Transverse-Momentum-Dependent Distributions and Color Entanglement in QCD

Lecture 2 – TMDs and Collinear Twist-3 Correlation Functions

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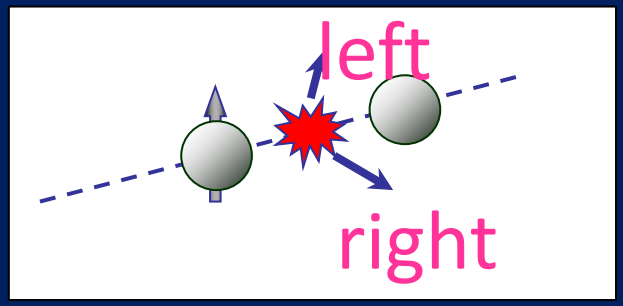
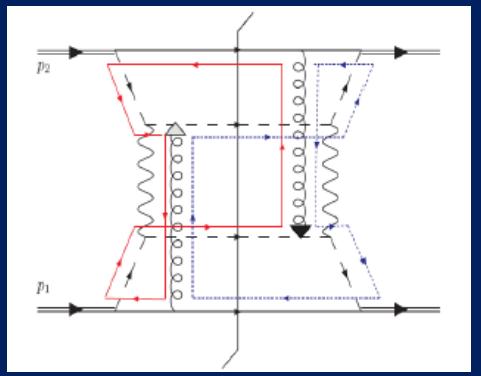


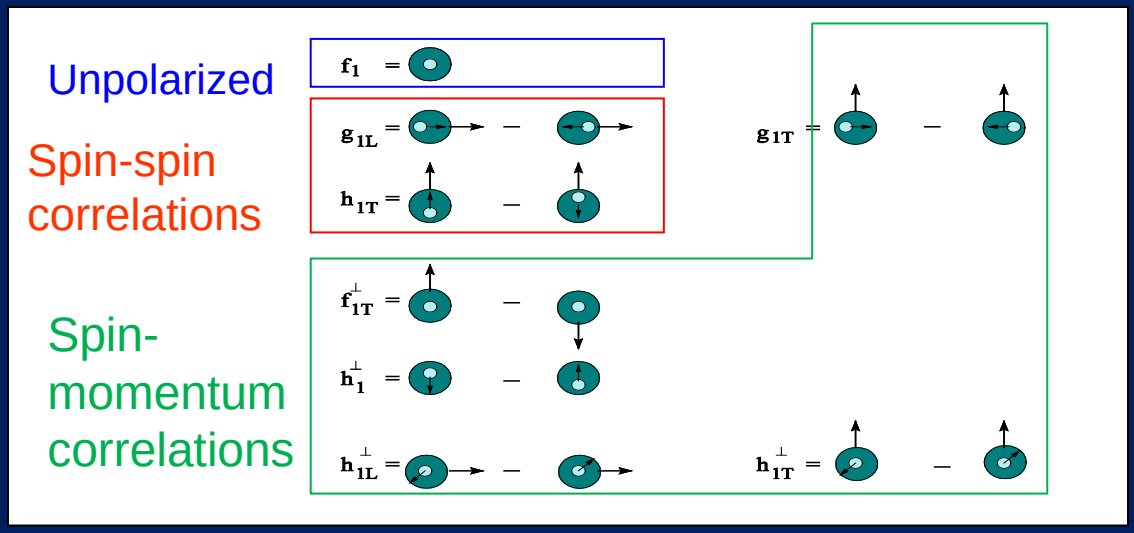


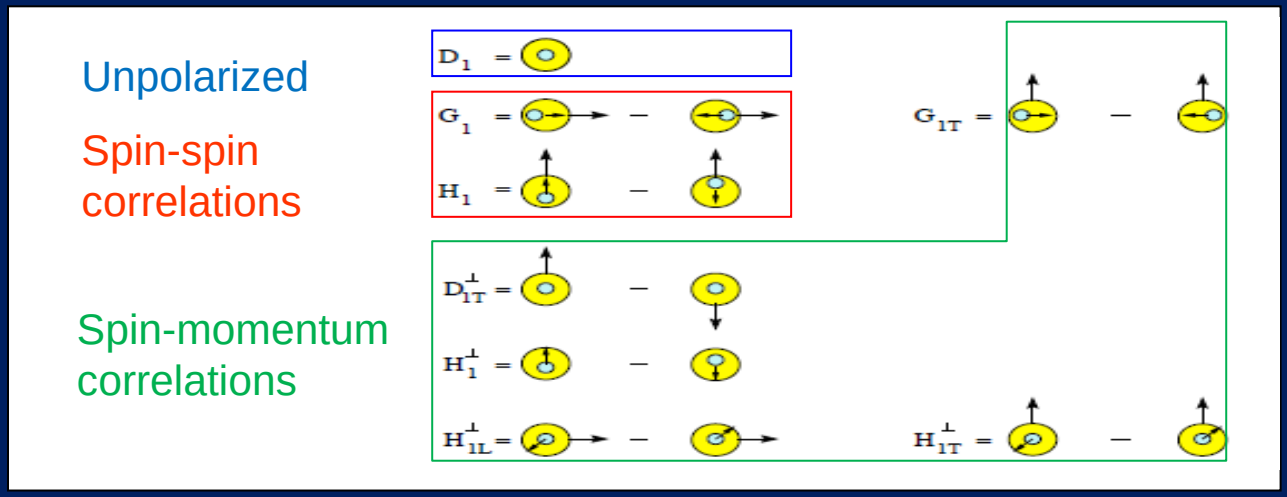
Hampton University Graduate Studies Program

Jefferson Lab

June 2016

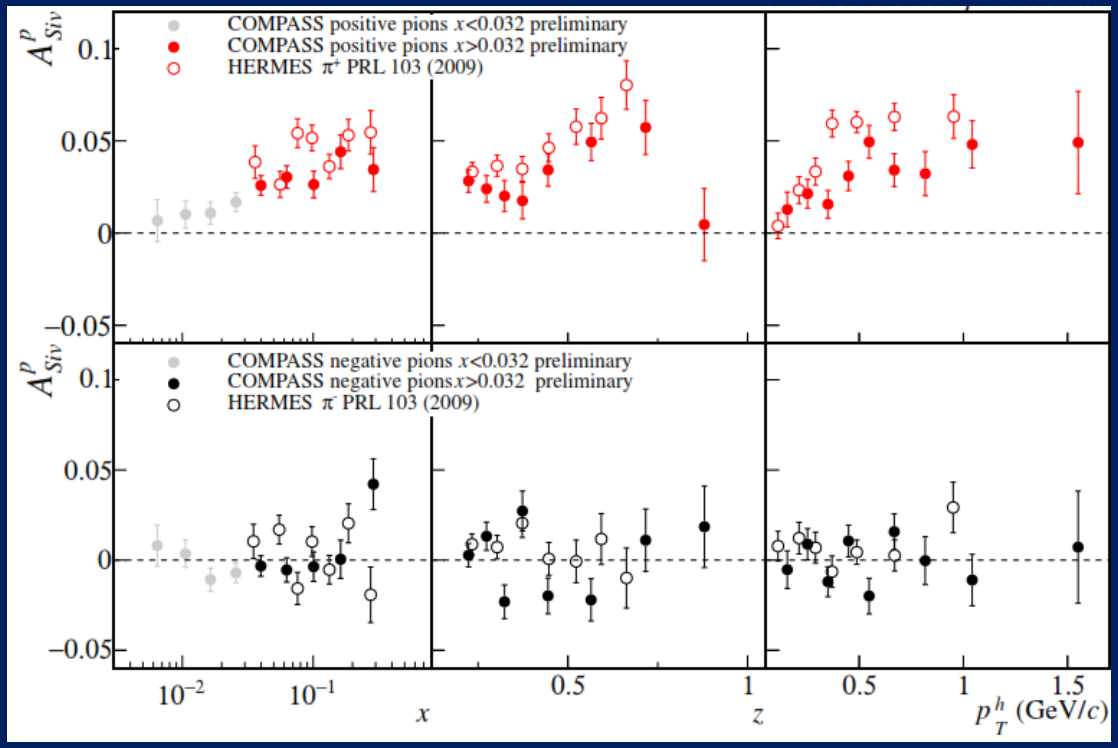
Lots of TMD pdfs and FFs: What do we know from experiment?

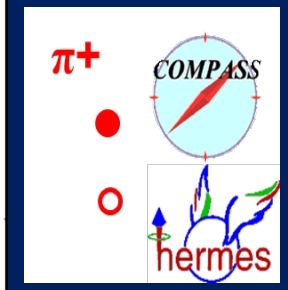


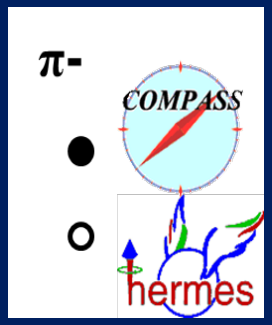


Sivers asymmetry in SIDIS

Charged pions (and kaons), HERMES and COMPASS

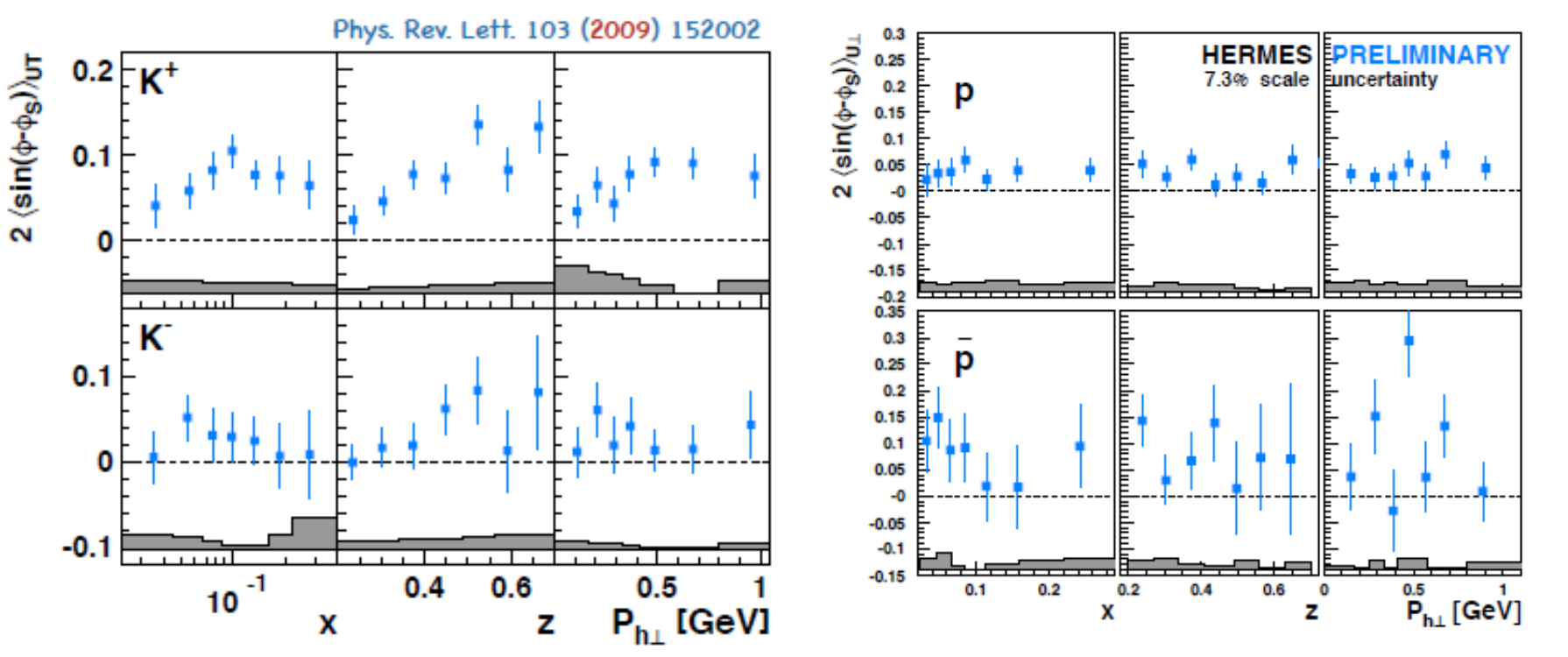






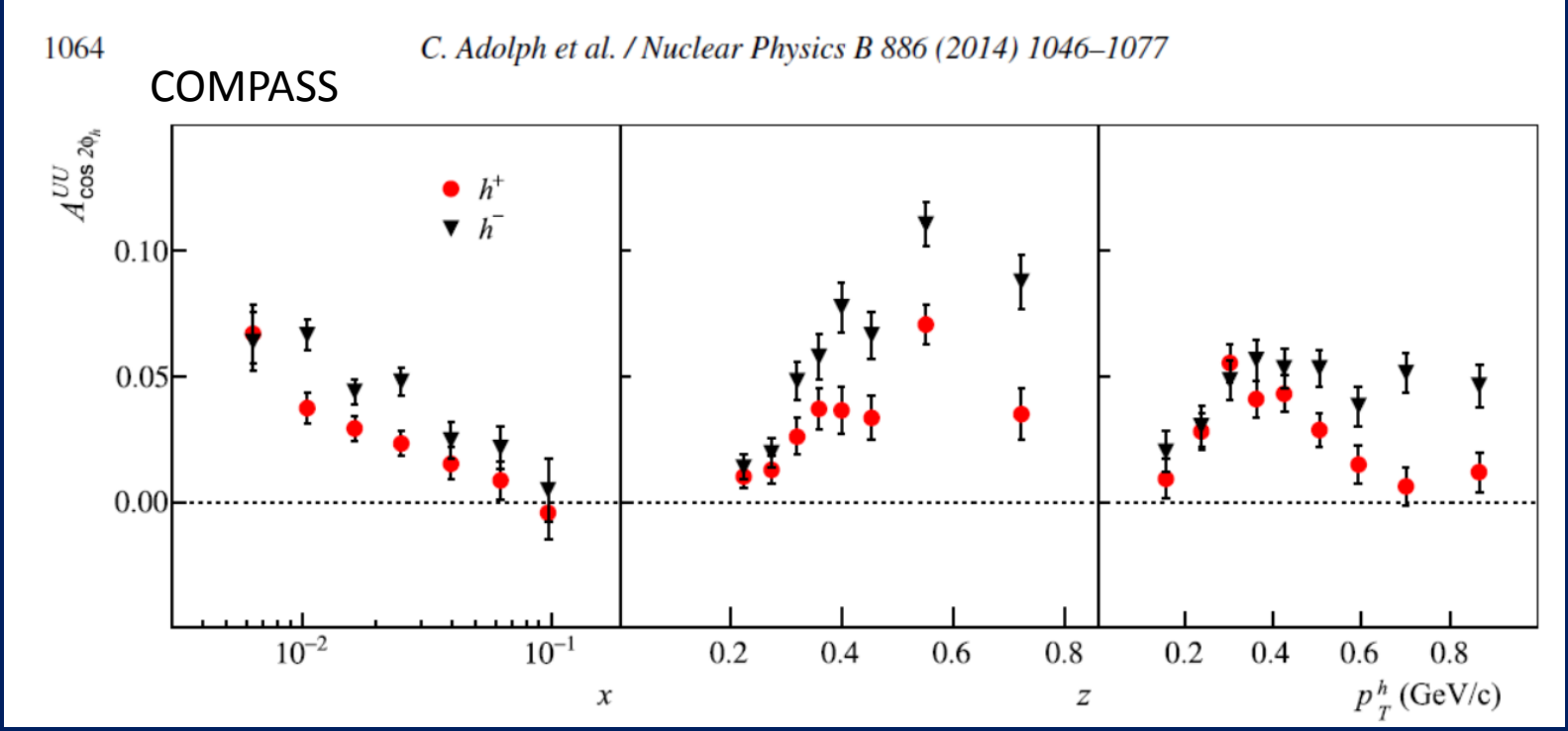
- Sivers TMD pdf – correlation between proton transverse spin and quark transverse momentum. PT-odd
- Clearly nonzero for positive pions. Cancellations between up and down quarks lead to smaller negative pion asymmetries?

Sivers asymmetry in SIDIS for kaons and protons



Nonzero for positive kaons and protons, hints for negative kaons and antiprotons. Identified particles help give *flavor separation* for Sivers TMD pdf

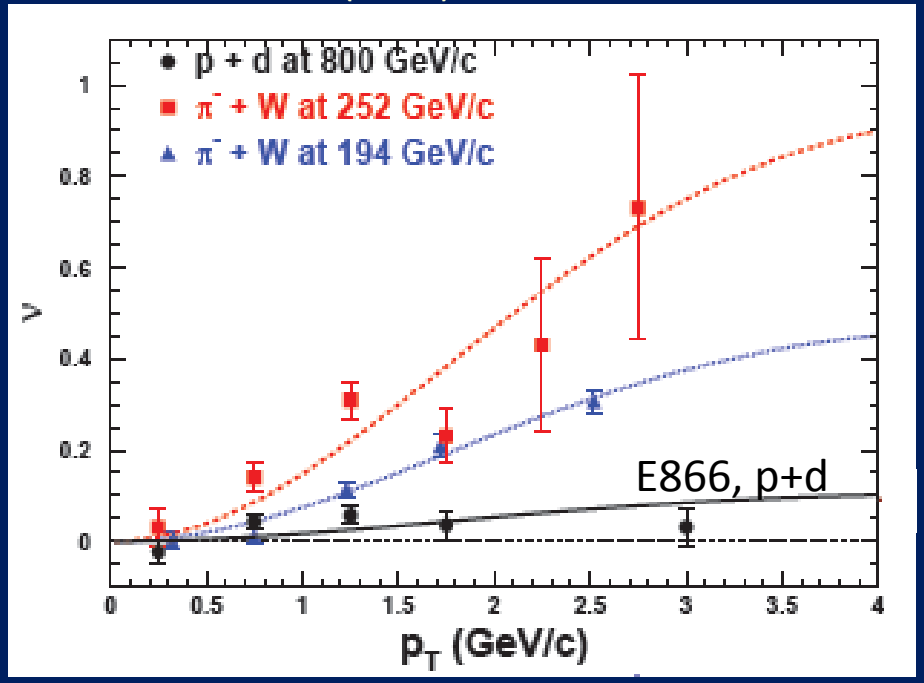
Boer-Mulders ×Collins asymmetry from SIDIS



- Boer-Mulders TMD pdf – correlation between quark transverse spin and its own transverse momentum. PT-odd, chiral-odd
- Chiral-odd → need another chiral-odd function to measure it. Here the Collins TMD FF
- Clearly nonzero for positive and negative hadrons
- Also measured by HERMES – PRD87, 012010 (2013)

Boer-Mulders ×Boer-Mulders asymmetry from Drell-Yan

E866, PRL 99, 082301 (2007);
PRL 102, 182001 (2009)



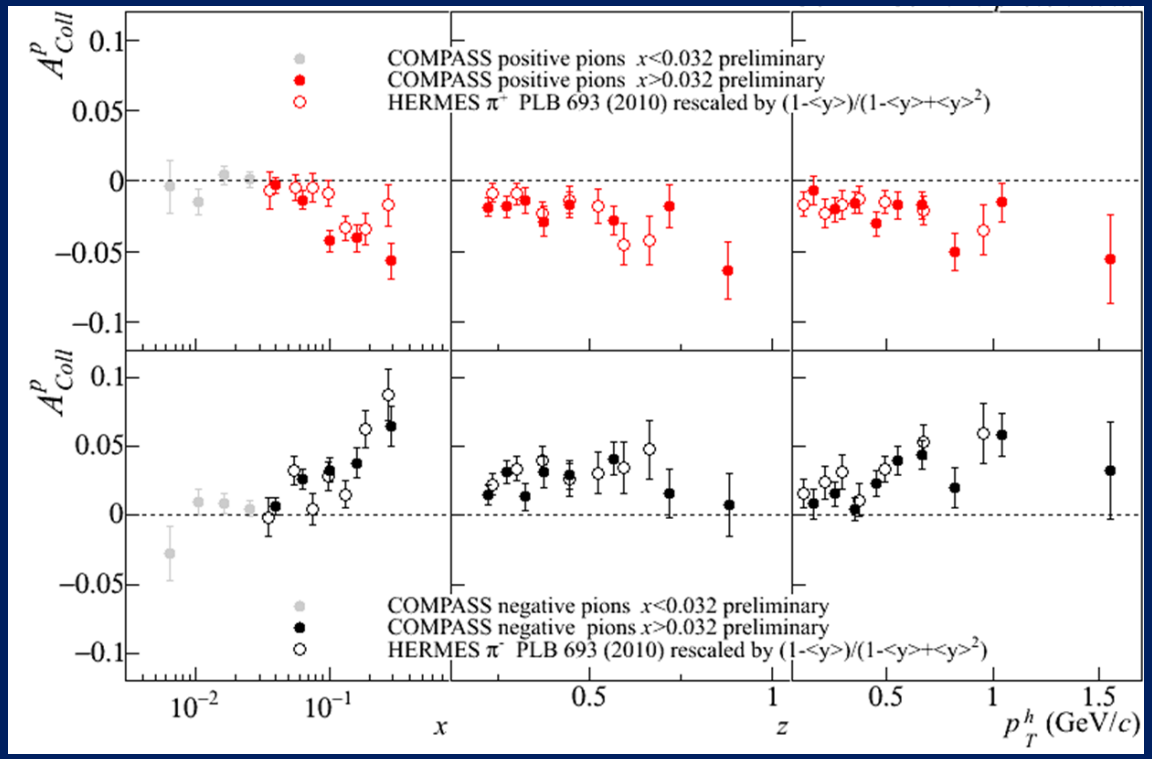
- Huge cos2ϕ dependence in pion-induced Drell-Yan
- Significantly reduced in proton-induced Drell-Yan
- Suggests sea quark transverse spin-momentum correlations small?

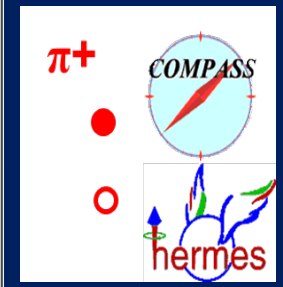
Boer - Mulders function $h_1^\perp$

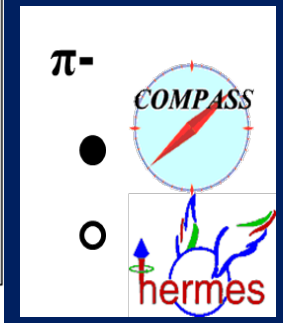
$\nu(\pi^- W \to \mu^+\mu^- X) \sim$ [valence $h_1^\perp(\pi)$] * [valence $h_1^\perp(p)$]

$\nu(pd \to \mu^+\mu^- X) \sim$ [valence $h_1^\perp(p)$] * [sea $h_1^\perp(p)$]

Transversity ×Collins asymmetry from SIDIS

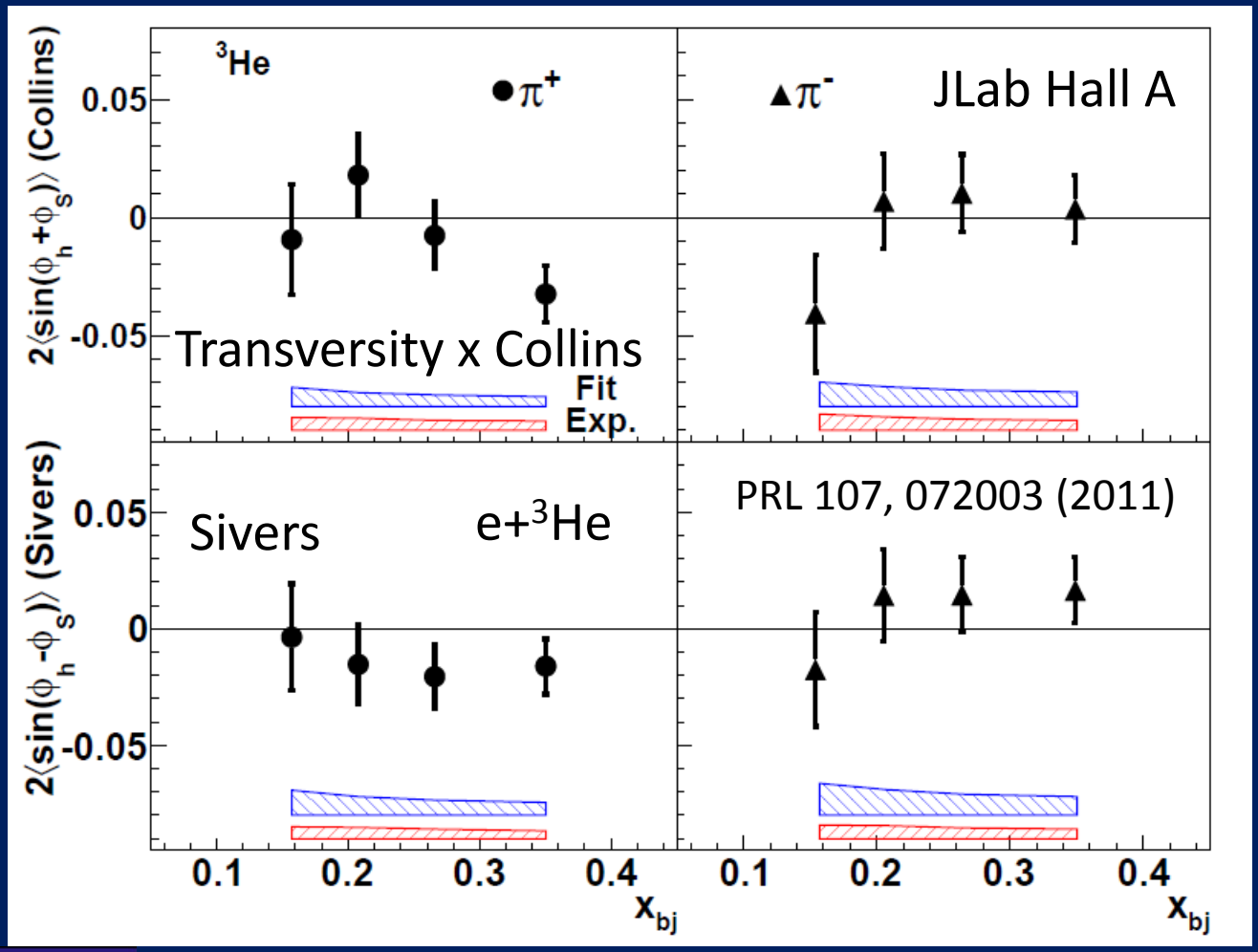






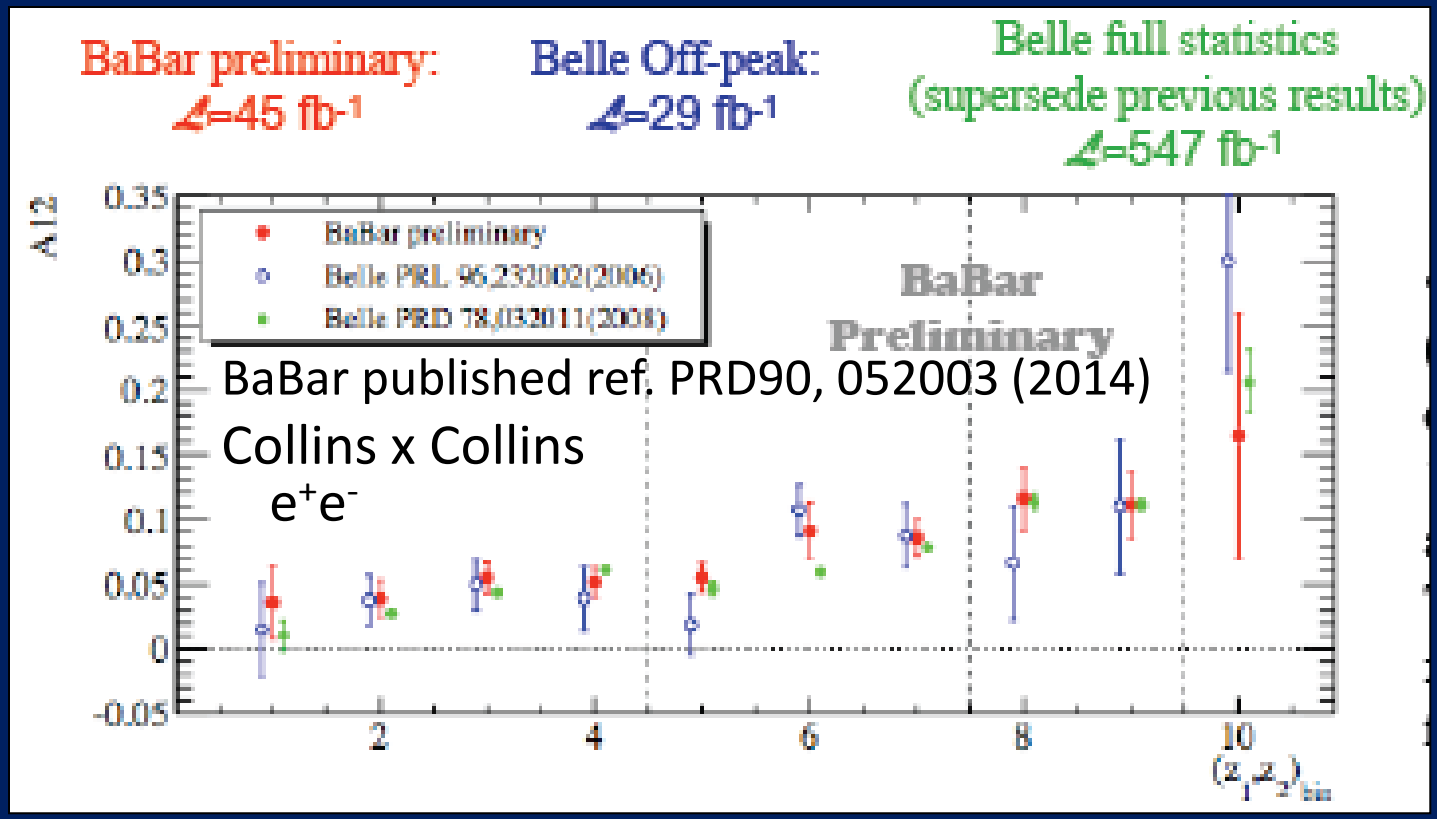
- Transversity pdf – correlation between proton transverse spin and quark transverse spin. Survives integration over k_T, chiral-odd
- Collins TMD FF – correlation between quark transverse spin and hadron transverse momentum. Chiral-odd
- Clearly nonzero for positive and negative pions

Hints from SIDIS on polarized ^{3}He



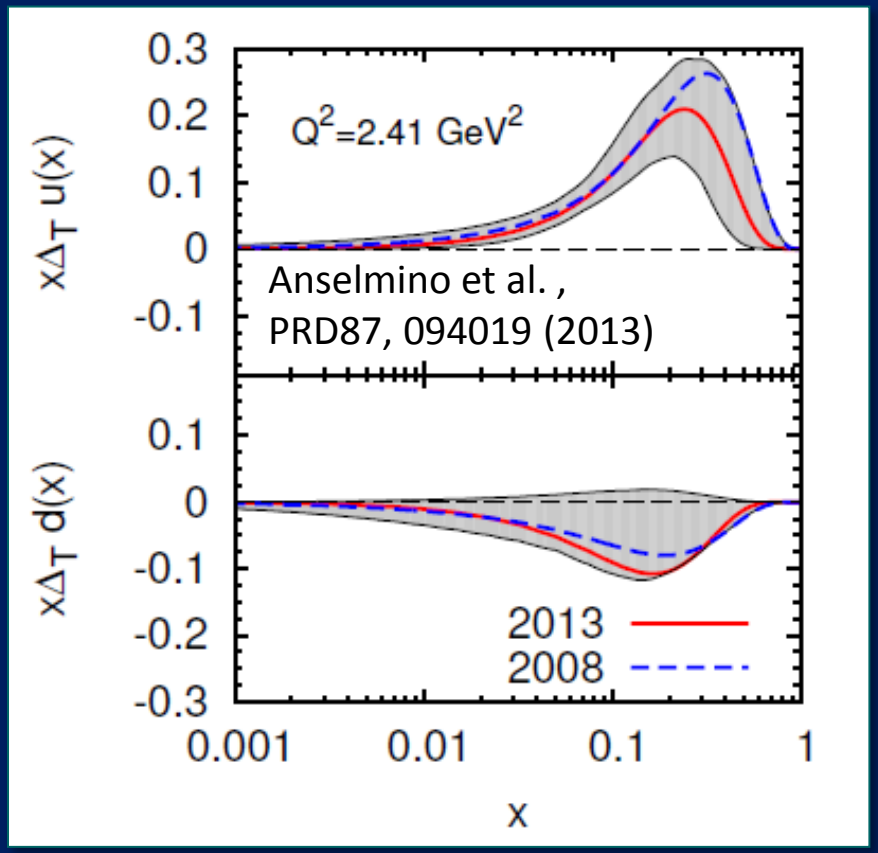
- Measurements on polarized neutrons help provide flavor information
- 12 GeV program will bring a lot more data!

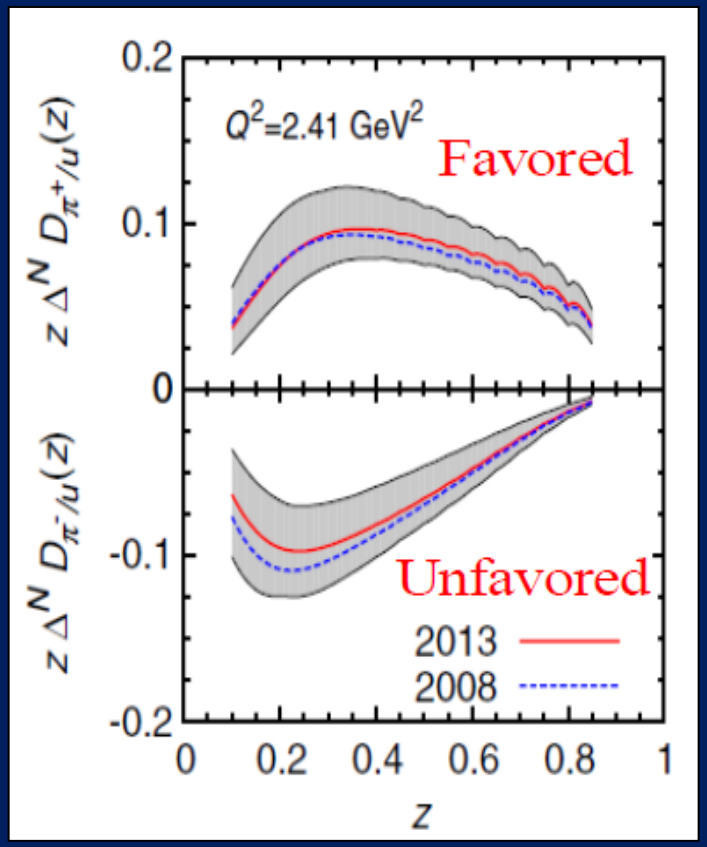
Collins ×Collins asymmetry from e+e-



- Collins TMD FF – correlation between quark transverse spin and hadron transverse momentum. Chiral-odd
- Clearly nonzero for charged pions

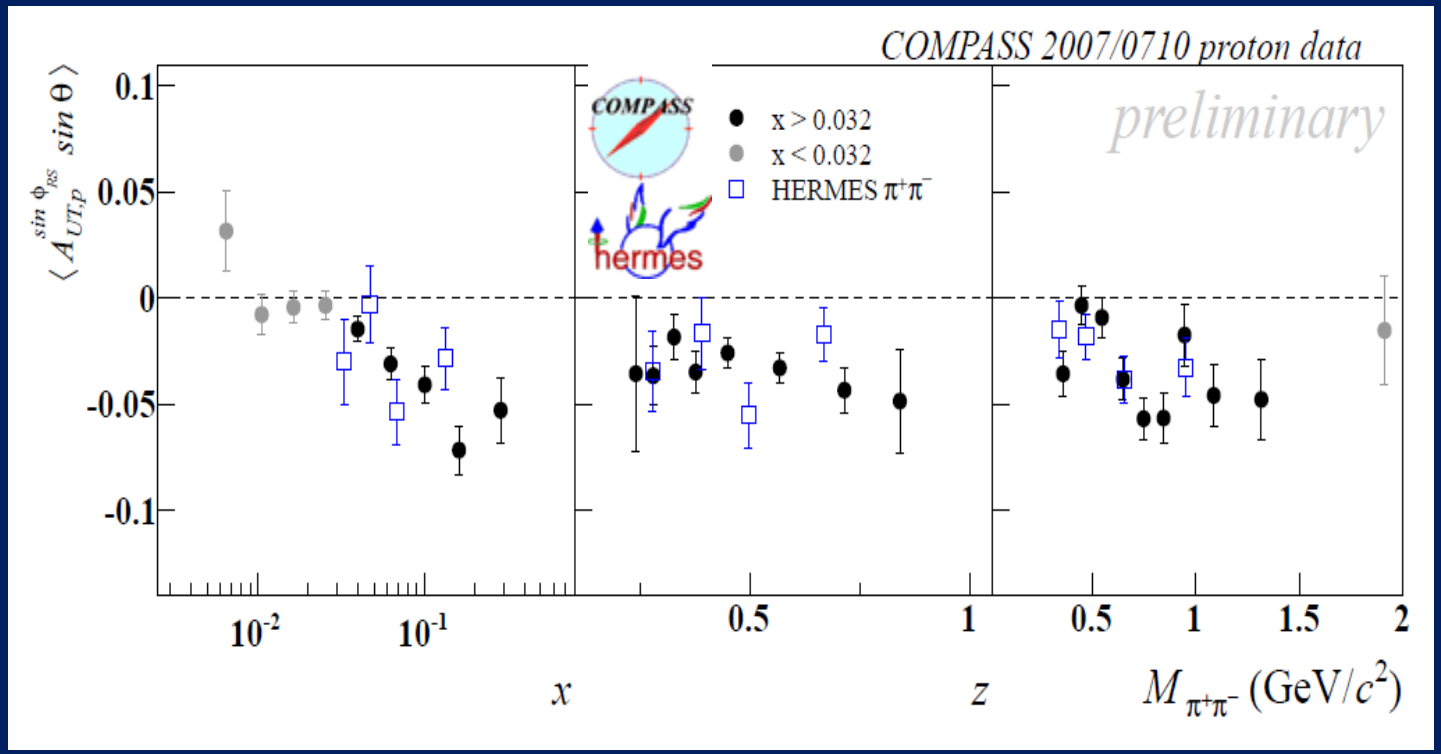
Simultaneous extraction of transversity pdf and Collins FF





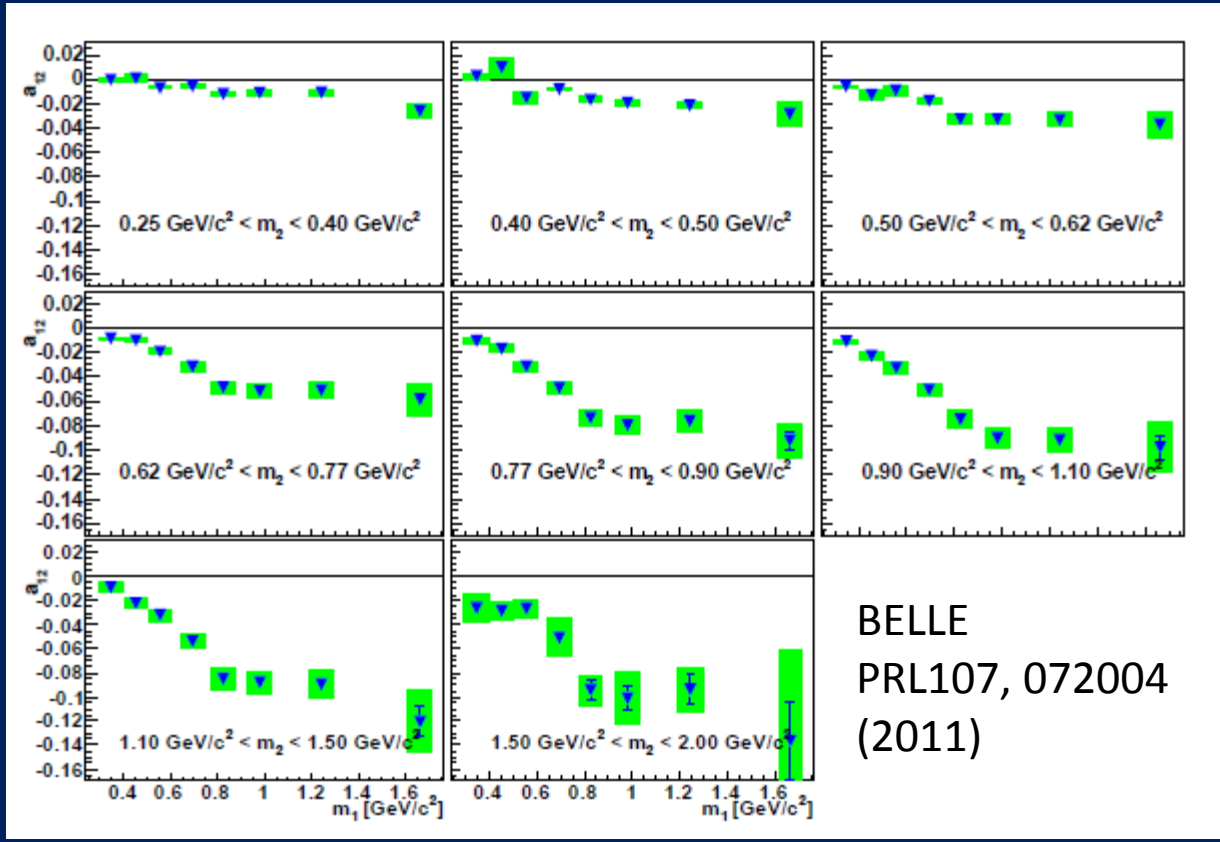
- Extracted from simultaneous fit to HERMES, COMPASS, and BELLE data

Transversity ×dihadron interference FF asymmetries in SIDIS



- Transversity pdf – correlation between proton transverse spin and quark transverse spin. Survives integration over k_T, chiral-odd
- Dihadron interference FF – correlation between quark transverse spin and angular distribution of two-particle production. Collinear, chiral-odd
- Clearly nonzero for charged pion pairs

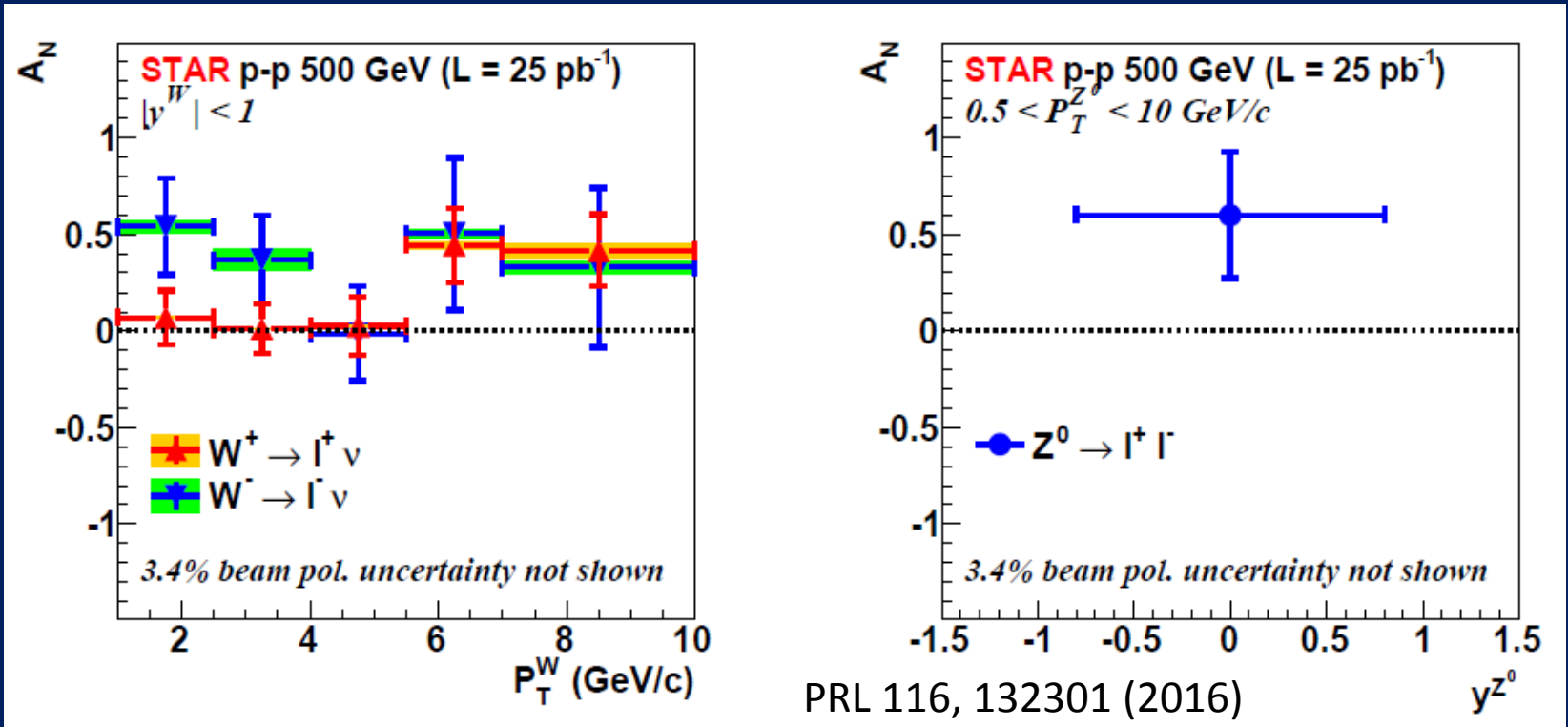
Dihadron interference FF × Dihadron interference FF asymmetry from e+e-



BELLE
PRL107, 072004 (2011)

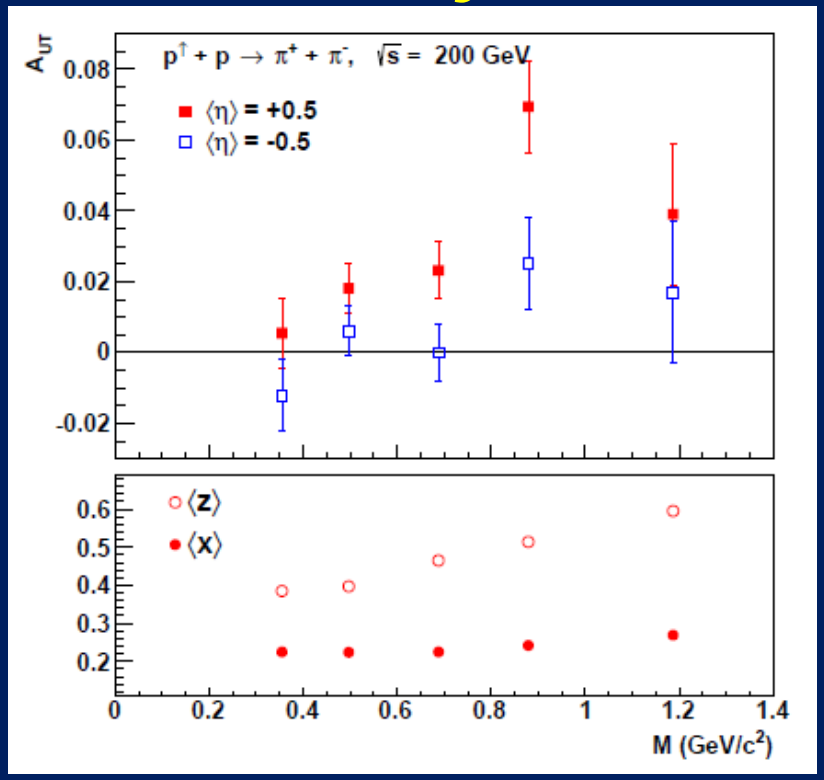
- Dihadron interference FF – correlation between quark transverse spin and angular distribution of two-particle production. Collinear, chiral-odd
- Clearly nonzero for charged pion pairs

Probing modified universality of the Sivers TMD pdf via W and Z production in p+p



Early measurement hints at nonzero asymmetries, but inconclusive for testing modified universality. Expect more data in 2017

Transversity ×dihadron interference FF asymmetries in p+p

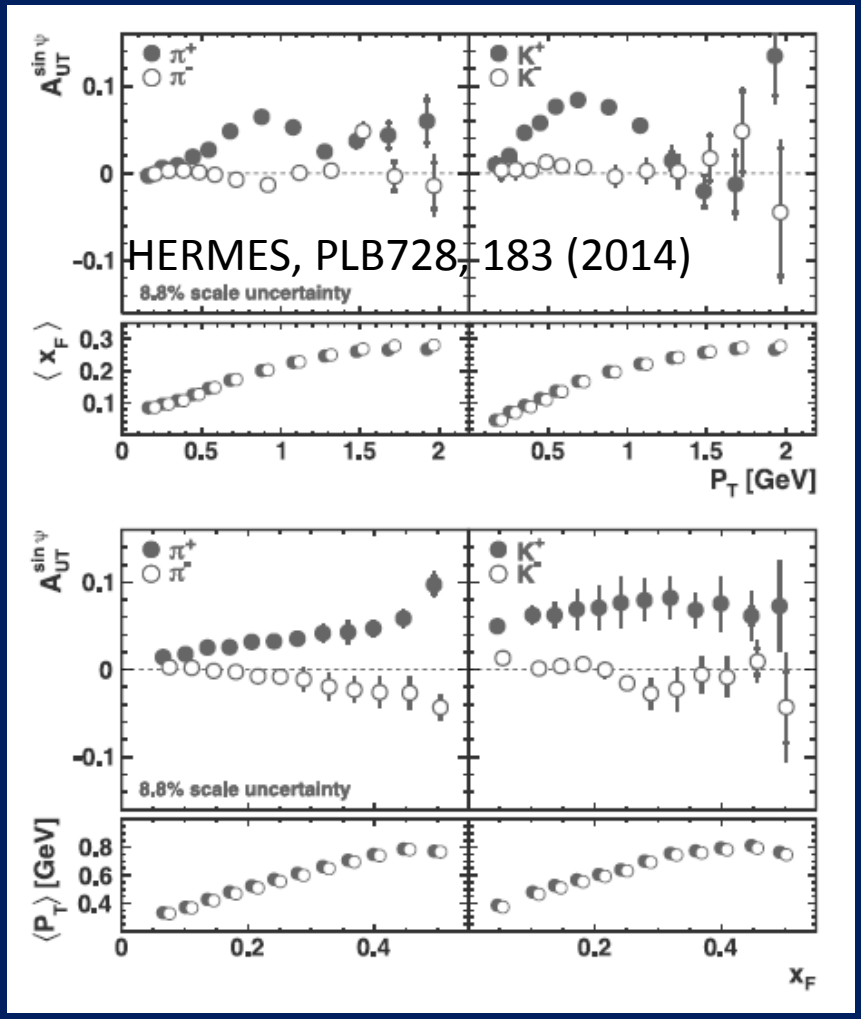


Purely collinear measurement
- No issues of TMD-factorization breaking. More in Lectures 4+5 . . .

- Transversity pdf – correlation between proton transverse spin and quark transverse spin. Survives integration over k_T, chiral-odd
- Dihadron interference FF – correlation between quark transverse spin and angular distribution of two-particle production. Collinear, chiral-odd
- Clearly nonzero for charged pion pairs

Inclusive hadron transverse single-spin asymmetries in e+p

- *No* scattered electron measured
- Shown here as function of p_T and x_F
- Also measured doubly differentially
- Clear nonzero asymmetries with interesting dependencies
- Not as easy to interpret . . .



Summary of spin-momentum correlation results

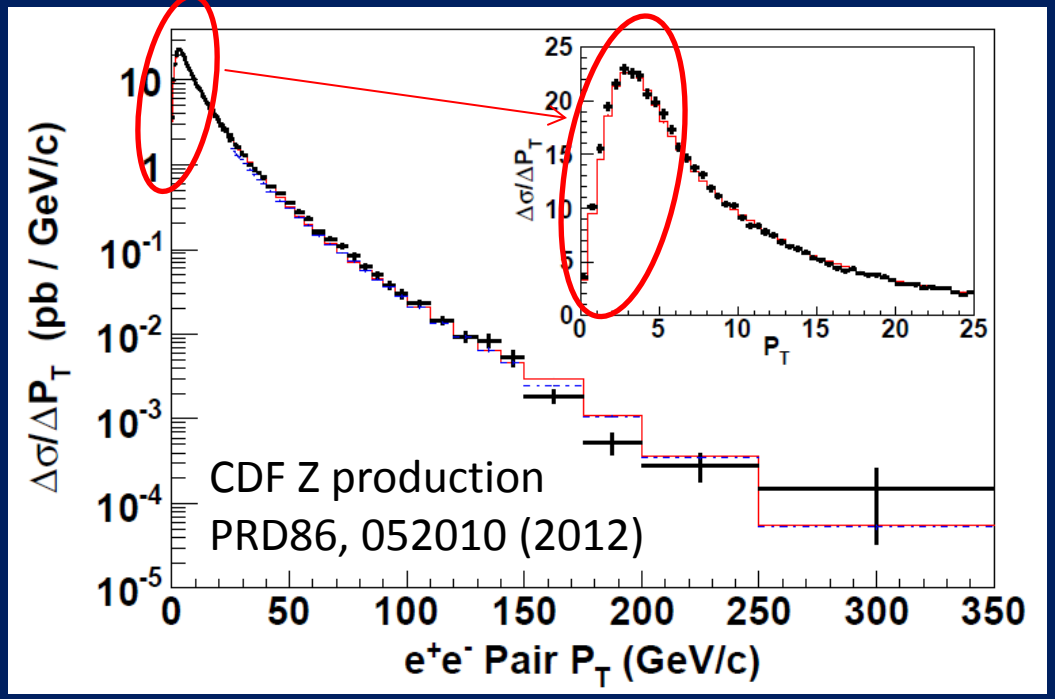
- Clear empirical evidence for nonzero
  - Sivers TMD pdf – correlation between proton transverse spin and quark transverse momentum
    - SIDIS
  - Collins TMD FF – correlation between quark transverse spin and transverse momentum of produced hadron
    - e+e-, SIDIS
  - Boer-Mulders TMD pdf – correlation between quark transverse spin and quark transverse momentum
    - Drell-Yan, SIDIS
- Hints from SIDIS measurements (in backup) of nonzero
  - Worm gear TMD pdf – correlation between proton transverse spin, quark longitudinal spin, quark transverse momentum
  - Pretzelosity TMD pdf – correlation between proton transverse spin, perpendicular quark transverse spin, quark transverse momentum
- Also clear evidence for nonzero helicity and transversity collinear pdfs from SIDIS and p+p, collinear dihadron interference FF from e+e-, SIDIS, p+p

What about unpolarized TMD functions? Unpolarized TMD pdfs

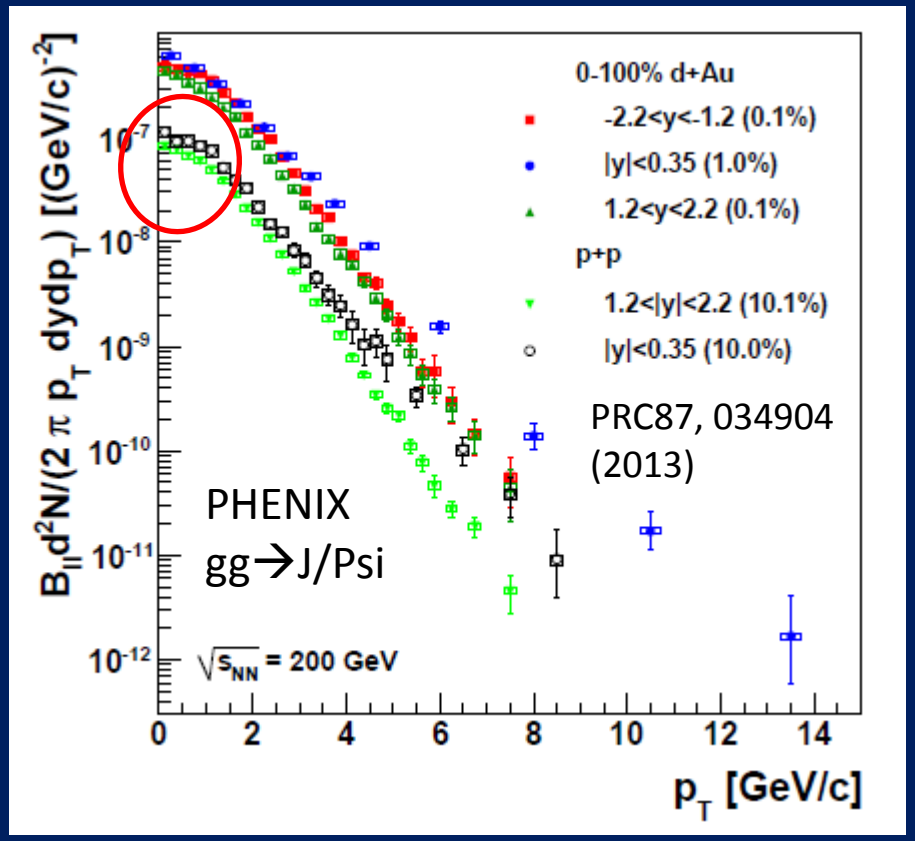
- Can access via transverse-momentum-dependent Drell-Yan, Z, and W boson production
  - Isolate initial state, i.e. access pdfs without FFs
  - Transverse momentum of the final-state Drell-Yan lepton pair, Z, or W for small (nonperturbative) transverse momentum values due to initial-state k_T of the interacting quark and antiquark
    - Larger final-state transverse momenta generated perturbatively via gluon radiation

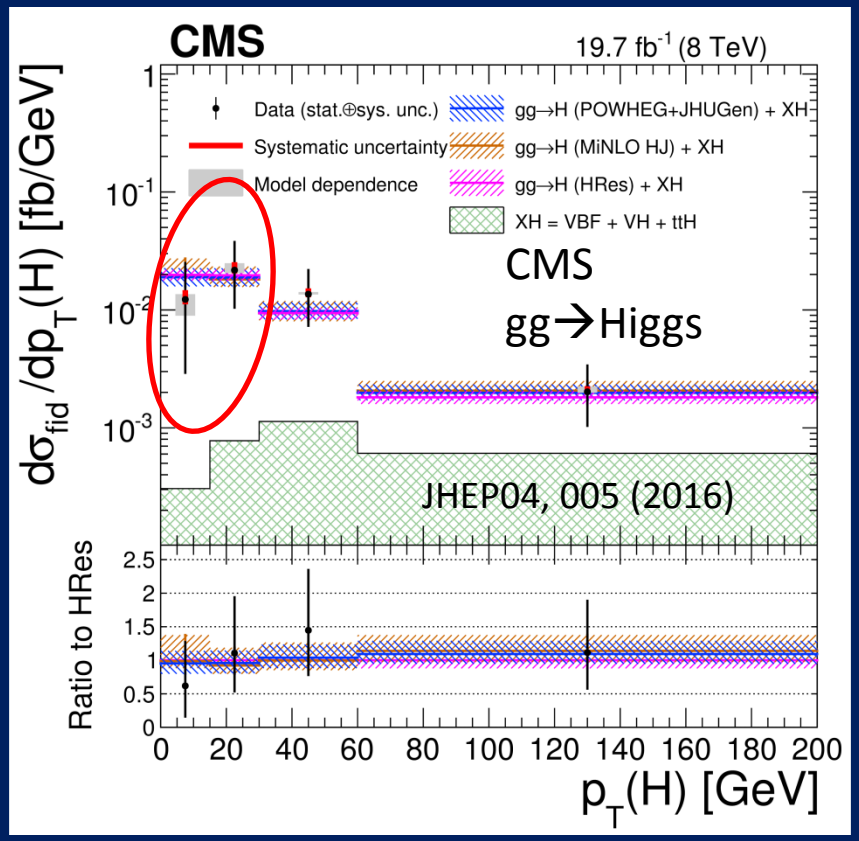
Unpolarized quark TMD pdfs

- p_T of Z in this region due to k_T vectors of annihilating quark and antiquark
- Perturbatively generated tail out to 350 GeV



Unpolarized gluon TMD pdfs

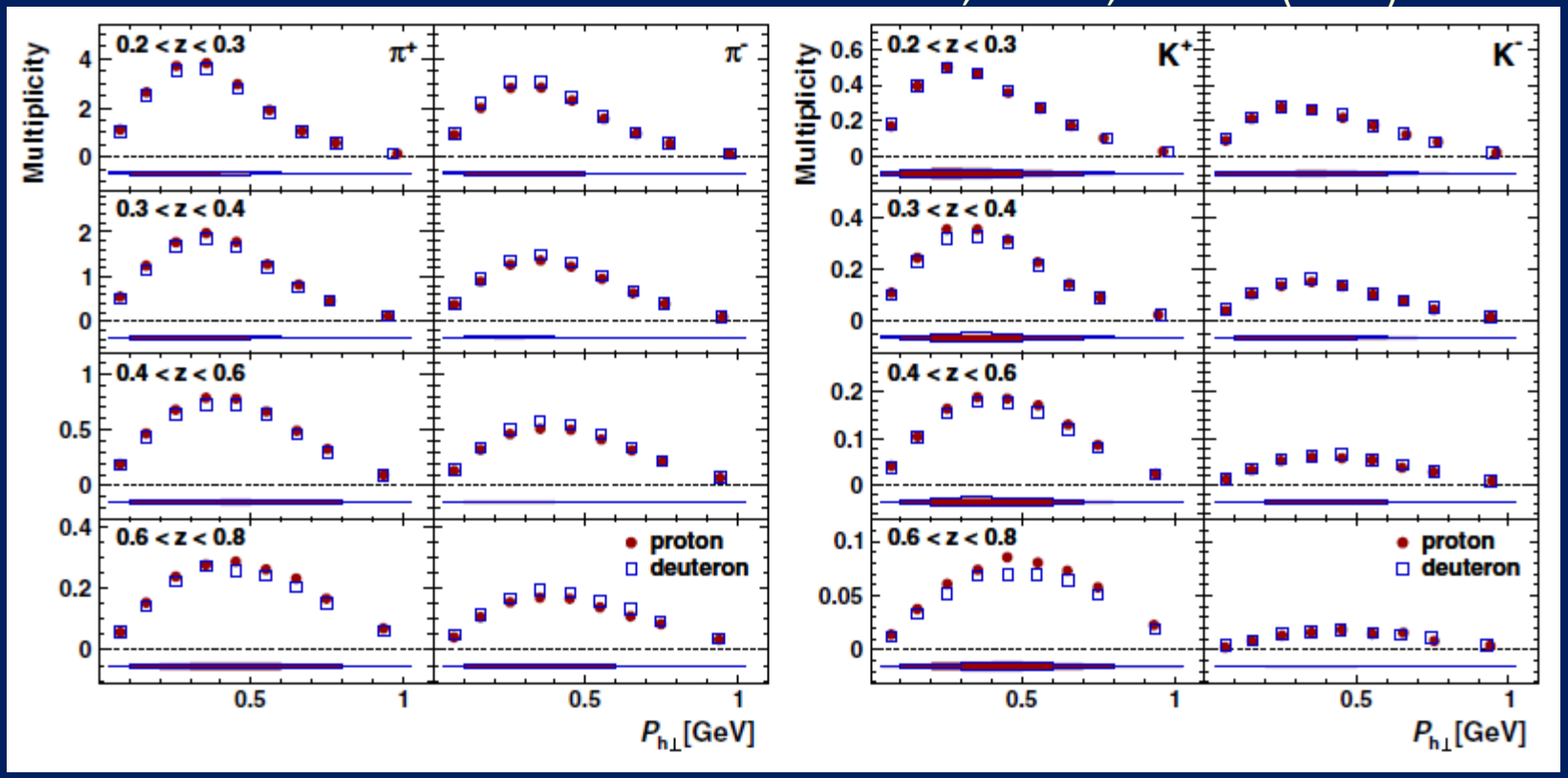




- Need more data, but same idea as for Drell-Yan and Z boson production
- k_T vectors of fusing gluons lead to nonperturbative p_T of J/Psi or Higgs; then long perturbative tail

Unpolarized TMD FFs: Semi-inclusive DIS TMD multiplicities

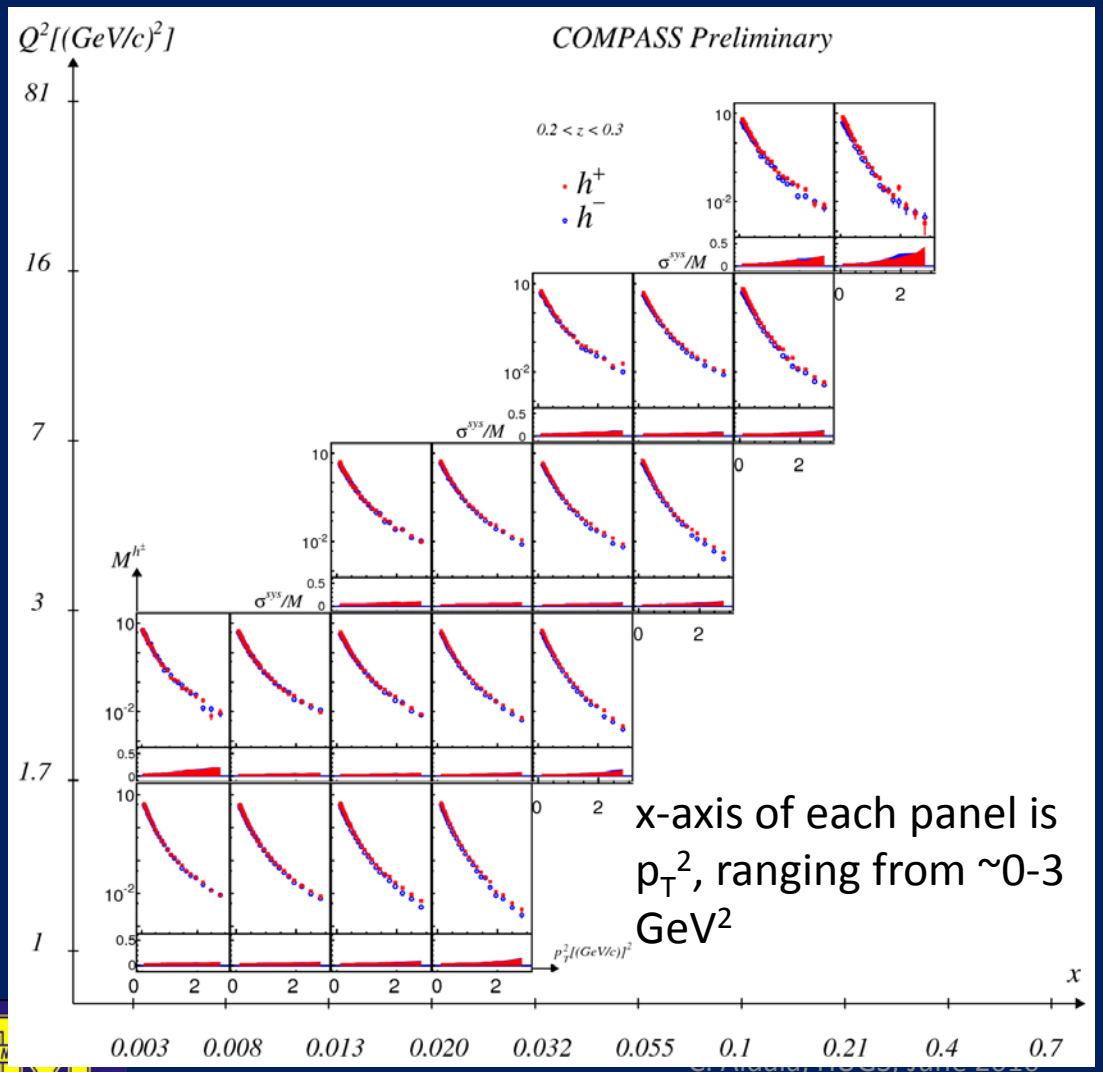
HERMES, PRD87, 074029 (2013)



π+-, K+-, multidifferential in p_T, z

Convolution of TMD pdfs and FFs

Unpolarized TMD FFs: Semi-inclusive DIS TMD multiplicities



x-axis of each panel is p_T^2, ranging from ~0-3 GeV^2

Positive and negative hadron production, multidifferential in x, Q^2, p_T^2

Recent availability of multidifferential measurements should greatly improve constraints on TMD functions

Awaiting unpolarized TMD measurements from e+e- . . .

High-energy QCD: Thinking in terms of individual partons

- Pdfs are *single-parton* functions in *single* nucleons
  - Or in nuclei, but typically still think of partons in individual nucleons within nucleus

- Can we go beyond this single-parton picture while staying in the hard (short-distance) limit of perturbative QCD?

An alternative approach to describing the large single-spin asymmetries: Higher-twist multiparton correlations

- Extend our ideas about (single-parton) pdfs to correlation functions that can't be associated with a single parton
- Non-perturbative structure → matrix elements involving the quantum mechanical *interference* between scattering off of a (quark+gluon) and scattering off of a single quark (of the same flavor and at the same x)
  - Can also have interference between (gluon+gluon) and single gluon
  - No explicit dependence on partonic transverse momentum
  - Efremov+Teryaev 1981, 84; Qiu+Sterman 1991, 98

Beware: Two common usages of the term "twist"

- Formal definition of twist: "mass dimension minus spin" of the operator in a matrix element within the Operator Product Expansion
  - "Leading twist" is twist-2
  - Twist-n *matrix element* carries a factor of $1/Q^{(n-2)}$

- But – *observables* with measurable contributions from terms suppressed by a factor of $1/Q^{(n-2)}$ often referred to as sensitive to "twist-n" contributions
  - Never measure a matrix element, only matrix elements squared!
  - To get 1/Q term describing an *observable*, need interference term in the square modulus:
    - A = order 1 + order 1/Q + order $1/Q^2$ + …
    - $|A|^2$ = $|\text{order } 1|^2$ + $|\text{order } 1/Q|^2$ + (order 1)(order 1/Q)* + (order 1)*(order 1/Q) + …
  - So twist-3 term in matrix element times *twist-2* term gives 1/Q
  - Square modulus of *twist-3* term gives $1/Q^2$, sometimes referred to as "twist-4"

Transverse single-spin asymmetries provide <u>new</u> information on hadron structure

- <u>Leading</u> contribution to transverse single-spin asymmetries comes from *either*:
  - Convolution of two twist-2 *transverse-momentum-dependent* parton distribution functions and/or fragmentation functions, or . . .
  - Convolution of one twist-2 collinear pdf or fragmentation function and one twist-3 (collinear) *multiparton correlation* matrix element

Multiparton correlations in hadronization

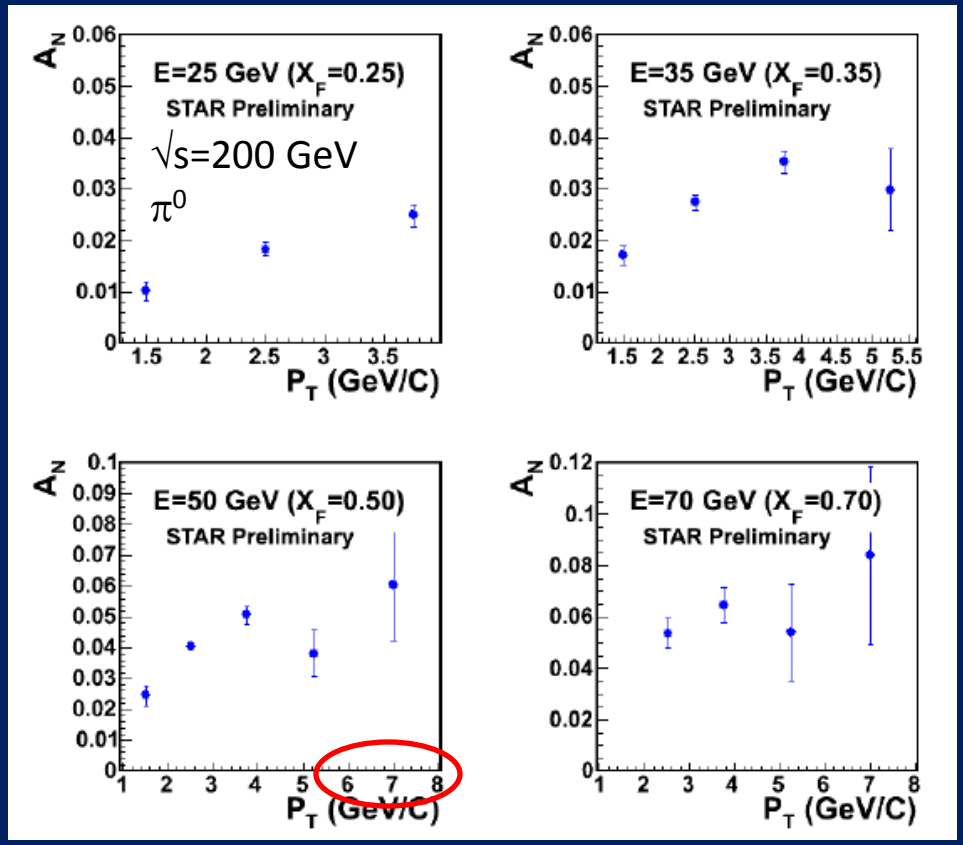
- Traditional fragmentation functions describe probability of single parton to hadronize into particular hadron, as function of momentum fraction (z) of parton carried by the final hadron
- Can have matrix elements describing *multiparton correlations in hadronization*
  - Interference between a (quark+gluon) hadronizing and only a quark
  - Similarly, interference between (gluon+gluon) and only a single gluon
  - Kanazawa+Koike, 1991

Transverse-momentum-dependent functions and twist-3 multiparton correlators

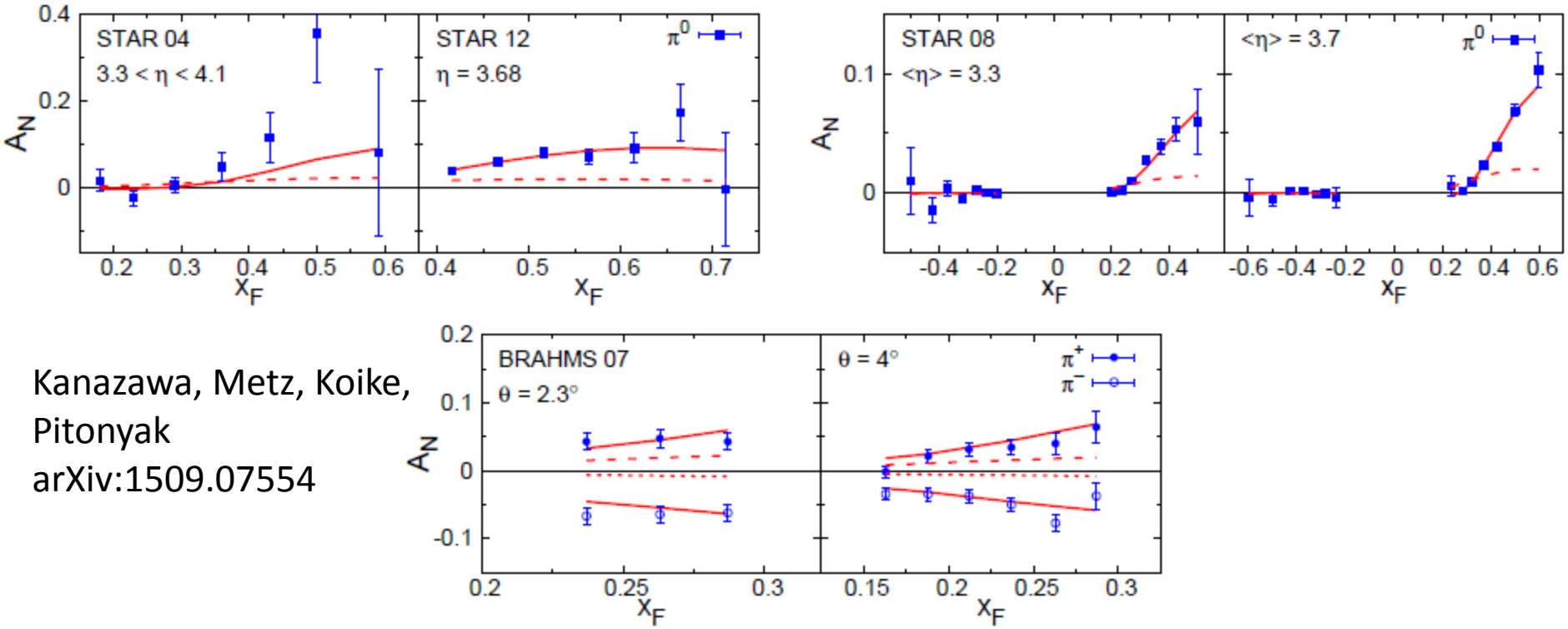
- Twist-3 (collinear) multiparton correlators believed to be related to k_T-moments of (twist-2)TMD pdfs and fragmentation functions
  - NPB667, 201 (2003); PRL97, 082002 (2006)
- To directly constrain TMD functions with experimental data, need *two* scales
  - Hard momentum
  - Observable sensitive to parton intrinsic momentum
  - Recall: Original p+p→pion+X asymmetries only measured a single scale

Transverse single-spin asymmetry in p+p → hadron + X: Only measure one momentum scale

- For high enough p_T of produced hadron (>1-2 GeV) have hard scale, so can apply perturbative calculations
  - Clear nonzero asymmetries out to 8 GeV → $Q^2 \sim 64$ GeV^2
- Can have contributions from initial-state and final-state effects
- Inclusive measurement—don't measure the combination of a hard plus a nonperturbative momentum scale required to (directly) apply TMD framework in pQCD calculations



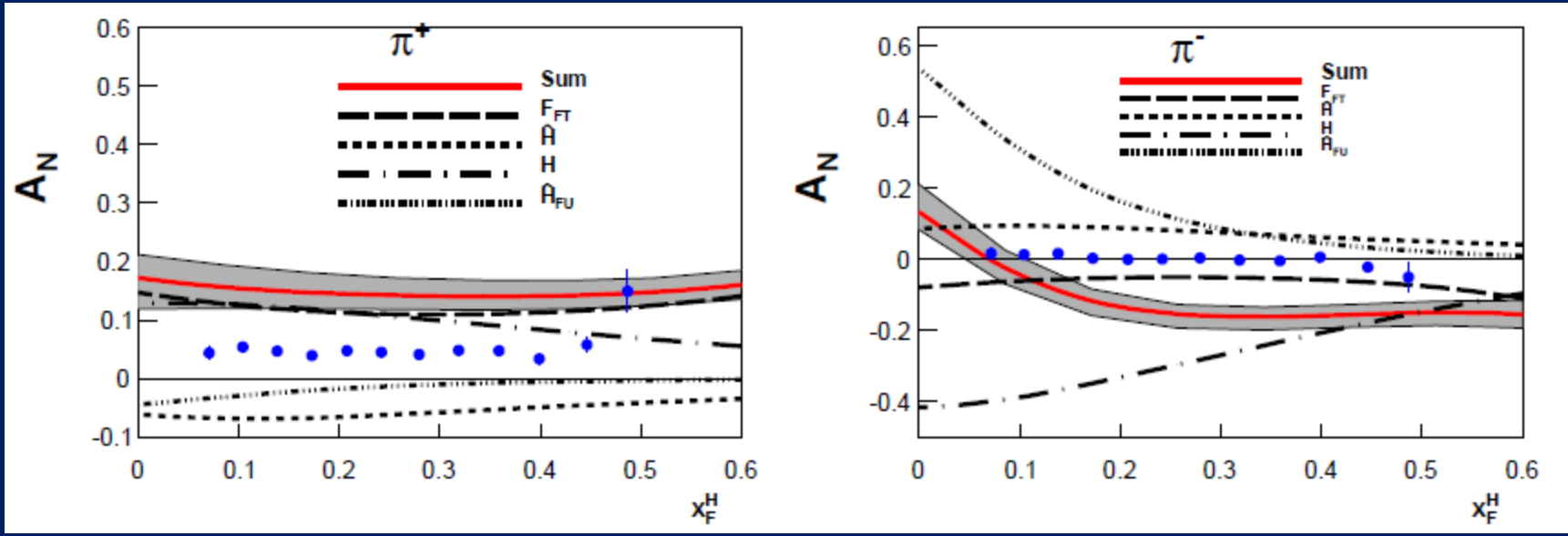
Twist-3 multiparton correlations to try to interpret inclusive A_N data from RHIC



Kanazawa, Metz, Koike, Pitonyak
arXiv:1509.07554

Find dominant contribution from twist-3 correlation in hadronization

Twist-3 correlations to interpret ***inclusive*** *hadron* A_N *in* $e+p$



Gamberg et al., PRD90, 074012 (2014)
Data from HERMES

Twist-3 phenomenology still in early stages!

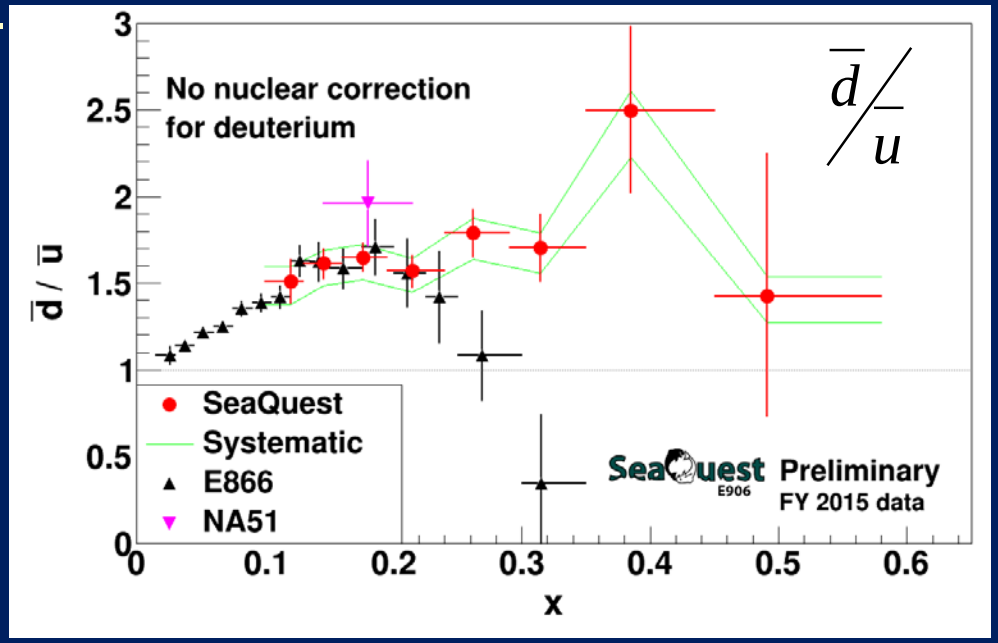
Sea quarks and sea quark dynamics

- Proton-hydrogen and proton-deuterium collisions

$$\frac{\sigma^{pd}(x_t)}{2\sigma_{pp}(x_t)} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x)}{\bar{u}(x)}\right]^{*}$$

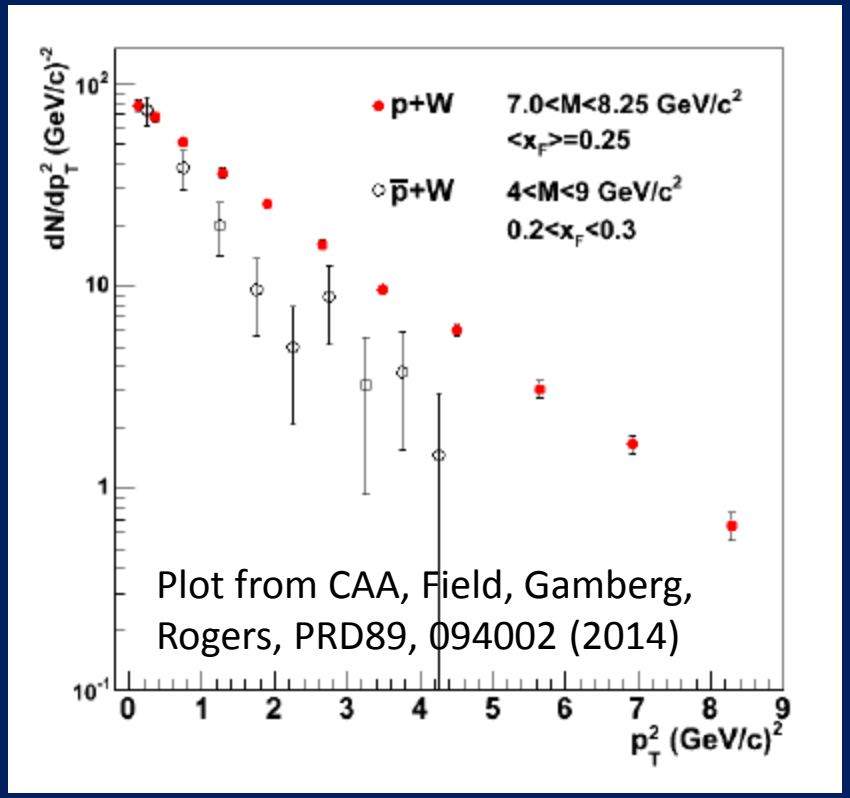
*simplest leading-order expression

- Expect anti-down/anti-up ratio of 1 if sea quarks only generated by gluon splitting
- Indicates additional mechanism to generate sea quarks—still not well understood
  - Recent review: Chang and Peng, Prog. Part. Nucl. Phys. 79, 95 (2014)



Fermilab E866 data: PRD64, 052002 (2001)
CERN NA51 data: PLB332, 244 (1994)

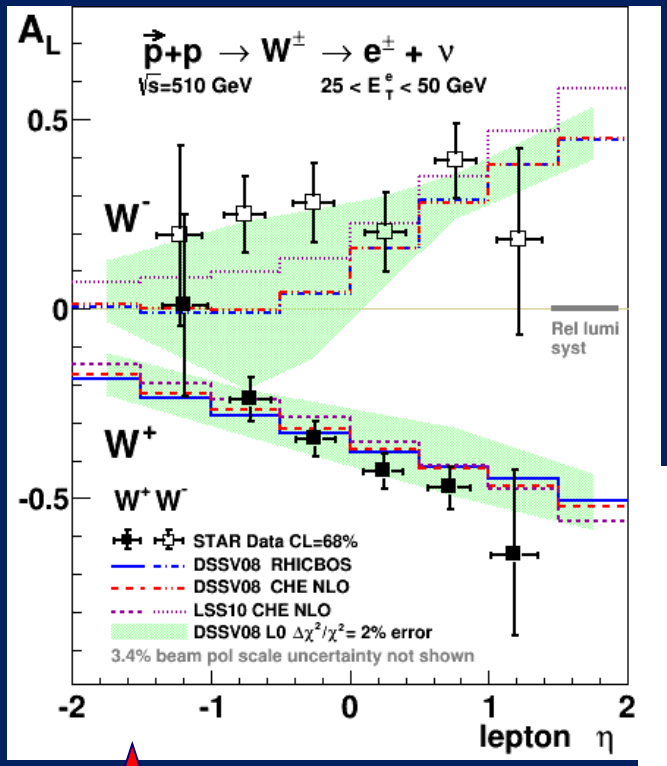
Sea quarks—other hints of interesting behavior



Data from E537 (pbar+W): PRD38, 1377 (1988)
E439: (p+W): AIP Conf. Proc. 45, 93 (1978)

- p+W: (Valence) quark from p, (sea) antiquark from W
- pbar+W: (Valence) quark from W, (valence) antiquark from pbar
- (Valence × sea) spectrum harder → Larger mean k_T for sea than valence quarks?
  - Agrees with chiral soliton model predictions (e.g. Schweitzer, Strikman, Weiss 2013)
  - Consistent with work by Bacchetta et al.

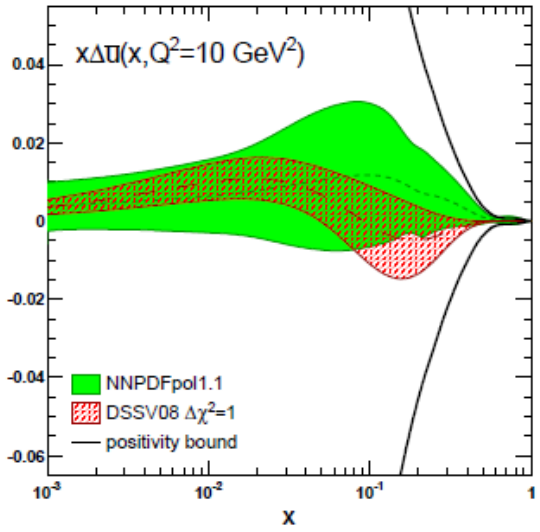
Flavor asymmetry in the sea helicity distributions

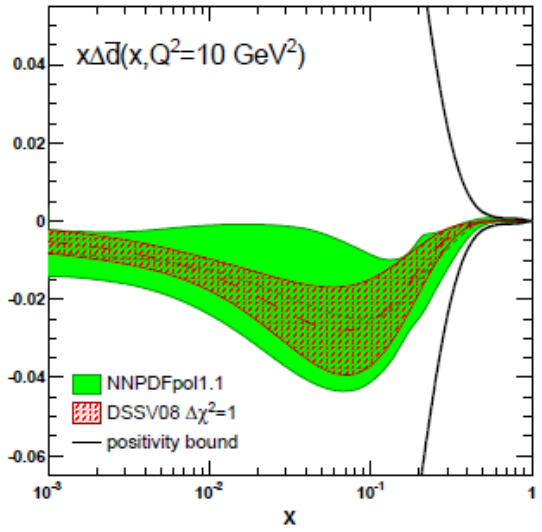


STAR, PRL 113, 72301 (2014)

(DSSV08 before RHIC W data)

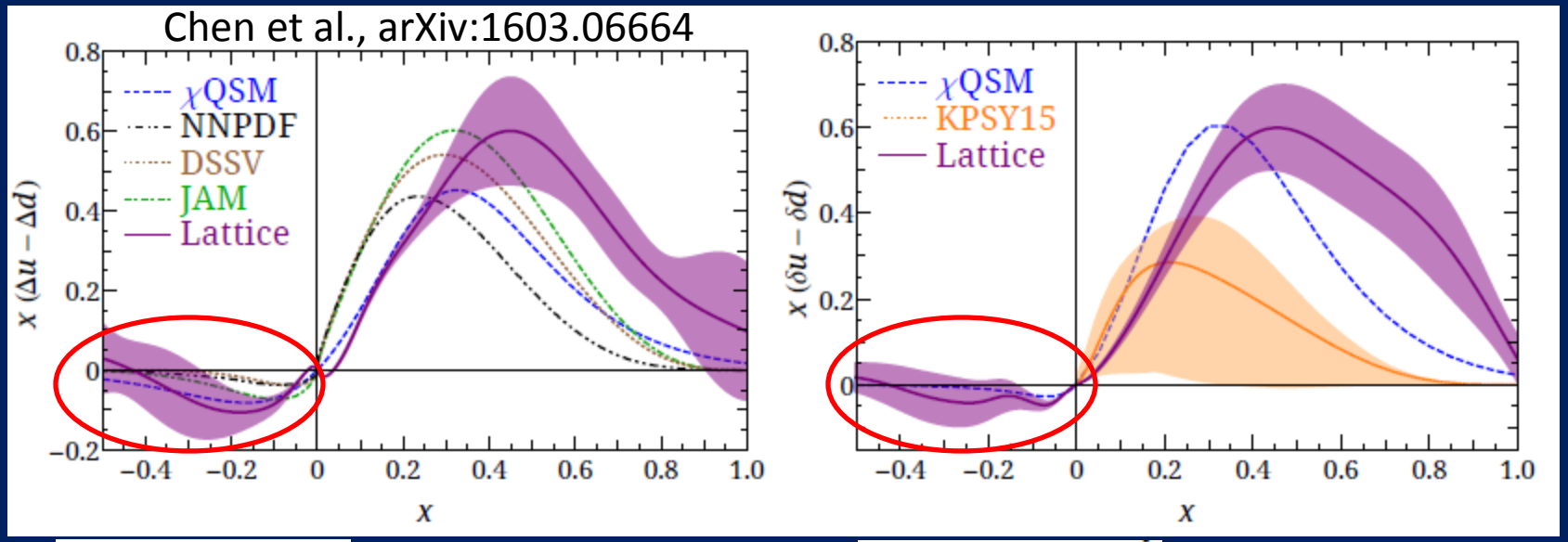
NNPDF, NPB 887.276 (2014)





Helicity and transversity distributions for sea quarks from lattice(!)

Chen et al., arXiv:1603.06664

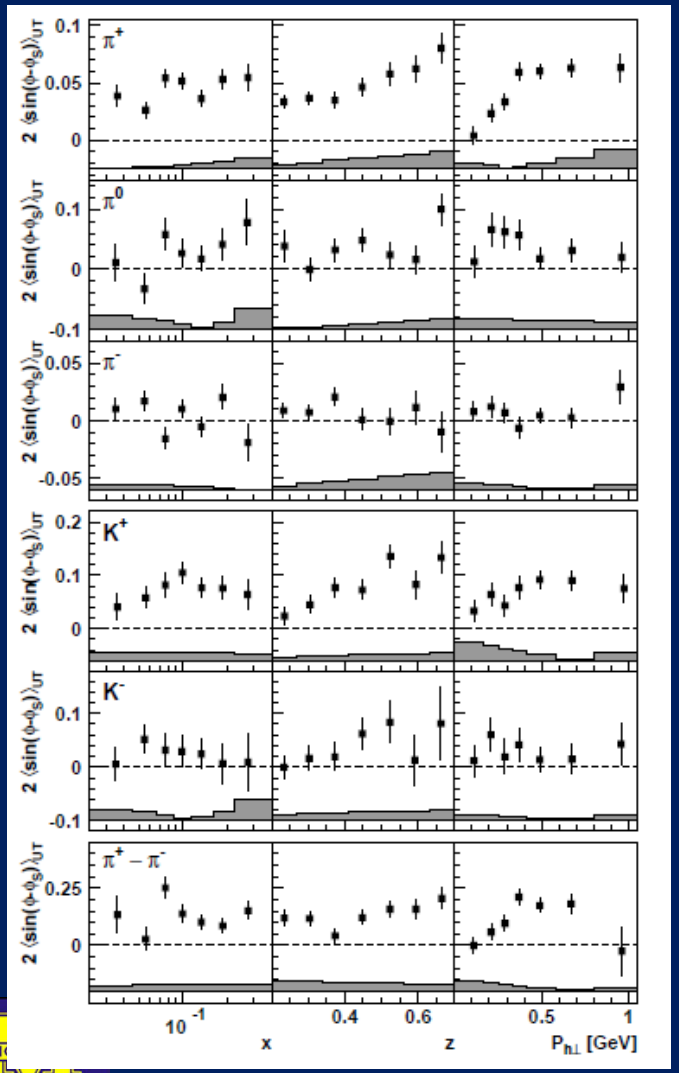


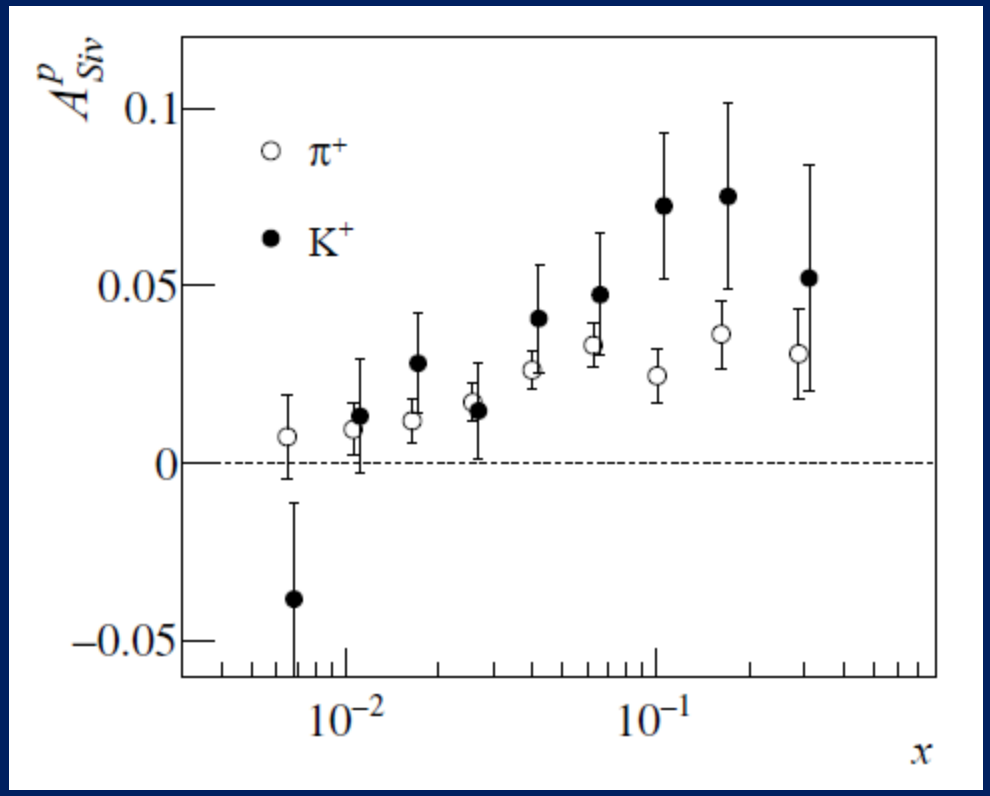
$\Delta\overline{q}(x) = \Delta q(-x)$

$\delta\overline{q}(x) = -\delta q(-x)$

- Lattice calculations of x-dependent pdfs, rather than moments, just starting to be published!
- Lattice confirms experimental evidence for flavor asymmetry in sea helicity distributions
- Lattice calculation finds transversity for sea nonzero and flavor-asymmetric . . .
- x-dependent unpolarized sea distributions: PRD91, 054510 (2015)

SIDIS Sivers asymmetries larger for K^+ than π^+

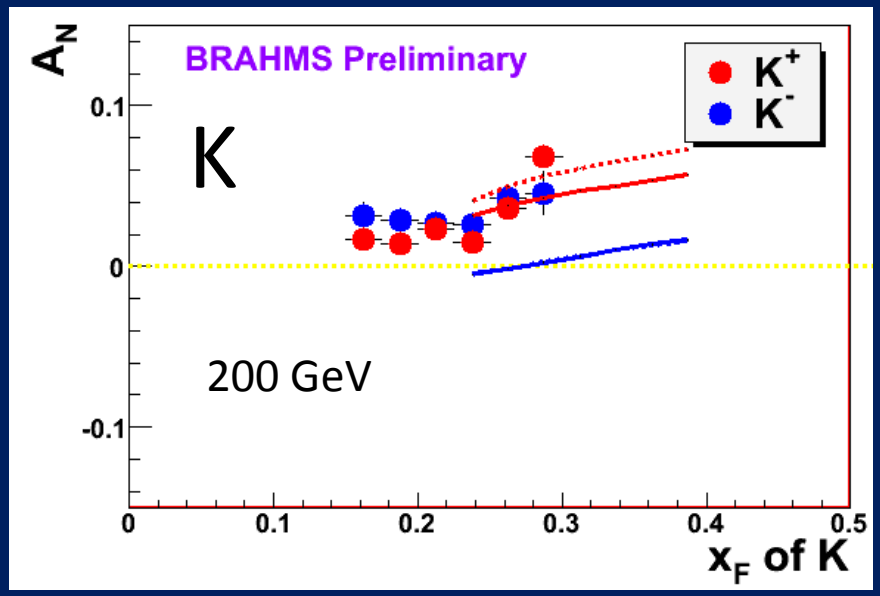


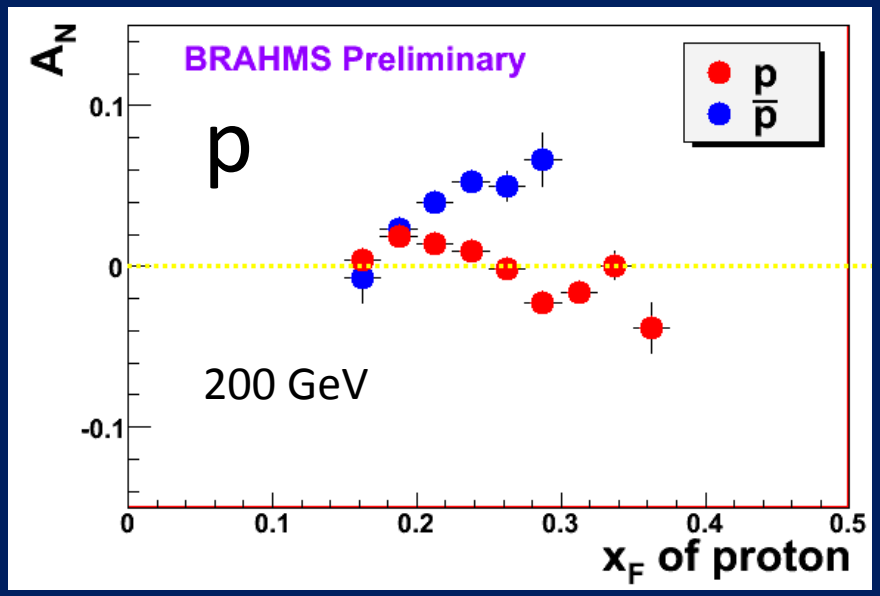


COMPASS, PLB744, 250 (2015)

HERMES, PRL103, 152002 (2009)

Large K^- and antiproton(!) transverse single-spin asymmetries in p+p

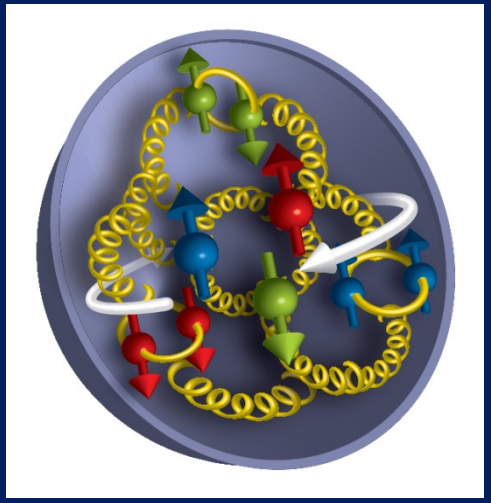




BRAHMS

Need more data for sea quarks!

- And with more measurements to provide meaningful constraints, will need consistent treatment of sea quarks in theory/phenomenology



- Understanding the *dynamics* of sea quarks, which probe beyond static pictures of antiquarks in the nucleon, will be crucial to understanding how the nucleon sea is generated (and what in fact it is!)

Summary: Lecture 2

- Have experimental evidence from SIDIS, Drell-Yan, e+e-, and p+p that numerous spin-momentum correlations described by TMD pdfs and FFs are nonzero in nature
  - Others remain to be measured
  - Important probes of parton dynamics, along with unpolarized TMD measurements
- Collinear twist-3 multiparton correlation functions can also generate single-spin asymmetries
  - Can be related to moments of TMD functions
  - Go beyond traditional thinking in terms of single-parton scattering or hadronization
- Increasing interest in sea quarks—probing spin-spin and spin-momentum correlations for sea quarks will be important in understanding what's really going on in the sea

Extra

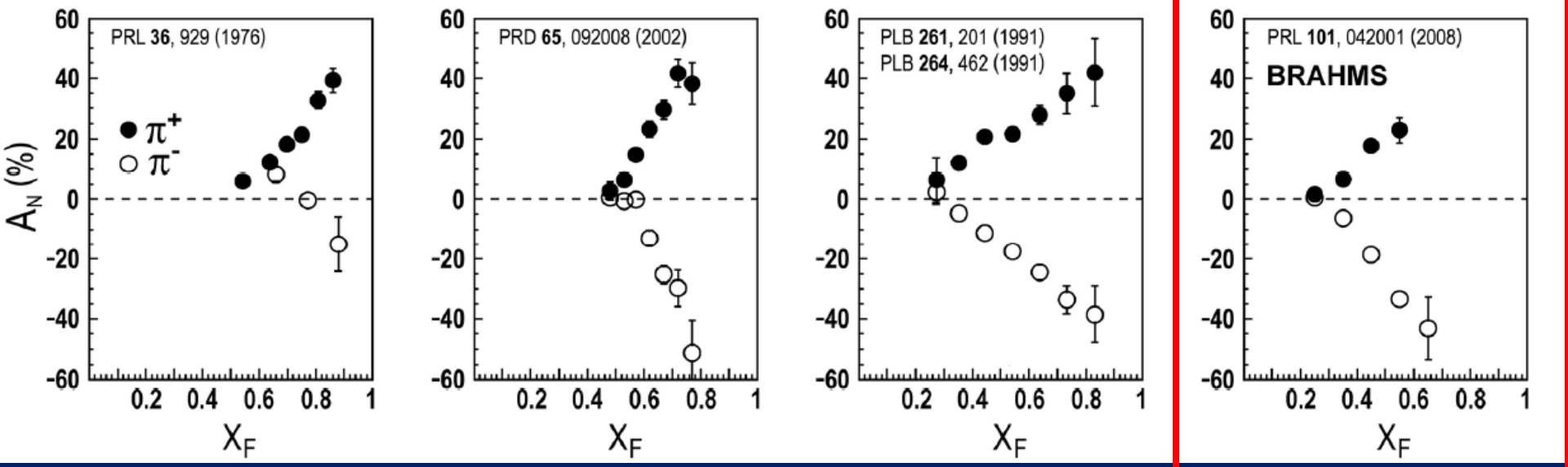
Transverse single-spin asymmetries: From low to high energies!

ANL
$\sqrt{s}$=4.9 GeV

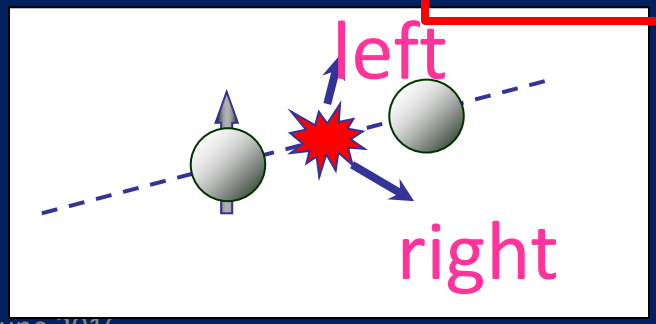
BNL
$\sqrt{s}$=6.6 GeV

FNAL
$\sqrt{s}$=19.4 GeV

RHIC
$\sqrt{s}$=62.4 GeV



$$x_F = 2p_{long}/\sqrt{s}$$



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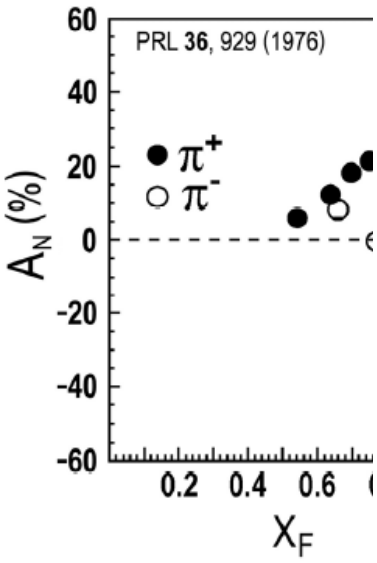
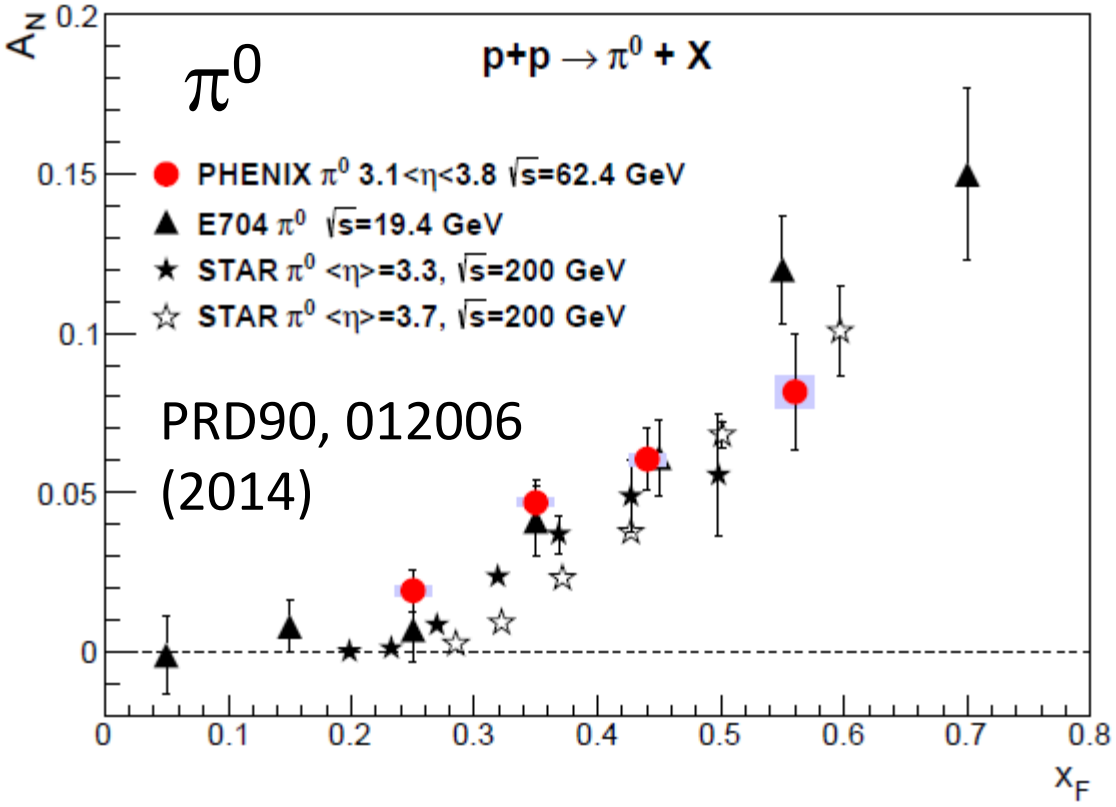
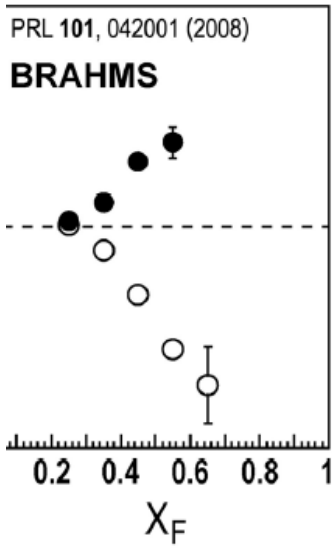


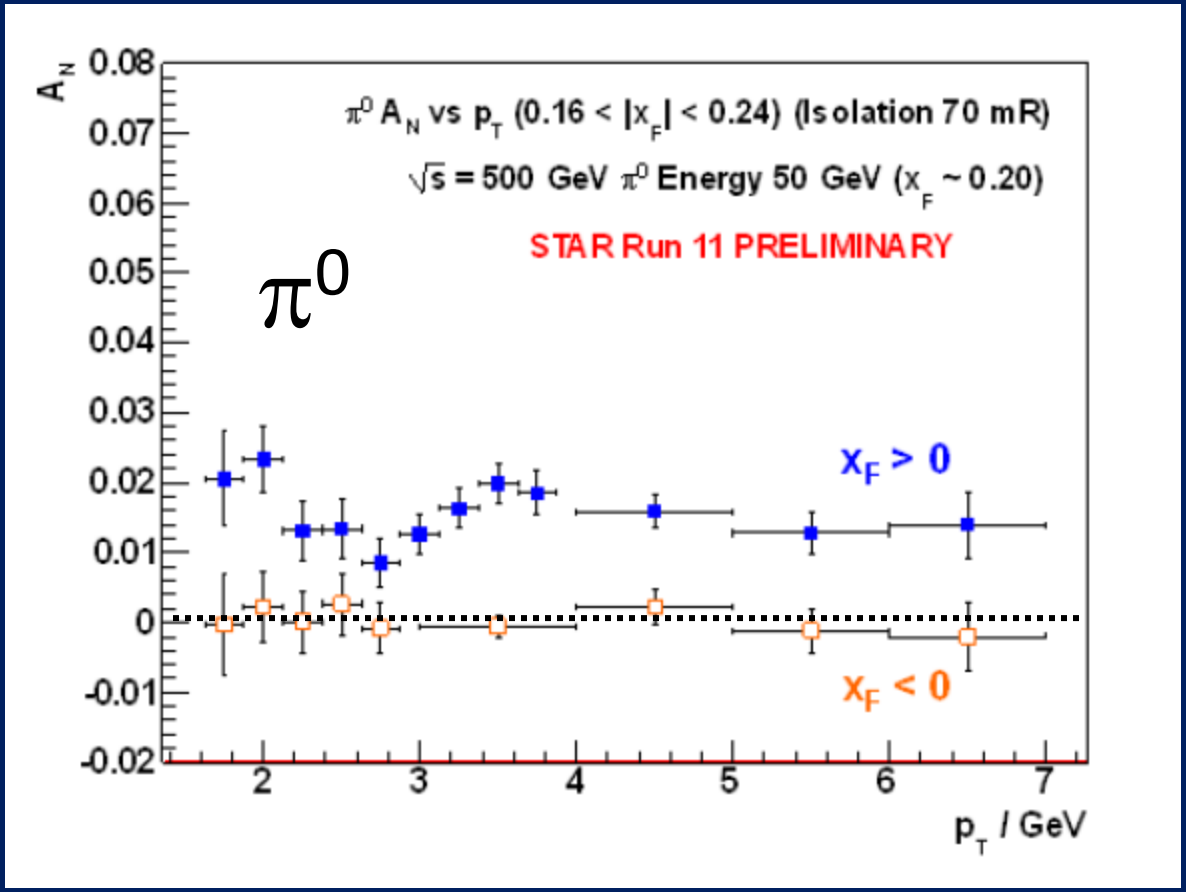




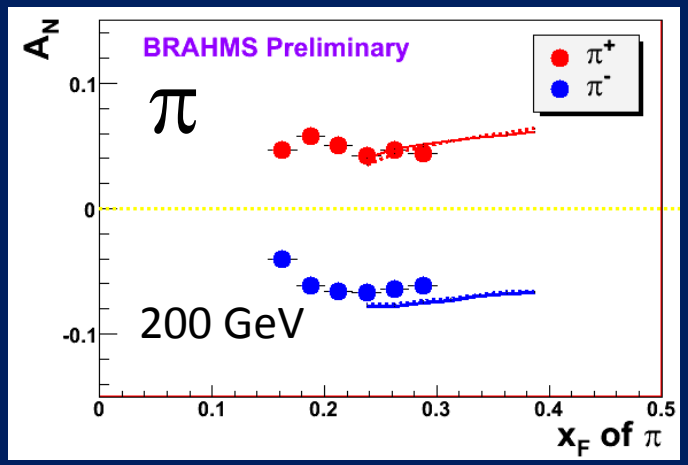
$$x_F =$$

right

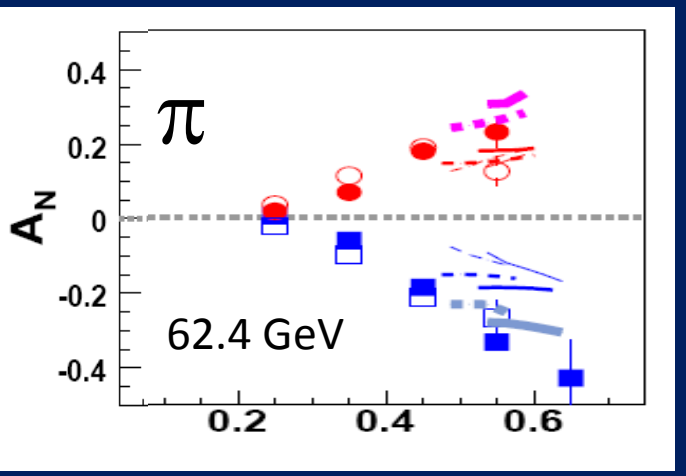
Effects persist up to transverse momenta of 7(!) GeV/c at √s=500 GeV



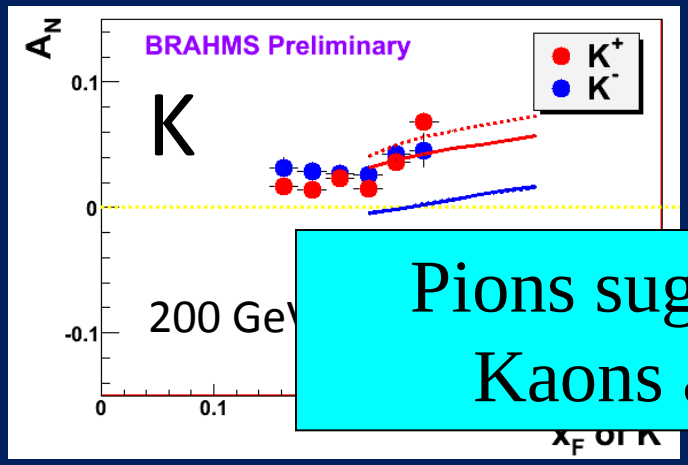
- Can try to interpret these non-perturbative effects within the framework of perturbative QCD.
- Haven't yet disentangled all the possible contributing effects to the (messy) process of p+p to pions



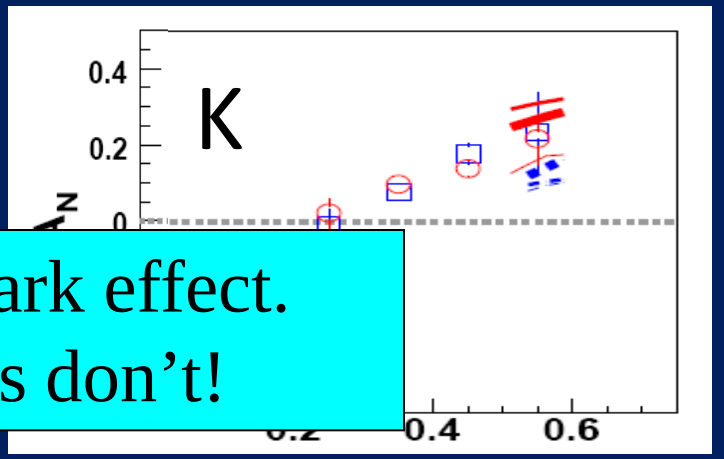
π, K, p at 200 and 62.4 GeV



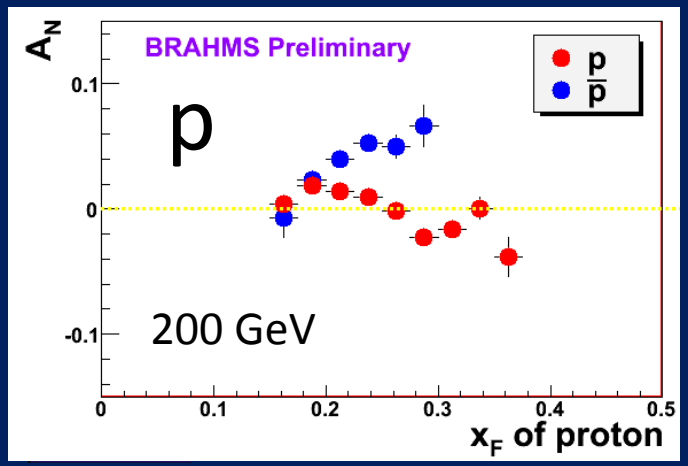
Note different scales



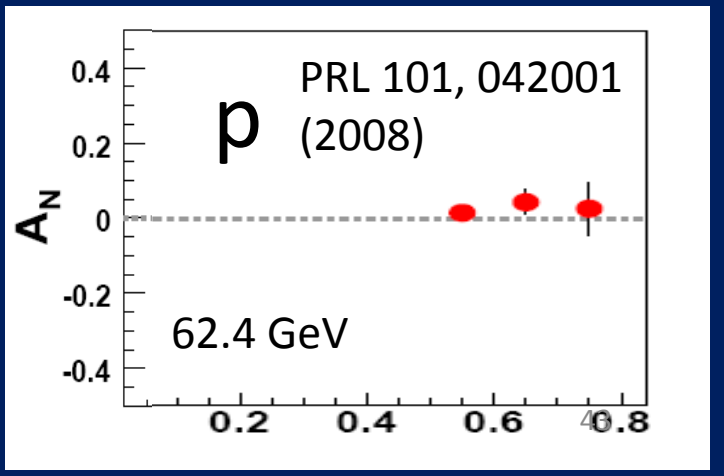
K- asymmetries underpredicted



Pions suggest valence quark effect.
Kaons and (anti)protons don't!

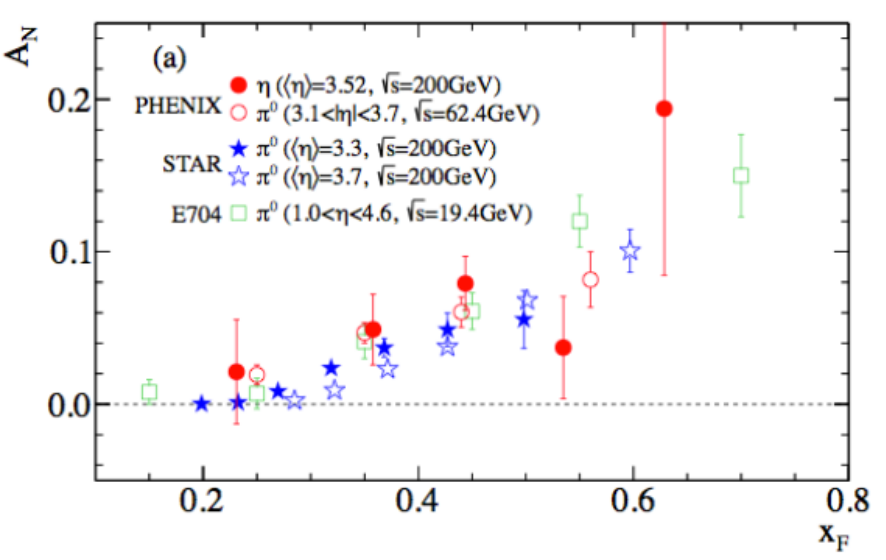


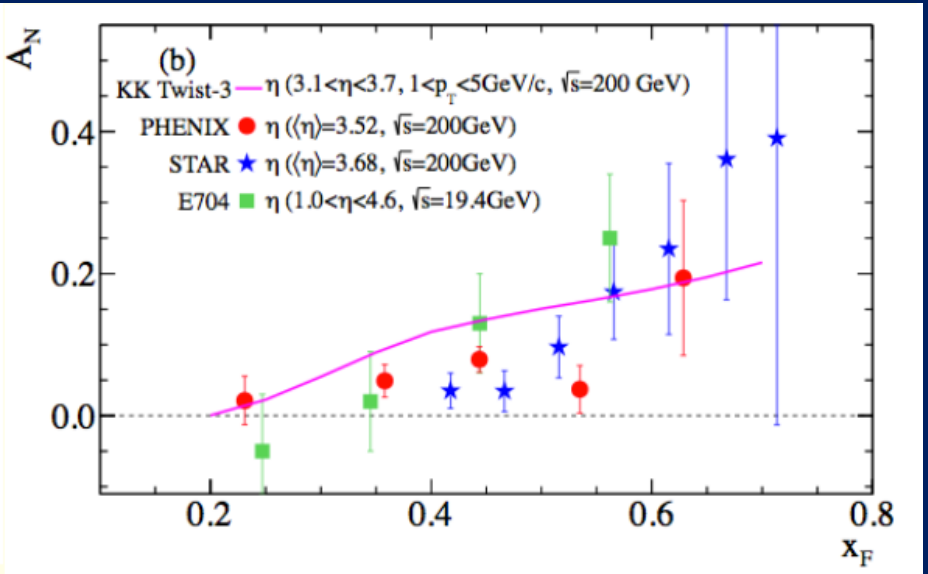
Large antiproton asymmetry??
Unfortunately no 62.4 GeV measurement



Transverse single-spin asymmetry in $p+p \rightarrow \eta+X$

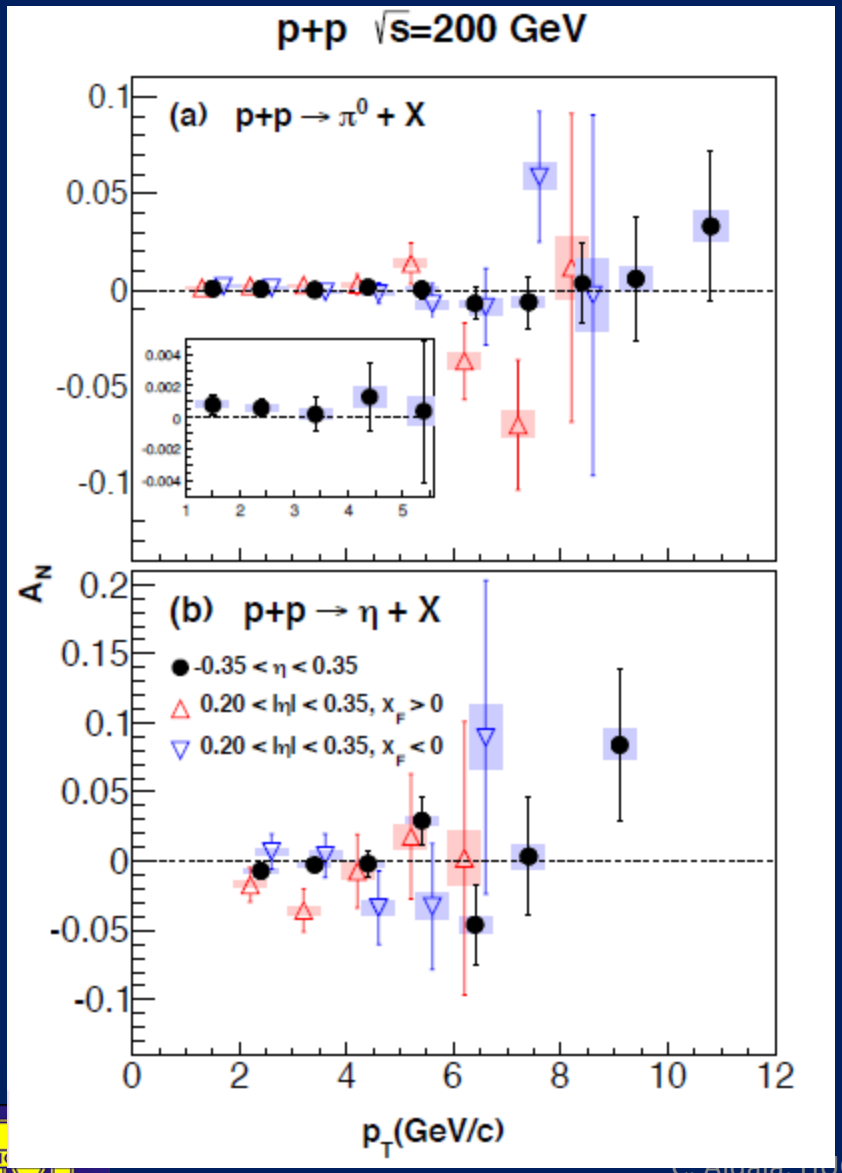
PRD90, 072008 (2014)



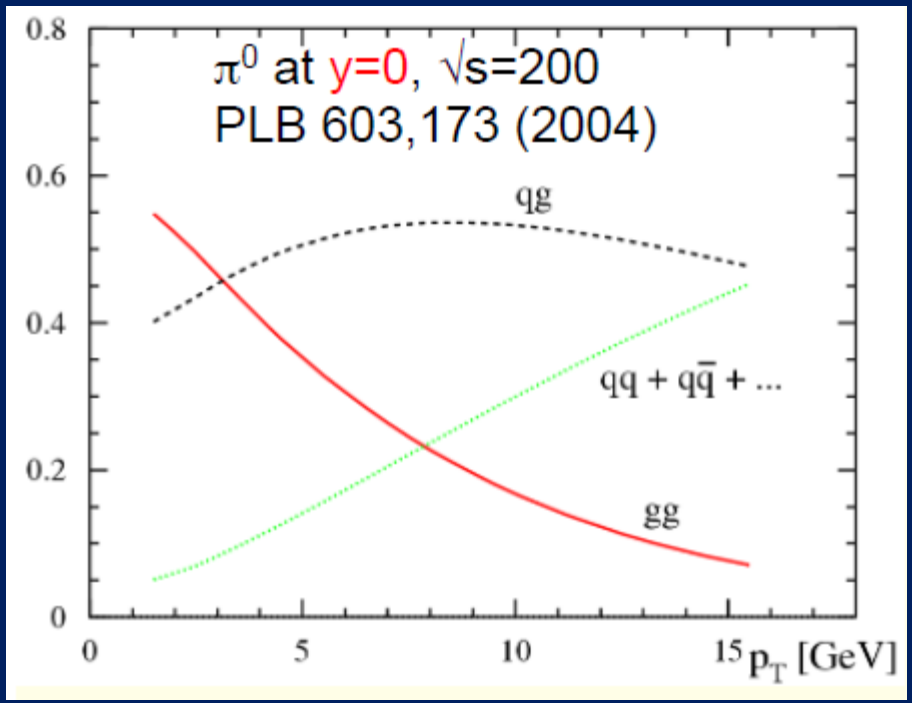


- Large η A_N observed by STAR and PHENIX (and Fermilab E704), similar in magnitude to π^0

η and π^0 A_N at midrapidity



PHENIX collaboration: PRD90, 012006 (2014)

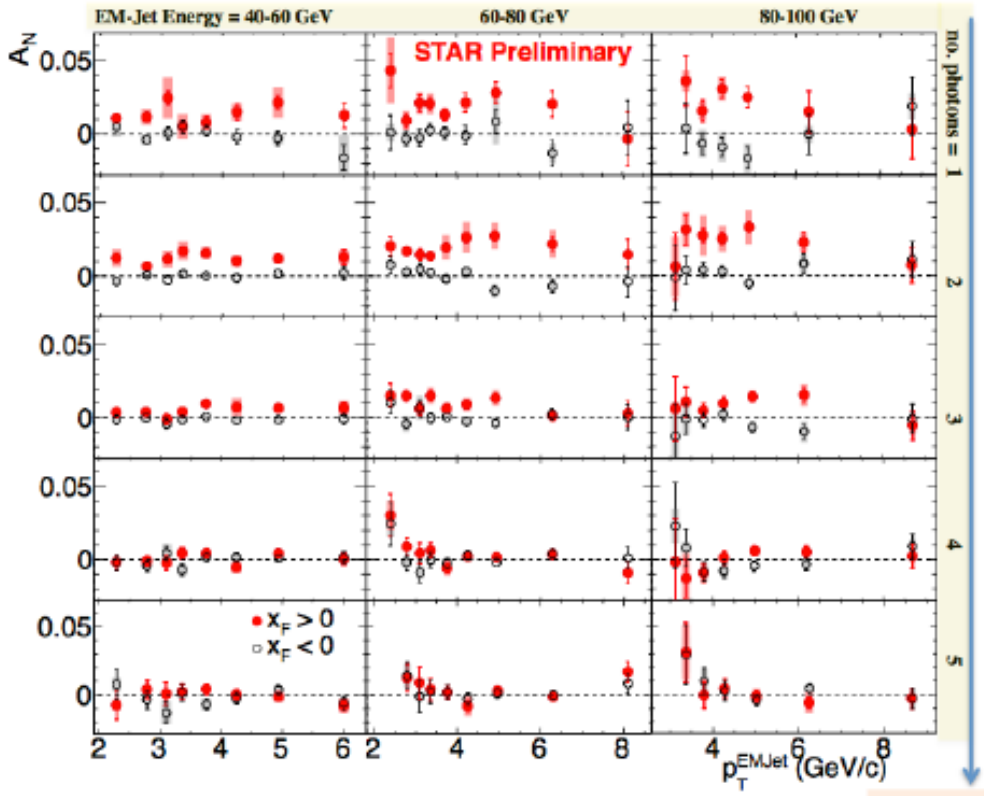


Sensitive to gg, qg scattering
Consistent with zero

Enhanced A_N for isolated forward neutral pions

Transverse Spin Phenomena - Large Forward A_N

The puzzle continues...



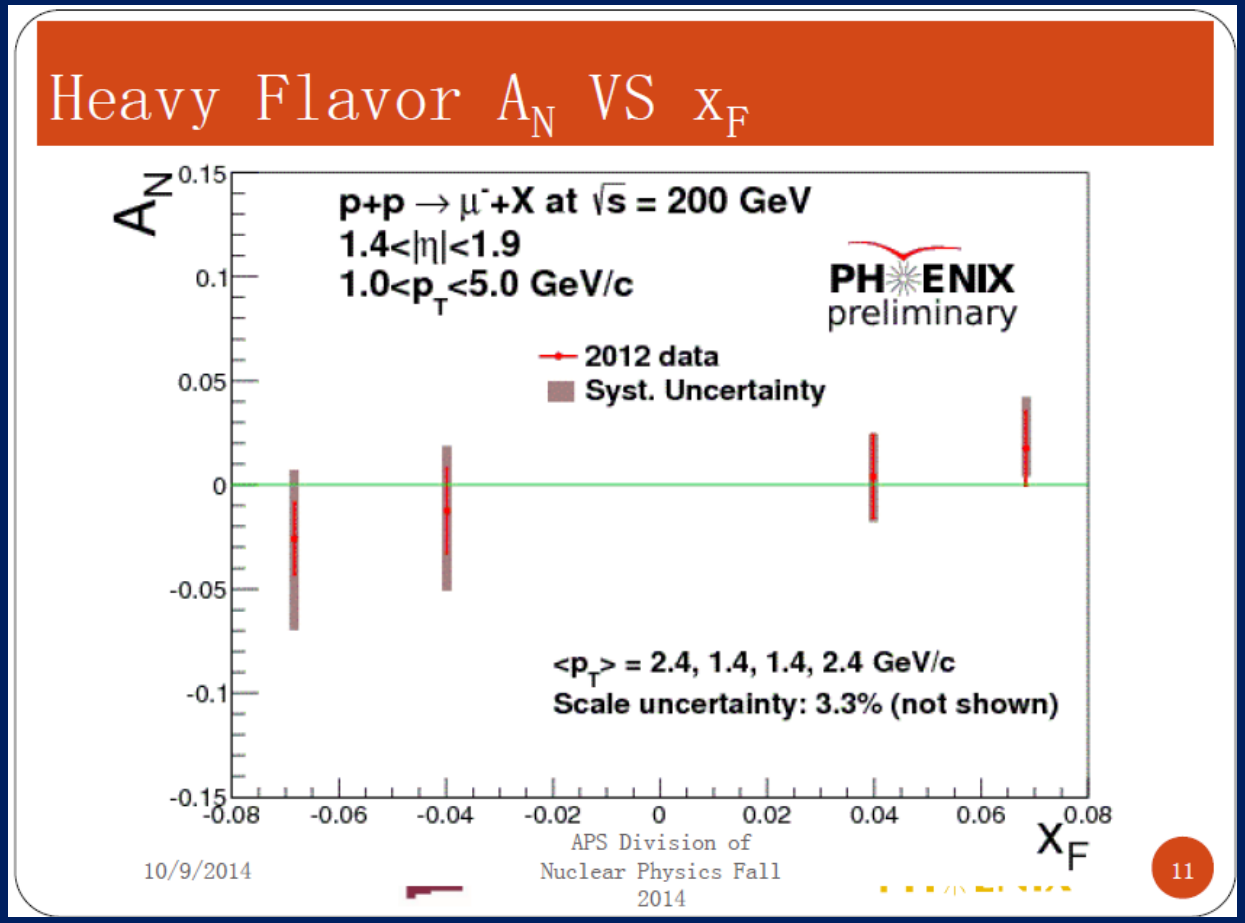
Jettier events

- 1-photon events, which include a large π^0 contribution in this analysis, are similar to 2-photon events
- Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π^0's
- A_N decreases as the event complexity increases (i.e., the "jettiness"
- A_N for #photons >5 is similar to that for #photons = 5

Mriganka Mondal, for the collaboration (DIS 2014)

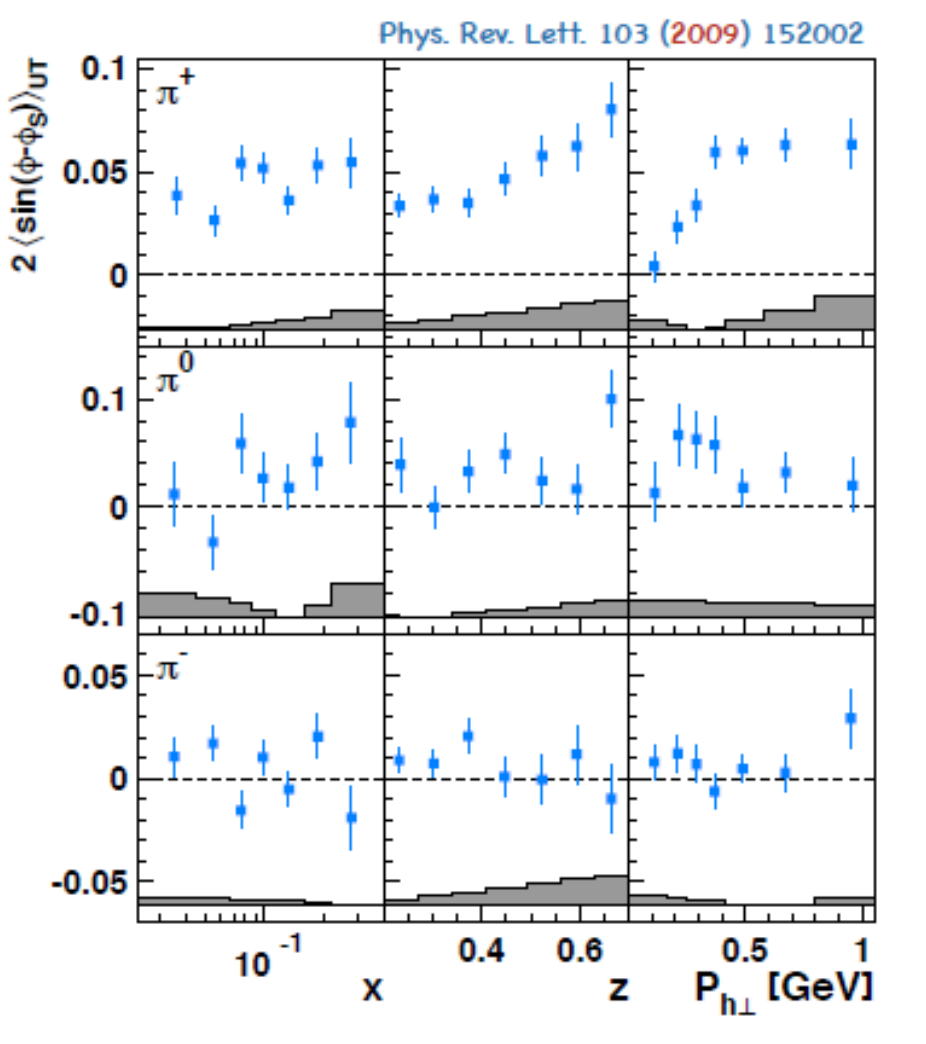
and points to a need for qualitatively new instrumentation and measurements

Open heavy flavor A_N to probe twist-3 trigluon correlations

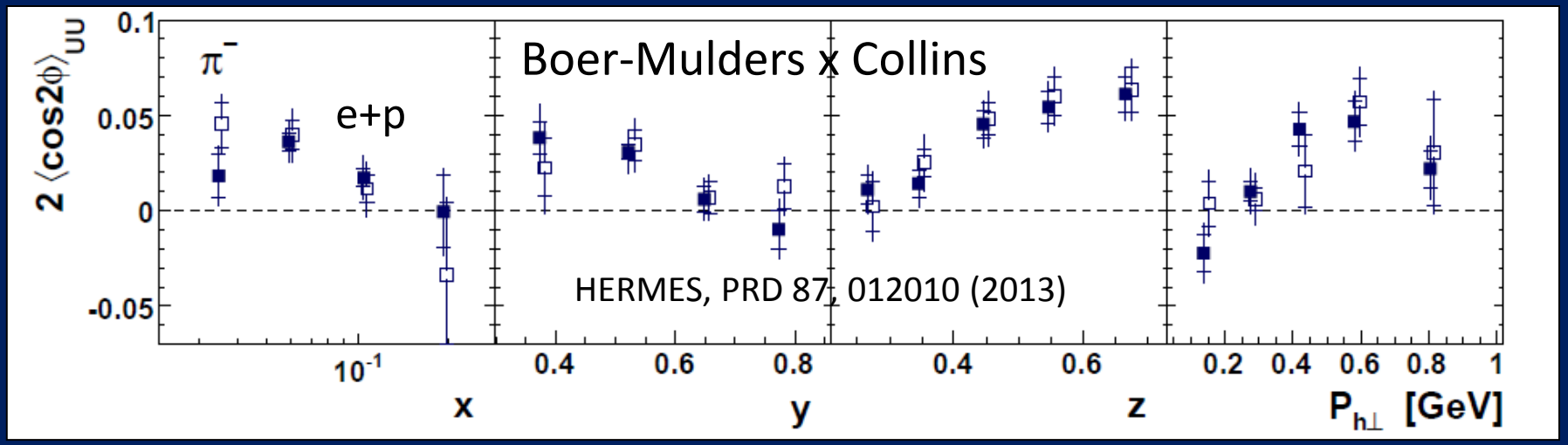


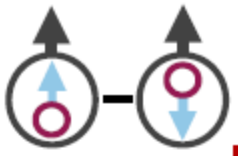
Expect measurement with ~0.01 accuracy from 2015 data, with displaced vertex heavy flavor tagging

HERMES Sivers for pions



Boer-Mulders ×Collins asymmetry from SIDIS

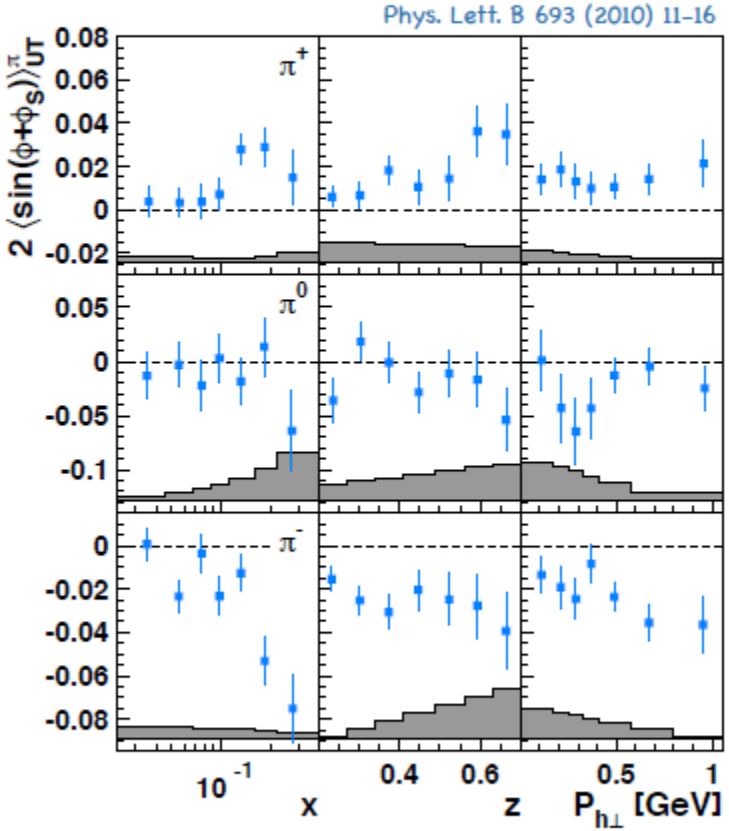


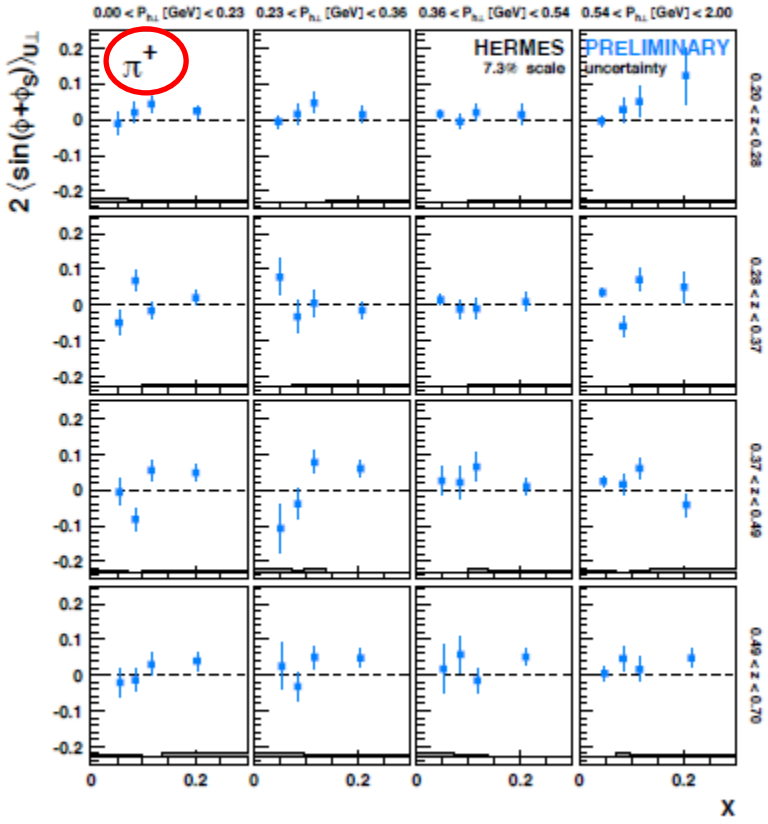


pions

Collins amplitudes

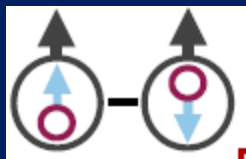
$\propto h_{1T}^{q} \otimes H_1^{\perp,q}$





- π^+ amplitudes positive; π^- amplitudes negative
- π^- amplitudes increasing with x

From C. van Hulse, DIS 2016



pions

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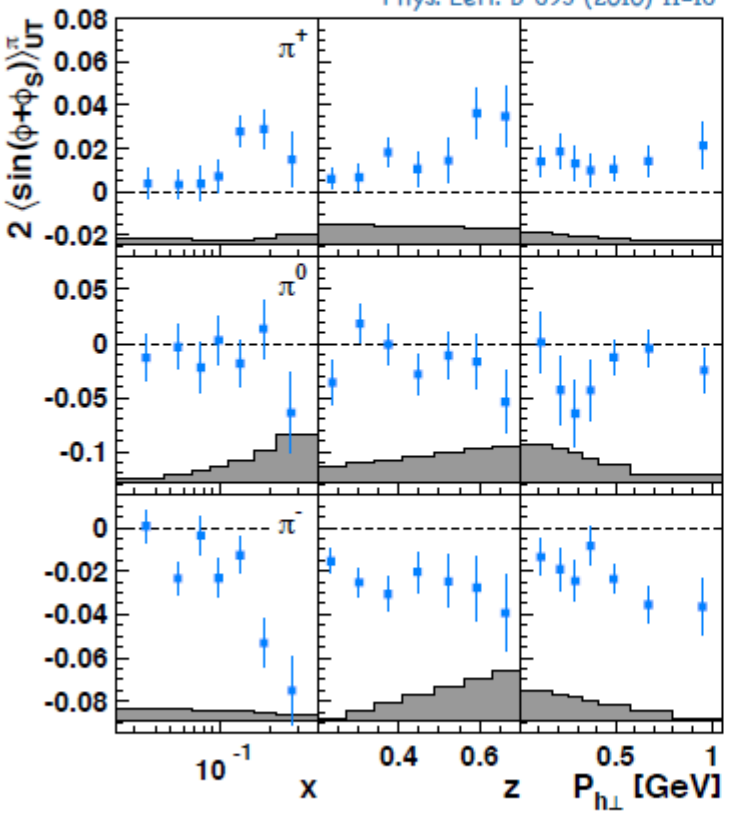
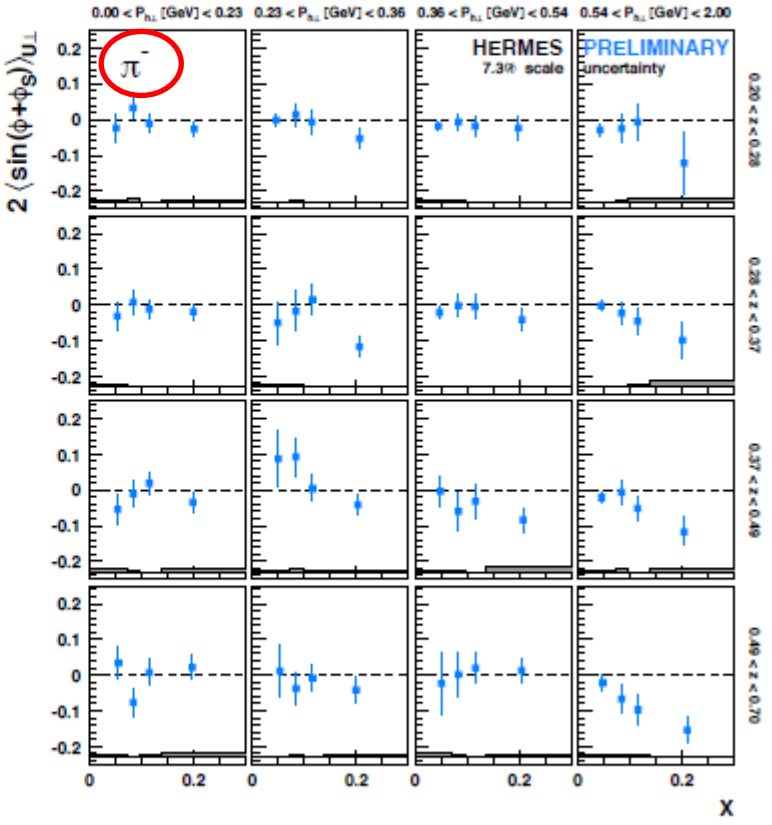
Phys. Lett. B 693 (2010) 11-16

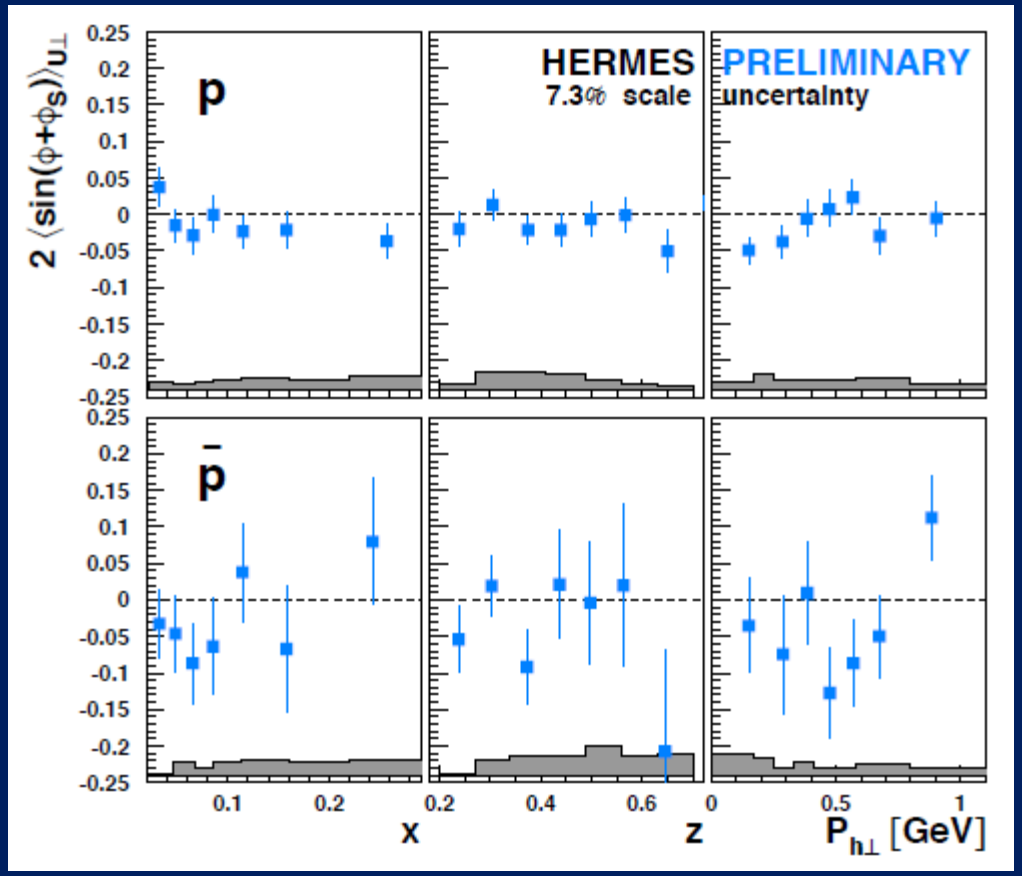




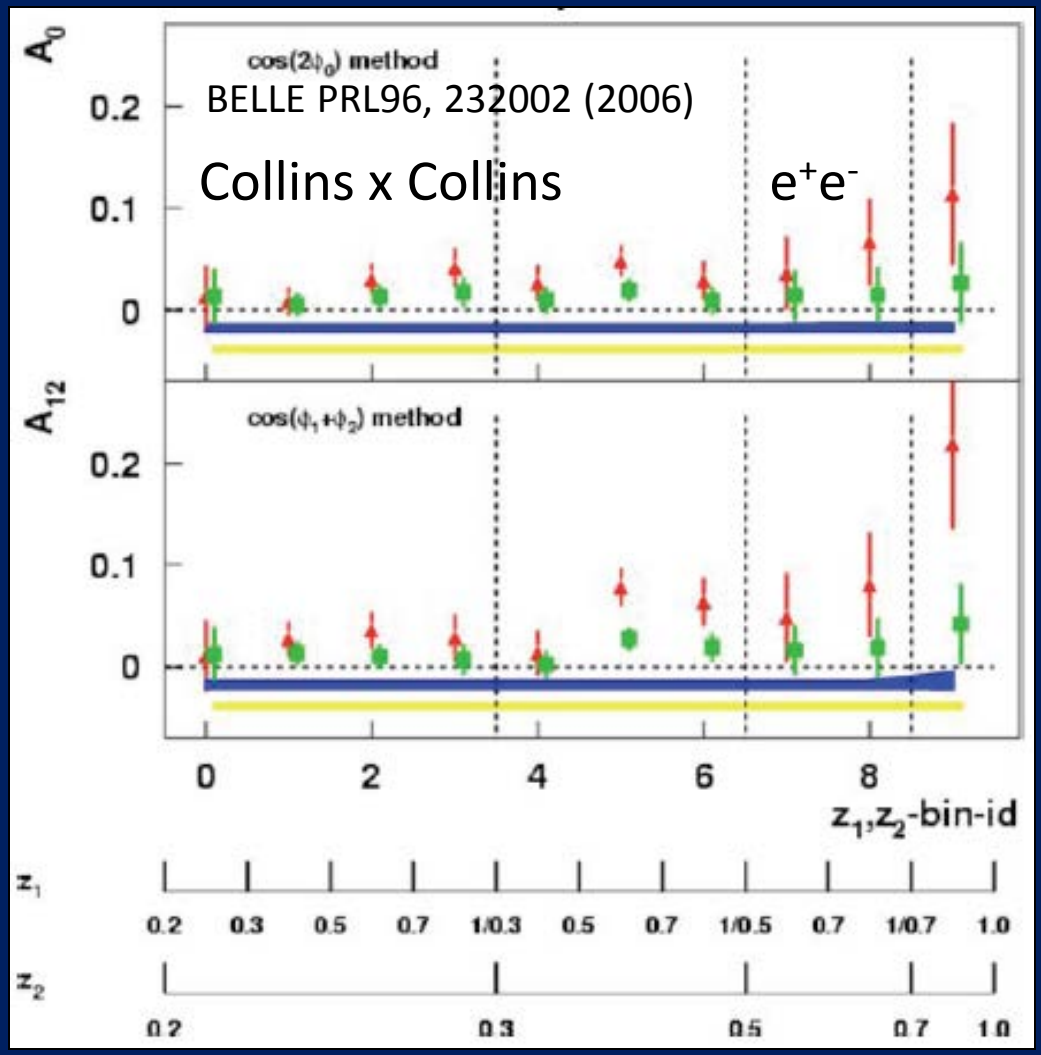
- π^+ amplitudes positive; π^- amplitudes negative
- π^- amplitudes increasing with x at large $P_{h\perp}$

From C. van Hulse, DIS 2016

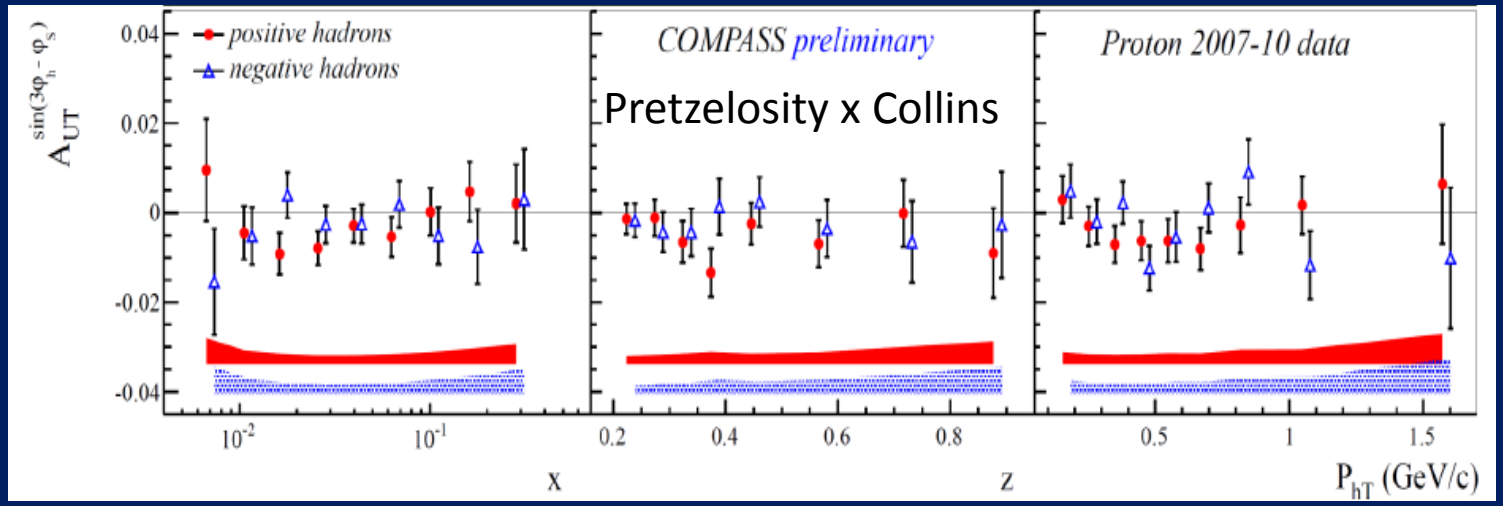
Transversity ×Collins asymmetry from SIDIS for protons and antiprotons



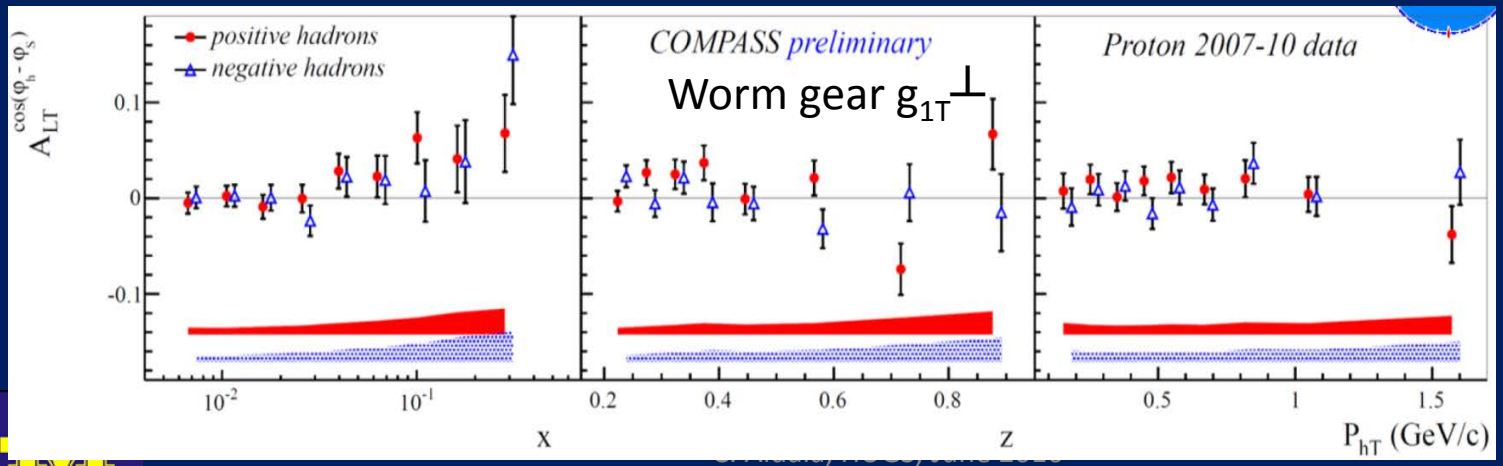
Collins ×Collins from e+e-



Other TMD pdf measurements in SIDIS

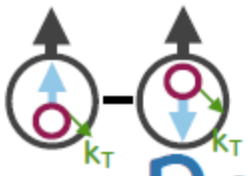


COMPASS



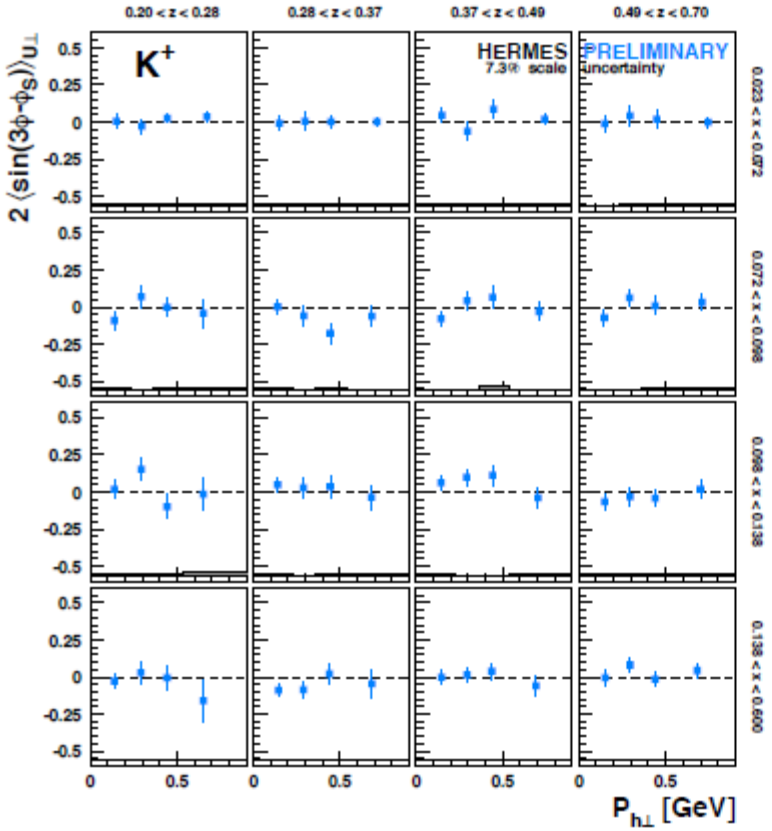
Other TMD pdf measurements in SIDIS

HERMES



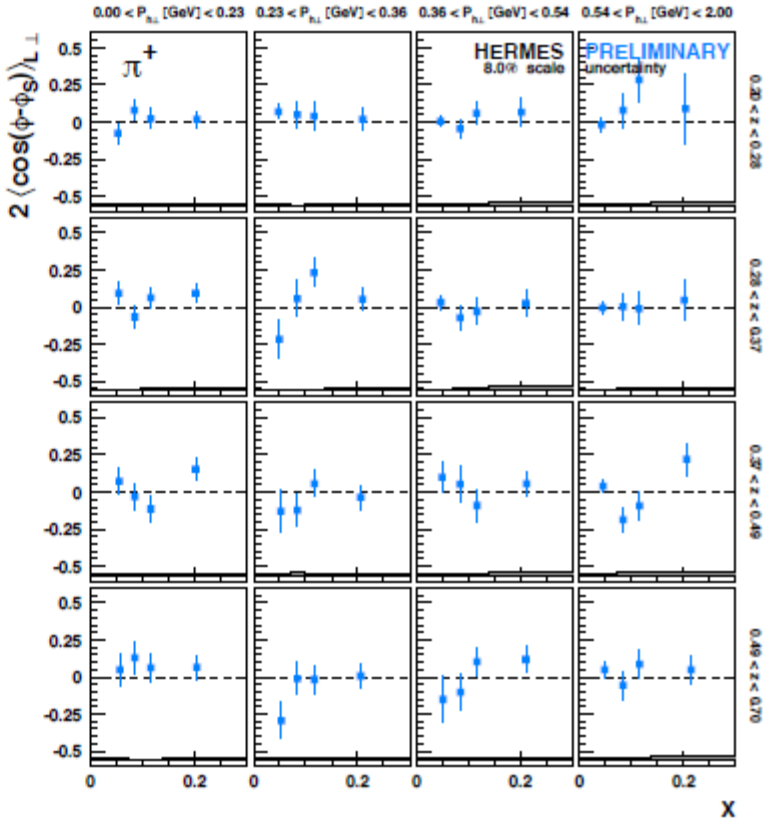
Pretzelosity

$\propto h_{1T}^{\perp,q} \otimes H_1^{\perp,q}$

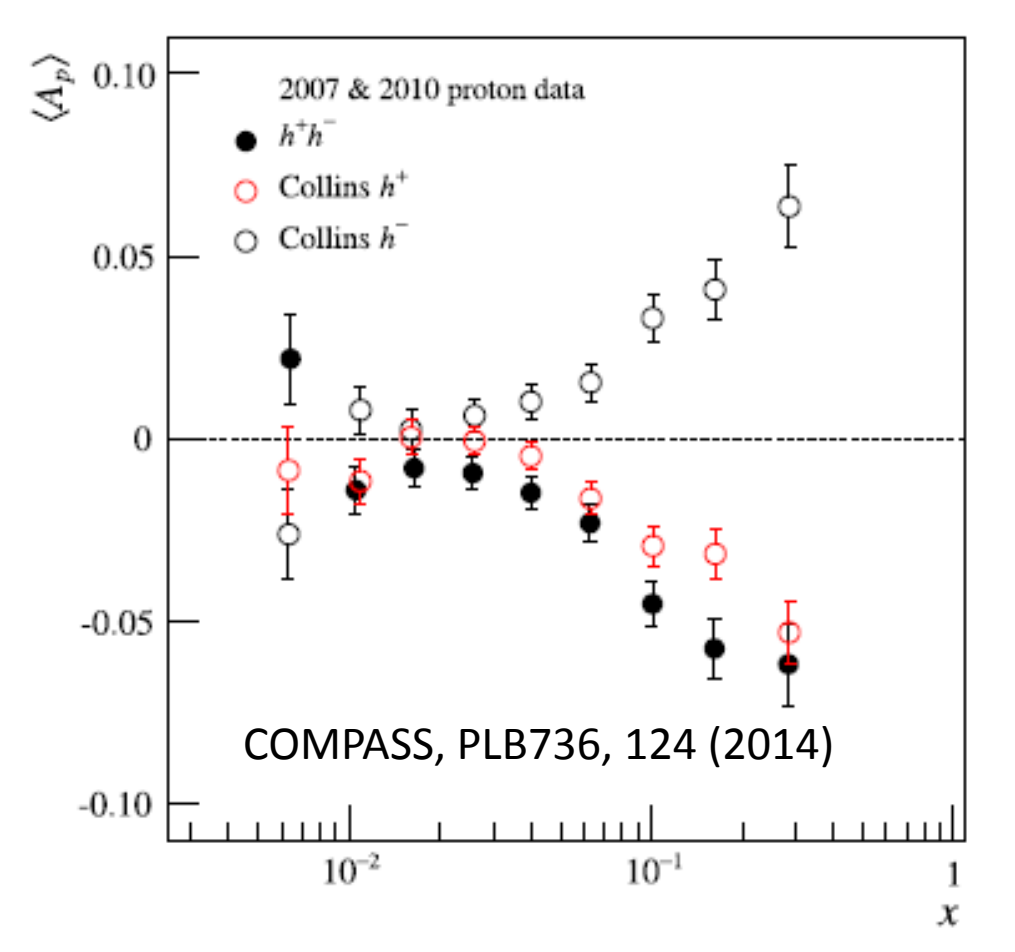


Worm-gear

$\propto g_{1T}^{\perp,q} \otimes D_1^q$



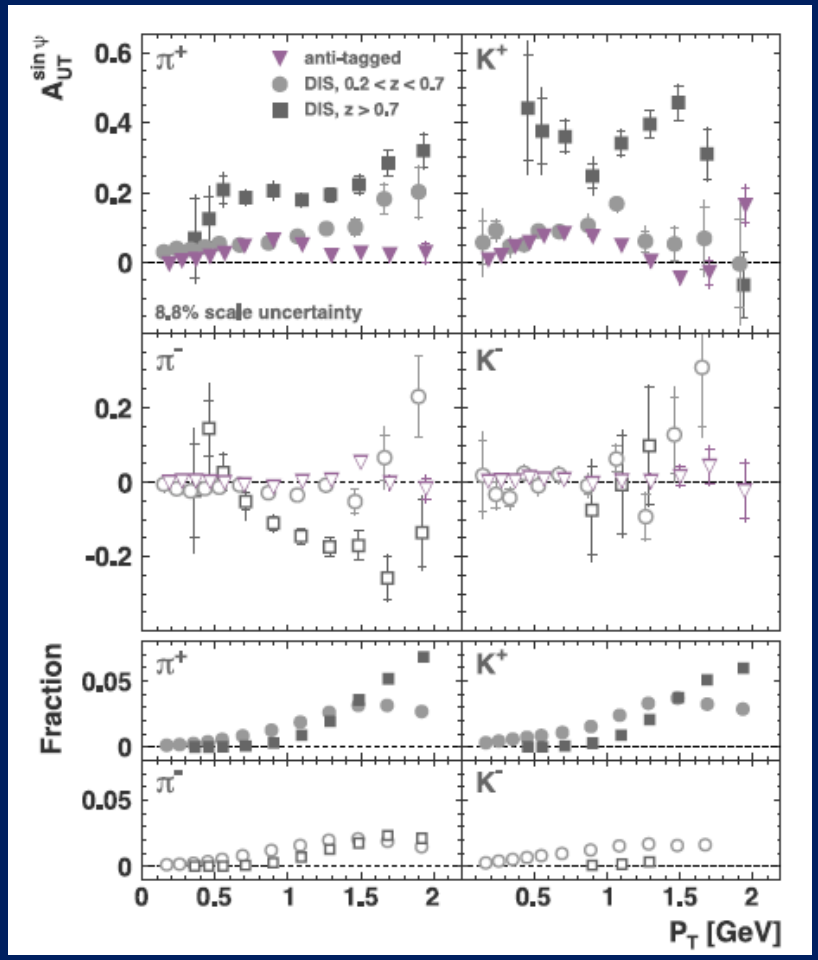
Similarity of Collins and dihadron interference FF asymmetry



Common hadron sample for Collins and interference FF analysis

Inclusive hadron transverse single-spin asymmetries in e+p

- Striking enhancement if measure scattered electron



HERMES, PLB728, 183 (2014)