Indiana University

STAR

Constraining the Gluon Helicity Distribution of the Proton with Inclusive Jet and Dijet Measurements at STAR

Scott Wissink

Indiana University

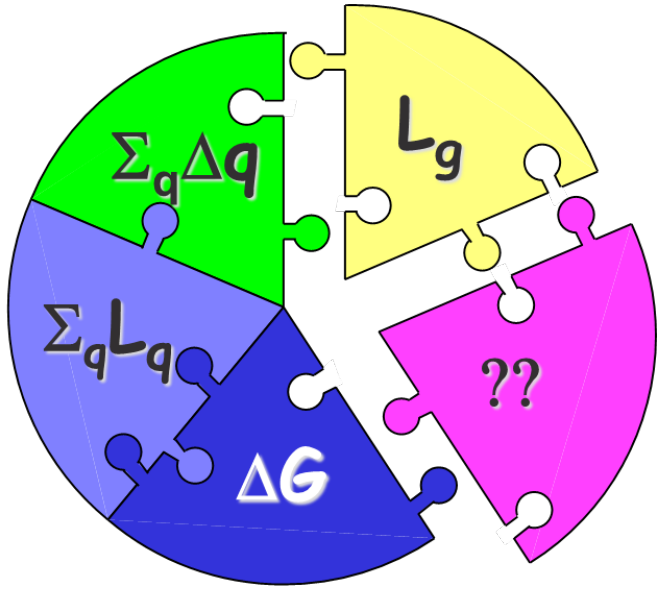
for the STAR Collaboration

Supported in part by:

NSF

U.S. DEPARTMENT OF ENERGY

Origin of the proton's spin: an evolving story



Naïve picture of proton properties determined largely by three valence quarks → replaced by a highly complex, *non-perturbative* system in which properties "emerge" from the interactions of quarks, anti-quarks, and gluons

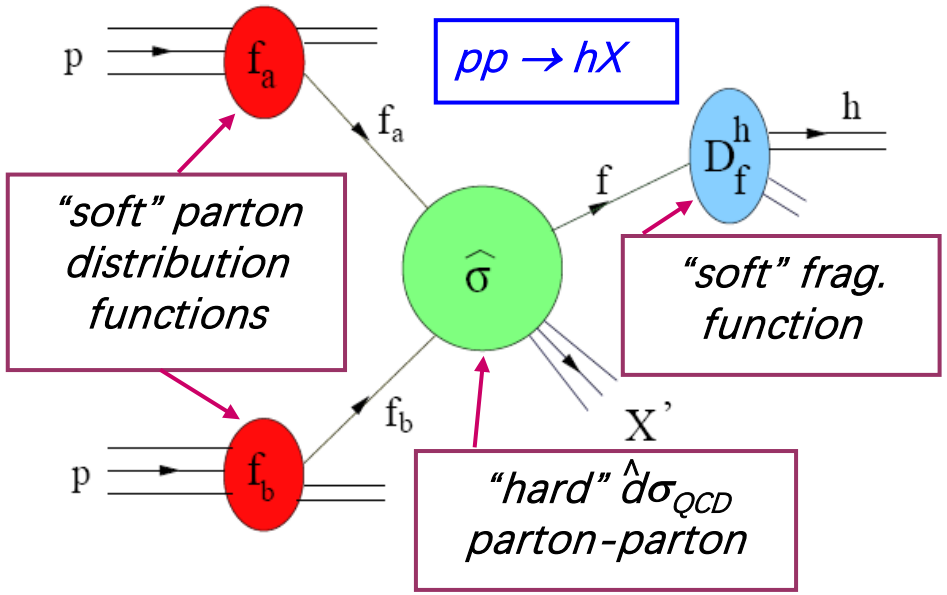
Decomposition not unique! For helicity distributions (collinear terms) most useful to use 'canonical' approach

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

R. L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990)

Precise DIS measurements have shown quark spins contribute only ~30% (ΔΣ term), but are sensitive to gluons only through scaling violations over limited (x,Q^2) space → need a (colored) probe that couples directly to gluons!

What high-energy $\vec{p}\vec{p}$ collisions bring to the table

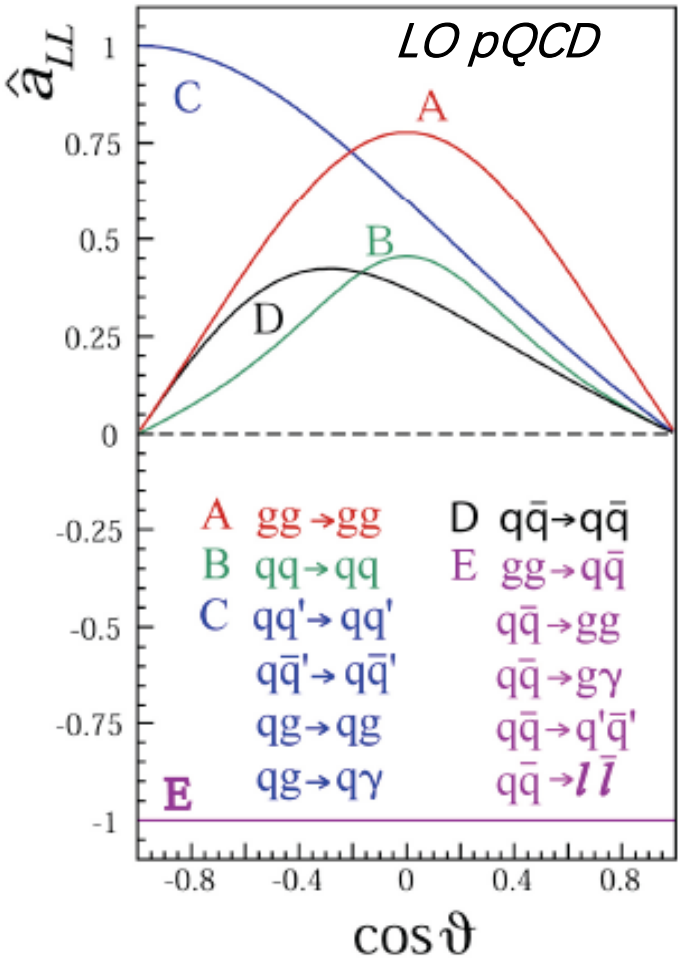


Hadronic beams provide polarized QCD probes of spin-dependent partonic structure!

Assume factorization works

+

Interaction calculable at partonic level

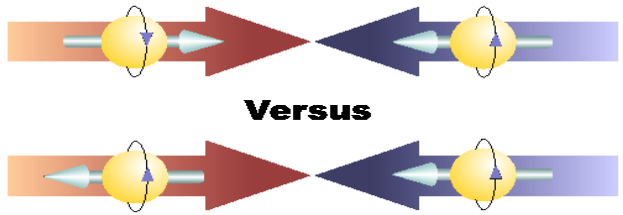


Allows us to ask:

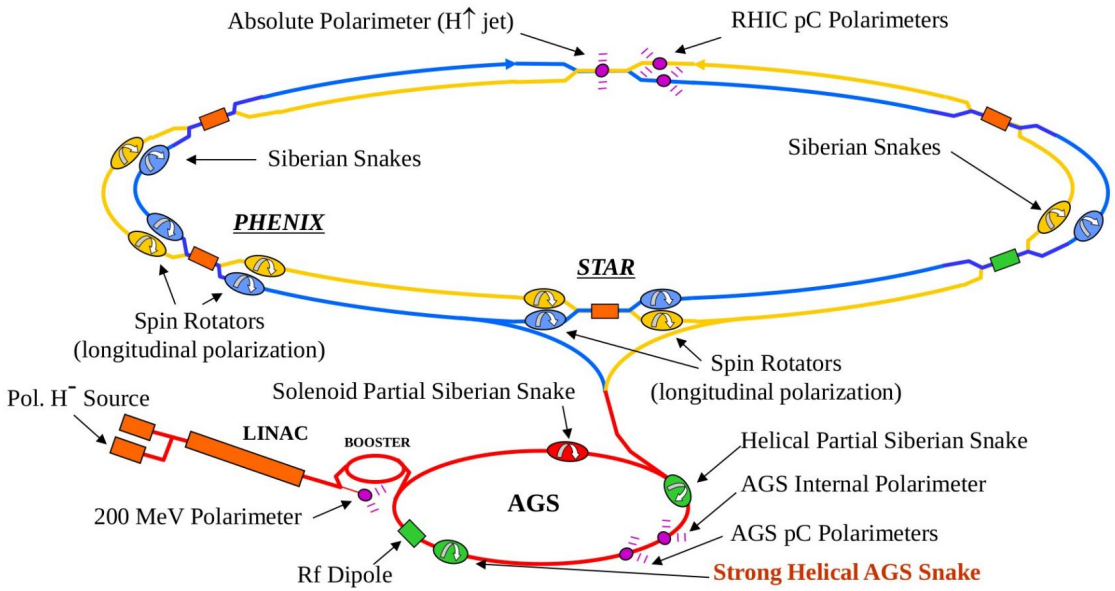
Does the gluon spin contribute <u>significantly</u> to that of the proton?

What about sea quarks?

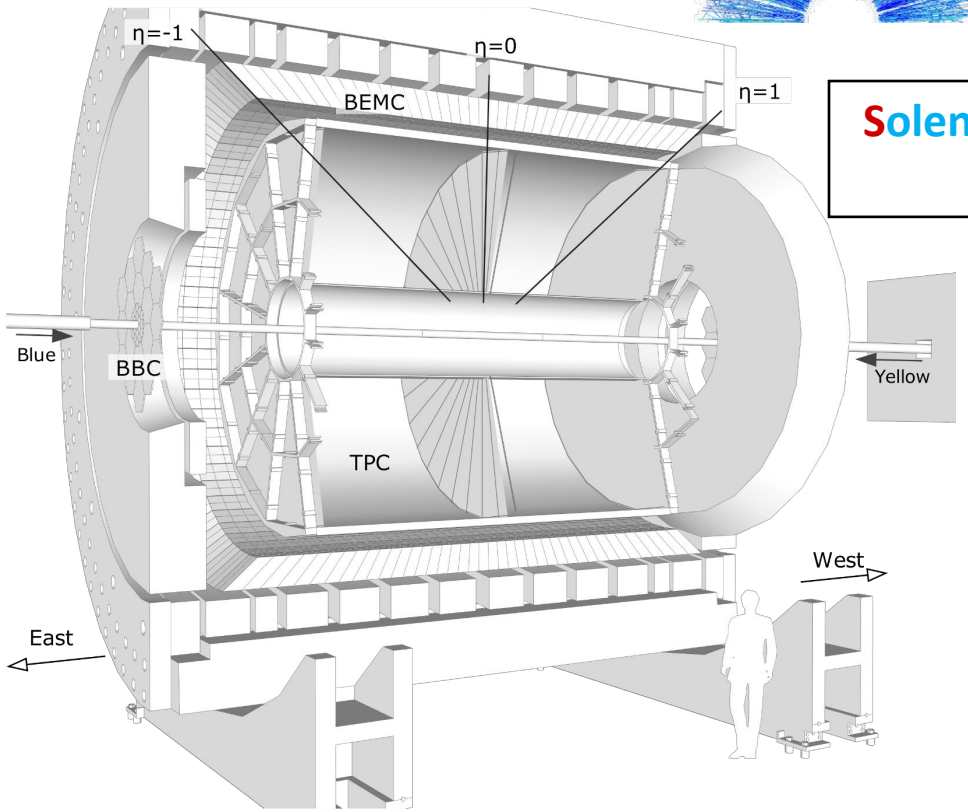
Or partonic OAM?



Facilities: RHIC & STAR at BNL



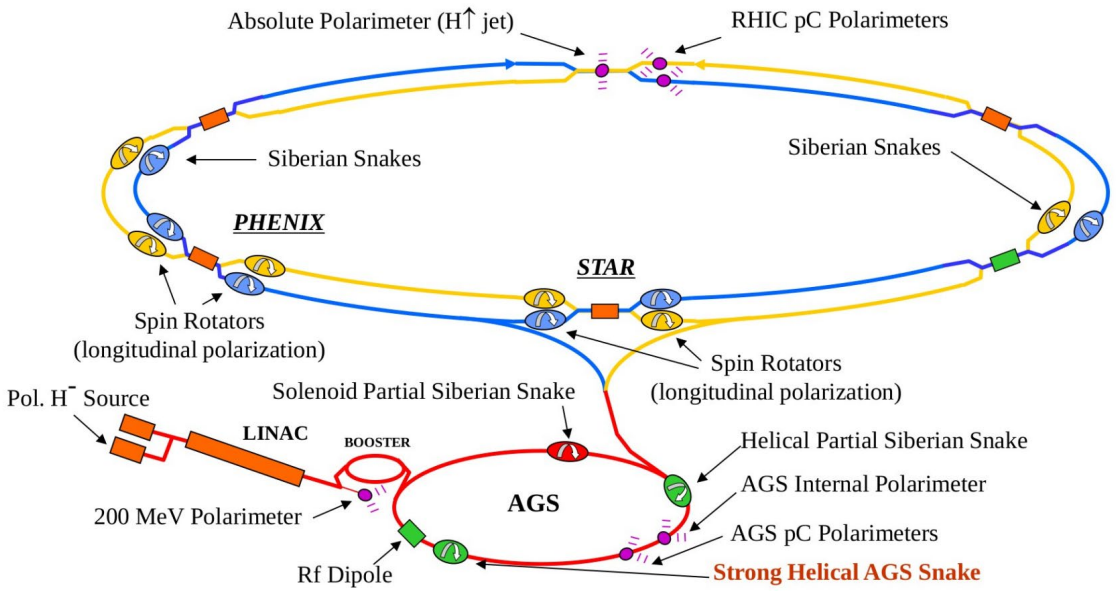
Year and √s	STAR L [pb^{-1}]
Longitudinal runs	
√s = 200 GeV	
2009	25
2015	52
√s = 500/510 GeV	
2009	10
2011	12
2012	82
2013	300

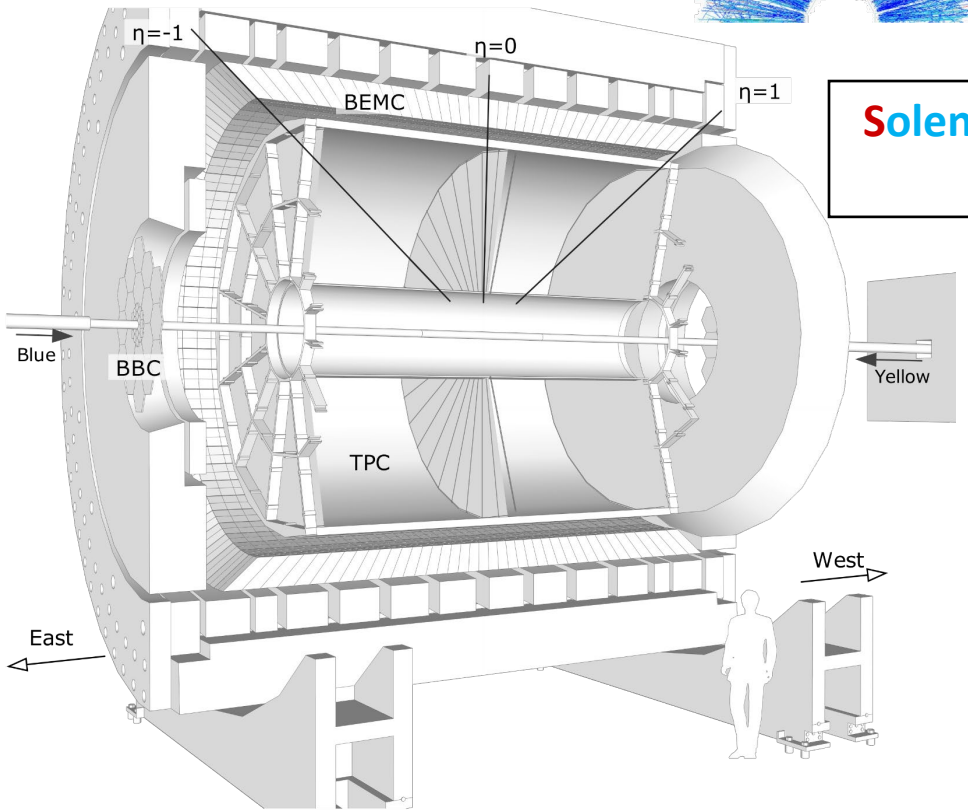


Solenoidal Tracker At RHIC

- RHIC: provides collisions of transversely or longitudinally polarized protons at energies up to $\sqrt{s}$ = 510 GeV
- STAR: allows for charged-particle track reconstruction for |η|< 1.3, and measures EM particle energies for -1< η <2, both over the full azimuthal range of 2π

Facilities: RHIC & STAR at BNL





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Final STAR longitudinal data sets!

- **RHIC: provides collisions of transversely or longitudinally rized protons at energies up to $\sqrt{s}$ = 510 GeV**
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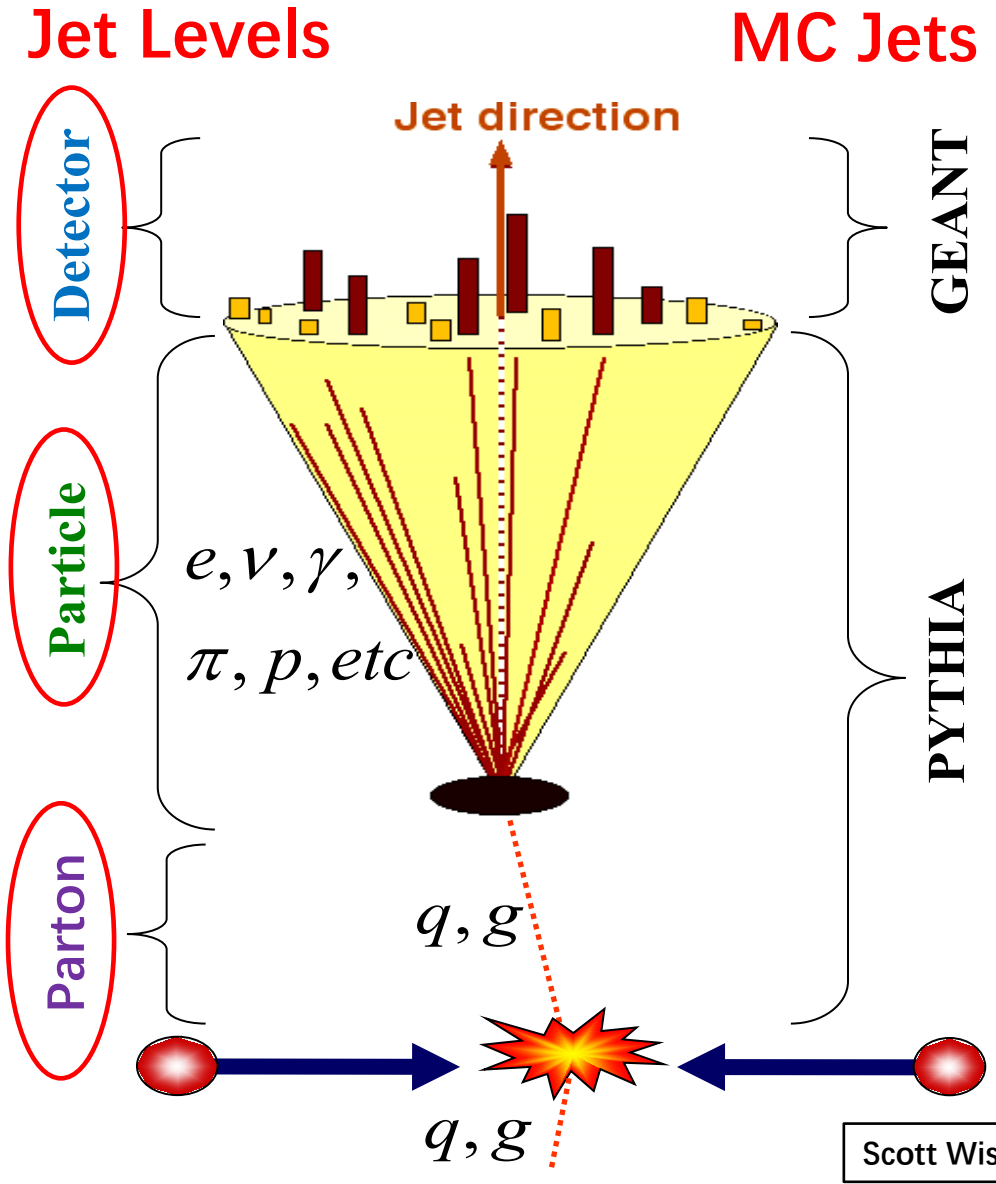
Jets: a robust proxy for scattered partons



Three Simulation Levels:

- Parton level – hard-scattered partons from a 2→2 hard scattering event from Pythia
- Particle level – partons propagate, then fragment and hadronize into stable, color-neutral particles
- Detector level – simulate STAR's response to produced particles (towers and tracks), "embed" response in real zero-bias data

Anti-k_T Algorithm:

- Radius = 0.5 or 0.6
- Less sensitive to underlying event and pile-up effects
- Used in both data and simulation

Jet spin asymmetries: probe $\Delta g(x)$ directly

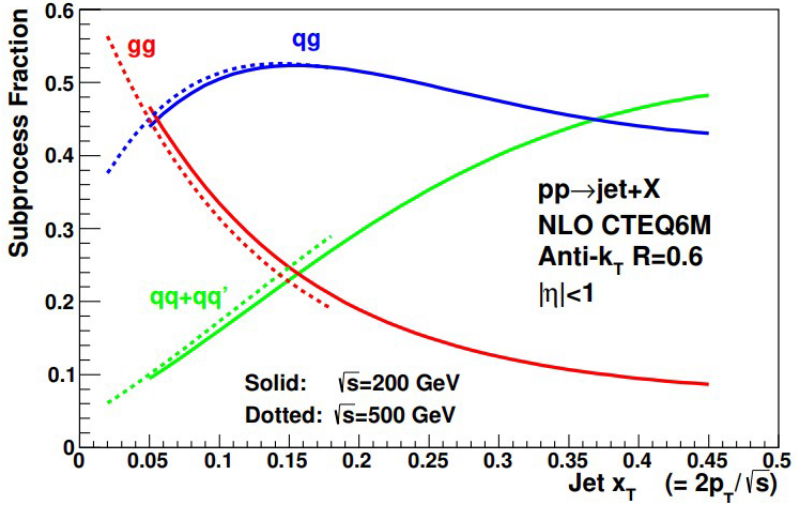
With longitudinally polarized beams, compare jet yields for colliding protons with same versus opposite helicities

What we measure — **What we hope to learn!**

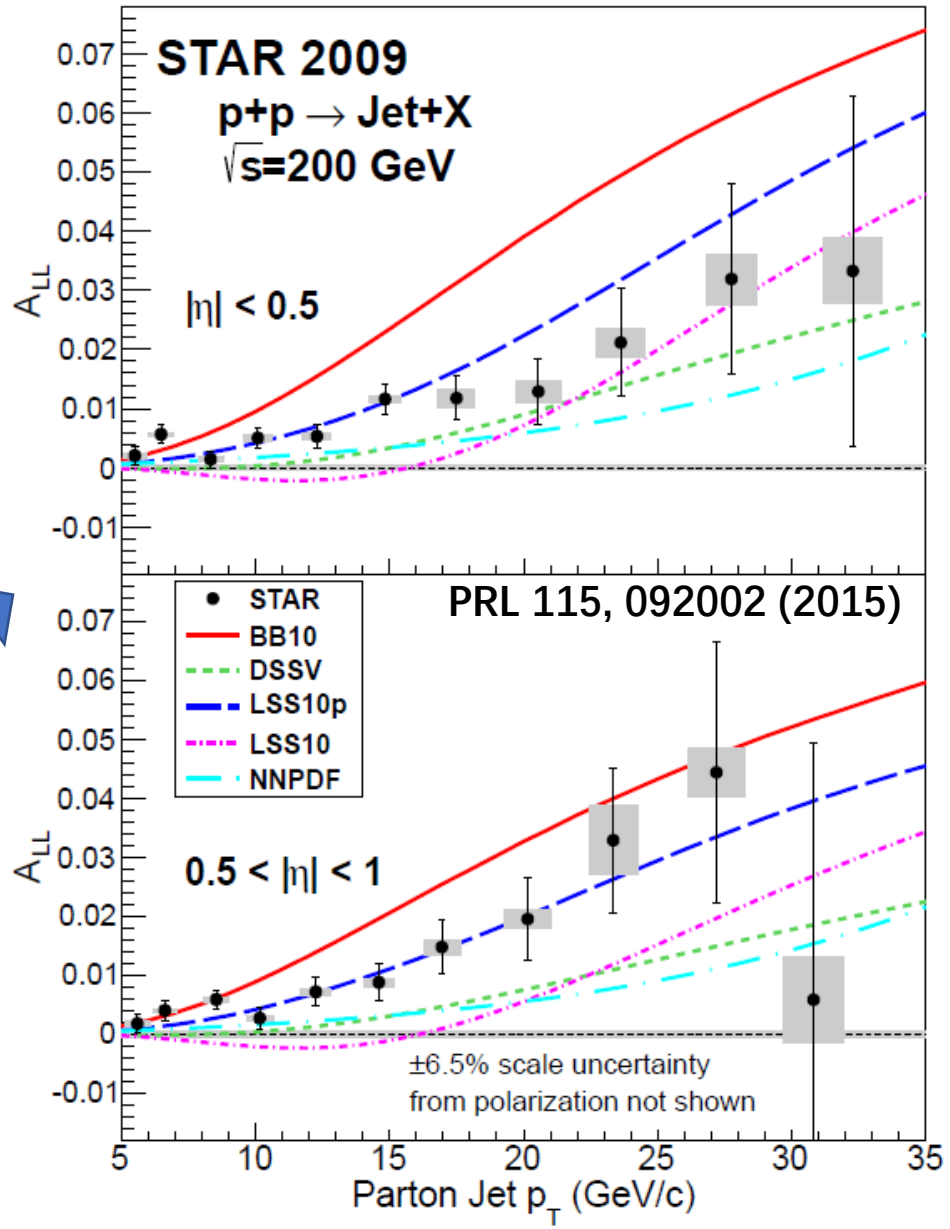
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} a_{LL}}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes}$$

What others measure — **What is calculable**

gg **and** ***qg*** **dominant at RHIC energies → gluons!**

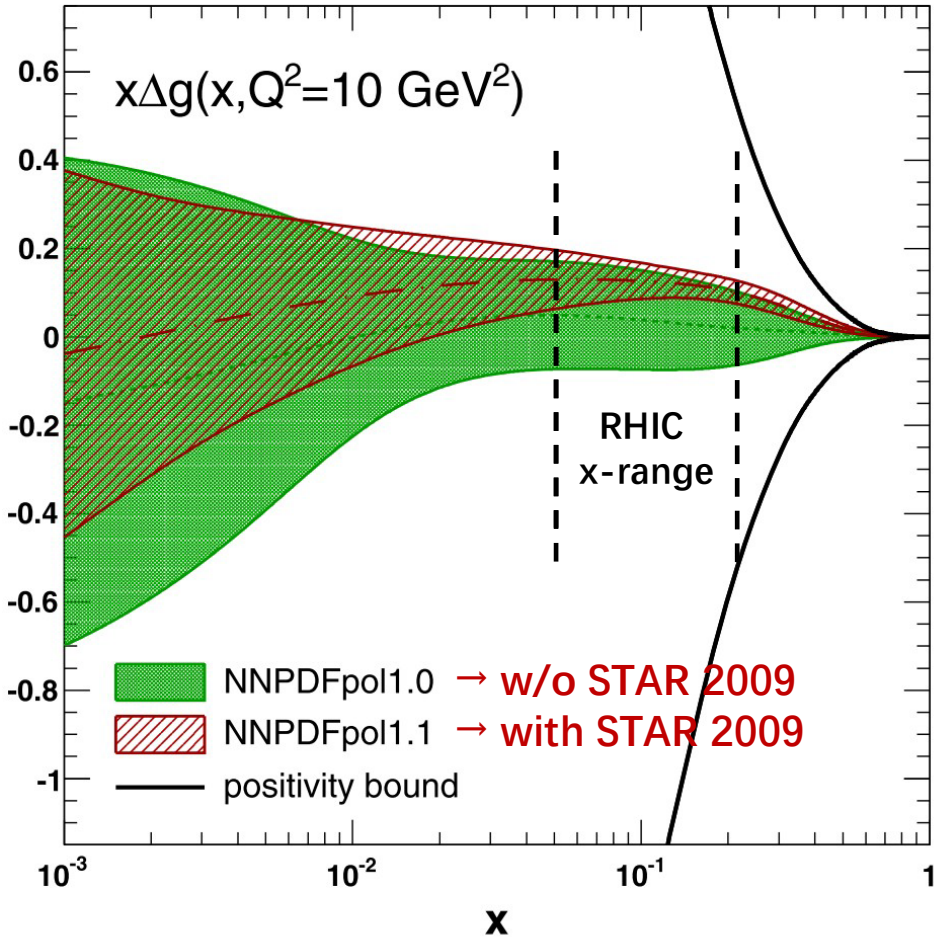


2009 – first large data set at √*s* = 200 GeV, showing positive A_{LL} → suggests $\Delta g(x) > 0$ in the regions of (x, Q^2) probed, roughly $0.05 < x < 0.2$, $Q^2 \sim 10$ GeV^2



2009 results: large impact on global analyses!

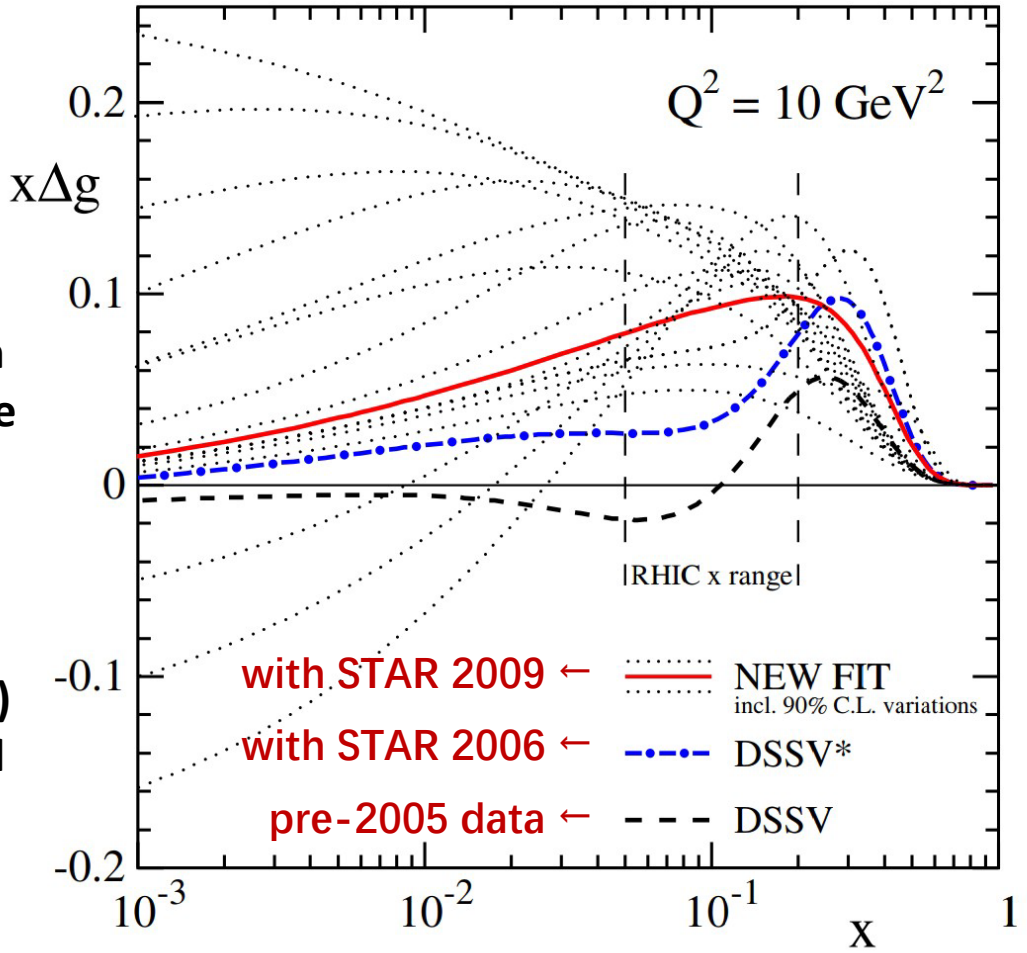
NNPDF, Nucl. Phys. B 887, 276 (2014)



Great progress in determining gluon contribution to the proton spin …

… but magnitude and shape of Δ*g*(*x*) still unconstrained for *x* below 0.05!

DSSV, PRL 113, 012001 (2014)

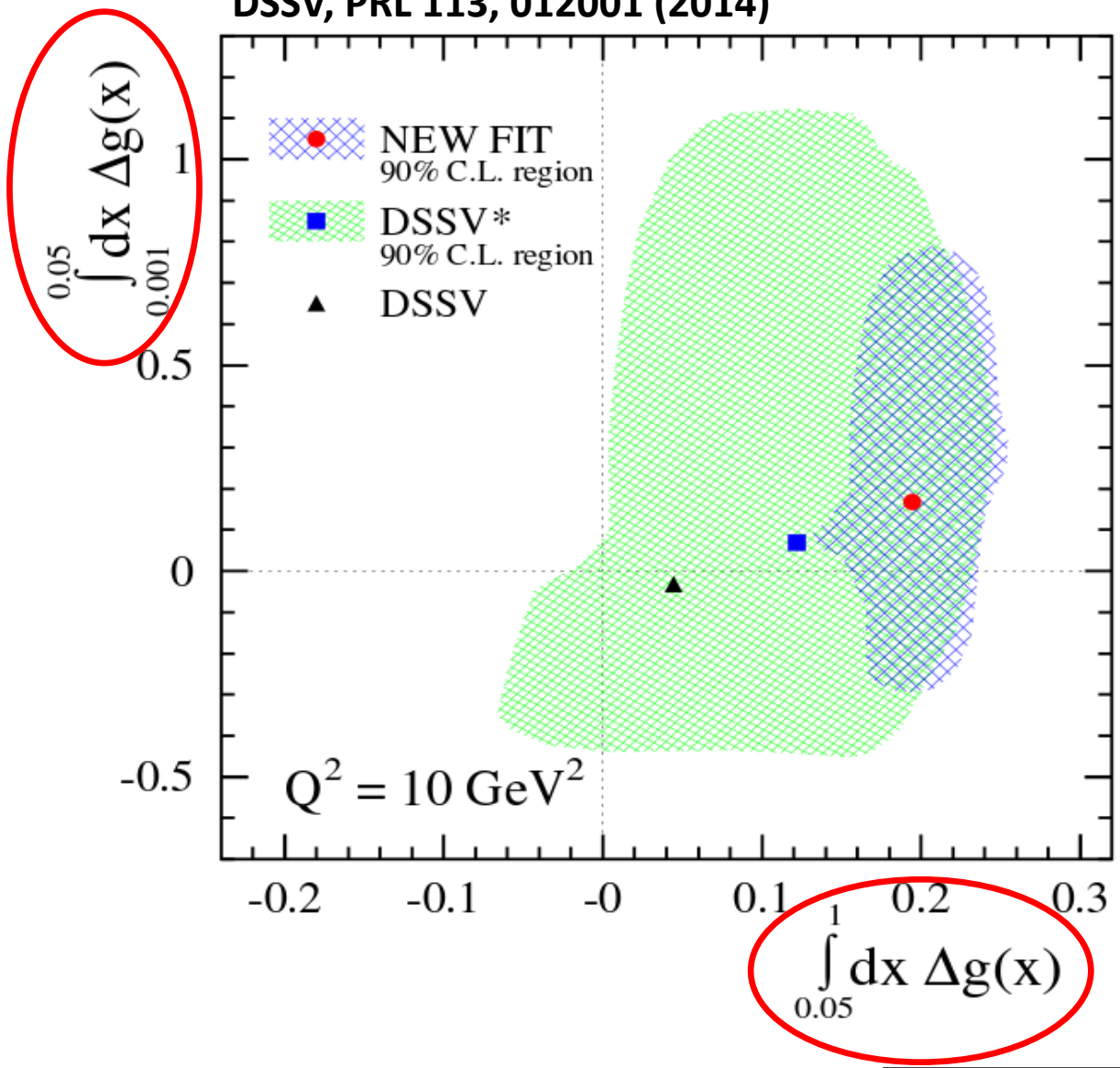


$$\int_{0.05}^{0.5} \Delta g(x,Q^2)dx = 0.23 \pm 0.07$$

$$\int_{0.05}^{1} \Delta g(x,Q^2)dx = 0.20^{+0.06}_{-0.07}$$

Probing $\Delta g(x)$: how low can you go?

DSSV, PRL 113, 012001 (2014)



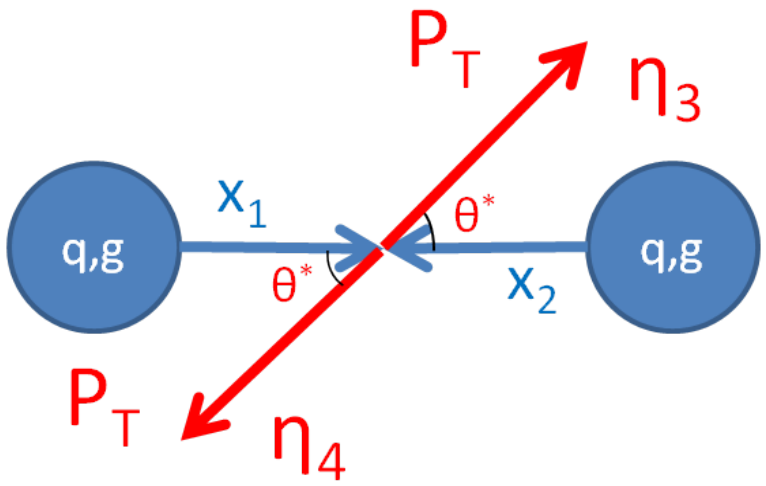
Though DSSV group finds substantial gluon polarization, with small uncertainties, for $x > 0.05$, region below this is wide open – note change of scales on two axes!

STAR's strategy for exploring low-*x* regime:

- **Increase size / integ'd $\mathcal{L}$ of data sets**
- **Focus on dijets, rather than inclusive jets**
- **Reconstruct jets at the highest possible η**
- **Take data at the highest possible energy**

Ultimately, carry out all of these improvements simultaneously!

Beyond inclusive jets: advantages of dijets



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

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

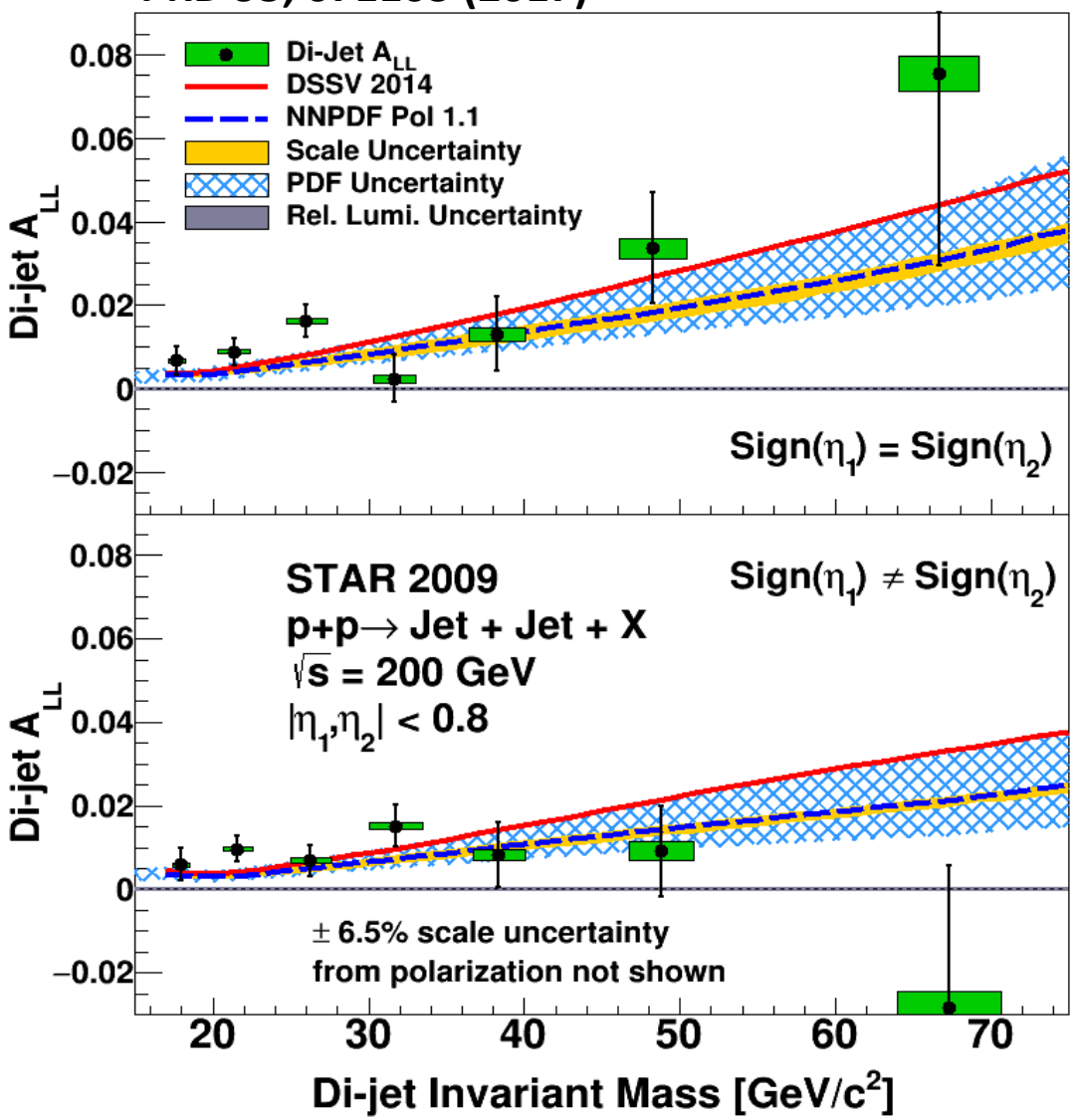
$$M = \sqrt{x_1 x_2 s}$$

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

- Correlation measurements, such as dijets, capture *more information* from the hard scattering and provide a more direct link to the initial kinematics than inclusive probes
- Dijets sample initial-state partonic *x* values over a more limited range than inclusive jets → constraints on *functional form* of $\Delta g(x,Q^2)$
- Leading order expressions at left show how different jet topologies (combinations of the two jet η ranges) are sensitive to different initial-state partonic momentum fractions

First STAR dijet results at $\sqrt{s}$ = 200 GeV

PRD 95, 071103 (2017)



Mid-rapidity dijet A_{LL} results presented for two topologies as a function of the dijet invariant mass corrected to parton level

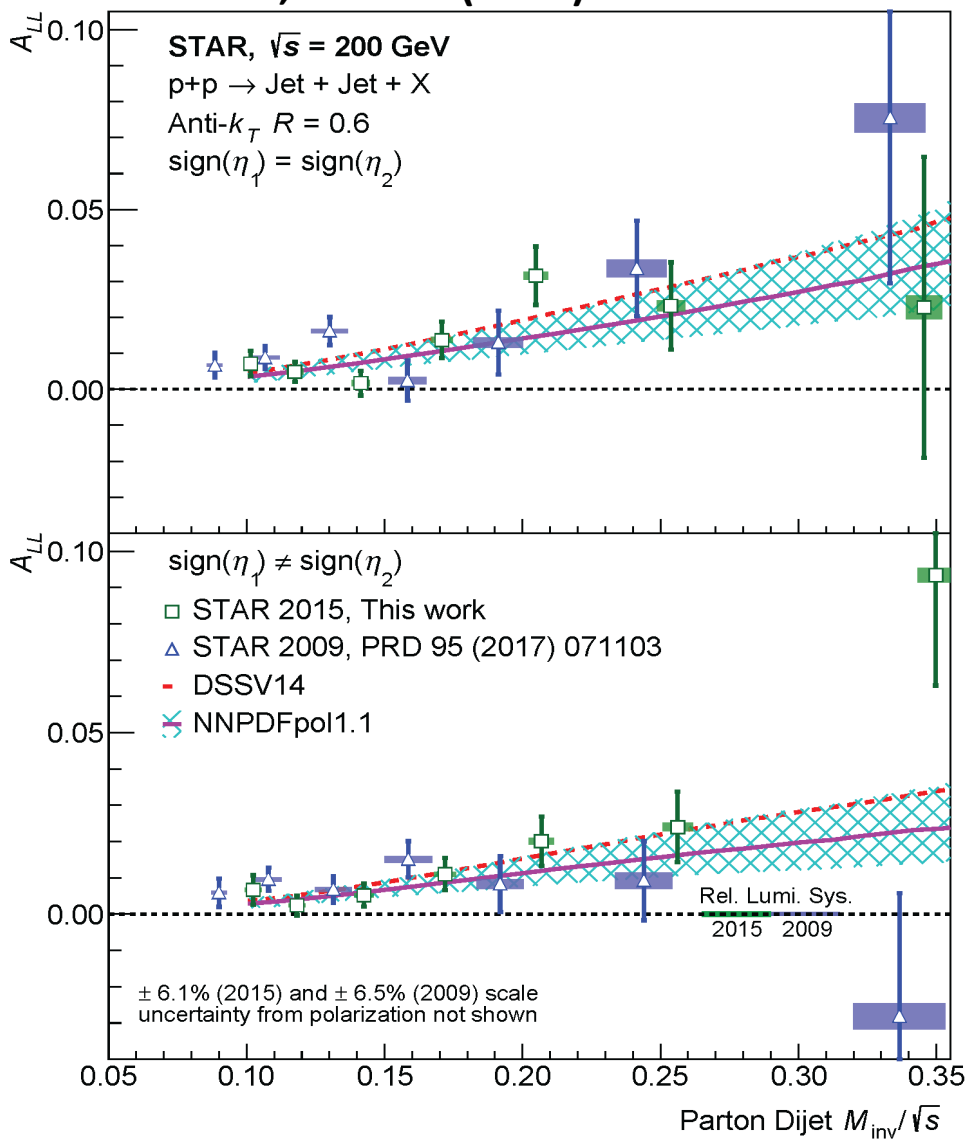
Data are compared to expectations from DSSV14 and NNPDFpol1.1 polarized PDFs, both of which include the 2009 inclusive jet results yet show significant differences

Scale and PDF uncertainty bands shown for NNPDFpol1.1 calculation

Dijet cross section also measured

Recent results: midrapidity dijets at 200 GeV

PRD 103, 091103 (2021)



Final longitudinal data set acquired by STAR (2015) at 200 GeV – 52 pb^{-1}, 2x 2009 data

Results for midrapidity inclusive jet and dijet asymmetries are seen to be consistent with those found in 2009, though with statistical errors ~1.5 times smaller

2015 data have additional corrections applied (primarily Underlying Event subtraction) to jet p_T , as well as greatly reduced systematic uncertainties.

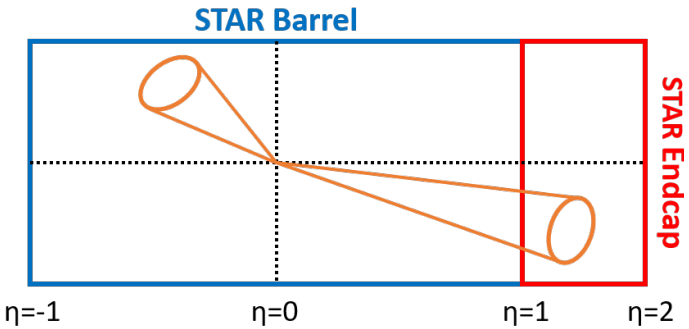
Detecting jets at more forward rapidities

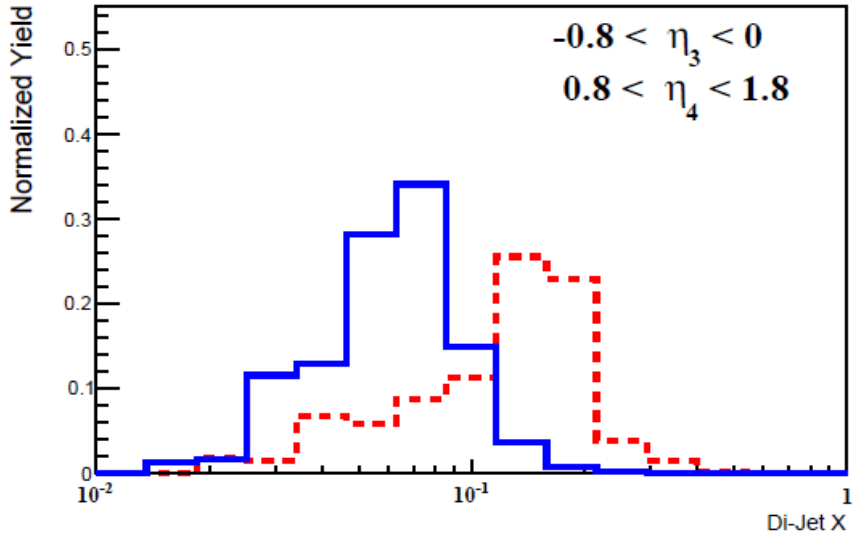
2→2 scattering kinematics:

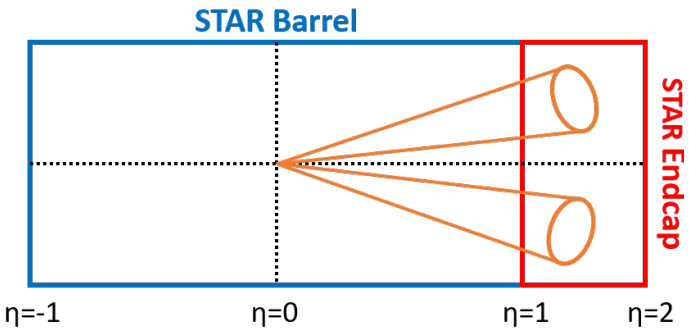
$$\eta_3 + \eta_4 = \ln(x_1/x_2)$$

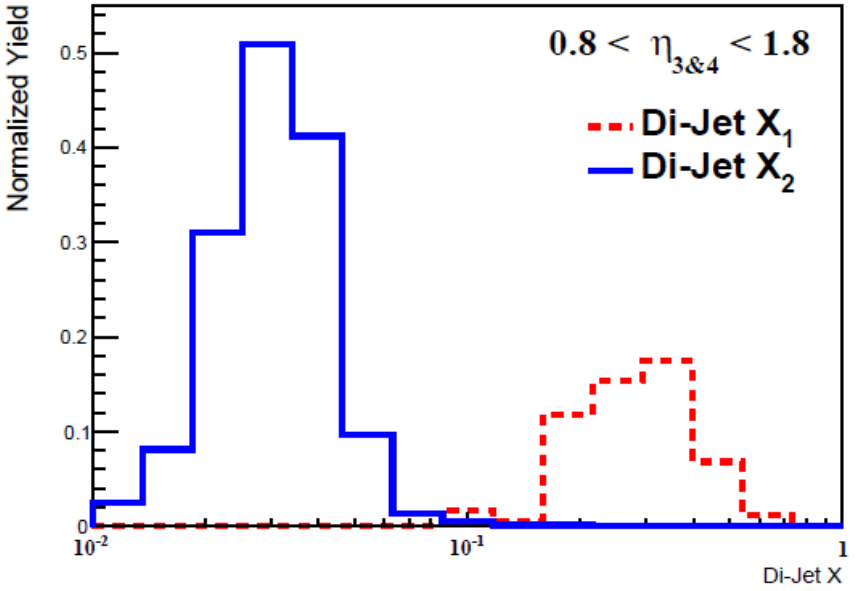
→ Shows that jet pairs found at higher pseudorapidities originate from collisions of partons with asymmetric momentum fractions

→ Jet pairs reconstructed in the STAR Endcap region, *e.g.*, will be dominated by high-x (and thus highly polarized) valence quarks interacting with the low-x gluons of primary interest



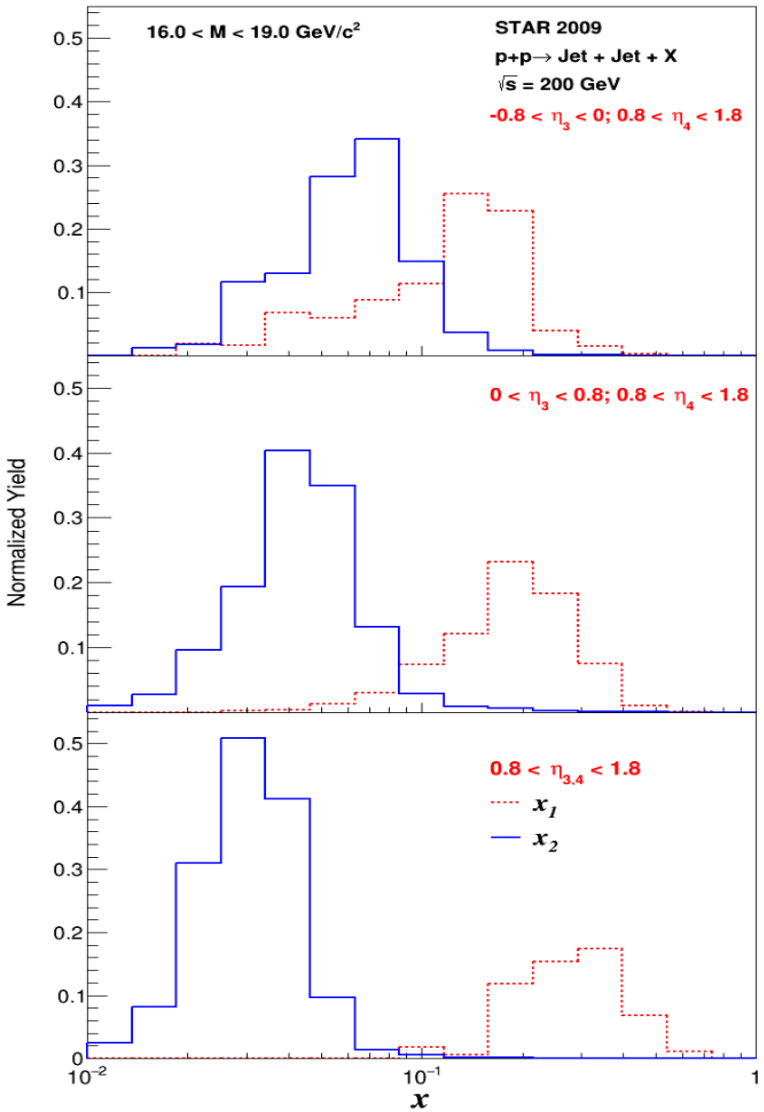


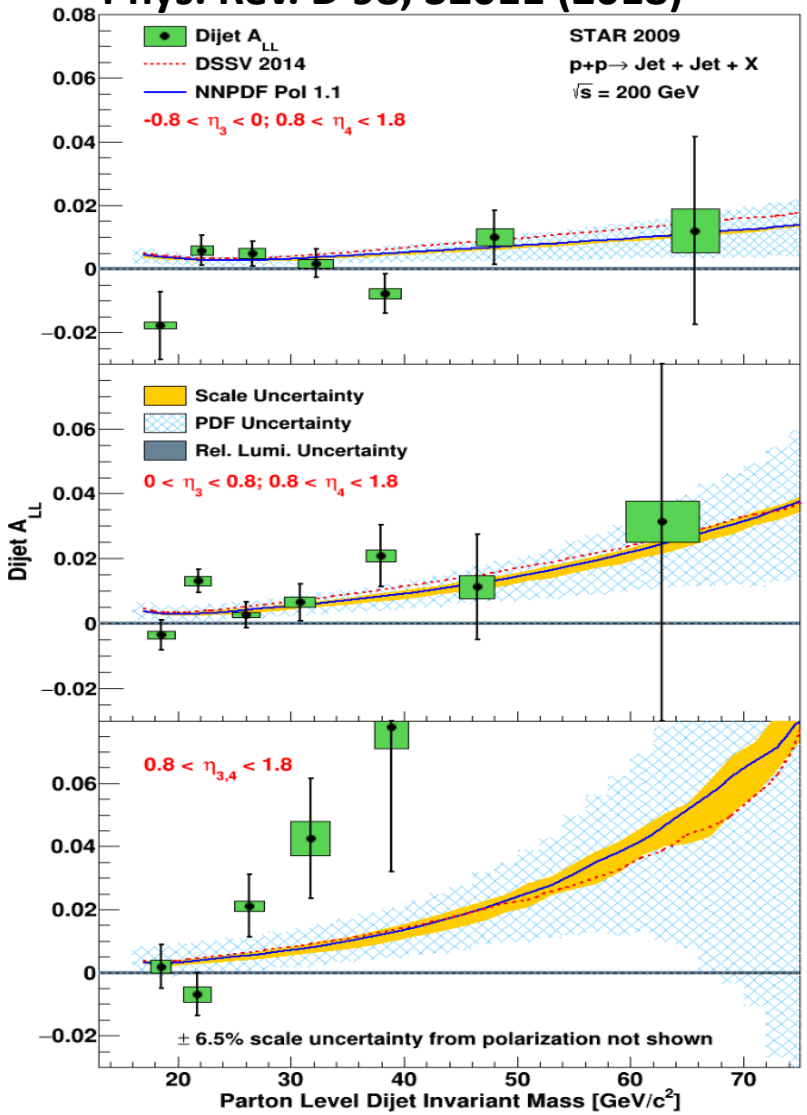




STAR dijets at forward rapidities (200 GeV)

Phys. Rev. D 98, 32011 (2018)





Dijet A_{LL} values shown for two Barrel-Endcap (East and West) and Endcap-Endcap topologies

With one jet in Endcap, can see increased x_1 / x_2 asymmetry as second jet moves forward in η

Results are again compared to DSSV14 and NNPDFpol1.1 expectations → with limited statistics, no clear preference, but data tend to exceed global fits with increased asymmetry in colliding parton *x* values

On to $\sqrt{s}$ = 510 GeV: Midrapidity inclusive jets

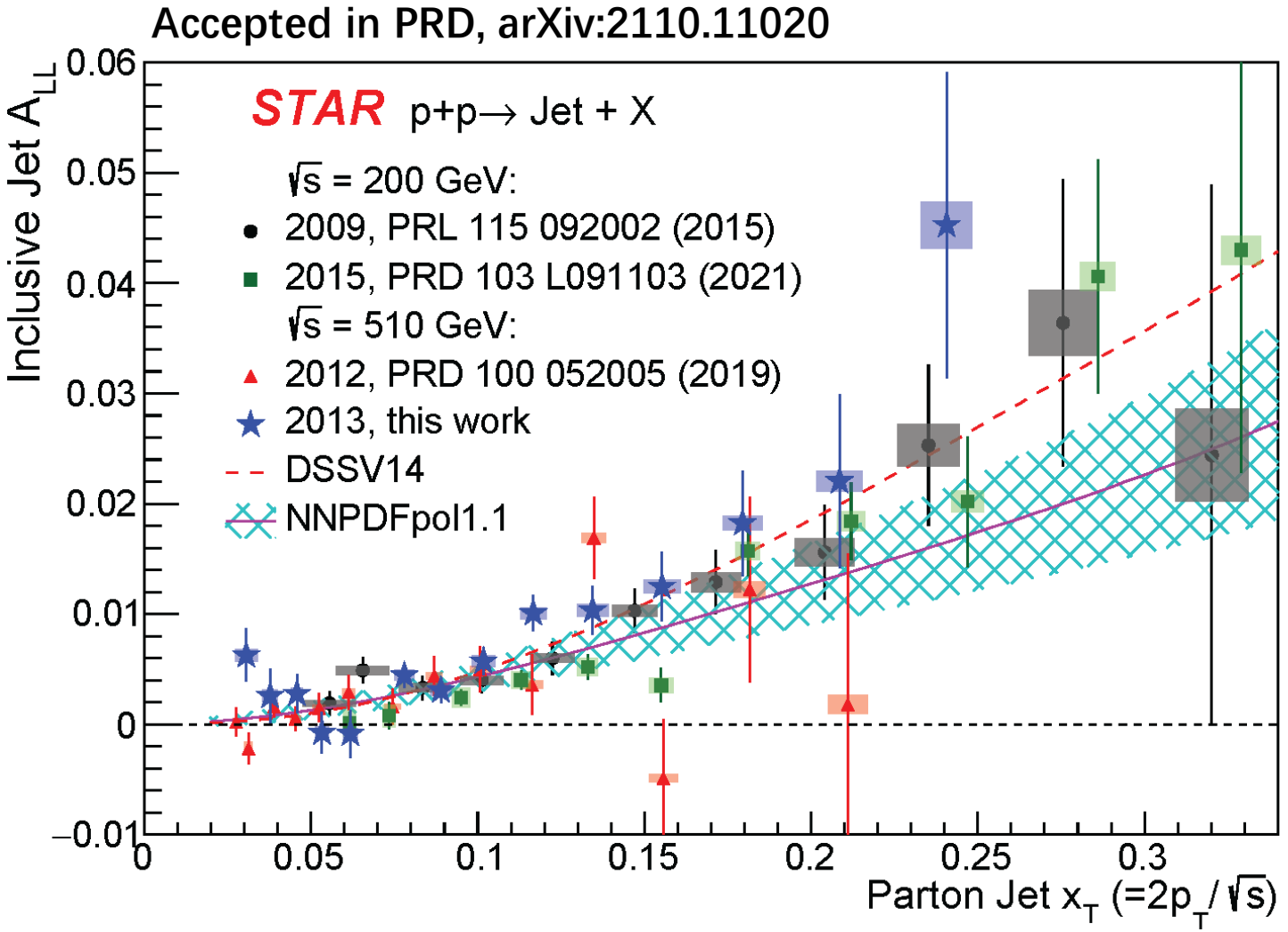
Why go to higher energy? Recall:

$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T_3}e^{\eta_3} + p_{T_4}e^{\eta_4}\right)$$

→ For jets detected at same p_T and η, higher $\sqrt{s}$ probes lower *x*

Plotted vs x_T, overall consistency seen among STAR data sets, with data generally above fits, with a slight preference for DSSV14

Results from 510 GeV push down to lower x_T, though predicted A_{LL} very small in this region



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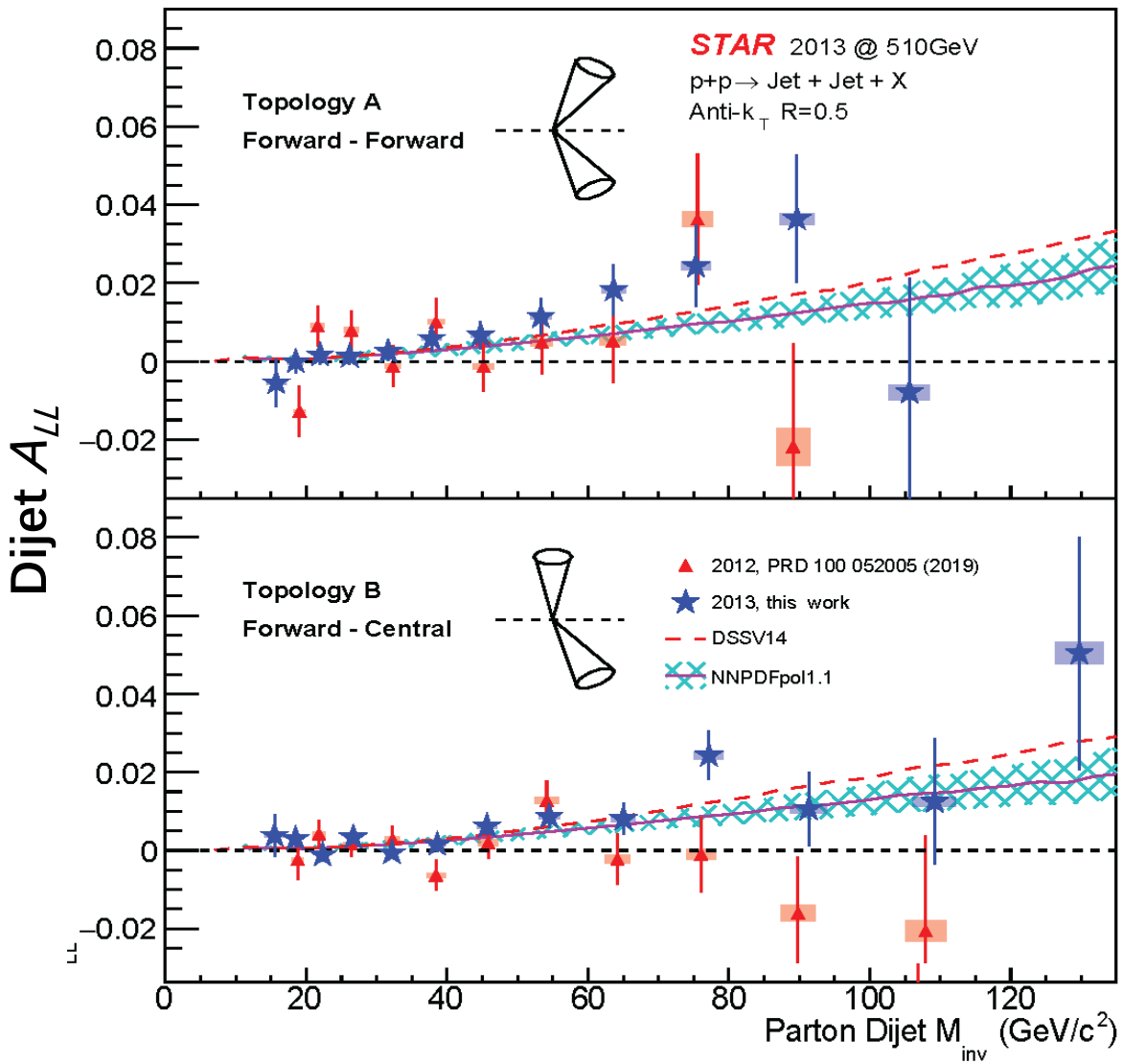
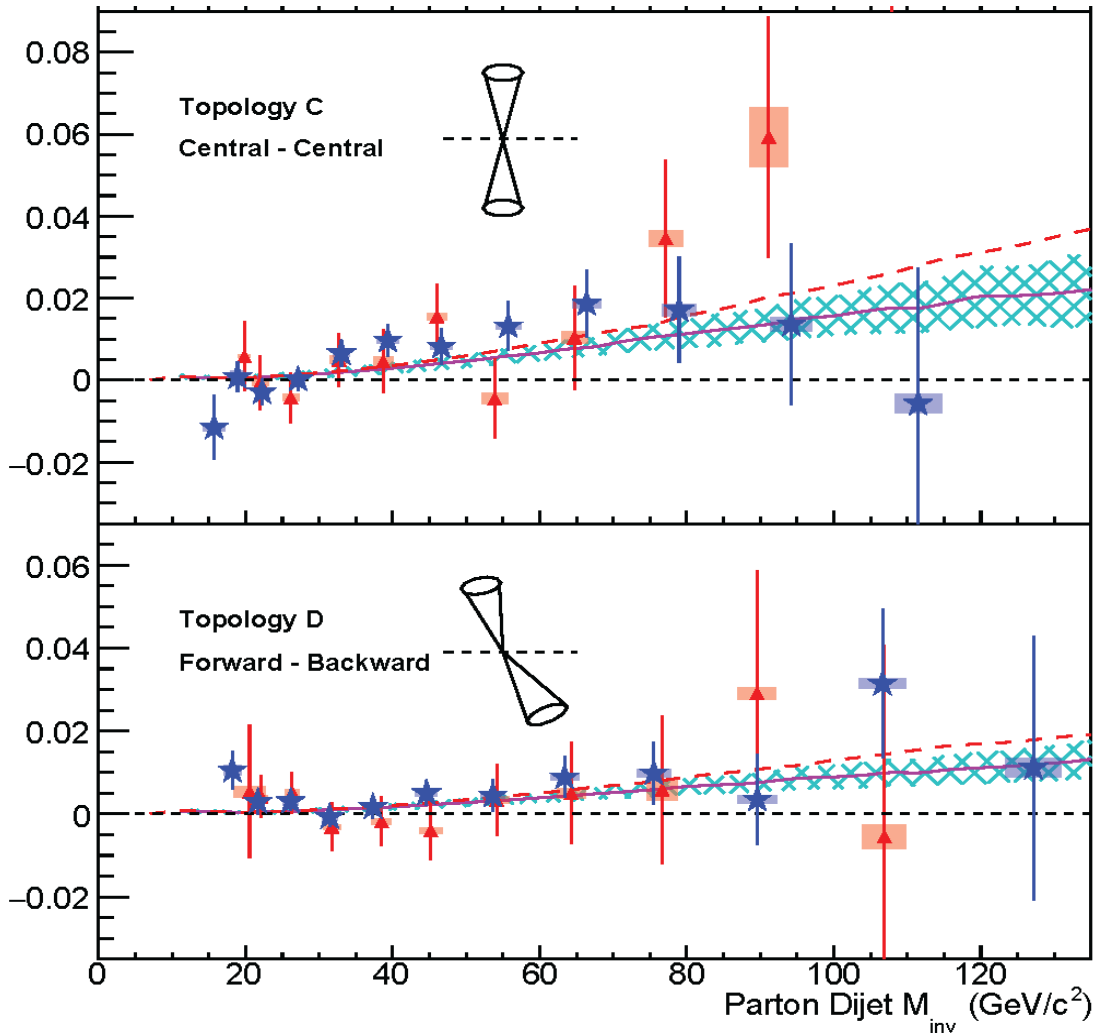
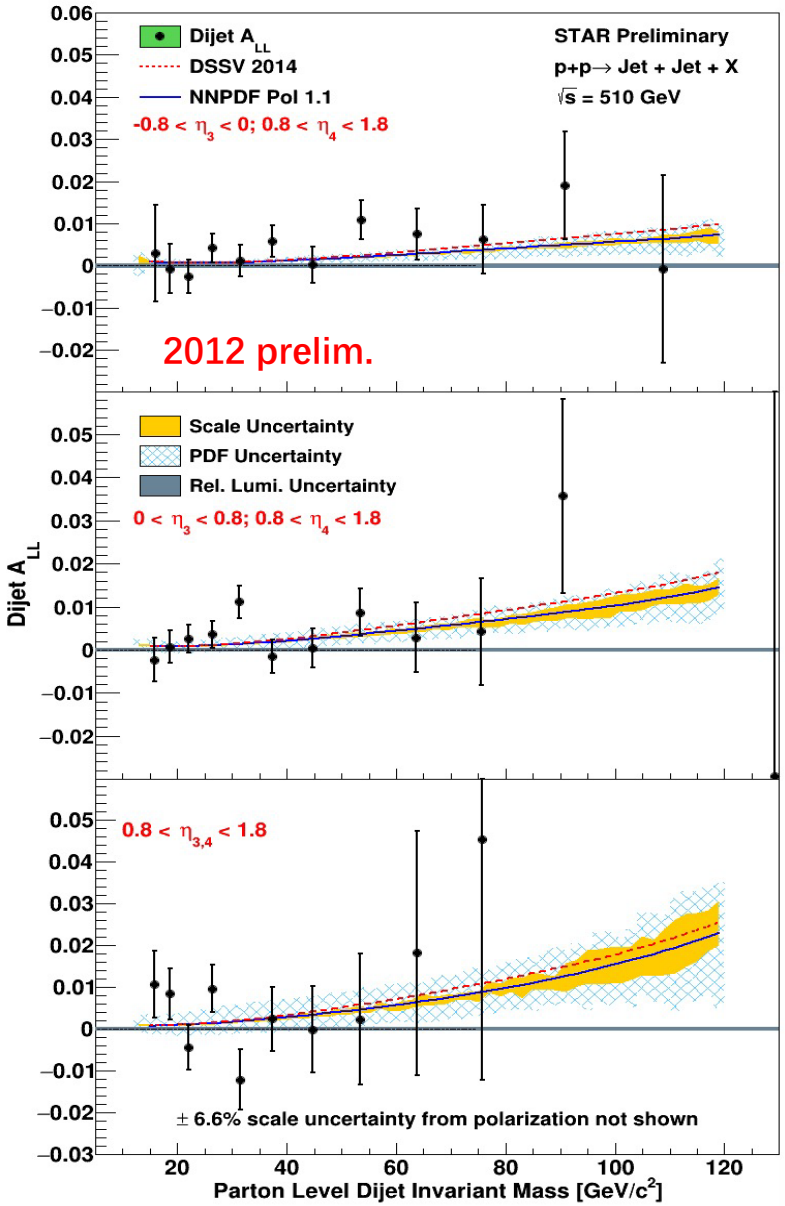




Accepted in PRD, arXiv:2110.11020

“Ultimate” data set: forward dijets at 510 GeV

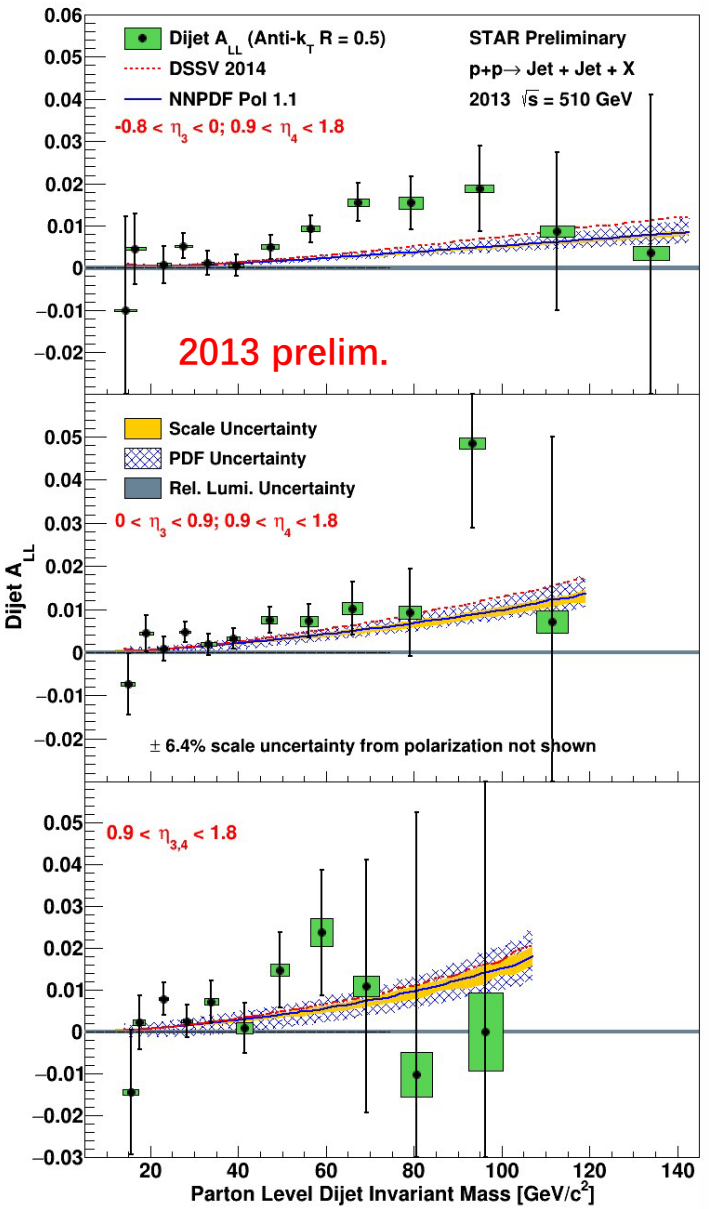


Final longitudinal data acquired by STAR (2012, 2013) at 500 GeV, ~250 pb^{-1} integrated lum.

“Pushes all the buttons” to reach lowest possible gluon *x* values: large η, highest √*s*, using dijets

Preliminary results for 2012 (left) and 2013 (right) are in excellent agreement with each other, both favoring A_{LL} values slightly higher than global fit expectations.

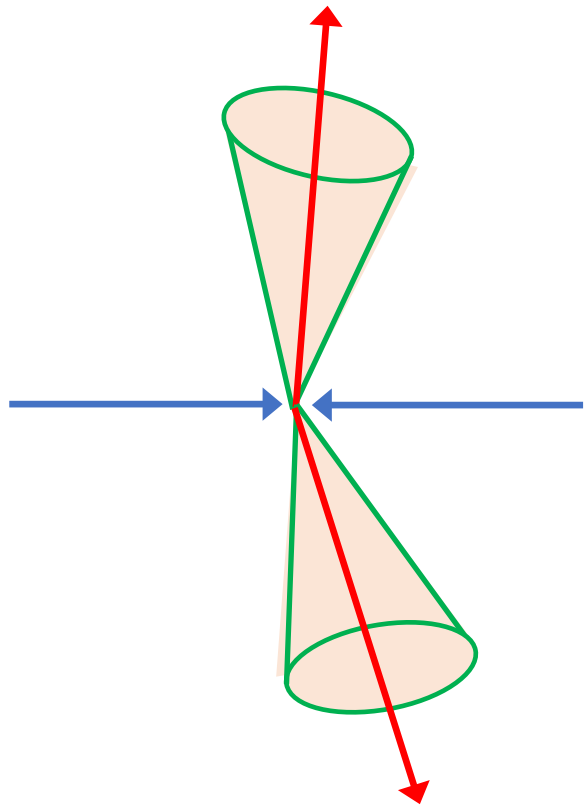
All systematic uncertainties for the two data sets are finalized, so a combined result (including their correlated uncertainties) can be published very soon.



Scott Wissink – DIS2022, May 2022

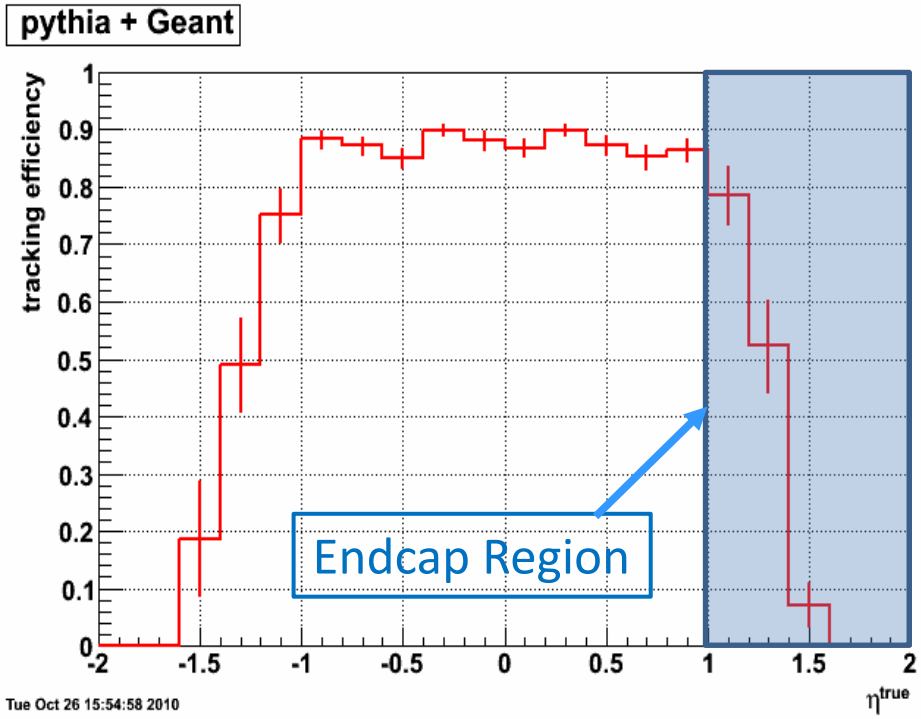
Summary and Outlook

- For almost two decades, STAR has carried out precise measurements of longitudinal double-spin asymmetries for inclusive and dijet production in pp collisions
- By studying A_{LL} over a wide range of kinematic regimes and at several energies, increasingly tight constraints have been placed on the gluon helicity distribution, $\Delta g(x)$, when results are included in global analyses by, *e.g.*, the DSSV, NNPDF, and JAM groups
- Midrapidity results indicate ~40% of the proton's spin may be due to contributions from the spins of gluons that each carry at least 5% of the proton's momentum
- New, higher statistics data at more forward rapidities and at higher collision energies have been recently or are soon to be published, which will provide much needed constraints in the low-x region.



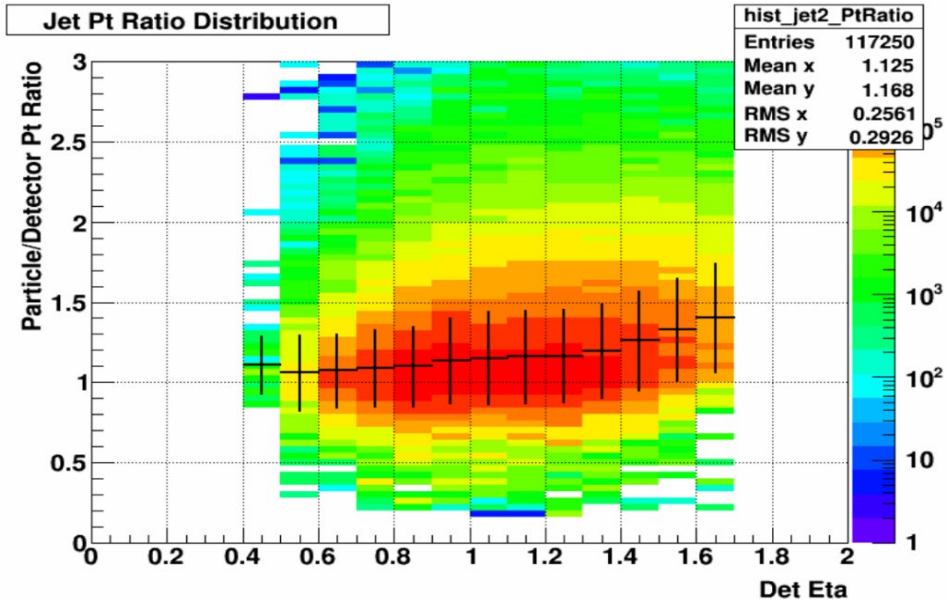
Backup material

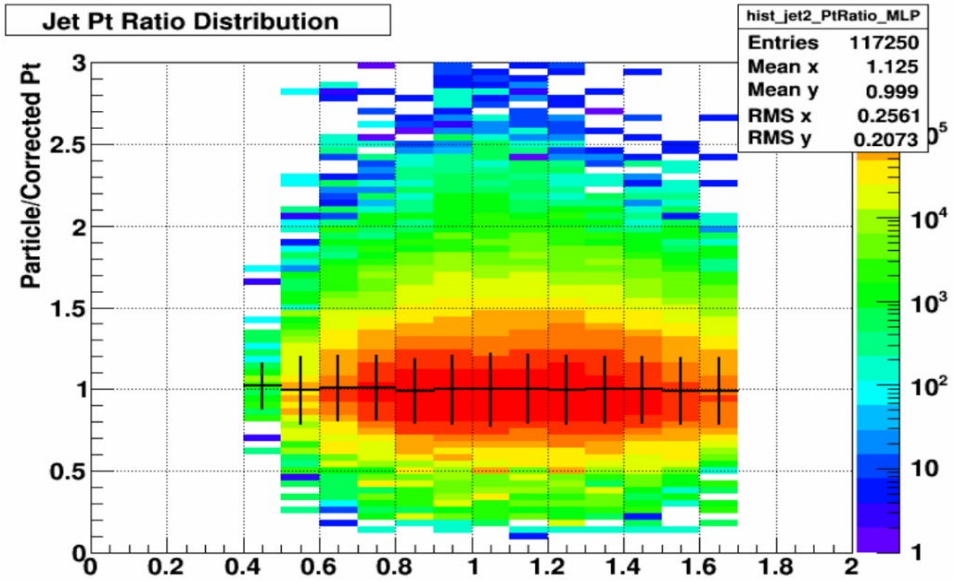
Technical challenges for jets in the STAR EEMC



Charged particle tracking efficiency falls off rapidly beyond η ~ 1.3

Increasingly poor determination of jet p_T and jet η in endcap region





Must correct reconstructed jet properties on an event-by-event basis for biases in p_T, η, R_T

→ Highly non-linear and correlated effects!

→ Use machine learning (Multilayer Perceptron)