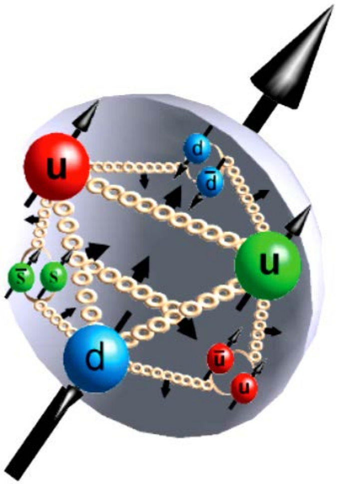


What makes the proton spin?

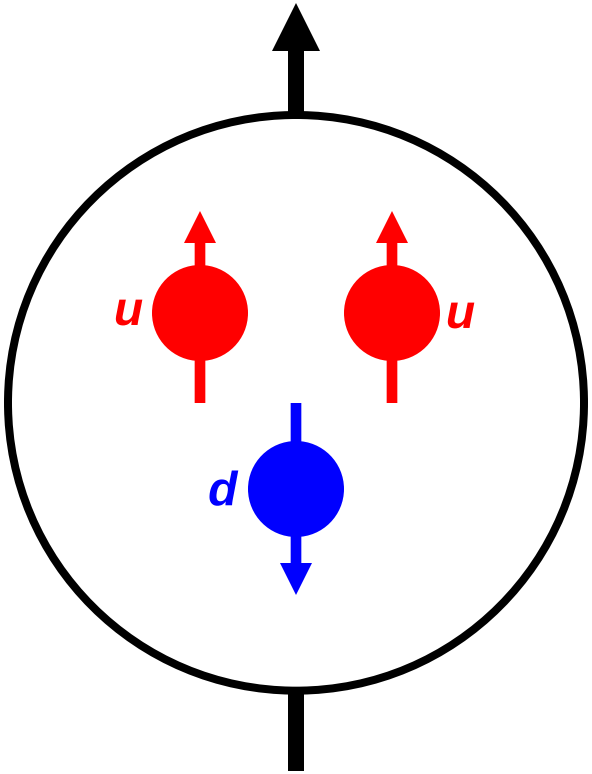
Carl Gagliardi

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

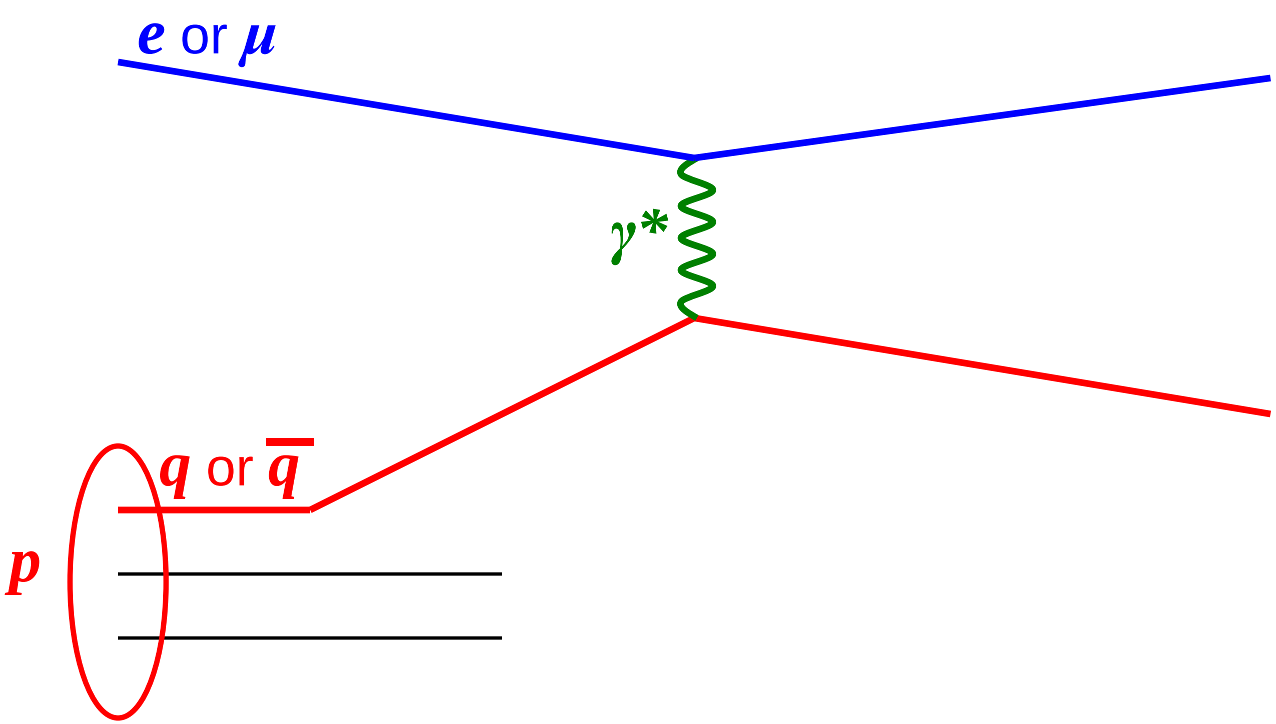
- The proton radius is ~0.85 fm
- Heisenberg Uncertainty Principle implies quark motion must be relativistic
- Relativistic quark model
  - Quarks are no longer restricted to *s*-wave states
  - Quark spin accounts for ~60% of the proton spin
  - Rest of proton spin comes from quark orbital angular momentum

- 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

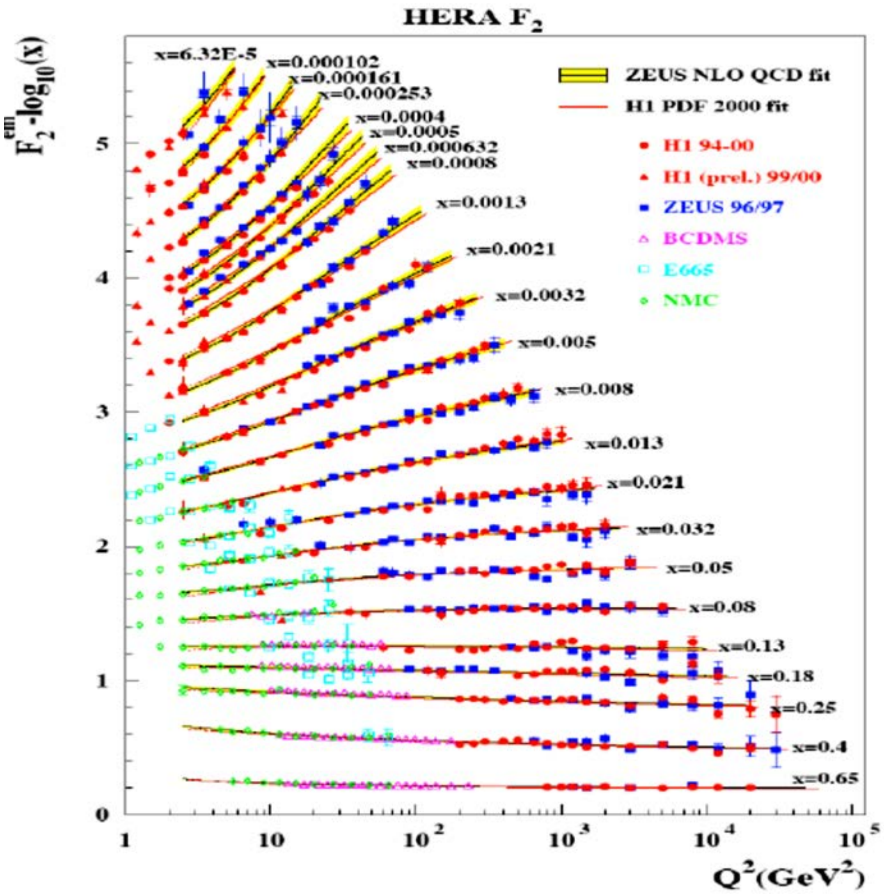
- **How can we observe these quarks, anti-quarks, and gluons?**

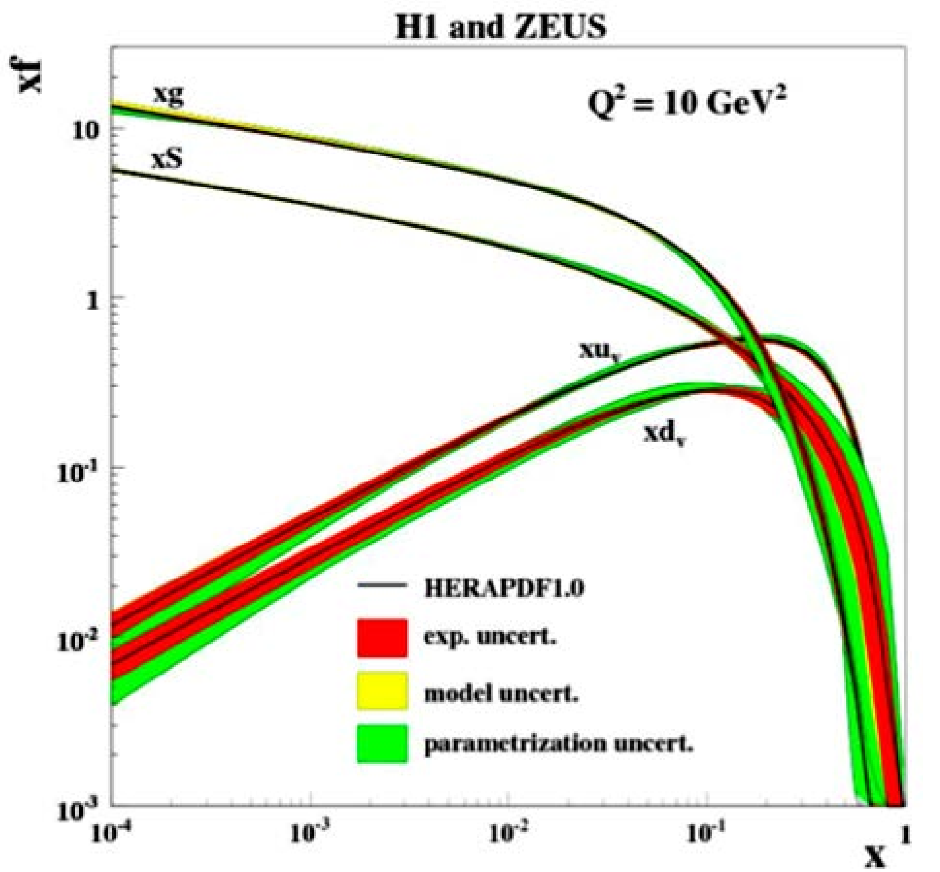
Looking inside the proton



- "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

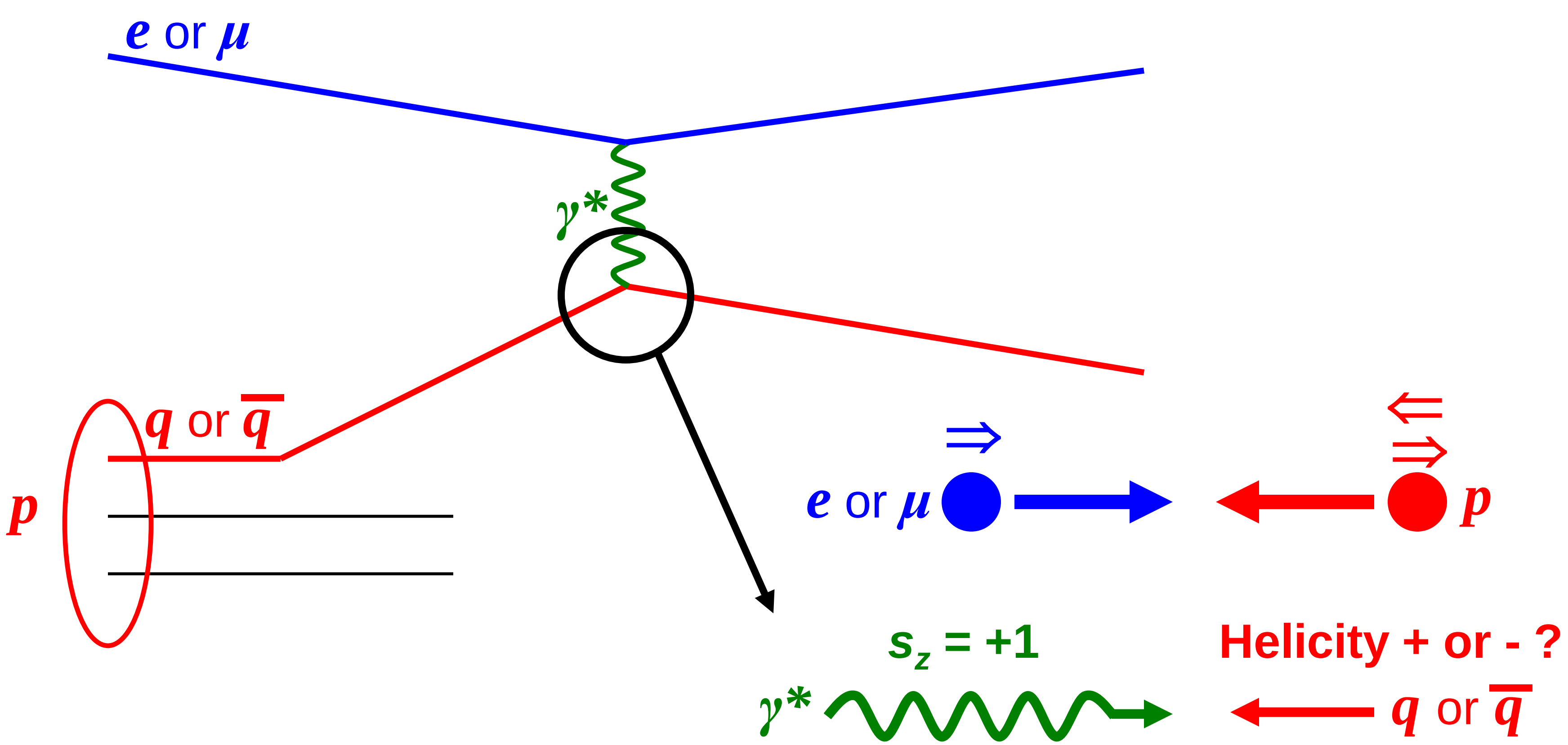
Parton distribution functions





- 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

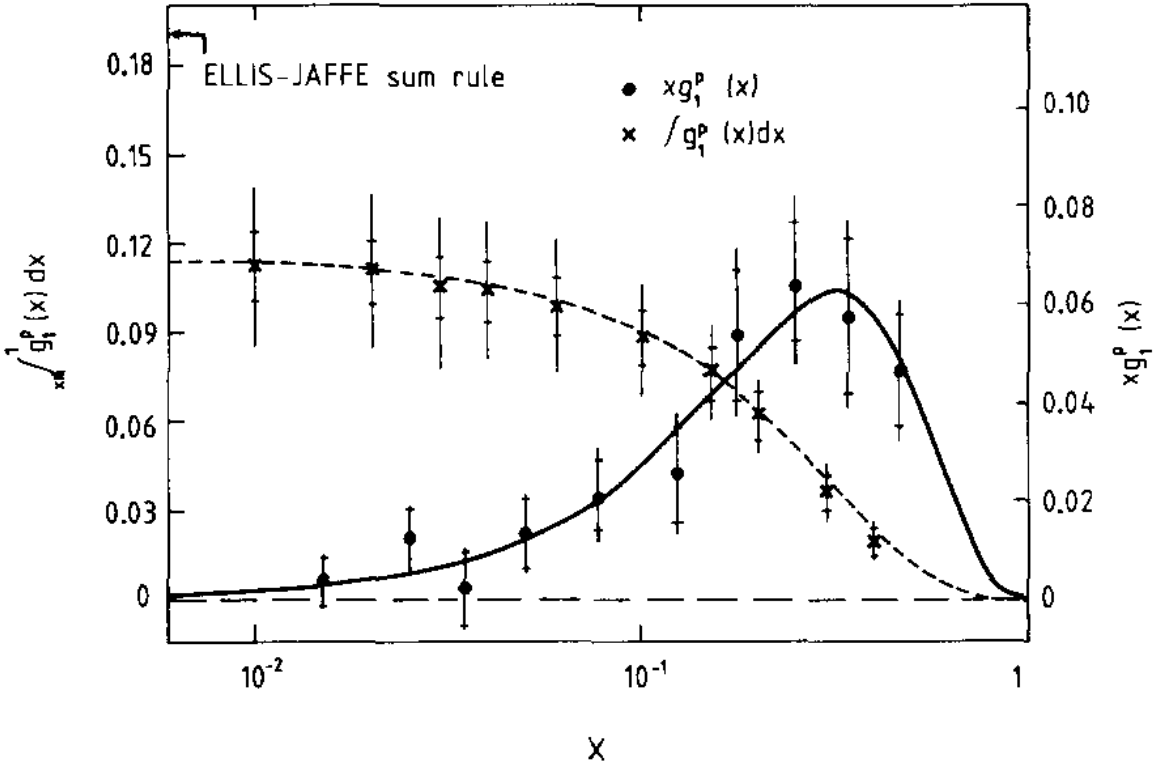
Microscopic origin of the proton spin



- 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"

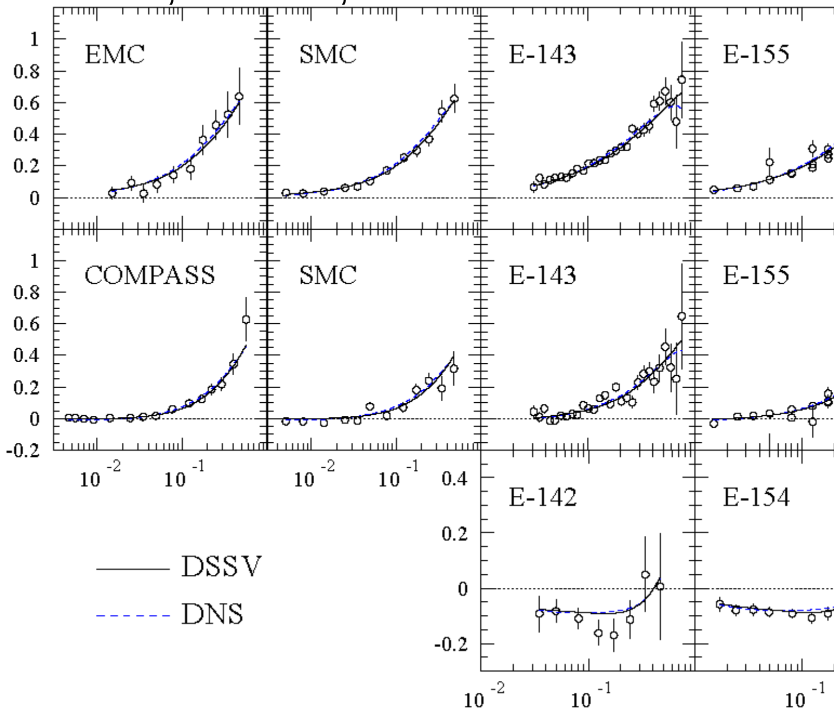
EMC, PLB 206, 364

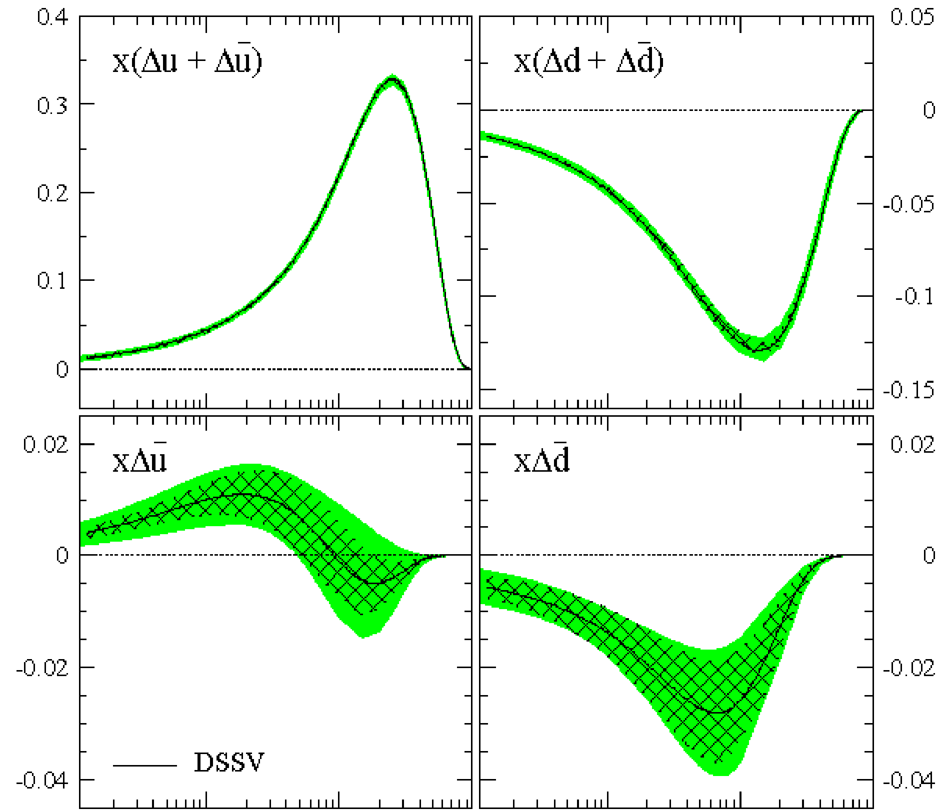


- First measurement over a broad kinematic region was performed by the European Muon Collaboration in the mid-'80s
- Found that quarks contribute only **(14 ± 9 ± 21)%** of the proton spin

Since EMC

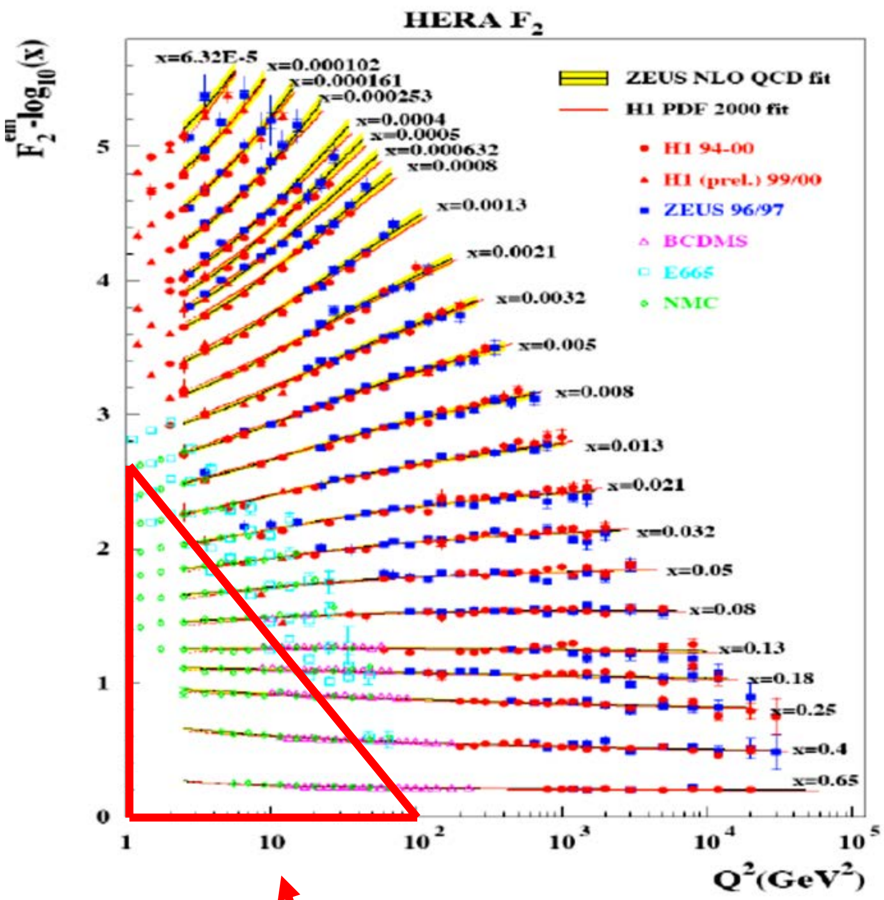
DSSV, PRD 80, 034030



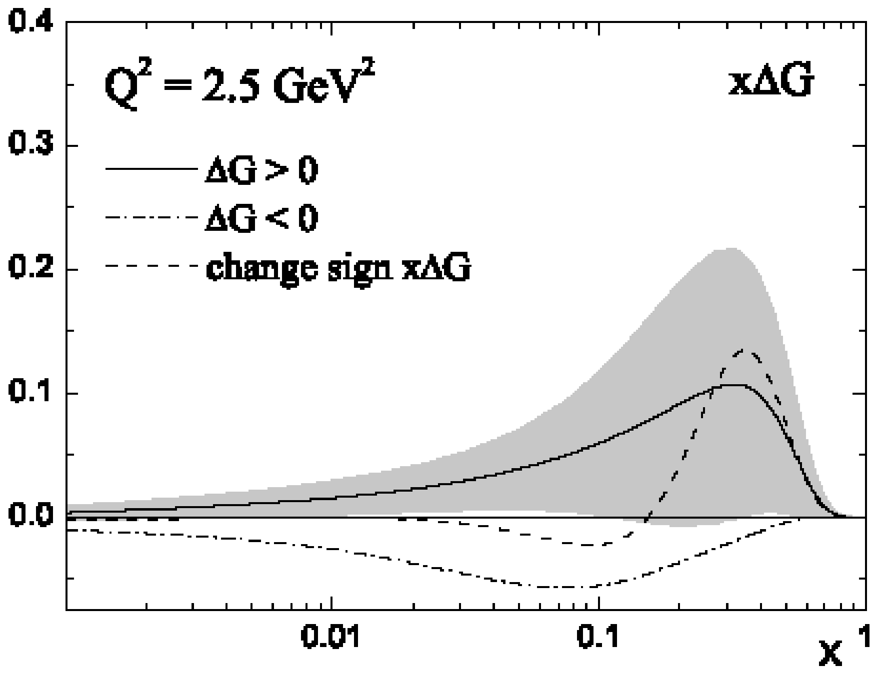


- Many subsequent measurements
- Results are well described by “global analyses” that find best-fit *polarized* parton distribution functions
- Polarization of $u+\bar{u}$ and $d+\bar{d}$ quarks well determined
  - Individual u, $\bar{u}$, d, $\bar{d}$ polarizations have much larger uncertainty
- Only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

What about gluon polarization?



Kinematic region of ***polarized*** measurements



Three fits of equal quality:

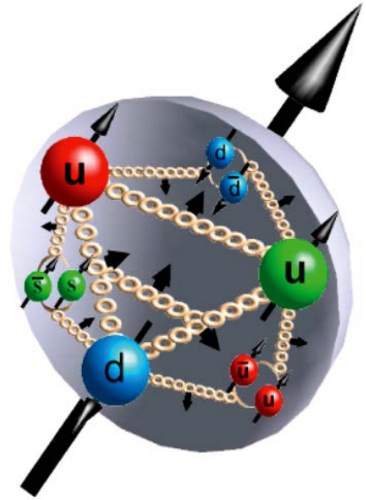
- $\Delta G = 0.13 \pm 0.16$
- $\Delta G \sim 0.006$
- $\Delta G = -0.20 \pm 0.41$

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

Leader et al, PRD 75, 074027

What contributes to the proton spin?

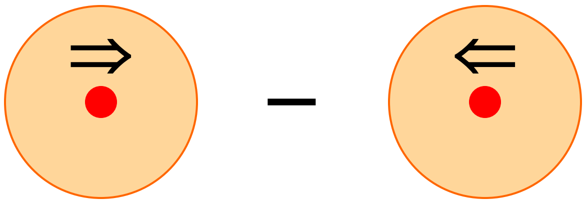
Consider a proton moving toward the right



Proton spin ⇒

Helicity

Δq(x)
Δg(x)



Polarized DIS: ~ 0.3

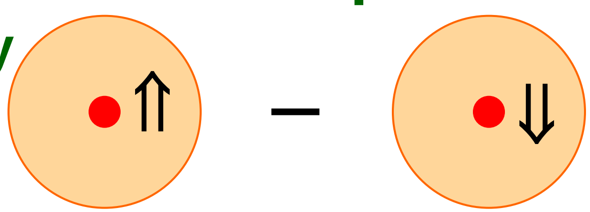
Poorly constrained

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

Proton spin ⇑

Transversity

δq(x)

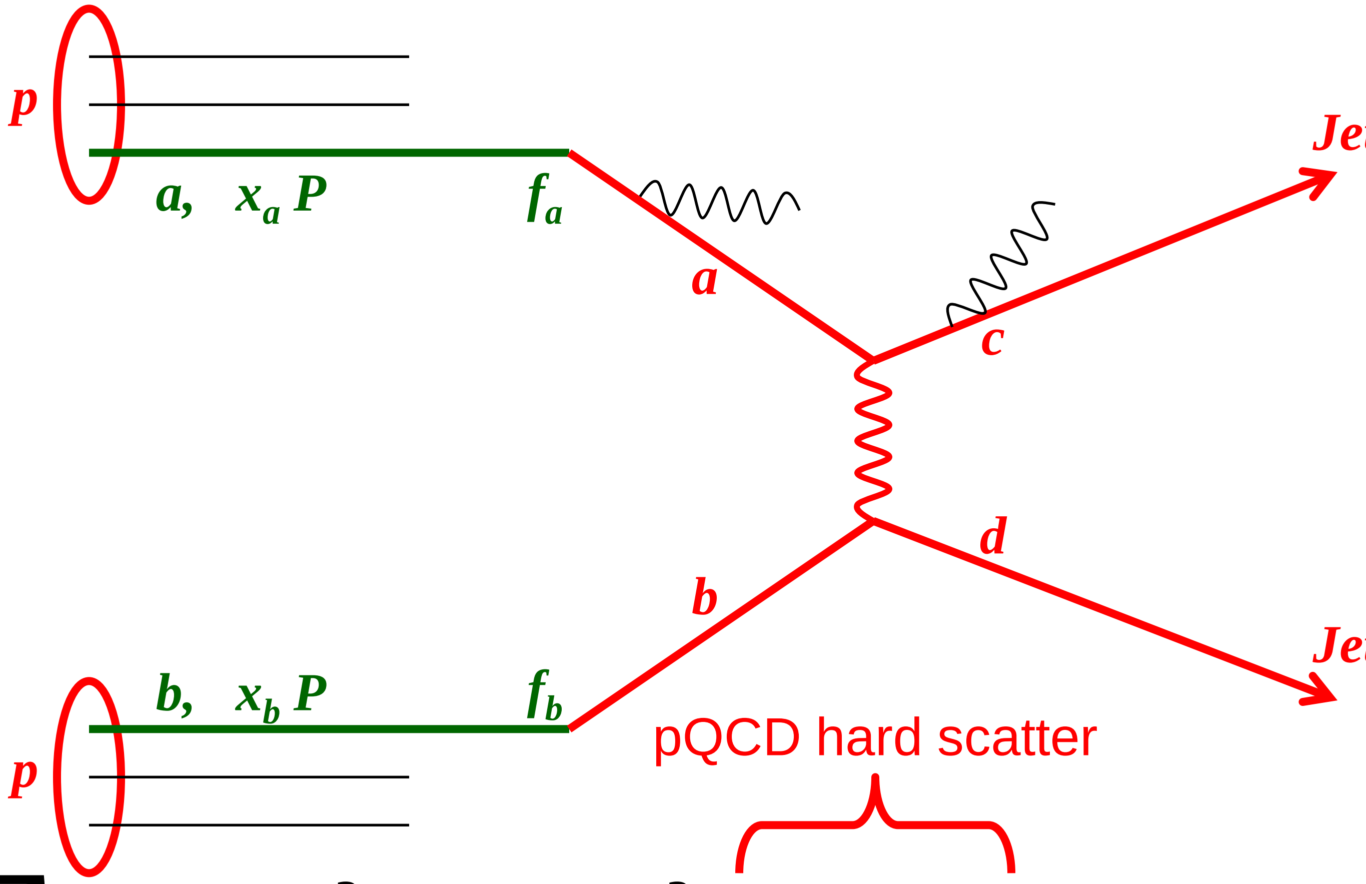


Very little data

RHIC spin program:

Exploring poorly determined components of the proton

$p + p$ collisions in perturbative QCD



pQCD hard scatter

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

Parton distribution functions

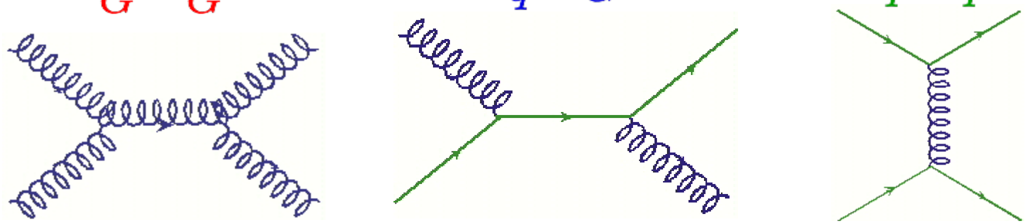
***a* and *b* can be quarks, gluons, or a combination**

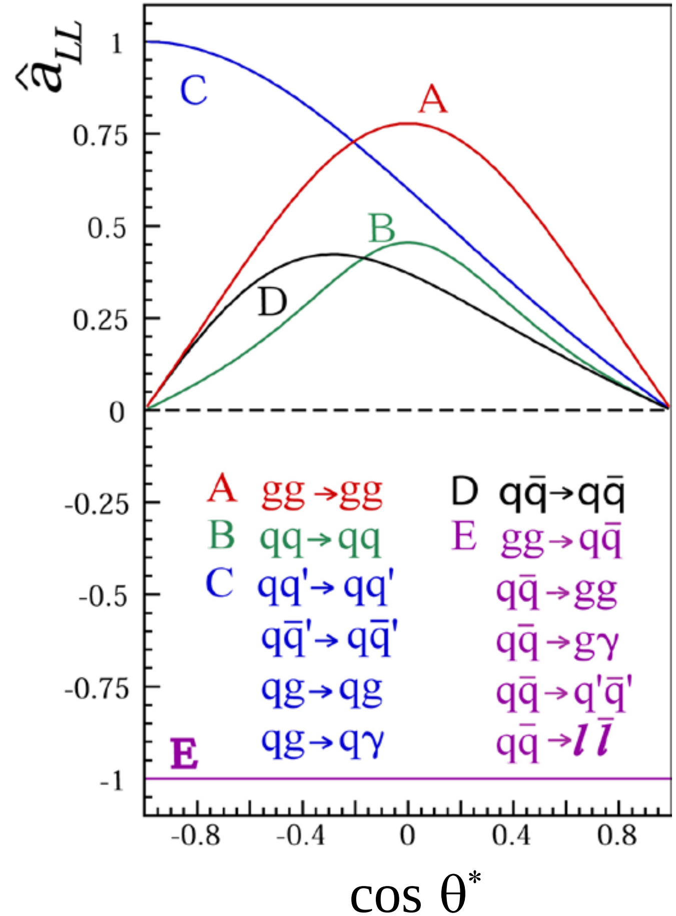
Exploring gluon polarization at RHIC

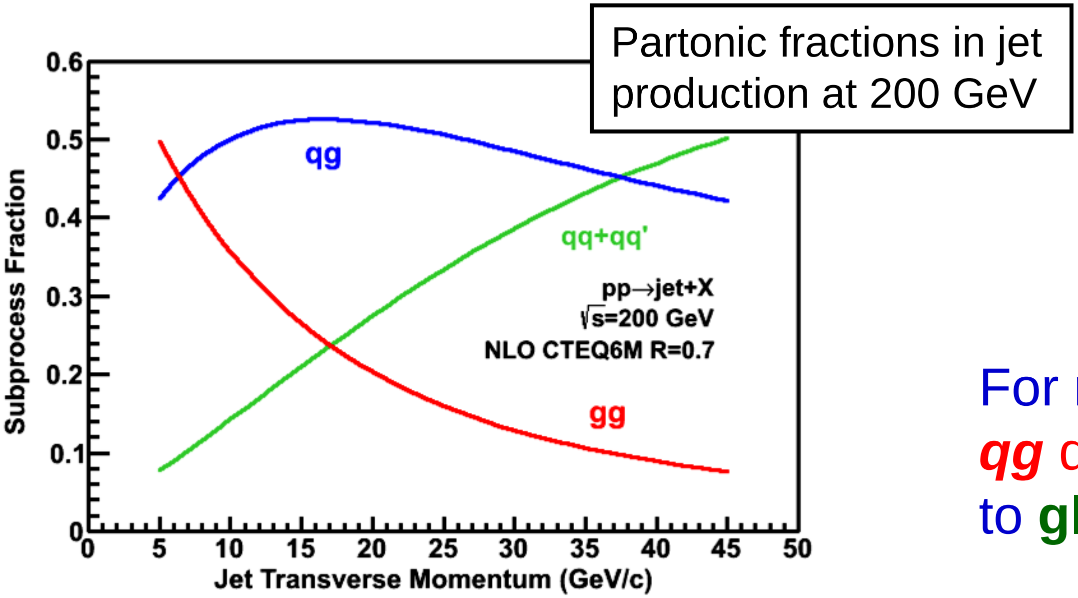
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

Δf: polarized parton distribution functions

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

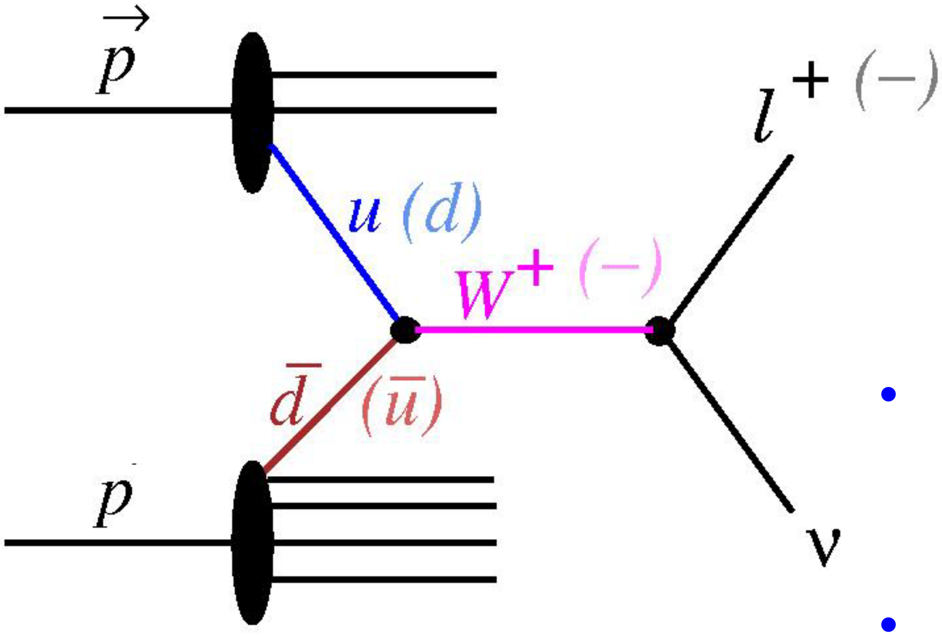






For most RHIC kinematics, ***gg*** and ***qg*** dominate, making $\boldsymbol{A_{LL}}$ sensitive to **gluon polarization**.

Separating quark and anti-quark polarizations



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

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

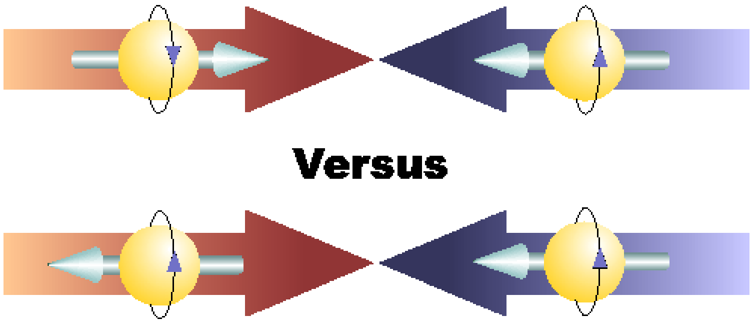
- Weak interaction process
  - Only left-handed quarks
  - Only right-handed anti-quarks
- Perfect spin separation

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 helicities same

N_{+-}: yield when helicities opposite

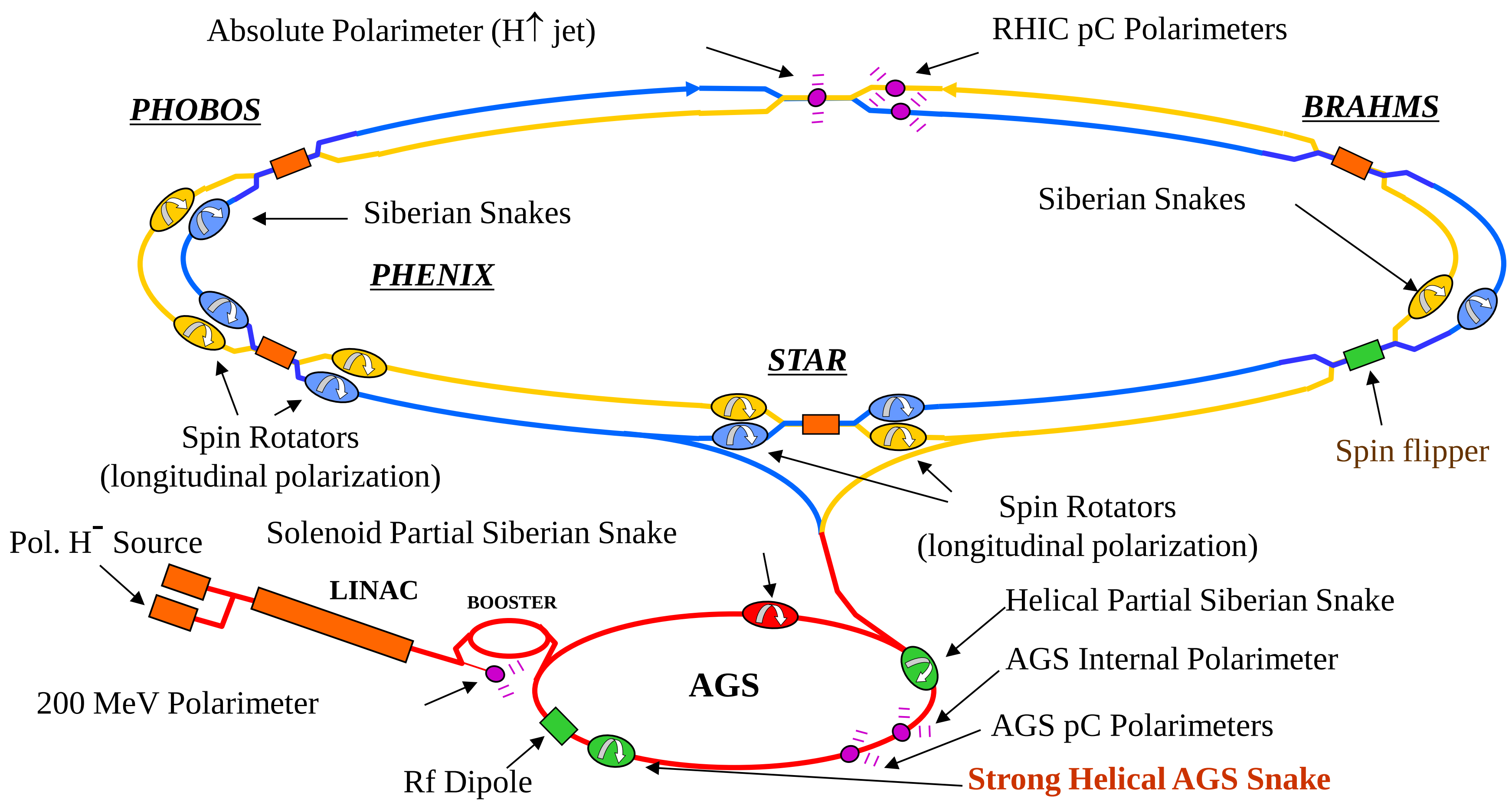
$$A_{LL} = \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}} \quad \text{where} \quad R = \frac{L_{++}}{L_{+-}}$$

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

RHIC: the **R**elativistic **H**eavy **I**on **C**ollider

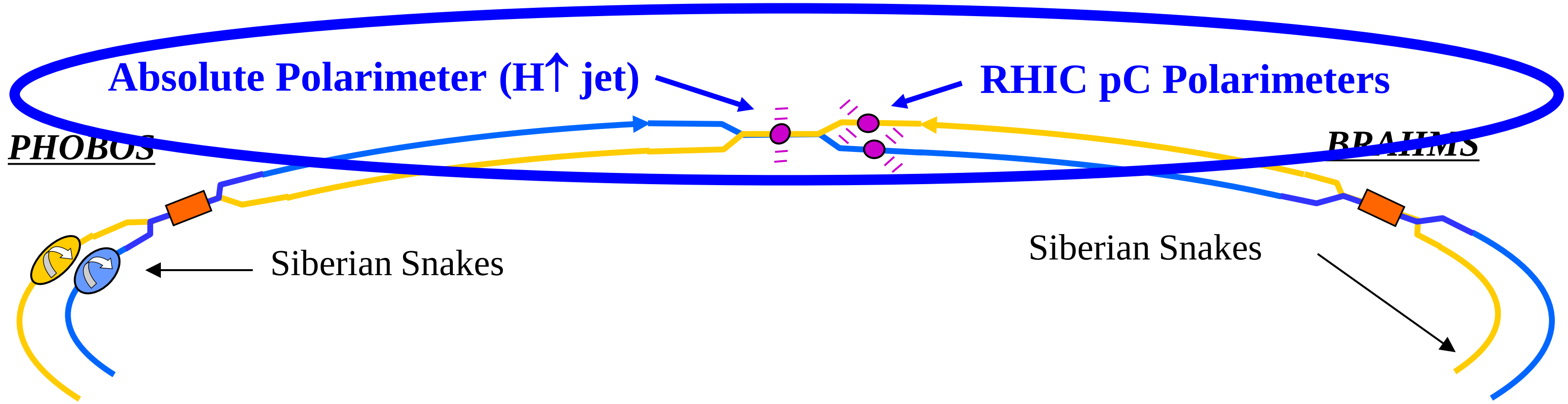
- Search for and study the Quark-Gluon Plasma
- **Explore the partonic structure of the proton**
- Determine the partonic structure of nuclei

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



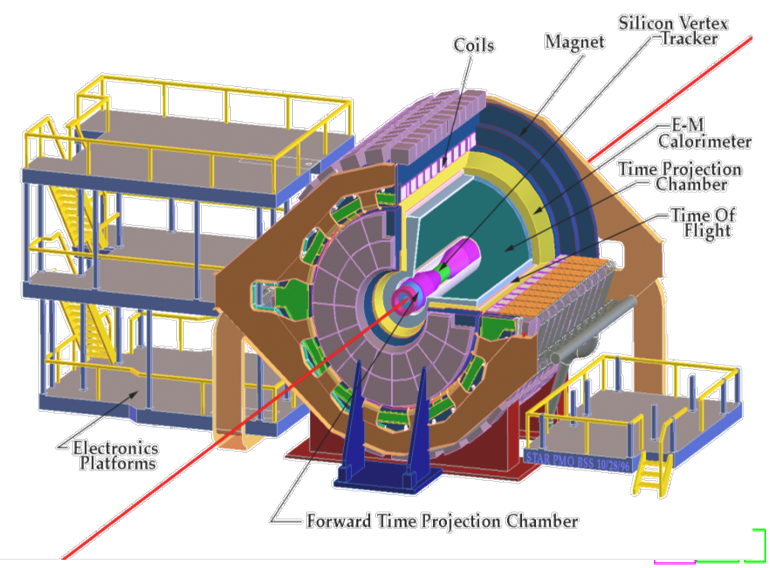
- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization

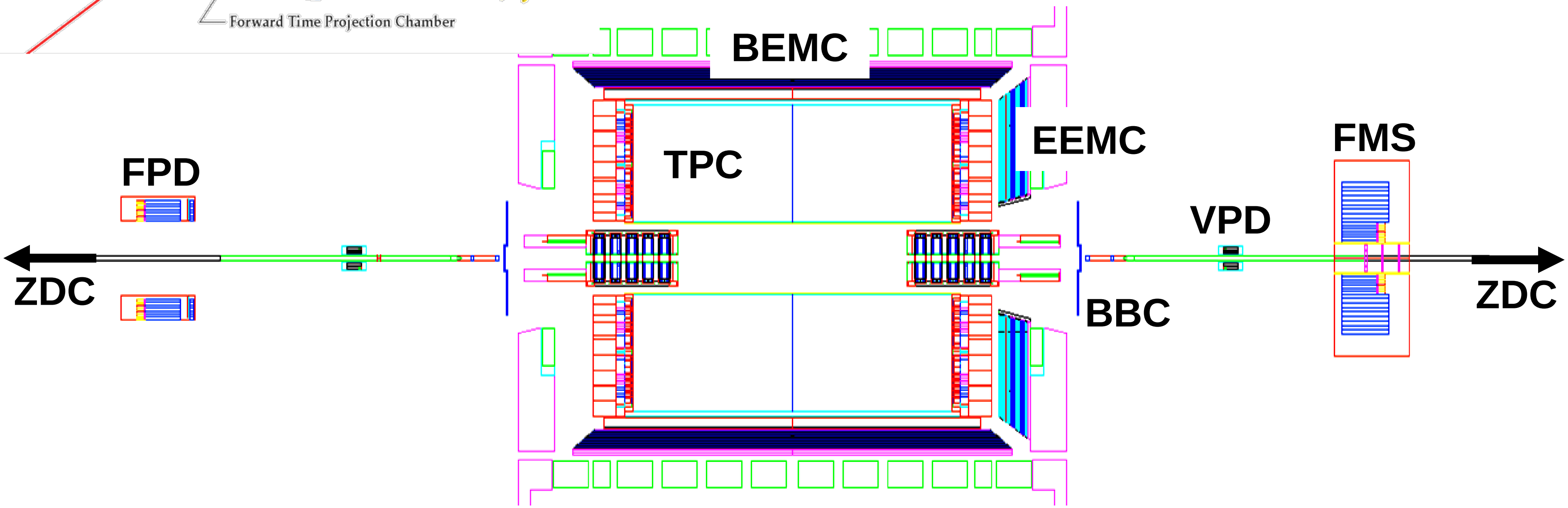
Measuring the polarization



- 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

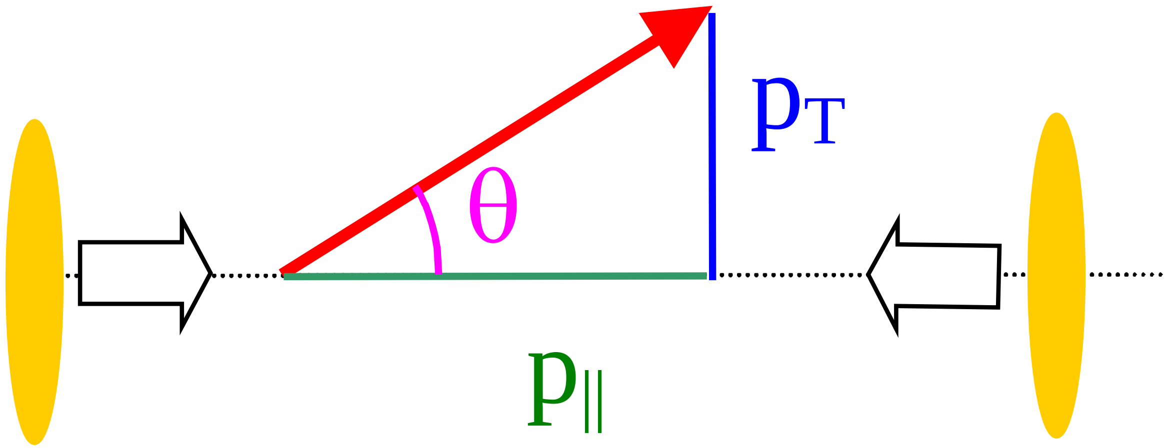




- High precision tracking with the TPC
- Electromagnetic calorimetry with the BEMC, EEMC, and FMS
- Additional detectors for relative luminosity, local polarimetry, and minbias triggering

What are we learning?

Kinematics for colliders



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

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

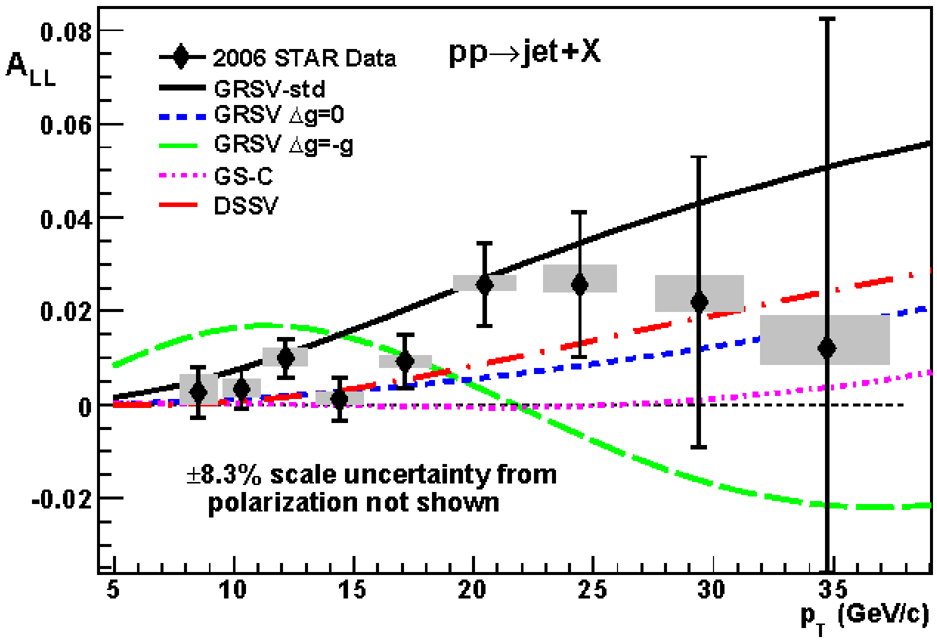
$$p_z = p_T \sinh(\eta)$$

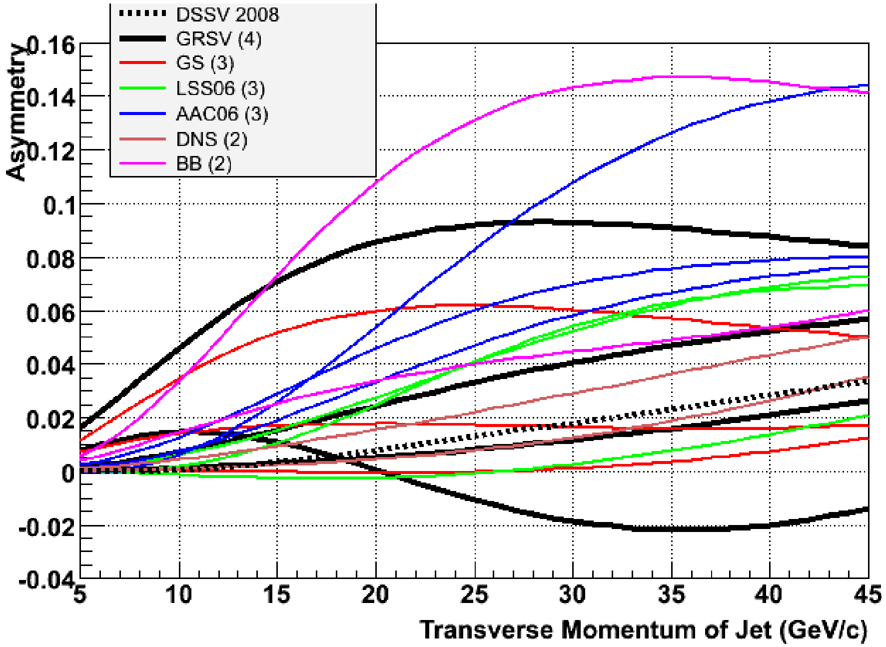
$$p_{tot} = p_T \cosh(\eta)$$

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 PRD 86, 032006

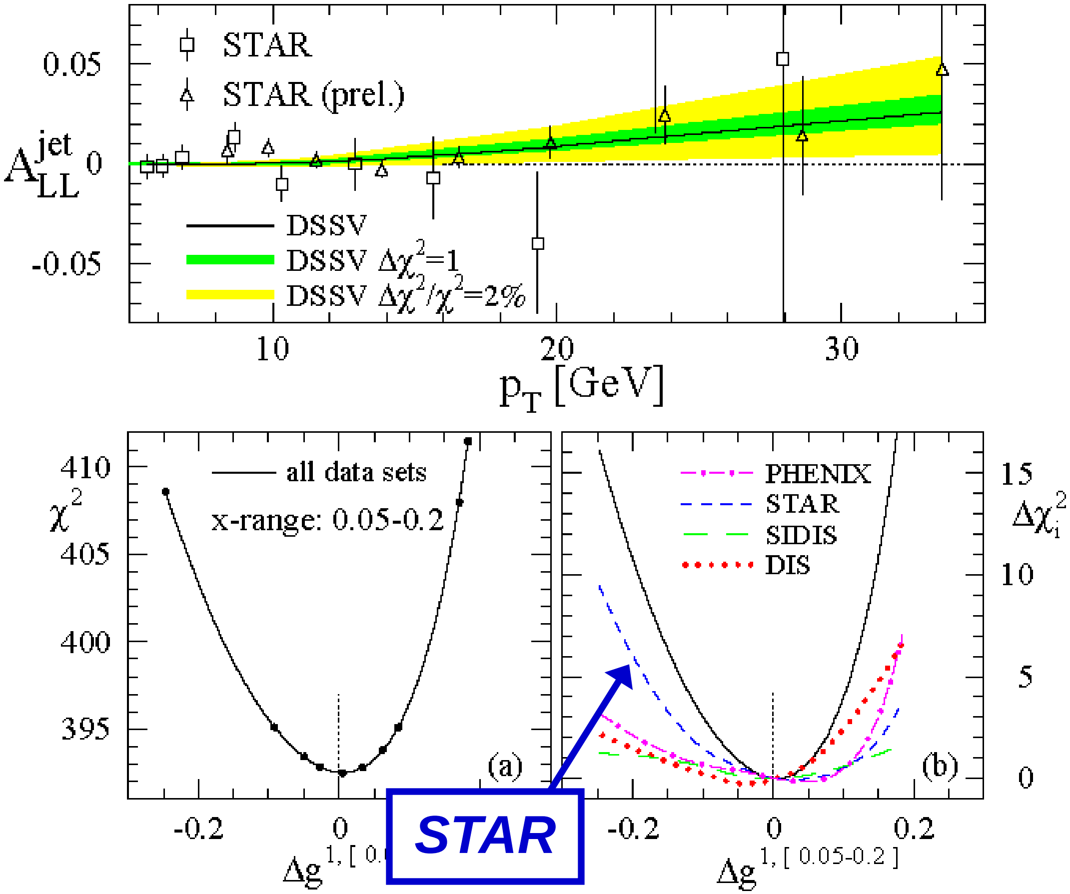


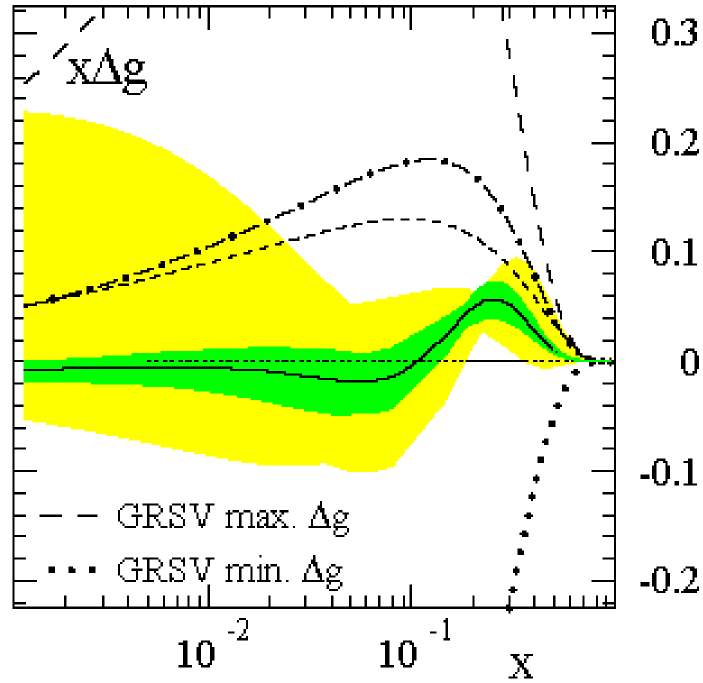


- ***STAR*** inclusive jet A_{LL} excludes those scenarios that have a large gluon polarization within the accessible *x* region

DSSV – first global analysis with polarized jets

de Florian et al., PRL 101, 072001

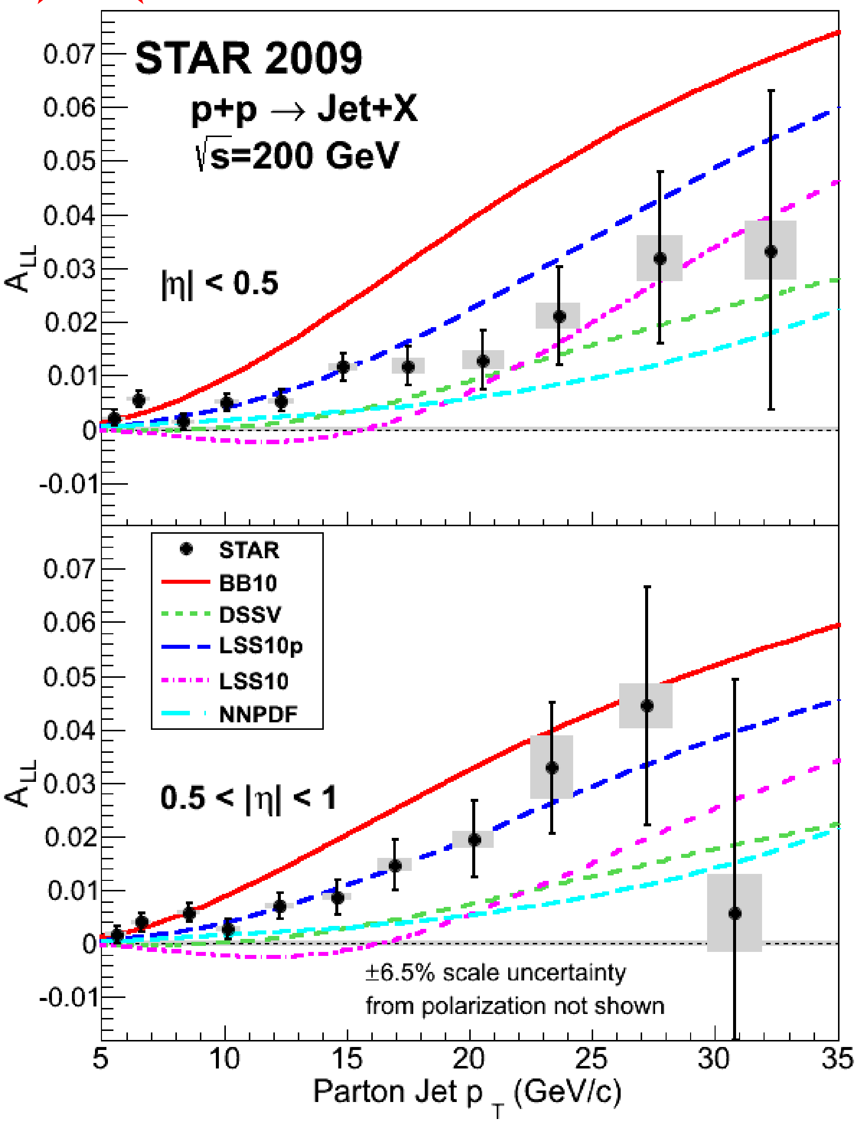




- The first global NLO analysis to include inclusive DIS, SIDIS, and RHIC pp data on an equal footing

A_{LL} for inclusive jets: 2006 to 2009

STAR arXiv:1405.5134

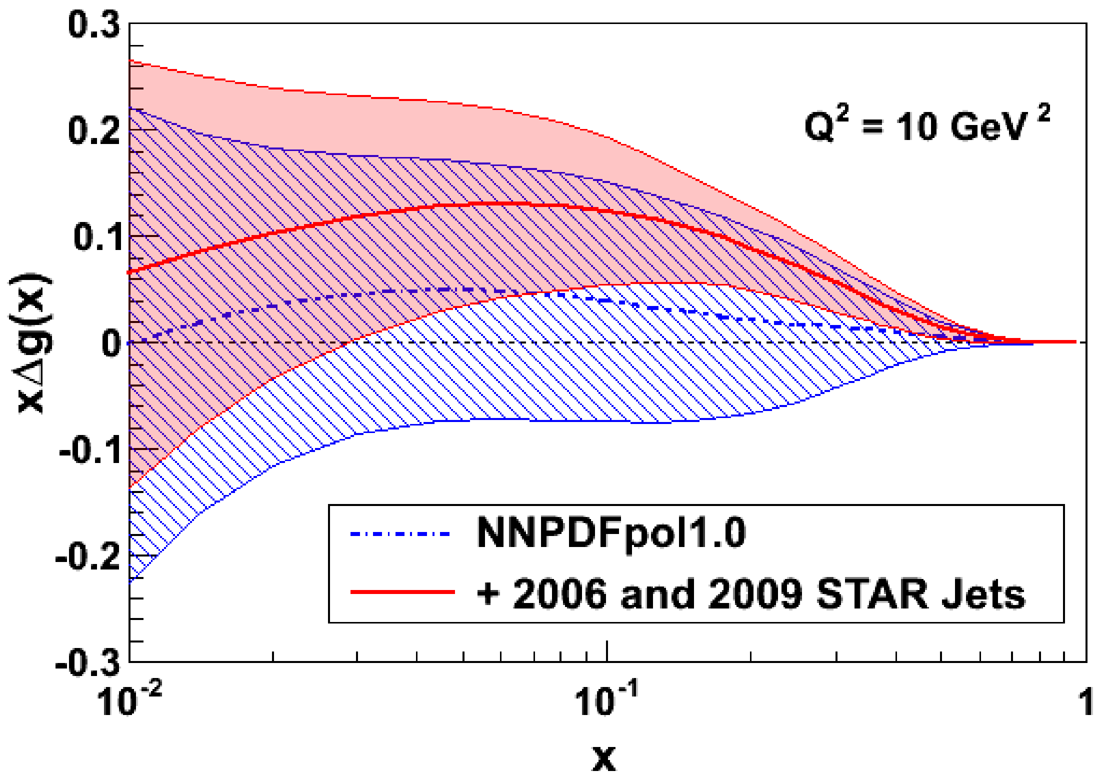


- 20-fold increase in event statistics
- Improved analysis procedures lead to smaller systematic uncertainties
- 2009 ***STAR*** inclusive jet A_{LL} measurements are a factor of 3 (high-p_T) to >4 (low-p_T) more precise than 2006
- **Measured asymmetries are larger than predictions from DSSV**
  - Points to a **larger gluon polarization**

STAR inclusive jets and NNPDF

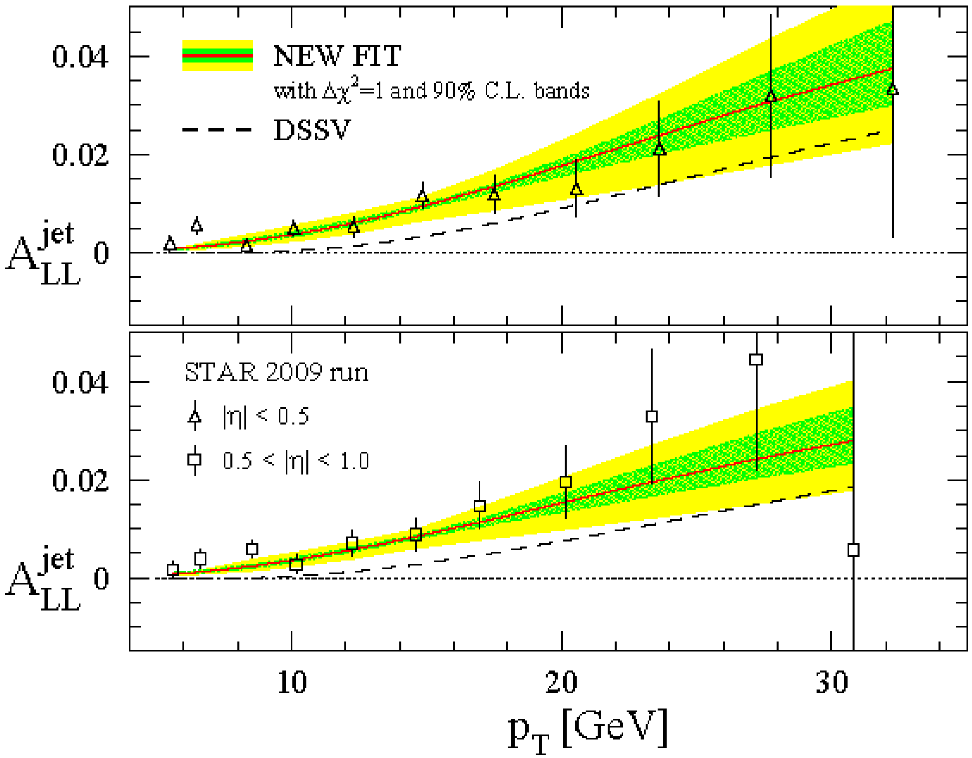
STAR

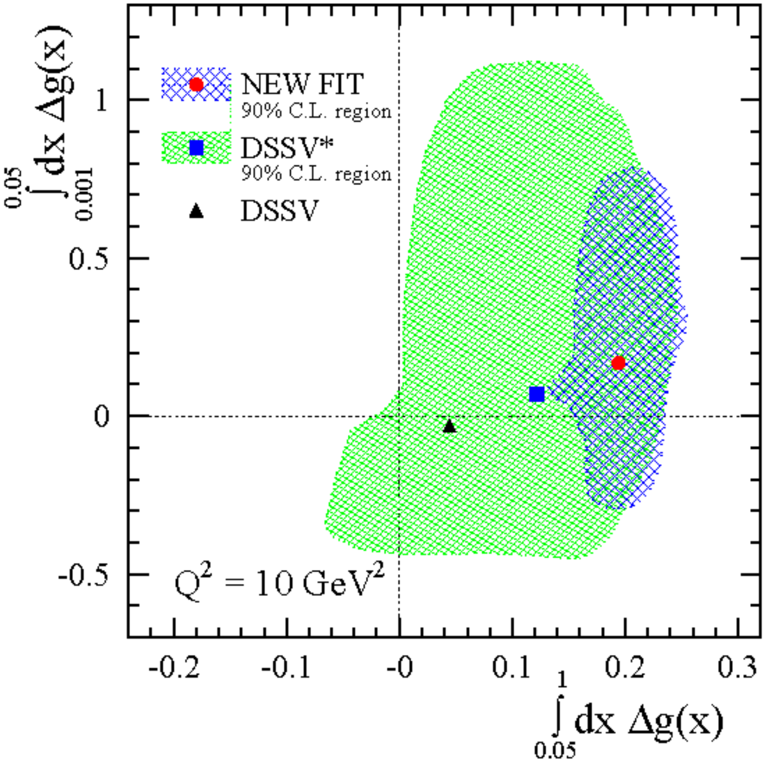
arXiv:1405.5134



- Included STAR inclusive jet A_{LL} results in NNPDF via reweighting
- Gluon polarization shifts positive, with much reduced uncertainties
- Integral of $\Delta g(x, Q^2 = 10\ \text{GeV}^2)$ over the range $0.05 < x < 0.5$ increases from 0.06 ± 0.18 to **0.21 ± 0.10**
- Preference for the **gluon helicity contribution to be positive** in the RHIC kinematic range

STAR inclusive jets and DSSV





- **New DSSV global analysis** that includes 2009 A_{LL} measurements from PHENIX and STAR

$$\int_{0.05}^{1} \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2)\, dx = 0.20^{+0.06}_{-0.07} \quad \text{at 90\% CL}$$

- ***STAR* jets provide evidence of positive gluon polarization** in the range $x > 0.05$

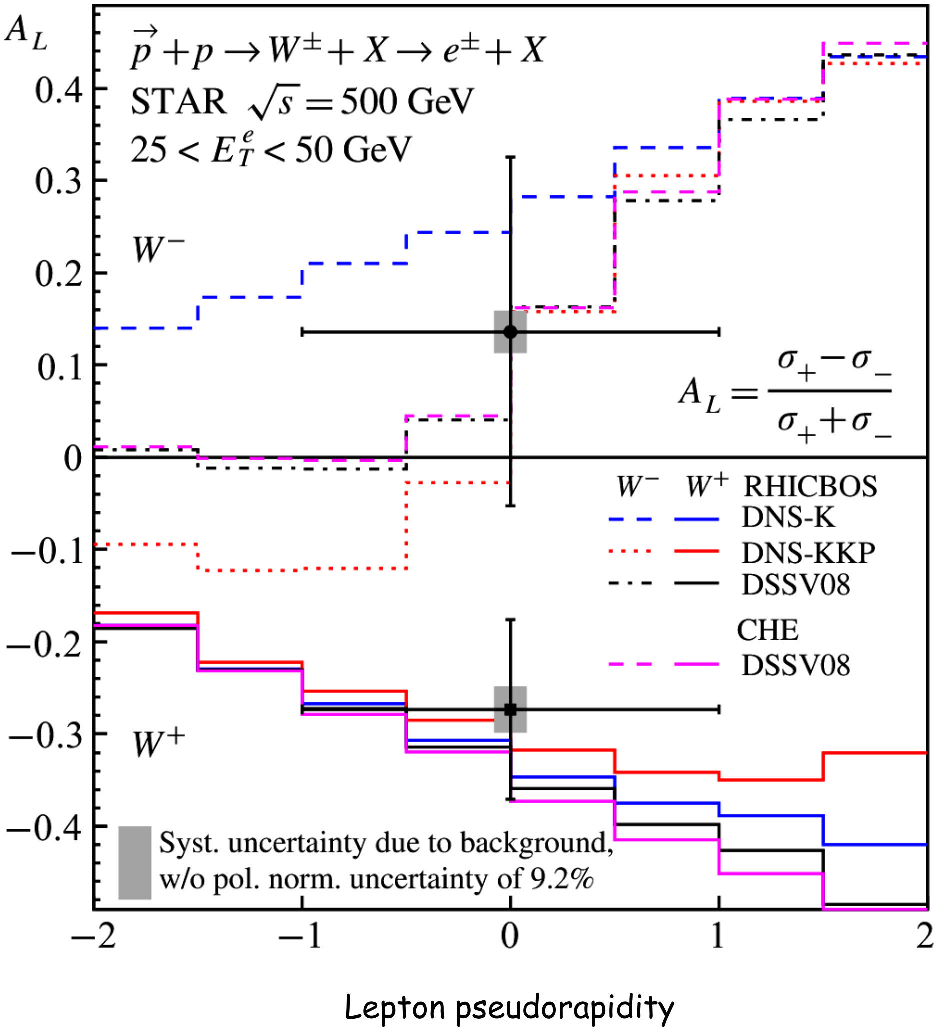
You in a few months?

Precision Measurement of the Longitudinal Double-spin Asymmetry for Inclusive Jet Production in Polarized Proton Collisions at $\sqrt{s} = 200$ GeV

L. Adamczyk,[1] J. K. Adkins,[23] G. Agakishiev,[21] M. M. Aggarwal,[35] Z. Ahammed,[53] I. Alekseev,[19] J. Alford,[22] C. D. Anson,[32] A. Aparin,[21] D. Arkhipkin,[4] E. C. Aschenauer,[4] G. S. Averichev,[21] A. Banerjee,[53] D. R. Beavis,[4] R. Bellwied,[49] A. Bhasin,[20] A. K. Bhati,[35] P. Bhattarai,[48] H. Bichsel,[55] J. Bielcik,[13] J. Bielcikova,[14] L. C. Bland,[4] I. G. Bordyuzhin,[19] W. Borowski,[45] J. Bouchet,[22] A. V. Brandin,[30] S. G. Brovko,[6] S. Bültmann,[33] I. Bunzarov,[21] T. P. Burton,[4] J. Butterworth,[41] H. Caines,[57] M. Calderón de la Barca Sánchez,[6] J. M. Campbell,[32] D. Cebra,[6] R. Cendejas,[36] M. C. Cervantes,[47] P. Chaloupka,[13] Z. Chang,[47] S. Chattopadhyay,[53] H. F. Chen,[42] J. H. Chen,[44] L. Chen,[9] J. Cheng,[50] M. Cherney,[12] A. Chikanian,[57] W. Christie,[4] J. Chwastowski,[11] M. J. M. Codrington,[48] G. Contin,[26] J. G. Cramer,[55] H. J. Crawford,[5] A. B. Cudd,[47] X. Cui,[42] S. Das,[16] A. Davila Leyva,[48] L. C. De Silva,[12] R. R. Debbe,[4] T. G. Dedovich,[21] J. Deng, A. A. Derevschikov,[37] R. Derradi de Souza,[8] S. Dhamija,[18] B. di Ruzza,[4] L. Didenko,[4] C. Dilks,[36] F. Ding,[6] P. Djawotho,[47] X. Dong,[26] J. L. Drachenberg,[52] J. E. Draper,[6] C. M. Du,[25] L. E. Dunkelberger,[7] J. C. Dunlop,[4] L. G. Efimov,[21] J. Engelage,[5] K. S. Engle,[51] G. Eppley,[41] L. Eun,[26] O. Evdokimov,[10] O. Eyser,[4] R. Fatemi,[23] S. Fazio,[4] J. Fedorisin,[21] P. Filip,[21] E. Finch,[57] Y. Fisyak,[4] C. E. Flores,[6] C. A. Gagliardi,[47] D. R. Gangadharan,[32] D. Garand,[38] F. Geurts,[41] A. Gibson,[52] M. Girard,[54] S. Gliske,[2] L. Greiner,[26] D. Grosnick,[52] D. S. Gunarathne,[46] Y. Guo,[42] A. Gupta,[20] S. Gupta,[20] W. Guryn,[4] B. Haag,[6] A. Hamed,[47] L.-X. Han,[44] R. Haque,[31] J. W. Harris,[57] S. Heppelmann,[36] A. Hirsch,[38] G. W. Hoffmann,[48] D. J. Hofman,[10] S. Horvat,[57] B. Huang,[4] H. Z. Huang,[7] X. Huang,[50] P. Huck,[9] T. J. Humanic,[32] G. Igo,[7] W. W. Jacobs,[18] H. Jang,[24] E. G. Judd,[5] S. Kabana,[45] D. Kalinkin,[19] K. Kang,[50]

First *STAR* W A_L

STAR PRL 106, 062002



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

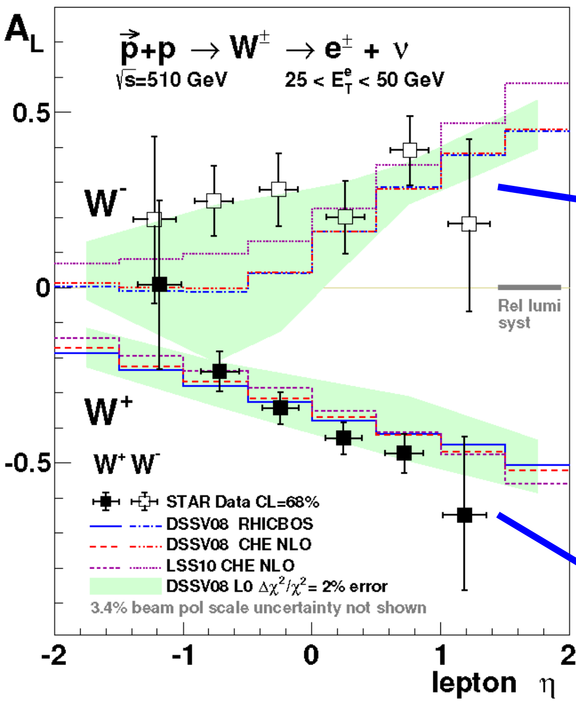
STAR 2009 Result

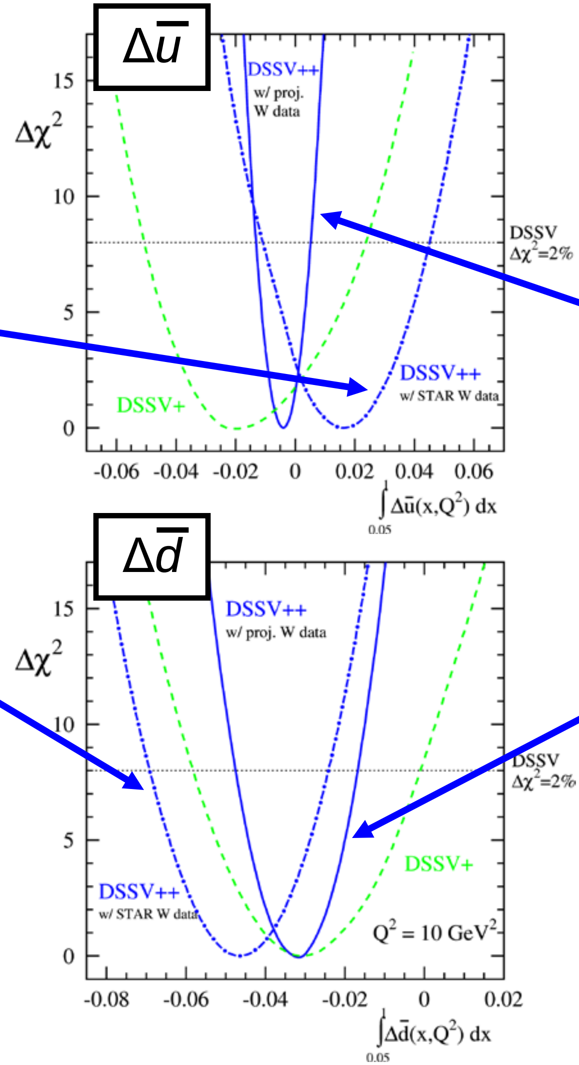
$$A_L(W^+) = -0.27 \pm 0.10(stat) \pm 0.02(syst)$$

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

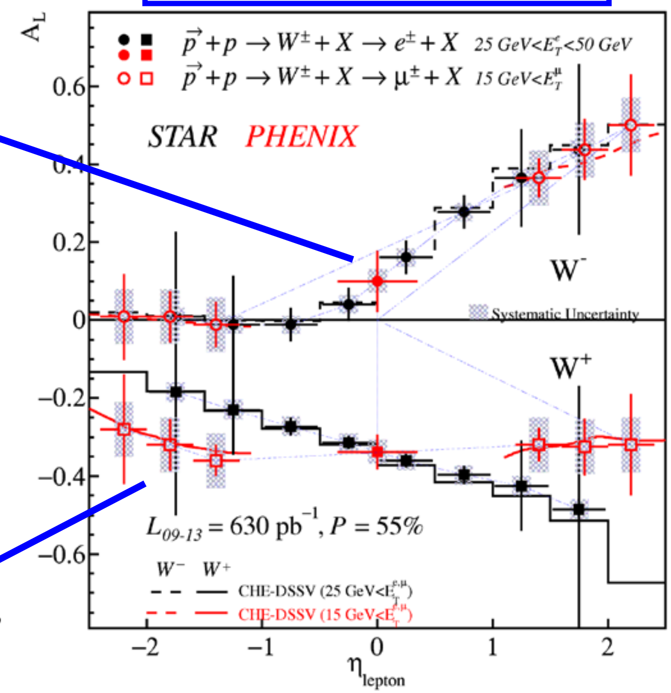
High precision *W* asymmetry era

STAR, arXiv:1404.6880





PHENIX and **STAR**
through 2013 run



- Results from 2011 and 2012 already provide substantial sensitivity
- Future results will provide a dramatic reduction in the uncertainties

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**
    - May contribute as much or more to the proton spin as the quarks and anti-quarks
  - **Flavor-separated quark and anti-quark polarizations**
  - **Transversity**

- Still more data have been **recorded and are being analyzed** at this moment. **Stay tuned!**