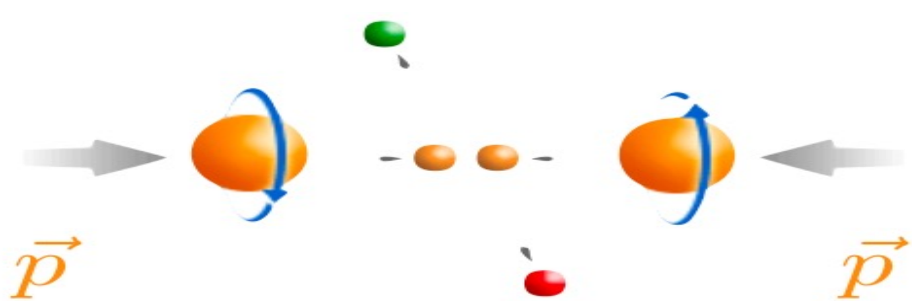
核子自旋结构研究的实验进展

徐庆华, 山东大学

Symposium on Nuclear Physics Frontiers and Intersections, Tsinghua, 2022.08



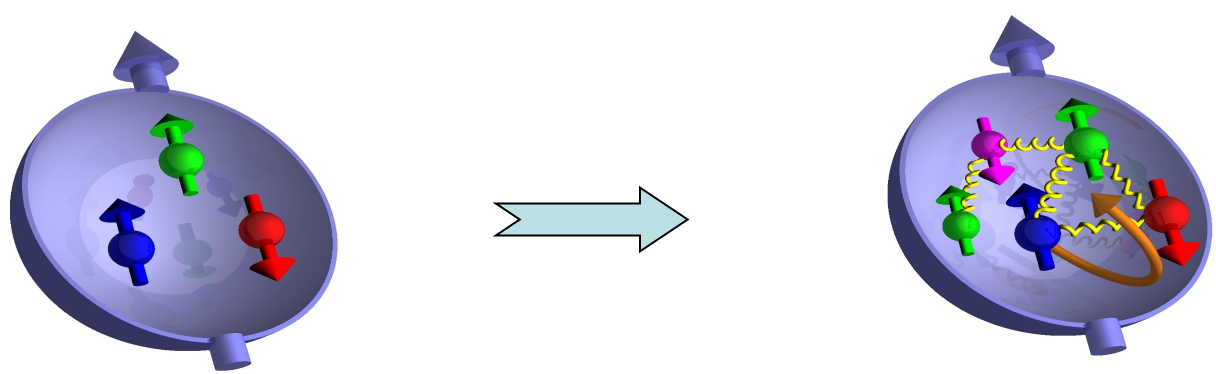
How does the spin of the nucleon arise?

- Spin, an important property of a nucleon, essential both to understanding atoms and their practical applications such as MRI. The origin of nucleon spin remains a fundamental question in QCD.

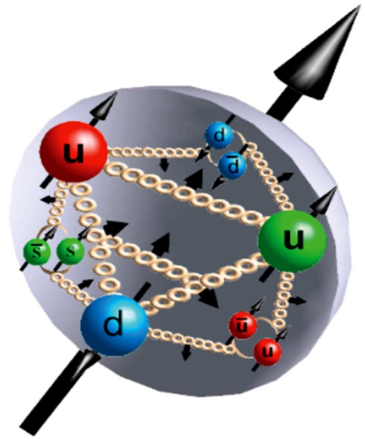
- In the naive Quark Model, the nucleon is made of three quarks - p(uud). The quark spins make up the nucleon spin, since the quarks are in the s-orbit:

$$\Delta\Sigma = 1 \qquad \left|p^{\uparrow}\right\rangle = \sqrt{\tfrac{2}{3}}\,u^{\uparrow}u^{\uparrow}d^{\downarrow} - \sqrt{\tfrac{1}{3}}\sqrt{\tfrac{1}{2}}\,(u^{\uparrow}u^{\downarrow} + u^{\downarrow}u^{\uparrow})\,d^{\uparrow}$$

- 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, sizable, ~40% RHIC

Orbital Angular Momenta Little known

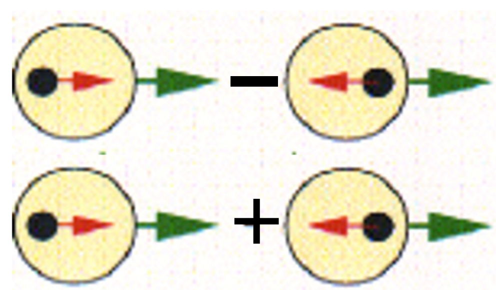
$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} \qquad [\Delta q = \int_0^1 \Delta q(x)dx]$$

-sea quark contribution still not well constrained yet!

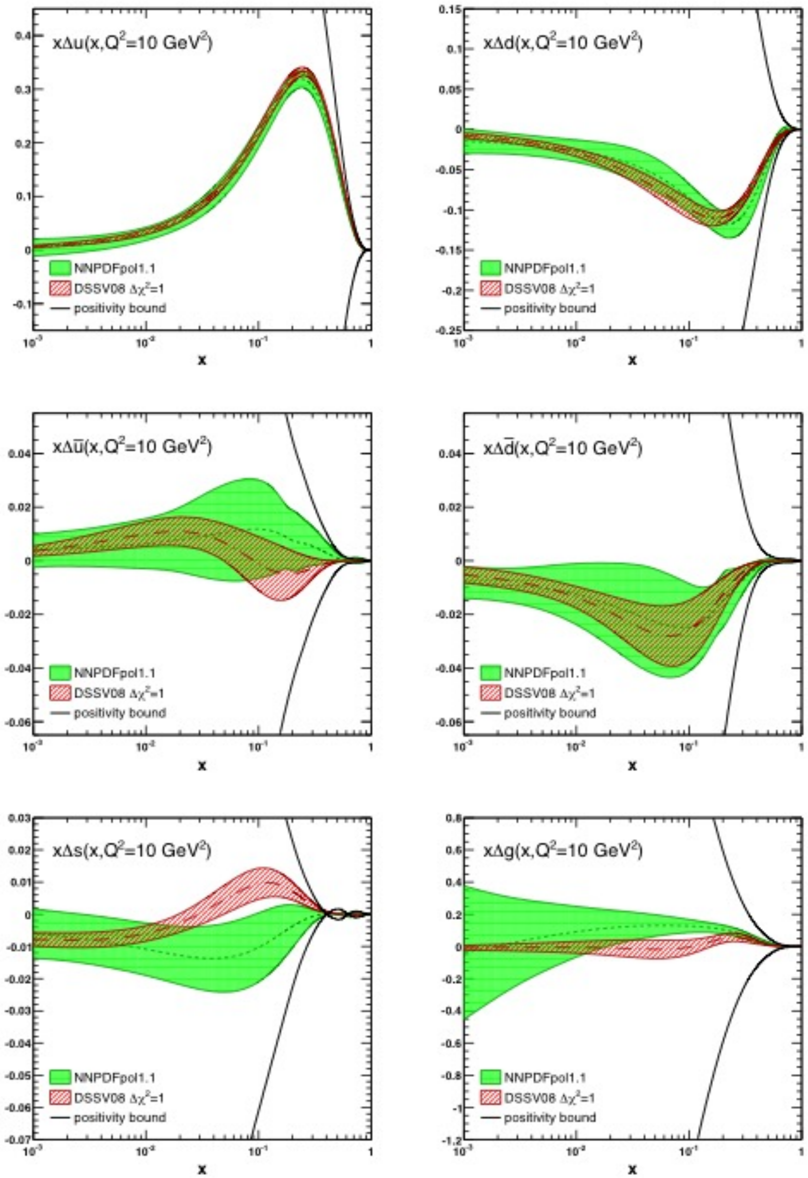
- Polarized parton densities:

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

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



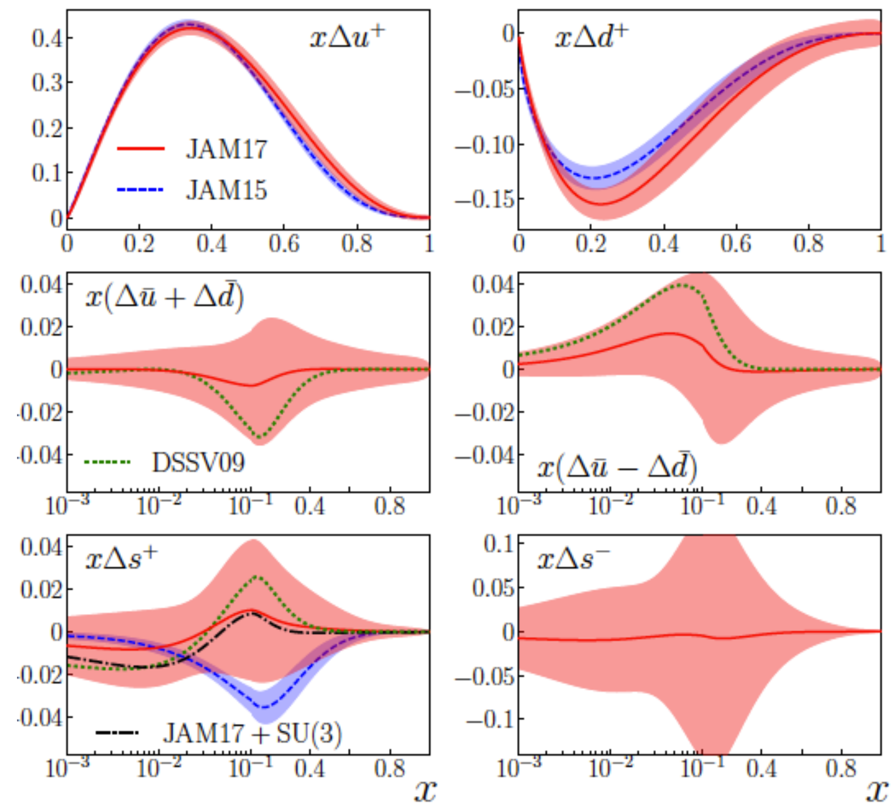
Detailed knowledge on Δq(x), Δg(x)- global fit



NNPDFpol1.1, NPB887（2014）276

- Valence quark helicity distribution well constrained, but still large uncertainty with sea quark and gluon parts

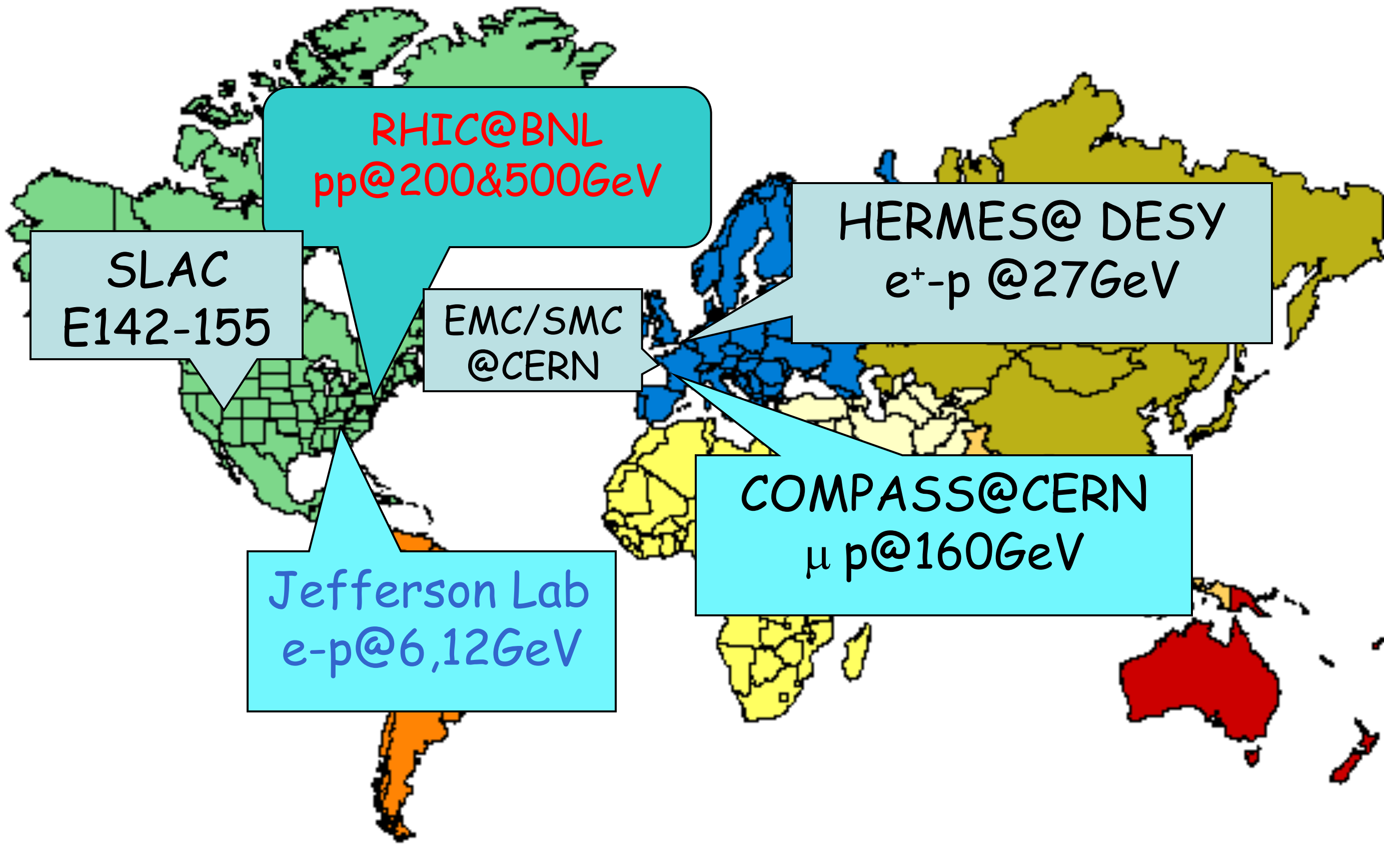
  -> more data needed!



JAM17, PRL**119**, 132001 (2017).

World efforts for spin physics facility

- Finished experiments: SLAC, EMC, SMC, HERMES
- Current running
  - Lepton-nucleon scattering: COMPASS, JLab
  - Polarized proton-proton scattering, RHIC (2001-)
- Future facilities
  - EIC (US, BNL)
  - EicC (China)
  - JPARC (Japan)
  - GSI-FAIR (Germany)
  - NICA (Russia)



They are complementary to each other

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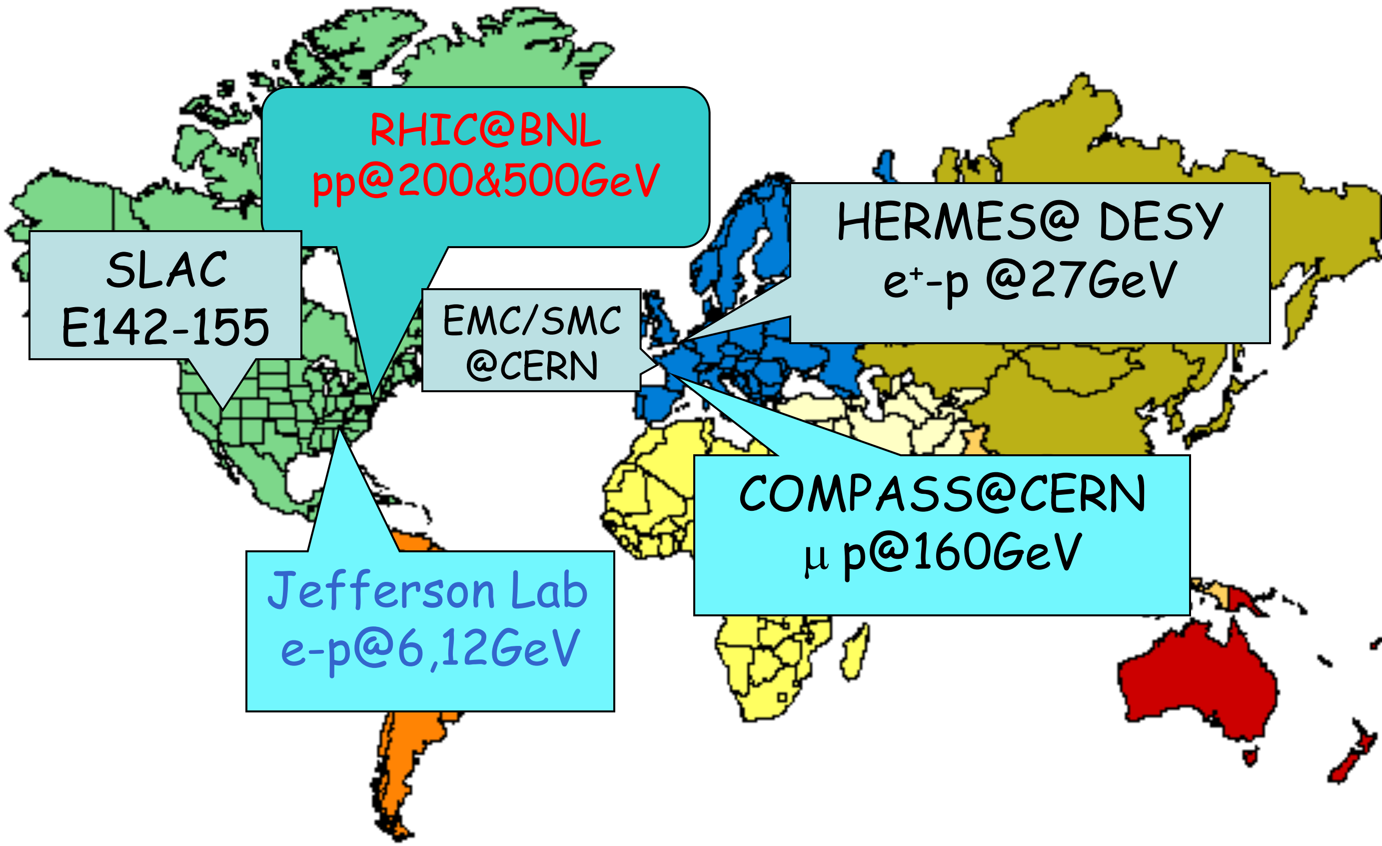


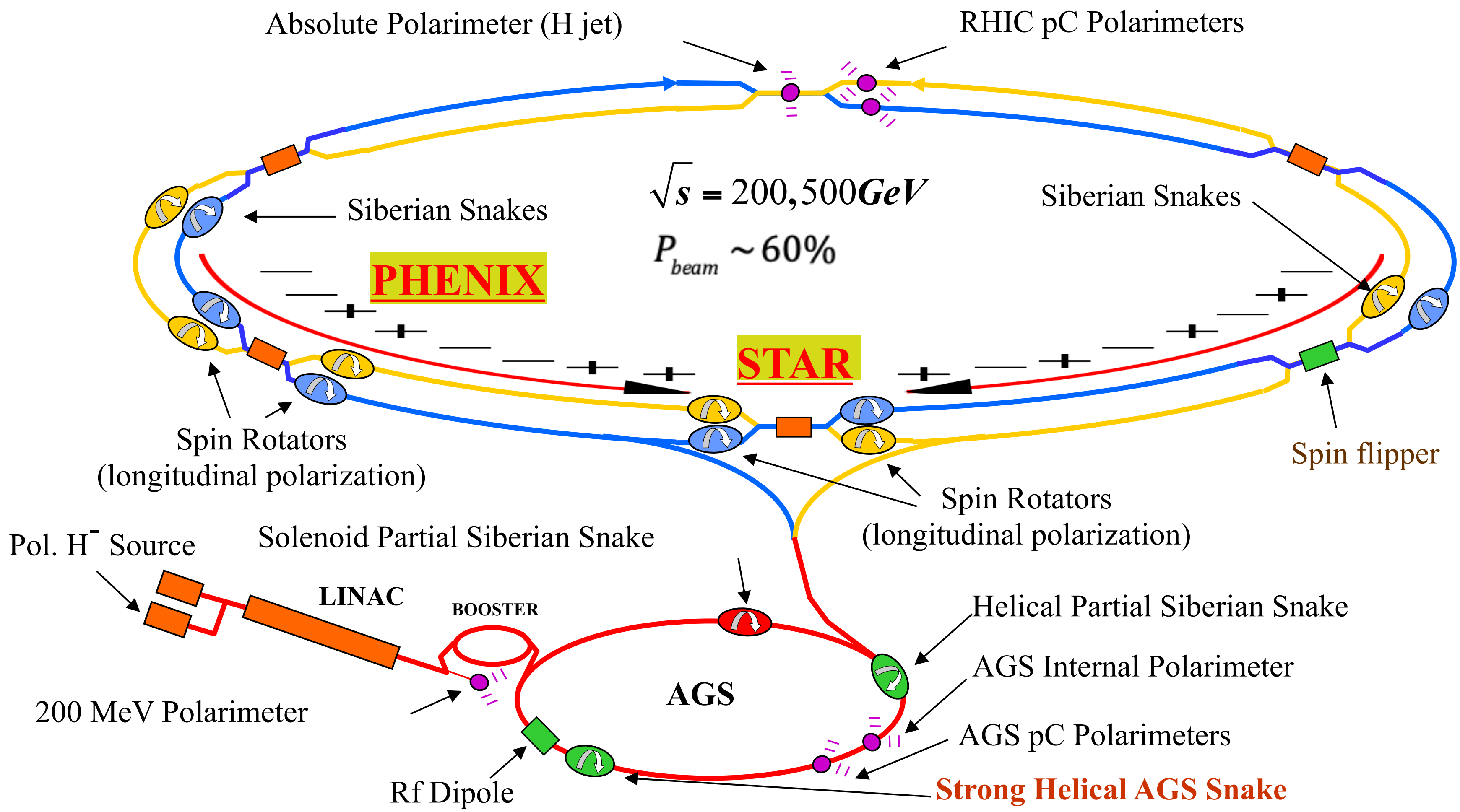
They are complementary to each other

*I will focus on the recent RHIC results

Outline:

- Experimental aspects: RHIC
- Recent RHIC-STAR spin highlights:
  - ✓ 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 (π^0, jets, W/Z): Collins & Sivers
- Future plan at RHIC and EIC/EicC
- Summary

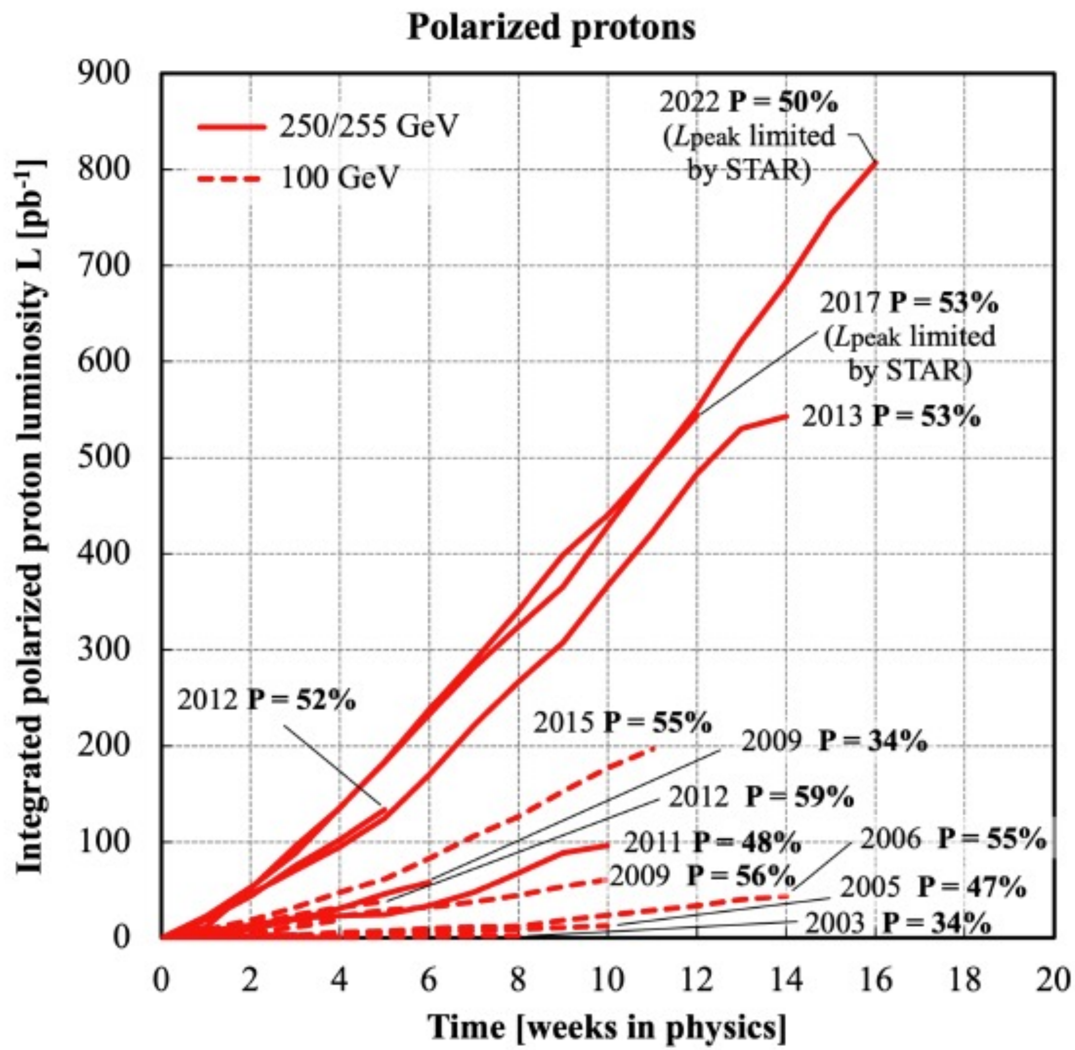
RHIC- 1st polarized proton-proton collider



- Spin direction changes from bunch to bunch, longitudinal or transverse
- Two main experiments: PHENIX & STAR, have been working since 2004
- STAR is only detector at RHIC during 2017-2022

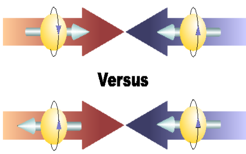
RHIC performance with pp collisions

- 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, 2015 at 200GeV and 2011, 2017, 2022 at 500 GeV.



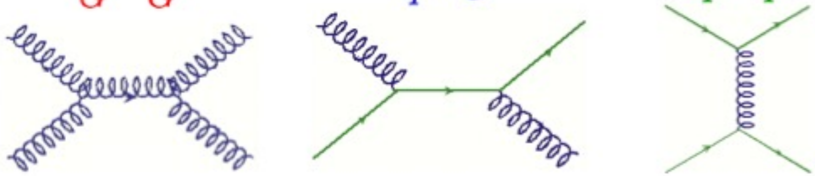
Accessing $\Delta g(x)$ in pp collision

- Longitudinal spin asymmetry: $\boxed{\Delta f_1}$ $\boxed{\Delta f_2}$ $\boxed{\hat{a}_{LL} = \frac{d\Delta\hat{\sigma}}{d\hat{\sigma}}}$ $\boxed{D_f^\pi}$

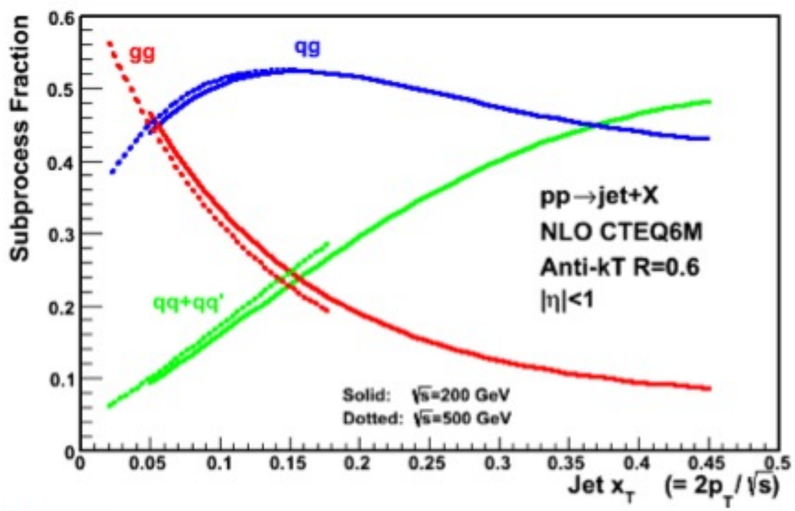


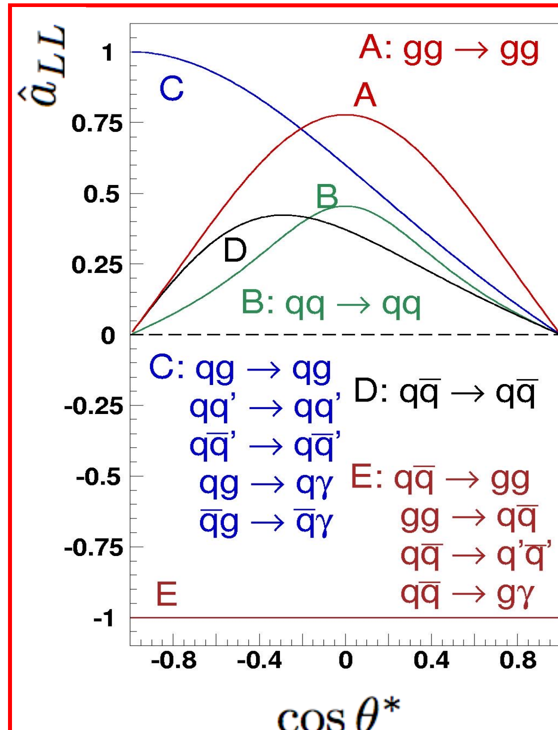
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \cdot \hat{a}_{LL}^{f_1 f_2 \to fX} \otimes D_f^\pi}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^\pi}$$

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



- Partonic fraction for jet/π^0 production:

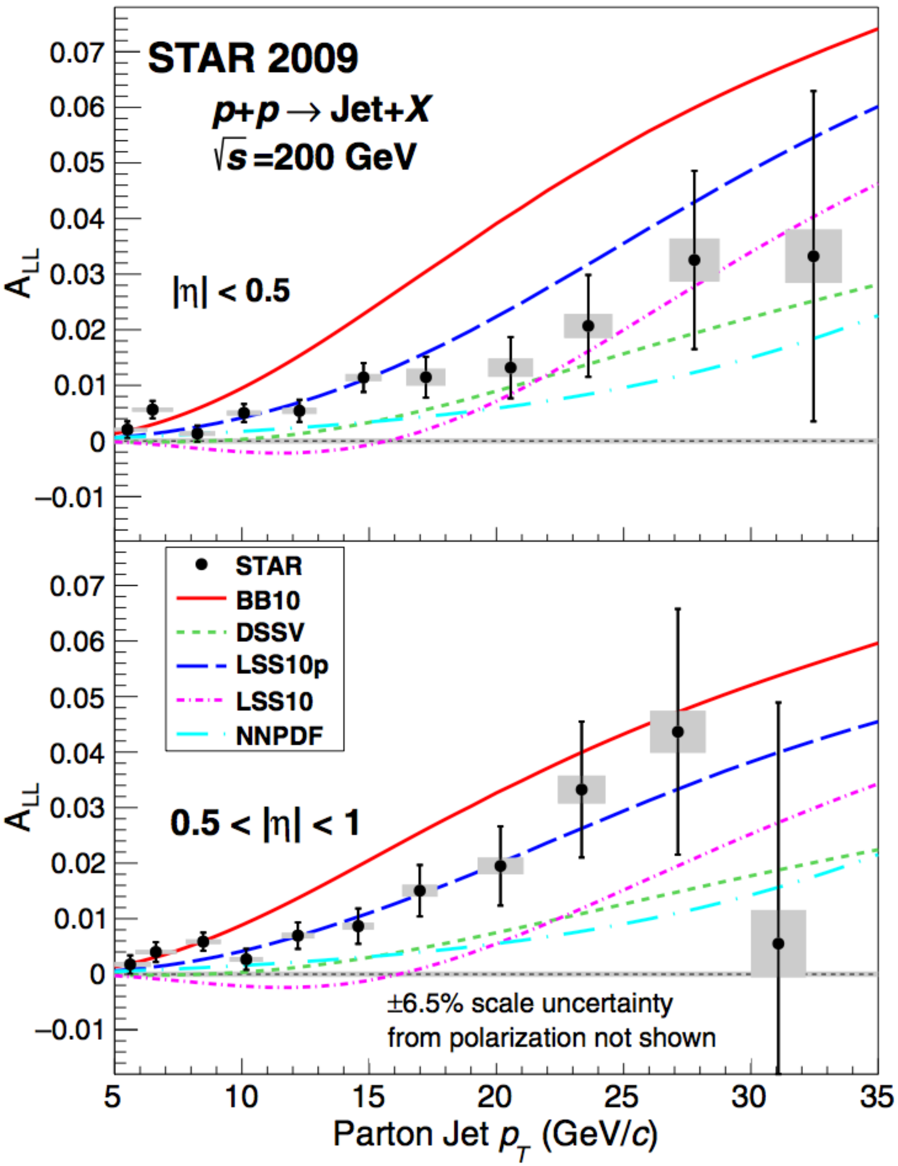




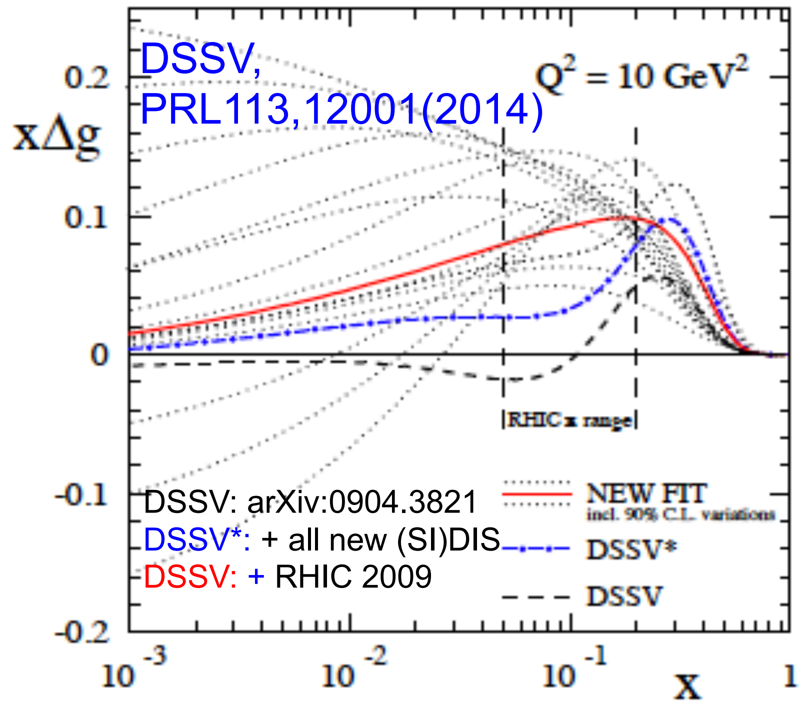
G. Bunce et al, Annu. Rev. Nucl. Part. Sci. 50, 525(2000)

STAR inclusive jet A_{LL} from 2009 data and Δg

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



- Impact of STAR data on Δg in DSSV global analysis:



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

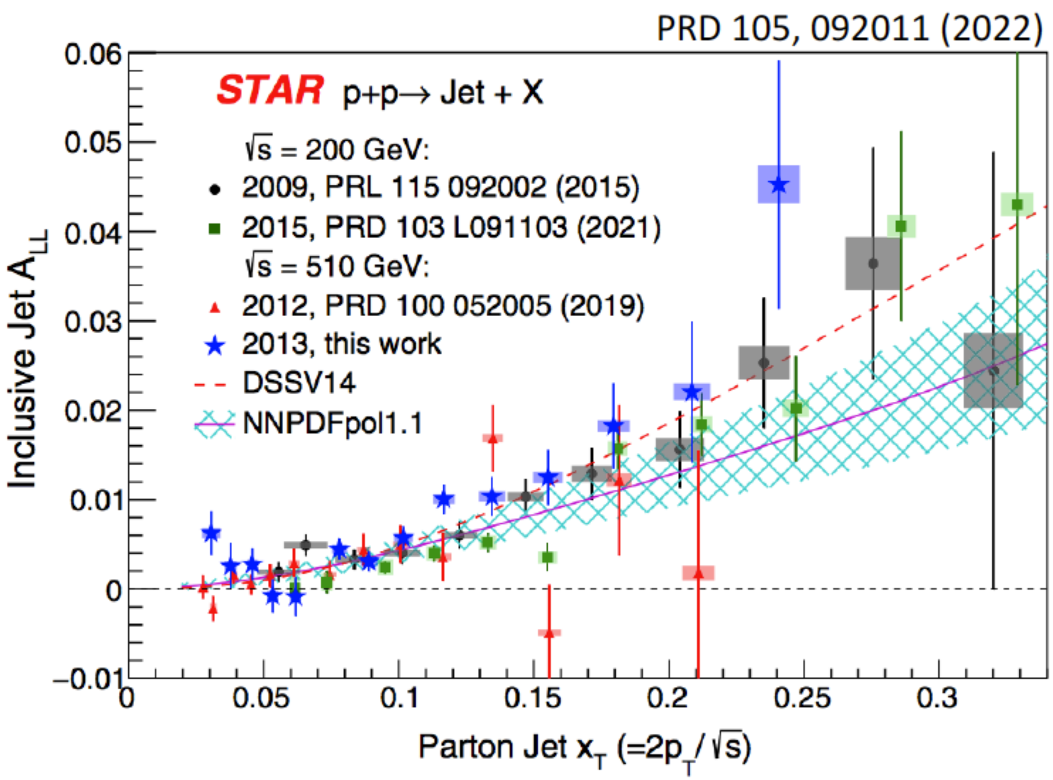
➢ 1st Lattice calculation:

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

χQCD, PRL118,102001(2017)

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

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



STAR jet A_{LL} data & publication:

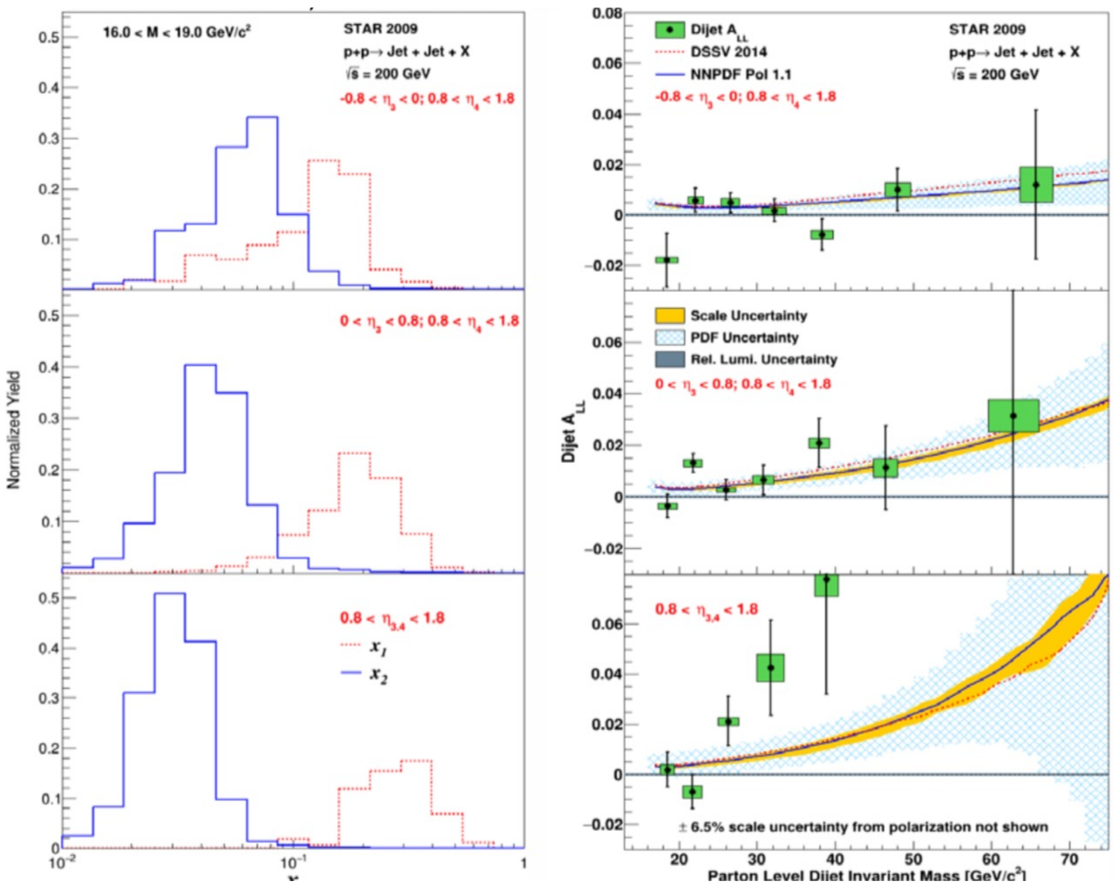
200GeV:
2009: PRL115,92002(2015)
2015: PRD103,91103(2021)

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

Di-jet A_{LL} results at STAR

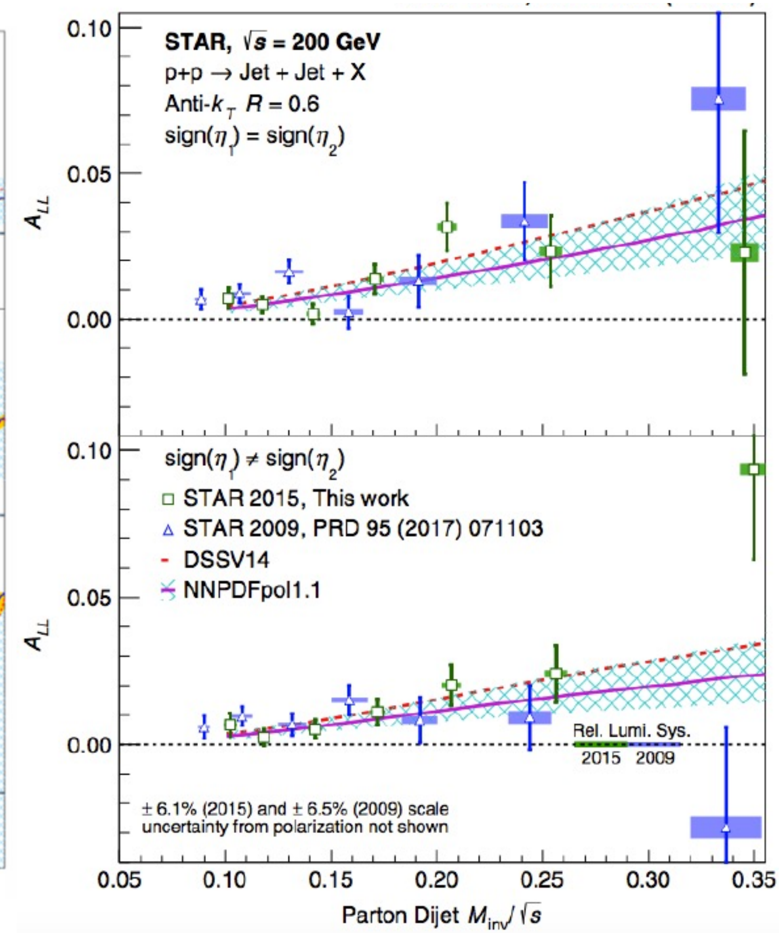
- Di-jet provide wider coverage to access lower x region:

STAR, PRD98,032011(2018)



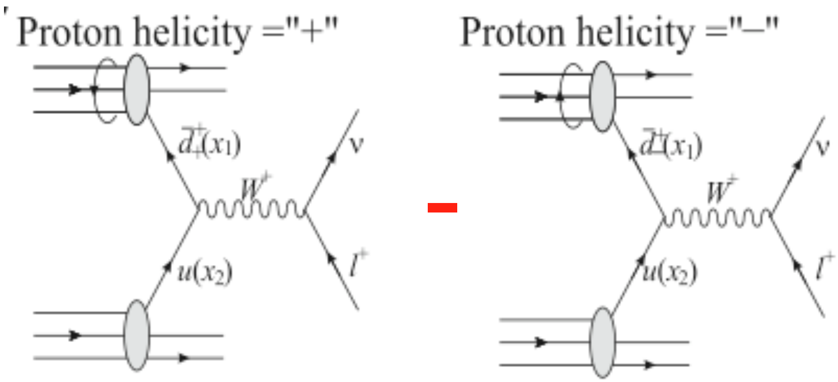
STAR, PRD105,92011(2022)

STAR, PRD103,91103(2021)



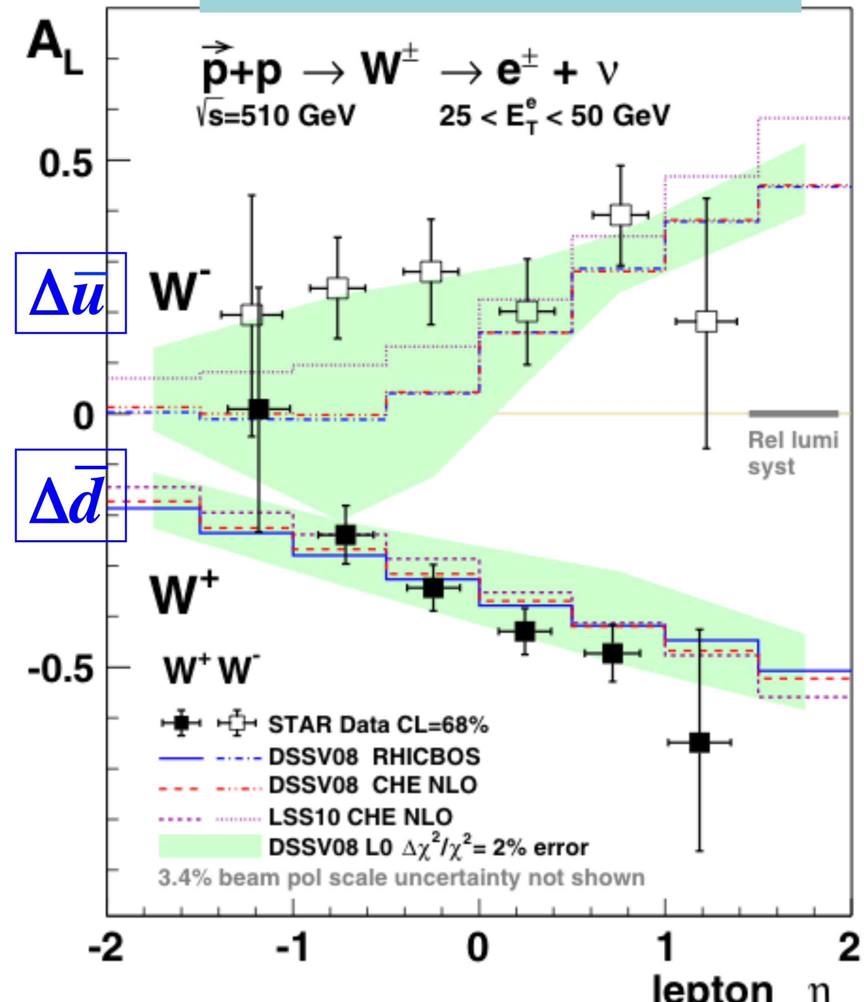
Probing sea quark polarization via W boson

- Unique quark polarimetry with W at RHIC:



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

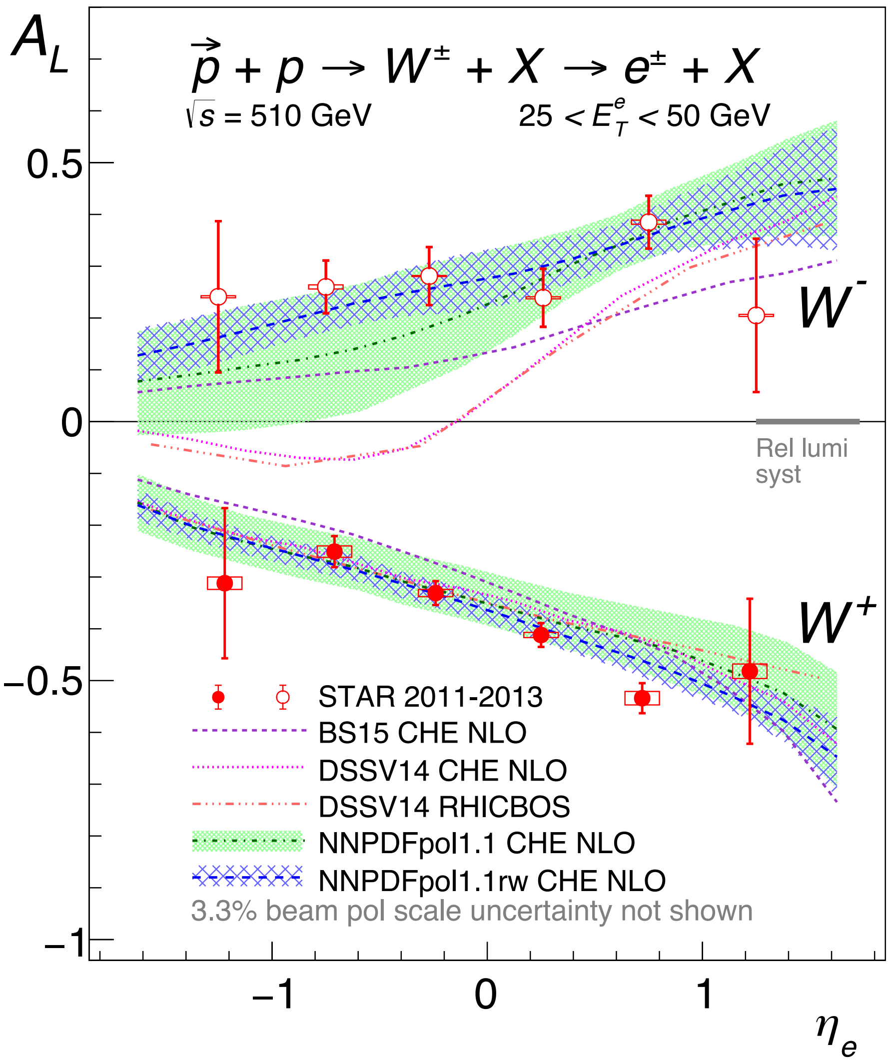
W A_L from 2011+2012



STAR, PRL113, 72301(2014)

- Spin asymmetry A_L measurements provides a powerful tool to probe sea quark polarization

STAR W A_L results – 2013



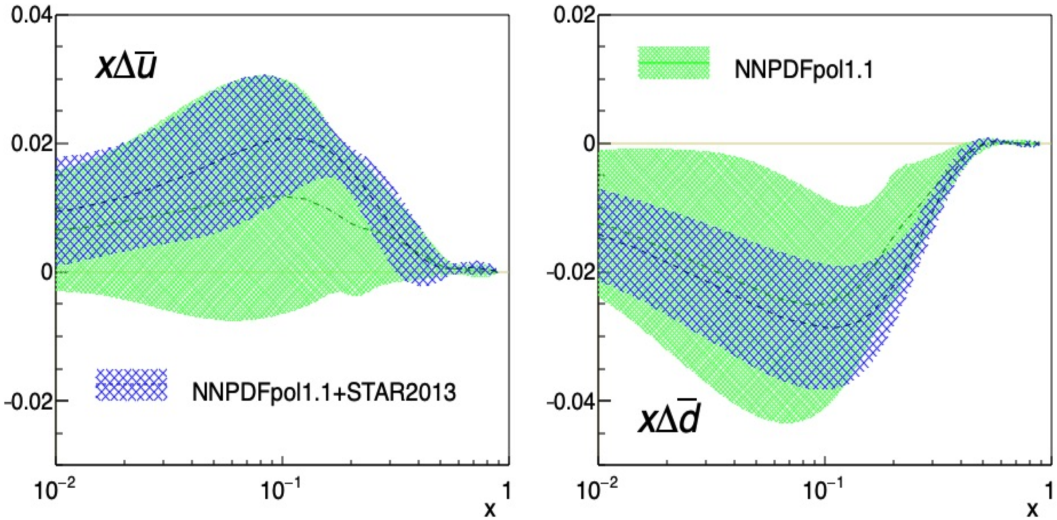
STAR, PRD99, 051102R(2019)

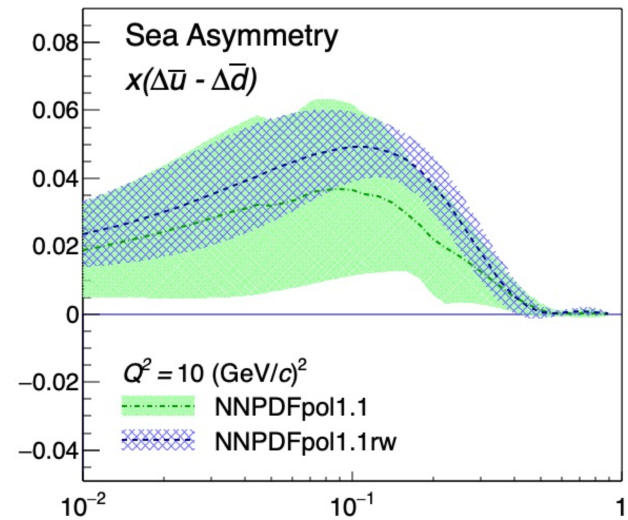
- ✓ Most precise W A_L results from 2013 STAR dataset
- ✓ Consistent with published RHIC results; with 40-50% smaller uncertainties than STAR 2011+2012 results
- ✓ Confirmed positively polarized anti-up quark first seen in the 2011+2012 data.

Impact of STAR 2013 W A_L results

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

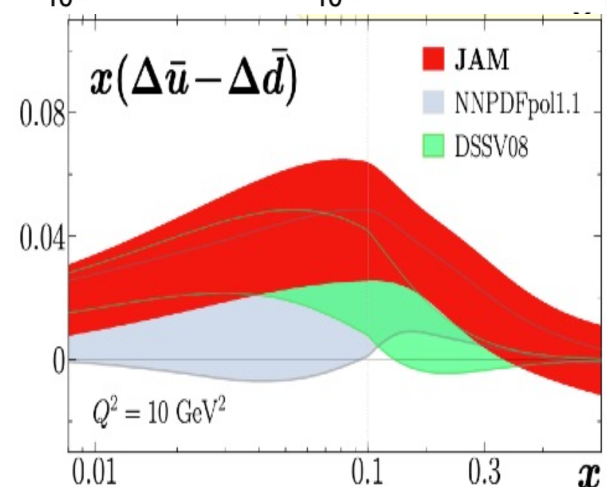
$\Delta\bar{u} > \Delta\bar{d}$





STAR, PRD99, 051102R(2019)

✓ Compatible with Pauli suppression by the polarized valence quarks, among different models.



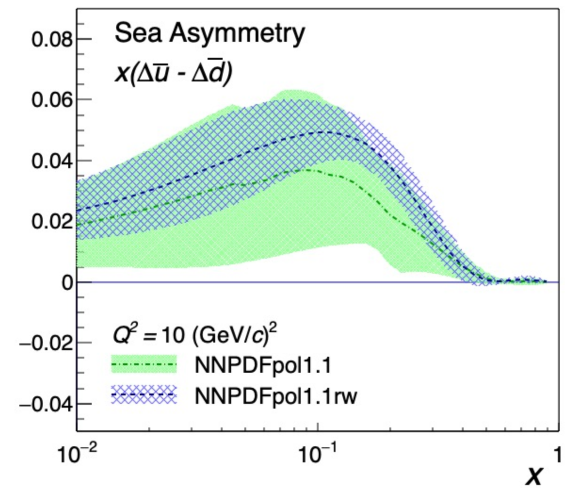
JAM, arXiv:2202.03372]

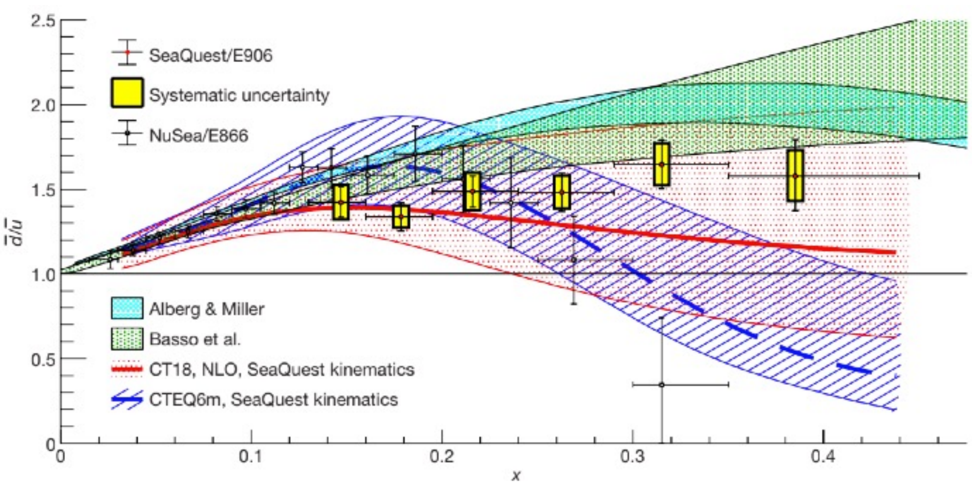
Impact of STAR 2013 W A_L results

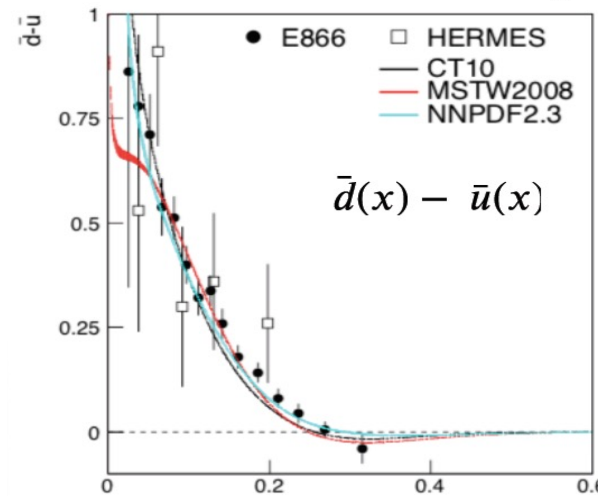
- SU(2) flavor asymmetry observed in the polarized sea quark distribution, confirmed by JAM and reweighting NNPDF:

$$\Delta\bar{u} > \Delta\bar{d}$$

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







- SeaQuest, Nature 590, (2021)561

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

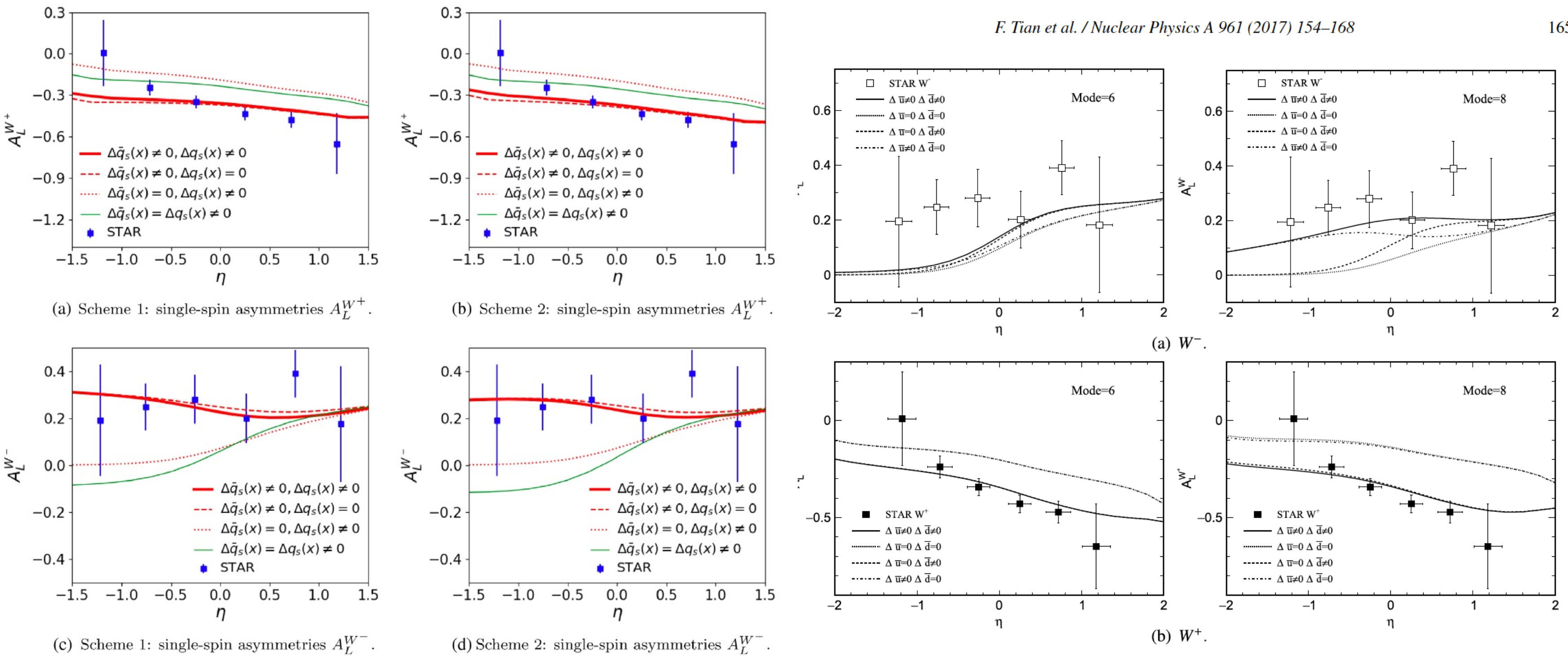
x

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)

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



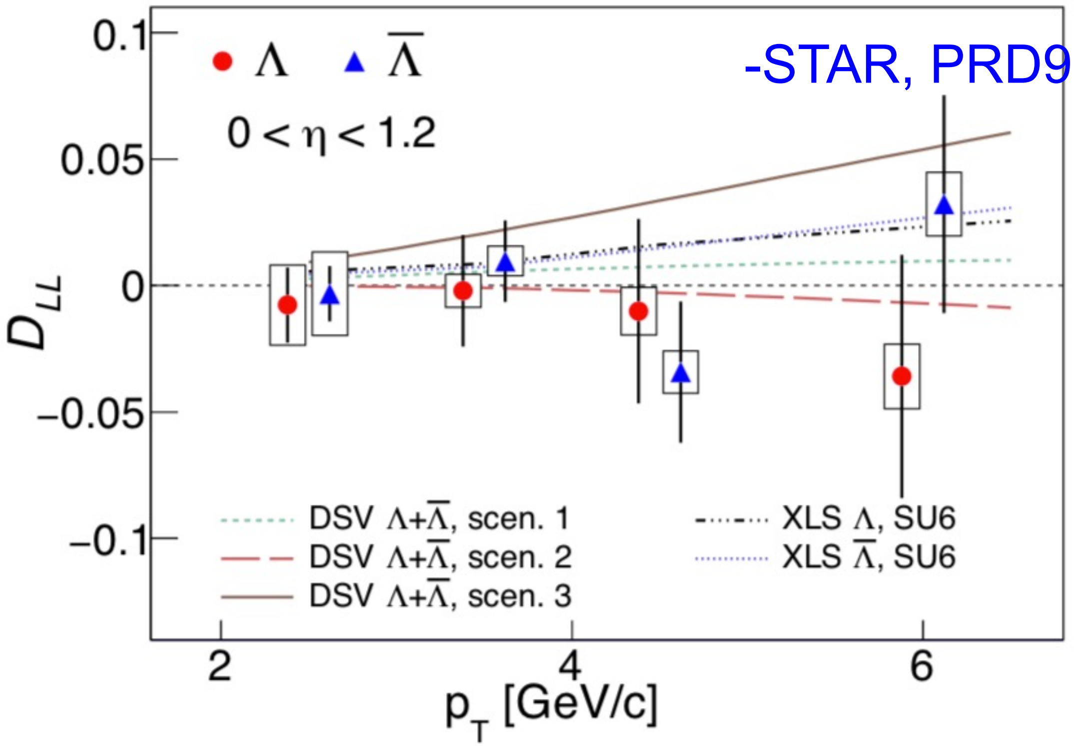
(a) Scheme 1: single-spin asymmetries $A_L^{W^+}$.
(b) Scheme 2: single-spin asymmetries $A_L^{W^+}$.
(c) Scheme 1: single-spin asymmetries $A_L^{W^-}$.
(d) Scheme 2: single-spin asymmetries $A_L^{W^-}$.
(a) W^-.
(b) W^+.

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

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

- Longitudinal spin transfer of Λ hyperons, D_{LL}, in pp collisions, can provide sensitivity to strange quark polarization Δs :

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



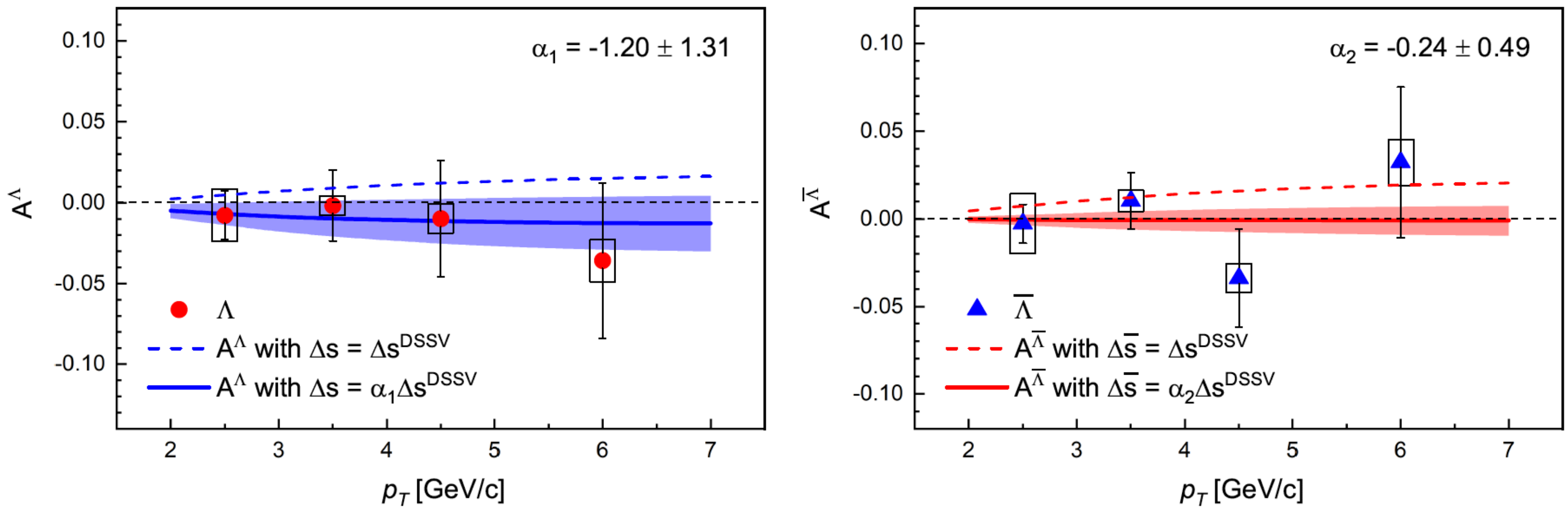
-STAR, PRD98, 112009 (2018)

- 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 of (anti-)Lambda at STAR

- Theoretical studies show impact on asymmetry of strange and anti-strange quark polarization:
  - X.N. Liu, B. Q. Ma, Eur.Phys.J. C79 (2019) 409



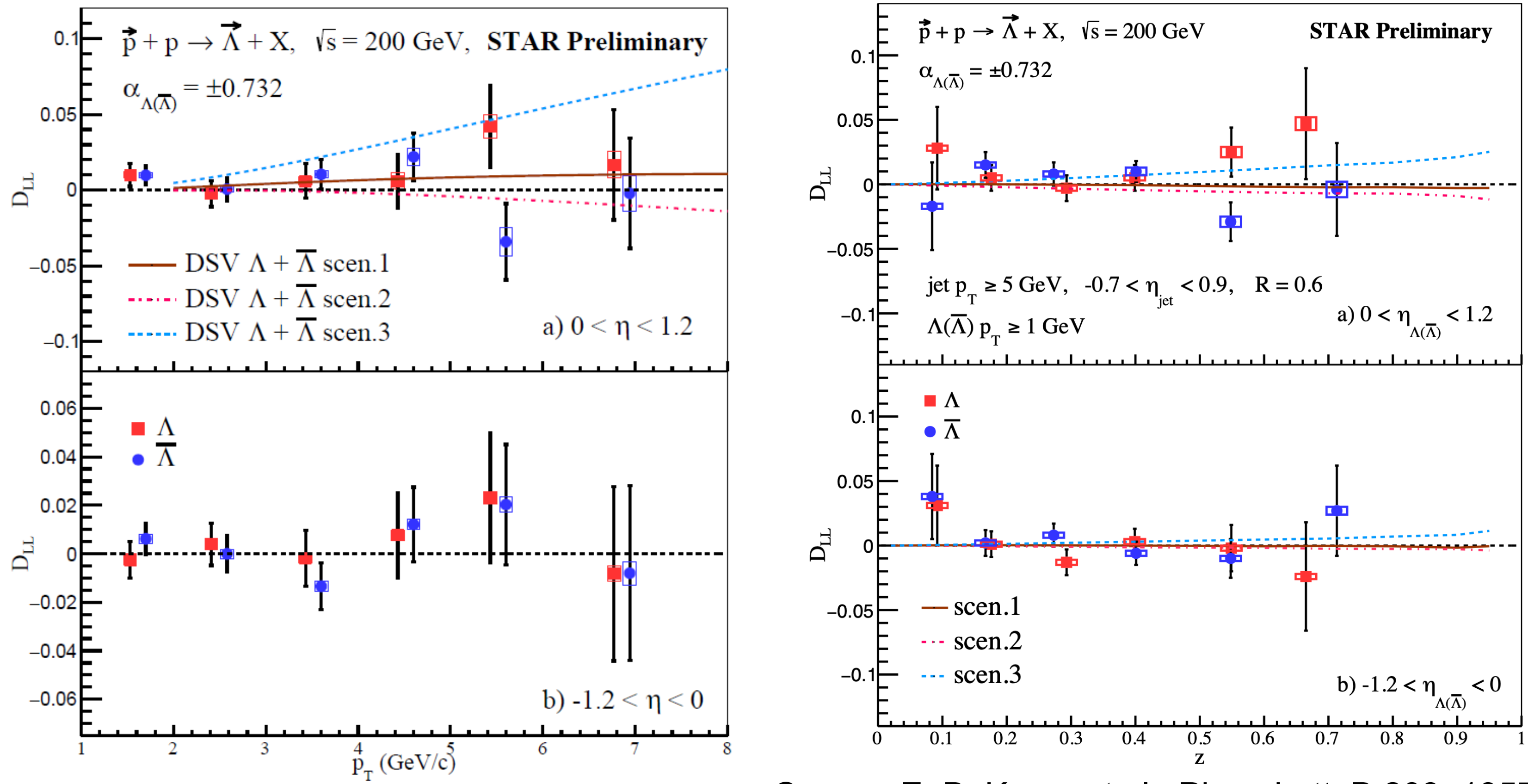
(a) Longitudinal spin transfer to Λ. (b) Longitudinal spin transfer to $\bar{\Lambda}$.

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

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

New D_{LL} results versus p_T and z at STAR

- The hyperon p_T range is extended up to ~ 7 GeV/c.
- Data are in agreement with various scenarios within uncertainties.
- Most precise measurements on D_{LL} to date.

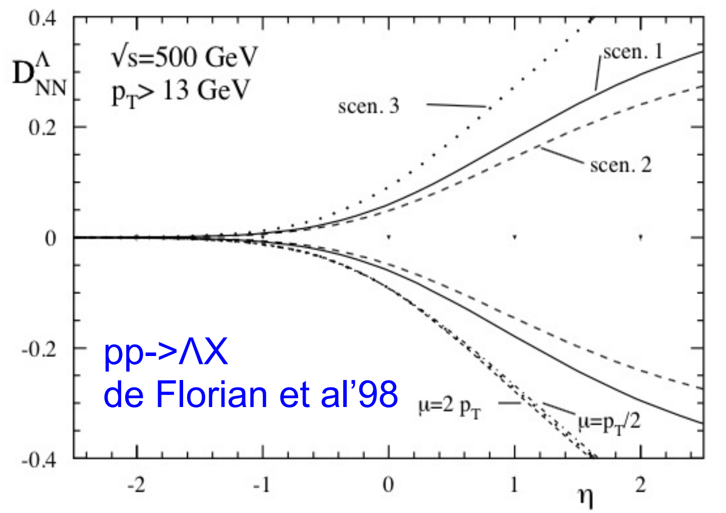


Curves: Z.-B. Kang, et al., Phys. Lett. B **809**, 135756 (2020).

Transverse spin transfer of hyperons and $\delta q(x)$

- Transverse spin transfer of hyperons provide access to transversity and transversely pol. frag. function:

$$D_{TT} \equiv \frac{d\sigma^{(p^\uparrow p \to H^\uparrow X)} - d\sigma^{(p^\uparrow p \to H^\downarrow X)}}{d\sigma^{(p^\uparrow p \to H^\uparrow X)} + d\sigma^{(p^\uparrow p \to H^\downarrow X)}} = \frac{d\Delta_T \sigma}{d\sigma}$$



$$d\Delta_T\sigma^{(pp\to HX)} \propto \sum_{abcd} \int dx_a\, dx_b\, dz\, \delta f_a(x_a) f_b(x_b) \Delta_T D_c^H(z) d\Delta_T \hat{\sigma}^{(ab\to cd)}$$

transversity distribution
Poorly known pol. pdf

Transversely polarized
fragmentation function

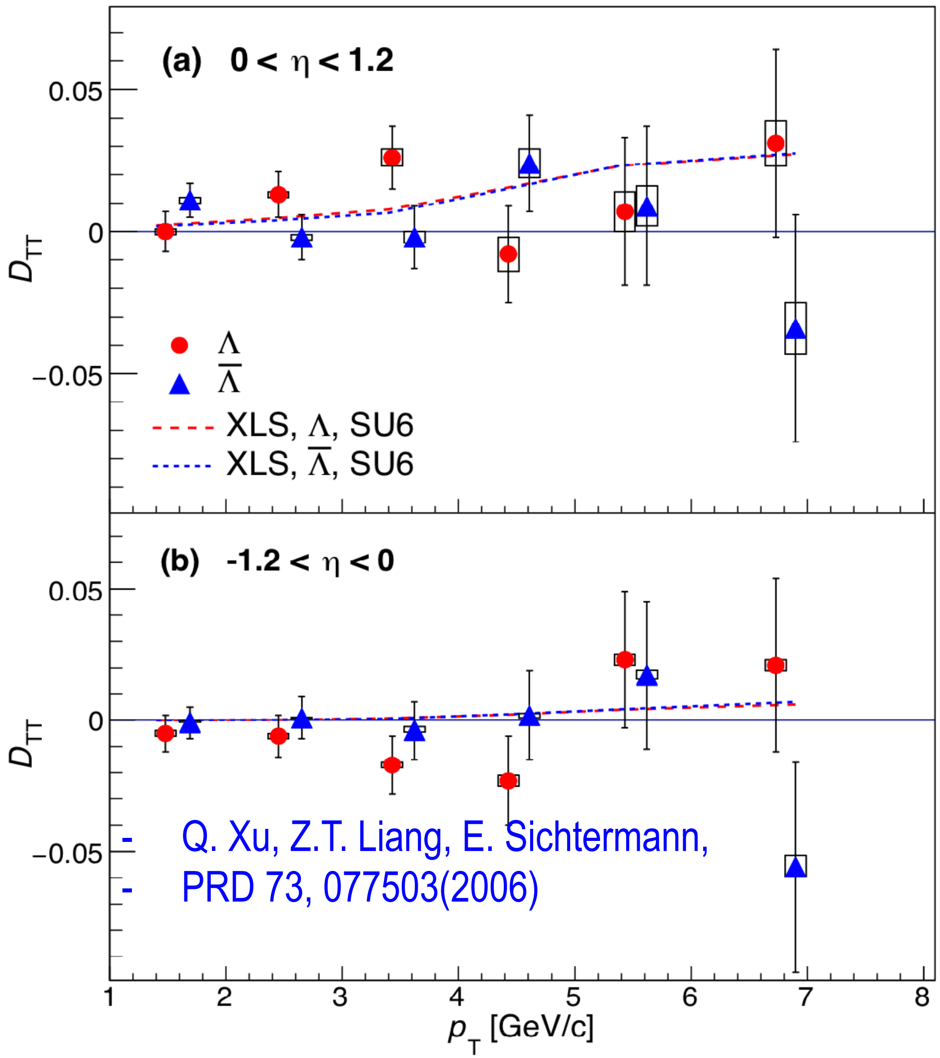
pQCD

- D. de Florian, J. Soffer, M. Stratmann, W. Vogelsang, PLB439, 176 (1998).
- Q. Xu , Z. T. Liang, PRD70, 034015 (2004).
- Q. Xu, Z. T. Liang, E. Sichtermann, PRD73, 077503 (2006).

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)



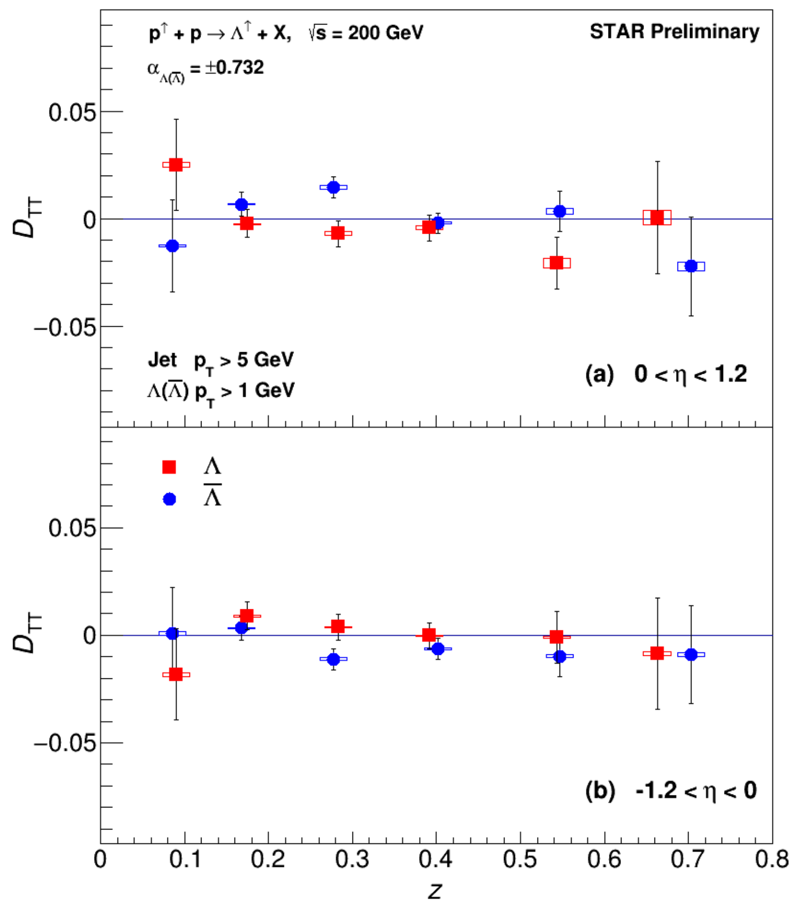
✓ 1st transverse spin transfer measurement in p+p collisions at RHIC.

✓ 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.

Transverse spin transfer D_{TT} results at STAR

- **First measurement of $\boldsymbol{D_{TT}}$ vs. z** for $\Lambda(\bar{\Lambda})$ in pp collisions.
- The results indicate that the strange quark transversity distribution and/or the polarized fragmentation function of $\Lambda(\bar{\Lambda})$ is small.



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

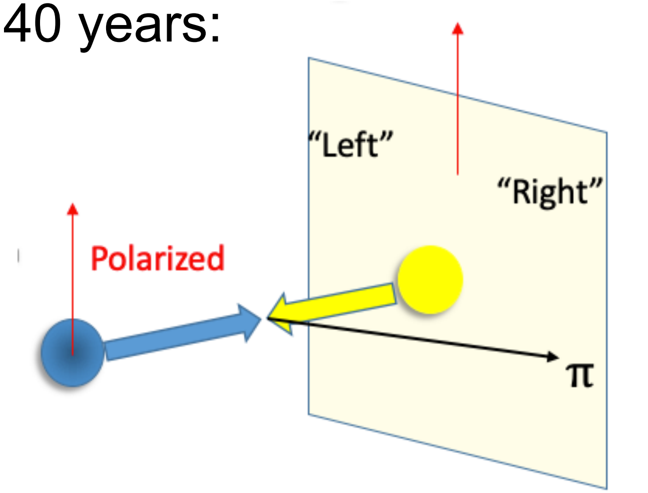
Transverse Single-spin Asymmetries

- Anomalously large A_N observed for nearly 40 years:

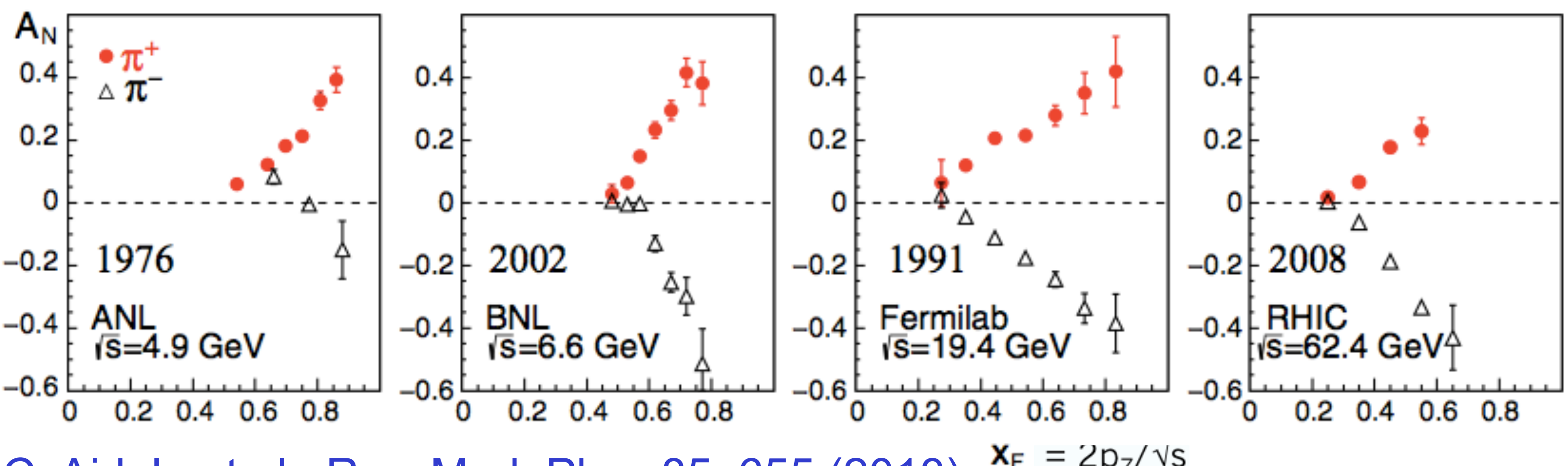
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

- LO QCD predicts $A_N \sim 0$

G. L. Kane, et al., PRL41, 1689 (1978)



- Left-right asymmetries for different hadrons at different beam energies



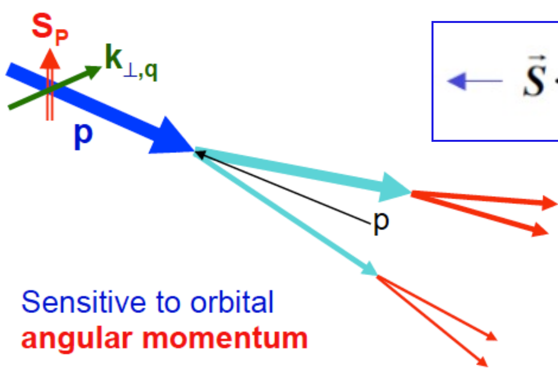
C. Aidala et al., Rev. Mod. Phys.85, 655 (2013)

Mechanisms for Transverse Single-spin Asymmetries

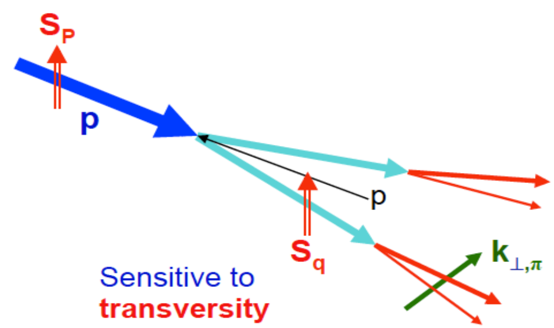
- Two QCD-based frameworks:

  - Transverse Momentum Dependent (TMD) parton distribution or fragmentation functions. Need two scales (Q and p_T), $Q \gg p_T$

    - **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)



$$\longleftarrow \vec{S}\cdot(\vec{p}\times\vec{k}_\perp) \longrightarrow$$



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

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

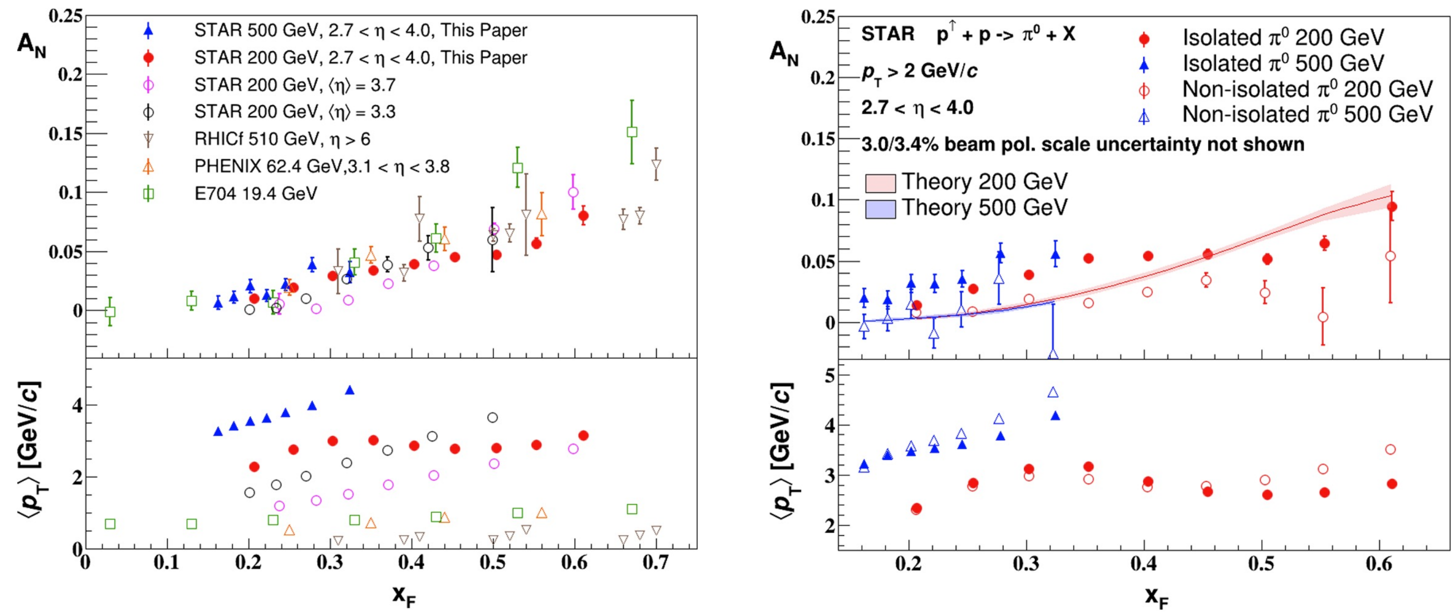
    Need one scale (Q or p_T), Q, $p_T \gg \Lambda_{QCD}$

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

Ji-Qiu-Vogelsang-Yuan,2006

Forward π^0，EM-jet A_N at STAR

- New precision results π^0 A_N from STAR at both 200 and 510 GeV
- New observation of topological dependence of π^0 A_N : isolated π^0 has larger A_N than other π^0 -> diffractive contribution?

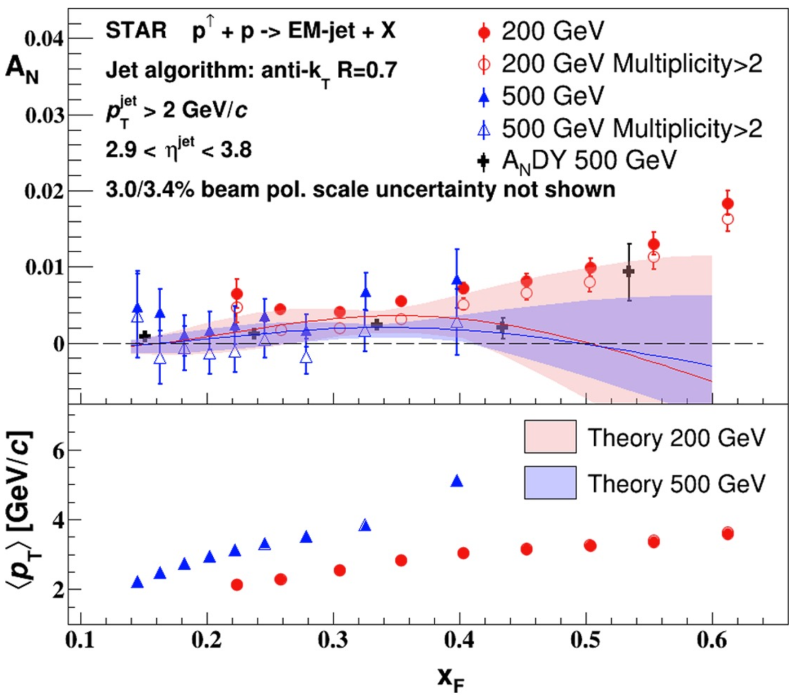


STAR, Phys. Rev. D103, 92009 (2021)

- For hadron SSA, both Sivers and Collins effects can contribute.
- Study of jet production can separate Collins & Sivers effects.

Searching A_N origin : EM-jet TSSA

- Jet A_N - sensitive to the initial state effect, related to Sivers effect, decoupled from Collins effect



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

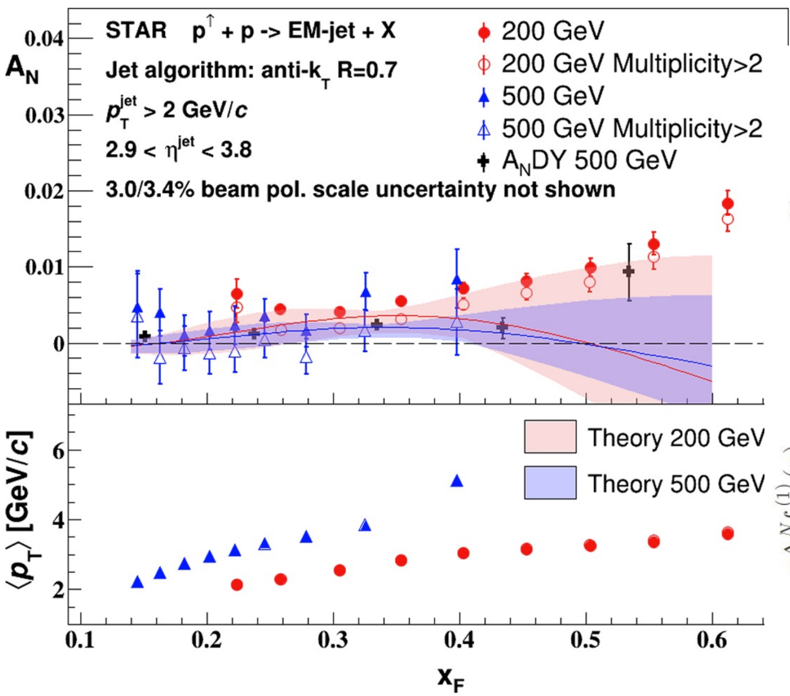
*L. Gamberg, Z. Kang, A. Prokudin, Phys.Rev.Lett.*110(2013)23,232301

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

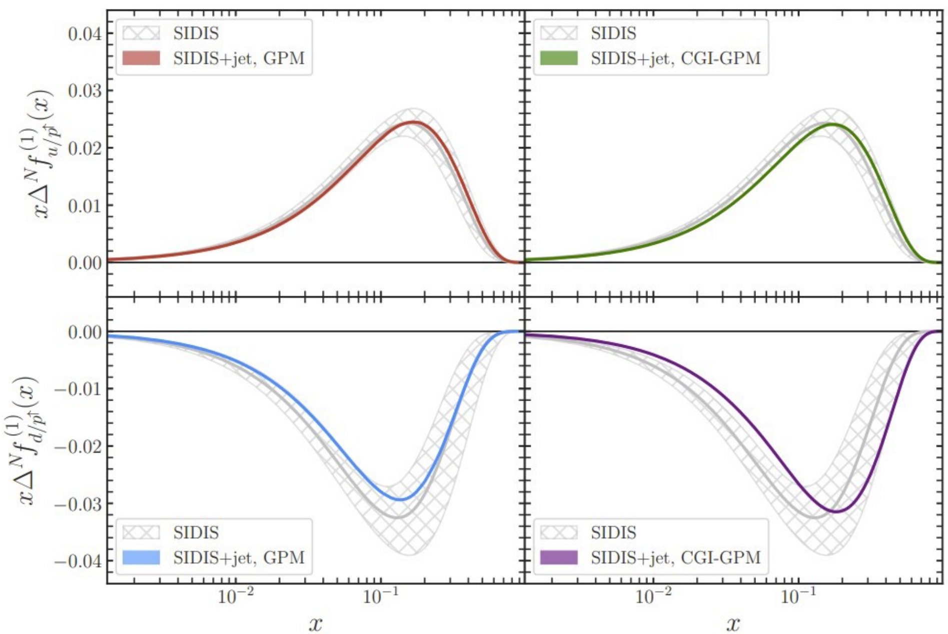
➢ Initial state effect is small

Searching A_N origin : EM-jet TSSA

- Jet A_N - sensitive to the initial state effect, related to Sivers effect, decoupled from Collins effect
- Impact of our data in constraining Sivers function via global analysis



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



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

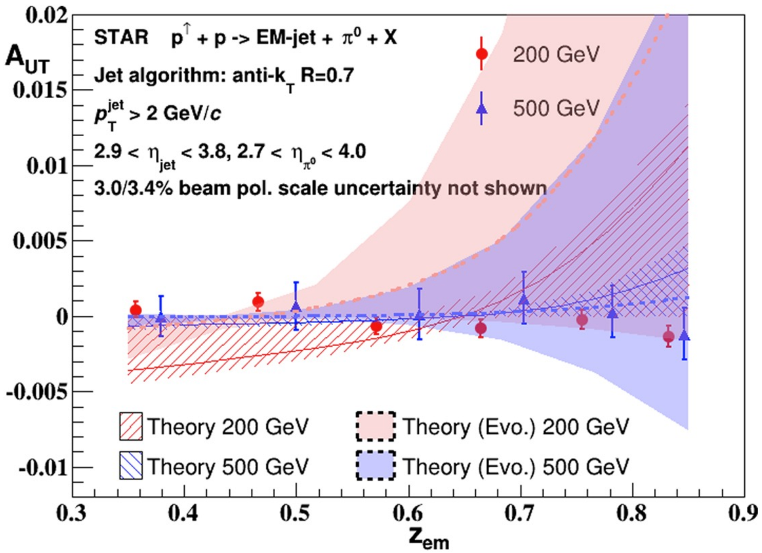
***L. Gamberg, Z. Kang, A. Prokudin, Phys.Rev.Lett.*110(2013)23,232301**

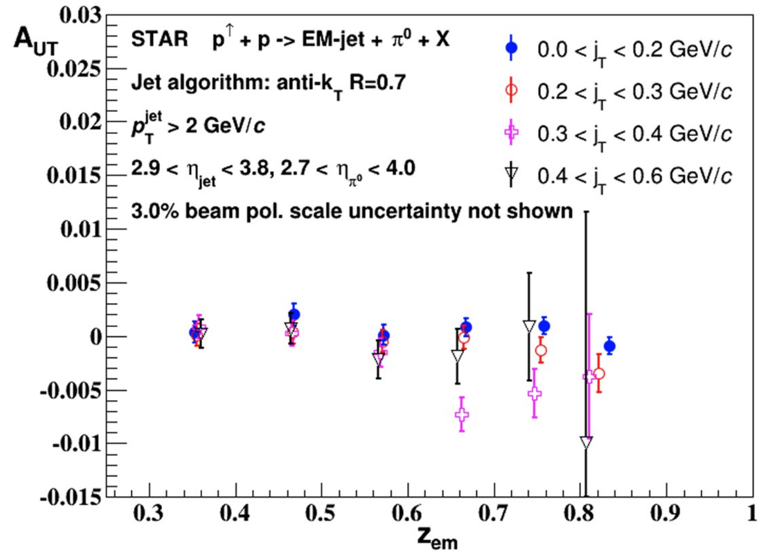
➢ Initial state effect is small

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

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





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.

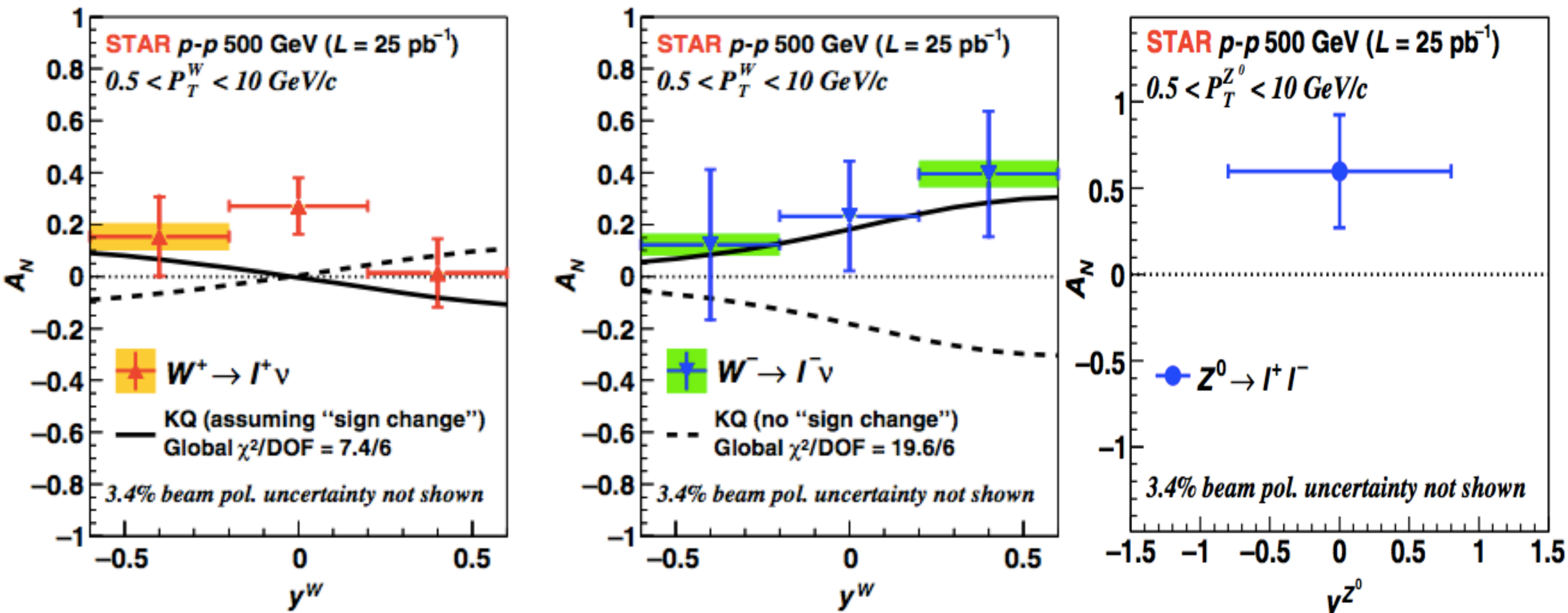
➢ Final state effect is small

W A_N from STAR and Sivers sign-change

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

$$\text{Sivers}_{DIS} = - \text{Sivers (DY or W or Z)}$$

- First A_N for $W^{\pm}$ and Z results :

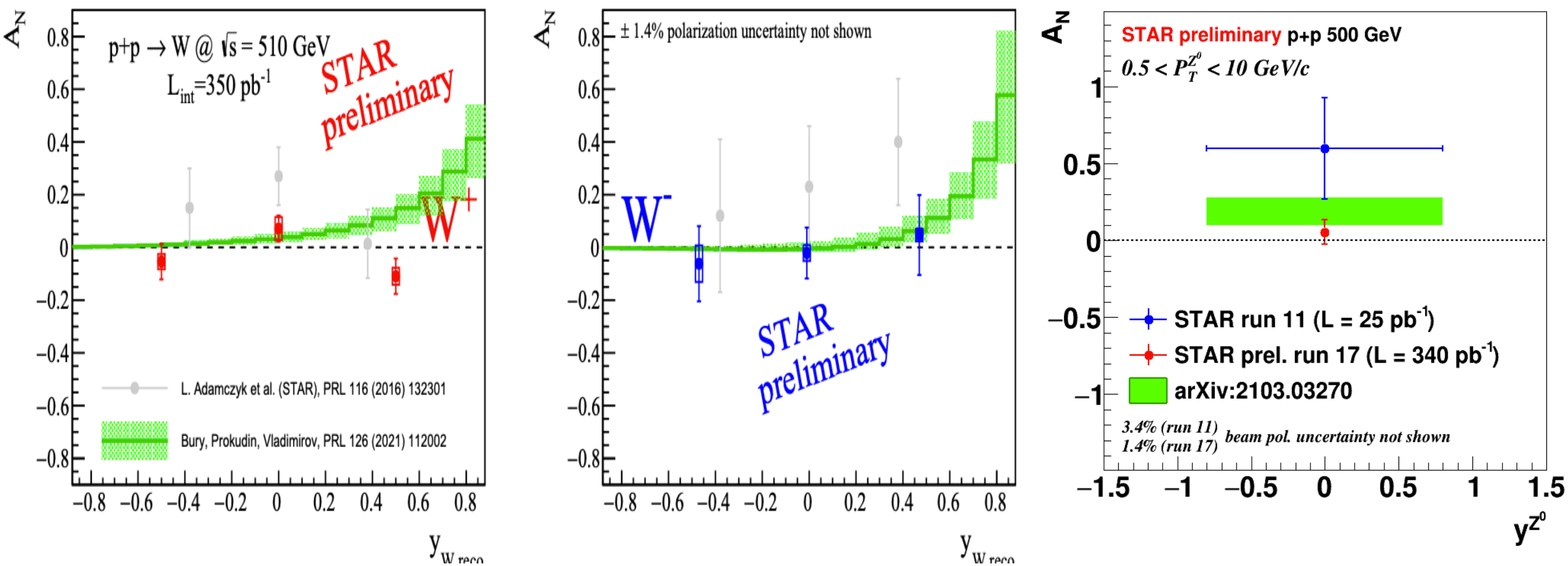


STAR, Phys. Rev. Lett. 116,132301(2016)

- Critical test for the understanding of TMD's and TMD factorization, indication is seen from 2016 data, but better statistics is highly required.

New results on W/Z A_N at STAR

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



> 2017 results have much improved precision over those from the initial measurement

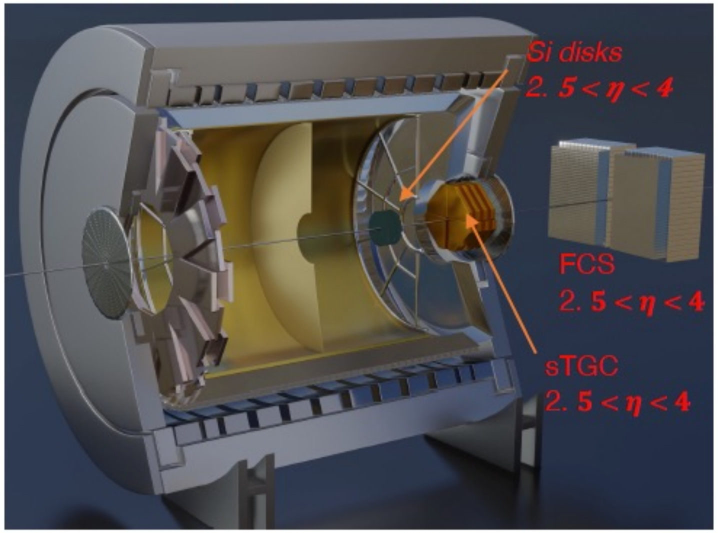
> New STAR data will have biggest impact on high-x region of the quark Sivers function.

Future RHIC Spin in 2022+

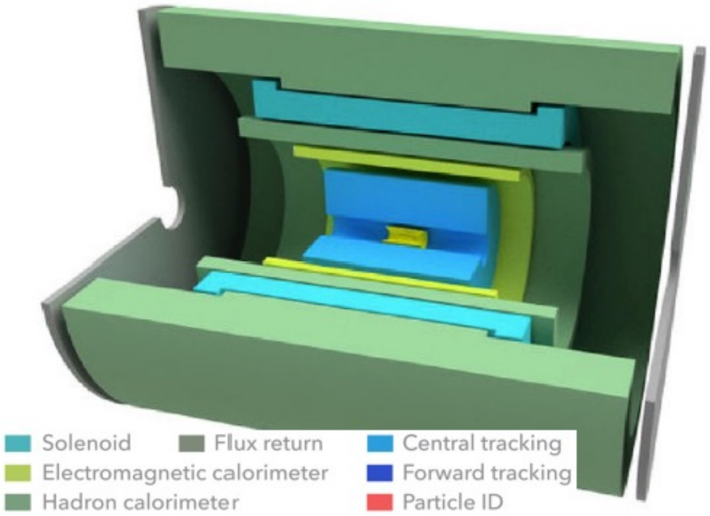
- Successful STAR run in 2022 with forward upgrade
- One more transverse spin run in 2024 before EIC, unique physics opportunities in pp and pA before EIC

$\sqrt{s}$ (GeV)	Species	Luminosity	Year
510	$p^{\uparrow}+p^{\uparrow}$	400 pb^{-1}	2022
200	$p^{\uparrow}+p^{\uparrow}$	235 pb^{-1}	2024
200	$p^{\uparrow}+Au$	1.3 pb^{-1}	2024

STAR w/ forward upgrade



sPHENIX



Electron-Ion Collider (EIC)

- **EIC Project Design Goals:**

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

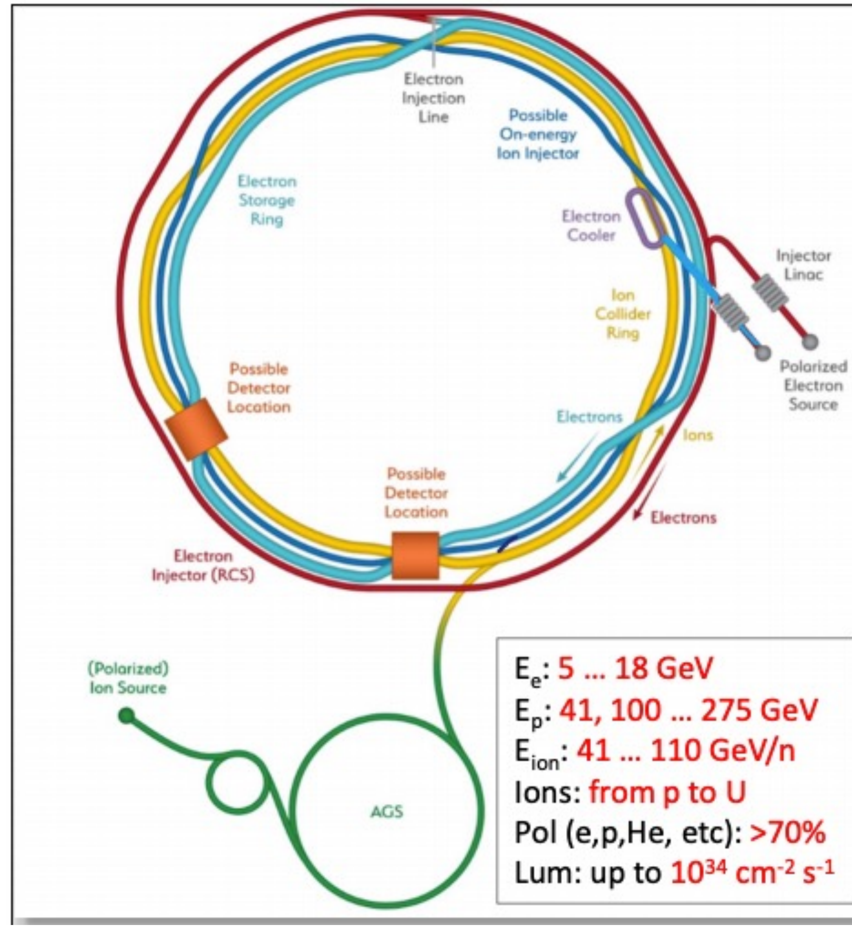
✓ Highly Polarized Beams: 70%

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

✓ Large Ion Species Range: protons – Uranium

✓ Large Detector Acceptance

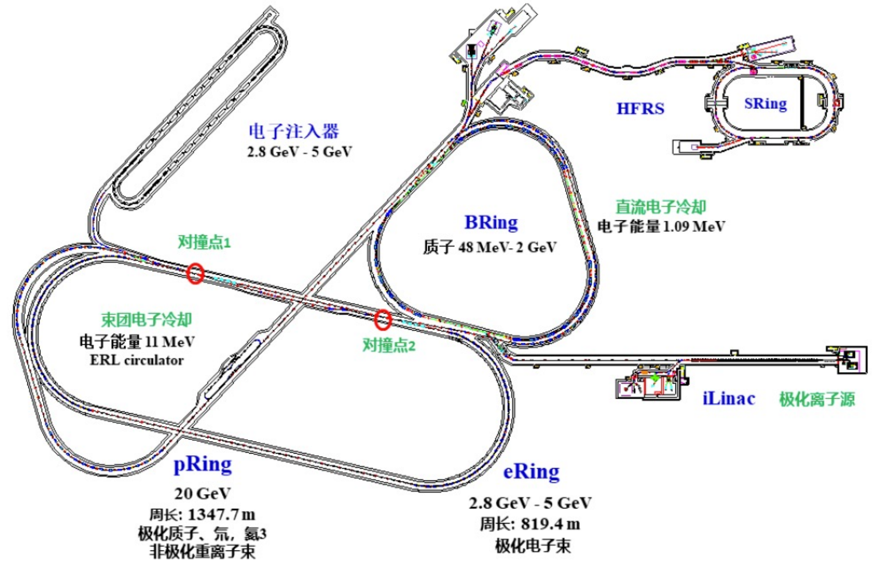
✓ Accommodate a Second Interaction Region (IR)



- EIC will be built at Brookhaven National Laboratory in ～2030

Electron-ion collider China(EicC)

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



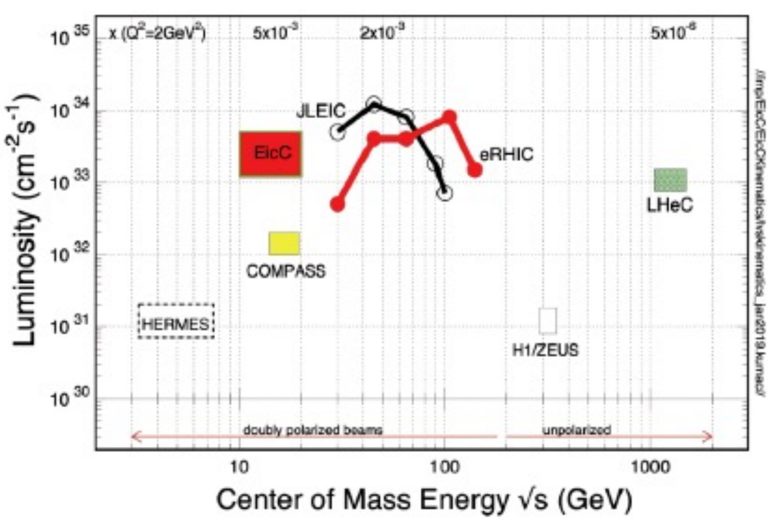
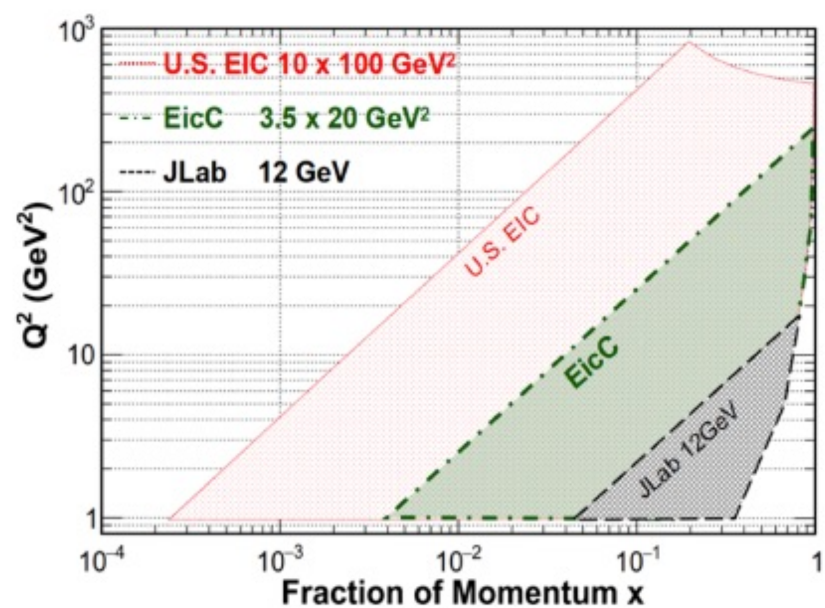


图 1.4: 国际上电子离子装置（包括拟建）亮度和质心系能量比较。



Summary of RHIC Spin

- Origin of proton spin remains a fundamental question in QCD.
- Observation of positive gluon polarization from RHIC:
  - Probes with jets, providing important constraints on ΔG
    Global analysis indicates sizable gluon polarization ($0.015<x<0.5$)
- Unique probe of sea quark polarization via W production:
  - clear evidence of the SU(2) symmetry breaking: $\Delta\bar{u} > \Delta\bar{d}$
- Hyperon spin transfer provide access to polarized strange quark distribution functions.
- Transverse spin physics at RHIC:
  - Results on π^0, EM-jet, W/Z spin asymmetries provide important information on underlying physics mechanism: Sivers & Collins, and more
- Future RHIC spin in 2022^+ & EIC/EicC in 2030+
  - Unique physics opportunities in pp and pA before EIC.
  - A ultimate QCD machine for proton structure: EIC/EicC !

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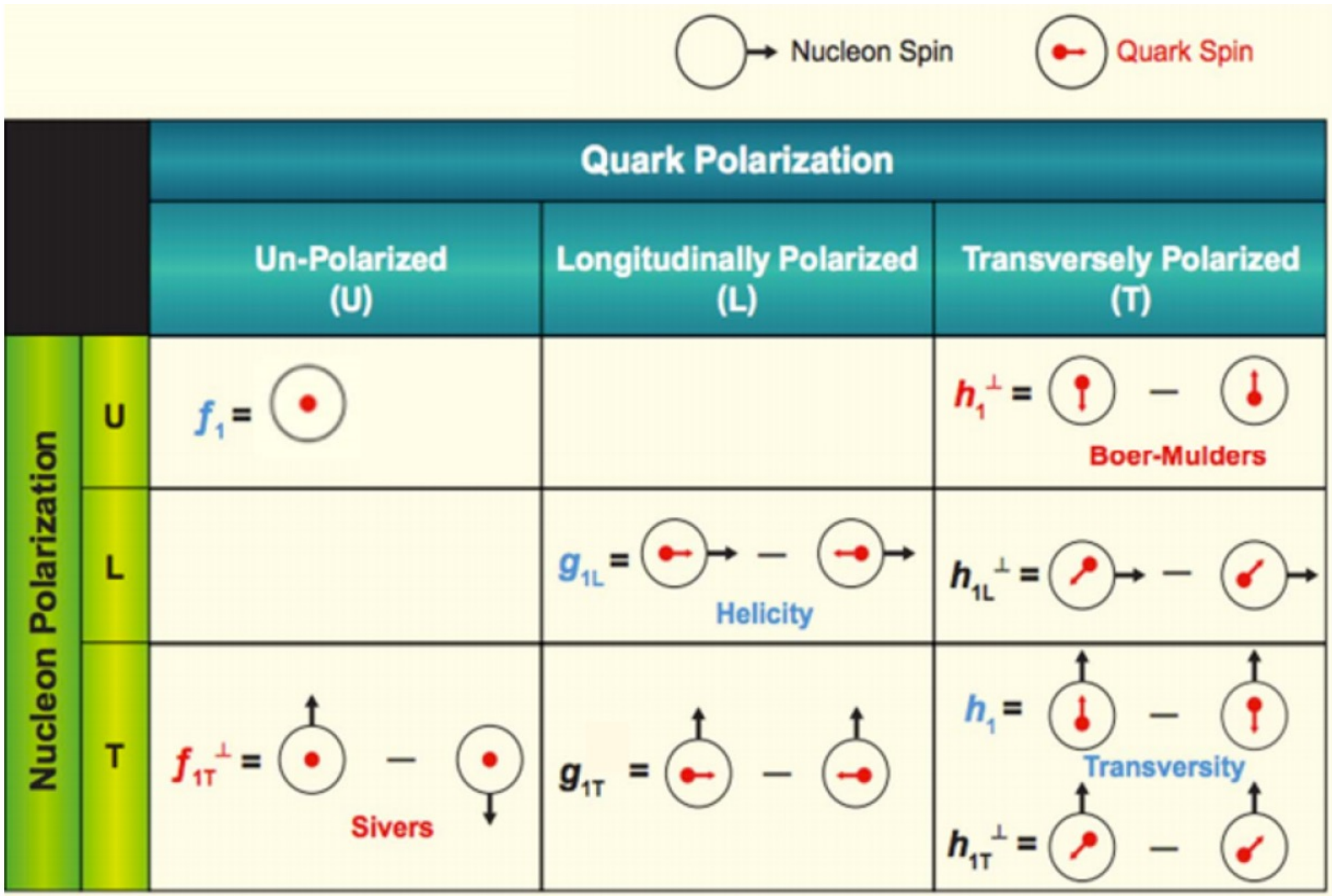
谢谢！

祝贺清华大学物理系复系40周年！

TMD distribution functions

- Transverse momentum dependent distribution (TMD):



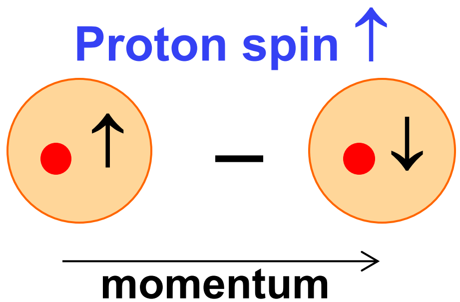
Sivers function: $f_q(x,k_\perp;S_\perp) = f_q(x,k_\perp) + \frac{1}{M}(\vec{k}_\perp \times \hat{\vec{p}}) \cdot \vec{S}_\perp \; f_{1T}^\perp(x,k_\perp)$

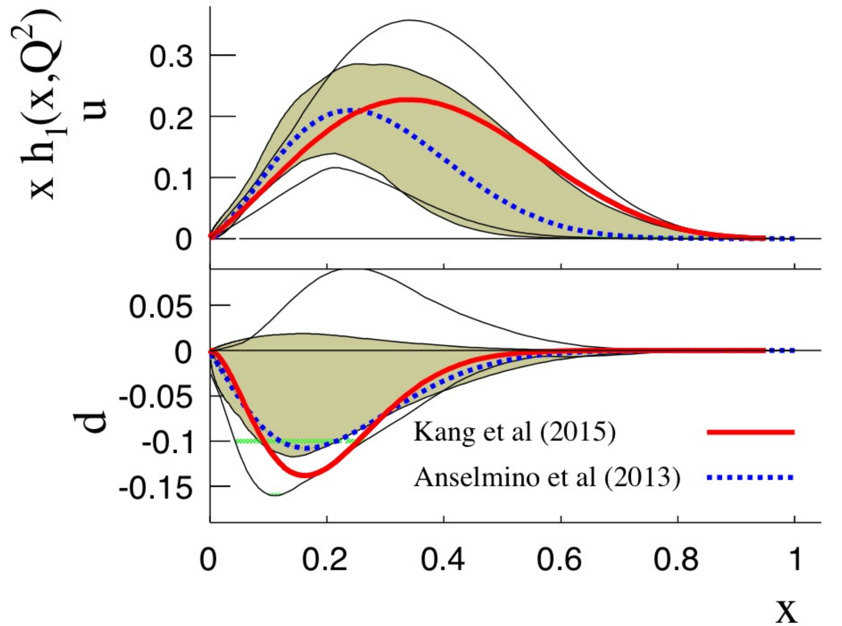
- correlation between parton transverse momentum, proton momentum and proton spin

Transverse 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)