第一届中国电子离子对撞机相关物理年会

The 1st Annual Conference on Electron-Ion Collider Physics in China

Highlights of RHIC Spin Physics

Jinlong Zhang (张金龙)

April 19-22, 2026

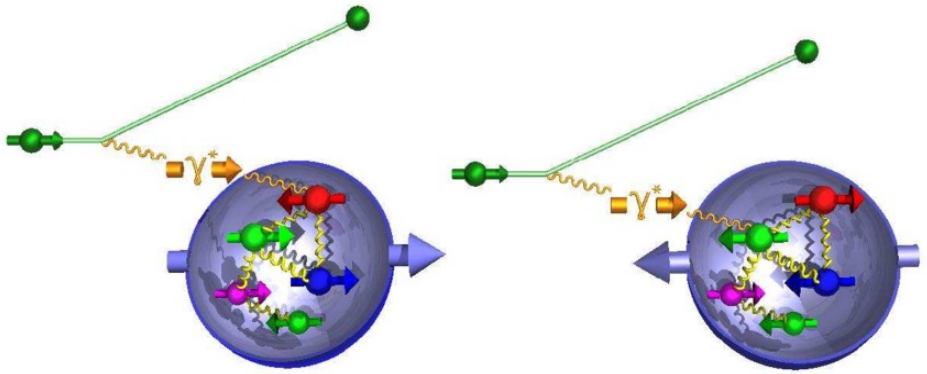
山东大学
SHANDONG UNIVERSITY

Outline

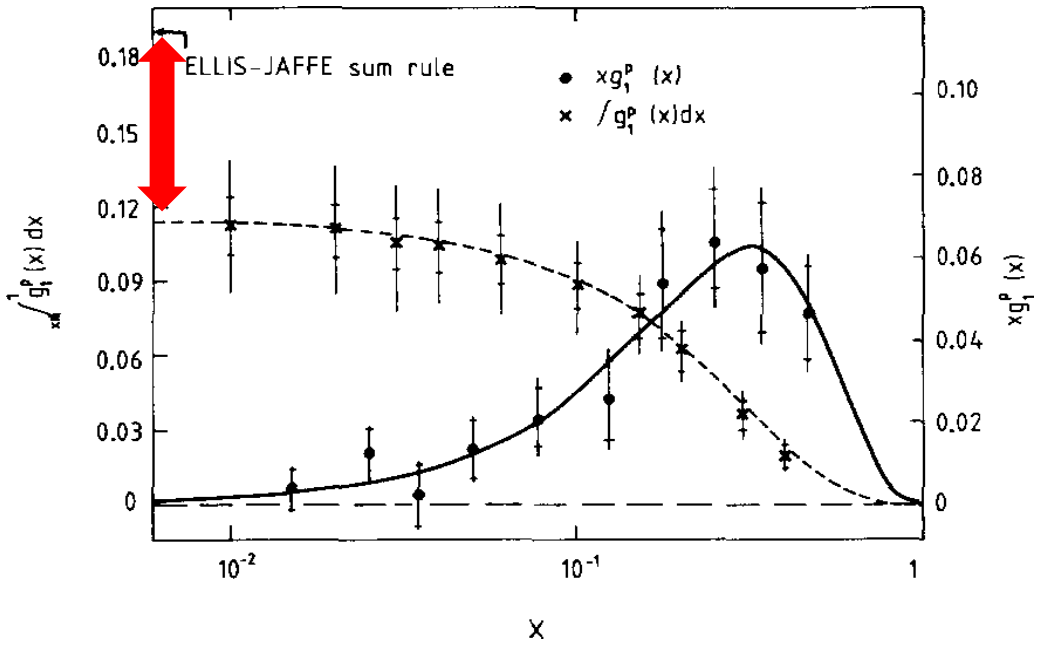
- Why do we need RHIC spin?
- What enables RHIC spin?
- What have we learned from RHIC spin?
- What remains to be explored with RHIC spin data?
- How does RHIC spin impact the EIC era?

Proton spin crisis

Deep-inelastic scattering with polarized leptons off polarized protons

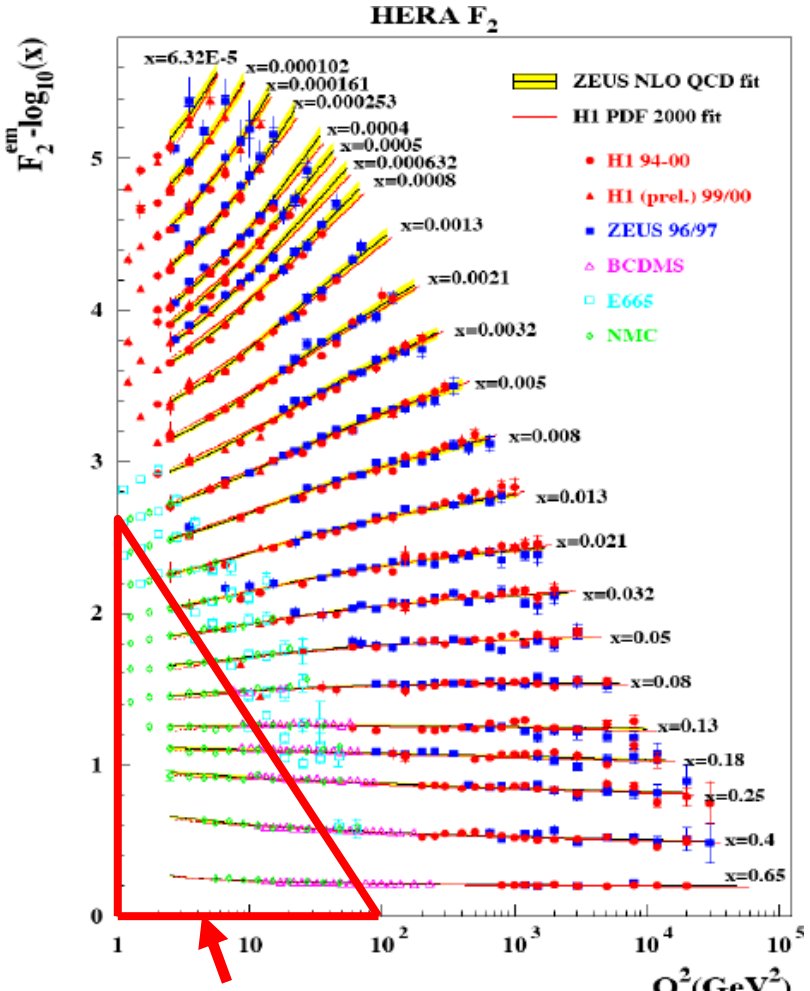


EMC, PLB 206, 364 (1988)



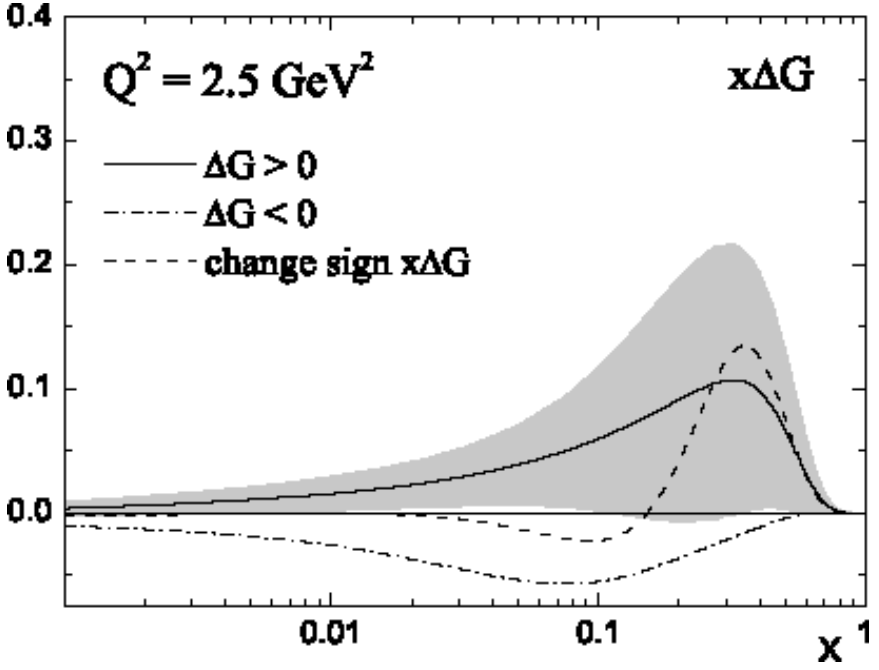
- First polarized DIS over a broad kinematic region was performed by EMC in the mid-'80s
- Found that quarks contribute only $(14 \pm 9 \pm 21)\%$ of the proton spin
- Many follow-up fixed target pDIS experiments, one ~25% of the proton spin arises from quarks and antiquarks

What about gluons?



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

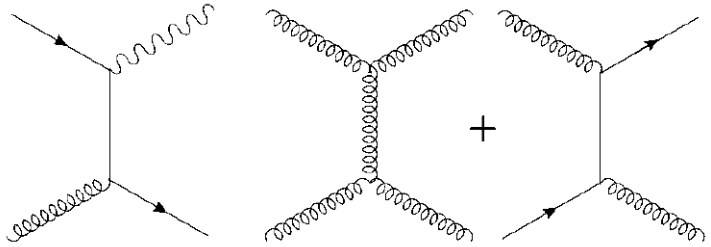
Leader et al, PRD 75, 074027 (2007)



Extraction of gluon polarization needed large Q2 arm, and fixed target experiments did not allow

Motivation of RHIC spin

Gluon polarization

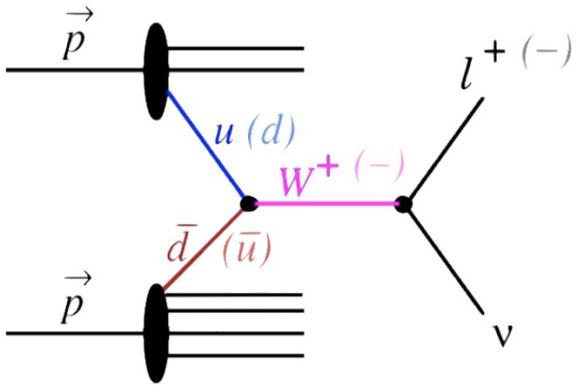


QCD Compton scattering

Quark-gluon, gluon-gluon scattering

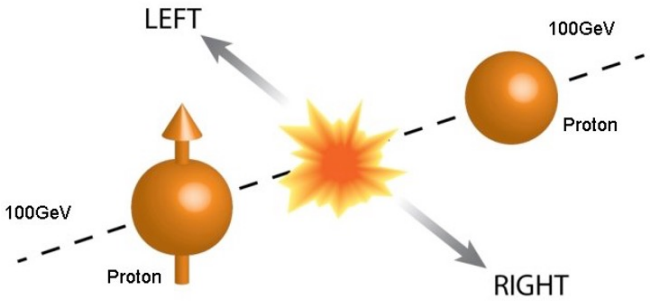
Tree-level sub-processes directly sensitive to gluon: jet, direct-γ

Sea quark polarization



W production and Λ spin transfer sensitive to flavor separated sea quark

Transverse spin physics



Severe need for investigations of the puzzling transverse spin effects

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*

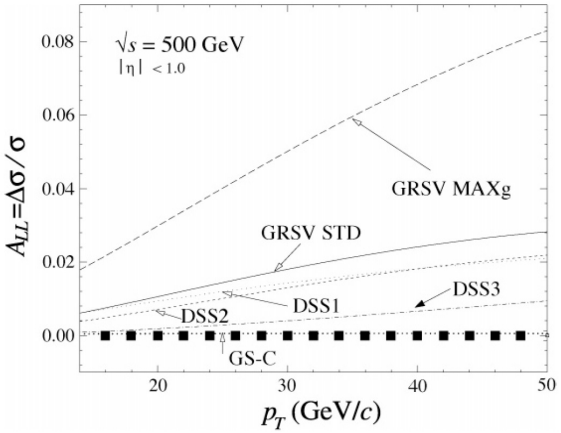
[4]*C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11794-3840 and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000; e-mail: wvogelsang@bnl.gov*

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

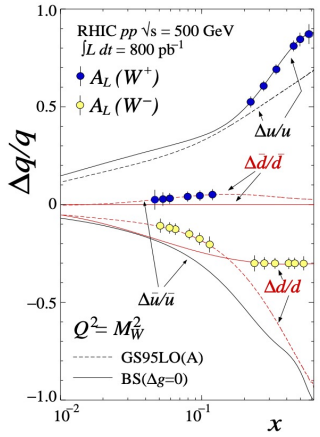
■ **Abstract** Colliding beams of 70% polarized protons at up to $\sqrt{s} = 500$ GeV, with high luminosity, $L = 2 \times 10^{32}\,cm^{-2}\,sec^{-1}$, will represent a new and unique laboratory for studying the proton. RHIC-Spin will be the first polarized-proton collider and will be capable of copious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

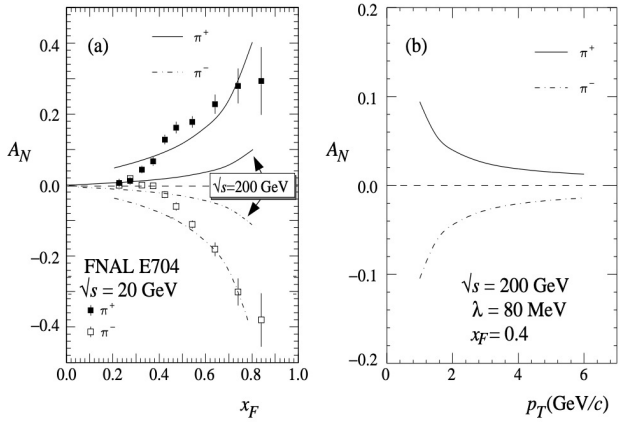
Jet production



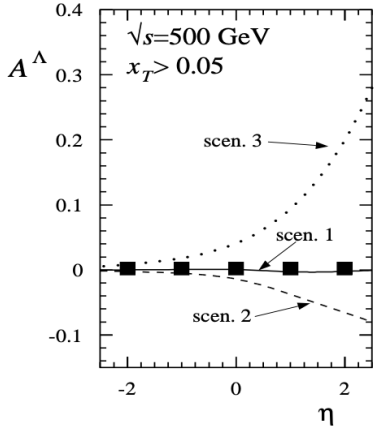
$W^{\pm}$ production



Transverse SSA

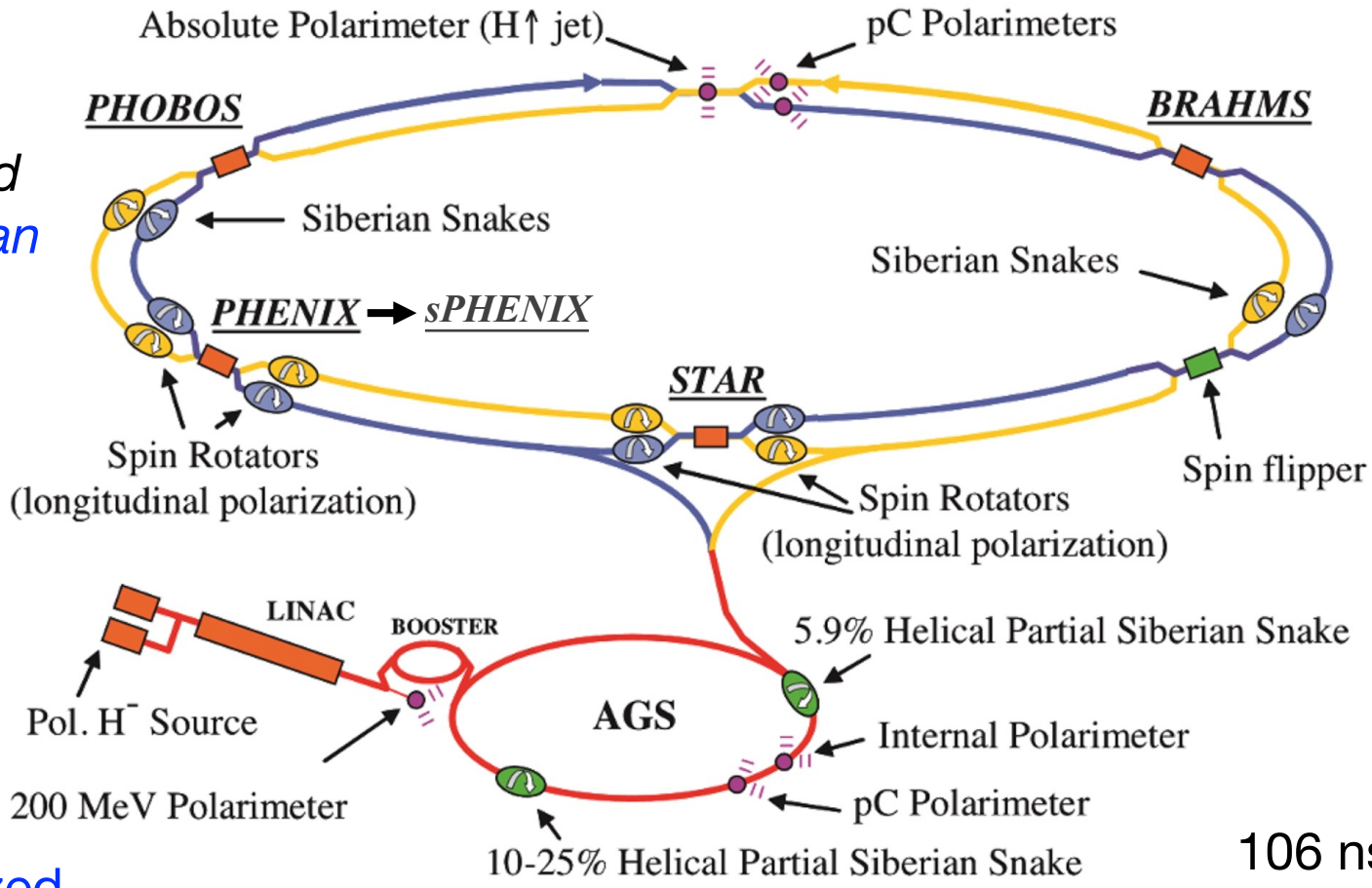


Lambda spin transfer



Polarized RHIC

Accelerate polarized protons with Siberian Snakes

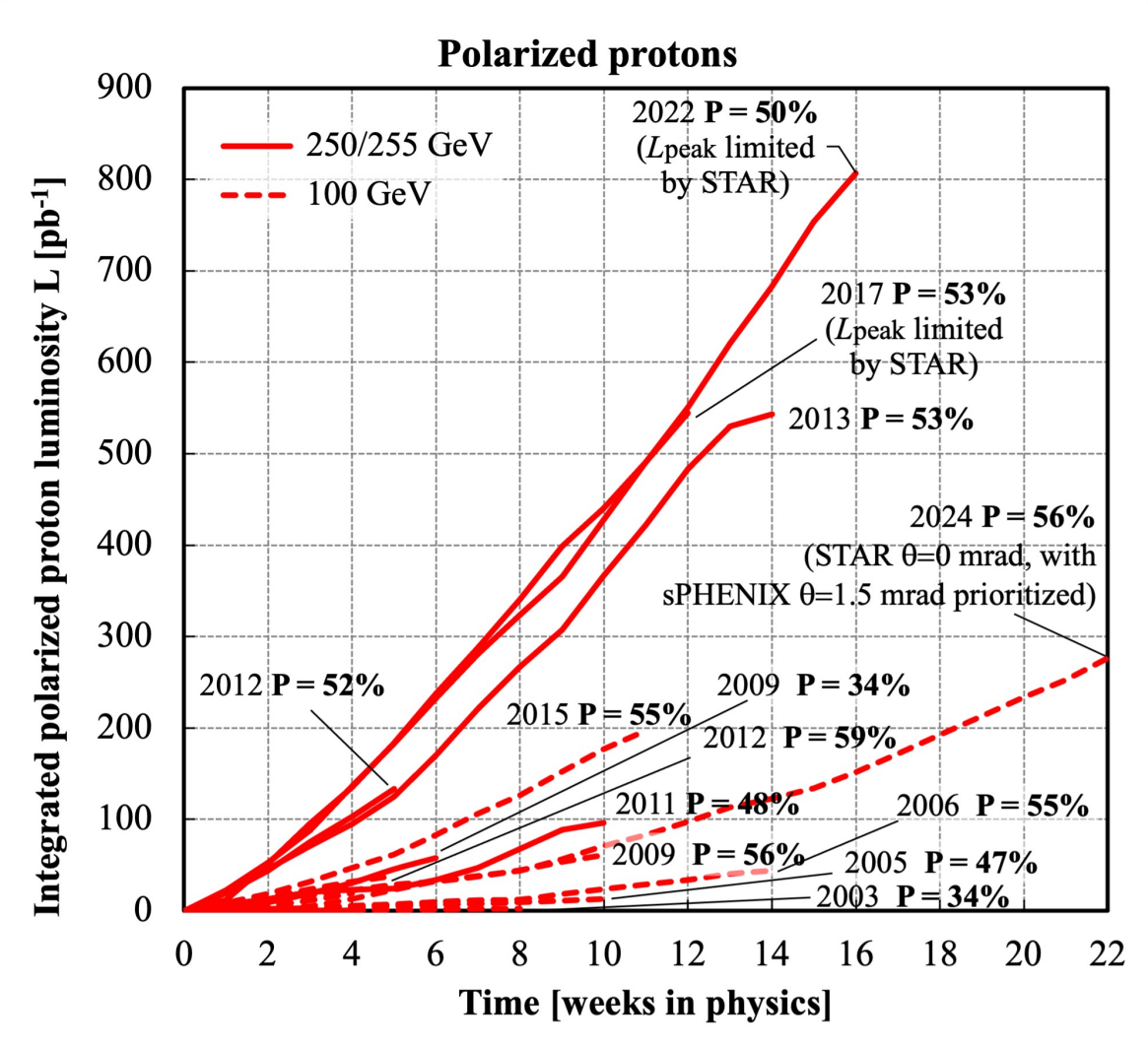


Manipulate spin direction with spin rotator

High current polarized proton source

106 ns bunch crossing with pre-determined spin directions

Data accumulation for spin physics

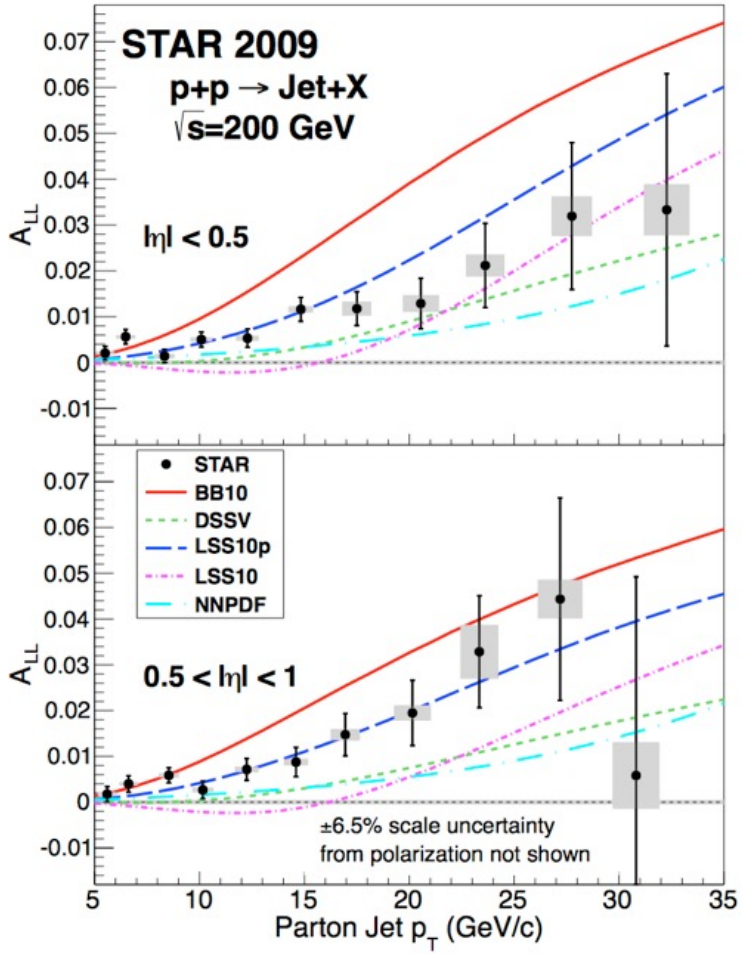


	Year	√s (GeV)	L (pb^{-1})	<P> (%)
Long	2006	62.4	--	48
		200	6.8	57
	2009	200	25	38
		500	10	55
	2011	500	12	48
	2012	510	82	56
	2013	510	256	56
	2015	200	52	53
Trans	2006	62.4	0.2	48
		200	8.5	57
	2008	200	7.8	45
	2011	500	25	55
	2012	200	22	60
	2015	200	52	53
	2017	510	350	55
	2022	508	400	52
	2024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

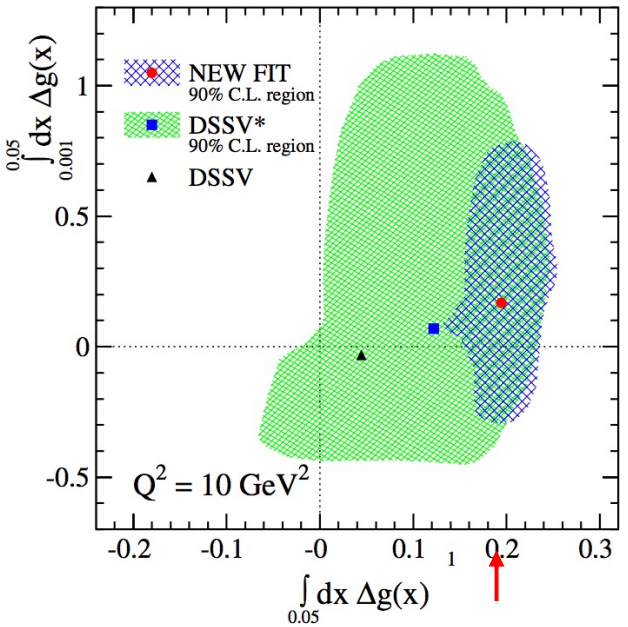
by STAR

Clear evidence for a positive gluon polarization

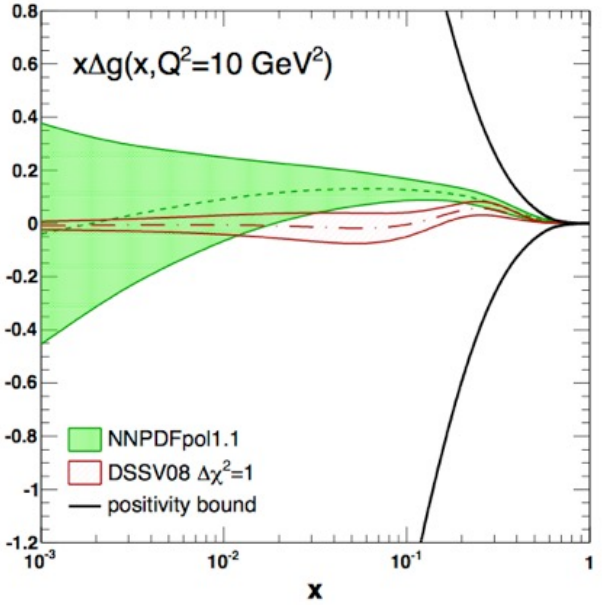
STAR, PRL115 (2015) 092002



DSSV, PRL113 (2014) 012001



NNPDF, NPB887 (2014) 276



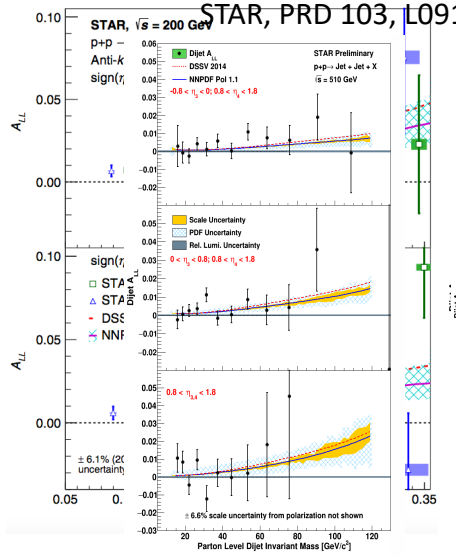
- **First evidence** of non-zero contributions from gluon spin at $Q^2 \sim 10\ GeV^2$

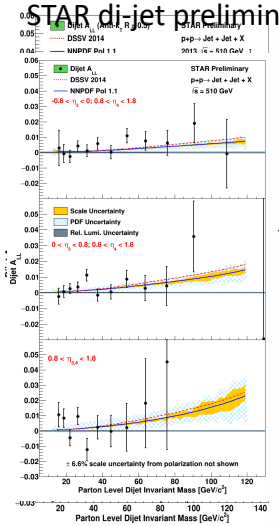
Precision constraints on gluon polarization

STAR, PRD 105, 092011 (2022)

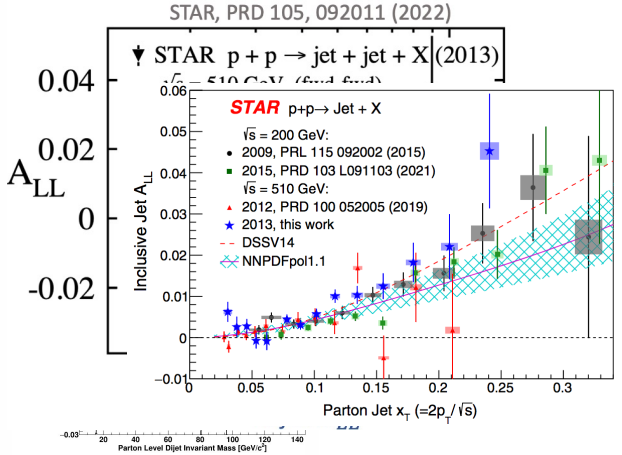
STAR, PRD 103, L091103 (2021)

STAR di-jet preliminary results



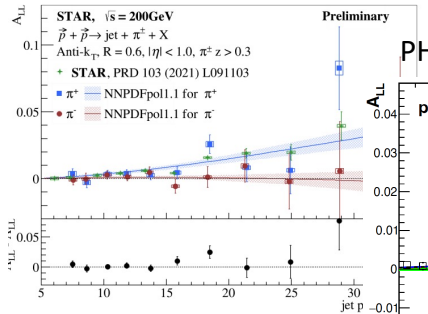


STAR, PRD 105, 092011 (2022)

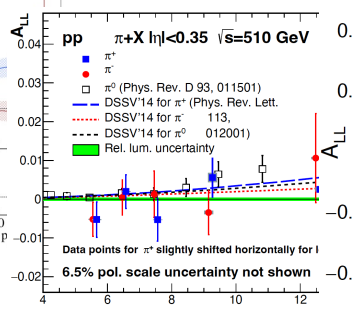


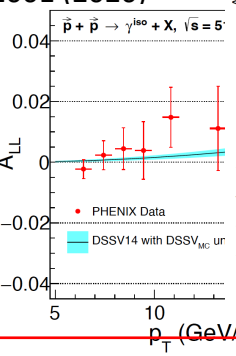
PHENIX, PRL130, 251901 (2023)

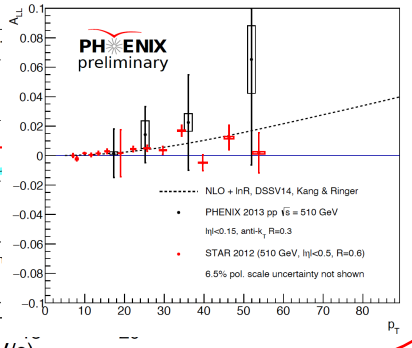
PHENIX, PRD 102, 032001 (2020)



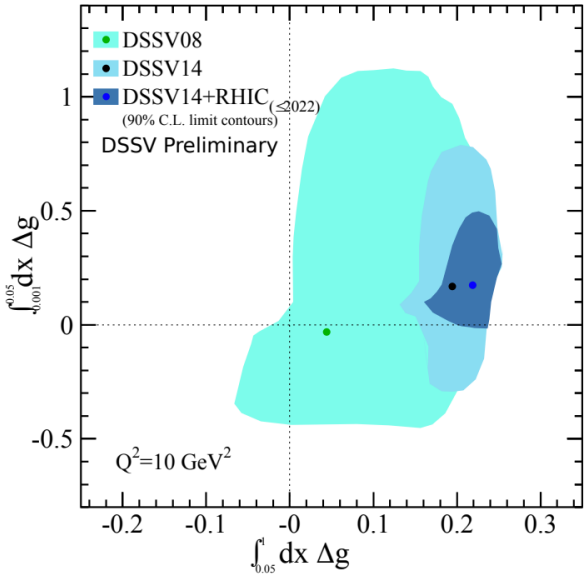
π tagged jet A_{LL}







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

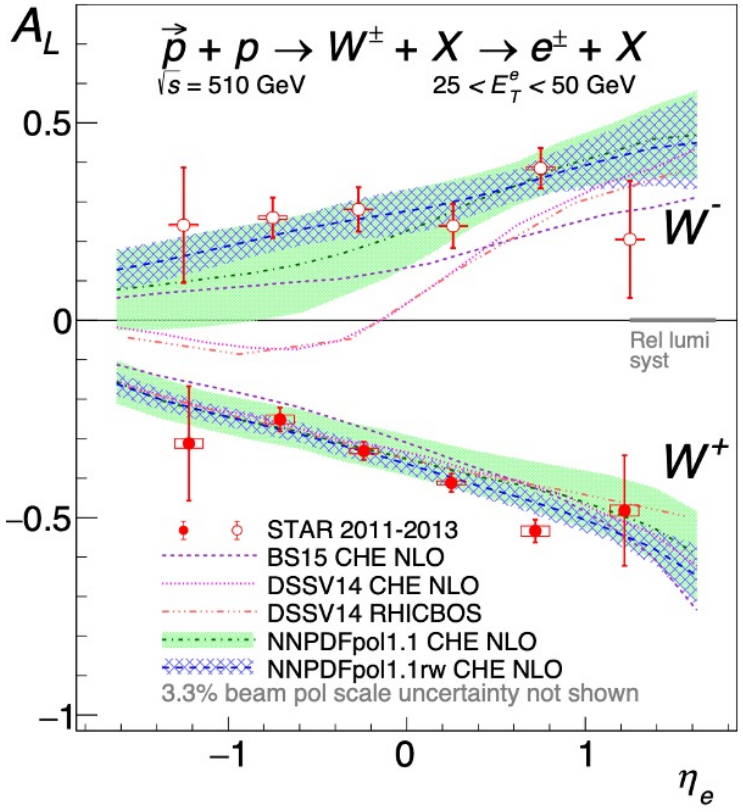


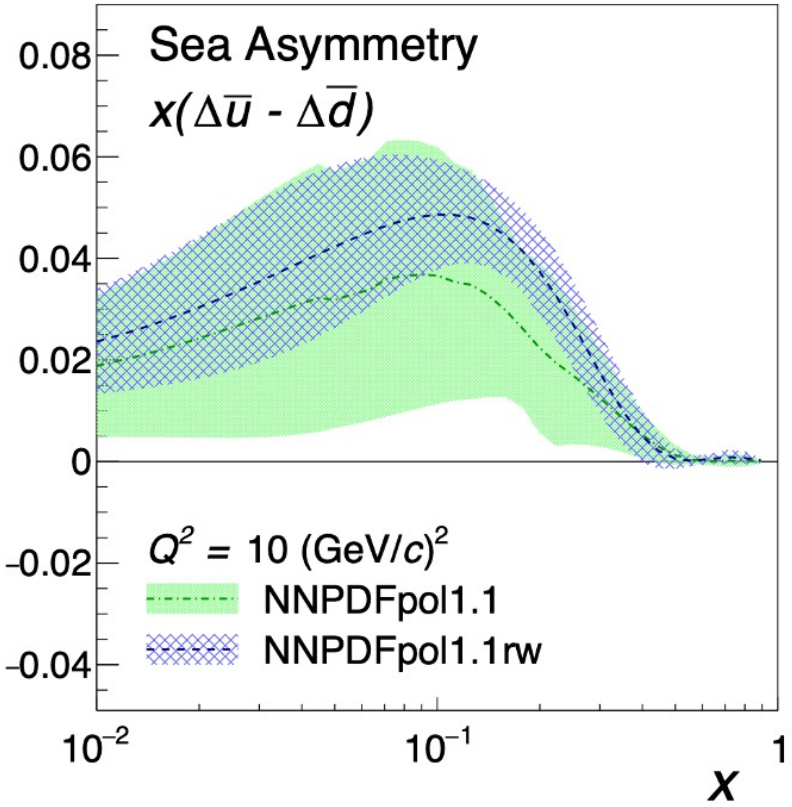
DSSV14 + RHIC (≤2022):

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

Impact of W results

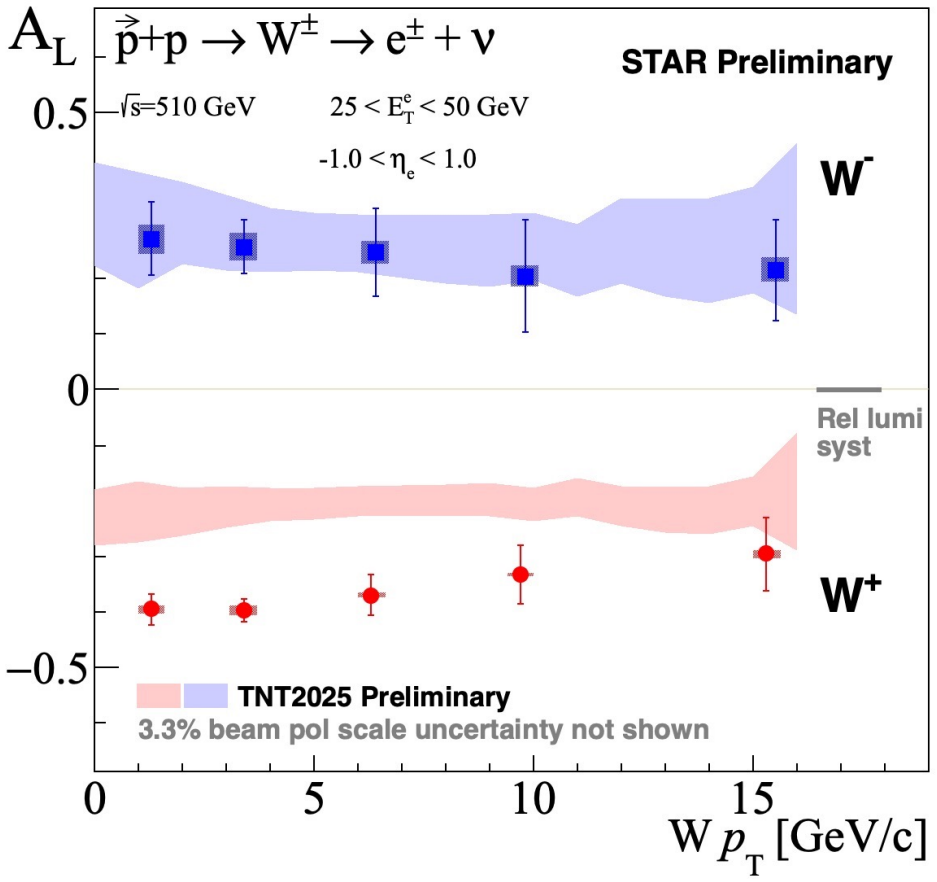
STAR, PRD99, 051102(R) (2019)





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

TMD W AL results

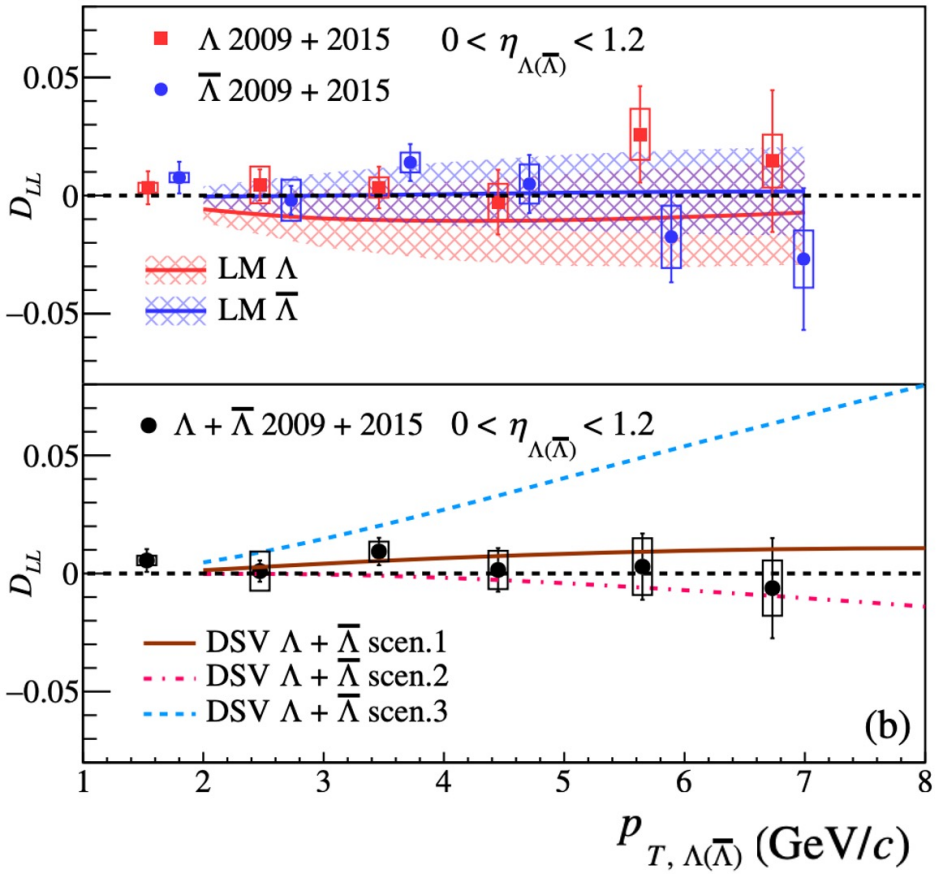


- ✓ TMD $W^{\pm}$ A_L expected to provide unique constraints for TMD helicity distributions.
- ✓ A_L has been extracted as the function of $W^{\pm}$ p_T .
  - As $W^{\pm}$ p_T increases, magnitude of A_L for $W^{\pm}$ decreases slightly.
  - Significant difference between data and TNT2025 predictions, especially for W^+ .

K.Yang et al., PRL 134, 121902 (2025)

Strange quarks polarization via Lambda spin transfer

STAR, PRD109, 012004 (2024)



Spin transfer:

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

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

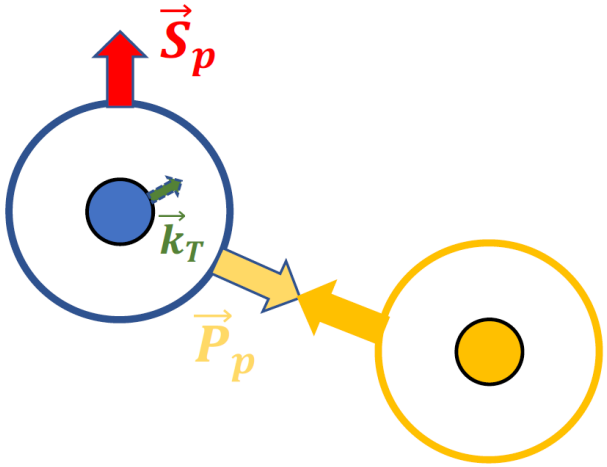
Polarized PDFs *Polarized FFs*

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

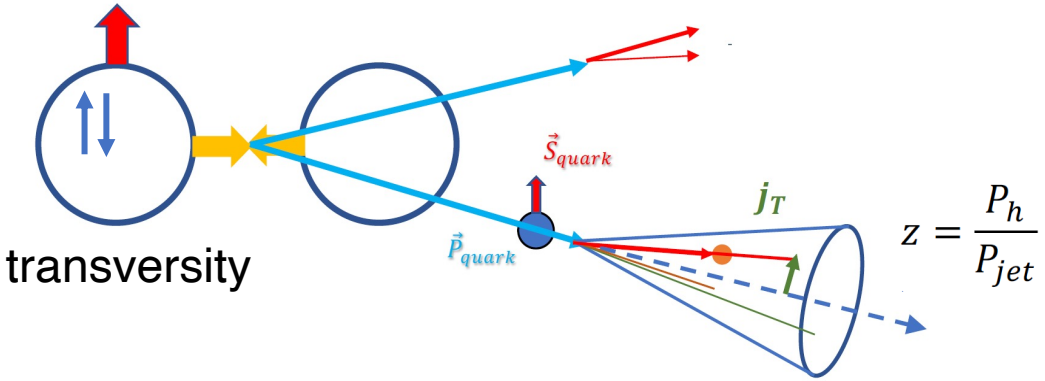
Possible origins of puzzling TSSA

Sivers effect



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

Collins effect

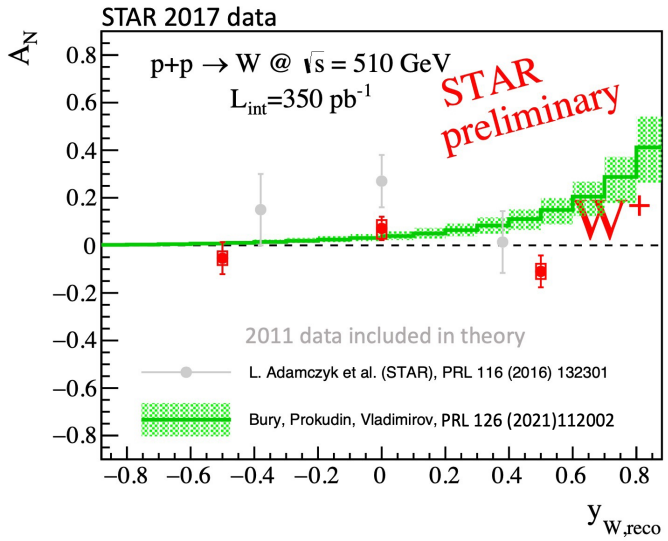


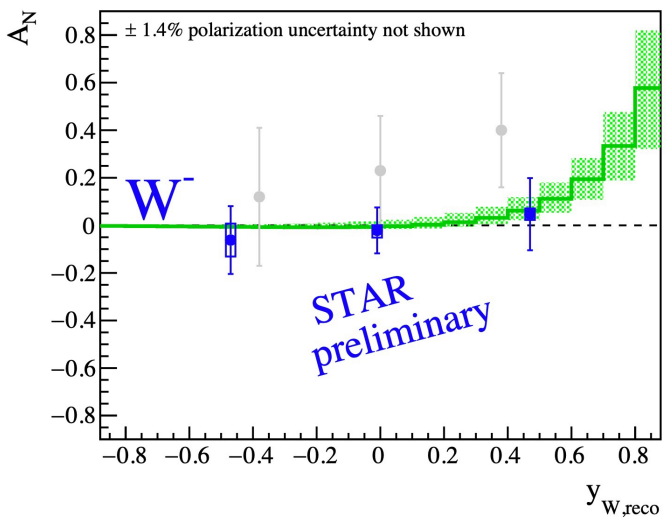
Asymmetry in the fragmentation hadrons: final state effect

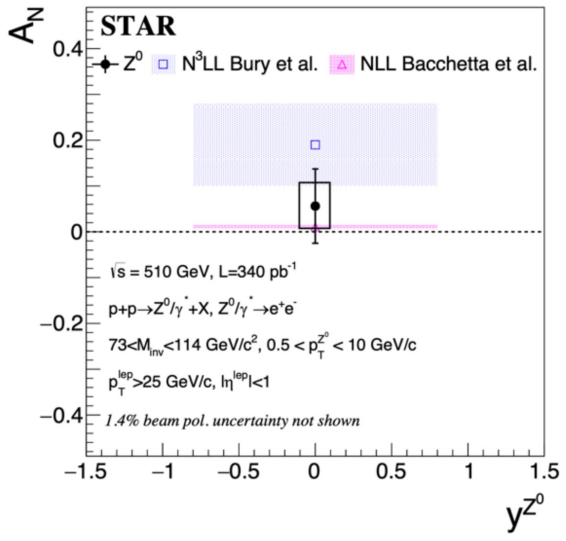
Weak bosons A_N – Sivers

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

PLB 854, 138715 (2024)



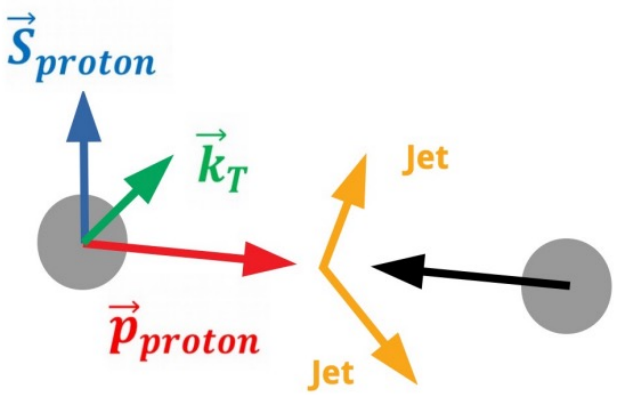


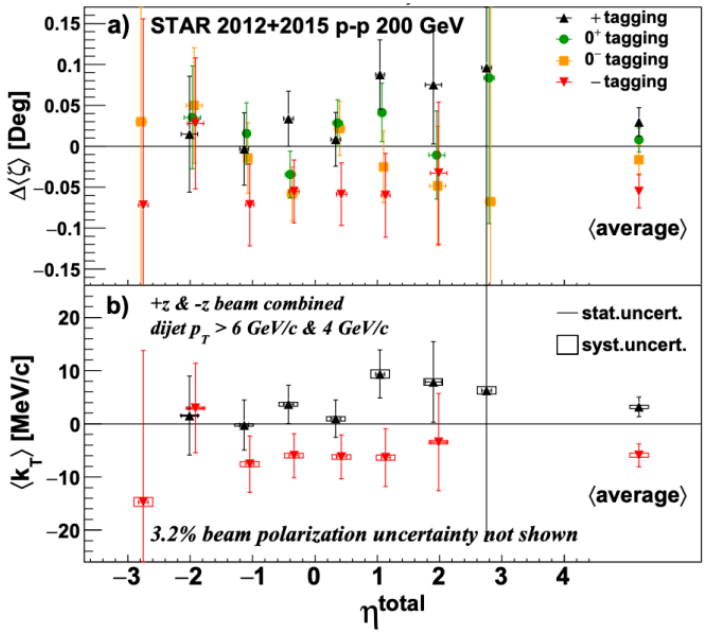


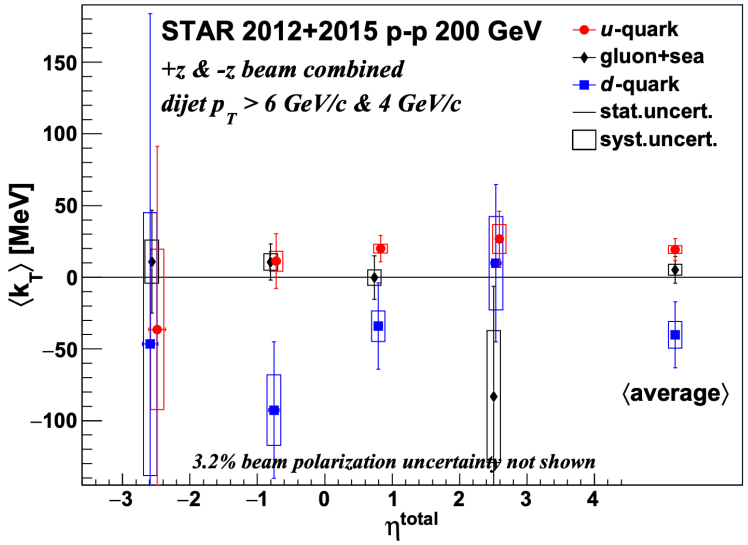
- Theoretical (PRL126,112002): extraction includes SIDIS, DY and 2011 STAR data with N3LO and NNLO accuracy of the TMD evolution *assuming sign-change*
- STAR preliminary with 2017 data with much improved precision, expect big impact in Sivers function at high-x in next global TMD fit

Dijet A_N – Sivers

arXiv: 2305.10359 (accepted by PRD Letter)



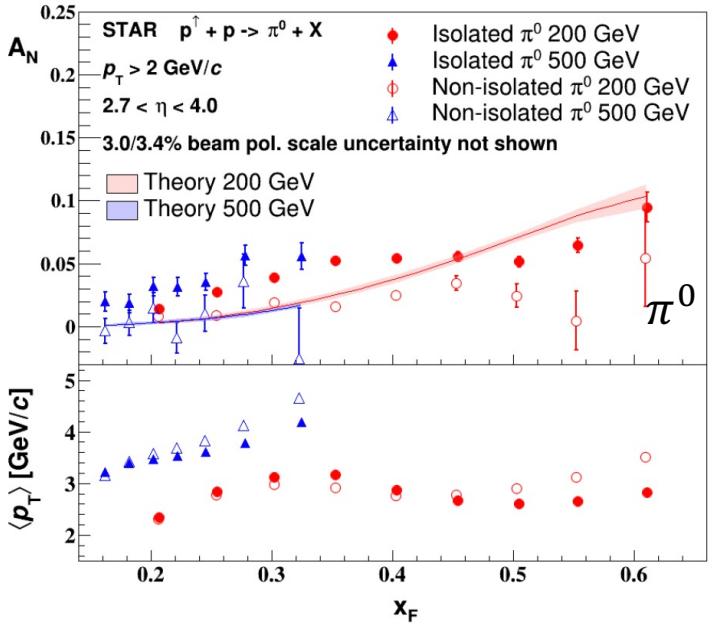


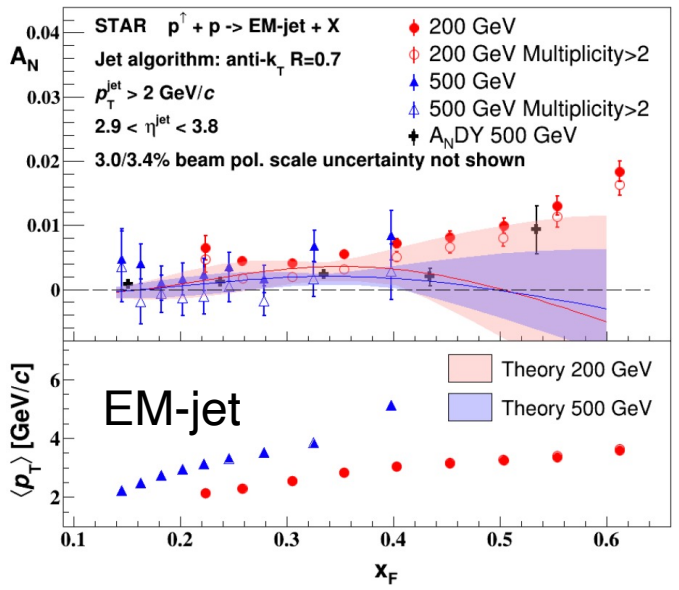


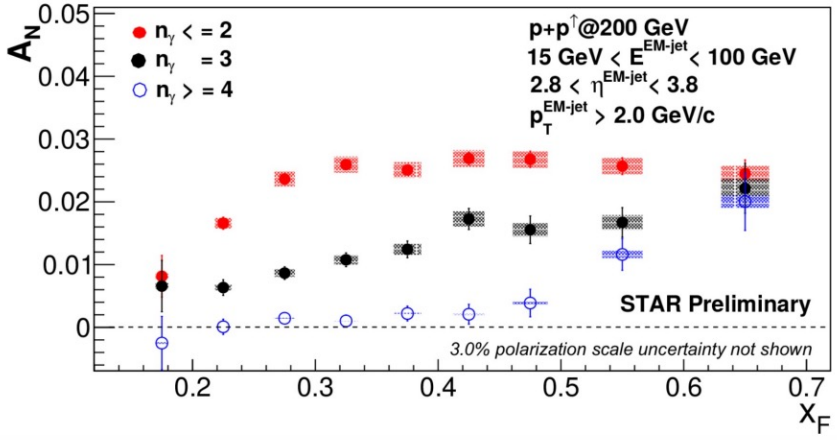
- Spin-dependent dijet opening angle sensitive to Sivers
- First observation of non-zero Sivers asymmetries in dijet production in polarized *p+p* collisions

Forward A_N π^0, EM-jet

STAR, PRD 103, 092009 (2021)



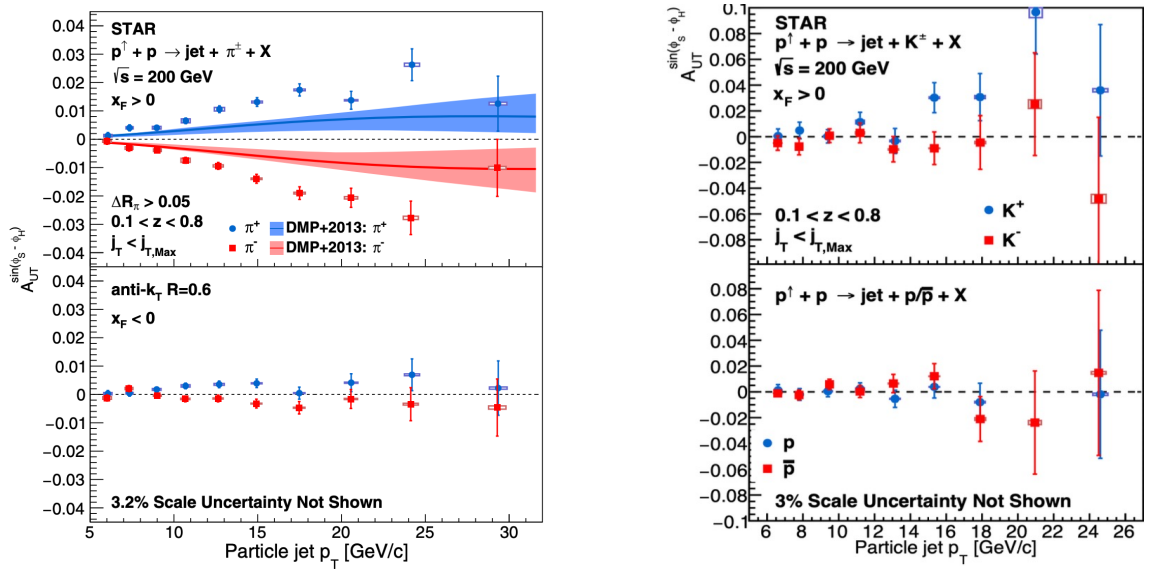




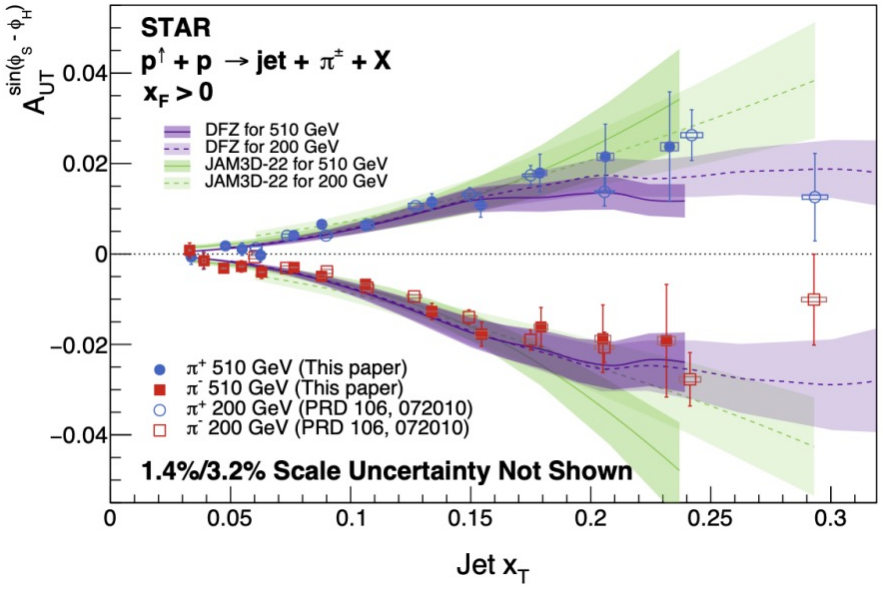
- A_N with forward EM-jets and π^0 in 200/500 GeV pp collisions
- Decreasing A_N as ”jet-ness” increasing (high multiplicity)
- Run2022 and 2024: improved statistic for various objects using Forward Upgrades

Hadron in Jet A_N – Transversity + Collins

STAR, PRD 106, 072010 (2022)



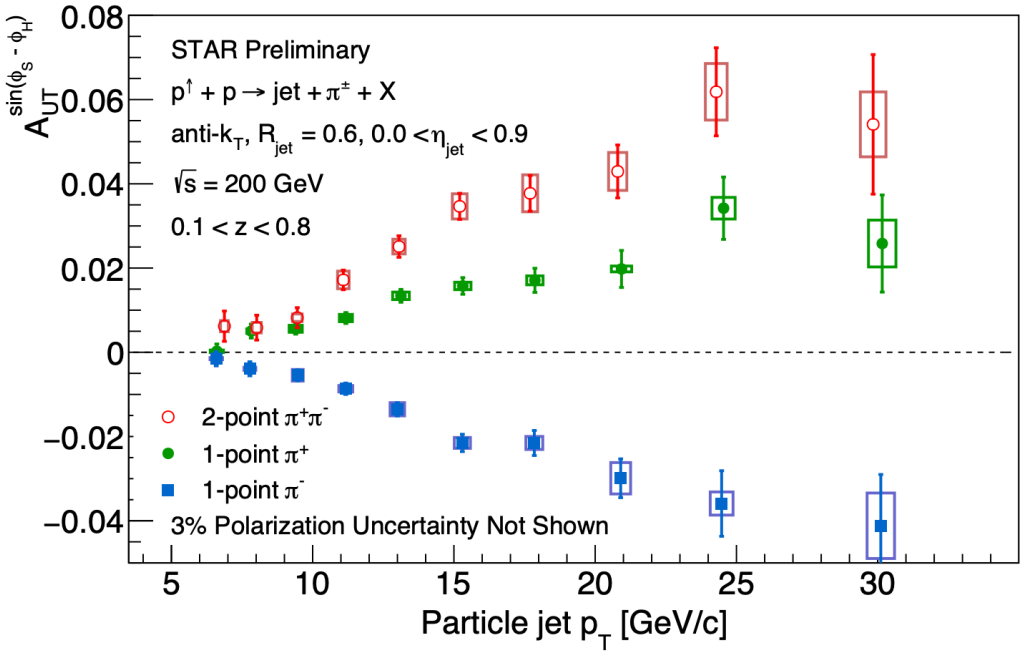
STAR, PRL 135, 261902 (2025)

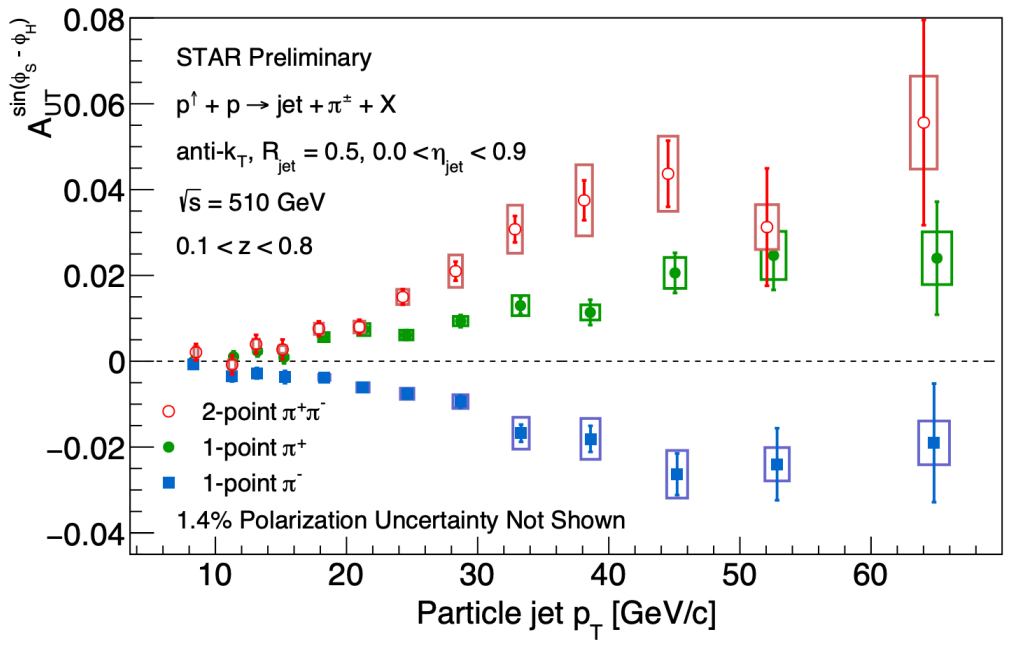


- Significant Collins asymmetries have been observed in 200 and 500 GeV
- New results show weak energy dependence and provide important constraints on the scale evolution for Collins asymmetry

Energy correlators within Jets

STAR, SPIN2025

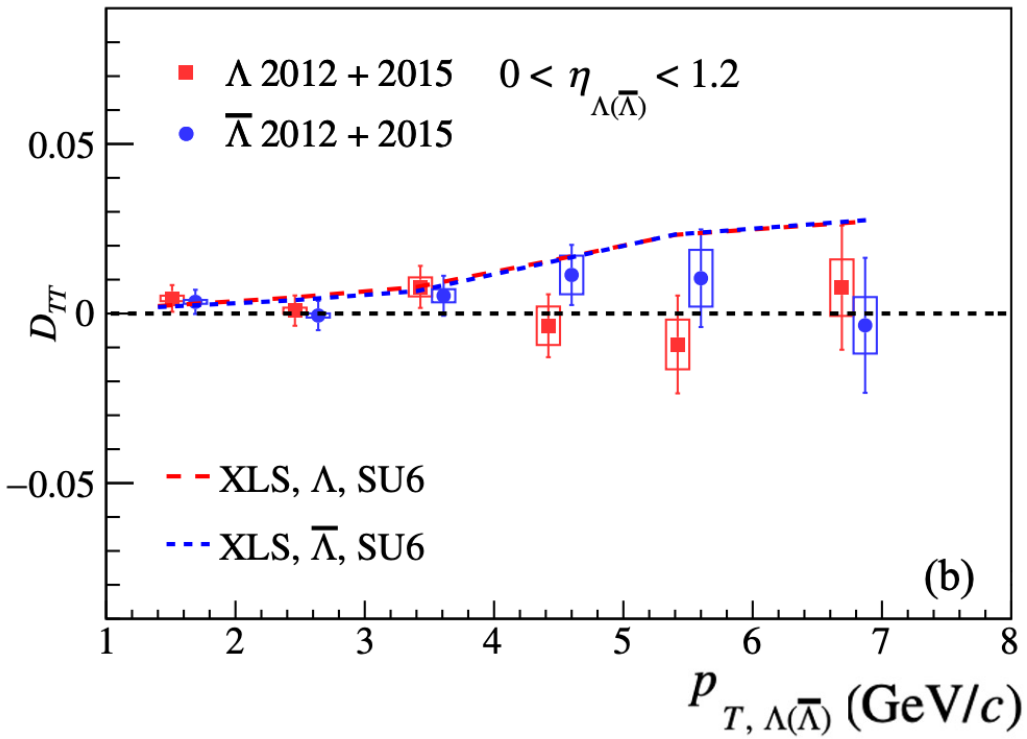




- Significant asymmetries and jet p_T dependence observed for one- and two-point EEC
- Establishes EECs as new observables for transverse spin physics

Lambda transverse spin transfer – Transversity + FFs

STAR, PRD109, 012004 (2024)



The results are consistent with model calculations within uncertainties.

Transverse spin transfer:

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

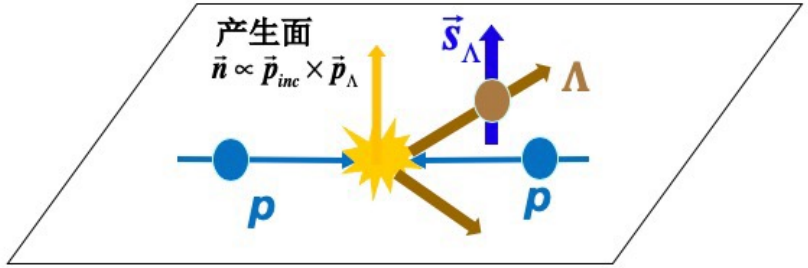
$$d\delta\sigma^{\Lambda} = \sum_{abcd}\int dx_a\, dx_b dz \underbrace{\delta f_a(x_a)}_{\text{Transversity PDF}} f_b(x_b) \underbrace{\delta\sigma^{(a^{\uparrow}b\to c^{\uparrow}d)}}_{\text{Transversity FF}} \delta D_c^{\Lambda}(z)$$

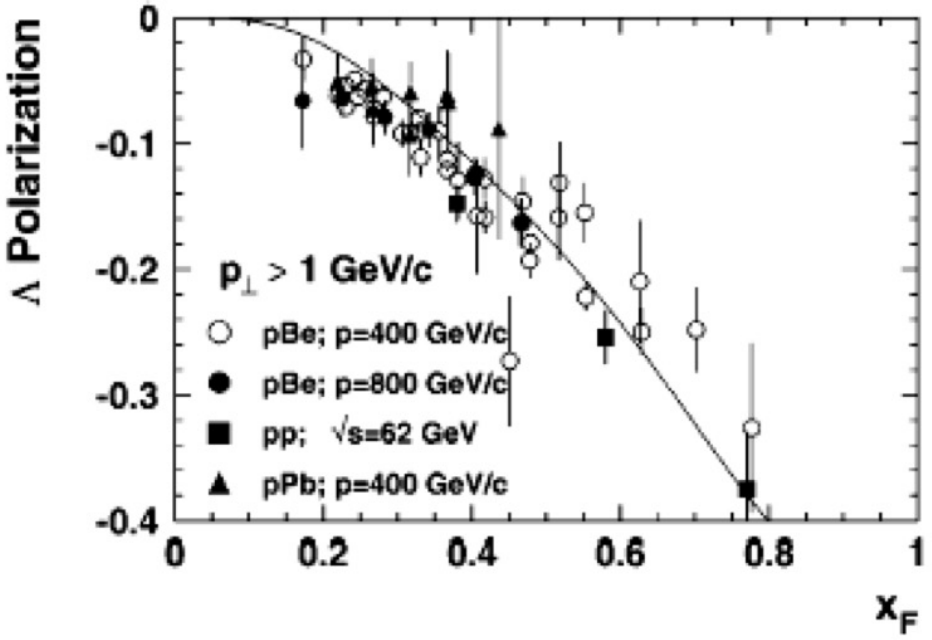
Access transversity fragmentation functions (FF) and transversity distributions (PDF) of strange quarks

- 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

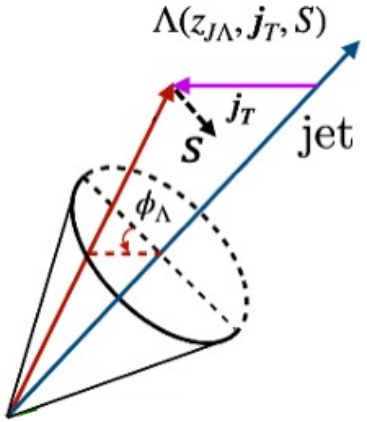




Liang and Boros, PRL79, 3608 (1997)

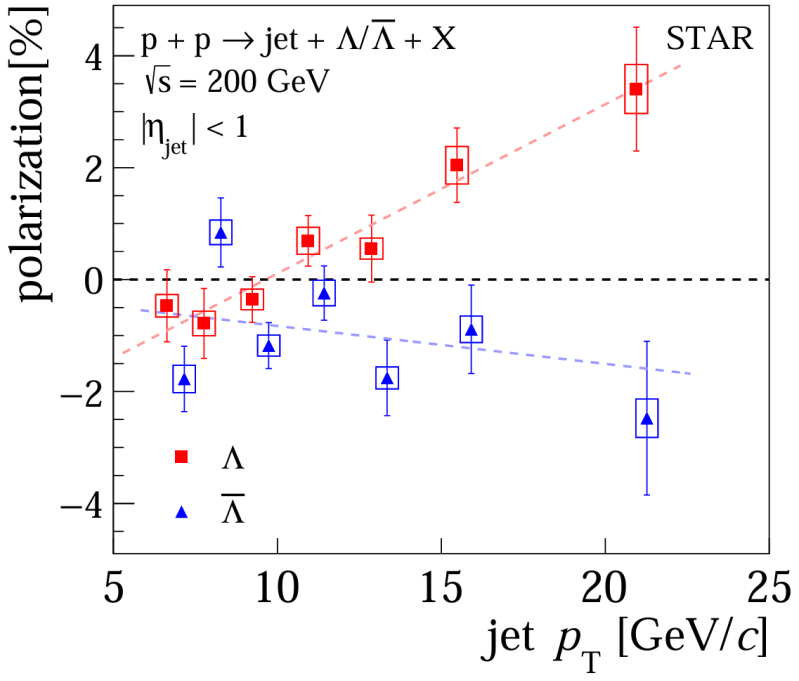
- Lambda transverse polarization is significant, while anti-lambda is not;
- Clear x_F and p_T dependence, while almost independent on energy;
- Weak target-mass dependence: pA ≈ pp, parton level reaction.

Polarization of Lambda-in-jet

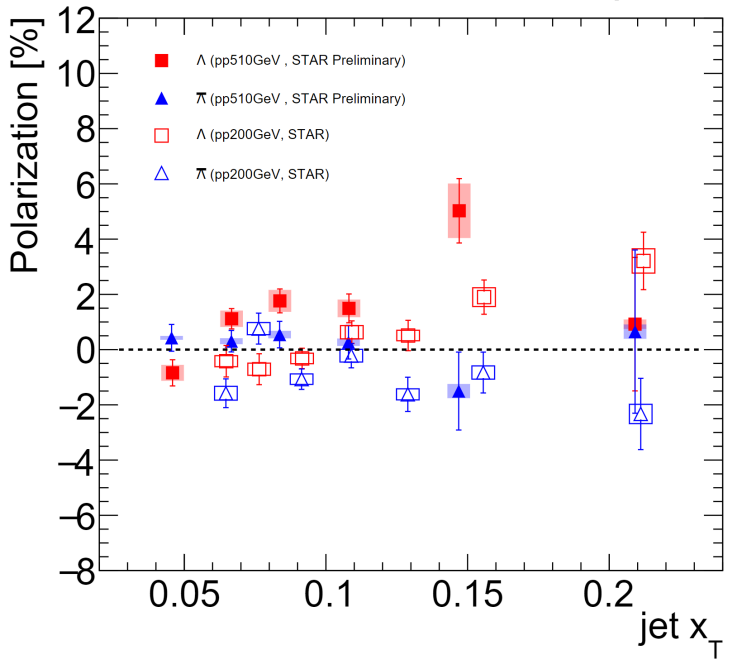


$\hat{S} = \hat{p}_{jet} \times \hat{p}_\Lambda$

arXiv:2509.17487



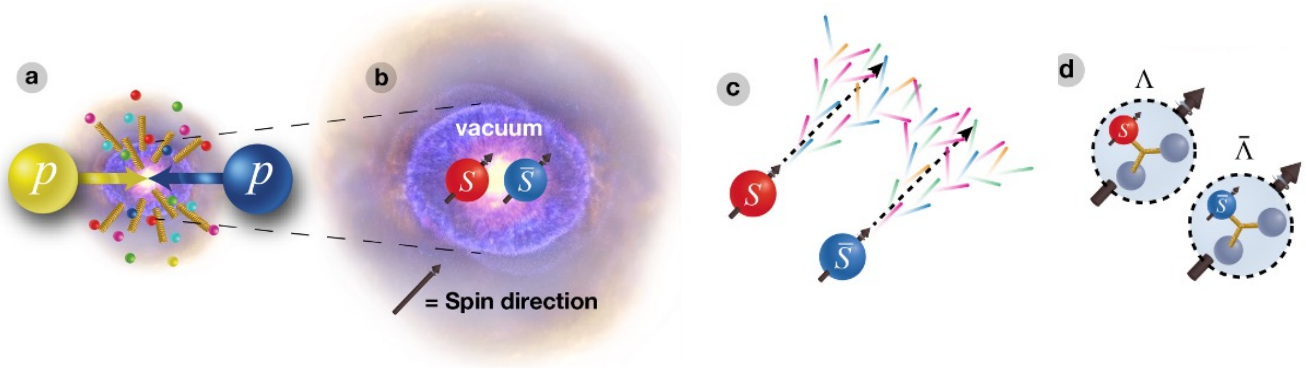
STAR, SPIN2025



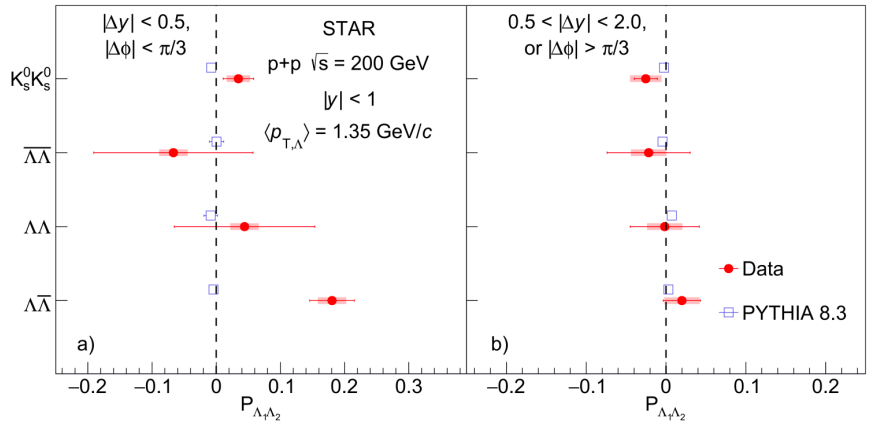
Probing polarizing FFs via polarization of Lambda-in-jet

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

Spin correlations in pp 200 GeV



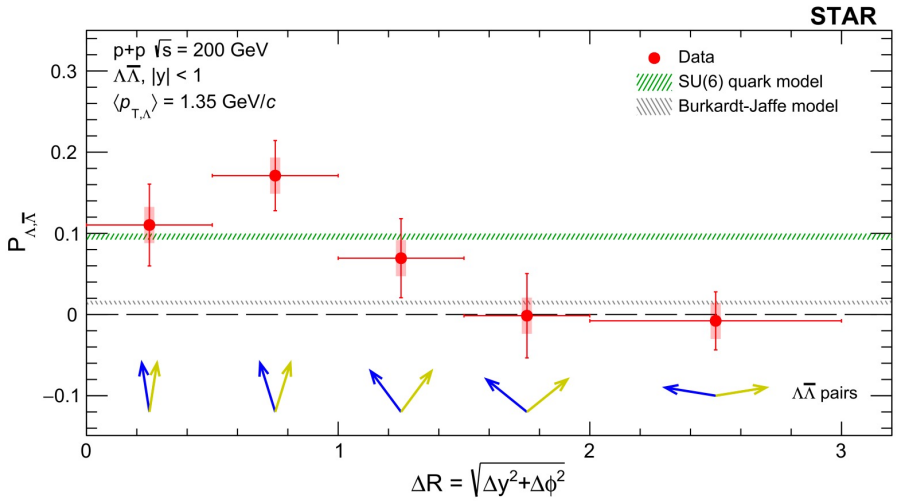
STAR, Nature 650, 65–71 (2026)



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.

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

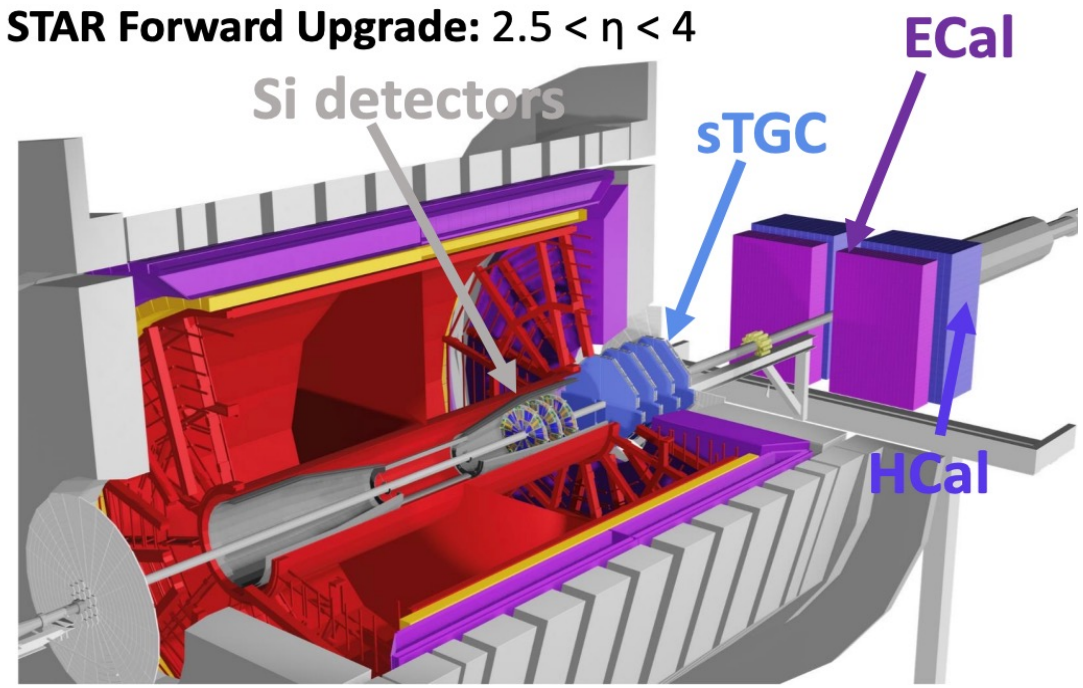
A: normalization, B: $\alpha_1\alpha_2 P_{\Lambda 1\Lambda 2}$



Short-range Long-range

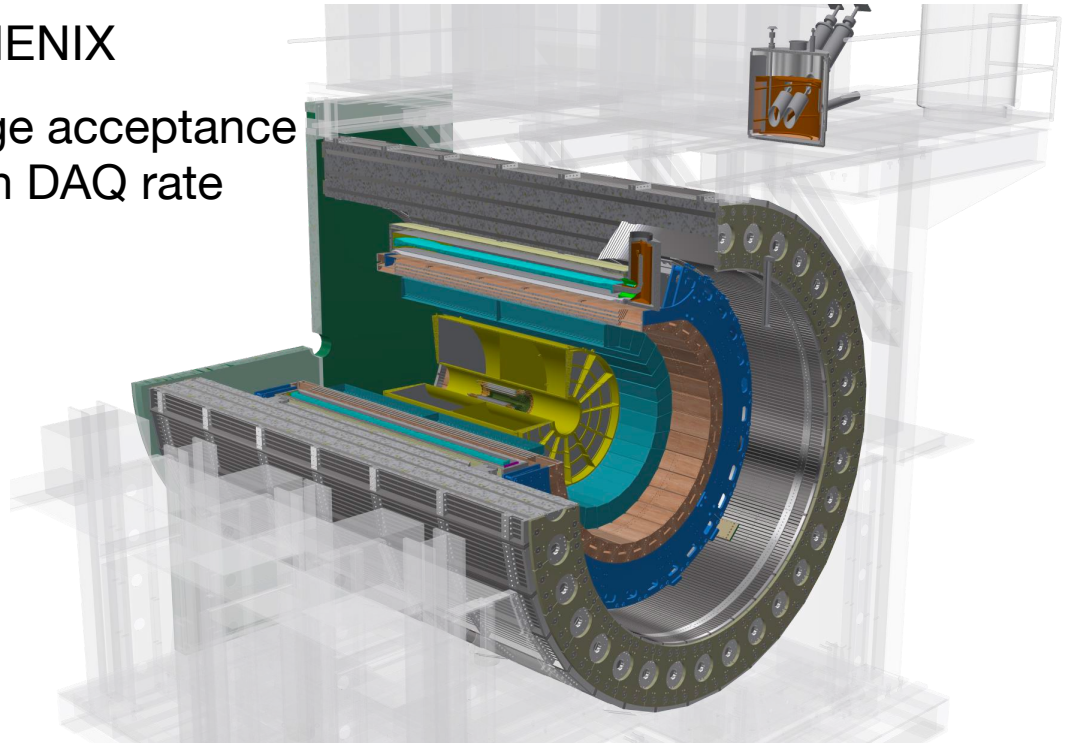
- Short-range $\Lambda\bar{\Lambda}$ pairs show non-zero spin correlation
- All other pairs are consistent with zero

STAR forward upgrade and new sPHENIX



sPHENIX

Large acceptance
High DAQ rate



- Successful RHIC spin run with STAR forward upgrades(2022/24) and new sPHENIX detector (2024).

RHIC spin: lasting contributions

Accelerator Capability

Enables precision spin control in a collider environment
– Siberian snakes, spin rotators, polarimetry

Analysis & Methodology

Establishes precision spin measurement techniques
– spin asymmetries at 10^{-3} level
– robust control of systematics

Physics Insights

Provides unique constraints on QCD spin
– gluon and sea quark helicity
– large transverse spin phenomena
– spin-dependent fragmentation and correlations

Summary

RHIC operation completed, transitioning to the construction of the US EIC

RHIC has made significant contributions to key aspects of QCD spin physics

Substantial physics potential remains in the existing data, with ongoing and future analyses

RHIC provides both essential physics insights and the technical and methodological foundation for the future Electron–Ion Collider

Thank you for your attention!