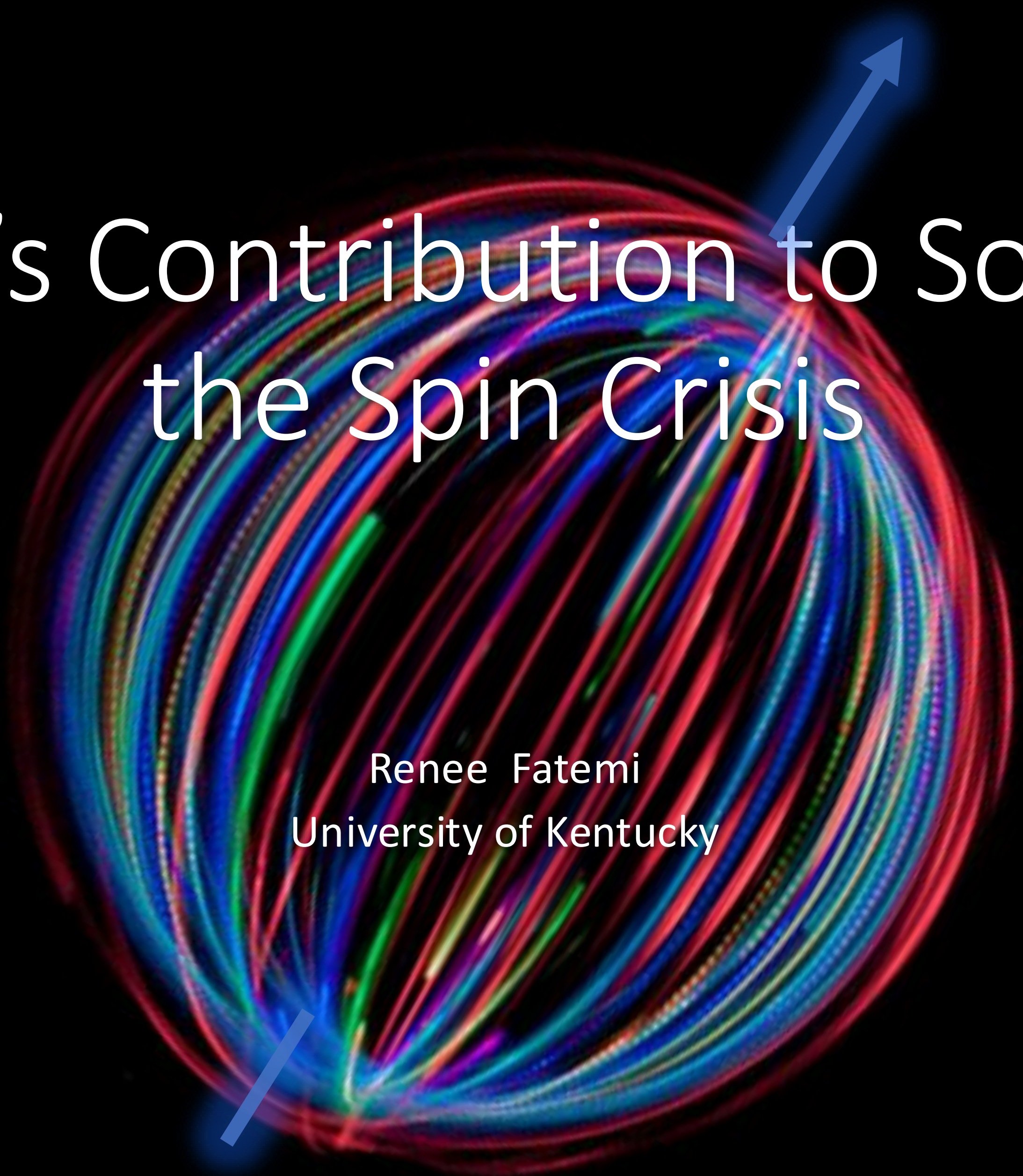
STAR's Contribution to Solving the Spin Crisis



Renee Fatemi
University of Kentucky

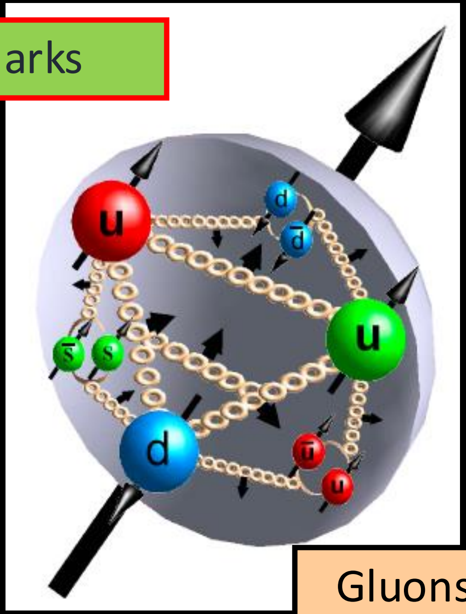
STAR 25 YEAR Celebration – December 18th, 2026

How do quarks and gluons combine to form the spin of the proton?

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

Proton

Quarks



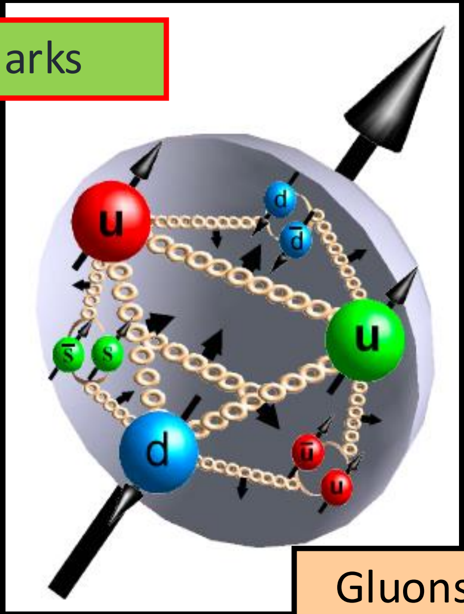
Gluons

Δq	**Quark helicity**
Δg	**Gluon helicity**
L_q	**Quark orbital angular momentum**
L_G	**Gluon orbital angular momentum**

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L_Q + L_G$$

Proton

Quarks



Gluons

Δq	Quark helicity
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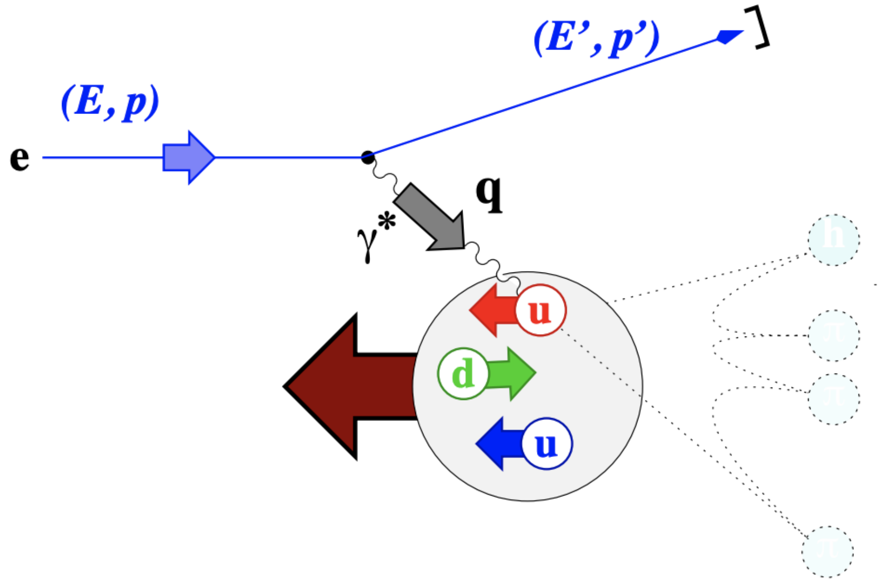
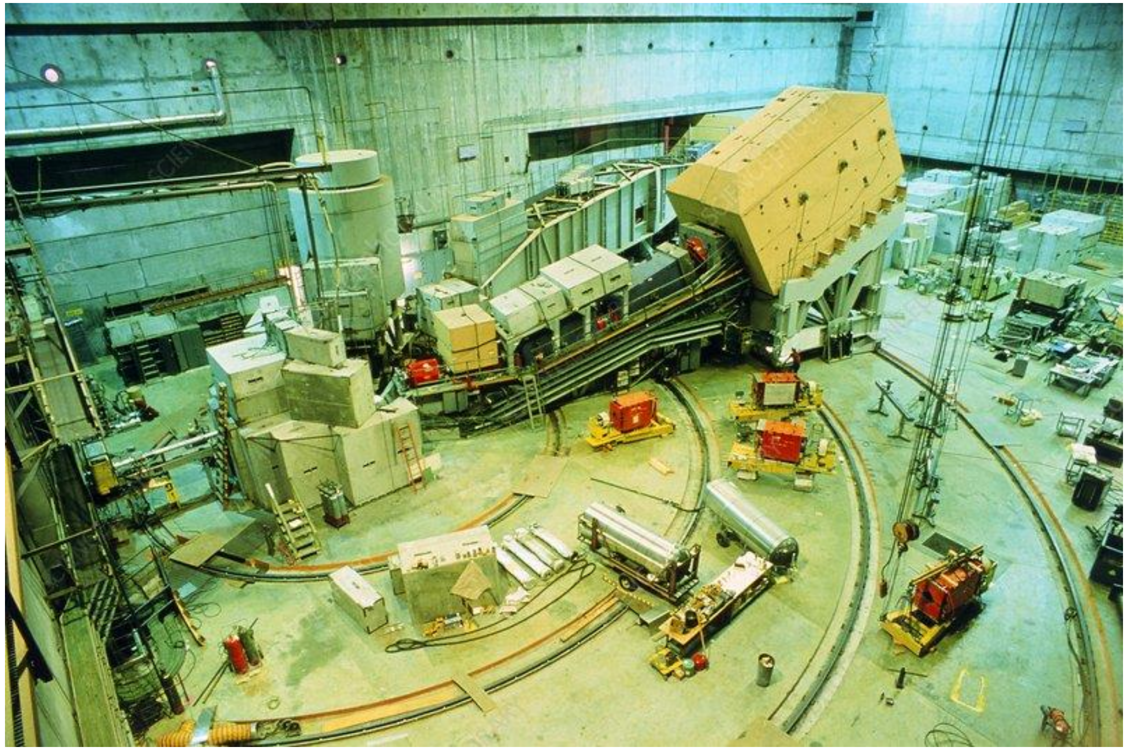
SLAC : First $\vec{e} + \vec{p}$ DIS experiments



E-80 and E-130

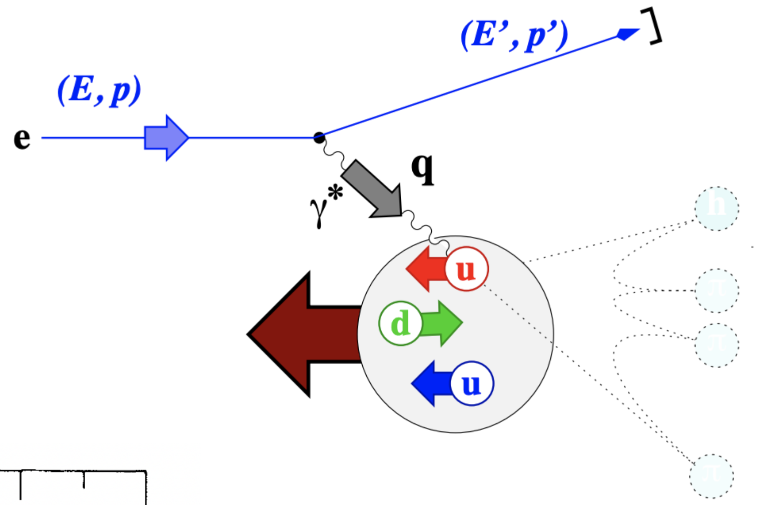
- Electron beams with energy 6-22 GeV and 50-80% polarization
- Butanol targets with ~60% proton polarization
- Electrons were detected in spectrometers located at End Station A.
- Mott and Moller polarimeters measure beam pol at source and ESA



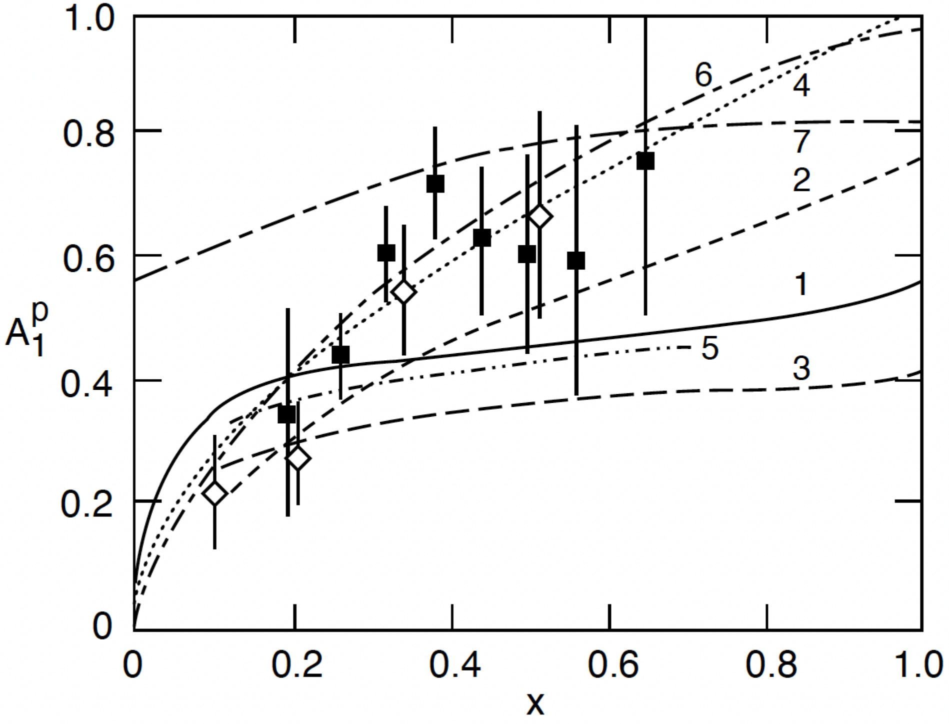
$$A_{||} = \frac{N^A - N^{\bar{A}}}{N^A + N^{\bar{A}}}$$

Allows for the first time the measurement of electron scattering rates, as a function of energy and scattering angle, when beam and target helicities are aligned (A) vs anti-aligned ($\bar{A}$)!

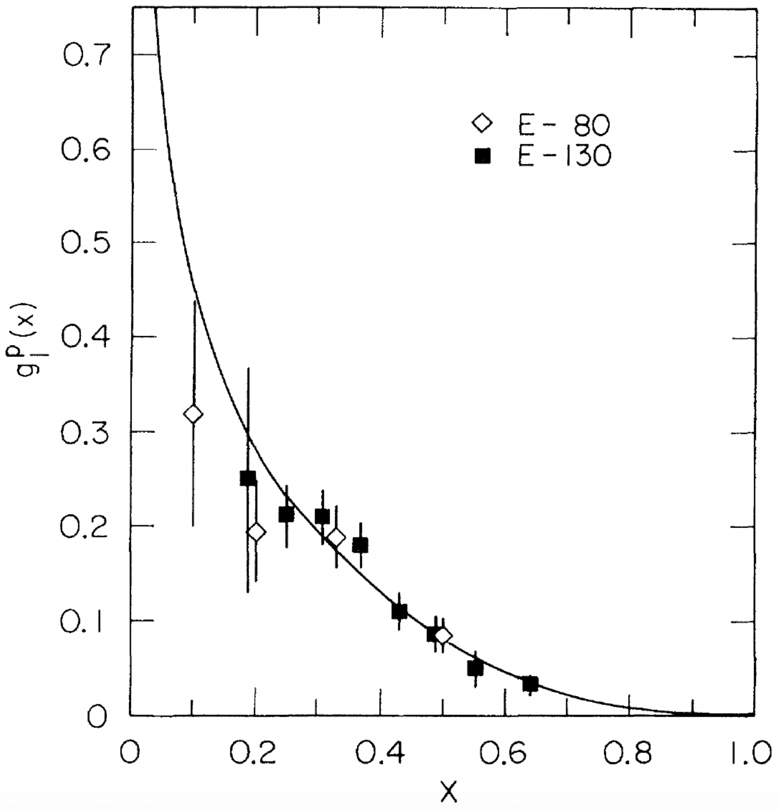
SLAC : First $\vec{e} + \vec{p}$ DIS experiments



$$A_{||} = D(A_1 + \eta A_2) \approx DA_1$$



$$g_1 \approx F_1 A_1$$



Quark Parton Model :

$$g_1(x) = \frac{1}{2} \sum_{q+\bar{q}} e_q^2 \Delta f_q(x)$$

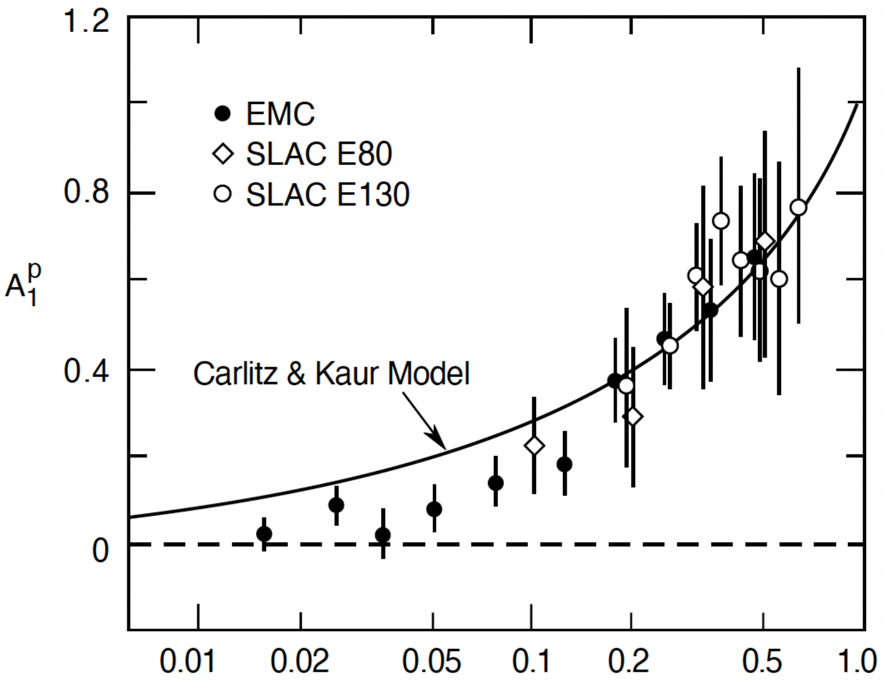
$$\Delta f(x) = f(x)^+ - f(x)^-$$

x = momentum fraction carried by struck quark

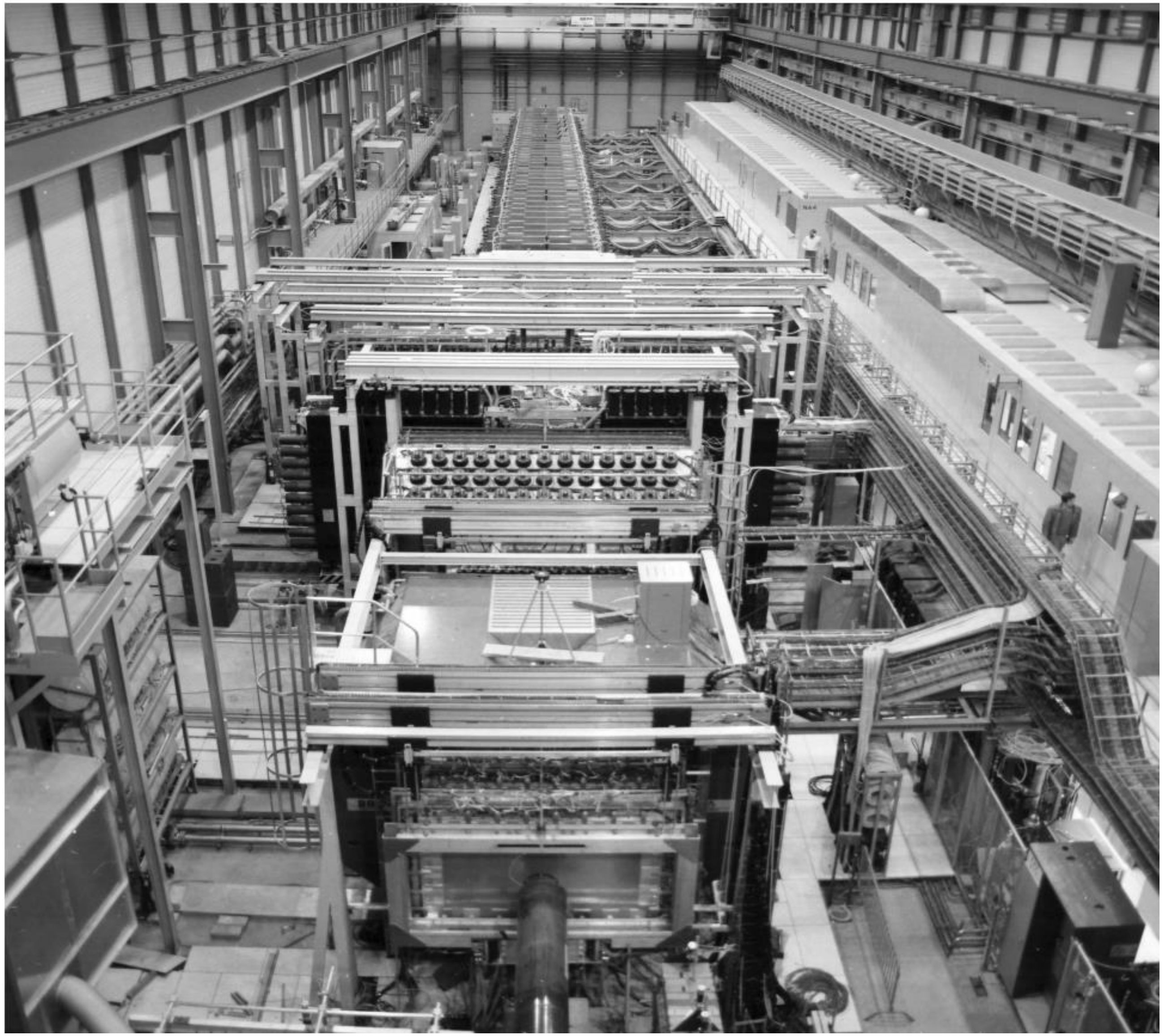
E-80 Phys. Rev. Lett. 37 (1976) 1261
E-130 Phys. Rev. Lett. 51 (1983) 1135

EMC @ CERN : First $\vec{\mu} + \vec{p}$ DIS experiments

- 100-200 GeV Muon beams with energy 100-200 GeV
- Pushes to higher Q^2 and lower x.
- Muon polarization ~80% from PV pion decays
- Intensity of muon beam was low and large transverse width
- Need a large target to maximize statistics -> 2m long ammonia target
- Target split in half and polarized in opposite directions to remove need to normalize to incoming beam luminosity
- Muons were detected in downstream spectrometers



Phys. Lett. B206 (1988) 364



The plot that launched the “spin-crisis”

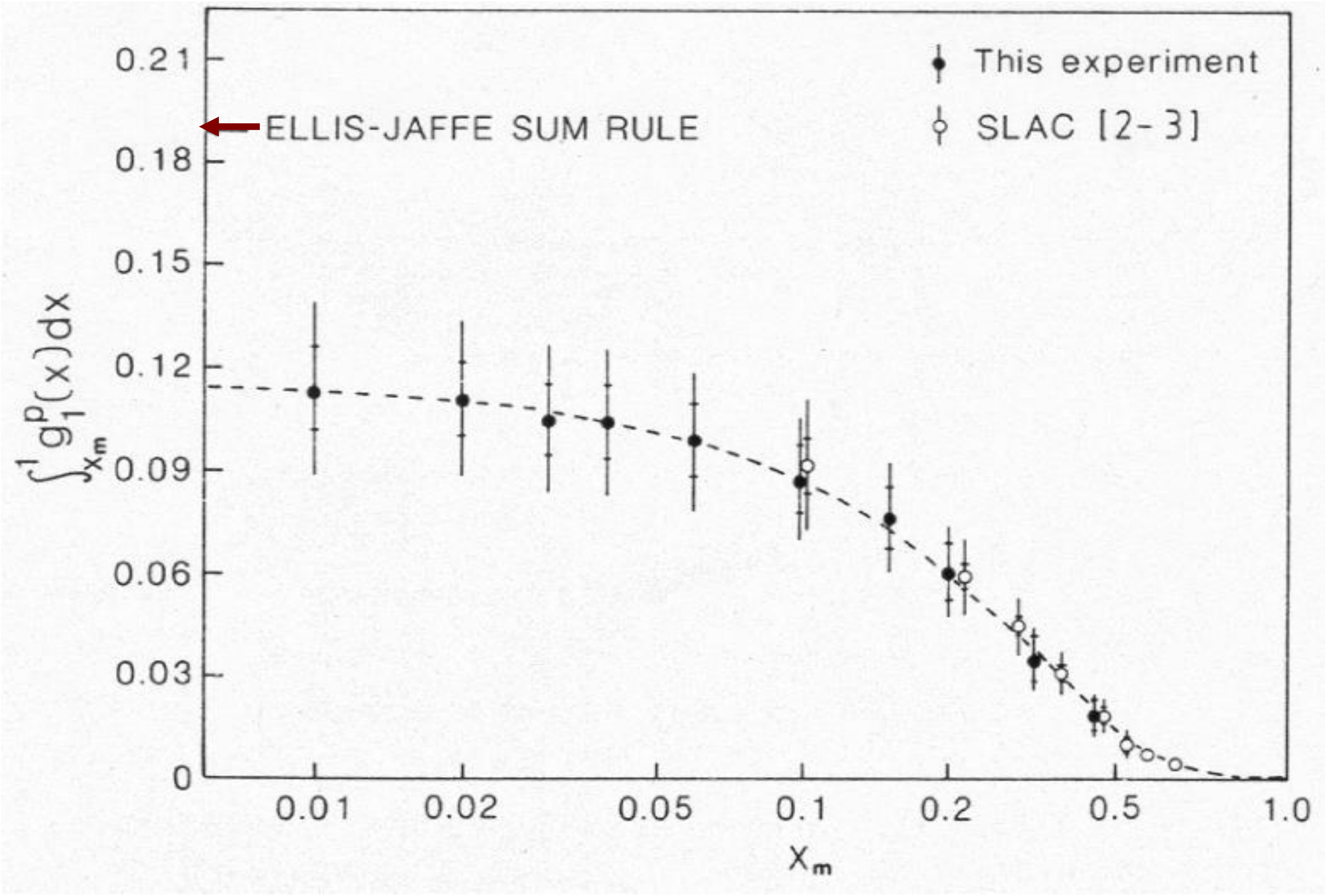
Conclusion was that quarks carry very little of the spin of the proton -> **$14 \pm 9 \pm 21\%$!**

The Ellis-Jaffe Sum Rule predicts a value for the integral of $g_1(x)$ over all x assuming:

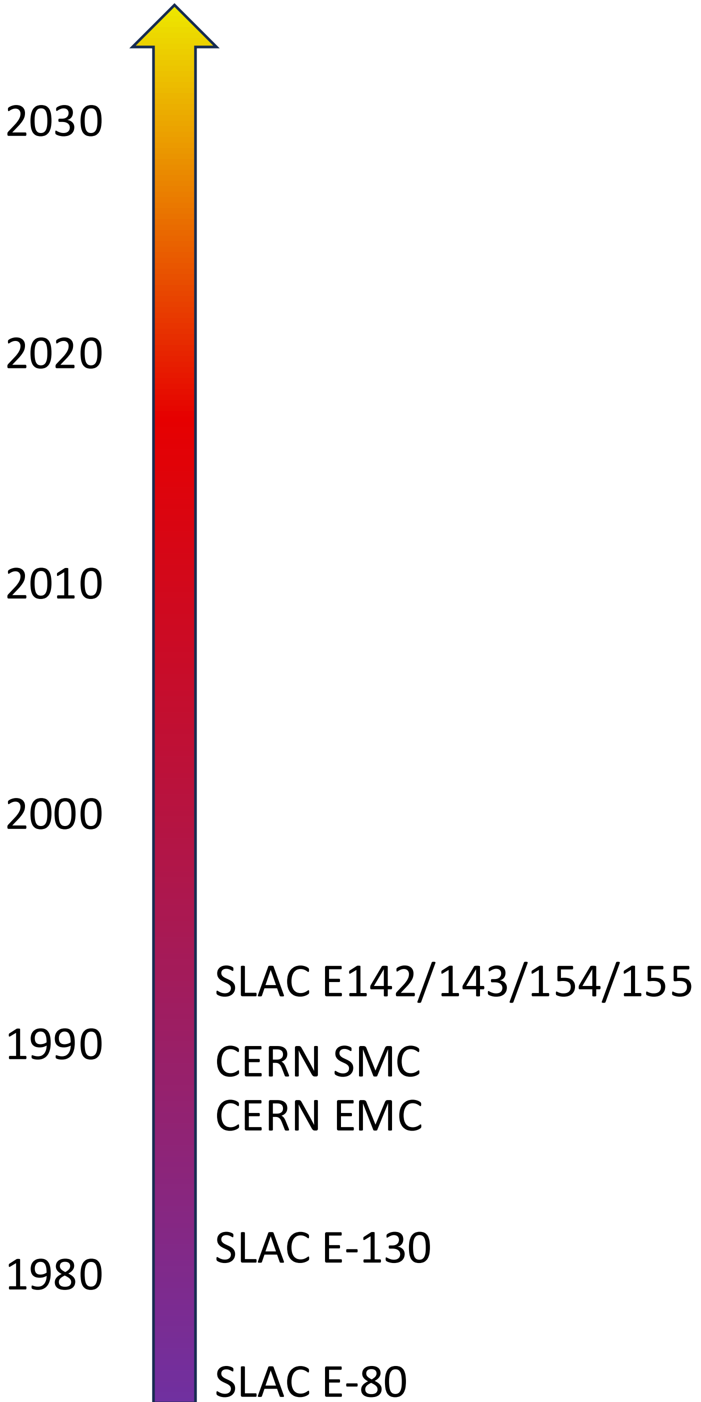
1) No gluon contribution to the spin of the proton
2) No strange sea contribution to spin of the proton.

Confirmed quickly by SMC @ CERN and additional SLAC experiments.

This generated a lot of discussion in the high energy physics community.



EMC Collaboration Nucl. Phys. B328, 1 (1989)


2030
2020
2010
2000
SLAC E142/143/154/155
1990
CERN SMC
CERN EMC
SLAC E-130
1980
SLAC E-80

2030

2020

2010

2000

1990

1980

SLAC E142/143/154/155

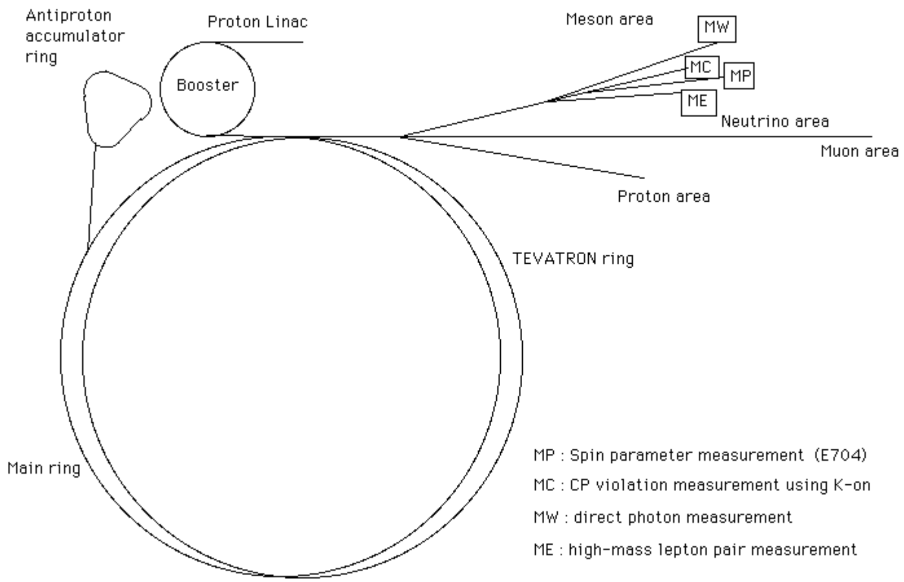
FNAL E581/704

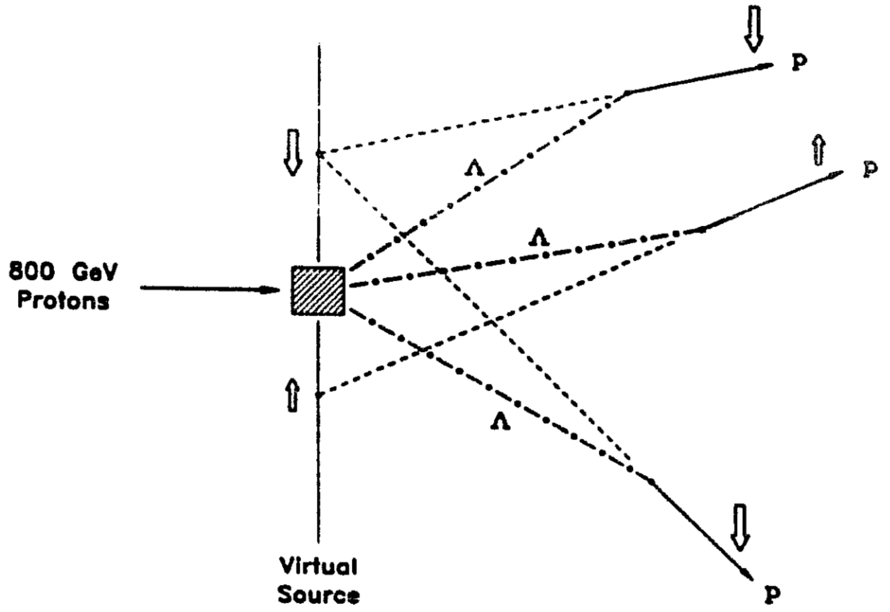
CERN SMC

CERN EMC

SLAC E-130

SLAC E-80



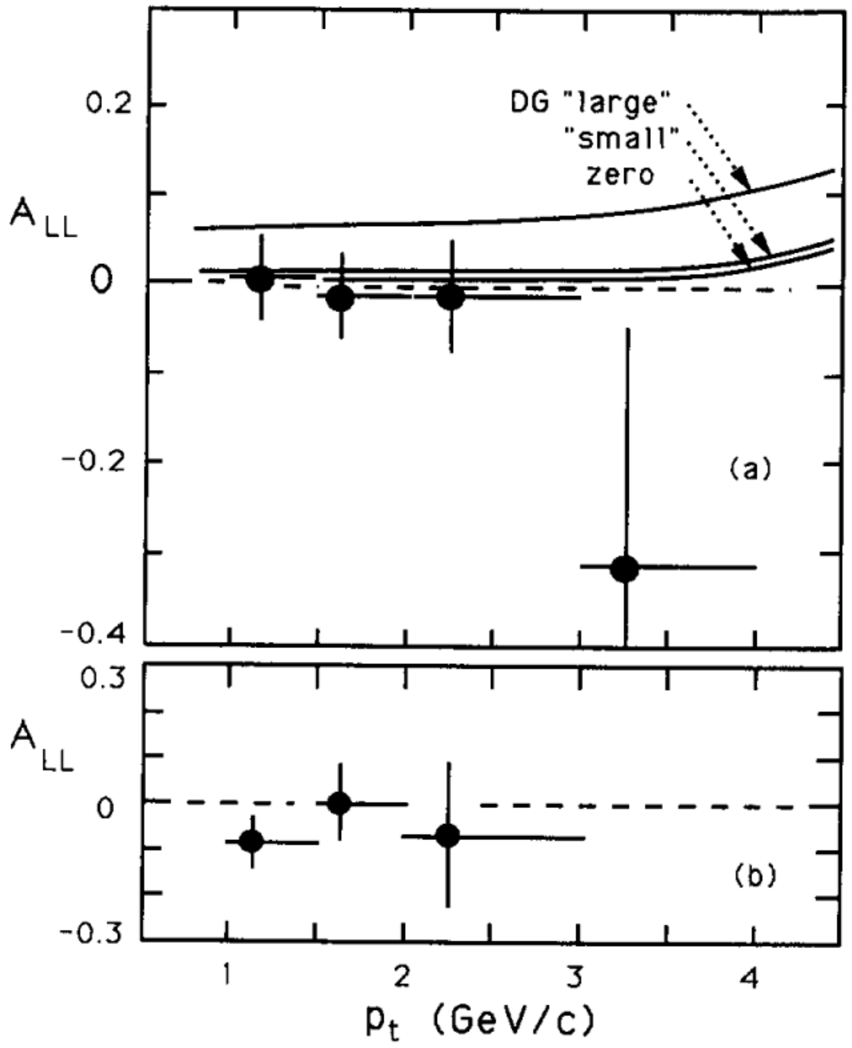


Fermilab Spin Physics Facility

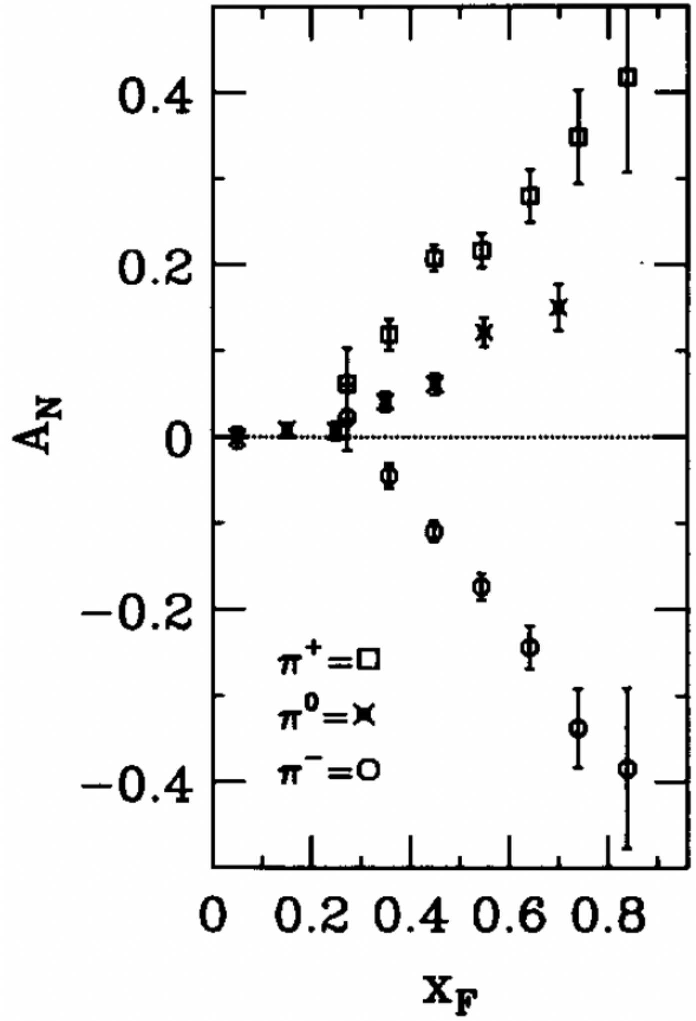
- 800 GeV protons from the Tevatron impinge a beryllium target
- $\Lambda + \bar{\Lambda}$ are produced and decay into protons ($\bar{p}$) + π^- (π^+)
- Proton spin is tagged via momentum and position reconstruction from hodoscopes in the beamline.
- Proton polarization flipped with spin rotators
- Result is 200 GeV protons beams with 45% polarization
- FNAL E851/E704 scattered polarized beam off LH2 and polarized pentanol target.

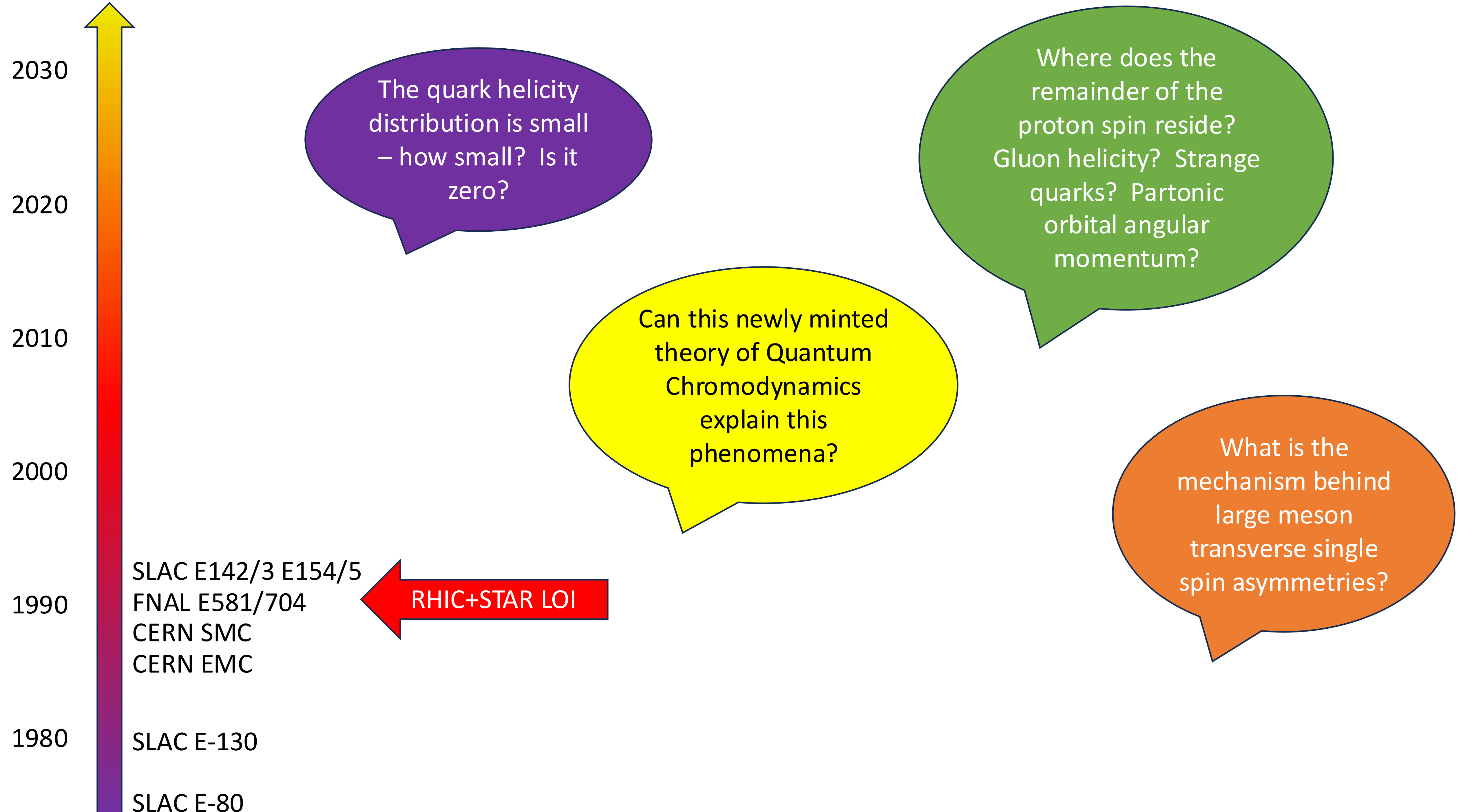
First measurement of A_{LL} and A_N in high energy $\vec{p}\vec{p}$ collisions

PLB 261 (1991), 197-200

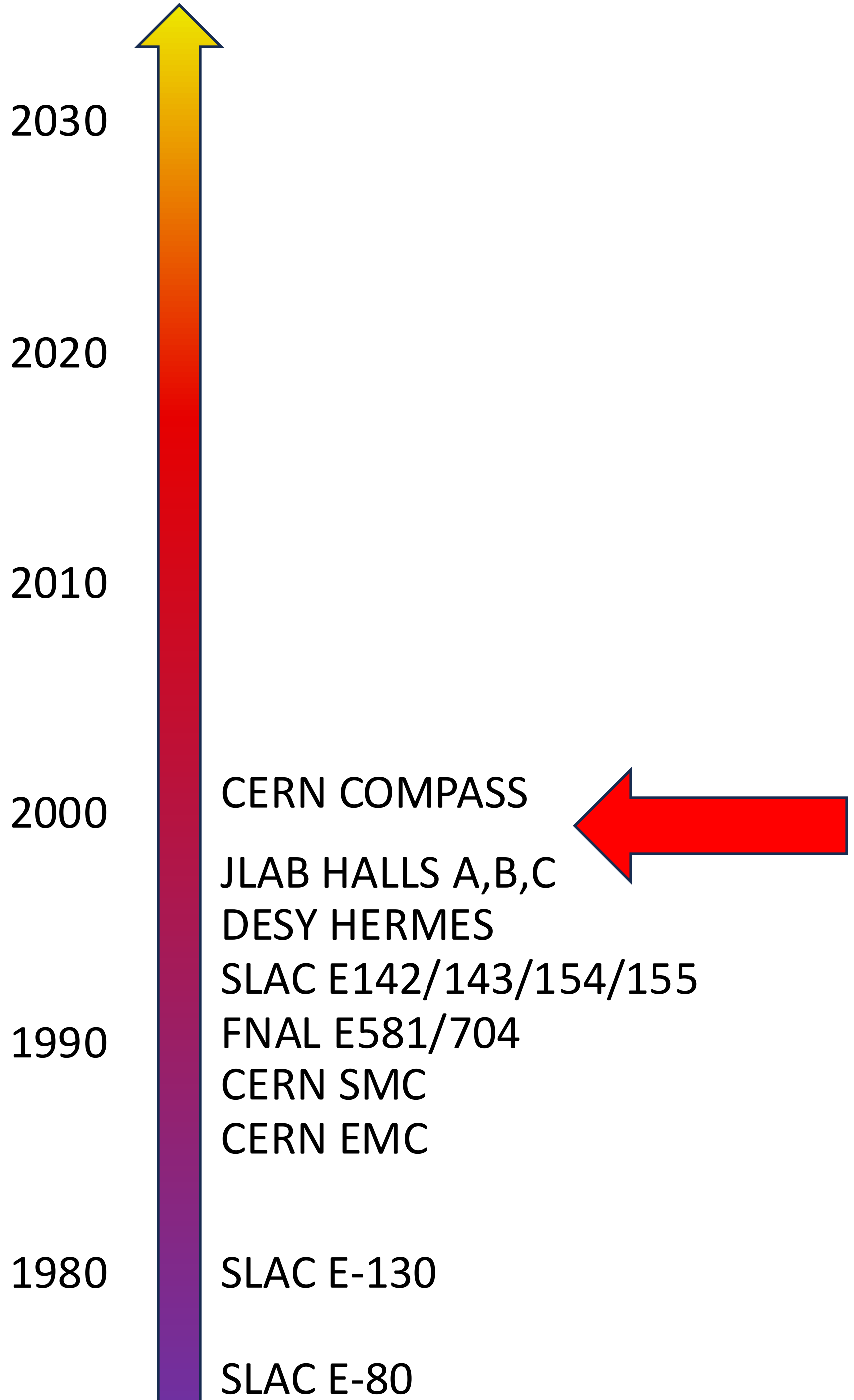


PRL 61 (1988) 1918
PLB 264 (1991) 462-466





2030
2020
2010
2000
1990
1980
The quark helicity distribution is small – how small? Is it zero?
Where does the remainder of the proton spin reside? Gluon helicity? Strange quarks? Partonic orbital angular momentum?
Can this newly minted theory of Quantum Chromodynamics explain this phenomena?
What is the mechanism behind large meson transverse single spin asymmetries?
SLAC E142/3 E154/5
FNAL E581/704
CERN SMC
CERN EMC
RHIC+STAR LOI
SLAC E-130
SLAC E-80



Annu. Rev. Nucl. Part. Sci. 2000. 50:525–75

Prospects for Spin Physics at RHIC

Gerry Bunce,[1] Naohito Saito,[2] Jacques Soffer,[3]
and Werner Vogelsang[4]

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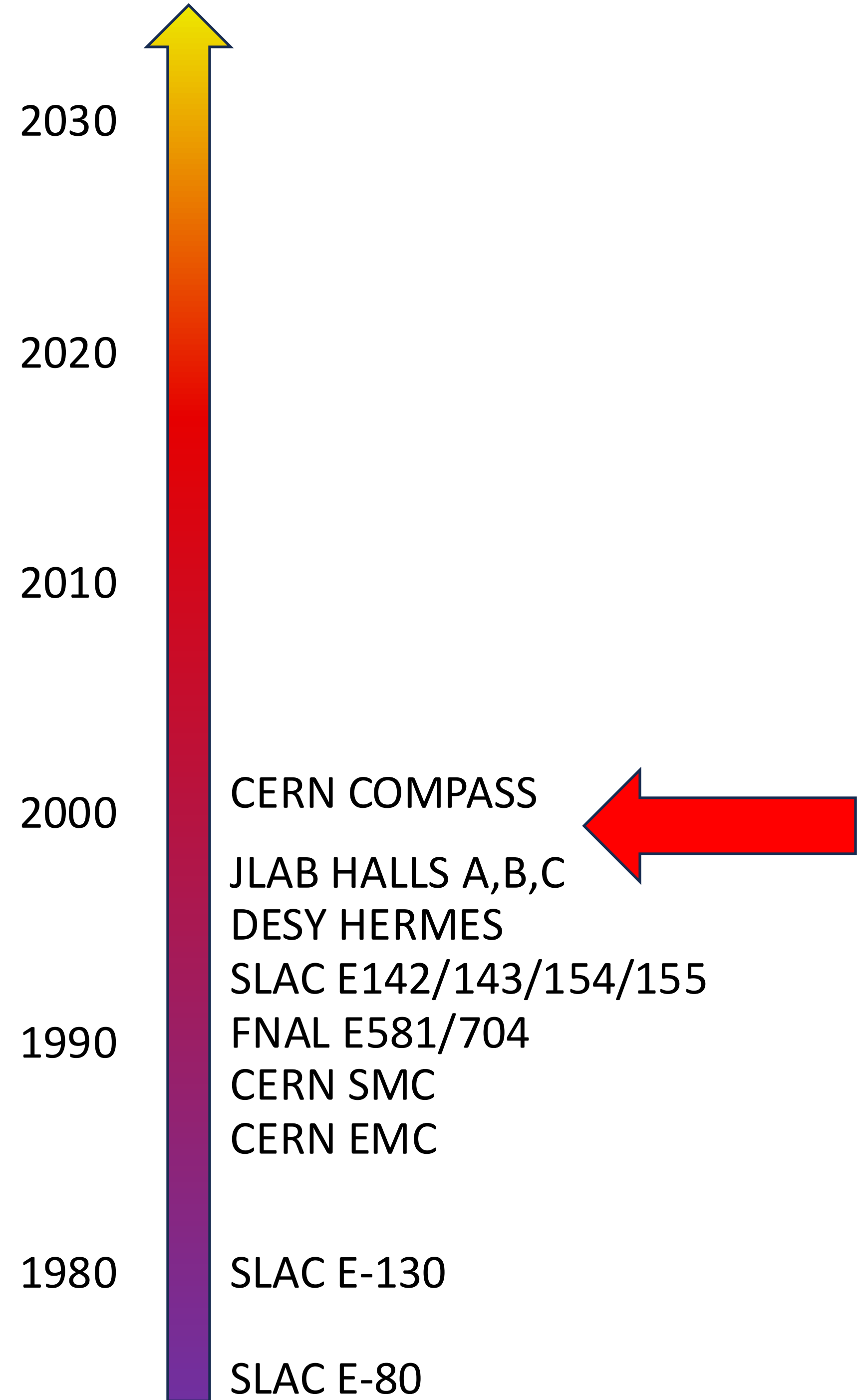
[4]*C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11794-3840 and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000; e-mail: wvogelsang@bnl.gov*

Key Words proton spin structure, spin asymmetries, quantum chromodynamics, beyond the standard model

■ **Abstract** Colliding beams of 70% polarized protons at up to $\sqrt{s} = 500$ GeV, with high luminosity, $L = 2 \times 10^{32}\,\text{cm}^{-2}\,\text{sec}^{-1}$, will represent a new and unique laboratory for studying the proton. RHIC-Spin will be the first polarized-proton collider and will be capable of copious production of jets, directly produced photons, and W and Z bosons. Features will include direct and precise measurements of the polarization of the gluons and of $\bar{u}$, $\bar{d}$, u, and d quarks in a polarized proton. Parity violation searches for physics beyond the standard model will be competitive with unpolarized searches at the Fermilab Tevatron. Transverse spin will explore transversity for the first time, as well as quark-gluon correlations in the proton. Spin dependence of the total cross section and in the Coulomb nuclear interference region will be measured at collider energies for the first time. These qualitatively new measurements can be expected to deepen our understanding of the structure of matter and of the strong interaction.



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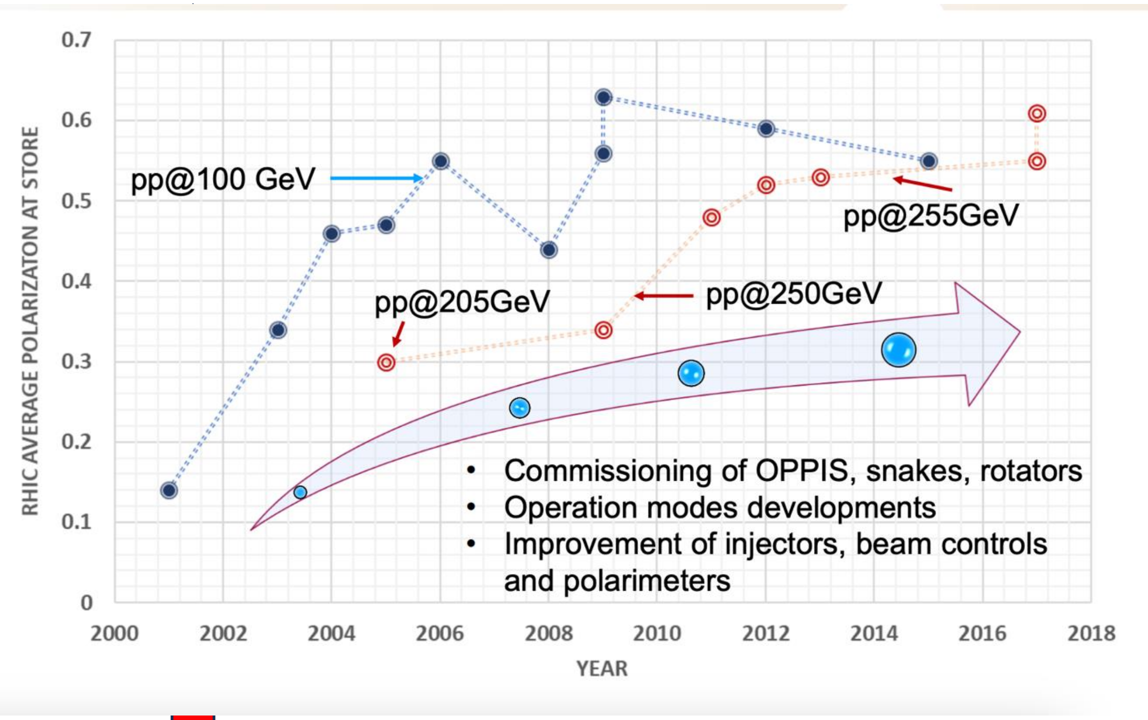
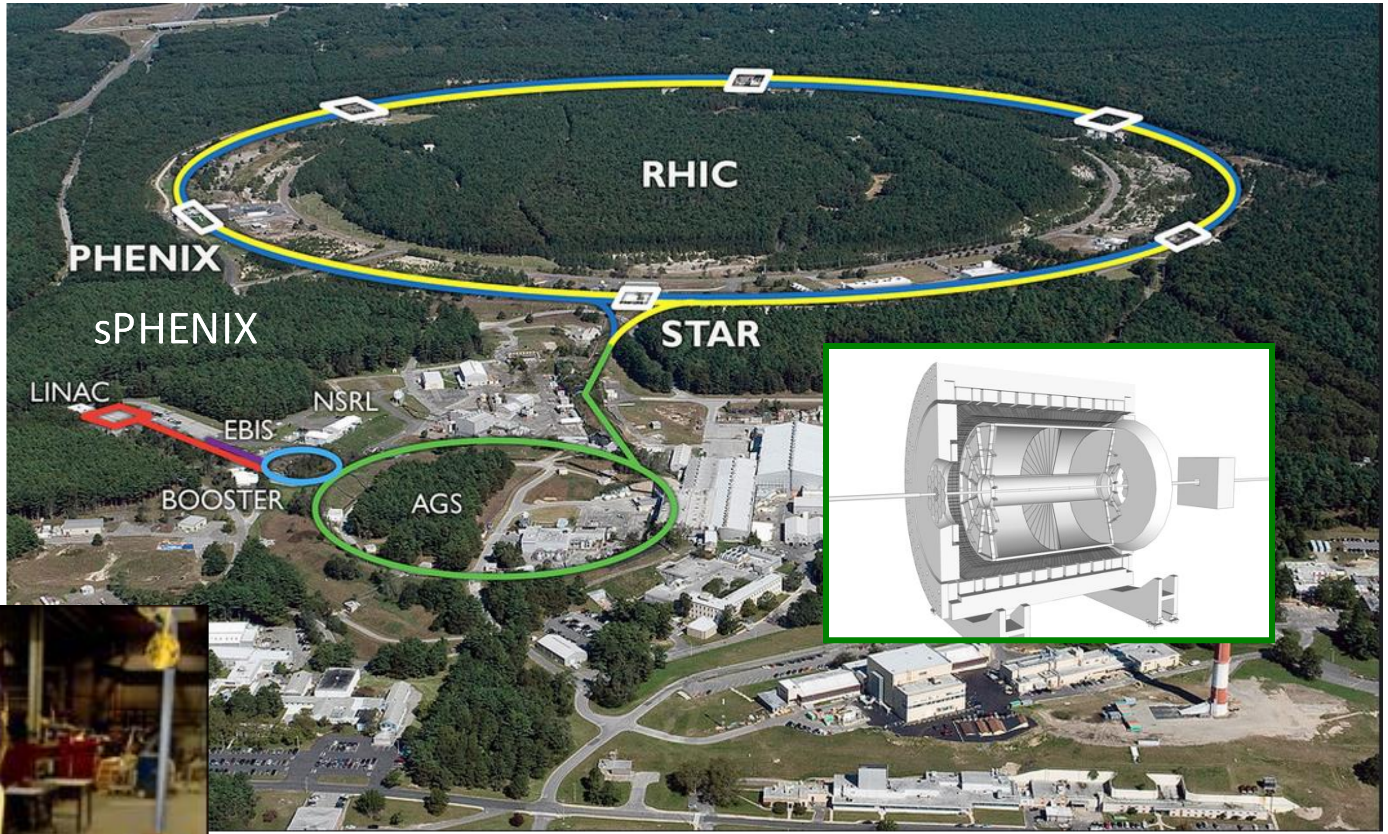
$\Delta G, \Delta u, \overline{\Delta u}, \Delta d, \overline{\Delta d}$ via jet, pion and W/Z production

First exploration of transversity and quark-gluon correlations



RELATIVISTIC HEAVY ION COLLIDER

… world's 1st high energy $\vec{p}\vec{p}$ collider

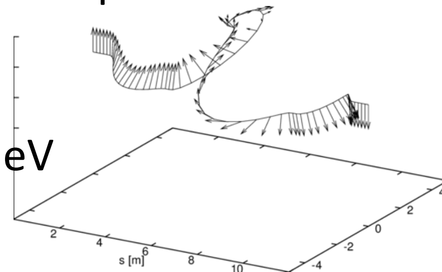


	BNL RHIC
2000	CERN COMPASS
	JLAB HALLS A,B,C
	DESY HERMES
	SLAC E142/143/154/155
1990	FNAL E581/704
	CERN SMC
	CERN EMC
1980	SLAC E-130
	SLAC E-80

Siberian snakes rotate proton spin vector by π, preserving spin tune through energy ramp.

Derbenev and Kondratanko in 1970.

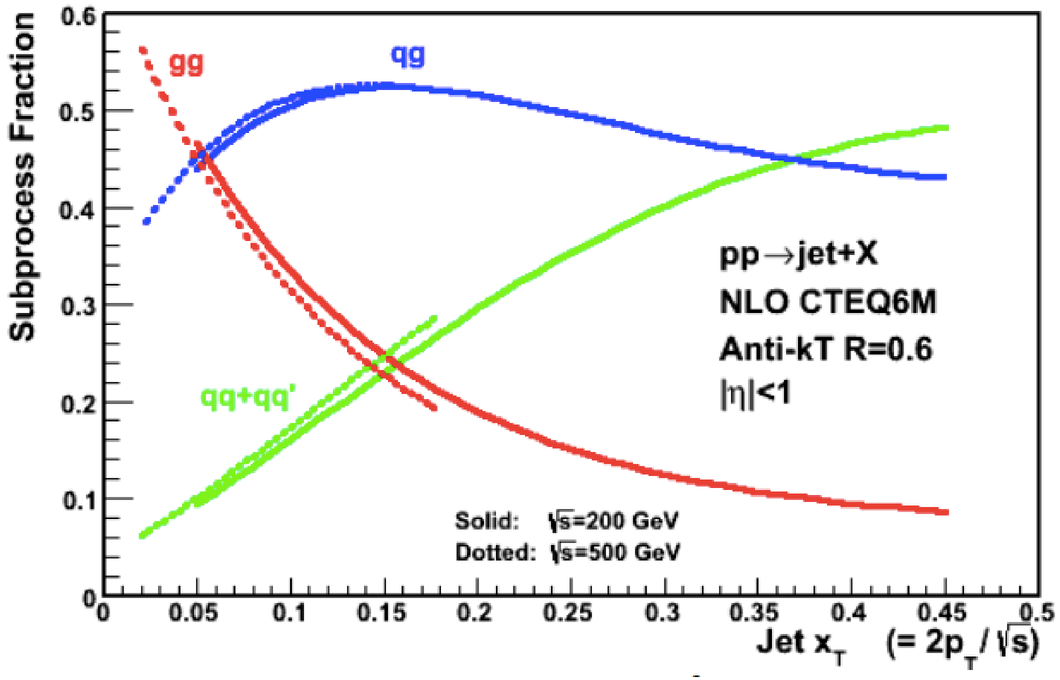
Beam energies range from 30-250 GeV with average polarization of 50-65%



ΔG in $\vec{p}\vec{p}$ collisions @ RHIC

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{f_A f_B f_C} \Delta f_A \Delta f_B \times \Delta\sigma_{AB\to CX} \times D_C}{\sum_{f_A f_B f_C} f_A f_B \times \sigma_{AB\to CX} \times D_C}$$

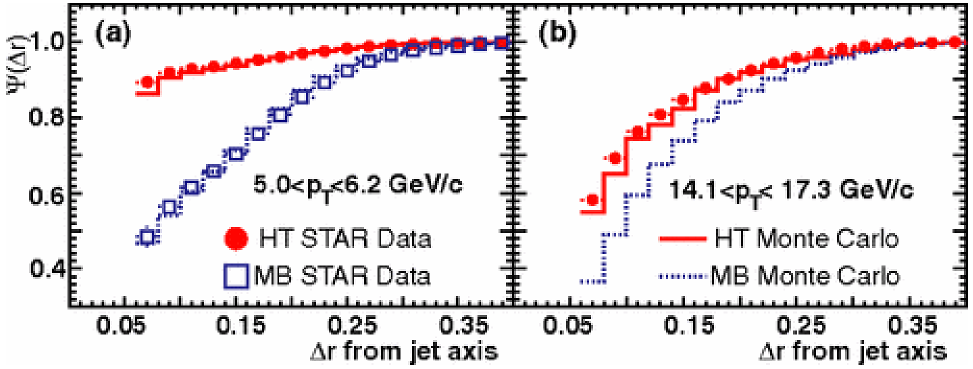
- Interpretation of charged and neutral pion A_{LL} requires additional uncertainties associated with fragmentation functions
- Jets do not rely on FF … nevertheless they are not as simple as they seem.



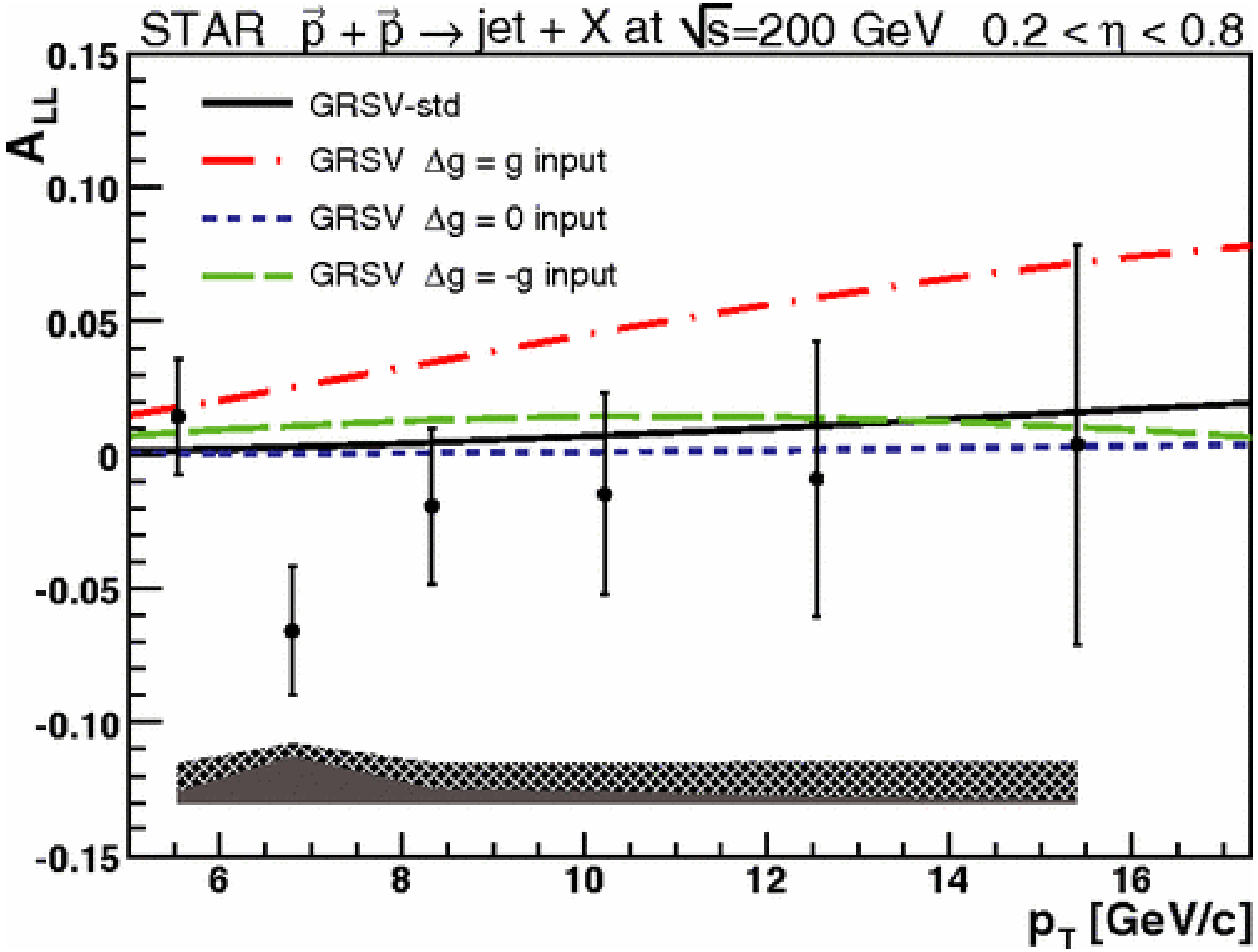
Jets? At $\sqrt{s} = 200$ GeV? … from a bunch of fixed target people?

First jet A_{LL}

1) First significant A_{LL} combined 2003+2004
2) First longitudinal pp runs <P_{beam}> = 30/45%
3) Midpoint cone algorithm (pre-anti-kT!)
4) R = 0.4 due to half of barrel + TPC
5) High tower trigger results in strong pT dependent bias

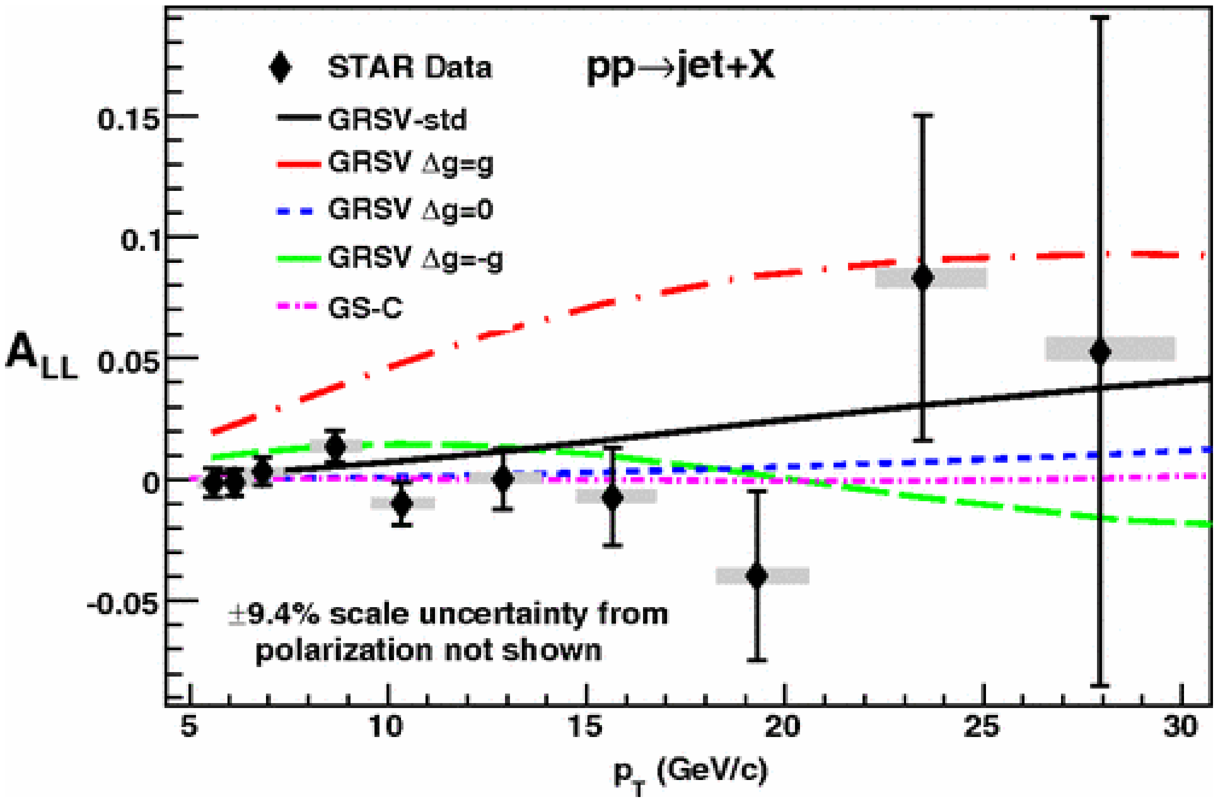


Ruled out maximal case of Δg but need more status to distinguish Δg = 0 and Δg = –g.



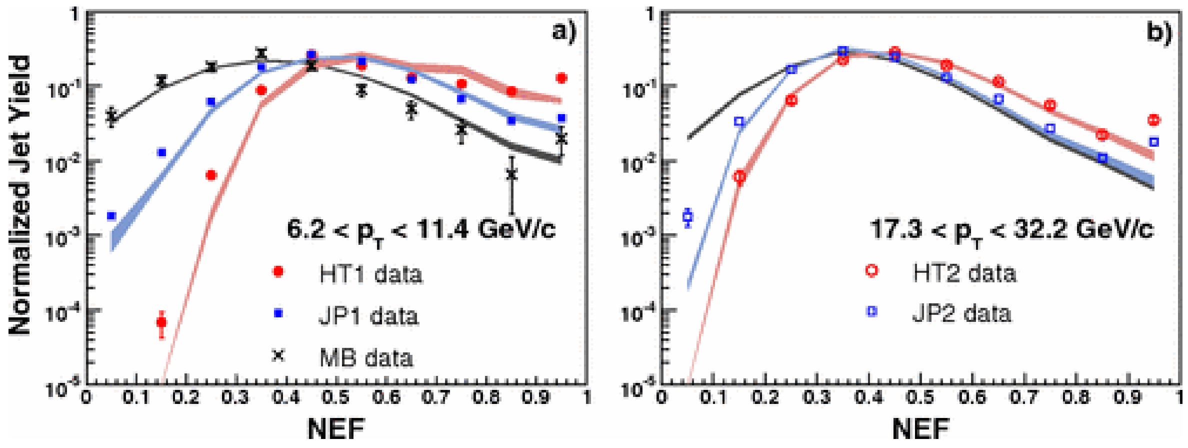
Phys. Rev. Lett. **97**, 252001

Precision Mid-rapidity Jets



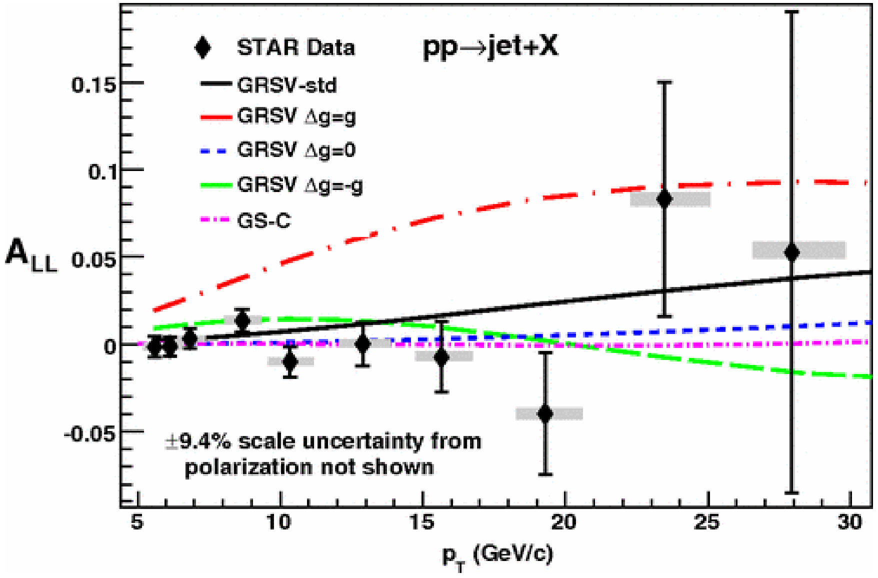
Phys. Rev. Lett. **100**, 232003

2005 $\langle P_{beam} \rangle = 52\%$
Introduced Jet Patch Triggers
Still midpoint cone R = 0.4

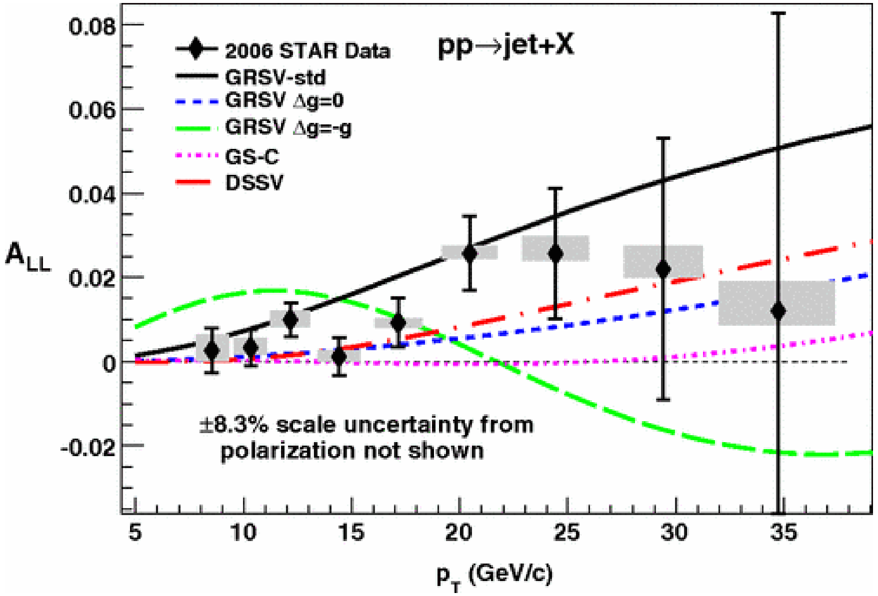


Precision Mid-rapidity Jets

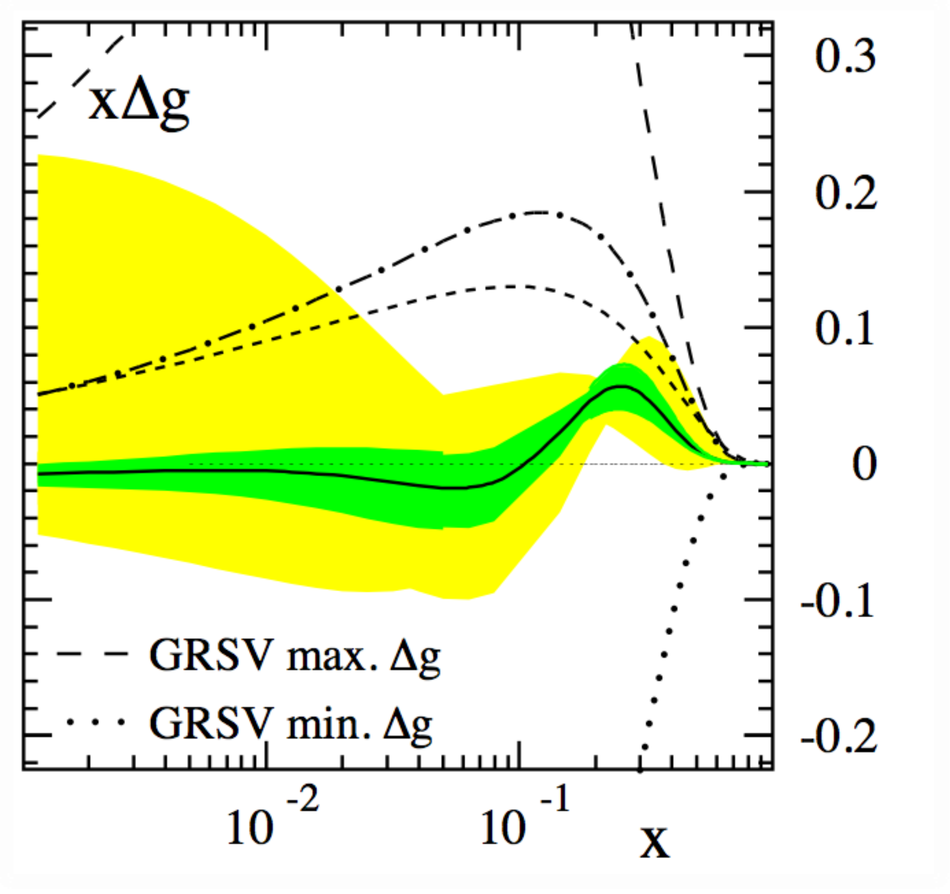
Phys. Rev. Lett. **100**, 232003
2005 Midpoint Cone R =0.4



Phys. Rev. D **86**, 032006
2006 Midpoint R =0.7

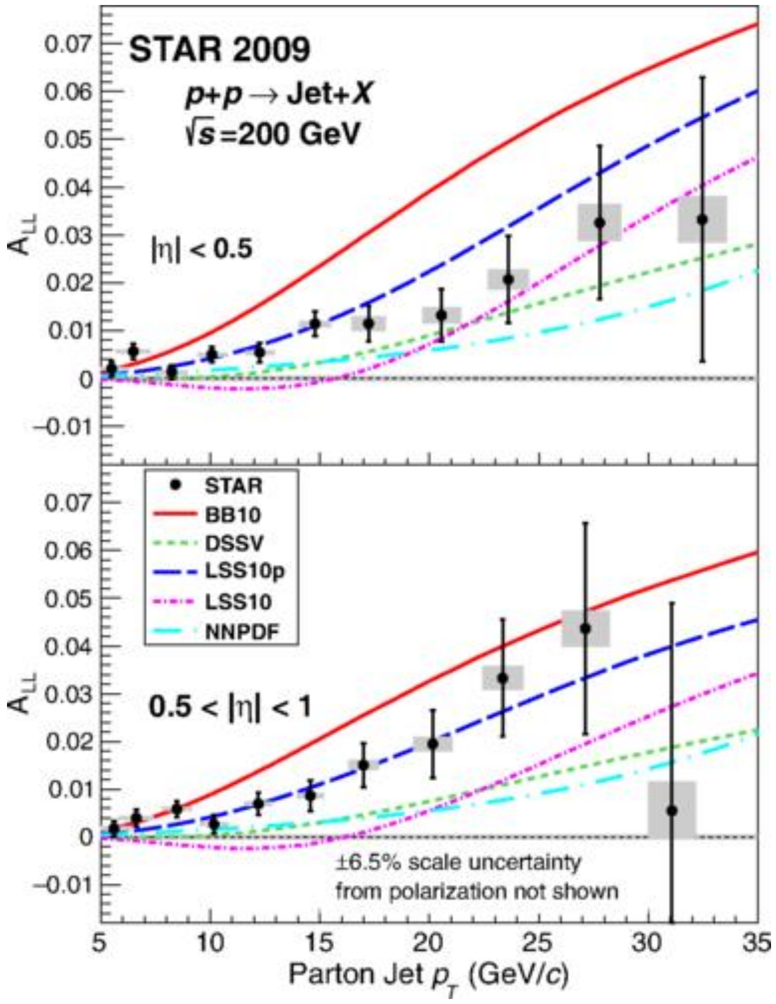


DSSV 08 -> 1st Helicity Global Analysis with Jets!



Phys.Rev.Lett. 101:072001

2009 jets -> 1st evidence of significant ΔG



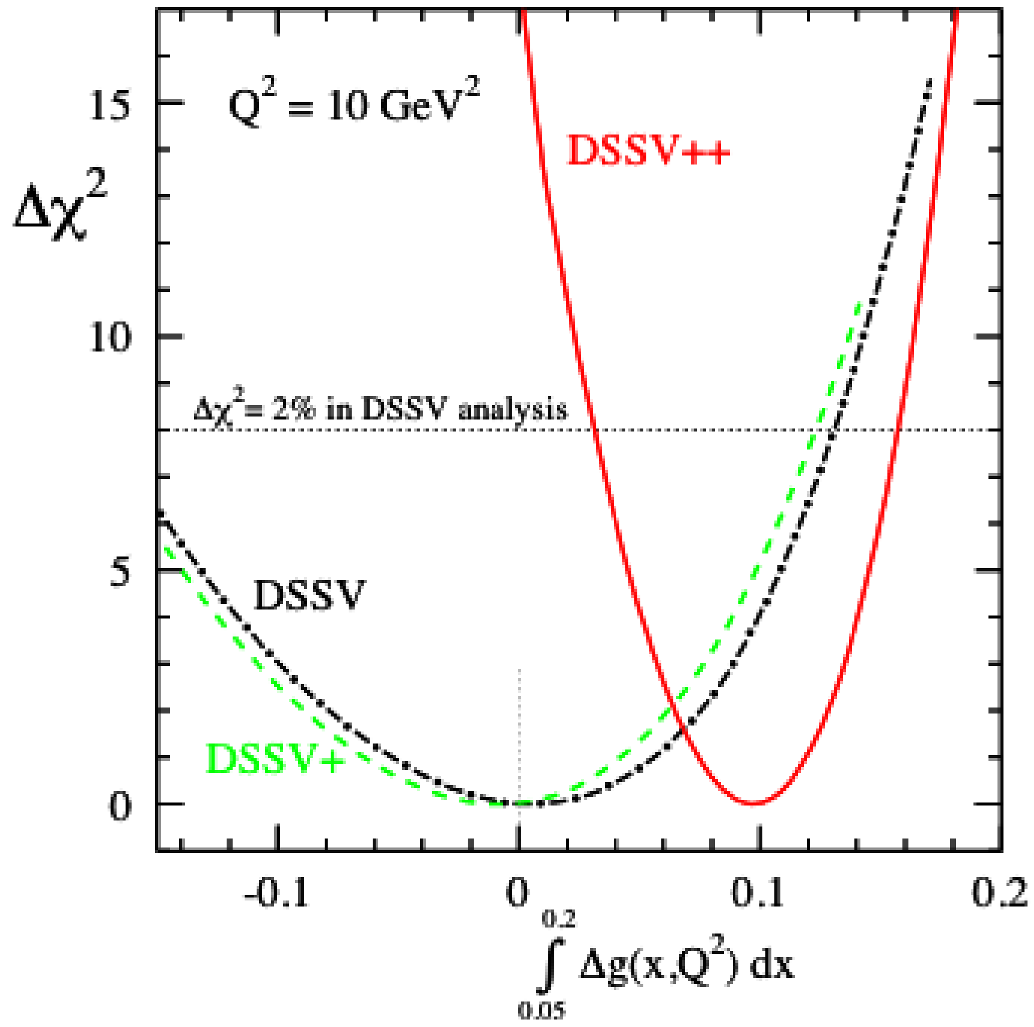
Phys. Rev. Lett. **115**, 092002

Anti-K_T R = 0.6

Two bins in eta

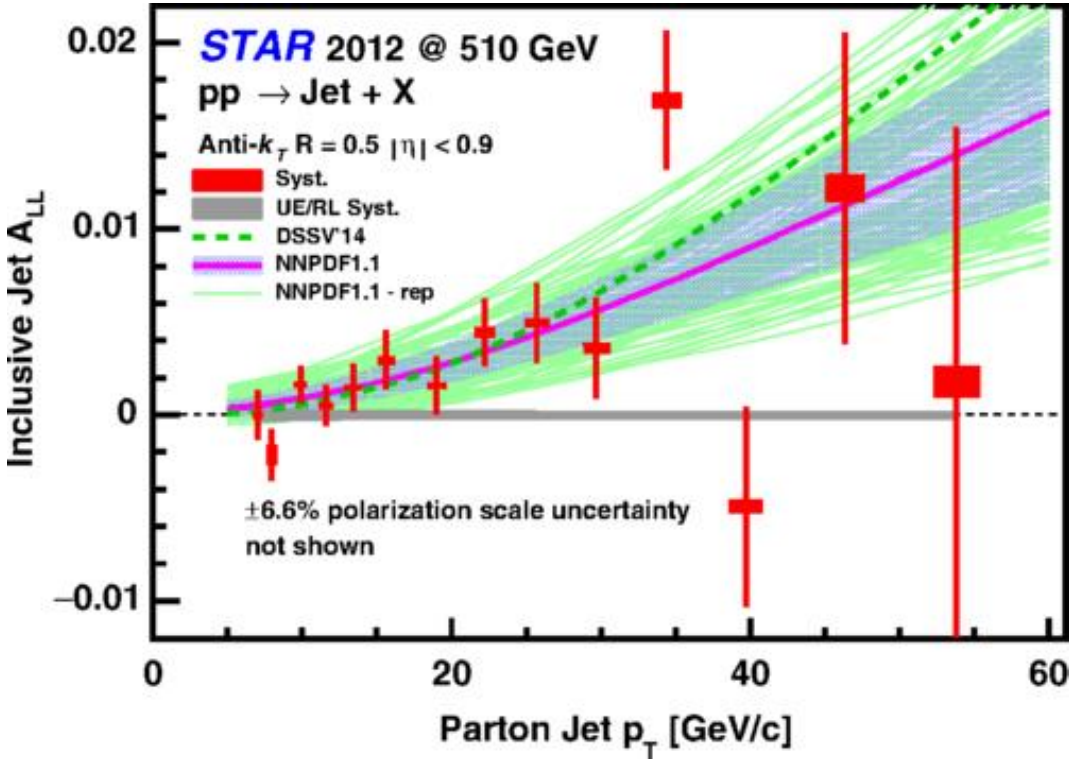
Updated MIP correction

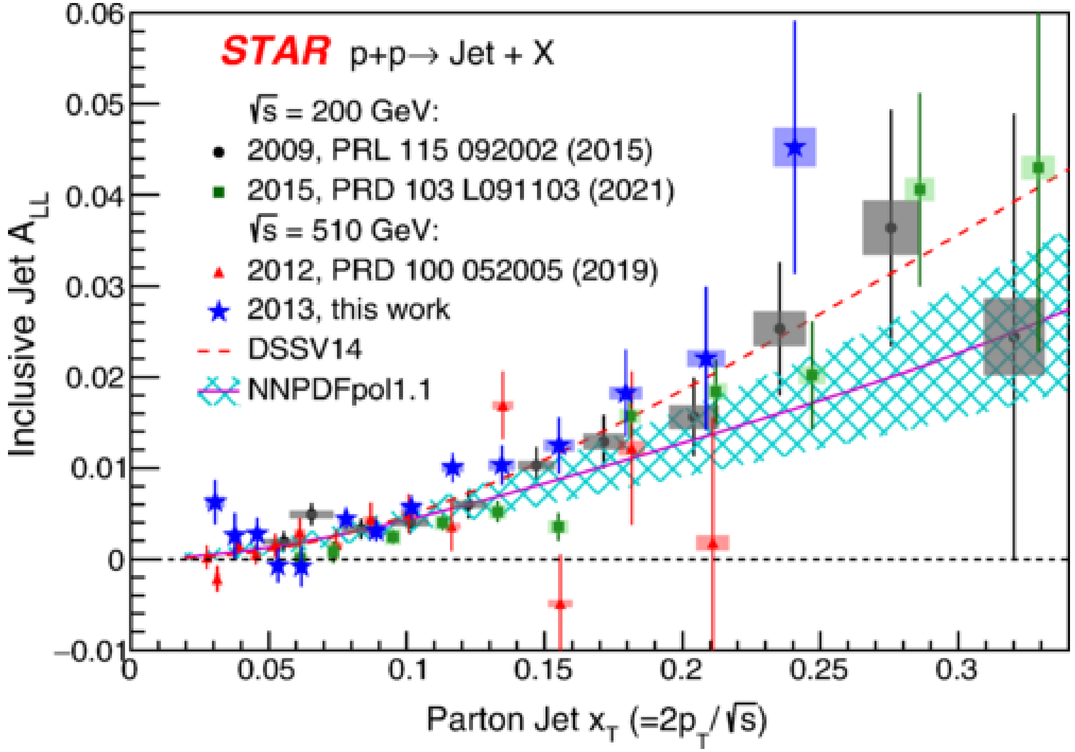
1st correction to Parton Level



Mid-rapidity Jets @ 510 GeV

$$x \approx x_T e^{\pm\eta} = \frac{2p_T}{\sqrt{s}} e^{\pm\eta}$$





Phys. Rev. D **100**, 052005
First time data driven UE subtraction is applied

Phys. Rev. D **105**, 092011

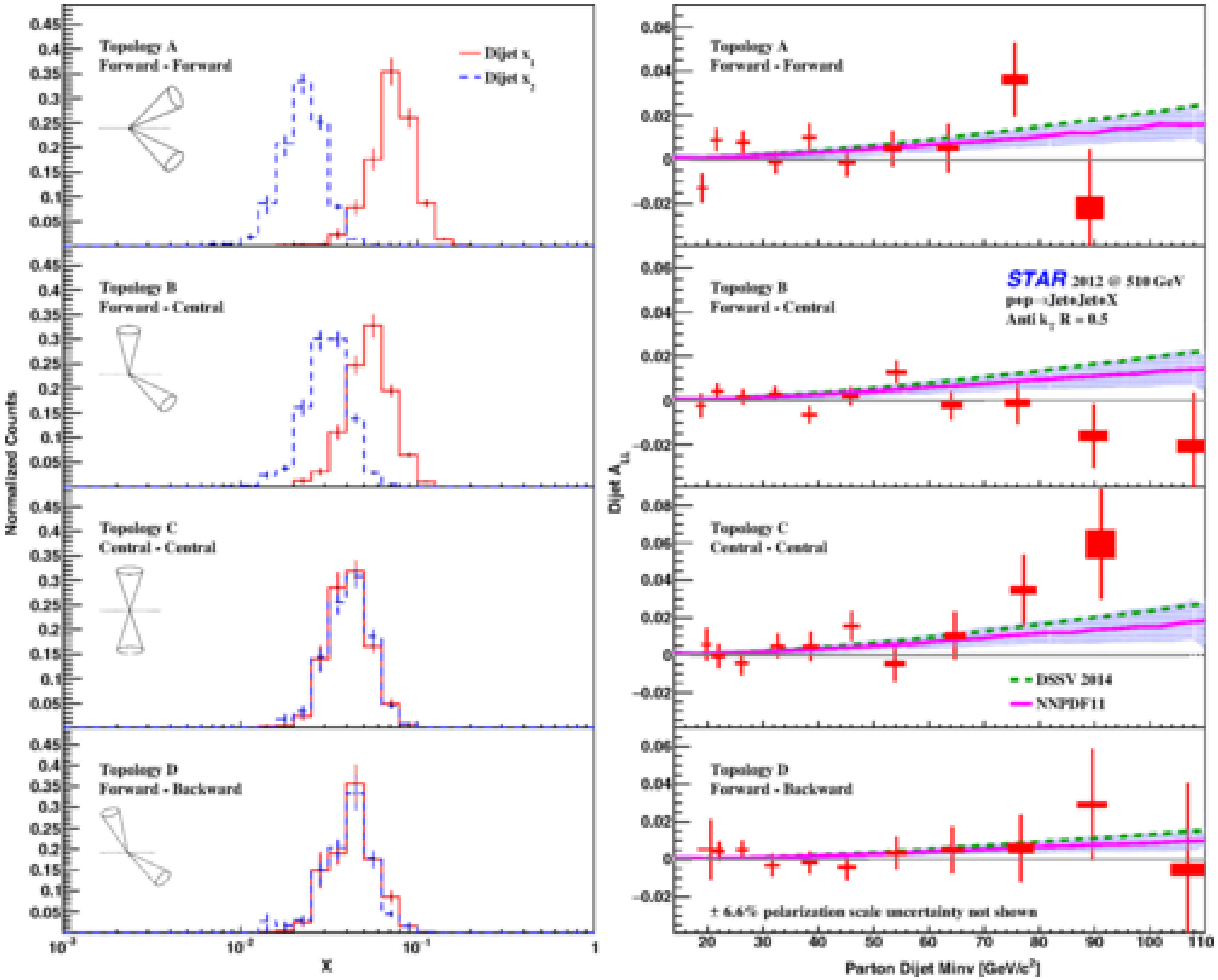
Mid-rapidity Dijets

- Inclusive jets sample **broad range** of parton momentum fraction x.
- This limits constraints on the functional form of $\Delta g(x)$ and **increases uncertainty at lower x**.
- Dijets allow for reconstruction of the **initial parton x_1 and x_2** at leading order.

$$x_{1,2} = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\pm\eta_3} + p_{T4}e^{\pm\eta_4}\right)$$

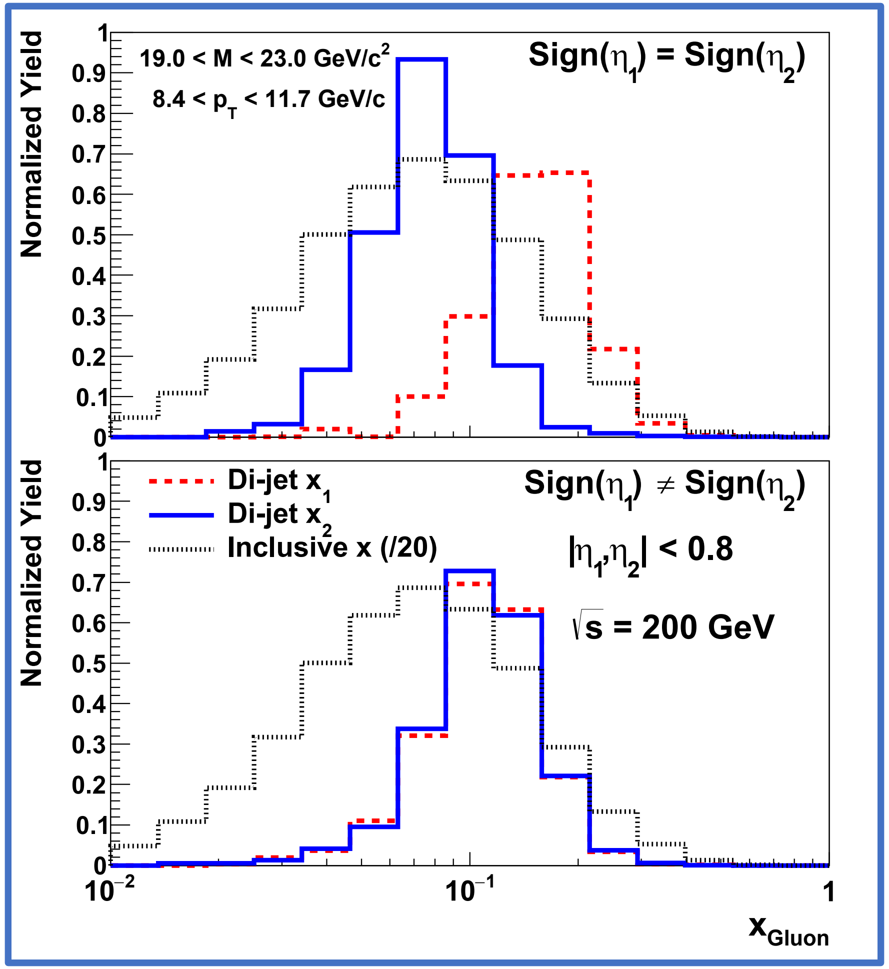
$$|\cos\theta^*| = \tanh\left|\frac{\eta_3 - \eta_4}{2}\right|$$

2012 510 GeV mid-rapidity dijets



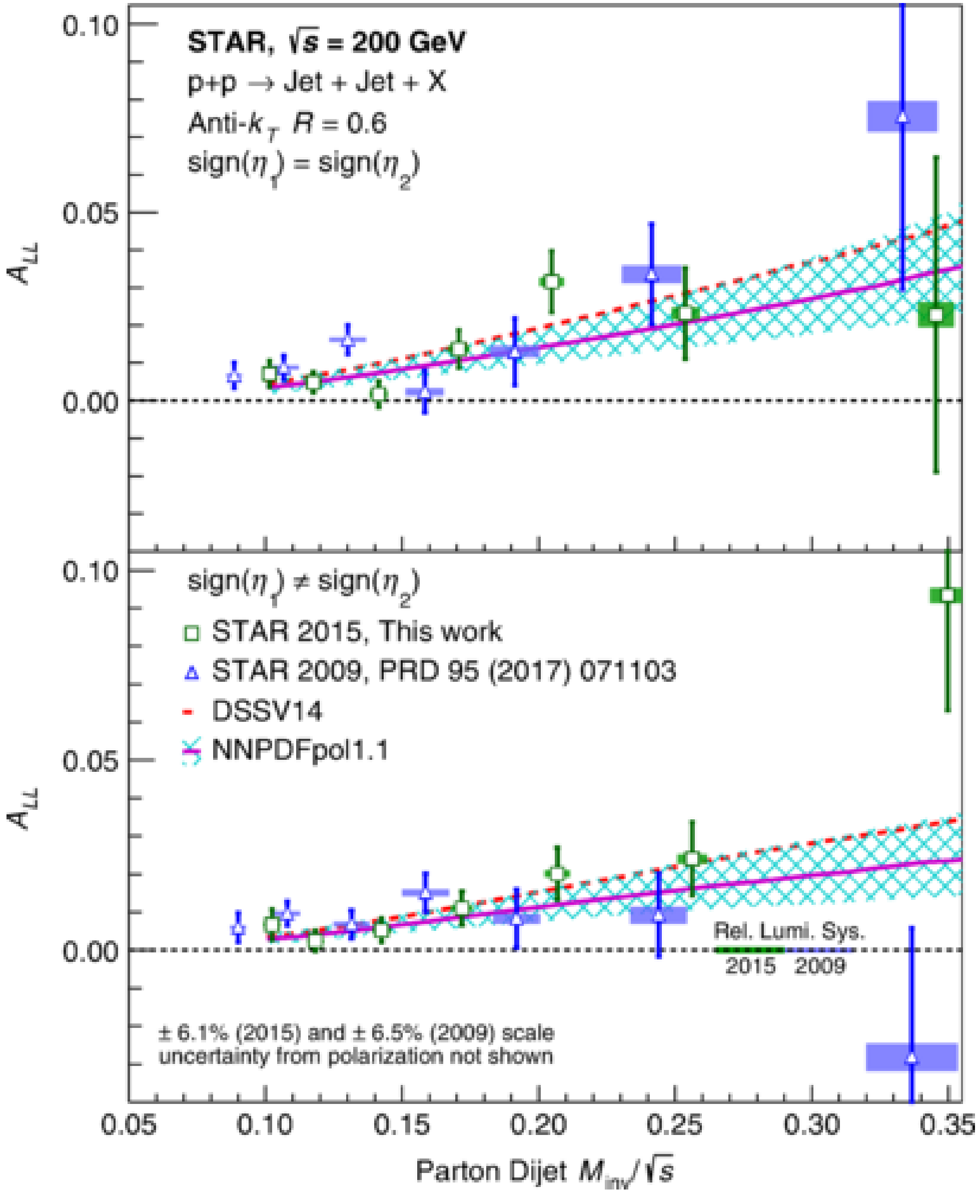
Phys. Rev. D **100**, 052005

Mid-rapidity Dijets

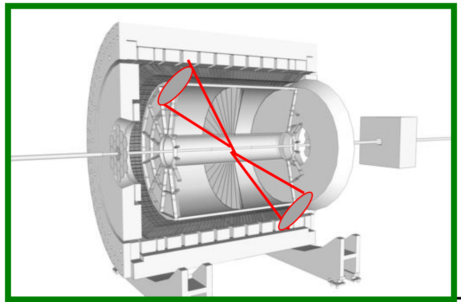


Phys. Rev. D **95**, 071103
Phys. Rev. D **103**, L091103

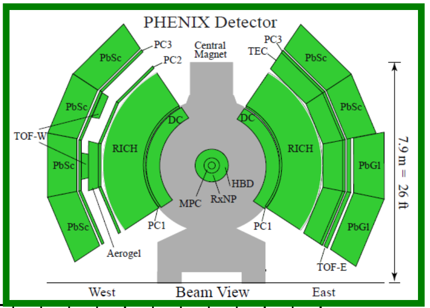
2012 200 GeV mid-rapidity dijets

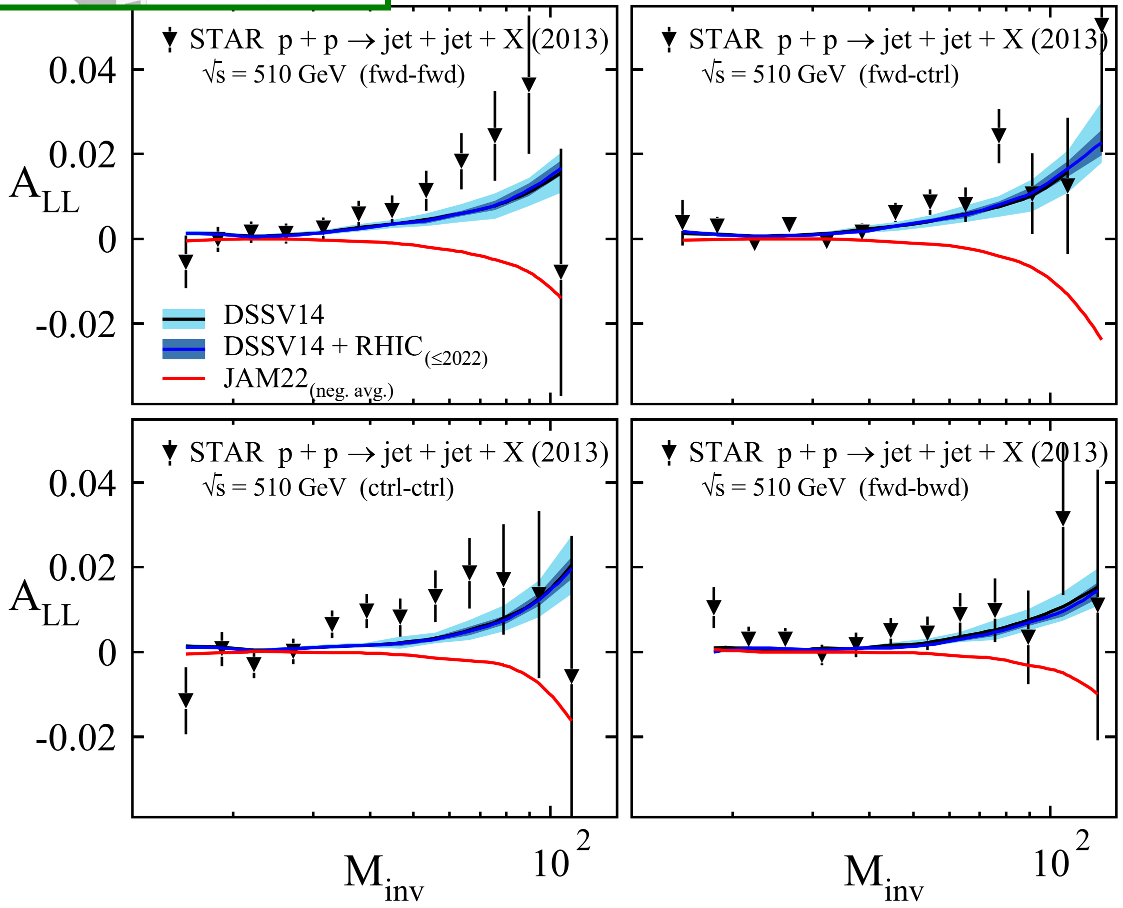


ΔG in $\vec{p}\vec{p}$ collisions @ RHIC

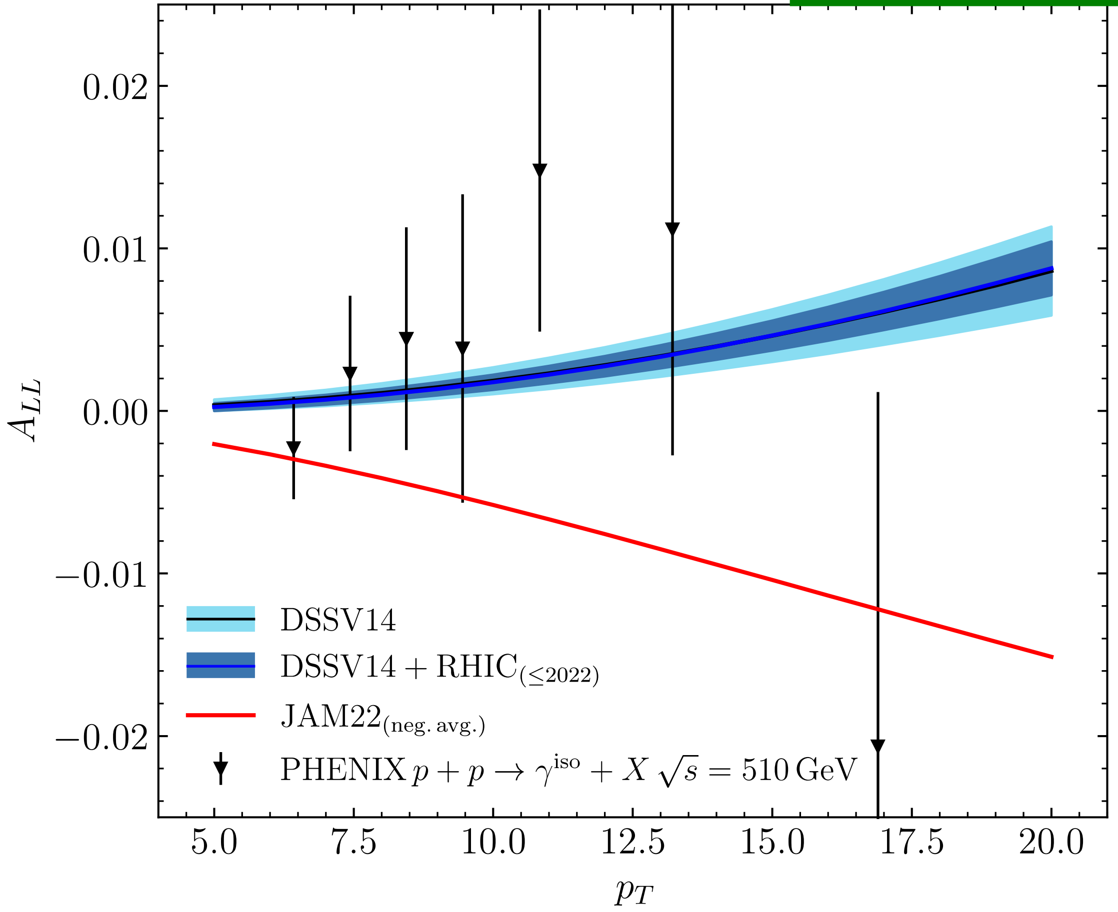


$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{f_A f_B f_C} \Delta f_A \Delta f_B \times \Delta\sigma_{AB\to CX} \times D_C}{\sum_{f_A f_B f_C} f_A f_B \times \sigma_{AB\to CX} \times D_C}$$



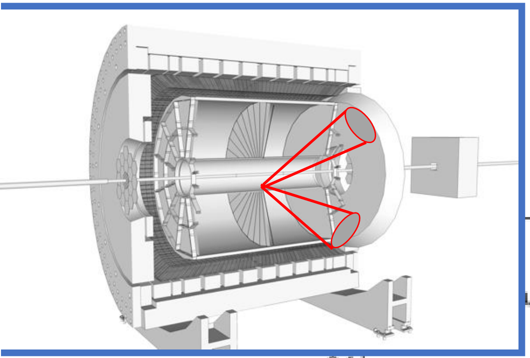


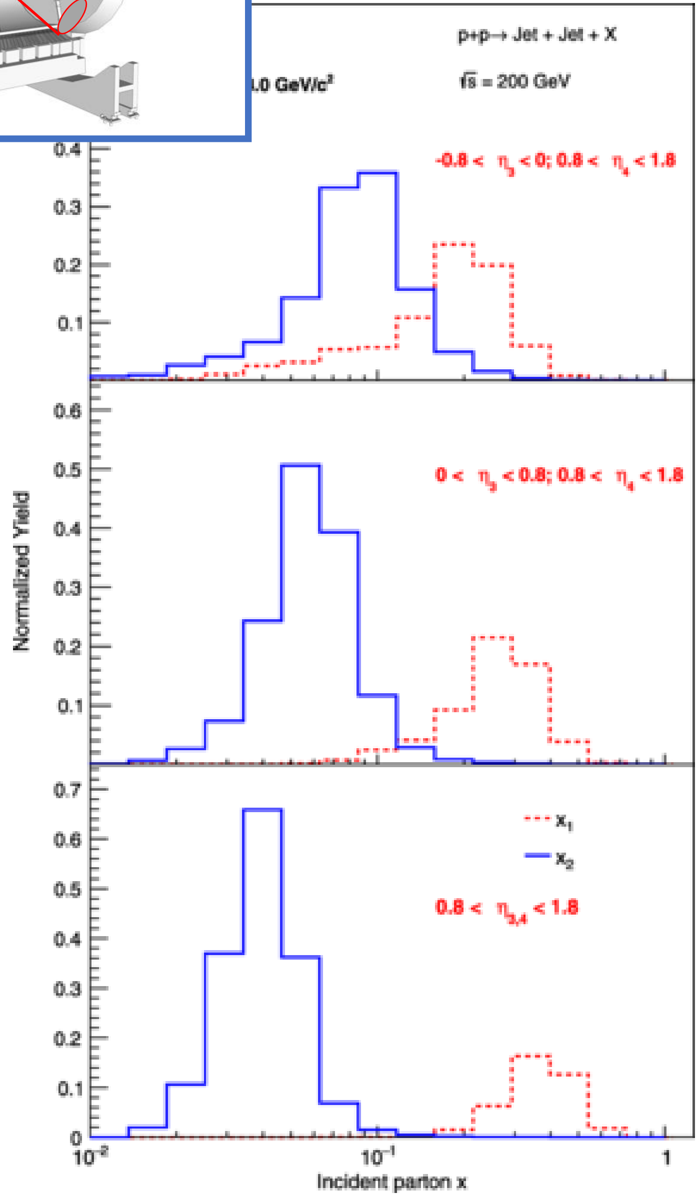
Phys. Rev. D **105**, 092011

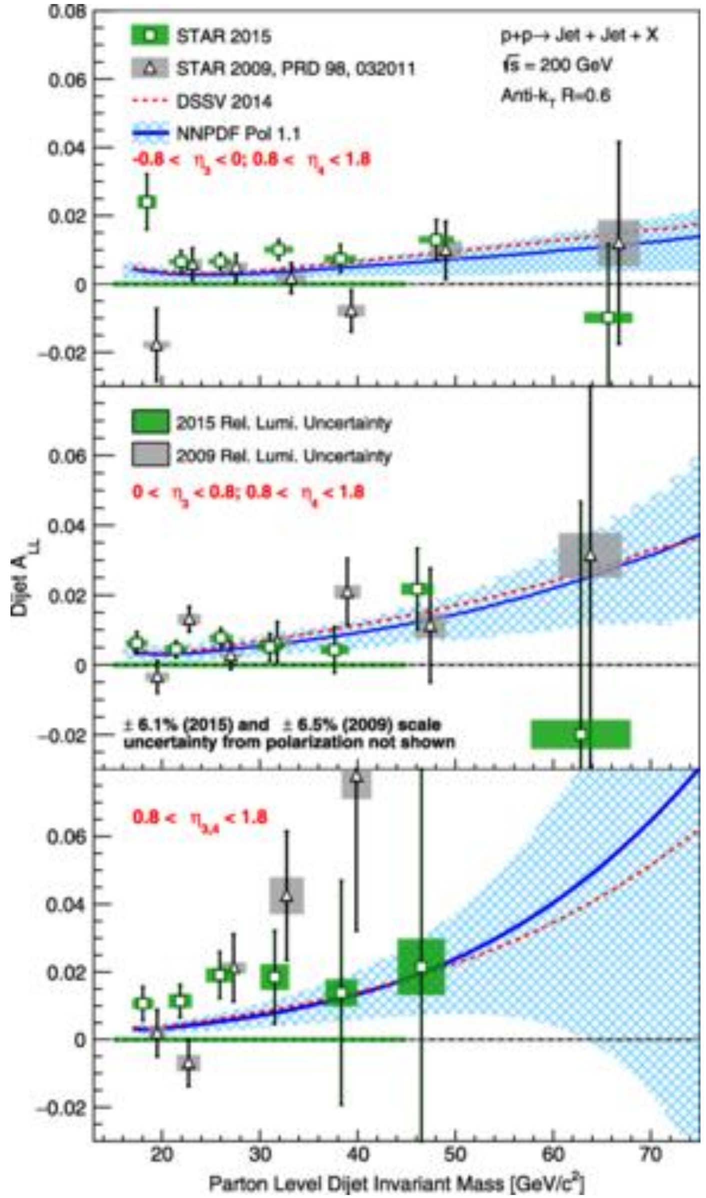


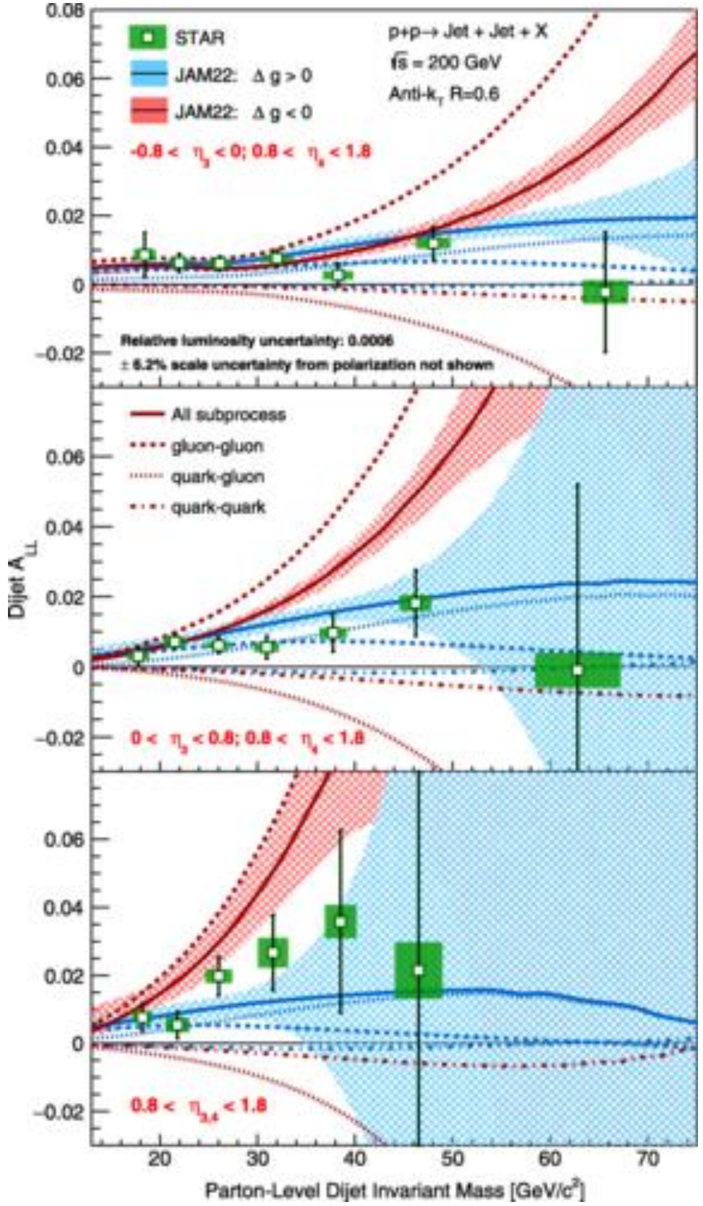
PRL 130 (2023) 251901

Pushing dijets forward @ 200 GeV









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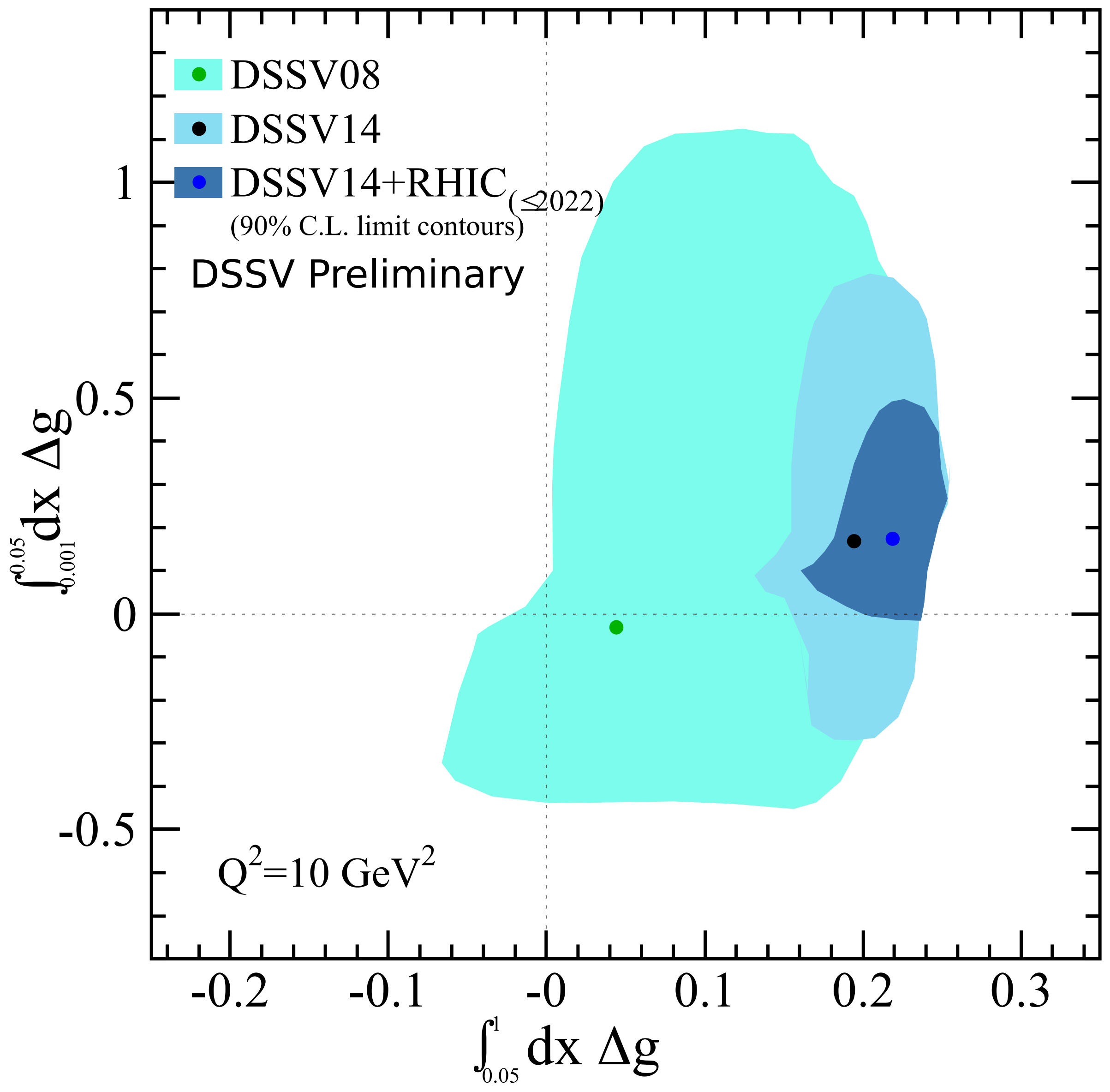
Global QCD Analyses : ΔG

- Inclusive DIS fixed target data do not cover a wide enough kinematic range to really constrain the gluon helicity distribution.
- Inclusive jet and pion A_{LL} results from RHIC have steadily narrowed the contribution from gluon for x > 0.05.
- Dijet and prompt photon A_{LL} show clearly that ΔG is positive.
- Large uncertainties remain for the low-x gluons
- High x gluons appear to contribute 40% to a high energy proton's spin.



What about quark helicity?

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{f_A f_B f_C} \Delta f_A \Delta f_B \times \Delta\sigma_{AB \to CX} \times D_C}{\sum_{f_A f_B f_C} f_A f_B \times \sigma_{AB \to CX} \times D_C}$$

2030

2020

2010

BNL RHIC

CERN COMPASS

2000

JLAB HALLS A,B,C

DESY HERMES

SLAC E142/143/154/155

1990

FNAL E581/704

CERN SMC

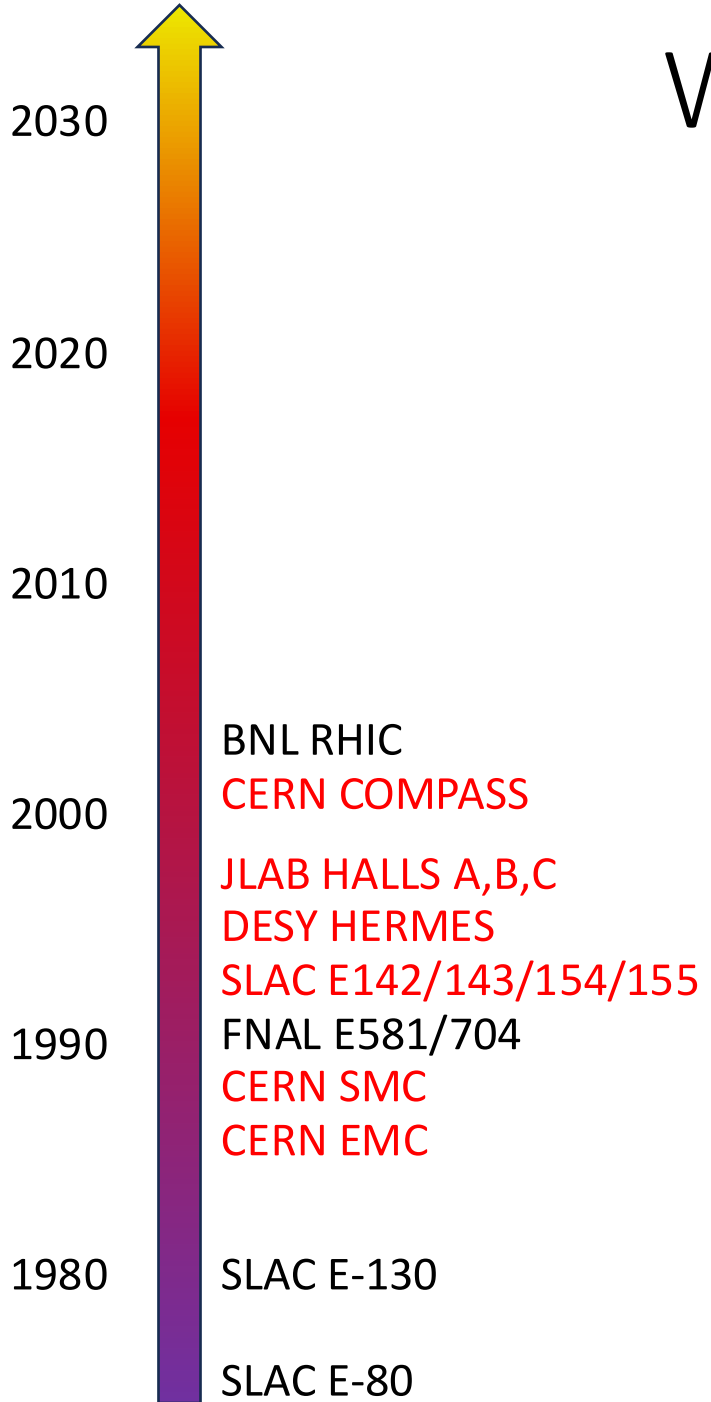
CERN EMC

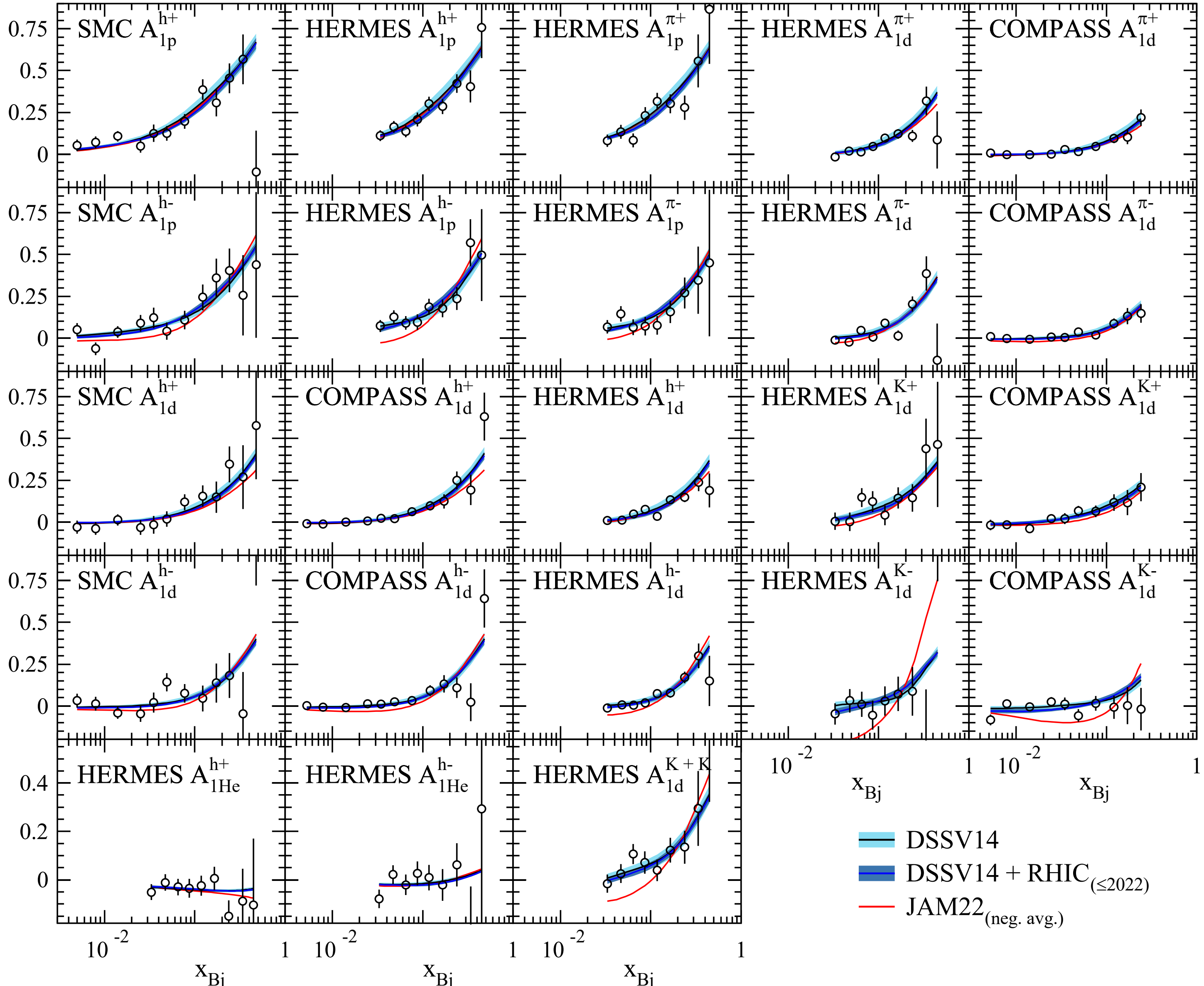
1980

SLAC E-130

SLAC E-80

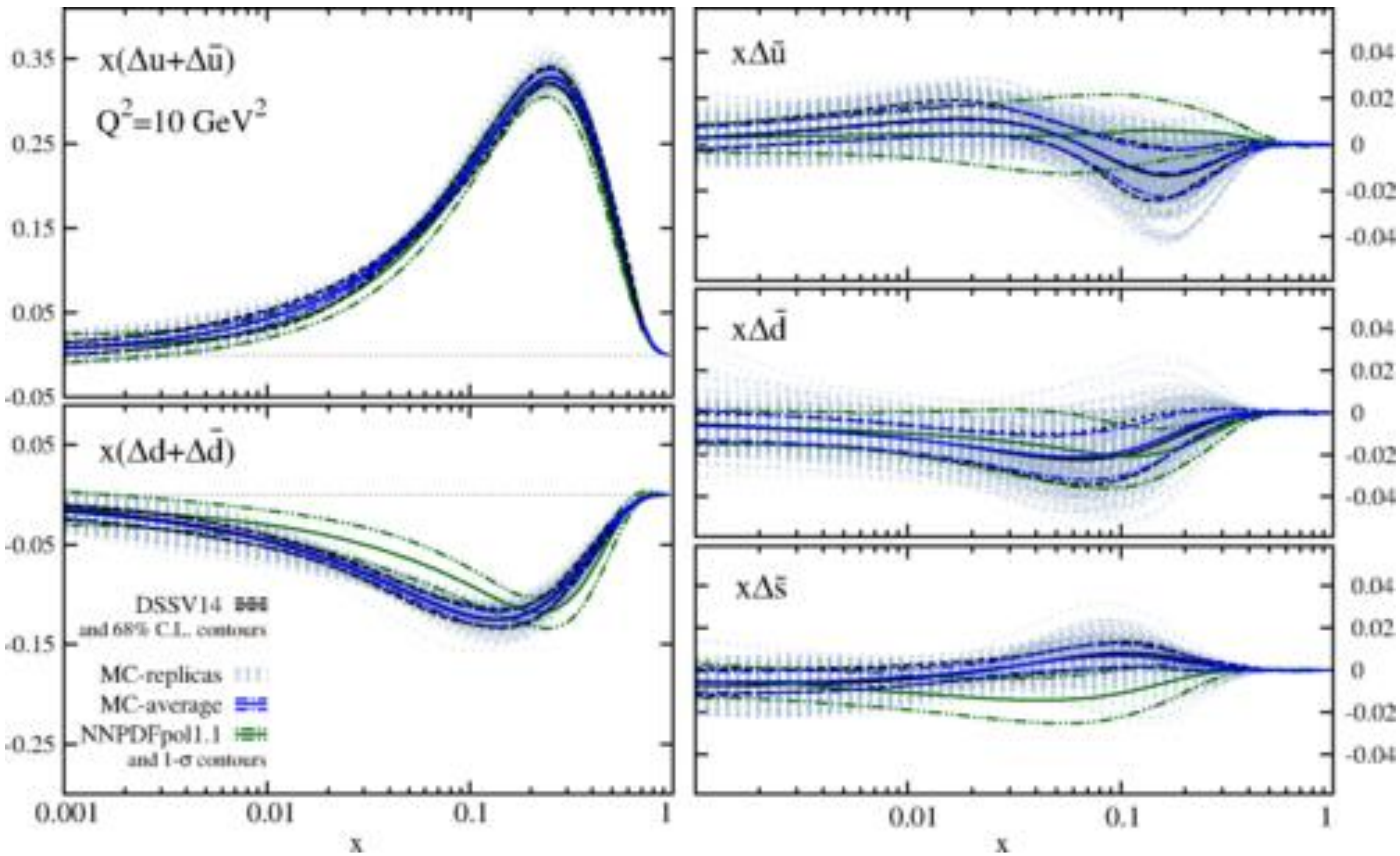
What about quark helicity?





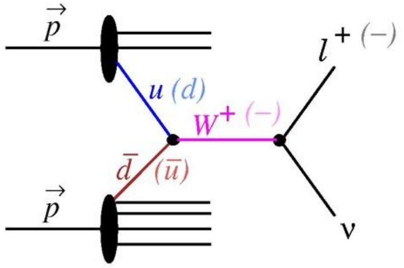
Global Analysis : Helicity Distributions

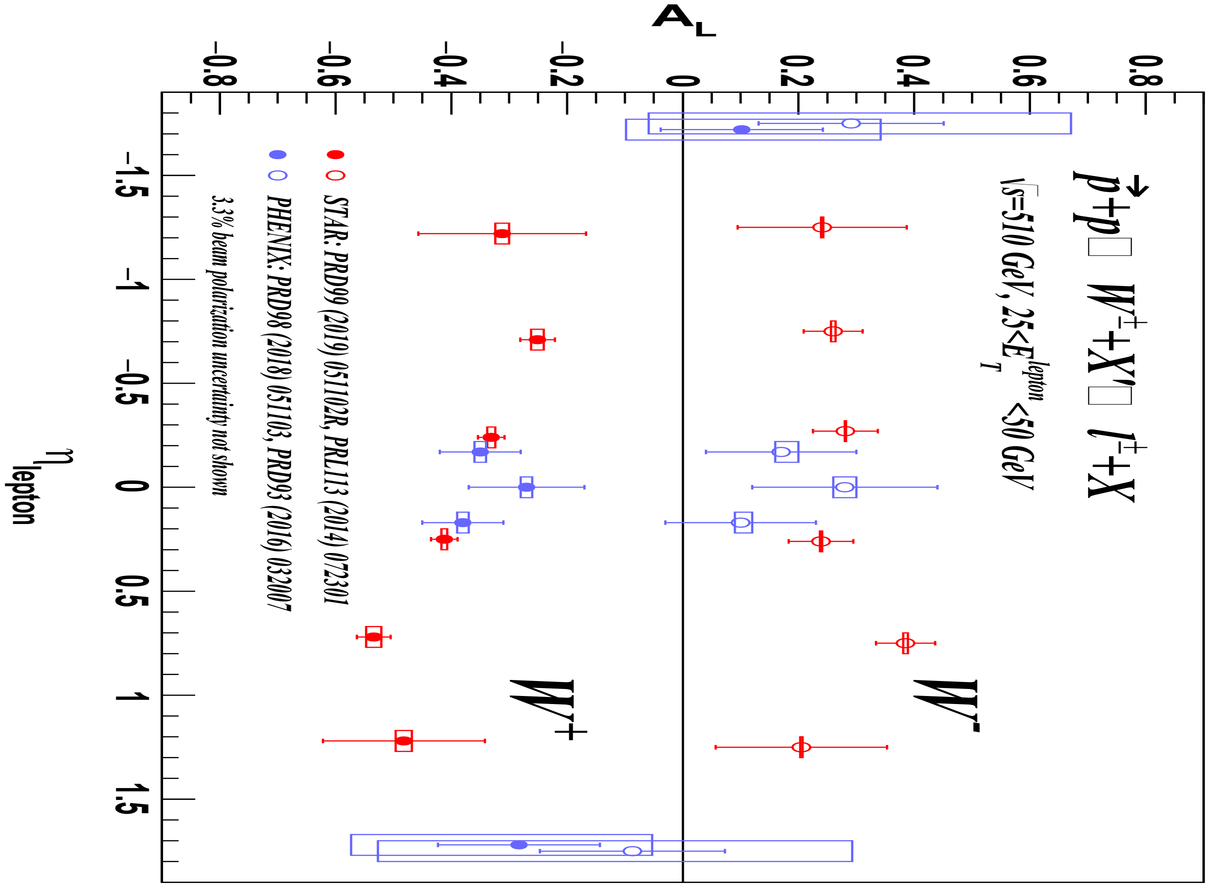
- Total Quark Contribution to proton 25% at Q^2 = 10 GeV
- Precision is driven by existing DIS + SIDS data
- Quark helicities evolve slowly with Q^2 -> lots of room for additional contributions from strange quarks, gluons, orbital angular momentum….

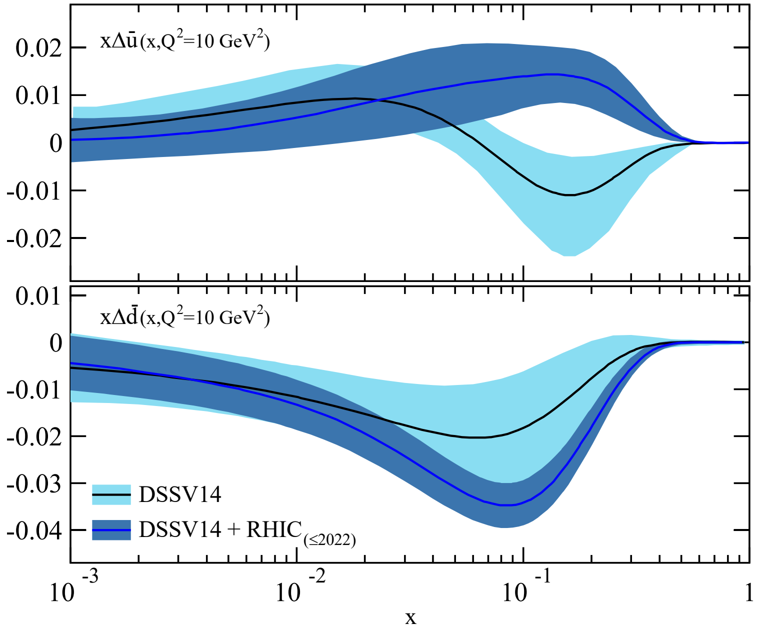


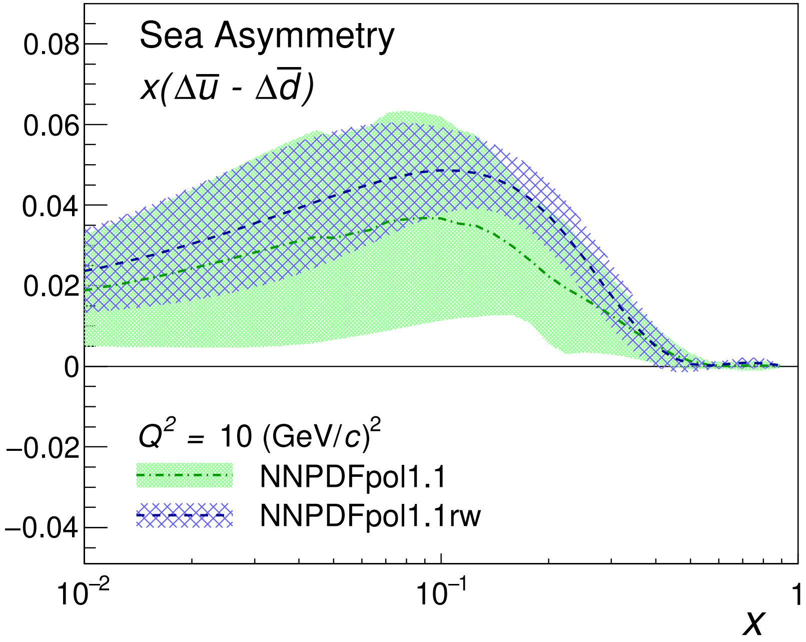
Accessing polarized sea with $W^{+/-}$

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



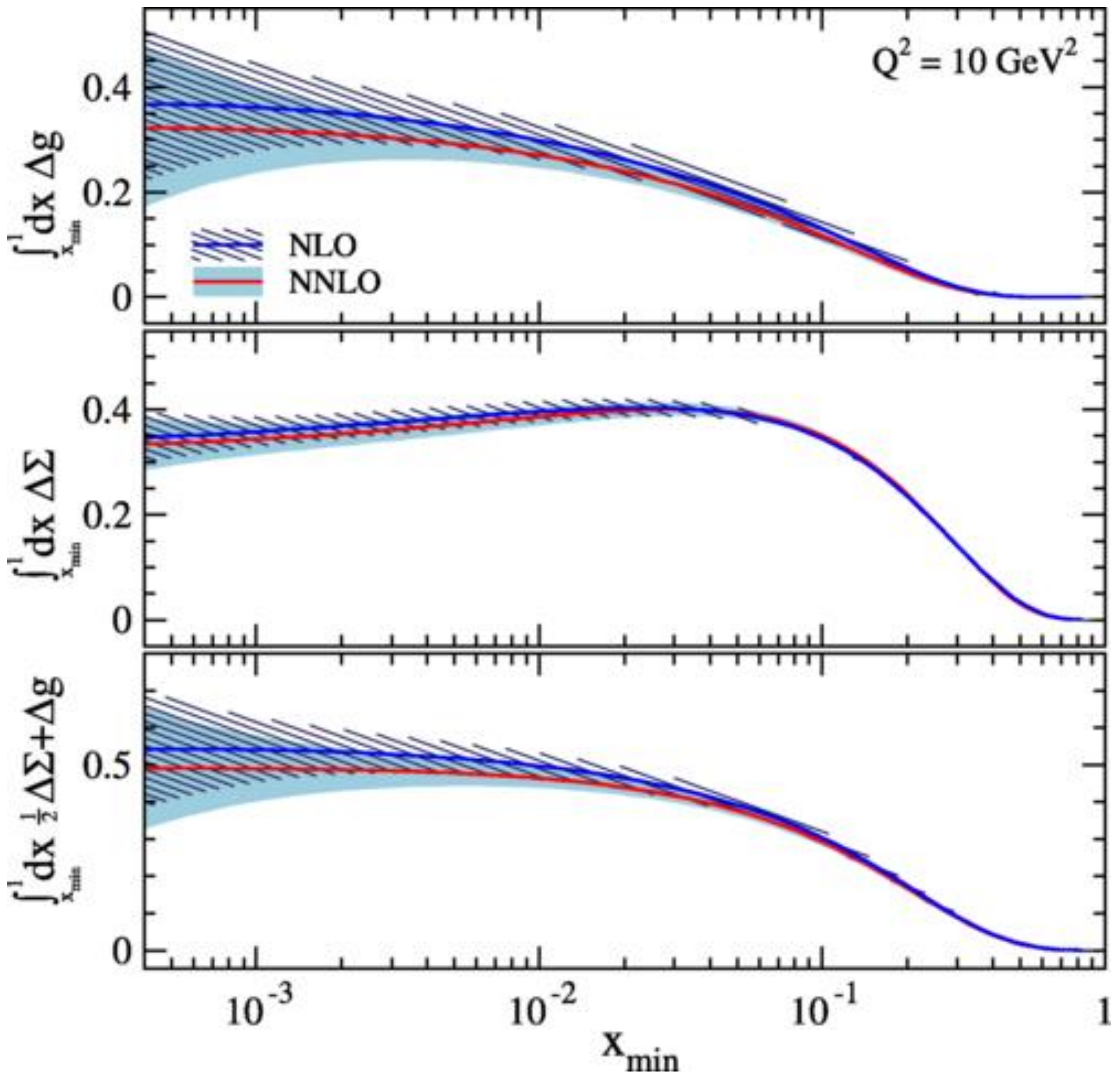






How does it all add up?

DSSV24 Phys. Rev. Lett. **133**, 151901



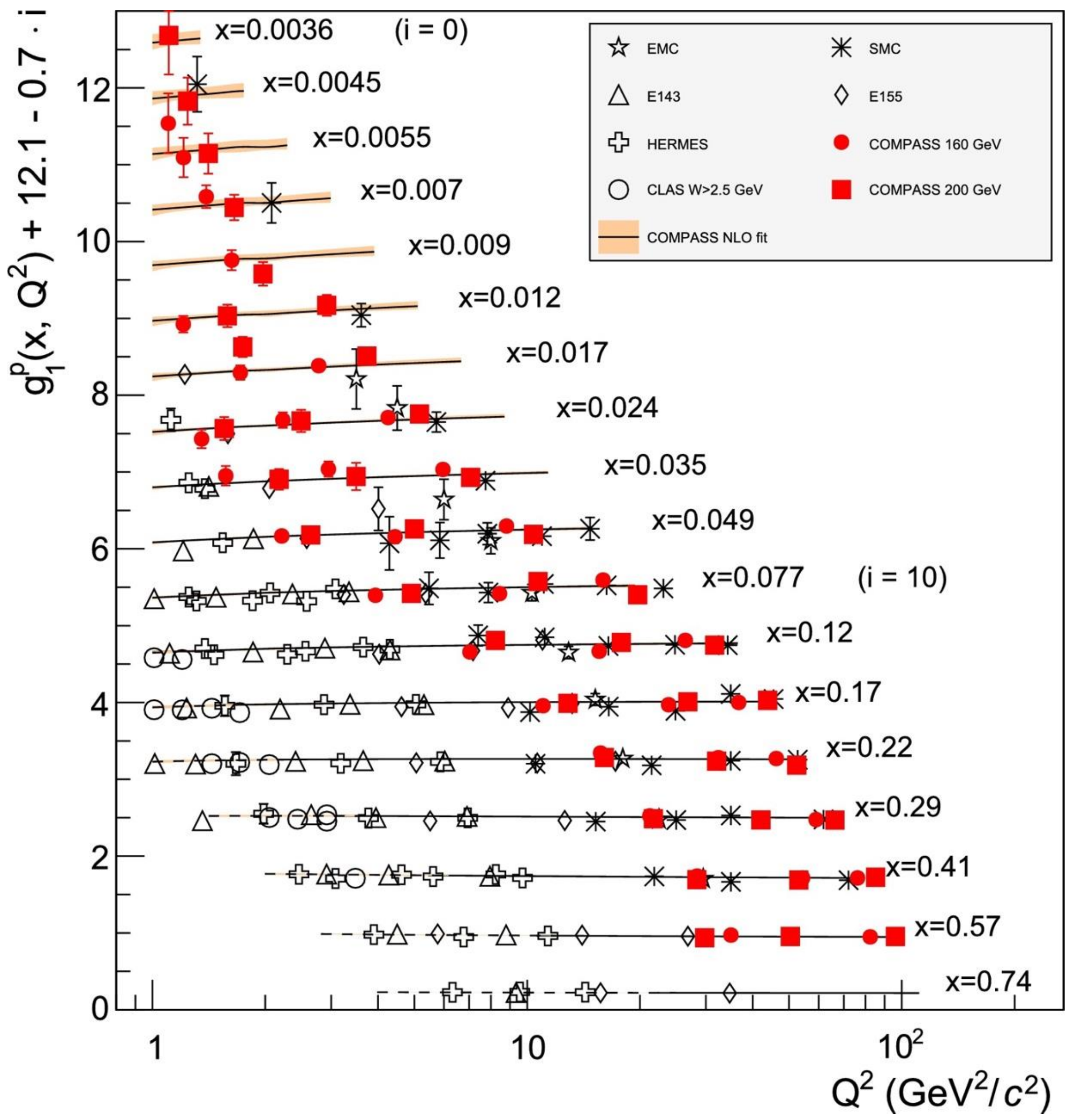
Look at most recent NNLO analysis by DSSV24

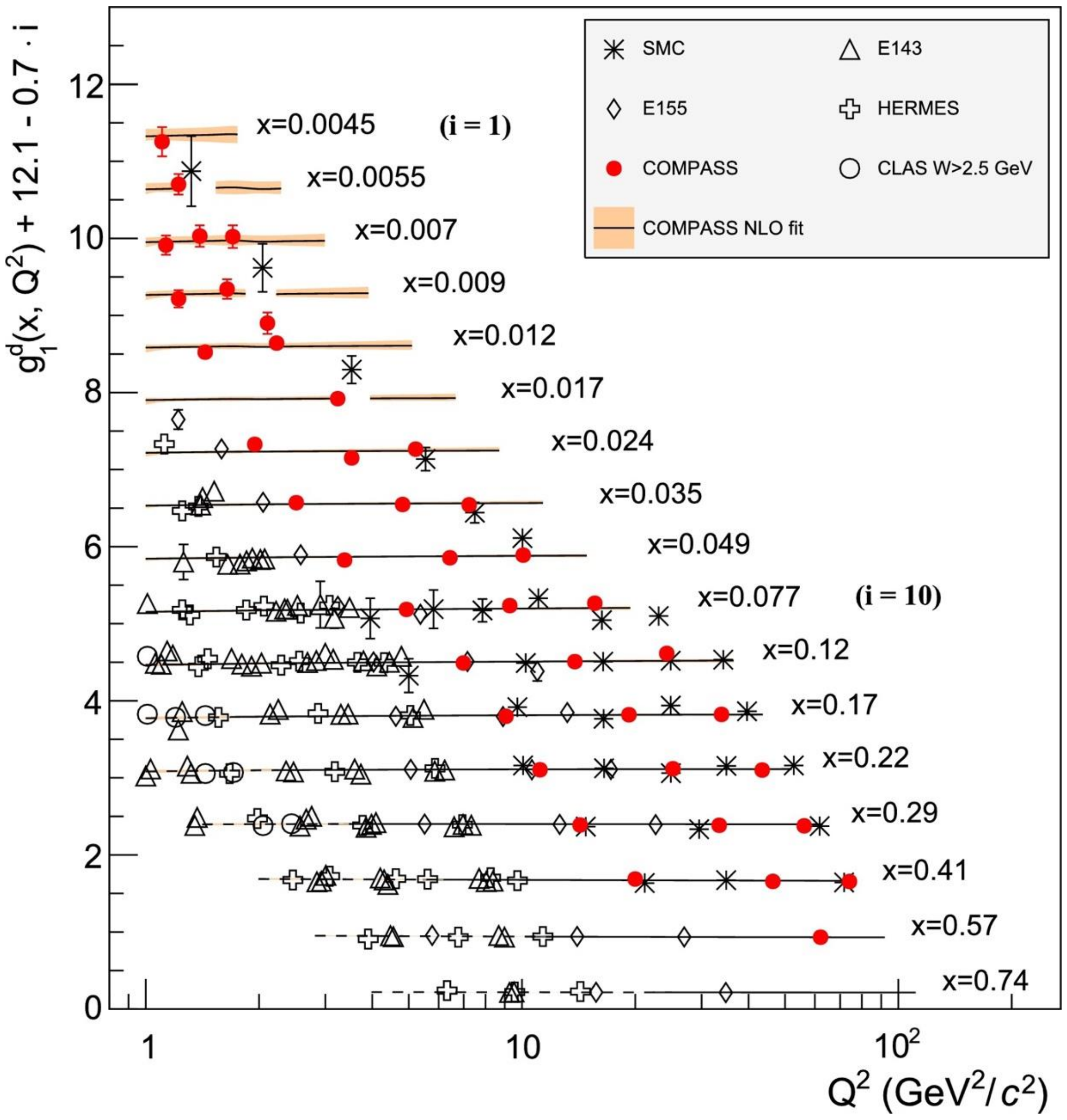
- RHIC data definitively shows that the gluon contribution to the spin puzzle is positive..
- 60% of proton spin in region x > 0.01 comes from gluons. Error bars grow substantially x < 0.001.
- 20% of the proton spin originates with the quarks (@ Q^2=10 GeV^2) Note this is consistent with original EMC result $14\ \pm 9\ \pm 21\%$!
- To date, only quantitative estimate of OAM comes from the remainder of the gluon and quark helicity distributions

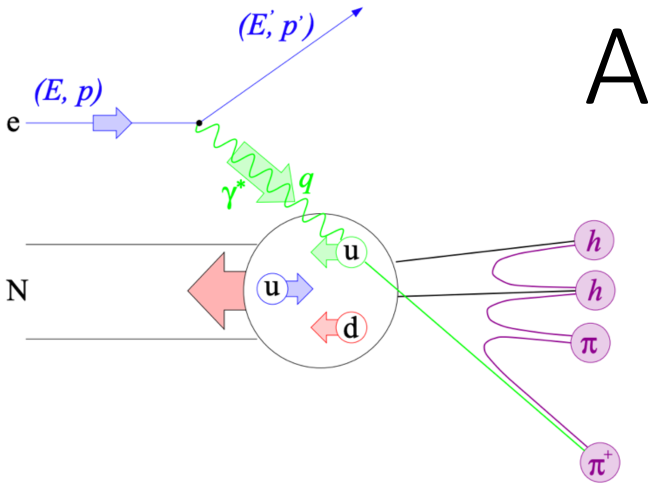
$$½ = ½\Delta\Sigma + \Delta G + L_Q + L_G$$

Postcard credit : CERN

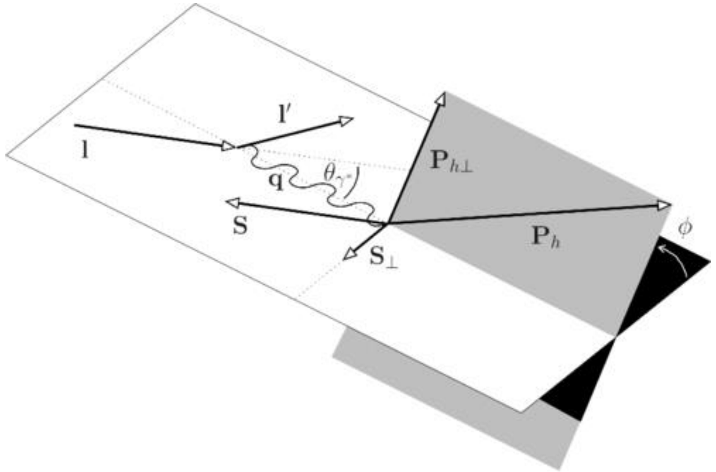
Four experimental programs & 25 years later



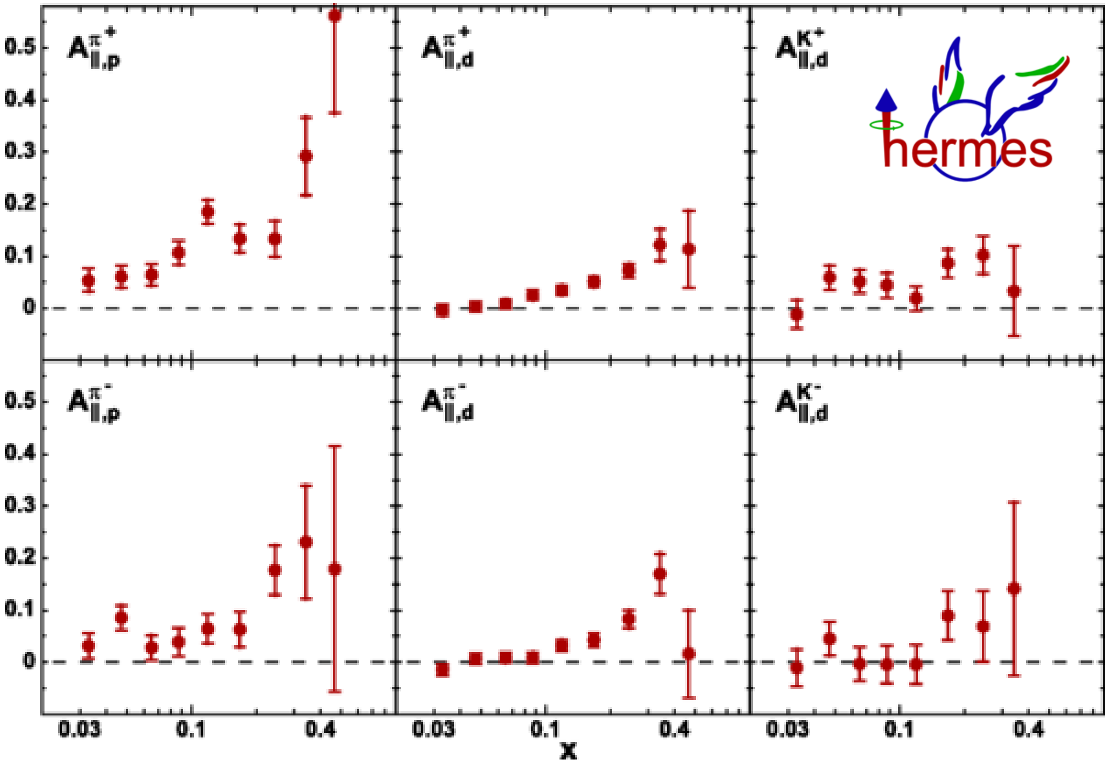


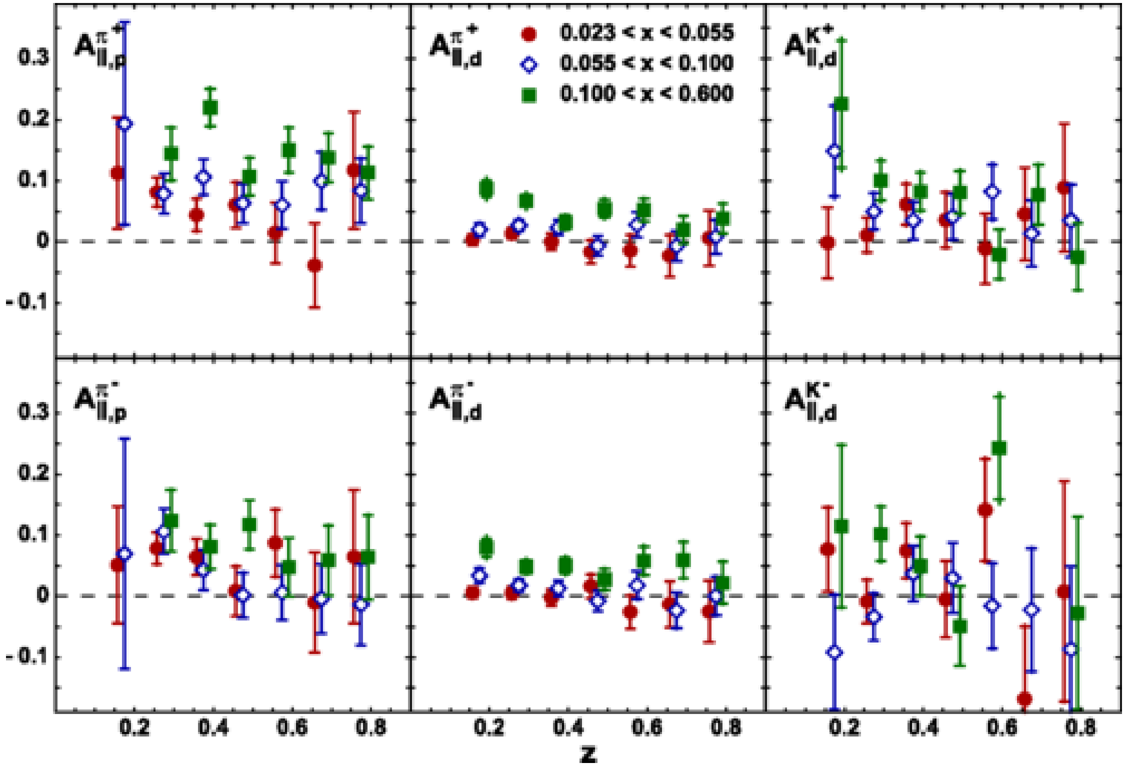


Also, semi-inclusive DIS



Allows for flavor tagging and extraction of information about individual quark helicity distributions. Requires information about associated fragmentation functions.





Phys. Rev. D 99, 112001

Global QCD Analysis : inclusive + SIDIS

Need NLO theoretical framework to interpret data and extract the helicity distributions,

- **DSSV**

  PRL 101 (2008) 072001

  PRD 80 (2009) 034030

  PRL 113 (2014) 012001

  PRD 100 (2019) 114027

- **JAM**

  PRD 93 (2016) 074005

  PRL 119 (2017) 132001

  PRD 104 (2021) L031501

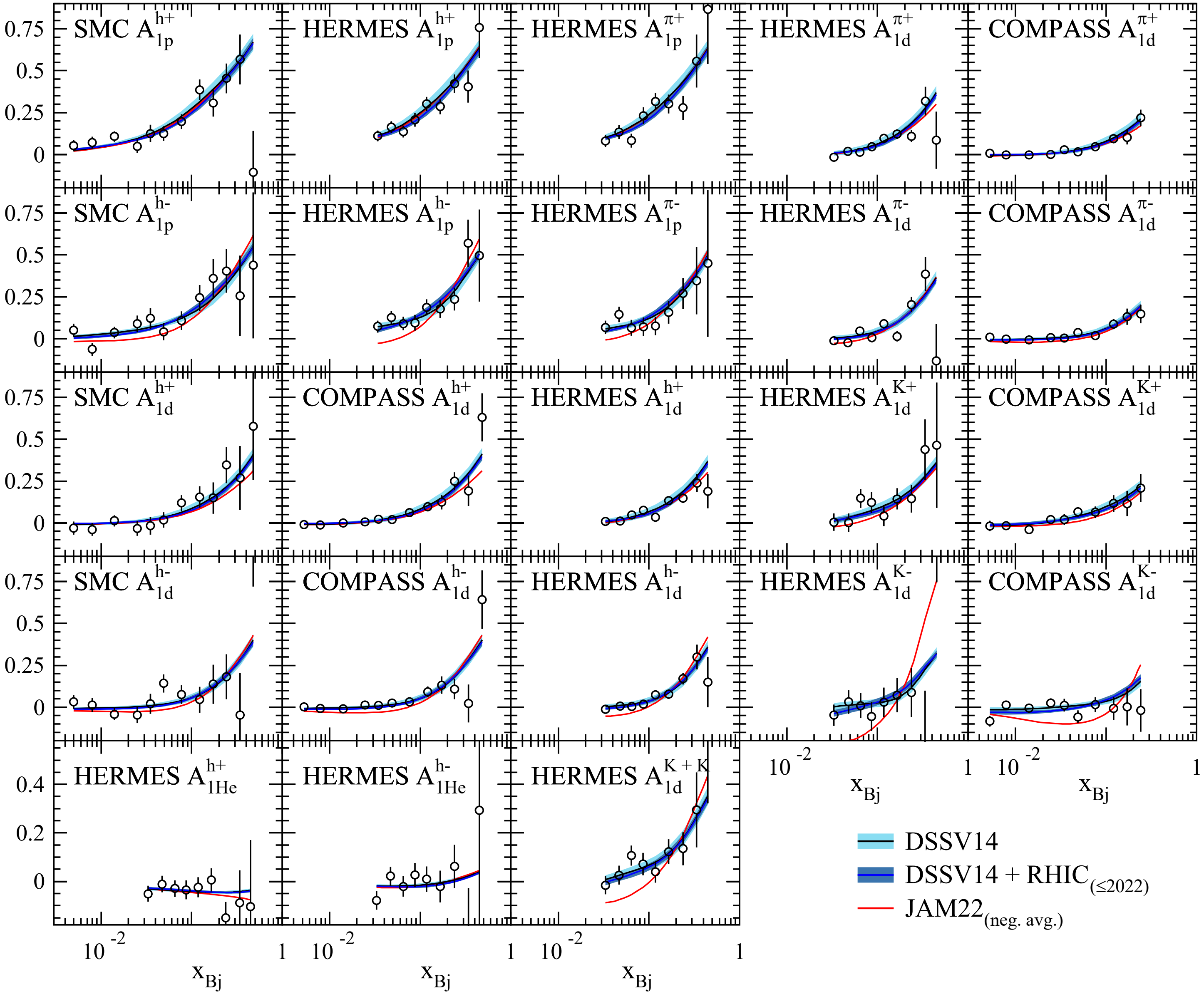
- **NNPDF** **only inclusive*

  NPB 874 (2013) 36

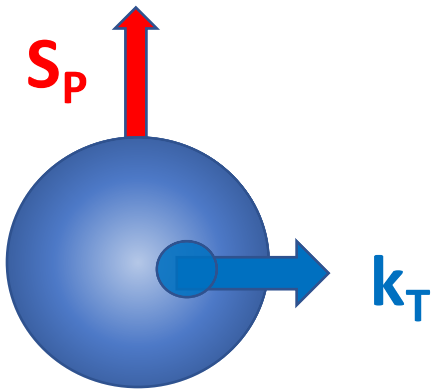
  NPB 887 (2014) 276

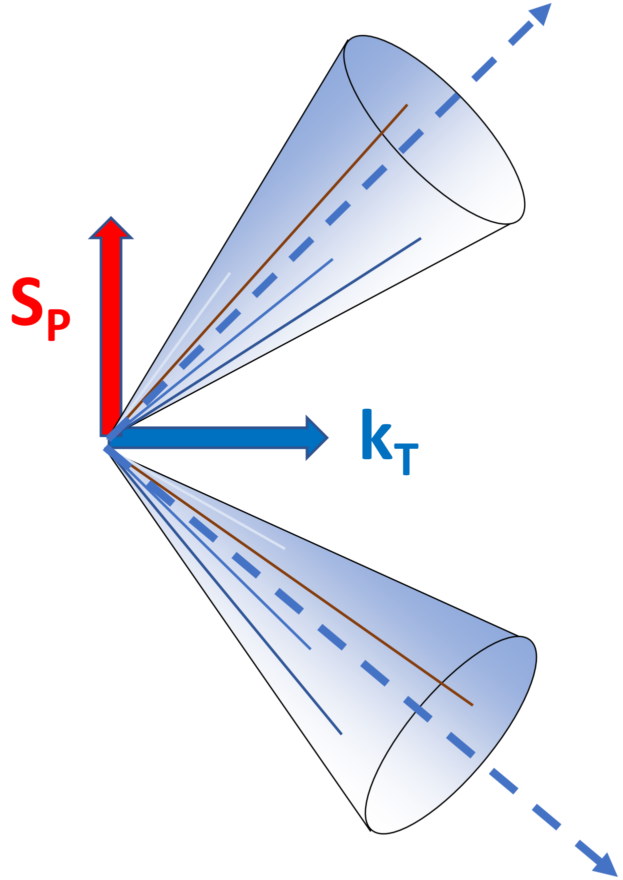
  arXiv : 1510.04248

  arXiv : 1702.05077



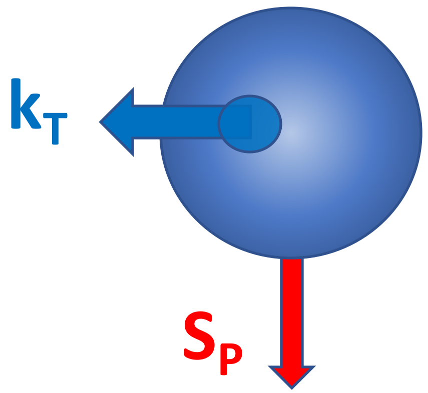
Sivers Effect in DiJET Production



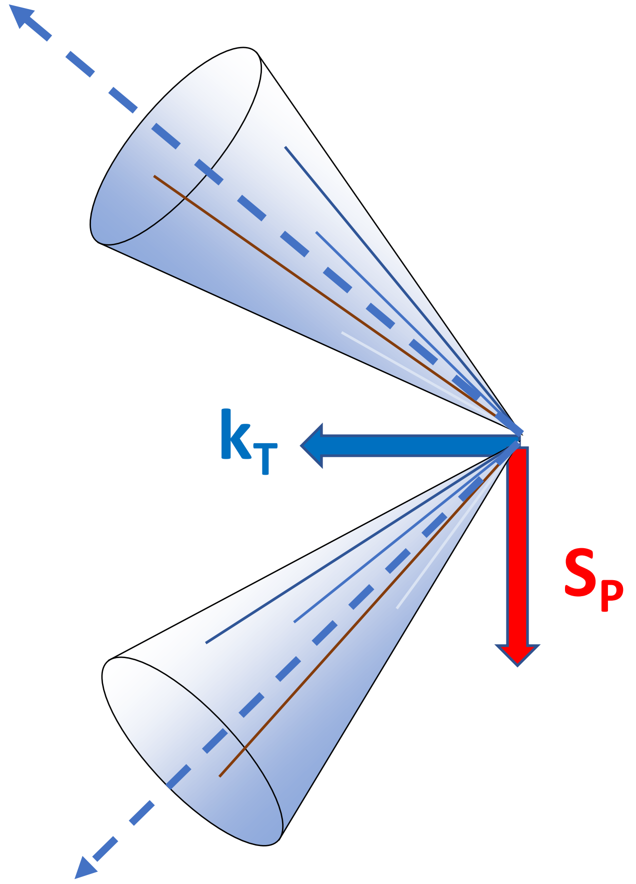


$$\langle \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T) \rangle$$

Sivers Effect in DiJET Production



$$\langle \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T) \rangle$$



Jet Flavor “TaGGING”

arXiv:2305.10359

Tag associated jets to enhance the purities of ***u*-quarks and *d*-quarks** separately.

-

$$Q = \sum_{\substack{all\ the\ tracks \\ with\ pT > 0.8GeV}} \frac{track\ pT}{jet\ pT} \cdot track\ charge$$