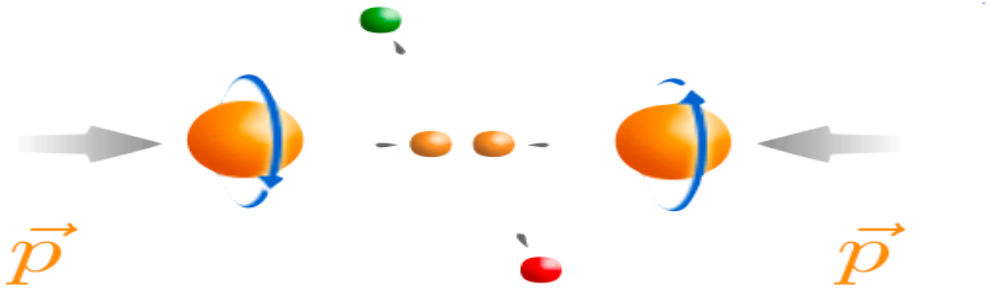
# Recent results on cold-QCD from RHIC

Qinghua Xu （Shandong University)

for the STAR collaboration

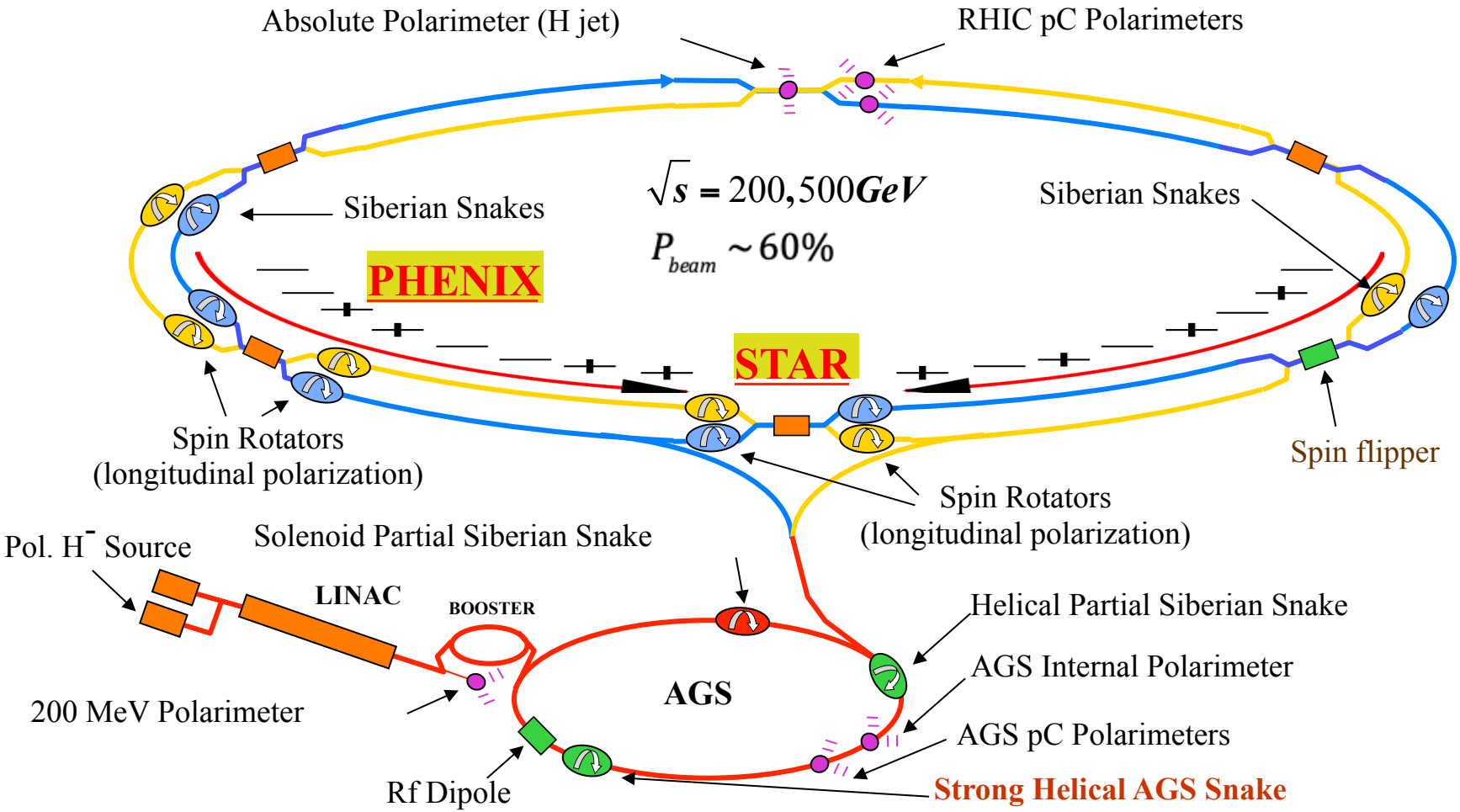
ISMD 2019, Santa Fe, Sep. 9, 2019



# Outline:

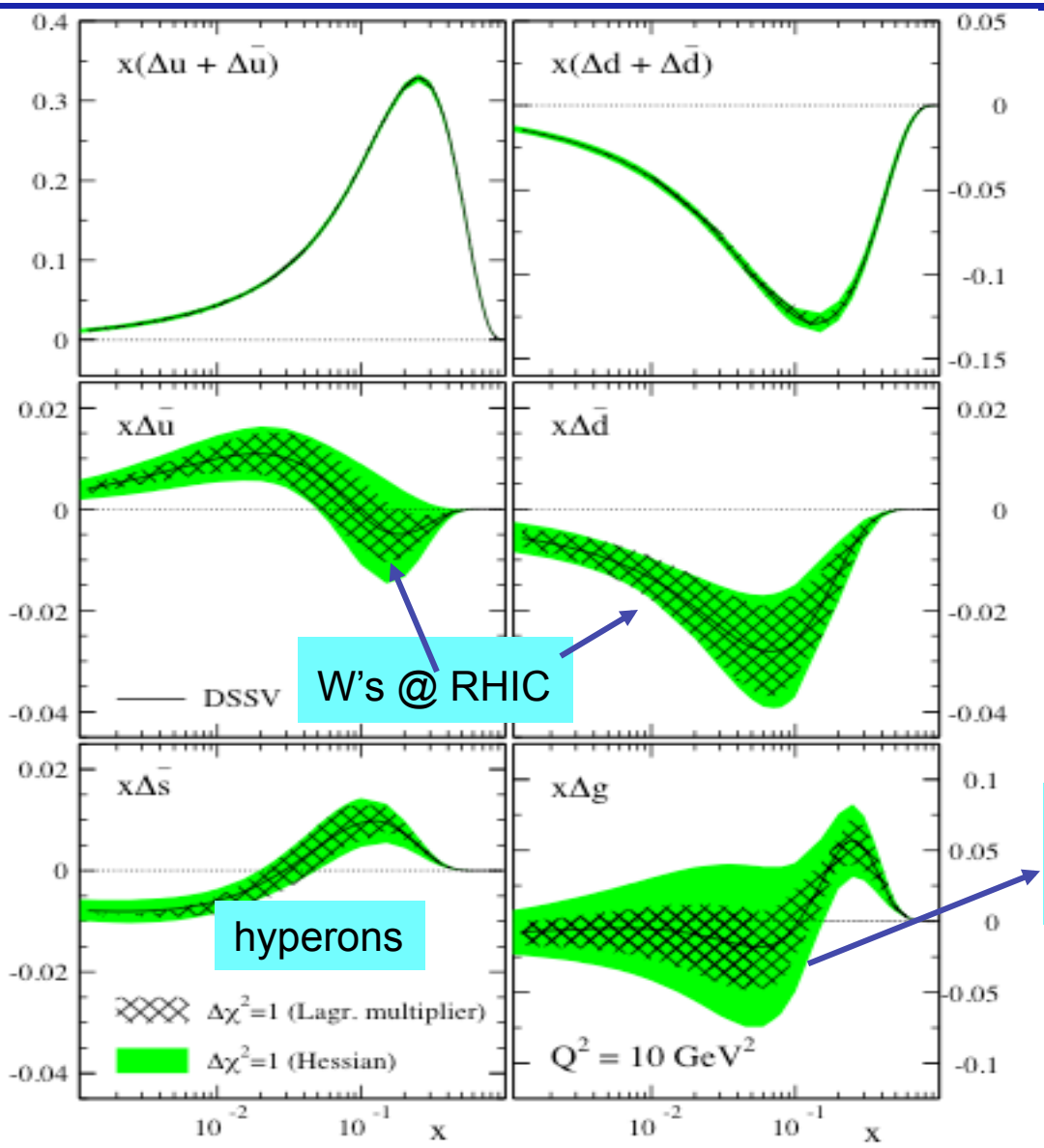
- Experimental aspects: RHIC
- Recent spin highlights:
  - ✓ Gluon polarization (Jet production, $\pi^0$): gluon polarization $\Delta g$
  - ✓ Quark/Anti-quark polarization (W/Z production): sea quark $\Delta q$
  - ✓ Transverse spin asymmetry (W/Z production): Sivers function
  - ✓ Transverse spin asymmetry (Hadron production): Collins & IFF
- Upgrade plans for cold-QCD physics in 2021+ at RHIC
- Summary

# RHIC- 1st polarized proton-proton collider




- World's only polarized hadron-hadron collider: longitudinal & transverse
- Spin direction changes from bunch to bunch
- Two main experiments: STAR & PHENIX

# Δq(x), Δg(x)- global analysis of data




- Spin sum rule (longitudinal):

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

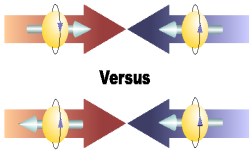
| Quark spin, (~30%) -DIS | Gluon spin, Poorly known, RHIC | Orbital Angular Momenta Little known |
|---|---|---|

RHIC (jet, $\pi^0$, photon) 200 GeV, 500 GeV

D. De Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRD80(2009)

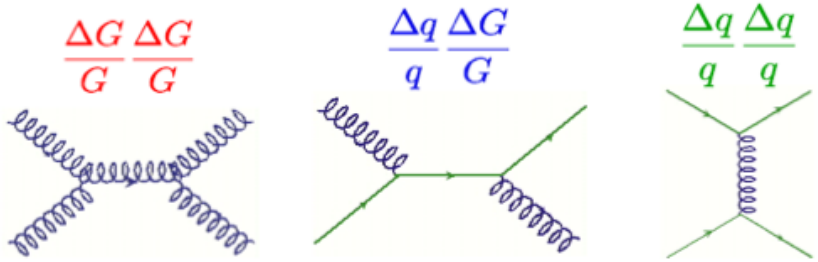
# Accessing Δg(x) in pp collision

- Longitudinal spin asymmetry:

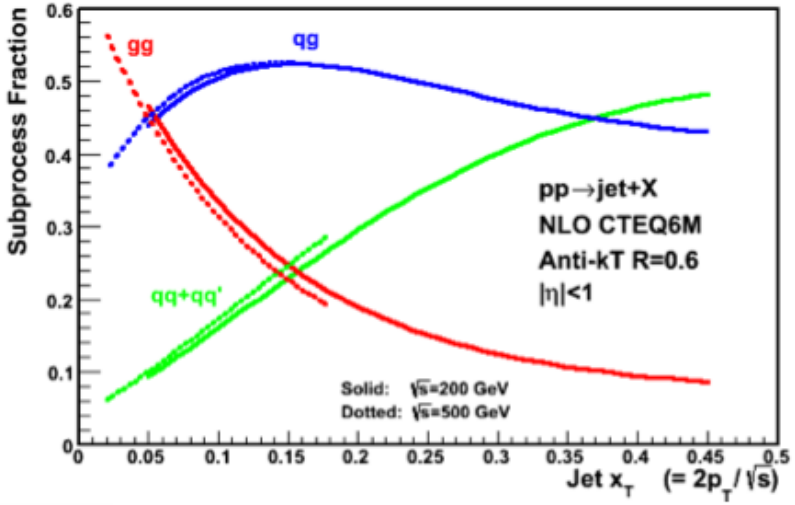


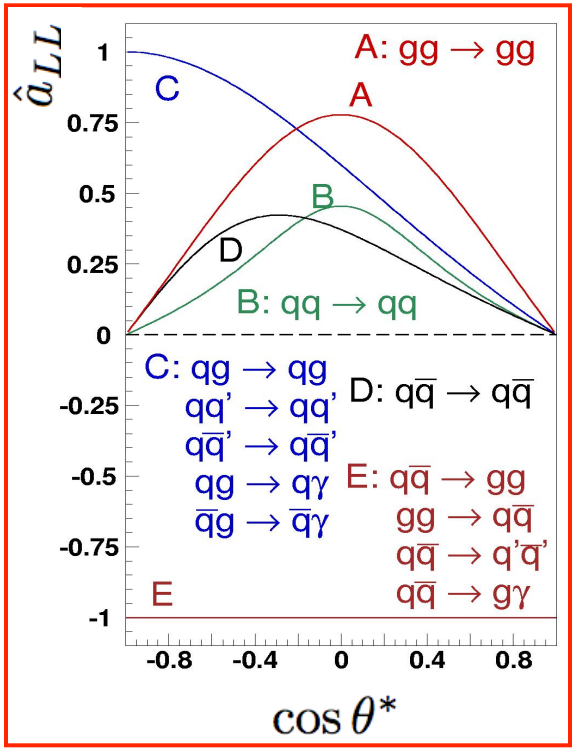

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \cdot \hat{a}_{LL}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}$$

$\Delta f_1$ $\Delta f_2$ $\hat{a}_{LL} = \frac{d\Delta\hat{\sigma}}{d\hat{\sigma}}$ $D_f^{\pi}$




- Partonic fraction for jet/$\pi^0$ production:

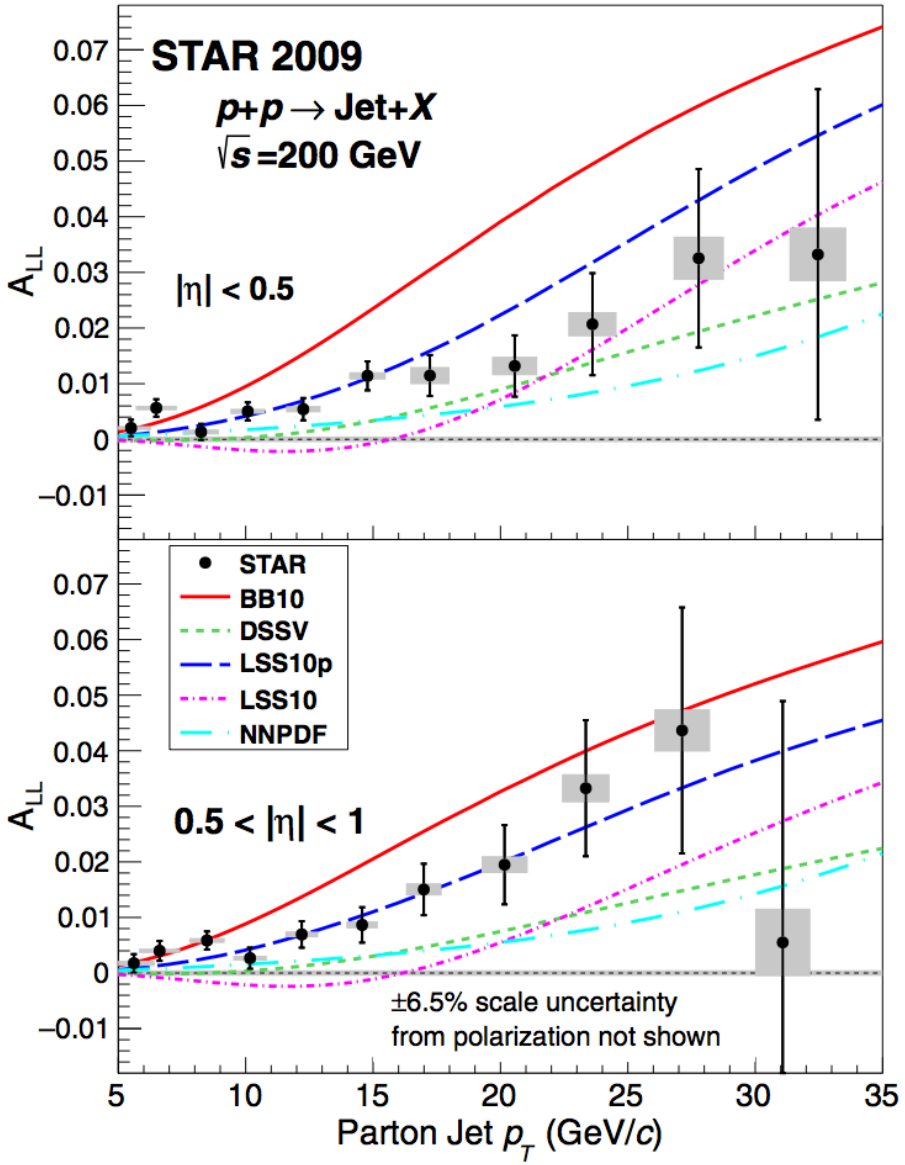


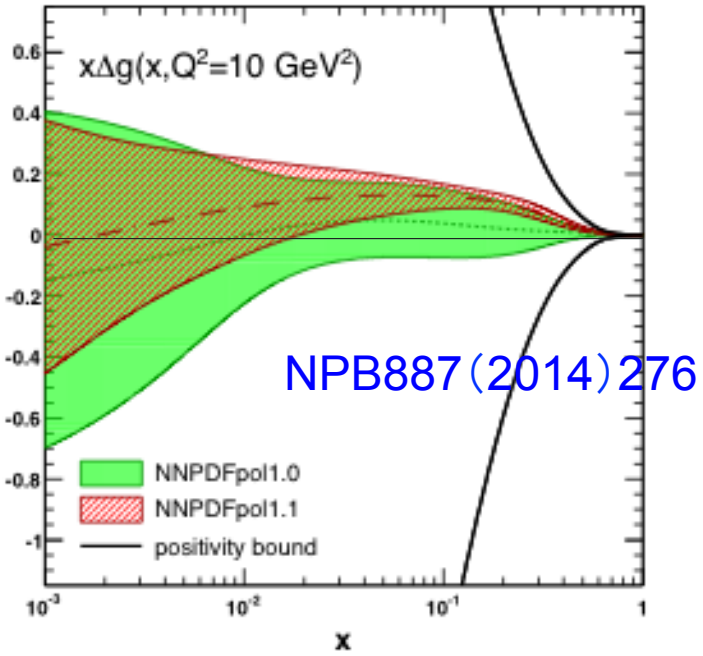

G. Bunce et al, Annu. Rev. Nucl. Part. Sci. 50, 525(2000)

# STAR inclusive jet $A_{LL}$ from 2009 data

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




- 2009 STAR data at 200 GeV.
- The $A_{LL}$ asymmetry is small, but clearly non-zero !
- Impact of STAR data on Δg in NNPDF global analysis:

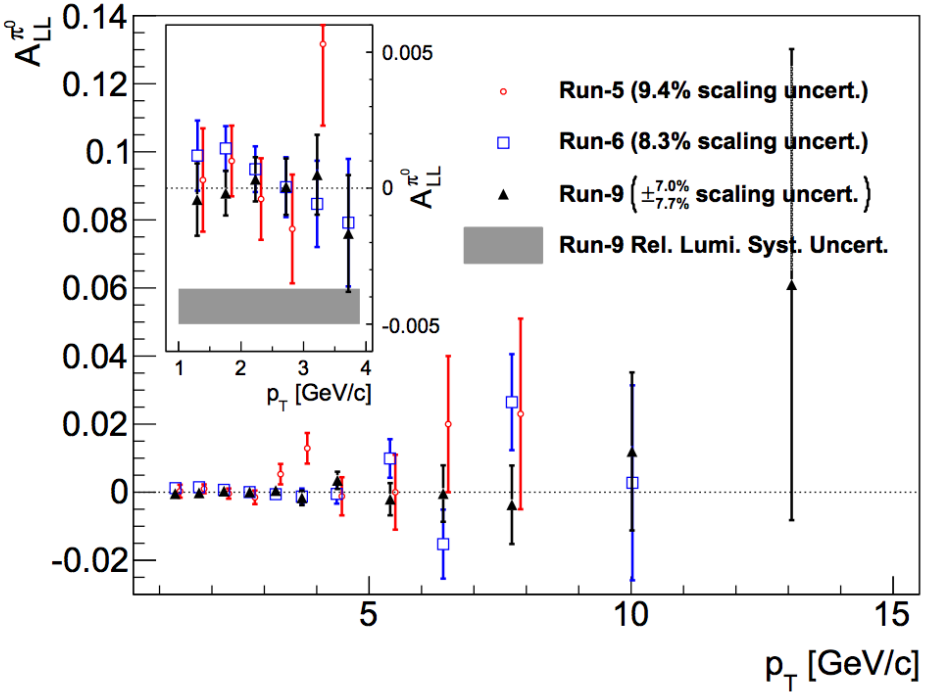


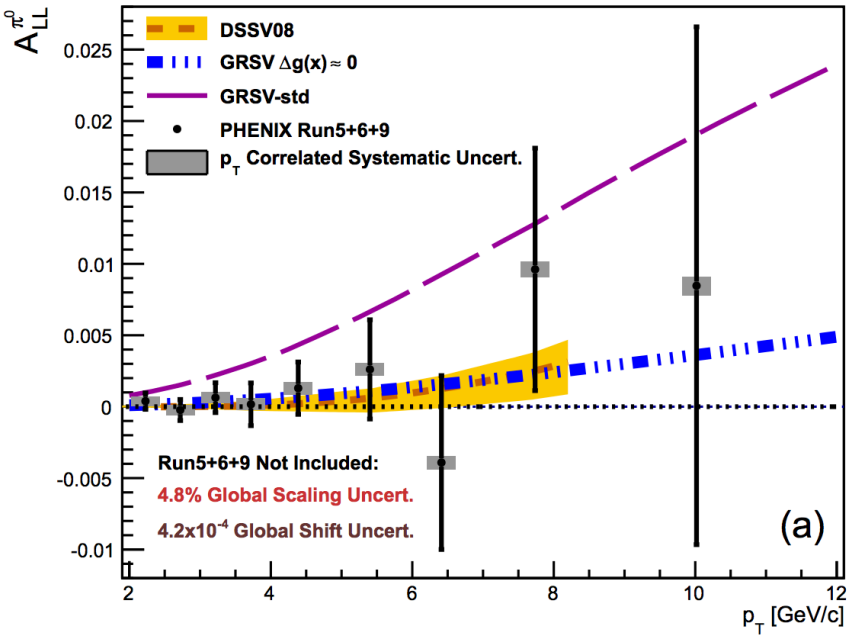

NPB887（2014）276

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

# PHENIX results on $\pi^0$ $A_{LL}$

**PHENIX-Phys. ReV. D 90, 12007(2014) [pp @ 200 GeV]**

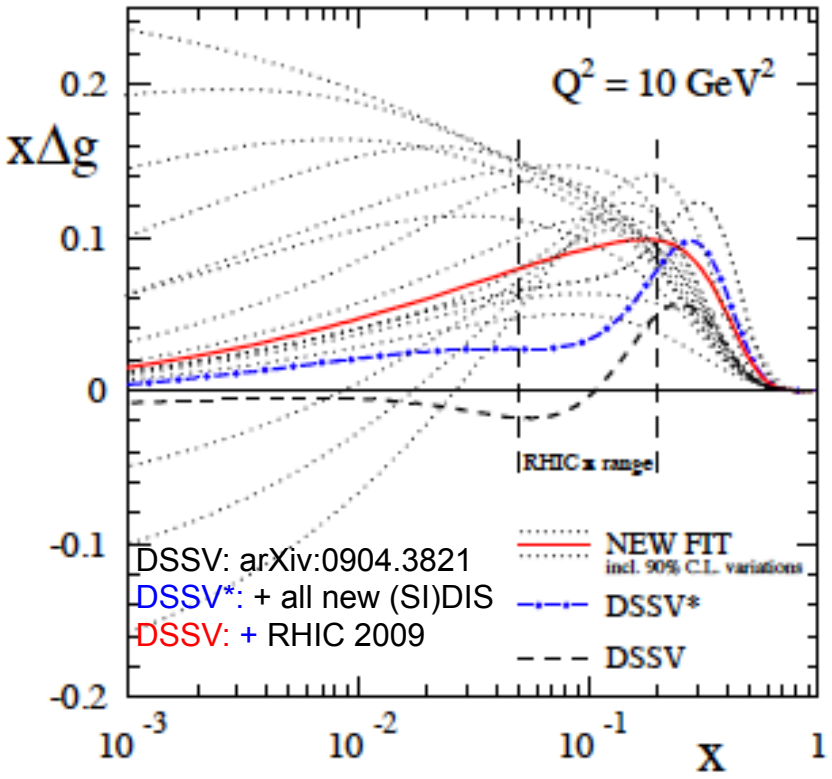


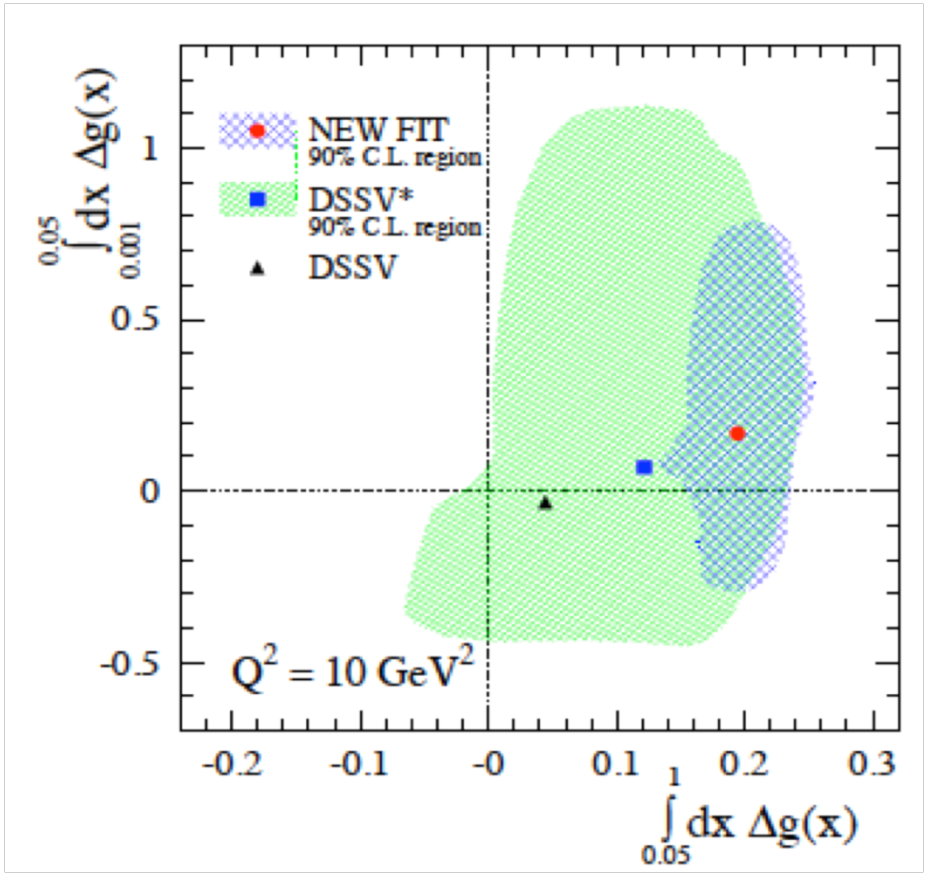

- High precision measurement at mid-rapidity
- Results are consistent with zero within uncertainty

# DSSV global analysis including STAR/PHENIX data -Observation of gluon polarization

DSSV, PRL113,12001(2014)




$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} @\ 10\ GeV^2$$




To further constrain Δg(x), need to go to lower x

-> higher energy, forward di-jets

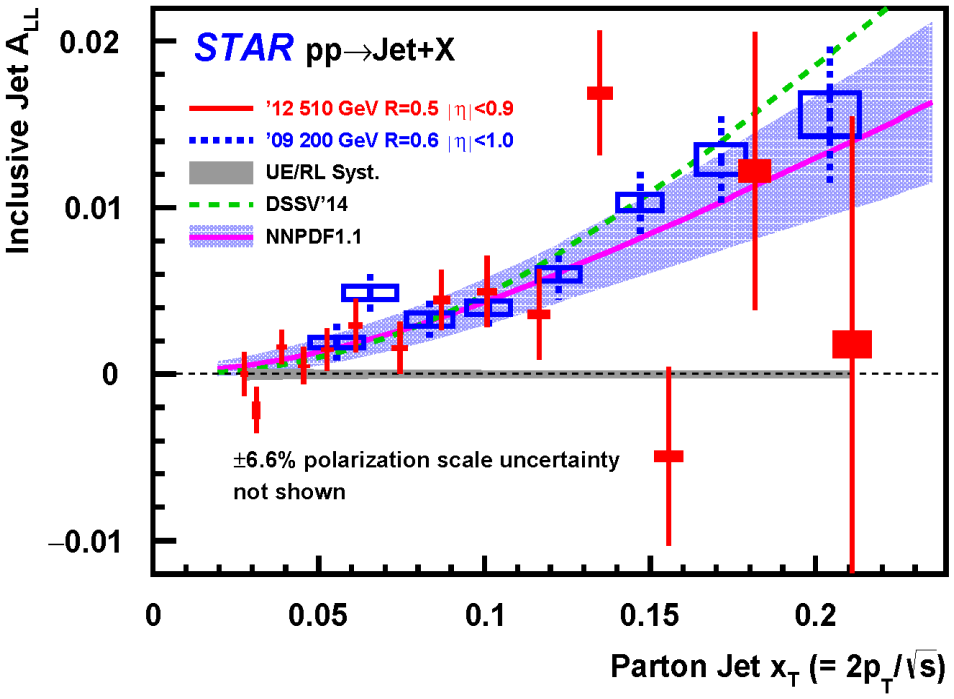
- 1st Lattice calculation:

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

χQCD, PRL118,102001(2017)

# $A_{LL}$ results on jet/$\pi^0$ at 510 GeV from STAR

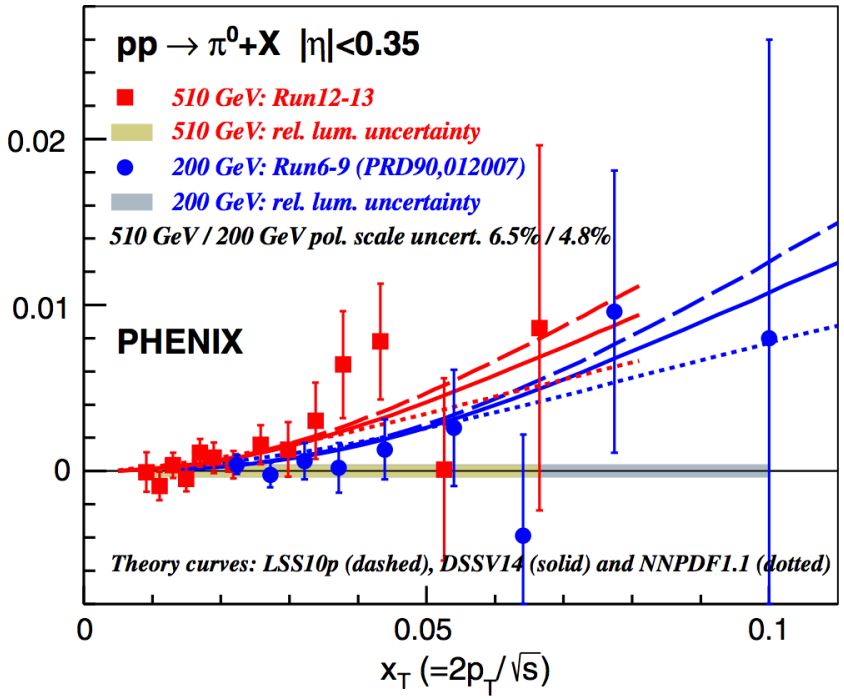
- Can we further improve our knowledge on $\Delta g(x)$? Yes!




STAR, arXiv:1906. 02740, PRD accepted

- PHENIX $\pi^0$ $A_{LL}$ at 510 GeV, which is also sensitive to $\Delta g$ in small x region

- STAR jet $A_{LL}$ at 510 GeV, access small x region down to x~0.015, compared to x~0.05 at 200GeV.

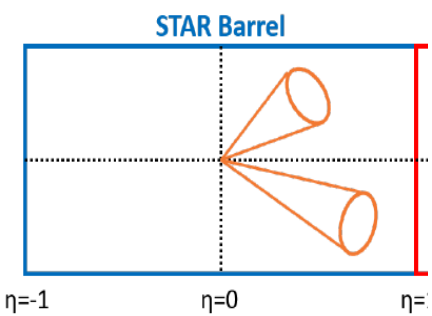


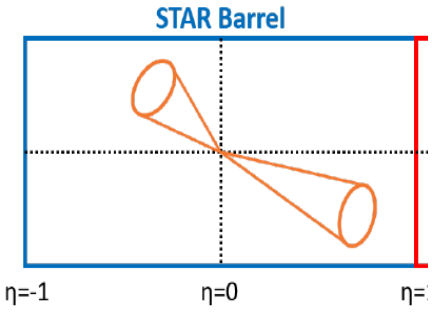

PHENIX, PRD 93, 011501 (2016)

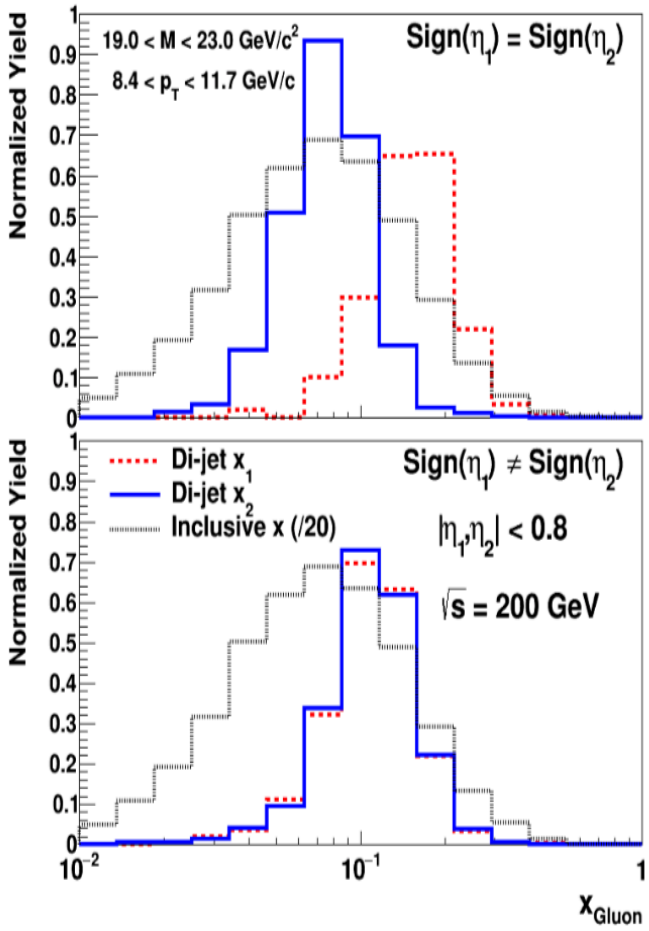
# Central di-jet $A_{LL}$ at 200 GeV at STAR

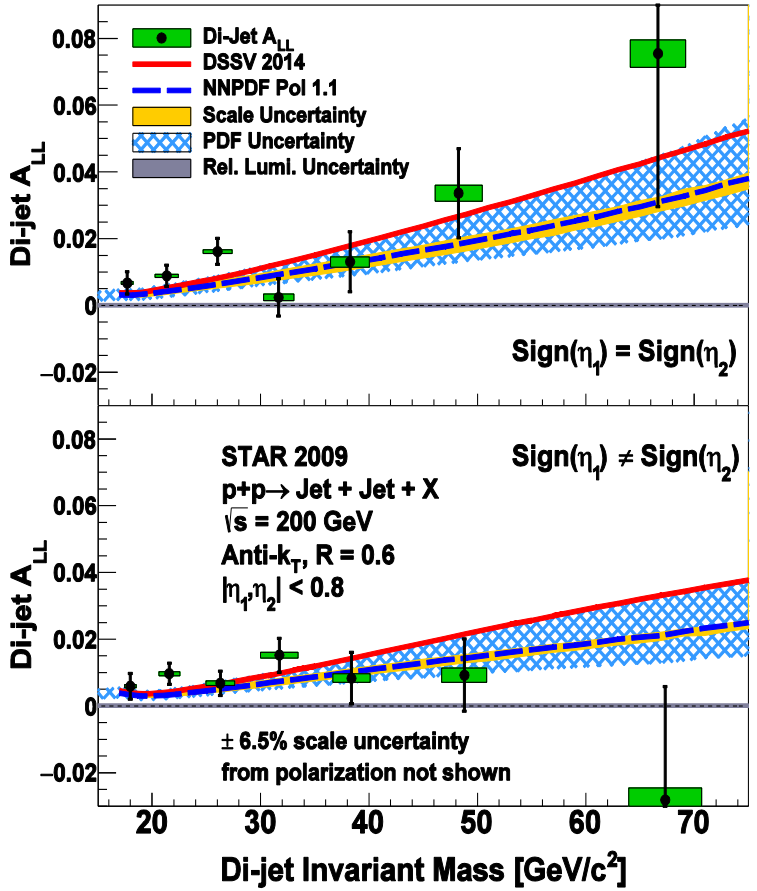
- Di-jet $A_{LL}$ for two topologies, allowing for constraints on the shape of $\Delta g(x)$

STAR, PRD95,071103(2017)



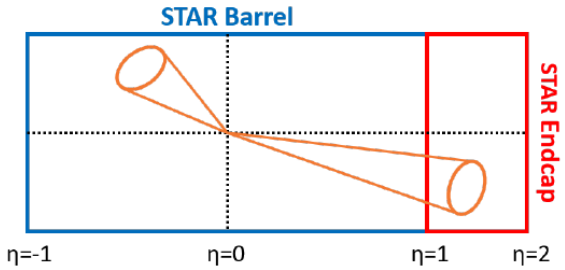



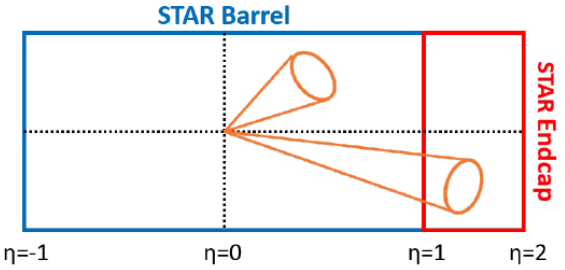



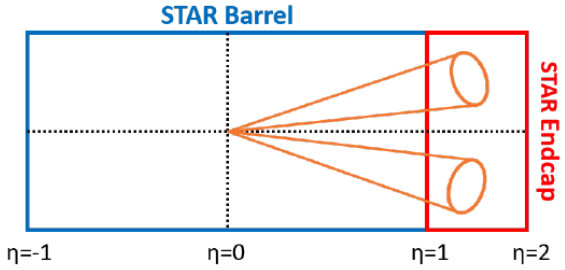
# Central-forward di-jet at 200 GeV at STAR

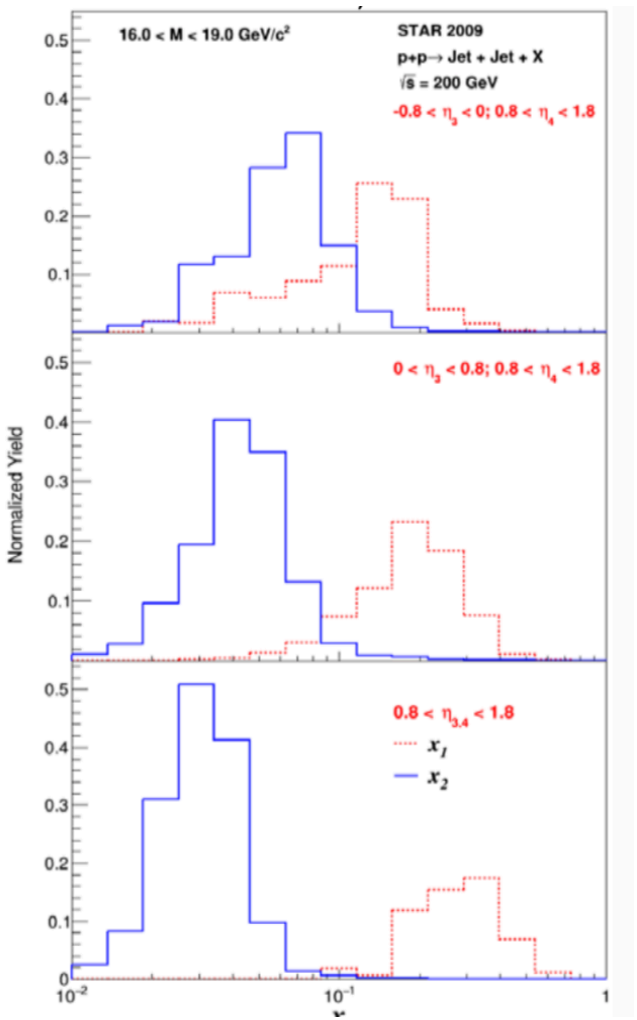
STAR, PRD98,032011(2018)

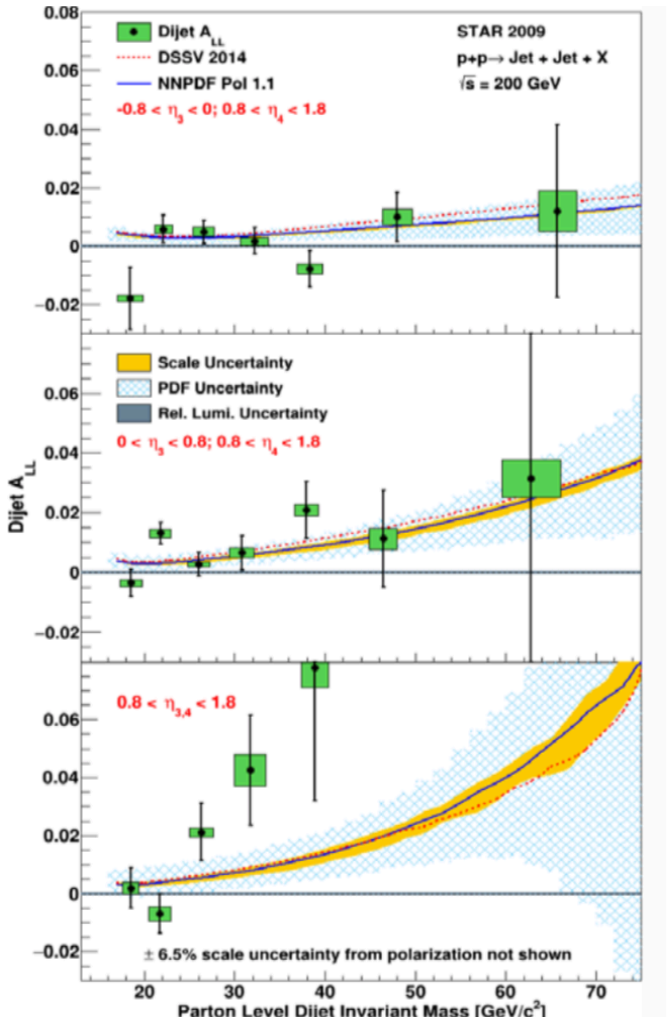
Wider rapidity coverage!



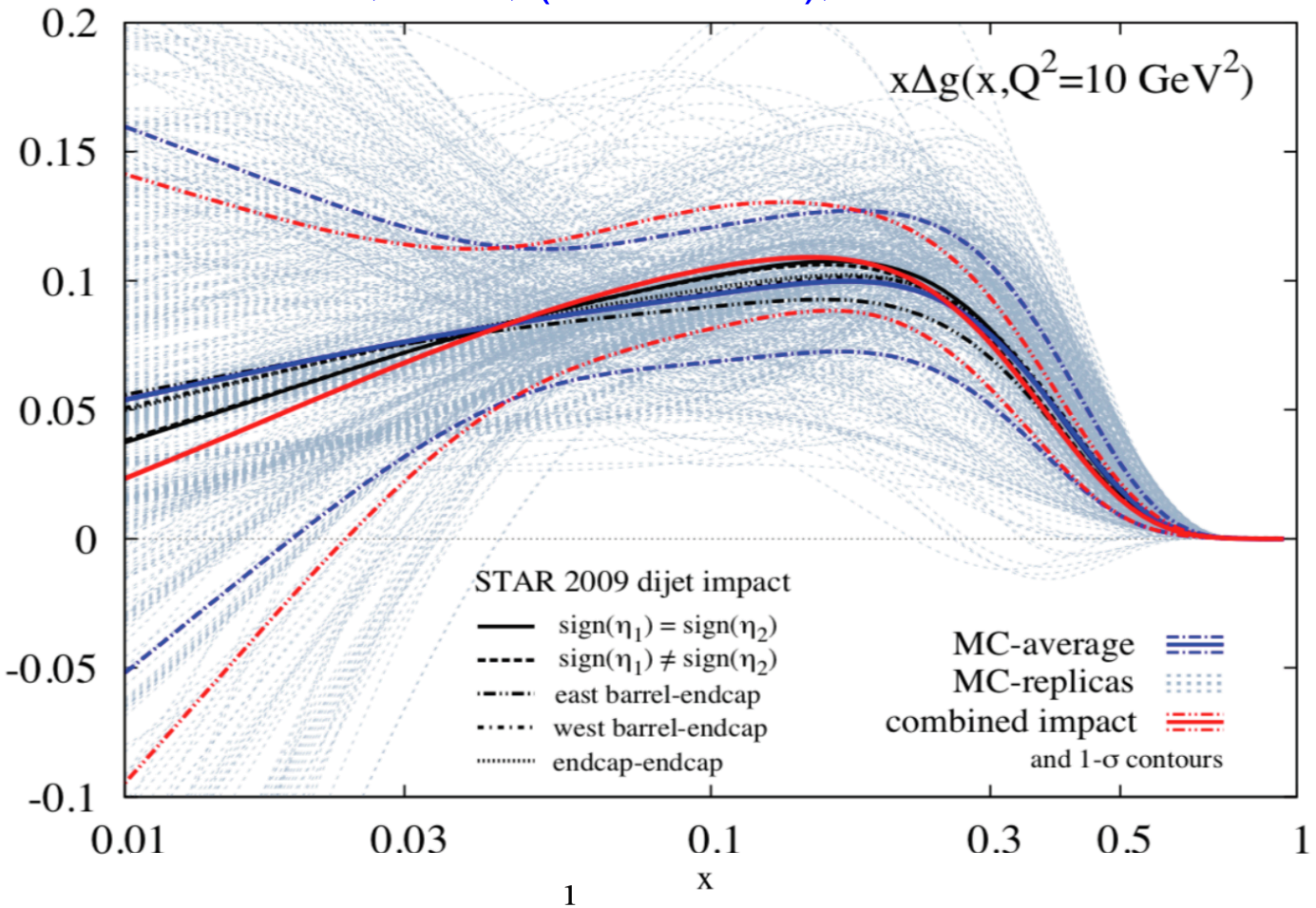



# Impact of STAR di-jet $A_{LL}$ to $\Delta g$ global fit

D. de Florian, et al., (DSSV2018), arXiv:1902.10548

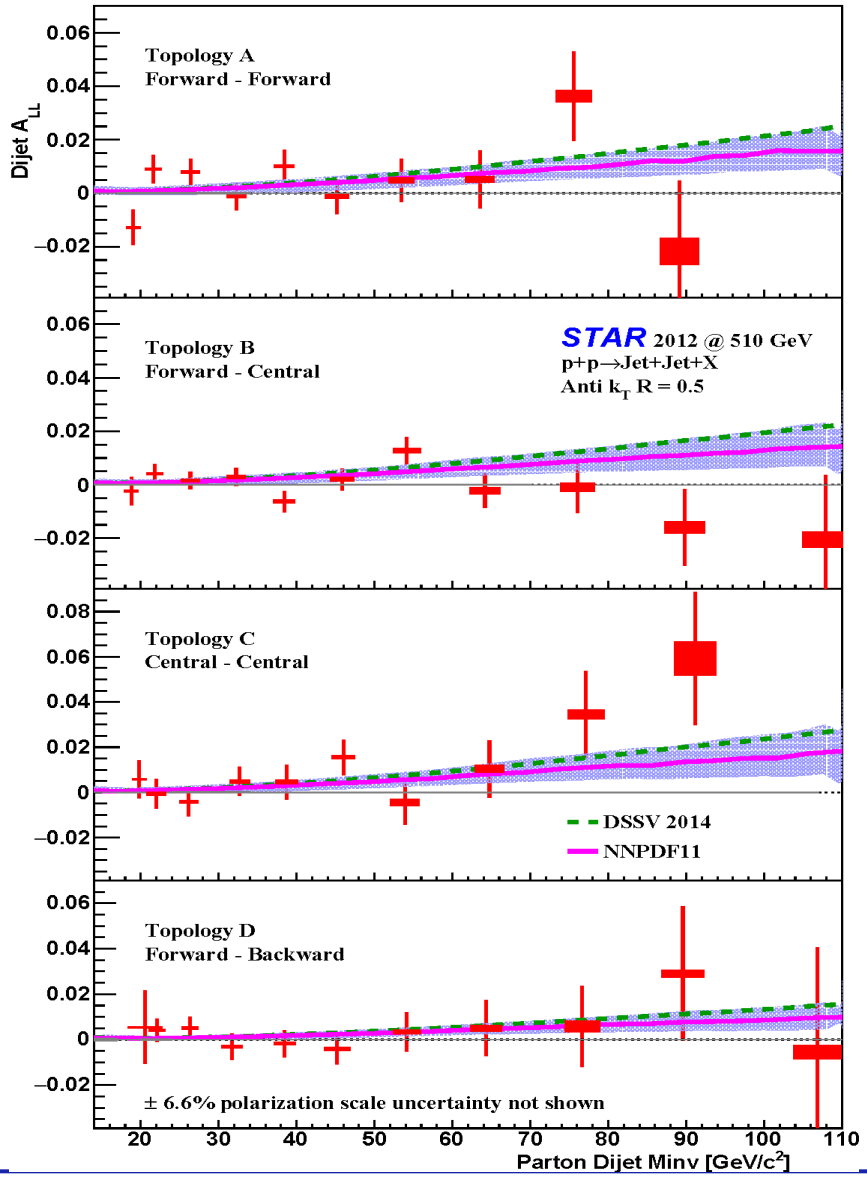



Before reweighting: $\int_{0.1}^{1} \Delta g(x)\,dx = 0.133 \pm 0.035$

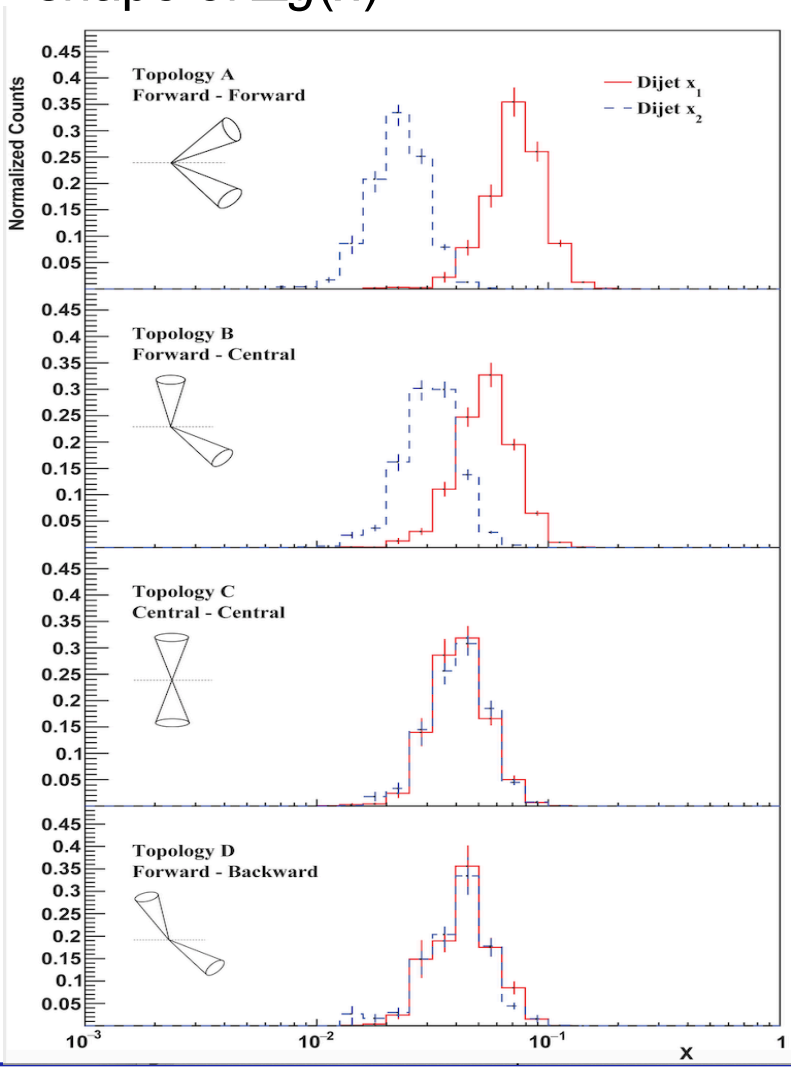
**After reweighting:** $\int_{0.1}^{1} \Delta g(x)\,dx = 0.126 \pm 0.023$

# Di-jet $A_{LL}$ at 510 GeV at STAR

STAR, arXiv:1906. 02740, PRD accepted

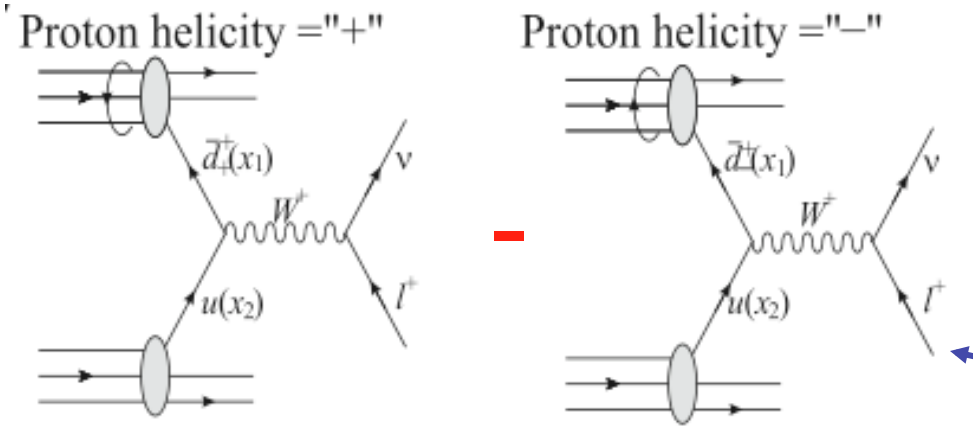



- New results on di-jet $A_{LL}$ at 510 GeV, further constraints on the shape of $\Delta g(x)$



# Probing sea quark polarization via W production

- Quark polarimetry with W-bosons:




$$\propto \Delta\bar{d}(x)u(x)$$

W-detection through high energy lepton

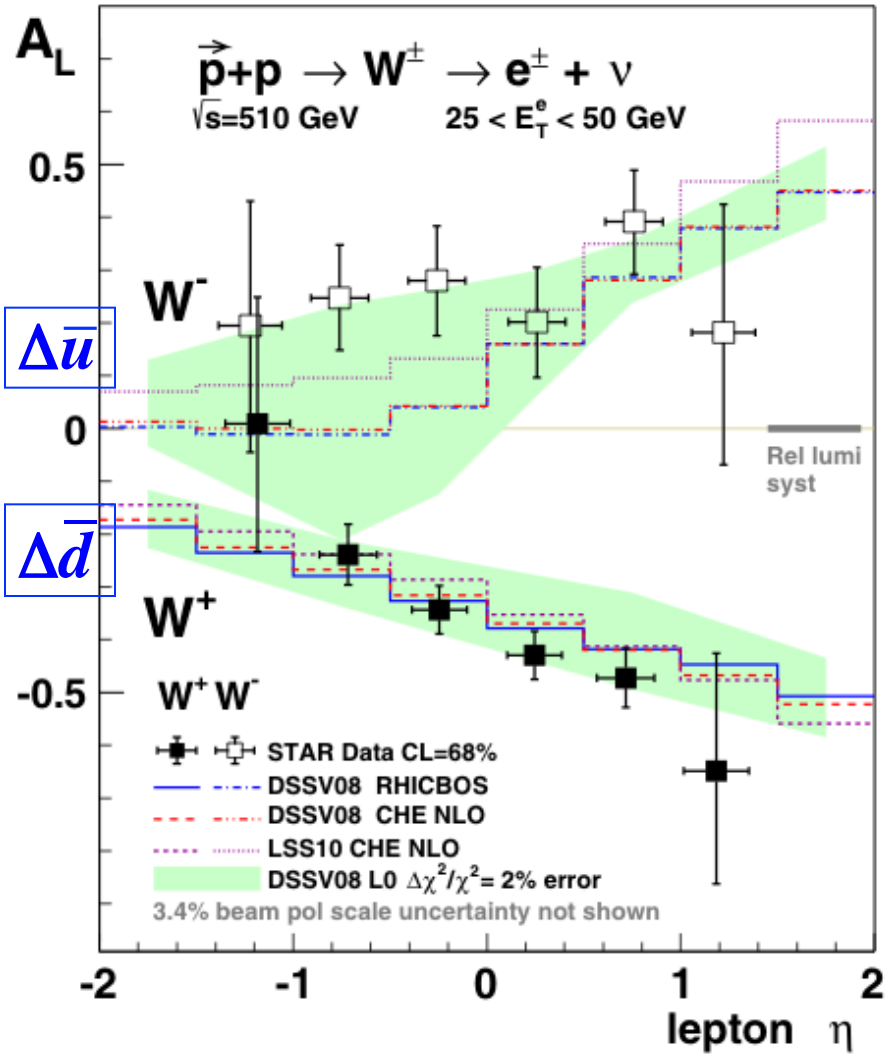
- Spin asymmetry measurements:

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

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

# STAR mid-rapidity W $A_L$ –2011+2012

- First multiple-eta-bin $A_L$ results from 2011+2012 data:




- $A_L$ of $W^-$ shows indication that data are larger than the DSSV predictions
- $A_L$ of $W^+$ is consistent with theoretical predictions with DSSV pdf.
- Indication of symmetry breaking of polarized sea.

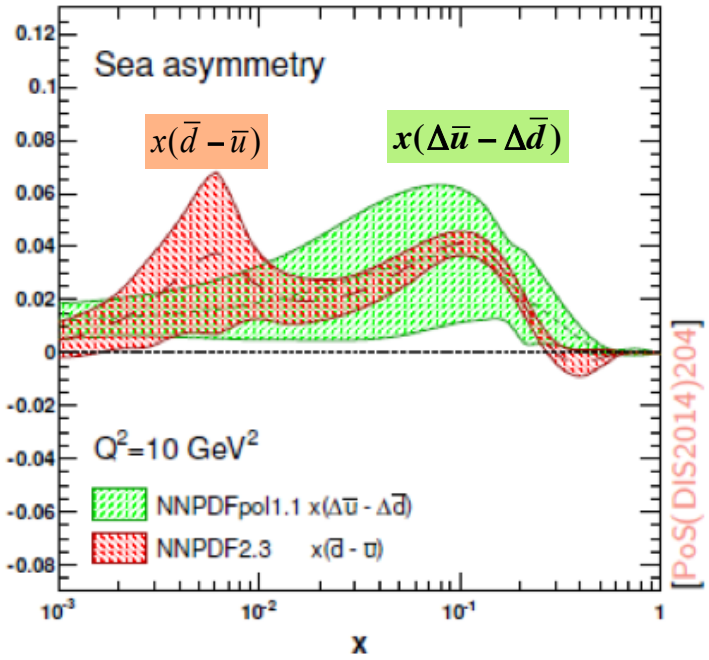
**STAR, PRL113, 72301(2014)**

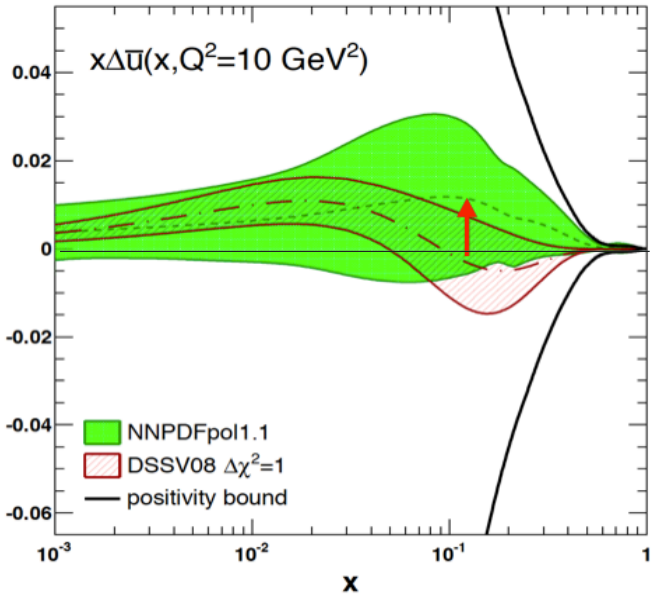
# Global Analysis with STAR W $A_L$ results

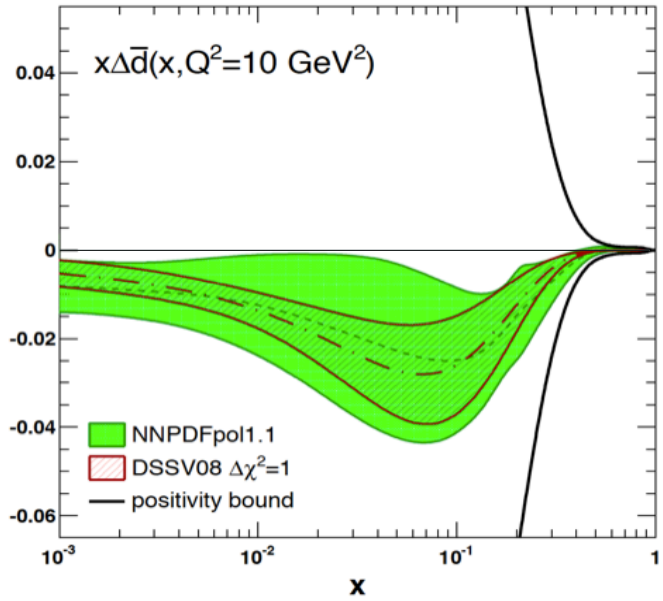
- Big impact seen in NNPDFpol1.1 global analysis after including STAR $A_L$ data.

NNPDF1.1, Nucl.Phys. B887,276 (2014)

- Polarized sea asymmetry:

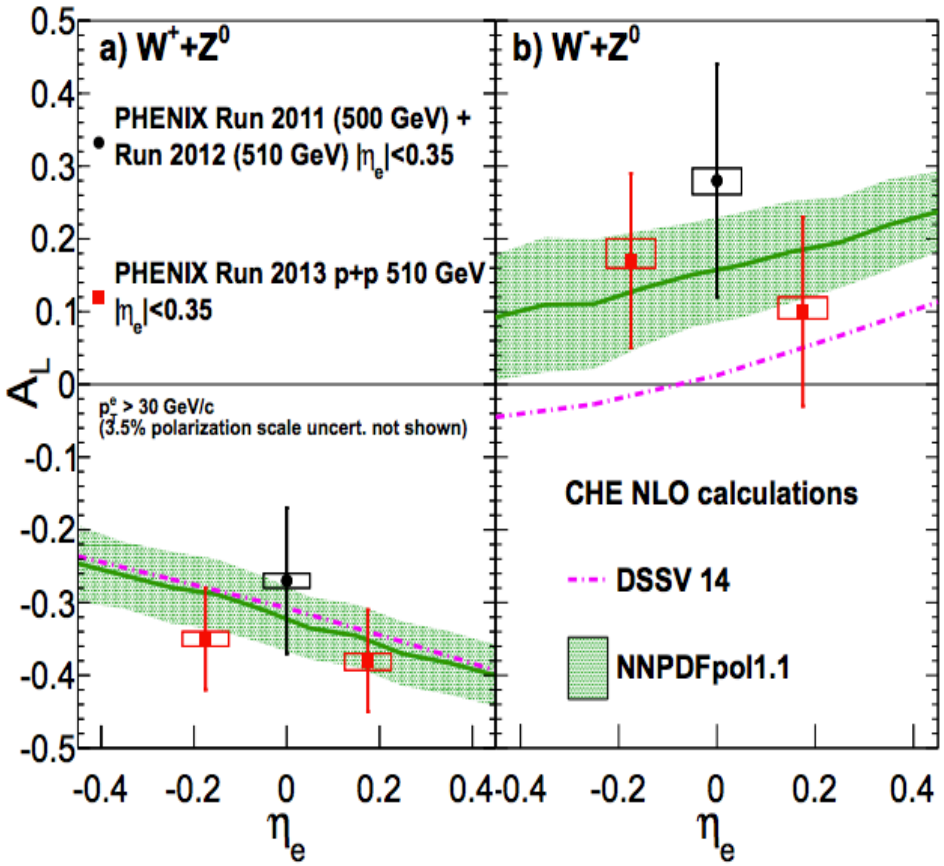


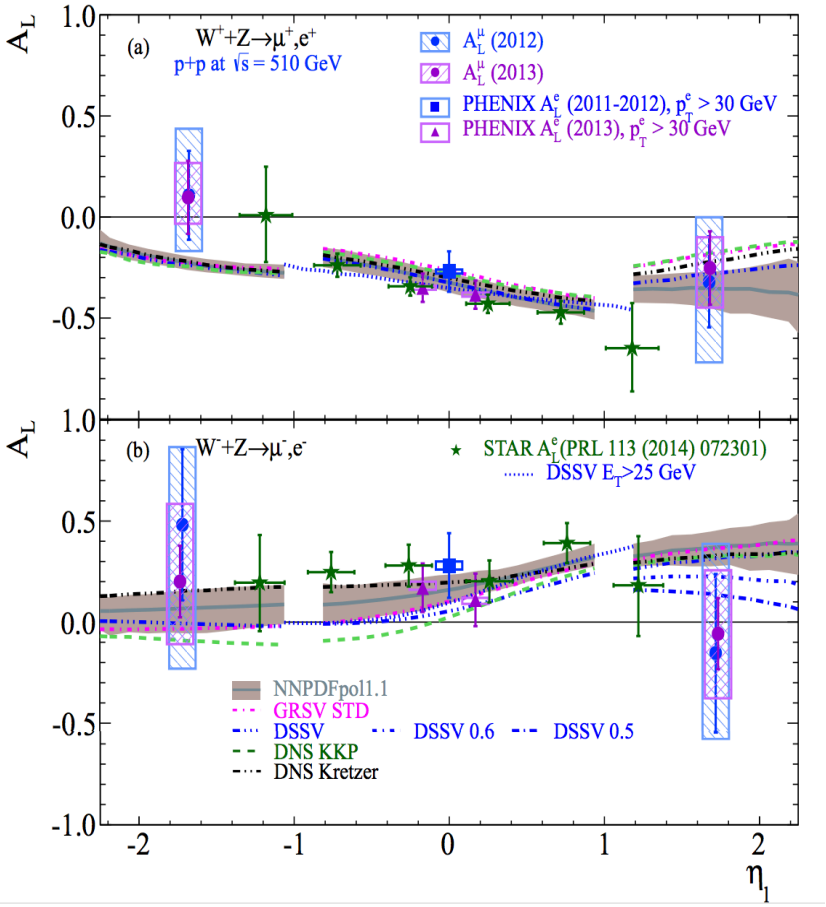



# PHENIX results on W $A_L$

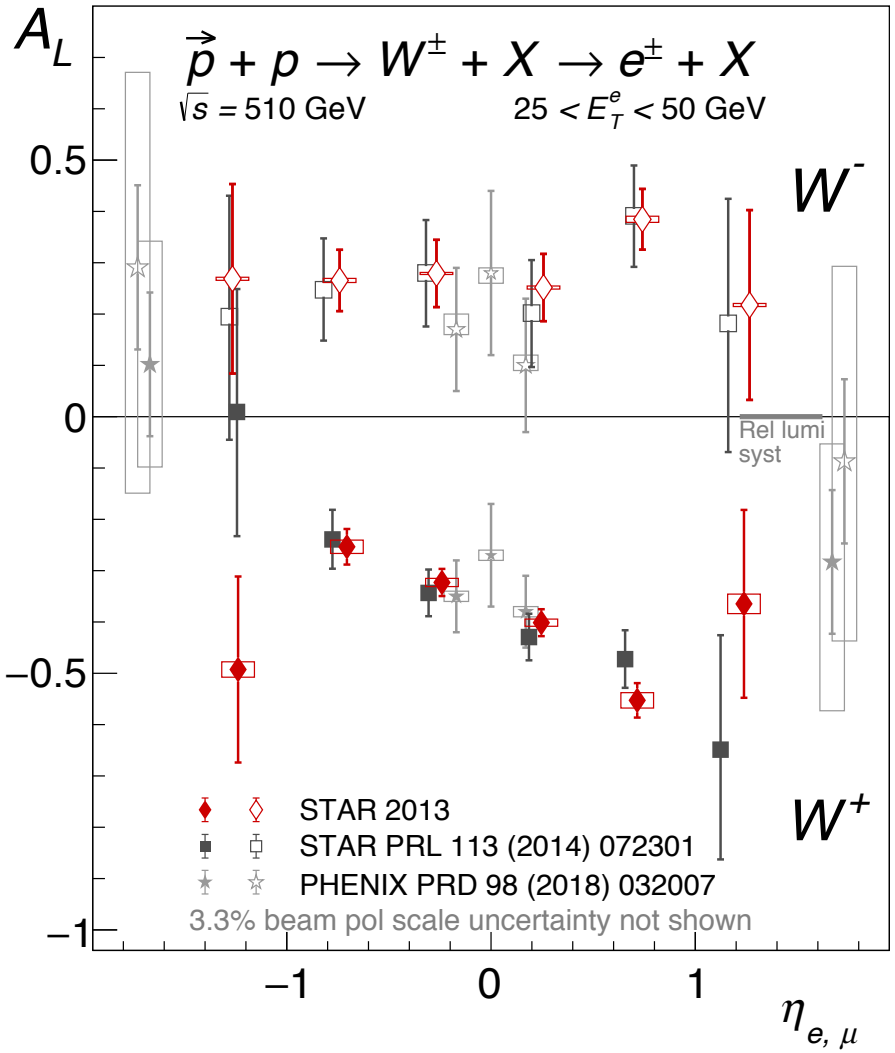
- PHENIX central and forward rapidity $A_L$ results from 2011-2013:




PHENIX, PRD 93, 51103 (2016), PRD98, 032007(2018)

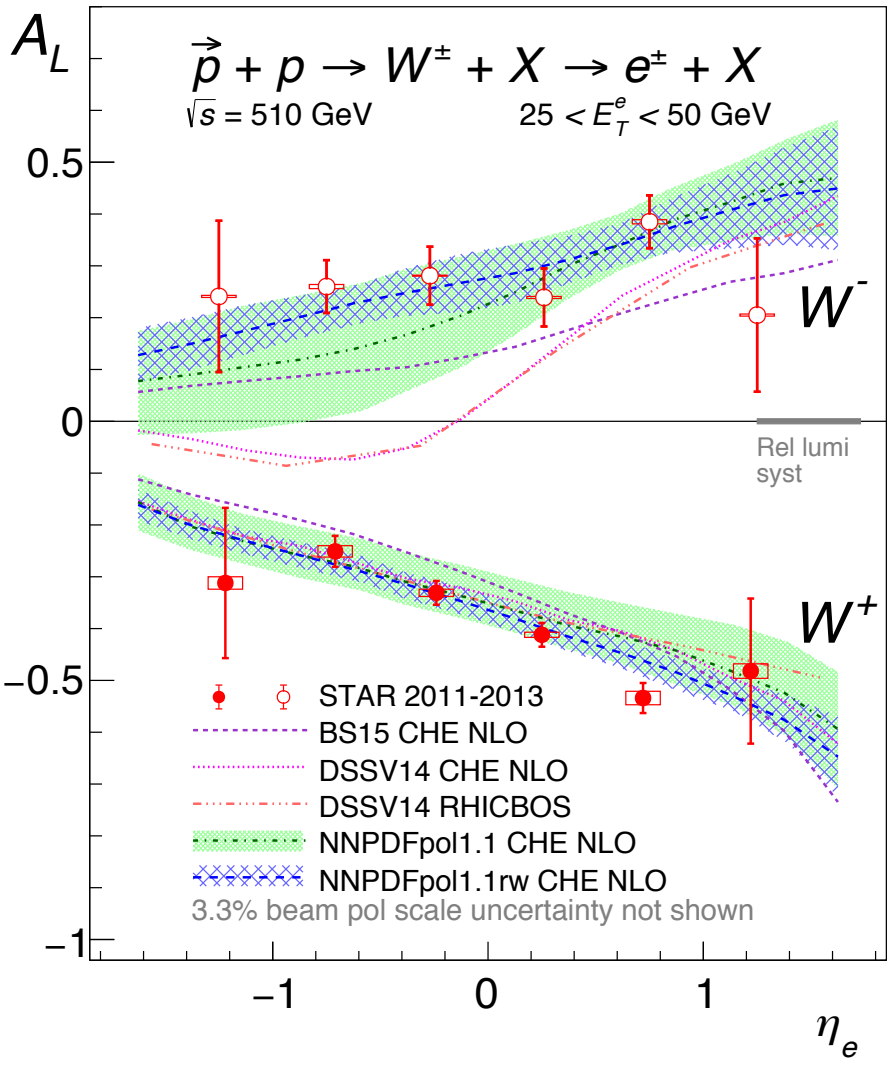
# W $A_L$ results – STAR 2013




STAR, PRD99, 051102R(2019)

- ✓ Most precise W $A_L$ results from 2013 STAR dataset
- ✓ Consistent with published RHIC results; with 40-50% smaller uncertainties than STAR 2011+2012 results
- ✓ Confirmed positively polarized anti-up quark first seen in the 2011+2012 data.

# W $A_L$ results – STAR 2013



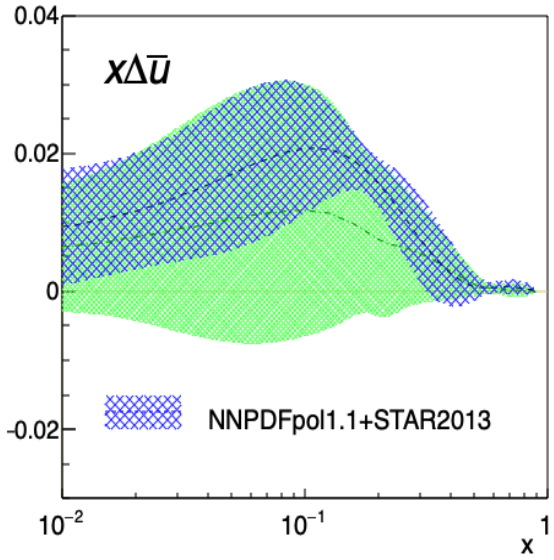

STAR, PRD99, 051102R(2019)

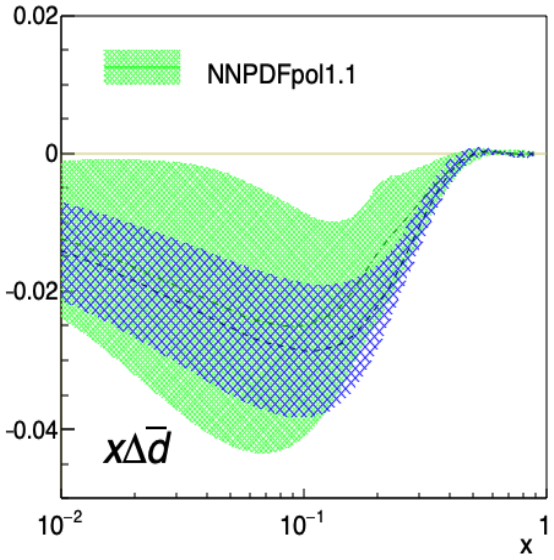
- ✓ Most precise W $A_L$ results from 2013 STAR dataset
- ✓ Consistent with published RHIC results; with 40-50% smaller uncertainties than STAR 2011+2012 results
- ✓ Confirmed positively polarized anti-up quark first seen in the 2011+2012 data.
- ✓ Combined STAR 2011-2013 results in comparison with theoretical predications

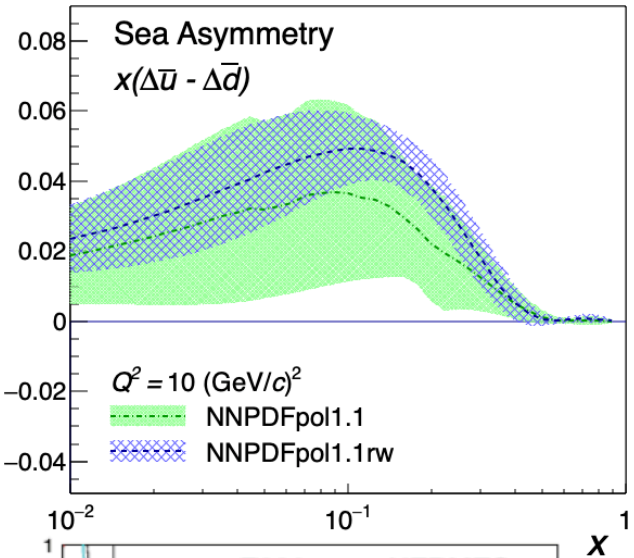
# Impact of STAR 2013 W $A_L$ results

- Reweighting based on NNPDF pol1.1 confirmed the polarized sea asymmetry: $\Delta\bar{u} > \Delta\bar{d}$

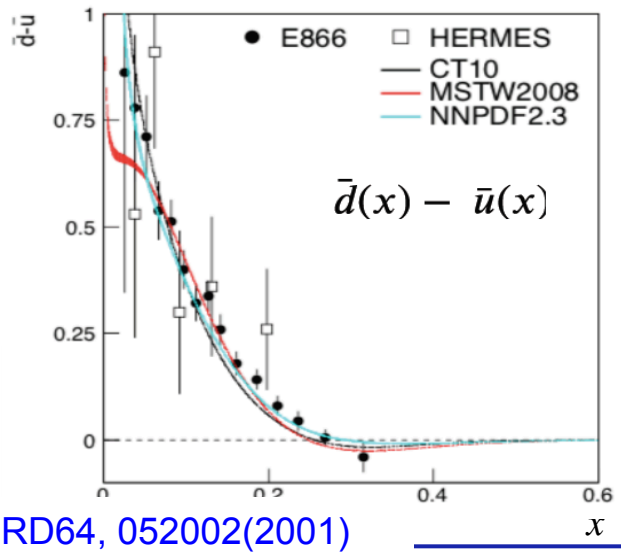
STAR, PRD99, 051102R(2019)



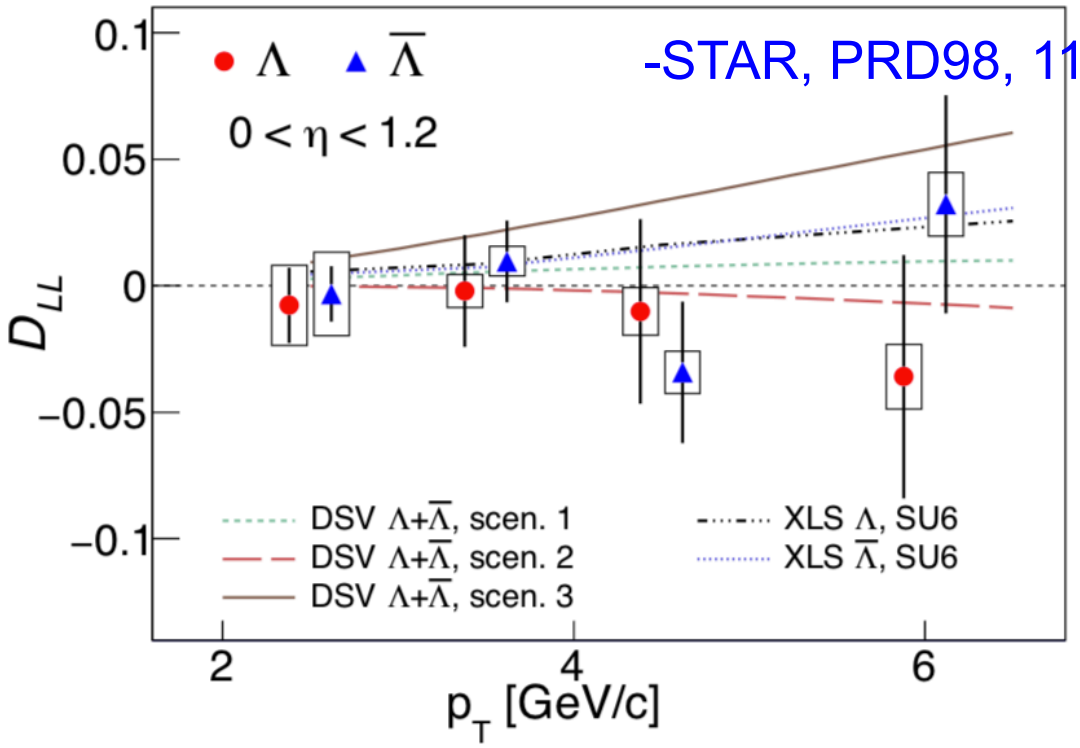

- ✓ The polarized flavor asymmetry is opposite to the unpolarized case !
- ✓ Compatible with Pauli suppression by the polarized valence quarks, among different models.




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

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

- $D_{LL}$ 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)

✓ $D_{LL}$ results are still consistent with zero within the uncertainties.

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

# Transverse spin physics at RHIC

- Transverse spin asymmetry (W/Z production):

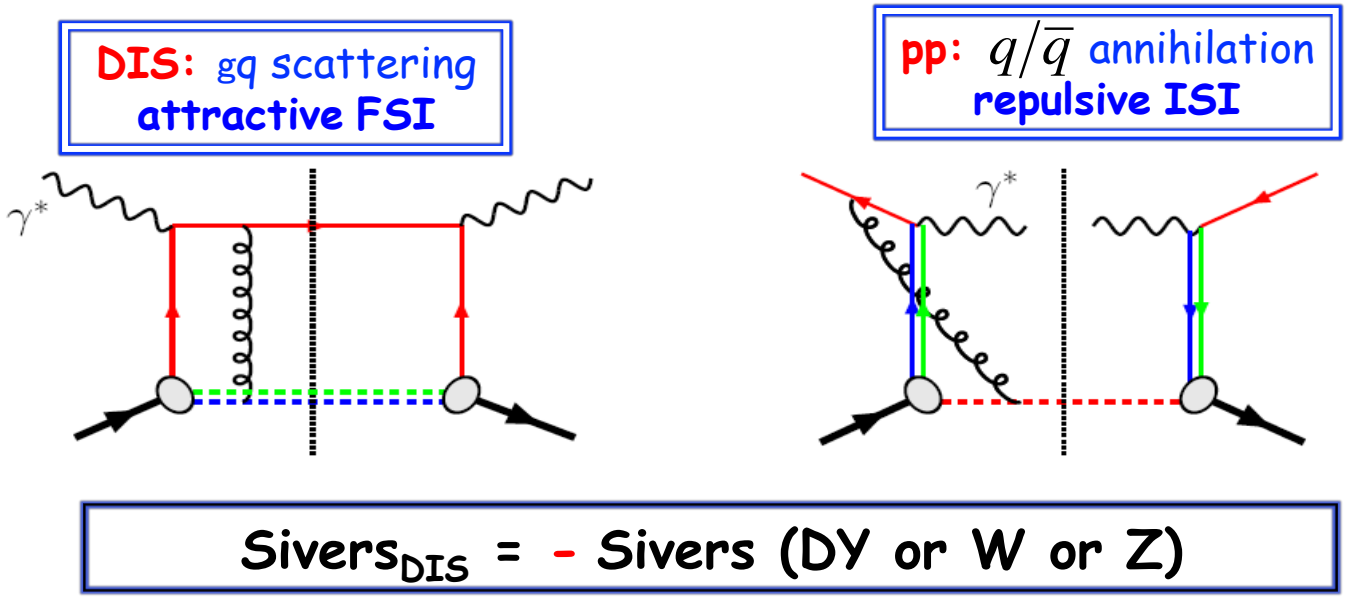
  Sign-change of Sivers function

- Transverse spin asymmetry (Hadron production):

  Access to transversity via Collins & IFF asymmetry

# Transverse single spin asymmetry ($A_N$) of W boson

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



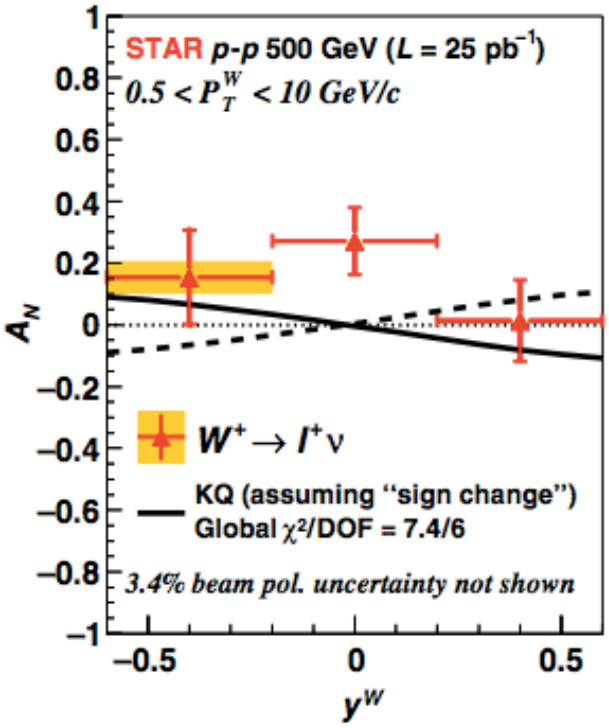

**$Sivers_{DIS}$ = - Sivers (DY or W or Z)**

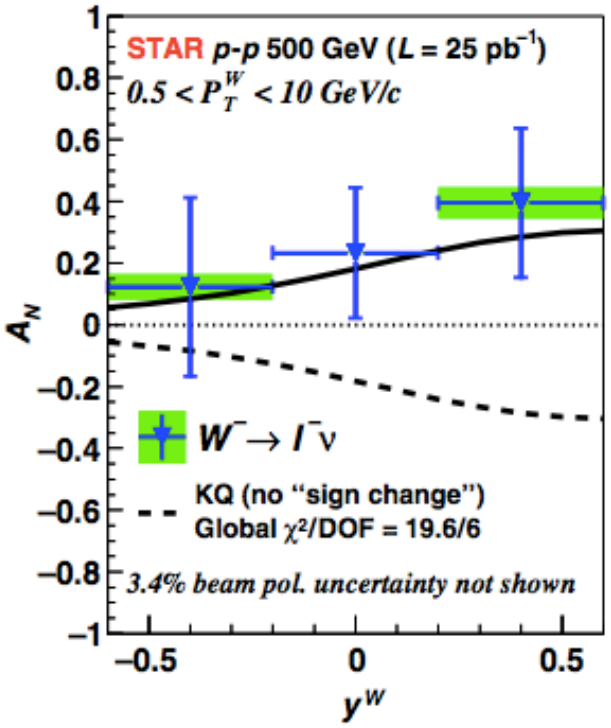
-Critical test for our understanding of TMD's and TMD factorization

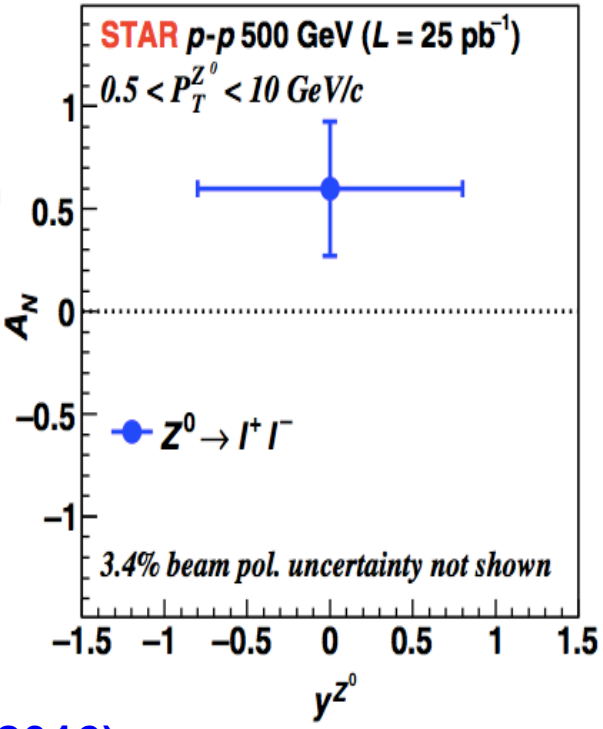
- Active experimental programs at CERN-COMPASS (DY), Fermi -SpinQuest (E1039,DY), and RHIC (W production).
- Advantages of weak boson production
  - Low background
  - High $Q^2$-scale (~ W/Z boson mass)

# First W, Z $A_N$ results at 500 GeV from STAR

- Data: STAR 2011 transverse run at 500 GeV, integrated luminosity ~25 $pb^{-1}$
- First $A_N$ for $W^{\pm}$ and Z results : $A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$



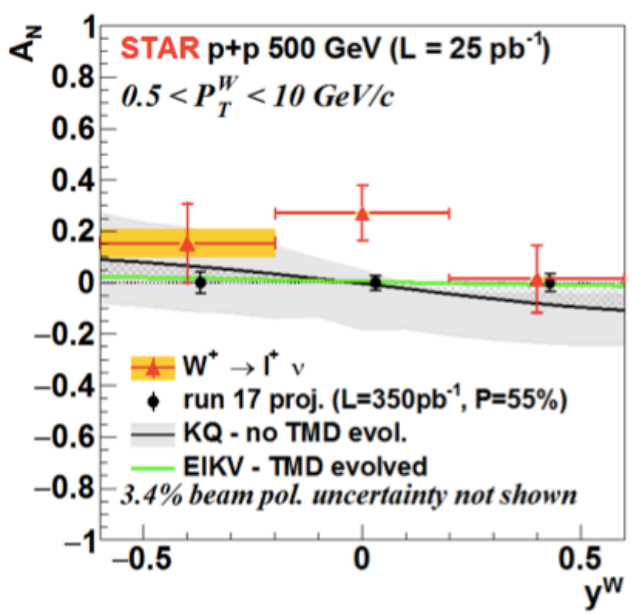



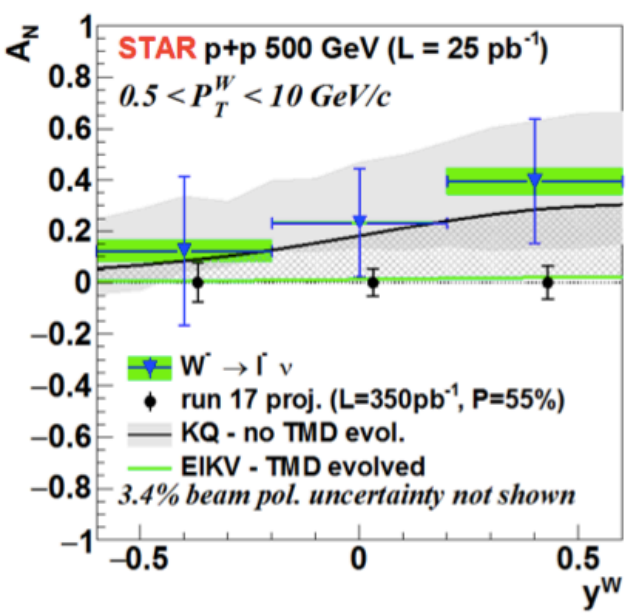

**STAR, Phys. Rev. Lett. 116,132301(2016)**

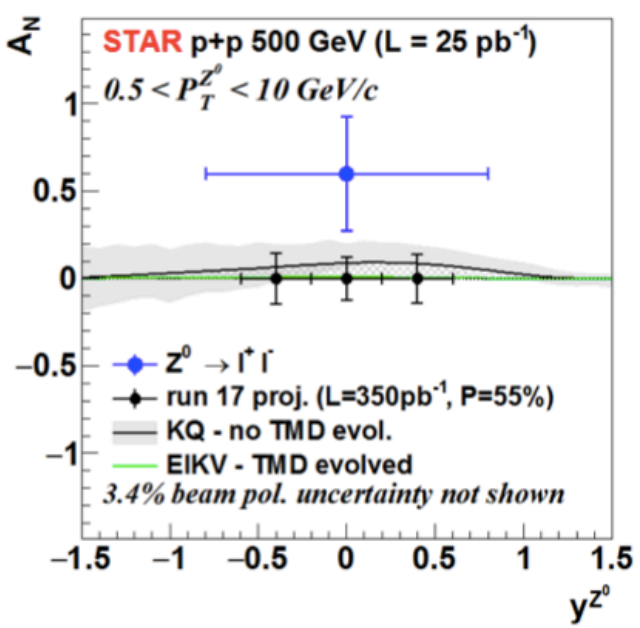
- Sivers sign-change scenario preferred over no-sign change scenario.

# Coming measurements of W/Z $A_N$ at STAR

- STAR collected ~350 $pb^{-1}$ of transverse pp in 2017:



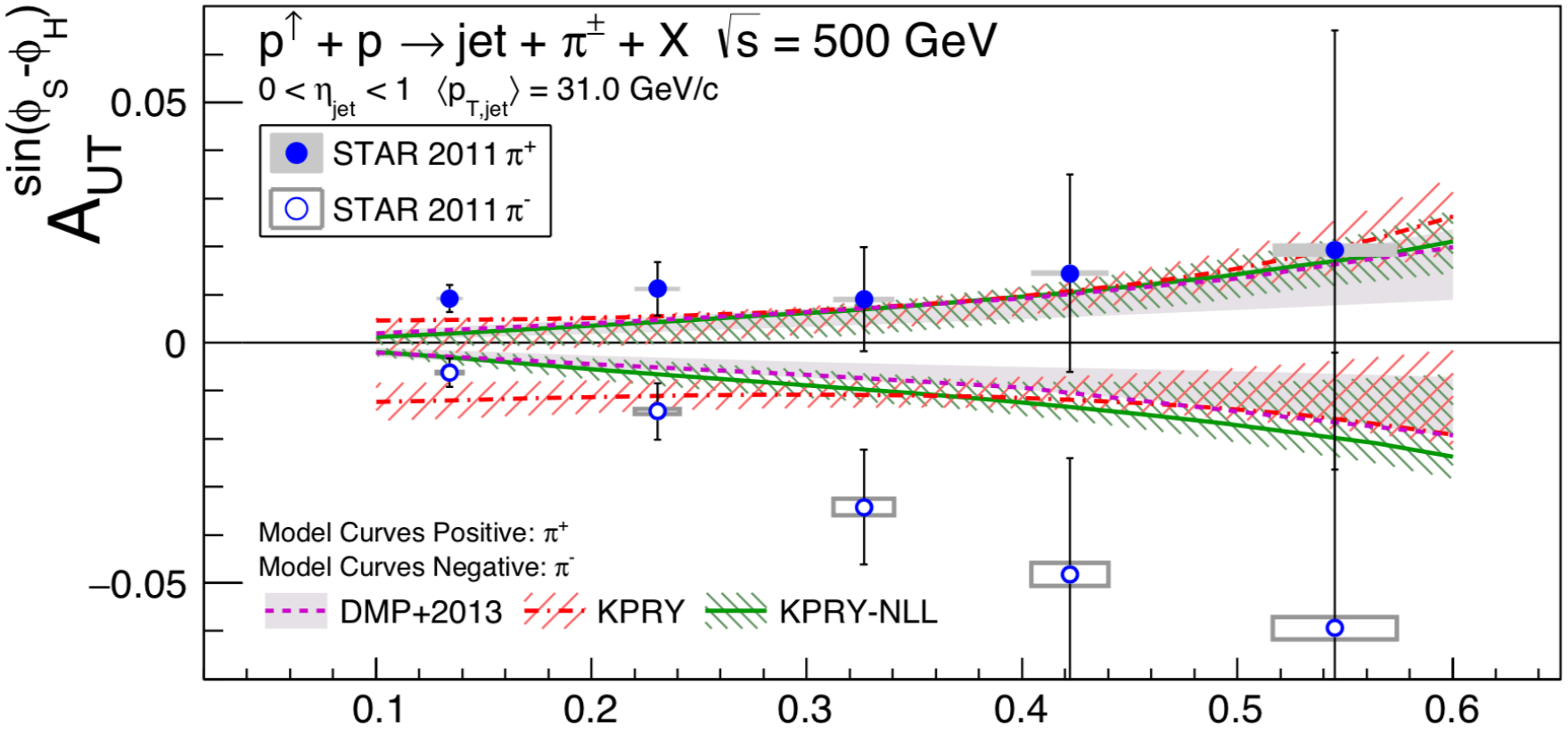




**Goal:**

- ✓ Constrain TMD evolution sea-quark Sivers function
- ✓ Test sign-change if TMD-evolution suppression factor ~5 or less

# Collins asymmetries at STAR

- Collins asymmetries at 500 GeV & comparison with theory curves:

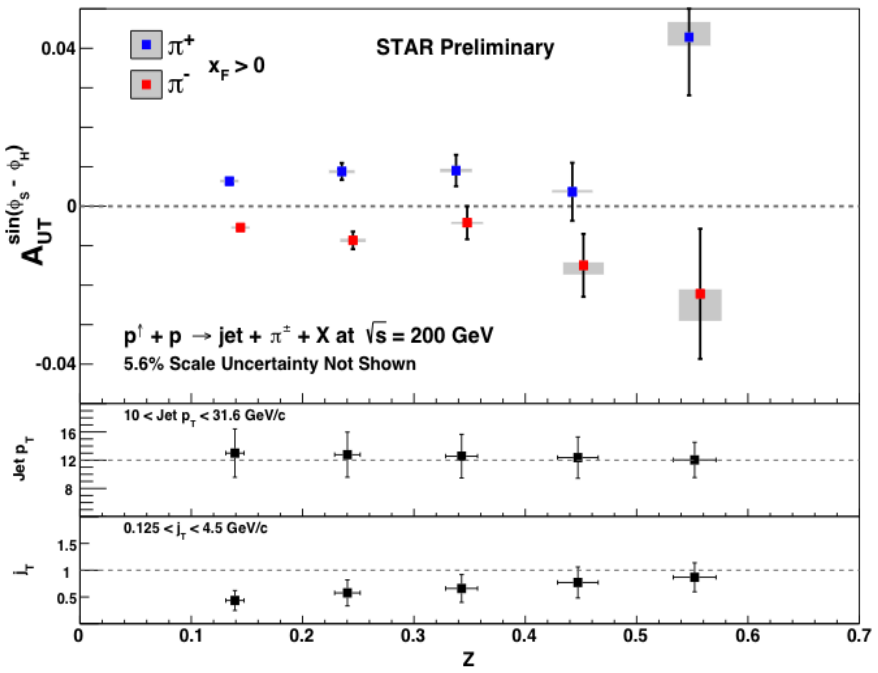



STAR, Phys. Rev. D **97**, 32004(2018)

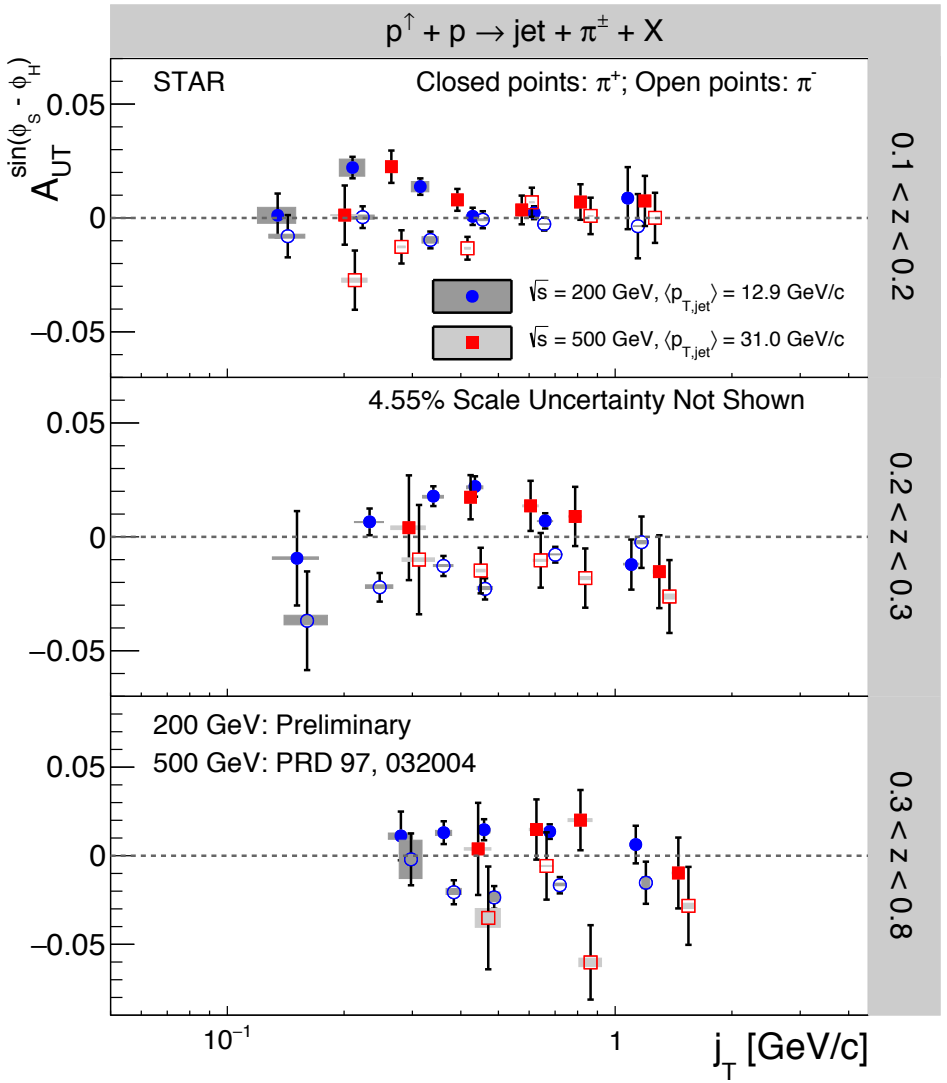
- Collins asymmetries observed in p+p collisions, providing information for scale dependence, also access to transversity.

# Collins asymmetries at STAR

- Non-zero Collins asymmetries observed in p+p collisions at both 200 & 500 GeV, providing access to transversity distribution:



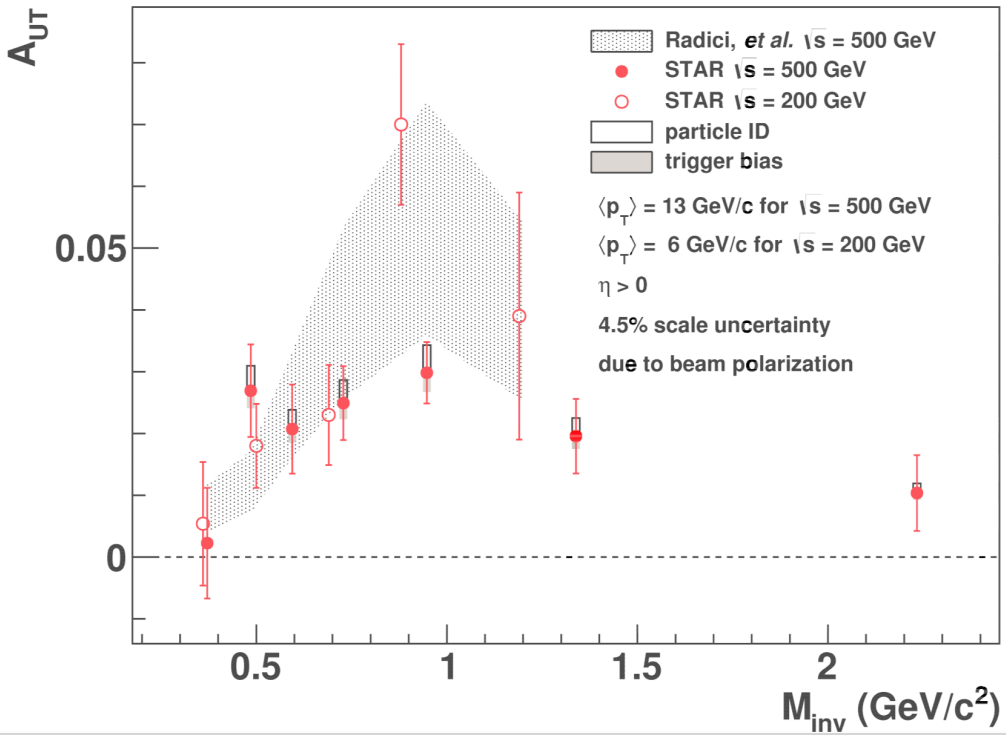

500 GeV: STAR, PRD 97, 032004 (2018)
200 GeV: Int. J. Mod. Phys. Conf. Ser. 40, 1660040



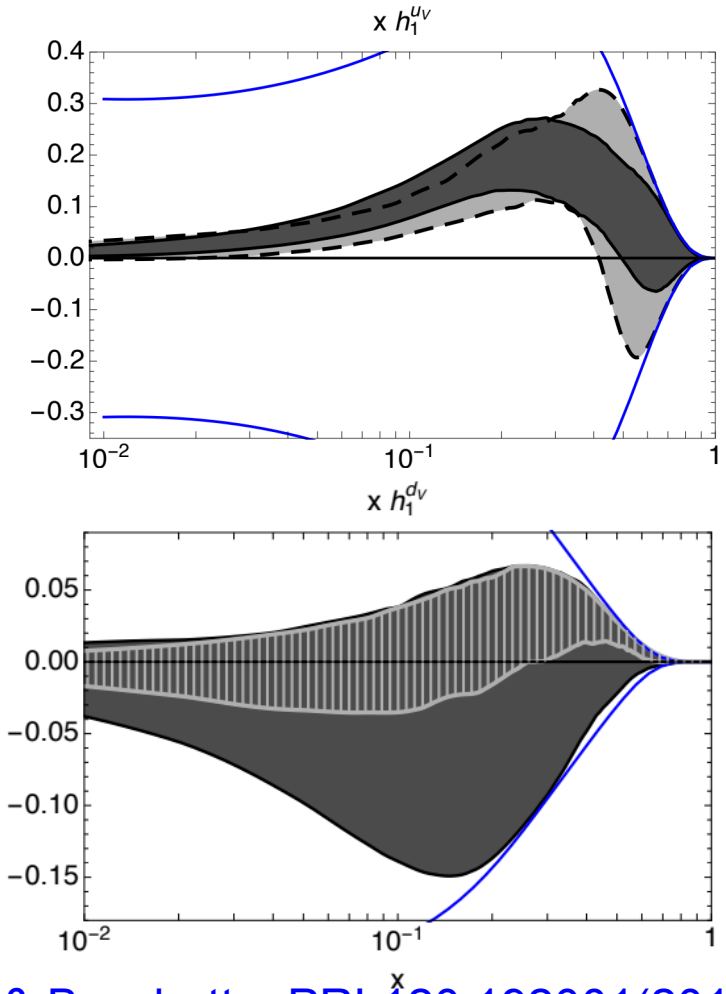
# Di-hadron spin asymmetries at STAR

- Significant di-hadron asymmetries at STAR (200 & 500 GeV).

  -200 GeV data provided significant constraints in transversity global fit!




200GeV: STAR, PRL115, 242501(2015)
500GeV: STAR, PLB780, 332(2018)

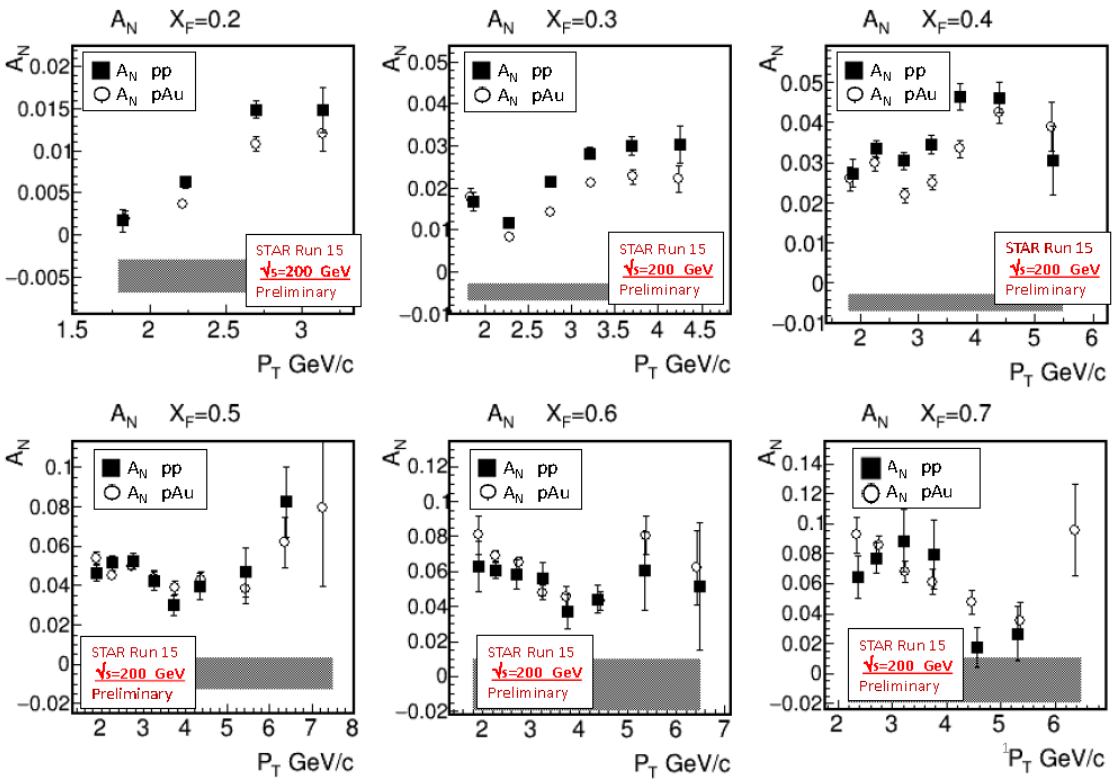


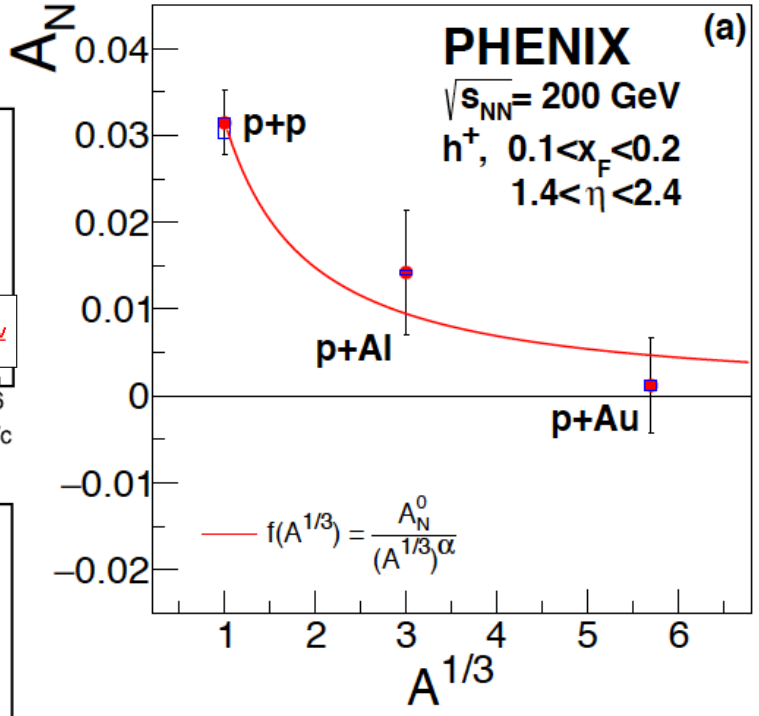

Radici & Bacchetta, PRL120,192001(2018)

# Single spin asymmetry $A_N$ : pp vs pA

- Models predict possible gluon saturation suppresses $A_N$ by ~$A^{1/3}$
  i.e., J. Zhou, PRD92, 14034(2015), Y. Hatta et al, PRD94,54013(2016), PRD95,14008(2017)

  May also be A-independent from different contributions:
  i.e., S. Benic, Y. Hatta, PRD99, 094012(2019)
- STAR results are not conclusive on A dependence, while PHENIX results show the trend.



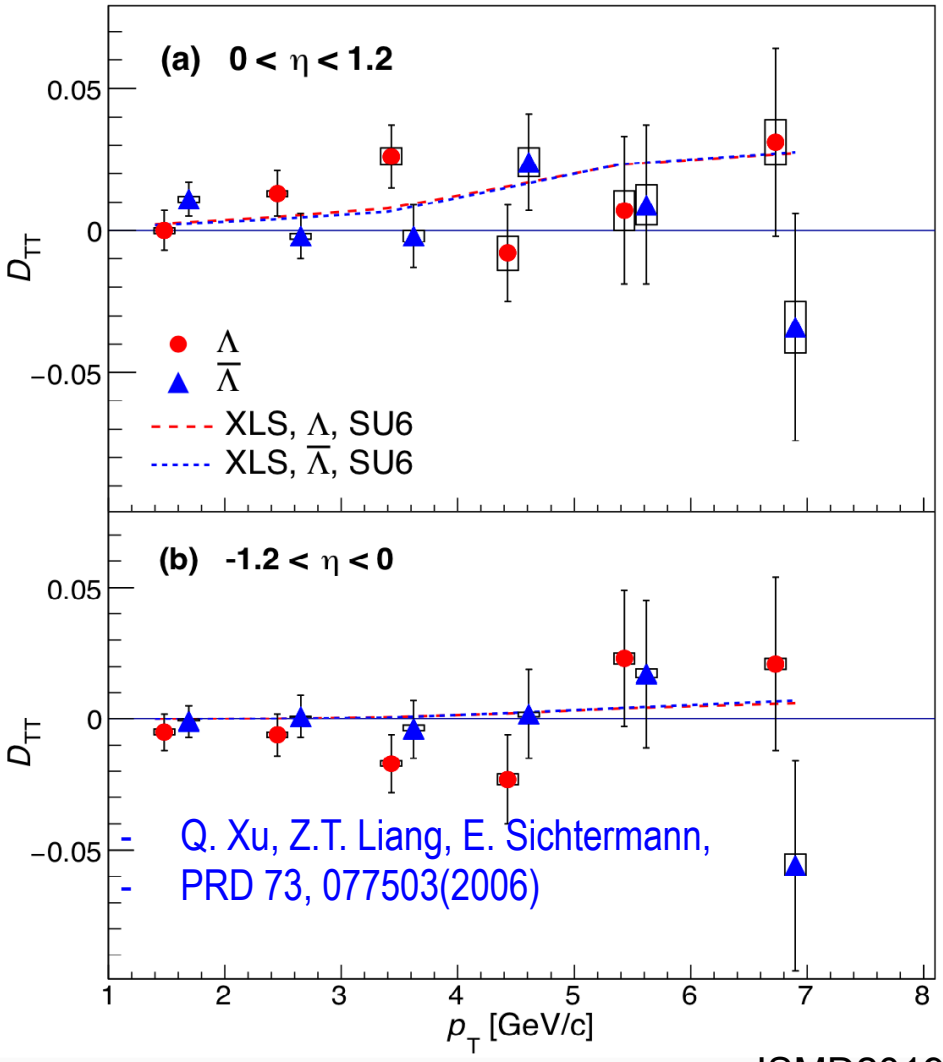




PHENIX, arXiv:1903.07422

# 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)




- ✓ 1st transverse spin transfer measurement in p+p collisions at RHIC.
- ✓ Most precise measurement on hyperon polarization in p+p collision at RHIC, which reach $p_T$ ~6.7 GeV/c with statistical uncertainty of 0.04.
- ✓ $D_{TT}$ of $\Lambda / \overline{\Lambda}$ are consistent with a model prediction, also consistent with zero within uncertainty.

# Future RHIC Spin in 2021+

STAR

| Year | √s (GeV) | Delivered Luminosity | Scientific Goals | Observable | Required Upgrade |
|---|---|---|---|---|---|
| 2021/22 | $p^{\uparrow}p$ @ 510 | 1.1 $fb^{-1}$ 10 weeks | TMDs at low and high $x$ | $A_{UT}$ for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ | Ecal + Hcal +Tracking |
| 2021/22 | $\vec{p}\vec{p}$ @ 510 | 1.1$fb^{-1}$ 10 weeks | $\Delta g(x)$ at small $x$ | $A_{LL}$ for jets, di-jets, h/γ-jets at $\eta > 1$ | Ecal + HCal |
| 2024 | $p^{\uparrow}p$ @ 200 | 300 $pb^{-1}$ 8 weeks | Subprocess driving the large $A_N$ at high $x_F$ and $\eta$ | $A_N$ for charged hadrons and flavor enhanced jets | Ecal + Hcal +Tracking |
| 2024 | $p^{\uparrow}Au$ @ 200 | 1.8 $pb^{-1}$ 8 weeks | Nature of the initial state and hadronization in nuclear collisions<br><br>Clear signatures for Saturation | $R_{pAu}$ direct photons and DY<br><br>Dihadrons, γ-jet, h-jet, diffraction | Ecal + Hcal +Tracking |
| | $p^{\uparrow}Al$ @ 200 | 12.6 $pb^{-1}$ 8 weeks | A-dependence of nPDF,<br><br>A-dependence for Saturation | $R_{pAl}$: direct photons and DY<br><br>Dihadrons, γ-jet, h-jet, diffraction | Ecal + Hcal +Tracking |


Forward detector upgrade required

STAR → sPHENIX

EIC

- RHIC is the world's only polarized hadron-hadron collider.
- Unique physics opportunities in pp and pA.
- NSF MRI grant approved for STAR forward calorimeter upgrade.

# Summary & outlook

- Observation of positive gluon polarization from RHIC:
  - Probes with jets and pion, are providing important constraints on ΔG
    Global analysis indicates sizable gluon polarization (0.05<x<0.2)
- Unique probe of sea quark polarization via W production:
  - Final $A_L$ results for $W^{\pm}$ from RHIC run 13 data concludes RHIC W program,
    further confirm the SU(2) symmetry breaking: $\Delta\bar{u} > \Delta\bar{d}$
- Transverse spin physics
  - $A_N$ for W,Z at STAR: 1st results obtained, run 17 to study Sivers sign change
  - Results on Collins & IFF asymmetries represent the first ever observations of transversity in hadron-hadron collisions.
- Future RHIC spin in 2021+ -- Cold QCD plan
  - Unique physics opportunities in pp and pA, essential to fully realize the scientific promise of the EIC.