QCD and Baryon Polarization

Lecture 2:
Spin-momentum correlations in the nucleon

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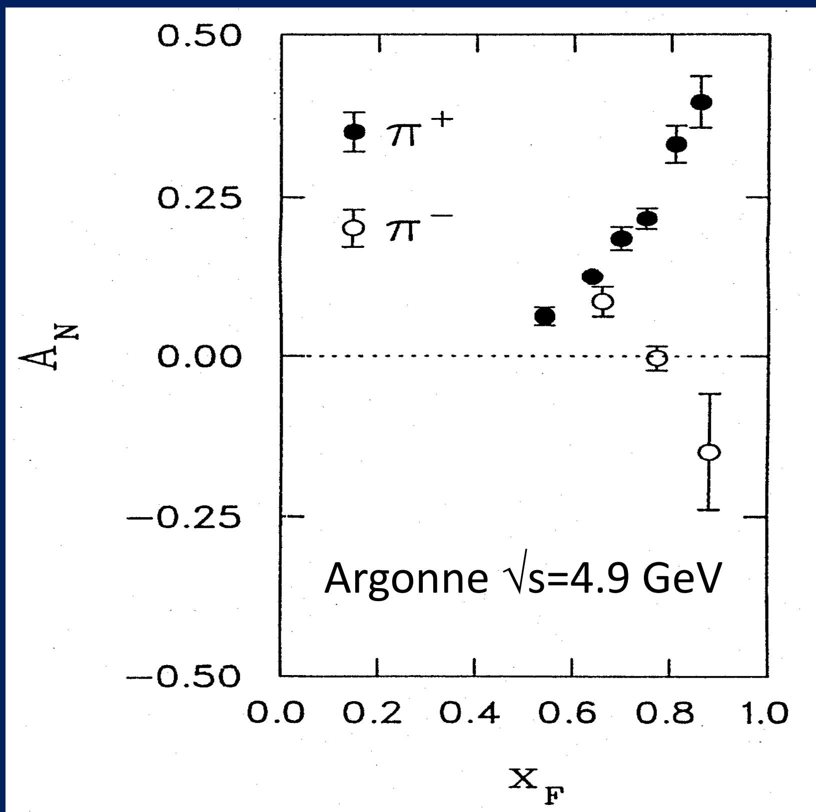
Outline of lectures

1. Introduction; collinear and TMD nucleon structure
2. *Spin-momentum correlations in the nucleon in terms of TMD PDFs and collinear twist-3 multiparton correlations*
3. Hadronization: collinear and TMD fragmentation functions, collinear twist-3 correlations; dihadron FFs; different hadronization mechanisms/pictures
4. Hadron structure and hadronization: Sea quarks/non-valence quarks
5. Hyperon and heavy flavor baryon polarization I
6. Hyperon and heavy flavor baryon polarization II

Spin-momentum correlations: 1976 discovery in p+p collisions

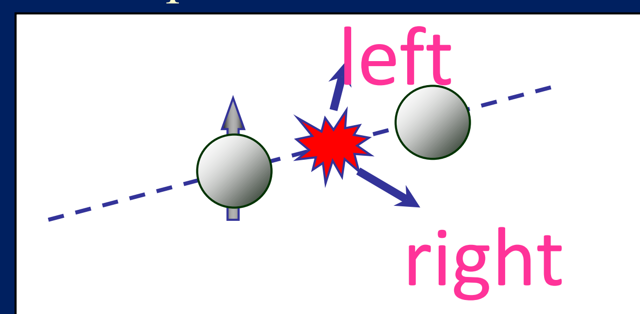
Argonne √s=4.9 GeV



W.H. Dragoset et al., PRL36, 929 (1976)

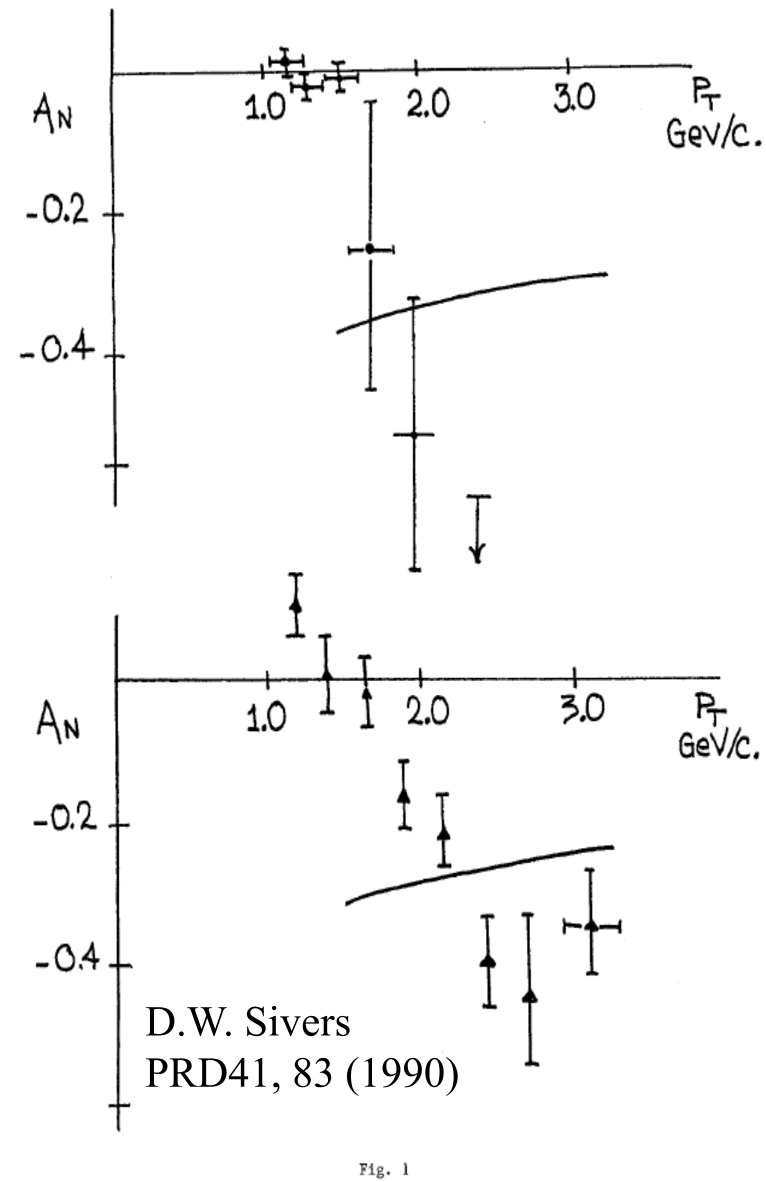
Charged pions produced preferentially on one or the other side with respect to the transversely polarized beam direction—by up to 40%!!

Had to wait more than a decade for the birth of a new subfield in order to explore the possibilities . . .



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

Transverse-momentum-dependent distributions and single-spin asymmetries



D.W. Sivers
PRD41, 83 (1990)

- 1990: D.W. Sivers departs from traditional *collinear* factorization assumption in pQCD and proposes correlation between the *intrinsic transverse motion* of the quarks and gluons and the proton’s spin

$$s\cdot(p_1\times p_2)$$

Spin and momenta of quarks and/or bound states

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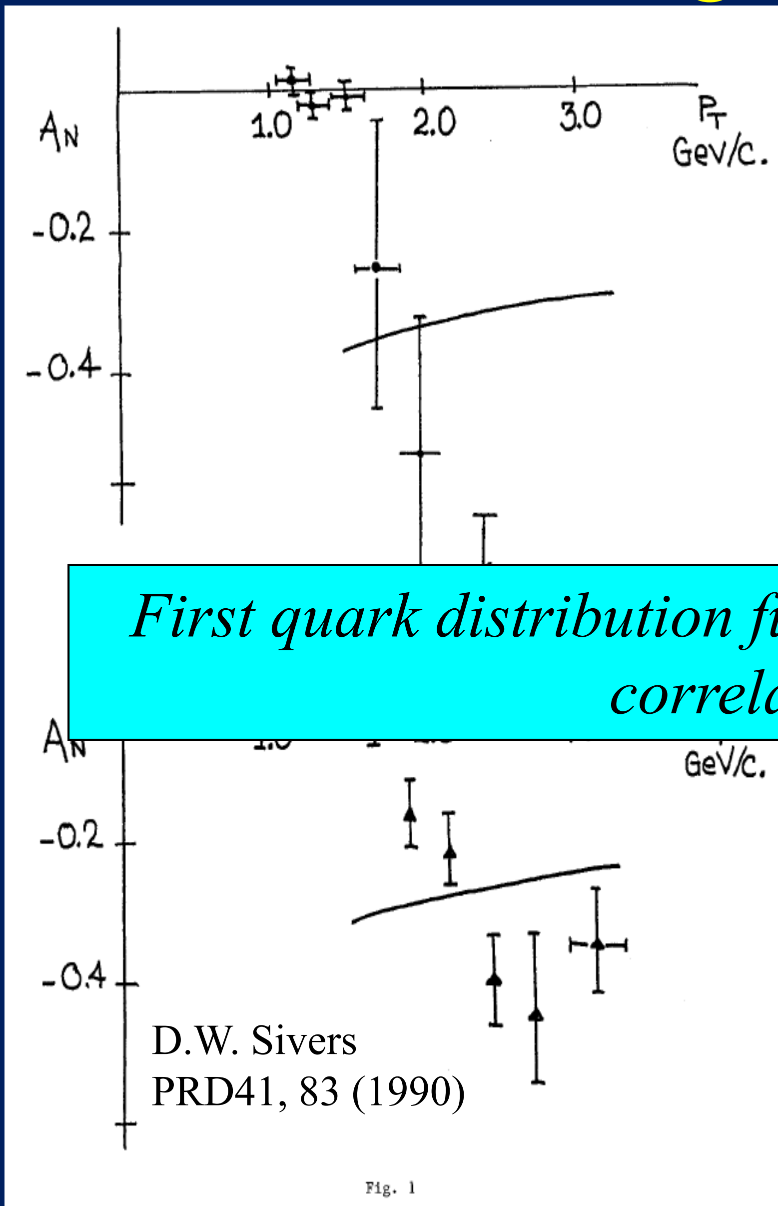

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First quark distribution function describing a spin-momentum correlation in the proton

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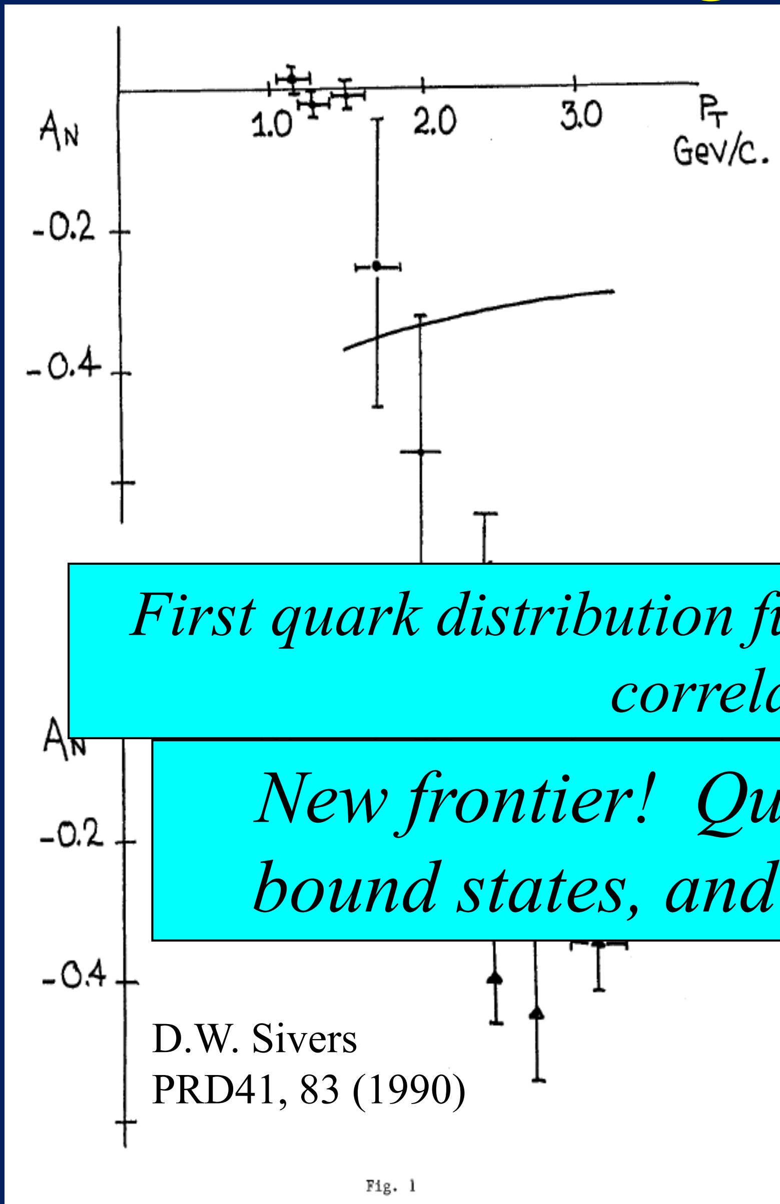

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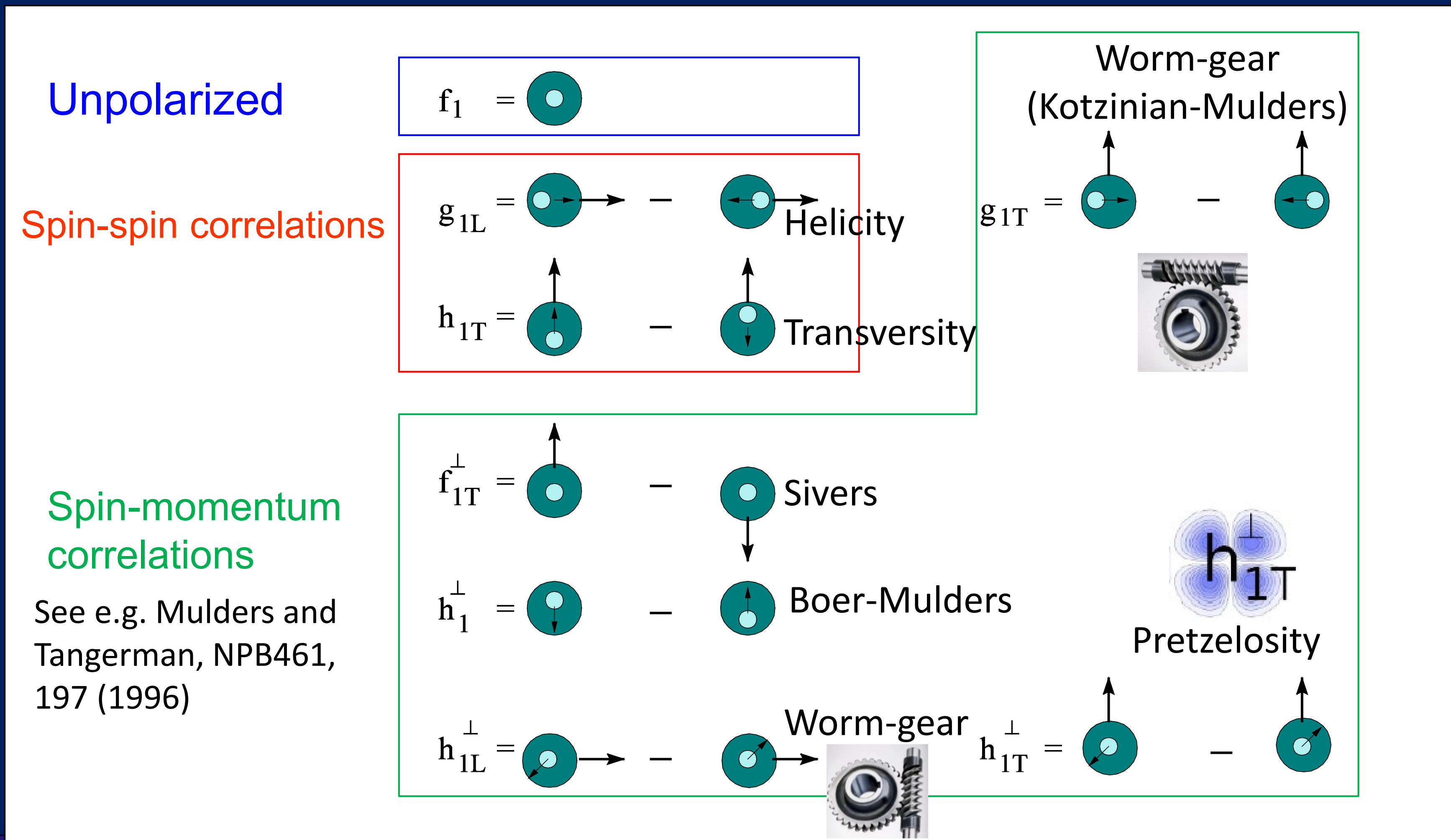
New frontier! Quark ***dynamics*** *inside QCD bound states, and in their formation process*

$$s \cdot (p_1 \times p_2)$$

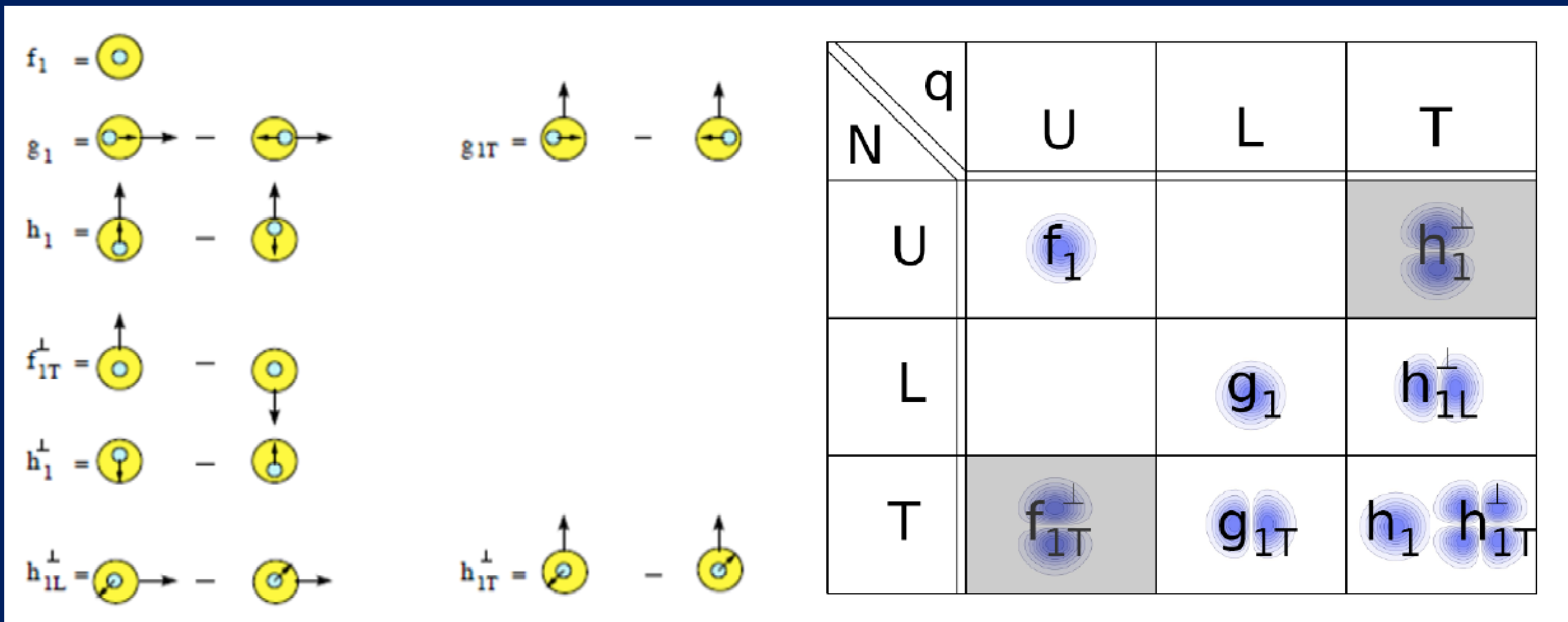
Spin and momenta of quarks and/or bound states

Transverse-momentum-dependent PDFs



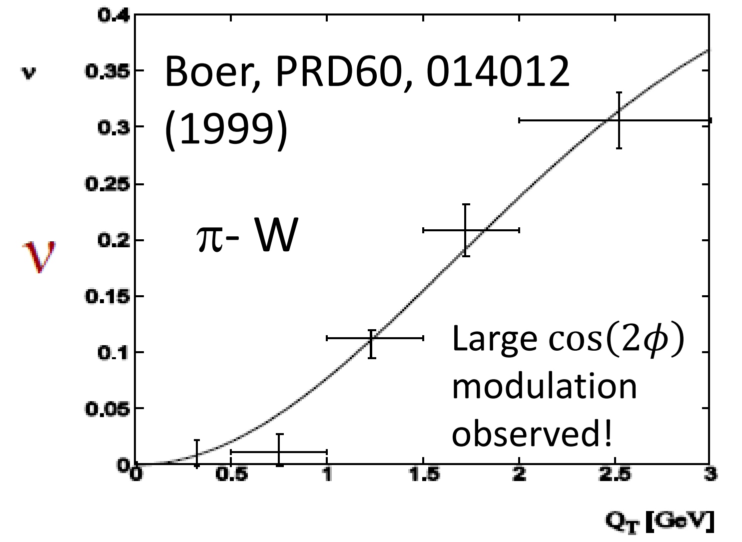
Transverse-momentum-dependent PDFs

U = unpolarized L = longitudinally polarized T = transversely polarized
N = nucleon q = quark



TMD PDFs predict specific angular dependences of cross sections

But pQCD can't make ab initio predictions of *magnitude* of effects—TMD PDFs are nonperturbative and need to be constrained from experimental data



General expression for angular dependence of *unpolarized* Drell-Yan (qqbar → dileptons):

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

Boer-Mulders TMD PDF leads to cos 2ϕ dependence.

- Correlation between transverse spin of (anti-)quark and its own transverse momentum (spin-orbit)

$$\nu\propto\left(\frac{h_1^\perp}{f_1}\right)\left(\frac{\overline{h}_1^\perp}{\overline{f}_1}\right)$$

Drell-Yan angular-dependent cross section in terms of structure functions

$$
\begin{aligned}
\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{F\,q^2}\times & \\
\Big\{ \Big(& (1+\cos^2\theta)\,F_{UU}^1 + (1-\cos^2\theta)\,F_{UU}^2 + \sin 2\theta\cos\phi\,F_{UU}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{UU}^{\cos 2\phi}\Big) \\
& + S_{aL}\Big(\sin 2\theta\sin\phi\,F_{LU}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{LU}^{\sin 2\phi}\Big) \\
& + S_{bL}\Big(\sin 2\theta\sin\phi\,F_{UL}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{UL}^{\sin 2\phi}\Big) \\
& + |\vec{S}_{aT}|\Big[\sin\phi_a\Big((1+\cos^2\theta)\,F_{TU}^1 + (1-\cos^2\theta)\,F_{TU}^2 + \sin 2\theta\cos\phi\,F_{TU}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{TU}^{\cos 2\phi}\Big) \\
& \qquad + \cos\phi_a\Big(\sin 2\theta\sin\phi\,F_{TU}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{TU}^{\sin 2\phi}\Big)\Big] \\
& + |\vec{S}_{bT}|\Big[\sin\phi_b\Big((1+\cos^2\theta)\,F_{UT}^1 + (1-\cos^2\theta)\,F_{UT}^2 + \sin 2\theta\cos\phi\,F_{UT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{UT}^{\cos 2\phi}\Big) \\
& \qquad + \cos\phi_b\Big(\sin 2\theta\sin\phi\,F_{UT}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{UT}^{\sin 2\phi}\Big)\Big] \\
& + S_{aL}\,S_{bL}\Big((1+\cos^2\theta)\,F_{LL}^1 + (1-\cos^2\theta)\,F_{LL}^2 + \sin 2\theta\cos\phi\,F_{LL}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{LL}^{\cos 2\phi}\Big) \\
& + S_{aL}\,|\vec{S}_{bT}|\Big[\cos\phi_b\Big((1+\cos^2\theta)\,F_{LT}^1 + (1-\cos^2\theta)\,F_{LT}^2 + \sin 2\theta\cos\phi\,F_{LT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{LT}^{\cos 2\phi}\Big) \\
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& \qquad + \sin\phi_a\Big(\sin 2\theta\sin\phi\,F_{TL}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{TL}^{\sin 2\phi}\Big)\Big] \\
& + |\vec{S}_{aT}|\,|\vec{S}_{bT}|\Big[\cos(\phi_a+\phi_b)\Big((1+\cos^2\theta)\,F_{TT}^1 + (1-\cos^2\theta)\,F_{TT}^2 + \sin 2\theta\cos\phi\,F_{TT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{TT}^{\cos 2\phi}\Big) \\
& \qquad + \cos(\phi_a-\phi_b)\Big((1+\cos^2\theta)\,\bar{F}_{TT}^1 + (1-\cos^2\theta)\,\bar{F}_{TT}^2 + \sin 2\theta\cos\phi\,\bar{F}_{TT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,\bar{F}_{TT}^{\cos 2\phi}\Big) \\
& \qquad + \sin(\phi_a+\phi_b)\Big(\sin 2\theta\sin\phi\,F_{TT}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{TT}^{\sin 2\phi}\Big) \\
& \qquad + \sin(\phi_a-\phi_b)\Big(\sin 2\theta\sin\phi\,F_{TT}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{TT}^{\sin 2\phi}\Big)\Big]\Big\}. \qquad (57)
\end{aligned}
$$

Arnold, Metz, + Schlegel, PRD79, 034005 (2009)

For any dilepton rest frame

Lots of terms!!

(Structure functions can be related to TMD PDFs)

TMD PDFs: Some properties

- PDFs involving transversely polarized quarks are chiral-odd—can only be observed experimentally in conjunction with a second chiral-odd function
  - Another PDF or a FF
  - Transversity, Boer-Mulders, pretzelosity, one of the worm gears (all the ‘h’ PDFs)
- TMD PDFs involving a single spin vector are “naïve-time-reversal-odd,” i.e. PT-odd
  - “Sivers” and “Boer-Mulders”

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  - "Sivers" and "Boer-Mulders"
- What about TMD PDFs for gluons?
  - Gluons massless—can't have helicity-flip states, i.e. transversely polarized gluons
  - However, can have TMD PDFs for linearly polarized gluons, similar to linearly polarized photons—relatively less explored than TMD PDFs for quarks
  - Unpolarized and longitudinally polarized TMD PDFs no problem for gluons

Transverse single-spin asymmetries

- General form for transverse single-spin asymmetries: $S \cdot \left(p_1 \times p_2 \right)$
  - Collinear momenta would produce no effect
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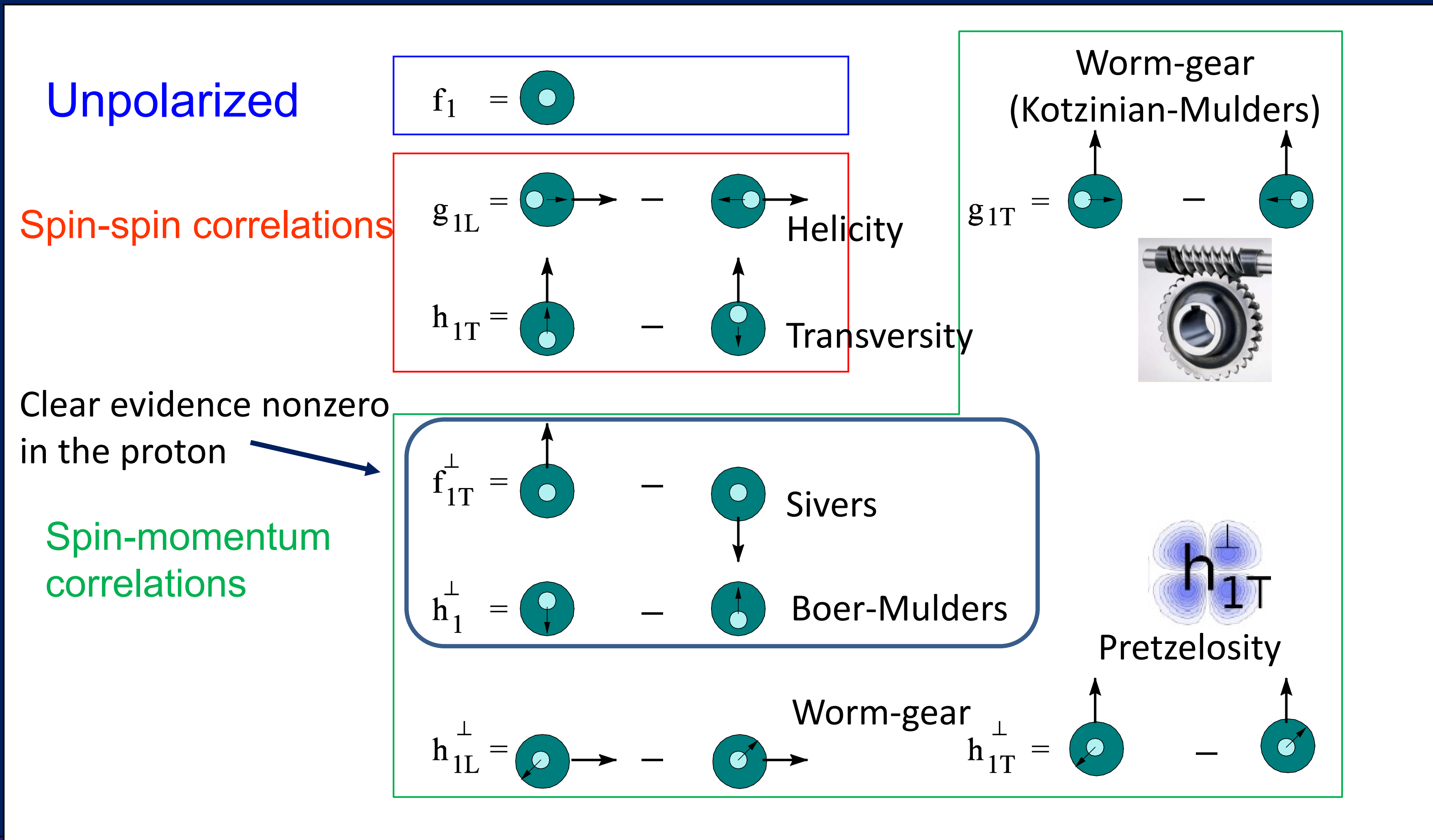
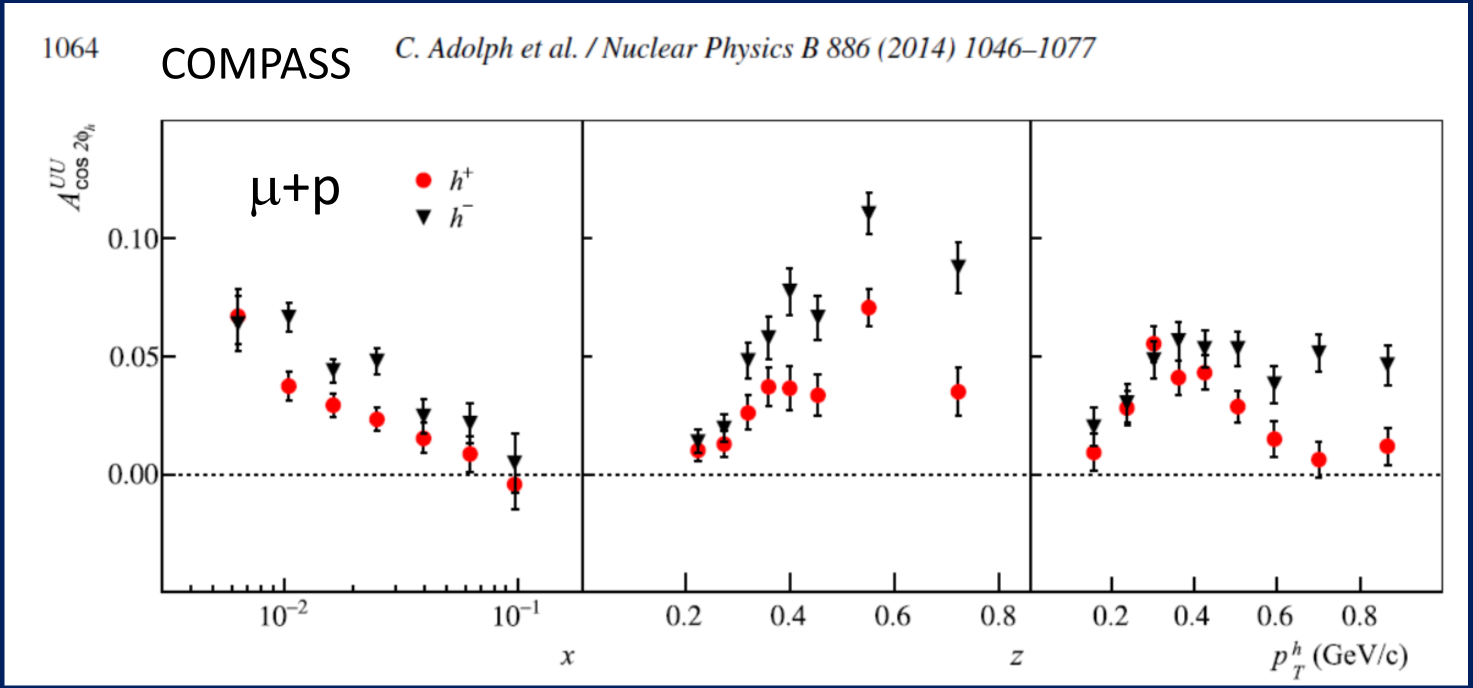
- Spin could be of initial proton, struck quark, fragmenting quark, produced hadron
- Possible momentum vectors include initial proton momentum, final-state particle or jet momentum, k_T of parton within proton, j_T of final-state particle with respect to jet axis
- Lots of combinations possible!

Spin-spin and spin-momentum correlations in QCD bound states



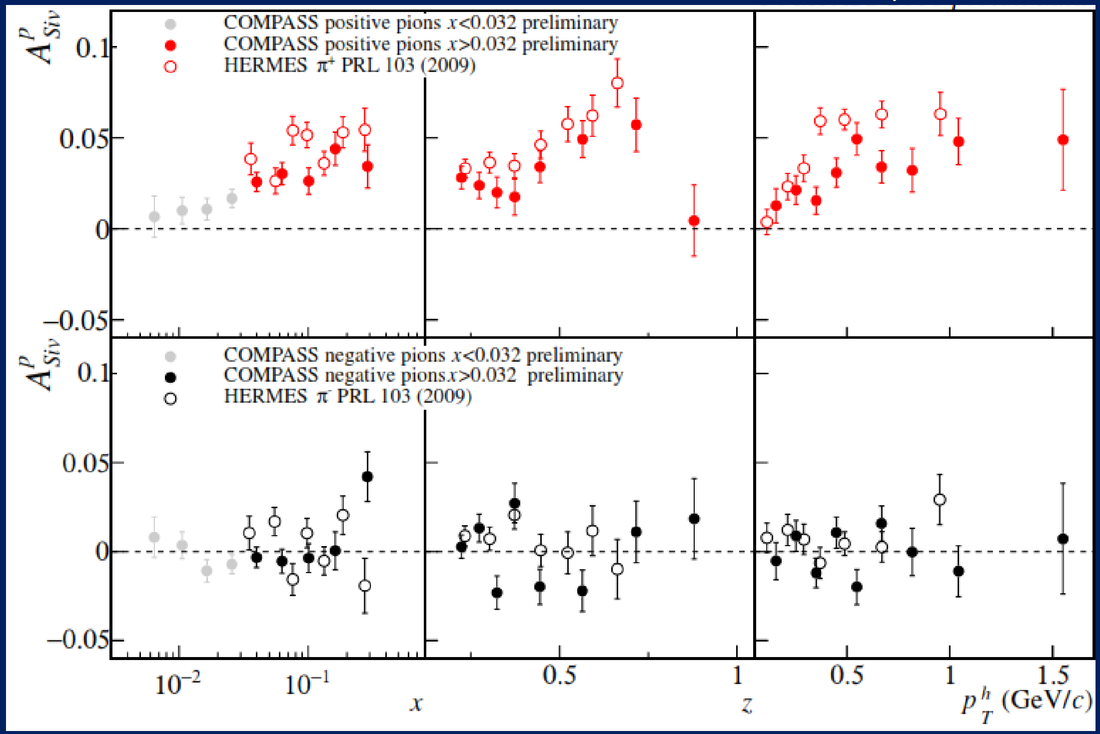
Boer-Mulders TMD PDF ×Collins TMD FF asymmetry from semi-inclusive DIS

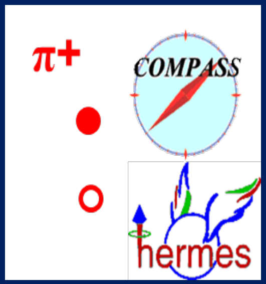


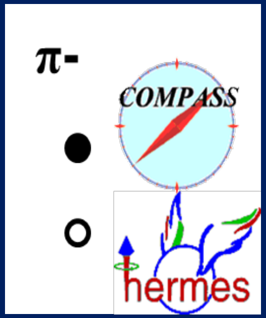
- Boer-Mulders TMD PDF – correlation between quark transverse spin and its own transverse momentum. Chiral-odd. Zero if orbital angular momentum zero.
- Chiral-odd → need another chiral-odd function to measure it. Here the Collins TMD FF
- Clearly nonzero for positive and negative hadrons
- Also measured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

Sivers TMD PDF asymmetry from semi-inclusive DIS

Charged pions, HERMES (e+p) and COMPASS (μ+p)



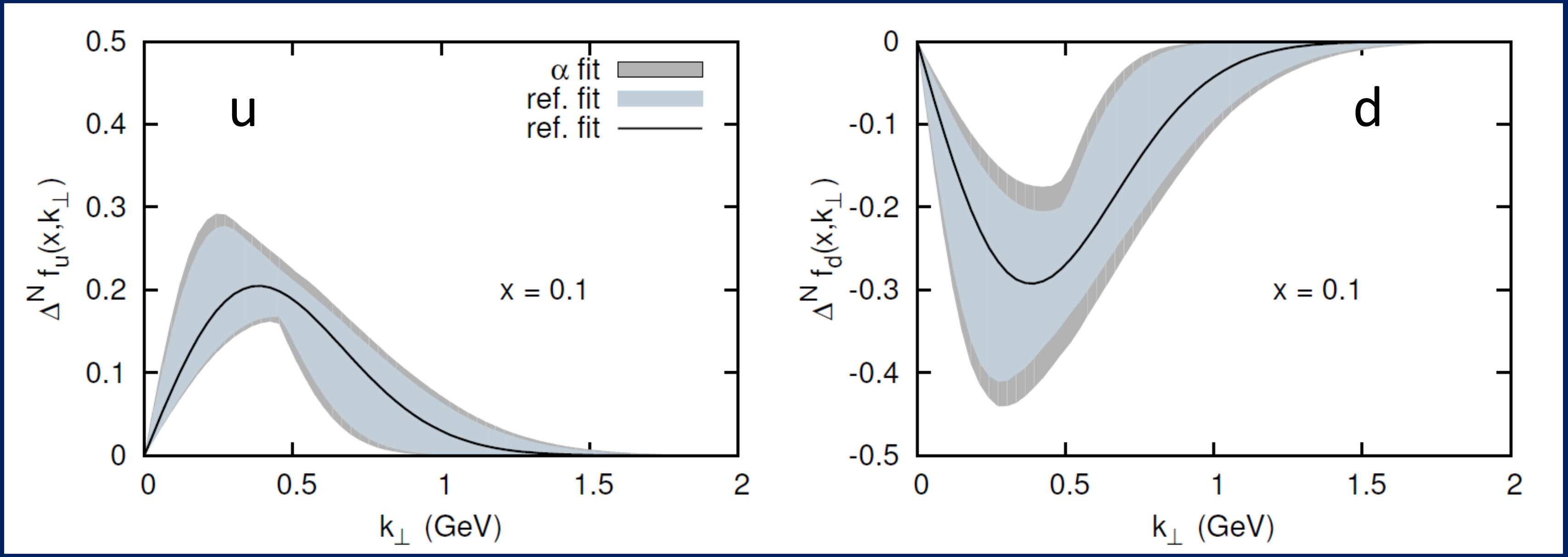




- Sivers TMD PDF – correlation between proton transverse spin and quark transverse momentum. Zero if orbital angular momentum zero.
- Clearly nonzero for positive pions. Cancellations between up and down quarks lead to smaller negative pion asymmetries.

Example: Fit of Sivers TMD PDF

Boglione, D'Alesio, Flore, Gonzalez-Hernandez, JHEP 07, 148 (2018)



- Recall: Sivers TMD PDF describes correlation between tranverse spin of proton and intrinsic motion of quark.
- Fit based on semi-inclusive DIS data on transversely polarized targets from COMPASS and HERMES.
- 220 points (compare to thousands for unpolarized, collinear PDF extraction).
- Clear opposite spin-momentum correlation for up versus down quarks.

Different symmetry properties for different spin-momentum correlations

- Some transverse-momentum-dependent quark distribution functions odd under a parity- and time-reversal (PT) transformation

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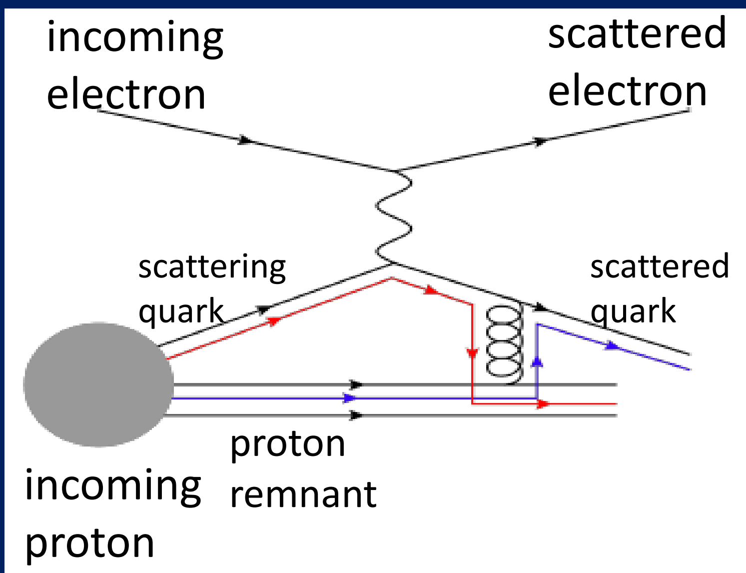
Different symmetry properties for different spin-momentum correlations

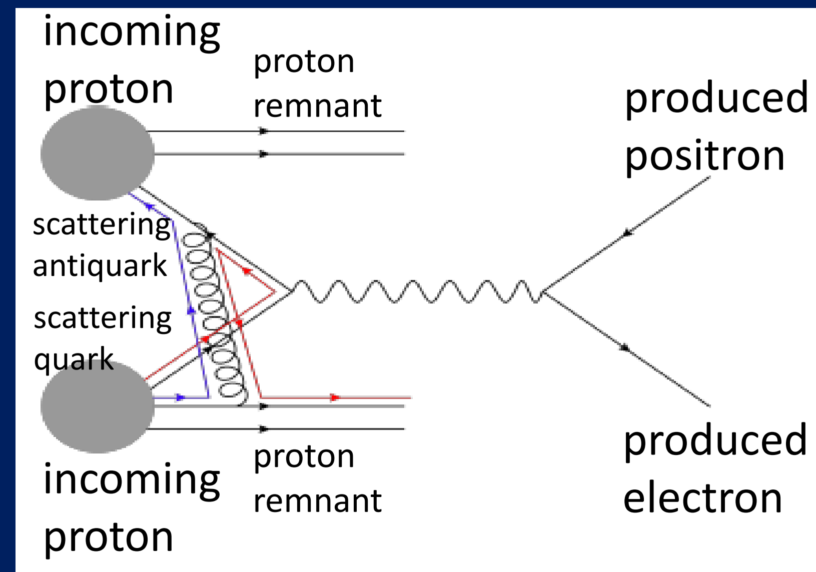
- Some transverse-momentum-dependent quark distribution functions odd under a parity- and time-reversal (PT) transformation
- In 1993, after original 1990 paper by D.W. Sivers, J.C. Collins claimed such functions must vanish
- Only realized in 2002 by Brodsky, Hwang, and Schmidt that could be nonvanishing if *phase interference effects due to color interactions* present

<u>Modified universality</u> of PT-odd correlations: Color in action!

Deep-inelastic lepton-nucleon scattering: Final-state color exchange



Quark-antiquark annihilation to leptons: Initial-state color exchange



Figures by J.D. Osborn

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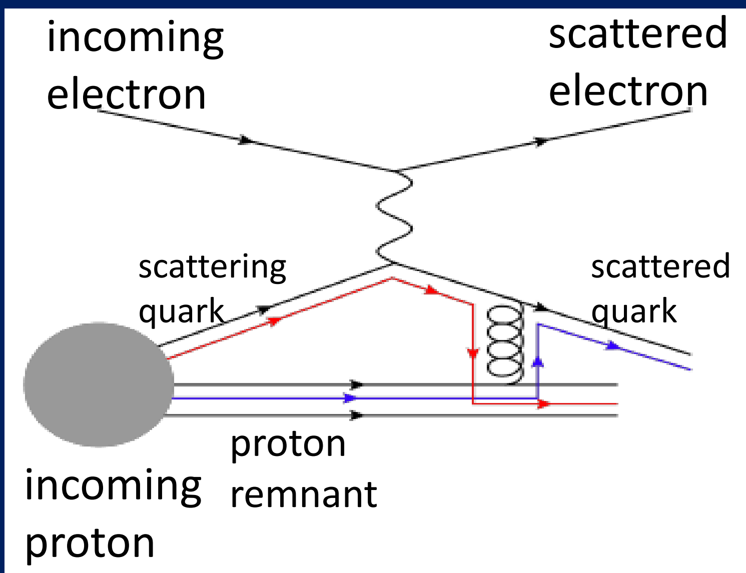

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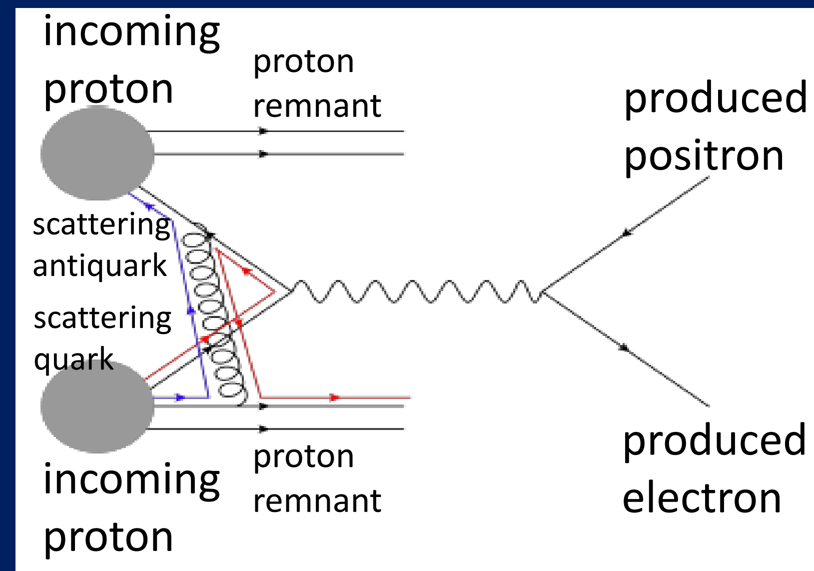
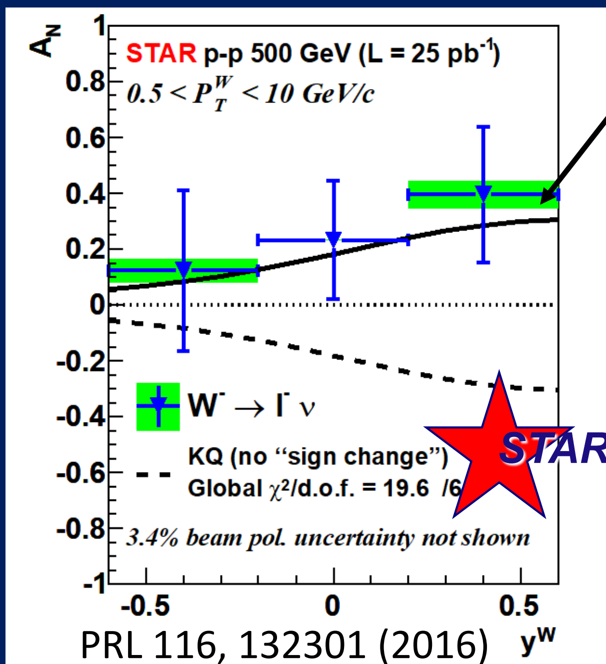


***Opposite sign* for PT-odd spin-momentum correlations in the proton measured in these two processes: *process-dependent*! (Collins 2002)**

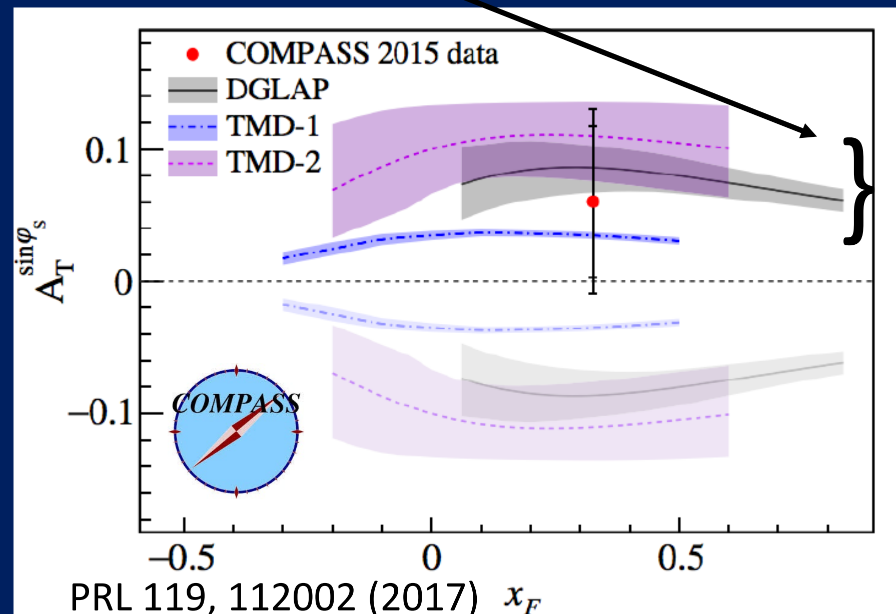
Figures by J.D. Osborn

Modified universality: Initial experimental hints

Predictions including sign change



PRL 116, 132301 (2016)



PRL 119, 112002 (2017)

First measurements by STAR at the Relativistic Heavy Ion Collider and COMPASS at CERN suggestive of predicted sign change in color-annihilation processes compared to quark knock-out by a lepton. More statistics forthcoming . . .

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

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 $1/Q^{(n-2)}$

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- 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

- Leading 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

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

- Twist-3 (collinear) multiparton correlators are related to k_T-moments of (twist-2) TMD PDFs and fragmentation functions
  - NPB667, 201 (2003); PRL97, 082002 (2006)

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

- Twist-3 (collinear) multiparton correlators are 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
    - In semi-inclusive DIS, have (large) Q^2 from scattered lepton and (small) p_T of measured hadron
    - In qqbar → dileptons, have (large) invariant mass and (small) p_T of lepton pair
  - Recall: Original p+p→pion+X asymmetries only measured a single scale

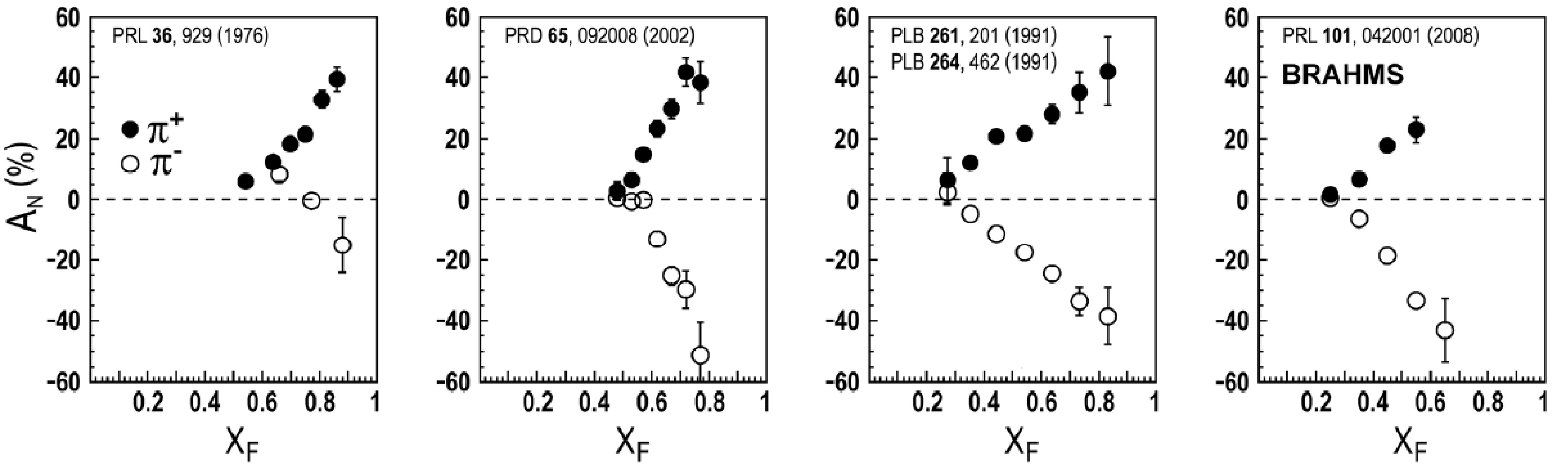
Transverse single-spin asymmetries in p+p across energies

ANL
√s=4.9 GeV

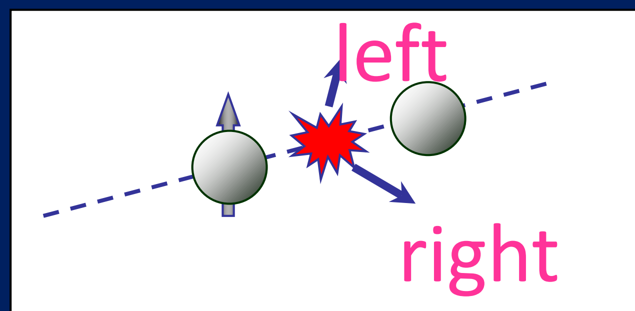
BNL
√s=6.6 GeV

FNAL
√s=19.4 GeV

RHIC
√s=62.4 GeV



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



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BRAHMS

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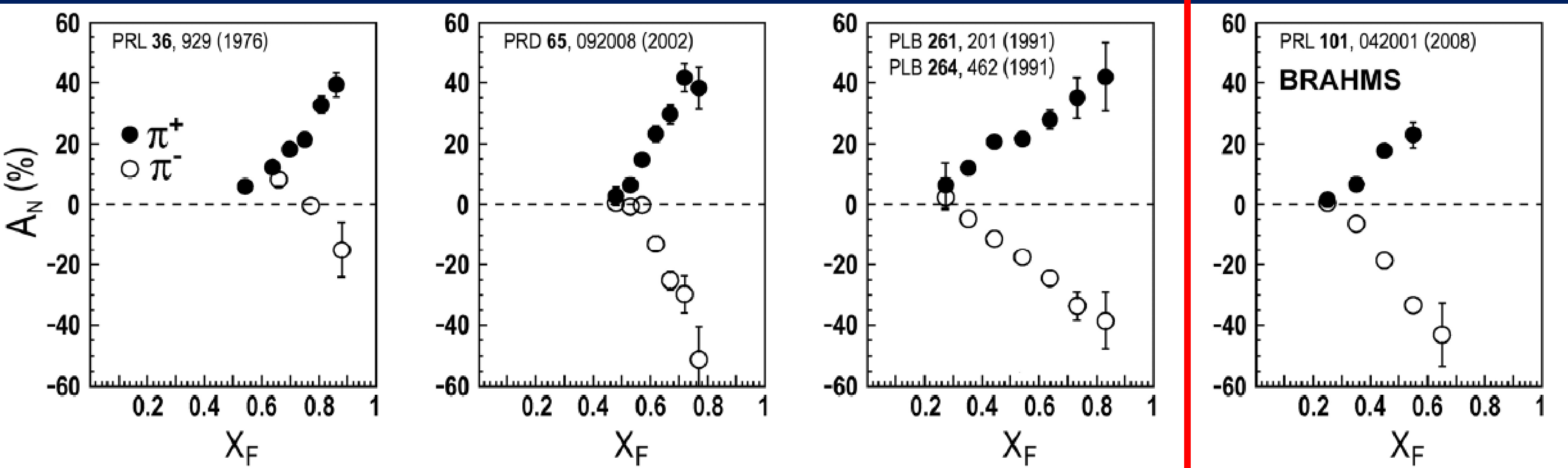

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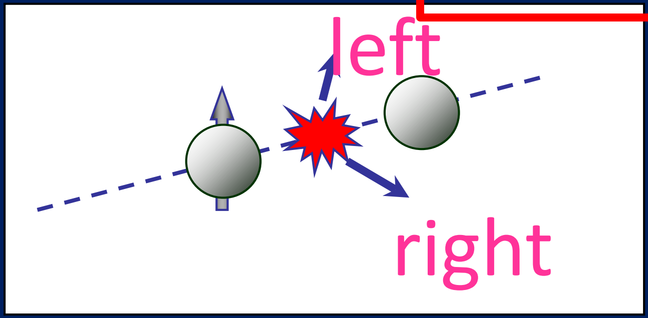

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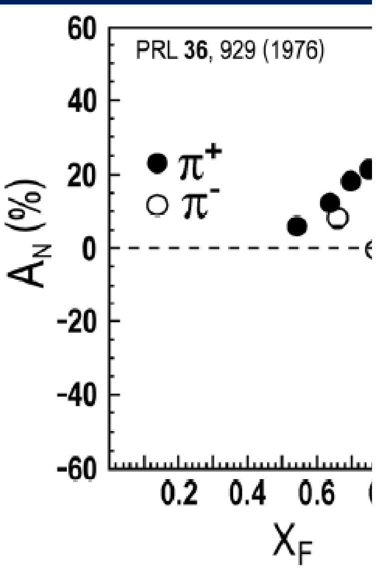
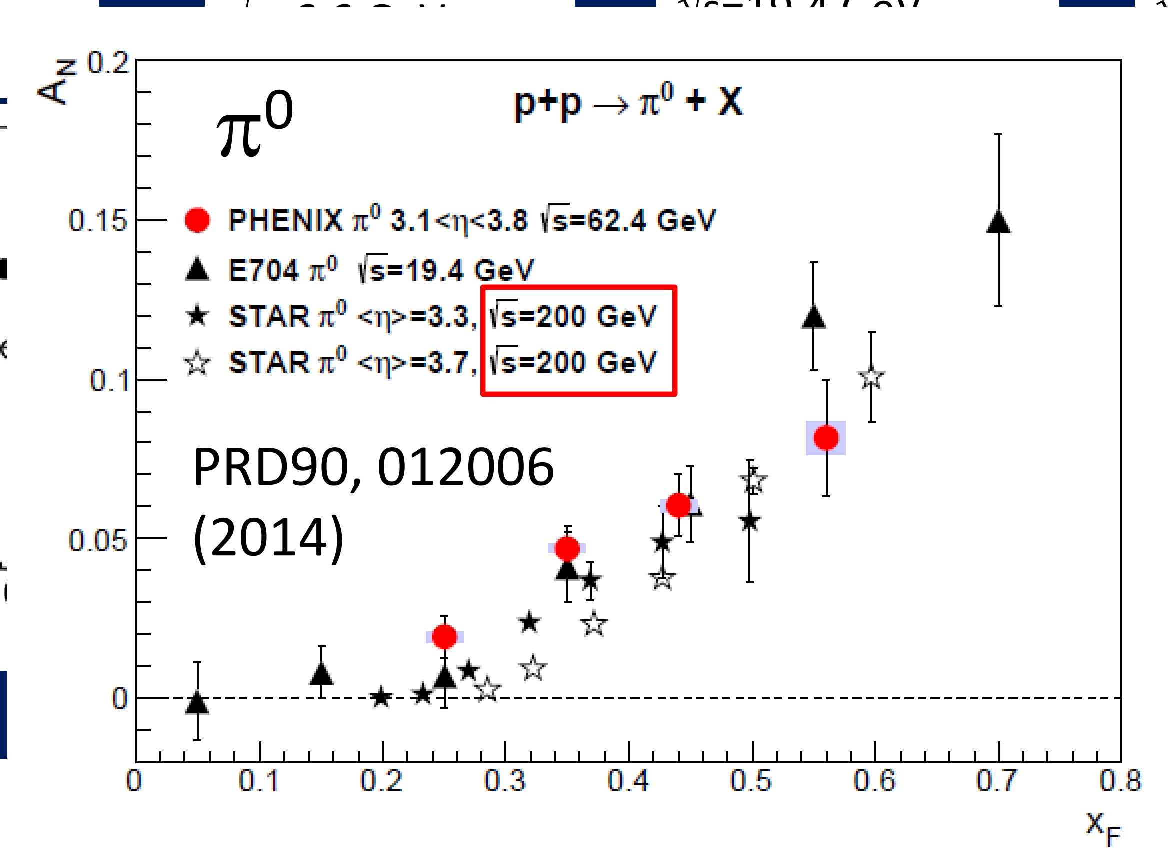
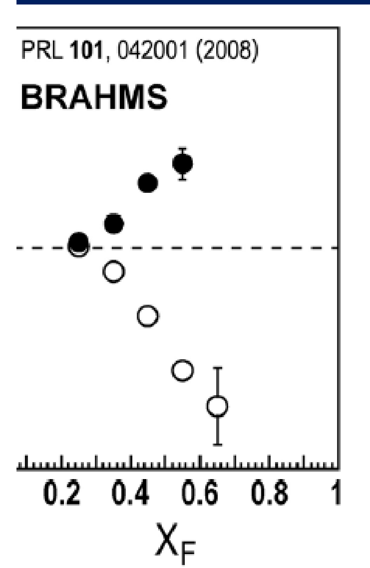
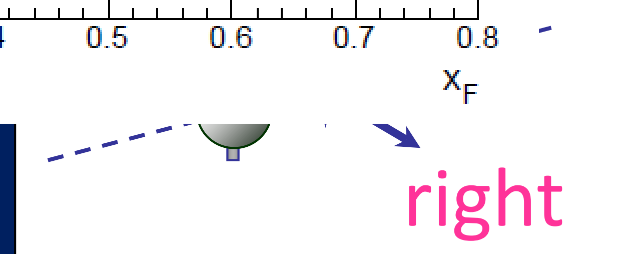




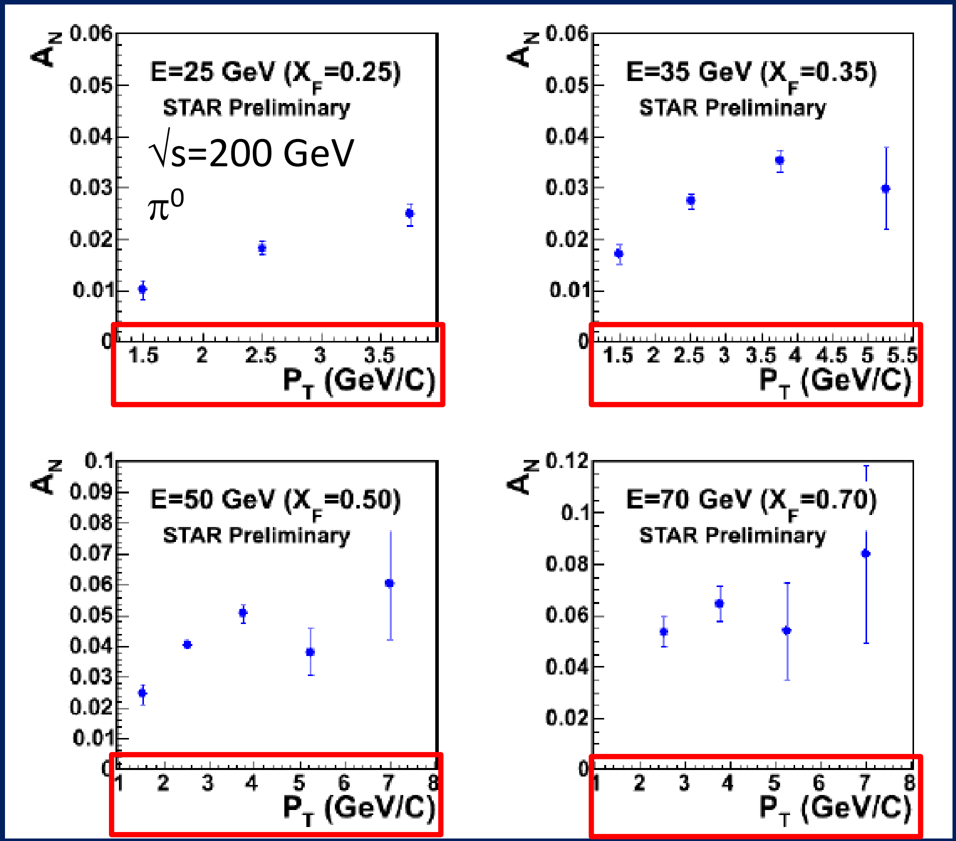


$x_F =$



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

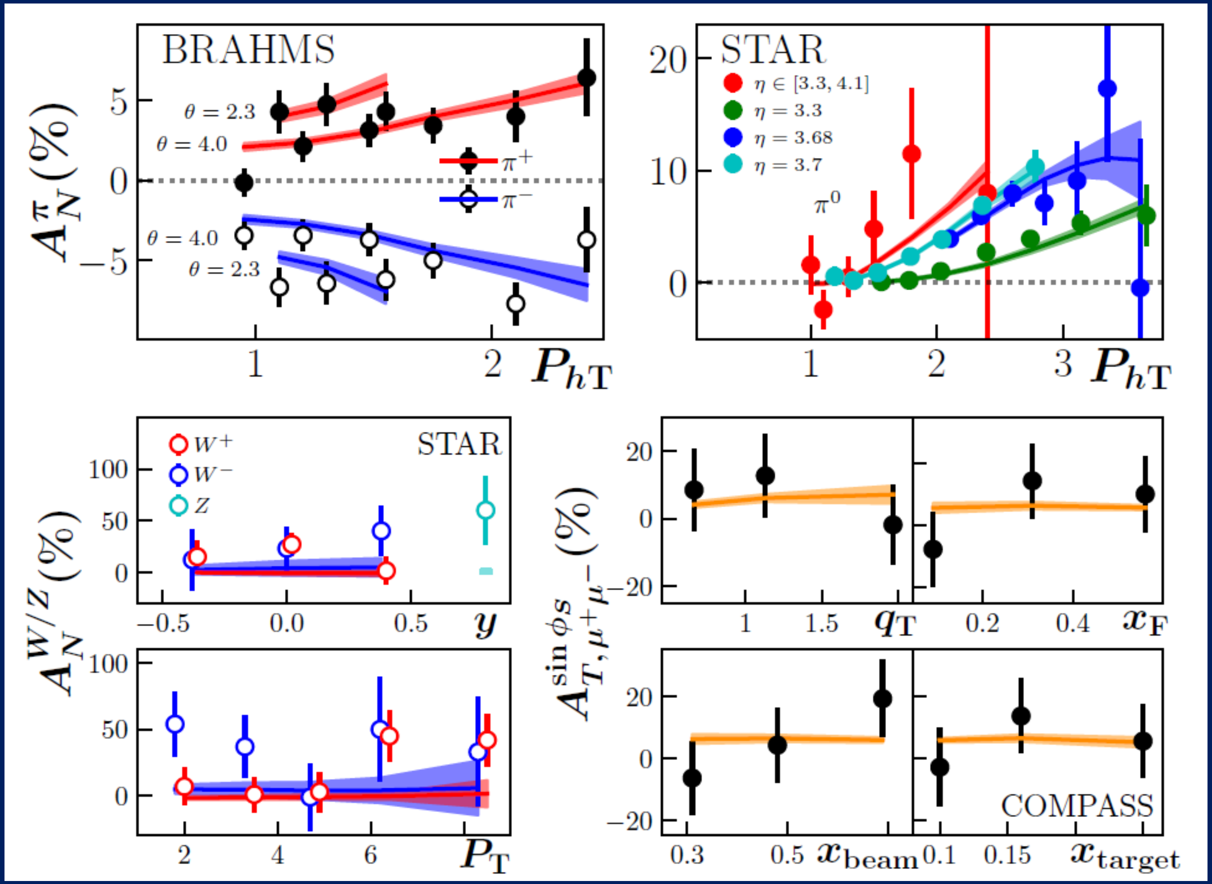
- For high enough p_T of produced hadron (>1-2 GeV) have hard scale, so can apply perturbative calculations
  - Clear nonzero asymmetries out to 8 GeV → $Q^2 \sim 64$ GeV^2
- Can have contributions from initial-state and final-state effects (spin-momentum correlations in the proton and in hadronization)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



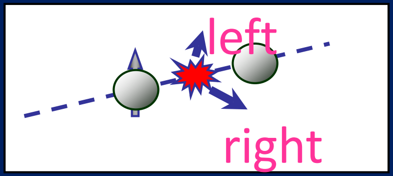
*First global fit of transverse-single spin asymmetries using **both** TMD functions and twist-3 correlators*

Just came out!

- Fit
  - semi-inclusive DIS,
  - Drell-Yan,
  - e+e- annihilation, and
  - p+p→h+X
- *Simultaneously* extract nonperturbative spin-momentum correlations as TMD PDFs and twist-3 correlators in the proton and in hadronization

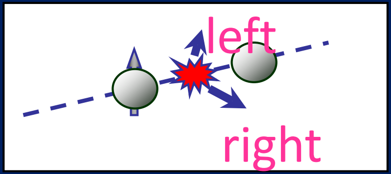


Jefferson Lab Angular Momentum Collaboration, arXiv:2002.08384



Summary: Lecture 2

- Striking spin-momentum correlations (up to tens of percent!) in collisions involving transversely polarized protons were first observed in the 1970s
  - Opened up new field of parton *dynamics* within the proton



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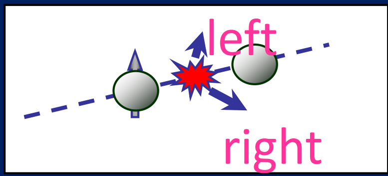
  - Transverse-momentum-dependent PDFs
  - Collinear twist-3 multiparton correlators in the proton
  - Both of these encode additional information beyond traditional collinear PDFs
  - Multiparton correlators are related to k_T moments of TMD PDFs



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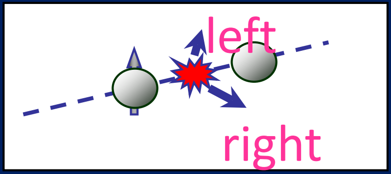
  - Sivers, describing “spin-orbit” coupling between *proton* spin and quark orbital motion
  - Boer-Mulders, describing “spin-orbit” coupling between *quark* spin and quark orbital motion
  - Others remain to be measured with higher precision



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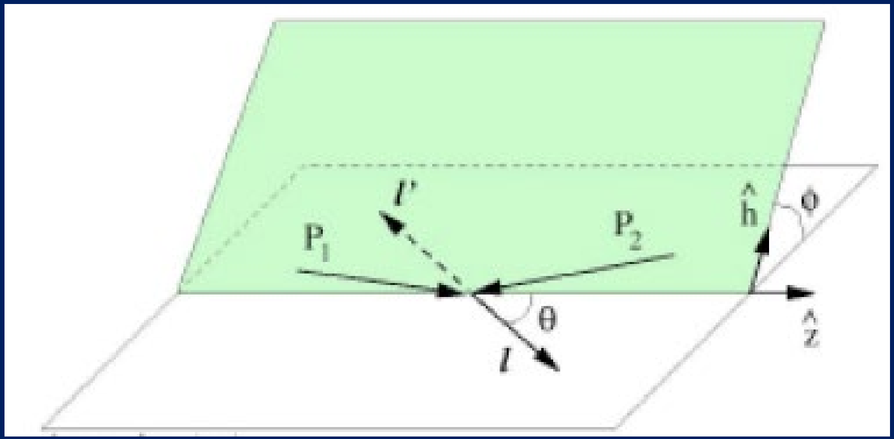
- Food for thought – Should we expect isospin symmetry between the proton and neutron when investigating parton *dynamics*??

Extra

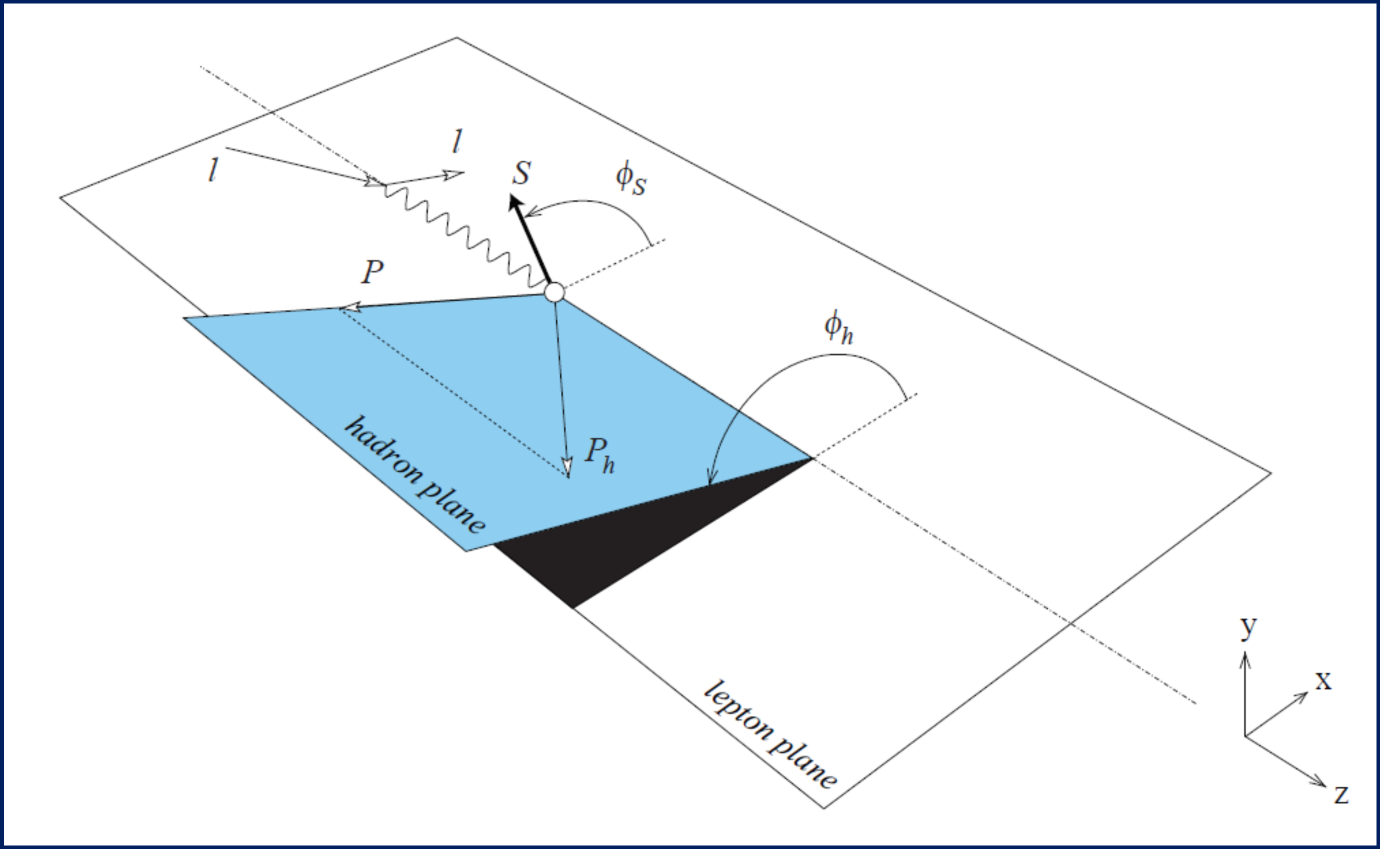
Drell-Yan vector diagram for TMD PDF measurements

- One plane formed by produced lepton pair; other by incoming quark and antiquark
  - Incoming quark and antiquark cannot be collinear, otherwise can't define a plane!

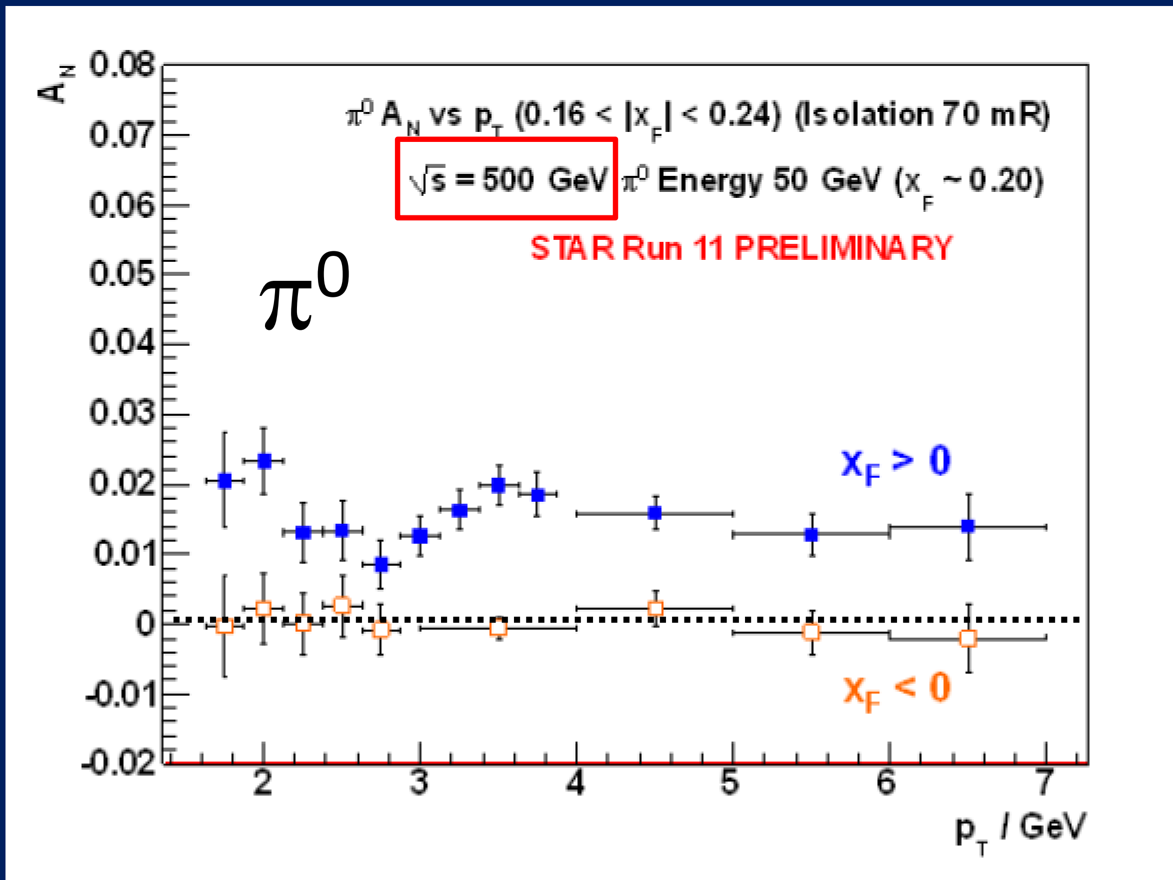


Dilepton rest frame

Semi-inclusive DIS vector diagram for TMD PDF measurements

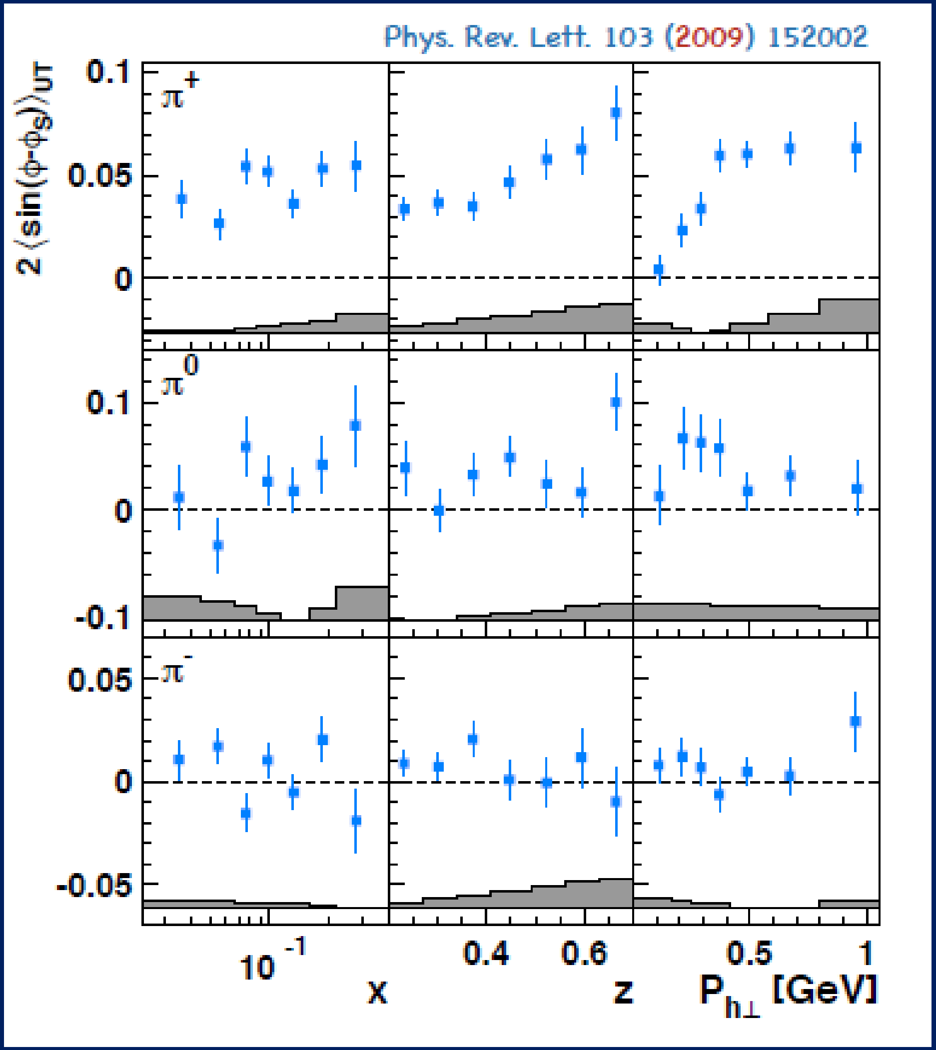


Effects persist up to transverse momenta of 7(!) GeV/c at √s=500 GeV

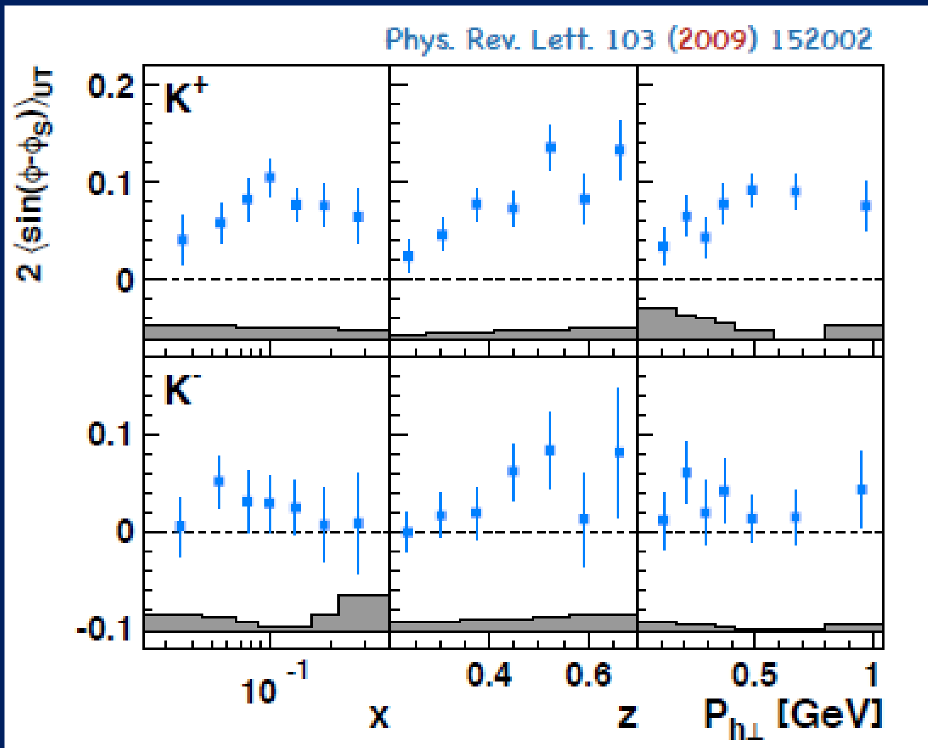


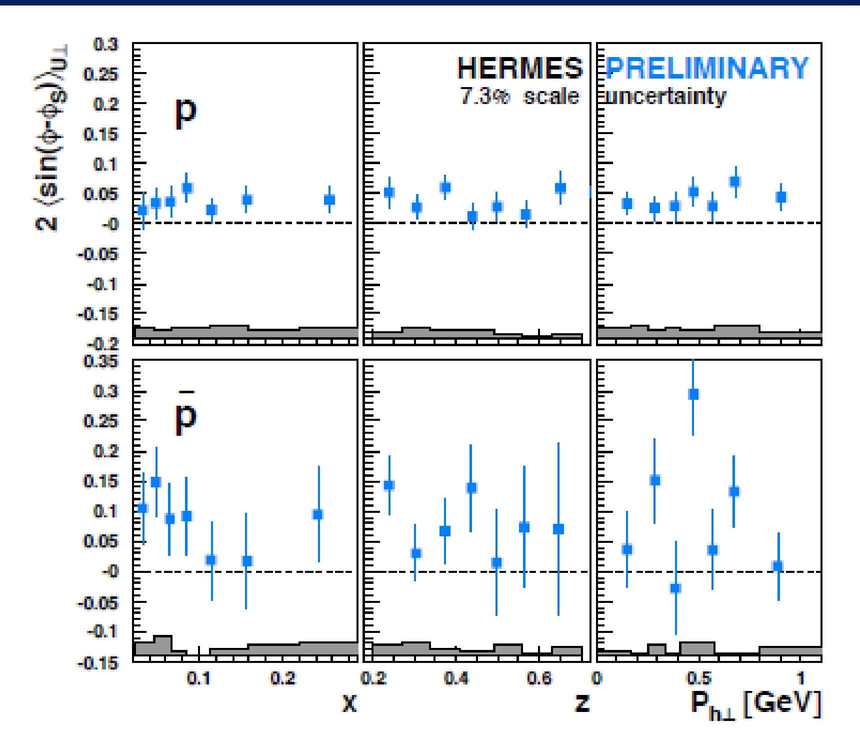
- Can try to interpret these non-perturbative effects within the framework of perturbative QCD.
- Haven't yet disentangled all the possible contributing effects to the (messy) process of p+p to pions

HERMES Sivers for pions



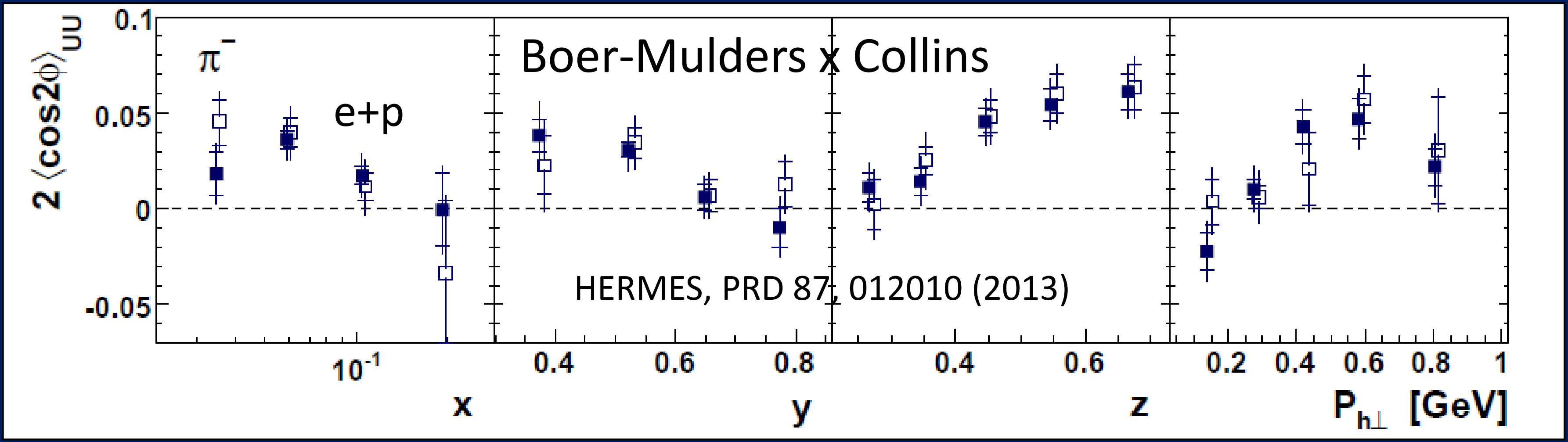
Sivers asymmetry in SIDIS for kaons and protons





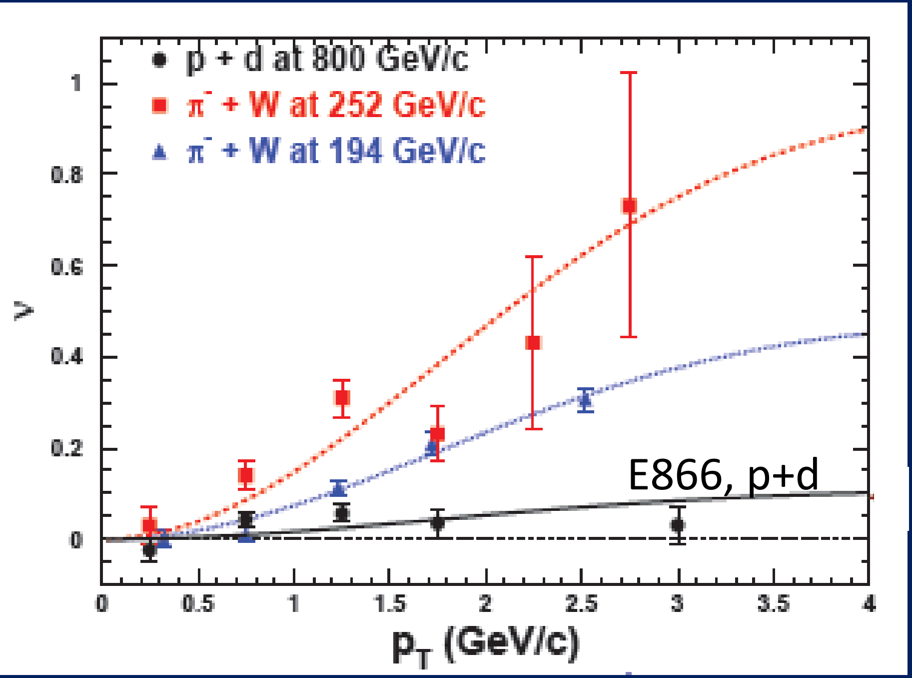
Nonzero for positive kaons and protons, hints for negative kaons and antiprotons. Identified particles help give *flavor separation* for Sivers TMD PDF

Boer-Mulders ×Collins asymmetry from SIDIS



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

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



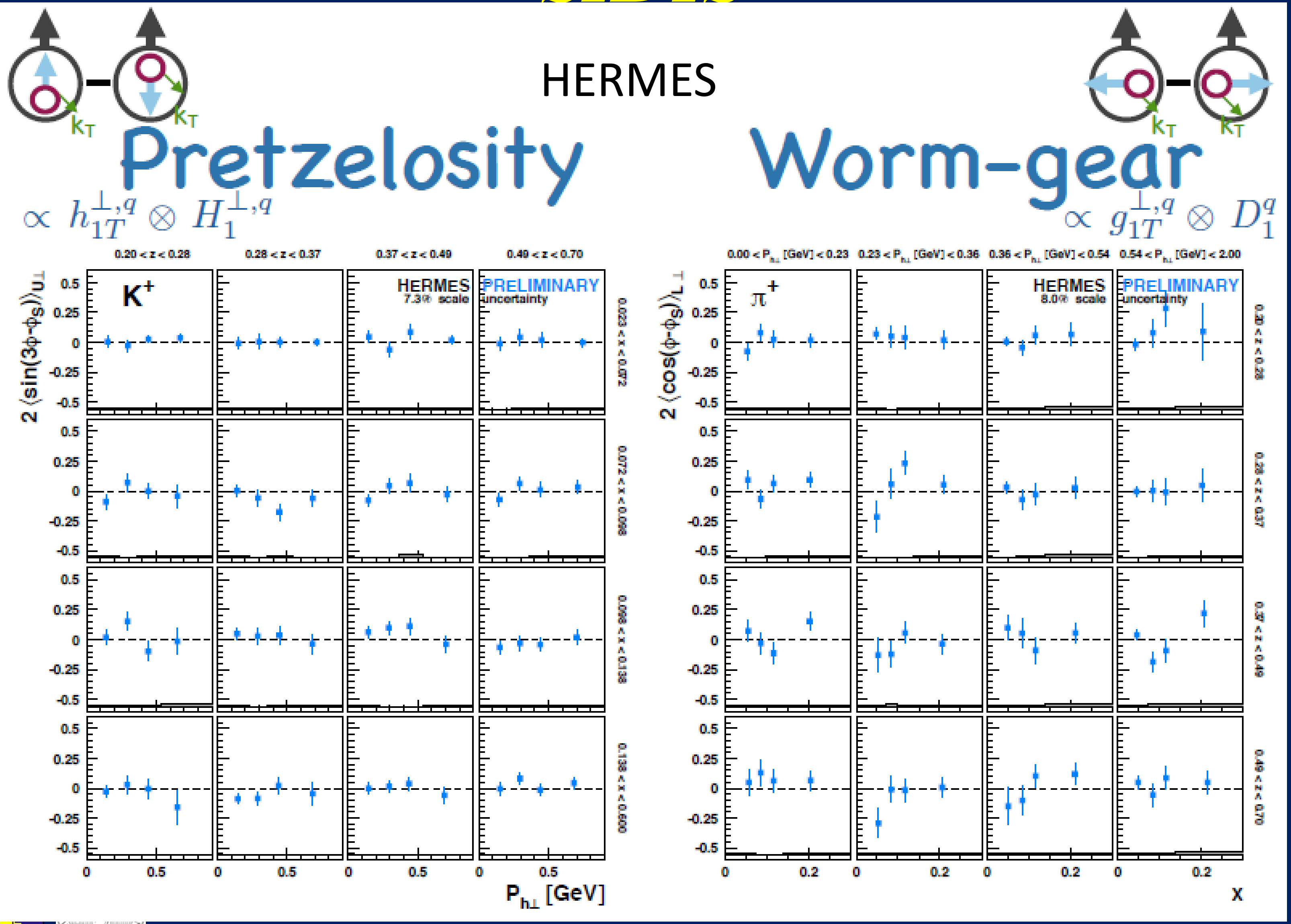
- Huge cos2ϕ dependence in pion-induced Drell-Yan
- Significantly reduced in proton-induced Drell-Yan
- Suggests sea quark transverse spin-momentum correlations small?

Boer - Mulders function $h_1^{\perp}$

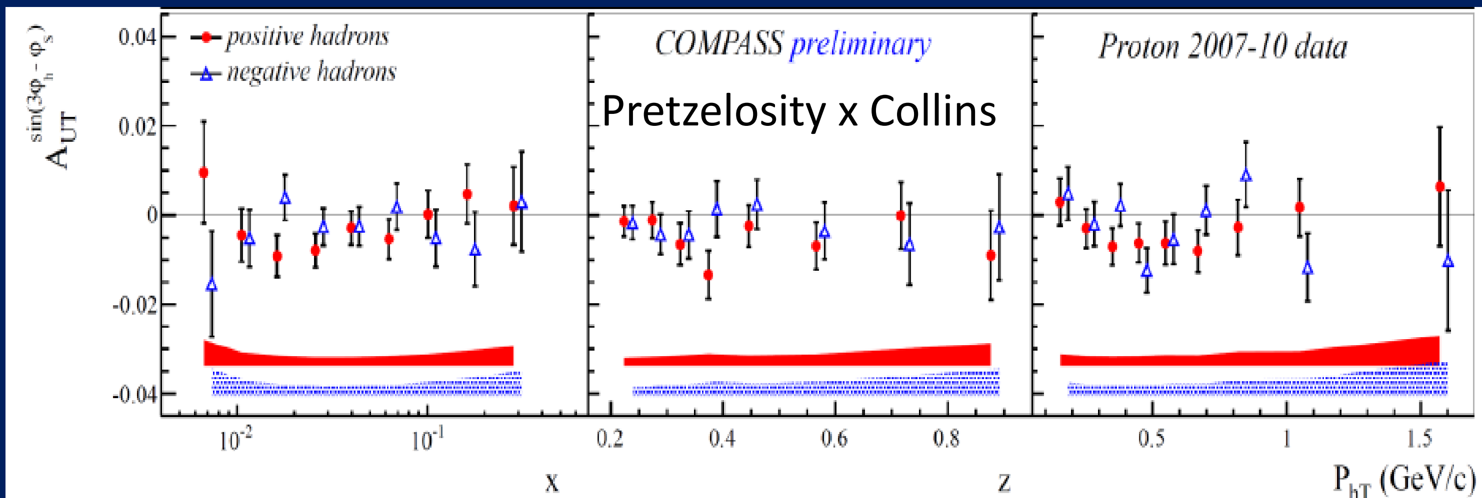
$\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(\pi)$] * [valence $h_1^{\perp}(p)$]

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

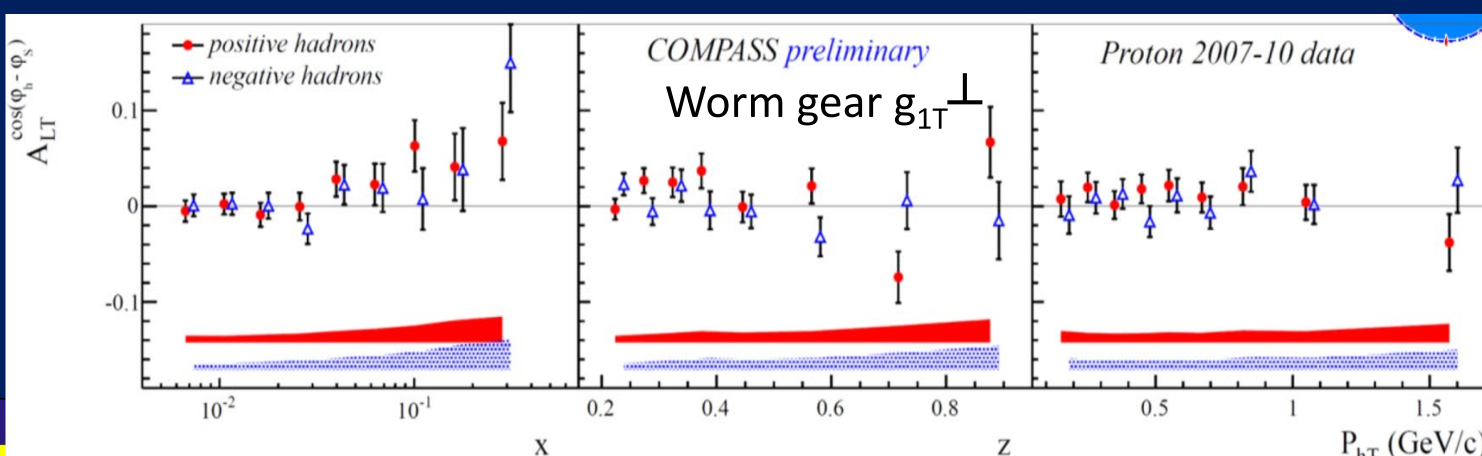
Other TMD PDF measurements in SIDIS



Other TMD PDF measurements in SIDIS

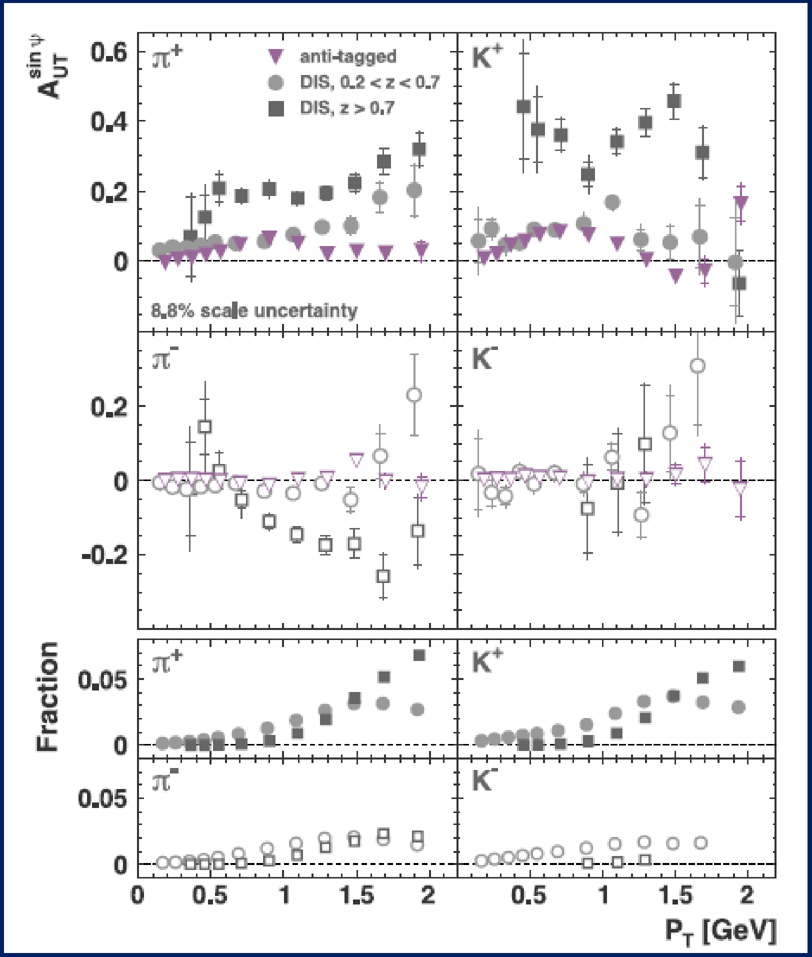


COMPASS



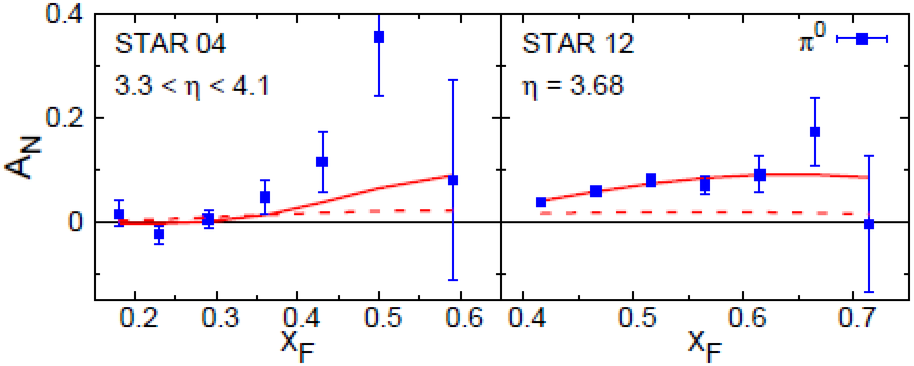
Inclusive hadron transverse single-spin asymmetries in e+p

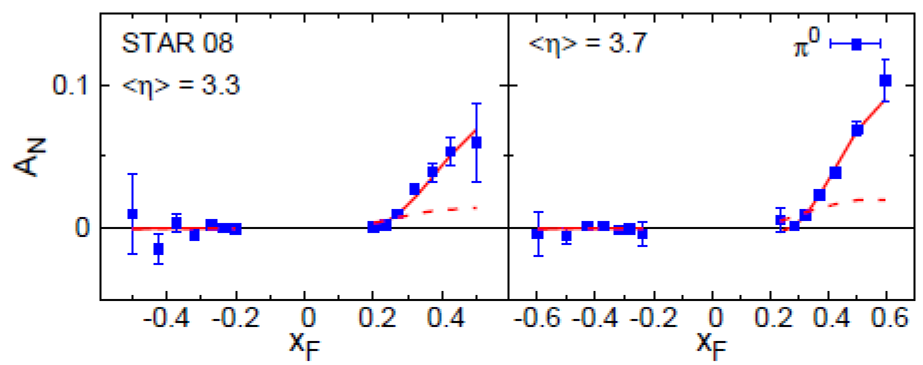
- Striking enhancement if measure scattered electron



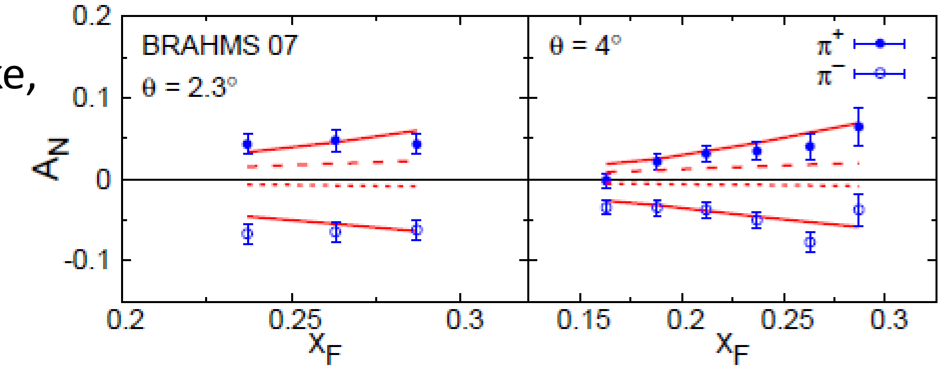
HERMES, PLB728, 183 (2014)

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





Kanazawa, Metz, Koike, Pitonyak
arXiv:1509.07554



Find dominant contribution from twist-3 correlation in hadronization

Midrapidity direct photon transverse single-spin asymmetry in p+p

Will improve constraints on twist-3 trigluon spin-momentum correlator