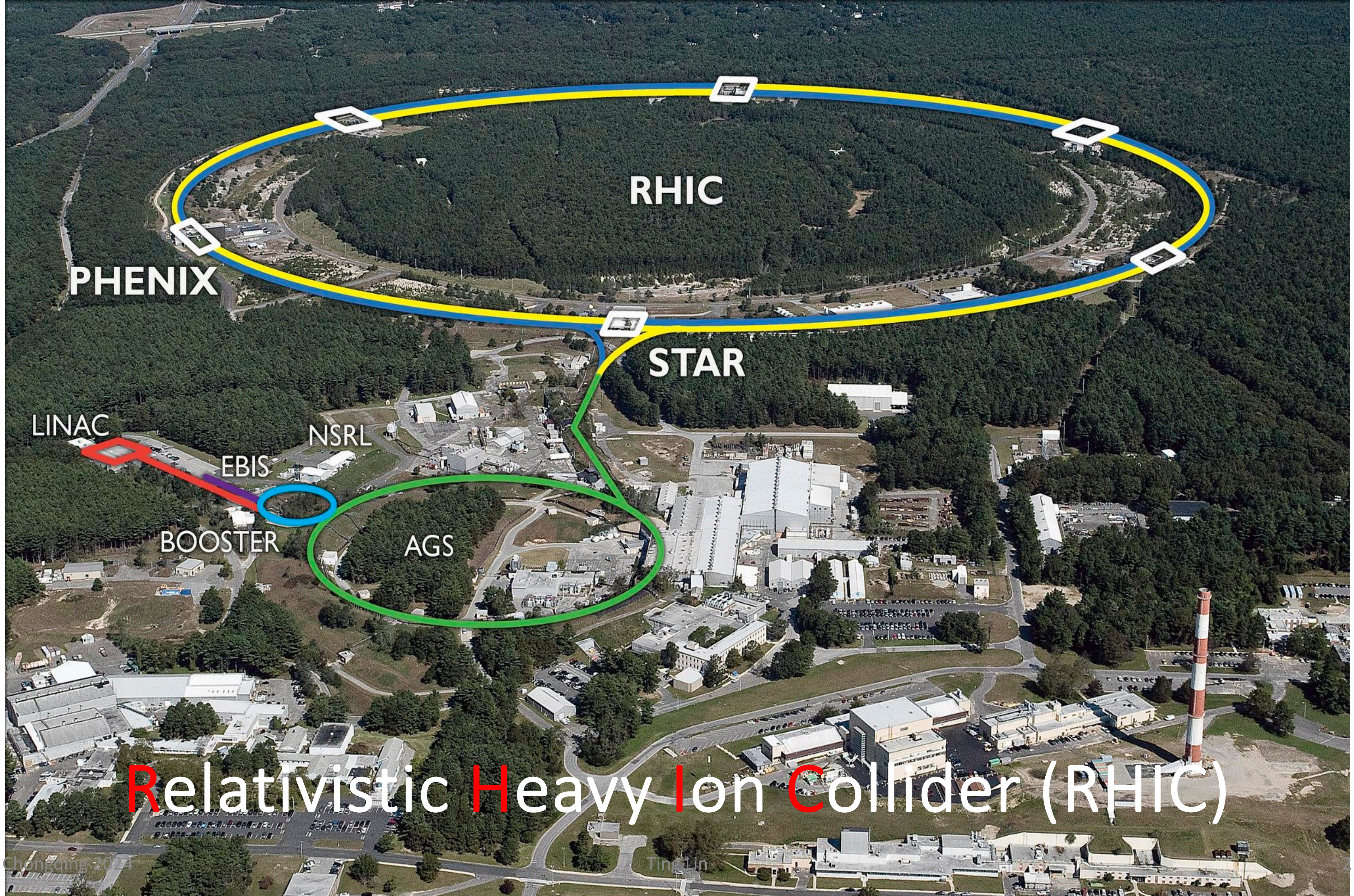
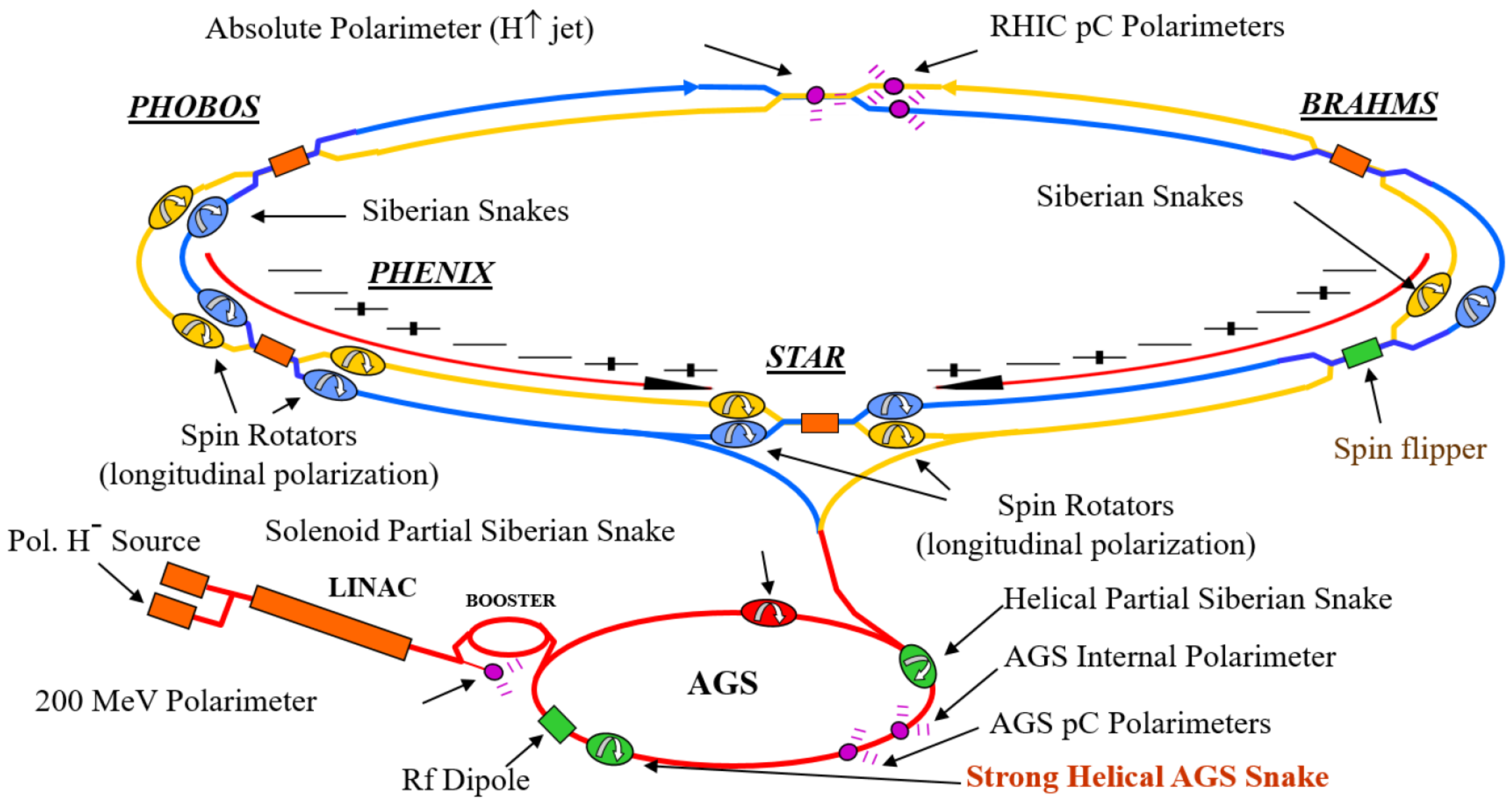
STAR 区域研讨会
Oct 10 – 15, 2024
重庆大学虎溪校区

Constraining the Gluon Helicity at STAR

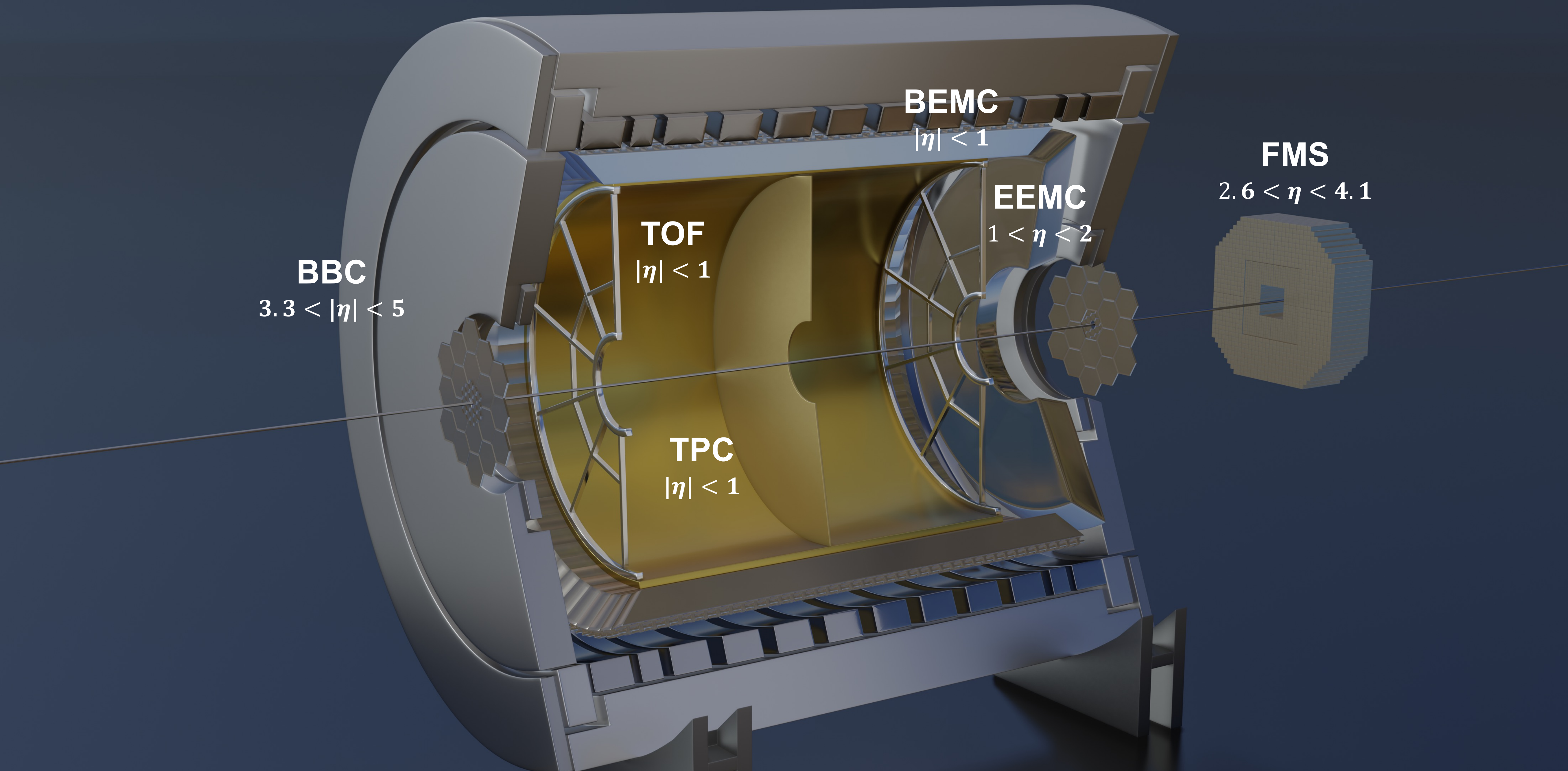
Ting Lin (林挺)
Shandong University (山东大学)


RHIC
PHENIX
STAR
LINAC
NSRL
EBIS
BOOSTER
AGS
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.

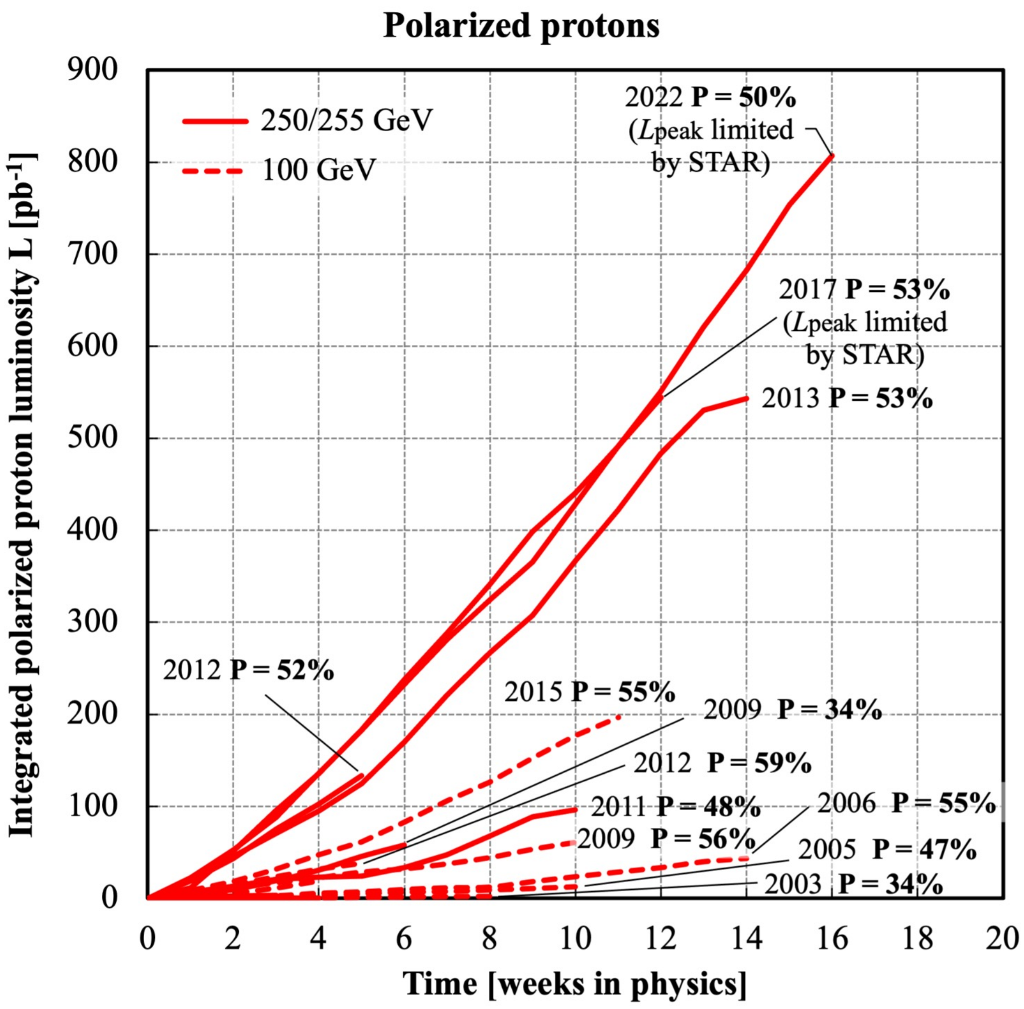


The Solenoidal Tracker At RHIC (STAR)

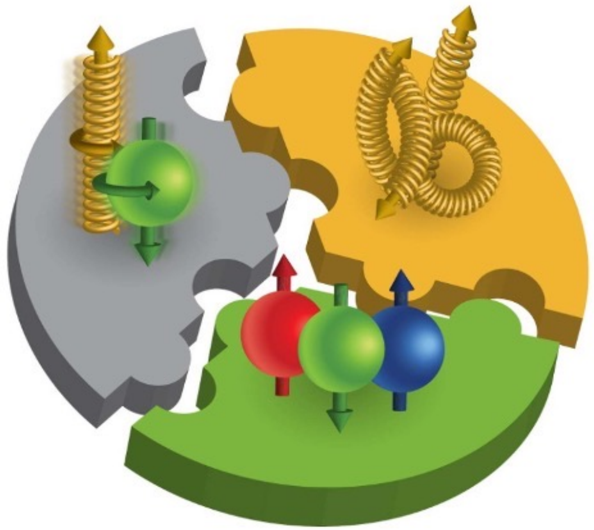
STAR Longitudinal Polarization Data

Year	2009	2009	2011	2012	2013	2015
$\sqrt{s}$ (GeV)	200	500	500	510	510	200
$L_{int}\ (pb^{-1})$	25	10	12	82	300	52
Polarization	55%	39%	48%	53%	55%	58%

- RHIC has concluded the longitudinal polarized data taking in 2015;
- Most STAR key measurements using the longitudinal polarized data have been published in the last few years, with few to be published soon.



Spin of the Proton

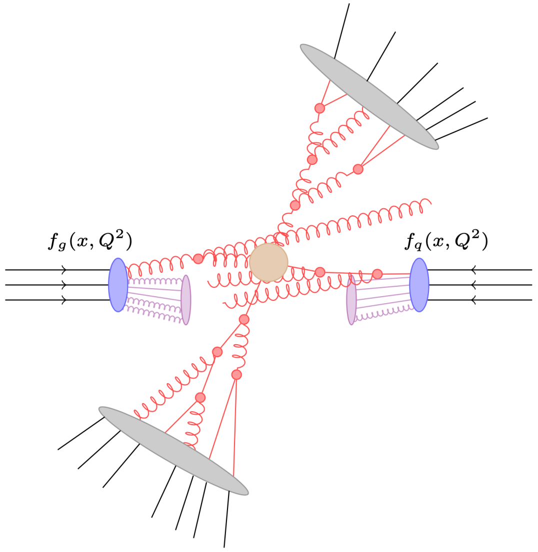


- For helicity distributions (collinear terms) in ‘canonical’ approach, the proton’s spin can be decomposed into:

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

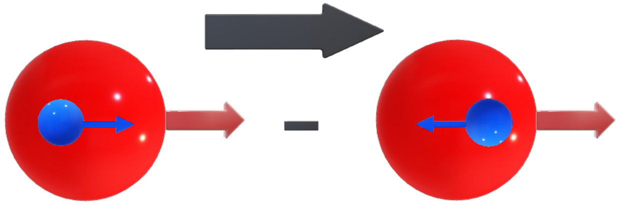
R. L. Jaffe and A. Manohar, NPB 337, 509 (1990)

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



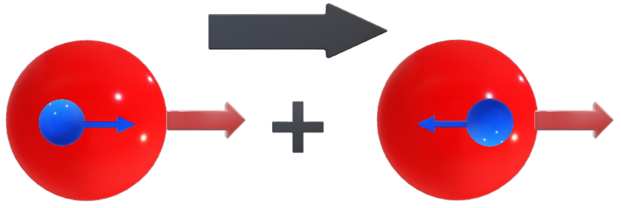
$$d\sigma_{pp\to jet+X} = \sum_{ab} \int f_a(x_1, Q^2) f_b(x_2, Q^2) d\hat{\sigma}_{a+b\to jet+X}(x_1, x_2, Q^2) dx_1 dx_2$$

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



$f^+(x)$ − $f^-(x)$

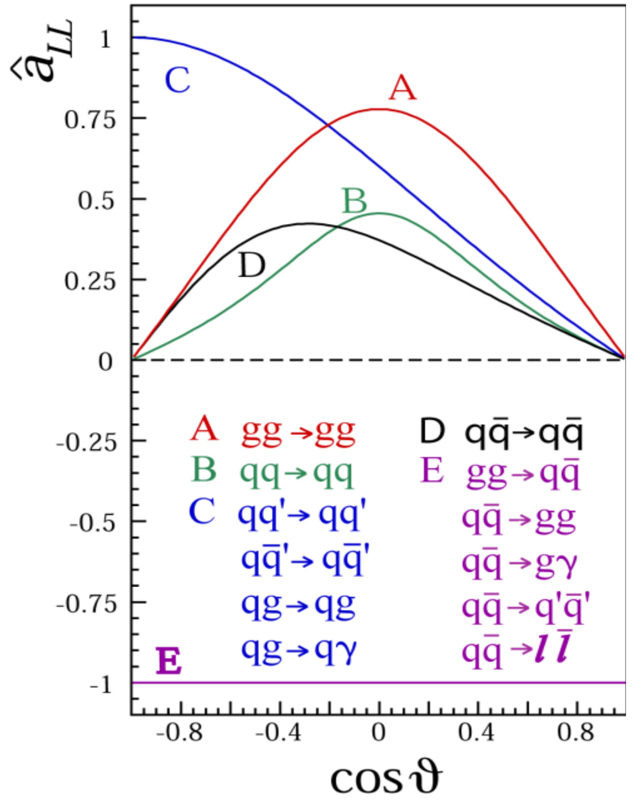
- Unpolarized PDF, $f(x) =$



$f^+(x)$ + $f^-(x)$

Probing the Gluon Helicity at RHIC

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



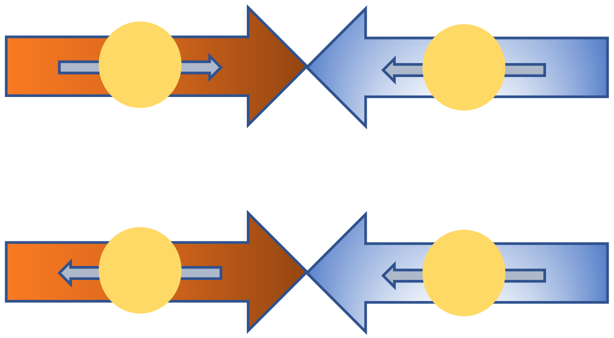
What we measured

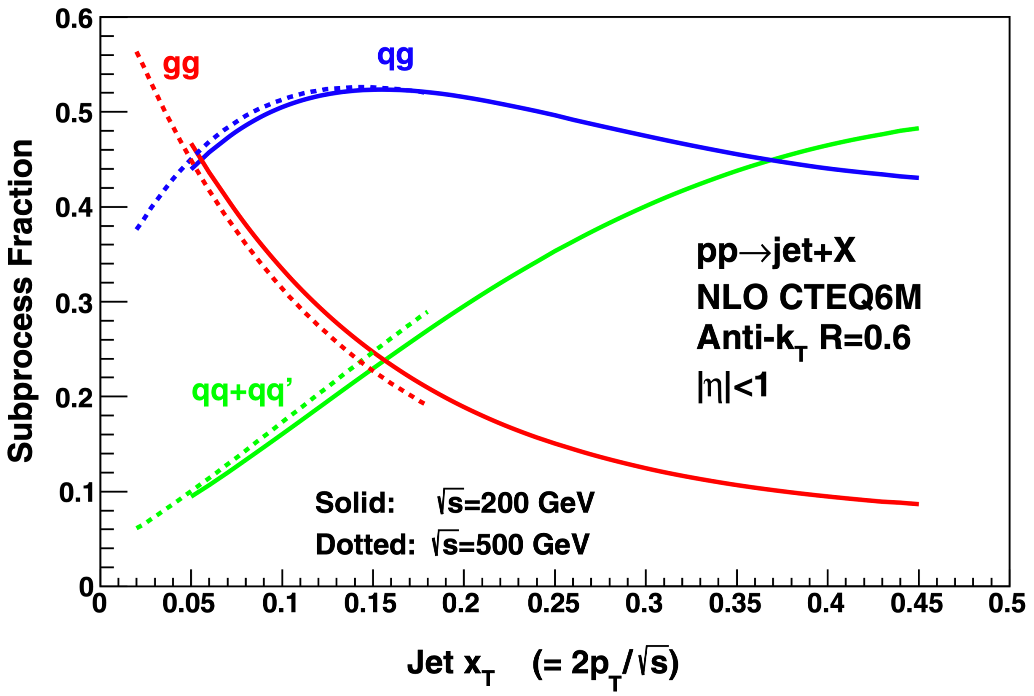
What we hope to learn

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

Measured by others

Calculable

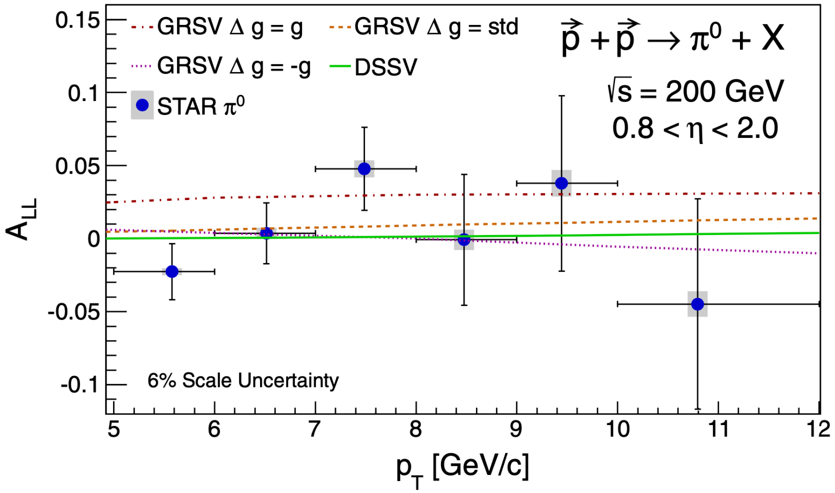


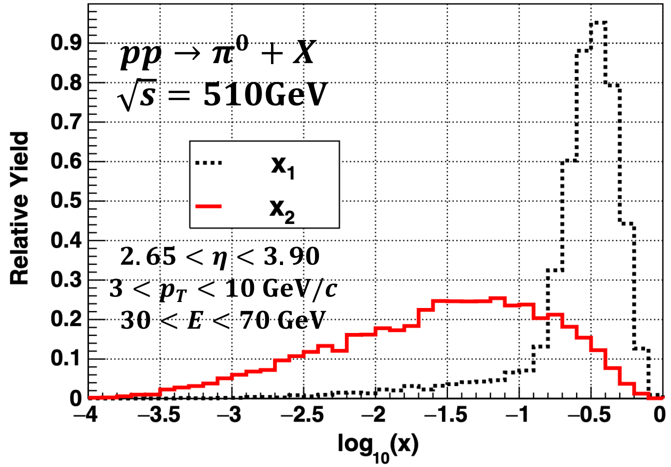


- At the parton level, helicity correlations are very large in leading-order QCD;
- For most RHIC kinematics, gg and qg dominate, making A_{LL} sensitive to gluon polarization.

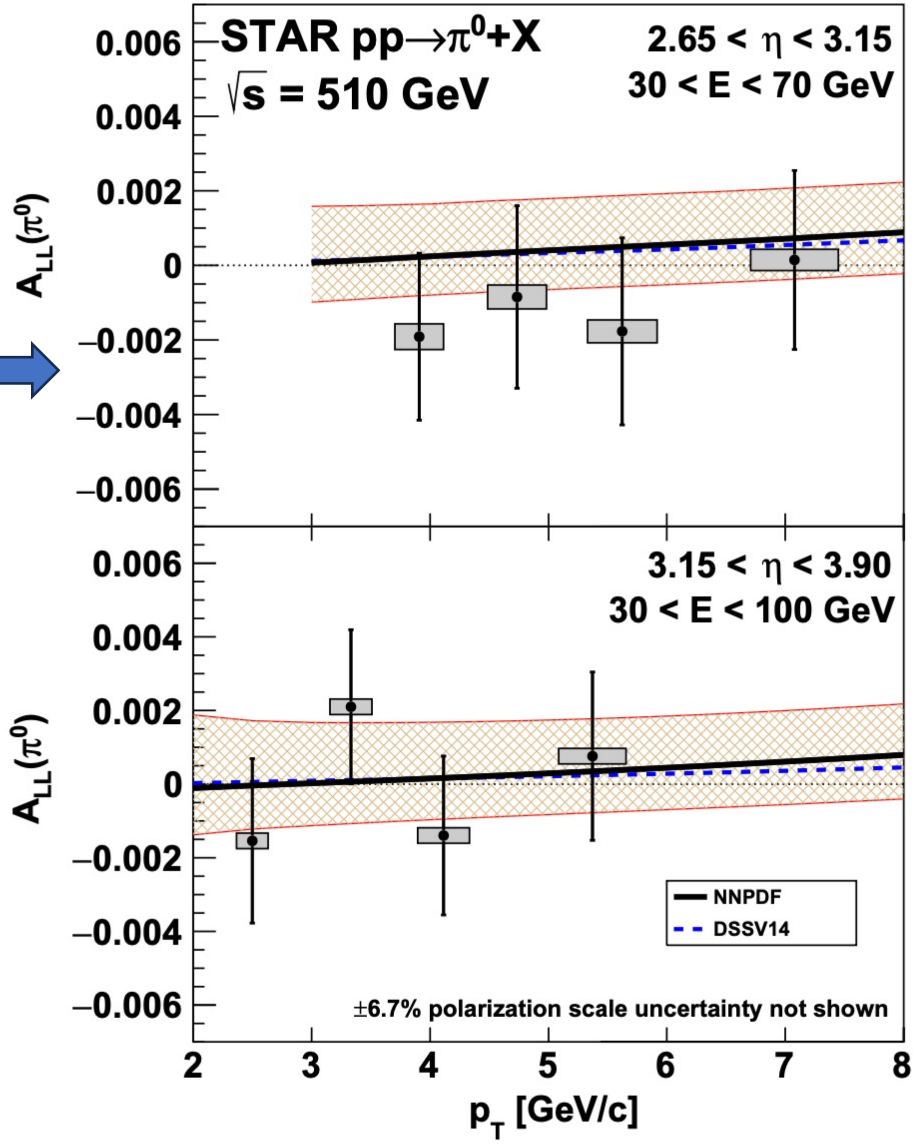
A_{LL} Results from π^0 Production

STAR, PRD 89, 012001 (2014)





STAR, PRD 98, 032013 (2018)



- π^0 results at intermediate pseudorapidities provide sensitivity to the gluon polarized PDF in the region x ~ 0.01 - 0.05;
- Results from forward rapidity push the sensitivity for $\Delta g(x)$ to x ~ 0.001;
- Measured results are consistent with both NNPDF and DSSV extrapolations of A_{LL}, assuming proper $\Delta g(x)$ shape at low x and using DSS fragmentation functions.

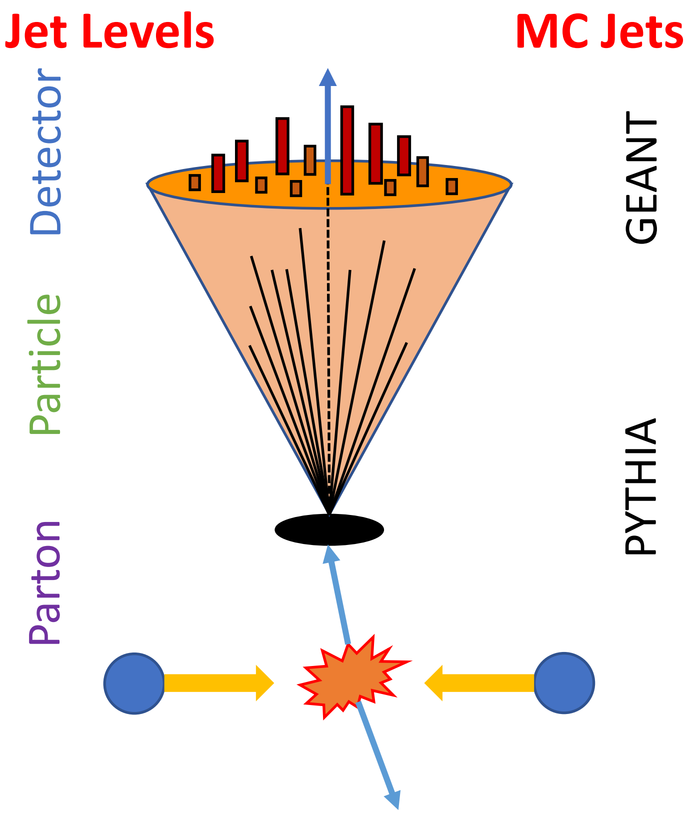
Jet Reconstruction at STAR

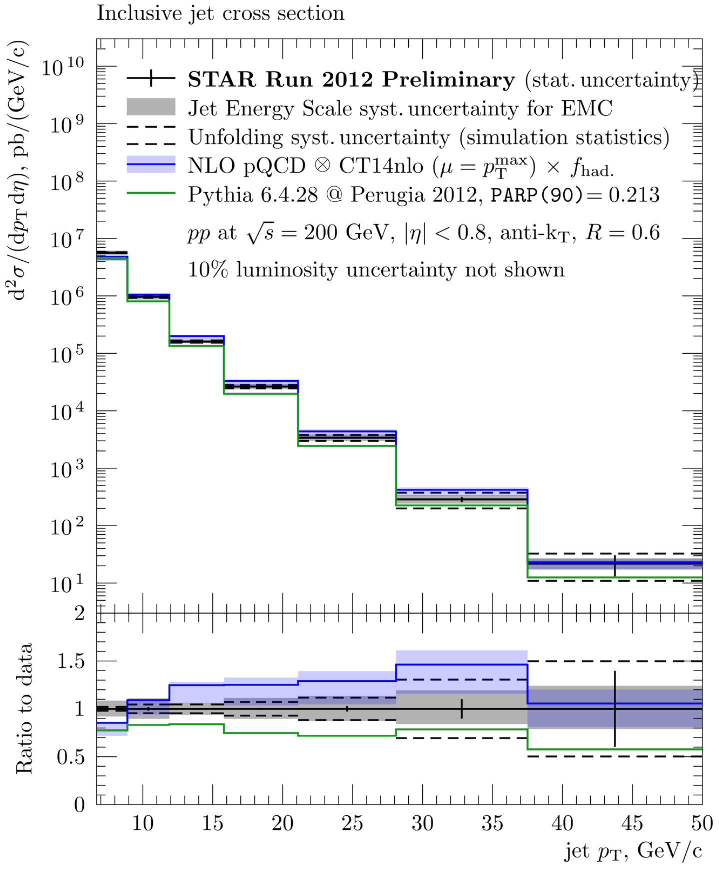
Anti-k_T Algorithm:

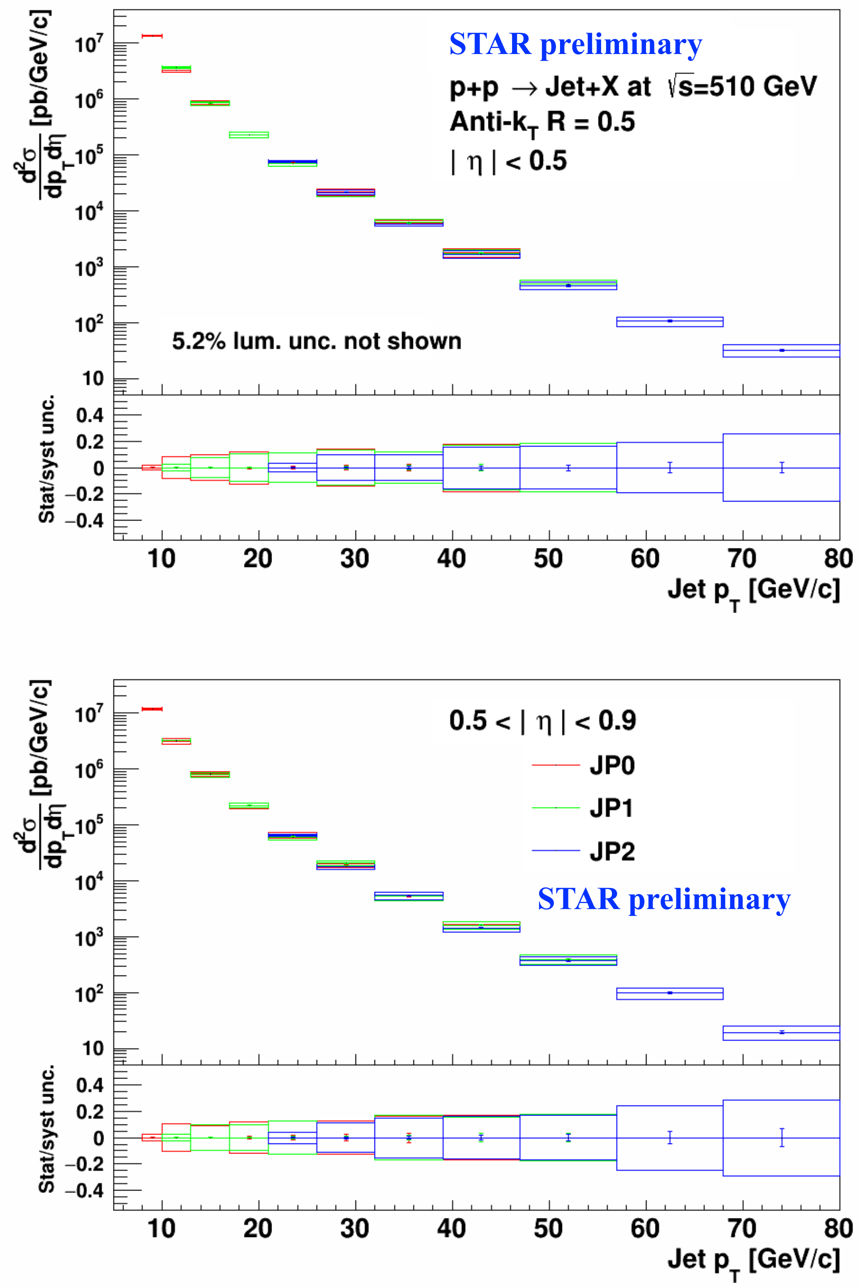
- Radius = 0.6 for pp 200 GeV
- Radius = 0.5 for pp 510 GeV

Simulation:

- PYTHIA 6.4 Perugia0
- PYTHIA 6.4 Perugia2012, PARP(90) = 0.213

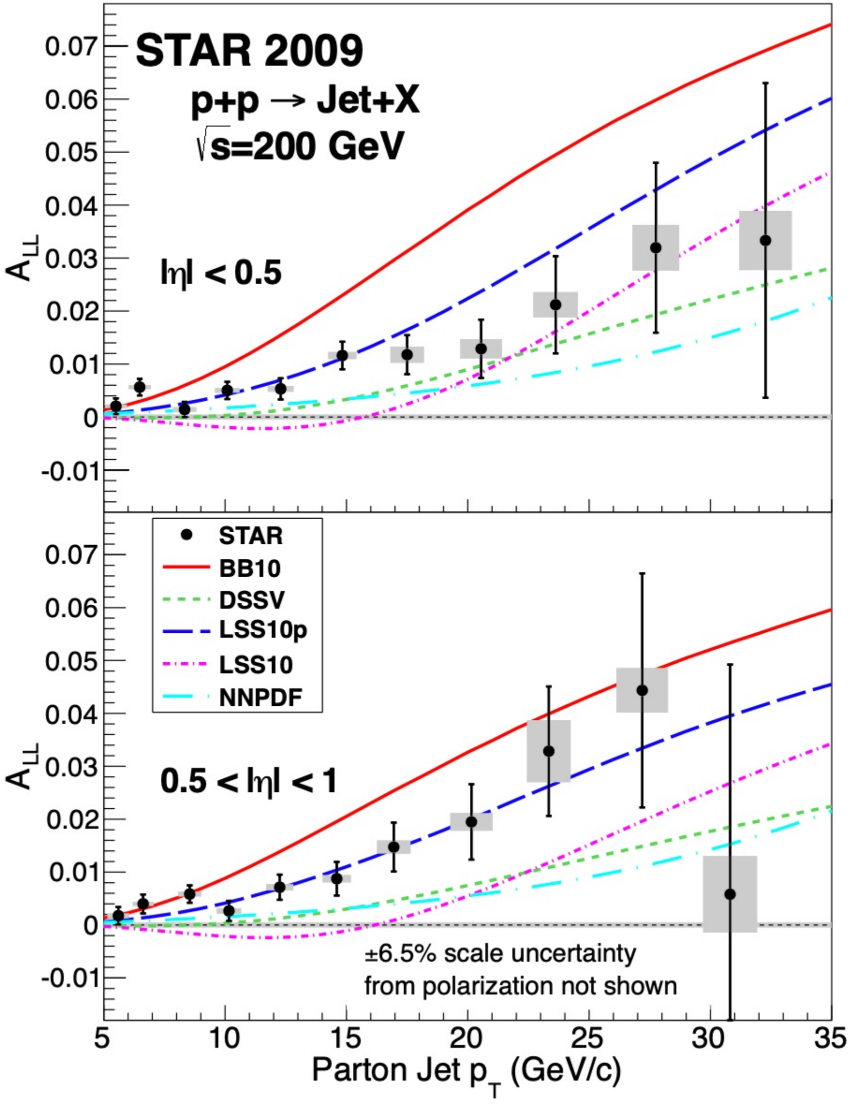




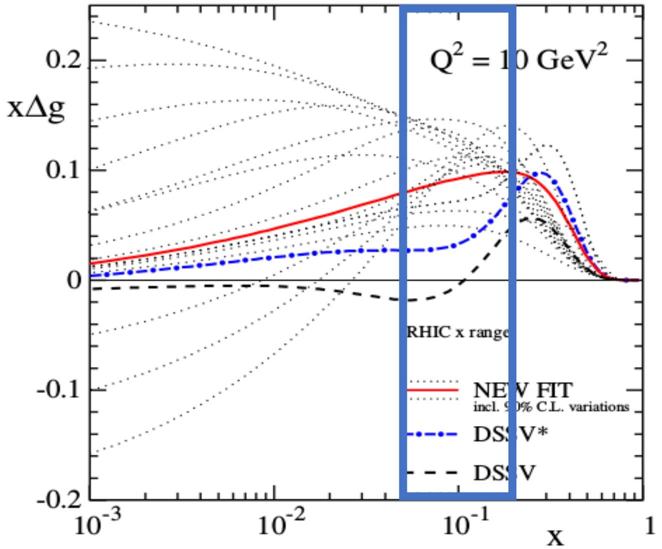


Evidence of Positive ΔG

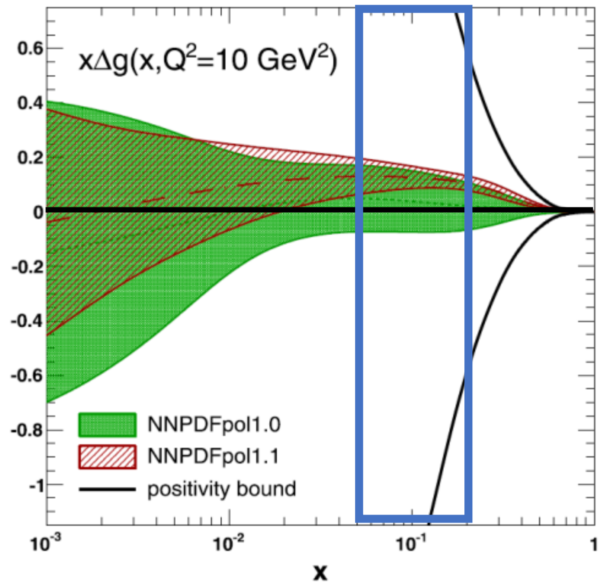
STAR, PRL **115**, 092002 (2015)



DSSV, PRL 113, 012001(2014)



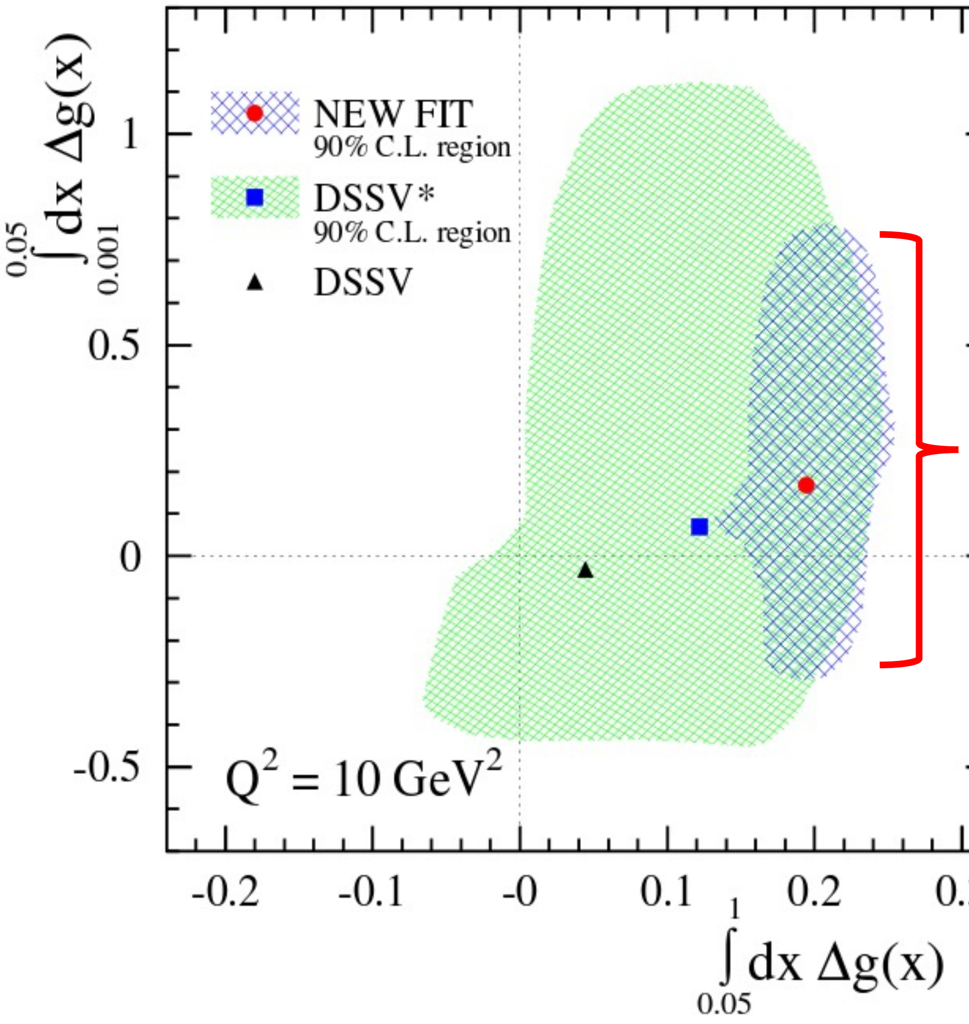
NNPDF, Nucl. Phys. B 887, 276 (2014)



- 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

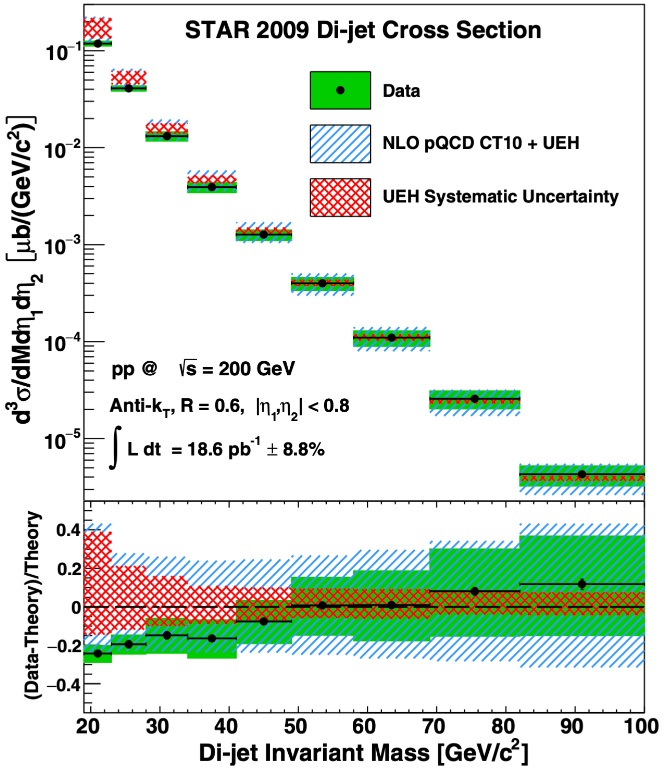
DSSV PRL 113, 012001(2014)

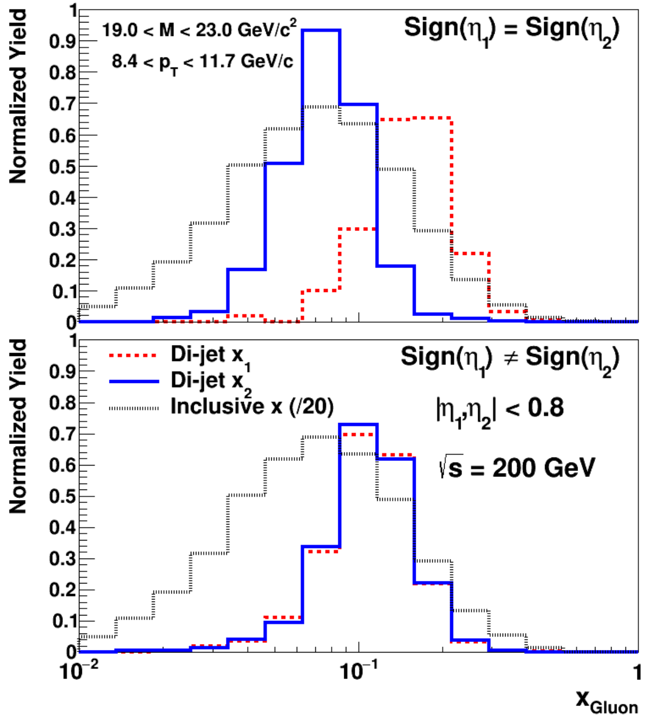


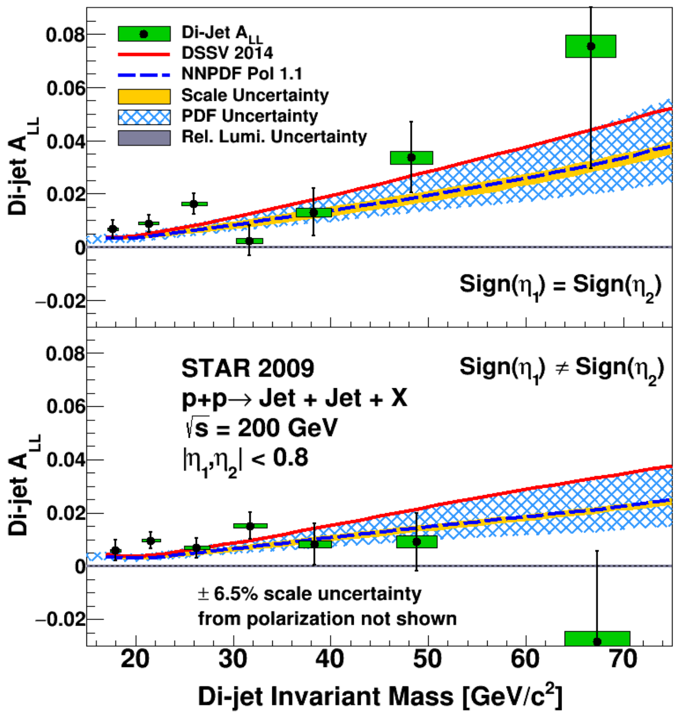
- The low x behavior and shape of Δg(x) are still poorly constrained:
  - $\Delta G = \int_{0.05}^{1} \Delta g(x)dx = 0.20 \pm 0.06$
  - $\Delta G = \int_{0.001}^{0.05} \Delta g(x)dx = 0.15 \pm 0.50$
- STAR's strategies to explore low-*x* regime:
  1. Extend to dijet measurement;
  2. Reconstruct jet 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)

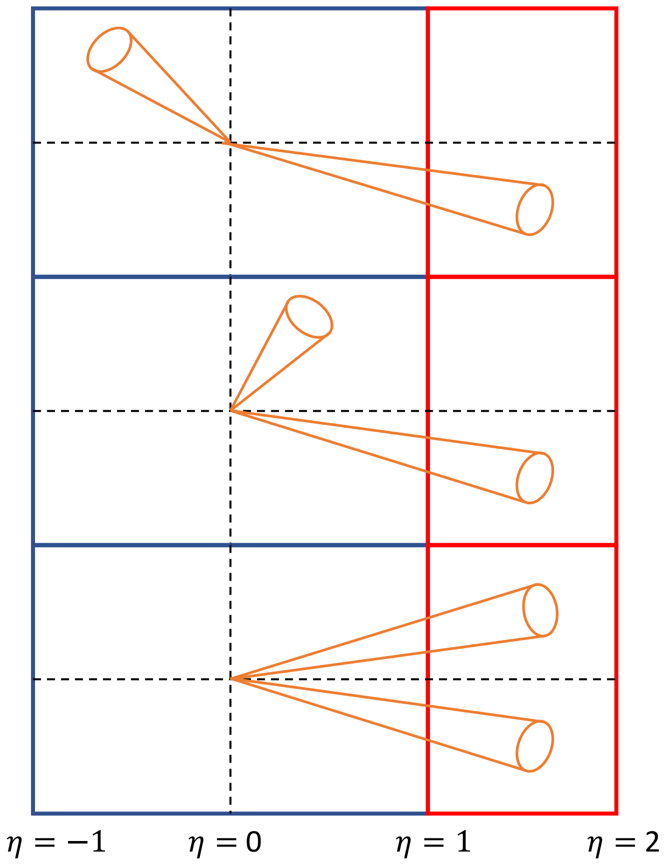


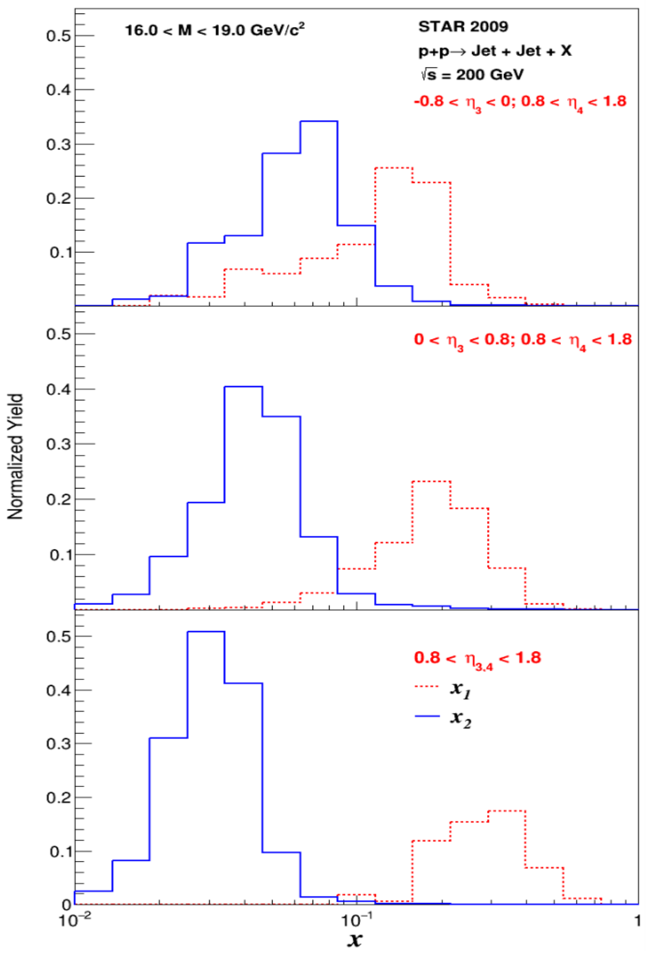




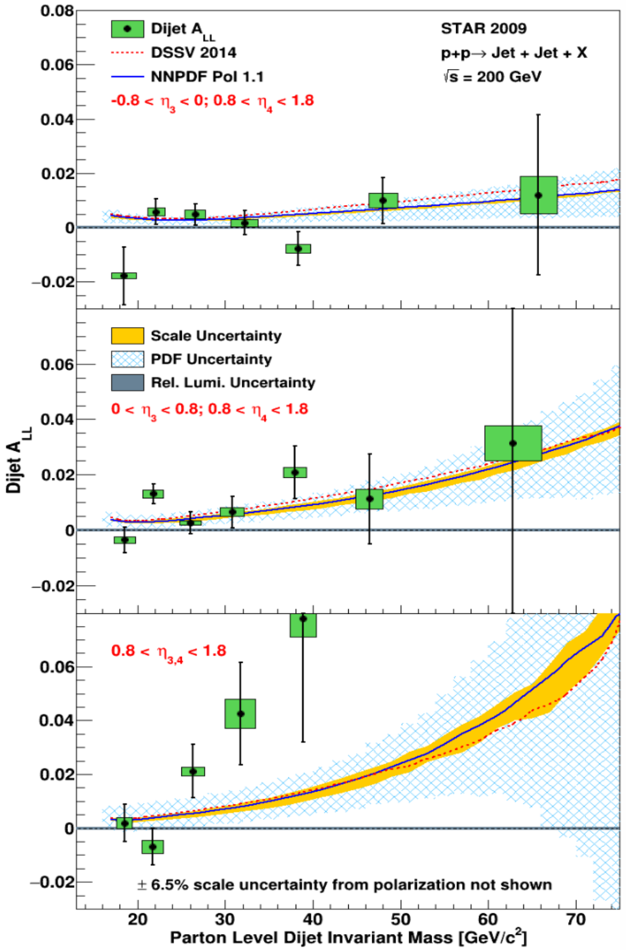
- Dijet measurements capture more information from the hard scattering and provide a more direct link to the initial parton level kinematics than inclusive measurements;
- Mid-rapidity di-jet A_{LL} presented for two topologies as a function of di-jet invariant mass corrected to parton level;
- Data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

Intermediate Rapidity Dijet A_{LL}





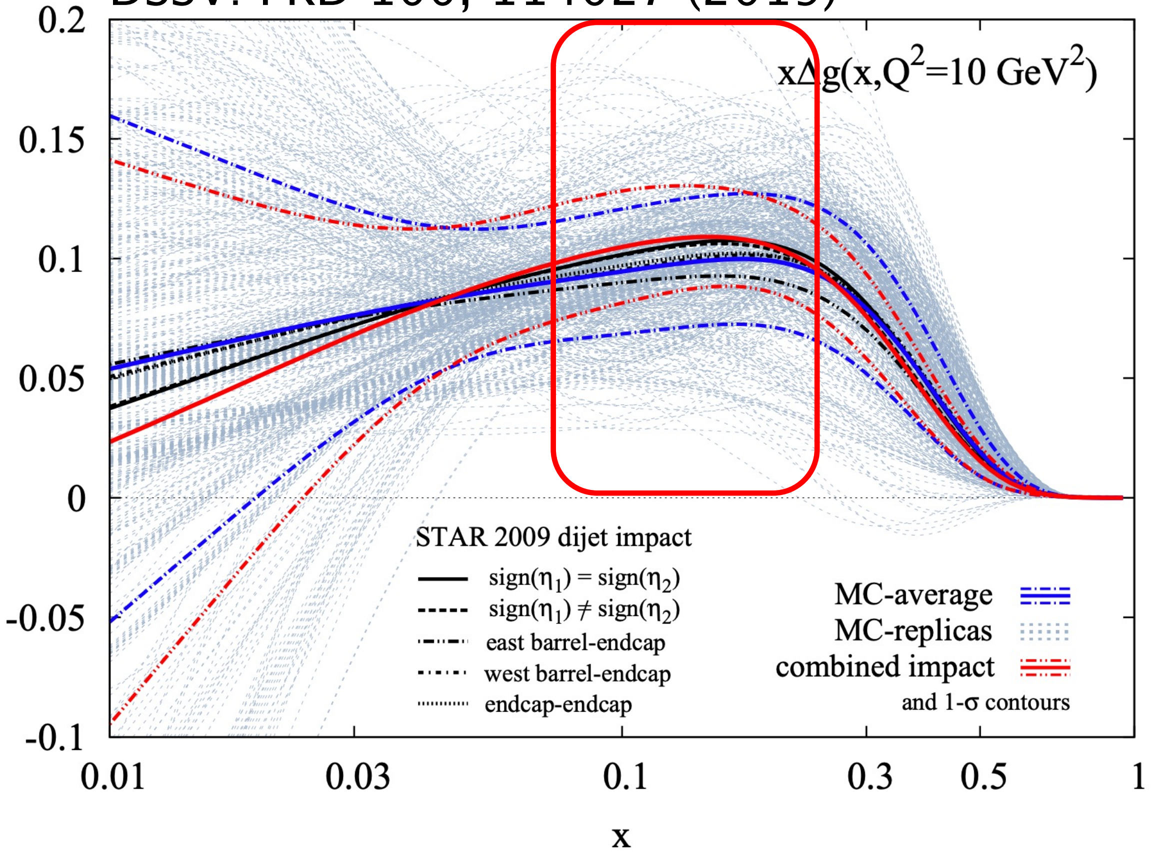
STAR, Phys. Rev. D 98, 032011 (2018)



- 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:

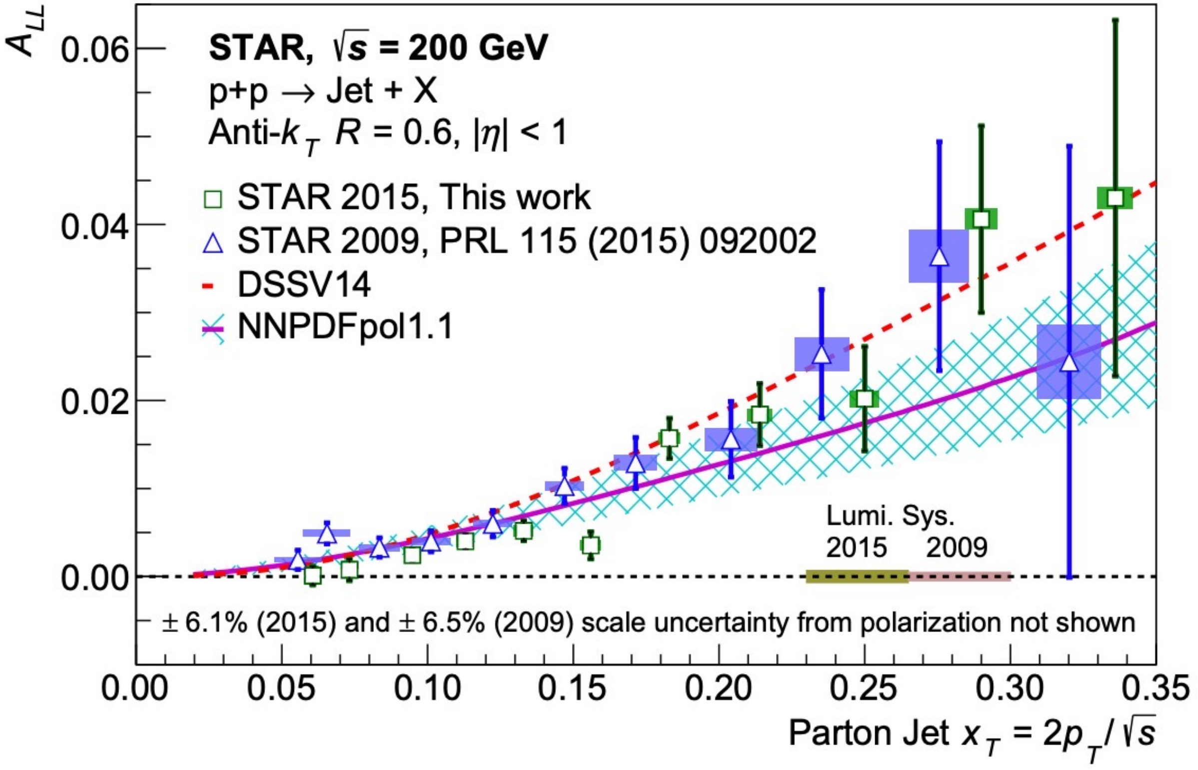
DSSV: PRD 100, 114027 (2019)



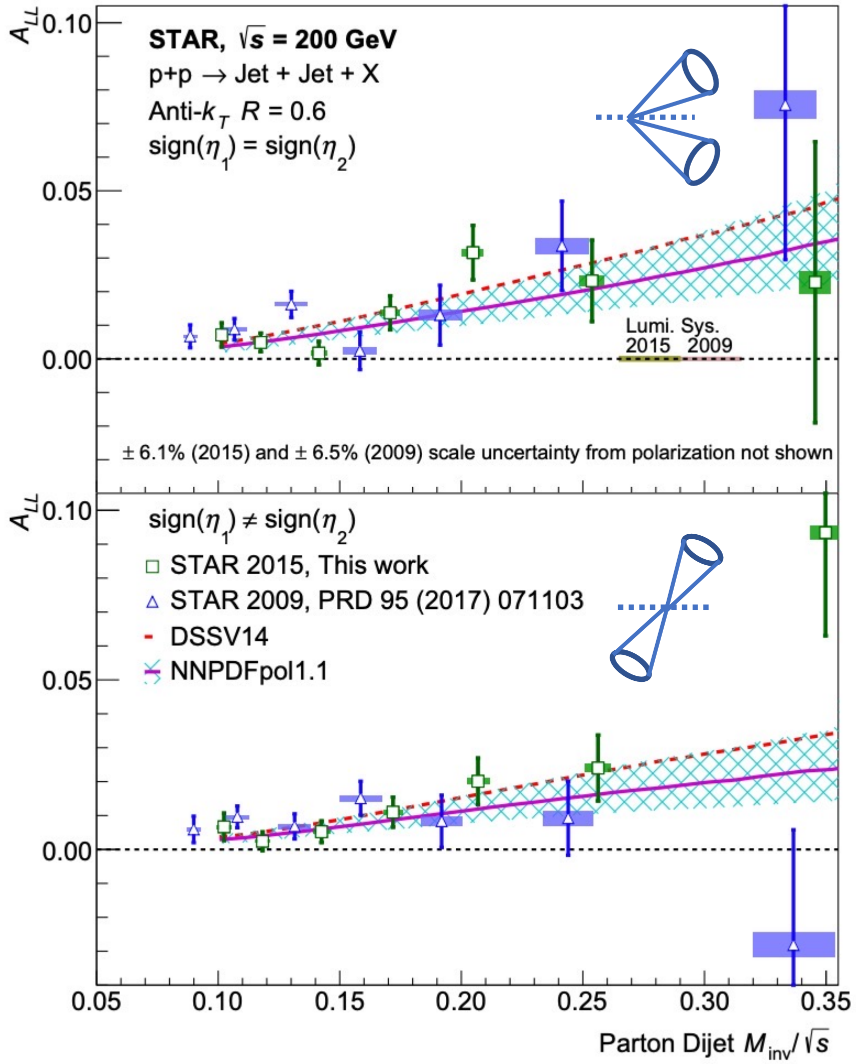
- Gluon polarization in the region ***x* > 0.1**:
  - before: $\Delta G = \int_{0.1}^{1} \Delta g(x)dx =$ 0.133 ± 0.035
  - after: $\Delta G = \int_{0.1}^{1} \Delta g(x)dx =$ 0.126 ± 0.023
- In the region ***x* > 0.01**:
  - before: $\Delta G = \int_{0.01}^{1} \Delta g(x)dx =$ 0.309 ± 0.109
  - after: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

New A_{LL} Results at 200 GeV

STAR, PRD 103 (2021) L091103



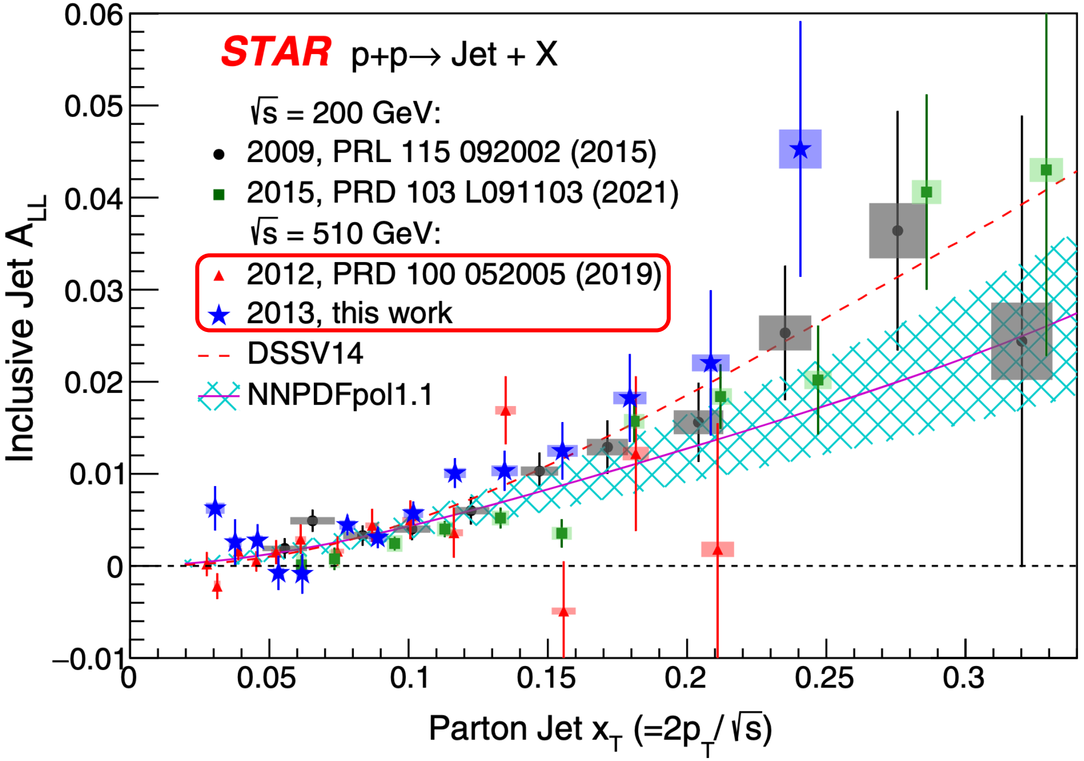
Year and $\sqrt{s}$	STAR L $[pb^{-1}]$
$\sqrt{s}$ = 200 GeV	
2009	25
2015	52
$\sqrt{s}$ = 510 GeV	
2012	82
2013	300



- 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

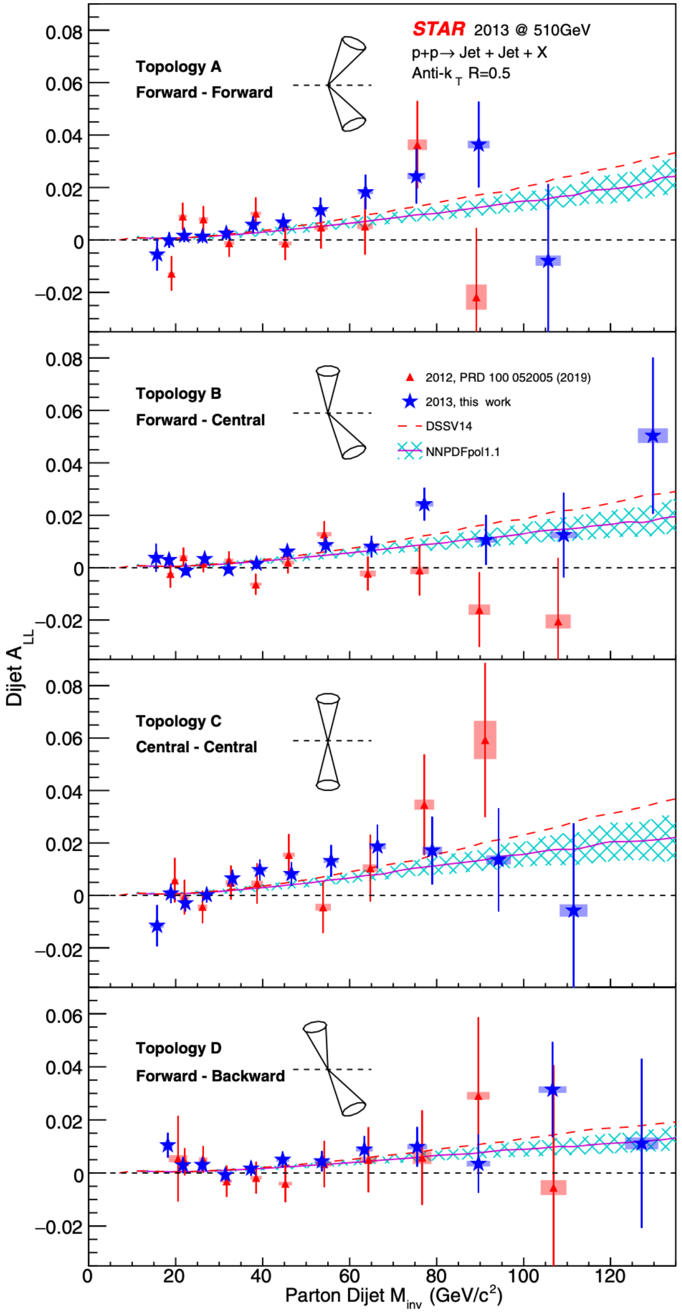
STAR, PRD 100, 052005 (2019)
STAR, PRD 105, 092011 (2022)



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

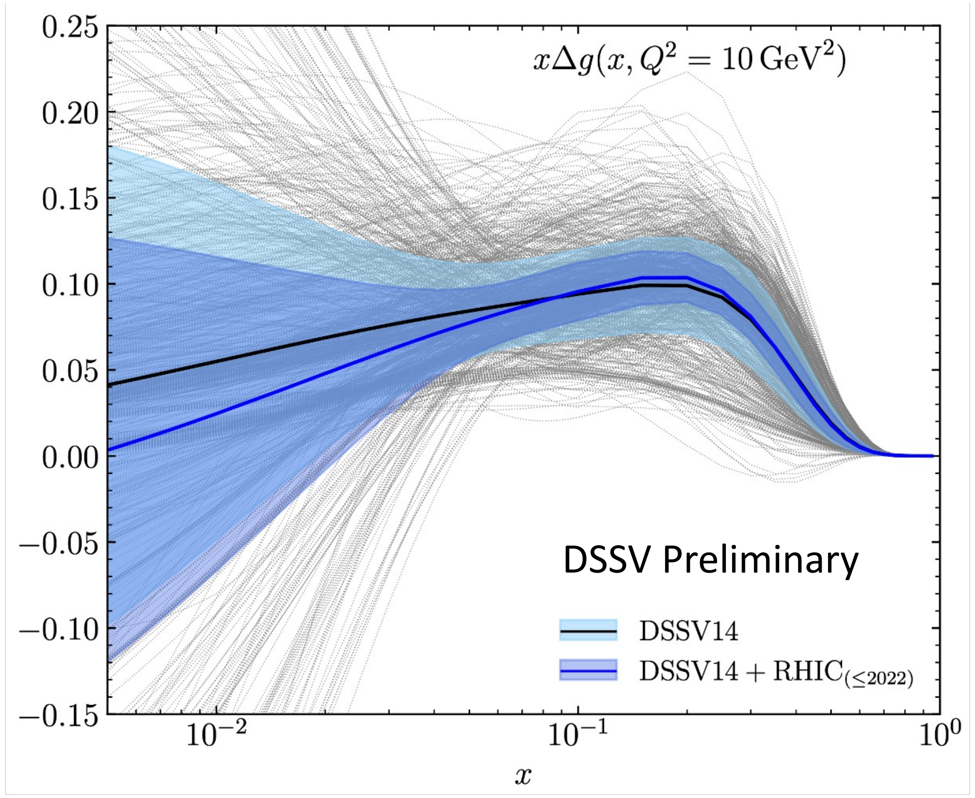
$$x_2 \sim \frac{1}{\sqrt{s}}\left(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4}\right)$$

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

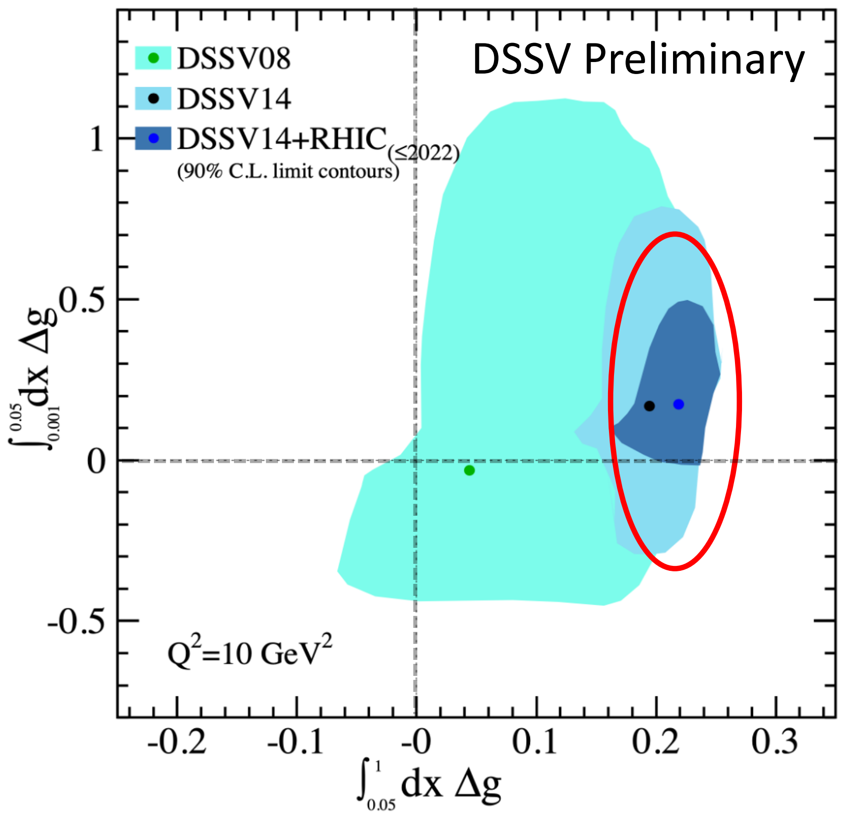


- Higher center-of-mass energy probes lower x partons;
- Plotted vs x_T , overall consistency seen among STAR data sets;
- Well described by global fits that previously gave a good description of the 200 GeV results.

Impact of the RHIC Results



The RHIC Cold QCD Program, arXiv:2302.00605



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

DSSV14 + RHIC (≤2022):

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

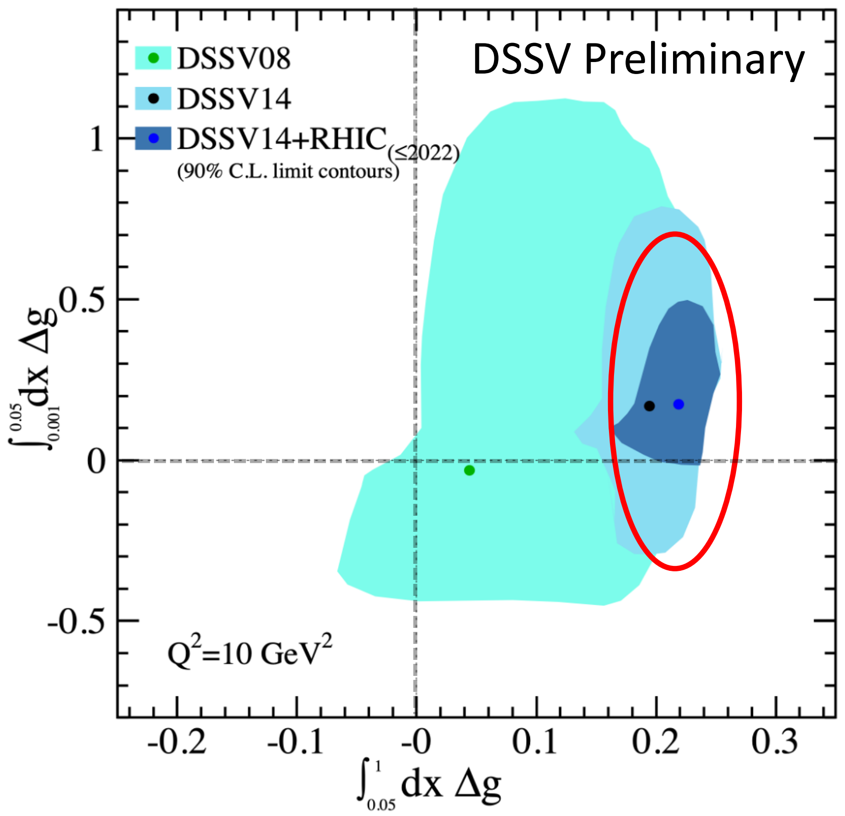
Proton Spin Puzzle Solved?

Enormous recent progress on helicity PDFs

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

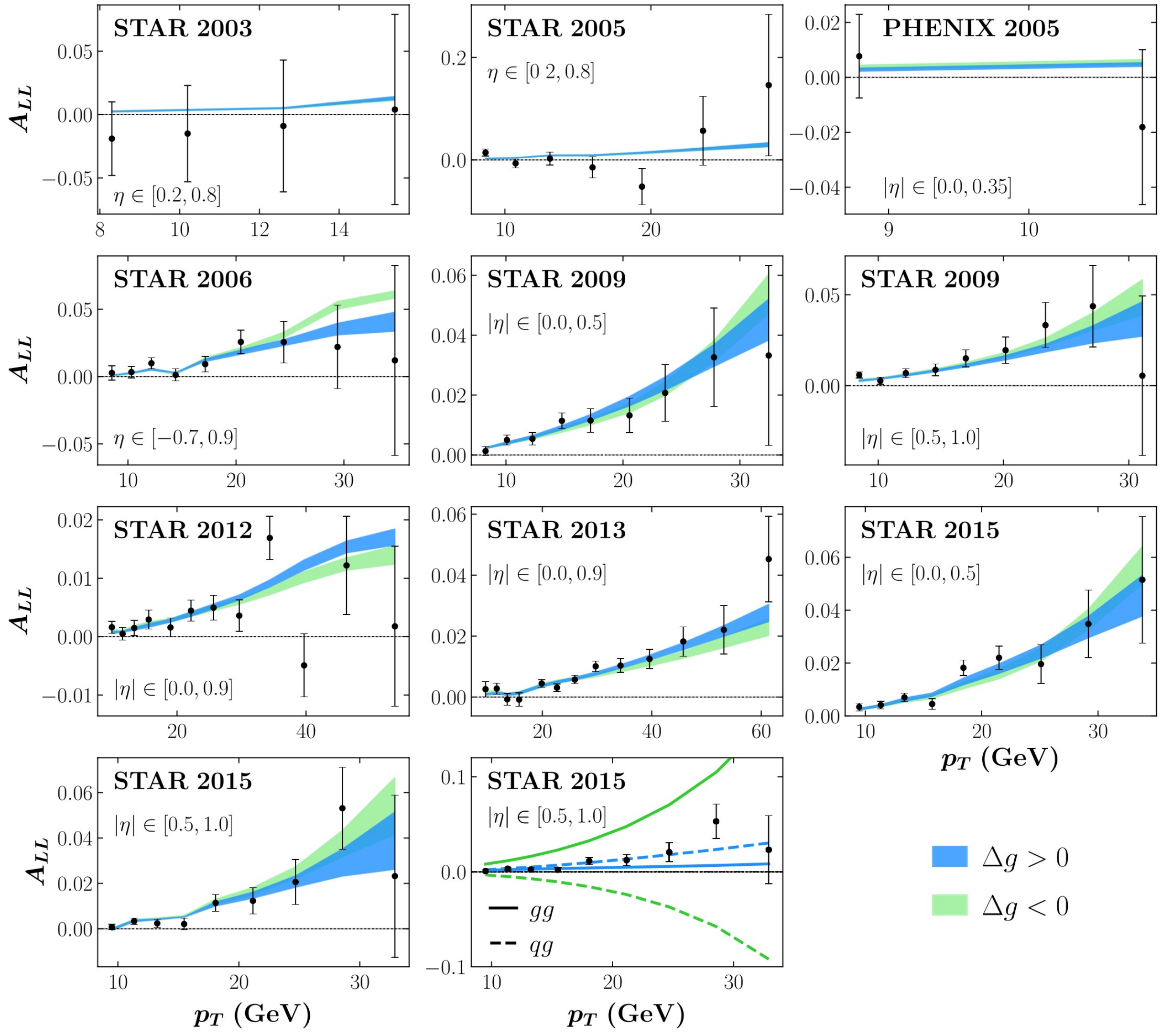
Werner Vogelsang, Spin2023

The RHIC Cold QCD Program, arXiv:2302.00605

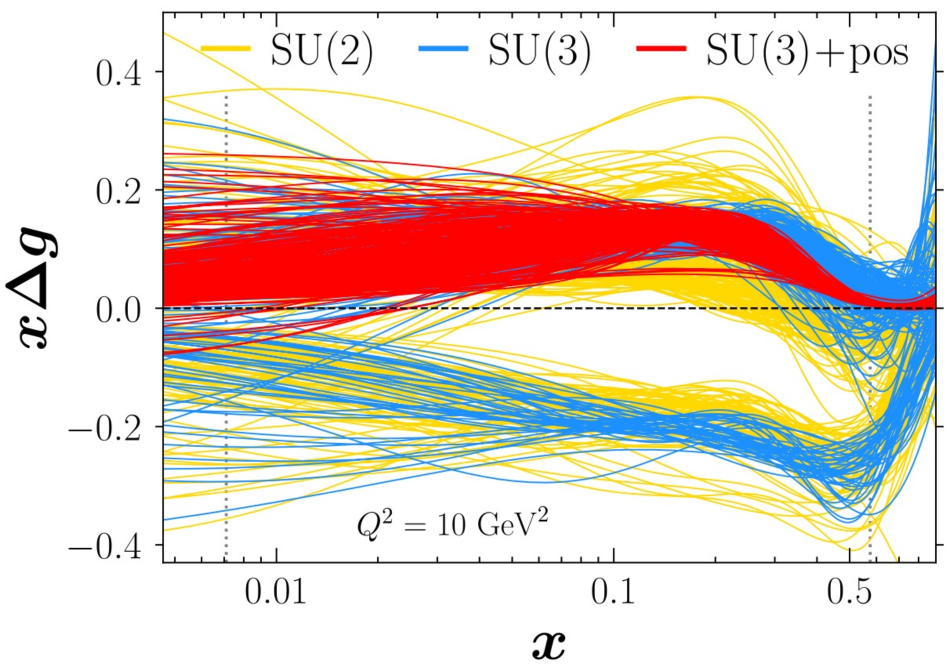


$$\langle S_z^p \rangle = \frac{1}{2}\Delta\Sigma + \Delta G = 0.515 \pm 0.108$$

Negative Gluon Polarization?



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

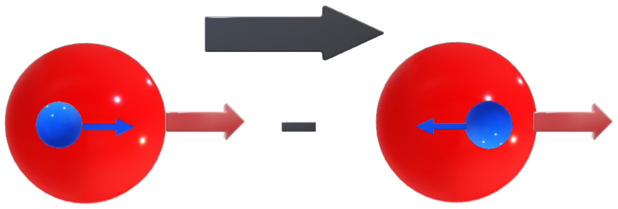


- Negative gluon polarization can also describe the STAR inclusive jet results well.

The Positivity Constraint

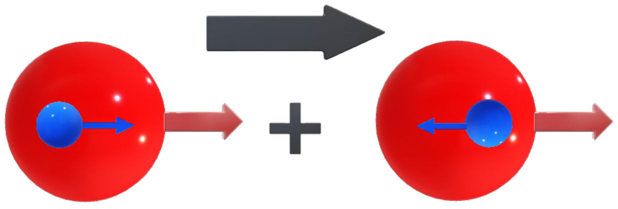
$$|\Delta f_i(x, Q^2)| < f_i(x, Q^2)$$

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



$$f^+(x) \quad - \quad f^-(x)$$

- Unpolarized PDF, $f(x) =$



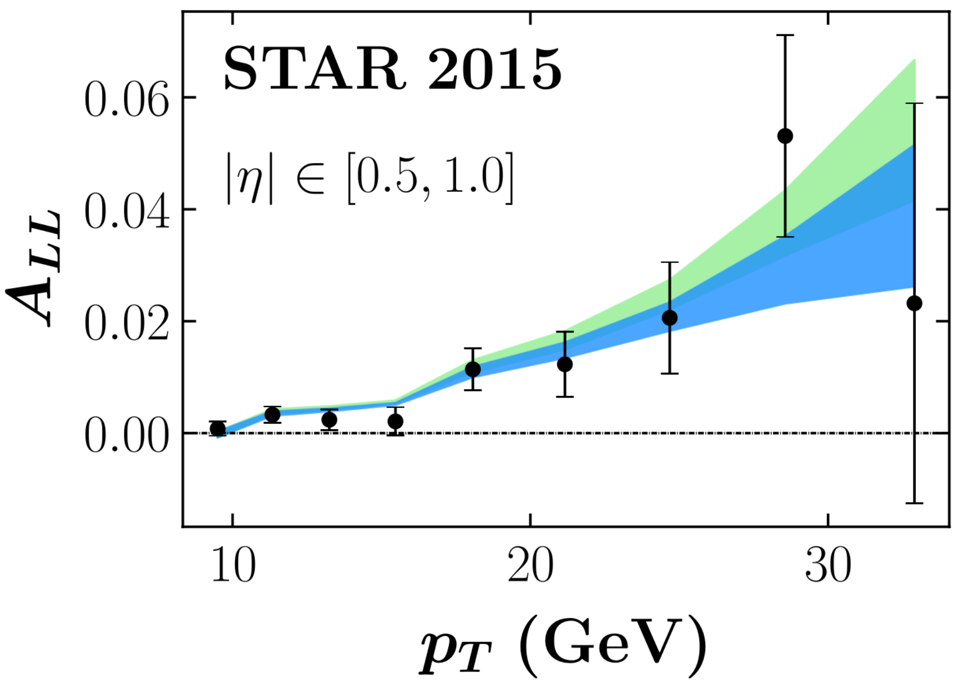
$$f^+(x) \quad + \quad f^-(x)$$

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

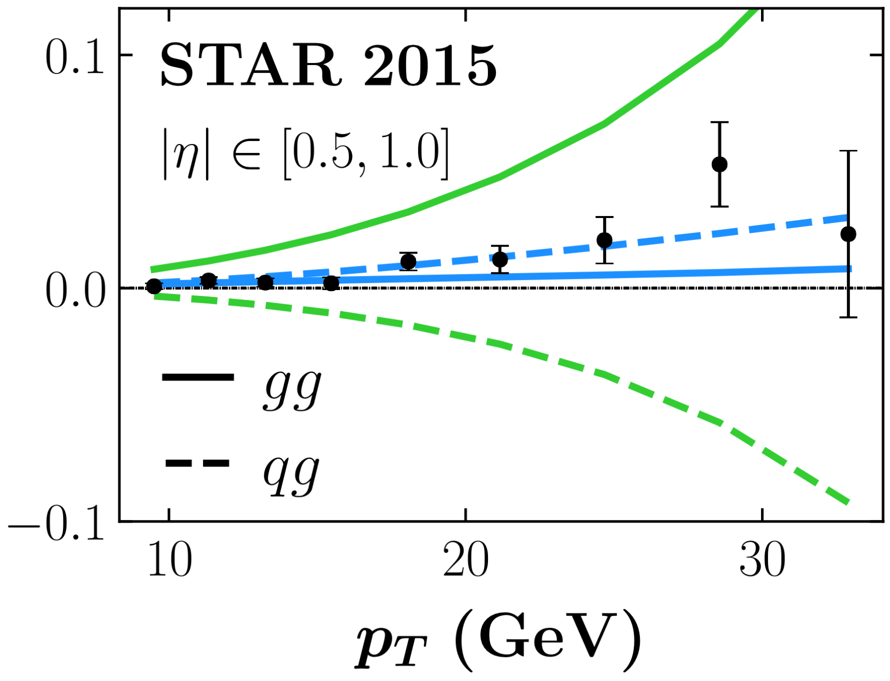
G. Altarelli, S. Forte, and G. Ridolfi, Nucl. Phys. B 534, 277 (1998)

- 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)

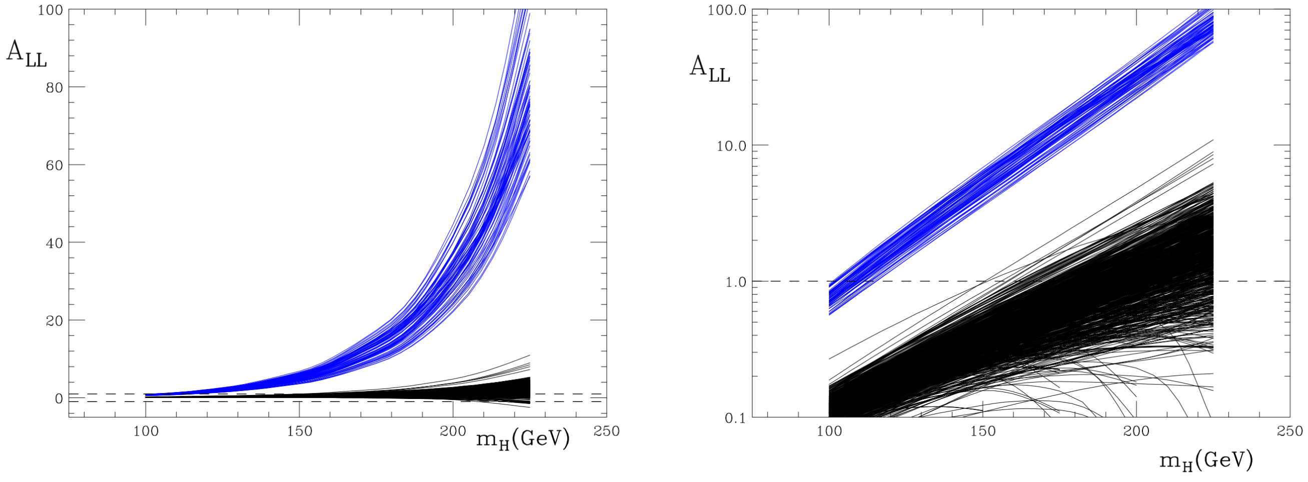
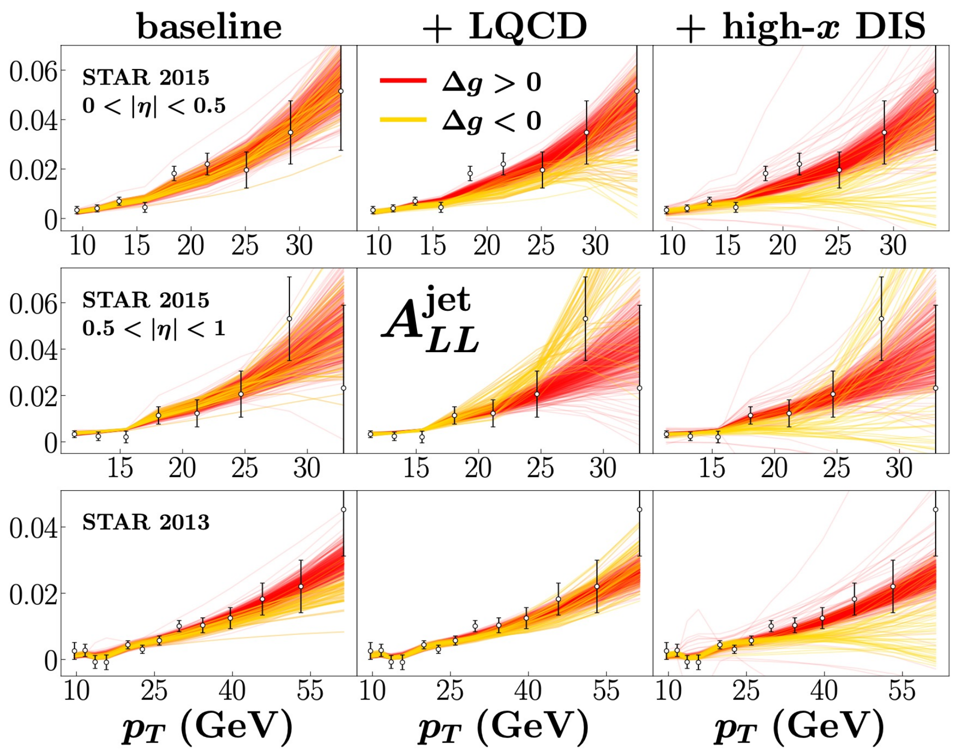


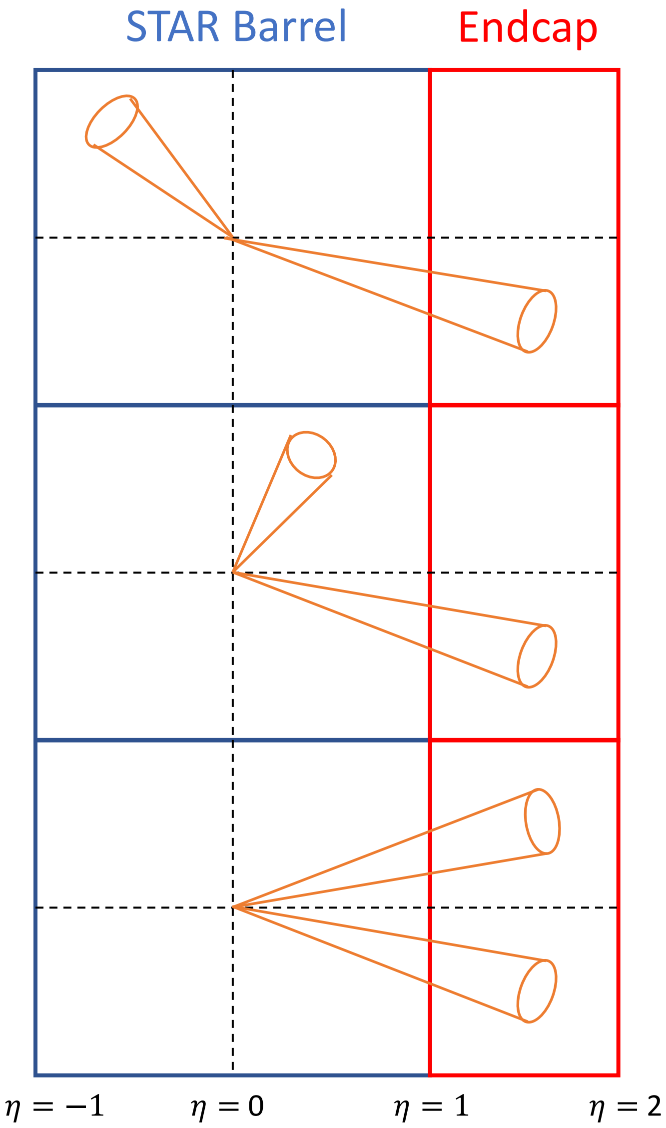
Figure 2: *Double-helicity asymmetry for Higgs production at RHIC ($\sqrt{s} = 510$ GeV) plotted as a function of the Higgs mass, with a linear (left) or logarithmic (right) scale on the vertical axis. The upper bands show A_{LL} as obtained for the gluon distribution shown in Fig. 1, while the lower 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 $|A_{LL}| = 1$.*

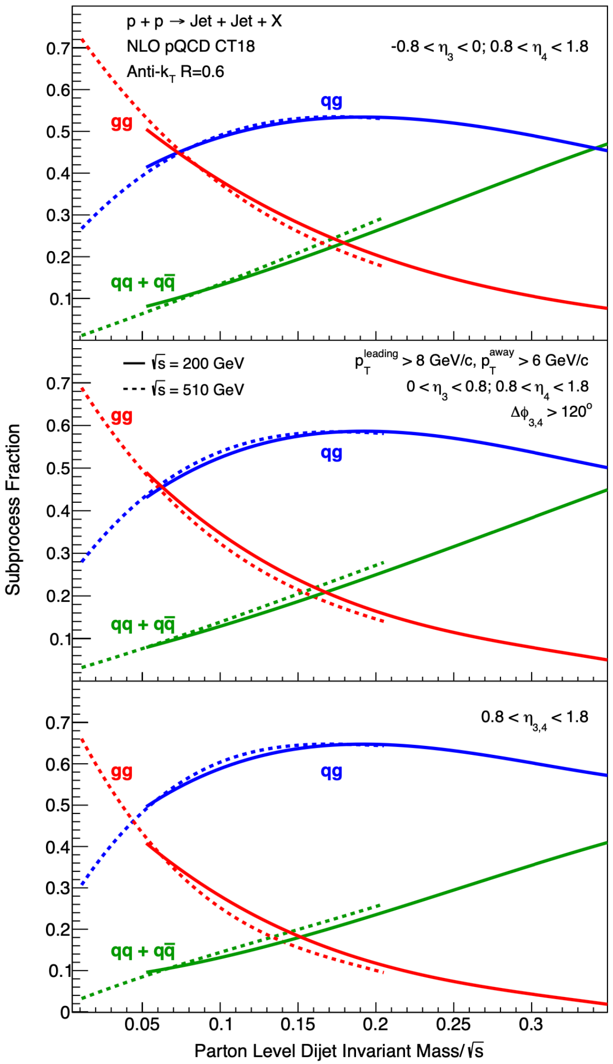
N. T. Hunt-Smith et.al. arXiv:2403.08117 [hep-ph]

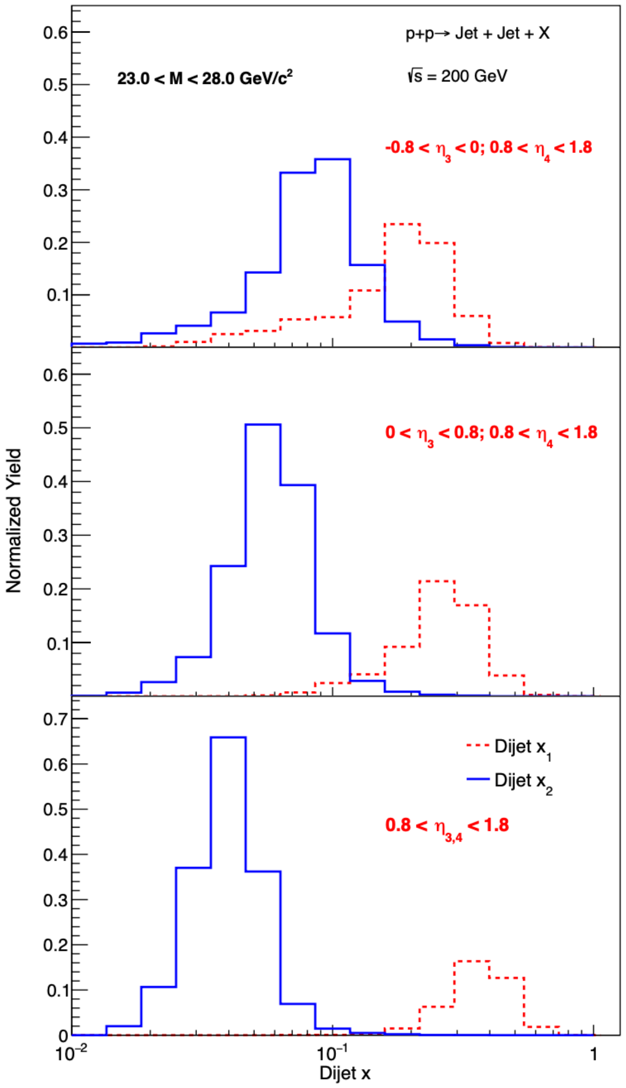


- Violation of the positivity bounds could exhibit hard processes with unacceptable negative cross-sections, for example, the Higgs boson production;
- Negative gluon polarization solution cannot simultaneously account for high-x polarized DIS data along with lattice and polarized jet data.

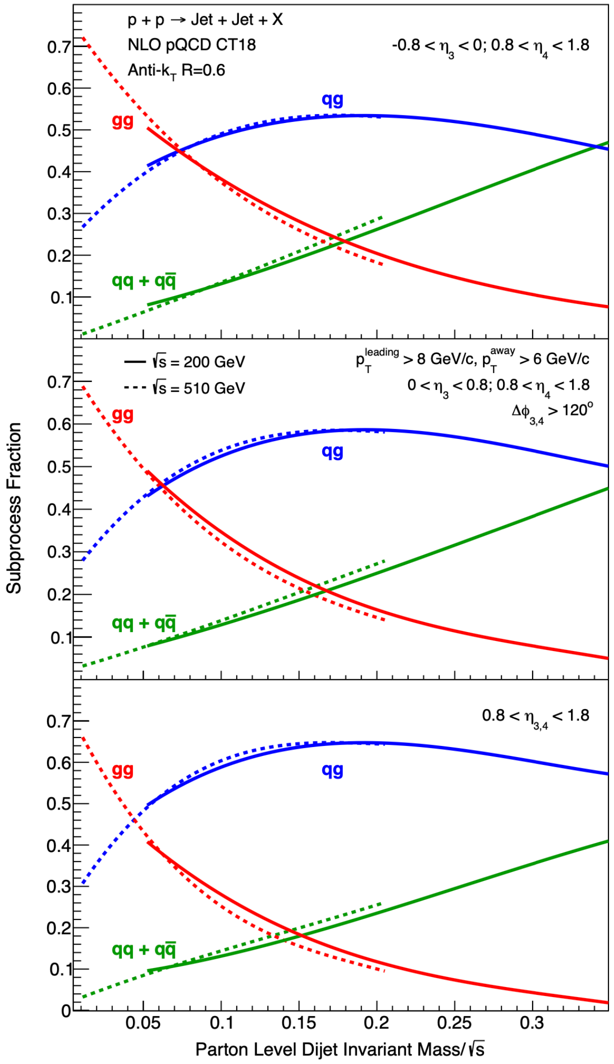
Dijet Measurement at Intermediate Pseudorapidity

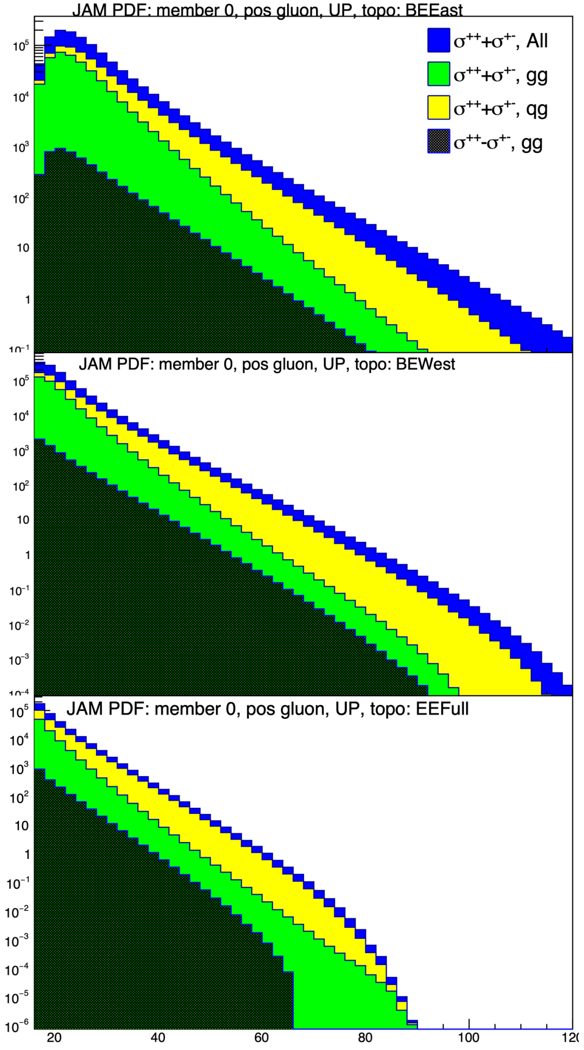


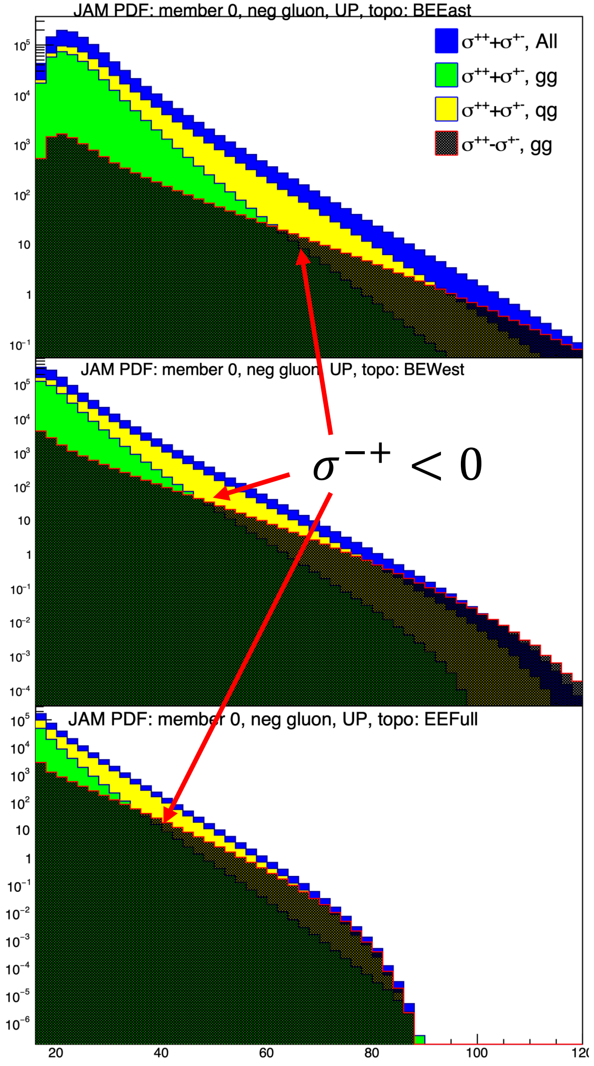




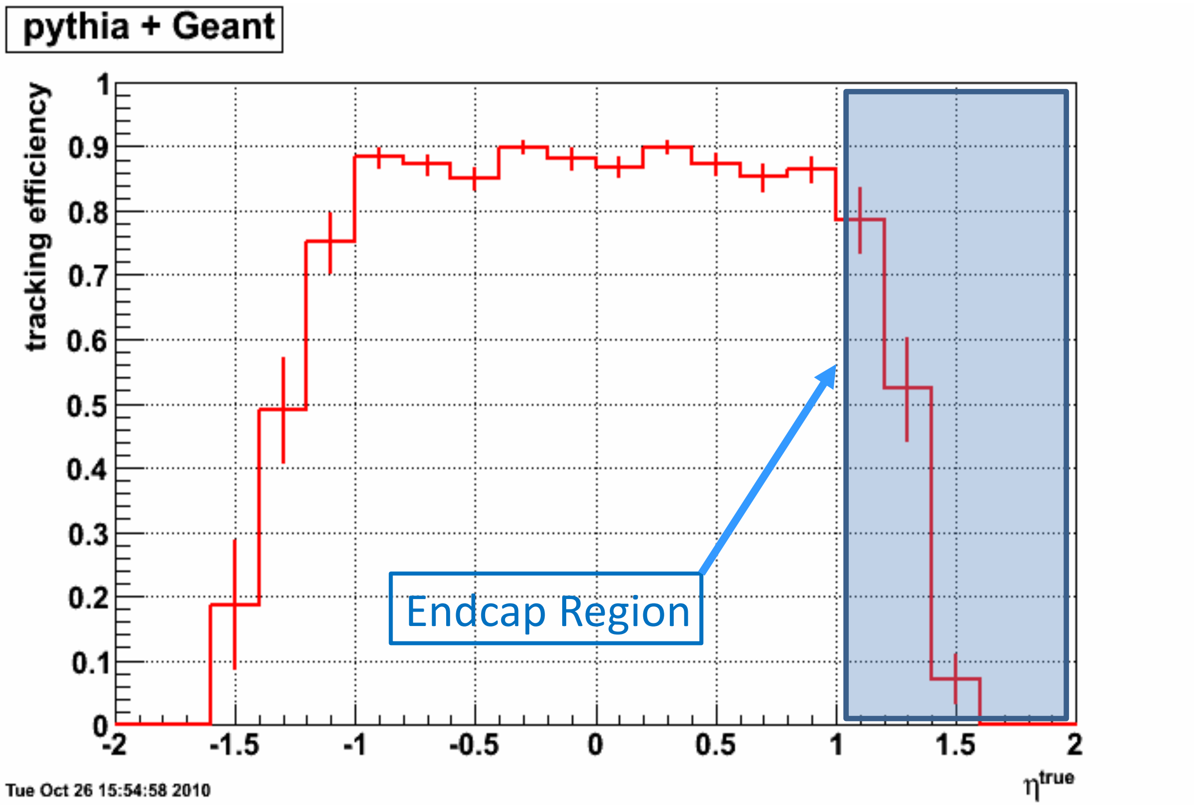
Dijet Measurement at Intermediate Pseudorapidity

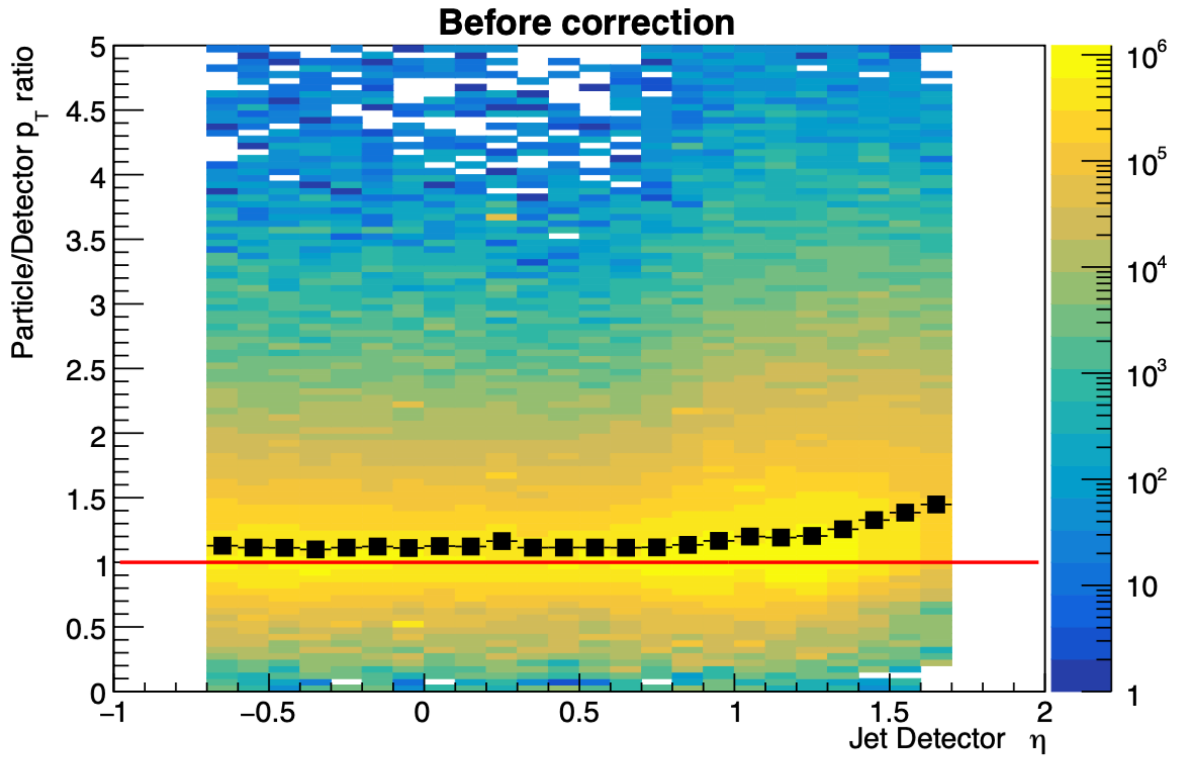






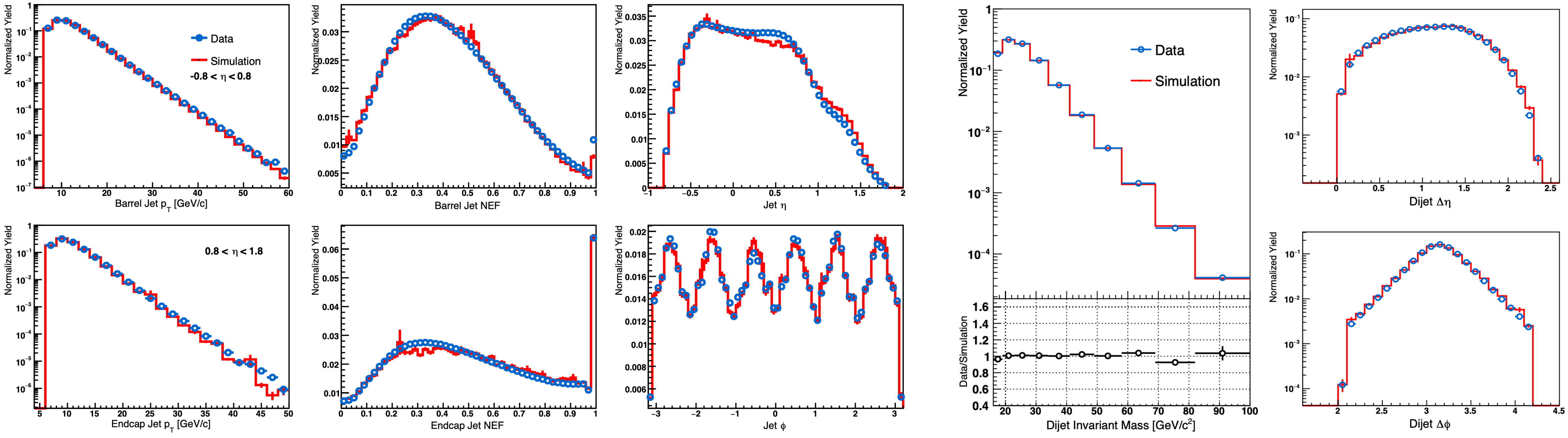
Challenge at Endcap Region





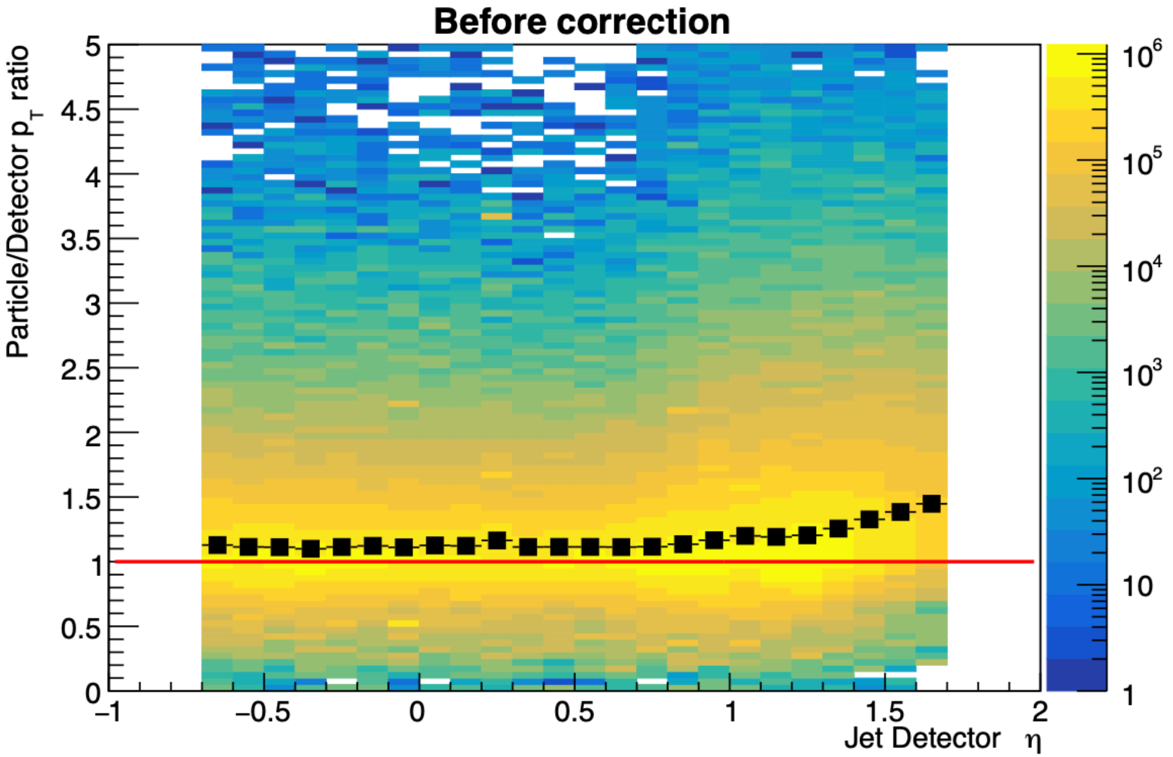
- TPC efficiency decreases in forward region;
- Fewer tracks means reconstructed jets will have lower p_T and jet mass on average;
- Inaccurate p_T reconstruction skews extraction of partonic momenta.

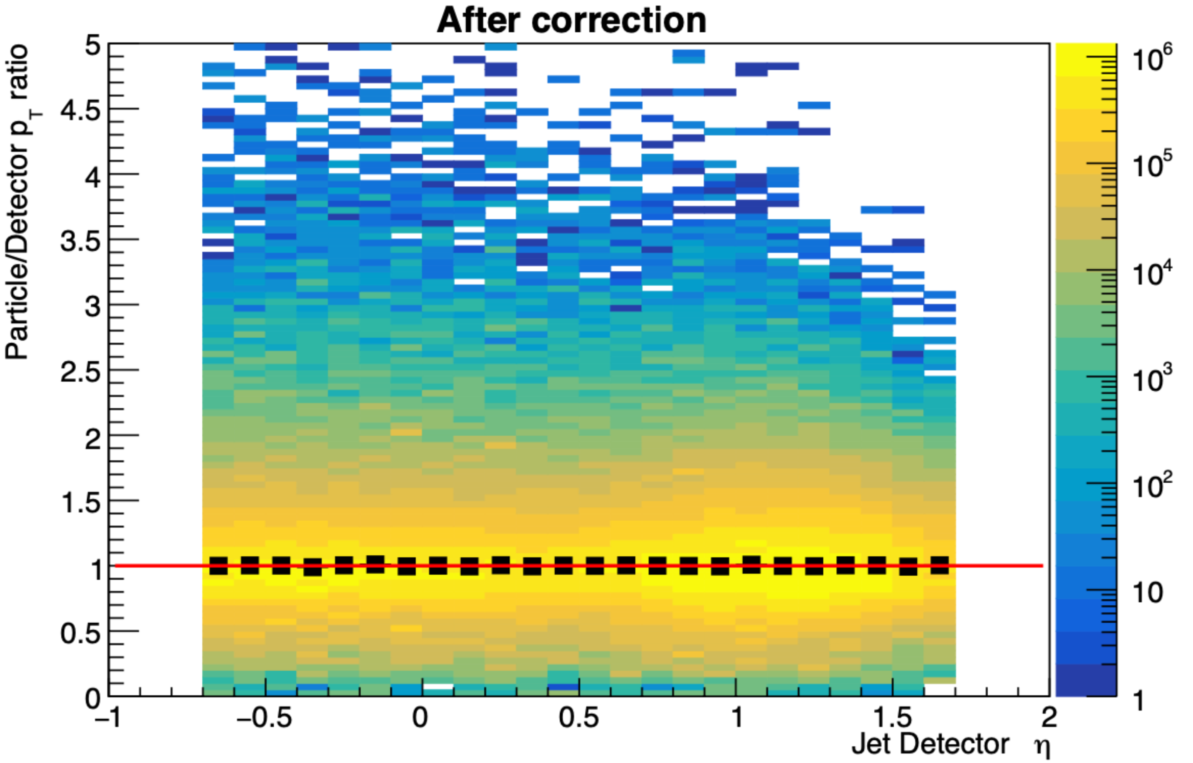
Data and Simulation Comparisons



- Simulation with PYTHIA 6.4 Perugia2012, PARP(90) = 0.213, then going through a STAR detector response model based on GEANT 3, and then embedded into Zero-Bias data;
- Good agreement between data and simulation for single jet and dijet kinematic quantities.

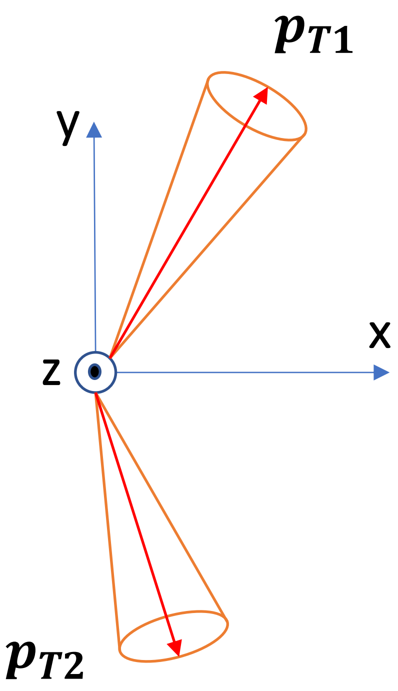
Machine Learning Method

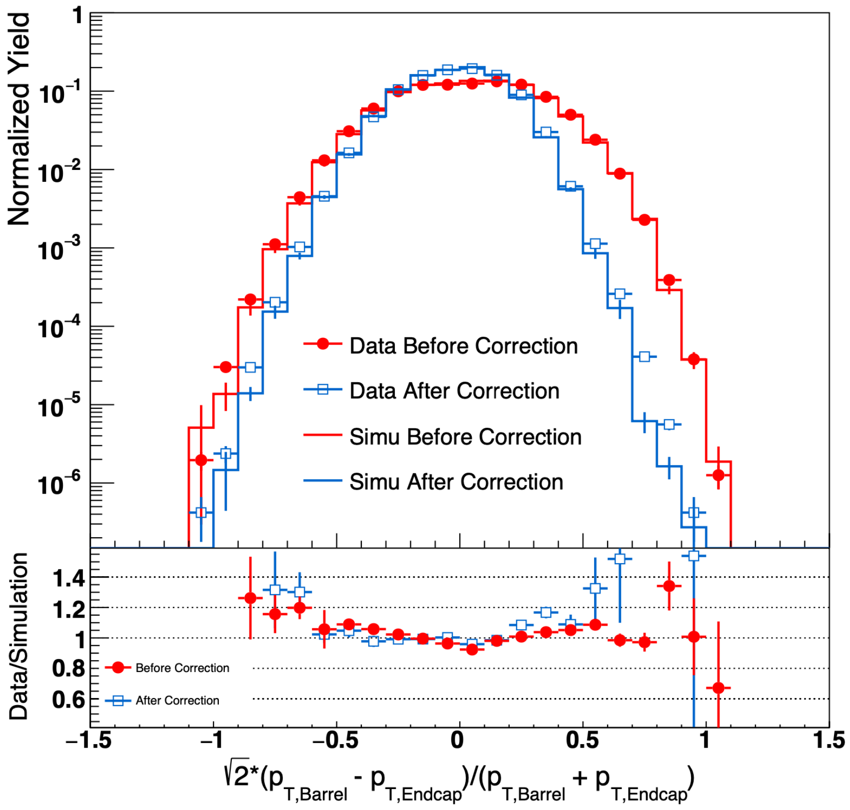




- **Machine Learning:** Multilayer Perceptron (MLP)
- **Variables:** Endcap jet detector level p_T , detector eta, neutral energy fraction, Barrel jet p_T
- **Target:** particle level jet p_T

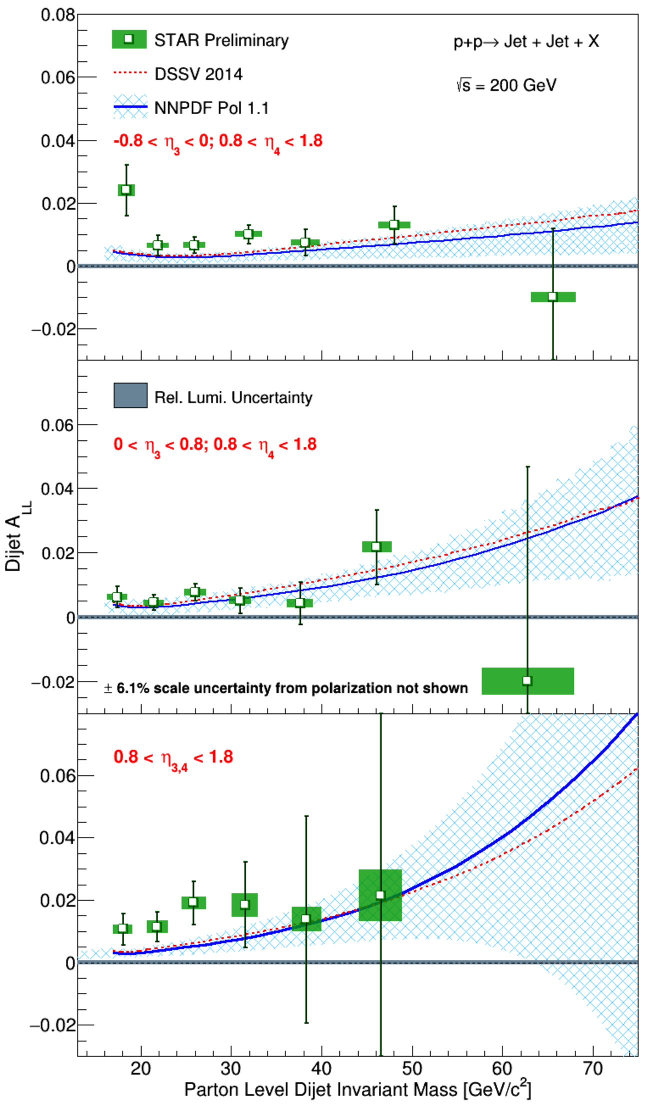
Apply the Correction to Data

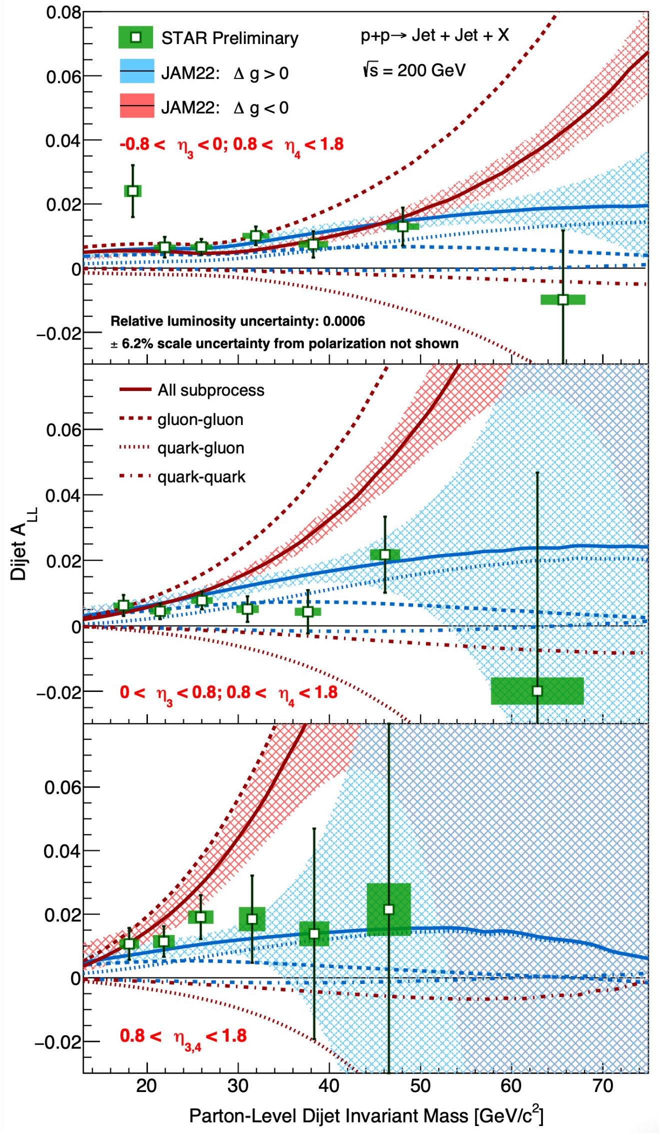




- Barrel and Endcap jets are separately corrected in p_T and mass using similar methods;
- Dijet invariant masses are calculated using the corrected jet transverse momentum and mass from machine learning.

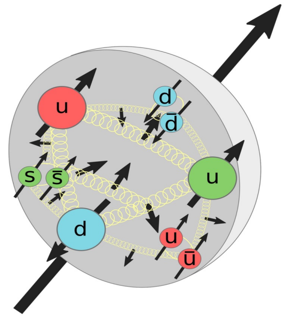
New Results





- Different dijet topologies provide sensitivity to different kinematics: different sub-process fractions and sample x_1 and x_2 simultaneously in different ranges;
- Preliminary results for show good agreement with theoretical predictions with positive gluon polarization;
- Intermediate pseudorapidity results disfavor the negative gluon polarization from JAM group.

Summary



- RHIC has concluded the longitudinal polarized data taking;
- For almost two decades, the longitudinal polarization measurements contribute significantly to our understanding of the proton's spin structure;
- Several new results will soon to be published, which will provide new insight into the gluon helicity distributions.