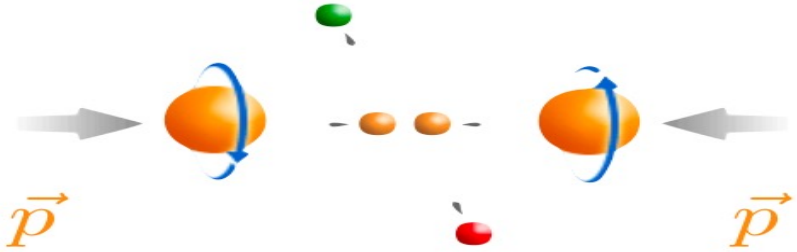
Nucleon spin structure study at RHIC



Qinghua Xu (徐庆华),

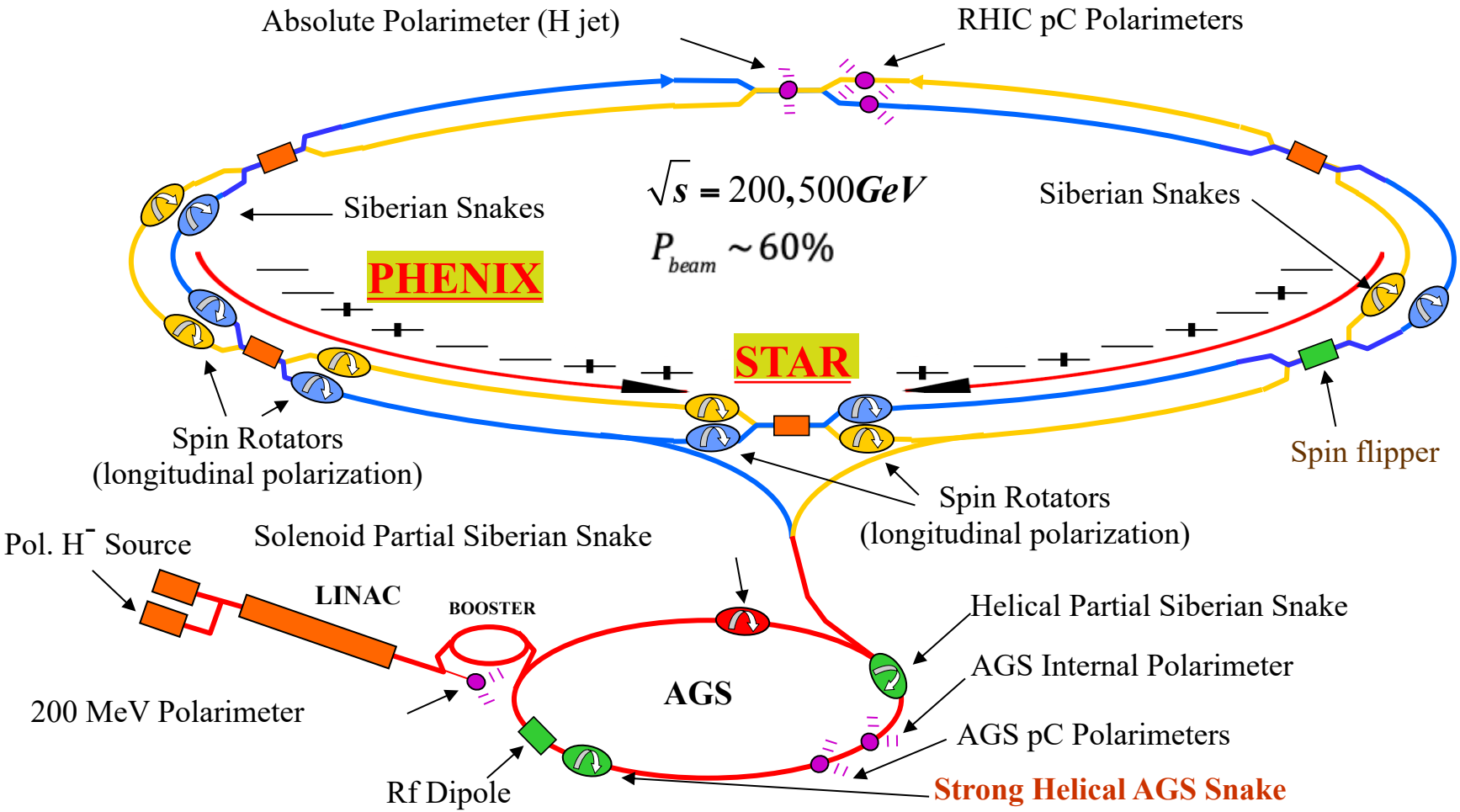
Shandong University（山东大学）

12th Workshop on Hadron Physics and Opportunities Worldwide, Dalian, 8.5-9, 2024

Outline

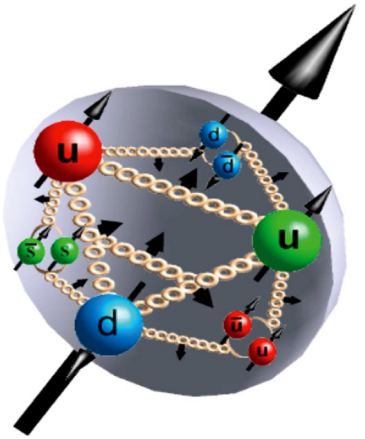
- Introduction
- Recent spin highlights in p+p collisions from RHIC:
  - ✓ Gluon polarization (Jet, π^0 production): gluon polarization Δg
  - ✓ Quark/Anti-quark polarization (W/Z): sea quark $\Delta\bar{u}/\Delta\bar{d}$
  - ✓ Hyperon spin transfer (Λ): strange quark polarization
  - ✓ Transverse spin asymmetry (W/Z, jet): Sivers function
  - ✓ Transverse spin asymmetry (Hadron in jet): Collins & transversity
- Summary & outlook

RHIC- 1st polarized proton-proton collider



- Spin direction changes from bunch to bunch, longitudinal or transverse
- Two main experiments: sPHENIX (PHENIX) & STAR

Spin structure of nucleon



- Spin sum rule (longitudinal case):

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

Quark spin, (~30%)-DIS

Gluon spin, RHIC

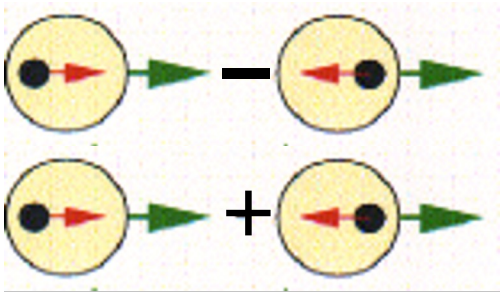
Orbital Angular Momenta Little known

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} \qquad [\Delta q = \int_0^1 \Delta q(x)dx]$$

- Polarized parton densities:

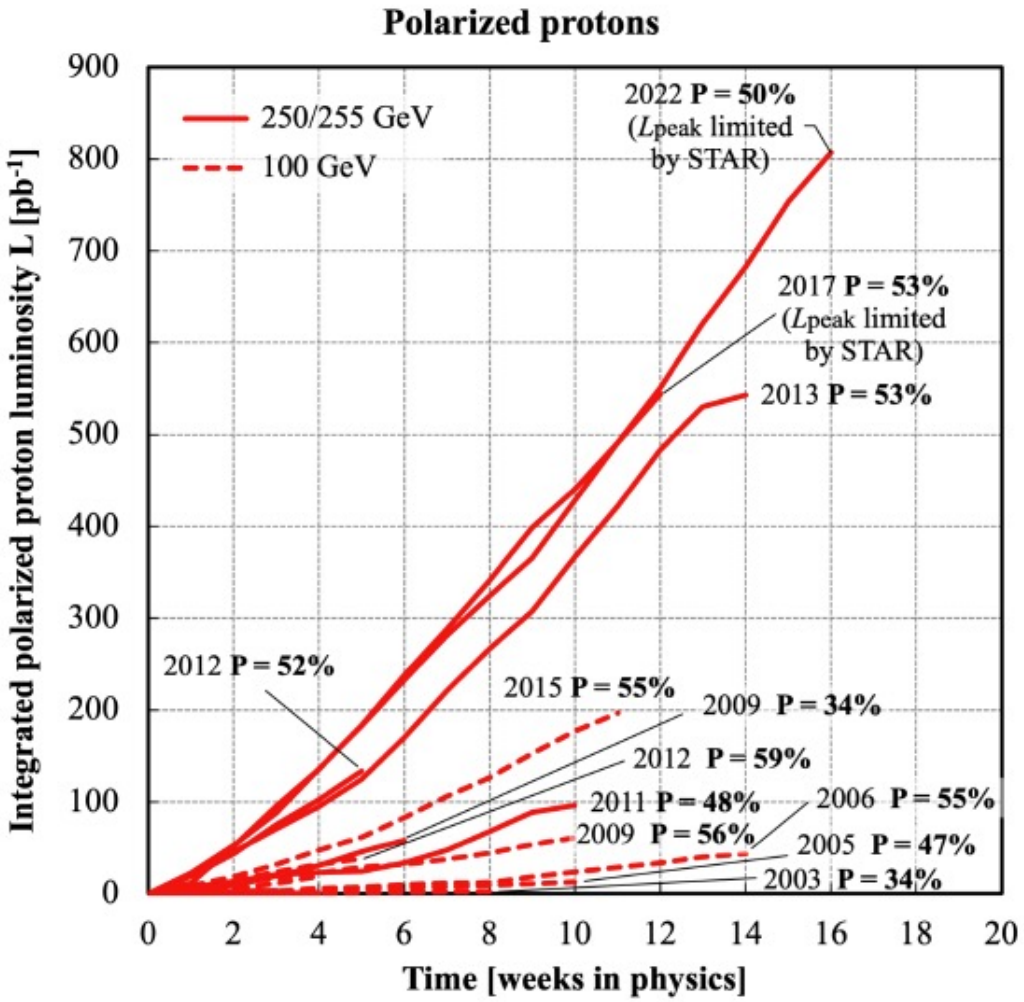
$$\Delta q(x,Q^2) = q^+(x,Q^2) - q^-(x,Q^2)$$

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



RHIC performance with p+p collisions

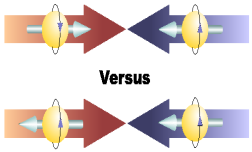
- Long runs with long. pol. at 200 GeV in 2005, 2006, 2009, 2015.
- Collisions at 500 GeV with long. pol. in 2009, 2012 and 2013.
- Long runs with trans. pol. in 2006, 2008, 2012, 2015 at 200GeV and 2011, 2017, 2022 at 500 GeV.



➢ Run24 with transversely polarized p+p at 200GeV is ongoing!

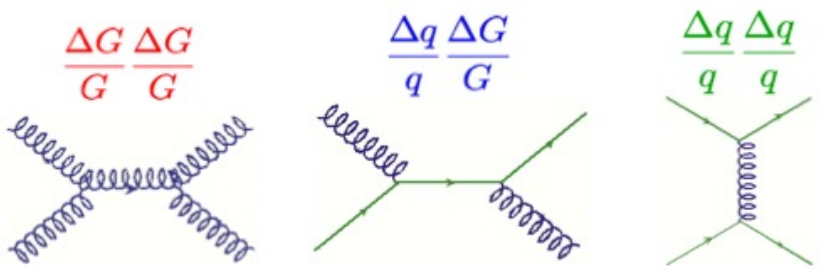
Accessing Δg(x) in pp collision

- Longitudinal spin asymmetry:

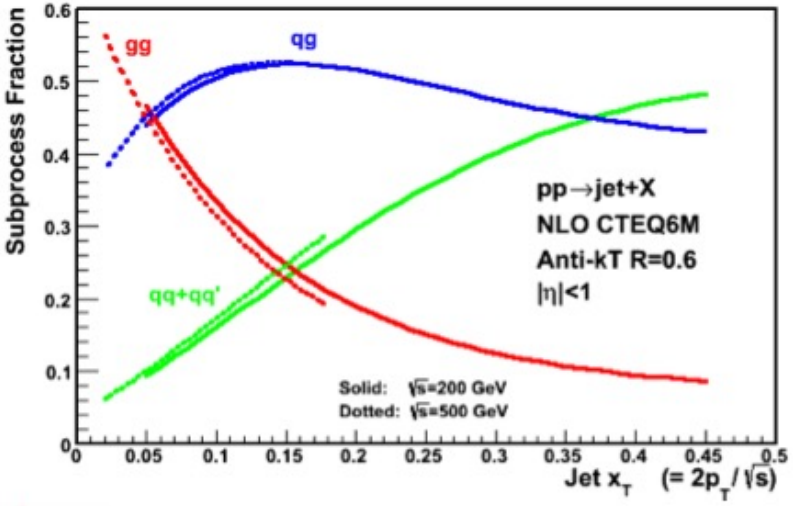


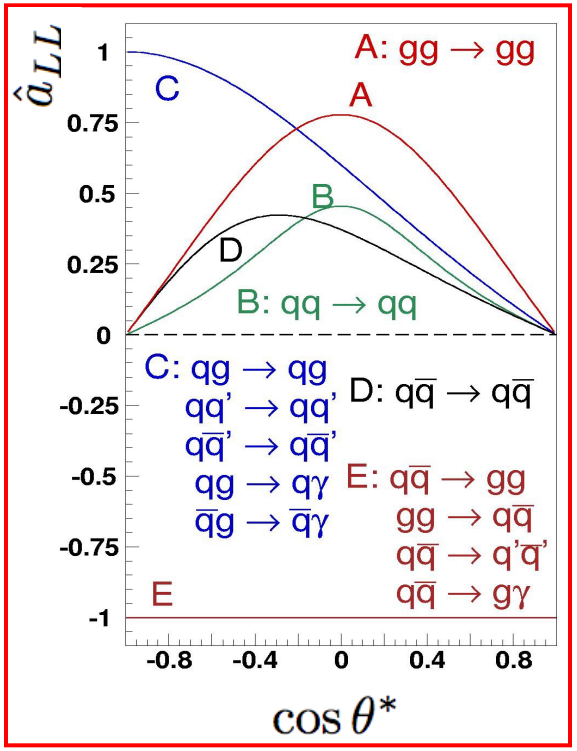
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \cdot \hat{a}_{LL}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}$$

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:

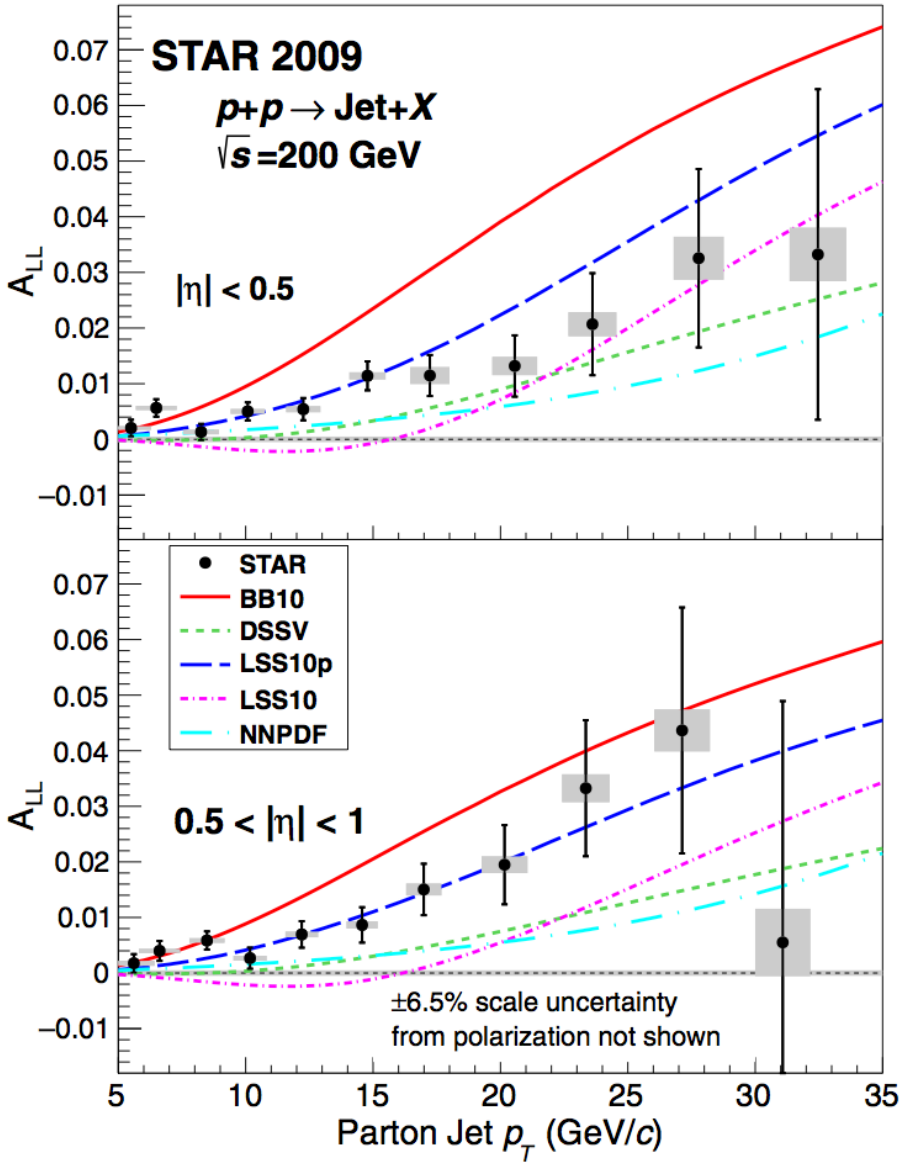




G. Bunce et al, Annu. Rev. Nucl. Part. Sci. 50, 525(2000)

STAR inclusive jet A_{LL} from run9

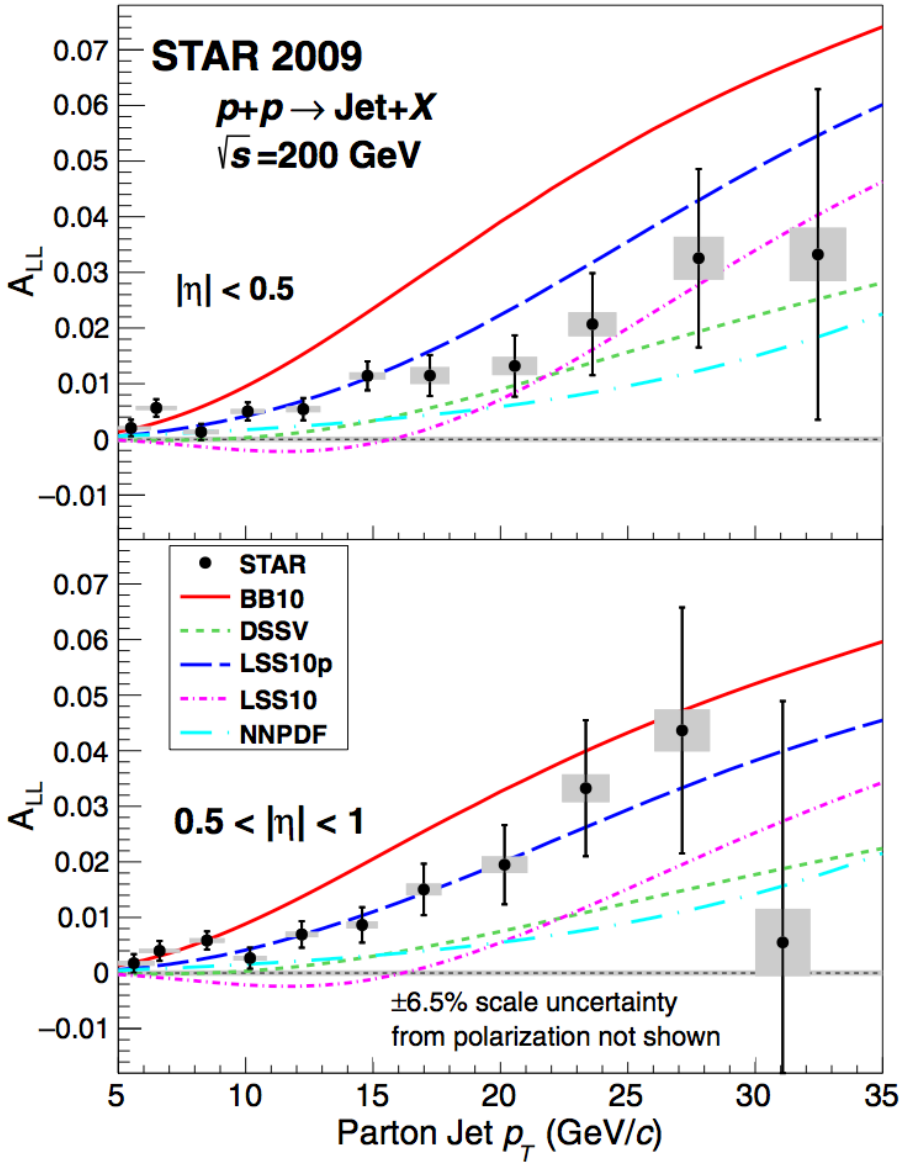
STAR, Phys. Rev. Lett. 115(2015) 92002



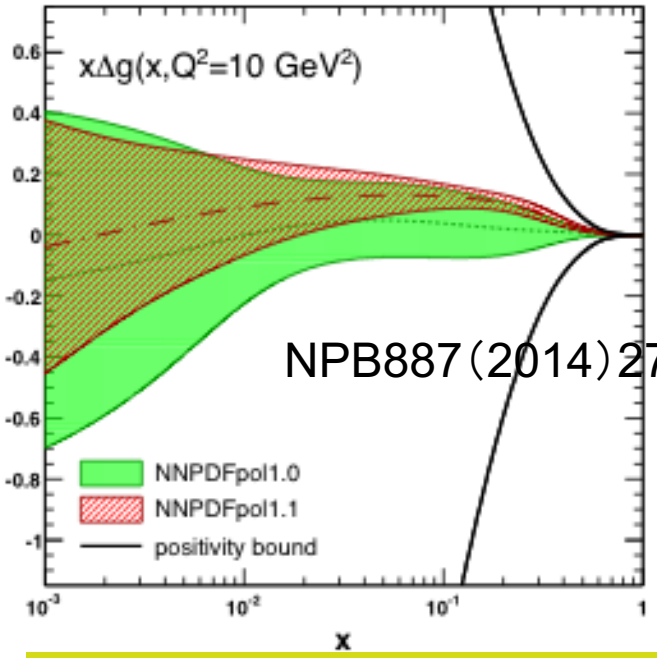
- 2009 STAR data is a factor of 4 more precise than 2006.
- The A_{LL} asymmetry is small, but clearly non-zero !

STAR inclusive jet A_{LL} from run9

STAR, Phys. Rev. Lett. 115(2015) 92002



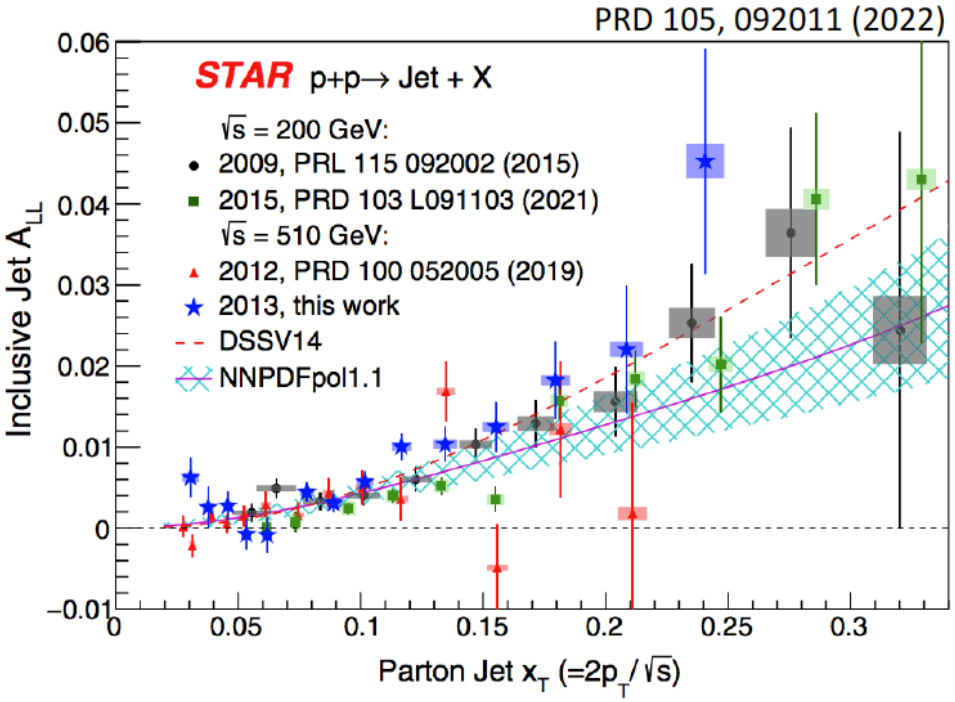
- 2009 STAR data is a factor of 4 more precise than 2006.
- The A_{LL} asymmetry is small, but clearly non-zero !
- Impact of STAR data in NNPDF:



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

A_{LL} results on jet/π^0 at 510 GeV from RHIC

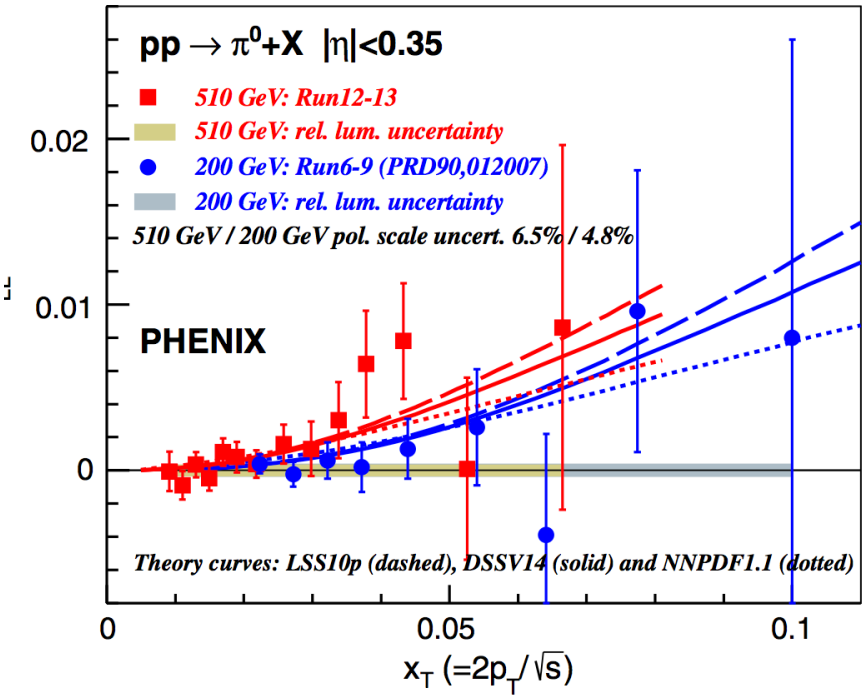
- Further measurements to improve our knowledge on Δg(x)



STAR, PRD103,91103(2021)

STAR, PRD105,92011(2022)

- STAR jet A_{LL} at 510 GeV, access small x region down to x~0.015.
- Most precision A_{LL} results at 200GeV from STAR 2015.

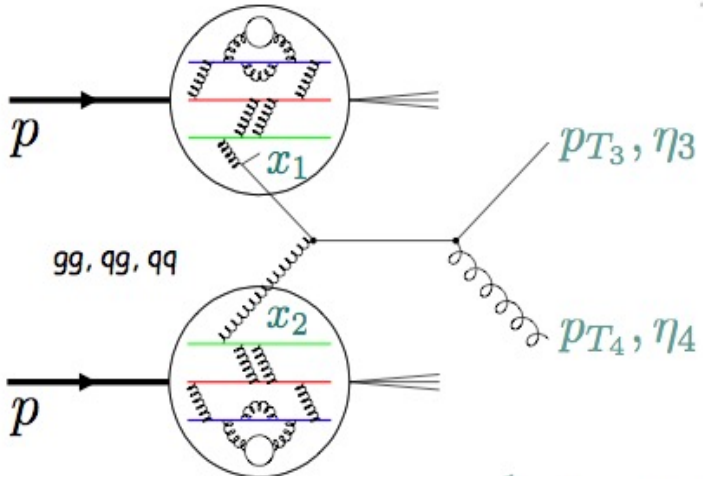


PHENIX, PRD 93, 011501 (2016)

- PHENIX π^0 A_{LL} at 510 GeV, which is also sensitive to Δg in small x region

Correlation measurements with partonic kinematics

- Access to partonic kinematics through di-jet production



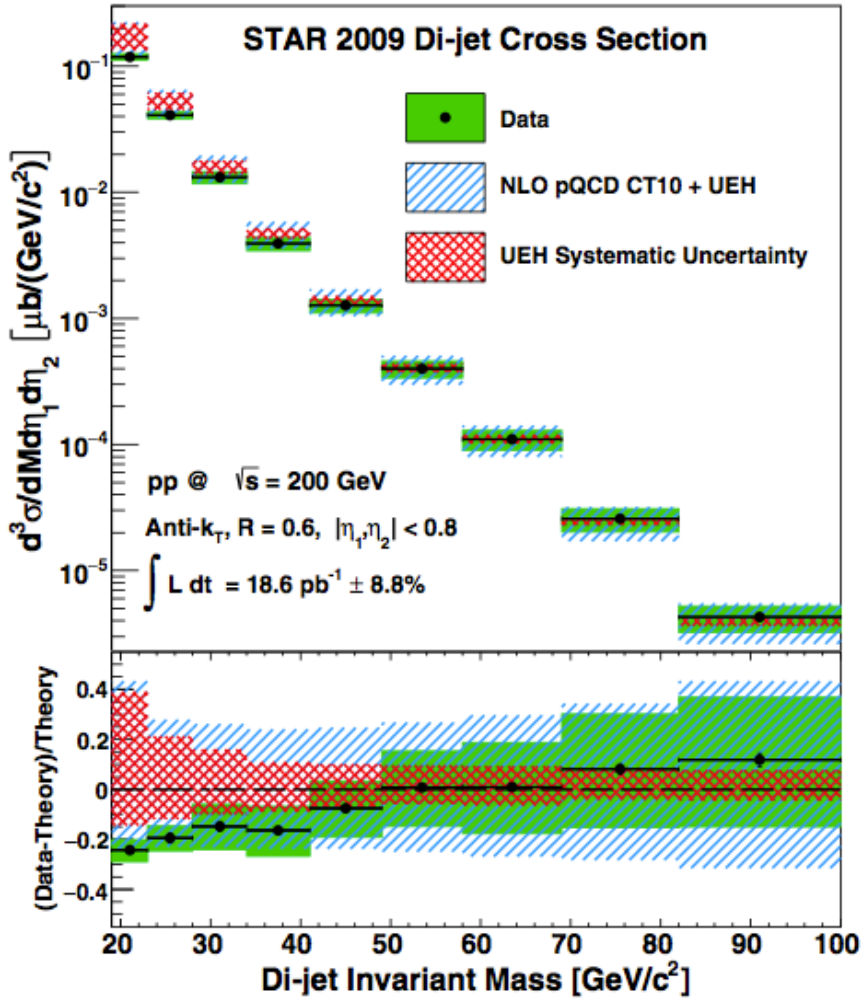
$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4}\right)$$

$$M = \sqrt{x_1 x_2 s}$$

$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$

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

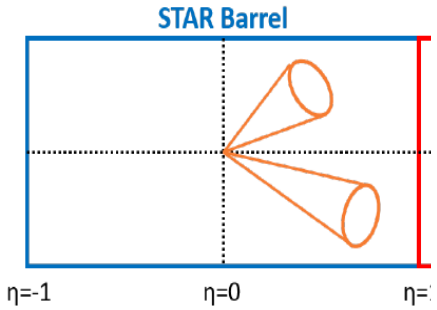


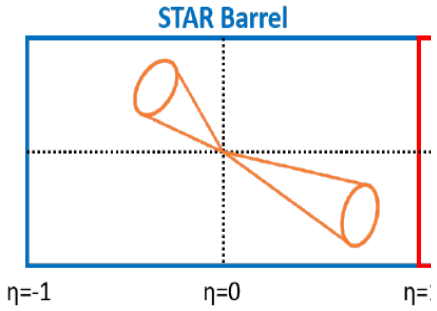
STAR, Phys. Rev. D95,071103(2017)

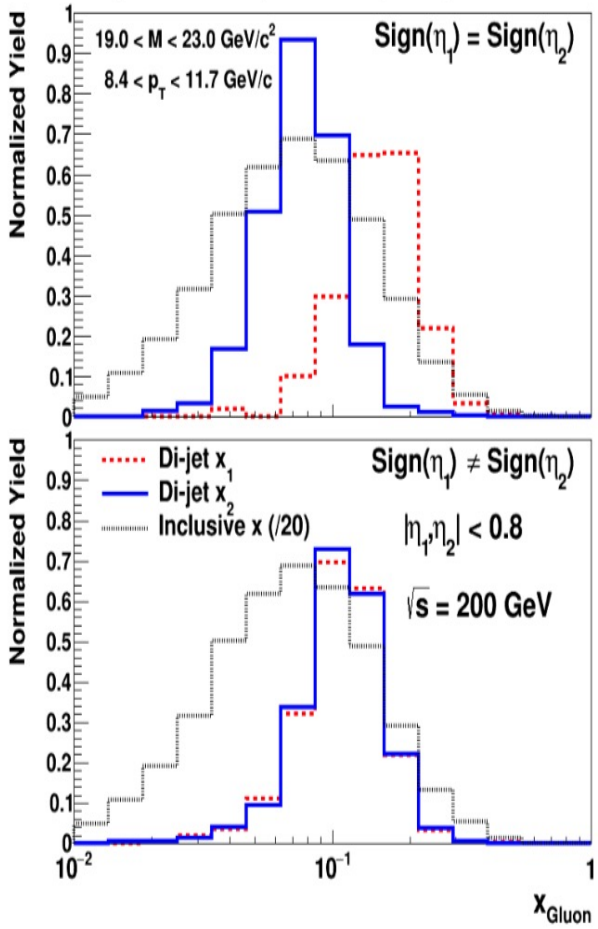
Central di-jet A_{LL} at 200 GeV at STAR

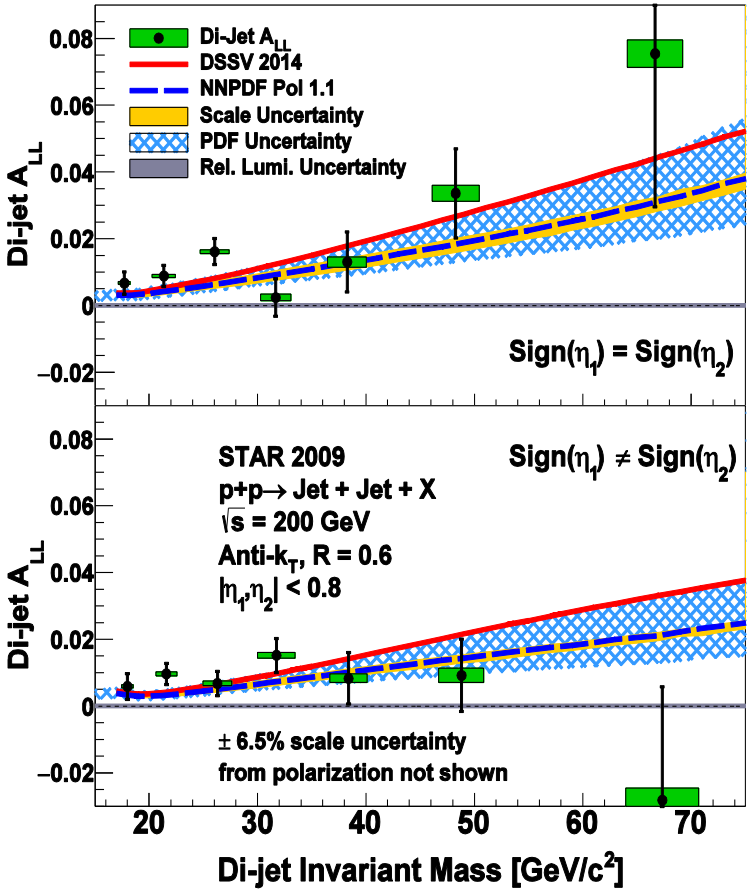
- Di-jet A_{LL} for two topologies, allowing for constraints on the shape of $\Delta g(x)$

STAR, PRD95,071103(2017)





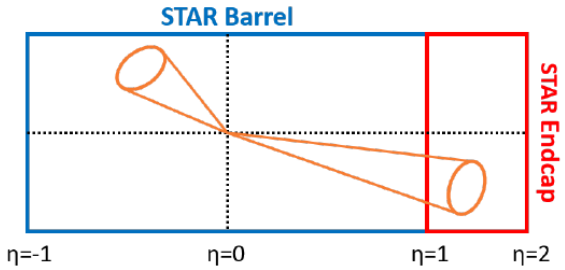


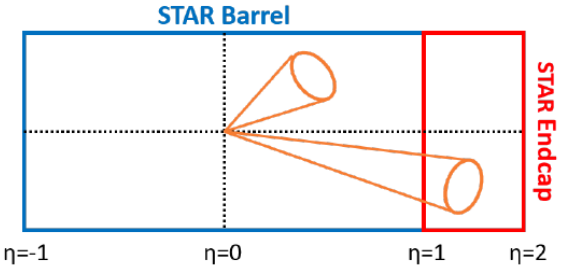


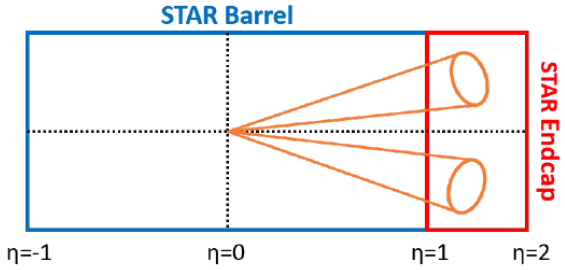
Central-forward di-jet at 200 GeV at STAR

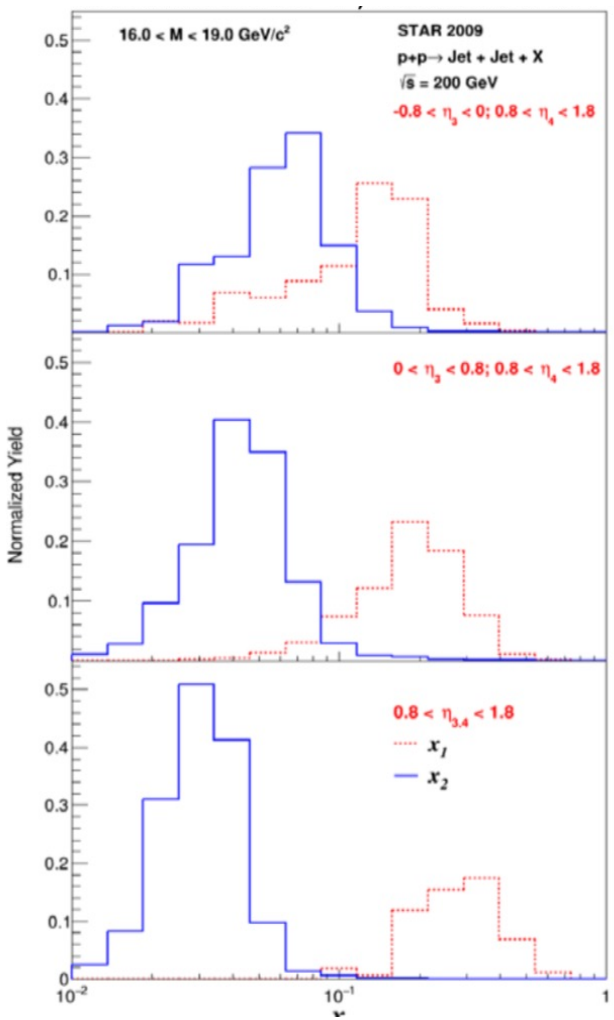
STAR, PRD98,032011(2018)

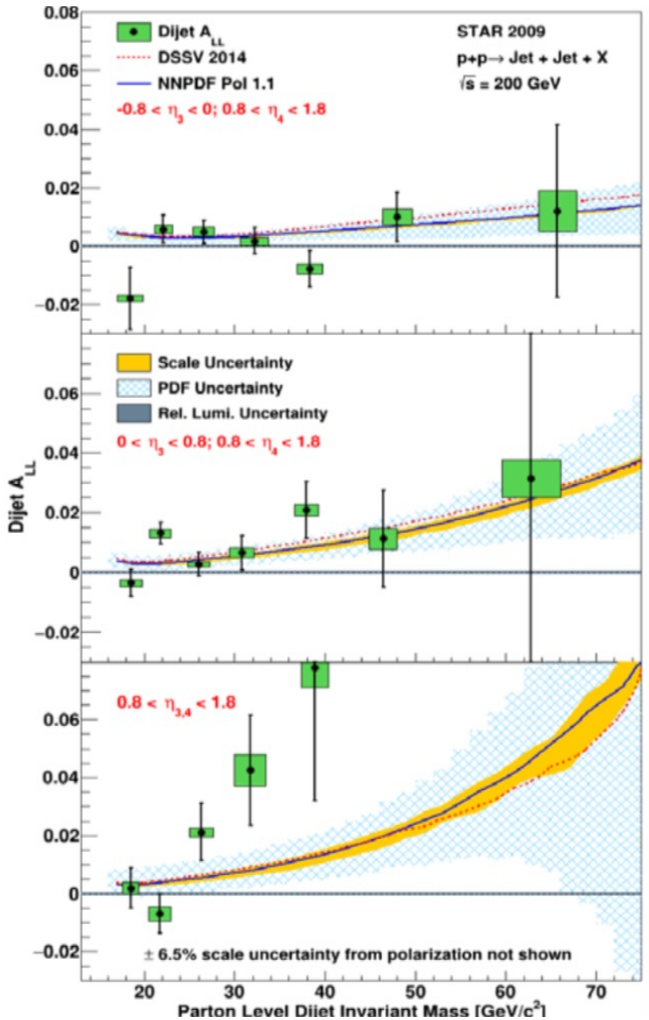
Wider rapidity coverage!





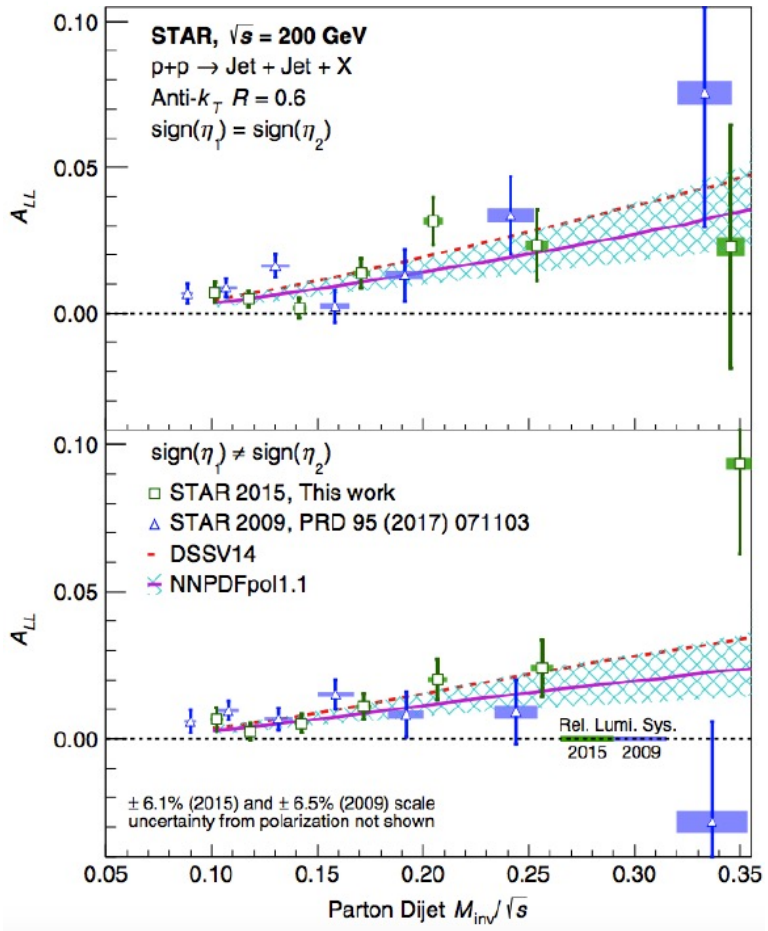




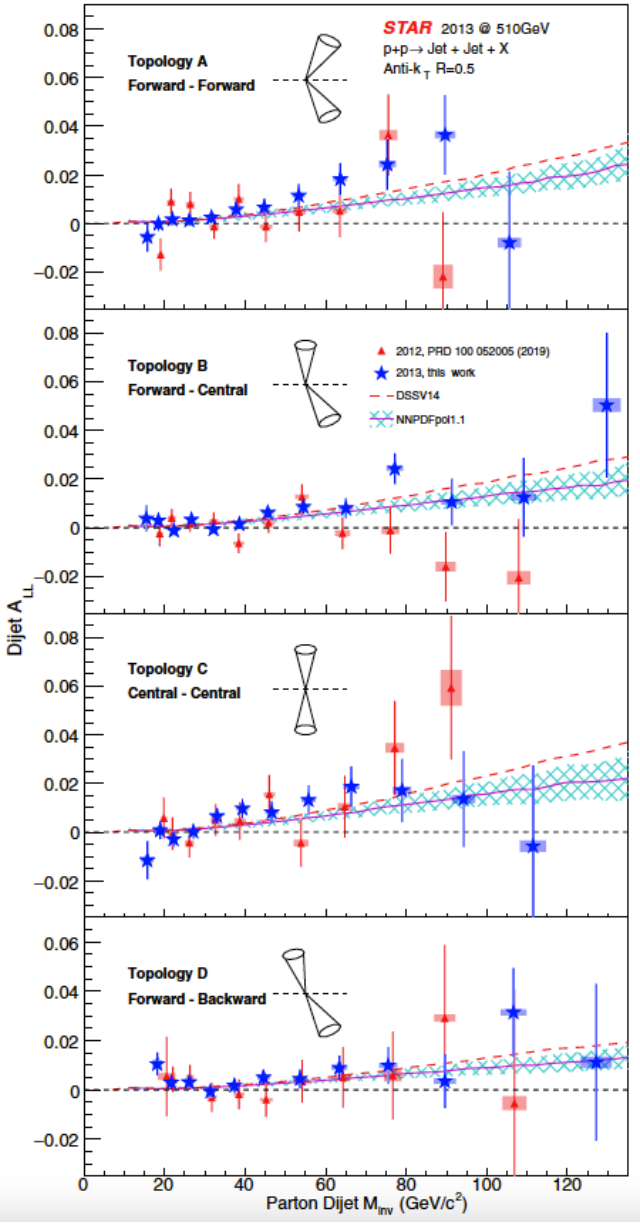


Recent STAR di-jet A_{LL} results

STAR, PRD103, 091103(2021)

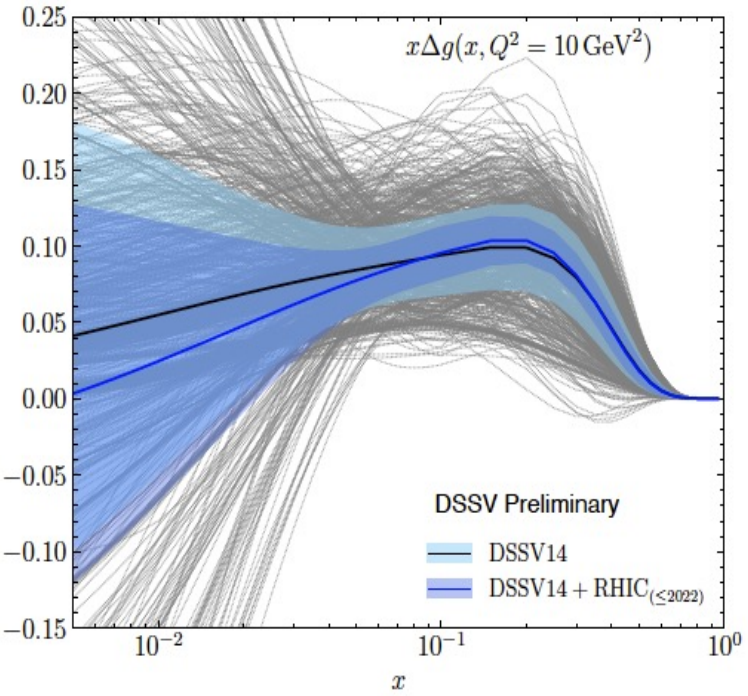


STAR, PRD105,92011(2022)

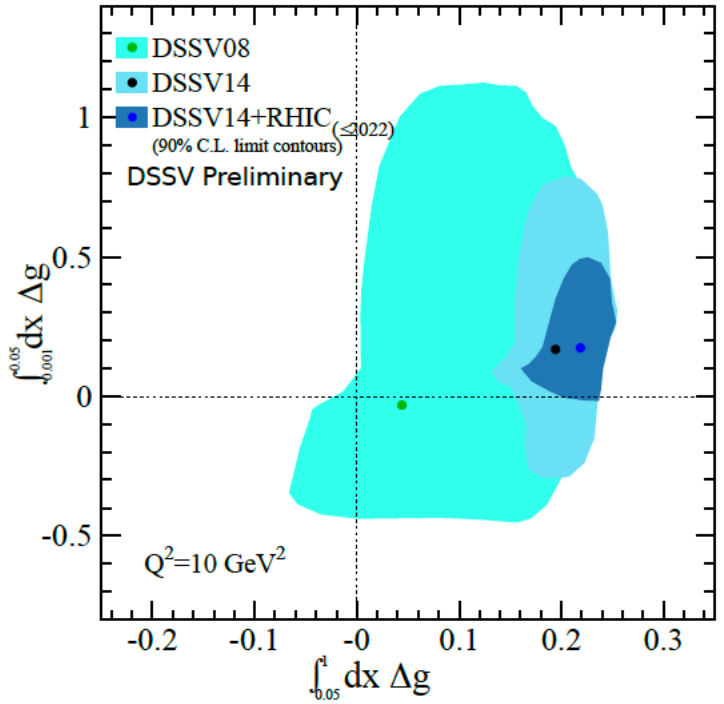


Most recent updates from DSSV group on Δg

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



RHIC Cold QCD White paper, arXiv2302.00605



➢ 1st Lattice calculation:

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

χQCD, PRL118,102001(2017)

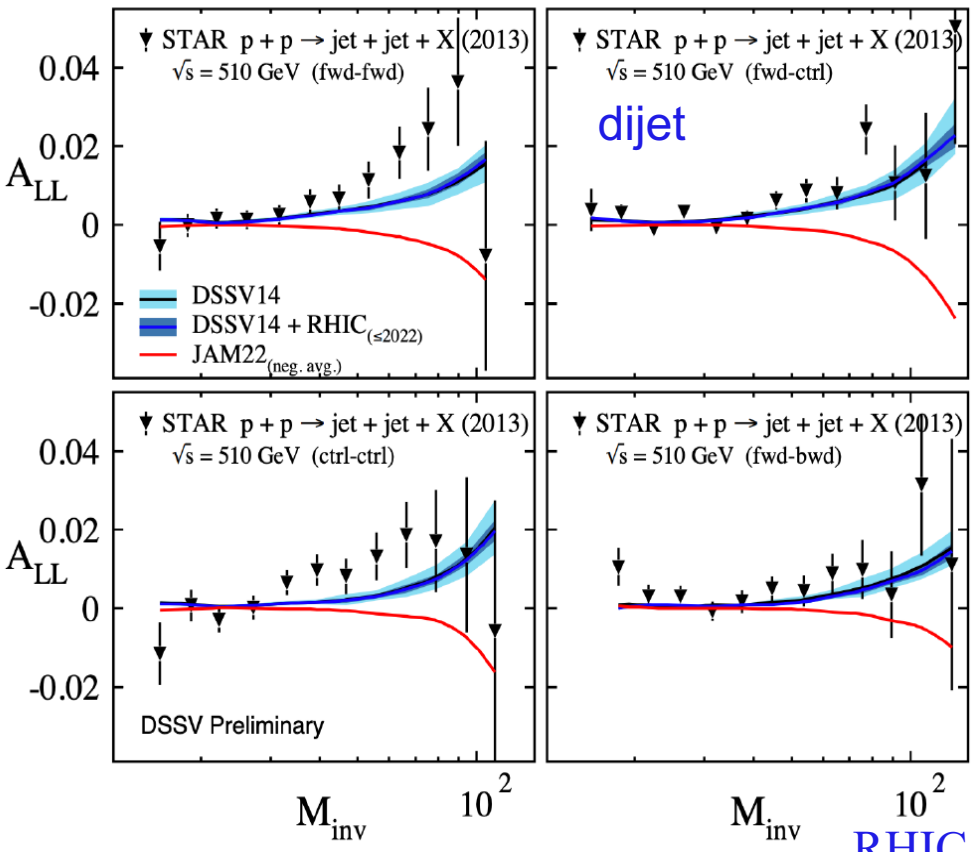
$$\int_{0.05}^{1} \Delta g(x, Q^2)dx = 0.218 \pm 0.027$$

~40% of proton spin with 8σ

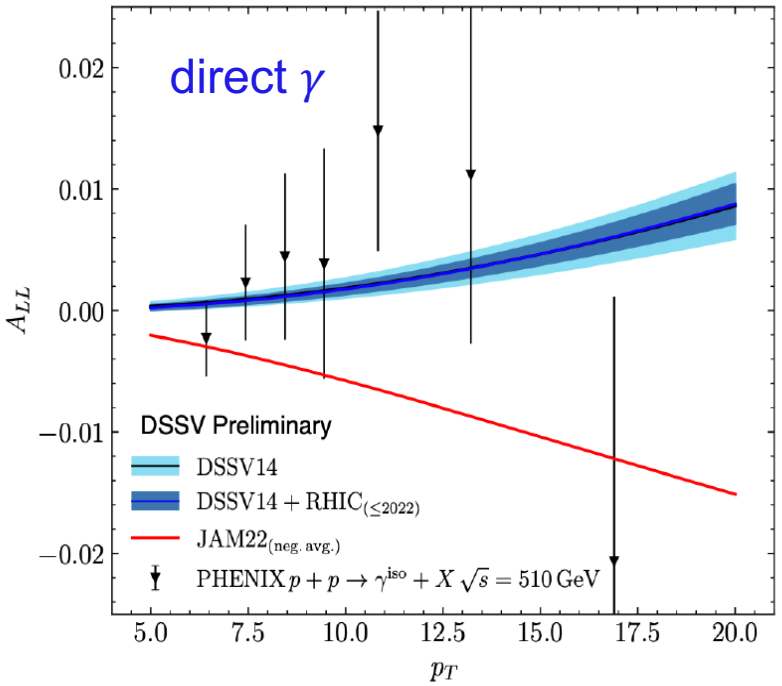
Recent progress on the sign of Δg

- Could Δg be negative?

STAR, PRD105, 092011(2022)



PHENIX, PRL130, 251901(2023)
JAM, PRD105, 074022 (2022)



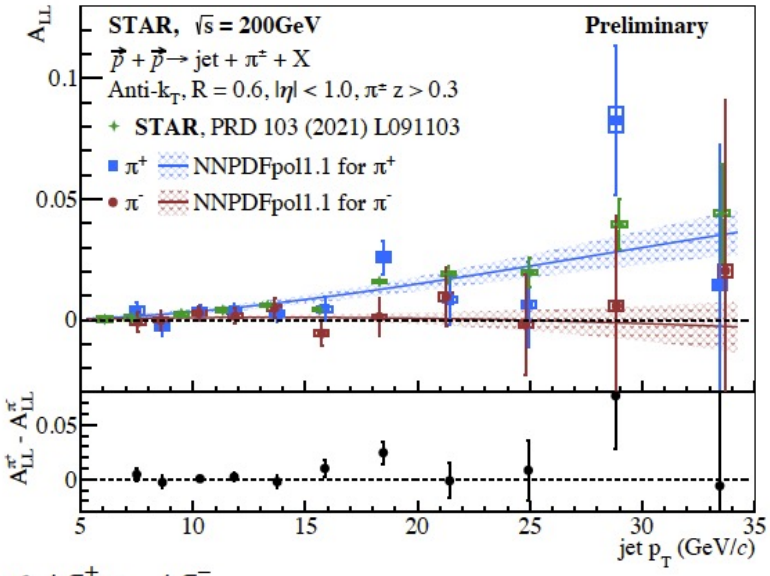
RHIC, arXiv2302.00605

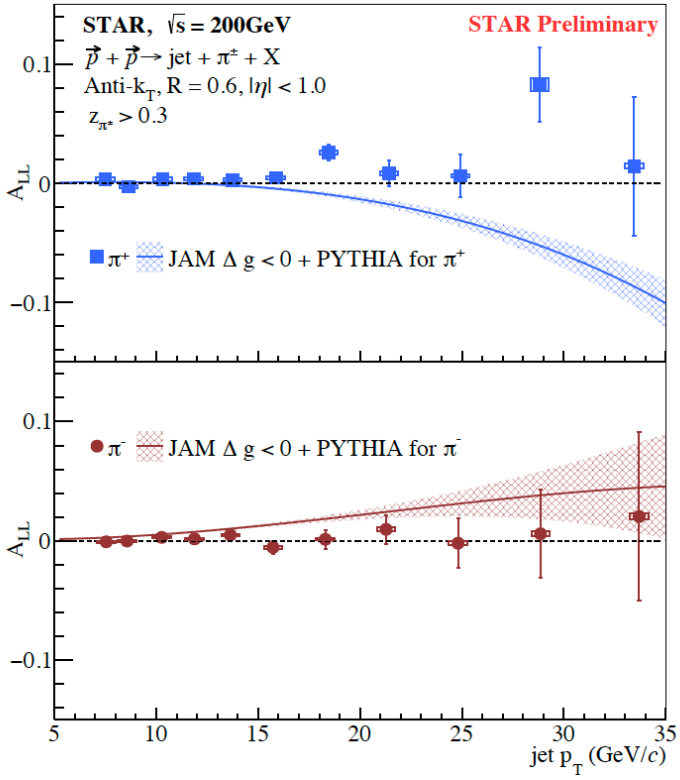
- JAM global QCD fit indicate possible negative Δg with inclusive jet A_{LL} data only
- STAR dijet + PHENIX direct photo data disfavor negative Δg
- New results with pion tagged jet also support positive Δg

Recent progress on the sign of Δg

- New results with pion tagged jet A_{LL} also support positive Δg

$\pi^{\pm}$-tagged A_{LL} with $z > 0.3$





- Indication of $A_{LL}^{\pi^+} > A_{LL}^{\pi^-}$
- Larger separation between predictions
- The results are close to the predictions

- Yi Yu @SPIN2023

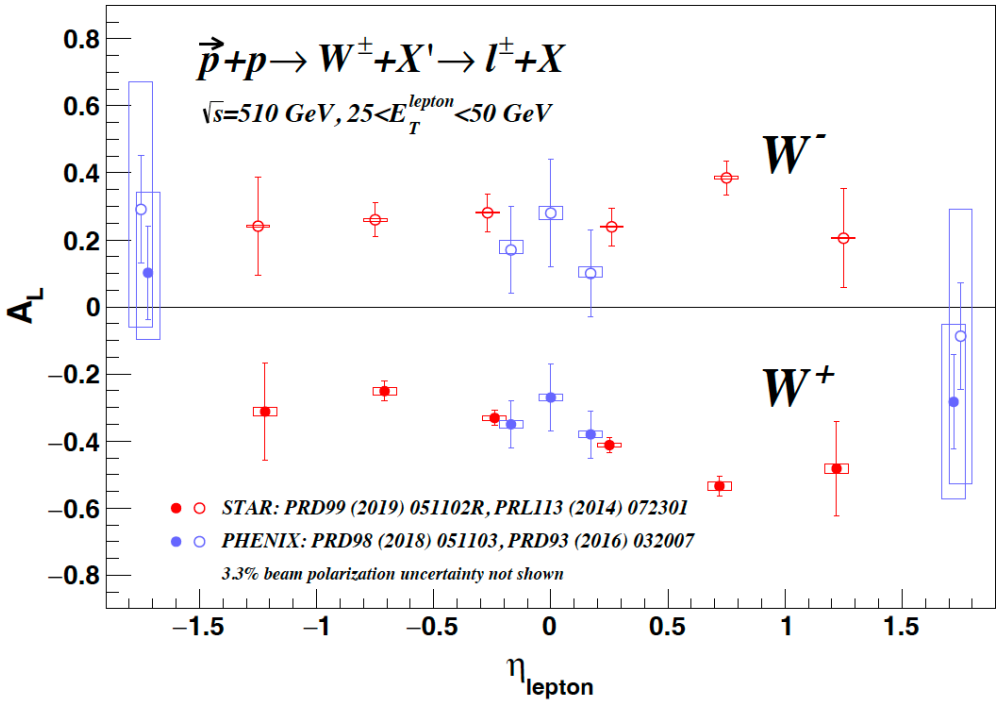
Probing sea quark polarization via W production

- Unique quark polarimetry with W-bosons at RHIC:

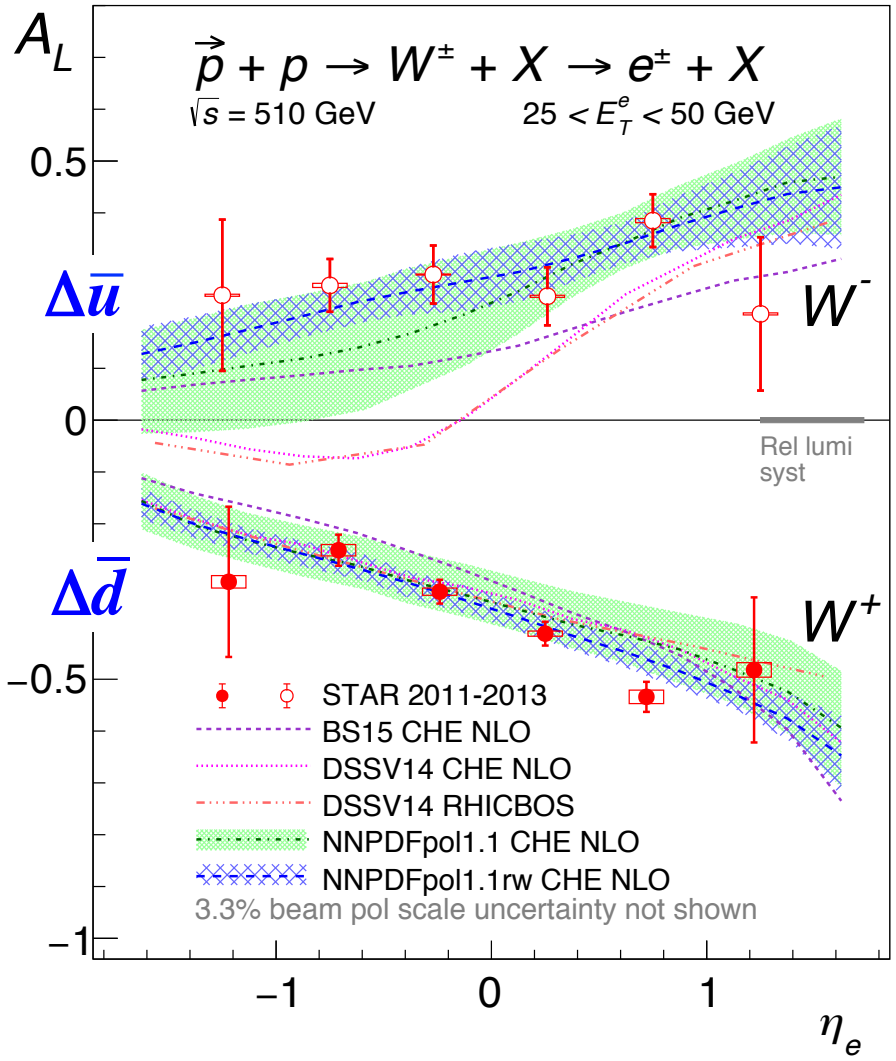
$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \sim \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \end{cases}$$

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

- Dedicated 500GeV p+p run at RHIC during 2011-2013
  - W-detection through high p_T lepton
  - A_L measurements at PHENIX and STAR



W A_L results – STAR 2013



STAR, PRD99, 051102R(2019)

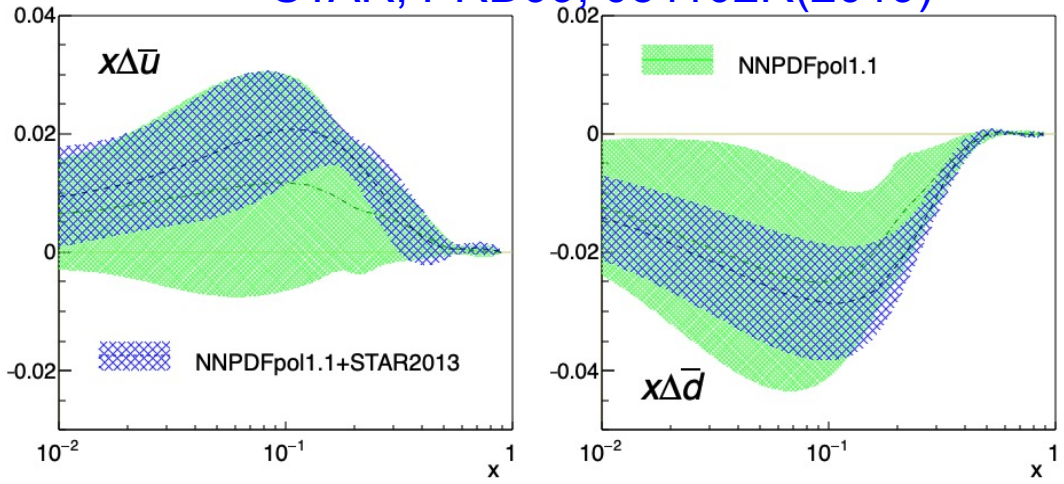
- Combined STAR 2011-2013 results in comparison with theoretical predications
- A_L of W^- shows indication that data are larger than the DSSV predictions
- A_L of W^+ is consistent with theoretical predictions using global fits based on DIS data

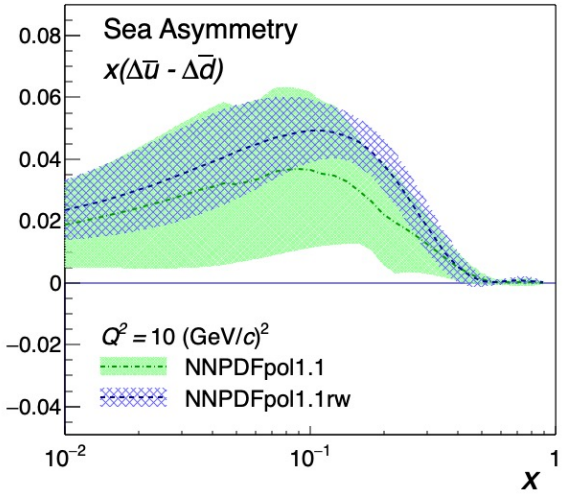
  -> universality

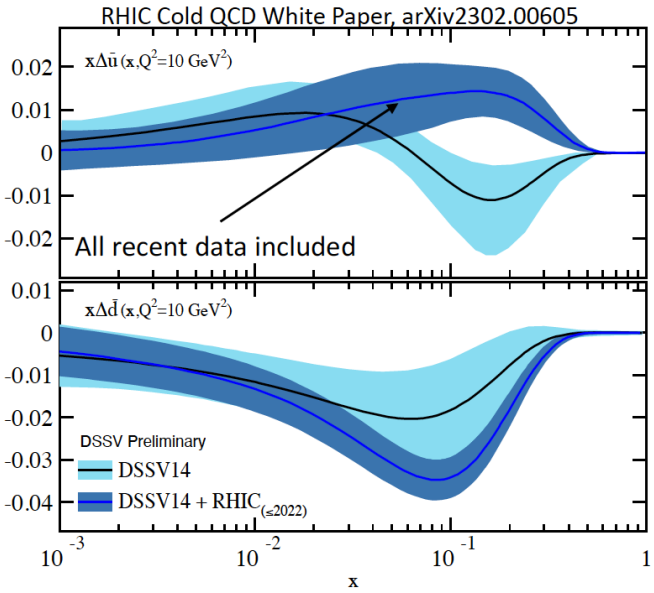
Impact of STAR 2013 W A_L results

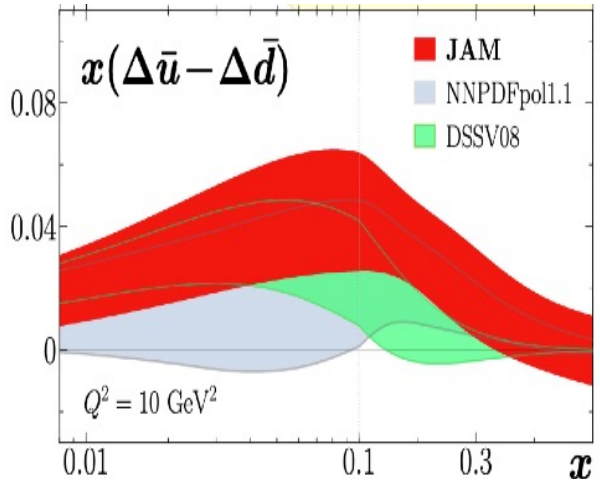
- SU(2) flavor asymmetry observed in the polarized sea quark distribution, confirmed by JAM and reweighting NNPDF, DSSV:

STAR, PRD99, 051102R(2019)









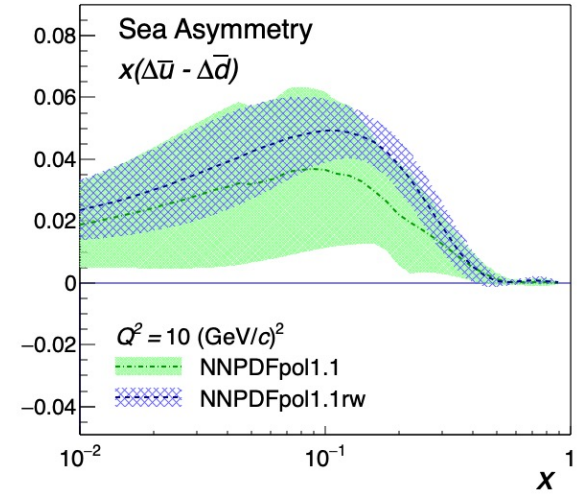
JAM, PRD106, 031502(2022)

Impact of STAR 2013 W A_L results

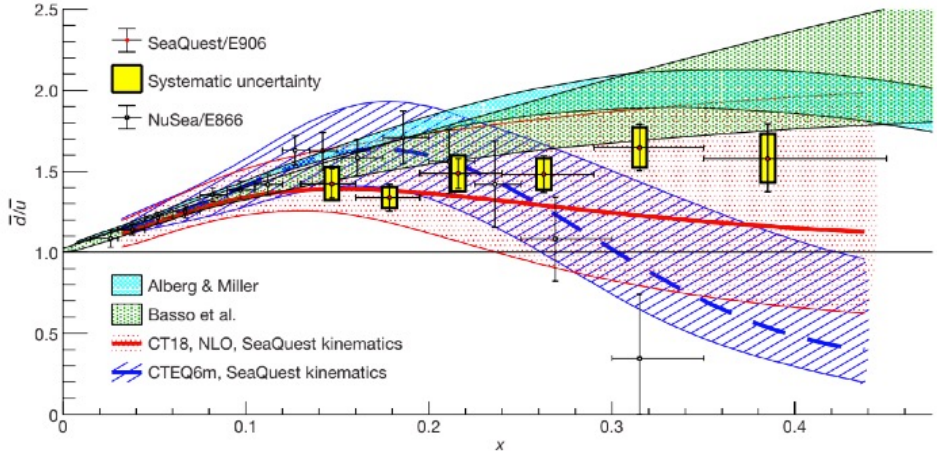
- SU(2) flavor asymmetry observed in the polarized sea quark distribution, confirmed by JAM and reweighting NNPDF, DSSV:

$$\Delta\bar{u} > 0 > \Delta\bar{d},\ |\Delta\bar{d}| > |\Delta\bar{u}|$$
$$\Delta_s = \Delta\bar{u} - \Delta\bar{d}$$
$$\int_{0.04}^{0.4} dx\, \Delta_s(x, Q^2 = 10\,\text{GeV}^2) = +0.06 \pm 0.03$$

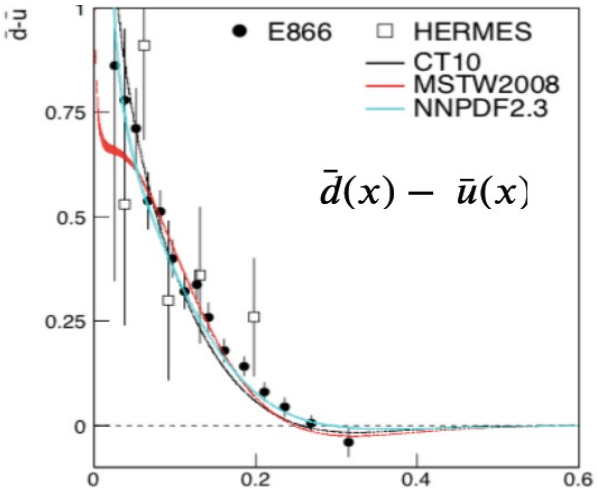
- E. Nocera @ Hadron2019 $\rightarrow +0.07 \pm 0.01$



- The polarized flavor asymmetry is opposite to the unpolarized case !



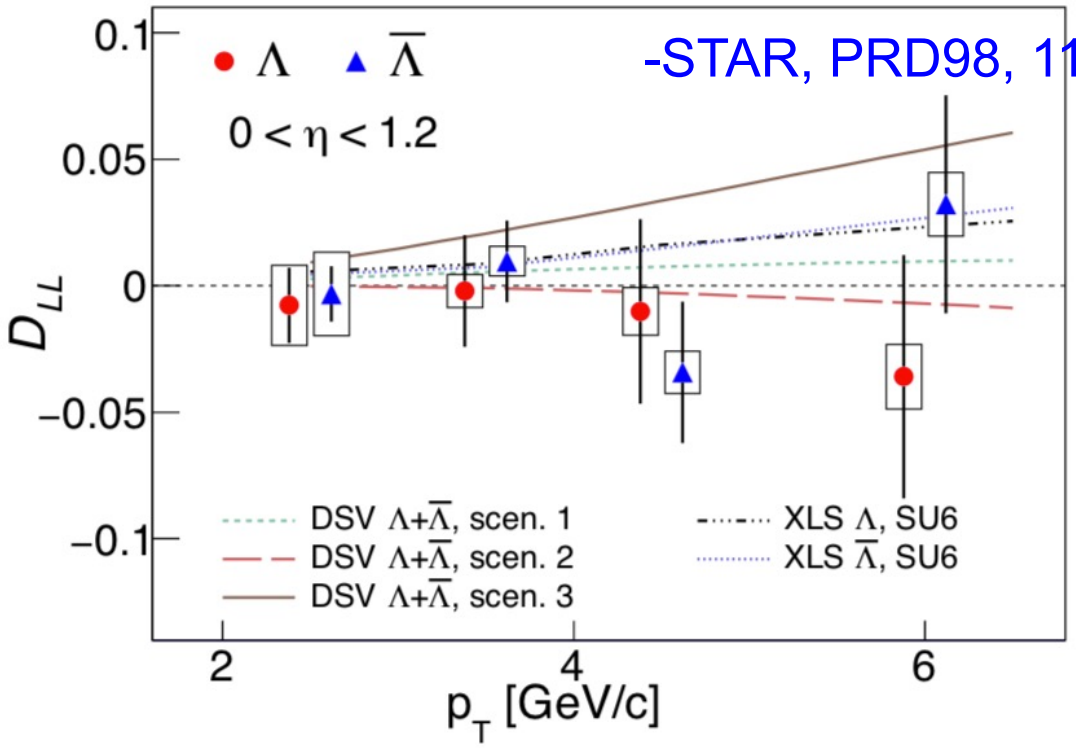
- SeaQuest, Nature 590, 561(2021)



- E866, PRD64, 052002(2001)
- NNPDF2.3, NPB867, 244(2013)

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

- D_{LL} measurements from STAR 2009 data, which is expected to provide sensitivity to strange quark polarization Δs.



-STAR, PRD98, 112009 (2018)

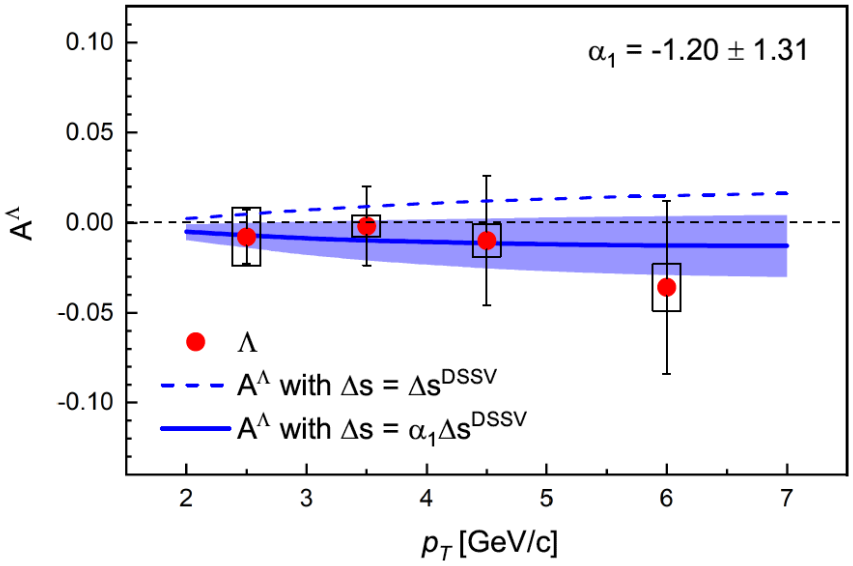
- D.de Florian, M.Stratmann, and W.Vogelsang, PRL81,530(1998)
- Q. Xu, Z.T. Liang, E. Sichtermann, PRD 73, 077503(2006)

➢ Statistics uncertainties are comparable to the spread of models calculations.

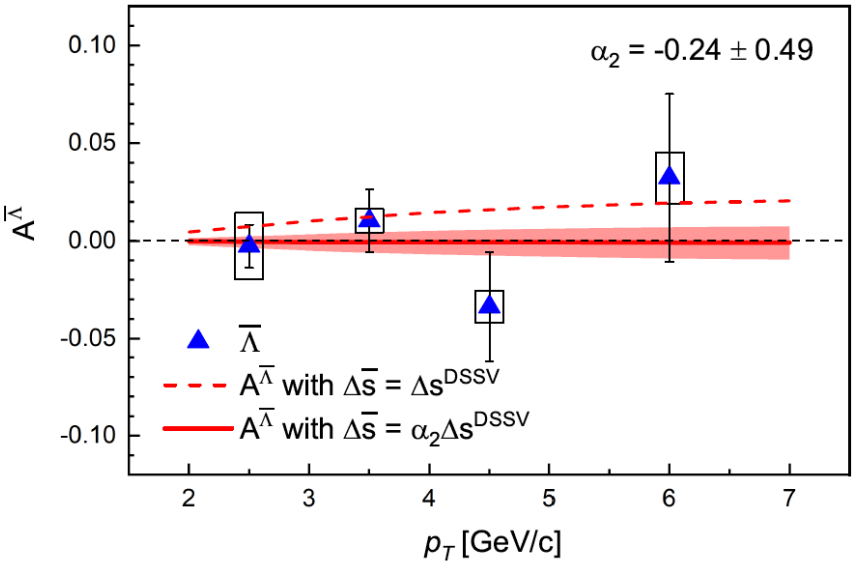
D_{LL} results of (anti-)Lambda at STAR

- Theoretical studies show impact on asymmetry of strange and anti-strange quark polarization:

  X.N. Liu, B. Q. Ma, Eur.Phys.J. C79 (2019) 409



(a) Longitudinal spin transfer to Λ.



(b) Longitudinal spin transfer to $\bar{\Lambda}$.

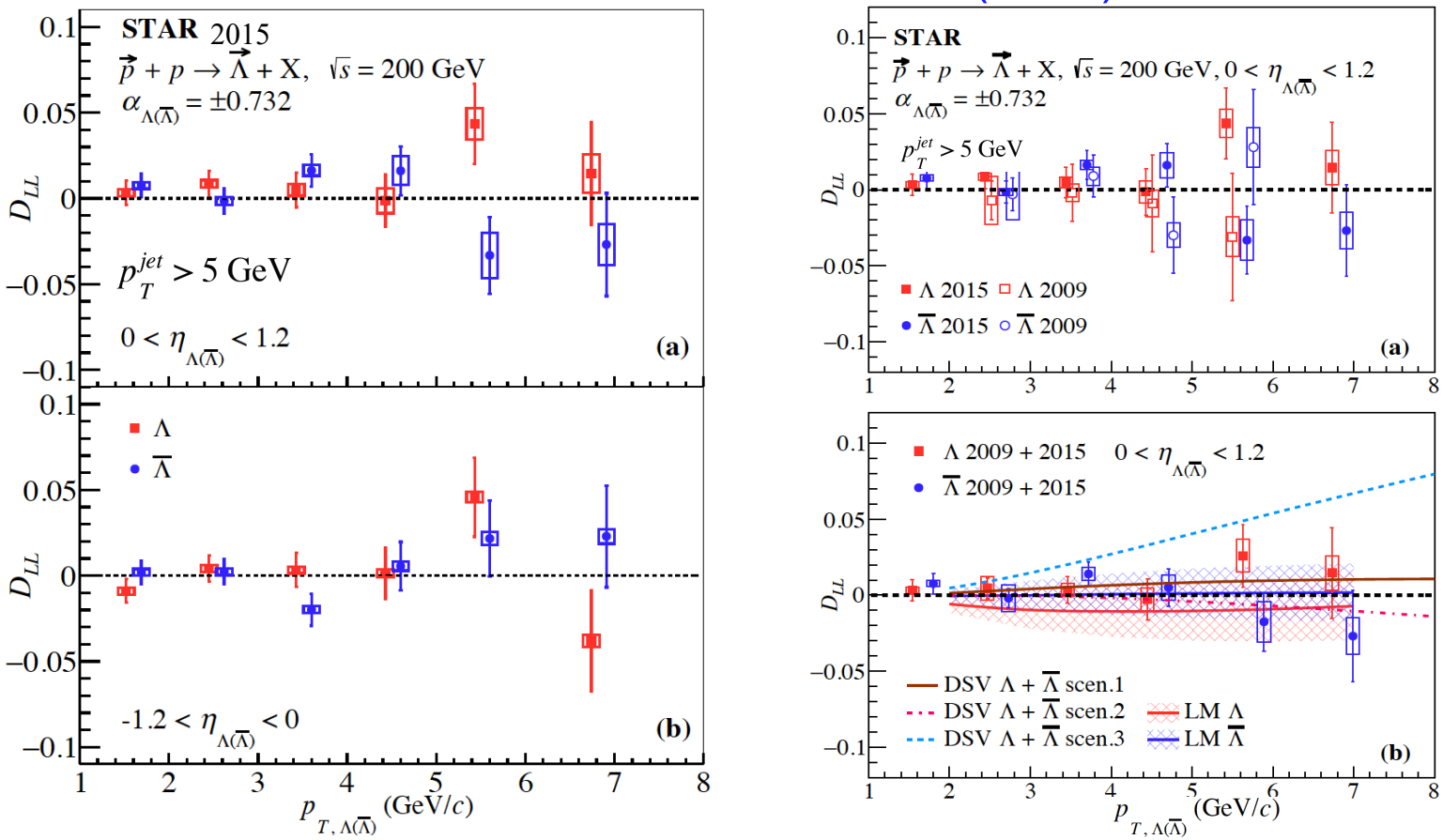
Table 1 Fitting results of α_i and calculated results of Δs and $\Delta \bar{s}$

coefficient	value	Δs	$\Delta \bar{s}$	χ^2_{min}
α_1	−1.20±1.31	−0.014±0.015		0.37
α_2	−0.24±0.49		−0.003±0.005	2.48

New D_{LL} results with STAR 2015 data

- New results with twice statistics
- Results in agreement with various model predictions, except “DSV” calculation with “scen. 3” of polarized fragmentation function.

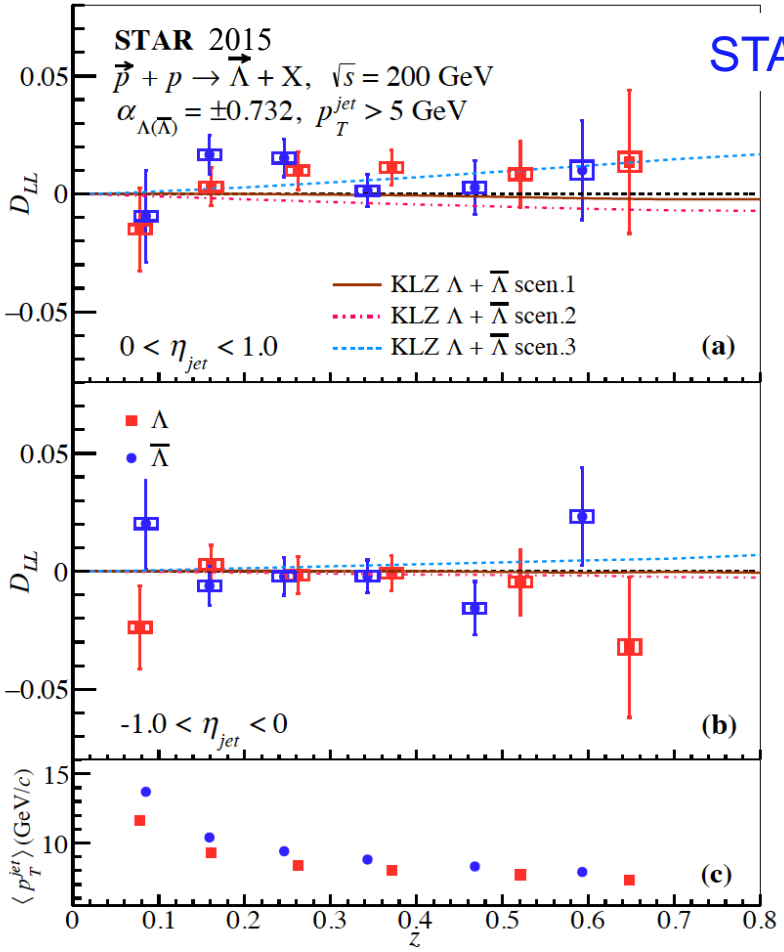
STAR, PRD109, 012004 (2024)



- D.de Florian, M.Stratmann, W.Vogelsang, PRL81,530(1998); - X.N. Liu, B.Q. Ma, EPJC 79,409 (2019)

D_{LL} vs z results with STAR 2015 data

- First measurements of D_{LL} vs z in polarized p+p collisions, directly probing the polarized fragmentation functions.
- The results are comparable to model prediction within uncertainties.



STAR, PRD109, 012004 (2024)

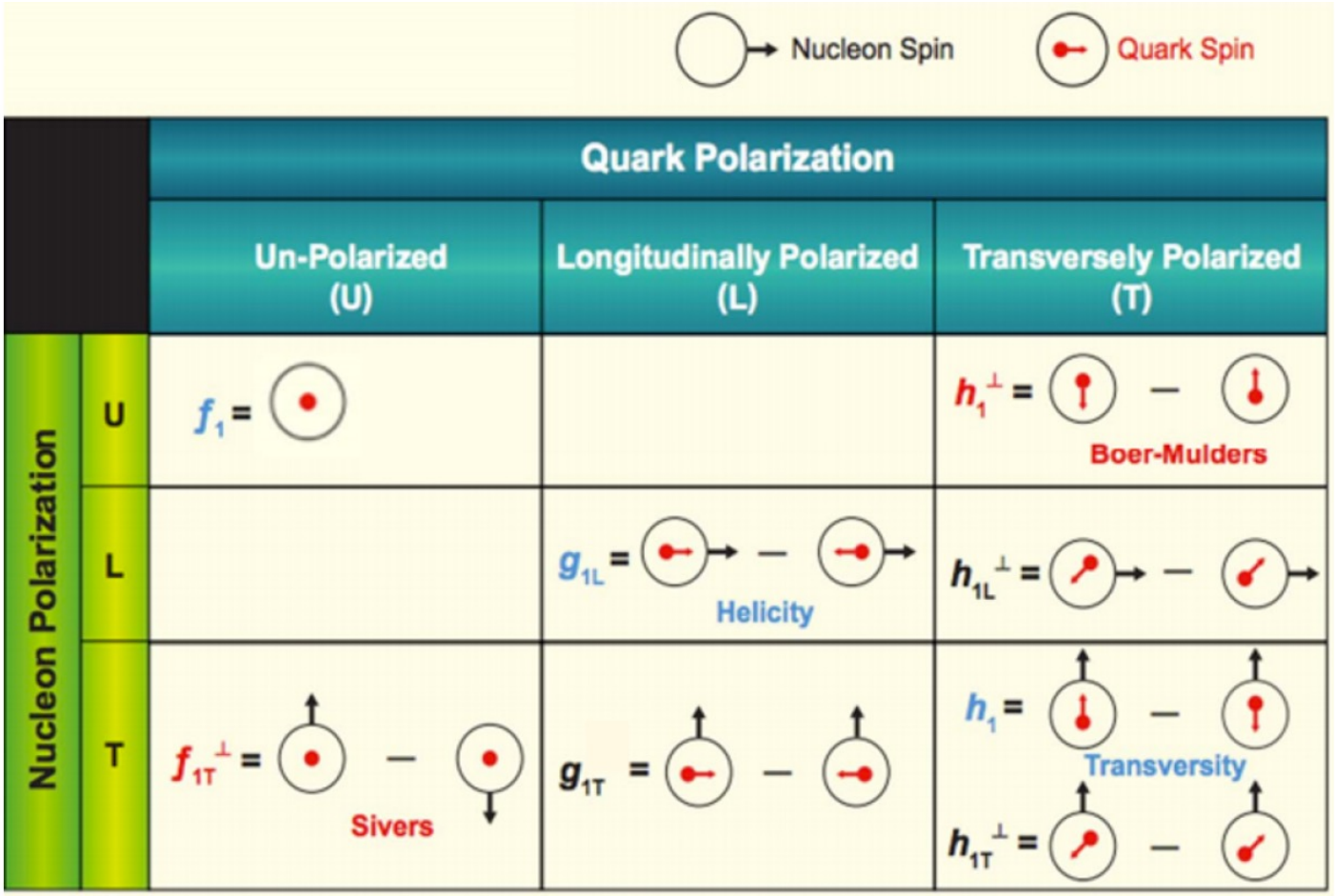
$$z = \frac{\boldsymbol{p}_{\Lambda} \cdot \boldsymbol{p}_{jet}}{|\boldsymbol{p}_{jet}|^2}$$

z: Jet momentum fraction carried by hyperon

- Z.-B. Kang, K. Lee, F. Zhao, Phys. Lett. B **809**, 135756 (2020).

Nucleon 3d-structure & TMD distribution

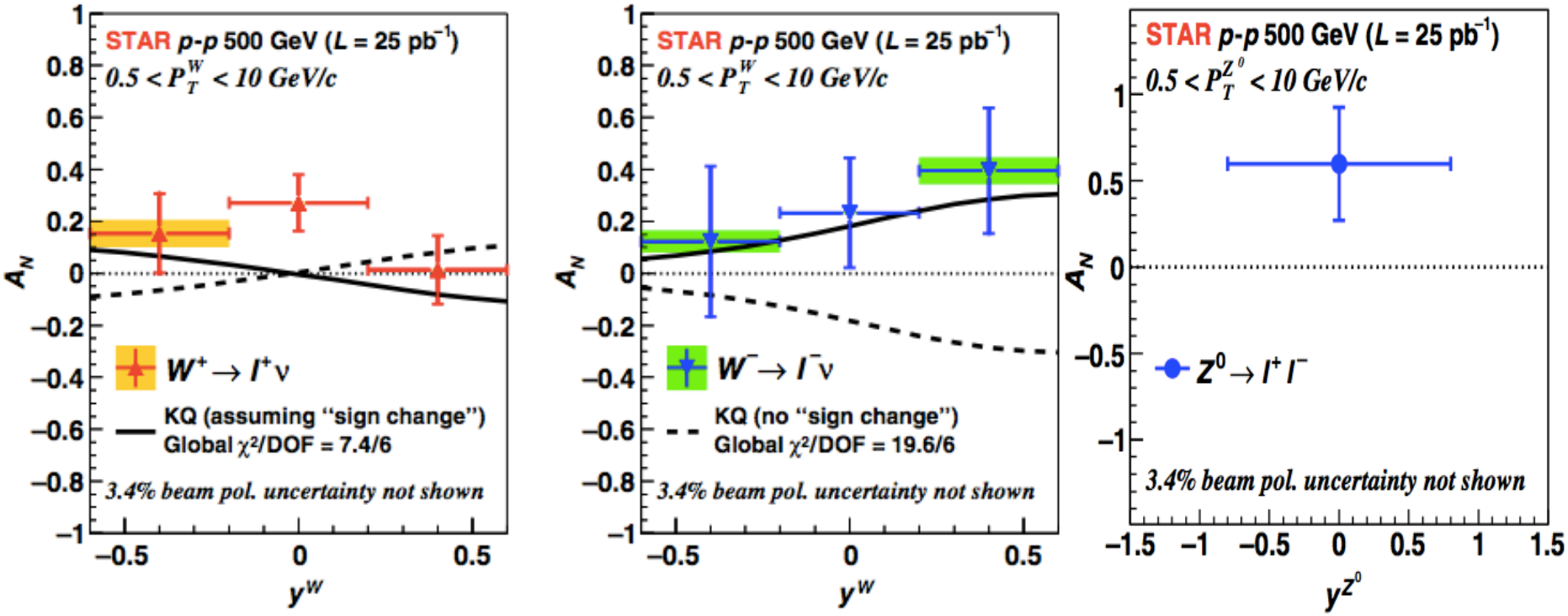
- Transverse momentum dependent distribution (TMD):



➢ Sivers, Transversity, Collins related measurements at RHIC

First W, Z A_N results at 500 GeV from STAR

- QCD predicts there is Sivers sign change in DIS and W/Z process in pp
- First A_N for $W^{\pm}$ and Z results : $A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$

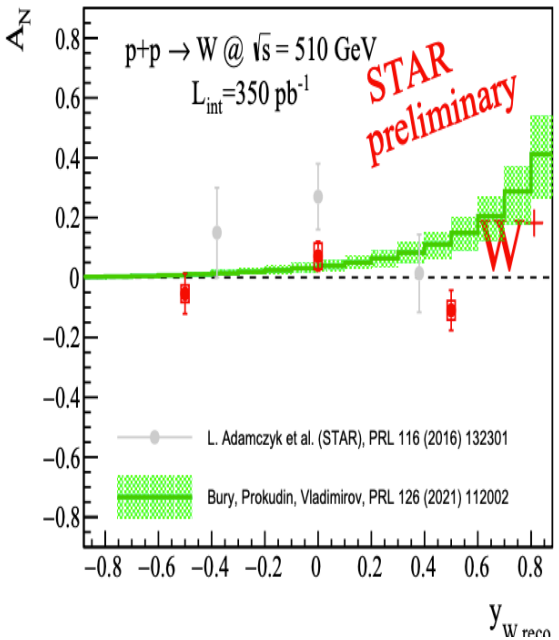


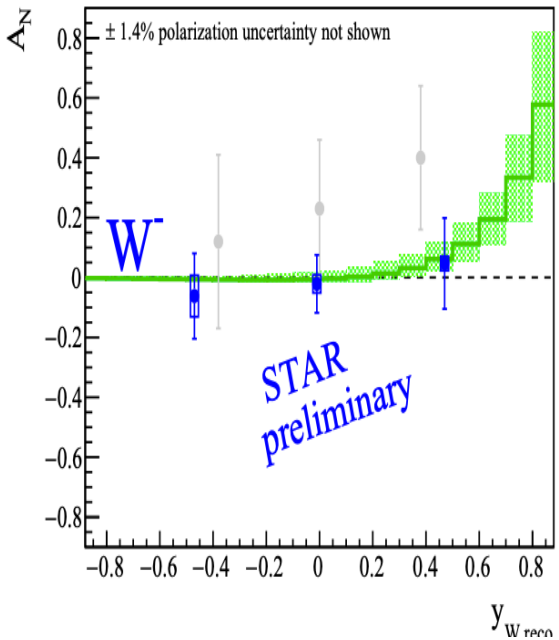
STAR, PRL116,132301(2016)

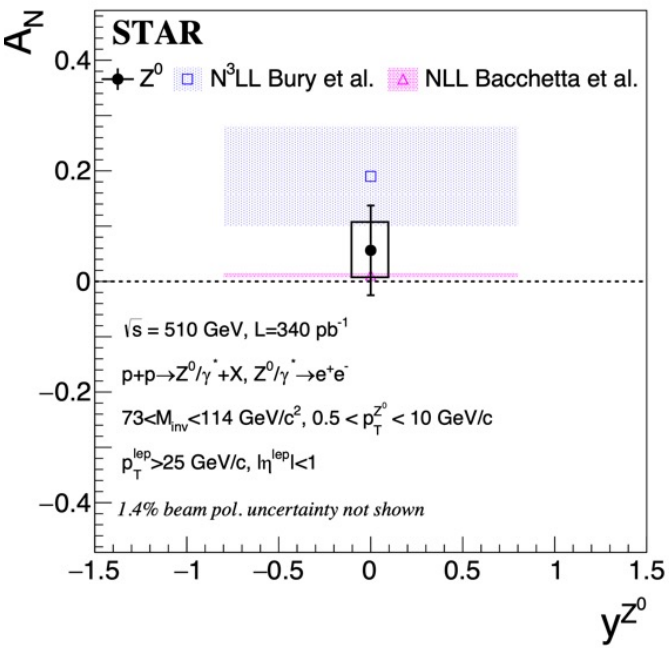
- Sivers sign-change scenario preferred over no-sign change scenario.

Coming measurements of W/Z A_N at STAR

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





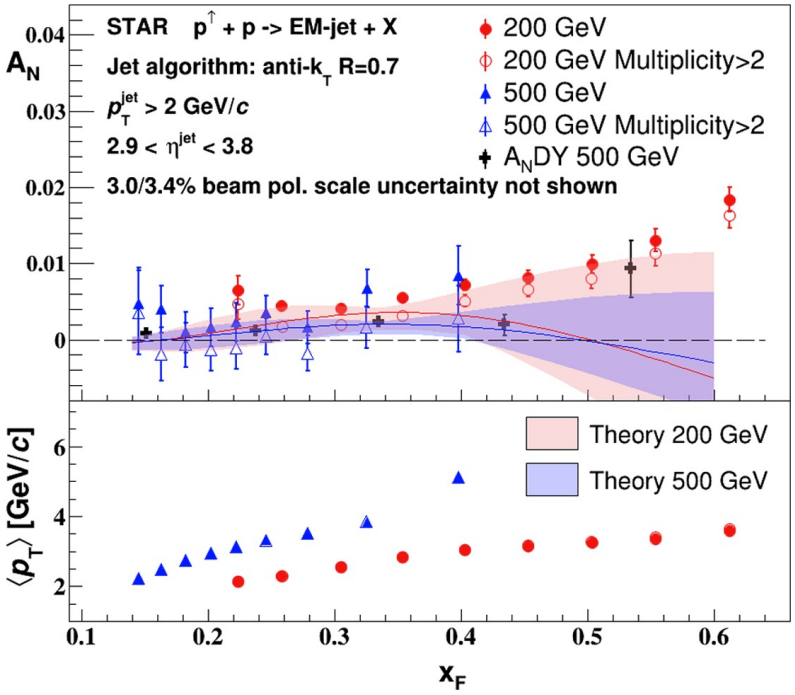


STAR, PLB 854, 138715(2024)

- 2017 results have much improved precision over those from the initial measurement
- New STAR data will have biggest impact on high-x region of the quark Sivers function.

Transverse spin asymmetry & TMDs

- STAR EM Jet A_N - sensitive to the initial state effect, Sivers effect



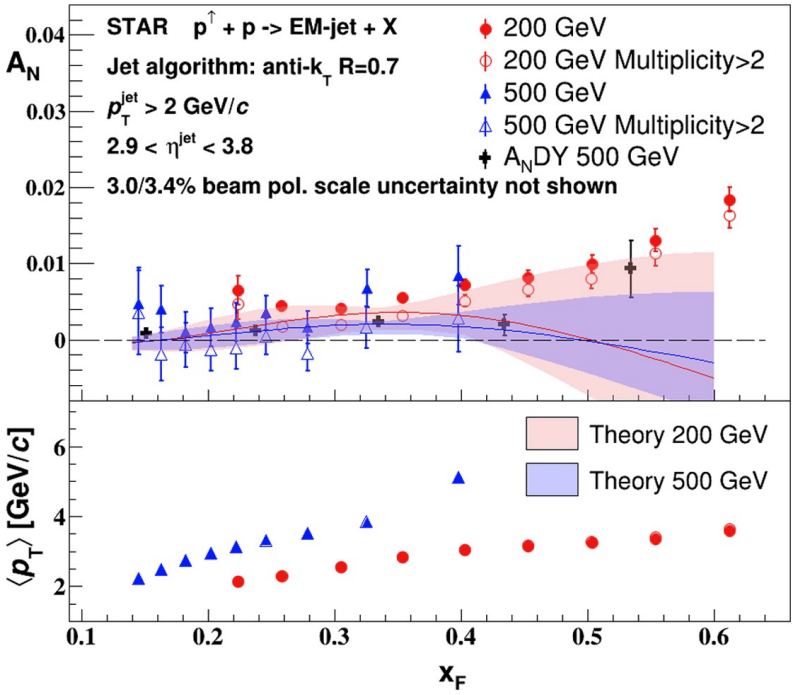
STAR, Phys. Rev. D103, 92009 (2021).

***L. Gamberg, Z. Kang, A. Prokudin, Phys.Rev.Lett.*110(2013)23,232301**

- The jet TSSA is a few times smaller than the π^0 TSSA in the same xF bin.
- The jet with photon multiplicity minimum requirement has significant smaller TSSA.
- The ANDY result shows the TSSA of the full jet, and is consistent with the result of the EM-jet which has at least 3 photons.

Transverse spin asymmetry & TMDs

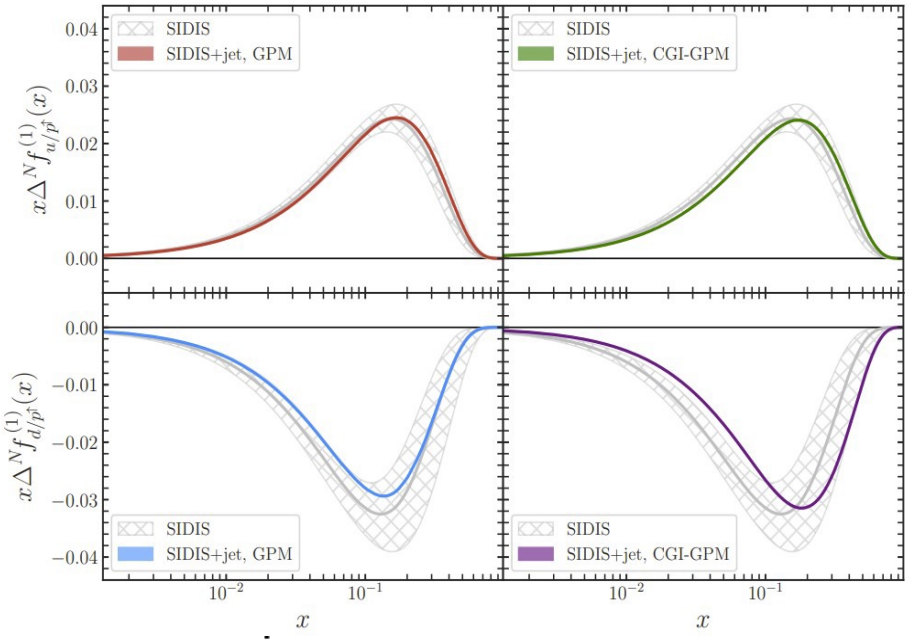
- STAR EM Jet A_N - sensitive to the initial state effect, Sivers effect
- Impact of our data in constraining Sivers function via global analysis



STAR, Phys. Rev. D103, 92009 (2021).

***L. Gamberg, Z. Kang, A. Prokudin, Phys.Rev.Lett.*110(2013)23,232301**

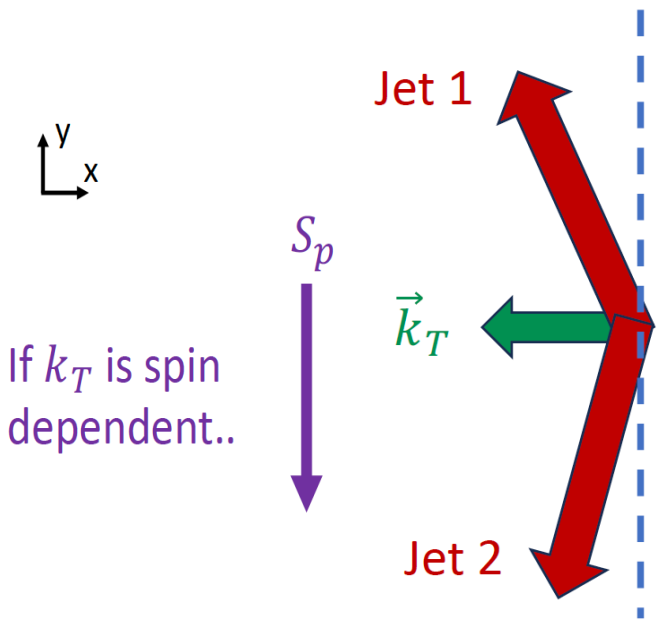
M.Boglione, et al., Phys. Lett. B 815 (2021) 136135



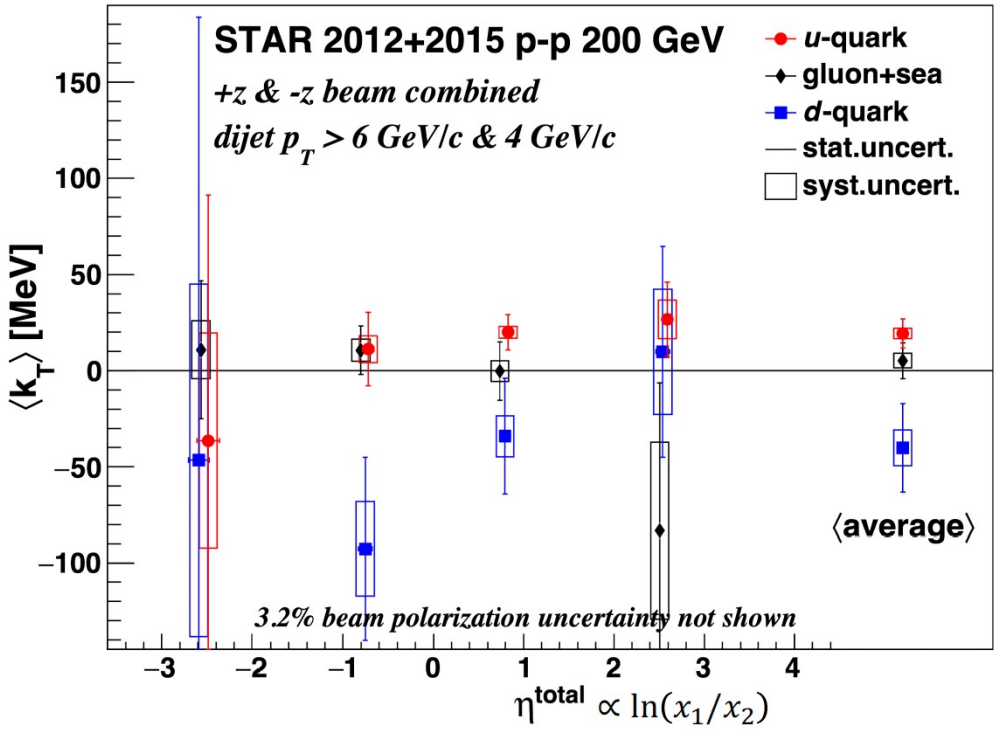
Probing Sivers effect using dijet production in p+p

- k_T provides a kick to the dijet, makes it fold 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>



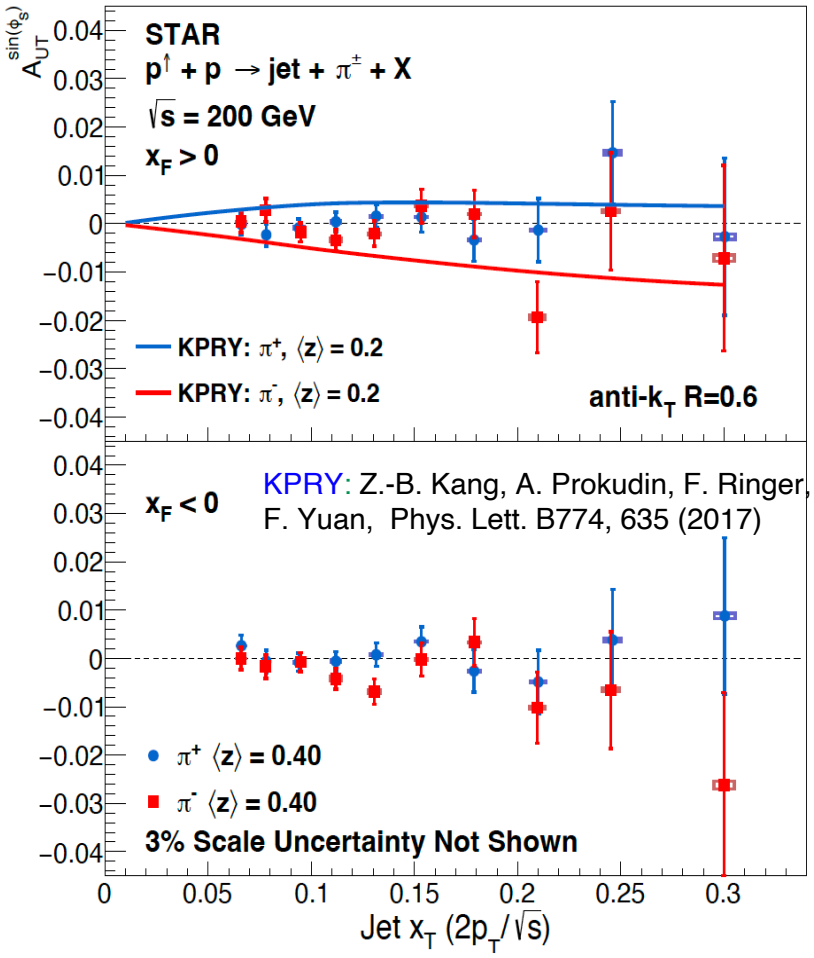
STAR, arXiv:2305.10359

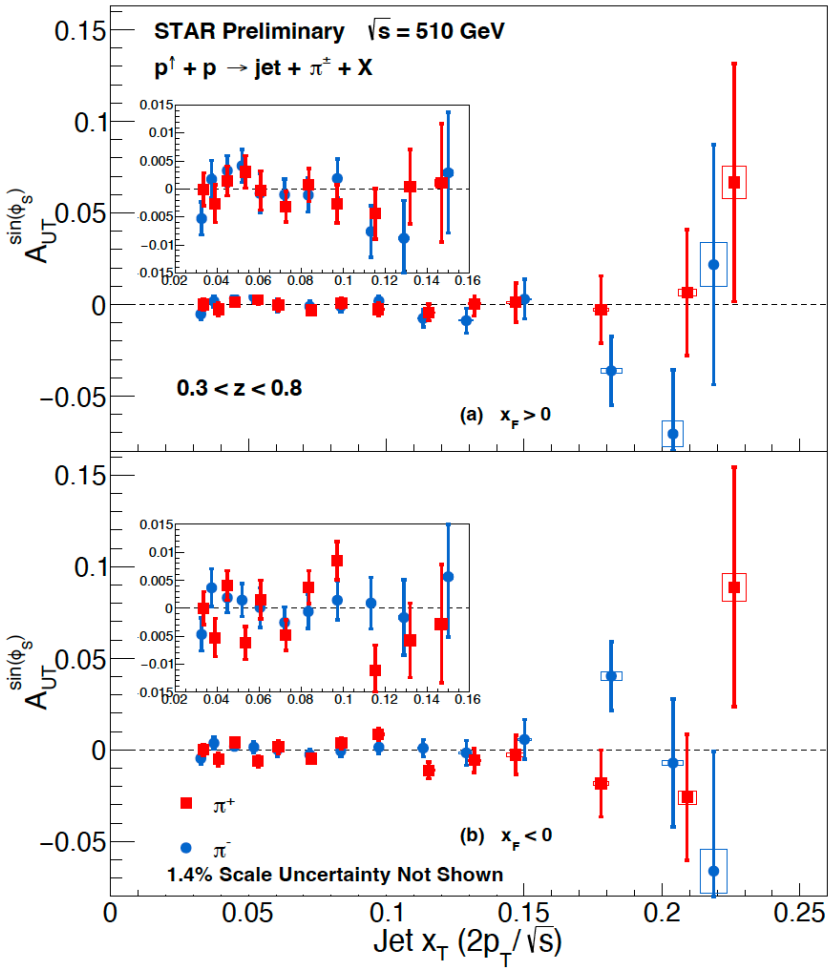


- Results: d-quark $\langle k_T \rangle \approx -2$ u-quark $\langle k_T \rangle$
- For the first time, there is evidence of non-zero Sivers effect using dijets

Jet A_N at mid-rapidity in p+p collisions

STAR, PRD106, 072010 (2022)

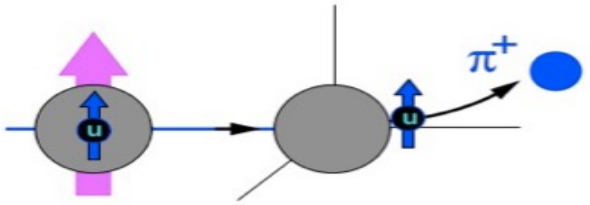




- Full jet A_N providing sensitivity to the twist-3 correlators associated with the quark Sivers function

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 asymmetries:

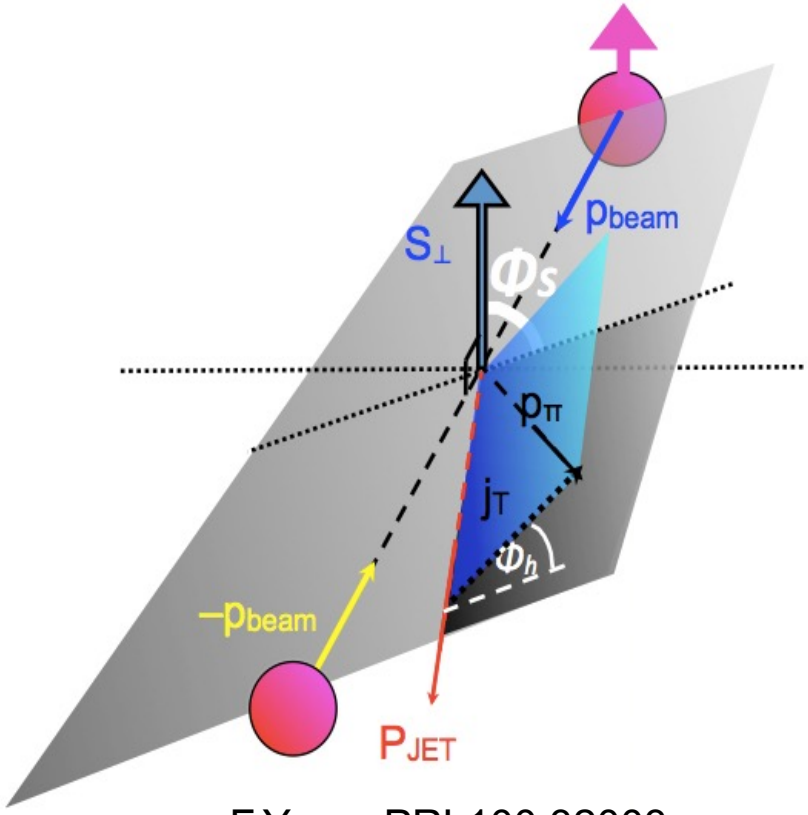
Collins angle: $\Phi_c=\Phi_s-\Phi_h$

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 asymmetries in p+p at STAR

- High precision data on Collins asymmetry in p+p collisions at 200 GeV, providing access to transversity:

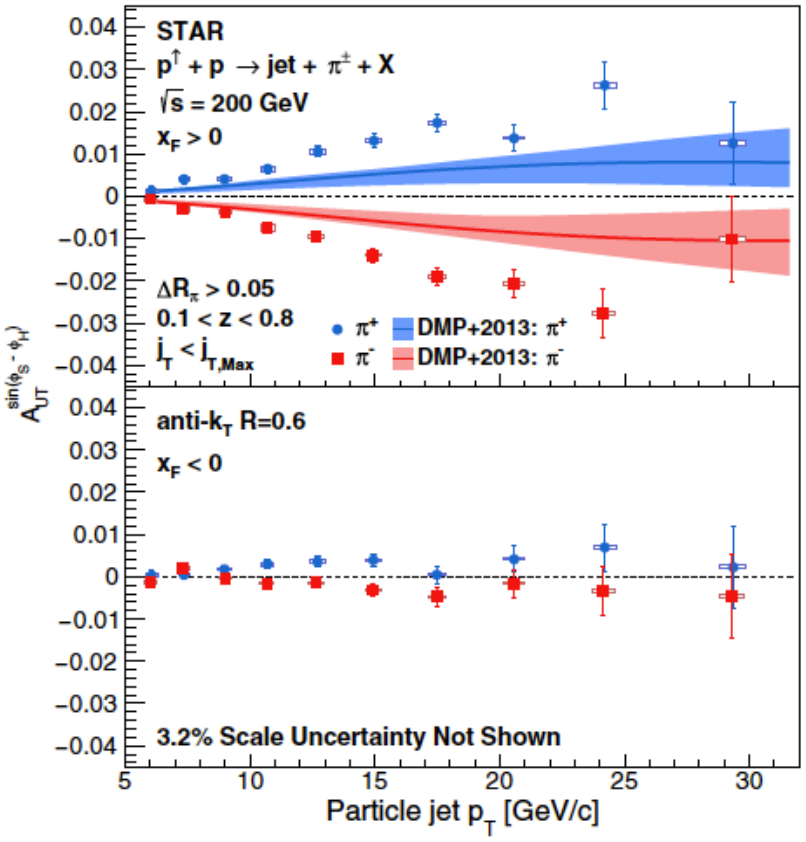
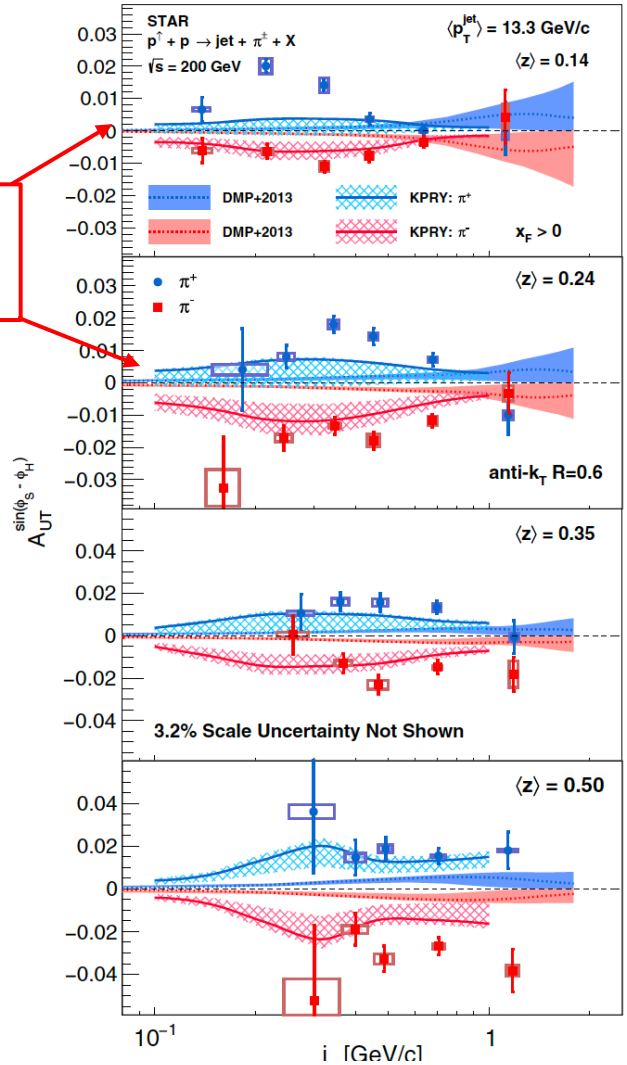


Figure shown in 2023 LRP

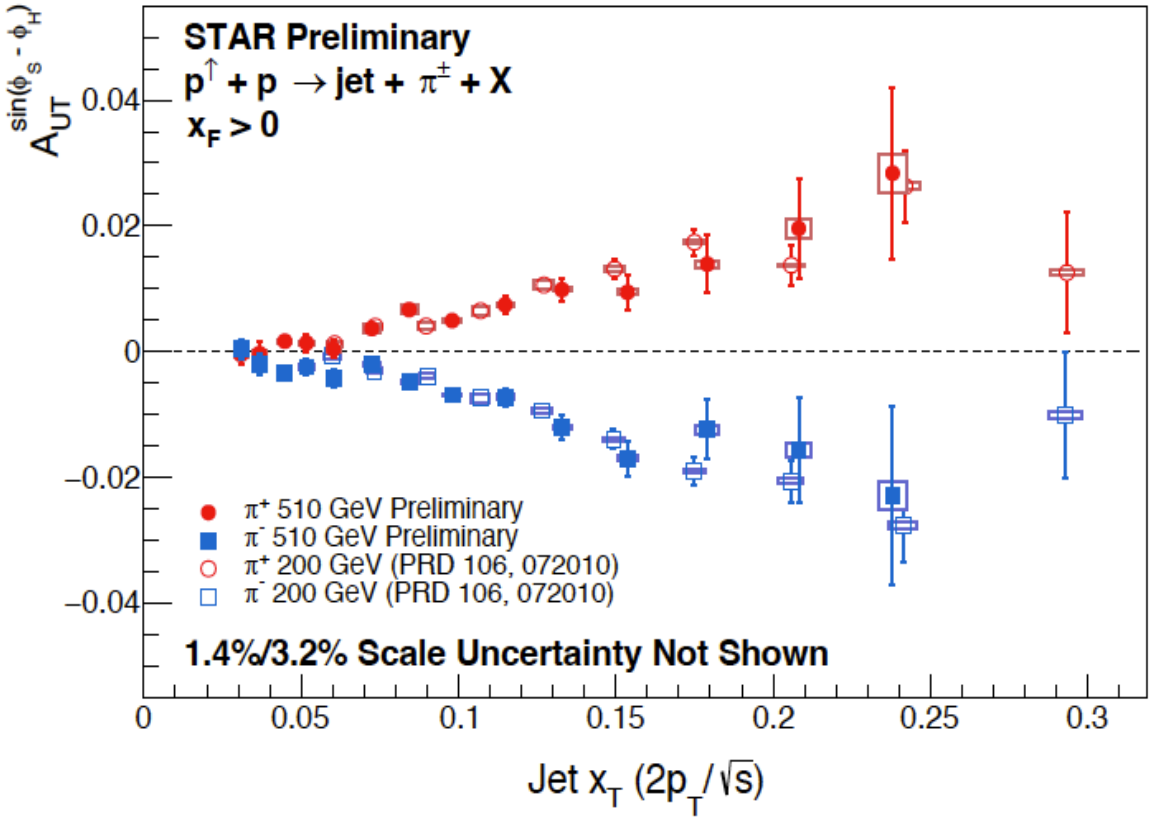


STAR, PRD106, 072010 (2022)

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

New Collins results from STAR

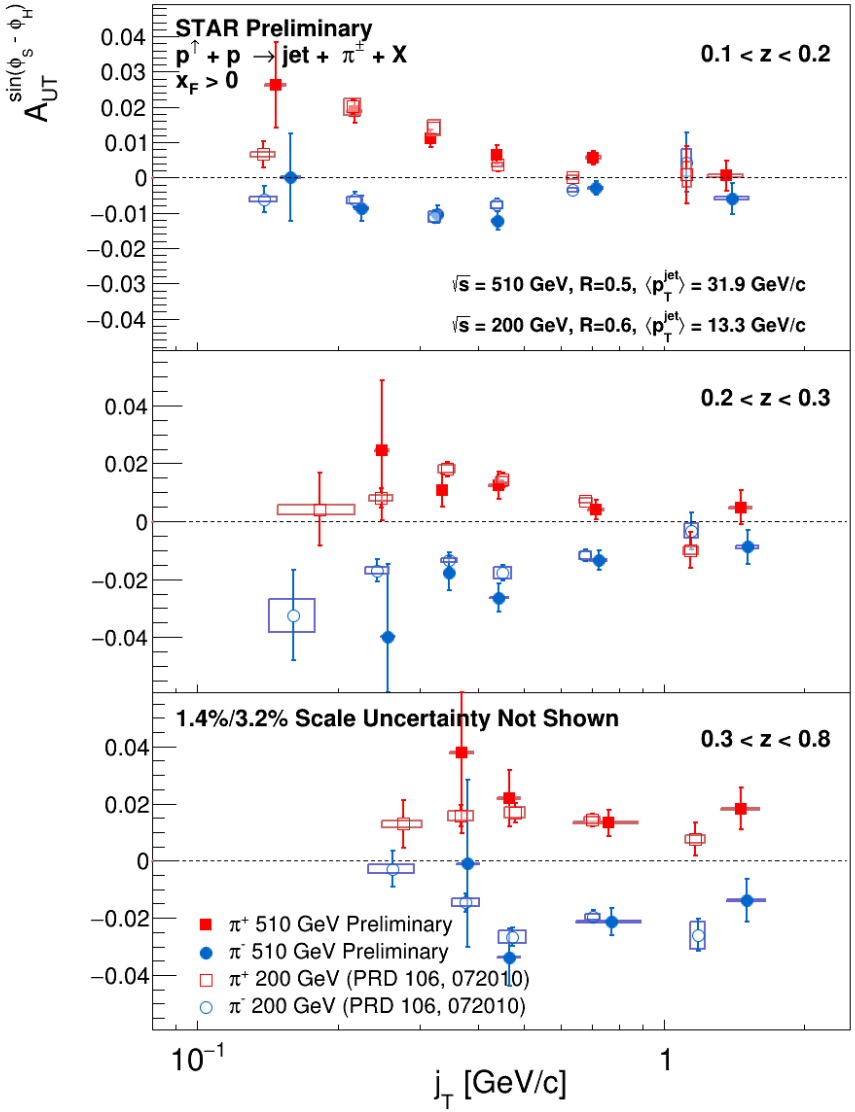
- New results on Collins asymmetry in p+p collisions at 510 GeV, in excellent agreement with 200 GeV data at same x_T:



- Striking comparison indicating weak energy dependence,
- Provides important constraints on TMD evolution of Collins function

New Collins results at 510 GeV & comparison to 200 GeV

- Collins results as a function of j_T :



j_T : pion's transverse momentum relative to the jet axis

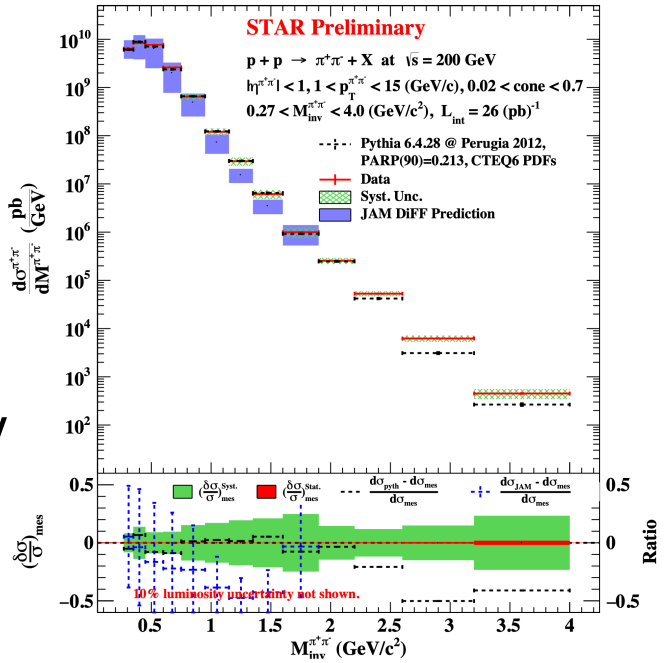
- Indication of weak energy dependence again!

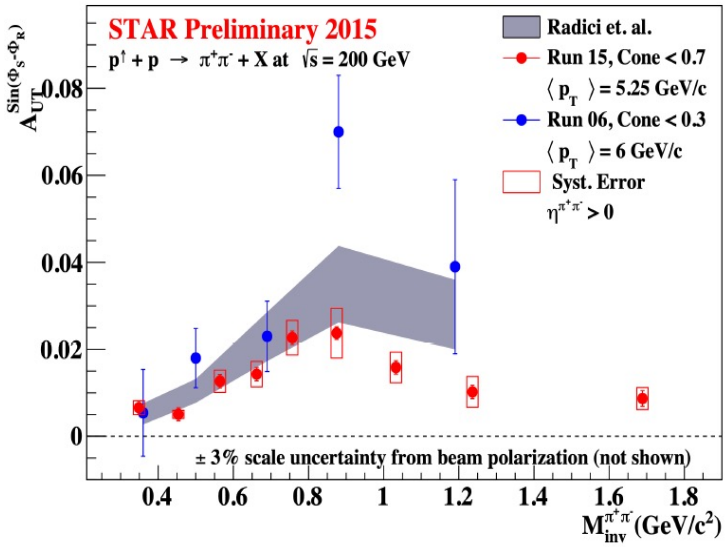
Di-hadron spin asymmetries at STAR

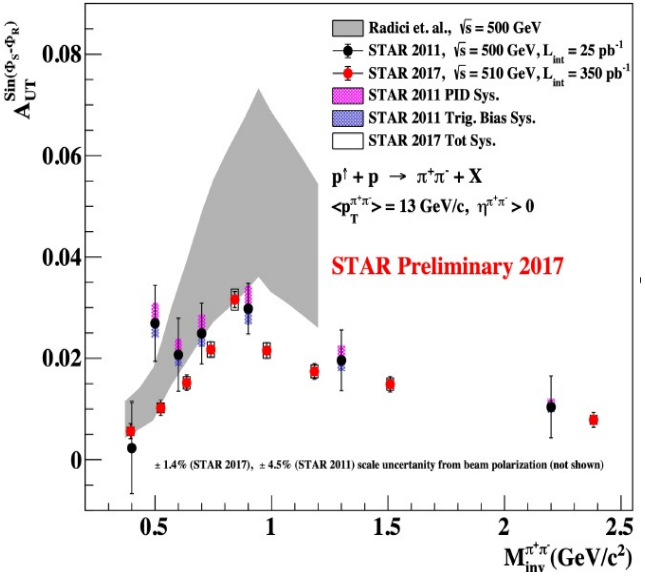
- New measurements of di-pion asymmetries in p+p collisions at 200 and 510 GeV
- First measurement of unpolarized di-pion cross section at 200 GeV

➢ model independent extraction of transversity

Radici & Bacchetta, PRL120,192001(2018)



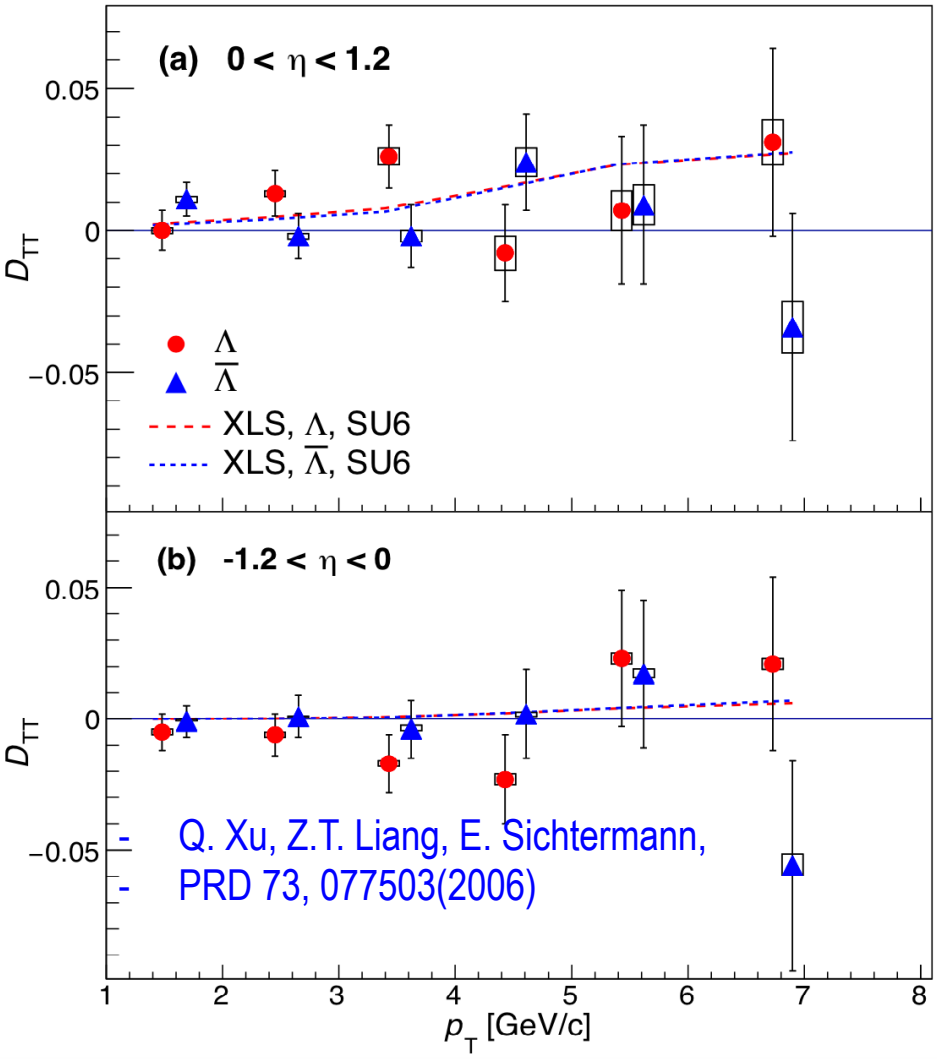




Transverse spin transfer D_{TT} results at STAR

- First D_{TT} measurements in p+p collision at 200 GeV at RHIC:

-STAR, PRD98, 091103R (2018)

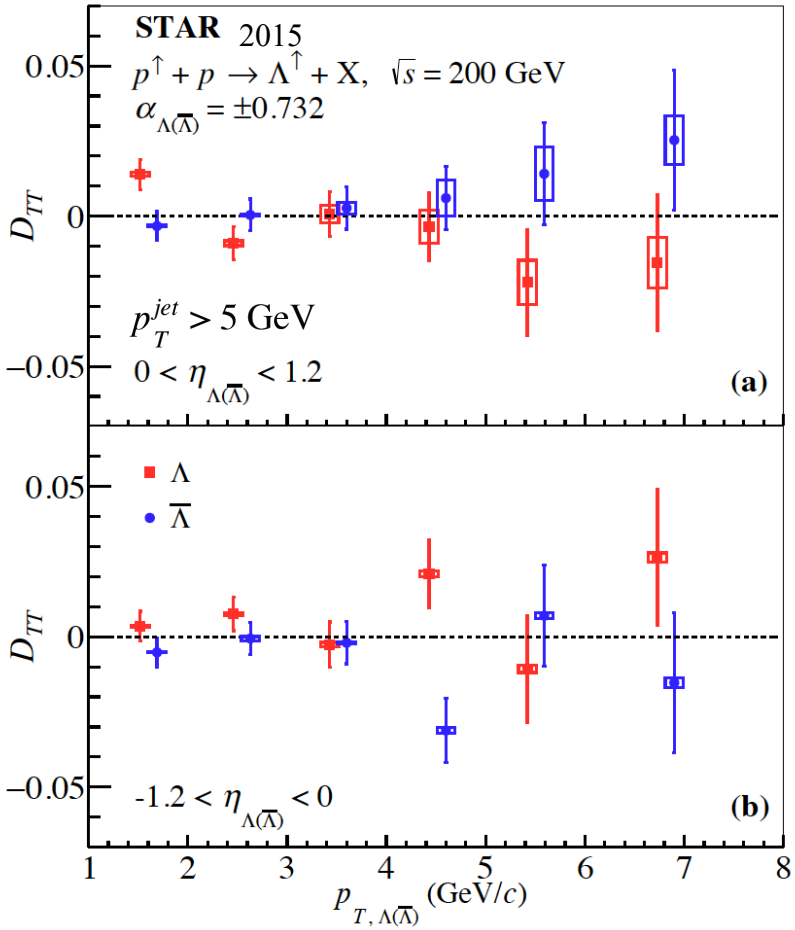


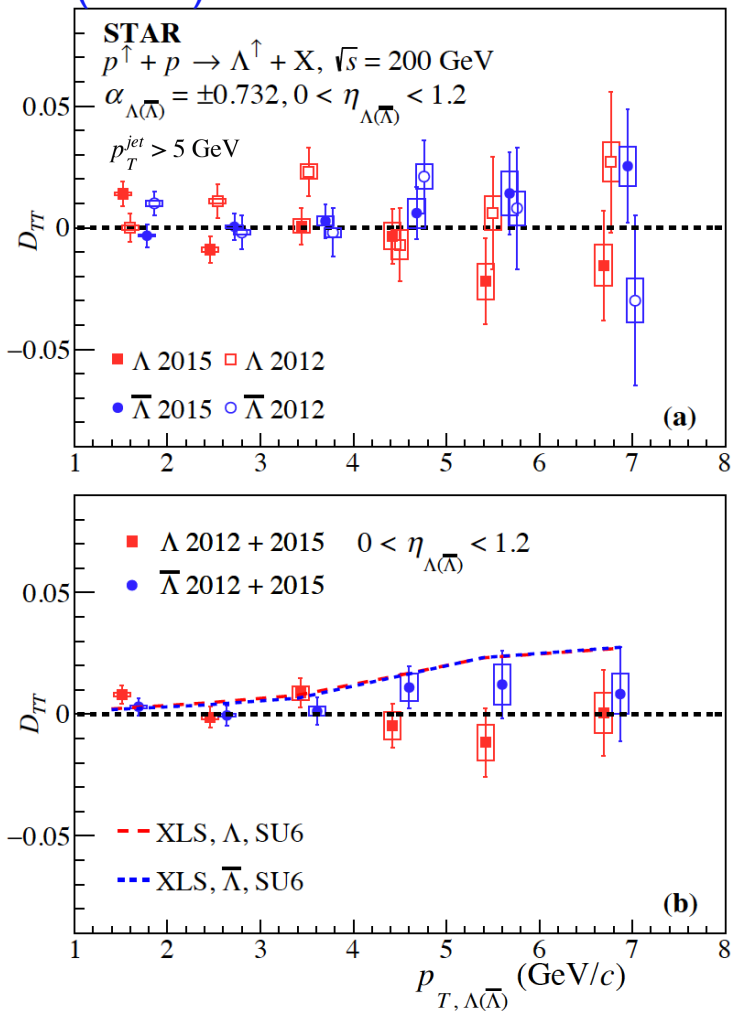
- ✓ D_{TT} is connected to strange quark transversity and transversely polarized fragmentation function.
- ✓ D_{TT} of $\Lambda / \overline{\Lambda}$ are consistent with a model prediction, also consistent with zero within uncertainty.

New D_{TT} results from STAR

- New D_{TT} results from 2015 with twice statistics. Most precise data up to date.
- D_{TT} is consistent with the model predictions within uncertainties.

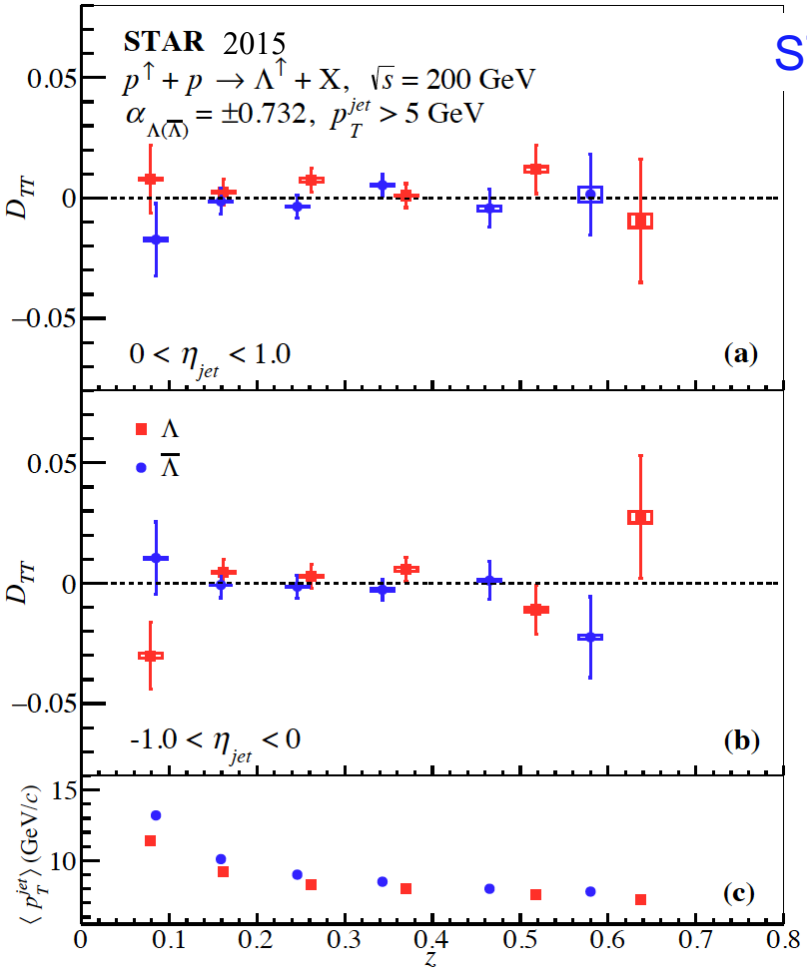
STAR, PRD109, 012004 (2024)





New D_{TT} results from STAR

- First measurement of D_{TT} vs. z for $\Lambda(\bar{\Lambda})$ in p+p collisions, providing constraints on transversely polarized fragmentation functions.
- Results are consistent with zero within uncertainties.



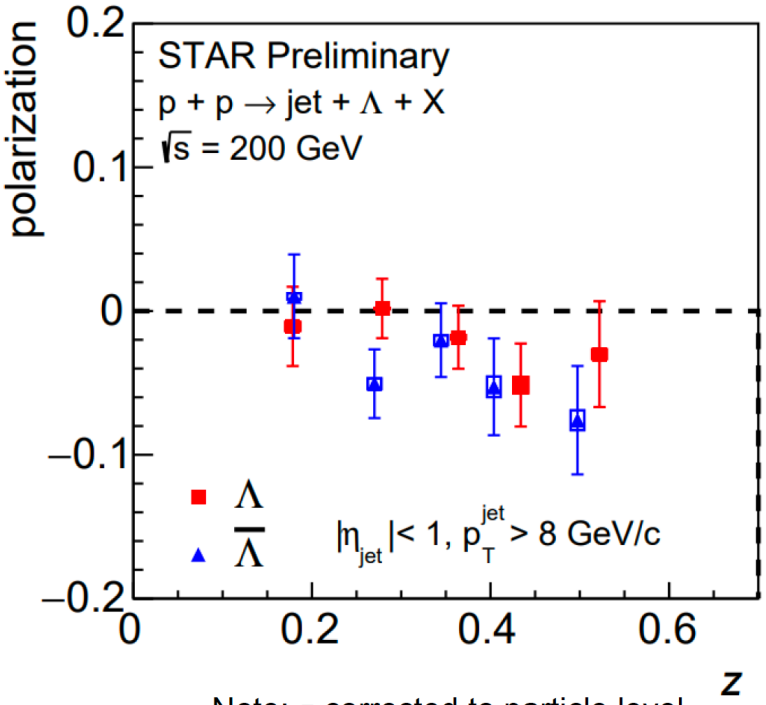
STAR, PRD109, 012004 (2024)

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

z: Jet momentum fraction carried by hyperon

Λ polarization within a jet in unpolarized p+p collision

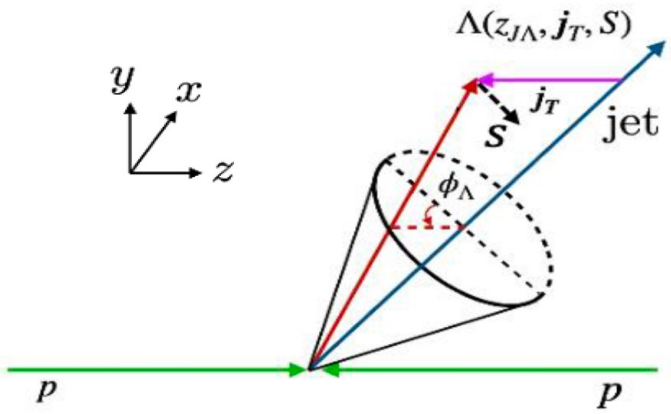
- 1st measurement on polarizing fragmentation function in p+p:



Note: z corrected to particle level

$$z = \frac{p_\Lambda * p_{jet}}{|p_{jet}| * |p_{jet}|}$$

Jet momentum fraction carried by $\Lambda(\overline{\Lambda})$



- Average polarization
  - $\Lambda : 1.72 \pm 1.13(\text{stat.}) \pm 0.08\%(\text{syst.})$
  - $\overline{\Lambda} : 3.42 \pm 1.30(\text{stat.}) \pm 0.32\%(\text{syst.})$
- Constraint for collinear fragmentation functions
- Λ polarization is consistent with 0
- Indication of negative transverse polarization of $\overline{\Lambda}$ $(\sim 2.6\sigma)$

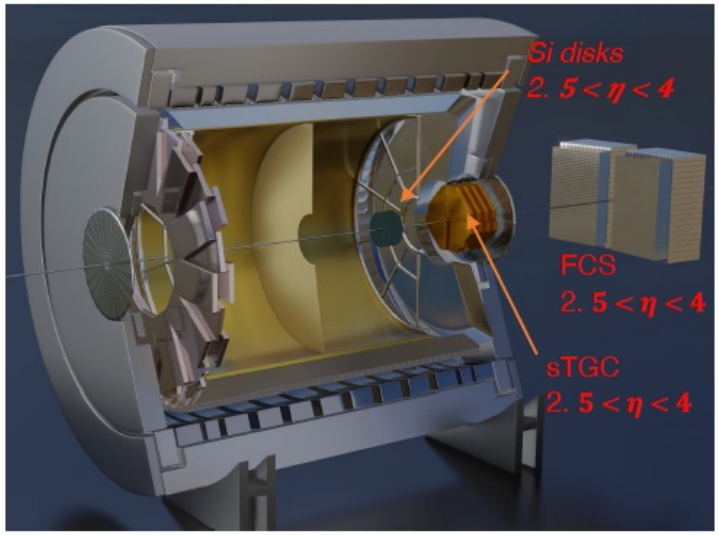
- Taoya Gao @SPIN2023

RHIC p+p running until 2025

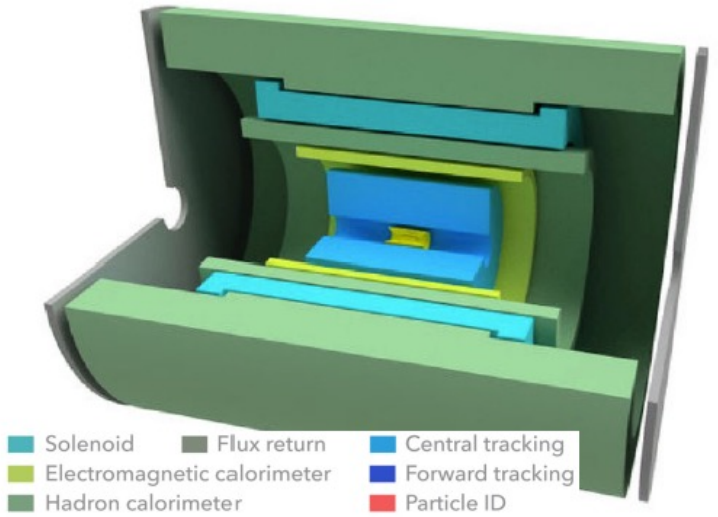
- Successful p+p run in 2022 with forward detector upgrade (2.5<η<4)
- Last transverse spin run in 2024 (ongoing), unique physics opportunities in p+p and p+A before EIC

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	p+p	142 pb^{-1}/12w	2024
200	p+Au	0.69 pb^{-1}/10.5w	2024
200	Au+Au	18B / 32.7 nb^{-1}/40w	2023+2025

STAR w/ forward upgrade



sPHENIX



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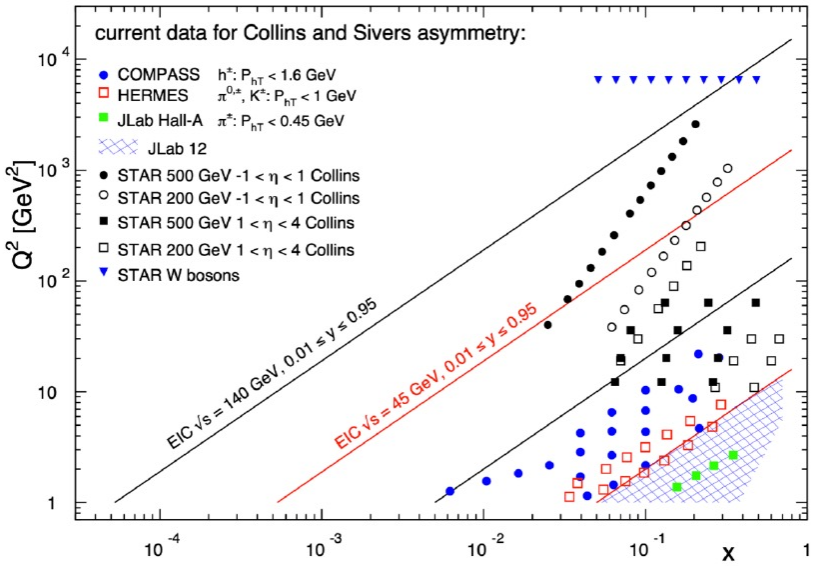
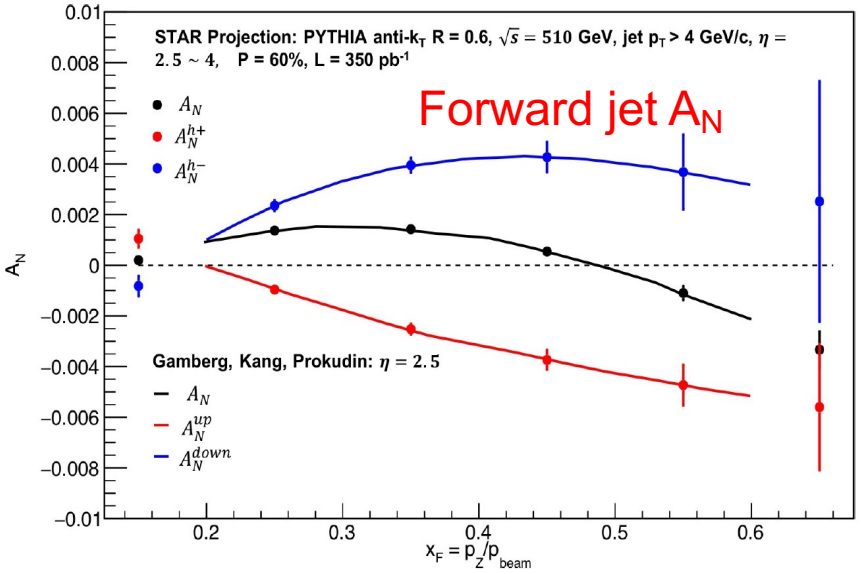




➢ Essential x-Q^2 overlap with EIC, full jet reconstruction + charge-sign tagging

Summary

- Great achievements from RHIC spin program in ~20 years
- Observation of positive gluon polarization from RHIC:

  -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, $\pi^{\pm}$ spin asymmetries provide important information on underlying physics mechanism: Sivers & Collins, and transversity
- Future RHIC spin run until 2025

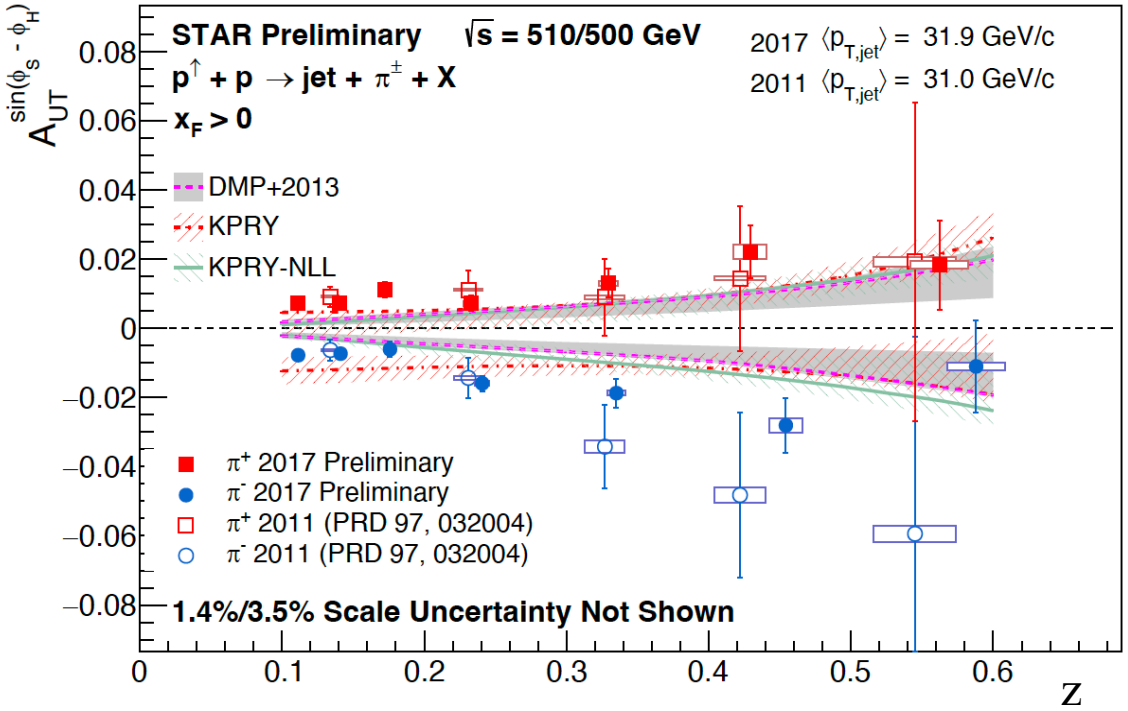
  - Unique physics opportunities in pp and pA before EIC

谢谢！

Backup slides

New Collins results from STAR

- Collins results vs. z : comparison to theoretical calculations



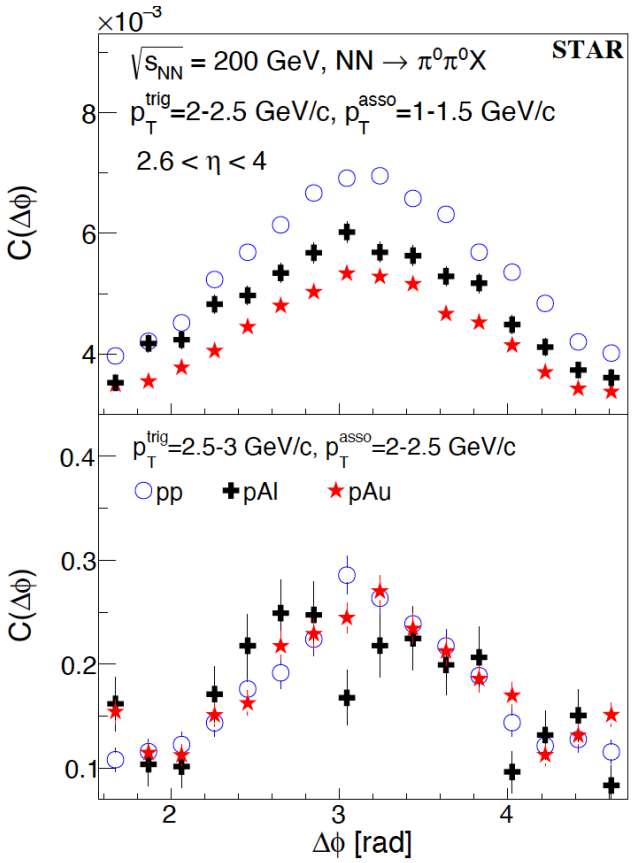
U. D'Alesio, F. Murgia, and C. Pisano, Phys. Lett. B 773, 300 (2013)
Z.-B. Kang, A. Prokudin, F. Ringer, and F. Yuan, Phys. Lett. B 774, 635(2017)

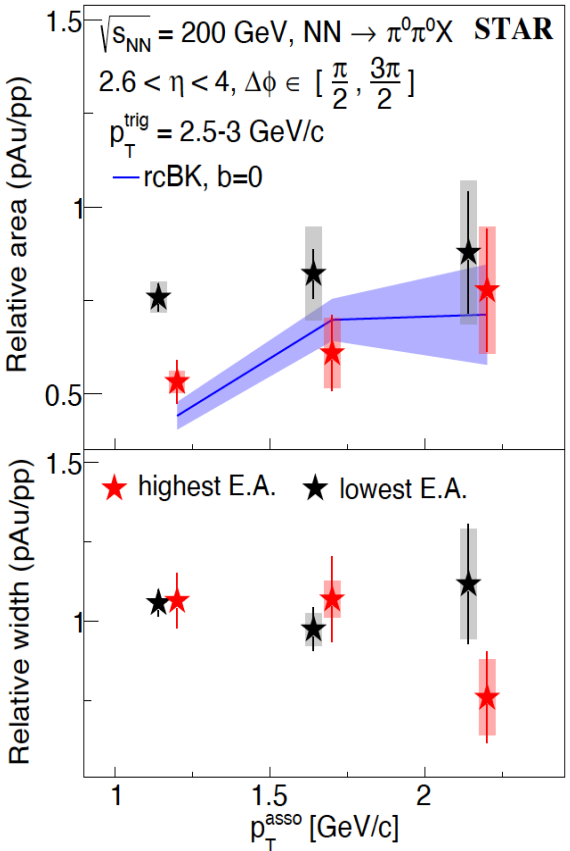
- DMP, KPRY use global fit of Collins from SIDIS and e^+e^- data, without TMD evolution
- KPRY-NLL consider TMD evolution at next leading log

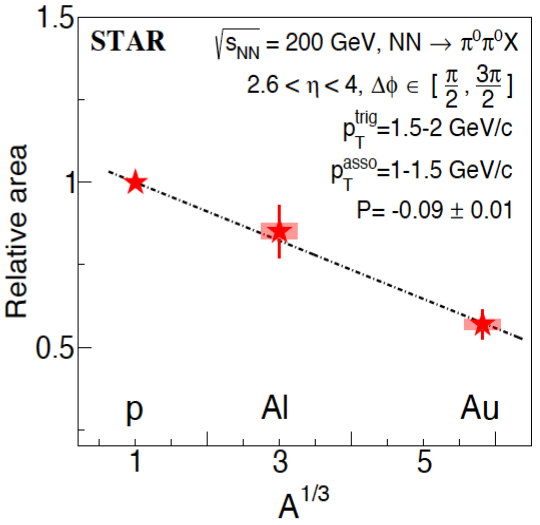
Evidence for Nonlinear Gluon Effects & the A Dependence

- Di-π^0 correlation in forward region in p+p and p+A at 200 GeV
- A clear suppression of the correlated yields of back-to-back pairs in p+Al and p+Au compared to p+p data.

STAR, PRL**129**, 092501(2022)





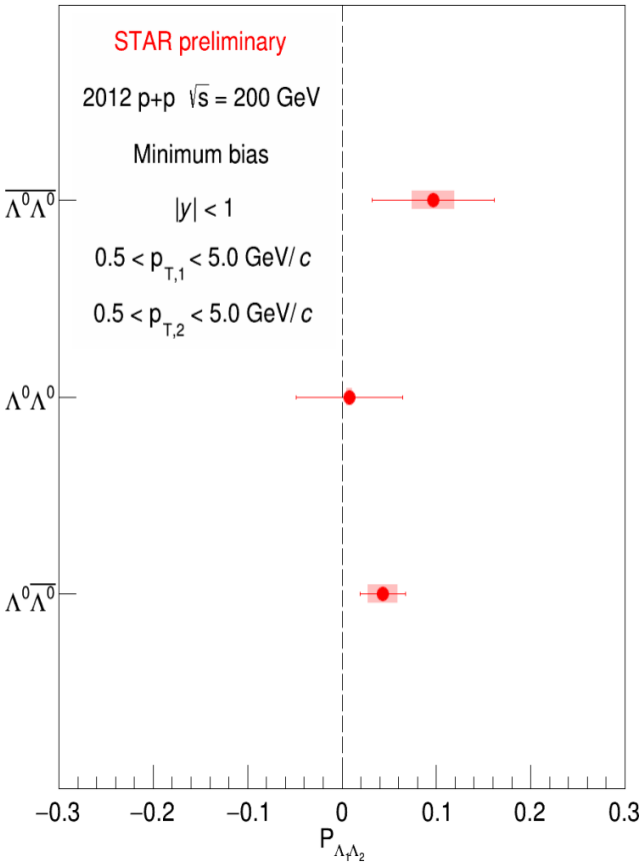


-A linear dependence of the suppression as a function of $A^{1/3}$

-The suppression in high-activity p+Au collisions is consistent with theoretical predictions including gluon saturation effects.

Lambda spin correlations in pp collisions

- $P_{\Lambda_1\Lambda_2}$ are consistent with zero within uncertainties
- Hint of spin-spin correlation signal for $\Lambda^0\overline{\Lambda}^0$ pairs at 2σ statistical significance
- Data suggest no significant spin-spin correlation of initial state s (anti-)quark pair
  - This measurement provides upper limit on Λ^0 hyperon spin-spin correlations in p+p collisions at $\sqrt{s} = 200$ GeV
- First experimental search for Λ^0 hyperon spin-spin correlations



- Measure angle θ^* between the two boosted protons
  - The distribution of pair angle is given by:

$$\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} \sim 1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)$$

  - α_1 and α_2 are α_+ or α_-, depending on Λ^0 hyperon pair

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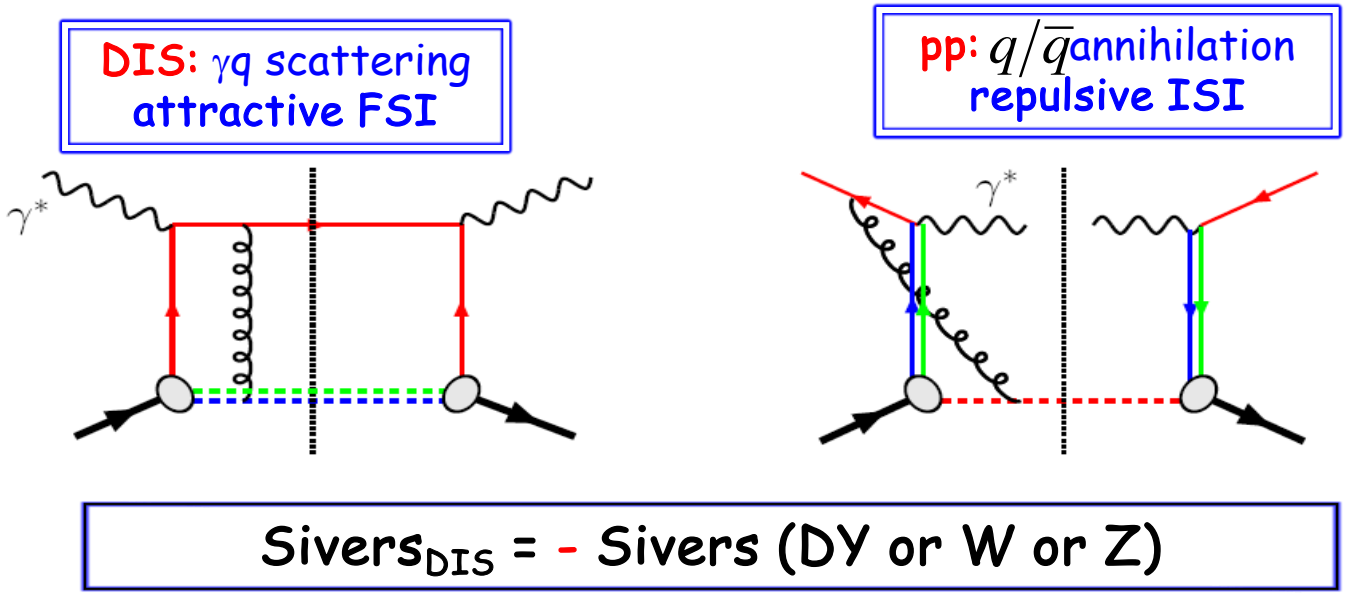
Transverse single spin asymmetry (A_N) of W boson

- 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

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