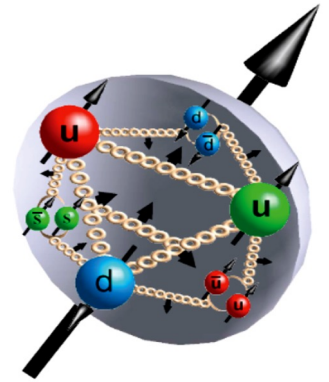
Nucleon spin structure study at STAR

Qinghua Xu (徐庆华),

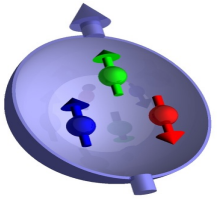
Shandong University（山东大学）



International Workshop on "Frontiers in high-energy nuclear physics", Beijing, July 20, 2026

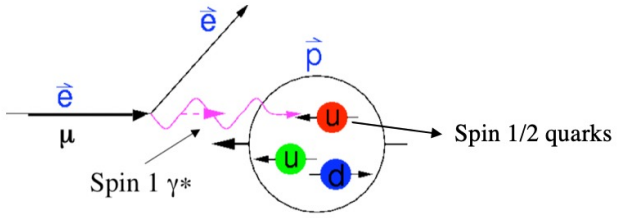
Spin structure of nucleon

- In the naive Quark Model, nucleon is made of three quarks - p(uud), n(udd)
  The nucleon spin is completely carried by the quark spin:



$$\Delta\Sigma = 1$$

- 1988 - European Muon Collaboration (polarized DIS)
  "Spin Crisis"--- proton spin carried by quark spin is rather small: $\Delta\Sigma \sim 0.2 \pm 0.2$



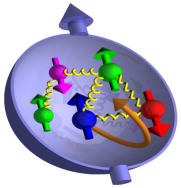
A Measurement of the Spin Asymmetry and Determination of the Structure Function g(1) in Deep Inelastic Muon-Proton Scattering

European Muon Collaboration • J. Ashman (Sheffield U.) et al. (Dec, 1987)

Published in: *Phys.Lett.B* 206 (1988) 364 • Contribution to: CERN SMC Meeting on Internal Spin Structure of the Nucleon, 340-346

DOI cite datasets claim reference search 2,421 citations

- Where are the rest of proton spin?



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + < L_{q,g} >$$

Quark spin, (~30%)-DIS

Gluon spin, RHIC

Orbital Angular Momenta Little known

Jaffe & Manohar, 1990; X. Ji, 1996

$$\int_0^1 g_1^p(x)dx = \frac{1}{2}\int \sum_i e_i^2 \Delta q_i(x)$$

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

$$[\Delta q = \int_0^1 \Delta q(x)dx]$$

$$\Delta q(x,Q^2) = q^+(x,Q^2) - q^-(x,Q^2)$$

Outline

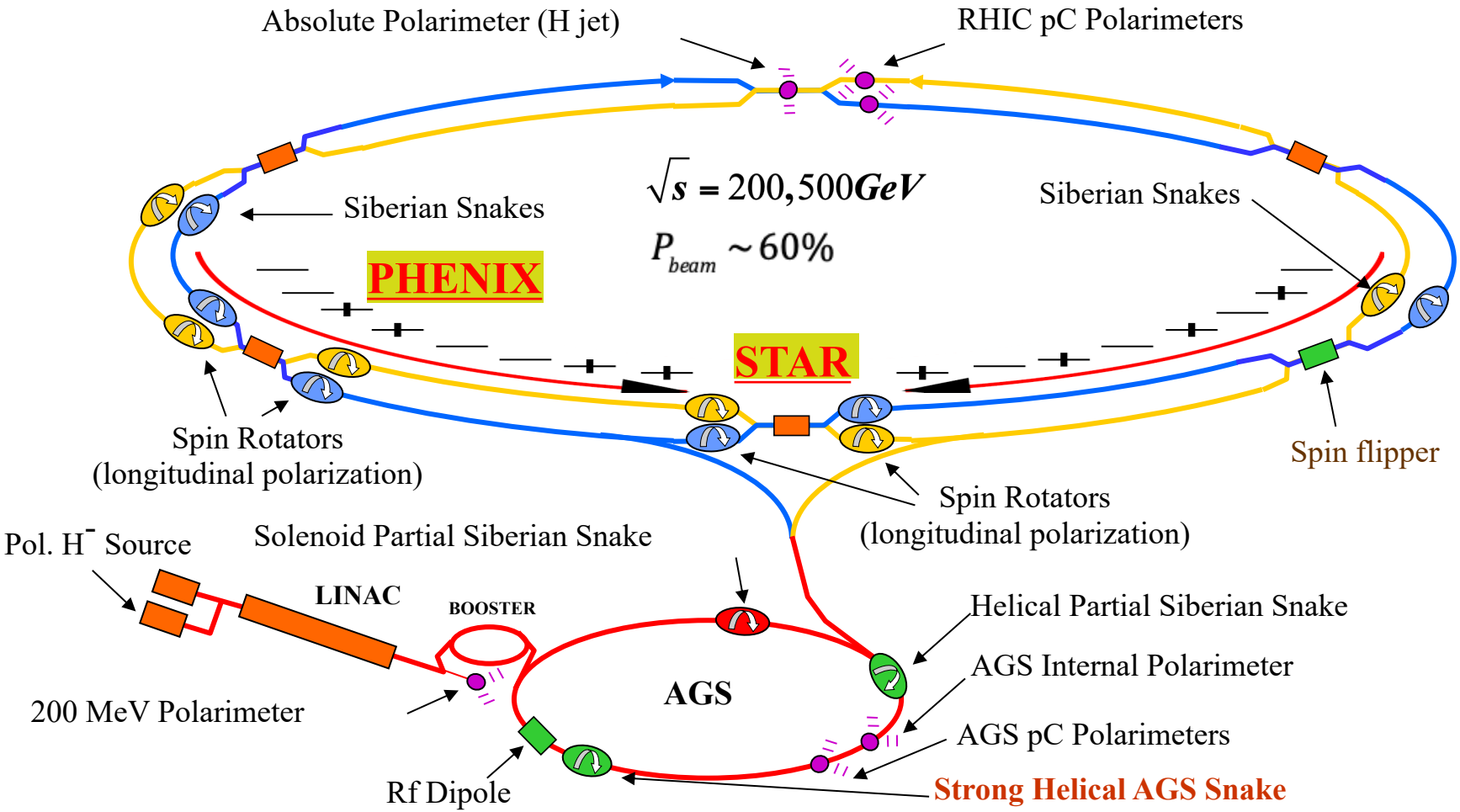
- Introduction
- Achievements from STAR spin program:
  - ✓ Gluon polarization (Jet production): gluon polarization Δg
  - ✓ Quark/Anti-quark polarization (W/Z): sea quark $\Delta\bar{u}/\Delta\bar{d}$
  - ✓ Hyperon polarization (Λ): strange quark polarization
  - ✓ Transverse spin asymmetry (W/Z, jet): Sivers function
  - ✓ Transverse spin asymmetry (Hadron in jet, IFF): Collins & transversity
- Summary & outlook

Outline

- Introduction
- Achievements from STAR spin program:
  - ✓ Gluon polarization (Jet production): gluon polarization Δg
  - ✓ Quark/Anti-quark polarization (W/Z): sea quark $\Delta\bar{u}/\Delta\bar{d}$
  - ✓ Hyperon polarization (Λ): strange quark polarization
  - ✓ Transverse spin asymmetry (W/Z, jet): Sivers function
  - ✓ Transverse spin asymmetry (Hadron in jet, IFF): Collins & transversity
- Summary & outlook

- SDU group (Jinlong Zhang, Ting Lin, QX) has made key contributions to STAR spin program

RHIC- 1st polarized proton-proton collider



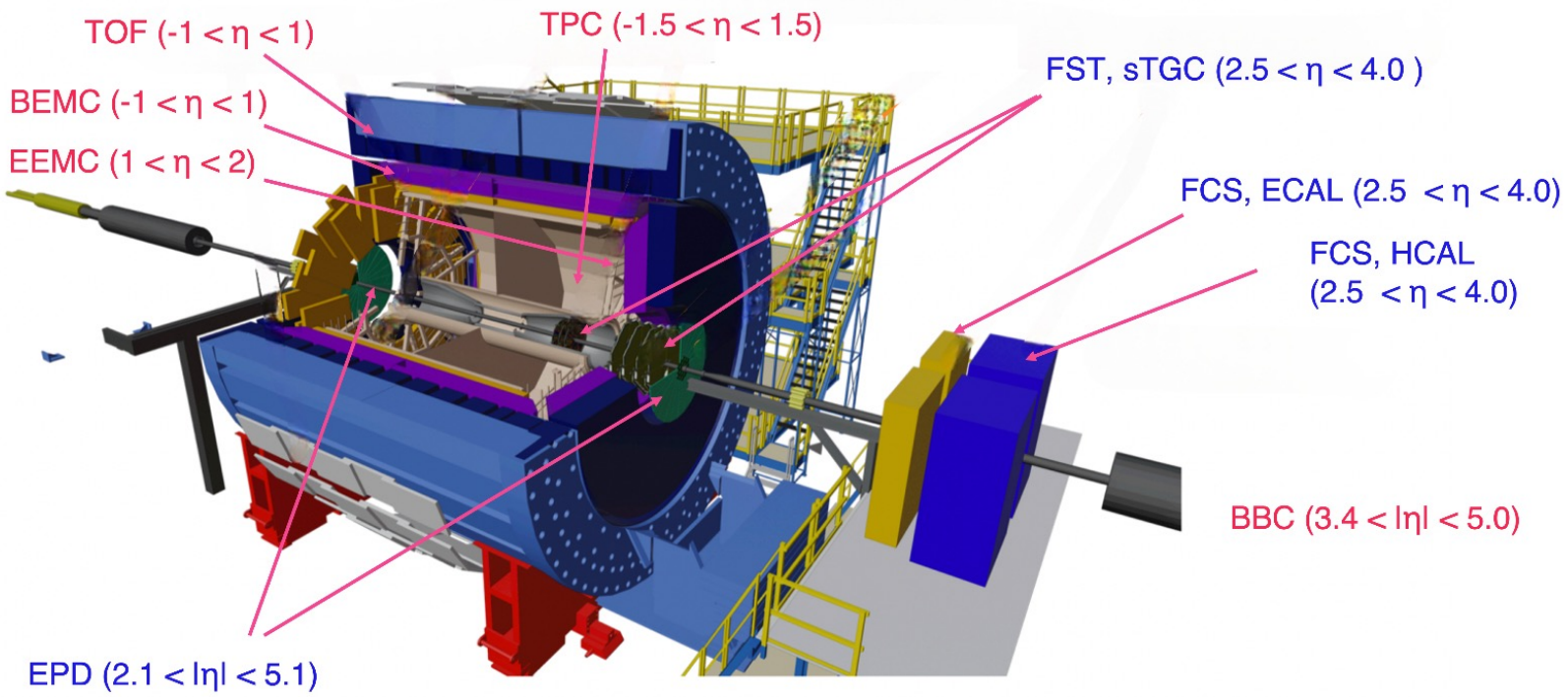
- Polarized p+p collision at √s=200, 500/510 GeV since 2000, longitudinal or transverse
- Two main experiments: PHENIX (sPHENIX) & STAR

STAR - Solenoid Tracker At RHIC

- Beautiful detector for tracks, π^0, jets….

- 0.5 T Solenoid

-Forward upgrade 2022-2024



✓ Targeted upgrades (23 in total) to make most of the RHIC program, with key contributions from STAR-China group for TOF, iTPC, eTOF, EPD, FST, sTGC etc

✓ STAR collaboration consists of 700 scientists from 74 institutions across 14 countries/regions

What was expected from RHIC spin program in 2000?

arXiv:hep-ph/0007218

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*

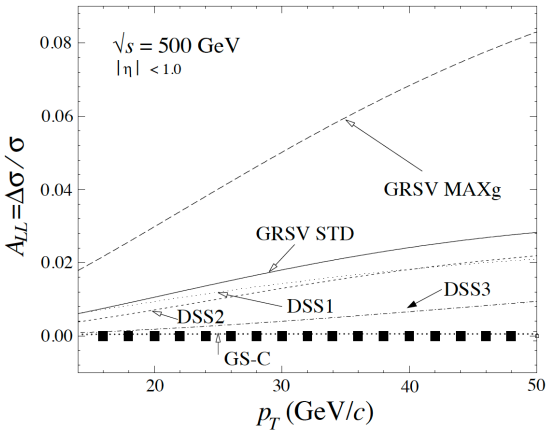
[4]*C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11794-3840 and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000; e-mail: wvogelsang@bnl.gov*

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

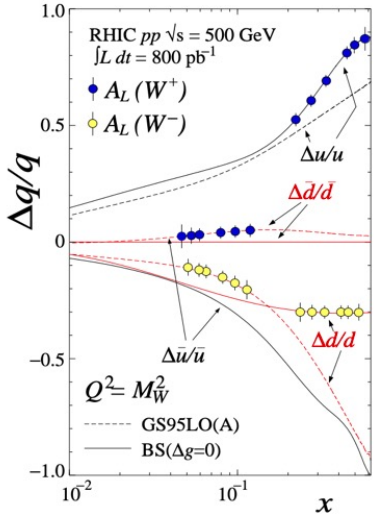
■ **Abstract** Colliding beams of 70% polarized protons at up to $\sqrt{s} = 500$ GeV, with high luminosity, $L = 2 \times 10^{32}\,cm^{-2}\,sec^{-1}$, will represent a new and unique laboratory for studying the proton. RHIC-Spin will be the first polarized-proton collider and will be capable of copious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

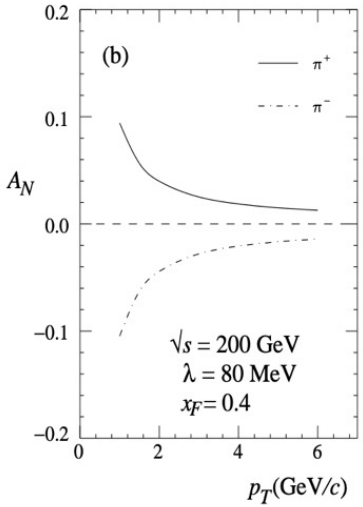
Gluon polarization Δg via jet A_{LL}



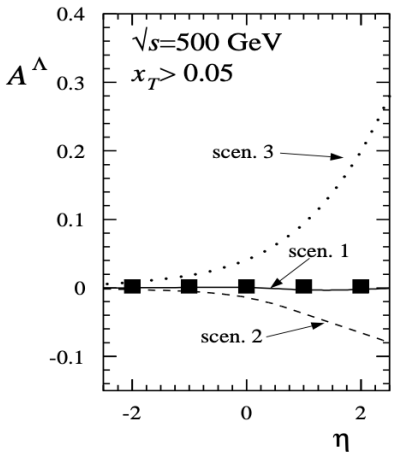
Sea quark polarization via W-boson A_L



Transverses spin physics

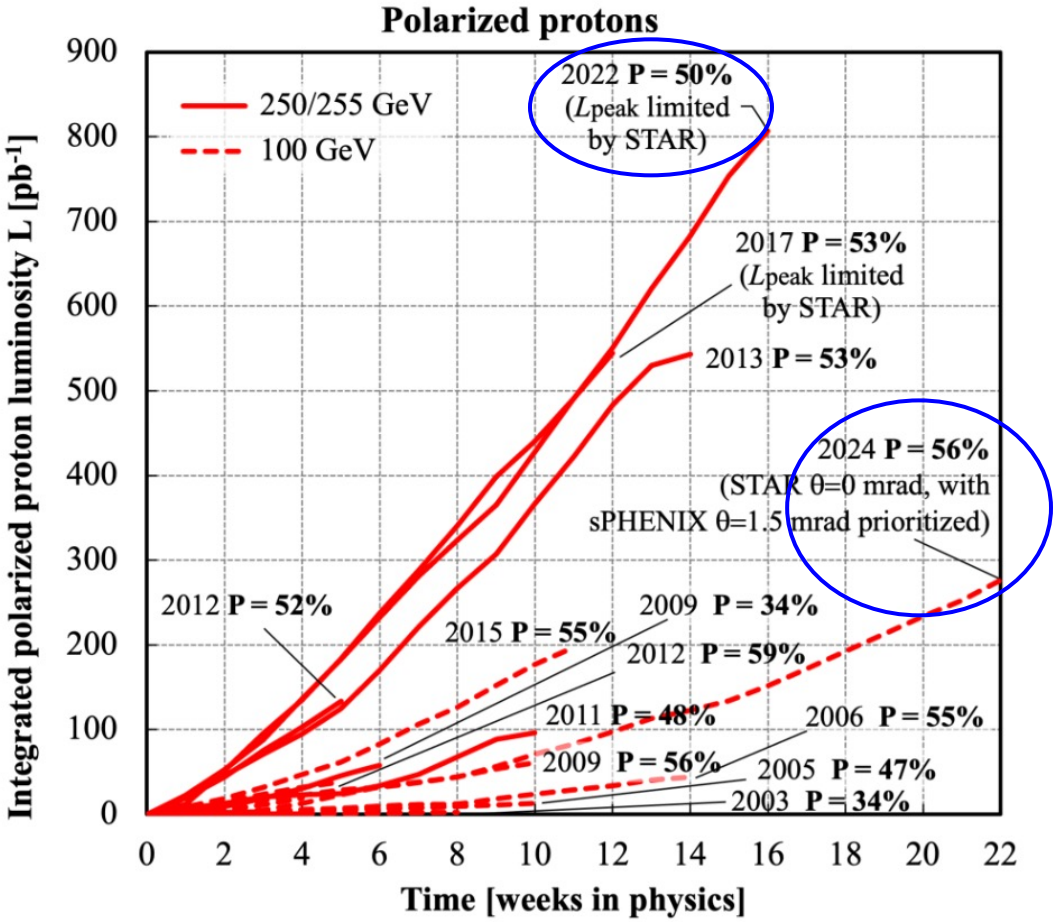


Λ polarized fragmentation



RHIC/STAR performance with p+p collisions

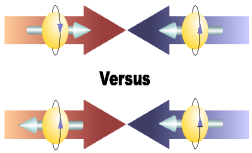
- Longitudinal pol. at 200 GeV in 2003, 2005, 2006, 2009, 2015.
- Longitudinal pol. at 500 GeV in 2009, 2011, 2012 and 2013.
- Transverse pol. at 200 GeV in 2006, 2008, 2012, 2015, 2024;
- Transverse pol. at 500 GeV in 2011, 2017, 2022.



✓ Run2022 and 2024 with STAR forward detector upgrade

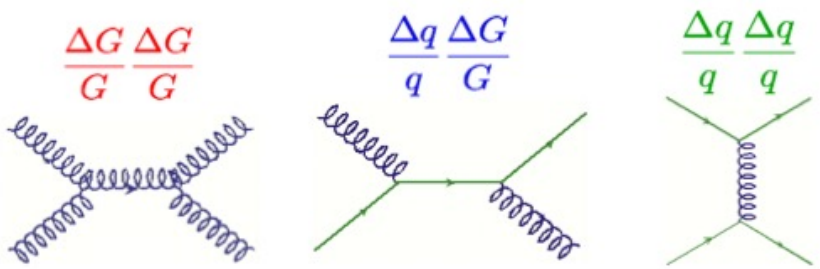
Accessing Δg(x) in p+p collision

- Longitudinal double-spin asymmetry:

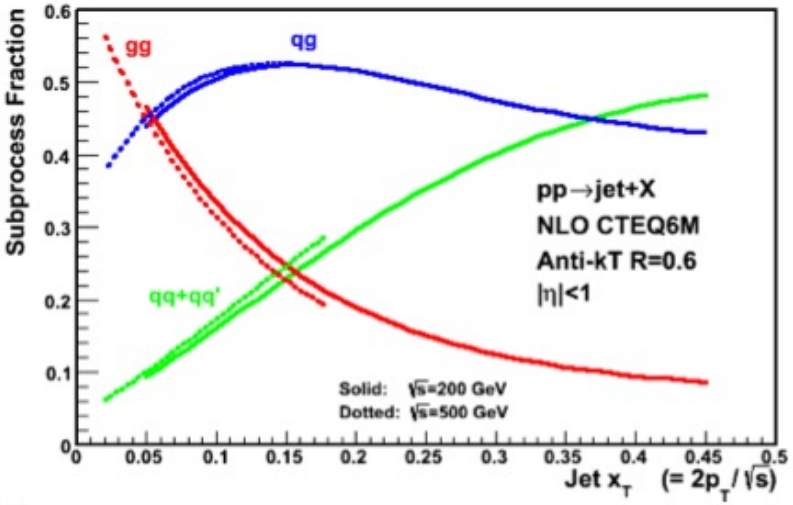


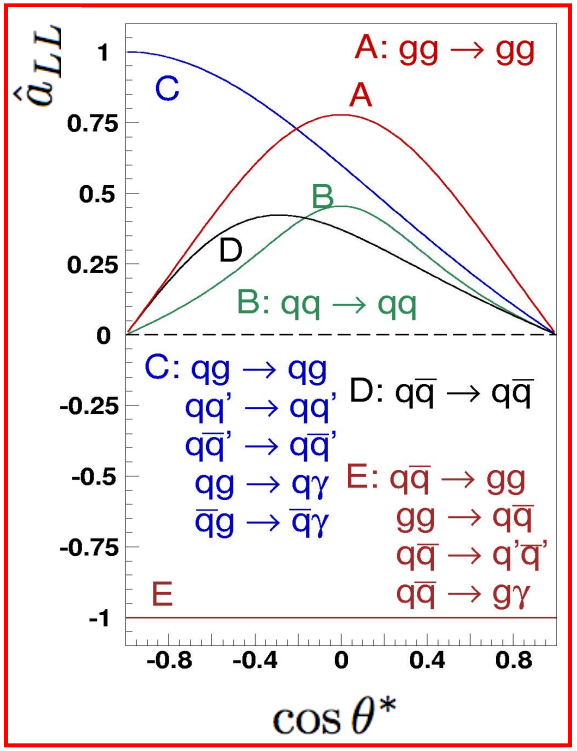
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \cdot \hat{a}_{LL}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}$$

Δf_1 Δf_2 $\hat{a}_{LL} = \frac{d\Delta\hat{\sigma}}{d\hat{\sigma}}$ D_f^{π}



- Partonic fraction for jet/π^0 production:

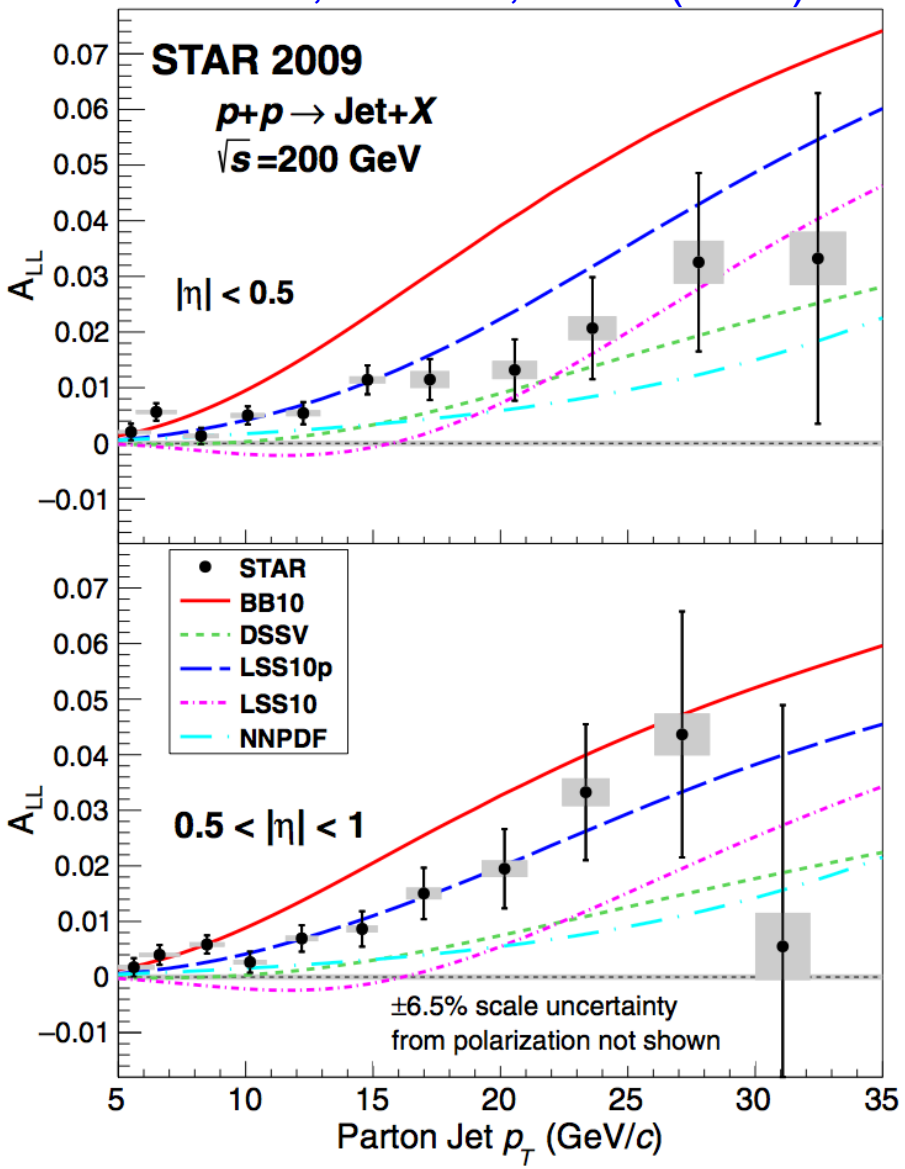




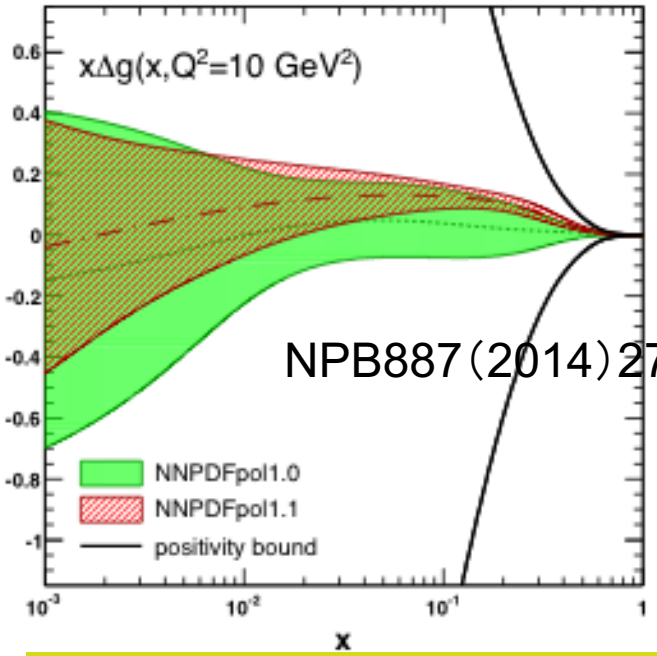
G. Bunce et al, Annu. Rev. Nucl. Part. Sci. 50, 525(2000)

STAR inclusive jet A_{LL} from run9

STAR, PRL115, 92002(2015)



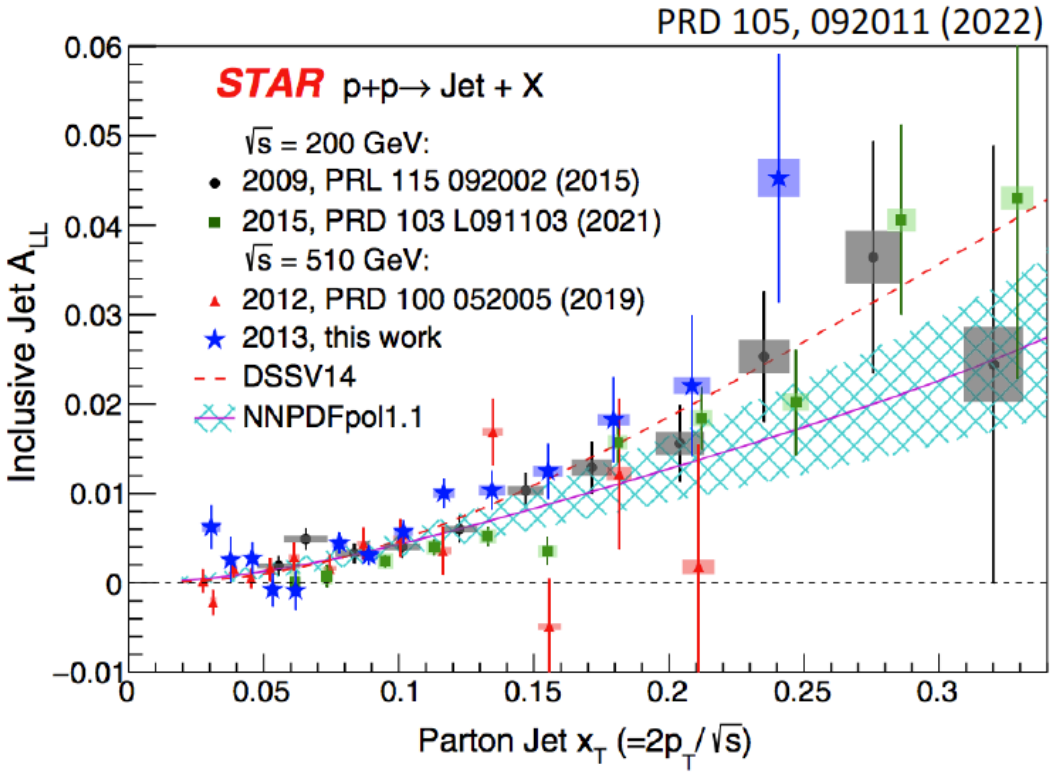
- 1st non-zero asymmetry from 2009 STAR data, factor of 4 more precise than 2006 data
- The A_{LL} asymmetry is small, but clearly non-zero !
- Impact of STAR data in NNPDF:



$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10 GeV^2) dx = 0.17 \pm 0.06$$

A_{LL} results on jet at 510 GeV from STAR

- Can we further improve our knowledge on Δg(x)? Yes!
  - ✓ STAR jet A_{LL} at 510 GeV with data in 2012 and 2013, accessing small x region down to x~0.015, compared to x~0.05 at 200GeV.
  - ✓ Precision data at 200 GeV from 2015, concluding STAR longitudinal spin program.



STAR jet A_{LL} data & publication:

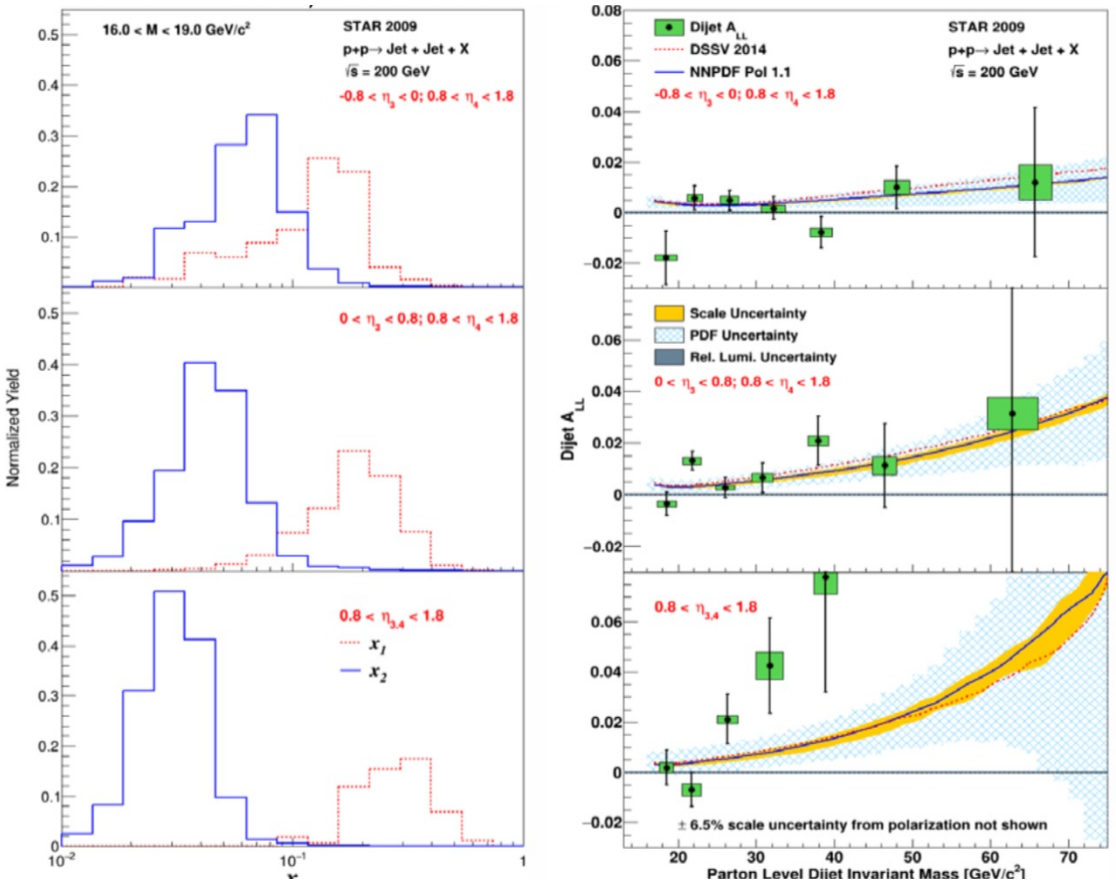
200 GeV:
2009: PRL115,92002(2015)
2015: PRD103,91103(2021)

510 GeV:
2012: PRD100,52005(2019)
2013: PRD 105,92011(2022)

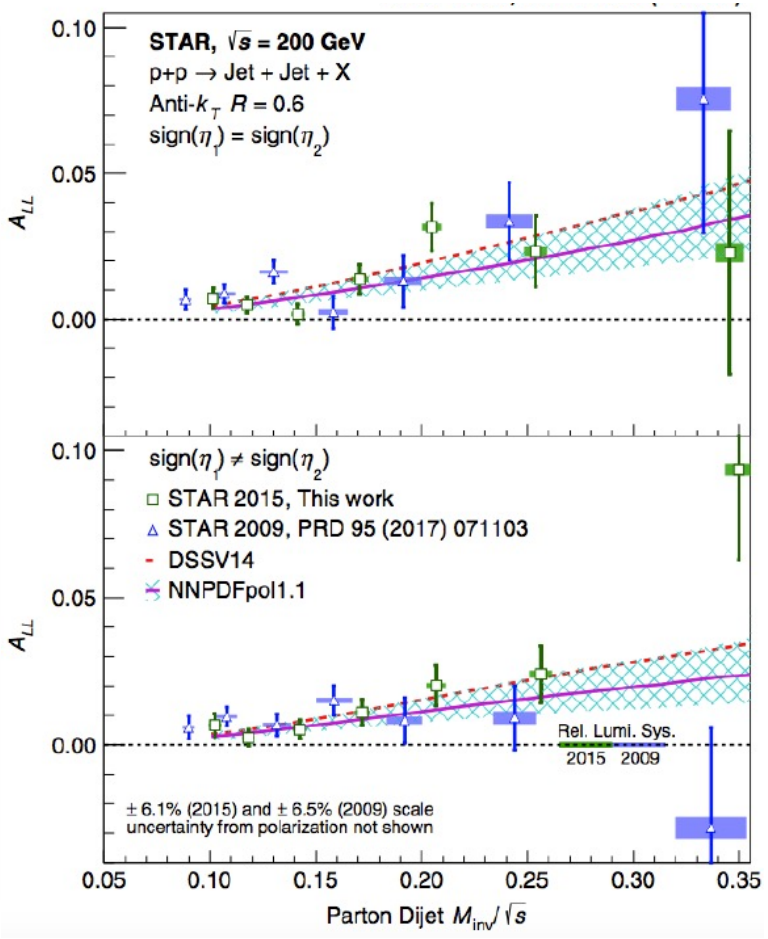
Recent di-jet A_{LL} results at STAR

- Di-jet provides wider coverage to access lower x region, allowing for constraints on the shape of $\Delta g(x)$

STAR, PRD95,071103(2017)
STAR, PRD98,032011(2018)

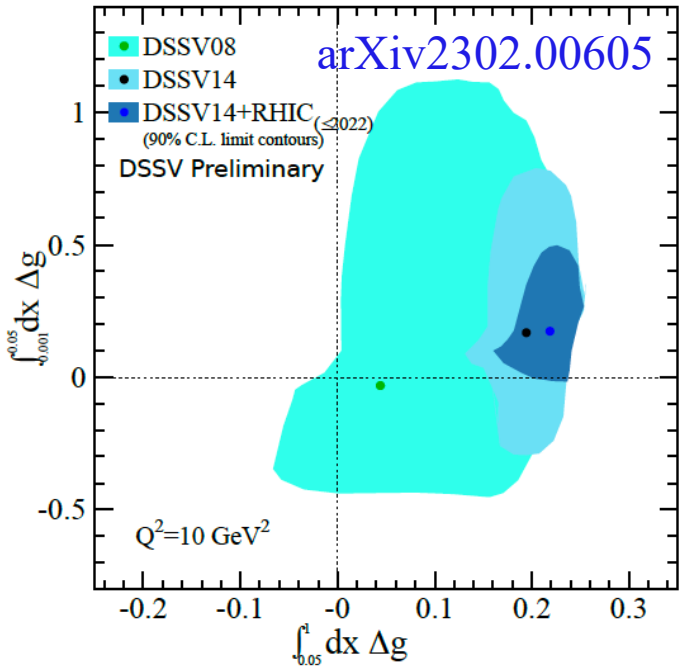


STAR, PRD105,92011(2022)
STAR, PRD103,91103(2021)

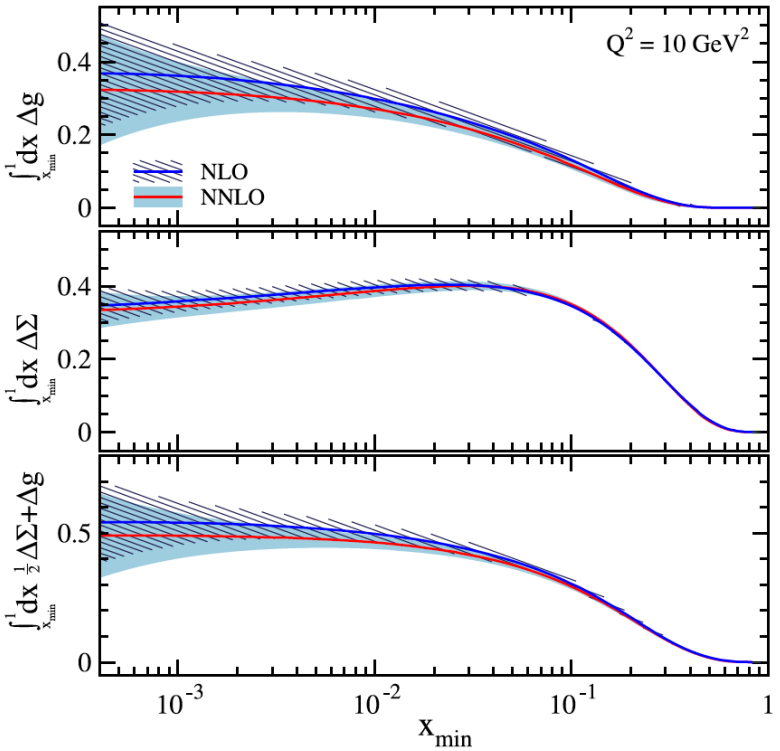


Recent updates from DSSV group on Δg

- The impact of RHIC 2014+ data on gluon polarization Δg :



- How does it all add up to proton spin? Recent NNLO analysis by DSSV24
  - ✓ 55% of proton spin in x > 0.01 comes from gluons.
  - ✓ 40% of the proton spin in x > 0.01 comes from quarks.



BDSSV, PRL133, 151901(2024)

- Consistent with 1st lattice calculation:

$$\int_0^1 dx\Delta g(x) = 0.251 \pm 0.047(\text{stat.}) \pm 0.016(\text{syst.})$$

χQCD, PRL118,102001(2017)

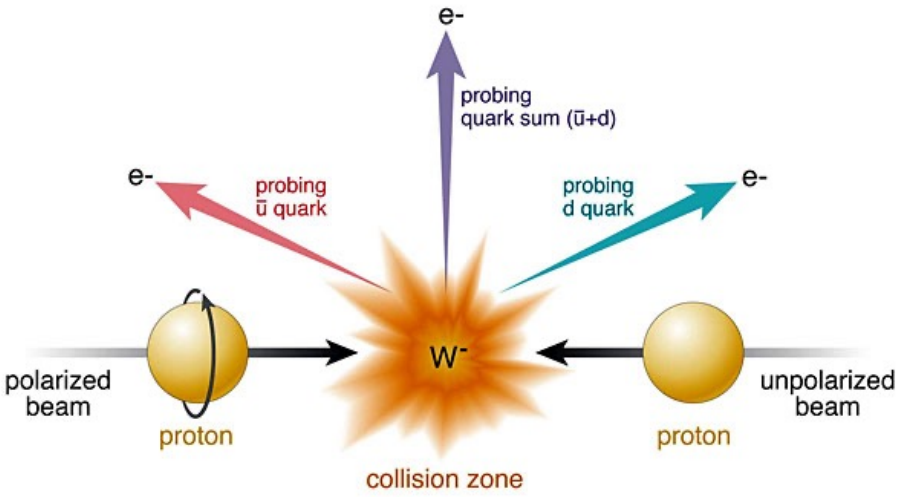
Probing sea quark polarization via W production

- Unique quark polarimetry with W-bosons at RHIC:

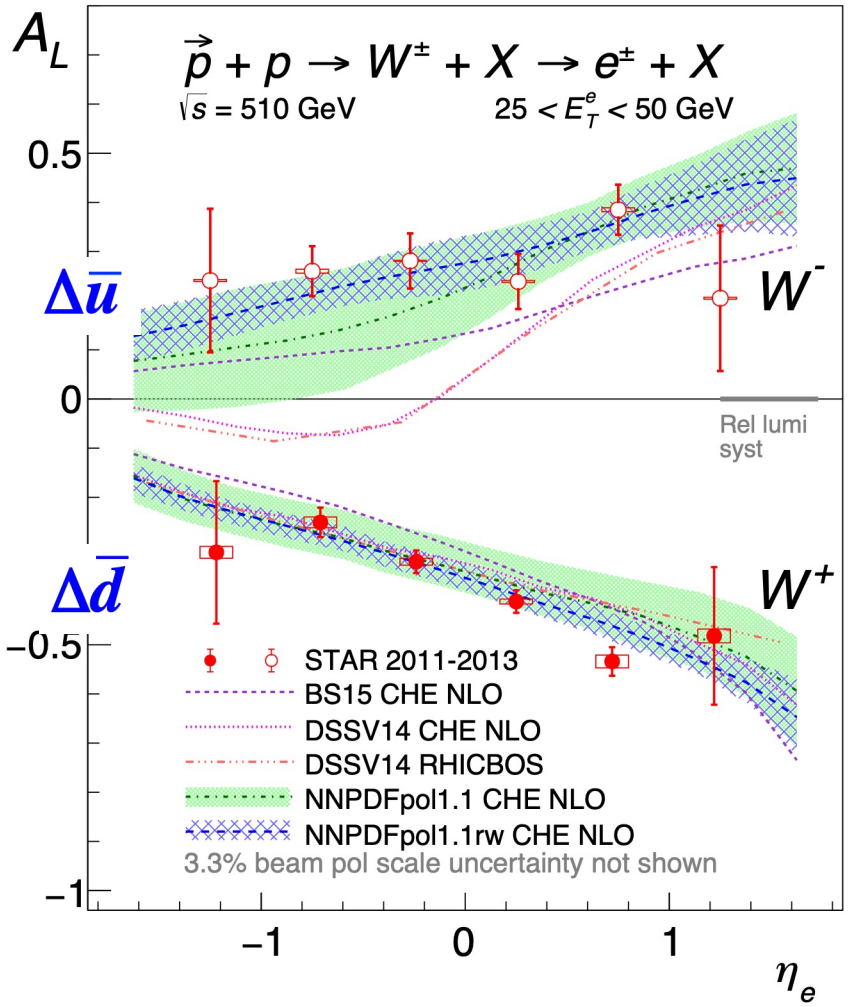
$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \sim \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \end{cases}$$

$$A_L^{W^-} \sim \begin{cases} -\dfrac{\Delta d(x_1)}{d(x_1)}, & y_{W^-} >> 0 \\ \dfrac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}, & y_{W^-} << 0 \end{cases}$$

- Dedicated 500 GeV p+p run at RHIC during 2011-2013
  - W-detection through high p_T lepton
  - no fragmentation function involved



Final W A_L results – STAR 2011-2013



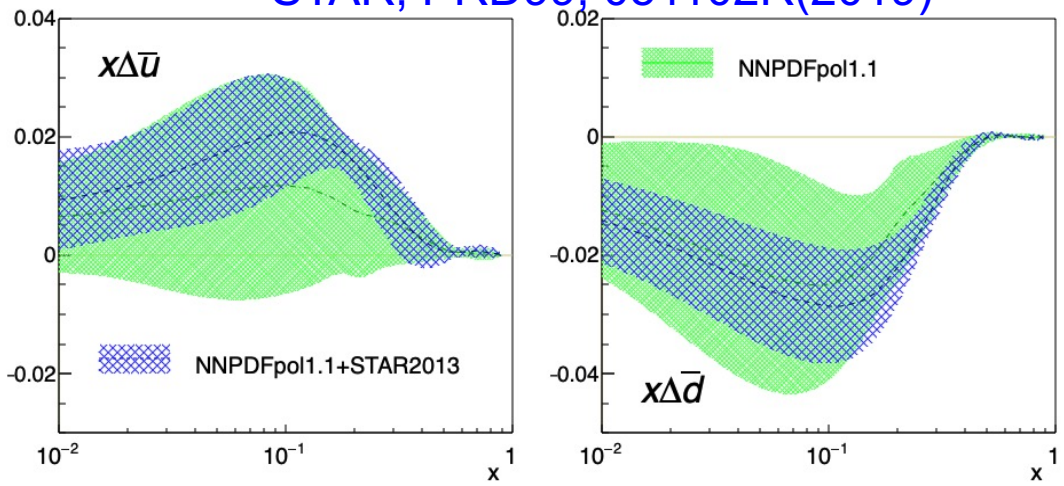
STAR, PRL113, 072301 (2014)
PRD99, 051102R(2019)

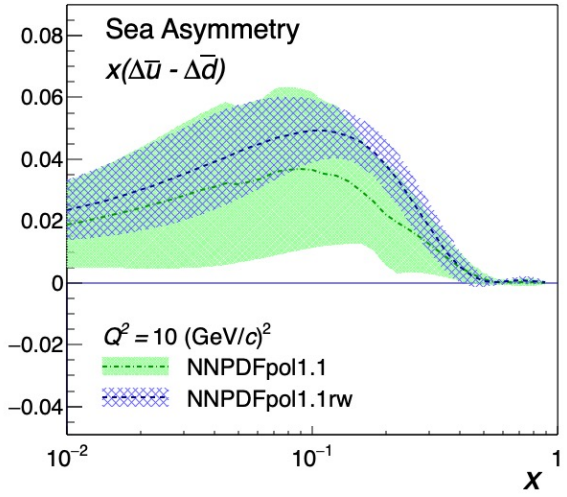
- Combined STAR 2011-2013 results in comparison with theoretical predications
- A_L of W^- shows that data are larger than the DSSV predictions
  -> new constraints
- A_L of W^+ is consistent with theoretical predictions using global fits based on DIS data
  -> universality

Impact of STAR W A_L results

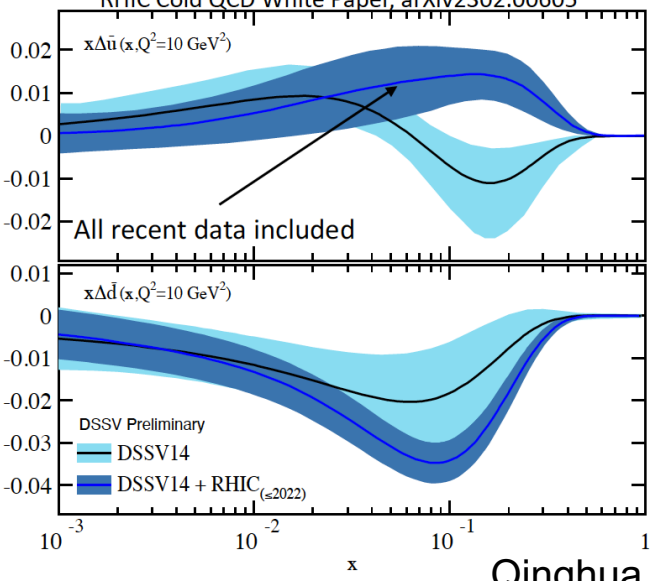
- SU(2) flavor asymmetry observed in the polarized sea quark distribution, confirmed by JAM, NNPDF(after reweighting) and DSSV:

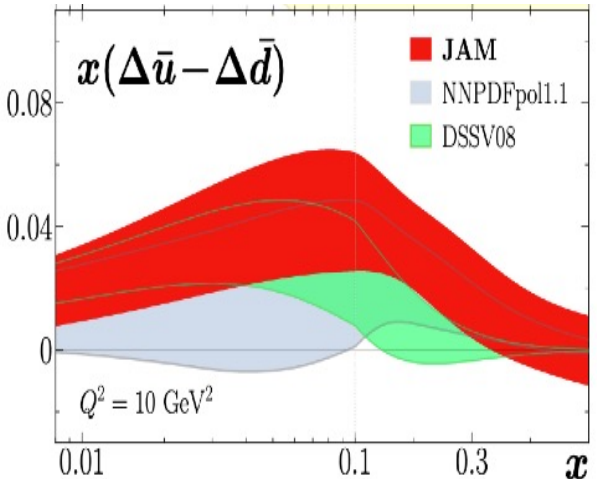
STAR, PRD99, 051102R(2019)





RHIC Cold QCD White Paper, arXiv2302.00605

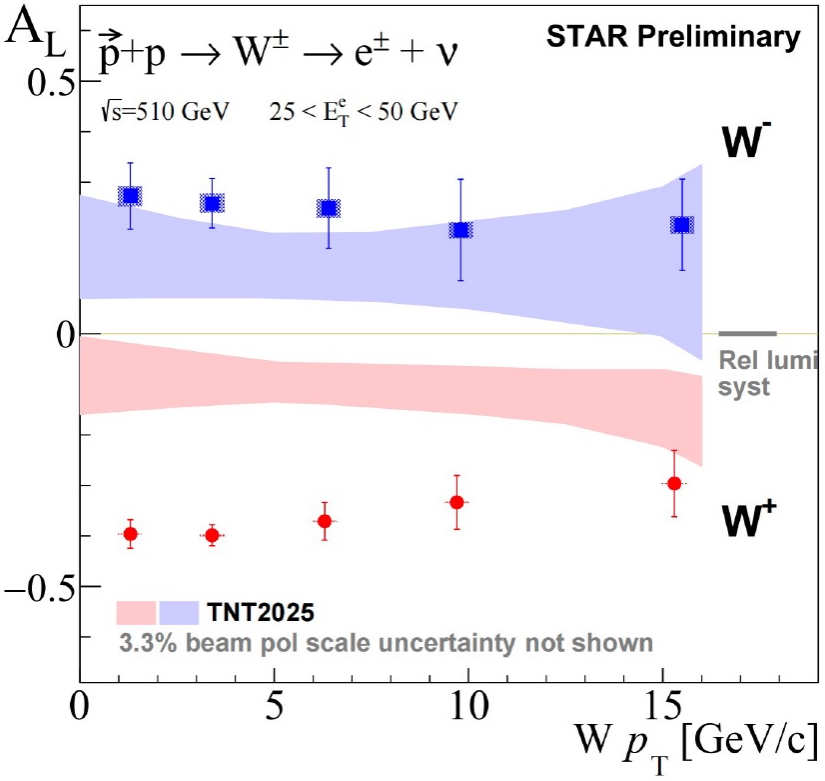


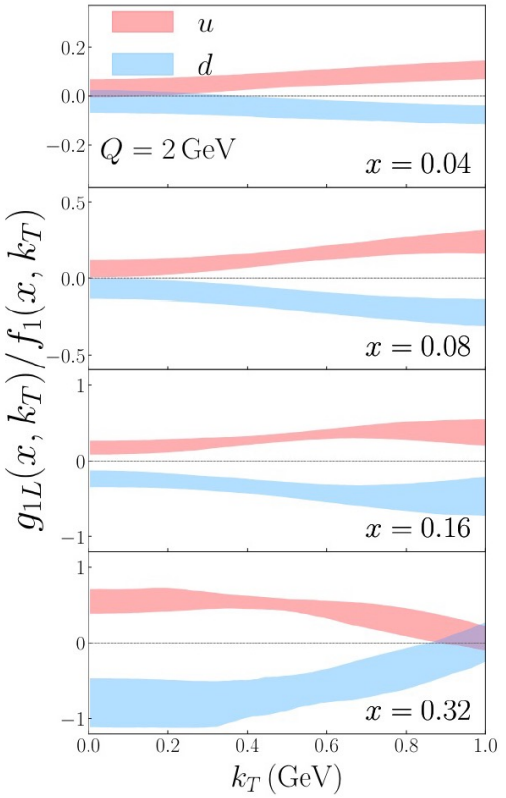


JAM, PRD106, 031502(2022)

W A_L and TMD helicity distributions

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





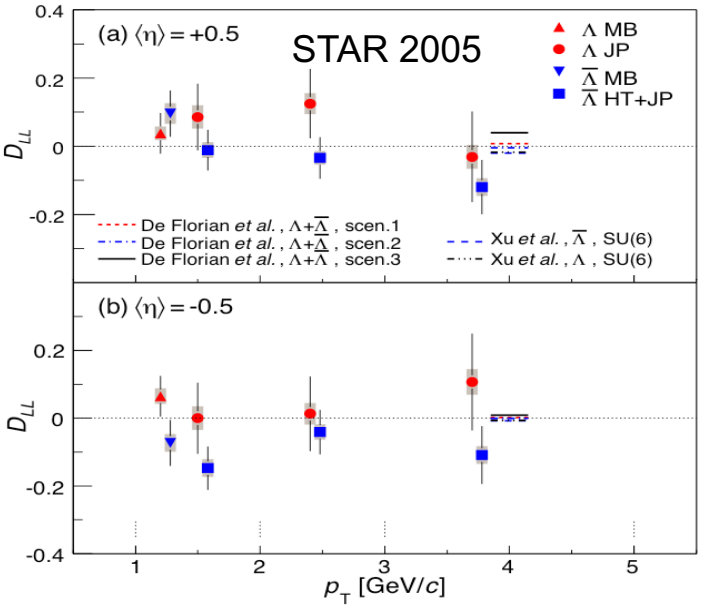
TNT: K.Yang , et al, PRL134, 121902 (2025)

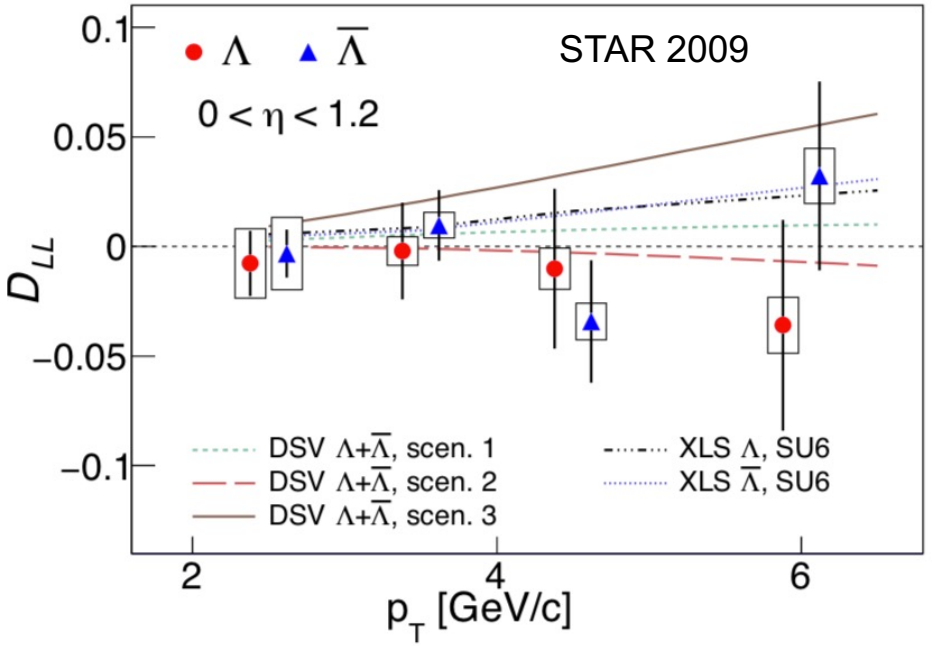
- ✓ The average A_L is consistent with published results
- ✓ Significant difference between data and TNT2025 predictions, especially for W^+

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.

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





- D.de Florian, M.Stratmann, W. Vogelsang, PRL81,530(1998)

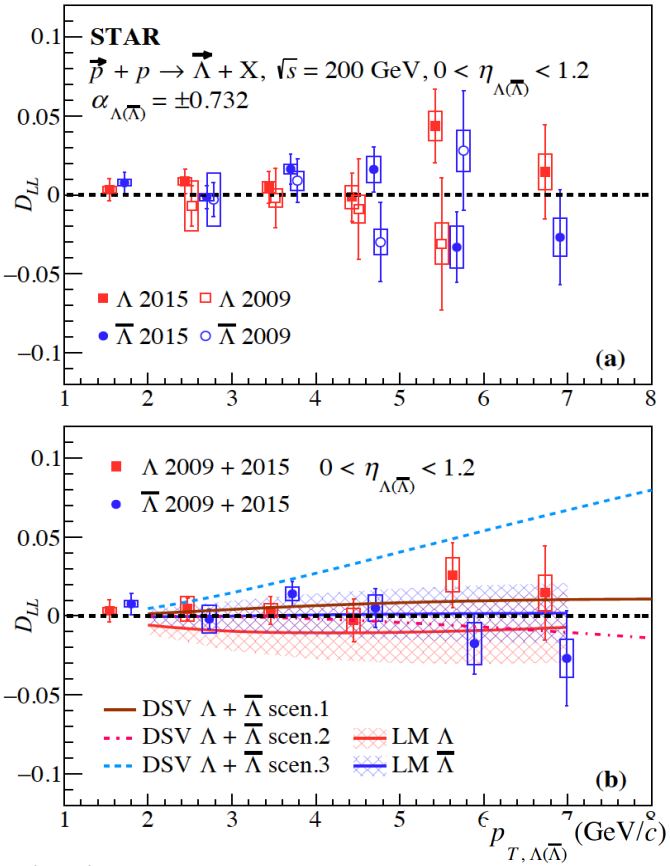
- Q. Xu, Z.T. Liang, E. Sichtermann, PRD 73, 077503(2006)

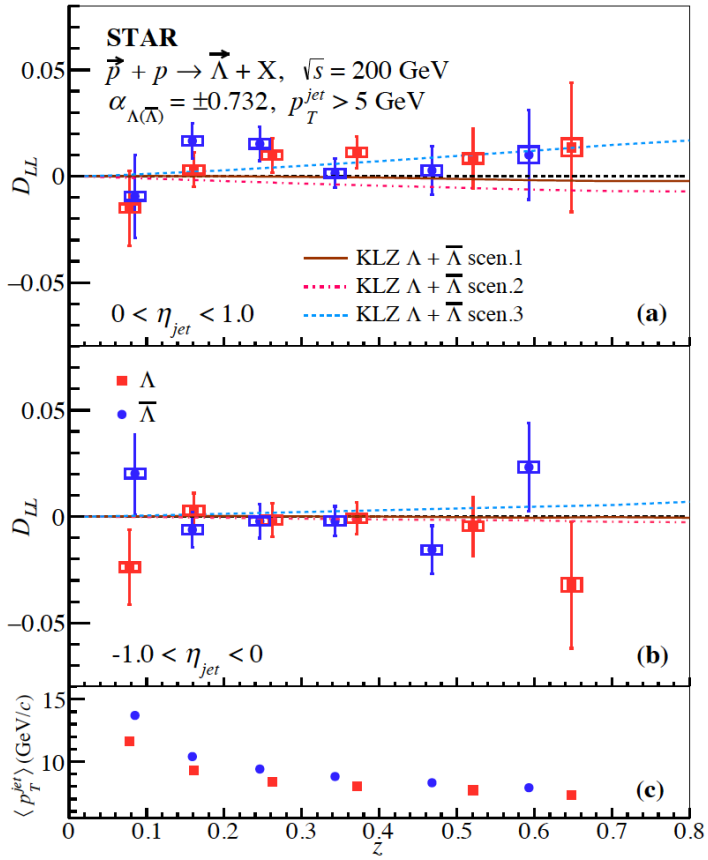
➢ Statistics uncertainties are comparable to the spread of model calculation.

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)





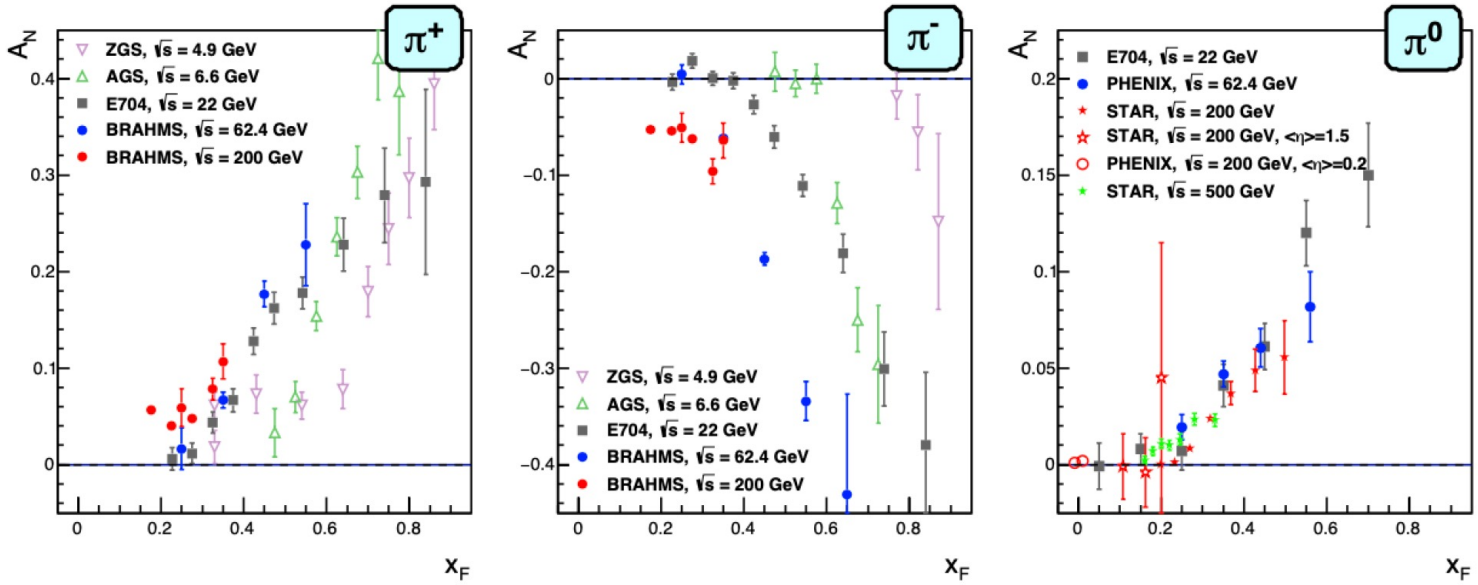
$$z=\frac{\boldsymbol{p}_{\Lambda}\cdot\boldsymbol{p}_{jet}}{|\boldsymbol{p}_{jet}|^2}$$

- *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 Single-Spin Asymmetry (TSSA)

- Anomalously large A_N in pp collisions observed for nearly 50 years

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



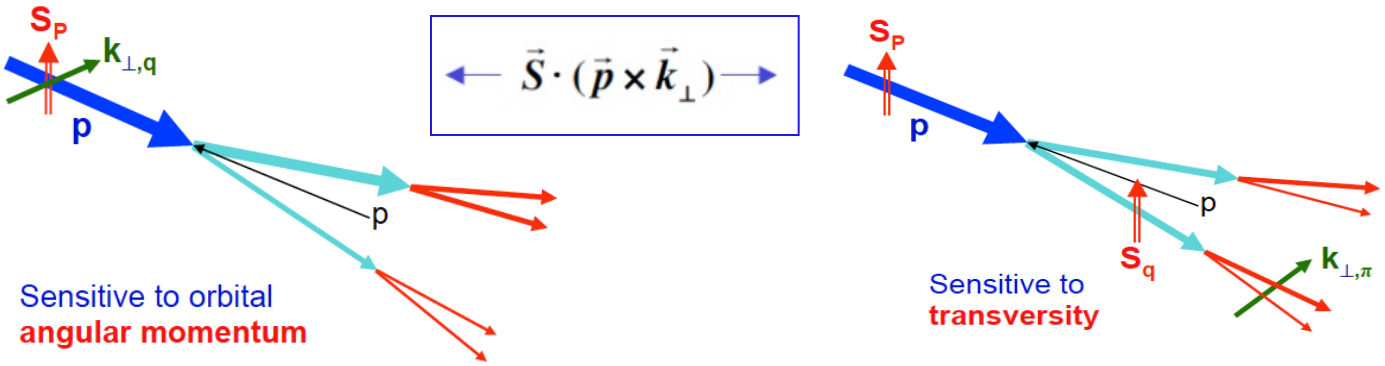
- LO pQCD predicts $A_N \sim 0$

  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

Transverse spin asymmetry & TMD distribution

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

Leading Quark TMDPDFs — Nucleon Spin, Quark Spin

Nucleon Polarization	Quark 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

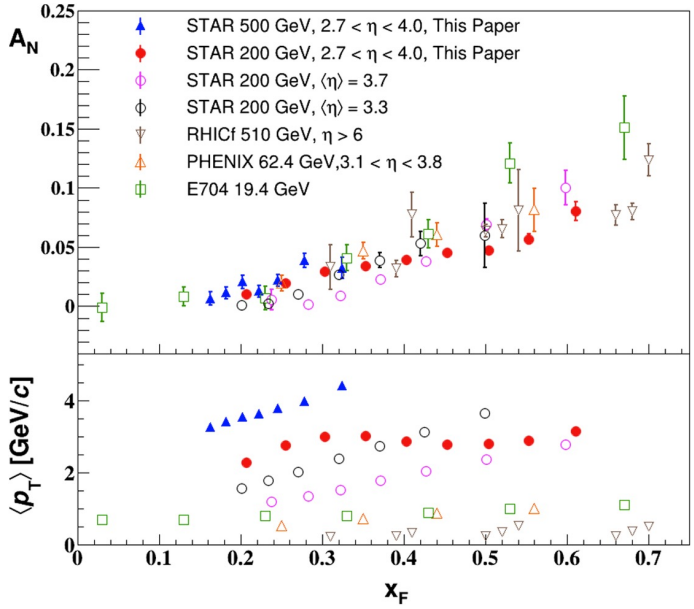
	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons	D_1 = Unpolarized		$H_1^\perp$ = Collins
Polarized Hadrons: L		G_1 = Helicity	$H_{1L}^\perp$
Polarized Hadrons: T	$D_{1T}^\perp$ = Polarizing FF	$G_{1T}^\perp$	H_1 = Transversity;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

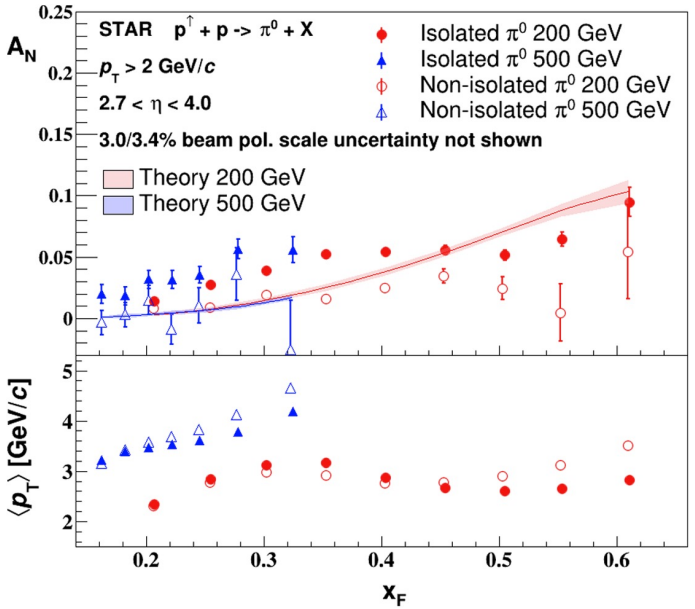
TMD handbook: ariXiv-2304.03302

➢ Sivers, Transversity, Collins related measurements at RHIC

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?





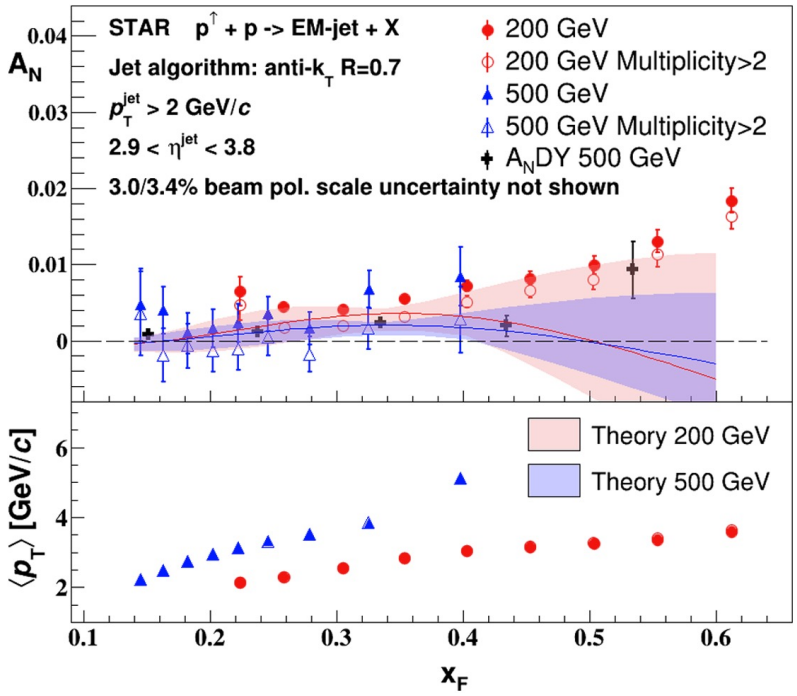
STAR, PRD103, 72005 (2021)
PRD103, 92009 (2021)

- 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

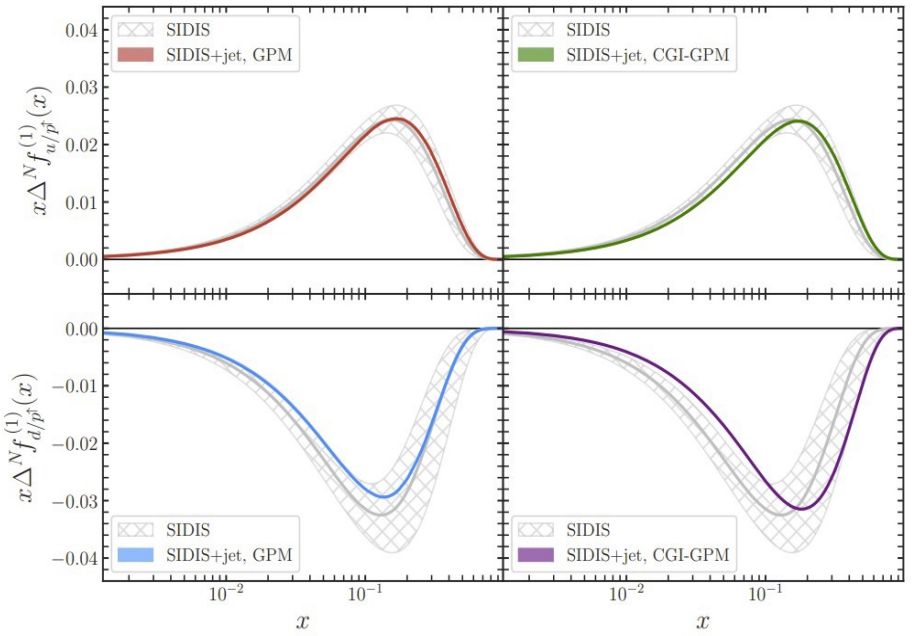
- STAR EM-jet A_N - sensitive to the initial state effect, Sivers effect
- Impact of STAR data in constraining Sivers function via global analysis

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

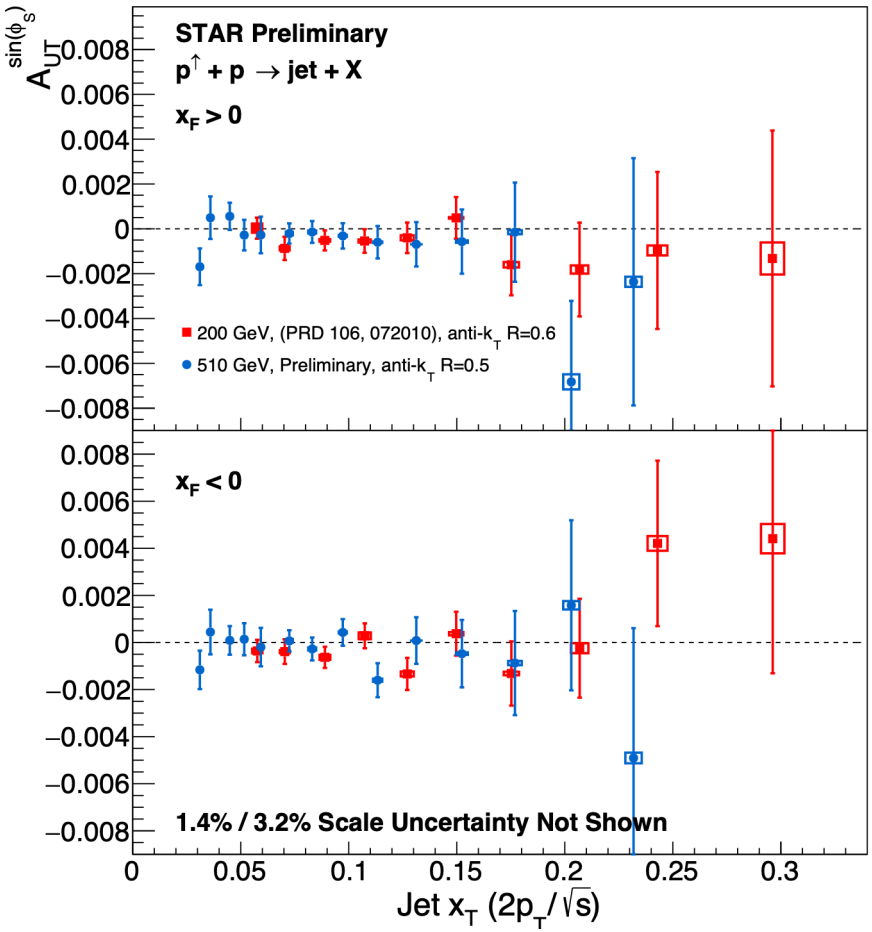


➢ Initial state effect is small

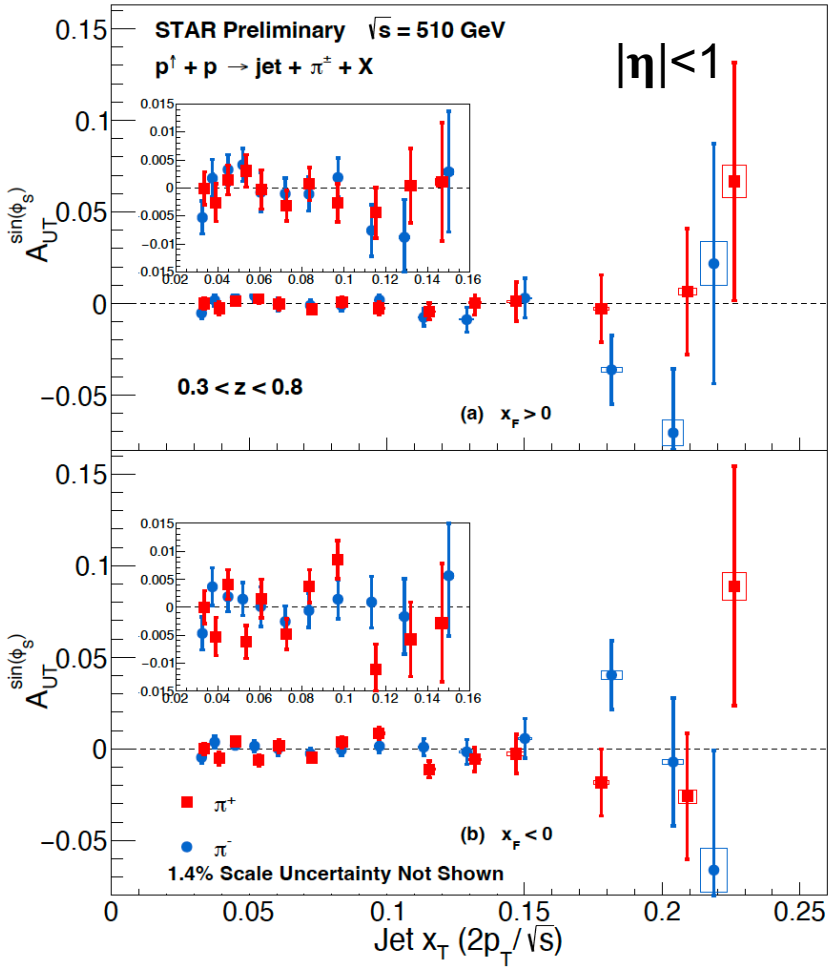
Jet A_N at mid-rapidity in p+p collisions

- A_N for inclusive jet

STAR, PRD106, 072010 (2022)



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

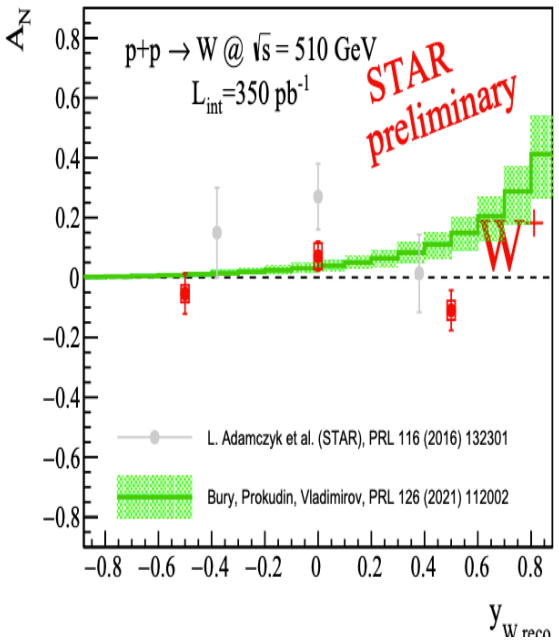


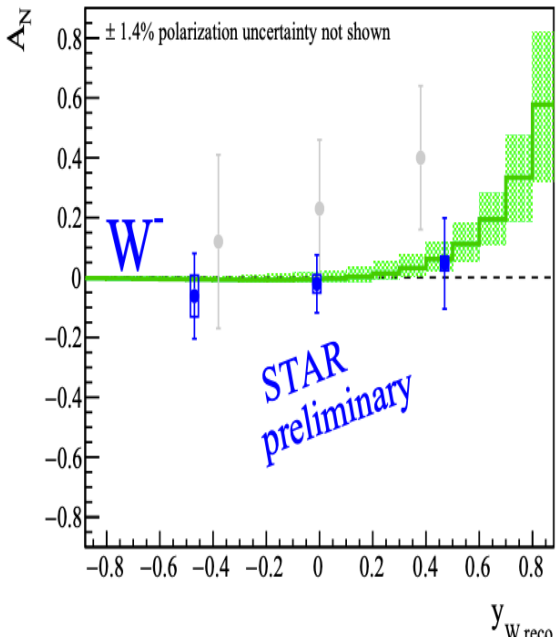
➢ Full jet A_N providing sensitivity to the twist-3 correlators associated with the gluon and quark Sivers function

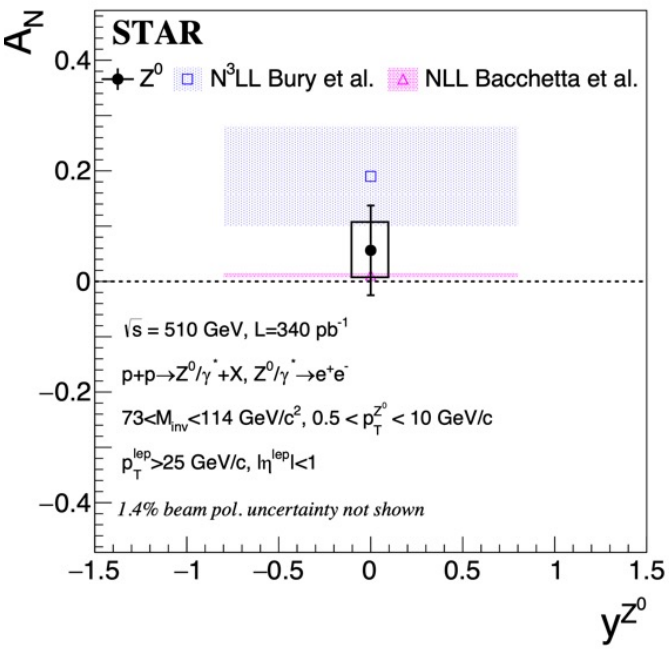
Recent measurements of W/Z A_N at STAR

- Testing Sivers sign-change in DIS and DY, W/Z process in pp
- STAR results with a much larger data sample taken in 2017:

STAR, PRL116,132301(2016) , PLB 854, 138715(2024)





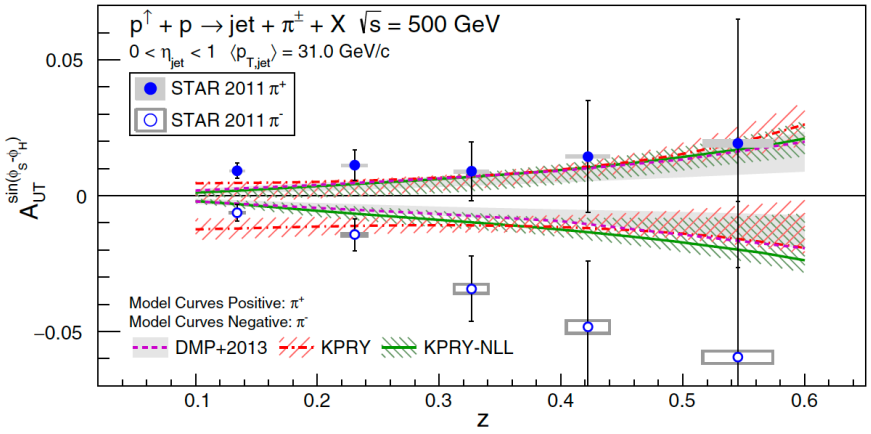


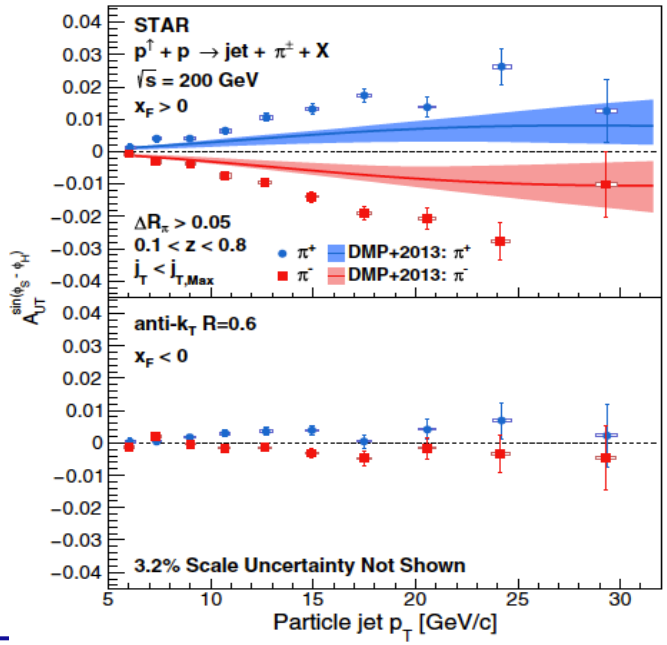
- 2017 results have much improved precision over those from the 2016 publication
- New STAR data (2017+2022) will have biggest impact on high-x region of the quark Sivers function.

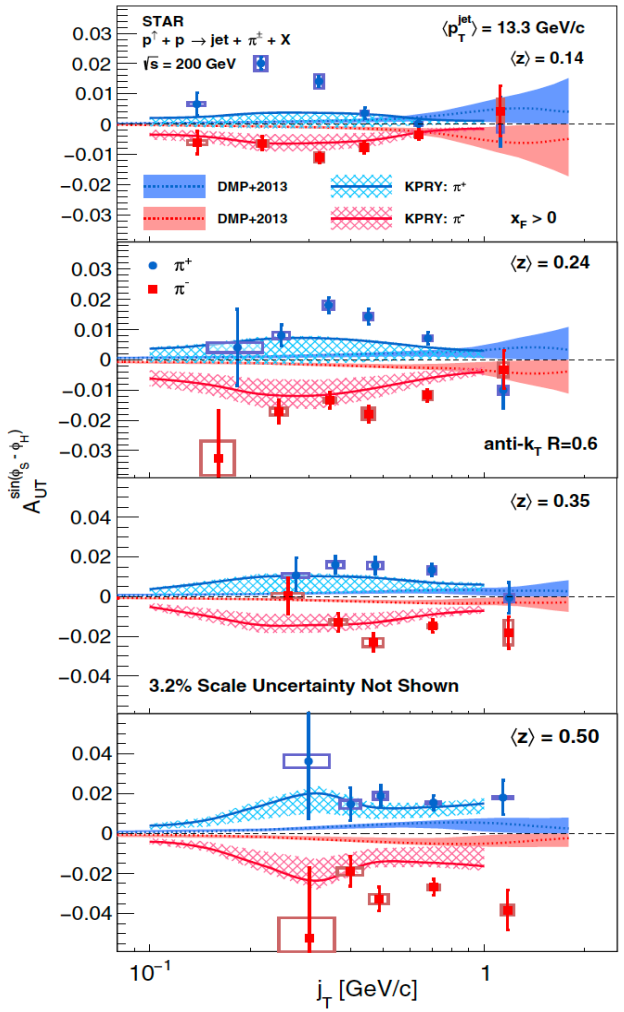
Collins asymmetry in p+p at STAR

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

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



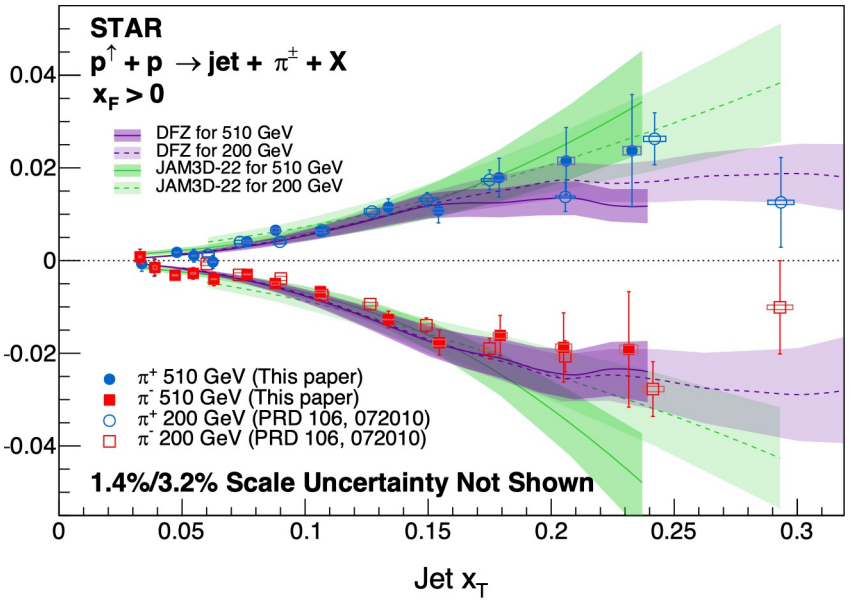


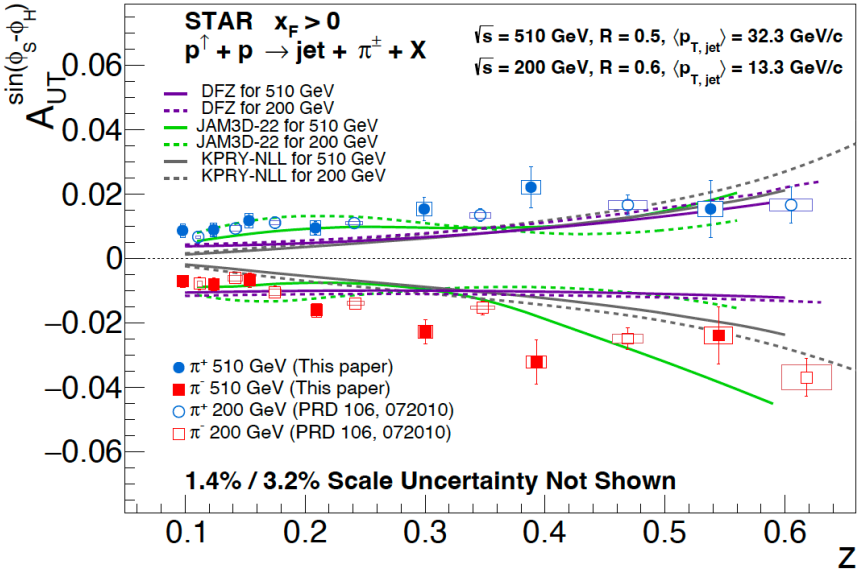


Energy dependence of Collins asymmetry

- Recent 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

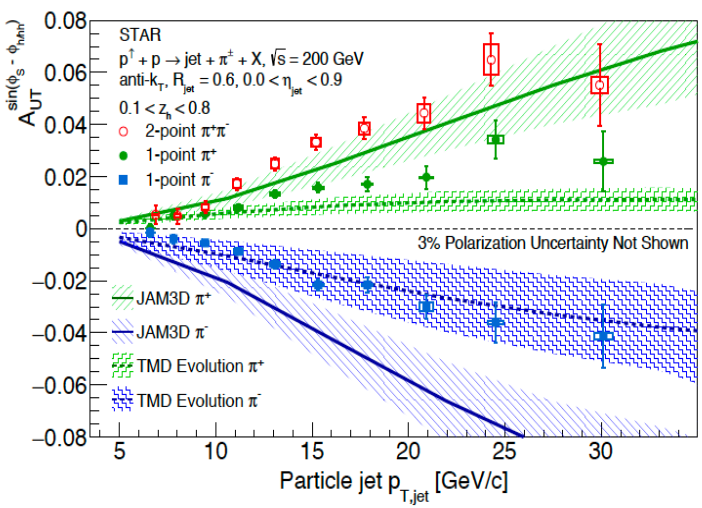
- Pol. EEC: Project spin–dependent frag. functions onto Mellin moments

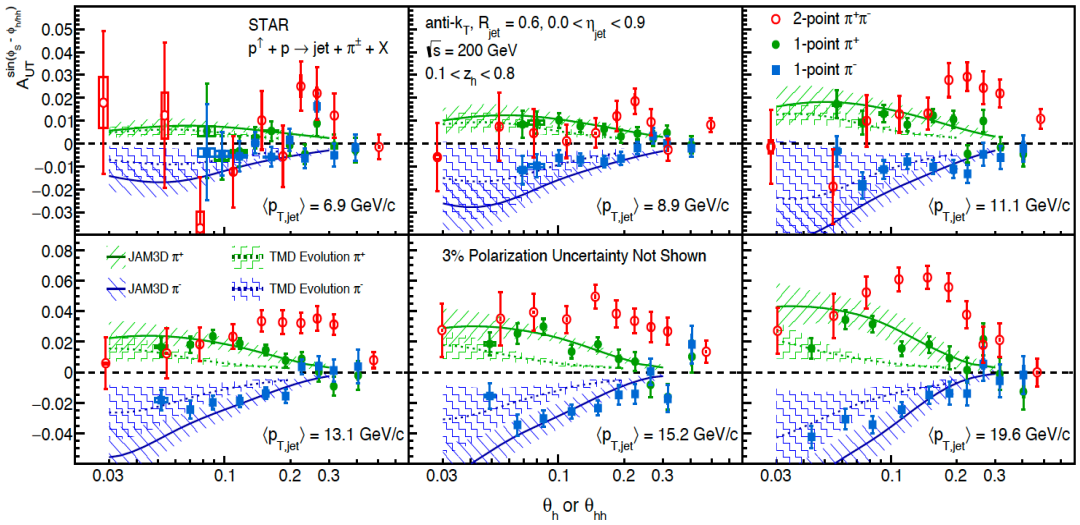
$$\mathrm{EEC}(\theta_h, \phi_h) = \frac{d(\sum_{jet}\sum_i z_{h,i})}{d\theta_h d\phi_h} \qquad z_h = \frac{p_h}{p_{jet}} \text{ , loop over all hadrons in jet}$$

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

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

STAR, arXiv:2604.15543



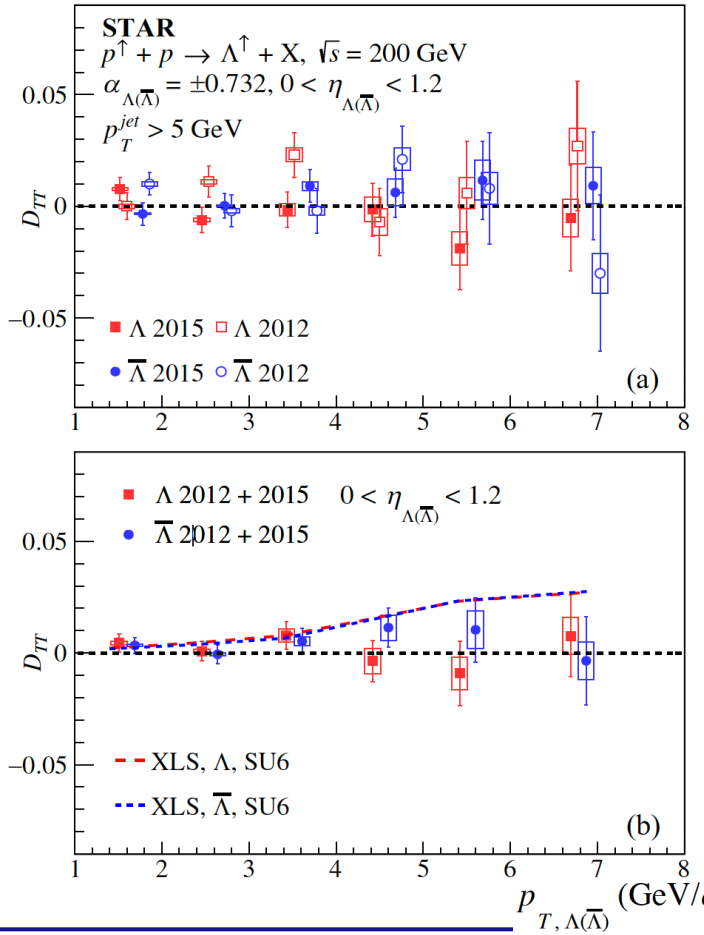


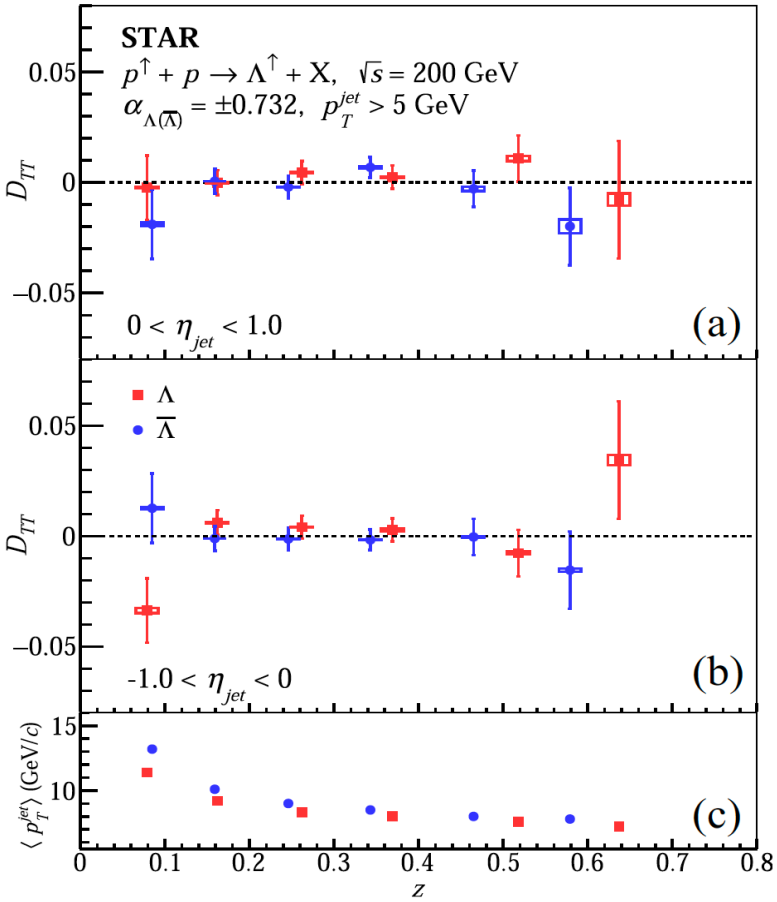
One point EC theory: Gao, Kang, Li, Shao, Zhao, PRL 136, 151902 (2026)

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)

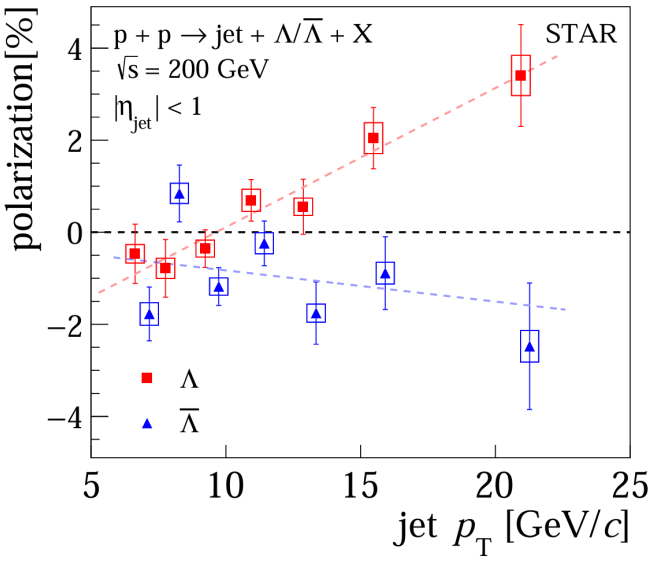


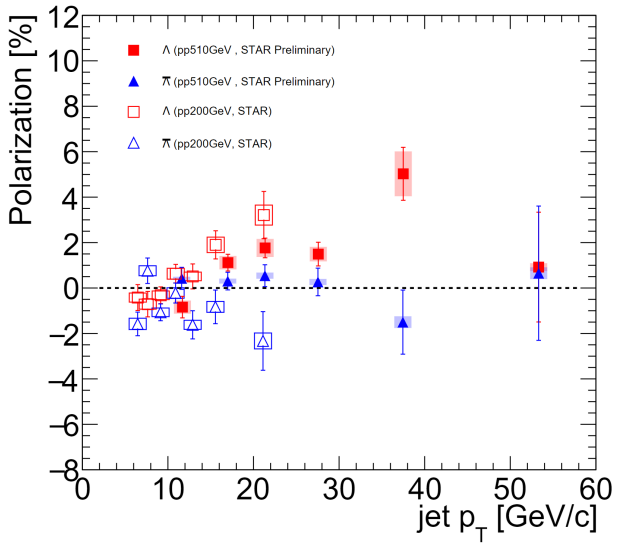


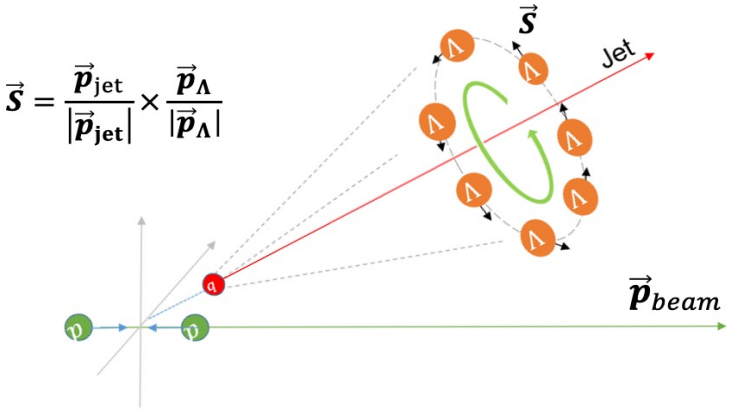
Λ polarization in jets in unpolarized p+p collision

- Λ polarization in jets in p+p -> polarizing fragmentation function at STAR:

STAR, JHEP 06 (2026) 050

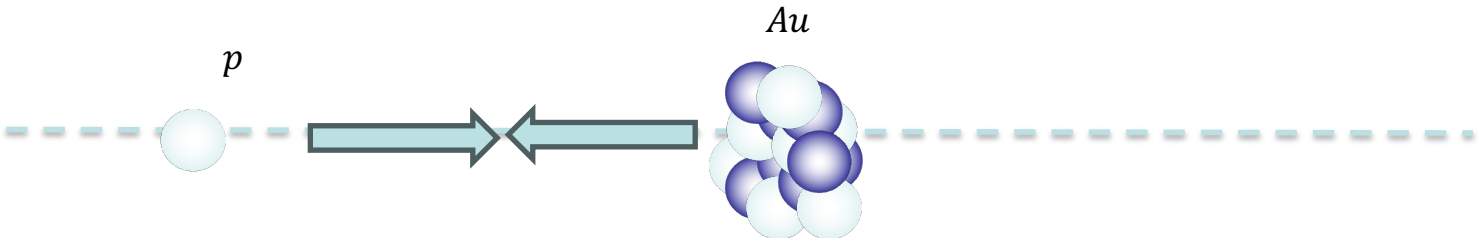


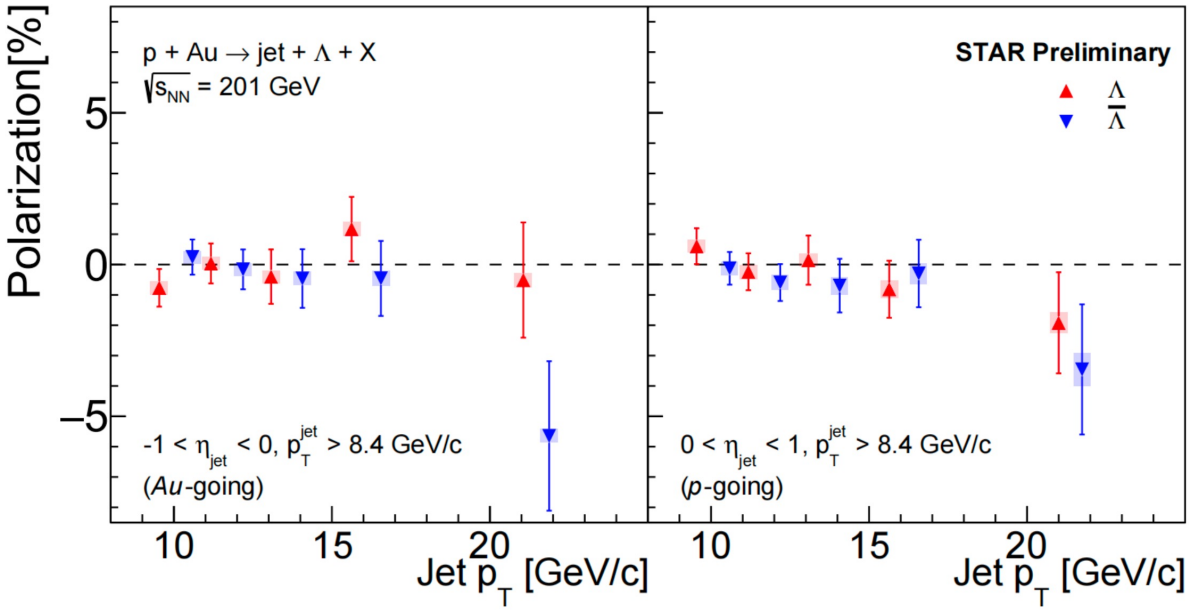




- First measurement of Λ polarization in jets in pp collisions
  - ✓ Clear jet p_T dependence of Λ polarization
  - ✓ $\bar{\Lambda}$ polarization mostly remains negative
  - ✓ First constraints on gluon PFF

Λ polarization in jets in unpolarized p+Au collision





- Polarization studied for *p* and *Au* side, for possible nuclear effect
- No significant transverse polarization is observed in p-Au collisions
- An indication of nuclear medium effects in p-Au collisions

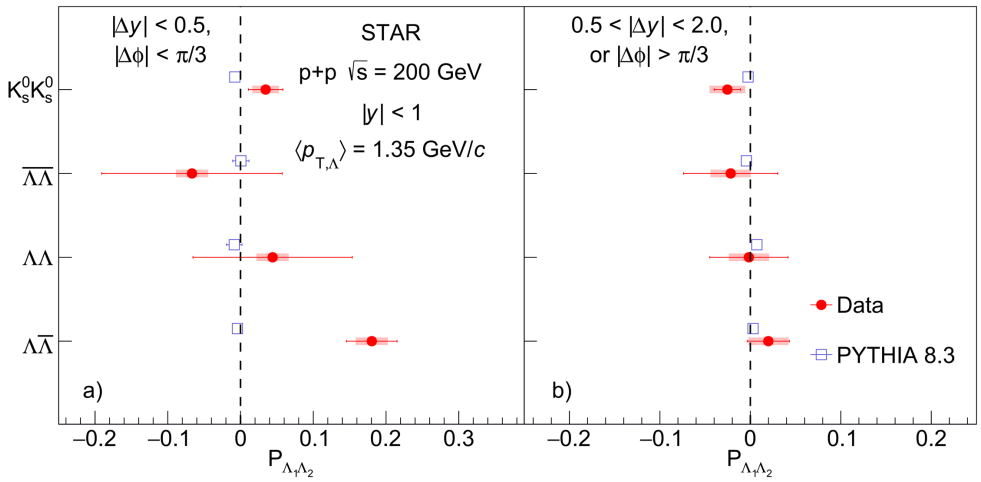
Λ - anti Λ spin correlations in p+p collision

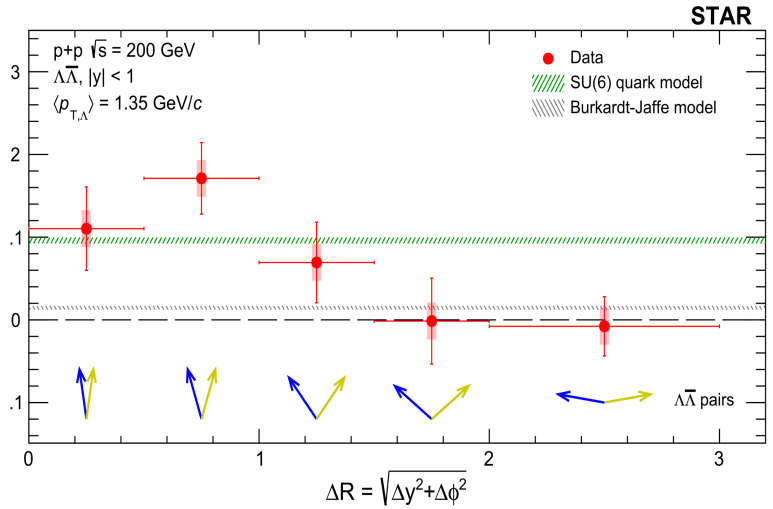
- Non-zero spin correlation for short range Λ - anti Λ pairs
- Correlation consistent with zero for long range pairs and other pairs

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

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

STAR, Nature 650, 65(2026)



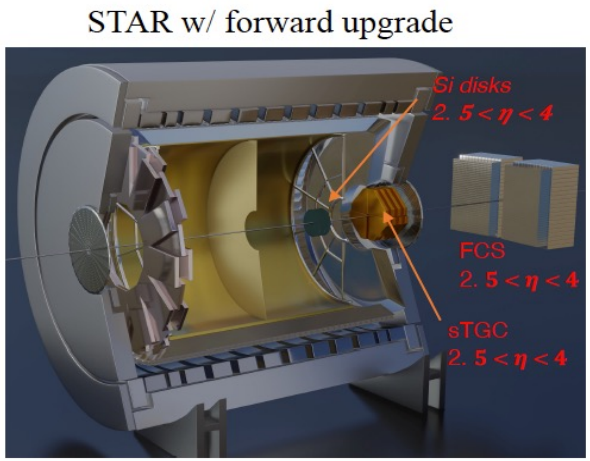


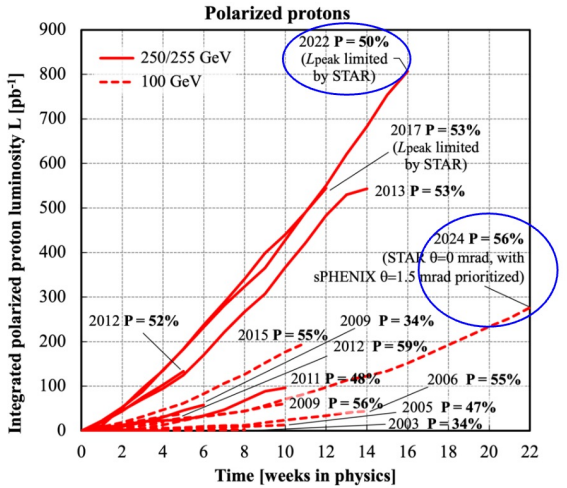
➢ Possible source: maximally entangled s - sbar spin correlation of pairs from QCD vacuum ?

- Data analysis with A+A collision is ongoing

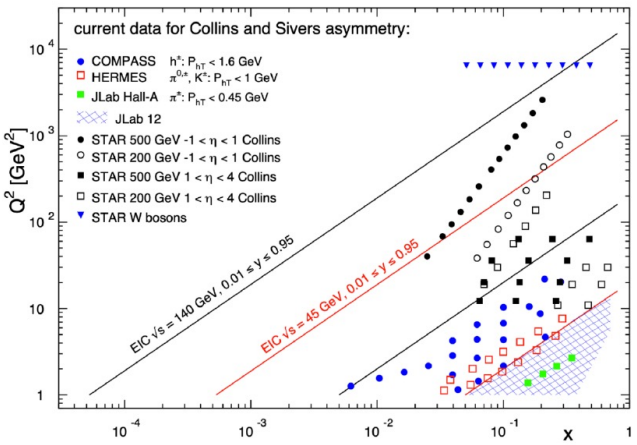
STAR p+p running with new forward detectors

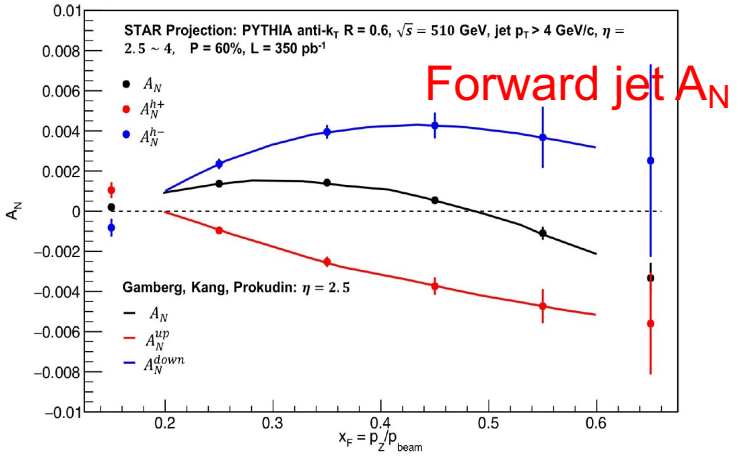
- Successful p+p runs in 2022+2024 with STAR forward upgrade (2.5<η<4)
- Highest statistics at both 200 and 510 GeV with transverse beam polarization





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





Summary & Outlook

- Great achievements from STAR spin program in ~25 years
- Observation of significant gluon polarization via jet A_{LL}:

  -probes with jets indicates sizable gluon polarization ($\Delta G \sim 0.2$)
- Unique probe of sea quark polarization via W production:

  - clear evidence of the SU(2) symmetry breaking: $\Delta\bar{u} > \Delta\bar{d}$
- Hyperon spin transfer provide access to polarized strange quark distribution and polarized fragmentation functions
- Transverse spin physics at RHIC:

  - Results on W/Z, EM-jet, π^0 spin asymmetries provide unique constraints on TMD physics: Sivers & Collins, and transversity
- More exciting spin results in p+p (p+A)

  - High statistics p+p data taken in recent years with upgraded detectors

Happy 70th Birthday to Prof. Zhuang

- A great hornor in organizing RHIC workshop with Prof. Zhuang in August 2009

Electron-Ion Collider (EIC)

- **EIC Project Design Goals:**

✓ High Luminosity: L= 10^{33} – 10^{34} $cm^{-2}s^{-1}$, 10～100 fb^{-1}/year

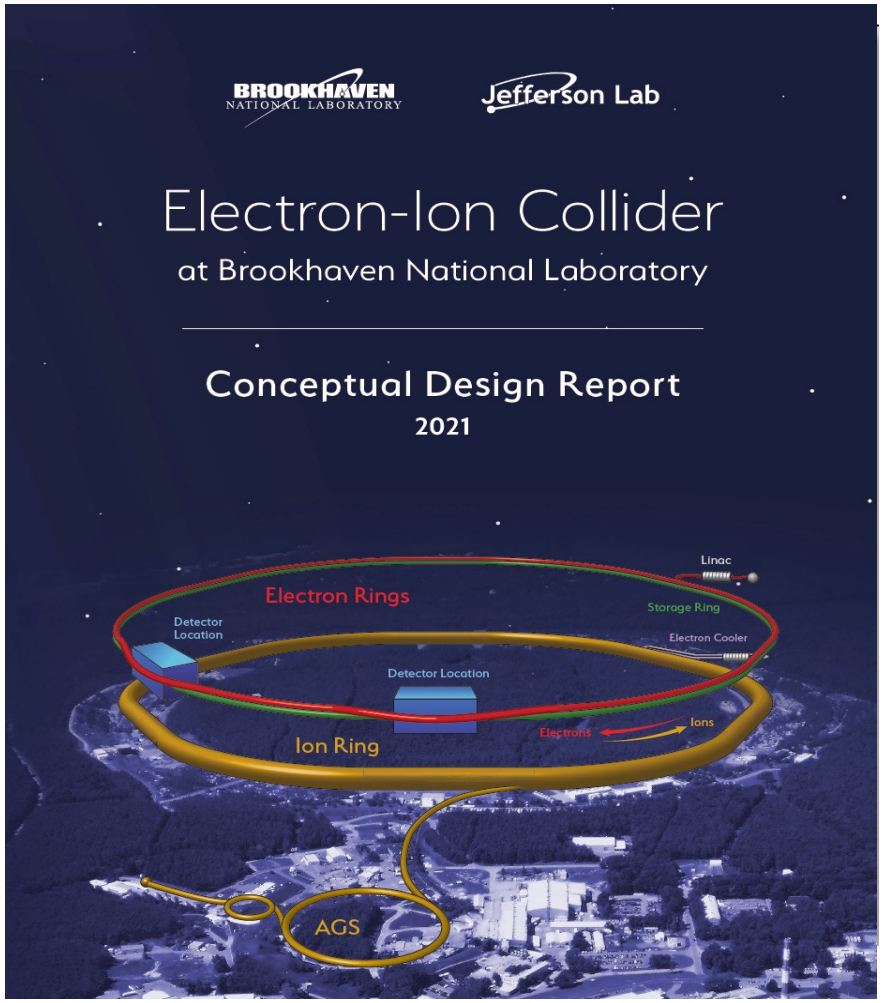
✓ Highly Polarized Beams: 70%

✓ Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV

✓ Large Ion Species Range: protons – Uranium

✓ Large Detector Acceptance

✓ Accommodate a Second Interaction Region (IR)



- EIC will be built at Brookhaven National Laboratory in ～2032+

Electron-ion collider China(EicC)

- **中国电子-离子对撞机计划EicC**
  - ✓ 电子能量2.8～5GeV
  - ✓ 质子/核能量～20GeV
  - ✓ 中等能区、高亮度
  - ✓ 与美国EIC物理互补
  - ✓ 中英文白皮书已发布
  - ✓ 基于兰州所HIAF装置(惠州,2032+)

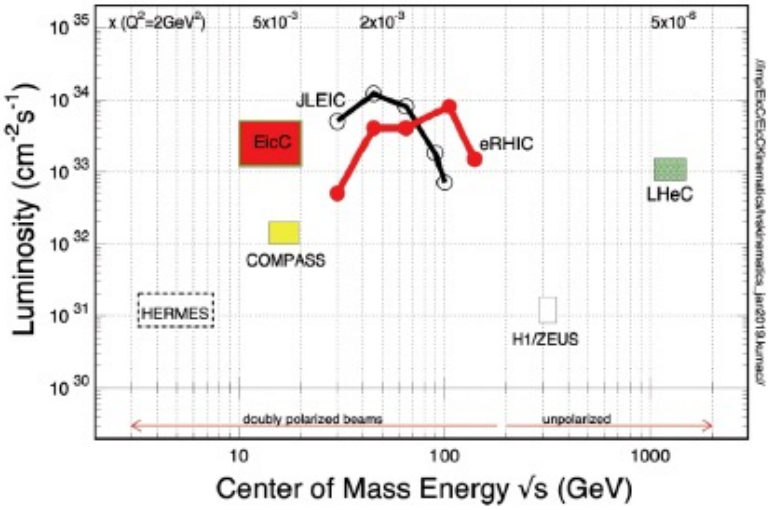


图 1.4: 国际上电子离子装置（包括拟建）亮度和质心系能量比较。

Front. Phys.16(6), 64701 (2021)