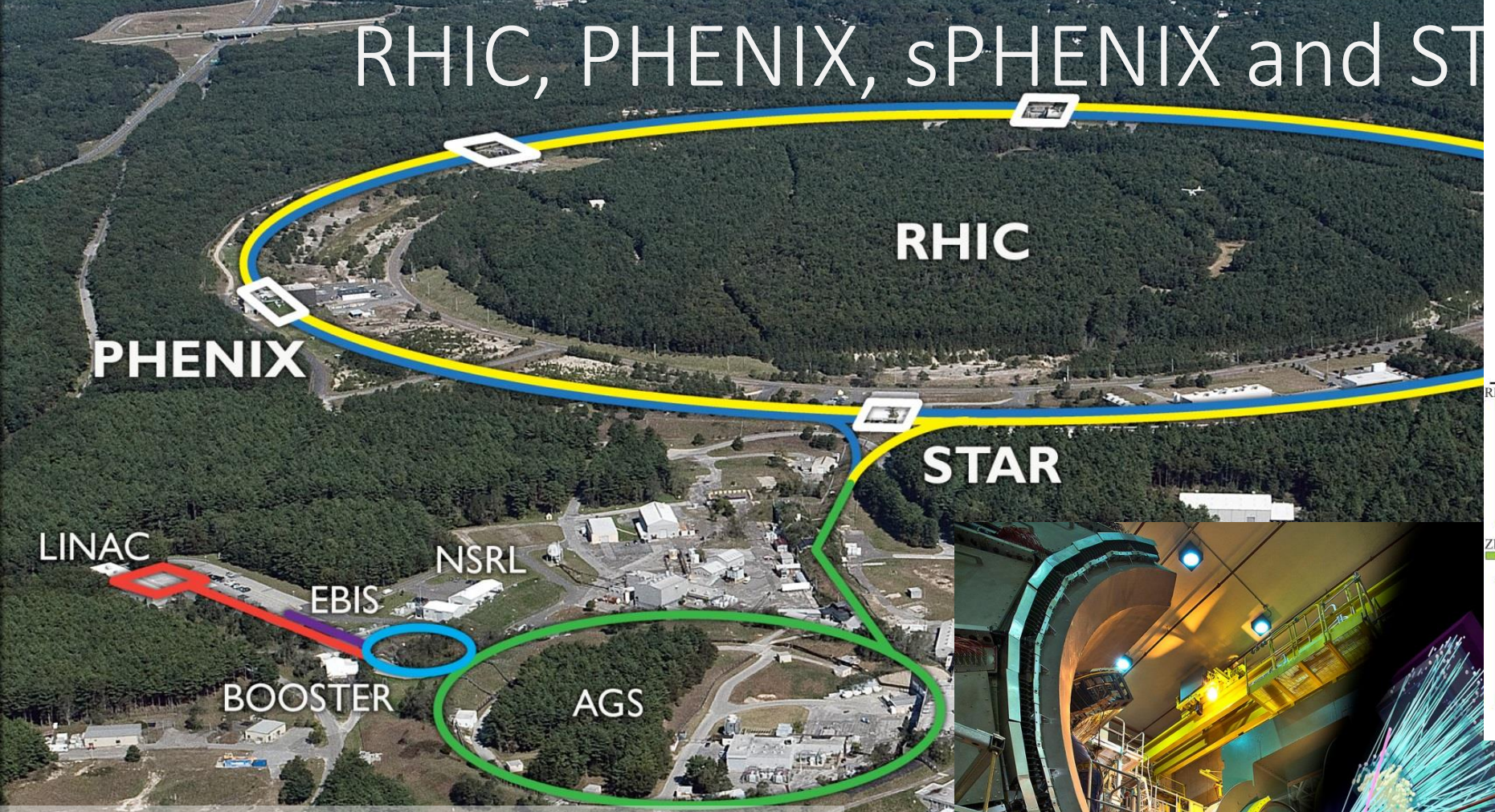
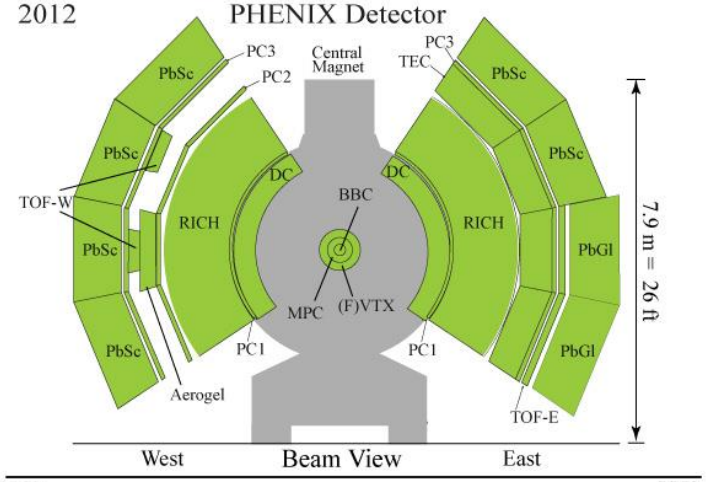
PHENIX cold QCD and Spin measurements

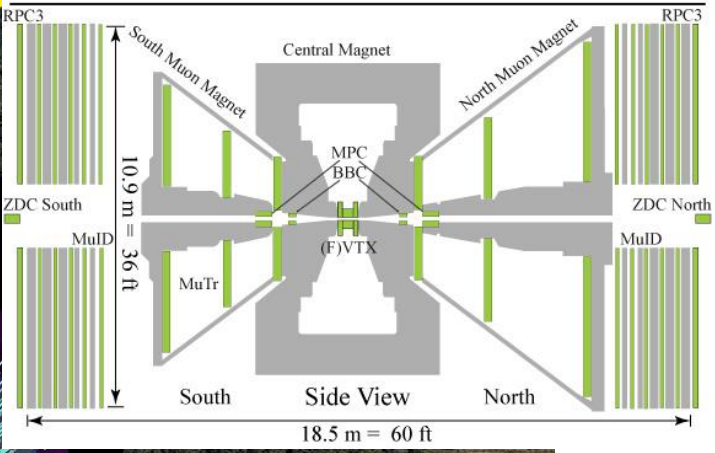
Hard Probes 2024,
Nagasaki
September 23

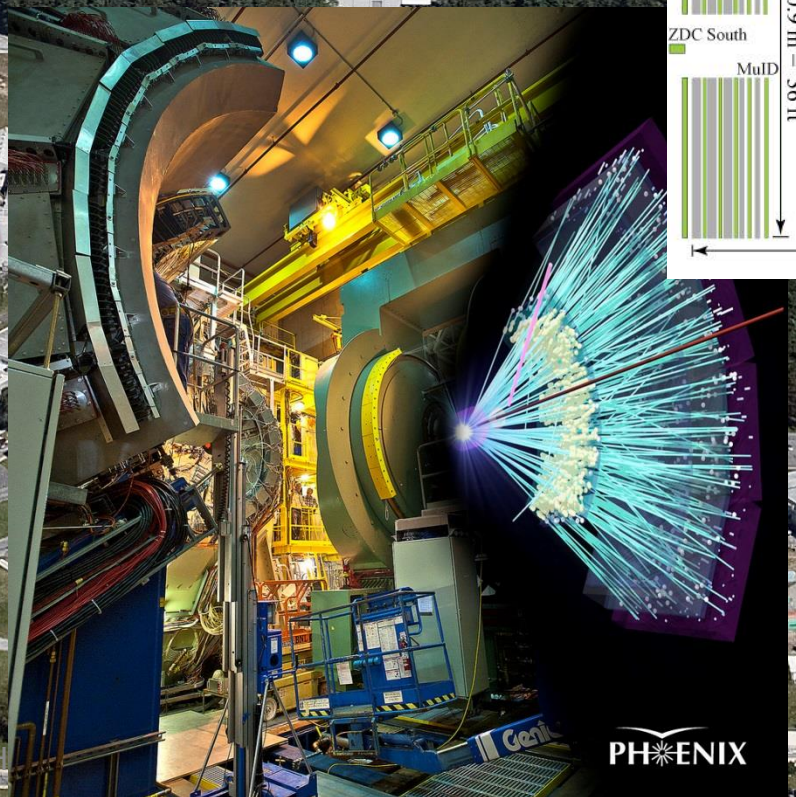
Ralf Seidl (RIKEN)

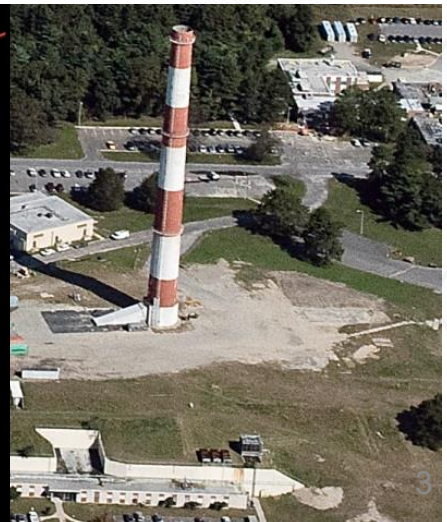
RHIC, PHENIX, sPHENIX and ST



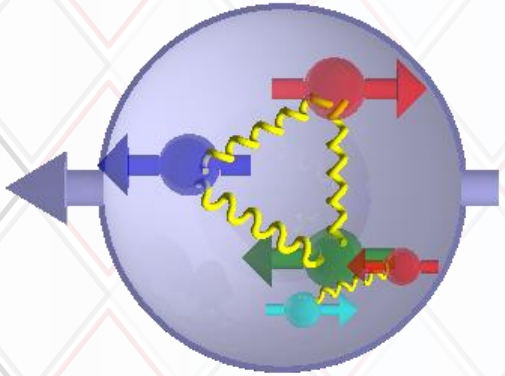








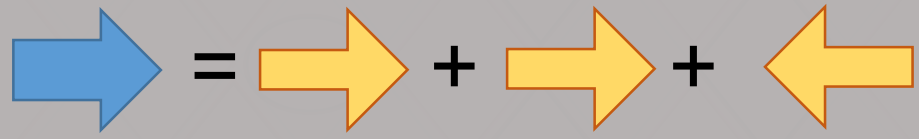
- Polarized proton beams from $\sqrt{s}$ of 62-510 GeV
- pA, AA collisions up to 200 GeV
- Spin rotators around PHENIX and STAR to select long. or transversely polarized beams
- Global and local polarimetry



Helicity PDFs, longitudinal spin

The Spin sum rule

Naïve Quark Model picture: 3 valence quarks make up the spin of the nucleon:



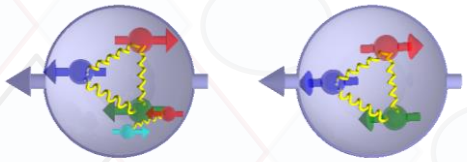
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$ Jaffe, Manohar

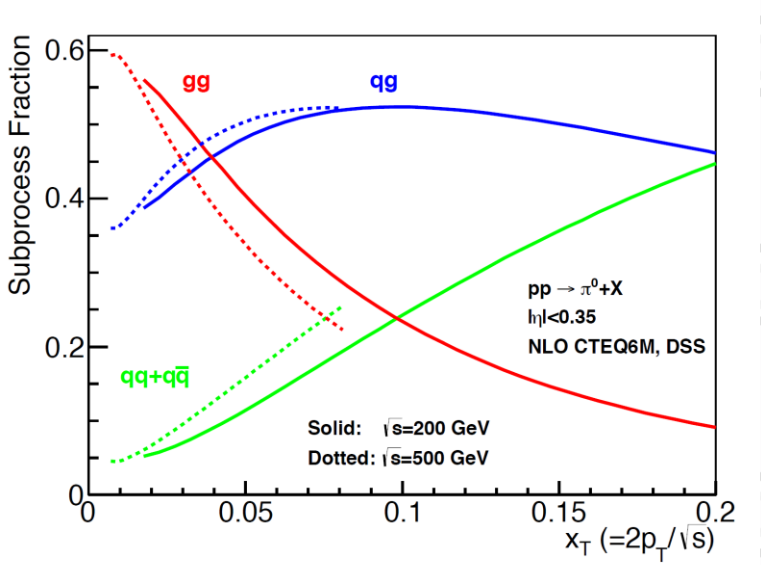
Quark spin | Gluon spin | Orbital angular momentum

$$\Delta\Sigma = \int dx \left[(\Delta u(x) + \Delta\overline{u}(x)) + (\Delta d(x) + \Delta\overline{d}(x)) + (\Delta s(x) + \Delta\overline{s}(x))\right]$$

- Spin Crisis (1980s): Quark spin contributes only little
- $\Delta\Sigma$ and ΔG can be accessed in longitudinally polarized (Sl)DIS and pp collisions (currently for x>0.01)
- Where is the rest of the spin? Gluons? Lower momentum fractions? Orbital angular momentum?

Hard processes at RHIC





- Most processes are dominated by gluon hard interactions at RHIC energies

➔Acccess to Gluon related spin and transverse spin effects!

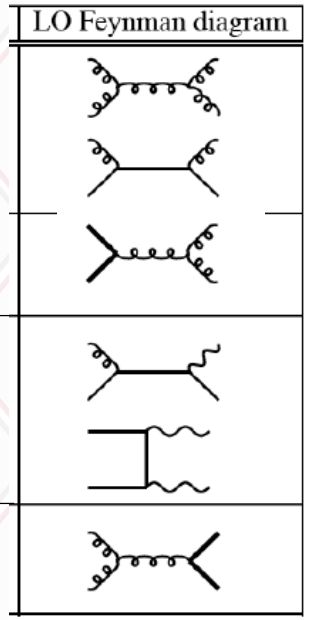
- Relative contributions different for different final states (flavor sensitivity)

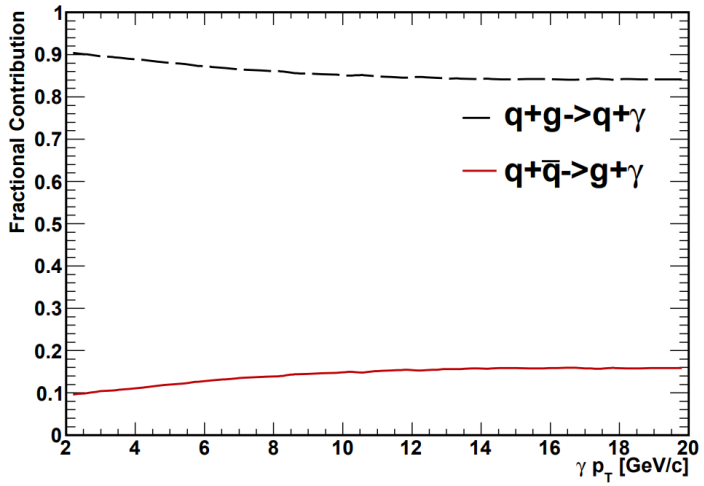
p+p→pion(s),eta + X

p+p→jet(s)+ X

p+p→γ + X

p+p→ B,D,J/ψ + X



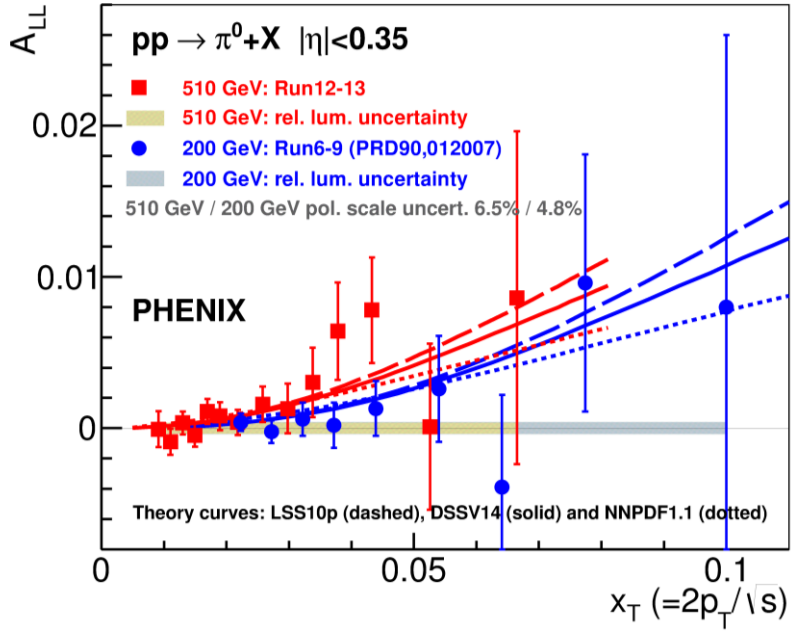


Underwood`92 Direct photons as golden channel for RHIC spin physics

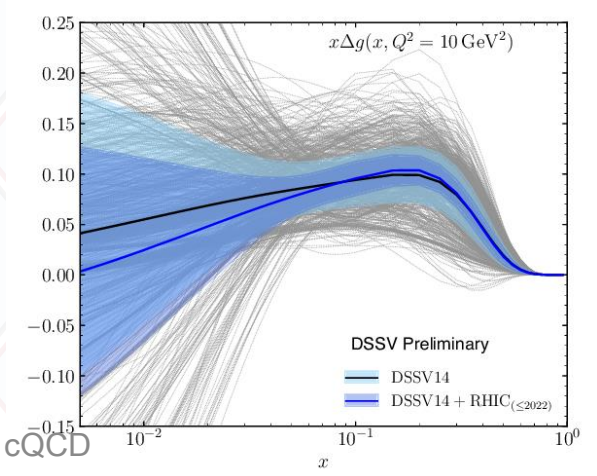
$\Delta g(x)$

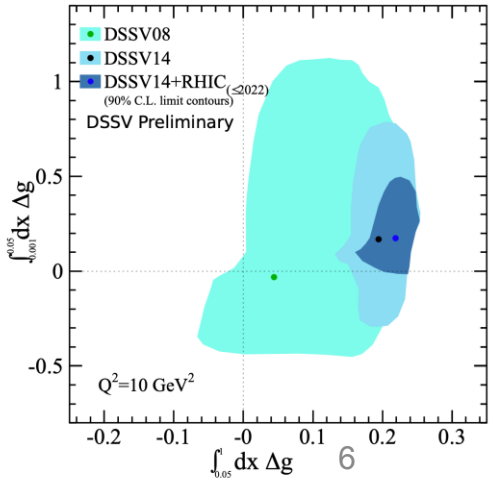
Nonzero Gluon spin: access to lower x with higher energies

- Nonzero gluon polarization established with RHIC √s = 200 GeV data
- RHIC √s = 510 GeV data (>2011) confirmed it in workhorse (jet, pion) measurements
- Extend access to lower x by higher energy (now~ 10^{-2})



PRD 93 (2016) 011501

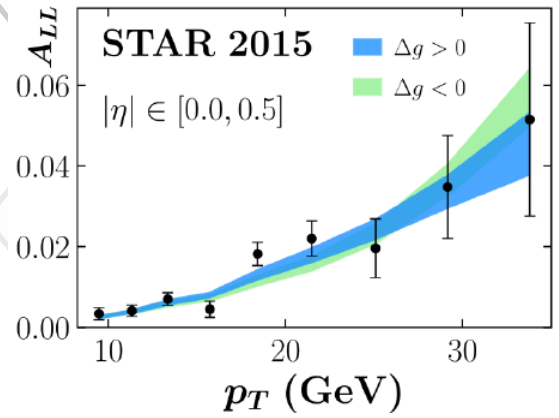


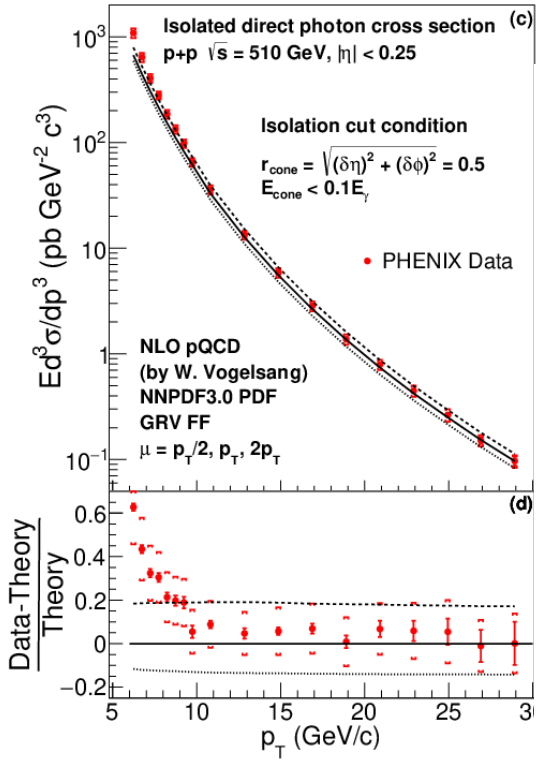


First direct photon xsec and A_{LL} at 510 GeV

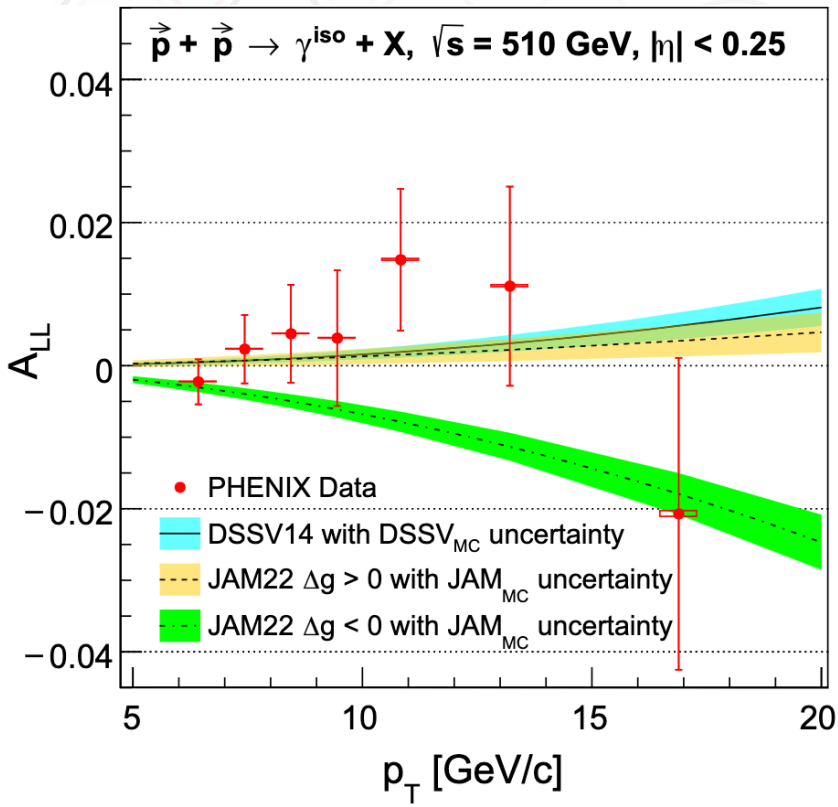
$\Delta g(x)$

JAM: ambiguity* of gluon spin sign?
PRD 105 (2022) 074022

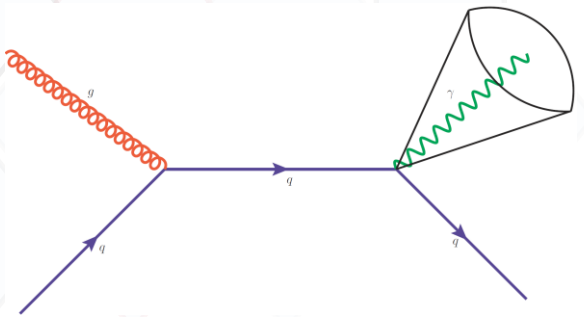




PRL 130 (2023) 251901



- Part of initial RHIC-Spin goals in the `90s
- Theoretically, the Golden channel to access gluon polarization as hard interaction mostly q-g
- Since EM process, statistically limited but consistent with global fit results
- Clear preference for positive gluon polarization in measured range

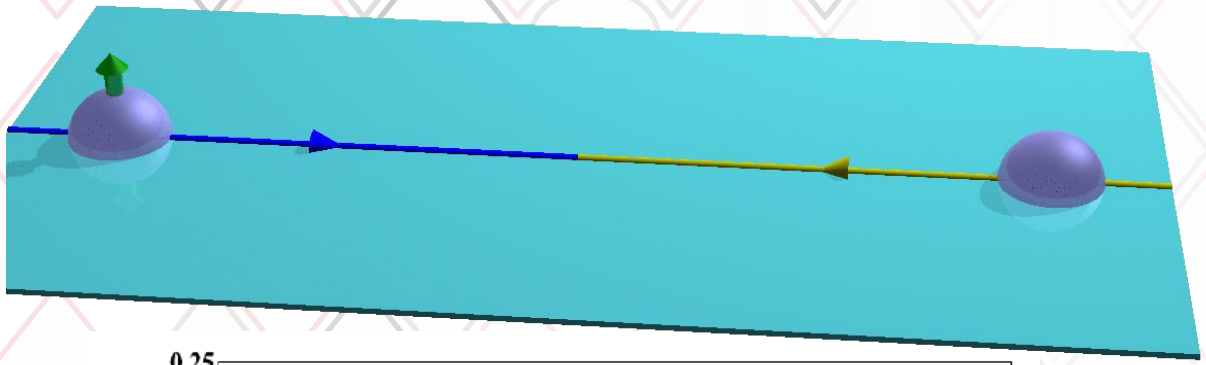


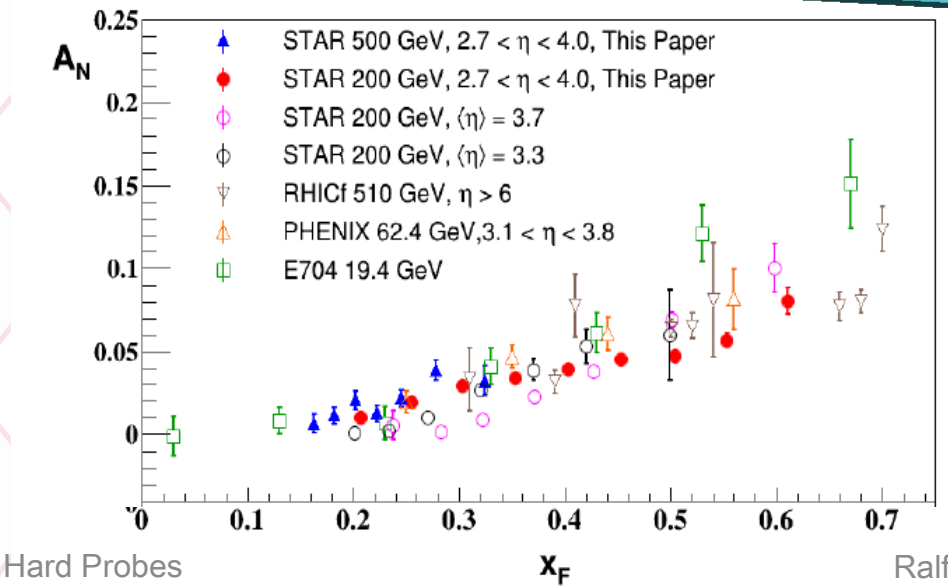
DOE Science Highlight

Transverse Single spin asymmetries (TSSAs)

- Left-Right asymmetries :

$$A_N = \frac{1}{P}\frac{N^L - N^R}{N^L + N^R}$$





- Relative to the polarized proton spin direction more particles get produced to the left than to the right wrt. spin direction
- The cross section is spin (and azimuthal angle) dependent
- Initially expected to be zero in perturbative QCD (helicity-flip of nearly massless quarks) - G. L. Kane, J. Pumplin, and W. Repko *PRL***41**, 1689 (1978):

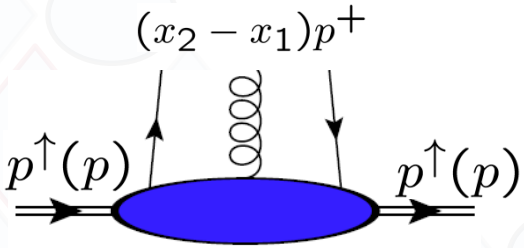
$$A_N \propto \frac{m_q \alpha_S}{P_T} \approx 0.001$$

TSSAs at RHIC→Quark-gluon dynamics!

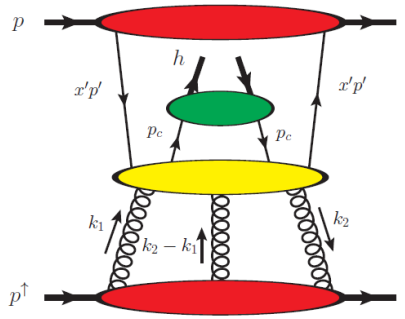
- Sivers and Collins effects rely on an explicitly transverse momentum dependent (TMD) framework where two scales are observed: high scale (typically Q^2) and intermediate scale (transverse momentum $P_T << Q^2$)
- In inclusive pp measurements usually only one, hard scale accessible (transverse momentum P_T)

→requires higher Twist, collinear framework, contributions are multi-parton correlators (both in initial state and final state)

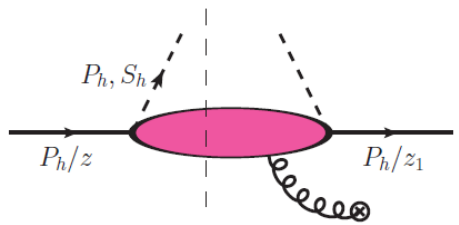
- Both frameworks found to be related via moments over intrinsic transverse momenta



q-g correlation (↔ quark Sivers)



g-g correlation (trigluon ↔ gluon Sivers)



q-g FF correlation (↔ Collins)

Single spin asymmetry contributions in p+p

pol proton PDF* unpol proton PDF* FS particle FF*

$$A_N \approx \sum_{a,b,c} \phi^{(3)}_{a/A}(x_1, x_2, s) \otimes \phi_{b/B}(x') \otimes D_{c\to C}(z)$$

$$+ \sum_{a,b,c} \delta q_{a/A}(x, s) \otimes \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes D_{c\to C}(z)$$

$$+ \sum_{a,b,c} \delta q_{a/A}(x, s) \otimes \phi_{b/B}(x') \otimes D^{(3)}_{c\to C}(z_1, z_2)$$

a,b/c initial/final parton flavors
A,B/C initial/final hadron/particle types

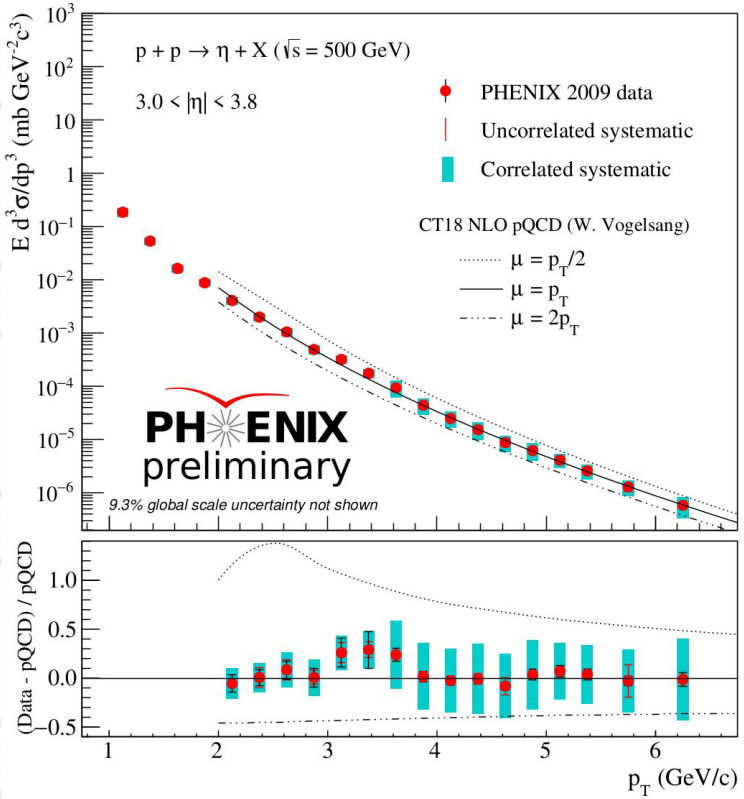
Efremov, Teryaev Phys.Lett.B 348 (1995) 577
Qiu, Sterman Phys.Rev.D 59 (1999) 014004
Kanazawa, Koike Phys.Lett.B 478 (2000) 121-126
Metz, Pitonyak Phys.Lett.B 723 (2013) 365-370

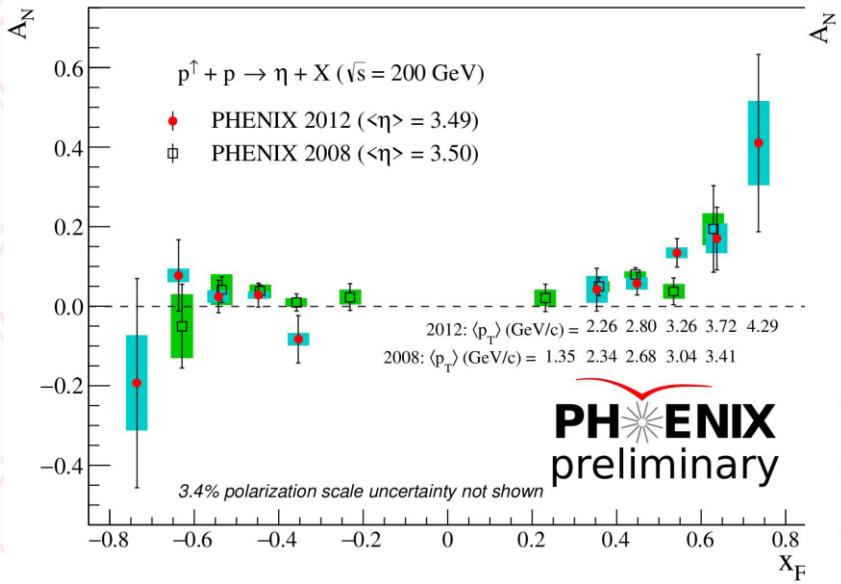
- Generally three pieces to p+p single transverse spin asymmetries:
  - Twist three correlation functions (quarks or gluons) in polarized proton ↔ Sivers function
  - Twist three correlation function in unpolarized proton (with transversity) ↔ Boer Mulders function
  - Twist three correlation in fragmentation ↔ Collins function

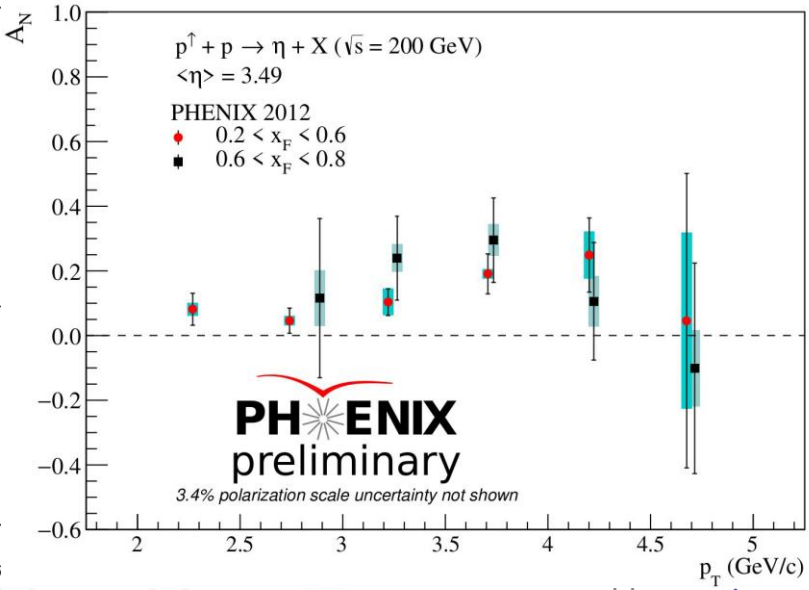
➔Different final states single out different contributions (via hard processes)

Forward eta cross sections and A_Ns

- First forward η cross sections at 500 GeV → more impact on η FFs
- Update of forward η A_N measurements with better statistics
- Asymmetries sizeable, maybe a hint of turnaround expectedat higher p_T due to HT nature of asymmetries



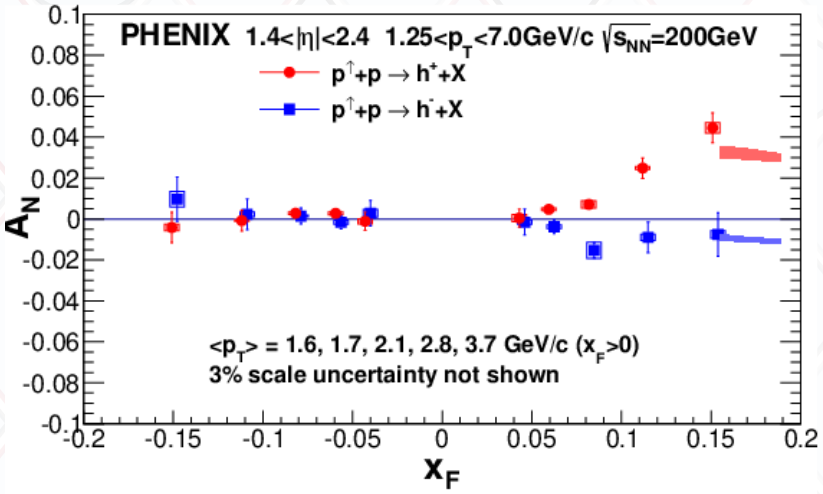


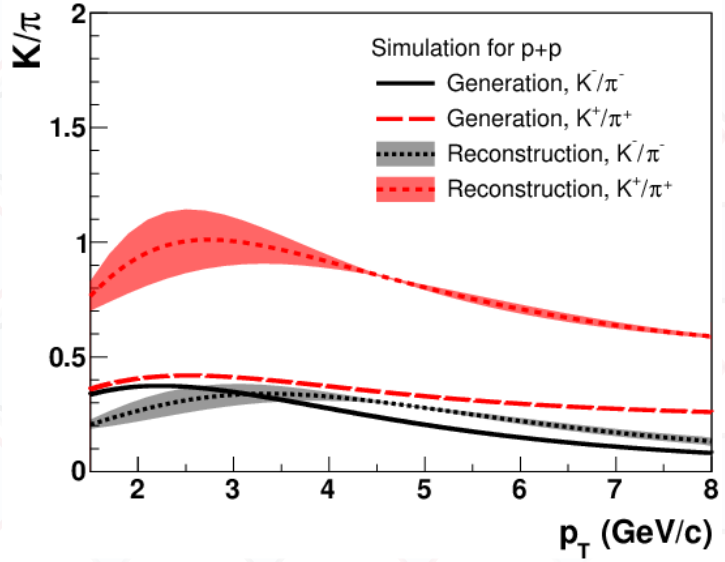


Forward charged hadron A_ns

- Also more detailed forward ($1.4<\eta<2.4$) charged hadrons
- For proton collisions sizeable positive asymmetries for h^+, slightly negative for h^-
- h^- results expected due to mix of pions (negative) and kaons (positive)
- Negative kaons are enhanced due to the absorbing material

PRD 108 (2023) 072016





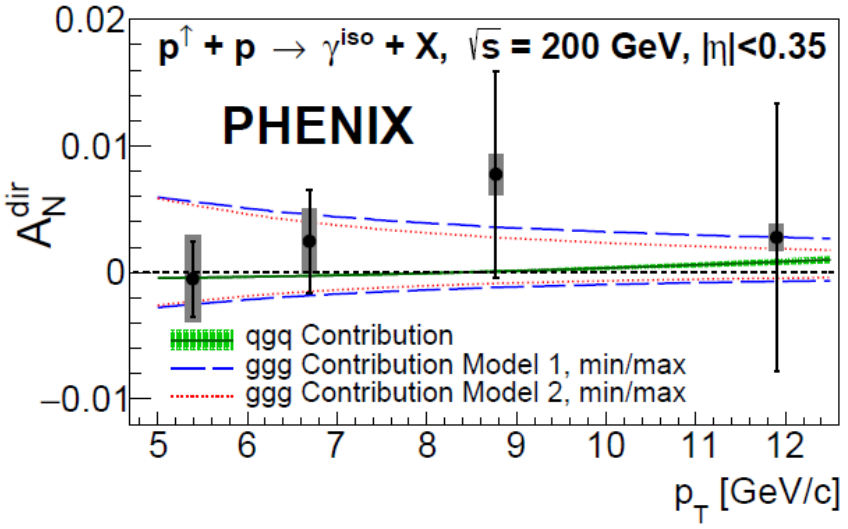
First direct photon A_Ns

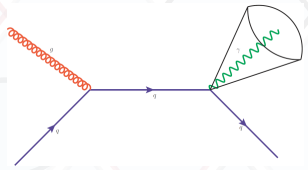
- First direct photon A_N extracted at RHIC
- Mostly sensitive to initial state effects (no fragmentation) → quark-gluon and gluon-gluon correlation functions
- Power to constrain gluon-gluon correlation function well, since quark impact expected to be small

RIKEN Press release: https://www.riken.jp/press/2021/20211015_1/index.html

BNL Press release: https://www.bnl.gov/newsroom/news.php?a=119077

PRL 127 (2021) 162001

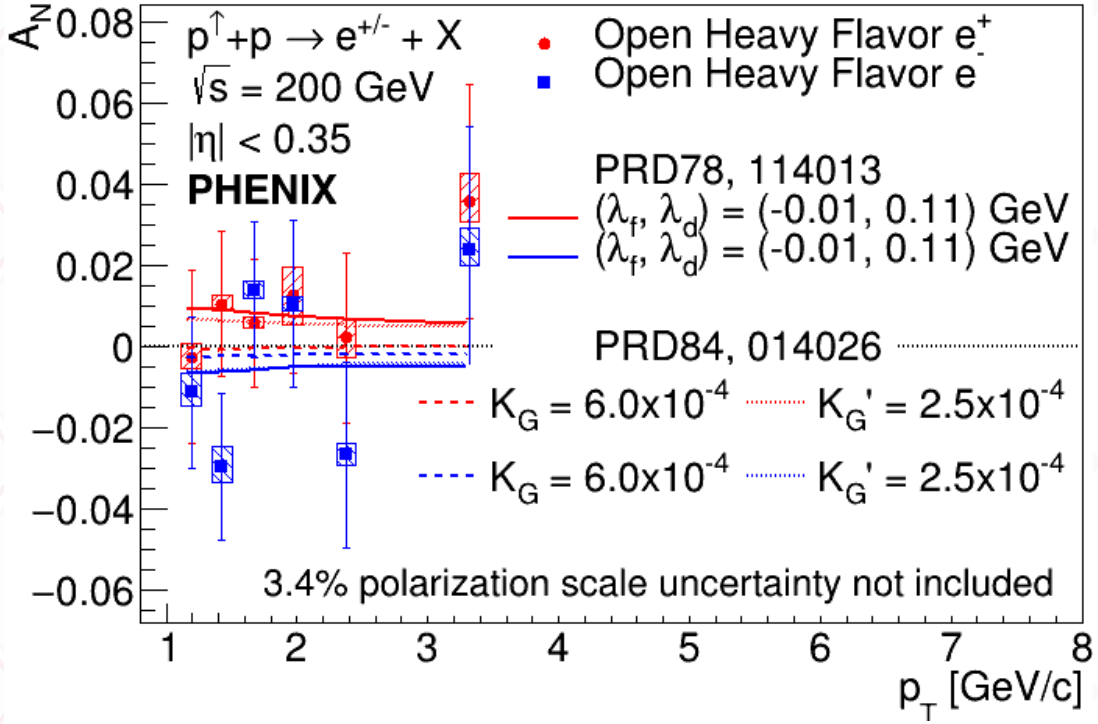


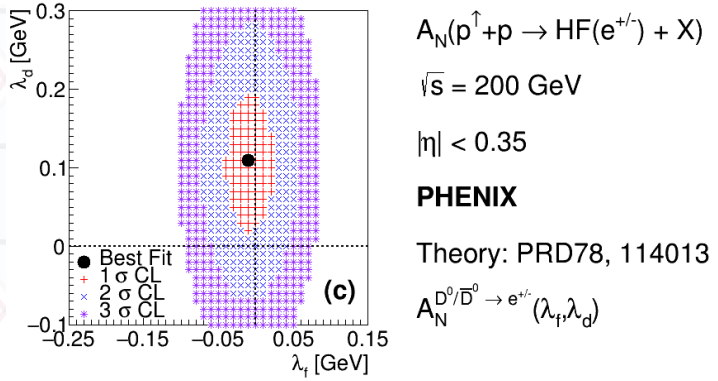


Heavy Flavor electron A_Ns

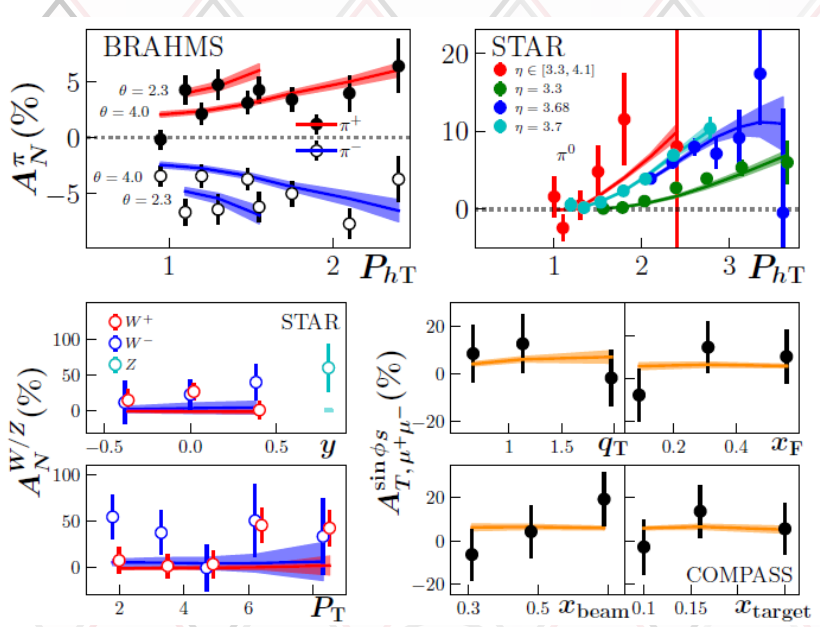
PRD 107 (2023) 052012.

- Almost only gluon related, no final state effects → tri-gluon correlation
- Potential to constrain parameter ranges in D meson A_N theory calculations: PRD78, 114013 (Z.B. Kang, J.W. Qiu, W. Vogelsang, F. Yuan)
- Comparison or charges provides further sensitivity



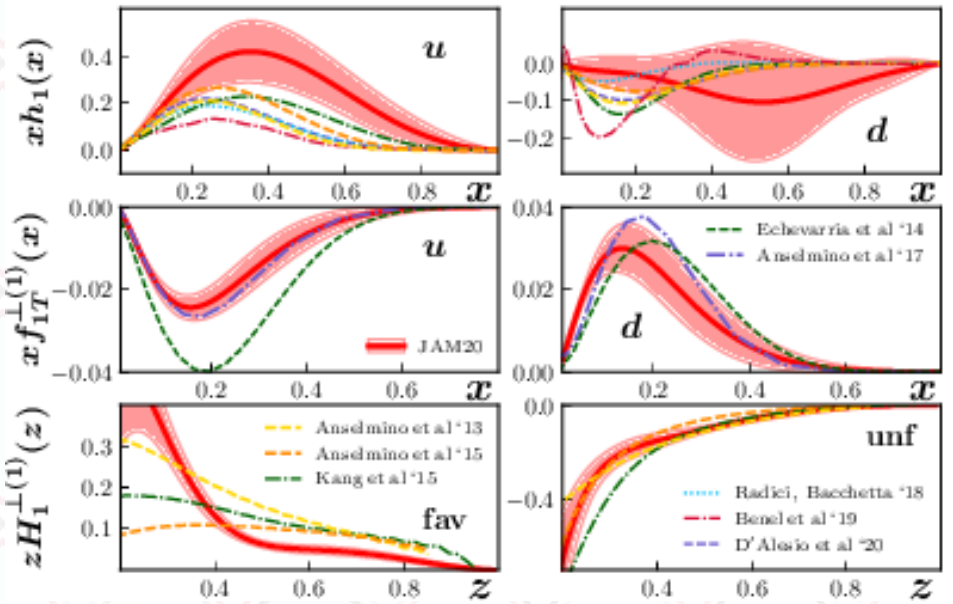


Where to go from here? Global fits on transverse quark-gluon structure

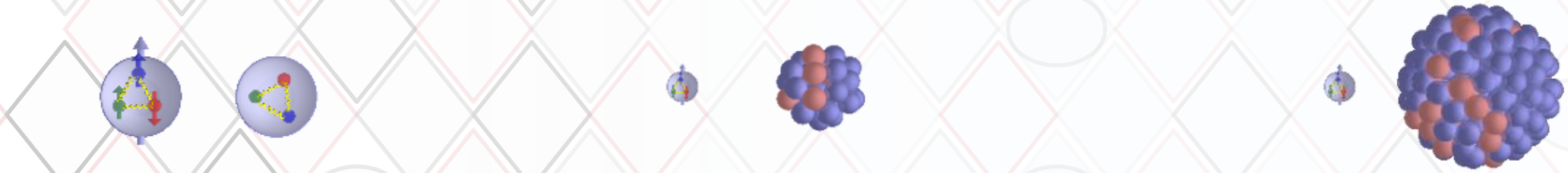


RHIC, SIDIS, DY included

Cammarota et al, PRD 102 (2020) 054002



- Recent central rapidity PHENIX results (π,η,Heavy flavor electons, direct photons) NOT yet included
- Impact on gluon Sivers function (tri-gluon correlator) expected

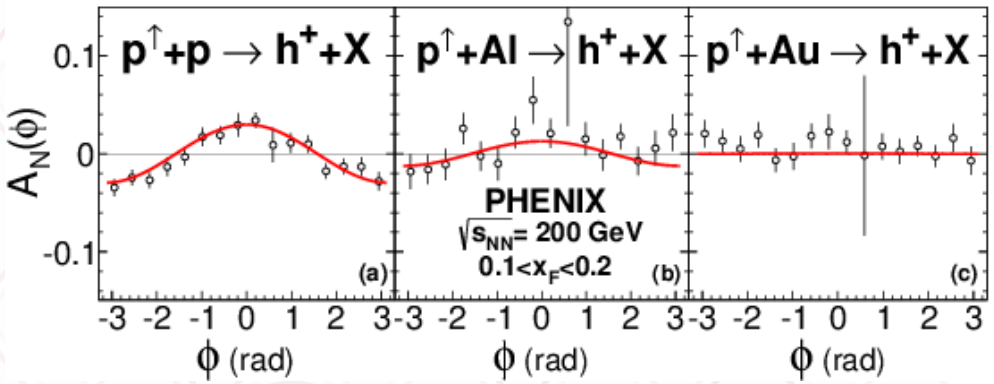


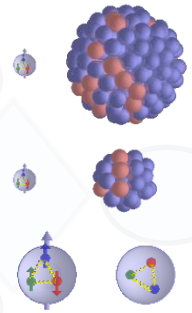
Nuclear PDFs and spin effects

A dependence of A_Ns

- Asymmetries consistent with $A^{1/3}$ dependence as (initially) predicted by some CGC related nuclear effects (Hatta`17)
- No A dependence is ruled out
- Also consistent with suppression with increasing number of binary collisions
- Lower suppression seen by STAR for neutral pions at slightly higher x_F
- Probed x and scale too large for expected CGC effects! (S.Benic and Y.Hatta, PRD99(2019), 094012 - Twist-3 fragmentation + gluon saturation)
- $A^{-1/3}$ dependence also suggested by Gao et.al *PRC* 81 (2010) 065211

Phys.Rev.Lett. 123 (2019) 122001





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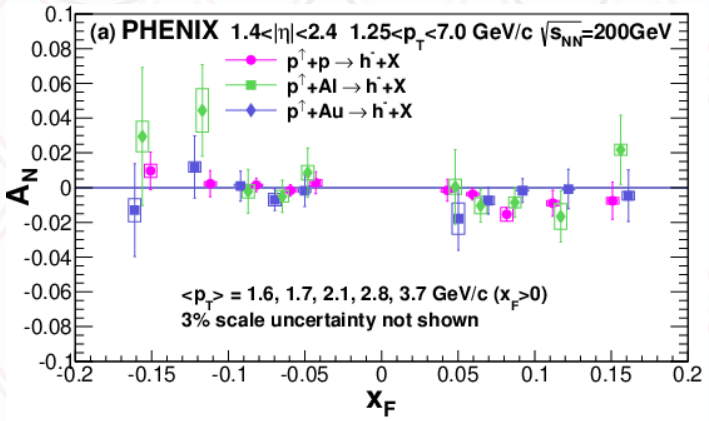
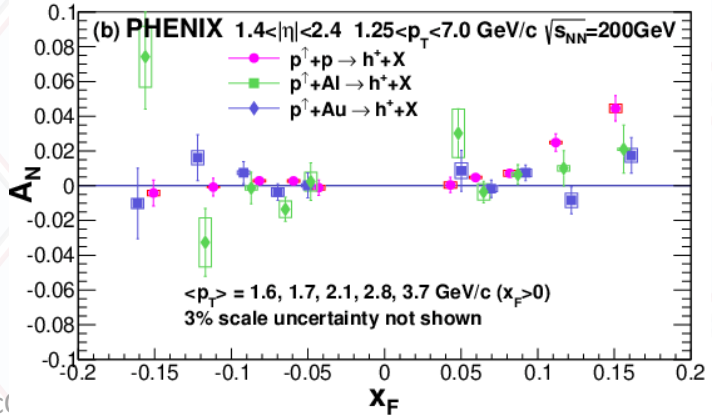
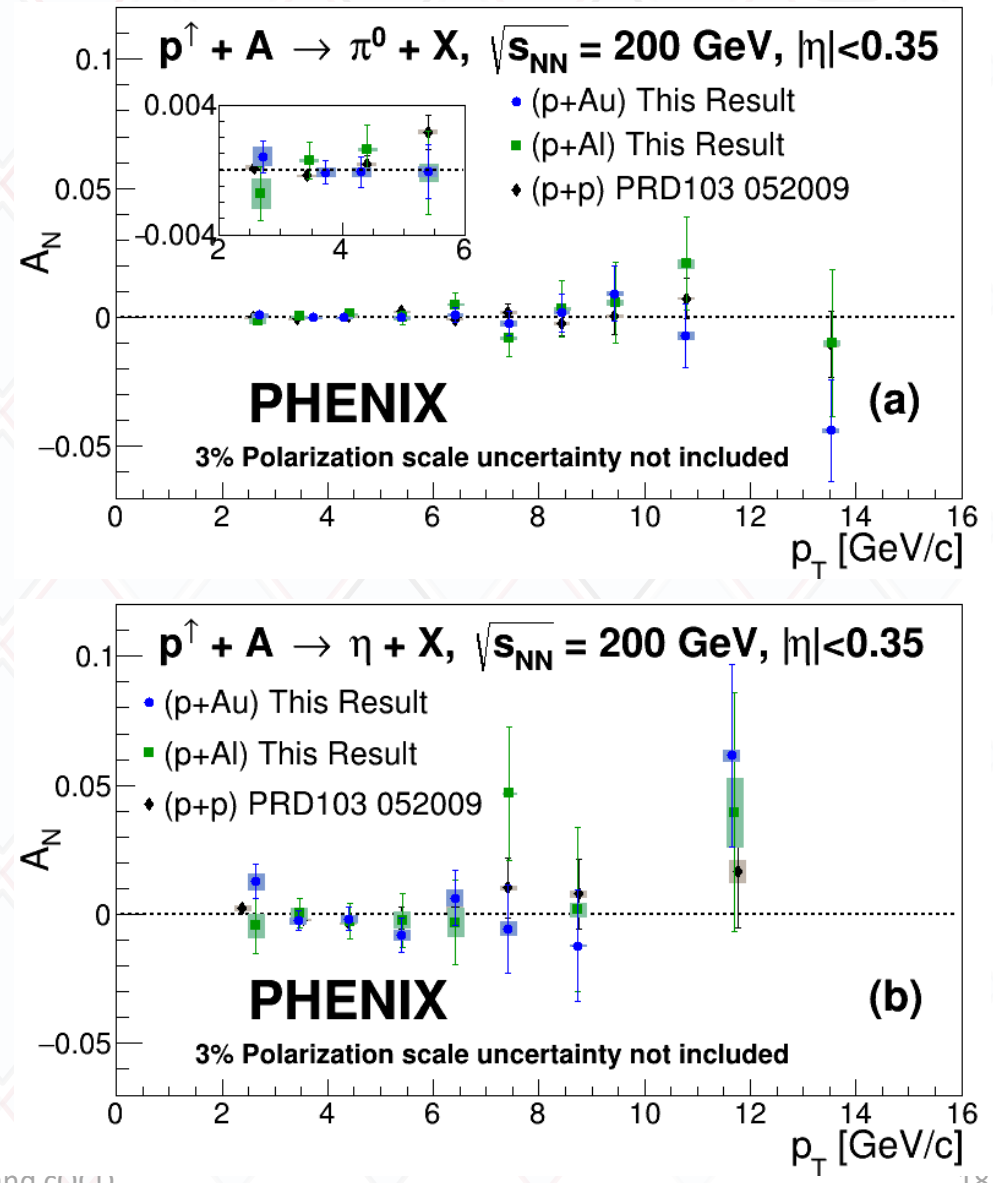




Also central p+A asymmetries

- Recently also neutral pion and eta results obtained from p+Al and p+Au collisions at √s 200 GeV
- A dependence of central rapidities consistent with zero
- Not surprising since p+p asymmetries have previously been found to be zero within less than a percent

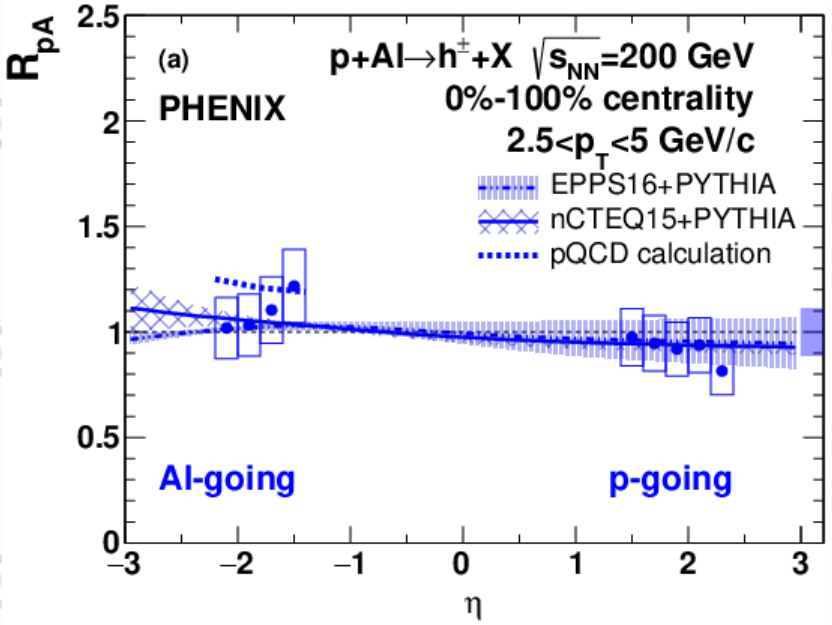
PRD 107 (2023) 112004

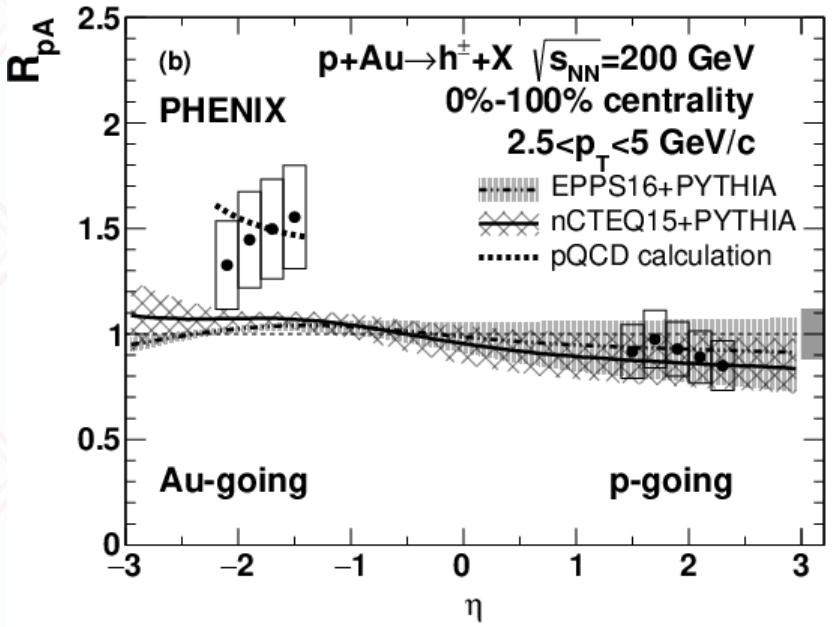


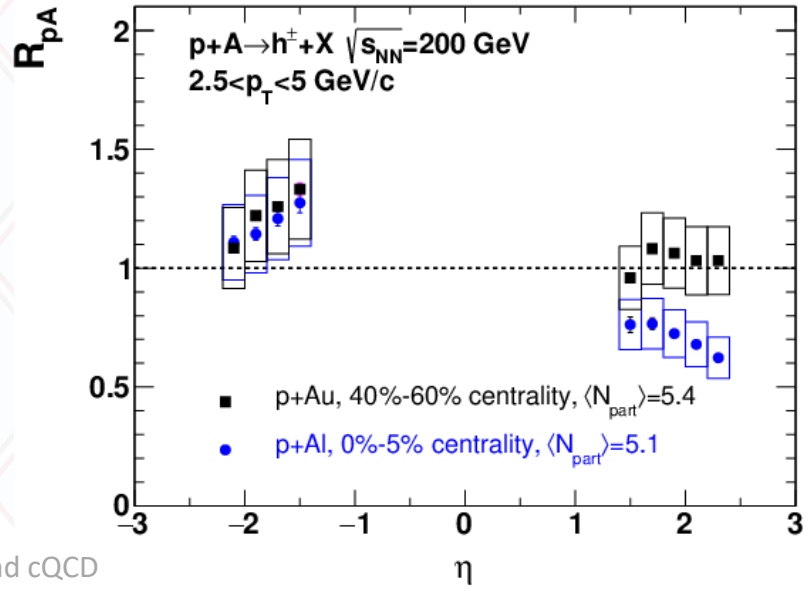
Nuclear modification of fw/bw charged hadrons

PRC 101 (2020) 034910

- Marginal suppression seen in p-going direction,
- Enhancement seen in Au-going direction
- However, suppression visible for more central collisions



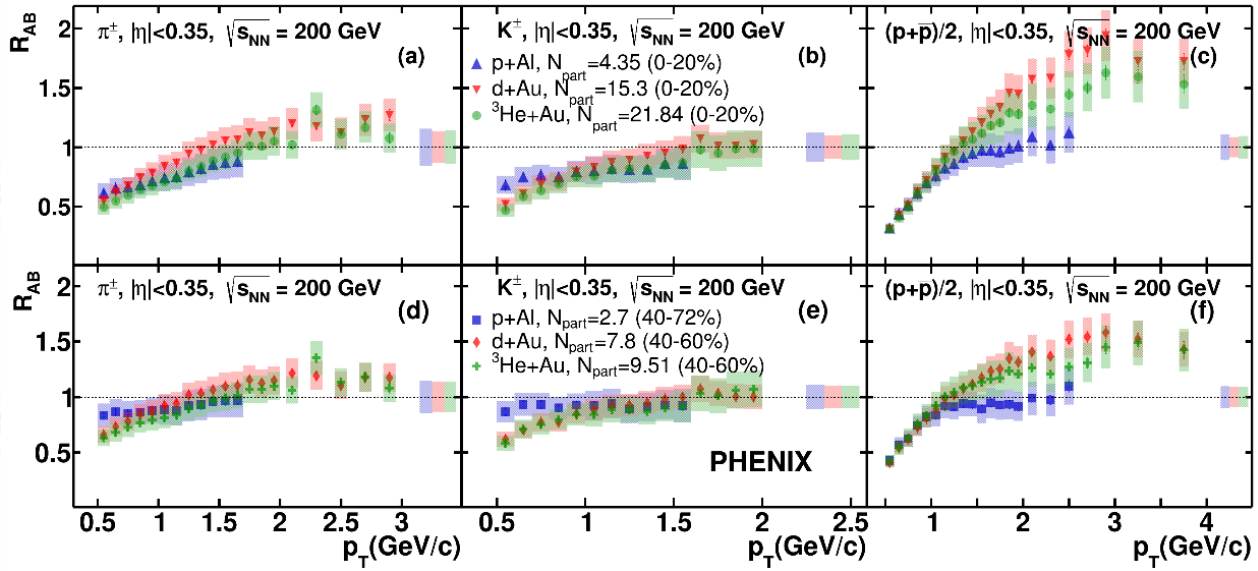




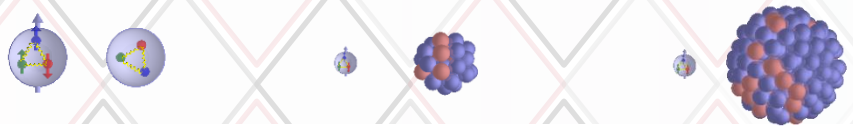
Hadron spectra in p+Al, d+Au and ^{3}He+Au at central rapidities

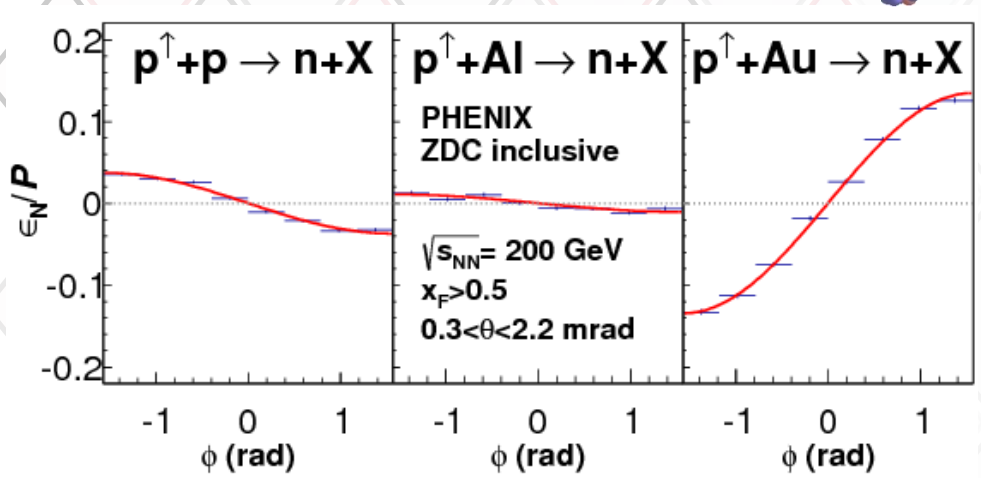
- Similar suppressions seen between d+Au and ^{3}He+Au at low P_T, but slightly more pronounced for ^{3}He
- Kaons at low P_T less suppressed than other systems
- At high P_T proton enhancement in larger systems over p+Al

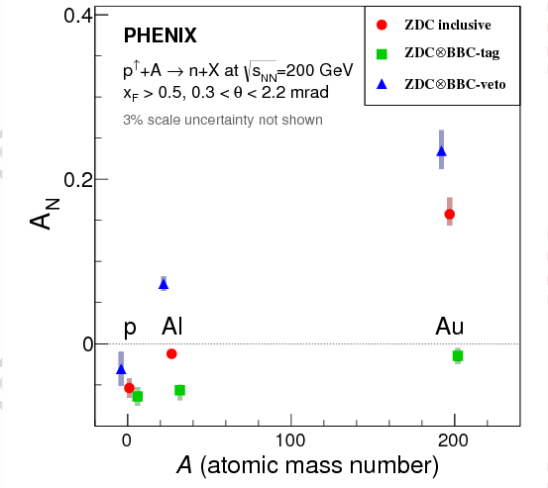
PRC 109 (2024) 054910



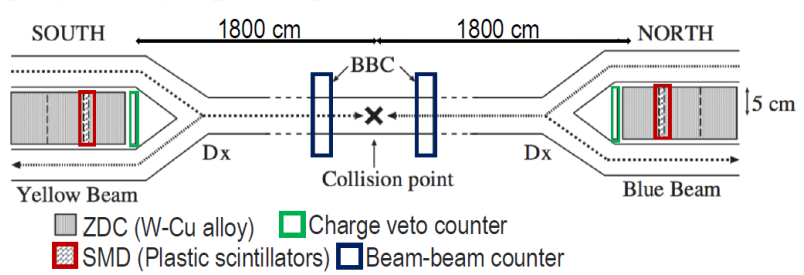
neutron asymmetries from p+p to p+A







[PRL 120 (2018), 022001]

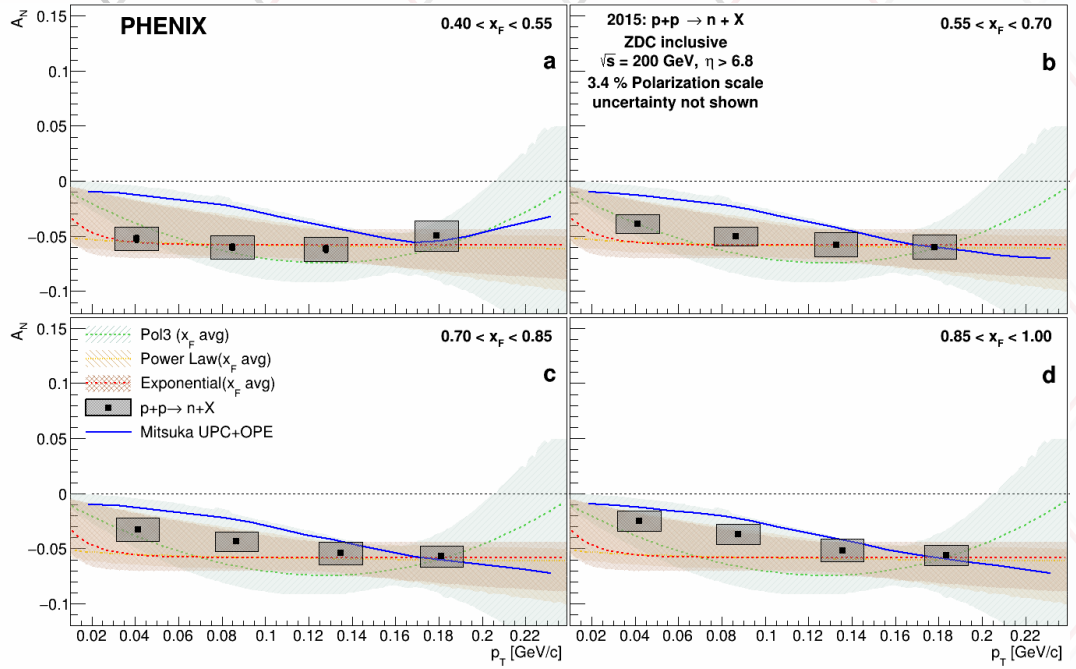


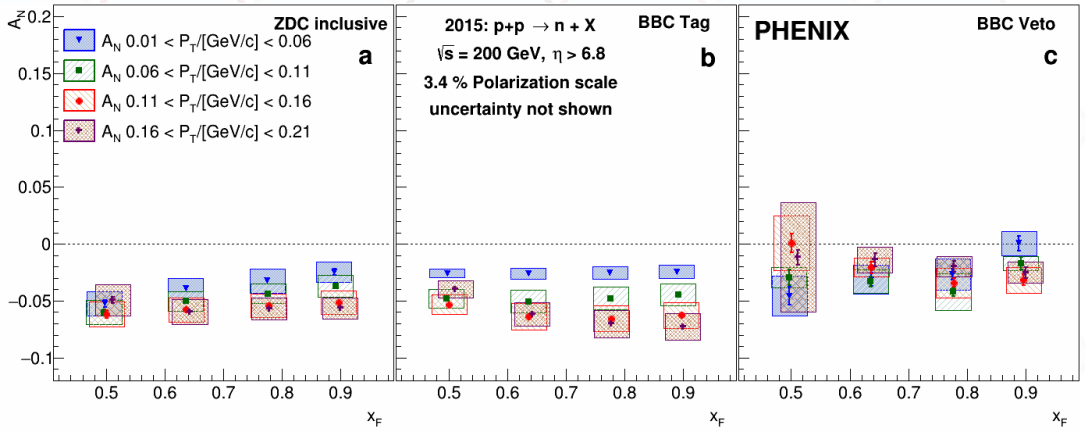
- Unexpectedly large A dependence in neutron asymmetries, sign change
- OPE model does not predict such a change in asymmetries
- Coincidence with charged particle activity in forward and backward region (BBC) enhances hard interactions → asymmetries stay negative
- Veto enhances UPC contribution → p+Al asymmetries already positive

→study also the actual x_F and P_T dependence for actual interplay

Inclusive neutron asymmetries in p+p

PRD 105 (2022) 032004





Dashed areas: best parameterizations of x_F integrated asymmetries using Pol3, Power law or Exponential

- Magnitude increasing with P_T except for low x_F
- Only weak x_F dependence in hadronic events, slightly larger in BBC vetoed events
- Comparable to (OPE dominated) model curves

Very forward neutron asymmetries in p+Au

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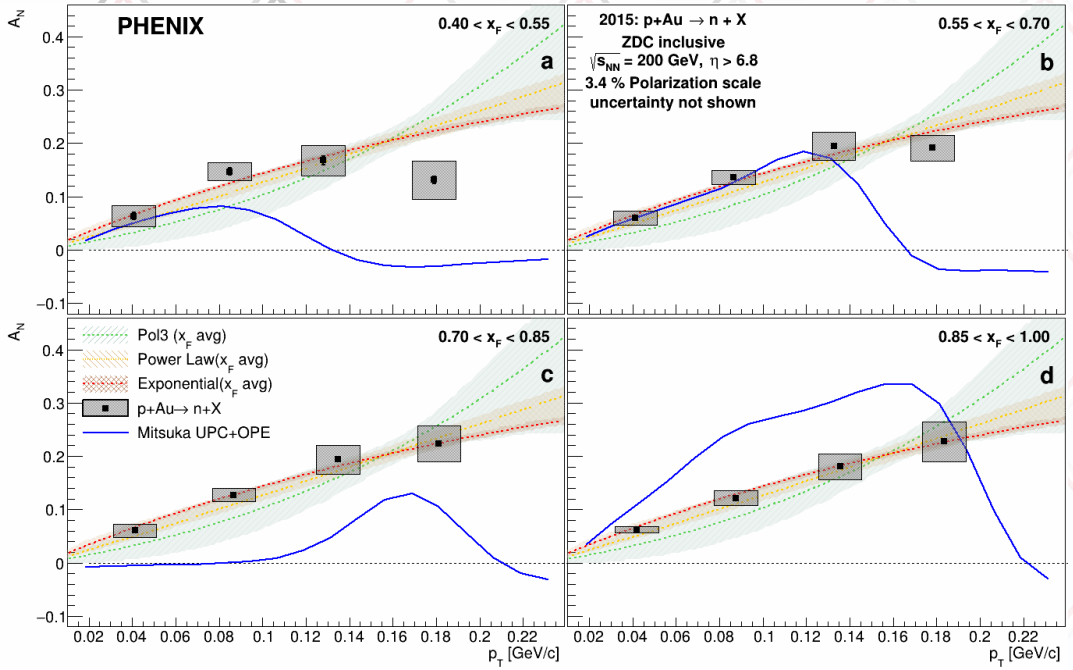

- Large, increasing asymmetries seen with likely a hint of decrease at high P_T for lower x_F
- Roughly similar behavior in model seen but details shifted – possibly due to inclusion of single pion resonances only

Model calculations:
Mitsuka PRC95 (2017) 044908 +
Kopeliovich et al: PRD 84 (2011) 114012 (OPE)

Summary

- Longitudinal spin measurements from PHENIX for various final states pin down gluon and sea quark spins
- “Golden Channel” direct photon A_{LL} to clearly provide sign of gluon spin contribution, also from di-jet measurements
- Improved measurements for transverse spin asymmetries in p+p collisions will provide more information about quark-gluon and tri-gluon correlations
- nontrivial A dependence in inclusive hadron asymmetries
- More results on nuclear PDFs via forward and central hadron production
- Far forward neutron asymmetries with A dependence through UPC contribution, now also x_F and p_T dependence