Recent results on nucleon spin structure study at RHIC/STAR

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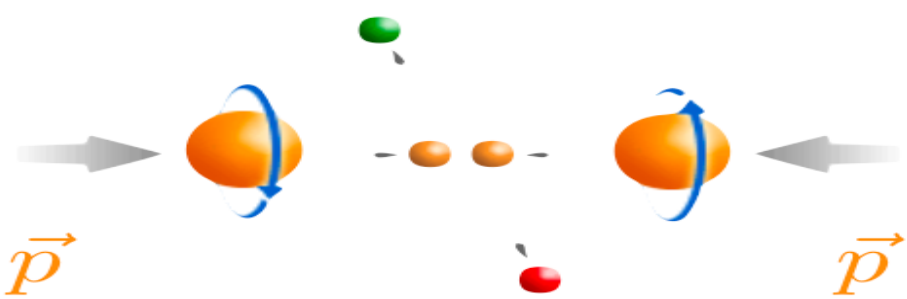
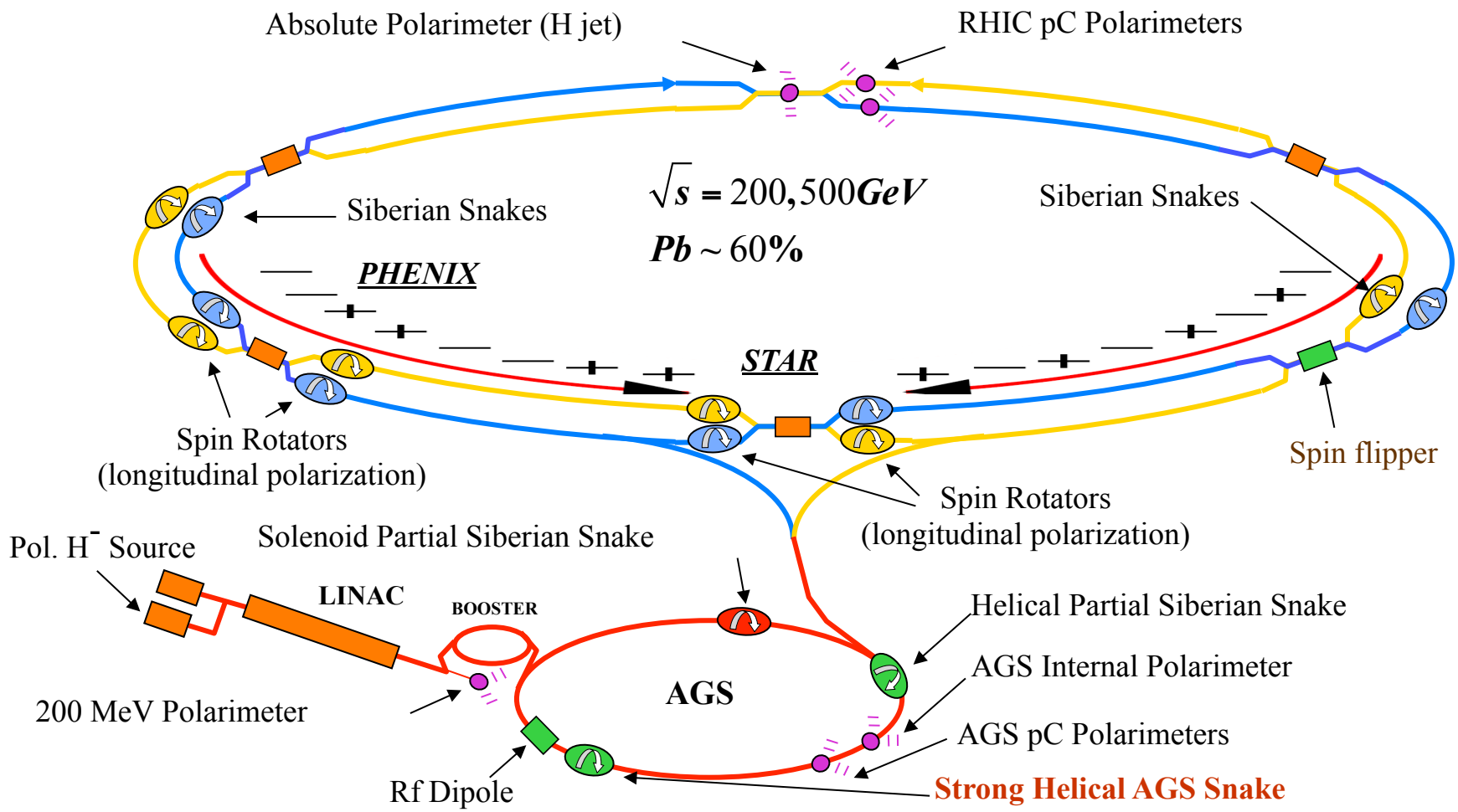
长沙，6月21-25, 2019



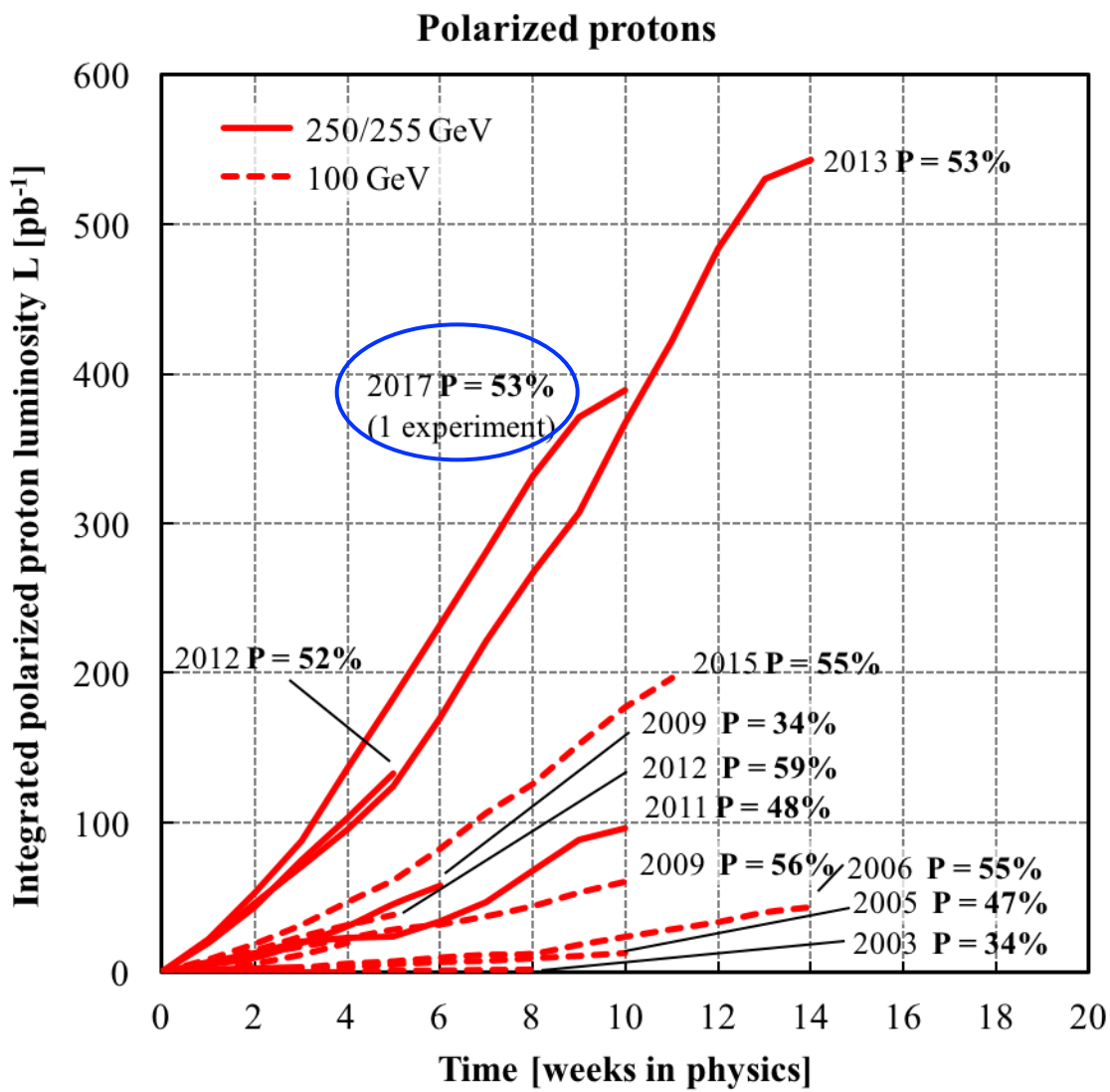
RHIC- 1st polarized proton-proton collider



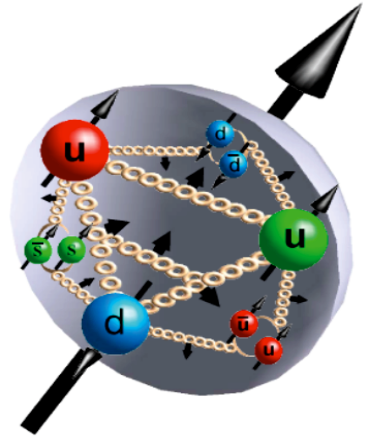
- World's only polarized hadron-hadron collider
- Polarization direction changes from bunch to bunch
- Spin rotators provide choice of spin orientation

RHIC performance with pp collisions

- Long runs with long. polarization 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 at 200GeV and 2011, 2017 at 500 GeV.



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

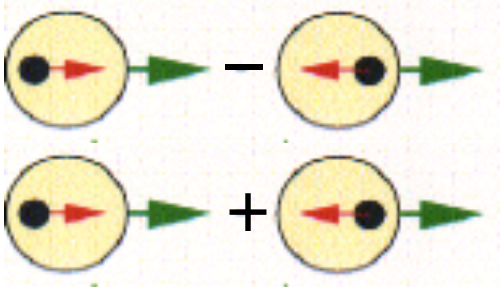
Orbital Angular Momenta Little known (DVCS)

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

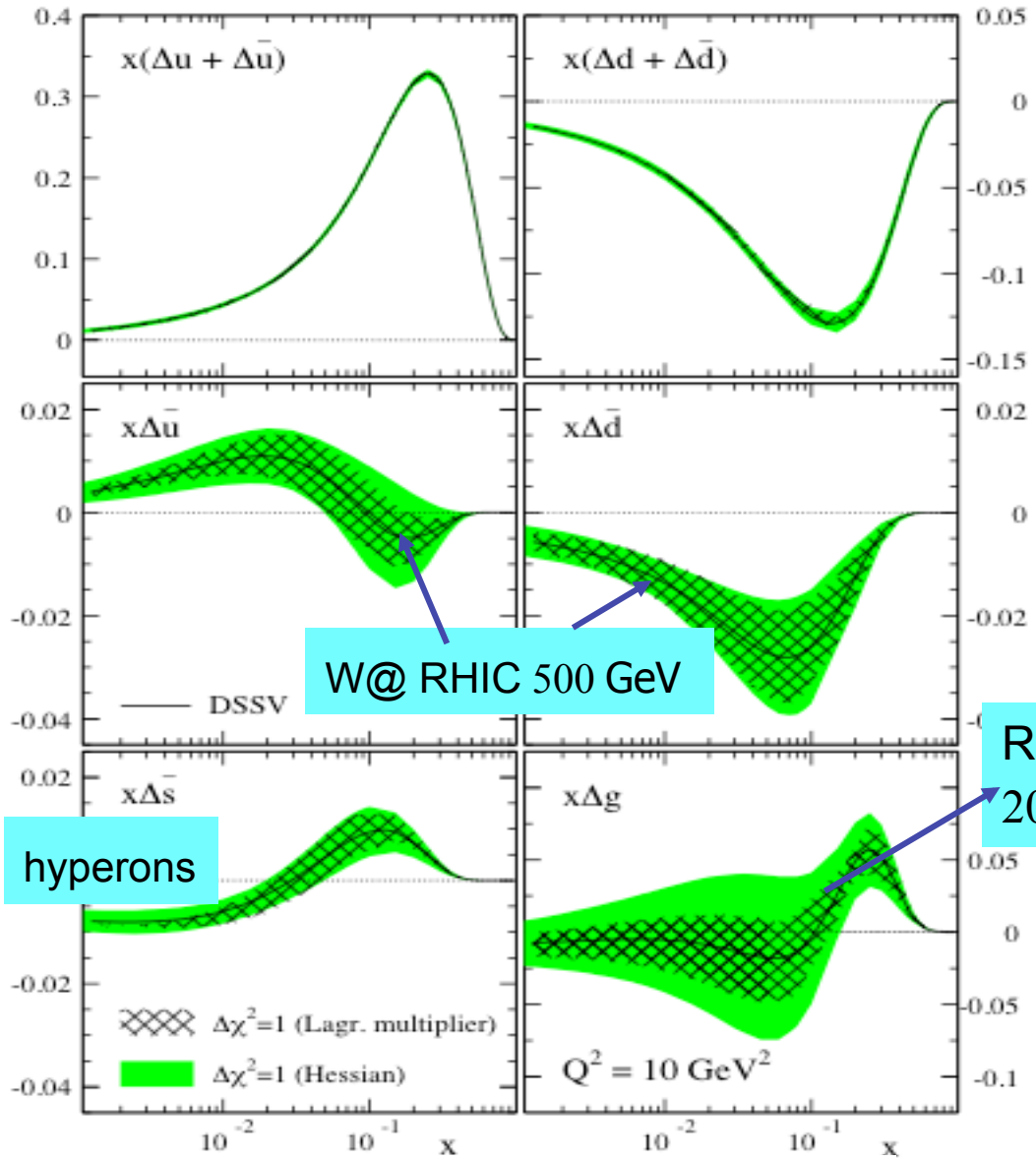
- Polarized parton densities:

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

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



$\Delta q(x)$, $\Delta g(x)$ - global analysis of data



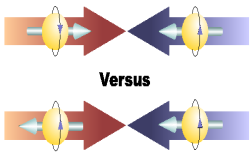
D. De Florian,et al., PRD80,34030(2009)

Outline:

- Experimental aspects: RHIC / STAR
- Recent STAR spin highlights:
  - ✓ Gluon polarization (Jet production, π^0): gluon polarization Δg
  - ✓ Quark/Anti-quark polarization (W/Z production): sea quark Δq
  - ✓ Transverse spin asymmetry: Sivers sign change
- Upgrade plan for spin physics in 2021+ at RHIC
- Summary & outlook

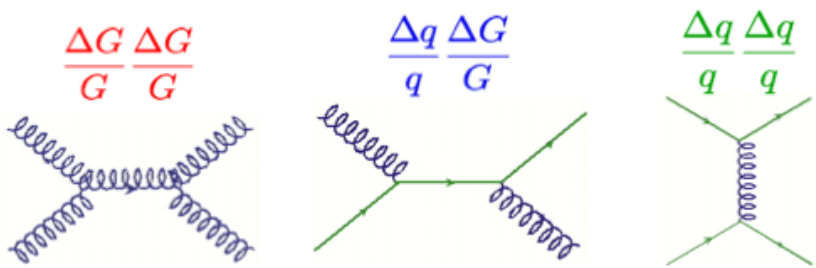
Accessing Δg(x) in pp collision

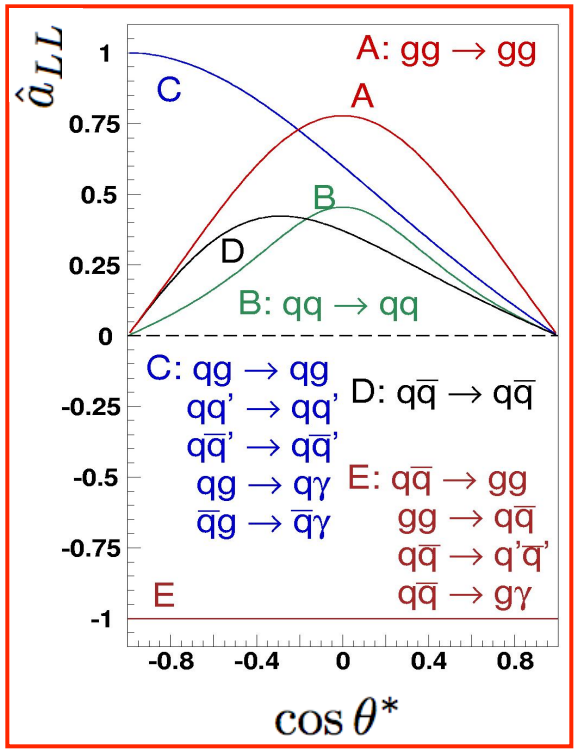
- Longitudinal spin asymmetry:



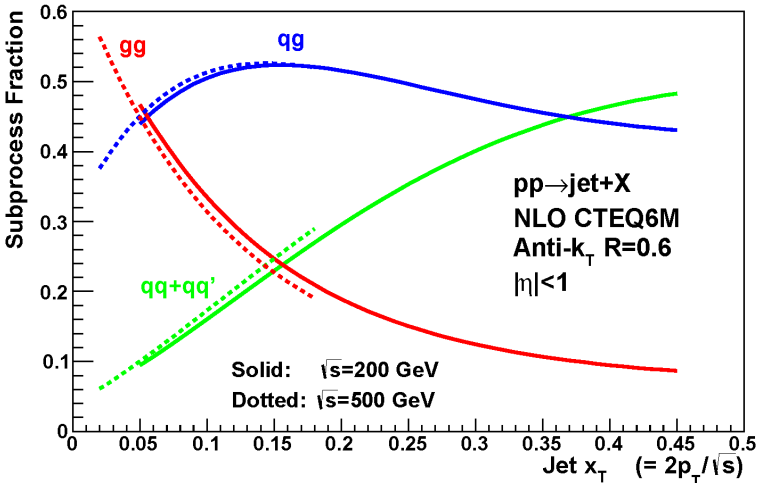
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \cdot \hat{a}_{LL}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}$$

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:



Mukherjee, Vogelsang, PRD86,094009(2012)

STAR - Solenoid Tracker At RHIC

Magnet

- 0.5 T Solenoid

Triggering & Luminosity Monitor

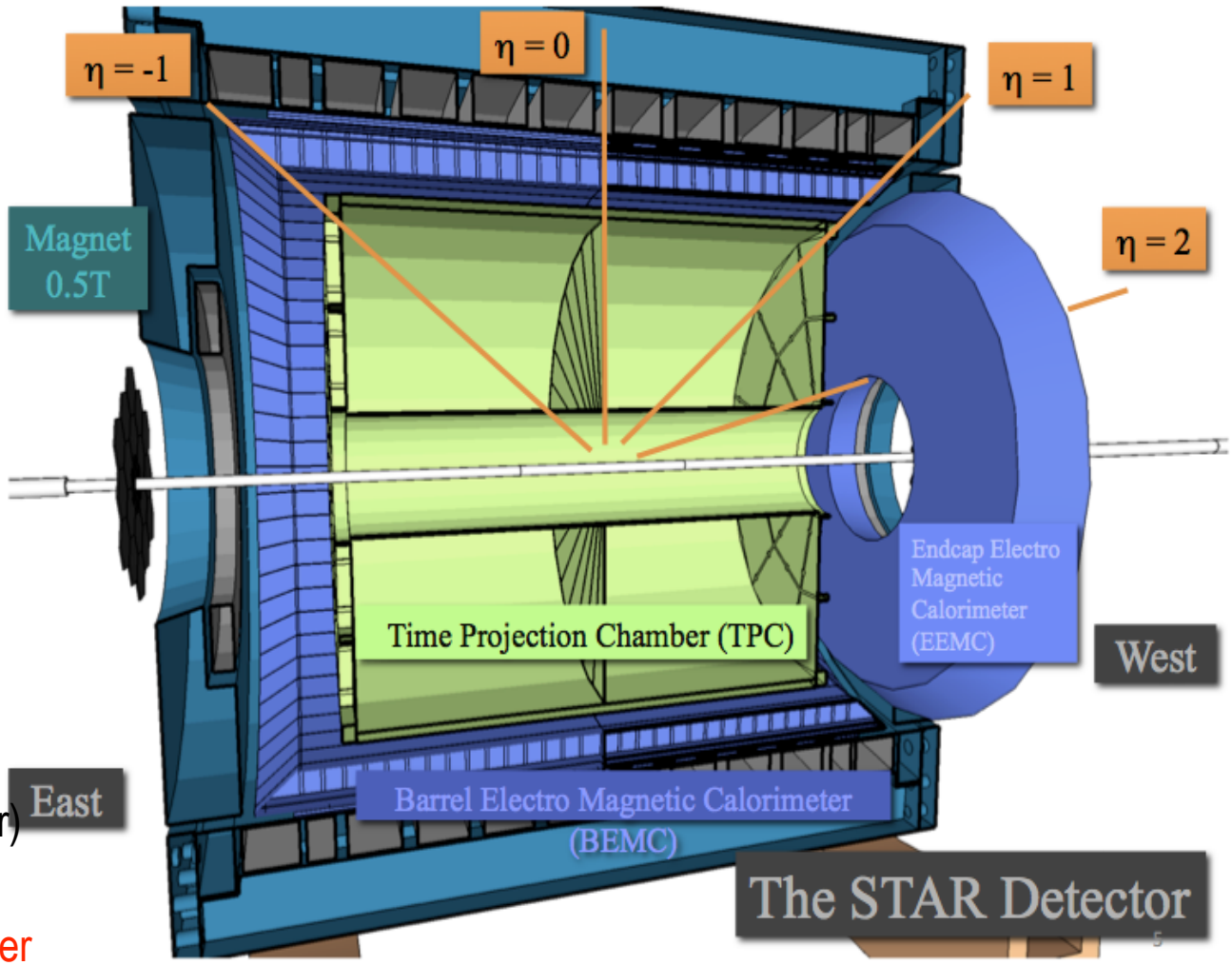
- Beam-Beam Counters
  - $3.4 < |\eta| < 5.0$
- Zero Degree Calorimeters
- Vertex Position Detector

Central Tracking

- Large-volume TPC
  - $|\eta| < 1.3$

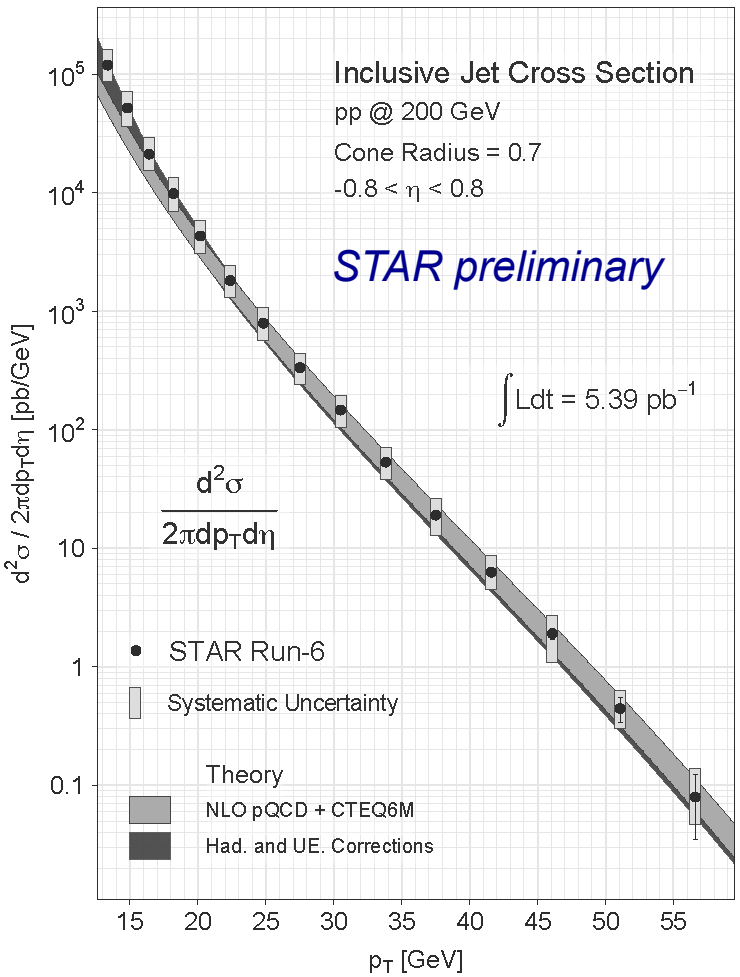
Calorimetry

- Barrel EMC (Pb/Scintilator)
  - $|\eta| < 1.0$
- Endcap EMC (Pb/Scintillator)
  - $1.0 < \eta < 2.0$
- Forward Meson Spectrometer
  - $2.5 < \eta < 4.0$

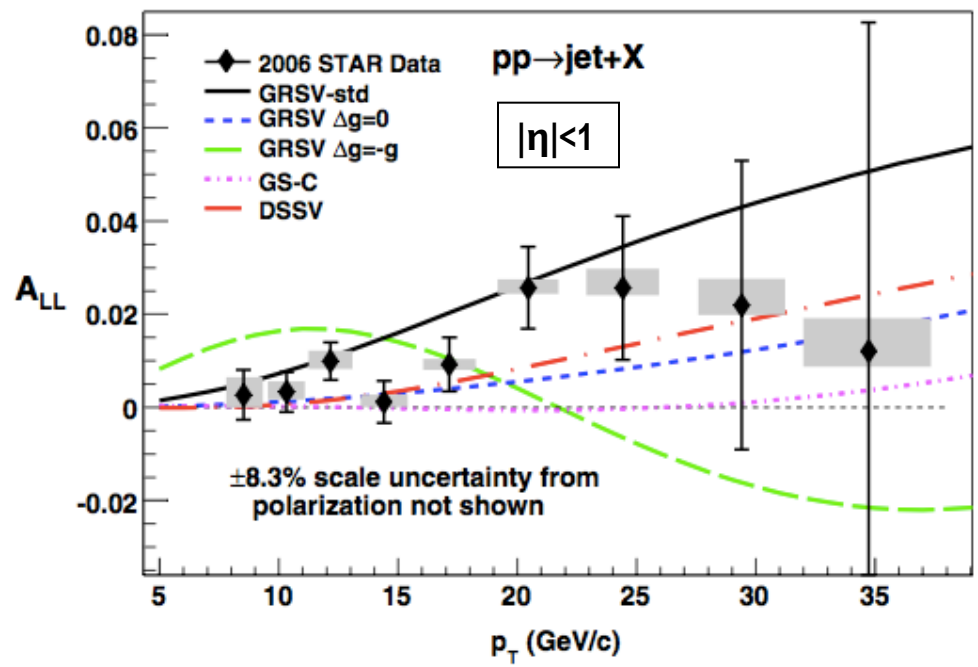


STAR run6 results on jet x-section and A_{LL}

- Cross section well described by NLO pQCD+Hadronization



STAR, PRD86, 32006(2012)



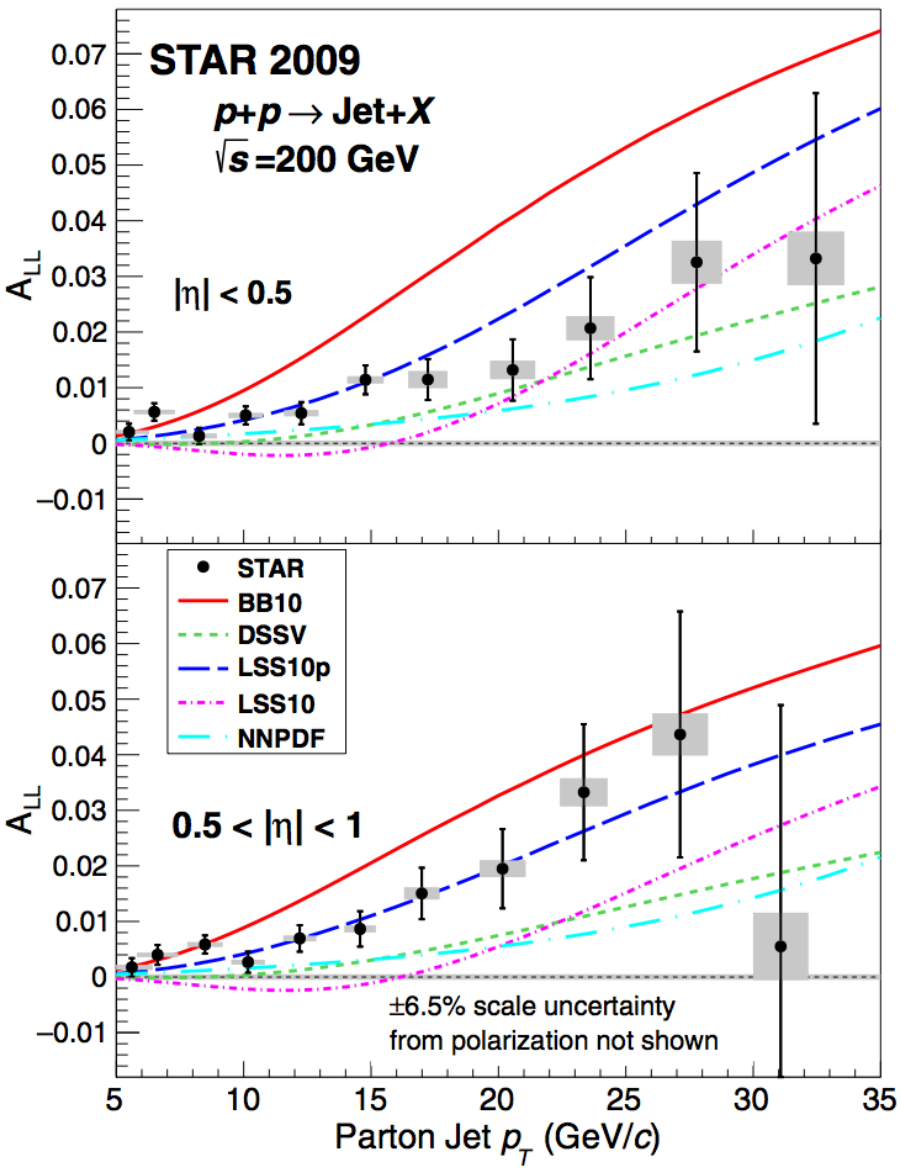
STAR run6 data rule out several previous models of gluon polarization, and included in the DSSV global analysis together with PHENIX π^0 results.

$$\int_{0.05}^{0.2} \Delta g(x)dx = 0.005 \pm^{0.129}_{0.164}$$ at $Q^2 = 10 GeV^2$

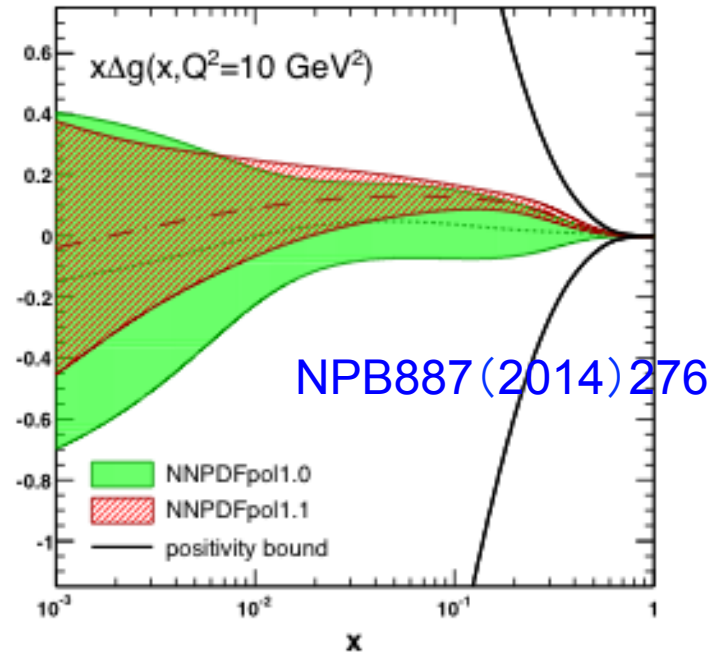
-arXiv:1304.0079

STAR inclusive jet A_{LL} from run9

STAR, PRL115, 92002(2015)



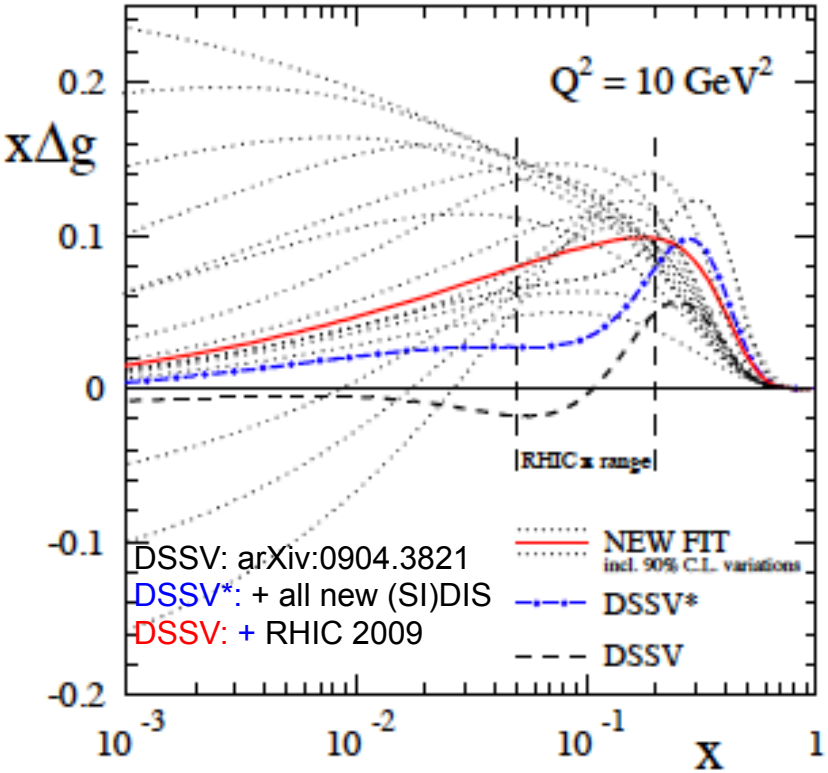
- 2009 STAR data is a factor of 4 more precise than 2006.
- The A_{LL} asymmetry is small, but clearly non-zero !
- Impact of STAR data in NNPDF:



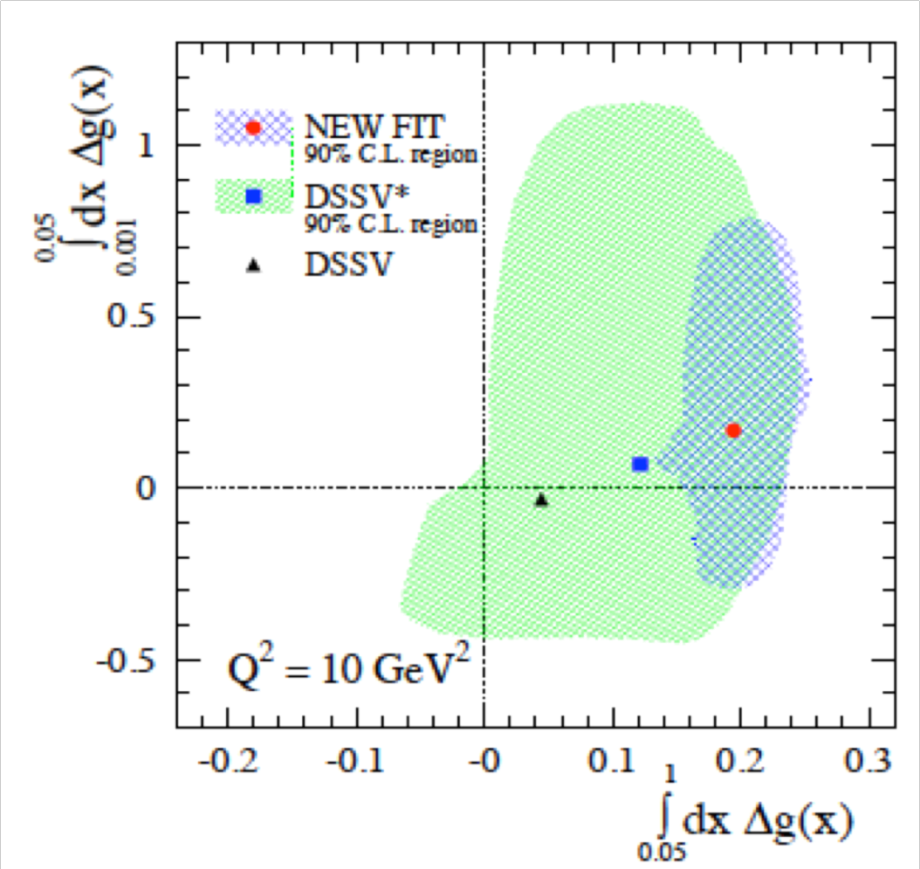
$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10 GeV^2) dx = 0.17 \pm 0.06$$

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:

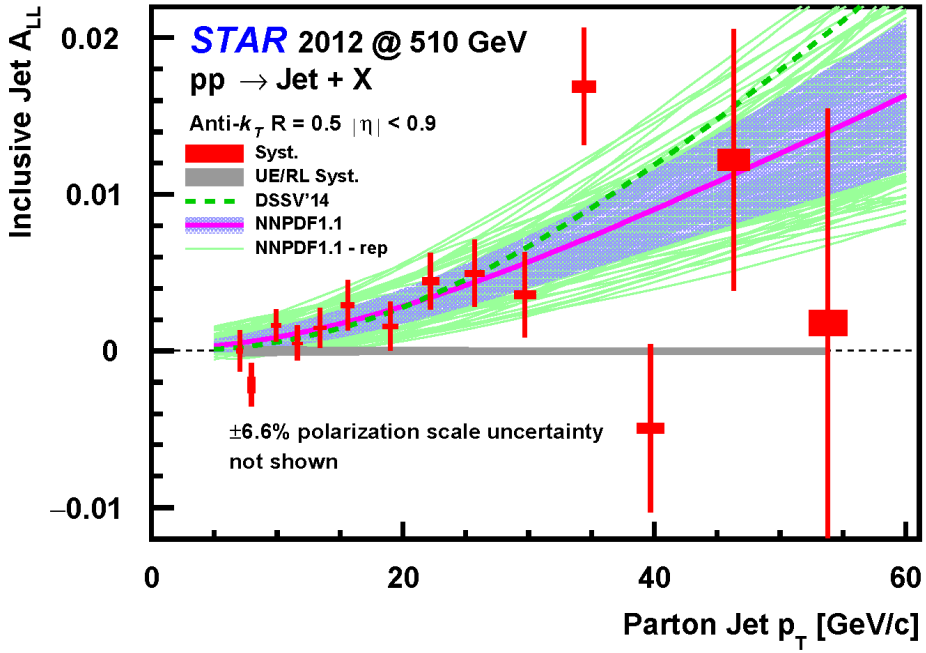
$$\int_0^1 dx\Delta g(x) = 0.251 \pm 0.047(\text{stat.}) \pm 0.016(\text{syst.})$$

χQCD, PRL118,102001(2017)

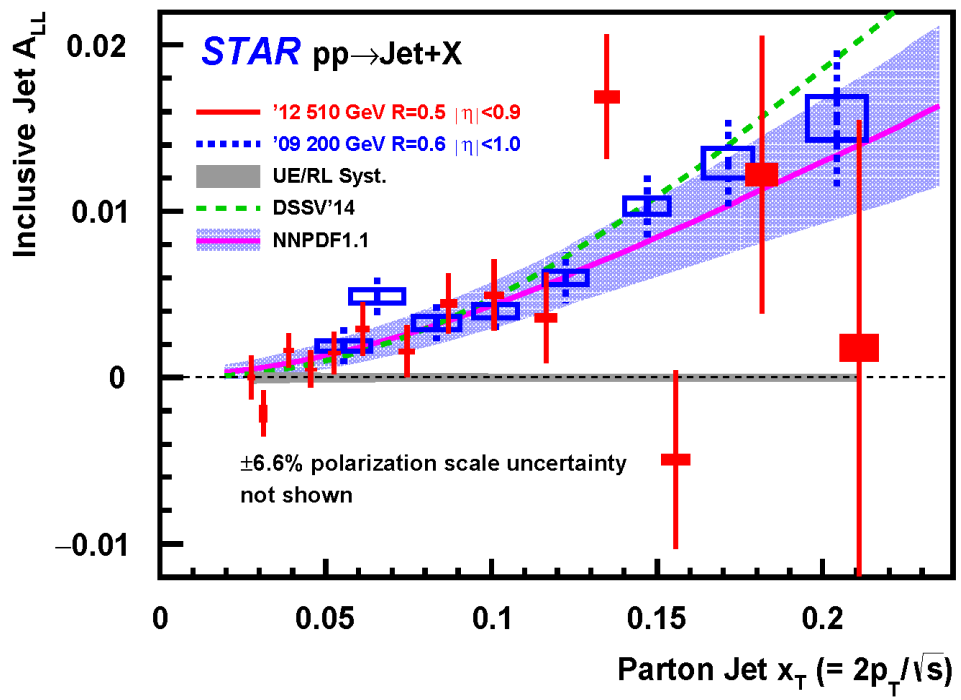
New A_{LL} results at 500 GeV

- *Can we further improve our knowledge on Δg(x)? Yes!*

STAR, arXiv:1906. 02740



- STAR jet A_{LL} at 500 GeV, access small x region down to x~0.015, compared to x~0.05 at 200GeV.



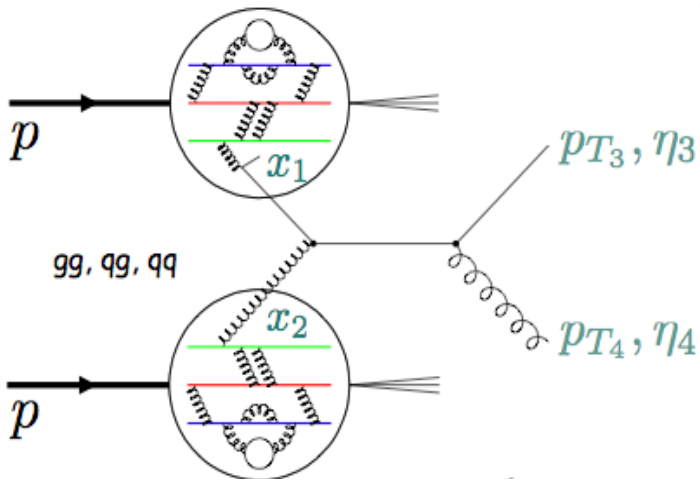
- Consistent with 200GeV data at same x_T .

STAR, arXiv:1906. 02740

Correlation measurements with partonic kinematics

- Access to partonic kinematics through di-jet production

Better constrain the functional form of Δg



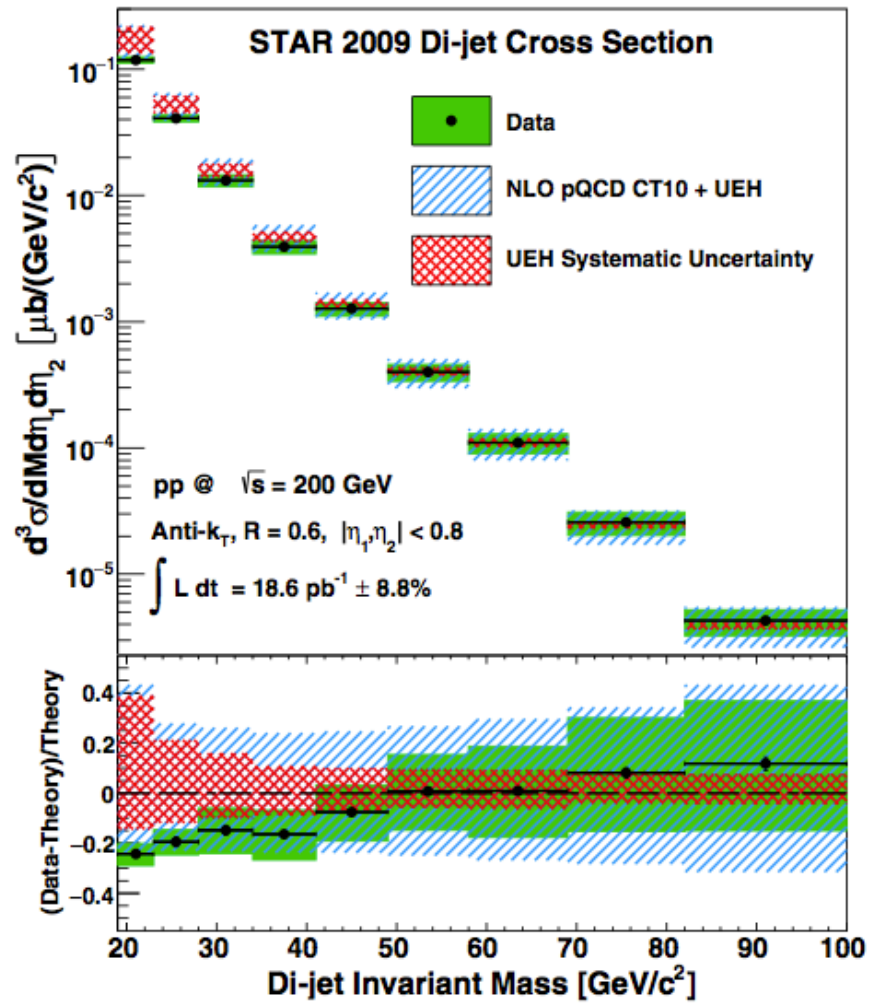
$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

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

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

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

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

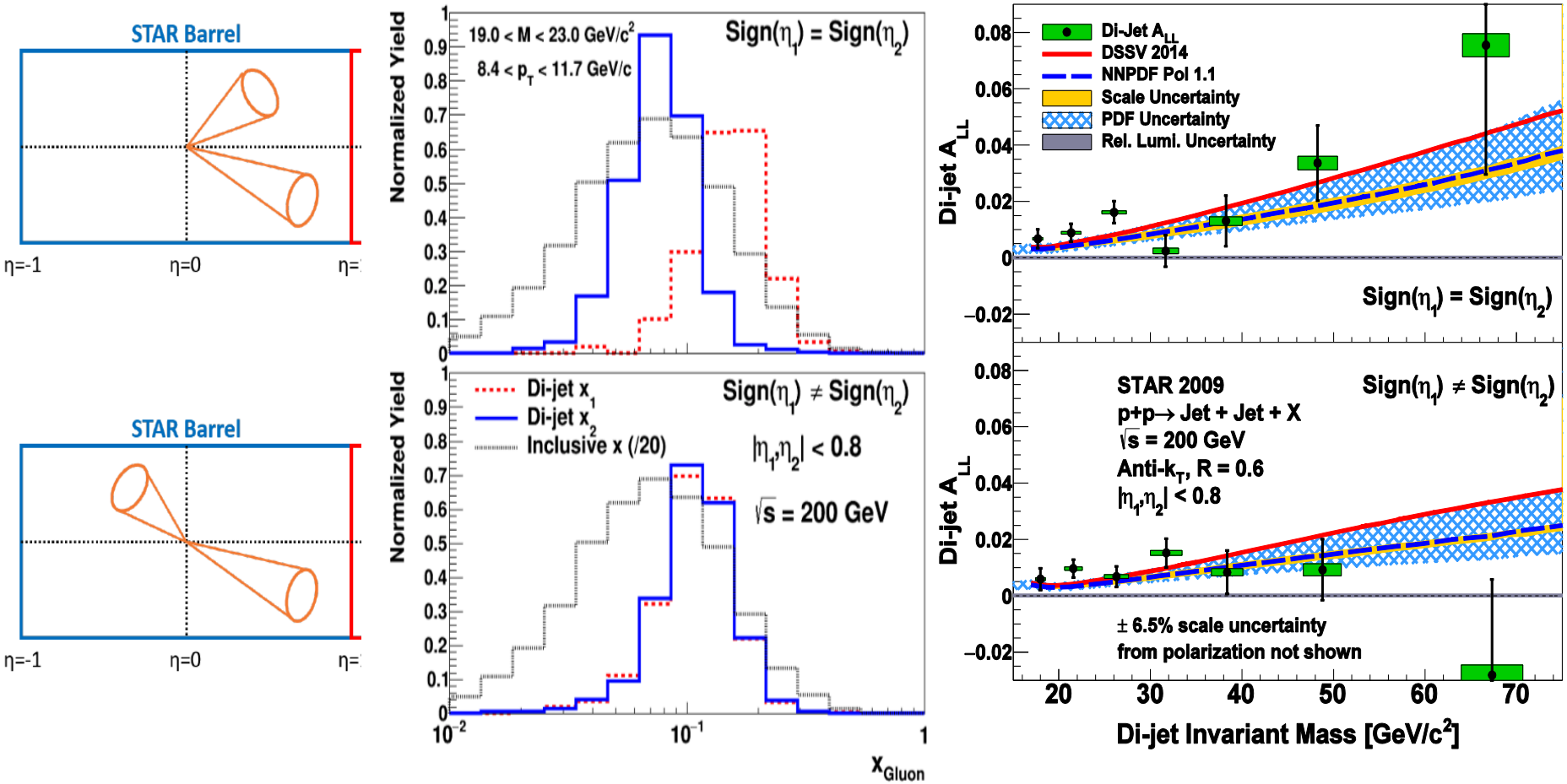


STAR, PRD95,071103(2017)

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

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

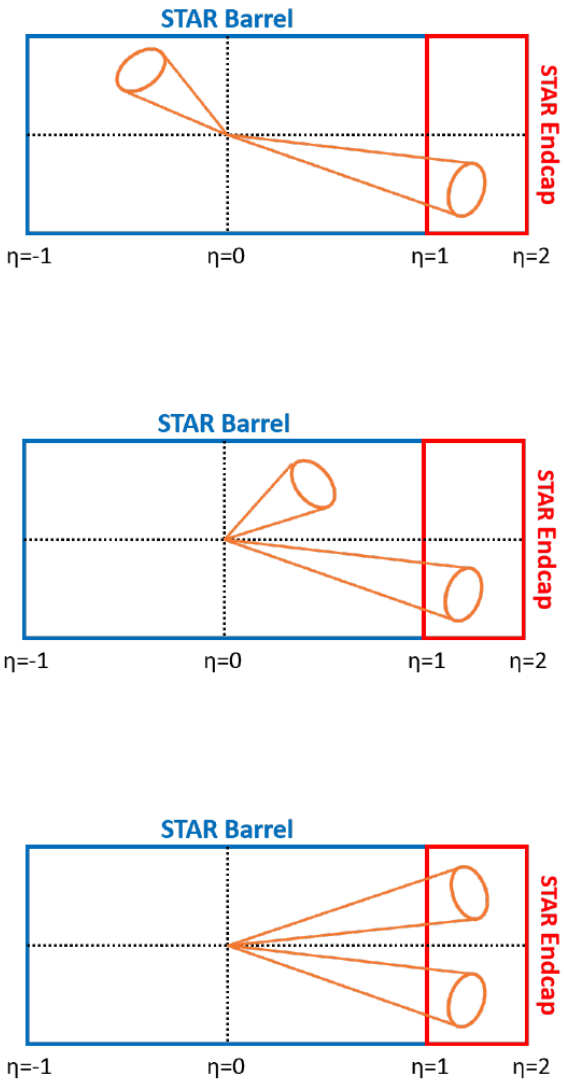
STAR, PRD95,071103(2017)

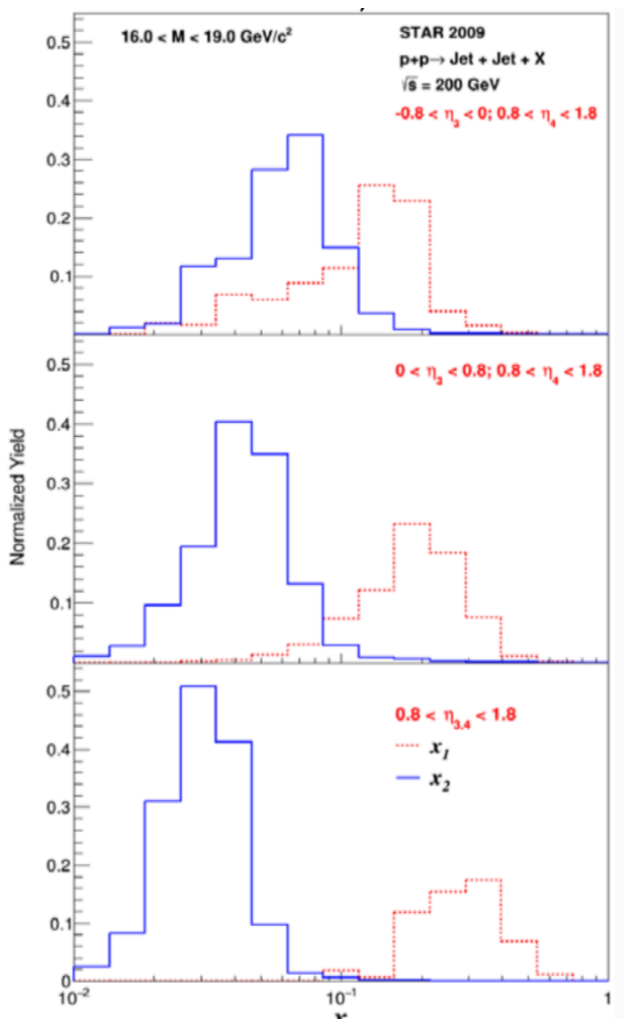


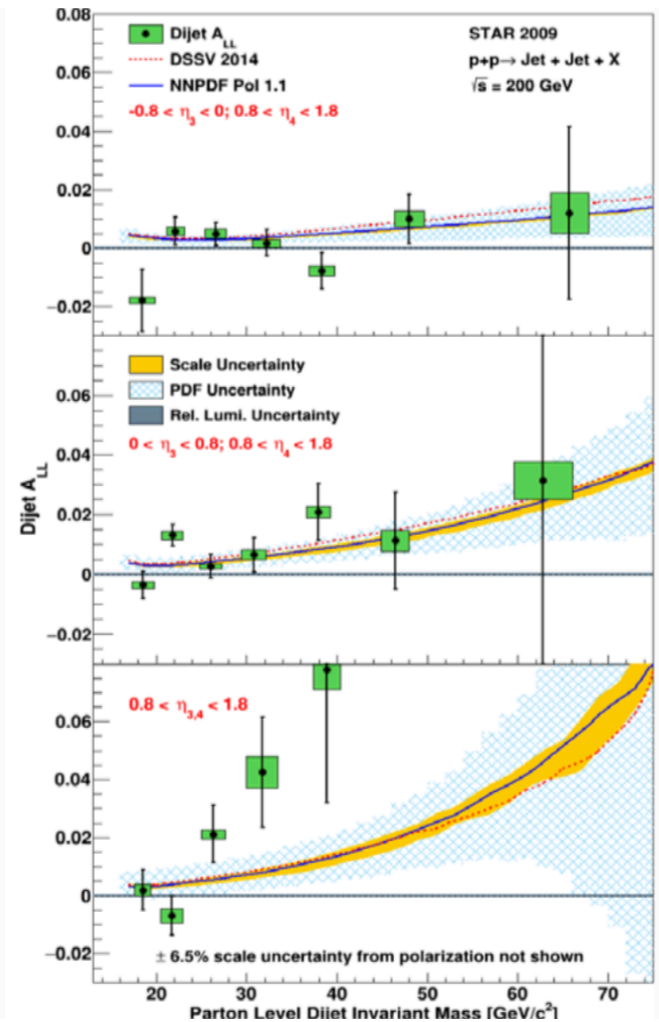
Central-forward Di-jet at 200 GeV at STAR

STAR, PRD98,032011(2018)

Wider rapidity coverage!

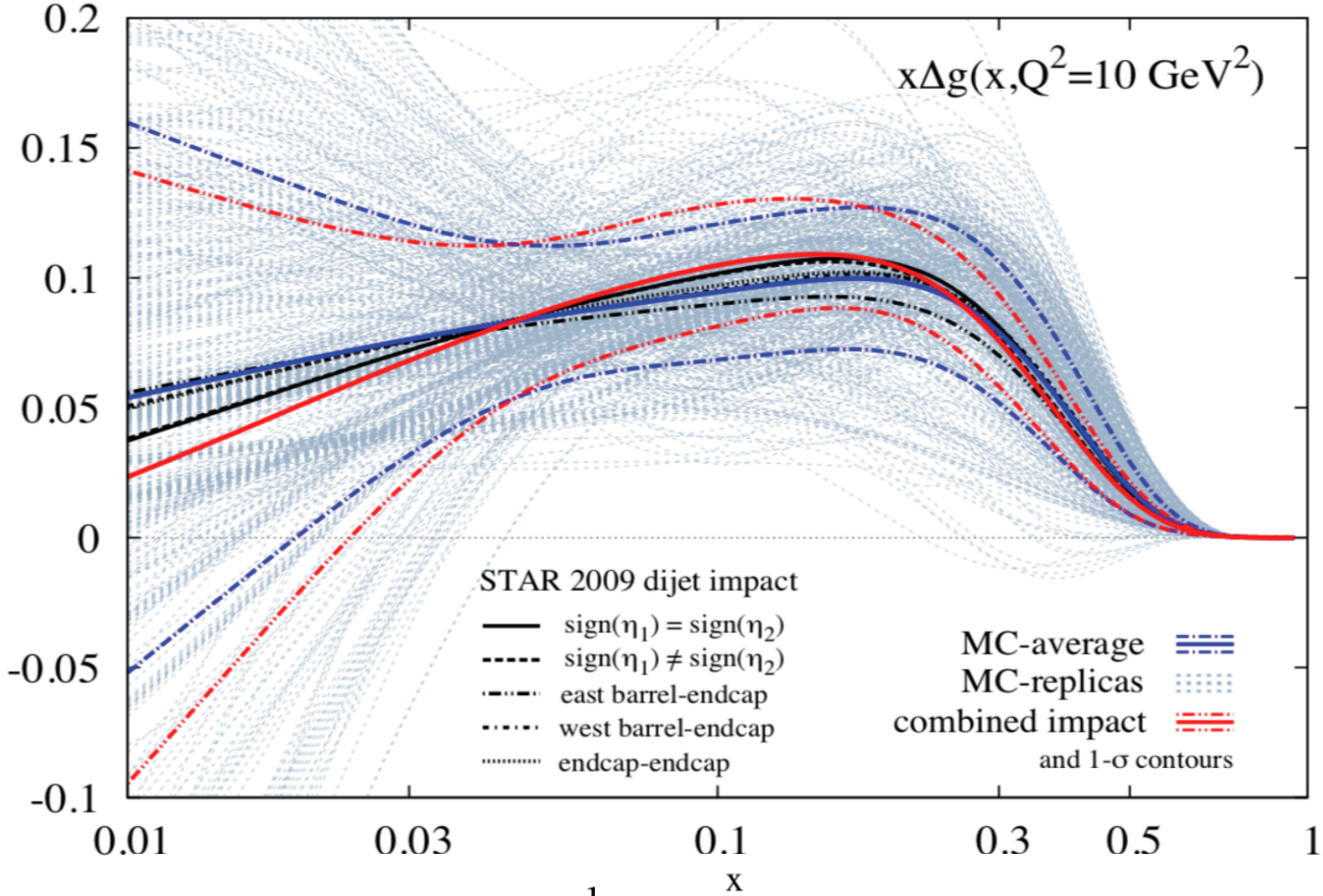






Impact of STAR di-jet A_{LL} to Δg global fit

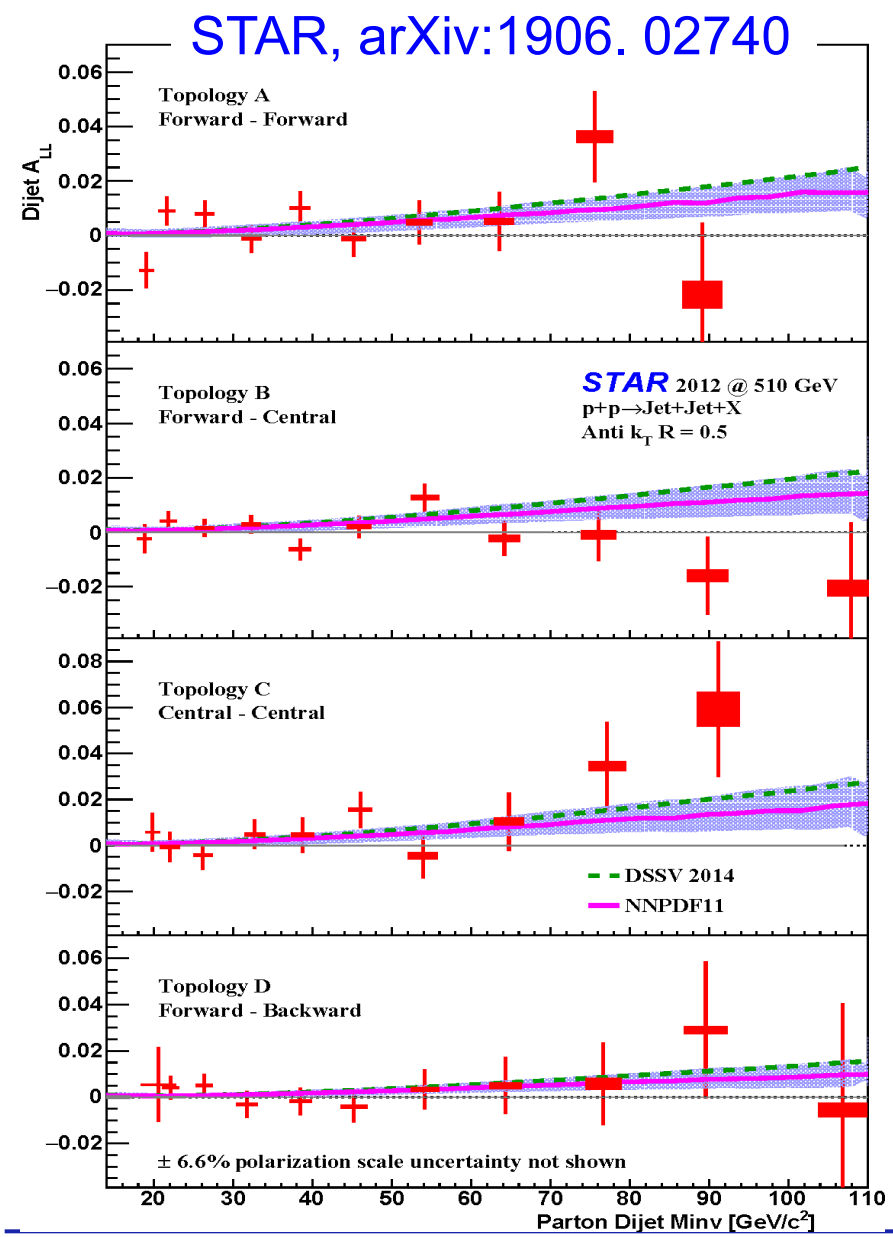
D. de Florian, et al., (DSSV2018), arXiv:1902.10548



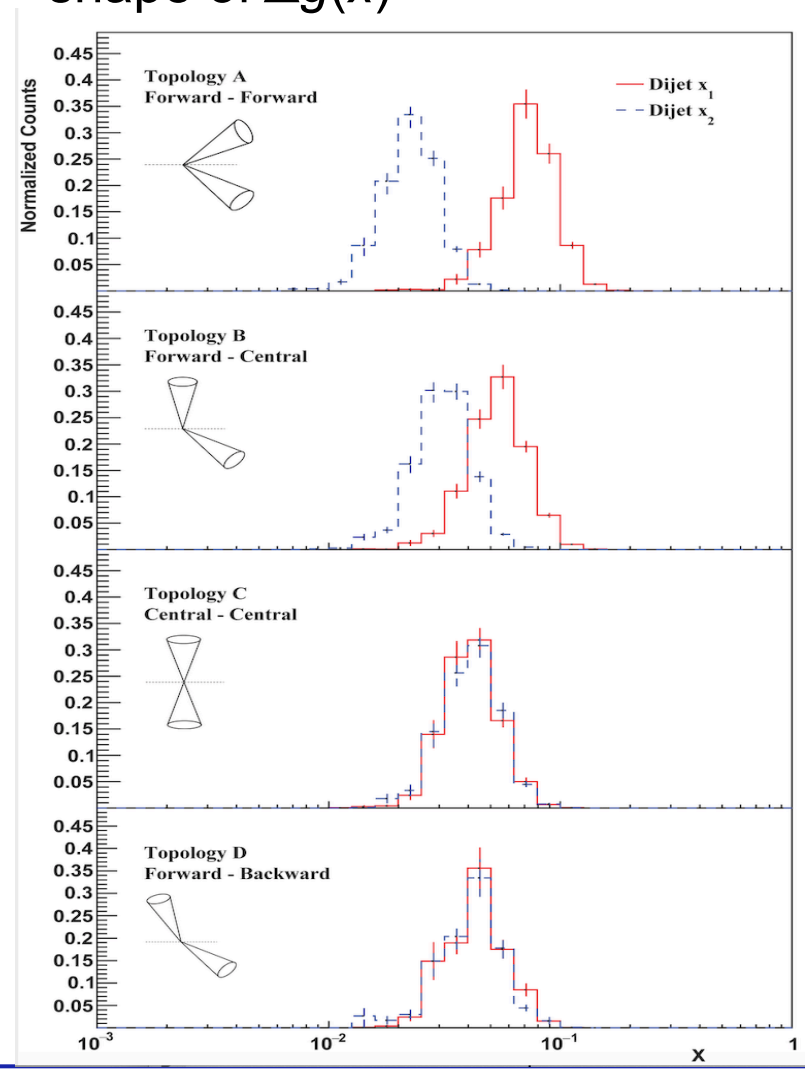
Before reweighting: $\int_{0.1}^{1} \Delta g(x)\,dx = 0.133 \pm 0.035$

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

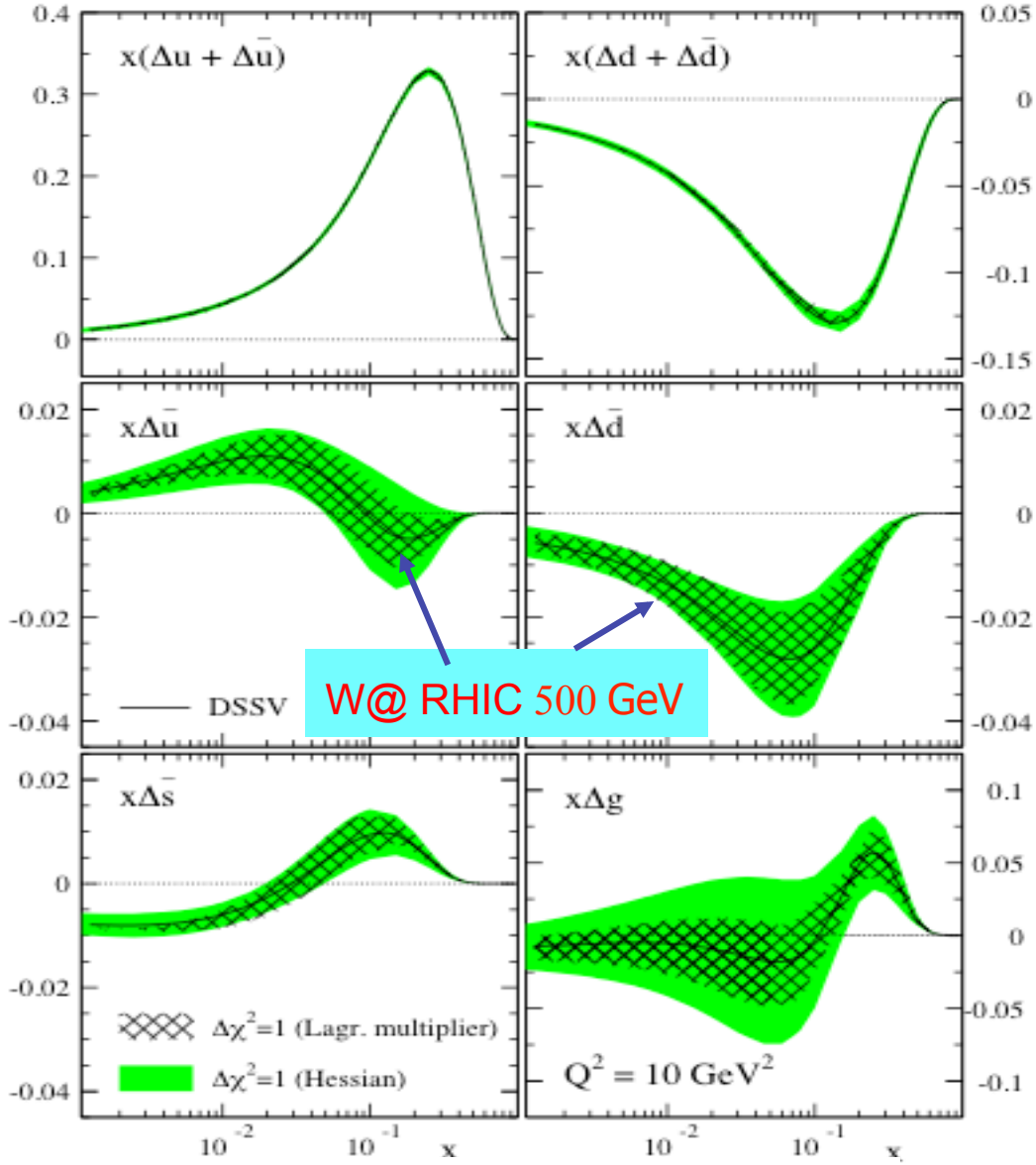
Di-jets A_{LL} at 500 GeV at STAR



- New results on di-jet A_{LL} at 500 GeV, further constraints on the shape of $\Delta g(x)$



$\Delta q(x)$, $\Delta g(x)$ - global analysis of data

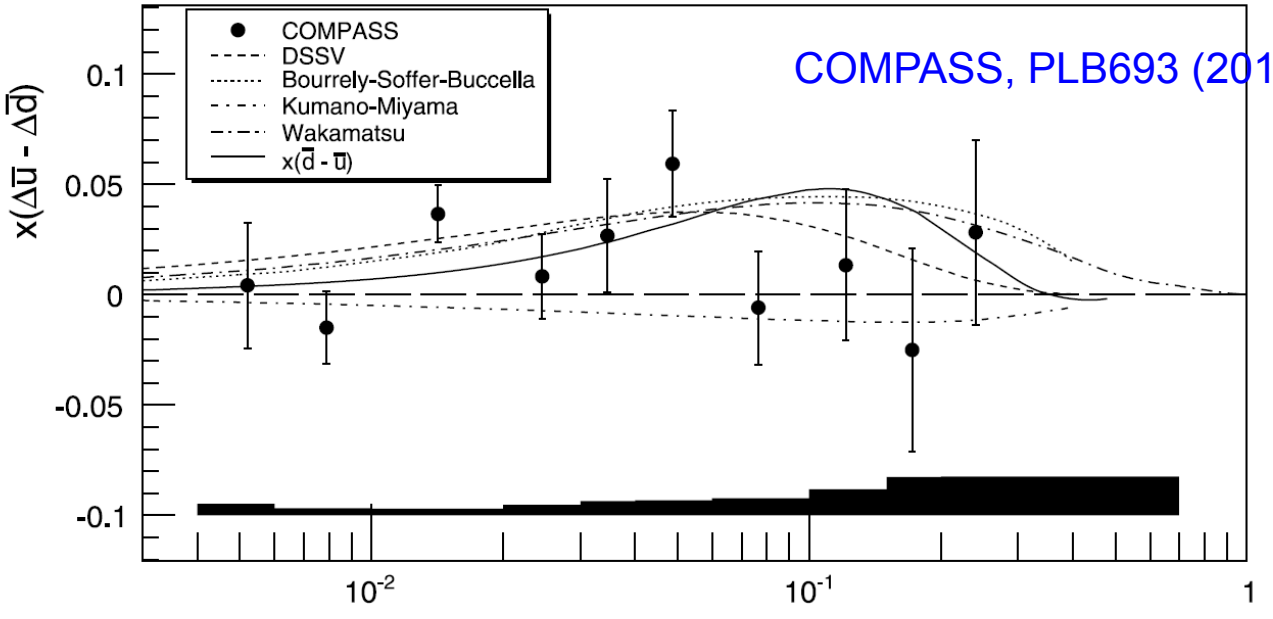


Sea quark

D. De Florian,et al., PRD80,34030(2009)

Flavor symmetry of the polarized sea ?

- Do we expect a symmetry breaking in the polarized sea?



COMPASS, PLB693 (2010) 227

COMPASS $\int_{0.004}^{0.3} \left(\Delta\bar{u}-\Delta\bar{d}\right)dx = 0.06 \pm 0.04 \pm 0.02 \quad @ \quad Q^2 = 3\ \left(GeV/c\right)^2$

HERMES $\int_{0.023}^{0.6} \left(\Delta\bar{u}-\Delta\bar{d}\right)dx = 0.048 \pm 0.057 \pm 0.028 \quad @ \quad Q^2 = 2.5\ \left(GeV/c\right)^2$

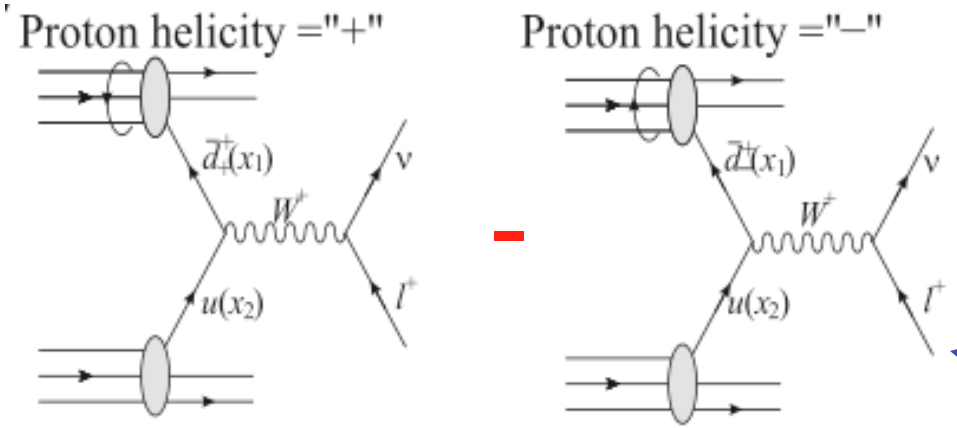
- HERMES, PRD 71 (2005) 012003

unp. E866 $\int_{0}^{1} \left(\bar{u}-\bar{d}\right)dx = -0.118 \pm 0.012 \quad @ \quad Q^2 = 54\ \left(GeV/c\right)^2$

- E866, Phys. Rev. D64 (2001) 052002

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:

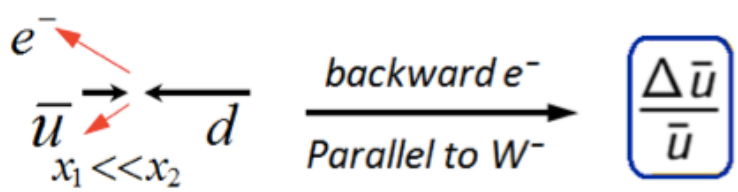
$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} = \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \end{cases}$$

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

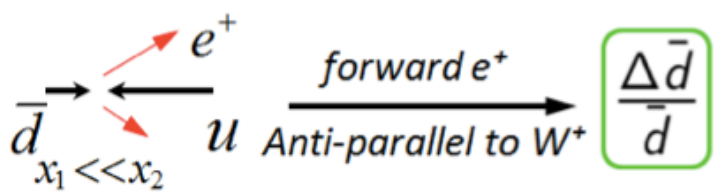
Expectation of W A_L at RHIC

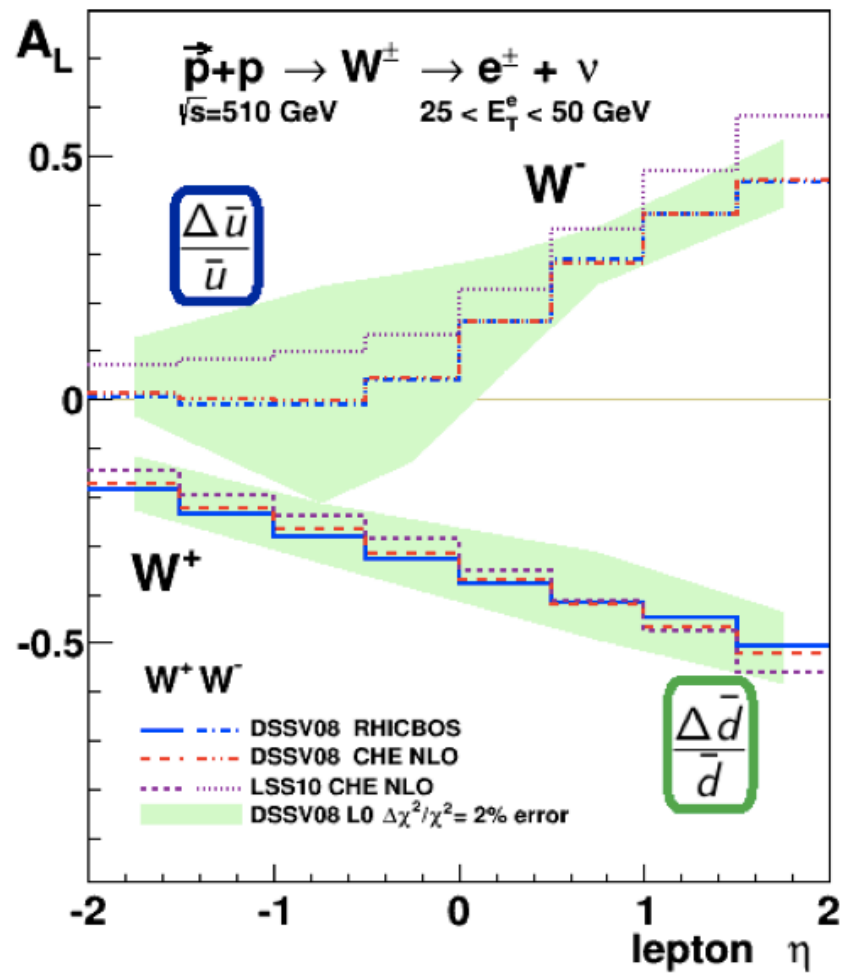
- Large parity-violating asymmetries expected.
- Simplified interpretation at forward and backward rapidity:

$$A_L^{W^-} \propto \frac{-\Delta d(x_1)\bar{u}(x_2)+\Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2)+\bar{u}(x_1)d(x_2)}$$



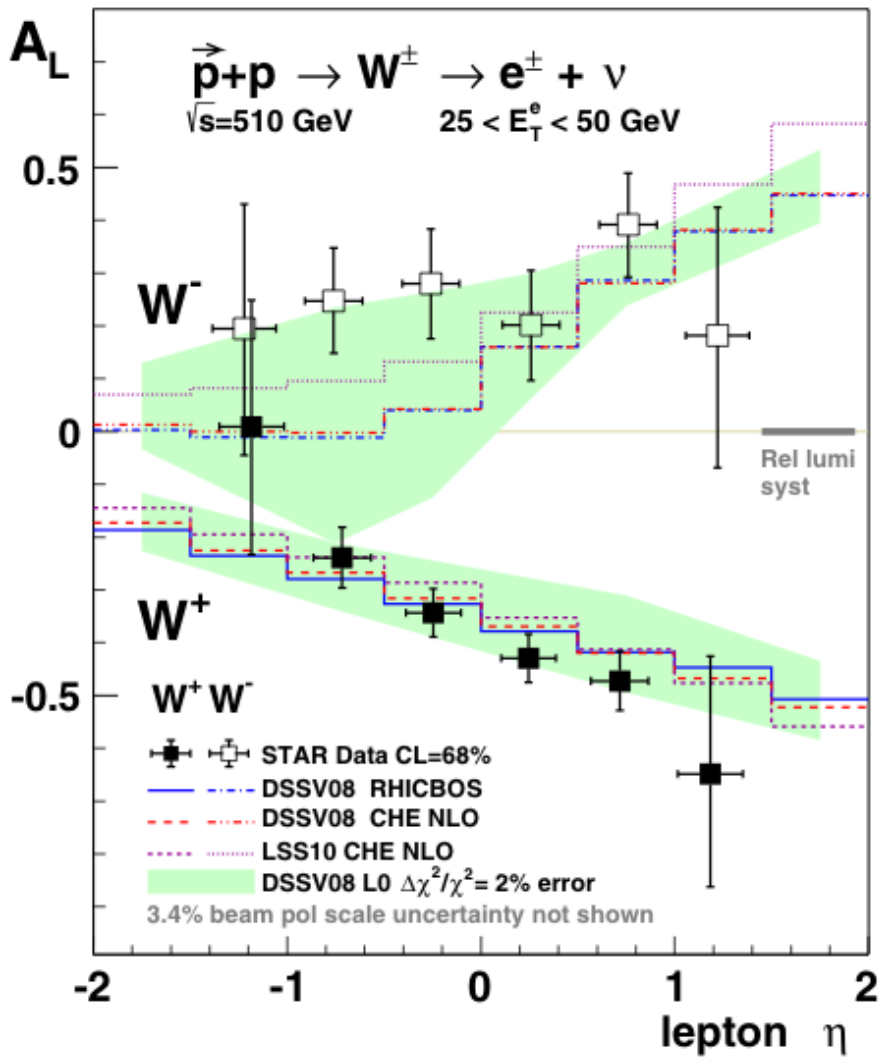
$$A_L^{W^+} \propto \frac{-\Delta u(x_1)\bar{d}(x_2)+\Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2)+\bar{d}(x_1)u(x_2)}$$





STAR mid-rapidity W A_L –2011+2012

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

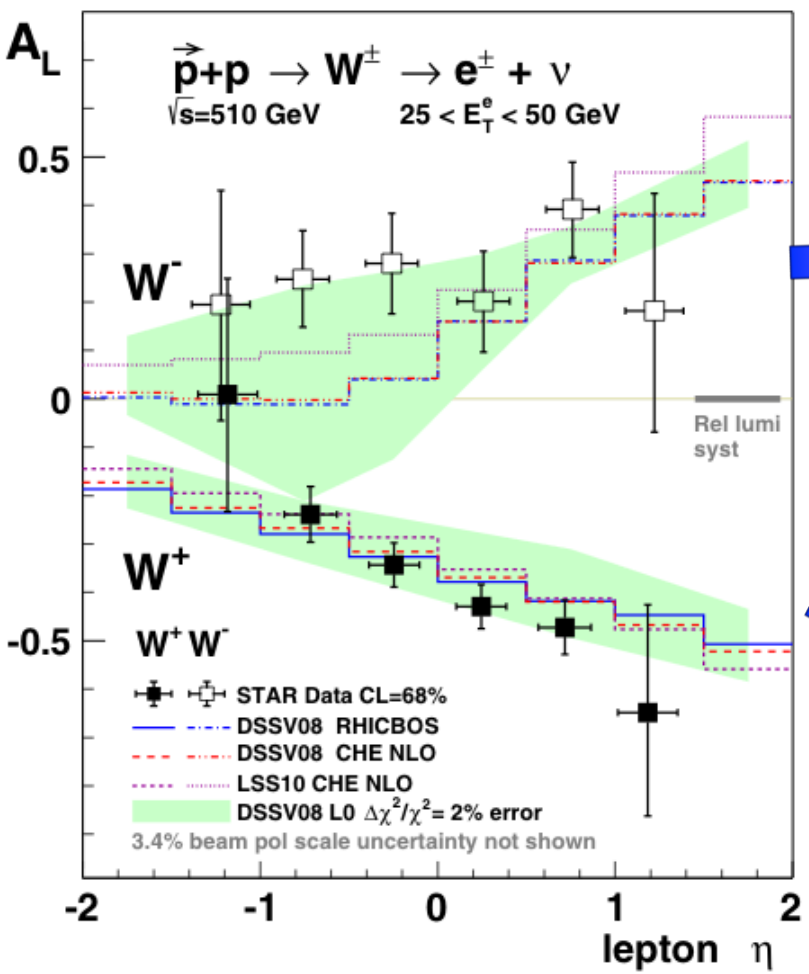


STAR, PRL113(2014)72301

- 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.

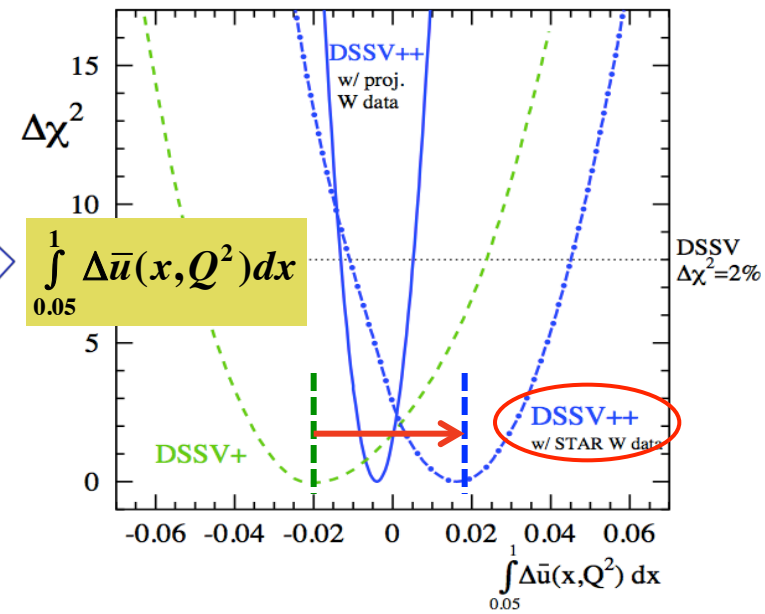
Global Analysis with STAR W A_L 2012

STAR, PRL113(2014)72301

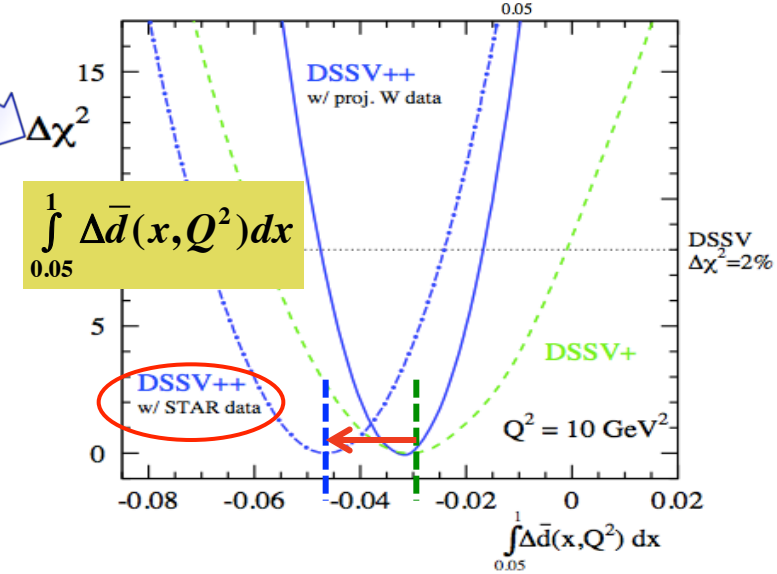


arXiv:1304.0079

$\Delta\bar{u}$



$\Delta\bar{d}$



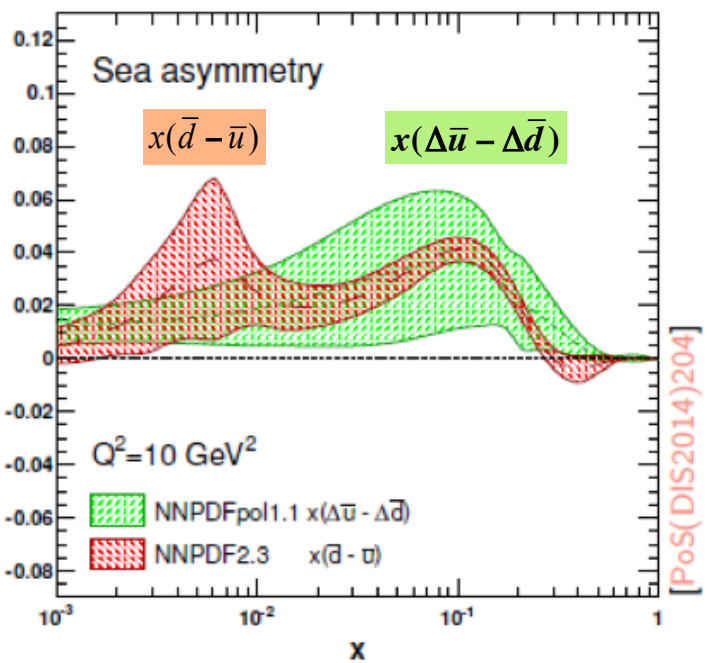
STAR 2012 W results provide significant constraints on $\Delta\bar{u}, \Delta\bar{d}$.

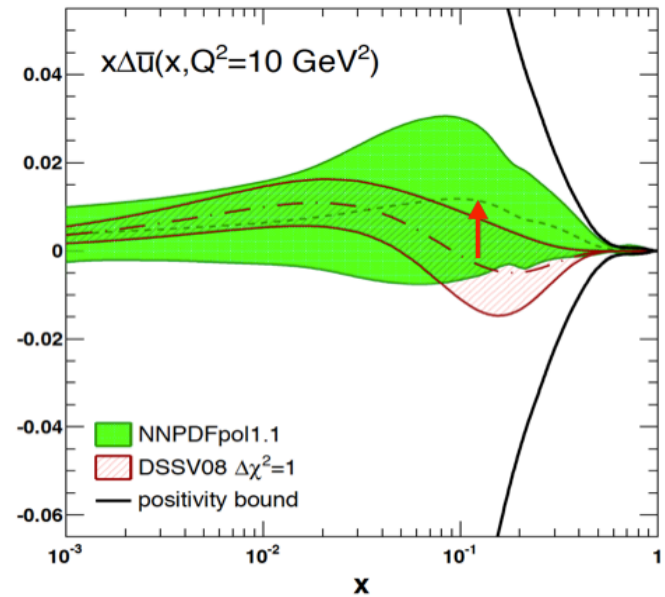
Global Analysis with STAR W A_L results

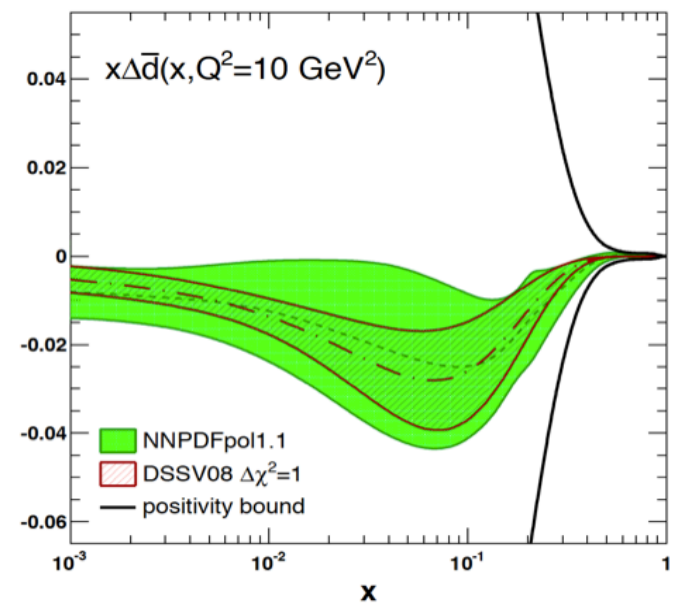
- Big impact seen in NNPDFpol1.1 global analysis after including STAR A_L data.

NNPDF1.1, NPB887,276 (2014)

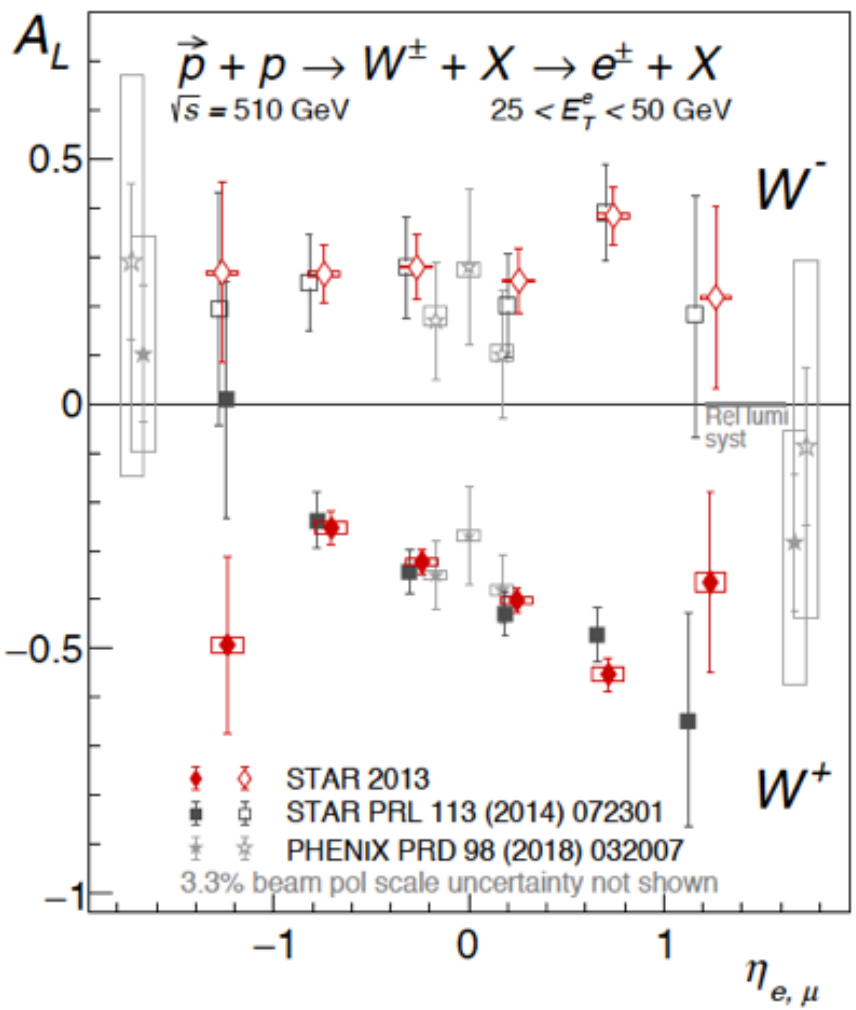
- Polarized sea asymmetry: opposite as unpolarized case!







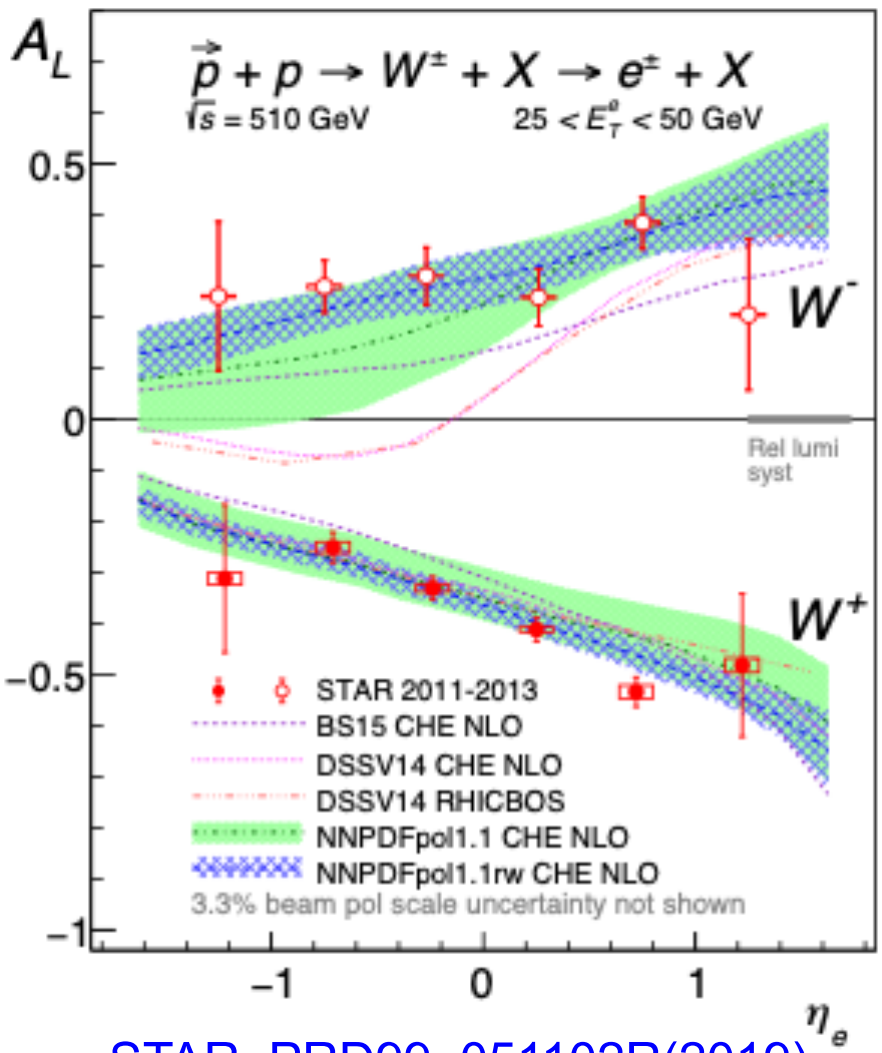
W A_L results – STAR 2013



STAR, PRD99, 051102R(2019)

- ✓ Most precise W AL results from 2013 dataset
- ✓ Consistent with published RHIC results; with 40-50% smaller uncertainties than STAR 2011+2012
- ✓ Confirmed the larger than initially expected anti-up quark polarization first seen in the 2011+2012 data.

W A_L results – STAR 2013



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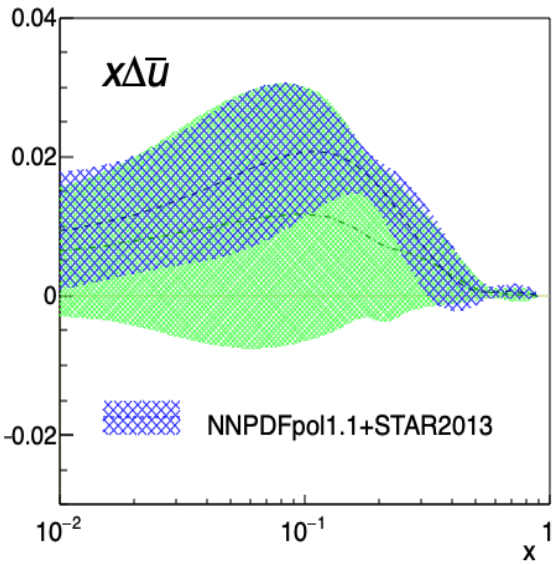
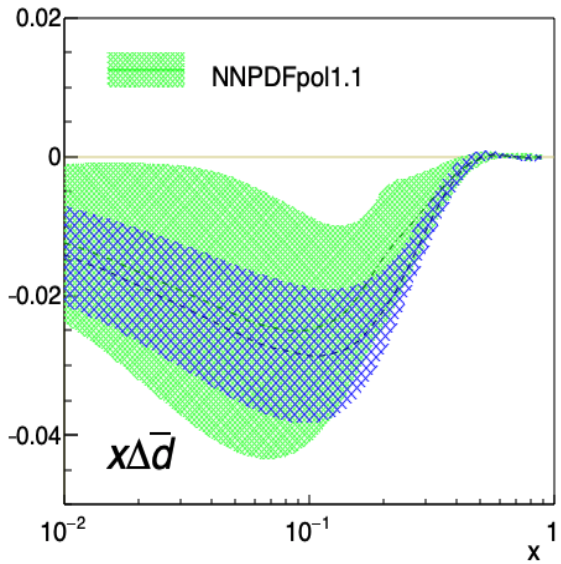
- ✓ Consistent with published RHIC results; with 40-50% smaller uncertainties than STAR 2011+2012
- ✓ Confirmed the larger than initially expected anti-up quark polarization first seen in the 2011+2012 data.
- ✓ Combined results in comparison with theoretical predications

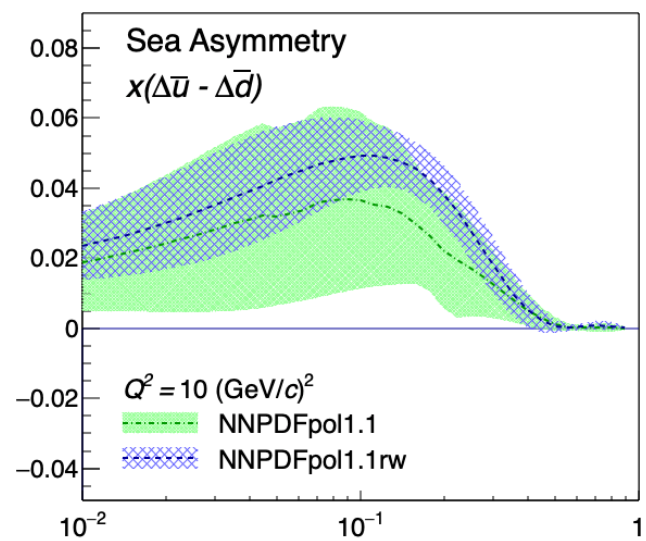
Impact of STAR 2013 W A_L results

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

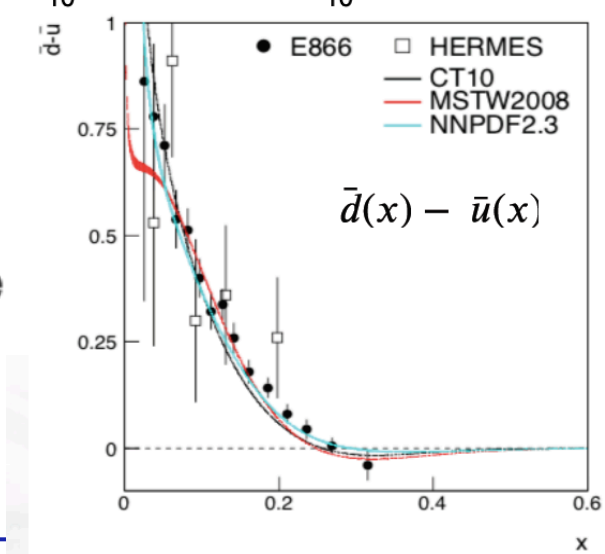
STAR, PRD99, 051102R(2019)







- Delta u-bar is now known to be positive
- Delta d-bar is now known to be negative
- The flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ similar size but opposite sign to the unpolarized flavor asymmetry $\bar{u} - \bar{d}$



Is polarized sea asymmetry surprising?

- Asymmetric polarized sea, is compatible with Pauli suppression by the polarized valence quarks, among different models.

-W. Chang, J. C. Peng, Prog. Part. Nucl. Phys. 79: 95 (2014)

Table 5: Prediction of various theoretical models on the integral $I_\Delta = \int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)]dx$

Model	I_Δ prediction	Ref.
Meson cloud (π-meson)	0	[31, 127]
Meson cloud (ρ-meson)	$\simeq -0.0007$ to -0.027	[117]
Meson cloud ($\pi - \rho$ interf.)	$= -6 \int_0^1 g^p(x)dx$	[118]
Meson cloud (ρ and $\pi - \rho$ interf.)	$\simeq -0.004$ to -0.033	[119]
Meson cloud (ρ-meson)	< 0	[120]
Meson cloud ($\pi - \sigma$ interf.)	$\simeq 0.12$	[132]
Pauli-blocking (bag-model)	$\simeq 0.09$	[119]
Pauli-blocking (ansatz)	$\simeq 0.3$	[128]
Pauli-blocking	$= \frac{5}{3} \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx \simeq 0.2$	[129]
Chiral-quark soliton	0.31	[130]
Chiral-quark soliton	$\simeq \int_0^1 2x^{0.12}[\bar{d}(x) - \bar{u}(x)]dx$	[131]
Instanton	$= \frac{5}{3} \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx \simeq 0.2$	[123]
Statistical	$\simeq \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx \simeq 0.12$	[41]
Statistical	$> \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx > 0.12$	[126]

Is polarized sea asymmetry surprising?

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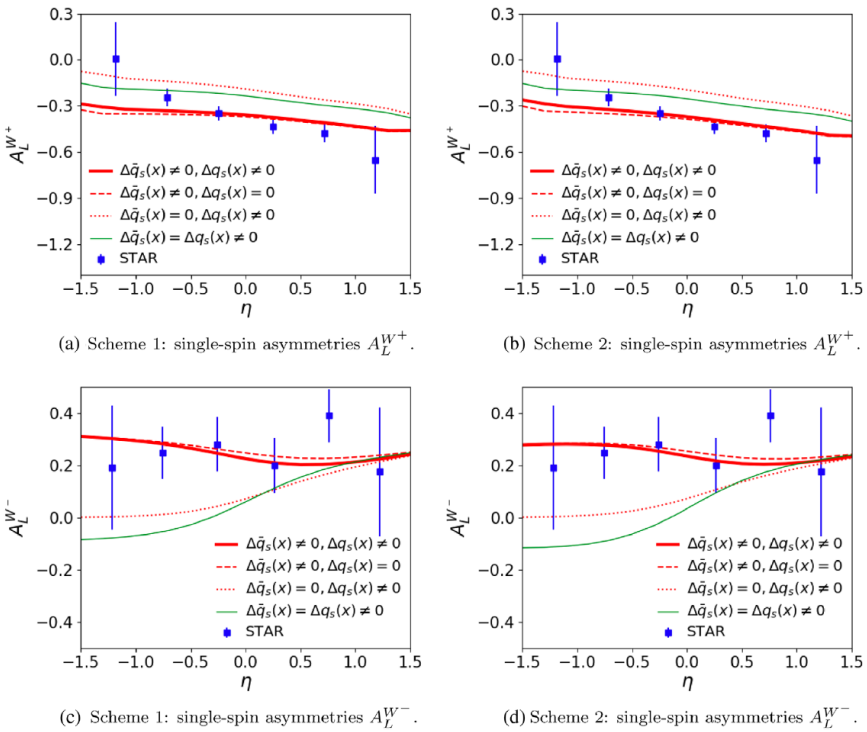
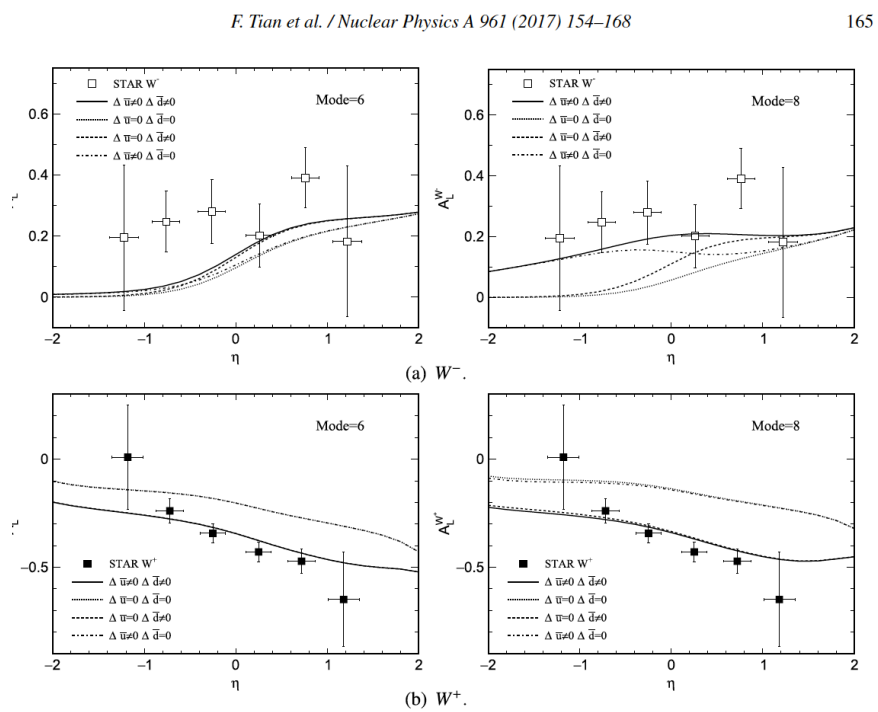
  -W. Chang, J. C. Peng, Prog. Part. Nucl. Phys. 79: 95 (2014)

- Recent model calculations by B. Q. Ma et al.



(a) Scheme 1: single-spin asymmetries $A_L^{W^+}$. (b) Scheme 2: single-spin asymmetries $A_L^{W^+}$.

(c) Scheme 1: single-spin asymmetries $A_L^{W^-}$. (d) Scheme 2: single-spin asymmetries $A_L^{W^-}$.



(a) W^-.

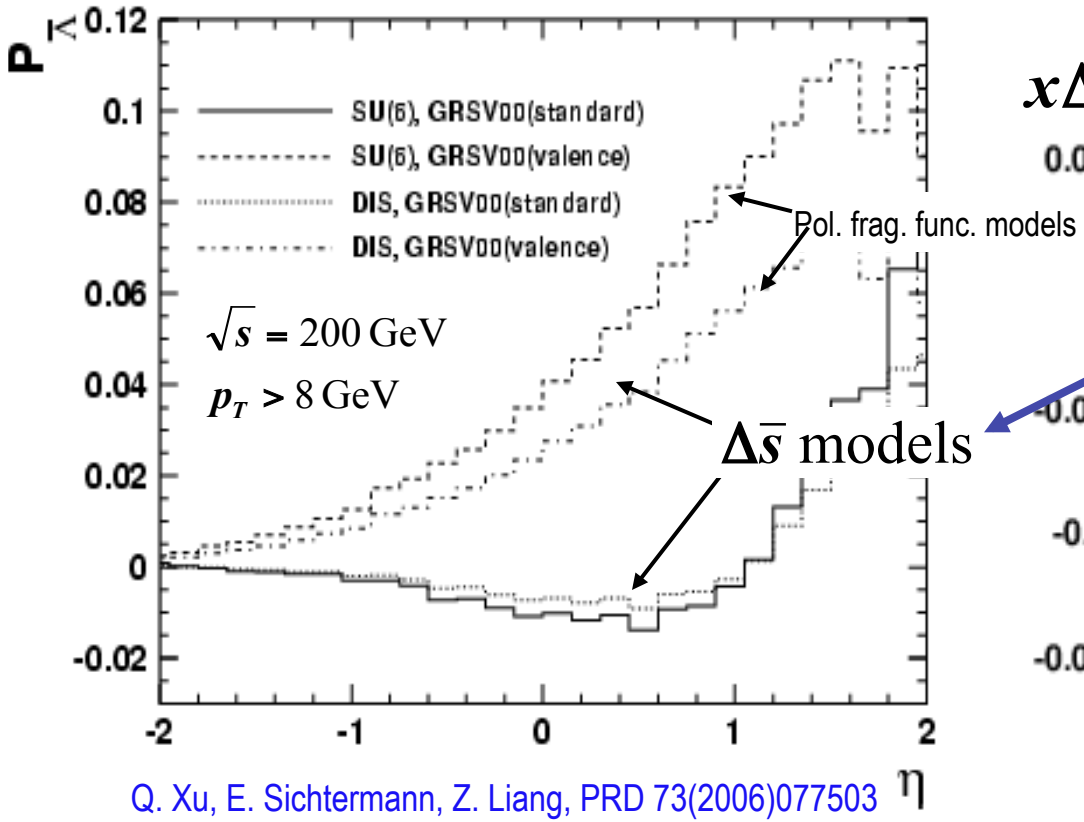
(b) W^+.

- M.Y. Liu, B. Q. Ma, PRD98, 036024 (2018)
- F. Tian, C. Gong, B. Q. Ma, NPA 961, 154(2017)

D_{LL}-Longitudinal spin transfer & strange quark polarization

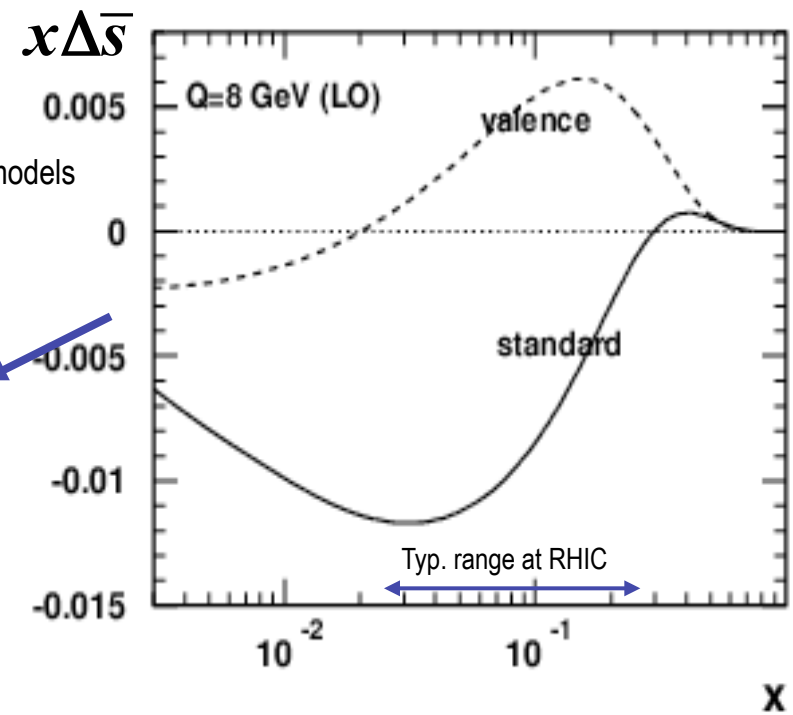
- Expectations at LO show sensitivity of D_{LL} for anti-Lambda to $\Delta\bar{s}$:

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



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

GRSV00-M.Gluck et al, Phys.Rev.D63(2001)094005

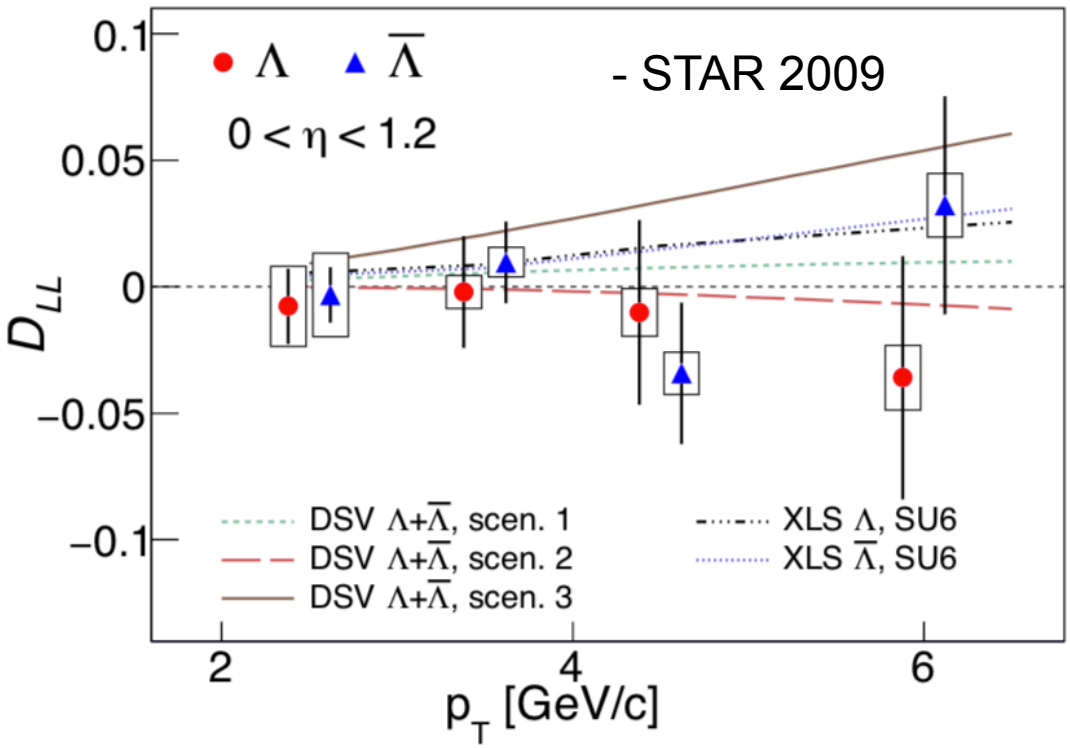


- Λ D_{LL} is less sensitive to Δs, due to large u,d quark fragmentation.
- $\bar{\Lambda}$ Promising measurements for anti-strange quark polarization.

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

- Improved D_{LL} measurements from STAR 2009 data:

-STAR, PRD98, 112009 (2018)



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

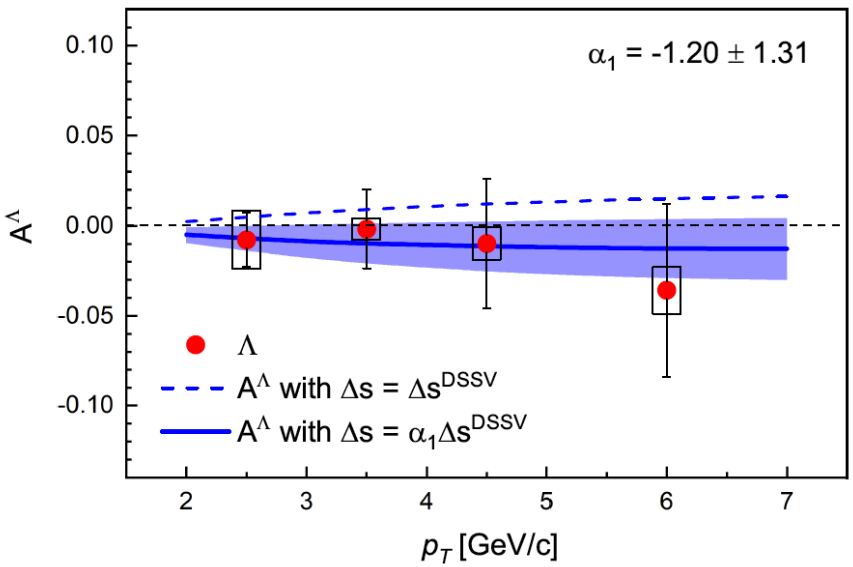
✓ D_{LL} results are still consistent with zero within the uncertainties.

✓ The statistics are similar to the spread of different models.

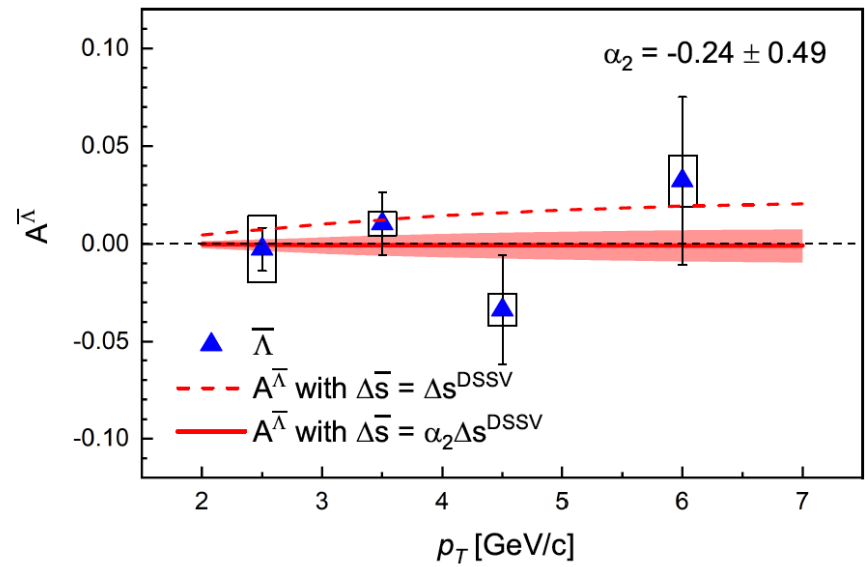
D_{LL} results of (anti-)Lambda at STAR

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

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



(a) Longitudinal spin transfer to Λ.



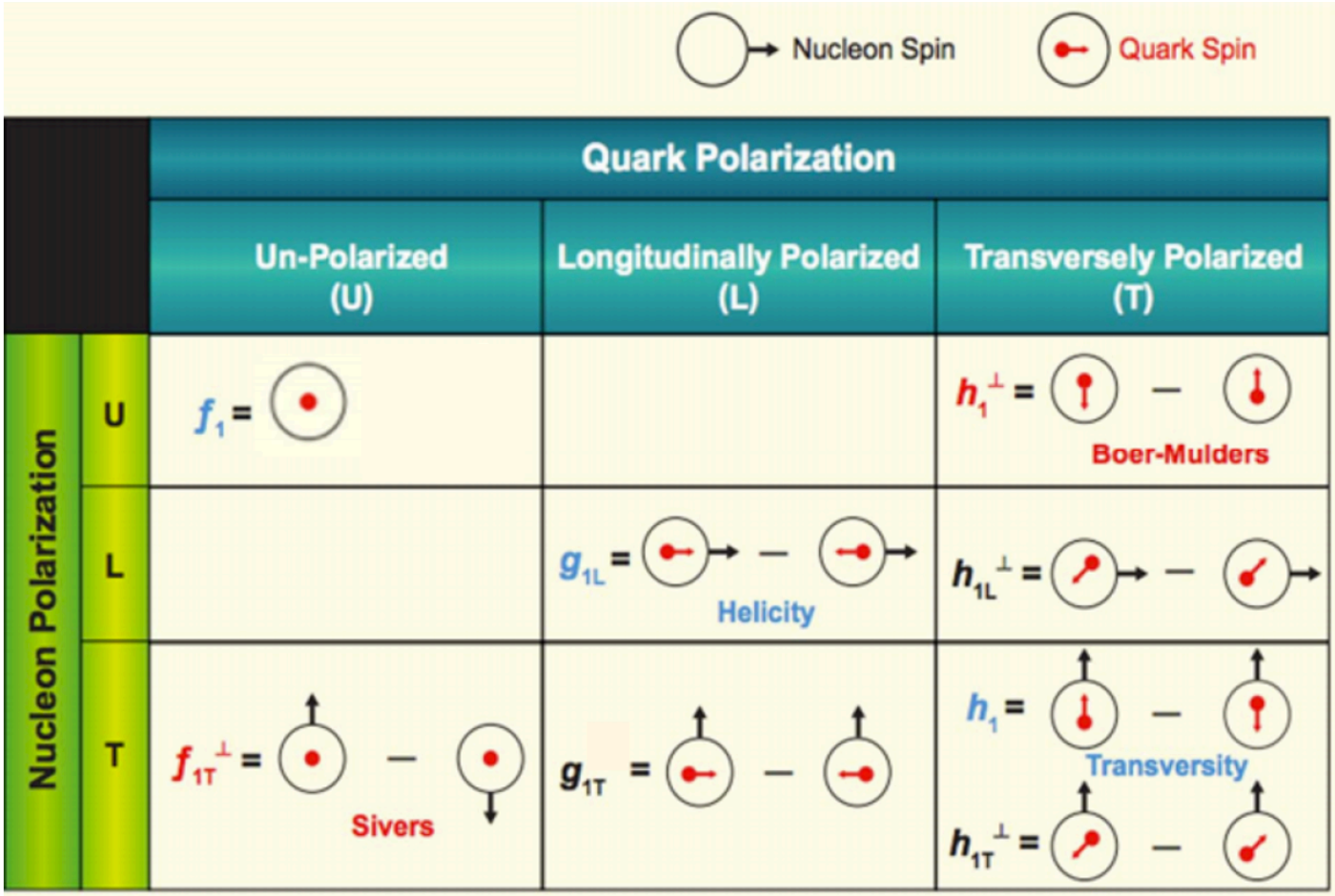
(b) Longitudinal spin transfer to $\bar{\Lambda}$.

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

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

Transverse spin asymmetry & TMD

- Transverse momentum dependent distribution (TMD):

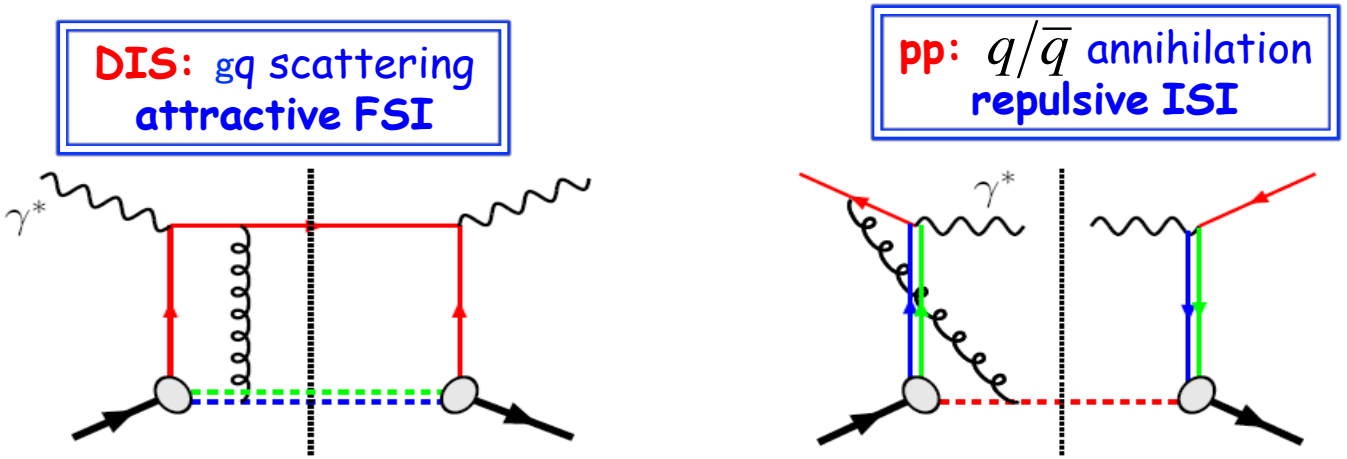


Sivers function: $f_q(x,k_\perp;S_\perp) = f_q(x,k_\perp) + \frac{1}{M}(\vec{k}_\perp \times \hat{\vec{p}})\cdot\vec{S}_\perp \, f_{1T}^\perp(x,k_\perp)$

- correlation between parton transverse momentum, proton momentum and proton spin

Transverse single spin asymmetry (A_N) of W boson

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



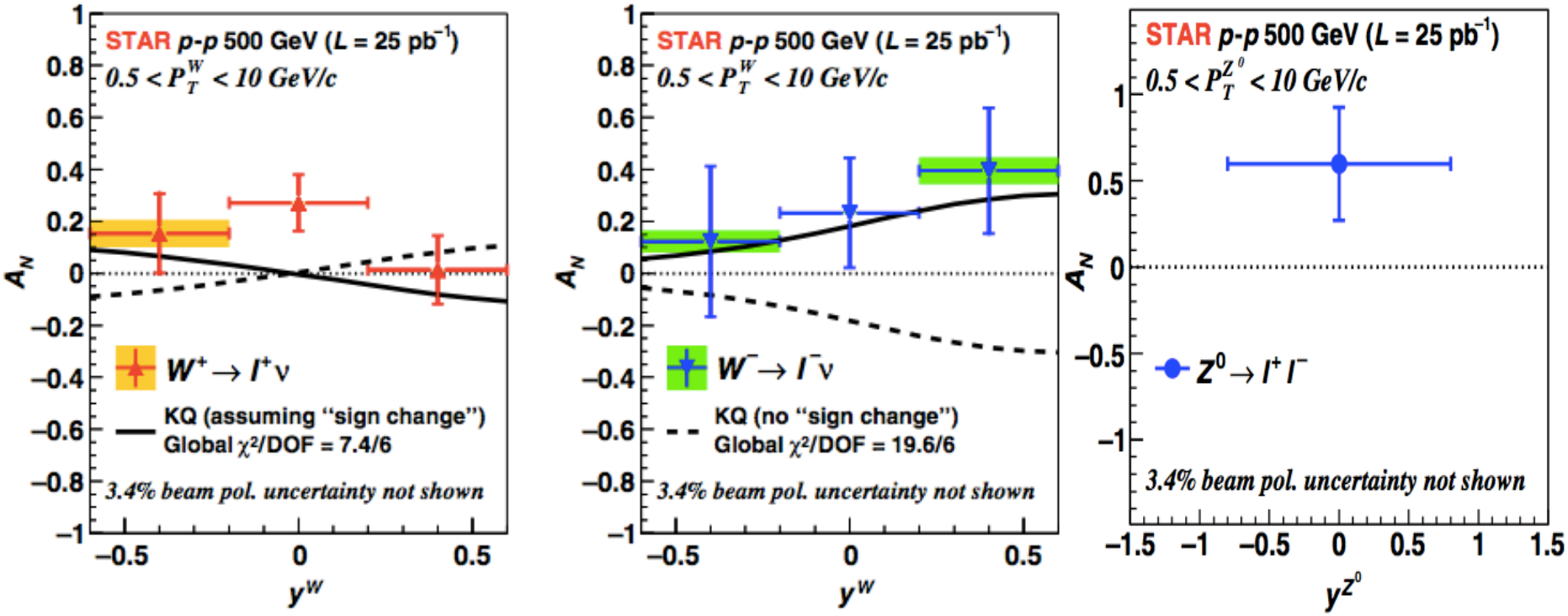
Sivers_{DIS} = - Sivers (DY or W or Z)

-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, total luminosity ~25 pb^{-1}
- First A_N for $W^{\pm}$ and Z results : $A_N \equiv \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$

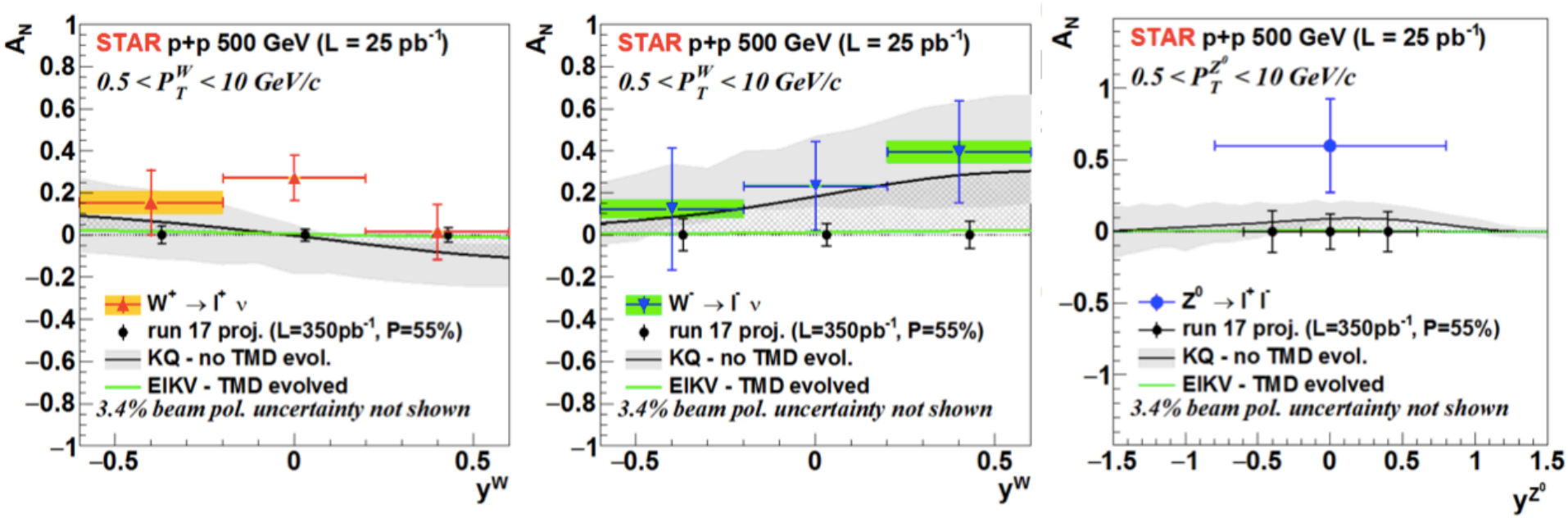


STAR, PRL 116 (2016)132301

- Sivers sign-change scenario preferred over no-sign change scenario.
- Precision measurements from run 17, x14 times in integrated luminosity!

Coming measurements of W/Z A_N at STAR

- STAR collected ~400 pb^{-1} transverse pp in 2017:



Goal:

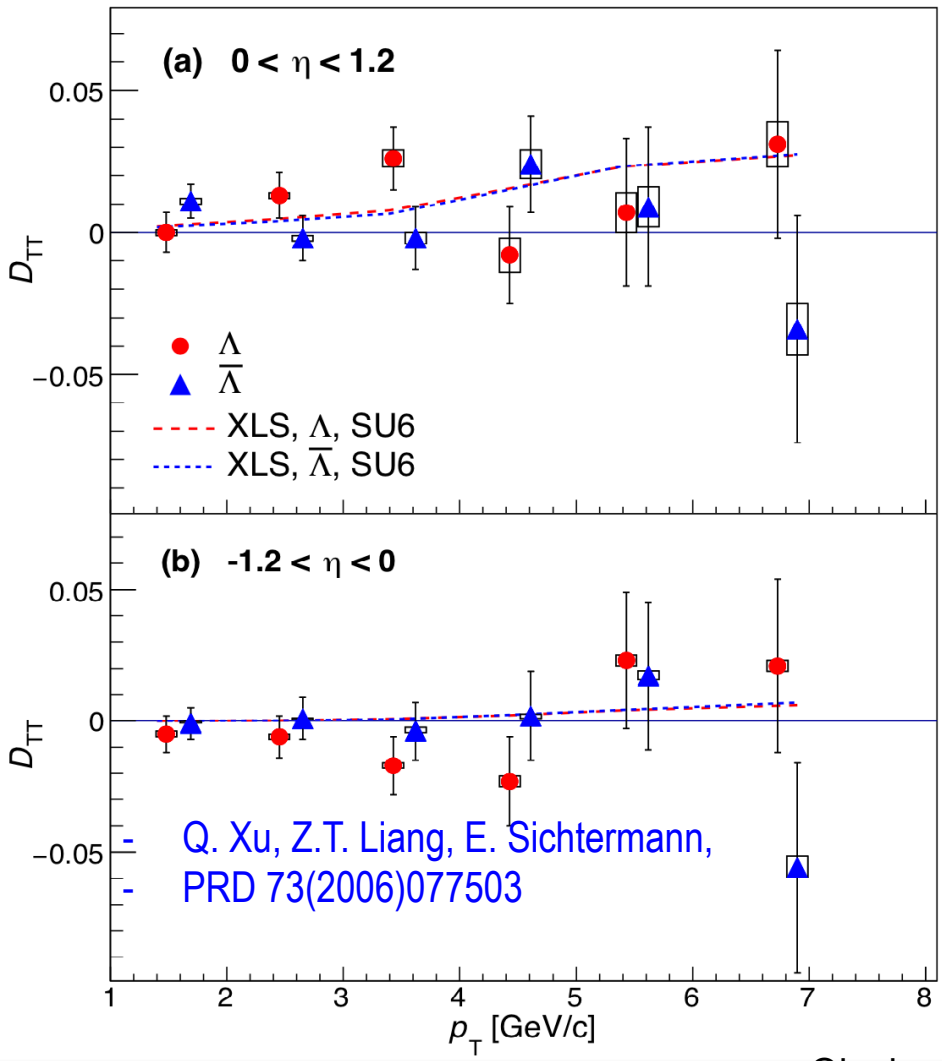
✓Constrain TMD evolution sea-quark Sivers function

✓Test sign-change if TMD-evolution suppression factor ~5 or less

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 $\Lambda/\bar{\Lambda}$ are consistent with a model prediction, also consistent with zero within uncertainty.

Future RHIC Spin in 2021+

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	1.1fb^{-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 η	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 Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Ecal + Hcal +Tracking
	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Ecal + Hcal +Tracking

Forward detector upgrade required

STAR → sPHENIX

EIC detector

- RHIC is the world's only polarized hadron hadron collider
- Unique physics opportunities in pp and pA

Summary & outlook

- Observation of positive gluon polarization from RHIC:

  - Probes with jets and pion, are providing important constraints on ΔG

    Global analysis indicates non-zero 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: Sivers sign-change

  - A_N for W,Z at STAR: 1st results obtained, run 17 to study Sivers sign change

- 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.

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谢谢！