# NEW RESULTS FROM THE RHIC-SPIN PROGRAM

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U.S. DEPARTMENT OF ENERGY | Office of Science

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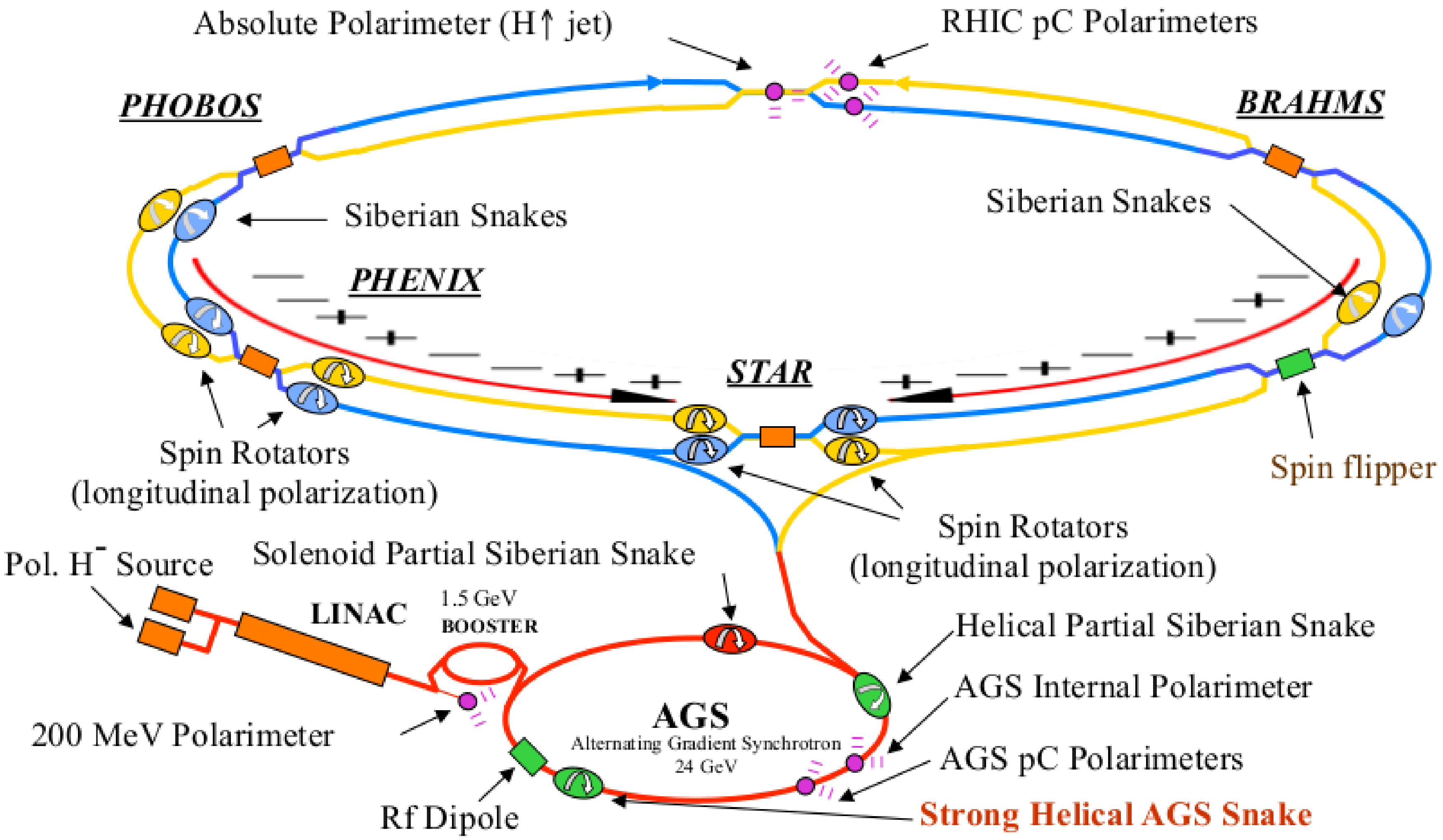
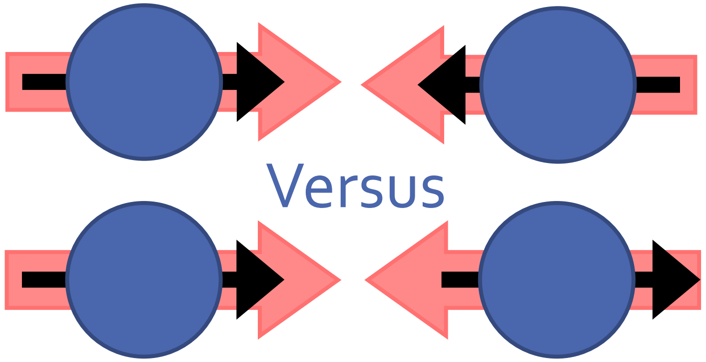
# Relativistic Heavy Ion Collider (RHIC)

## Only collider in the world able to run polarized proton beams

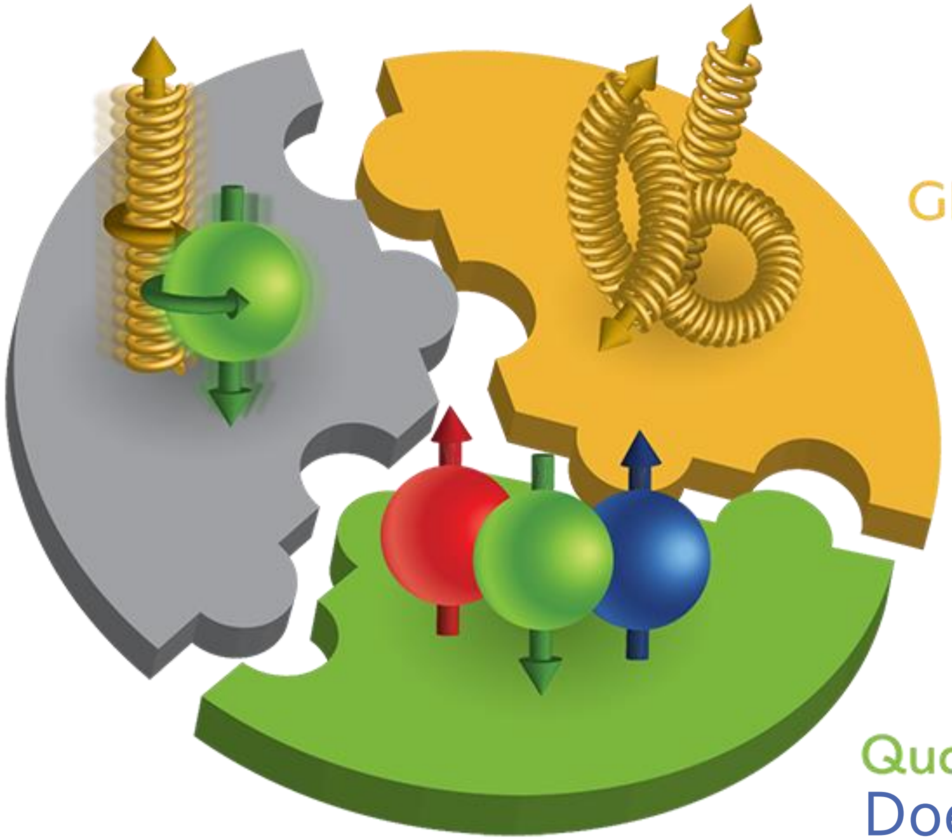


# Longitudinally Polarized Measurements



# The Proton Spin Puzzle

Quark and gluon internal motion



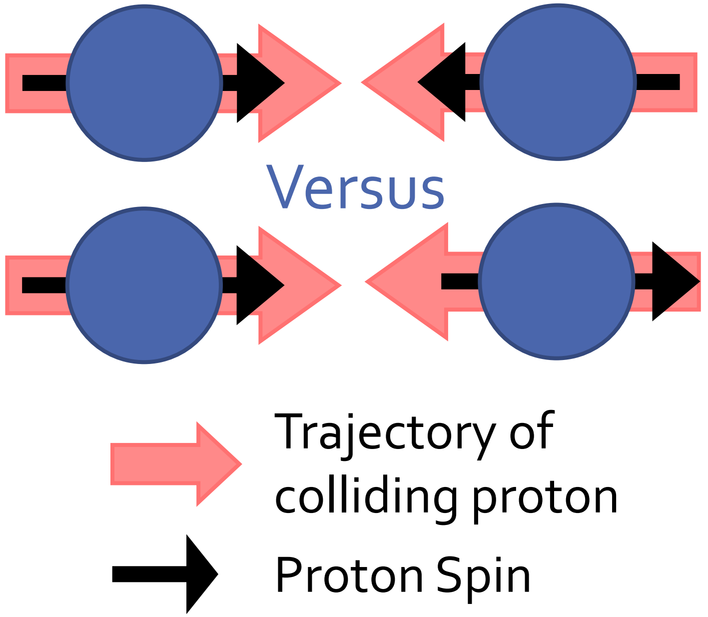
Gluon spin

Relatively unconstrained
Proton-proton collisions are sensitive to gluon dynamics at leading order

Quark spin

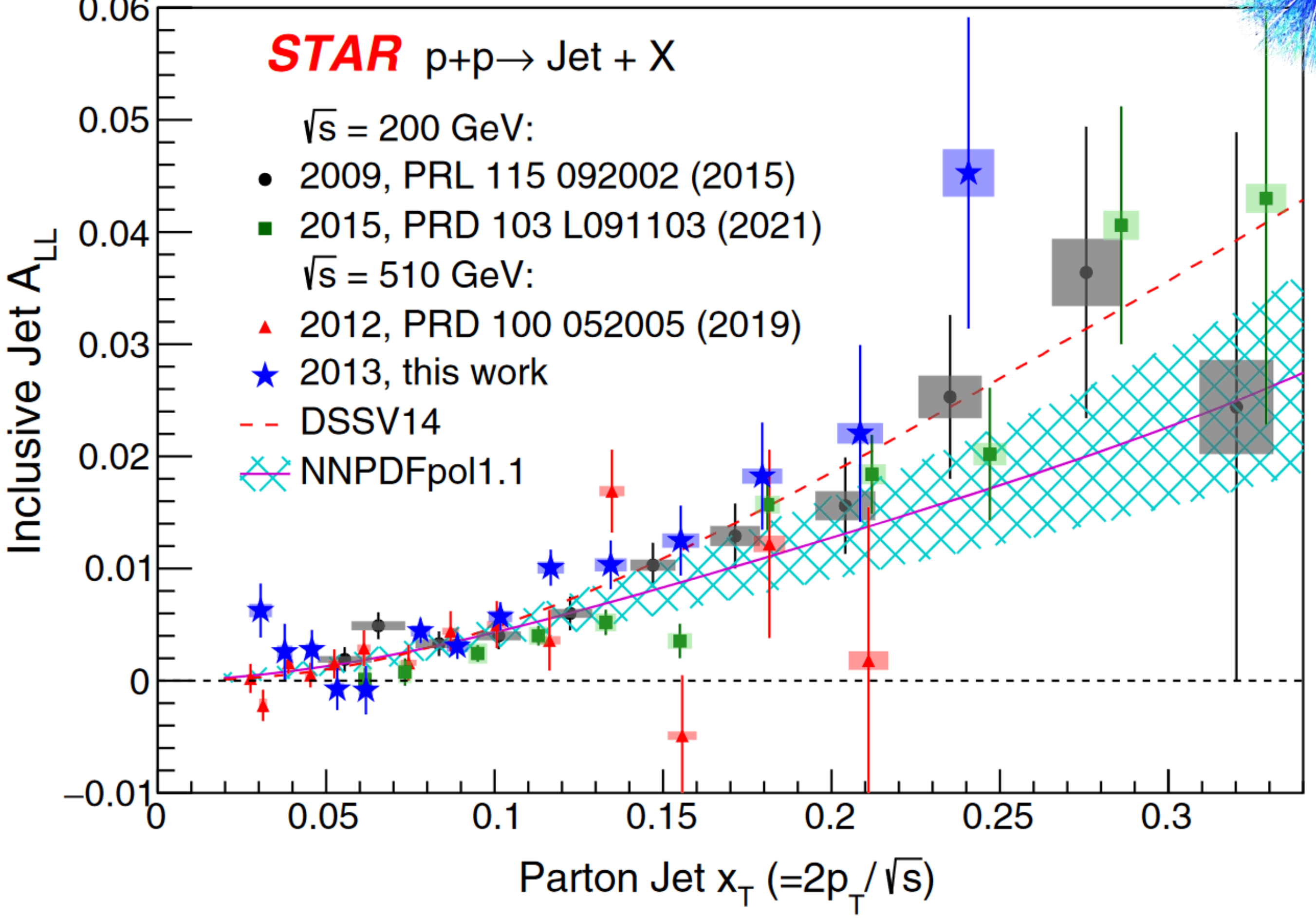
Does not account for the full spin of the proton

# Inclusive Jet $A_{LL}$




$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

STAR, PRD **105,** 092011 (2022)




The jet $A_{LL}$ is sensitive to the gluon polarization at leading order, dominating processes at RHIC $gg$ and $qg$ scattering

- Higher collision energy → access to lower $x$

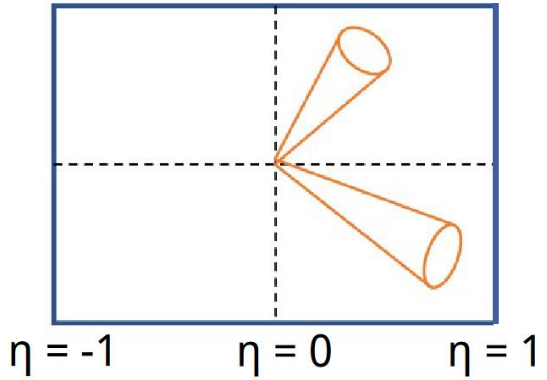
# Di-Jet $A_{LL}$

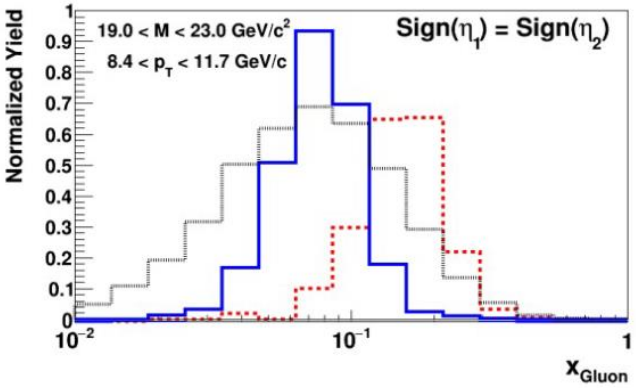
Stricter constraints on underlying partonic kinematics

Better constraints on the $x$-dependences of $\Delta g(x, Q^2)$

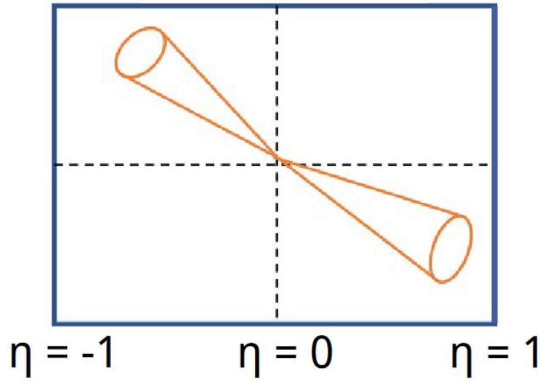
STAR, PRD **103**, 091103 (2021)

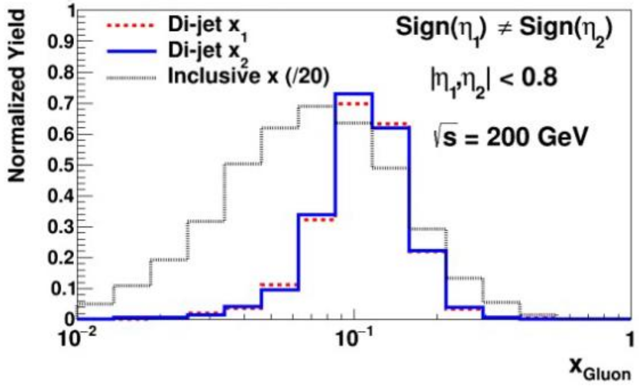
$\mathrm{sign}(\eta_1) = \mathrm{sign}(\eta_2)$

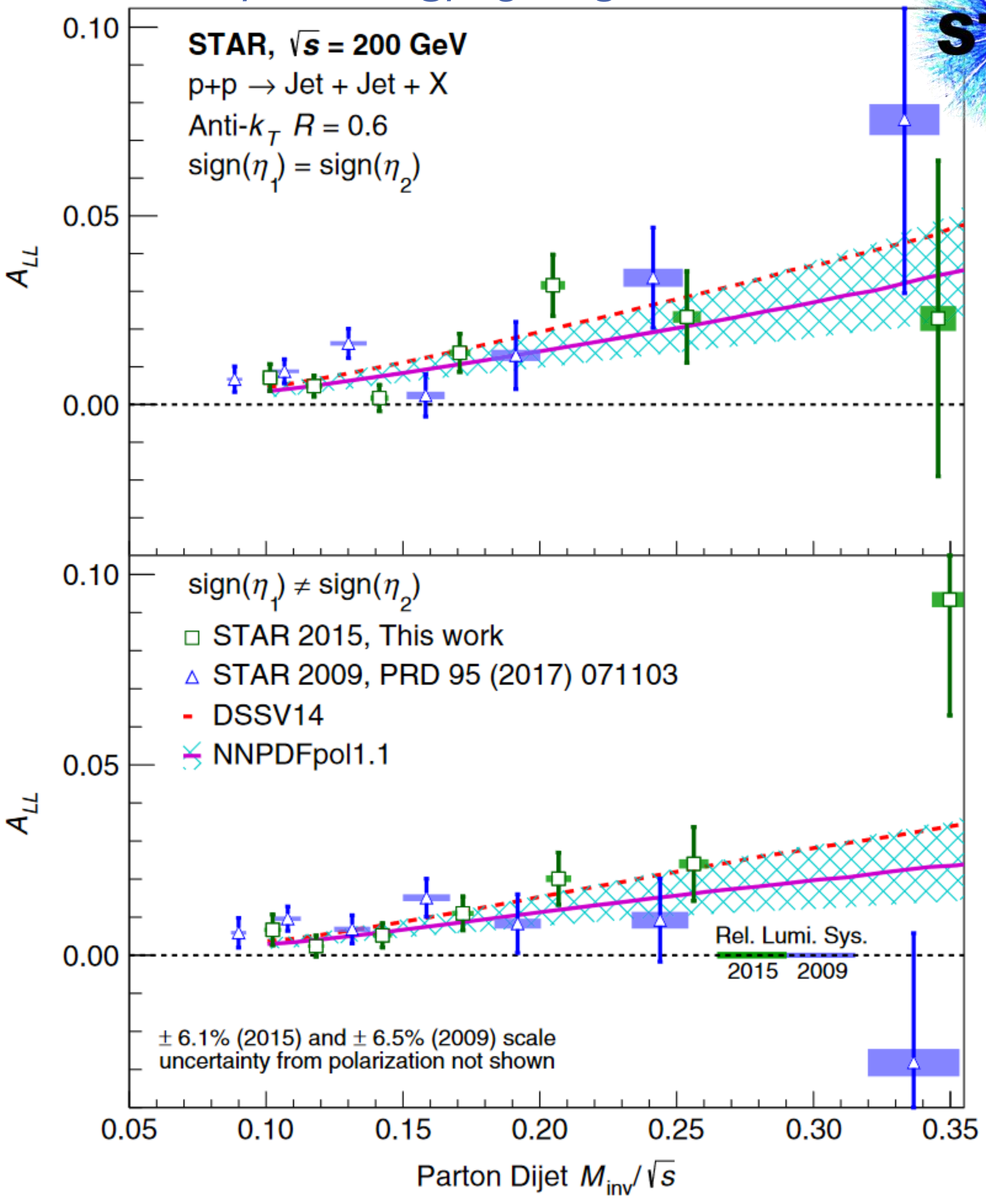



$\mathrm{sign}(\eta_1) \neq \mathrm{sign}(\eta_2)$

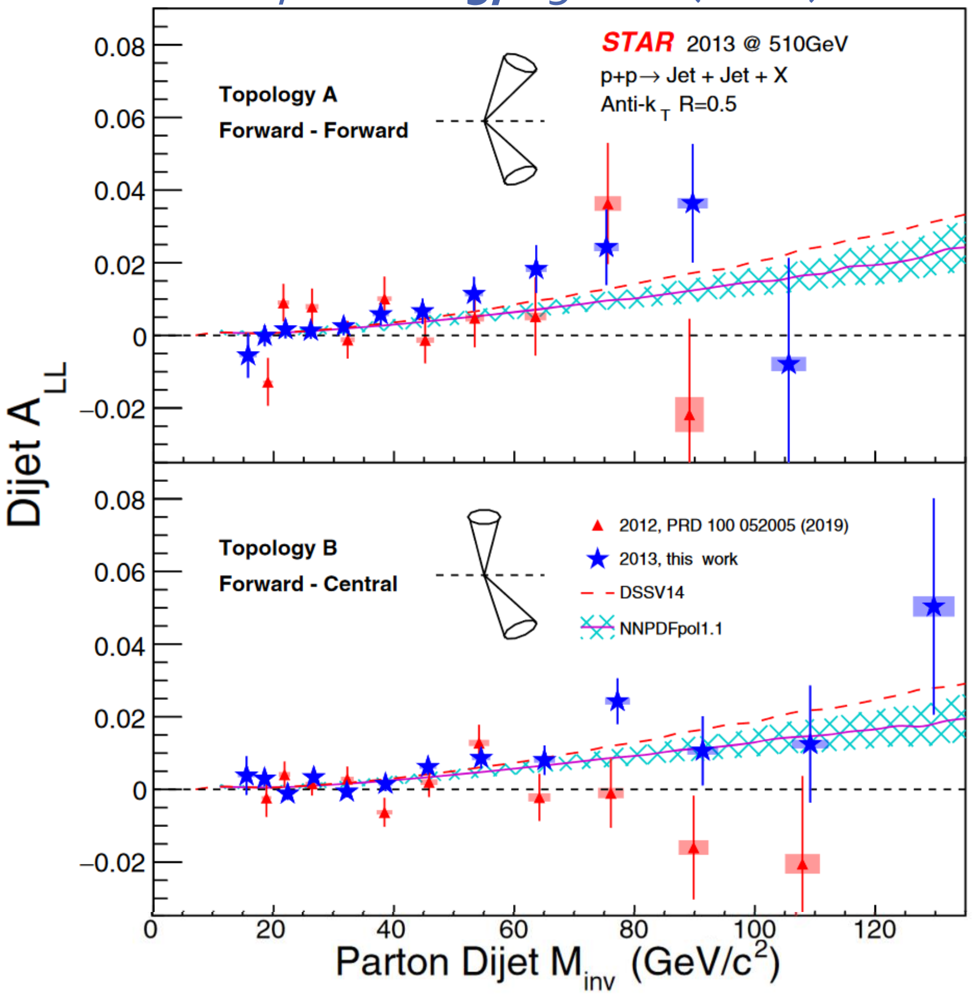


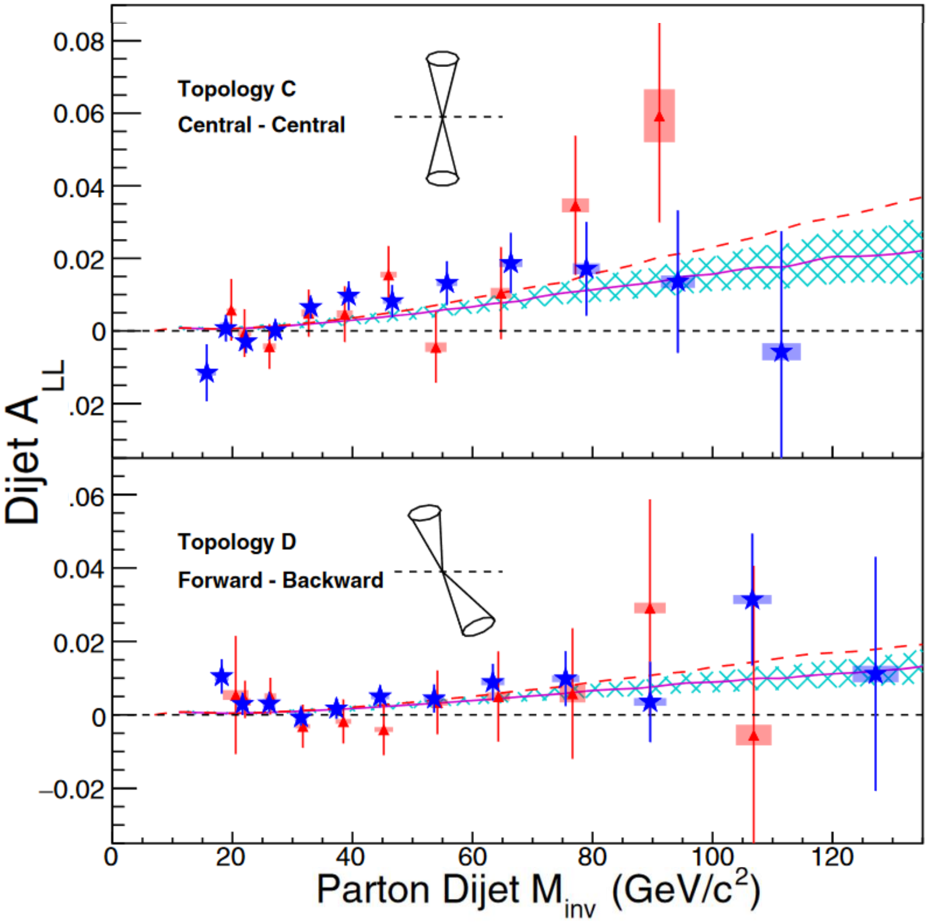
# Di-Jet $A_{LL}$

STAR, PRD **105,** 092011 (2022)




$\sqrt{s} = 510$ GeV $pp$ data from 2013

- High statistics → finer binning in jet topologies
- Higher collision energy → access to lower $x$, down to $x \sim 10^{-2}$



# Direct Photon $A_{LL}$

See Sook Hyun Lee's Talk during this session

PHENIX

Photons that come *directly* from the hard interaction

- Only sensitive to initial state effects, no effects from hadronization
- Production dominated by quark-gluon Compton scattering
- Isolation cut reduces the contribution of fragmentation and Bremsstrahlung photons

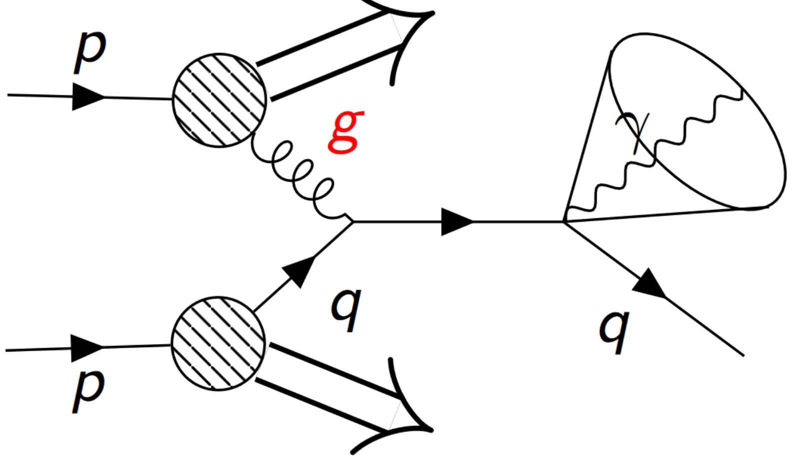
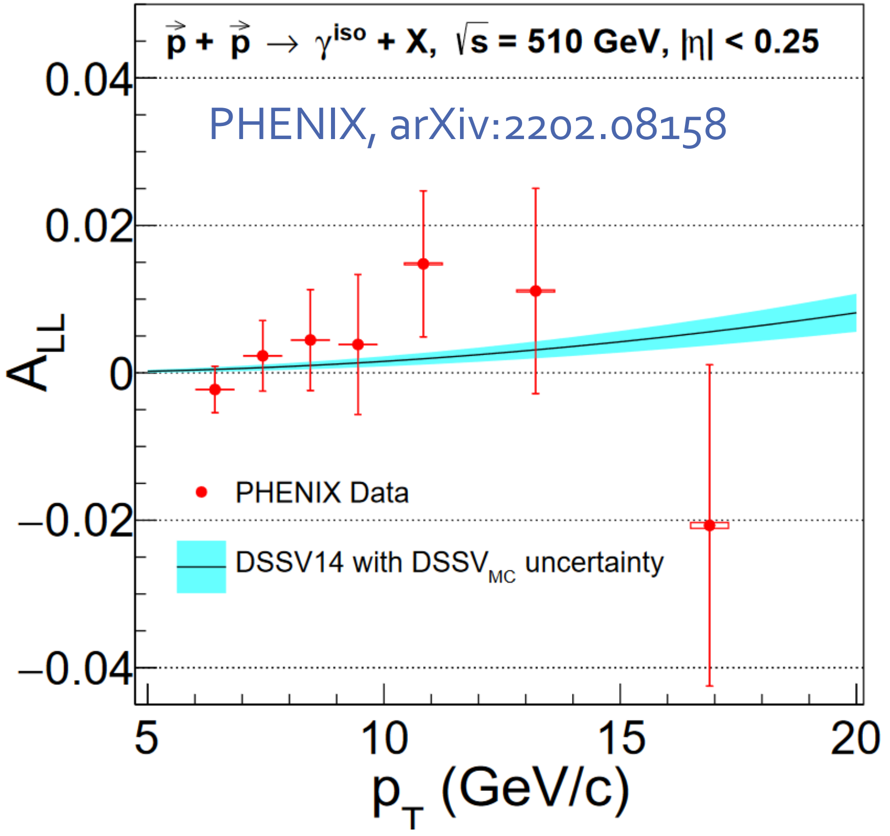


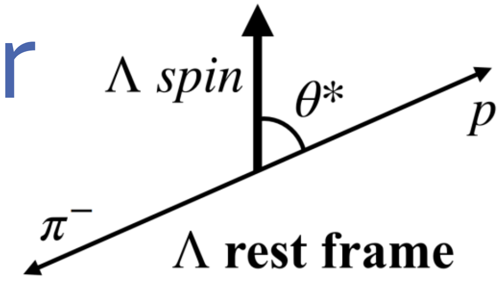

Figure from Zhongling Ji, DIS 2021

First published direct photon $A_{LL}$ result

Cleanly sensitive to gluon dynamics, will help constrain $\Delta g$ for $0.02 < x < 0.08$

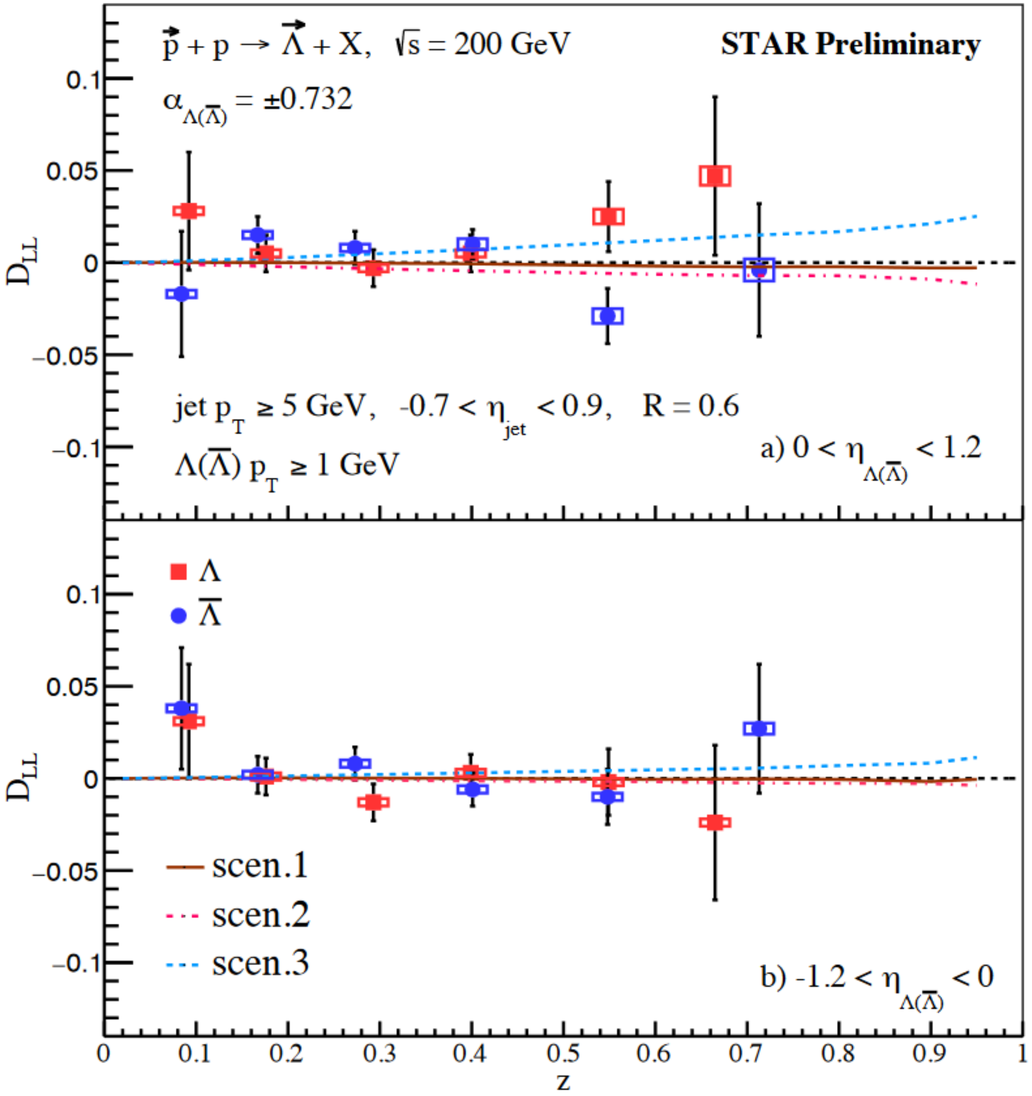


# Hyperon Longitudinal Spin Transfer




$\vec{p} + p \rightarrow \vec{\Lambda} + X$

Yi Yu, DIS 2022

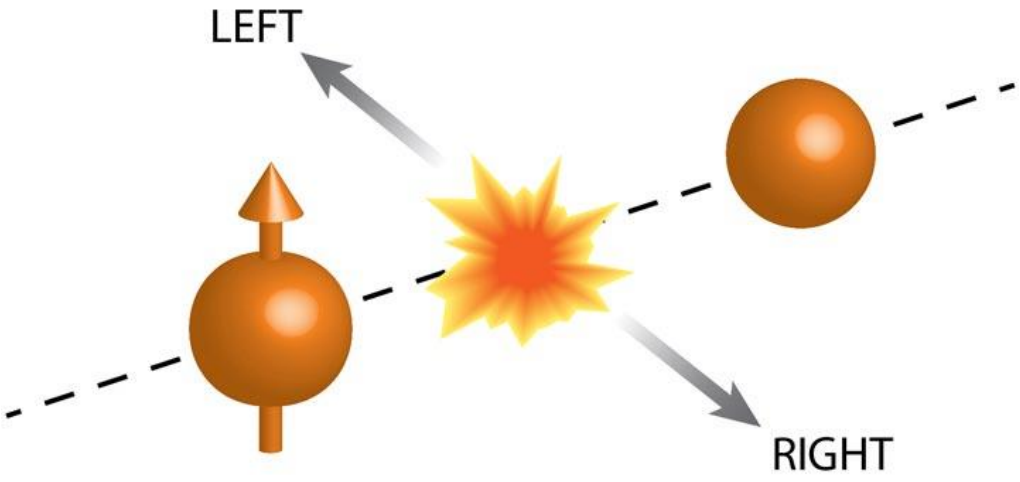



Theory curves: Kang et al, PLB **809**, 135756 (2020)

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

- Direct probe of polarized fragmentation function
- Sensitive to strange quark's contribution to the proton's spin
- First measurement of $D_{LL}^{\Lambda}$ as a function of $z = \frac{p_\Lambda \cdot p_{\text{jet}}}{|p_{\text{jet}}|^2}$
  - Most precise measurement of $D_{LL}^{\Lambda}$ to date

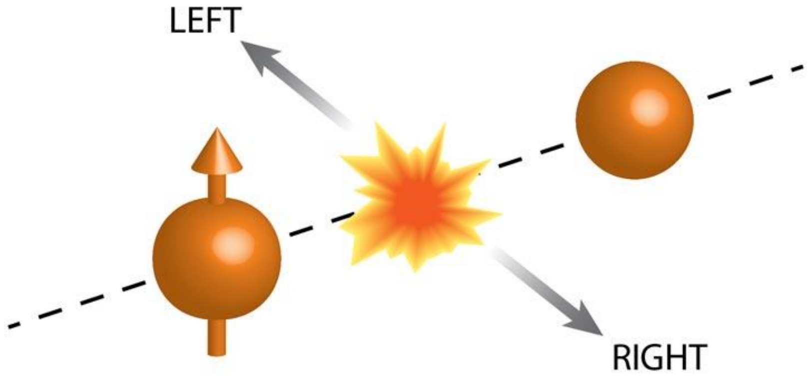
# Transversely Polarized Measurements



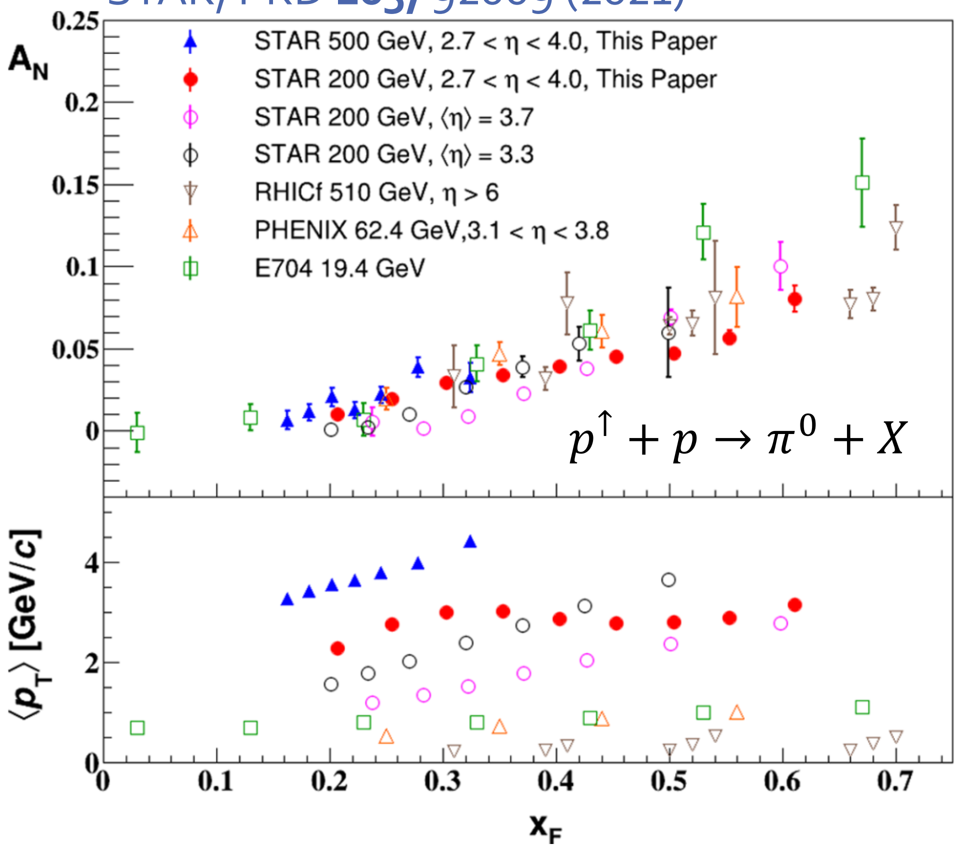
# Transverse Single-Spin Asymmetries

## Probing hadrons in three dimensions

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




STAR, PRD **103,** 92009 (2021)




TSSA due to ***perturbative*** QCD effects:

$$A_N \propto \frac{m_q \alpha_s}{p_T} \approx 0.001$$

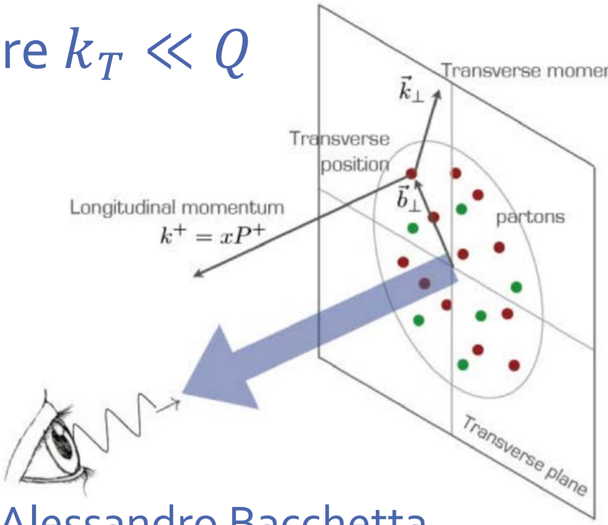
G. L. Kane, J. Pumplin, and W. Repko *PRL* **41**, 1689 (1978)

# Nonperturbative Spin-Momentum Correlations

Large spin-momentum correlation that can't be explained by the perturbative part of hadronic scattering→ must be nonperturbative dynamics

## Transverse Momentum Dependent (TMD) Functions

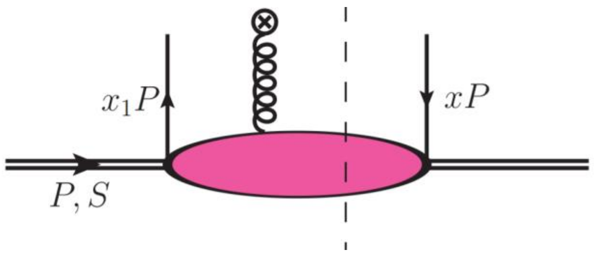
- Two scale process: explicit dependence on nonperturbative parton transverse momentum, $k_T$
- Where $k_T \ll Q$



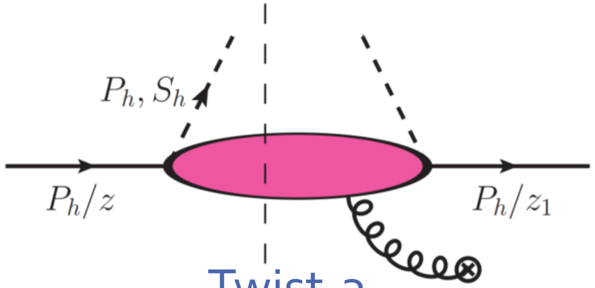

From Alessandro Bacchetta

## Twist-3 Collinear Correlation Functions

- Quantum interference between scattering off of one parton versus scattering off of two partons at the same $x$
- Measurements only need to be sensitive to a single, hard scale




Twist-3
Initial State

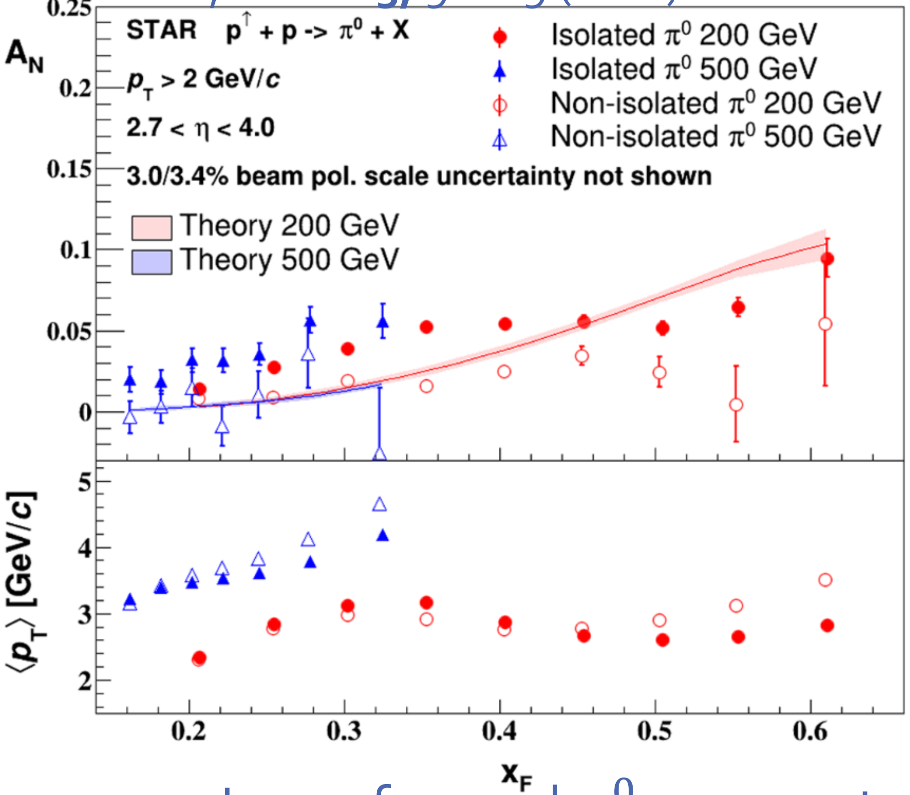


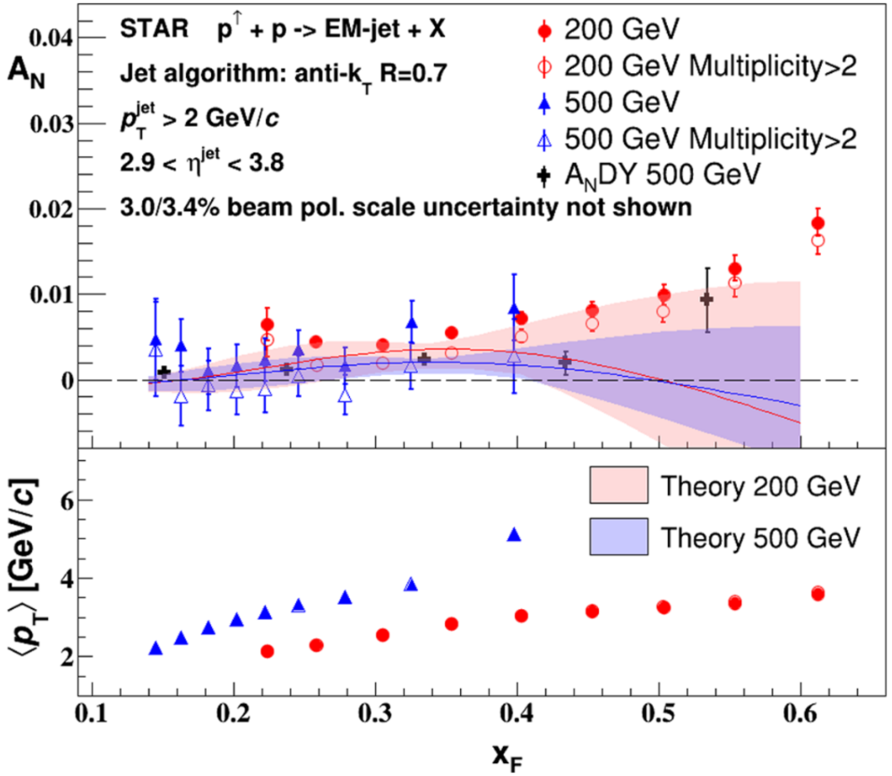

Twist-3
Final State

Daniel Pitonyak, arXiv:1608.05353

# Origin of Large Forward Asymmetries

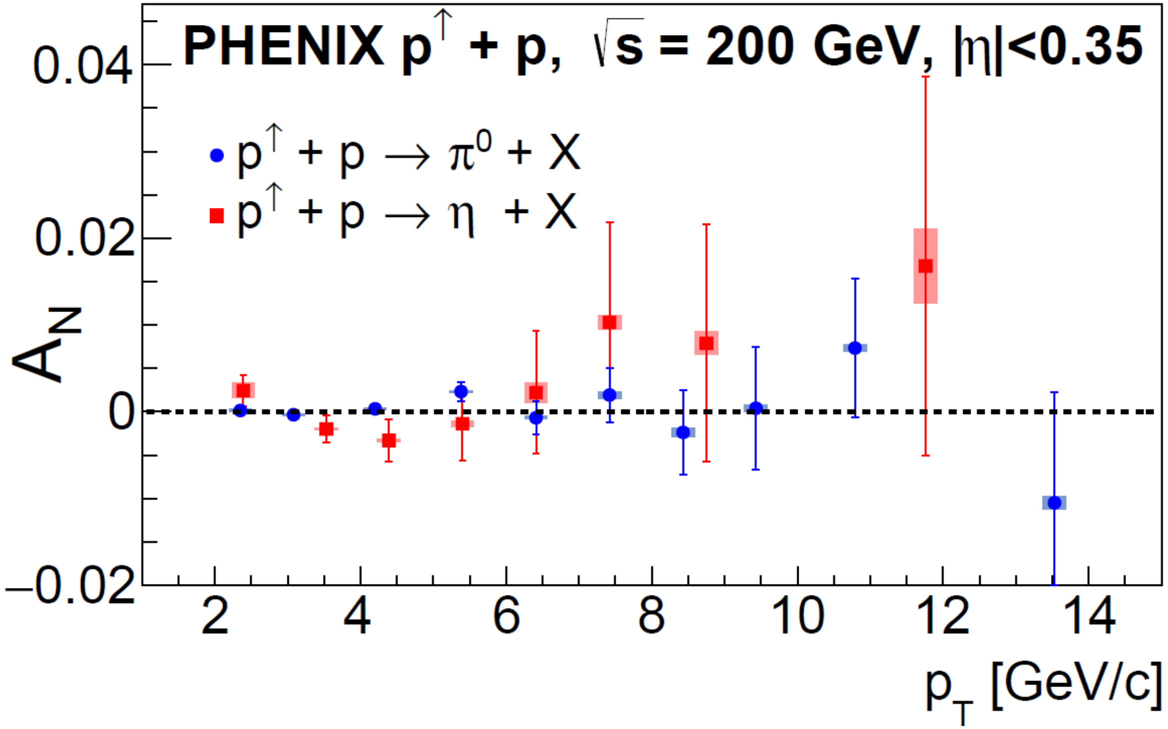
STAR, PRD **103,** 92009 (2021)



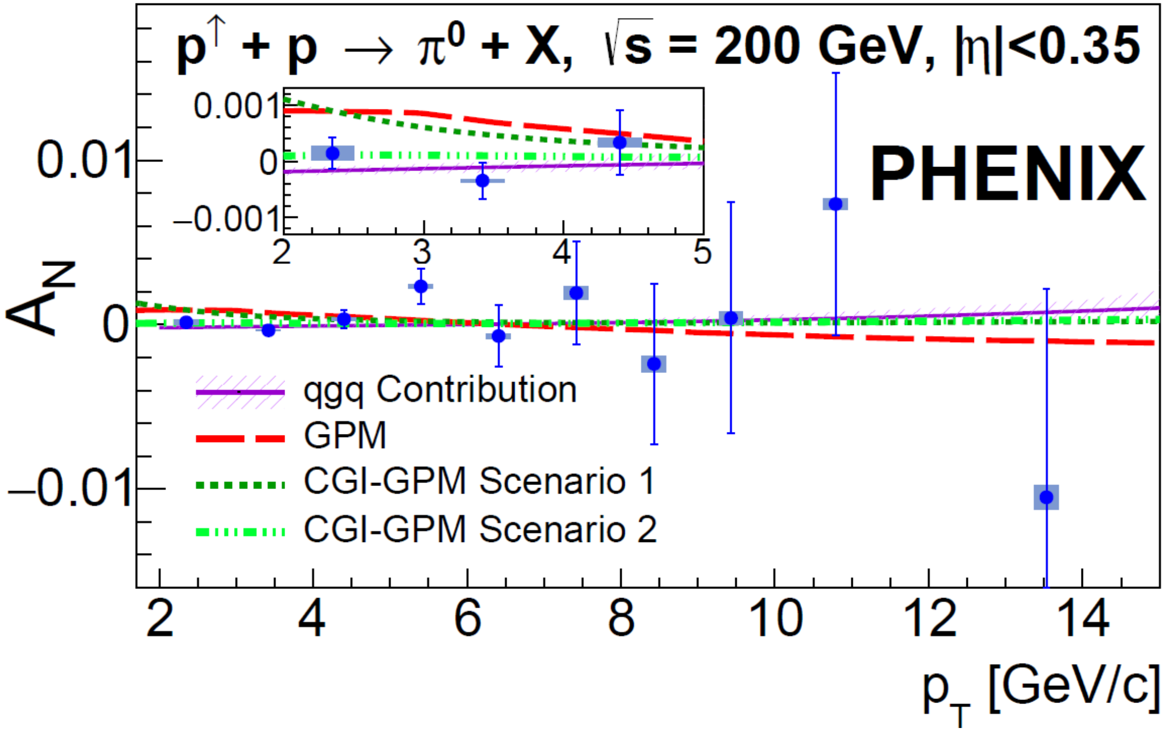




- Large forward $\pi^0$ asymmetry is larger for isolated $\pi^0$
  - Possibly because of a larger contribution from diffractive processes?
  - Non-isolated $\pi^0$s → part of a jet which has fragmented from a parton
- Small $A_N$ for EM-jets, smaller for Multiplicity > 2
- Weak dependence on center of mass energy

# Midrapidity $\pi^0$ and $\eta$ $A_N$




PHENIX, PRD **103**, 052009 (2021)

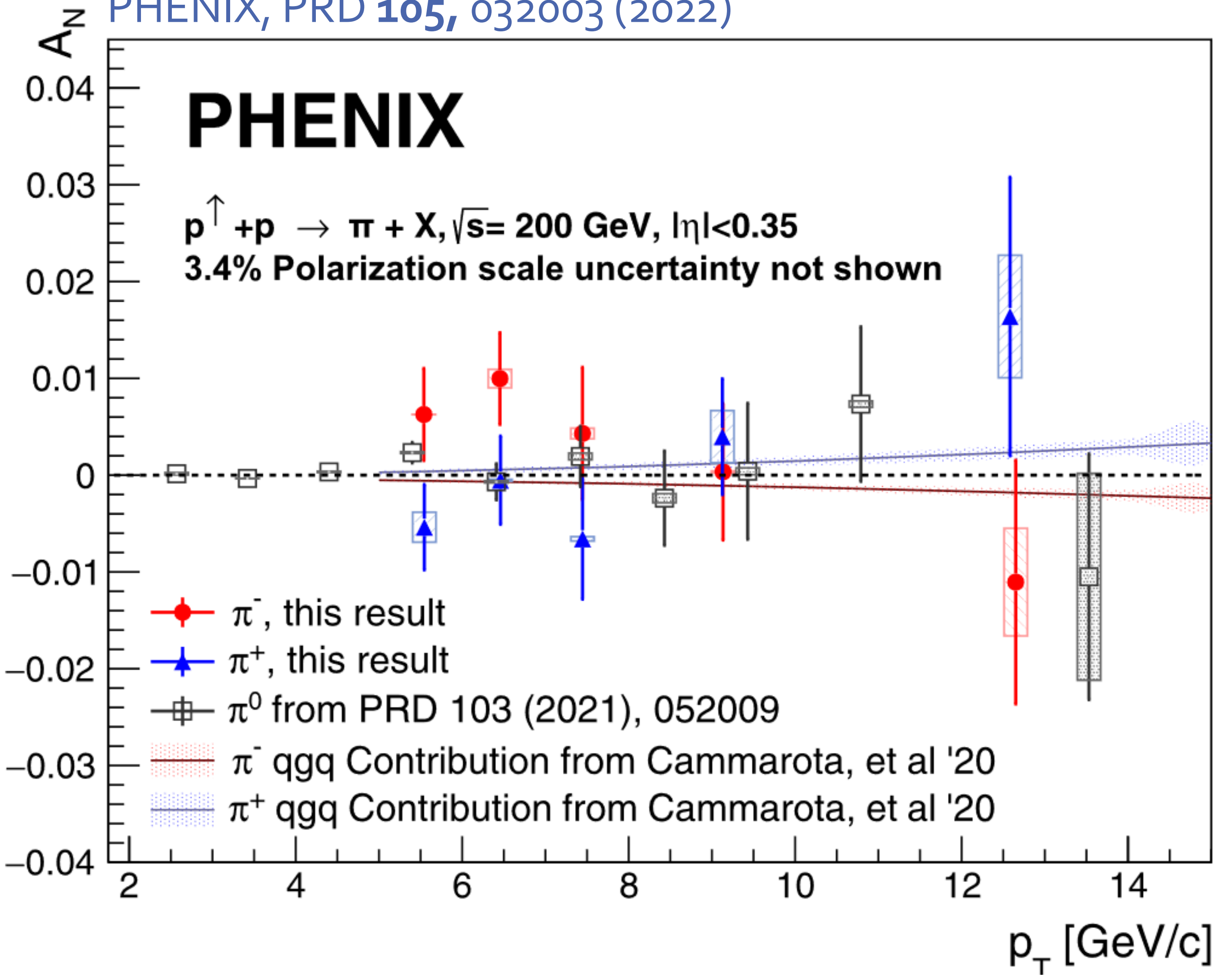



- Factor of three increase in precision compared to previously published results and higher reach in $p_T$
- Sensitive to both initial and final state effects, sensitive to gluon spin-momentum correlations at leading order

# Charged Pion $A_N$

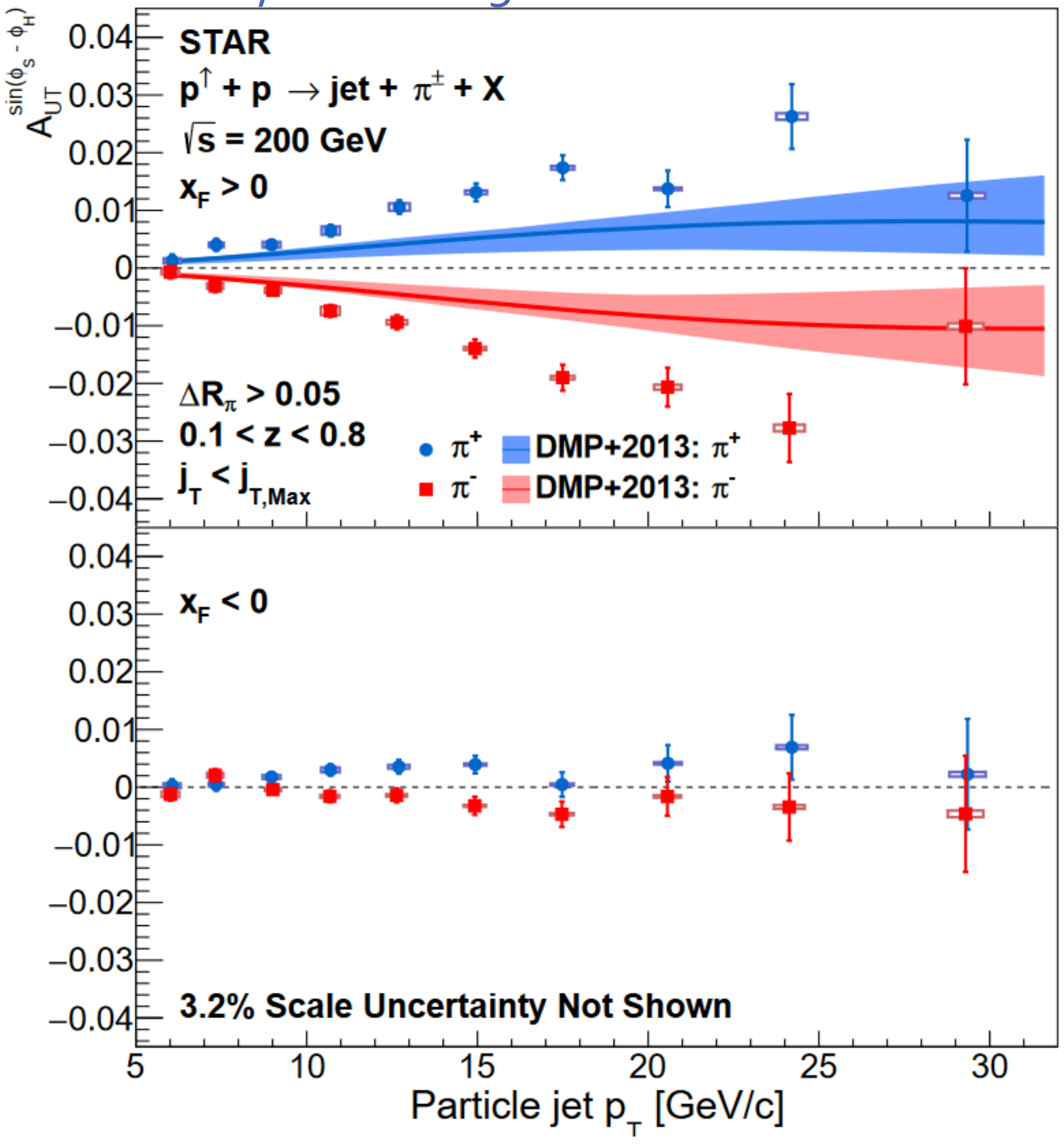
- First results of midrapidity charged pion $A_N$ from PHENIX
- $\pi^{\pm}$ $A_N$ consistent with zero and with the $\pi^0$ asymmetry
- Some indication that $\pi^{\pm}$ might behave differently (potential flavor dependence)

PHENIX, PRD **105,** 032003 (2022)

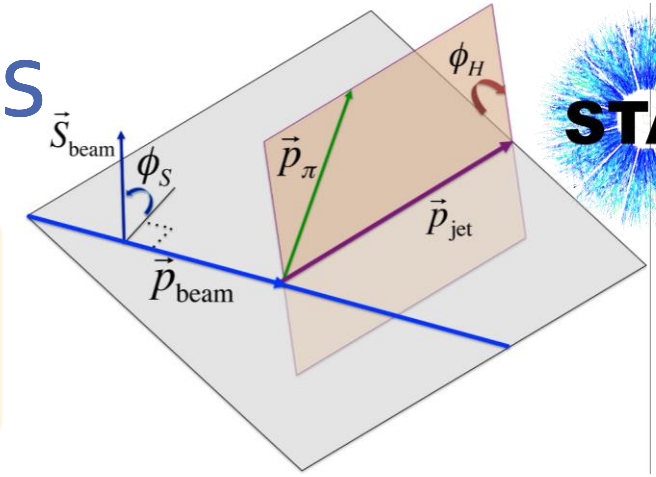


# Collins Asymmetry with $\pi^{\pm}$ in Jets

STAR, arXiv:2205.11800



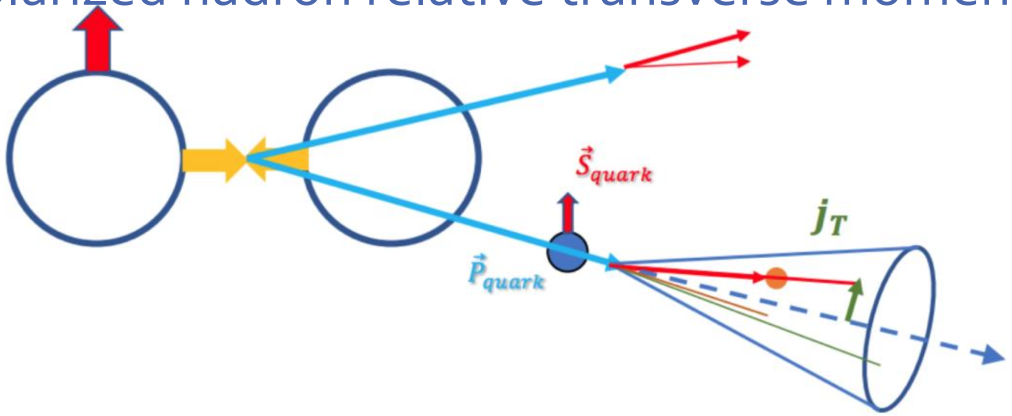

See talk by Kevin Adkins
QCD-PDF Joint Session
Friday 9/1




**Spin-dependent modulation of hadrons in jets**

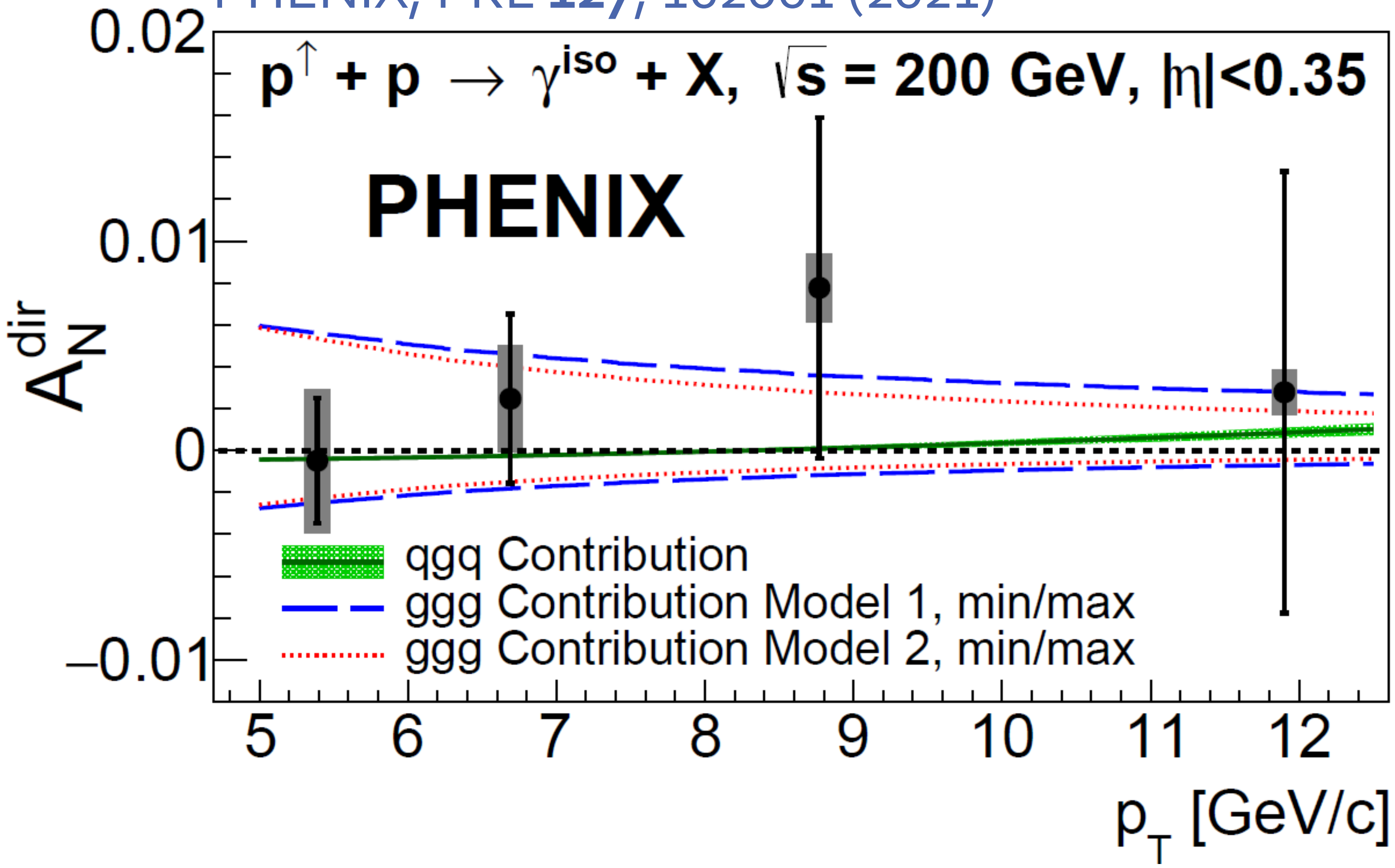
**Transversity Function –** Collinear PDF for the transversely polarized proton

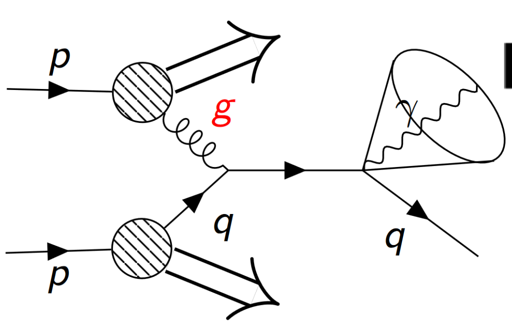
**Collins function** -TMD Fragmentation Function Correlation between quark transverse spin and unpolarized hadron relative transverse momentum



# Direct Photon $A_N$

PHENIX, PRL **127**, 162001 (2021)




PHENIX

Figure from Zhongling Ji, DIS 2021

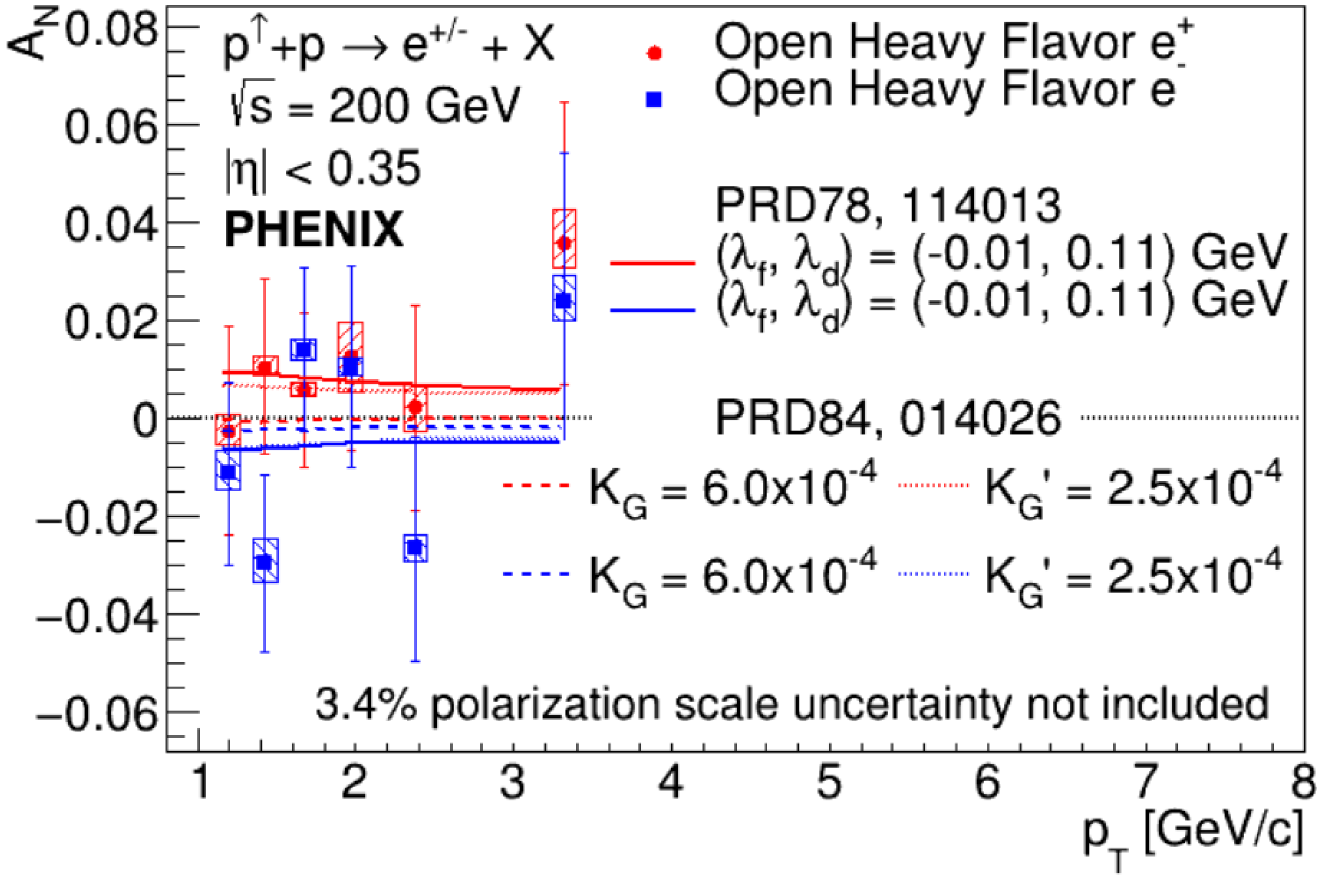
Measured for the first time at RHIC

Consistent with zero to within ~2%

This result will also help constrain the twist-3 collinear trigluon function

# Open Heavy Flavor $A_N$

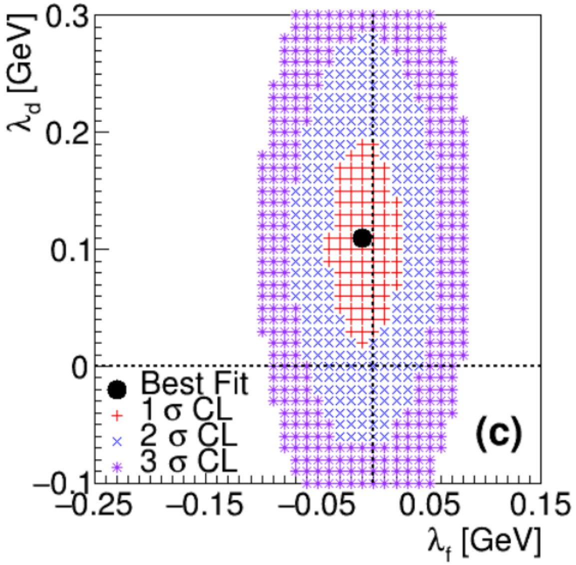
PHENIX, arXiv:2204.12899




Cleanly sensitive to gluon spin-momentum correlations in the proton

Will help constrain the twist-3 collinear trigluon correlation function

$$T_G^{(f,d)}(x,x) = \lambda_{f,d}G(x)$$




$A_N(p^{\uparrow}+p \rightarrow HF(e^{+/-}) + X)$

$\sqrt{s}$ = 200 GeV

$|\eta| < 0.35$

**PHENIX**

Theory: PRD78, 114013

$A_N^{D^0/\bar{D}^0 \rightarrow e^{+/-}}(\lambda_f,\lambda_d)$

Theory Curves: Z. Kang, *et al*, PRD **78**, 114013 (2008)
Y. Koike, S. Yoshida, PRD **84**, 014026 (2011)

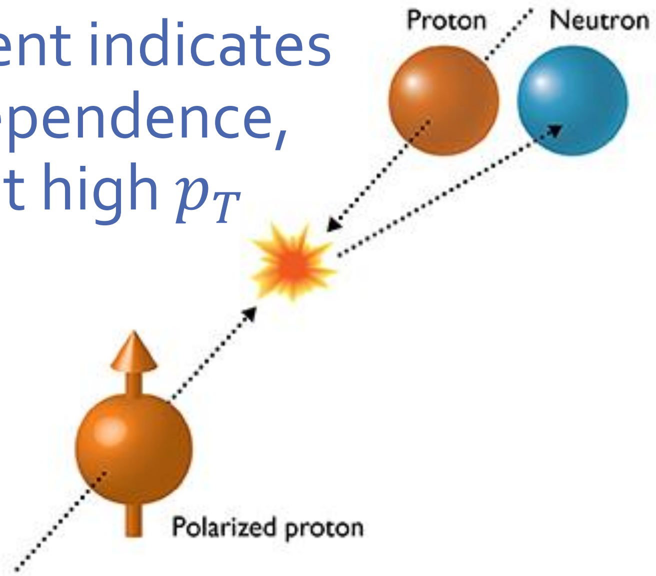
# Far - Forward Neutron $A_N$
# The RHICf experiment

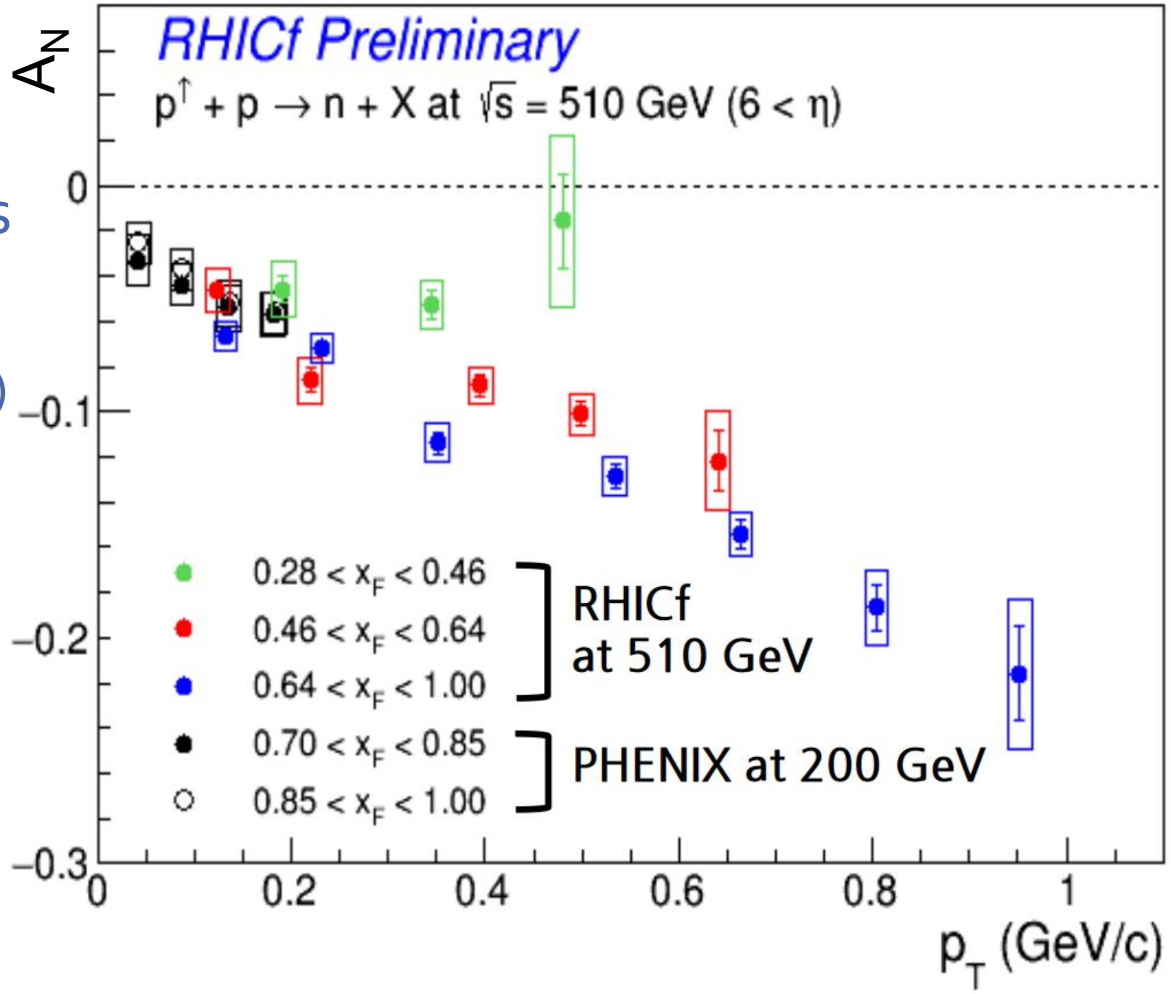
**See Sook Hyun Lee's talk during this session for PHENIX results in $pp$ and $pA$**

- $\pi$ and a1-Reggeon exchanges model predicts no $x_F$ dependence and $A_N$ gets more negative with $p_T$

  B. Z. Kopeliovich, *et al* PRD **84**, 114012 (2011)

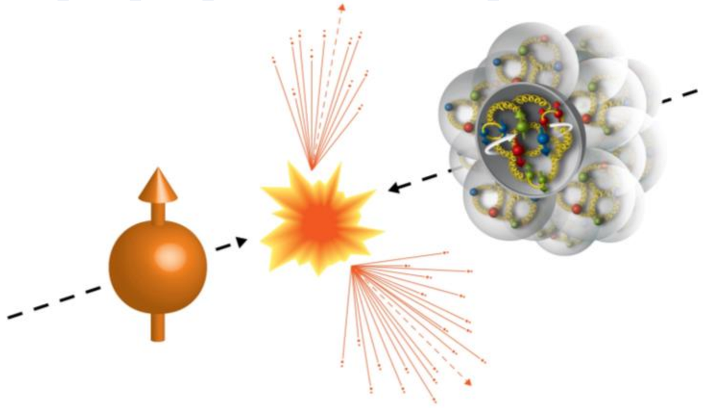
- Measurement indicates some $x_F$ dependence, especially at high $p_T$



# Nuclear Dependence of $A_N$

In 2015 RHIC took transversely polarized data for $p^{\uparrow}p$, $p^{\uparrow}$Al and $p^{\uparrow}$Au



**PHENIX charged hadron $A_N$**

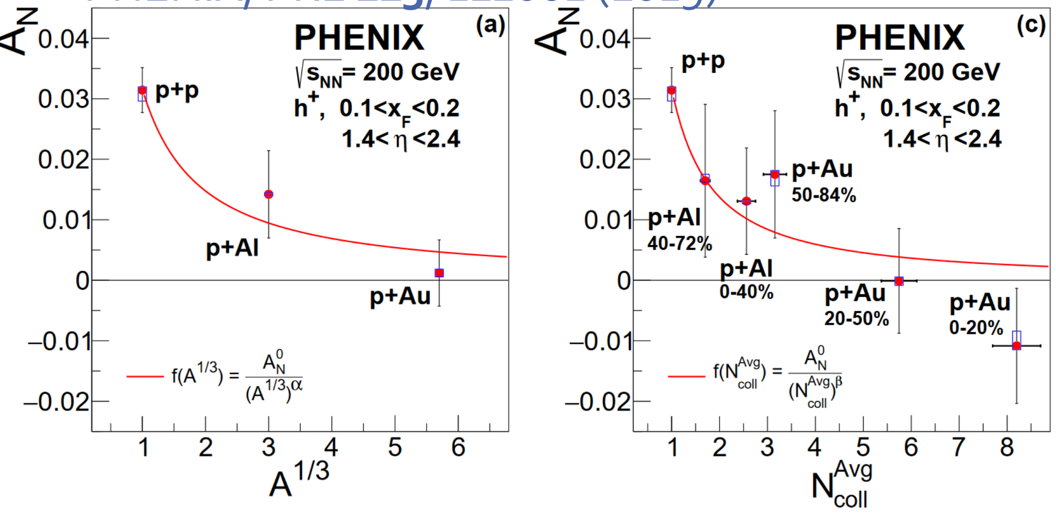
$1.4 < \eta < 2.4$

$0.1 < x_F < 0.2$

$1.8 < p_T < 7$ GeV/$c$

Noticeable $A_N$ suppression in $pA$ collision

PHENIX, PRL **123**, 122001 (2019)




**STAR forward $\pi^0$ $A_N$**

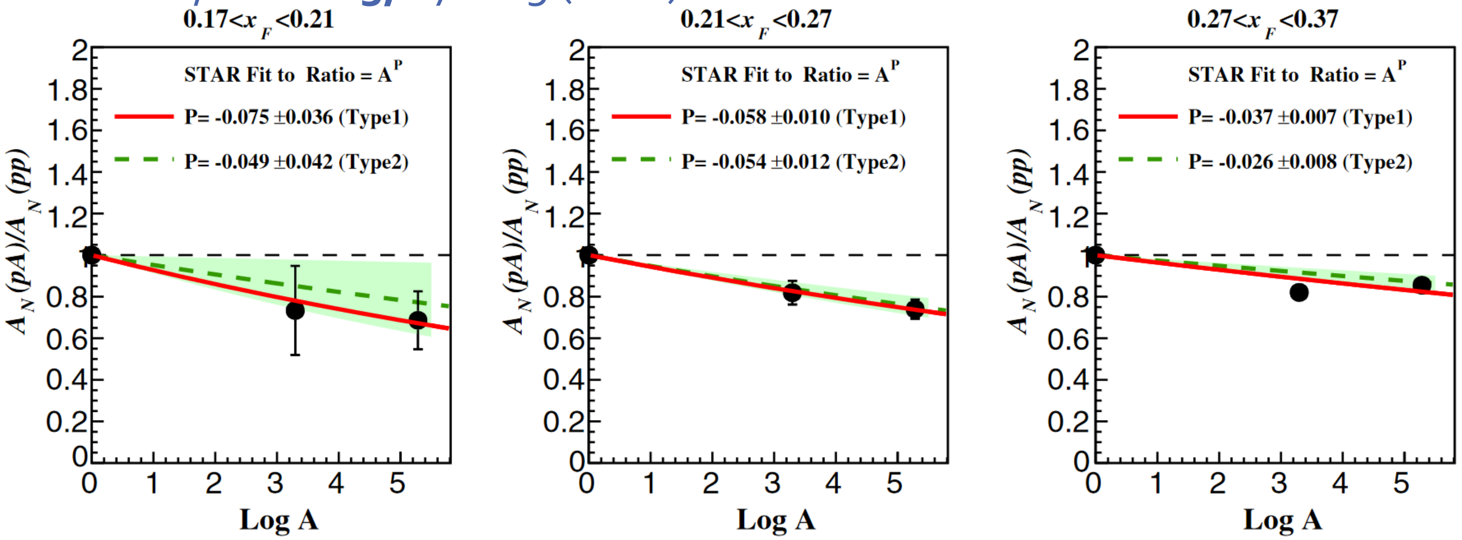
$2.6 < \eta < 4.0$

$0.2 < x_F < 0.7$

$1.5 < p_T < 7$ GeV/$c$

Less strong $A$ dependence

STAR, PRD **103**, 072005 (2021)

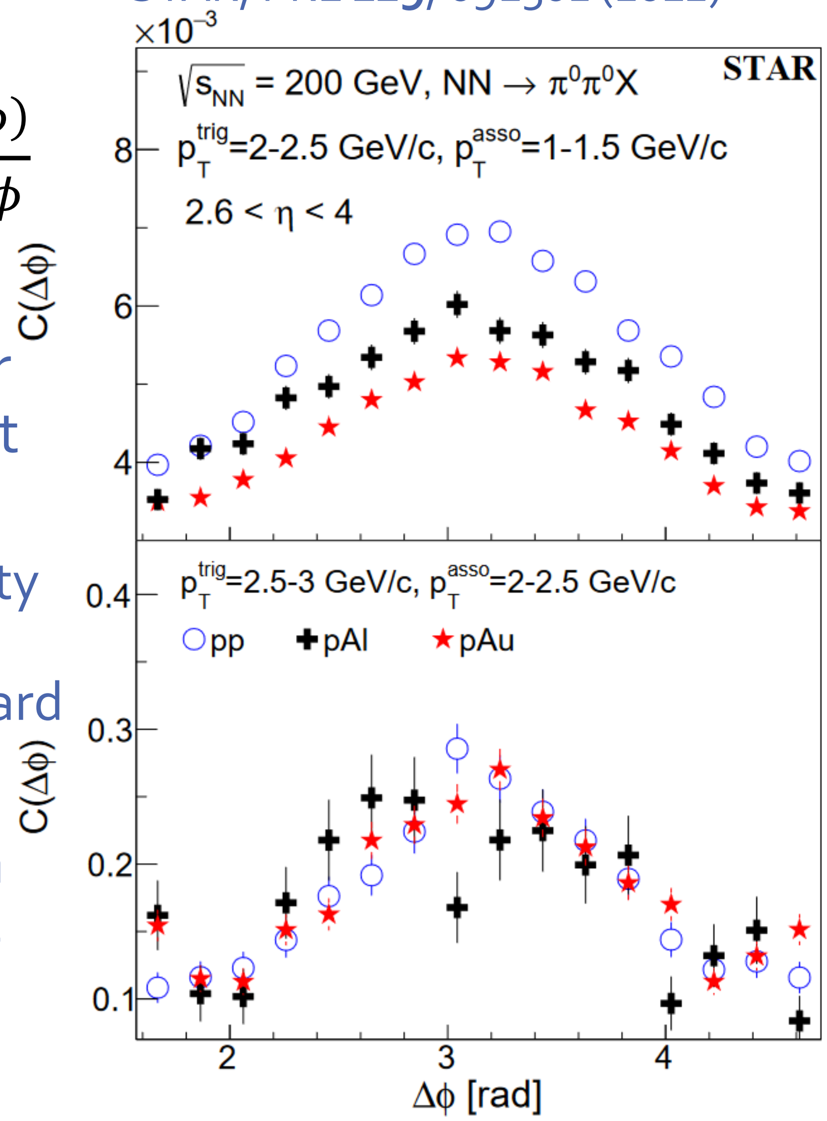


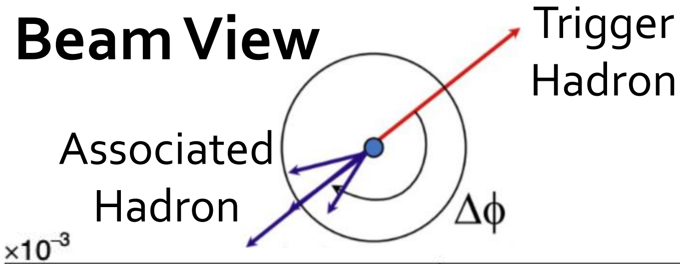
# Di-Hadron Correlations

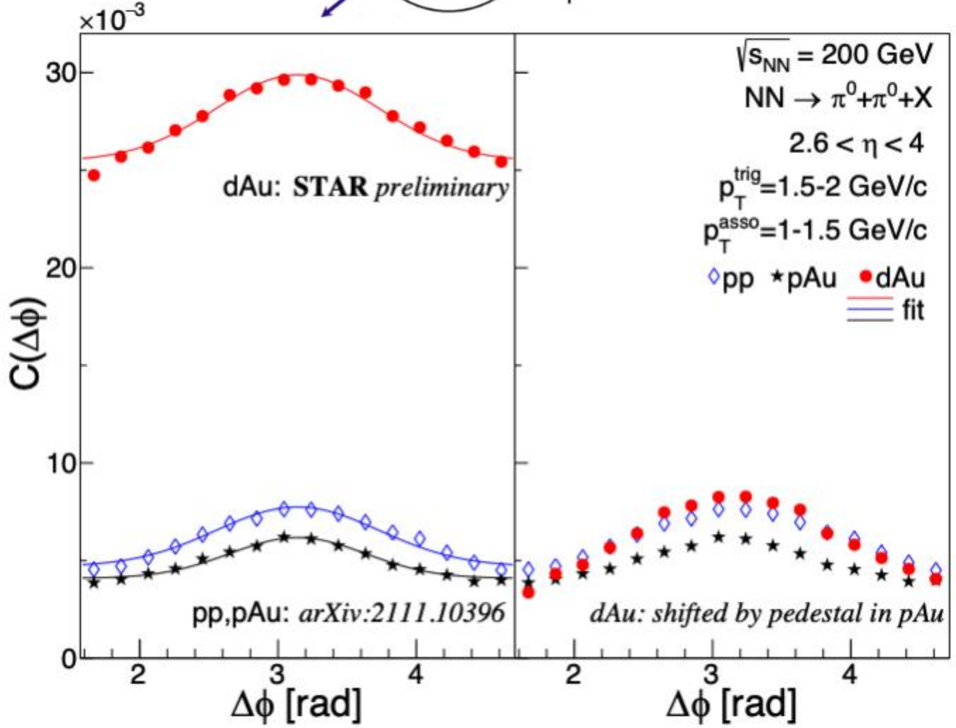
$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \Delta\phi}$$

- Probing nonlinear gluon dynamics at small $x$
  - High gluon density environment provided at forward rapidity at STAR
- Clear suppression of $C(\Delta\phi)$ in $pA$ at low $p_T$

STAR, PRL **129**, 092501 (2022)



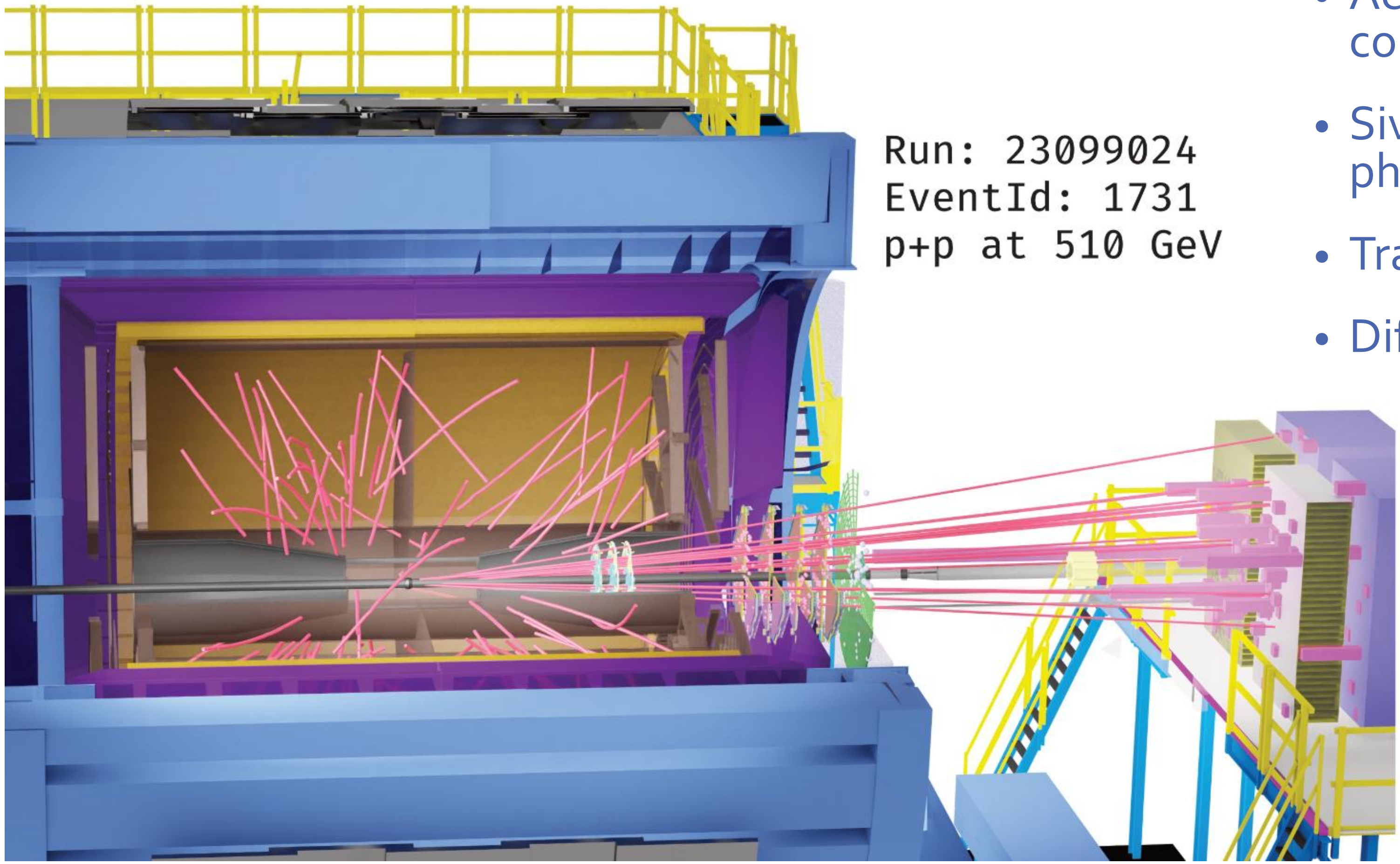




$dAu$ has a × 5 higher pedestal compared to $pp$ and $pAu$

- Could be explained through Double Parton Scattering (DPS): two separate hard interactions in a single collision

# Future Measurements with the RHIC Spin-Program

# STAR Forward Upgrade




STAR Beam Use Request for Run-23-25

**Installed in time for Run 2022**

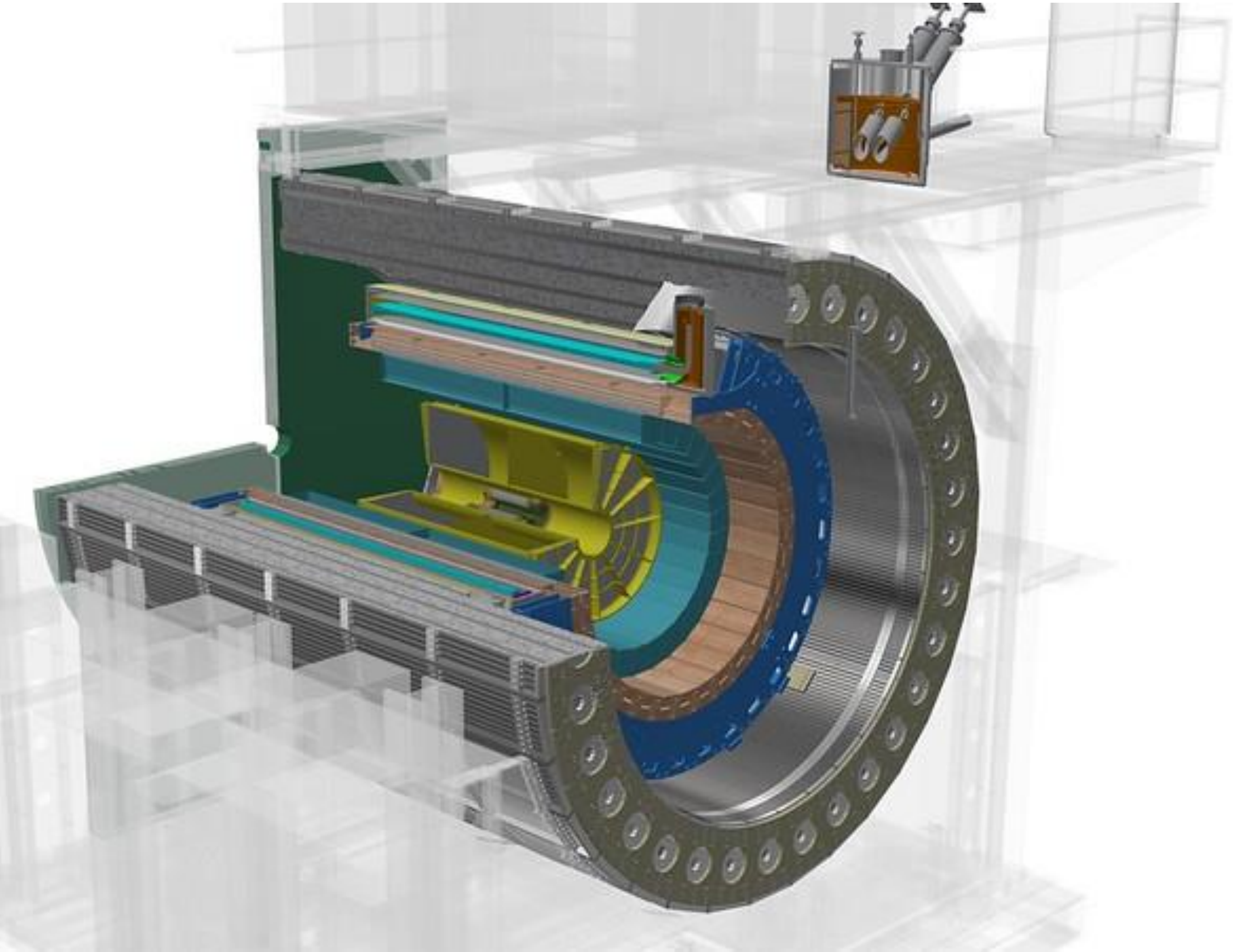
**Forward Rapidity $2.5 < \eta < 4$**

- Access to highly asymmetric partonic collisions: high-$x$ quark and low-$x$ gluon
- Sivers function through tagged jets, direct photon
- Transversity at high $x$ + Collins and IFF
- Diffractive Process

**Midrapidity $-1.5 < \eta < 1.5$**

- Improved statistical precision and the extended acceptance with iTPC
- Sivers with $W/Z$ and di-jet
- Transversity + Collins/IFF
- Unpolarized $W/Z$ cross section

# sPHENIX



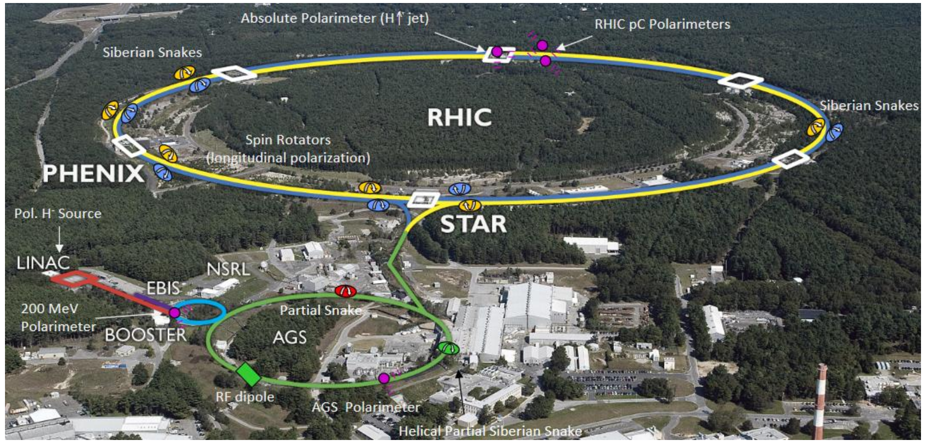
**Currently being installed, going to start taking data in 2023**

The sPHENIX barrel will be able to measure jets, heavy flavor, direct photons to probe

- Sivers effect with $\gamma$-jet, di-jet
- Transversity with Collins and IFF through $h$ in jet and di-hadron
- Trigluon correlation function with direct photons and heavy flavor
- Hadron $A_N$ in $pp$ vs $pA$

# Summary

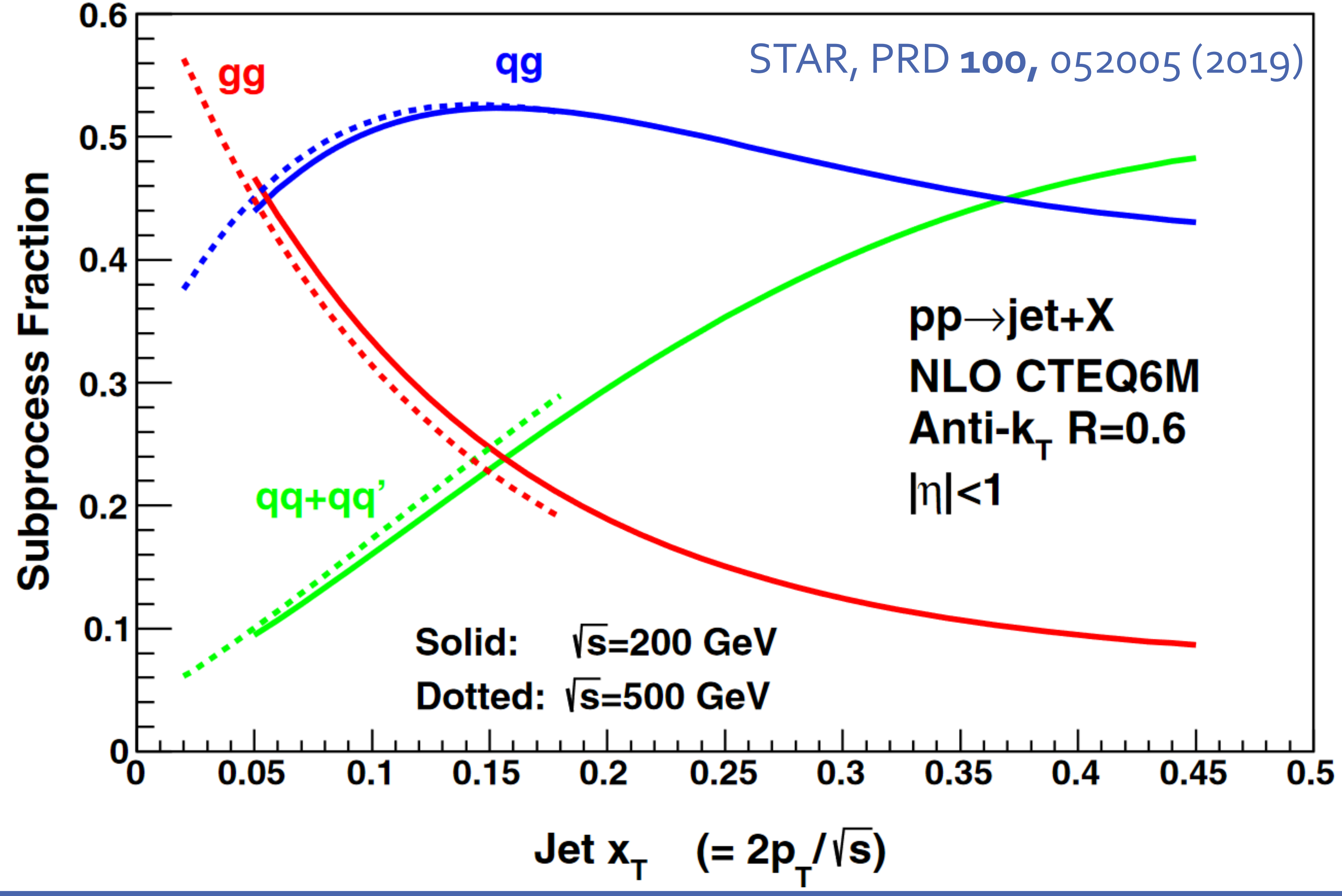
## RHIC has played a critical role in expanding our knowledge of the internal structure of the proton



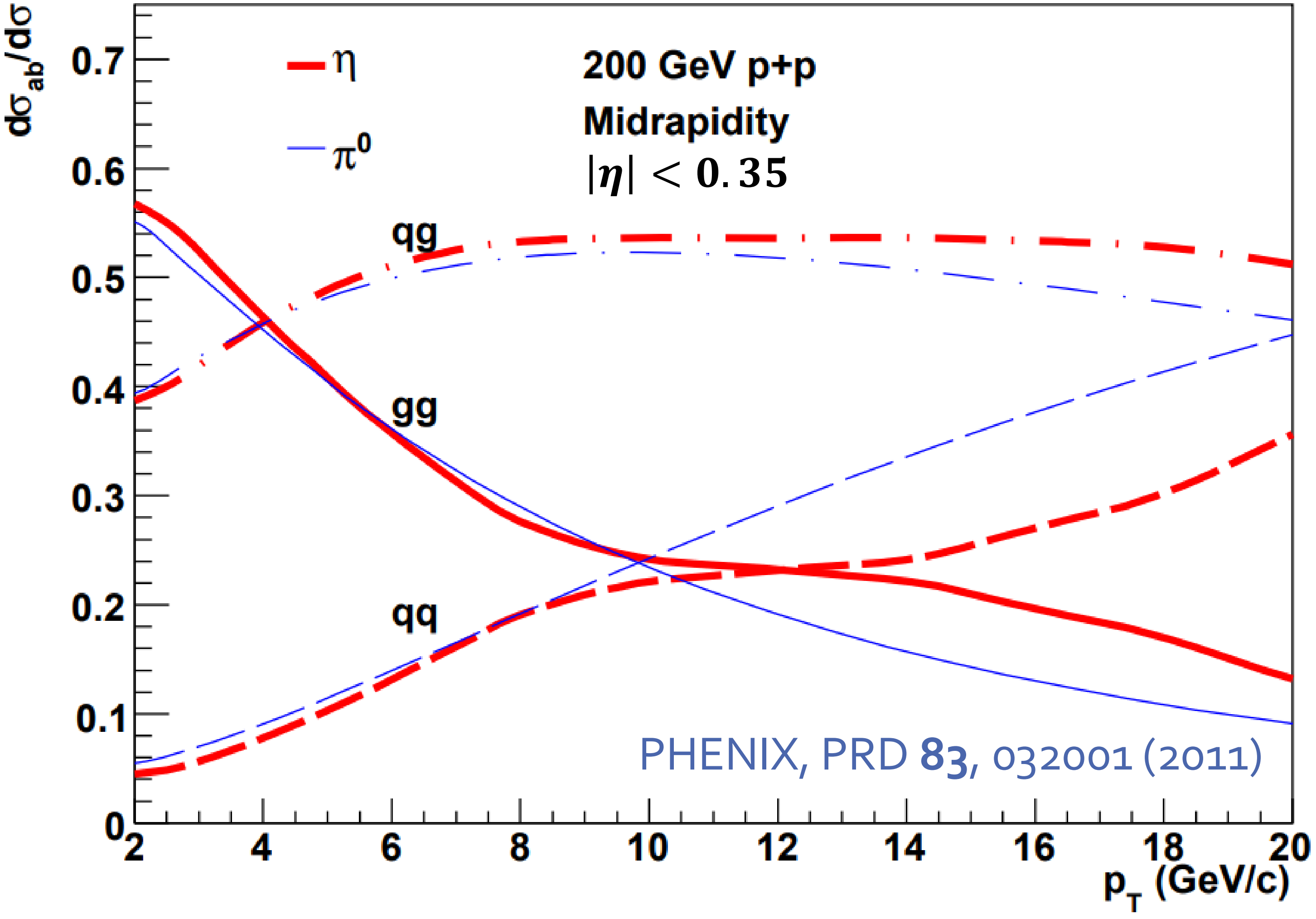

- Spin structure of proton through longitudinally polarized collisions
  - Constraints on the polarized gluon distribution
- Transversely polarized collisions probe the 3D structure of the proton
  - Twist-3 gluon dynamics with direct photons and heavy flavor
  - Transversity through Collins asymmetry
- Ongoing upgrades will provide unique physics opportunities into:
  - Understanding the origin of large forward $A_N$
  - Testing TMD evolution
  - Understanding the nature of initial-state and hadronization effects in $pA$ collisions

# Back Up

# Partonic Fractional Contributions to Central Jets at STAR

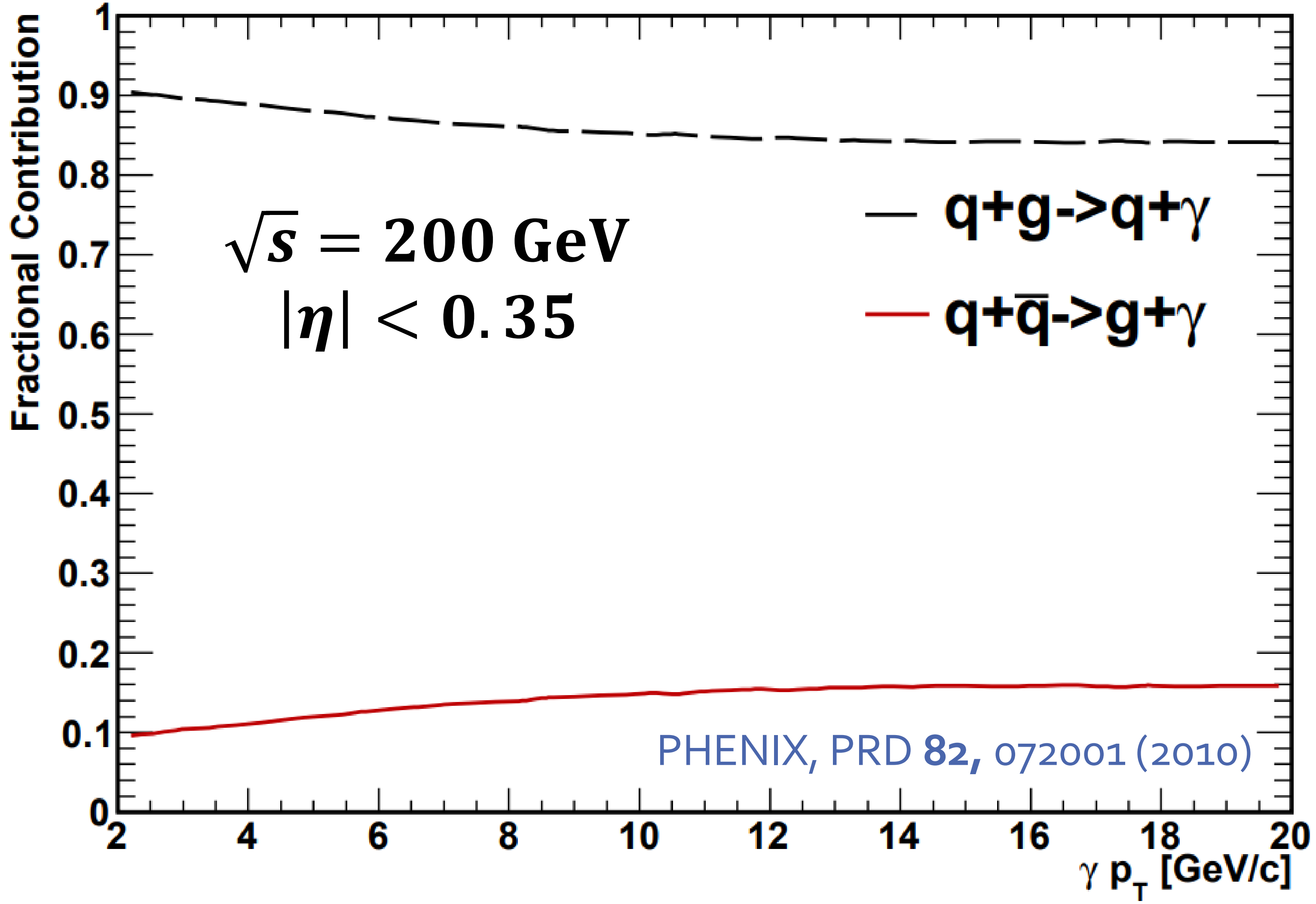


# Partonic Fractional Contributions to Midrapidity $\pi^0$ and $\eta$ Mesons at PHENIX




PHENIX, PRD **83**, 032001 (2011)

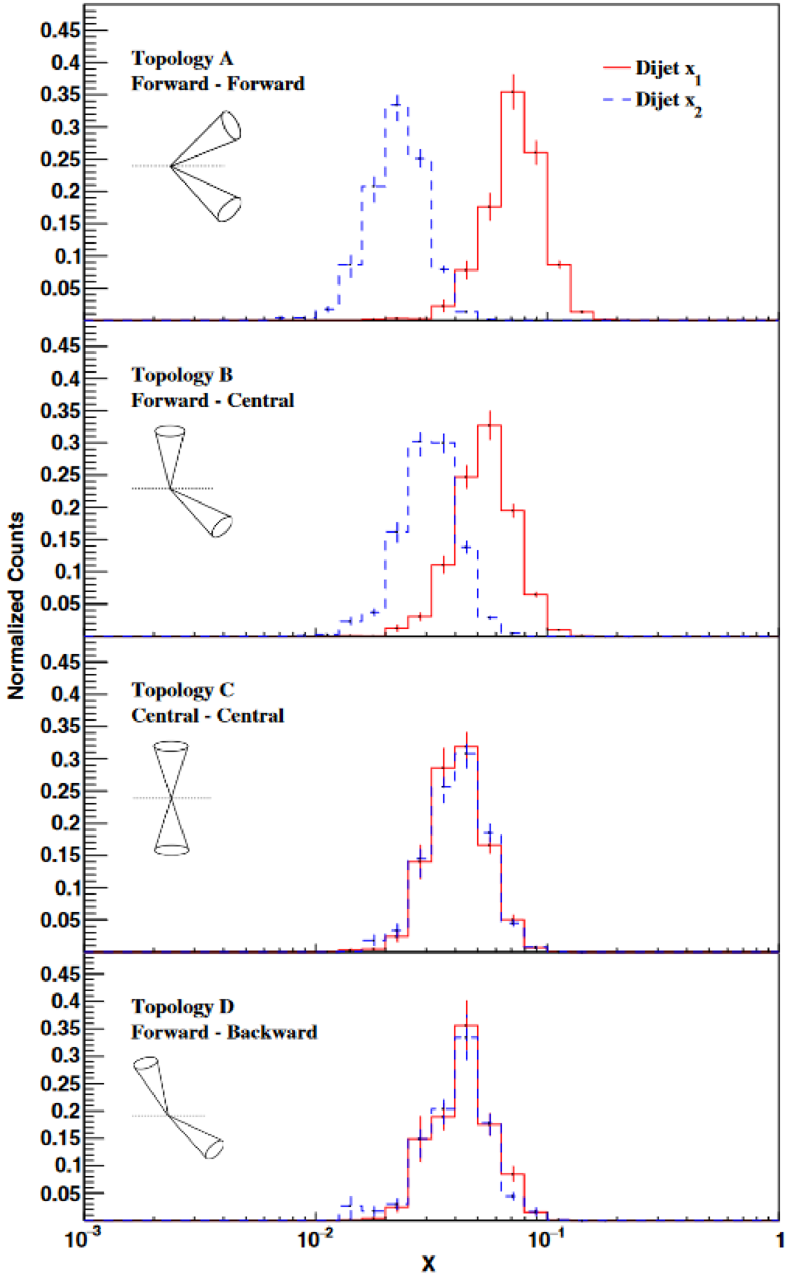
# Partonic Fractional Contributions to Midrapidity Direct Photons at PHENIX



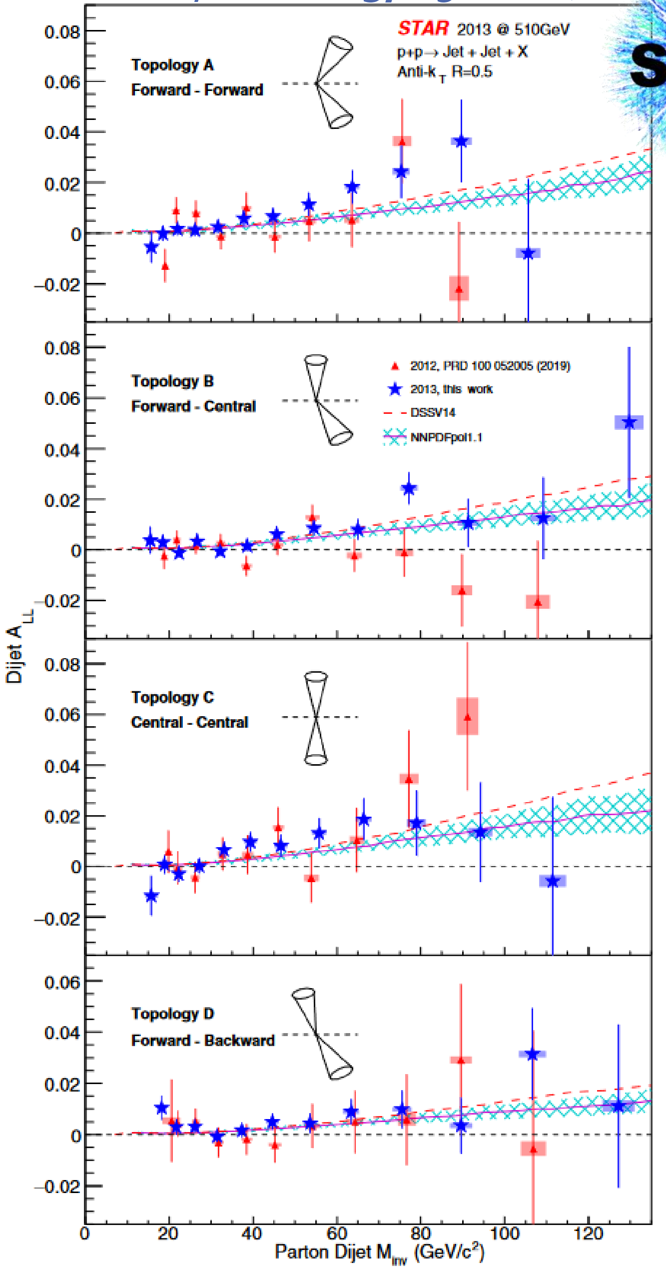
# Di-jets at $\sqrt{s} = 510$ GeV Event Topology

Four different $\eta$ topology bins, different di-jet configurations are sensitive to different kinematic regions

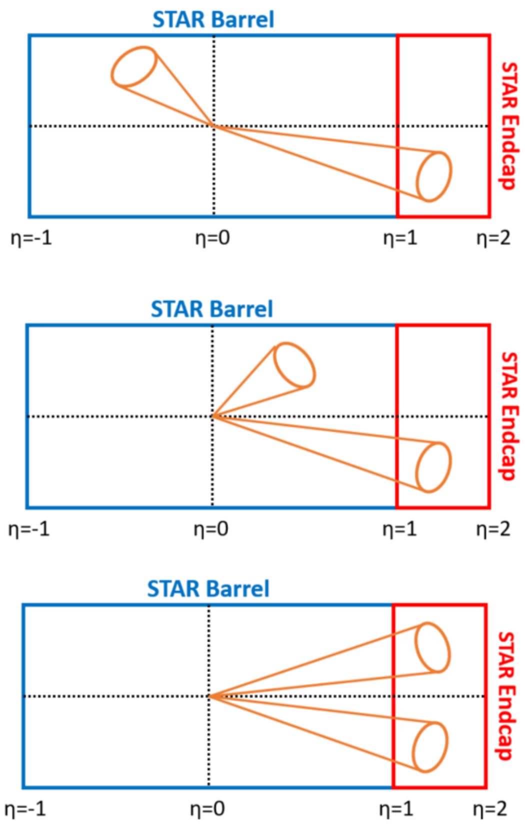
STAR, PRD **100,** 052005 (2019)

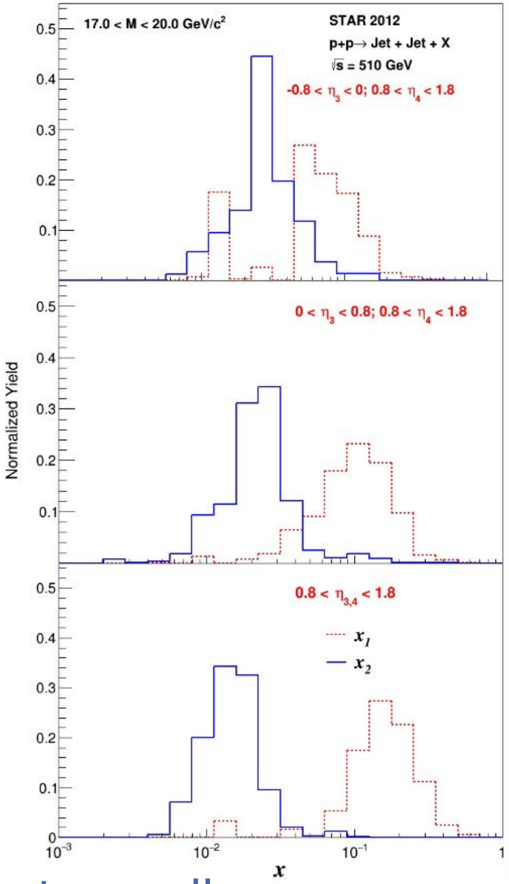



STAR, PRD **105,** 092011 (2022)

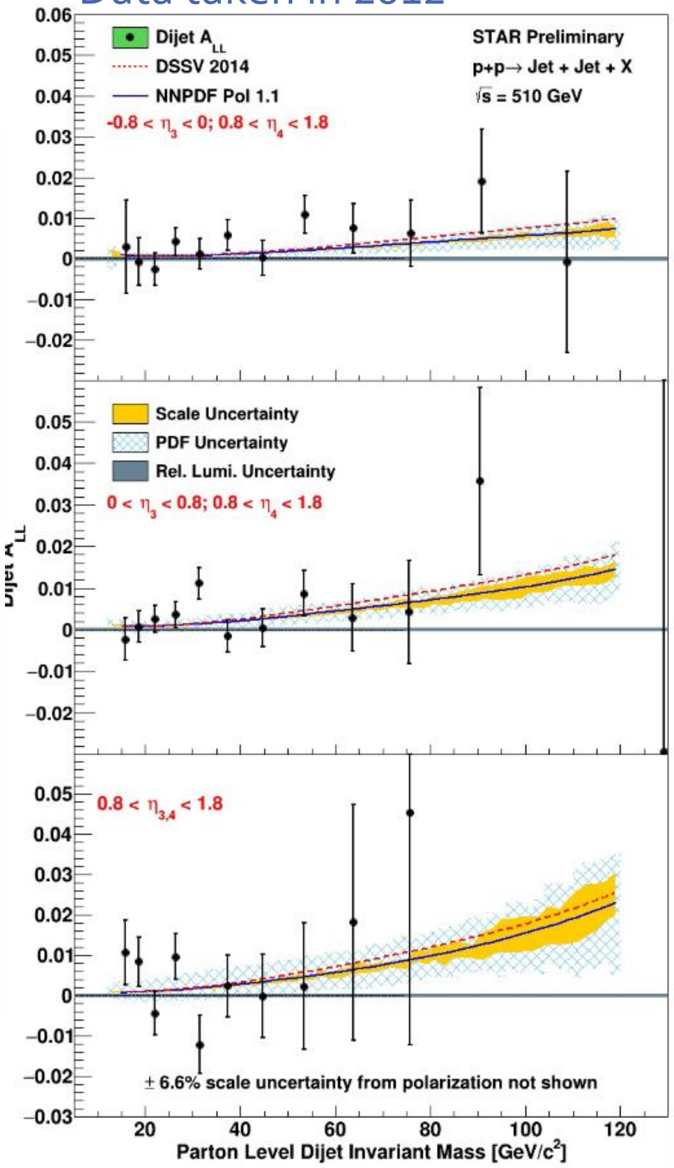


# Di-jets at $\sqrt{s} = 510$ GeV and $-0.8 < |\eta| < 1.8$

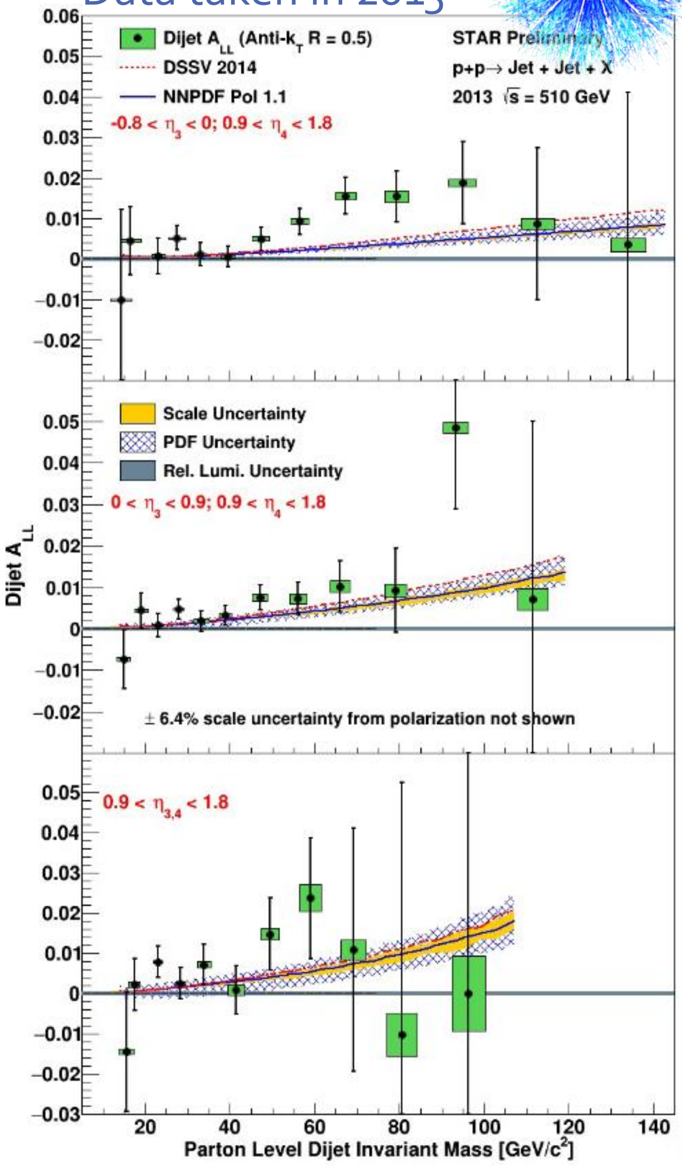



Data taken in 2012



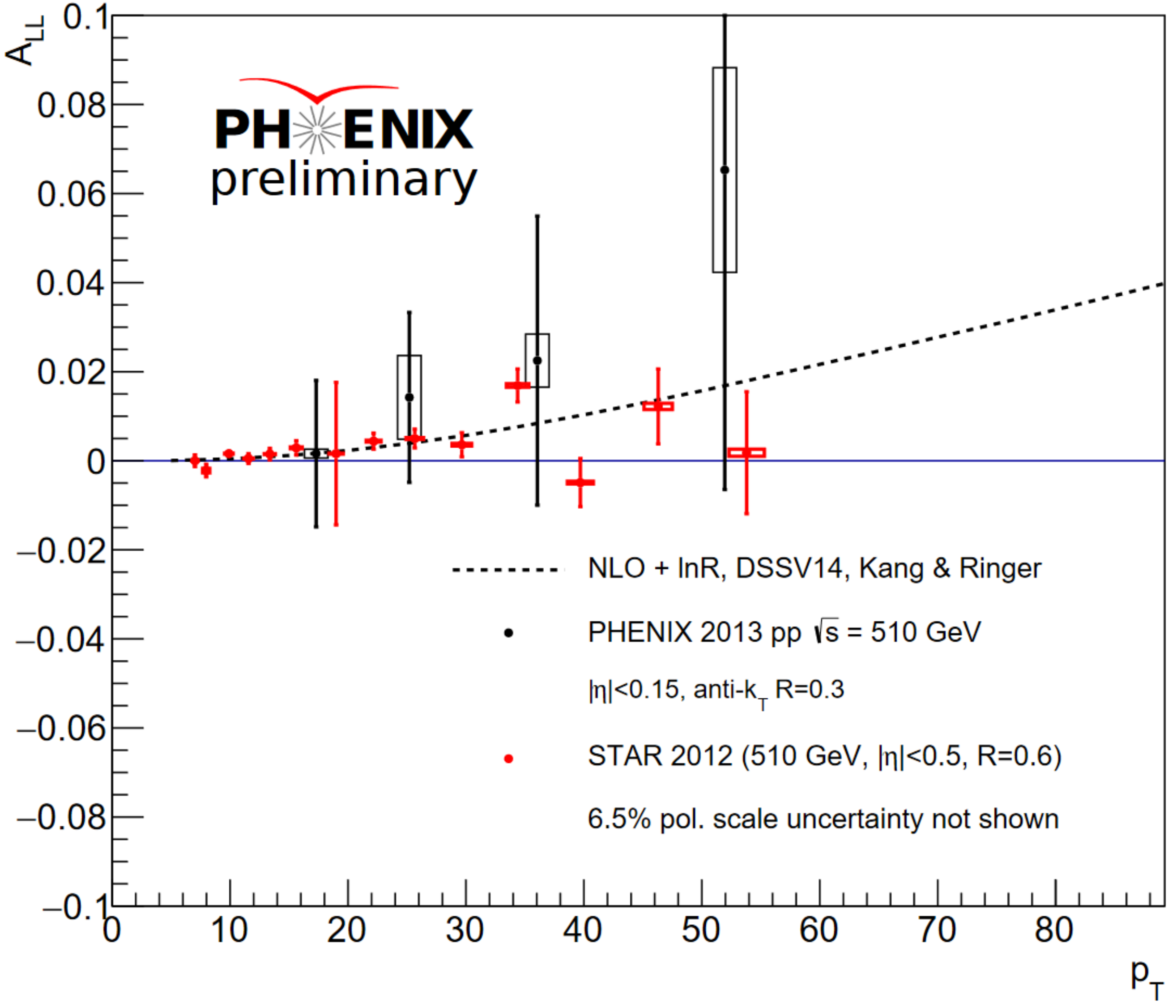

Data taken in 2013



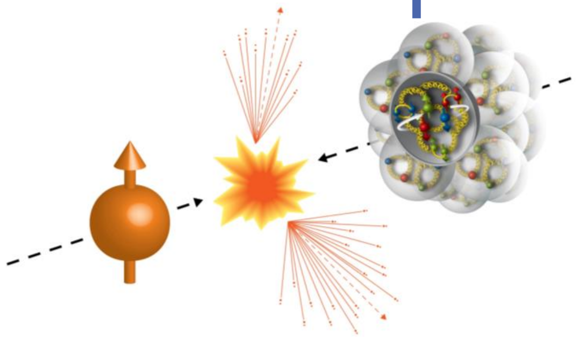

Preliminary results are in excellent agreement with each other and results using 2009 data: STAR, PRD **98**, 032001 (2018)

# Inclusive Jet $A_{LL}$ for $\sqrt{s} = 510$ GeV

- Higher $\sqrt{s}$ pushes the sensitivity to lower $x$
  - Inclusive jet at 510 GeV provides constraints for $x > 0.015$
- Agreement between experiments

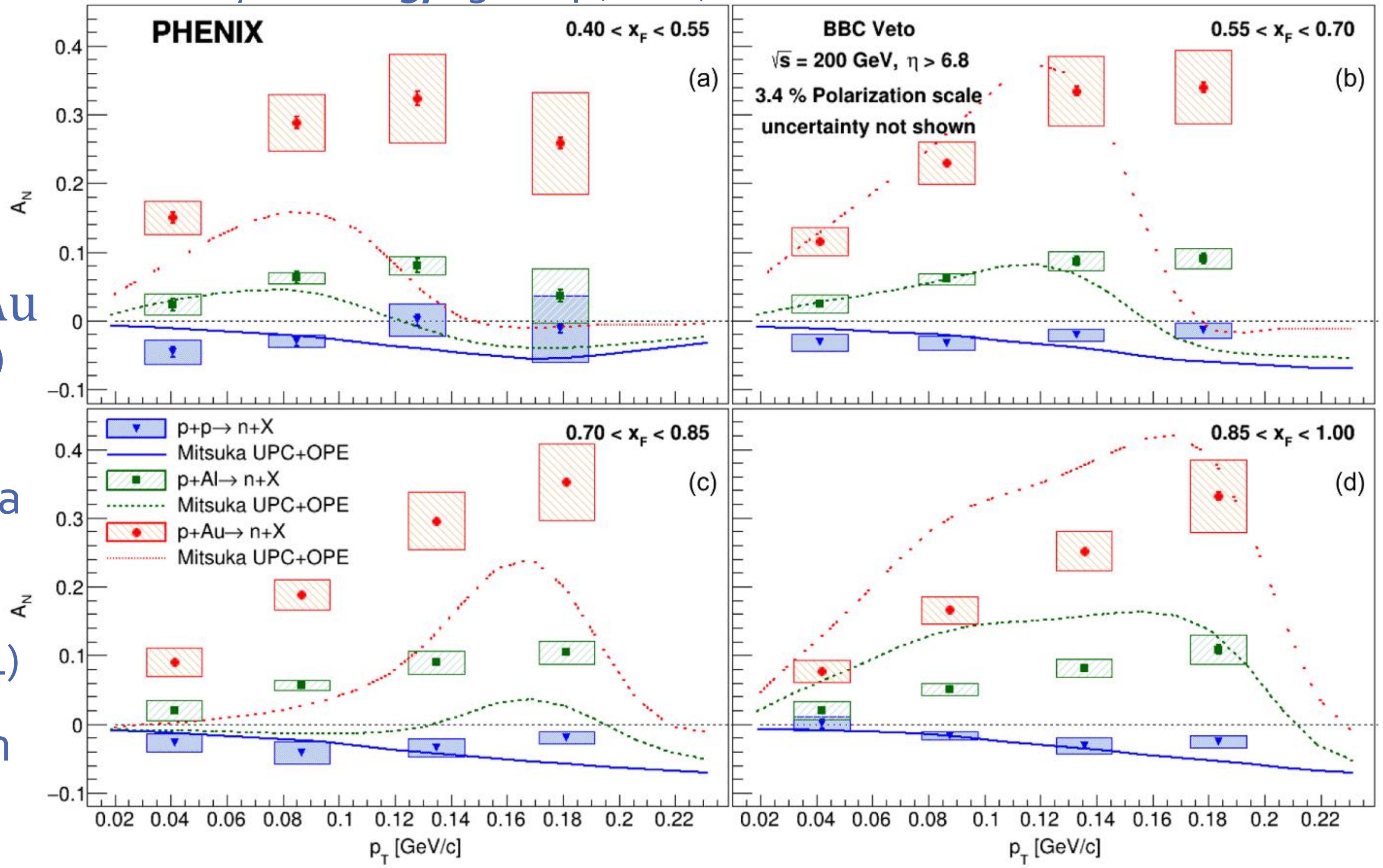


# Nuclear Dependence of Forward Neutron $A_N$



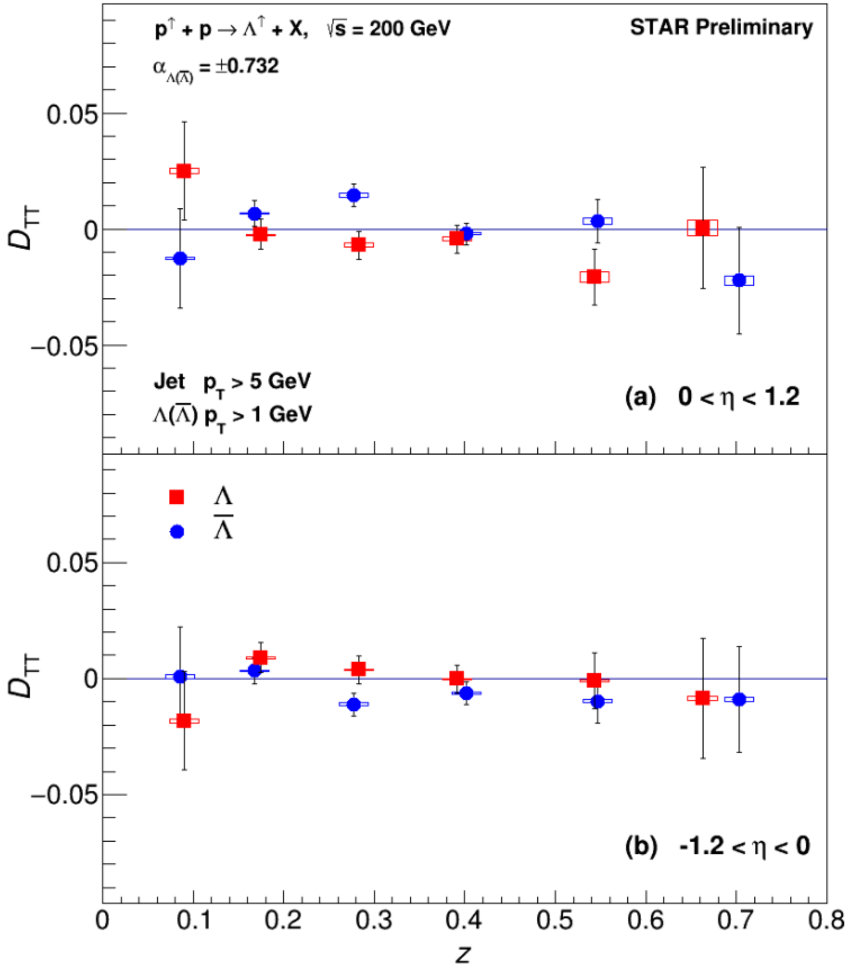
- Large nuclear dependence measured in $pp$, $p\mathrm{Al}$ and $p\mathrm{Au}$
  PHENX, PRL **120**, 022001 (2018)
- $p_T$ dependence for $A_N$ in $pp$ collisions extracted by using a bootstrapping unfolding technique
  PHENIX, PRD **103**, 032007 (2021)
- **Recently Published:** neutron $A_N$ in $pA$ as a function of $p_T$ and $x_F$

PHENIX, PRD **105,** 032004 (2022)



# $\Lambda$ Transverse Spin Transfer

$\Lambda$ reconstructed through weak decay channel, access to polarization: $\Lambda \rightarrow p + \pi^{-}$

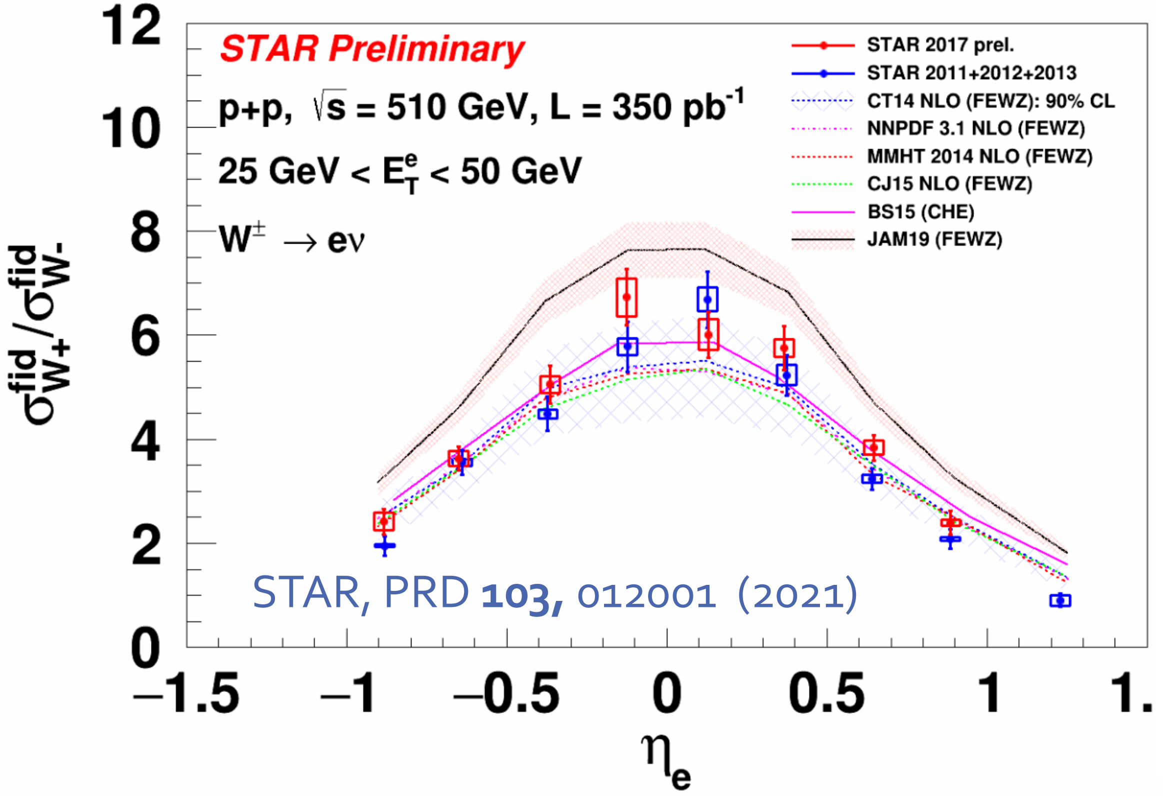


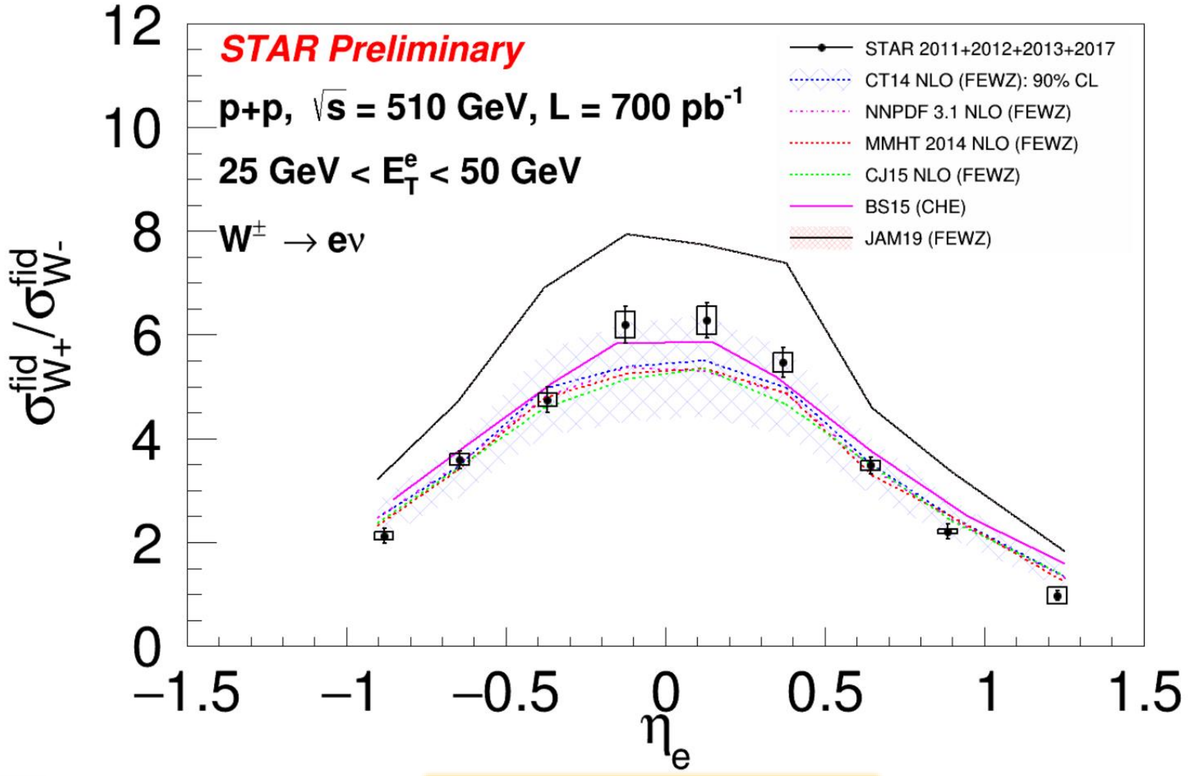

$$D_{TT}^{\Lambda} \propto \frac{\sqrt{N^{\uparrow}(\cos\theta^*)N^{\downarrow}(-\cos\theta^*)} - \sqrt{N^{\uparrow}(-\cos\theta^*)N^{\downarrow}(\cos\theta^*)}}{\sqrt{N^{\uparrow}(\cos\theta^*)N^{\downarrow}(-\cos\theta^*)} + \sqrt{N^{\uparrow}(-\cos\theta^*)N^{\downarrow}(\cos\theta^*)}}$$

- First measurement of $D_{TT}^{\Lambda}$ as a function of $z = \frac{p_{\Lambda} \cdot p_{\text{jet}}}{|p_{\text{jet}}|^2}$ in $p + p$
- Consistent with zero within uncertainties
- May indicate that the to strange quark transversity distribution and/or polarized fragmentation function of $\Lambda$ ($\bar{\Lambda}$) is small

# Cross Section Ratio for W Production

## Sensitive to the unpolarized $\bar{d}(x)/\bar{u}(x)$ quark distribution




$W^+/W^-$ cross section ratio complementary to the Drell-Yan data

**See talk by Jae Nam**
**PDF Session**
**Tuesday 8/30**