Probing the Hadronic Spin Structure and Dynamics in High-Energy Polarized Proton-Proton Collisions at RHIC

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College of Science and Technology
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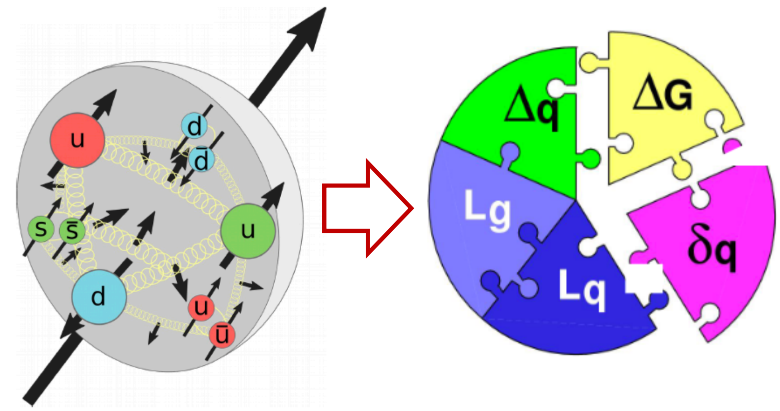
Proton Structure and QCD Effects

❑ Questions

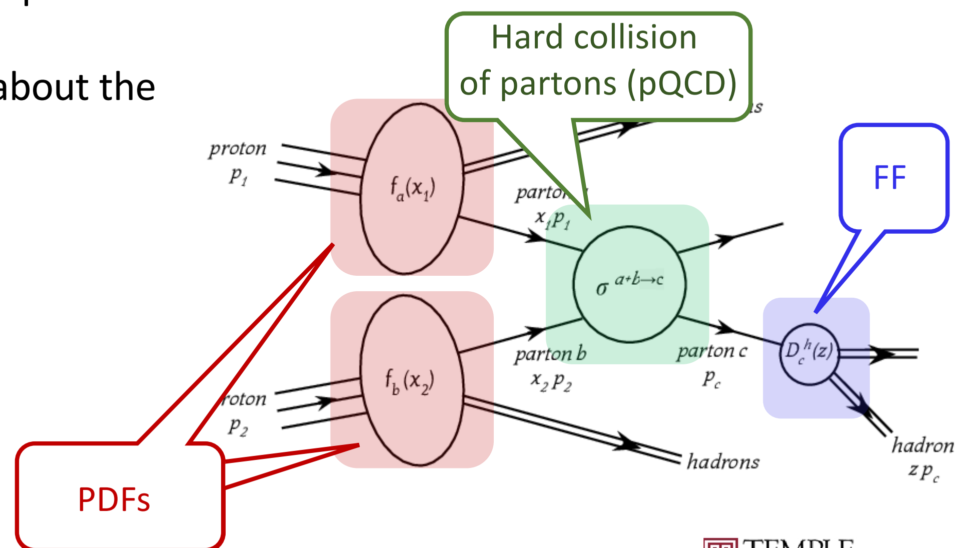
1. How do quarks, gluons and their dynamics contribute to the proton spin?

$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q,g}$$

2. How is the **transverse spin structure** (δq) of the proton distributed?
3. What do transverse-spin phenomena teach us about the structure of the proton and properties of QCD?

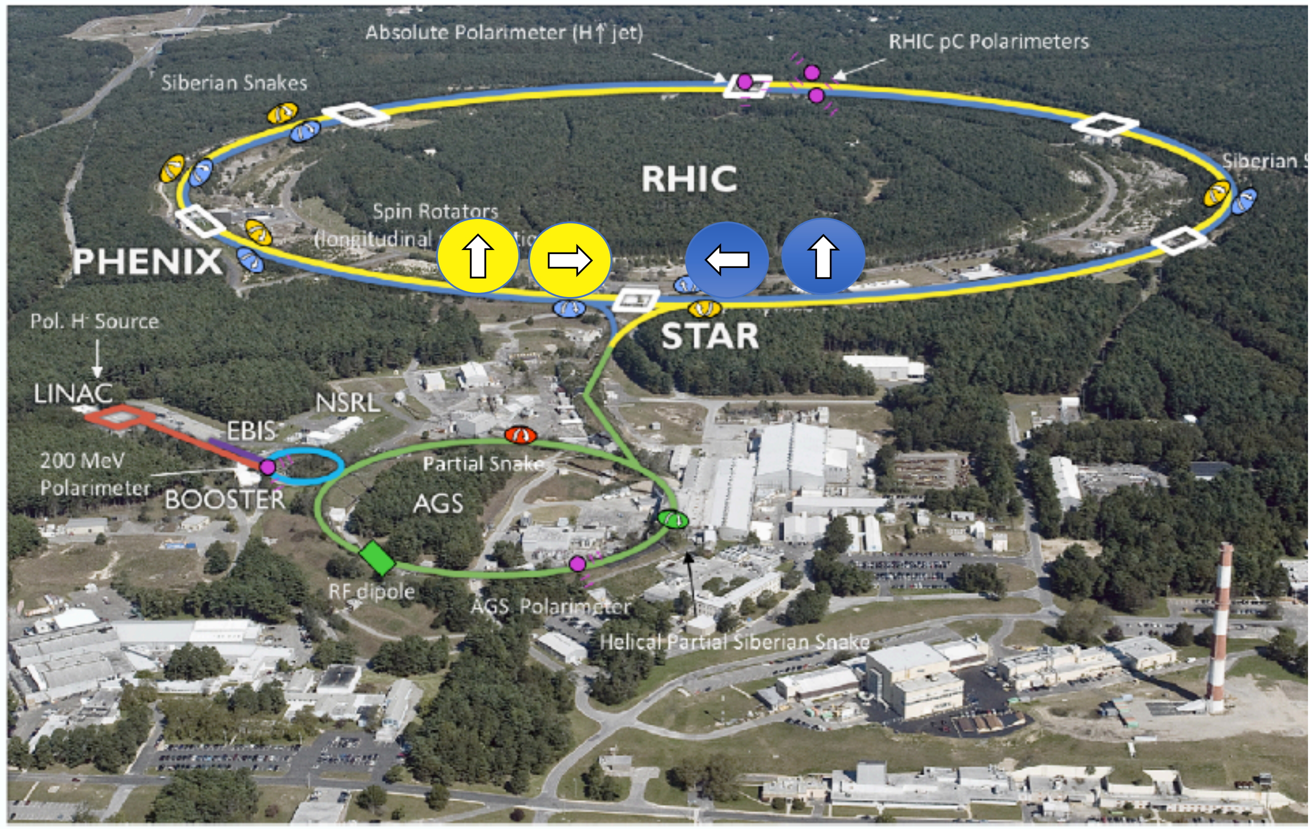


❑ Probing the proton structure via strong interactions in polarized proton-proton collisions
- Sensitive to polarized **parton distribution functions (PDFs)**, **fragmentation functions (FFs)**, **spin-momentum correlations**



Relativistic Heavy Ion Collider

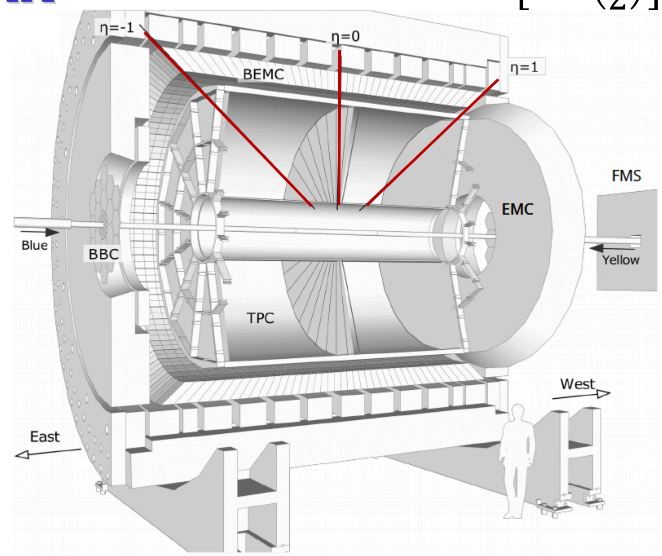
- **RHIC** at Brookhaven National Laboratory
  - World's only polarized proton collider
  - Proton collisions at center of mass energies of 62, 200, and 510 GeV
  - Transverse and longitudinal polarization
  - Polarized protons can also collide with nuclei, e.g. d, Al, Au

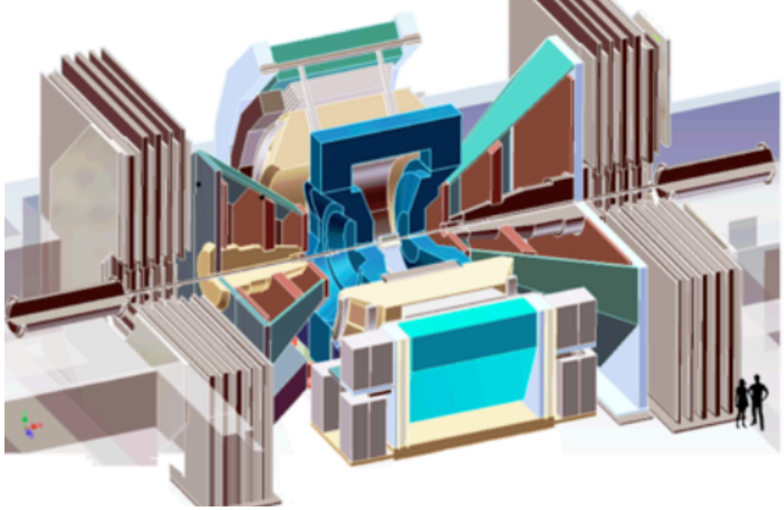


RHIC: The Main Experiments

- **STAR**
  - Large acceptance and PID for $|\eta| < 1, \Delta\phi \sim 2\pi$
  - Complimented with forward EM calorimetry $(1 < \eta < 2)$
  - FMS $(2.6 < \eta < 4)$
  - Well suited for jets and correlations
  - Current upgrades: forward calorimeter and tracking systems

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

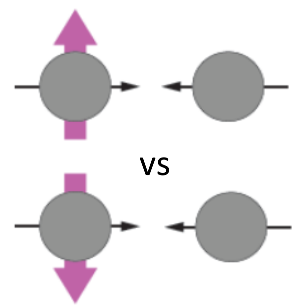




- **PHENIX**
  - High resolution and rate capabilities
  - Central arms $(|\eta| < 0.35, \Delta\phi \sim \pi)$ well suited for π^0 and η
  - Forward muon arms $(1.2 < |\eta| < 2.4)$
  - Final run in 2016
  - Being replaced by sPHENIX

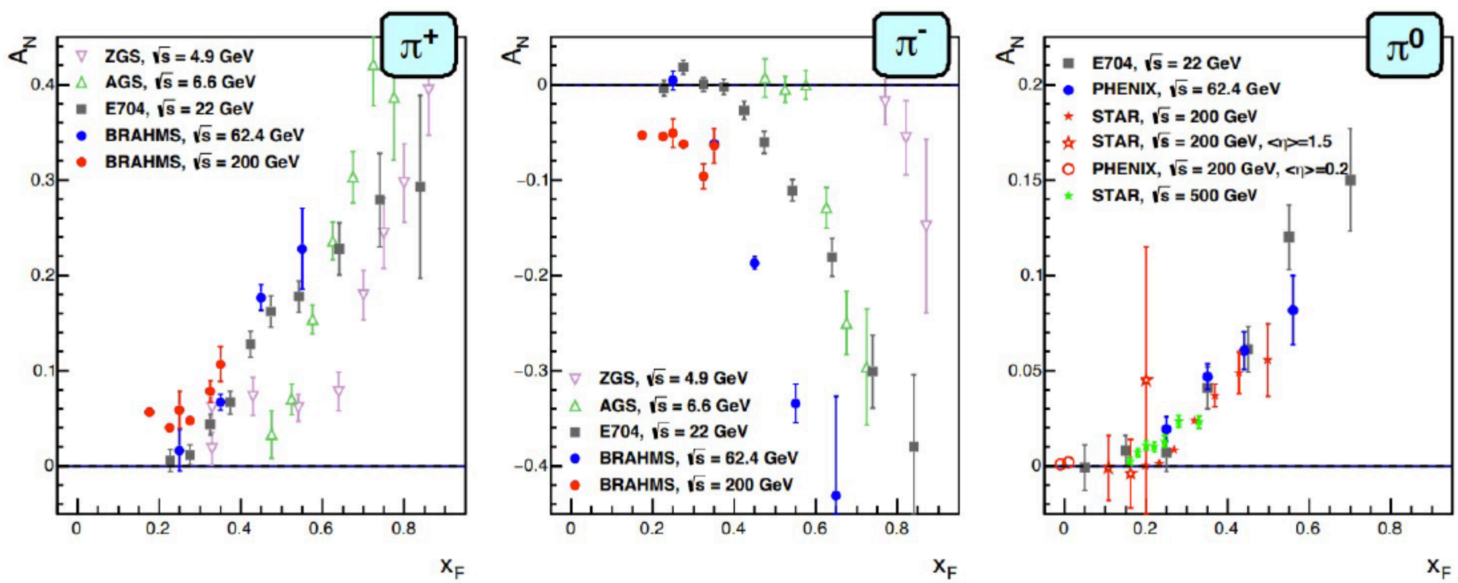
A_N Puzzle

- Large **forward** transverse single spin asymmetry (A_N) puzzle
  - Predicted to be small from pQCD (PRL 41, 1689 (1978))
  - FNAL E704 found large A_N – **significant non-perturbative effects**
  - Large A_N measured by many over many years
    - Large energy range $\sqrt{s}$ from 4.9 to 510 GeV
    - Weak energy dependence



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

arXiv: 1602.03922

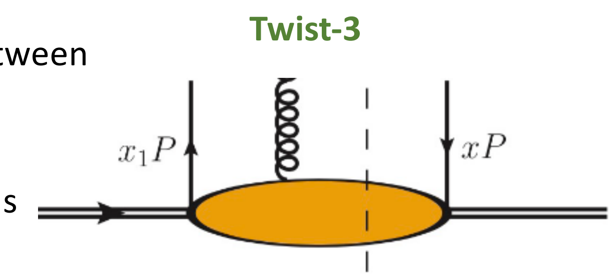


$$x_F = \frac{2p_L^h}{\sqrt{s}}$$

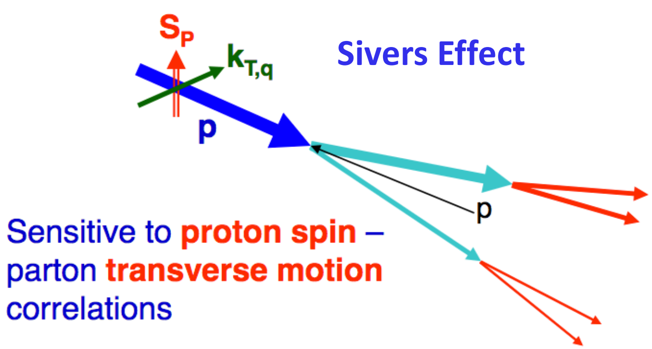
Mechanisms for A_N

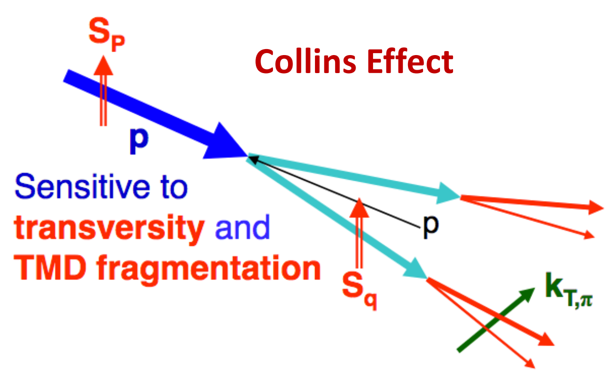
- Two theoretical QCD frameworks used to try to explain and reproduce A_N

1. **Colinear/twist-3** formalism (Efremov-Teryaev'82, Qui-Sterman'91)
   - Multiparton correlations and fragmentation functions
   - Describe spin momentum correlations from quantum mech. interference between scattering off one parton verses scattering off of two.
     - Two types: **qgq** and **ggg**



2. **Transverse Momentum Dependent (TMD)** patron distributions or fragmentations
   - Depend on transverse momentum k_T
   - Two types of effects correlating spin and k_T
     - Sivers Mechanism (Sivers '90): Correlation between nucleon spin and parton k_T in the initial state
     - Collins Mechanism (Collins'93): Correlation between quark spin and k_T in the fragmentation process



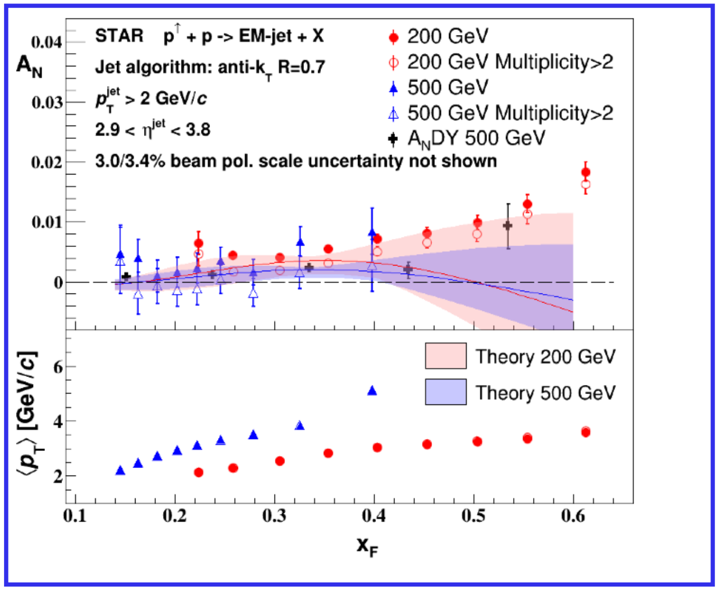


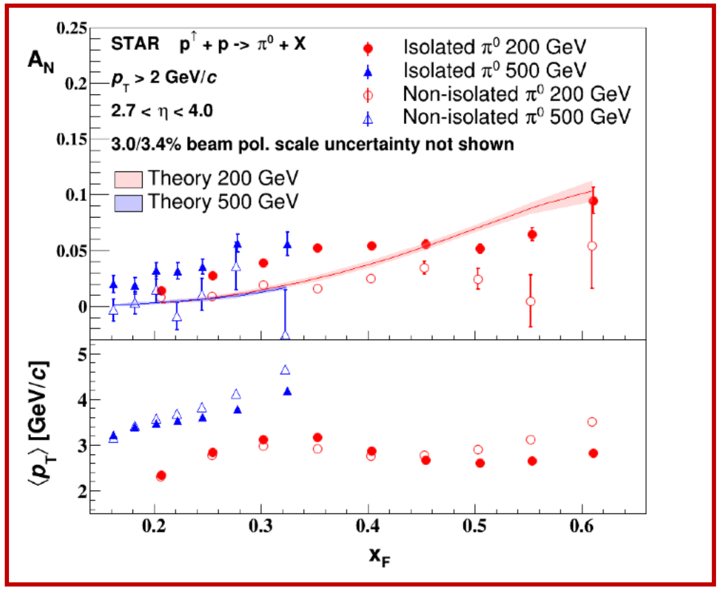
Searching for Origins of A_N

- $p^{\uparrow}p \rightarrow EM\ jet + X$
  - EM-Jet A_N are considered to be sensitive to initial state effects
  - Collins asymmetry, the azimuthal asymmetry of a hadron within a jet originating from the fragmentation of a transversely polarized quark, is sensitive to final state effects is small

- $p^{\uparrow}p \rightarrow \pi^0 + X$
  - Isolated π^0 A_N much larger than non-isolated π^0 A_N → not understood
    - Larger than jet A_N

arXiv:2012.11428 (accepted to PRD)

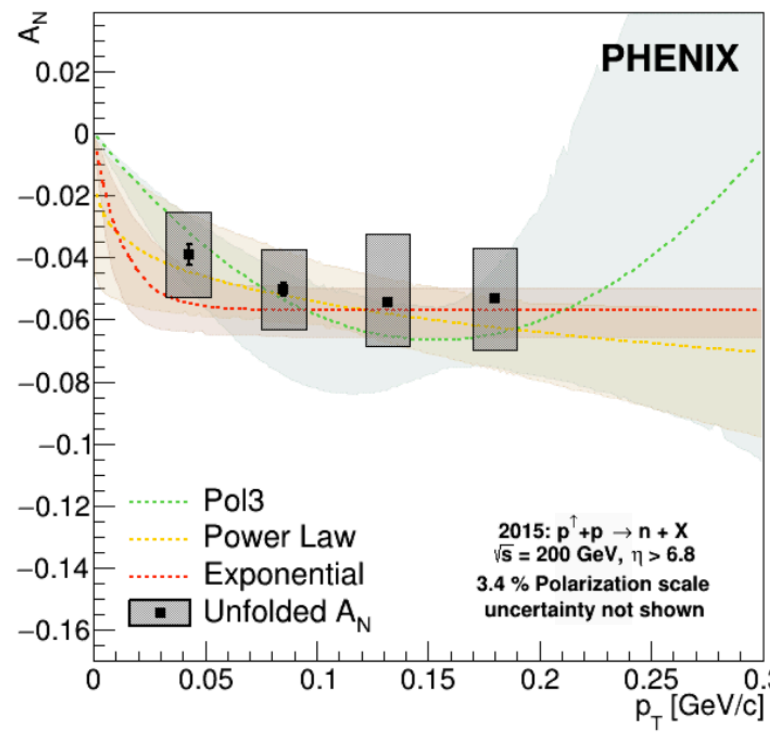




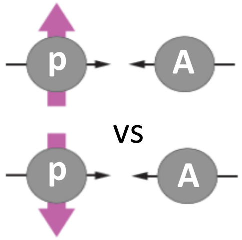
Searching for Origins of A_N

- ❑ $p^{\uparrow}p \rightarrow n + X$
  - ○ A_N of n at very forward rapidity
  - ○ Help aid in understanding underlying n A_N mechanism

PHENIX, PRD 103, 032007 (2021)

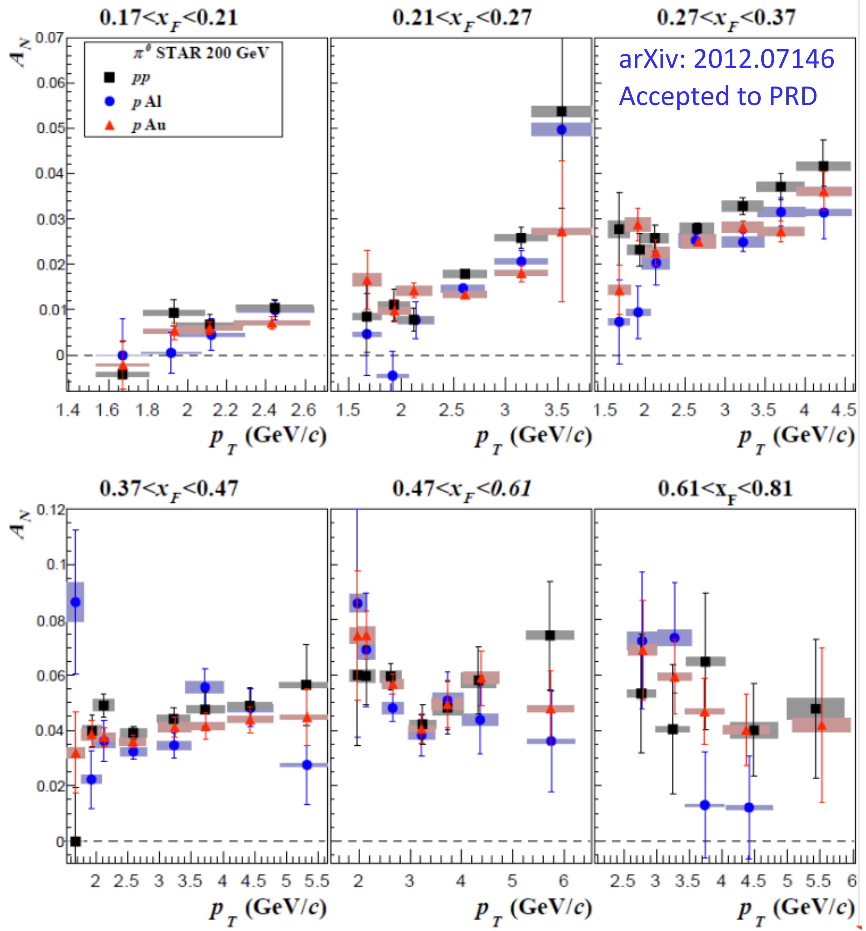


A_N In pA Collisions

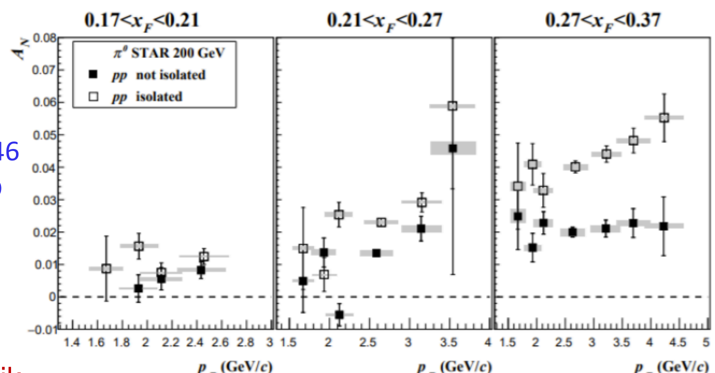


$$A_N(pA) \equiv \frac{\sigma_{pA}^{\uparrow} - \sigma_{pA}^{\downarrow}}{\sigma_{pA}^{\uparrow} + \sigma_{pA}^{\downarrow}}$$

- A_N is sensitive to the environment, including initial or final state interactions of hard scattering partons
- STAR measured A_N in pp, pAl, and pAu and found
  - Similar asymmetries amongst the three collision types – weak nuclear dependence
  - A_N rises with p_T (~< 5 GeV) for x_F ~< 0.5
  - Isolated π^0 A_N is larger than non-isolated π^0 (found for pp, pAl, and pAu)



arXiv: 2012.07146
Accepted to PRD

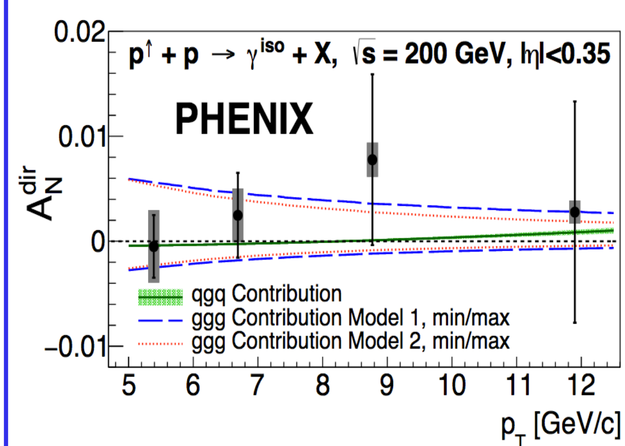


arXiv: 2012.07146
Accepted to PRD

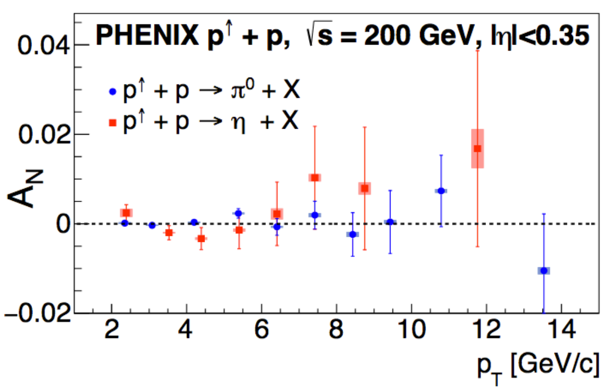
Twist-3 Correlations and Gluon Sivers Functions

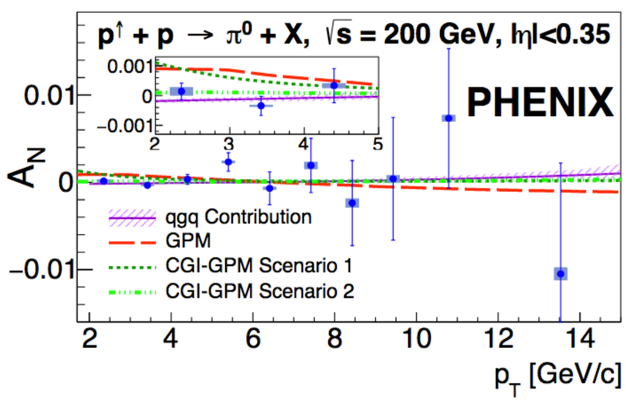
- Midrapidity is sensitive to **trigluon twist-3 correlation function** and gluon **Sivers function**
- $p^{\uparrow}p \rightarrow \eta/\pi^0 + X$
  - A_N of η mesons are potentially sensitive to effects from strange quark contributions, isospin differences and/or hadron mass
  - Mid-rapidity π^0 and η A_N are consistent with each other and zero
- $p^{\uparrow}p \rightarrow \gamma^{iso} + X$
  - Sensitive to the gluon spin-momentum correlations in the proton (twist-3 trigluon correlation function)
  - Isolated direct photon A_N is **not sensitive** to hadronization effects or final-state color interactions
  - Small **qgq contribution** is expected

PHENIX, arXiv:2102.13585

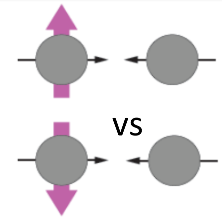


PHENIX, PRD 103, 052009 (2021)

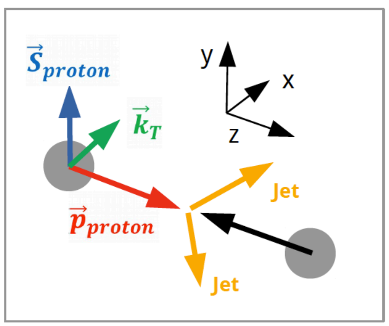


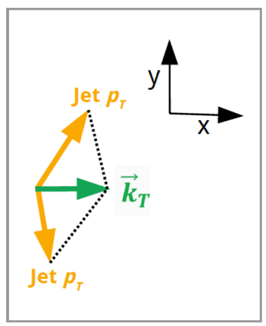


- Sivers Effect
  - Measures spin-dependent parton k_T
  - Non-zero k_T leads to tilt of di-jet opening angle in the transverse plane
  - Tag jet based on momentum weighted track curvature – allows more sensitivity to parton type

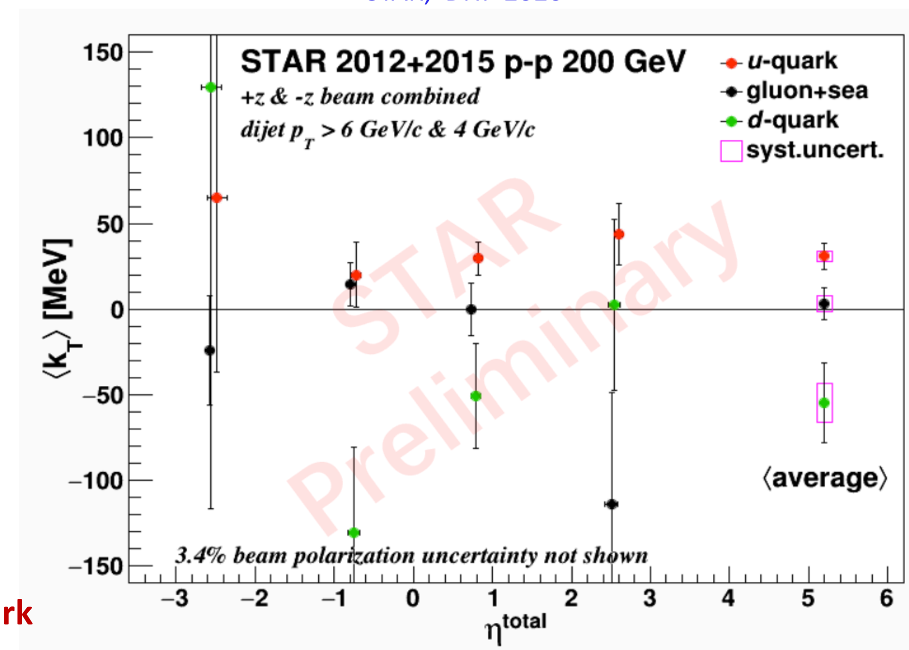


$$\langle \vec{S}_{proton} \cdot (\vec{p}_{proton} \times \vec{k}_T)\rangle \neq 0$$





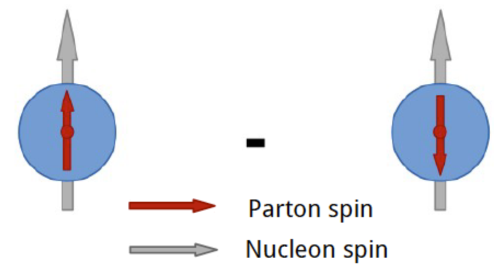
STAR, DNP 2020



- Significant η-average effects
- Flavor dependence
  - u and d quark **opposite** sign
  - d **quark** about **twice** as large as average k_T for u **quark**

Transversity

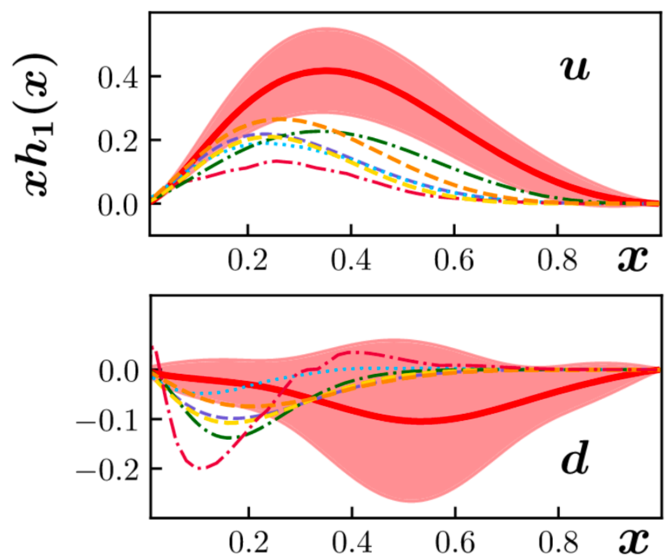
- Transversity – net density of transversely polarized quarks in a transversely polarized nucleon
  $$h_1(x,Q^2) = q^{\uparrow}(x,Q^2) - q^{\downarrow}(x,Q^2)$$
  - Least known of the three leading twist colinear PDFs.



- In pp collisions, transversity couples to FF: **Collins FF** and **Interference FF (IFF)**
  - Creates **azimuthal modulations** in the cross section which leads to obser asymmetries
  - The **transverse spin transfer** to hyperons, $D_{TT,}$ is sensitive to **strange quark** transversity (and polarized FF)

$$D^{\Lambda}_{TT} \equiv \frac{\sigma^{(p^{\uparrow}p\to\Lambda^{\uparrow}X)} - \sigma^{(p^{\uparrow}p\to\Lambda^{\downarrow}X)}}{\sigma^{(p^{\uparrow}p\to\Lambda^{\uparrow}X)} + \sigma^{(p^{\uparrow}p\to\Lambda^{\downarrow}X)}} = \frac{d\delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

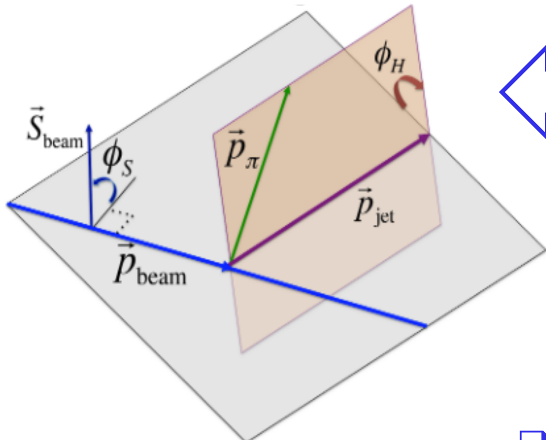
$$d\delta\sigma^{\Lambda} \sim \boldsymbol{h_1(x_1)} \otimes f_b\,(x_2) \otimes \Delta\hat{\sigma} \otimes \boldsymbol{\delta D}$$



PRD 102, (2020) 054002

Transversity

$p^{\uparrow} + p \to Jet + h^{\pm} + X$

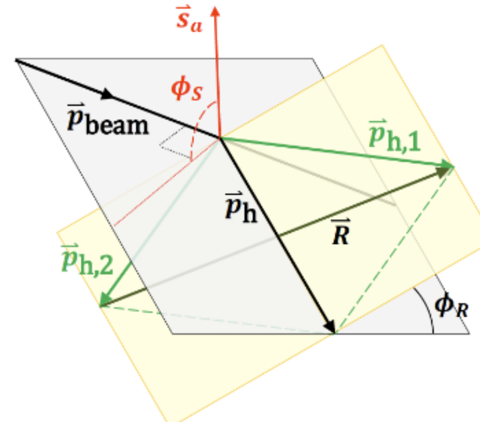


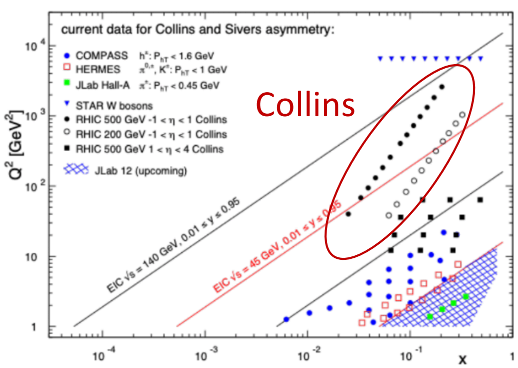
- Sivers, $\phi \to \phi_s$
- **Collins, $\phi_s \to \phi_s - \phi_H$**
- Collins-Like, $\phi_s \to \phi_s - 2\phi_H$

- **IFF, $\phi \to \phi_s - \phi_R$**

$$A_{UT}^{\sin(\phi)} \sin(\phi) = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)}$$

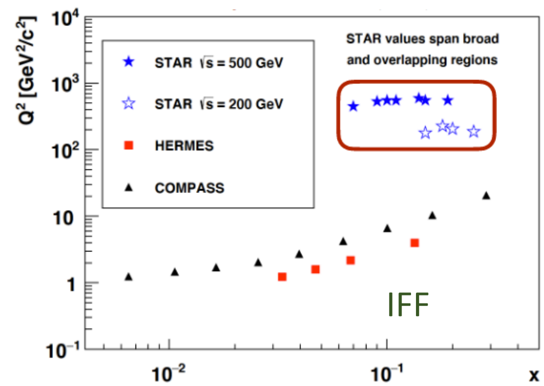
$p^{\uparrow} + p \to h^{+}h^{-} + X$





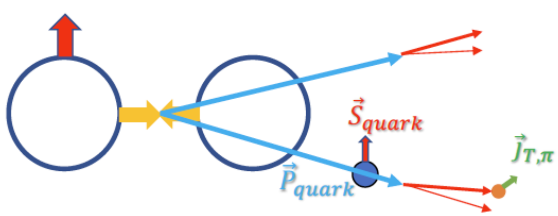
- $p^{\uparrow} + p \to Jet + h^{\pm} + X$
  - Different modulations can be used to isolate various contributions
  - Other modulations also measured
- $p^{\uparrow} + p \to h^{+}h^{-} + X$
  - IFF
- RHIC Kinematics
  - provides large Q^2 coverage and broad x reach
  - complimentary to SIDIS

STAR, PLB 780 (2018) 332

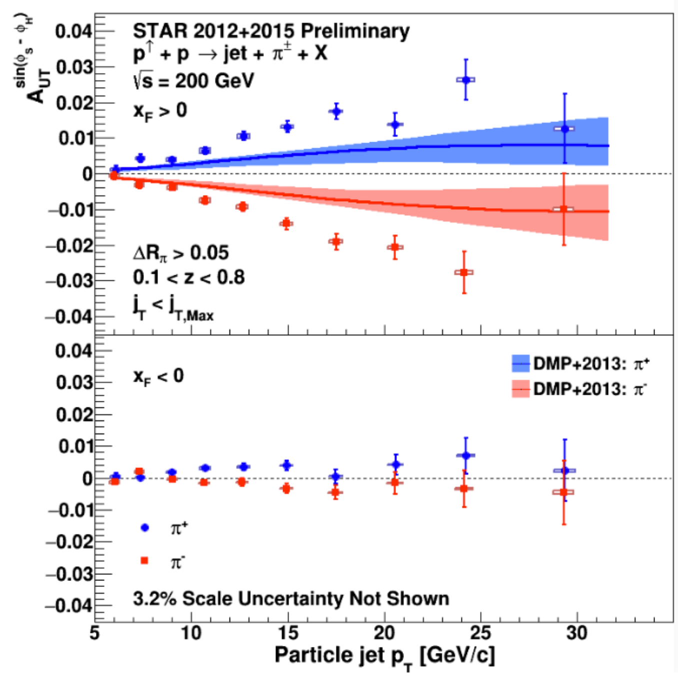


Transversity: Collins Asymmetry

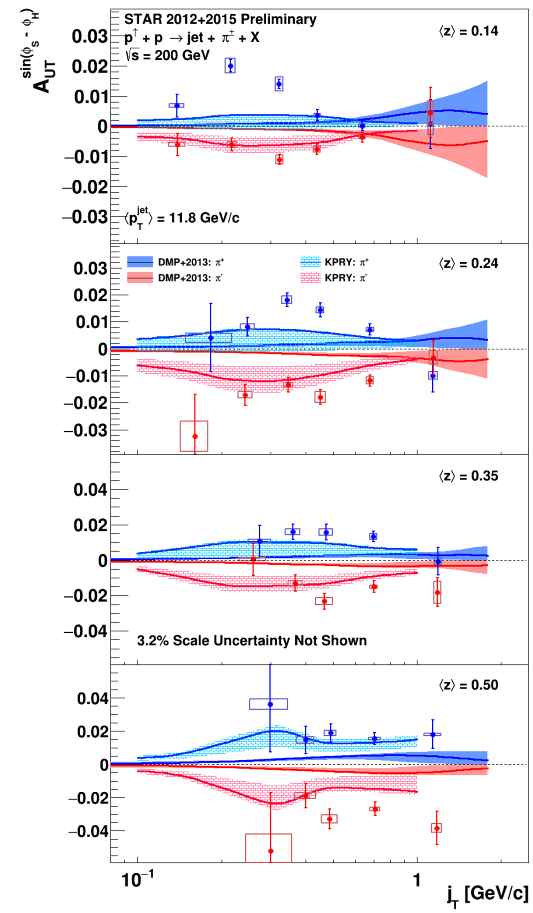
- **Collins asymmetry**
  - $\boldsymbol{K^{\pm}}$ and $\boldsymbol{p(\bar{p})}$ also measured
  - $\boldsymbol{K^{+}}$ positive and similar magnitude as $\boldsymbol{\pi^{+}}$ (within uncertainty)
  - Other azimuthal asymmetries also measured (Sivers, Collins-Like)
  - Polarized FF more sensitive to $\boldsymbol{j_T}$ dependence



STAR, DIS 2021

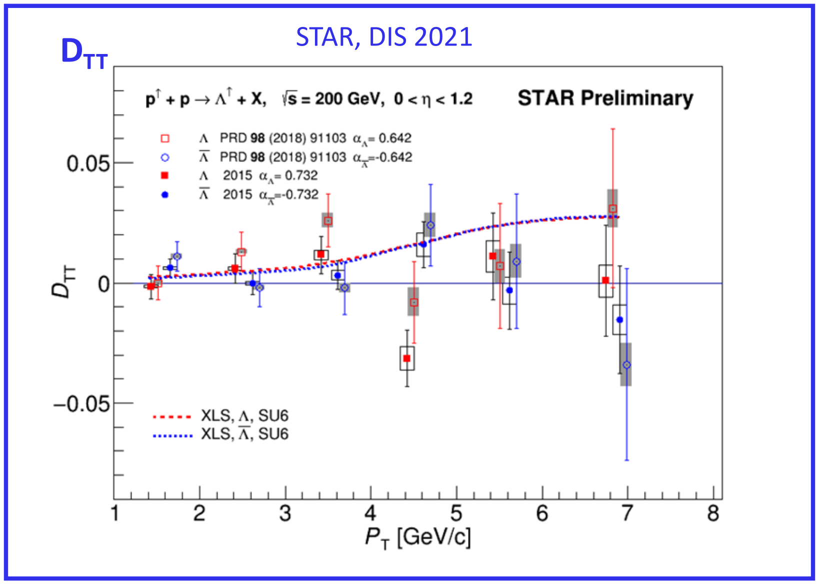


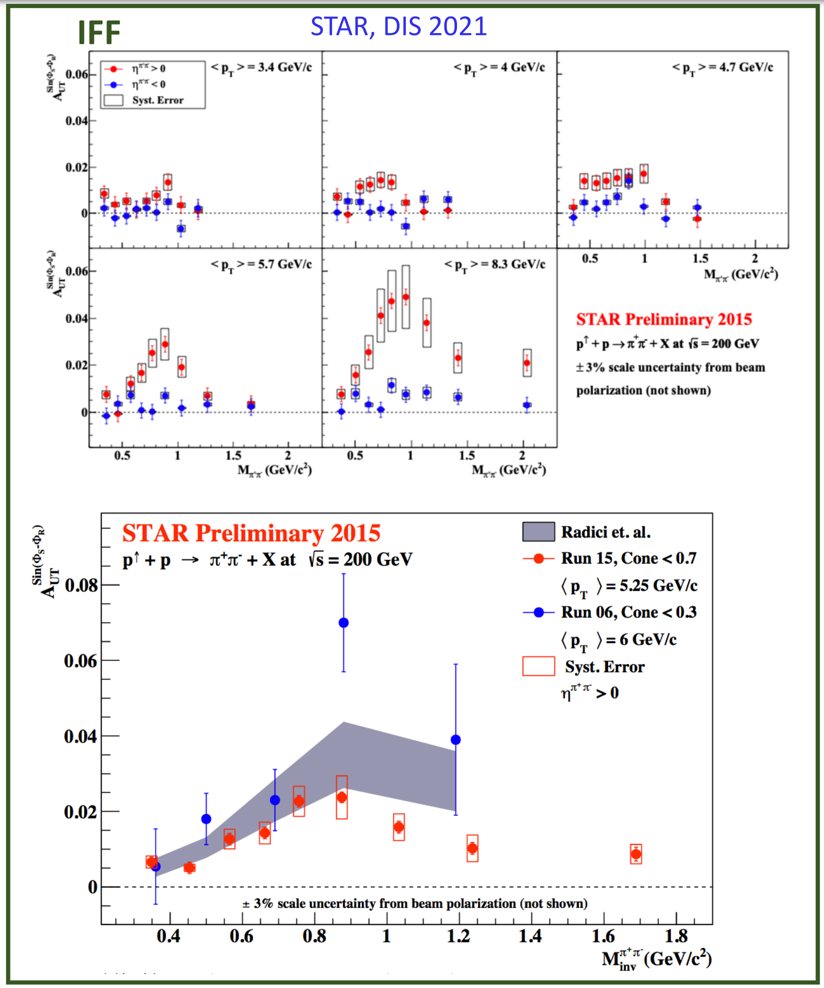
STAR, DIS 2021



Transversity: IFF and Spin Transfer

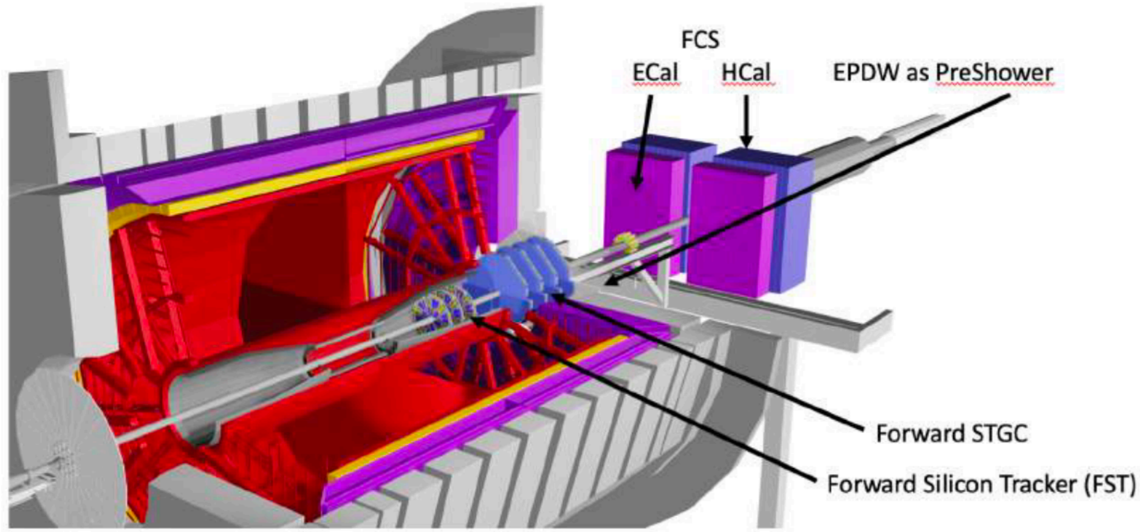
- **IFF**: $p^{\uparrow} + p \rightarrow \pi^{+}\pi^{-} + X$
  - Large asymmetry
  - Enhancement near ρ mass (~0.78 GeV/c²)
- **Spin transfer D_{TT}**: $p^{\uparrow} + p \rightarrow \Lambda^{\uparrow} + X$
  - STAR can measure Λ through the weak decay channel
    - $\Lambda \rightarrow p + \pi^{-}, \bar{\Lambda} \rightarrow \bar{p} + \pi^{+}$





STAR Forward Upgrade

- ❑ STAR Forward Upgrade
  - ○ **Tracking**: Si disks and small Thin Gap Chambers
  - ○ **Calorimetry**: hadronic and electromagnetic
- ❑ Ensure jet capability and charge-sign discrimination
- ❑ Cover forward rapidity $2.5 < \eta < 4$



- ❑ Data Taking
  - ○ $\sqrt{s} = 510$ GeV transversely polarized p+p run in 2022
  - ○ Other data (p+p, p+A) taken in parallel with sPHENIX

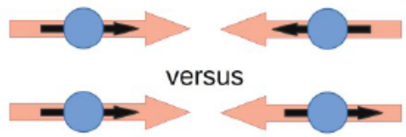
Summary

- RHIC is playing a critical and complementary role in resolving the structure of the proton
- Investigating QCD Effects
    - A_N origin at forward rapidity
        - pp and pA collisions
    - Constrain twist-3 correlation function (trigluon)
    - Study Sivers effect using di-jets
- Transvers spin structure
    - Constrain transversity through Collins, IFF, and D_{TT} asymmetries
- STAR forward physics program begins in 2022
- Many new and exciting results to come!

Gluon Polarization

- How do gluons contribute to the proton spin?

$\vec{p} + \vec{p} \rightarrow$ jet/ dijet/ hadron + X

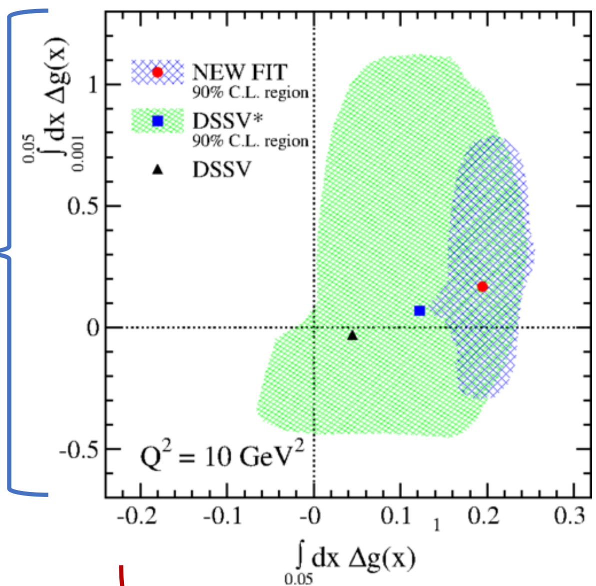


$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} a\hat{_{LL}} \otimes D}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes D}$$

LO for illustration

PRL 113, (2014) 012001

Low-x poor constraint



High-x better constraint

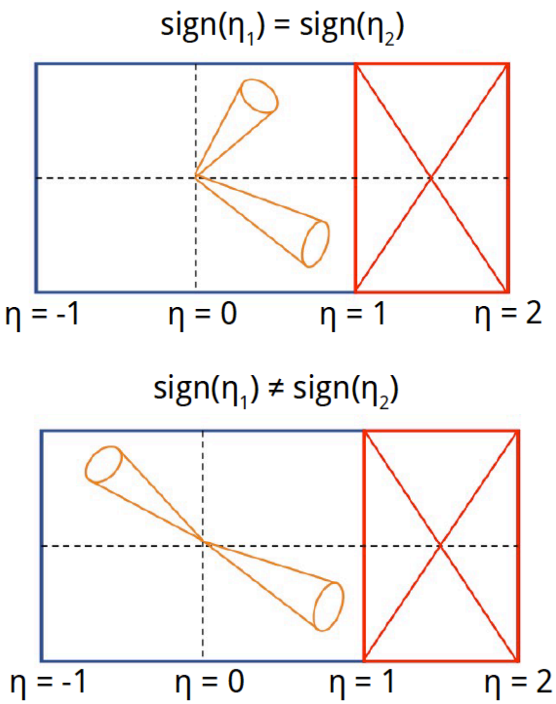
- 2009 RHIC data has played a critical role in providing constraints on the polarized gluon distribution
- **Integral of $\Delta g(x > 0.05) \sim 0.2$** (from global analyses)
- Need to push sensitivity to **lower x**

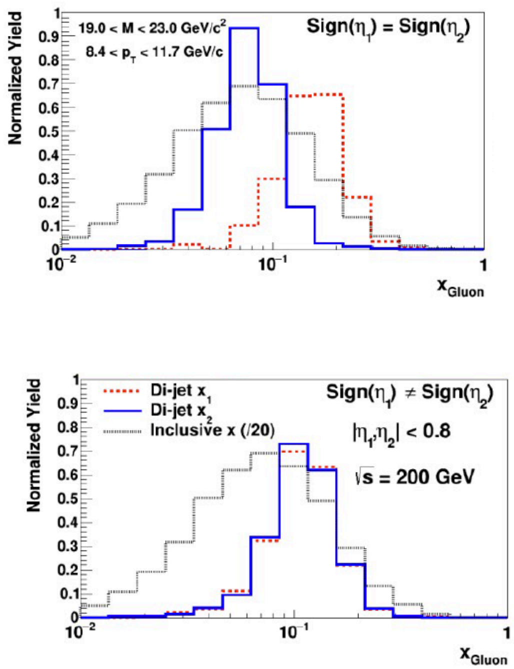
1. Higher center of mass energy: $x_g \propto s^{-\frac{1}{2}}$
2. Forward rapidity: $x_g \propto \exp(-\eta)$

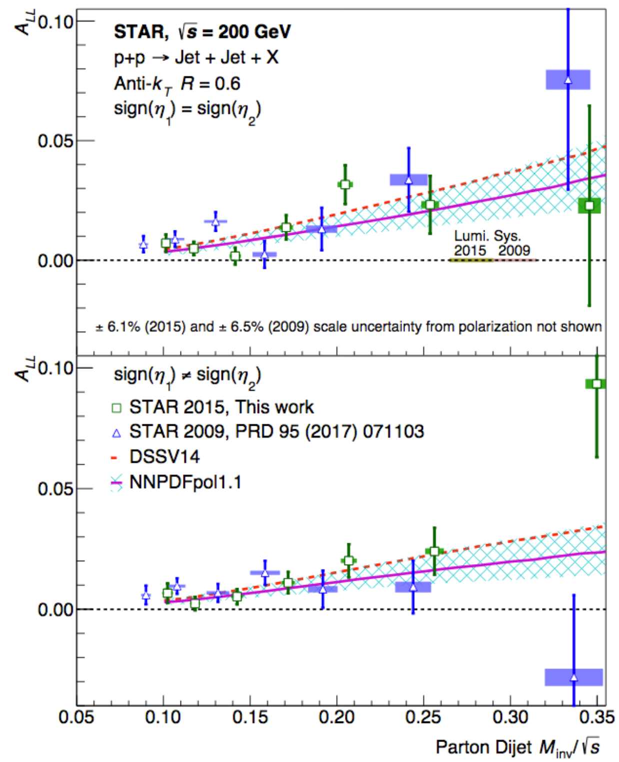
Gluon Polarization

- Dijets provide better control of underlying partonic kinematics
  - Better constraint of the shape of $\Delta g(x)$ functional form
  - More forward production is sensitive to lower x (down to ~**0.01**)
  - Including **STAR EEMC** allows sensitivity to **x > 0.004** (analysis of high stat. 2013 data set in progress)

STAR, arXiv: 2103.05571 Submitted to PRL D.



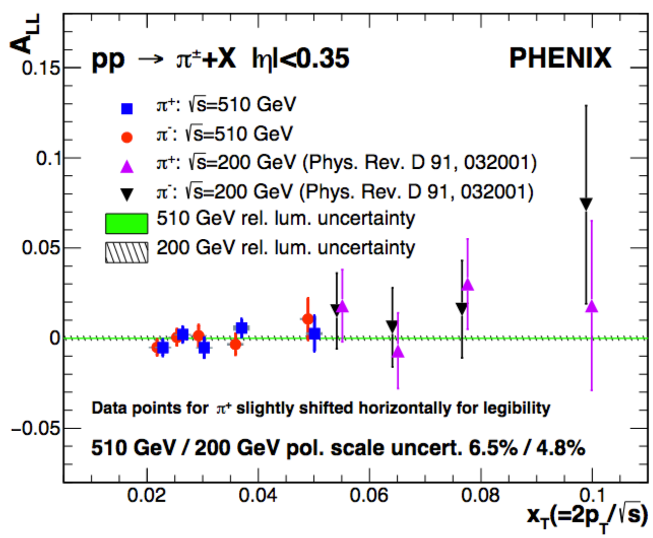




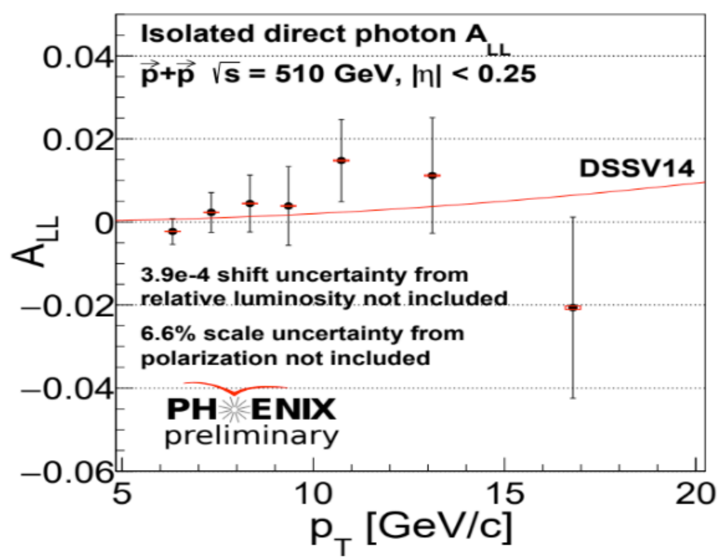
Gluon Polarization

- ❑ **Higher center** of mass pushes to lower **x > 0.02**
  - ○ Pions and photons provide complimentary probes
  - ○ Charged pions measured by PHENIX
  - ○ Direct photon sensitive to gluon polarization
    - ○ $qg \rightarrow \gamma q$ (no hadronization)

PHENIX, PRD 102 (2020) 032001



PHENIX, RAUM 2020

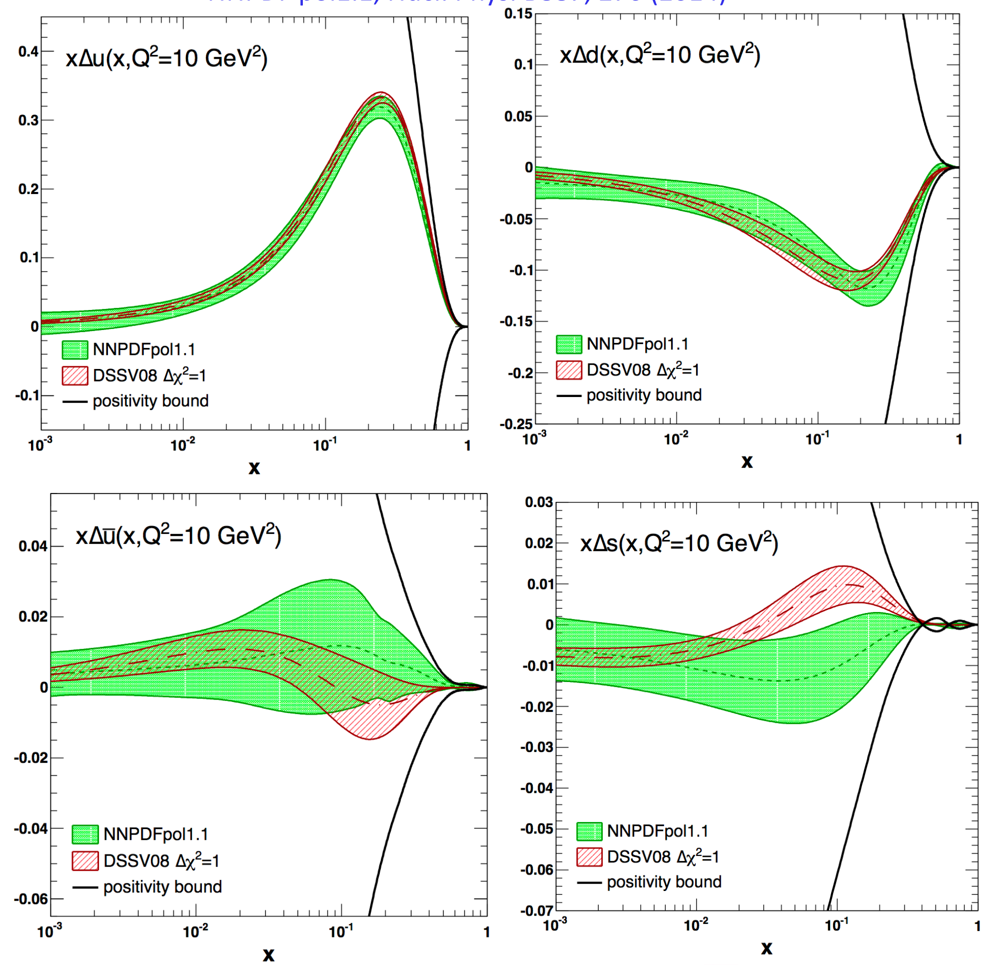


Quark Helicity

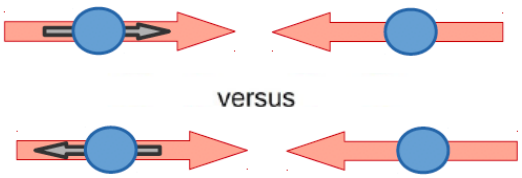
- Sea quark helicity distributions
  - Not known as well as the valence quarks
  - Still not well constrained from experiment, in particular the strange quark
- Polarized Λ hyperons are sensitive to the strange quark helicity distribution
  - contain constituent strange quark which is expected to carry majority of Λ spin.
  - Can be produce in polarized proton collisions

$$\vec{p} + p \rightarrow \vec{\Lambda} + X$$

NNPDF pol1.1, Nucl. Phys. B887, 276 (2014)



Quark Helicity



$$D_{LL}^{\Lambda} \equiv \frac{\sigma^{(p^+p\to\Lambda^+X)} - \sigma^{(p^+p\to\Lambda^-X)}}{\sigma^{(p^+p\to\Lambda^+X)} + \sigma^{(p^+p\to\Lambda^-X)}} = \frac{d\Delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

$$d\Delta\sigma^{\Lambda} \sim \boldsymbol{\Delta f_a(x_1)} \otimes f_b\,(x_2) \otimes \Delta\hat{\sigma} \otimes \boldsymbol{\Delta D}$$

- STAR can measure Λ through the weak decay channel
  - $\Lambda \to p + \pi^-, \bar{\Lambda} \to \bar{p} + \pi^+$
- Longitudinal spin transfer, D_{LL}, provides sensitivity to strange quark helicity distribution and polarized fragmentation functions.
- New STAR measurements consistent with previous.
- D_{LL} found to be small

STAR, DIS 2021