Stony Brook University

Recent spin results from PHENIX

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Spin Physics Detector Collaboration Meeting 2021

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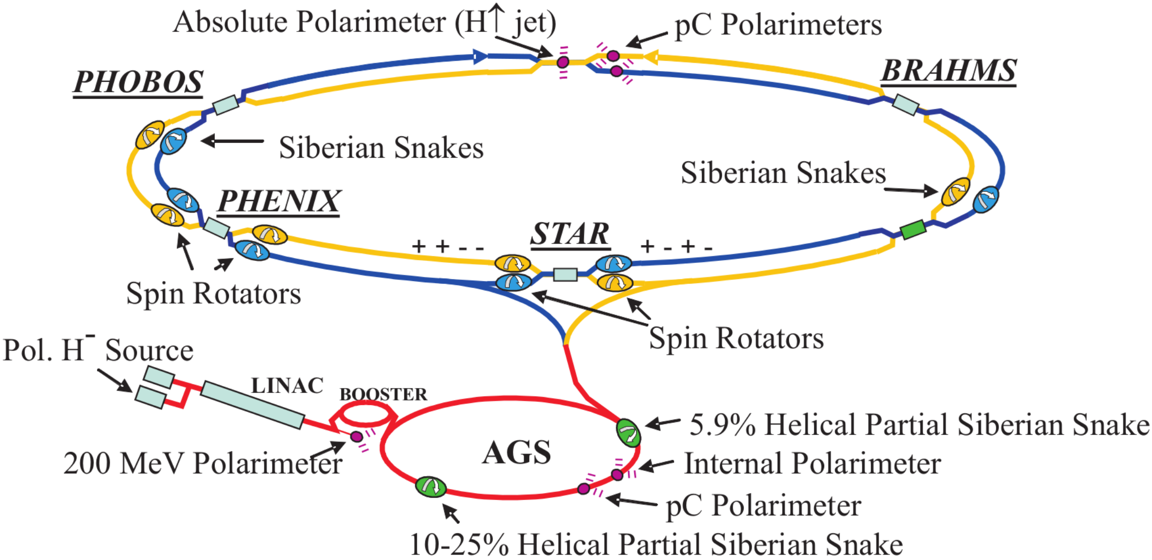
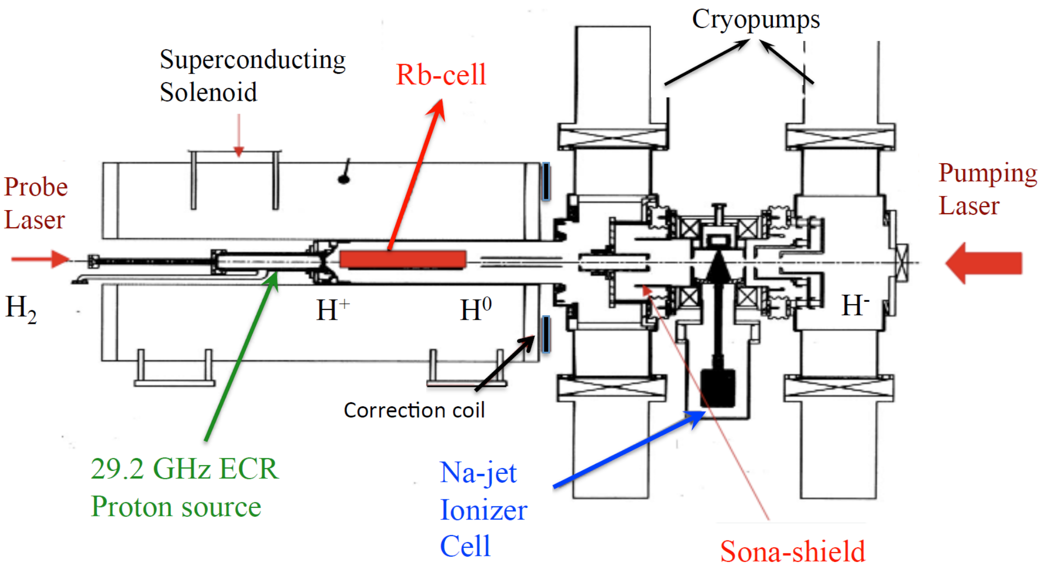
Outline

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
   - Forward neutron
   - J/ψ
   - Preliminary A_N results
4. Summary

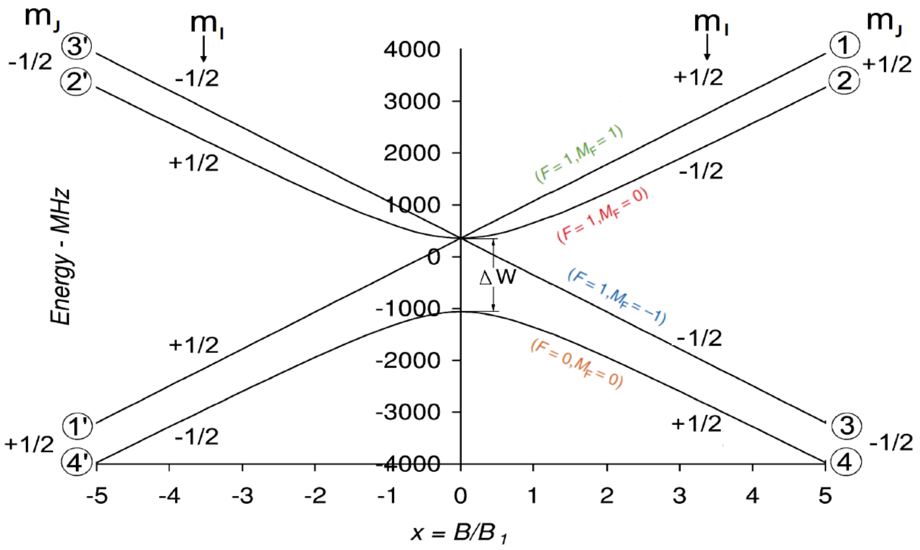
Polarized protons at RHIC



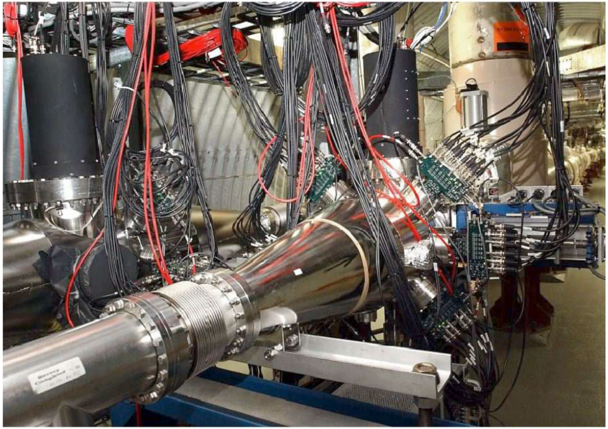
Optically Pumped Polarized Ion Source

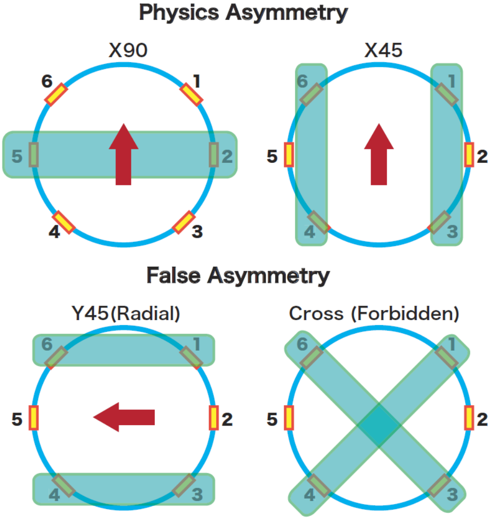


Sona transition



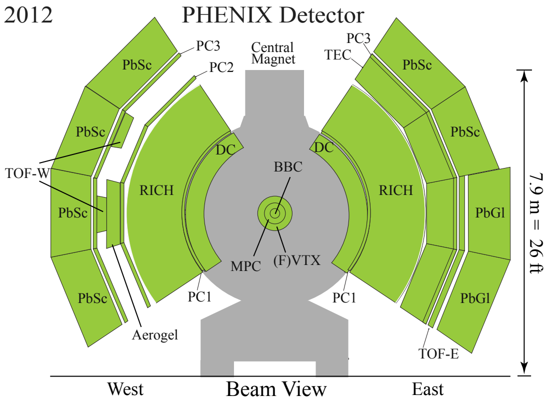
p-C polarimeters





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.

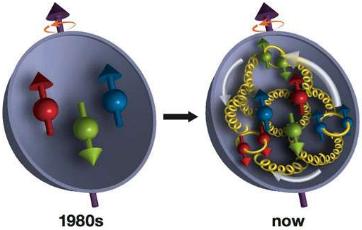


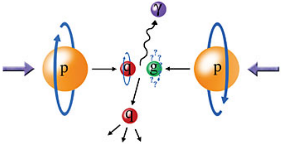
Probing the gluon spin inside the proton

- The proton spin can be decomposed as

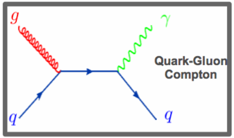
$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \Delta g + L_q + L_g$$

- Gluon spin Δg is important for the proton spin puzzle.



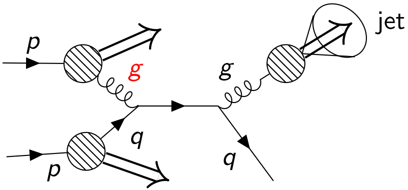


$$A_{LL}^{pp\to\gamma X} \sim \frac{\Delta q(x_q)}{q(x_q)} \cdot \frac{\Delta g(x_g)}{g(x_g)} \cdot a_{LL}^{qg\to\gamma q}$$

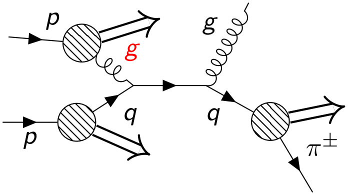


- $A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$
- Little fragmentation contributions to direct photon production.

Jet and charged pion production

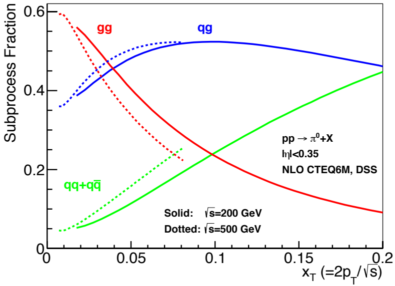


Jet production



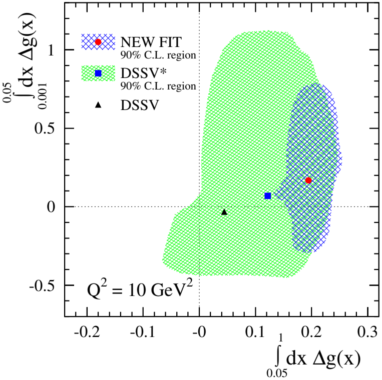
Charged pion production

- Larger statistics: not suppressed by small QED coupling.
- $\pi^{\pm}$: separate u and d quark.
- RHIC 200 GeV data probe $0.05 < x < 0.2$.
- RHIC 510 GeV data probe $0.02 < x < 0.08$.



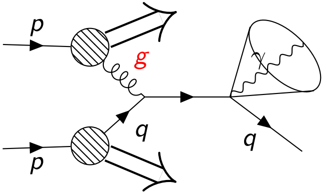
From A_{LL} to Δg

- 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)

Isolation cut for direct photon

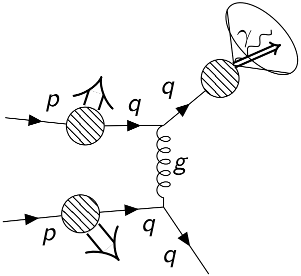


$$r_{cone} = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$$

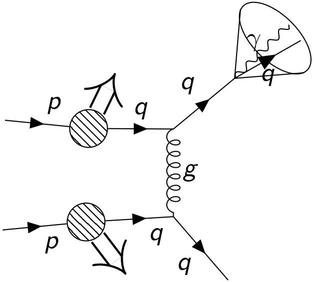
Isolation cut requirement:

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

Quark-gluon Compton scattering: Easy to pass isolation cut



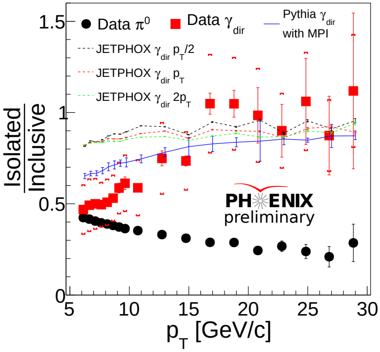
Fragmentation:
Hard to pass
isolation cut

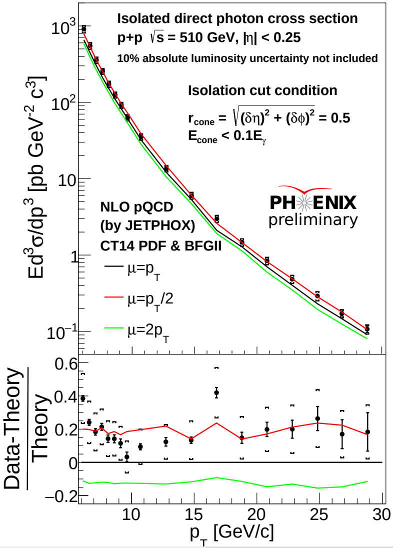


Bremsstrahlung:
Hard to pass
isolation cut

Direct photon cross section

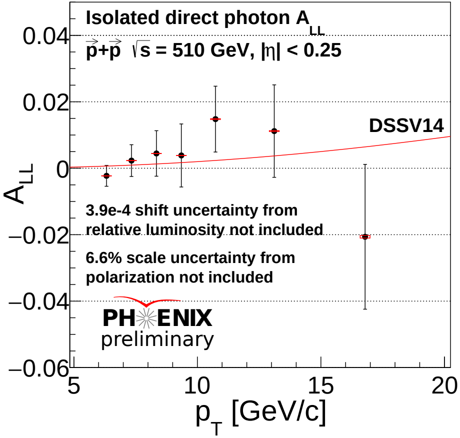
- Consistent with NLO pQCD.
- MPI and parton shower are important for inclusive direct photon production.
- Constrain unpolarized gluon PDF.





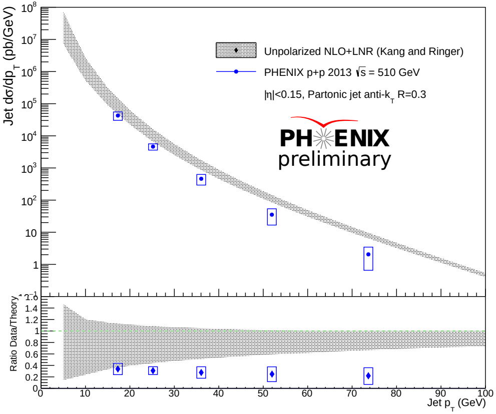
Direct photon A_{LL}

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



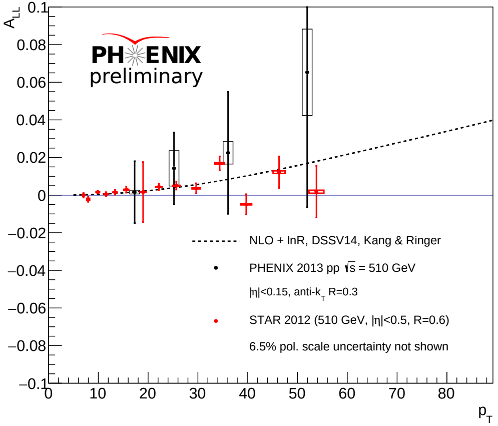
Jet cross section

- 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.

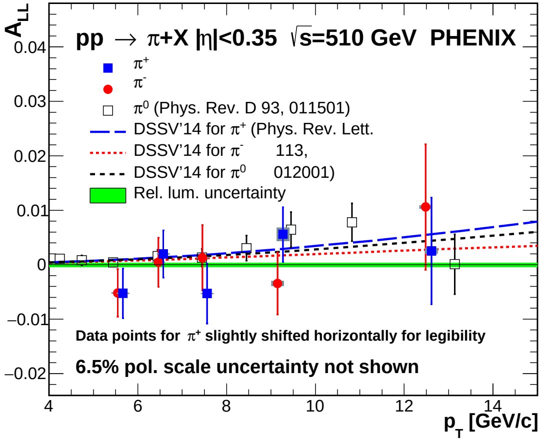


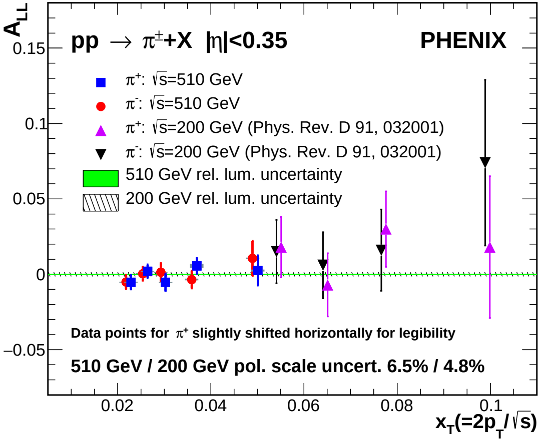
Jet A_{LL}

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



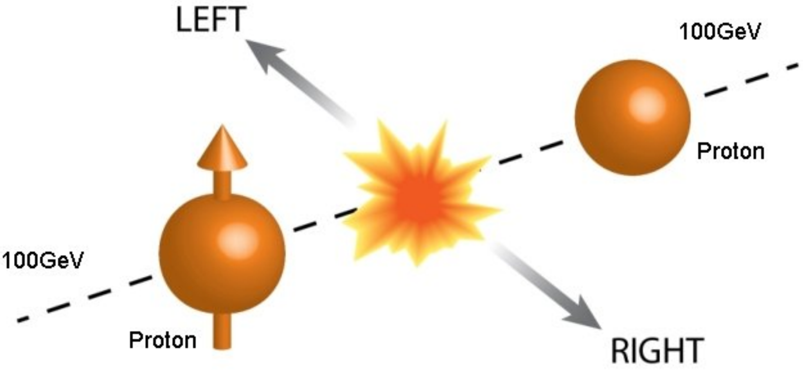
Charged pion A_{LL}





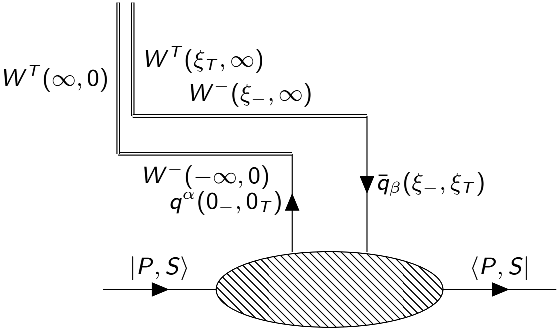
- PRD 102, 032001 (2020)
- Consistent with DSSV14.
- 510 GeV data probe low x range.
- Not enough statistics to decide $\pi^{\pm}$ order.

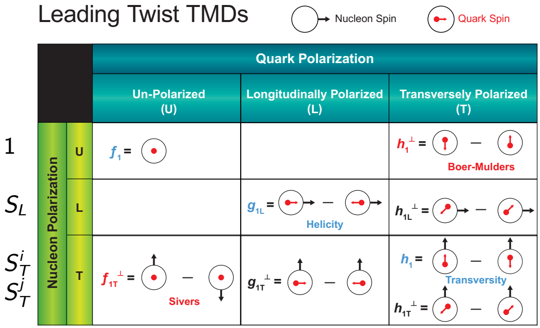
Transverse Single Spin Asymmetry (TSSA)



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

Origin of TSSA: TMD





Γ : 1 γ^5 $\gamma^i\gamma^5$

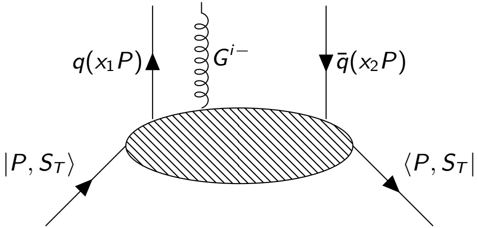
When $Q \gg k_T \gtrsim \Lambda_{QCD}$:

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

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

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

Origin of TSSA: Collinear twist-3



$$\text{When } Q, k_T \gg \Lambda_{QCD}:$$

$$\text{Collinear twist-3 function } T(x_1, x_2) \sim$$

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

$$\begin{aligned}\Delta\sigma_{CO}(S_T) =& H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{C/c(2)} \to \text{Sivers type} \\ &+ H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{C/c(2)} \to \text{Boer-Mulders type} \\ &+ H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{C/c(3)} \to \text{Collins type}\end{aligned}$$

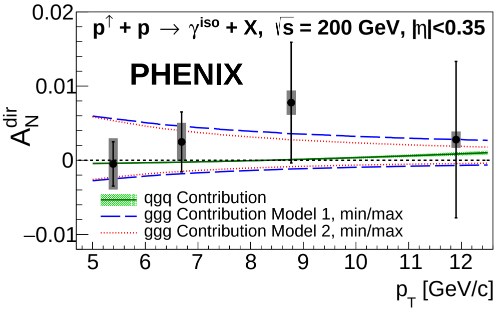
When $Q \gg k_T \gg \Lambda_{QCD}$, relation between TMD and collinear twist-3 :

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

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

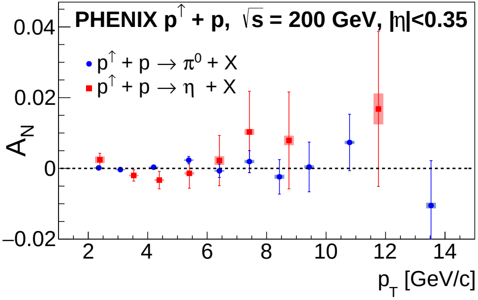
Direct photon A_N

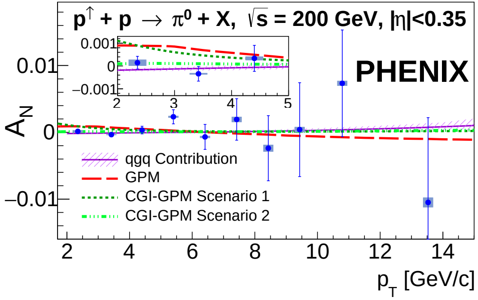
- First direct photon A_N.
- Measured A_N consistent with zero.
- Small contribution from qgq correlation.
- Clean extraction of tri-gluon ggg correlation.
- ggg model 1 and 2 have different gluon PDF.
- Constrain gluon spin-momentum correlations.



arXiv:2102.13585 (2021)

π^0 and η A_N



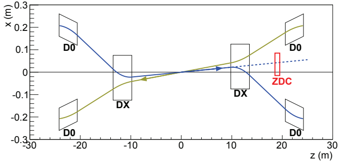


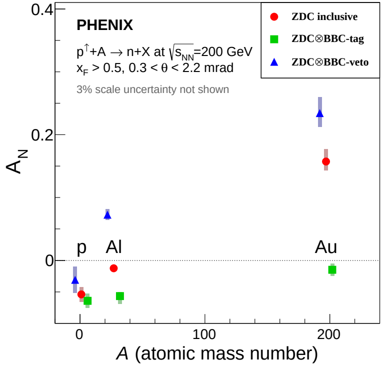
- PRD 103, 052009 (2021)
- Improved stat. uncertainty.
- Consistent with previous measurement and with zero.
- $A_N^{\pi^0}$ vs A_N^{η}: strangeness, isospin and mass.

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

Forward neutron A_N in p+A

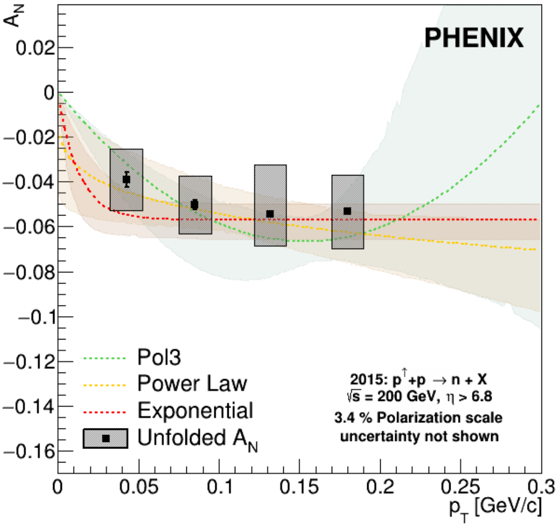
- Inclusive = BBC-tag($N \cap S$) + BBC-veto($\overline{N} \cap \overline{S}$) + ...
- Unexpected strong A dependence in inclusive and BBC-veto.
- Very different behavior in BBC-tag.
- BBC requirement or veto influence activity near detected neutron.
- Possible explanation: EM processes, which suppressed (enhanced) in BBC-tag (BBC-veto).
- Need further study.
- PRL 120, 022001 (2018)



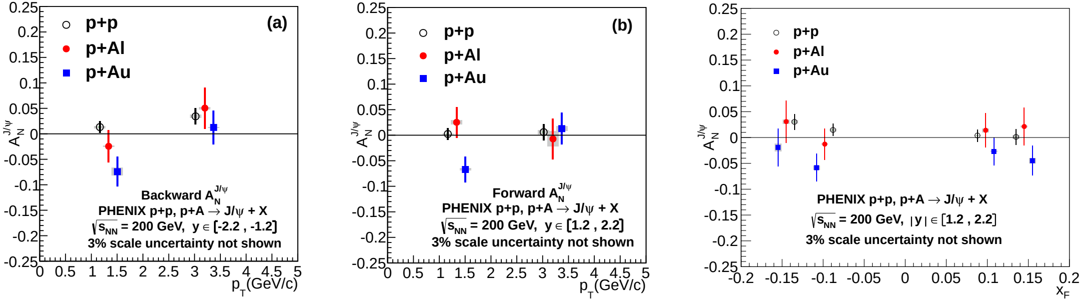


Forward neutron A_N in p+p

- p_T unfolding:
  - Different MC generators.
  - Different spin-dependent weight functions.
  - An empirical distribution of forward neutrons from one pion exchange.
- Very different asymmetries in ultraperipheral collisions in p+A.
  - Limited EM interactions in p+p.
- PRD 103, 032007 (2021)

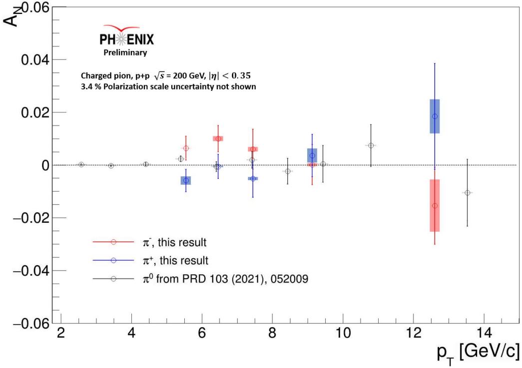


J/ψ A_N in p+A

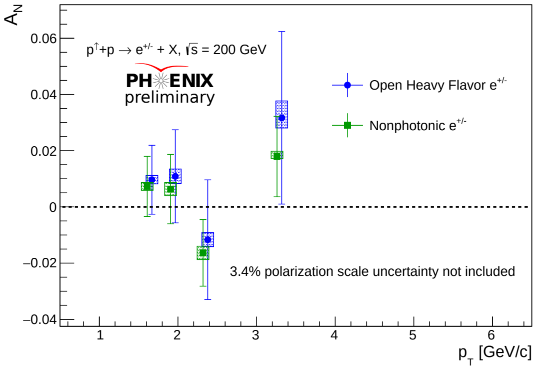


- Access to the spin-dependent gluon distribution and higher-twist correlation functions.
- Indication of EM interactions.
- PRD 98, 012006 (2018)

Preliminary A_N results



Charged pion



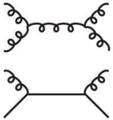
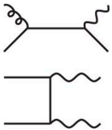
Heavy flavor

Summary

- 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.
- $\pi^{\pm}$ measurement can separate u and d quark contributions.
- Contribute to future global analysis together with forward cluster and forward/central η A_{LL}.
- TSSA measurements from direct photon, π^0 and η are important to understand the qgq and ggg correlations in collinear twist-3 formalism as well as the TMD functions.
- The nuclear dependence in forward neutron A_N indicates possible EM interactions and needs further study.

Backup

Processes

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