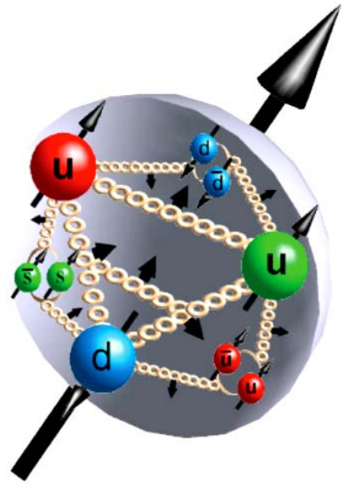


What makes the proton spin?

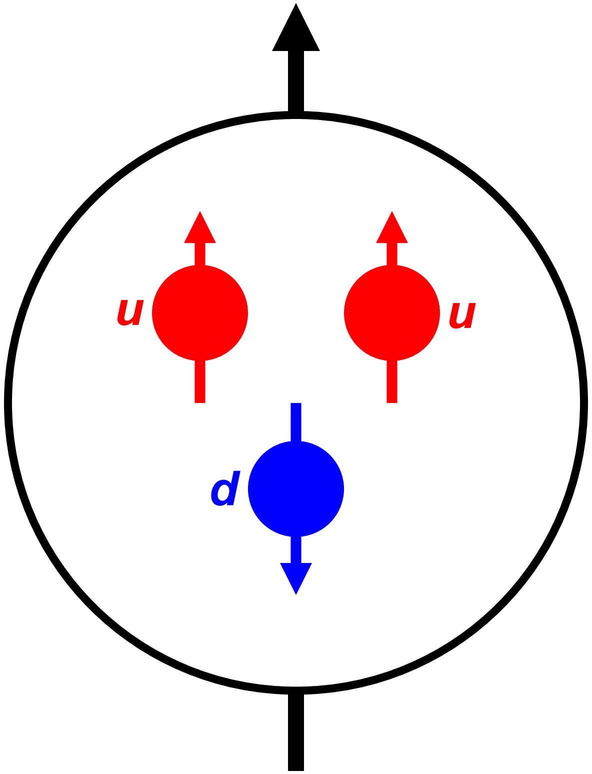
Carl Gagliardi

Texas A&M University

Outline

- Why do we care about the proton spin?
- How do we study it?
- What are we learning?

The proton in the quark model



- We've known that the proton is made of quarks since the 1960's
- The 2 up quarks and 1 down quark together explain the proton quantum numbers: charge, parity, *spin*, …

- **Spin** is a particularly useful tool to explore the proton structure because it arises from **intrinsic quantum mechanical dynamics**

Proton wavefunction in the static quark model

$$\sqrt{\frac{2}{9}}\left|(u\uparrow)(u\uparrow)(d\downarrow)\right\rangle-\sqrt{\frac{1}{18}}\left|(u\uparrow)(u\downarrow)(d\uparrow)\right\rangle-\sqrt{\frac{1}{18}}\left|(u\downarrow)(u\uparrow)(d\uparrow)\right\rangle+$$
$$\sqrt{\frac{2}{9}}\left|(d\downarrow)(u\uparrow)(u\uparrow)\right\rangle-\sqrt{\frac{1}{18}}\left|(d\uparrow)(u\uparrow)(u\downarrow)\right\rangle-\sqrt{\frac{1}{18}}\left|(d\uparrow)(u\downarrow)(u\uparrow)\right\rangle+$$
$$\sqrt{\frac{2}{9}}\left|(u\uparrow)(d\downarrow)(u\uparrow)\right\rangle-\sqrt{\frac{1}{18}}\left|(u\downarrow)(d\uparrow)(u\uparrow)\right\rangle-\sqrt{\frac{1}{18}}\left|(u\uparrow)(d\uparrow)(u\downarrow)\right\rangle$$

x (totally anti-symmetric color wavefunction)

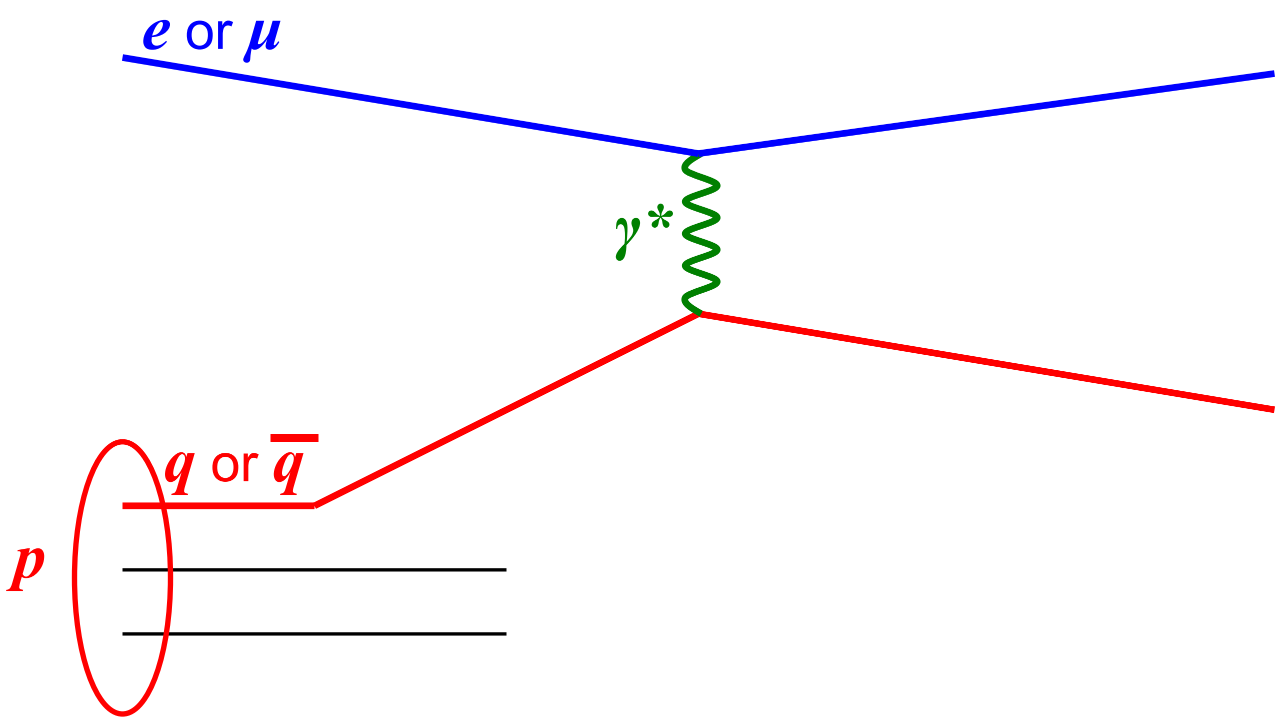
- If $m_u = m_d = m_p/3$. Then:
- Proton magnetic moment:
  - Calculate +3 μ_N; find +2.793 μ_N
- Neutron magnetic moment:
  - Calculate -2 μ_N; find -1.913 μ_N
- Ratio matches prediction to ~3%

If assume quarks are slightly heavier to allow for some binding energy, can match the observed magnetic moments very well

Too good to be true

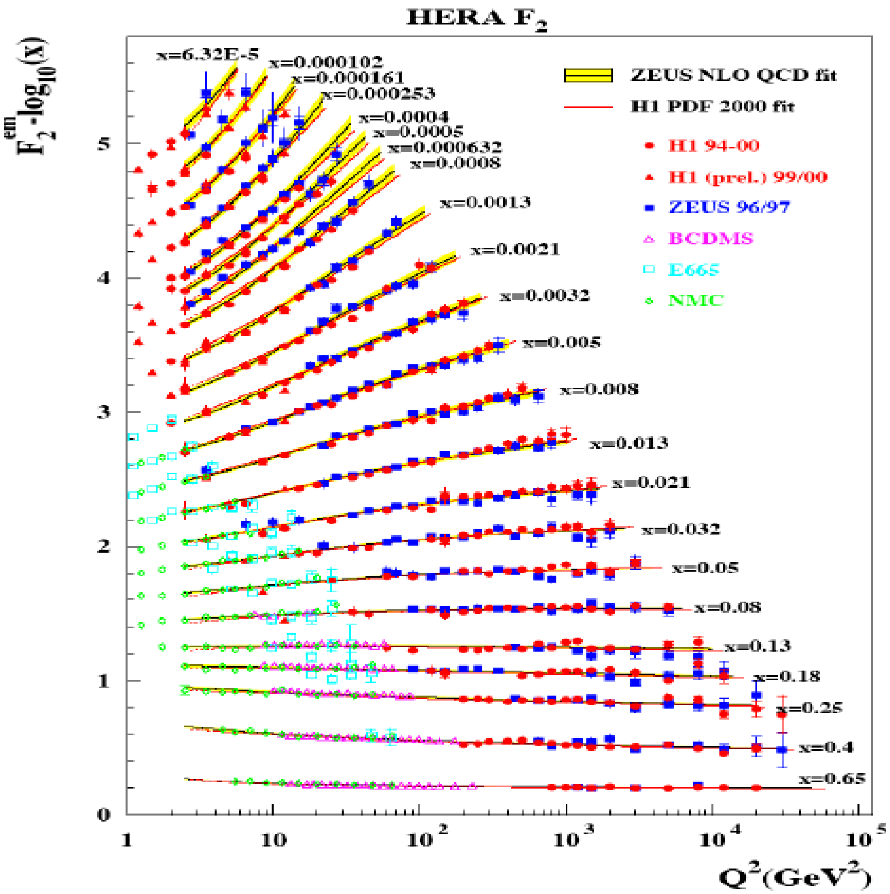
- The proton radius is ~0.85 fm
- Heisenberg Uncertainty Principle implies quark motion must be relativistic
- Relativistic quark model
  - Quarks are no longer restricted to *s*-wave states
  - Quark spin accounts for ~60% of the proton spin
  - Rest of proton spin comes from quark orbital angular momentum
- No binding force in these calculations
- Strong force (Quantum Chromodynamics) provides the quark binding
  - Gluons must also be present
  - Can also have additional quark-antiquark pairs
- **How can we observe these quarks, antiquarks, and gluons?**

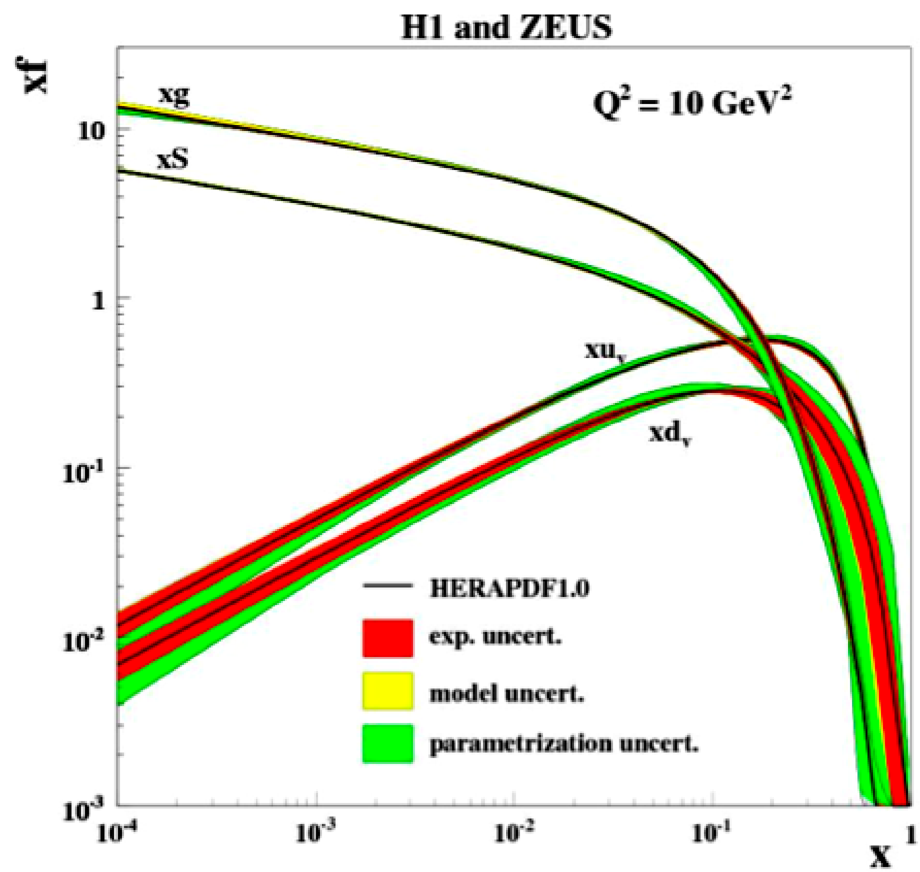
Looking inside the proton



- "Deep-inelastic scattering" (DIS) of electrons and muons off protons has taught us a great deal about the internal structure of the proton
- Interaction is electromagnetic → only quarks and anti-quarks participate directly
- Obtain information about gluons indirectly

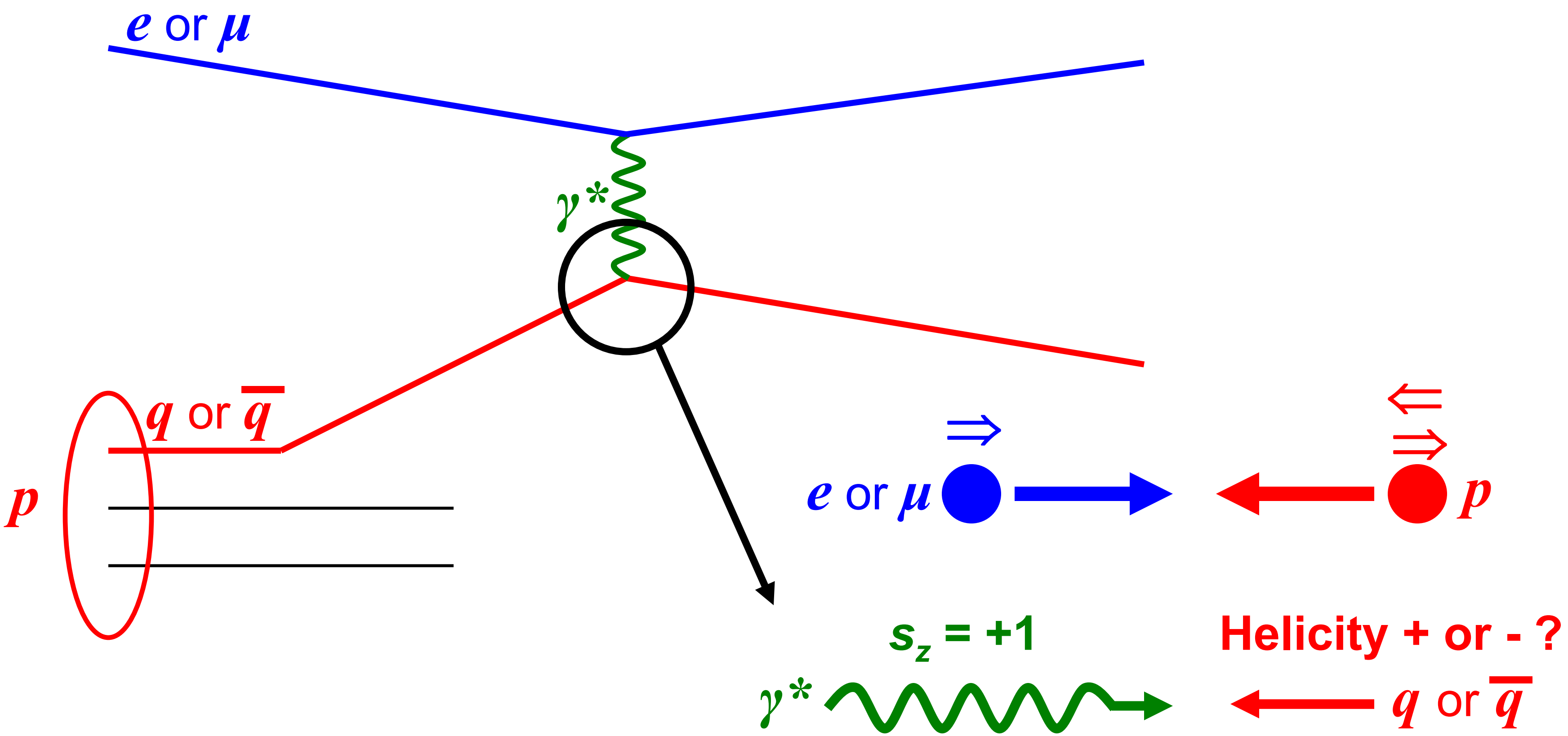
Parton distribution functions





- Probability of finding a quark or gluon inside the proton carrying a fraction *x* of the total momentum of the proton
- Find **more gluons** than anything else
- Gluons carry **half the momentum** of the proton

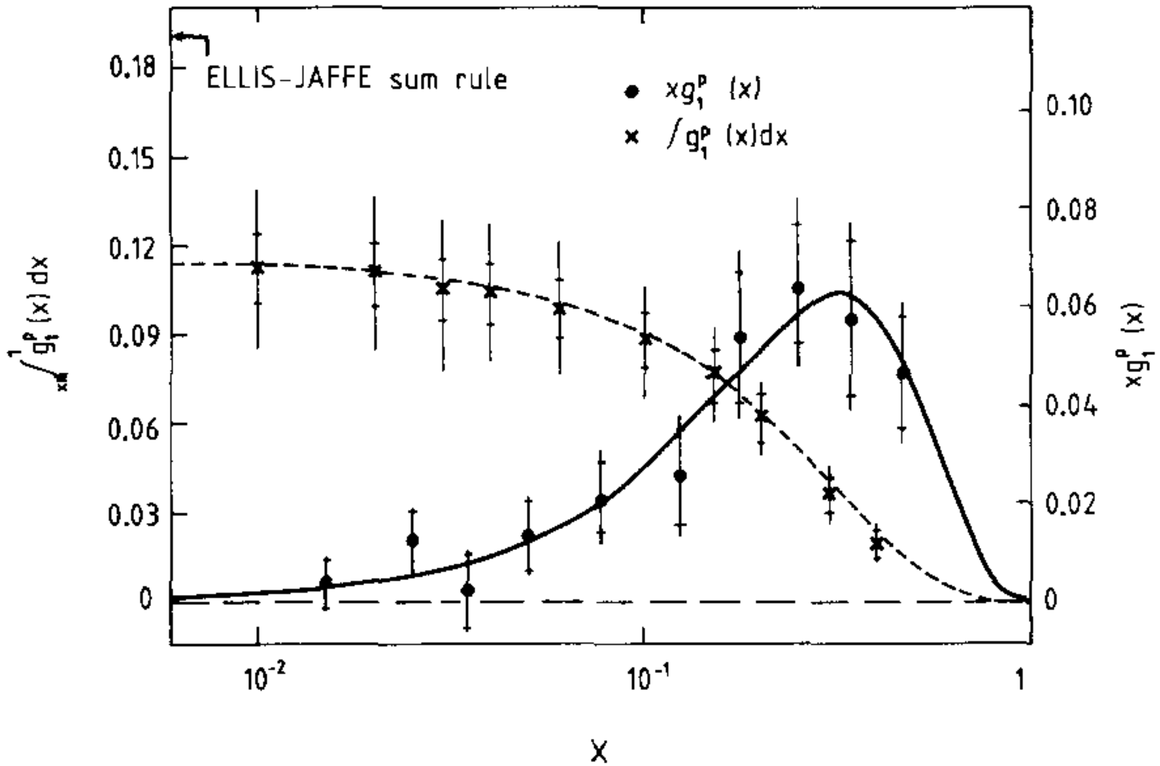
Microscopic origin of the proton spin



- Measure deep-inelastic scattering with polarized electrons or muons off polarized protons
- Difference in cross section for like vs. unlike helicity beams provides information about spin orientations of the quarks inside the polarized proton

Proton "spin crisis"

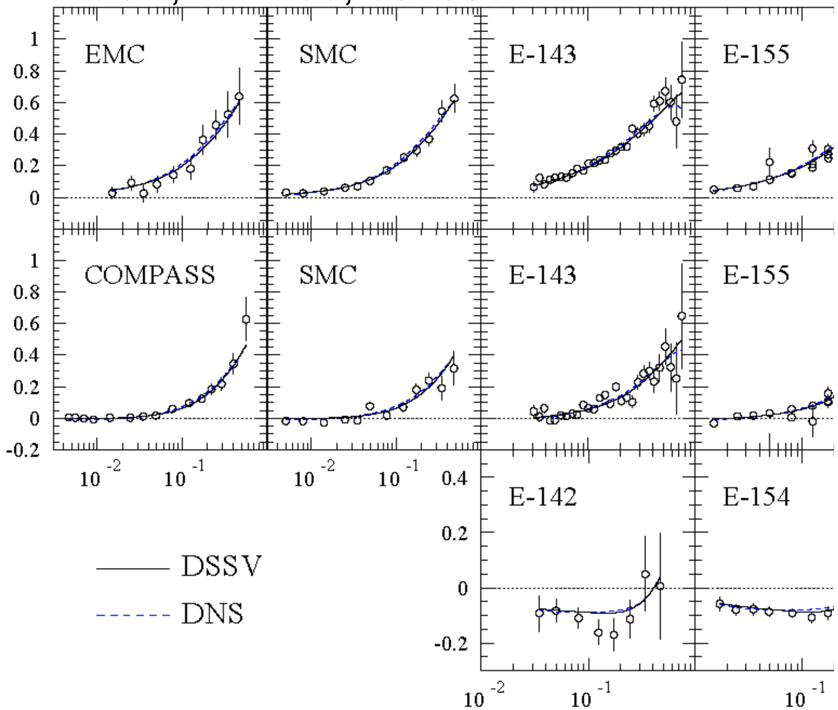
EMC, PLB 206, 364

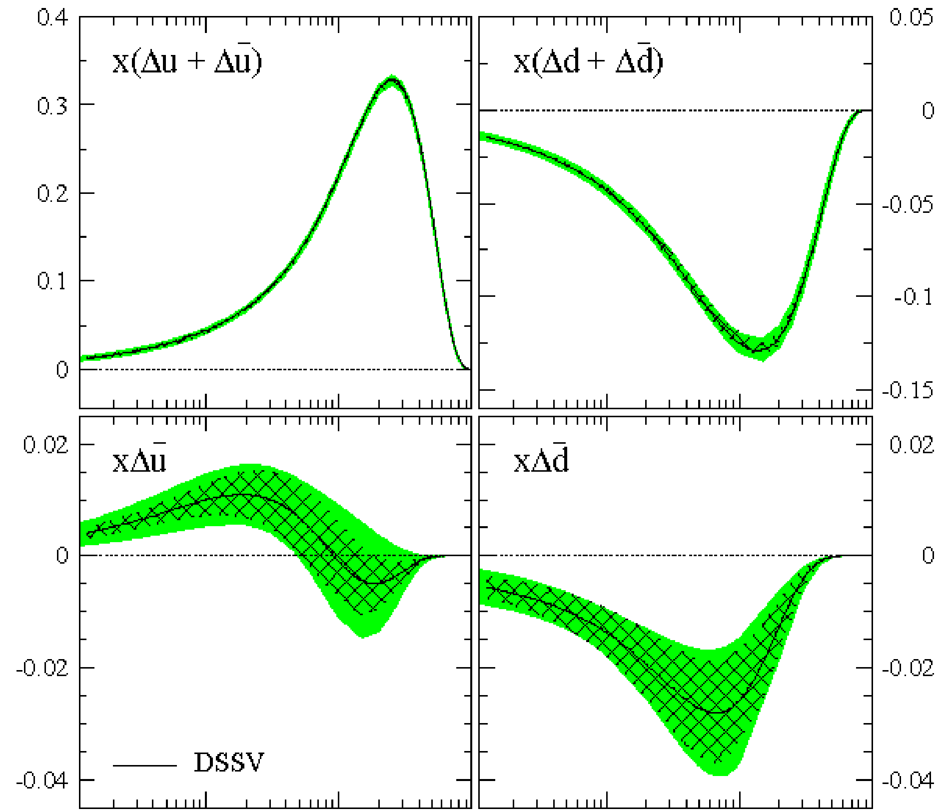


- First measurement over a broad kinematic region was performed by the European Muon Collaboration in the mid-'80s
- Found that quarks contribute only **(14 ± 9 ± 21)%** of the proton spin

Since EMC

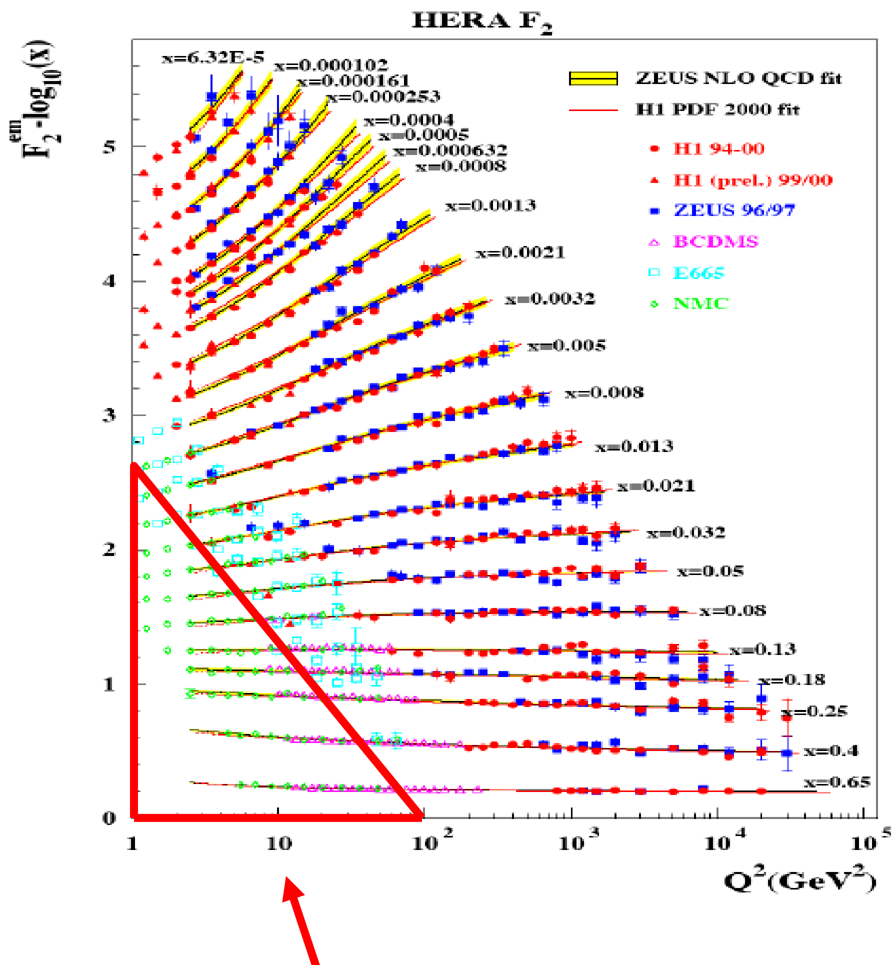
DSSV, PRD 80, 034030



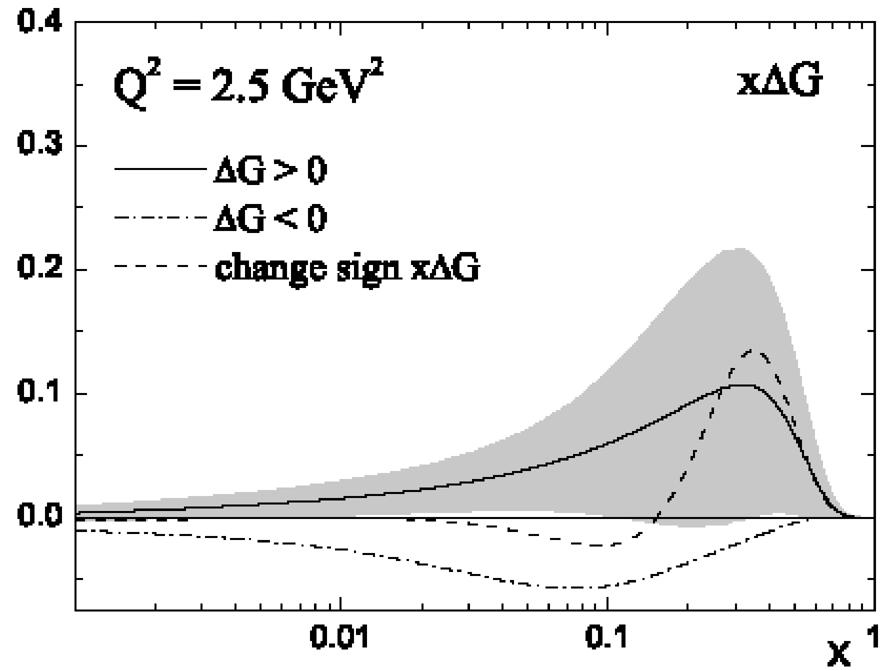


- Many subsequent measurements
- Results are well described by "global analyses" that find best-fit *polarized* parton distribution functions
- Polarization of $u+\bar{u}$ and $d+\bar{d}$ quarks well determined
  - Individual u, $\bar{u}$, d, $\bar{d}$ polarizations have much larger uncertainty
- Only **~30% of the proton spin** arises from quarks and antiquarks

What about gluon polarization?



Kinematic region of ***polarized*** measurements



Three fits of equal quality:

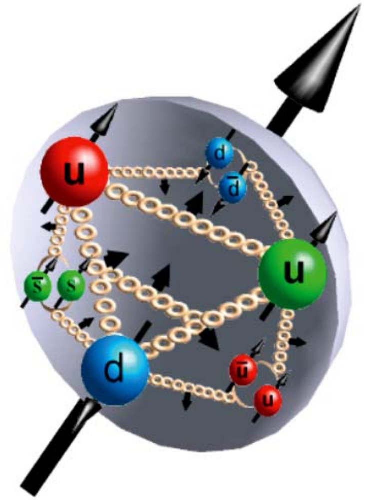
- $\Delta G = 0.13 \pm 0.16$
- $\Delta G \sim 0.006$
- $\Delta G = -0.20 \pm 0.41$

all at $Q^2 = 1$ GeV^2

Leader et al, PRD 75, 074027

What contributes to the proton spin?

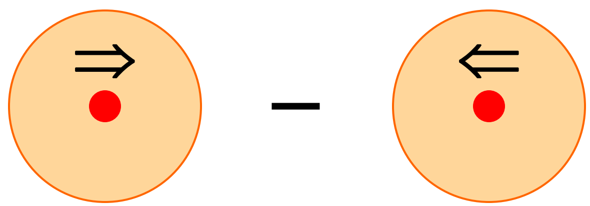
Consider a proton moving toward the right



Helicity

Δq(x)
Δg(x)

Proton spin ⇒

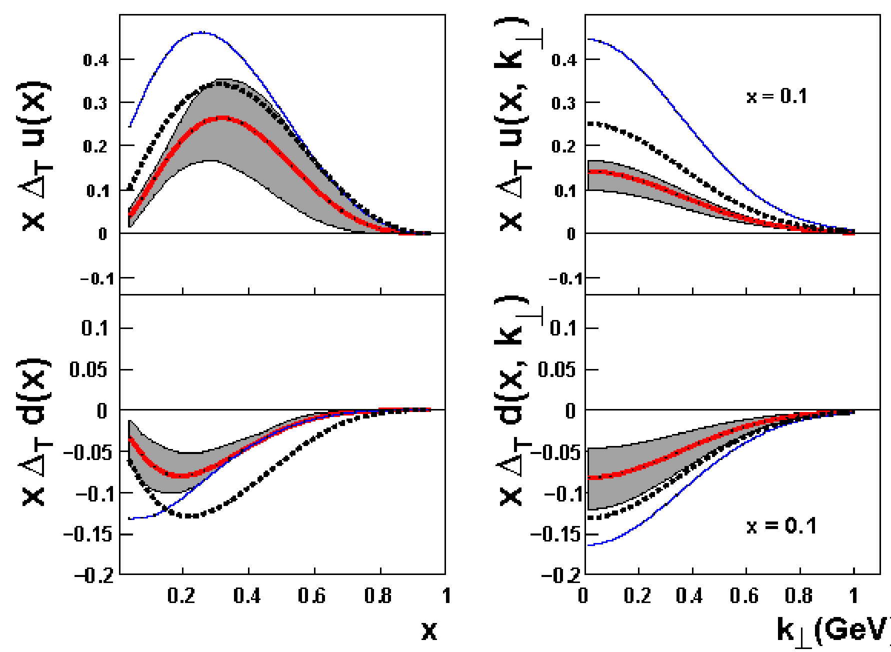


Polarized DIS: ~ 0.3

Spin sum rule: $\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma$

Poorly

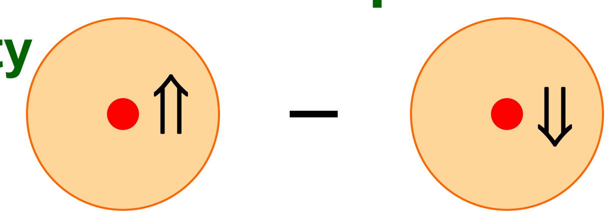
Anselmino et al, arXiv:0812.4366



Proton spin ⇑

Transversity

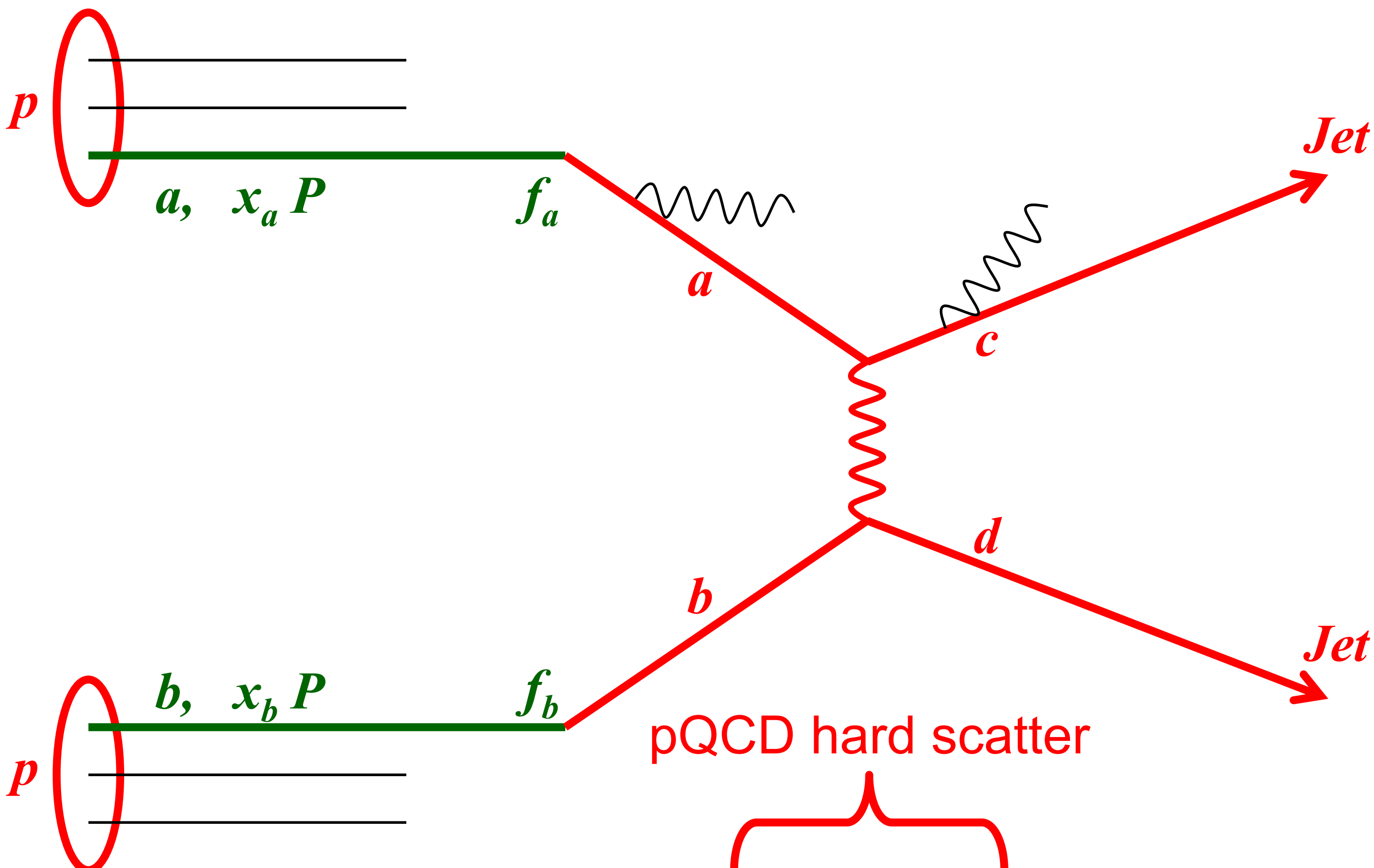
δq(x)



Very little data

What makes the proton spin?

$p + p$ collisions in perturbative QCD



pQCD hard scatter

$$\sigma = \sum f_a(x_a, Q^2) f_b(x_b, Q^2) \hat{\sigma}_{a+b \to c+d}$$

Parton distribution functions

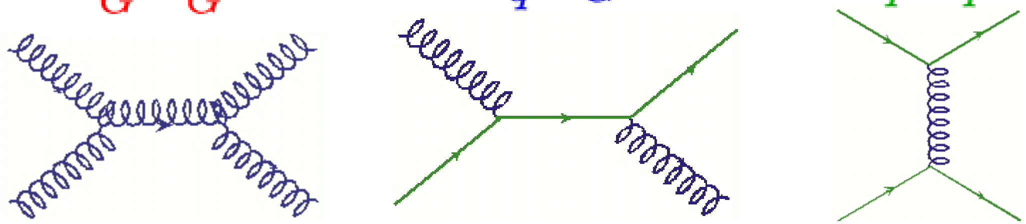
***a* and *b* can be quarks, gluons, or a combination**

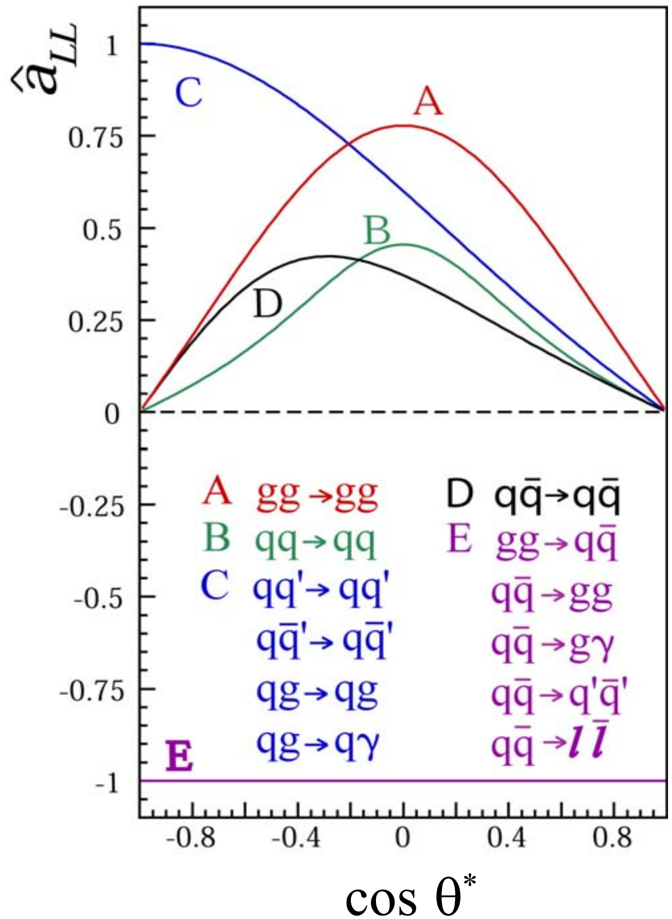
Exploring gluon polarization at RHIC

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

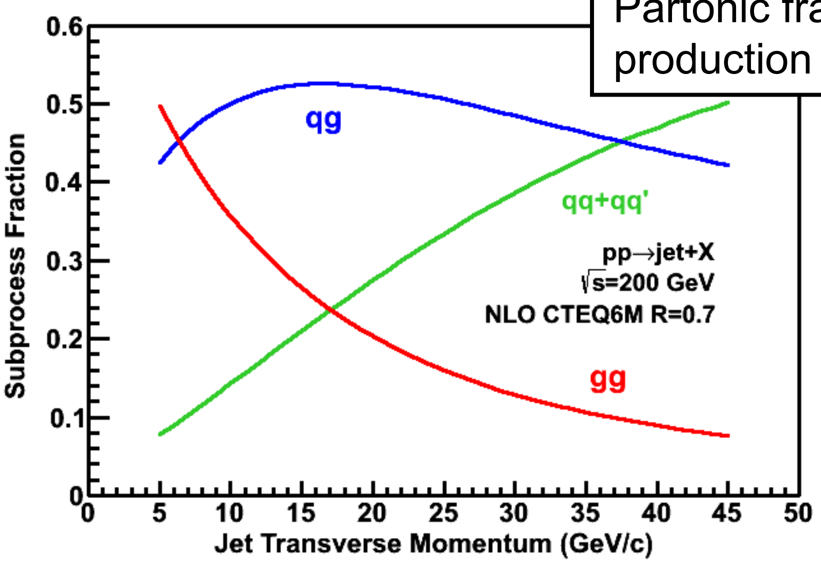
Δf: polarized parton distribution functions

$\frac{\Delta G}{G} \frac{\Delta G}{G}$ $\frac{\Delta q}{q} \frac{\Delta G}{G}$ $\frac{\Delta q}{q} \frac{\Delta q}{q}$



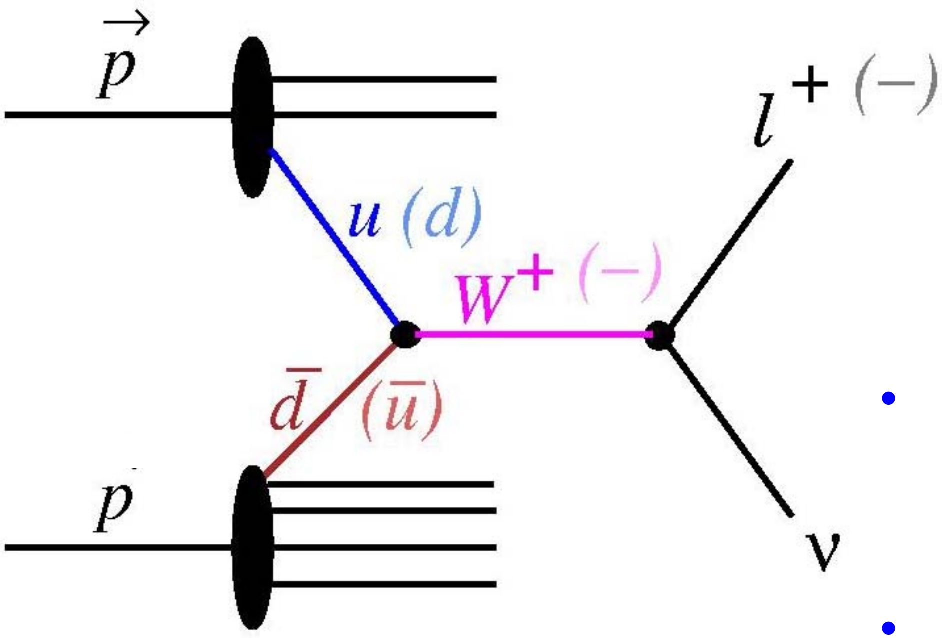


Partonic fractions in jet production at 200 GeV



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

Separating quark and anti-quark polarizations



$$u + \bar{d} \rightarrow W^{+} \rightarrow e^{+} + \nu$$

$$\bar{u} + d \rightarrow W^{-} \rightarrow e^{-} + \bar{\nu}$$

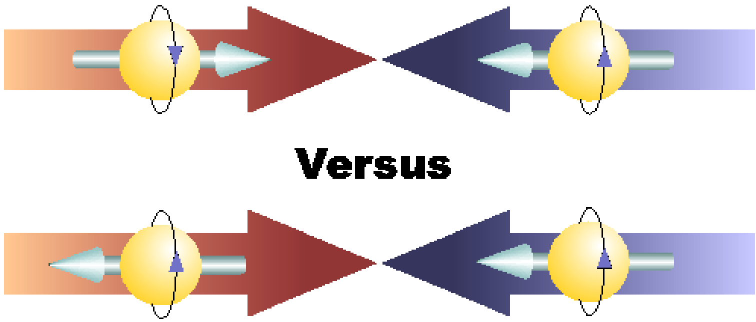
- Weak interaction process
  - Only left-handed quarks
  - Only right-handed anti-quarks
- Perfect spin separation

Measure parity violating single helicity asymmetry A_L

(Helicity flip in one beam while averaging over the other)

$$A_L^{W-} \propto -\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2) \qquad A_L^{W^+} \propto -\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)$$

What's needed to determine A_{LL}?



N_{++}: yield when helcities same

N_{+-}: yield when helcities opposite

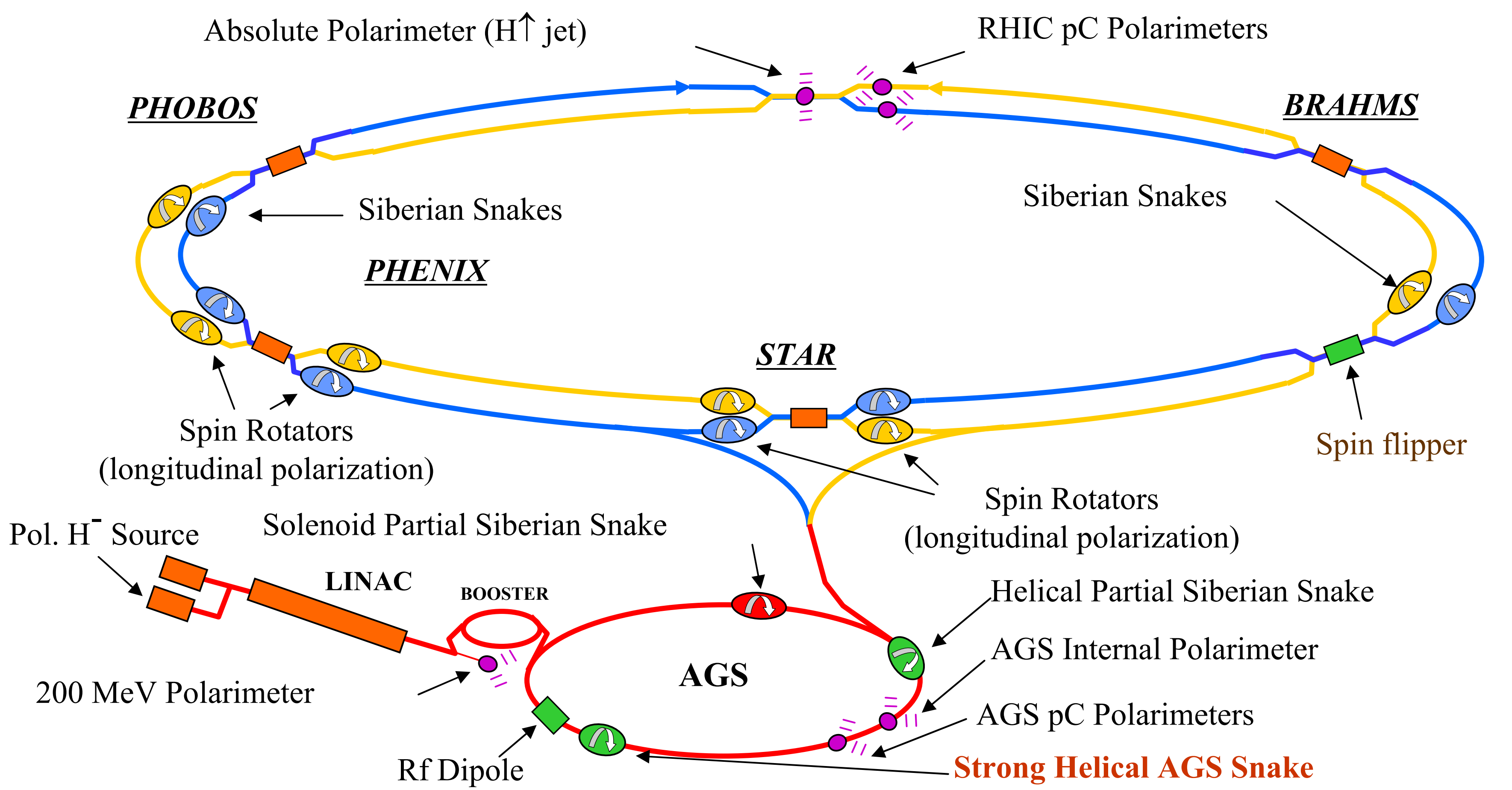
$$A_{LL} = \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}} \quad \text{where} \quad R = \frac{L_{++}}{L_{+-}}$$

- Three concurrent measurements:
  - Beam polarizations
  - Relative luminosities
  - Event yields
- A_L is done similarly, but with one beam polarized and one unpolarized

RHIC: the Relativistic Heavy Ion Collider

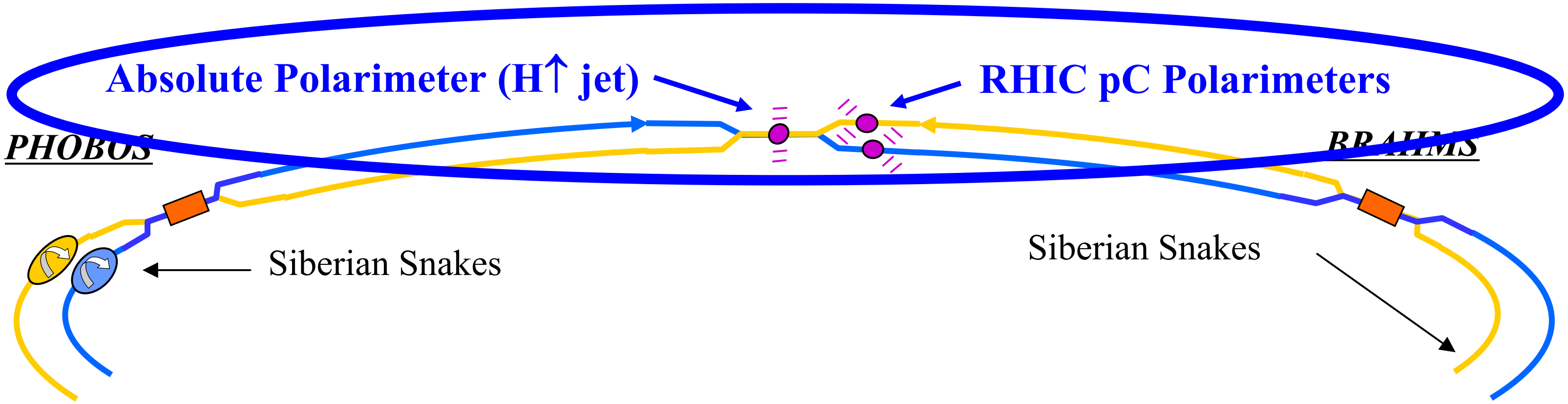
- Search for and study the Quark-Gluon Plasma
- **Explore the partonic structure of the proton**
- Determine the partonic structure of nuclei

RHIC: the world's first (and only!) polarized hadron collider



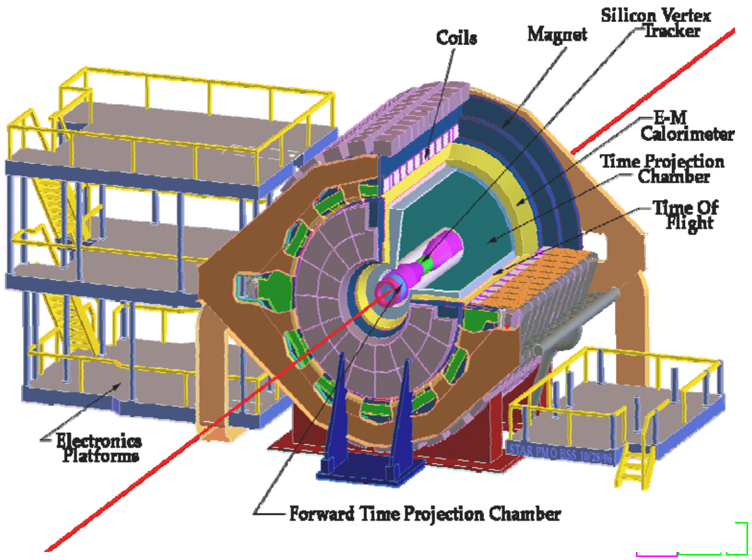
- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization

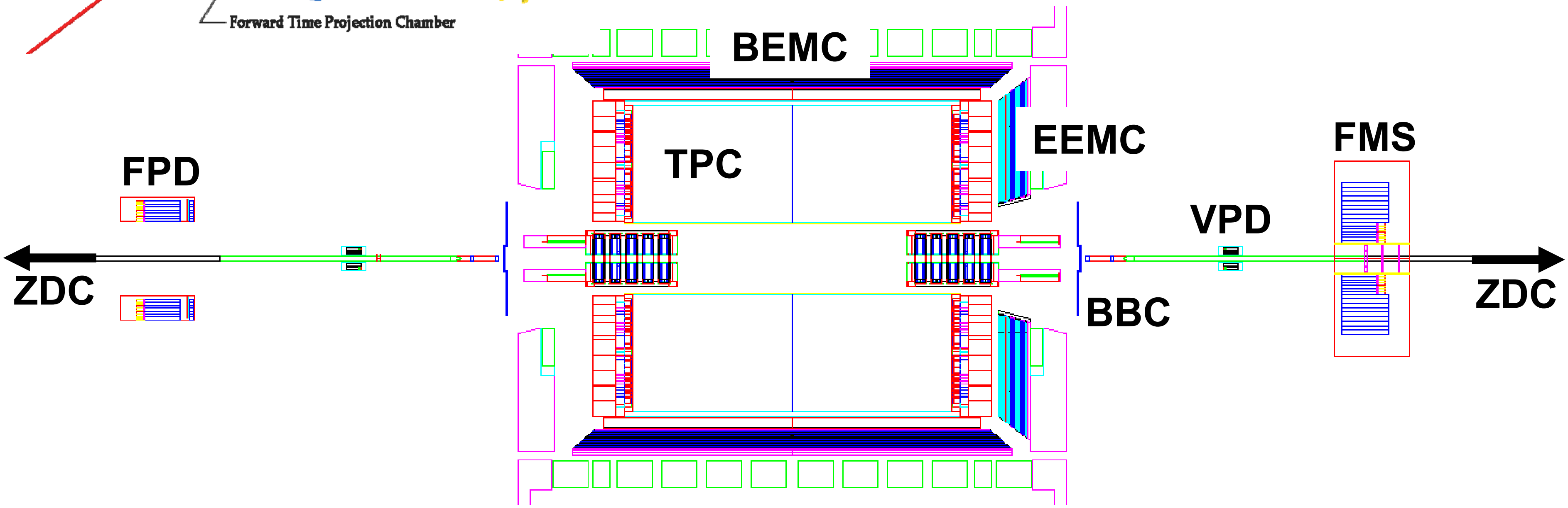
Measuring the polarization



- p-Carbon
  - Quick measurements
  - Determine beam polarization and intensity profiles
  - Multiple measurements give time dependence during a fill
  - Only give relative measurements
- H Jet
  - Circulating beams scatter off a polarized H atomic beam
    - Atomic beam polarization known with high precision
  - Provides absolute determination of the circulating beam polarizations averaged over each fill

Event yields and luminosity: the ***STAR*** detector in two views

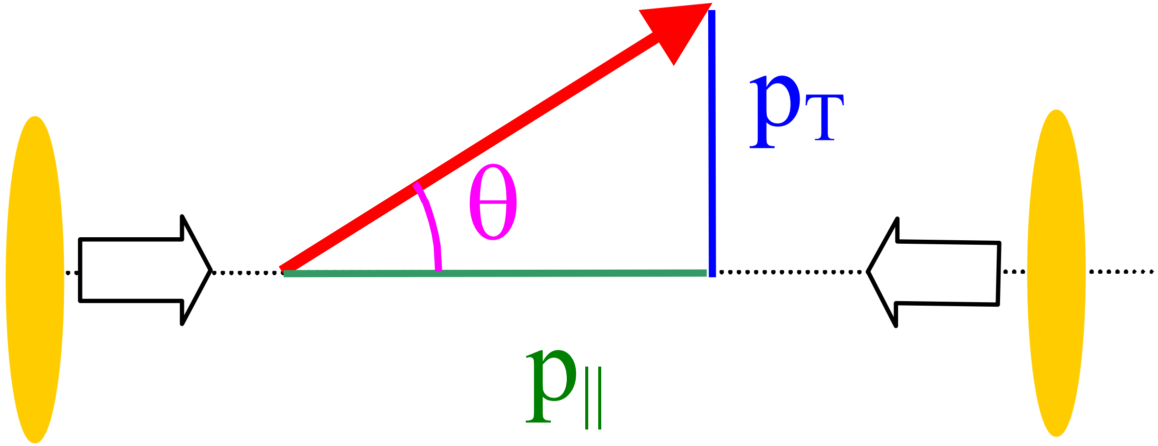




- High precision tracking with the TPC
- Electromagnetic calorimetry with the BEMC, EEMC, and FMS
- Additional detectors for relative luminosity, local polarimetry, and minbias triggering

What are we learning?

Kinematics for colliders



Pseudo-rapidity: $\eta = -\ln[\tan(\theta/2)]$

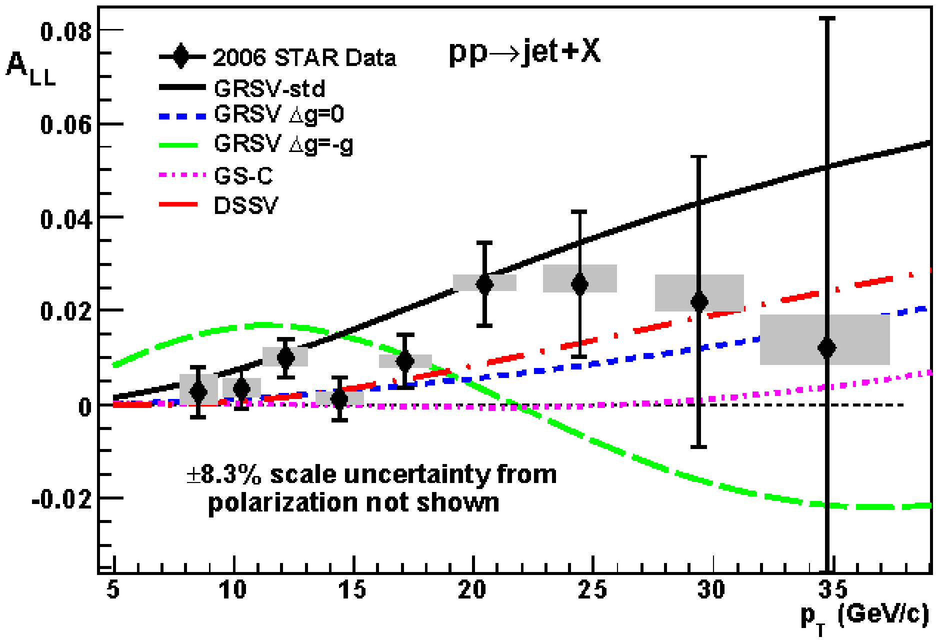
Transverse momentum (p_T) and pseudorapidity (η) provide a convenient description

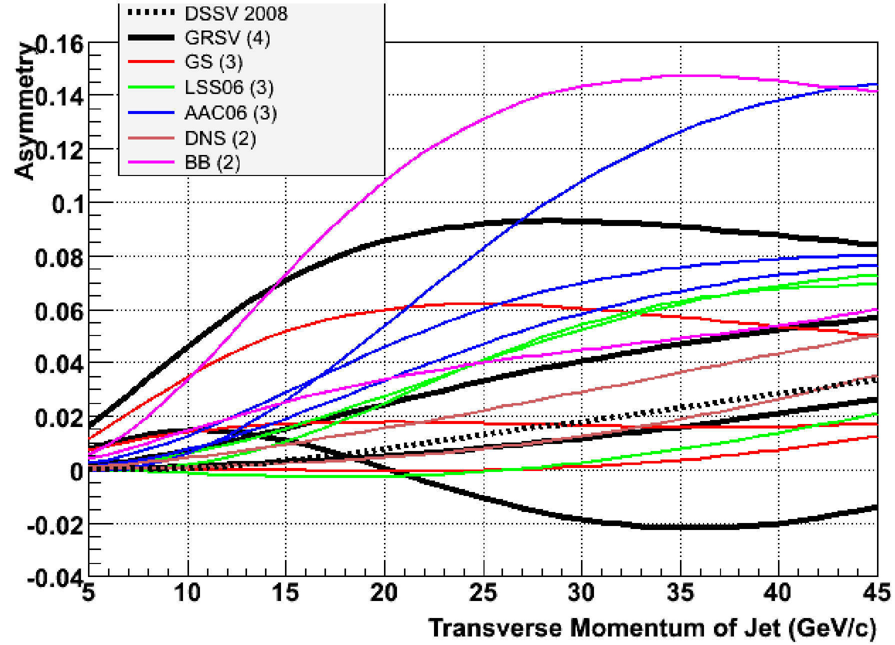
$$p_z = p_T \sinh(\eta)$$

$$p_{tot} = p_T \cosh(\eta)$$

Mid-rapidity:	$\eta = 0$, perpendicular to the incident beams
$\eta = 1$:	Scattering at $\theta \sim 40^0$ in the CM (or lab) frame
$\eta = 2$:	Scattering at $\theta \sim 15^0$ in the CM (or lab) frame

STAR inclusive jet A_{LL} from 2006

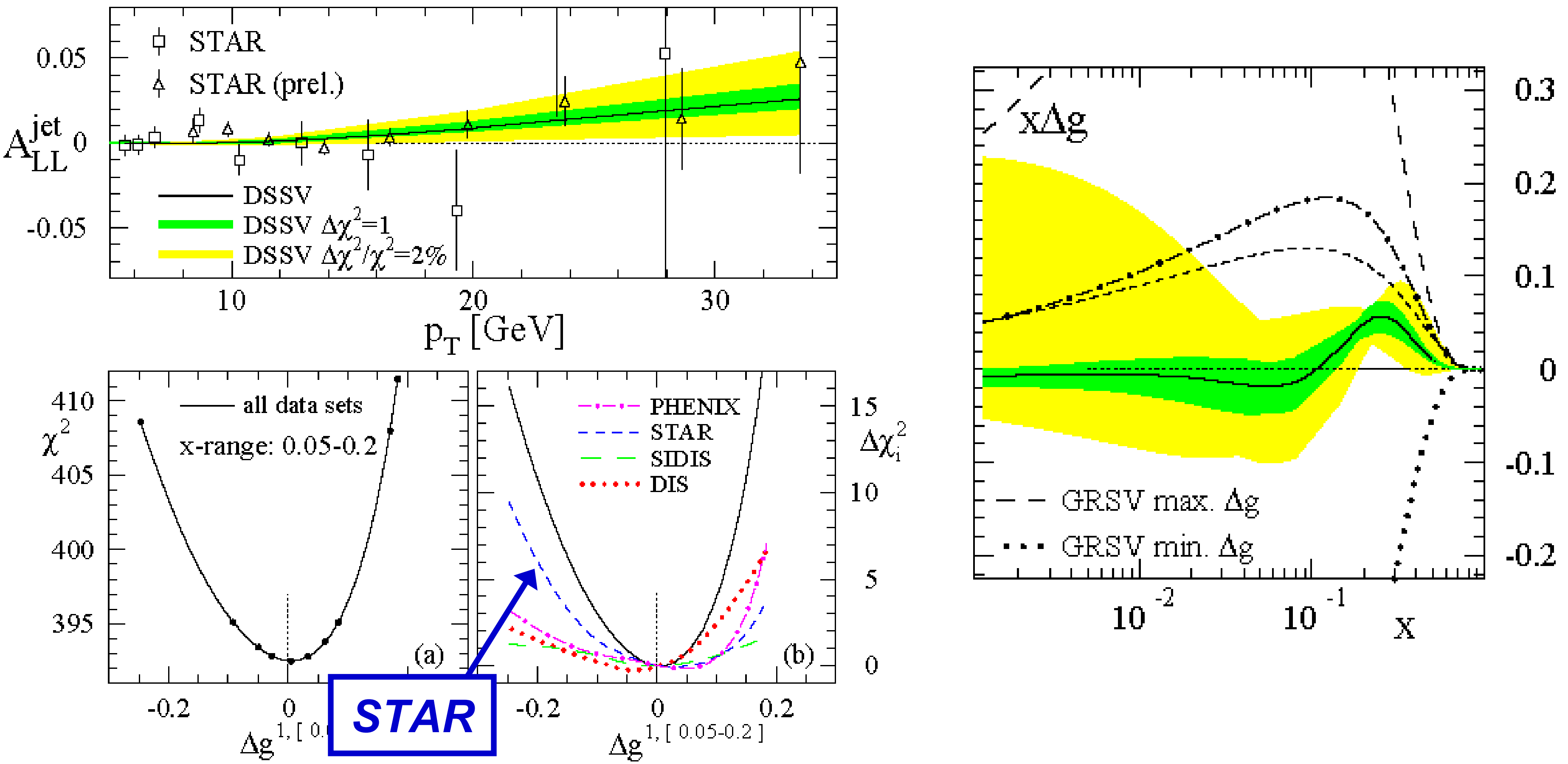




- ***STAR*** inclusive jet A_{LL} excludes those scenarios that have a large gluon polarization within the accessible *x* region

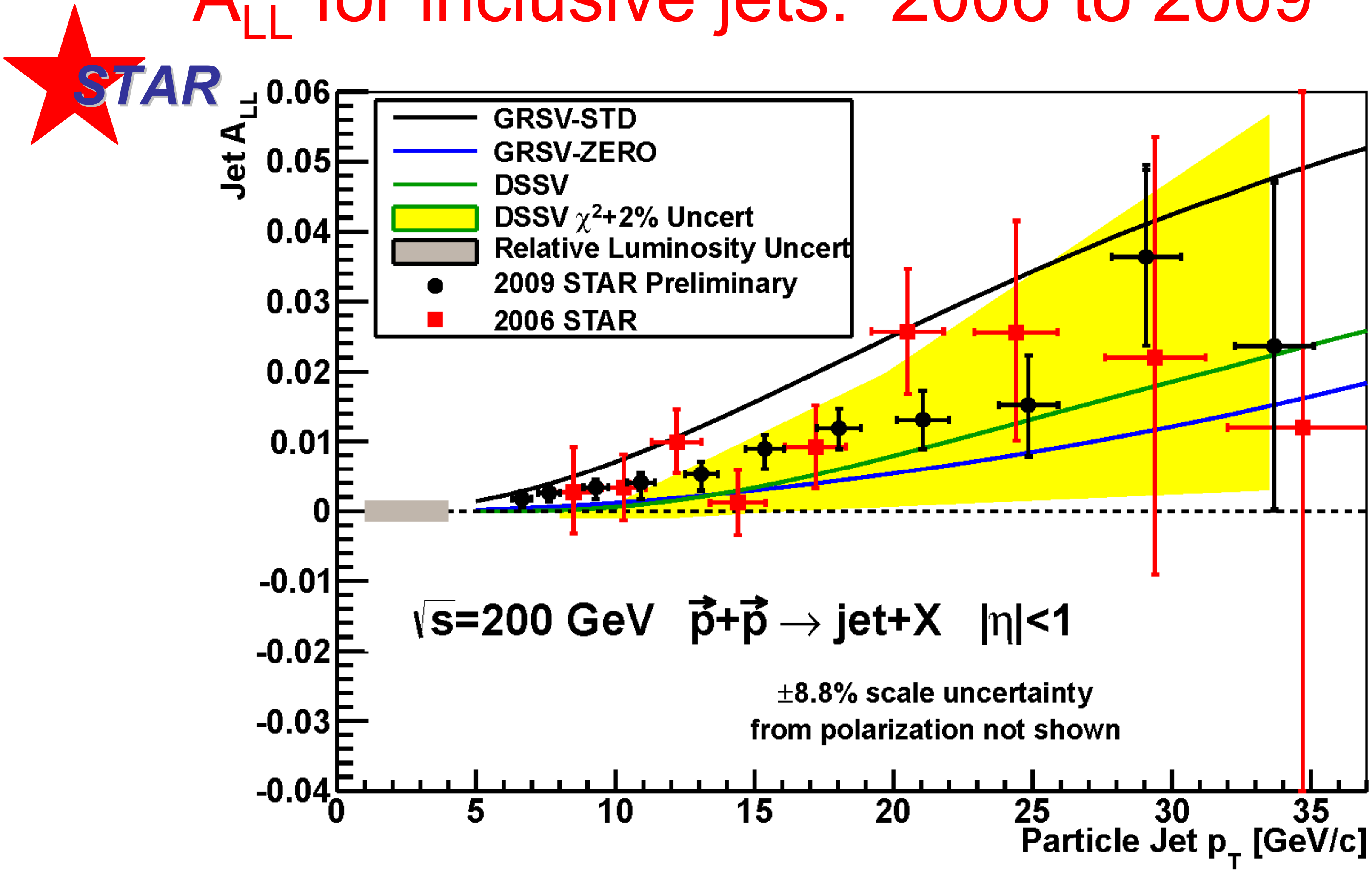
DSSV – first global analysis with polarized jets

de Florian et al., PRL 101, 072001



- The first global NLO analysis to include inclusive DIS, SIDIS, and RHIC pp data on an equal footing

A_{LL} for inclusive jets: 2006 to 2009

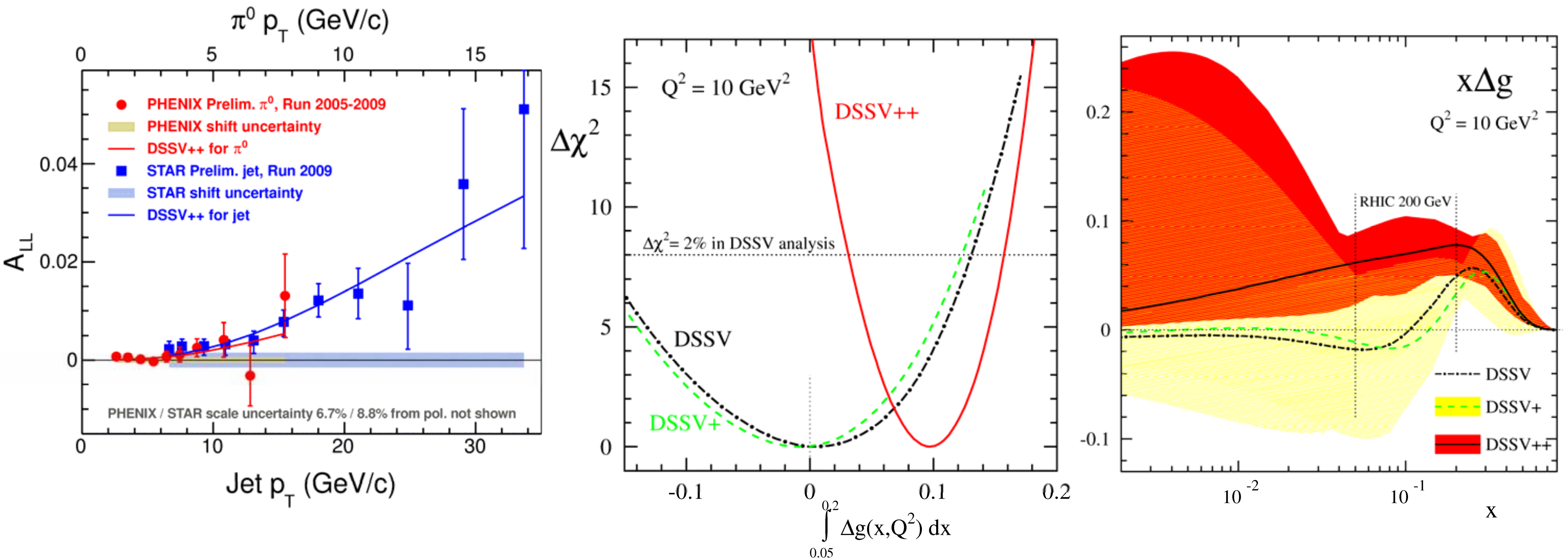


- 2009 ***STAR*** inclusive jet A_{LL} measurements are a factor of 3 (high-p_T) to >4 (low-p_T) more precise than 2006
- **Results fall between predictions from DSSV and GRSV-STD**

New global analysis with 2009 RHIC data

arXiv:1304.0079

Special thanks to the DSSV group!

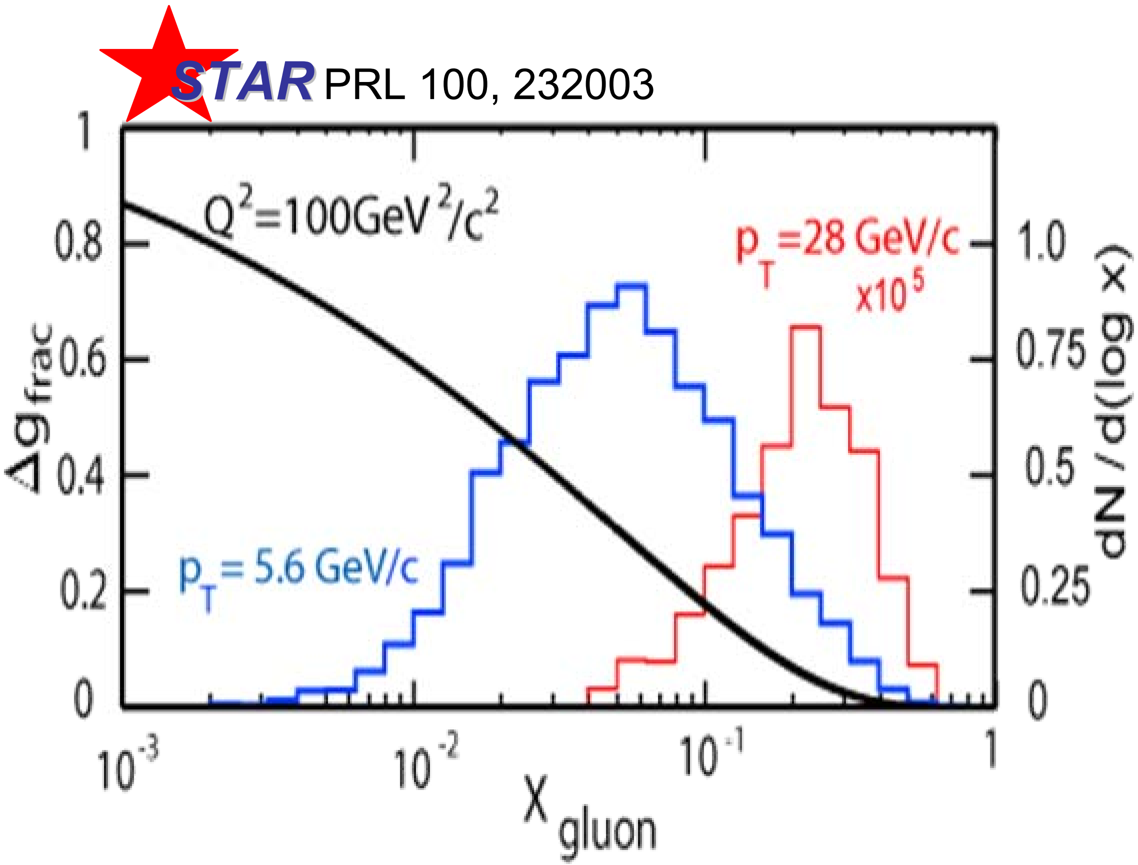


- **DSSV++** is a new, preliminary global analysis from the DSSV group that includes preliminary 2009 A_{LL} measurements from PHENIX and STAR

$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2)\,dx = 0.10^{+0.06}_{-0.07}$$

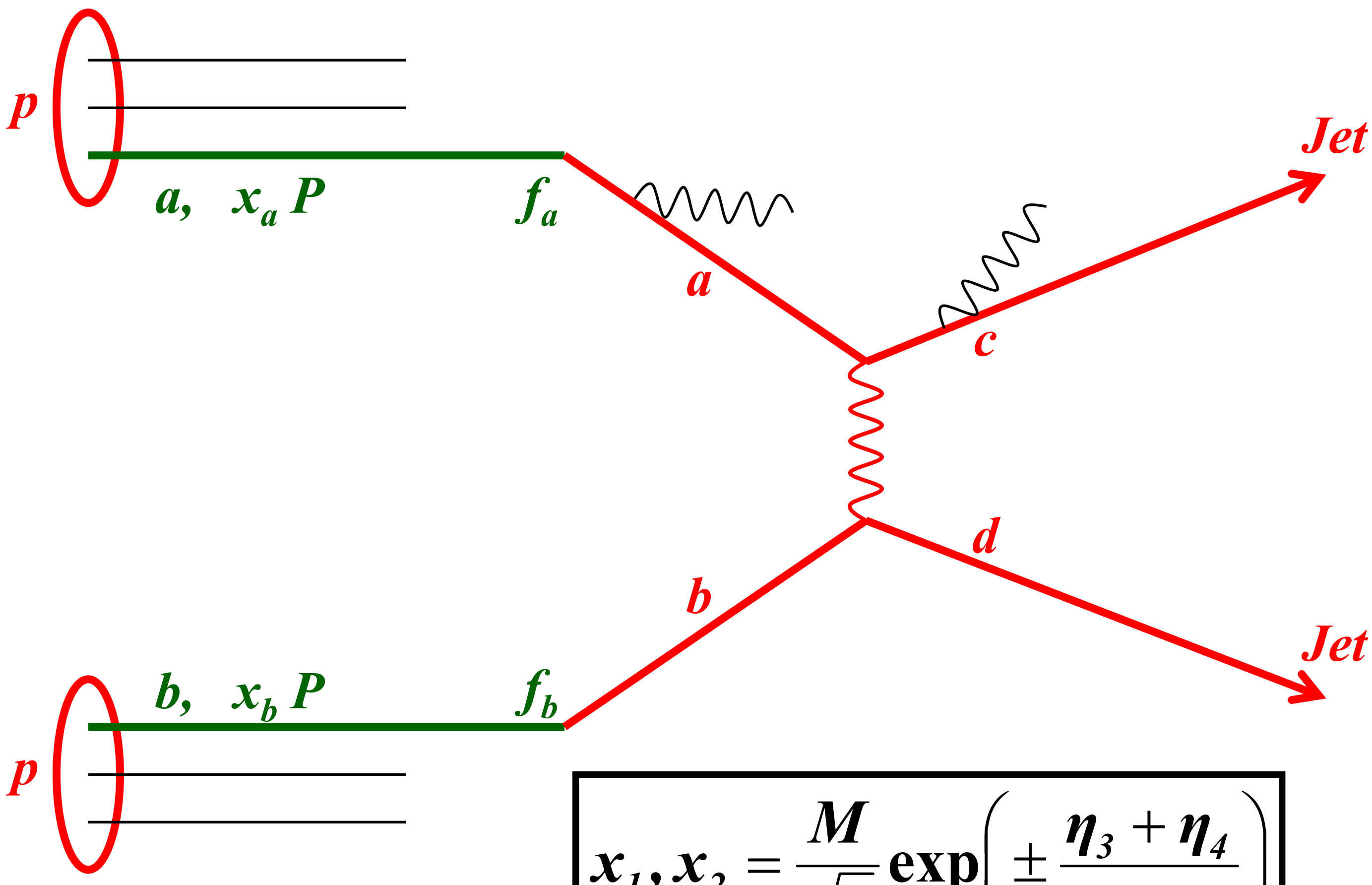
- **First experimental evidence of non-zero gluon polarization** in the RHIC range (0.05 < x < 0.2)

Beyond inclusive A_{LL} measurements



- Inclusive A_{LL} measurements at fixed p_T average over a **broad x range**.
- Can hide considerable structure if $\Delta g(x)$ has a node
- **Di-jet measurements can constrain the shape of $\Delta g(x)$**

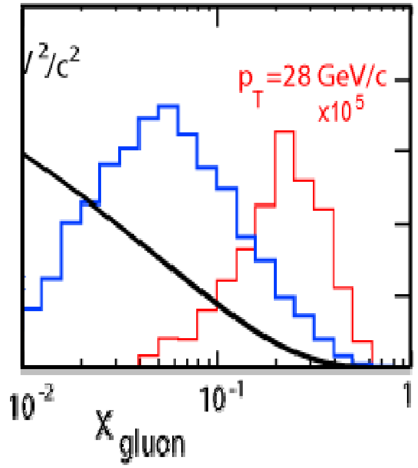
$p + p$ collisions in perturbative QCD

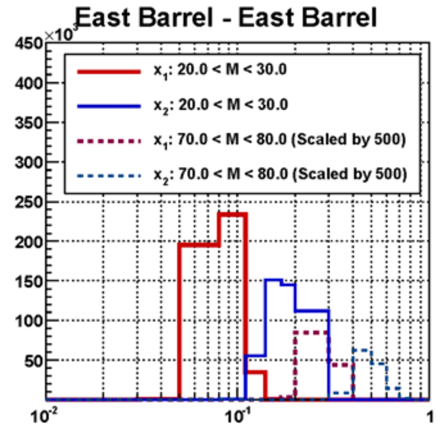


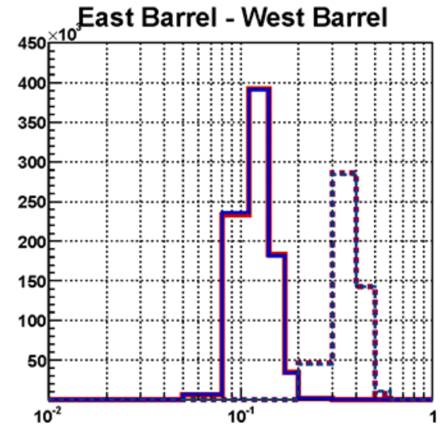
$$x_1, x_2 = \frac{M}{\sqrt{s}} \exp\left(\pm \frac{\eta_3 + \eta_4}{2} \right)$$

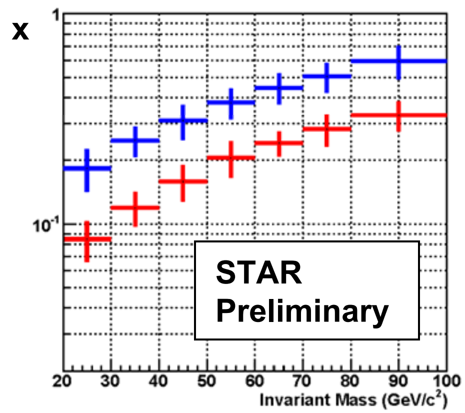
- Di-jets provide direct access to parton kinematics at leading order

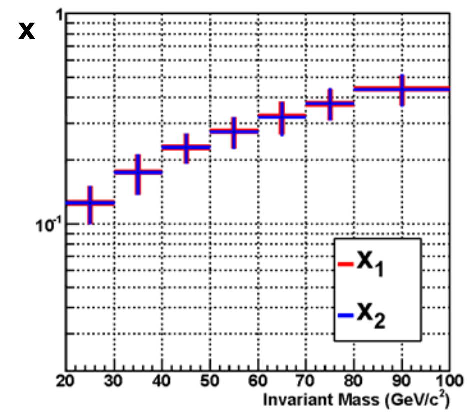
2009 ***STAR*** di-jet partonic coverage











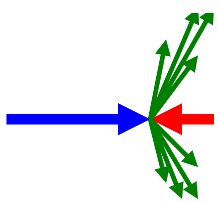
$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T,3}e^{\eta_3} + p_{T,4}e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T,3}e^{-\eta_3} + p_{T,4}e^{-\eta_4}\right)$$

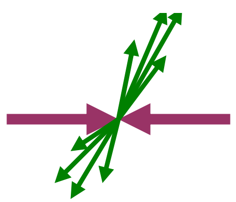
$$M = \sqrt{x_1 x_2 s}$$

$$y = \frac{1}{2}\ln\frac{x_1}{x_2} = \frac{\eta_3 + \eta_4}{2}$$

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



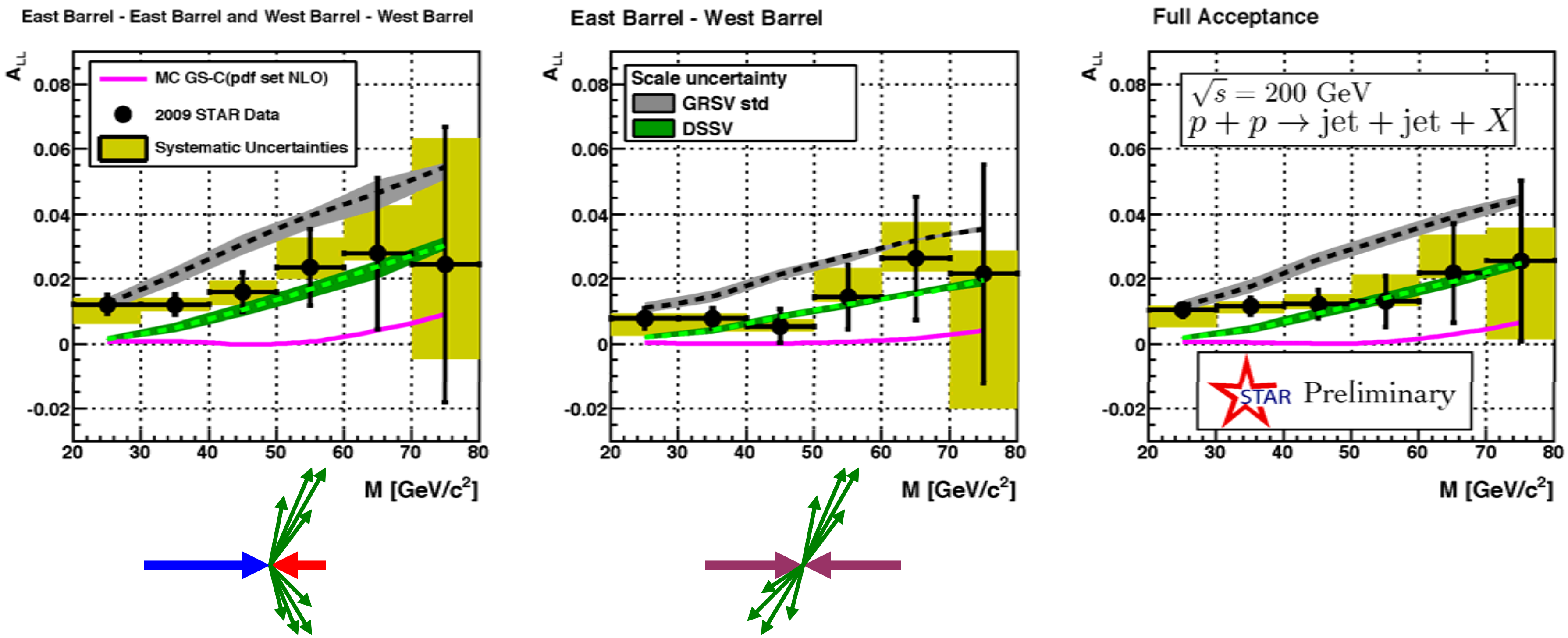
Asymmetric collisions



Symmetric collisions

2009 ***STAR*** di-jet A_{LL}

STAR



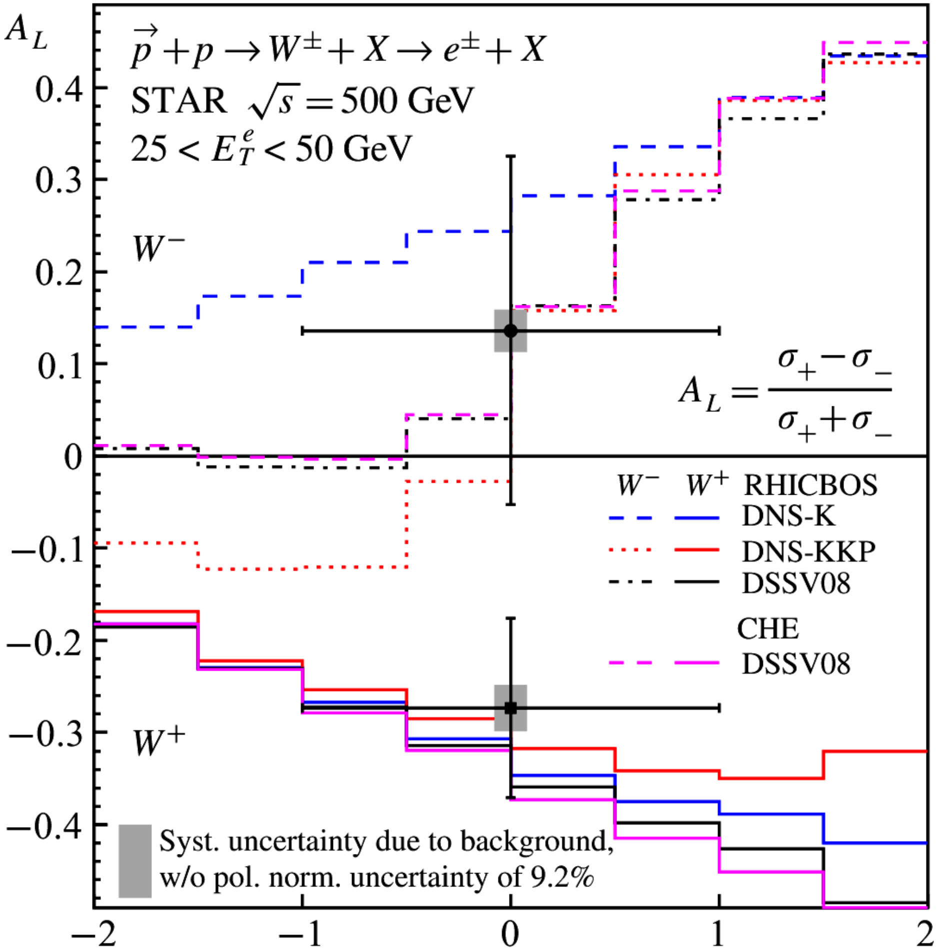
Asymmetric collisions

Symmetric collisions

- For fixed M, different kinematic regions sample different *x* ranges
- **Results fall between predictions from DSSV and GRSV-STD**

First ***STAR*** W A_L

STAR PRL 106, 062002



Lepton pseudorapidity

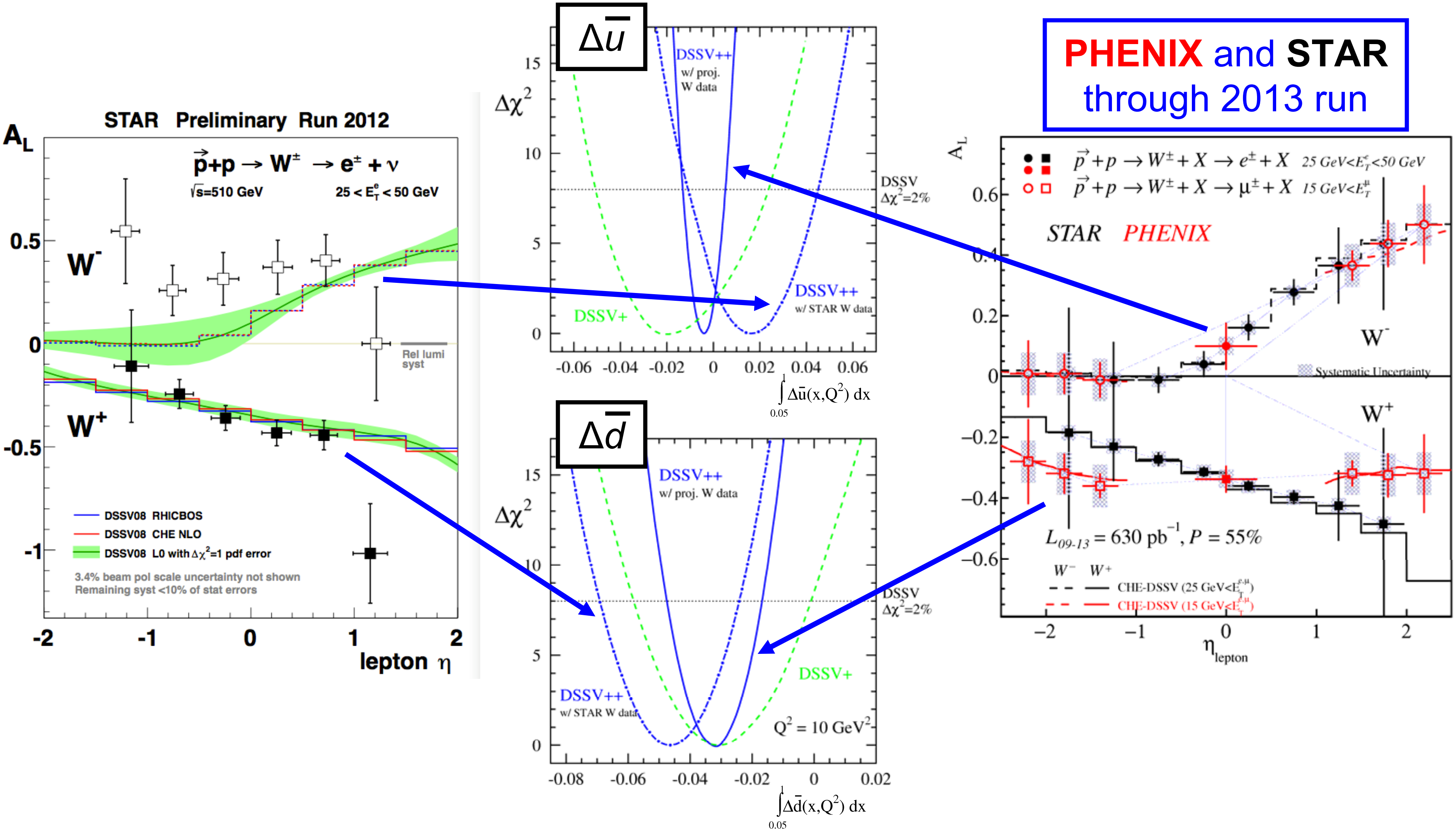
$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

STAR 2009 Result

$$A_L(W^+) = -0.27 \pm 0.10(stat) \pm 0.02(syst)$$

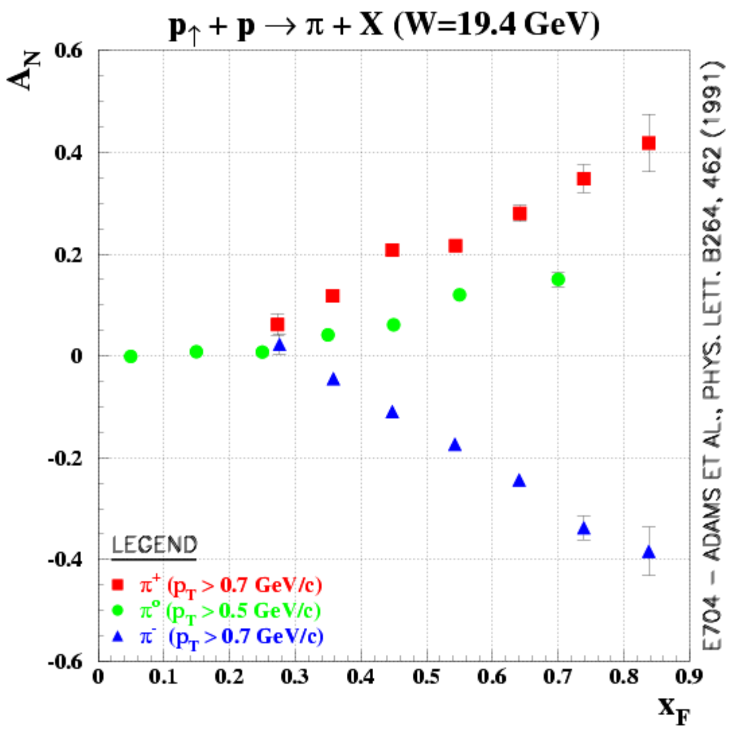
$$A_L(W^-) = 0.14 \pm 0.19(stat) \pm 0.02(syst)$$

High precision *W* asymmetry era

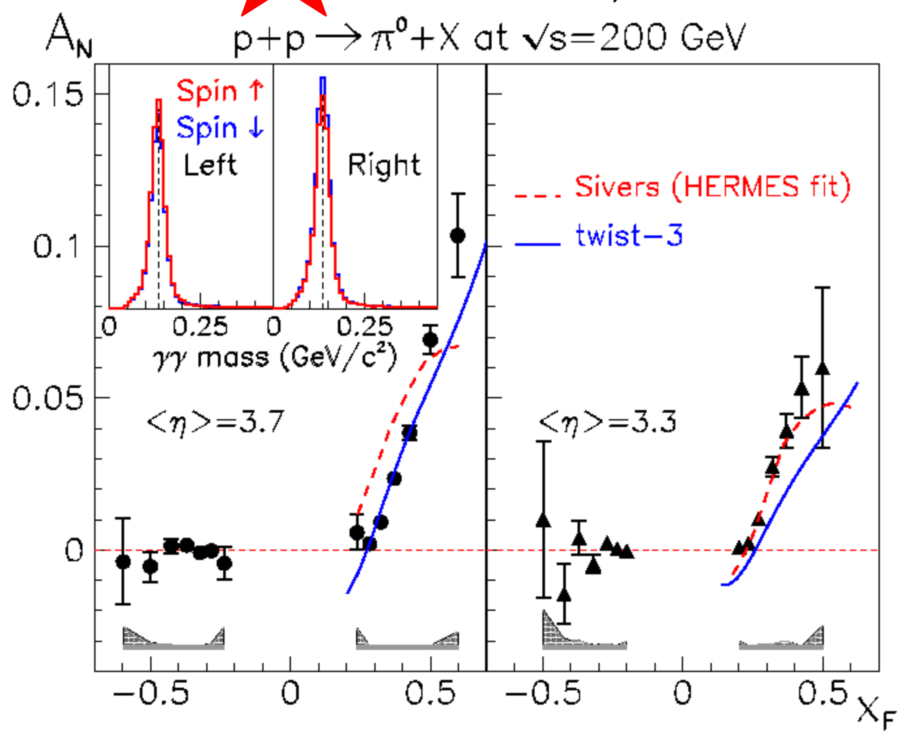


- First preliminary results from 2012 already provide substantial sensitivity
- Future results will provide a dramatic reduction in the uncertainties

Transverse single-spin asymmetries at forward rapidity



STAR PRL 101, 222001



- Large single-spin asymmetries at CM energies of 20 and 200 GeV
- **Weren't supposed to be there** in naïve pQCD

$$A_N \propto \alpha_S m_q / p_T$$

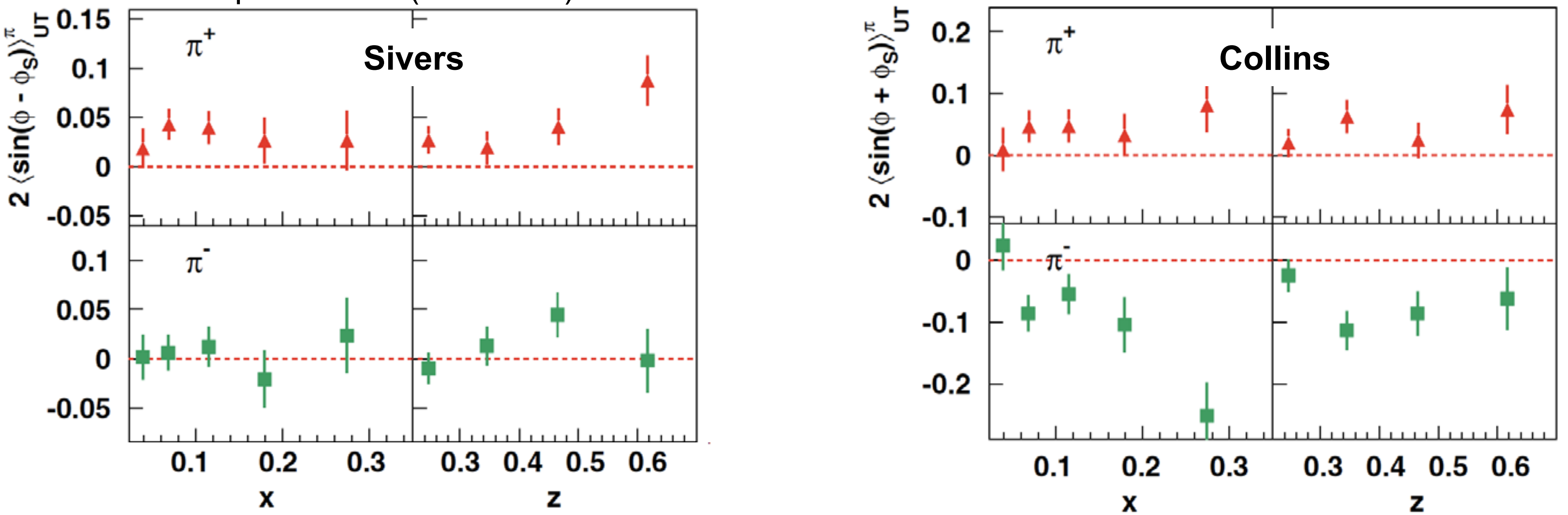
- May arise from the Sivers effect, Collins effect, or a combination

Sivers effect → **Parton orbital motion**

Collins effect → **Transversity**

Sivers and Collins effects in deep-inelastic scattering

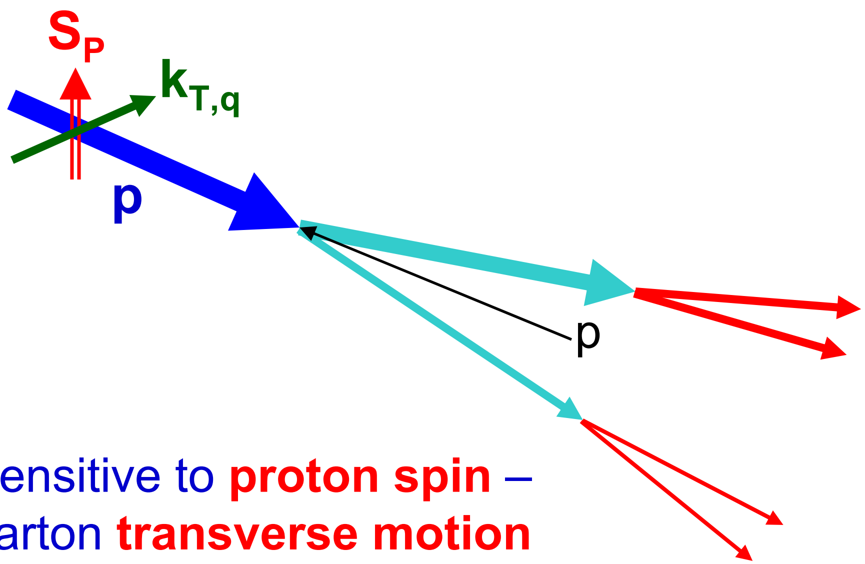
A. Airapetian et al (HERMES)



- Semi-inclusive DIS can distinguish the Sivers and Collins effects
- HERMES finds both are non-zero
- COMPASS finds consistent Collins effects; smaller Sivers effects

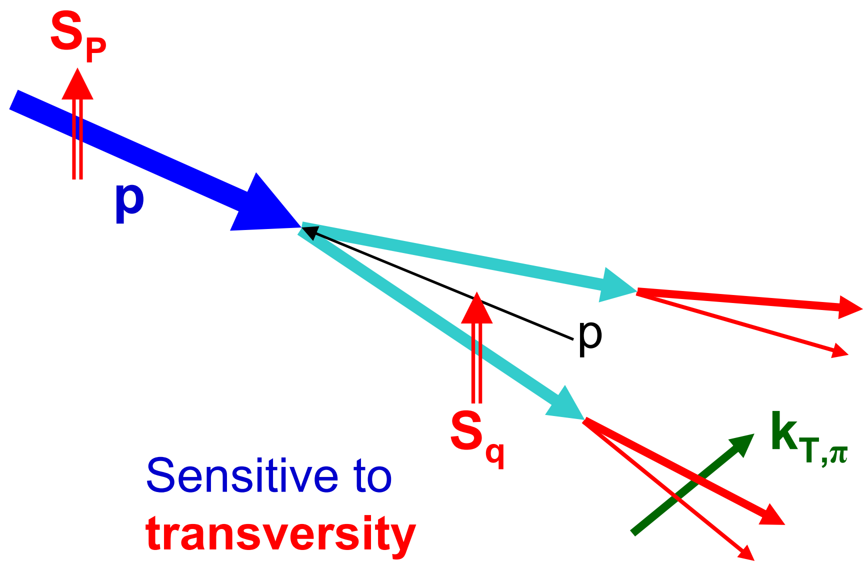
Sivers and Collins effects in pp collisions

Sivers mechanism: asymmetry in the forward jet production



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

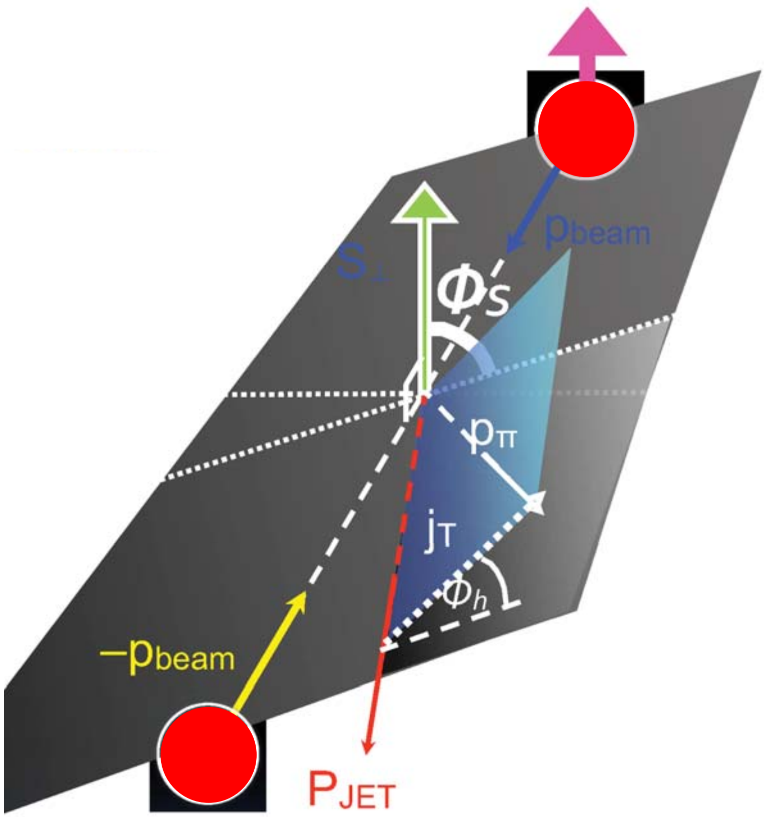
Collins mechanism: asymmetry in the forward jet fragmentation



Sensitive to **transversity**

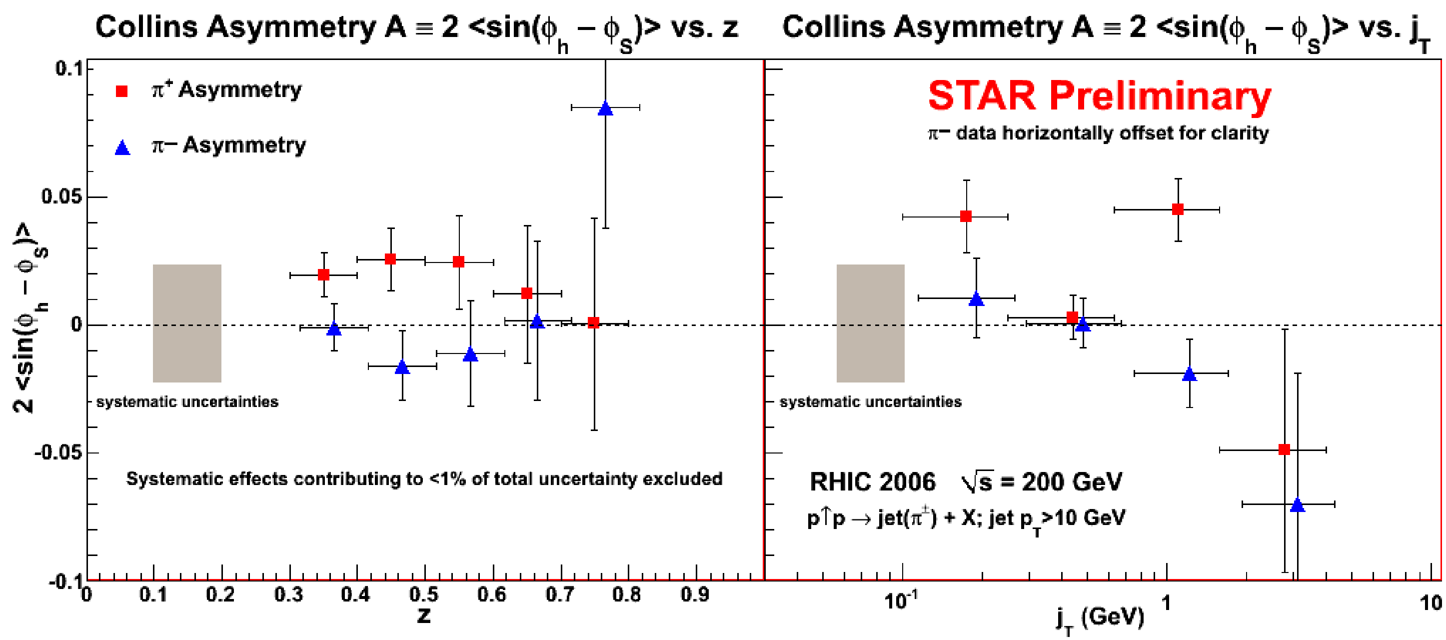
- Need to go **beyond inclusive hadrons**
- Limited (no more?) time: focus on **jet measurements of transversity**

Observing the Collins effect in jets



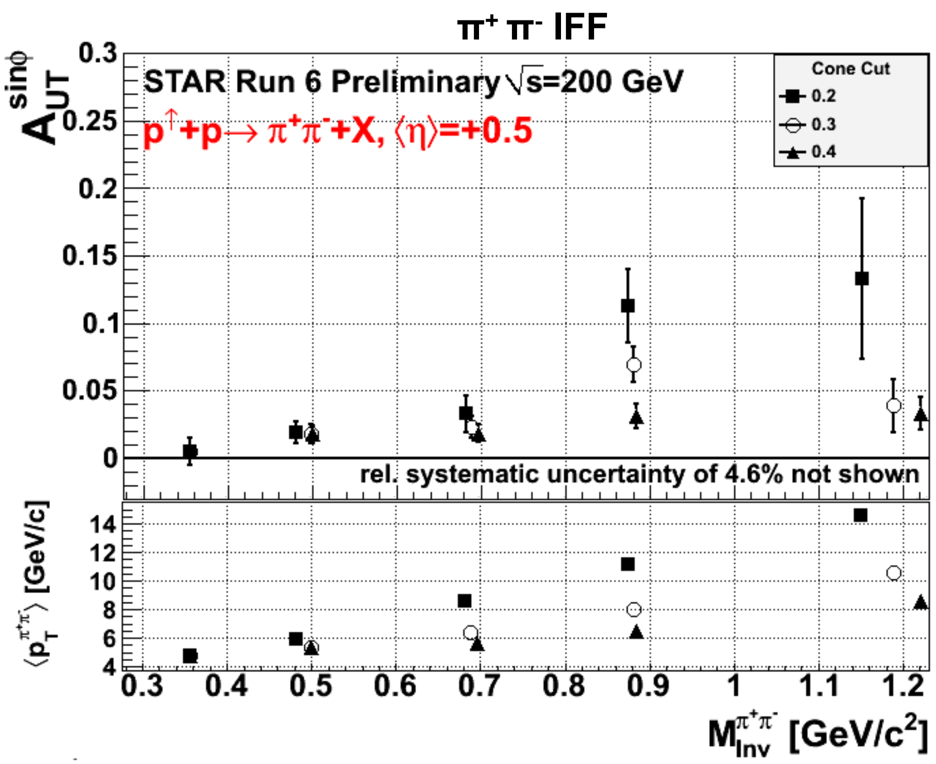
- A spin-dependent azimuthal variation in hadron production around the jet thrust axis
- Alternative approach: Interference Fragmentation Function (IFF)
  - Di-hadron as surrogate for the jet
  - Examine di-hadron relative angle, measured around the pair momentum

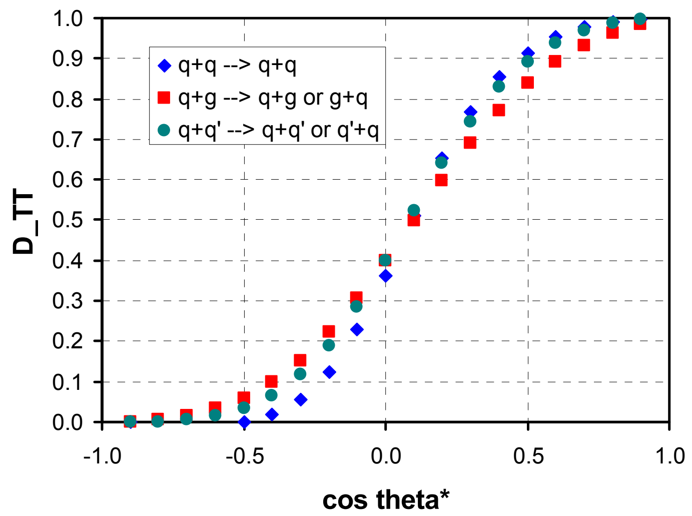
Leading pions in mid-rapidity jets

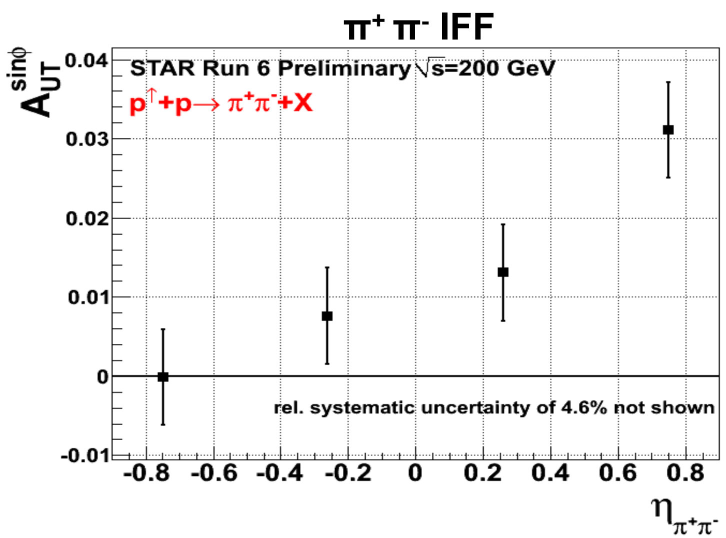


- Azimuthal asymmetries measured within fully reconstructed jets
- Average asymmetries:
  - π^+ = 0.021 +/- 0.006 +/- 0.023
  - π^- = -0.004 +/- 0.007 +/- 0.023
  - Expected asymmetry from global analysis ~ +/- 0.07

Mid-rapidity interference fragmentation functions







- Clear signature of quark transversity in p+p collisions at RHIC

Conclusions

- We still have a great deal to learn about the structure of the proton
- **RHIC is making significant contributions** to three poorly constrained pieces of the puzzle
  - **Gluon polarization**
  - **Flavor-separated quark and anti-quark polarizations**
  - **Transversity**
- Andrew will have more to say about gluon polarization in his, "What I did during my summer vacation," talk. **Stay tuned!**