PHENIX Cold QCD Highlights

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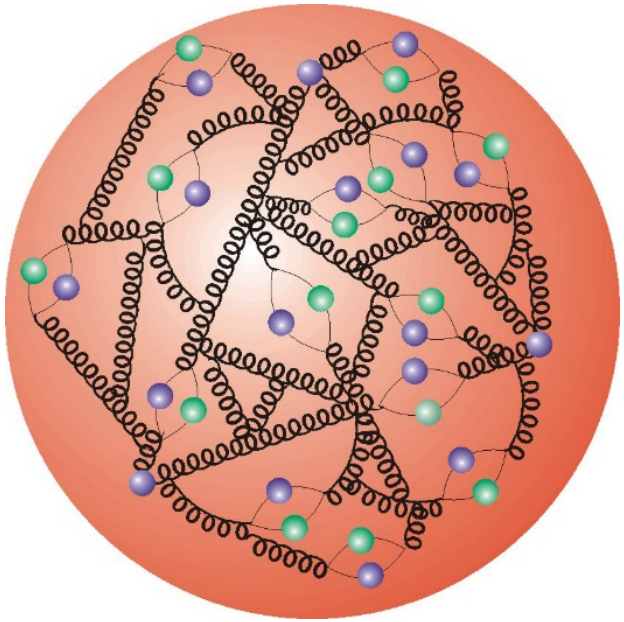
IOWA STATE UNIVERSITY

PHENIX

Proton Spin Structure

- Polarized DIS discovered the proton spin crisis: quarks only carry small fraction of spin

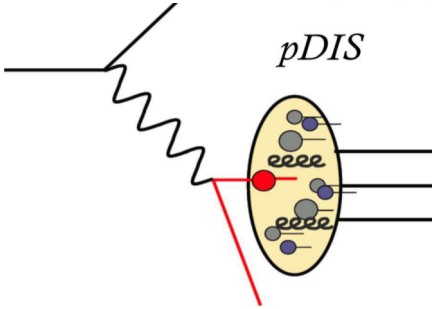


Total Quark Spin

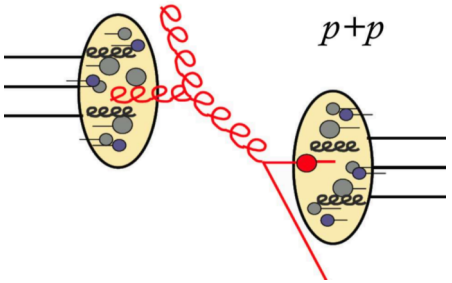
Orbital Angular Momentum

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

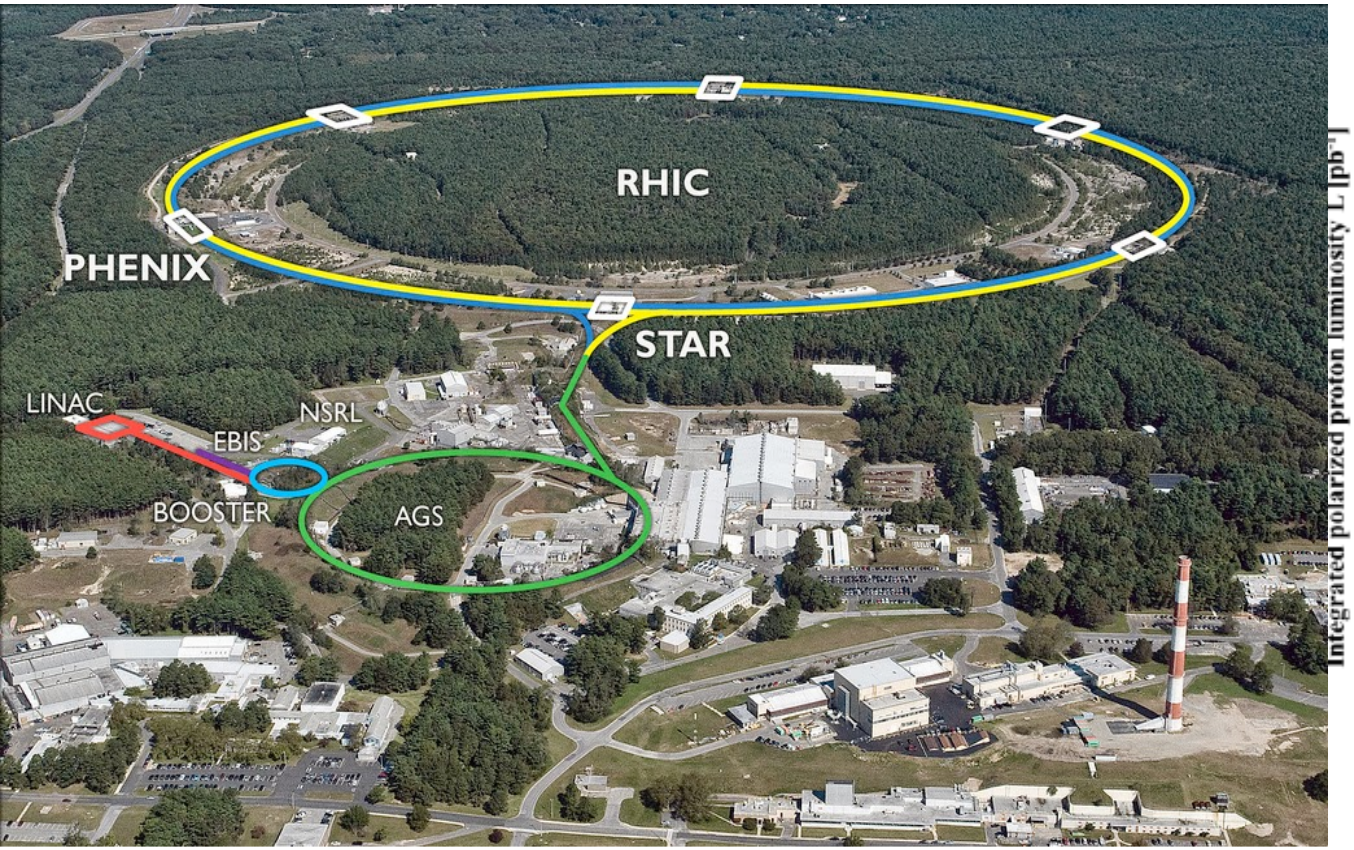
Gluon Spin

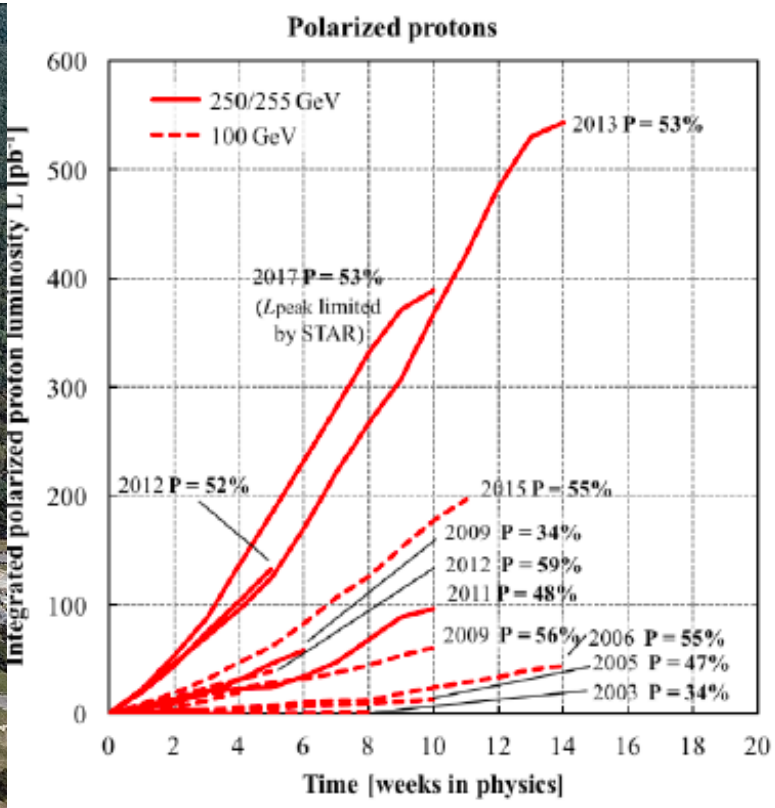


Gluons poorly constrained by DIS
(indirect access via scaling violation)
p+p provides direct access to gluons



RHIC Spin Program



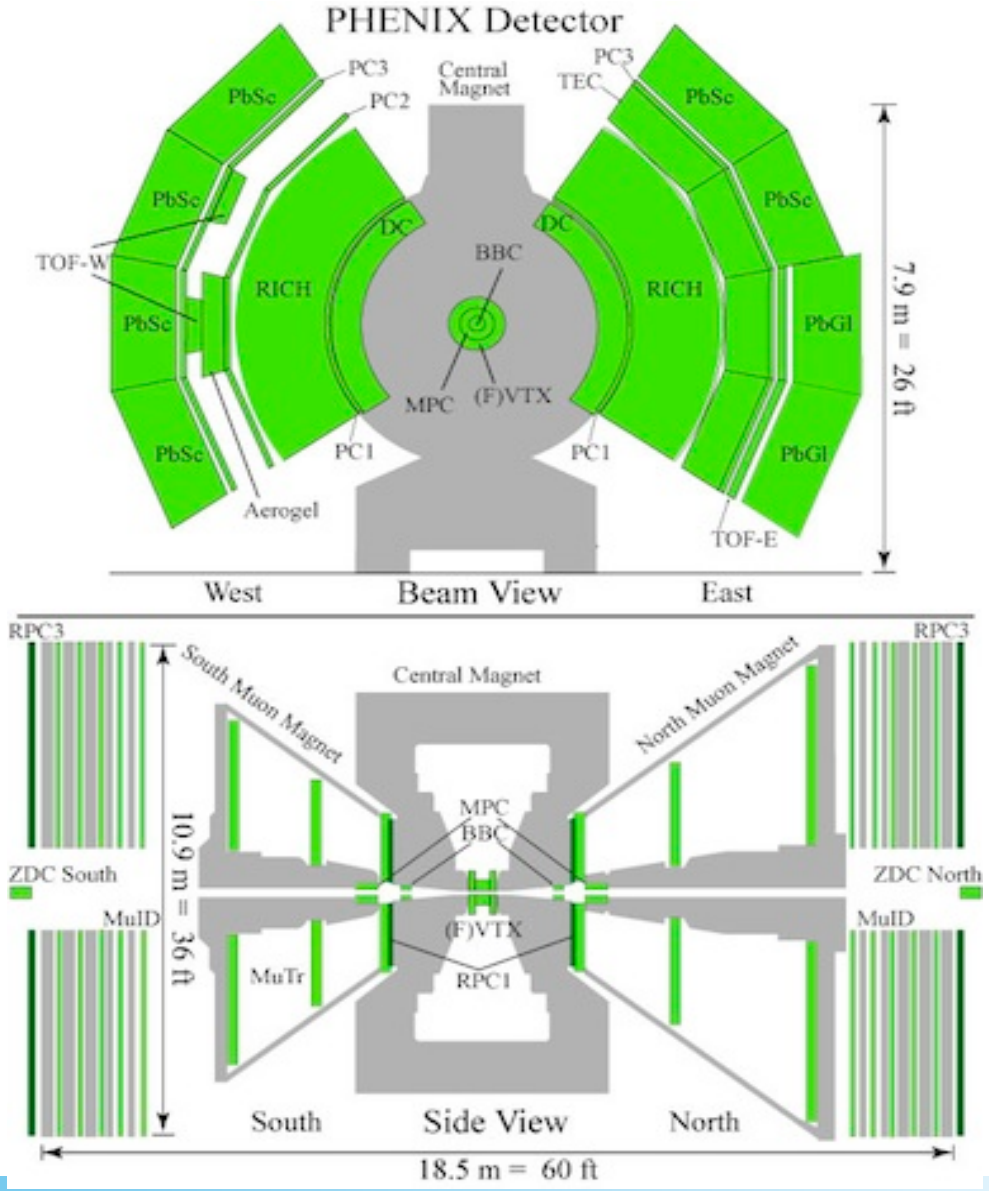


- What is the gluon contribution to the proton spin?
- What do transverse spin phenomena teach us about proton structure?

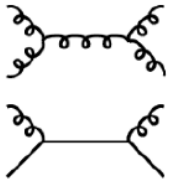
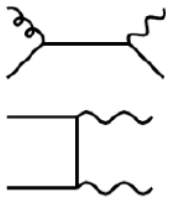
arXiv: 1501.01220

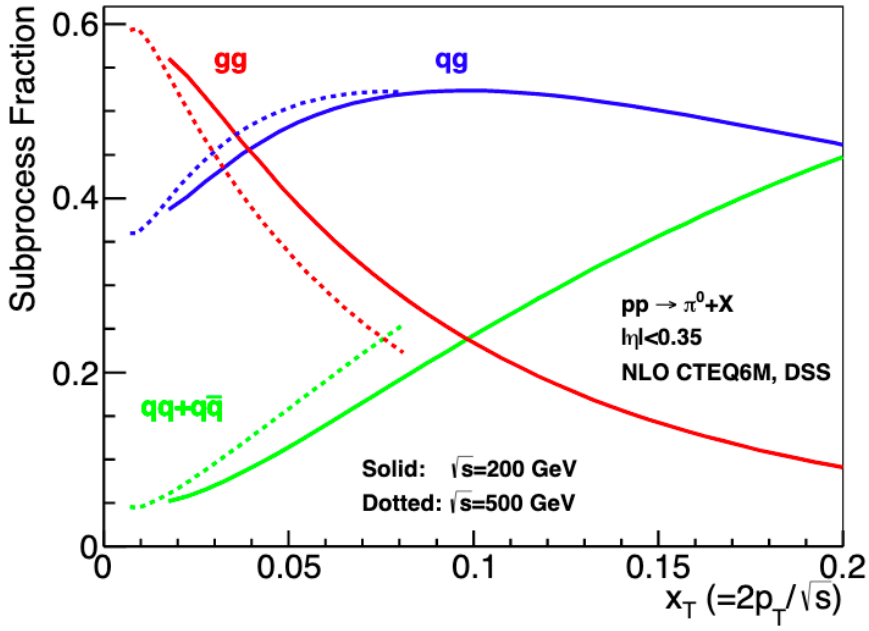
PHENIX Experiment

- Central Arms (|η| < 0.35)
  - Tracking: DC and PC
  - EM Calorimeter
- Forward Arms
  - Muon arms (1.2 < |η| < 2.4)
  - Zero Degree Calorimeter (ZDC)



Access to Gluons

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	
$\vec{p}\vec{p} \to \mathrm{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \mathrm{jet} + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$	Δg Δg	
$\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{\bar{q}} \to \gamma\gamma$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	



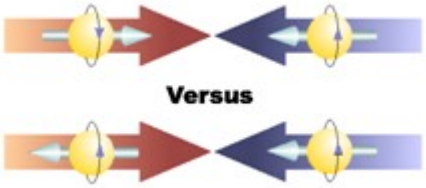
At RHIC kinematics, the qq and qg LO processes dominate.

Gluon Spin

- Gluon helicity distribution function Δg(*x*) is measured to find Δ*G*, the gluon spin contribution.

$$\Delta G \equiv \int_0^1 \Delta g(x) dx$$

- The Δg(*x*) is found via the longitudinal double spin asymmetry, A_{LL}



Polarized PDFs

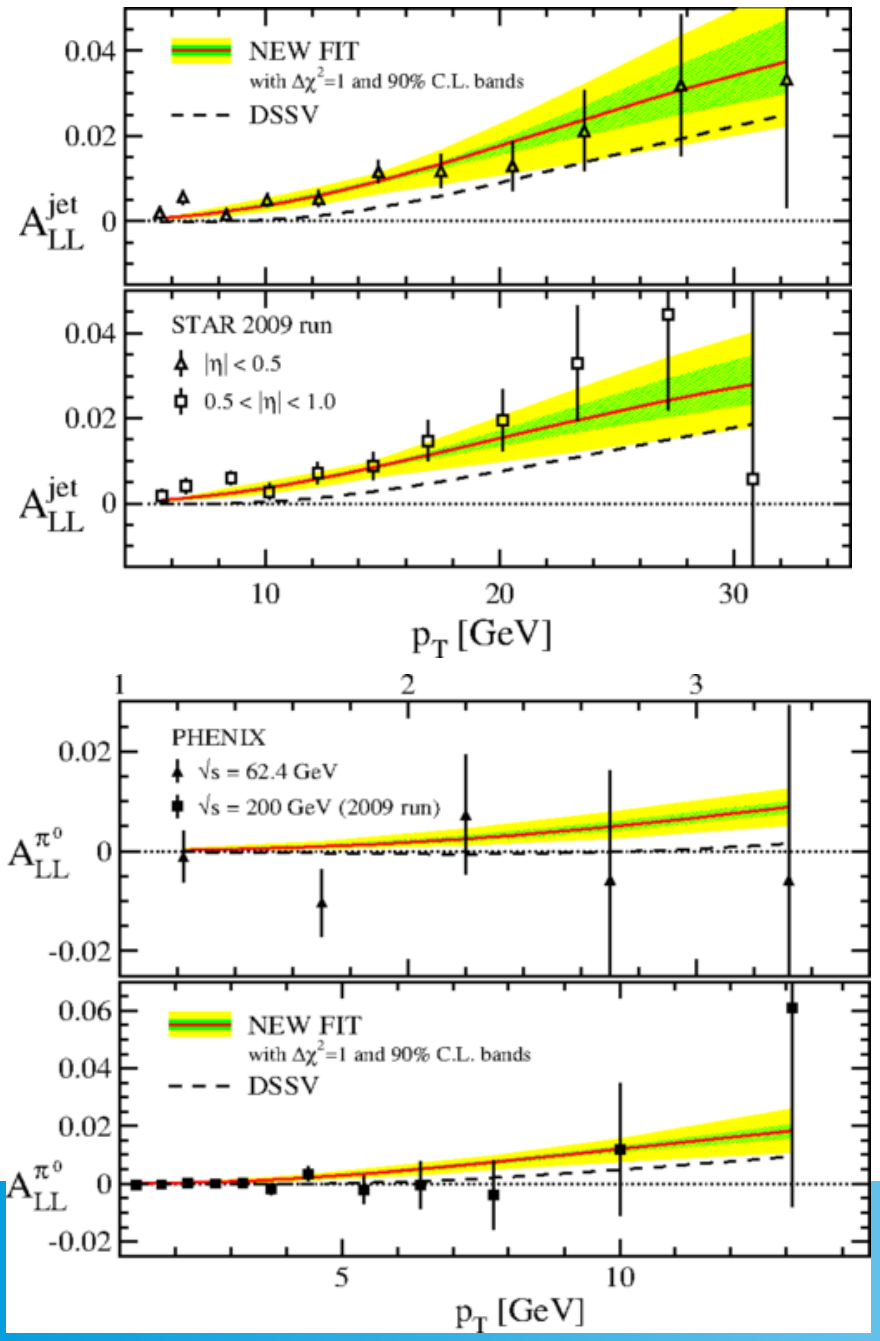
Parton-level hard scattering cross section calculable in pQCD

$$A_{LL} \equiv \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \propto \frac{\sum_{a,b,c=q,\bar{q},g} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^{\pi^0}}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes \hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^{\pi^0}}$$

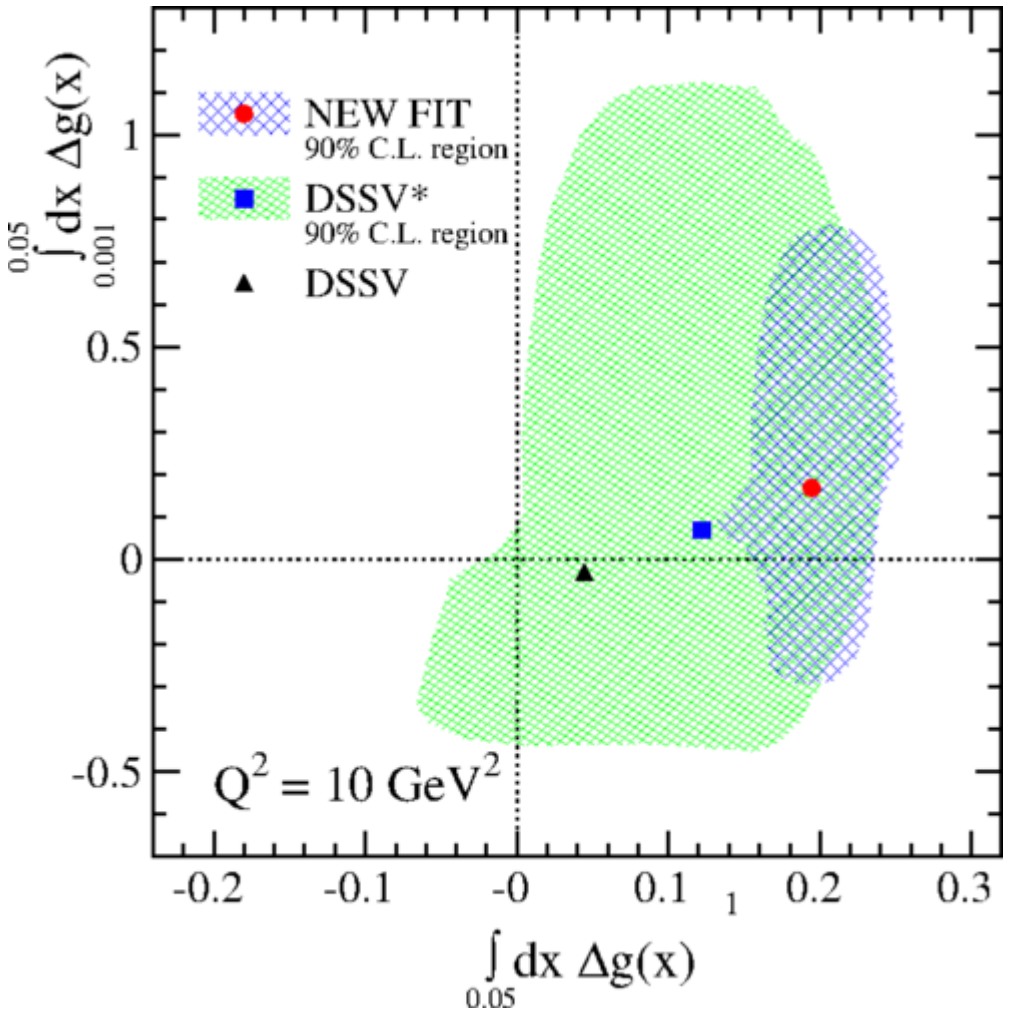
Unpolarized PDFs

Fragmentation functions from e+e- scattering

Gluon Spin



Phys. Rev. Lett. 113 (2014) 012001

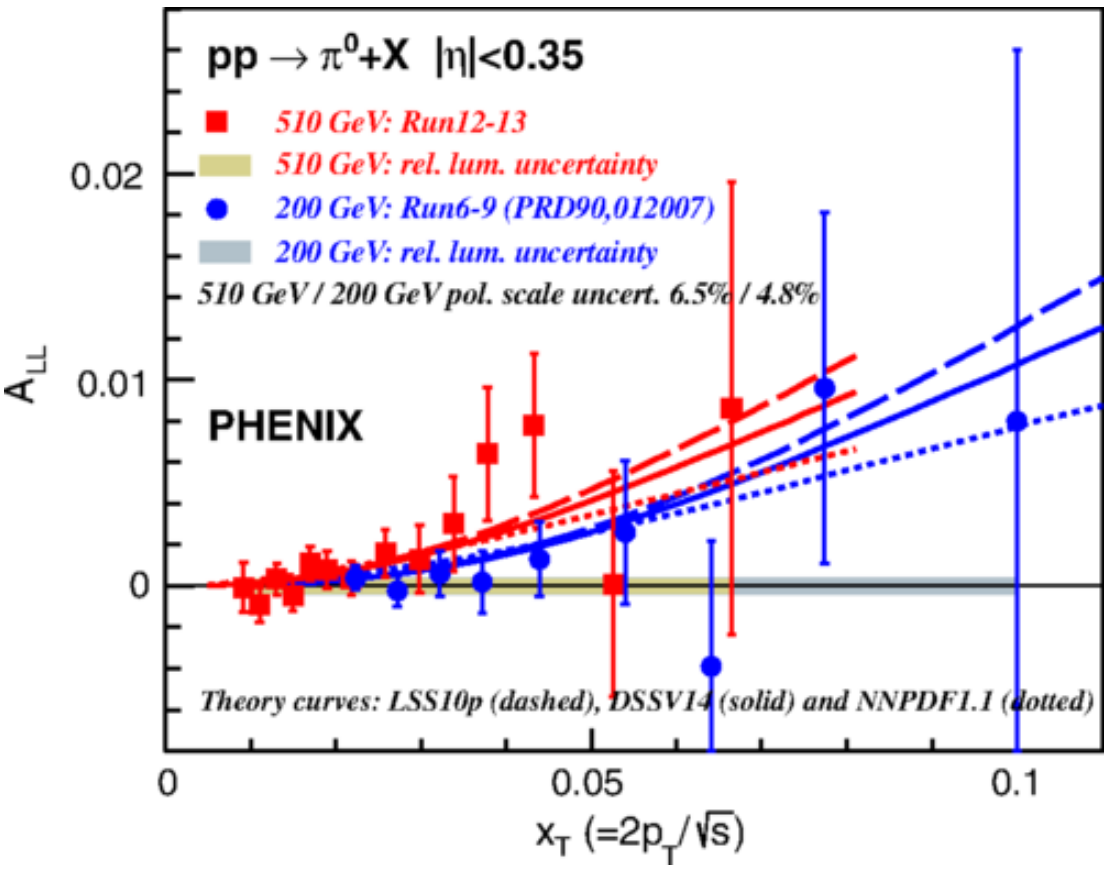


$$\int_{0.05}^{1} dx \Delta g(x) = 0.2^{+0.06}_{-0.07} (Q^2 = 10 GeV^2)$$

Gluon Spin III

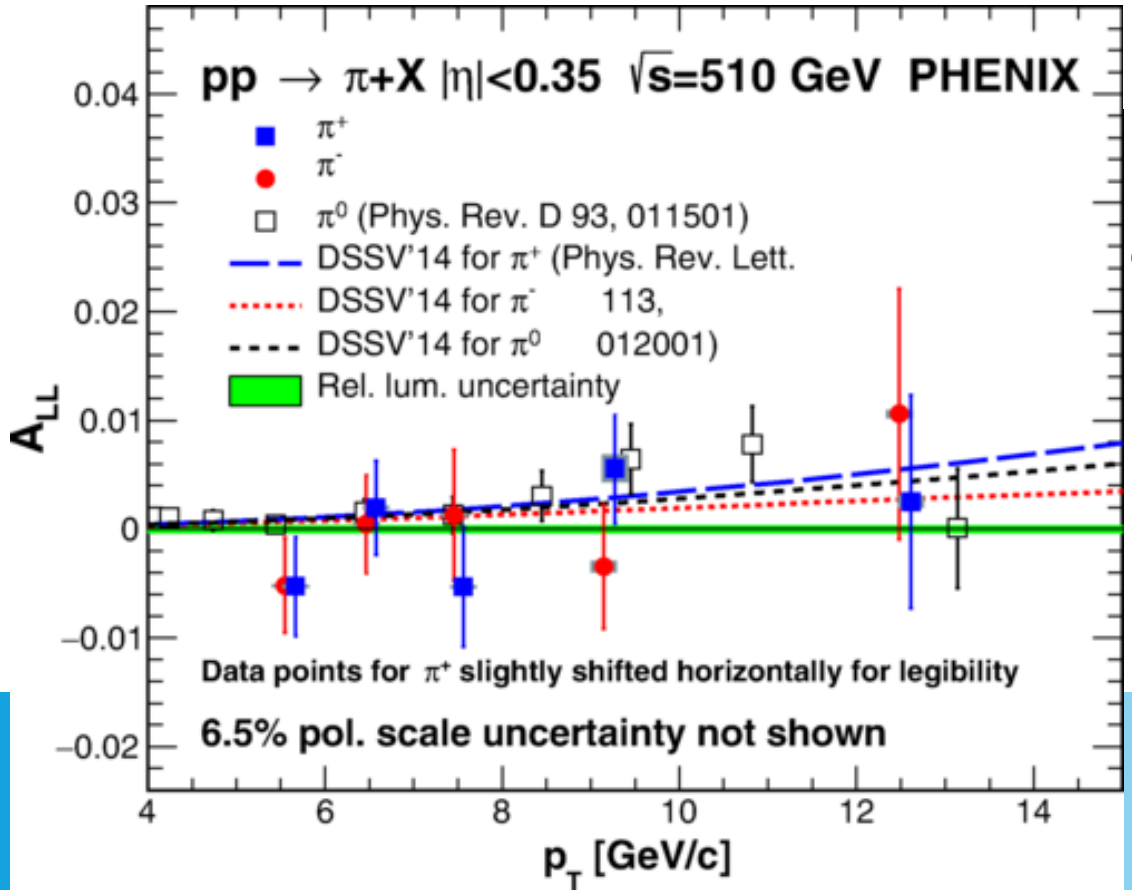
- 510 GeV data confirmed non-zero gluon spin
- Extended x down to ~10^{-2}

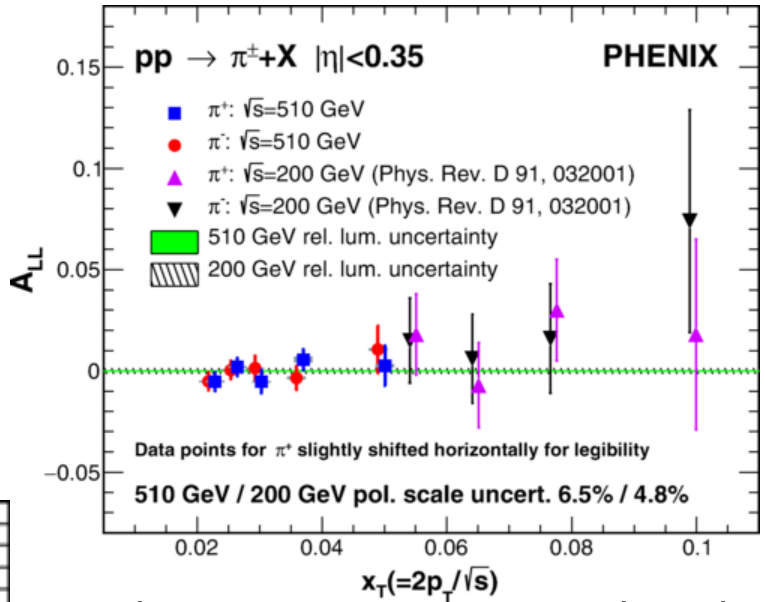
Phys.Rev. D93 (2016) no.1 011501



Charged Pion A_{LL} at 510 GeV

- First PHENIX measurement at 510 GeV
- Consistent with DSSV global fits within statistical uncertainty



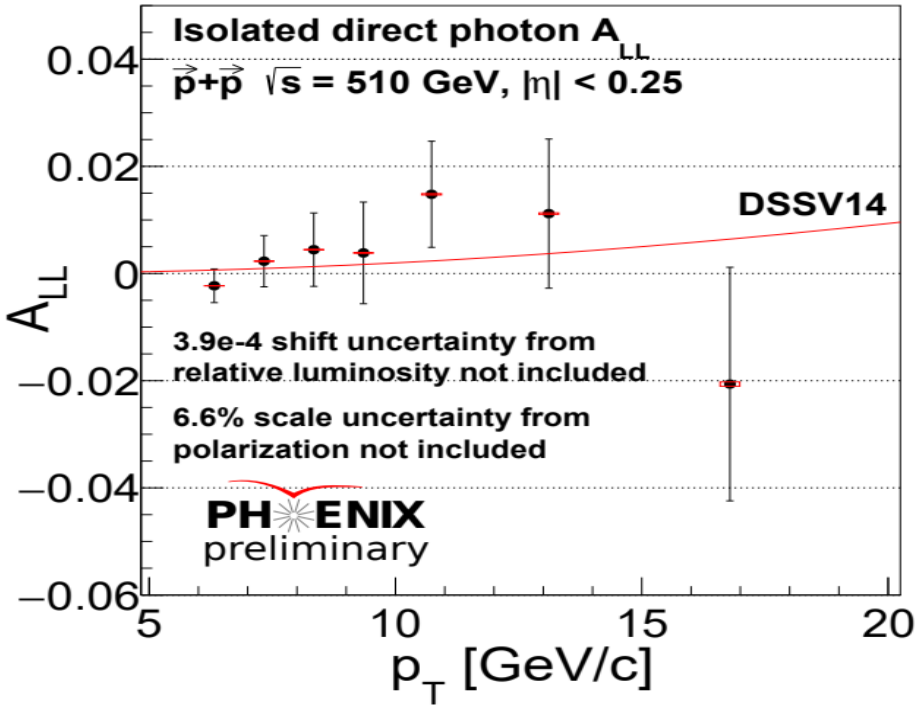


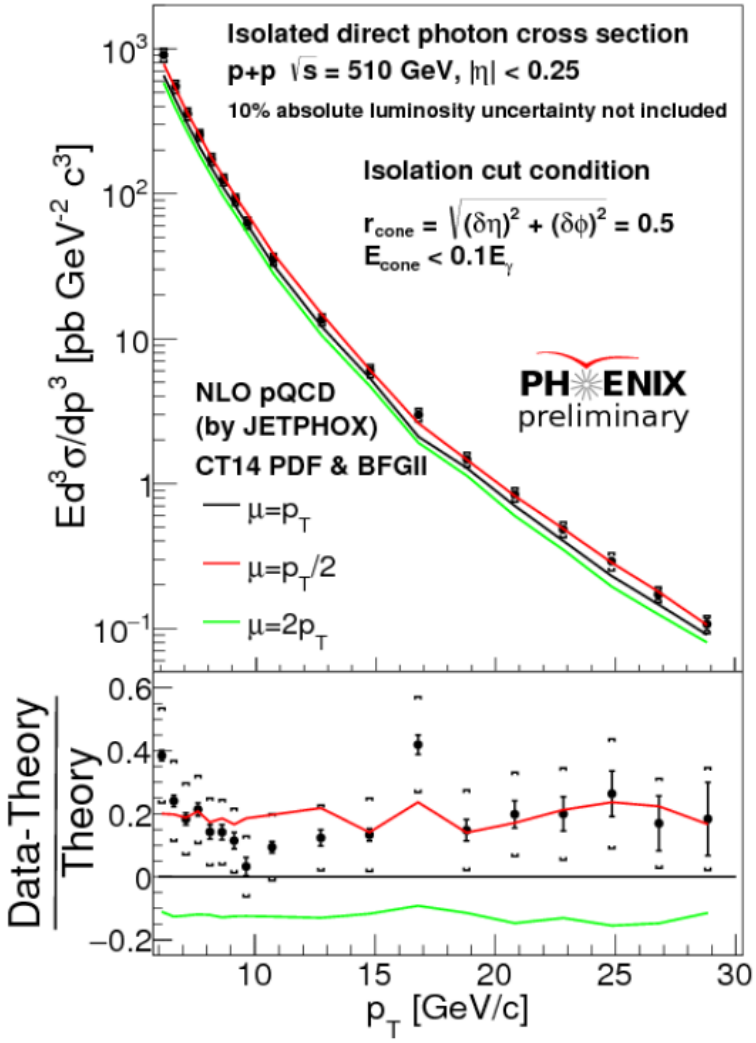
Phys. Rev. D 102, 032001 (2020)

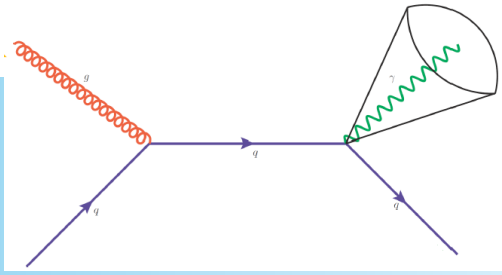
- Charged pions potential indicator for sign of Δg via pion A_{LL} ordering

Direct Photon A_{LL} at 510 GeV

- First PHENIX direct photon cross section and A_{LL} at 510 GeV
- "Golden" channel to access gluon polarization since hard interaction is mostly q-g





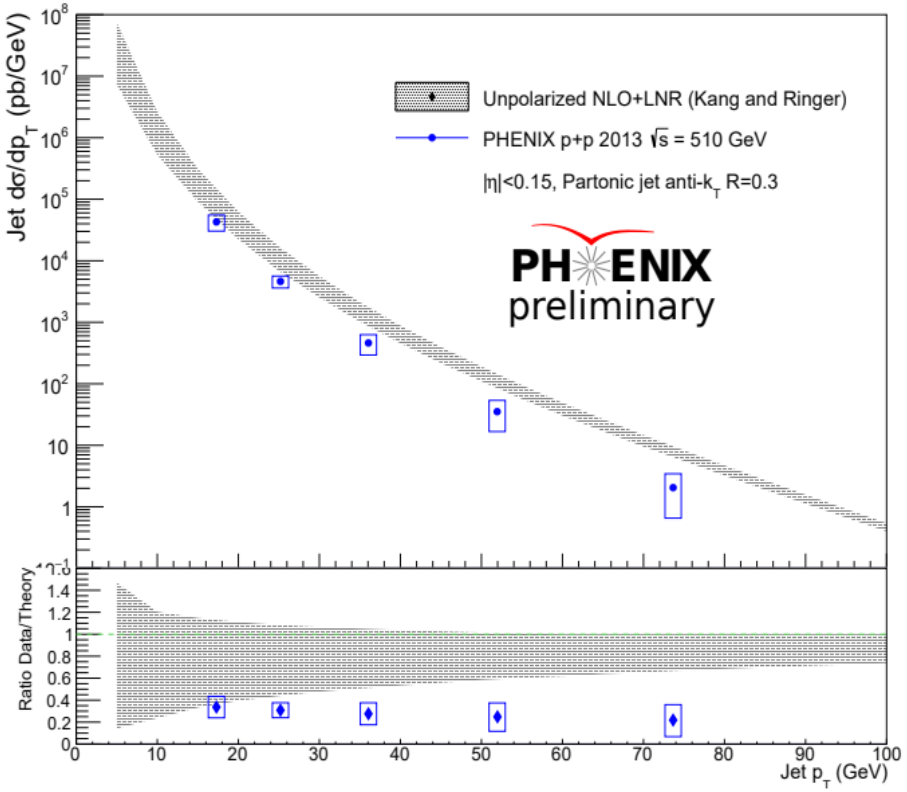


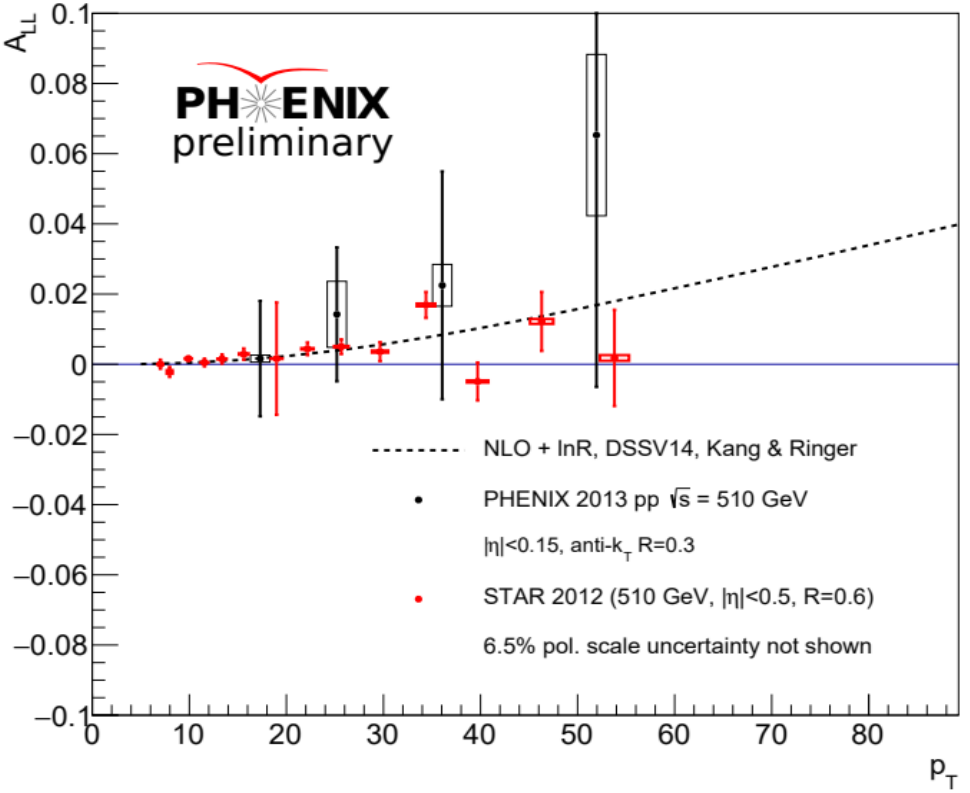
Jet A_{LL} at 510 GeV

- Jets present a challenge in PHENIX due to limited acceptance
- Jes reconstructed with anti-k_T $R(\Delta\eta, \Delta\varphi) = 0.3$
- Unfolded to correct for underlying event and detector effects
  - Use Pythia simulations to generate response matrix which correlates true and reconstructed jetss

Jet A_{LL} at 510 GeV II

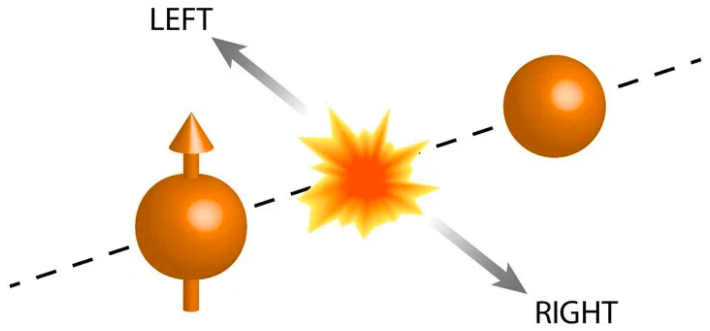
- First jet A_{LL} at PHENIX
- Cross section below NLO prediction
  - Similar to LHC finding for small R





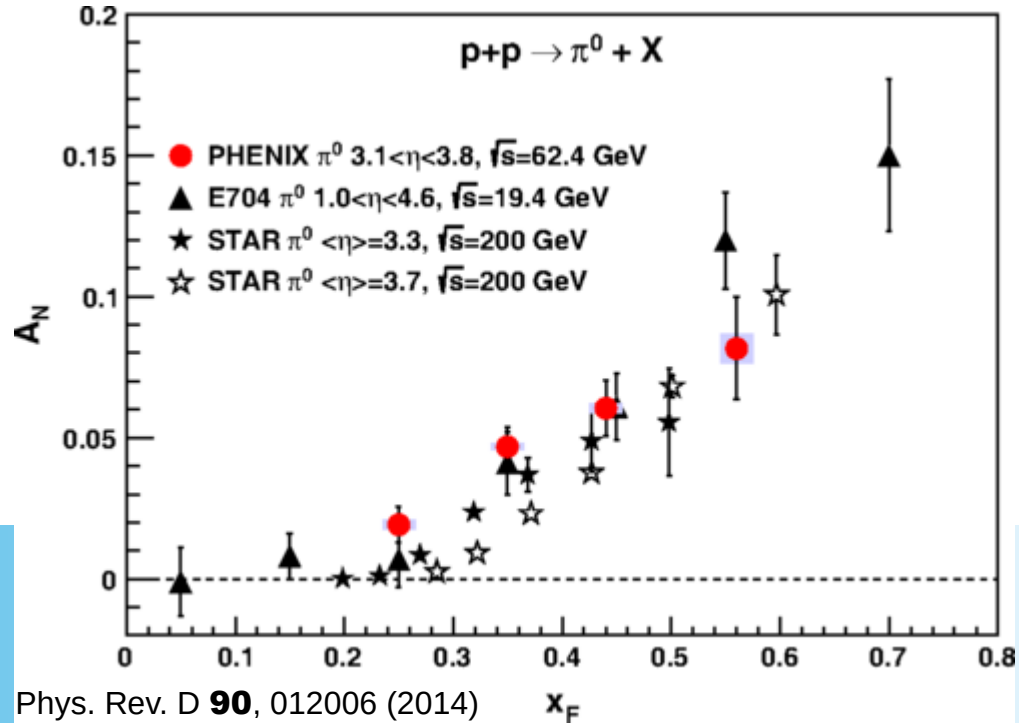
Transverse Spin

- Prediction of small asymmetry (PRL 41 1689 (1978))
- Found surprisingly large TSSA observed (FNAL E704)
- Asymmetry survive at higher energy at various collision energies



Transverse single spin asymmetry (TSSA)

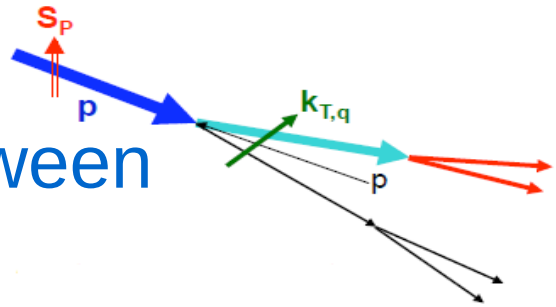
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

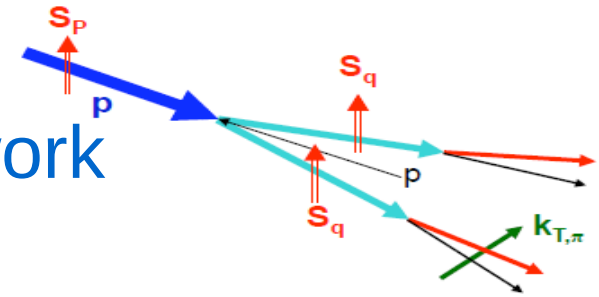


Phys. Rev. D **90**, 012006 (2014)

Origin of TSSAs

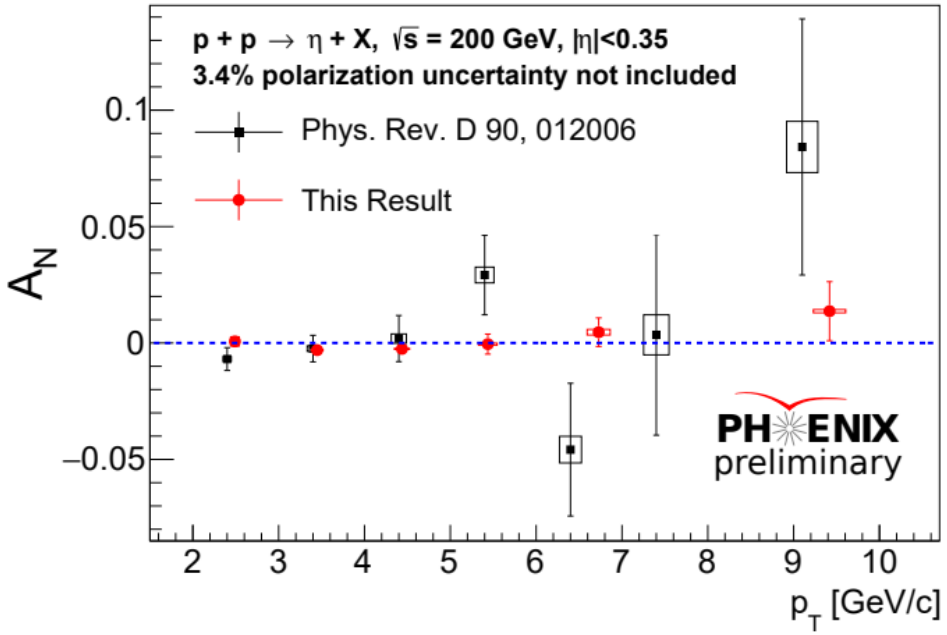
- Transverse momentum dependent (TMD) distributions and fragmentations
  - Sivers effect (initial state): correlation between nucleon spin and parton momentum
  - Collins effect (final state): correlation between fragmenting parton and hadron transverse momentum
- Multi-parton correlation in collinear framework
  - Initial state or in fragmentation process
  - SSA appears as twist-3 observable

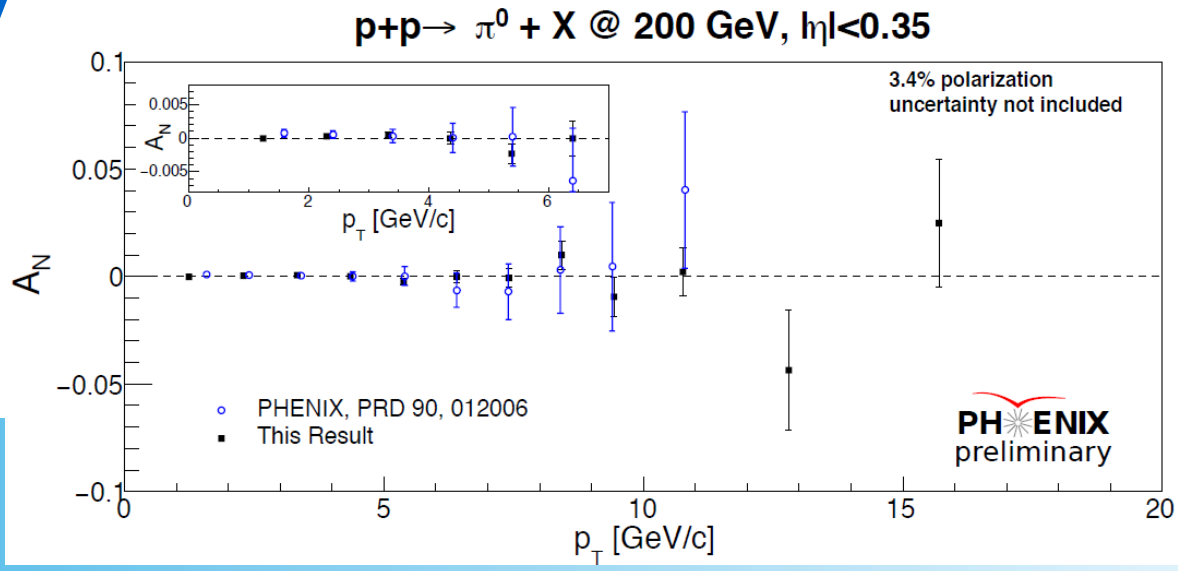




η and π^0 A_N at 200 GeV

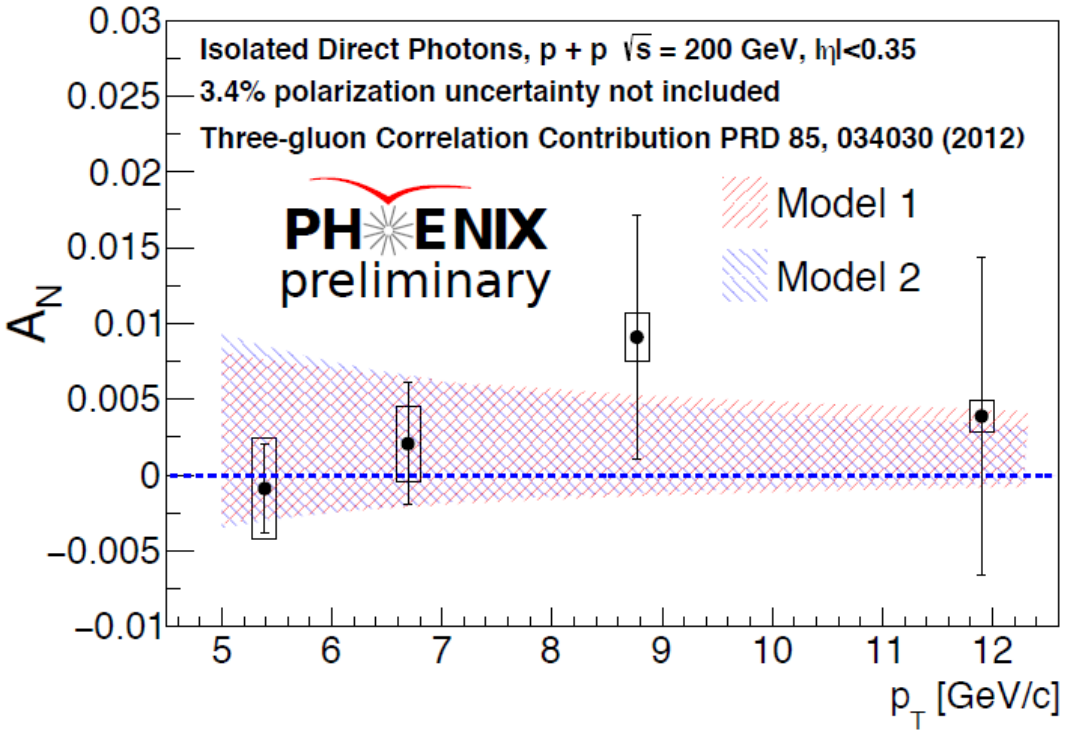
- Sensitive to both initial and final state effects
- Mid-rapidity sensitive to gluon spin-momentum correlations
- New data significantly improves precision
- Asymmetries consistent with zero

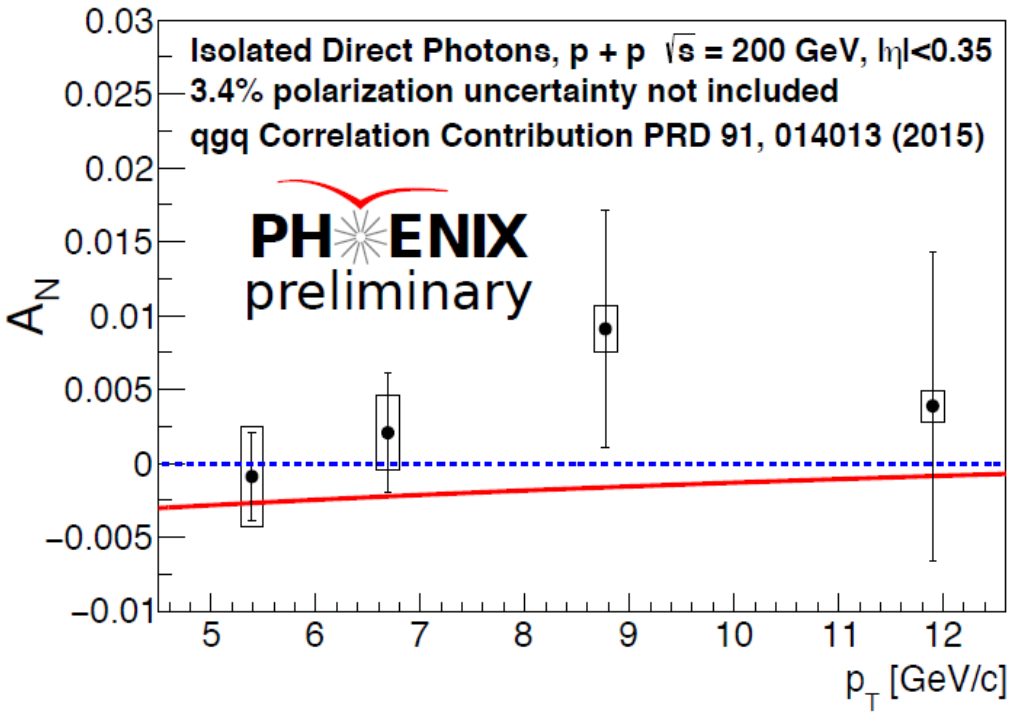




Direct Photon A_N at 200 GeV

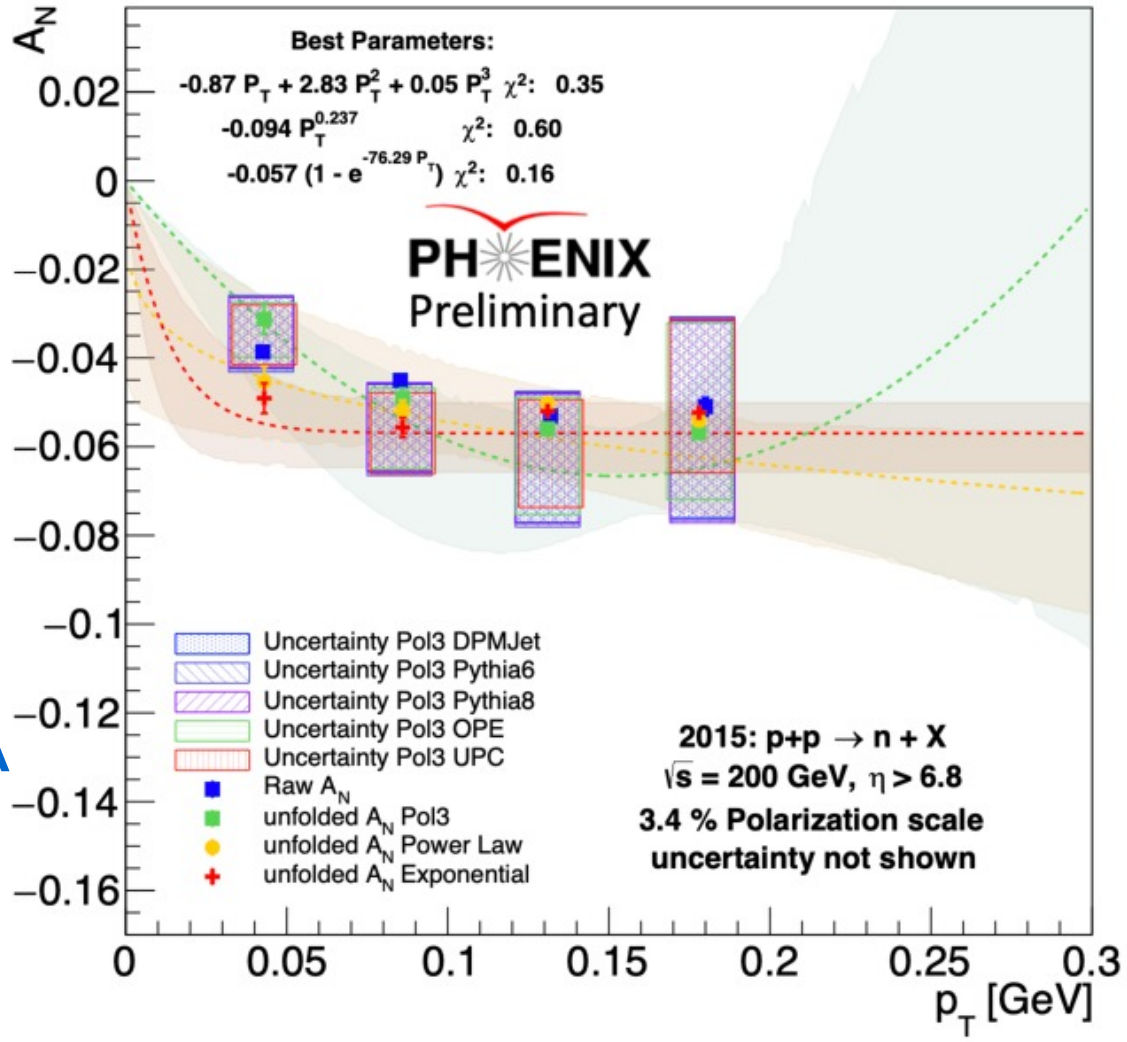
- Sensitive to initial state effects
- Production dominated by q+g → q+γ
- First measurement at PHENIX
  - Help constrain theory models





Neutron A_N at 200 GeV

- Forward measurement using ZDC
- Unfolded using different functional forms
- Improve understanding of forward neutron SSA

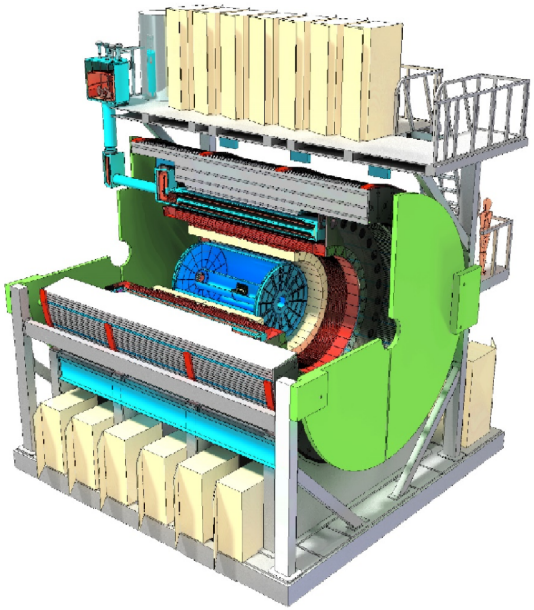


Summary

- PHENIX spin program continues to elucidate our understanding of QCD
- Results:
  - Longitudinal spin analyses:
    - Jet, direct photon, charged pion A_{LL}
  - Transverse spin analyses:
    - Direct photon, π^0 and η, and neutron A_N
- Still more to come in the future!

Future Spin Program

- sPHENIX cold QCD program: arXiv: 1602.03922
  - Improved acceptance and detectors
  - Precision measurement of jets, DY, and more!



- Electron Ion Collider (EIC)
- Polarized eN, eA collider
  - Many complementary processes
- Wide kinematic range (x, Q^2)