

From RHIC to EIC

At the QCD Frontiers

June 7-10, 2022

Topical Workshops: June 7-8, 2022

Plenary Session: June 9-10, 2022

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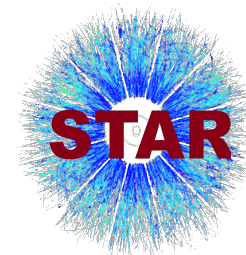
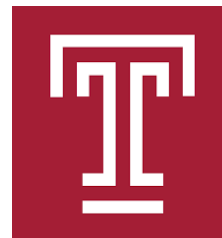
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Recent Highlights from the STAR Spin/Cold-QCD Physics Program

Jae D. Nam,
for the STAR collaboration

RHIC/AGS Annual Users Meeting

Jun 7-10 2022



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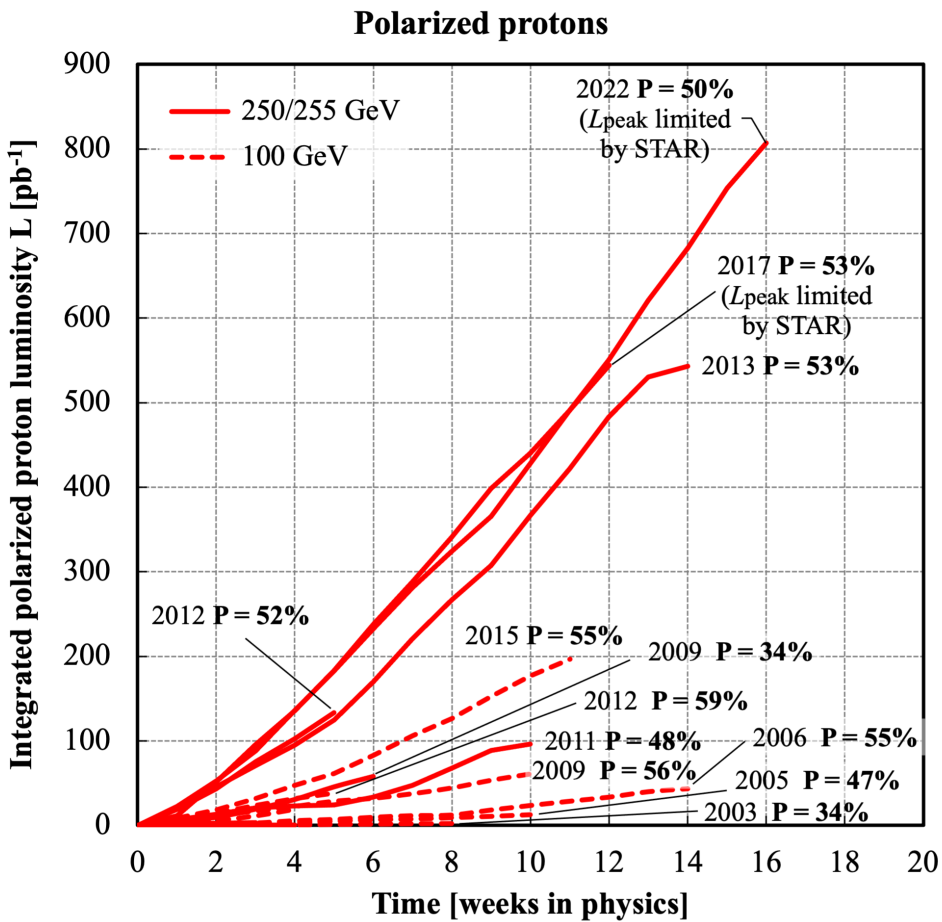


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Overview



RHIC Run Overview – BNL

Available at: <https://www.rhichome.bnl.gov/RHIC/Runs/index.html>

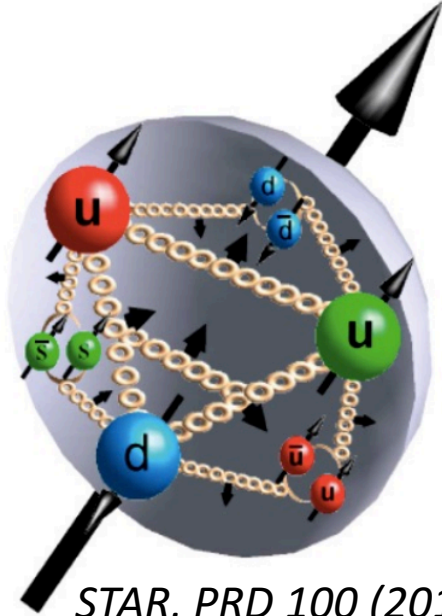
- RHIC is the world’s first and only polarized pp collider.
- STAR Spin/Cold-QCD group investigates the inner structure of the proton with the longitudinally-/transversely-polarized/unpolarized beams.
- Overview
 - Longitudinal polarization
 - Spin composition
 - Transverse polarization
 - 3D image of the proton
 - Unpolarized beams
 - Parton distributions
 - Non-linear gluon effects



Longitudinally-Polarized Beams



Proton Spin Decomposition



STAR, PRD 100 (2019) 5, 052005

- Jaffe-Manohar Spin Sum Rule:
 - R.L. Jaffe, A. Manohar, *Nucl. Phys. B* 337, 509 (1990)

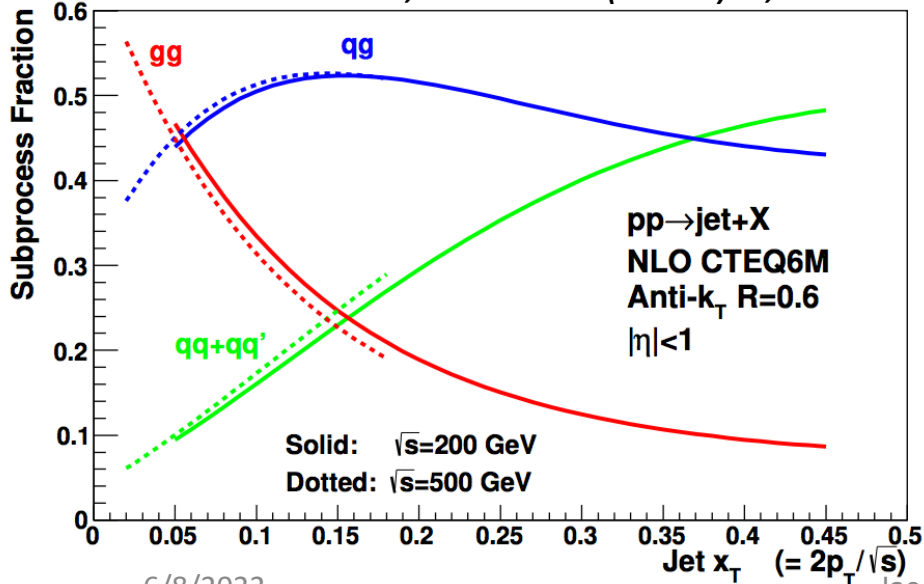
$$S = \frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L$$

- The spin contribution from quarks, $\Delta\Sigma$, only accounts for less than half of proton spin.

- Midrapidity jets at STAR mostly originate from qg and gg scatterings

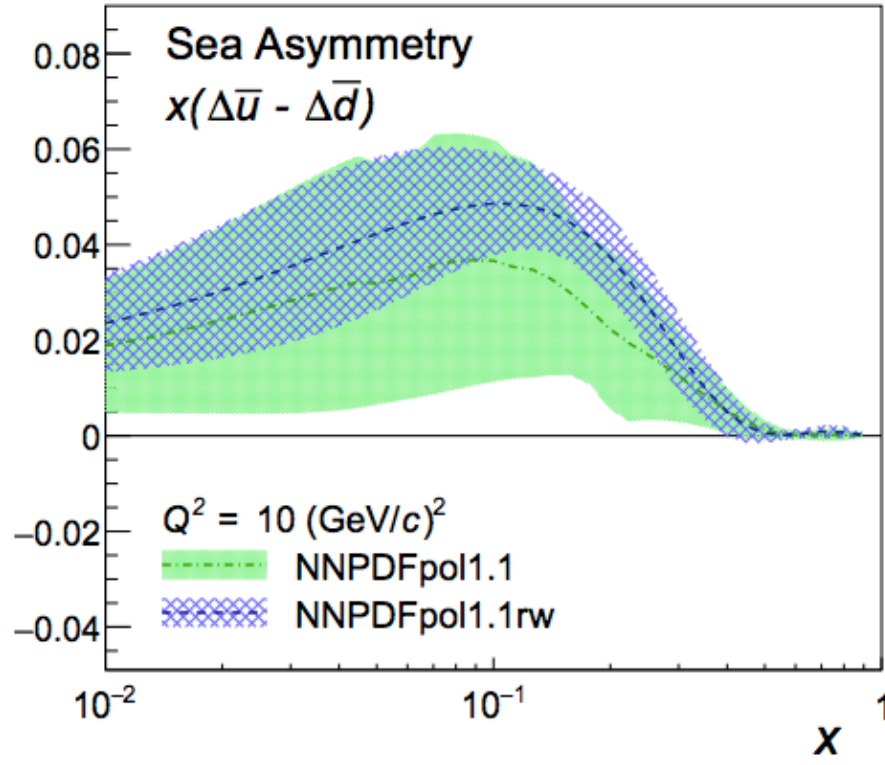
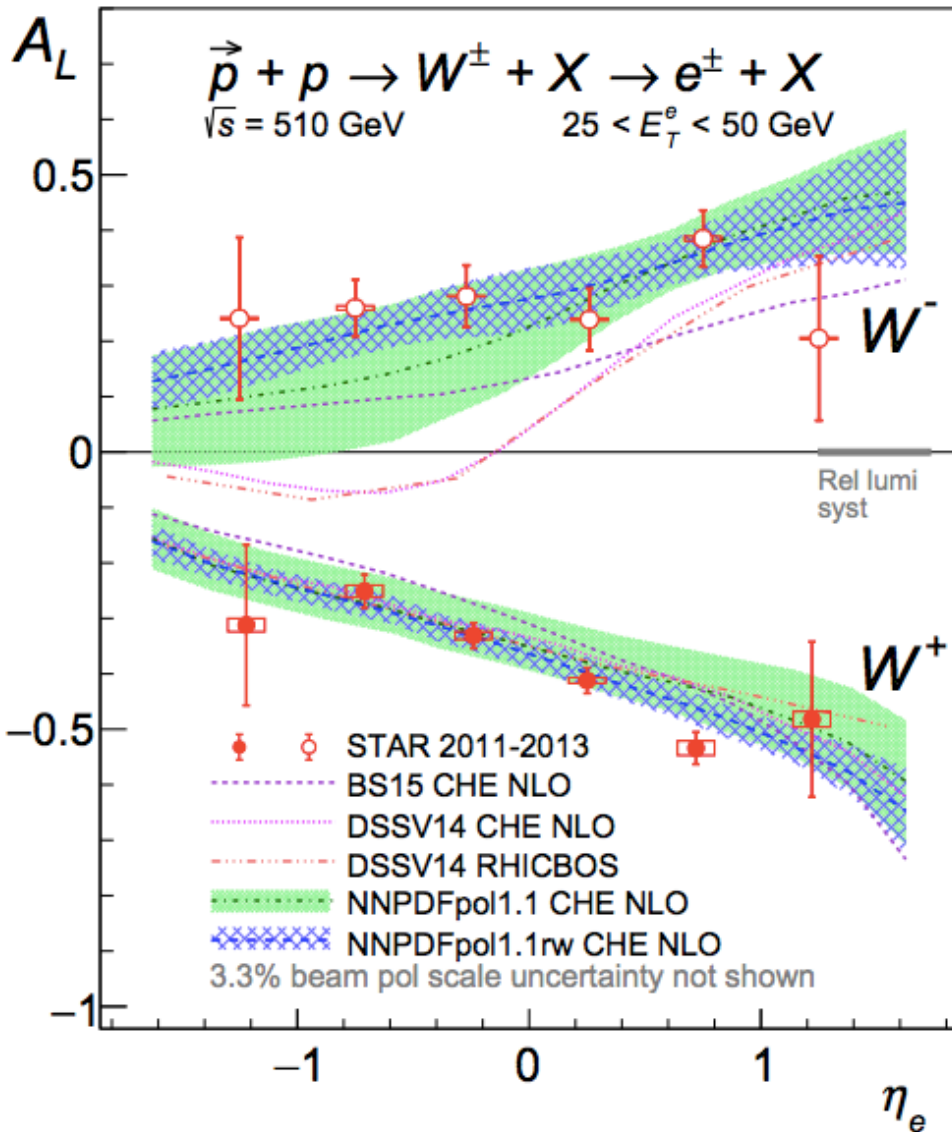
- Probe the gluon contribution, $\Delta G = \int_0^1 \Delta g(x, Q^2) dx$.
- Measurements of longitudinal double spin asymmetry.

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



Proton Spin Decomposition (Cont'd)

PRD 99 (2019) 5, 051102

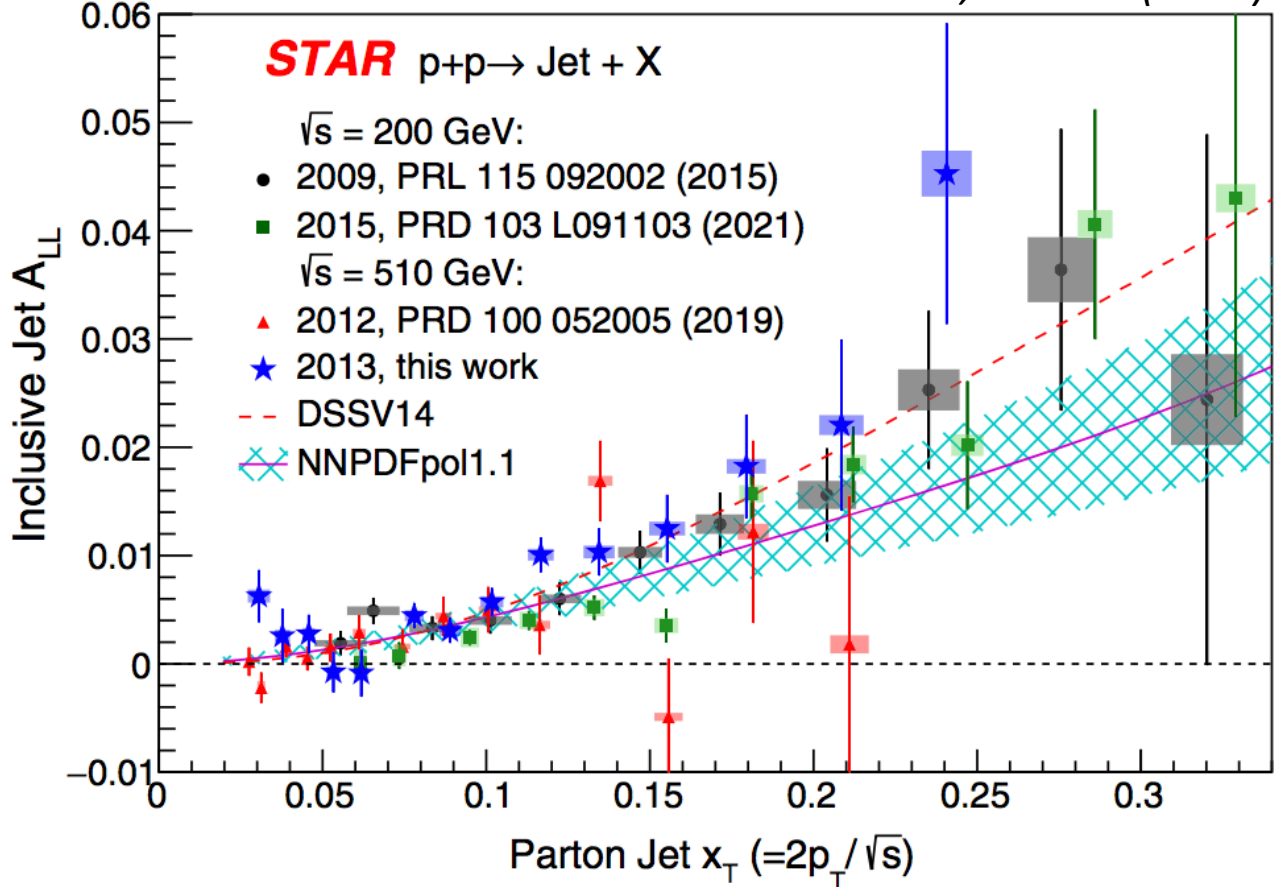


- Earlier measurements of $W A_L$ at STAR investigated the light quark contribution to the proton spin.
- Improved understanding of light quark spin contribution further motivates investigation of gluon polarization.



Inclusive Jets at STAR

PRD 105, 092011 (2022)

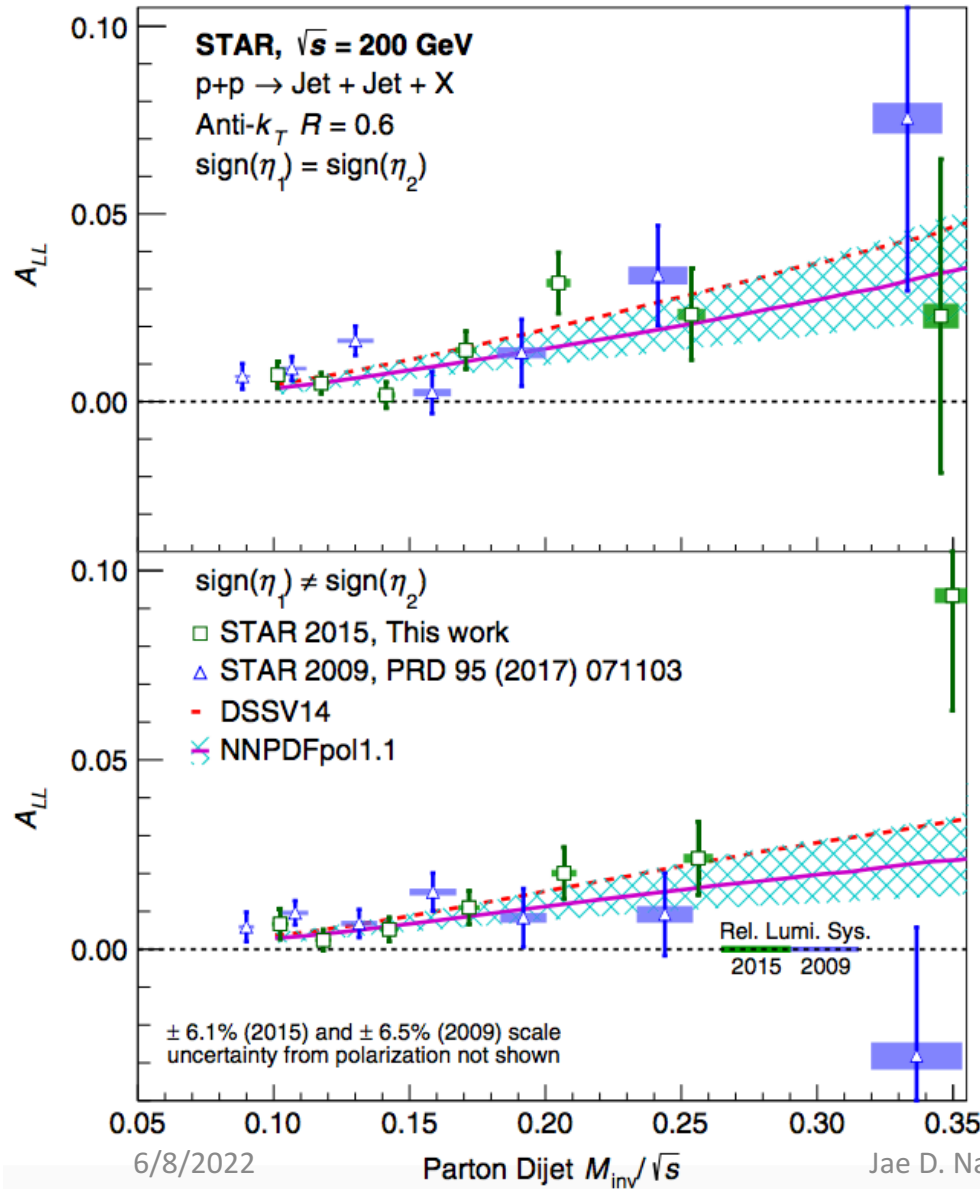


- A_{LL} with inclusive jets at STAR midrapidity.
- Features two different collision energies, probing the gluon helicity distribution in a wide range in x .
- Improved precision by including the latest datasets (STAR Run 2013/2015).
 - Slight preference for DSSV14.
 - Concludes the longitudinal spin data-taking program.



Dijets at Midrapidity at 200 GeV

PRD 103, 091103 (2021)

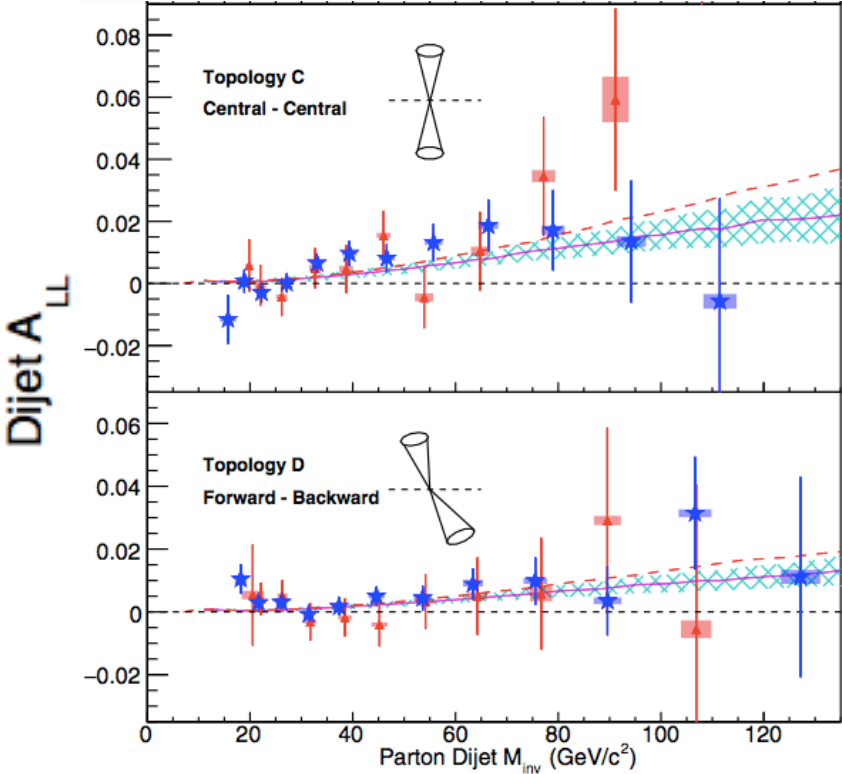
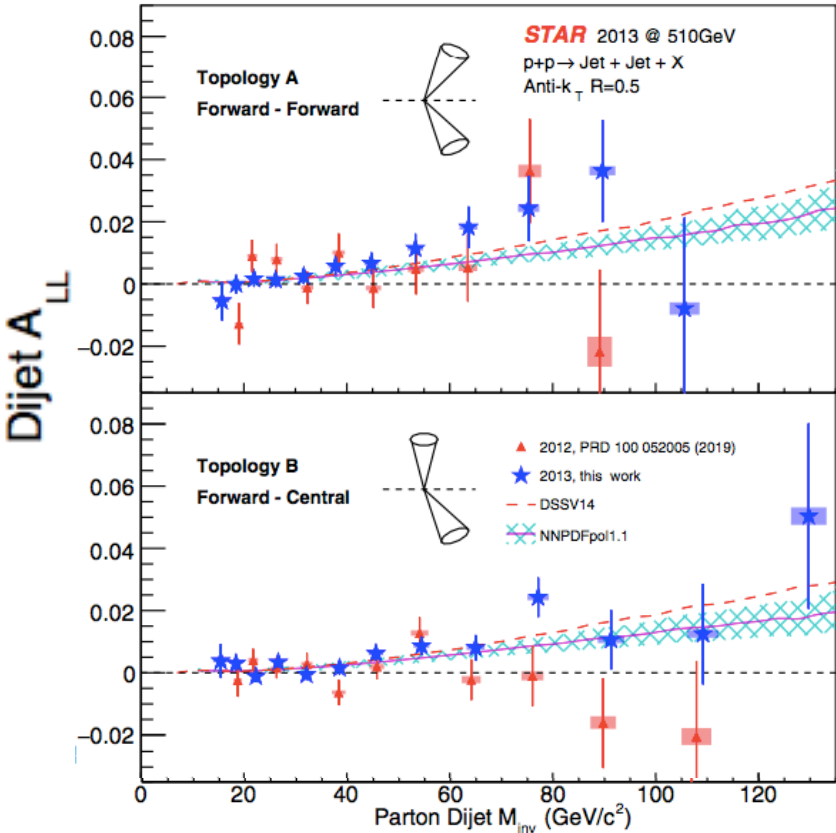


- Correlation measurements with dijets provide more stringent constraints on the initial state kinematics.
 - The jet topology sensitive to the different ranges of x .
- Presented on the left are A_{LL} as a function of relative dijet mass, $M_{inv}/\sqrt{s} = \sqrt{x_1 x_2 s}/\sqrt{s}$, in two different topologies with two different 200 GeV pp datasets.
 - STAR Run 2009:
 - PRD 95, 071103 (2017)
 - Features $\sim 20 \text{ pb}^{-1}$
 - STAR Run 2015:
 - PRD 103, 091103 (2021)
 - Doubles the statistics of 2009.
 - Additional background rejection scheme employed, greatly reducing systematic uncertainty.



Dijets at Higher Energy

PRD 105, 092011 (2022)

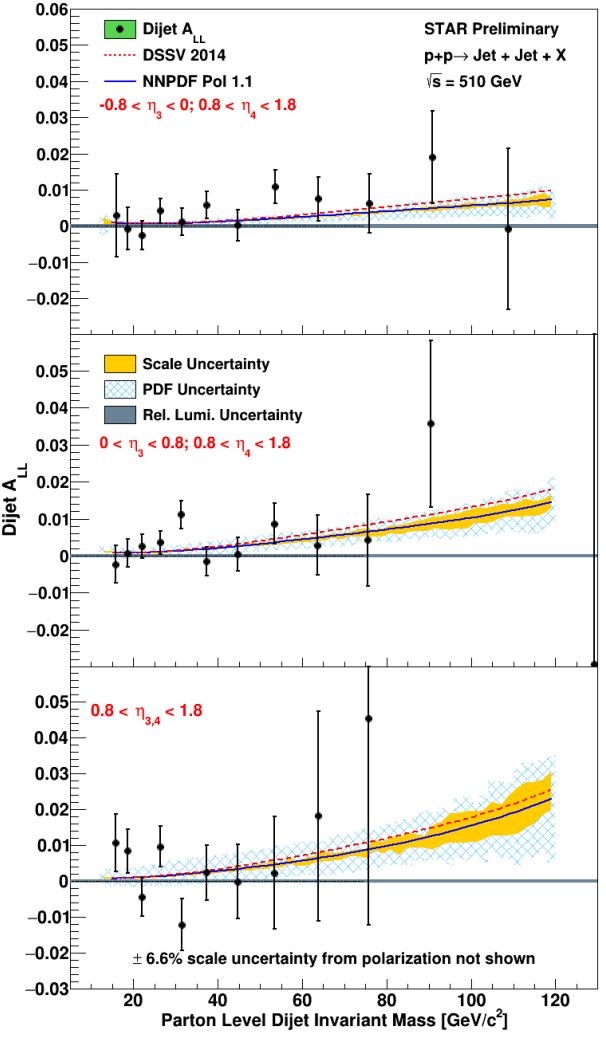


- The latest dijet study has been published along with inclusive jet study.
 - 510 GeV pp sample from 2013
 - Finer bins in jet topologies allowed by higher statistics.

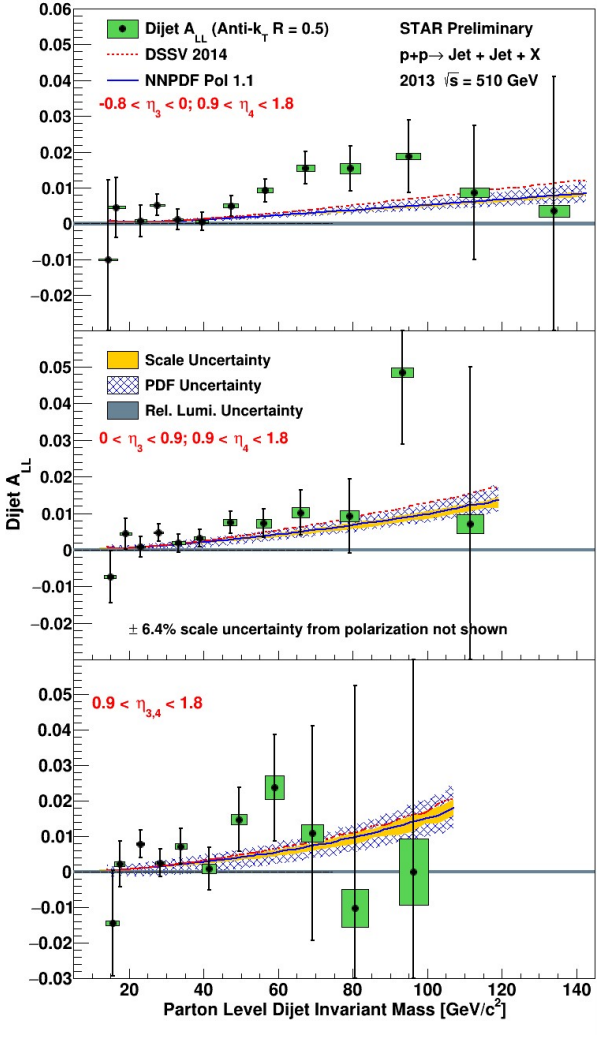


Dijets in Intermediate Rapidity

STAR Run 2012



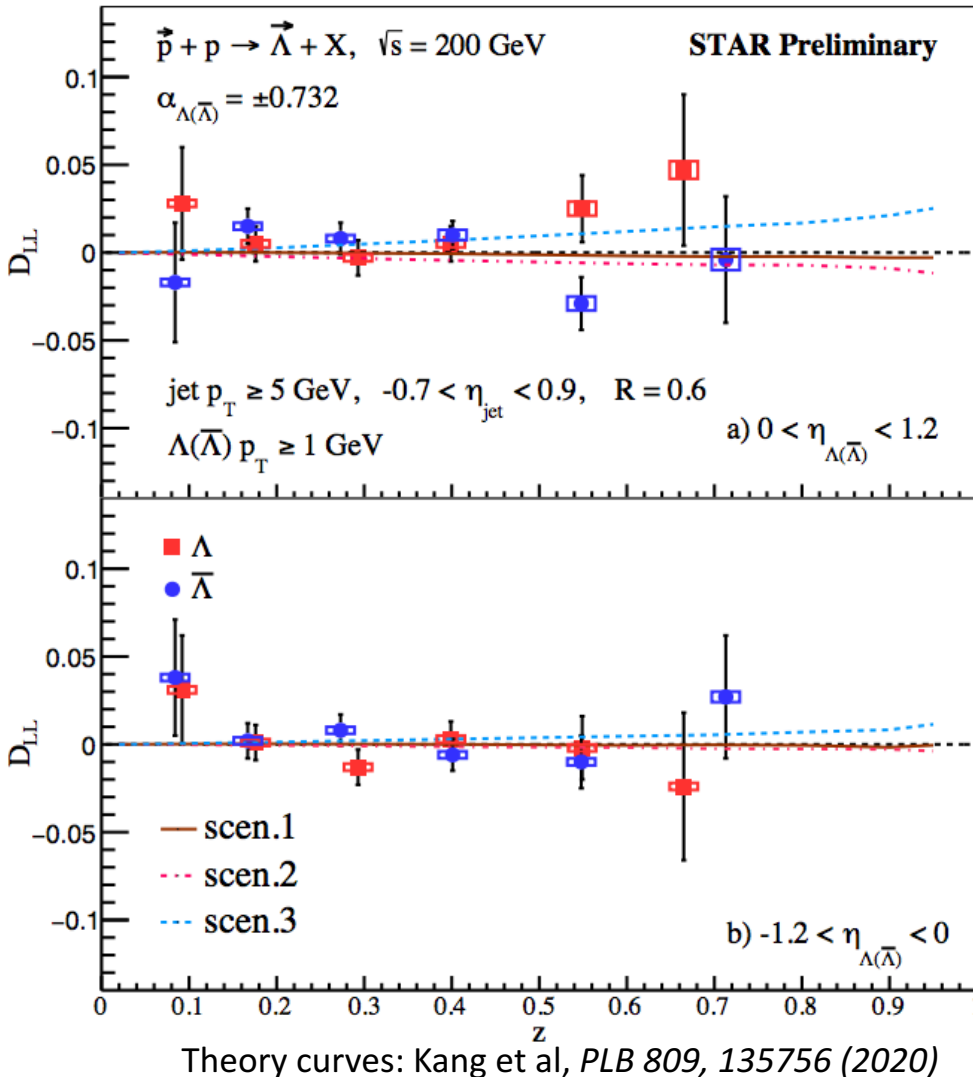
STAR Run 2013



- Jets that are reconstructed in the endcap region ($0.8 < \eta < 1.8$) can be used to extend the kinematic reach into low x regime.
- Measurements show higher values of A_{LL} than the global fit predictions.
- Combined results being finalized.



Λ Hyperon in Polarized pp Collisions



- Λ hyperon production in pp collisions can be used to probe the strange contribution to the Lambda spin via polarized FF (D^Λ).

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

$$= \frac{\Sigma \Delta f_a \otimes f_b \otimes \Delta \sigma \Delta D^\Lambda}{\Sigma f_a \otimes f_b \otimes \sigma}$$

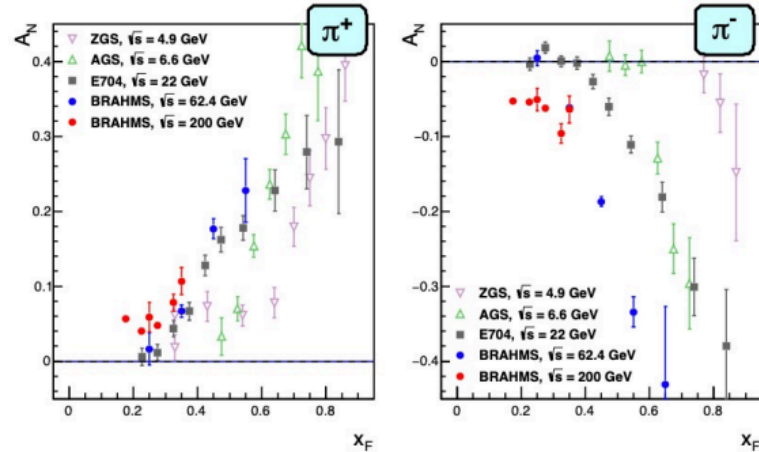
- First measurement of $D_{LL}(z)$; $z = \frac{\vec{p}_\Lambda \cdot \vec{p}_{\text{jet}}}{\vec{p}_{\text{jet}} \cdot \vec{p}_{\text{jet}}}$.
- Provides direct probe of polarized FF.
- Compared to few different scenarios with different assumptions on u, d, s contribution to the Lambda spin.
- The new preliminary results (Run 2015) consistent with the previous measurements (Run 2009).
- Consistent between Λ and $\bar{\Lambda}$.
- Most precise measurement to date.

Transversely-Polarized Beams

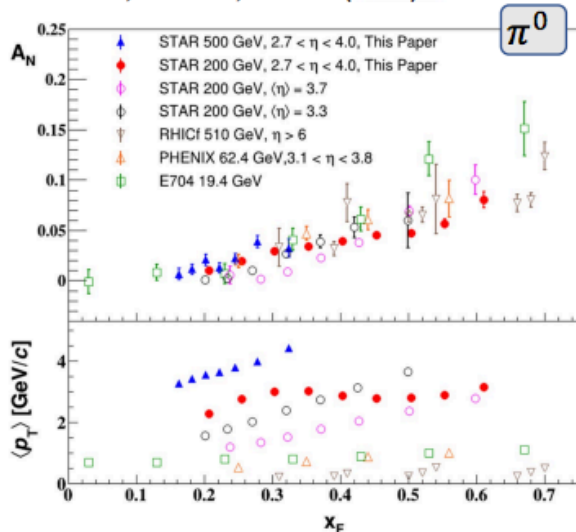


Transverse Single Spin Asymmetry, A_N

Elke Aschenauer *et al.* arXiv:1602.03922 [nucl-ex]



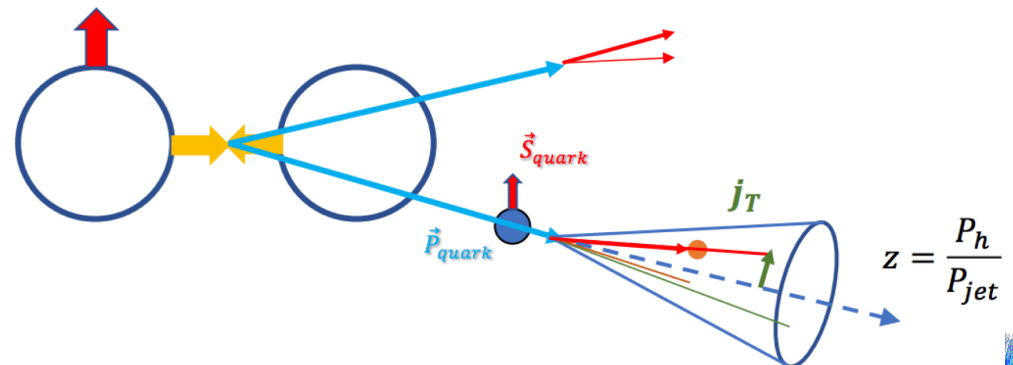
STAR, PRD 103, 092009 (2021)



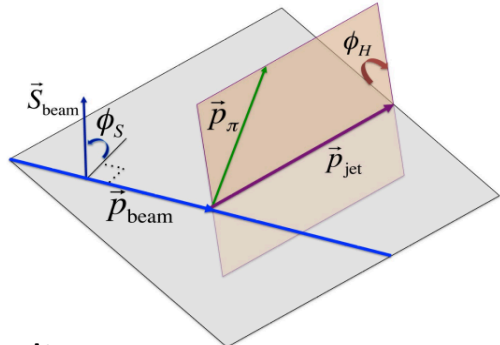
- pQCD's prediction of TSSA:

$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \sim 0$$

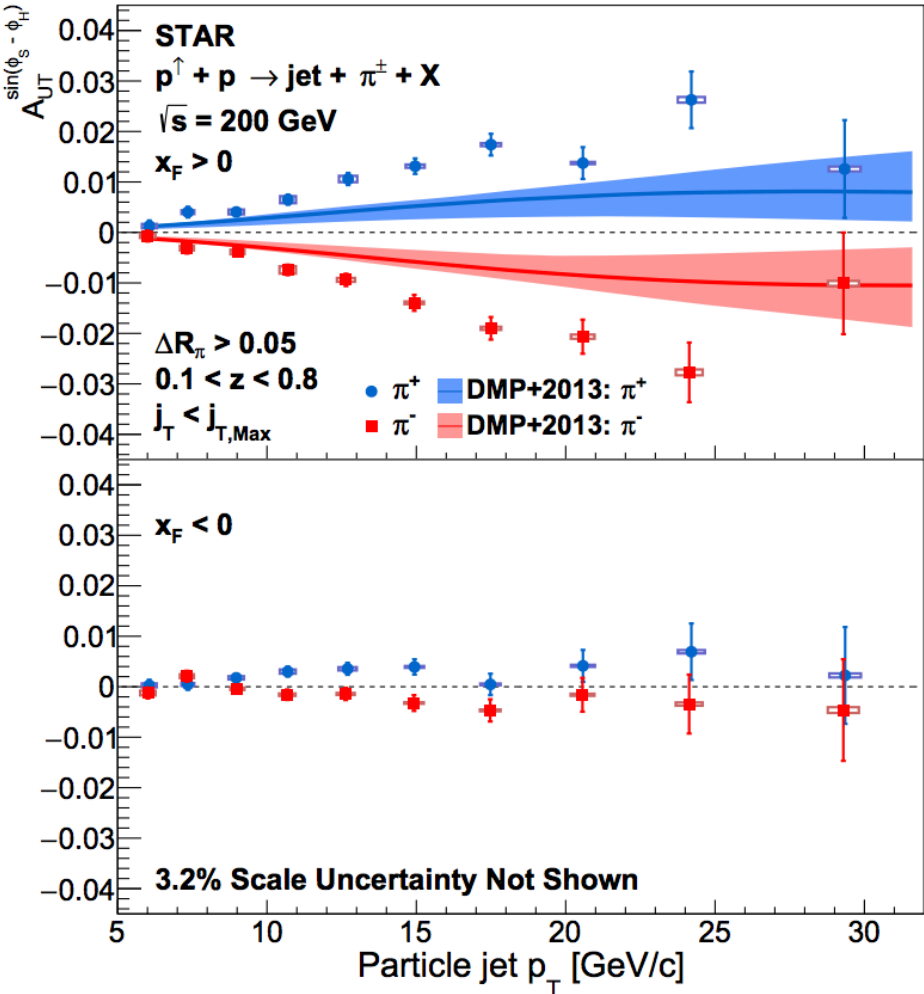
- Large values of A_N observed in $p^\uparrow p$ collisions at forward rapidity.
- TMD frameworks that account for higher twist effects have been developed.
- Collins effect
 - Correlation between the spin of scattered quark and p_T of fragmented hadron (j_T) in transversely polarized pp collisions.



Collins Effect with Pions



arXiv:2205.11800, submitted to PRD



- Based on QCD formalism, we define Collins azimuthal spin asymmetry,

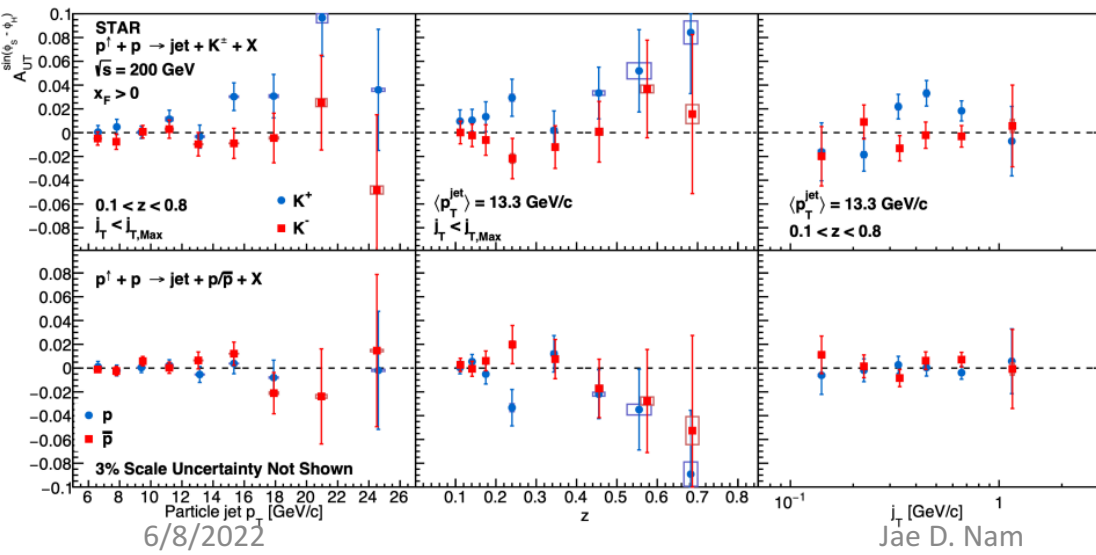
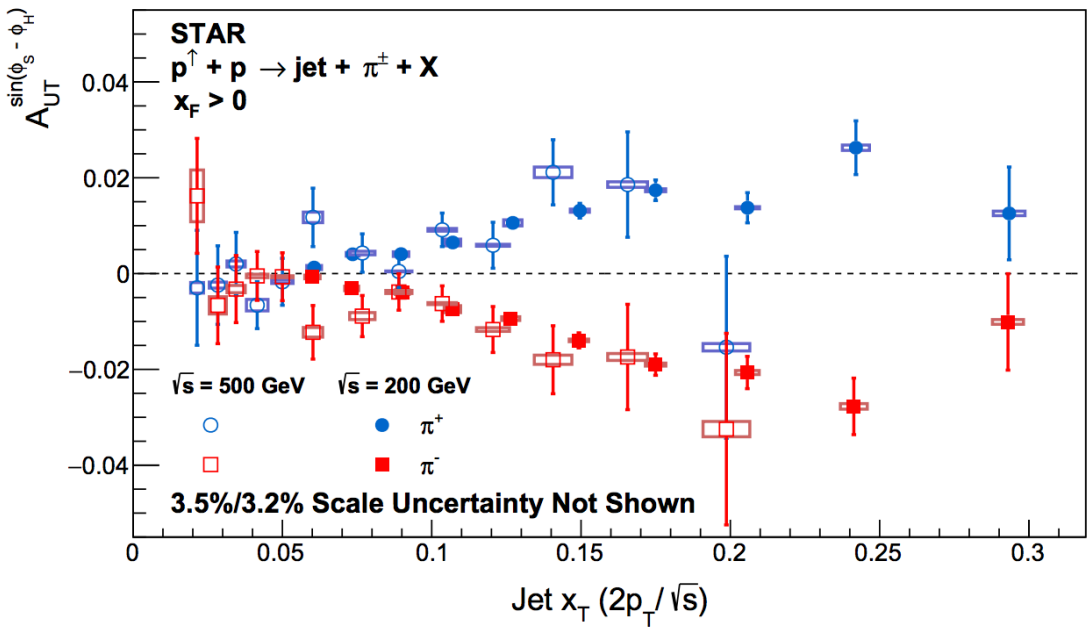
$$A_{UT}^{\sin \phi} \sin \phi = \frac{\sigma^\uparrow(\phi) - \sigma^\downarrow(\phi)}{\sigma^\uparrow(\phi) + \sigma^\downarrow(\phi)}$$

$$= \frac{\sum h_1^a \otimes f_b \otimes \sigma_{ab \rightarrow c}^{\text{Collins}} H_{1,h/c}^\perp}{\sum f_a \otimes f_b \otimes \sigma_{ab \rightarrow c}^{\text{unpol}} D_{h/c}}$$

- $h_1^a =$ Collinear transversity
- $H_{1,h/i}^\perp =$ TMD Collins frag. func.
- Theory prediction (D'Alesio et al, *PLB* 773 (2017) 300) based on SIDIS (transversity) and e^+e^- (Collins FF) experiments.
- In general, the observed asymmetry is larger than the theory predictions.



Collins Effect (Continued)



- Collision energy dependence
 - Results from $\sqrt{s} = 200$ and 500 GeV samples have been compared.
 - Weak dependence in collision energy found.
- Analysis has been expanded to investigate Collins effect with K^{\pm} and p/\bar{p} for the first time at ST.
 - Asymmetry of K^+ similar to π^+ .
 - K^- asymmetry consistent with zero as it originates from unfavored fragmentation.
 - p/\bar{p} asymmetry consistent with zero.

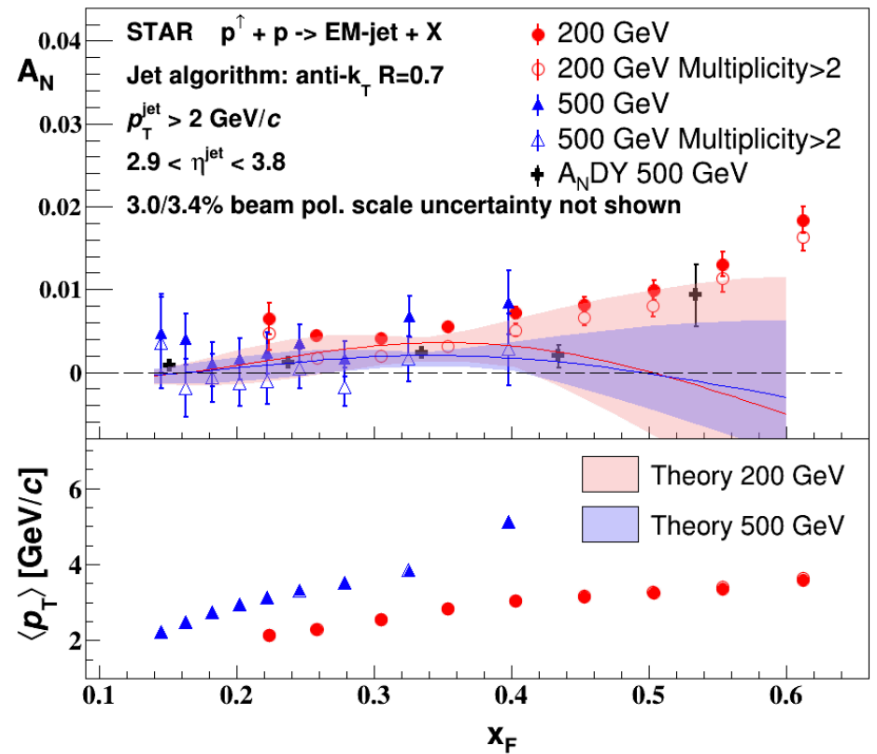
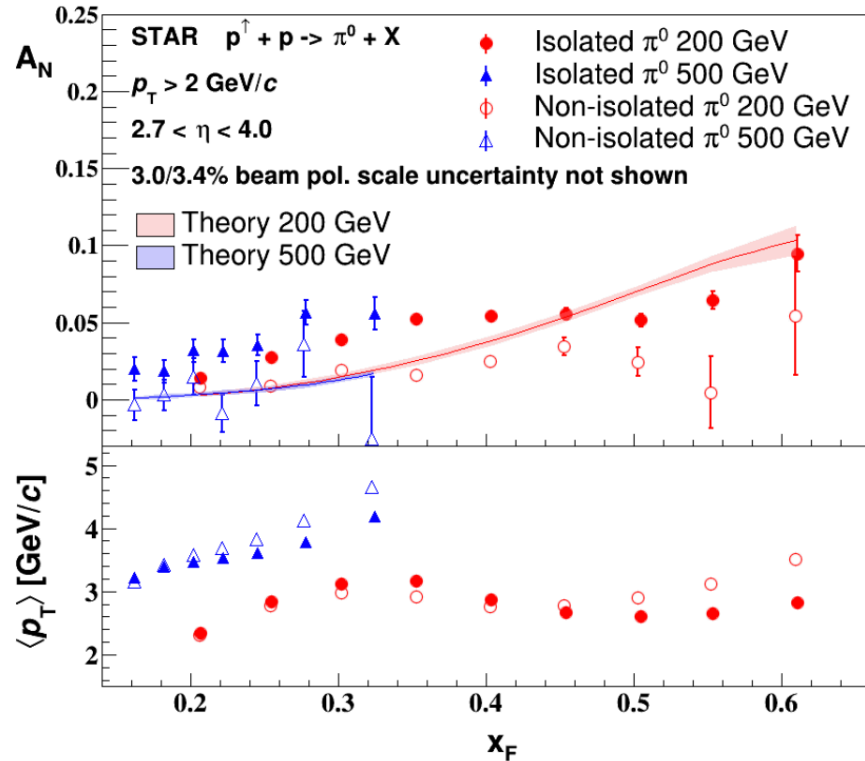
6/8/2022

Jae D. Nam



A_N in the Forward Rapidity

PRD 103 (2021) 9, 092009



- A_N measured with forward EM-jets and π^0 in 200/500 GeV pp collisions.
- No significant collision energy dependence observed.

- High multiplicity EM-jets ($n_\gamma > 2$) and non-isolated π (w/ nearby γ) tend to generate smaller A_N .

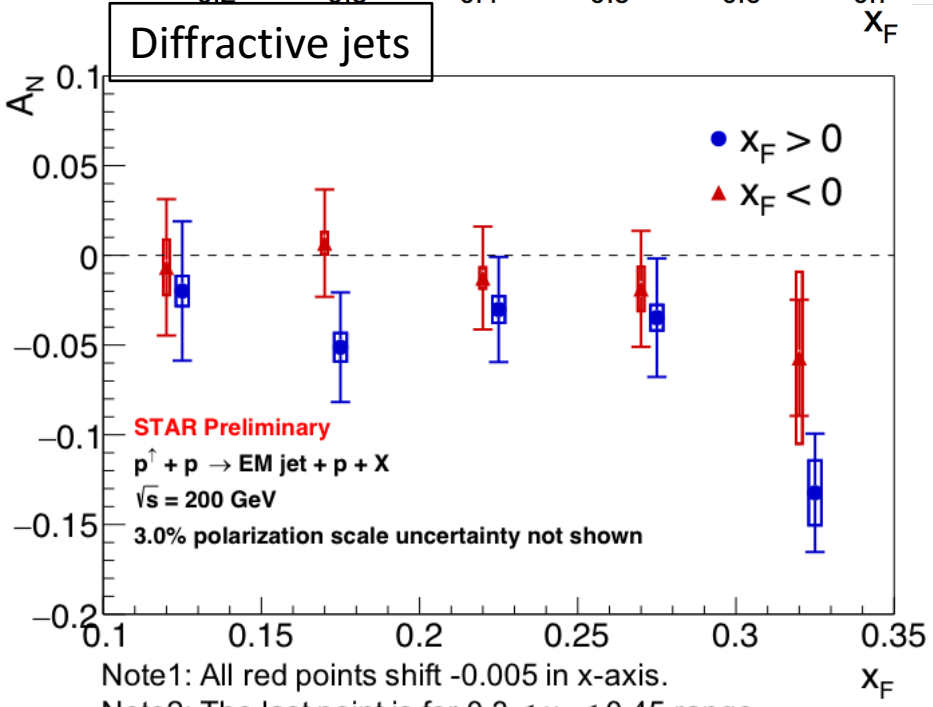
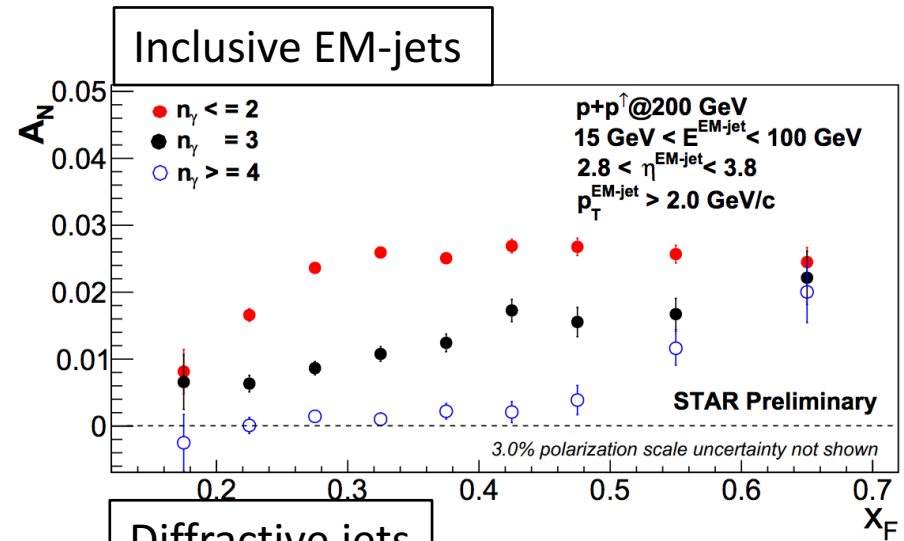
→ Contribution from diffractive process?

Theory curves:

- EM-jet: Gamberg et al, *PRL* 110, 232301 (2013)
- Pion: Cammarota et al, *PRD* 102, 054002 (2020)



Diffractive Jets in the Forward Region

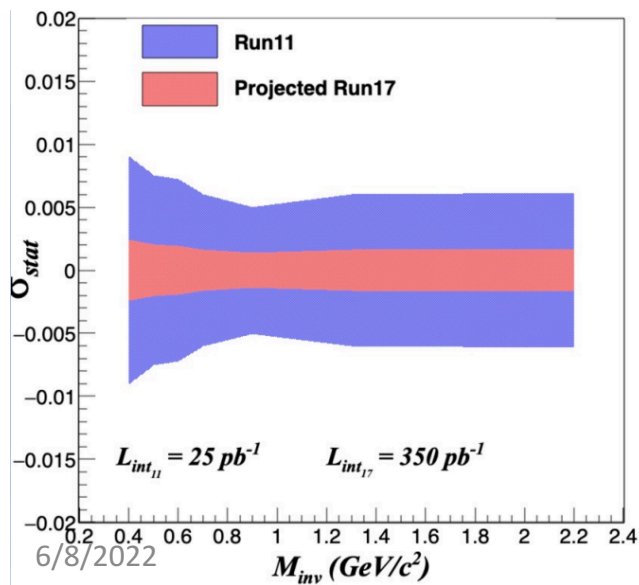
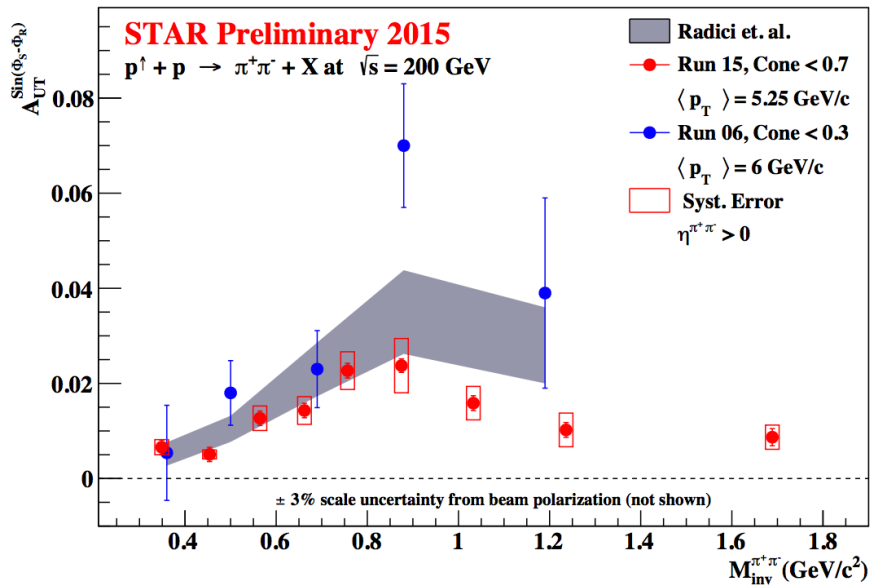


- Inclusive EM-jets further subdivided based on the γ multiplicity.
- Clear trend has been observed where higher multiplicity EM-jets produce smaller asymmetry.
- Protons from diffractive processes tagged by using Roman Pot.
- A_N for diffractive jets in $x_F < 0$ region is consistent with zero.
- Theoretical inputs needed to understand the negative sign of A_N .

Note1: All red points shift -0.005 in x-axis.
 Note2: The last point is for $0.3 < x_F < 0.45$ range
 6/8/2022



Asymmetry with Di-hadron process



- A more exclusive channel involving hadron pairs in the same jet, $p^\uparrow p \rightarrow h^+ h^- X$, may help access the transversity, h_1 , via coupling with Interference Fragmentation Function (IFF), H_1^\perp .

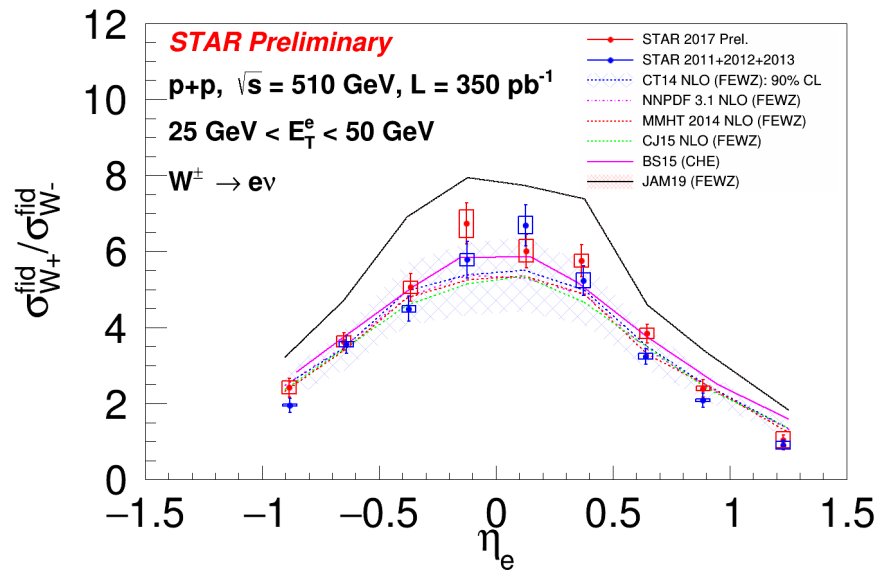
$$d\sigma_{UT} \propto \sin \phi_{pair} \Sigma h_1^a \otimes f_b \otimes H_1^\perp$$

- Initial measurements based on STAR Run 2006 ($\sqrt{s} = 200$ GeV) and Run 2011 ($\sqrt{s} = 500$ GeV) data have been revisited with the latest pp 200/510 GeV samples taken in 2015 and 2017, respectively.
- Significant reduction in δ_{stat} observed with Run 2015.
- Results with Run 2017 in progress.

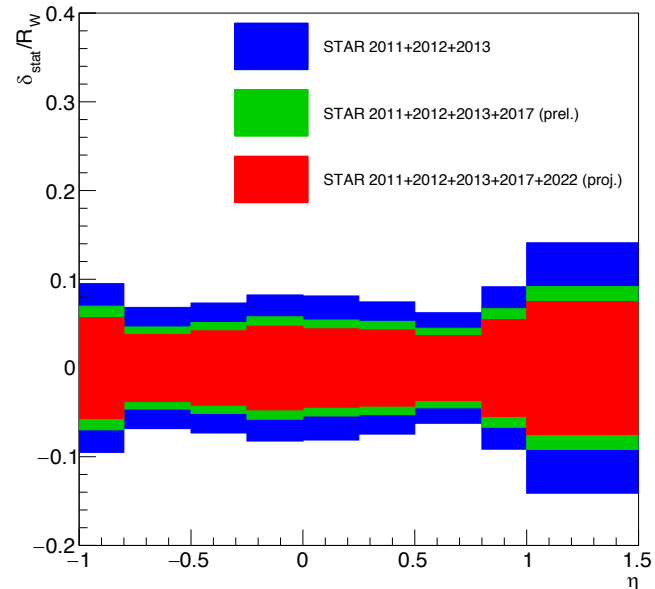
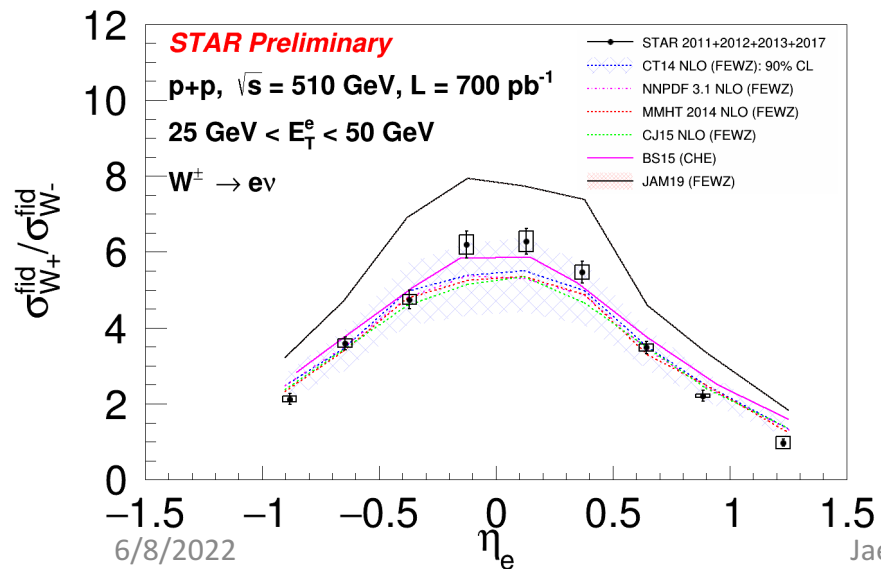
Unpolarized Beams



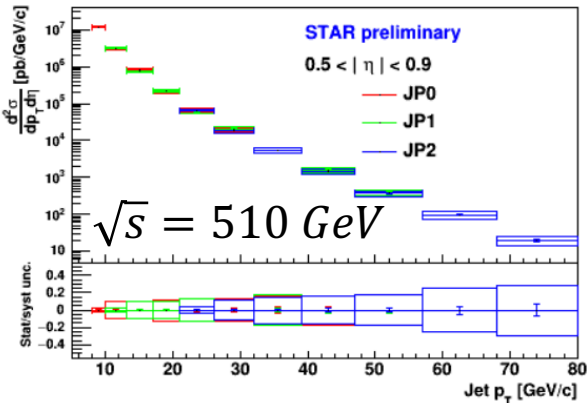
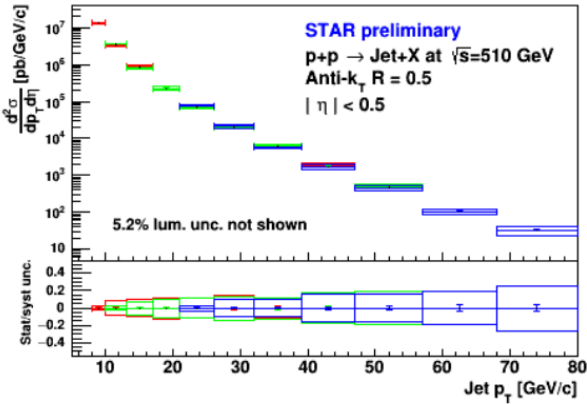
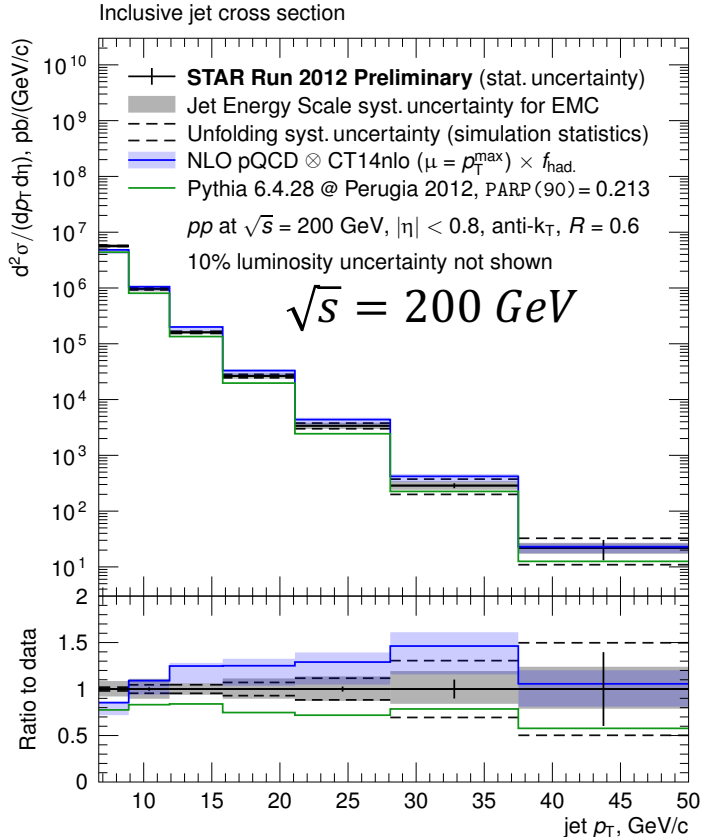
Accessing \bar{d}/\bar{u} with W production



- W^+/W^- production ratio at STAR can be used to probe the \bar{d}/\bar{u} asymmetry in the proton sea.
- Recent publication (STAR, *PRD 103, 012001*) features data sets from 2011-2013 ($L = 350 \text{ pb}^{-1}$).
- Preliminary release with STAR 2017 data set which adds another 350 pb^{-1} .
- Statistical precision expected to be further improved with the latest STAR 2022 data set.



Accessing Gluon PDF with Inclusive Jets



- Measurements of inclusive jet cross section at STAR midrapidity can probe gluon density in the high x regime.
- Initial measurements based on Run 2003-04 ($\sqrt{s} = 200 \text{ GeV}$) and Run 2009 ($\sqrt{s} = 500 \text{ GeV}$) suffered from large systematic uncertainties due to underlying events.

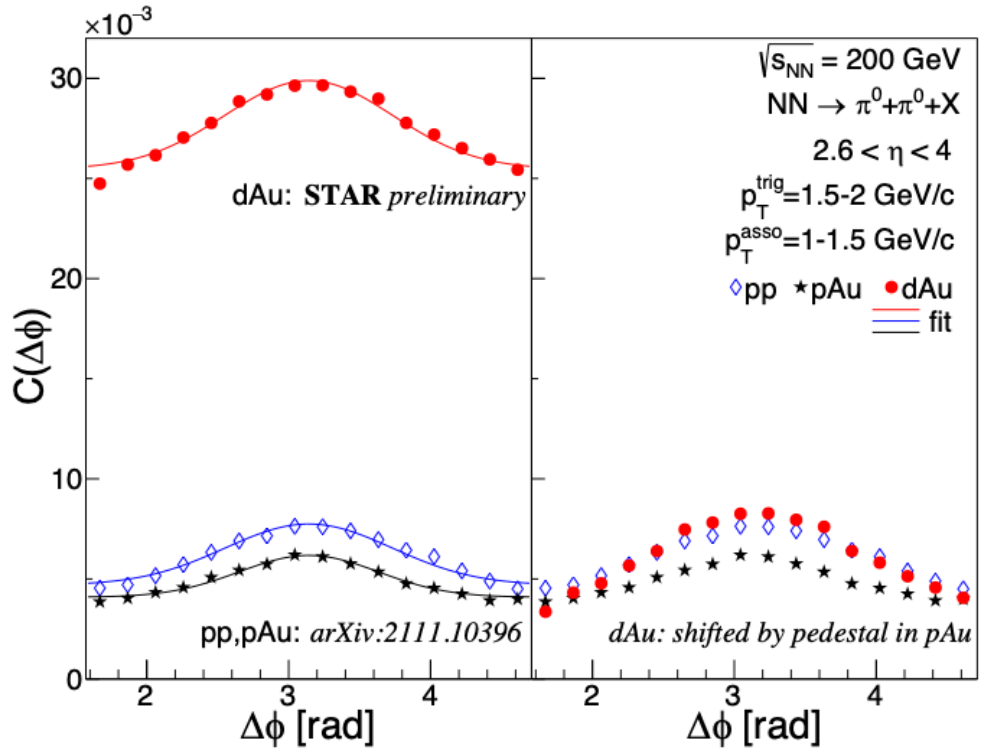
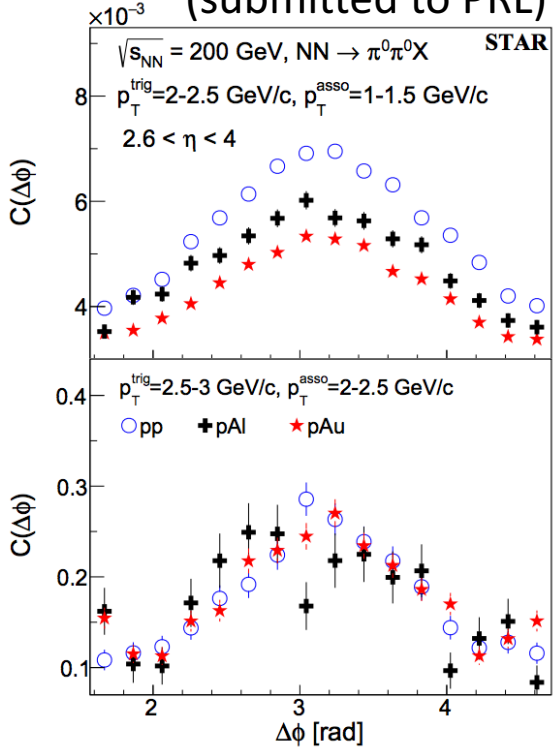
- Two energy modes provide access to different regions in kinematics:
 - $pp \sqrt{s} = 200 \text{ GeV}: 0.067 < x_T < 0.5$
 - $pp \sqrt{s} = 510 \text{ GeV}: 0.021 < x_T < 0.32$



Nonlinear Gluon Effects in QCD

arXiv:2111.10396

(submitted to PRL)



- Nonlinear gluon effects in high gluon density environment provided at forward rapidity at STAR.

- Di-hadron ($\pi^0\pi^0$) observable:

$$C(\Delta\phi) = \frac{N_{\text{pair}}(\Delta\phi)}{N_{\text{trig}} \times \Delta\phi_{\text{bin}}}$$

- Clear suppression in $C(\Delta\phi)$ in pA

- Run 2016 $dAu \sqrt{s_{NN}} = 200 \text{ GeV}$ set included (preliminary).

- $\times 5$ higher pedestal with dAu compared to $pp(Au)$.

- Double Parton Scattering (DPS) may provide an explanation to the high pedestal; DPS contribution may exceed the leading-twist.



Recent Publications

Publication	Title
PRD 105 (2022) 92011	Longitudinal double-spin asymmetry for inclusive jet and dijet production in polarized proton collisions at $\sqrt{s} = 510 \text{ GeV}$
PRD 103 (2021) L091103	Longitudinal double-spin asymmetry for inclusive jet and dijet production in polarized proton collisions at $\sqrt{s} = 200 \text{ GeV}$
PRD 103 (2021) 72005	Comparison of transverse single-spin asymmetries for forward π_0 production in polarized pp , pAl and pAu collisions at nucleon pair c.m. energy $\sqrt{s_{NN}} = 200 \text{ GeV}$
arXiv:2205.11800 (submitted to PRD)	Azimuthal transverse single-spin asymmetries of inclusive jets and identified hadrons within jets from polarized pp collisions at $\sqrt{s} = 200 \text{ GeV}$
PRD 103 (2021) 92009	Measurement of transverse single-spin asymmetries of π_0 and electromagnetic jets at forward rapidity in 200 and 500 GeV transversely polarized proton-proton collisions
PRD 103 (2021) 012001	Measurements of W and Z/γ^* Cross Section and Cross-Section Ratios in $p + p$ Collisions at RHIC
arXiv:2111.10396 (submitted to PRL)	Evidence for Nonlinear Gluon Effects in QCD and their A Dependence at STAR



Summary

- Longitudinal polarization data-taking program at STAR concluded with the inclusion in STAR Run 2015.
 - Measurements at STAR investigate the proton spin composition in a wide range in x by using inclusive jets/dijets with a variety of collision energies and jet topologies.
- Transversely-polarized pp collisions.
 - The proton transversity (h_1), Collins FF (H_1^\perp) and Interference FF (IFF, $H_1^<$) probed with hadron(s) in jets.
 - A_N for inclusive and diffractive EM-jets are both measured, with an opposite sign from diffractive process.
- Unpolarized pp collisions.
 - The \bar{d}/\bar{u} asymmetry probed with W production measurements.
 - Inclusive jet productions at STAR midrapidity provide constraints to the gluon density in the high- x regime.
 - Nonlinear gluon effects have been investigated with forward di-hadron correlation at STAR.



Backup

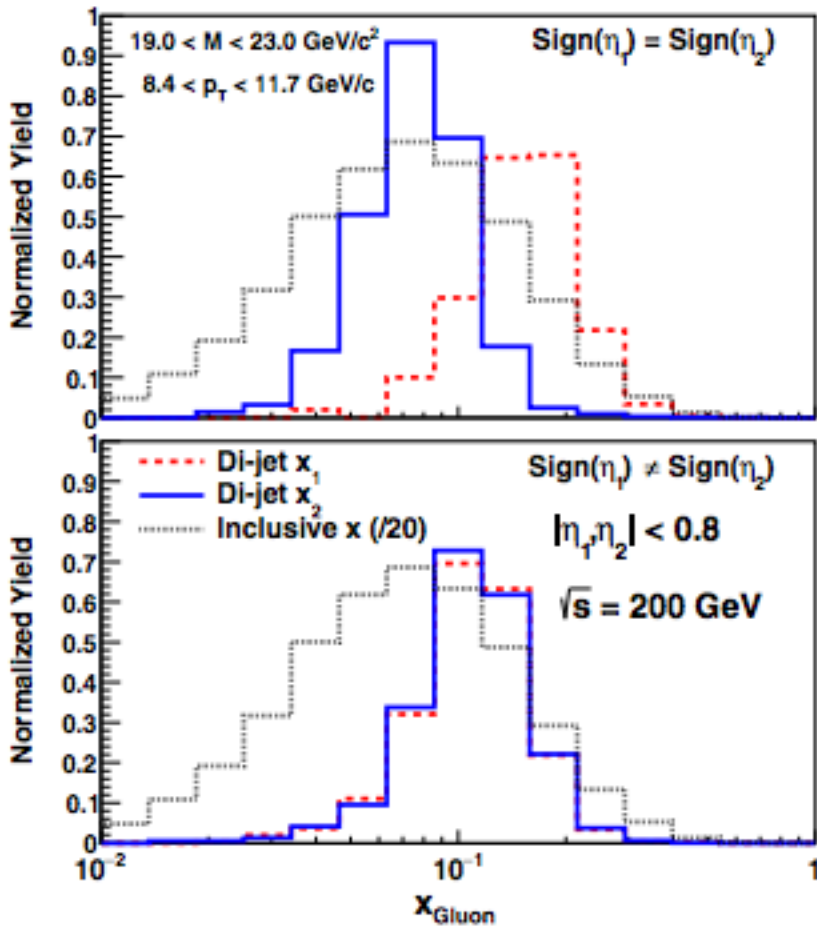


Recent Talks

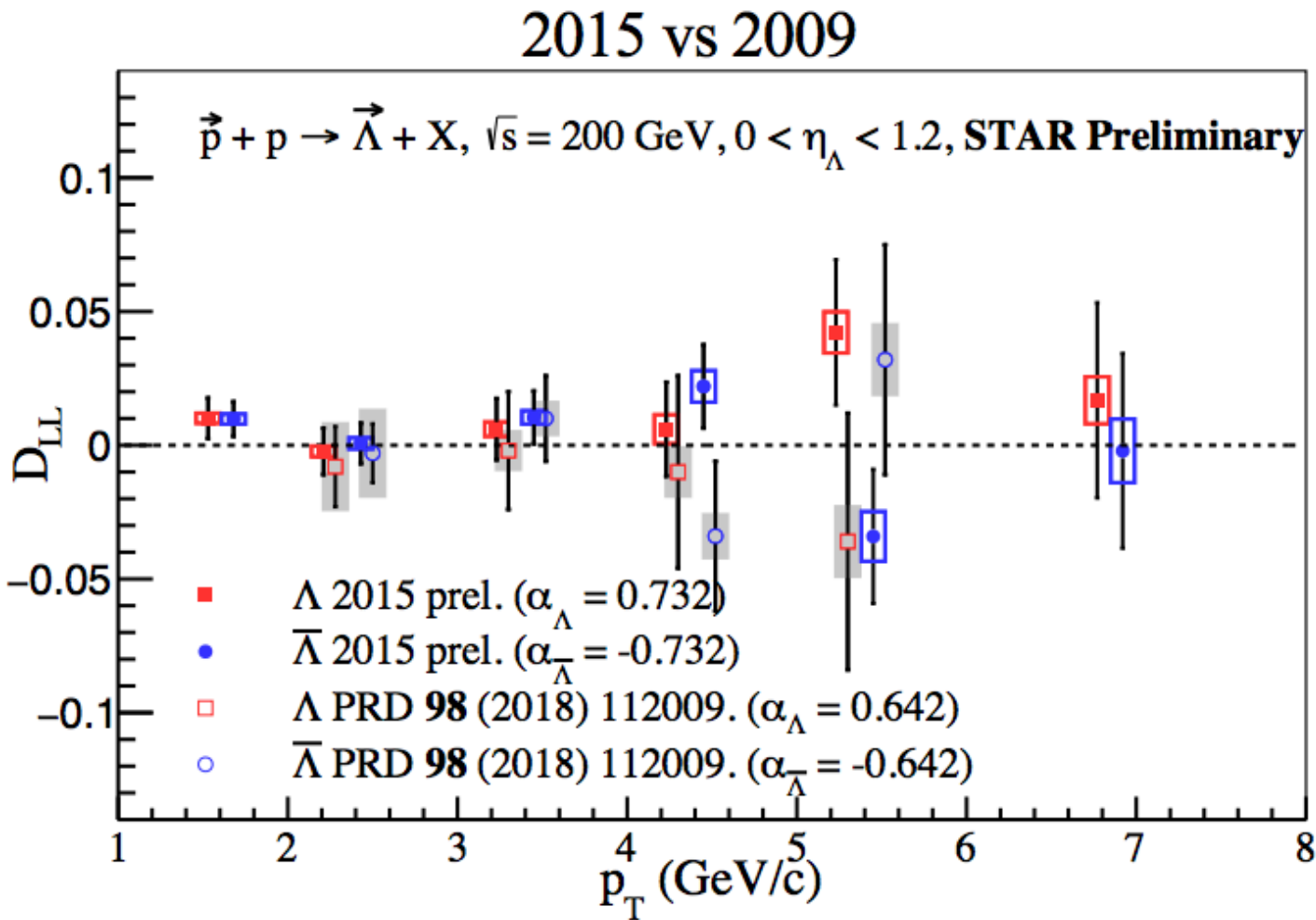
Presenter	Title
S. Wissink (DIS 2022)	Constraining the Gluon Helicity Distribution of the Proton with Inclusive Jet and Dijet Measurements at STAR
Yi Yu (DIS 2022)	Measurement of longitudinal spin transfer of $\Lambda(\bar{\Lambda})$ hyperon in polarized $p + p$ collisions at $\sqrt{s} = 200 \text{ GeV}$ at RHIC-STAR
X. Liang (DIS 2022)	Transverse Single-Spin Asymmetry for Inclusive and Diffractive Electromagnetic Jets at Forward Rapidities in $p^\uparrow + p$ Collisions at $\sqrt{s} = 200 \text{ GeV}$ and 510 GeV at STAR
T. Lin (DIS 2022)	Azimuthal Transverse Single-Spin Asymmetries of Inclusive Jets and Identified Hadrons Within Jets from Polarized pp Collisions at 200 GeV
N. Ghimire (DIS 2022)	Transverse Spin Dependent Azimuthal Correlations of Charged Pion Pairs in $p^\uparrow p$ collisions at $\sqrt{s} = 200 \text{ GeV}$ and $\sqrt{s} = 510 \text{ GeV}$ at STAR
T. Gao (DIS 2022)	Measurement of transverse polarization for Lambda production in pp collisions at STAR
J. Nam (DIS 2022)	Measurements of W^+/W^- cross-section ratio in pp collisions at STAR
D. Kalinkin (DIS 2022)	Inclusive Jet Cross Sections in pp Collisions at $\sqrt{s} = 200$ and 510 GeV



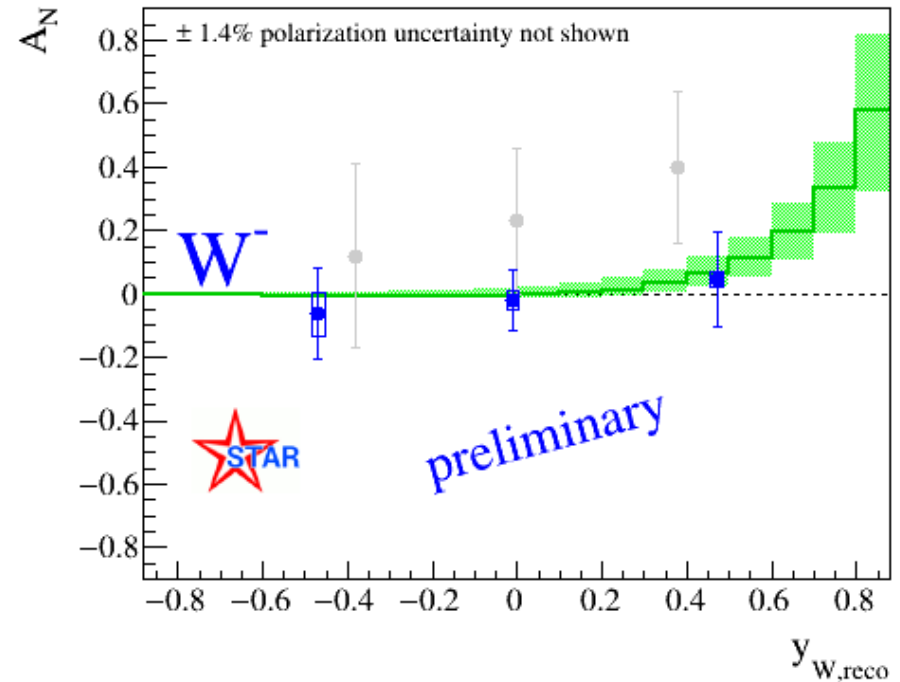
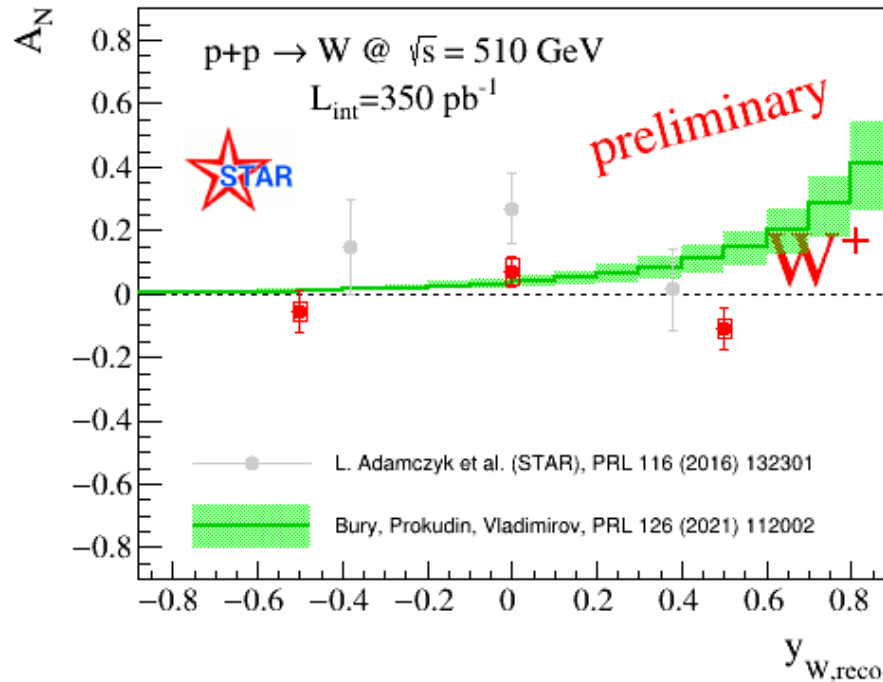
Dijet kinematics 200 GeV



Comparison between 2009 and 2015 (Λ Hyperon)



Sivers Effect via $W-A_N$



- Sivers effect provides correlation between the spin of the incoming proton (polarized) and the p_T of struck parton.
- Process-dependent color force \rightarrow opposite sign in SIDIS vs pp.
- Preliminary results compared to the latest N3LO predictions (PRL 126 (2021) 112002)