sPHENIX spin and cold QCD

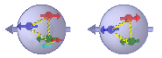
sPHENIX RBRC workshop
July 22

Ralf Seidl (RIKEN)

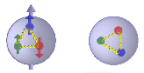
Main QCD Spin Questions

- How is the spin of the proton distributed? What is the role of gluons and sea quarks?
- What is the origin of transverse spin effects and how does it relate to the 3D momentum and position structure of the Nucleon?
- Closely intertwined: How does QCD create 99% of the visible mass of the universe? How does confinement work?
- From nucleus to nuclei, high gluon densities

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_G + \mathcal{L}_q$$

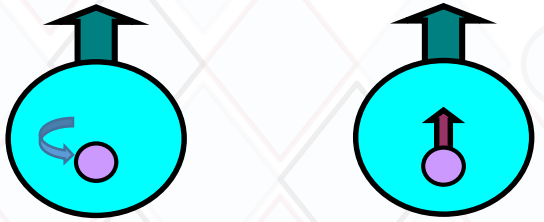


➔Sivers, Collins effects, TMDs GPDs, orbital angular momentum, Tomography

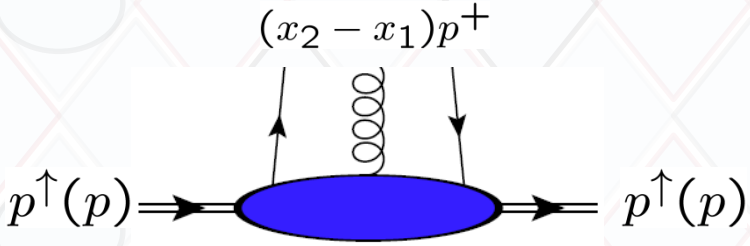


➔Fragmentation functions and their spin, flavor, type, long. and transverse momentum dependence

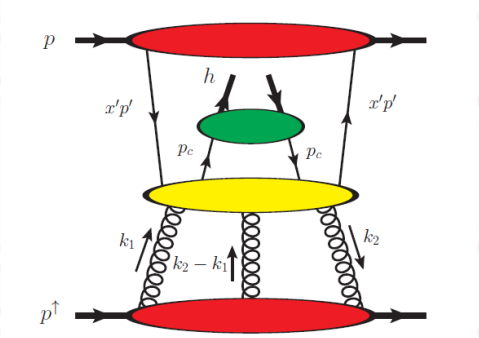
➔ nuclear modification of PDF/FFs, low-x behavior



Sivers Transversity



q-g correlation



g-g correlation (trigluon)

Transverse spin

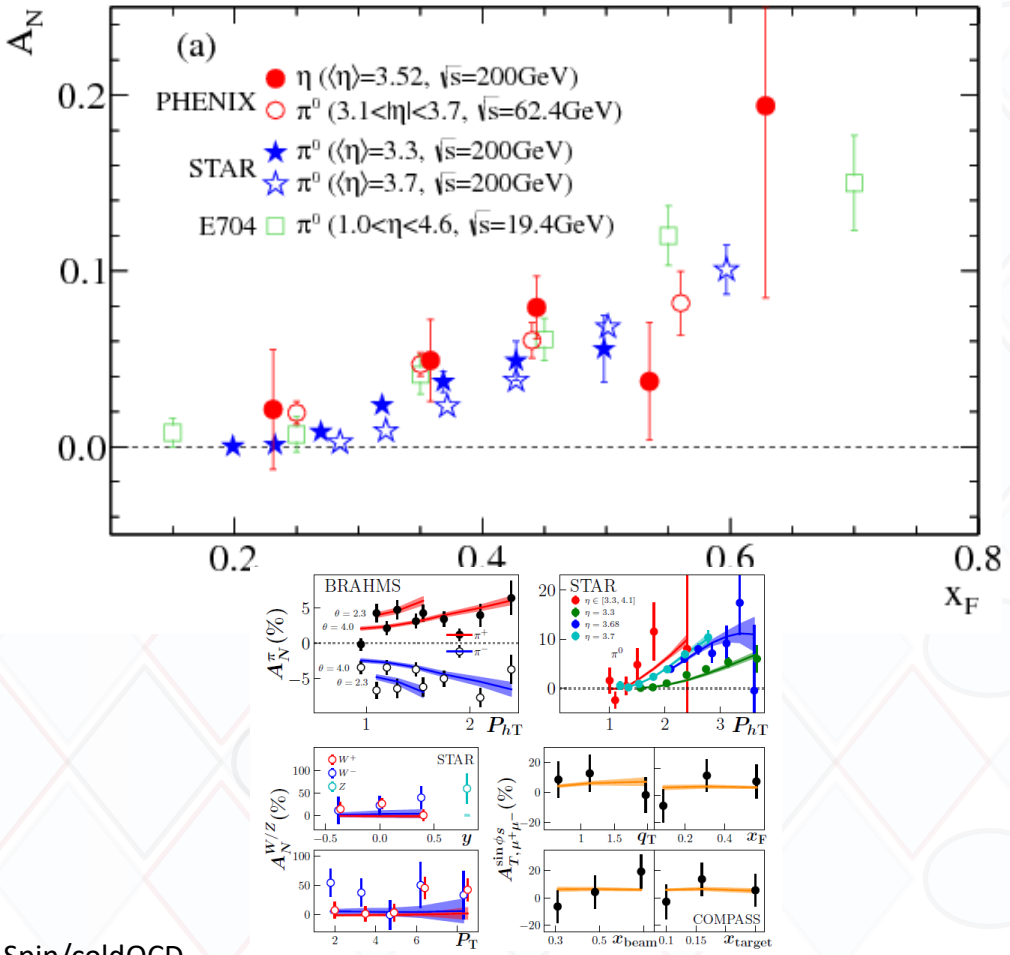
Main questions:

- Origin of large A_Ns: initial state? Final state?
- Connections between higher twist and TMDs
- Nuclear/low-x modification of A_Ns?

Transverse single spin asymmetries

- Large left-right asymmetries A_N seen in polarized pp collisions from low energies up to highest RHIC energies
- Both initial state and final state effects contribute in the same asymmetries
- TMD interpretation not directly applicable as only one scale process instead of 2 scales (P_T in p+p vs Q^2 and P_{hT})
- Higher twist interpretation is applicable; related to the TMD moments

Phys.Rev. D90 (2014) 7, 072008
Phys.Rev. D90 (2014) 1, 012006

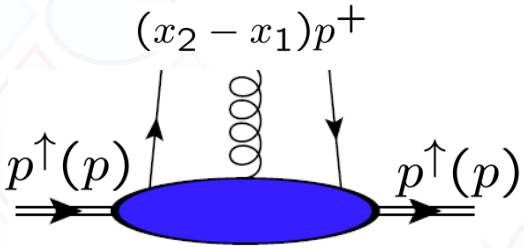


TSSAs at RHIC→Quark-gluon dynamics!

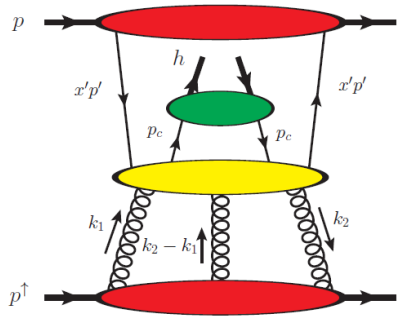
- Sivers and Collins effects rely on an explicitly transverse momentum dependent (TMD) framework where two scales are observed: high scale (typically Q^2) and intermediate scale (transverse momentum $P_T << Q^2$)
- In inclusive pp measurements usually only one, hard scale accessible (transverse momentum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

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

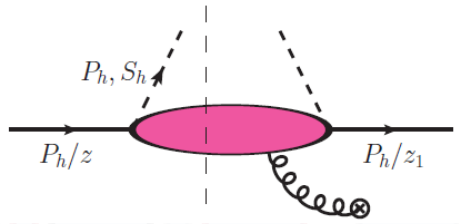
- Both frameworks found to be related via moments over intrinsic transverse momenta



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*

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

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

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

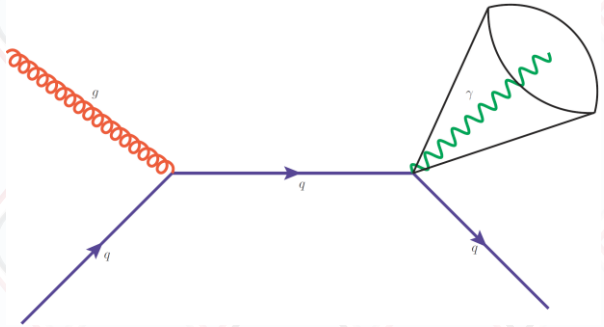
a,b/c initial/final parton flavors
A,B/C initial/final hadron/particle types

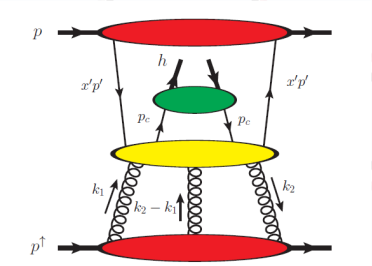
Efremov, Teryaev Phys.Lett.B 348 (1995) 577
Qiu, Sterman Phys.Rev.D 59 (1999) 014004
Kanazawa, Koike Phys.Lett.B 478 (2000) 121-126
Metz, Pitonyak Phys.Lett.B 723 (2013) 365-370

- 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

Direct photon measurements: the golden channel

- As photon interacts only electromagnetically there are no final state effects → only probe initial state effects
- Hard process contributions strongly favor quark-gluon interaction (very little quark-quark contributions)
- Excellent probe of the tri-gluon correlator
- But EM interaction costs you $\frac{1}{\sqrt{\alpha_{EM}}}$ →statistically difficult



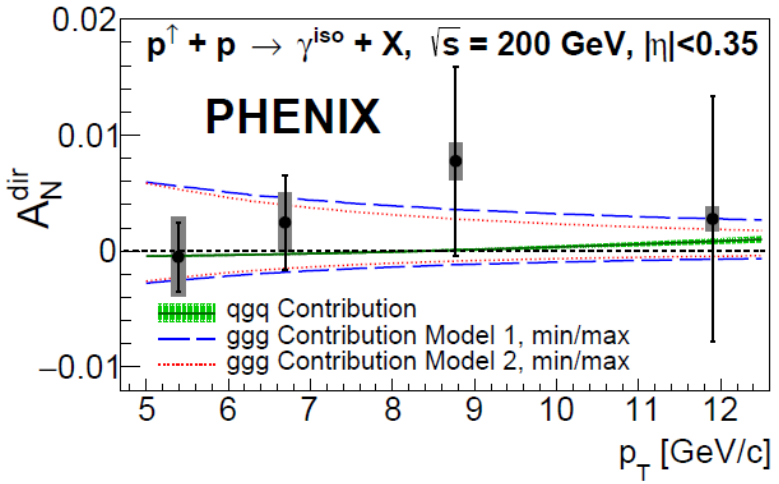


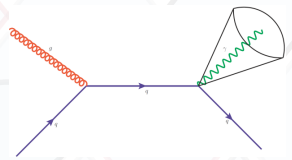
- Also not all photons produced directly → need to understand and measure Background and its asymmetry

First direct photon ANs

- 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

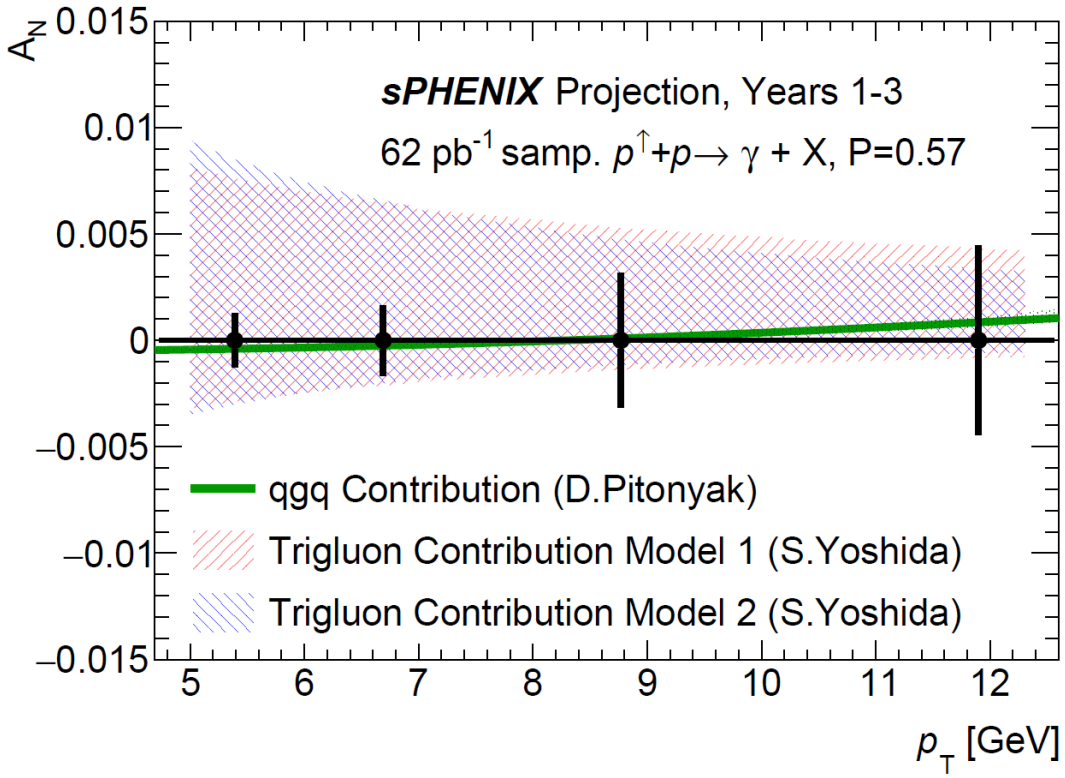
Phys.Rev.Lett. 127 (2021) 162001

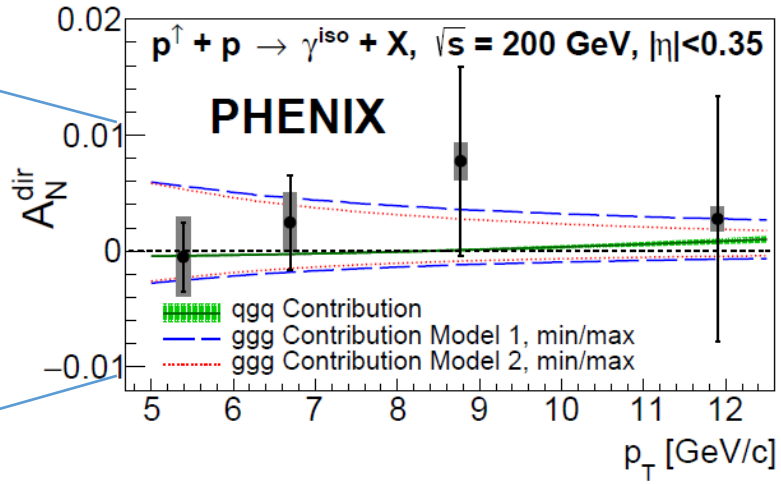




Gluon dynamics via γ, HF TSSA

- TSSA of prompt photon EMCal-based trigger
- Substantial improvement possible with sPHENIX





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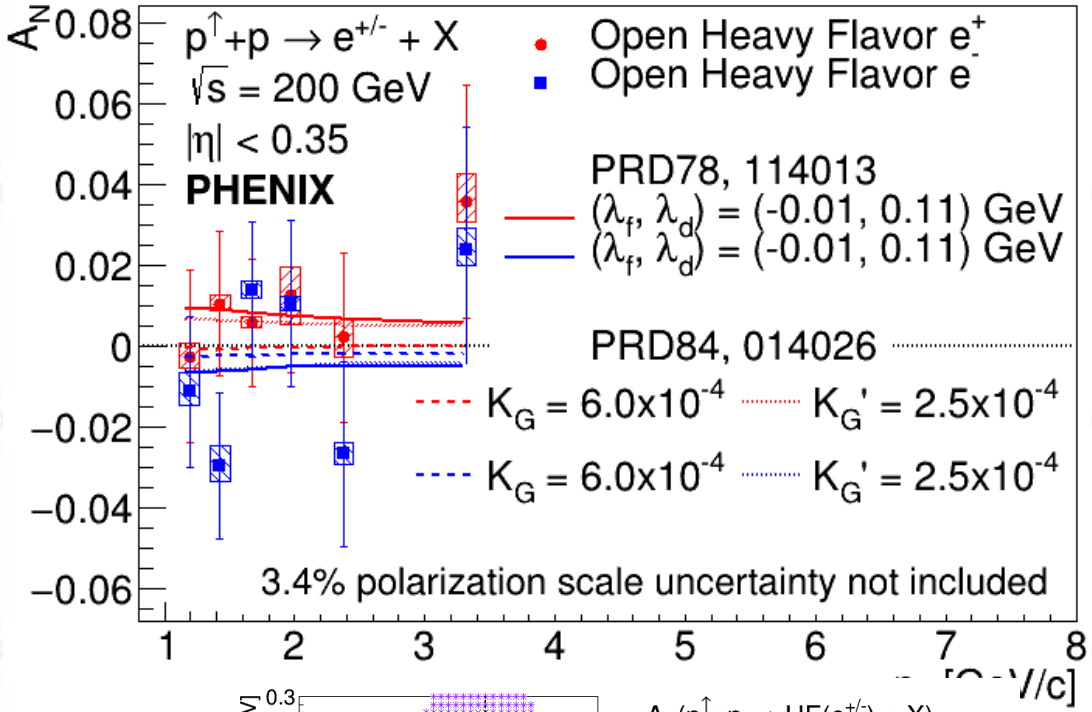
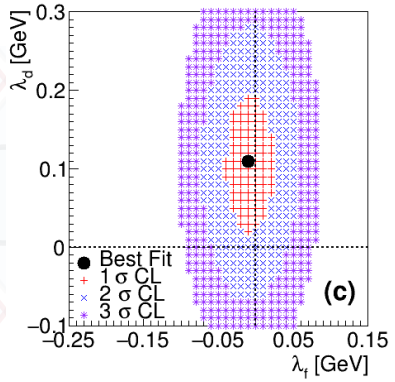
Heavy Flavor electron A_Ns

- 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

PHENIX, submitted to PRL
https://arxiv.org/abs/2204.12899





$A_N(p^{\uparrow}+p \rightarrow HF(e^{+/-}) + X)$

$\sqrt{s}$ = 200 GeV

$|\eta| < 0.35$

PHENIX

Theory: PRD78, 114013

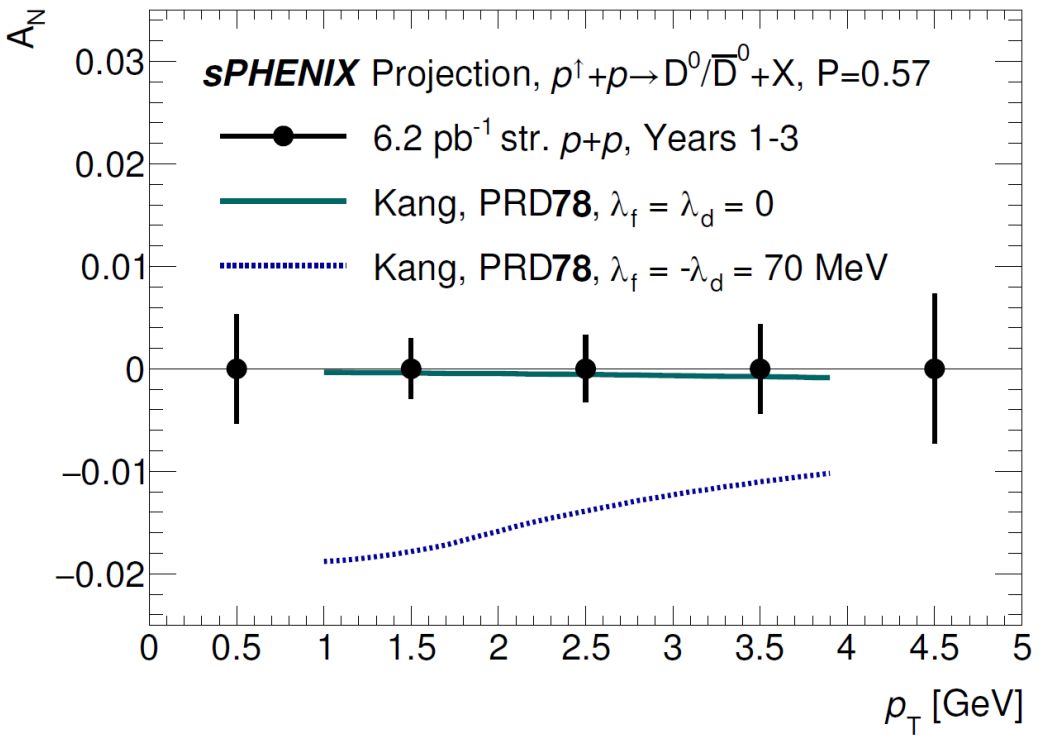
$A_N^{D^0/\bar{D}^0 \rightarrow e^{+/-}}(\lambda_f, \lambda_d)$

Gluon dynamics via HF TSSA

- In sPHENIX possiblity to actually measure D meson asymmetries
- Ordering of asymmetries for D and Dbar will constrain tri-gluon correlations further

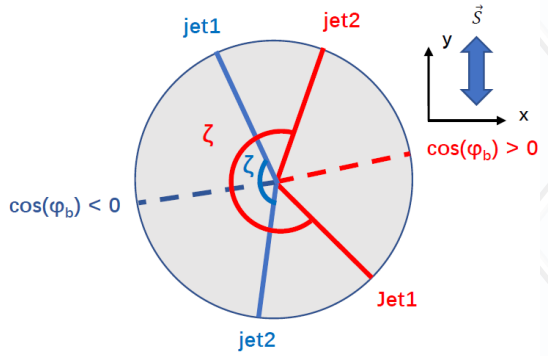
sPHENIX BUP2021 [sPH-TRG-2021-001]

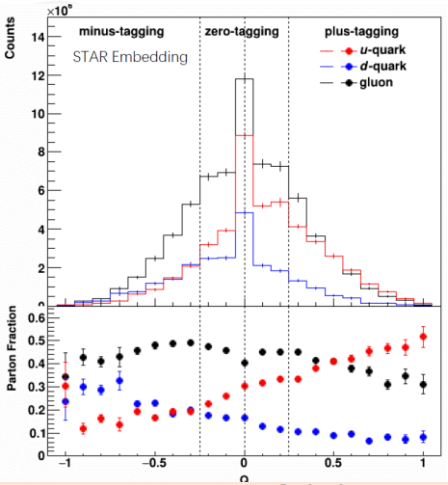
- TSSA of prompt $D^0 \rightarrow \pi K$ Enabled by streaming readout



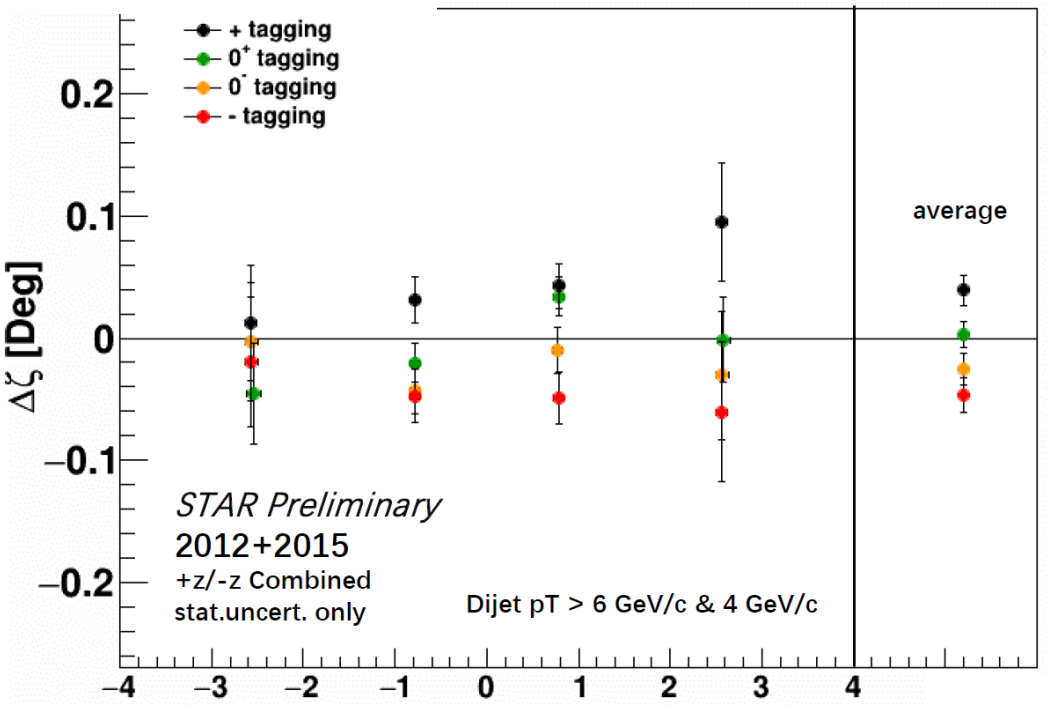
Di-jet spin-dependent imbalance

- Use di-jet imbalance and calculate single spin asymmetry
- Sensitive to spin dependent intrinsic transverse momentum kt 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





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



Figures taken fro S.Wissink's Spin2021 presentation

Nature of hadron A_N in pp and its nuclear modification

- PHENIX and STAR show significant different suppression of hadron A_N from pp to pA in distinct kinematic regions
- sPHENIX hadron A_N will explore wider region to help disentangle initial/final state effects
- Enabled by streaming recorded $p + p$ collision from far vertex collisions

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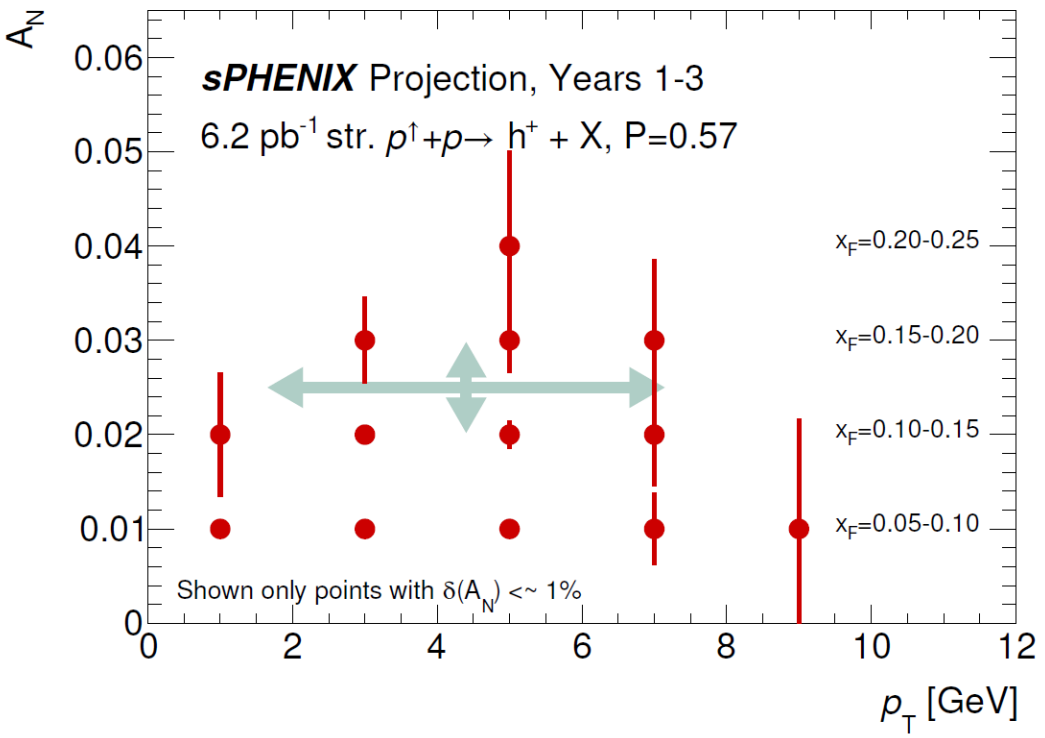
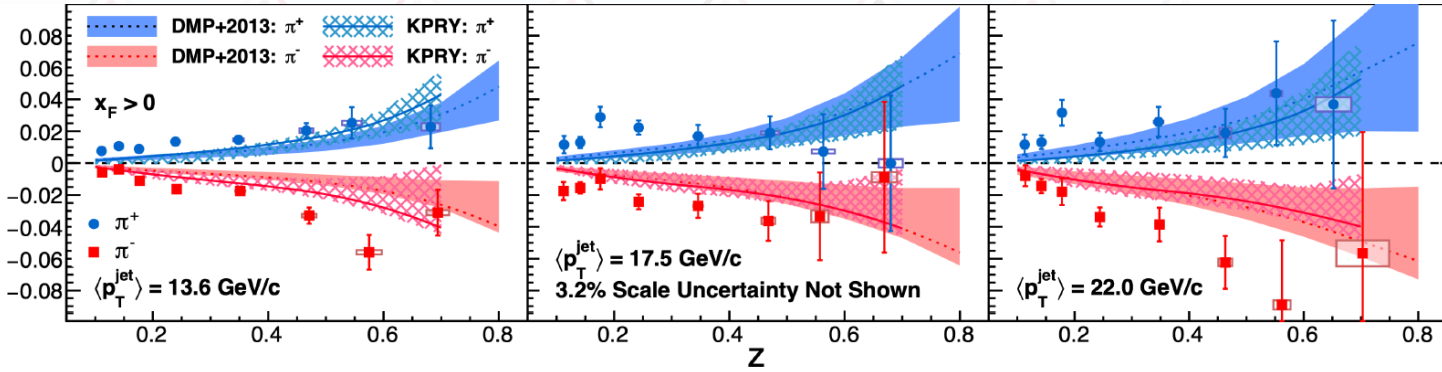
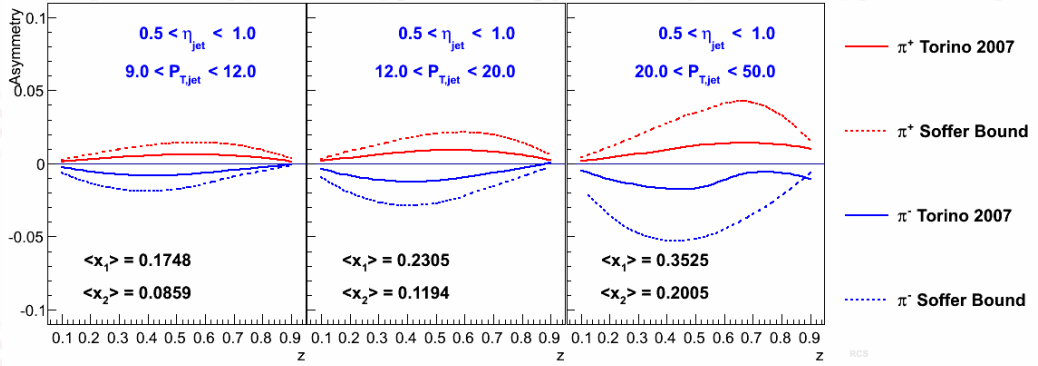


Transversity measurements →tensor charge

- Try to add to transversity/tensor charge measurements:
  - Most of the data from SIDIS fixed target measurements + e+e- Fragmentation data
  - Little sensitivity to d quarks so far (u quark dominance in DIS)
  - p+p has more sensisitivy to d quark contributions

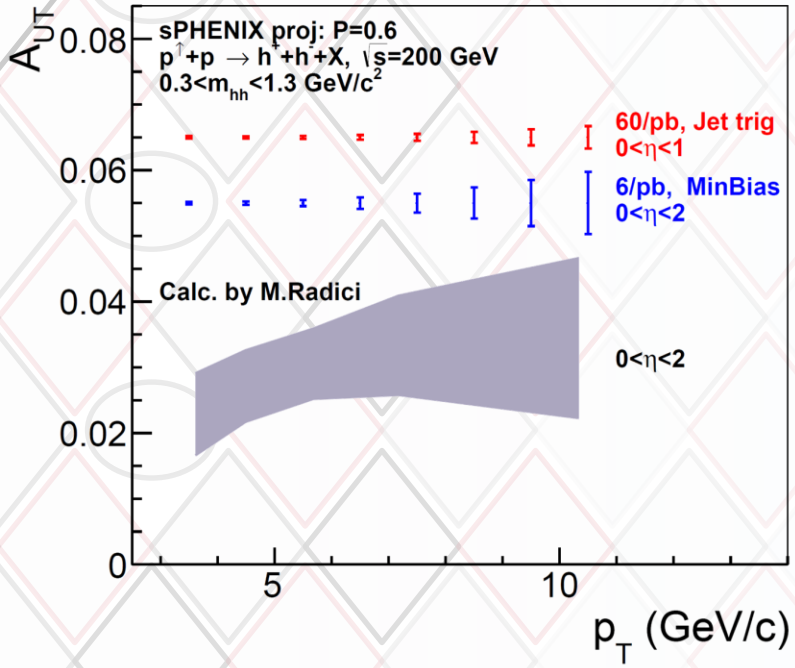
STAR: https://arxiv.org/abs/2203.00180

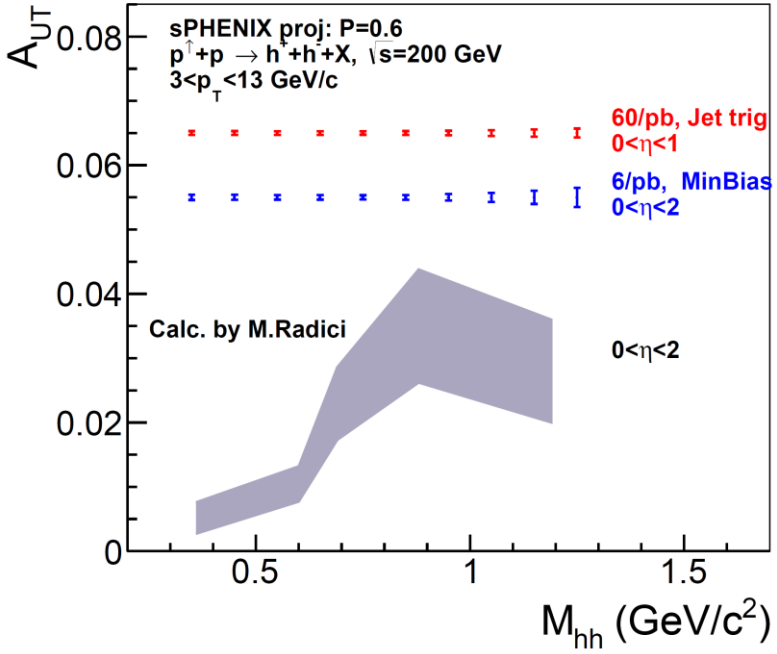




Transversity via charged particle IFF

- Good statistics enabled by both calorimetric jet trigger and streaming readout
- Need theory collaboration in the treatment of no-PID charged tracks & multi-dim binning

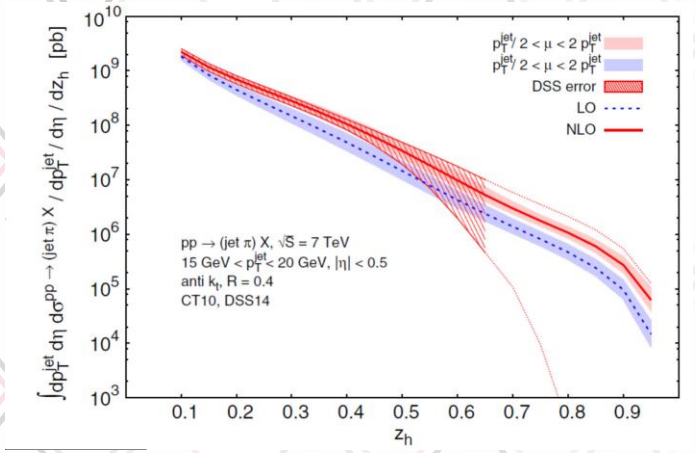


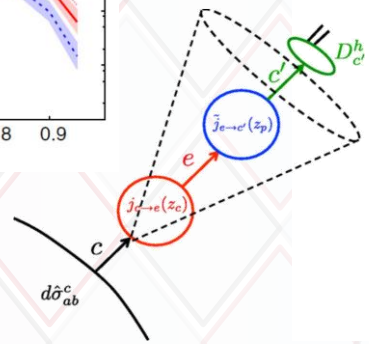


Fragmentation in p+A

- Access gluon fragmentation function (FF) in $p+p$, $p+A$ via jet FF
- Calorimetric triggered jet + precision tracking

Kaufmann et al. PRD 92 5, 054015





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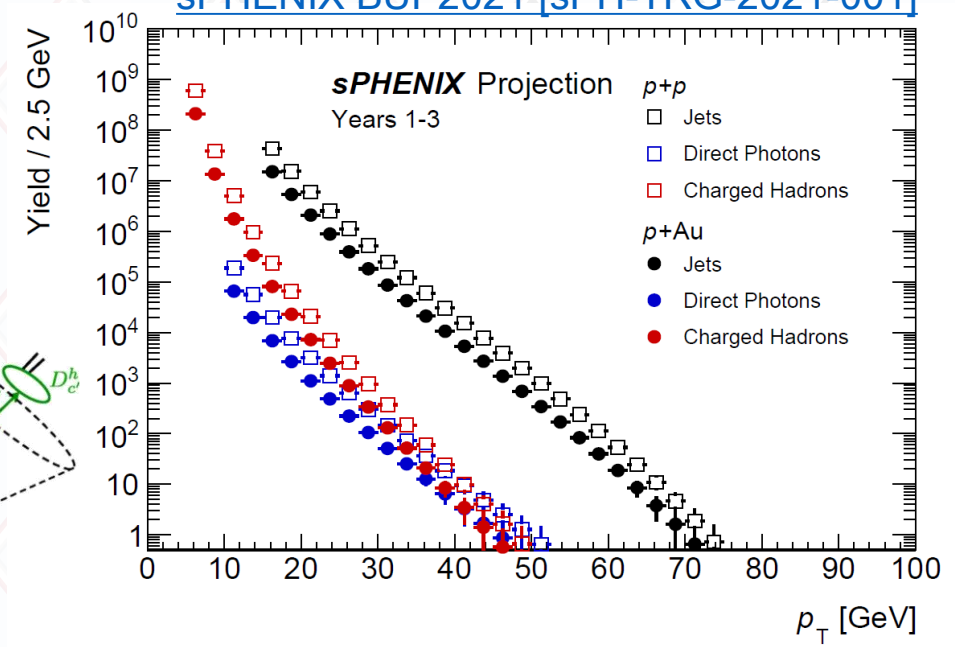

Summary

- Improved measurements for transverse spin asymmetries, nontrivial A dependence, new ideas coming out of existing RHIC measurements
- sPHENIX provides unique opportunities for spin/cQCD measurements using jet and rate capabilities to pin down
  - Transverse spin effects for direct photons, D meson asymmetries,
  - Collins and di-hadron Transversity access
  - Nuclear dependence of asymmetries and fragmentation functions
- Preparations for actual spin running QA ongoing

Proposed run schedule, year 1-3

sPHENIX asked to consider
20-28 week runs in 2024

- (Trans-)polarized $p+p$, $p+A$ with streaming readout for 28 weeks in Run24
- But short Run24 would endanger the $p+A$ data!

sPHENIX BUP2021 [sPH-TRG-2021-001], 24 (& 28) cryo-week scenarios

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert$ <10 cm	Samp. Lum. $\lvert z\rvert$ <10 cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}