Recent spin results from PHENIX

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for the PHENIX Collaboration

UCLA

RHIC & AGS 2022

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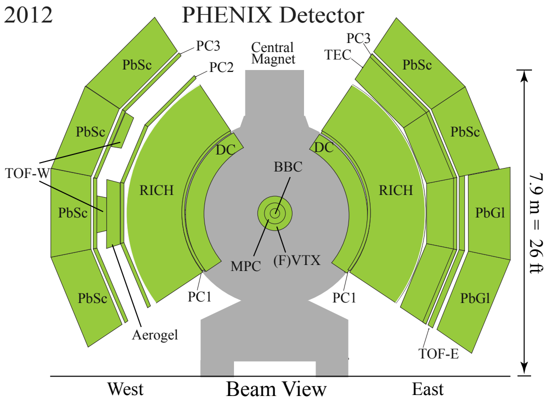
Outline

1. Experimental setup
2. Longitudinal double spin asymmetry A_{LL}
   - Direct photon
   - Jet
   - Charged pion
3. Transverse single spin asymmetry A_N
   - Direct photon
   - π^0 and η
   - Charged pion
   - Open heavy flavor
   - Forward neutron
4. Summary

PHENIX detector

- $|\eta| < 0.35$ and π coverage for ϕ.
- EMCal: primary detector for photons.
- EMCal trigger: select high energy particles.
- DC: measure charged particles.
- PC3: track matching.
- RICH: PID from Čerenkov light.



Probing the gluon spin inside the proton

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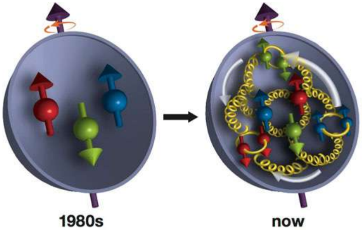
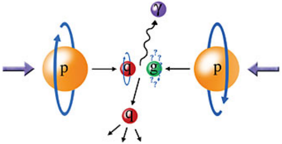
- The proton spin can be decomposed as

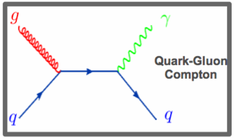
$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + {\color{red}\Delta g} + L_q + L_g$$

- Gluon spin ${\color{red}\Delta g}$ is important for the proton spin puzzle.



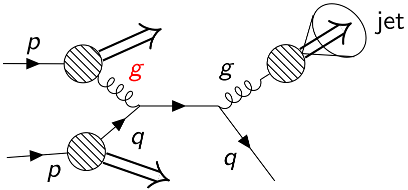


$$A_{LL}^{pp\to\gamma X} \sim \frac{\Delta q(x_q)}{q(x_q)} \cdot \frac{{\color{red}\Delta g(x_g)}}{{\color{red}g(x_g)}} \cdot a_{LL}^{qg\to\gamma q}$$

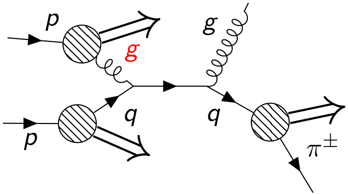


- $A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$
- Little fragmentation contributions to direct photon production.

Jet and charged pion production

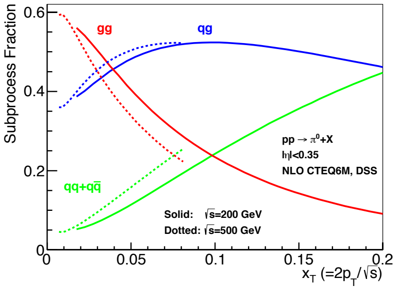


Jet production



Charged pion production

- Larger statistics: not suppressed by small QED coupling.
- RHIC 200 GeV data probe $0.05 < x < 0.2$.
- RHIC 510 GeV data probe $0.02 < x < 0.08$.



From A_{LL} to Δg

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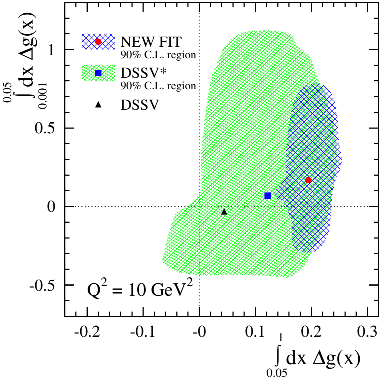
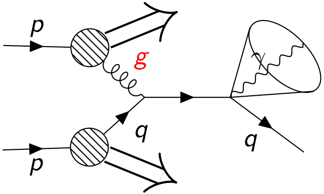
- Existing RHIC data mainly probe $0.05 < x_g < 0.2$.
- PHENIX π^0 A_{LL} at 510 GeV confirms a nonzero Δg and extend x_g to 0.01.
- STAR jet data clearly imply a polarization of gluons in this range.
- Results from γ, jet and $\pi^{\pm}$ will add additional independent constraints on the Δg.



PRL 113, 012001 (2014)

Identifying direct photon through isolation

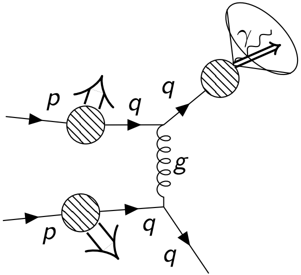


$$r_{cone} = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$$

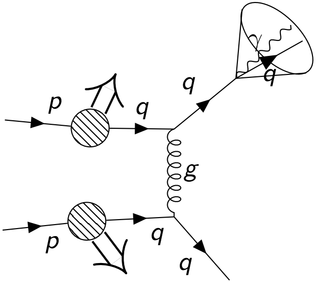
Isolation cut requirement:

$$\sum E_{in\ cone} < 0.1 E_\gamma$$

Quark-gluon Compton scattering: Easy to pass isolation cut



Fragmentation:
Hard to pass
isolation cut



Bremsstrahlung:
Hard to pass
isolation cut

Direct photon cross section

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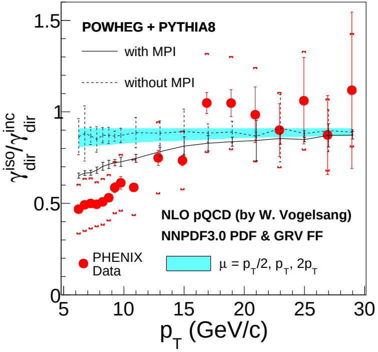
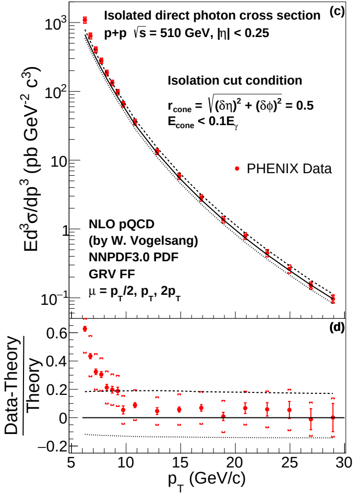
- Consistent with NLO pQCD.
- MPI and parton shower are important for inclusive direct photon production.
- Constrain unpolarized gluon PDF.

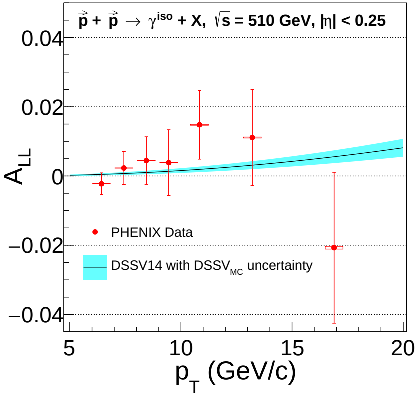




arXiv:2202.08158

Direct photon A_{LL}

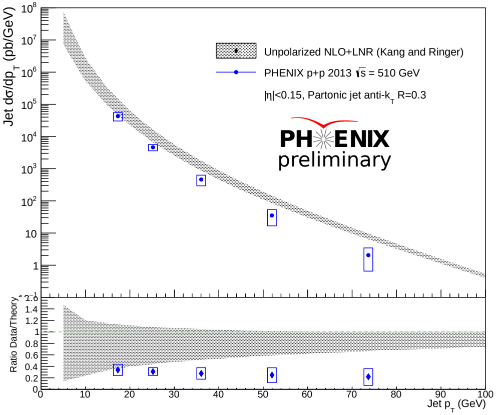
- Consistent with NLO DSSV14.
- Will be the first published direct photon A_{LL}.
- Constrain polarized gluon PDF Δg.



arXiv:2202.08158

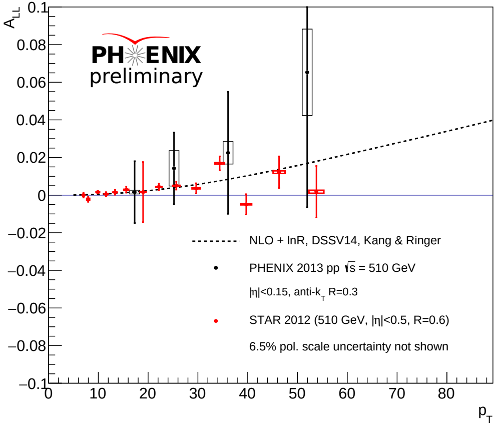
Jet cross section

- Calculation from NLO + ln(R) resummation overestimates data.
- The calculation is at partonic level: MPI and parton shower are important.
- Similar observation from CMS, for small R anti-k_T.

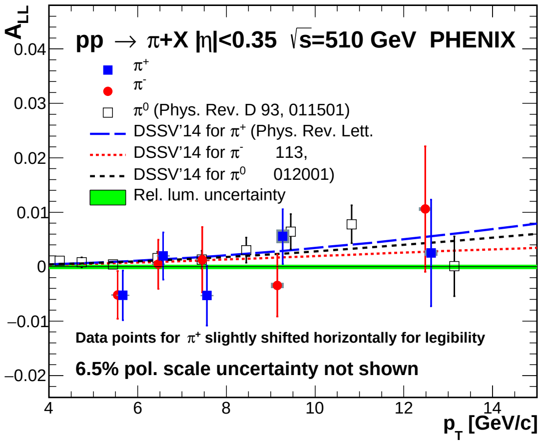


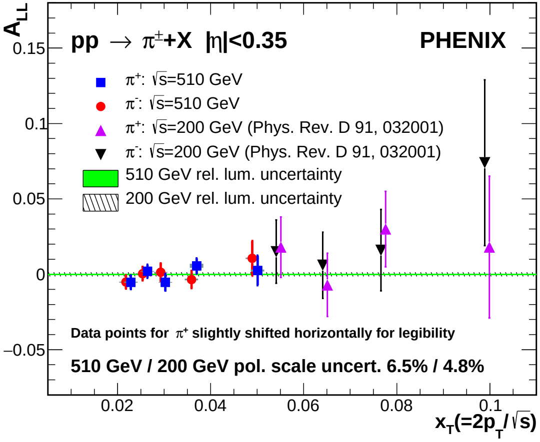
Jet A_{LL}

- Consistent with DSSV14 at NLO + ln(R) resummation.
- Independent constraint on polarized gluon PDF Δg.
- Uncertainty are correlated due to unfolding.



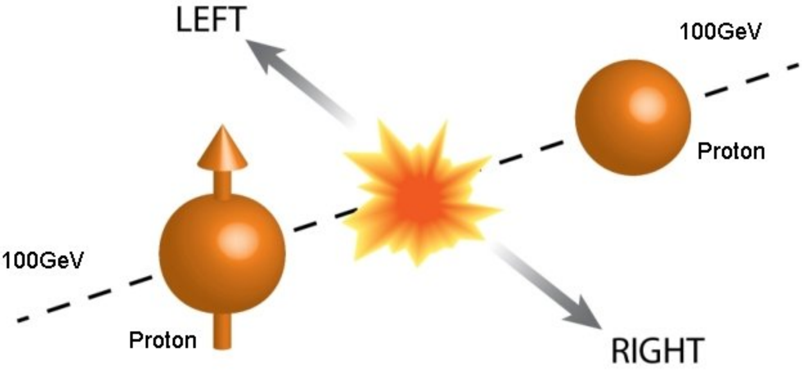
Charged pion A_{LL}





- PRD 102, 032001 (2020)
- Consistent with DSSV14.
- 510 GeV data probe low x range.
- Not enough statistics to decide $\pi^{\pm}$ order.

Transverse Single Spin Asymmetry (TSSA)



$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Origin of TSSA: TMD

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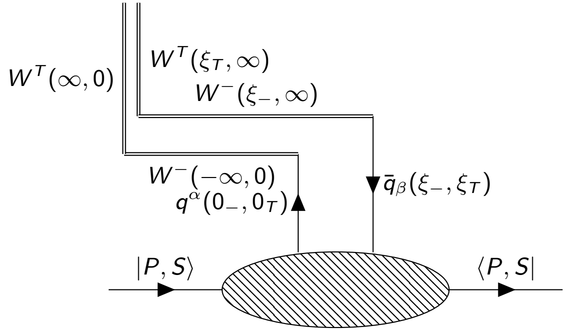

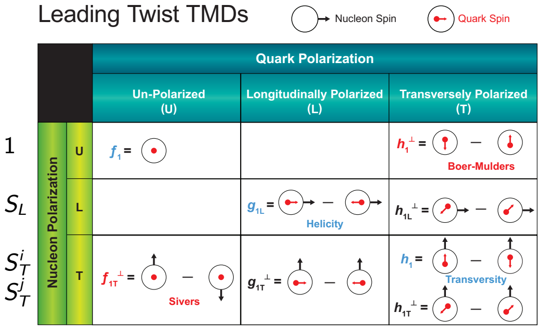

Γ : 1 γ^5 $\gamma^i\gamma^5$

When $Q \gg k_T \gtrsim \Lambda_{QCD}$:

Quark correlation matrix $\Phi^\alpha{}_\beta(x, \mathbf{k_T}) \sim$

$$\langle P, S|\bar{q}_\beta(\xi_-, \xi_T) W^-(\xi_-, \infty) W^T(\xi_T, \infty) \times$$
$$W^T(\infty, 0) W^-(-\infty, 0) q^\alpha(0_-, 0_T)|P, S\rangle$$

$Tr[\Gamma\gamma^+\Phi(x, \mathbf{k_T})] \rightarrow$ TMD functions

[Progress in Particle and Nuclear Physics 65, 267]

Origin of TSSA: Collinear twist-3

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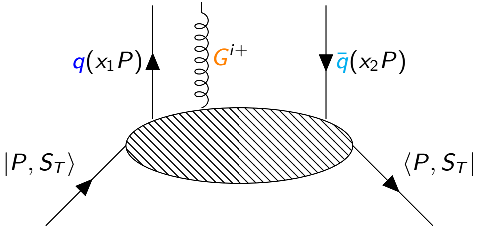


[PRL 67, 2264] When $Q, k_T \gg \Lambda_{QCD}$:

Collinear twist-3 function $\Phi^{(3)}(x_1, x_2, S_T) \sim$

qgq : $\langle P, S_T|\bar{q}(x_2 P)\gamma^+\epsilon_{ij} G^{i+} S_T^j q(x_1 P)|P, S_T\rangle$

ggg : $C^{abc} G^+_{a\rho}\epsilon_{ij} G_b^{i+} S_T^j G_c^{\rho+}$, $C^{abc} = if^{abc}$ or d^{abc}

$$\Delta\sigma_{CO}(S_T) \approx \Phi^{(3)}(x_1, x_2, S_T) \otimes \Phi^{(2)}(x') \otimes \hat{\sigma} \otimes D^{(2)}(z) \rightarrow \text{Sivers type}$$

[PRD 59, 014004] $+\,\delta q^{(2)}(x, S_T) \otimes \Phi^{(3)}(x_1', x_2') \otimes \hat{\sigma}' \otimes D^{(2)}(z) \rightarrow$ Boer-Mulders type

$$+\,\delta q^{(2)}(x, S_T) \otimes \Phi^{(2)}(x') \otimes \hat{\sigma}'' \otimes D^{(3)}(z_1, z_2) \rightarrow \text{Collins type}$$

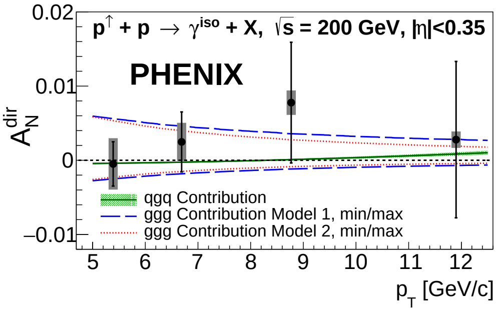
[PRL 97, 082002] When $Q \gg k_T \gg \Lambda_{QCD}$, relation between collinear twist-3 and TMD :

$$\Phi^{(3)}(x, x, S_T) \sim \int d^2\mathbf{k_T}(k_T^2/M_P) f_{1T}^{\perp}(x, \mathbf{k_T}),$$

$$\Delta\sigma_{CO}(S_T) = \Delta\sigma_{TMD}(S_T) \text{ at leading } k_T/Q.$$

Direct photon A_N

- First direct photon A_N.
- Measured A_N consistent with zero.
- Small contribution from qgq correlation.
- Clean extraction of ggg correlation.
- ggg models have different gluon PDFs.
- Constrain gluon spin-momentum correlations.



PRL 127, 162001 (2021)

π^0 and η A_N

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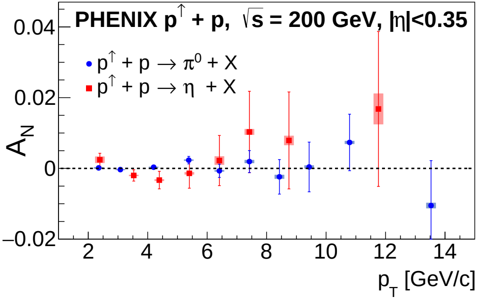
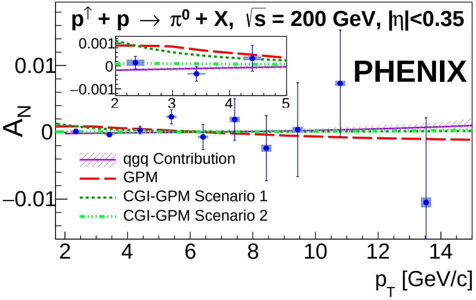


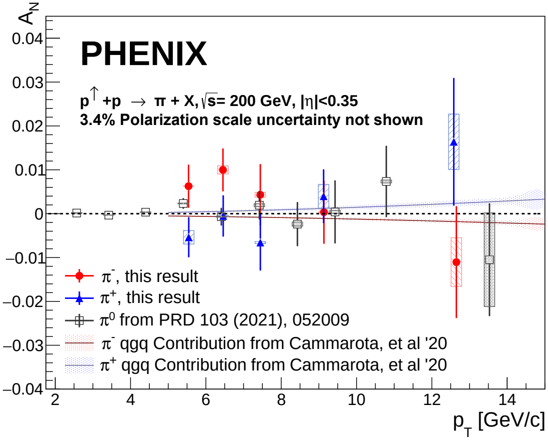


- PRD 103, 052009 (2021)
- Improved stat. uncertainty.
- Consistent with previous measurement and with zero.
- $A_N^{\pi^0}$ vs A_N^{η}: strangeness, isospin and mass.

- Small qgq and constrain ggg.
- Sivers TMD PDF: GPM and CGI-GPM.
- CPI-GPM include initial- and final-interactions to reproduce Sivers sign change.
- Scenario 1 (2) maximize (minimize) open heavy flavor TSSA.

Charged pion A_N

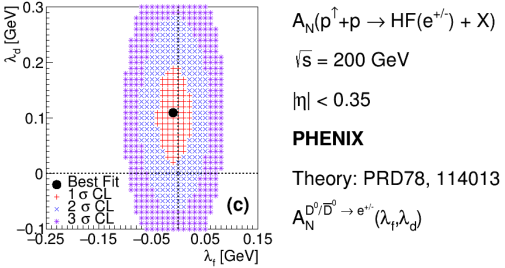
- Low statistics due to few $\pi^{\pm}$ fire triggers.
- $\chi^2 \approx 9$ (ndf $= 5$) between $\pi^{\pm}$.
- Indicate differences between $\pi^{\pm}$.

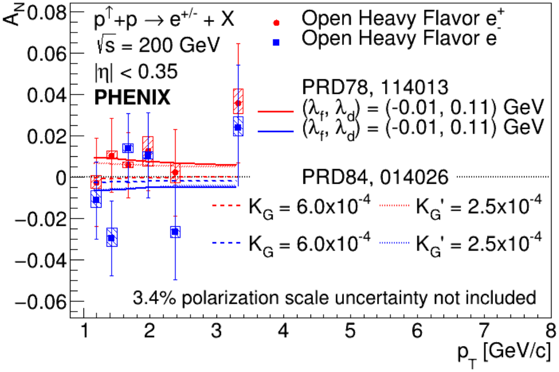


PRD 105, 032003 (2022)

Open heavy flavor $e^{\pm}$ A_N in p+p

- Signal: OHF dacay $e^{\pm}$.
- Backgrounds:
  - $e^{\pm}$ from π^0, η, γ^{dir}, J/ψ, K_S^0, $K^{\pm}$.
  - Misidentified $e^{\pm}$ (primary $\pi^{\pm}$).
- Mainly from gg hard interactions
  $\rightarrow$ Sensitive to ggg correlators $T_G^{(f,d)}$.



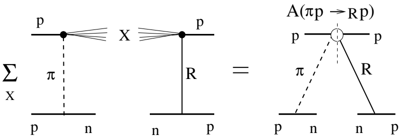


arXiv:2204.12899

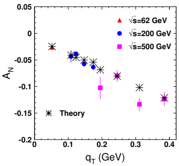
$$T_G^{(f,d)}(x,x) = \lambda_{f,d}G(x)$$

Forward neutron A_N in p+p

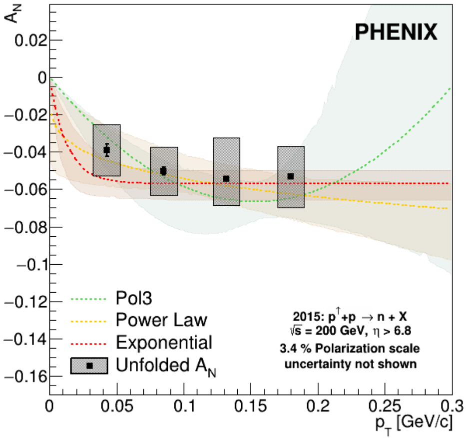
- Mainly from π-R interference in hadronic interactions.
- Negative A_N with linear p_T dependence.



π-R interference



PRD 84, 114012 (2011)



PRD 103, 032007 (2021)

Forward neutron A_N in p+A

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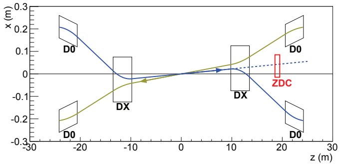
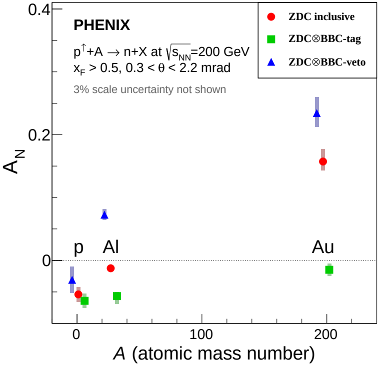
- UPC: Positive A_N with Z^2 dependence.
- $A_N^{\text{UPC+HAD}} = \frac{\sigma_{\text{UPC}} A_N^{\text{UPC}} + \sigma_{\text{HAD}} A_N^{\text{HAD}}}{\sigma_{\text{UPC}} + \sigma_{\text{HAD}}}$
- PRC 95, 044908 (2017)





- ZDC⊗BBC-tag($N \cap S$): Select hadronic interactions.
- ZDC⊗BBC-veto($\overline{N} \cap \overline{S}$): Select UPC interactions.
- Strong A dependence in inclusive and BBC-veto.
- PRL 120, 022001 (2018)

Forward neutron A_N vs p_T and x_F

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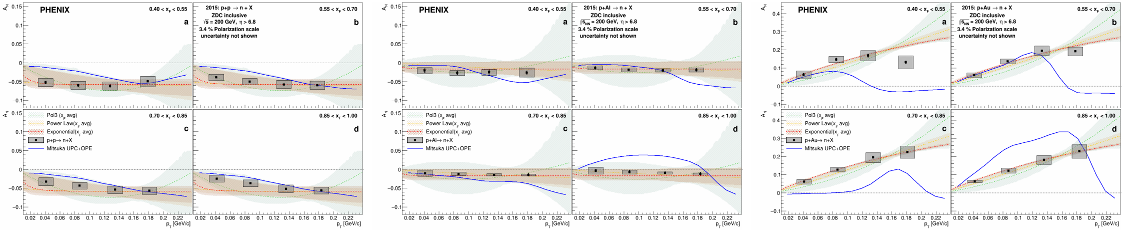

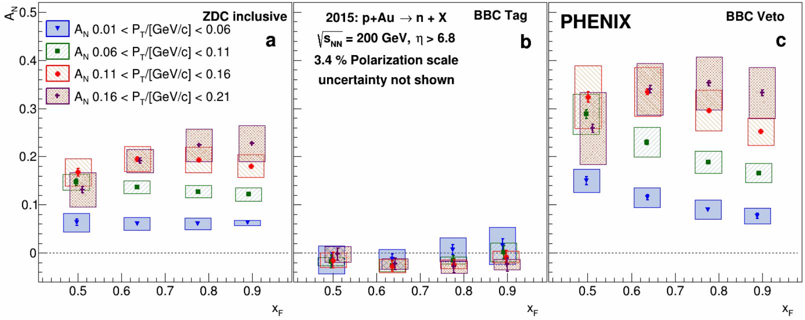

PRD 105, 032004 (2022)

Summary

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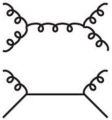
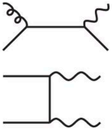
- Gluon spin is important for proton spin decomposition and the proton spin puzzle.
- Direct photon production have little fragmentation contributions.
- Jet and $\pi^{\pm}$ production have larger statistics.
- Contribute to future global analyses together with forward cluster and forward/central η A_{LL}.
- TSSA measurements from γ, π^0, η, $\pi^{\pm}$, OHF $e^{\pm}$ are important to understand the qgq and ggg correlations in collinear twist-3 formalism as well as the TMD functions.
- Forward neutron A_N in p+A results from both hadronic and EM interactions.

Backup

Processes

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg