Spin Physics at PHENIX

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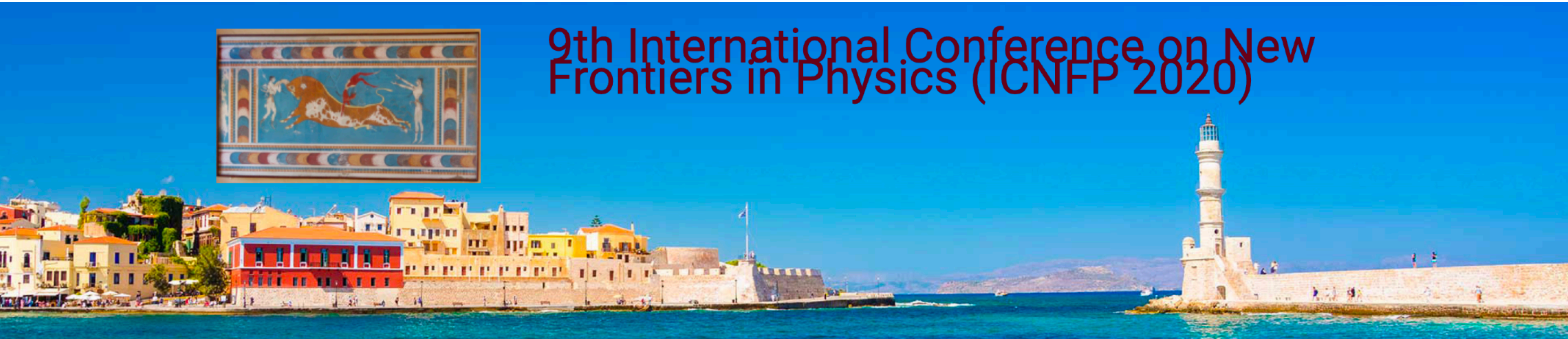
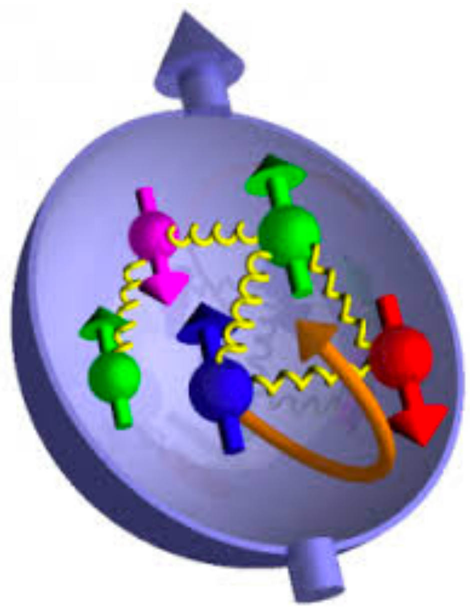
On behalf of the PHENIX collaboration



Proton longitudinal spin structure



total quark spin

orbital angular momentum

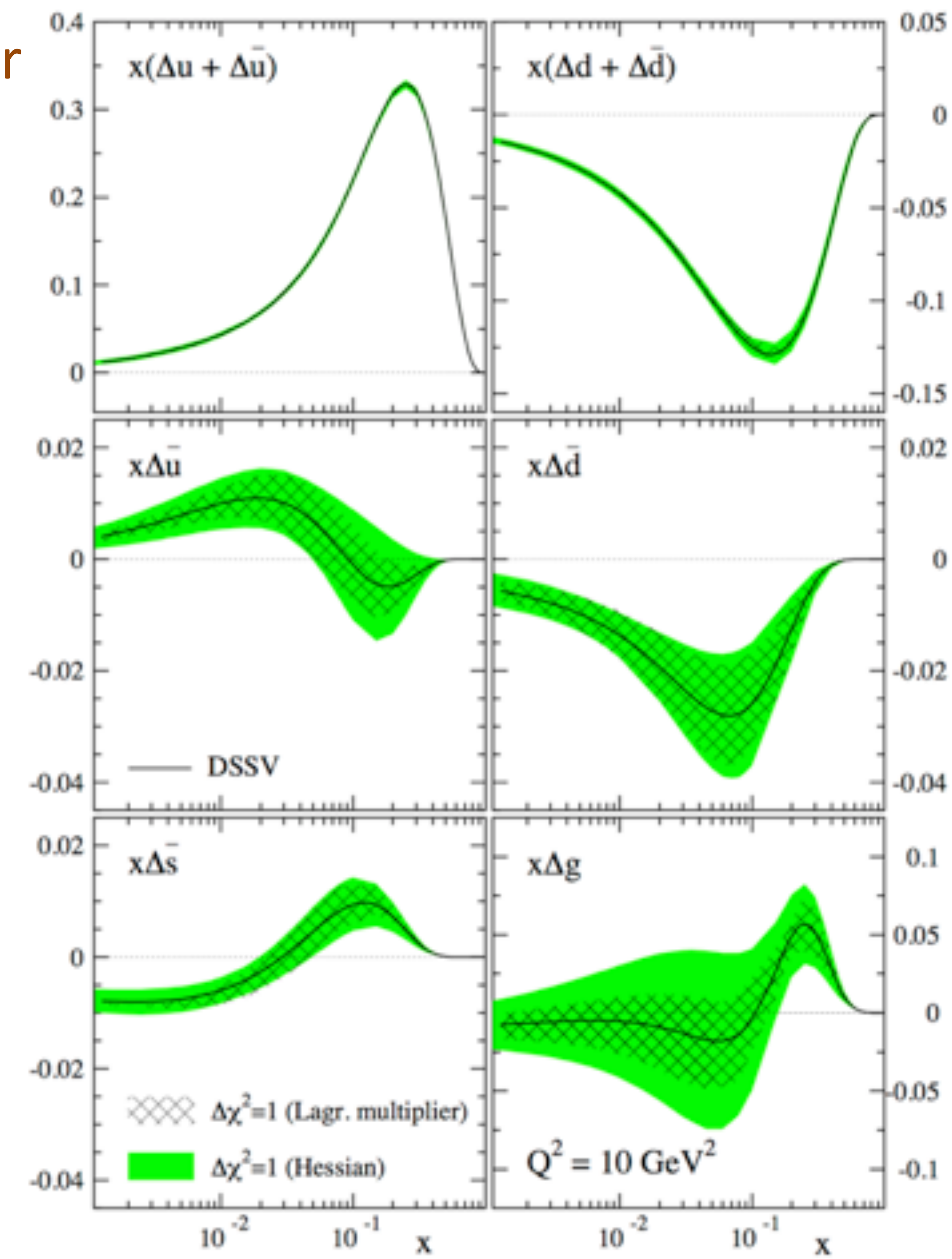
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

gluon spin

- Combined quark and antiquark contribution well constrained

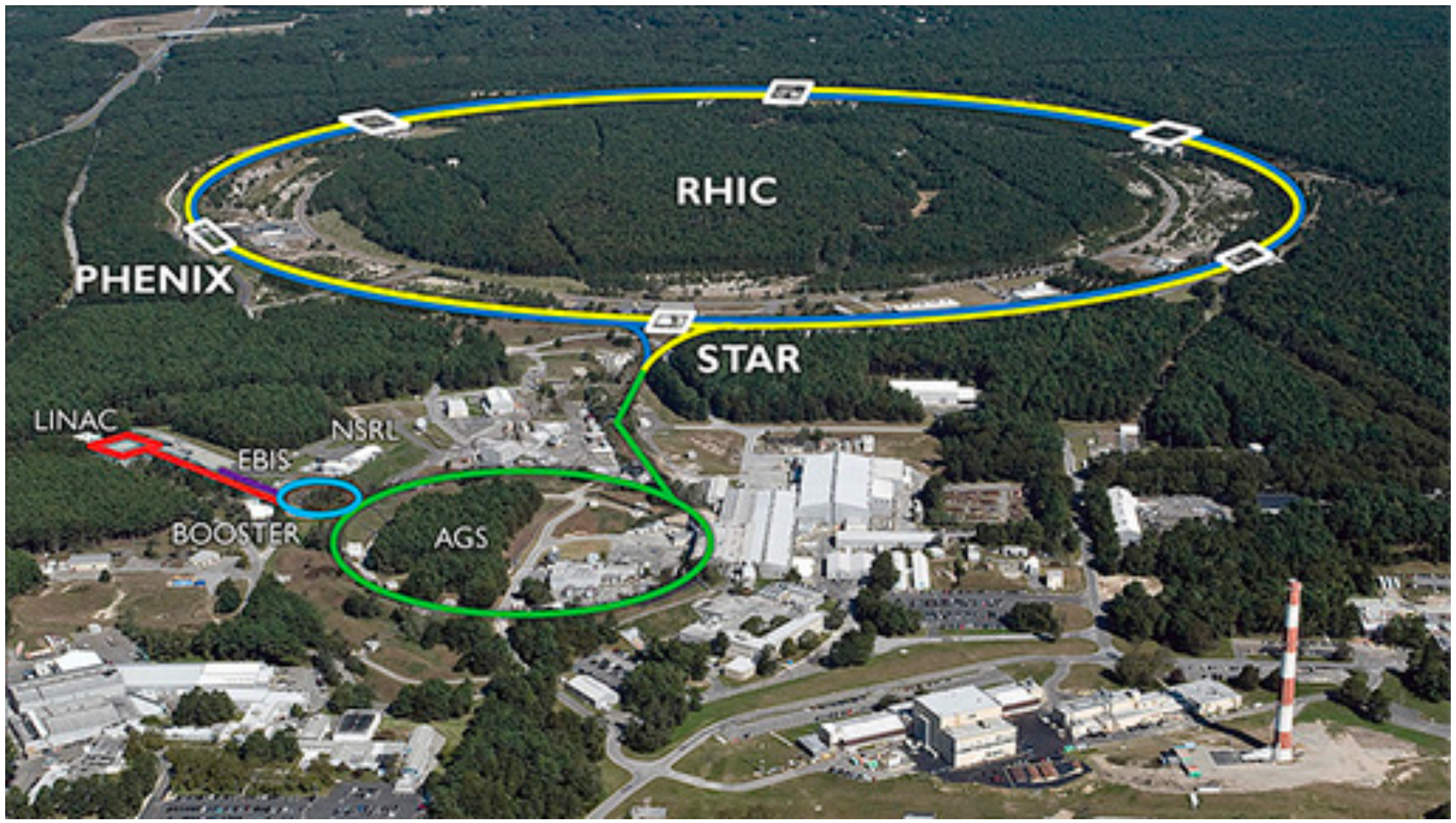
- Antiquark mostly extracted by SIDIS
  - RHIC W data provides clean and direct sensitivity to light sea quarks

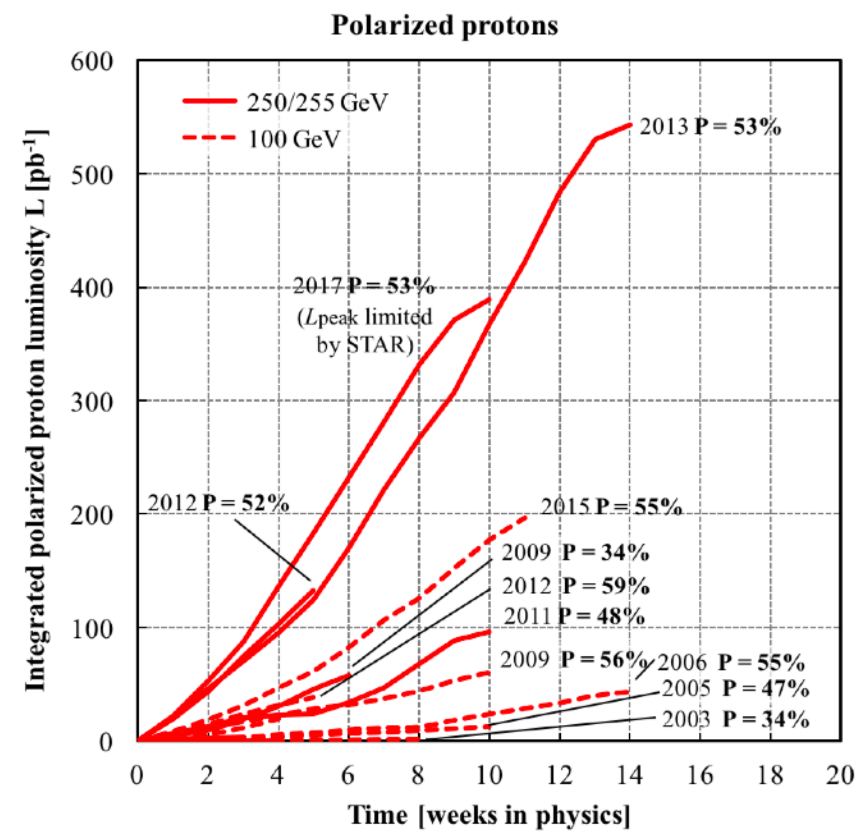
- gluons only poorly constrained by DIS (indirect access via scaling violation)
  - p+p allows direct access to gluons



Phys. Rev. D80, 034030 (2009)

RHIC Spin Program

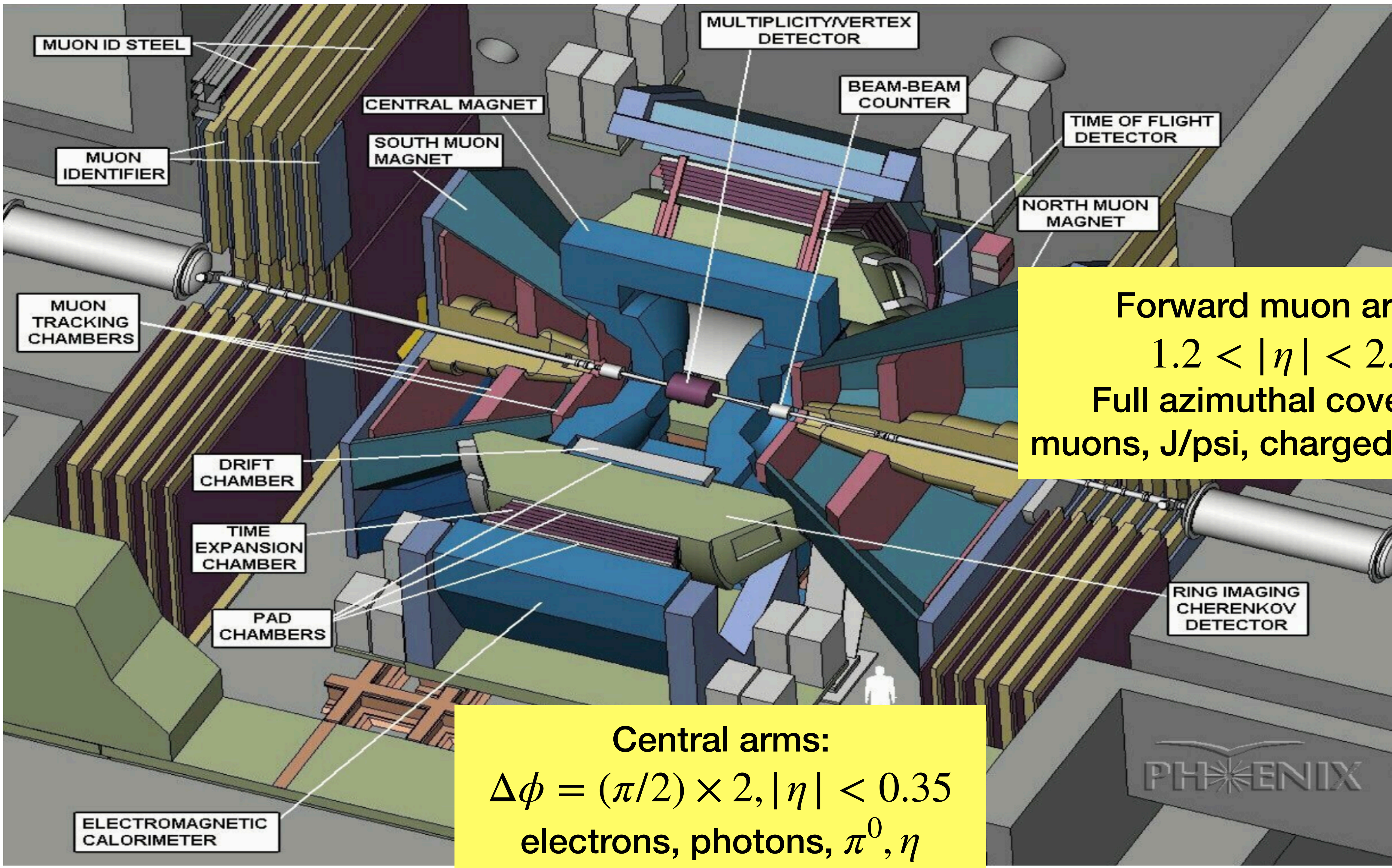




- **How do gluons contribute to the proton spin?**
- **What is the landscape of the polarized sea in the nucleon?**
- **What do transverse spin phenomena teach us about proton structure?**

arXiv: 1501.01220

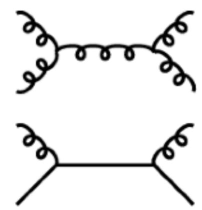
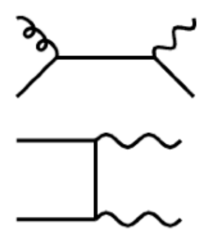
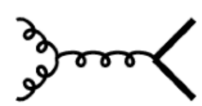
PHENIX experiment

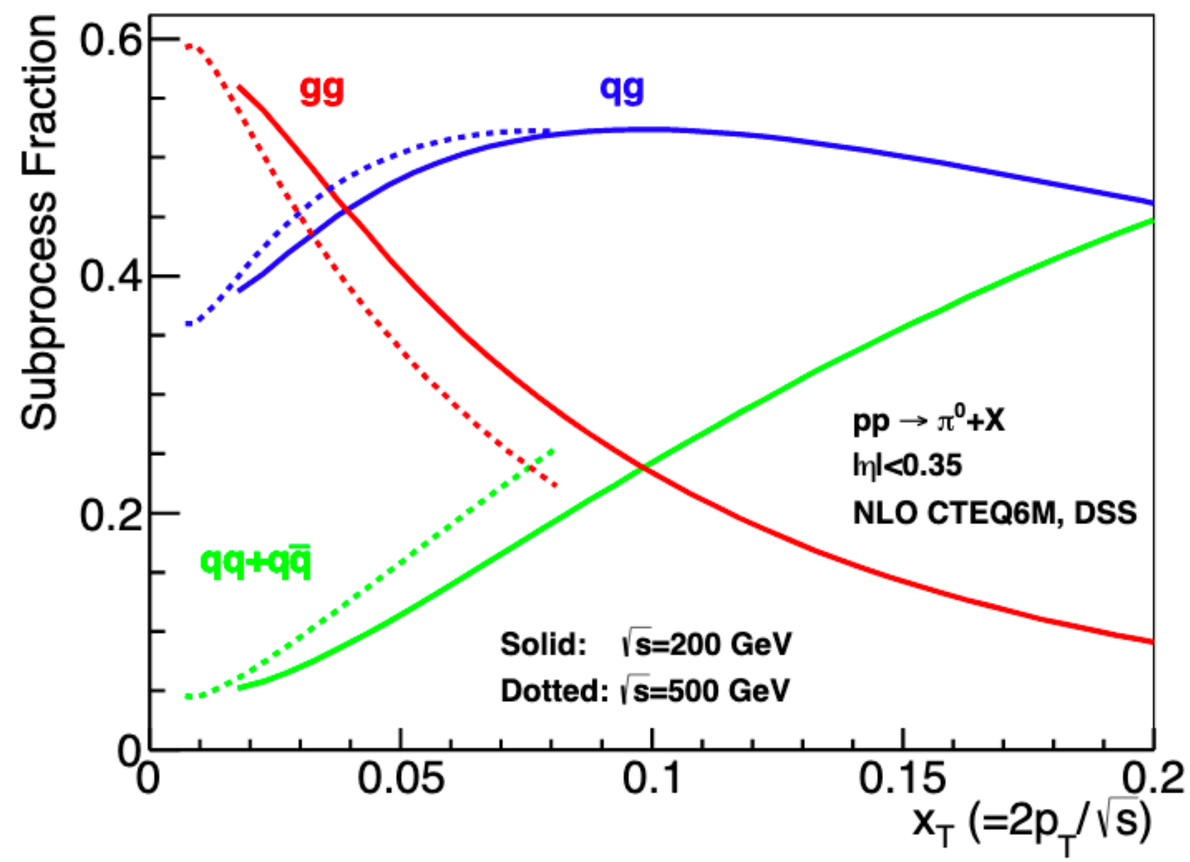


Forward muon arms:
$1.2 < |\eta| < 2.4$
Full azimuthal coverage
muons, J/psi, charged hadrons

Central arms:
$\Delta\phi = (\pi/2) \times 2, |\eta| < 0.35$
electrons, photons, π^0, η
charged hadrons

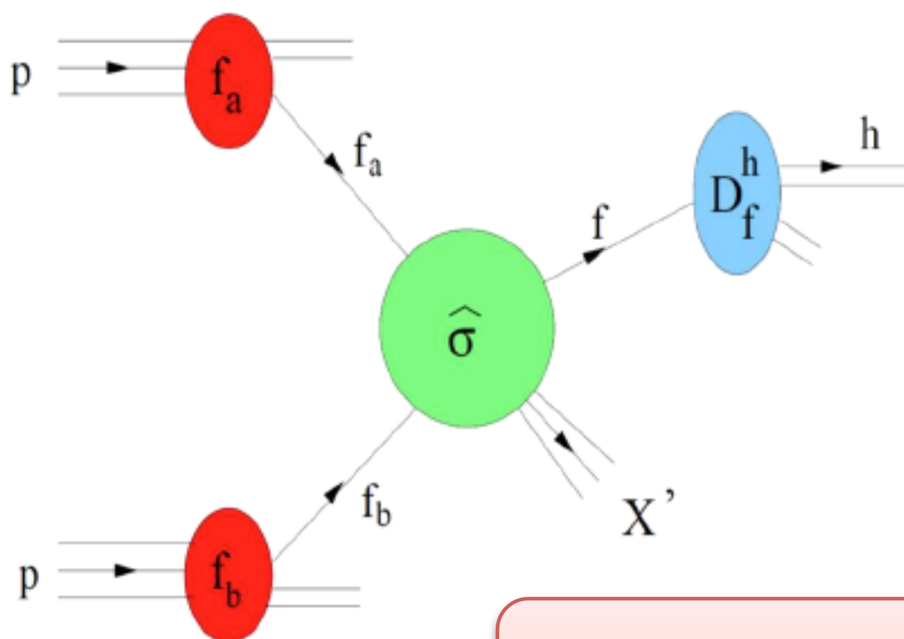
Access gluons

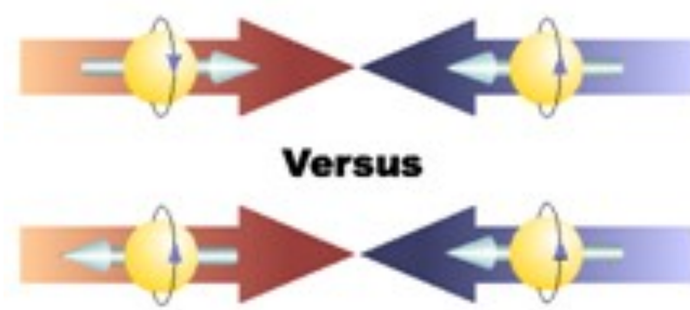
Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet}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



gg and qg dominant at RHIC kinematics
Access gluons in LO processes

Double spin asymmetries





Polarized PDFs

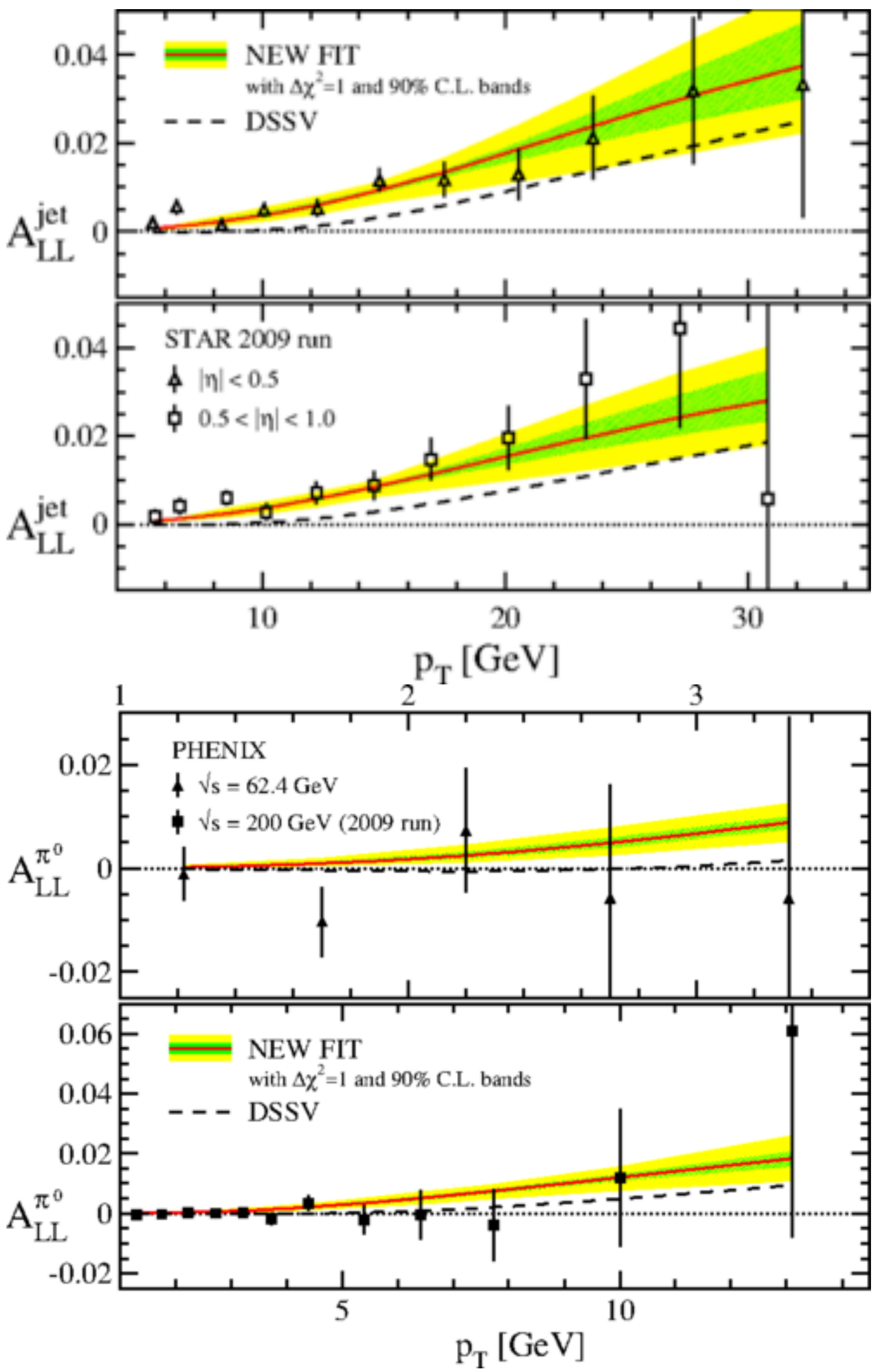
Parton-level hard scattering
cross section
calculable in pQCD

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

Unpolarized PDFs

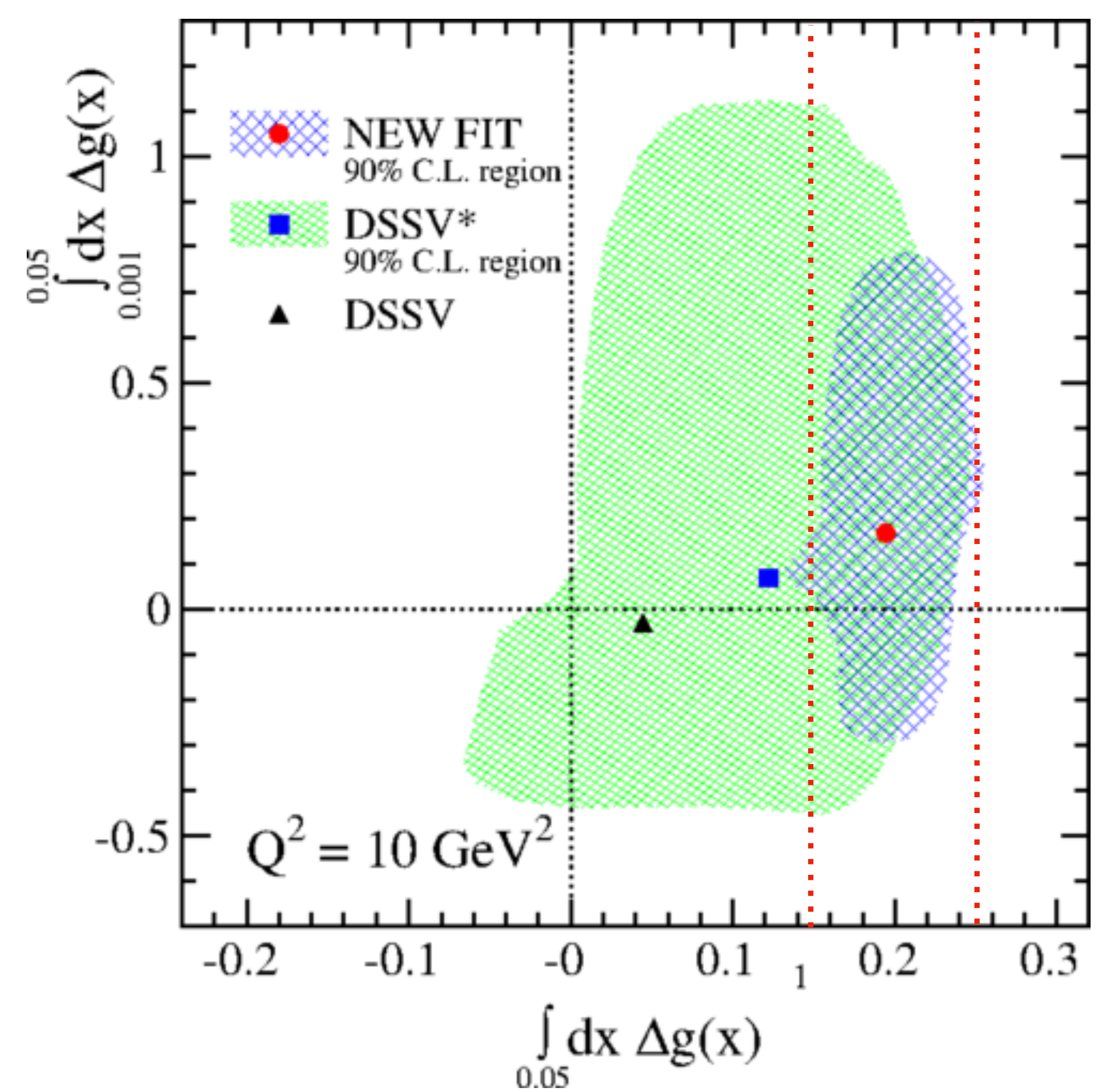
Fragmentation functions
from e+e- scattering

First evidence of non-zero gluon spin



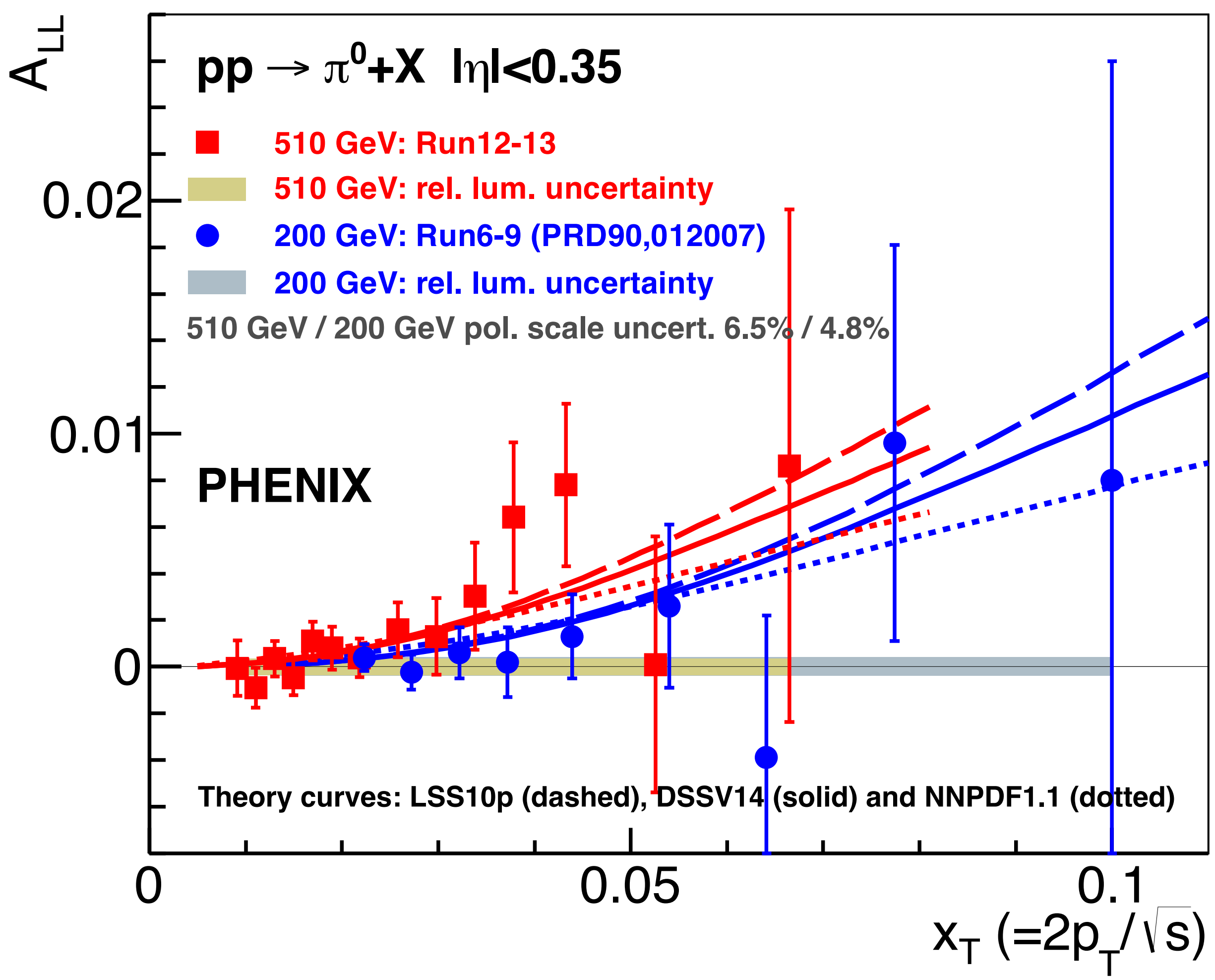
Phys. Rev. Lett. 113 (2014) 012001

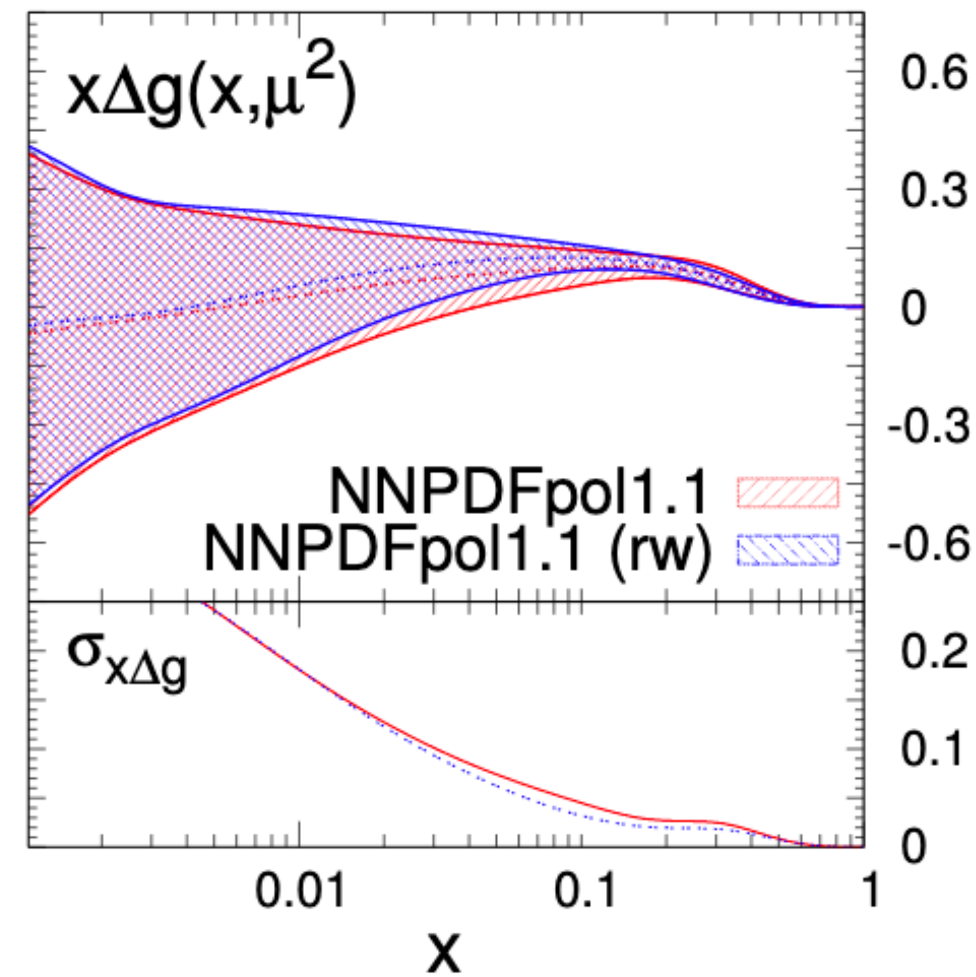
$$\int_{0.05}^{1} dx\Delta g(x) = 0.2^{+0.06}_{-0.07}(Q^2 = 10\text{GeV}^2)$$



510 GeV data confirm non-zero gluon spin

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



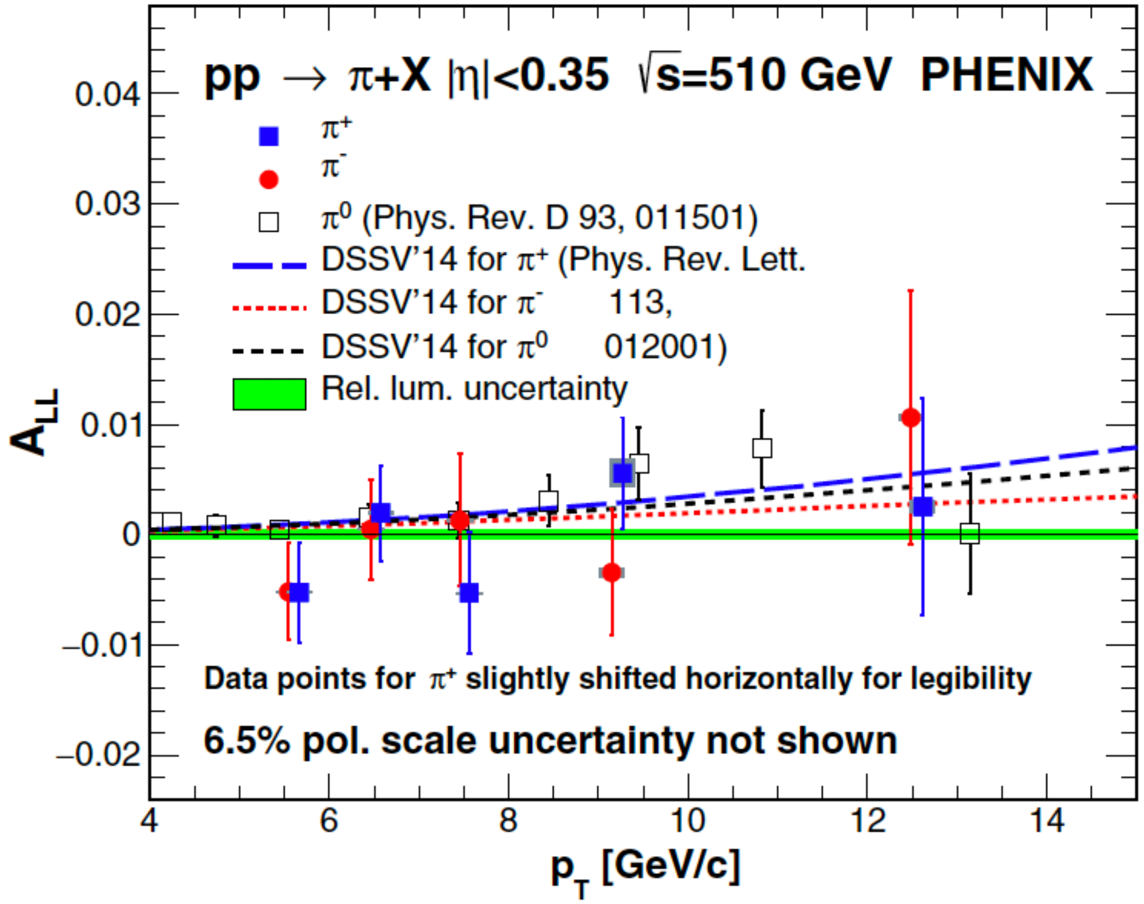


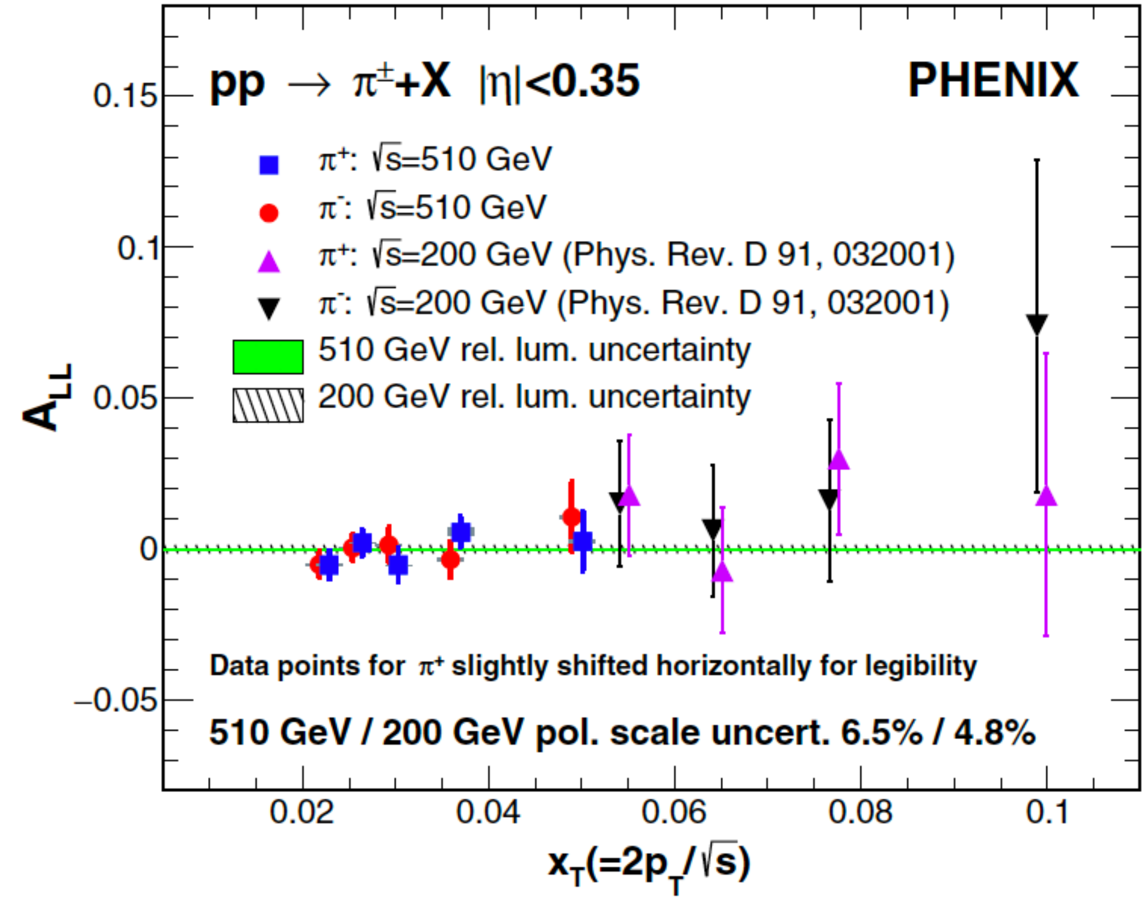
- 510 GeV data (PHENIX pi0, STAR jet) confirmed non-zero gluon spin
- Extended x coverage down to ~10^{-2} by higher energy

NNPDF reweighing including STAR 200 GeV di-jet and PHENIX pi0 data (arXiv:1702.05077)

Other Δg measurements

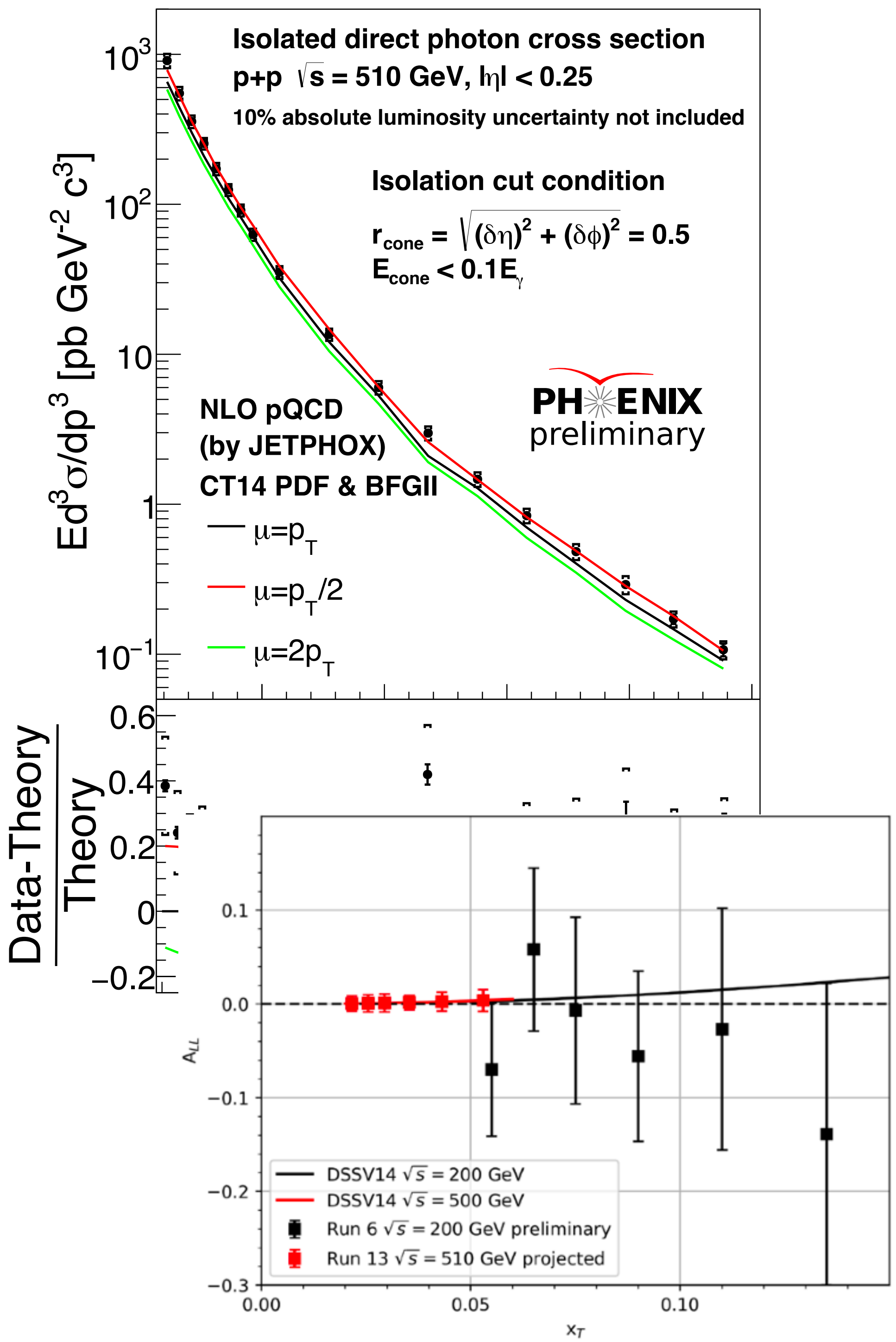
Phys. Rev. D 102, 032001 (2020)





- First measurement at 510 GeV, consistent with the positive gluon polarization from DSSV global fits within statistical uncertainty
- Charged pions potential indicator for sign of Δg via pion A_{LL} ordering
- Future sPHENIX will be able to measure it much precisely

Other Δg measurements



- Direct photons: theoretically clean measurement

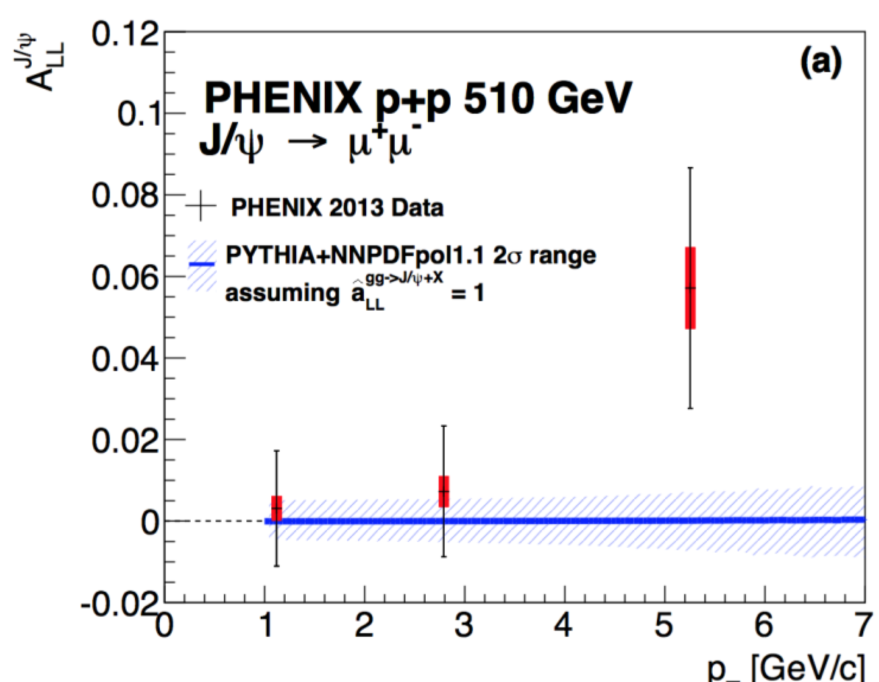
  quark-gluon Compton dominates cross section

  First measurement at 510 GeV, analysis being finalized

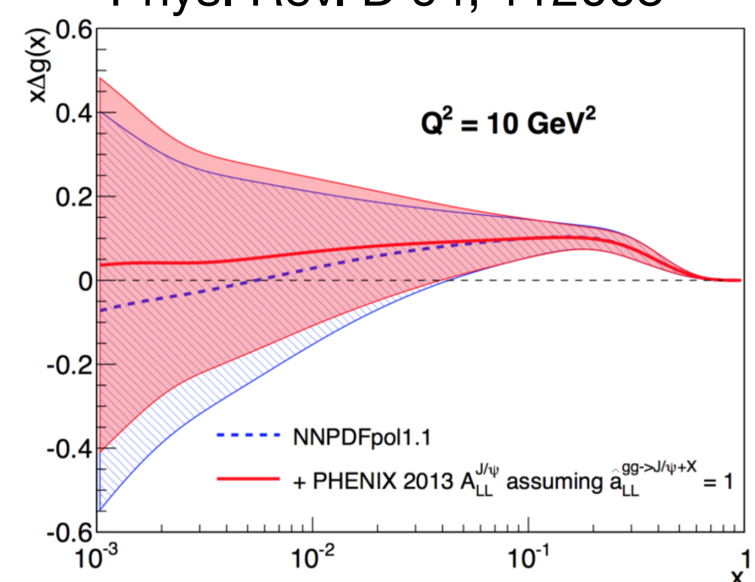
- Forward measurements: extending access to lower x (~10^{-3})

  J/psi measurements, dominated by gg fusion

  MPC cluster A_{LL} analysis ($3.1<|\eta|<3.9$) ongoing

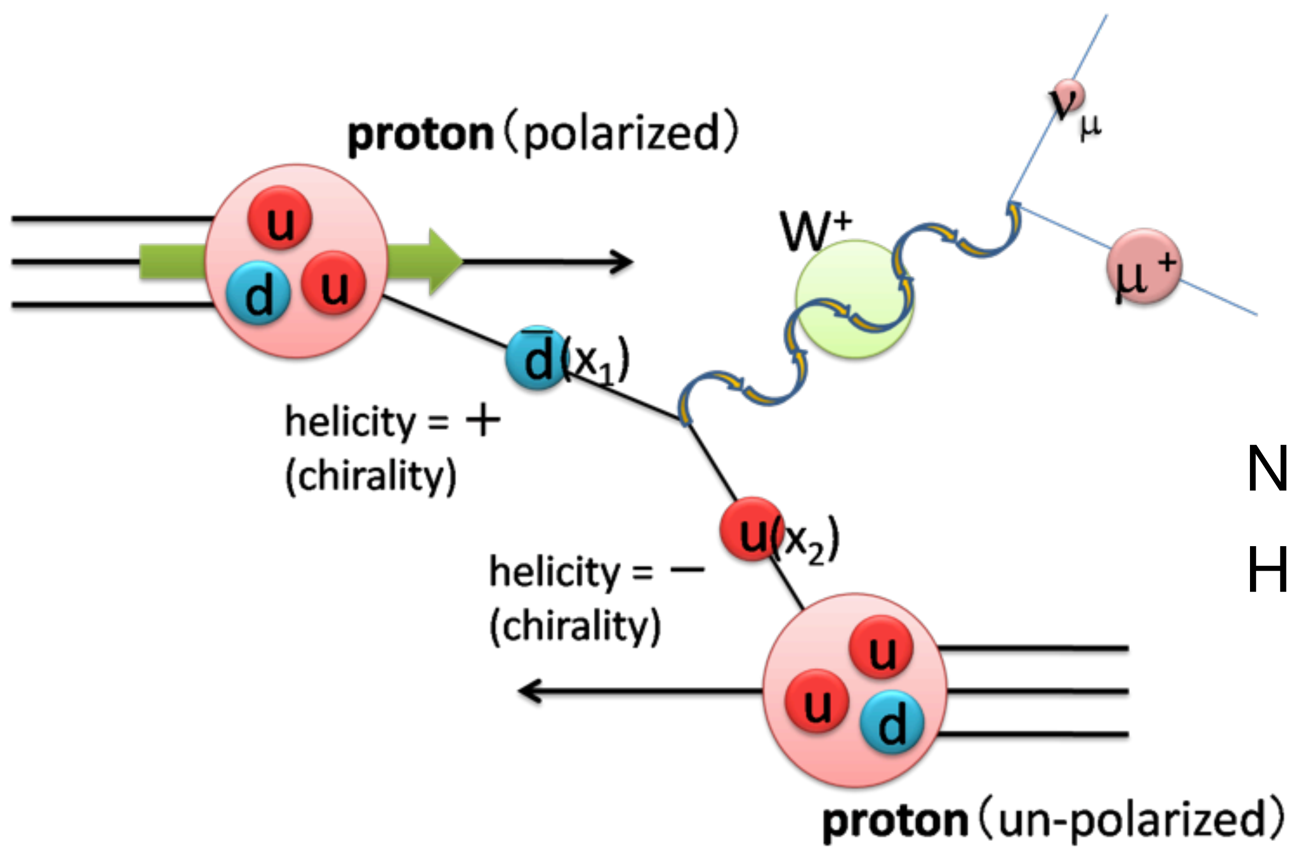


Phys. Rev. D 94, 112008



W measurements: Separating quark flavor

- Clean and direct sensitivity to light sea quark helicity distributions via parity violating W production
- Flavor asymmetry of the sea: unpolarized sea asymmetry -> Is polarized sea asymmetric?

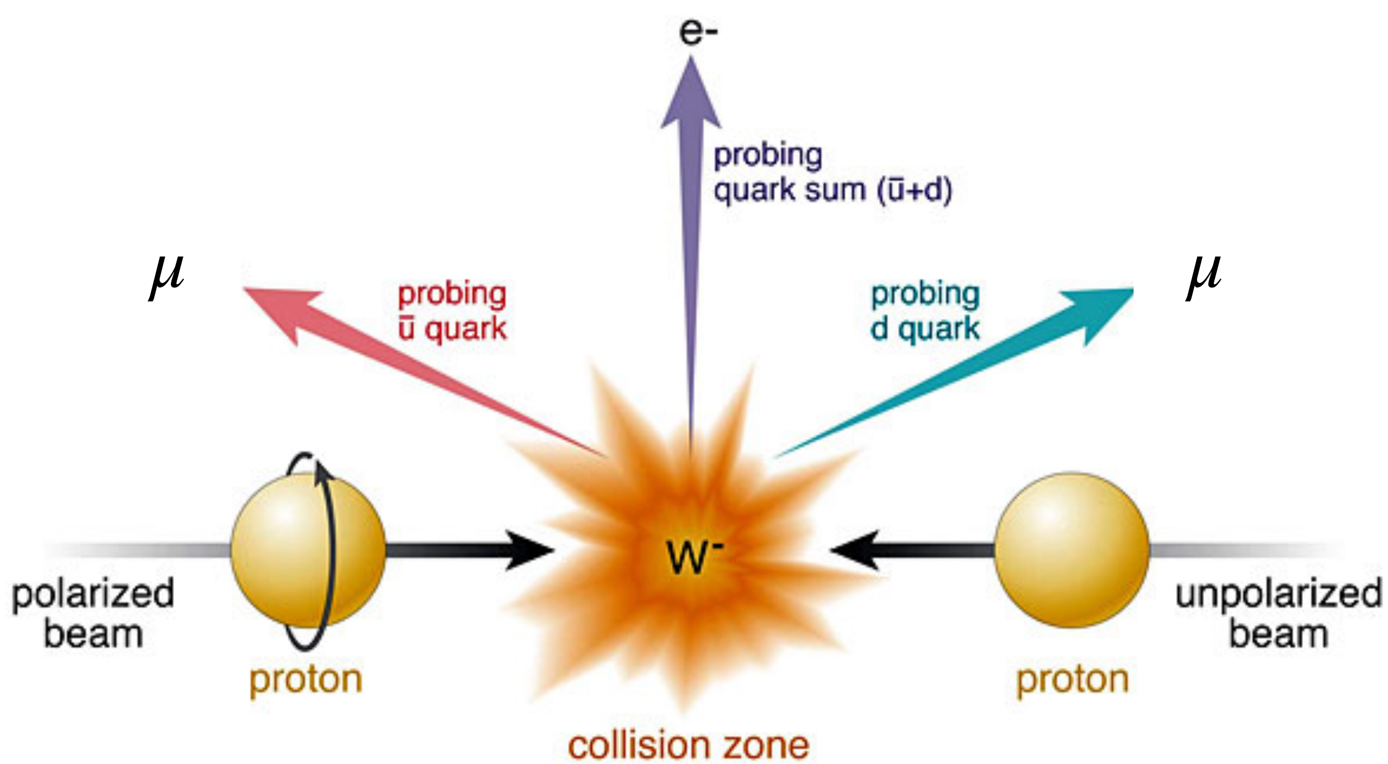


$$u_L \bar{d}_R \rightarrow W^+$$
$$d_L \bar{u}_R \rightarrow W^-$$

No fragmentation function needed

High Q2 set by W mass

Parity violating spin asymmetries



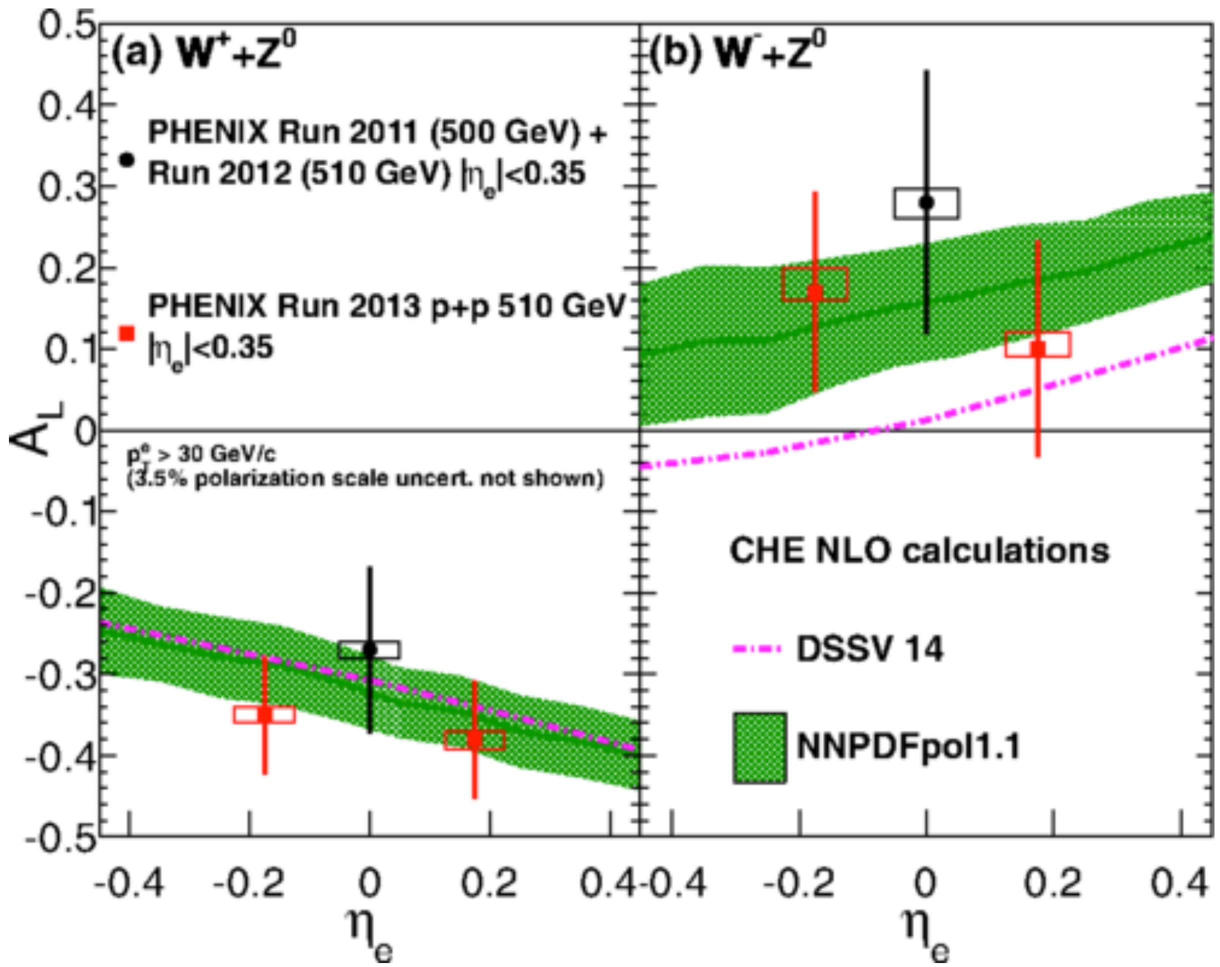
- Longitudinal single spin asymmetry direct access to quark helicity PDFs
- Combined with weak decay kinematics
  - quark flavor mixed at mid-rapidity
  - sensitive to anti-quark polarization at forward/backward rapidity measurement

$$A_L^{W^- \to \ell^-} \approx \frac{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}{\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}$$

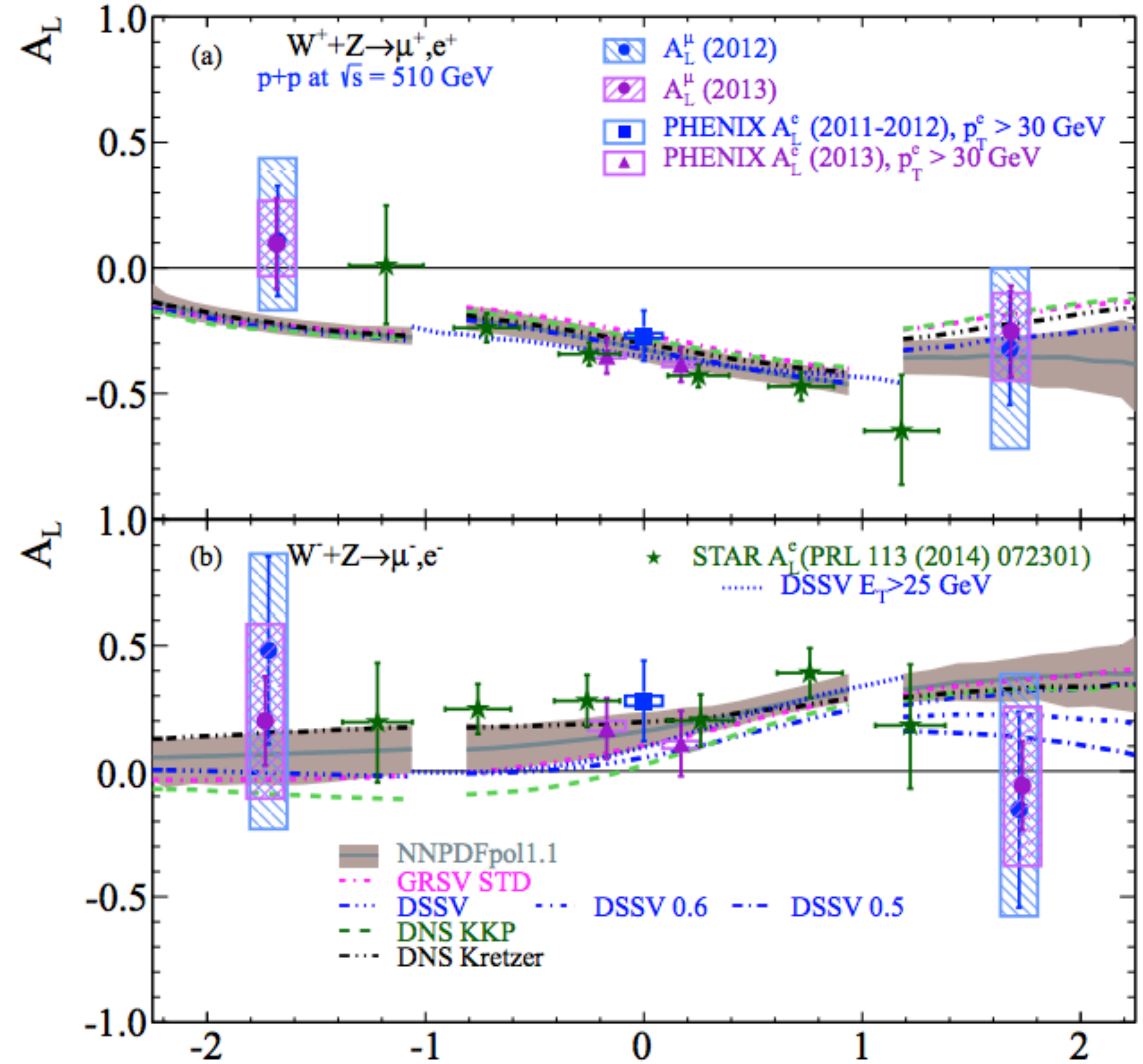
$$A_L^{W^+ \to \ell^+} \approx \frac{\Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2}{\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 + u(x_1)\bar{d}(x_2)(1-\cos\theta)^2}$$

Parity violating spin asymmetries

Phys.Rev. D93 (2016), 051103

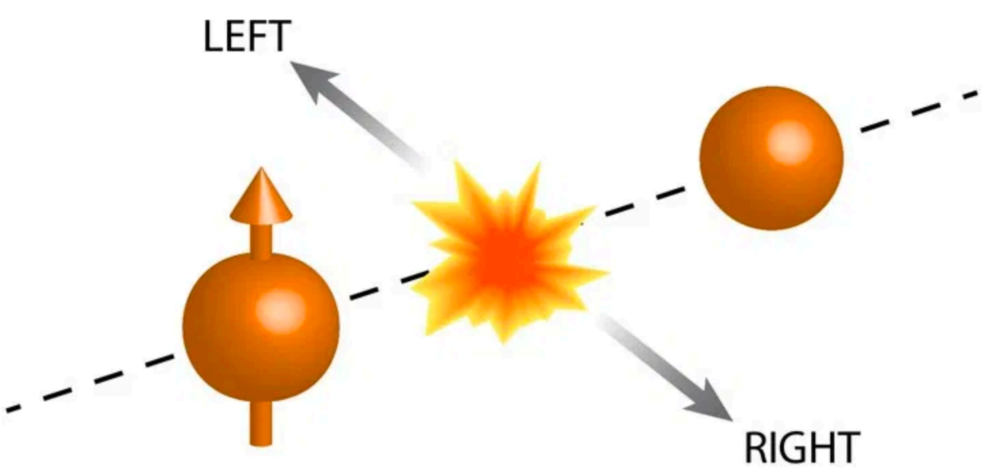


Phys. Rev. D 98 (2018), 032007



- Data above DSSV14 global fit for e⁻, indicating larger $\Delta\bar{u}$ contribution in the covered x region (~0.16)
- First measurement of muon decay channel, consistent with theory calculations within uncertainties

Transverse spin phenomena:
Spin-momentum correlation

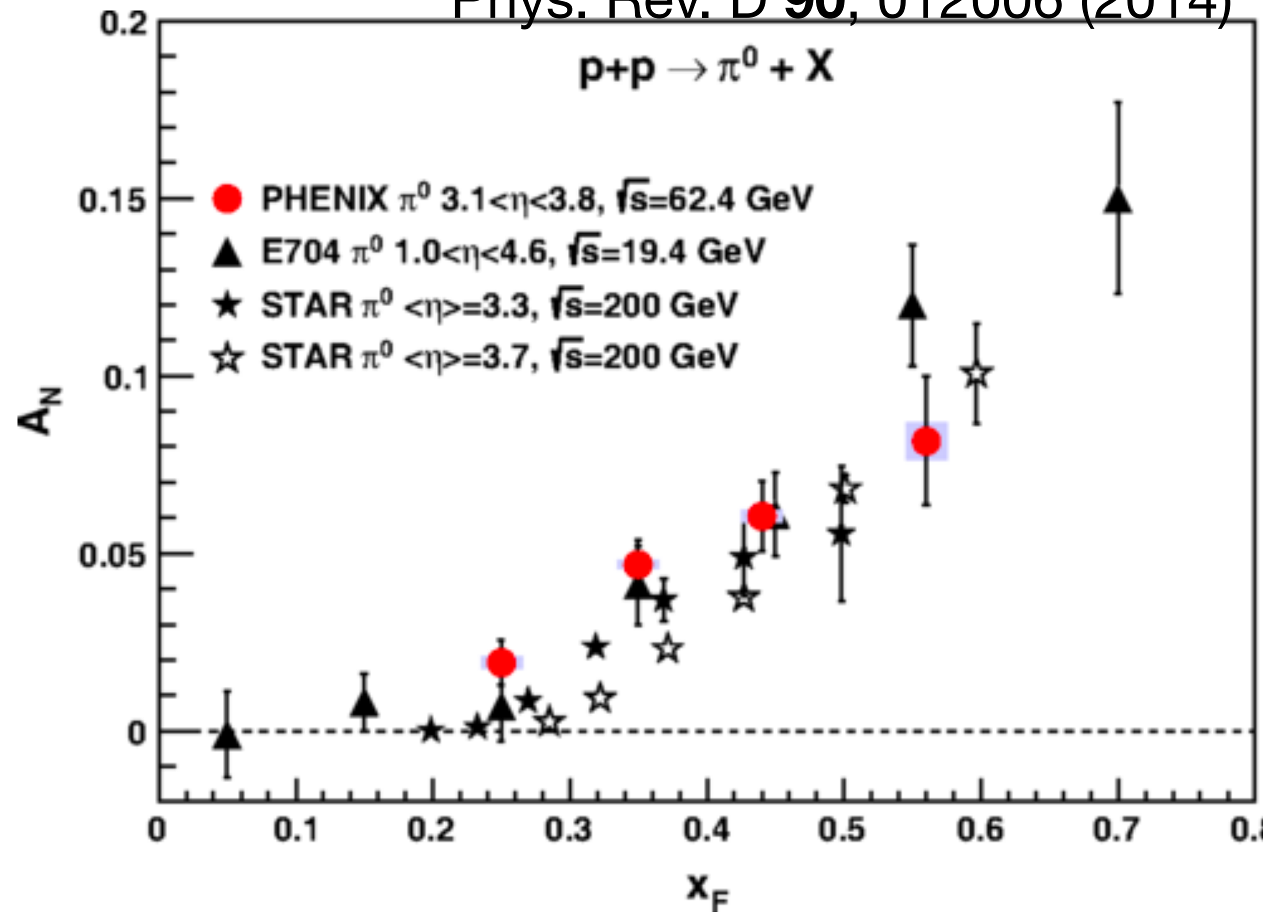


Transverse single spin asymmetry (TSSA)

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

- Naïve pQCD predicted very small asymmetry (PRL 41 1689 (1978))
- Surprisingly large TSSAs observed A_N ~ 40% (FNAL E704)
- Asymmetries survive at higher energy, nearly independent of collision energies

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

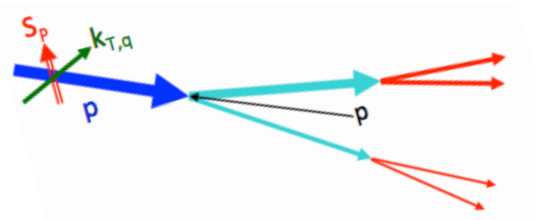


Towards the understanding the origin of TSSAs

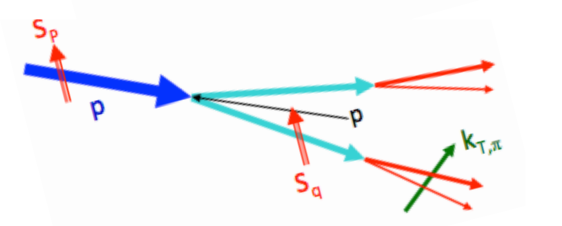
- Transverse-momentum-dependent (TMD) distributions and fragmentations

  Need one hard (Q^2) and soft (pT) scale to be applicable

  Initial state correlation: Sivers effect; proton spin and parton momentum correlation

  Final state correlation: Collins effect; fragmenting parton spin and hadron transverse momentum correlation

- Multi-parton correlation in collinear framework

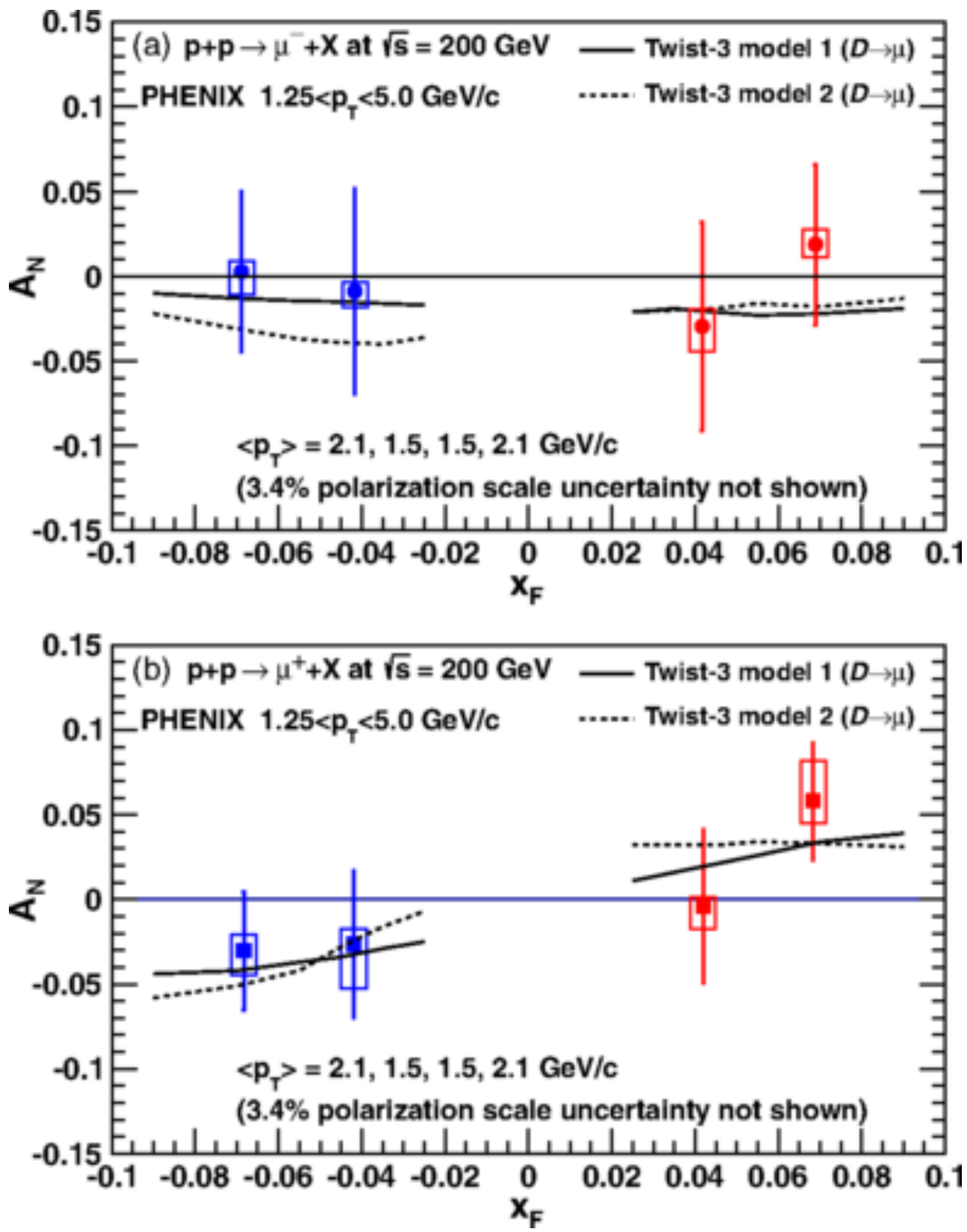
  Need one hard scale (pT), relevant to such as inclusive hadron productions in p+p

  SSA appears as twist-3 observable

  Multi-parton correlations in the initial state or in the fragmentation process

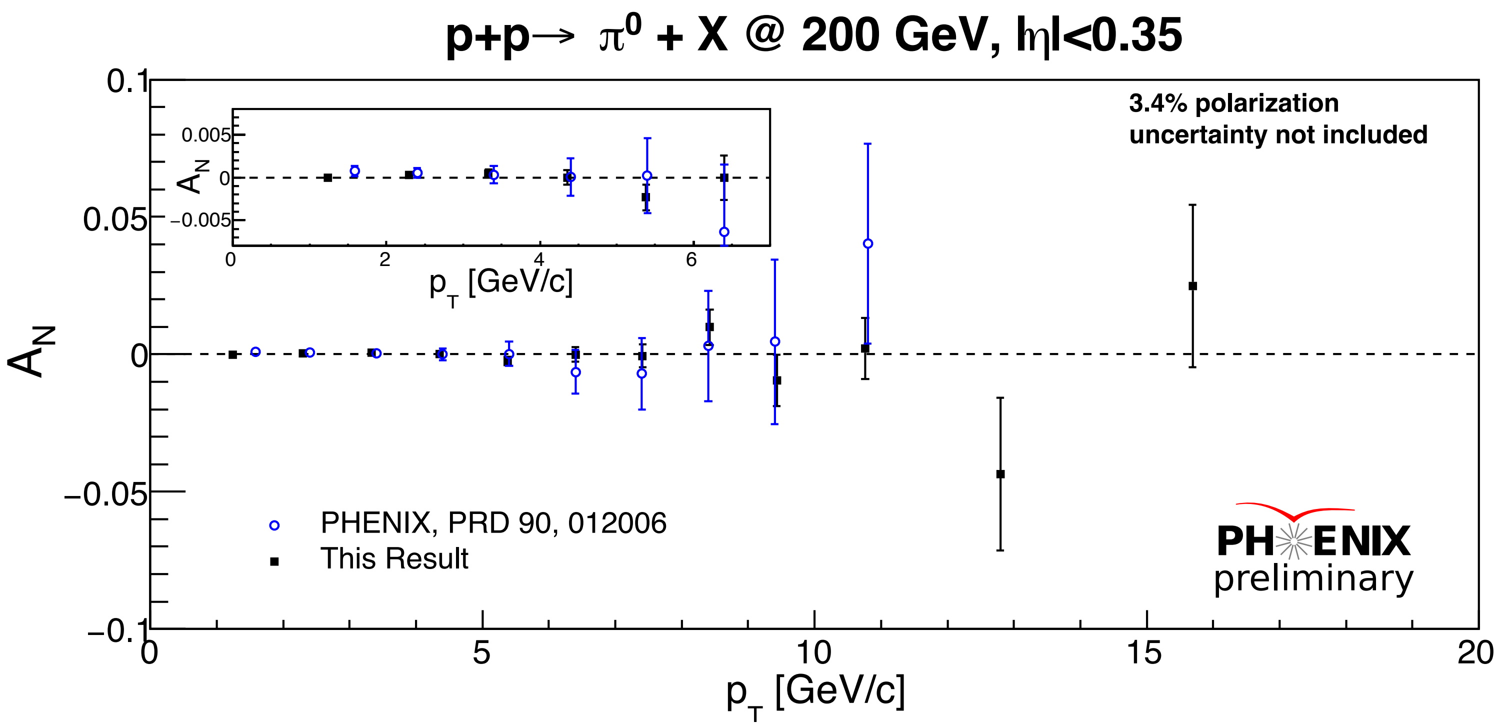
A_N: Open heavy flavor

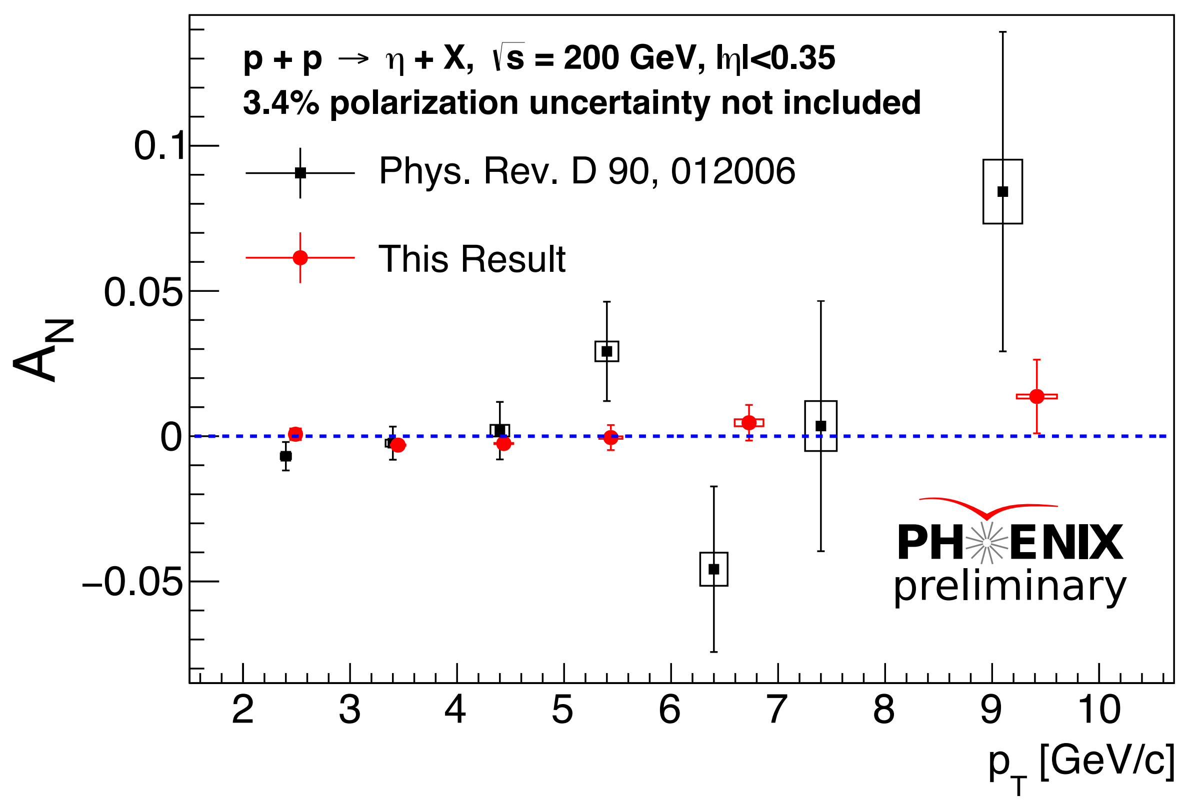
Phys. Rev. D 95, 112001



- At RHIC energies, mostly produced by gg fusion, ideal to investigate gluon distributions
- Sensitive to gluon Sivers-type effect, three-gluon correlations in the collinear factorization framework
- No clear indication of non-zero asymmetries within the uncertainty
- Theory calculations agree with data
- New high statistics data analysis ongoing

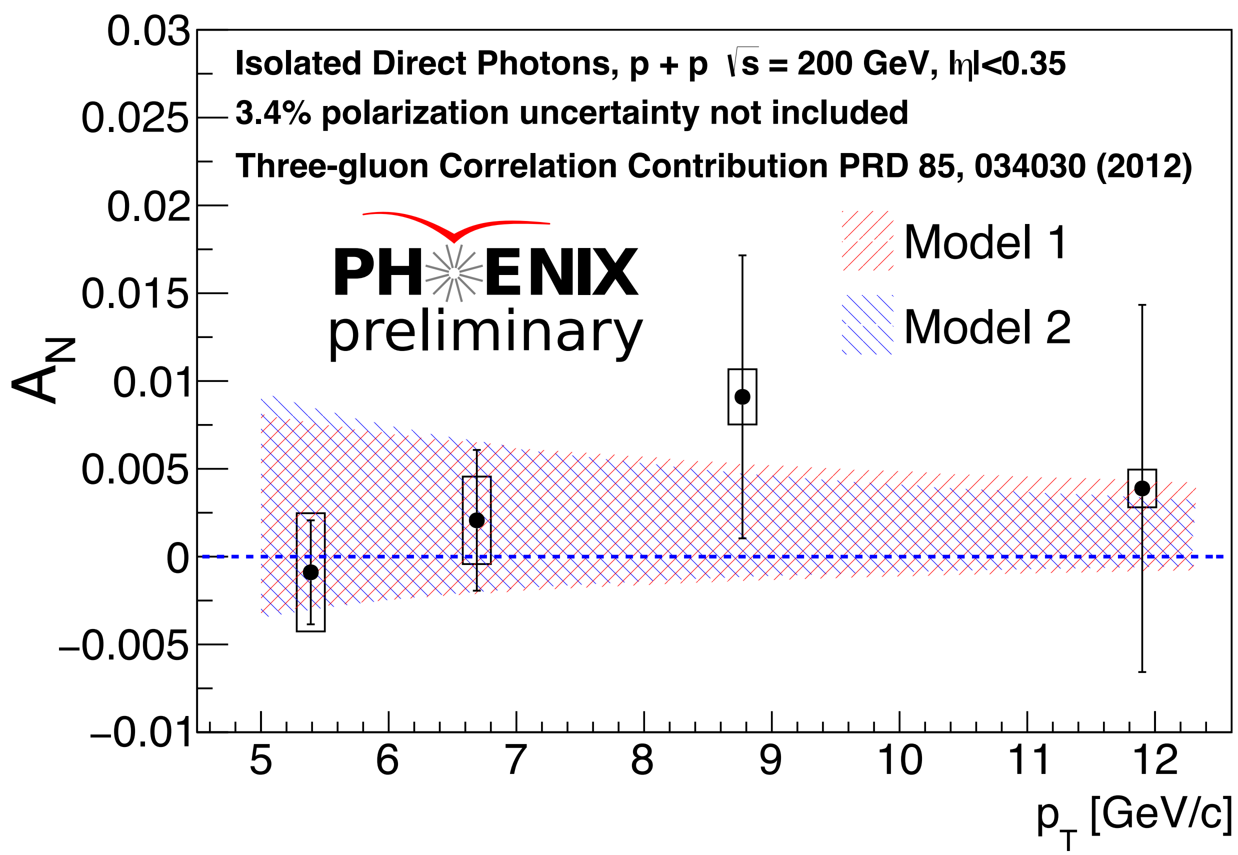
A_N: π^0 and η

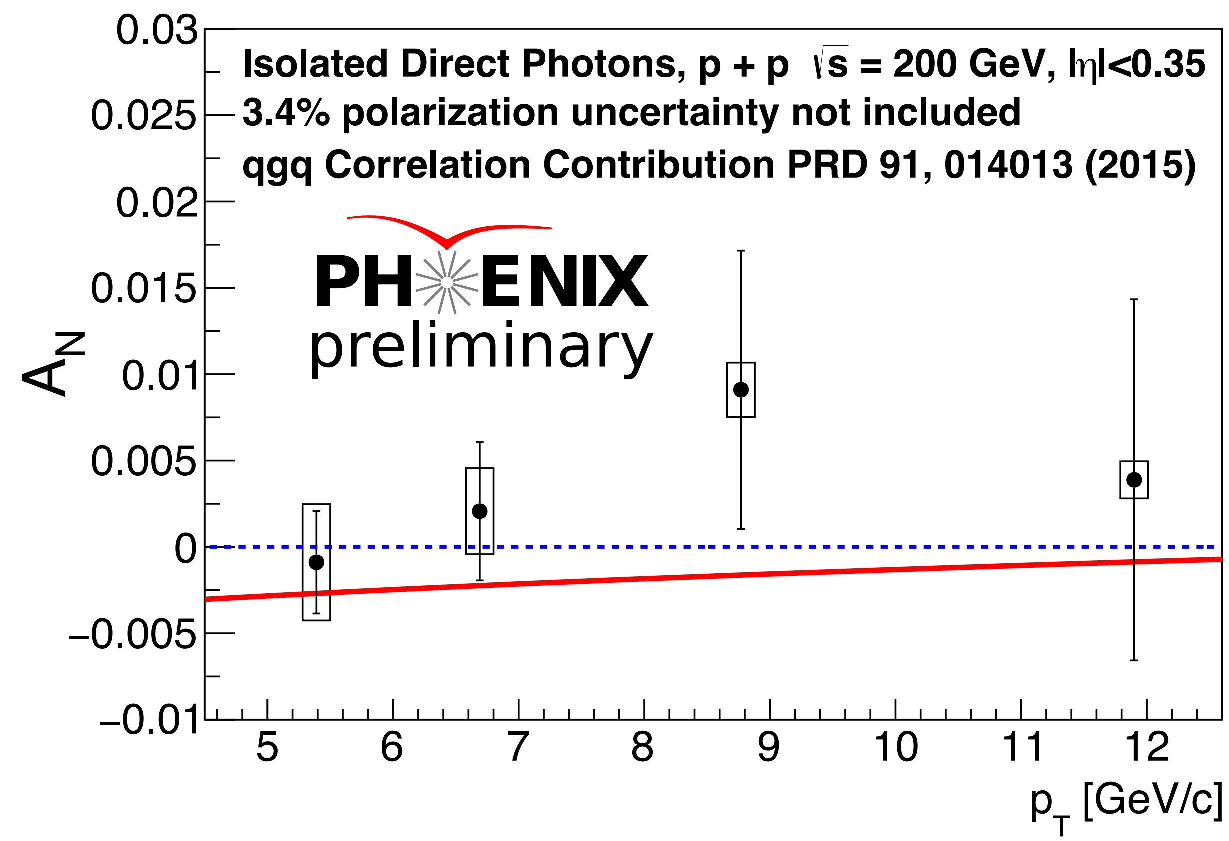




- Sensitive to both initial state and final state effects
- Mid-rapidity measurements sensitive to gluon spin-momentum correlations
- Asymmetries consistent with zero, new data significantly improved precision
- Publication in preparation

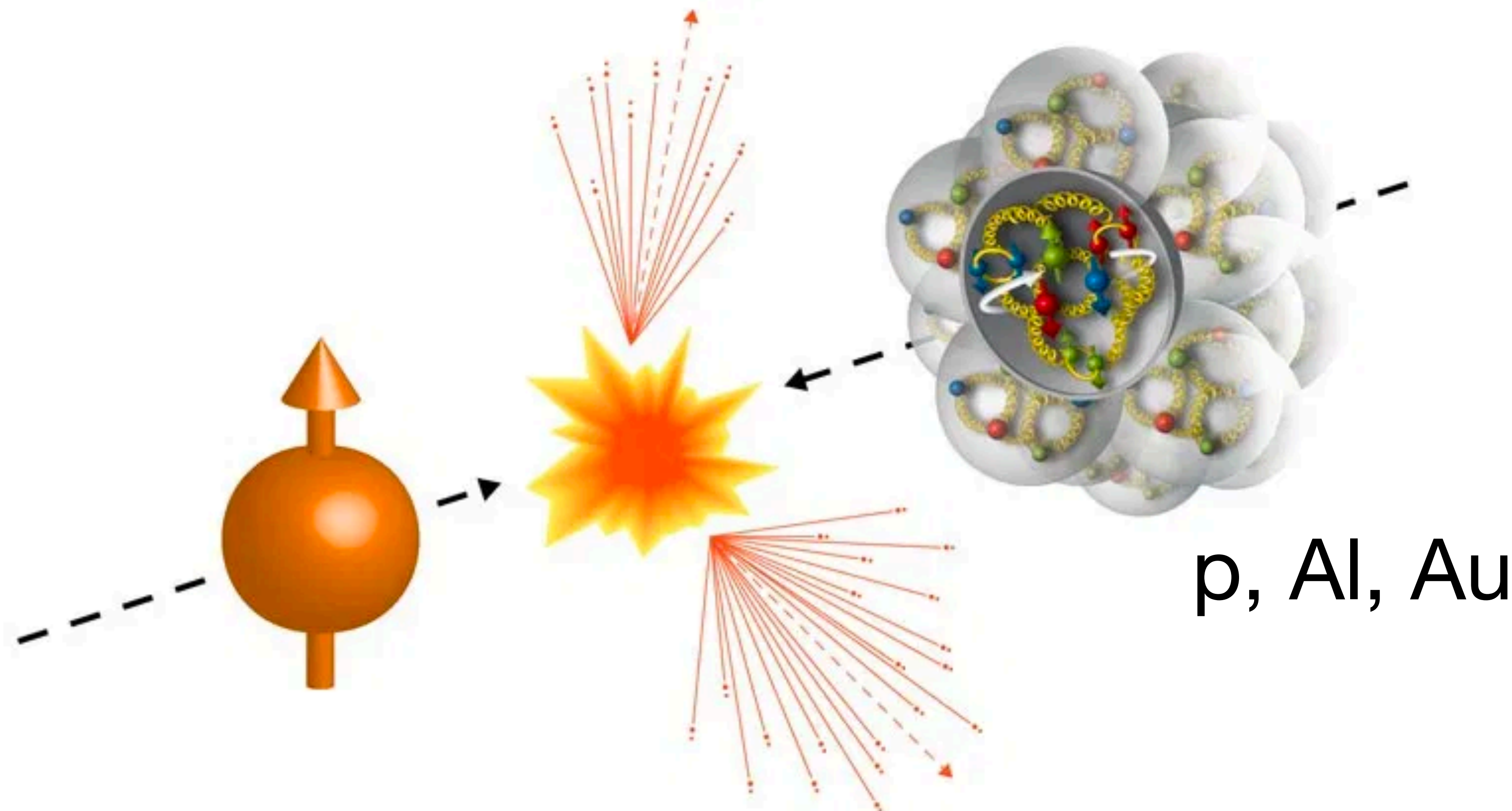
A_N: Direct photon





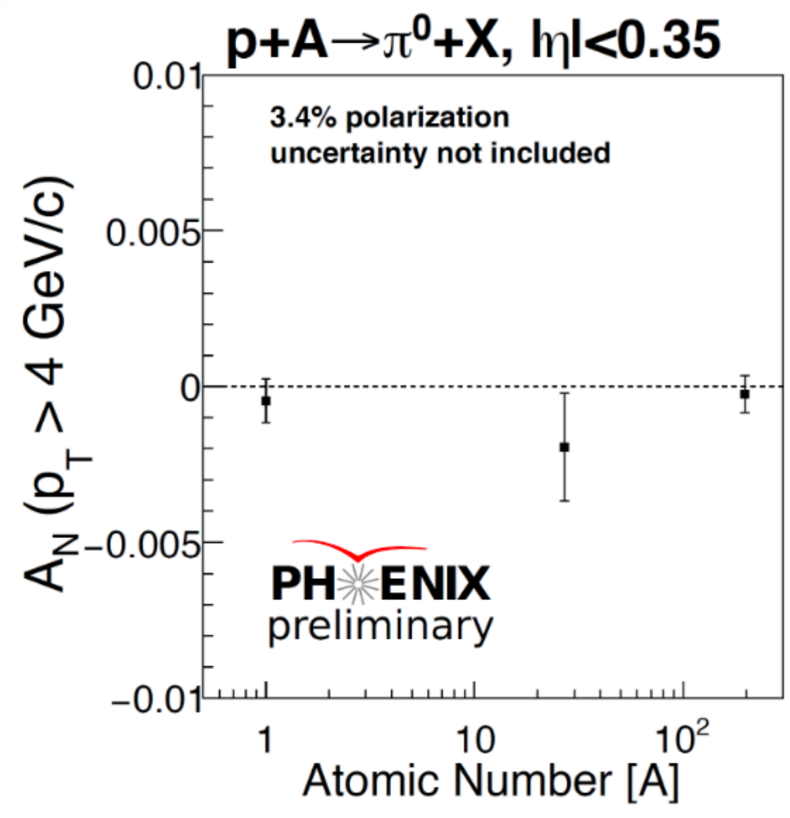
- Production cross section dominated by $q+g \rightarrow q+\gamma$
- Sensitive to initial state effects
- First measurement at RHIC, publication in preparation

TSSAs in nuclear environment

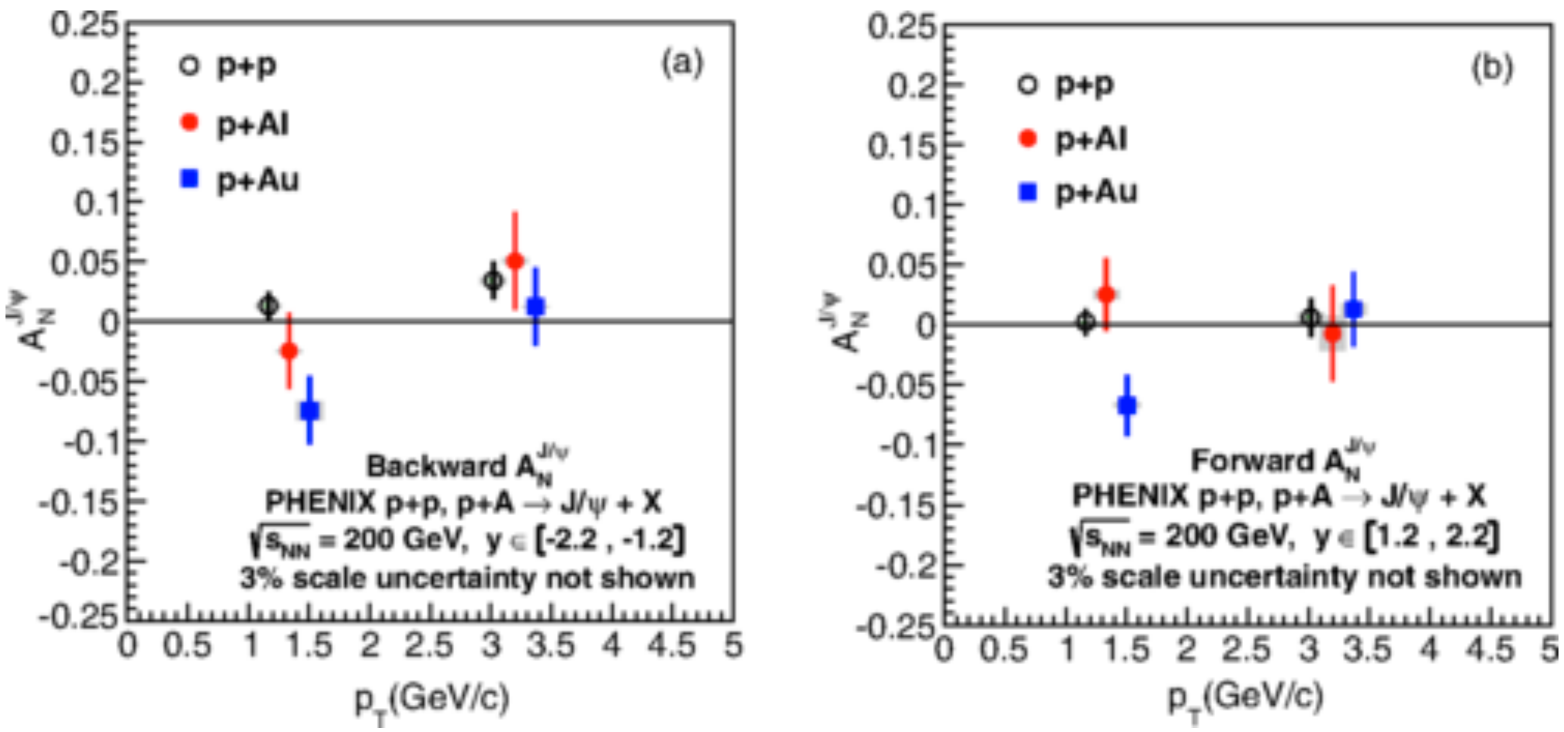


- First time polarized p+A collisions in 2015
- Study nuclear effects in A_N

TSSAs in p+A



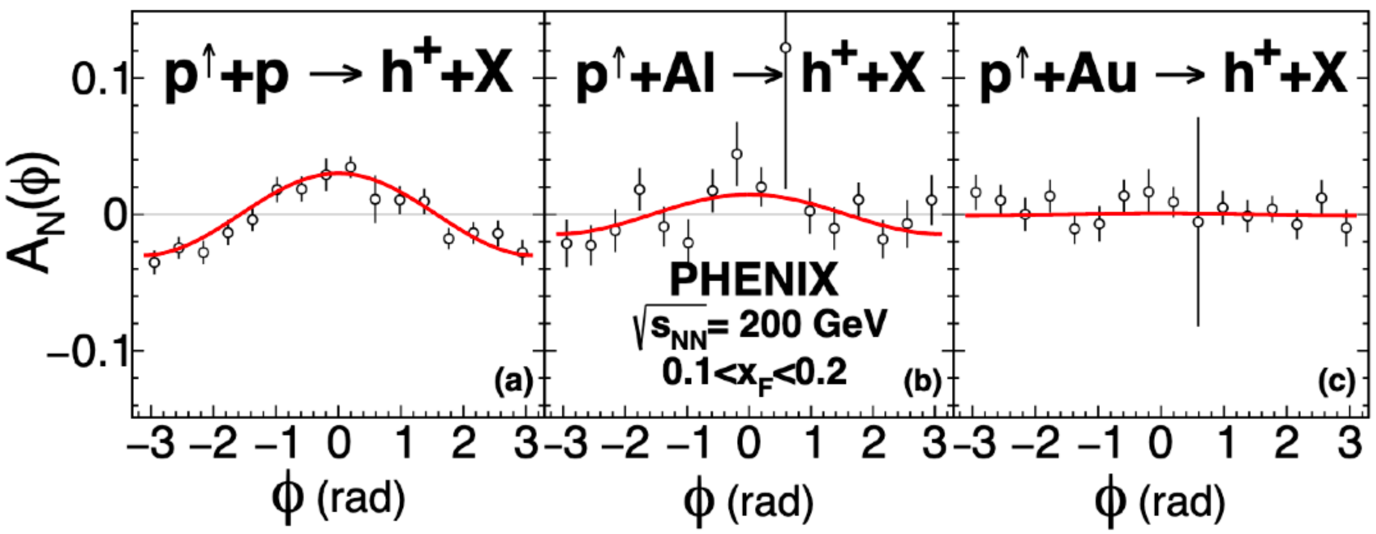
Phys. Rev. D 98, 012006



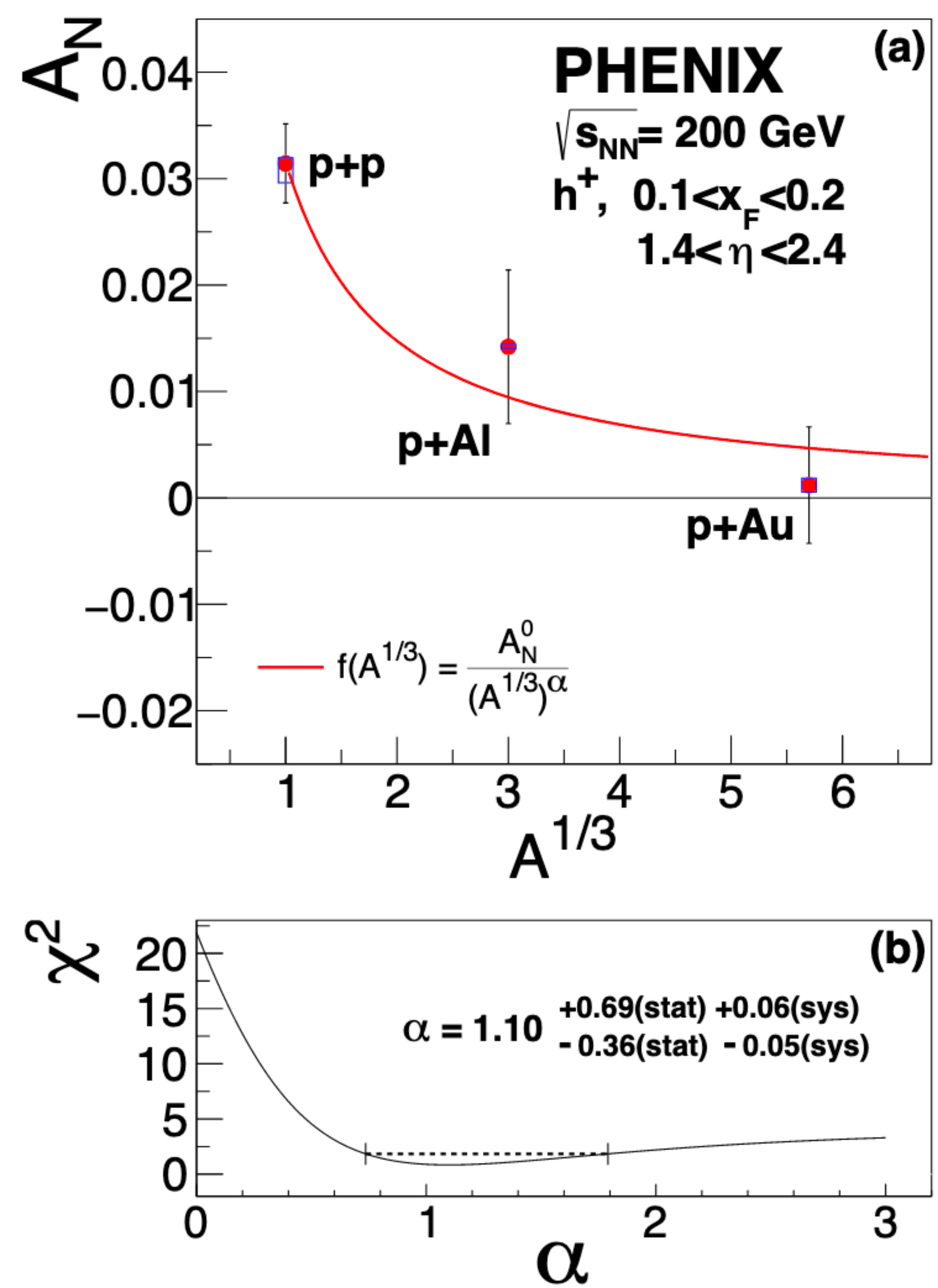
- Mid-rapidity pi0 measurement: no A-dependence observed
- Forward J/psi measurements:

  p+p results consistent with previous measurements
  2-sigma level asymmetry observed in p+Au in both forward and backward rapidity
  Large unexpected effects at low pT

Charged hadron A_N



Phys. Rev. Lett. 123, 122001 (2019)

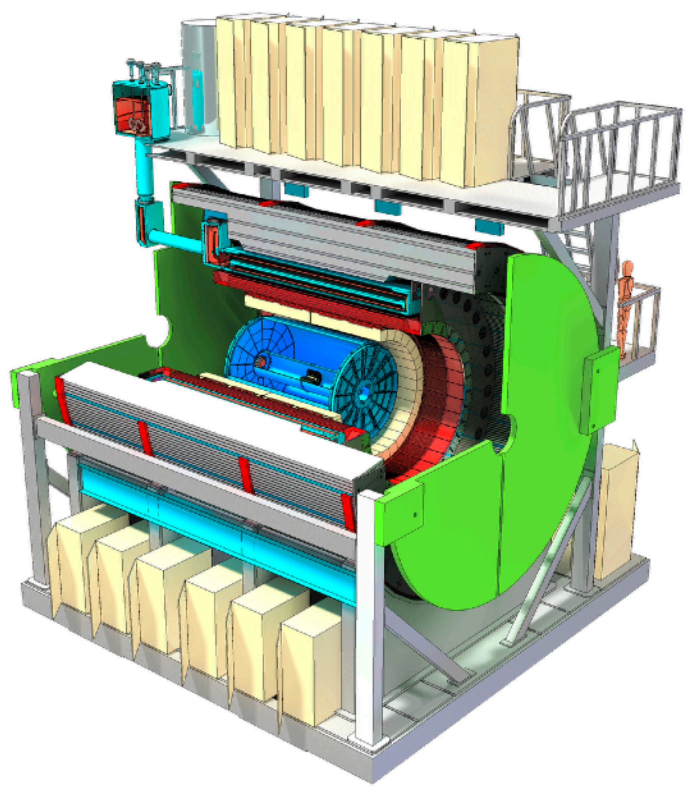


- Inclusive positively charged hadrons AN
- Particle composition $\pi^+/K^+/p$: 45%/47%/5%
- Suppression of A_N in p+Au observed
  - Suppression in p+A is sensitive to saturation scale
  - $A^{1/3}$ suppression in models with gluon saturation effects:

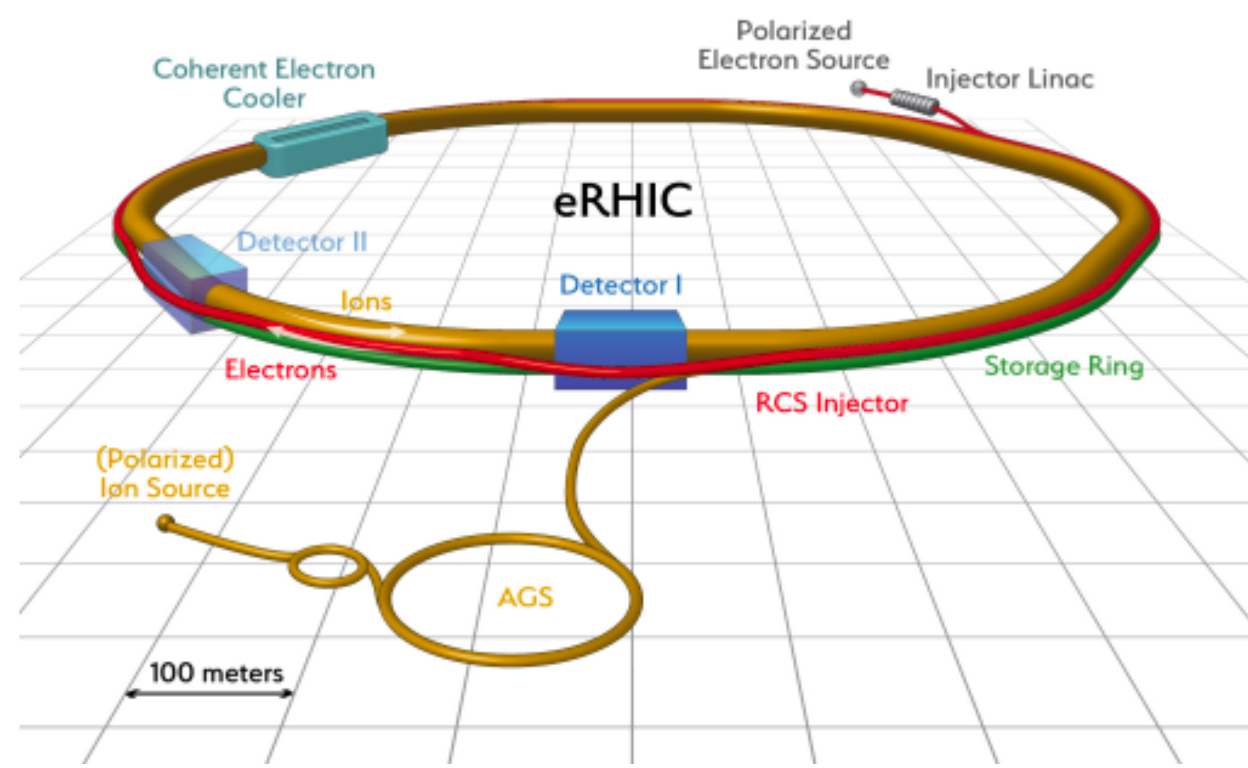
    PRD84 (2011) 034019, PRD95 (2017) 014008
  - <pT> of this measurement > saturation scale in Au

Future Spin Program

- sPHENIX Cold QCD program
- Broad range of high precision measurements:
  - Precision measurements of jet and DY… and more!
- pp/pA program essential to fully realize the scientific promise of the EIC



- Electron Ion Collider (EIC)
- Polarized eN, eA collider
- <u>Many complementary processes at one facility</u>
- Wide kinematic range (x, Q^2)

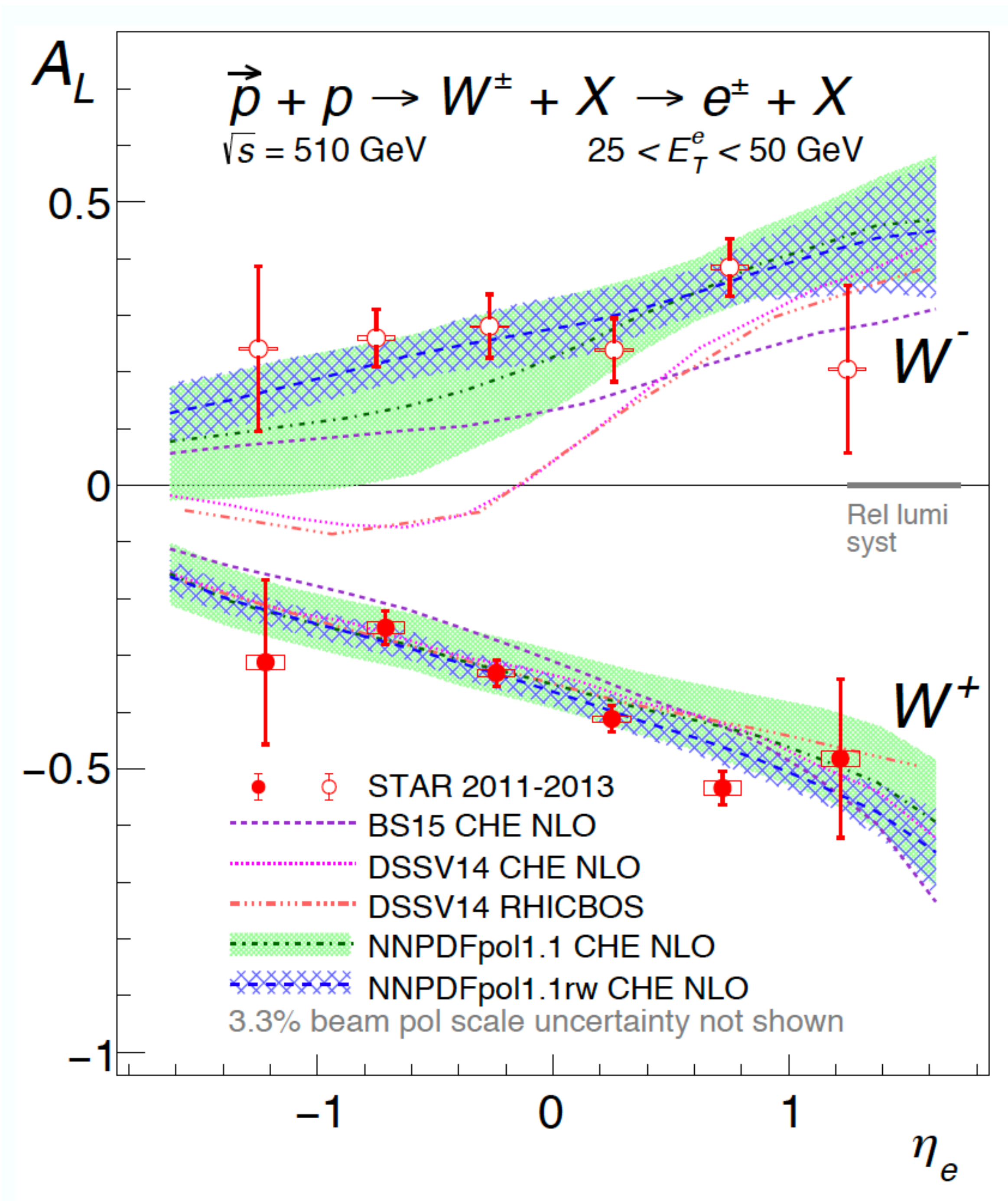


Summary

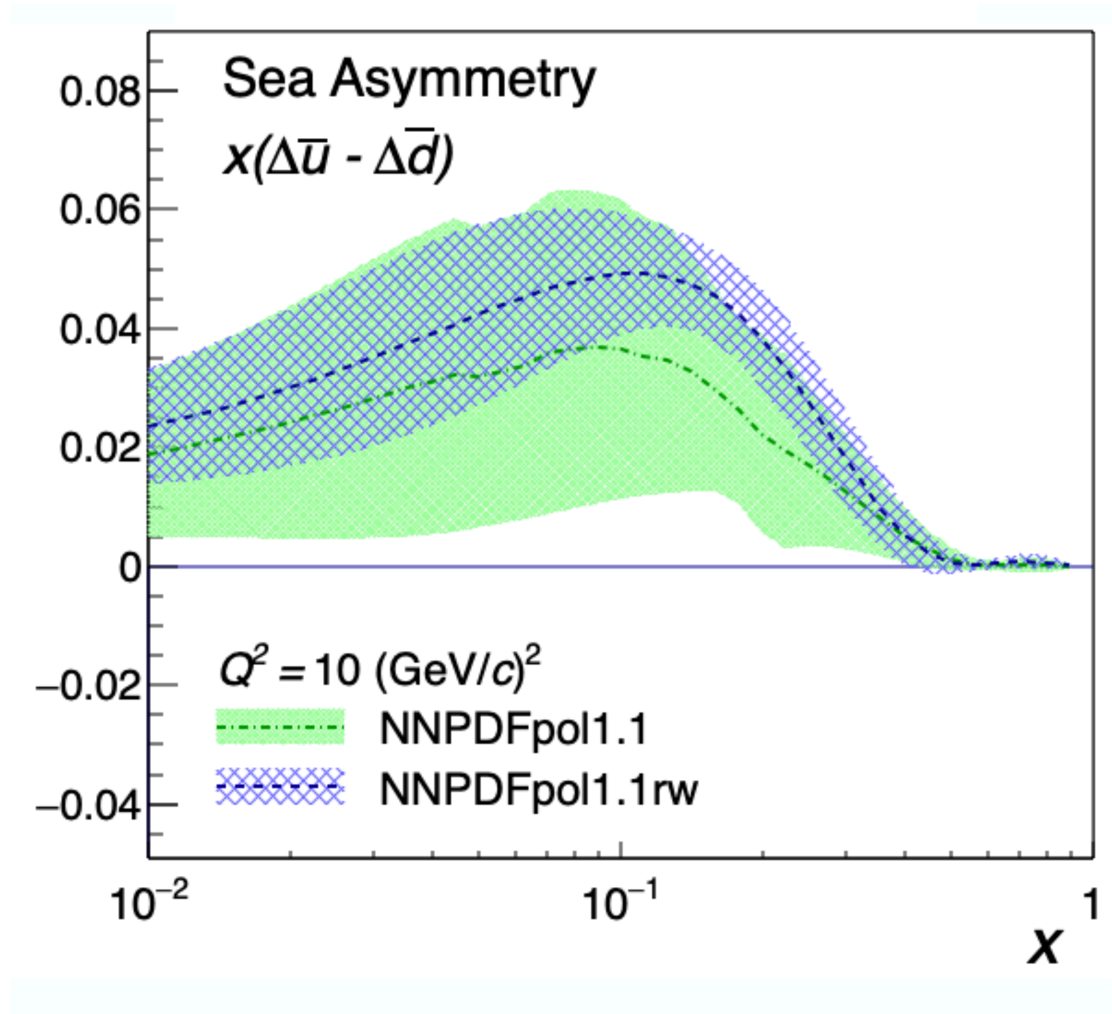
- PHENIX spin program has been playing a key role for our understanding of QCD with unique data sets
    - Confirmed non-zero gluon polarization
    - W program to disentangle quark and antiquark helicity distributions
    - Various observables to understand transverse spin asymmetries
    - p+A data provides new surprises and insights
- More new results to come and exciting future opportunities

Backup

Flavor asymmetry of polarized sea



PRD 99, 051102(R) (2019)



- Polarized light sea quark asymmetry
- Almost same size as its unpolarized counterpart, but opposite sign

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TMD vs Collinear

Ann.Rev.Nucl.Part.Sci. 65 (2015) 429-456

Transverse Momentum Dependent distributions

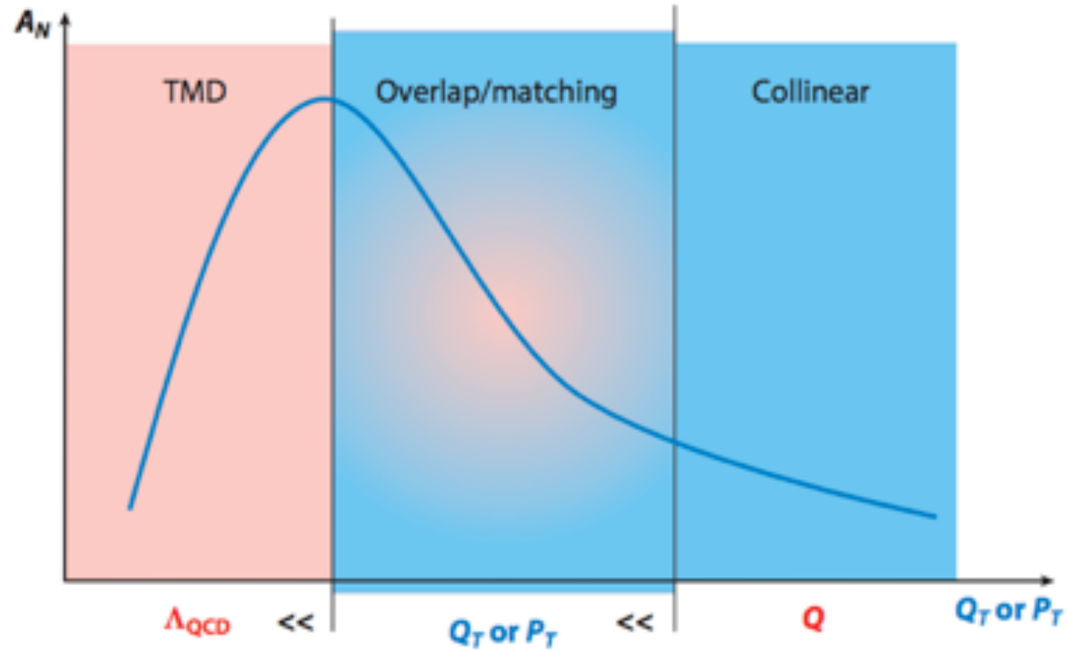
$$f(x, k_\perp; Q^2)$$

Need two observed scales Q^2 and p_T

$Q >> Q_T \sim \Lambda_{QCD}$

CSS (Collins-Soper-Sterman) evolution

Observables in p +p:
DY, W/Z production
hadrons within jets (TMD FF)



pT << Q

pT ~ Q

both formalisms are applicable and related

Collinear distributions

$$f(x; Q^2)$$

Need one observed momentum scale

$Q, Q_T >> \Lambda_{QCD}$

DGLAP evolution

Beyond leading twist:
Twist-3 effects

Observables in p+p:
Inclusive jet and hadrons,
HF, direct photon