

# Recent Highlights from the PHENIX Cold-QCD Physics Program 2021 (Spin Workshop)



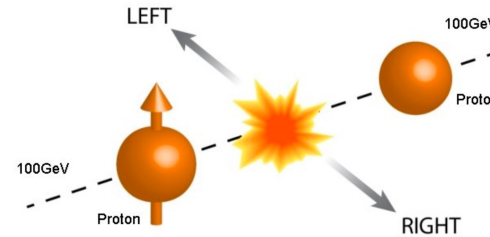
*Benard Mulilo for the* **PH<sup>\*</sup>ENIX** *Collaboration*  
*Korea University*  
*RIKEN*  
*University of Zambia*

**2021 RHIC/AGS Annual Users Meeting (AUM)**  
*June 8, 2021*

# Transverse Single Spin and Longitudinal Double Helicity Asymmetries for various Particle Species

Transverse single spin asymmetry ( $A_N$ ) is quantified by counts on either side of the polarized proton-going direction (i.e. measure azimuthal asymmetry).

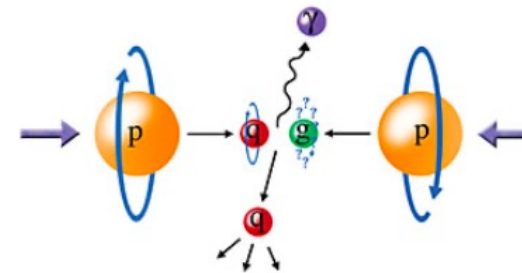
$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$



- $A'_N$ s of various particles: neutrons, pions, eta mesons, electrons and photons have been studied.

Longitudinal double helicity asymmetry ( $A_{LL}$ ):

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

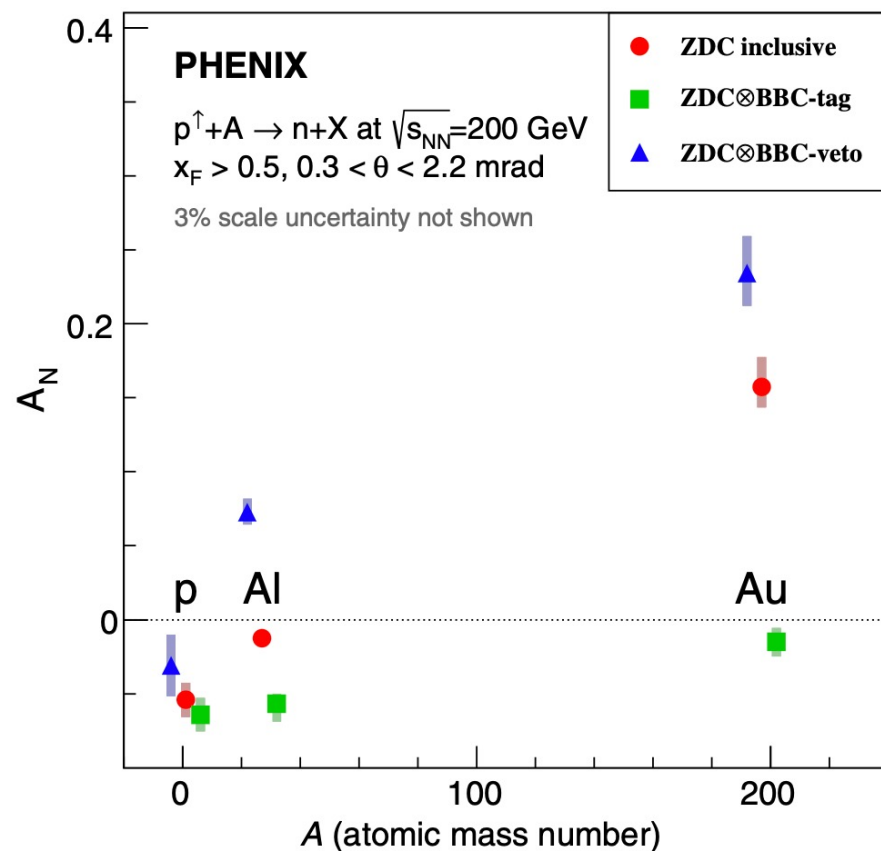


- Longitudinal double helicity asymmetry of  $\gamma^{dir}$  and jet results have also been obtained.

These studies are vital in understanding particle production mechanisms and the proton spin puzzle.

# Forward Neutron $A_N$ : Strong Nuclear Dependence in $p^\uparrow + A$ Collisions at $\sqrt{s_{NN}} = 200$ GeV (2015 Data)

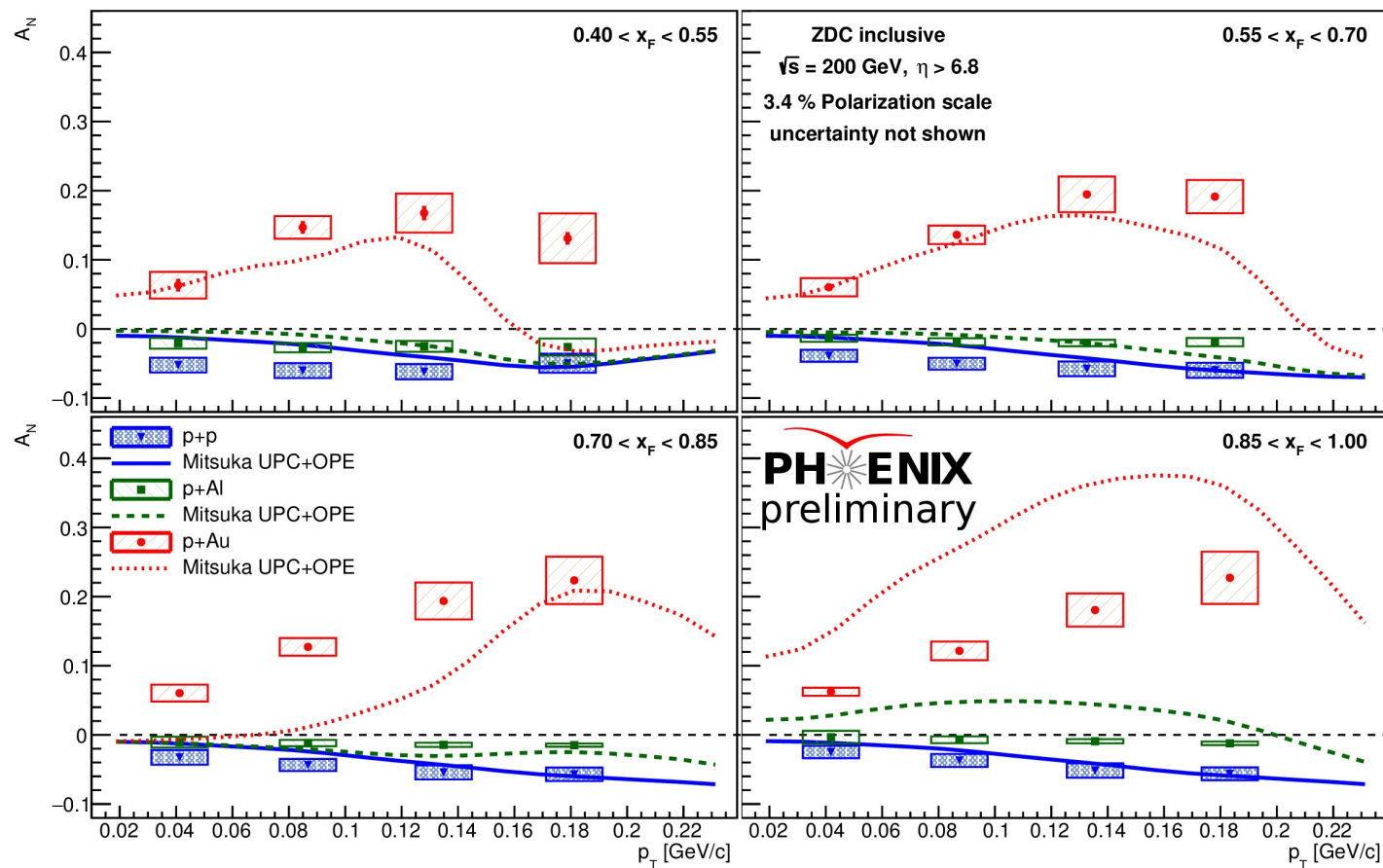
PRL 120, 022001 (2018)



- Neutron  $A_N$  in pA for  $A = 1$  (p), 27 (Al) and 197 (Au) for ZDC inclusive, ZDC  $\otimes$  BBC-tag and ZDC  $\otimes$  BBC-veto triggered samples.
- Strong nuclear dependence of asymmetries observed in pA contrary to pp expectation. This was quite surprising.
- Motivated further study to understand explicit  $p_T$  and  $x_F$  dependence of these asymmetries by invoking unfolding.

# Detector Correlation and $p_T$ dependent forward Neutron $A_N$ in $p^\uparrow + p$ , $p^\uparrow + \text{Al}$ , $p^\uparrow + \text{Au}$ Collisions at $\sqrt{s} = 200$ GeV (2015 Data)

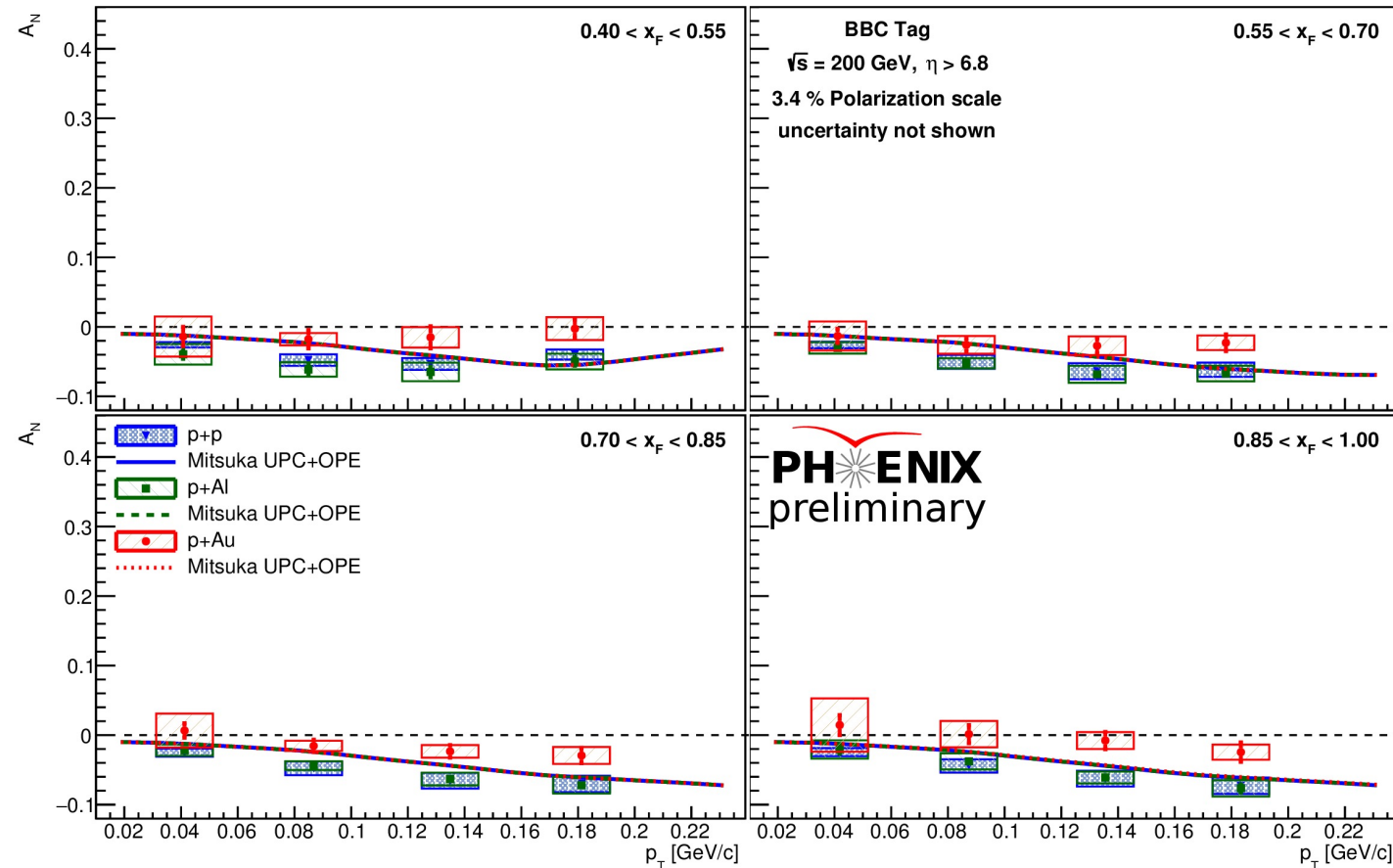
## ZDC inclusive



Inclusive neutrons display very different  $A_N$  behavior likely from the interplay between hadronic and UPC contributions.

# Detector Correlation and $p_T$ dependent forward Neutron $A_N$ in $p^\uparrow + p$ , $p^\uparrow + \text{Al}$ , $p^\uparrow + \text{Au}$ Collisions at $\sqrt{s} = 200$ GeV (2015 Data)

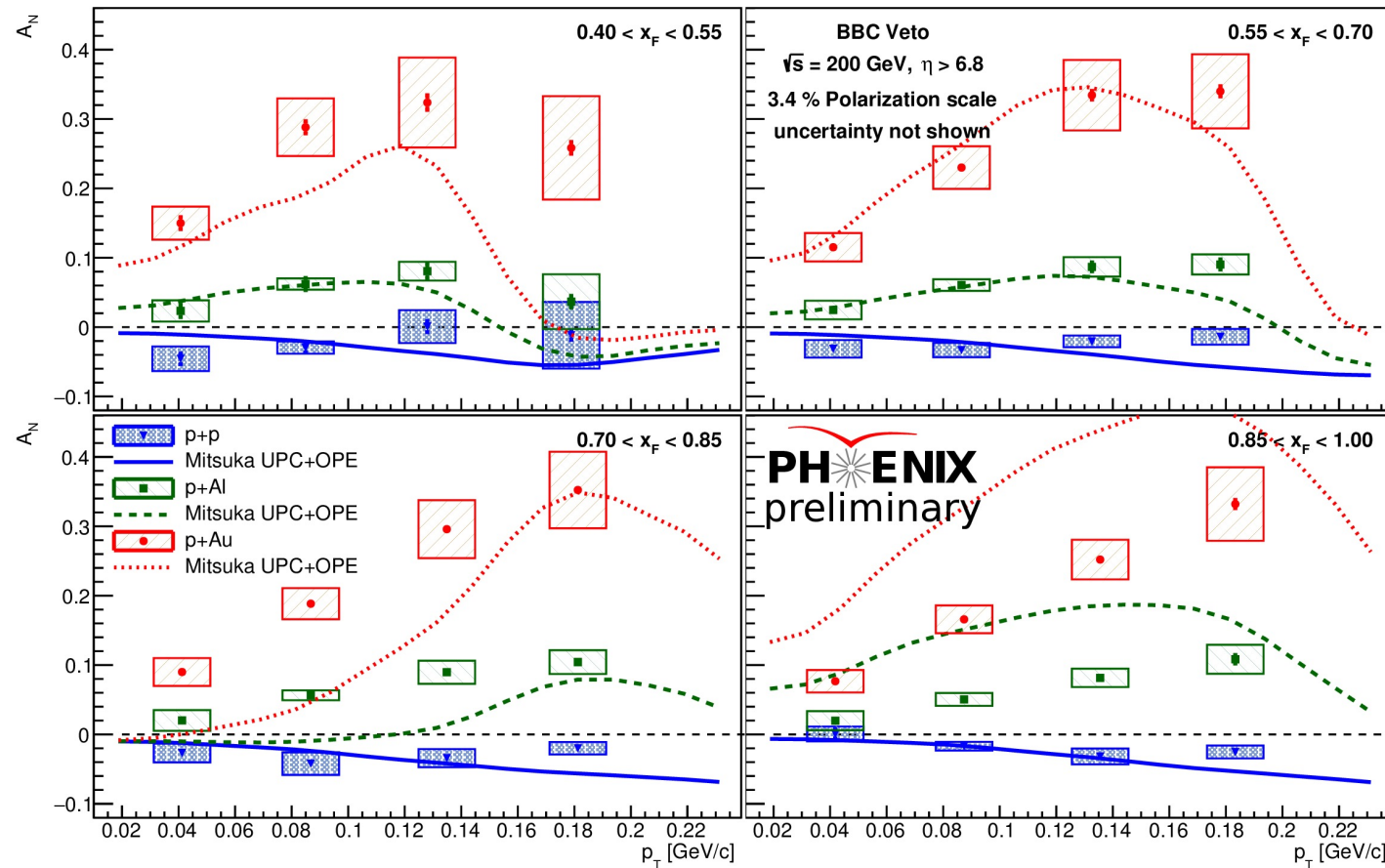
BBC tag



BBC tagging enhances hadronic contributions resulting in asymmetries that are mostly negative for all three collision species.

# Detector Correlation and $p_T$ dependent forward Neutron $A_N$ in $p^\uparrow + p, p^\uparrow + \text{Al}, p^\uparrow + \text{Au}$ Collisions at $\sqrt{s} = 200$ GeV (2015 Data)

## BBC veto



In BBC veto, UPC asymmetry contribution dominates over hadronic resulting in large and now positive asymmetries in pA.

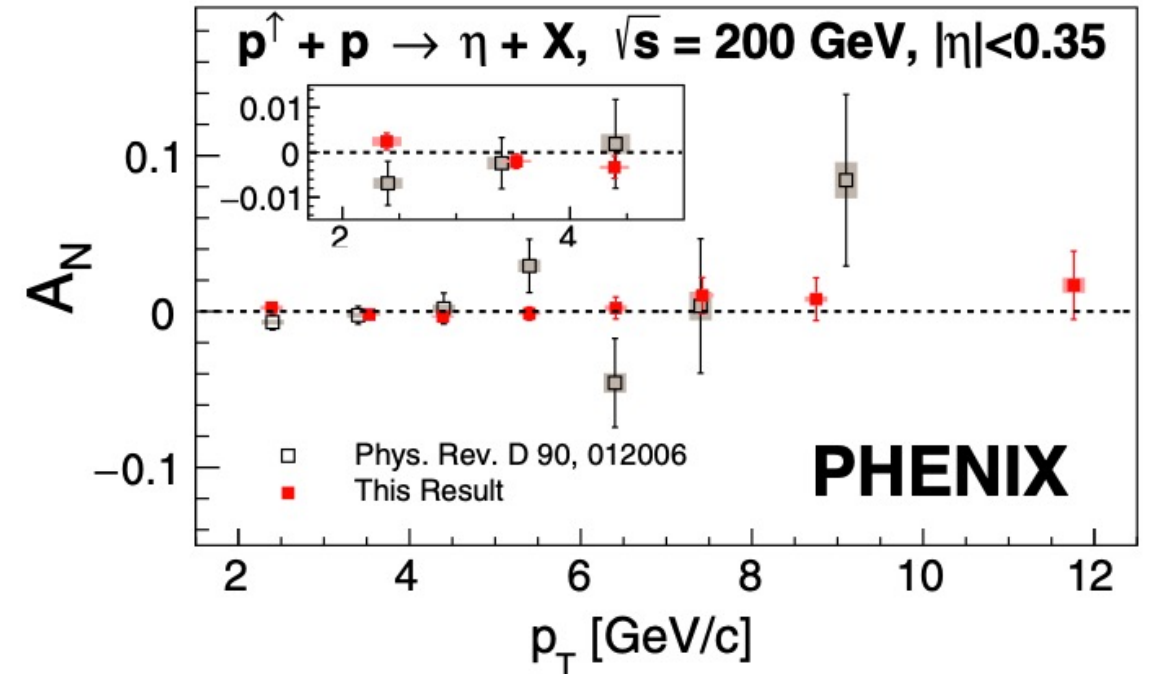
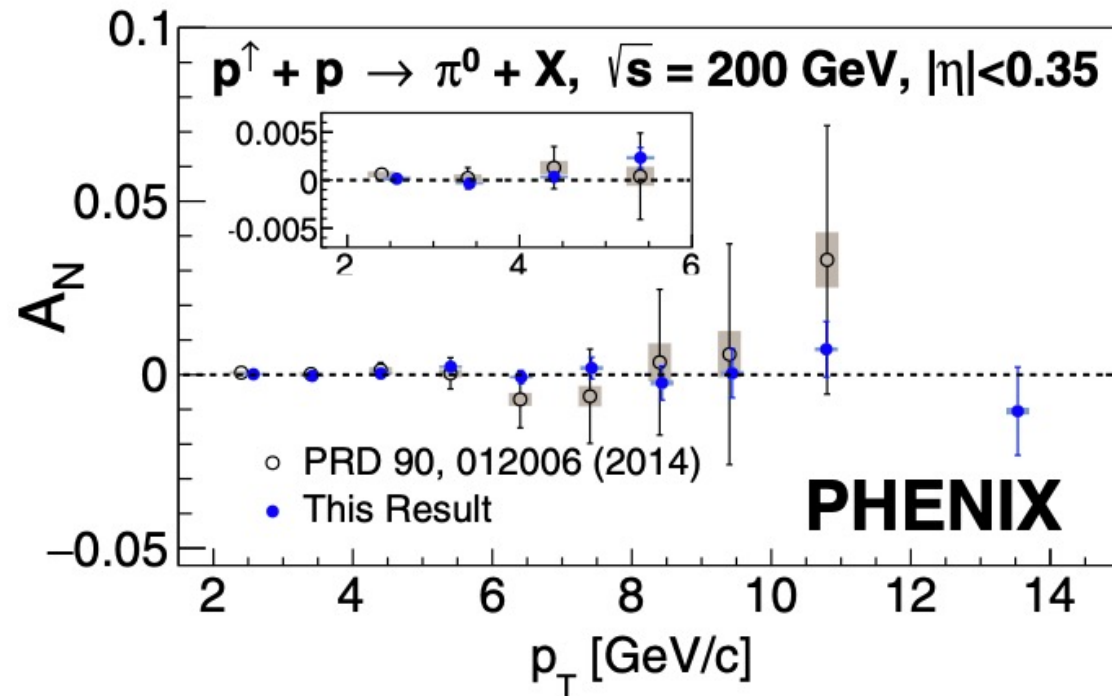


# Transverse single-spin asymmetries of midrapidity $\pi^0$ and $\eta$ mesons in $p^\uparrow + p$ collisions at $\sqrt{s} = 200$ GeV (2015 Data)

TSSA of  $\pi^0$  measured at  $|\eta| < 0.35$  in  $p^\uparrow + p$  collisions at  $\sqrt{s} = 200$  GeV.

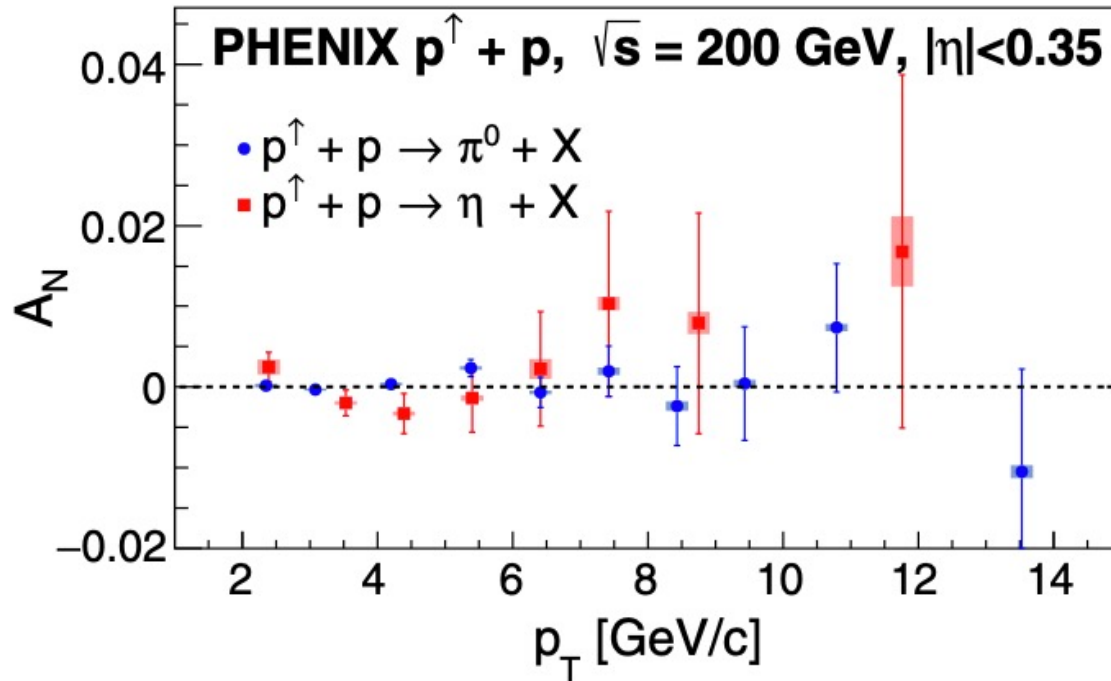
TSSA of  $\eta$  mesons measured at  $|\eta| < 0.35$  in  $p^\uparrow + p$  collisions at  $\sqrt{s} = 200$  GeV.

[\(PRD.103.052009\)](#)

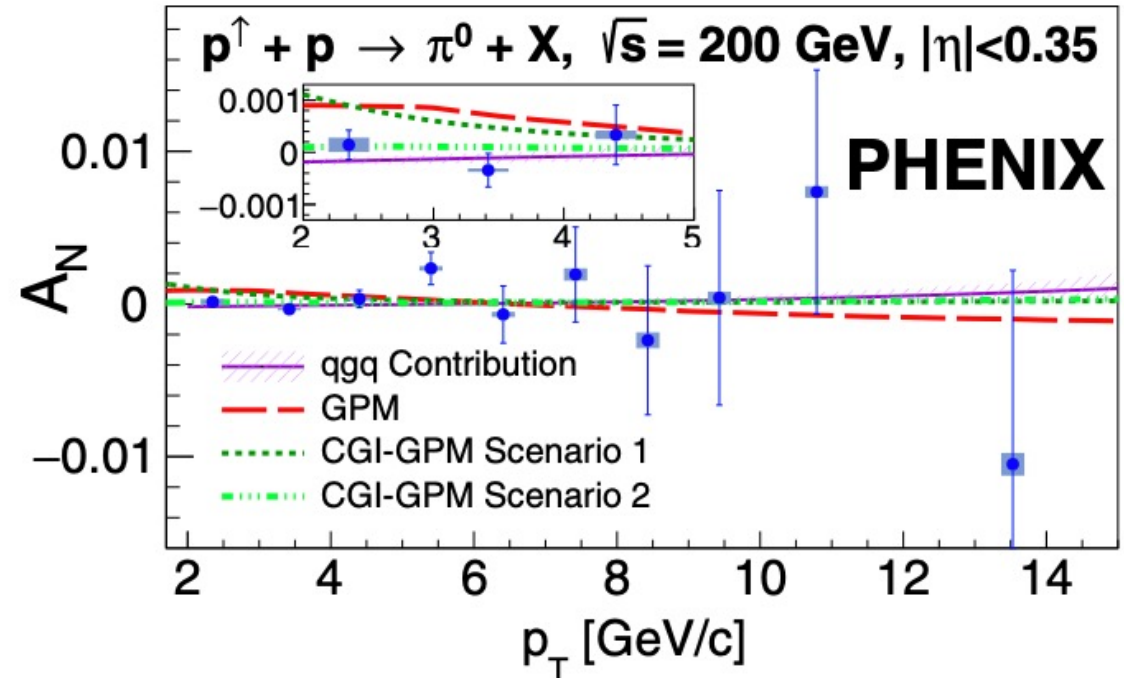


# Transverse Single Spin Asymmetries of Midrapidity $\pi^0$ and $\eta$ Mesons in $p^\uparrow + p$ Collisions at $\sqrt{s} = 200$ GeV (2015 Data)

([PRD.103.052009](#))



TSSA comparison of  $\pi^0$  and  $\eta$  mesons measured at  $|\eta| < 0.35$  in  $p^\uparrow + p$  collisions at  $\sqrt{s} = 200$  GeV.

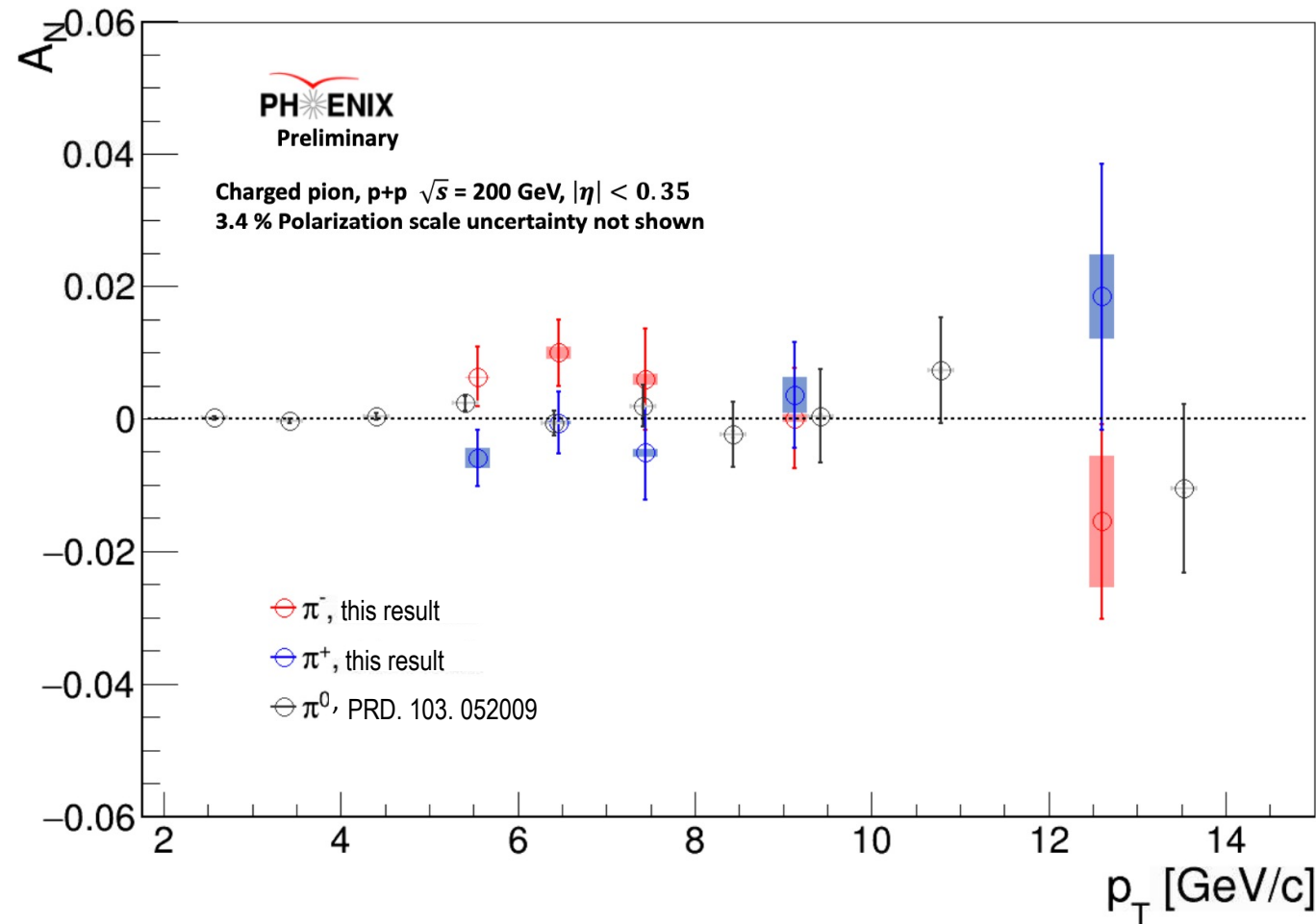


TSSA of  $\pi^0$  result plotted with theory in collinear twist-3 and TMD framework predictions.

$\pi^0$  and  $\eta$  meson asymmetries are consistent with zero. Larger asymmetry contribution is from gluon dynamics at midrapidity.

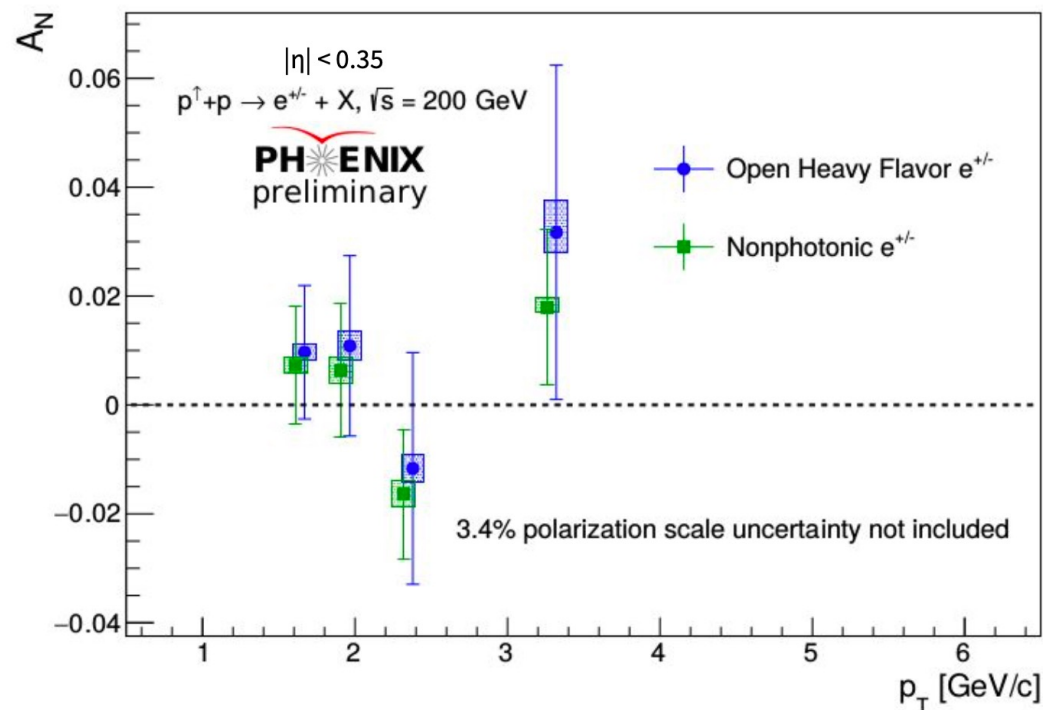


# Transverse Single Spin Asymmetry via Charged Pion Production in $p^\uparrow + p$ at 200 GeV Collisions at Midrapidity (2015 Data)



$A_N$  of  $\pi^\pm$  is consistent with zero, with a slight indication of differences. Hint  $\rightarrow$  possibility of different  $A_N$  from up and down quarks.

# Transverse Single Spin Asymmetries of Heavy Flavor Electrons in 200 GeV $p^\uparrow + p$ Collisions at Midrapidity (2015 Data)



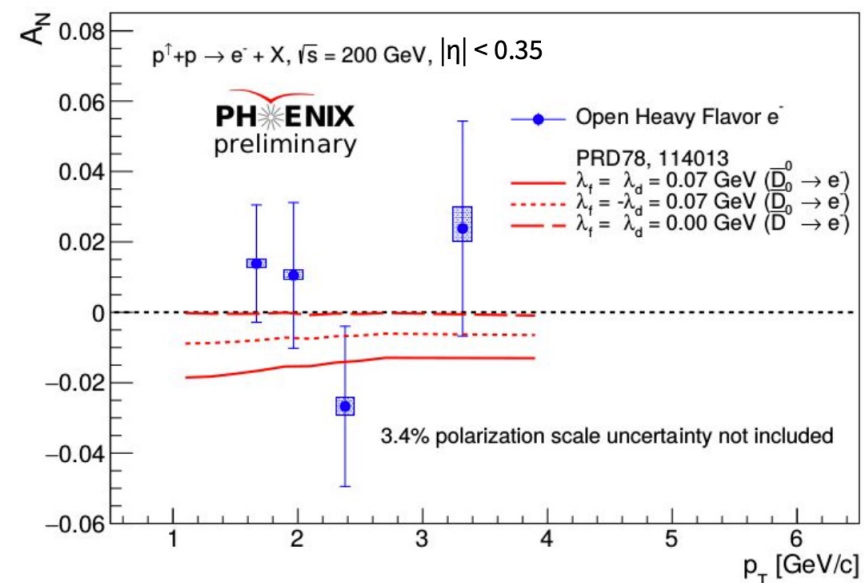
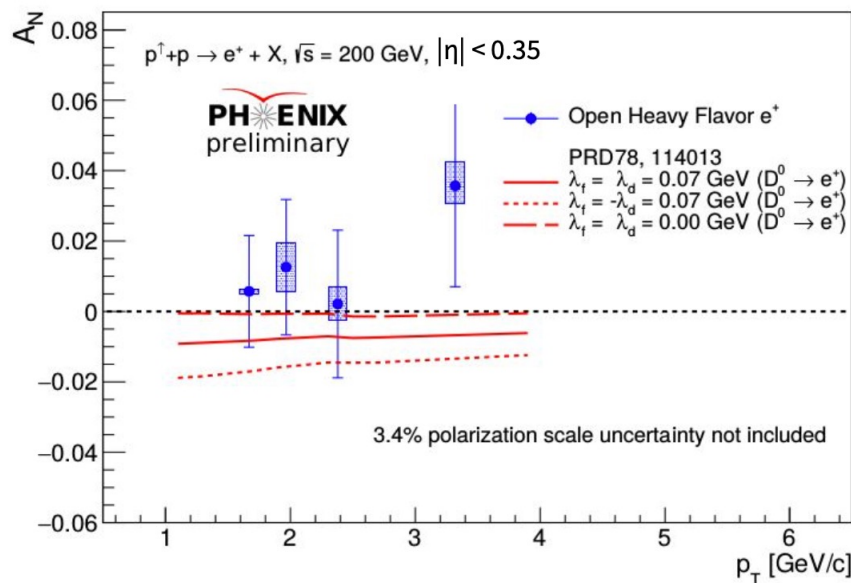
Charge combined open heavy flavor electron  $A_N$ .

Precise measurement of nonphotonic electron and open heavy flavor TSSA at midrapidity.

Consistent with zero in the measured  $p_T$  range.

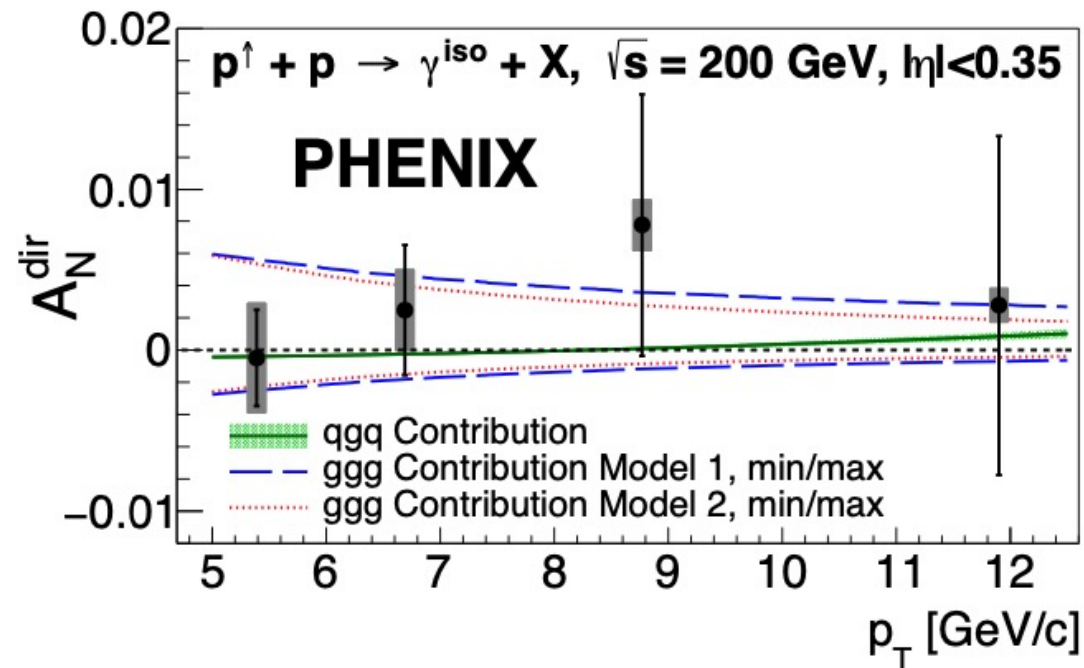
# Transverse Single Spin Asymmetries of Heavy Flavor Electrons in 200 GeV $p^\uparrow + p$ Collisions at Midrapidity (2015 Data)

Charge separated open heavy flavor electron  $A_N$



- Red curves indicate  $D^0 \rightarrow e^\pm$  contributions as calculated in **PRD78, 114013**.
- Ordering of curves is different for charge separated  $A_N \rightarrow$  sensitivity to constrain  $\lambda$  parameters.
- $\lambda$  parameters correspond to normalizations of ggg correlators w.r.t. to unpolarized gluon PDF.

# Probing Gluon Spin-Momentum Correlations in $p^\uparrow$ through Midrapidity Isolated Direct Photons in $p^\uparrow + p$ Collisions at $\sqrt{s} = 200$ GeV (2015 Data)



$A_N$  of isolated direct photons measured at midrapidity  $|\eta| < 0.35$  in  $p + p$  collisions at  $\sqrt{s} = 200$  GeV.

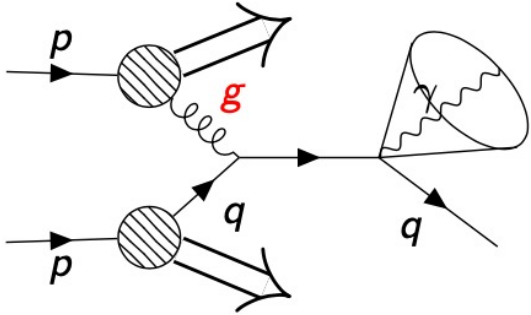
$A_N$  of midrapidity direct photons is consistent with zero.

First measurement in  $\sim 30$  years by PHENIX experiment in higher  $p_T$  range.

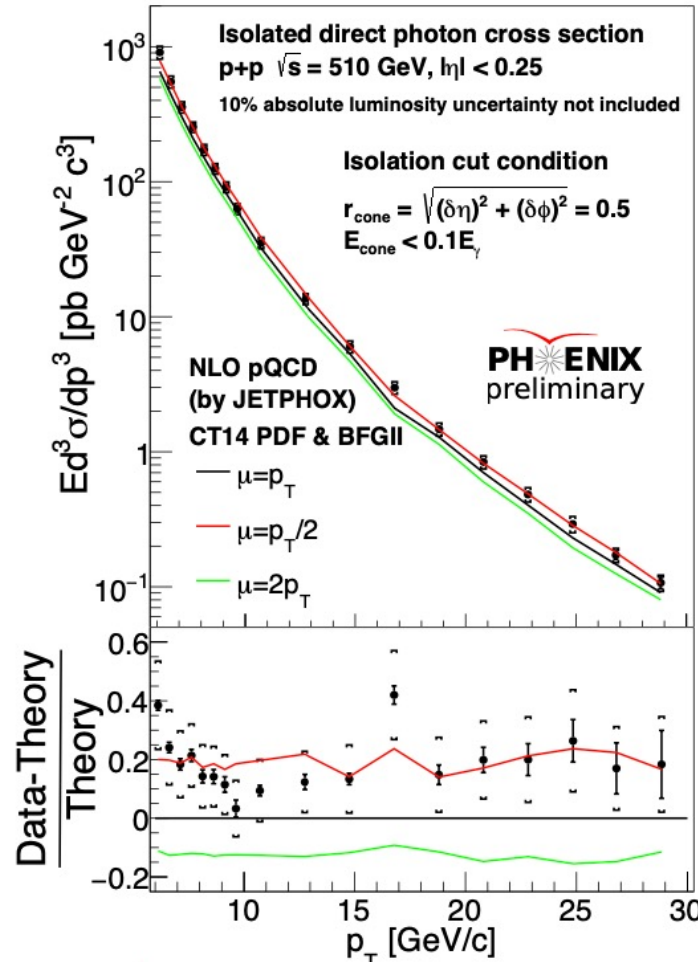
Clean probe of proton structure with no contribution from final-state QCD effects, sensitive to gluon dynamics. If included in global analysis of  $A_N$  data, will constrain gluon-momentum correlations in  $p^\uparrow$ , a vital step toward creating a more 3-D proton structure picture.

# Cross Section and Longitudinal Double Helicity Asymmetry of Direct Photons in $\vec{p} + \vec{p}$ collisions at $\sqrt{s} = 510$ GeV (2013 Data)

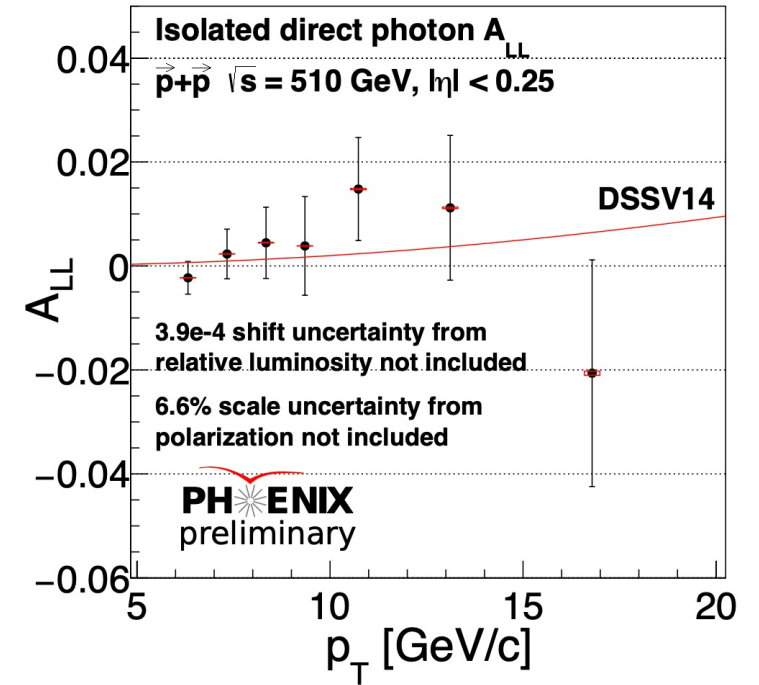
## Direct photon cross section



- $\gamma^{dir}$  measurement  $\rightarrow$  more directly sensitive to gluons.
- Main interaction process is Quark-gluon Compton scattering.



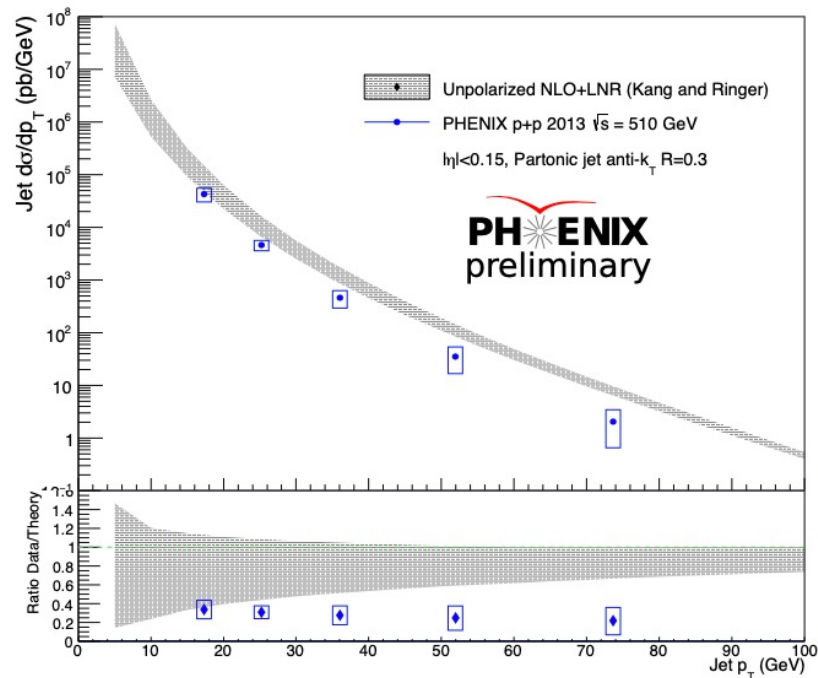
## Direct photon $A_{LL}$



- Consistent with NLO DSSV14
- Constrain polarized gluon PDF  $\Delta g$ .
- Will be first published  $\gamma^{dir} A_{LL}$  result.

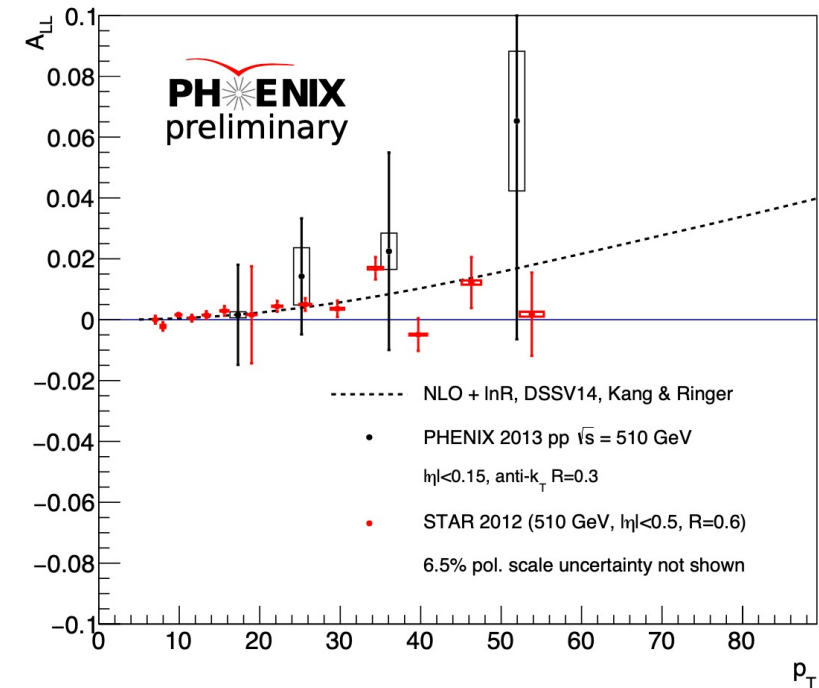
# Cross Section and Longitudinal Double Helicity Asymmetry $A_{LL}$ of Jet Production in $\vec{p} + \vec{p}$ Collisions at $\sqrt{s} = 510$ GeV (2013 Data)

Jet cross section



- NLO +  $\ln(R)$  resummation overestimates data.
- Calculation is at partonic level: MPI & parton shower vital.
- For small  $R$  anti- $k_T$ , similar observation from CMS.

Jet  $A_{LL}$



Consistent with DSSV14 at NLO+ $\ln R$  resummation.  
Independent constraint on polarized gluon PDF  $\Delta g$ .  
Uncertainties are correlated due to the unfolding.



# Summary

- Large and positive neutron  $A_N$  previously observed by PHENIX in pA is due to UPC dominating hadronic contribution.
- $\pi^0$  and  $\eta$  asymmetries are largely due to gluon dynamics and are consistent with zero in measured  $p_T$  range.
- $\pi^\pm A_N$  may help check if u and d quarks result in different  $A_N$  if probe with improved statistics is used.
- Open heavy flavor electron  $A'_N$ s have been precisely measured by PHENIX and are consistent with zero.
- At midrapidity,  $\gamma^{dir} A_N$  is a clean probe of proton structure with no contribution from final-state QCD effects.
- $\gamma^{dir} A_{LL}$  is more directly sensitive to gluons as q-g Compton scattering is main interaction process.
- Measured longitudinal double helicity asymmetry ( $A_{LL}$ ) of jet is consistent with DSSV14 at NLO +  $\ln(R)$  resummation.