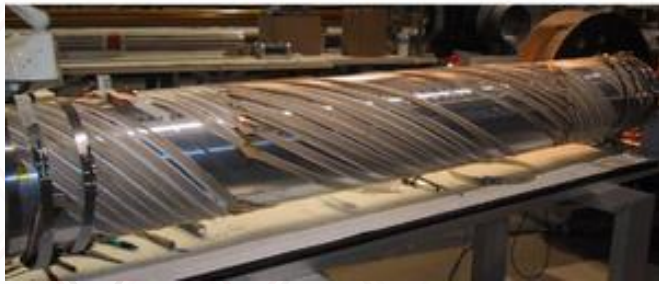
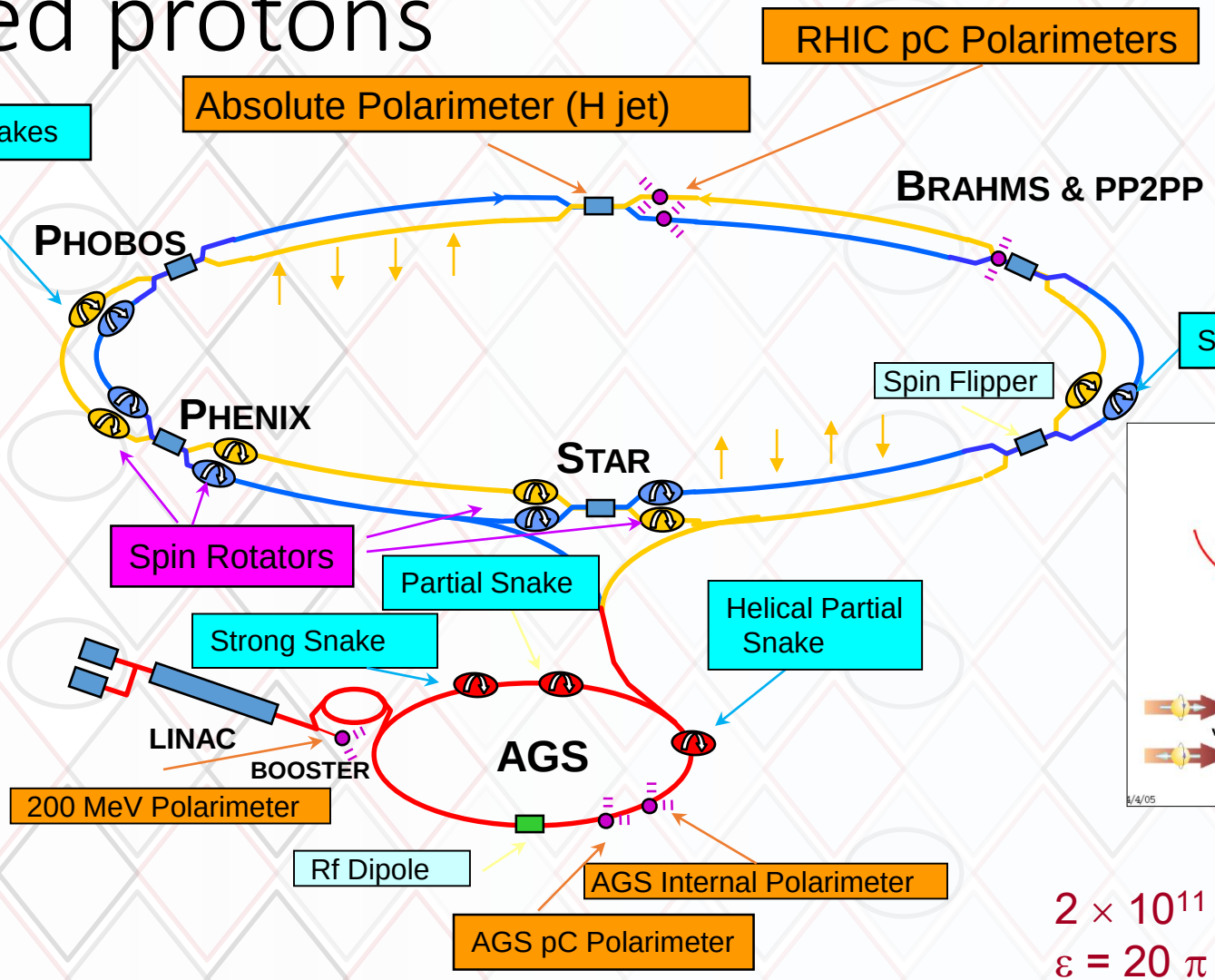
The RHIC Spin physics program

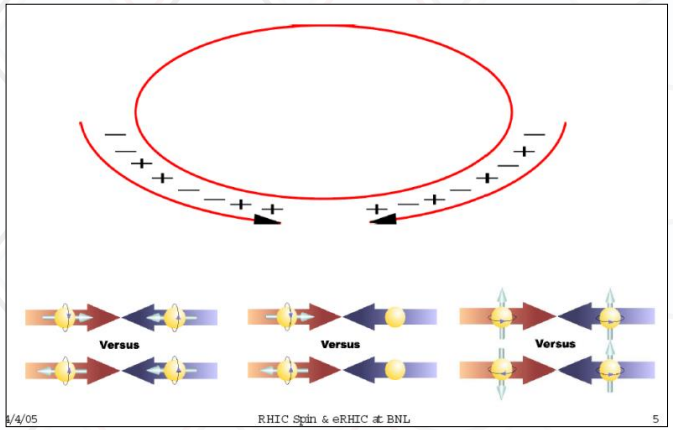
Diffraction and Low-x 2024,
Palermo, Sicily
September 12

Ralf Seidl (RIKEN)

The RHIC ring(s) with polarized protons







$L_{max} = 2 \times 10^{32} s^{-1} cm^{-2}$

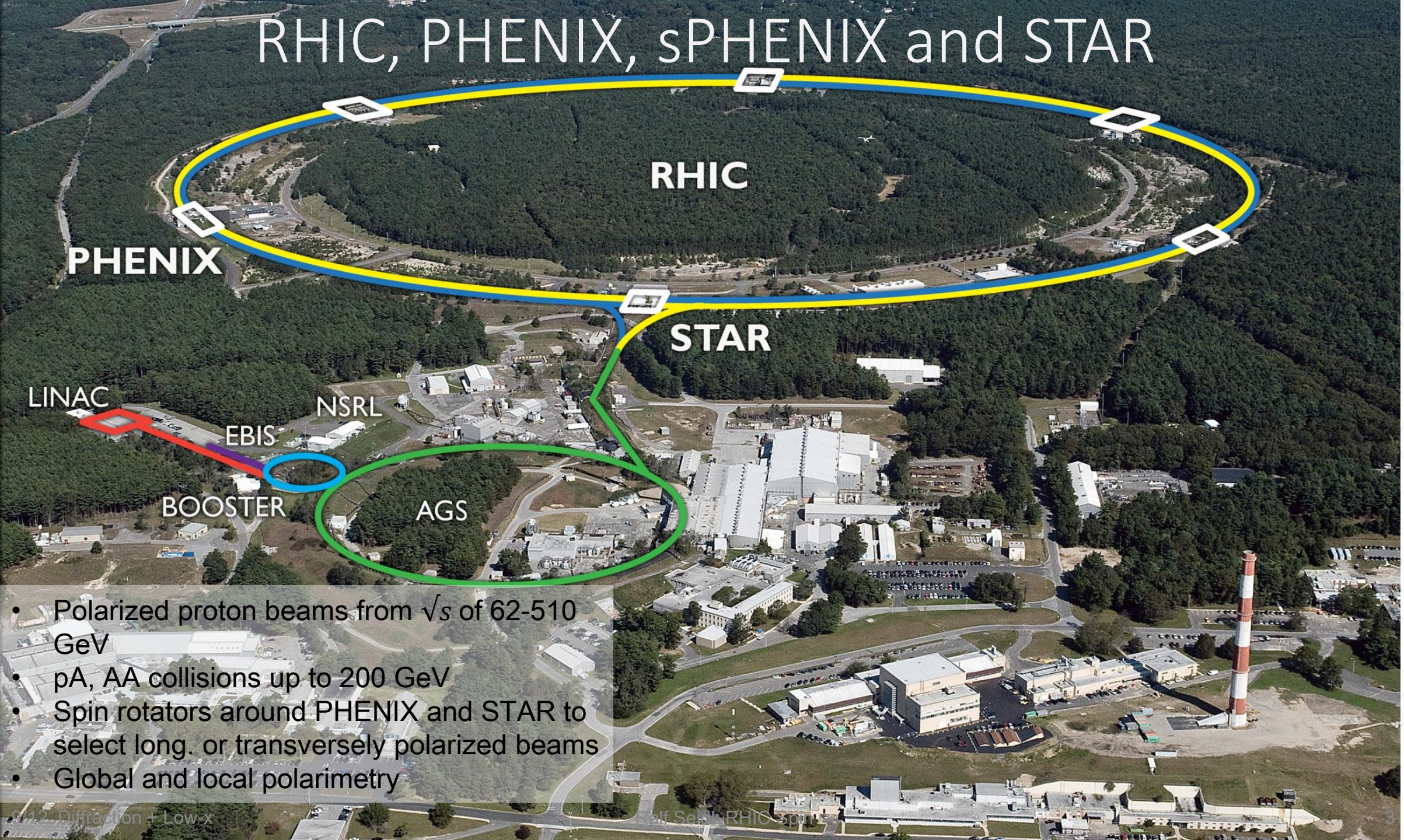
$50 < \sqrt{s} < 500\ GeV$

~ 70% Polarization

2×10^{11} Pol. Protons / Bunch

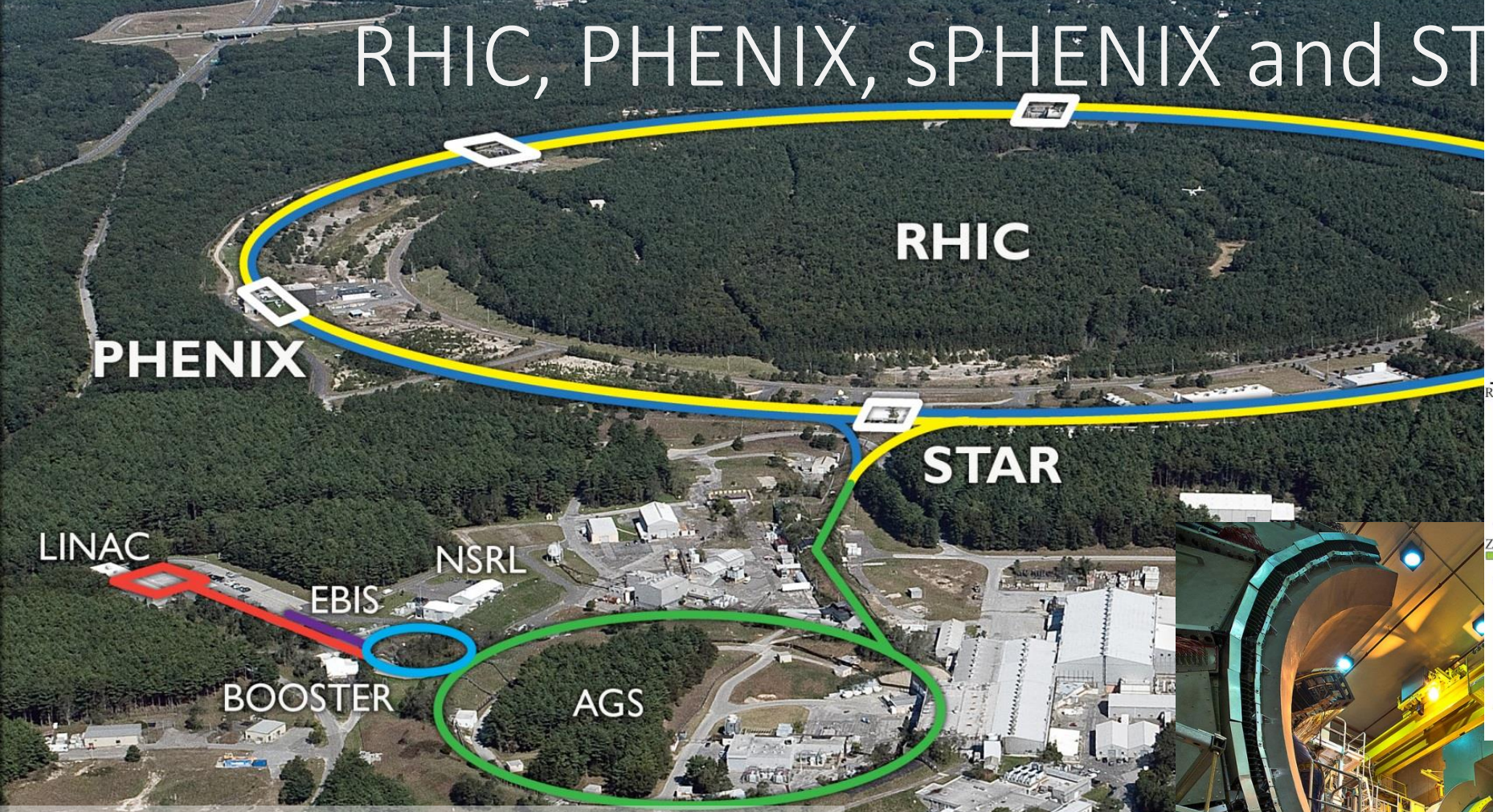
$\varepsilon = 20\ \pi$ mm mrad

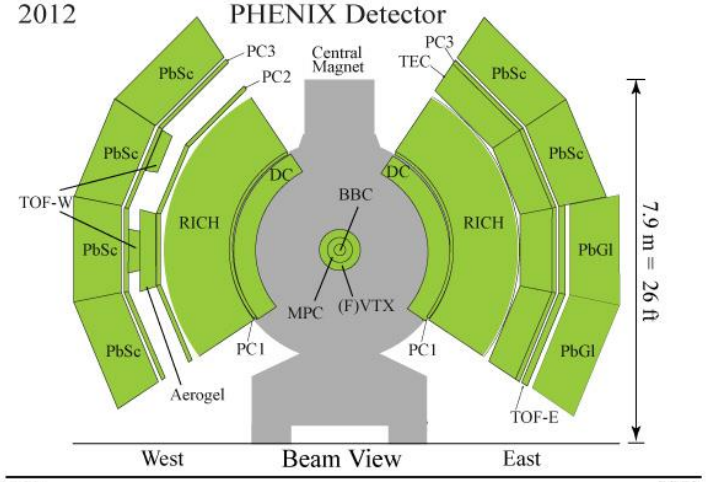
RHIC, PHENIX, sPHENIX and STAR

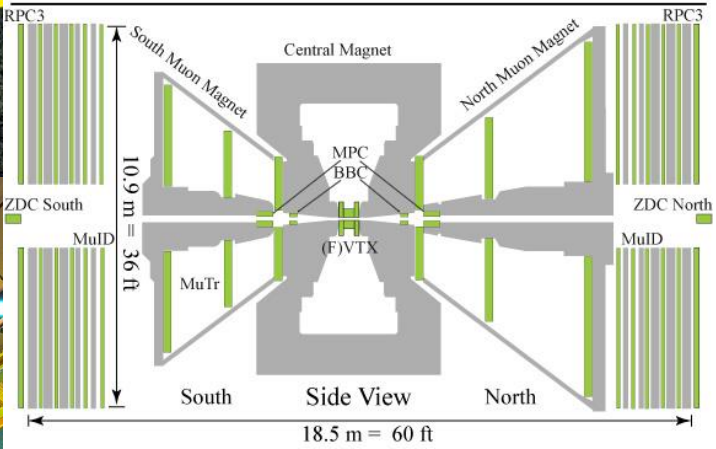


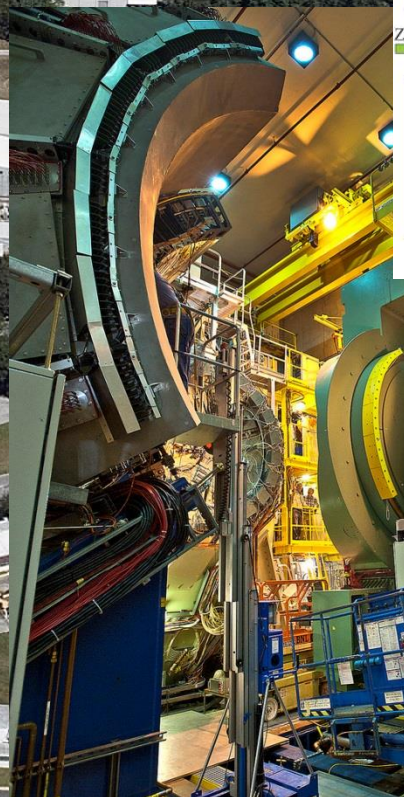
- Polarized proton beams from $\sqrt{s}$ of 62-510 GeV
- pA, AA collisions up to 200 GeV
- Spin rotators around PHENIX and STAR to select long. or transversely polarized beams
- Global and local polarimetry

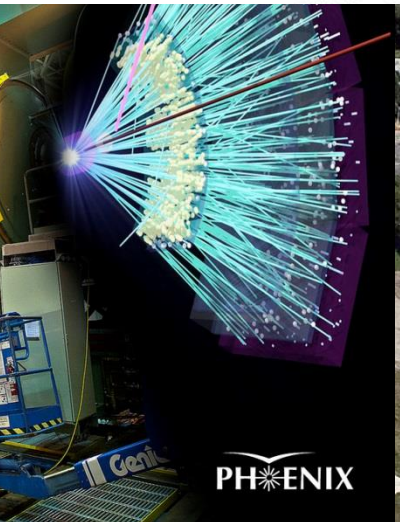
RHIC, PHENIX, sPHENIX and ST

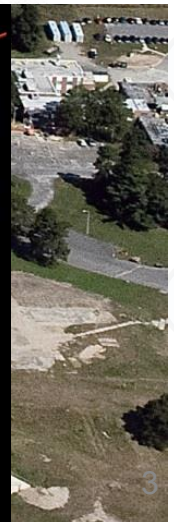






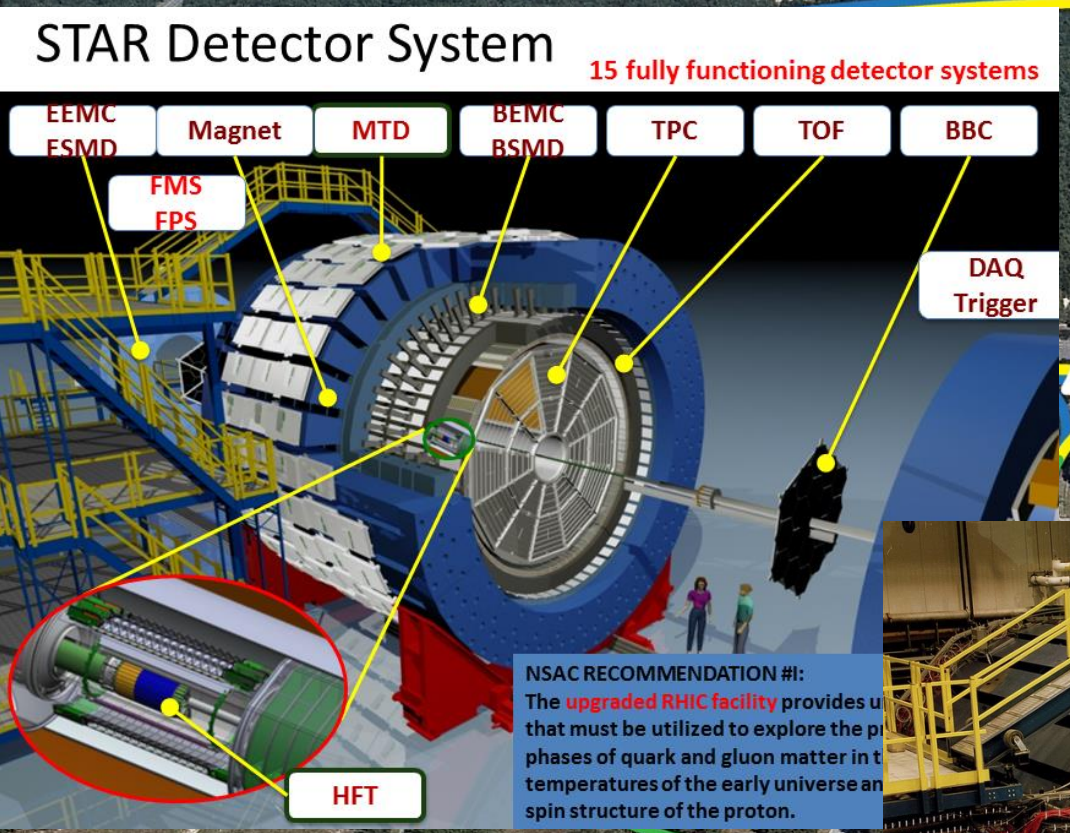


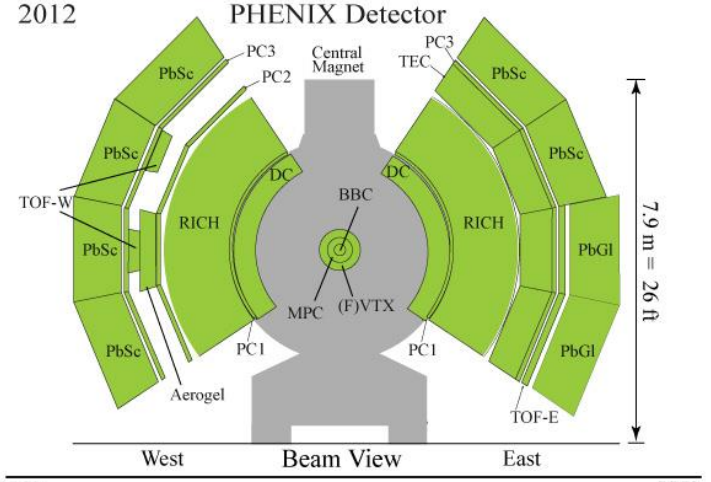


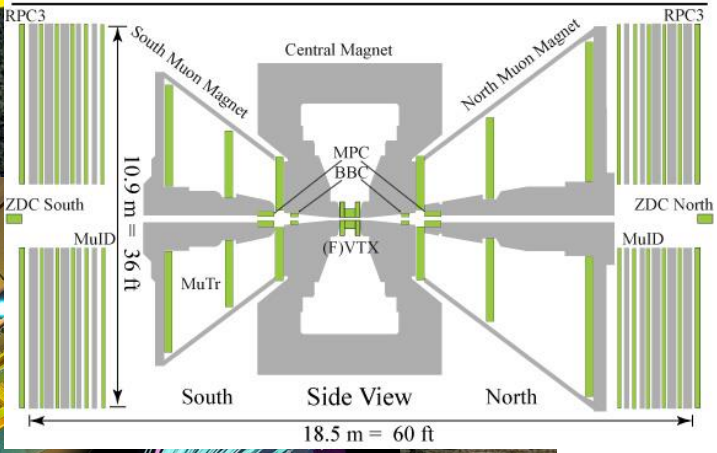


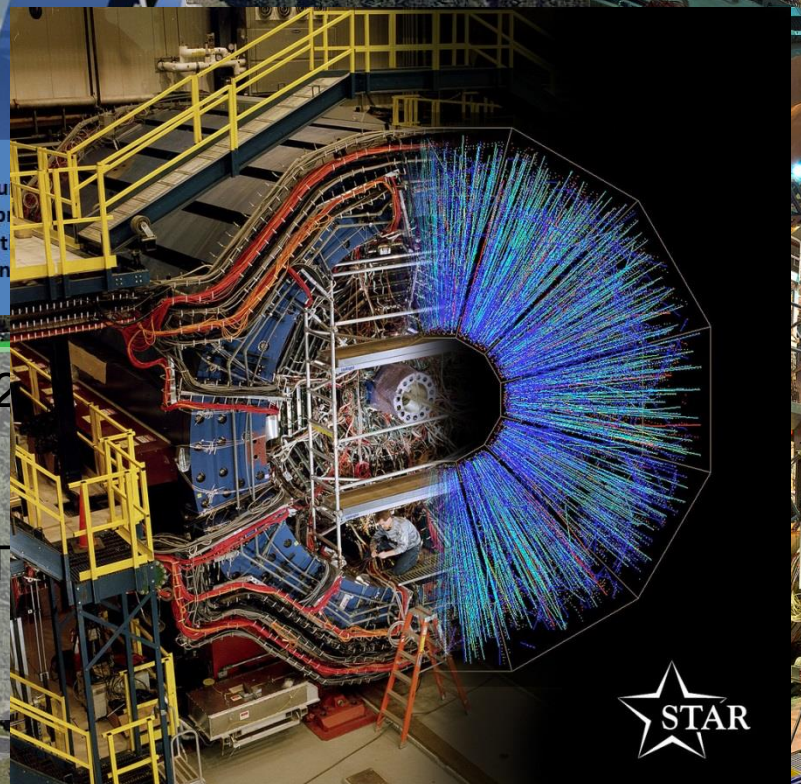
- Polarized proton beams from $\sqrt{s}$ of 62-510 GeV
- pA, AA collisions up to 200 GeV
- Spin rotators around PHENIX and STAR to select long. or transversely polarized beams
- Global and local polarimetry

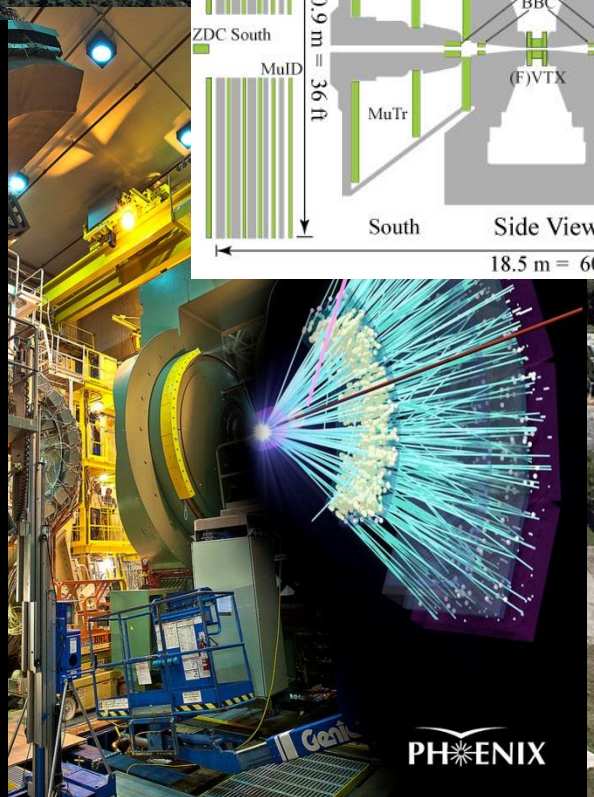
RHIC, PHENIX, sPHENIX and ST





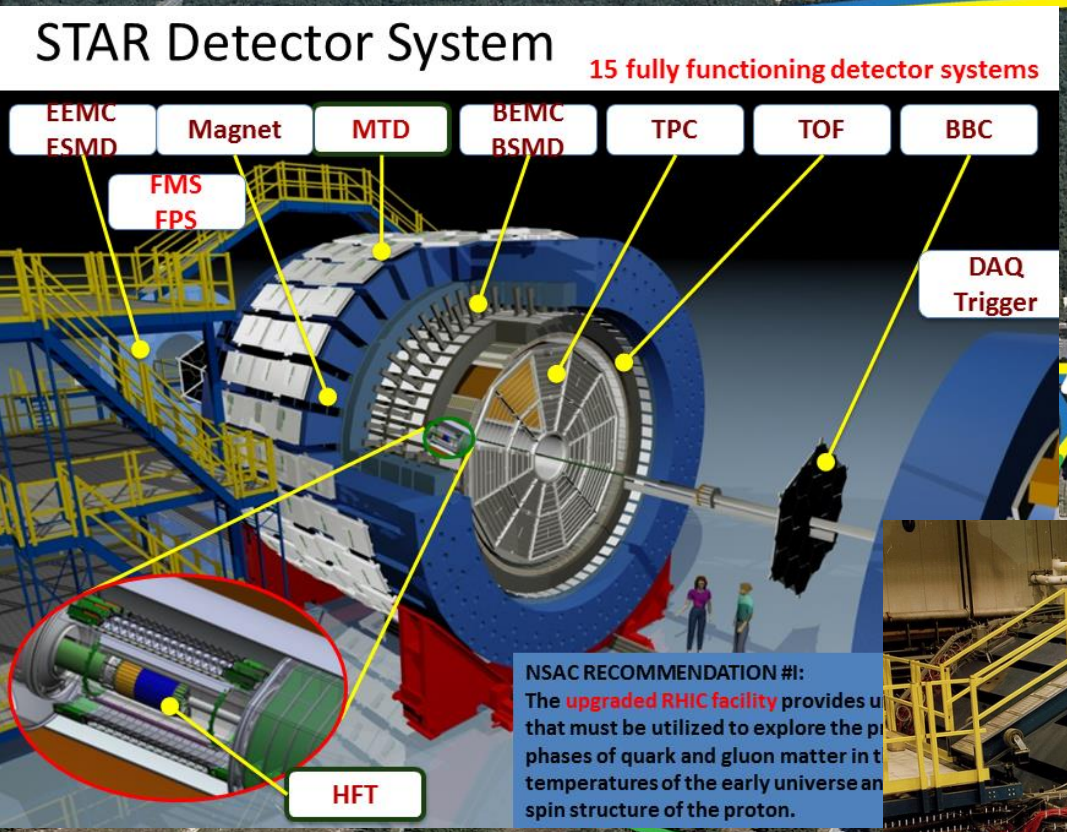


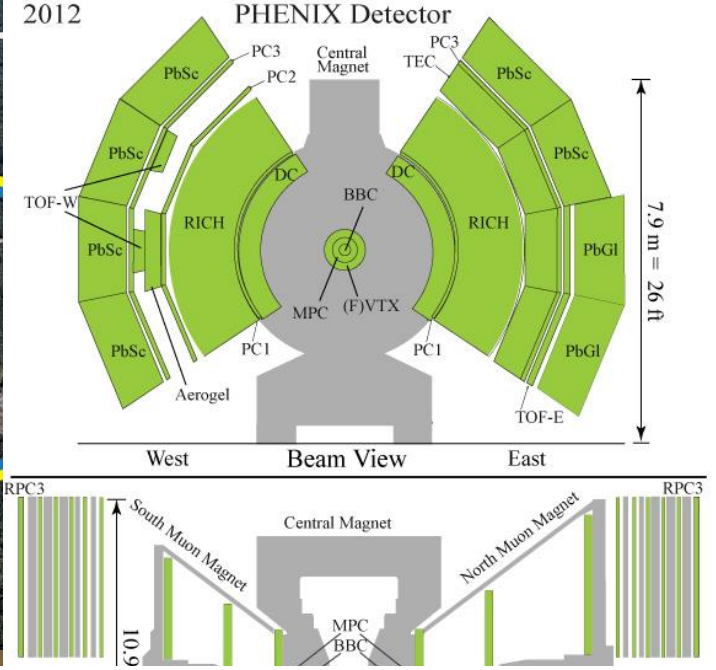




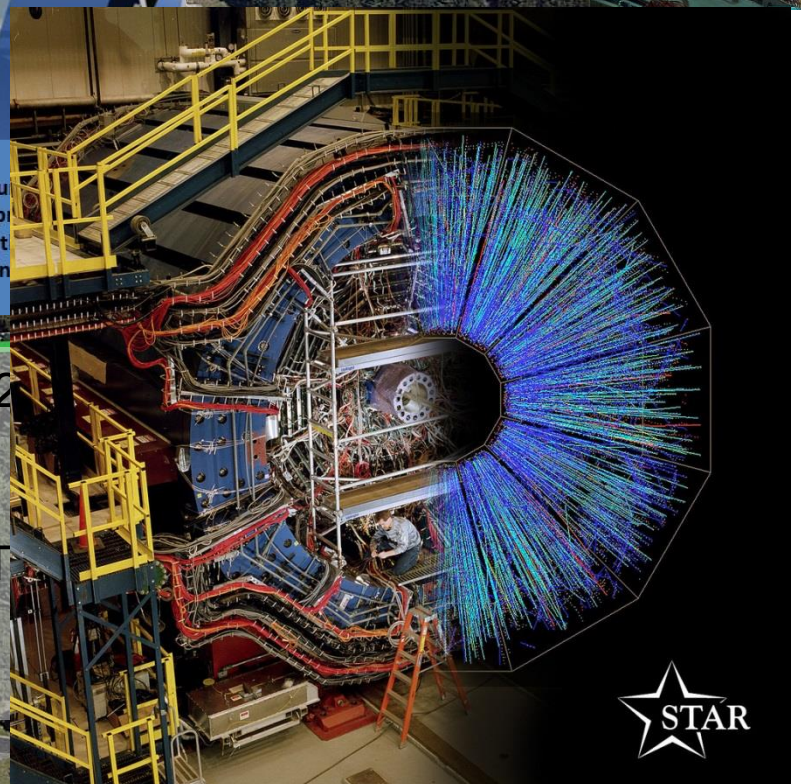
- Polarized proton beams from $\sqrt{s}$ of 62 GeV
- pA, AA collisions up to 200 GeV
- Spin rotators around PHENIX and ST select long. or transversely polarized
- Global and local polarimetry

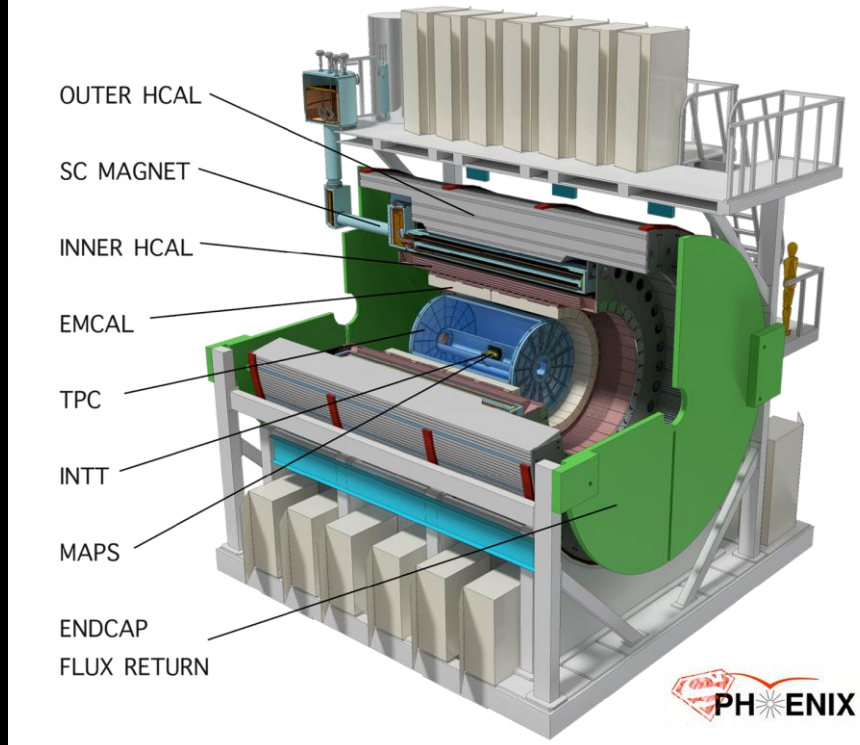
RHIC, PHENIX, sPHENIX and ST

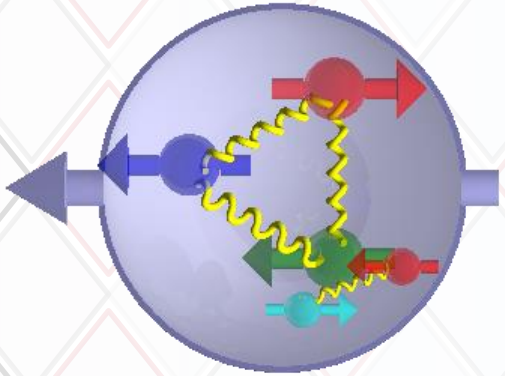




- Polarized proton beams from $\sqrt{s}$ of 62 GeV
- pA, AA collisions up to 200 GeV
- Spin rotators around PHENIX and ST select long. or transversely polarized
- Global and local polarimetry



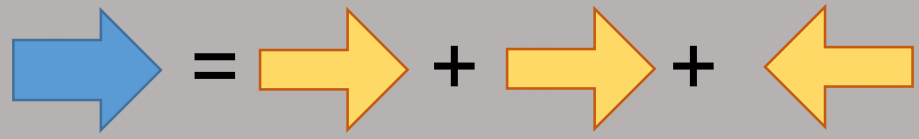




Helicity PDFs, longitudinal spin

The Spin sum rule

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



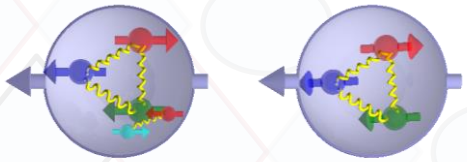
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$ Jaffe, Manohar

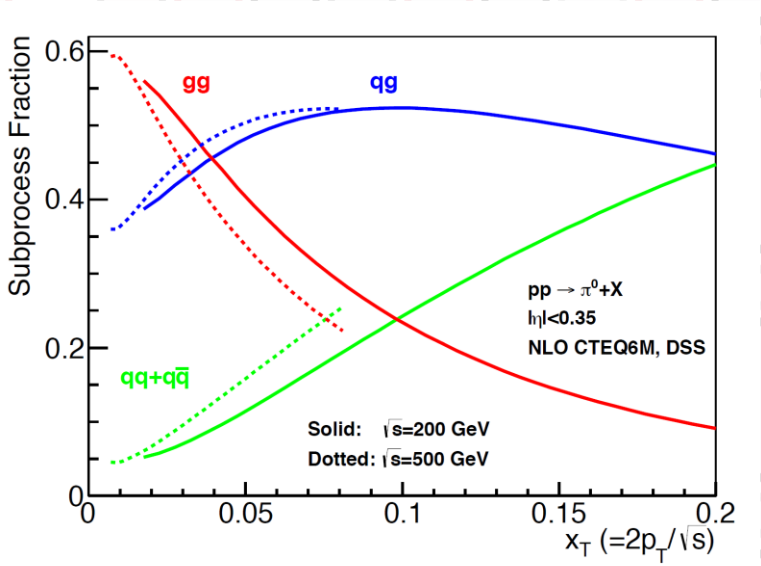
Quark spin | Gluon spin | Orbital angular momentum

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

- Spin Crisis (1980s): Quark spin contributes only little
- $\Delta\Sigma$ and ΔG can be accessed in longitudinally polarized (SI)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!

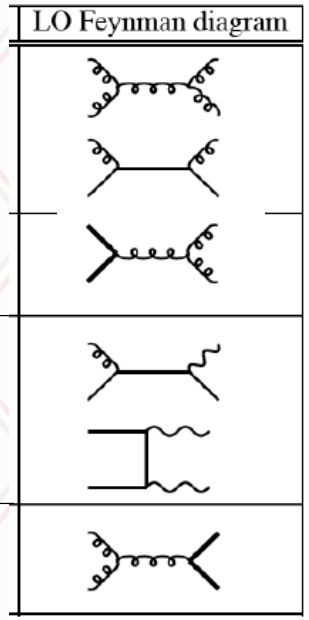
- Relative contributions different for different final states (flavor sensitivity)

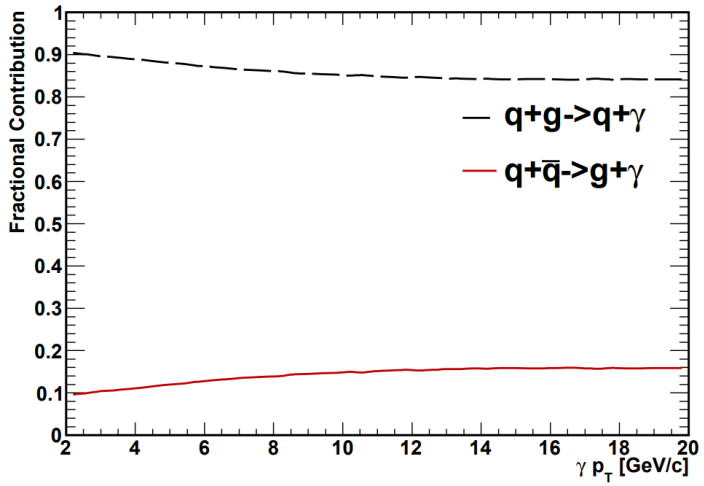
p+p→pion(s),eta + X

p+p→jet(s)+ X

p+p→γ + X

p+p→ B,D,J/ψ + X



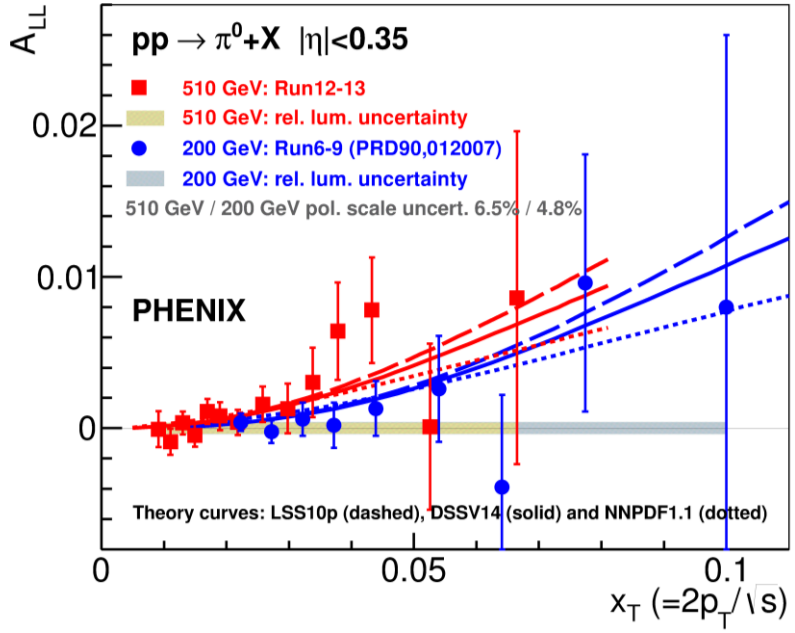


Underwood`92 Direct photons as golden channel for RHIC spin physics

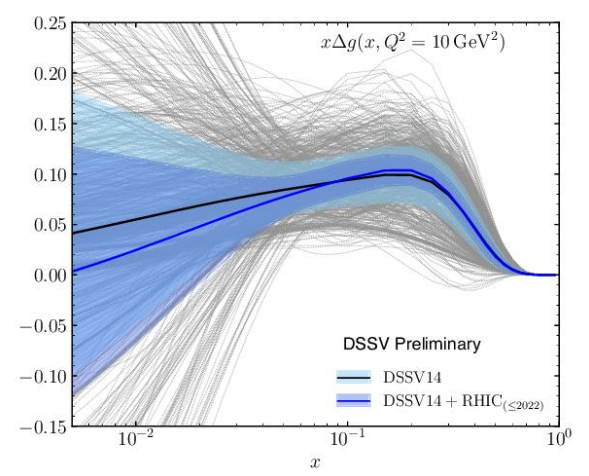
$\Delta g(x)$

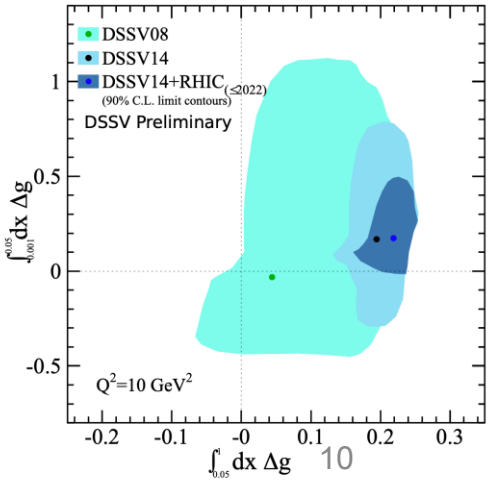
Nonzero Gluon spin: access to lower x with higher energies

- Nonzero gluon polarization established with RHIC √s = 200 GeV data
- RHIC 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

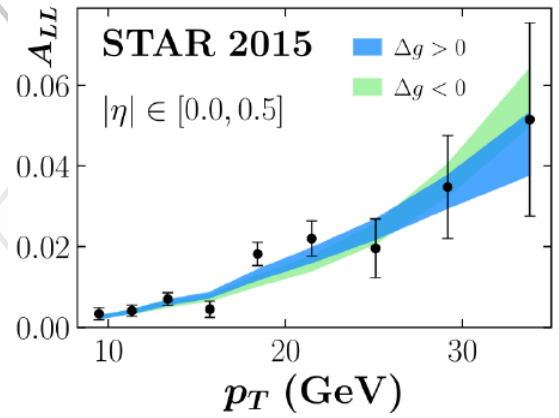


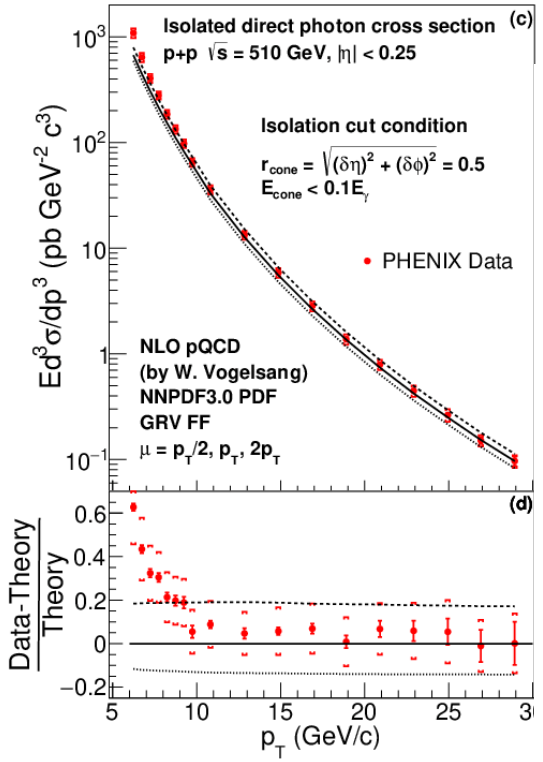


First direct photon xsec and A_{LL} at 510 GeV

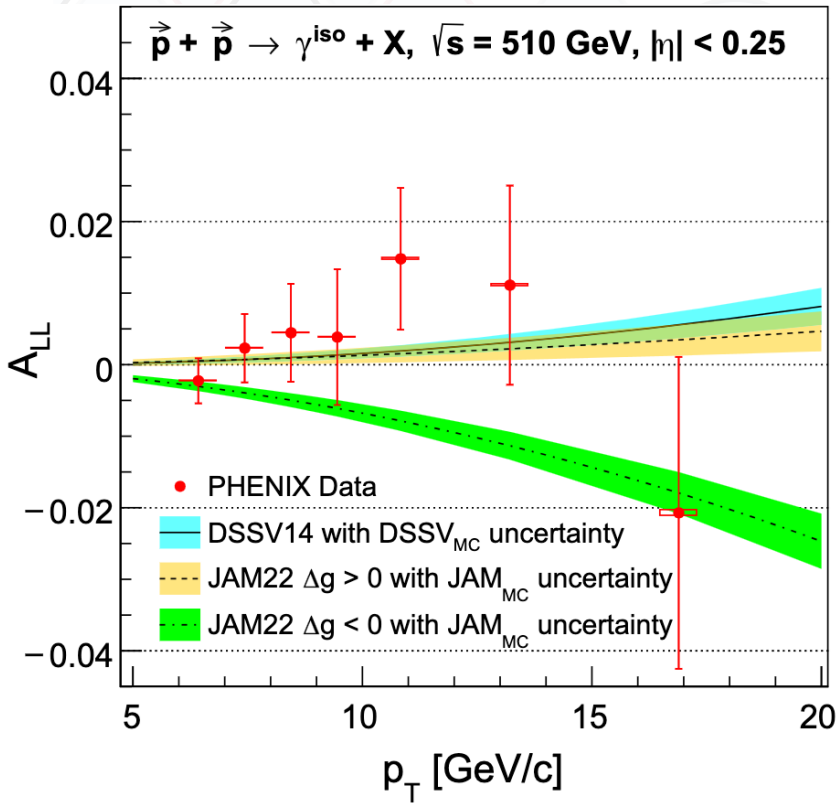
$\Delta g(x)$

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



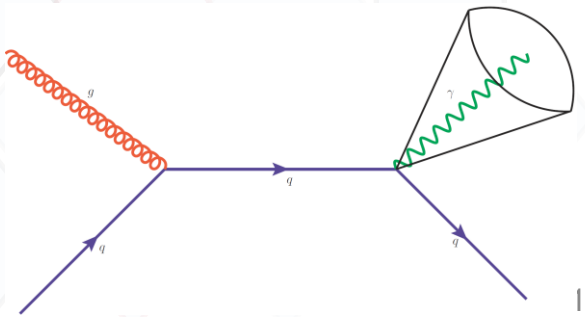


PRL 130 (2023) 251901



- 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

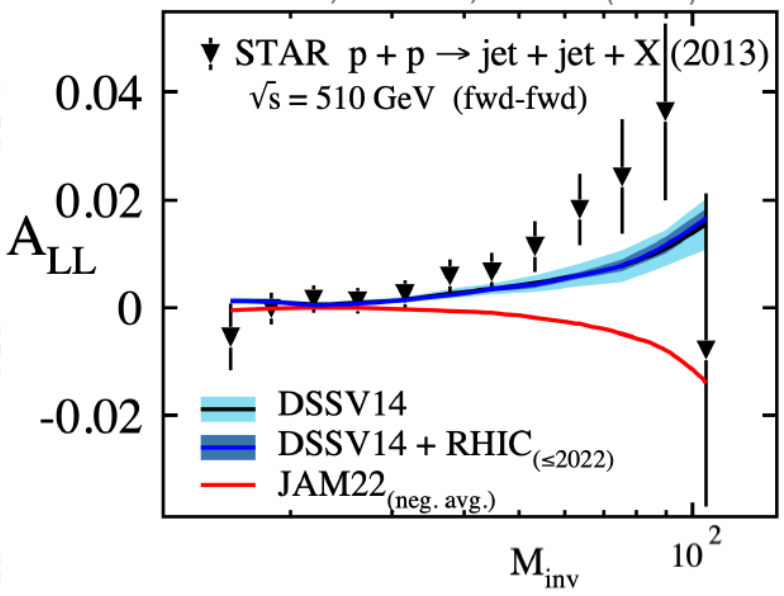
DOE Science Highlight

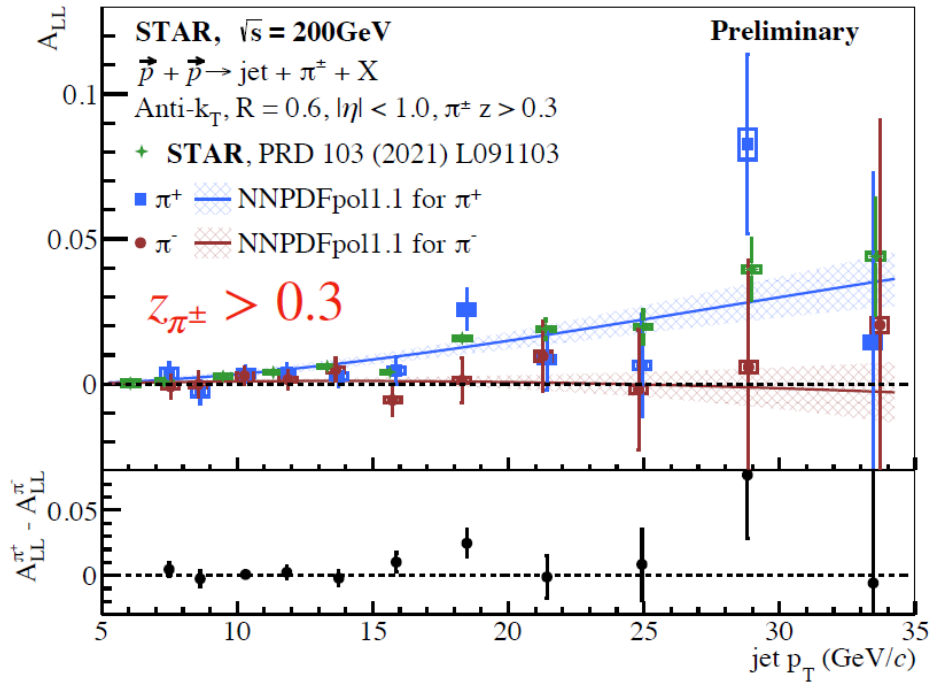


Jet A_{LL}s

- Single jet measurements workhorse measurements at STAR
- Di-jet A_{LL}s with good x sensitivity via invariant mass and jet rapidities
- Pion tagged jets: clear separation by pion charge – ordering confirms positive gluon polarization

STAR, PRD 105, 092011 (2022)





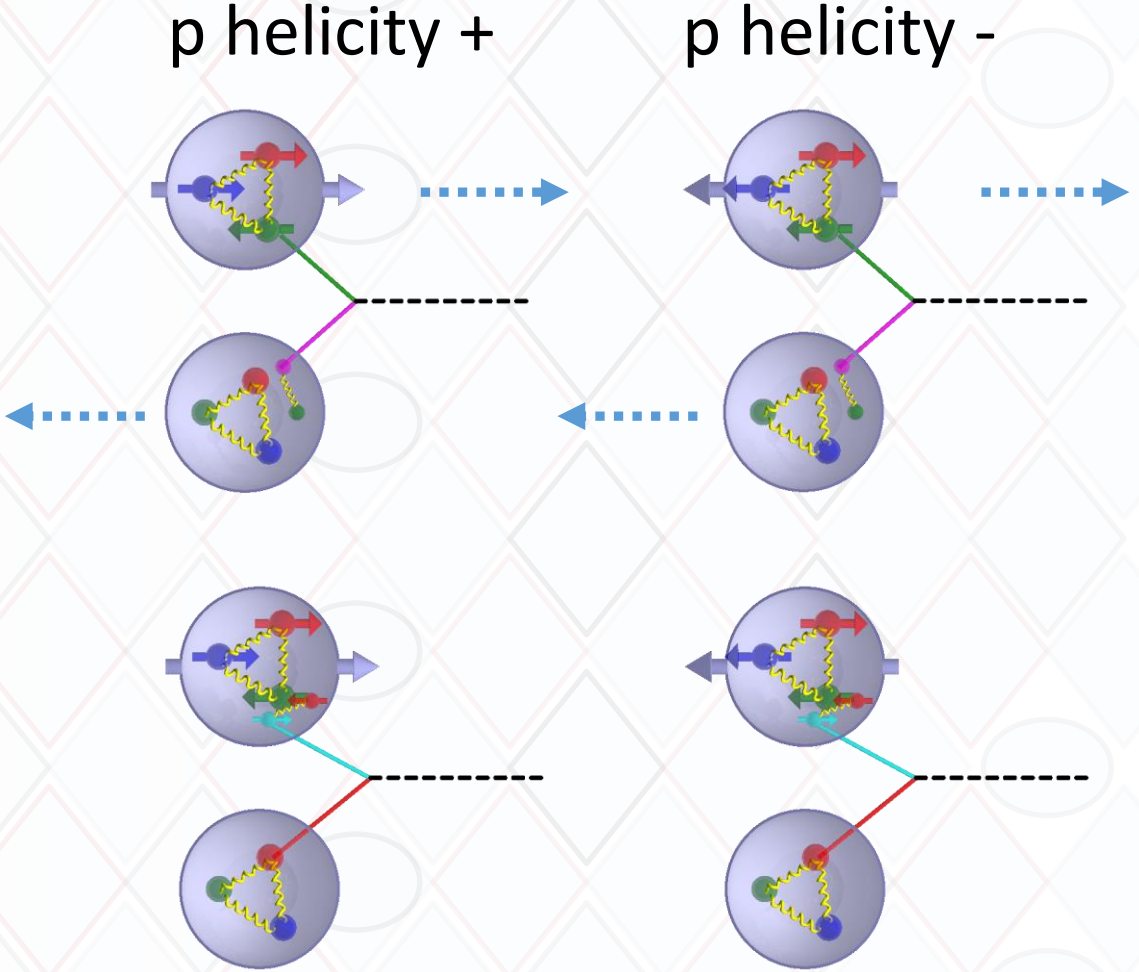
Real W production as access to (anti)quark helicities

- Maximally parity violating V-A interaction selects only lefthanded quarks and righthanded antiquarks:

➔Having different helicities for the incoming proton then selects spin parallel or antiparallel of the quarks

➔Difference of the cross sections gives quark helicities $\Delta q(x)$

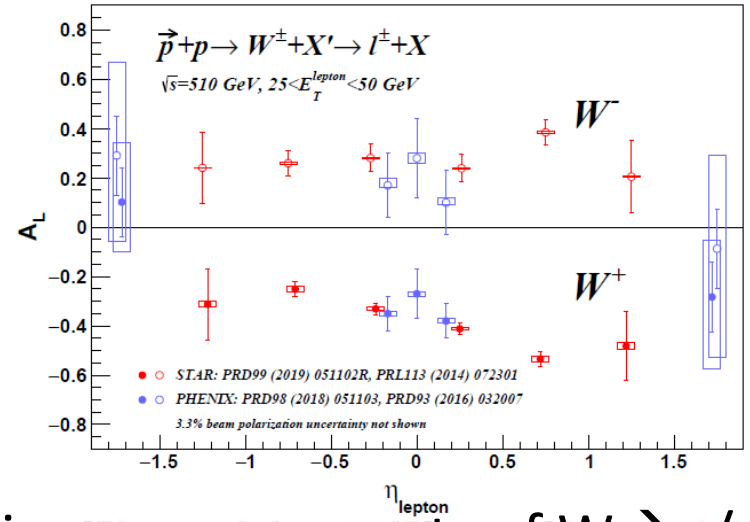
- No Fragmentation function required
- Very high scale defined by W mass



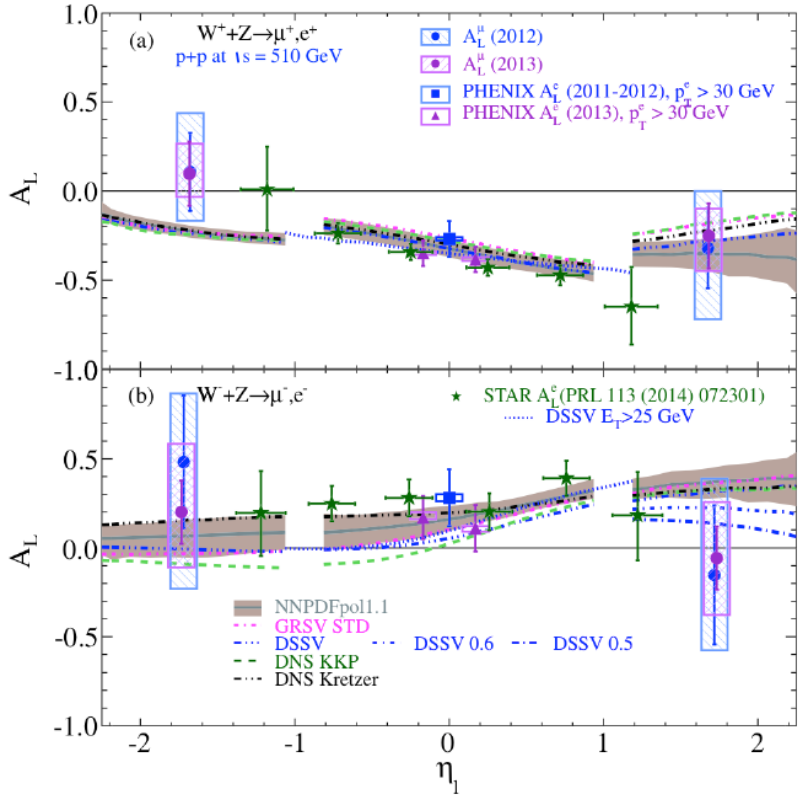
Bourrely , Soffer
Nucl.Phys. B423 (1994) 329-348

Forward W+Z →μ asymmetries

STAR: Phys.Rev.D 99 (2019) 051102



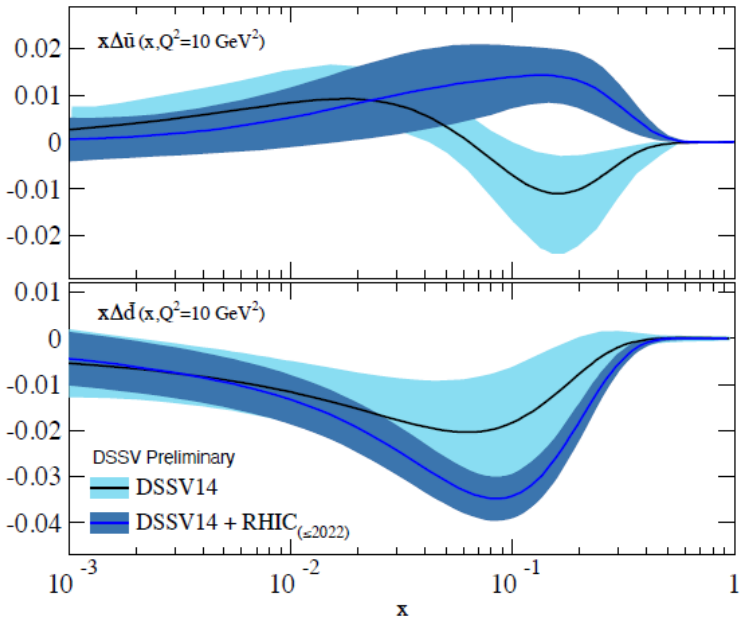
- Precise measurements of W→e/m asymmetries
- Asymmetries overall as expected (dominated by quark helicities)
- clear preference wrt to parameterization uncertainty bands determines sea quark helicities



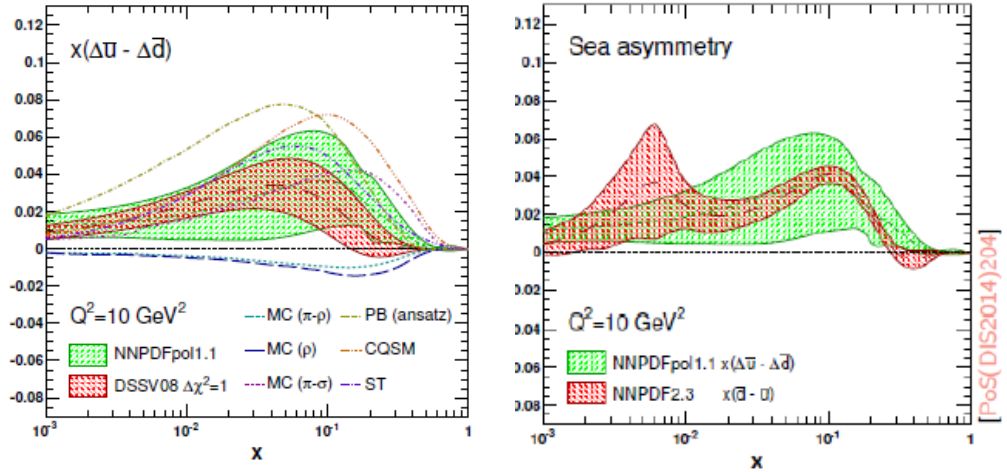
PHENIX:
Phys.Rev.D 98 (2018) 032007 ,
Phys.Rev.D 93 (2016) 051103

Sea quark helicites

- RHIC data at boundary of DSSV/NNPDFpol1.1 uncertainty bands
- Reweighted NNPDFpol1.1 and DSSV14 fits shows substantial polarized light sea asymmetry
- opposite sign to most pion cloud models (where polarized and unpolarized light sea asymmetries have same sign)



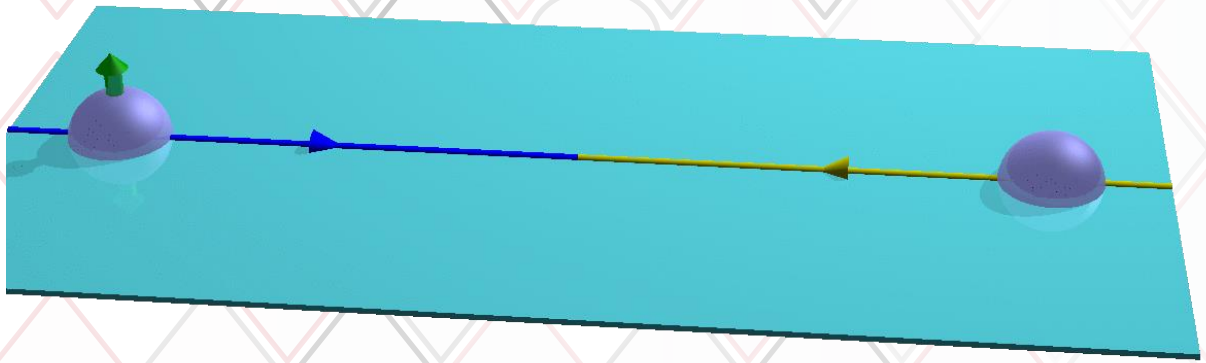
NNPDFpol1.1: arXiv:1406.7122

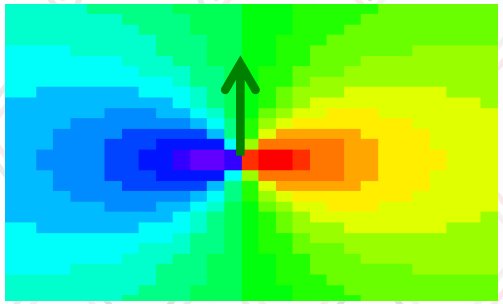


Transverse Single spin asymmetries (TSSAs)

- 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):

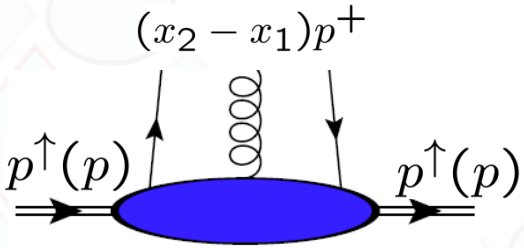
$$A_N \propto \frac{m_q \alpha_S}{P_T} \approx 0.001$$

TSSAs at RHIC→Quark-gluon dynamics!

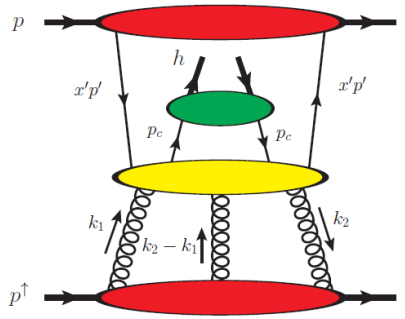
- Sivers and Collins effects rely on an explicitly transverse momentum dependent (TMD) framework where two scales are observed: high scale (typically Q^2) and intermediate scale (transverse momentum $P_T << Q^2$)
- In inclusive pp measurements usually only one, hard scale accessible (transverse momentum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

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

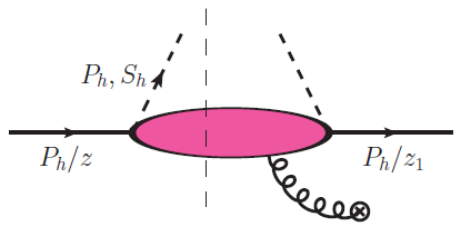
- Both frameworks found to be related via moments over intrinsic transverse momenta



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

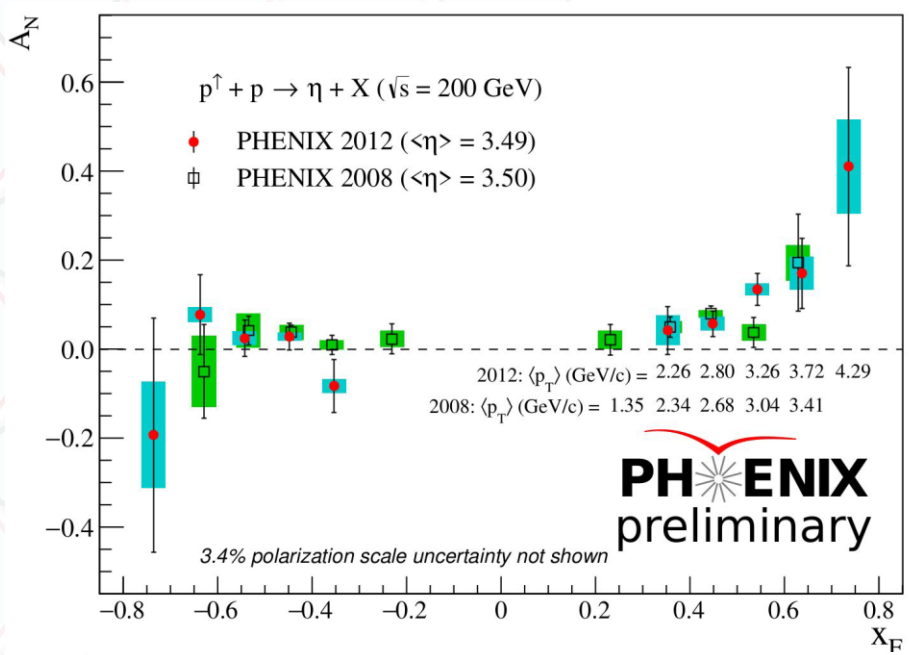
Efremov, Teryaev Phys.Lett.B 348 (1995) 577
Qiu, Sterman Phys.Rev.D 59 (1999) 014004
Kanazawa, Koike Phys.Lett.B 478 (2000) 121-126
Metz, Pitonyak Phys.Lett.B 723 (2013) 365-370

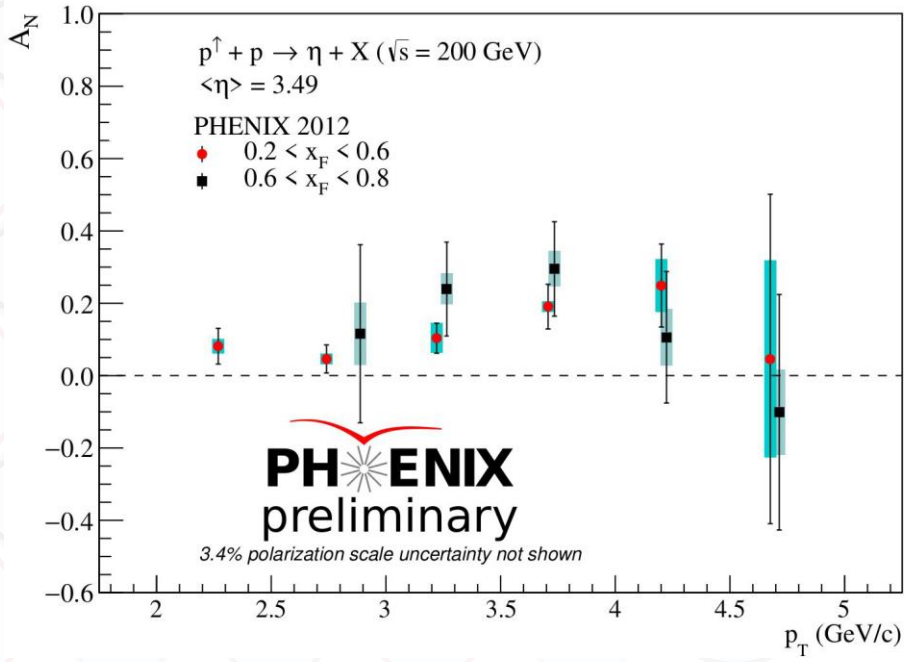
- Generally three pieces to p+p single transverse spin asymmetries:
  - Twist three correlation functions (quarks or gluons) in polarized proton ↔ Sivers function
  - Twist three correlation function in unpolarized proton (with transversity) ↔ Boer Mulders function
  - Twist three correlation in fragmentation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

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

Forward eta A_Ns

- Update of forward η A_N measurements with better statistics
- Asymmetries sizeable, maybe a hint of turnaround expected at higher p_T due to HT nature of asymmetries

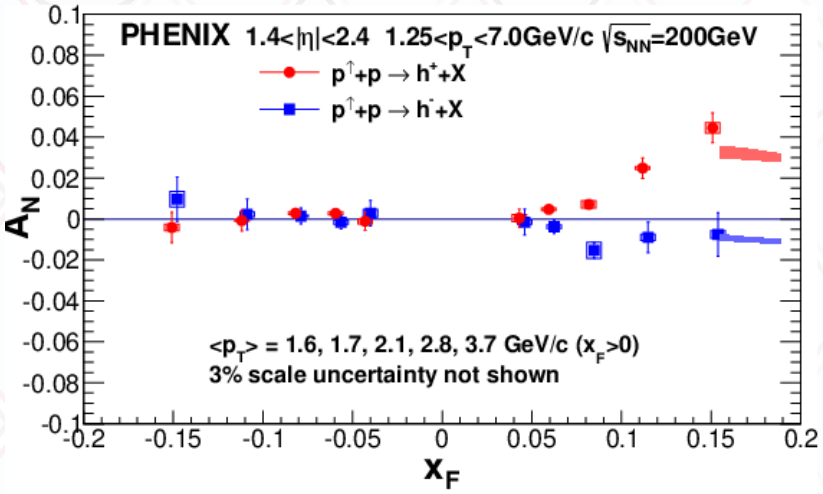


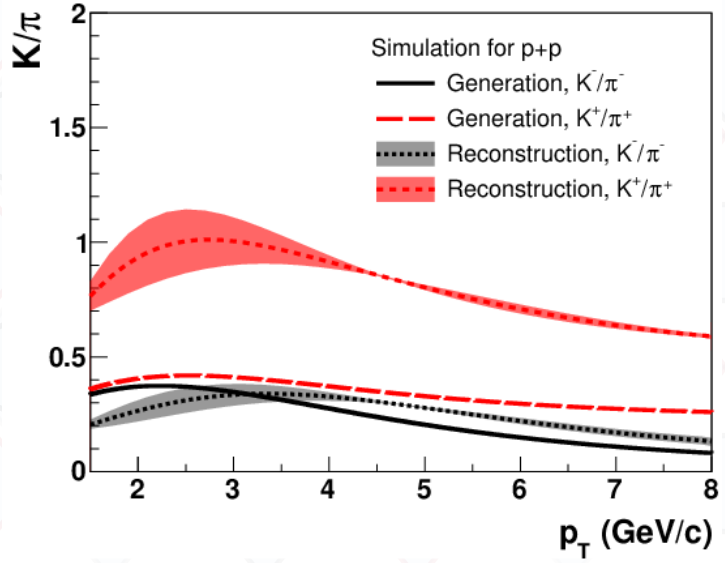


Forward charged hadron A_ns

- 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



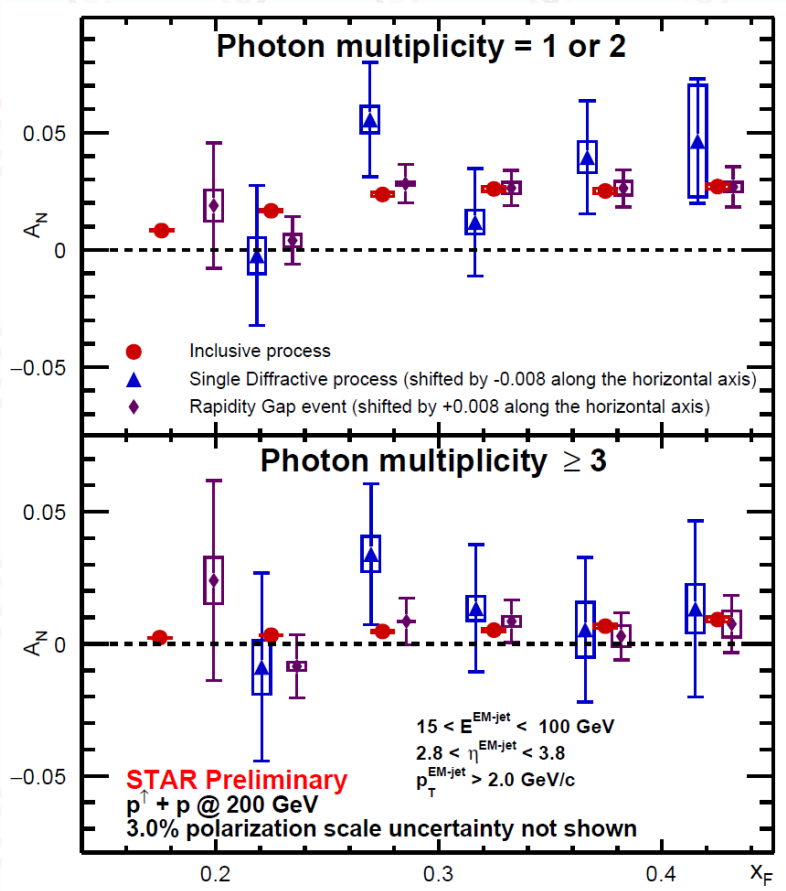


Diffractive contributions?

→Liang, Tuesday

- Both single diffractive and rapidity gap events show asymmetry comparable to inclusive asymmetry
- To compensate for small contribution of diffractive events to inclusive events asymmetry had to be much larger
- Conclusion: Diffractive events are not main cause for nonzero A_Ns

STAR forward EM-"jet" ANs



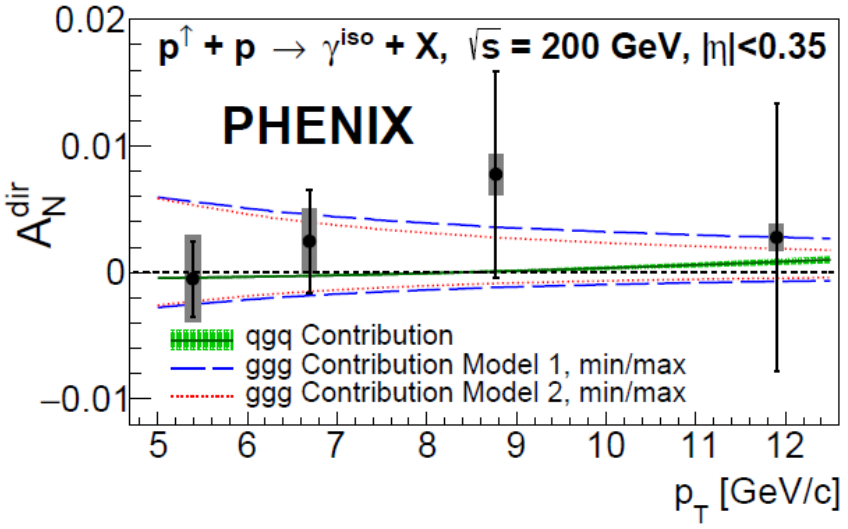
First direct photon A_Ns

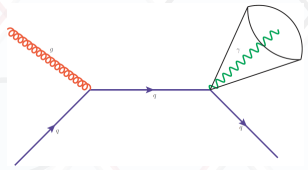
- First direct photon A_N extracted at RHIC
- Mostly sensitive to initial state effects (no fragmentation) → quark-gluon and gluon-gluon correlation functions
- Power to constrain gluon-gluon correlation function well, since quark impact expected to be small

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

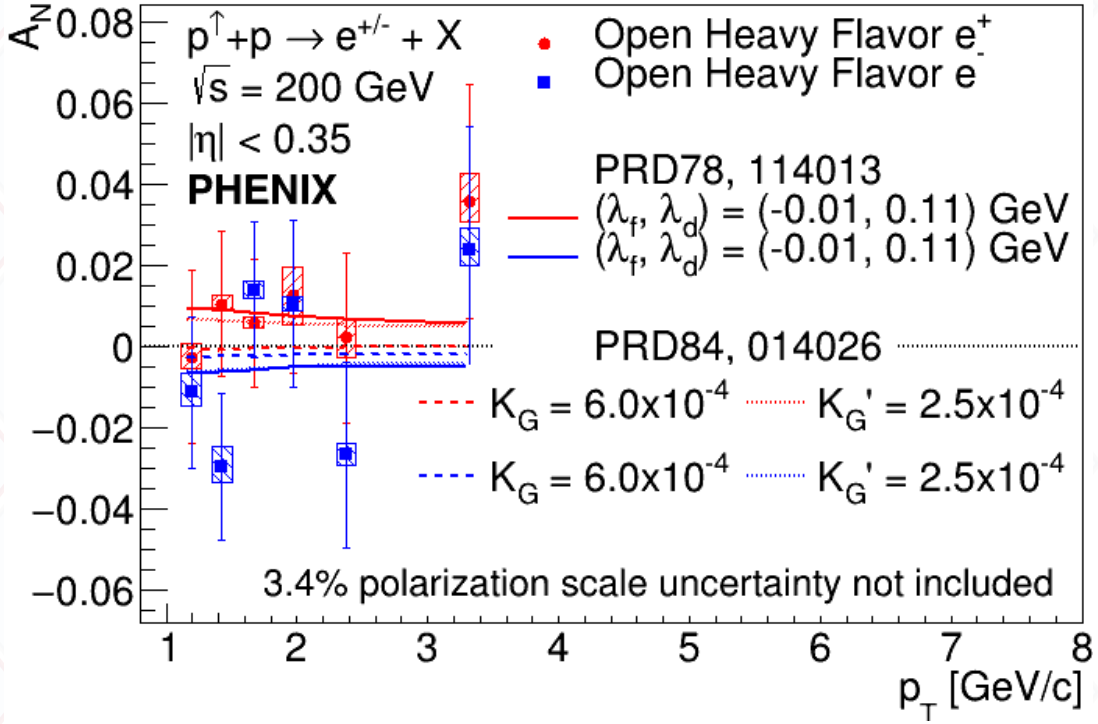


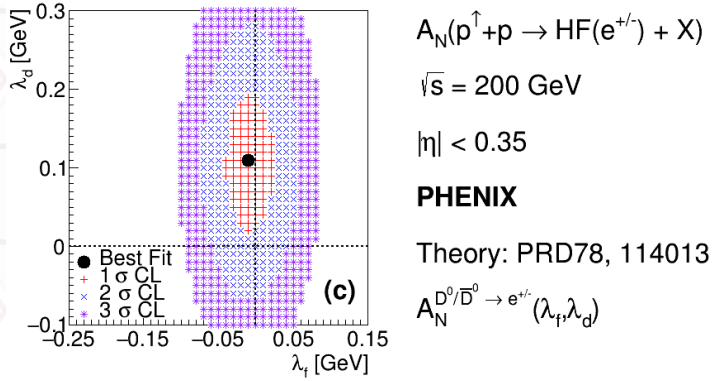


Heavy Flavor electron A_Ns

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

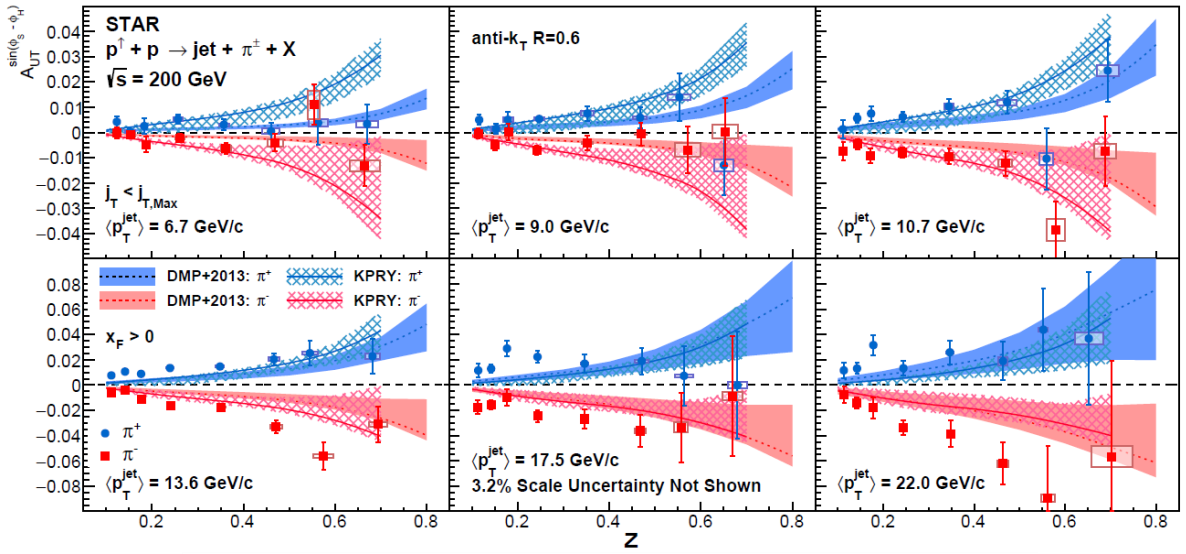


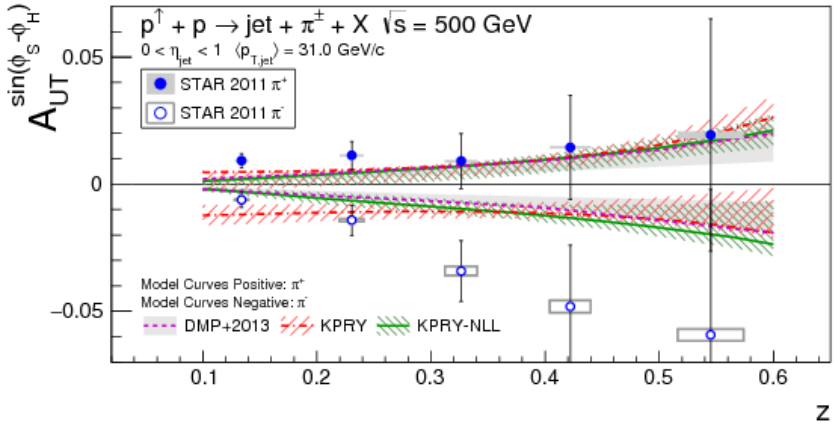


Transversity in proton collisions

- Nonzero Collins asymmetries (hadron in jets) at central rapidities at 200 and 500 GeV
- Substantial theoretical progress for hadron in jet measurements
  - unpolarized: Kaufmann et al.
  - polarized Kang et al.
- For roughly same x and kt similar size → evolution effects moderate?
- But generally slightly larger than global fits from SIDIS/e^+e^-
- More to come from sPHENIX in near future

STAR: Phys.Rev.D 106 (2022) 072010, 2022





STAR: Phys.Rev.D 97 (2018) 032004

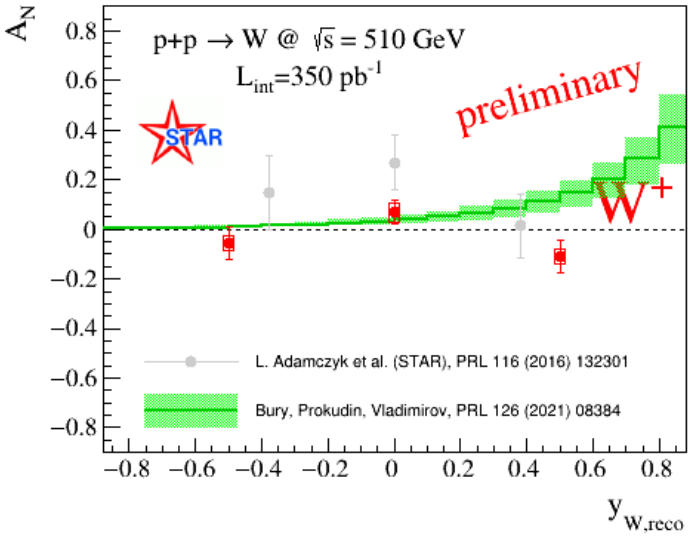
Towards the Sivers sign change

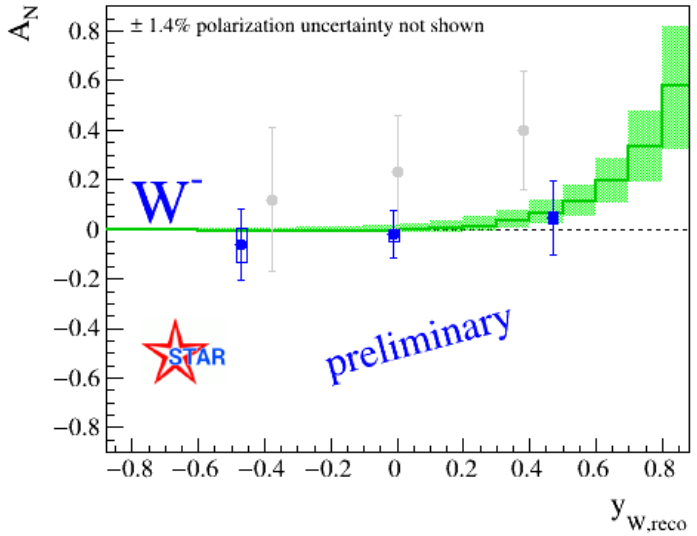
$$f_{1T,q}^{\perp DY}(x,k_T) \stackrel{?}{=} -f_{1T,q}^{\perp DIS}(x,k_T)$$

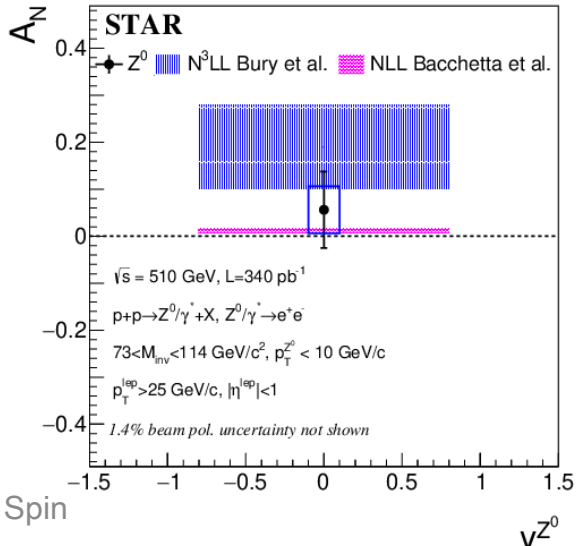
→Chiu, Tuesday

- STAR: Using recoil method reconstruct W transverse momentum and azimuthal asymmetry
- First indication of expected sign change! Weaker after including 2017 data
- Evolution effects could reduce size of asymmetries
- Now also Z cross sections and asymmetries

STAR: PRL 116 (2016) 132301



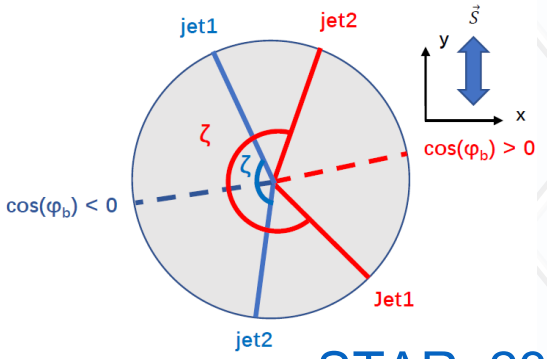


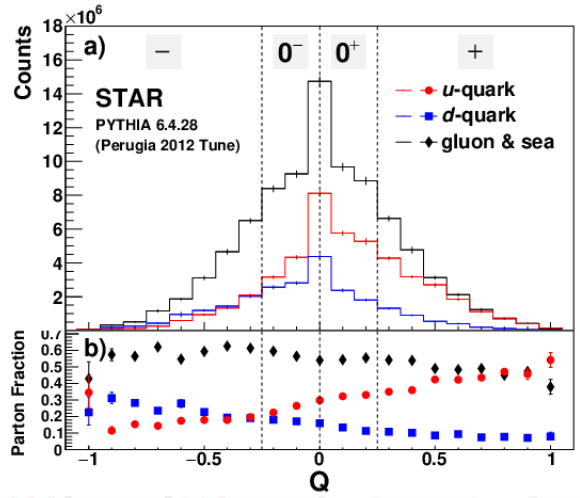


STAR *PLB 854 (2024) 138715*

Di-jet spin-dependent imbalance

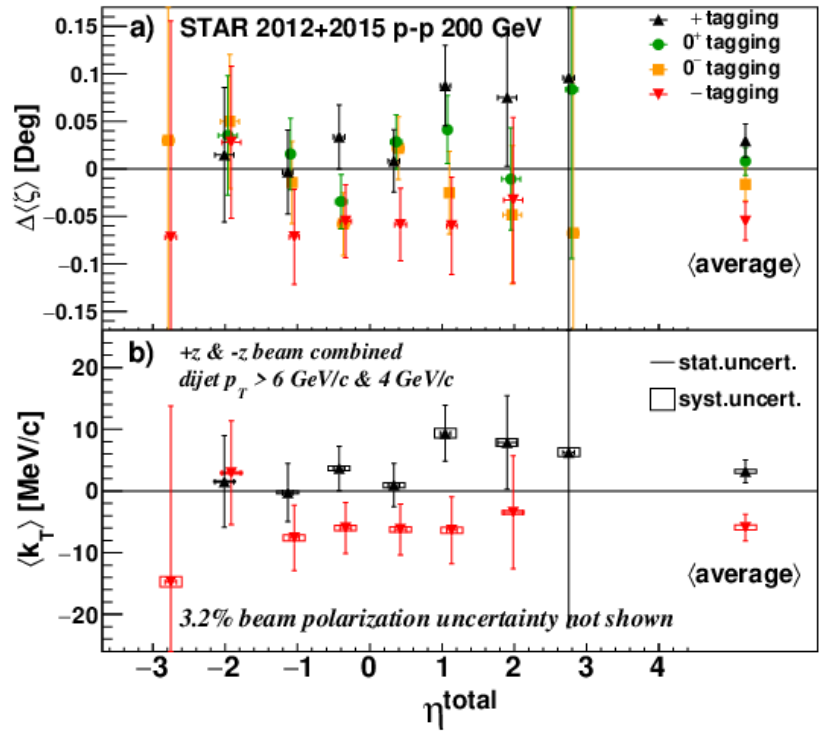
- Use di-jet imbalance and calculate single spin asymmetry
- Sensitive to spin dependent intrinsic transverse momentum k_t kick (from Sivers effect)
- First indications seen by STAR after enhancing up or down flavors via jet charge selection
- Model-dependent extraction of up, down and g+sea contributions



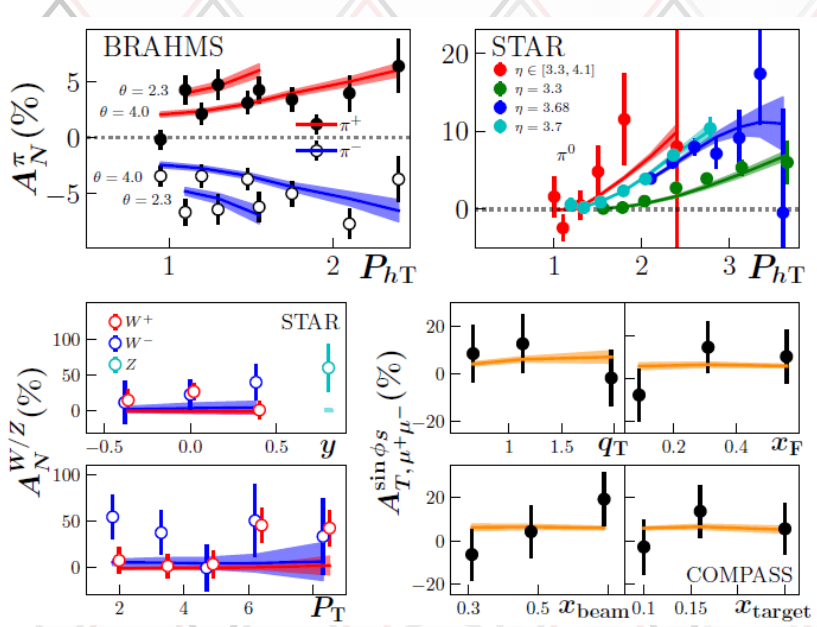


$$Q = \sum_{\substack{all\ the\ tracks \\ with\ pT>0.8GeV}} \frac{track\ |p|}{jet\ |p|} \cdot track\ charge$$

STAR: 2305.10359

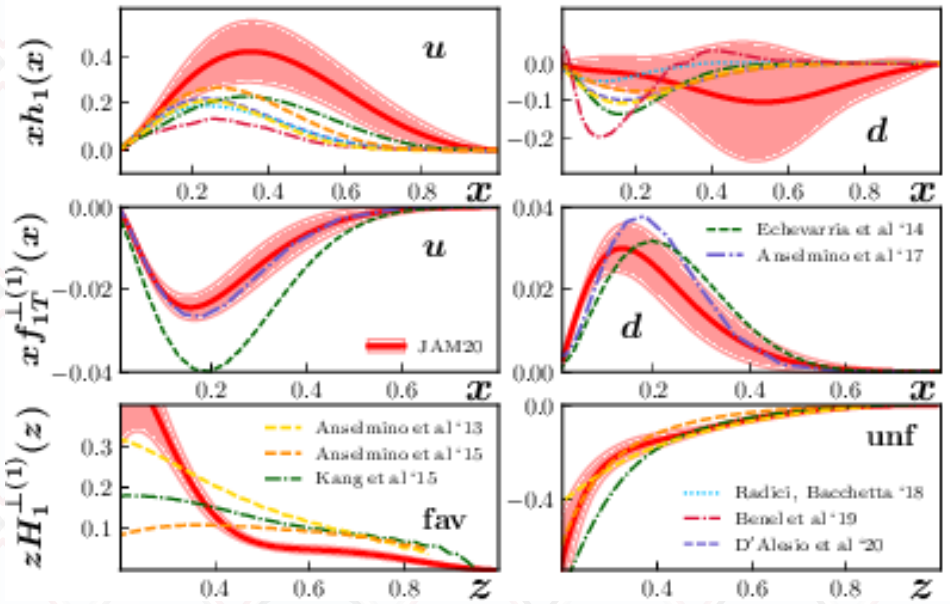


Where to go from here? Global fits on transverse quark-gluon structure



RHIC, SIDIS, DY included

Cammarota et al, PRD 102 (2020) 054002



Transversity

Sivers function

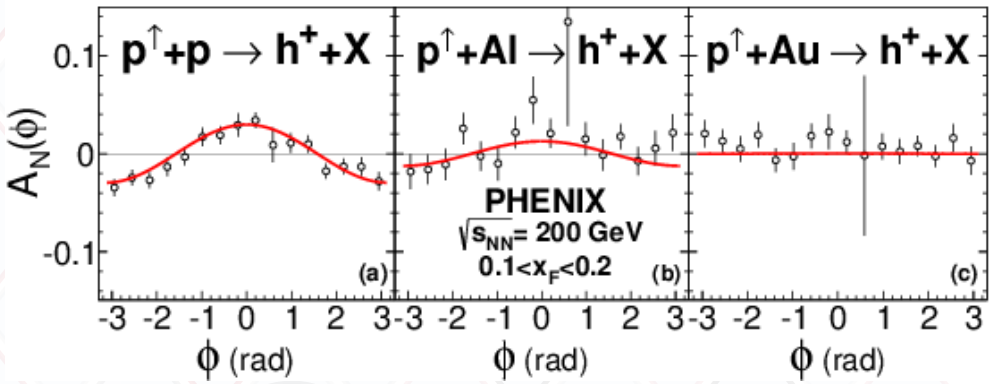
Collins FF

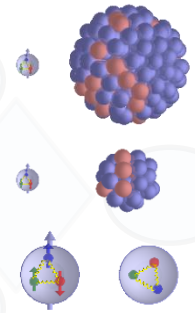
- Recent central rapidity PHENIX results (π,η,Heavy flavor electons, direct photons) NOT yet included
- Impact on gluon Sivers function (tri-gluon correlator) expected

A dependence of A_Ns

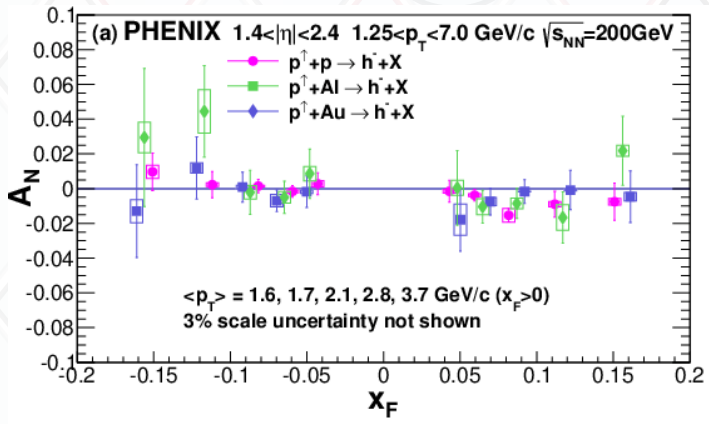
- Asymmetries consistent with $A^{1/3}$ dependence as (initially) predicted by some CGC related nuclear effects (Hatta`17)
- No A dependence is ruled out
- Also consistent with suppression with increasing number of binary collisions
- Lower suppression seen by STAR for neutral pions at slightly higher 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

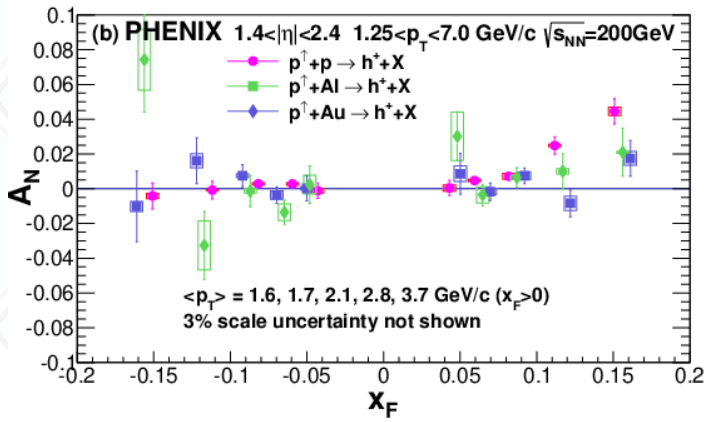
Phys.Rev.Lett. 123 (2019) 122001



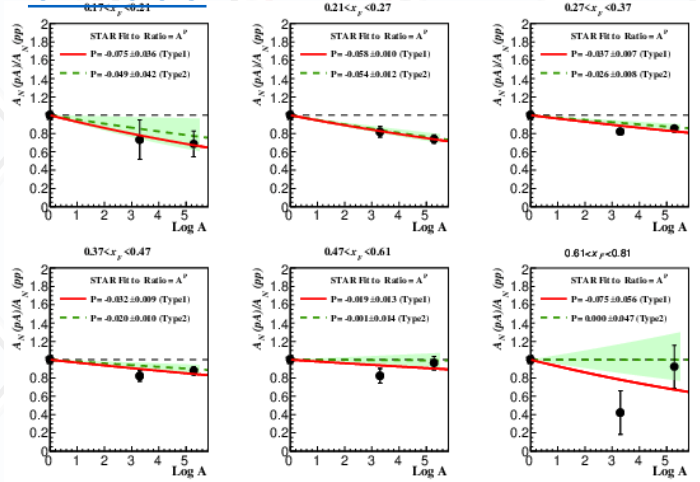


PRD 108 (2023) 072016

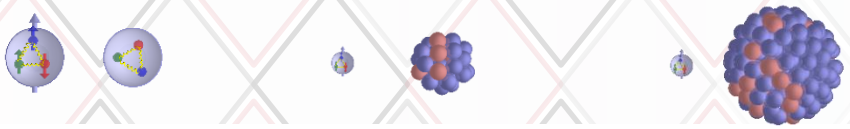


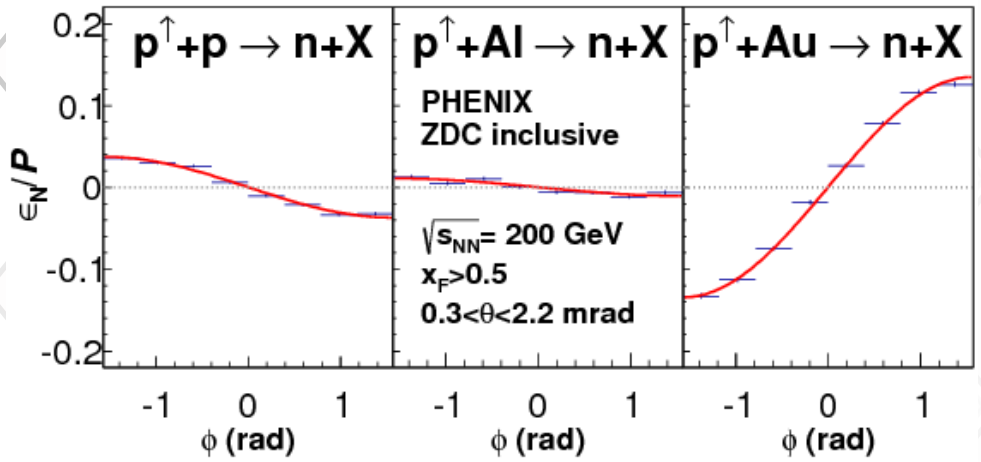


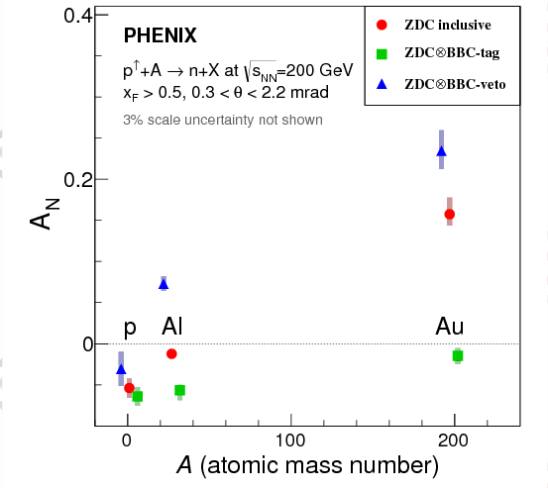
STAR: PRD 103 (2021) 072005



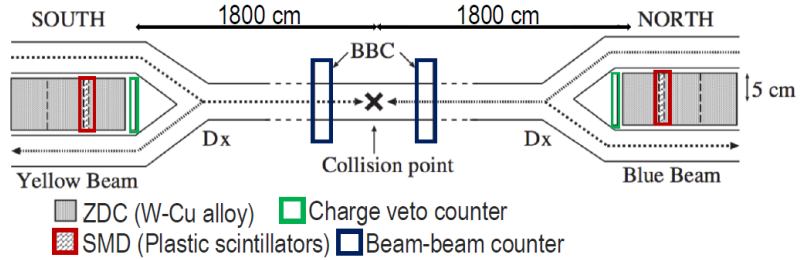
neutron asymmetries from p+p to p+A







[PRL 120 (2018), 022001]

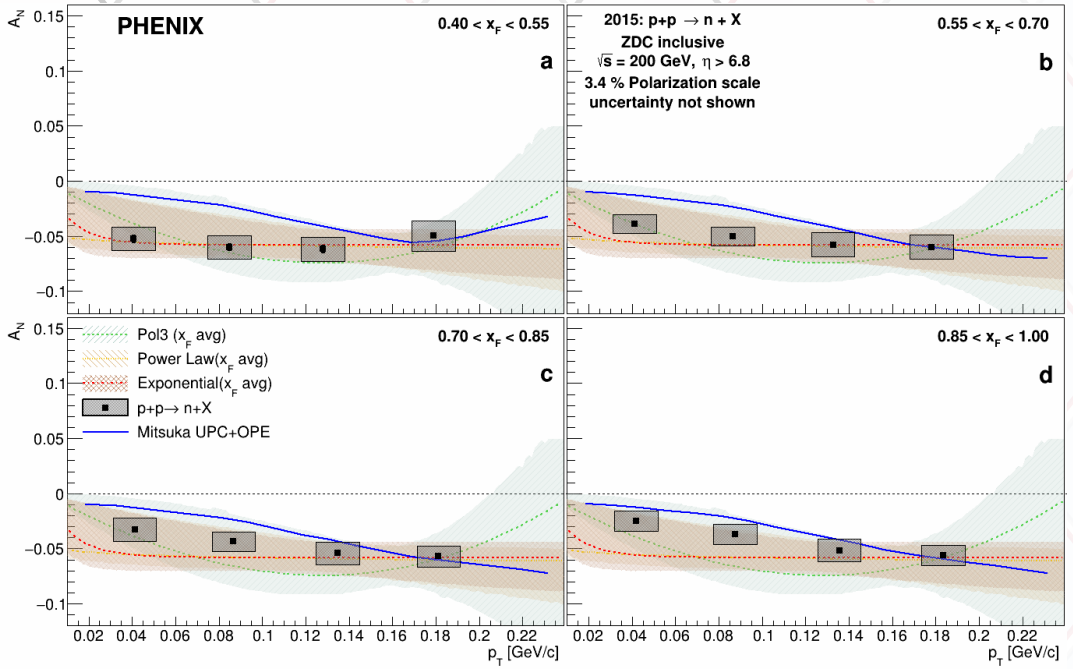


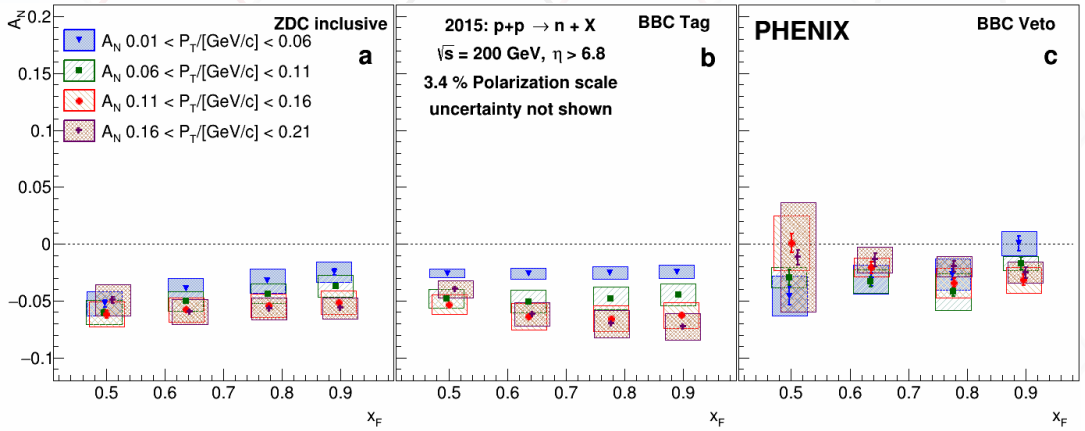
- Unexpectedly large A dependence in neutron asymmetries, sign change
- OPE model does not predict such a change in asymmetries
- Coincidence with charged particle activity in forward and backward region (BBC) enhances hard interactions → asymmetries stay negative
- Veto enhances UPC contribution → p+Al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

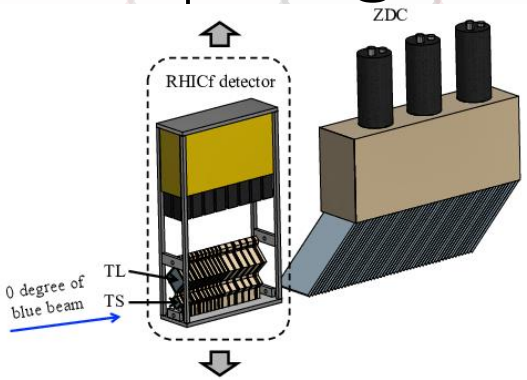


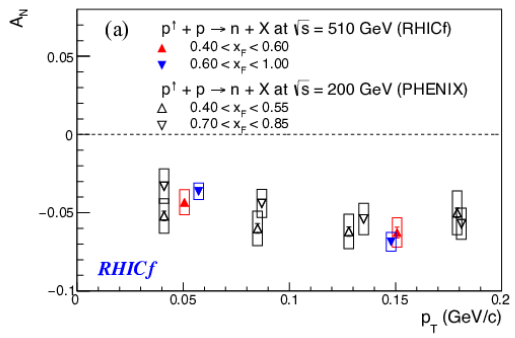


Dashed areas: best parameterizations of x_F integrated asymmetries using Pol3, Power law or Exponential

- 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

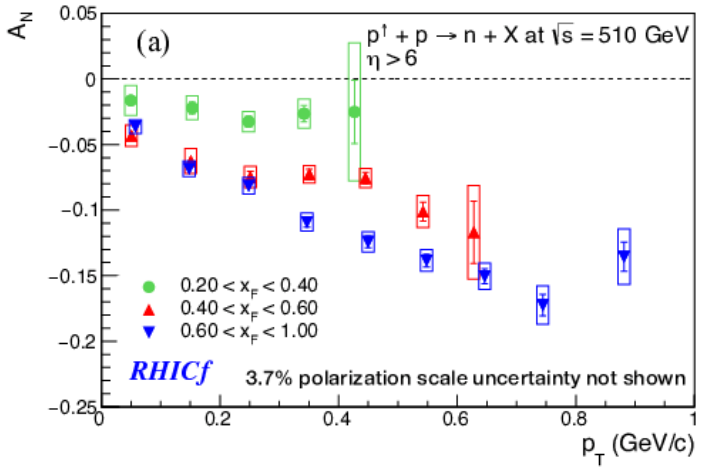
P_T range extension by RHICf experiment @510 GeV

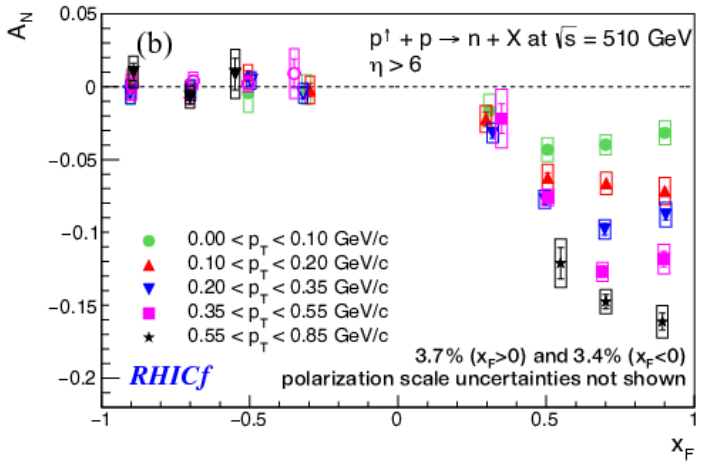




- Movable detector allows to scan a larger range in transverse momentum
- Overlap consistent with PHENIX results at 200 GeV
- Higher x_F range also consistent with OPE model *Kopeliovich et al: PRD 84 (2011) 114012*

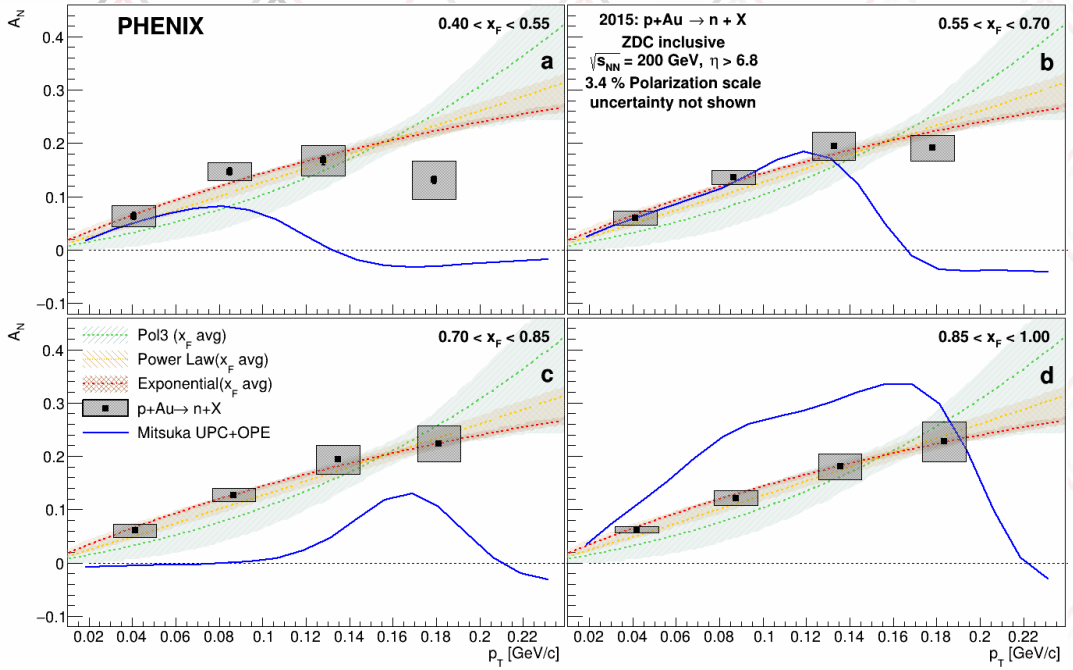
RHICf: PRD 109 (2024) 012003





Very forward neutron asymmetries in p+Au

PRD 105 (2022) 032004



- 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 and STAR 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 measurments
- 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
- Far forward neutron asymmetries with A dependence through UPC contribution, now also x_F and p_T dependence
- Also, new STAR and sPHENIX results expected from 2024 and recent runs