Recent TMD measurements at STAR and the connection to EIC

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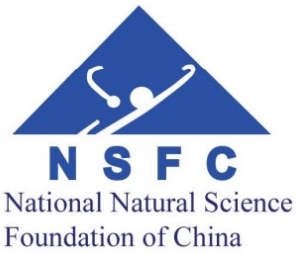
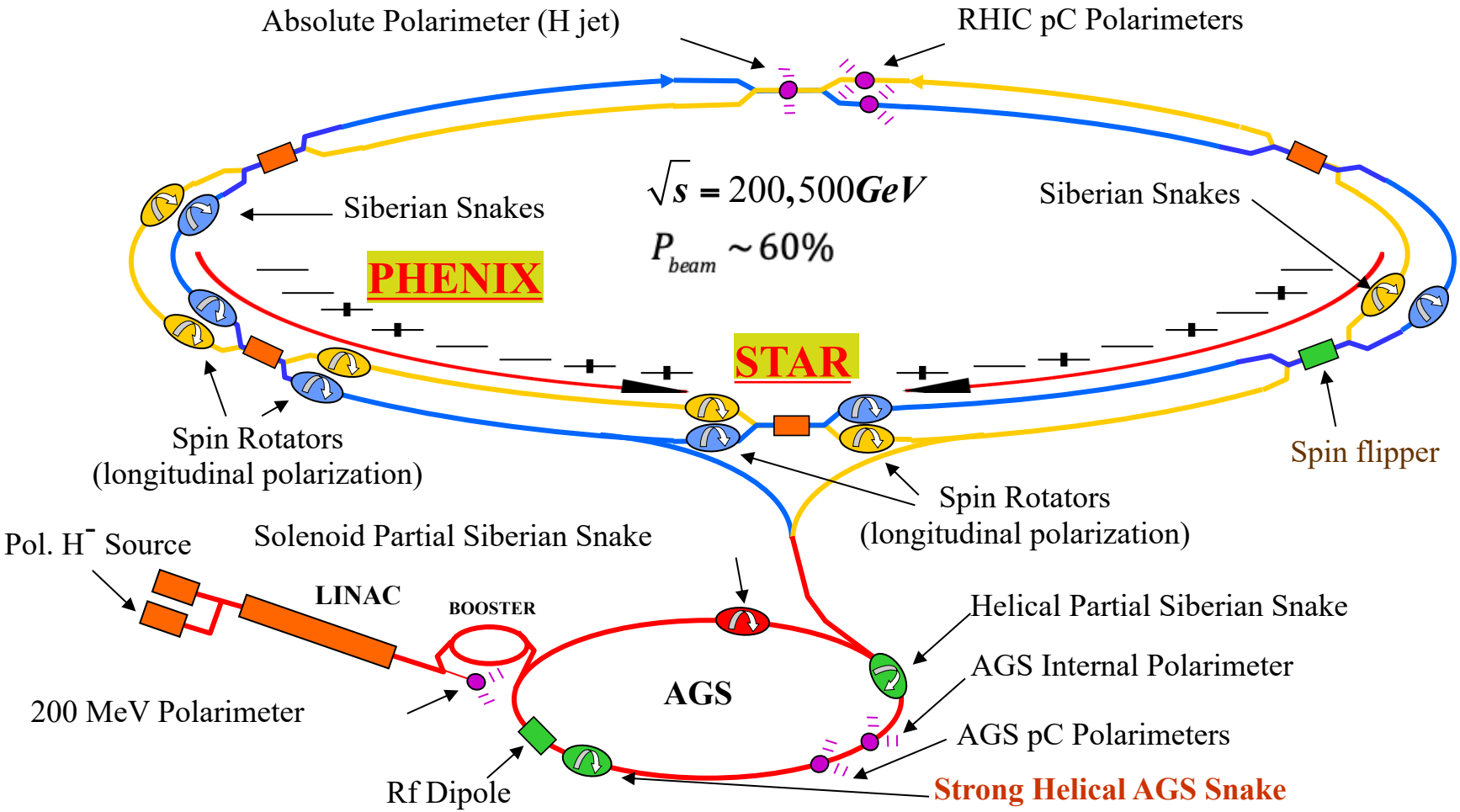


Outline

- Introduction
- Overview of TMD measurement from STAR :
  - ✓ Transverse spin asymmetry (W/Z, jet): Sivers function
  - ✓ Transverse spin asymmetry (Hadron in jet, IFF): Collins & transversity
  - ✓ Hyperon polarization (Λ): strange quark polarization & pol. FF
- Summary & Outlook

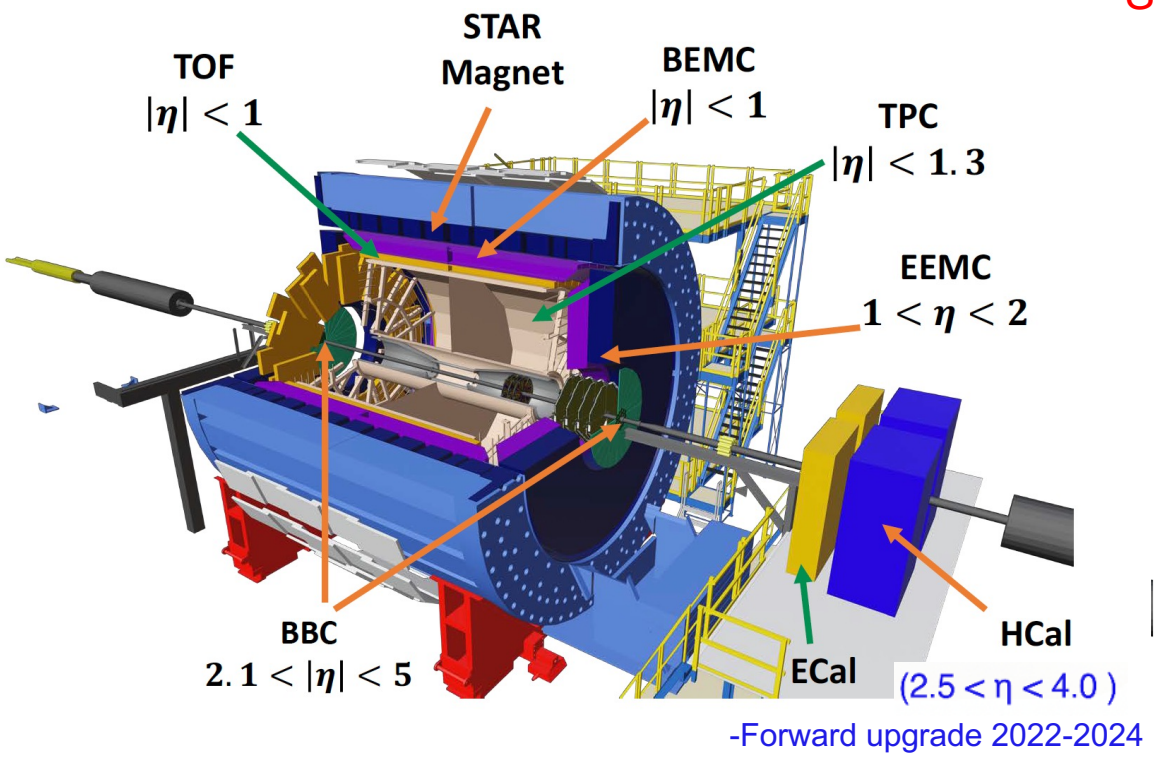
RHIC- 1st polarized proton-proton collider



- Polarized p+p collision at √s=200, 500/510 GeV since 2003, longitudinal or transverse
- Two main experiments: PHENIX (sPHENIX) & STAR

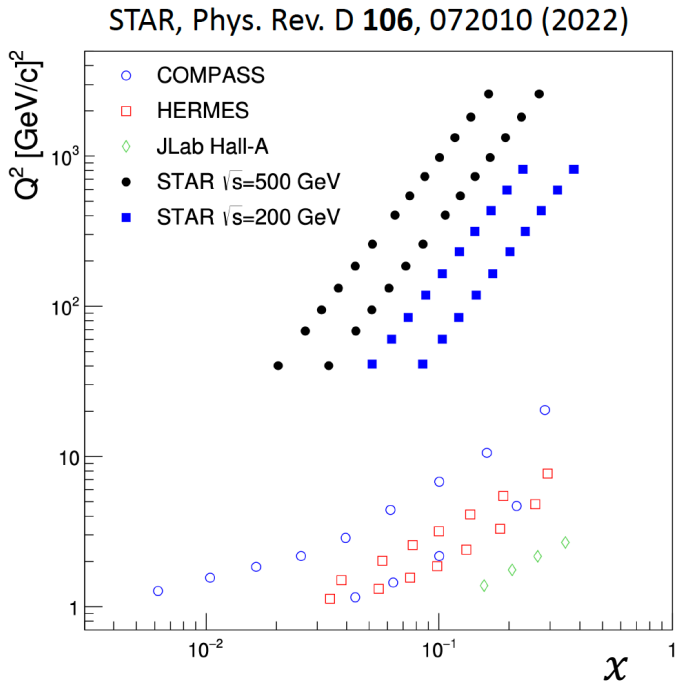
STAR - Solenoid Tracker At RHIC

- STAR detector:



-Forward upgrade 2022-2024

Similar x coverage, but at higher Q when compared to SIDIS



- Recent pp data with transverse polarization:

Year	2011	2012	2015	2017	2022*	2024*
$\sqrt{s}$ (GeV)	500	200	200	510	510	200
L_{int} (pb^{-1})	25	22	52	320	430	160
Polarization	53%	57%	57%	55%	51%	55%

* Data taken with forward upgrade

Transverse Single-Spin Asymmetry (TSSA)

- Anomalously large A_N in pp collisions observed for nearly 40 years

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

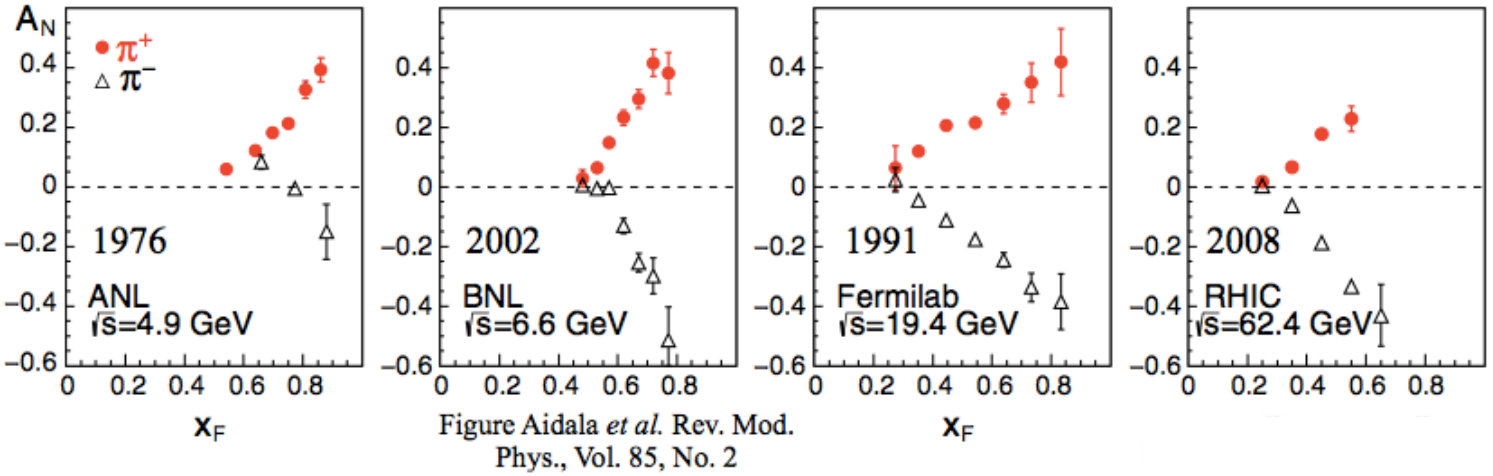


Figure Aidala *et al.* Rev. Mod. Phys., Vol. 85, No. 2

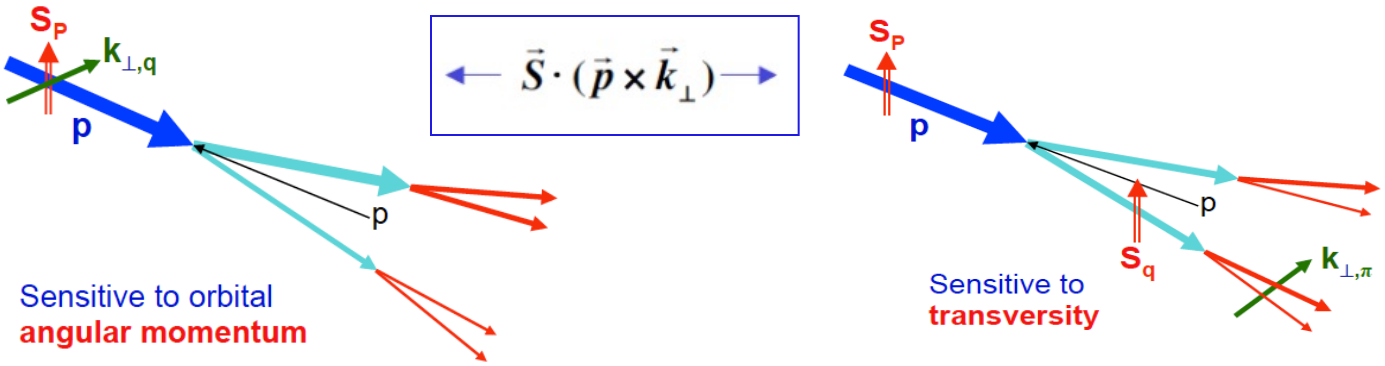
- LO pQCD predicts $A_N \sim 0$

  G. Kane, J. Pumplin, W. Repko, Phys. Rev. Lett 41,1689 (1978)

- Stable in different C.M. energies
- Interpreted by the twist-3 and transverse-momentum-dependent (TMD) formalisms

Mechanisms for transverse spin asymmetries

- Two QCD-based frameworks:
  - Transverse Momentum Dependent (TMD) parton distribution or fragmentation functions. Need two scales (Q and p_T), $Q>>p_T$
    - Sivers effect (*Sivers'90*): parton spin and $k_\perp$ correlation in initial state (related to orbital angular momentum)
    - Collins effect (*Collins'93*): quark spin and k_T correlation in fragmentation process (related to transversity)



  - Twist-3 mechanism (*Efremov-Teryaev'82, Qiu-Sterman'91*):

    Collinear/twist-3 quark-gluon correlation + fragmentation function

    Need one scale (Q or p_T), Q, $p_T>>\Lambda_{QCD}$

  - Both mechanisms apply when **$Q>>p_T>>\Lambda_{QCD}$**

Ji-Qiu-Vogelsang-Yuan,2006

TMD distributions: PDF and FF

- Transverse momentum dependent distribution (TMD) parton distribution function (PDF) and fragmentation functions (FF):

Leading Quark TMDPDFs — Nucleon Spin, Quark Spin

Nucleon Polarization	Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^\perp$ = Boer-Mulders
L		g_1 = Helicity	$h_{1L}^\perp$ = Worm-gear
T	$f_{1T}^\perp$ = Sivers	$g_{1T}^\perp$ = Worm-gear	h_1 = Transversity; $h_{1T}^\perp$ = Pretzelosity

Leading Quark TMDFFs — Hadron Spin, Quark Spin

	Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons	D_1 = Unpolarized		$H_1^\perp$ = Collins
Polarized Hadrons L		G_1 = Helicity	$H_{1L}^\perp$
Polarized Hadrons T	$D_{1T}^\perp$ = Polarizing FF	$G_{1T}^\perp$	H_1 = Transversity; $H_{1T}^\perp$

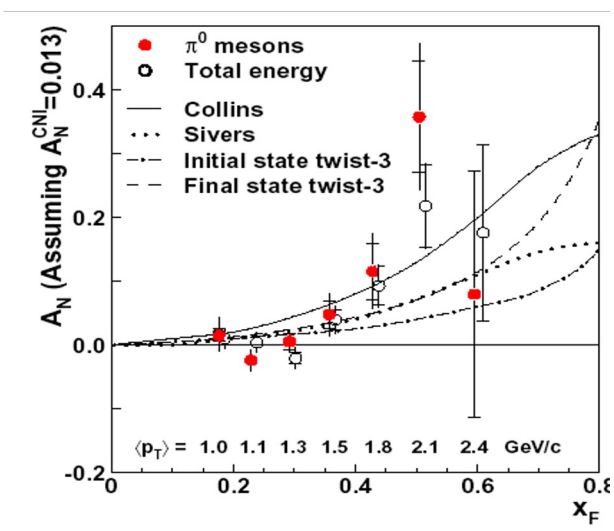
-TMD handbook: ariXiv-2304.03302

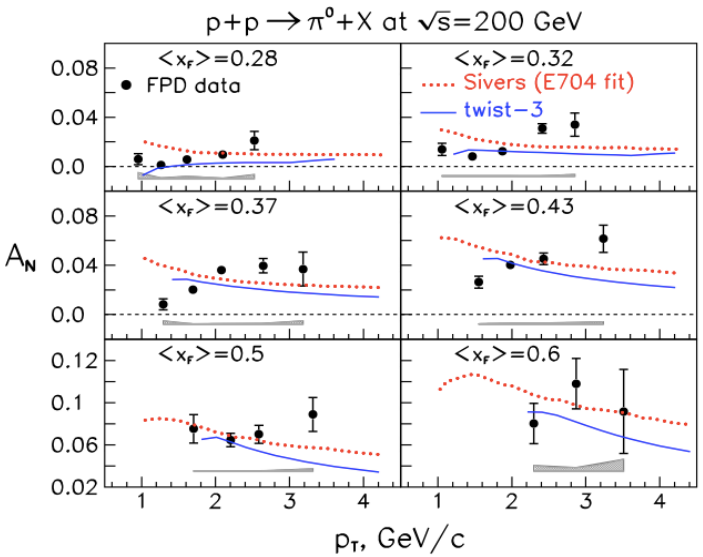
STAR Measurements	Mechanisms
Jet asymmetry, $\langle \boldsymbol{k_T} \rangle$ via dijet, W/Z asymmetry	Sivers function $\boldsymbol{f_{1T}^\perp}$
Hadron in jet asymmetry	Transversity $\boldsymbol{h_1}$ + Collins function $\boldsymbol{H_1^\perp}$
Di-hadron asymmetry	Transversity $\boldsymbol{h_1}$ + IFF $\boldsymbol{H_1^\sphericalangle}$
Hyperon spin transfer	Transversity $\boldsymbol{h_1}$ + Polarized FF $\boldsymbol{H_1}$
$\boldsymbol{\Lambda(\bar{\Lambda})}$ in jet polarization	Polarizing FF $\boldsymbol{D_{1T}^\perp}$

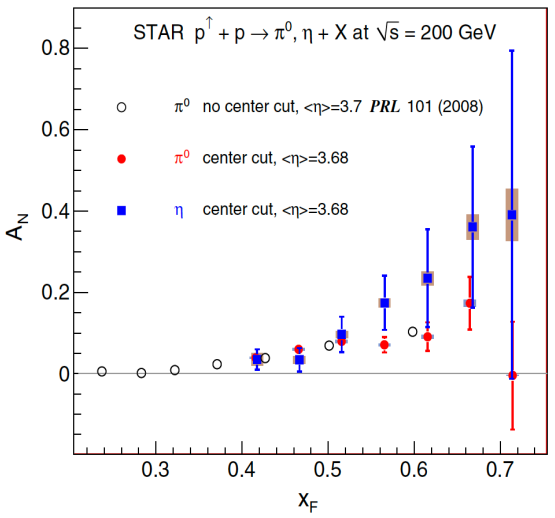
Transverse single spin asymmetries of forward π^0,η

- 1st STAR spin paper is on the TSSA of forward π^0 using FPD, compared with TMD and twist-3 calculations

STAR, PRL**92,** 171801(2004) STAR, PRL**101,** 222001(2008); PRD86, 051101R (2012)



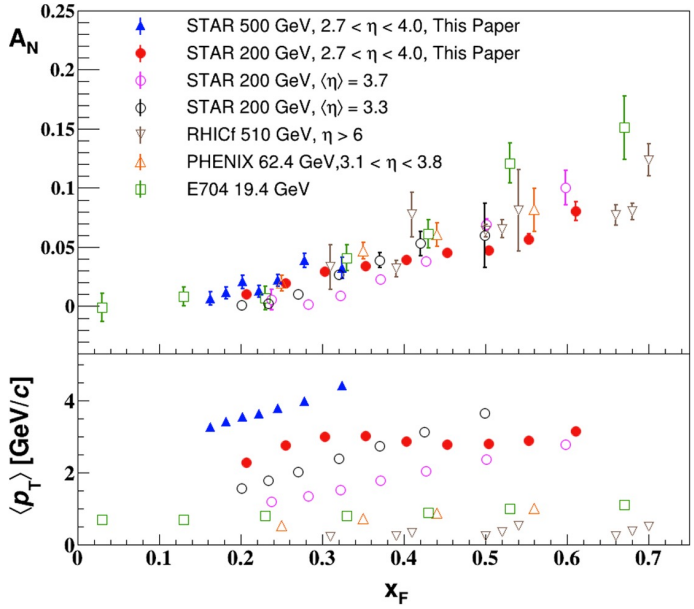


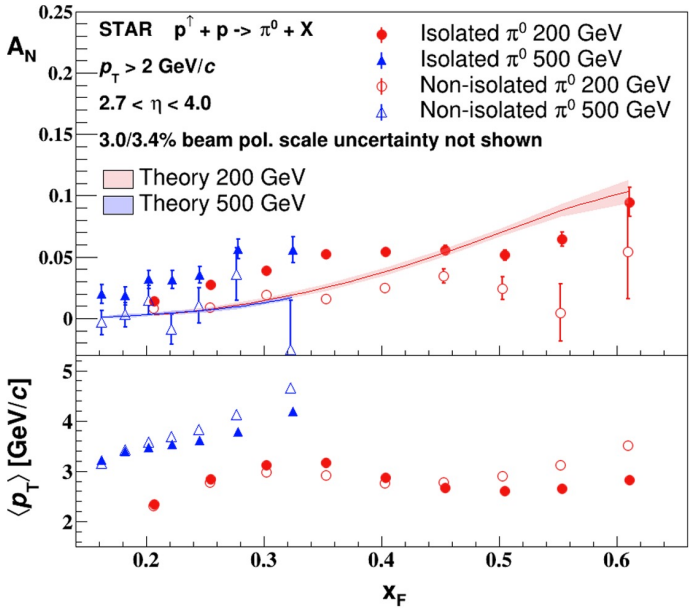


- ✓ A_N increases with x_F, in agreement with QCD model calculation.
- ✓ pQCD based models predicted decreasing A_N with p_T, not consistent with data.

Forward π^0 , EM-jet A_N at STAR

- High precision π^0 A_N from STAR at both 200 and 510 GeV
- Observation of topological dependence of π^0 A_N : isolated π^0 has larger A_N than other π^0 -> diffractive contribution?





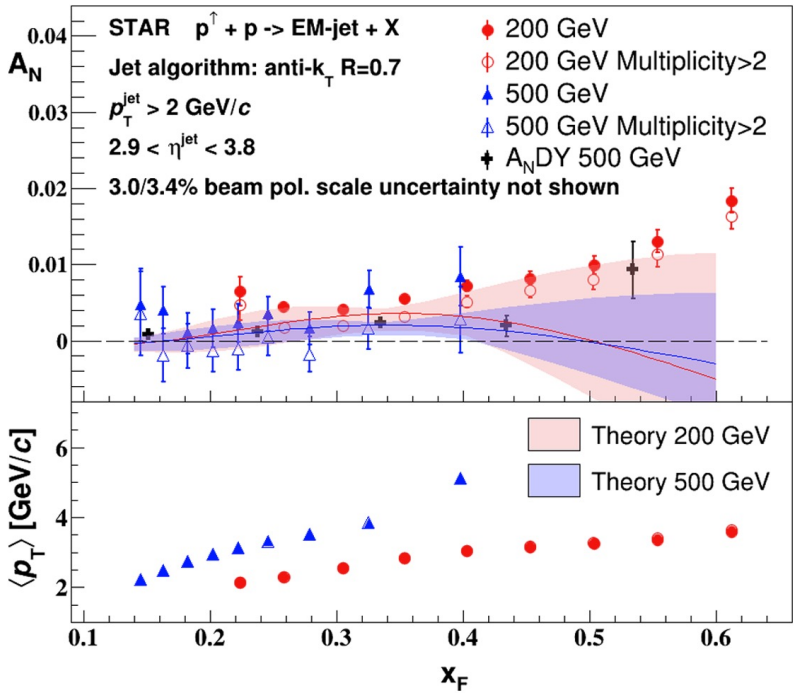
STAR, PRD103, 72005 (2021)
PRD103, 92009 (2021)

- For hadron SSA, both Sivers and Collins effects can contribute.
- Study of jet production can separate Collins & Sivers effects.

Searching A_N origin : EM-jet TSSA

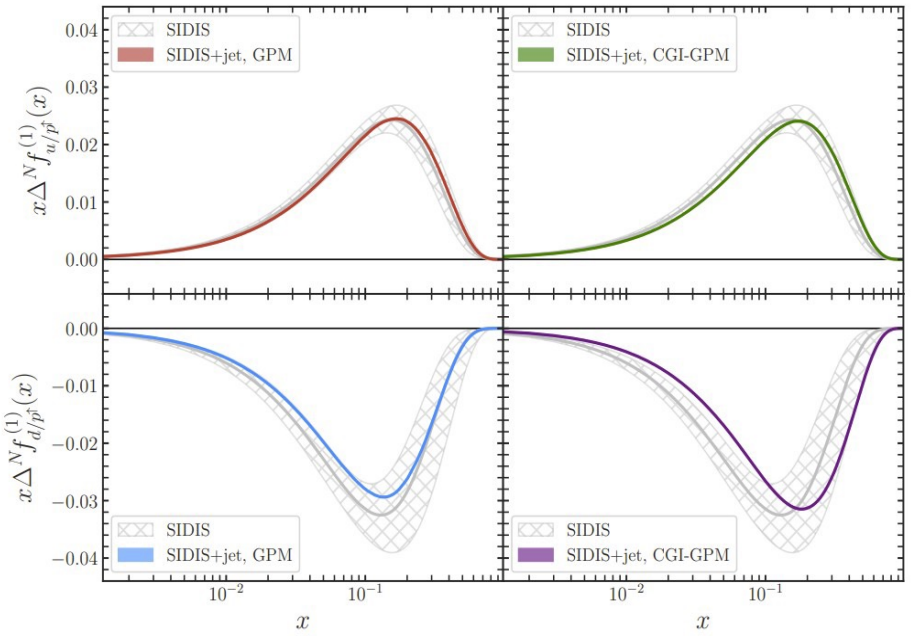
- STAR EM-jet A_N - sensitive to the initial state effect, Sivers effect
- Impact of STAR data in constraining Sivers function via global analysis

STAR, PRD103, 92009 (2021)



*Curve: L. Gamberg, Z. Kang, A. Prokudin, Phys.Rev.Lett.*110,232301 (2013)

M.Boglione, et al., Phys. Lett. B 815 (2021) 136135

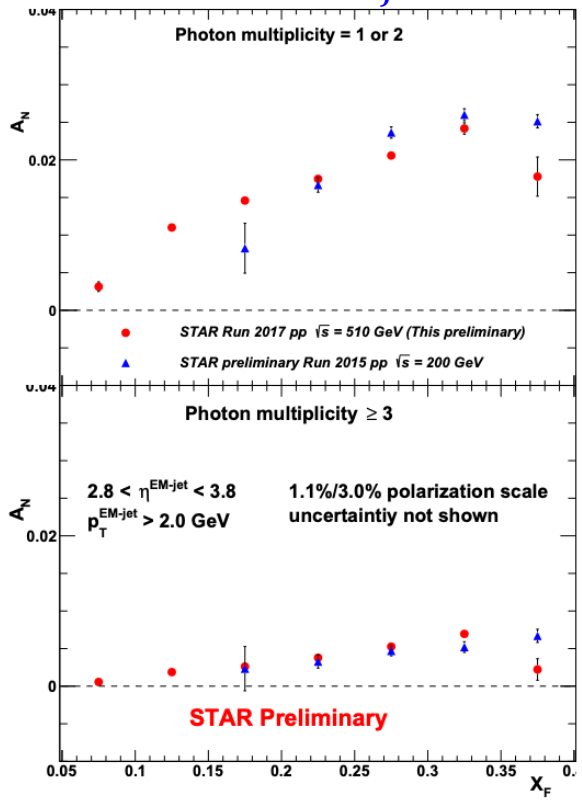


➢ Initial state effect is small

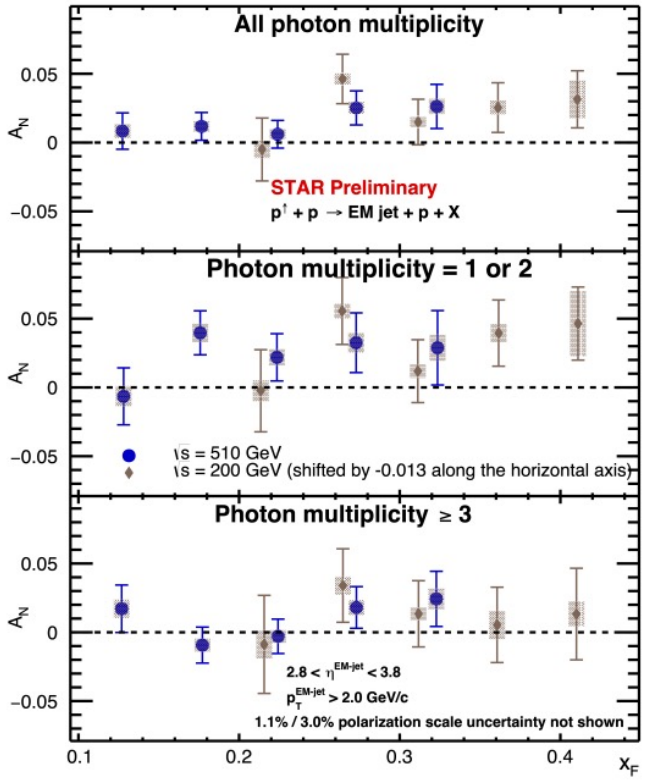
Searching A_N origin: EM-jet & Diffractive process

- Inclusive EM-jet A_N versus photon multiplicity in p+p collision
  - ✓ A_N increases with x_F in general
  - ✓ A_N decreases with photon multiplicity
- Diffractive processes alone cannot account for the large A_N

Inclusive jet



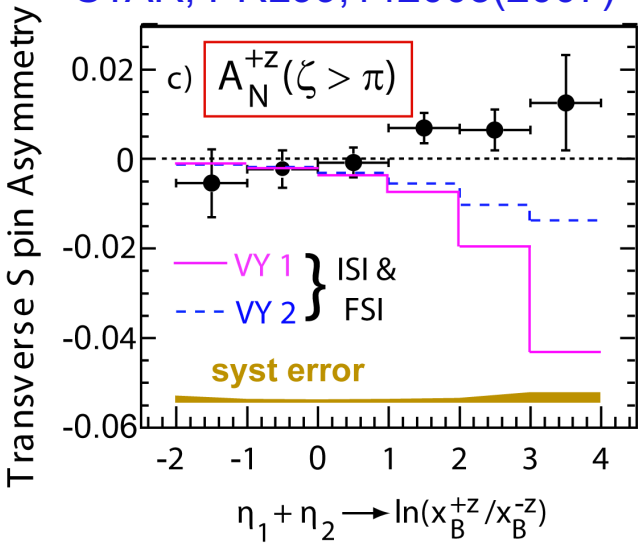
Single Diffractive

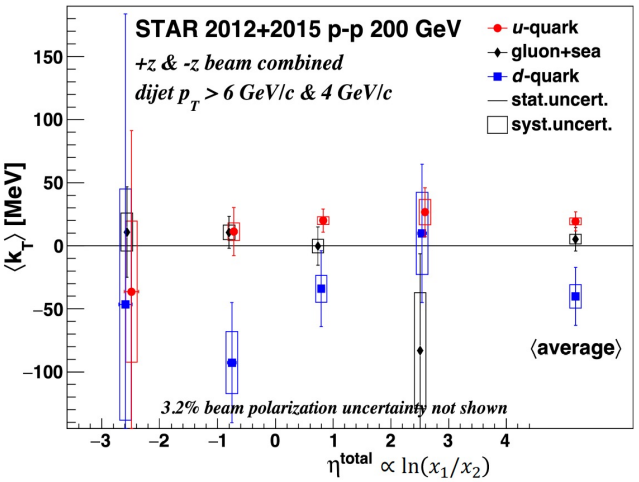


Probing Sivers effect using dijet in p+p

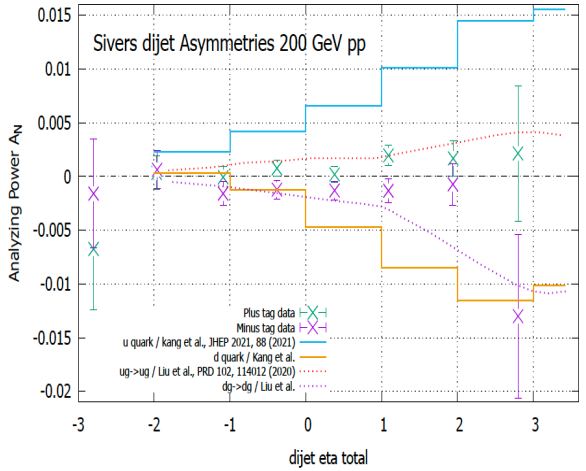
- Intrinsic k_T provides a kick to the back-to-back dijet, folded in the transverse momentum
- Jet charge tagging combined with unfolding to determine the quark flavor.
  Parton fractions from simulation used to extract the individual parton <k_T>

STAR, PRL99,142003(2007)





STAR, arXiv:2305.10359, PRD in press

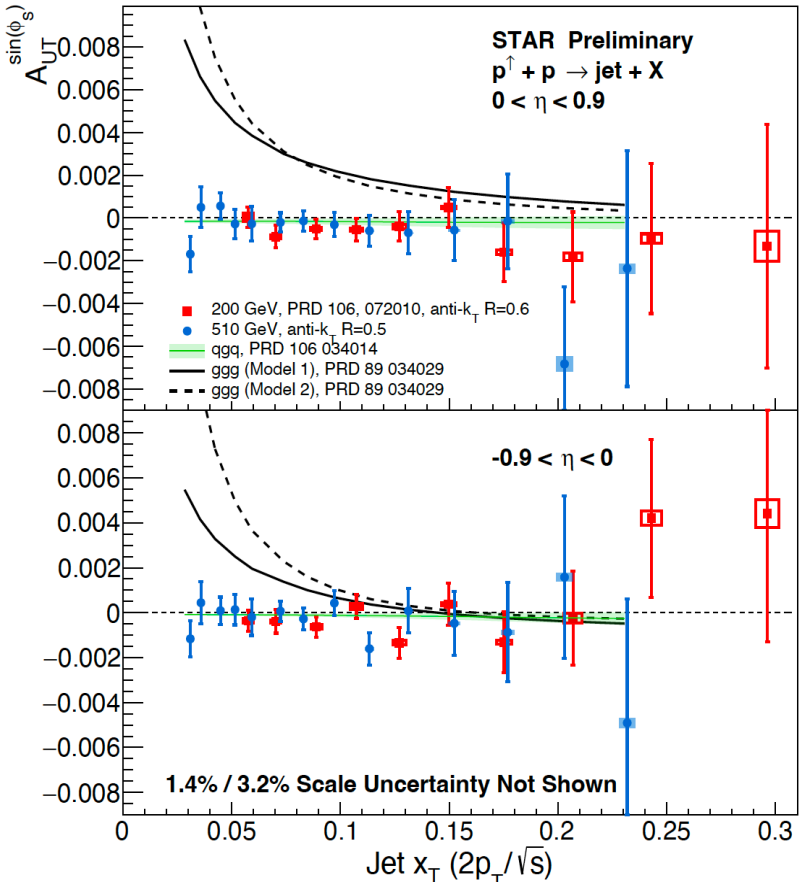


- Results: d-quark $\langle k_T \rangle \approx -2$ u-quark $\langle k_T \rangle$
- For the first time, there is evidence of non-zero Sivers effect

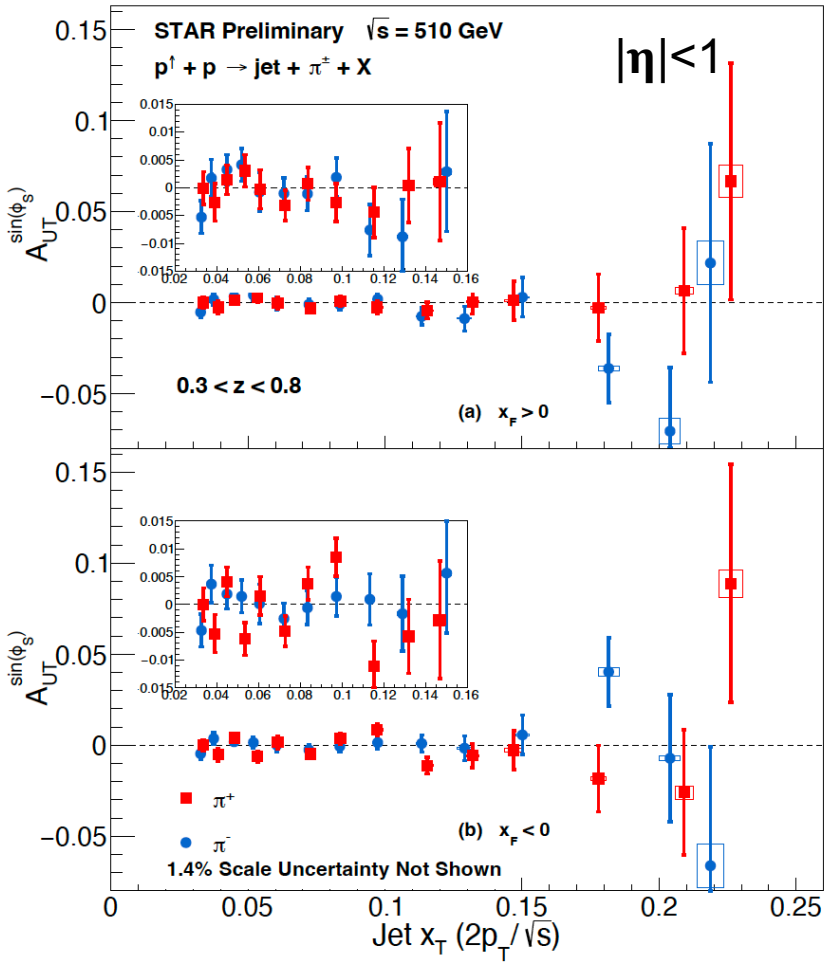
Jet A_N at mid-rapidity in p+p collisions

- A_N for inclusive jet

STAR, PRD106, 072010 (2022)



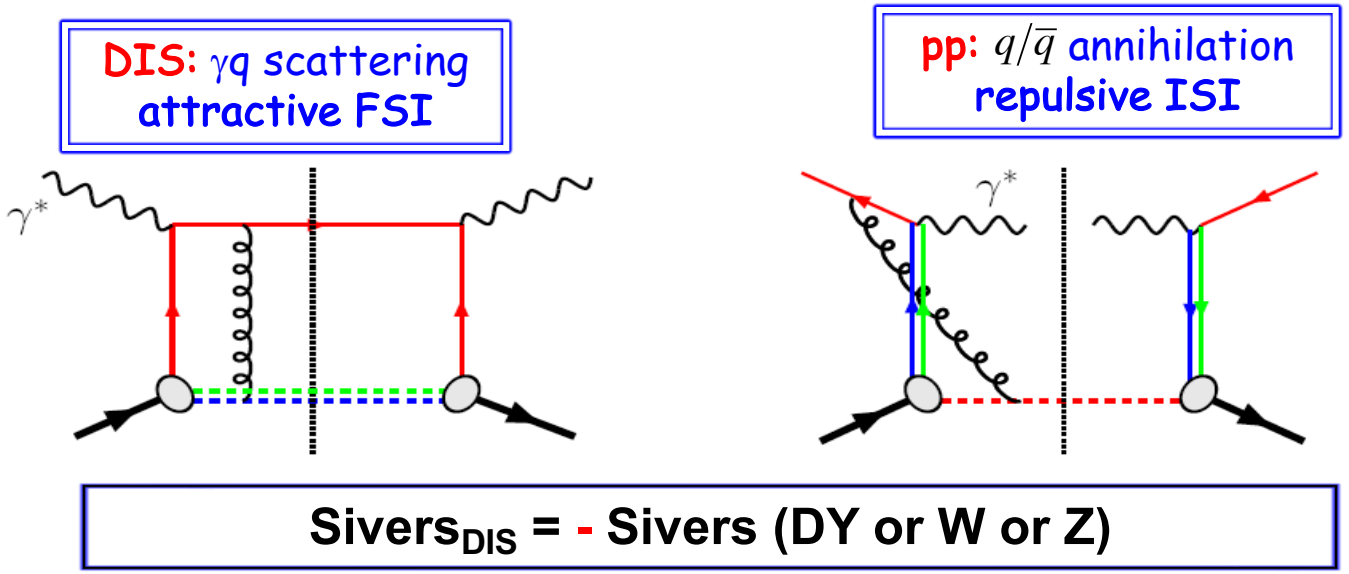
- A_N for $\pi^{\pm}$ tagged inclusive jet



➢ Full jet A_N providing sensitivity to the twist-3 correlators associated with the gluon and quark Sivers function

Transverse single spin asymmetry (A_N) of W boson

- Sivers sign change in DIS and DY/W/Z process:



$Sivers_{DIS}$ = - Sivers (DY or W or Z)

➢ Critical test for our understanding of TMD's and TMD factorization

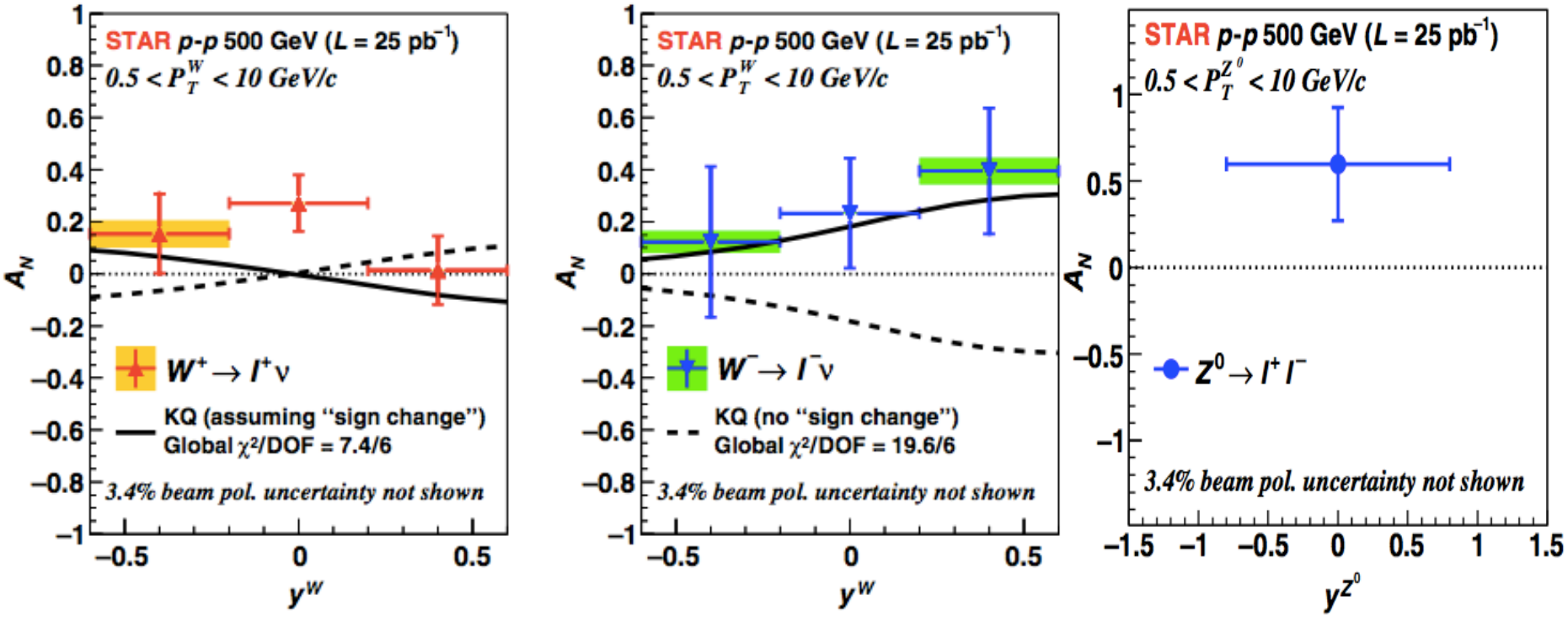
S. J. Brodsky, D. S. Hwang, I. Schmidt, Phys. Lett. B 530, 99 (2002);
X. Ji and F. Yuan, Phys. Lett. B 543, 66 (2002); J. C. Collins, Phys. Lett. B 536, 43 (2002).

- Active experimental programs at CERN-COMPASS (DY), RHIC (W-boson production), Fermi-SpinQuest (E1039,DY)
- Advantages of weak boson production in pp
  - ➢ Low background, high Q^2-scale (~ W/Z boson mass)

First W, Z A_N results at 500 GeV from STAR

- Critical test of Sivers sign-change in DIS and DY/W/Z process
- First A_N results for $W^{\pm}$ /Z at RHIC

STAR, PRL116,132301(2016)

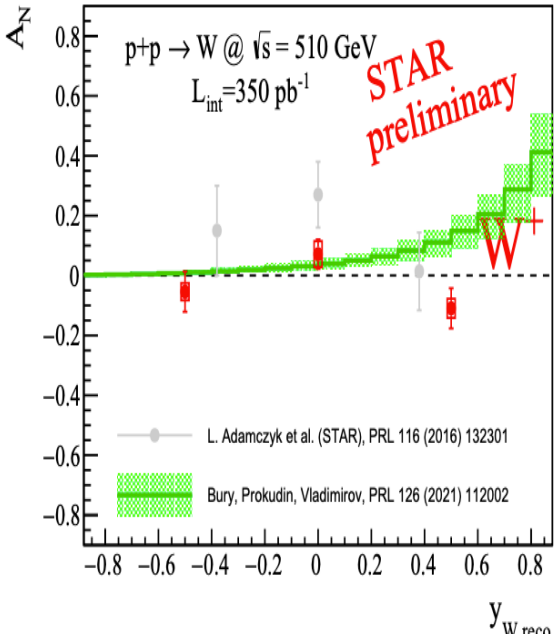


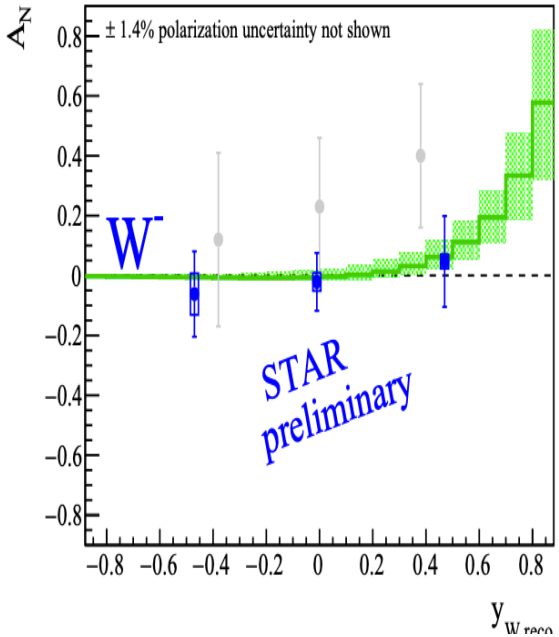
➢ Sivers sign-change scenario preferred over no-sign change scenario.

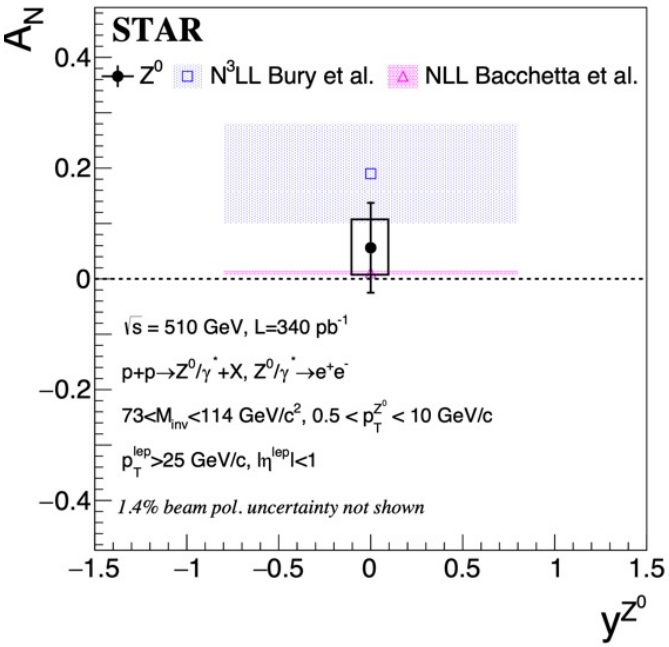
Recent measurements of W/Z A_N at STAR

- STAR results with a much larger data sample taken in 2017:

STAR, PLB 854, 138715(2024)



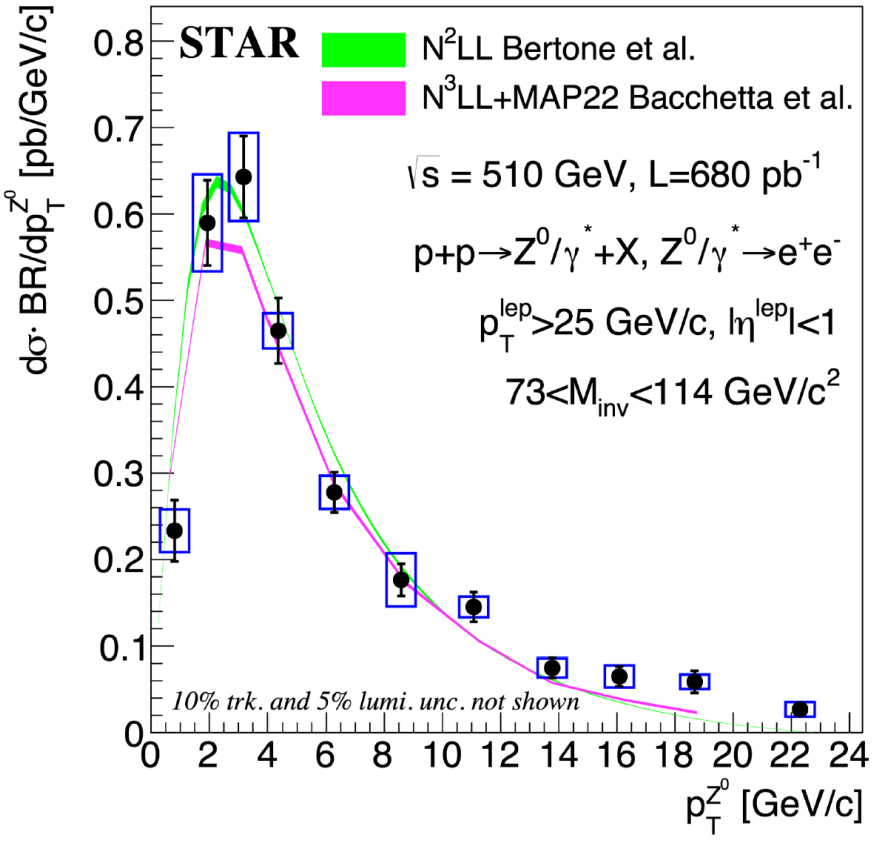




- 2017 results have much improved precision over those from the 2016 publication
- New STAR data (2017+2022) will have biggest impact on high-x region of the quark Sivers function.

Z/γ^* cross section and unpolarized TMD

STAR, *Phys. Lett.* B **854** (2024) 138715

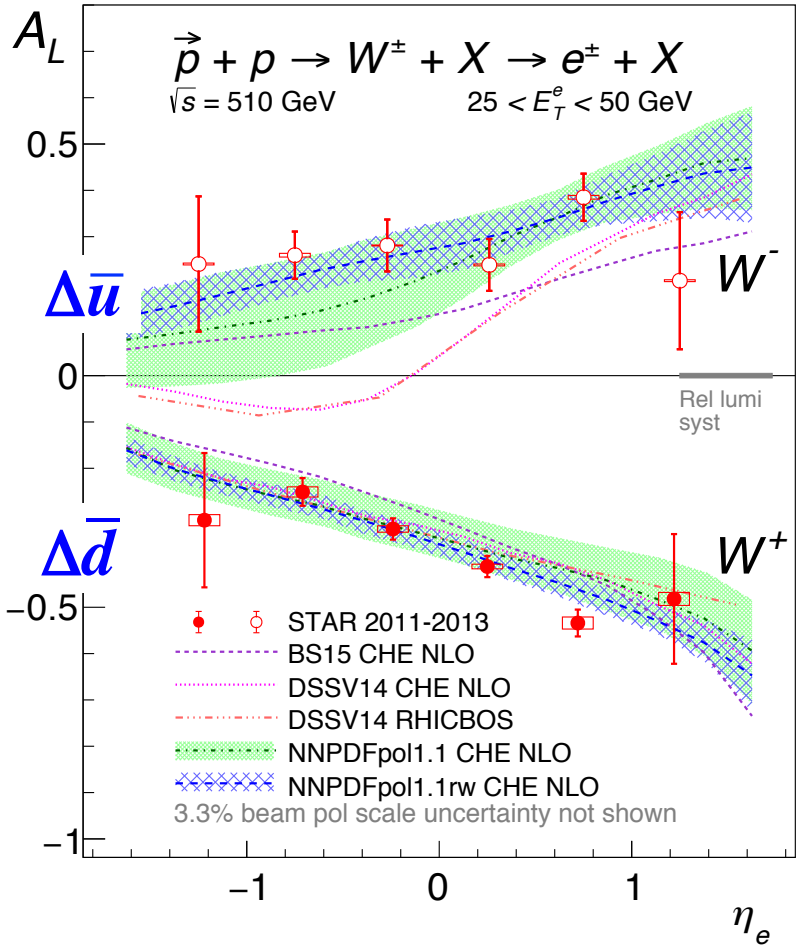


- Z^0 events are reconstructed via:

$$p + p \rightarrow Z^0 \rightarrow e^+ + e^-$$

- Serves as a test of the universality of unpolarized TMDs
- Provides insights into the x and Q^2 evolution of unpolarized TMDs
  - RHIC energies provide access to higher x compared to the Tevatron and LHC

W A_L and TMD helicity distributions

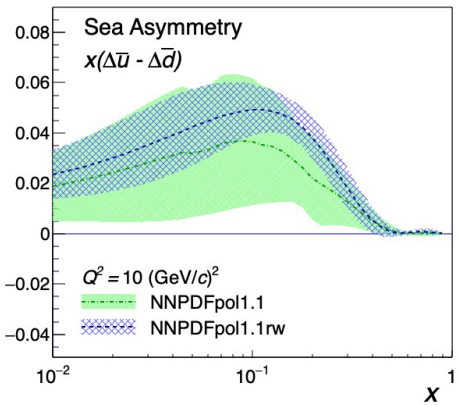


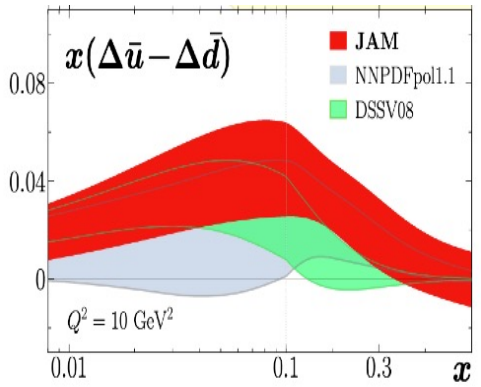
STAR, PRL113, 072301 (2014)
PRD99, 051102R(2019)

- Unique flavor separation with W boson in pp collision
- A_L of W^- larger than the DSSV predictions

  -> new constraints
- Clear flavor asymmetry:

$$\Delta\bar{u} > 0 \text{ and } \Delta\bar{d} < 0$$

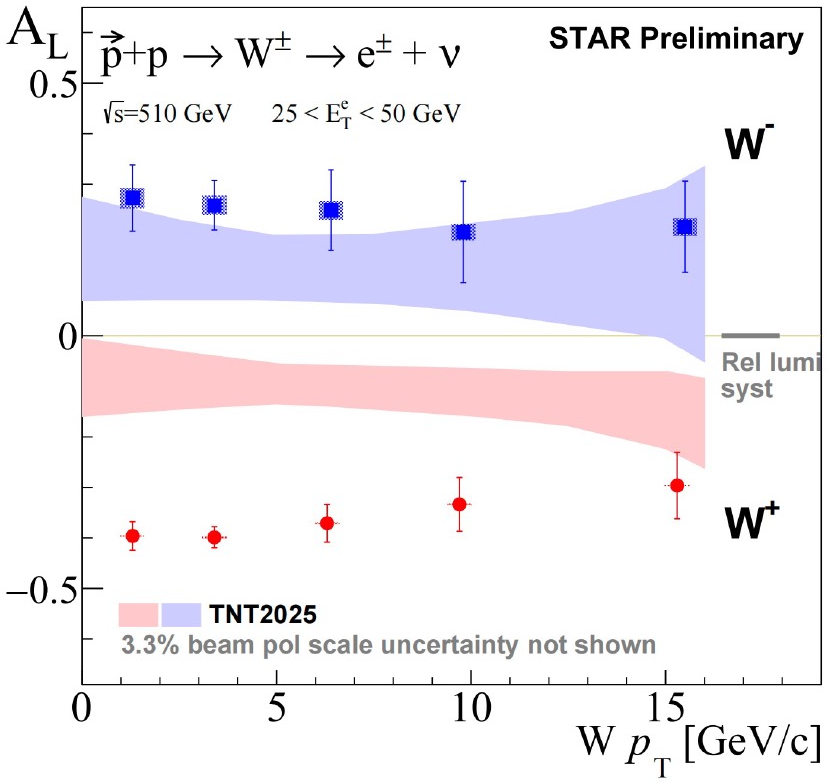


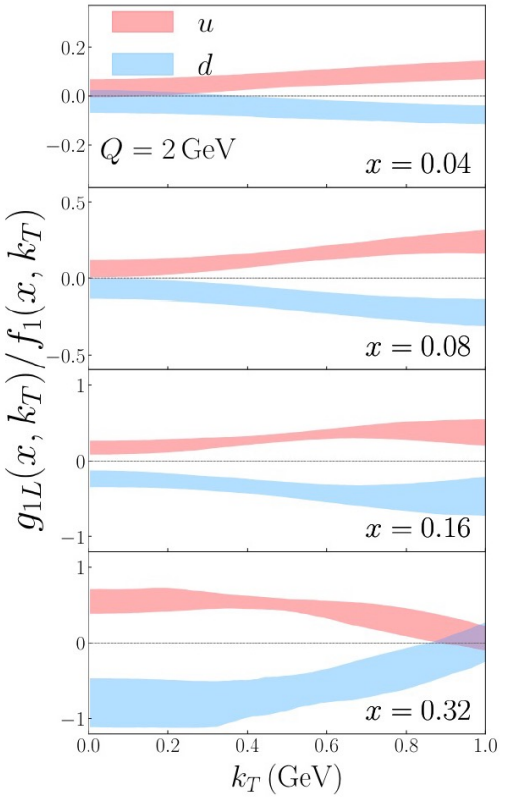


JAM, PRD106, 031502(2022)

W A_L and TMD helicity distributions

- p_T dependent W A_L help to constrain the TMD helicity distribution
- Full reconstruction of W p_T through unfolding



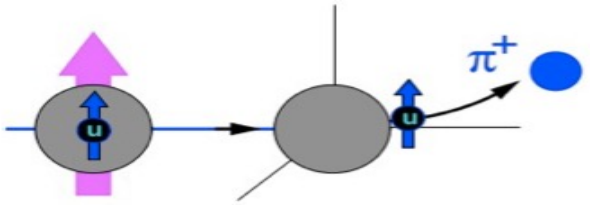


TNT: K.Yang , et al, PRL134, 121902 (2025)

- ✓ The average A_L is consistent with published results
- ✓ Significant difference between data and TNT2025 predictions, especially for W^+

Probing transversity via Collins asymmetry in p+p

- Study proton transversity through its coupling to Collins function:



$$A_{UT} \propto h_1(x) \otimes H_1^{\perp}(z, j_T)$$

- Collins asymmetry:

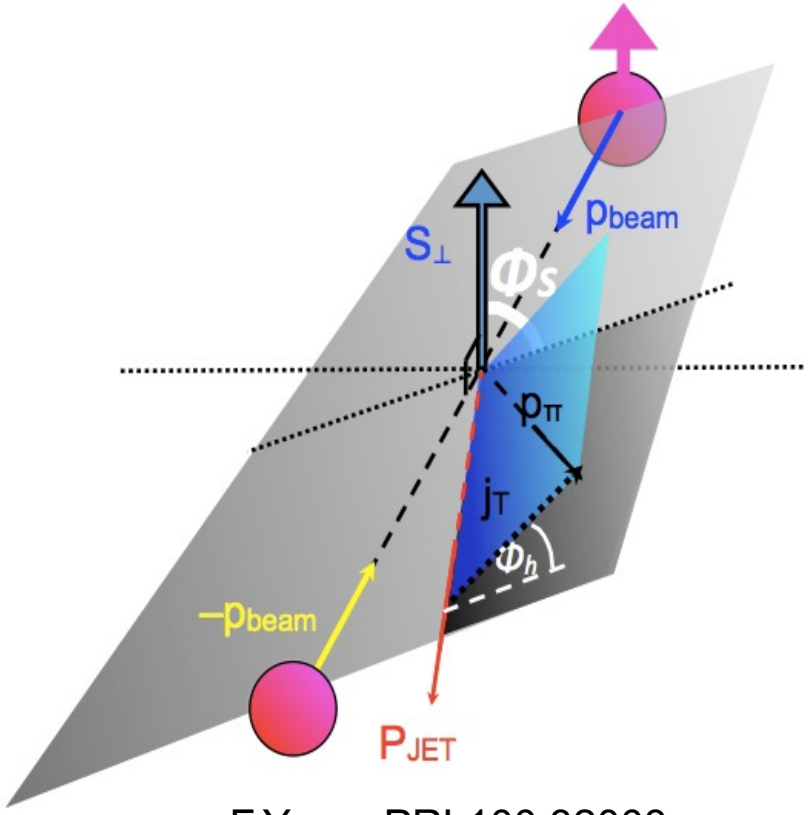
Collins angle: $\Phi_c=\Phi_s-\Phi_h$

Collins modulation: $\sin(\Phi_s-\Phi_h)$

j_T : transverse momentum in jet

Φ_s: azimuthal angle of beam spin

Φ_h: azimuthal angle of hadron

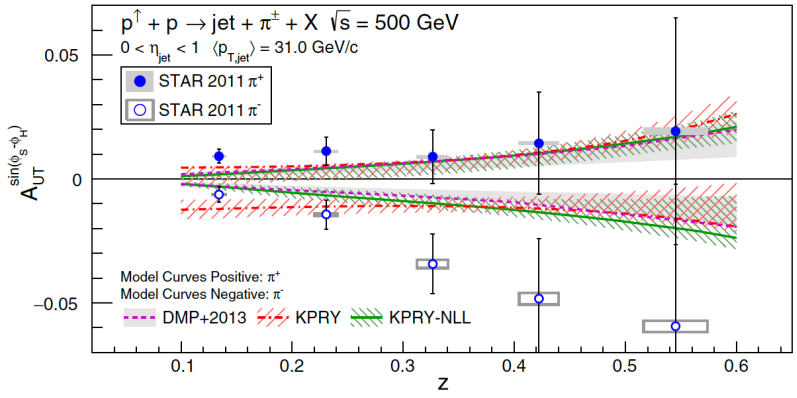


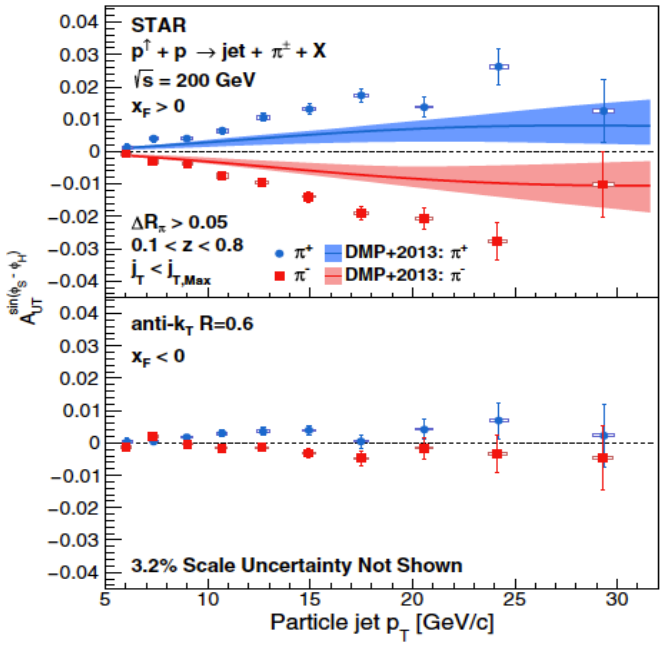
-F.Yuan, PRL100,32003

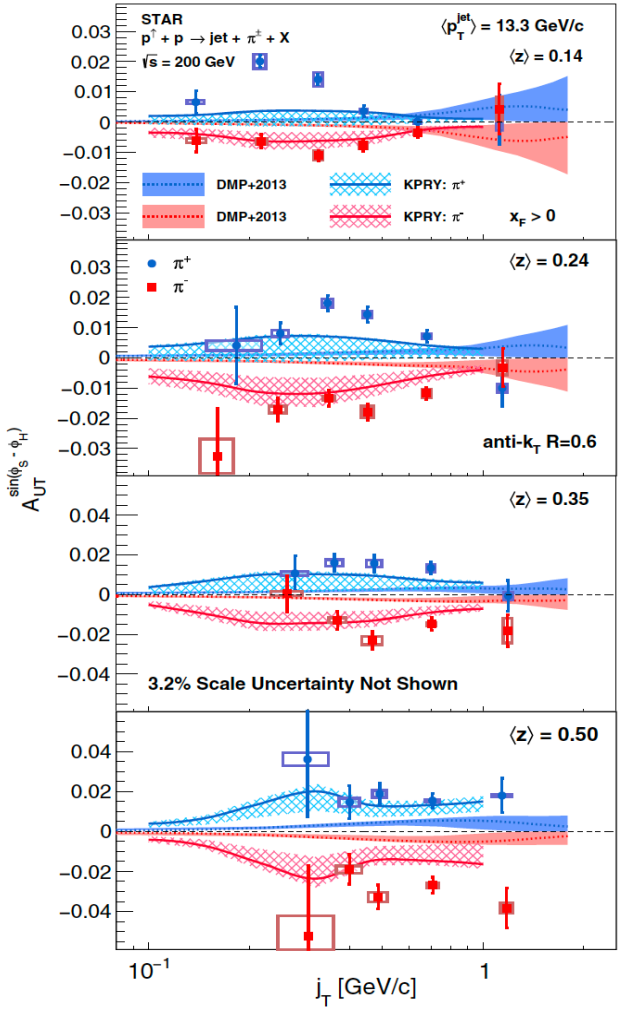
Collins asymmetry in p+p at STAR

- Hadron in jets Collins asymmetry in p+p collisions, covering high Q, providing access to transversity:

STAR, PRD97, 032004 (2018)
PRD106, 072010 (2022)





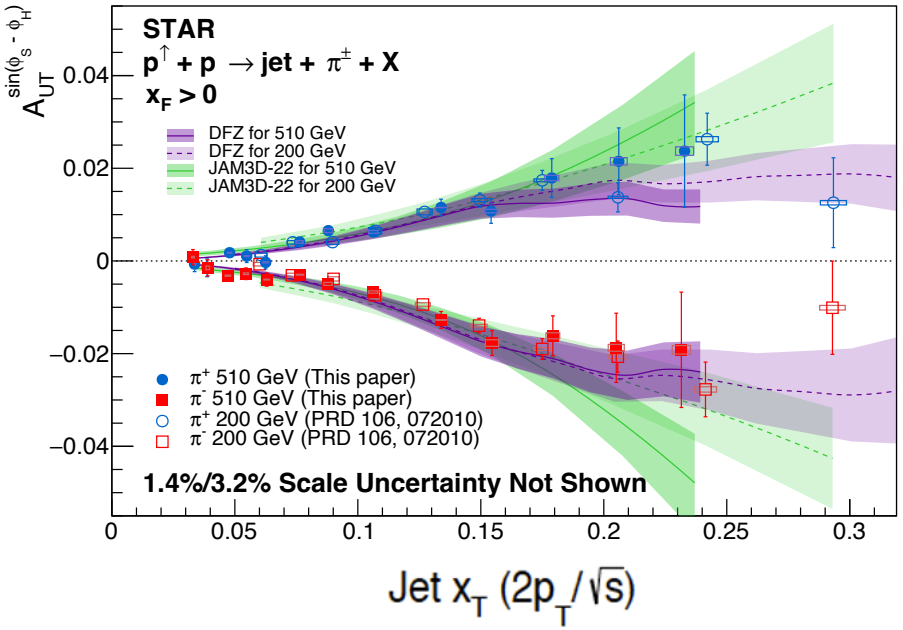


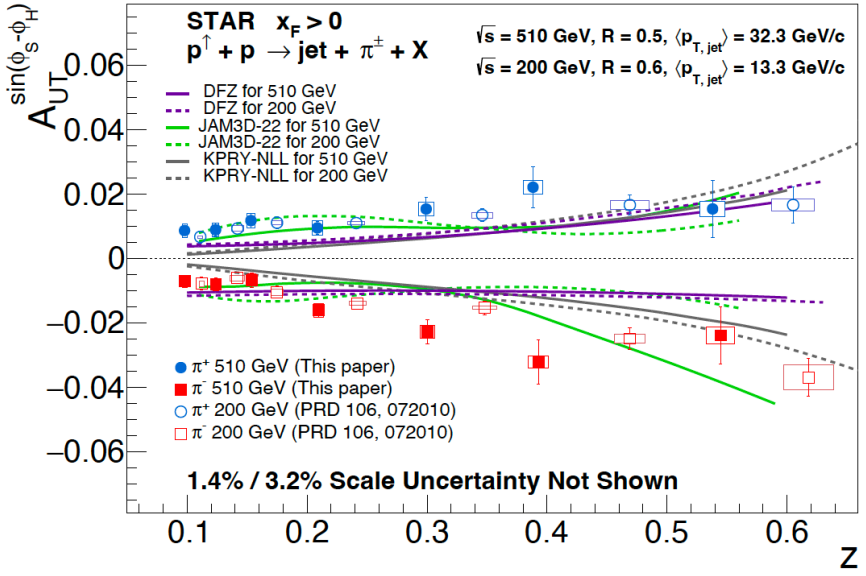
DMP: U. D'Alesio, F. Murgia, C. Pisano, PLB 773, 300 (2013)
KPRY: Z.-B. Kang, A. Prokudin, F. Ringer, F. Yuan, PLB 774, 635(2017)

New Collins results at 510 GeV

- New results on Collins asymmetry in p+p collisions at 510 GeV, in excellent agreement with 200 GeV data at same jet x_T:

STAR, PRL135, 261902 (2025)





- ➢ Comparison indicates striking weak energy dependence
- ➢ Providing important constraints on TMD evolution of Collins function

Polarized Energy Correlators in jets

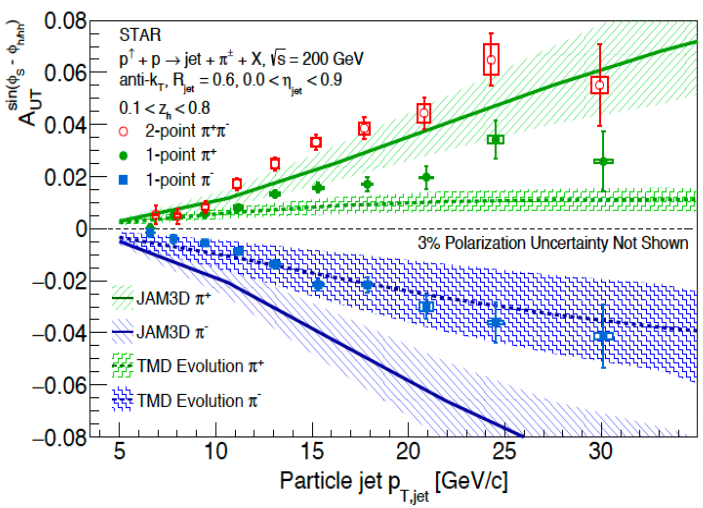
- Pol. EEC: Project spin–dependent frag. functions onto Mellin moments

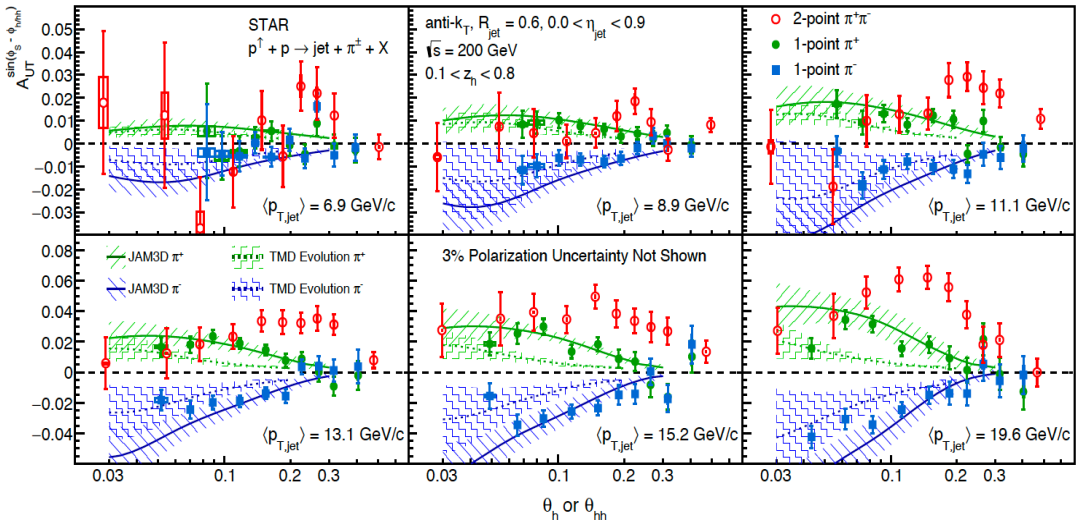
$$\mathrm{EEC}(\theta_h, \phi_h) = \frac{d(\sum_{jet} \sum_i z_{h,i})}{d\theta_h d\phi_h} \qquad z_h = \frac{p_h}{p_{jet}} \text{ , loop over all hadrons in jet}$$

$$A_{UT} = \frac{EEC^{\uparrow}(\phi_S - \phi) - EEC^{\downarrow}(\phi_S - \phi)}{EEC^{\uparrow}(\phi_S - \phi) + EEC^{\downarrow}(\phi_S - \phi)}$$

- Frist EEC spin asymmetries in pp collisions at 200 GeV:

STAR, arXiv:2604.15543

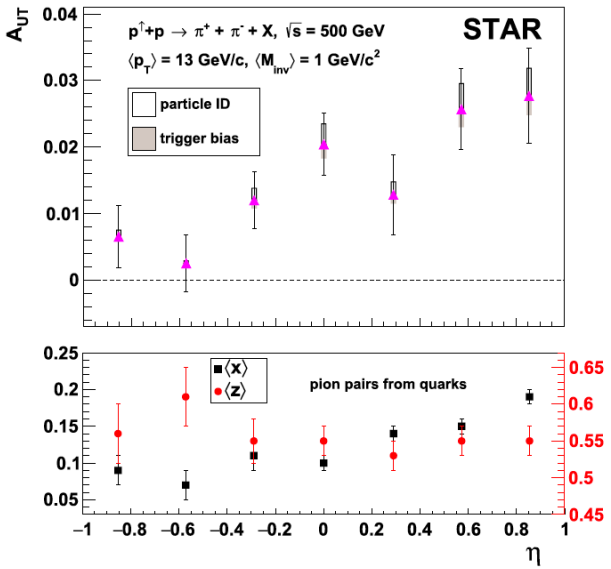


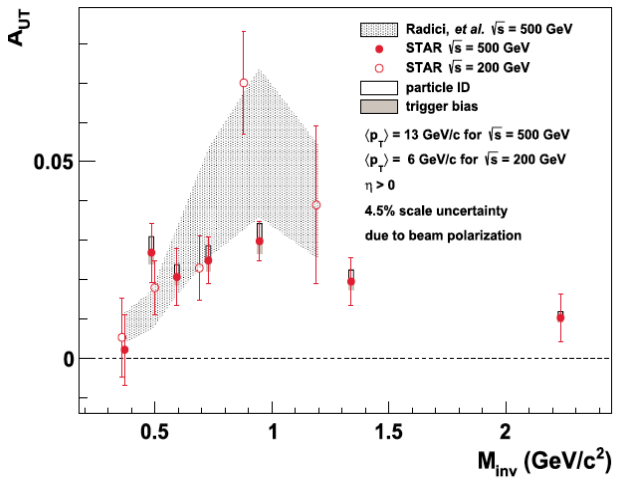


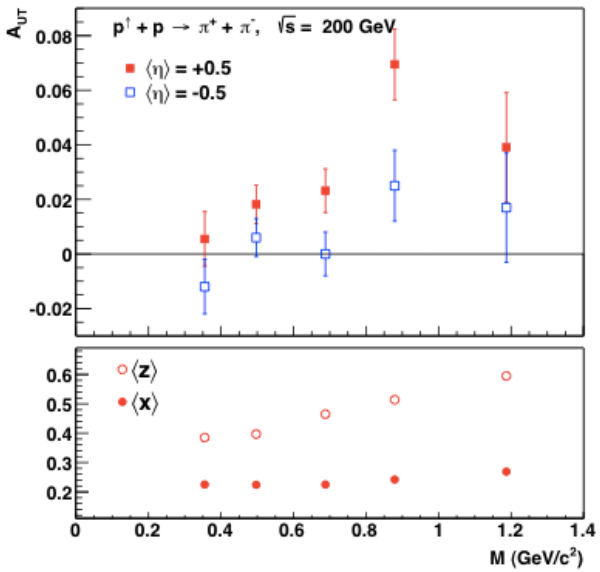
One point EC theory: Gao, Kang, Li, Shao, Zhao, PRL 136, 151902 (2026)

Di-hadron spin asymmetries at STAR

- Non-zero di-pion asymmetries in p+p provide constraints on transversity via Interference Fragmentation Function (IFF)
  - ➢ model independent extraction of transversity
    - *Radici & Bacchetta, PRL120,192001(2018)*





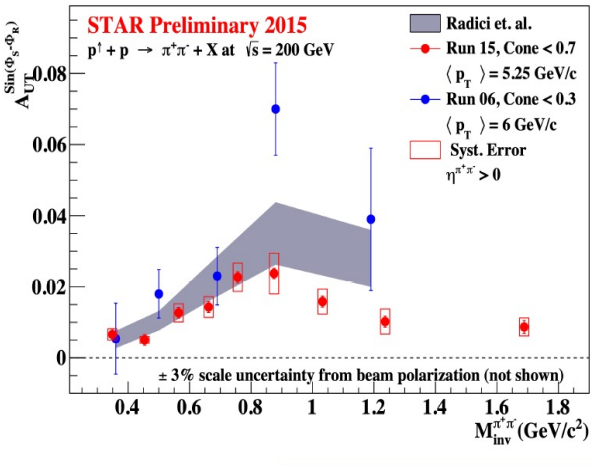


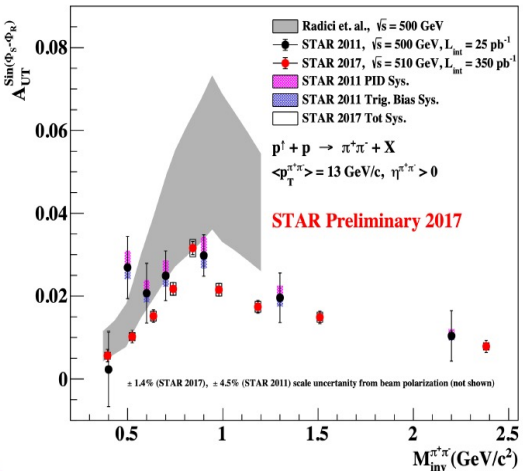
STAR, Phys. Lett. B780,332 (2018)

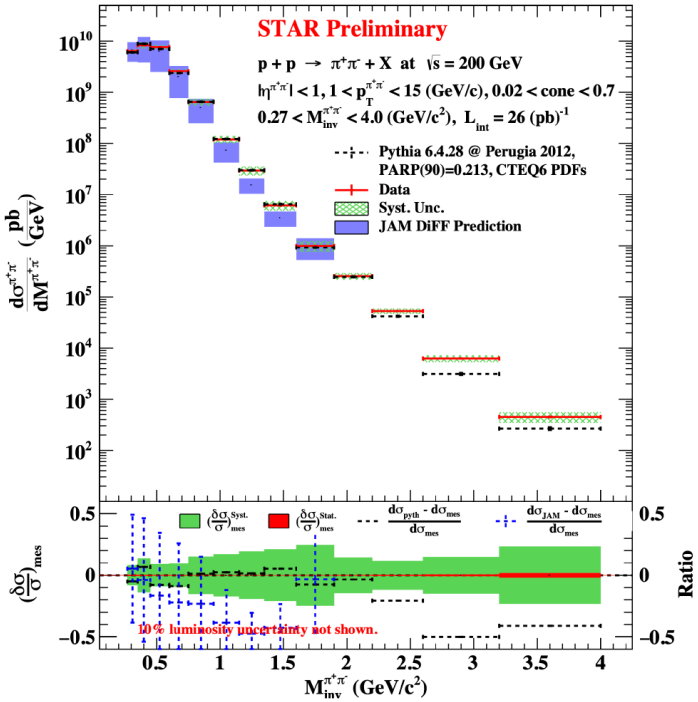
STAR, PRL115, 242501(2015)

Di-hadron spin asymmetries at STAR

- Non-zero di-pion asymmetries in p+p provide constraints on transversity via IFF
- Recent measurements of di-pion asymmetries in p+p collisions at 200 and 510 GeV
- First measurement of unpolarized cross section at 200 GeV







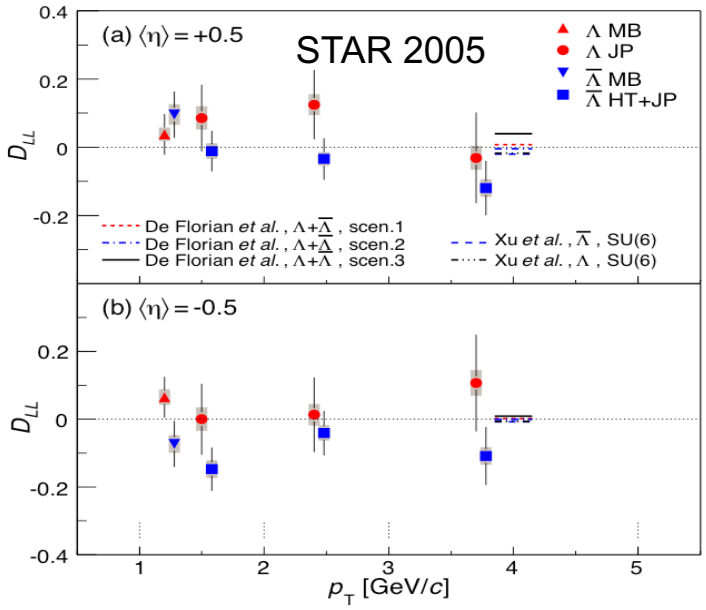
Longitudinal Λ spin transfer (D_{LL}) in p+p collisions

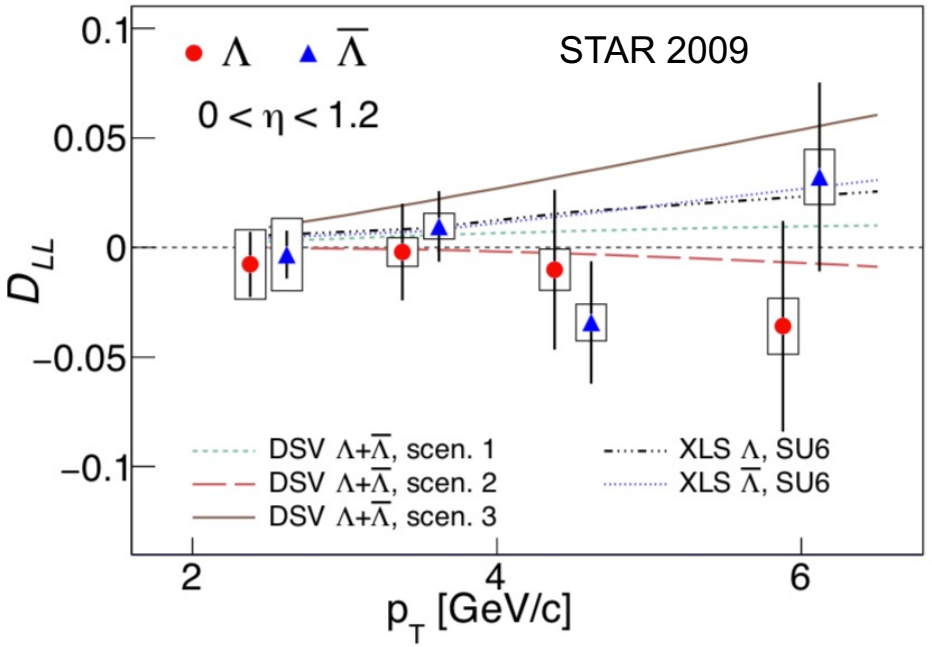
- D_{LL} for (anti)Lambda, which can provide sensitivity to strange quark polarization Δs, and polarized fragmentation function.

$$D_{LL}^{\Lambda} \equiv \frac{d\sigma(p^+p \to \Lambda^+X) - d\sigma(p^+p \to \Lambda^-X)}{d\sigma(p^+p \to \Lambda^+X) + d\sigma(p^+p \to \Lambda^-X)} = \frac{d\Delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}, \qquad d\Delta\sigma^{\Lambda} = \sum \int dx_a dx_b dz \Delta f_a(x_a) f_b(x_b) \Delta\sigma(ab \to cd) \Delta D^{\Lambda}(z)$$

Polarized PDFs — Polarized FFs

-STAR, PRD80, 111102R (2009) ; PRD98, 112009 (2018)



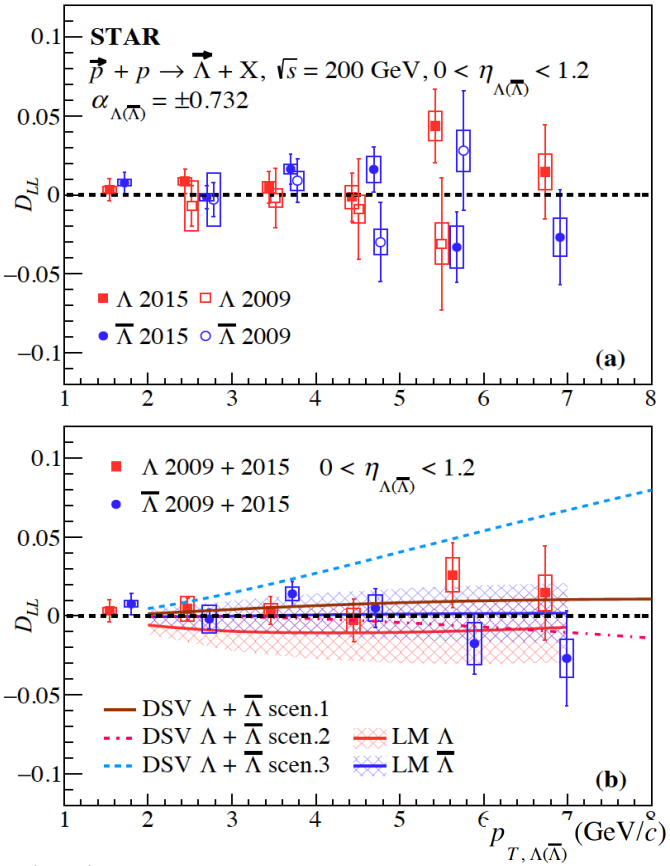


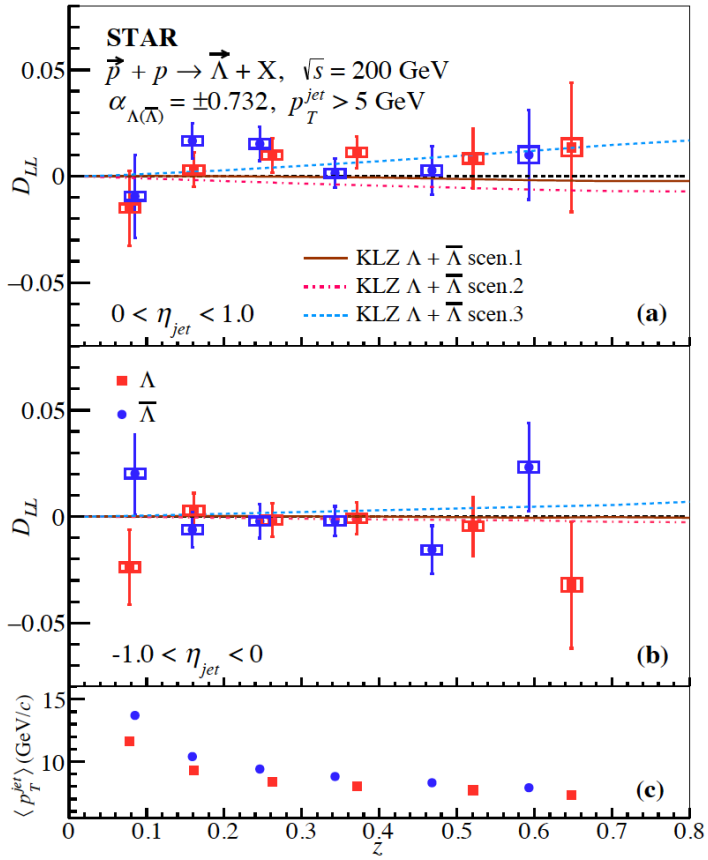
- D.de Florian, M.Stratmann, W. Vogelsang, PRL81,530(1998)
- Q. Xu, Z.T. Liang, E. Sichtermann, PRD 73, 077503(2006)

Improved D_{LL} results with STAR 2015 data

- Improved results vs. p_T agree with model predictions, except "DSV" calculation with "scen. 3" of polarized fragmentation function.
- First measurements of D_{LL} vs z in p+p, directly probing the polarized fragmentation function.

STAR, PRD109, 012004 (2024)





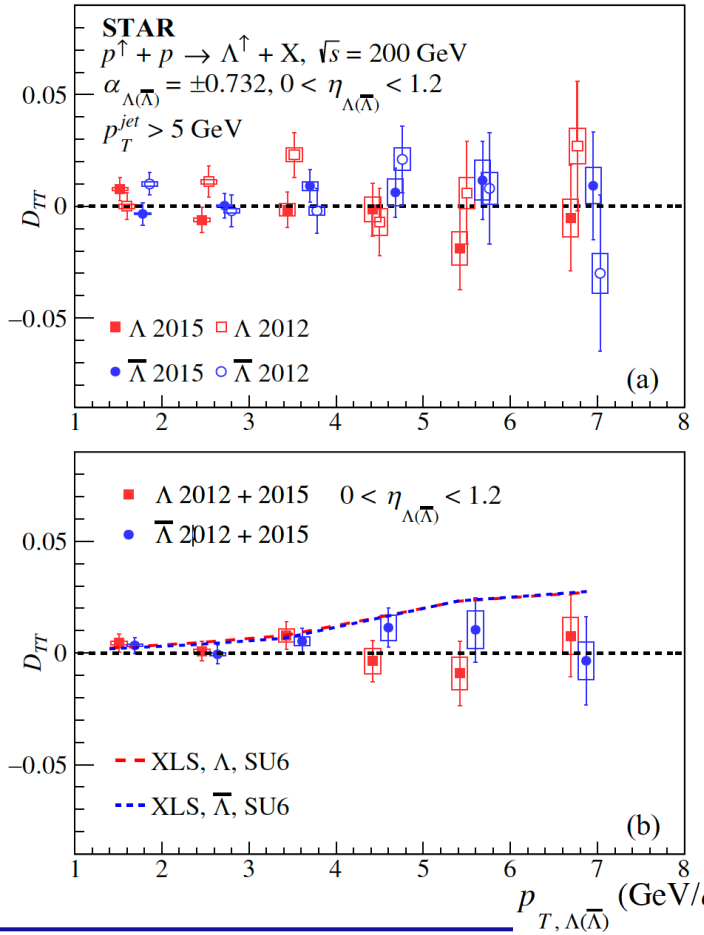
$$z=\frac{\boldsymbol{p}_{\Lambda}\cdot\boldsymbol{p}_{jet}}{|\boldsymbol{p}_{jet}|^2}$$

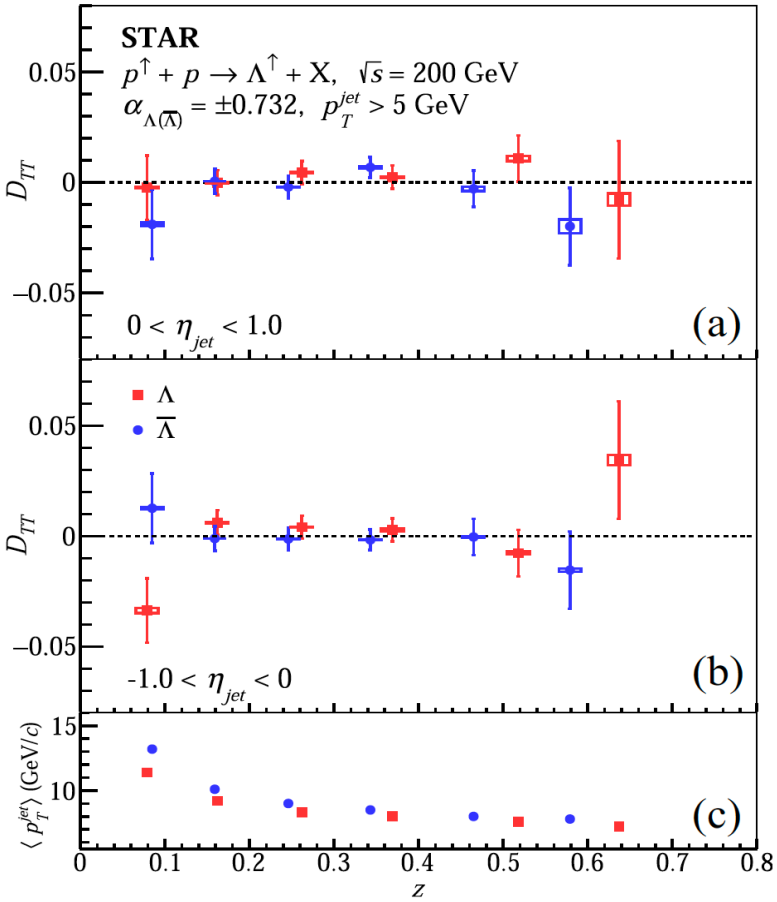
- *D.de Florian, M.Stratmann, W.Vogelsang, PRL81,530(1998);*
- *X.N. Liu, B.Q. Ma, EPJC 79,409 (2019)*
- *Z.-B. Kang, K. Lee, F. Zhao, PLB **809**, 135756 (2020).*

Transverse spin transfer D_{TT} results at STAR

- **Λ** hyperon D_{TT} is connected to strange quark transversity and transversely polarized fragmentation function.
- D_{TT} is consistent with the model predictions within uncertainties.

STAR, PRD98, 112009 (2018); PRD109, 012004 (2024)

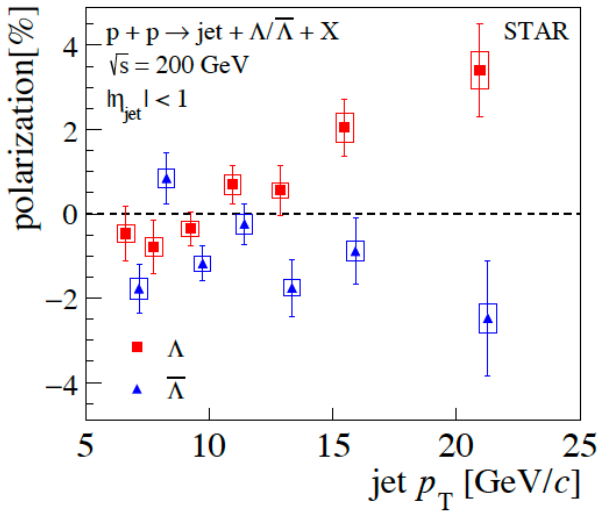


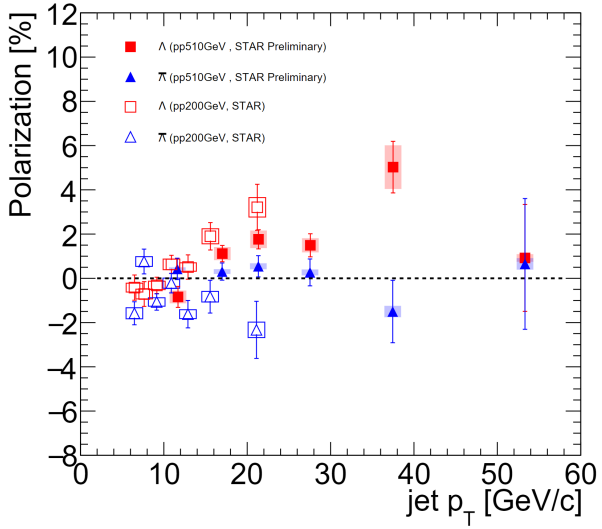


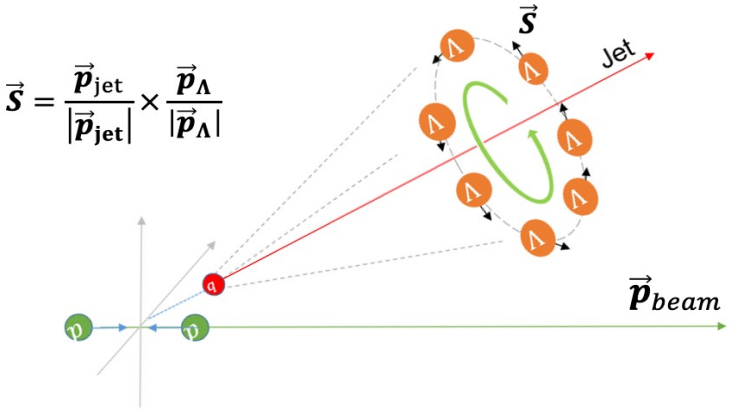
Λ polarization in jets in unpolarized p+p collision

- Λ polarization in jets in p+p -> polarizing Frag. Function (pFF) at STAR:

STAR, arXiv:2509.17487, JHEP in press







- First measurement of Λ polarization in jets in pp collisions
  - ✓ Clear jet p_T dependence of Λ polarization
  - ✓ $\bar{\Lambda}$ polarization mostly remains negative
  - ✓ First constraints on gluon pFF
- ➢ Measurements in pAu to study possible medium effect for pFF -> DIS2026

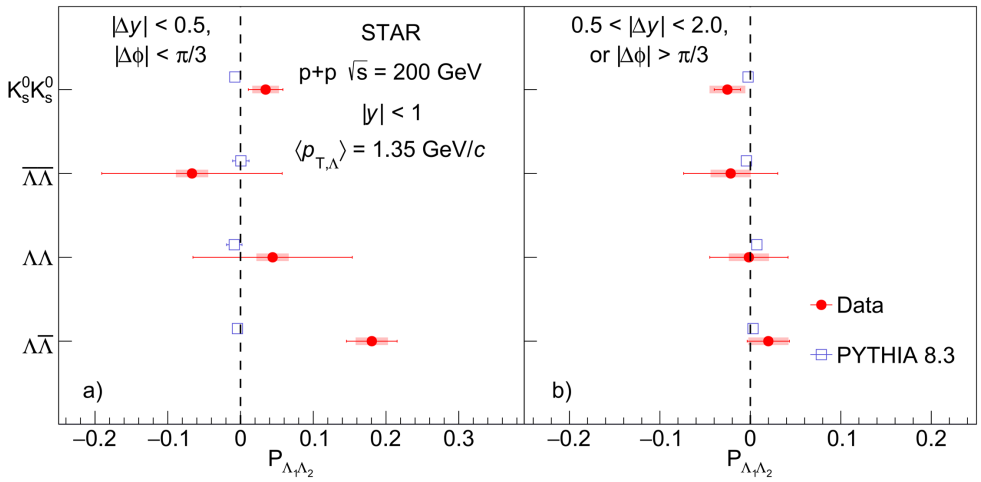
Λ - anti Λ spin correlations in p+p collision

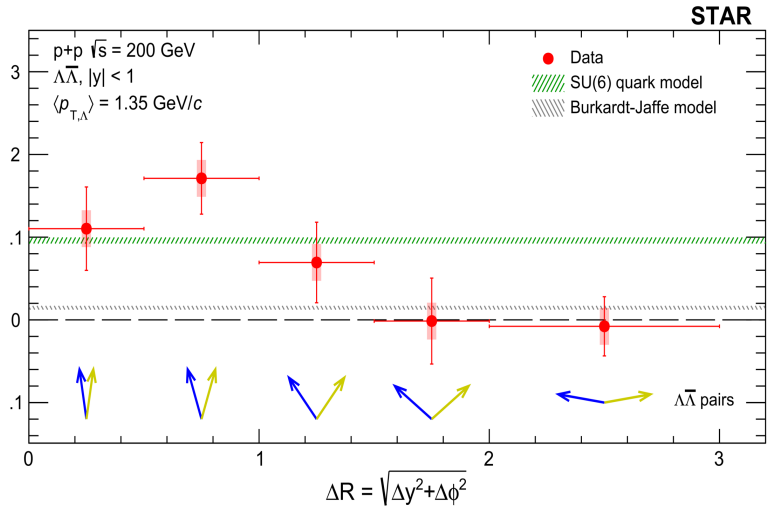
- Non-zero spin correlation for short range Λ - anti Λ pairs
- Correlation consistent with zero for long range pairs and other pairs

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} = \frac{1}{2}\left[1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)\right]$$

θ* - difference between decay proton angles in rest frames of parent Λ

STAR, Nature 650, 65(2026)

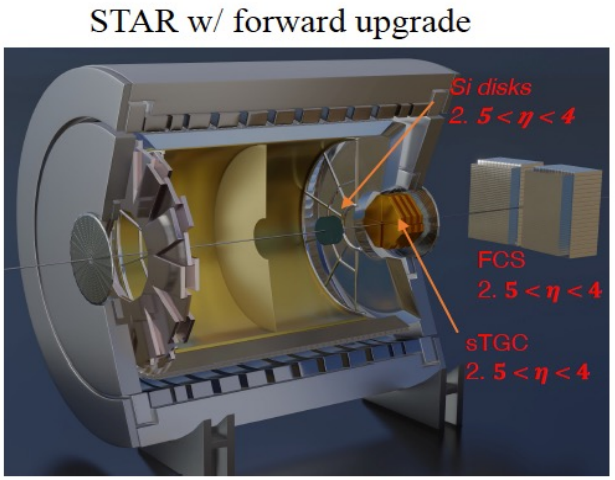


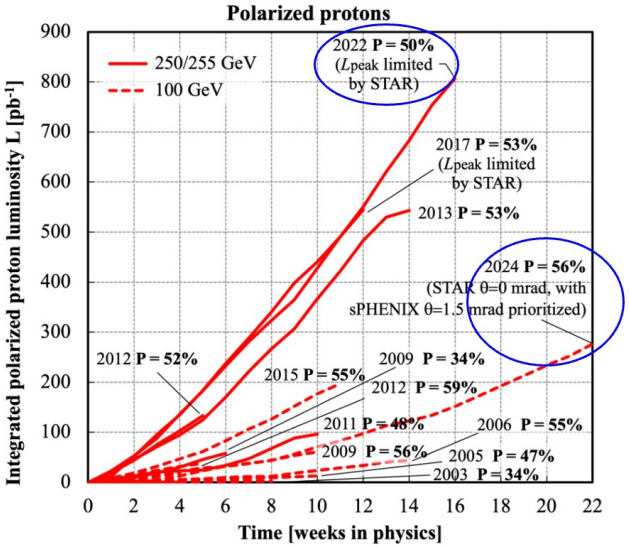


➢ Possible source: maximally entangled s - sbar spin correlation of pairs from QCD vacuum ?

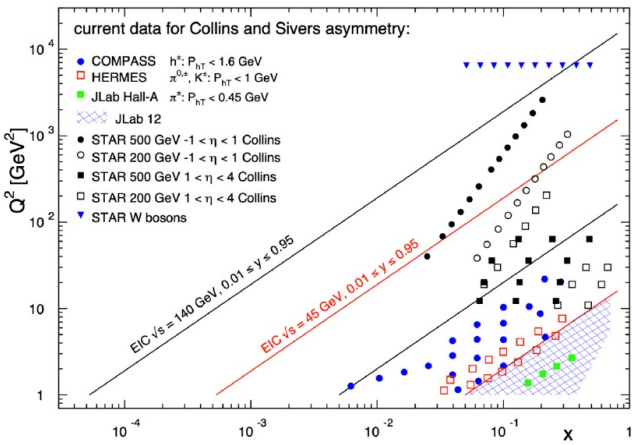
STAR p+p running with new forward detectors

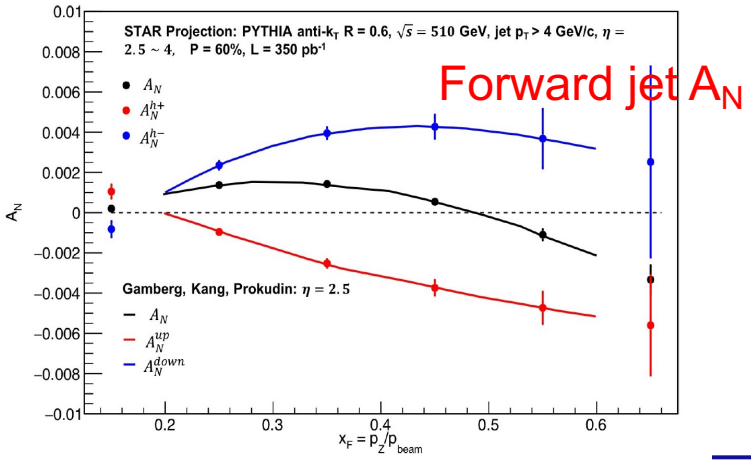
- Successful p+p runs in 2022+2024 with STAR forward upgrade (2.5<η<4)
- Highest statistics at both 200 and 510 GeV with transverse beam polarization





➢ Essential x-Q^2 overlap with EIC, full jet reconstruction + charge-sign tagging





Summary & Outlook

- Great achievements from STAR spin program in 20+ years
- Recent TMD measurements at STAR:
  - ✓ **Transverse spin asymmetry (W/Z, jet): Sivers function**
  - ✓ **Transverse spin asymmetry (Hadron in jet, IFF): Collins & transversity**
  - ✓ **Hyperon polarization (Λ): strange quark polarization & pol. FF**
- Stay tuned for more TMD results from STAR in p+p (p+A)
  - High statistics p+p data taken in recent years with upgraded detectors

Thanks !