Cold QCD and Spin measurements

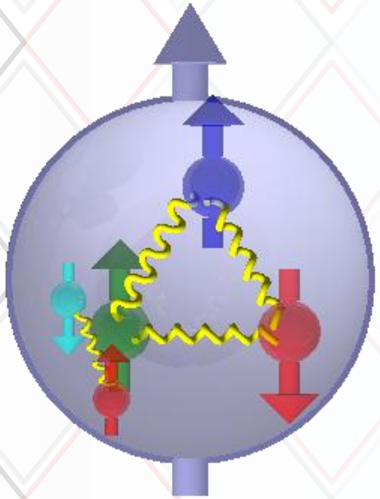
INTT workfest,

Korea University, Nov 18-29

Ralf Seidl (RIKEN)

Outline

- Left-right asymmetries
- Transverse spin and momentum structure and effects
  - Transversity and tensor charge
  - Sivers function and other TMDs
- Access to transverse spin effects in $p^{\uparrow}$+p(A) collisions
- Possibilities with sPHENIX
- Summary

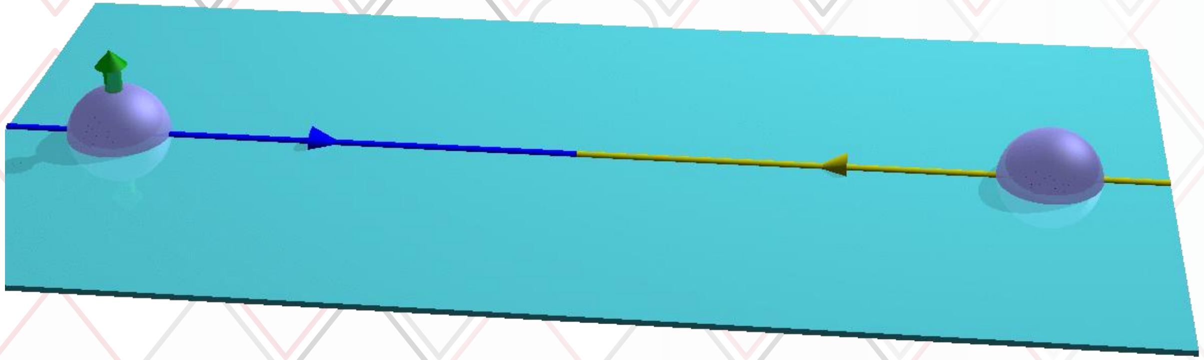


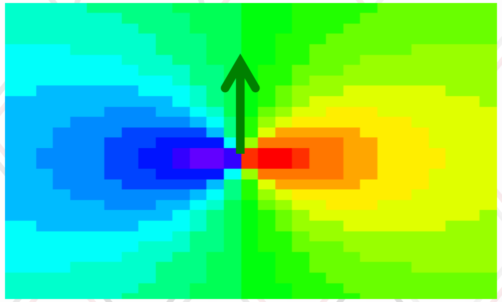
Transverse spin and TMDs

Transverse Single spin asymmetries (TSSAs)

- Left-Right asymmetries :

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





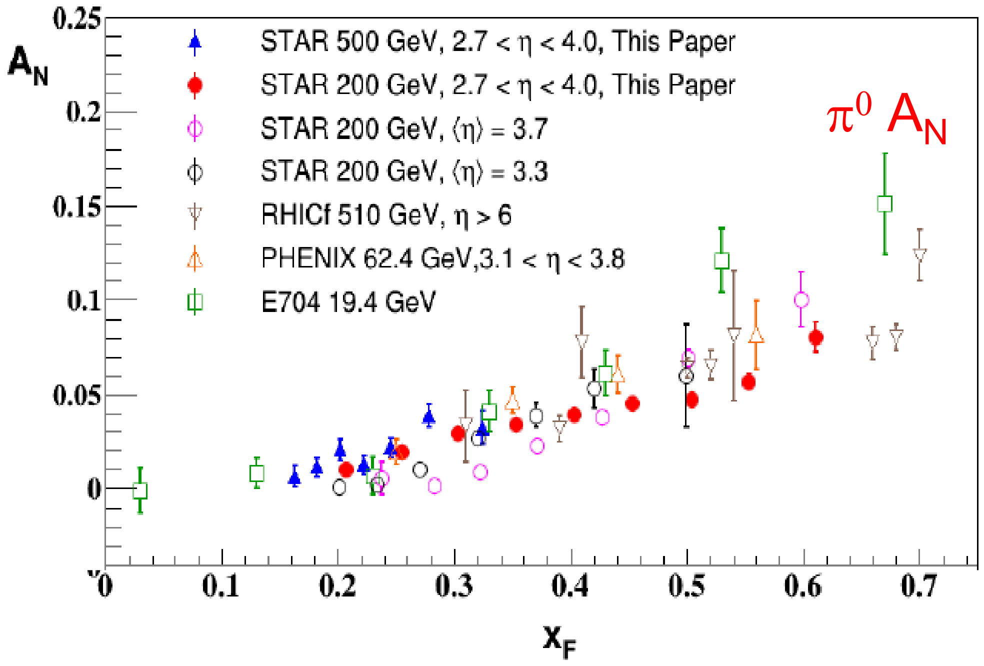
- Relative to the polarized proton spin direction more particles get produced to the left than to the right wrt. spin direction
- The cross section is spin (and azimuthal angle) dependent
- Initially expected to be zero in perturbative QCD (helicity-flip of nearly massless quarks) - G. L. Kane, J. Pumplin,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

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

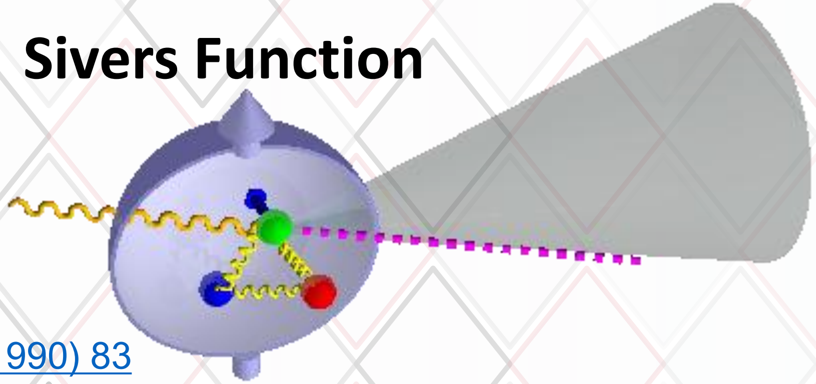
Transverse single spin asymmetries (TSSA)

- Large left-right asymmetries A_N seen in polarized p+p collisions from low energies up to RHIC energies at forward rapidities
- Both initial state and final state effects can contribute in forward pion asymmetries
- other origins (diffractive) could potentially also contribute
- A_Ns in p+A collisions of interest for low x behavior of cold nuclear matter → A dependence of single spin asymmetries?

$$A_N = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

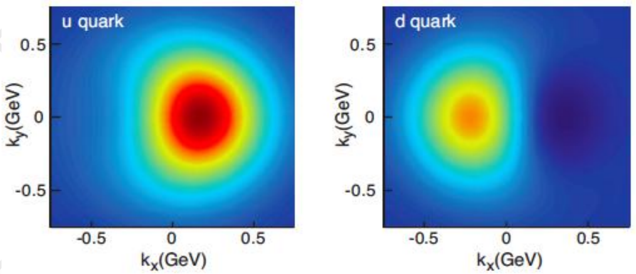


Sivers Function



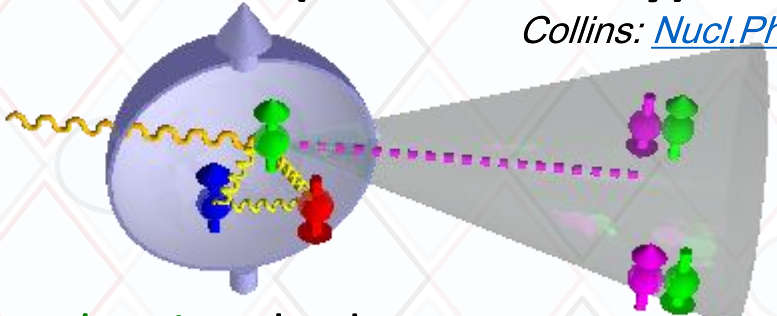
Sivers: Phys.Rev.D 41 (1990) 83

- Proton–spin – quark orbit (k_T) correlation (relation to orbital angular momentum)
- Transverse momentum imbalance in nucleon creates asymmetry
- Suggested by Sivers (1990), initially dismissed by Collins, resurrected by Brodsky (2002), Collins →special process dependence (sign change DY↔SIDIS)



Collins Function (x Transversity)

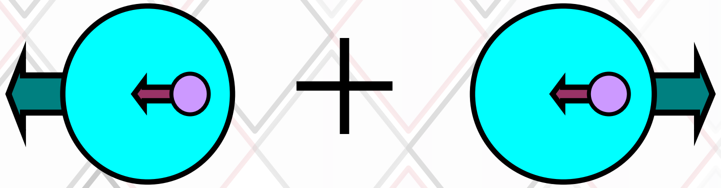
Collins: Nucl.Phys.B 396 (1993) 161



- Quark spin – hadron transverse momentum correlation (in fragmentation)
- Preferred direction of hadron creates asymmetry
- Analyzer for quark transversity (transverse quark spin) → access to tensor charge (Lattice, BSM?)
- A polarized (ie signed) fragmentation function

Both effects measured separately for quarks in SIDIS, FFs in e^+e^-

Transverse quark polarization

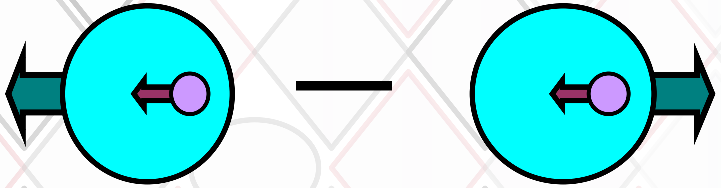


Unpolarized distribution function $q(x)$

Sum of quarks with parallel and antiparallel polarization relative to proton spin

(well known from Collider DIS experiments)

$q(x), G(x)$

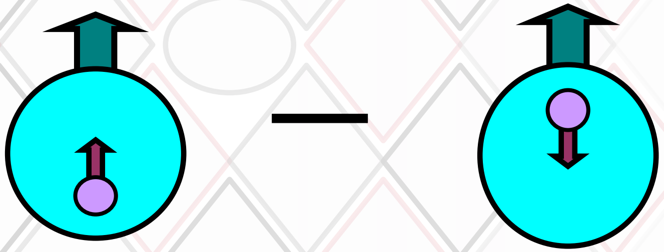


Helicity distribution function $\Delta q(x)$

Difference of quarks with parallel and antiparallel polarization relative to longitudinally polarized proton

(known from fixed target (SI)DIS experiments)

$\Delta q(x), \Delta G(x)$



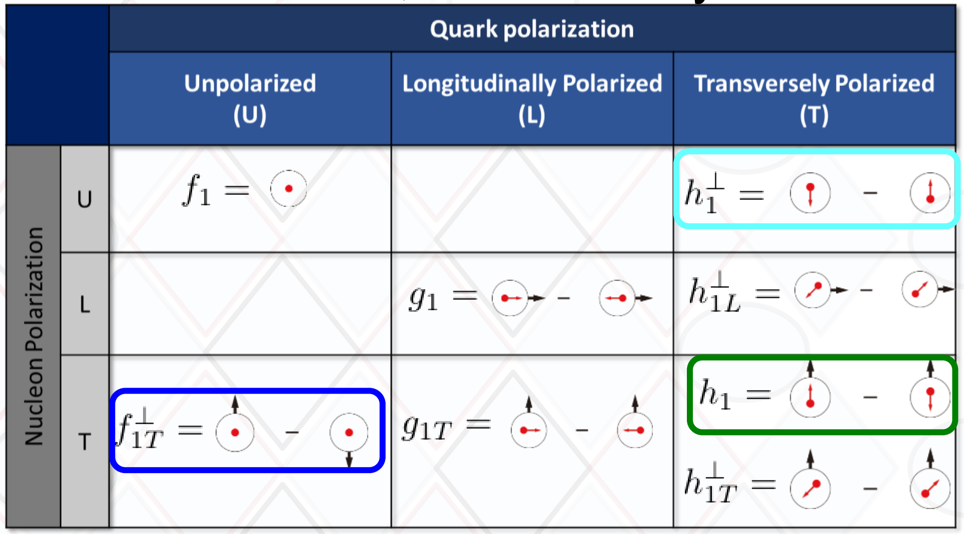
Transversity distribution function $\delta q(x)$

Difference of quarks with parallel and antiparallel polarization relative to transversely polarized proton

(first results from HERMES and COMPASS – with the help of Belle)

$\delta q(x)$

S.Pisano, Transversity 14



Transverse Spin and TMDs

TMD: transverse momentum dependent distribution and fragmentation functions, all except f_1,g_1 and h_1 cancel upon integration over k_T

- Transversity

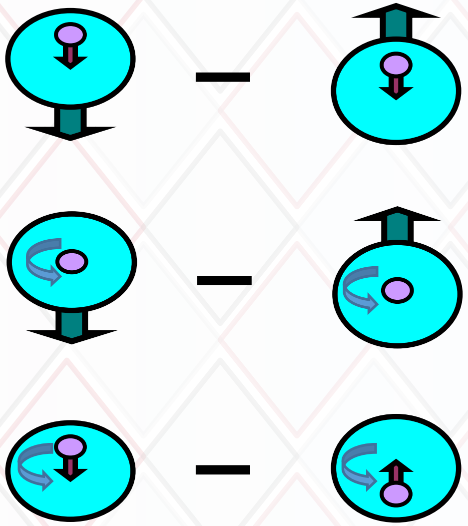
$h_{1,q}(x)$

- Sivers Function

$f_{1T,q}^{\perp}(x,k_T)$

- Boer Mulders function

$h_{1T,q}^{\perp}(x,k_T)$

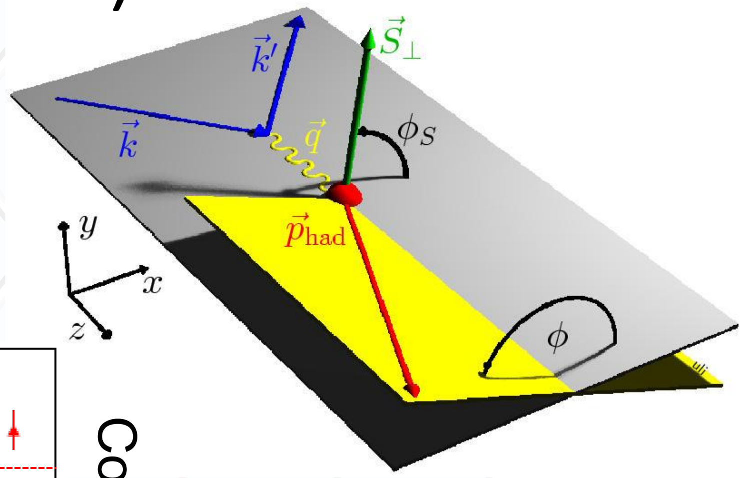


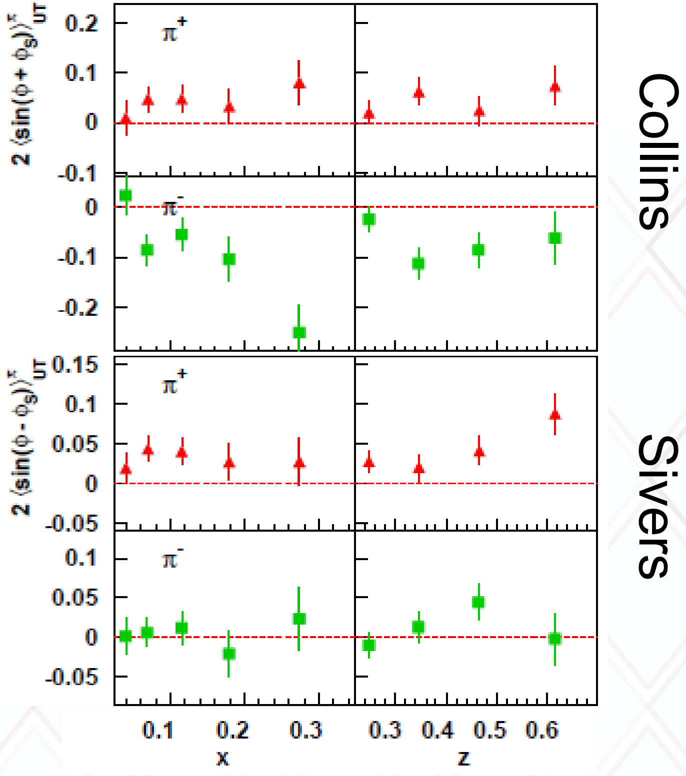
Closely related:

- Higher Twist correlations (TMD moments) $T_F(x,x)$
- TMD FFs (Collins, polarizing FFs, etc) $H_{1,q}^{\perp(1)}(z)$

Early HERMES findings (ca 2002)

- $ep^{\uparrow} \rightarrow e'hX$
- Both azimuthal modulations related to Sivers effect ($\sin(\phi-\phi_s)$) and Collins effect ($\sin(\phi+\phi_s)$) nonzero
- Large, negative Collins effect for negative pions hard to explain in u quark dominance



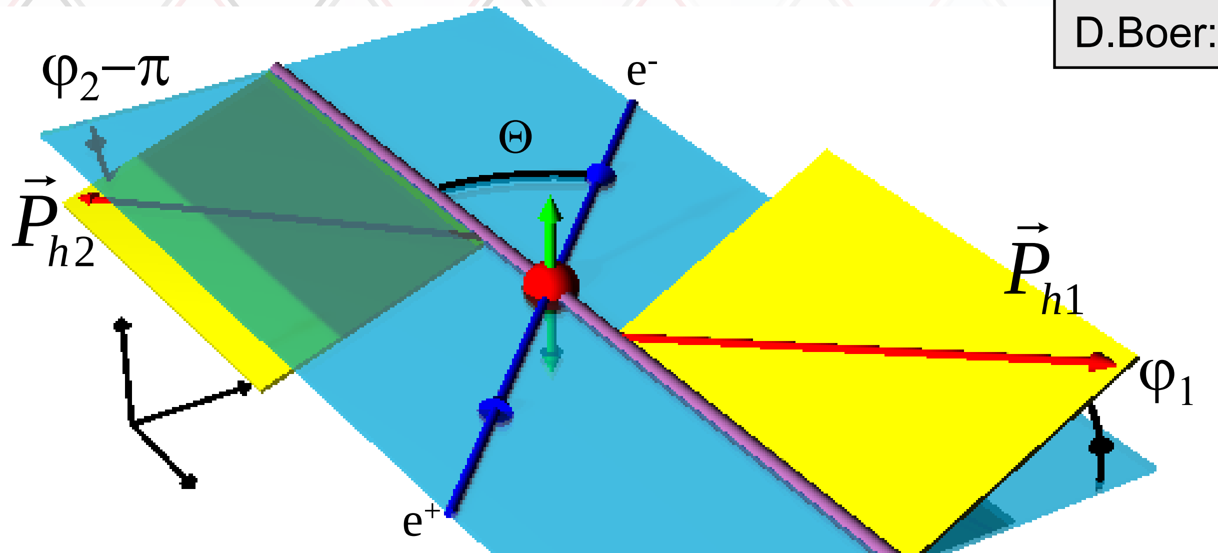


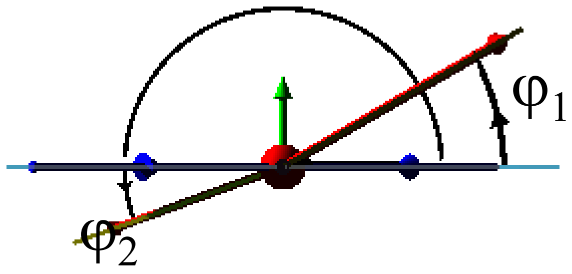
HERMES:
[PRL 94 (2005) 012002]

Collins fragmentation in e^+e^- :
Angles and Cross section $\cos(\phi_1+\phi_2)$ method

e^+e^- CMS frame:

D.Boer: **Nucl.Phys. B806 (2009) 23-6**





2-hadron inclusive transverse momentum dependent cross section:

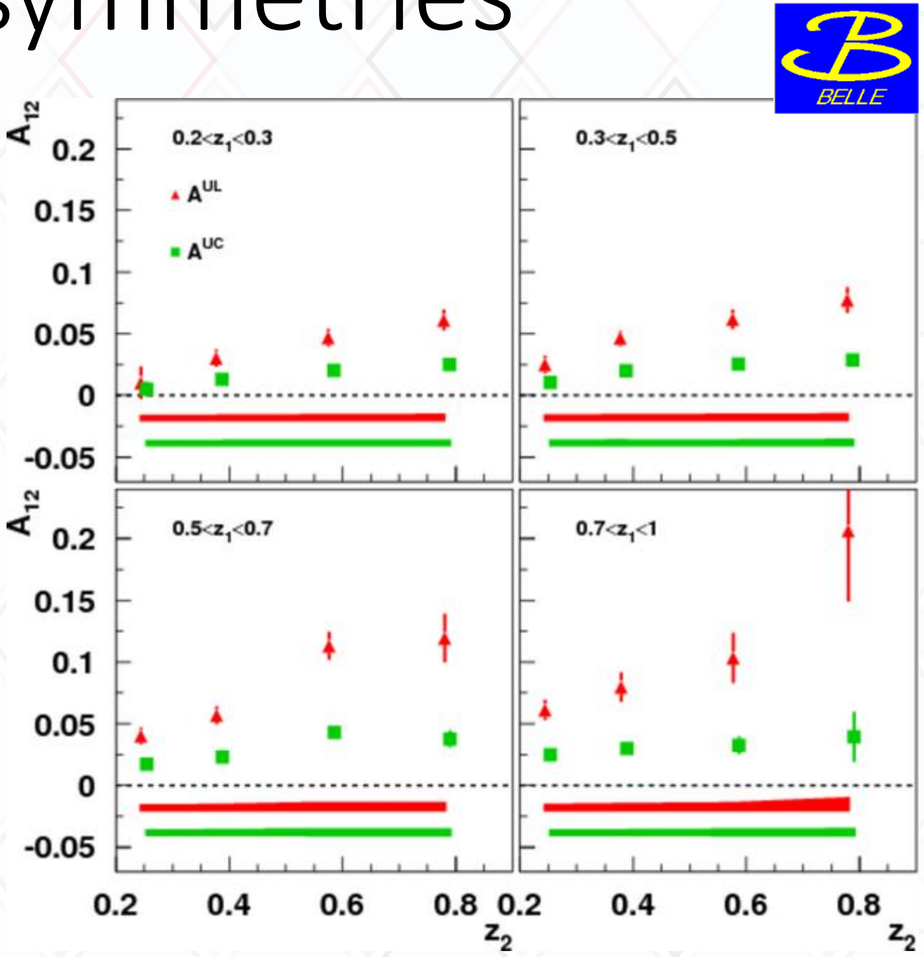
$$\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\cos(\varphi_1+\varphi_2)H_1^{\perp[1]}(z_1)\overline{H}_1^{\perp[1]}(z_2)$$

$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

Net (anti-)alignment of transverse quark spins

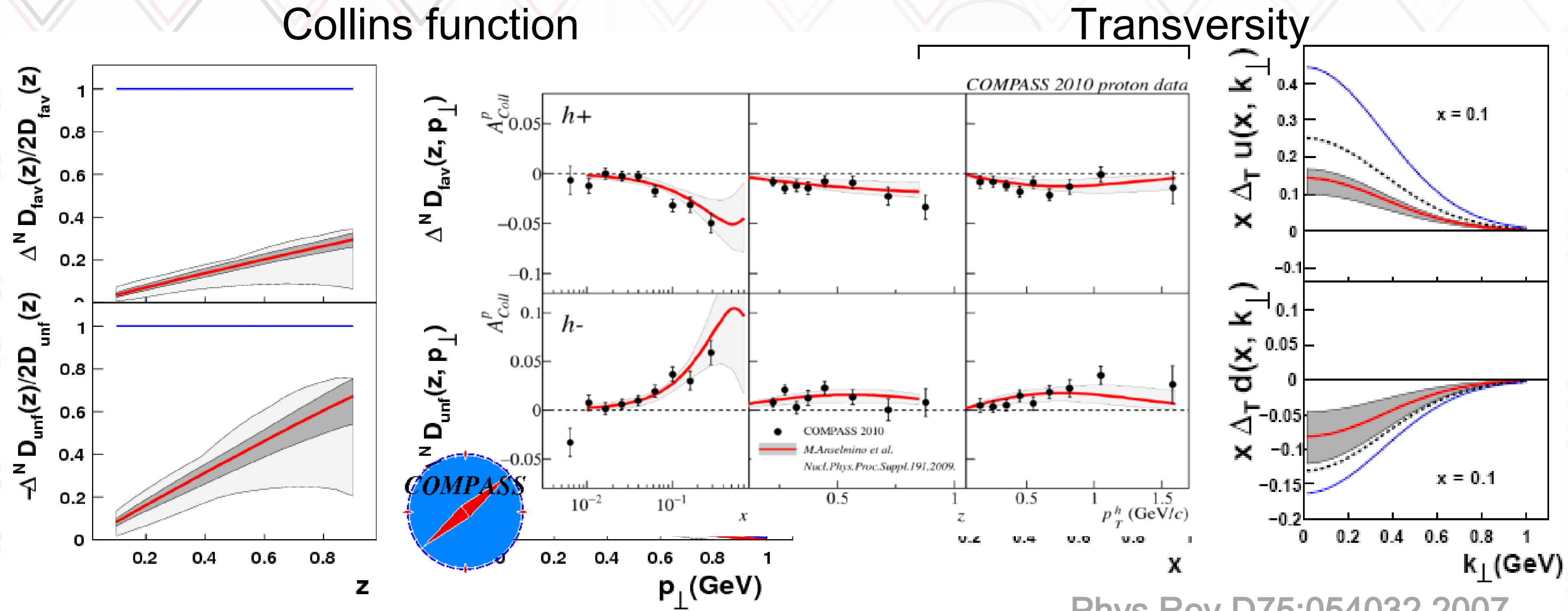
Belle Collins asymmetries

- Red points : $\cos(\phi_1 + \phi_2)$ moment of Unlike sign pion pairs over like sign pion pair ratio : A^{UL}
- Green points : $\cos(\phi_1 + \phi_2)$ moment of Unlike sign pion pairs over any charged pion pair ratio : A^{UC}
- Collins fragmentation is large effect
- Consistent with SIDIS indication of sign change between favored and disfavored Collins FF



RS et al (Belle), PRL96: 232002
PRD 78:032011, Erratum D86:039905

Global Fit of Collins FF and Transversity （HERMES, COMPASS d, Belle)



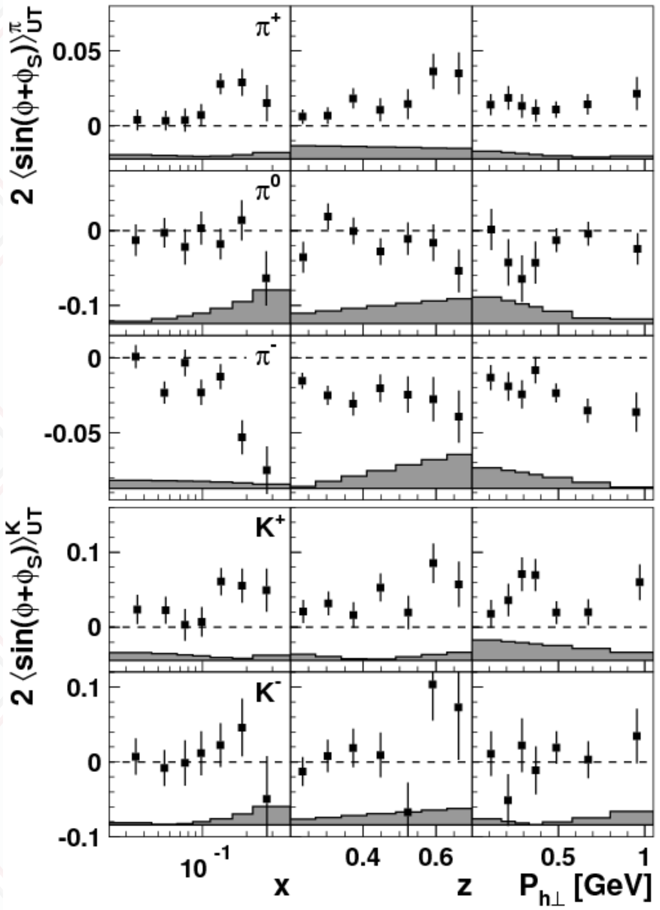
Phys.Rev.D75:054032,2007, update in Nucl.Phys.Proc.Suppl.191:98-107,2009

- Latest SIDIS data not included inFIT
- TMD evolution poorly known
- K_T dependence from Assumption
- Interference FF （IFF) as independent Cross check

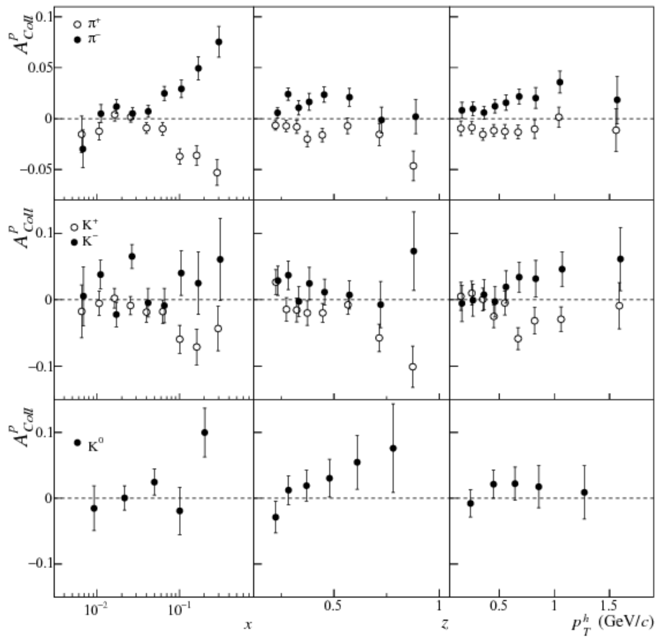
Latest SIDIS data

- Final Collins asymmetries of HERMES and COMPASS (<2017) published, including kaons
- More deuteron by COMPASS (<2023)
- Transverse target data expected from JLAB in near future

HERMES: *Phys.Lett.B 693 (2010) 11*



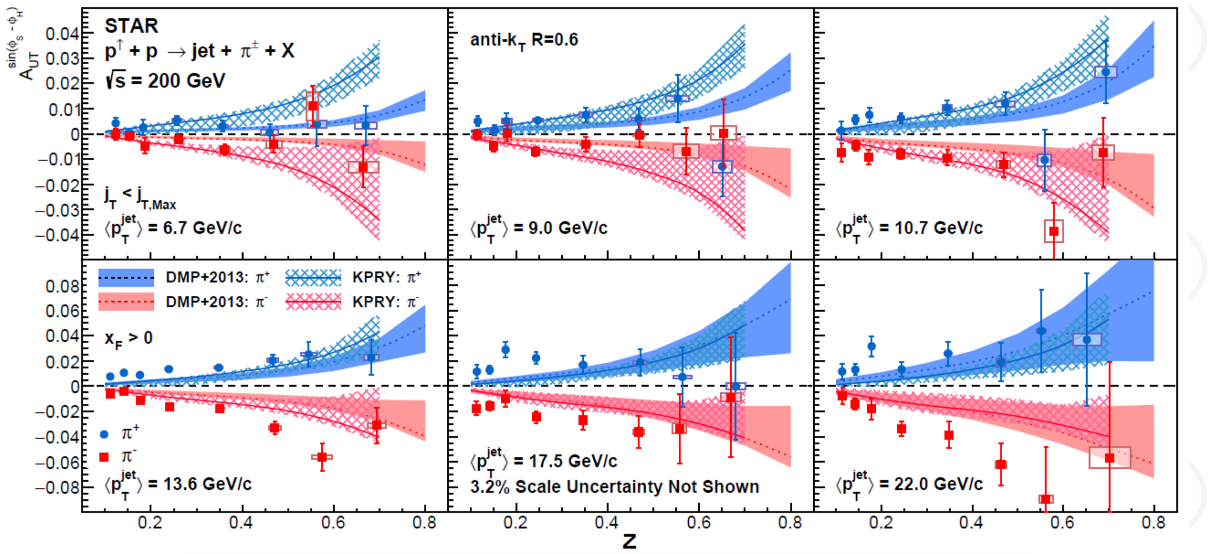
COMPASS: *Phys.Lett.B 744(2015) 250*

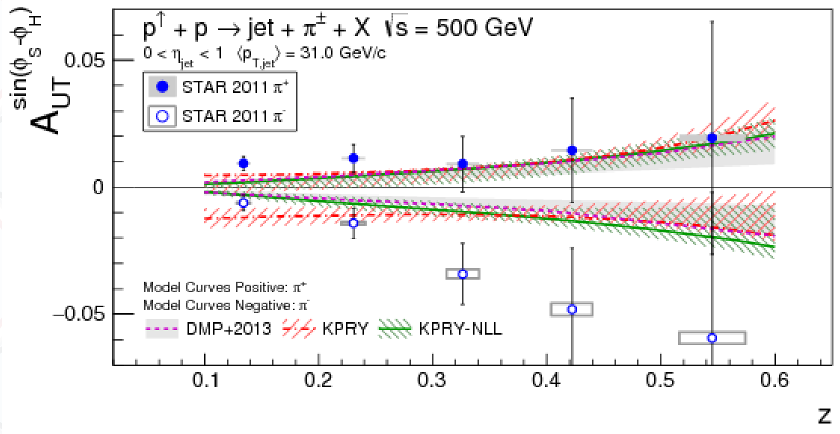


Transversity in proton collisions

- 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

Interference fragmentation as alternative Transversity channel

Interference fragmentation function $H_1^{\sphericalangle}$

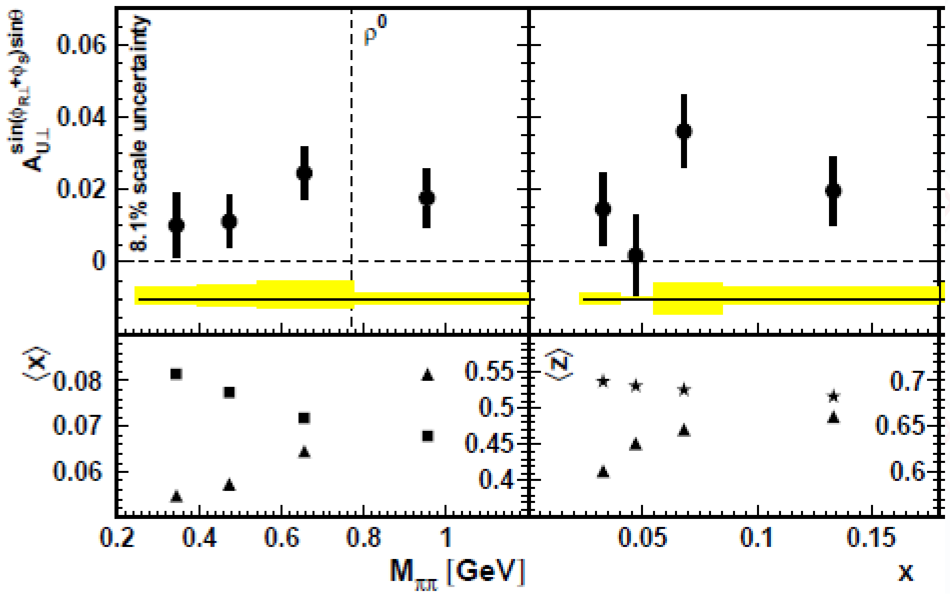
J. Collins, S.Heppelmann, G. Ladinsky, Nucl. Phys. B, 420 (1994) 565

- Di-hadron vs single hadron
  - Collinear factorization is shown to be valid → TMD factorization is less certain in p+p *(Rogers, Mulders, arXiv:1010.2977)*
  - No model uncertainties from transverse momentum dependence of FF and PDF
  - No need to separate Sivers/Collins effects as in single hadron measurement
  - Completely independent measurement
  - Doesn’t need jet reconstruction
  - Evolution is known
  - But unpolarized and polarized di-hadron fragmentation functions needed

(courtesy A. Bacchetta)

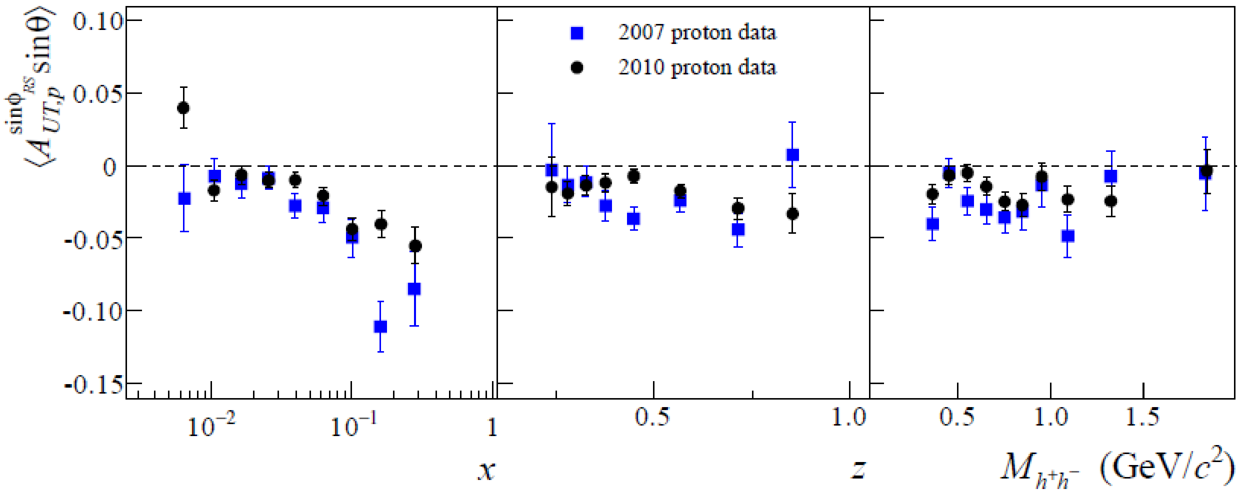
SIDIS IFF measurments

HERMES: JHEP 0806, 017 (2008)

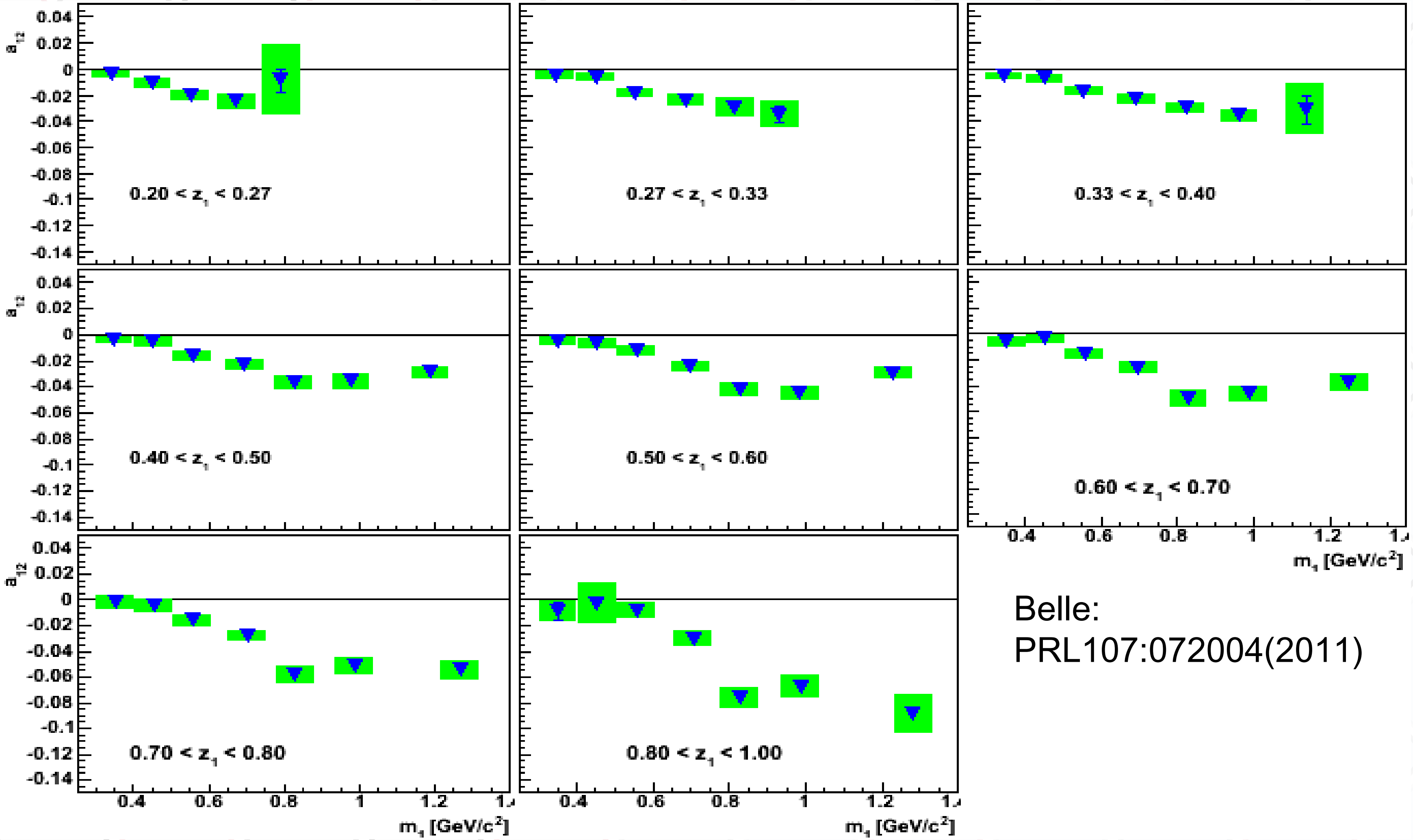


- Again sizeable asymmetries in SIDIS seen from HERMES and COMPASS
- Consistent with each other

COMPASS: Phys.Lett. B736 (2014)



Also Belle fragmentation measurements available



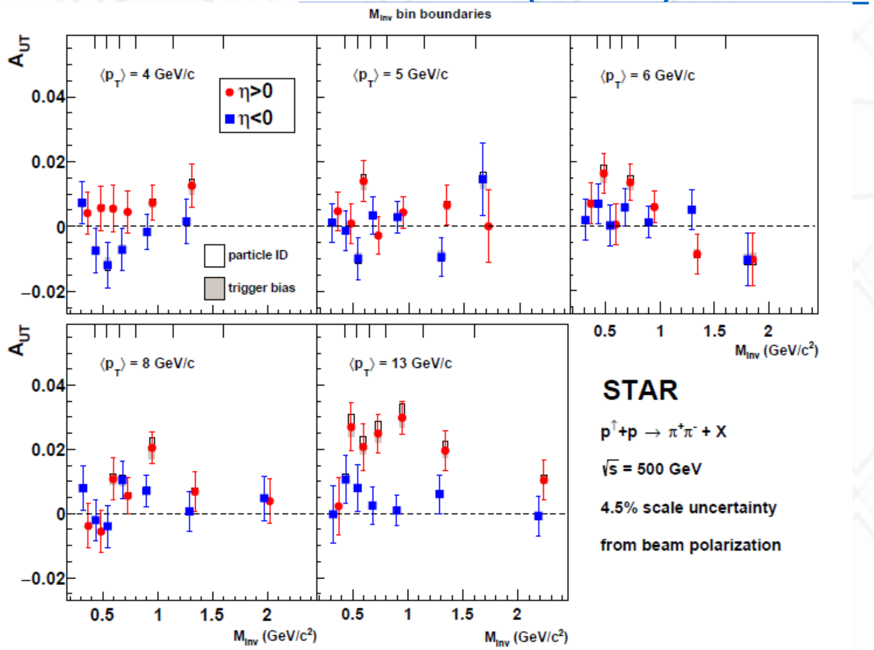
Belle:
PRL107:072004(2011)

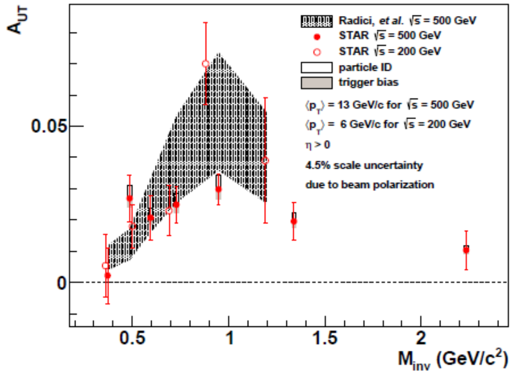
STAR IFF results

$h_{1,q}(x)\ H_{1,q}^{h_1 h_2}(z, M_{hh})$

STAR 510 GeV: PLB780 (2018) 332
200GeV: PRL 115 (2015) 242501

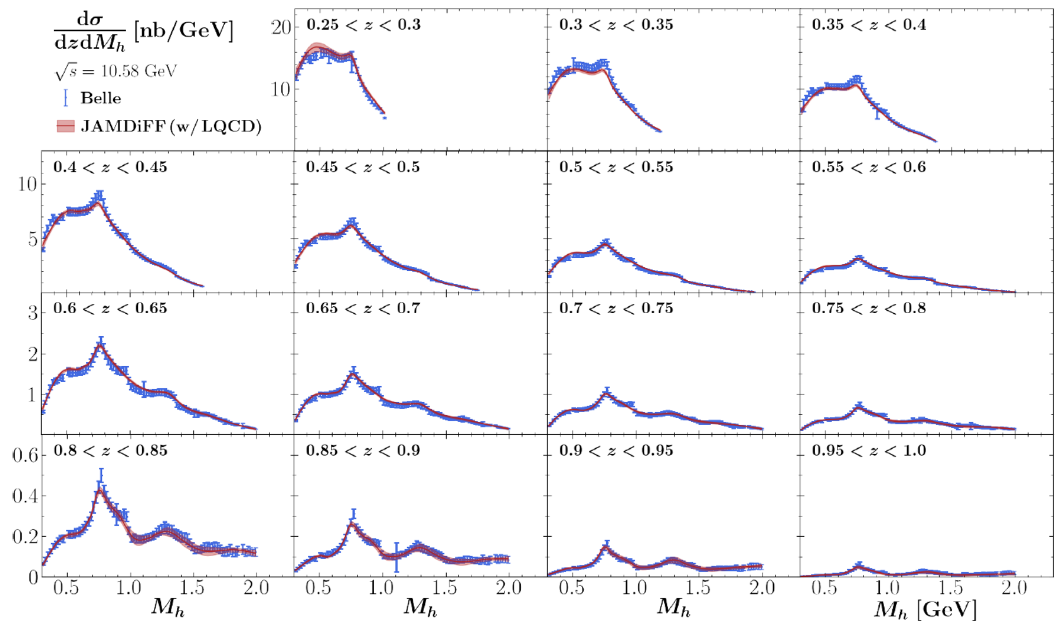
- Now both 200 and 510 GeV results finalized
- Both with substantial nonzero effects at:
  - Forward rapdities
  - Higher Pt
  - Masses around 1 GeV
- First theory predictions from SIDIS+Belle consistent with magnitude
  → will help improve transversity uncertainties
  →but gluon DIFFs not well known

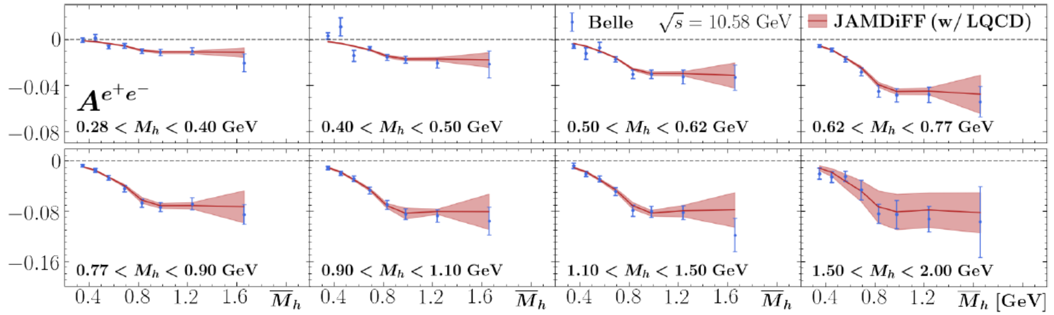


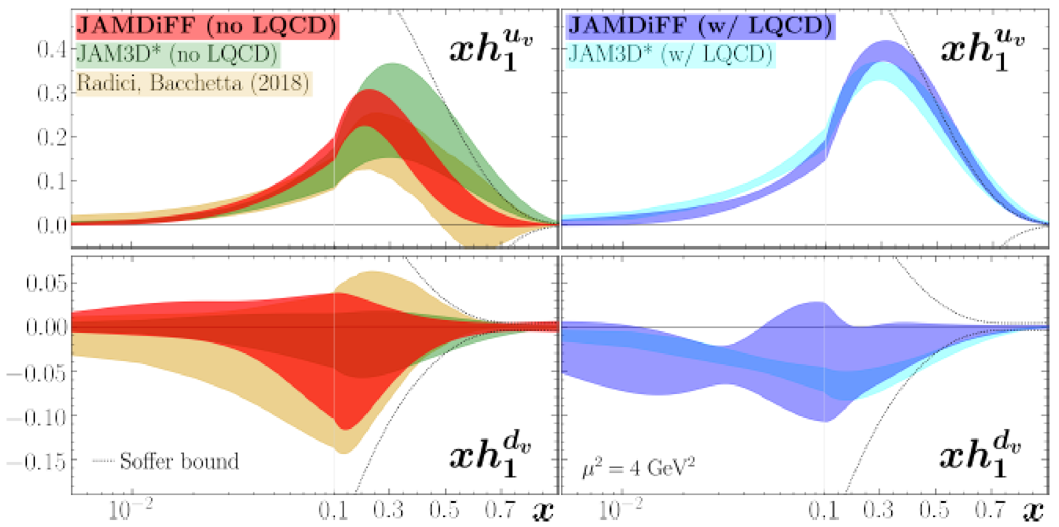


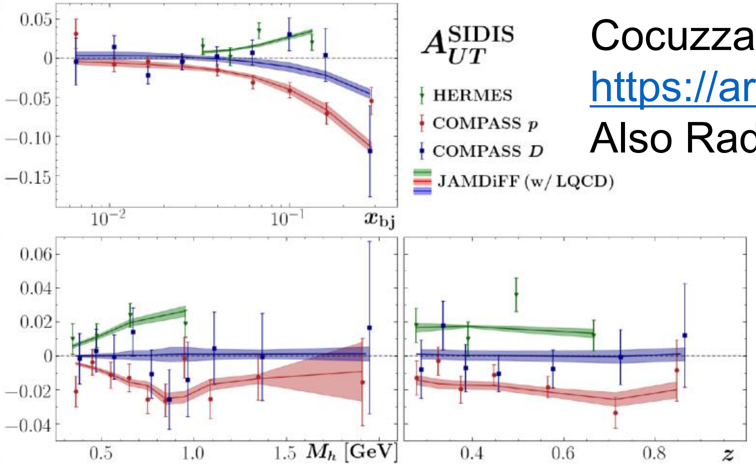
Radici et al: PRD97 (2018) 074019

Global fits of Dihadron FFs

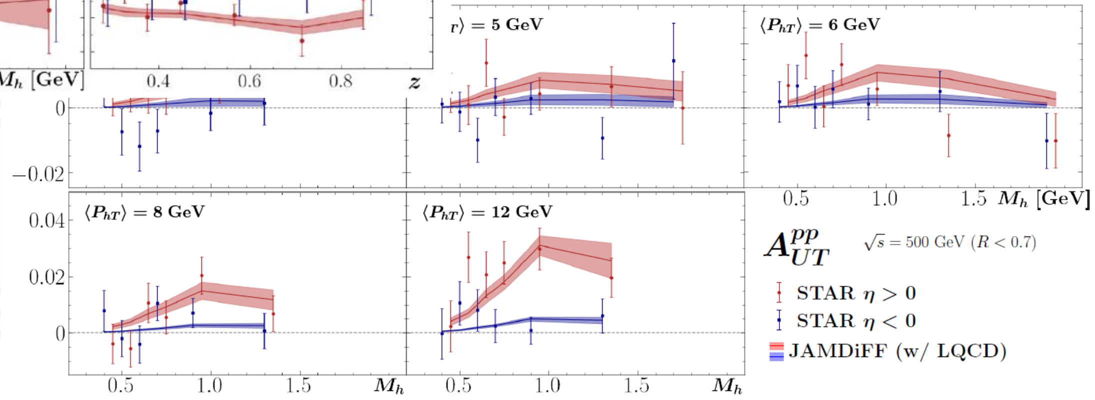








Cocuzza et al.
https://arxiv.org/abs/2306.12998
Also Radici et al. *PRL 120 (2018) 19, 192001*

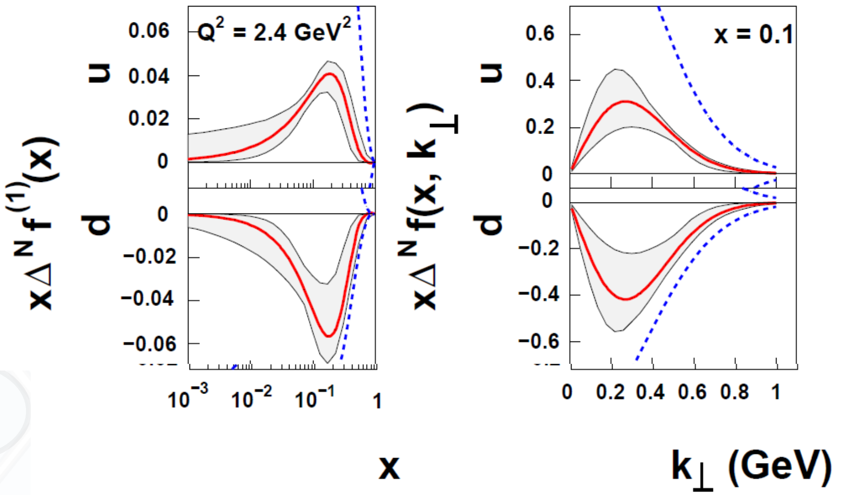


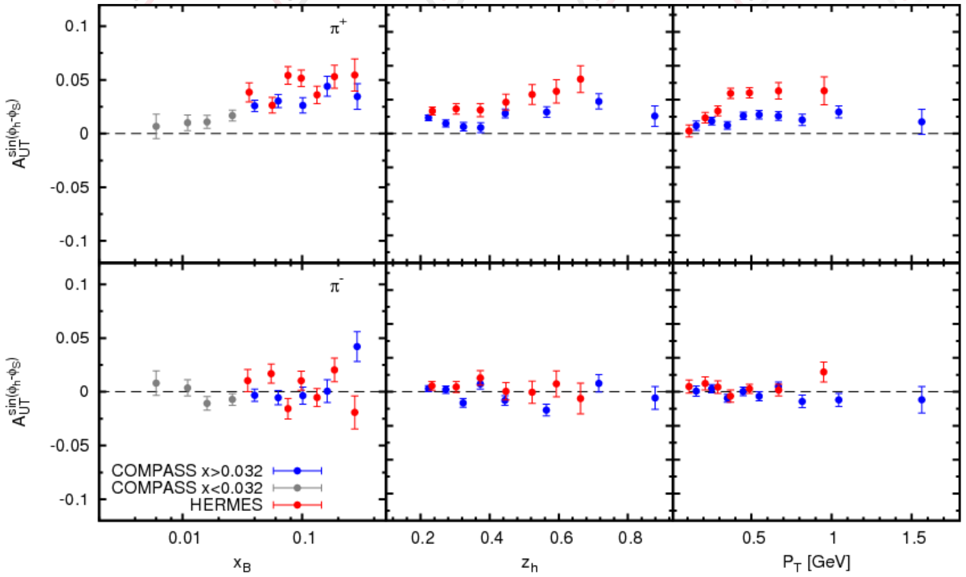
- Global fits taking SIDIS data, RHIC data, Belle data (polarized and unpolarized) into account

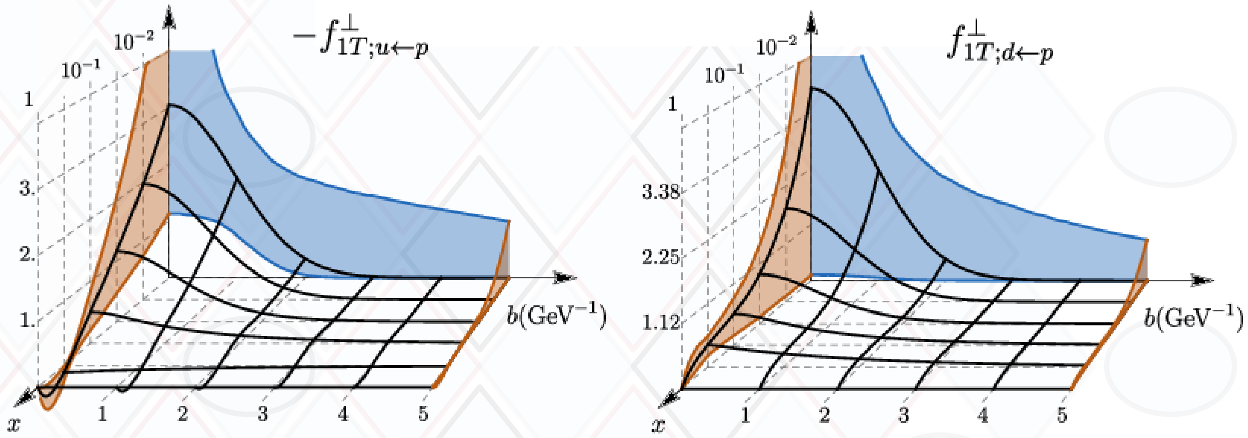
Anselmino et al. *Eur.Phys.J.A* 39 (2009) 89

Sivers Function measurements

- Early fits of SIDIS data show opposite signs, d quarks possibly larger
- Recent updates including evolution higher orders, and STAR W data







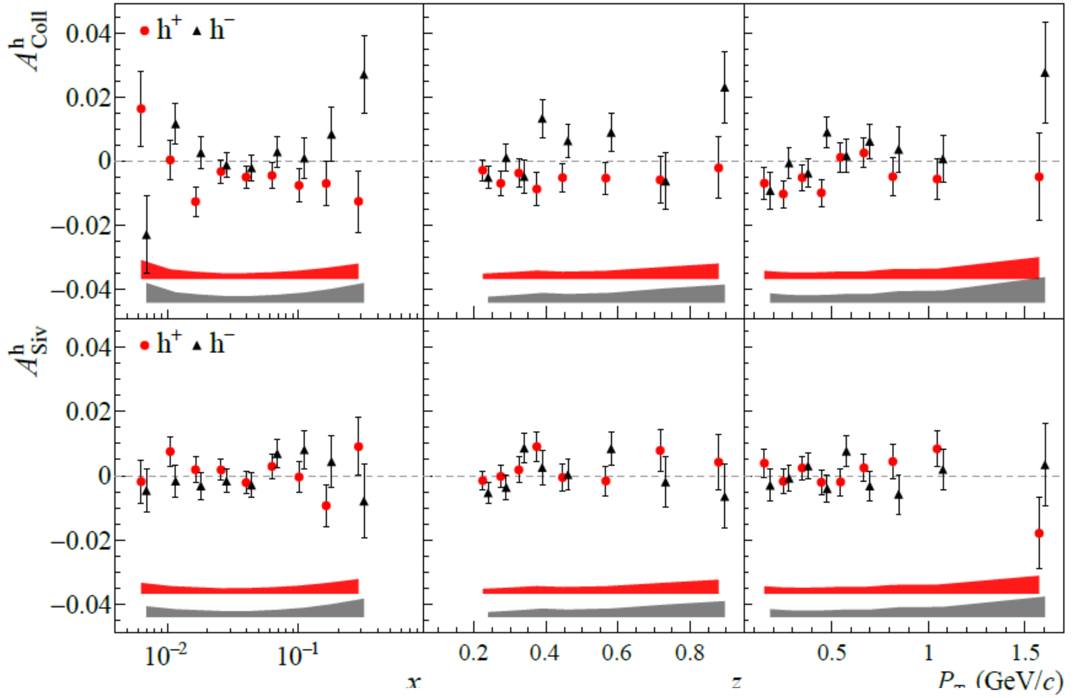
Bury et al. *Phys.Rev.Lett.* 126 (2021) 112002

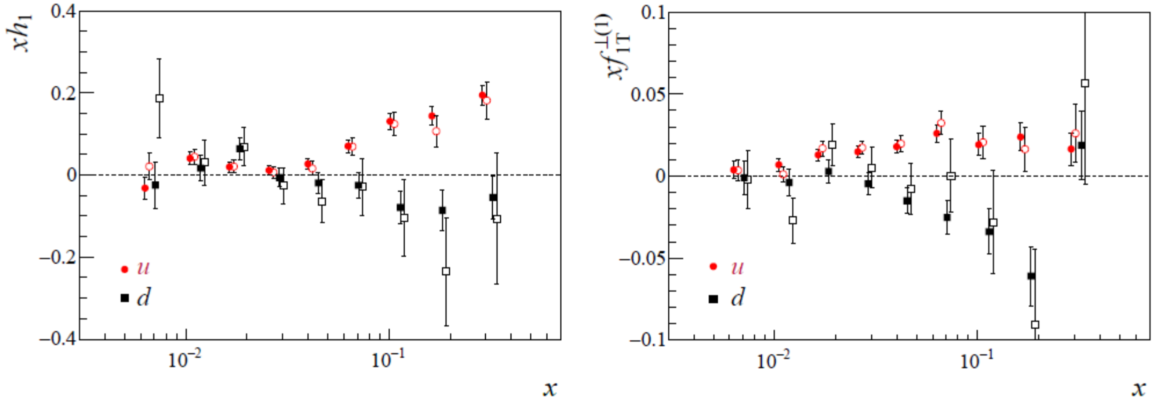
$$f^{\perp}_{1T,q}(x, k_T)$$

New COMPASS deuteron data

COMPASS: PRL 133 (2024) 101903

- Old COMPASS μ+d data consistent with zero due to cancellations (Collins + transversity, u and d Sivers)
- Larger statistics show slightly negative Collins asymmetries for h^+
- Improved sensitivity to d quarks compared to e+p → d transversity negative

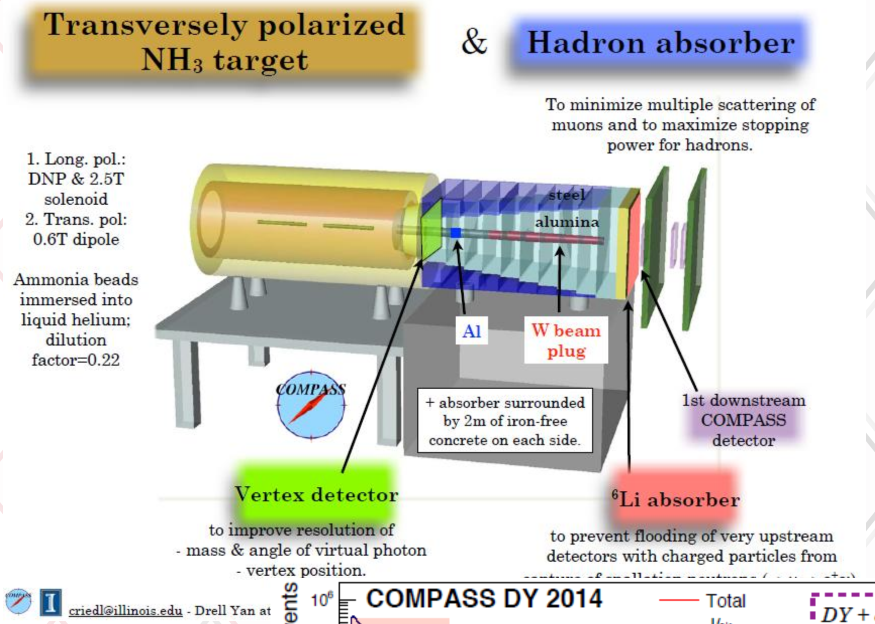


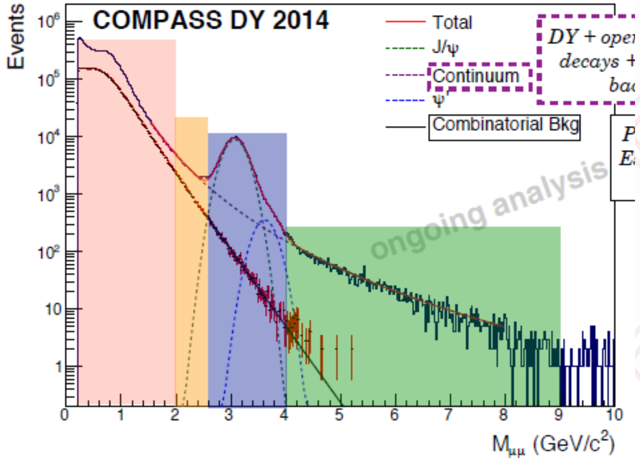


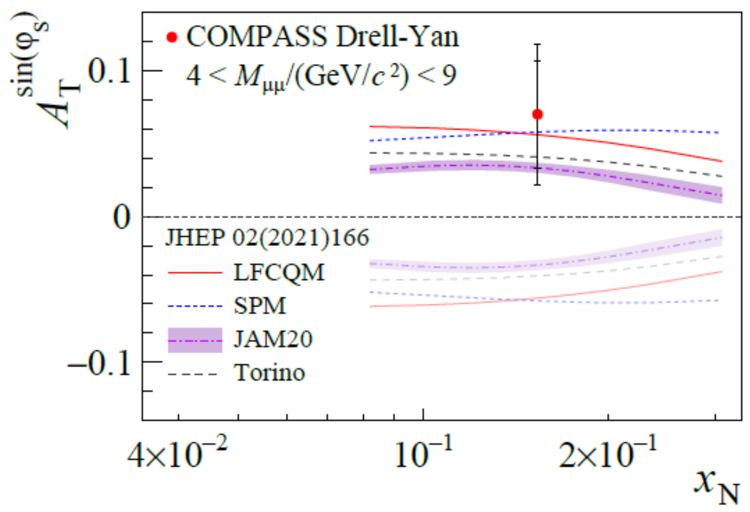
Sivers Sign change

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

COMPASS: polarized NH_3 target + 160 GeV π^- beam → Sensitivity to u quark Sivers and sign change







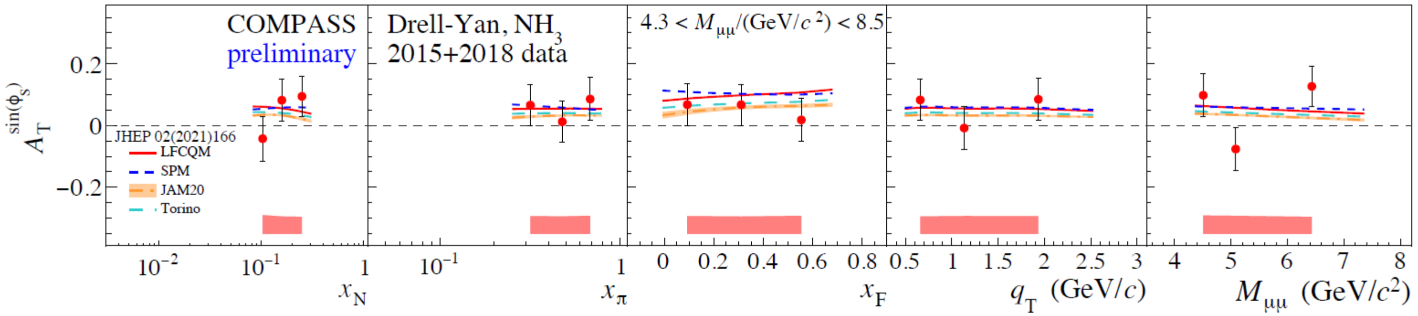
sign change

no sign change

COMPASS: PRL 133 (2024) 071902

- Now a rather clear indication of the sign change!

Curves from JHEP 02, 166 (2021)

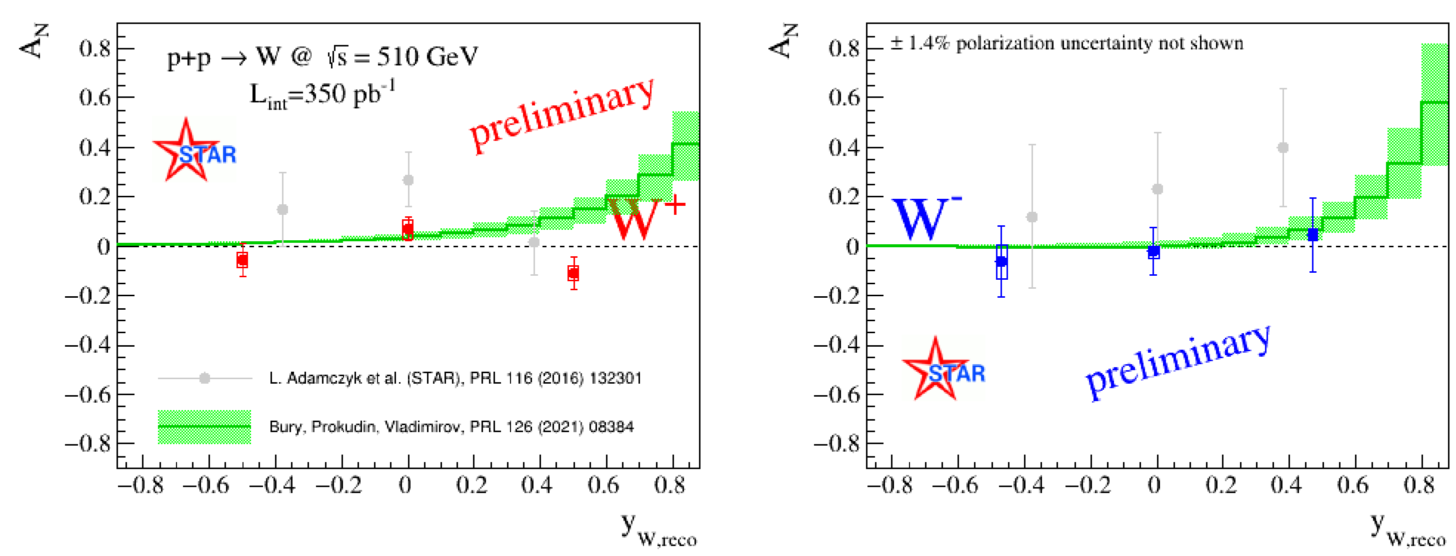


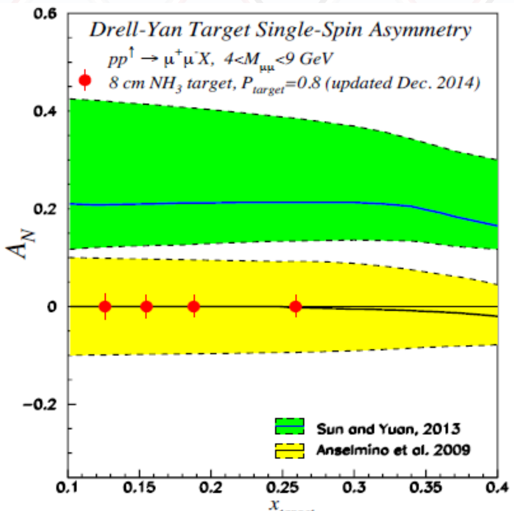
Towards the Sivers sign change

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

- 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
- E1039: fixed target polarized NH_3 target, unpolarized 125GeV p beam →Sensitivity to $\bar{u}$ Sivers

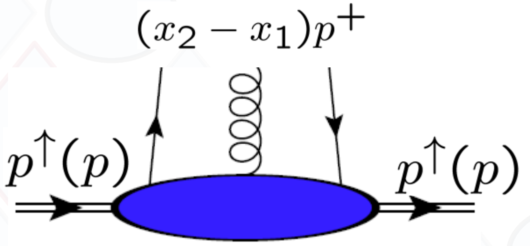
STAR: PRL 116 (2016) 132301





projection for 1year running

TSSAs at RHIC→Quark-gluon dynamics!

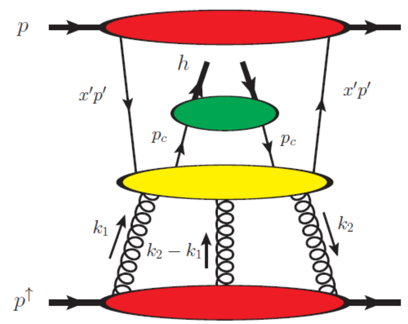


q-g correlation (↔ quark Sivers)

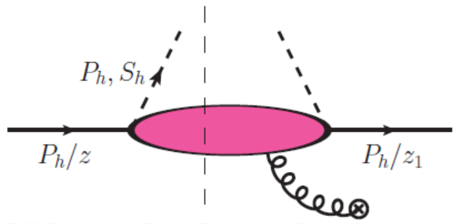
- Sivers and Collins effects rely on an explicitly transverse momentum dependent (TMD) framework where two scales are observed: high scale (typically Q^2) and intermediate scale (transverse momentum $P_T << Q^2$)
- In inclusive pp measurements usually only one, hard scale accessible (transverse momentum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



g-g correlation (trigluon ↔ gluon Sivers)



q-g FF correlation (↔ Collins)

Single spin asymmetry contributions in p+p

pol proton   unpol proton   FS particle

$$A_N \approx \sum_{a,b,c} \phi^{(3)}_{a/A}(x_1, x_2, s) \otimes \phi_{b/B}(x') \otimes D_{c\to C}(z)$$
$$+ \sum_{a,b,c} \delta q_{a/A}(x, s) \otimes \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes D_{c\to C}(z)$$
$$+ \sum_{a,b,c} \delta q_{a/A}(x, s) \otimes \phi_{b/B}(x') \otimes D^{(3)}_{c\to C}(z_1, z_2)$$

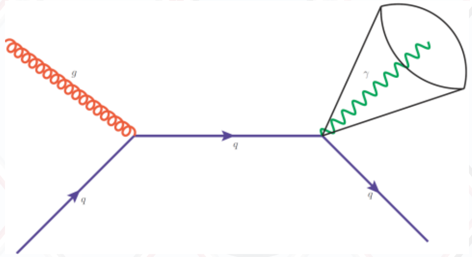
a,b/c initial/final parton flavors
A,B/C initial/final hadron/particle types

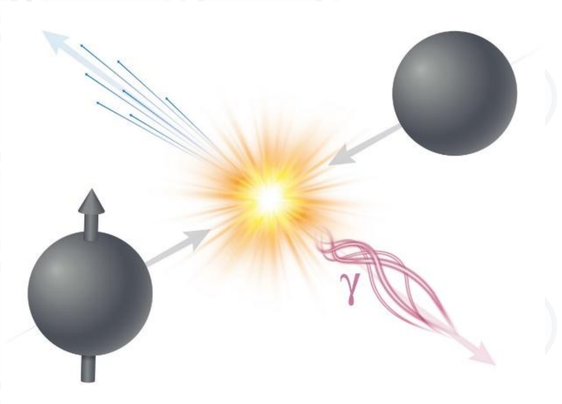
Efremov, Teryaev Phys.Lett.B 348 (1995) 577
Qiu, Sterman *Phys.Rev.D* 59 (1999) 014004
Kanazawa, Koike *Phys.Lett.B* 478 (2000) 121-126
Metz, Pitonyak *Phys.Lett.B* 723 (2013) 365-370

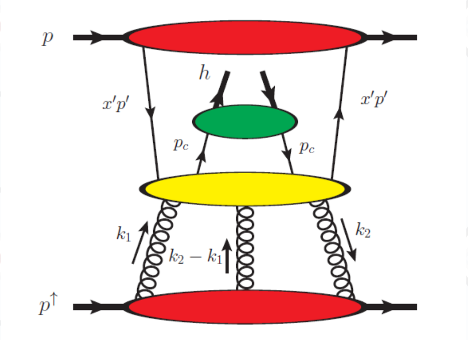
- Generally three pieces to p+p single transverse spin asymmetries:
  - Twist three correlation functions (quarks or gluons) in polarized proton ↔ Sivers function
  - Twist three correlation function in unpolarized proton (with transversity) ↔ Boer Mulders function
  - Twist three correlation in fragmentation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

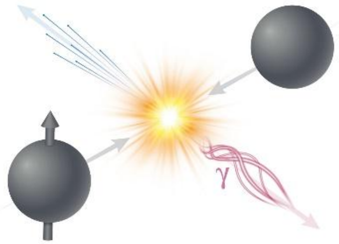






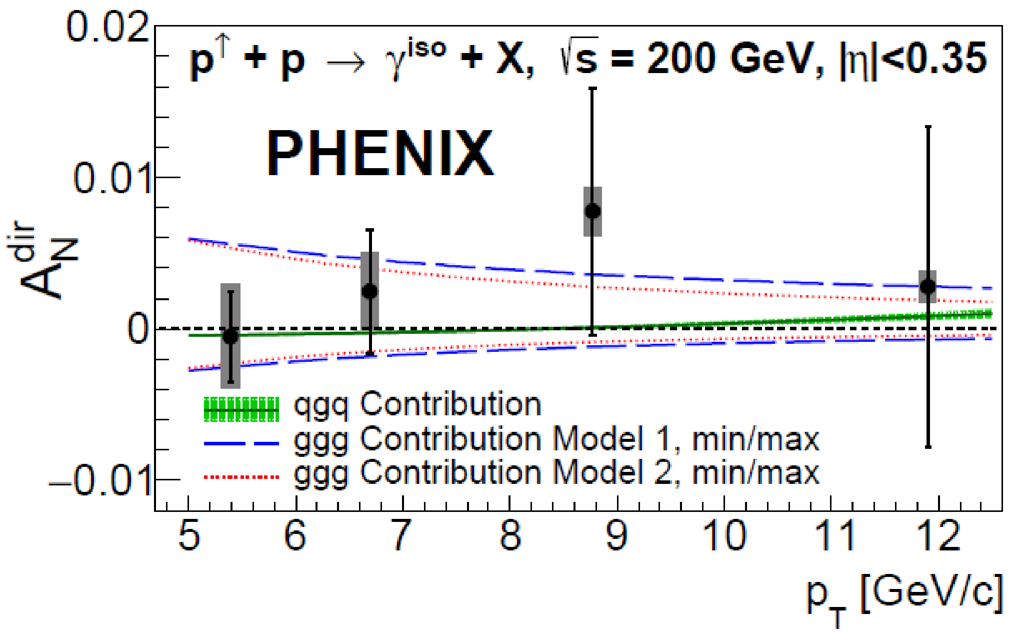
- Also not all photons produced directly → need to understand and measure Background and its asymmetry

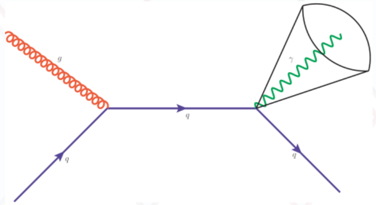
First direct photon A_Ns



- 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

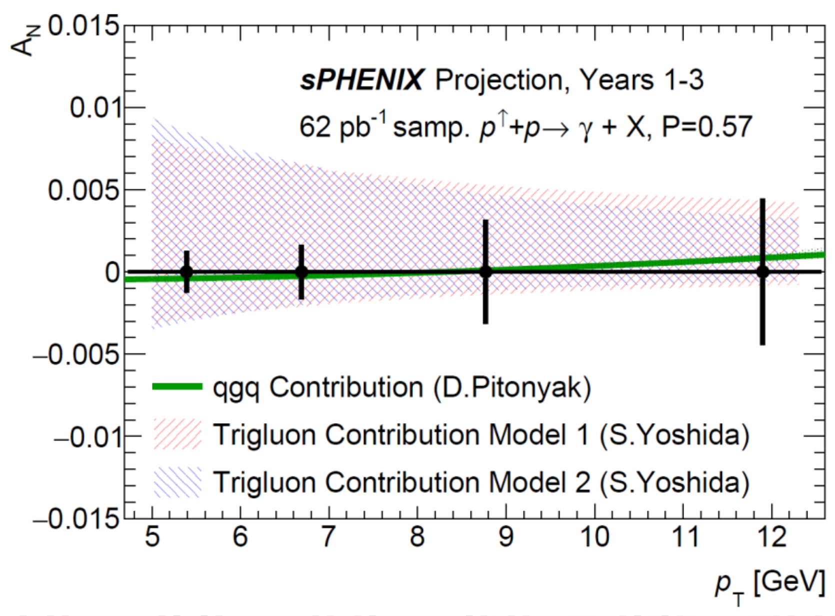
Phys.Rev.Lett. 127 (2021) 162001

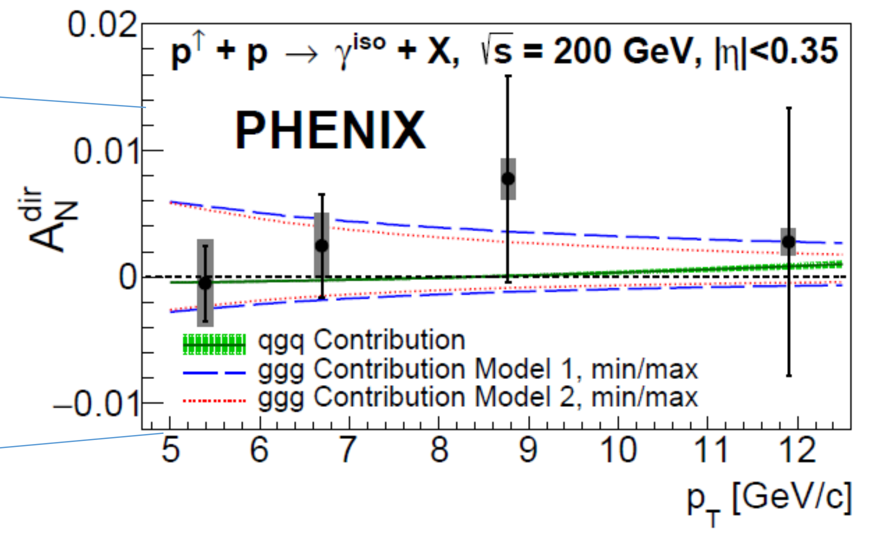




Gluon dynamics via direct photons in sPHENIX

TSSA of prompt photon
EMCal-based trigger



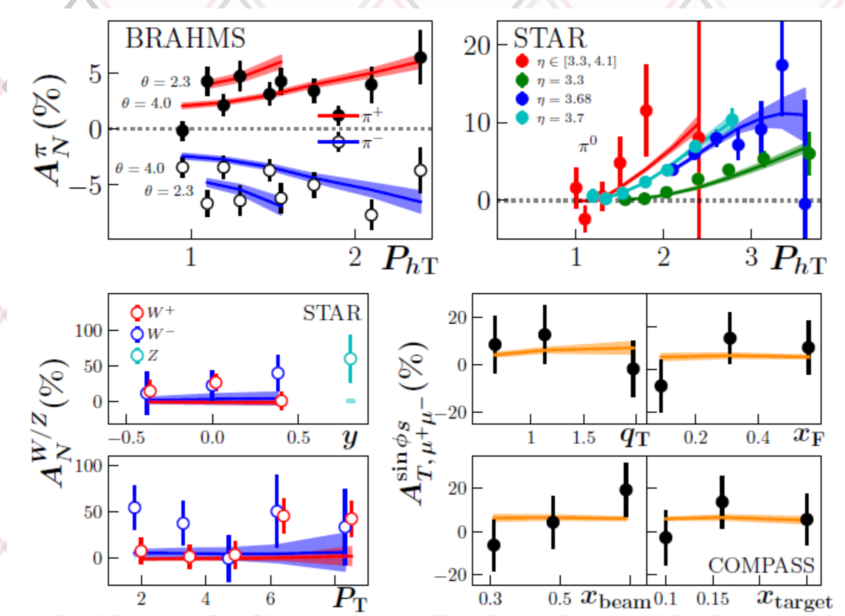


[sPHENIX BUP2021 [sPH-TRG-2021-001]]

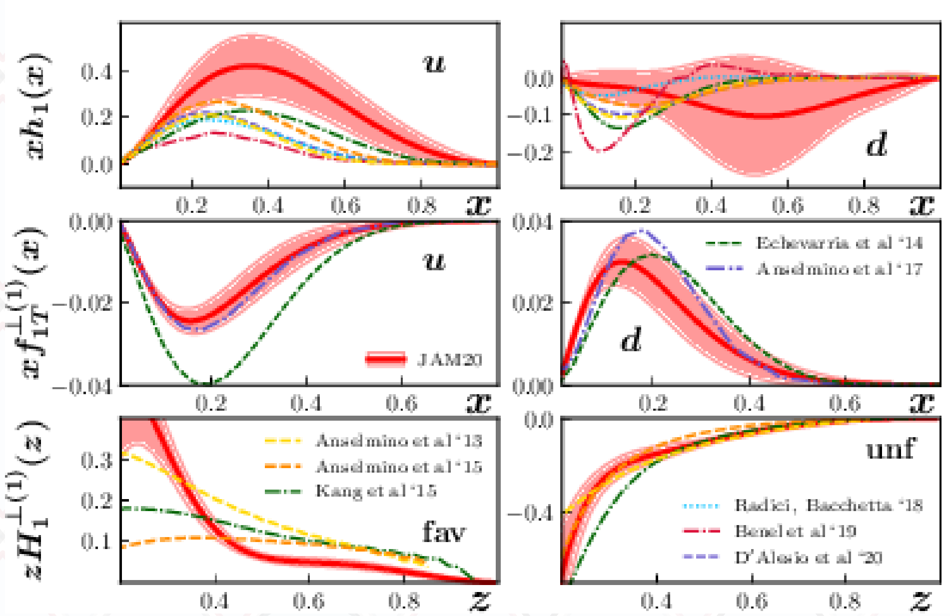
- Substantial improvement possible with sPHENIX

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

[Cammarota et al, PRD 102 (2020) 054002](#)



RHIC, SIDIS, DY included

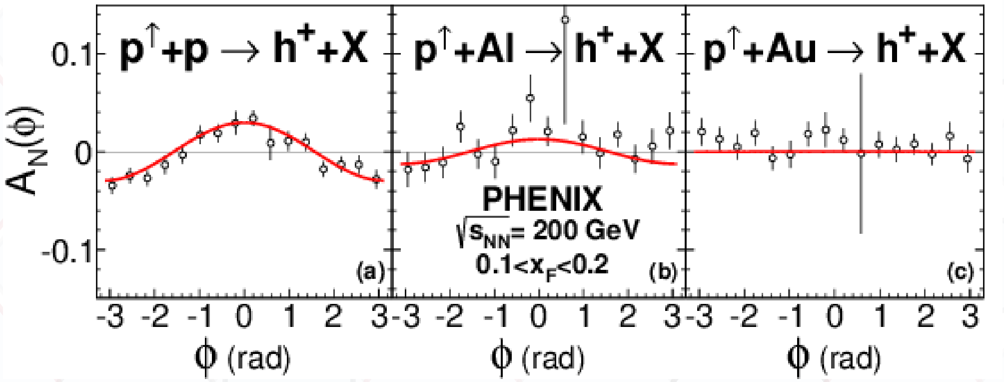


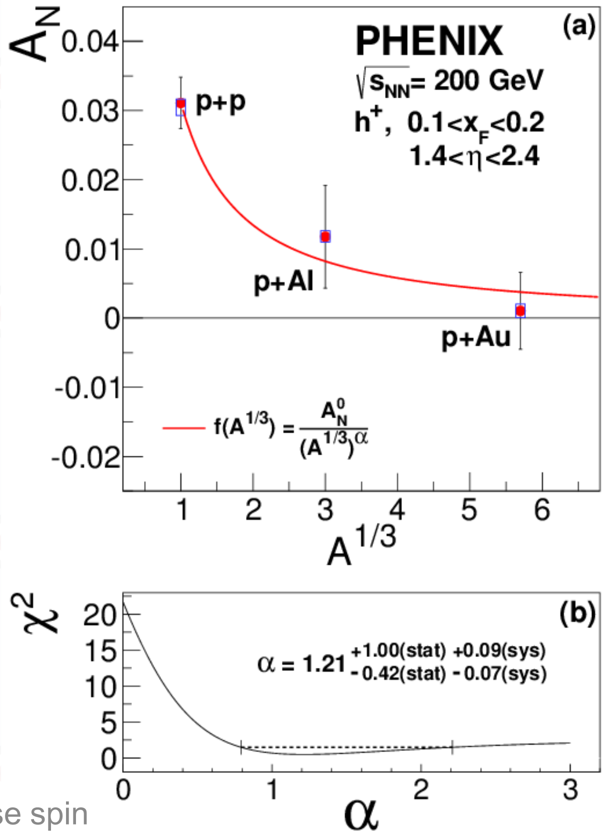
- Recent central rapidity PHENIX results (π,η,Heavy flavor electons, direct photons) not yet included
- Impact on gluon Sivers function (tri-gluon correlator) expected

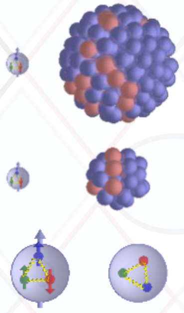
A dependence of A_Ns

- 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
- However, probed x and scale too large for expected CGC effects! (S.Benic and Y.Hatta, PRD99, 094012 - Twist-3 fragmentation + gluon saturation)

Phys.Rev.Lett. 123 (2019) 122001



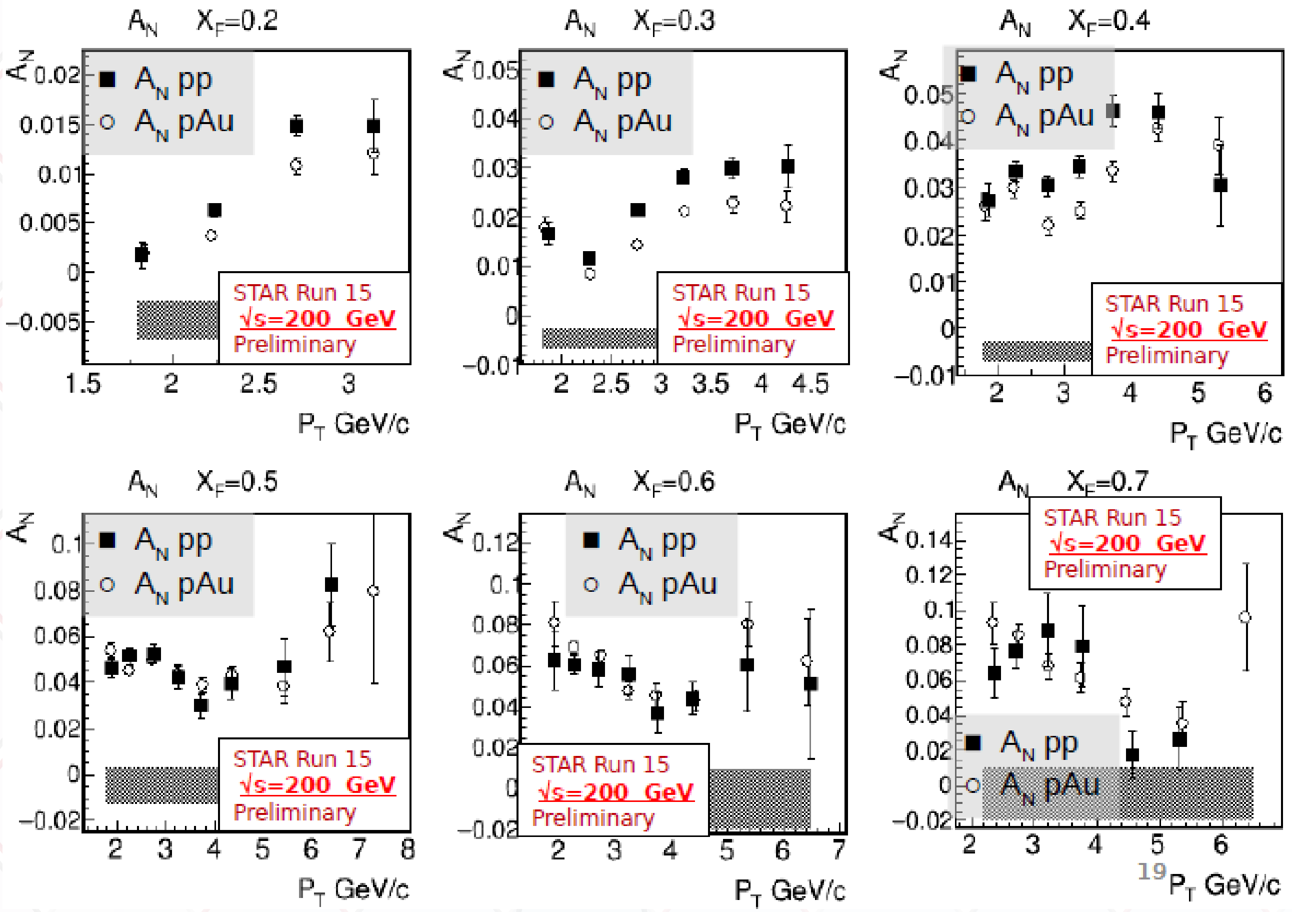




Transverse spin asymmetries in pA

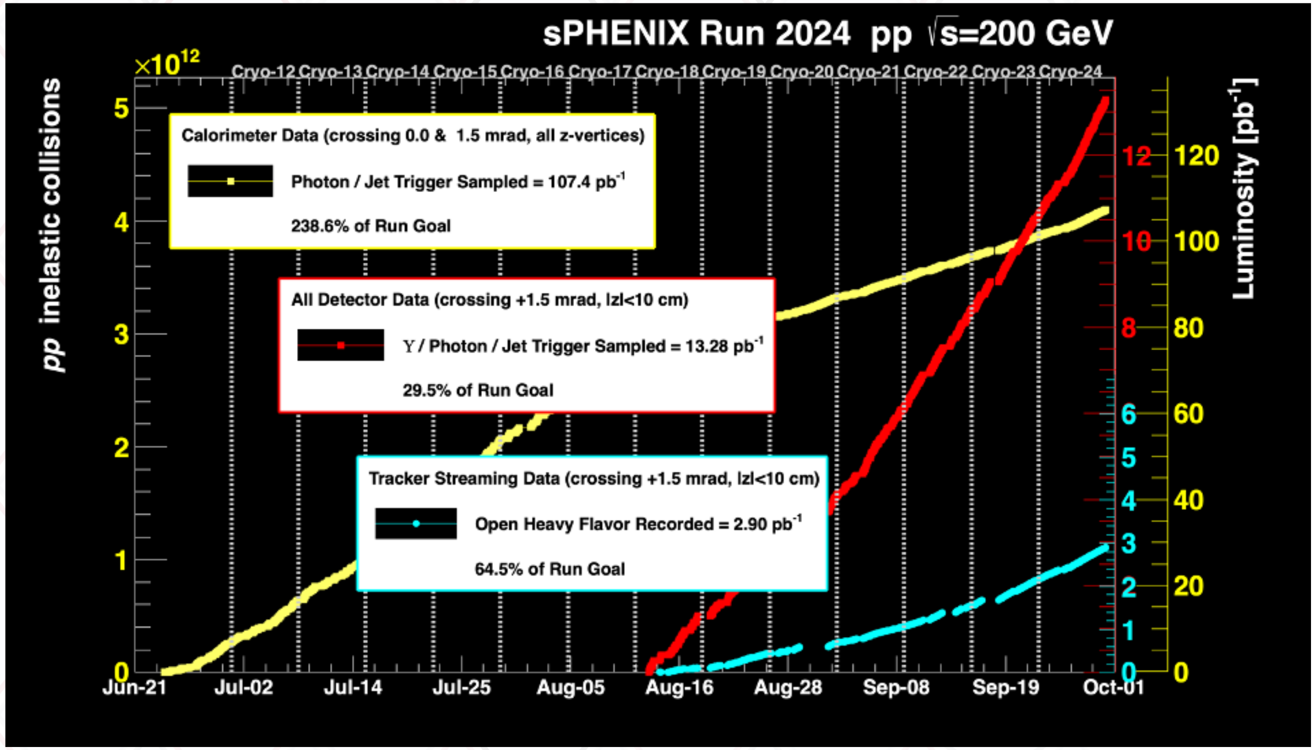
2015: p↑+A collision at $\sqrt{s_{NN}} = 200$ GeV

- Several theory predictions of diminished pA asymmetries due to nonlinear low-x behavior (either final or initial state effects)
- No substantial reduction seen in 2015 STAR data
- However, origin of A_N asymmetries still unclear



Luminosities

- Calorimeter triggers:
  - Up to 107 pb^{-1} (lower jet p_T thresholds prescaled)
  - Some INTT/MVTX information available
- Calorimeter triggers with full tracking system data
  - 13.3 pb^{-1}
  - Lower momenta prescaled
- Streaming readout
  - Minimum Bias events, full tracking information, calorimetry information not available
  - 2.9 pb^{-1}

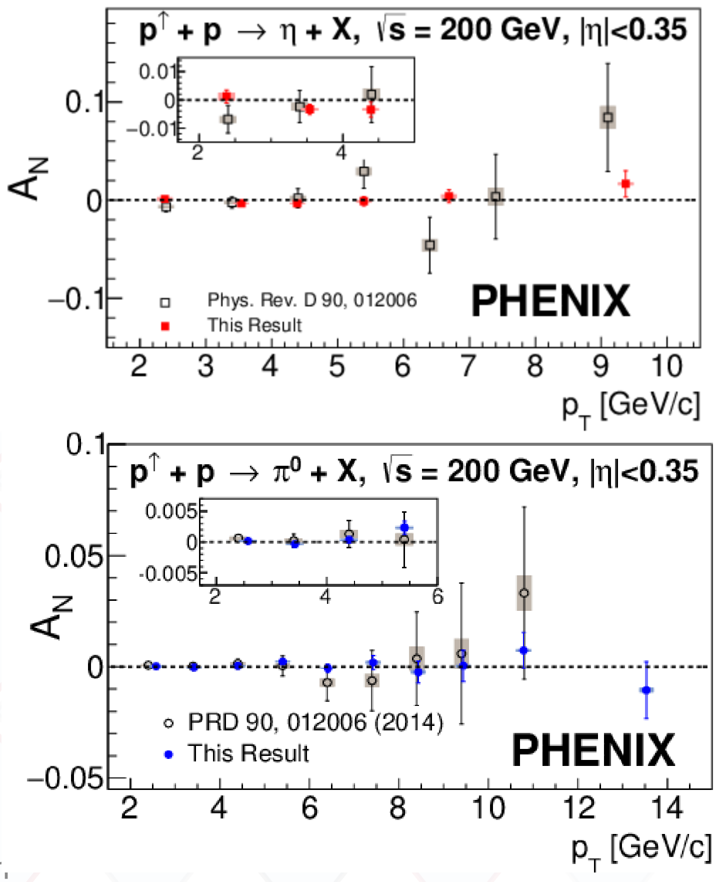


π^0 / η A_N measurements (higher twist correlators - initial + final states)

Full Jet trigger sample

- Requires only prerequisites + EMCAL information
- Signal and BG from mass peak fits
- Possible acceptance inefficiencies (hot/dead towers) cancel in asymmetries
- Use of sqrt formula available (relative luminosity just as cross check)
- At least simple cross check of cross section
- However, only confirmation of very precise PHENIX results

PRD 103 (2021) 052009

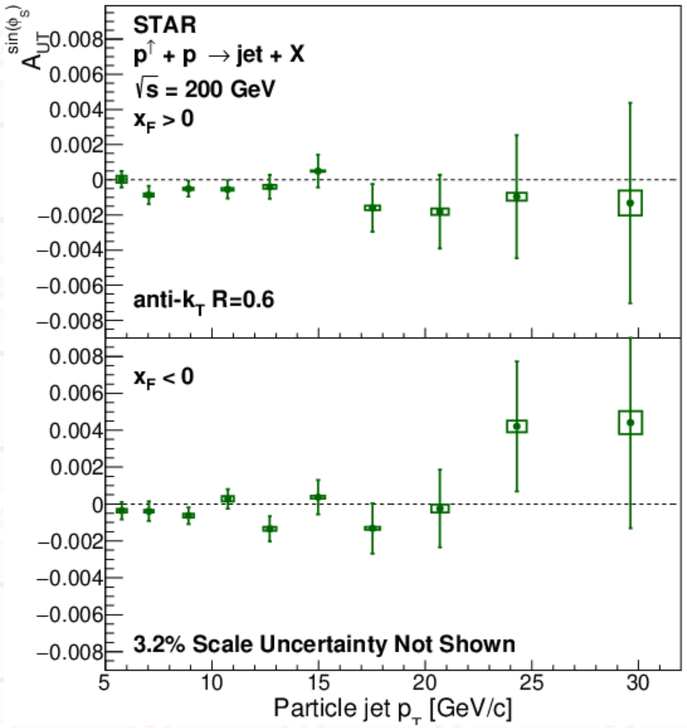


Jet A_N (higher twist correlators – initial state only)

Full Jet trigger sample

- Likely first as calorimeter jets
- could be expanded to particle flow jets (requires tracking information)

PRD 106 (2022) 072010



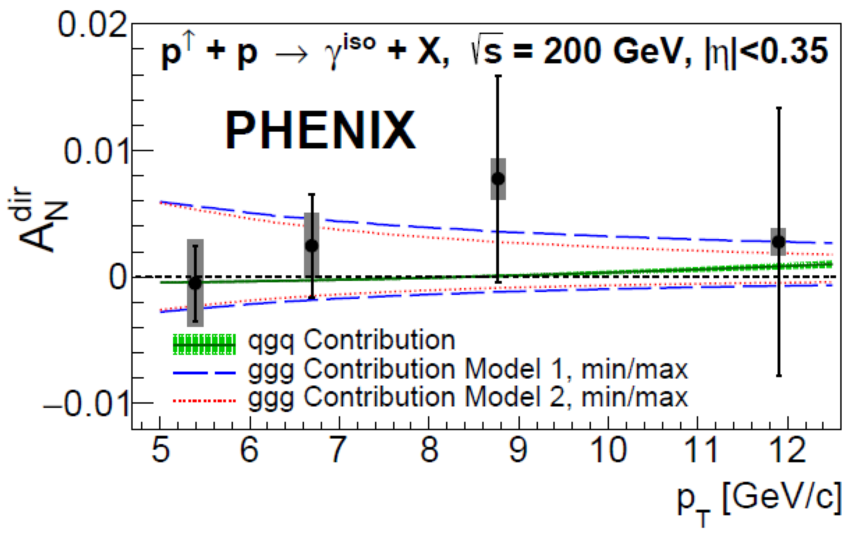
107 pb^{-1} (>10 GeV jets)

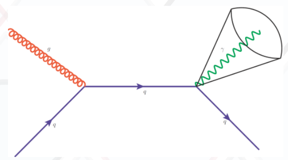
First direct photon A_Ns

Full Jet trigger sample

- 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

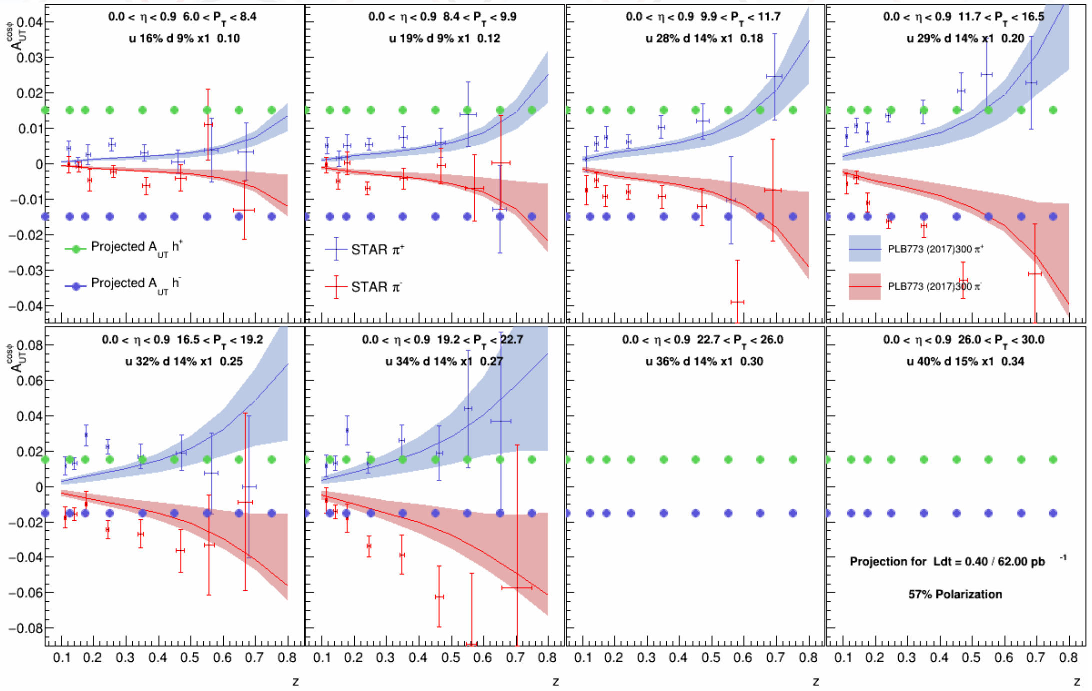




Collins II: charged hadron in Jet azimuthal asymmetries

Jet triggered + full tracking detectors sample

- Use calorimeter jets for jet reconstruction
- Reconstruct charged hadrons
- Obtain azimuthal transverse single spin asymmetries around jet axis



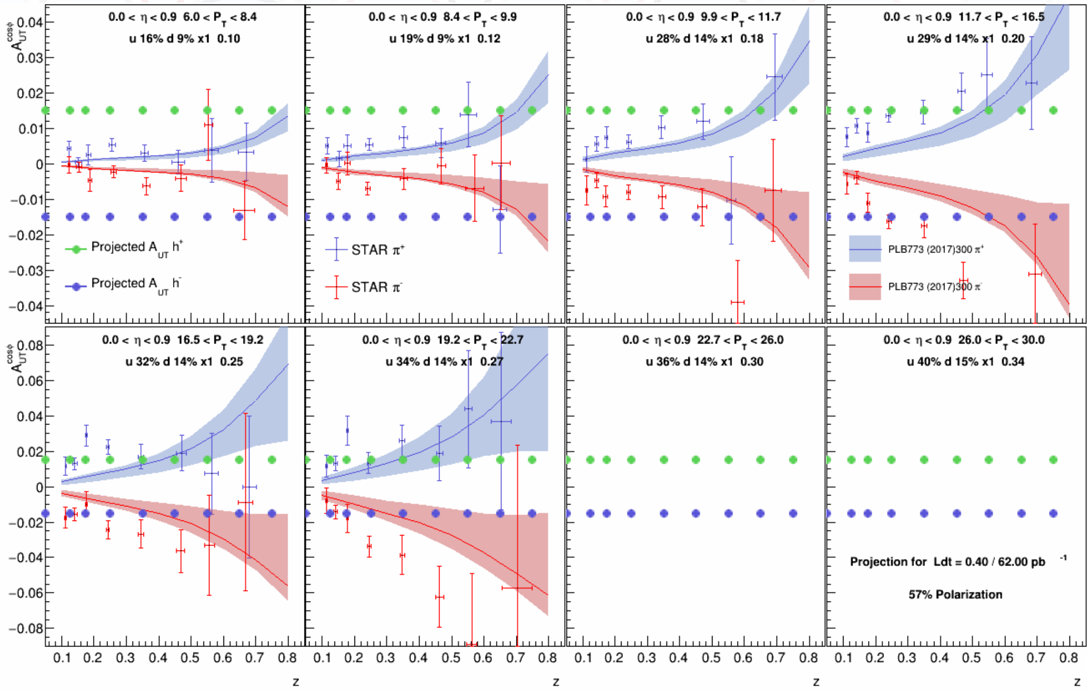
63 →13 pb^{-1} (>10 GeV jets)

0.6→?

Collins I: π^0 in jet Azimuthal asymmetries

Full Jet trigger sample

- Use calorimeter jets for jet reconstruction
- Reconstruct neutral pions from Calorimeters
- Obtain azimuthal transverse single spin asymmetries around jet axis
- Asymmetries will be smaller as favored/disfavored Collins and u,d Transversity will partially cancel each other
- Also combinatorial background

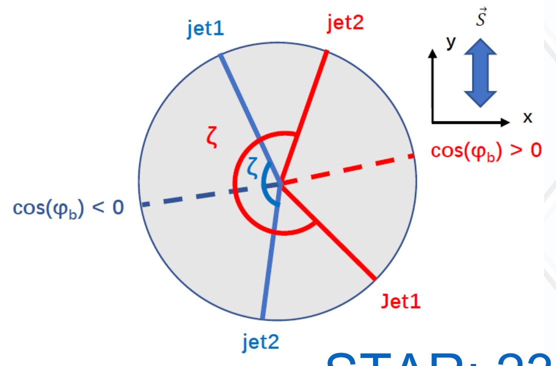


107 pb^{-1} (>10 GeV jets)

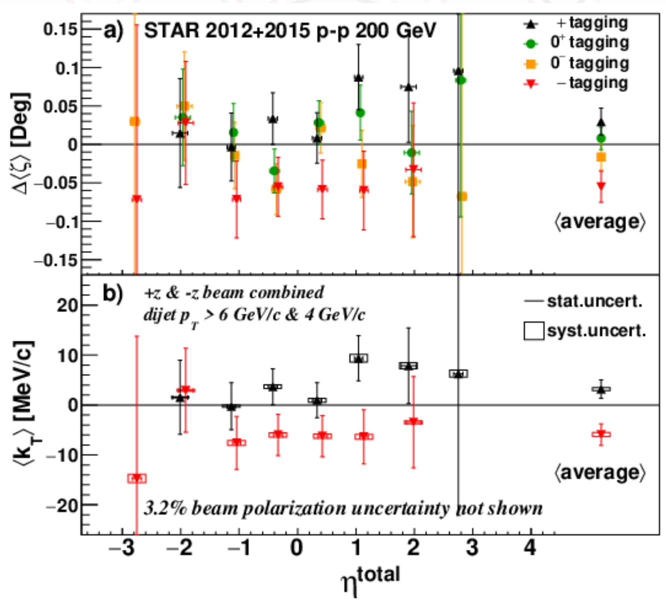
Di-jet q_T spin asymmetries (jet charge separated)

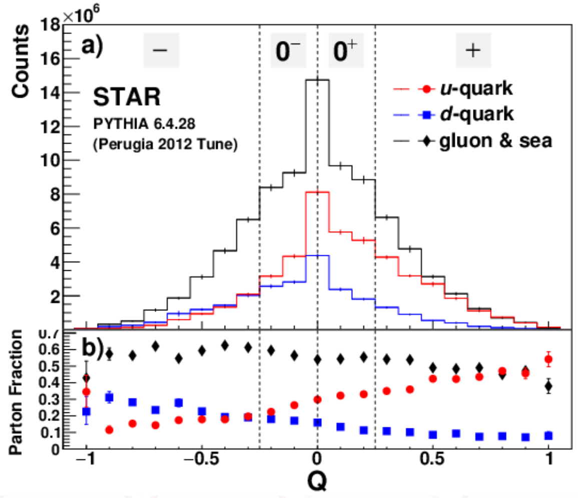
Jet triggered + full tracking detectors sample

- 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



STAR: 2305.10359





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

Photon-Jet q_T asymmetries

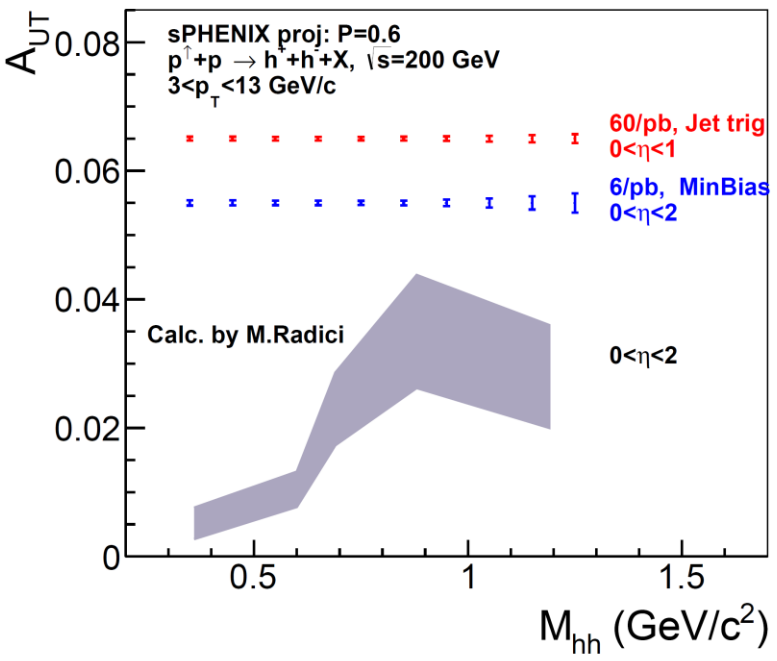
Jet triggered + full tracking detectors sample

- Similar to di-jet qT asymmetries, but cleaner quark-gluon hard interaction
- Likely also cleaner jet-charge <-> quark flavor association

Di-hadron asymmetries (Interference fragmentation – quark tensor charge/transversity)

Jet triggered + full tracking detectors sample

- Requires oppositely charged track pair or charged track + π^0 pair
- Azimuthal angular modulations of single spin asymmetries as function of inv mass, pair p_T, and x_F/η
- Partially cross check of STAR results, π^0 – track pairs new
- Corresponding p+p cross sections unknown (needed together with Belle results for gluon FF)



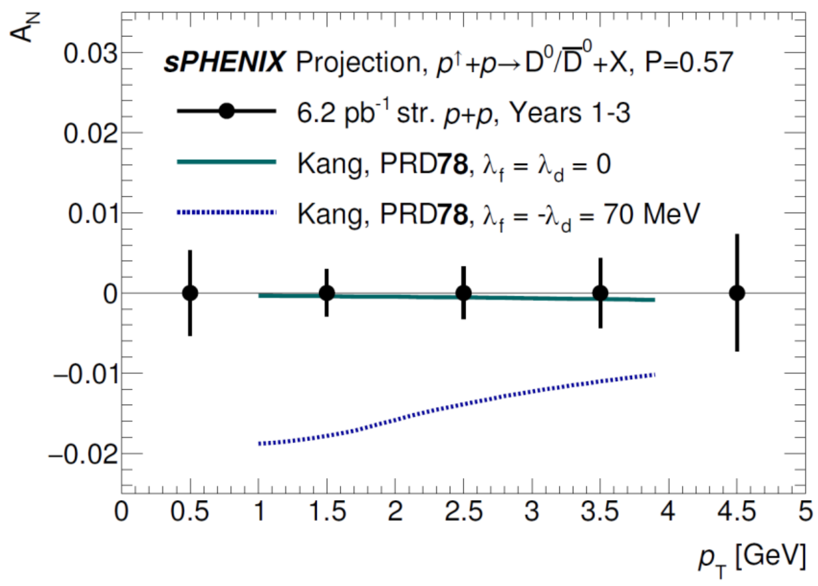
D^0 A_N

Streaming readout sample

- In sPHENIX possiblity to actually measure D meson asymmetries
- Ordering of asymmetries for D and Dbar will constrain tri-gluon correlations further (possibility to identify charges via kaon pion separation?)

[sPHENIX BUP2021 [sPH-TRG-2021-001]]

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



Summary

- (transverse) spin physics accesses the spin-orbit correlations in the nucleon
- Sizeable effects are known, but not well measured
- RHIC can access these effects via higher twist
- Plenty of interesting possibilities with current $p^{\uparrow}$+p data, potentially more with $p^{\uparrow}$+A