Nucleon spin structure study at RHIC
-Overview & Outlook

徐庆华, 山东大学

华中师范大学粒子物理研究所论坛

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What is SPIN?

- As a fundamental observable of (sub)-atomic physics, "spin" was introduced by Goudsmit & Uhlenbeck (1925)

"This is a good idea. Your idea may be wrong, but since both of you are so young without any reputation, you would not loose anything by making a stupid mistake."

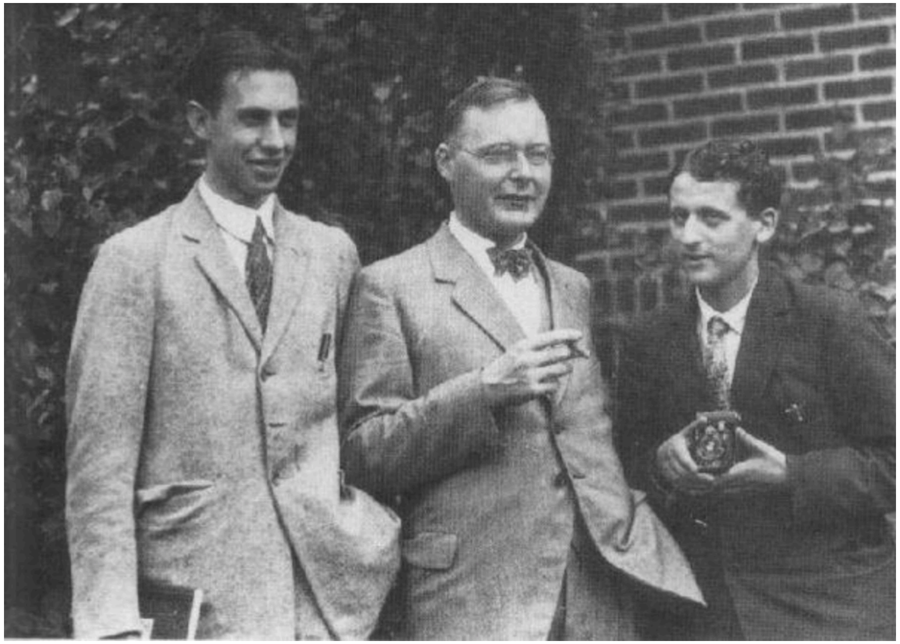
-Ehrenfest upon receiving the paper by Goudsmit & Uhlenbeck

- Original measurement (1922) by Stern & Gerlach
- In non-relativistic theory: operator $\boldsymbol{S}_i$:

$$\hat{\mathbf{s}} \equiv (\hat{s}_x, \hat{s}_y, \hat{s}_z)$$

$$[\hat{s}_j, \hat{s}_k] = i\epsilon_{jkl}\hat{s}_l$$

- In relativistic theory, spin is a consequence of space-time symmetry!

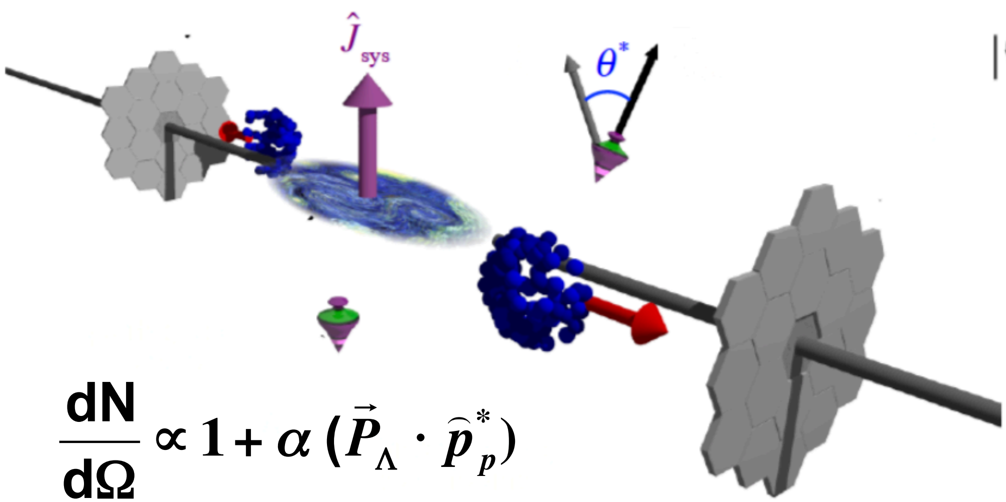


Uhlenbeck , Ehrenfest, Goudsmit

Λ Global polarization in heavy ion collisions

- Λ global polarization observed at STAR (Nature cover) , as predicted by Z.T. Liang and X.N. Wang in 2004.

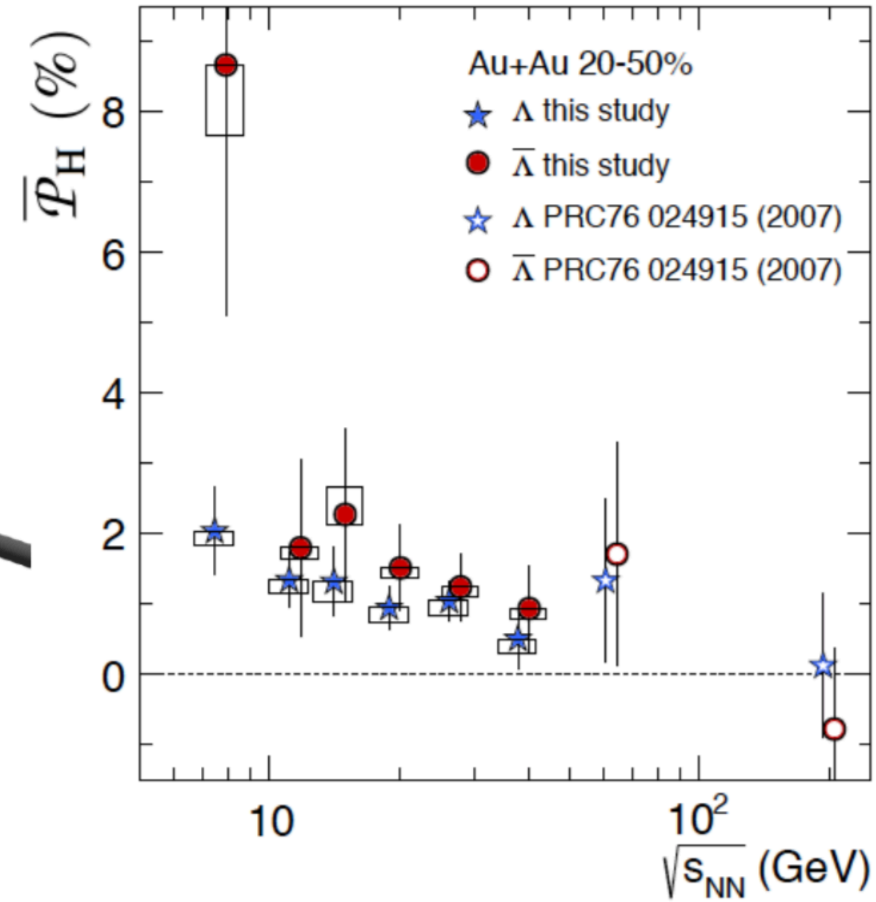
$$\cos\theta^* \propto \vec{P}_\Lambda \cdot \vec{p}_p^{\,*}$$



$$\frac{\mathbf{dN}}{\mathbf{d\Omega}} \propto 1 + \alpha\,(\vec{P}_\Lambda \cdot \hat{p}_p^{\,*})$$

非零角动量可以转化成流体涡旋，
并极化超子

STAR, Nature 548(2017)62



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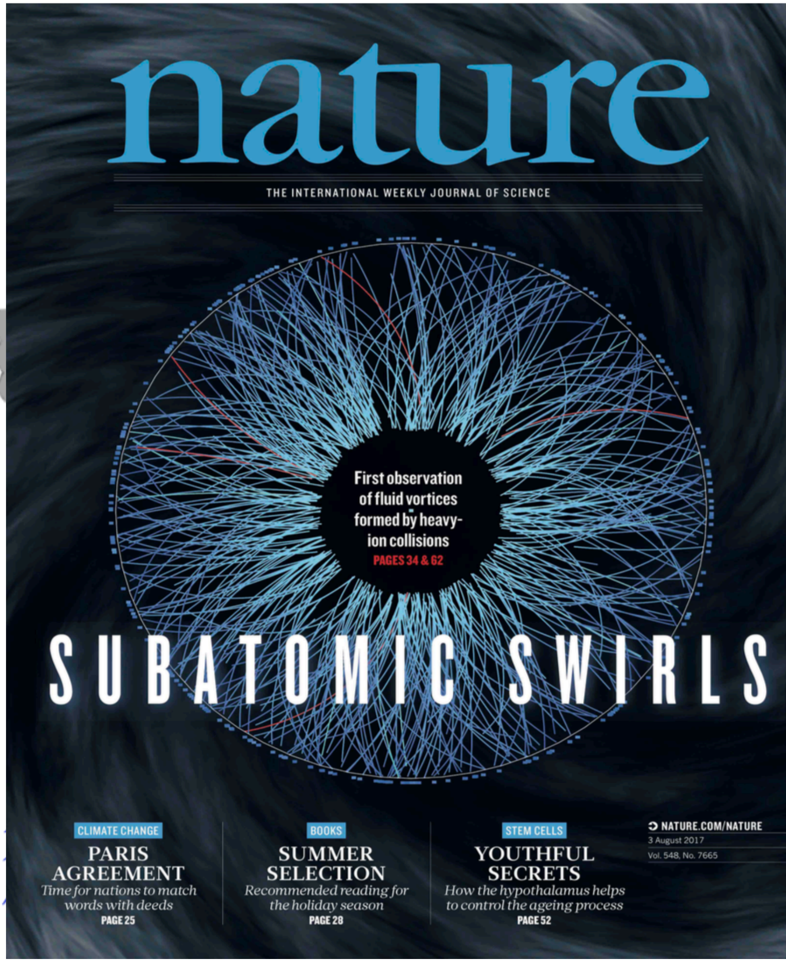
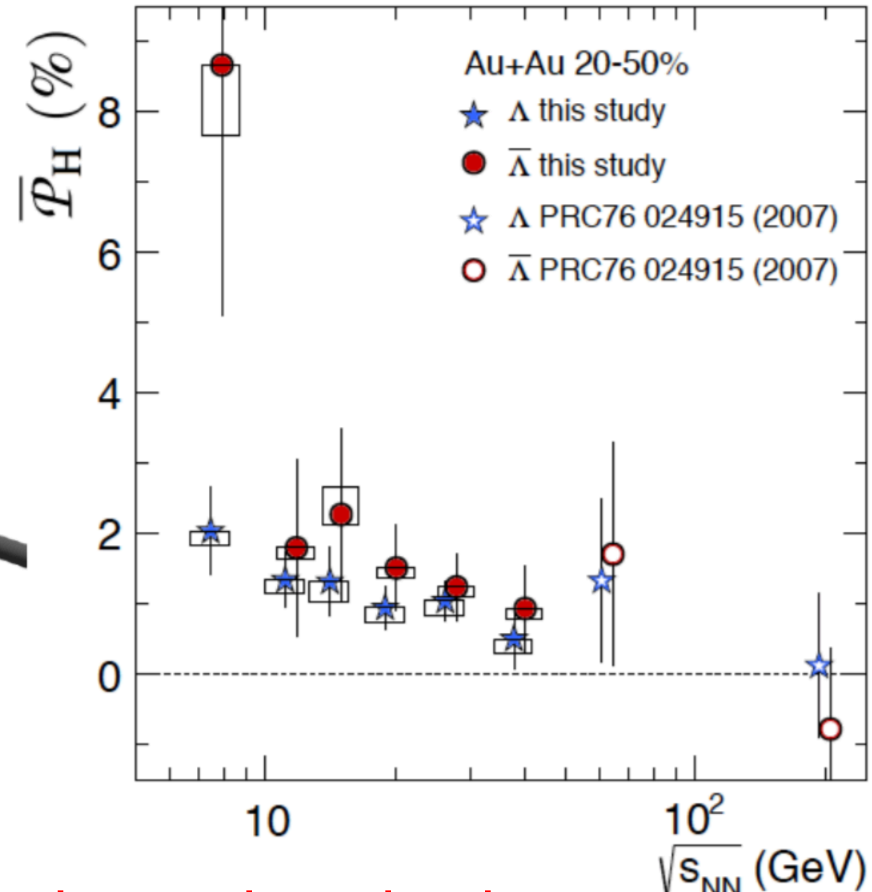


非零
并极

STAR, Nature 548(2017)62



-An example you may be familiar in heavy ion physics, but I will talk about the proton spin today

Spin structure of nucleon

In the naive Quark Model, the nucleon is made of three quarks - p(uud)
The quark spins make up the nucleon spin, since the quarks are in the s-orbit:

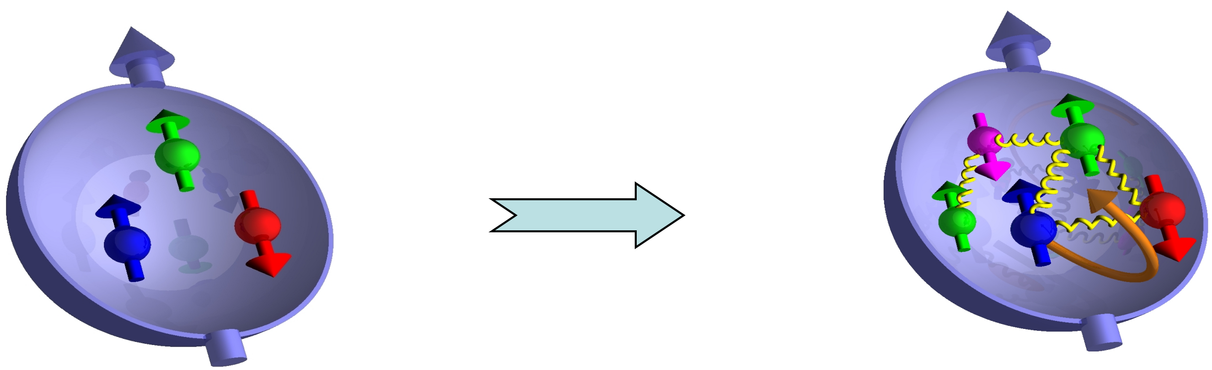
$\Delta\Sigma = 1$

$$\begin{cases} \left|p^{\uparrow}\right\rangle = \sqrt{\tfrac{2}{3}}u^{\uparrow}u^{\uparrow}d^{\downarrow} - \sqrt{\tfrac{1}{3}}\sqrt{\tfrac{1}{2}}(u^{\uparrow}u^{\downarrow} + u^{\downarrow}u^{\uparrow})d^{\uparrow} \\ \Delta U = \frac{4}{3},\ \Delta D = -\frac{1}{3} \end{cases}$$

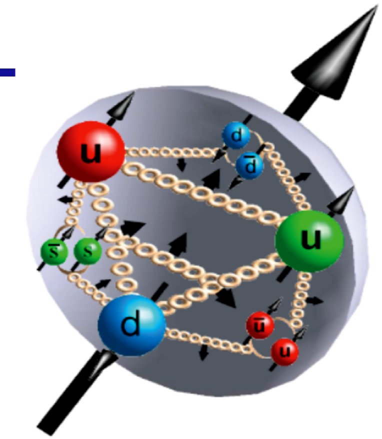
1974: With Parton Model (sea quark, gluon) but assumes strange quarks carry no net polarization (Ellis-Jaffe sum rule):

$\Delta\Sigma \approx 0.6$

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



Spin structure of nucleon



- Spin sum rule (longitudinal case):

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

Quark spin,
Best known
(~30%)-DIS

Gluon spin,
Non-zero,
RHIC

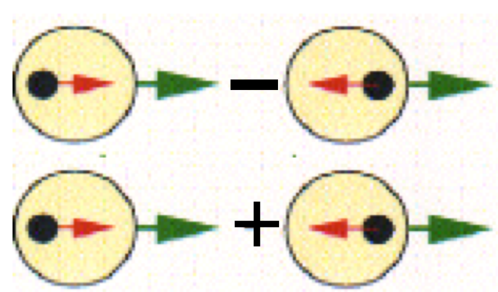
Orbital Angular Momenta
Little known

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

- Polarized parton densities:

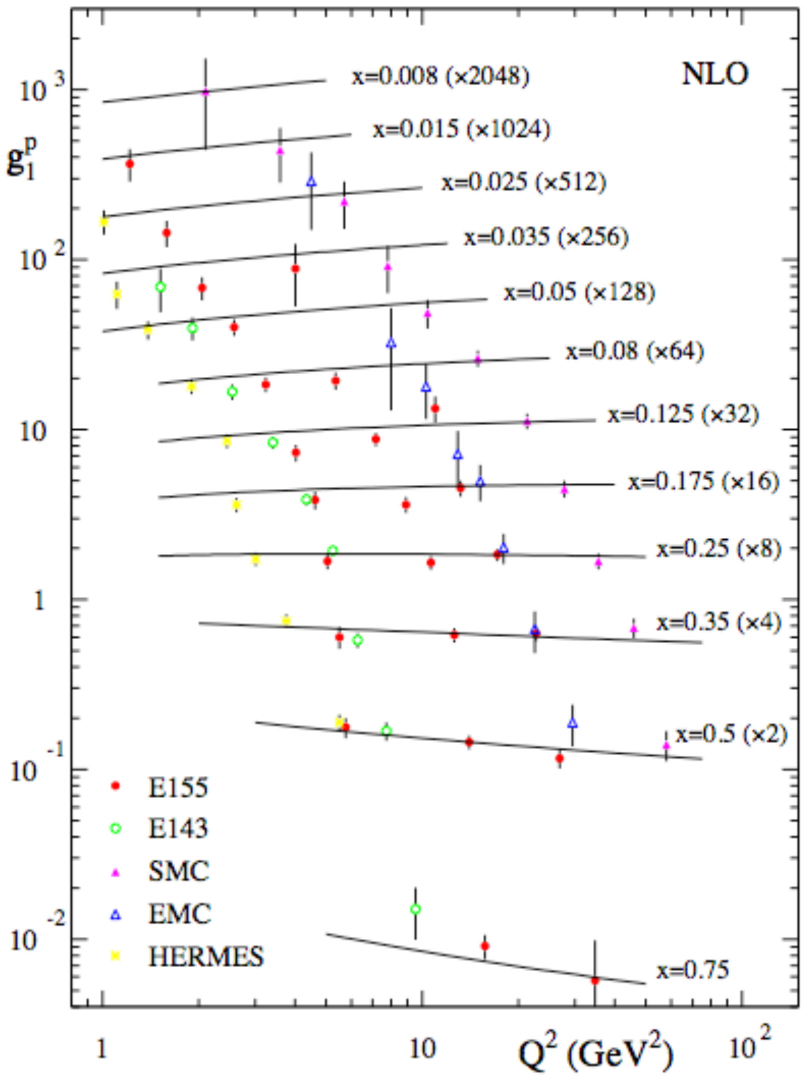
$$\Delta q(x,Q^2) = q^+(x,Q^2) - q^-(x,Q^2)$$

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



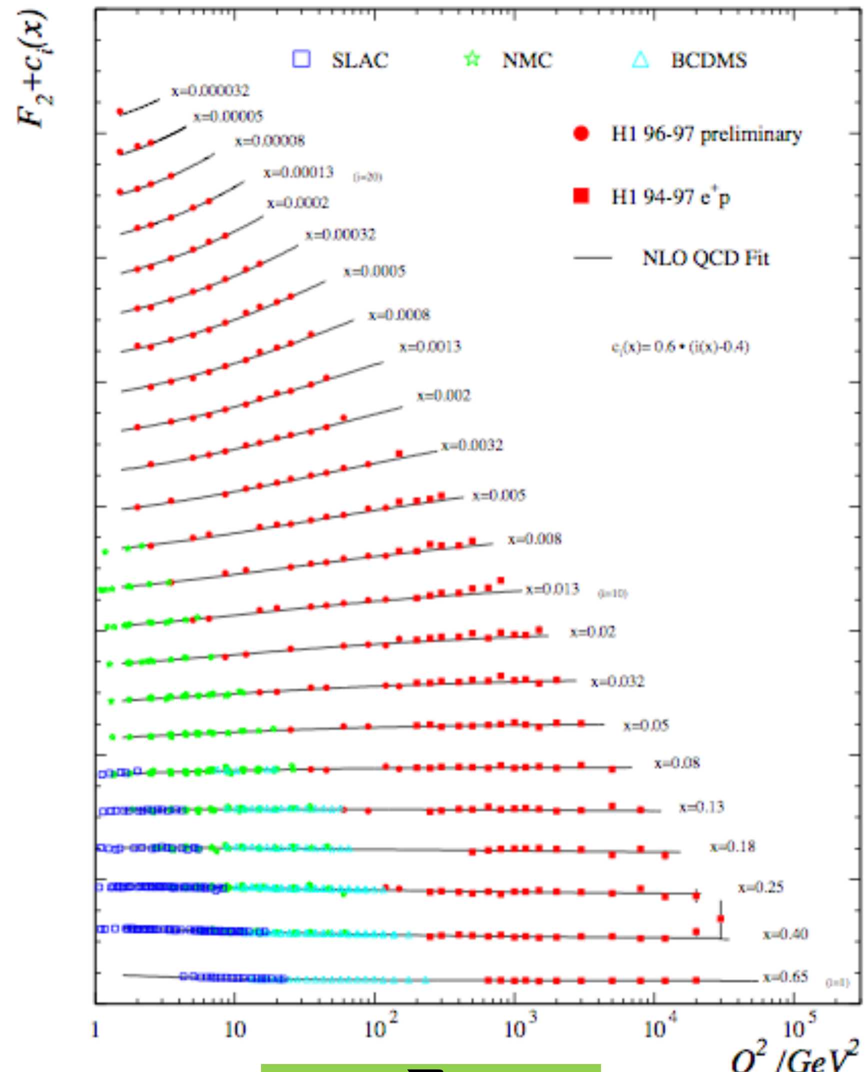
World data on pol. and unpol. deep-inelastic scattering

polarized



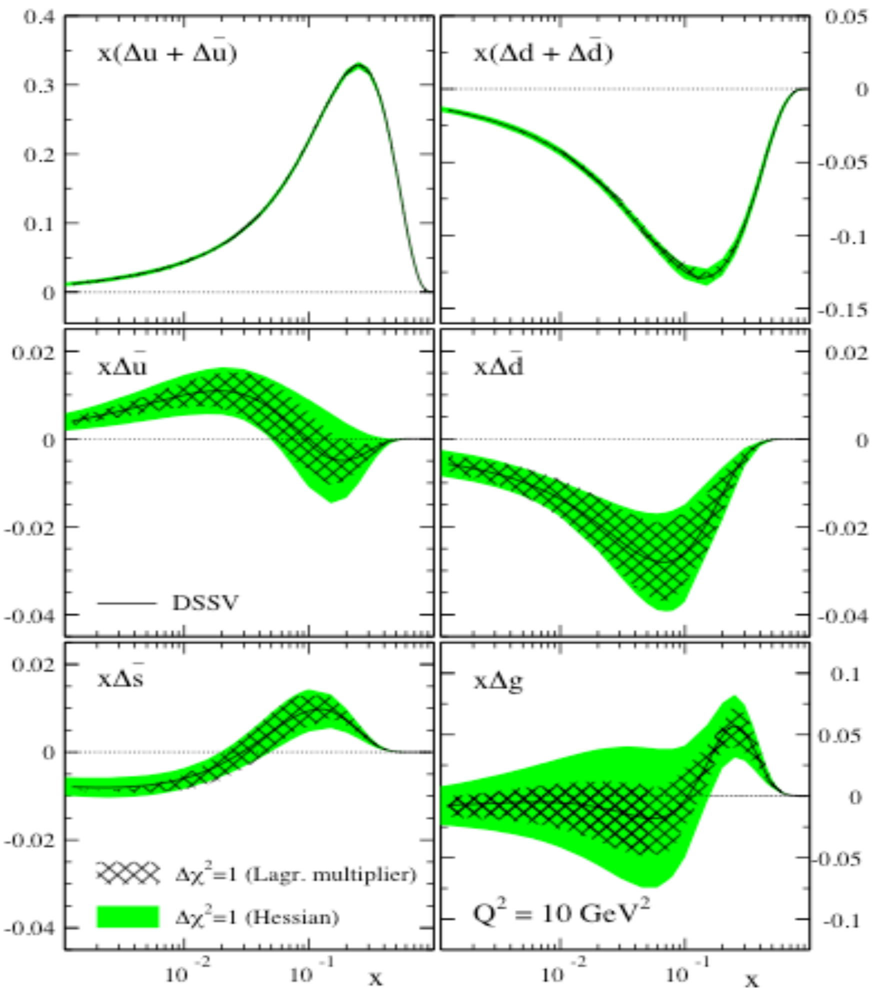
$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

unpolarized

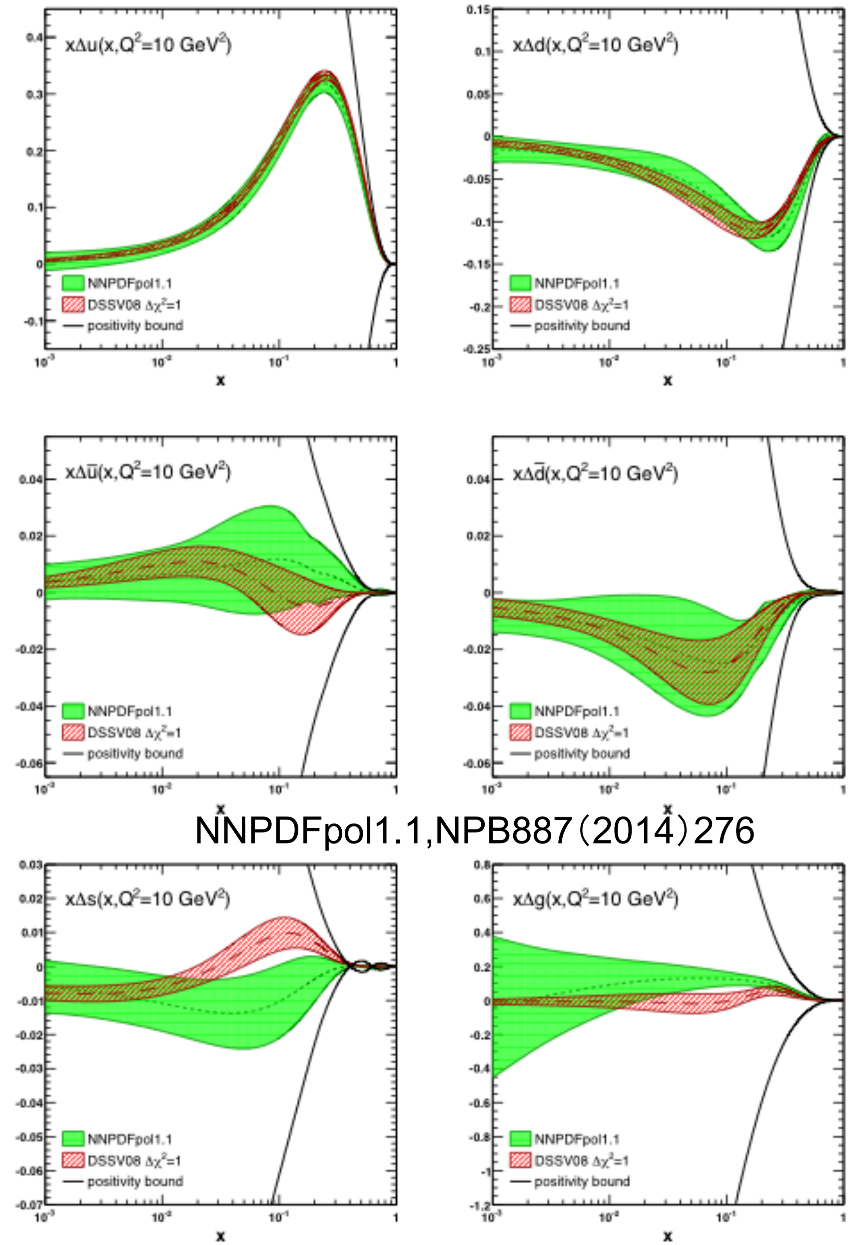


$$F_2(x) = \sum_i e_i^2 x q_i(x)$$

Detailed knowledge on Δq(x), Δg(x)- global fit using DIS and pp data



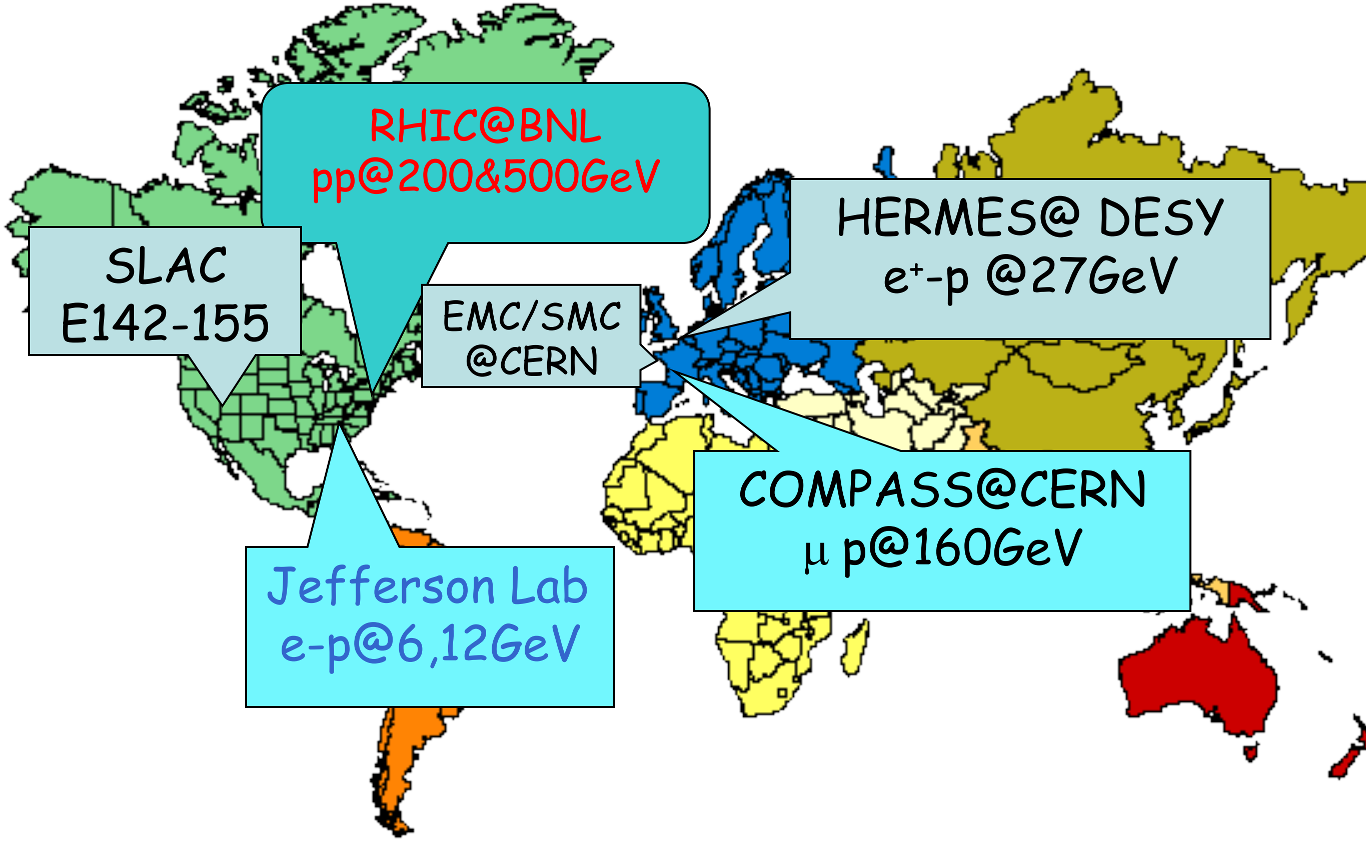
D. De Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRD80(2009)



NNPDFpol1.1,NPB887（2014）276

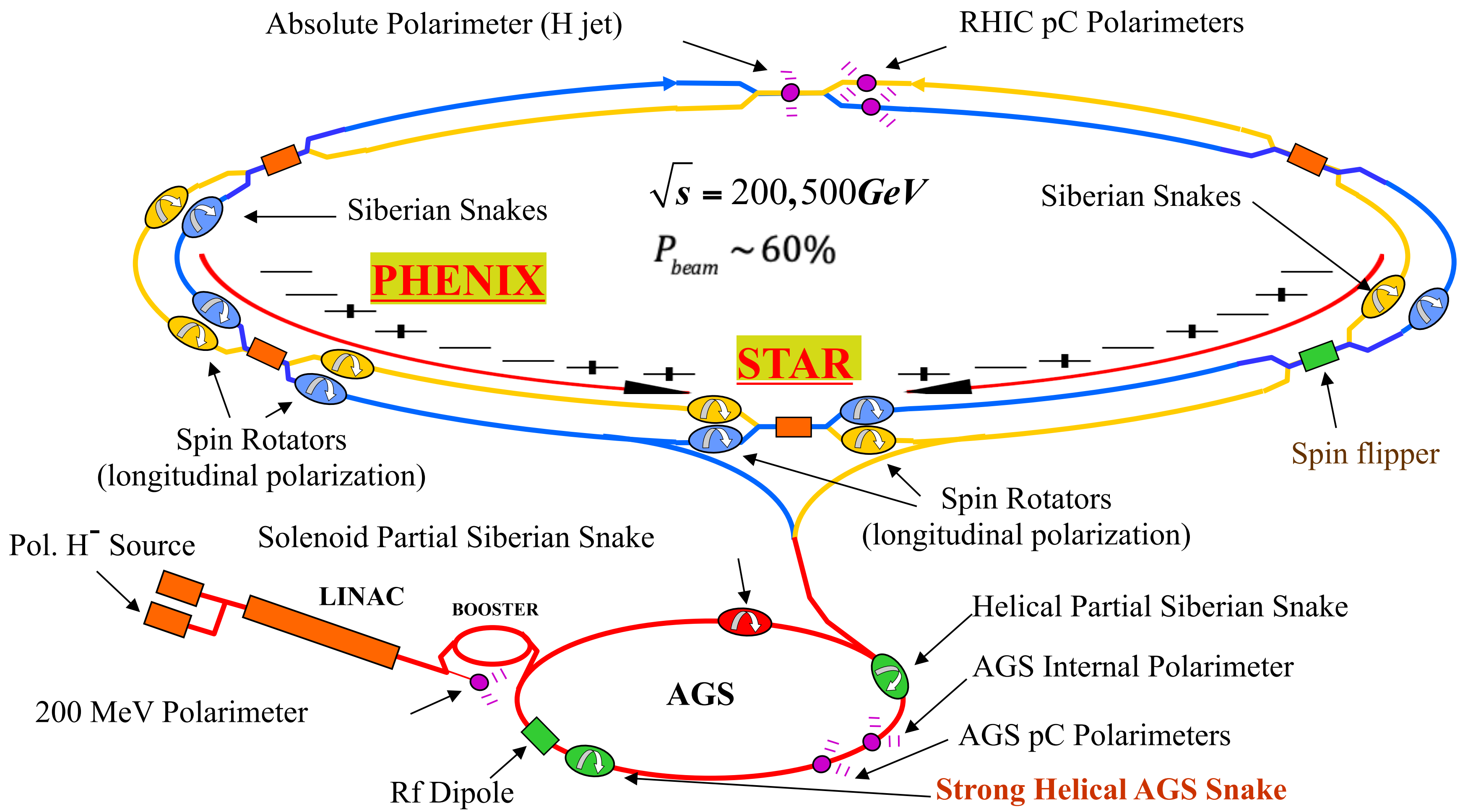
World efforts for spin physics

- Finished experiments: SLAC, EMC, SMC, HERMES
- Current running
  - Lepton-nucleon scattering: COMPASS, JLab
  - Polarized proton-proton scattering, RHIC
- Future facilities
  - **EIC (US, BNL)**
  - EicC (China)
  - JPARC (Japan)
  - GSI-FAIR (Germany)
  - NICA (Russia)



-Courtesy of Feng Yuan

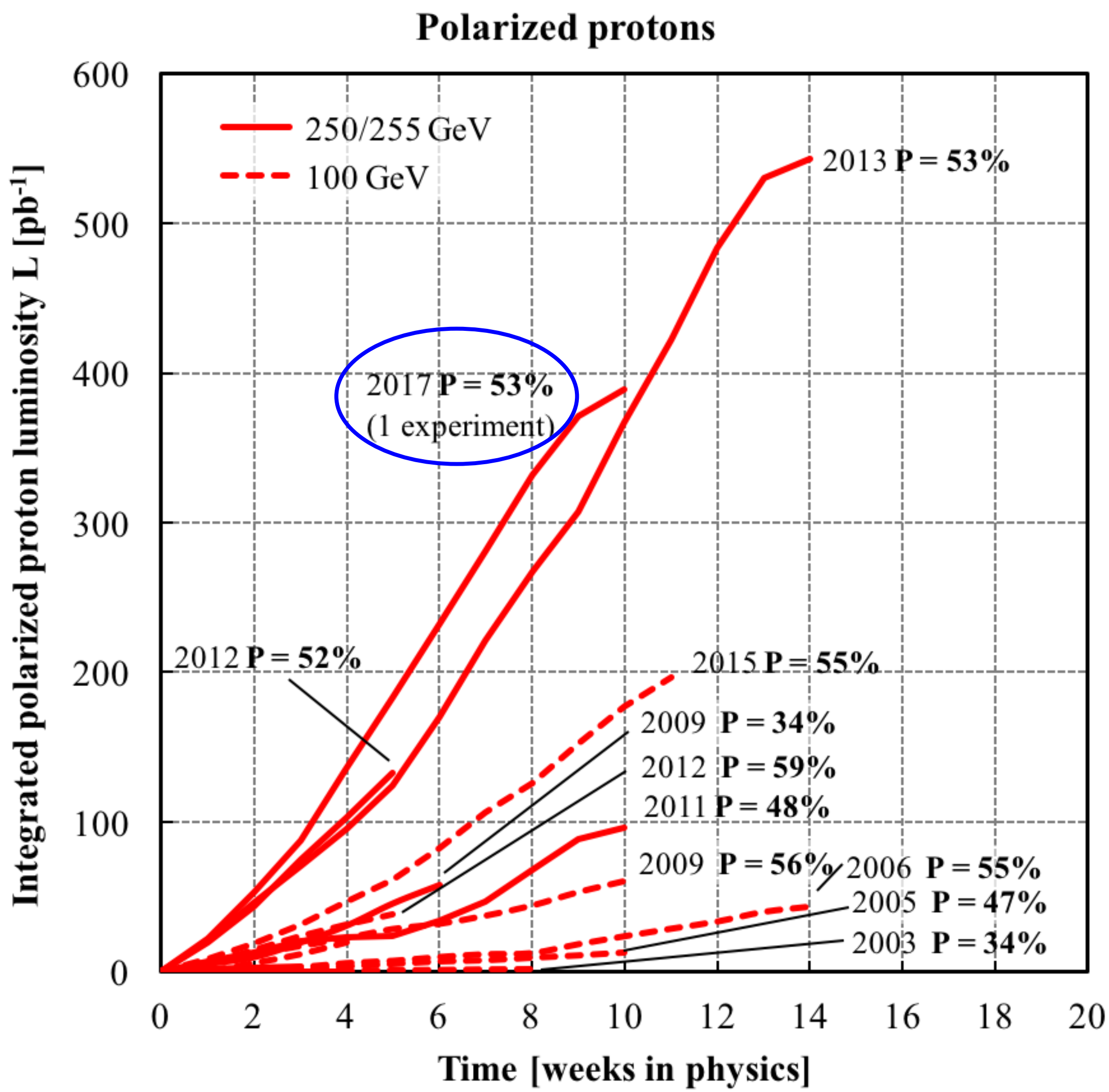
RHIC- 1st polarized proton-proton collider



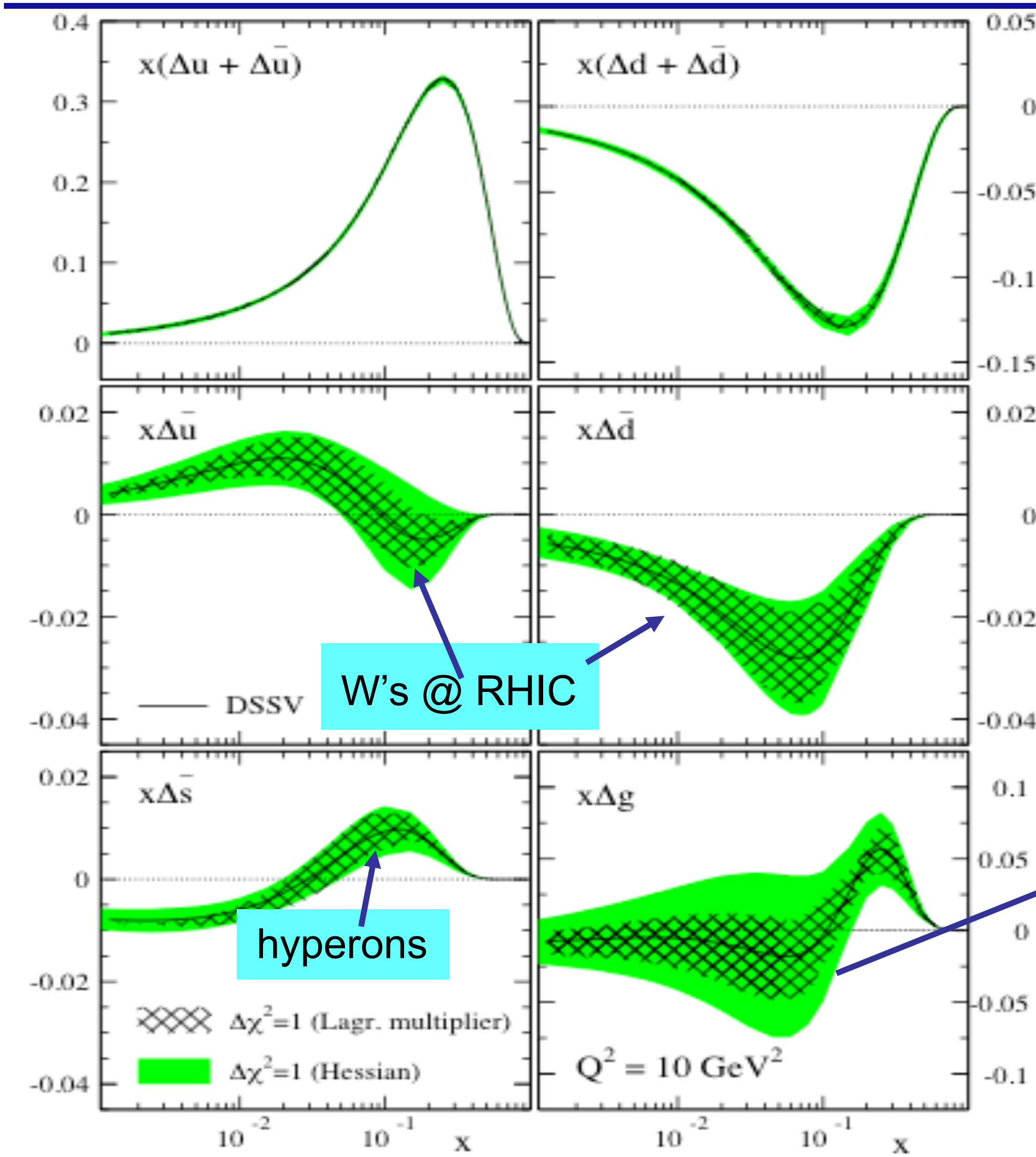
- World's only polarized hadron-hadron collider: longitudinal & transverse
- Spin direction changes from bunch to bunch
- Two main experiments: PHENIX (till 2016) & STAR

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.



$\Delta q(x)$, $\Delta g(x)$- 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, Non-zero, RHIC

Orbital Angular Momenta Little known

RHIC (jet, π^0)
200 GeV, 500 GeV

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

RHIC spin program

- Experimental aspects: RHIC
- Recent highlights on RHIC/STAR spin:
  - ✓ Gluon polarization (Jet, π^0 production): gluon polarization Δg
  - ✓ Quark/Anti-quark polarization (W/Z production): sea quark Δq
  - ✓ Hyperon spin transfer : strange quark polarization
  - ✓ Transverse spin asymmetry (Hadron production): Collins & Sivers
  - ✓ Transverse spin asymmetry (W/Z production): Sivers function

-current focus of SDU group

- Upgrade plans for cold-QCD physics in 2021+ at RHIC

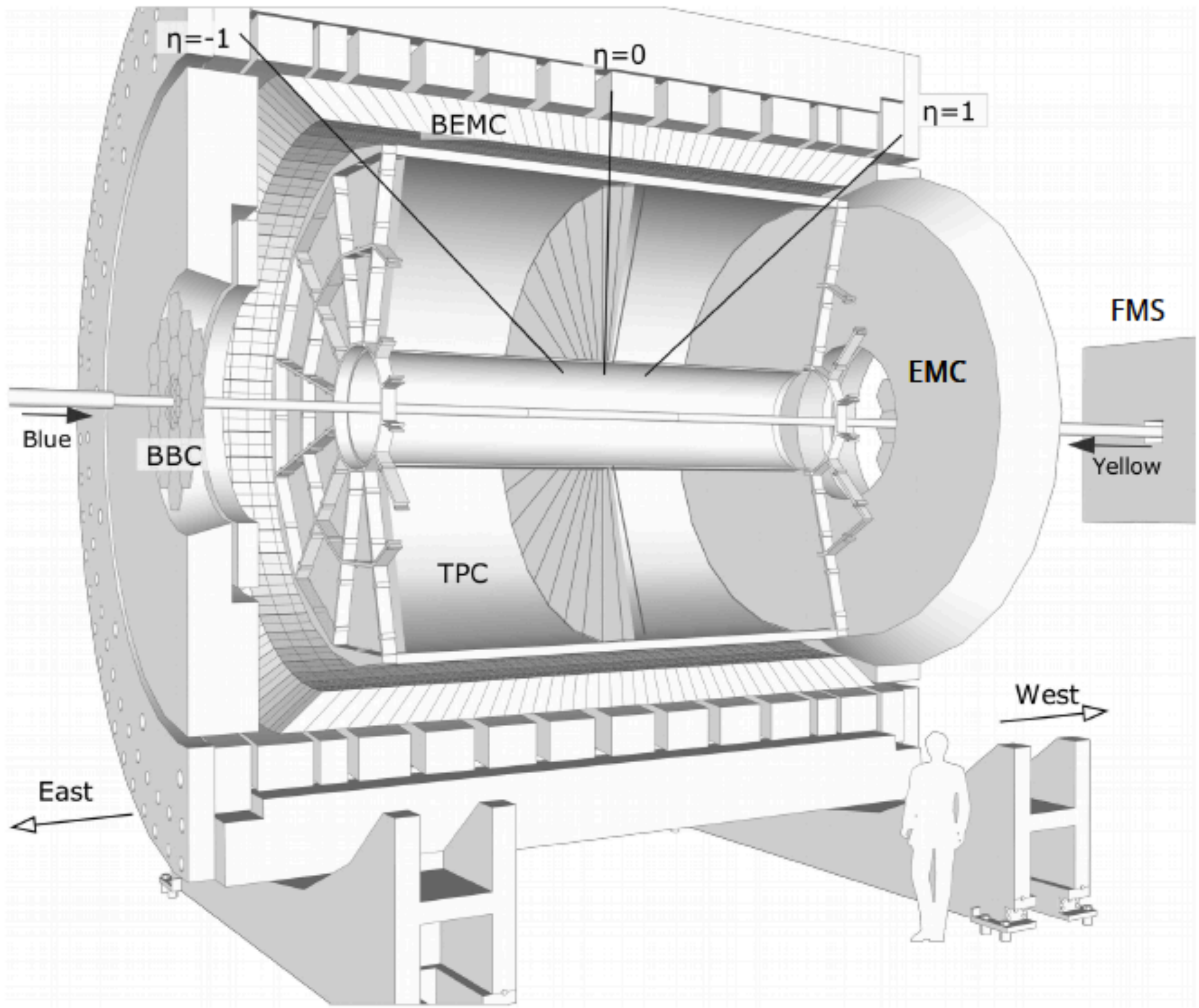
STAR - Solenoid Tracker At RHIC

Magnet
- 0.5 T Solenoid

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

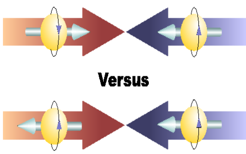
Central Tracking
- Large-volume TPC
  - $|\eta| < 1.3$

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



Accessing Δg(x) in pp collision

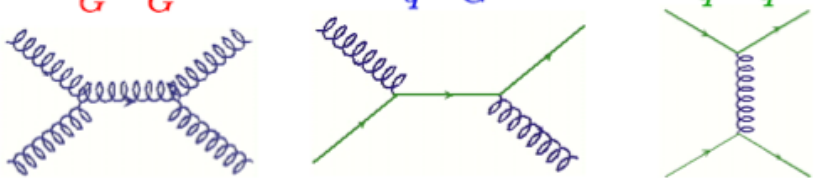
- Longitudinal spin asymmetry:



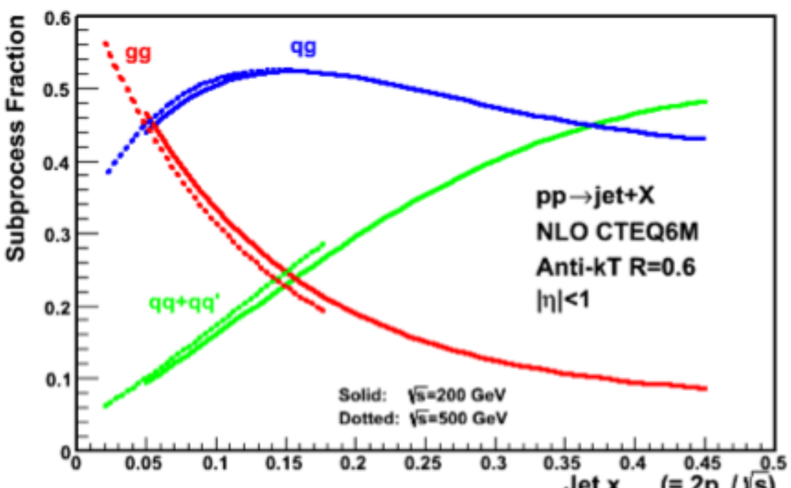
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \cdot \hat{a}_{LL}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}$$

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

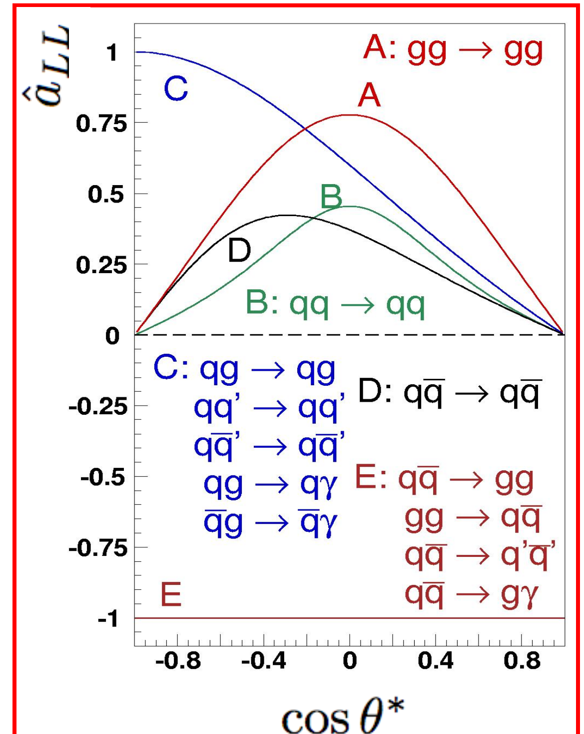
$\frac{\Delta G}{G} \frac{\Delta G}{G}$ $\frac{\Delta q}{q} \frac{\Delta G}{G}$ $\frac{\Delta q}{q} \frac{\Delta q}{q}$



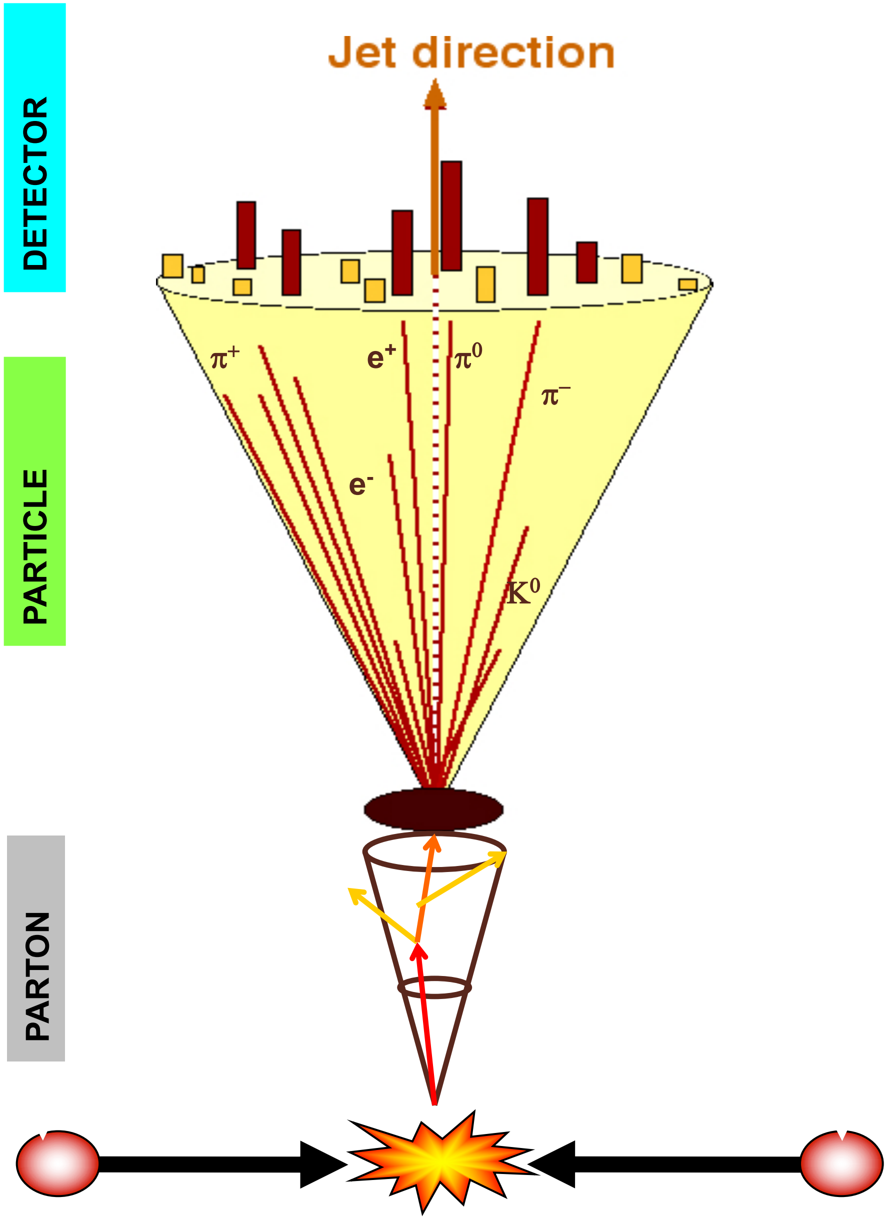
- Partonic fraction for jet/π^0 production:



Mukherjee and Vogelsang, PRD.86.094009



Jet Reconstruction in pp at STAR



1) Midpoint cone algorithm
(Adapted from Tevatron II - hep-ex/0005012)

- Seed energy E_T^{seed} = 0.5 GeV
- Cone radius $R = \sqrt{\Delta\eta^2+\Delta\varphi^2} = 0.7$
- Split/merge fraction f = 0.5

2) Anti-K_T algorithm
([arXiv:0802.1189])

- Successive Combination
- Radius R = 0.6

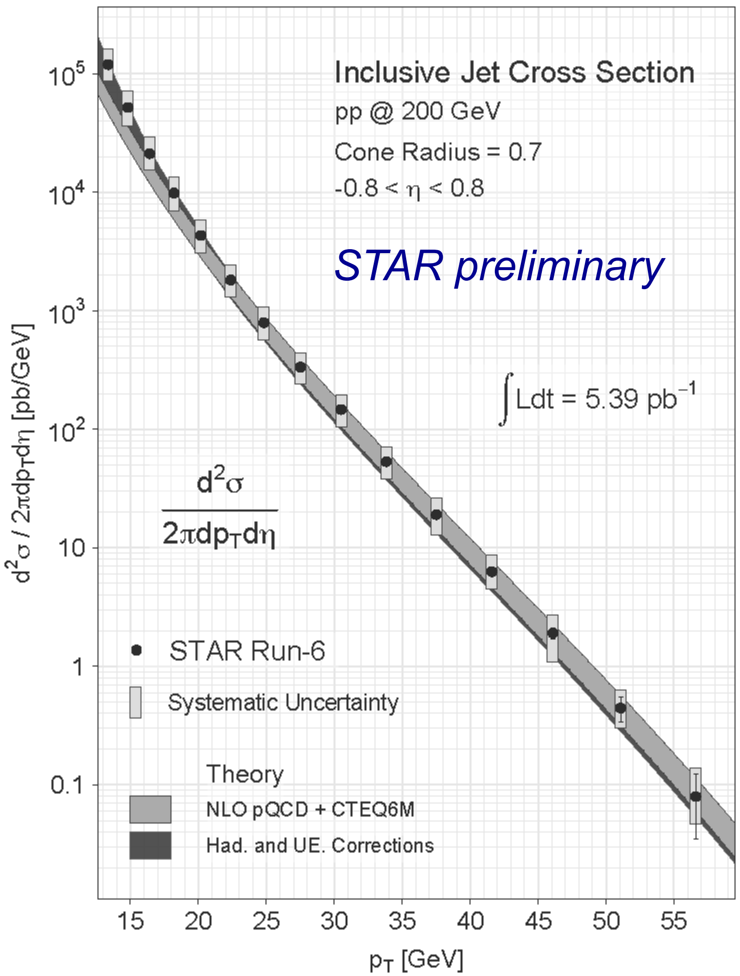
$$d_{ij} = \min\left(\frac{1}{k_{Ti}^2}, \frac{1}{k_{Tj}^2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = \frac{1}{k_{Ti}^2}$$

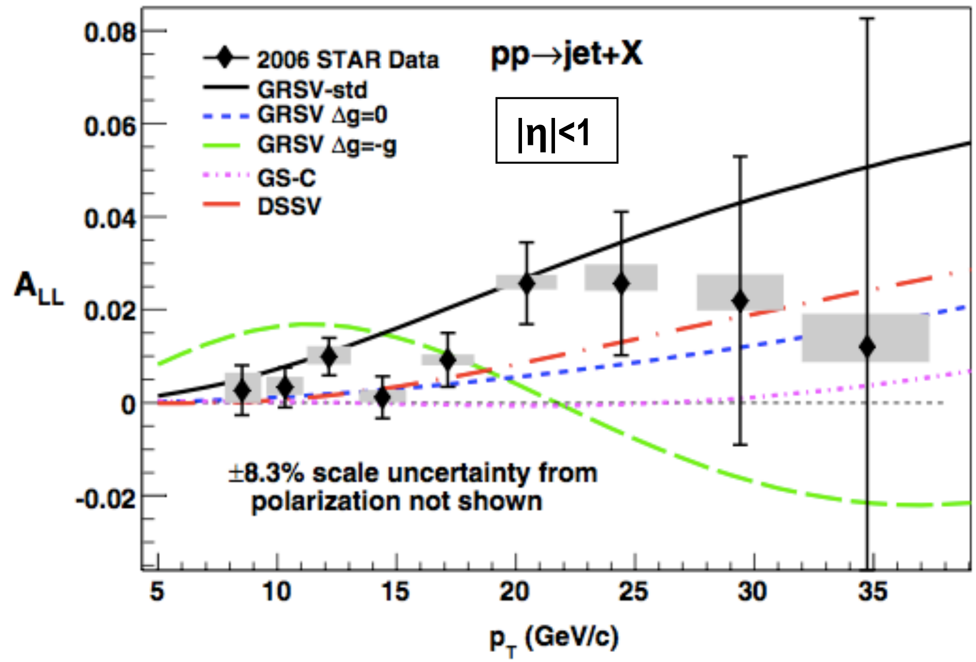
1) was used in previous years, now 2) is widely used.

STAR Run6 results on jet x-section and A_{LL}

- Cross section well described by NLO pQCD+Hadronization



STAR, PRD86, 32006(2012)



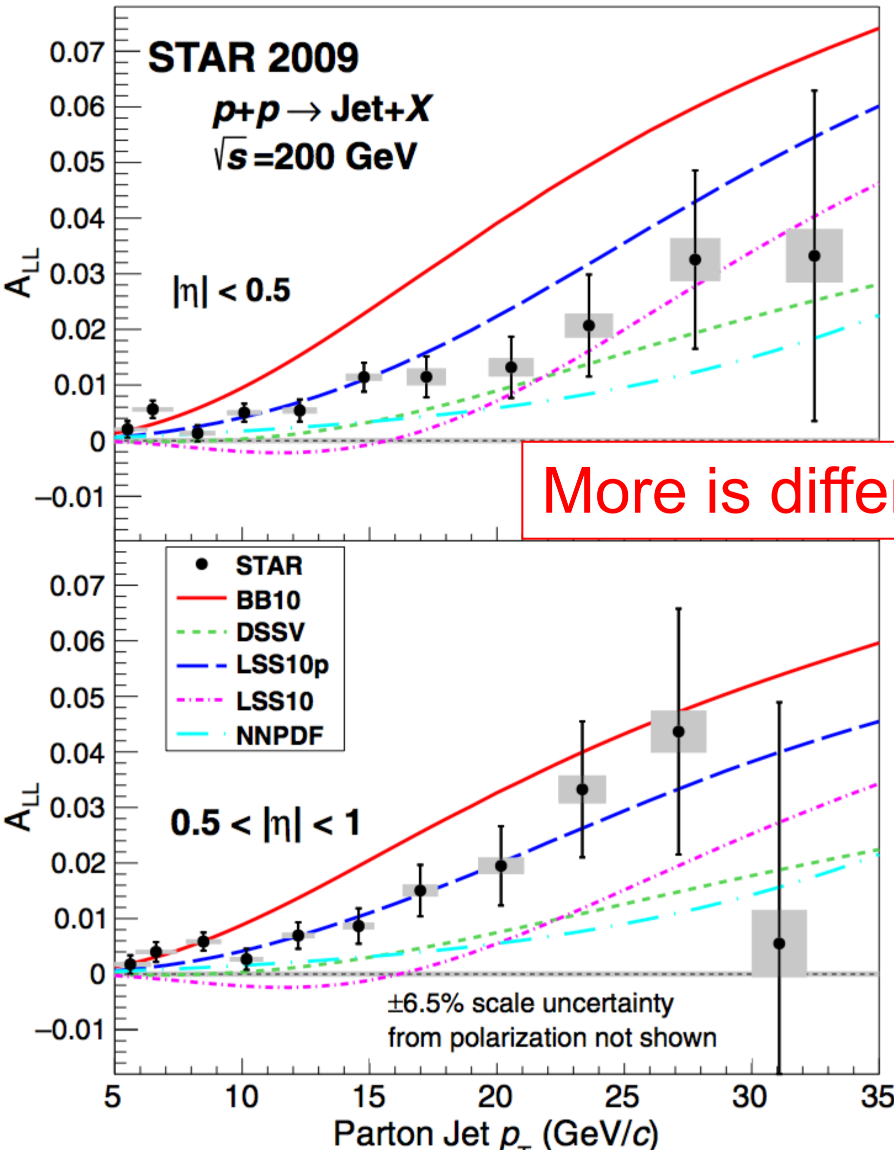
- STAR run6 data rule out several previous models of gluon polarization, and included in the DSSV global analysis together with PHENIX π^0 results.

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

-arXiv:1304.0079

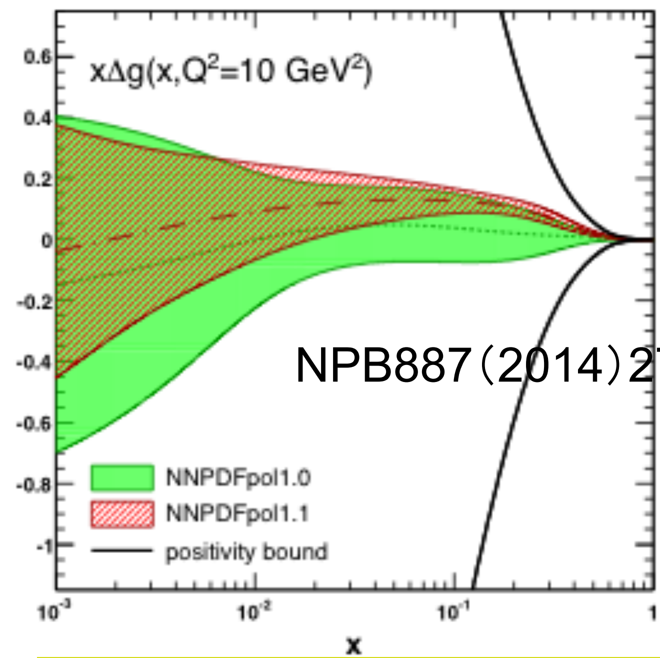
STAR inclusive jet A_{LL} from run9

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



More is different!

- 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:

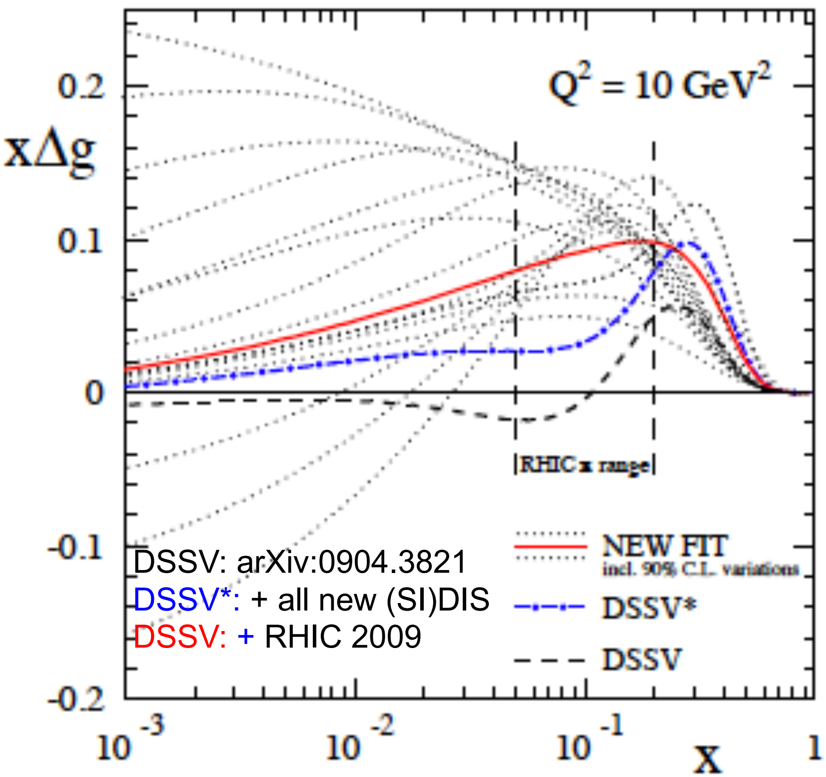


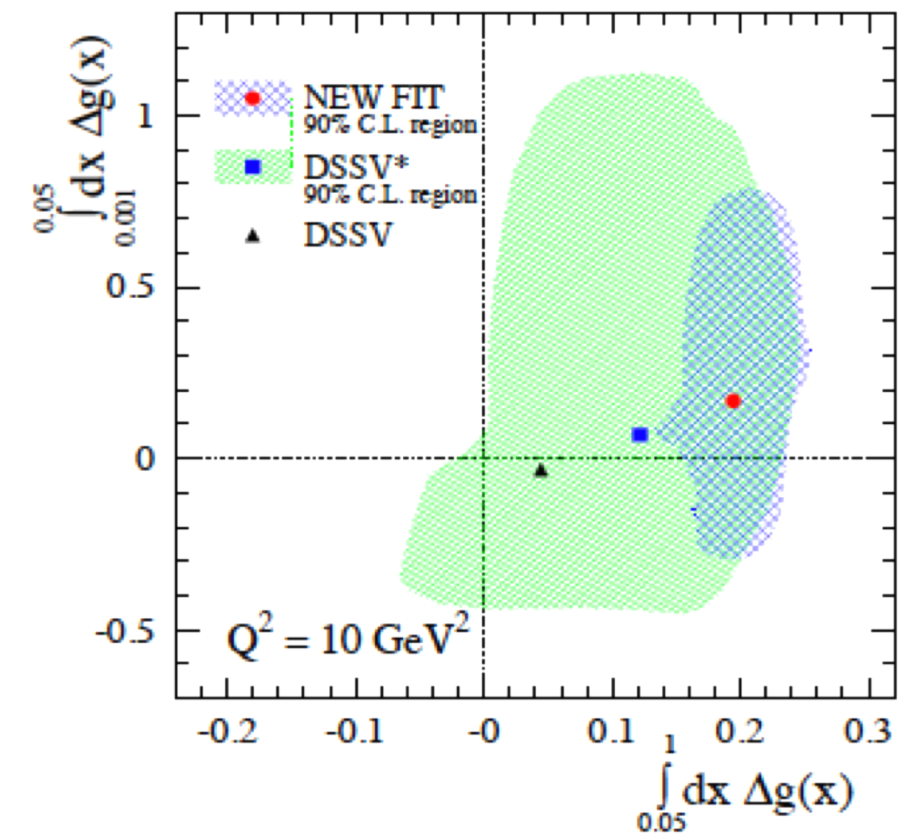
NPB887 (2014) 276

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

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

DSSV, PRL113,12001(2014)





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

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

-> higher energy, forward di-jets

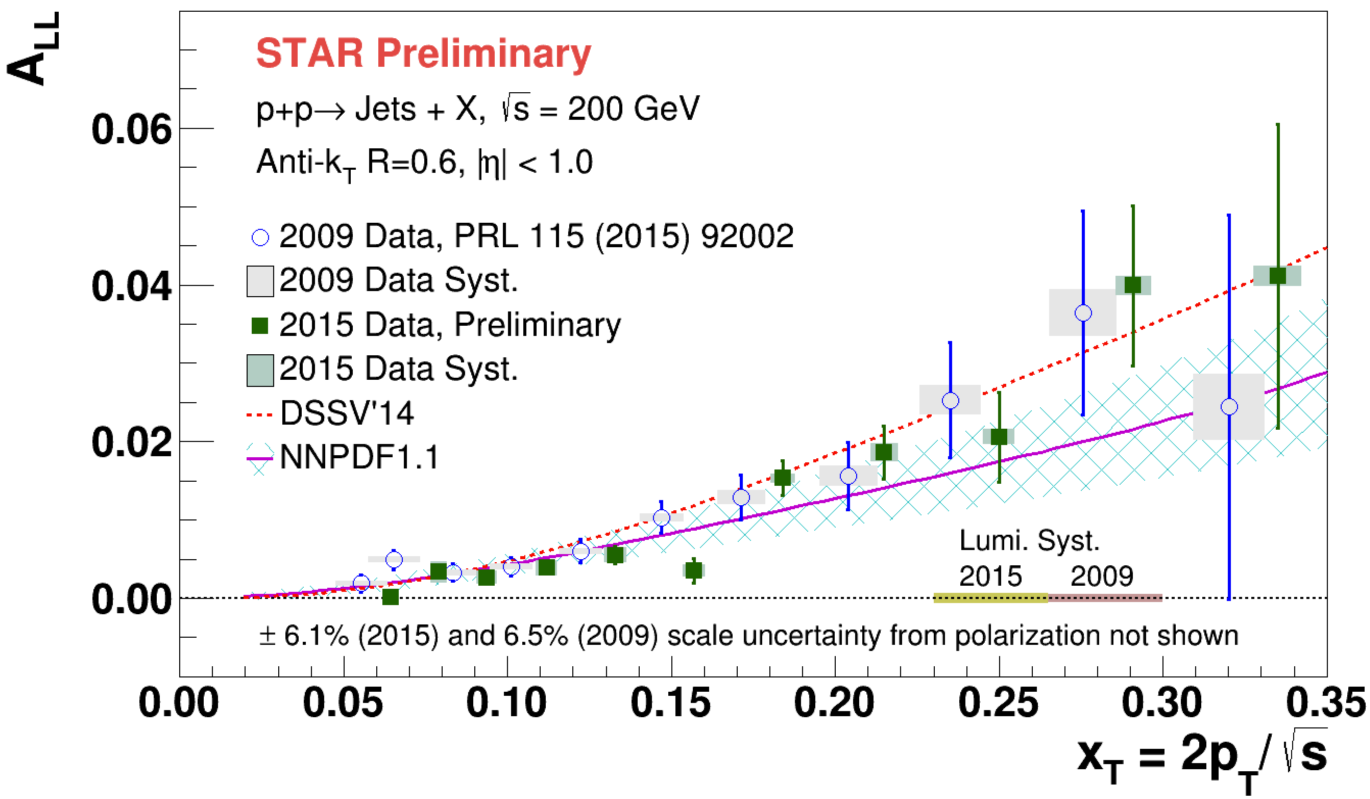
- 1st Lattice calculation:

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

χQCD, PRL118,102001(2017)

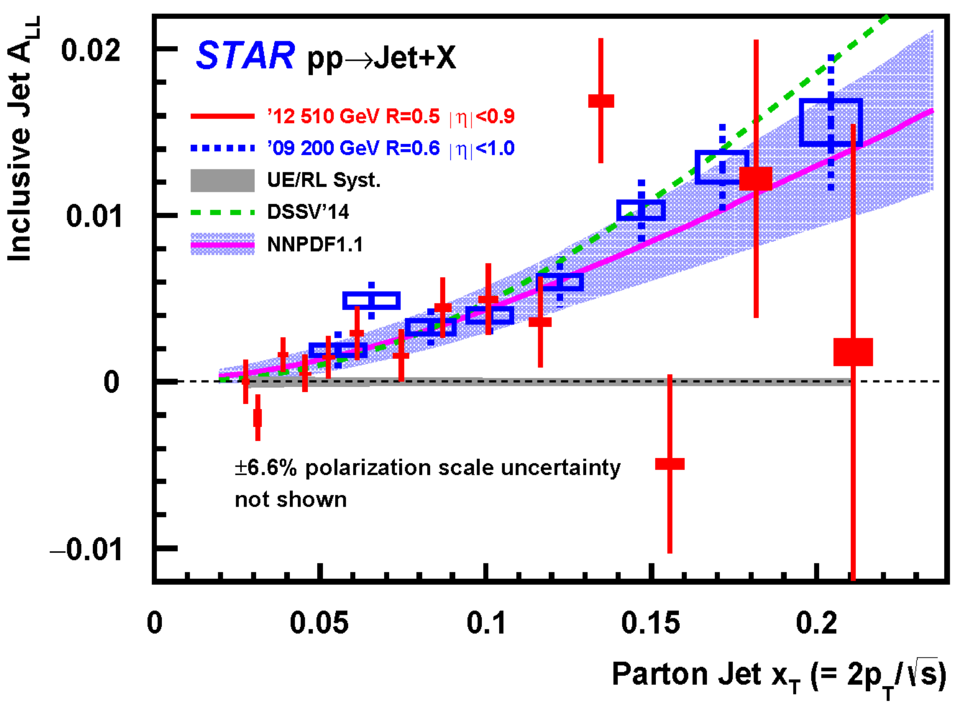
New results on jet A_{LL} from 2015 data

- New result on A_{LL} of inclusive jet production from 2015 data at 200 GeV.
- Consistent with 2009 data, twice in figure-of-merit (LP4) with improved systematic uncertainty
- Provide more constraints on gluon polarization with global analysis



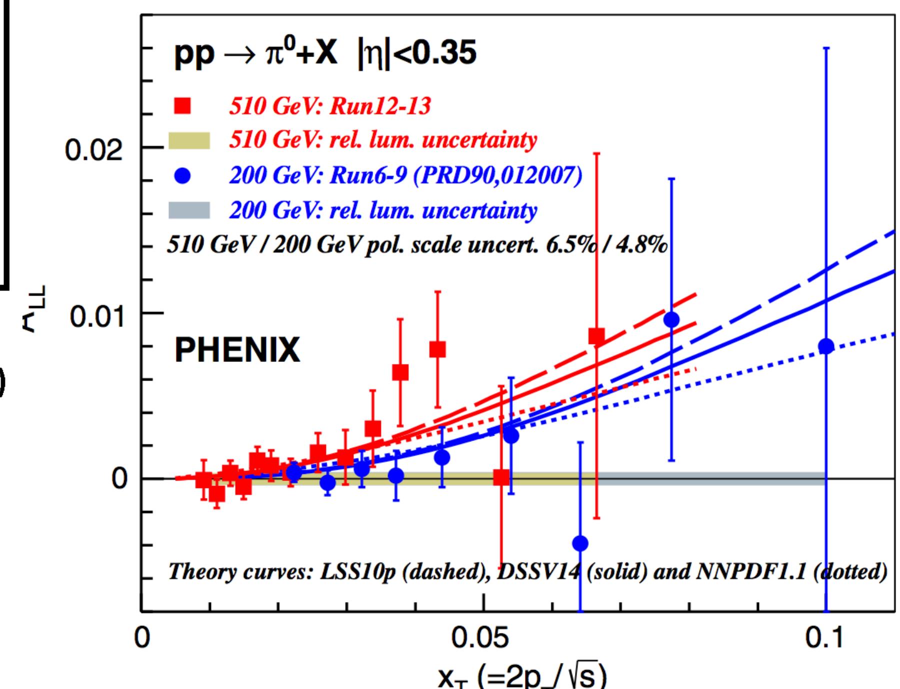
A_{LL} results on jet/π^0 at 510 GeV from RHIC

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



STAR, PRD100,52005(2019)

- ◻ 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)

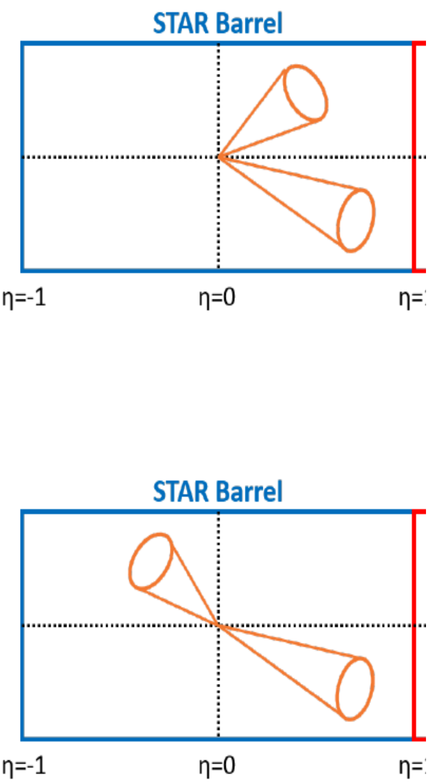
- ◻ PHENIX π^0 A_{LL} at 510 GeV, which is also sensitive to Δg in small x region

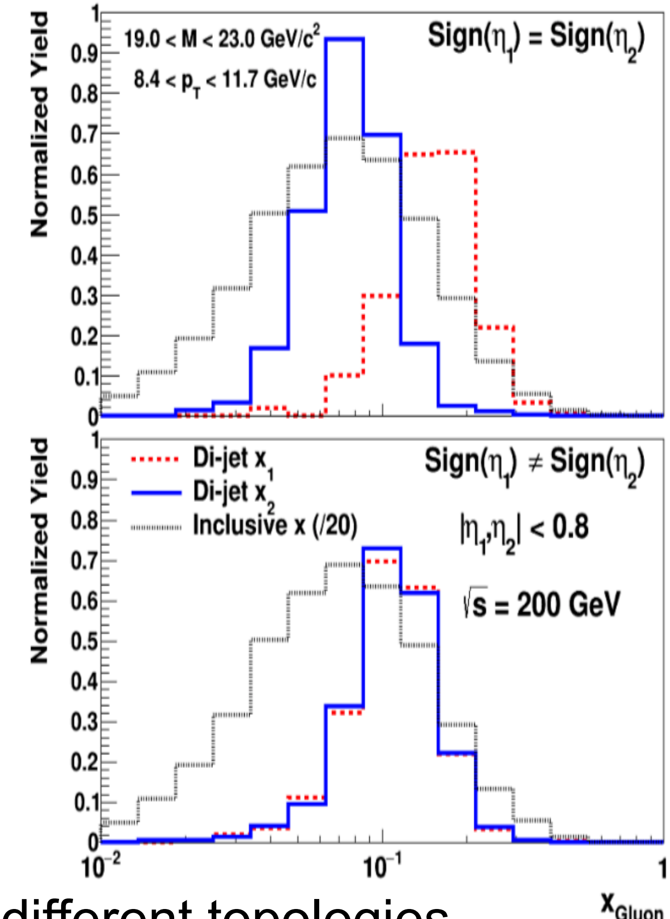
Central di-jet A_{LL} at 200 GeV at STAR

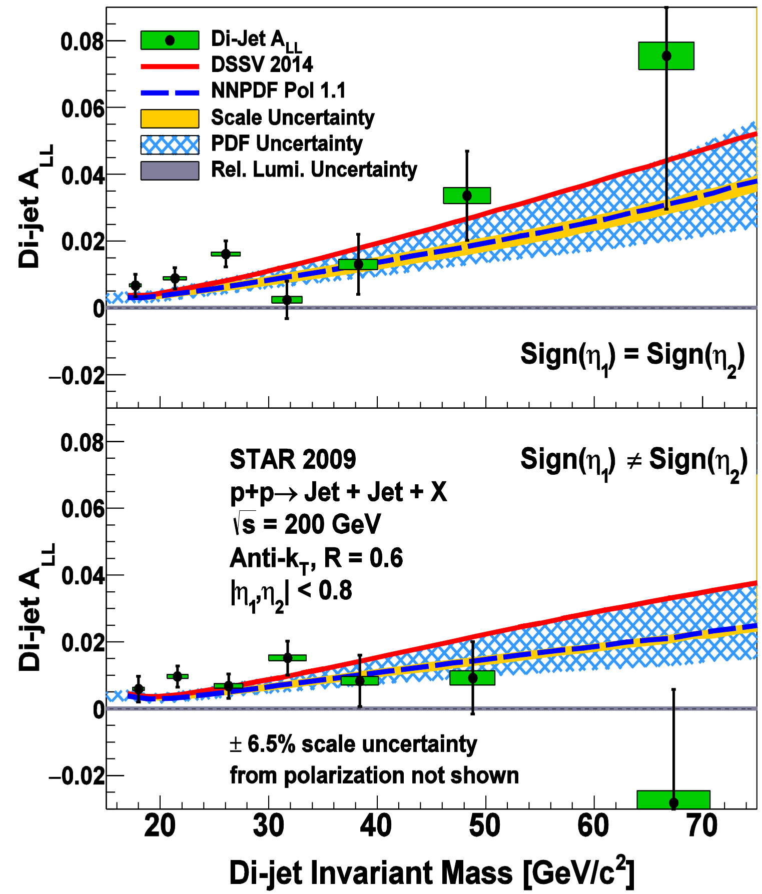
- Access to partonic kinematics via di-jet:

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

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







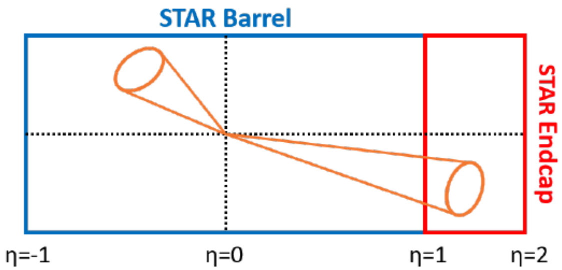
- Di-jet A_{LL} for different topologies, allowing for constraints on the shape of $\Delta g(x)$

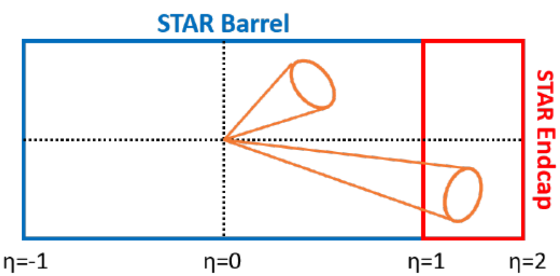
STAR, PRD95,071103(2017)

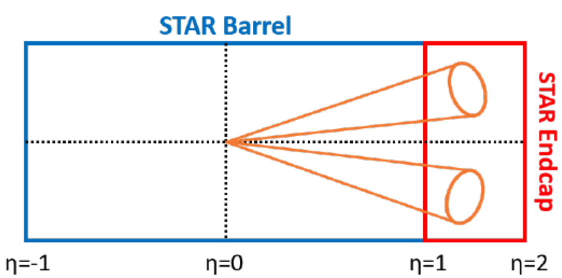
Central-forward di-jet at 200 GeV at STAR

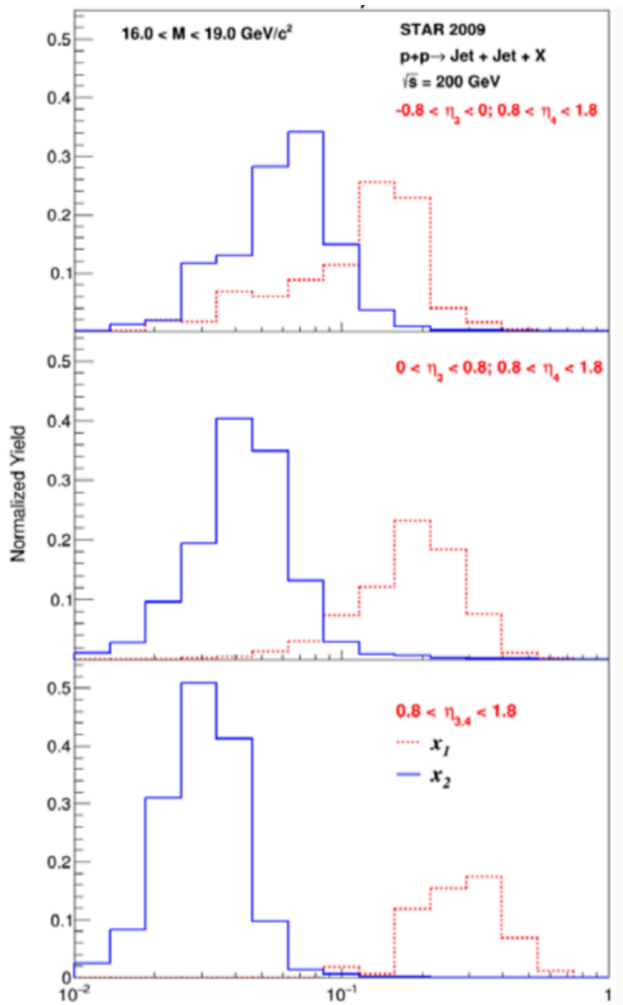
STAR, PRD98,032011(2018)

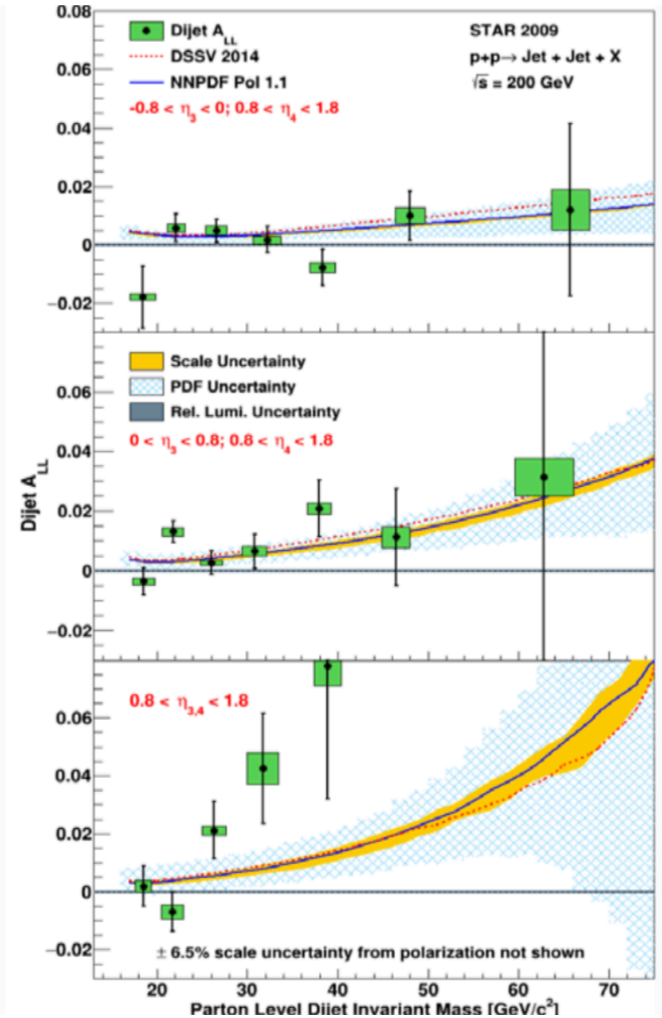
Wider rapidity coverage!





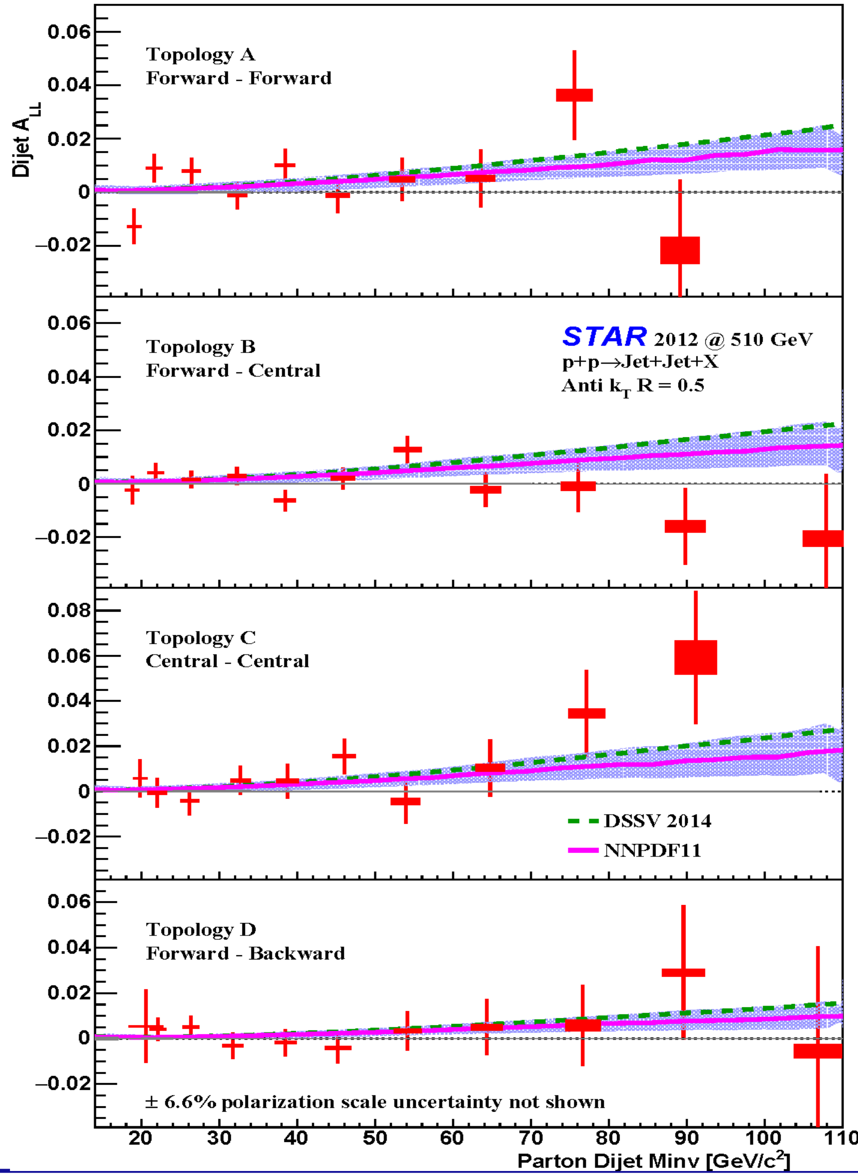




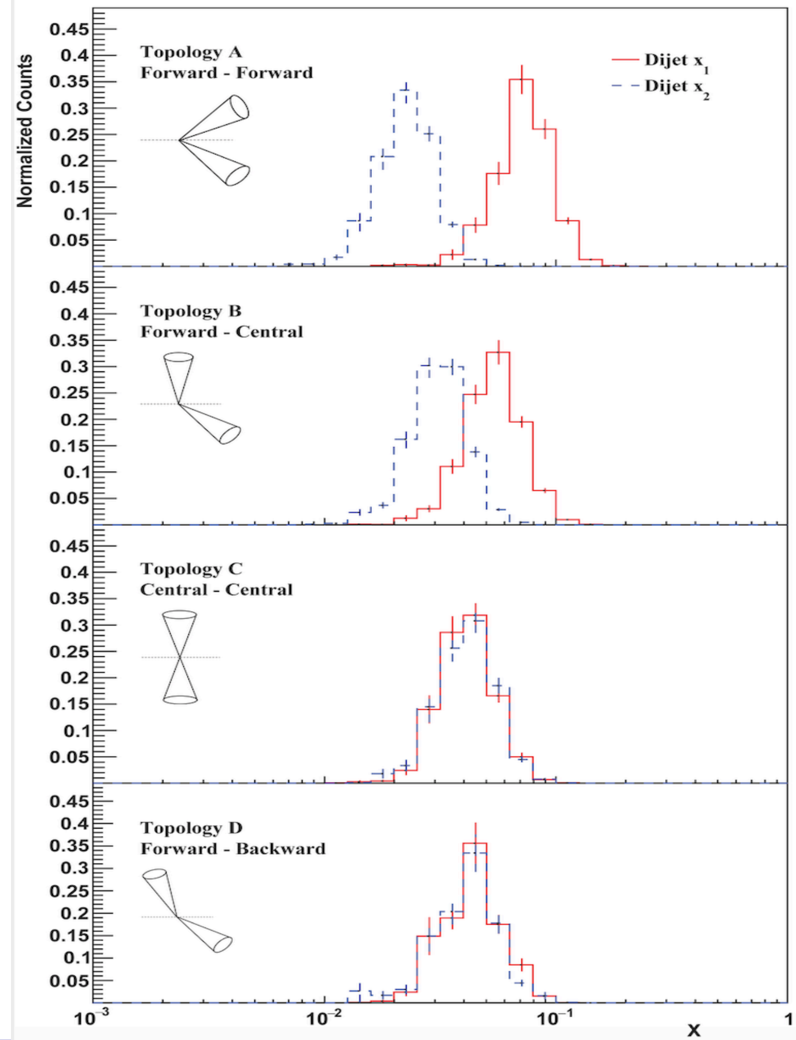


Di-jet A_{LL} at 510 GeV at STAR

STAR, PRD100,52005(2019)

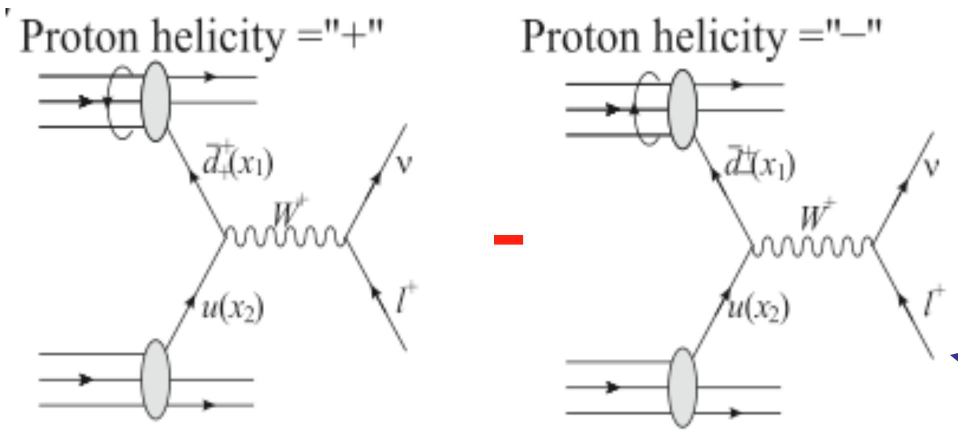


- New results on di-jet A_{LL} at 510 GeV, further constraints on the shape of $\Delta g(x)$



Probing sea quark polarization via W production

- **Unique quark polarimetry with W-bosons at RHIC:**



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

W-detection through high energy lepton

- **Spin asymmetry measurements:**

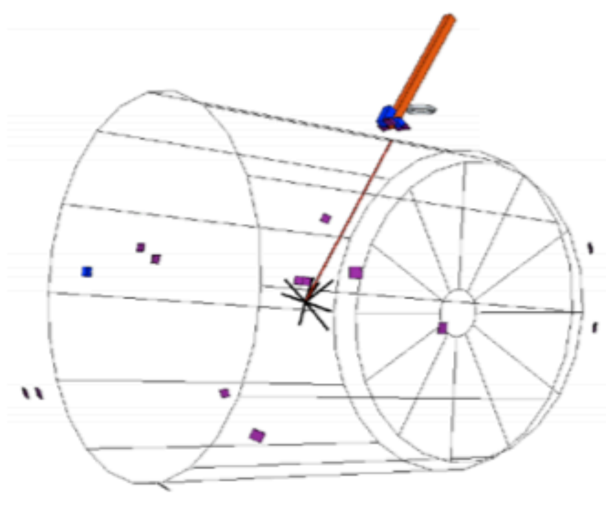
$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \sim \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \end{cases}$$

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

W selection via W -> eν at STAR

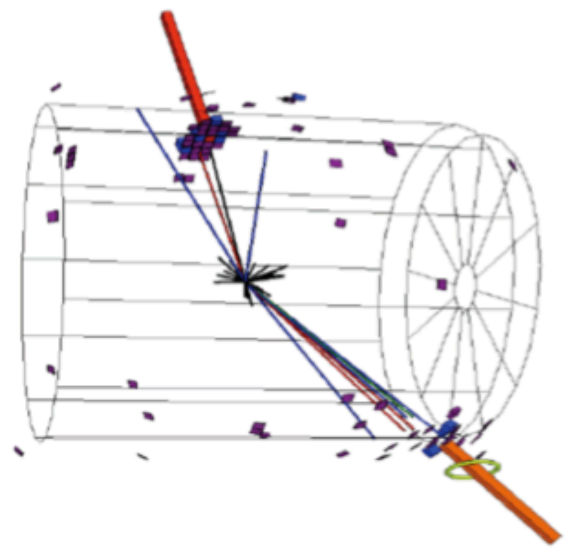
$W \rightarrow e + \nu$ Candidate Event:

- Isolated track pointing to isolated EM cluster in calorimeter
- Large "missing energy" opposite the electron candidate

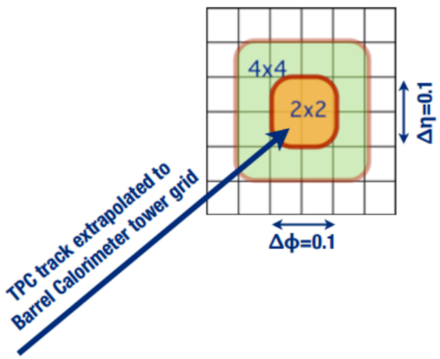


QCD Background Event

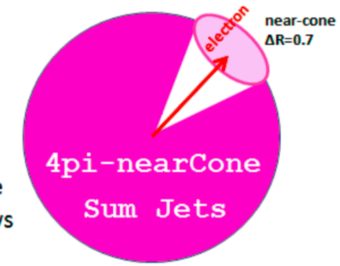
- Several tracks pointing to energy deposit in several towers
- p_T sum is balanced by di-jet, no large "missing energy"



W selection at STAR : Jacobian peak



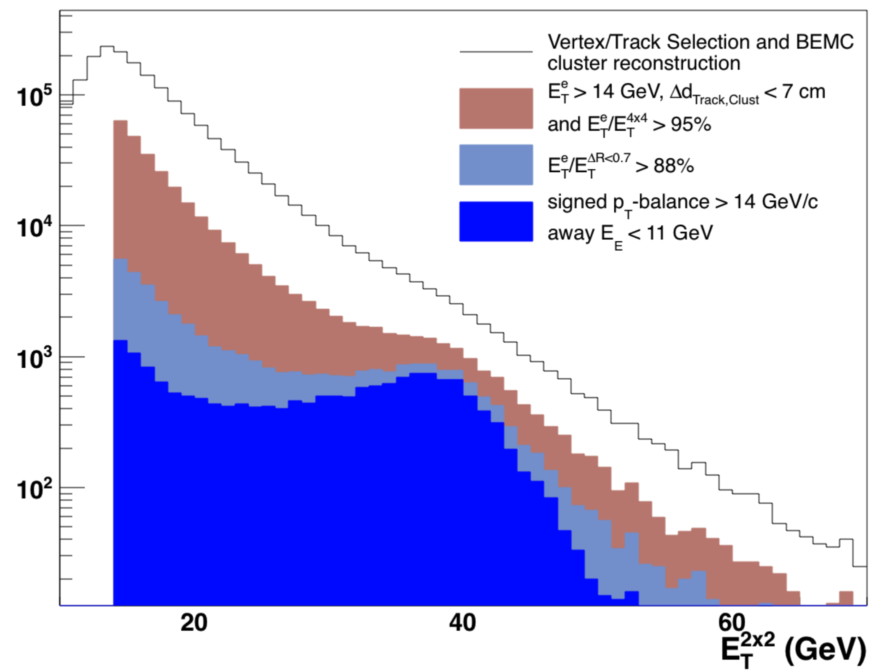
Transverse
Plane views



$$\vec{p_T}^{bal} = \vec{p_T}^{e} + \sum_{\Delta R > 0.7} \vec{p_T}^{jets}$$

- Isolation ratio $E_{2\times 2}/E_{4\times 4} > 95\%$
- Isolation ratio $E_T^e/E_T^{\Delta R<0.7} > 88\%$
- Signed P_T-balance $= \frac{\vec{p_T}^{e} \cdot \vec{p_T}^{bal}}{|\vec{p_T}^{e}|} > 14\text{GeV}$
- away $E_T < 11\text{GeV}$

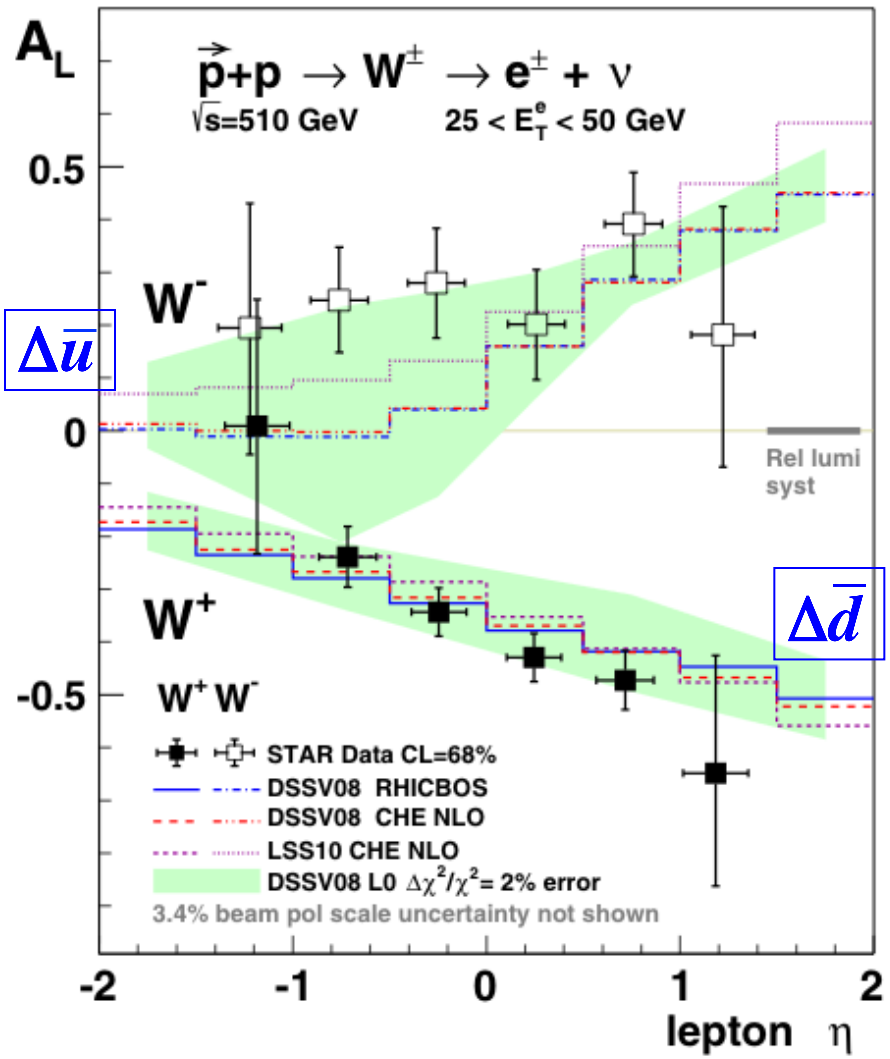
Signal of Jacobian peak with E_T distribution after selection :



-STAR 2013 with BEMC (|η|<1)

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.

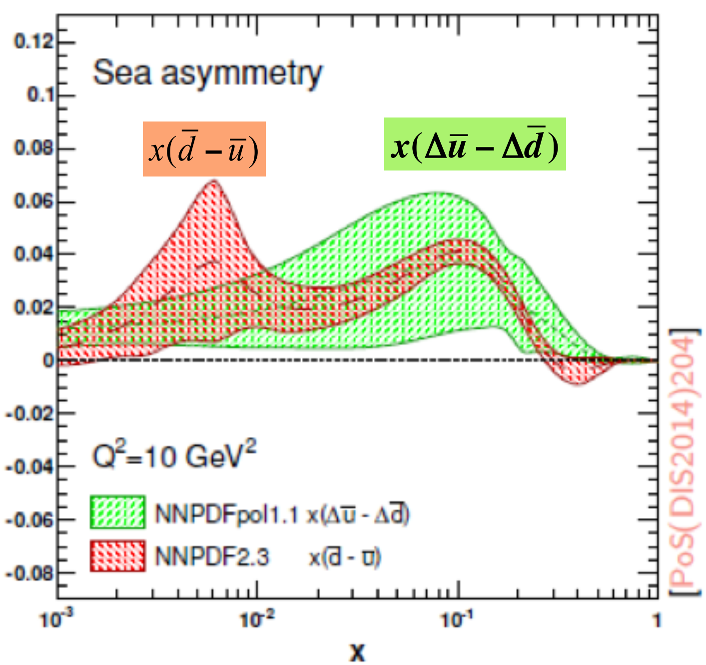
STAR, PRL113, 72301(2014)

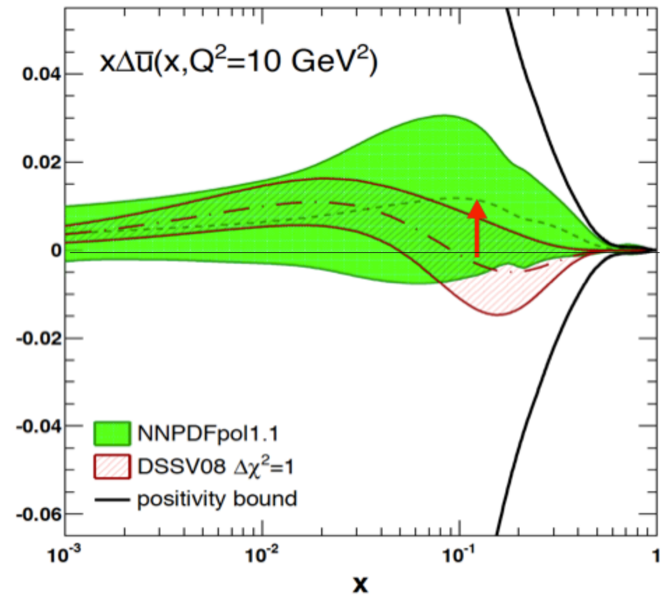
Global Analysis with STAR W A_L results

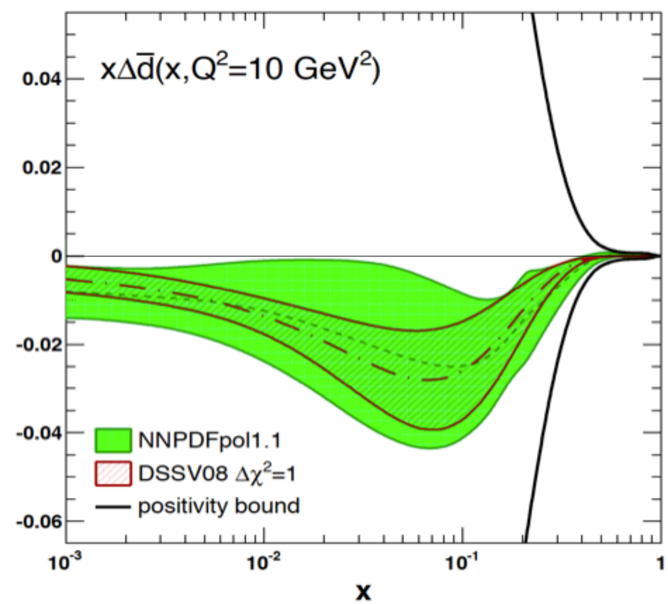
- Big impact seen in NNPDFpol1.1 global analysis after including STAR A_L data.

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

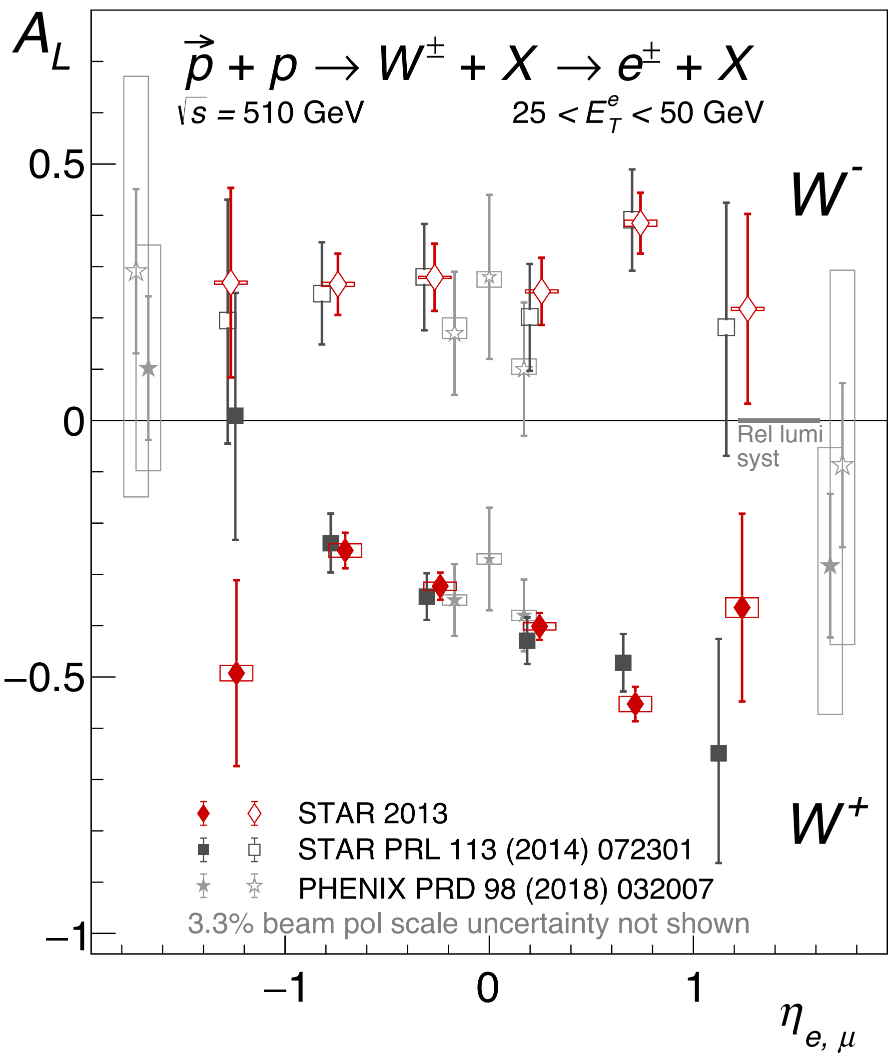
- Polarized sea asymmetry:







W A_L results – STAR 2013

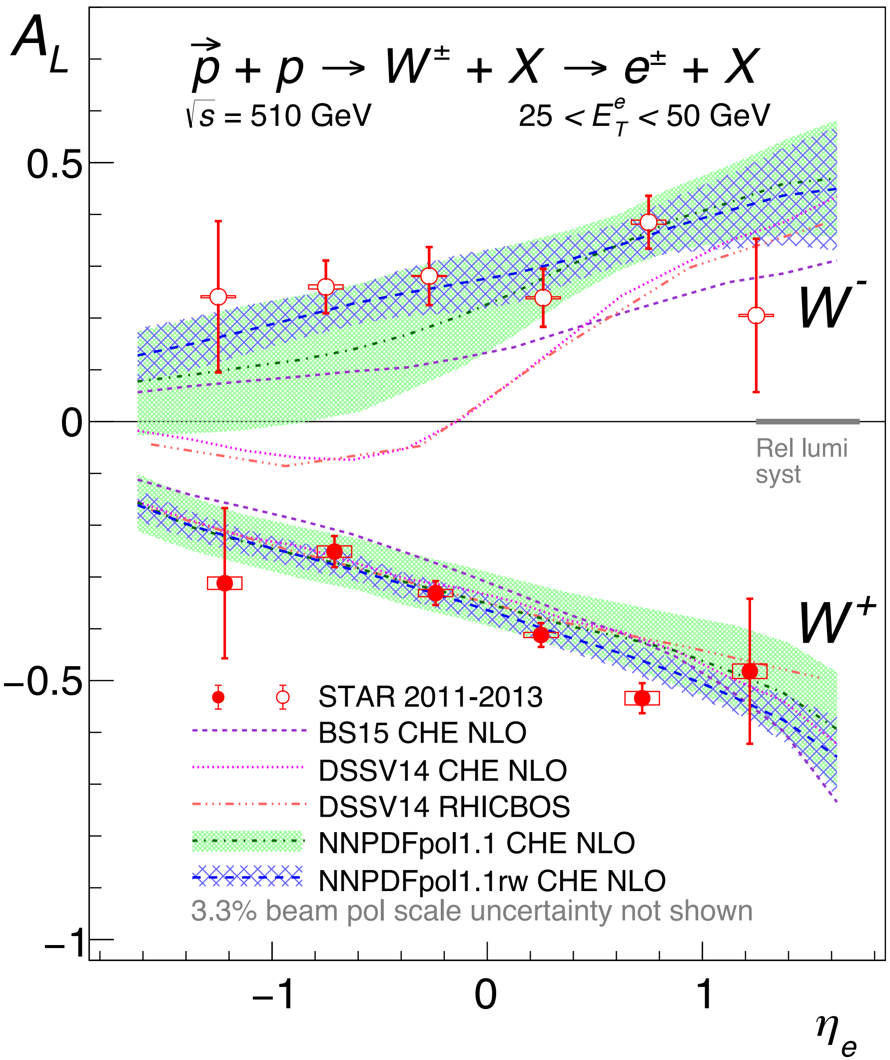


- ✓ Most precise W A_L results from 2013 STAR dataset
- ✓ Consistent with published RHIC results; with 40-50% smaller uncertainties than STAR 2011+2012 results
- ✓ Confirmed positively polarized anti-up quark first seen in the 2011+2012 data.

STAR, PRD99, 051102R(2019)

@Jinlong Zhang's thesis

W A_L results – STAR 2013



STAR, PRD99, 051102R(2019)

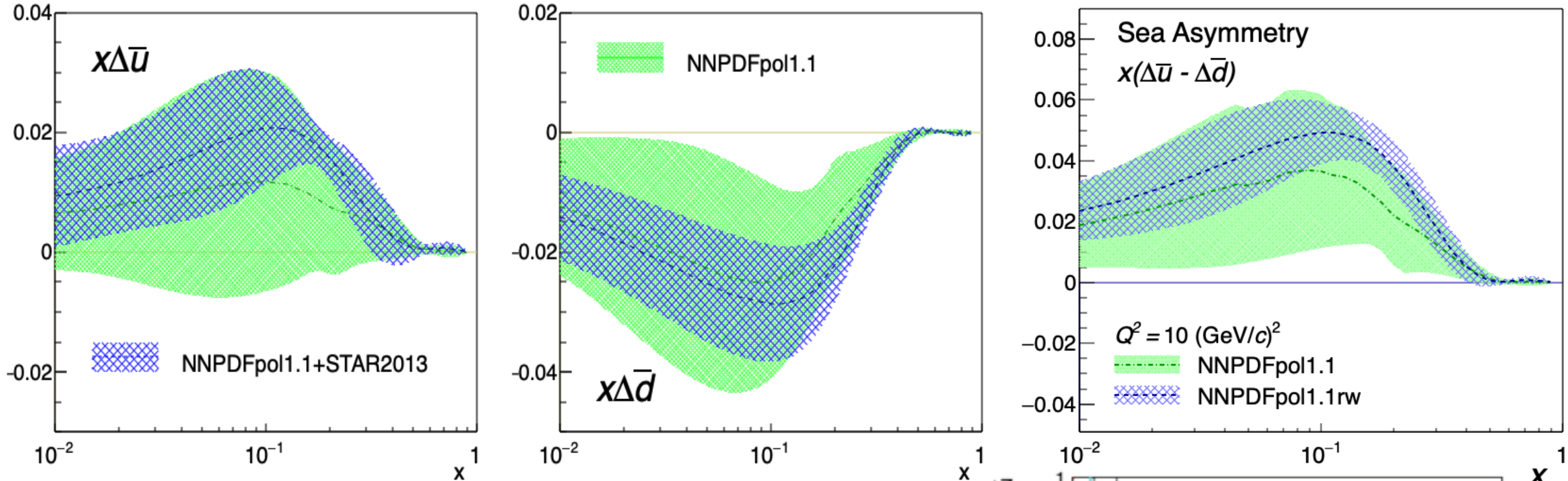
- ✓ Most precise W A_L results from 2013 STAR dataset
- ✓ Consistent with published RHIC results; with 40-50% smaller uncertainties than STAR 2011+2012 results
- ✓ Confirmed positively polarized anti-up quark first seen in the 2011+2012 data.
- ✓ Combined STAR 2011-2013 results in comparison with theoretical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

@Jinlong Zhang's thesis

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)



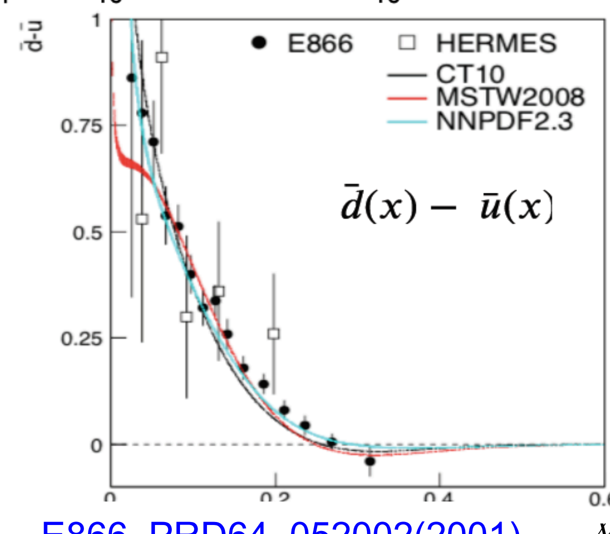
✓ The polarized flavor asymmetry is opposite to the unpolarized case !

$$\Delta\bar{u} > 0 > \Delta\bar{d},\ |\Delta\bar{d}| > |\Delta\bar{u}|$$

$$\Delta_s = \Delta\bar{u} - \Delta\bar{d}$$

$$\int_{0.04}^{0.4} dx\, \Delta_s(x, Q^2 = 10\,\text{GeV}^2) = +0.06 \pm 0.03$$

$$\rightarrow +0.07 \pm 0.01$$



-E. Nocera @ Hadron2019

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

Impact of STAR 2013 W A_L results

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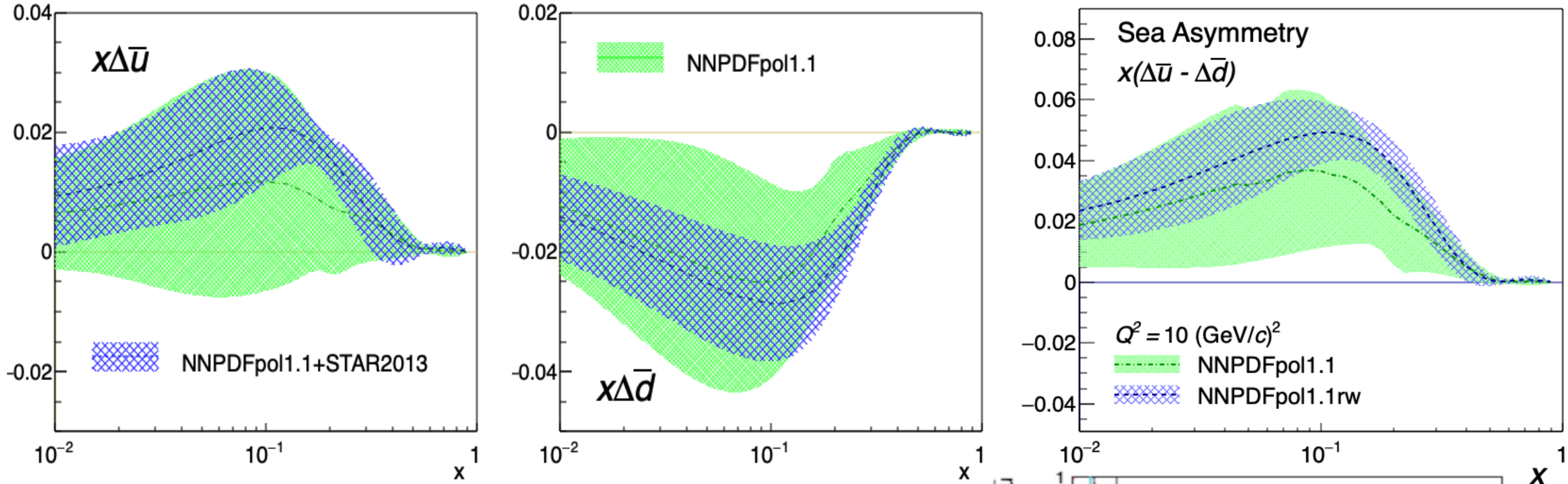
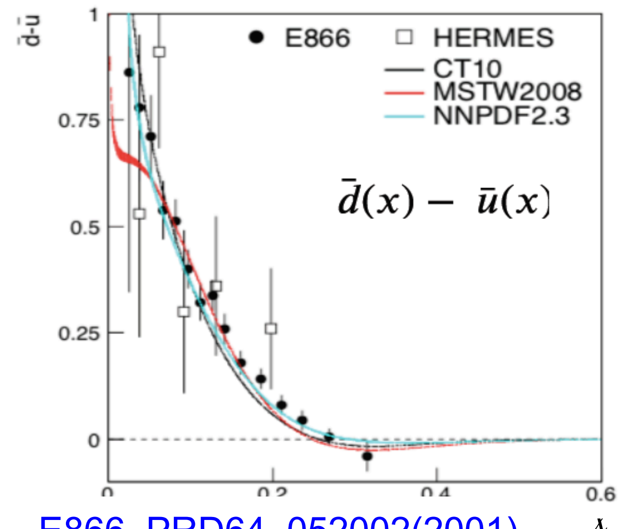
STAR, PRD99, 051102R(2019)



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

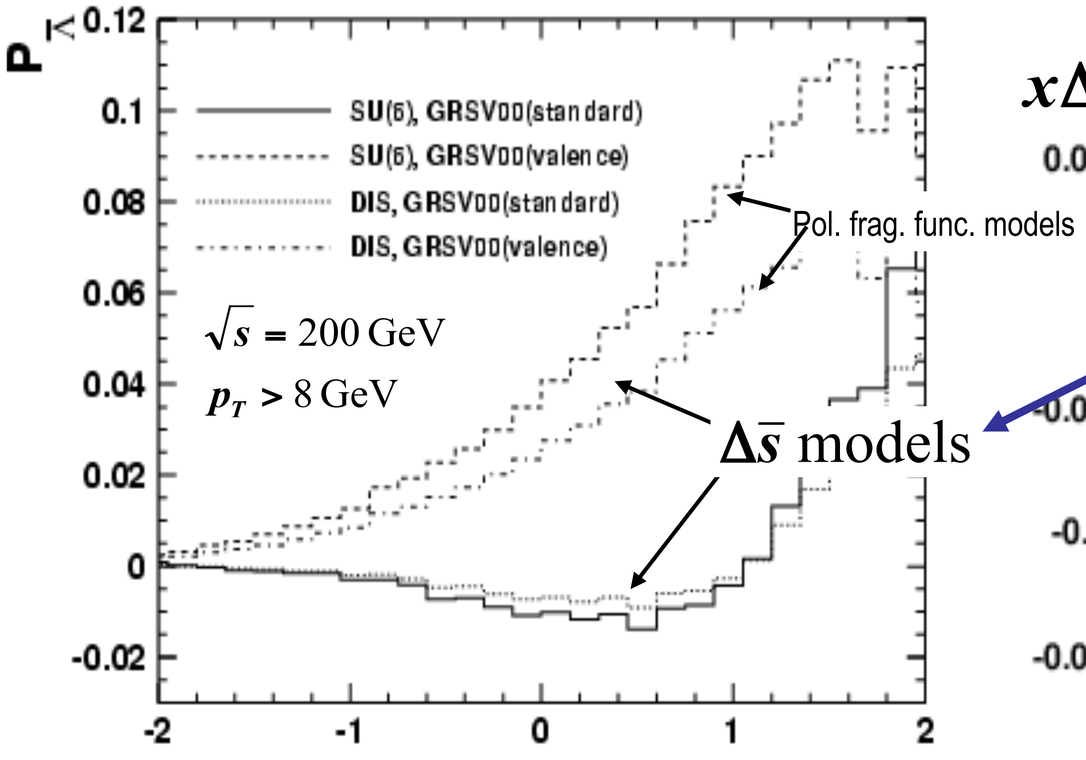


- E866, PRD64, 052002(2001)
- NNPDF2.3, NPB867,244(2013)

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

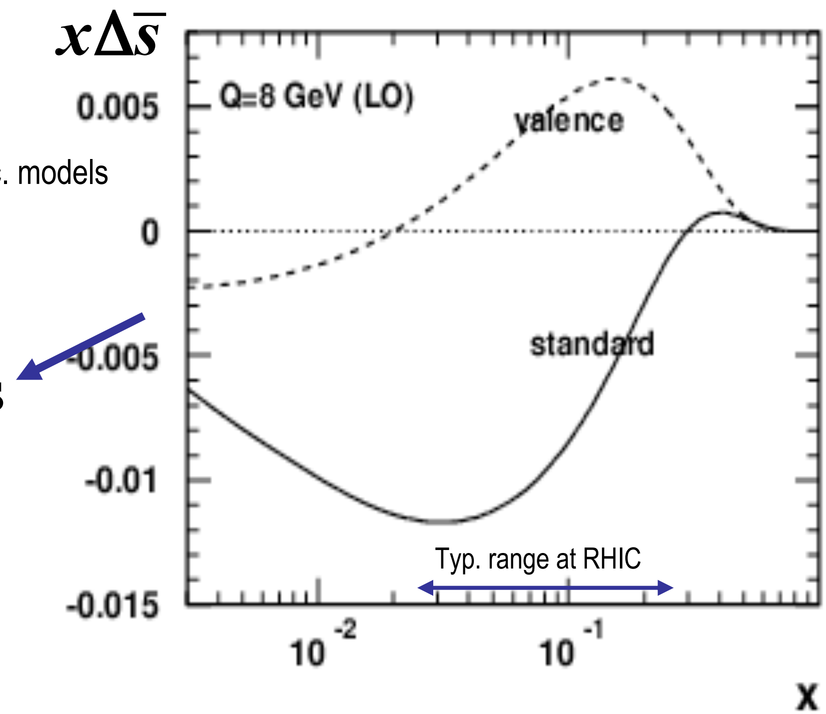
- Expectations at LO show sensitivity of D_{LL} for anti-Lambda to $\Delta\bar{s}$:

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



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

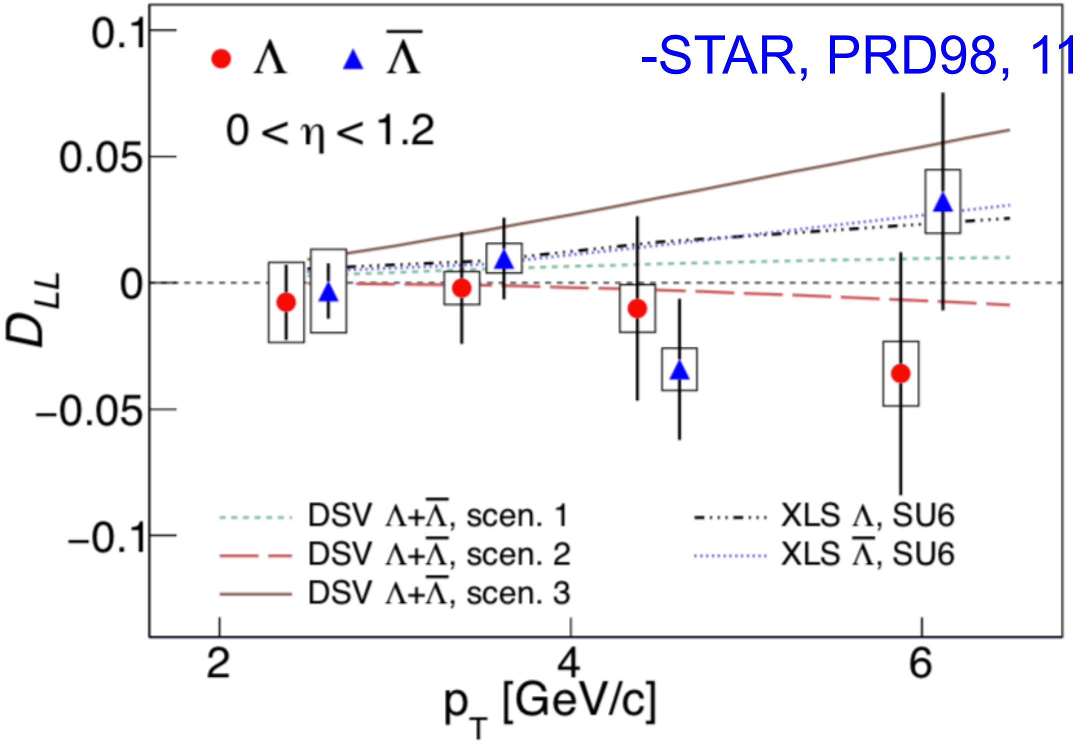
GRSV00-M.Gluck et al, Phys.Rev.D63(2001)094005



- 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

- 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)

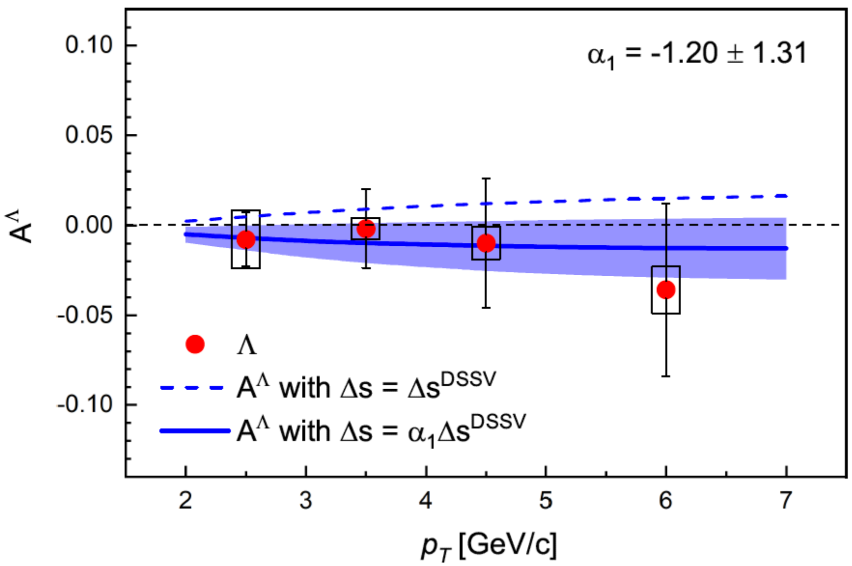
➢ D_{LL} results are still consistent with zero within the uncertainties.

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

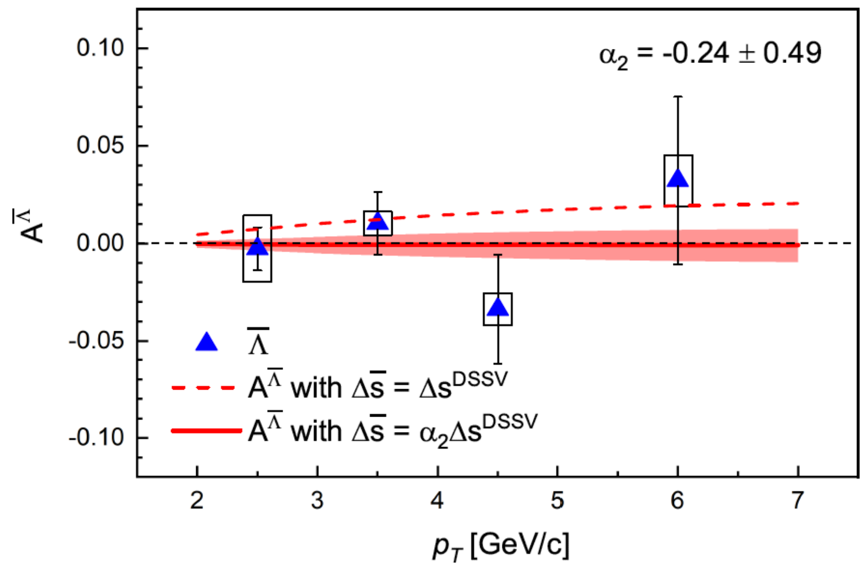
D_{LL} results of (anti-)Lambda at STAR

- 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.



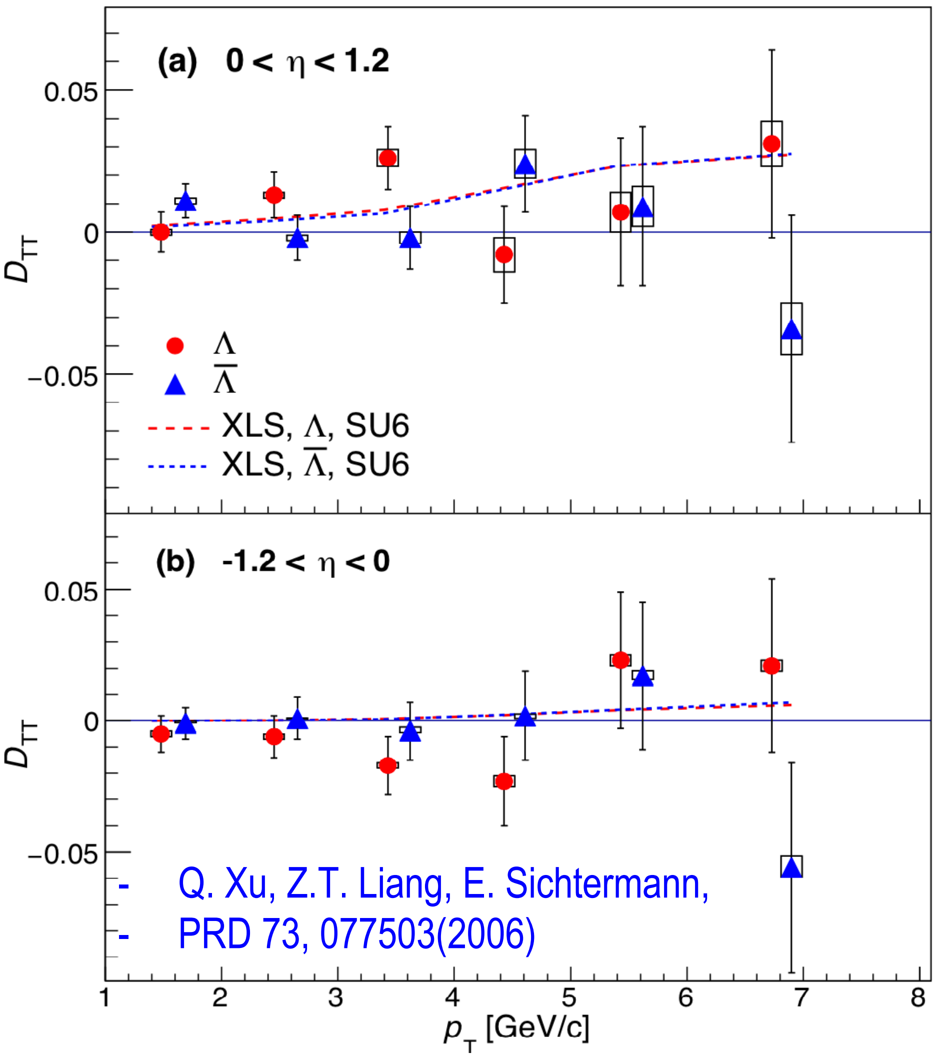
(b) Longitudinal spin transfer to $\bar{\Lambda}$.

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

Transverse spin transfer D_{TT} results at STAR

- D_{TT} measurements in p+p collision at 200 GeV, which is relevant to transversity and polarized fragmentation functions:



✓ 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.

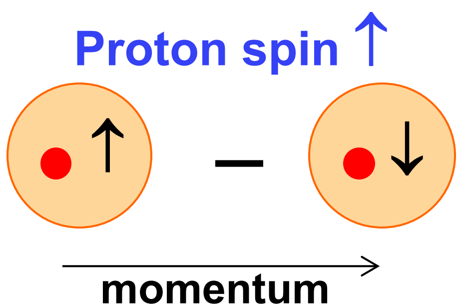
@Jincheng Mei's thesis

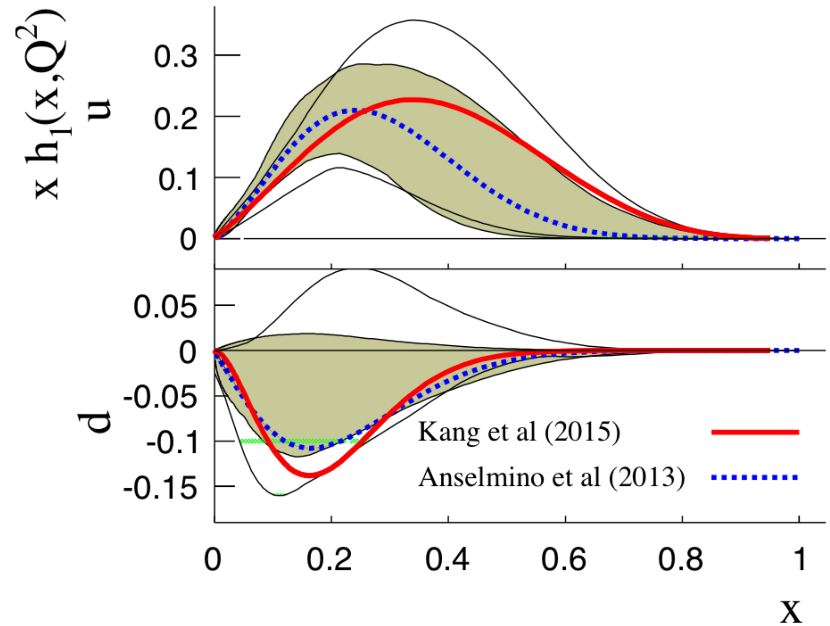
-STAR, PRD98, 091103R (2018)

Transverse spin structure of nucleon

- Transversity- least known pdf among 3 leading twist pdfs.

$$\delta q(x,Q^2) = q^{\uparrow}(x,Q^2) - q^{\downarrow}(x,Q^2)$$



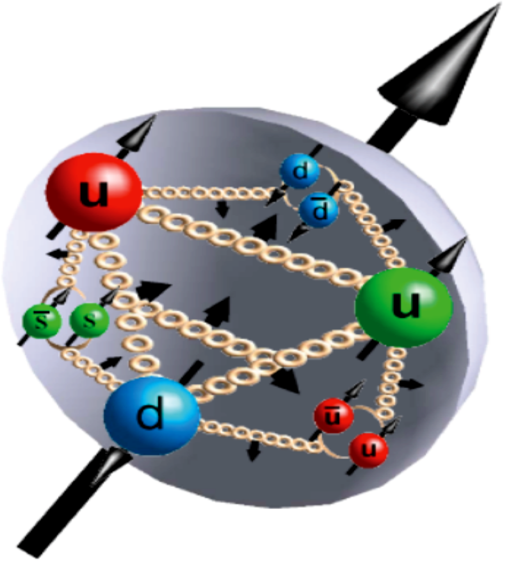


- Transversity involves helicity flip, thus no access in inclusive DIS process.

- Possible experimental measurements on $\delta q(x)$:
  - Via Collins function (SIDIS, p+p), di-hadron production (SIDIS and p+p)

    Several Global fits available: Anselmino et al'13, Kang et al'15, M. Radici et al'18
  - Transversely polarized Drell-Yan process
  - Transverse spin transfer to hyperons (DIS, p+p)

If you are not getting bored with these spinning ones….



Let’s continue with transverse spin 🙂

Transverse spin physics at RHIC

- Transverse spin asymmetry (Hadron production):

  Access to transversity via Collins & Siverse asymmetry

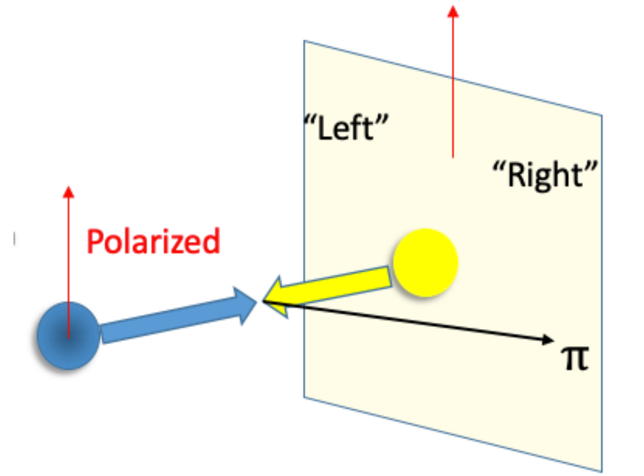
- Transverse spin asymmetry (W/Z production):

  Sign-change of Sivers function

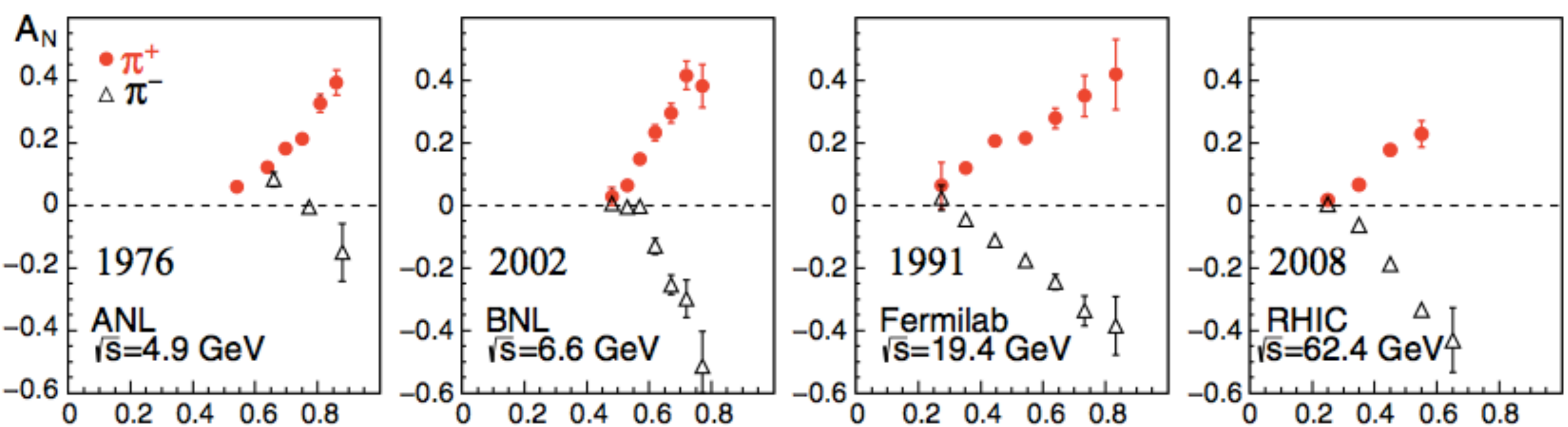
Transverse Single-spin Asymmetries

- Anomalously large A_N observed for nearly 40 years:

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



- "Left-right asymmetry"



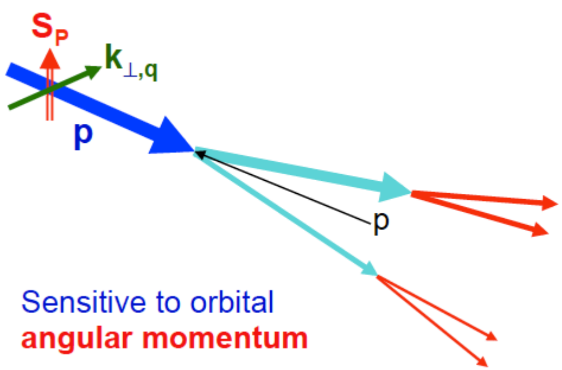
x_F

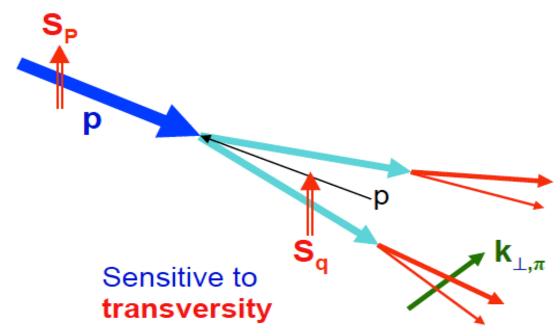
Figure Aidala *et al.* Rev. Mod. Phys., Vol. 85, No. 2

$x_F = 2p_Z/\sqrt{s}$

Mechanisms for Transverse Single-spin Asymmetries

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





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

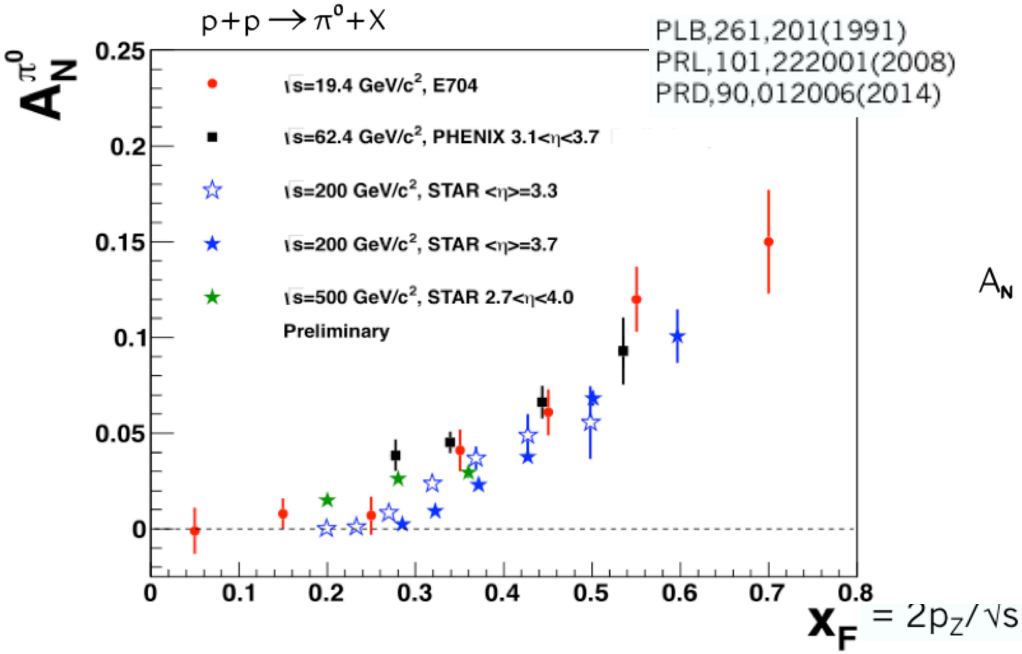
    Collinear/twist-3 quark-gluon correlation + fragmentation functions

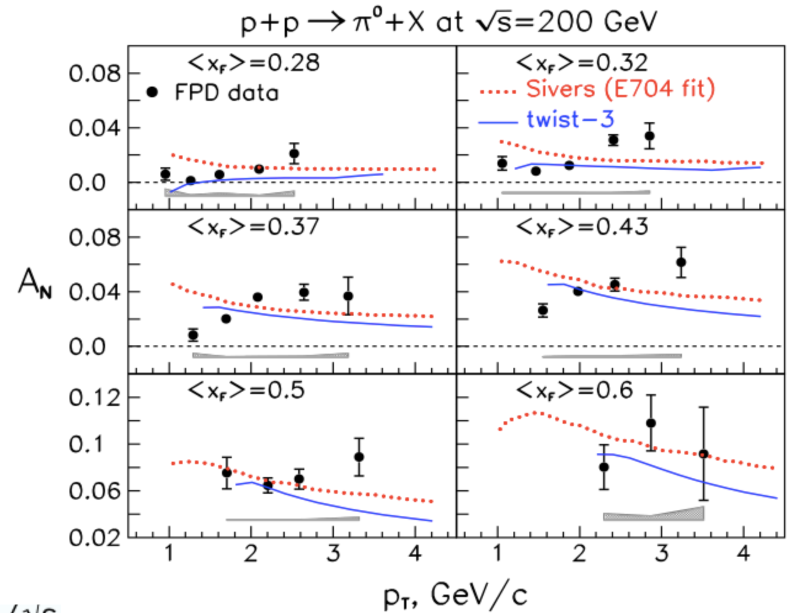
    Need one scale (Q or p_T), Q, $p_T>>\Lambda_{QCD}$

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

Ji-Qiu-Vogelsang-Yuan,2006

Forward π^0 A_N at RHIC-STAR





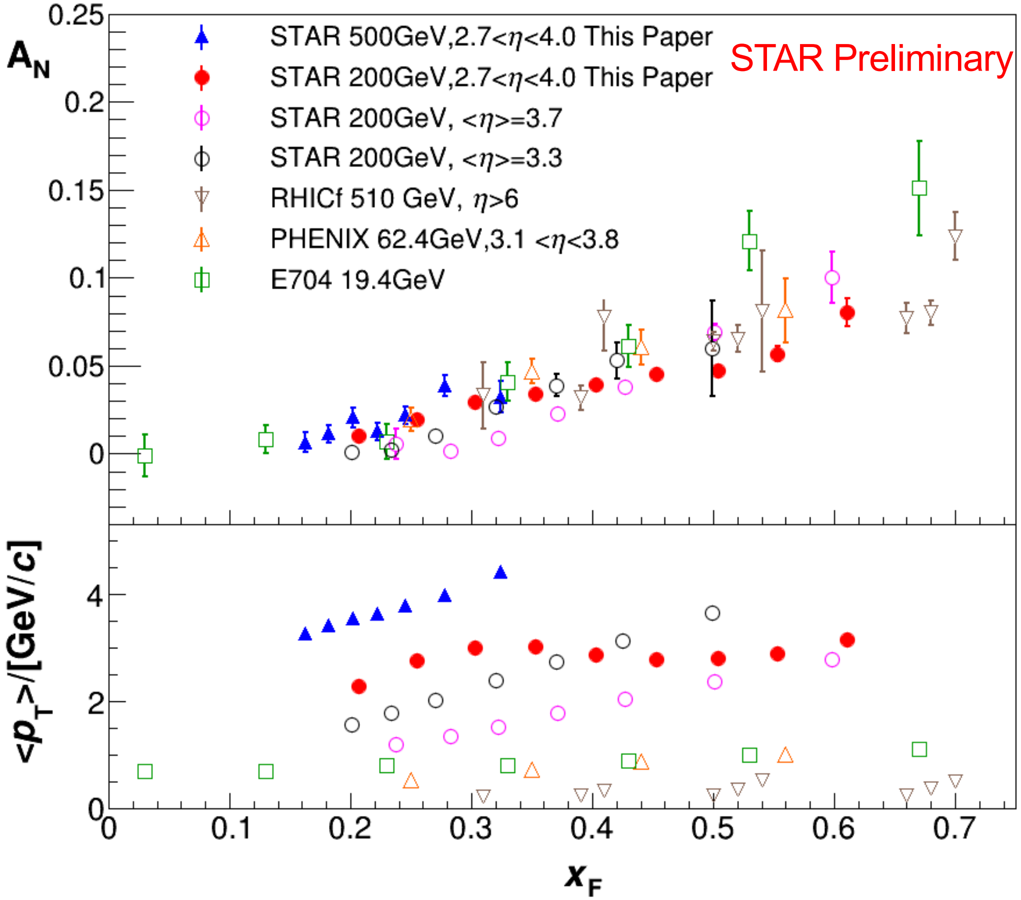
- Rising A_N with X_F, A_N nearly independent of $\sqrt{s}$ up to 200 GeV
- A_N persist at high $p_{T,}$ no falling evidence.

> For hadron SSA, both Sivers and Collins effects can contribute.

> Study of jet production can separate Collins & Sivers effects.

Forward π^0 A_N at RHIC-STAR

- New results π^0 A_N from STAR at both 200 and 510 GeV

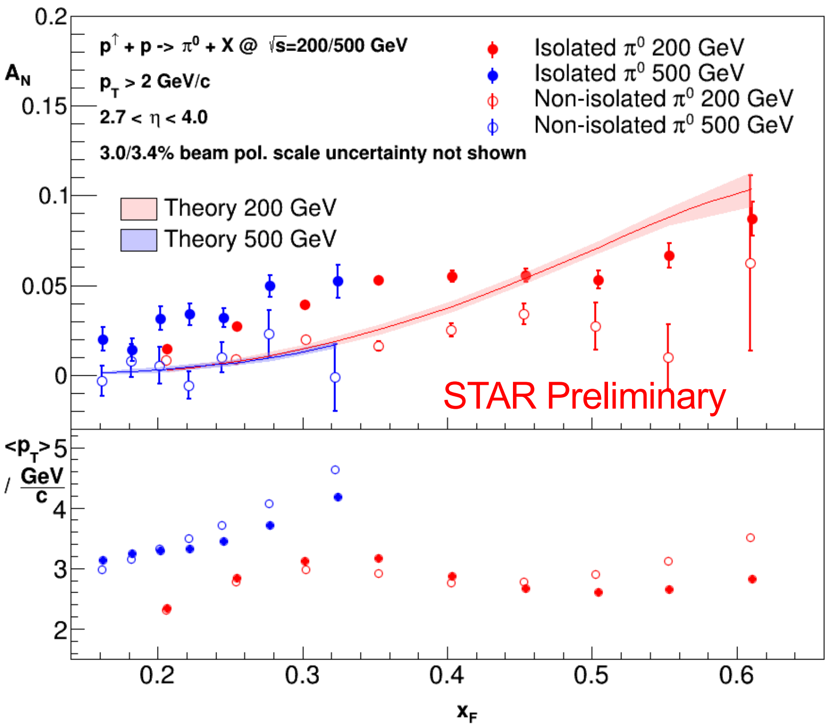


- ✓ Weak scale dependence of the π^0 TSSA for a center-of- mass range from 19.4 to 510 GeV
- ✓ Comparison to the former results at STAR shows higher TSSA in current measurement, which can be explained by the higher average pT.

Zhanwen Zhu @ BNL seminar March 2020

New observation: isolated π^0 A_N

- Definition: π^0 with no other energy around
- Method: Constructing a jet (anki-kT R=0.7) first, and if a π^0 is inside the jet and takes most of its energy, it is defined isolated.



Theory curves:
J. Cammarota, et al., arXiv:2002.08384

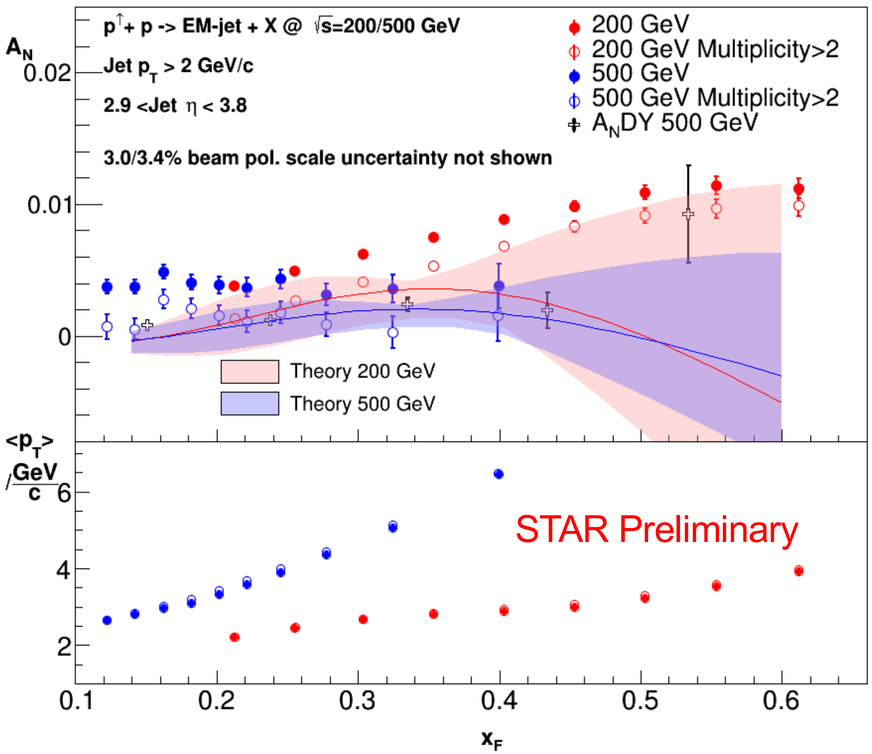
- The isolated π^0 A_N is significantly larger, which is separated from those from fragmentation process.
- The non-isolated π^0 A_N is very small, which are mostly from parton fragmentation process.
- Similar results at both energies.
- The physical origin and mechanism accounted for higher TSSA of isolated π^0 is not known yet.

-> diffractive process?
need more theory efforts!

Zhanwen Zhu @ BNL seminar March 2020

Searching A_N origin : EM-jet TSSA

- Jet A_N - sensitive to the initial state effect, related to Sivers effect, decoupled from Collins effect
- Anti-k_T algorithm is used for EM-jet reconstruction using FMS (EM calorimeter)



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

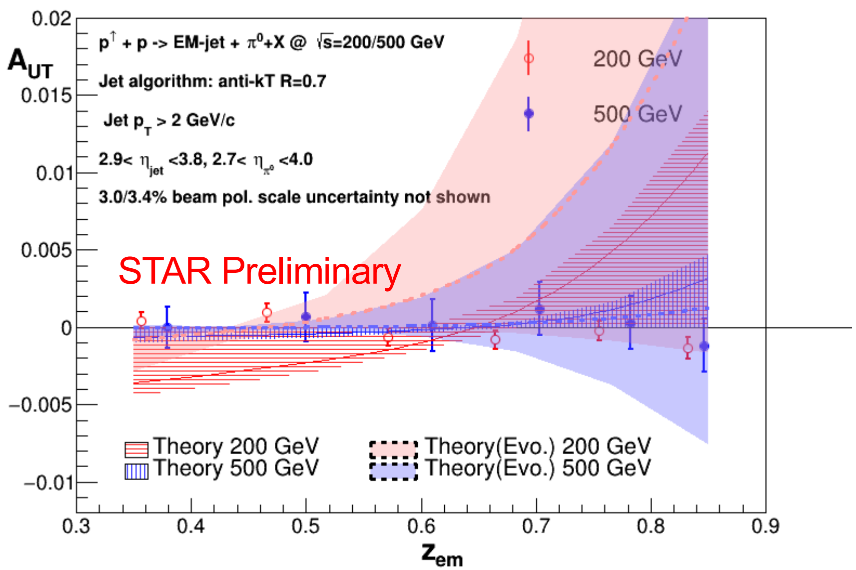
- The jet TSSA is a few times smaller than the π^0 TSSA in the same xF bin.
- The jet with photon multiplicity minimum requirement has significant smaller TSSA.
- The ANDY result shows the TSSA of the full jet, and is consistent with the result of the EM-jet which has at least 3 photons.

➢ Initial state effect is small

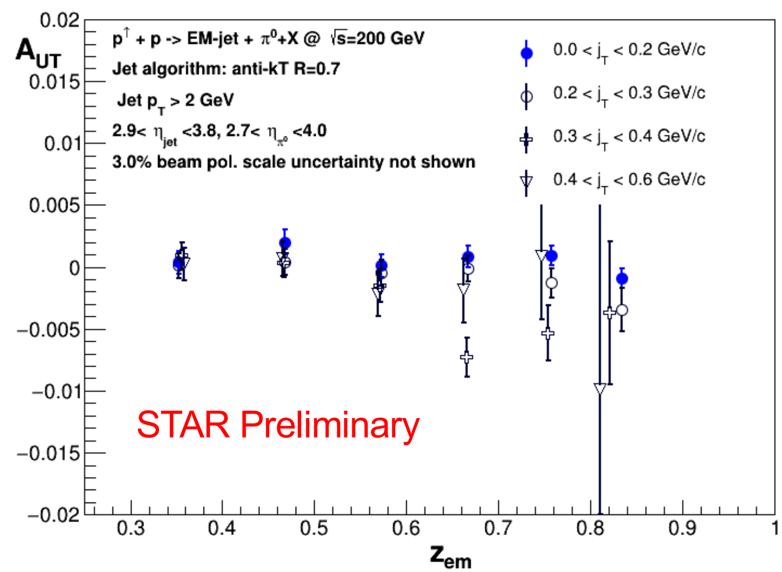
Zhanwen Zhu @ BNL seminar March 2020

Searching A_N origin : Collins asymmetry

- The Collins asymmetry – final state only
  the π^0 is a part of a jet, which is fragmented from a polarized parton



Z. Kang , A. Prokudin , F. Ringer , F. Yuan
Phys.Lett.B774(2017)635-642



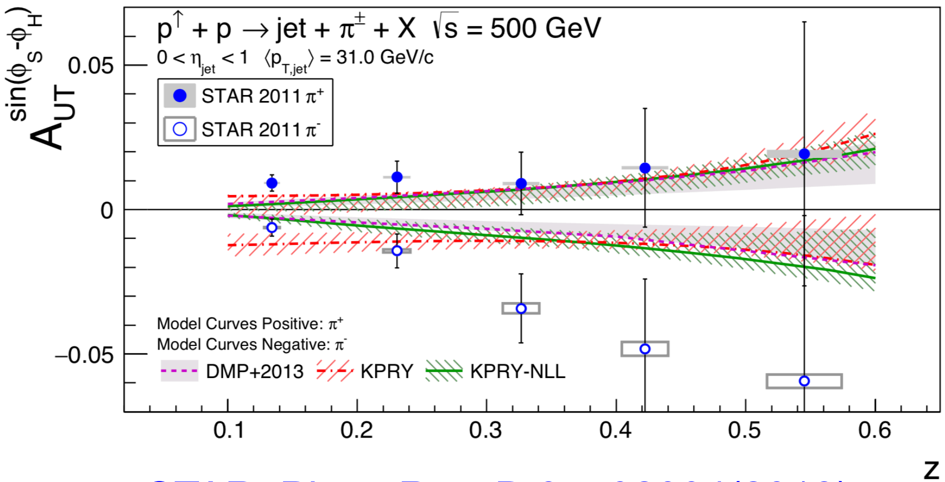
- For both energies, the Collins asymmetries are tiny, or consistent with zero, in agreement with the small A_N of non-isolated π^0 .
- Indication of j_T dependence, which was seen by mid-rapidity measurement at 200 GeV, underlying physics is understood yet.

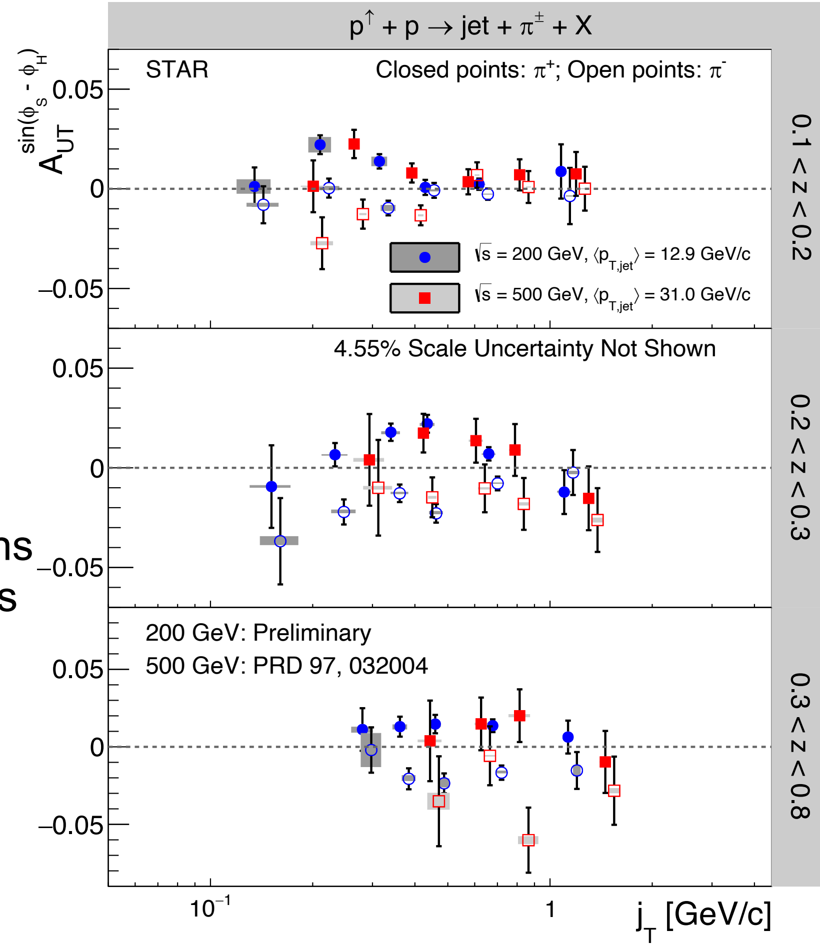
Zhanwen Zhu @ BNL seminar March 2020

➢ Final state effect is small

Collins asymmetries at STAR: mid-rapidity

- Collins asymmetries at 500 GeV & 200 GeV:





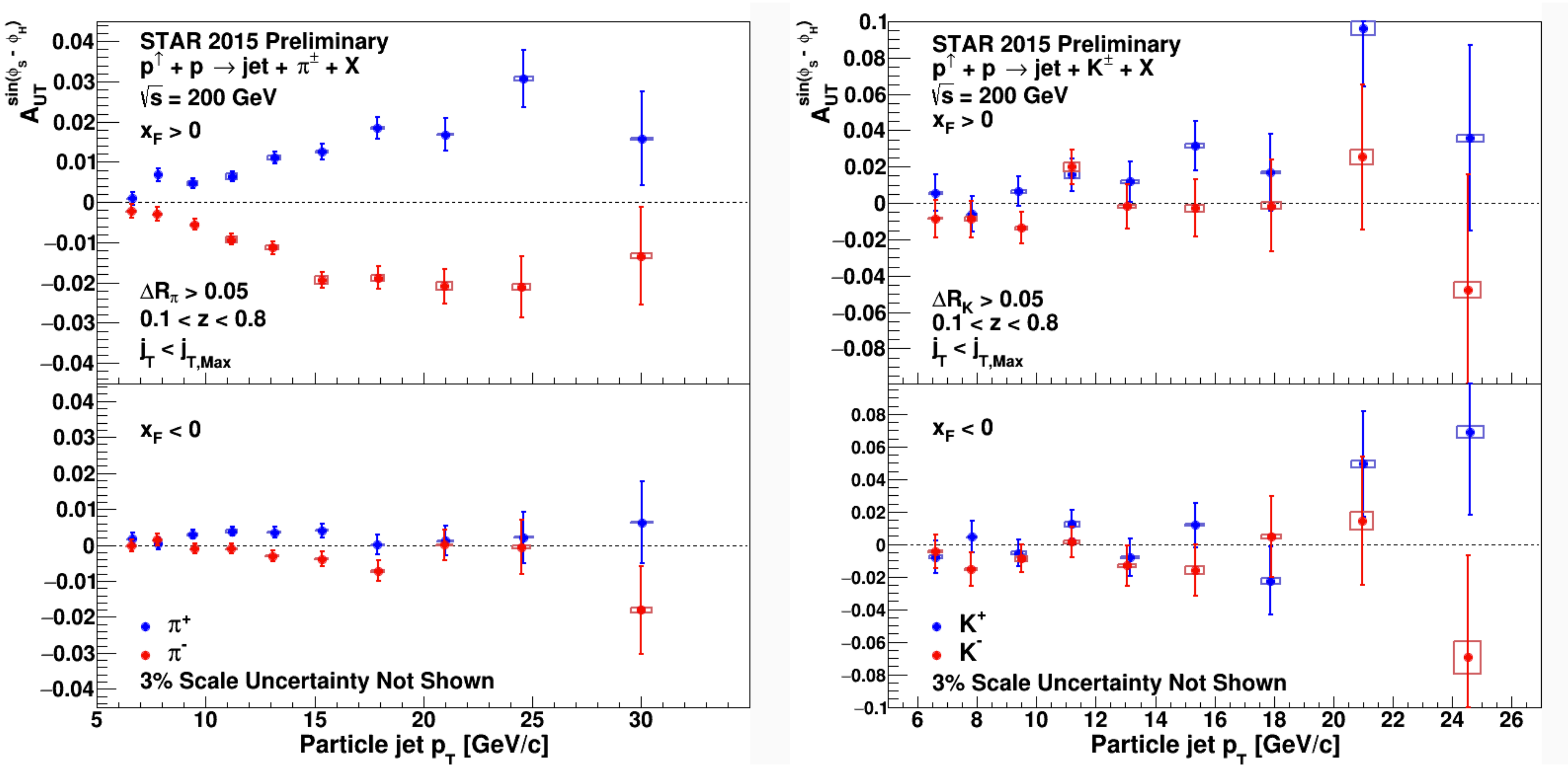
STAR, Phys. Rev. D **97,** 32004(2018)

- First Collins effect measurements in pp collisions reasonably described by two recent calculations that combine the transversity distribution from SIDIS with the Collins FF from e^+e^- collisions
- Both 200 and 500 GeV pp results hint that the asymmetry peak shifts to higher j_T as z increases

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

Collins asymmetries at STAR: mid-rapidity

- New results on Collins asymmetries for π and K in p+p collisions at 200 GeV

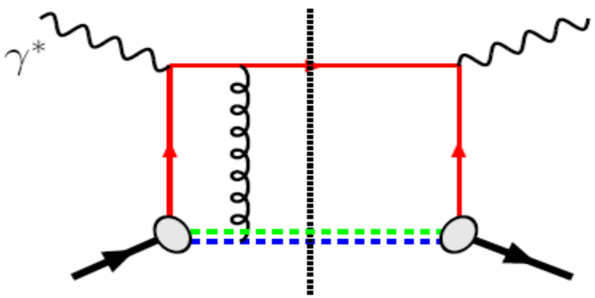


- K^{+} shows positive asymmetries for forward jets, consistent within the currently large statistical uncertainties with the π^{+} asymmetries;

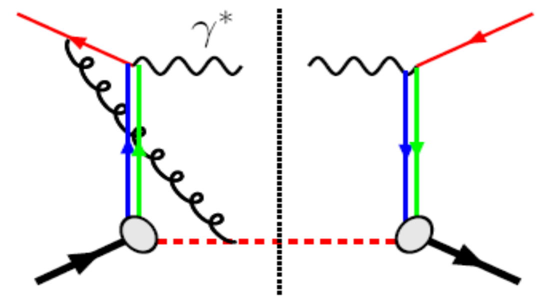
Transverse single spin asymmetry (A_N) of W boson

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

DIS: γq scattering
attractive FSI



pp: $q/\bar{q}$ annihilation
repulsive ISI



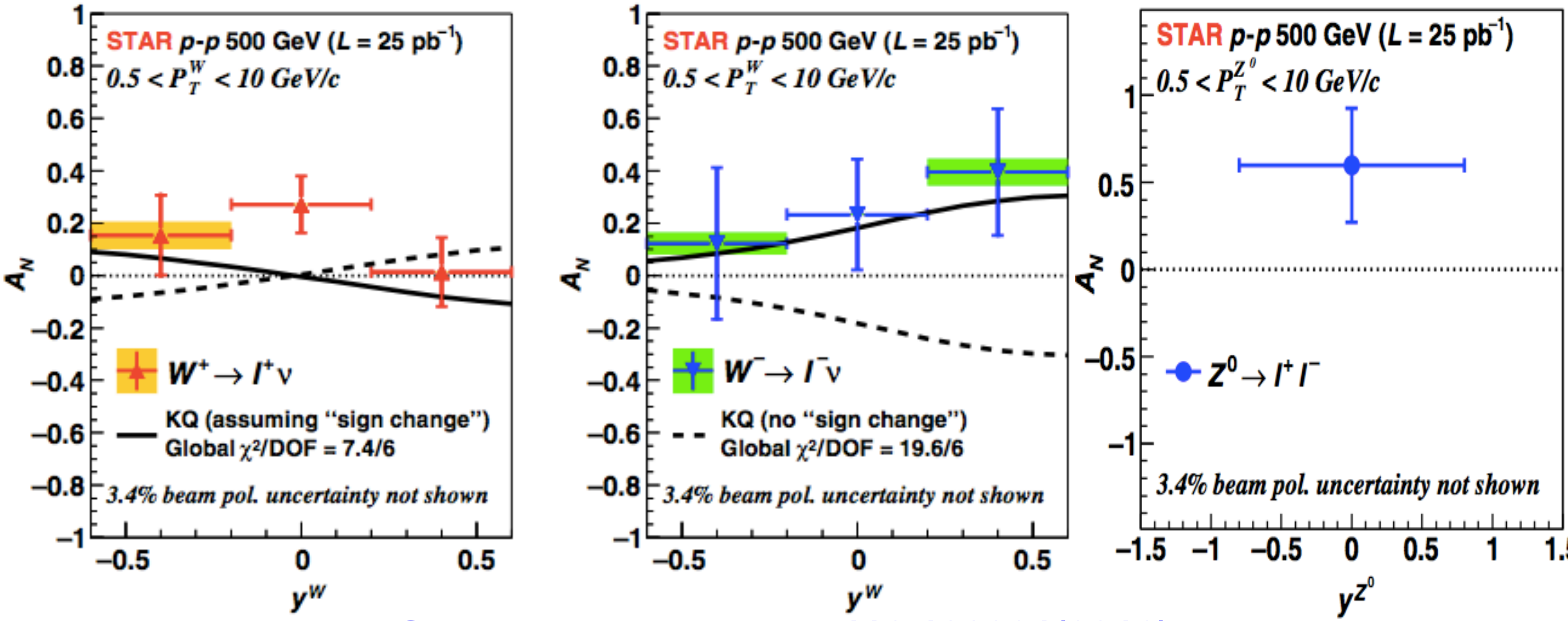
$Sivers_{DIS}$ = - Sivers (DY or W or Z)

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

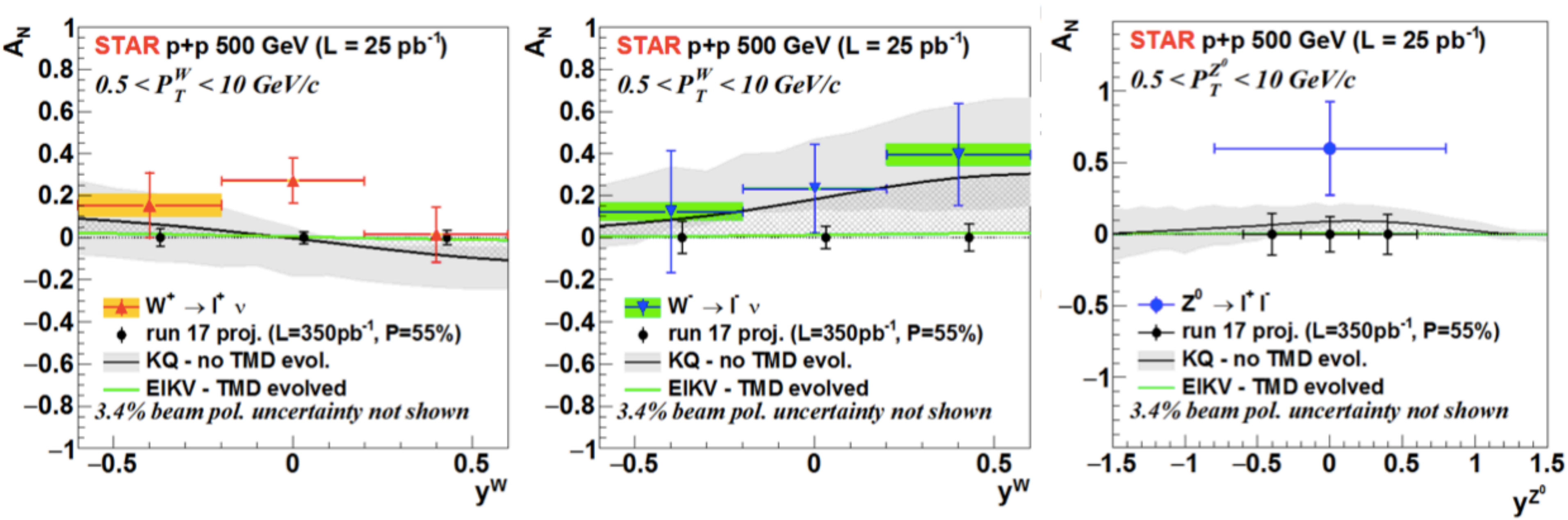


STAR, Phys. Rev. Lett. 116,132301(2016)

➢ 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:

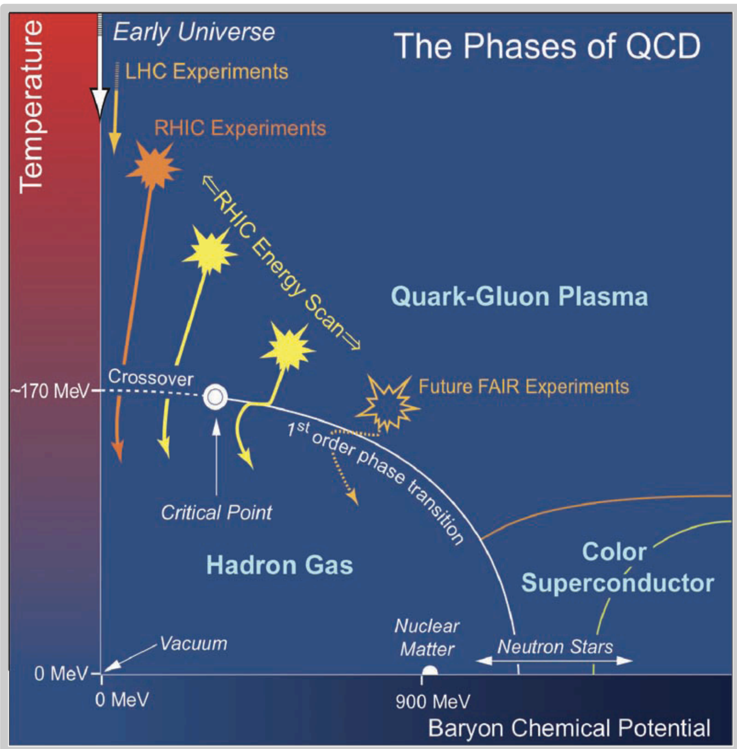


Goal:

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

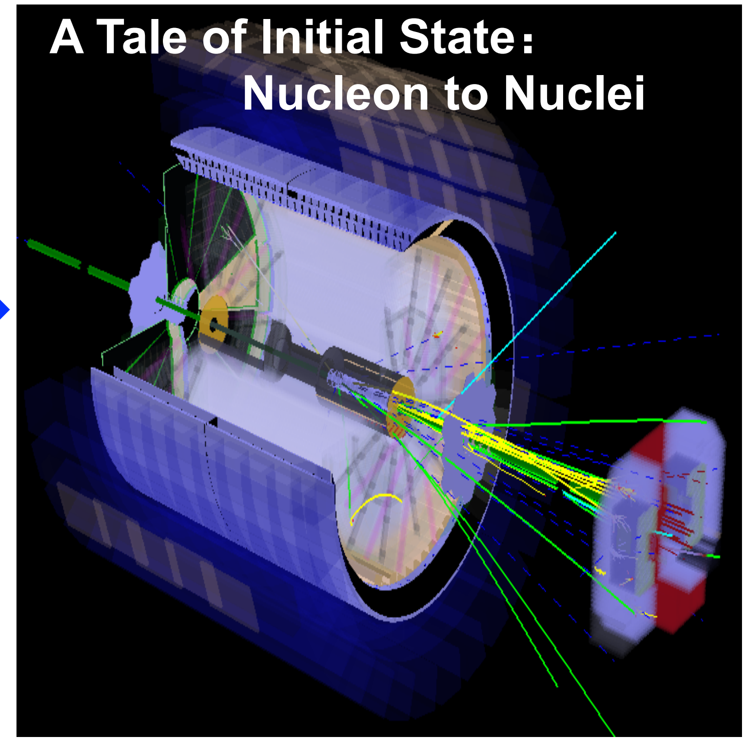
Looking Forward at STAR

Beam Energy Scan II
2019~2021



iTPC, eToF, EPD

Forward Physics ($2.5<\eta<4$)
2021+



- ✓ Forward Tracking System
  -> 4 sTGC+ 3 Silicon disks
- ✓ Forward Calorimeter System

Future RHIC Spin in 2021+

STAR

Year	$\sqrt{s}$ (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 (2.5<η<4)
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 (2.5<η<4)
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

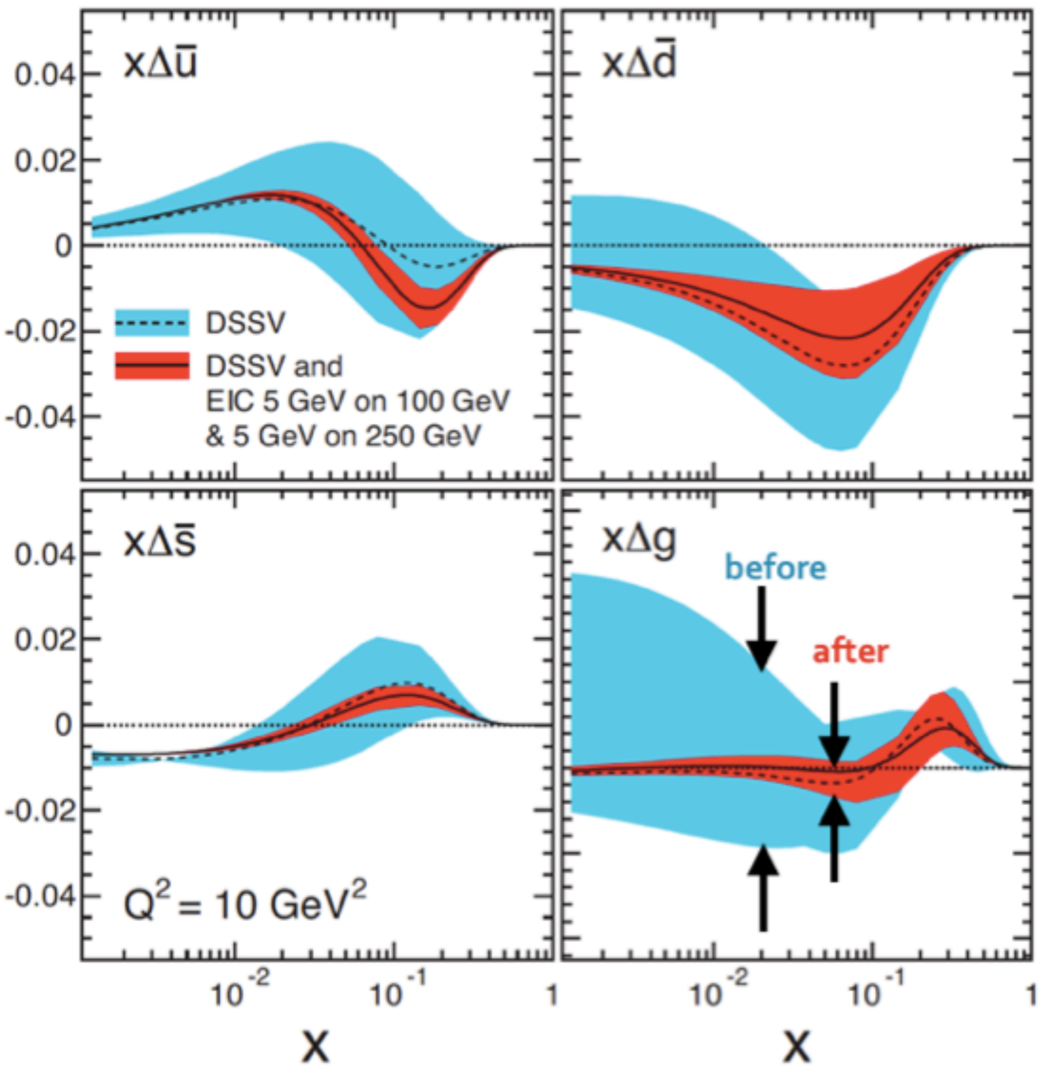
- RHIC is the world's only polarized hadron-hadron collider.
- Unique physics opportunities in pp and pA.

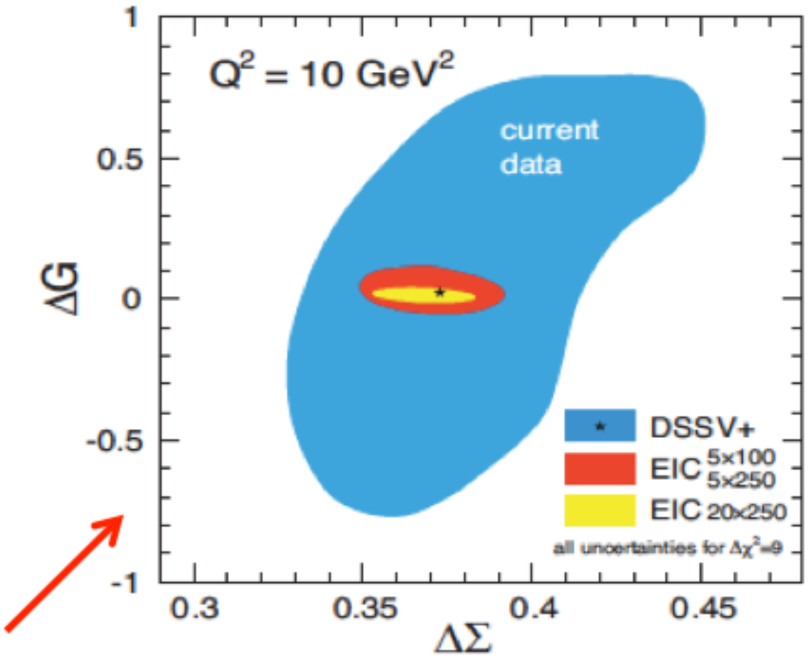
Summary of RHIC Spin

- Origin of proton spin remains a fundamental question in QCD.
- 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 at RHIC:
  - Results on Collins asymmetries & hyperon spin transfer provide window for transversity distribution of nucleon.
  - A_N for W,Z at STAR: 1st results obtained, run 17 to study Sivers sign change
- Future RHIC spin in 2021^{+} & EIC in 2028+
  - Unique physics opportunities in pp and pA, essential to fully realize the scientific promise of the EIC.
  - A ultimate QCD machine for proton structure: EIC/EicC !

Future on proton spin - eRHIC

EIC: arXiv:1212.1701

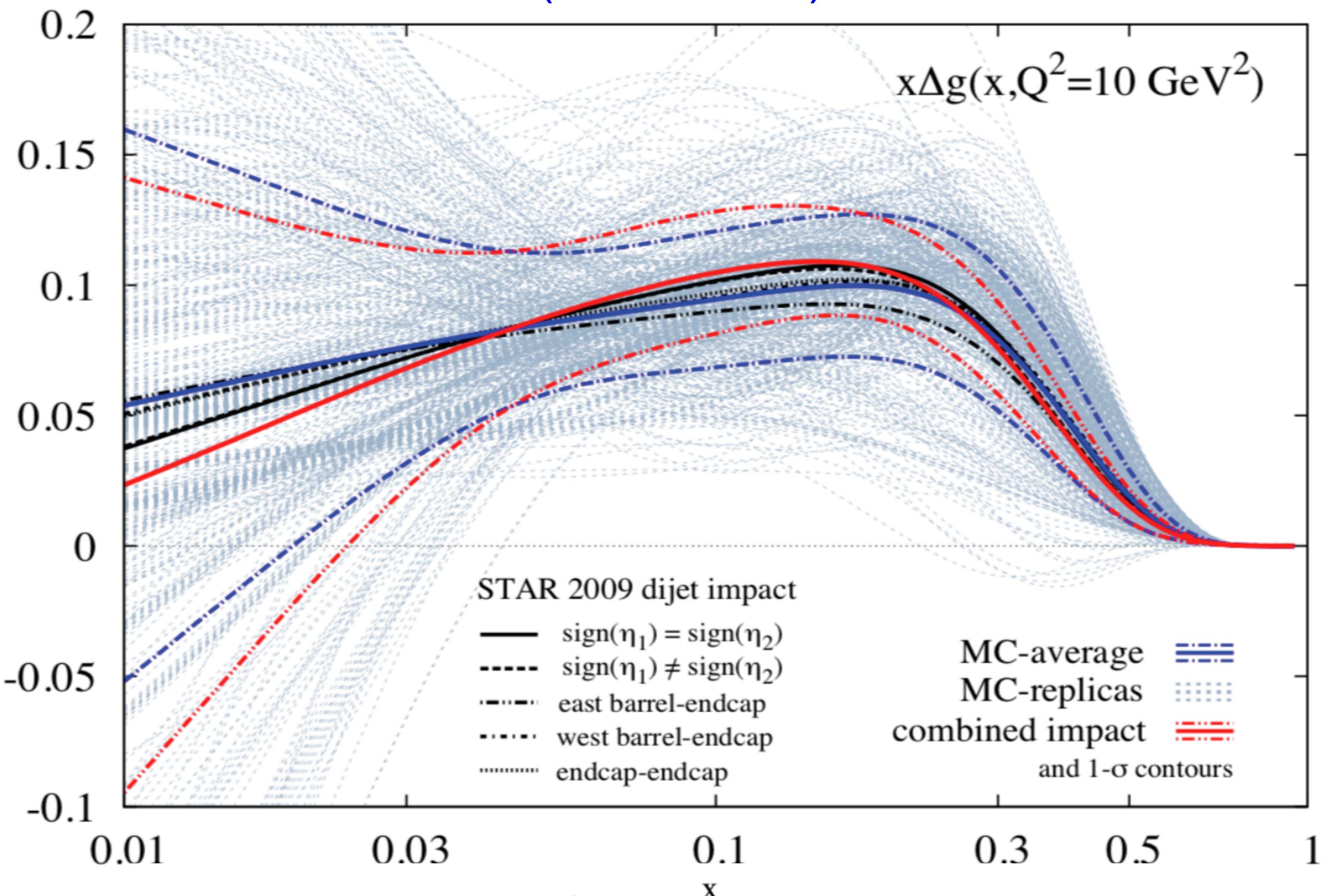




EicC：中国极化电子离子对撞机 白皮书 2020.1

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

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



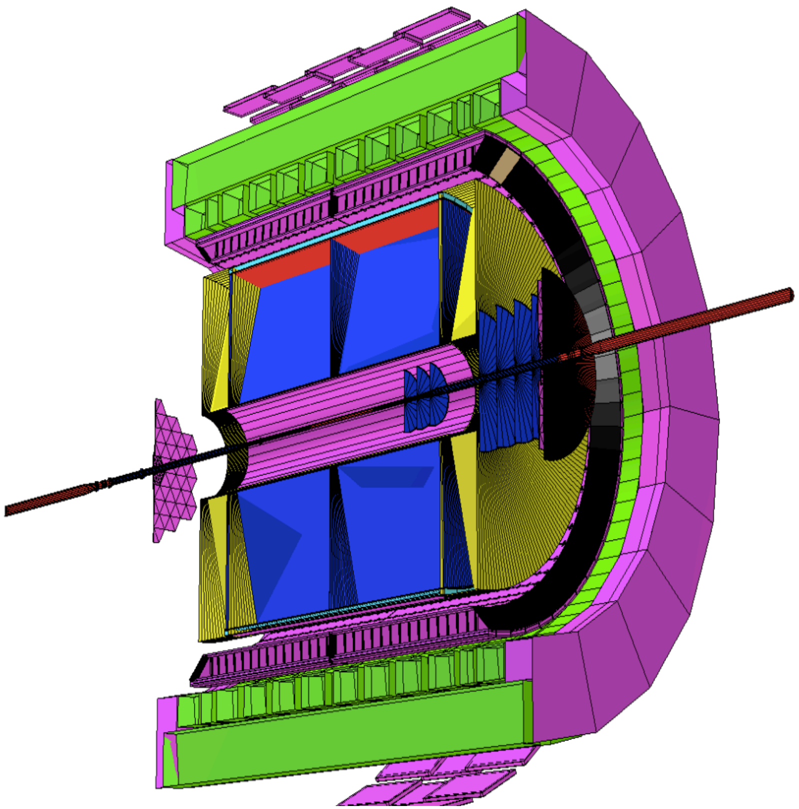
Before reweighting: $\int_{0.1}^{1} \Delta g(x)\,dx = 0.133 \pm 0.035$

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

Forward upgrade: FTS+FCS

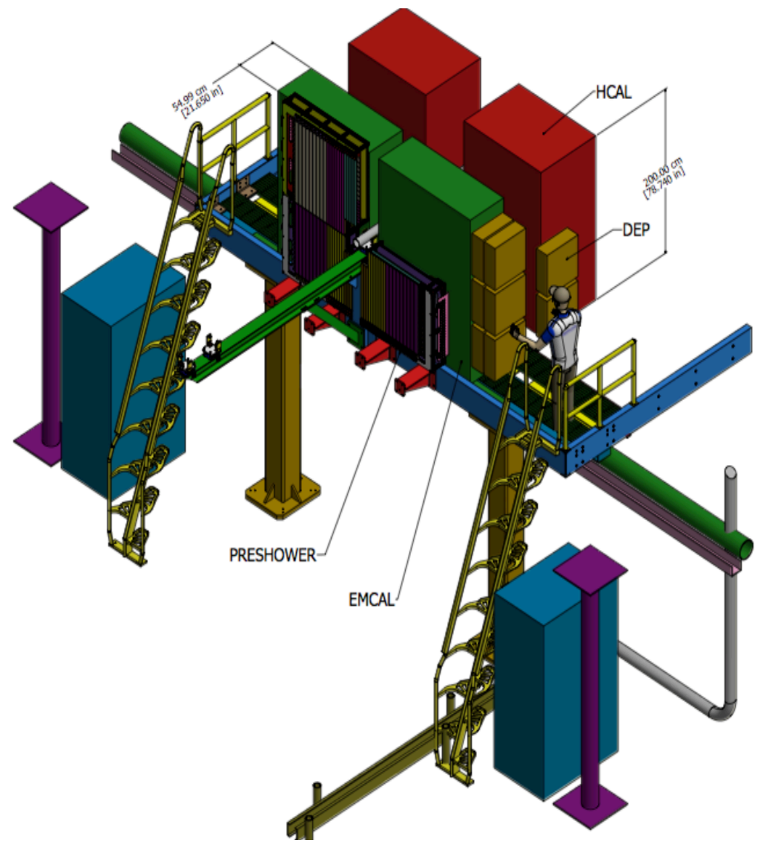
Forward Tracking System

Silicon + sTGC



Forward Calorimeter System

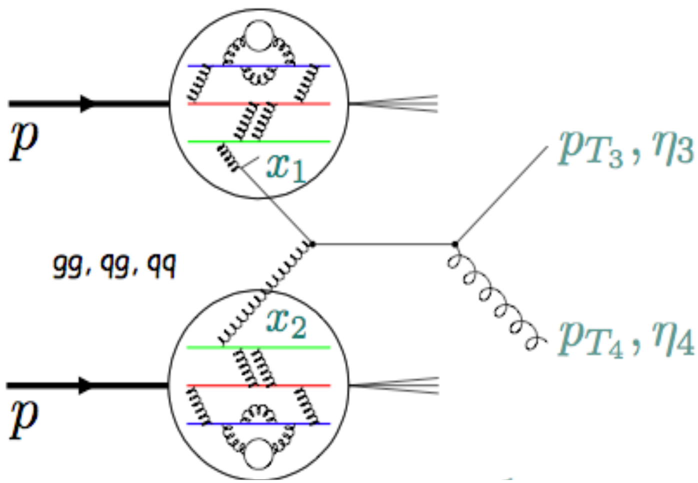
EM Cal + HCal



(2.5<η<4)

Correlation measurements with partonic kinematics

- Access to partonic kinematics through di-jet production



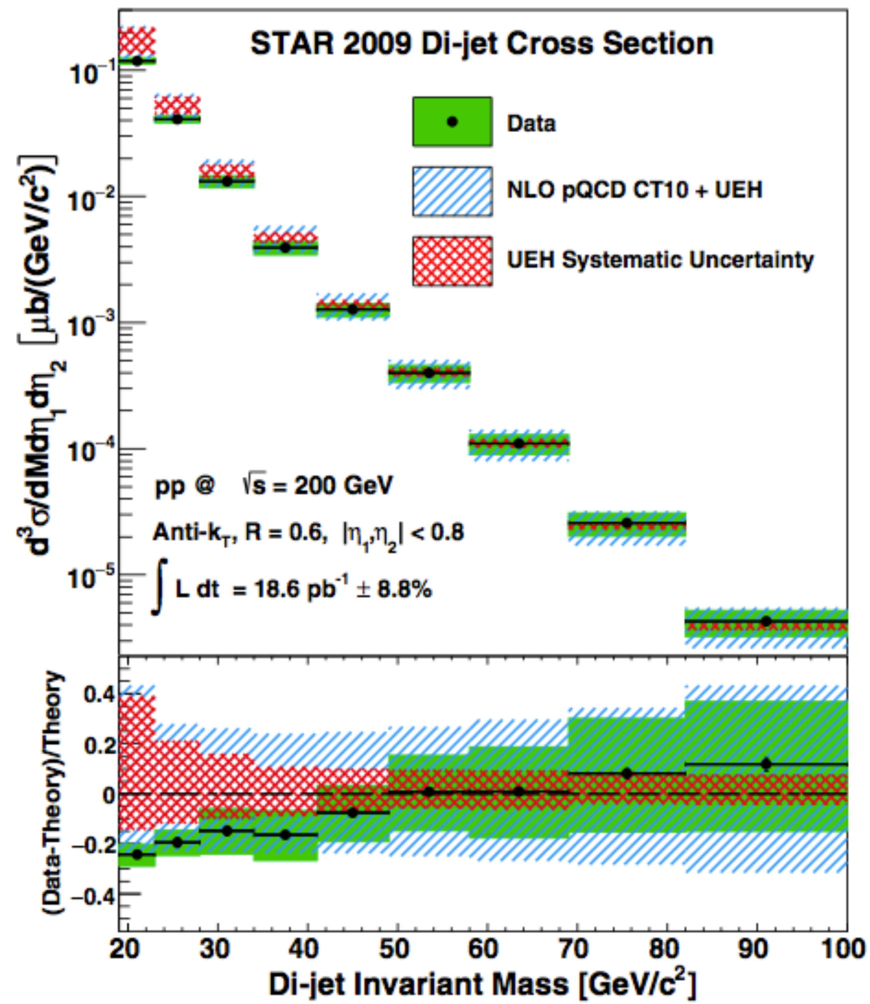
$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

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

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

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

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



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