Nucleon spin structure study with pp collisions & spin physics in heavy ion collisions

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华大QCD讲习班，2023.10.23-27

Outline for today's topic

- Introduction to SPIN & nucleon spin structure
- Recent spin highlights in pp collisions from RHIC:
  - ✓ Gluon polarization (Jet, π^0 production): gluon polarization Δg
  - ✓ Quark/Anti-quark polarization (W/Z production): sea quark Δq
  - ✓ Transverse spin asymmetry (W/Z production): Sivers function
  - ✓ Transverse spin asymmetry (Hadron production): Collins
- Global polarization in heavy ion collisions
  - ✓ Hyperon global polarization
  - ✓ Spin alignment of vector meson
- Future plans for spin physics in 2024+ at RHIC/EIC/EicC

What is SPIN?

- As a fundamental observable of (sub)-atomic physics, spin was introduced by S. Goudsmit & G. 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."

-R. Kronig,1926 (Pauli)

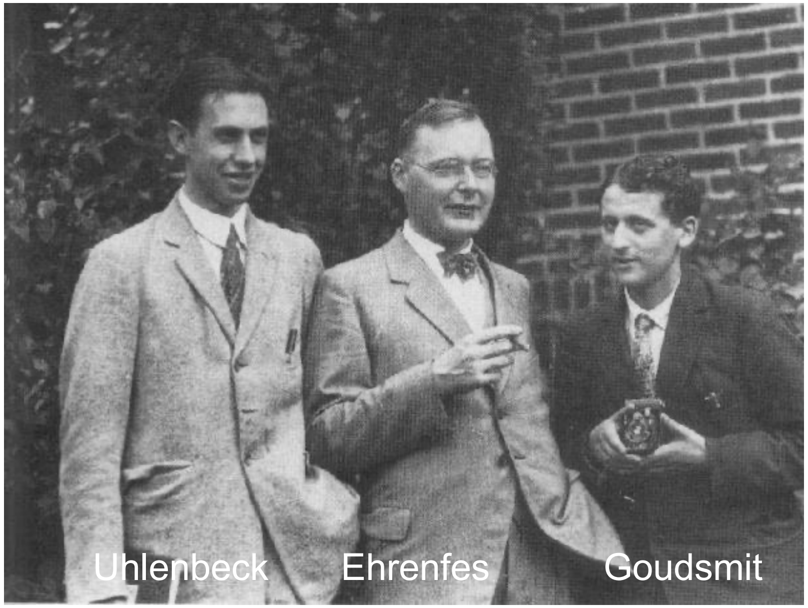
-Ehrenfest upon receiving the paper by Goudsmit & Uhlenbeck

- Original measurement (1922) by Stern & Gerlach

- In non-relativistic theory: operator ***S***$_i$

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

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



Spin in a relativistic theory

- Physics invariant under Lorentz boosts, rotations, and translations –> inhomogeneous Lorentz transformations

→ Poincare group/invariance of 3+1 Minkowski space-time

10 generators:

P^j, P^0 translations in space & time

$M^{\mu\nu} = -M^{\nu\mu}$ Lorentz boosts & rotations

→ $J_i \equiv -\varepsilon_{ijk} M^{jk}/2$ and $K^i \equiv M^{i0}$

pure rotations pure boosts

- generators satisfy algebra (= set of commutation relations), e.g., $[J_i, J_j] = i\,\varepsilon_{ijk} J_k$
- any physical system is a realization of this algebra

-E. Leader, 2001, "*Spin in particle physics*"

Spin in a relativistic theory

- Two group invariants (Casimir operators) define two universal observables:

$P_\mu P^\mu = m^2$ **mass**

$W_\mu W^\mu$ where $W_\mu = -\varepsilon_{\mu\nu\rho\sigma} M^{\nu\rho} P^\sigma / 2$ **spin !!**

$[W_\lambda, W_\mu] = i\epsilon_{\lambda\mu\nu\sigma} W^\nu P^\sigma$

Pauli-Lubanski operator

→ spin is a consequence of space-time symmetry

- for states at rest: $[W_i, W_j] = i\, m\, \varepsilon_{ijk} W^k$ → $S_i \equiv W_i / m$ (spin operator)
- eigenvalues $W_\mu W^\mu = m^2\, S(S+1)$ with $S = 0, 1/2, 1, \ldots$ (inv. spin quantum no.)
- states can be labelled as $|S, S_Z\rangle$

Leader, Stratmann

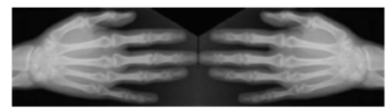
Spin ½ - most important example

- Longitudinal polarization: "Dirac equation"

$$n^\mu = \frac{1}{m}(|\vec{p}|, Ep^i/|\vec{p}|) \longrightarrow \Pi = \frac{\vec{J}\cdot\vec{p}}{|\vec{p}|}$$

"helicity"
-周光召& Shirokov 1958
-Jacob & Wick 1959

  - Eignvalue: helicity λ; helicity stats labelled as | p, λ>
  - High energy limit or m ~ 0
    - $\Pi \to \gamma_5$ and helicity = chirality



    - helicity becomes Lorentz-invariant

- Transverse polarization: $n^\mu = (0, \vec{n}_\perp, 0)$

- Spin polarization vector: $\vec{P} = \frac{\langle \vec{s} \rangle}{s} = \frac{\langle \vec{s} \rangle}{\hbar/2}$, $|P| \le 1$

- Spin density matrix: $\rho = \frac{1}{2}(1 + \vec{P}\cdot\vec{\sigma}),\ \vec{P} = Tr\rho\vec{\sigma}$

  $(\rho = \sum_i P_i |i\rangle\langle i|)$

Polarization determination example: Λ weak decay

- Λ polarization can be measured in experiment via weak decay:

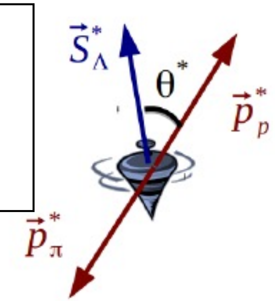
$\Lambda \to p\pi^-$(Br64%), $\Lambda \to n\pi^0$(Br36%) , -T.D.Lee, C.N.Yang(1957)

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

Unit vector along proton momentum in Λ's rest frame.
$\vec{P}_\Lambda \cdot \vec{p}_p^{*} = P_\Lambda \cos\theta^*$

decay parameter: 0.732($p\pi^-$)

Λ polarization vector



$\Lambda \to p + \pi^+$
(BR: 63.9%, cτ~7.9 cm)

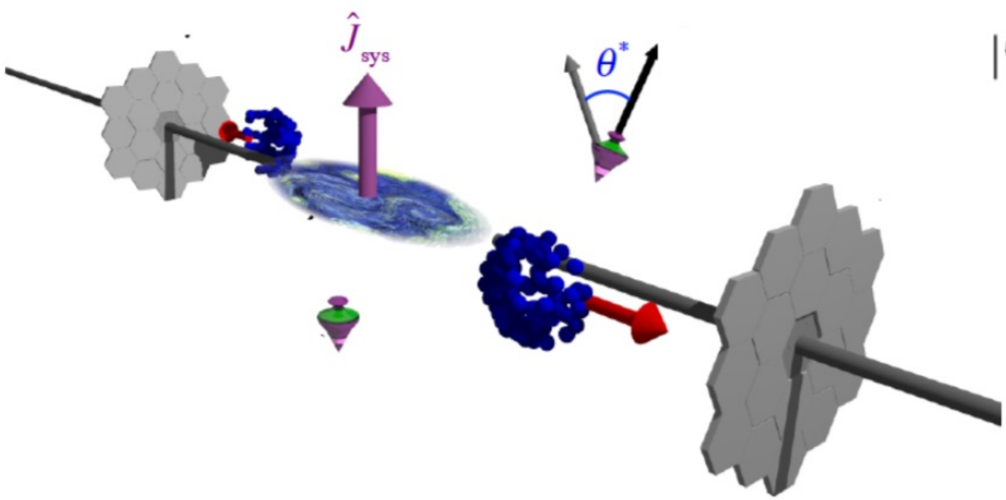
- Λ's contain a strange constitute quark, whose spin is expected to carry most of the Λ spin: $|\Lambda^\uparrow\rangle = (ud)_{00}\, s^\uparrow$

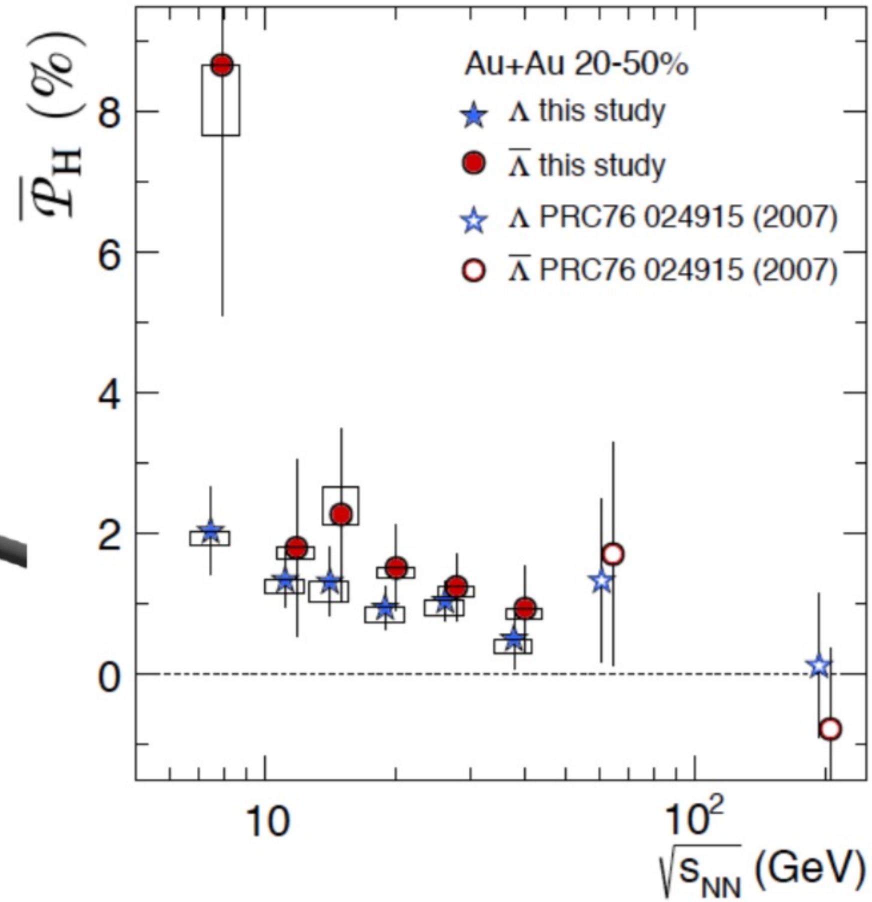
- Different method for proton/electron beam:
  -via spin asymmetry in scattering, for example proton polarimetry based on Coulomb Nuclear Interference

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.

STAR, Nature 548(2017)62





非零角动量可以转化成流体涡旋，
并极化超子

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, as the quarks are in the s-orbit:

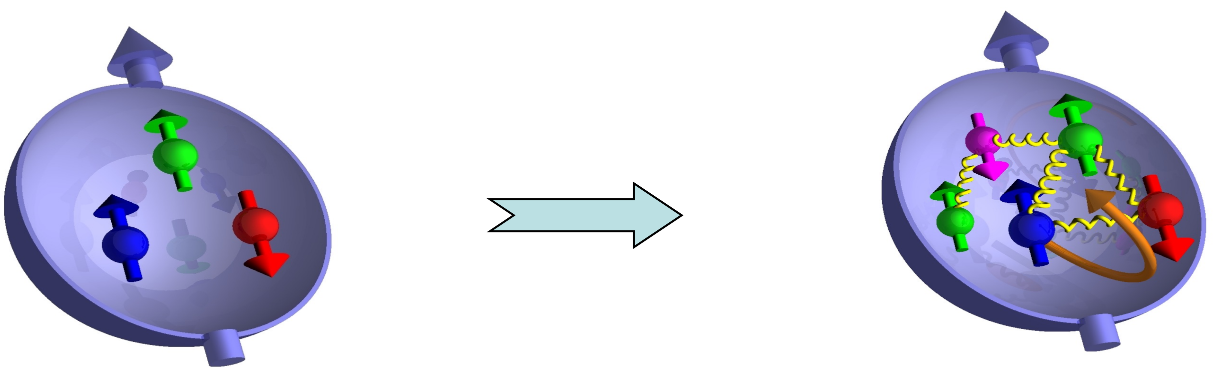
$\Delta\Sigma = 1$

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

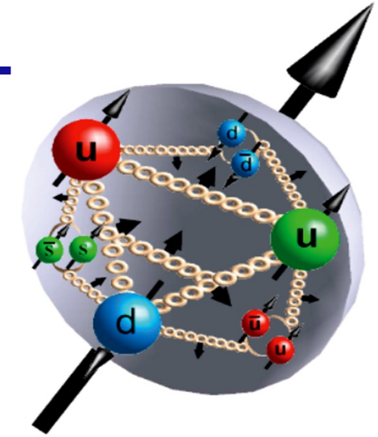
- With Parton Model (sea quark, gluon) but assumes $\Delta S=0$:

$\Delta\Sigma \approx 0.6$

- 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, Poorly known, RHIC

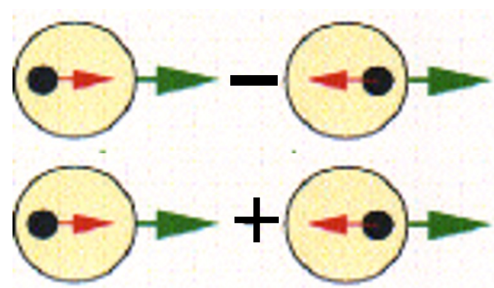
Orbital Angular Momenta Little known

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

- Polarized parton densities:

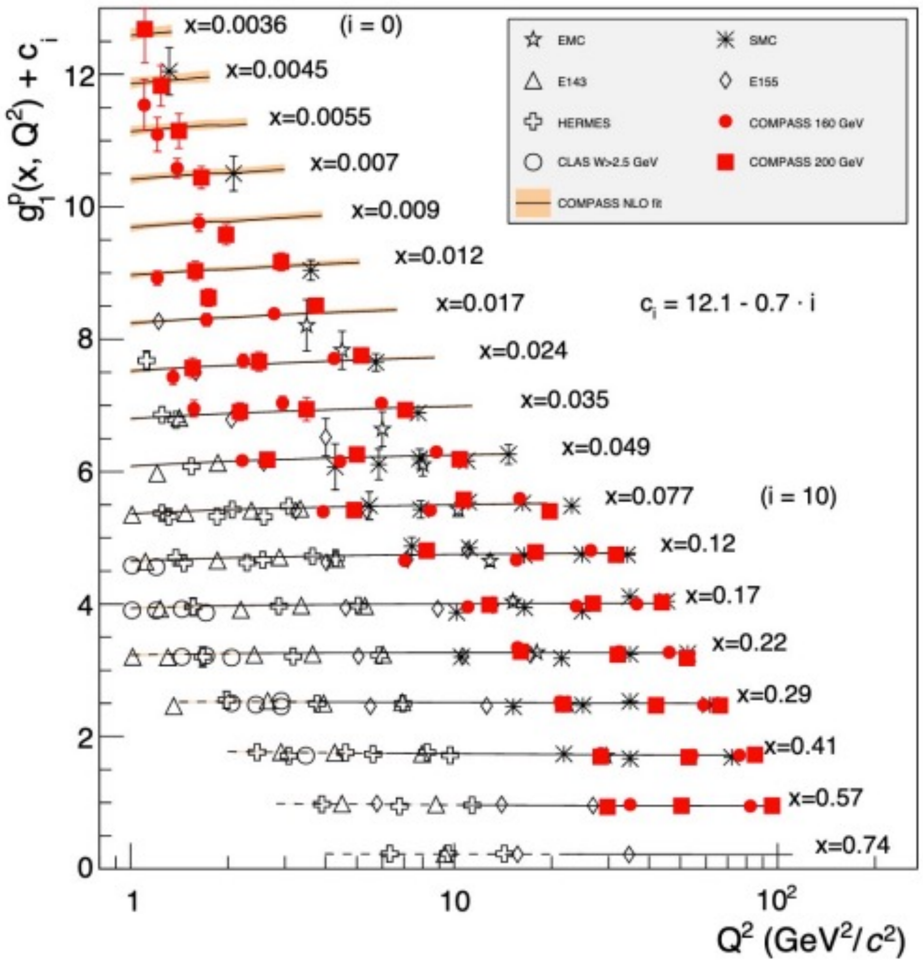
$$\Delta q(x,Q^2) = q^+(x,Q^2) - q^-(x,Q^2)$$

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



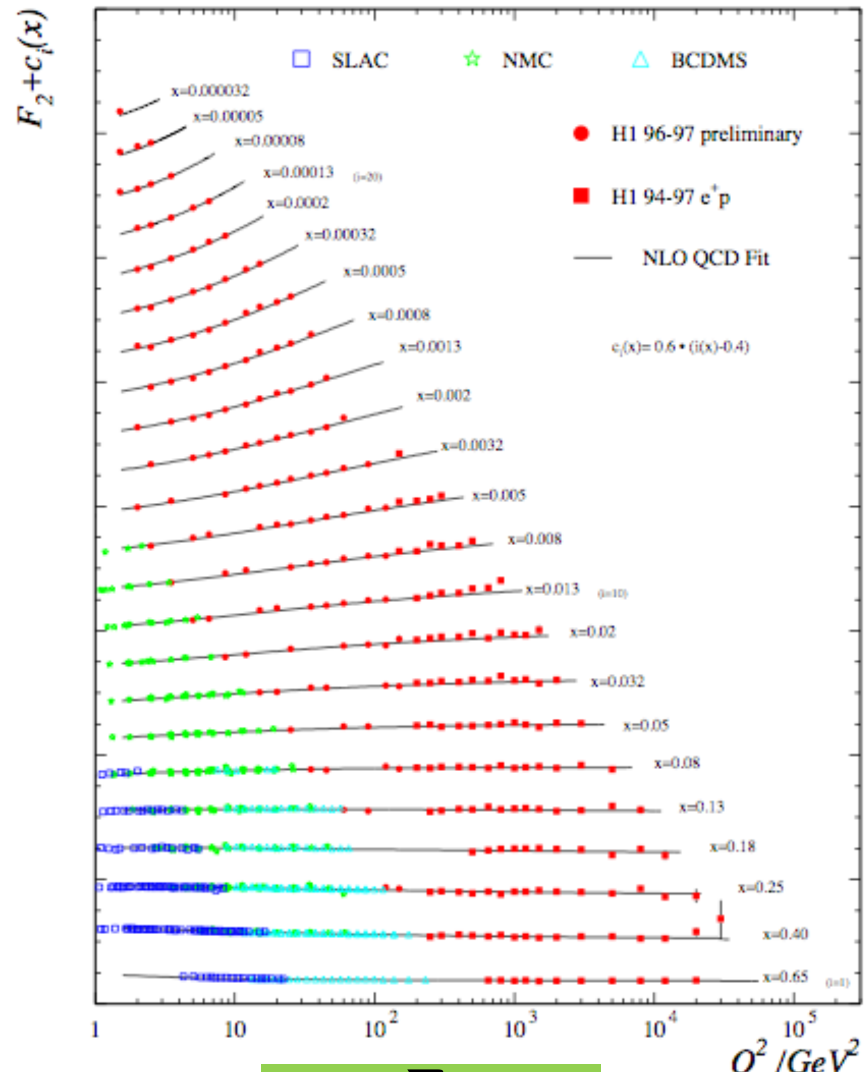
World data on pol. and unpol. deep-inelastic scattering

polarized



PDG (online 2023)

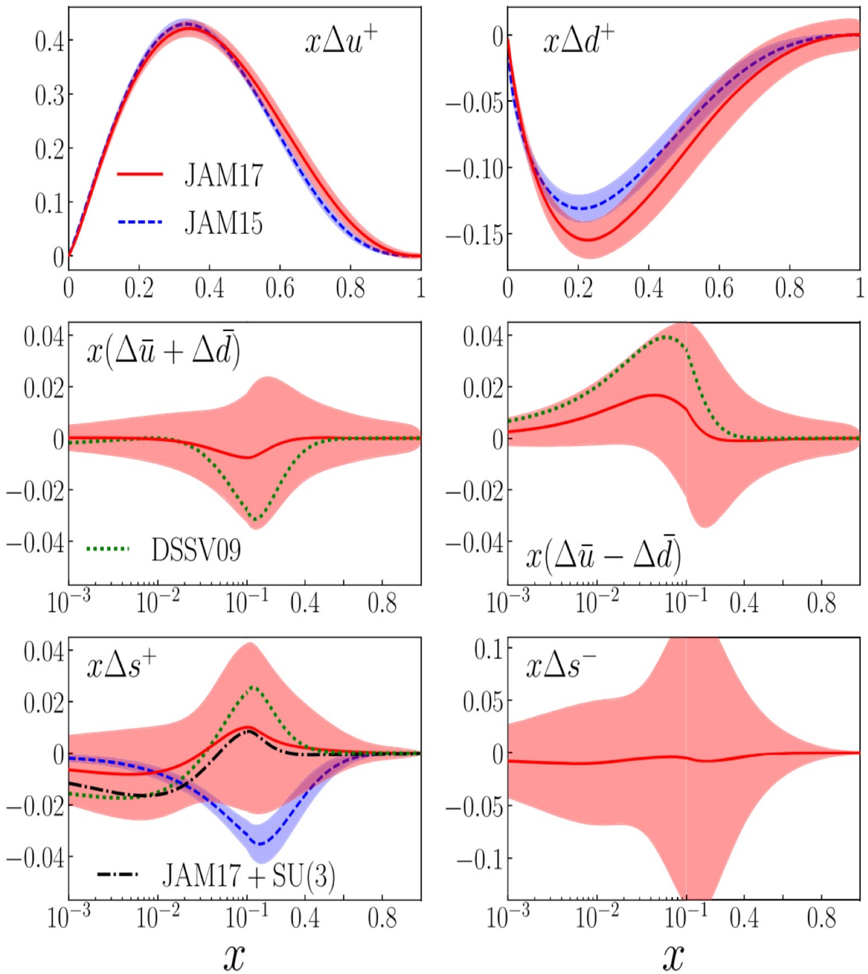
unpolarized



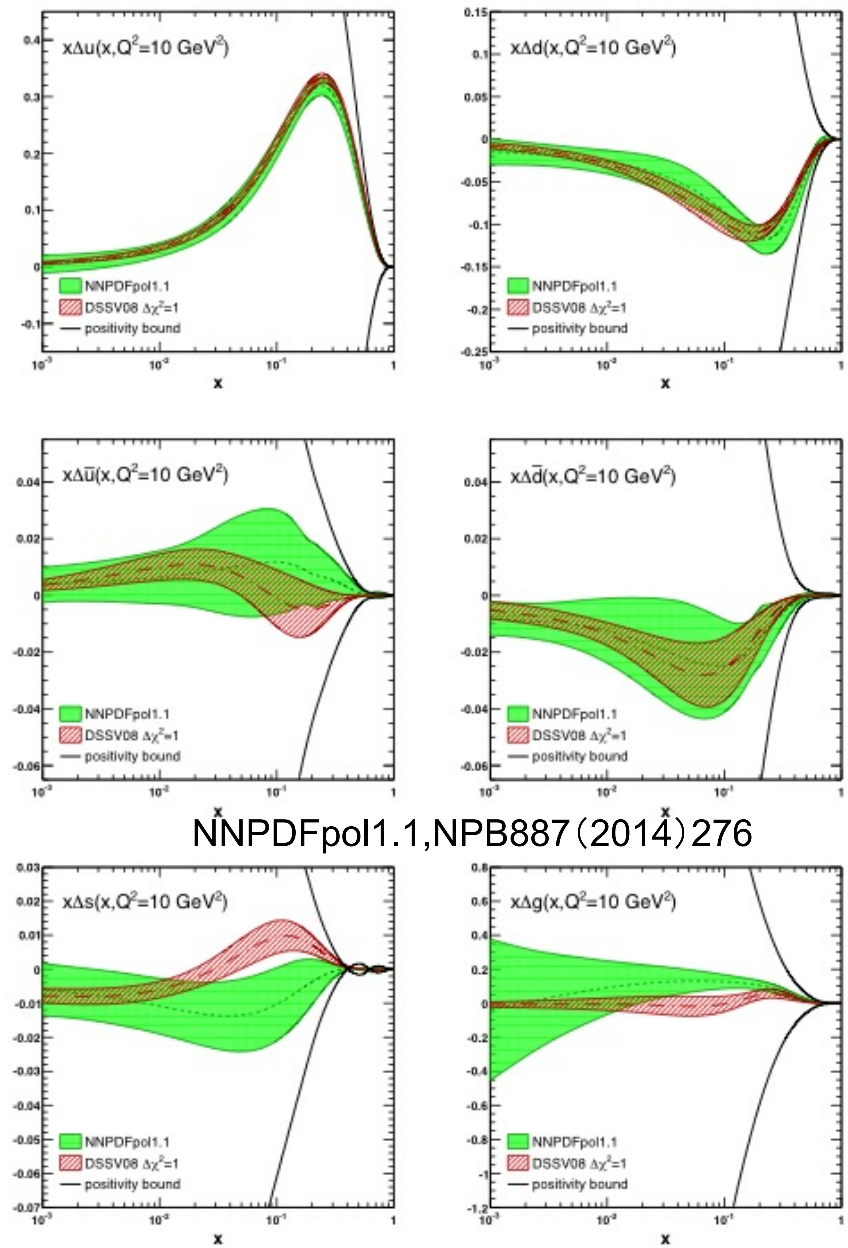
$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

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

Detailed knowledge on $\Delta q(x)$, $\Delta g(x)$- global fit using DIS and pp data



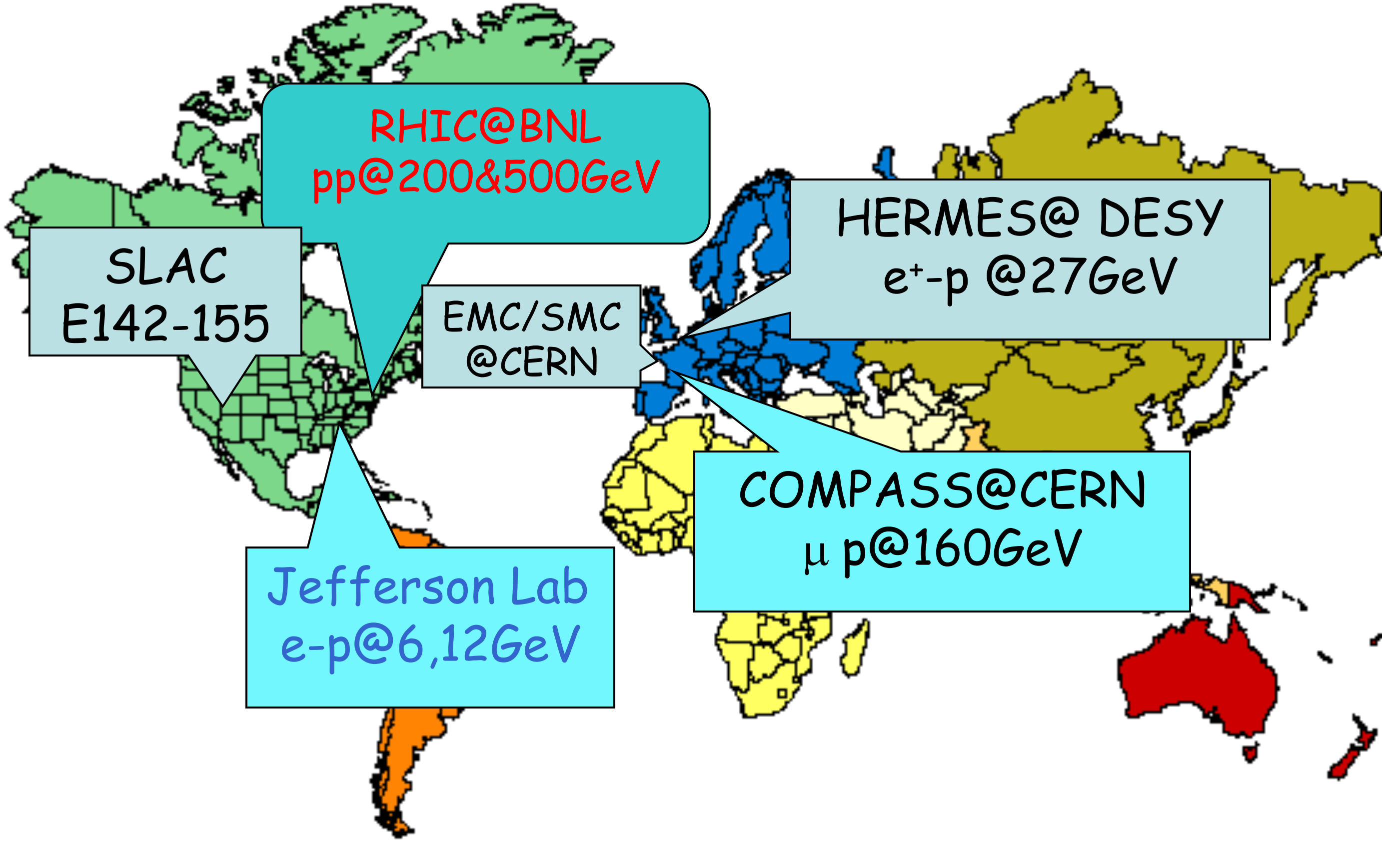
JAM2017:
J. Ethier et al, PRL**119**, 132001 (2017)



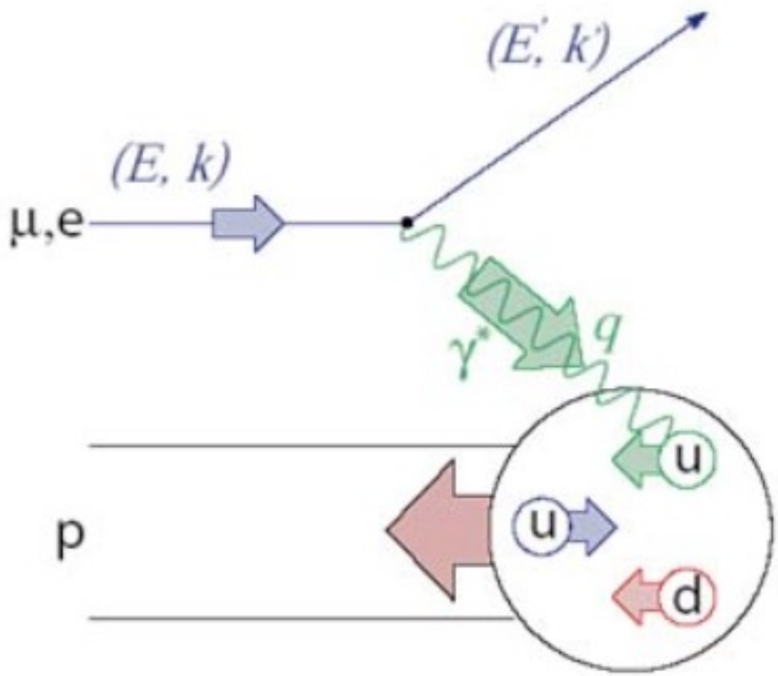
NNPDFpol1.1,NPB887（2014）276

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)



Polarized Deep Inelastic Scattering



$$Q^2 = -(k-k')^2 \overset{lab}{=} 4EE'\sin^2\frac{\vartheta}{2}$$

$$P\cdot q \overset{lab}{=} M\nu = M(E-E')$$

$$P\cdot k \overset{lab}{=} ME$$

Bjorken-x: fraction of longitudinal momentum carried by struck quark in infinite-momentum frame (Breit)

$$x \overset{lab}{=} \frac{Q^2}{2M\nu} = \frac{-q^2}{2P\cdot q}$$

$$y \overset{lab}{=} \frac{\nu}{E} = \frac{P\cdot q}{P\cdot k}$$

Q^2 corresponds to the "spatial resolution"

$$\lambda \approx \frac{1}{|\vec{q}\,|}$$

Structure Function and parton densities (PDF)

$F_1, \; F_2$ unpolarised structure functions: momentum distributions

$g_1, \; g_2$ polarised structure functions: spin distributions

QPM:

$$F_2(x) = 2xF_1$$ Calan Gross relation

$$g_2 = 0$$ twist-3 quark-qluon correlations

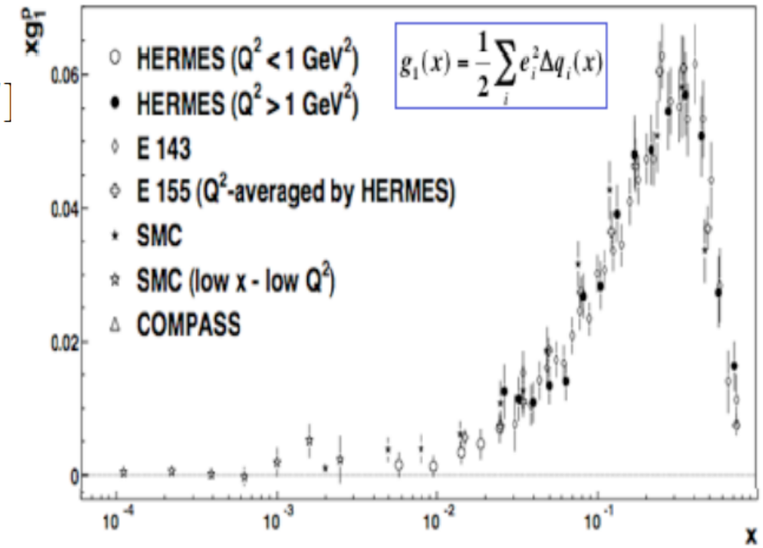
$$F_1(x) = \tfrac{1}{2}\textstyle\sum_f e_f^2 \left\{ q_f^+(x) + q_f^-(x) \right\} = \frac{1}{2}\sum_f e_f^2 q_f(x)$$

$$g_1(x) = \tfrac{1}{2}\textstyle\sum_f e_f^2 \left\{ q_f^+(x) - q_f^-(x) \right\} = \frac{1}{2}\sum_f e_f^2 \Delta q_f(x)$$

ΔU, ΔD, ΔS from polarized inclusive DIS

- Determination of ΔS , ΔΣ with polarized inclusive DIS:

$$\Gamma_1^p = \int_0^1 g_1^p(x)dx = \frac{1}{2}\int \sum_i e_i^2 \Delta q_i(x) = \frac{1}{18}[4\Delta U + \Delta D + \Delta S]$$



$$\Delta\Sigma = \underbrace{\Delta u + \Delta\bar{u}}_{\Delta U} + \underbrace{\Delta d + \Delta\bar{d}}_{\Delta D} + \underbrace{\Delta s + \Delta\bar{s}}_{\Delta S}$$

Each flavor's contribution to nucleon spin:

$$\Delta q = \int_0^1 \Delta q(x)dx$$

$\Delta q(x) = q^+(x) - q^-(x)$: helicity distribution function

- Together with neutron, hyperon β decay data using SU(3)_f symmetry:

⇒ ΔΣ= 0.33 ±0.03±0.01±0.03:
- ΔU~ 0.84,
- ΔD~ –0.43, (HERMES,Q^2=5 GeV^2)
- **ΔS~ –0.08**±0.01±0.01±0.01*

Sum rules

- with $\Delta q = \int \Delta q(x)\mathrm{d}x$ we get for the proton

$$\begin{aligned}\Gamma_1^{\mathrm{p}} &= \frac{1}{2}\left\{\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right\} \\ &= \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{\sqrt{3}a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}\end{aligned}$$

$$\Gamma_1^{\mathrm{p,n}} = \frac{1}{12}\left(\pm a_3 + \frac{1}{\sqrt{3}}a_8\right) + \frac{1}{9}a_0$$

Neutron decay
$a_3 = g_a$

Hyperon decay
(3F-D)/3

$\Delta\Sigma$

$a_3 = g_A = 1.267 \pm 0.0035$ (from neutron decay)

$a_8 = 0.58 \pm 0.03$ (assuming SU(3) symmetry)

-G. Mallot

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- Recent spin highlights in pp collisions from RHIC:
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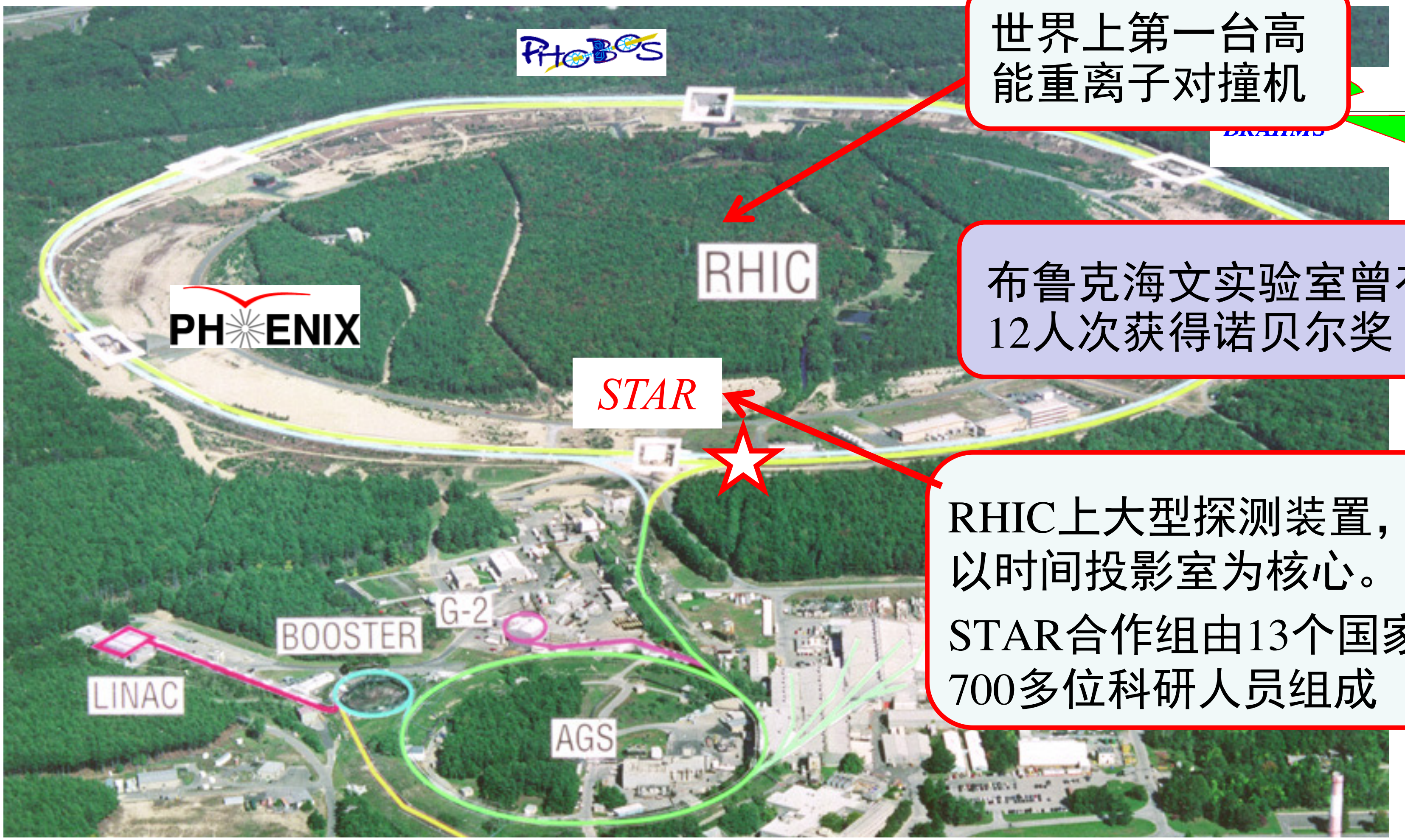
  - ✓ **Quark/Anti-quark polarization (W/Z production): sea quark Δq**
  - ✓ **Transverse spin asymmetry (W/Z production): Sivers function**
  - ✓ **Transverse spin asymmetry (Hadron production): Collins**
- Global polarization in heavy ion collisions
  - ✓ **Hyperon global polarization**
  - ✓ **Spin alignment of vector meson**
- Future plans for spin physics in 2024+ at RHIC/EIC/EicC

美国Brookheaven国家实验室的RHIC对撞机

Relativistic Heavy Ion Collider --- RHIC



世界上第一台高能重离子对撞机

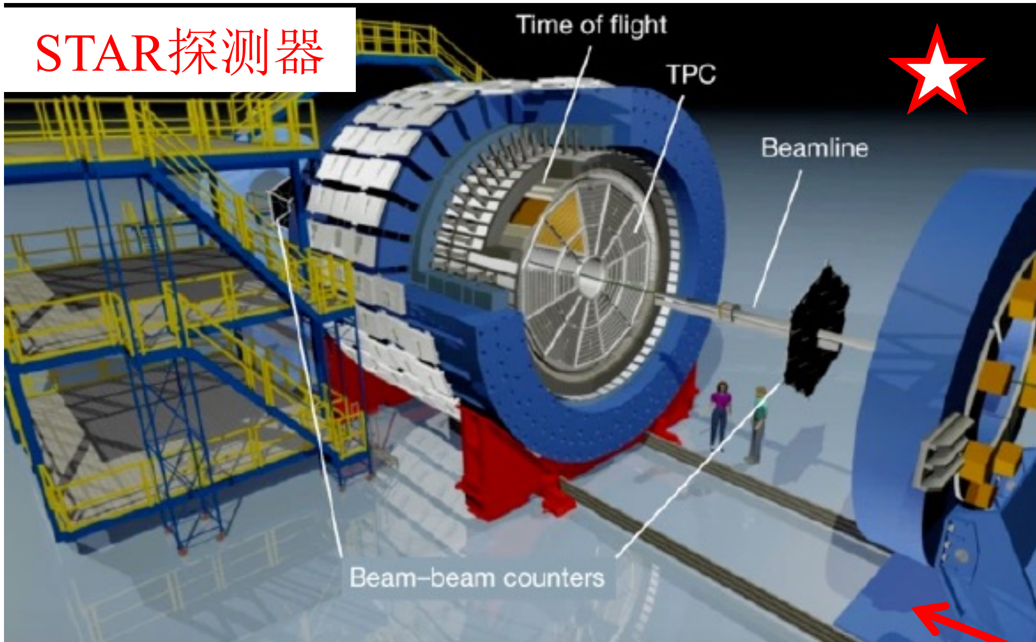
布鲁克海文实验室曾有12人次获得诺贝尔奖

RHIC上大型探测装置，以时间投影室为核心。

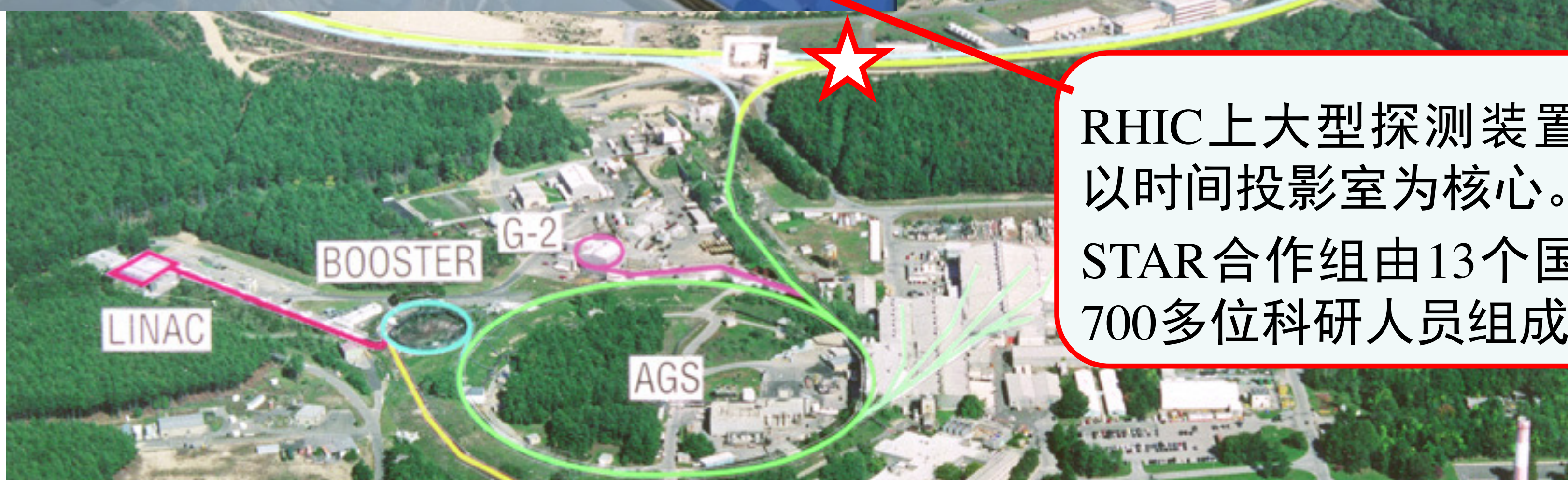
STAR合作组由13个国家700多位科研人员组成

美国Brookheaven国家实验室的RHIC对撞机

STAR探测器



Collider --- RHIC



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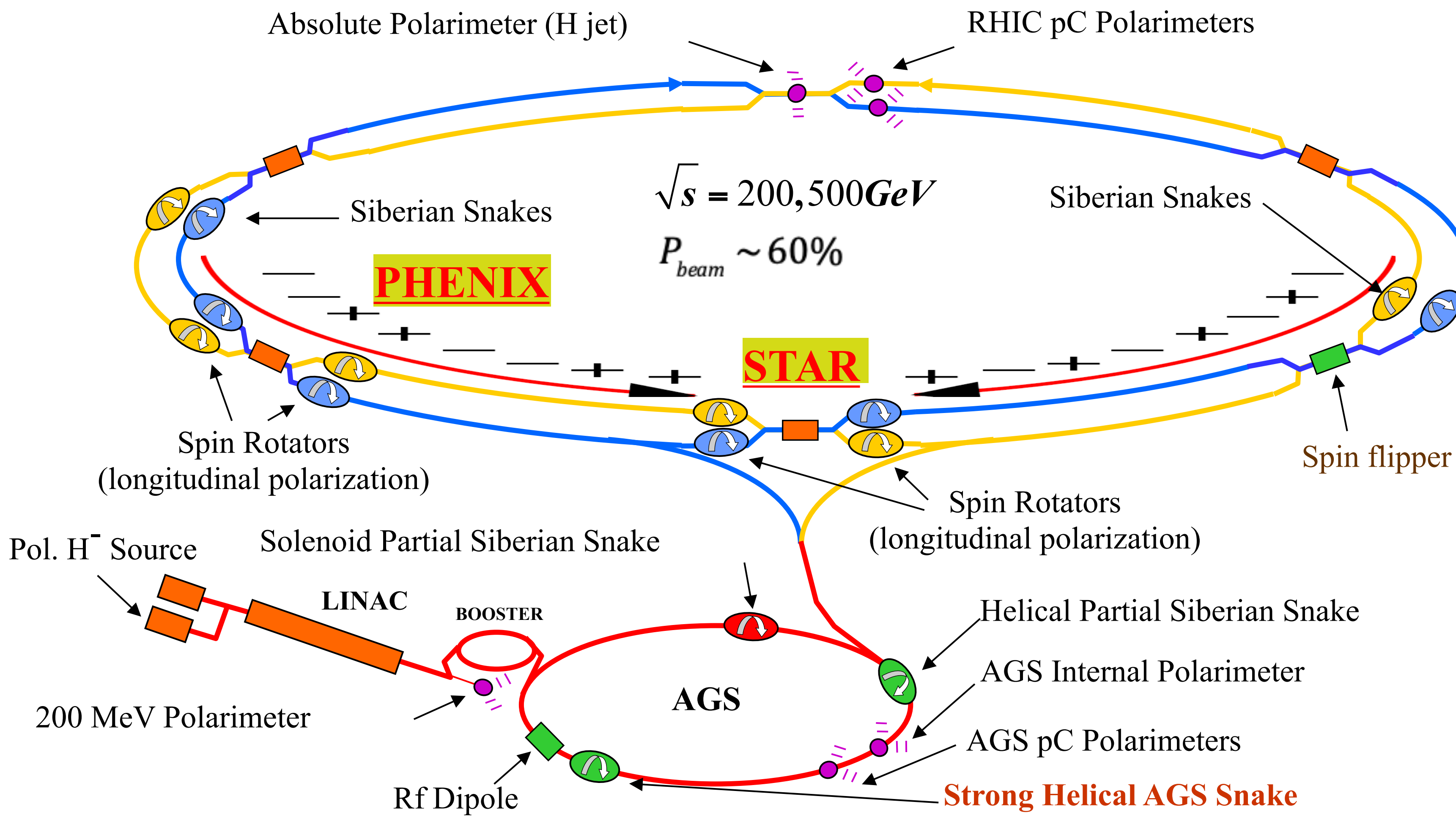
STAR中国组包括华中师范大学、中科院近代物理研究所、中科院上海应用物理研究所、中国科学技术大学、中国科学院大学、复旦大学、湖州师范学院、山东大学、清华大学等

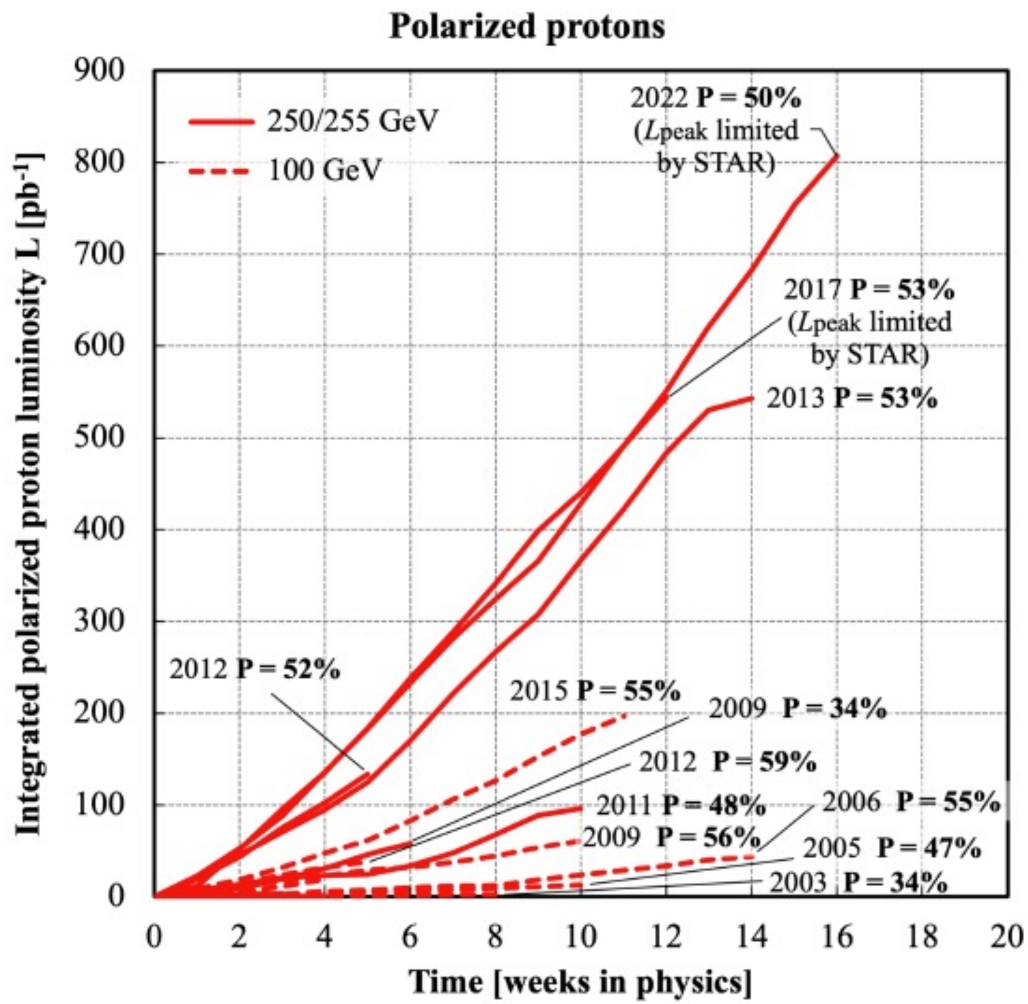
RHIC- 1st polarized proton-proton collider



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

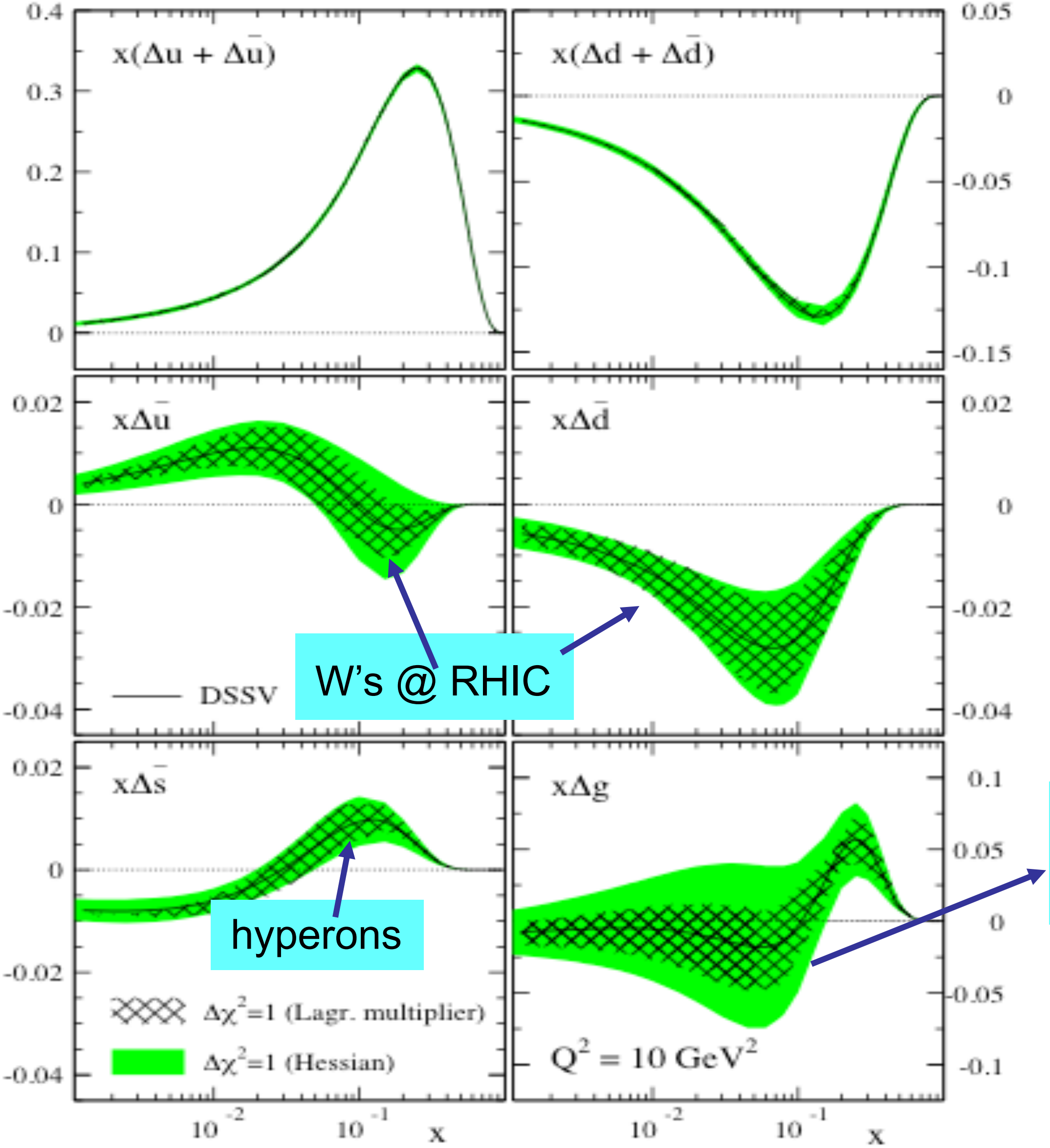
RHIC performance with pp collisions

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



- Last transversely polarized proton-proton run will be taken in 2024 at 200 GeV

Δq(x), Δg(x)- global analysis of data



- Spin sum rule (longitudinal):

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

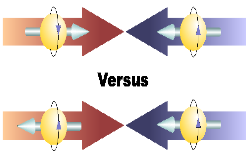
Quark spin, (~30%)- DIS	Gluon spin, Poorly known, RHIC	Orbital Angular Momenta Little known

RHIC (jet, π^0)
200 GeV, 500 GeV

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

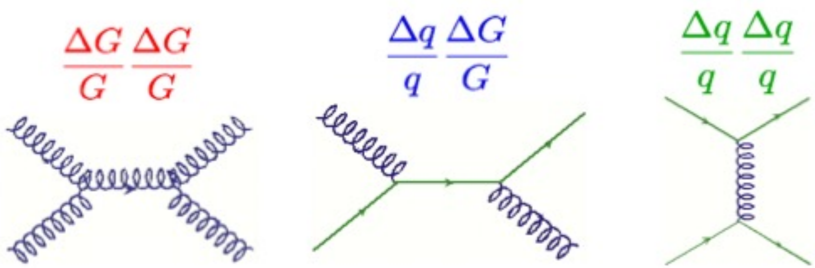
Accessing Δg(x) in pp collision

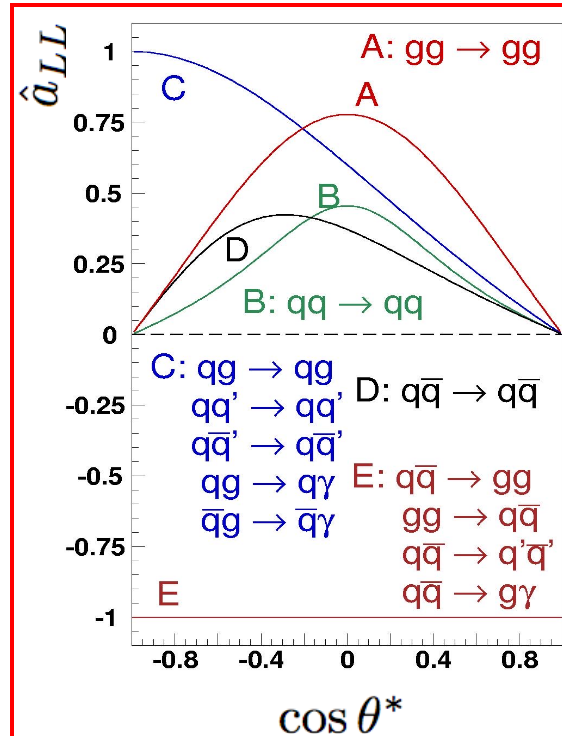
- Longitudinal spin asymmetry:



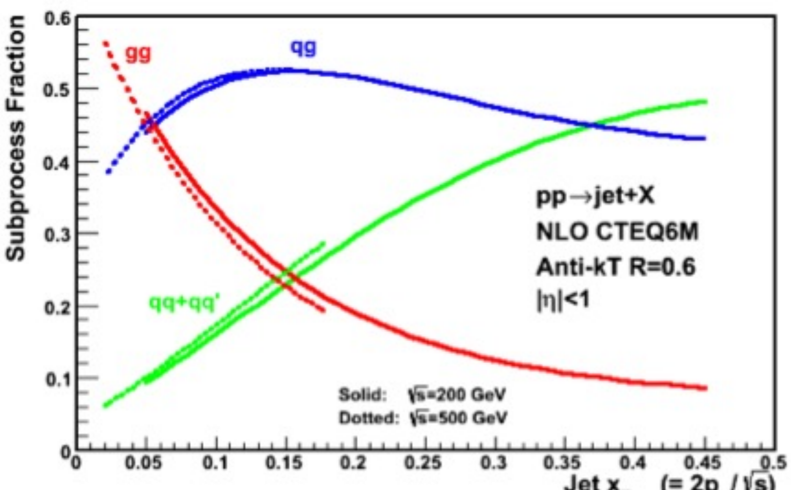
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \cdot \hat{a}_{LL}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}$$

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



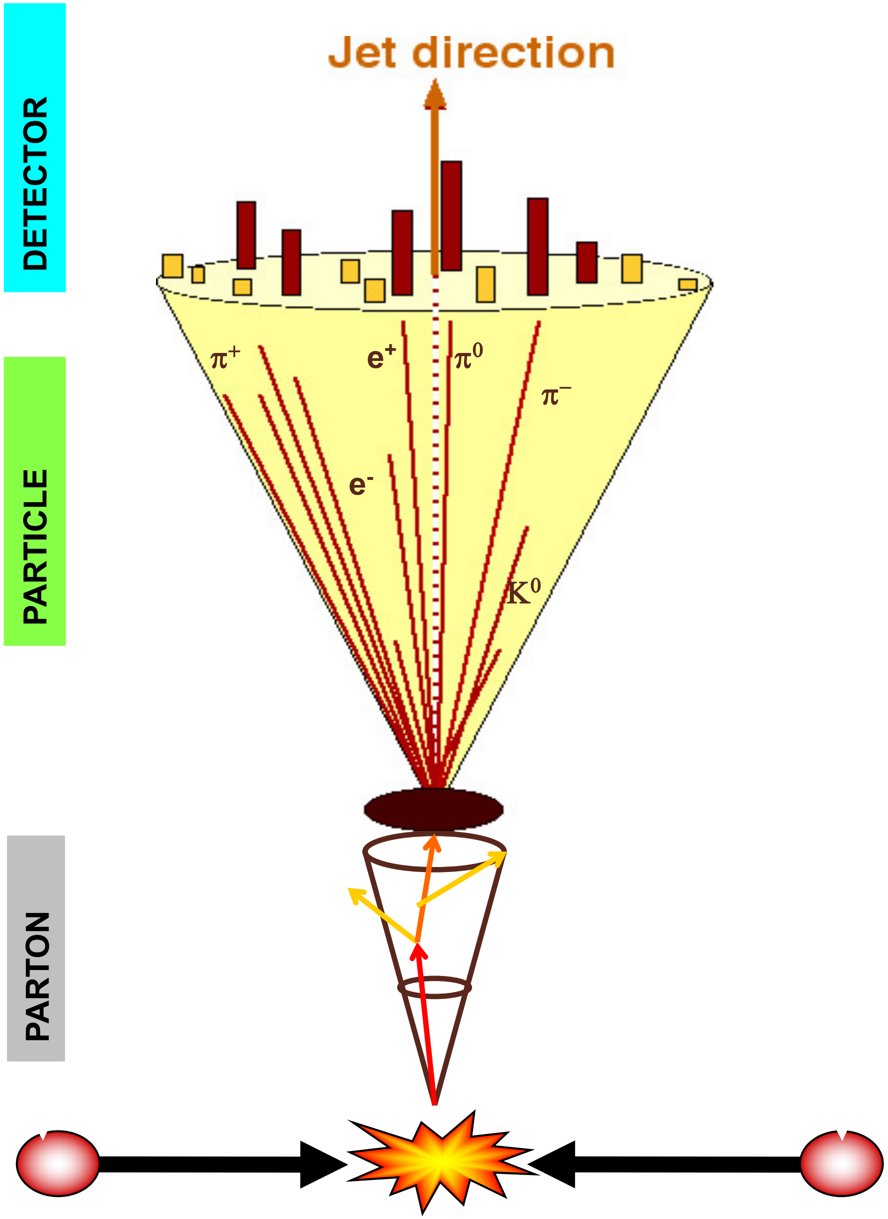


- Partonic fraction for jet/π[0] production:



Mukherjee 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 = 0.6/0.5

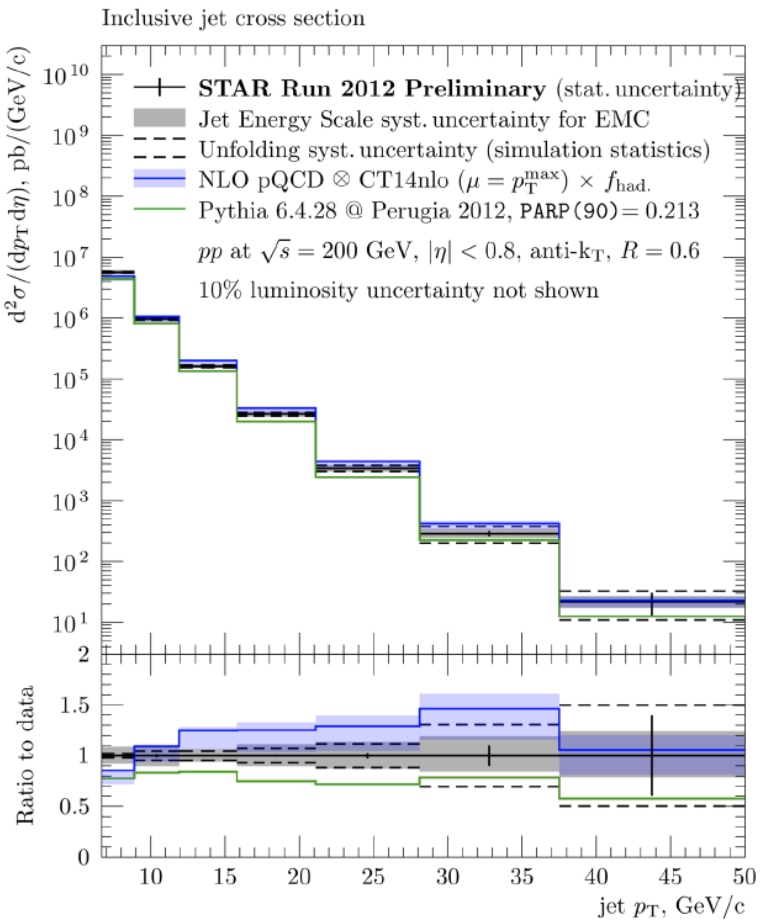
$$d_{ij} = \min\left(\frac{1}{k_{Ti}^2}, \frac{1}{k_{Tj}^2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

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

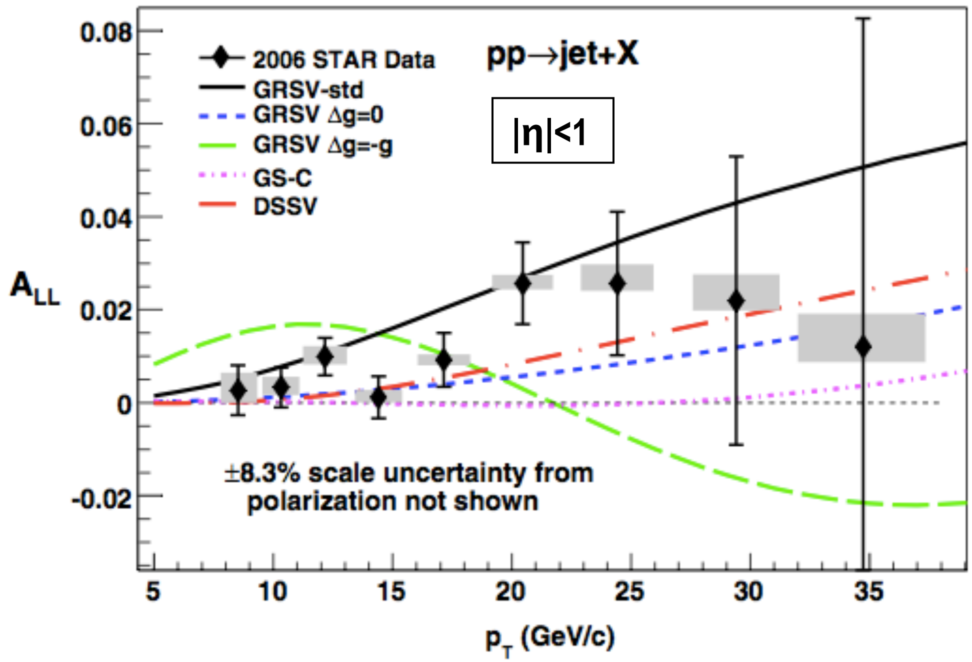
1) was used in previous years, now 2) is widely used.

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

- Cross section well described by NLO pQCD+Hadronization



STAR, PRD86, 32006(2012)



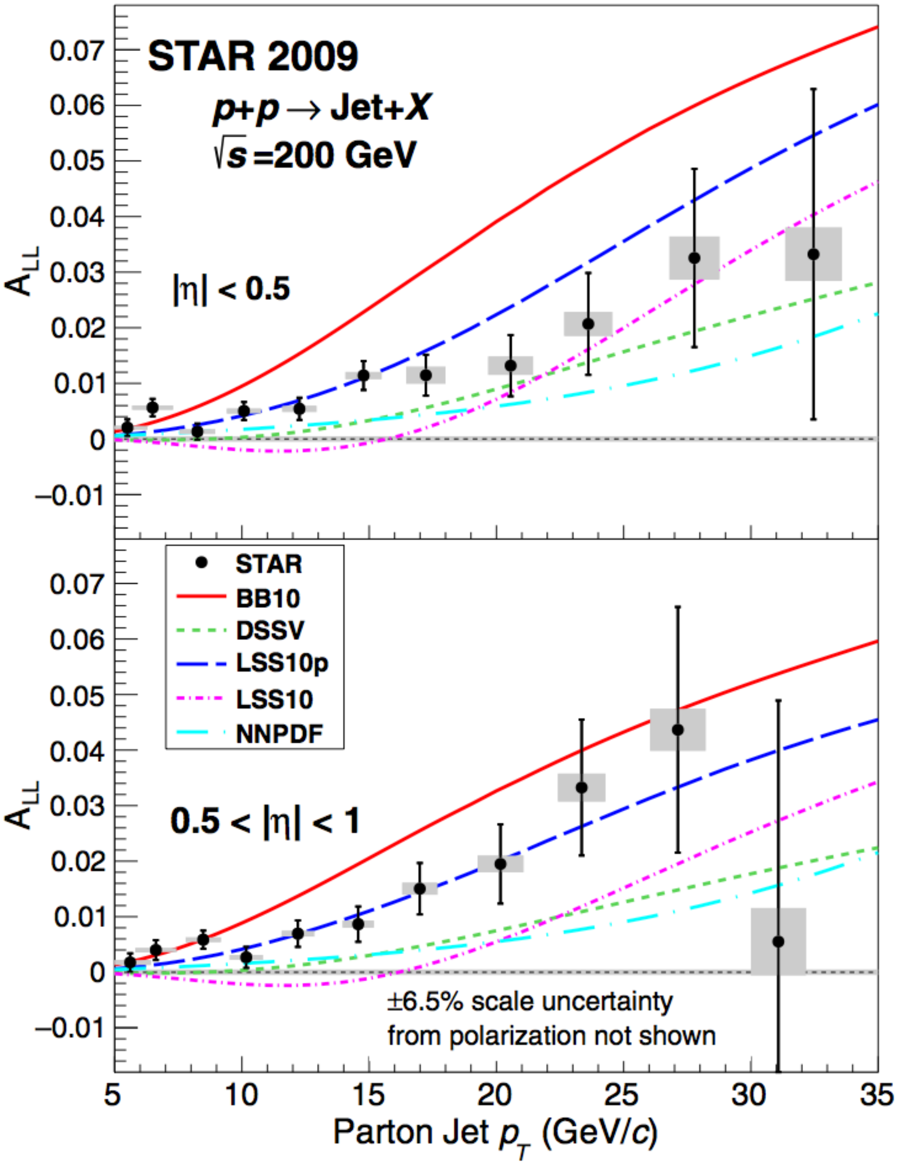
- STAR run6 data rule out several previous models of gluon polarization, and included in the DSSV global analysis together with PHENIX π^0 results.

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

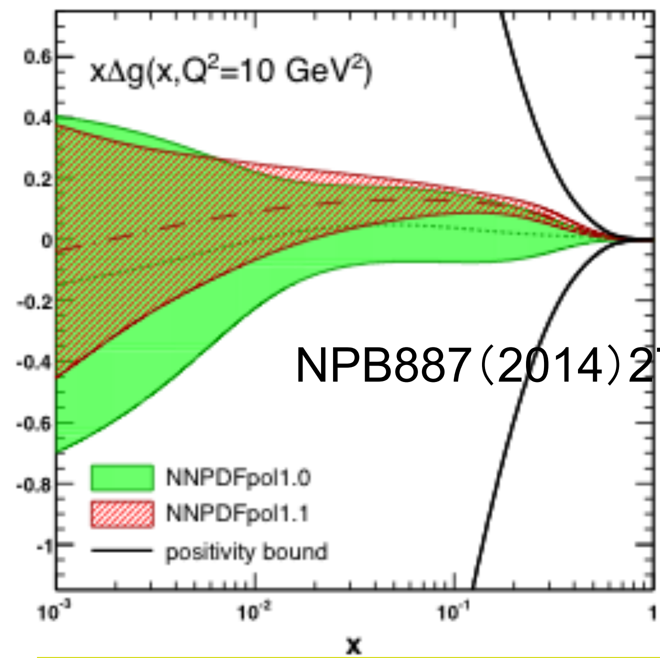
-arXiv:1304.0079

STAR inclusive jet A_{LL} from run9

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



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

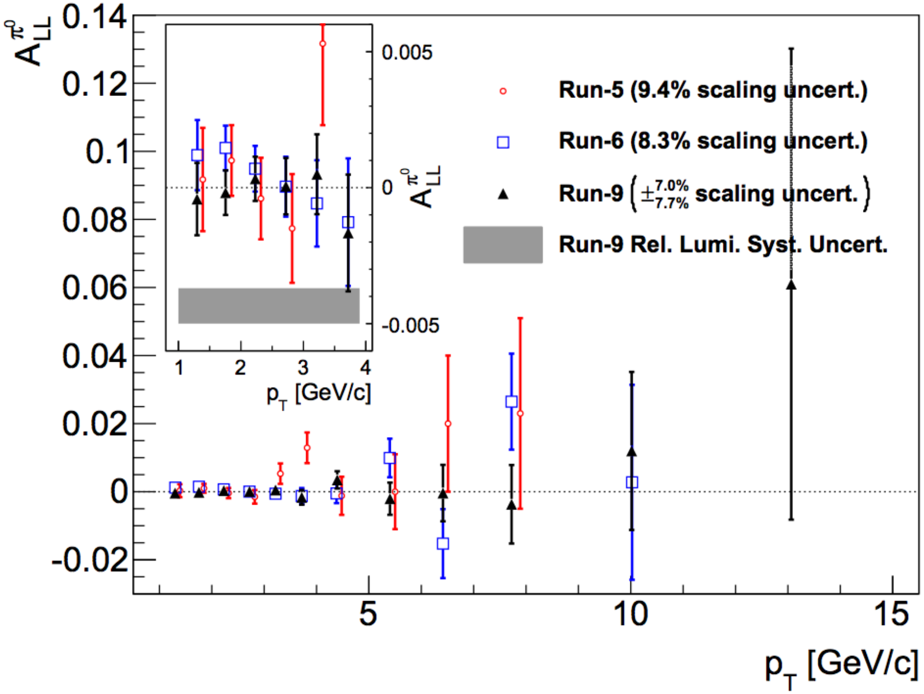


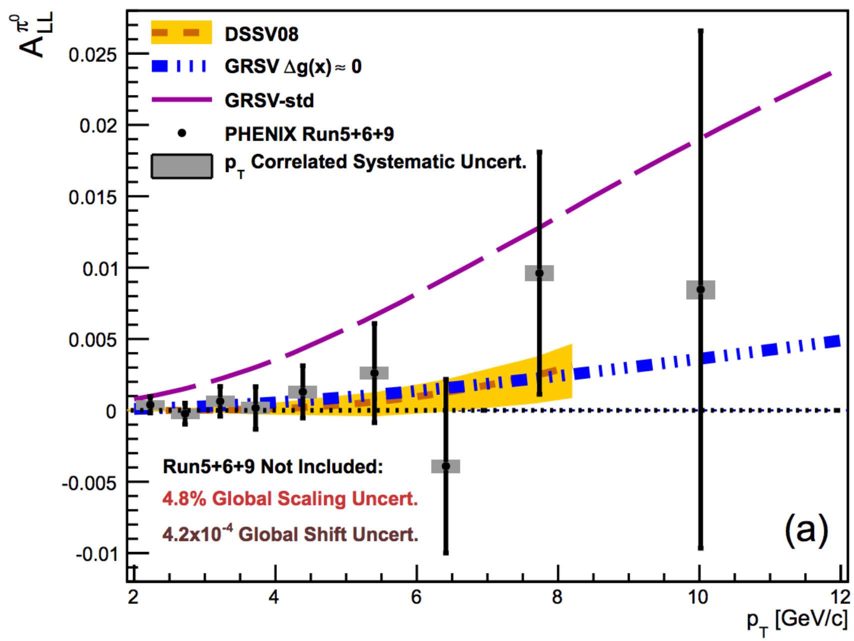
NPB887 (2014) 276

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

PHENIX results on π^0 A_{LL}

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

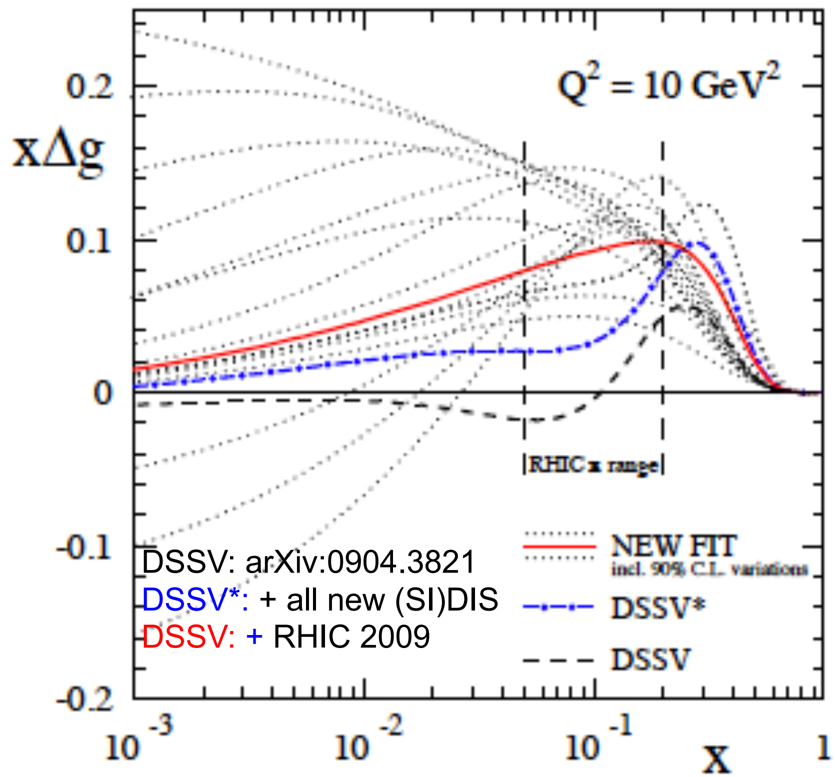


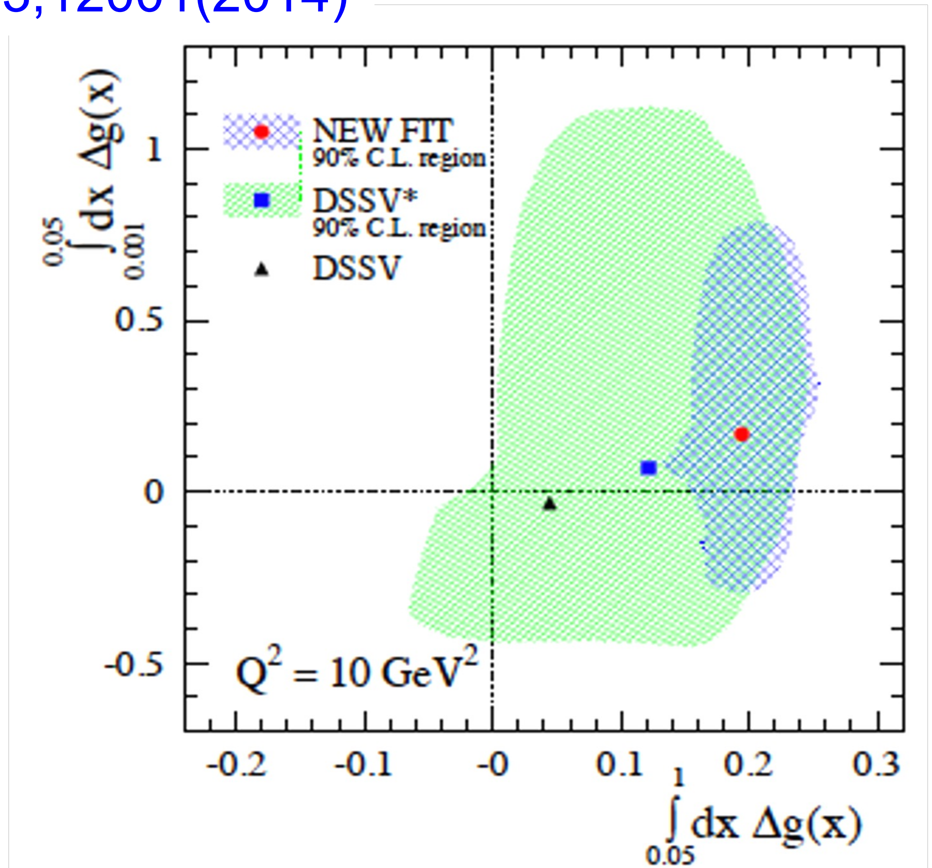


- High precision measurement at mid-rapidity
- Results are consistent with zero within uncertainty

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

DSSV, PRL113,12001(2014)





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

- 1st Lattice calculation:

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

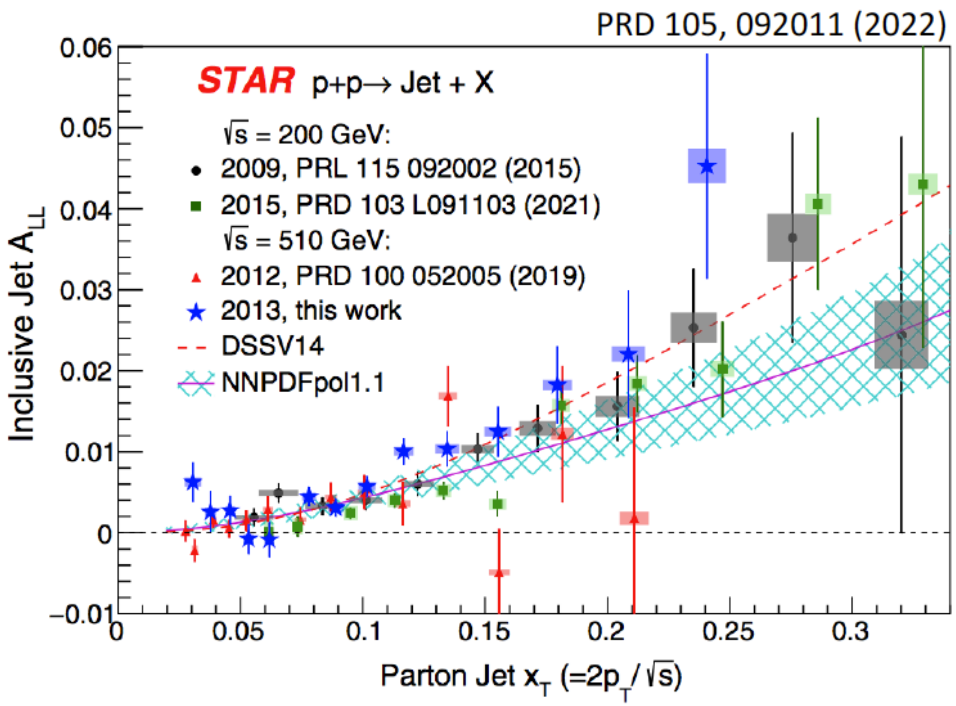
χQCD, PRL118,102001(2017)

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

-> higher energy, forward di-jets

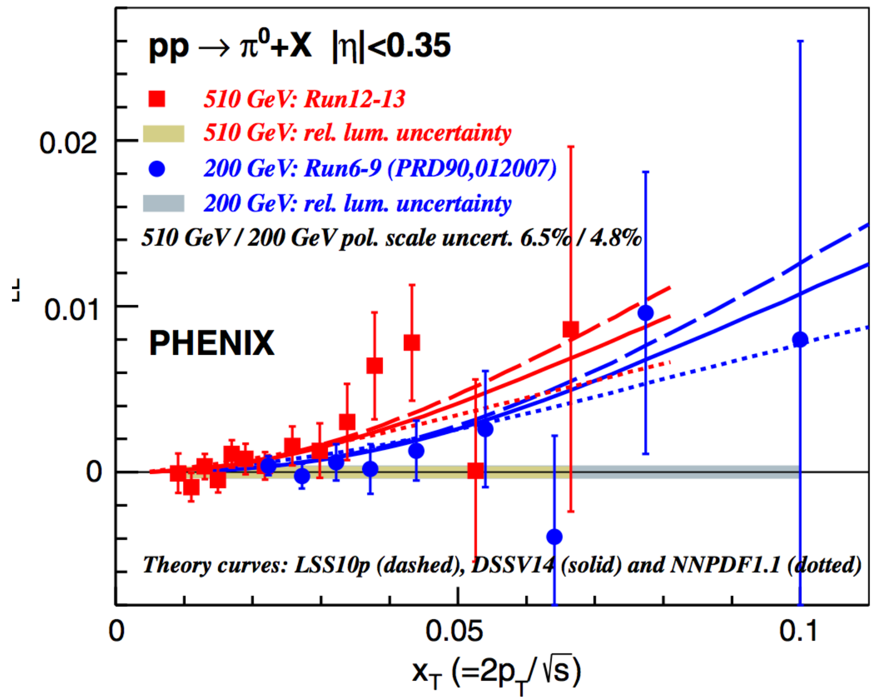
A_{LL} results on jet/π^0 at 510 GeV from RHIC

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



STAR, PRD103,91103(2021)
STAR, PRD105,92011(2022)

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

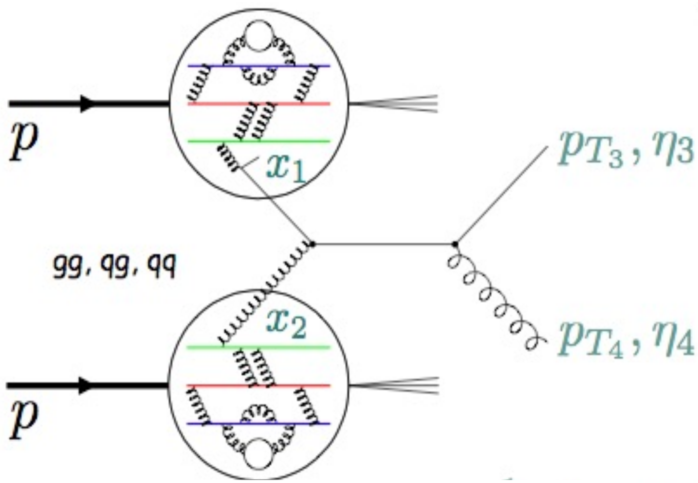


PHENIX, PRD 93, 011501 (2016)

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

Correlation measurements with partonic kinematics

- Access to partonic kinematics through di-jet production



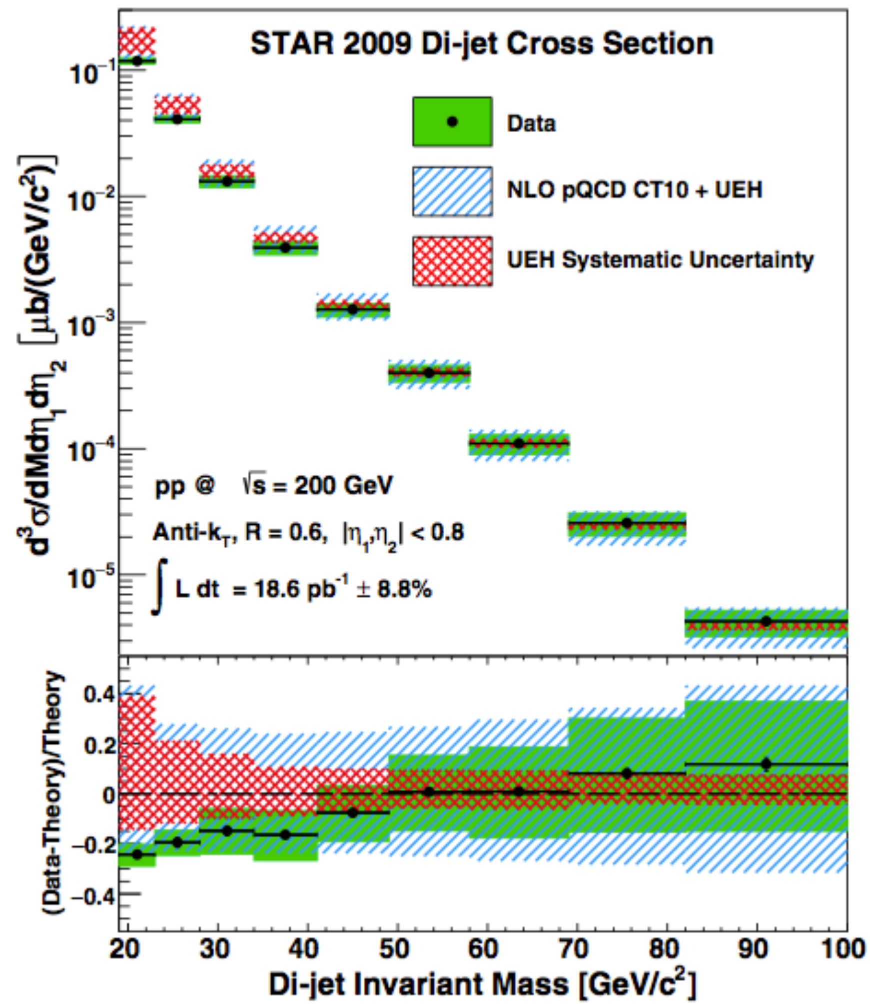
$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

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

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

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

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

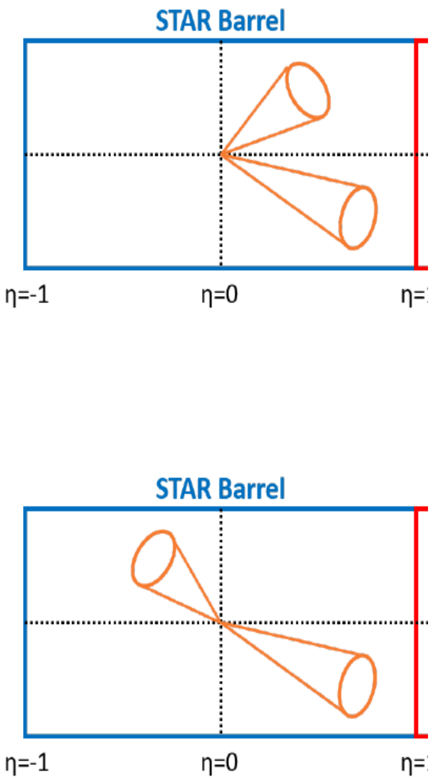


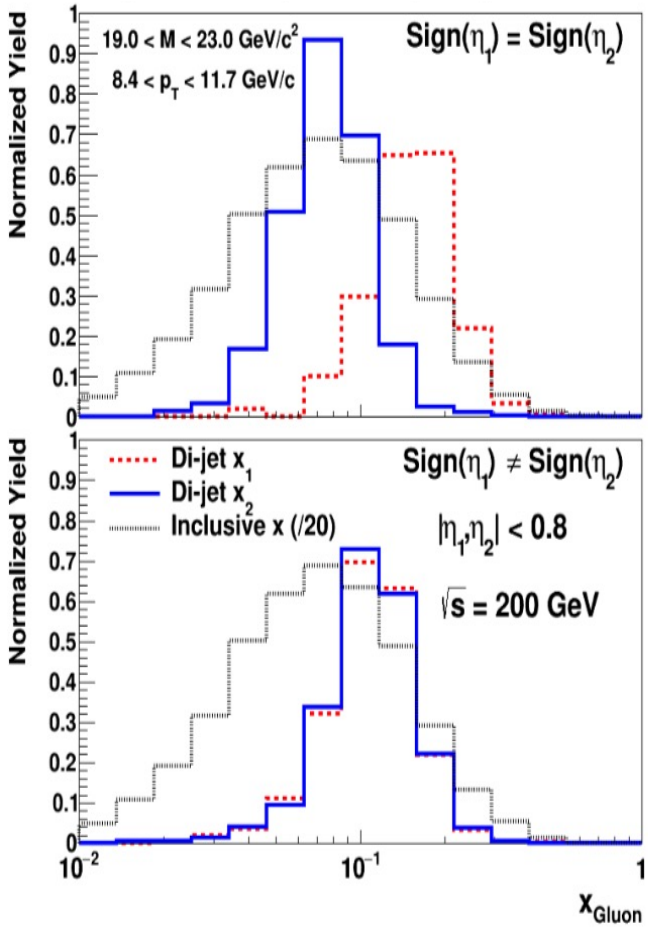
STAR, Phys. Rev. D95,071103(2017)

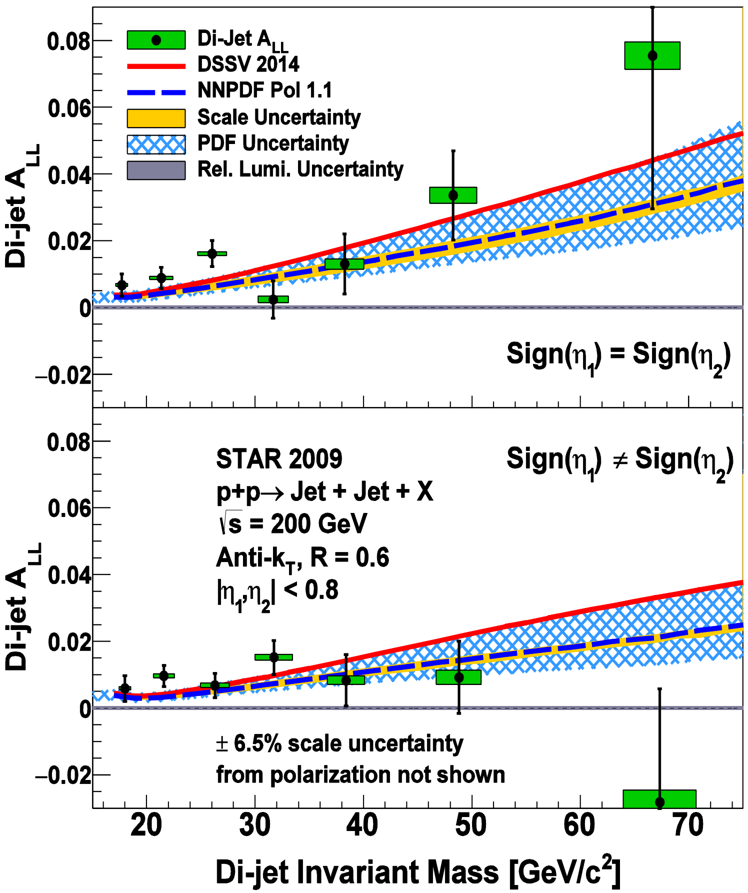
Central di-jet A_{LL} at 200 GeV at STAR

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

STAR, PRD95,071103(2017)



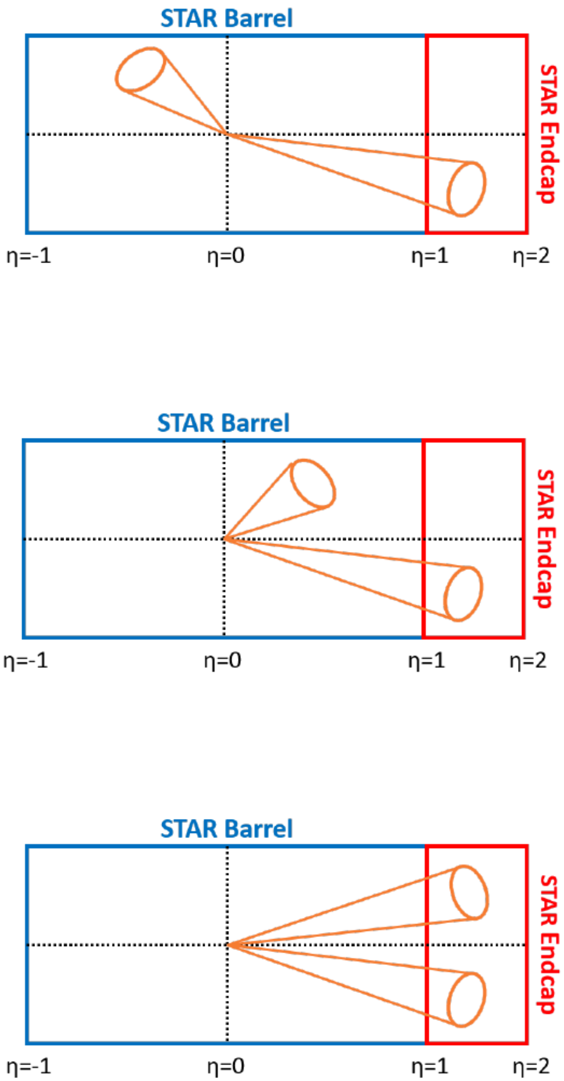


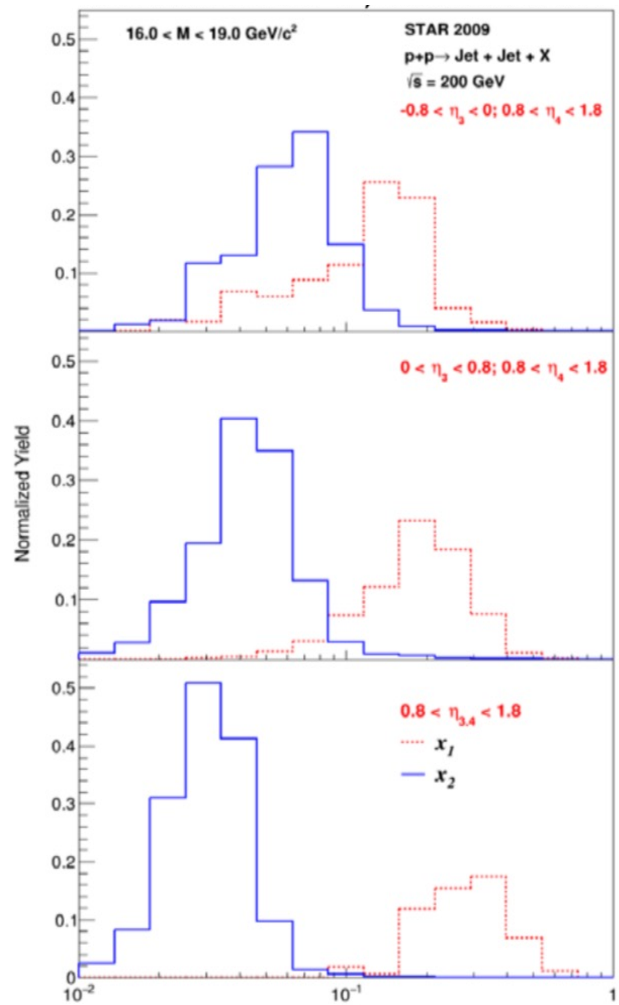


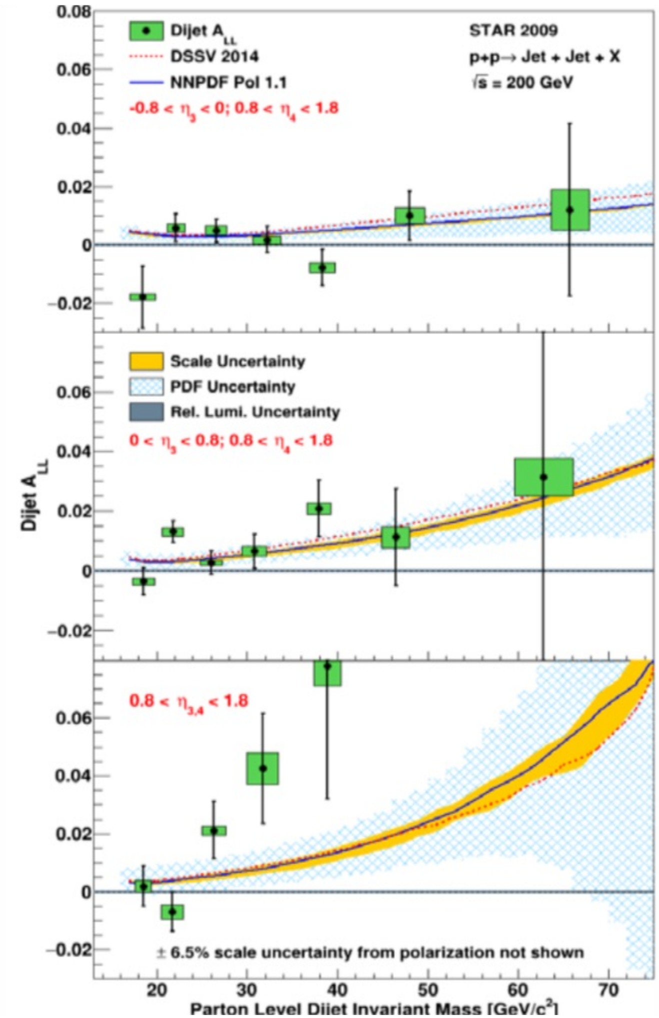
Central-forward di-jet at 200 GeV at STAR

STAR, PRD98,032011(2018)

Wider rapidity coverage!







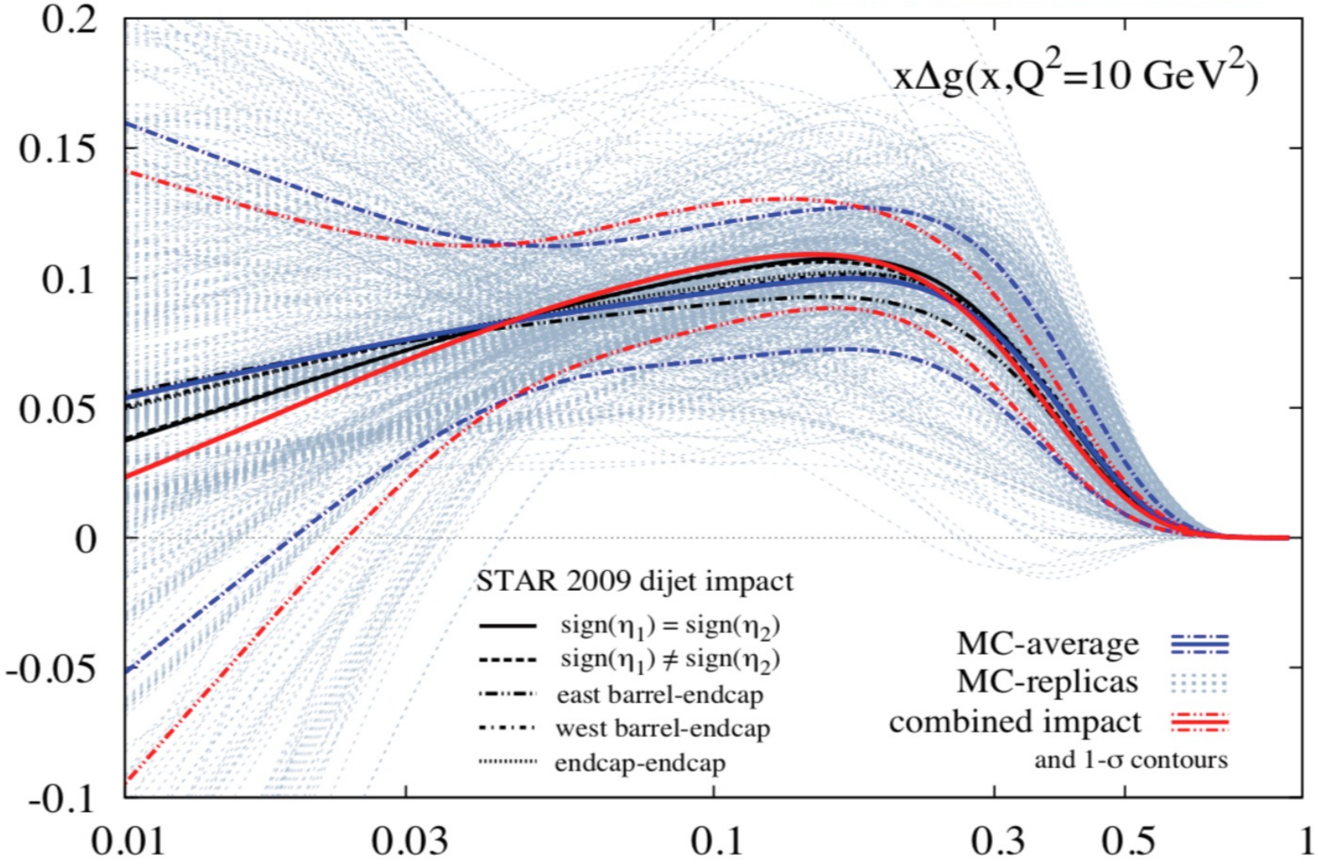
Impact of STAR di-jet A_{LL} to Δg global fit

D. de Florian, et al., (DSSV2018), PRD 100, 114027 (2019)

x

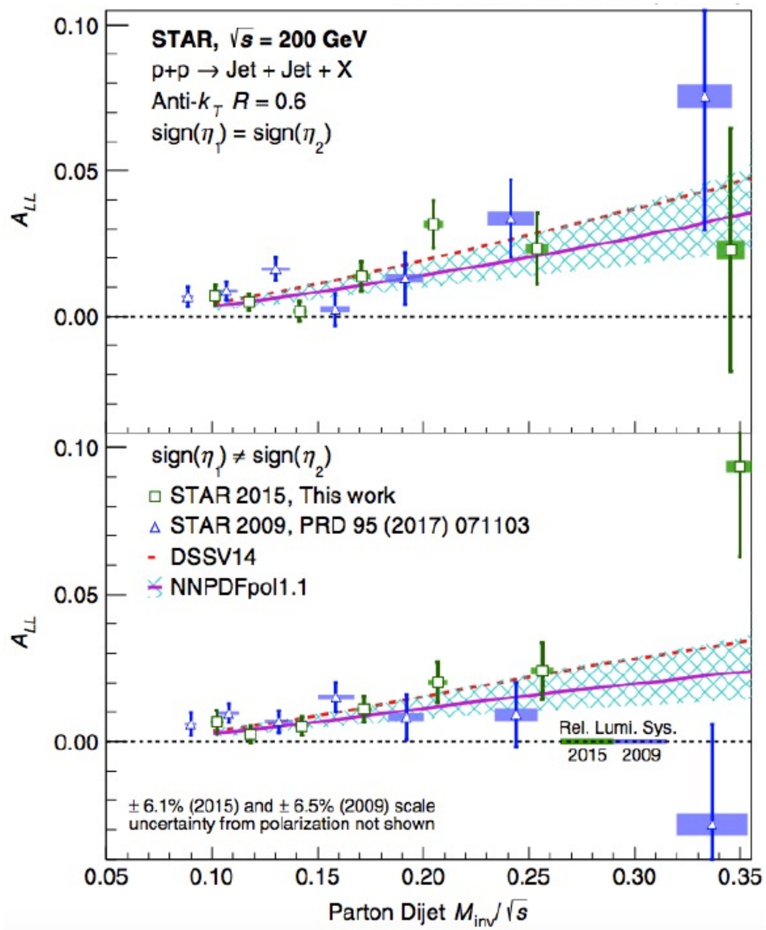
Before reweighting: $\int_{0.1}^{1} \Delta g(x)\,dx = 0.133 \pm 0.035$

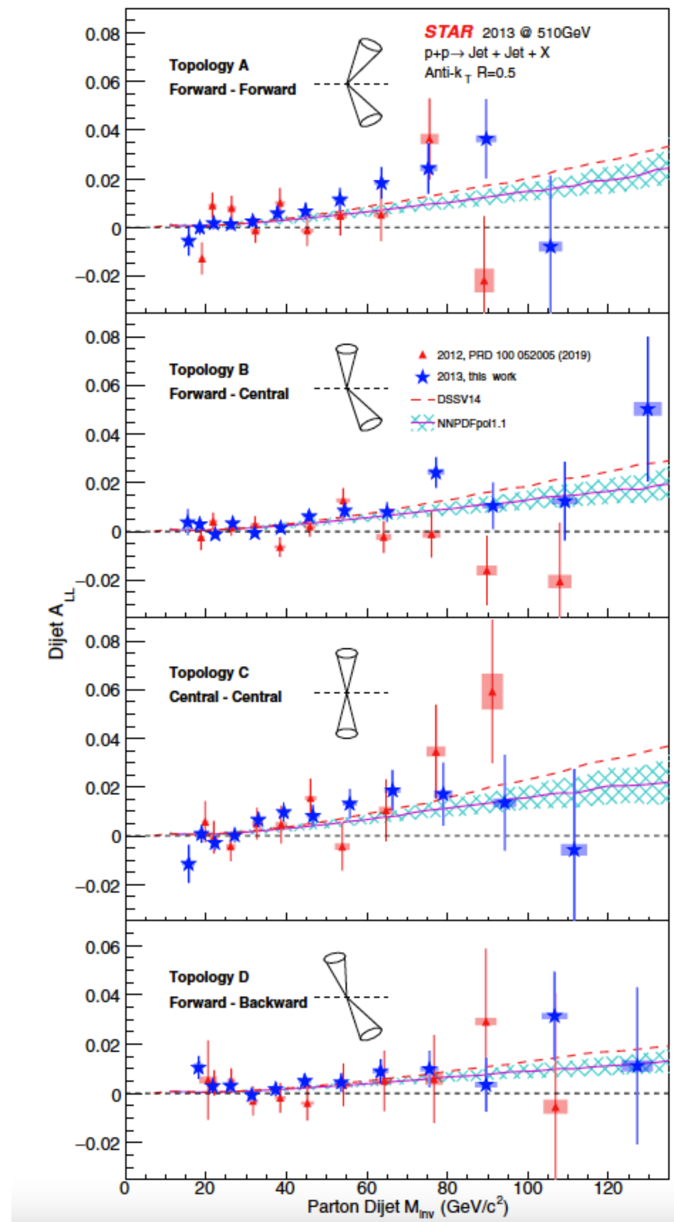
After reweighting: $\int_{0.1}^{1} \Delta g(x)\,dx = 0.126 \pm 0.023$



Recent new STAR di-jet A_{LL} results

STAR, PRD103,091103(2021)

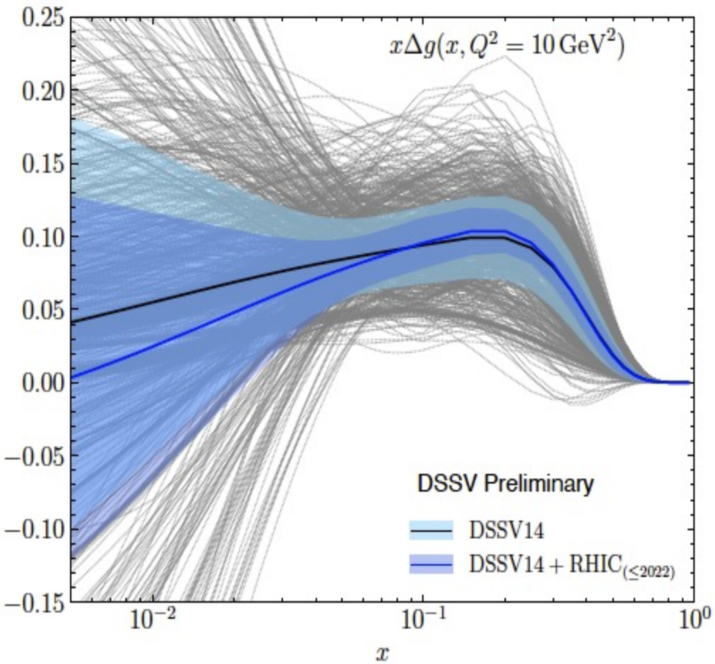


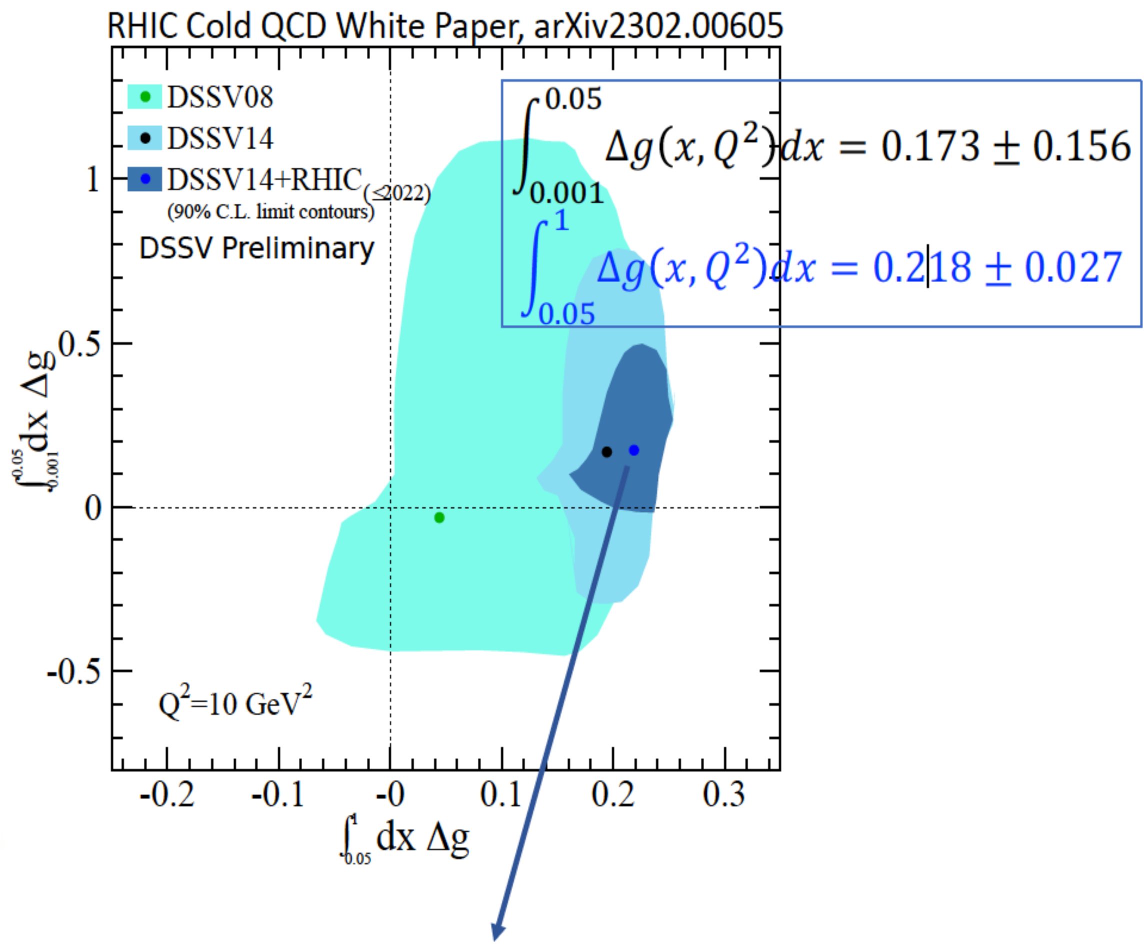


STAR, PRD105,92011(2022)

Most recent updates from DSSV group on Δg

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



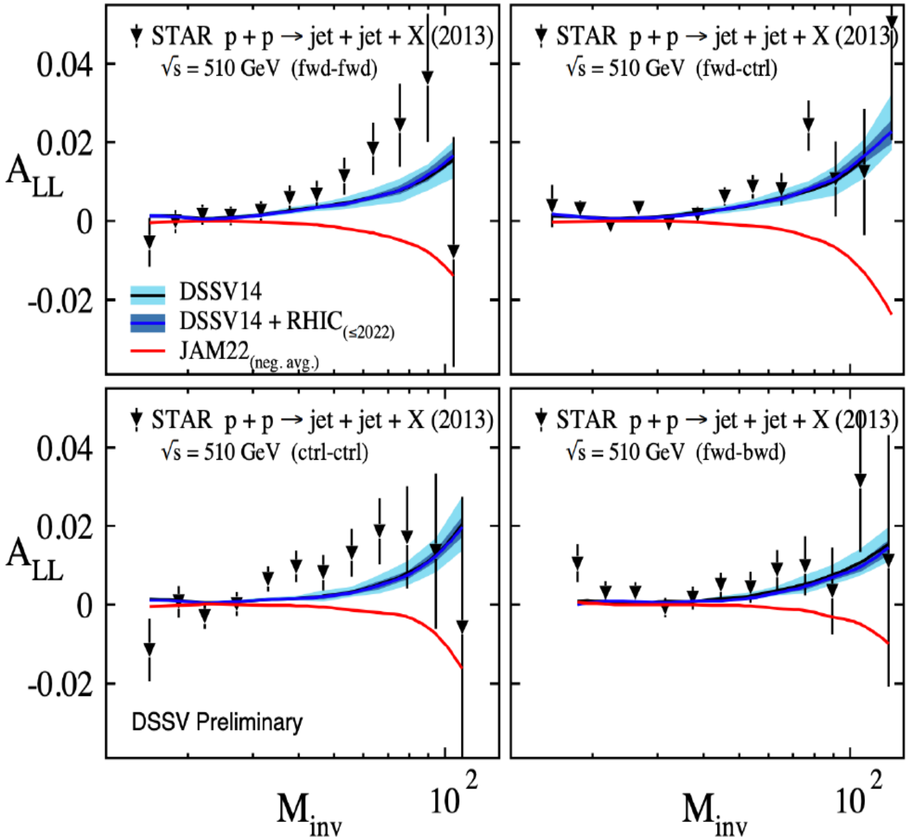


- Results show 8-σ positive gluon spin ΔG for $x > 0.05$.
- ΔG contributes **40%** of proton spin at $x > 0.05$.

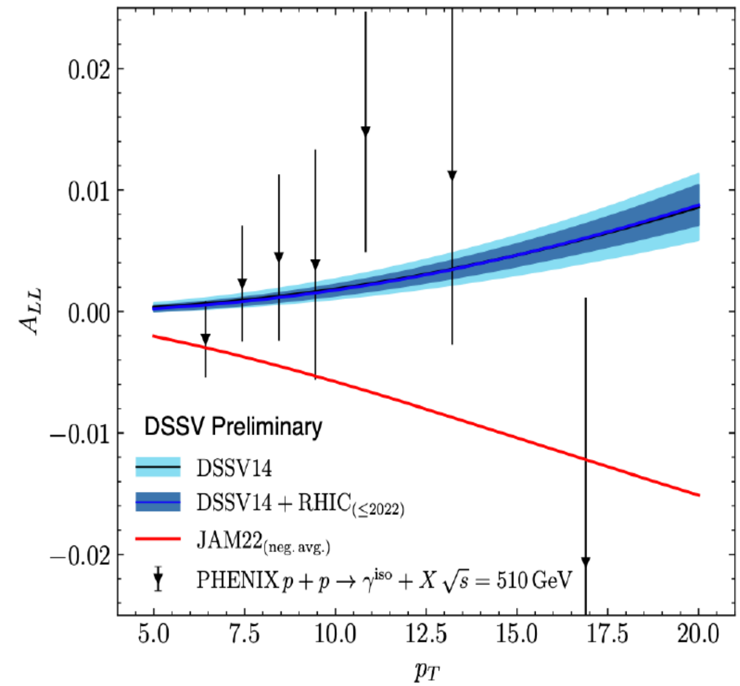
Most recent updates from DSSV group on Δg

- Could Δg be negative? no

STAR dijet PRD 105, 092011 (2022)



PHENIX direct γ 2202.08158
JAM, PRD 105, 074022 (2022)

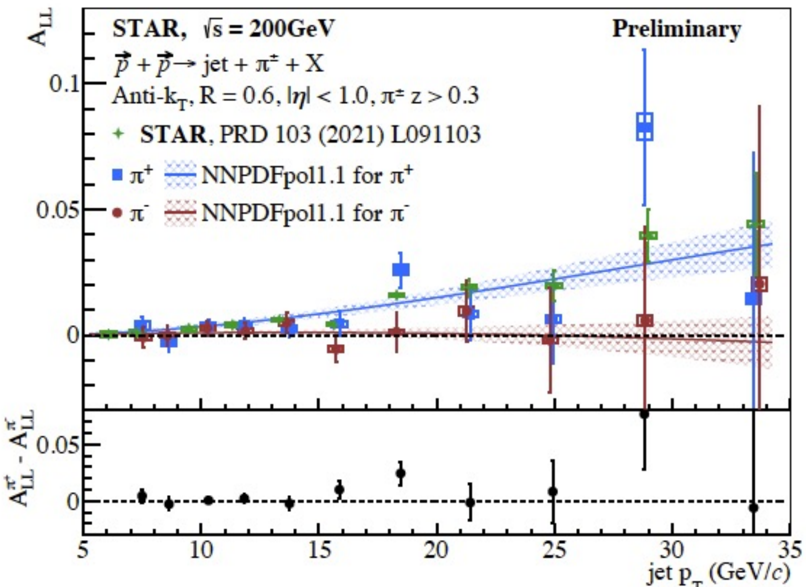


- ➢ JAM global QCD fit indicate possible negative Δg with inclusive jet ALL data only.
- ➢ STAR dijet + PHENIX direct photo data strong disfavor negative Δg
- ➢ New results with pion tagged jet also support positive Δg

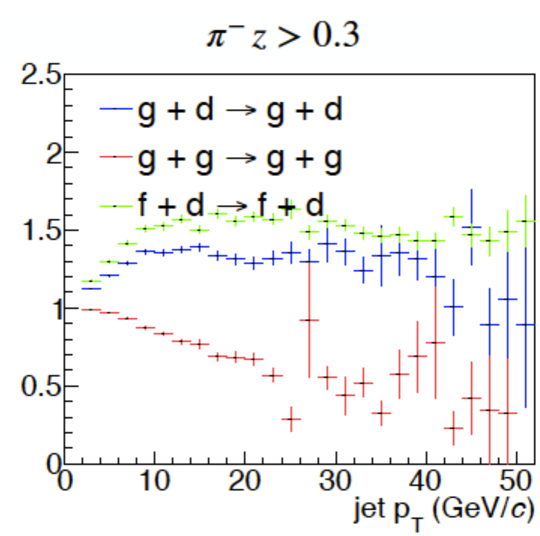
Most recent updates from DSSV group on Δg

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

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



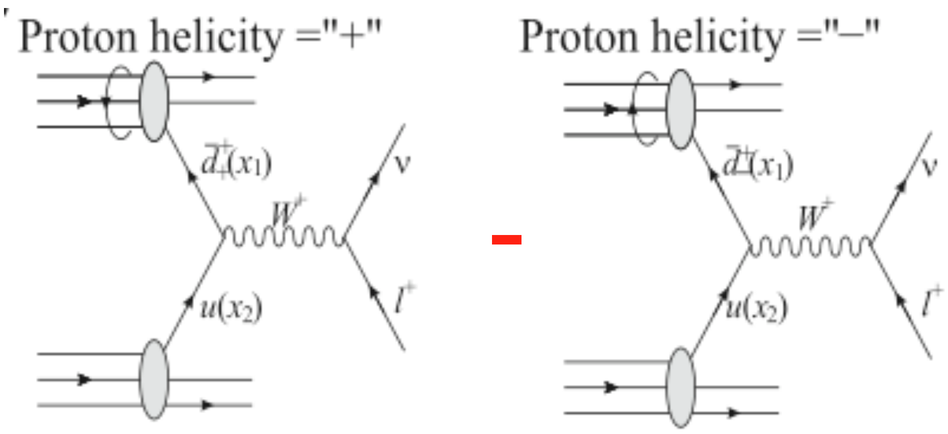
- Tagging suppresses g-g scattering
- π^+ tagging enhances u quark related subprocess up to 20%
- π^- tagging enhances d quark related subprocess up to 40%



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

Probing sea quark polarization via W production

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



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

- **Spin asymmetry measurements:**

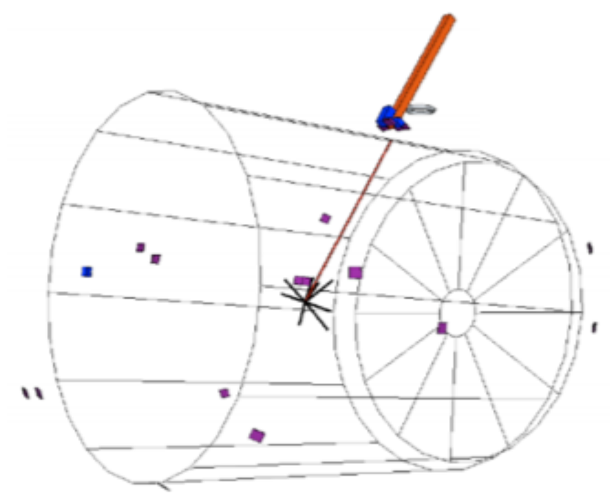
$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \sim \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \end{cases}$$

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

W selection via W -> eν at STAR

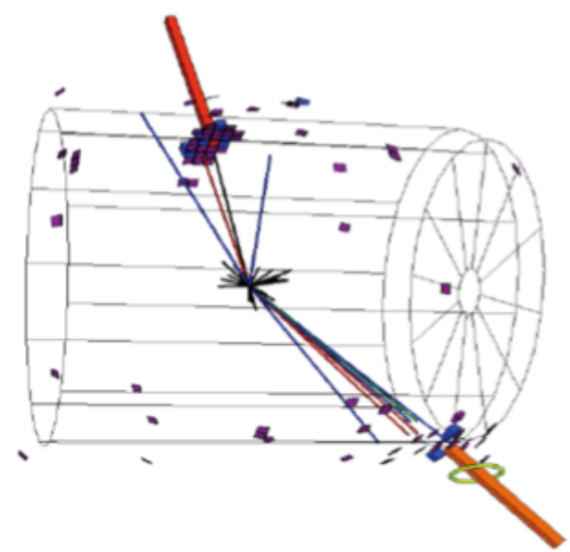
$W \rightarrow e + \nu$ Candidate Event:

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

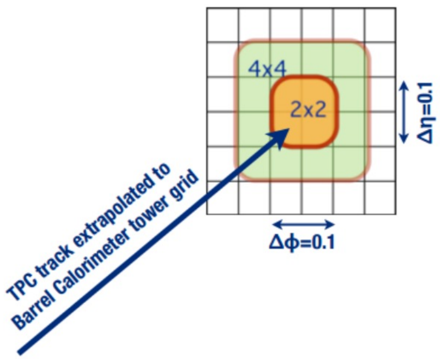


QCD Background Event

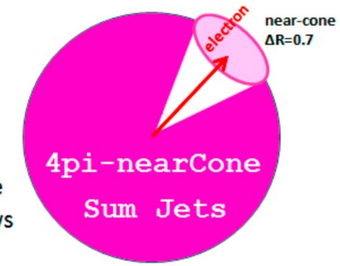
- Several tracks pointing to energy deposit in several towers
- p_T sum is balanced by di-jet, no large “missing energy”



W selection at STAR : Jacobian peak



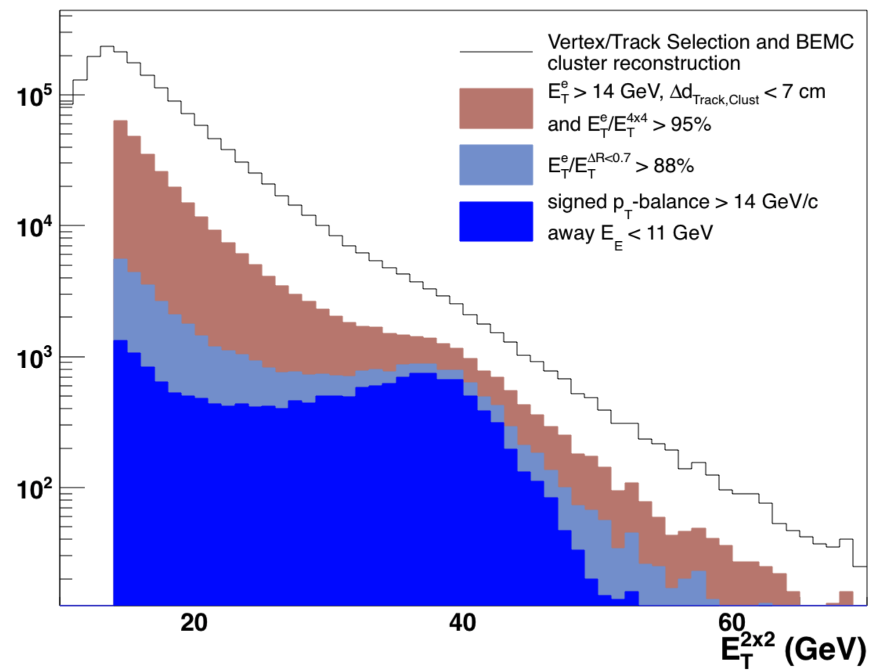
Transverse
Plane views



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

- Isolation ratio $E_{2\times2}/E_{4\times4} > 95\%$
- 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 $E_T < 11\text{GeV}$

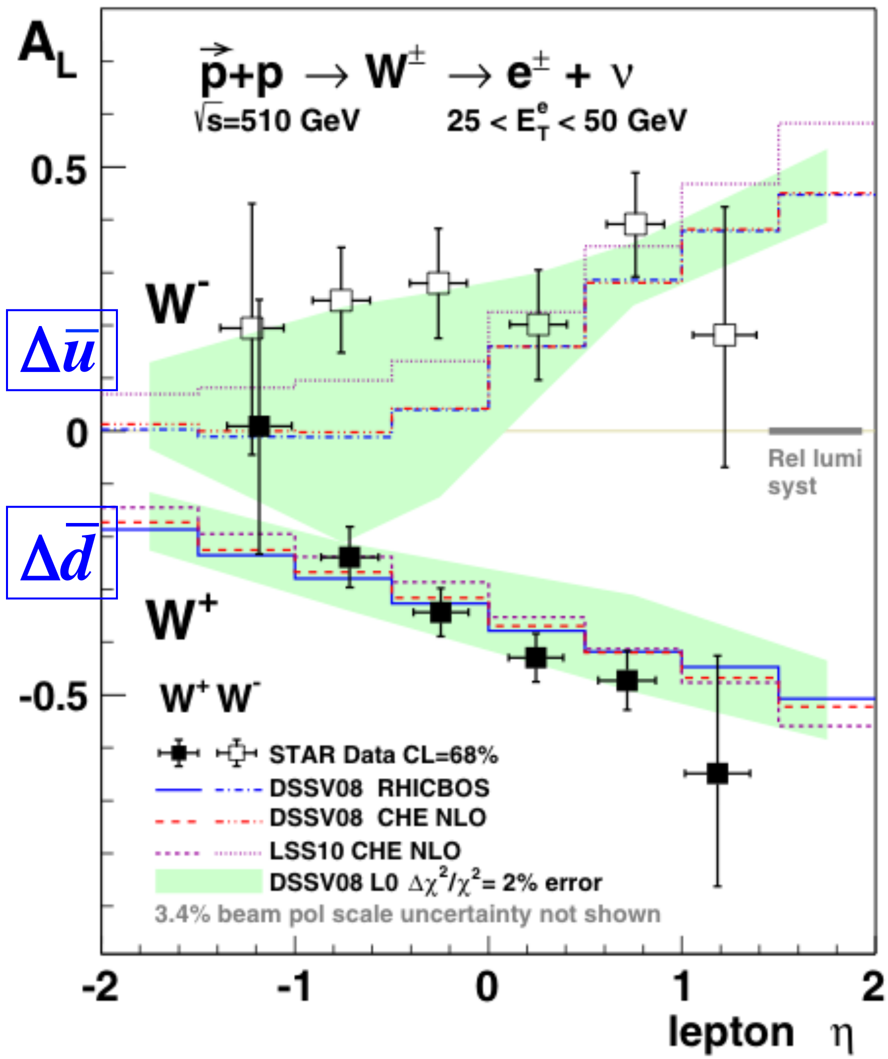
Signal of Jacobian peak with E_T distribution after selection :



-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.

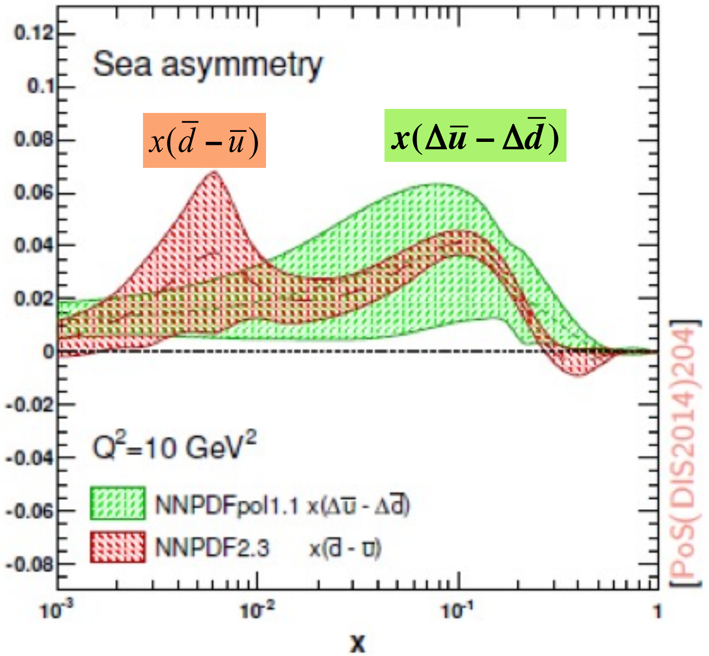
STAR, PRL113, 72301(2014)

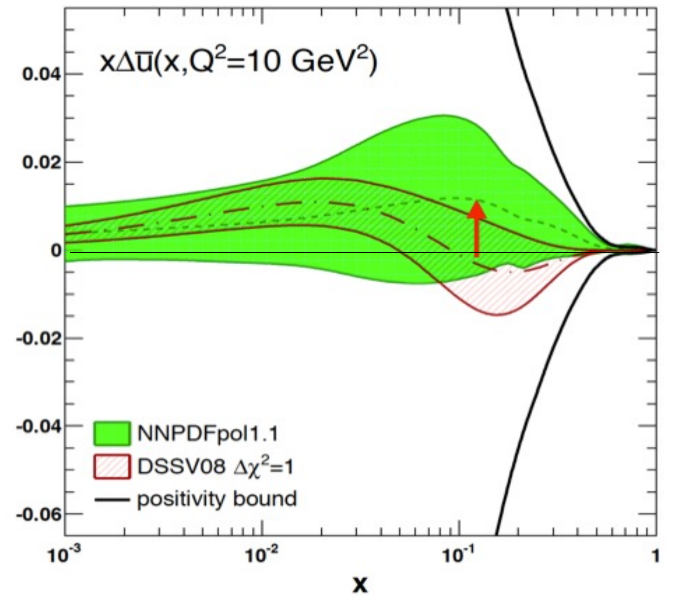
Global Analysis with STAR W A_L results

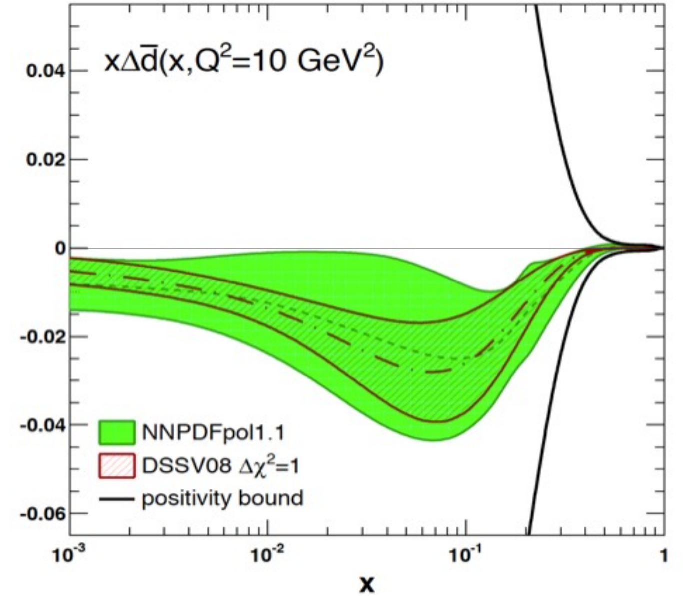
- Big impact seen in NNPDFpol1.1 global analysis after including STAR A_L data.

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

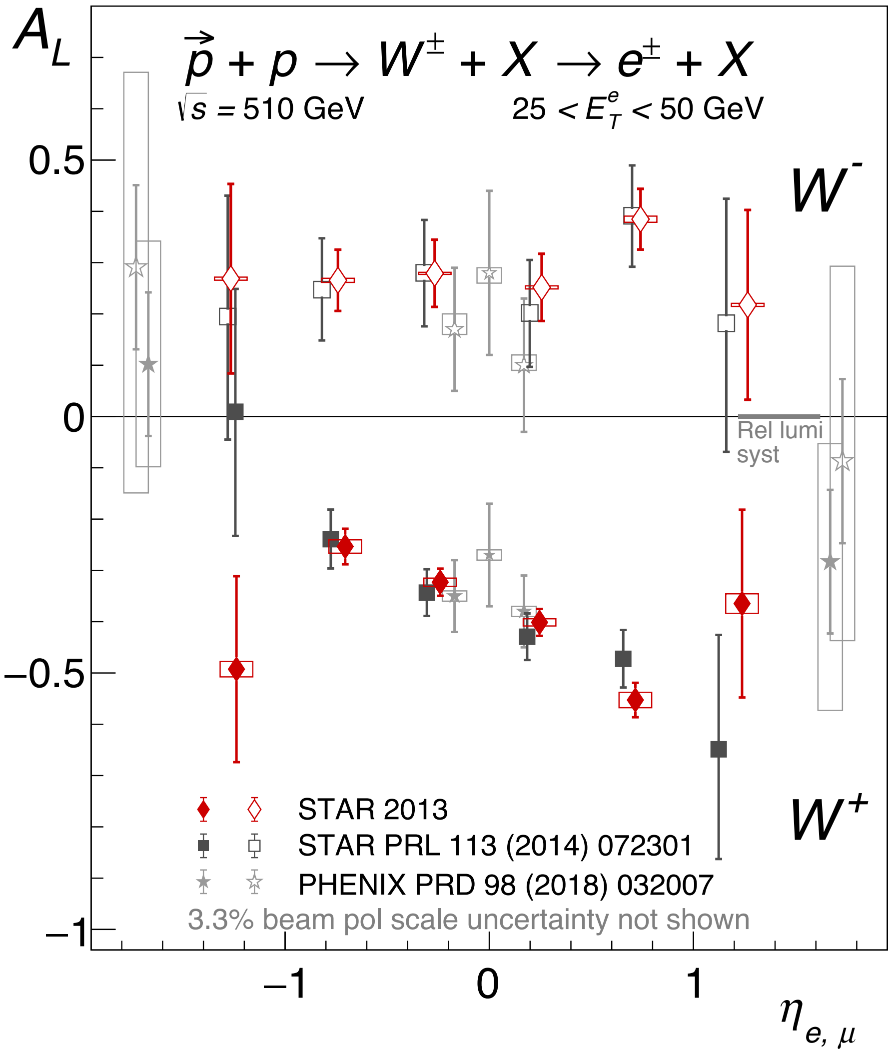
- Polarized sea asymmetry:







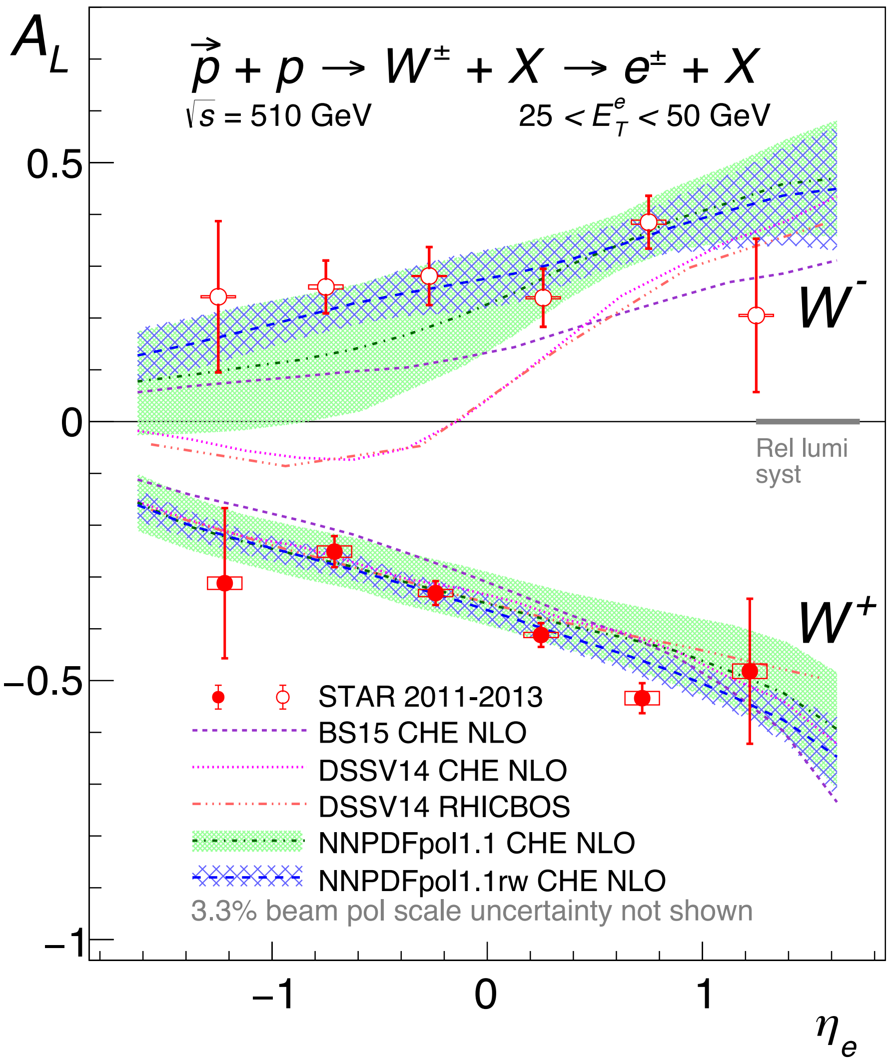
W A_L results – STAR 2013



STAR, PRD99, 051102R(2019)

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

W A_L results – STAR 2013

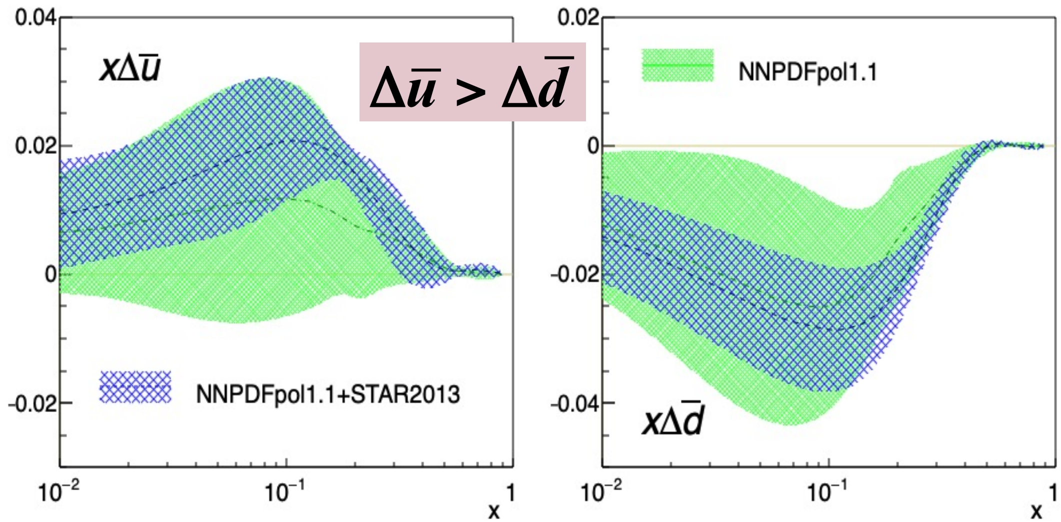


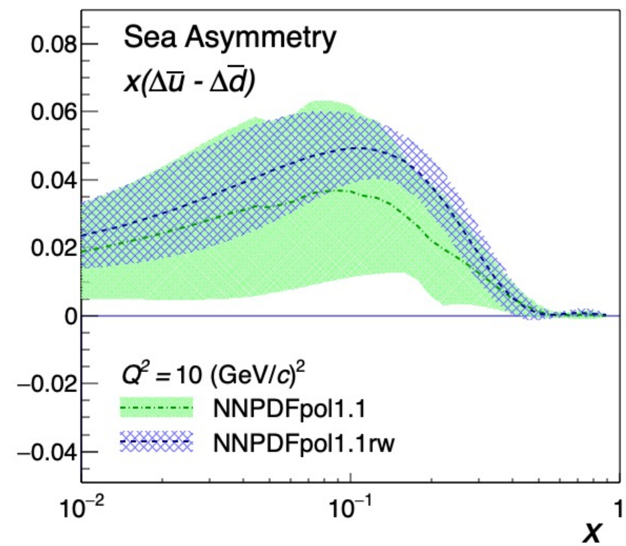
STAR, PRD99, 051102R(2019)

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

Impact of STAR 2013 W A_L results

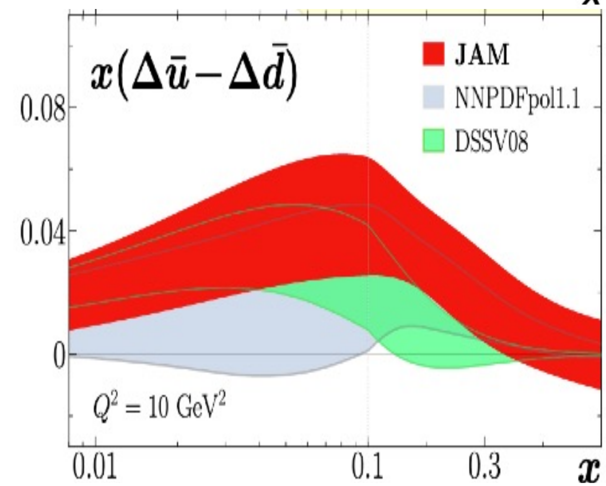
- SU(2) flavor asymmetry observed in the polarized sea quark distribution, confirmed by JAM and reweighting NNPDF:





STAR, PRD99, 051102R(2019)

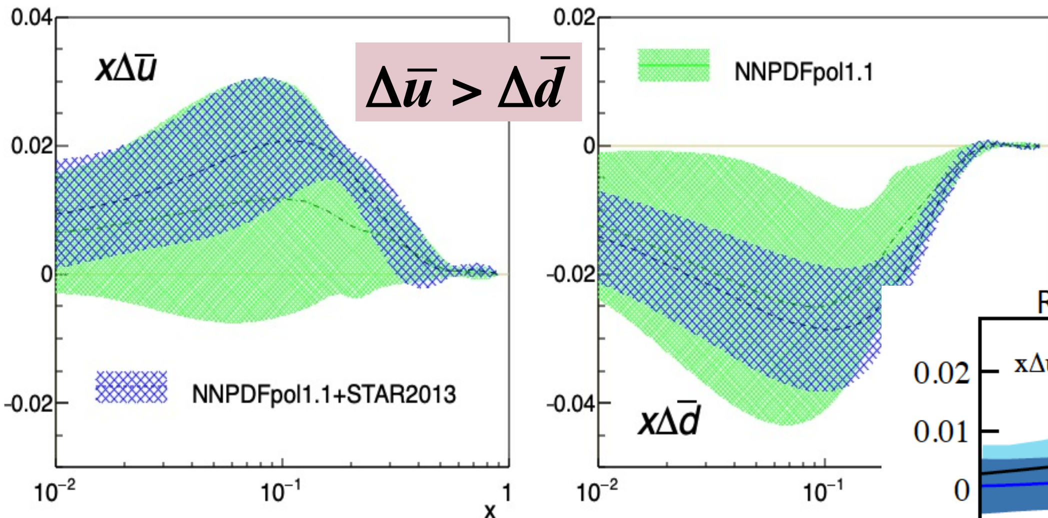
✓ Compatible with Pauli suppression by the polarized valence quarks, among different models.

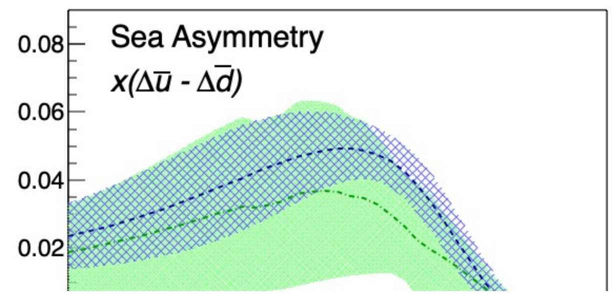


JAM, PRD.106.031502 (2022)

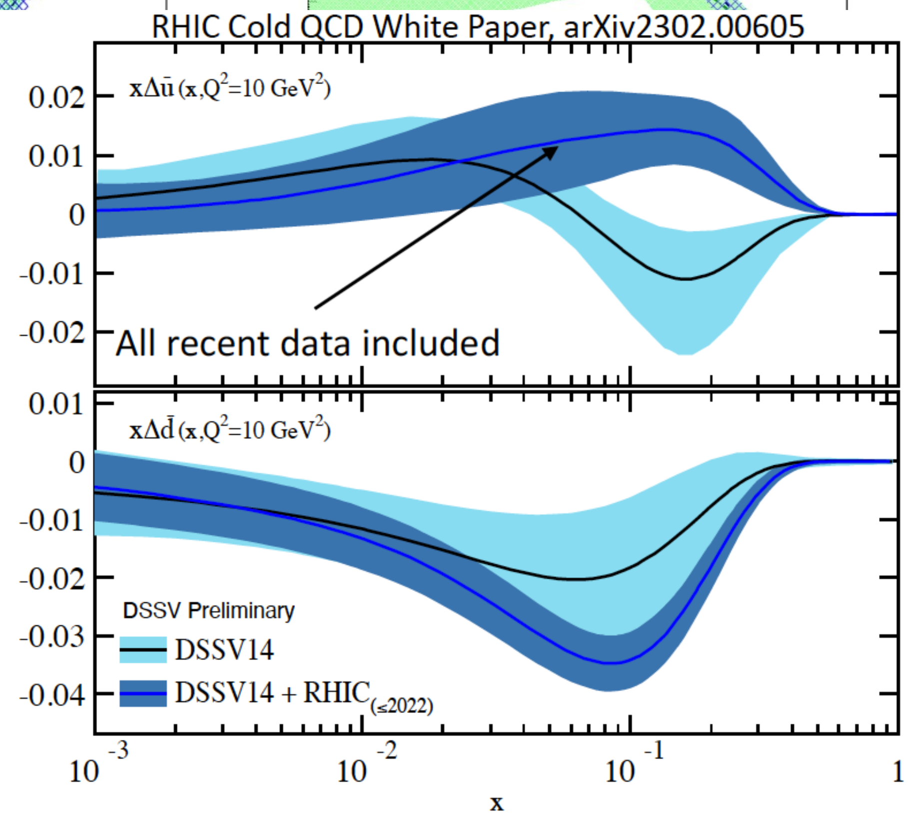
Impact of STAR 2013 W A_L results

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





STAR, PRD99, 051102R(2019)



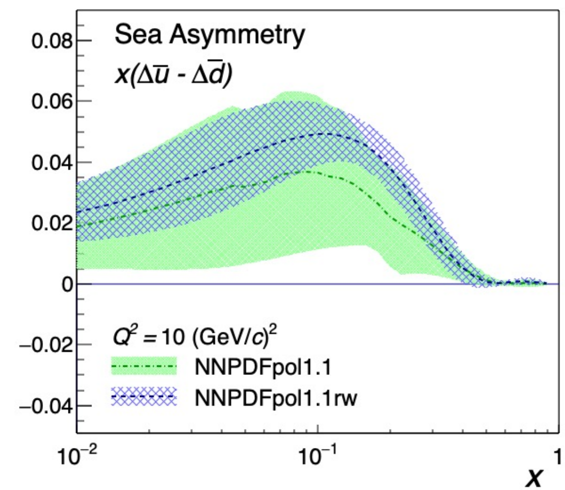
✓ Compatible with Pauli suppression the polarized valence quarks, amo different models.

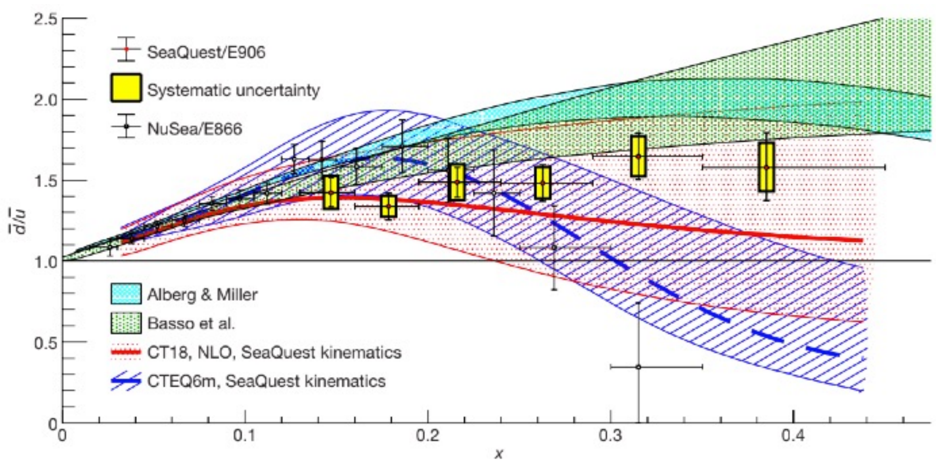
Impact of STAR 2013 W A_L results

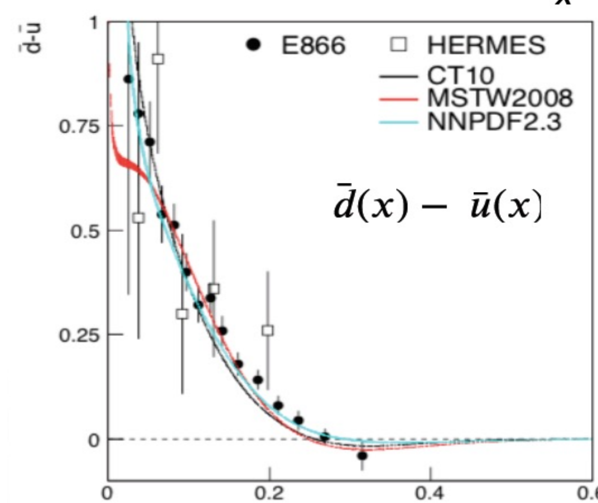
- SU(2) flavor asymmetry observed in the polarized sea quark distribution, confirmed by JAM and reweighting NNPDF:

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

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







- SeaQuest, Nature 590, (2021)561

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

Self analyzing Λ polarization via weak decay

- Λ polarization can be measured in experiment via weak decay:

Λ->pπ⁻(Br64%), Λ->nπ⁰(Br36%) ,

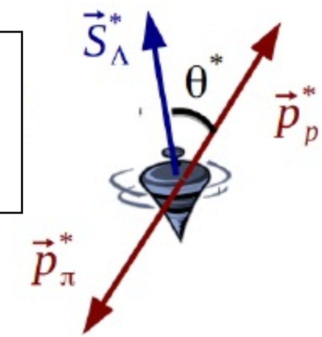
-T.D.Lee, C.N.Yang(1957)

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

Unit vector along proton momentum in Λ's rest frame.

decay parameter

Λ polarization vector



$\Lambda \rightarrow p + \pi^+$

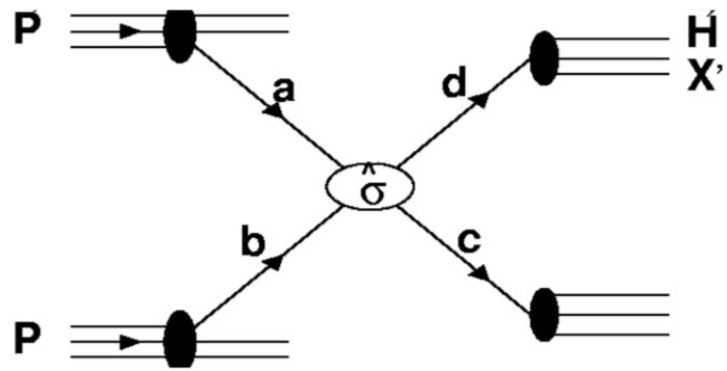
(BR: 63.9%, cτ~7.9 cm)

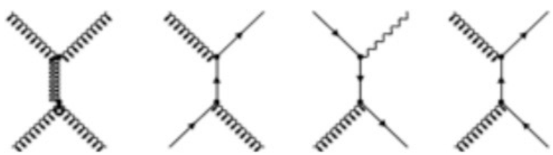
- Λ's contain a strange constitute quark, whose spin is expected to carry most of the Λ spin: $\left|\Lambda^\uparrow\right\rangle = (ud)_{00}\, s^\uparrow$

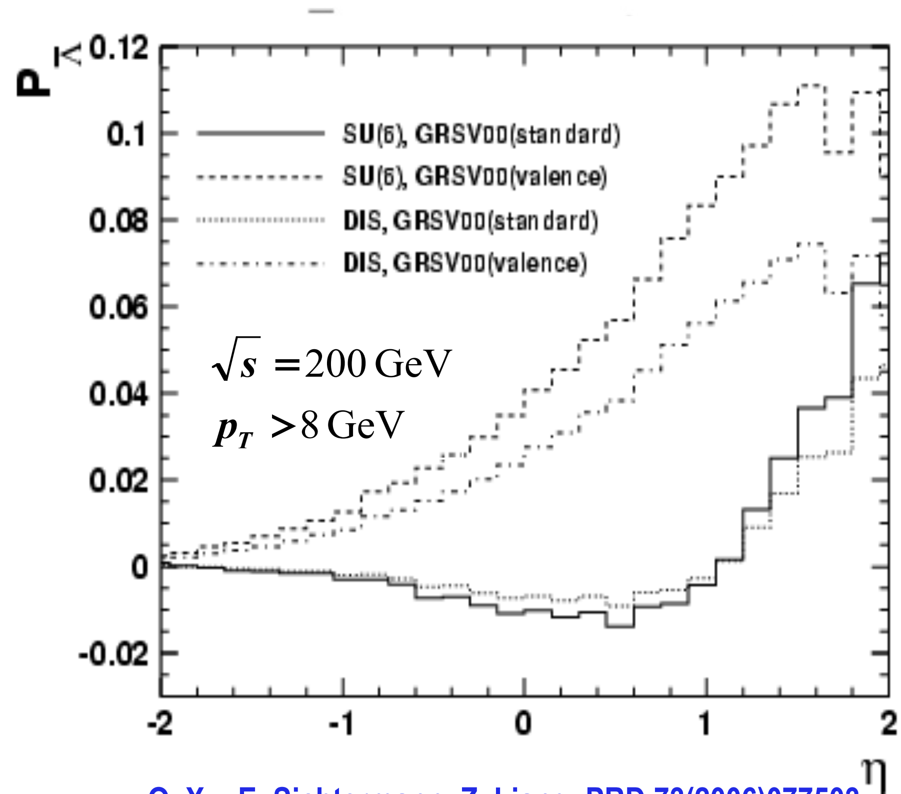
- Λ polarization can serve as a powerful tool in spin physics of different field.

Hyperon spin transfer in pp collision

- The factorized framework enables perturbative description,







$$d\sigma \propto \int f_a(x_1)\cdot f_b(x_2)\otimes d\hat{\sigma}\otimes D^{\Lambda}(z)$$

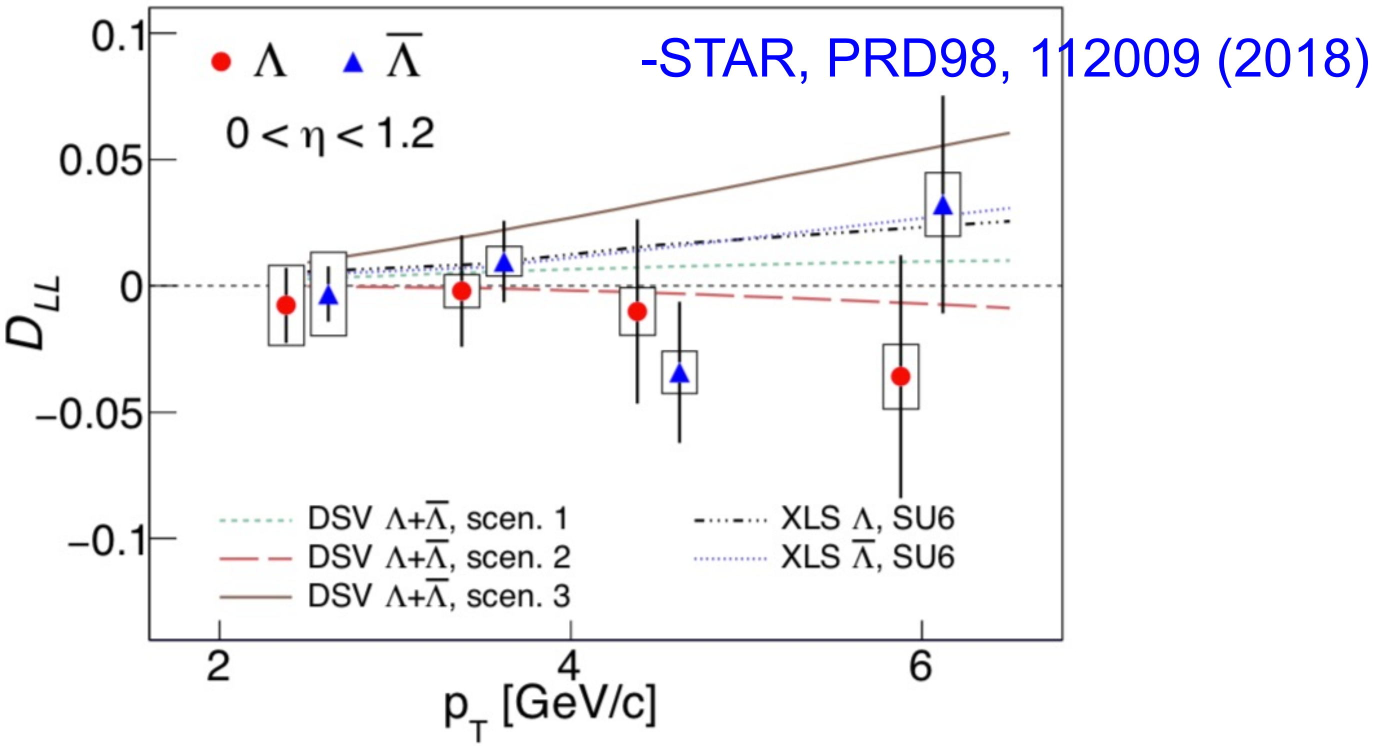
Q. Xu, E. Sichtermann, Z. Liang, PRD 73(2006)077503

- Hyperon spin transfer D_{LL} provides access to Δf and ΔD :

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

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.



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

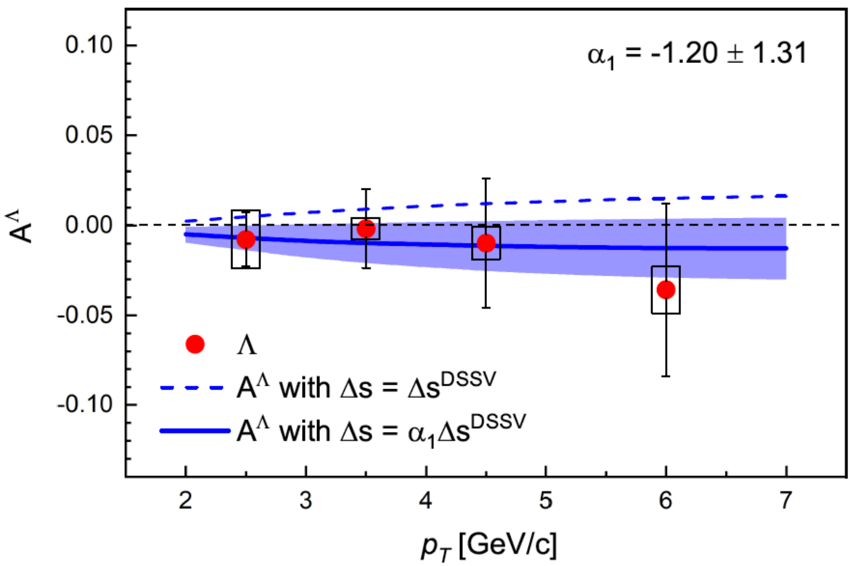
➢ D_{LL} results are still consistent with zero within the uncertainties.

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

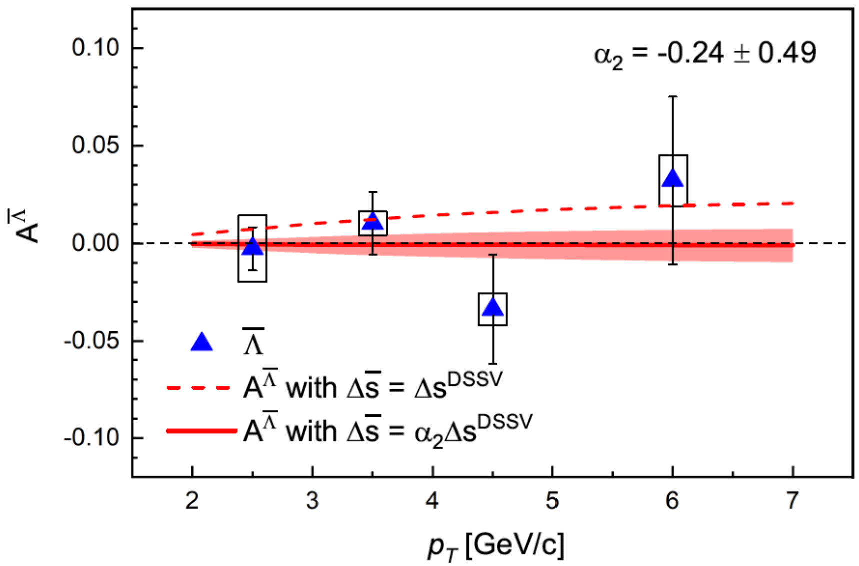
D_{LL} results of (anti-)Lambda at STAR

- 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 $\bar{\Lambda}$.

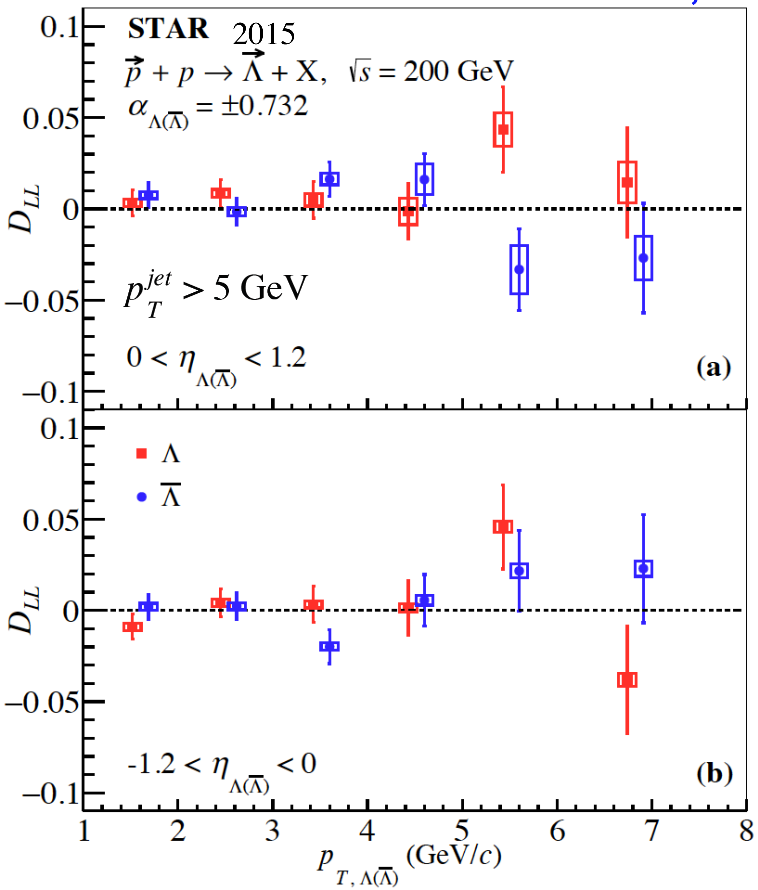
Table 1 Fitting results of α_i and calculated results of Δs and $\Delta \bar{s}$

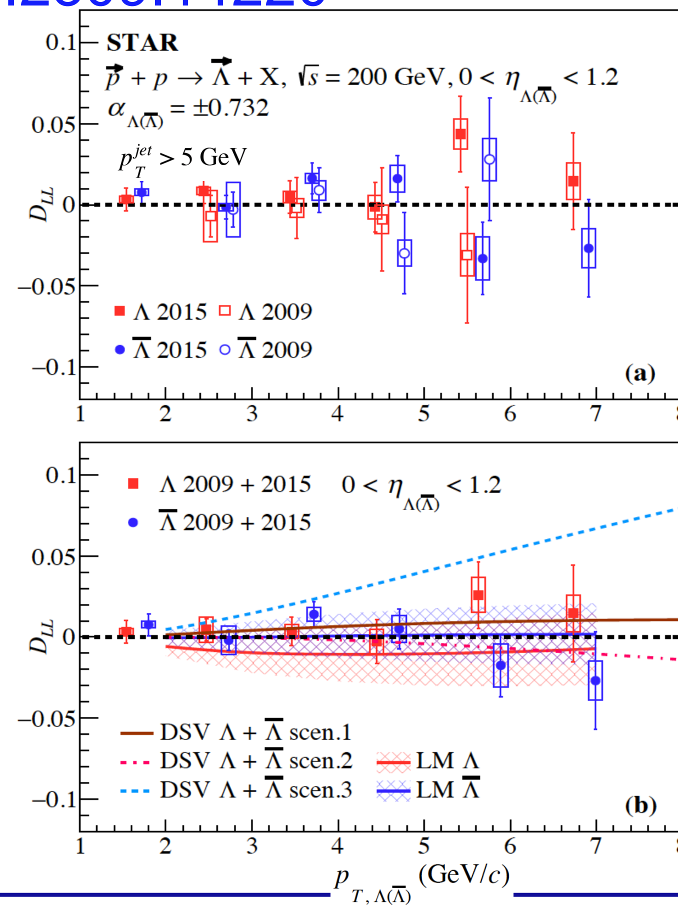
coefficient	value	Δs	$\Delta \bar{s}$	χ^2_{min}
α_1	-1.20 ± 1.31	-0.014 ± 0.015		0.37
α_2	-0.24 ± 0.49		-0.003 ± 0.005	2.48

New D_{LL} results with STAR 2015 data

- New results are in agreement with previous measurements, with twice statistics. No clear difference observed between Λ and $(\bar{\Lambda})$.
- Results are in agreement with various model predictions, except "DSV" calculation with "scen. 3" of polarized fragmentation function.

STAR, arXiv:2309.14220

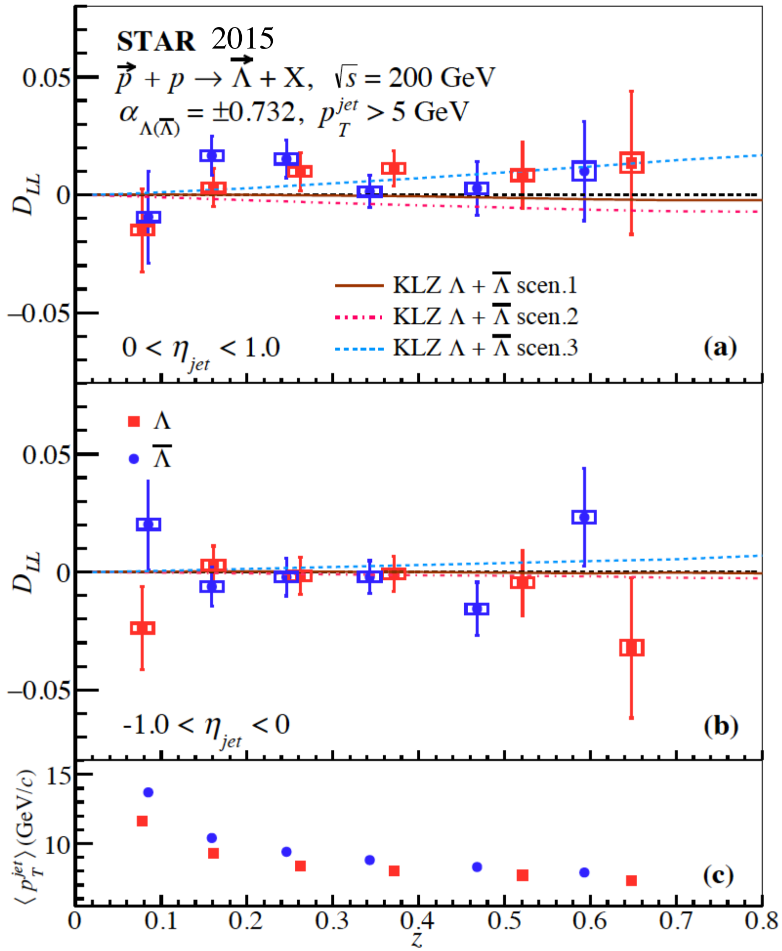




- D.de Florian, M.Stratmann, W.Vogelsang, PRL81,530(1998); - X.N. Liu, B.Q. Ma, EPJC 79,409 (2019)

D_{LL} vs z results with STAR 2015 data

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



STAR, arXiv: 2309.14220

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

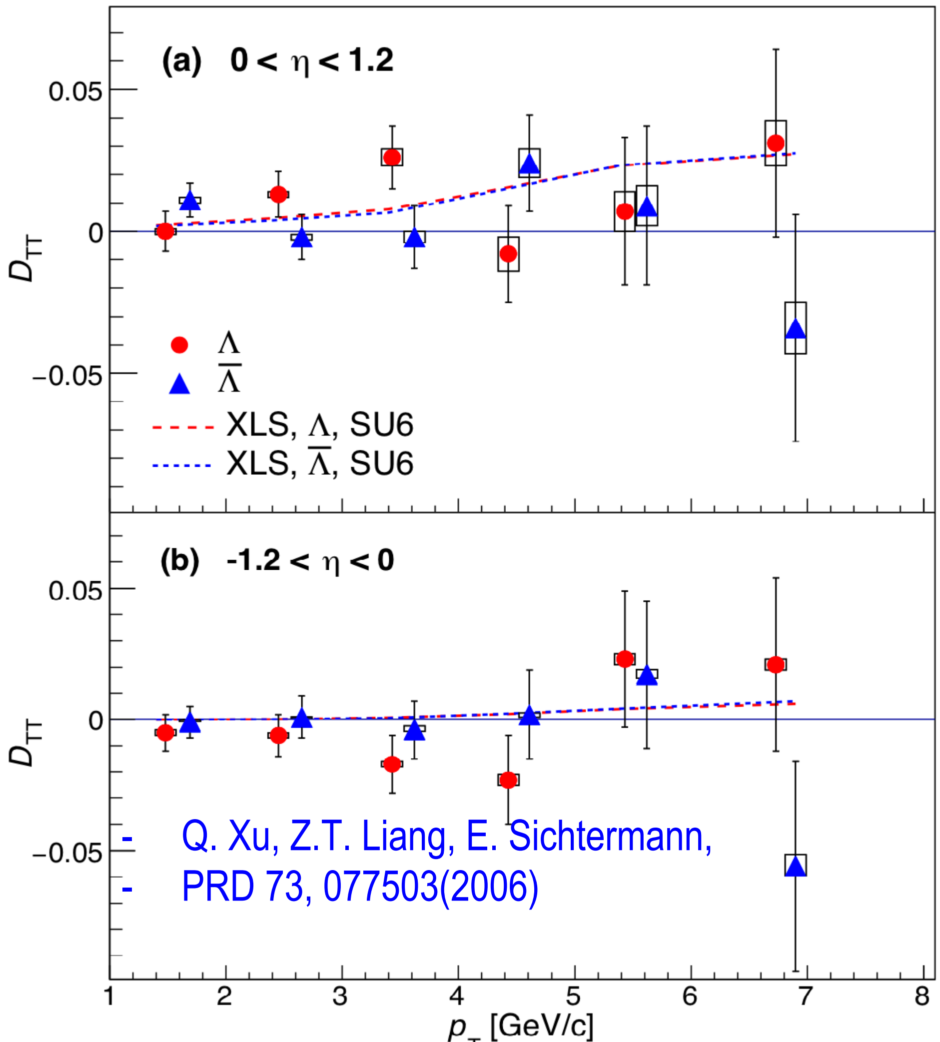
z: Jet momentum fraction carried by hyperon

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

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.

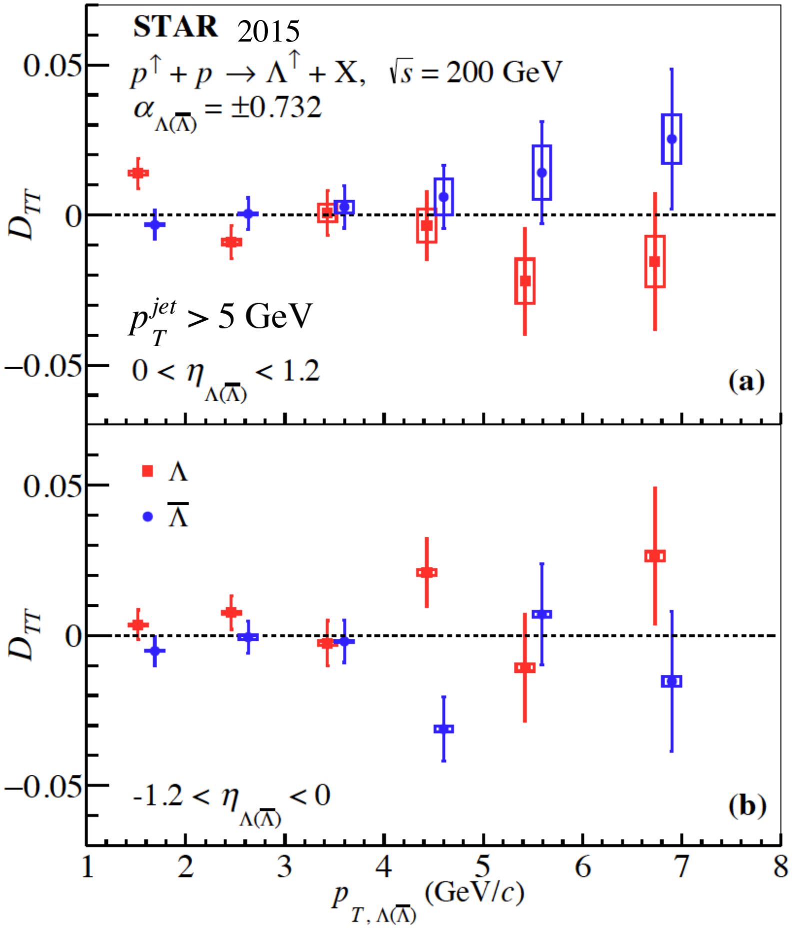
✓ Most precise measurement on hyperon polarization in p+p collision at RHIC, which reach p_T ~6.7 GeV/c with statistical uncertainty of 0.04.

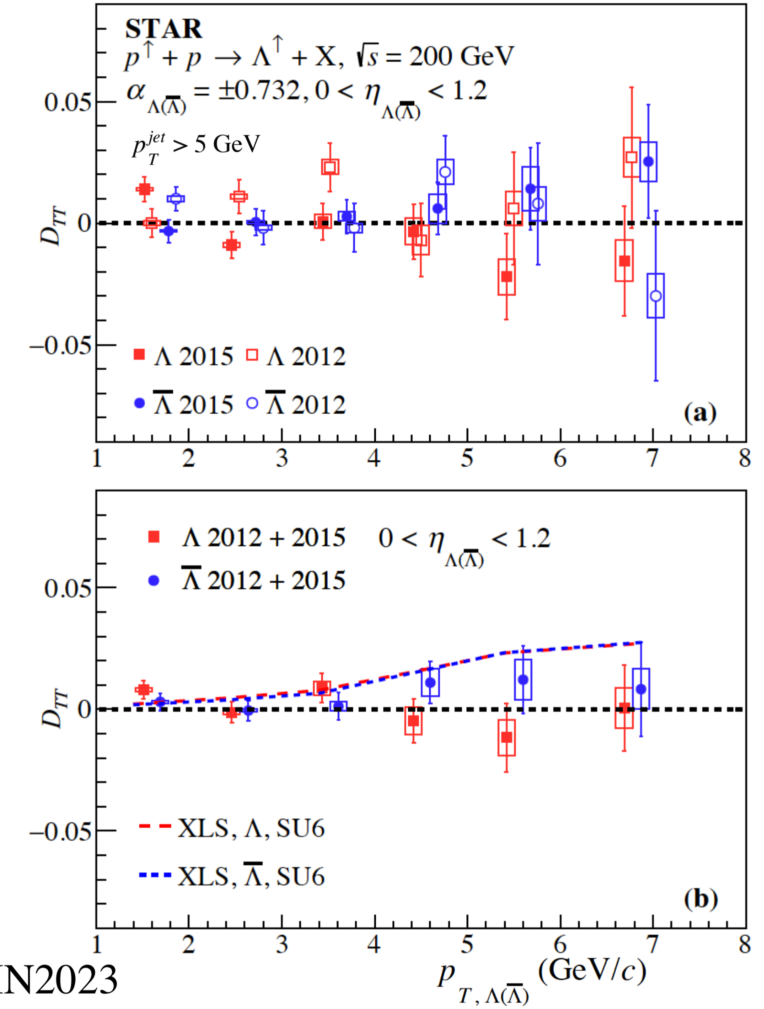
✓ D_{TT} of $\Lambda / \bar{\Lambda}$ are consistent with a model prediction, also consistent with zero within uncertainty.

New D_{TT} results with STAR 2015 data

- New D_{TT} results from 2015 are consistent with previous 2012 data, with twice statistics. Most precise data up to date.
- D_{TT} is consistent with the model predictions within uncertainties.

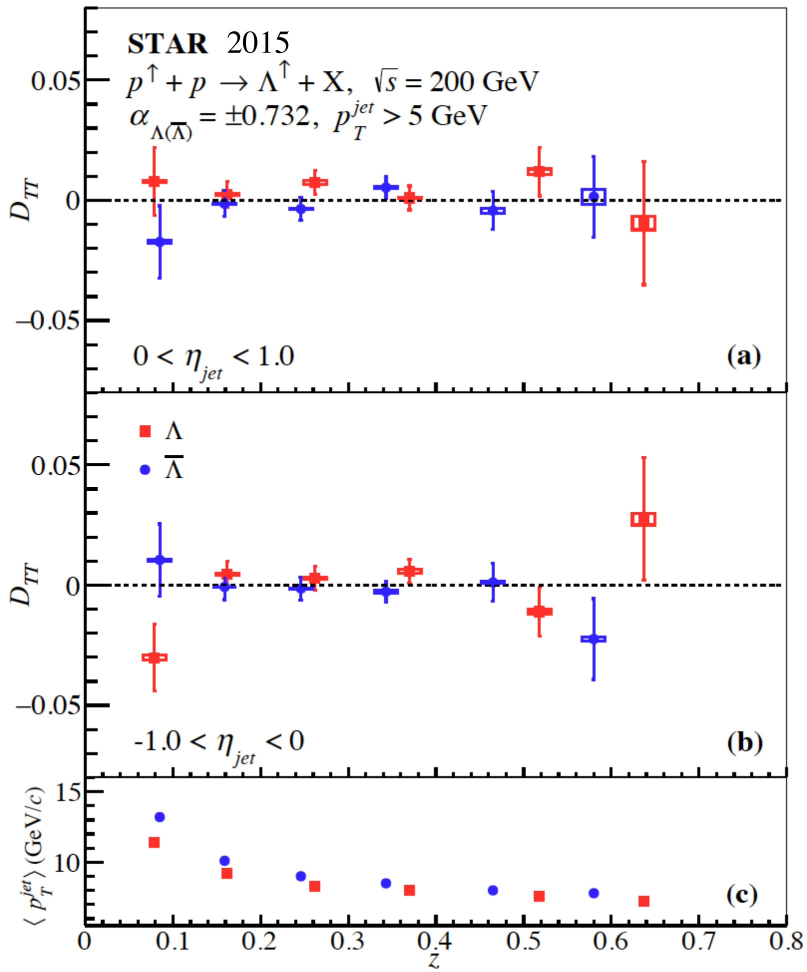
STAR, arXiv: 2309.14220





New D_{TT} results STAR 2015 data

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



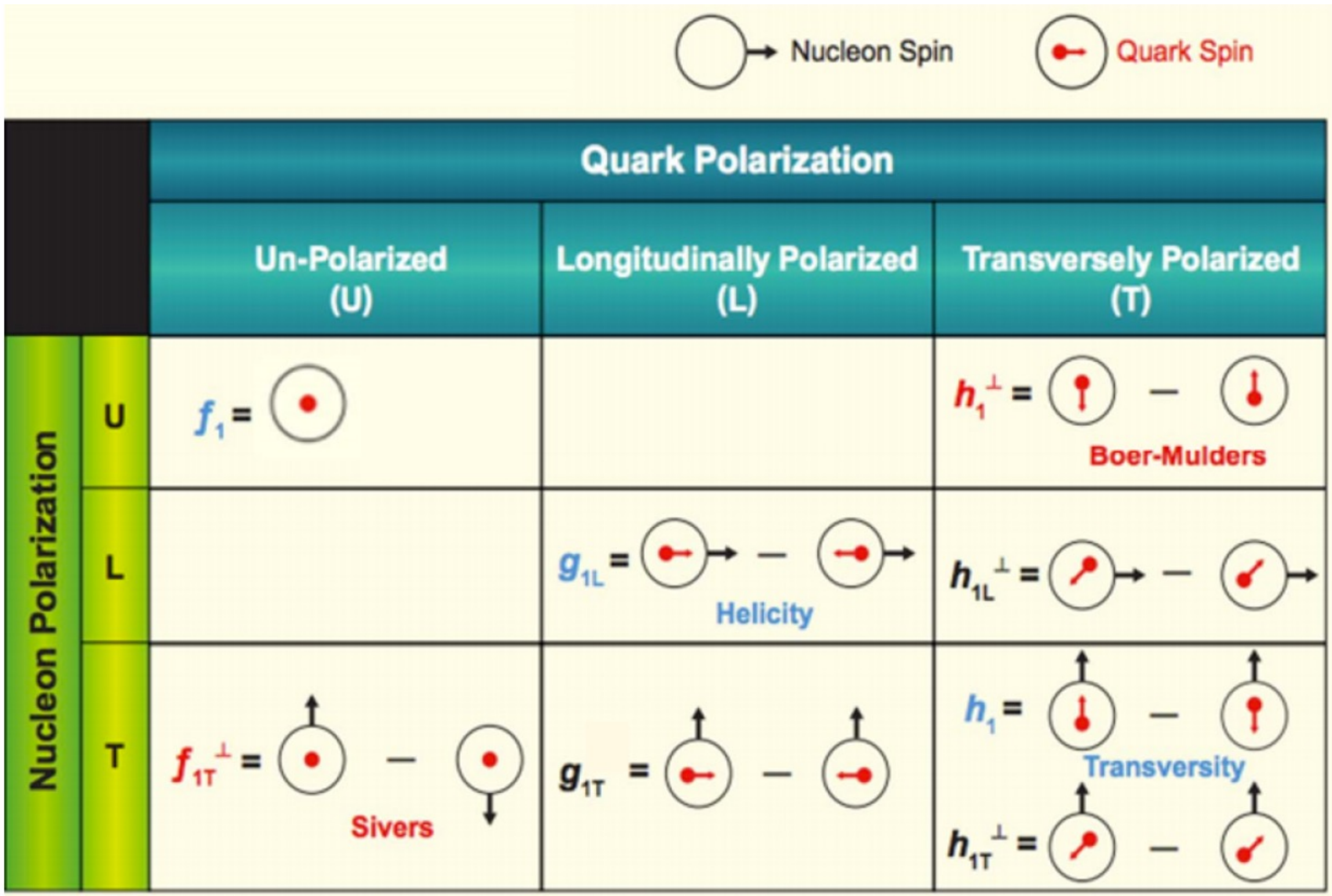
STAR, arXiv: 2309.14220

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

z: Jet momentum fraction carried by hyperon

Nucleon 3d-structure & TMD distribution

- 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 physics at RHIC

- Transverse spin asymmetry (W/Z production):

  Sign-change of Sivers function

- Transverse spin asymmetry (Hadron production):

  Access to transversity via Collins & IFF asymmetry

- Transverse spin transfer of Lambda hyperons

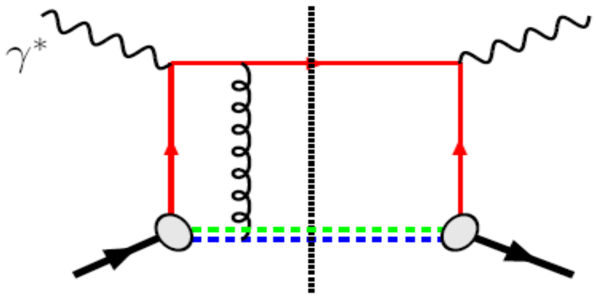
  Access to strange quark transversity

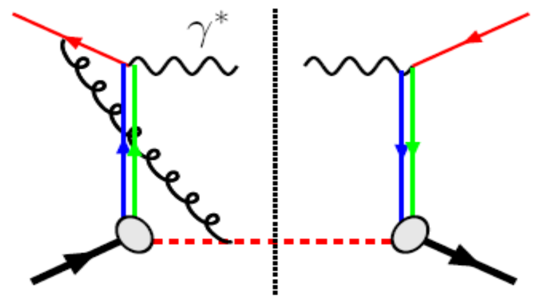
Transverse single spin asymmetry (A_N) of W boson

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

DIS: γq scattering
attractive FSI

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





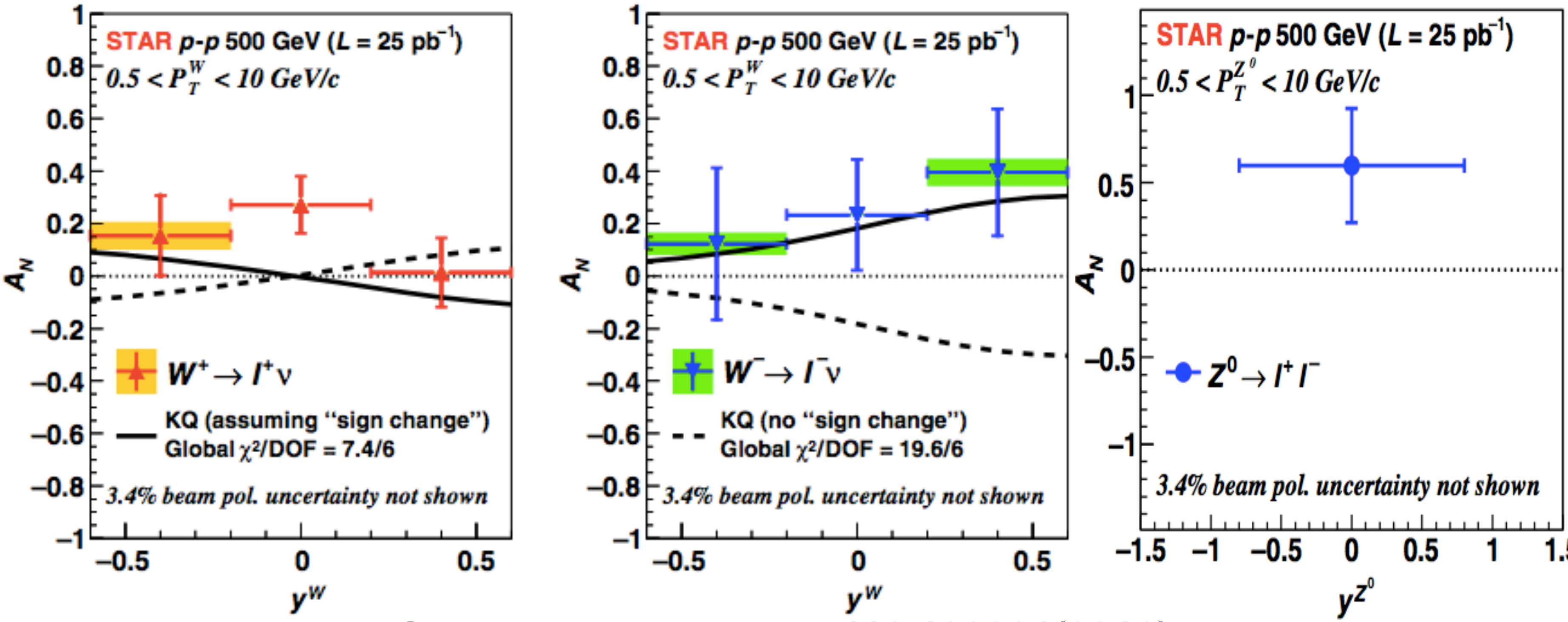
$$\text{Sivers}_{DIS} = - \text{Sivers (DY or W or Z)}$$

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

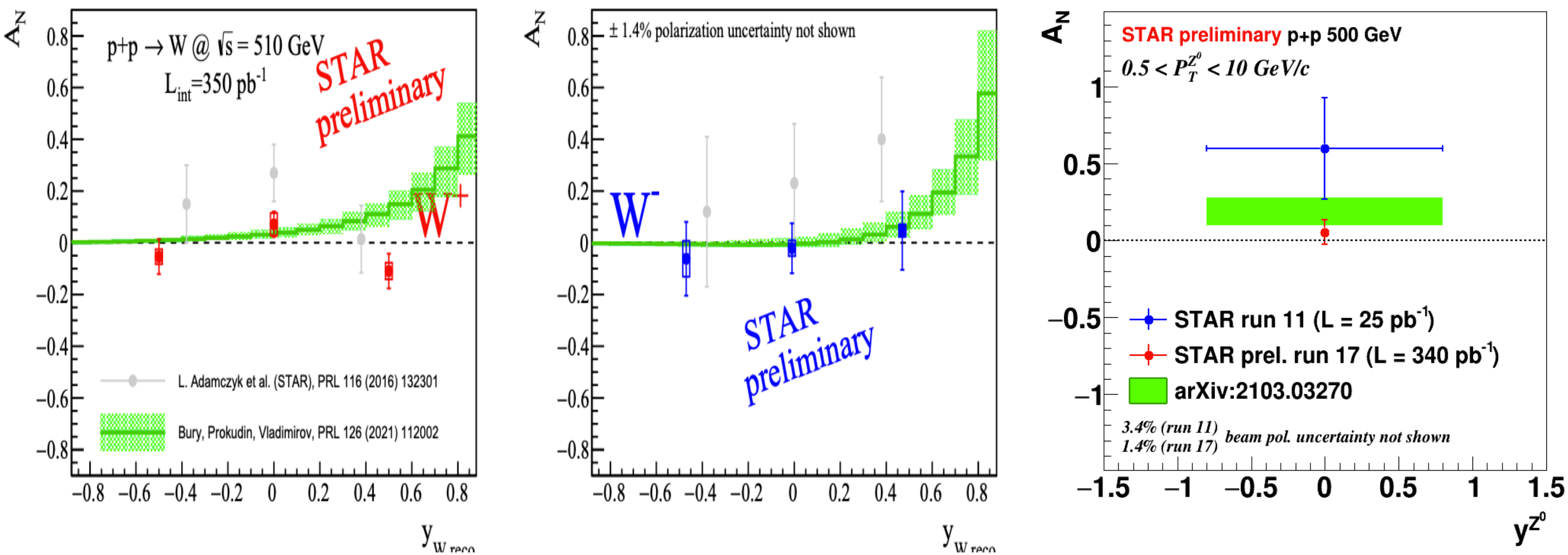


STAR, Phys. Rev. Lett. 116,132301(2016)

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

Coming measurements of W/Z A_N at STAR

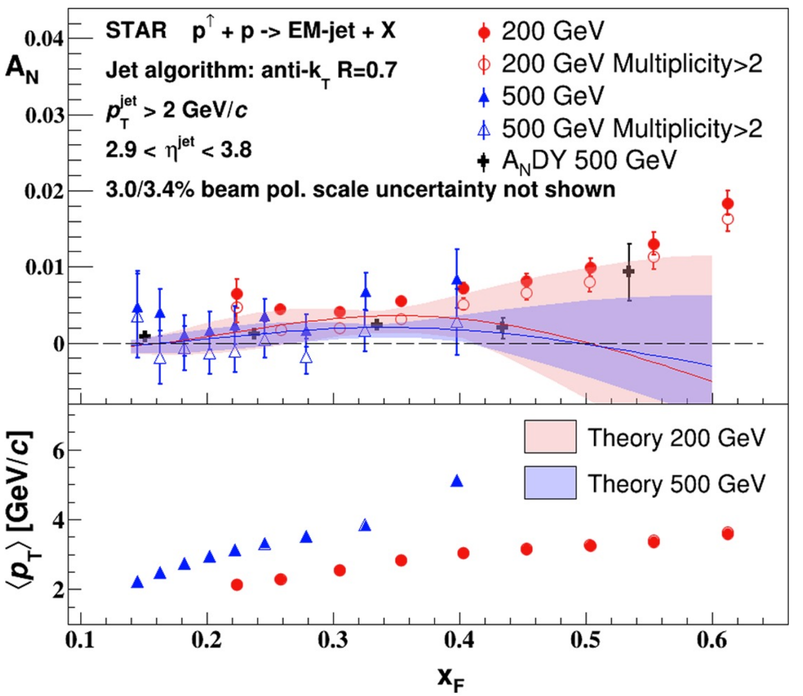
- New STAR results with a much larger data sample taken in 2017:



- 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.

Transverse spin asymmetry & TMDs

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



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

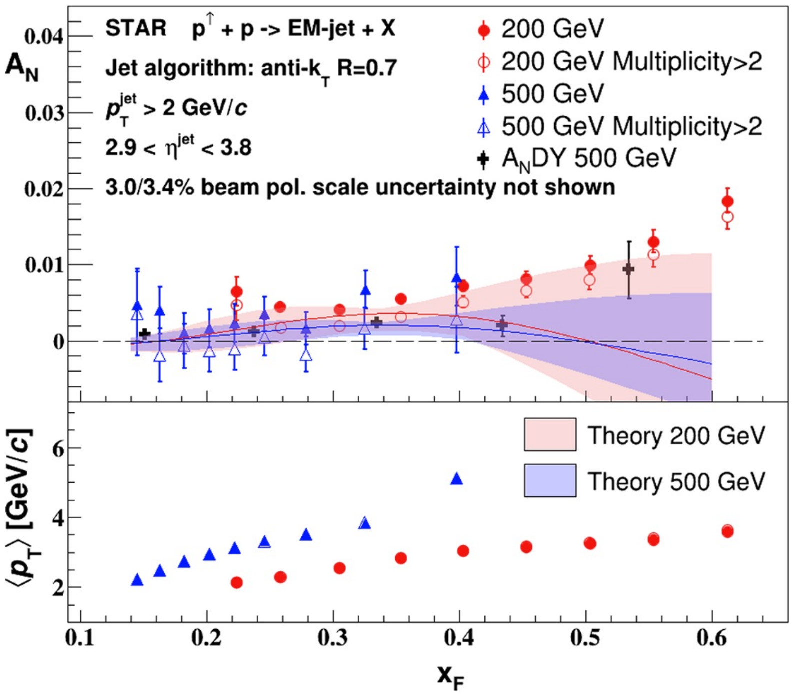
*L. Gamberg, Z. Kang, A. Prokudin, Phys.Rev.Lett.*110(2013)23,232301

- 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

Transverse spin asymmetry & TMDs

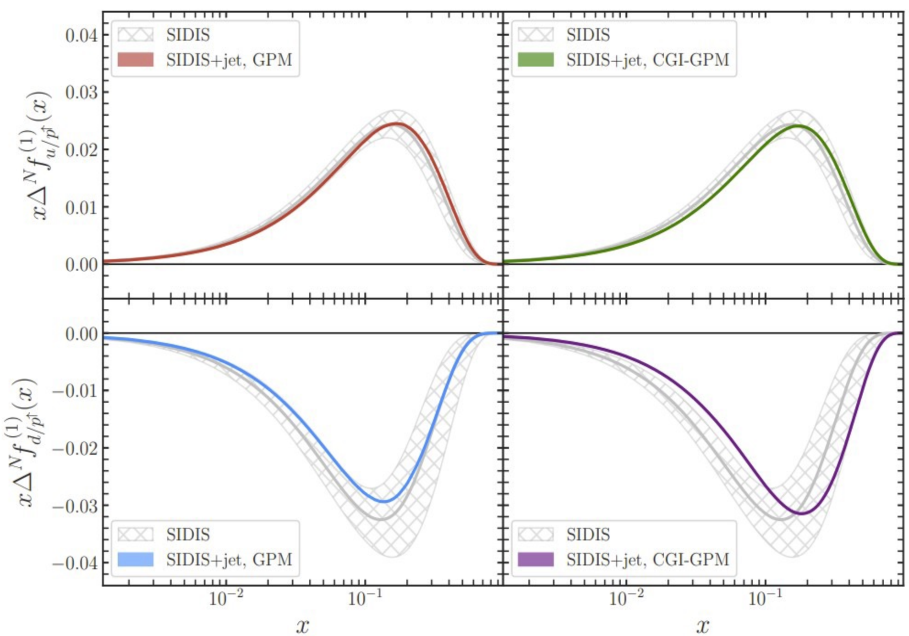
- Jet A_N - sensitive to the initial state effect, related to Sivers effect, decoupled from Collins effect
- Impact of our data in constraining Sivers function via global analysis



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

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

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

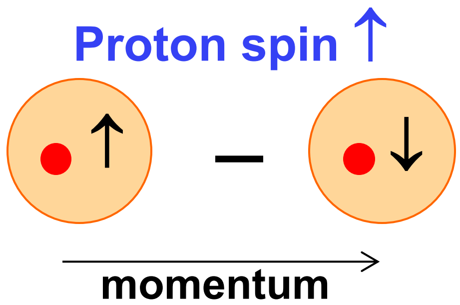


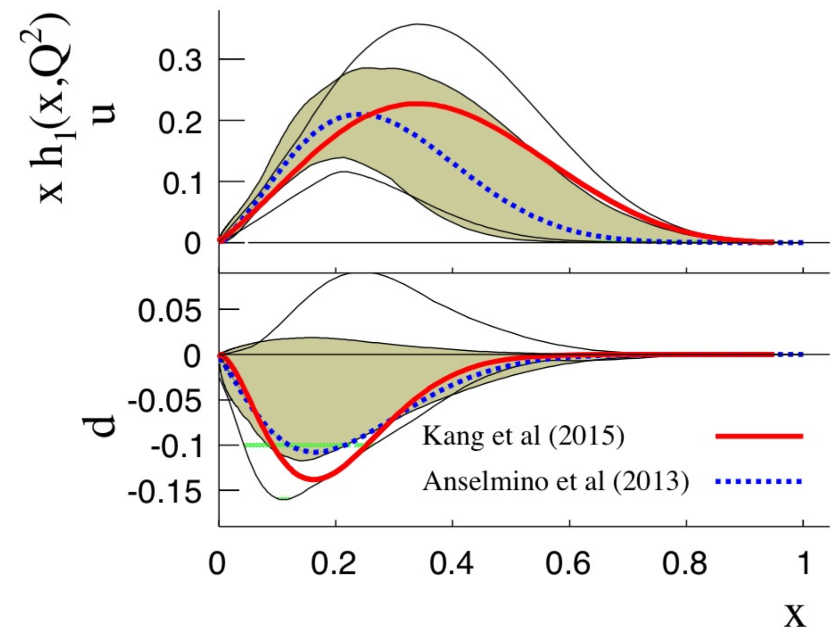
➢ Initial state effect is small

Transverse spin structure of nucleon

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

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





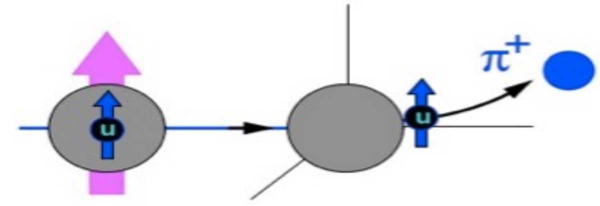
- Transversity involves helicity flip, thus no access in inclusive DIS process.

- 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)

Mid-rapidity hadron-jet correlations (Collins)

- Study proton transversity through its coupling to Collins function:



$$A_{UT} \propto \mathbf{h_1(x)} \otimes \mathbf{H_1^{\perp}(z, j_T)}$$

- Collins asymmetries:

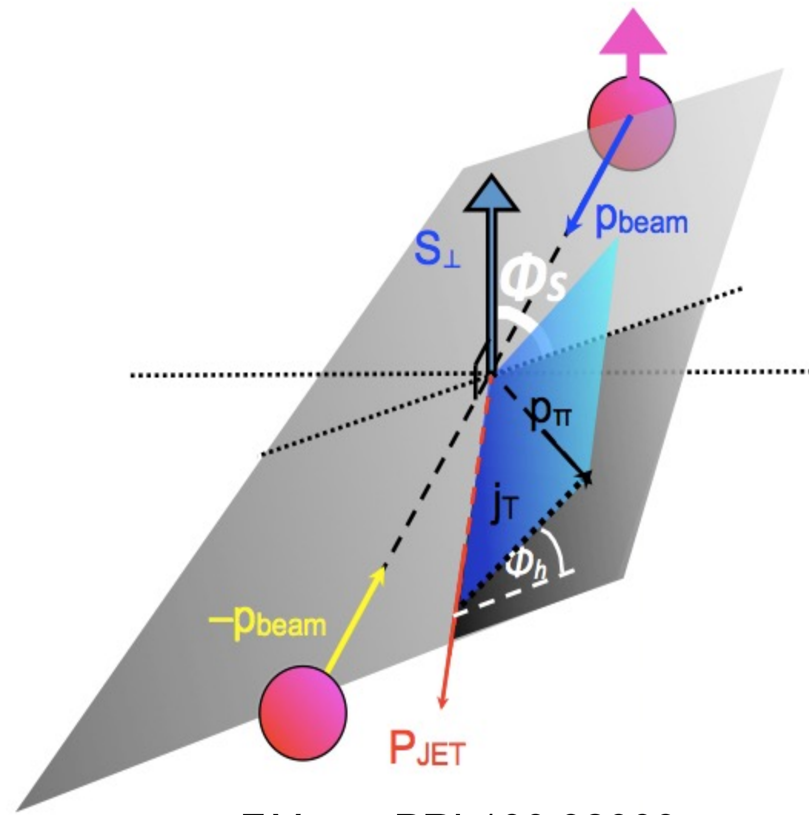
Collins angle: $\Phi_c = \Phi_s - \Phi_h$

Collins modulation: $\sin(\Phi_s - \Phi_h)$

j_T : transverse momentum in jet

Φ_s: azimuthal angle of beam spin

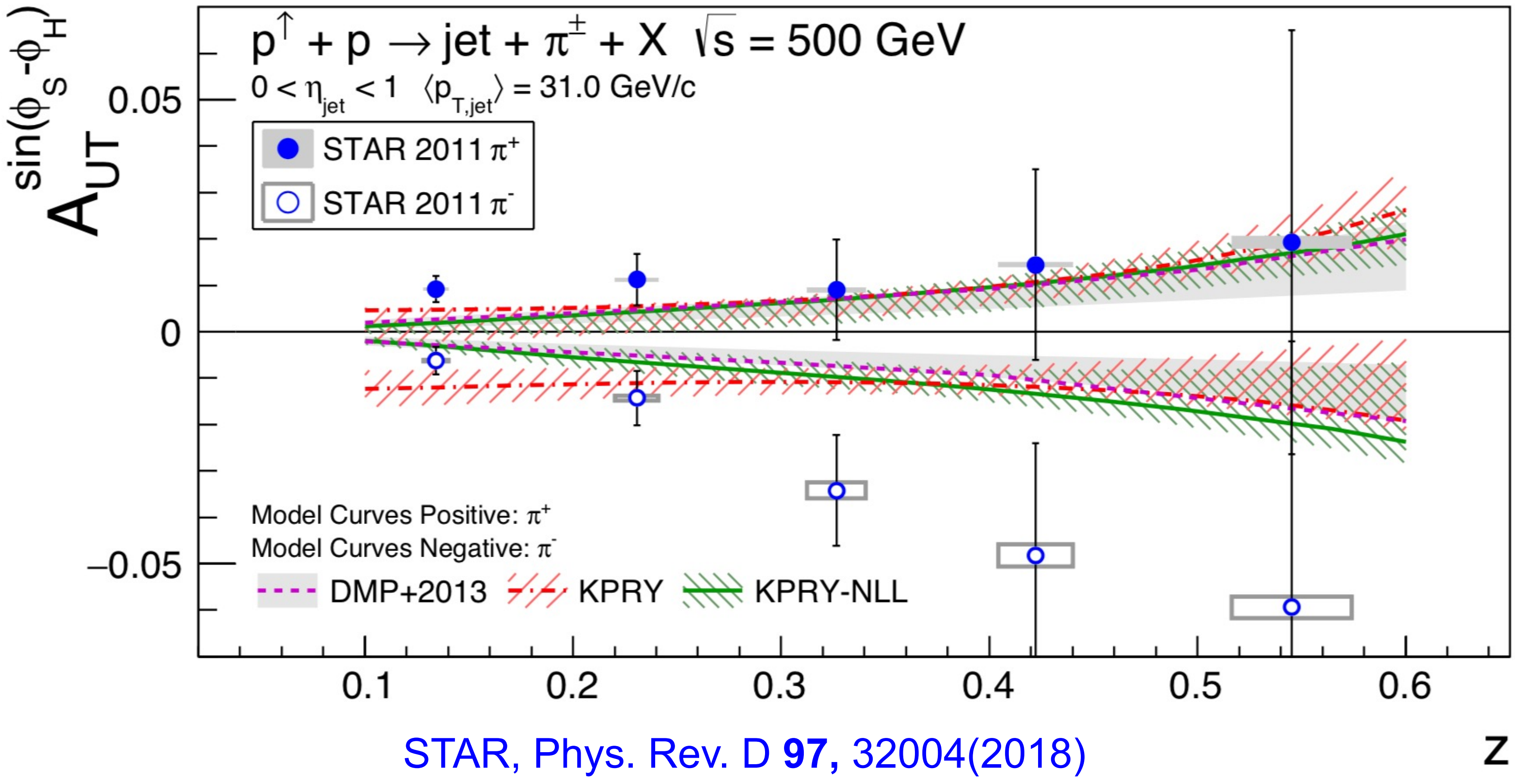
Φ_h: azimuthal angle of hadron



-F.Yuan, PRL100,32003

Collins asymmetries at STAR

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



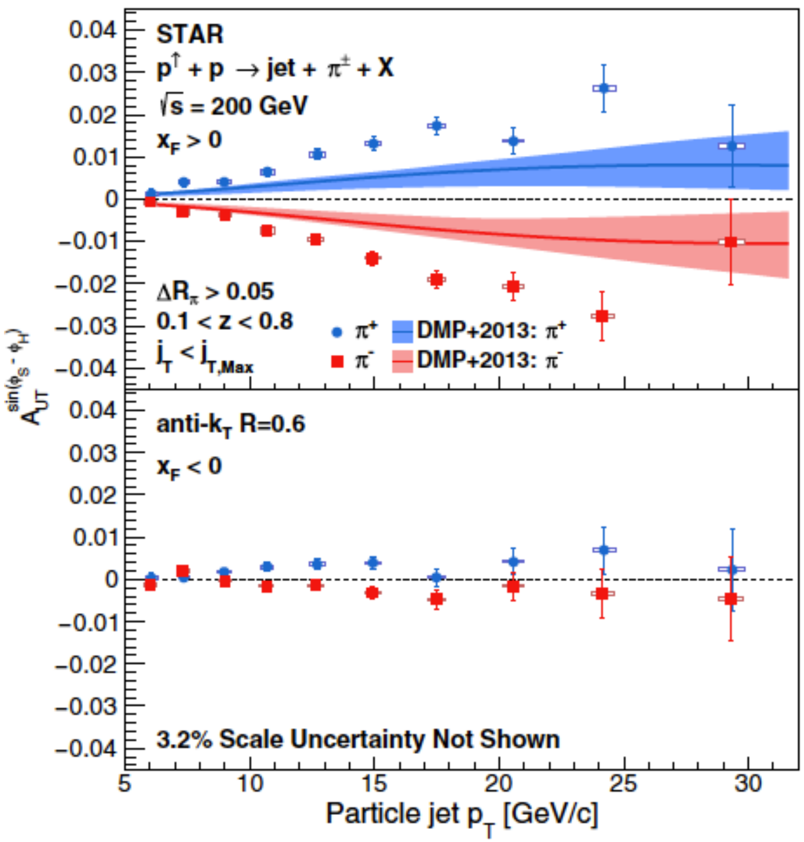
STAR, Phys. Rev. D **97,** 32004(2018)

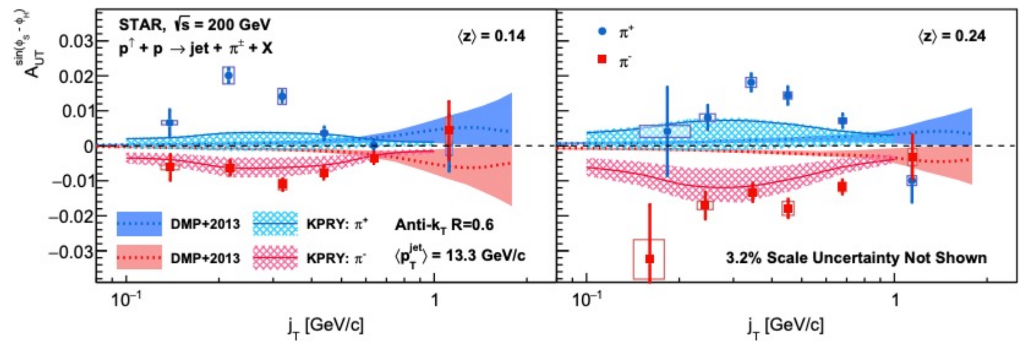
- Collins asymmetries observed in p+p collisions, providing information for scale dependence, also access to transversity.

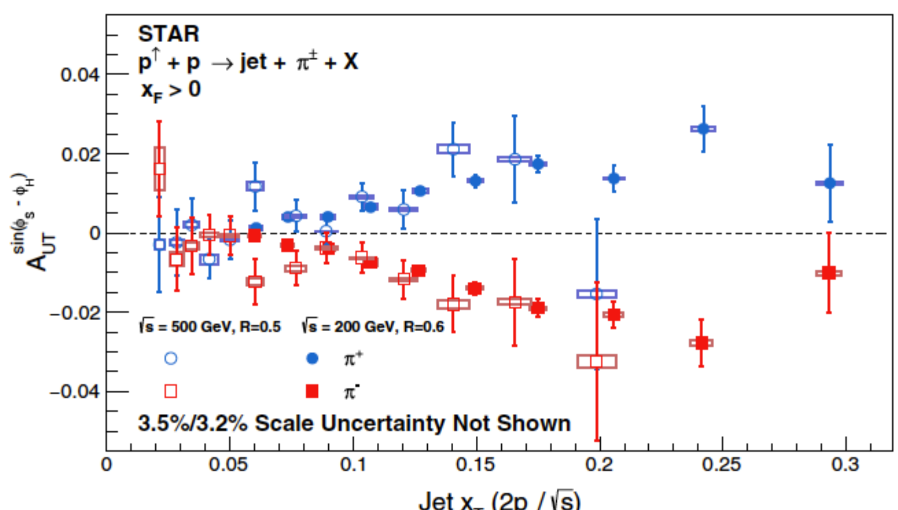
Collins asymmetries at STAR

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

STAR, PRD 106, 072010 (2022)

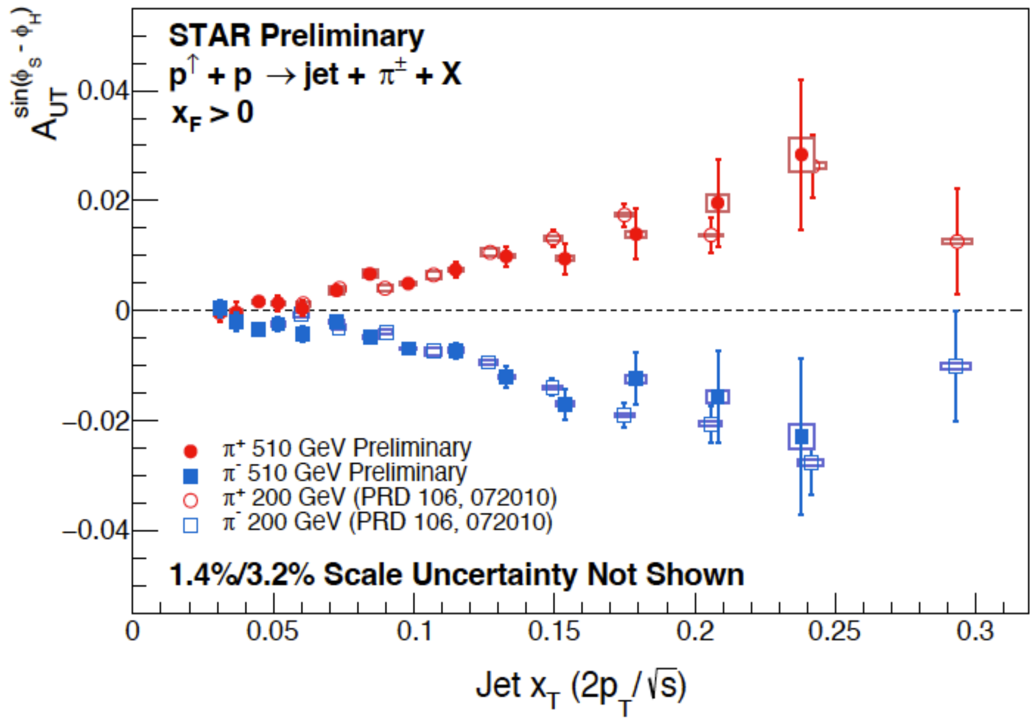






New Collins results at 510 GeV & comparison to 200 GeV

- Collins results as a function of x_T for 200 GeV and 510GeV:

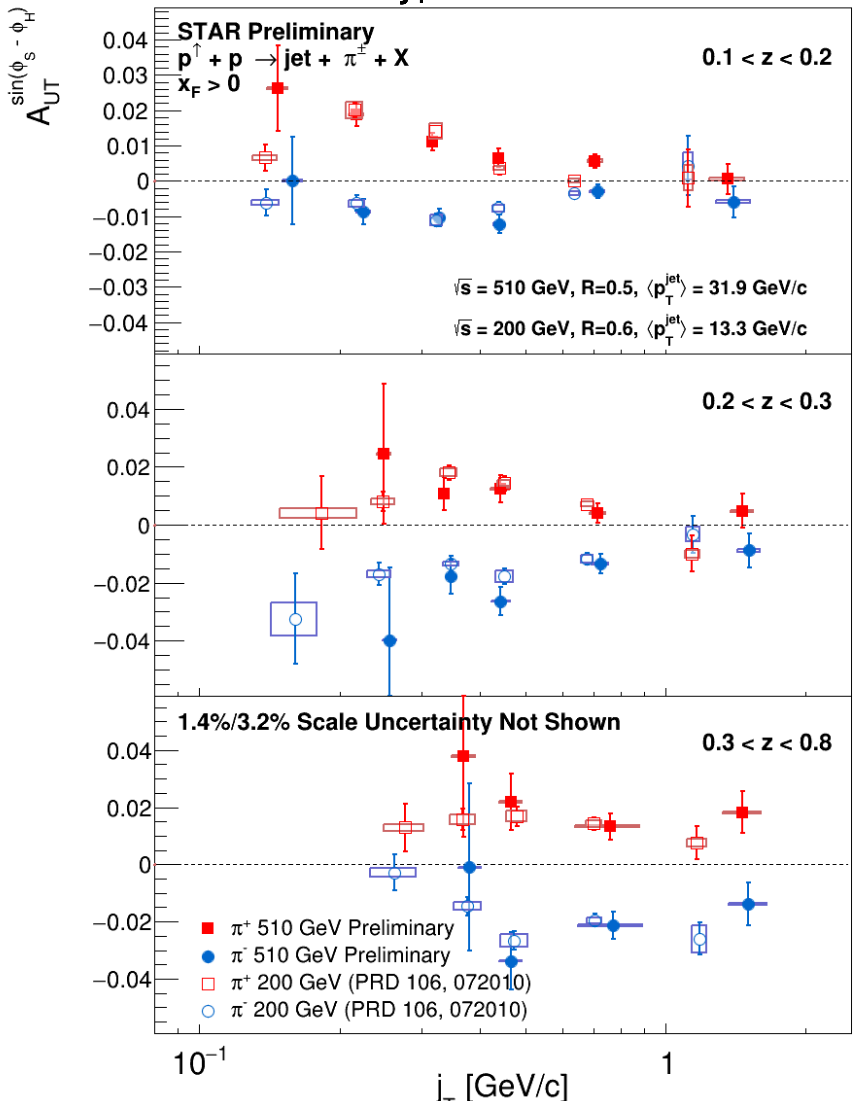


- The high precision Collins results of 510 GeV and 200 GeV nicely align with jet x_T scale, giving almost no energy dependence.
- These data provide important constraints on the scale evolution for Collins asymmetry.

Striking comparison indicating weak energy dependence !

New Collins results at 510 GeV & comparison to 200 GeV

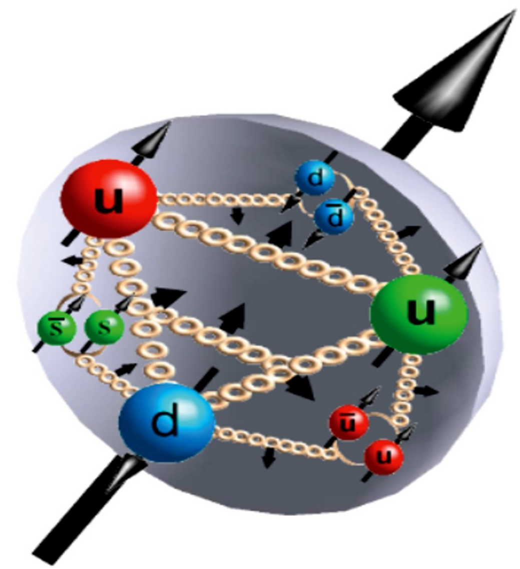
- Collins results as a function of j_T :



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

Striking comparison indicating weak energy dependence !

If you are not getting bored with these spin thing….



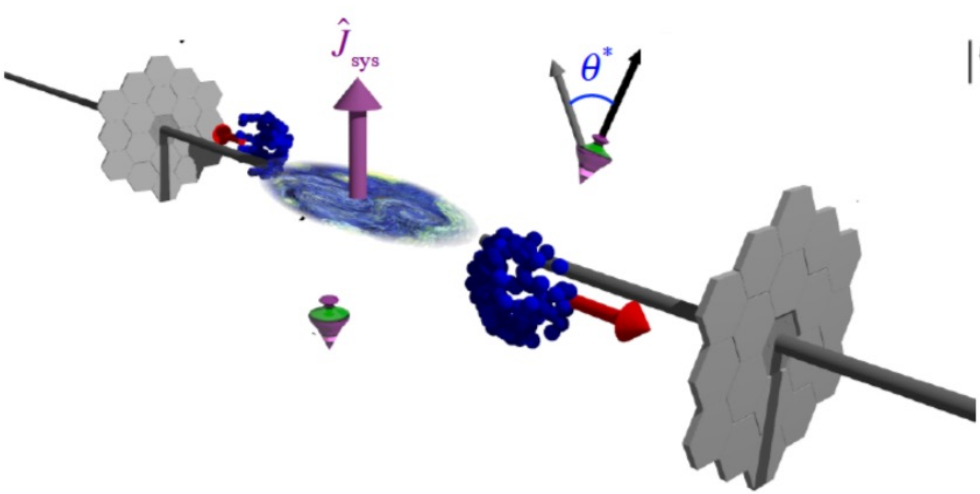
Let's continue with some spin physics in heavy ion collisions 🙂

Outline for today's topic

- Introduction to SPIN & nucleon spin structure
- Recent spin highlights in pp collisions from RHIC:
  - ✓ Gluon polarization (Jet, π^0 production): gluon polarization Δg
  - ✓ Quark/Anti-quark polarization (W/Z production): sea quark Δq
  - ✓ Transverse spin asymmetry (W/Z production): Sivers function
  - ✓ Transverse spin asymmetry (Hadron production): Collins
- Global polarization in heavy ion collisions
  - ✓ **Hyperon global polarization**
  - ✓ **Spin alignment of vector meson**
- Future plans for spin physics in 2024+ at RHIC/EIC/EicC

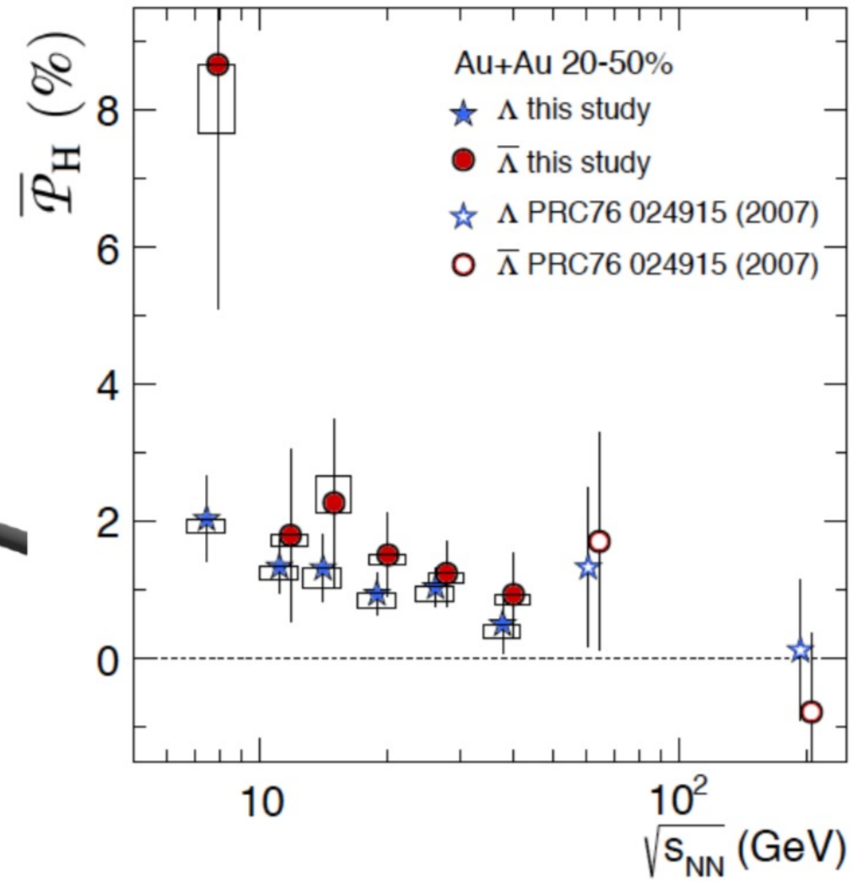
Λ Global polarization in heavy ion collisions

- Λ global polarization observed at STAR (Nature cover) , as predicted by Z.T. Liang and X.N. Wang in *PRL94,102301(2005)*



非零角动量可以转化成流体涡旋，
并极化超子

STAR, Nature 548(2017)62



Λ Global polarization in heavy ion collisions

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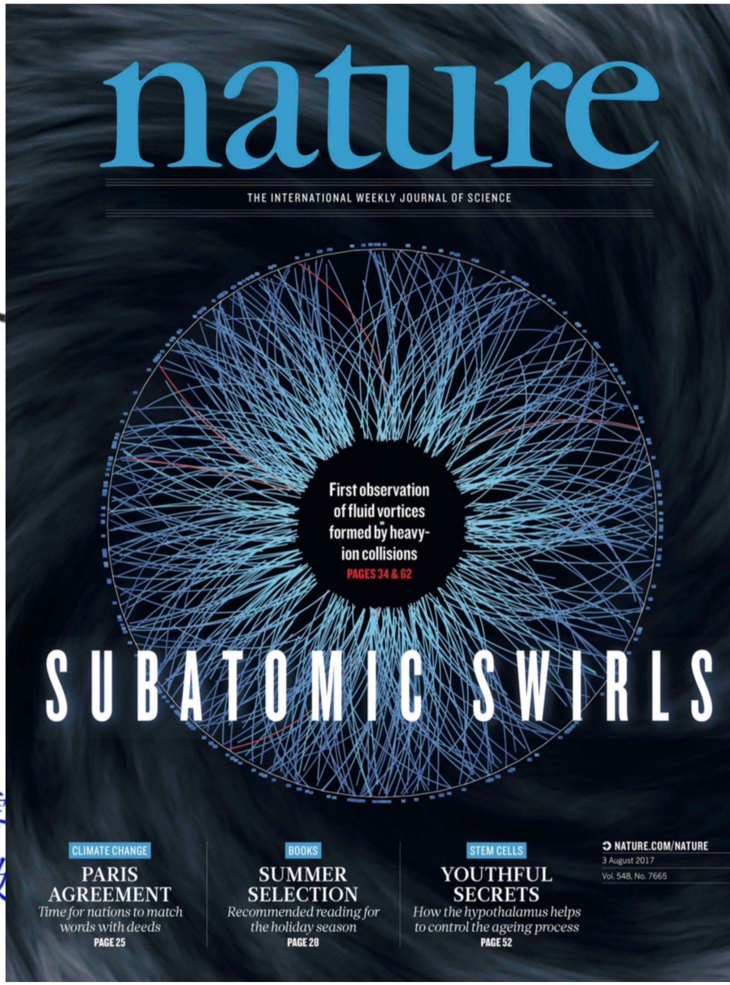
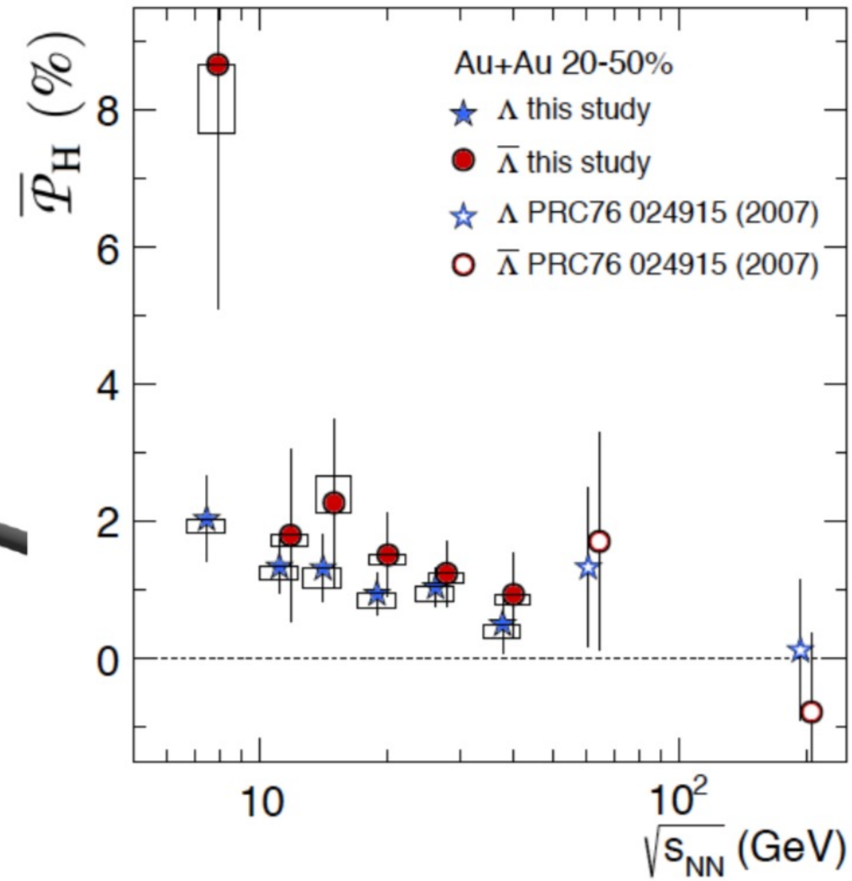
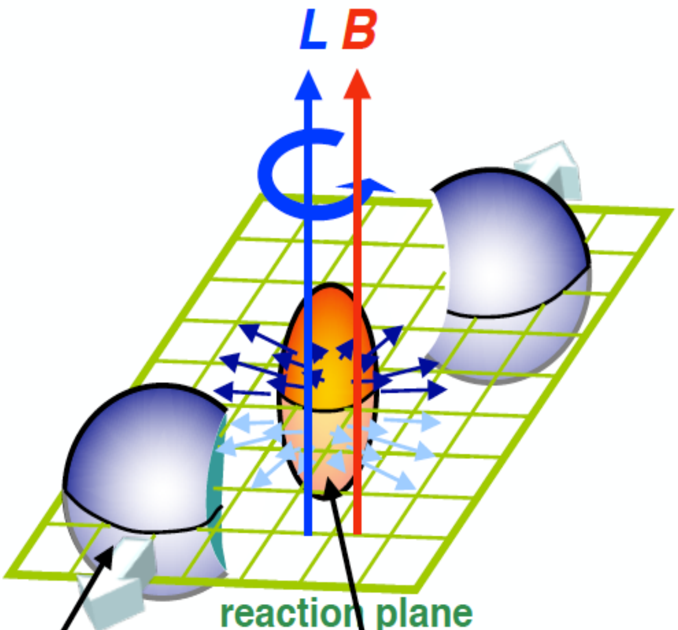


STAR, Nature 548(2017)62



非零
并极

Orbital angular momentum/magnetic field in HIC



Orbital angular momentum

Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)

$$\mathbf{L} = \mathbf{r} \times \mathbf{p}$$

$$\sim bA\sqrt{s_{NN}} \sim 10^6 \hbar$$

Strong magnetic field

$$B \sim 10^{13}\ \mathrm{T}$$

$$(eB \sim m_\pi^2\ (\tau \sim 0.2\ \mathrm{fm}))$$

D. Kharzeev, L. McLerran, and H. Warringa, Nucl. Phys. A803, 227 (2008)
L. McLerran and V. Skokov, Nucl. Phys. A929, 184 (2014)

magnetar

$B \sim 10^{11}$ T

T. Niida

物 理 学 报 *Acta Phys. Sin.* Vol. 72, No. 7 (2023) 072401

专题: 高能重离子碰撞过程的自旋与手征效应

重离子碰撞中 QCD 物质整体极化的实验测量*

孙旭[1] 周晨升[2] 陈金辉[2)†] 陈震宇[3]
马余刚[2] 唐爱洪[4] 徐庆华[3)‡]

Measurement of global polarization at STAR

- The Λ polarization can be determined through the angular distribution of its weak decay product.

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \boldsymbol{P}_H^* \cdot \widehat{\boldsymbol{p}}_B^*)$$

$\boldsymbol{P}_H$: *hyperon polarization*
$\widehat{\boldsymbol{p}}_B$: *unit vector of daughter baryon momentum*
α_H: *hyperon decay parameter*

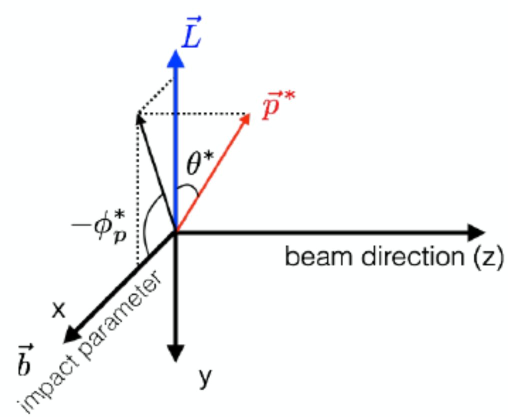
- At STAR, the global polarization has been extracted with

First adopted in PRC76, 024915 (2007)

$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \frac{1}{A_0} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{Res(\Psi_1)}$$

$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$

Ψ_1: azimuthal angle of 1st order reaction plane

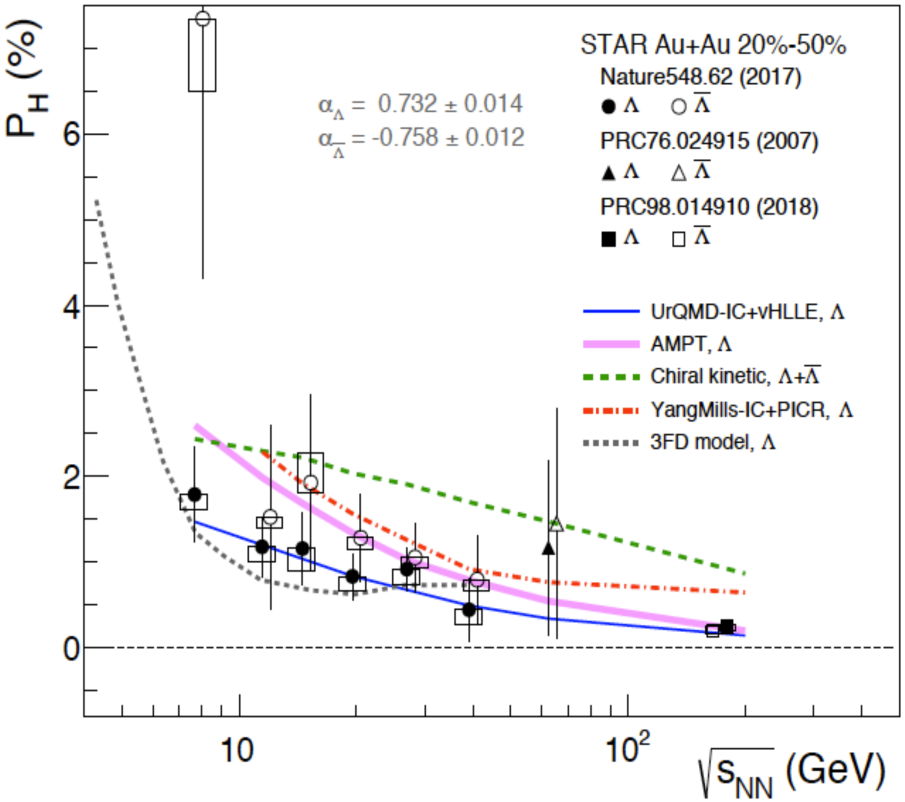


-In this way, the detector acceptance is largely avoided, but rather a scale effect with A_0

Global polarization in heavy ion collisions

- Spin-orbit coupling leads to spin polarization of produced particles, like Λ
- Effects to global polarization from the magnetic field

STAR, Nature 548, 62 (2017)
STAR, PRC90, 014910 (2018)



- Indication of thermal vorticity

$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T} \qquad \omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{22}\mathrm{s}^{-1}$$

F. Becattini et al., PRC95.054902 (2017)

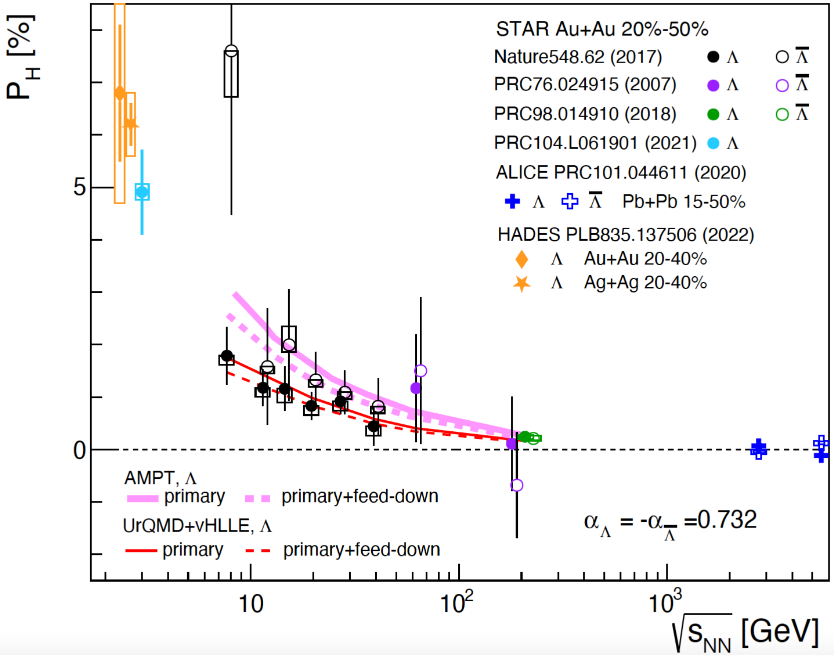
μ_Λ: Λ magnetic moment
T: temperature at thermal equilibrium

- Increasing trend toward lower energies, described well by various theoretical models

I. Karpenko and F. Becattini, EPJC(2017)77:213, UrQMD+vHLLE
H. Li et al., PRC96, 054908 (2017), AMPT
Y. Sun and C.-M. Ko, PRC96, 024906 (2017), CKE
Y. Xie et al., PRC95, 031901(R) (2017), PICR
Y. B. Ivanov et al., PRC100, 014908 (2019), 3FD model

- Possible difference between Λ and anti-Λ

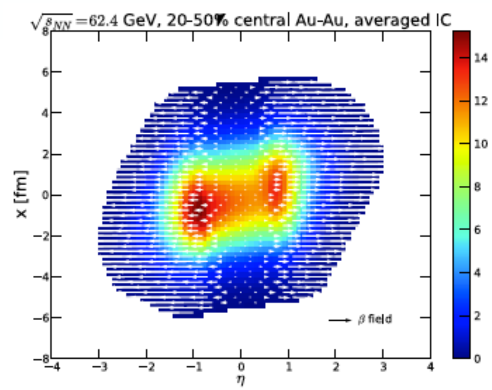
Energy dependence of global polarization

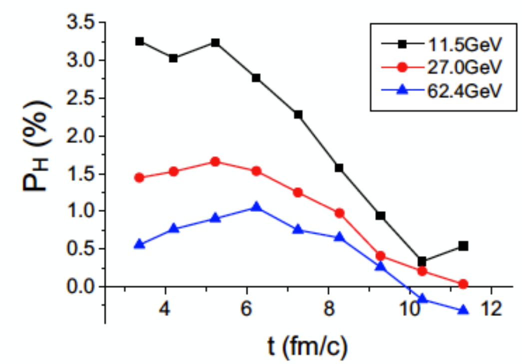


- HADES data at 2.4GeV Au+Au and 2.7 GeV Ag+Ag
- STAR data at 3 GeV
- ALICE results at 2.76 and 5.02 TeV Pb+Pb, consistent with zero within uncertainties
- More data coming from STAR BES-II +FXT

- Stronger shear flow in forward/ backward regions+ baryon stopping with limited acceptance (also related to unknown rapidity dependence)
- Longer lifetime of system may dilute the polarization

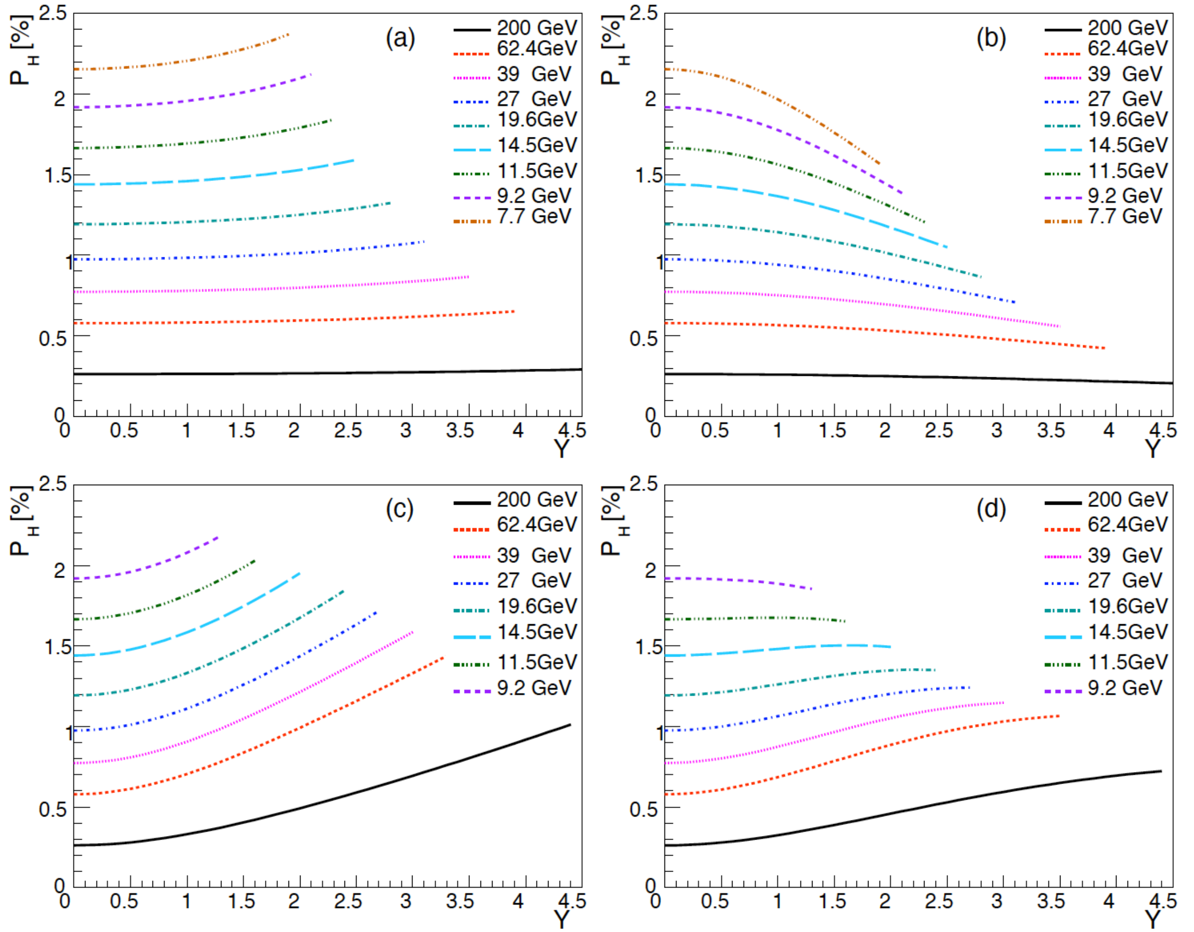
I.Karpenko, F. Becattini, EPJ(2017)77.213
Y. Xie, D. Wang, L. P. Csernai, PRC95, 031901(R) (2017)





Rapidity dependence of global polarization

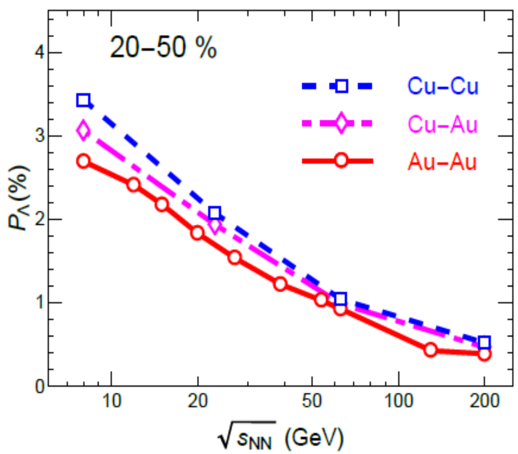
- Zuo-Tang Liang, Jun Song, Isaac Upsal, Qun Wang and Zhang-Bu Xu, *Chin. Phys.C* 45 (2021), 014102

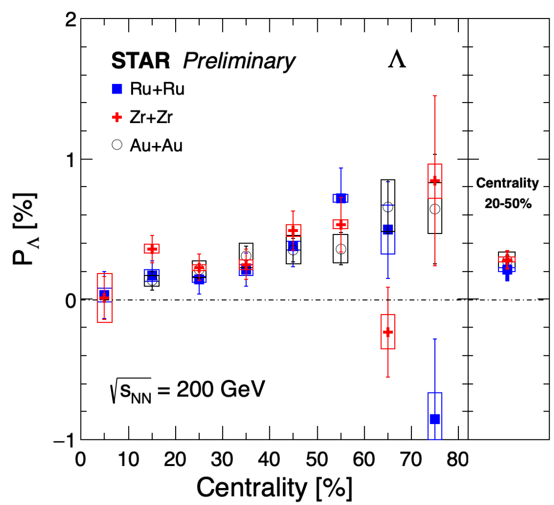


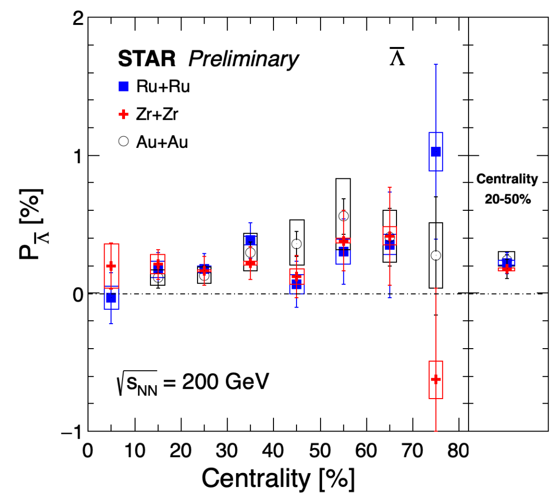
Global polarization in Ru+Ru and Zr+Zr collisions at 200 GeV

- Global polarization difference from different magnetic field in Zr+Zr and Ru+Ru?
- System size dependence of global polarization?

Shuzhe Shi, Kangle Li, Jinfeng Liao
PLB 788(2019) 409413







- Significant global polarization observed, P_Λ and $P_{\bar{\Lambda}}$ increase with centrality.
- No significant difference between P_Λ and $P_{\bar{\Lambda}}$ in Ru+Ru and Zr+Zr collisions.
- Global polarization of $\Lambda + \bar{\Lambda}$ are consistent between Ru+Ru/Zr+Zr and Au+Au collisions within uncertainties.

Ξ and Ω global polarization in 200 GeV Au+Au

- Two possible ways of measurement:

1) Direct measurement via weak decay, but subject to small decay parameters.

hyperon	decay mode	α_H	magnetic moment μ_H	spin
Λ (uds)	$\Lambda \rightarrow p\pi^-$ (BR: 63.9%)	0.732	-0.613	1/2
Ξ^- (dss)	$\Xi^- \rightarrow \Lambda\pi^-$ (BR: 99.9%)	-0.401	-0.6507	1/2
Ω^- (sss)	$\Omega^- \rightarrow \Lambda K^-$ (BR: 67.8%)	0.0157	-2.02	3/2

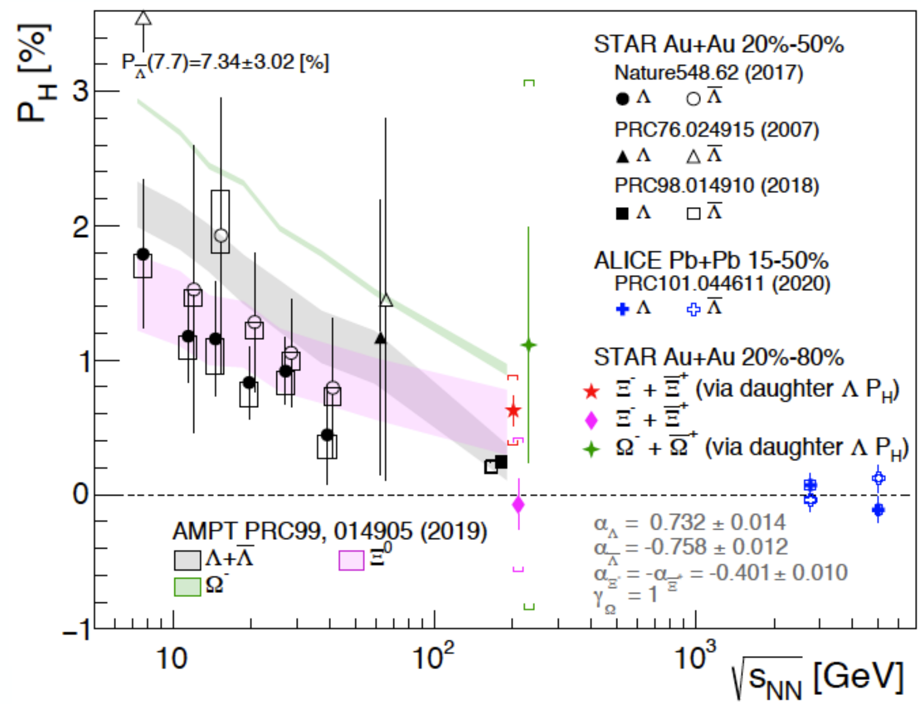
2) Through the polarization transfer to

$$\mathbf{P}^*_\Lambda = C_{\Xi^-\Lambda}\mathbf{P}^*_\Xi = \tfrac{1}{3}(1+2\gamma_\Xi)\,\mathbf{P}^*_\Xi. \quad C_{\Xi^-\Lambda} = +0.944$$

$$\mathbf{P}^*_\Lambda = C_{\Omega^-\Lambda}\mathbf{P}^*_\Omega = \tfrac{1}{5}(1+4\gamma_\Omega)\,\mathbf{P}^*_\Omega.$$

-γ_Ω is not known, with estimation ~1, C~1

STAR, PRL126, 162301 (2021)



➢ AMPT and hydro calculations capture the trend:

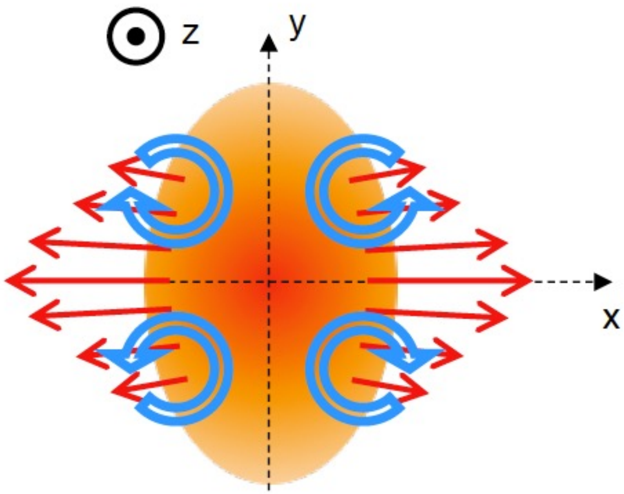
D.-X. Wei, W.-T. Deng, and X.-G. Huang, PRC99.014905 (2019)

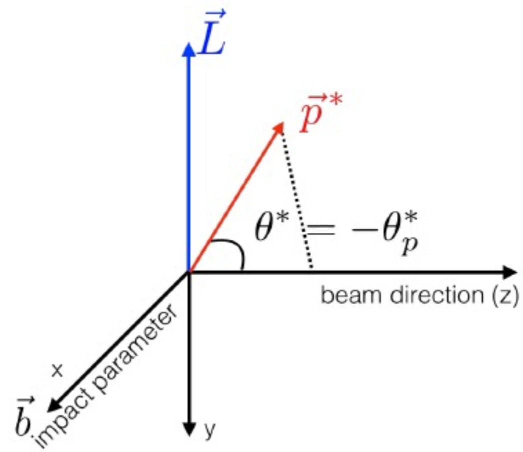
- STAR report different Ξ polarization with these two methods?

Polarization along the beam direction

"Local polarization"

F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, SQM2017





$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_\mathrm{H} \mathbf{P_H} \cdot \mathbf{p}_p^*)$$

$$\langle \cos\theta_p^* \rangle = \int \frac{dN}{d\Omega^*} \cos\theta_p^* d\Omega^*$$

$$= \alpha_\mathrm{H} P_z \langle (\cos\theta_p^*)^2 \rangle$$

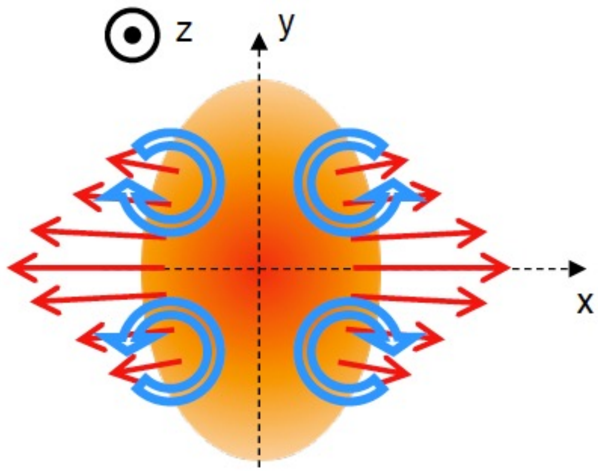
$$\therefore\ P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_\mathrm{H} \langle (\cos\theta_p^*)^2 \rangle}$$

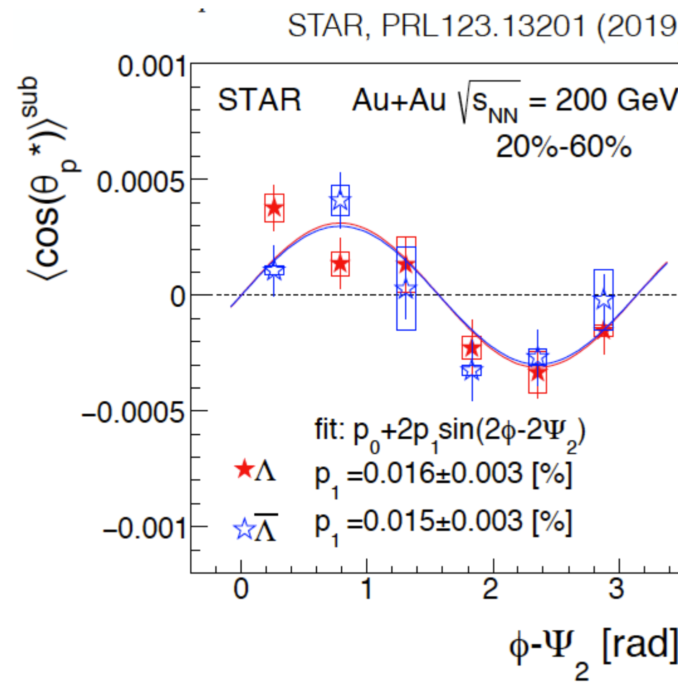
$$= \frac{3\langle \cos\theta_p^* \rangle}{\alpha_\mathrm{H}} \quad \text{(if perfect detector)}$$

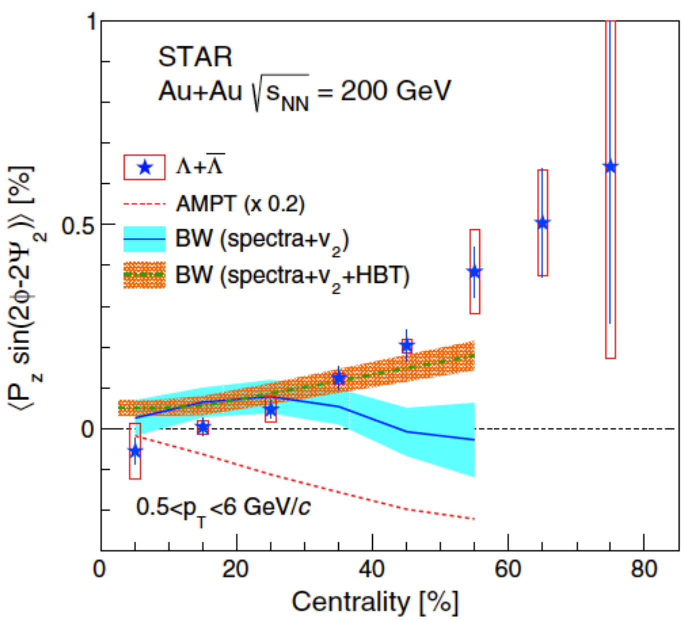
- Stronger flow in in-plane than in out-of-plane, known as elliptic flow, makes local vorticity (thus polarization) along beam axis.

Polarization along the beam direction

"Local polarization"



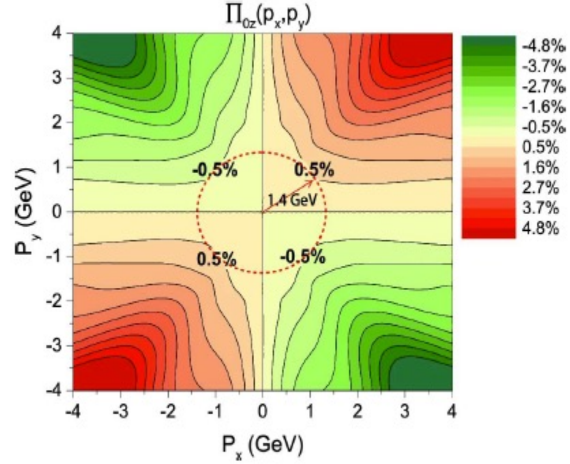


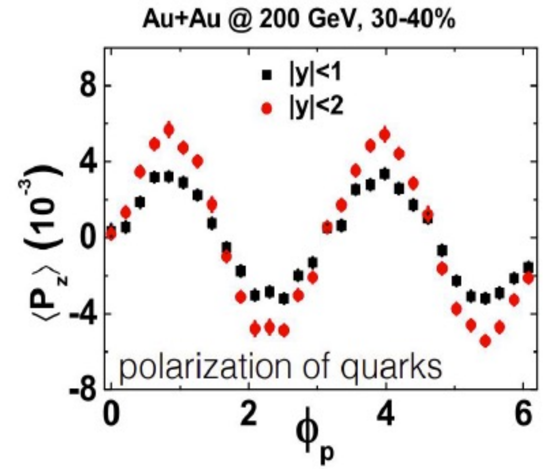


- Polarization along the beam direction expected from the "elliptic flow"
- STAR data indeed show such a longitudinal polarization Pz depending on azimuthal angle (sine function)
- BW model captures the trend with correct sign, while many others do not.

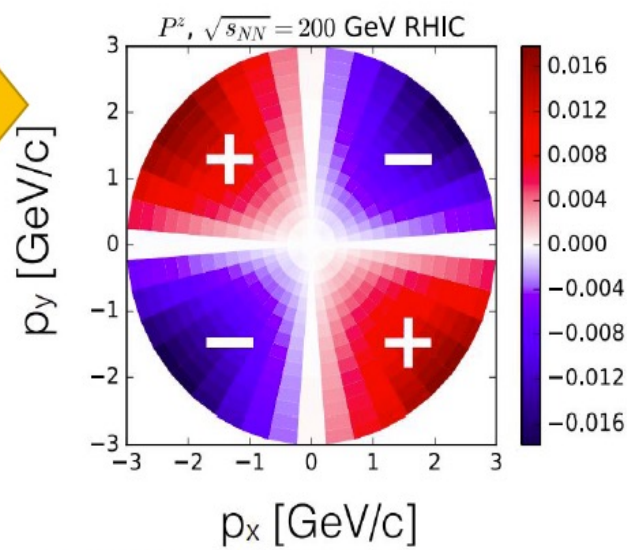
P_z: sign problem

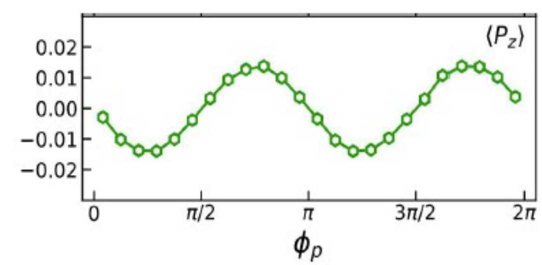
- Some model studies predicted this behavior with the correct sign
  - (3+1)D PICR hydro.: Y. Xie, *et. al.*, EPJ C 80, 39 (2020)
  - Chiral kinetic: Y. Sun, *et. al.*, PRC 99, 011903(R) (2019)

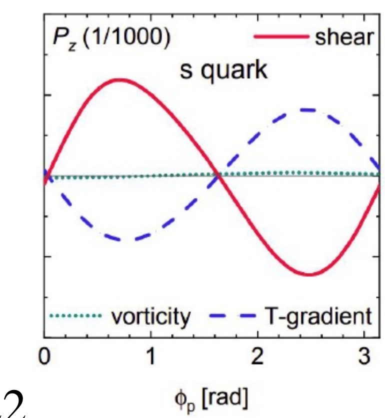




- Others predicted the incorrect sign
  - UrQMD+hydro: F. Becattini, *et. al.*, PRL.120.012302 (2018)
  - AMPT: X. Xia, *et. al.*, PRC98.024905 (2018)







- Recent considerations of a shear term may resolve the sign discrepancies

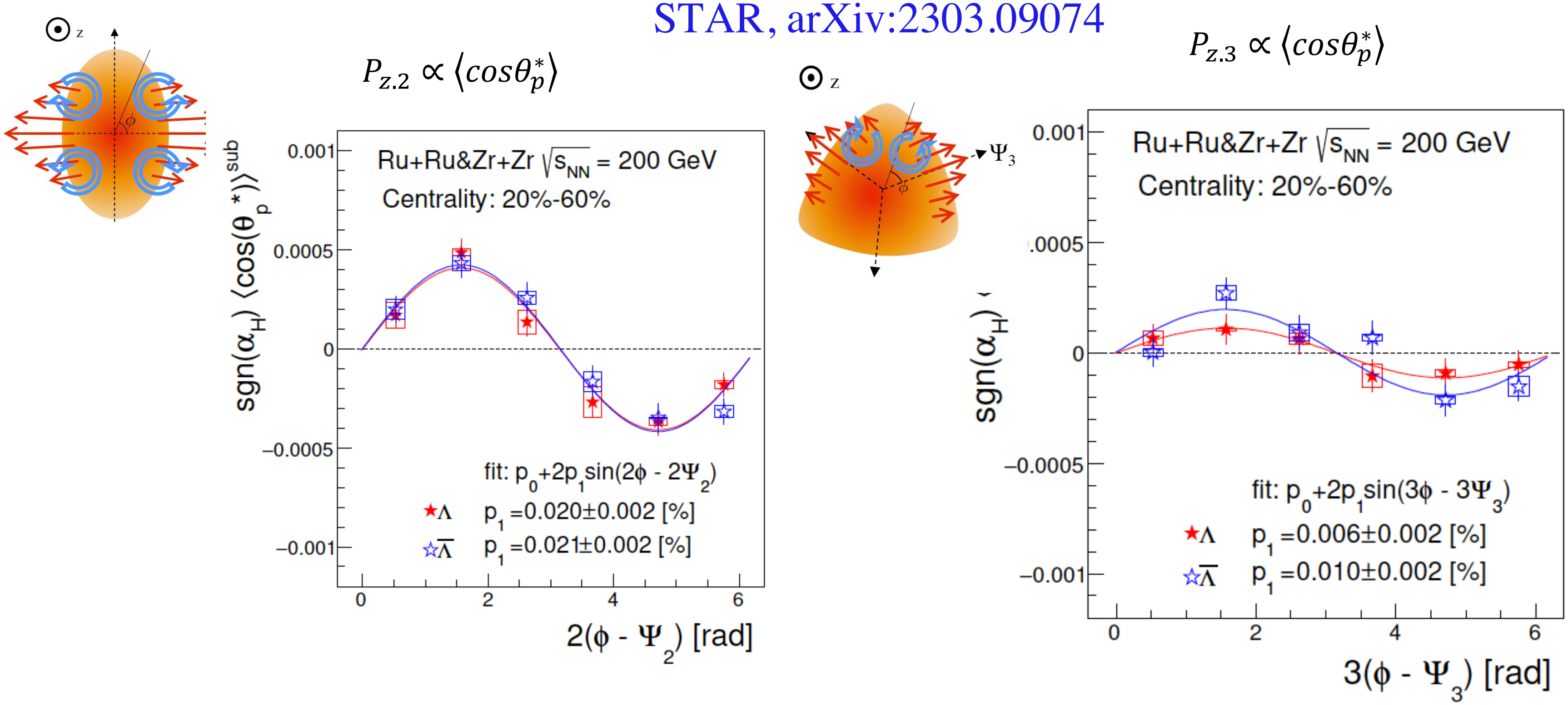
B. Fu et al., PRL 127 (2021) 14, 142301

F. Becattini et al., PRL 127, 272302 (2021)

-J. Adams, QM 2022

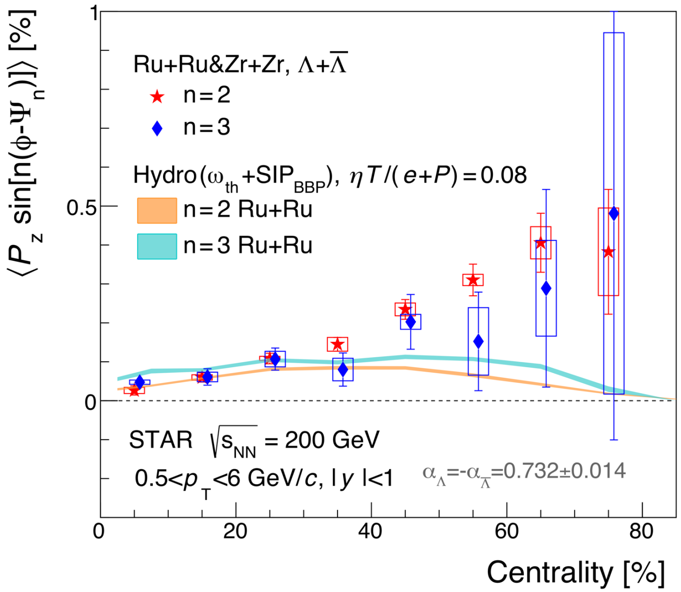
Local polarization in isobar collisions

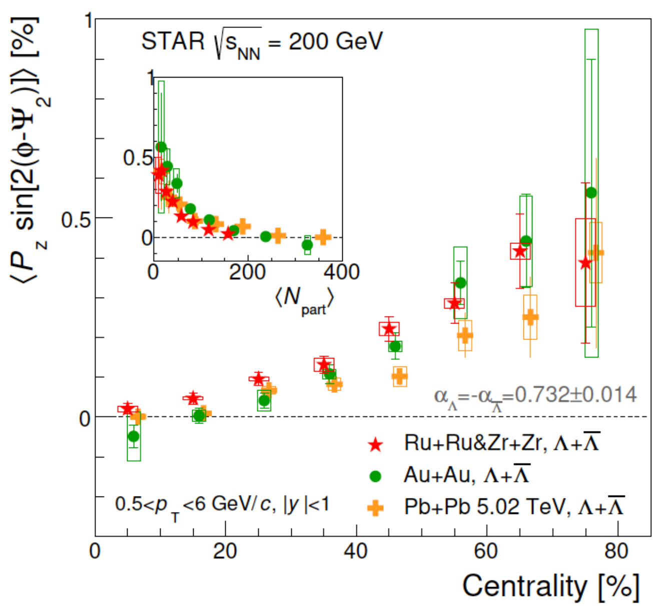
STAR, arXiv:2303.09074



- Polarization along the beam direction expected from the “elliptic flow”
- STAR data indeed show such a longitudinal polarization depending on azimuthal angle(sine function)
- First measurement relative to the 3^{rd}-order event plane Ψ_3
  - ➢ Similar pattern to the 2^{nd}-order, indicating v_3-driven polarization

Centrality dependence of $P_{z,n}$





- Comparable 2^{nd} and 3^{rd} order sine coefficients of $P_{z,n}$, especially in most central events
- Hydrodynamic models with shear term reasonably describes the data for central collisions, but not for peripheral, Additional constraint on shear viscosity
- $P(z,n)$ from Isobar data comparable to Au+Au and Pb+Pb
  - ✓ A hint of system size dependence rather than energy dependence

STAR, arXiv:2303.09074, to appear in PRL

Spin alignment of vector meson

- Spin density matrix of a vector meson: $\rho = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$

$$(\rho = \sum_i P_i \,|\, i >< i \,|)$$

- ρ_{mm}: the diagonal element of spin density matrix of V .

- ρ_{11}: the probability to be in $h=1$ state, similar for ρ_{-1-1} and ρ_{00} .

- For $V \rightarrow M_1+M_2$, M_1 and M_2 are two pseudo-scalar mesons,

$$\mathbf{W}(\cos\theta)^* = \frac{3}{4}[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta]^*$$

"Spin alignment", J.F. Donoghue, PRD19, 1979.

Θ*: angle between decay M and the spin quantization axis in rest frame of V

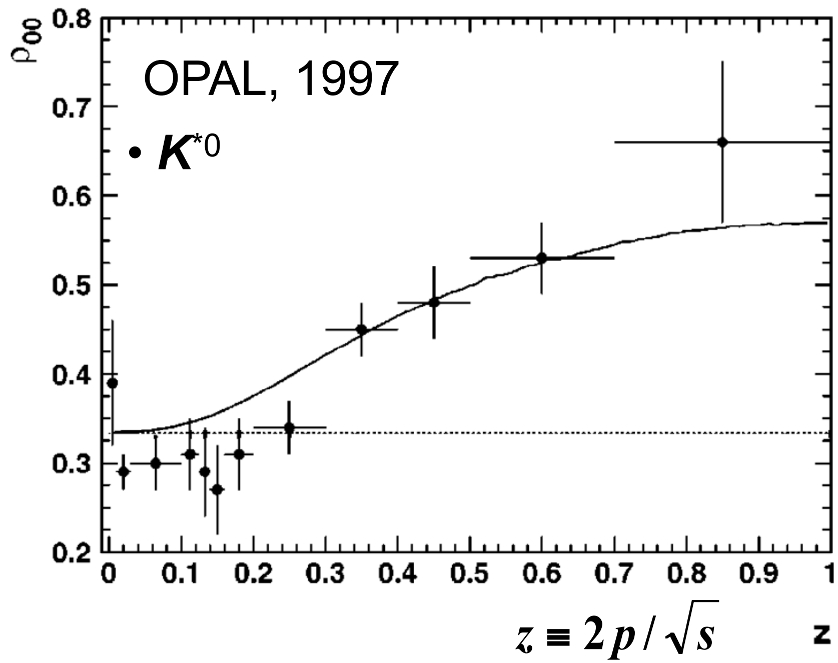
Spin alignment of vector meson in e^+e^-

- Polarization of V:

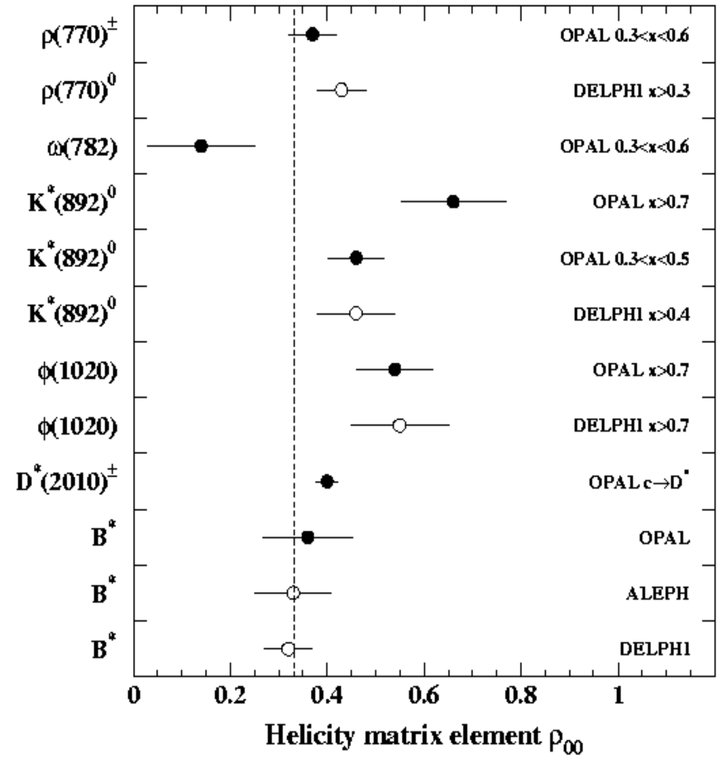
$$W(\cos\theta) = \frac{3}{4}[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*]$$

ρ_{00} : Prob. of being in h= 0 state.

- The data at LEP:



Q. Xu, Z. Liang,PRD63(2001)111301



➢ Spin alignment exists in fragmentation of a longitudinally polarized quark

Global spin alignment in heavy ion

- Spin alignment of ϕ, K* meson in Au+Au collision at STAR:

Yield of ϕ, K* is corrected for efficiency and acceptance using STAR embedding simulations, then fitted with decay angle distribution:

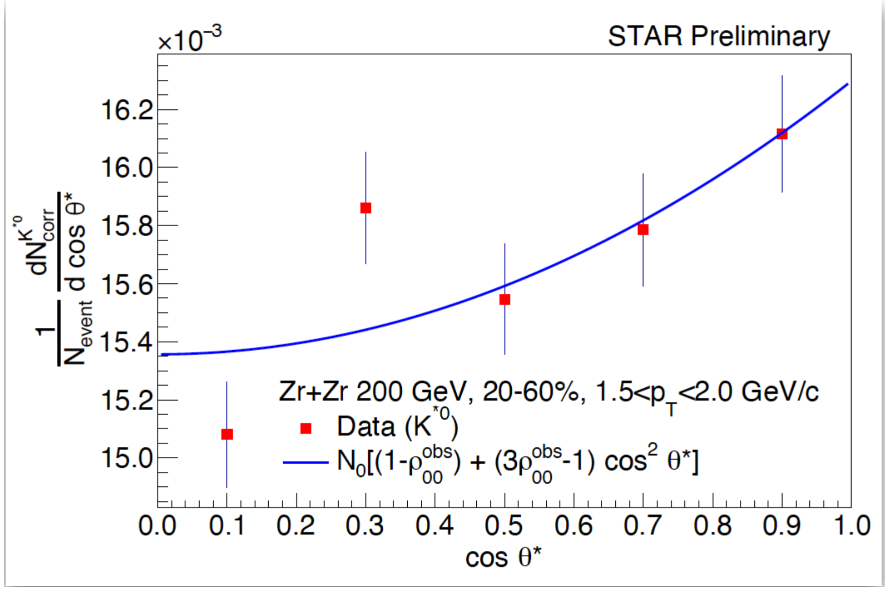
- Observed ρ_{00}^{obs} is calculated from fitting the yield with function:

$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}^{obs}) + (3\rho_{00}^{obs}-1)\cos^2\theta^*\right]$$

- Observed ρ_{00}^{obs} is corrected for TPC event plane resolution (R)

$$\rho_{00} - \frac{1}{3} = \frac{4}{1+3R}\left(\rho_{00}^{obs} - \frac{1}{3}\right)$$

Tang et. al., Phys. Rev. C 98, 044907 (2018)

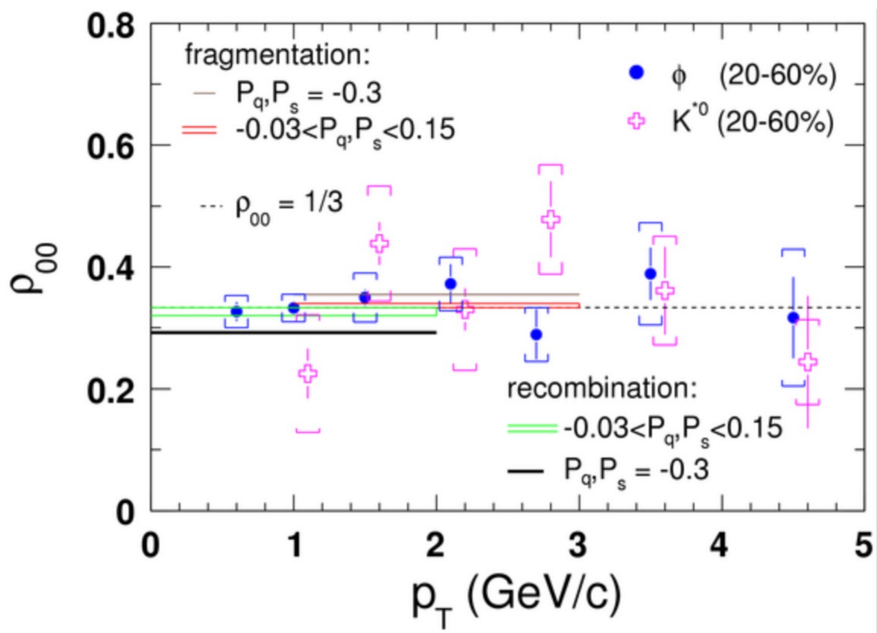


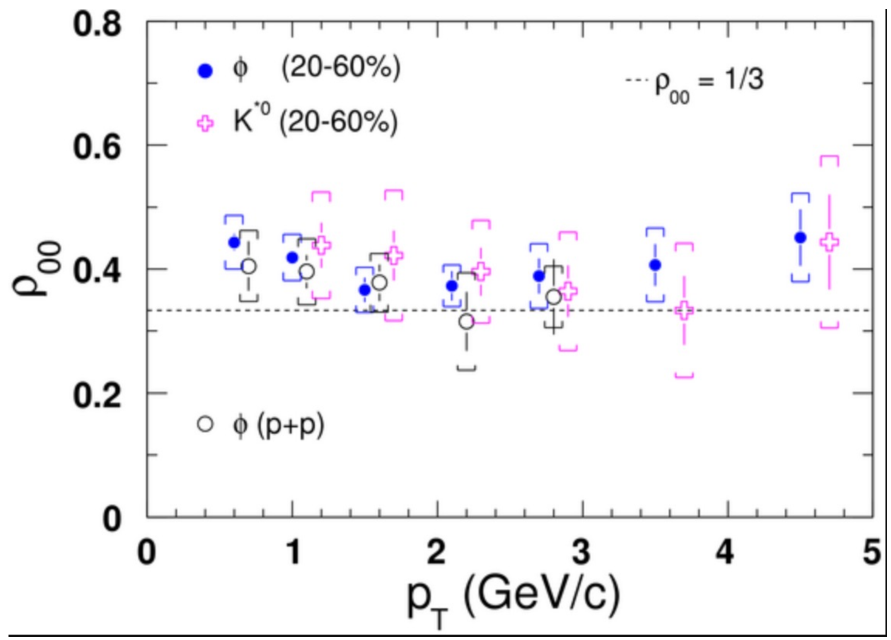
1st STAR paper on spin alignment

Spin alignment measurements of the $K^{*0}(892)$ and $\phi(1020)$ vector mesons in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV

B. I. Abelev *et al.* (STAR Collaboration)
Phys. Rev. C **77**, 061902(R) – Published 12 June 2008

J.H. Chen, Z.B. Tang et. al.



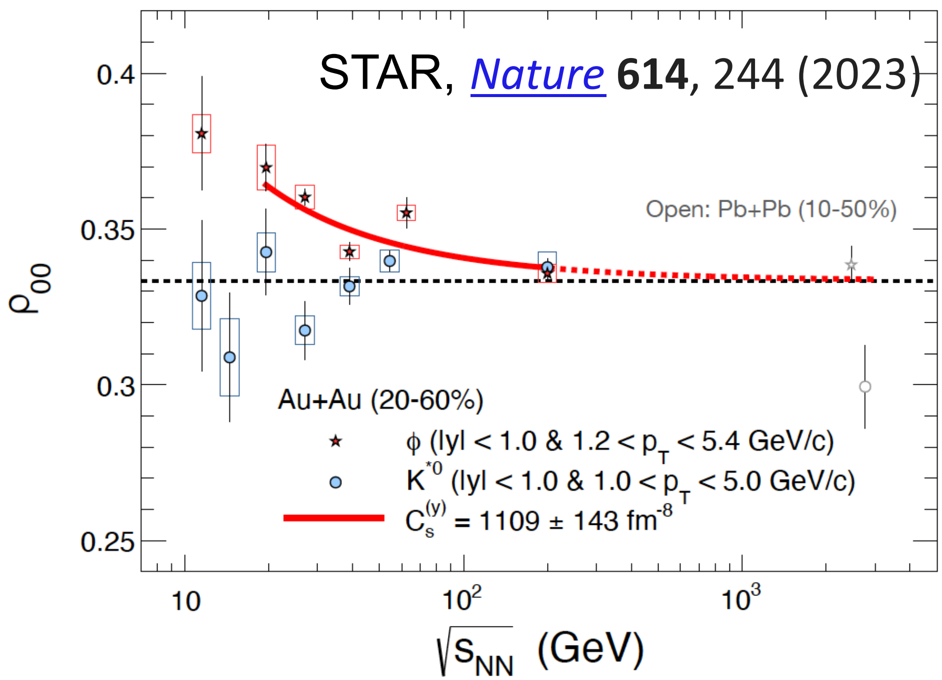


w.r.t. reaction plane

w.r.t. production plane

Global spin alignment in heavy ion

- **Vector mesons' ρ_{00} from Au+Au at STAR BES-I:**



Theoretical expectation for ρ_{00}

Vorticity	
recombination	$\rho_{00} < 1/3$
fragmentation	$\rho_{00} > 1/3$
Magnetic field	$\rho_{00} > 1/3$ (for neutral vector mesons)

Z. Liang, X.N. Wang, Phys. Lett. B 629, (2005)

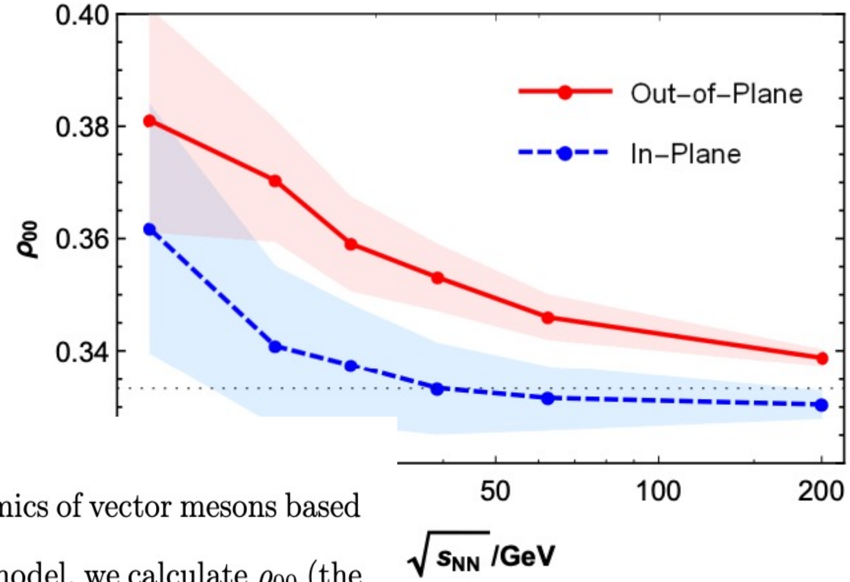
- Polarization by a strong force field of vector meson: presently only known mechanism that can produce large deviation for ϕ spin alignment:

X. Sheng, L. Oliva, and Q. Wang, PRD101.096005(2020)
X. Sheng, Q.Wang, and X. Wang, PRD102.056013 (2020)

Spin alignment of vector mesons in heavy-ion collisions

Xin-Li Sheng,[1] Lucia Oliva,[2,3] Zuo-Tang Liang,[4] Qun Wang,[5] and Xin-Nian Wang[6]

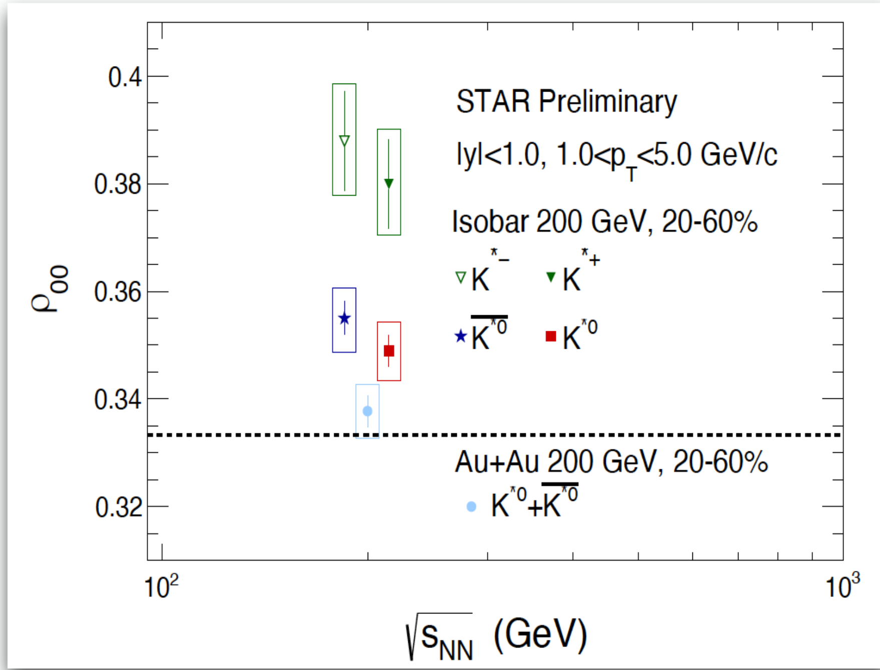
arXiv:2205.15689, PRL131, 042304



Abstract

We present a relativistic spin Boltzmann equation (SBE) for spin dynamics of vector mesons based on Kadanoff-Baym equations. Using SBE and an effective quark-meson model, we calculate ρ_{00} (the 00-element of the spin density matrix) for ϕ mesons formed by the coalescence of s and $\bar{s}$ quarks which are assumed to be polarized by the vorticity and ϕ fields. We show that the contributions to ρ_{00} from the vorticity and ϕ fields all appear as local correlation between strong force fields of the same kinds and same components. This indicates that fluctuations of strong force fields play an important role in ρ_{00}, which can be formulated and extracted in relativistic quantum transport theory. Our results on the colliding energy, transverse momentum and centrality dependence of ρ_{00} are in good agreement with recent STAR data for ϕ mesons.

K* ρ_{00} from Isobar collisions



- $K^{*+/-}$: First measurement of global ρ_{00}
- K^{*0} vs. $K^{*+/-}$: ~ 2.5σ difference
  - Ordering opposite to the expectation from **B** field *Yang, et. al., Phys Rev C 97, 034917 (2018)*
  - Effects from vector meson strong force field?

- Need inputs from theory to understand this behavior

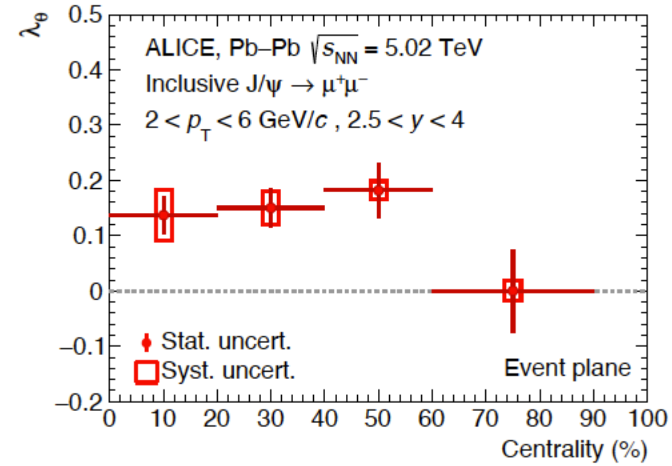
19 *Subhash Singha @ QM 2022*

Spin alignment becomes a new hot topic in heavy ion physics!

Global spin alignment of J/ψ

- 矢量介子不同产生机制：

ALICE, PRL131 (2023) 042303



J/ψ 介子

再产生效应 — QGP中 — 能量依赖性
硬散射产生 — 碰撞早期 — 强磁场

ϕ介子

再产生效应 — QGP中

- J/ψ 自旋排列实验抽取方法：碰撞系统角动量方向作为z轴方向

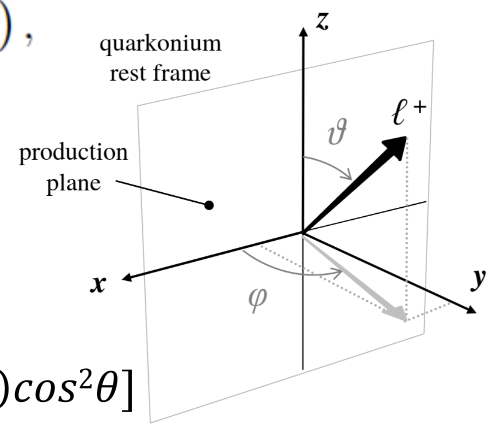
Decay channel : $J/\psi \rightarrow e^+e^-$

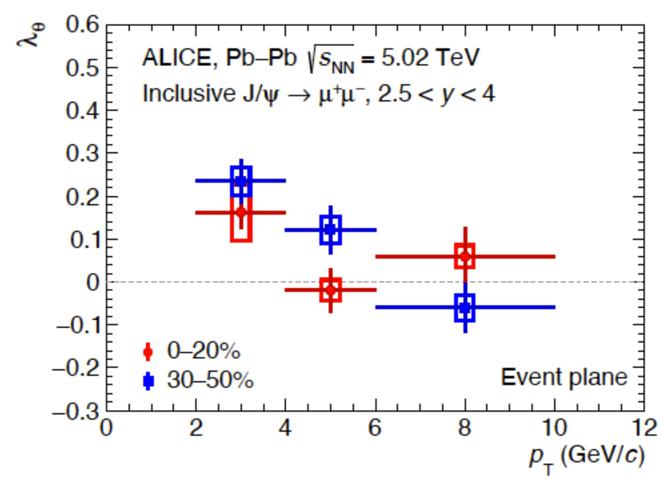
$$W(\theta) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta \cos^2\theta),$$

λ_θ=(1-3ρ_{00})/ (1+ρ_{00})

λ_θ = 1: transverse polarization
λ_θ = -1: longitudinal polarization
λ_θ = 0: no polarization

$$W(\theta) \propto [(1+\rho_{00}) + (1-3\rho_{00})cos^2\theta]$$

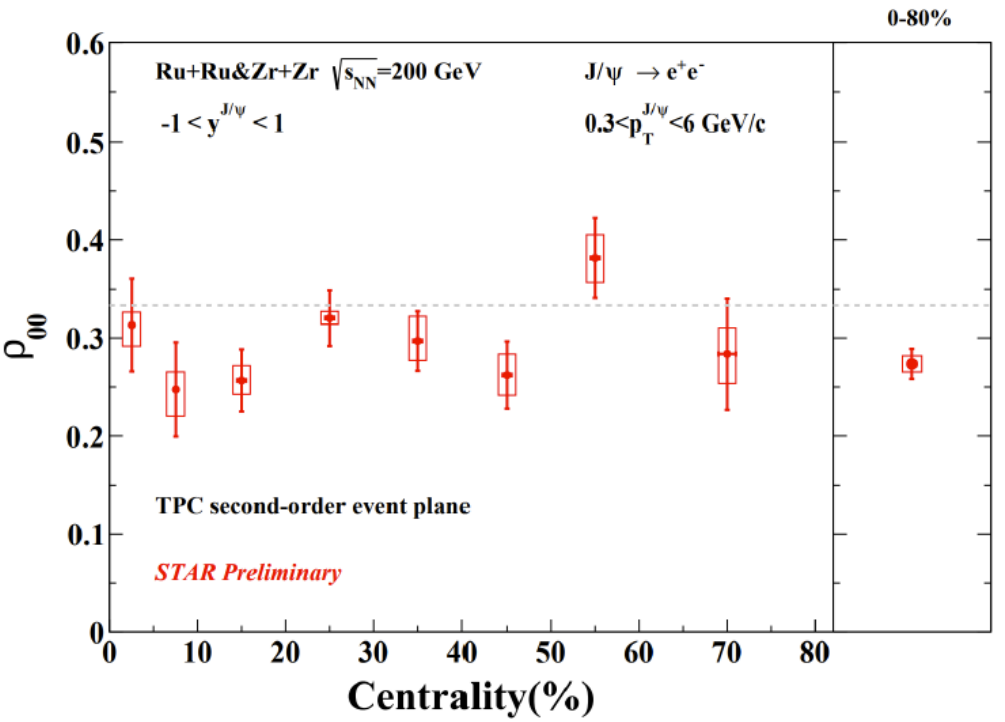




- P. Faccioli et al., Eur. Phys. J. C (2010) 69: 657

J/ψ global spin alignment in iso-bar at STAR

*New results just released in SPIN2023

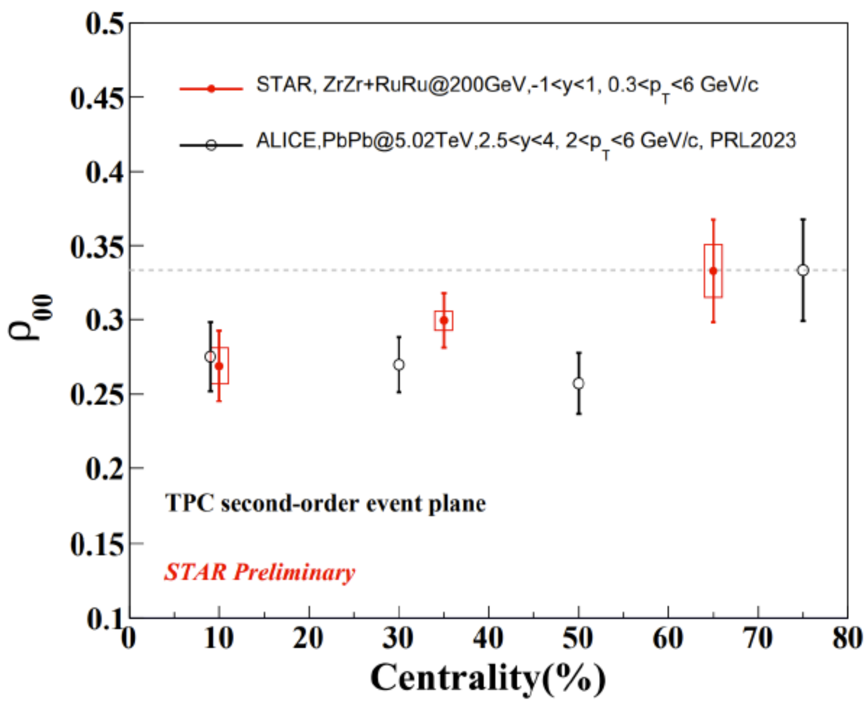


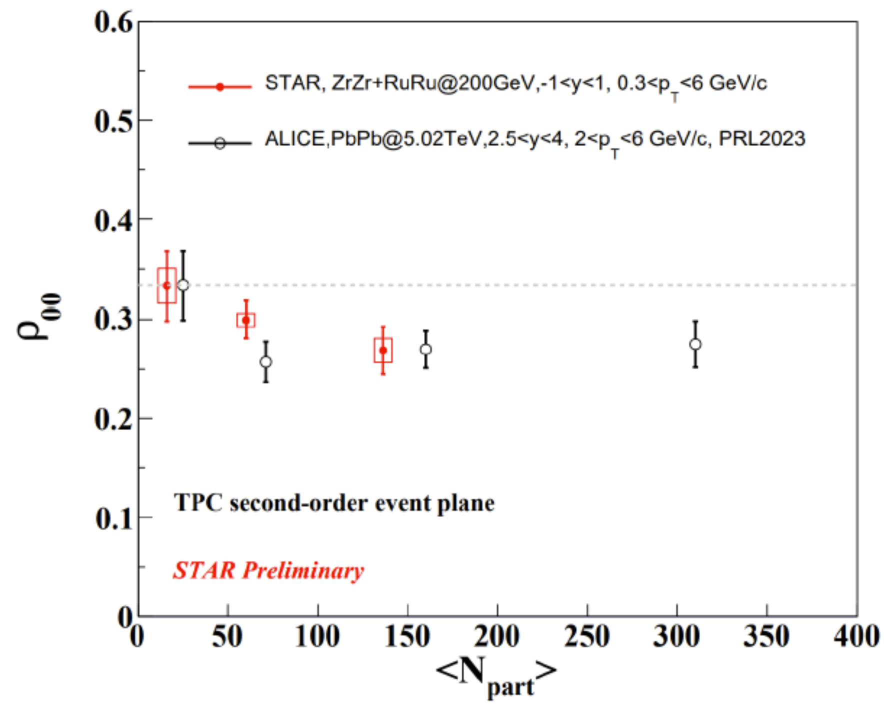
- First measurement of ρ_{00} using second-order event plane at RHIC
- ρ_{00} lower than 1/3 with a **significance of 3.5 σ** for p_T from 0.3 to 6 GeV/c and 0-80% centrality
- No significant centrality dependence within uncertainty.

09/26/2023 Dandan Shen @ SPIN 2023 18

J/ψ global spin alignment in iso-bar at STAR

*New results just released in SPIN2023





- The ρ_{00} at RHIC energy is comparable to LHC results, despite of very different collision energy, systems and rapidity

Outline for today's topic

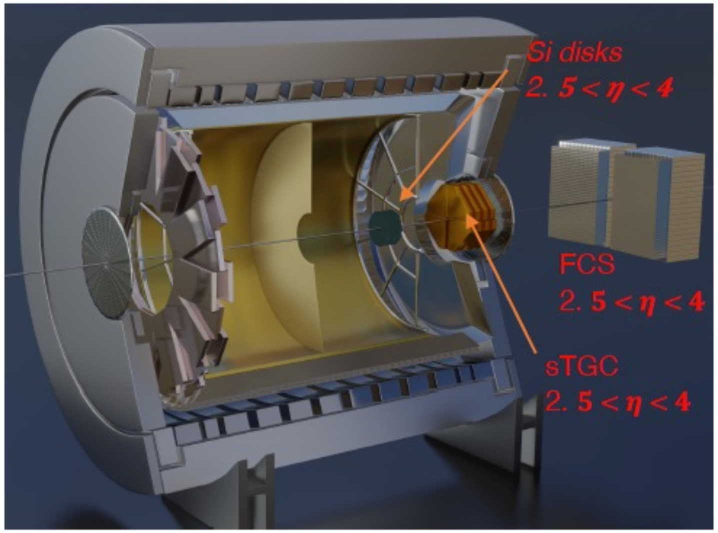
- Introduction to SPIN & nucleon spin structure
- Recent spin highlights in pp collisions from RHIC:
  - ✓ Gluon polarization (Jet, π^0 production): gluon polarization Δg
  - ✓ Quark/Anti-quark polarization (W/Z production): sea quark Δq
  - ✓ Transverse spin asymmetry (W/Z production): Sivers function
  - ✓ Transverse spin asymmetry (Hadron production): Collins
- Global polarization in heavy ion collisions
  - ✓ Hyperon global polarization
  - ✓ Spin alignment of vector meson
- Future plans for spin physics in 2024+ at RHIC/EIC/EicC

RHIC pp running until 2025

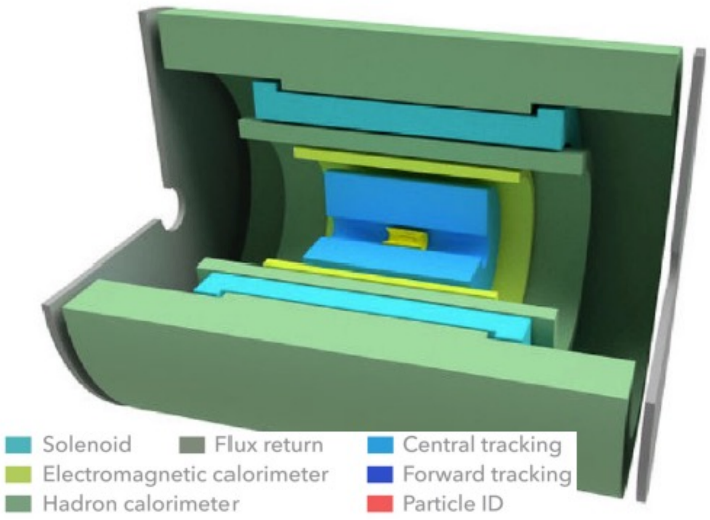
- Successful STAR run in 2022 with forward upgrade
- One more transverse spin run in 2024 before EIC, unique physics opportunities in pp and pA before EIC

$\sqrt{s}$ (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

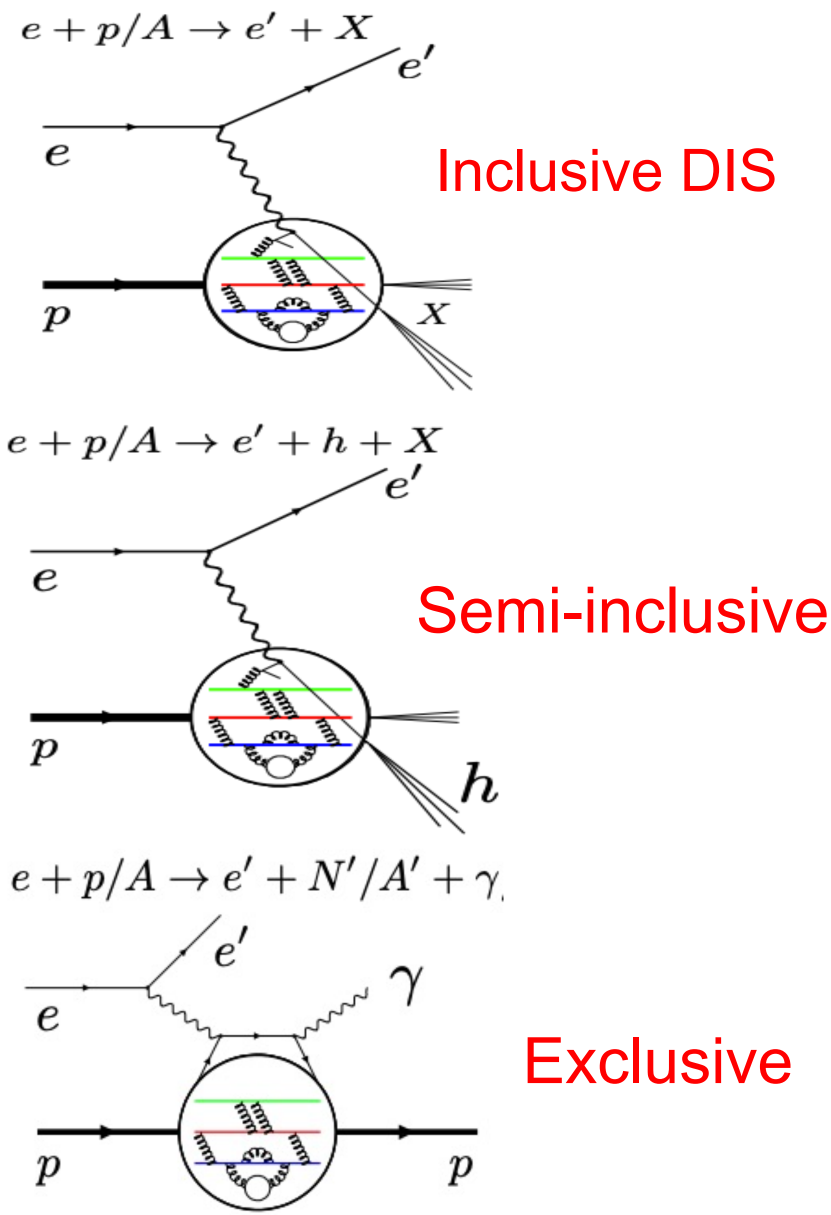
✓ Large Ion Species Range: protons – Uranium

✓ Large Detector Acceptance

✓ Accommodate a Second Interaction Region (IR)

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

Electron-Ion Collider (EIC)



- EIC key physics:

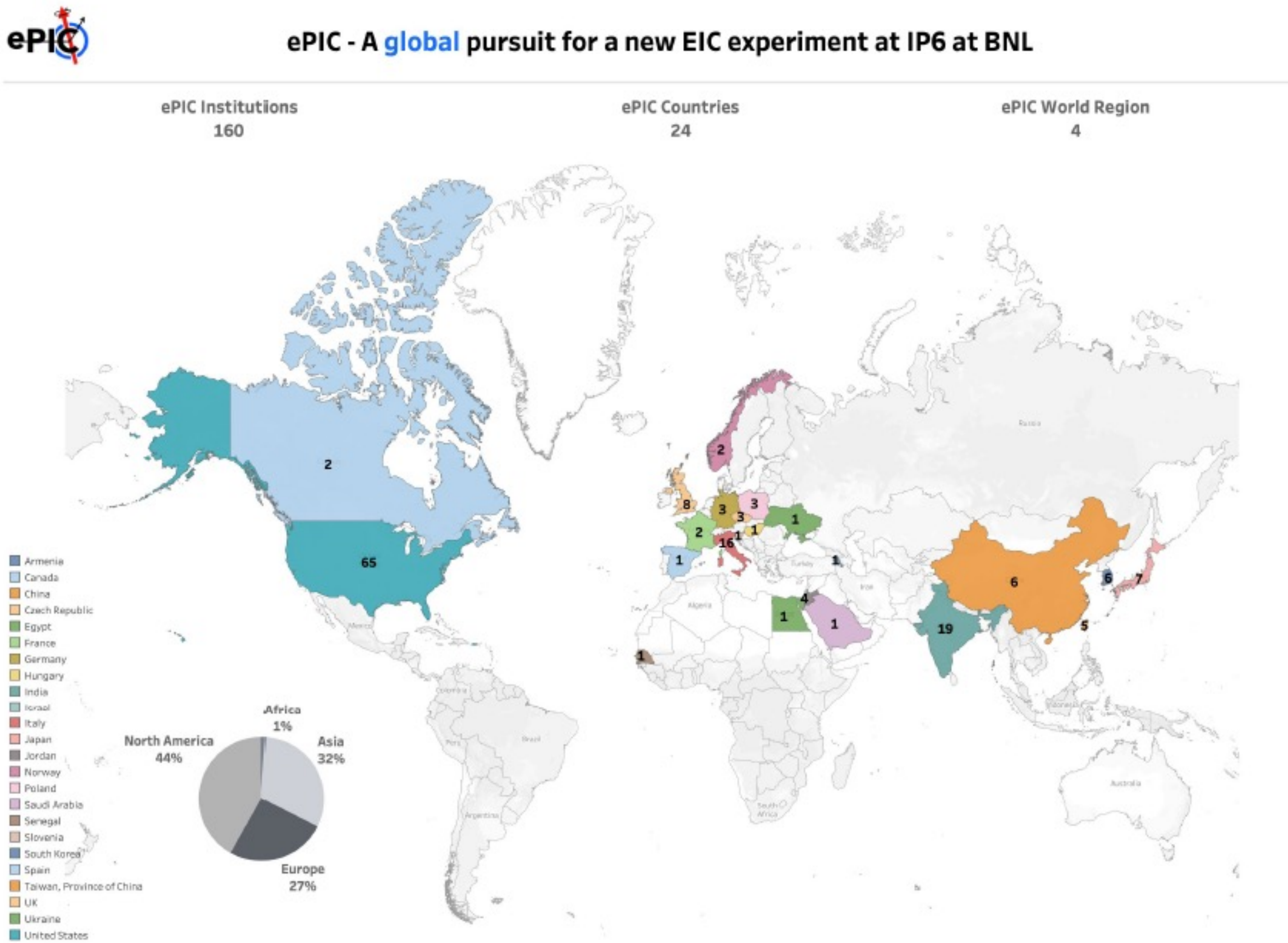
"An EIC can uniquely address three profound questions about nucleons - neutrons and protons - and how they are assembled to form the nuclei of atoms:

> - **How does the mass of the nucleon arise?**
> - **How does the spin of the nucleon arise?**
> - **What are the emergent properties of dense systems of gluons?"**

\- U.S. National Academy of Science Report (2018)

ePIC collaboration
(electron-Proton/Ion Collider)

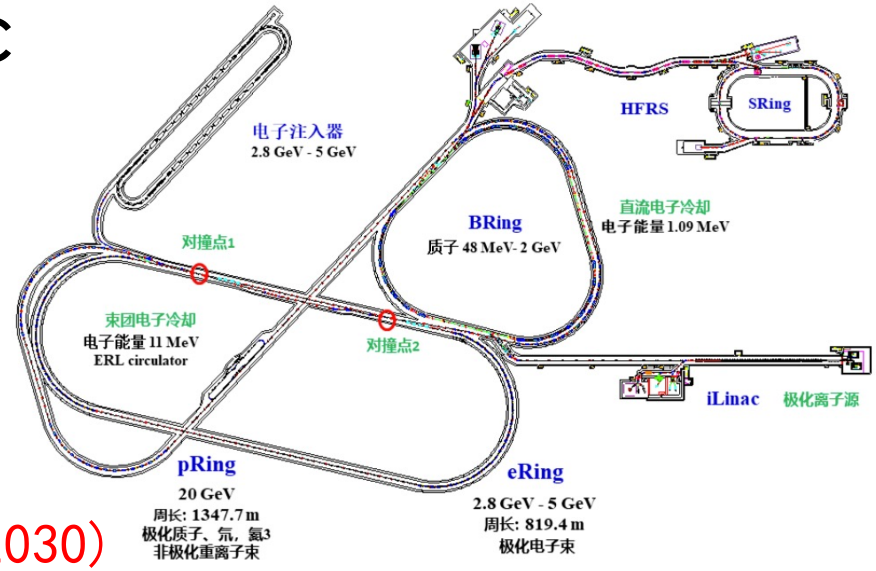
World Map - Institutions



CCNU,
Fudan,
SCNU,
Shandong
Tsinghua
USTC

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(惠州,～2030)



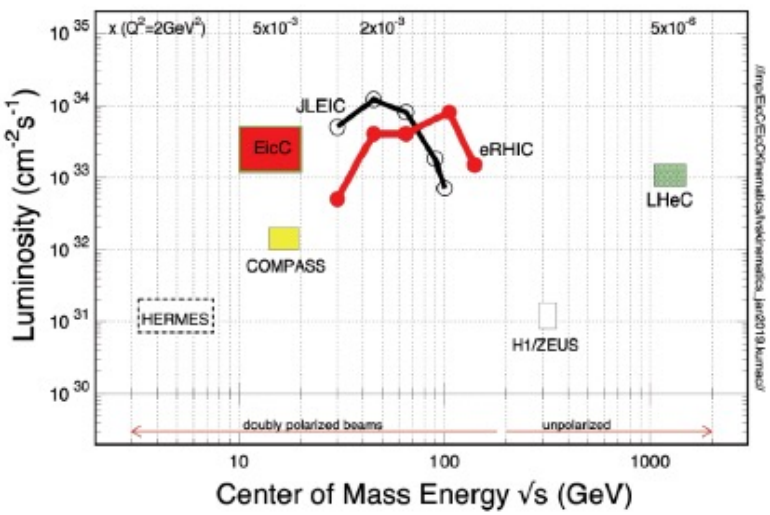
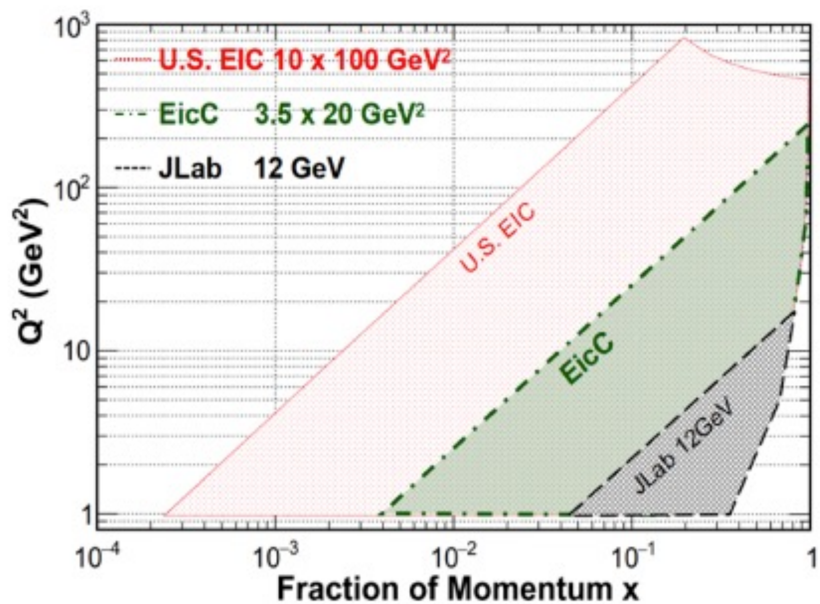


图 1.4: 国际上电子离子装置（包括拟建）亮度和质心系能量比较。



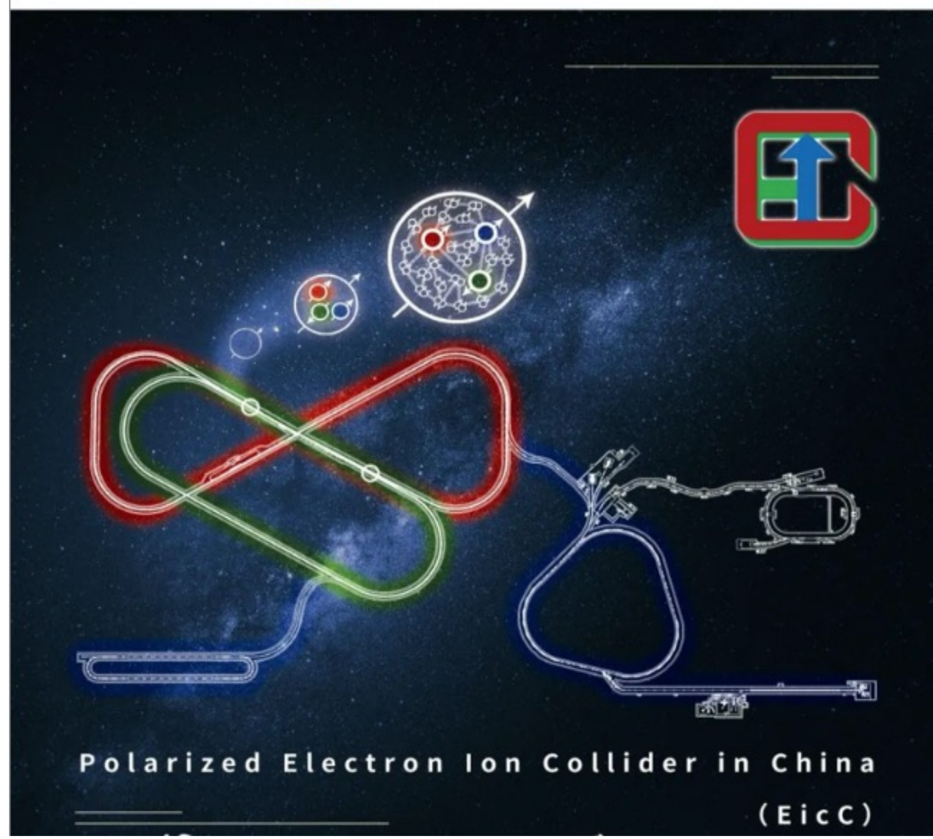
Electron-ion collider China(EicC)

- EicC中英文白皮书分别于2020/2021年发布

第43卷 第2期
2020年2月
核 技 术
NUCLEAR TECHNIQUES
Vol.43,No.2
February 2020

中国极化电子离子对撞机计划

Frontiers of Physics
ISSN 2095-0462
Volume 16 · Number 6
December 2021



Front. Phys.16(6), 64701 (2021)

Summary

- Origin of proton spin remains a fundamental question in QCD.
  - Observation of positive gluon polarization from RHIC
  - Unique probe of sea quark polarization via W production

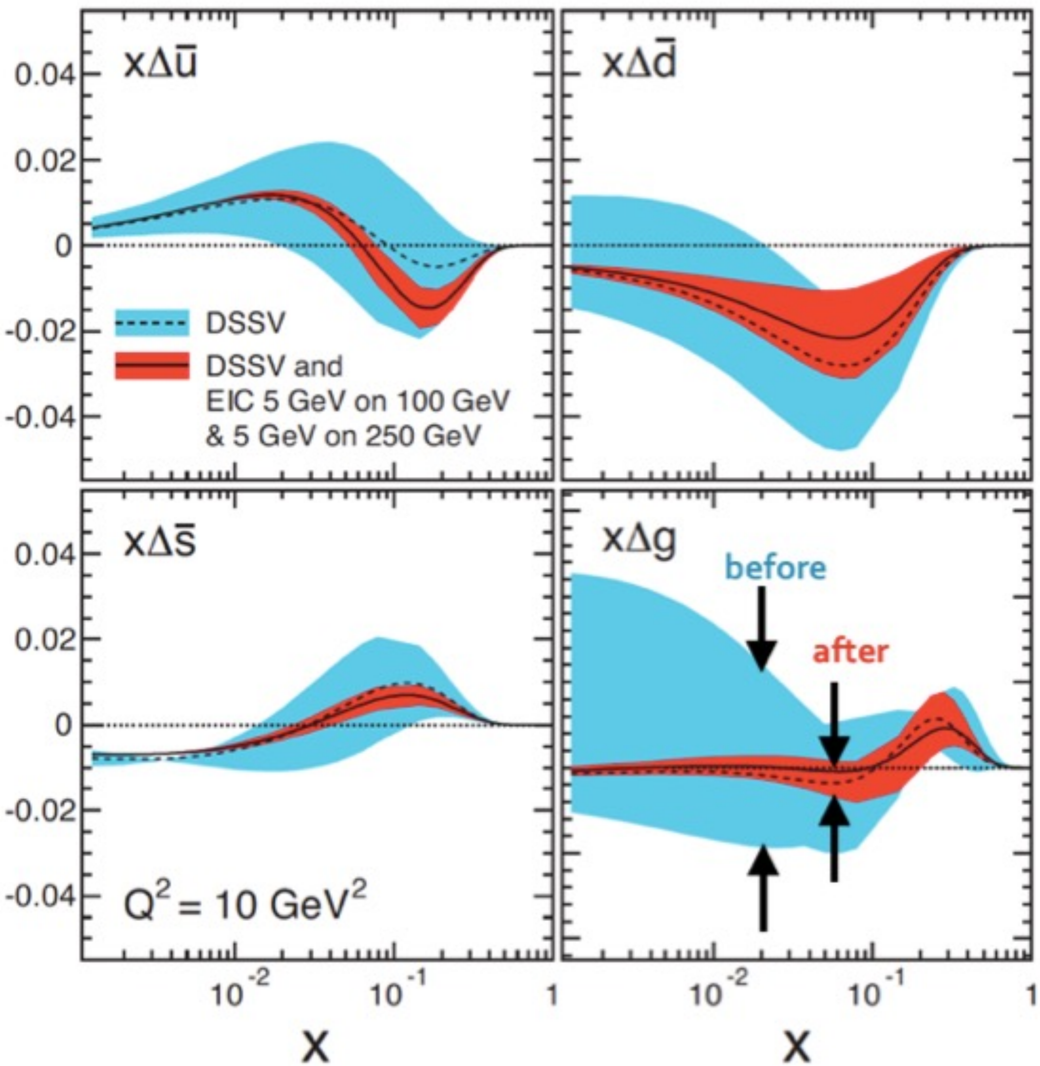
- Transverse spin physics at RHIC:
  - A_N for W,Z at STAR: Sivers sign change
  - Results on Collins asymmetries & hyperon spin transfer provide window for transversity distribution of nucleon.

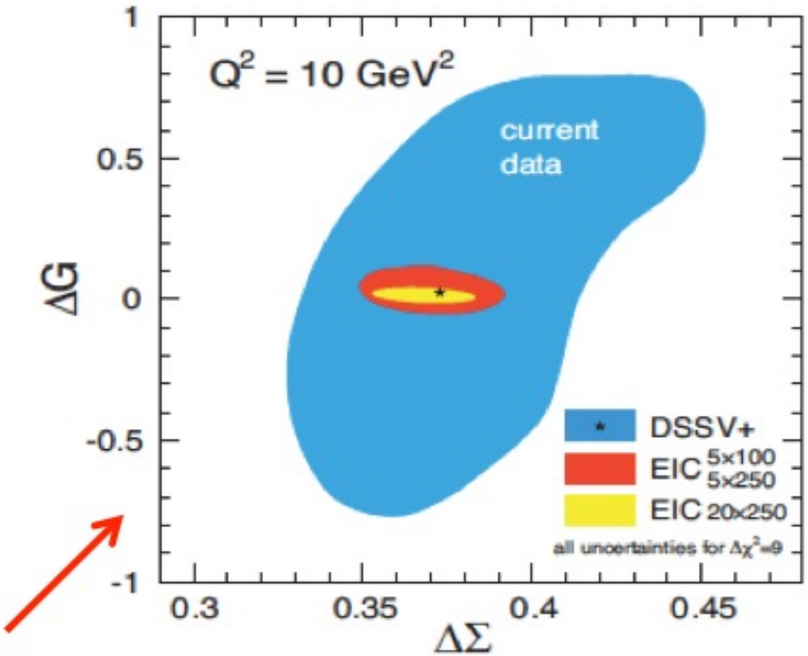
- Global polarization in heavy-ion collisions opened a new direction to study the QGP properties!

- Future RHIC spin in 2024^{+} & EIC/EicC in 2030+
  - 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

EIC participation from China-mainland

- **Oct 2020，8 institutions in China-mainland submitted EOI to EIC, with main detector interests on calorimetry and tracking**
- **Participation in Yellow Report from Chinese institutions (2020~2021)**
  - ✓ Authors from 14 Chinese institutions involved in YR writing including both theorists and experimentalist, Bowen Xiao served as co-convener of semi-inclusive working group
- **Chinese groups actively participated in EIC detector proposals (2021)**
  - ✓ 8 institutions joined ATHENA proposal, Qinghua Xu served as co-convener of inclusive working group, with detector interest on EMCal etc.
  - ✓ 6 institutions joined ECCE proposal, Wangmei Zha served as co-convener of jets and heavy flavor working group, with detector interest on silicon tracker, MPGD etc.
- **After DPAP decision on EIC detector proposal ~March 2022, 6 Chinese universities remain with EIC detector 1, i.e., ePIC experiment.** Wangmei Zha serves as co-convener of jets and heavy flavor working group.
  - ✓ Central China Normal University (CCNU), Fudan University, Shandong University (SDU) , South China Normal University (SCNU), Tsinghua University (THU), University of Science and Technology of China (USTC)