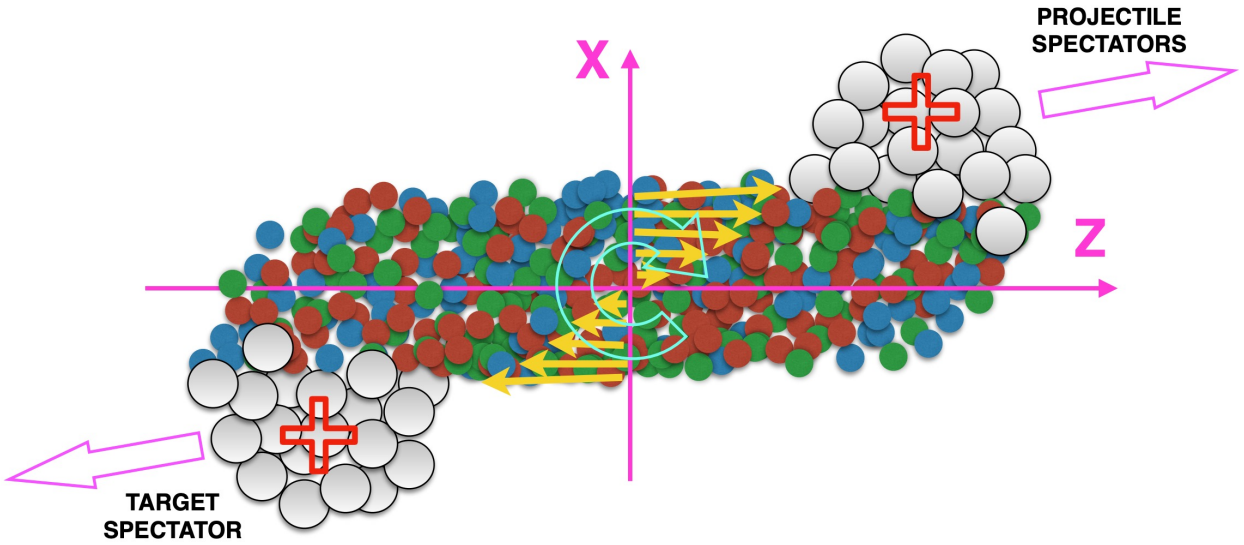
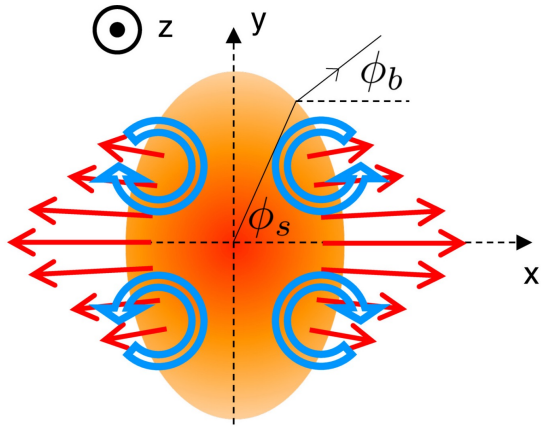
Workshop on Advances, Innovations, and Future Perspectives in High-Energy Nuclear Physics
Oct 19 – 24, 2024
Wuhan, China

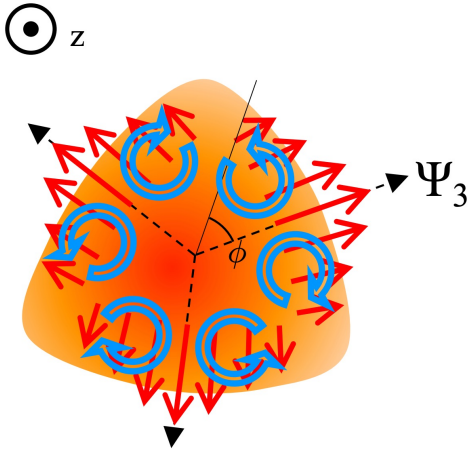
Constraining the Gluon Helicity at STAR

Ting Lin (林挺)
Shandong University (山东大学)

Spin in Heavy Ion Collisions



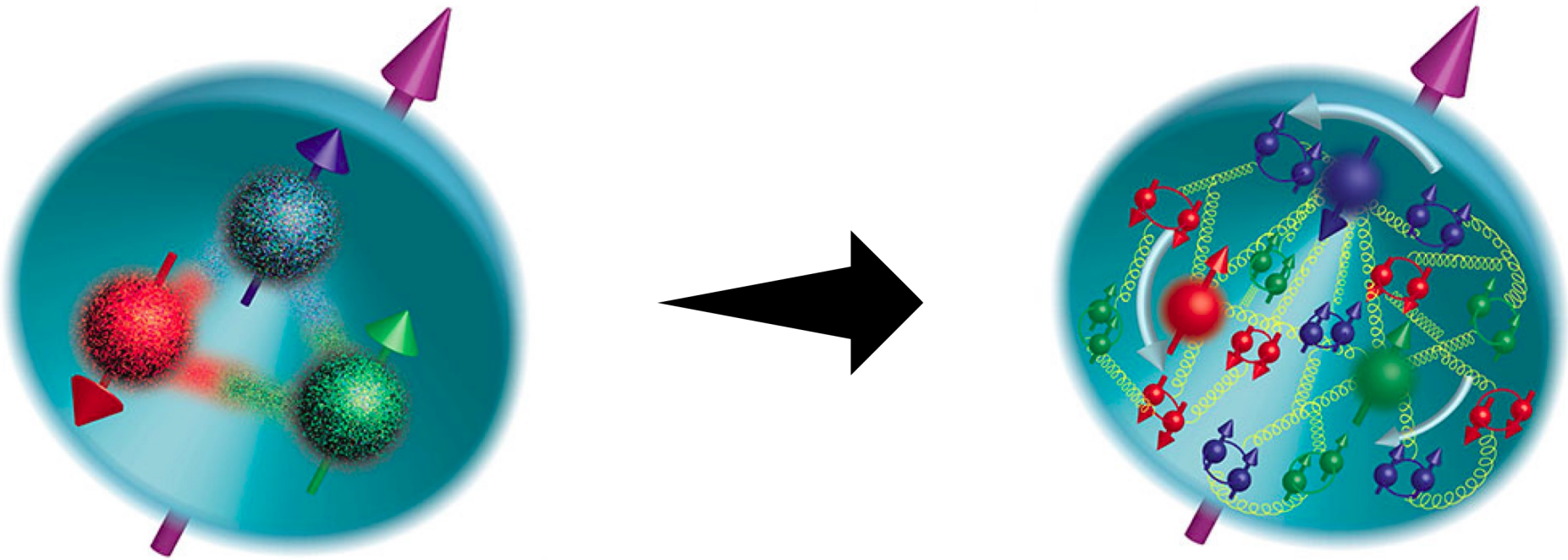




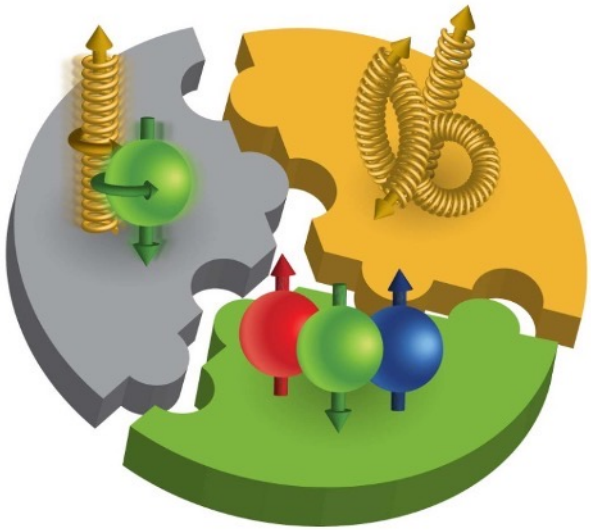
Takafumi Niida, Sergei A. Voloshin, arXiv:2404.11042 [nucl-ex]

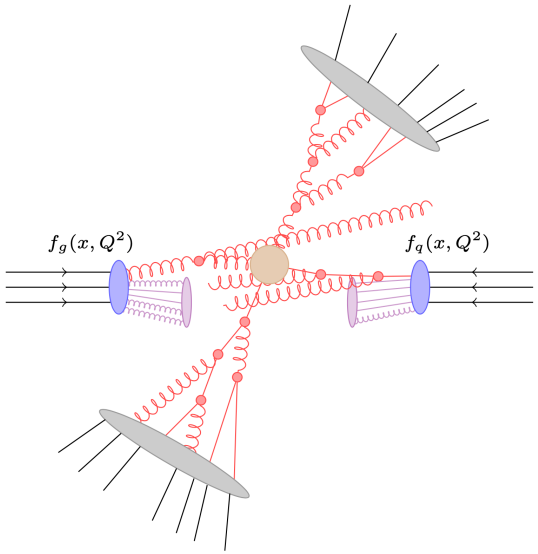
- Spin polarization in heavy ion collisions is largely driven by the vorticity and local angular momentum of the QGP;
- Opened new opportunities to study the collision dynamics and the properties of the QGP.

Spin of the Proton



Spin of the Proton





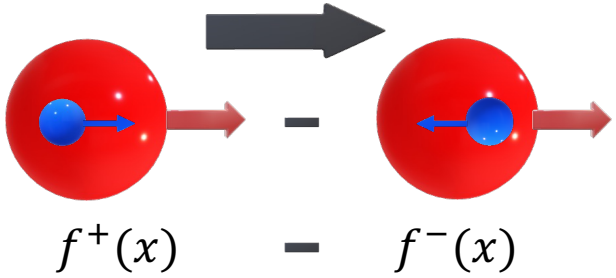
- For helicity distributions (collinear terms) in 'canonical' approach, the proton's spin can be decomposed into:

$$\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$

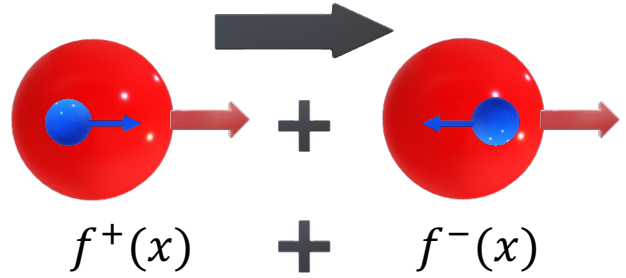
R. L. Jaffe and A. Manohar, NPB 337, 509 (1990)

  - $\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s})dx$
  - $\Delta G = \int \Delta g(x)dx$

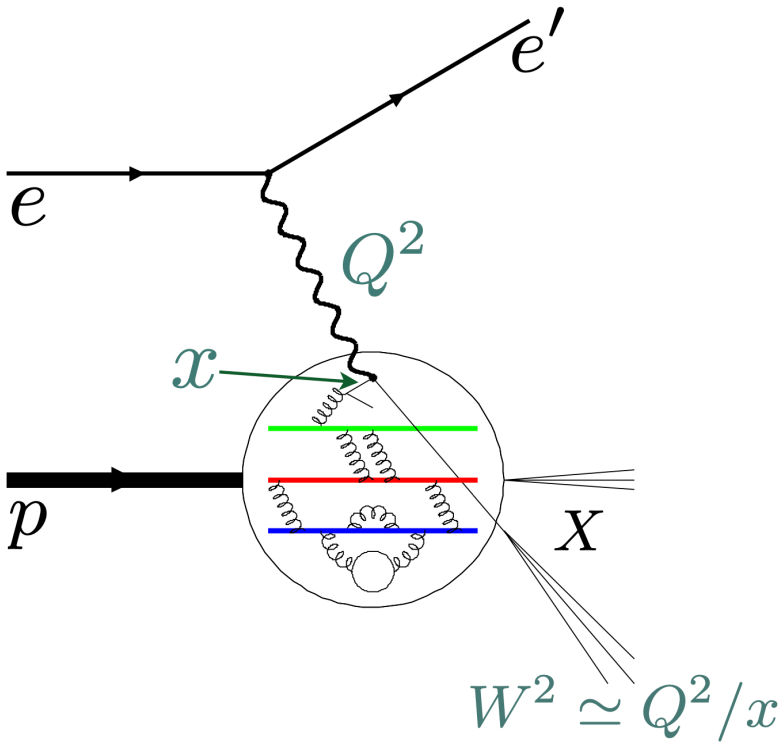
- Helicity PDF, $\Delta f(x) =$

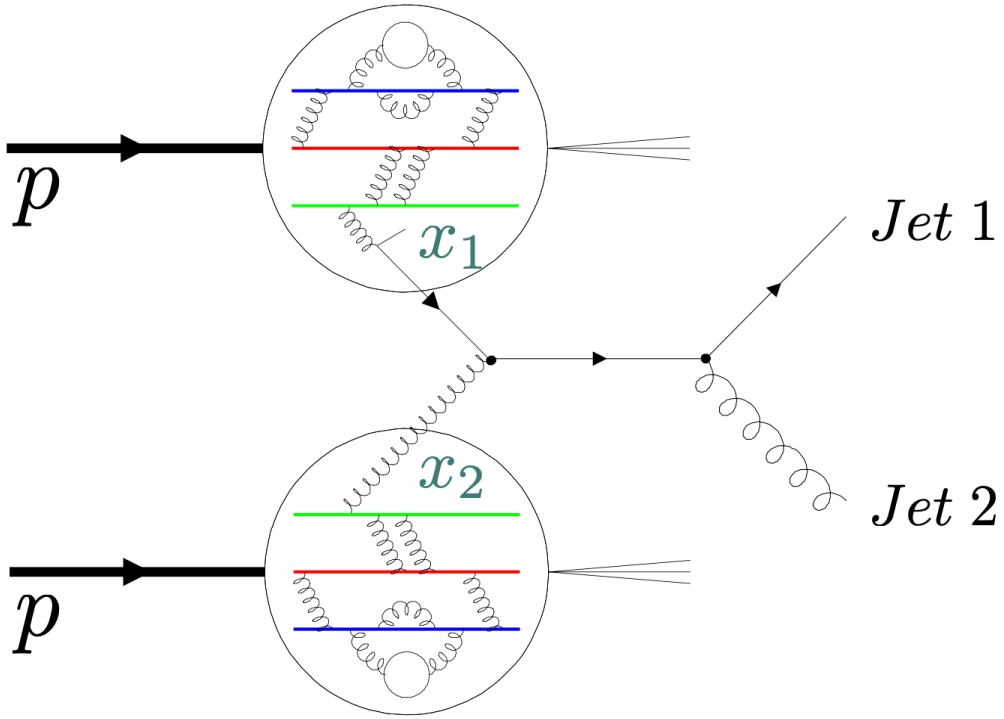


- Unpolarized PDF, $f(x) =$



Probing Parton Distribution Functions

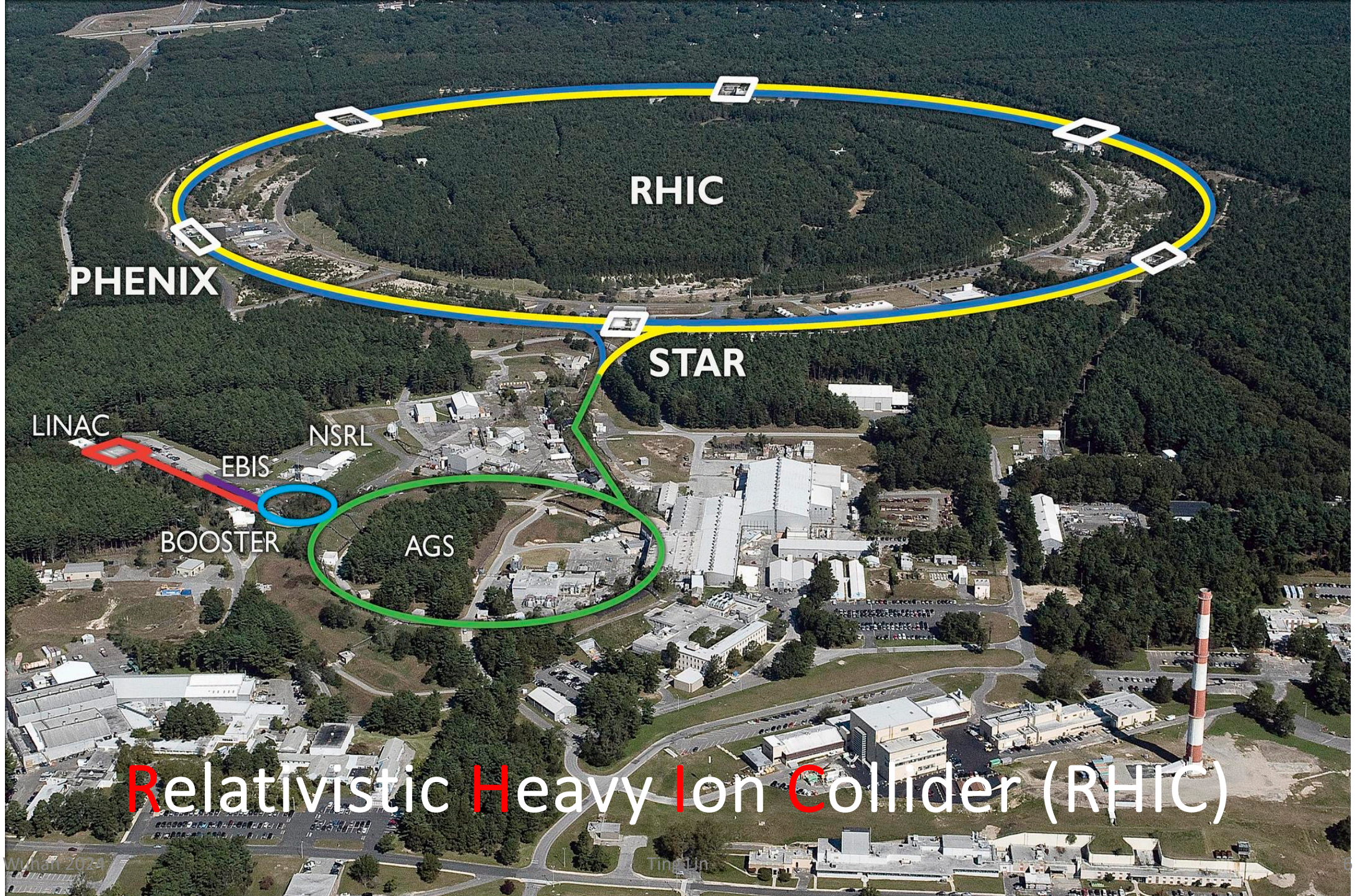




$$d\sigma_{ep} \propto F_2 = \sum_{ab} x e_q^2 \, f_q(x)$$

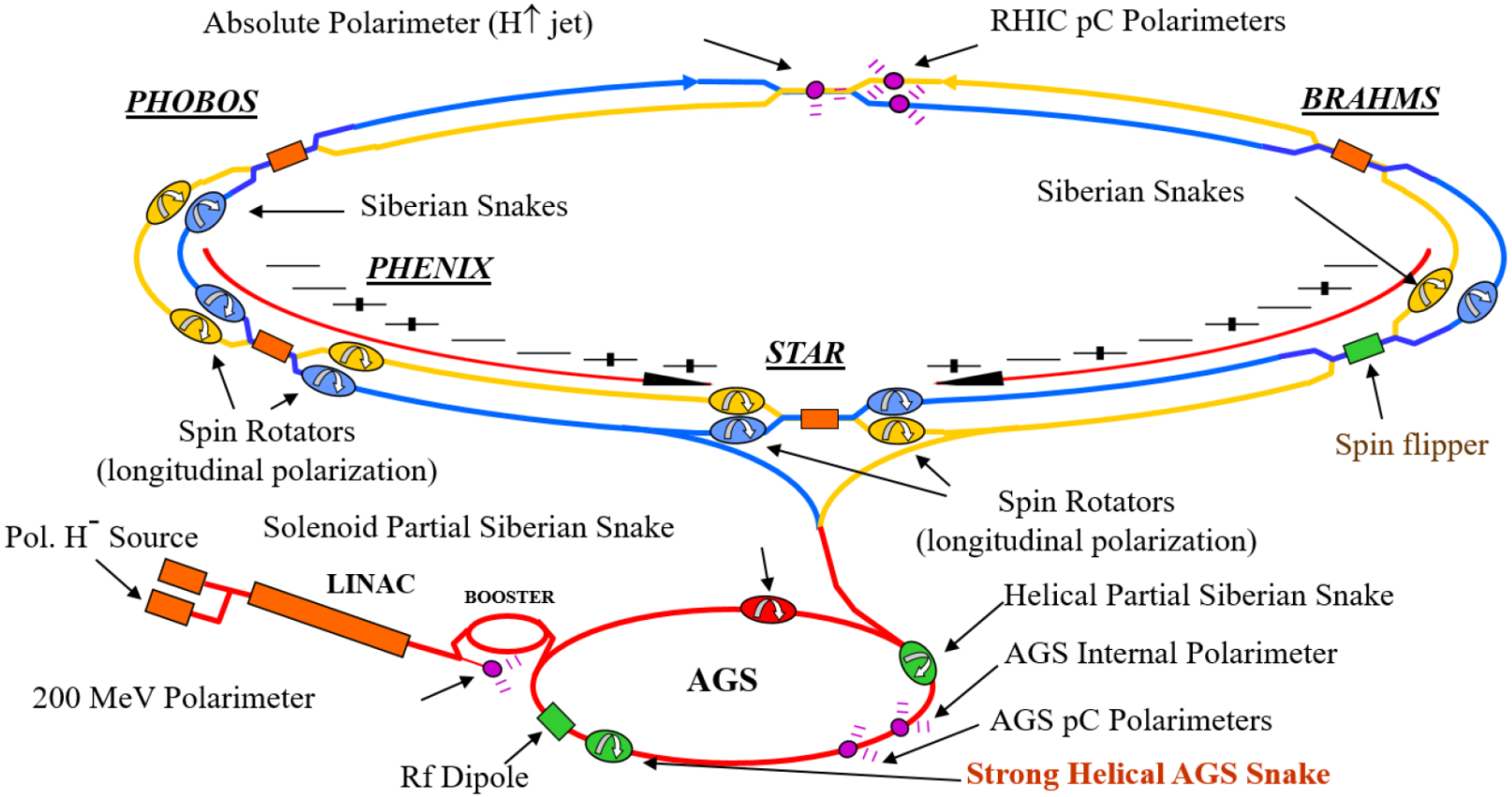
$$d\sigma_{pp\to jet+X} = \sum_{ab} \int f_a(x_1, Q^2) f_b(x_2, Q^2) d\hat{\sigma}_{a+b\to jet+X}(x_1, x_2, Q^2) dx_1 dx_2$$

Universality



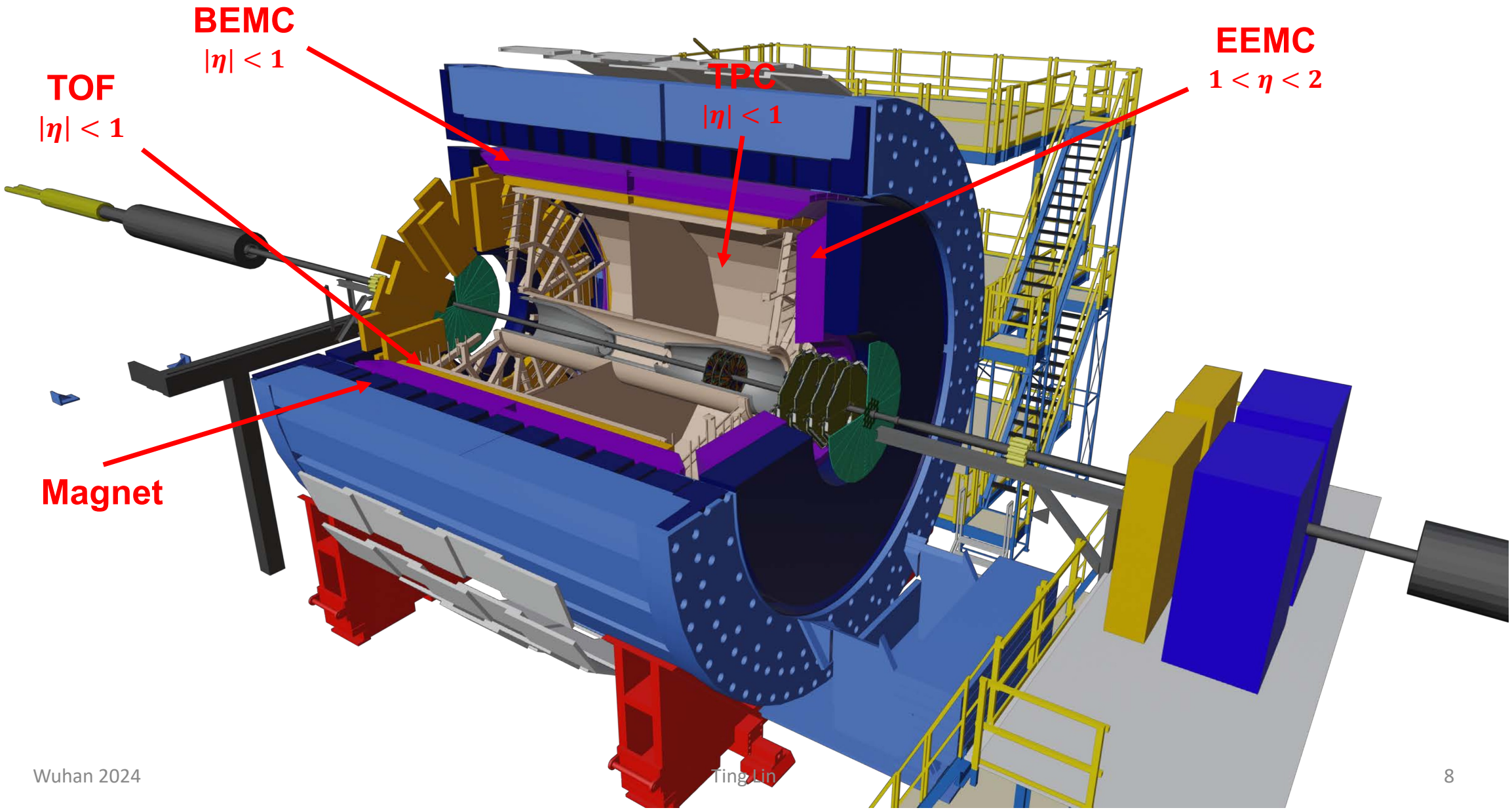
Relativistic Heavy Ion Collider (RHIC)

Relativistic Heavy Ion Collider (RHIC)



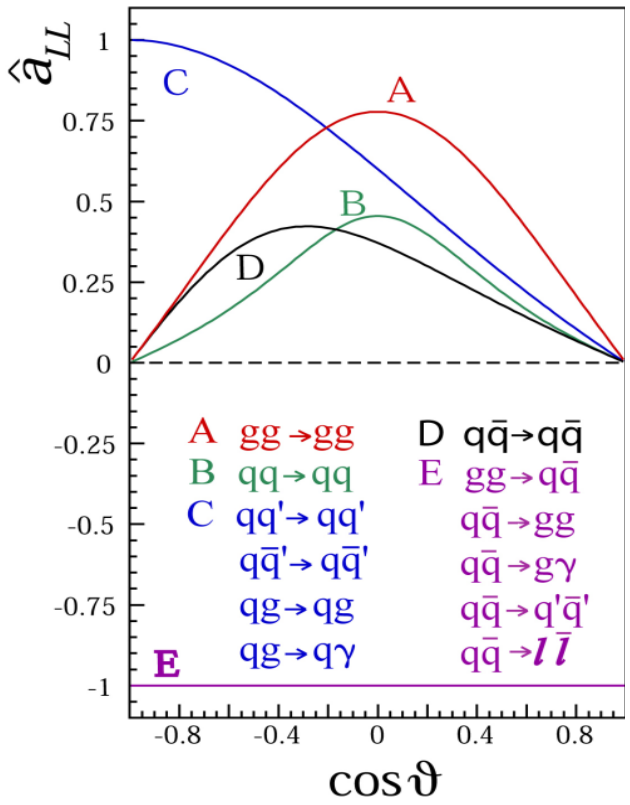
- Spin pattern changes from fill to fill with little depolarization;
- Siberian snakes preserve the polarization;
- Spin rotators select spin orientation;
- proton-Carbon (pC) polarimeters and hydrogen gas jet (H-Jet) measure the polarization.

Solenoidal Tracker At RHIC (STAR)



Probing the Gluon Helicity at RHIC

John Babcock *et al.* Phys.Rev.D 19, 1483 (1979)



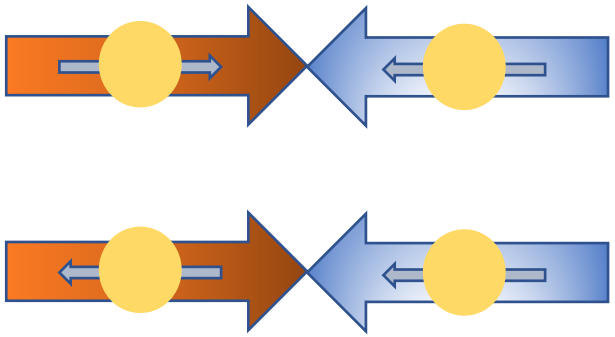
What we measured

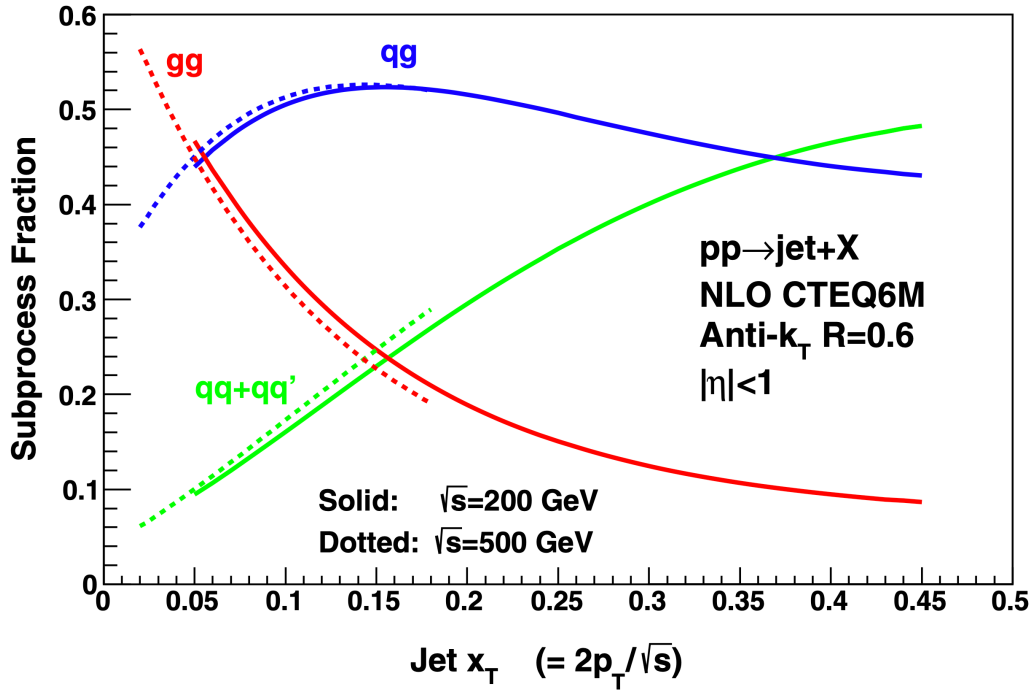
What we hope to learn

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \sim \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

Measured by others

Calculable

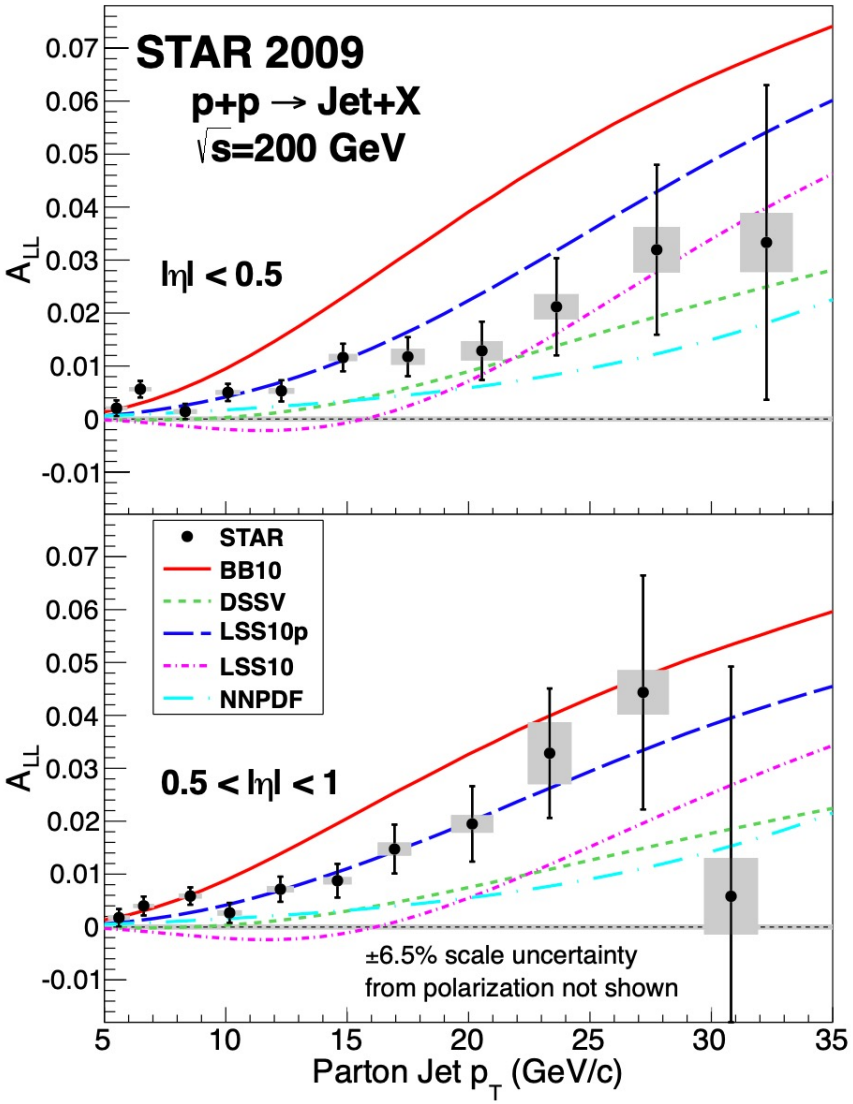




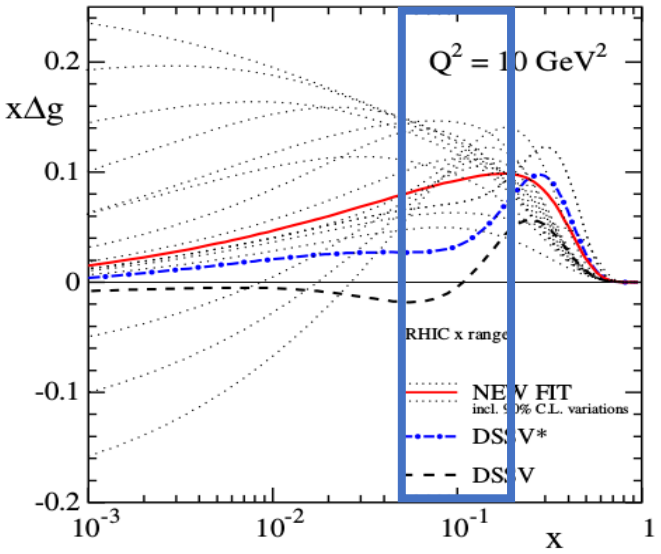
- At the parton level, helicity correlations are very large in leading-order QCD;
- For most RHIC kinematics, gg and qg dominate, making A_{LL} sensitive to gluon polarization.

Evidence of Positive ΔG

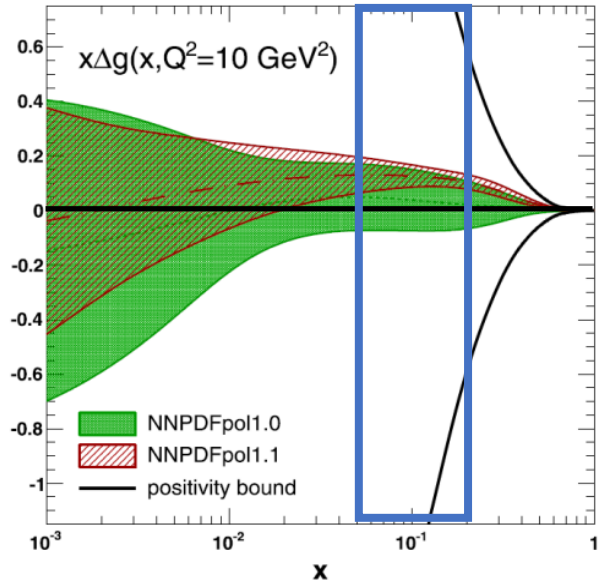
STAR, PRL **115**, 092002 (2015)



DSSV, PRL 113, 012001(2014)



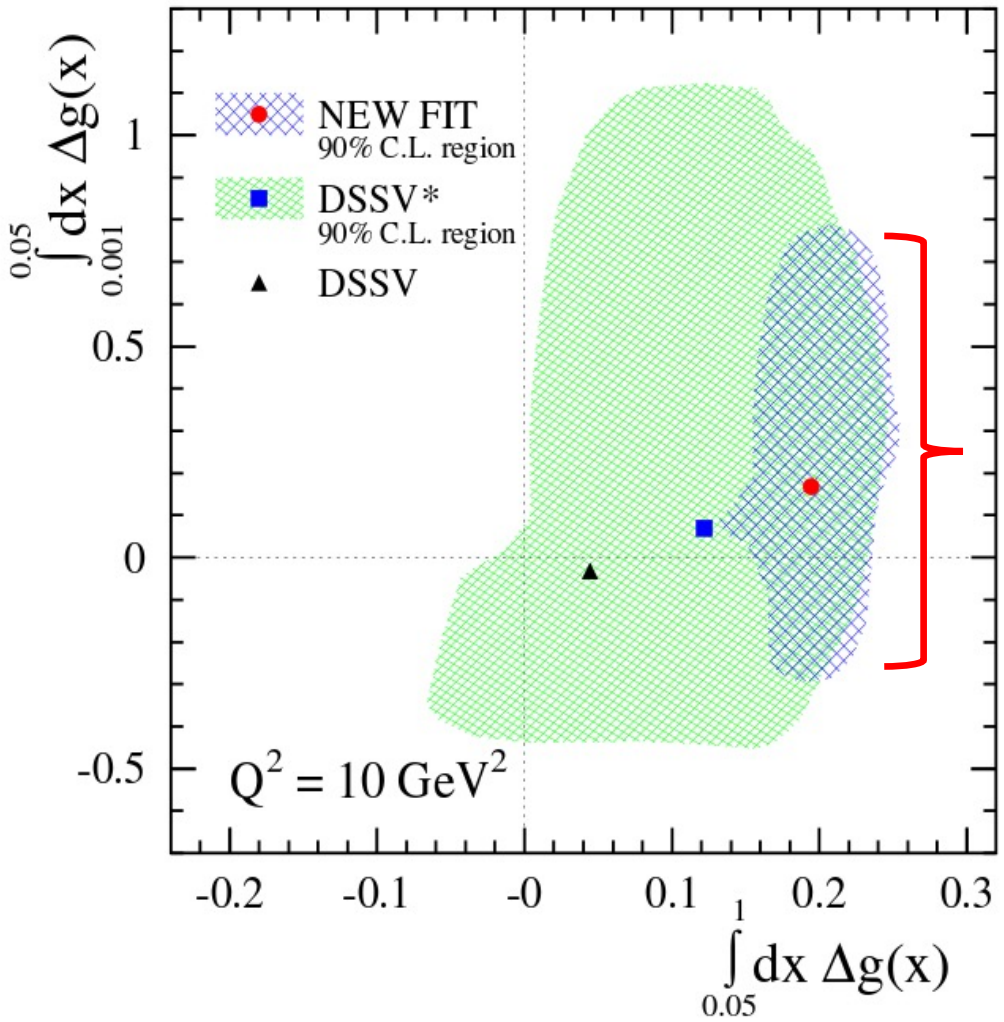
NNPDF, Nucl. Phys. B 887, 276 (2014)



- Both DSSV and NNPDF have performed new polarized PDF fits;
- Both find the **2009 RHIC results provide significantly tighter constraints on gluon polarization;**
- Both find **evidence for positive gluon polarization** in the region $x > 0.05$:
  - NNPDF: $\Delta G = \int_{0.05}^{0.5} \Delta g(x)dx = 0.23 \pm 0.06$
  - DSSV: $\Delta G = \int_{0.05}^{1} \Delta g(x)dx = 0.20 \pm 0.06$

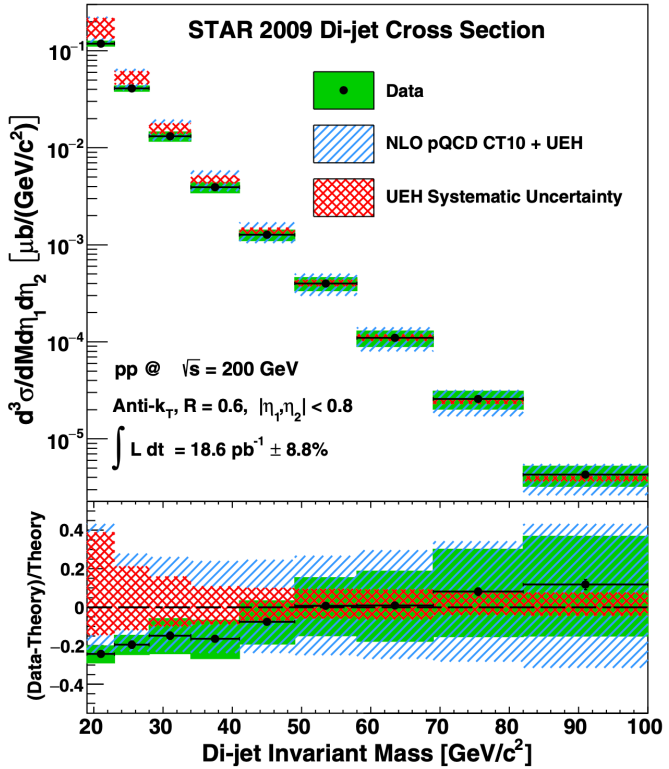
Gluon Polarization with RHIC Data

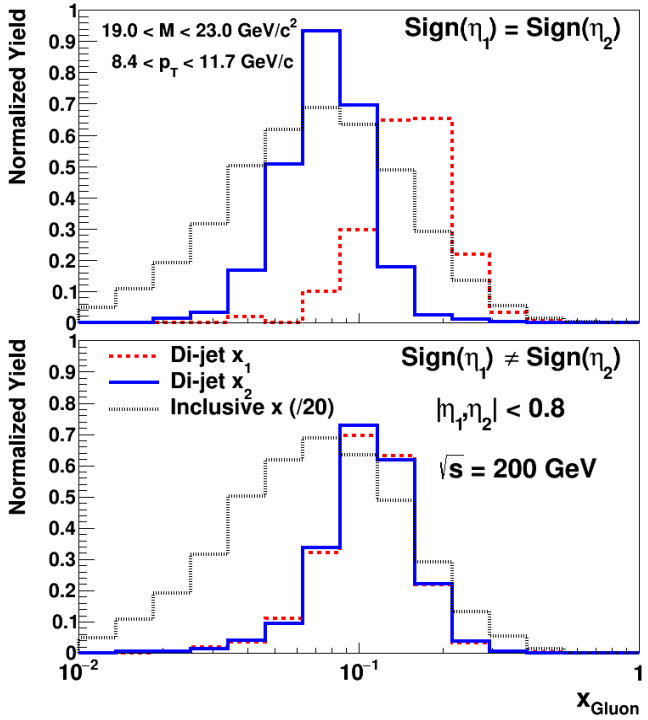
DSSV PRL 113, 012001(2014)



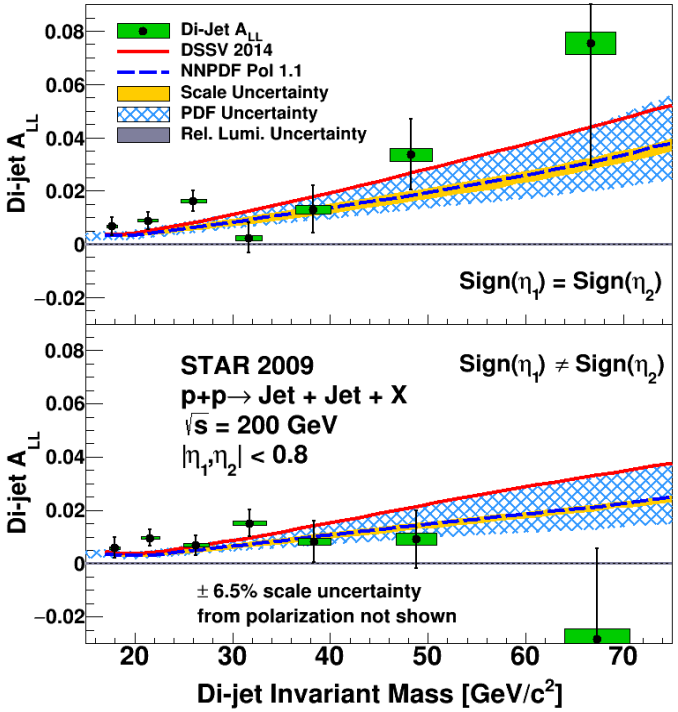
- The low x behavior and shape of Δg(x) are still poorly constrained:
  - $\Delta G = \int_{0.05}^{1} \Delta g(x) dx \ = 0.20 \pm 0.06$
  - $\Delta G = \int_{0.001}^{0.05} \Delta g(x) dx = 0.15 \pm 0.50$
- STAR's strategies to explore low-*x* regime:
  1. Extend to dijet measurement;
  2. Reconstruct jet at higher η;
  3. Increase the integrated luminosity of data;
  4. Take data with higher collision energy.

Mid-Rapidity Dijet A_{LL}



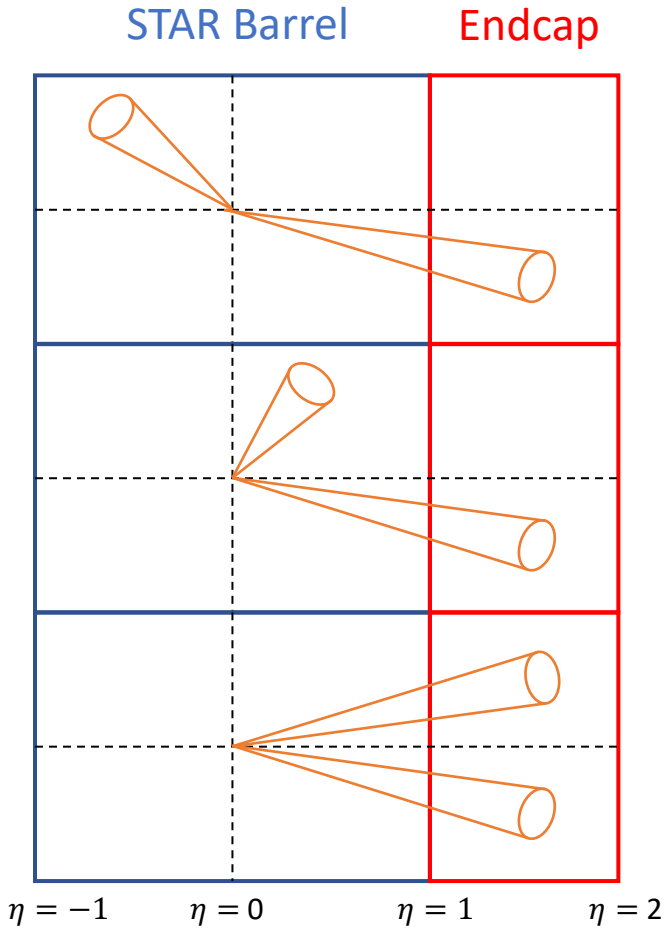


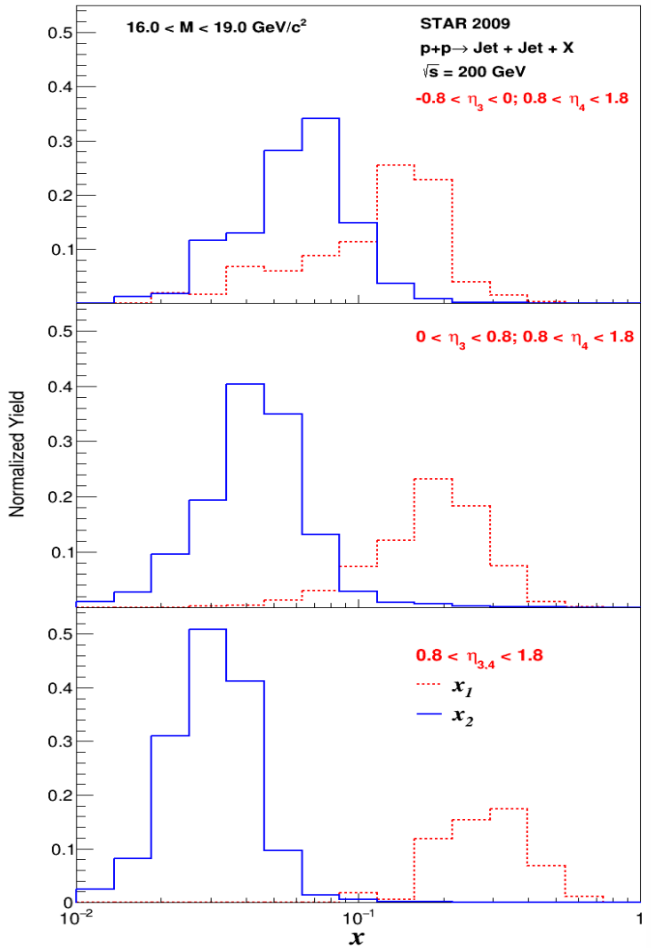
STAR, Phys. Rev. D 95, 071103 (2017)



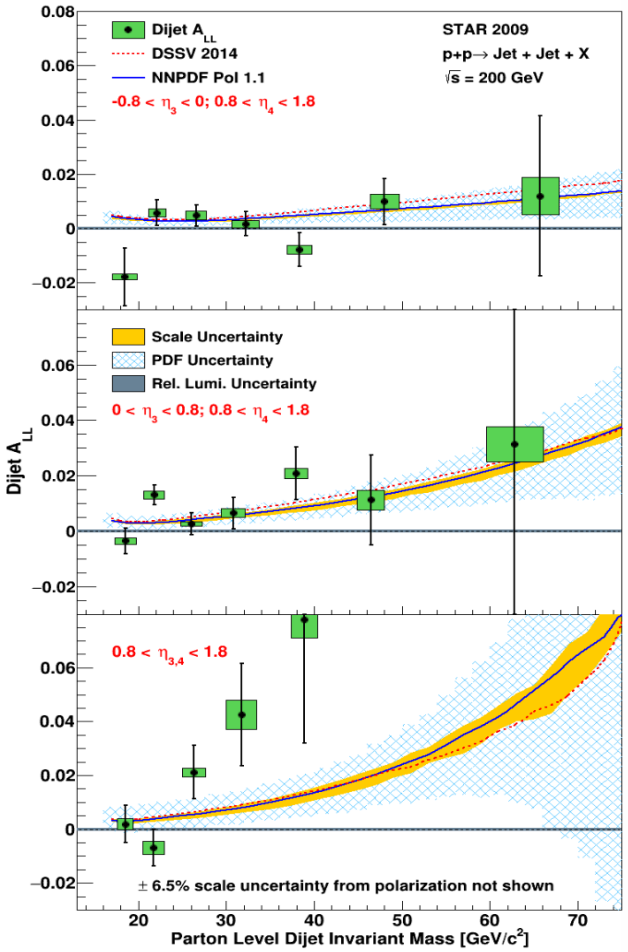
- Dijet measurements capture more information from the hard scattering and provide a more direct link to the initial parton level kinematics than inclusive measurements;
- Mid-rapidity di-jet A_{LL} presented for two topologies as a function of di-jet invariant mass corrected to parton level;
- Data compared to expectations from DSSV14 and NNPDFpol1.1 polarized PDFs, both contain 2009 inclusive jet results.

Intermediate Rapidity Dijet A_{LL}



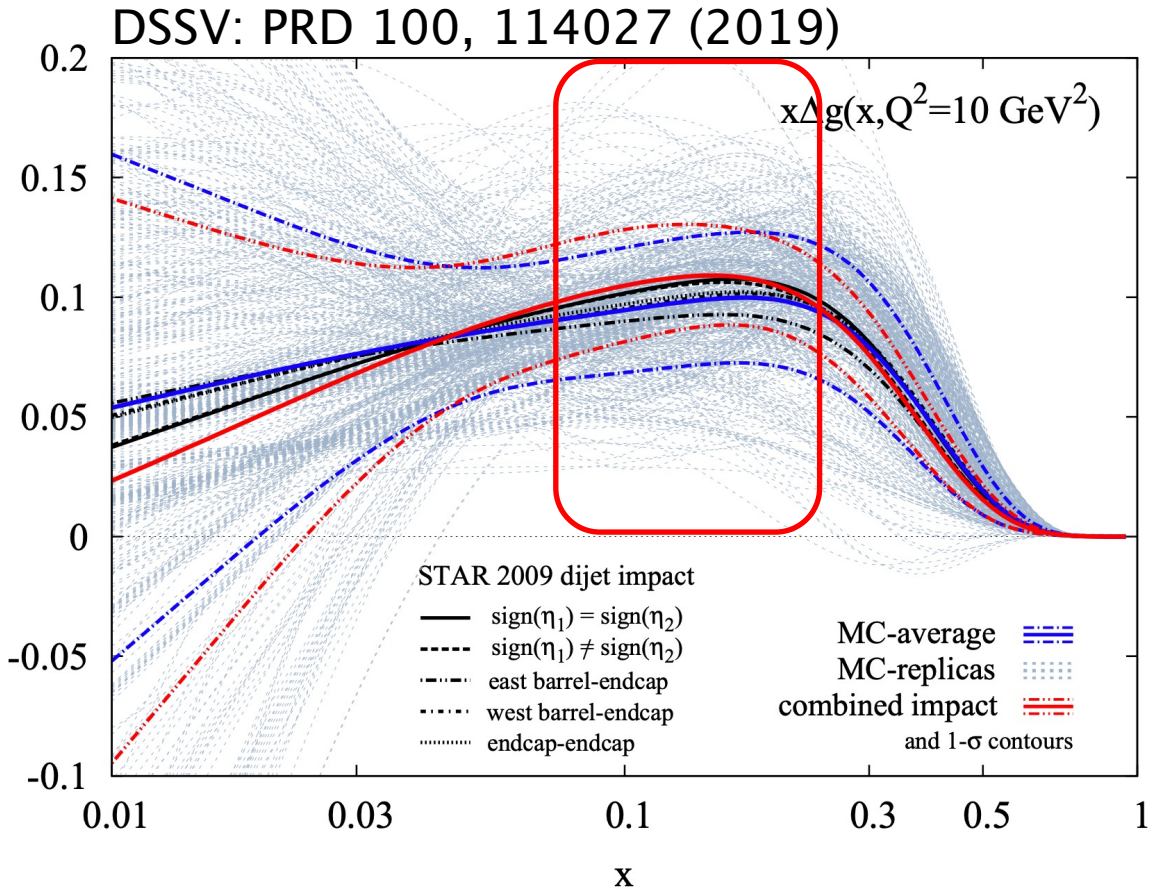


STAR, Phys. Rev. D 98, 032011 (2018)



- Adding the Endcap opens up several new dijet topologies;
- Forward jets probe lower values of gluon momentum fraction while selecting more asymmetric collisions.

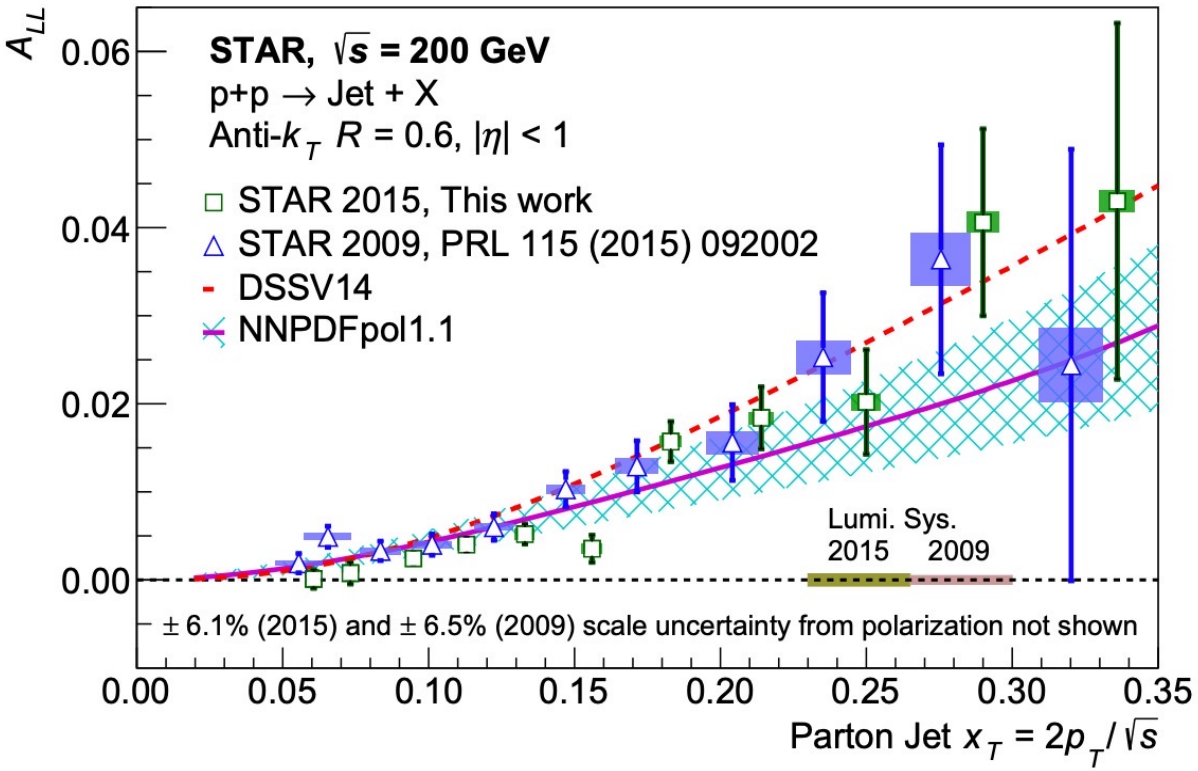
Impact of the Dijet Results:



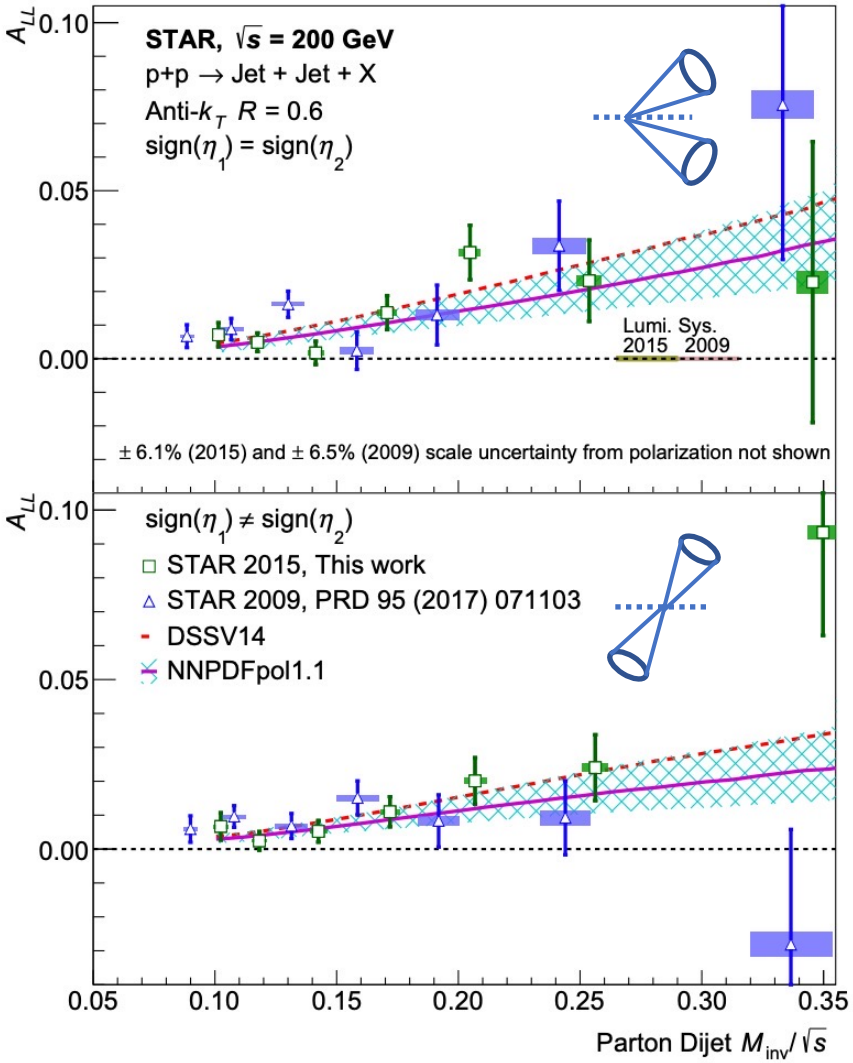
- Gluon polarization in the region ***x* > 0.1**:
  - before: $\Delta G = \int_{0.1}^{1} \Delta g(x)dx = 0.133 \pm 0.035$
  - after: $\Delta G = \int_{0.1}^{1} \Delta g(x)dx = 0.126 \pm 0.023$
- In the region ***x* > 0.01**:
  - before: $\Delta G = \int_{0.01}^{1} \Delta g(x)dx = 0.309 \pm 0.109$
  - after: $\Delta G = \int_{0.01}^{1} \Delta g(x)dx = 0.296 \pm 0.108$

New A_{LL} Results at 200 GeV

STAR, PRD 103 (2021) L091103



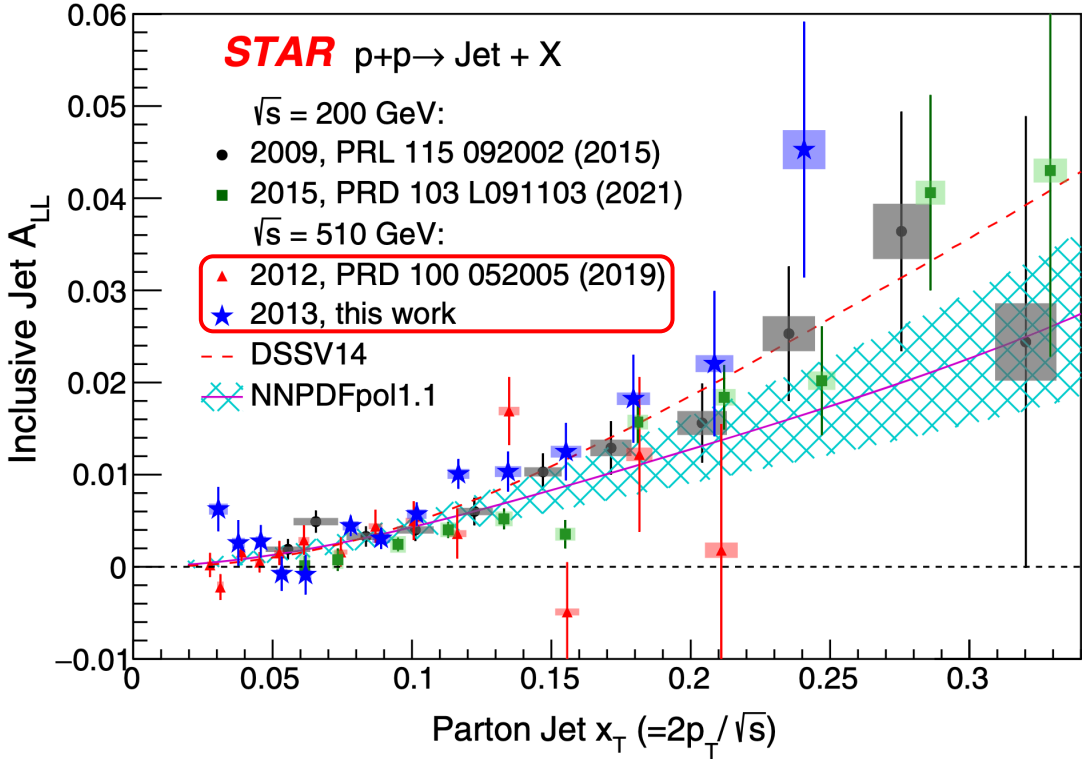
Year and $\sqrt{s}$	STAR L $[pb^{-1}]$
$\sqrt{s} = 200$ GeV	
2009	25
2015	52
$\sqrt{s} = 510$ GeV	
2012	82
2013	300



- Consistent with 2009 data, which provided first evidence for positive ΔG for x > 0.05;
- Improved statistical and systematic uncertainties;
- Will significantly reduce uncertainty on gluon polarization for x > 0.05 once included in global fits.

A_{LL} Results at 510 GeV

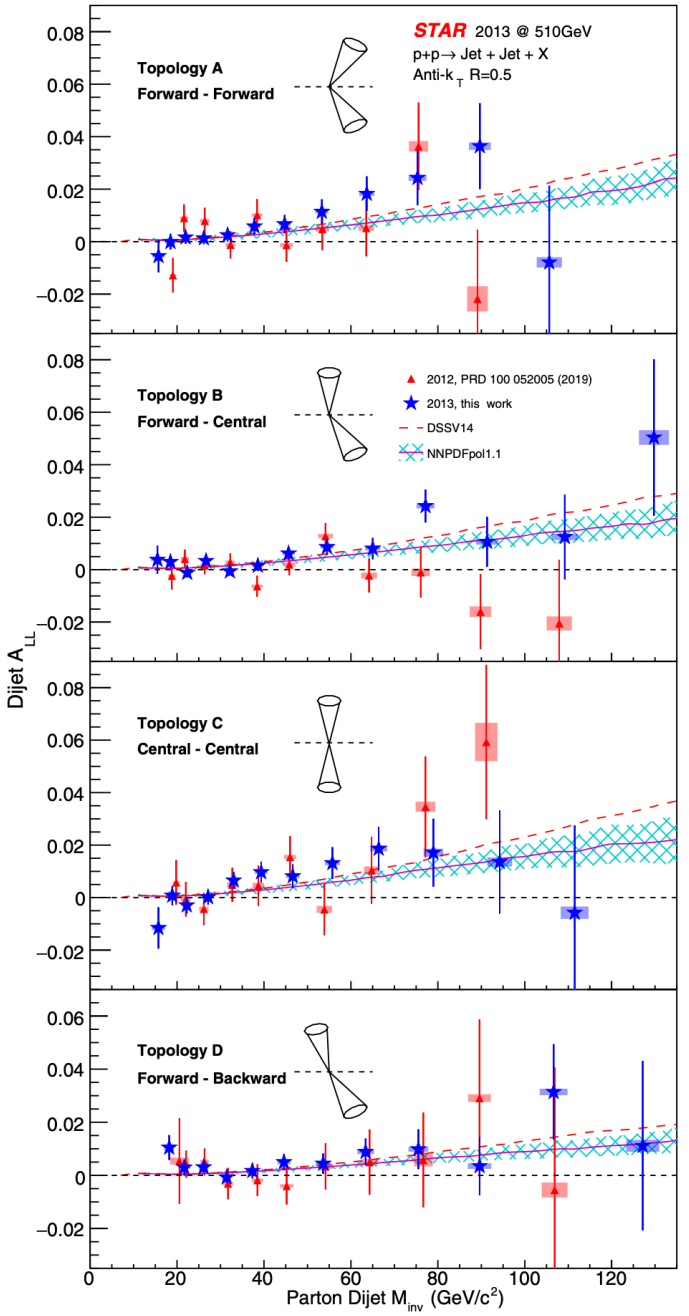
STAR, PRD 100, 052005 (2019)
STAR, PRD 105, 092011 (2022)



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

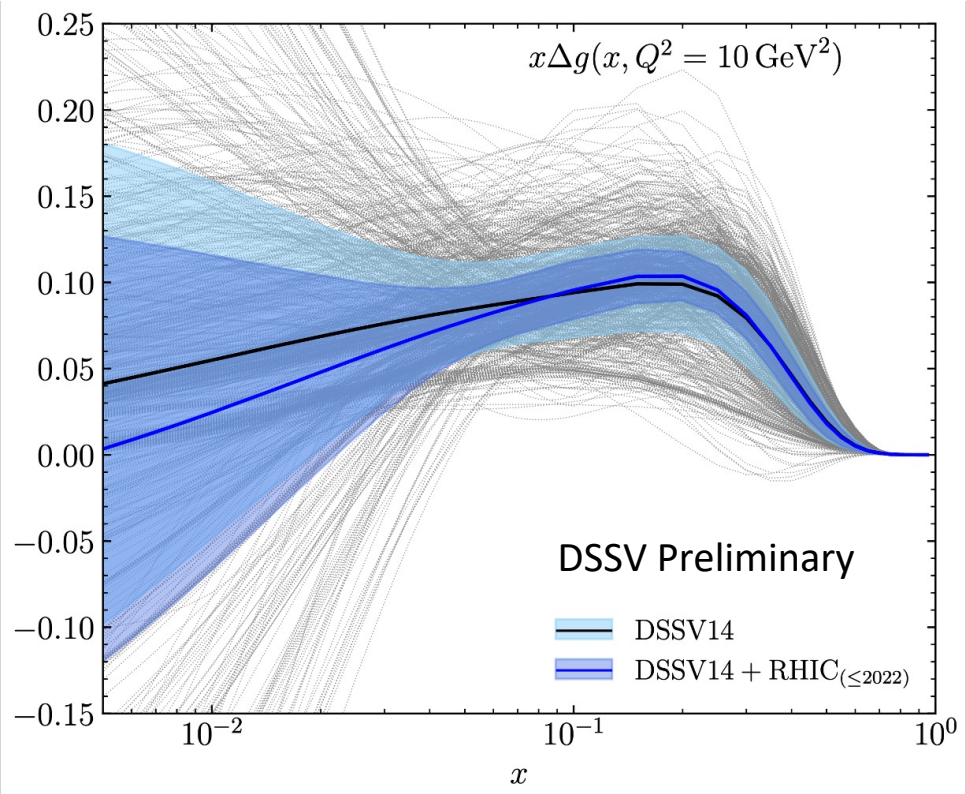
$$x_2 \sim \frac{1}{\sqrt{s}}\left(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4}\right)$$

Year and $\sqrt{s}$	STAR L $[pb^{-1}]$
$\sqrt{s} = 200$ GeV	
2009	25
2015	52
$\sqrt{s} = 510$ GeV	
2012	82
2013	300

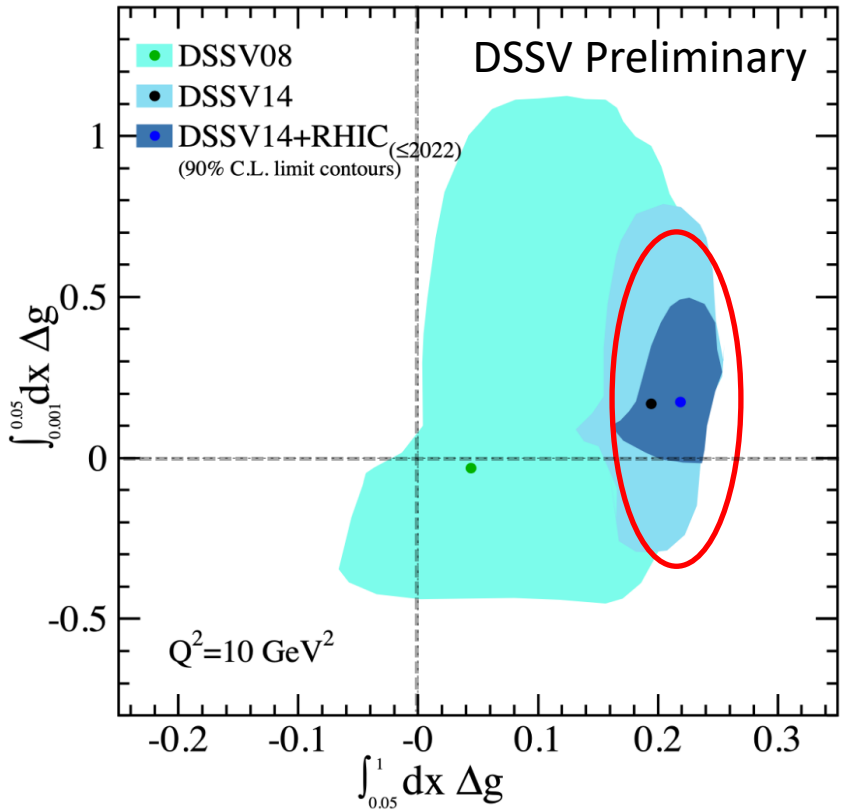


- Higher center-of-mass energy probes lower x partons;
- Plotted vs x_T , overall consistency seen among STAR data sets;
- Well described by global fits that previously gave a good description of the 200 GeV results.

Impact of the RHIC Results



The RHIC Cold QCD Program, arXiv:2302.00605

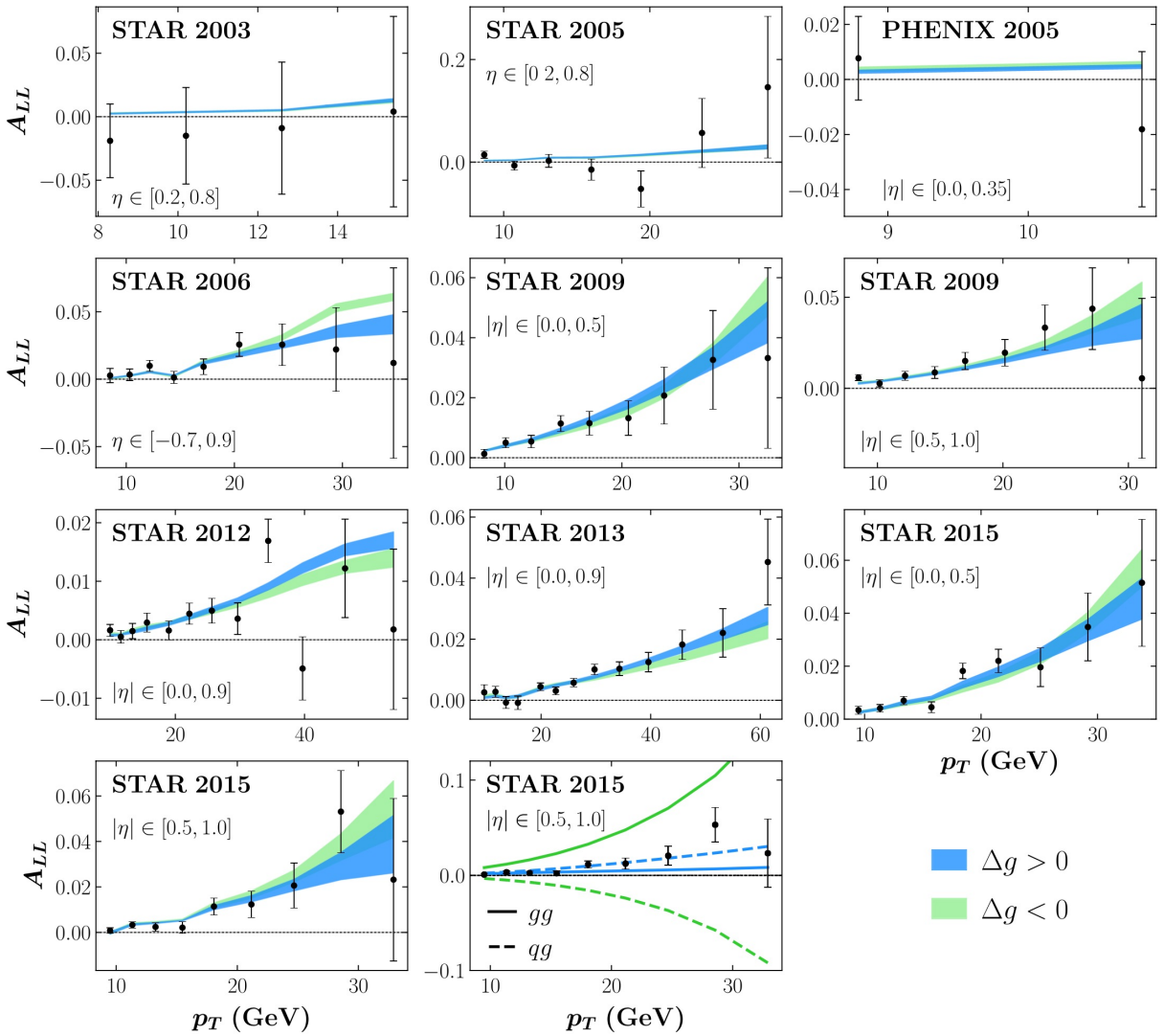


DSSV14 + RHIC (≤2022):

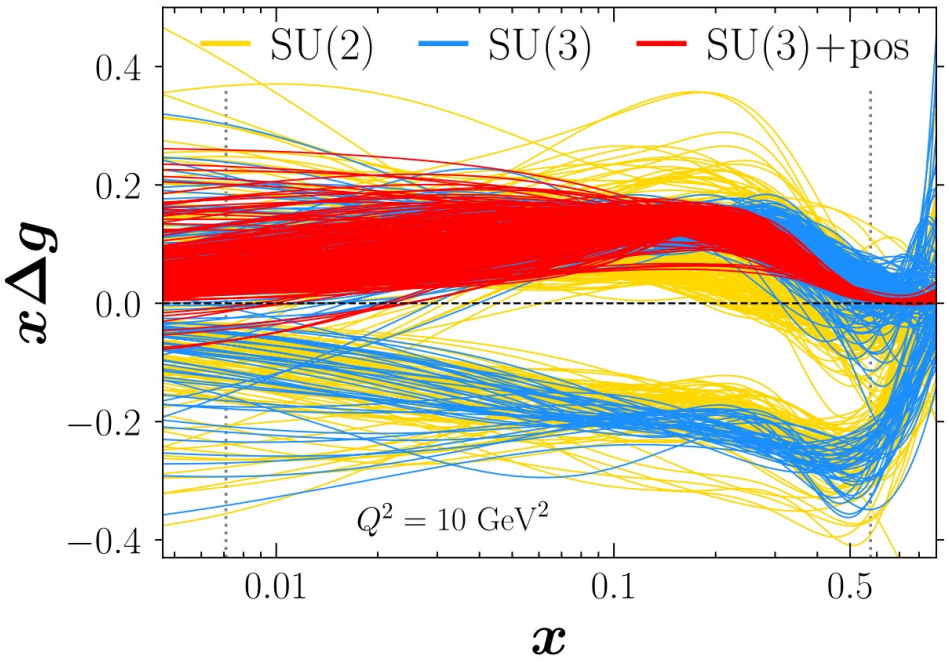
- $\Delta G = \int_{0.05}^{1} \Delta g(x) dx = 0.22 \pm 0.03$
- $\Delta G = \int_{0.001}^{0.05} \Delta g(x) dx = 0.17 \pm 0.20$

- New results from RHIC shows significant impact when constraining the gluon helicity distribution;

Negative Gluon Polarization?



Y. ZHOU, N. SATO, and W. MELNITCHOUK, PRD 105, 074022 (2022)

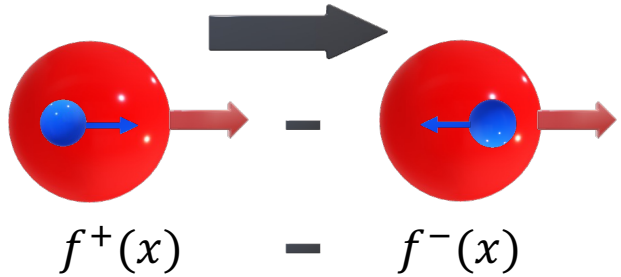


- Negative gluon polarization can also describe the STAR inclusive jet results well.

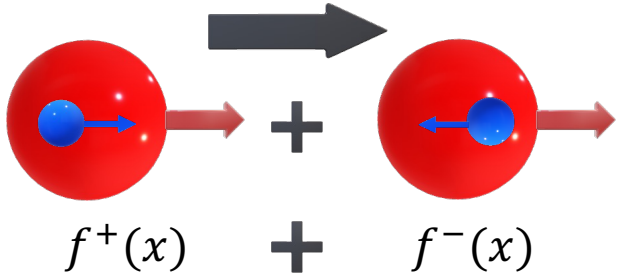
The Positivity Constraint

$$|\Delta f_i(x, Q^2)| < f_i(x, Q^2)$$

- Helicity PDF, $\Delta f(x) =$



- Unpolarized PDF, $f(x) =$

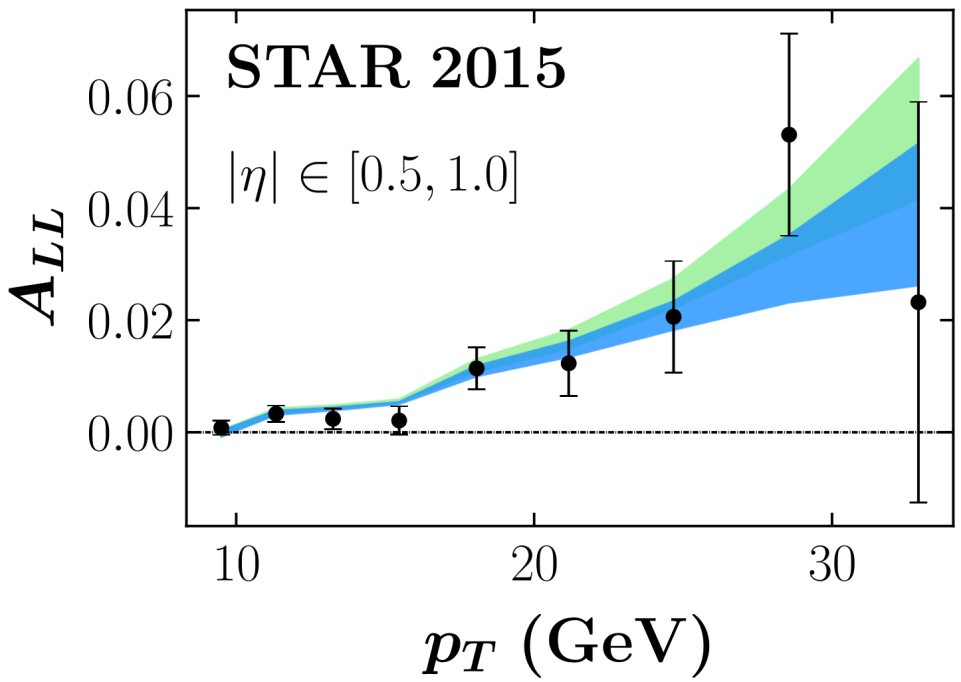


- The positivity bound naturally come from definitions in terms of the probabilistic interpretation;

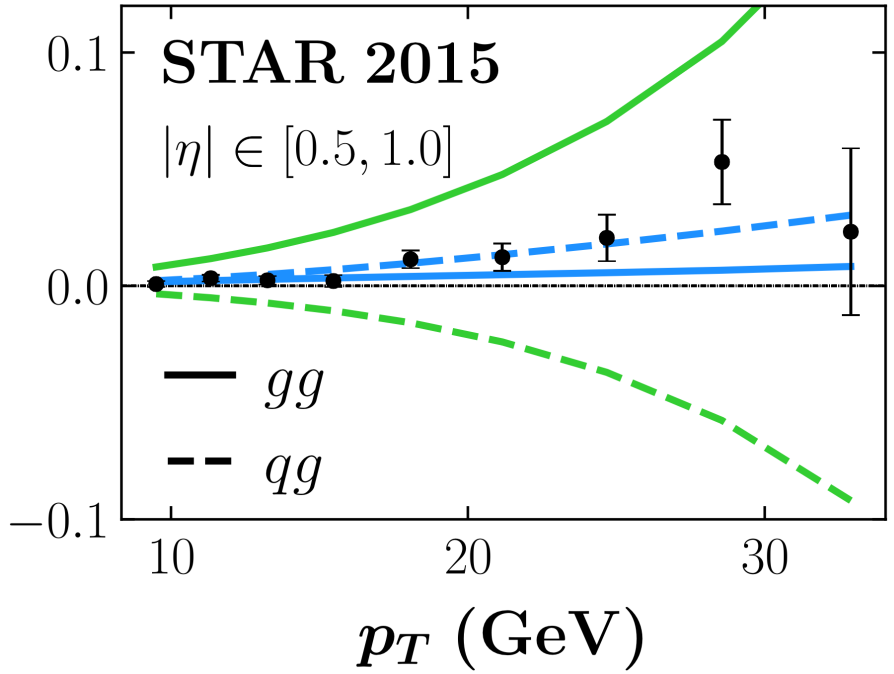
G. Altarelli, S. Forte, and G. Ridolfi, Nucl. Phys. B 534, 277 (1998)

- At leading order:
  - $f_1^{(0)}(\xi) = \frac{1}{4\pi}\int dy^- e^{-i\xi P^+ y^-}\langle P|\bar{\psi}_i(0, y^-, 0)\gamma^+\psi_i(0)|P\rangle$
  - $g_{1L}^{(0)}(\xi) = \frac{1}{8\pi}\int dy^- e^{-i\xi P^+ y^-}\langle P, +|\bar{\psi}_i(0, y^-, 0)\gamma^+\gamma_5\psi_i(0)|P, +\rangle - \langle P, -|\bar{\psi}_i(0, y^-, 0)\gamma^+\gamma_5\psi_i(0)|P, -\rangle$

How does it work?



Y. ZHOU, N. SATO, and W. MELNITCHOUK, PRD 105, 074022 (2022)



- The positive asymmetry from the gluon-gluon process offsets the negative asymmetry from quark-gluon scattering, ensuring a final asymmetry above zero.

Not Favor by Several Analysis

Daniel de Florian et.al., PRD 109, 074007 (2024)

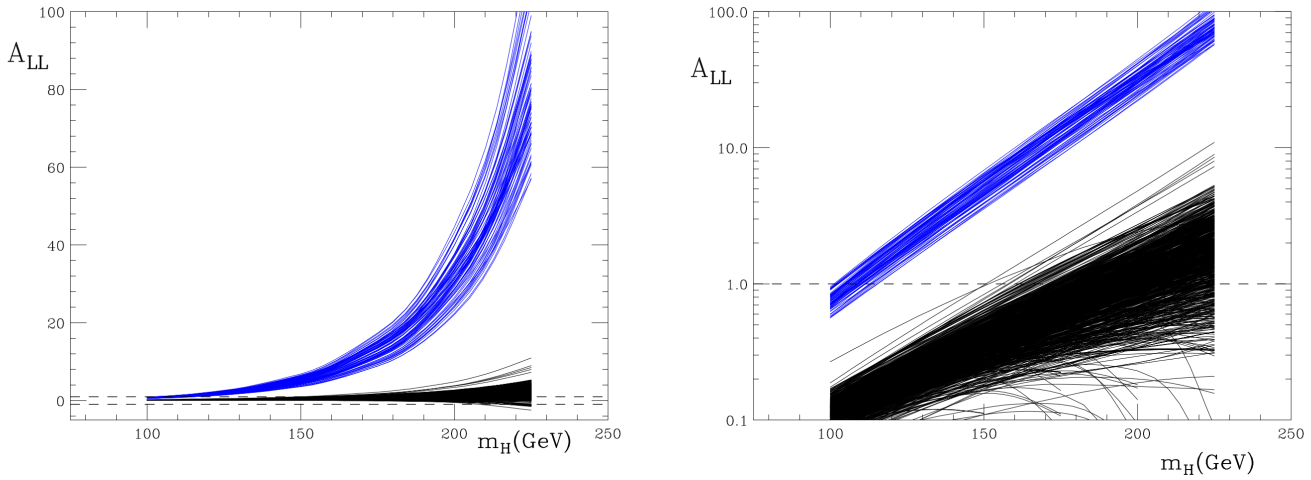
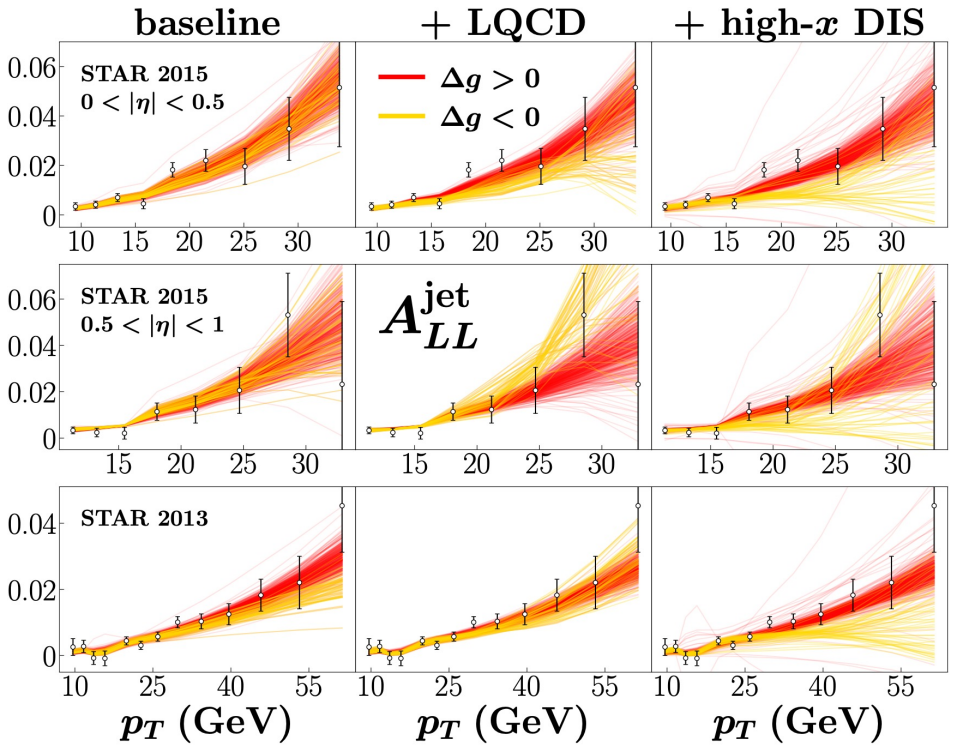


Figure 2: *Double-helicity asymmetry for Higgs production at RHIC ($\sqrt{s} = 510$ GeV) plotted as a function of the Higgs mass, with a linear (left) or logarithmic (right) scale on the vertical axis. The upper bands show A_{LL} as obtained for the gluon distribution shown in Fig. 1, while the lower bands provide the corresponding result for the sets of [7] with $\Delta g \geq 0$. In both plots, the dashed lines show the physical limit given by $|A_{LL}| = 1$.*

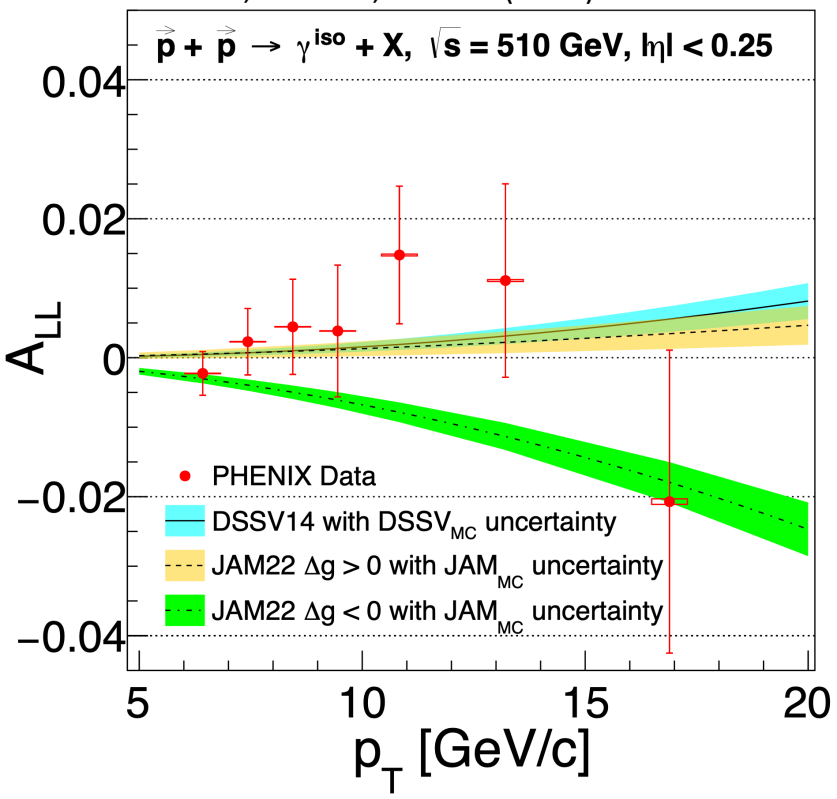
N. T. Hunt-Smith et.al. arXiv:2403.08117 [hep-ph]



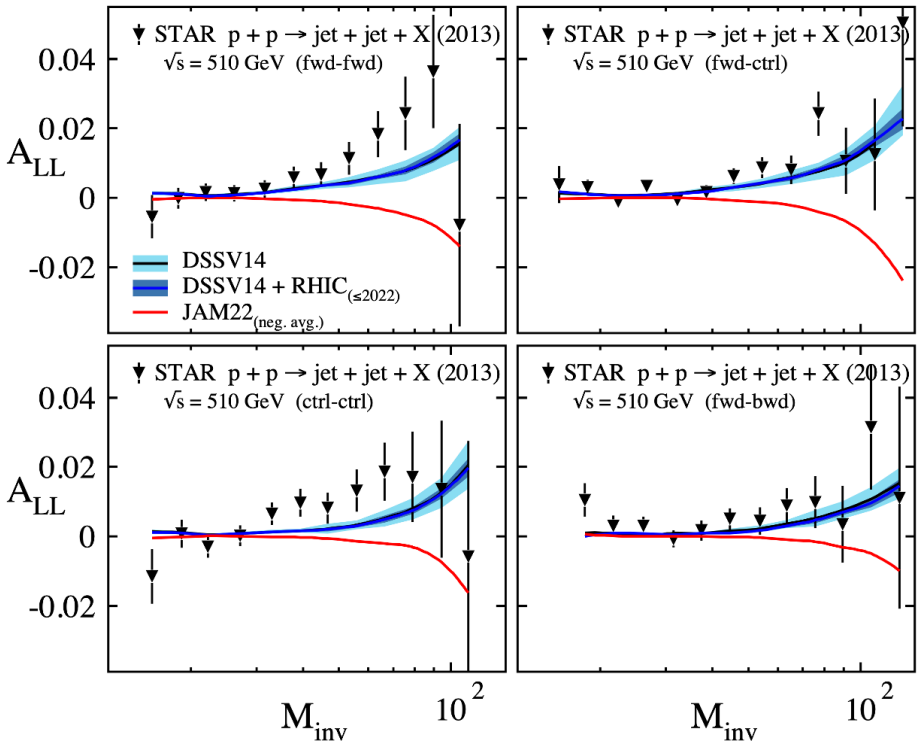
- Violation of the positivity bounds could exhibit hard processes with unacceptable negative cross-sections, for example, the Higgs boson production;
- Negative gluon polarization solution cannot simultaneously account for high-x polarized DIS data along with lattice and polarized jet data.

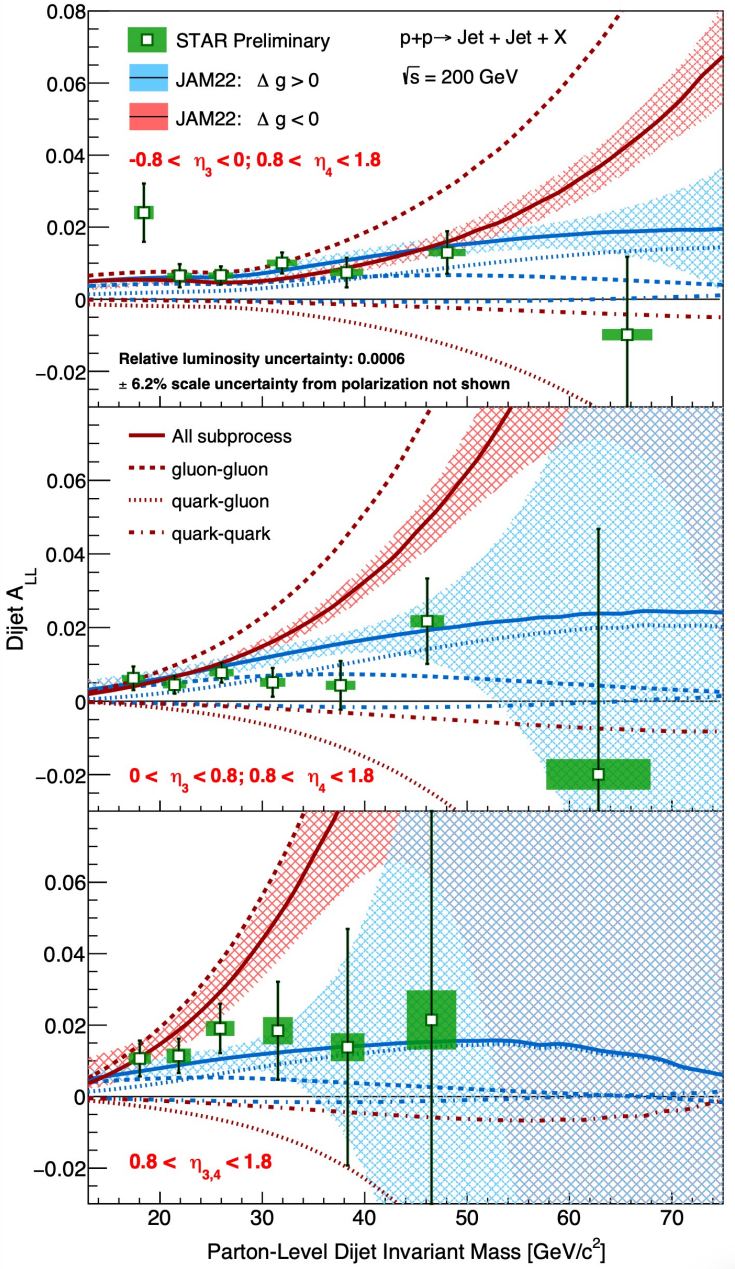
Not Favor by RHIC Data

PHENIX, PRL 130, 251901 (2023)



The RHIC Cold QCD Program, arXiv:2302.00605





- Both PHENIX direct photon and STAR dijet results disfavor the distributions with large and negative gluon polarization.

Proton Spin Puzzle Solved?

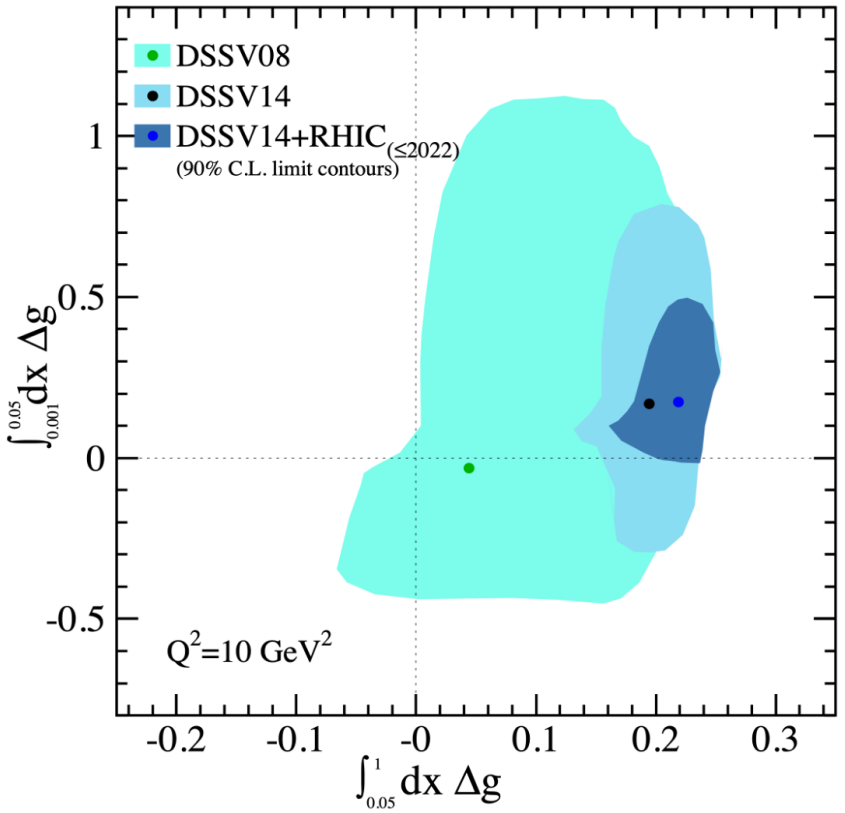
Enormous recent progress on helicity PDFs

- $\Delta\Sigma = \int_{0.01}^{1} \Delta q(x) dx = 0.43 \pm 0.08$
- $\Delta G = \int_{0.01}^{1} \Delta g(x) dx = 0.3 \pm 0.1$

Werner Vogelsang, Spin2023

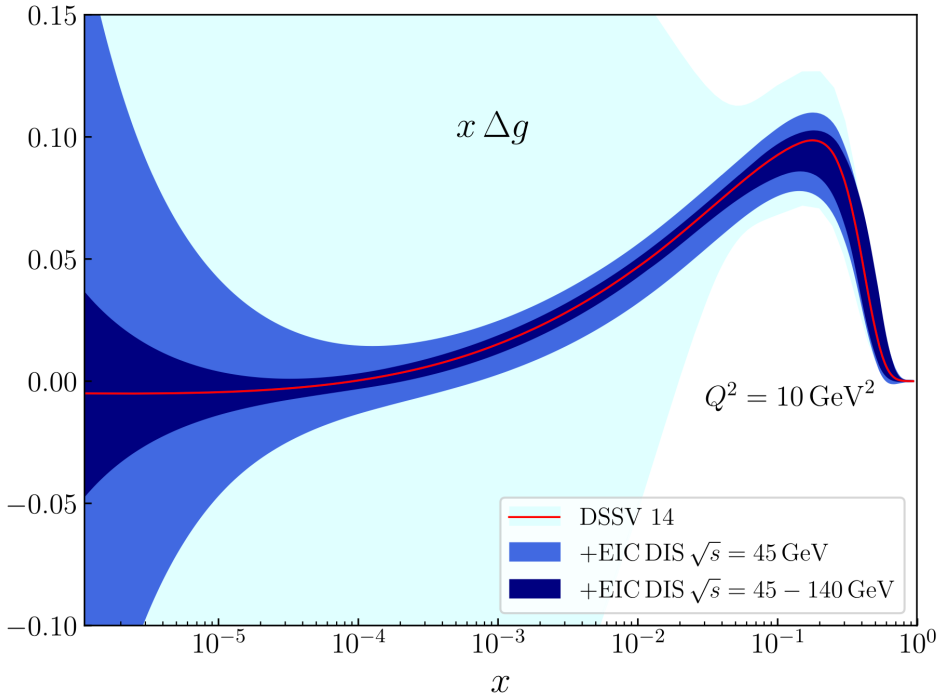
$$\langle S_z^p \rangle = \frac{1}{2}\Delta\Sigma + \Delta G = 0.515 \pm 0.108$$

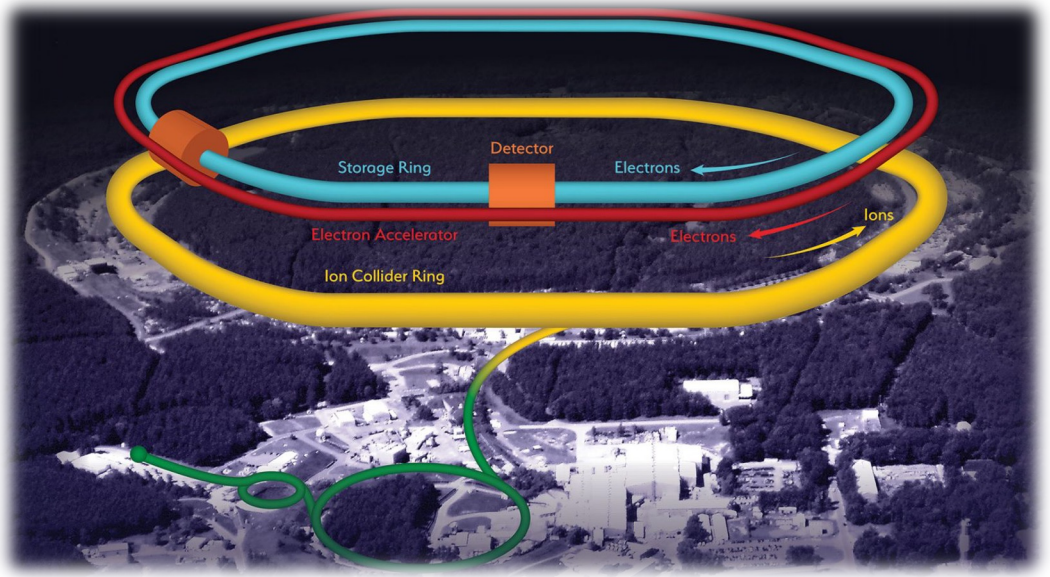
The RHIC Cold QCD Program, arXiv:2302.00605

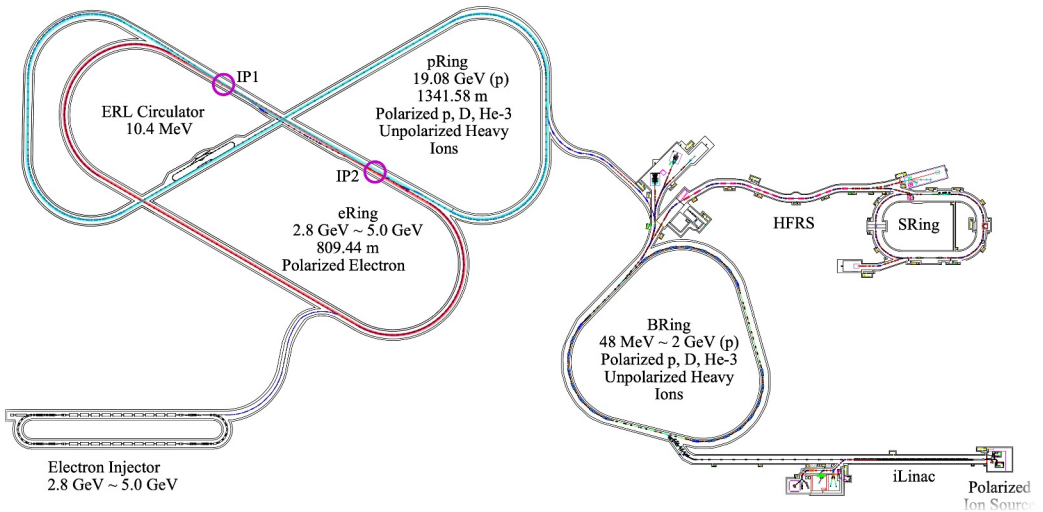


Outlook

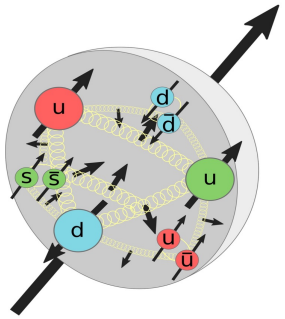
Ignacio Borsa , Gonzalo Lucero, and Rodolfo Sassot PRD 102, 094018 (2020)







Summary



- STAR has demonstrated non-zero gluon polarizations in the proton from a series of measurements of inclusive jet and dijet A_{LL};
- As indicated by recent global fits, especially the DSSV group, gluons contribute about 40% of the total proton spin at x > 0.05;
- After about 20 years, the longitudinally polarized p+p program concluded with the last measurement at 200GeV in 2015 and at 510GeV in 2013, which will be revisited in the future EIC/EicC.