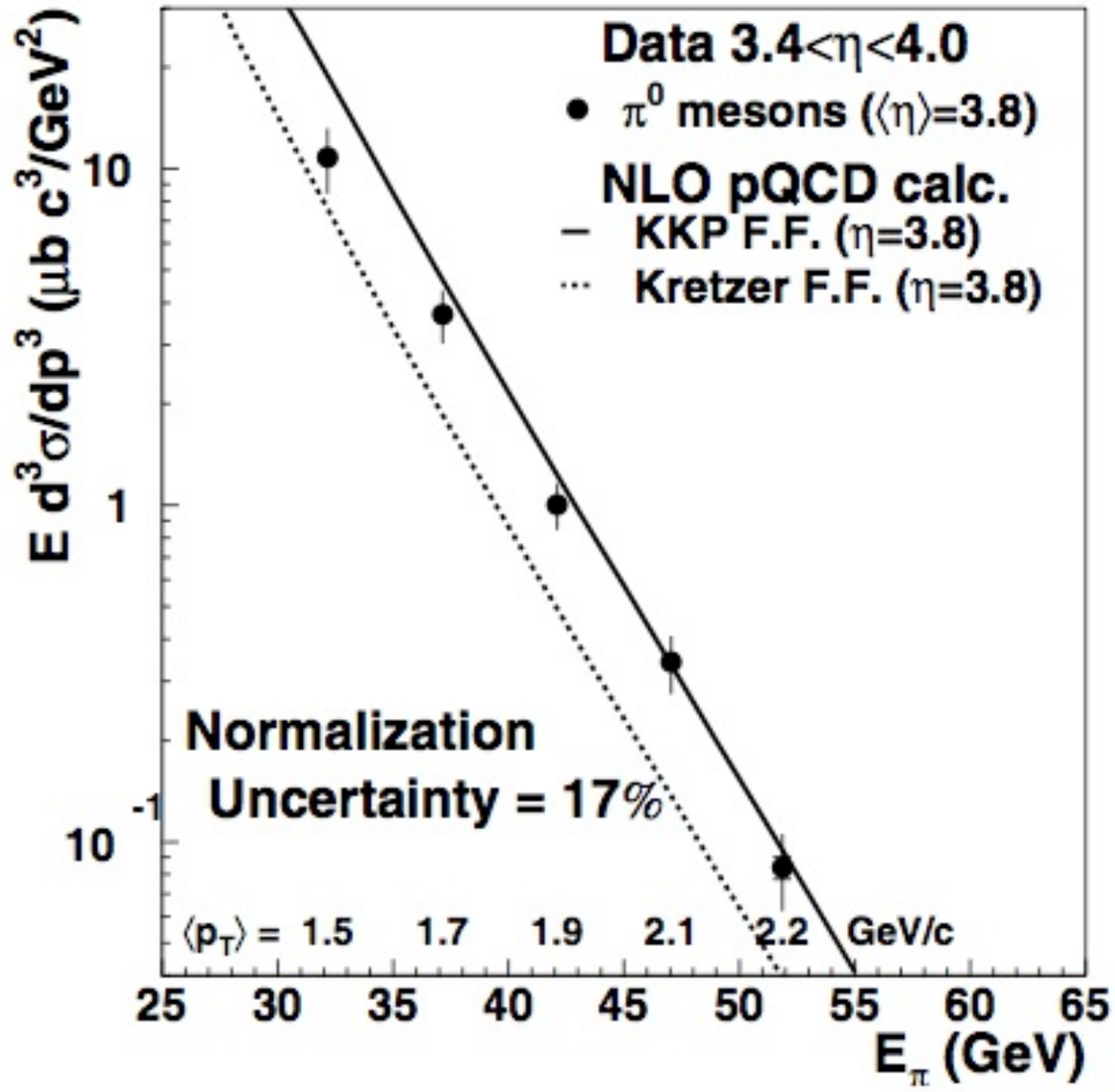


But, mind the uncertainties and extrapolations!

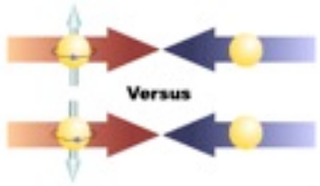
Is there (direct) evidence for orbital momenta?

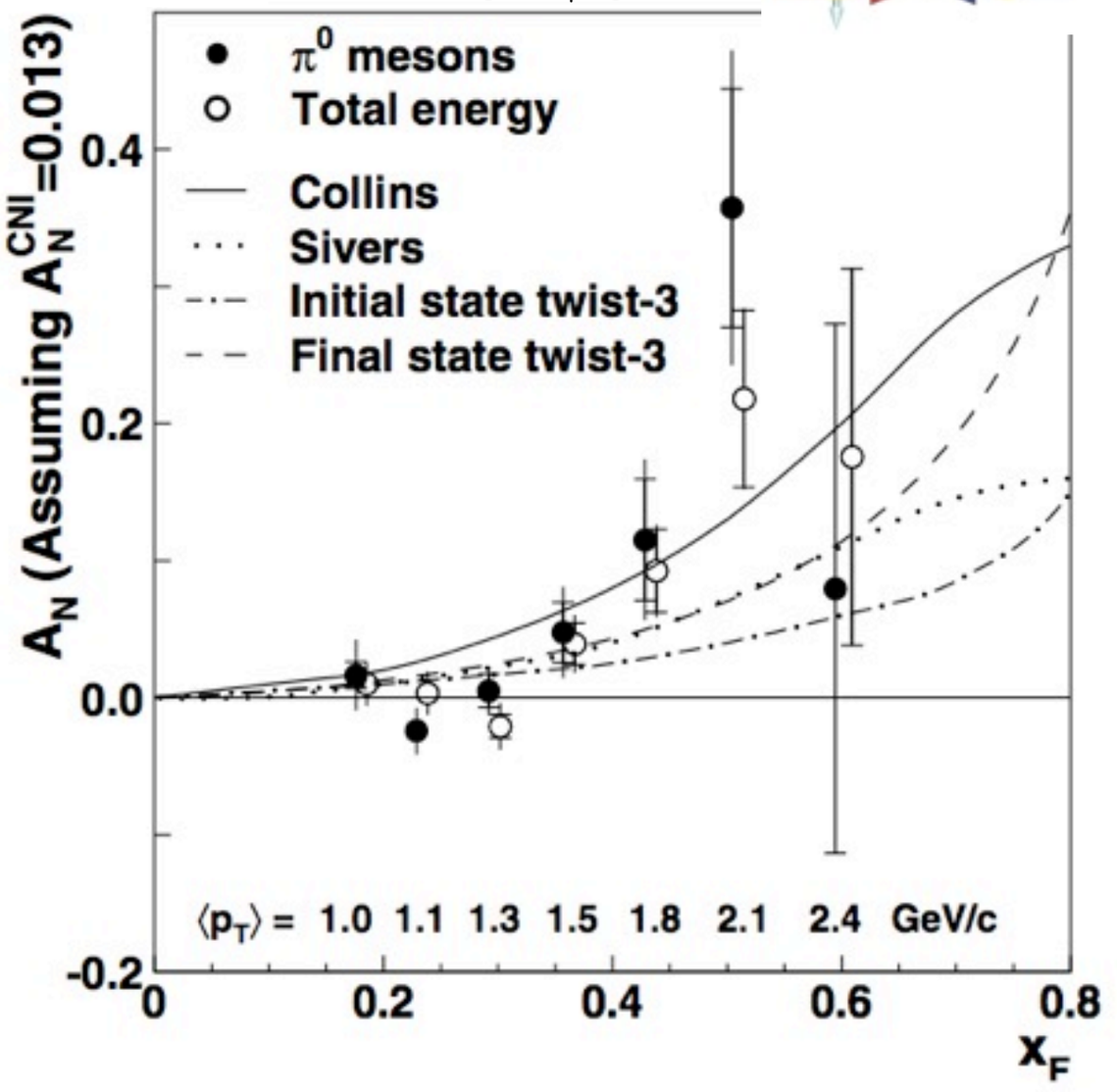
Renewed Interest in Transverse Spins

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



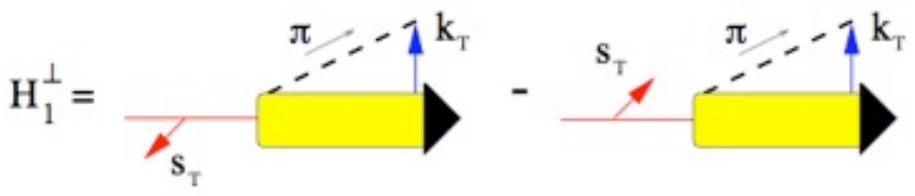
STAR $A_N=\dfrac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}}$



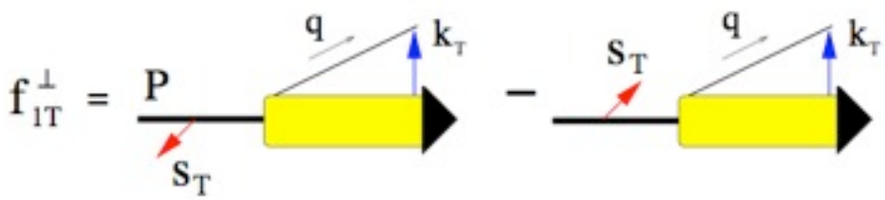


Phys. Rev. Letters 92, 171801 (2004) 100+ citations

Helicity conservation suppresses transverse spin effects. Who ordered this?



Collins (~transversity polarimeter)

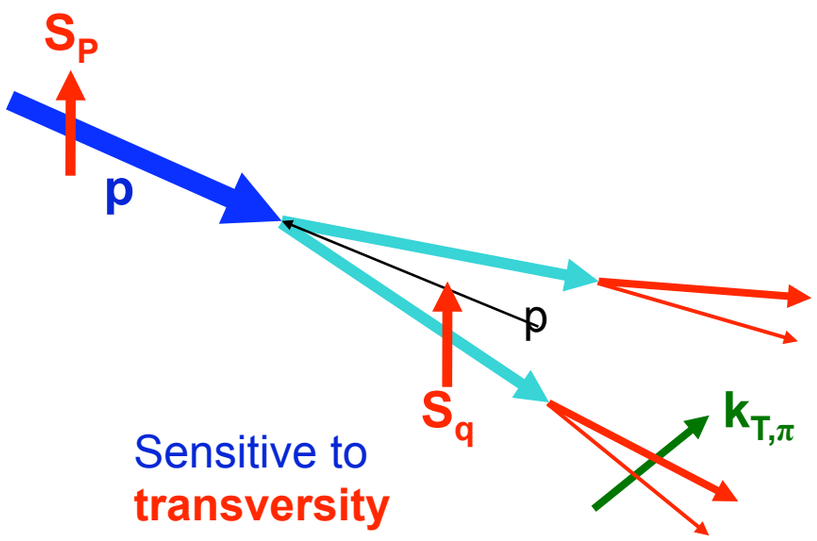


Sivers (intrinsic k_T, ~orbital momentum?)

Other?

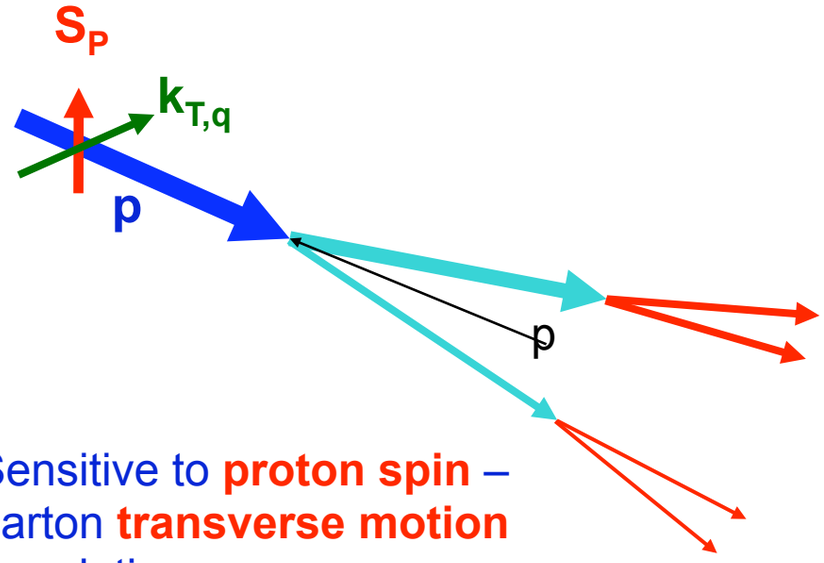
Disentangling Collins and Sivers Effect(s) at RHIC

Collins mechanism: asymmetry in the forward jet fragmentation



Sensitive to **transversity**

Sivers mechanism: asymmetry in the forward jet or γ production



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

Measure jets and/or direct photons to step beyond inclusive hadrons. Thus far, RHIC has (partially) mapped $A_N(x_F, p_T)$ for complementary hadrons.

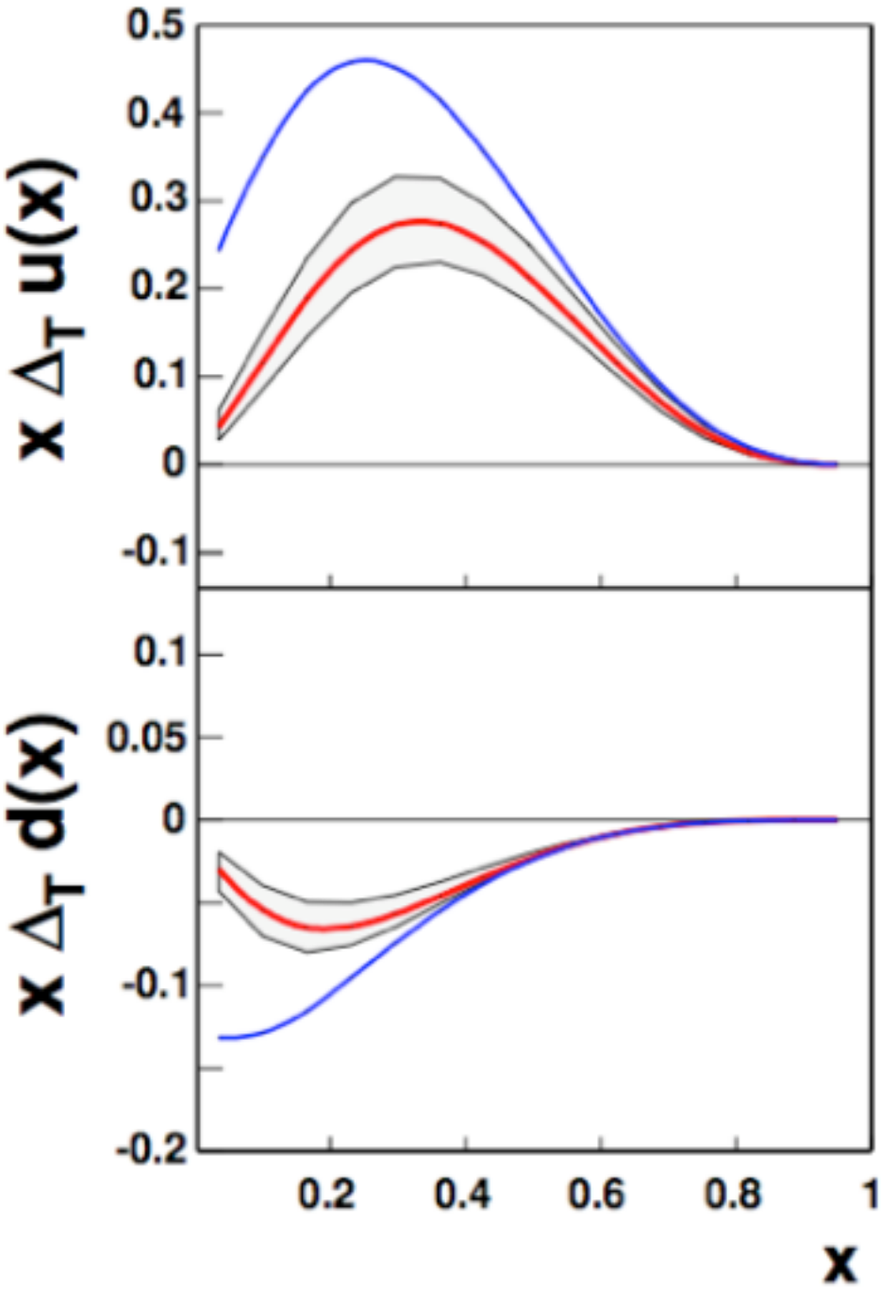
Collins Effect(s) from SIDIS

Non-zero Collins Asymmetries for proton target,
from both HERMES and COMPASS,

Zero Collins Asymmetries for deuteron target,

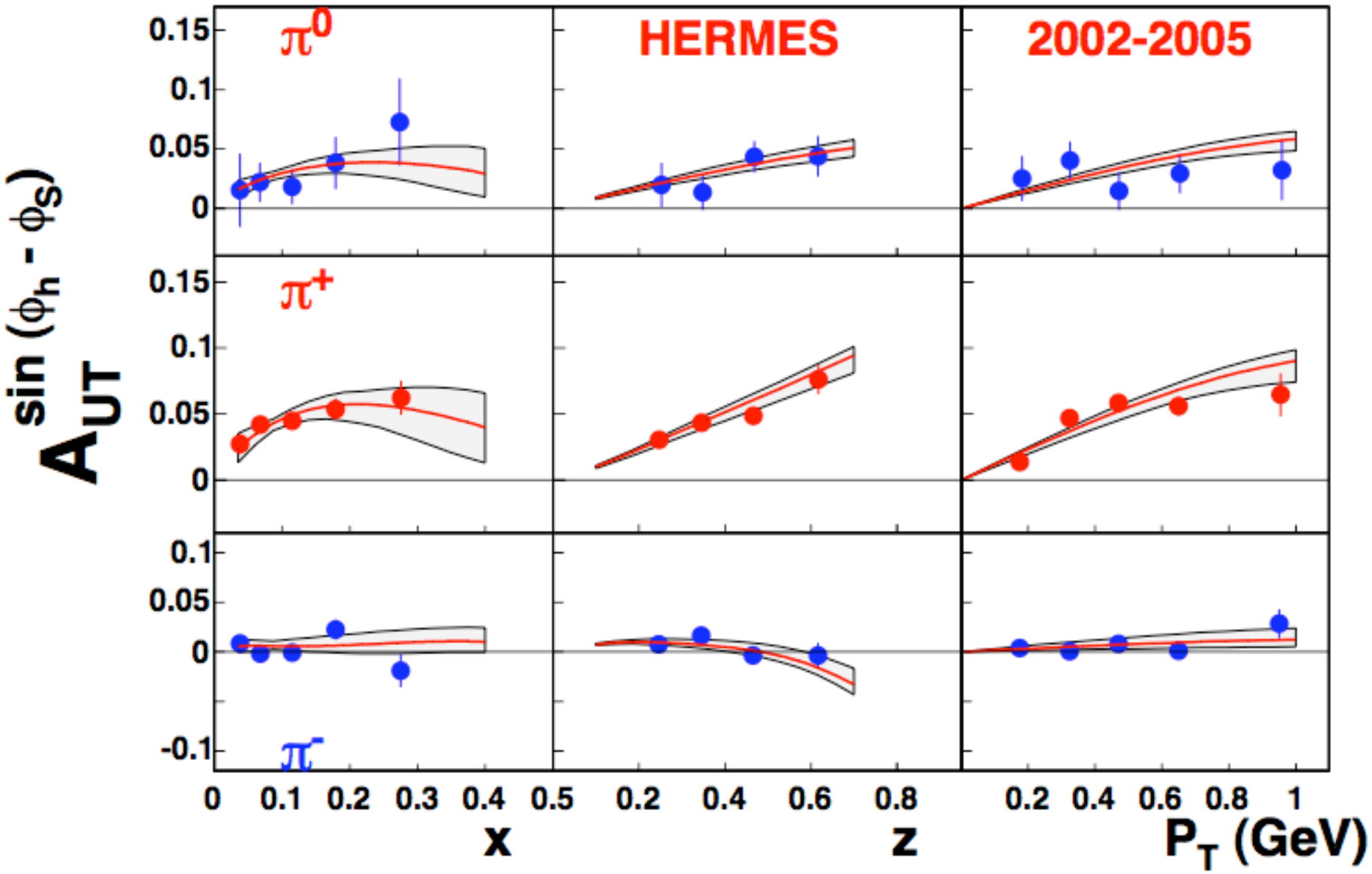
Non-zero Collins fragmentation functions from
e+e- measurements at Belle,

Allows extraction of quark transversity distributions.



Sivers Effect(s) from SIDIS

- Hermes measures non-zero Sivers Asymmetries for proton target,



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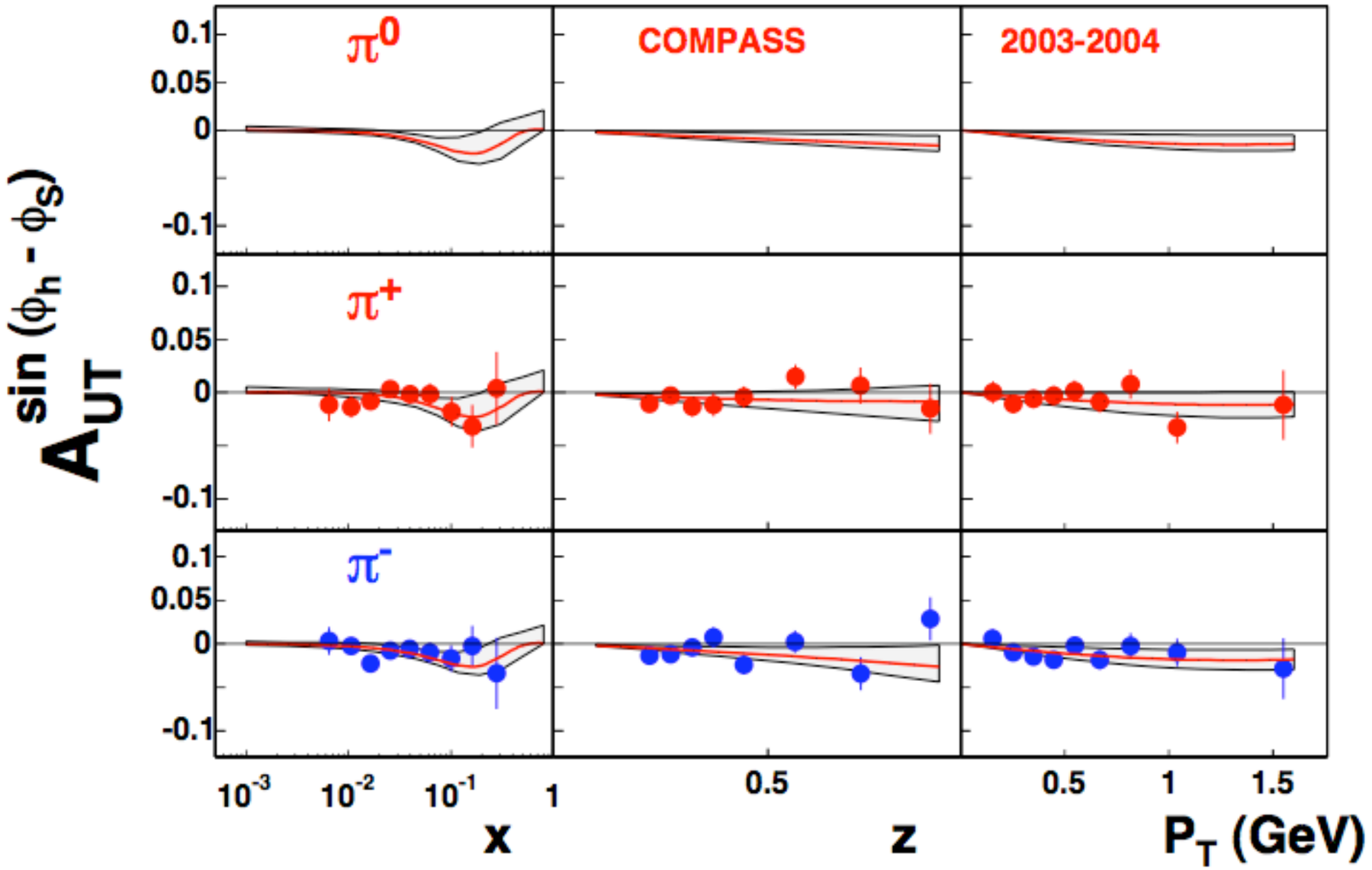
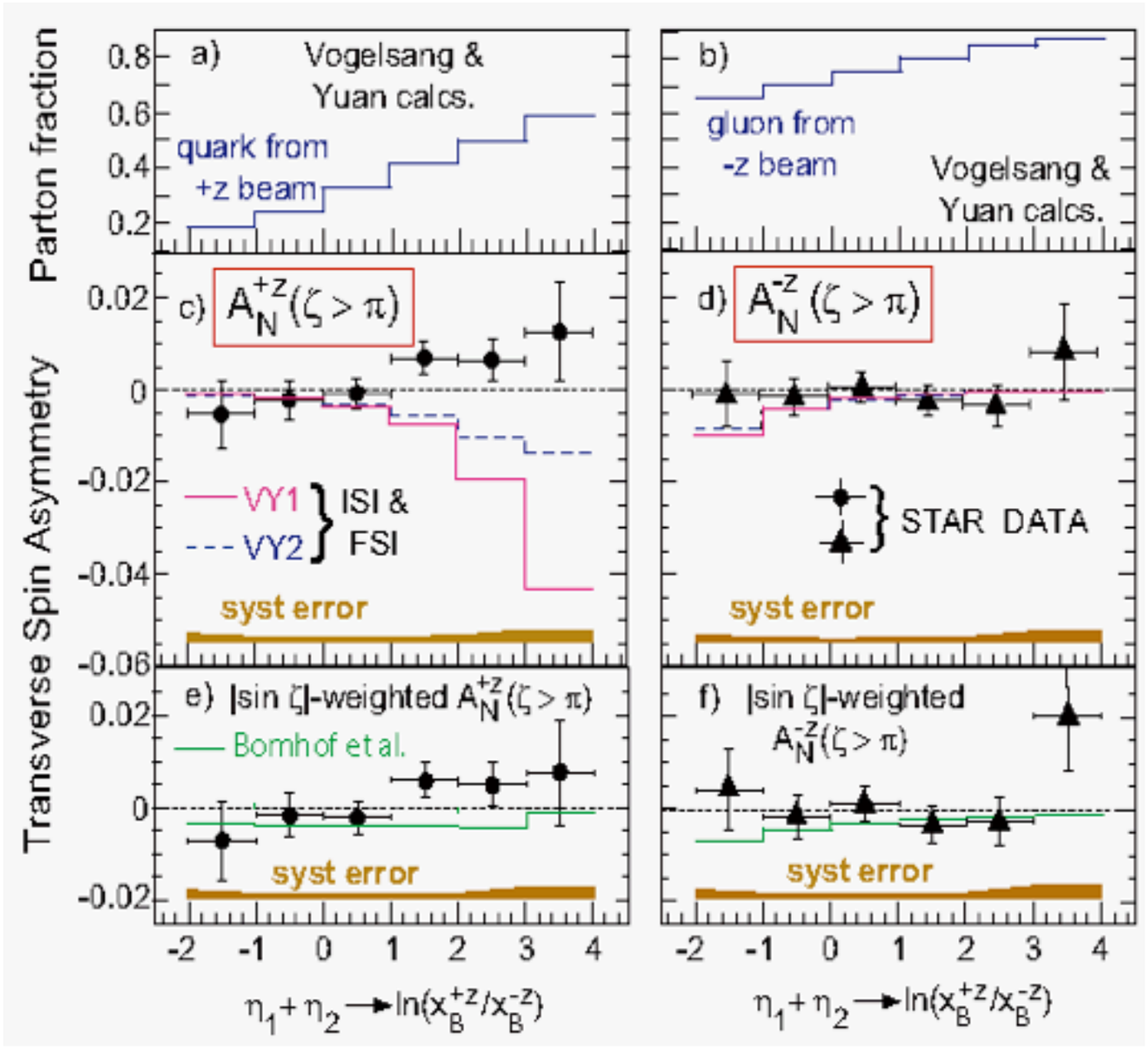


Sivers Effect(s) from SIDIS and RHIC

- Hermes measures non-zero Sivers Asymmetries for proton target,
- COMPASS measures zero Sivers Asymmetries for deuteron target,
- STAR measures zero Sivers di-jet Asymmetries with proton beams,



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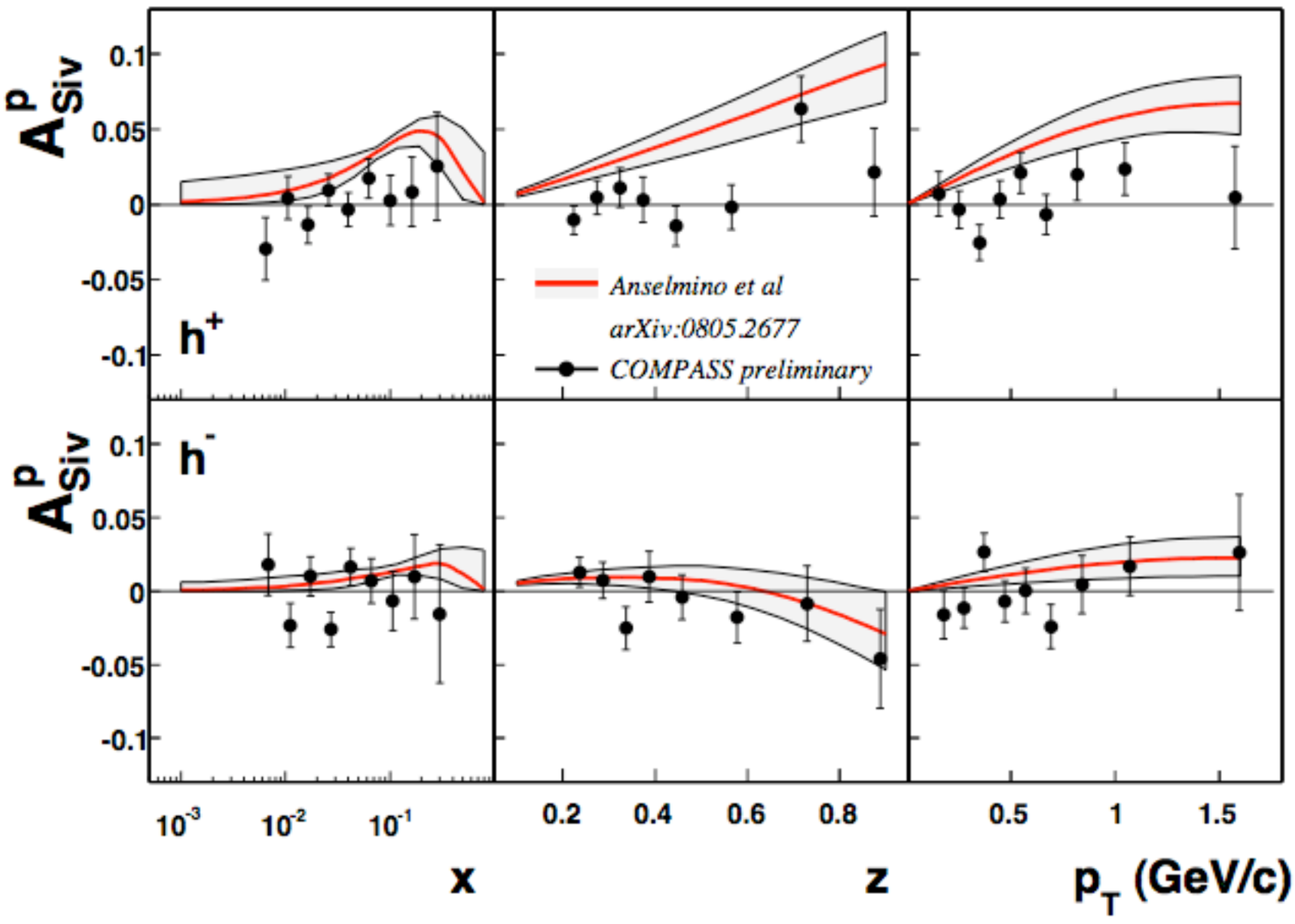

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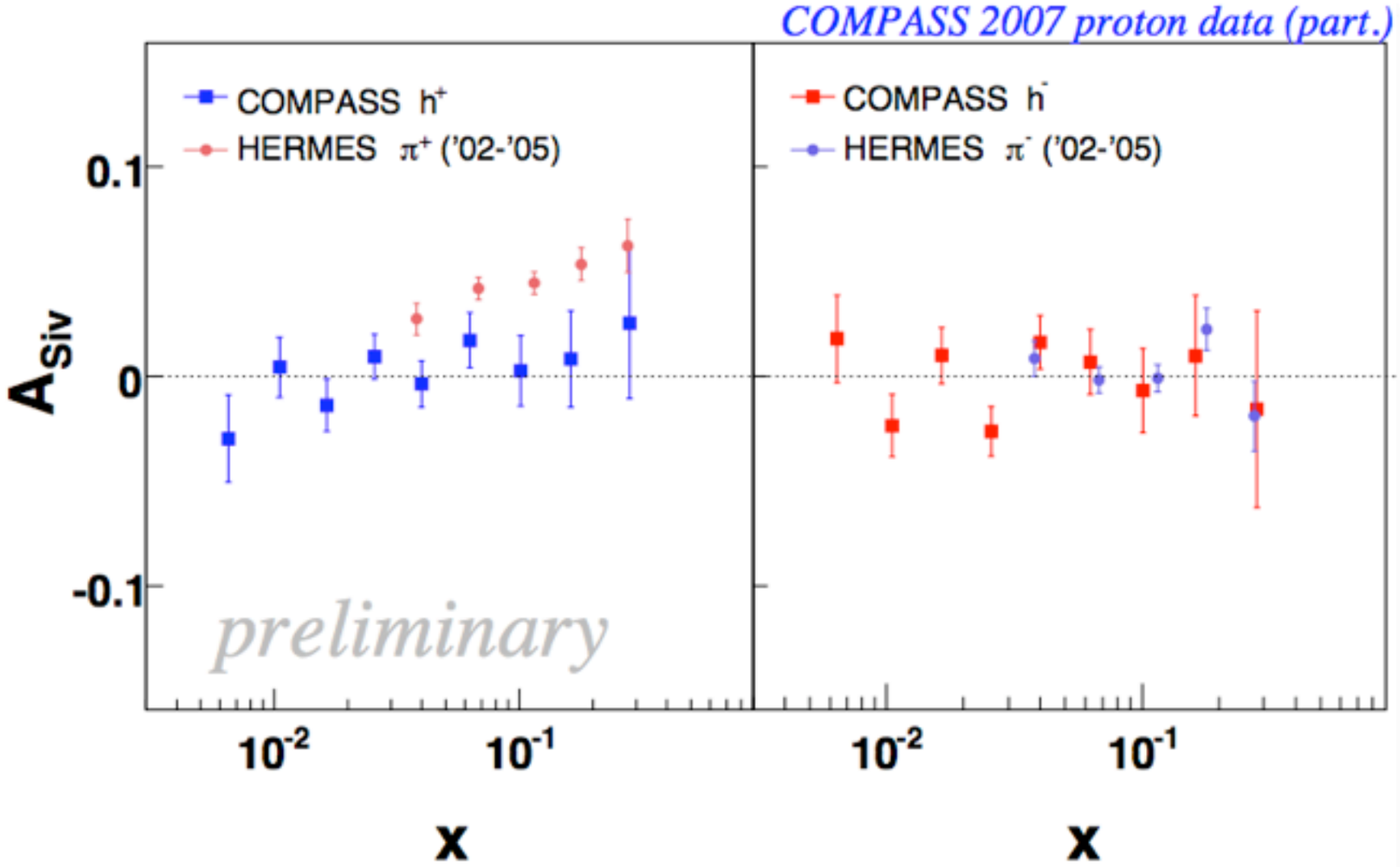
- Visible tension between data sets,



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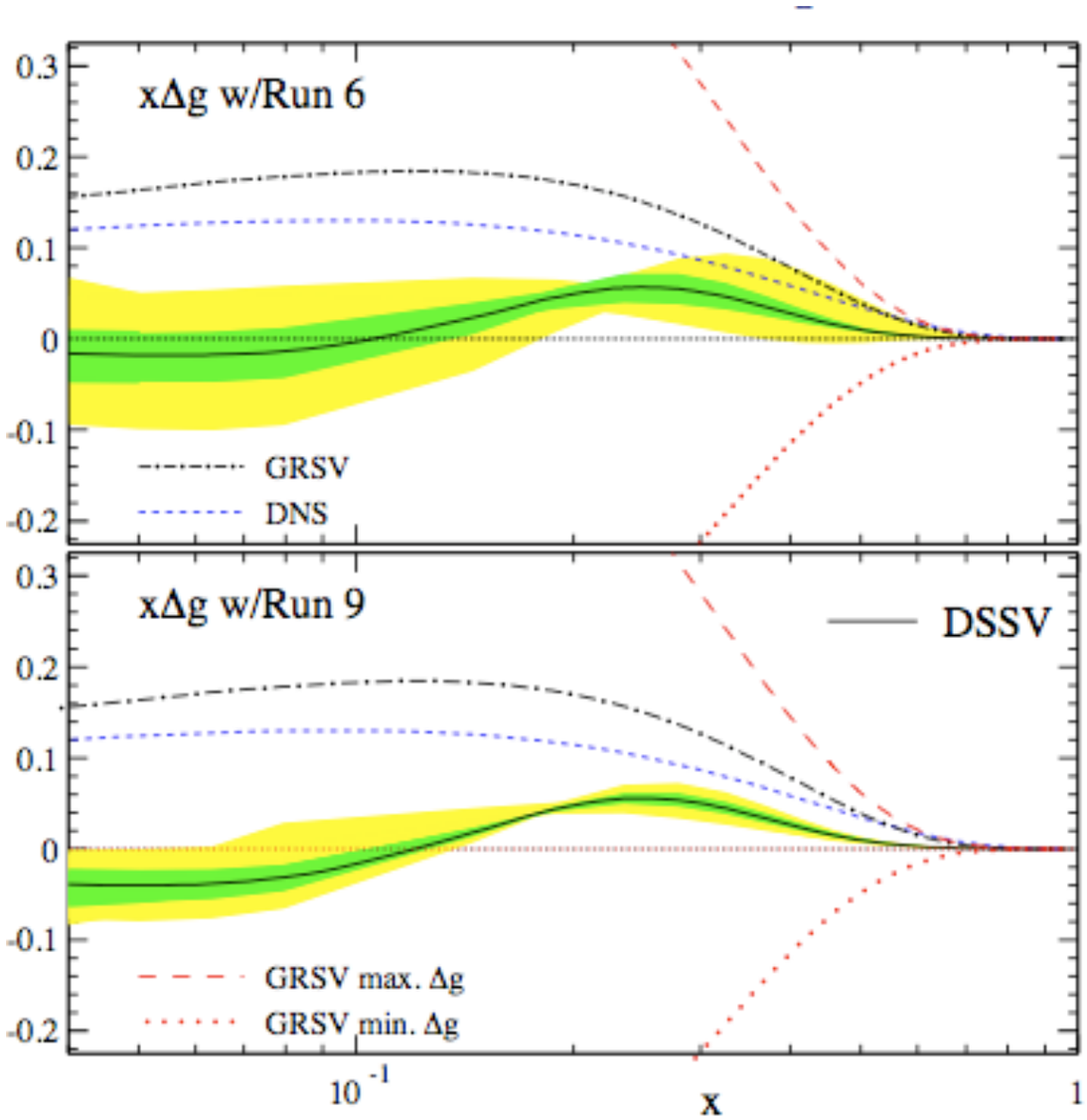
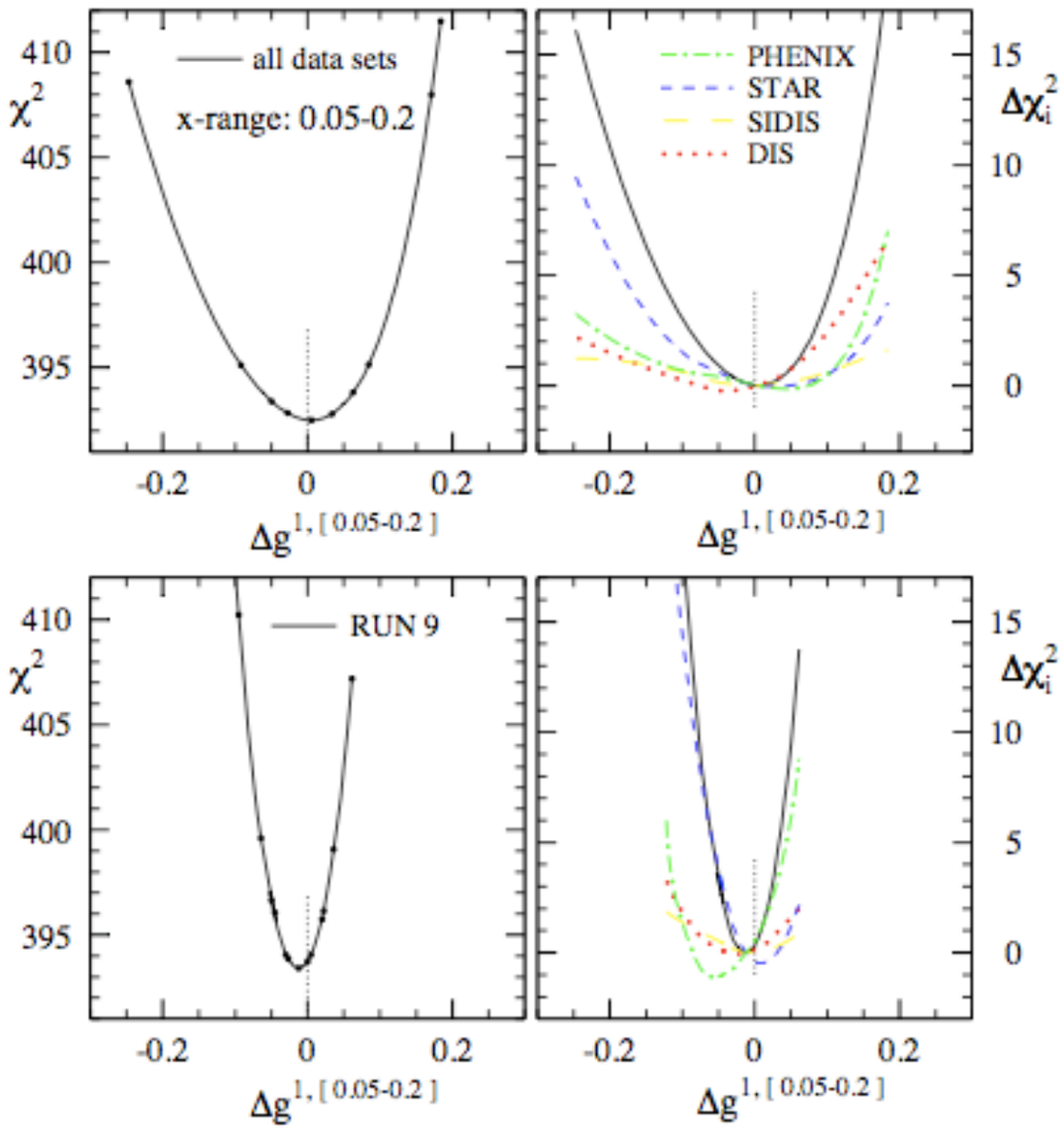
- STAR measures zero Sivers di-jet Asymmetries with proton beams,
- COMPASS measures zero Sivers Asymmetries for proton target,
- Visible tension between data sets,

- Clear roles for COMPASS - better precision,
  JLAB - independent measurement(s),
  RHIC (?) - expect opposite sign for Drell-Yan, photon+jet, and Z^0 production.

A Glimpse into the Near-Term Future

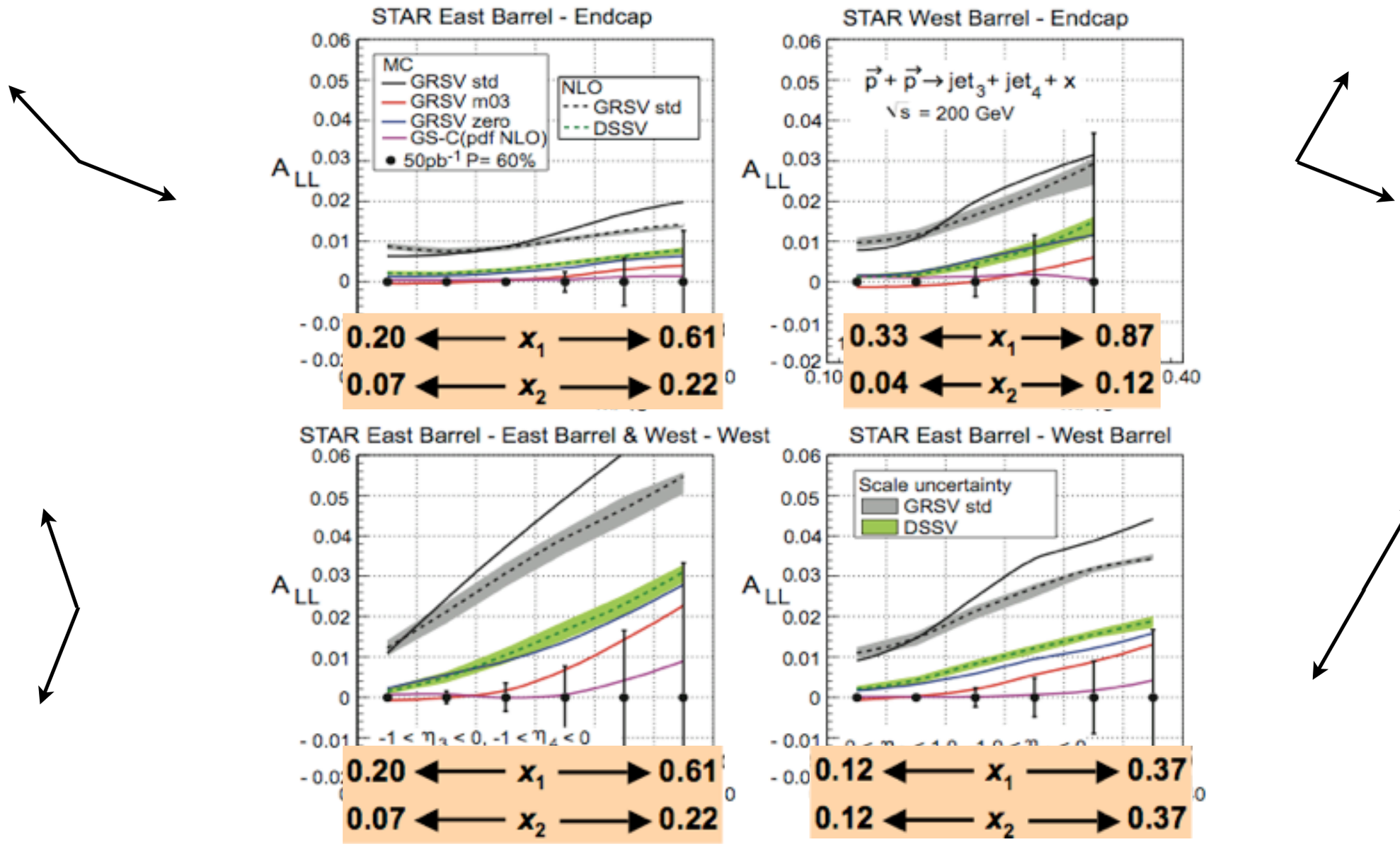
- *Determining* precision on gluon polarization from inclusive probes at RHIC,





A Glimpse into the Near-Term Future

- Determining precision from inclusive probes,
- Use large STAR acceptance to perform correlation (e.g. 2-jet) measurements to gain sensitivity to parton momentum fractions, *x*



- √s = 500 GeV to extend kinematic range and access (anti-)quark polarizations.

Summary

Surprisingly, Quark spins carry only a small fraction of the proton spin,

Polarized RHIC data are probing beyond Quarks,

Gluon spins could carry the rest,

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

or less, which would point at a role for angular momenta (hints from transverse data),

Transverse spin phenomena are a rapidly evolving playground for QCD dynamics,

A non-zero Sivers function, *if* established conclusively, would be *prima facie* evidence for orbital momenta and present a test of "*non-trivial"* universality.