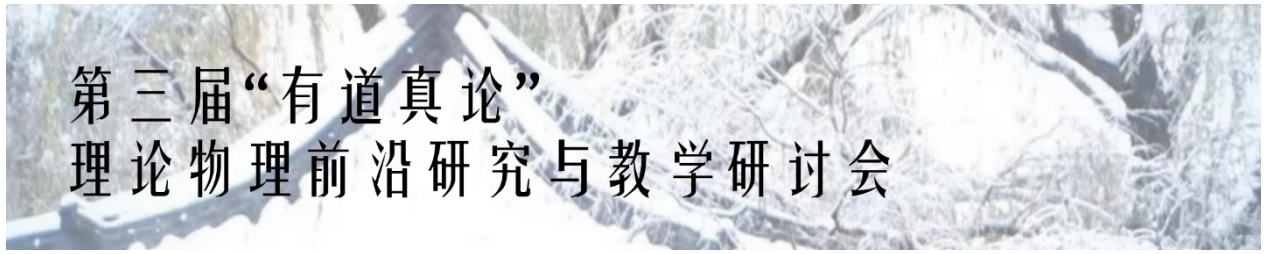


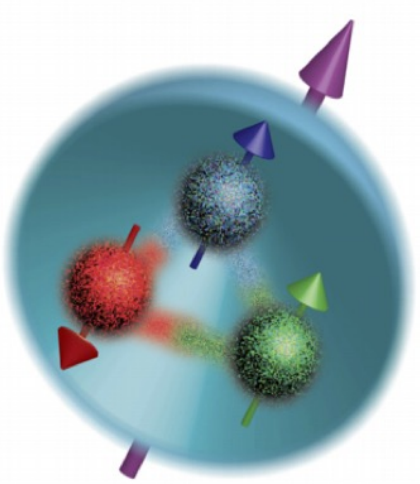
Highlights of STAR Spin Program

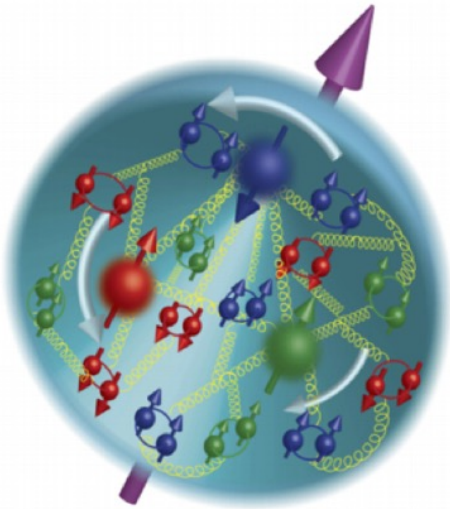
Jinlong Zhang (张金龙)

December 6-7, 2025

山东大学
SHANDONG UNIVERSITY

Proton spin structure





Jaffe-Manohar 1990

$$< S_p > = \frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

quark spin

$$< S_p > = \frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_g$$

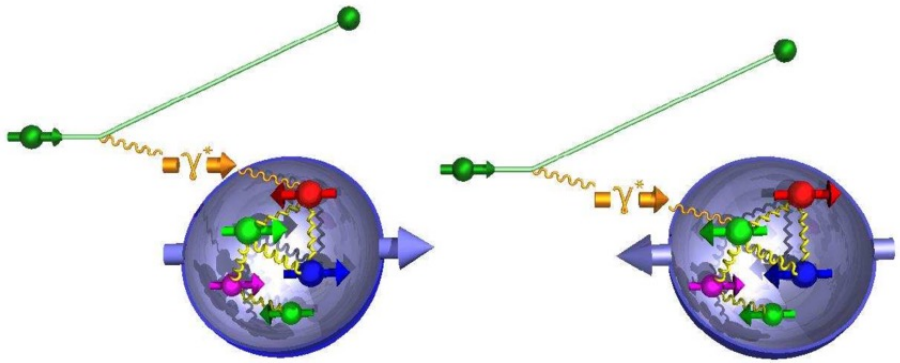
quark spin

gluon spin

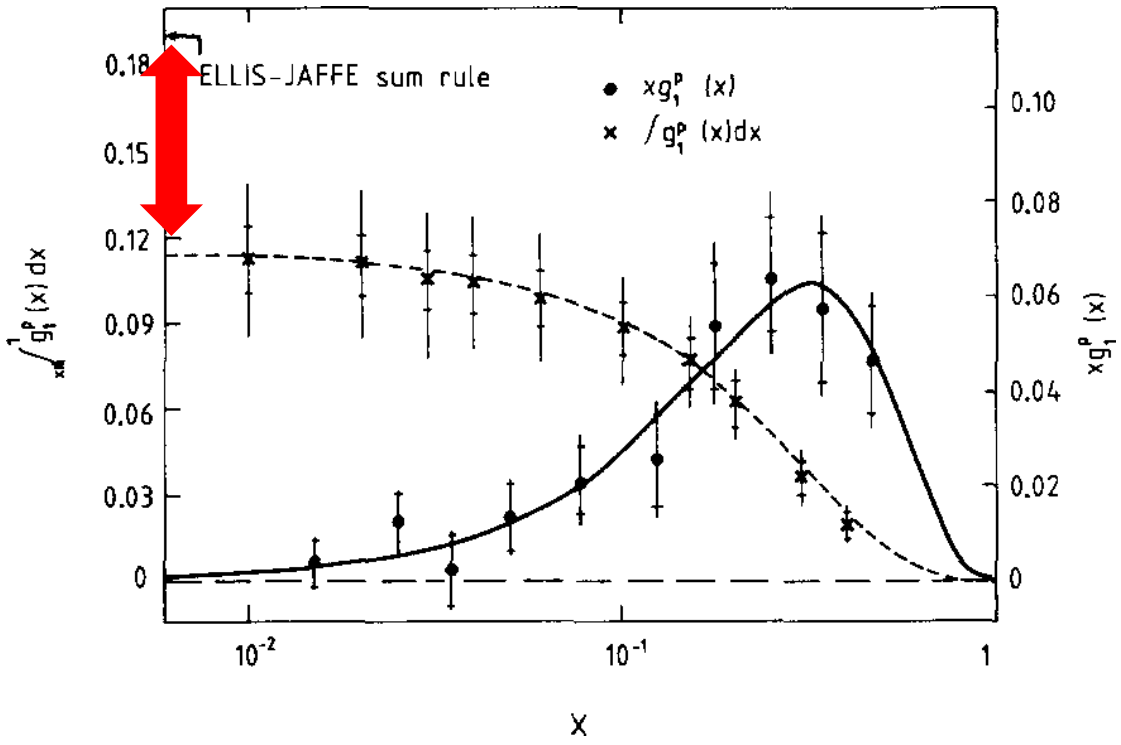
orbital angular momentum

Proton spin crisis

Deep-inelastic scattering with polarized electrons or muons off polarized protons



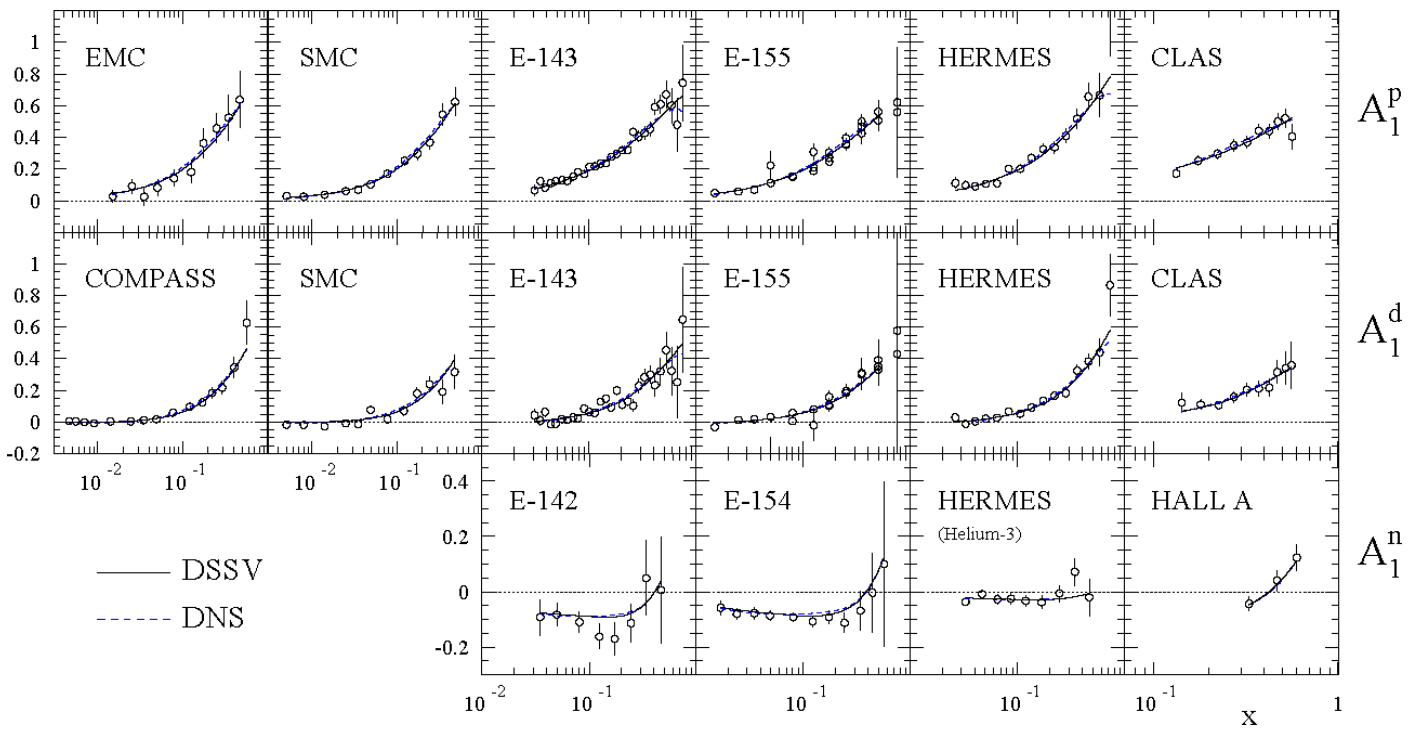
EMC, PLB 206, 364 1988

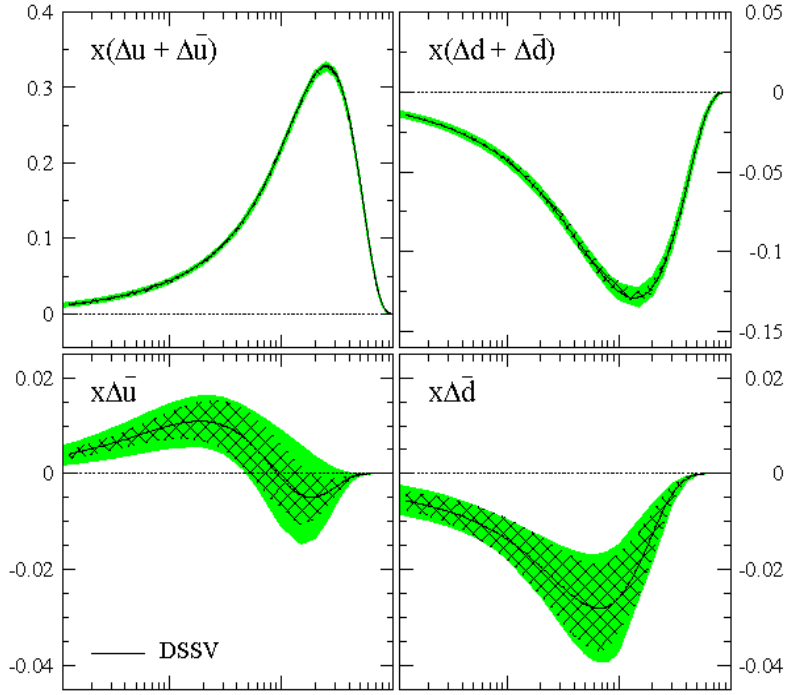


- First polarized DIS over a broad kinematic region was performed by the European Muon Collaboration in the mid-'80s
- Found that quarks contribute only **(14 ± 9 ± 21)%** of the proton spin

From spin crisis to spin puzzle

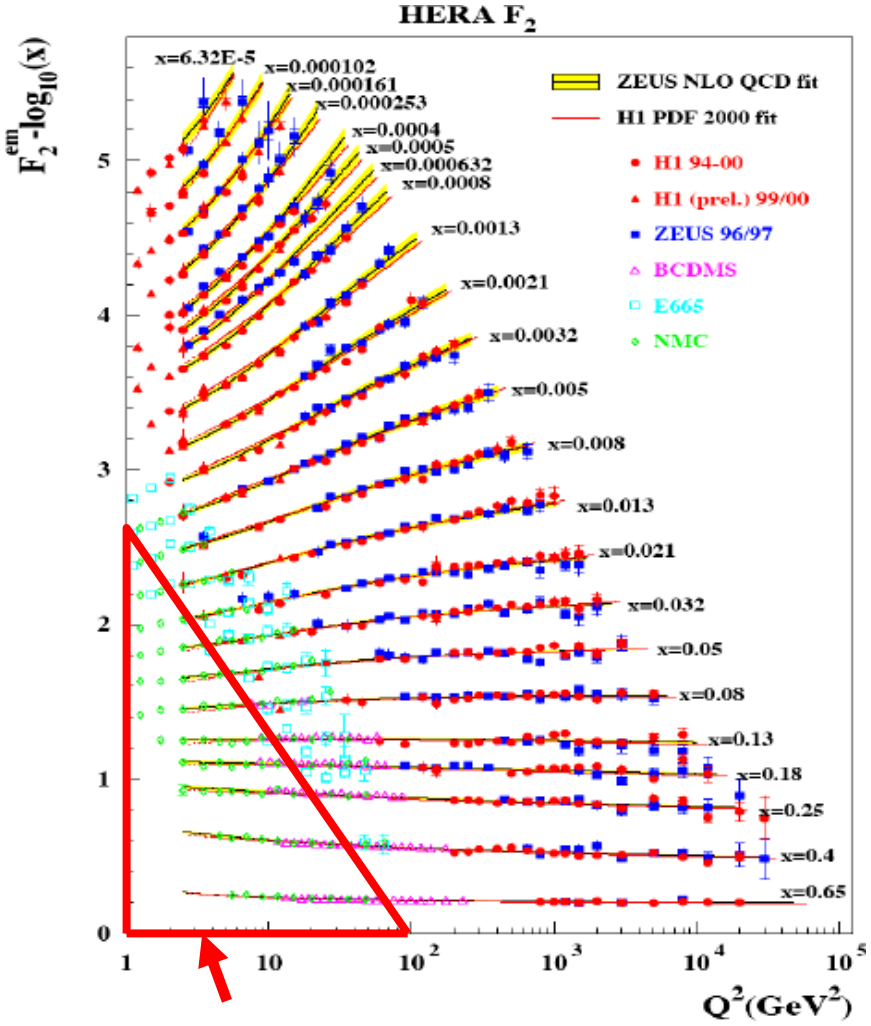
DSSV, PRD 80, 034030 (2009)



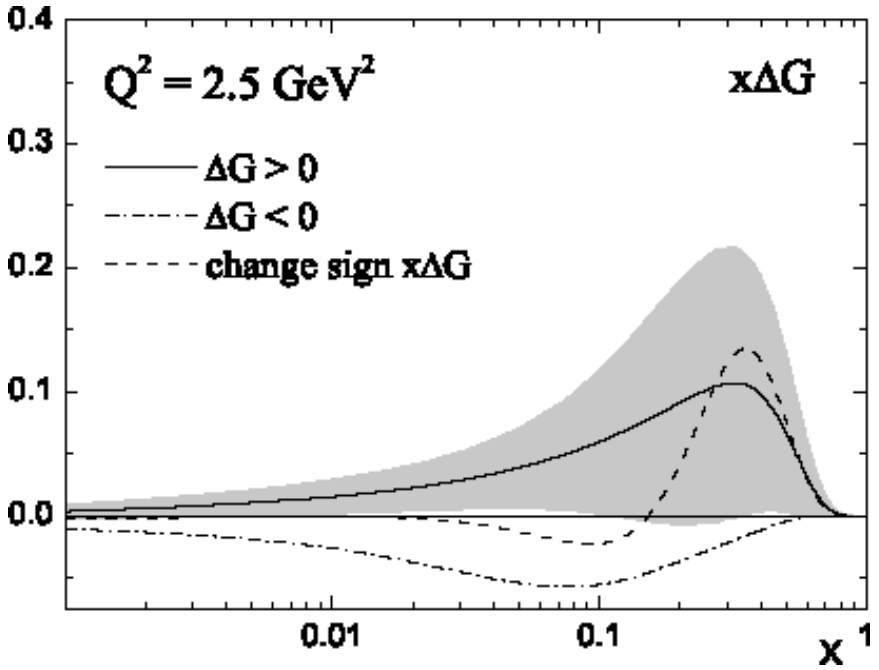


- Results are well described by "global analyses" that find best-fit *polarized* PDFs
- Polarization of $u + \bar{u}$ and $d + \bar{d}$ quarks well determined
  - Individual u, $\bar{u}$, d, $\bar{d}$ polarizations have much larger uncertainty
- Only **~30% of the proton spin** arises from quarks and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

What about gluons?



Kinematic region of **fix-target**
Polarized DIS measurements



Three fits of equal quality:

- ΔG = 0.13 ± 0.16
- ΔG ~ 0.006
- ΔG = -0.20 ± 0.41

all at Q^2 = 1 GeV^2

Leader et al, PRD 75, 074027

Motivation of RHIC spin

If gluons really carry the bulk of nucleon's spin, why not use polarized proton? (*known by then to be predominantly made of gluons)*

Why ΔΣ (quark + anti-quark's spin) small? Are quark and antiquark spins anti-aligned? Polarized p+p at high energy, through W+/- production could address this

A severe need for investigations of the surprising transverse spin effects was naturally possible and needed with the proposed polarized p+p collider…

Prospects for RHIC Spin Physics in 2000

PROSPECTS FOR SPIN PHYSICS AT RHIC

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

[1]*Brookhaven National Laboratory, Upton, New York 11973-5000 and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000; e-mail: bunce@bnl.gov*

[2]*RIKEN (The Institute of Physical and Chemical Research), Wako, Saitama 351-0198, Japan, and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000; e-mail: saito@bnl.gov*

[3]*Centre de Physique Théorique–CNRS–Luminy, Case 907, F-13288 Marseille Cedex 9, France; e-mail: Jacques.Soffer@cpt.univ-mrs.fr*

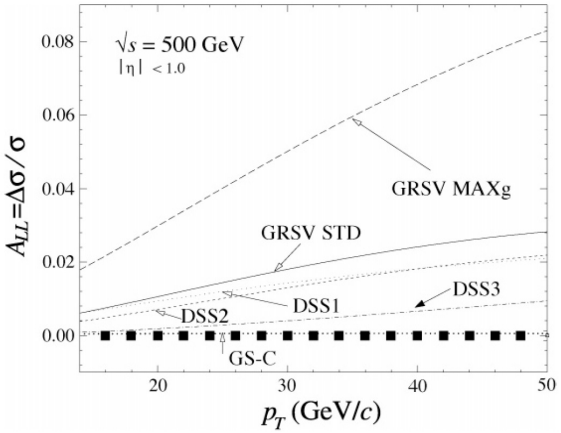
[4]*C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11794-3840 and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000; e-mail: wvogelsang@bnl.gov*

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

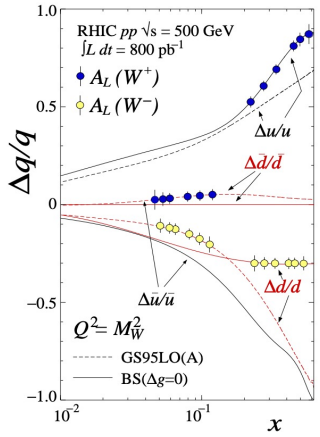
■ **Abstract** Colliding beams of 70% polarized protons at up to $\sqrt{s} = 500$ GeV, with high luminosity, $L = 2 \times 10^{32}\,cm^{-2}\,sec^{-1}$, will represent a new and unique laboratory for studying the proton. RHIC-Spin will be the first polarized-proton collider and will be capable of copious 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.

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

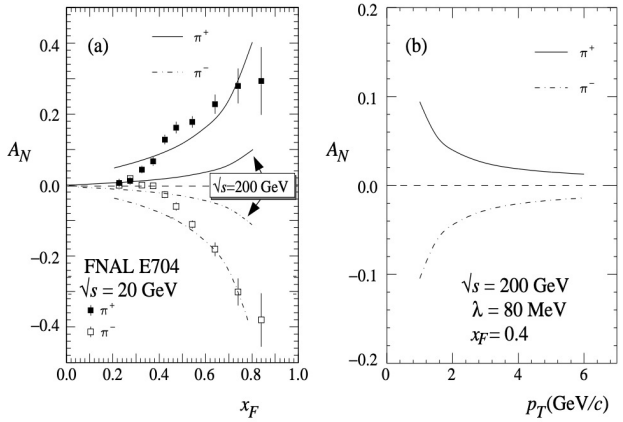
Jet production



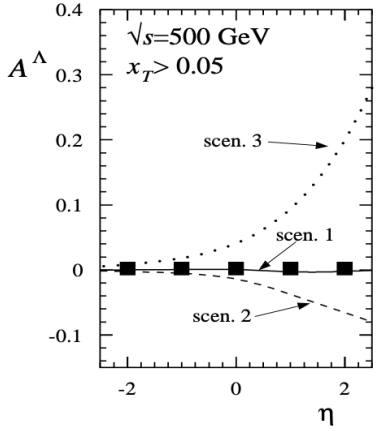
$W^{\pm}$ production



Transverse SSA

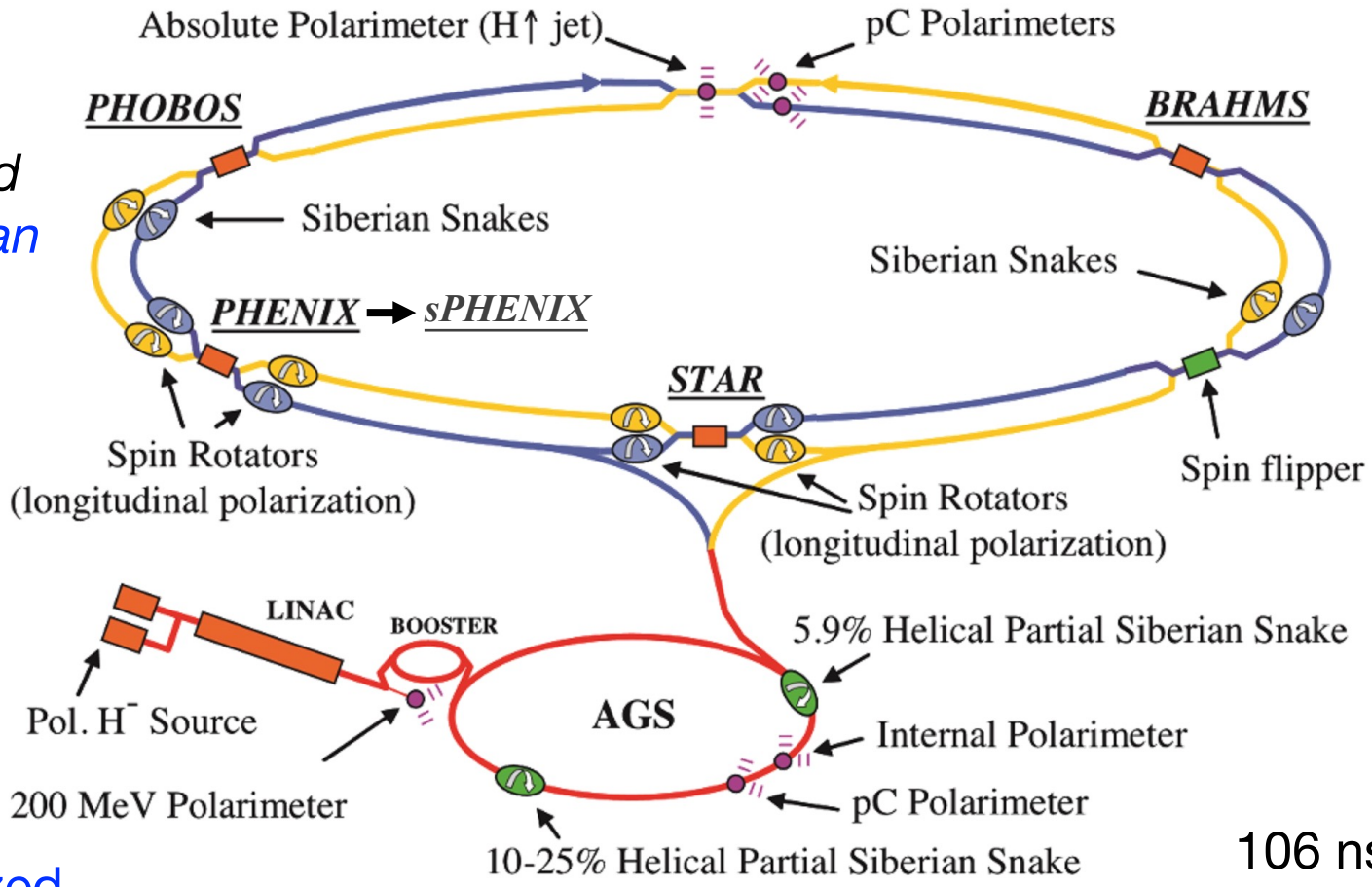


Lambda spin transfer



Polarized RHIC

Accelerate polarized protons with Siberian Snakes

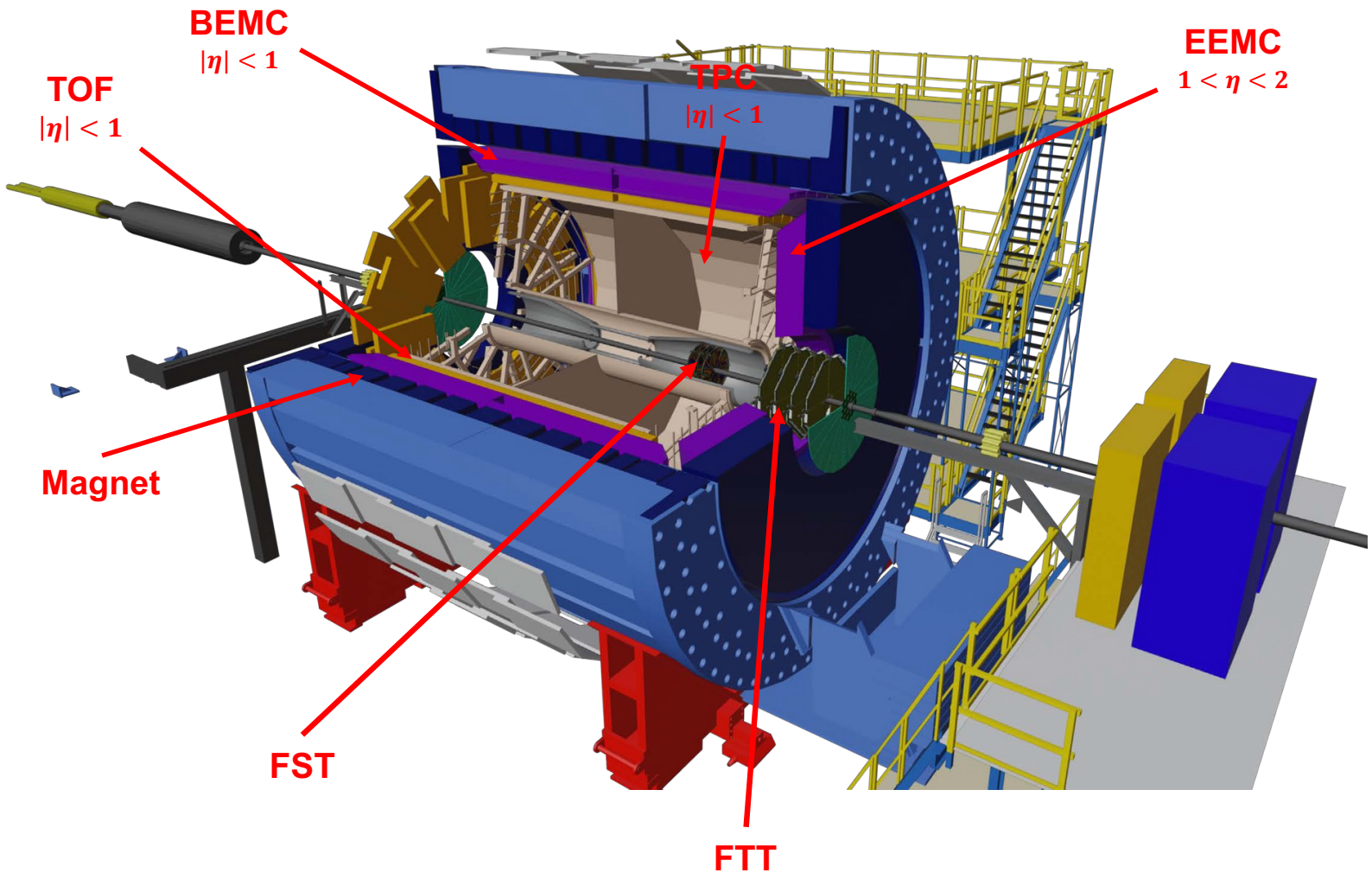


Manipulate spin direction with spin rotator

High current polarized proton source

106 ns bunch crossing with pre-determined spin directions

STAR detector overview



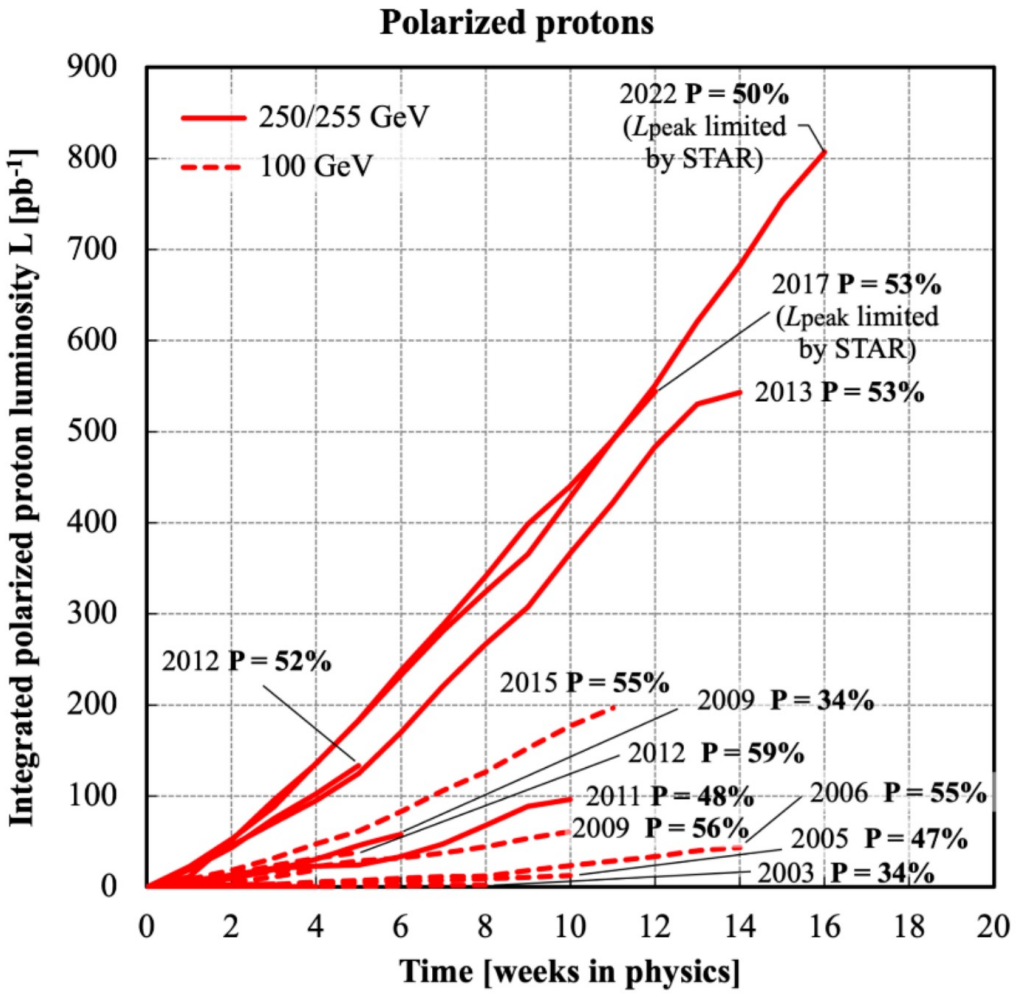
Time Projection Chamber
- charged track momentum msmt
- particle identification dE/dx,
- vertex reconstruction
- coverage $|\eta| < 1$

Time of Flight detector
- particle identification
- coverage $|\eta| < 1$

Barrel and Endcap E.M. Cal.
- towers and Shower Maximum Det.
- neutral EM energy measurement,
- trigger (towers, patches of towers)
- coverage $|\eta| < 1$ and $1 < \eta < 2$

Only running detector at RHIC in 2017-2022

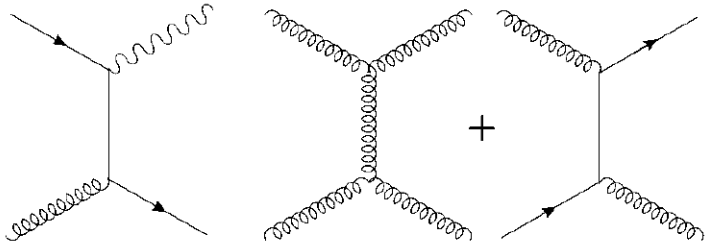
STAR spin data accumulation



	Year	√s (GeV)	L (pb^{-1})	<P> (%)
Long	2006	62.4	--	48
		200	6.8	57
	2009	200	25	38
		500	10	55
	2011	500	12	48
	2012	510	82	56
	2013	510	256	56
	2015	200	52	53
Trans	2006	62.4	0.2	48
		200	8.5	57
	2008	200	7.8	45
	2011	500	25	55
	2012	200	22	60
	2015	200	52	53
	2017	510	350	55
	2022	508	400	52
	2024	200	164	55

by STAR

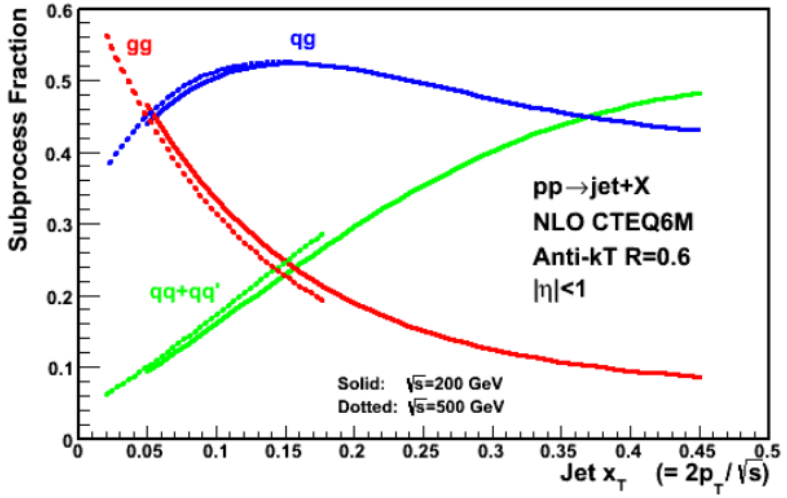
Probe gluon polarization



QCD Compton scattering

Quark-gluon, gluon-gluon elastic scattering

- Abundant yields of π and jets at RHIC
- Sub-processes directly sensitive to gluon
- $x_{g,q} \sim p_T^{\pi^0,\text{jets}} / \sqrt{s} \cdot e^{-\eta}$
- Constrain gluon helicity-dependent PDFs

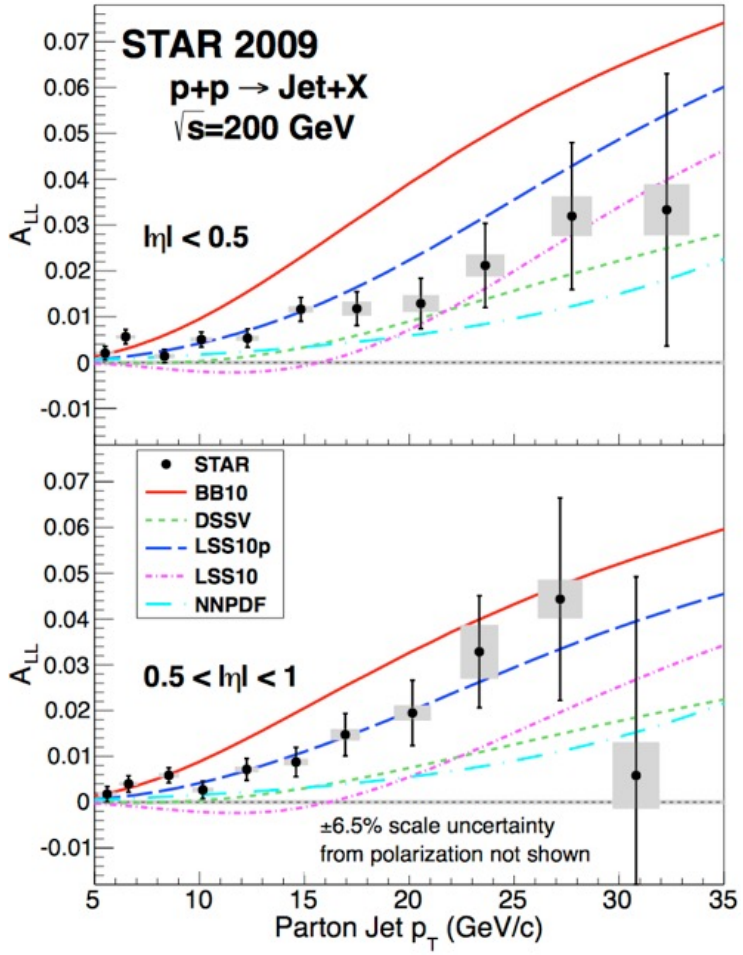


Measured double-spin asymmetry:

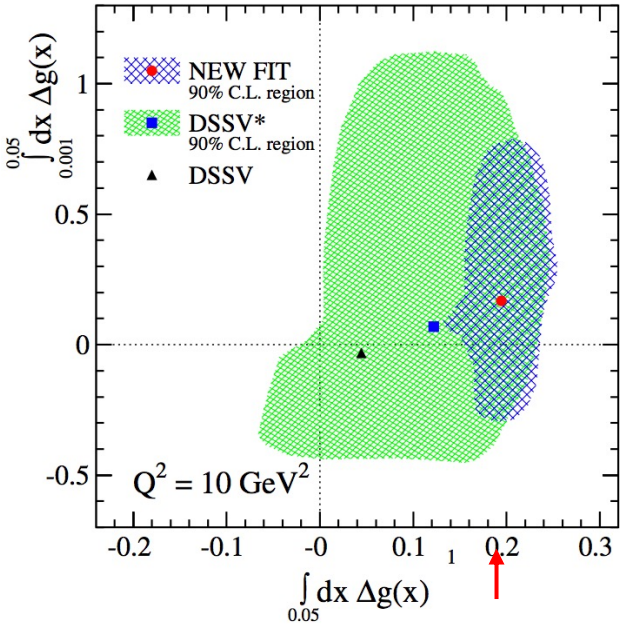
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \propto \overbrace{\frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2}}^{\text{probed}} \otimes \overbrace{\hat{a}_{LL} \otimes D_f^h}^{\text{inputs}}$$

Clear evidence for a positive gluon polarization

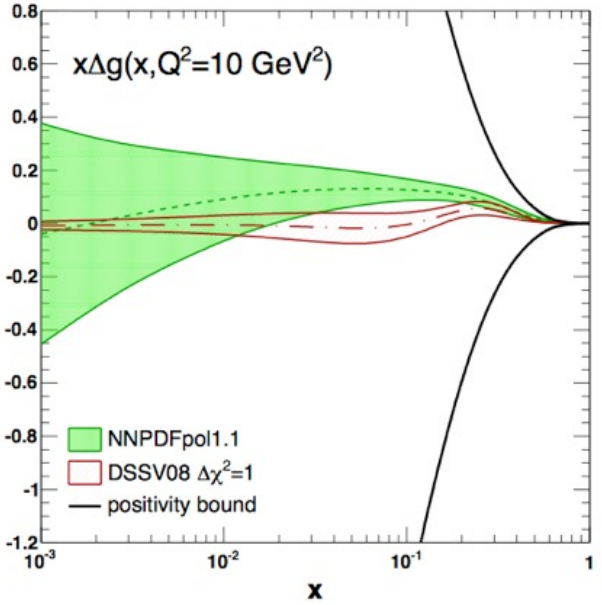
STAR, PRL115 (2015) 092002



DSSV, PRL113 (2014) 012001



NNPDF, NPB887 (2014) 276



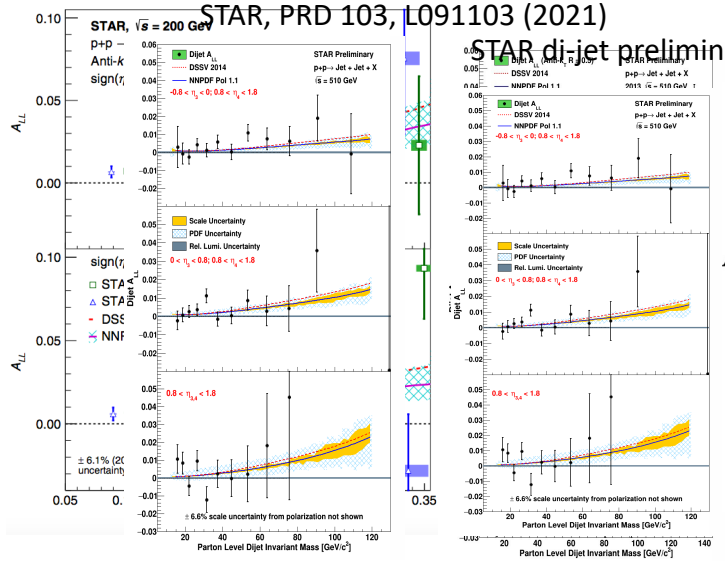
- **First evidence** of non-zero contributions from gluon spin at $Q^2 \sim 10$ GeV^2

A big wave of precision results

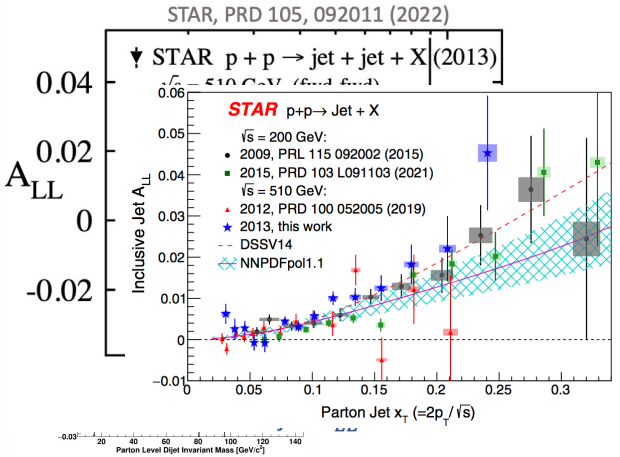
STAR, PRD 105, 092011 (2022)

STAR, PRD 103, L091103 (2021)

STAR di-jet preliminary results

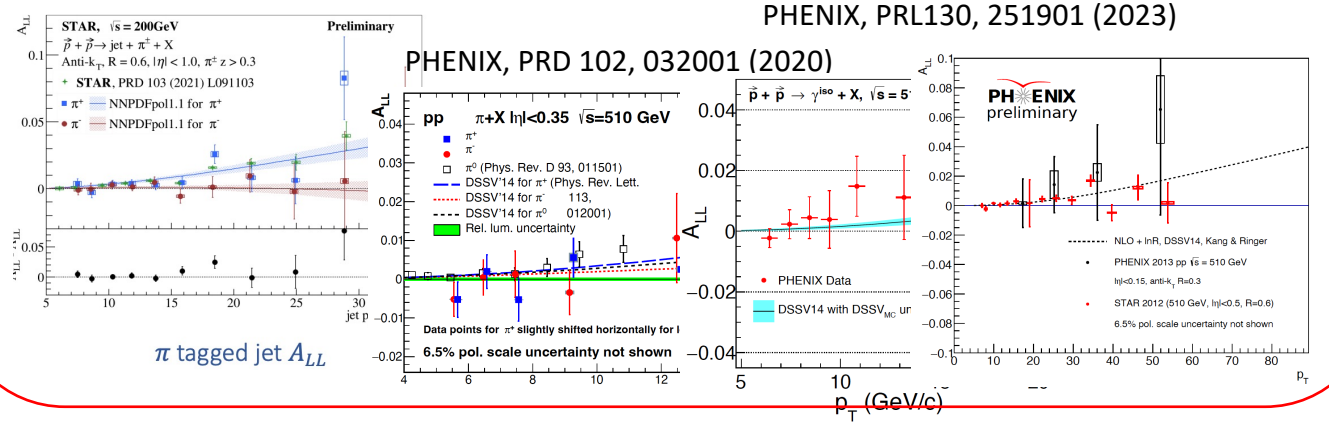


STAR, PRD 105, 092011 (2022)



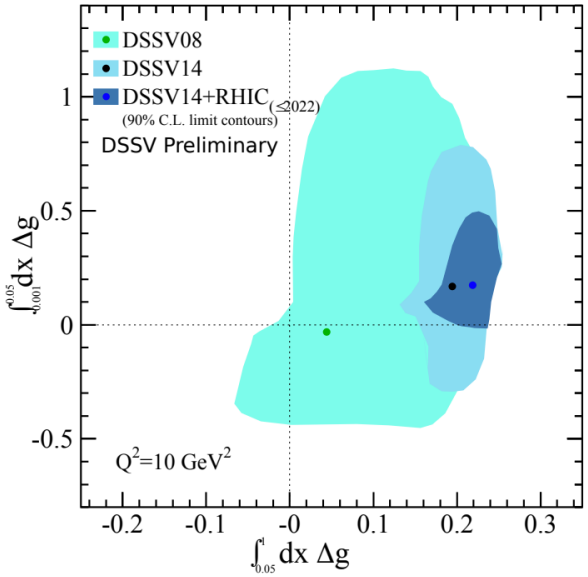
PHENIX, PRL130, 251901 (2023)

PHENIX, PRD 102, 032001 (2020)



π tagged jet A_{LL}

The RHIC Cold QCD Program, White Paper, arXiv:2302.00605



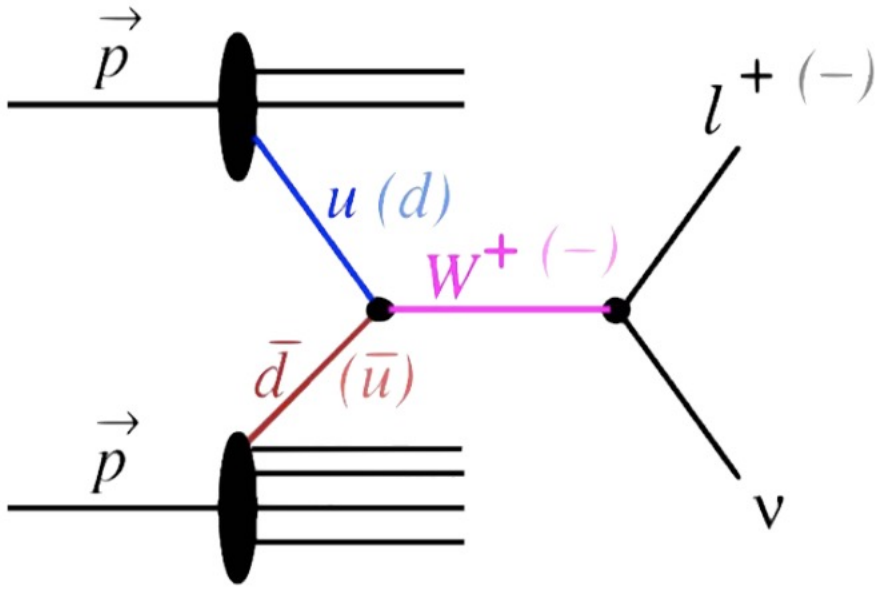
DSSV14 + RHIC (≤2022):

- $\Delta G = \int_{0.05}^{1} \Delta g(x)dx = 0.22^{+0.03}_{-0.06}$
- $\Delta G = \int_{0.001}^{0.05} \Delta g(x)dx = 0.17^{+0.33}_{-0.17}$

Flavor separation with W boson

Elegant way to study proton spin-flavor structure:

- W boson selects quarks/antiquarks with specific helicity.
- W bosons are measured via leptonic decay.

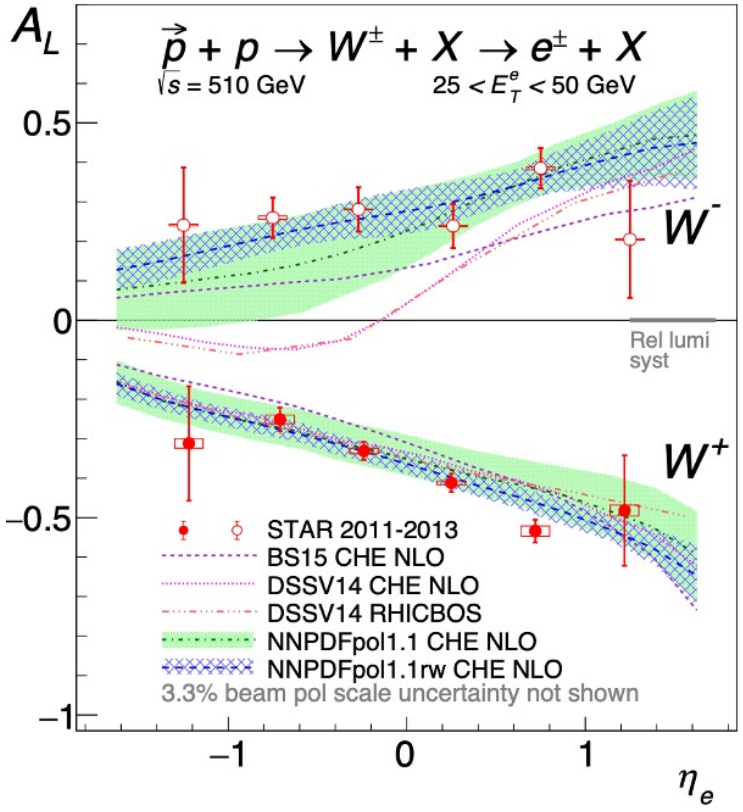


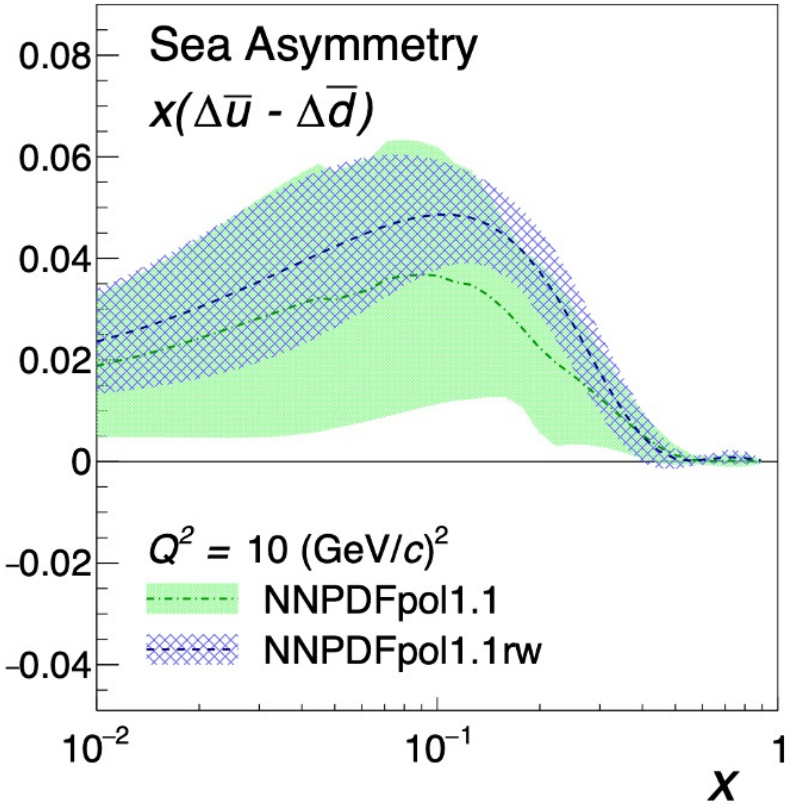
Parity violating
single-spin asymmetry:

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

Impact of W results

STAR, PRD99, 051102 (2019)

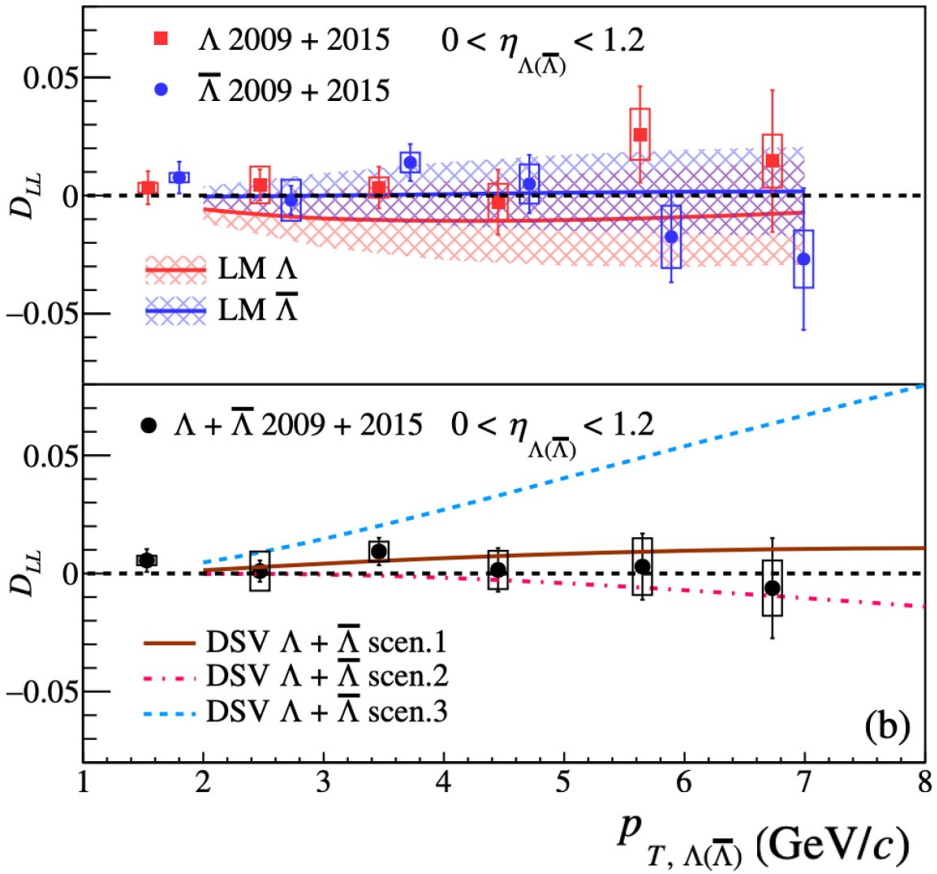




- Now we know: $\Delta\bar{u} > 0$ and $\Delta\bar{d} < 0$
- The flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ similar size but opposite sign to the unpolarized case.

Strange quarks polarization via Lambda spin transfer

STAR, PRD109, 012004 (2024)



Spin transfer:

$$D_{LL}^{\Lambda} \equiv \frac{d\sigma(p^+p \to \Lambda^+X) - d\sigma(p^+p \to \Lambda^-X)}{d\sigma(p^+p \to \Lambda^+X) + d\sigma(p^+p \to \Lambda^-X)} = \frac{d\Delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

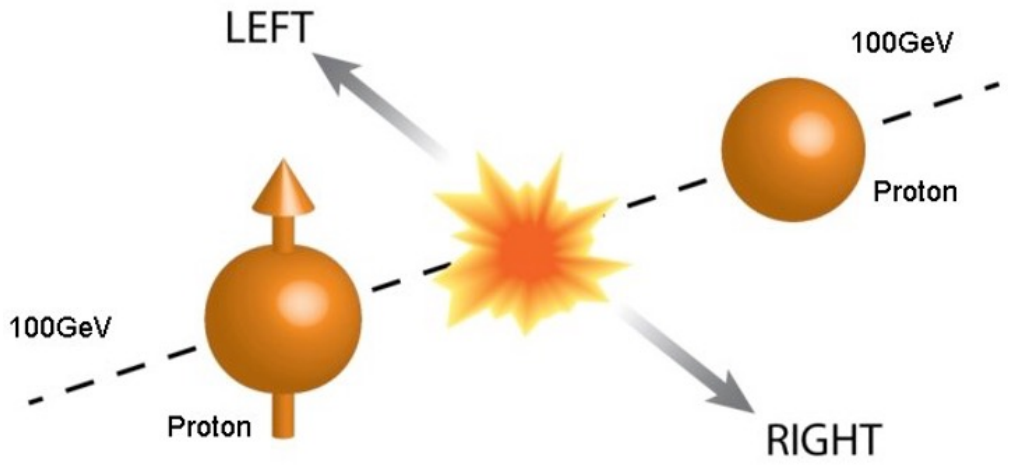
$$d\Delta\sigma^{\Lambda} = \sum \int dx_a dx_b dz \Delta f_a(x_a) f_b(x_b) \Delta\sigma(ab \to cd) \Delta D^{\Lambda}(z)$$

Polarized PDFs *Polarized FFs*

Access polarized FFs and PDFs of strange quarks

- Final state polarization accessible via weak decay
- Lambda's spin is expected to be carried mostly by its constituent strange quark

Another longstanding spin puzzle



Transverse single spin asymmetry:

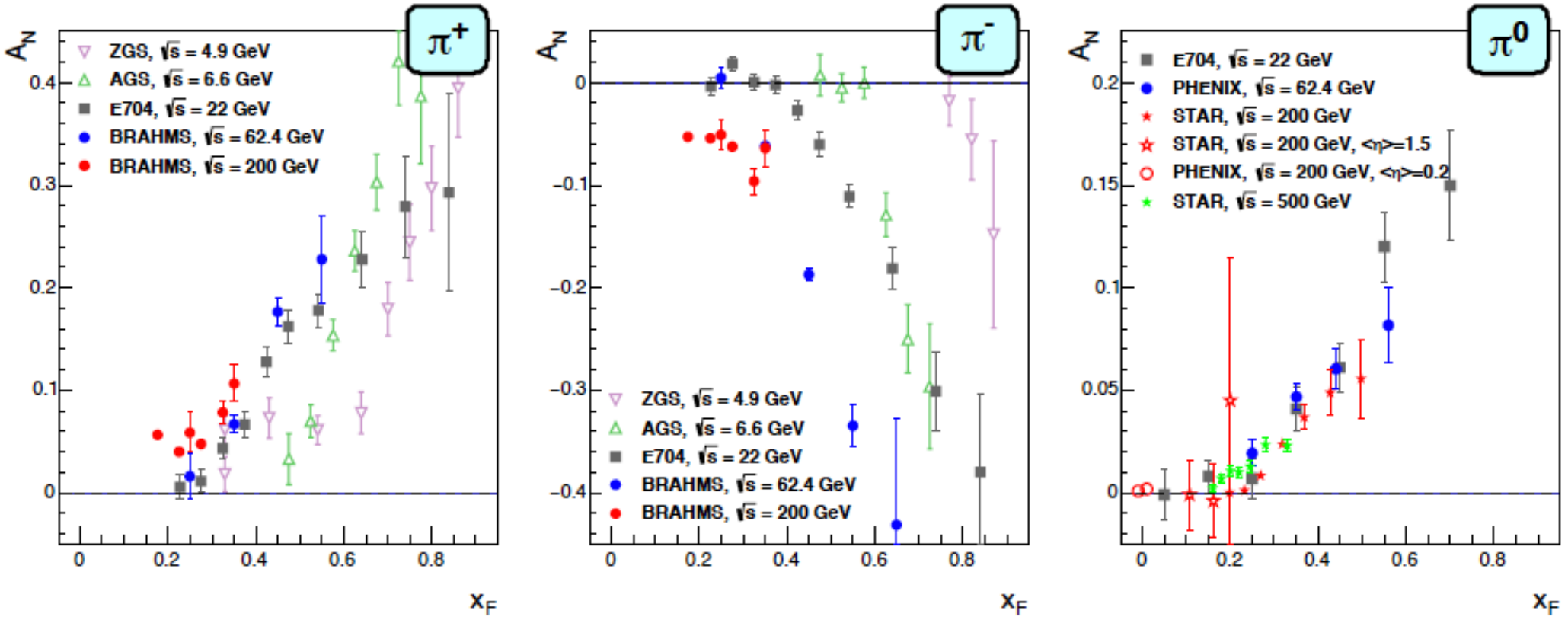
$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

Transverse spin effect expected to be small at high energies…

--- but FNAL came with a big surprise: it is very large!

Remains mystery after 40+ years

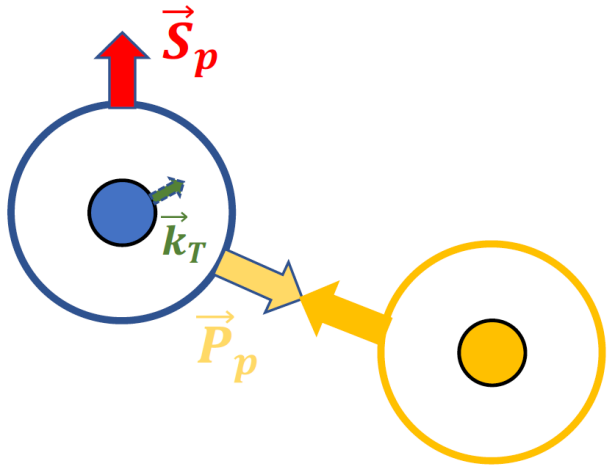
RHIC Cold QCD plan, arXiv: 1602.03922



Large asymmetry over a very wide range (√s: 4.9 GeV to 500 GeV)

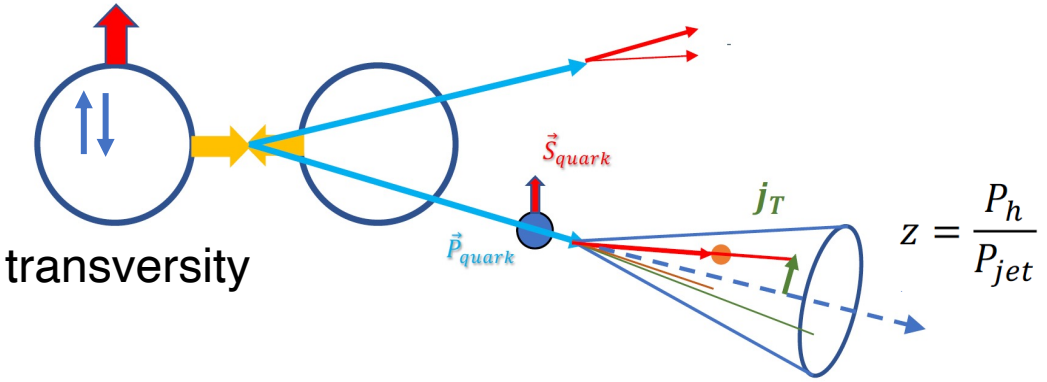
Possible origins

Sivers effect



Due to transverse motion of quarks in the nucleon: initial state effect

Collins effect

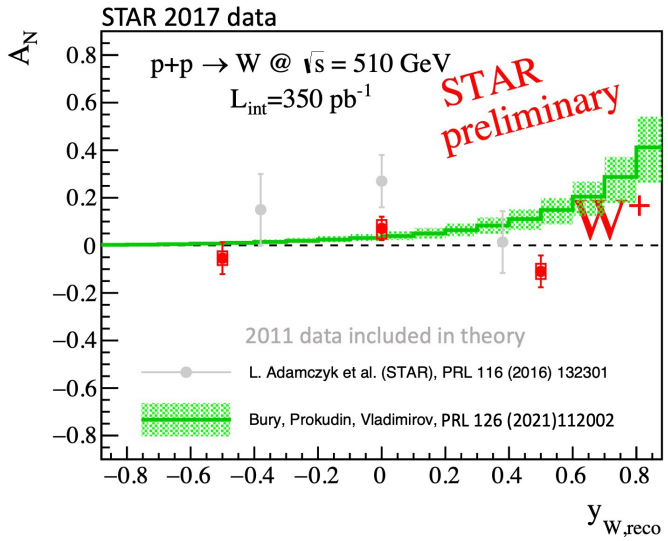


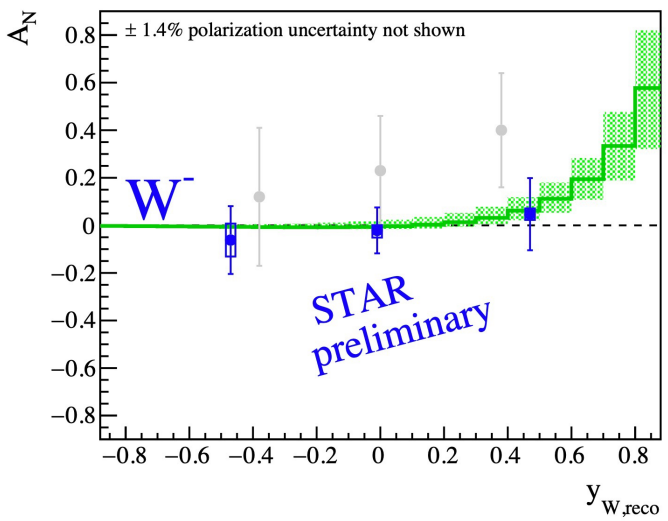
Asymmetry in the fragmentation hadrons: final state effect

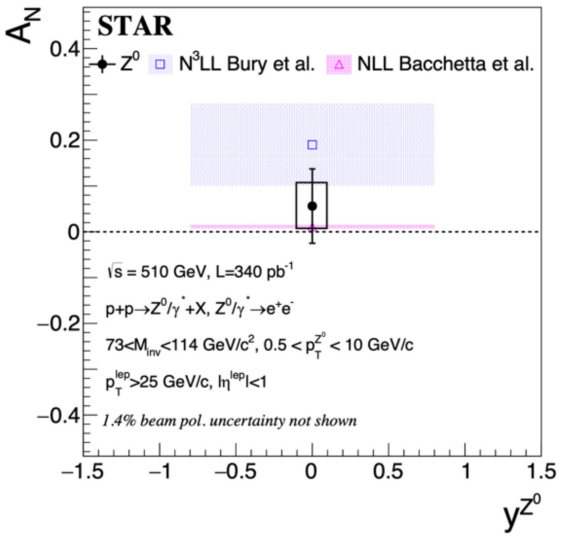
Weak bosons A_N – Sivers

- Universality test of Sivers function: sign-change from DIS to DY/W/Z

PLB 854 (2024) 138715



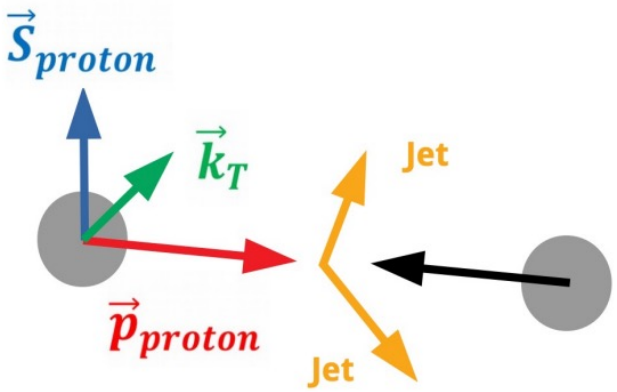


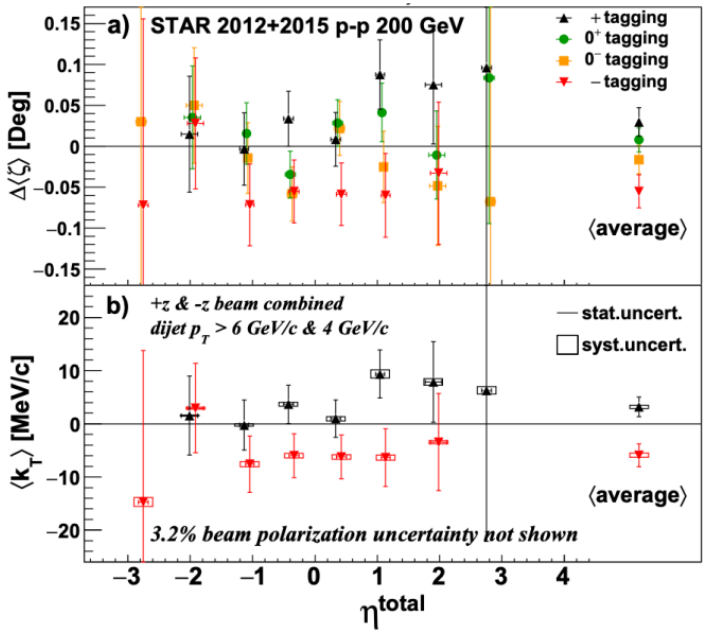


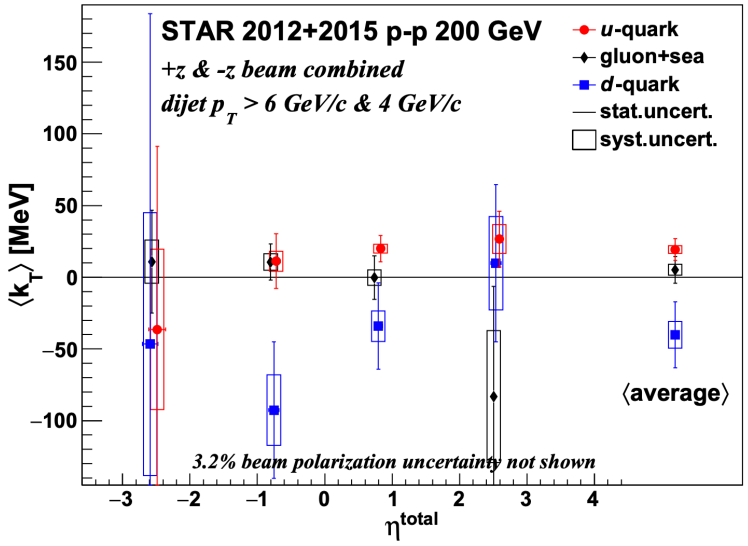
- Theoretical (PRL126,112002): extraction includes SIDIS, DY and 2011 STAR data with N3LO and NNLO accuracy of the TMD evolution *assuming sign-change*
- STAR preliminary with 2017 data with much improved precision, expect big impact in Sivers function at high-x in next global TMD fit

Dijet A_N – Sivers

arXiv: 2305.10359 (submitted to PRL)



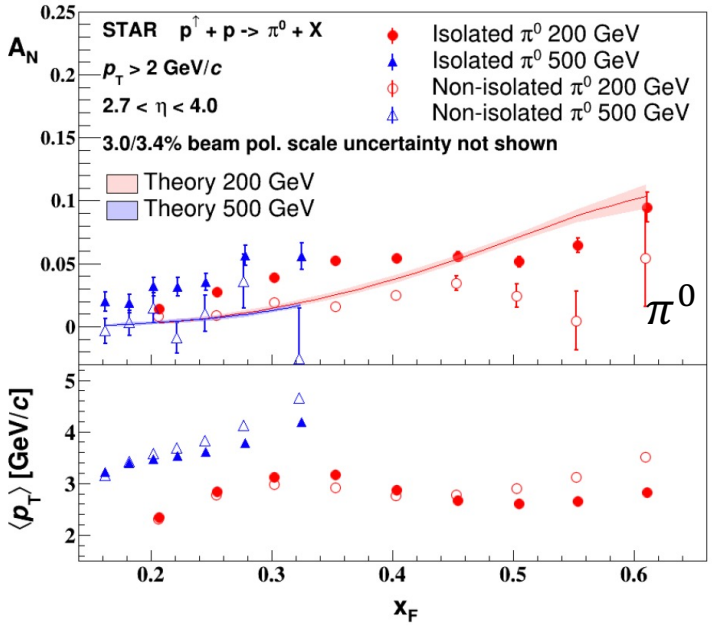


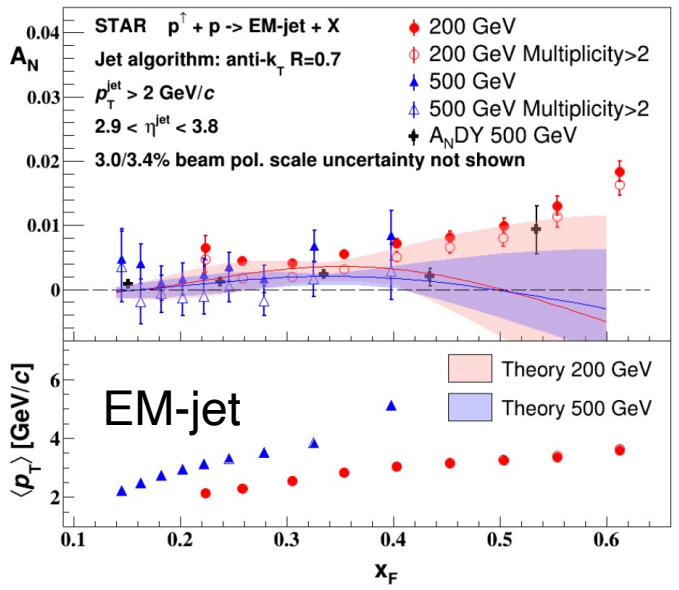


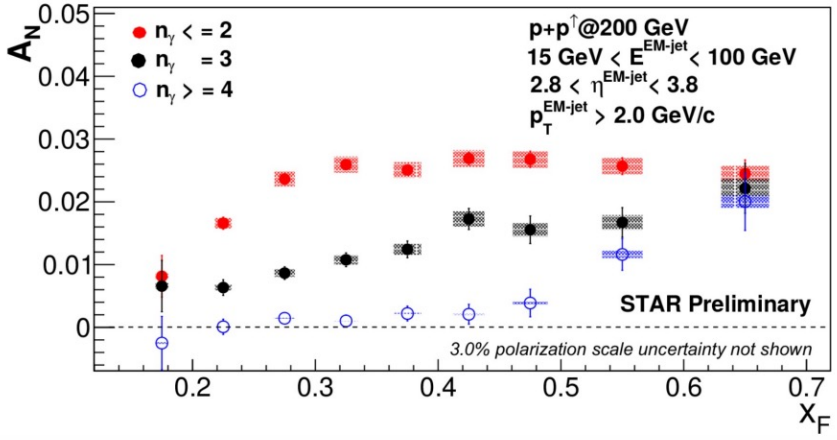
- Spin-dependent dijet opening angle sensitive to Sivers
- First observation of non-zero Sivers asymmetries in dijet production in polarized *p+p* collisions

Forward A_N π^0, EM-jet

STAR, PRD 103, 092009 (2021)



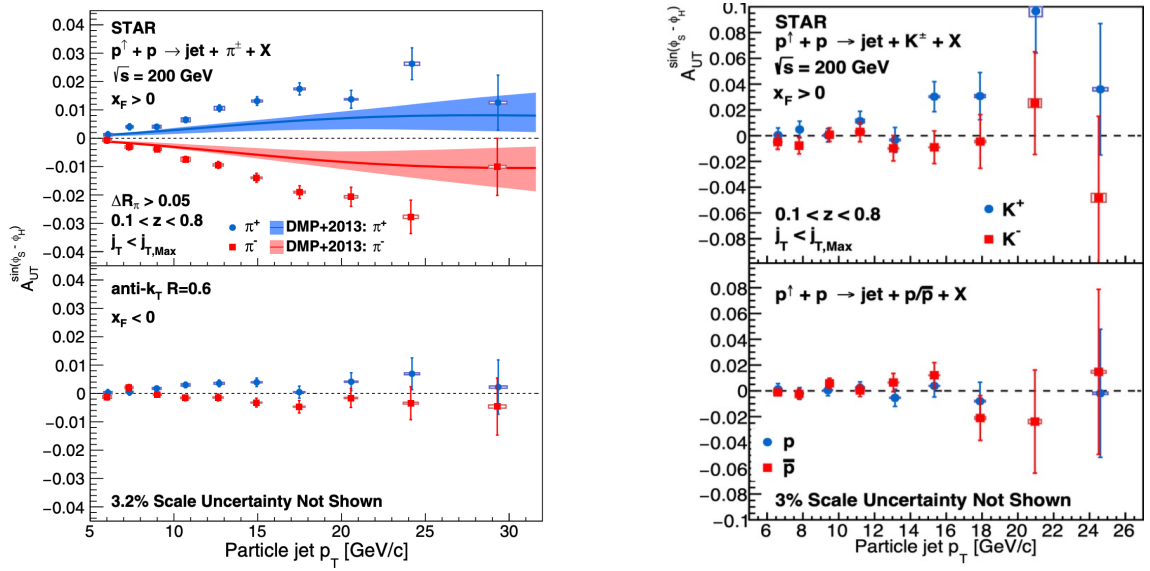




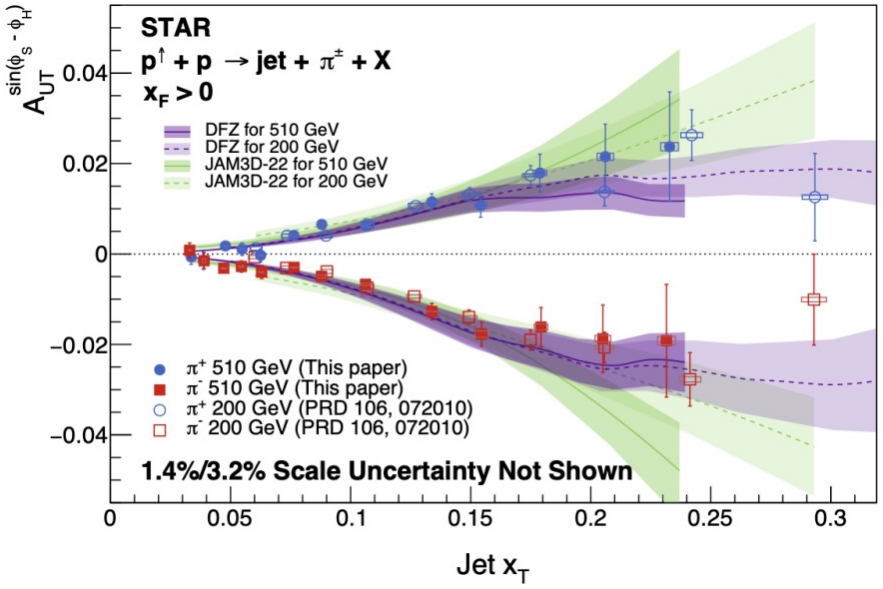
- A_N with forward EM-jets and π^0 in 200/500 GeV pp collisions
- Decreasing A_N as ”jet-ness” increasing (high multiplicity)
- Run2022 and 2024: improved statistic for various objects using Forward Upgrades

Hadron in Jet A_N – Transversity + Collins

STAR, PRD 106 (2022), 072010



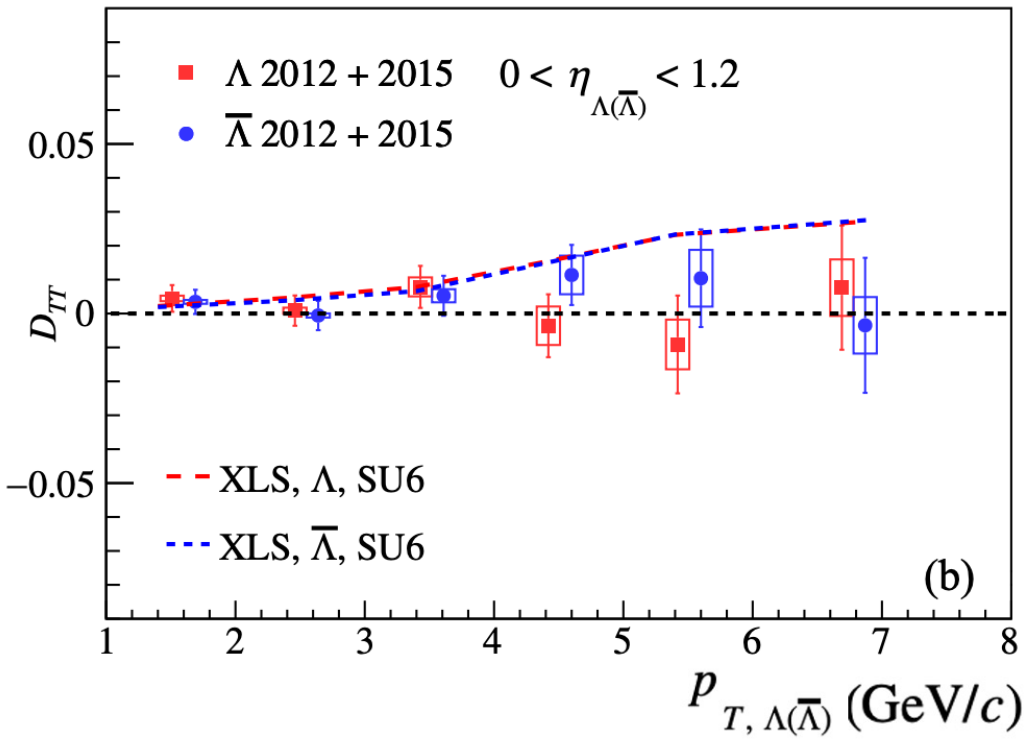
arXiv:2507.16355 (submitted to PRL)



- Significant Collins asymmetries have been observed in 200 and 500 GeV
- New results show weak energy dependence and provide important constraints on the scale evolution for Collins asymmetry

Lambda transverse spin transfer – Transversity + FFs

STAR, PRD109, 012004 (2024)



The results are consistent with model calculations within uncertainties.

Transverse spin transfer:

$$D_{TT}^{\Lambda} \equiv \frac{\sigma^{(p^{\uparrow}p\to\Lambda^{\uparrow}X)} - \sigma^{(p^{\uparrow}p\to\Lambda^{\downarrow}X)}}{\sigma^{(p^{\uparrow}p\to\Lambda^{\uparrow}X)} + \sigma^{(p^{\uparrow}p\to\Lambda^{\downarrow}X)}} = \frac{d\delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

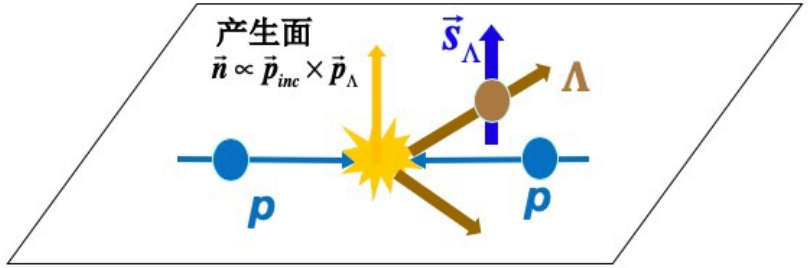
$$d\delta\sigma^{\Lambda} = \sum_{abcd} \int dx_a\, dx_b dz \underbrace{\delta f_a(x_a)}_{\text{Transversity PDF}} f_b(x_b) \underbrace{\delta\sigma^{(a^{\uparrow}b\to c^{\uparrow}d)}}_{\text{Transversity FF}} \delta D_c^{\Lambda}(z)$$

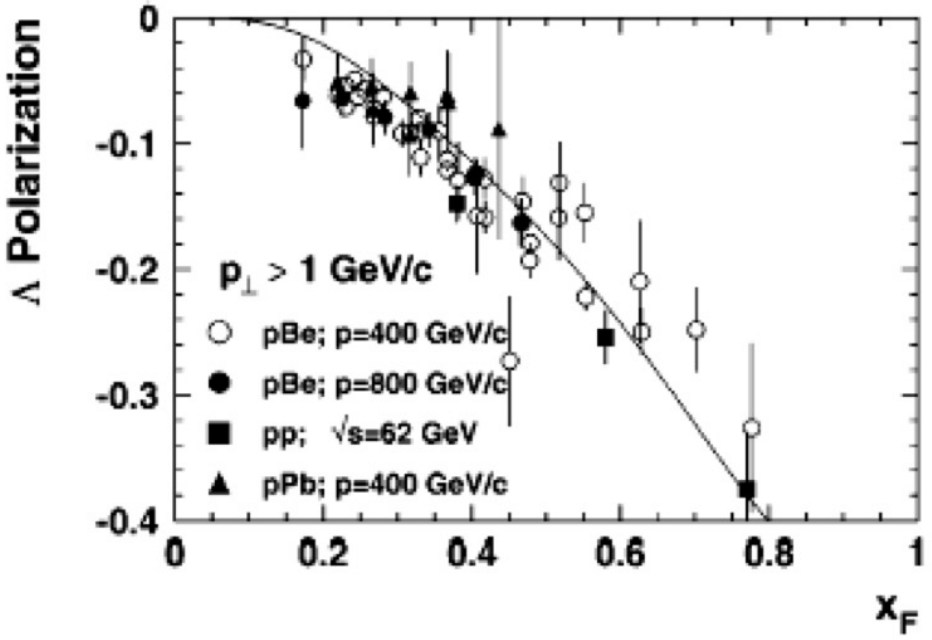
Access transversity fragmentation functions (FF) and transversity distributions (PDF) of strange quarks

- Final state polarization accessible via weak decay
- Lambda's spin is expected to be carried mostly by its constituent strange quark

One more longstanding spin puzzle

Lambda transverse polarization observed in unpolarized pBe scattering in 1976





Liang and Boros, PRL79, 3608 (1997)

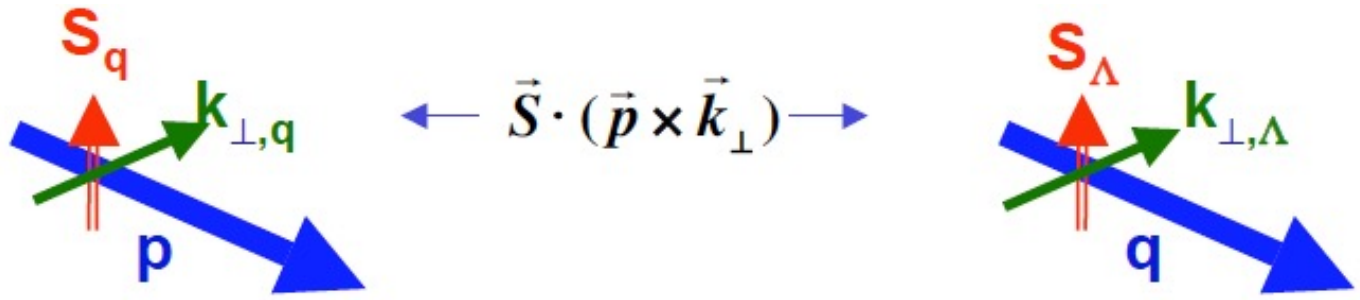
- Lambda transverse polarization is significant, while anti-lambda is not;
- Clear x_F and p_T dependence, while almost independent on energy;
- Weak target-mass dependence: pA ≈ pp, parton level reaction.

Non-perturbative effects

Partonic scattering (pQCD) cannot explain the large polarization.

Then, must be non-pQCD effects from *initial state and/or final state.*

Parton distributions



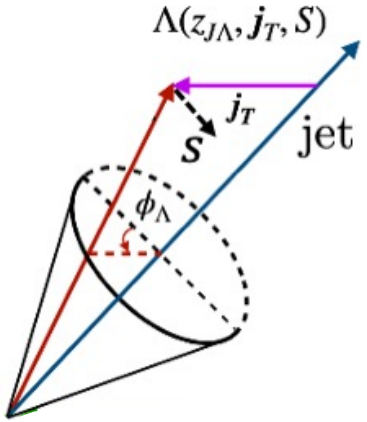
Parton fragmentations

Can not distinguish in pp;

ep and e^+e^- can separate.

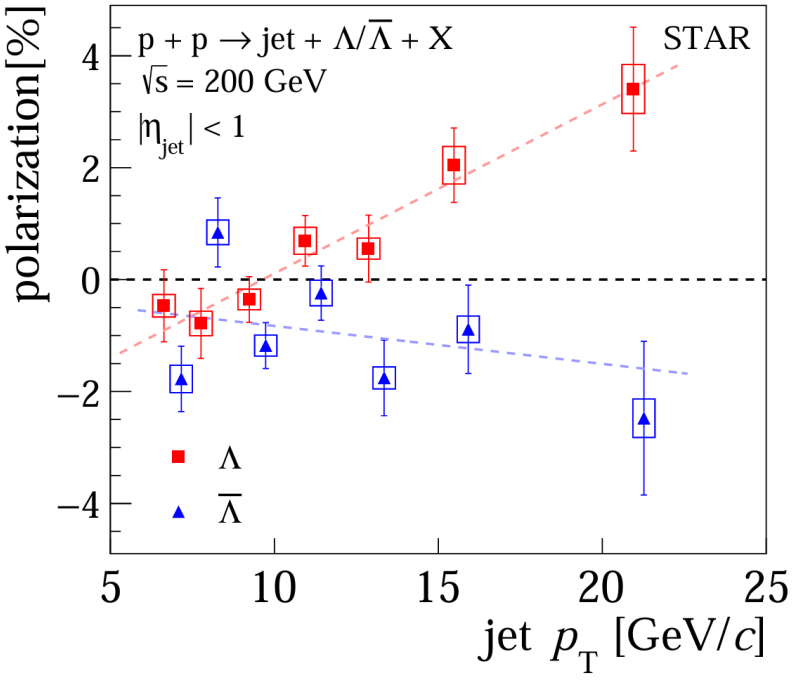
- Spin transfer from initial state: parton is polarized in polarized proton — Helicity/Transiversity
  parton is polarized in unpolarized proton — Boer-Mulders
- Polarization arising at final state: parton is unpolarized but fragmenting into polarized hadron. — Polarizing FFs

Polarization of Lambda-in-jet

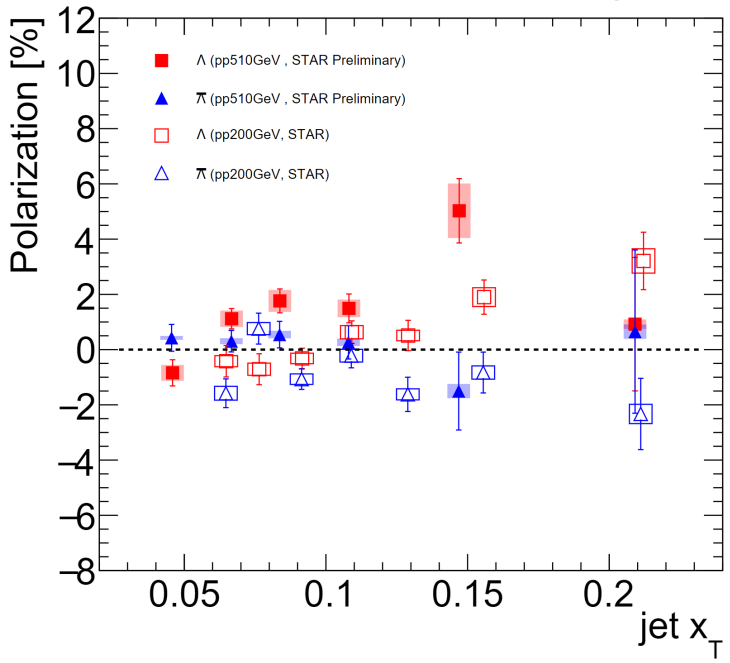


$\hat{S} = \hat{p}_{jet} \times \hat{p}_\Lambda$

arXiv:2509.17487 (submitted to PRL)



STAR, SPIN2025 (by Jinhao He)

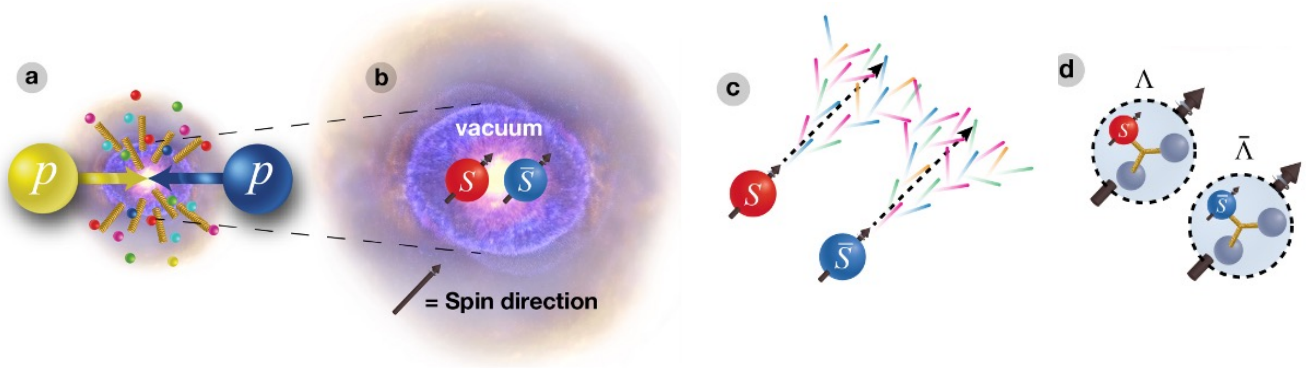


Probing polarizing FFs via polarization of Lambda-in-jet

- Significant jet p_T dependence for Λ in both 200 GeV and 510 GeV

Spin correlations in pp 200 GeV

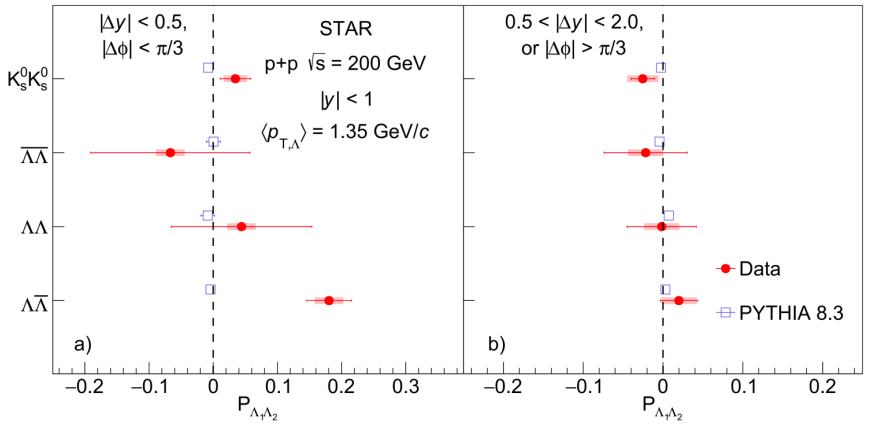
arXiv: 2506.05499, accepted by Nature

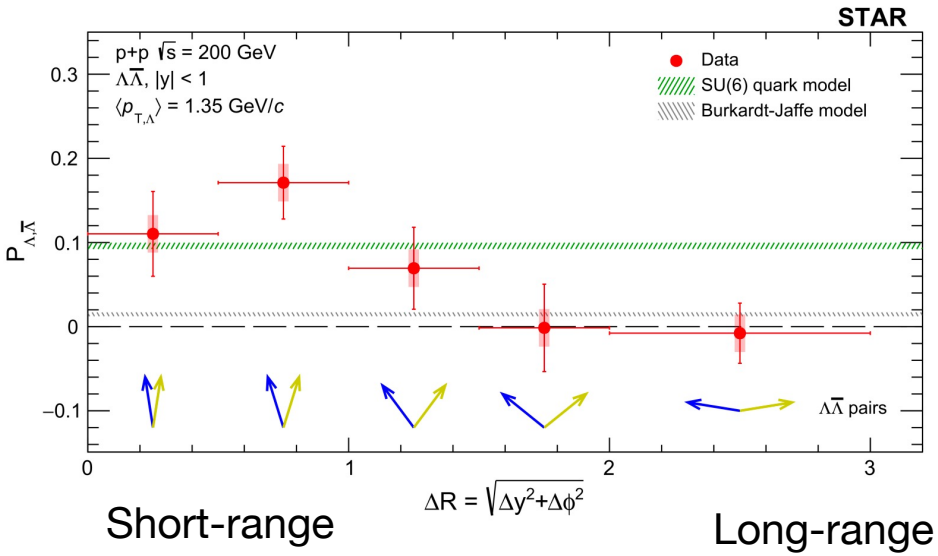


Spin correlation of $\Lambda/\bar{\Lambda}$ hyperon pairs measured in *p+p* collisions to study the hadronization of the entangled $s/\bar{s}$ quark pairs from the QCD vacuum.

$$dN/d\cos(\theta^*) = A\,(1 + B\cos\theta^*)$$

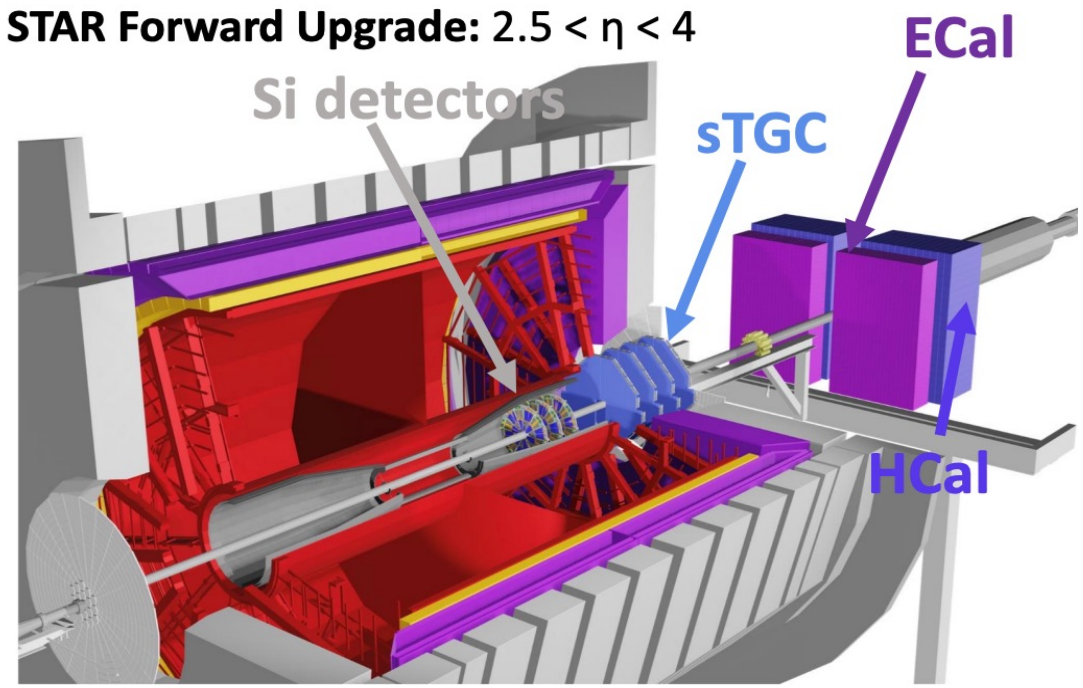
A: normalization, B: $\alpha_1\alpha_2 P_{\Lambda 1 \Lambda 2}$





- Short-range $\Lambda\bar{\Lambda}$ pairs show non-zero spin correlation
- All other pairs are consistent with zero

STAR forward upgrades



detector	pp and pA	AA
ECal	~10%/$\sqrt{E}$	~20%/$\sqrt{E}$
HCal	~50%/$\sqrt{E}$+10%	---
Tracking	charge separation photon suppression	0.2<p_T<2 GeV/c with 20-30% 1/p_T

- Successful RHIC spin run in 2022 and 2024 with STAR forward upgrades.

Summary

RHIC spin operation has concluded.

RHIC has been making significant contributions to serval poorly constrained pieces of the spin puzzles

- **Gluon polarization** $\Delta G > 0$
- **Flavor-separated quark and anti-quark polarizations** $\Delta\bar{u} > \Delta\bar{d}$
- **Transverse** program in progress: existing data being published/analyzed, **stay tuned**

Next generation: polarized Electron Ion Collider

Thank you for your attention!