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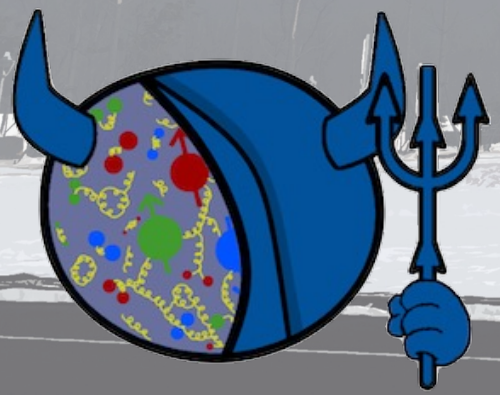
Constraining the Quark and Gluon Helicity at STAR

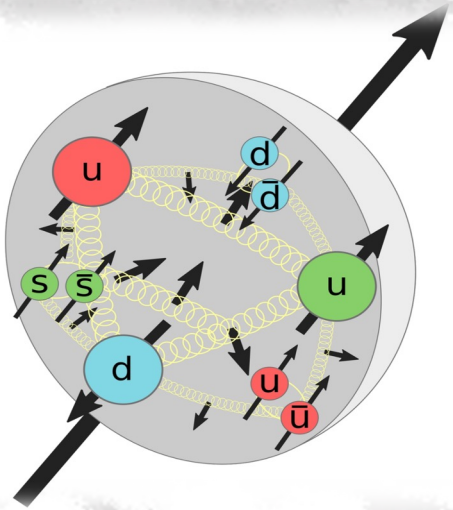
Ting Lin (林挺), for the STAR Collaboration
Shandong University (山东大学)



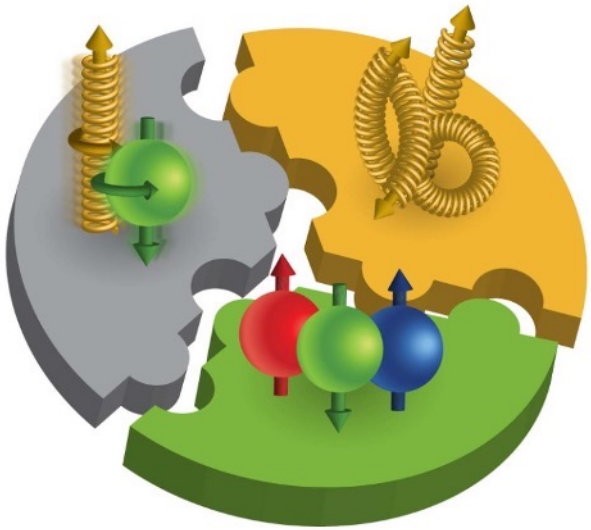
25th International Symposium on Spin Physics (SPIN 2023)

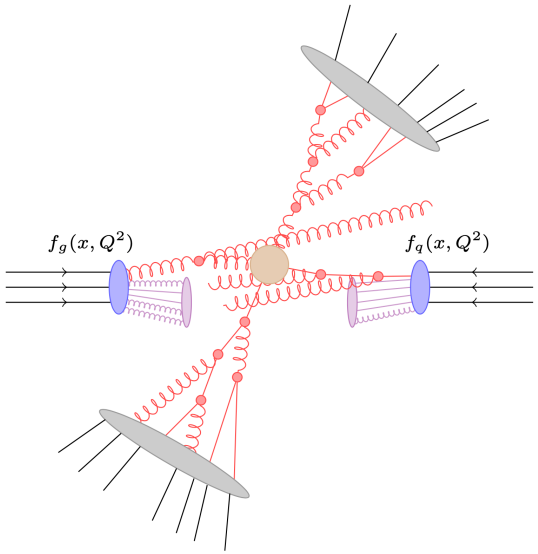
Outline

- Motivation
- RHIC Facility and STAR Detector
- Quark Polarization
- Gluon Polarization
- Summary



Spin of the Proton





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

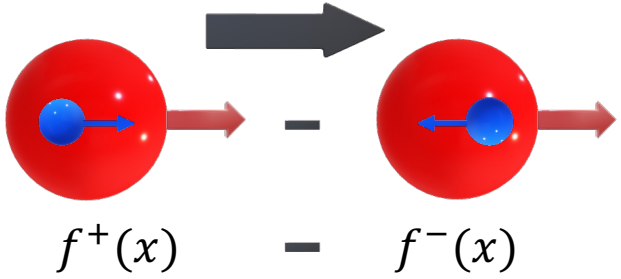
$$\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$

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

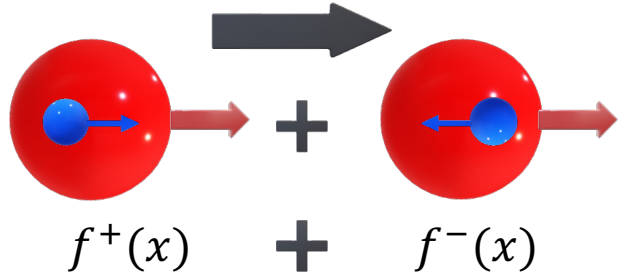
  - $\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s})dx$
  - $\Delta G = \int \Delta g(x)dx$

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

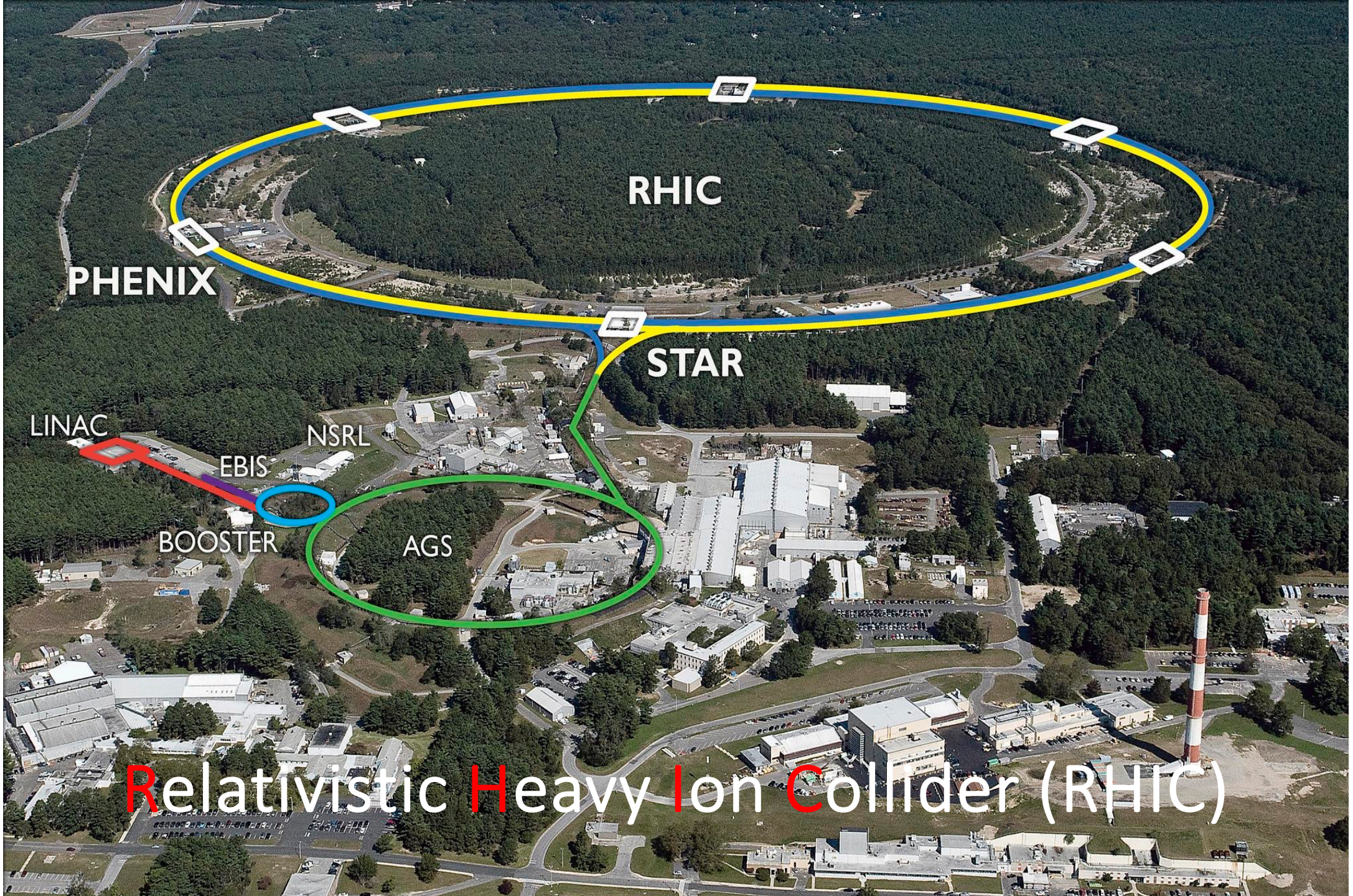
- Helicity PDF, $\Delta f(x) =$



- Unpolarized PDF, $f(x) =$



RHIC Facility and STAR Detector



Relativistic Heavy Ion Collider (RHIC)

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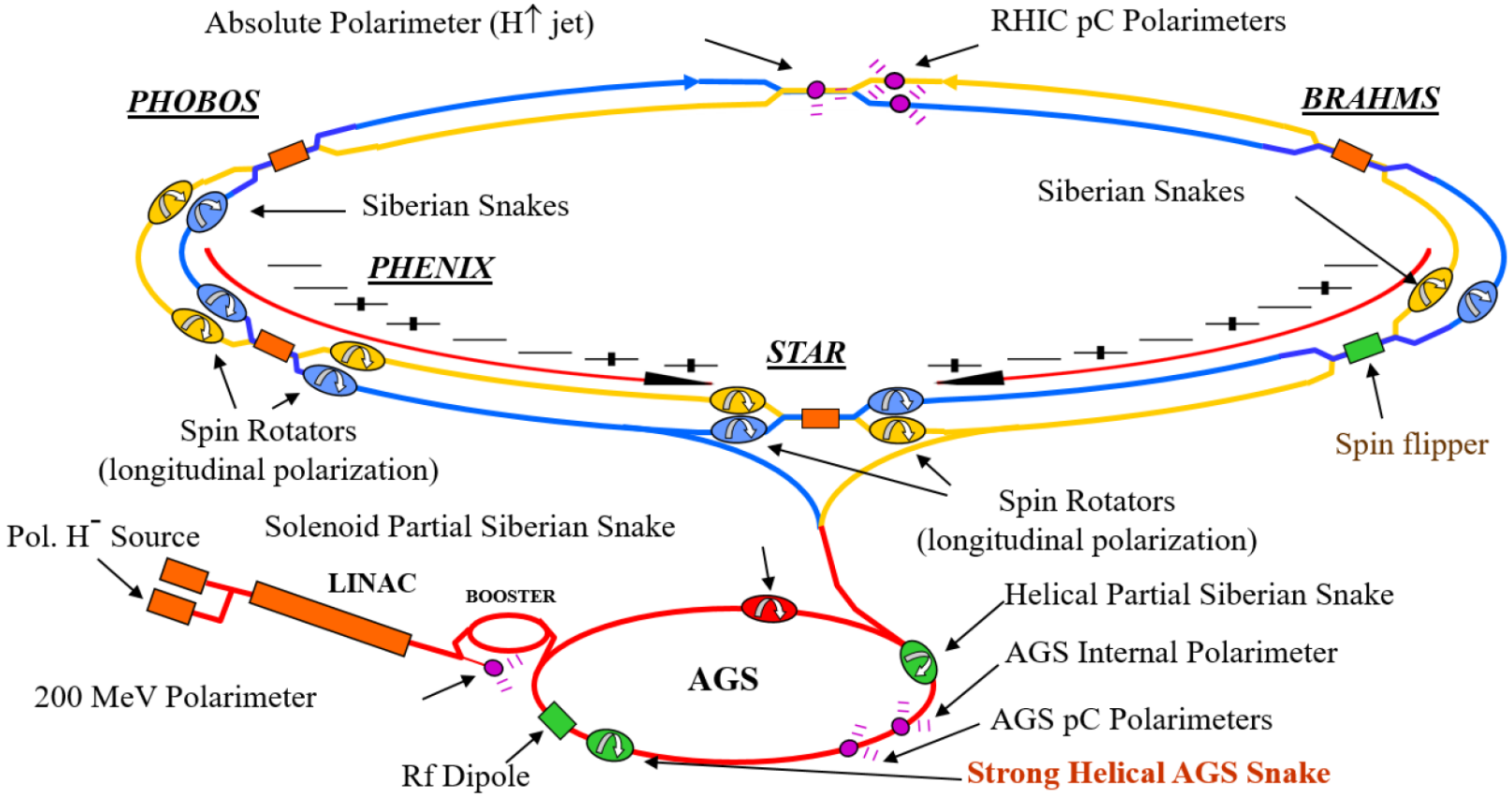
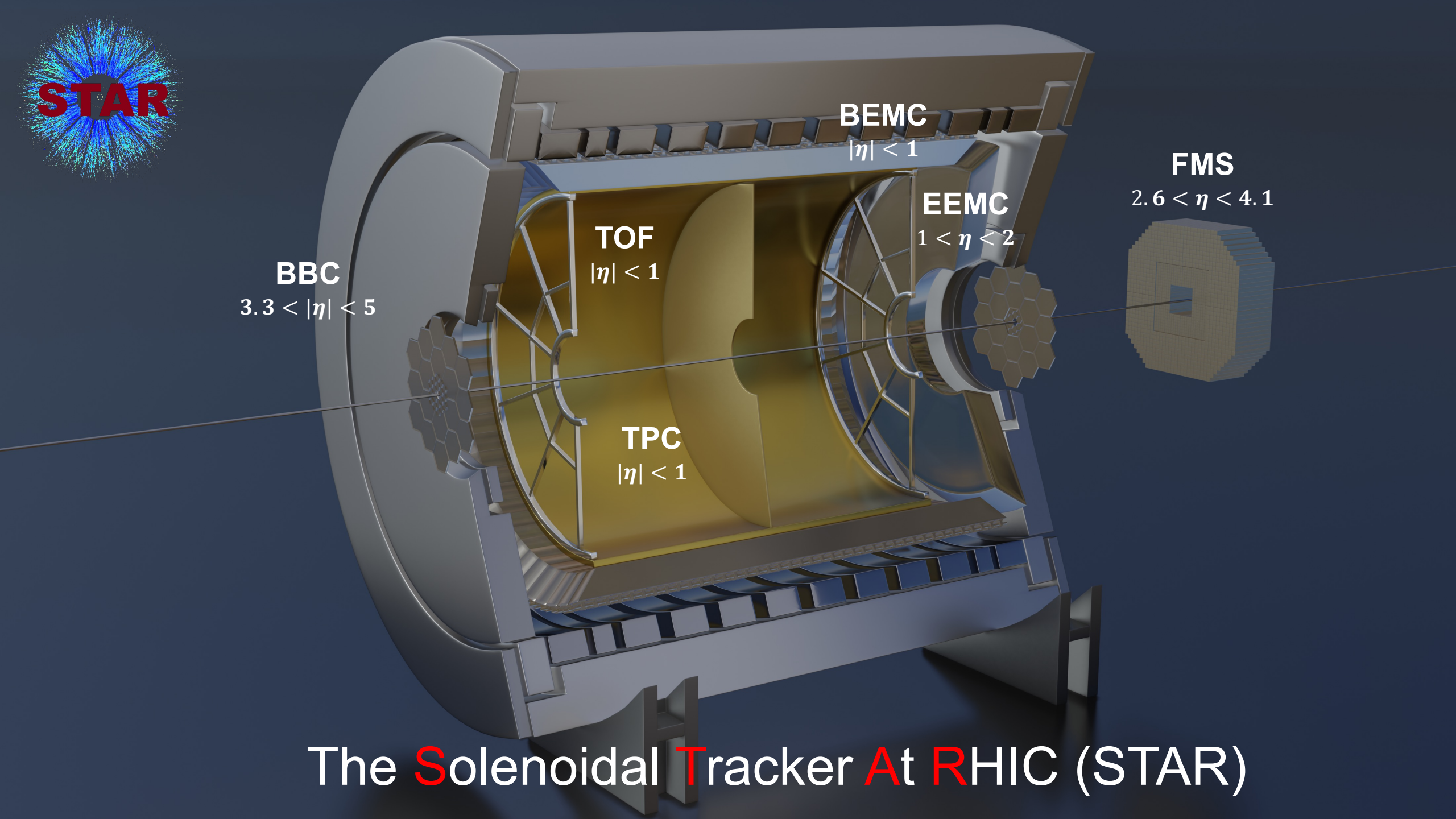


- Spin pattern changes from fill to fill with little depolarization;
- Siberian snakes preserve the polarization;
- Spin rotators select spin orientation;
- proton-Carbon (pC) polarimeters and hydrogen gas jet (H-Jet) measure the polarization.

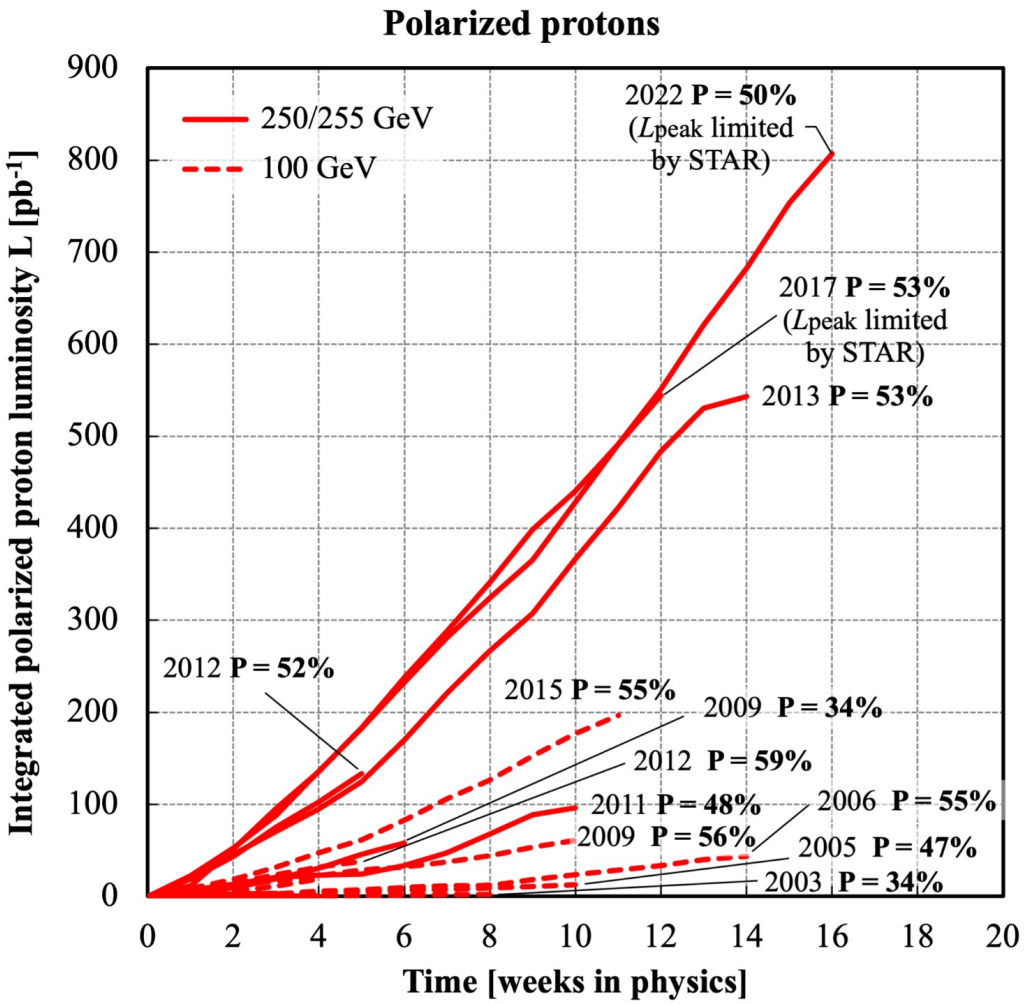


The Solenoidal Tracker At RHIC (STAR)

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%

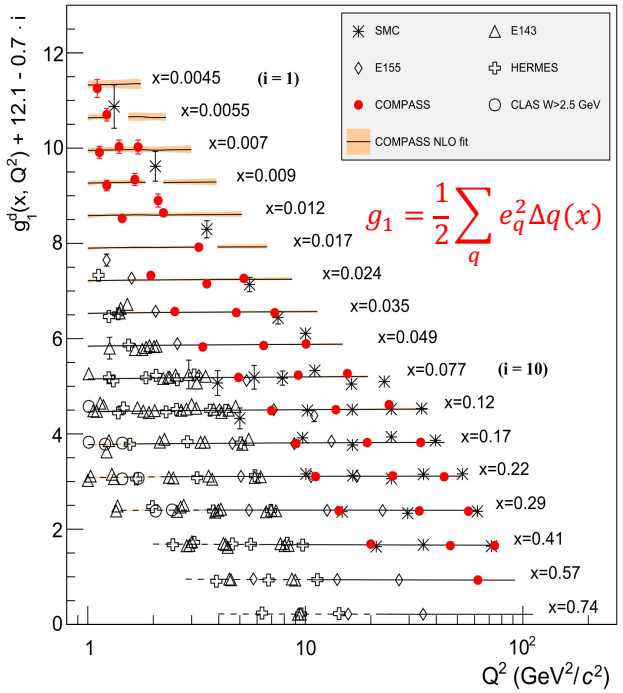
- RHIC has concluded the longitudinal polarized data taking in 2015;
- Most STAR key measurements using the longitudinal polarized data have been published in the last few years, with few to be published soon.



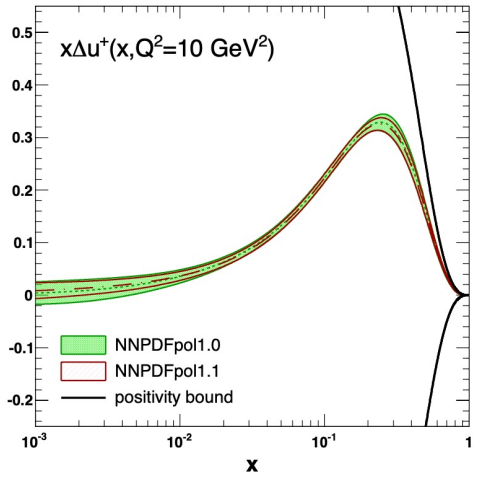
Quark Polarization

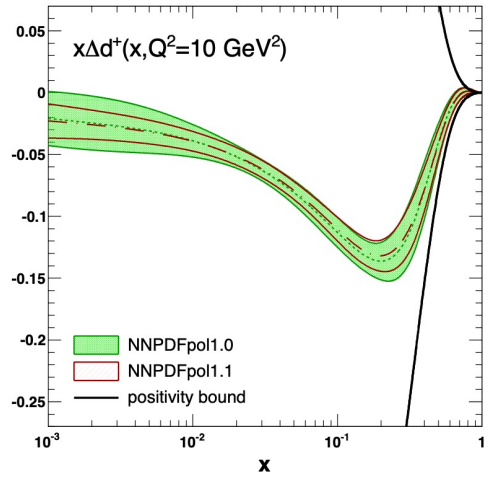
Quark Polarization

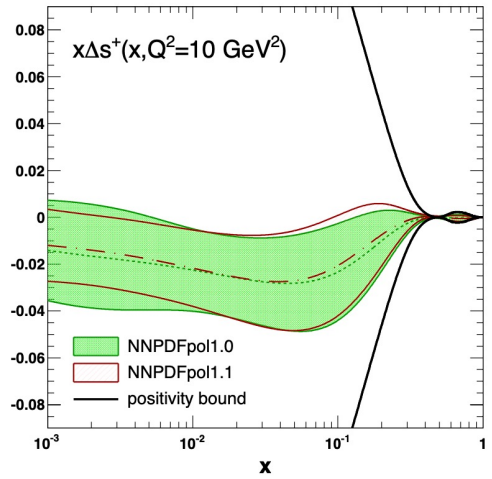
HERMES, PRD 75, 012007 (2007)
COMPASS, PLB 769 (2017) 34–41
NNPDF, Nucl. Phys. B 887, 276 (2014)



$$g_1 = \frac{1}{2}\sum_q e_q^2 \Delta q(x)$$

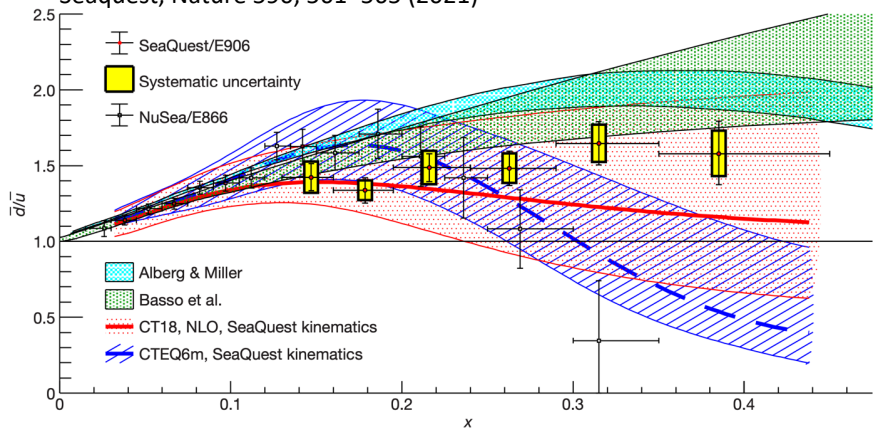






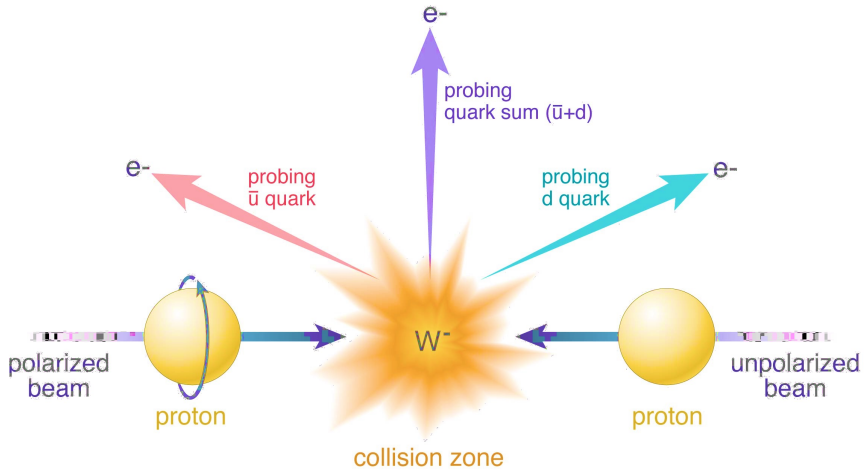
$$\Delta\Sigma = \int \left(\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s}\right)dx$$

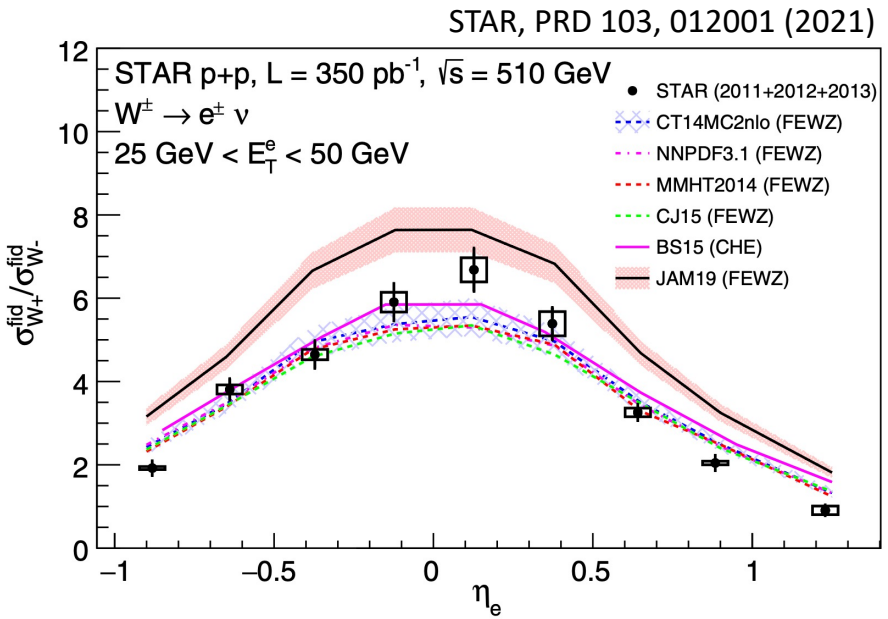
Seaquest, Nature 590, 561–565 (2021)



- Polarized inclusive DIS data measure $\Delta u + \Delta\bar{u}$ and $\Delta d + \Delta\bar{d}$;
  - HERMES: $\Delta\Sigma(Q^2 = 3\mathrm{GeV}) = 0.330 \pm 0.011\ (\mathrm{theo}) \pm 0.025\ (\mathrm{exp}) \pm 0.028\ (\mathrm{evol})$
  - COMPASS: $\Delta\Sigma(Q^2 = 5\mathrm{GeV}) = 0.32 \pm 0.02\ (\mathrm{stat}) \pm 0.04\ (\mathrm{syst}) \pm 0.05\ (\mathrm{evol})$
- Polarized SIDIS data provide flavor separation, but with large uncertainties;
- Surprising results were found in the unpolarized anti-quark distributions;
- Might the polarized anti-quark distributions also contain surprises?

Anti-Quark Polarization via $W^{\pm}$ Bosson





$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

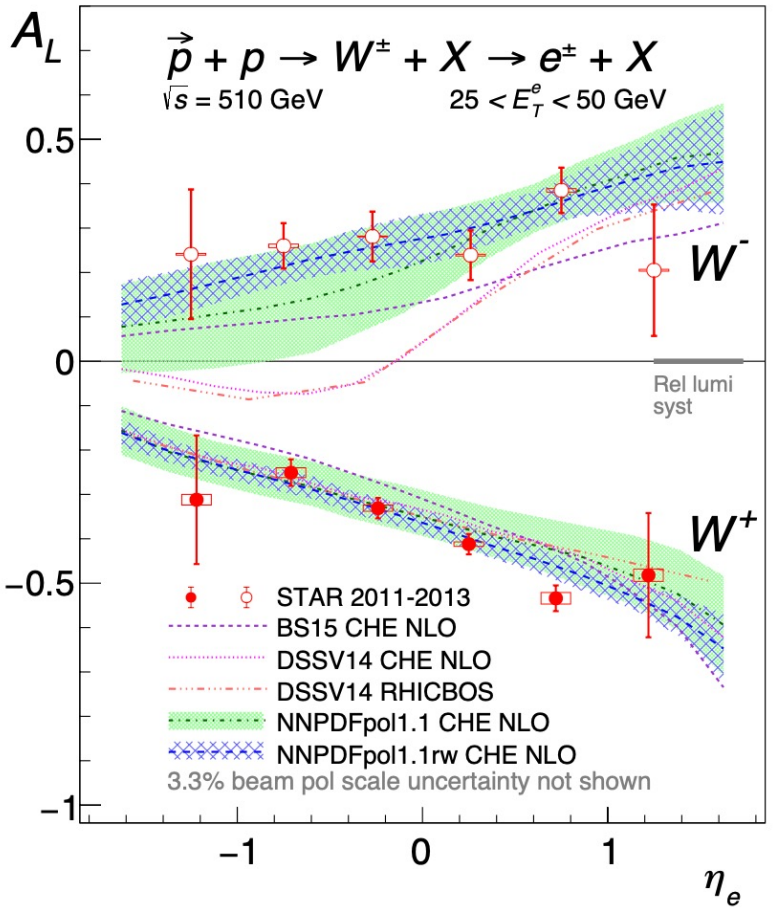
$$A_L^{W^+} \propto \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \simeq \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_W \gg 0 \ (x_1 \gg x_2) \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_W \ll 0 \ (x_1 \ll x_2) \end{cases}$$

$$A_L^{W^-} \propto \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} \simeq \begin{cases} -\dfrac{\Delta d(x_1)}{d(x_1)}, & y_W \gg 0 \ (x_1 \gg x_2) \\ \dfrac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}, & y_W \ll 0 \ (x_1 \ll x_2) \end{cases}$$

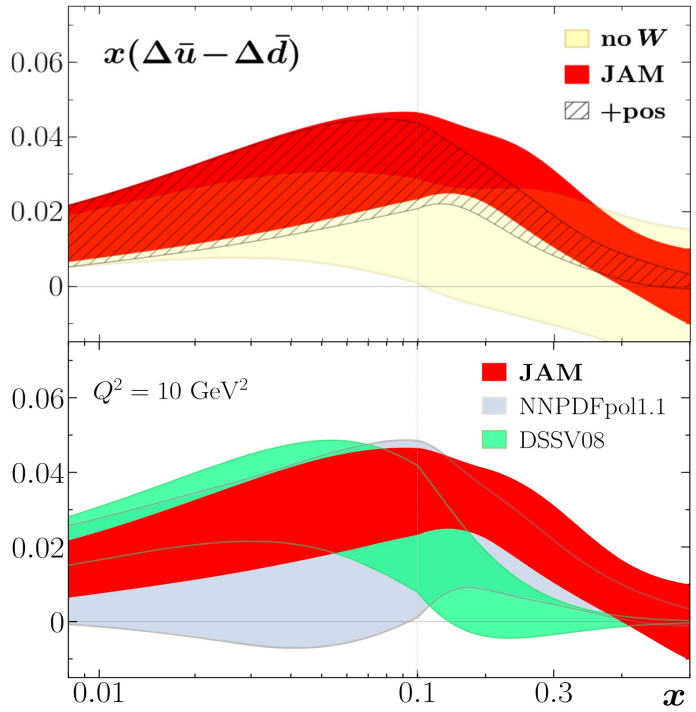
- Only left-handed quarks and right-handed anti-quarks participate;
- No fragmentation function uncertainties;
- $W^{\pm}$ measurement at RHIC provides a unique way to delineate the flavor structure of proton spin.

Anti-Quark Polarization from STAR

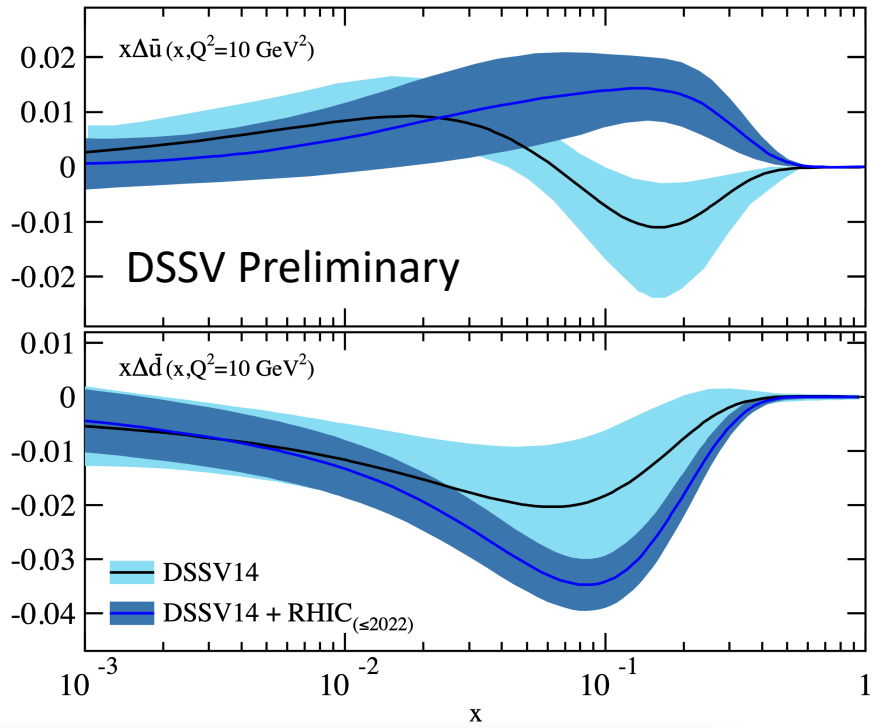
STAR, PRD 99, 051102(R) (2019)



JAM, PRD 106, L031502 (2022)



The RHIC Cold QCD Program, arXiv:2302.00605

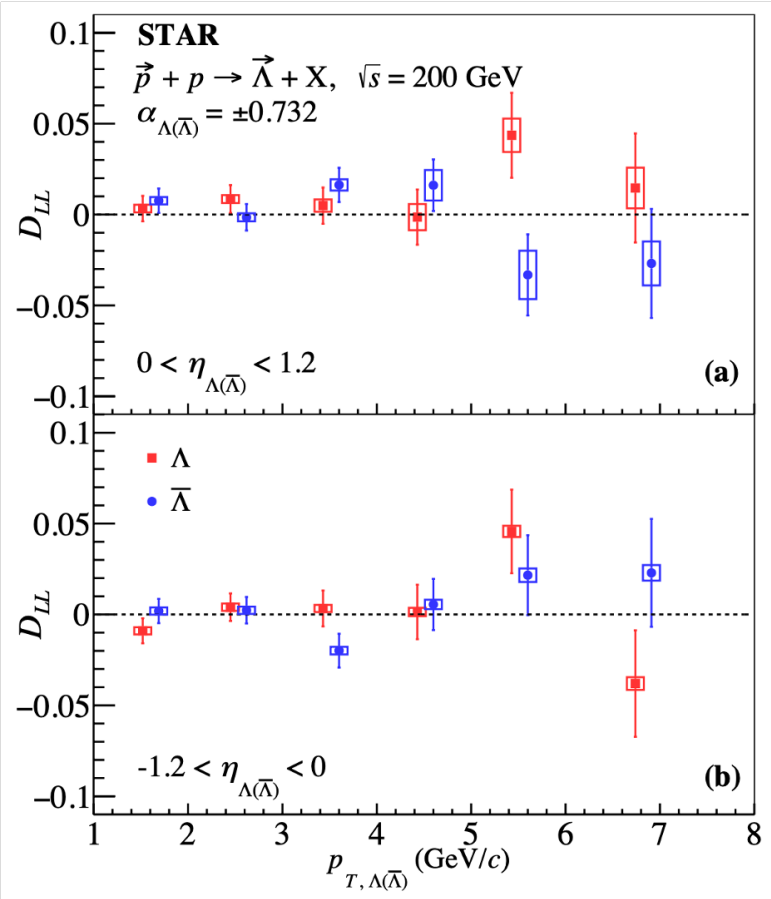


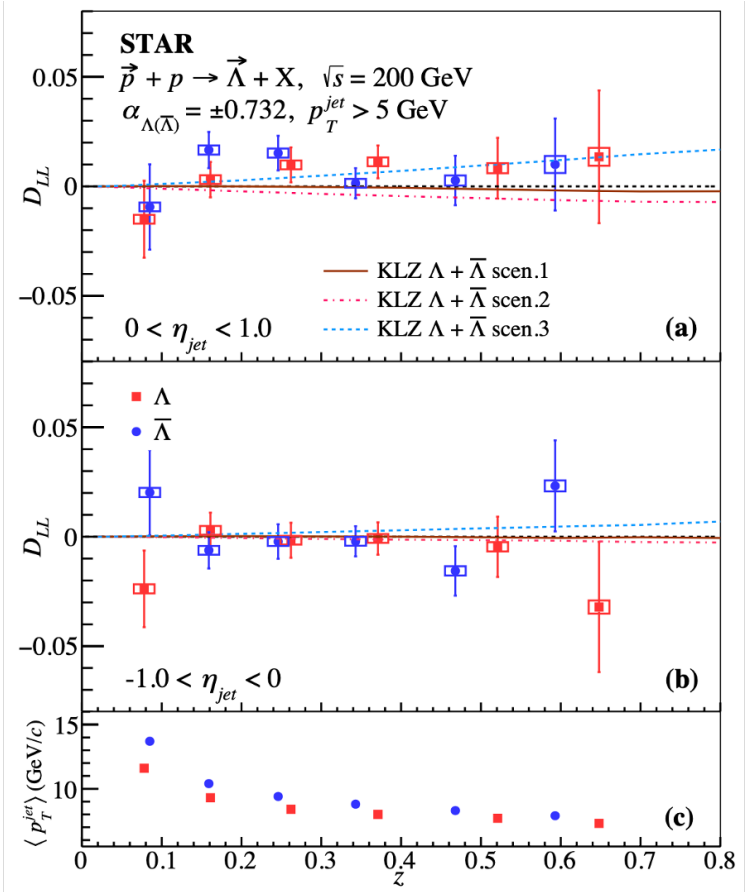
- Clearly demonstrate that $\Delta\bar{u} > \Delta\bar{d}$;
- This is opposite from the unpolarized distributions, which has $\bar{d} > \bar{u}$.

Strange Quark Polarization

See Qinghua Xu's talk
Sep. 26, 2023, 10:00 AM
3D Structure of the Nucleon

STAR, arXiv:******





$$D_{LL} = \frac{d\sigma^{(p^+p\to\Lambda^+X)} - d\sigma^{(p^+p\to\Lambda^-X)}}{d\sigma^{(p^+p\to\Lambda^+X)} + d\sigma^{(p^+p\to\Lambda^-X)}}$$

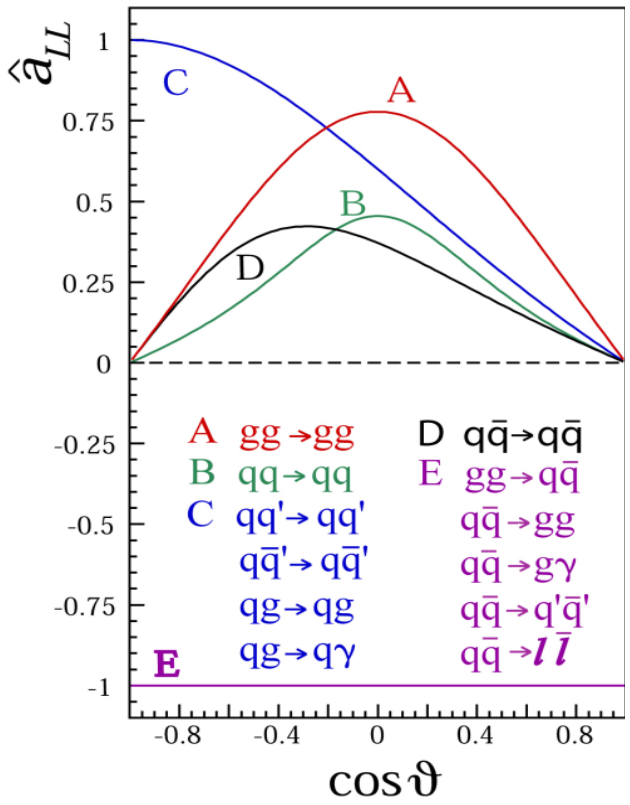
$$\frac{dN}{d\cos\theta^*} \propto A(1 + \alpha_\Lambda P_\Lambda \cos\theta^*)$$

- These results provide insights into the strange quark and anti-quark helicity distributions in the proton;
- The first measurement of the D_{LL} $vs.$ z directly probes the polarized fragmentation functions.

Gluon Polarization

Probing the Gluon Helicity at RHIC

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



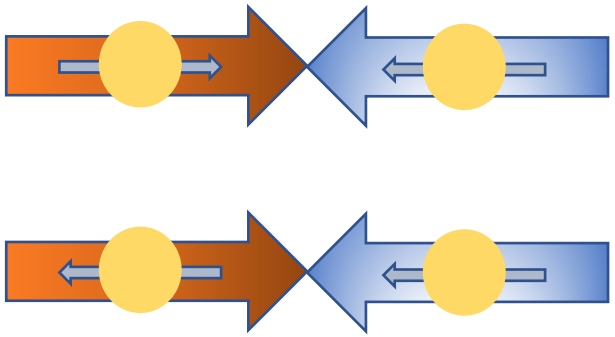
What we measured

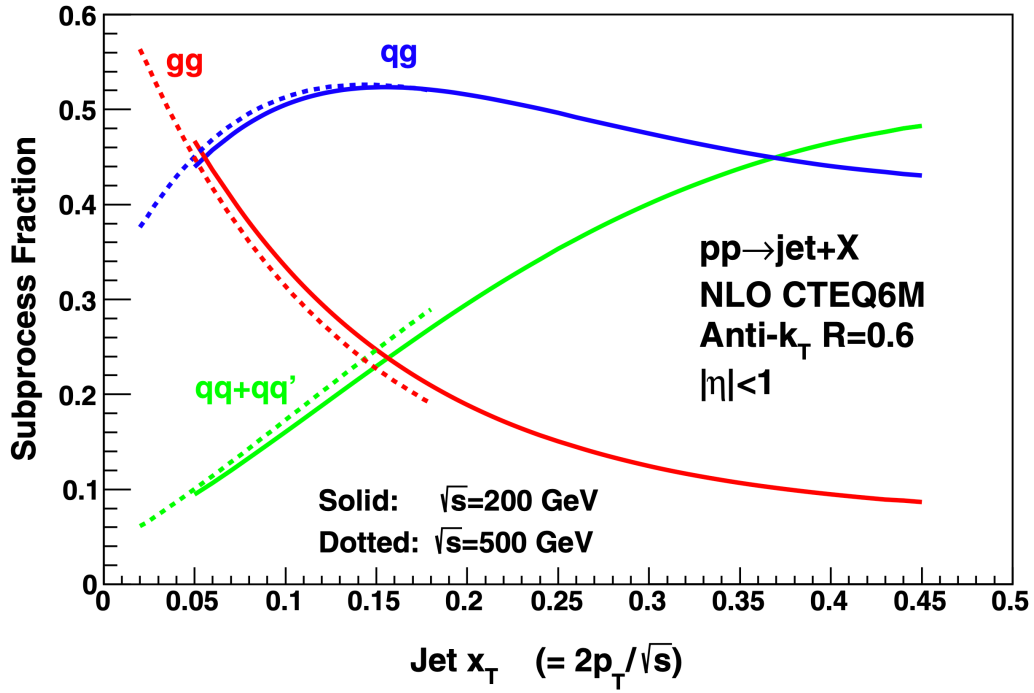
What we hope to learn

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

Measured by others

Calculable

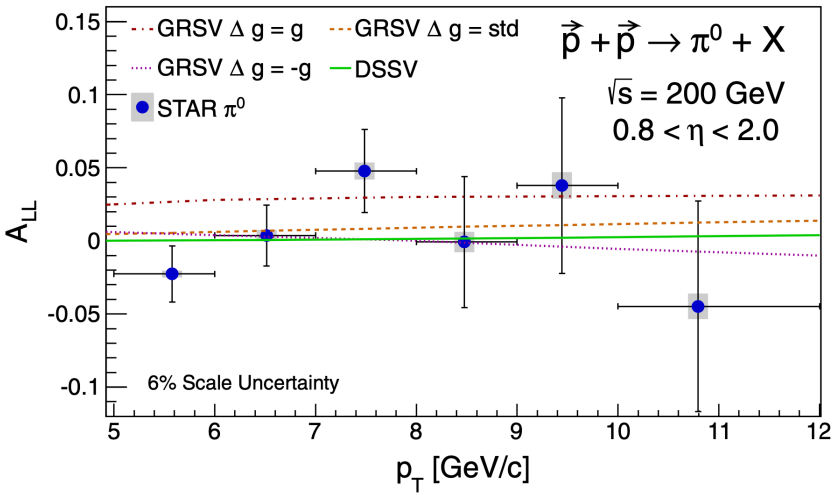


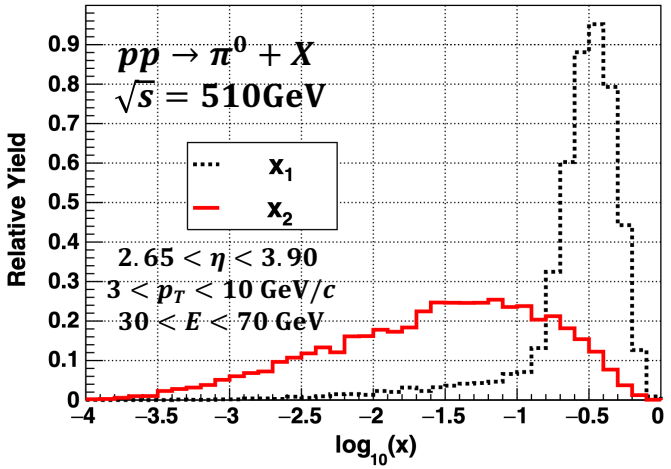


- At the parton level, helicity correlations are very large in leading-order QCD;
- For most RHIC kinematics, gg and qg dominate, making A_{LL} sensitive to gluon polarization.

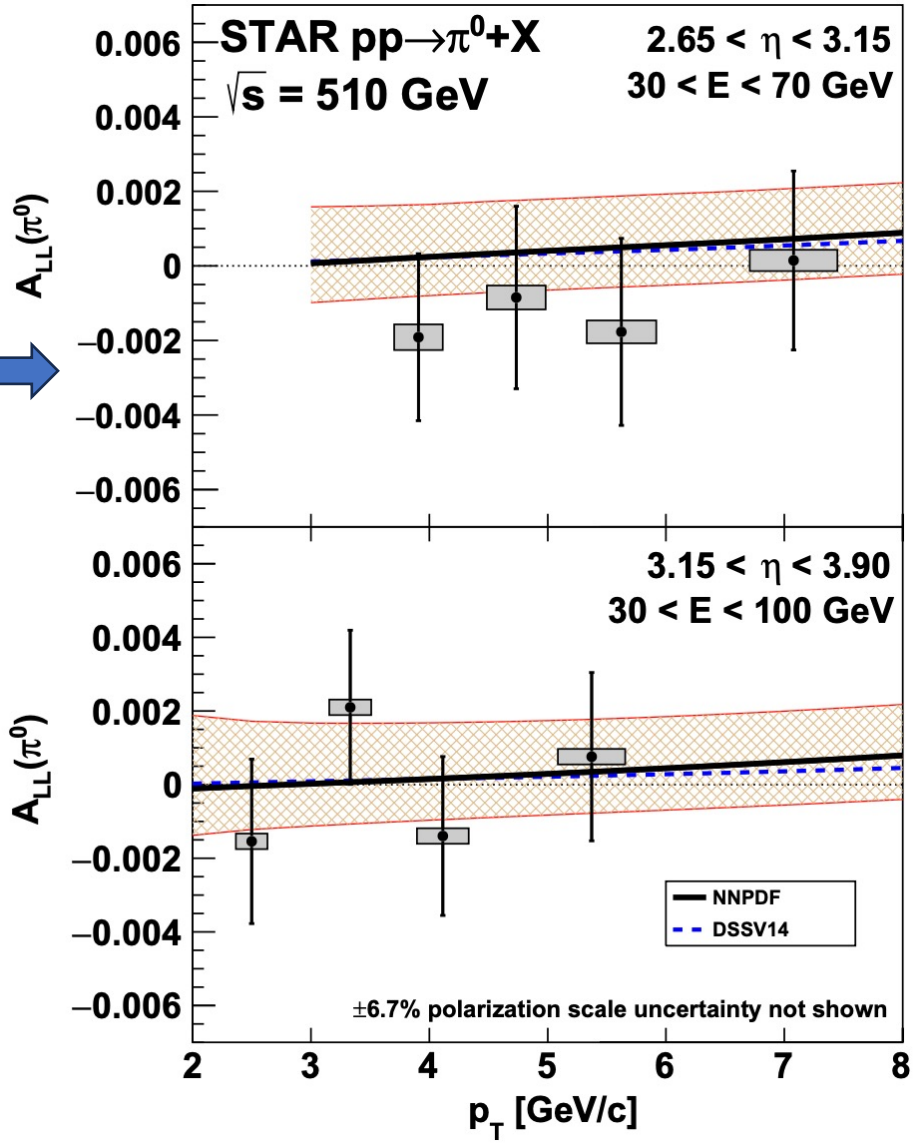
A_{LL} Results from π^0 Production

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

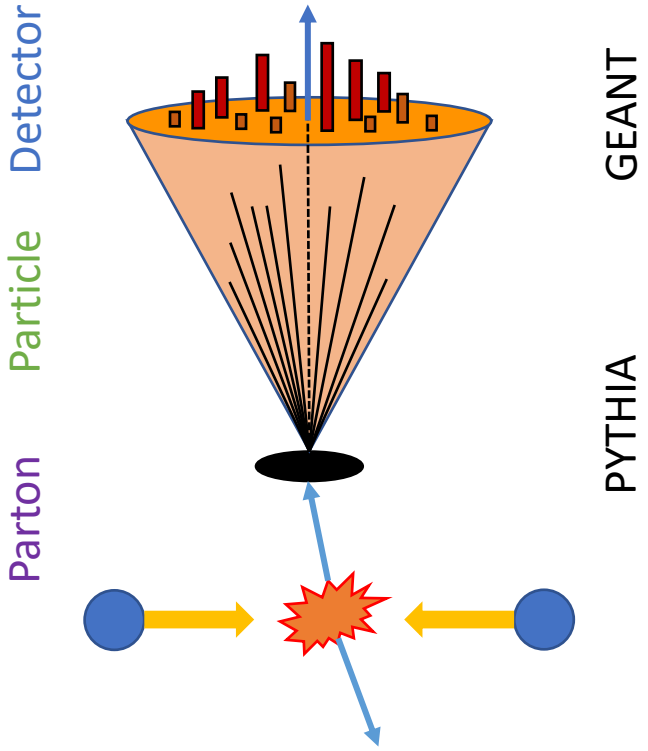
Anti-k_T Algorithm:

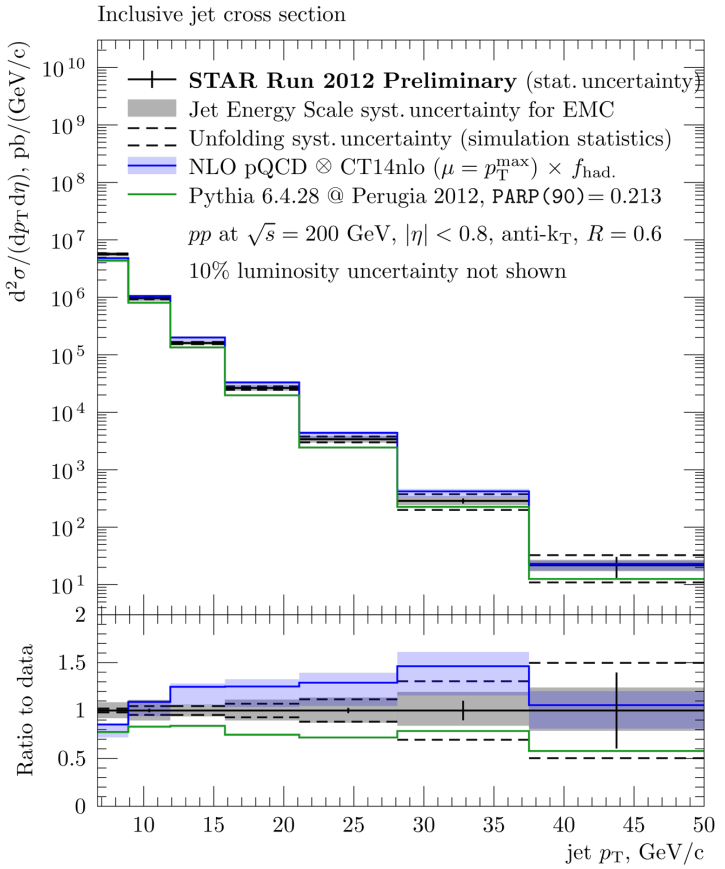
- Radius = 0.6 for pp 200 GeV
- Radius = 0.5 for pp 510 GeV

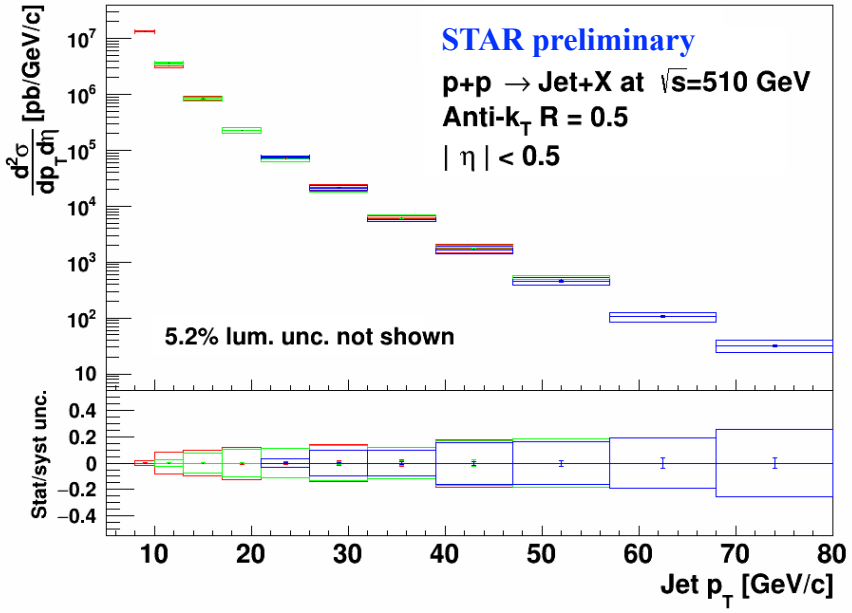
Simulation:

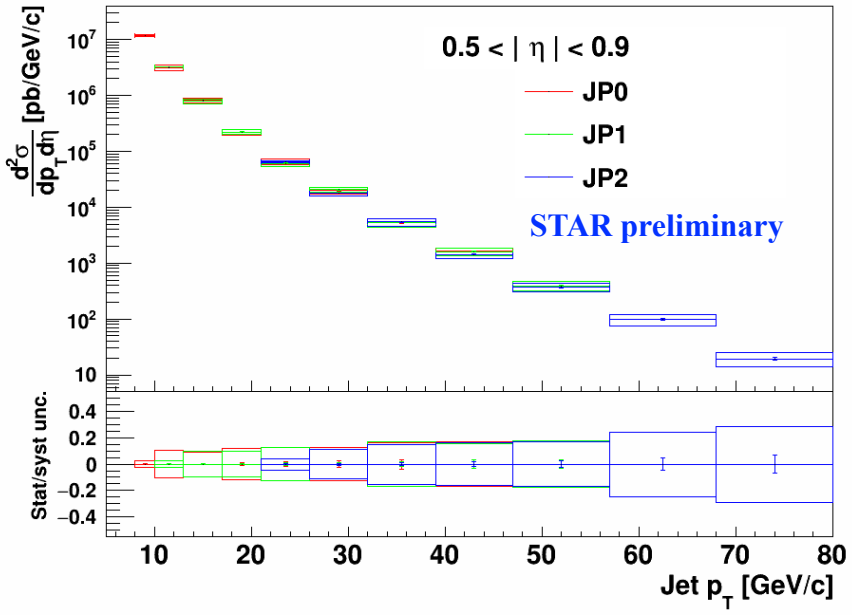
- PYTHIA 6.4 Perugia0
- PYTHIA 6.4 Perugia2012, PARP(90) = 0.213

Jet Levels **MC Jets**



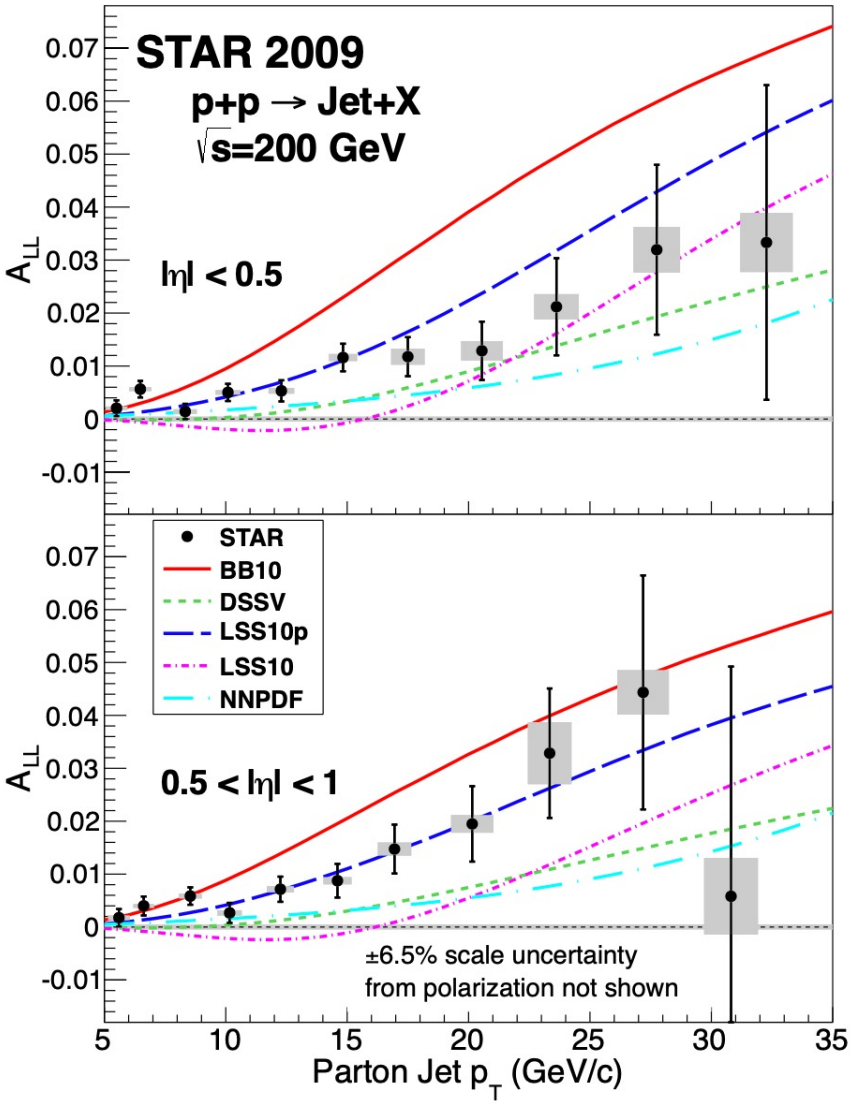




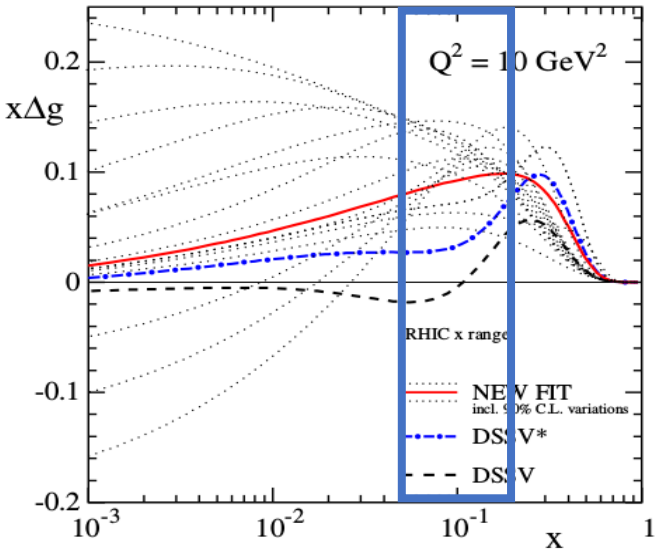


Evidence of Positive ΔG

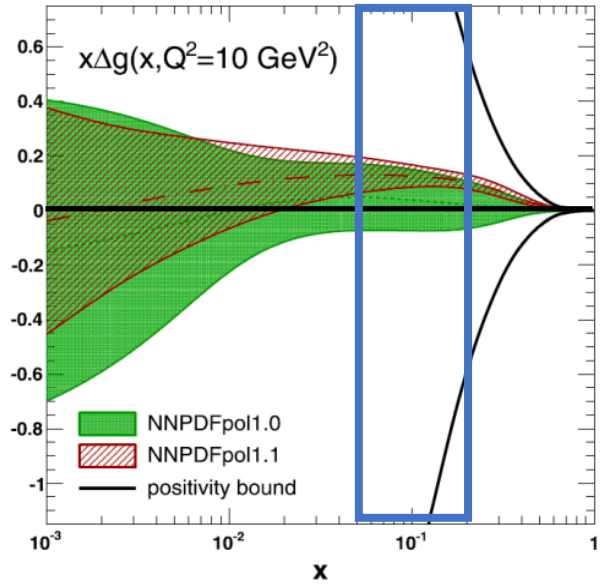
STAR, PRL **115**, 092002 (2015)



DSSV, PRL 113, 012001(2014)



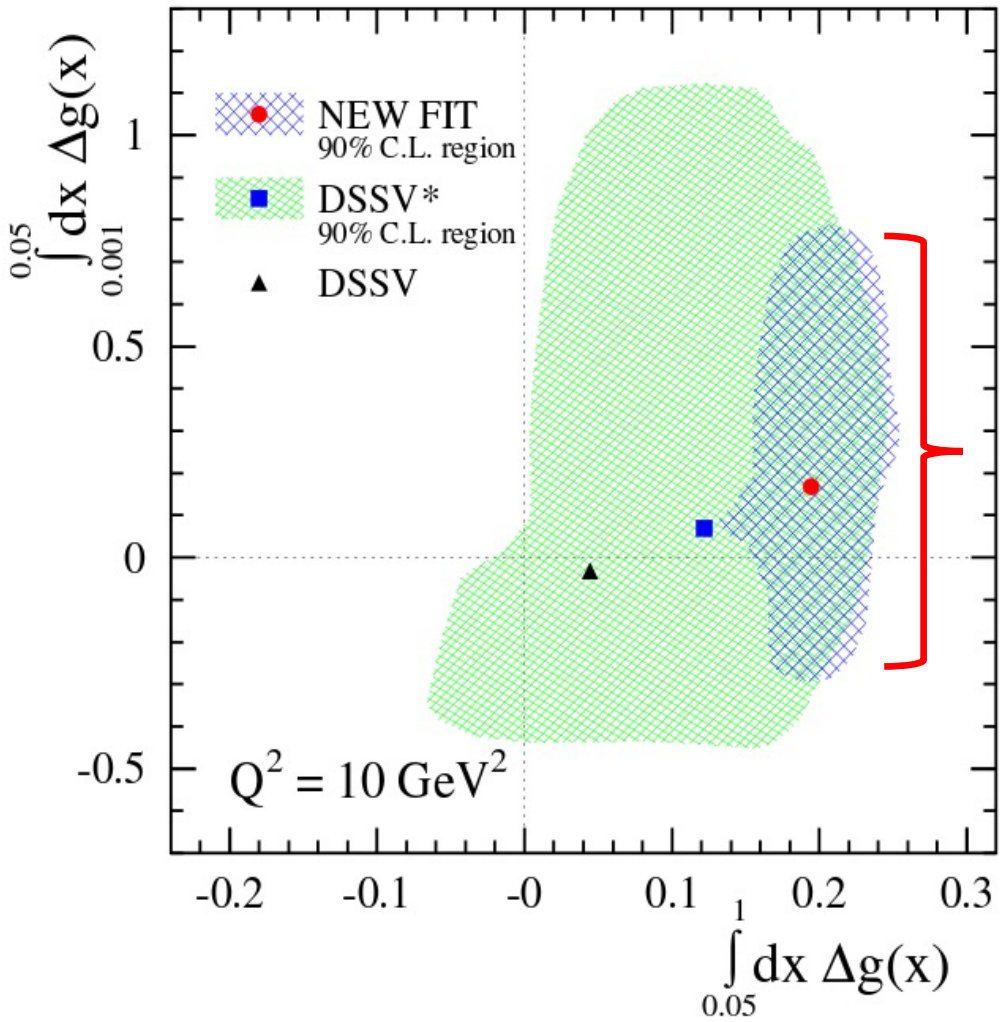
NNPDF, Nucl. Phys. B 887, 276 (2014)



- 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: $\Delta G = \int_{0.05}^{1} \Delta g(x)dx = 0.20 \pm 0.06$

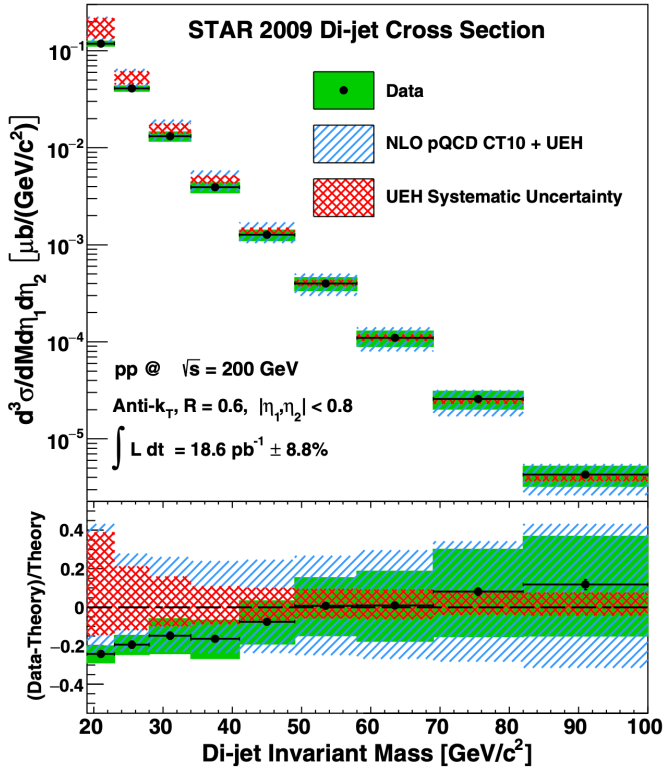
Gluon Polarization with RHIC Data

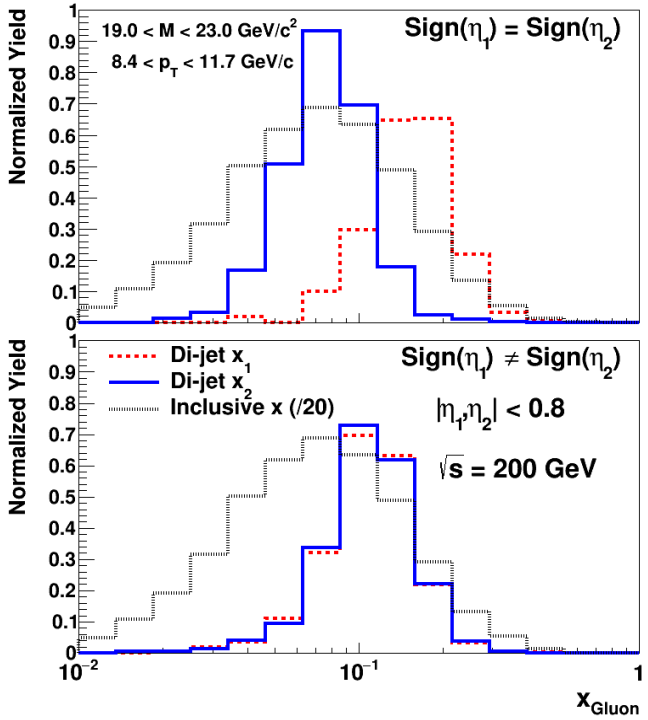
DSSV PRL 113, 012001(2014)



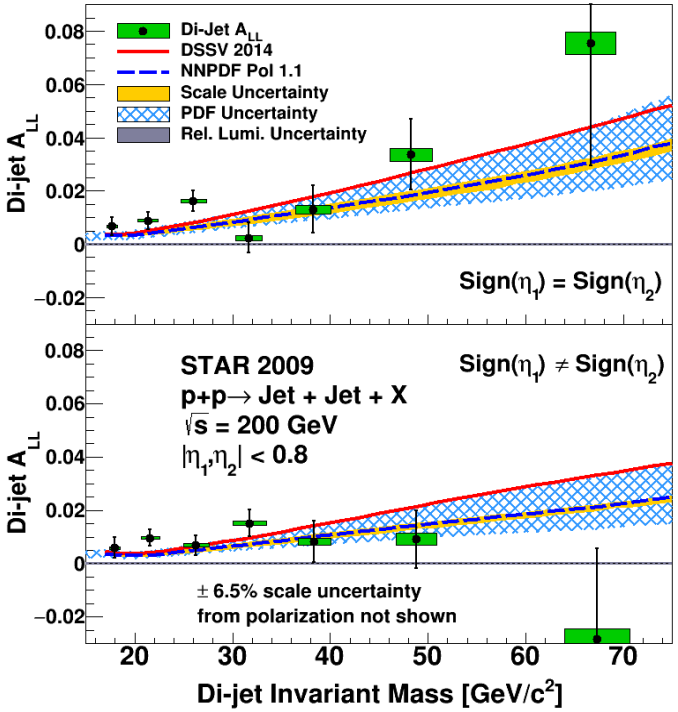
- The low x behavior and shape of Δg(x) are still poorly constrained:
  - $\Delta G = \int_{0.05}^{1} \Delta g(x) dx = 0.20 \pm 0.06$
  - $\Delta G = \int_{0.001}^{0.05} \Delta g(x) dx = 0.15 \pm 0.50$
- STAR's strategies to explore low-*x* regime:
  1. Extend to dijet measurement;
  2. Reconstruct jet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

Mid-Rapidity Dijet A_{LL}



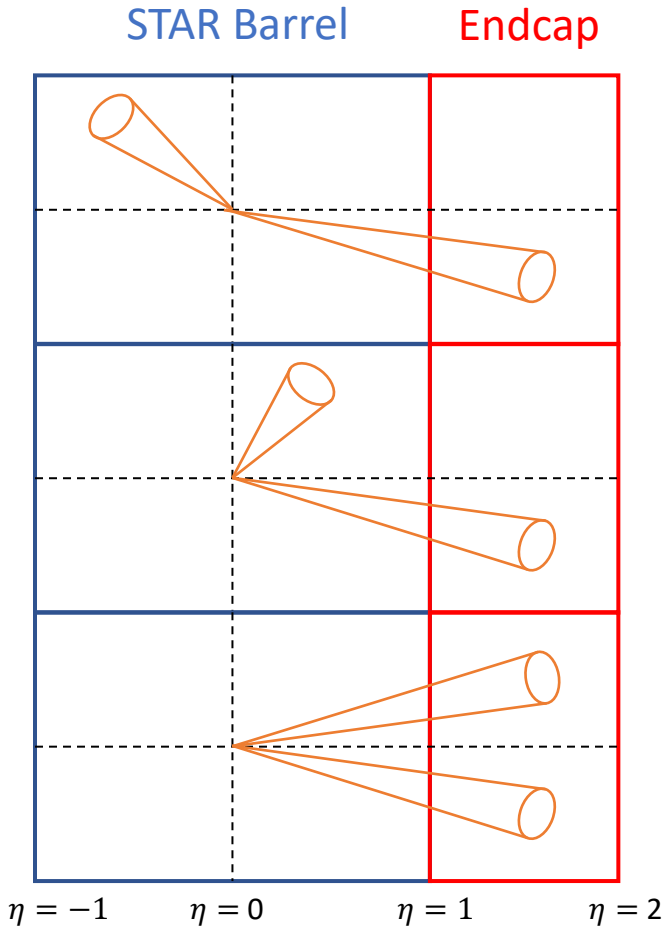


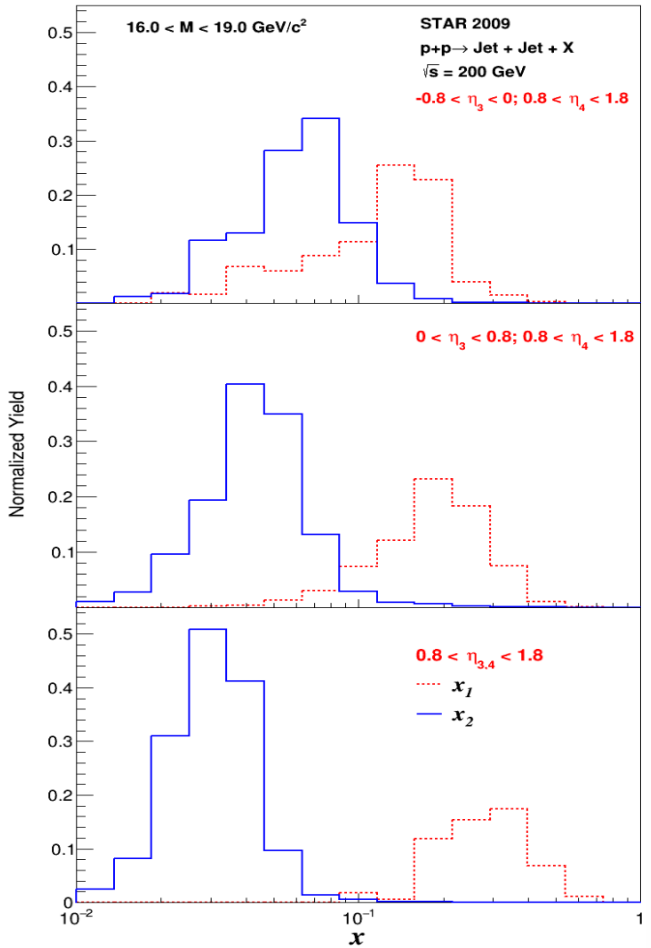
STAR, Phys. Rev. D 95, 071103 (2017)



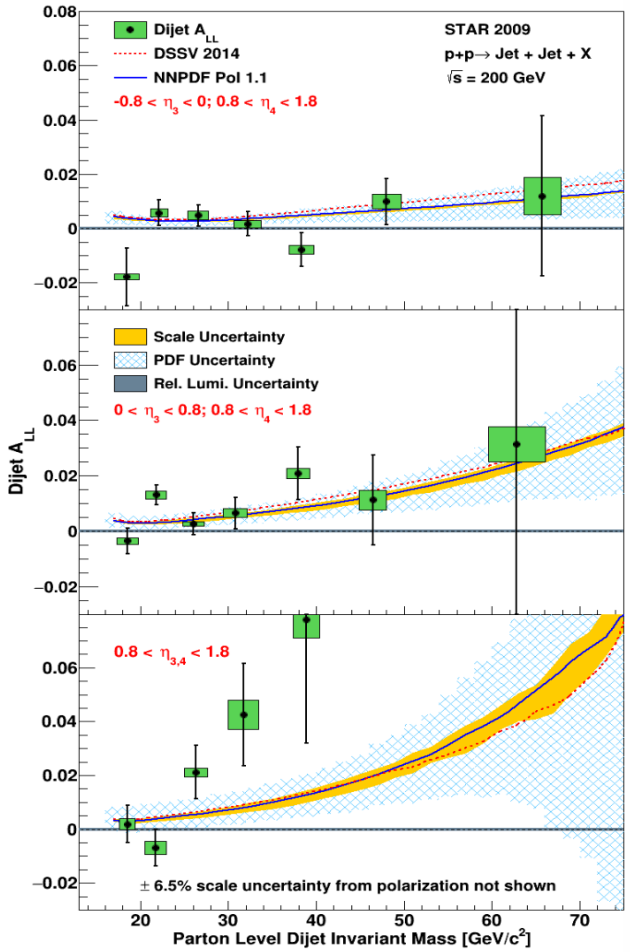
- Dijet measurements capture more information from the hard scattering and provide a more direct link to the initial parton level kinematics than inclusive measurements;
- Mid-rapidity di-jet A_{LL} presented for two topologies as a function of di-jet invariant mass corrected to parton level;
- Data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

Intermediate Rapidity Dijet A_{LL}



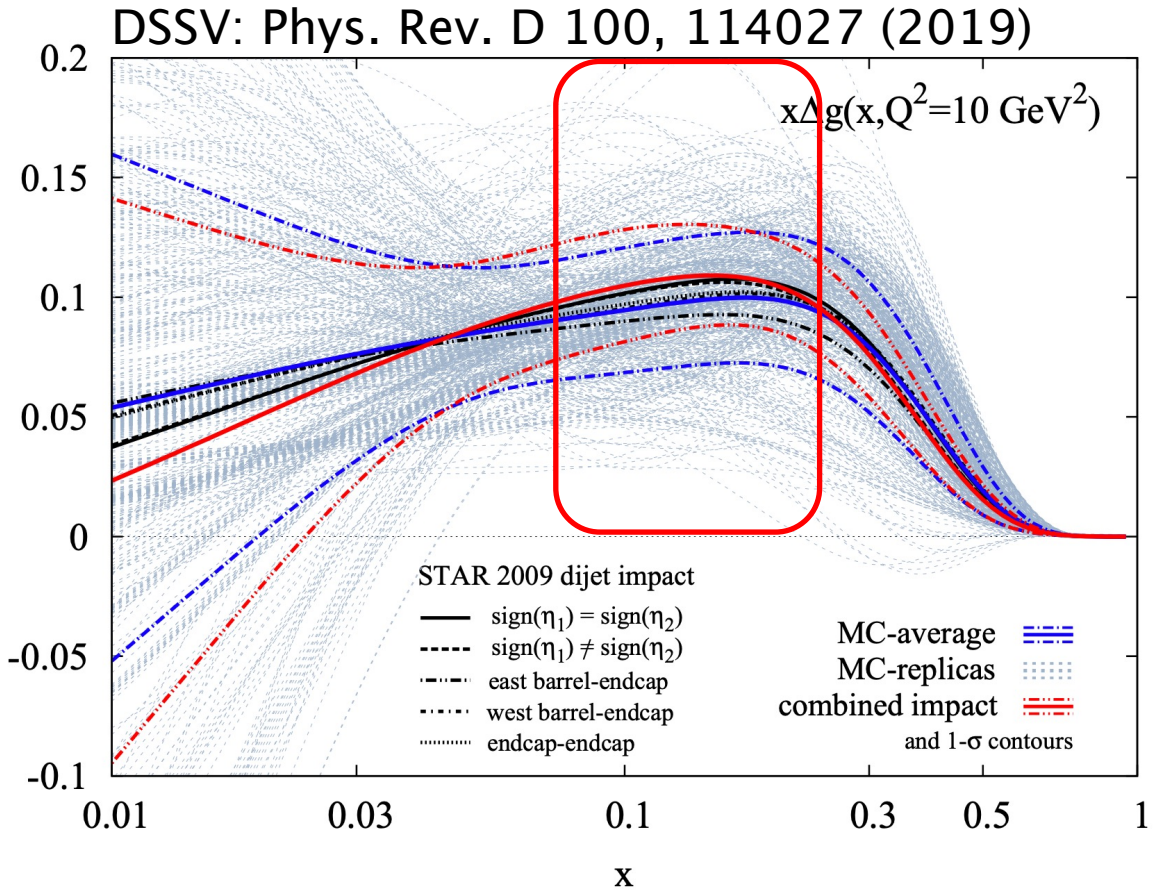


STAR, Phys. Rev. D 98, 032011 (2018)



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

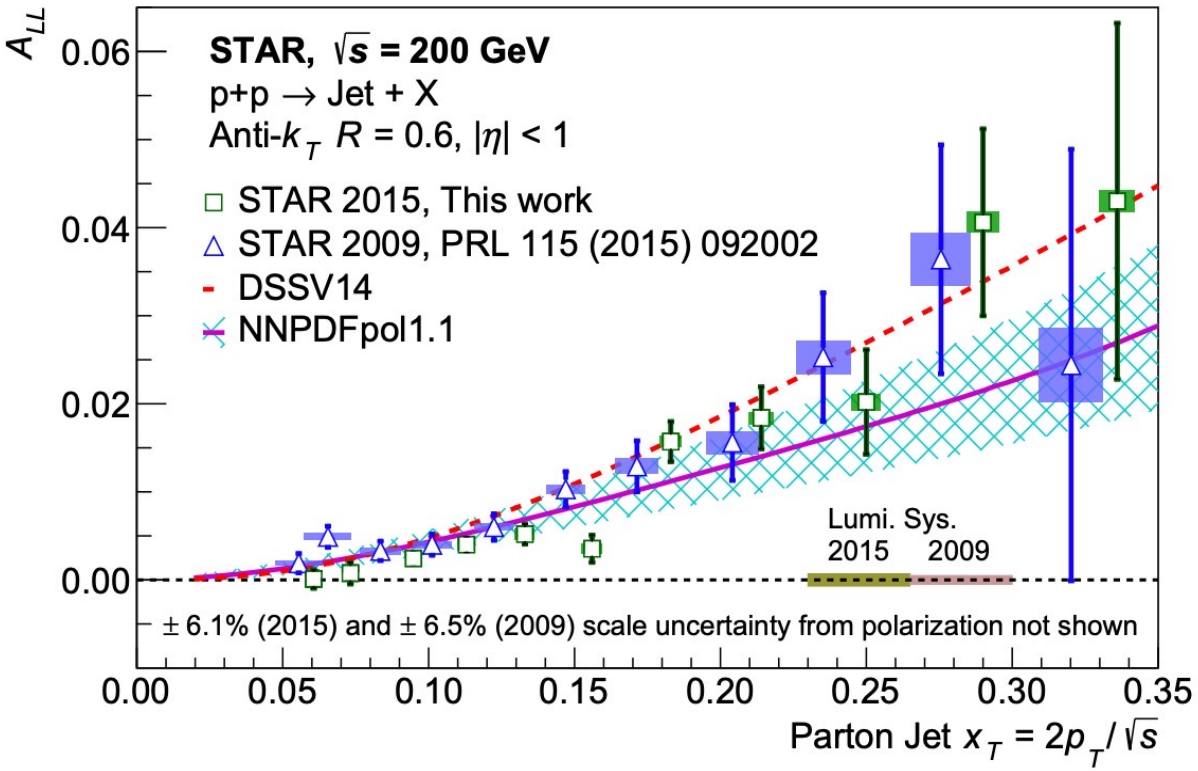
Impact of the Dijet Results:



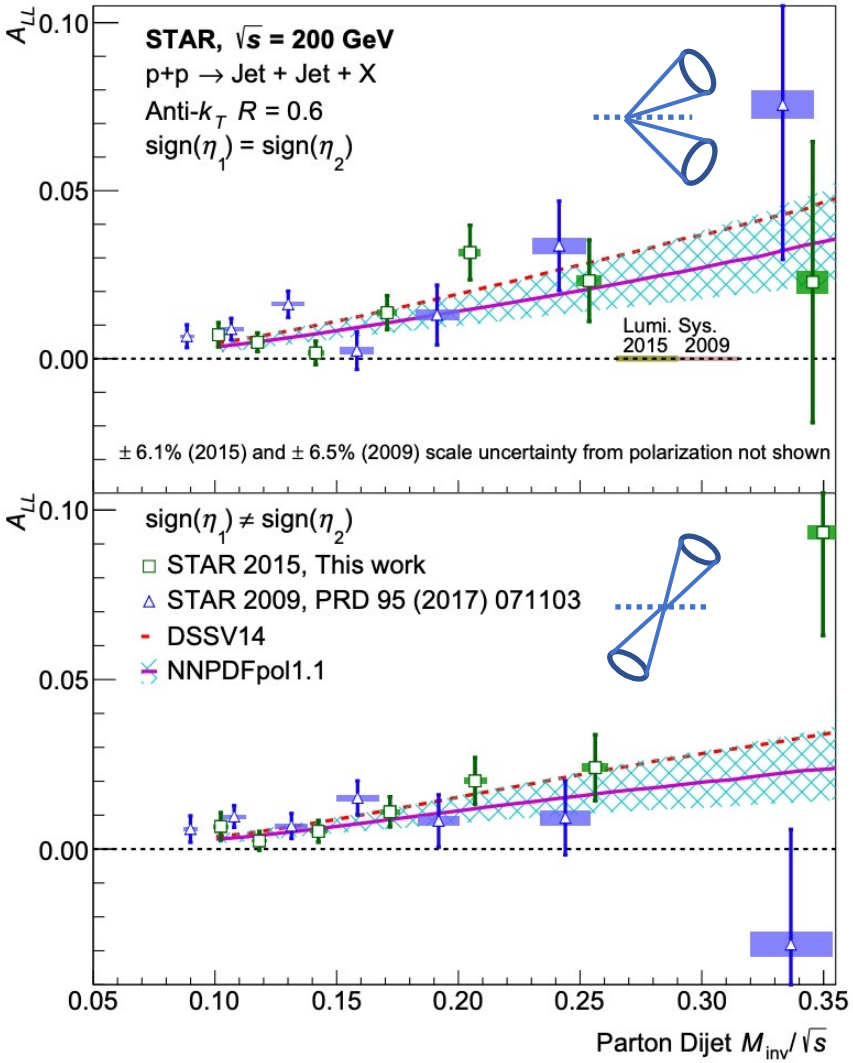
- Gluon polarization in the region ***x* > 0.1**:
  - before: $\Delta G = \int_{0.1}^{1} \Delta g(x)dx = 0.133 \pm 0.035$
  - after: $\Delta G = \int_{0.1}^{1} \Delta g(x)dx = 0.126 \pm 0.023$
- In the region ***x* > 0.01**:
  - before: $\Delta G = \int_{0.01}^{1} \Delta g(x)dx = 0.309 \pm 0.109$
  -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



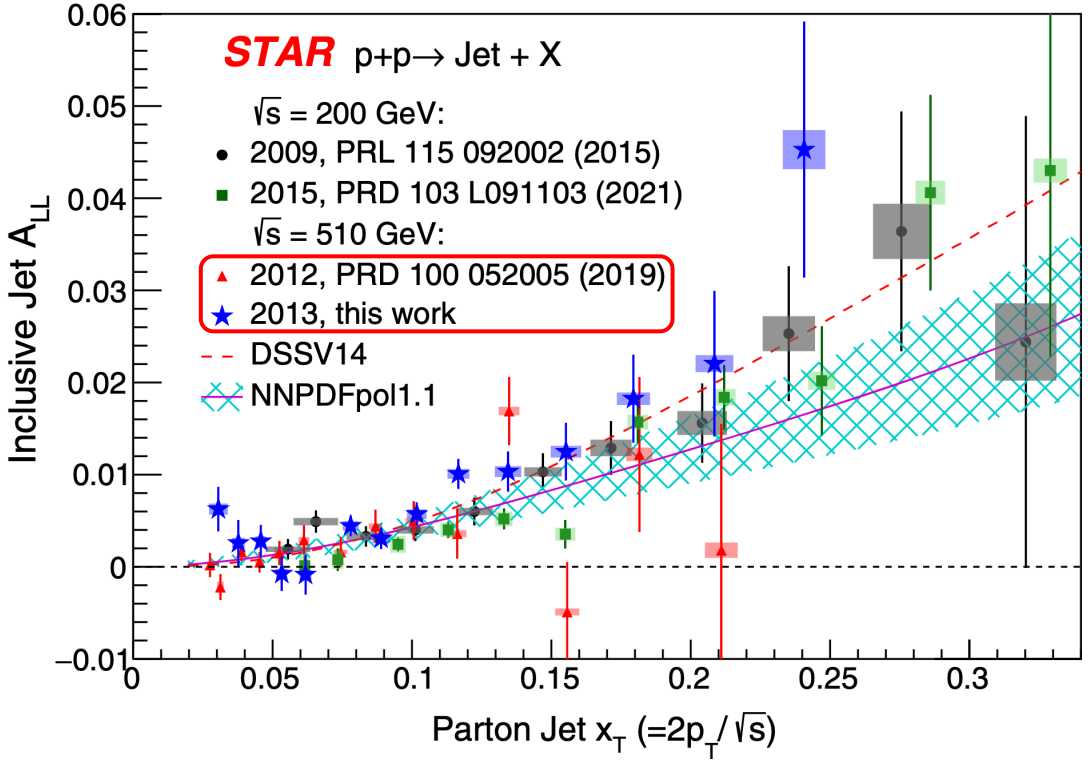
Year and $\sqrt{s}$	STAR L $[pb^{-1}]$
$\sqrt{s} = 200$ GeV	
2009	25
2015	52
$\sqrt{s} = 510$ GeV	
2012	82
2013	300



- 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 $[pb^{-1}]$
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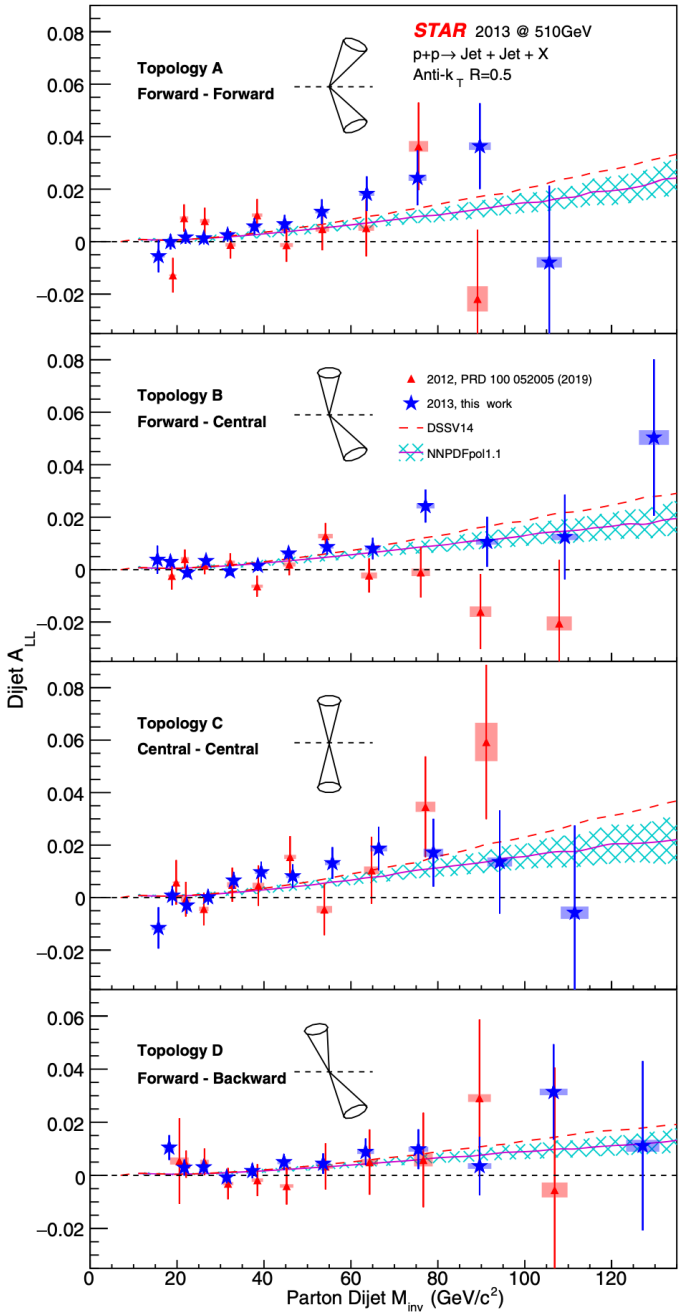
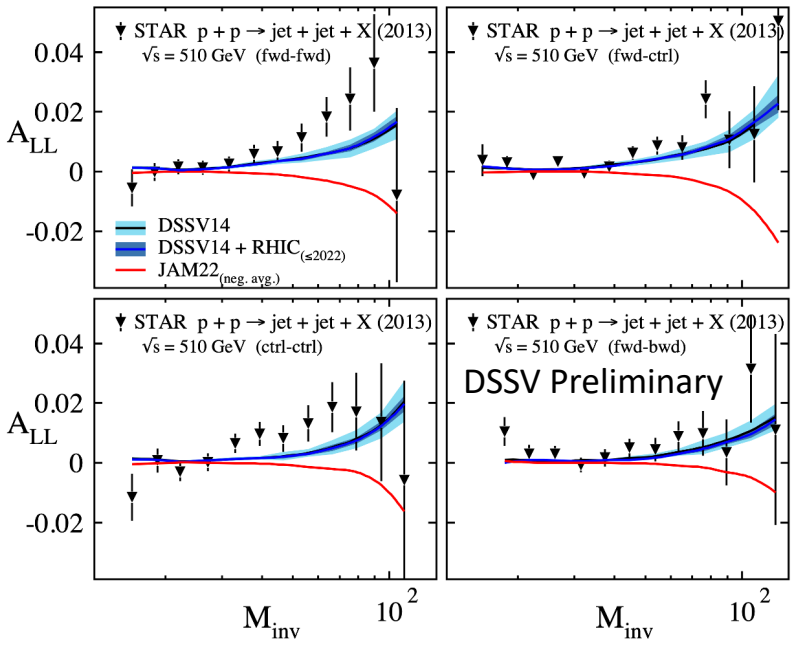
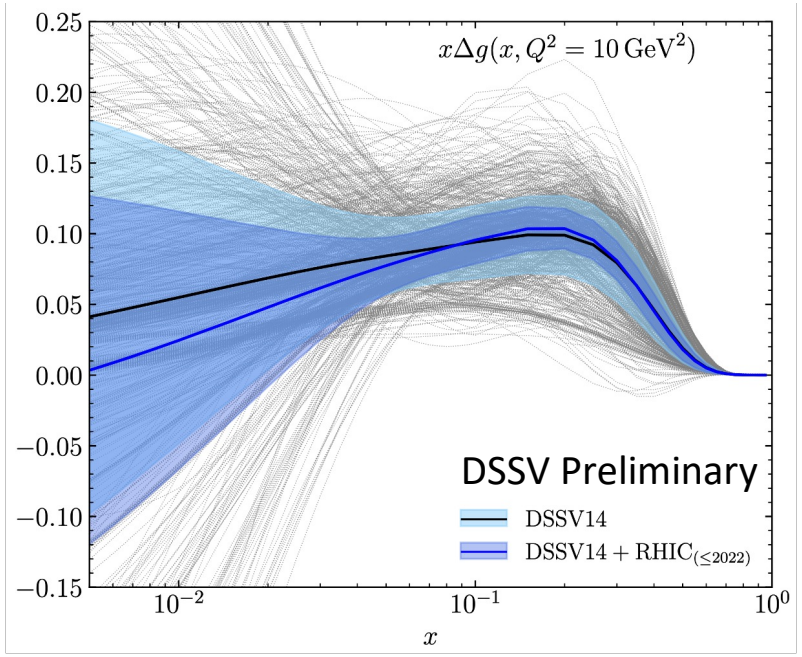
2012	82
2013	300



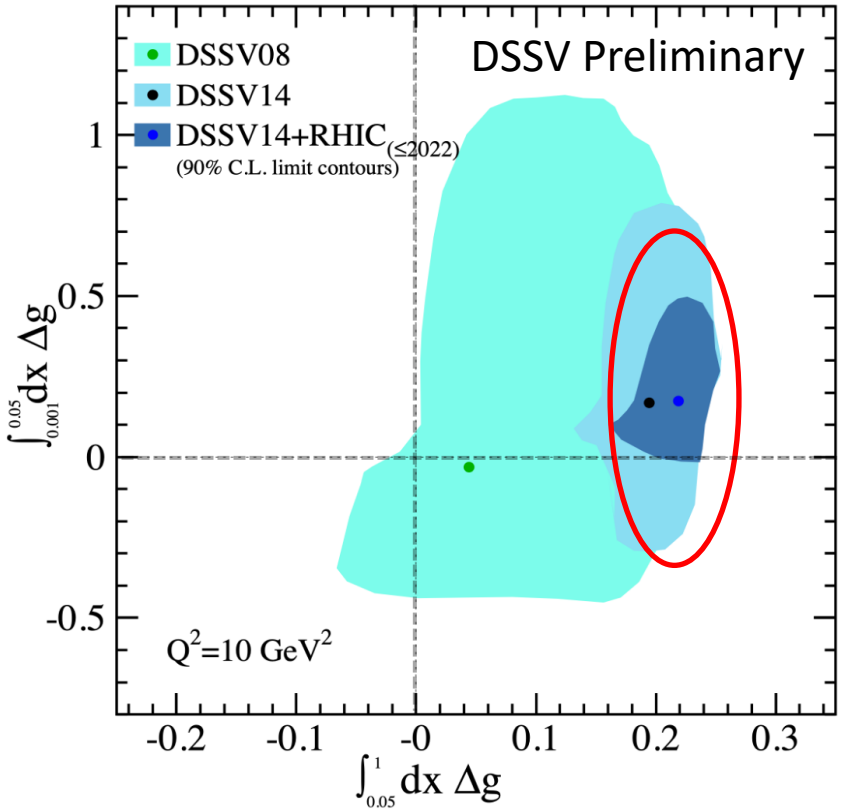
- Higher center-of-mass energy probes lower x partons;
- Plotted vs x_T , overall consistency seen among STAR data sets;
- Well described by global fits that previously gave a good description of the 200 GeV results.

Impact of the RHIC Results





The RHIC Cold QCD Program, arXiv:2302.00605

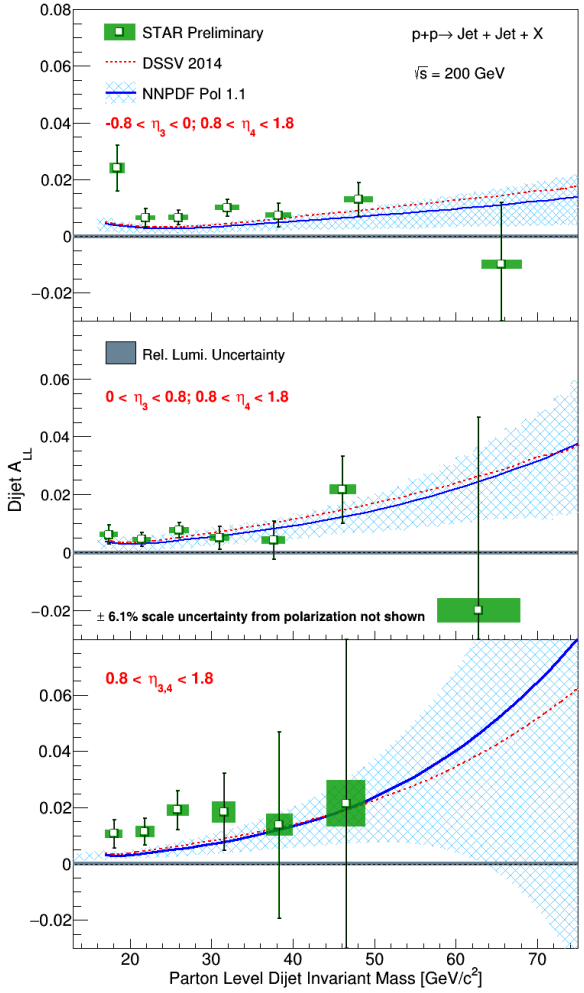


- New results from RHIC shows significant impact when constraining the gluon helicity distribution;
- STAR dijet data disfavor distributions with large and negative gluon polarization.

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 Dijet A_{LL} at Intermediate Pseudorapidity



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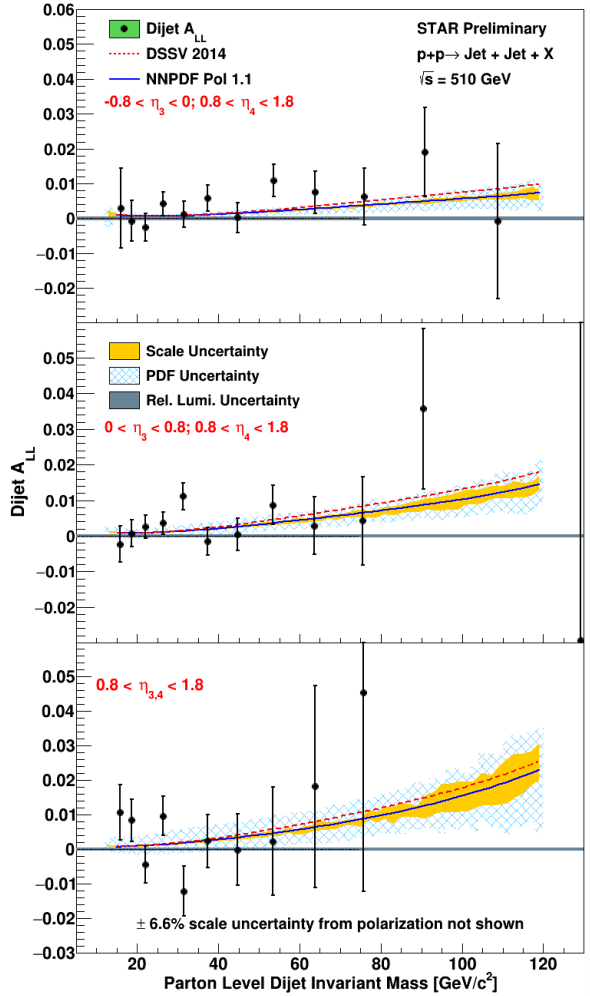
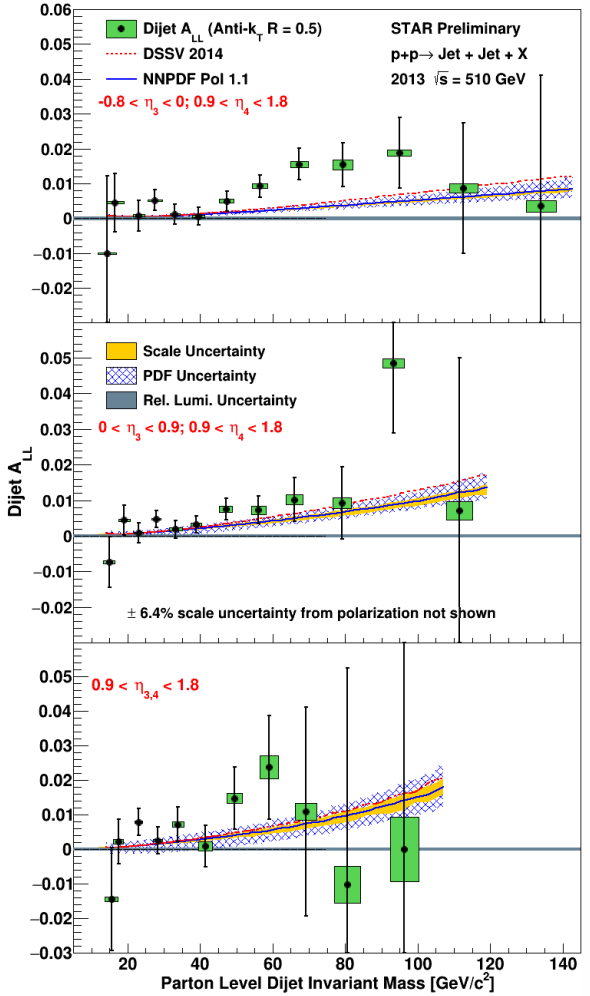
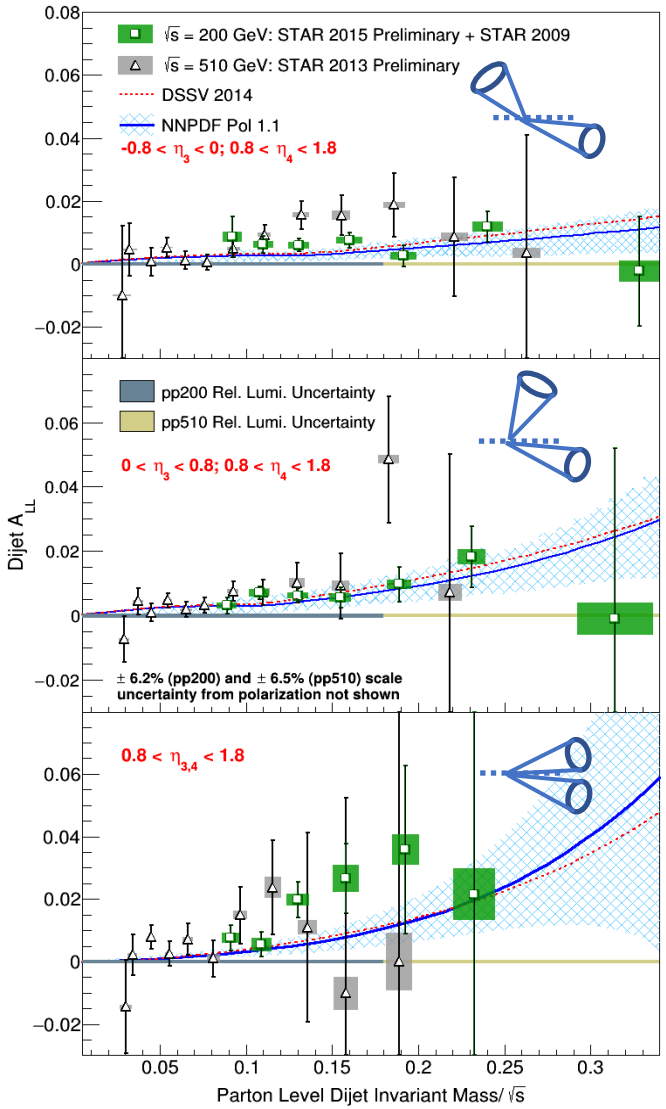


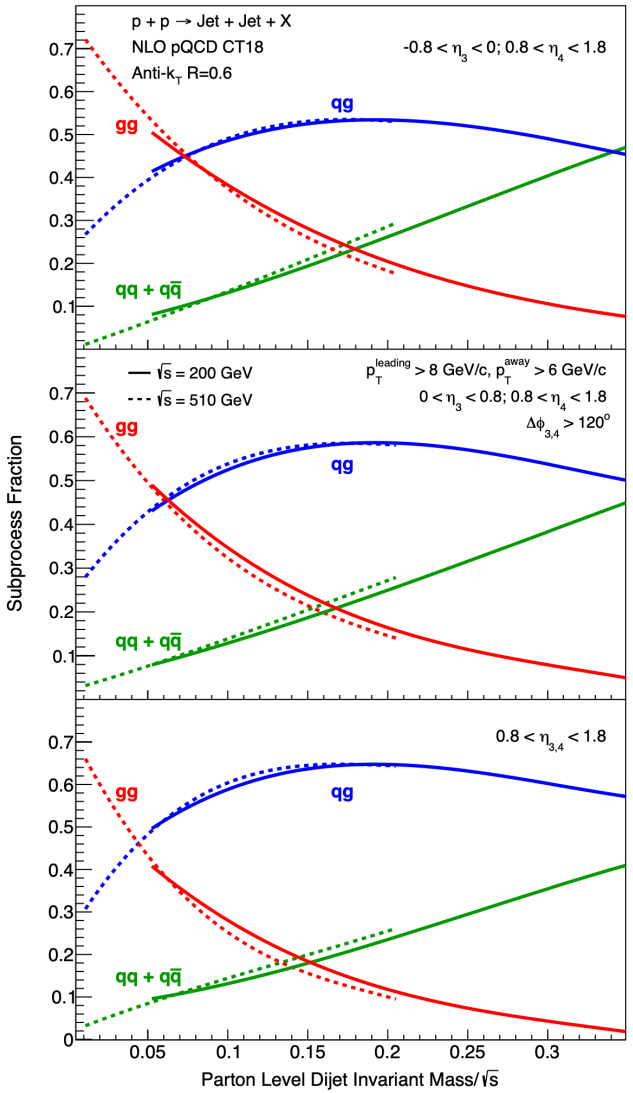


- Final longitudinal data acquired by STAR at 2012, 2013 and 2015;
- Preliminary results for 510 GeV and 200 GeV are well described by global fits.

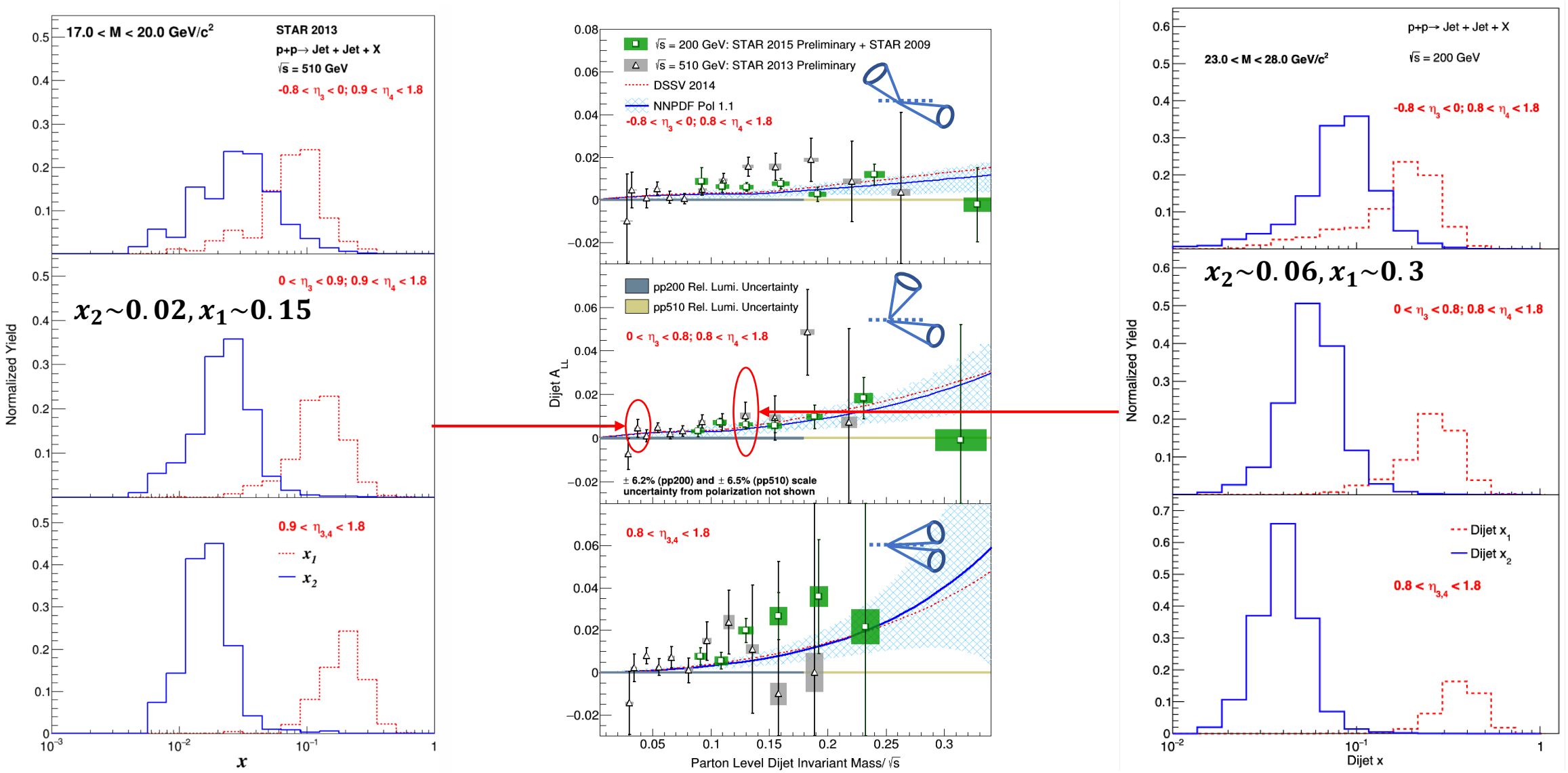
New Dijet A_{LL} at Intermediate Pseudorapidity

- Preliminary results for for 510 GeV and 200 GeV are in good agreement with $M/\sqrt{s}$ dependence;
- 510 GeV are dominated by gg process while 200 has more qg interactions;
- Different dijet topologies provide sensitivity to different kinematics: different sub-process fractions and sample x_1 and x_2 simultaneously in different ranges;
- Intermediate pseudorapidity results push to lowest possible gluon x values and high x quarks.

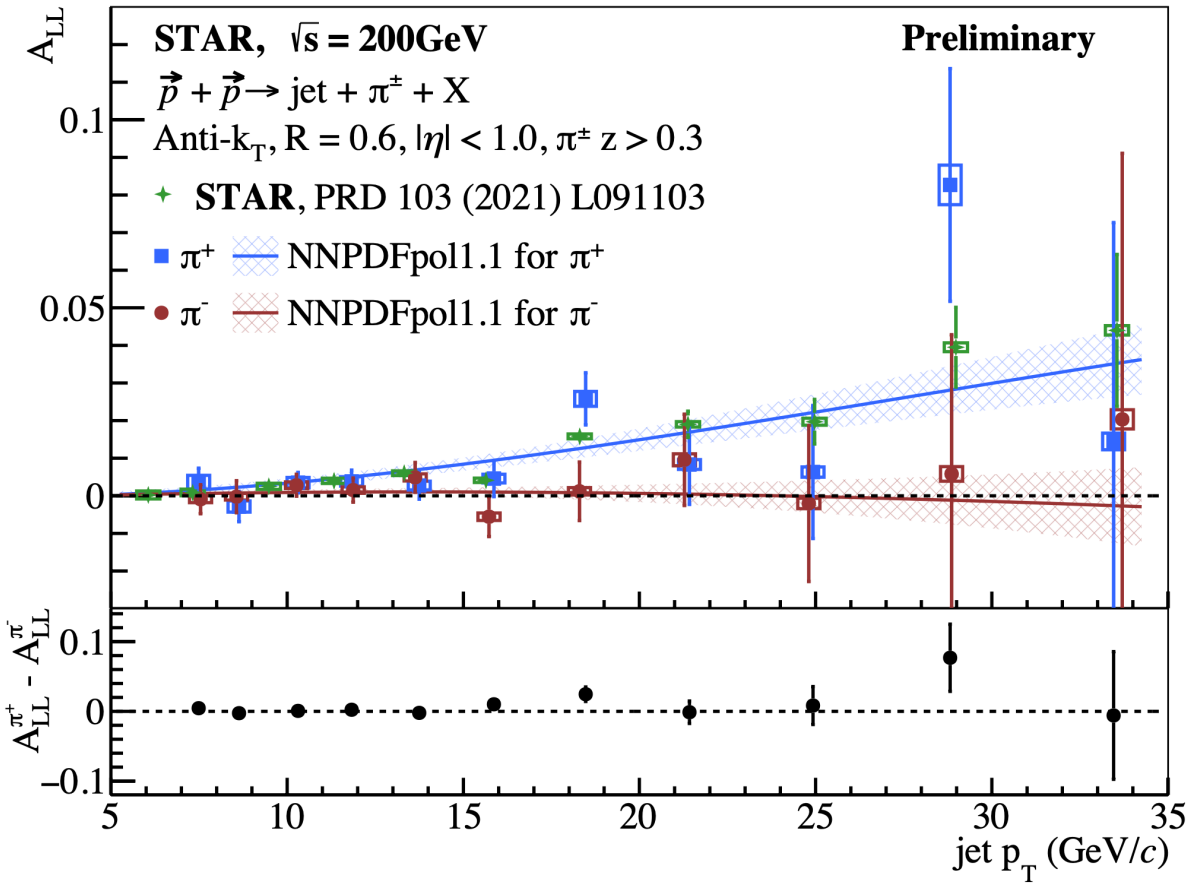


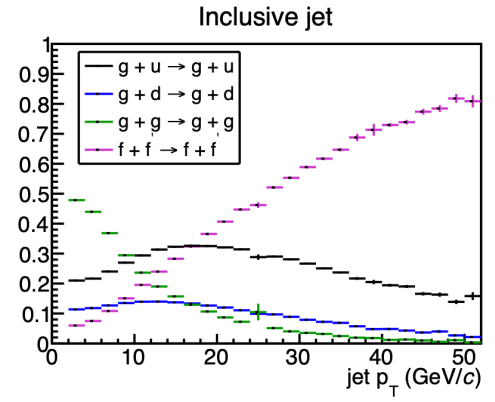


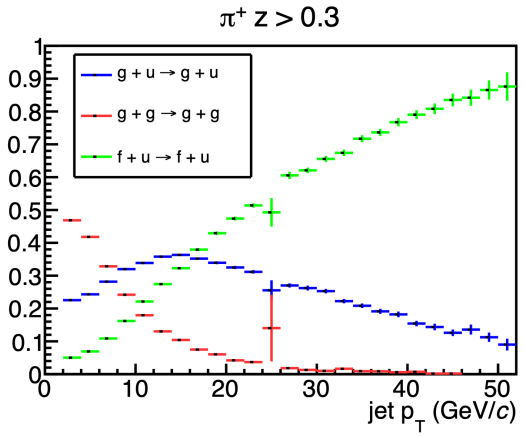
New Dijet A_{LL} at Intermediate Pseudorapidity

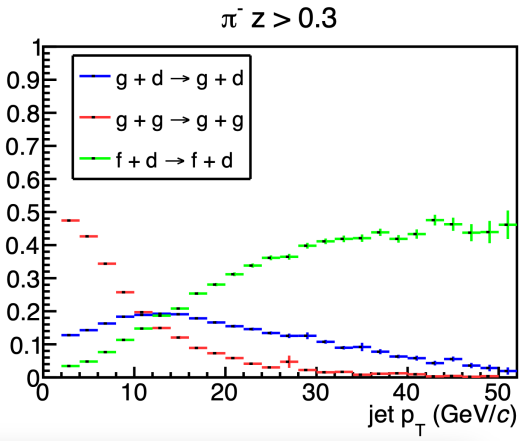


Jet A_{LL} Results with Charged Pion Tagging





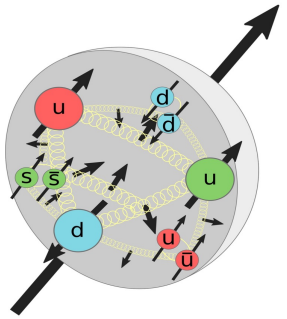




See Yi Yu's talk
Sep. 26, 2023, 3:00 PM
Nucleon Helicity Structure

- Different subprocess fractions for π^+ and π^- tagging jet A_{LL};
- Complementary constraint to gluon polarization with inclusive jet measurement.

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;
  - Found an asymmetry in the polarized anti-quark sea;
  - Found evidence for positive gluon polarization in the region $x > 0.05$;
- Several new results will soon to be published, which will provide constraints to both low-x gluons and high-x quarks.