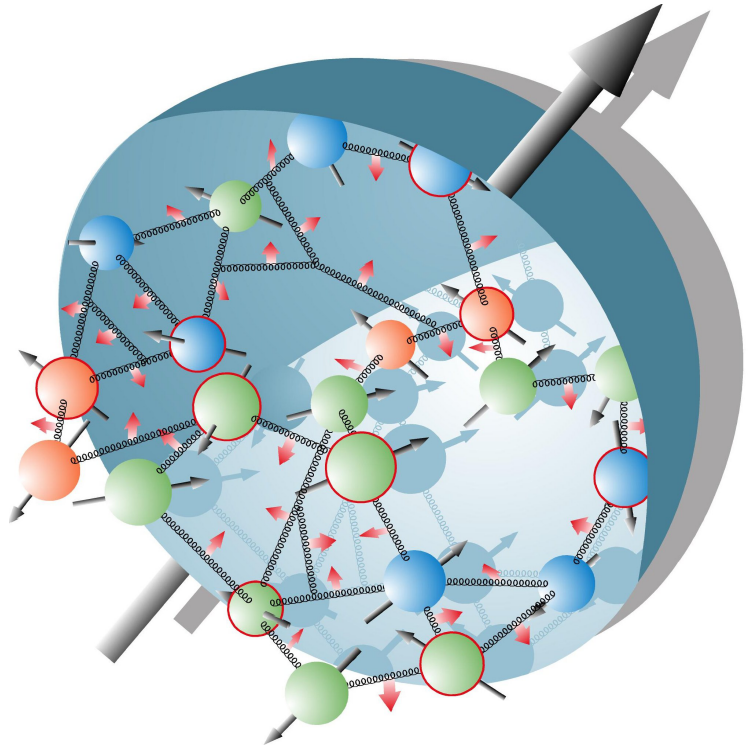
Overview of recent HERMES results on transverse-momentum dependent spin asymmetries

Markus Diefenthaler

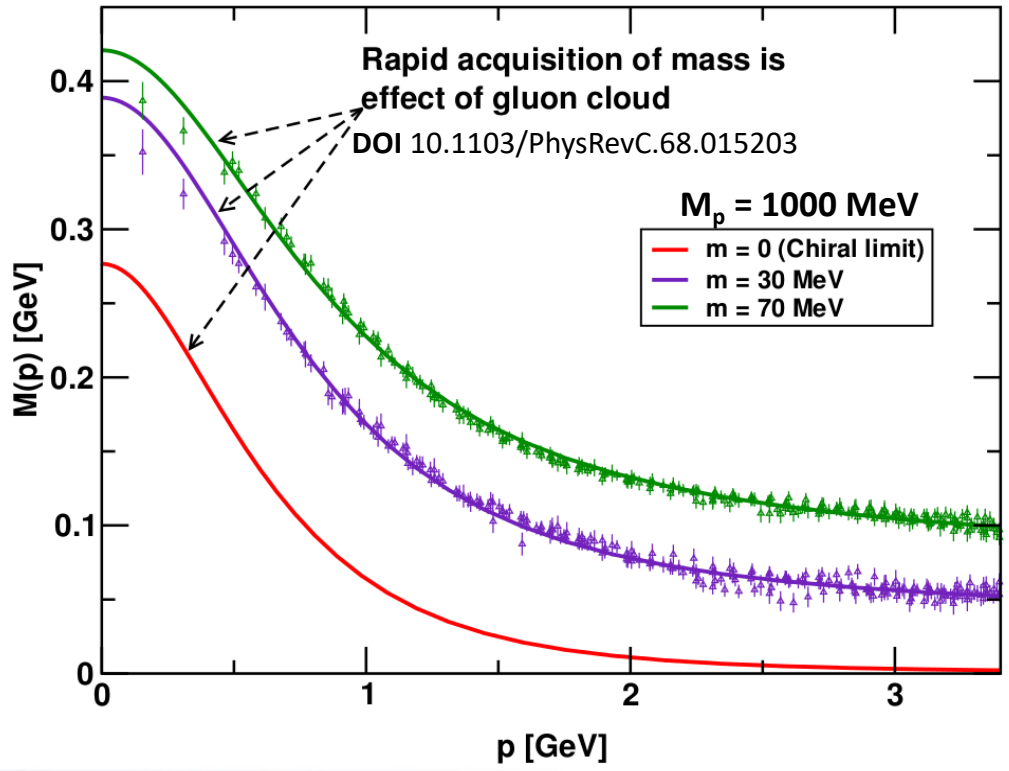
Jefferson Lab

The dynamical nature of nuclear matter

Nuclear Matter Interactions and structures, quark and gluons, are inextricably mixed up



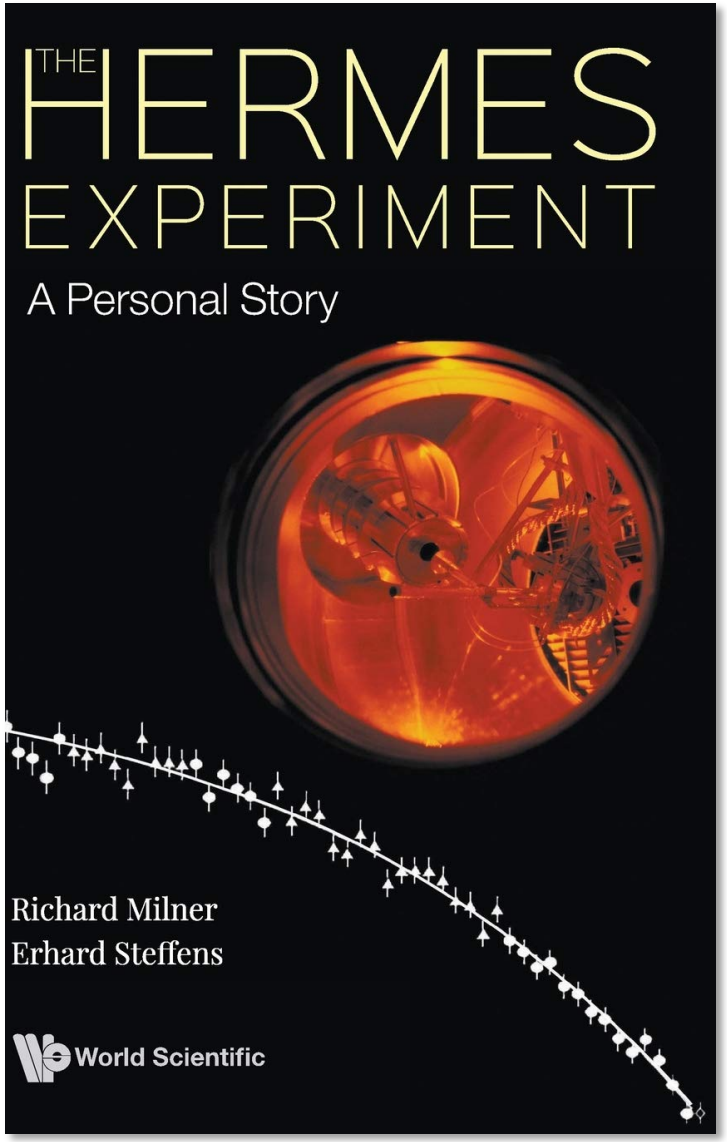
Observed properties such as mass and spin emerge out of the complex system



Ultimate goal Understand how matter at its most fundamental level is made

To reach goal precisely image quarks and gluons and their interactions

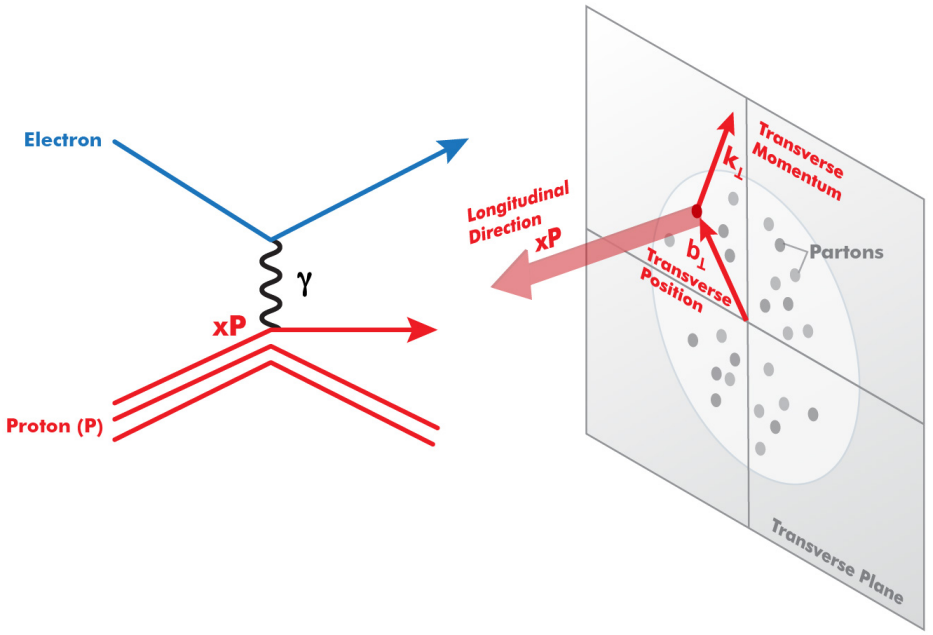
A reminiscence on the HERMES experiment



- **HERMES Collaboration (1988-now)**
  - Several hundred physicists from Europe and North America to study the **spin structure** of nuclear matter.
- **HERMES Experiment (1995-2007)**
  - Technically innovative HERMES experiment at the first electron-proton collider, HERA.
- **HERMES Legacy**
  - Considerable impact of scientific results with many pioneering measurements.
  - Shaped an entire generation of young people into scientific leaders.

Polarized DIS measurements

Novel QCD phenomena



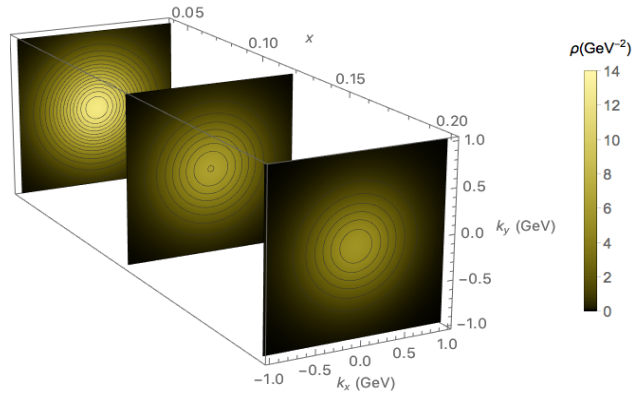
3D imaging in space and momentum

longitudinal structure (PDF)
+ transverse momentum information (TMDs)

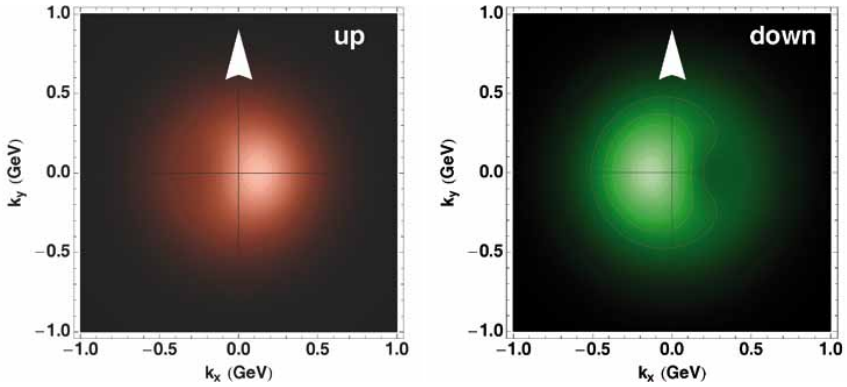
order of a few hundred MeV

Unpolarized nucleon

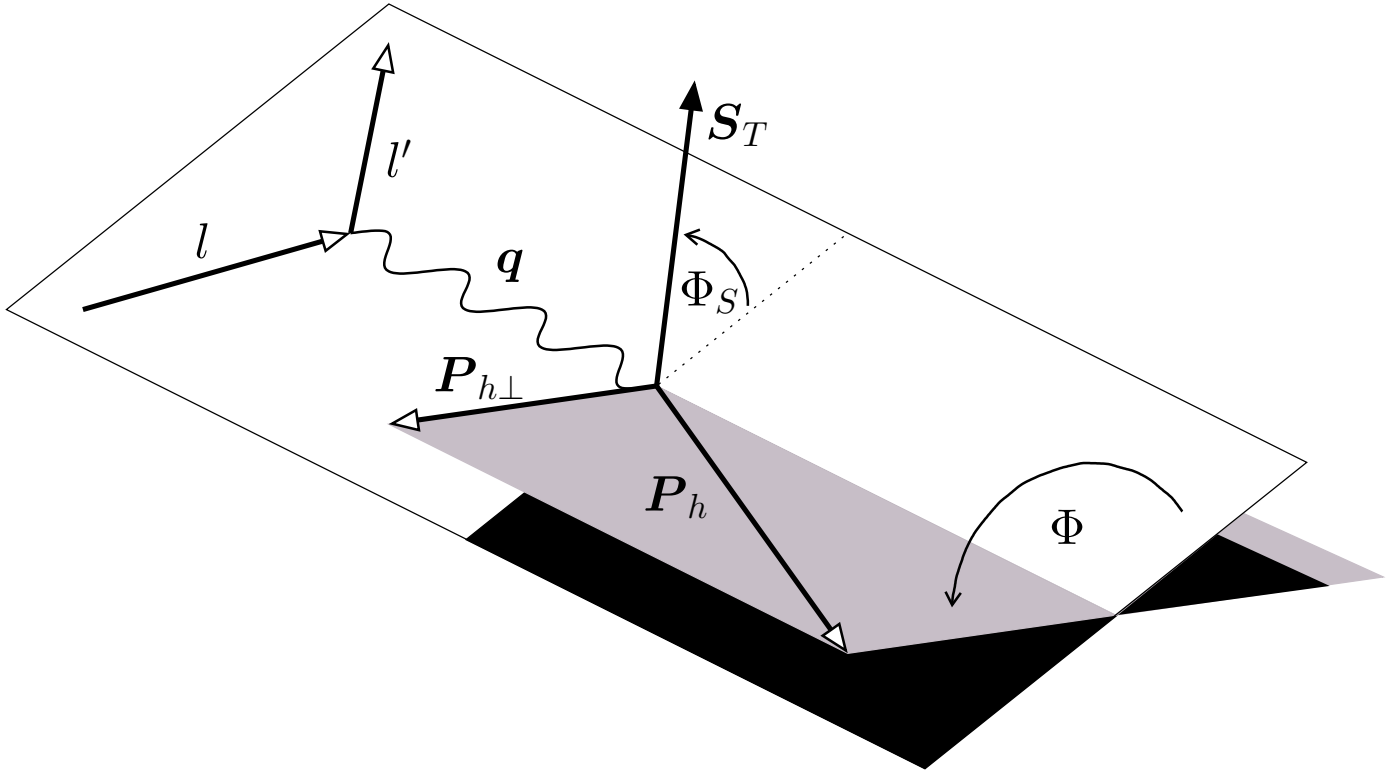
JHEP 1706 (2017) 081



Transversely polarized nucleon



SSA in SIDIS measurements at HERMES



TSSA at HERMES

- two naive-*T*-odd functions at leading twist:
  - Sivers TMD: **Sivers effect** $\mathbf{S}_N \cdot (\mathbf{q} \times \mathbf{P}_h)$
  - Collins FF: **Collins effect** $\mathbf{s}_q \cdot (\mathbf{p}_q \times \mathbf{P}_h)$

Signals for TMD PDFs and TMD FFs

Differential cross section

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

Cross section decomposition in terms of structure functions

$$\Big\{ \Big[F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \varepsilon\cos(2\phi) F_{UU}^{\cos(2\phi)}\Big]$$

Sivers effect

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right)$$

Collins effect

$$+\varepsilon\sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

Factorized results in terms of TMD PDFs and TMD FFs

at tree-level and twist-2 and twist-3 accuracy

Assuming one-photon exchange, current fragmentation only, TMD factorization hold, small transverse momenta, Gaussian Ansatz valid

Sivers TMD and spin-independent FF

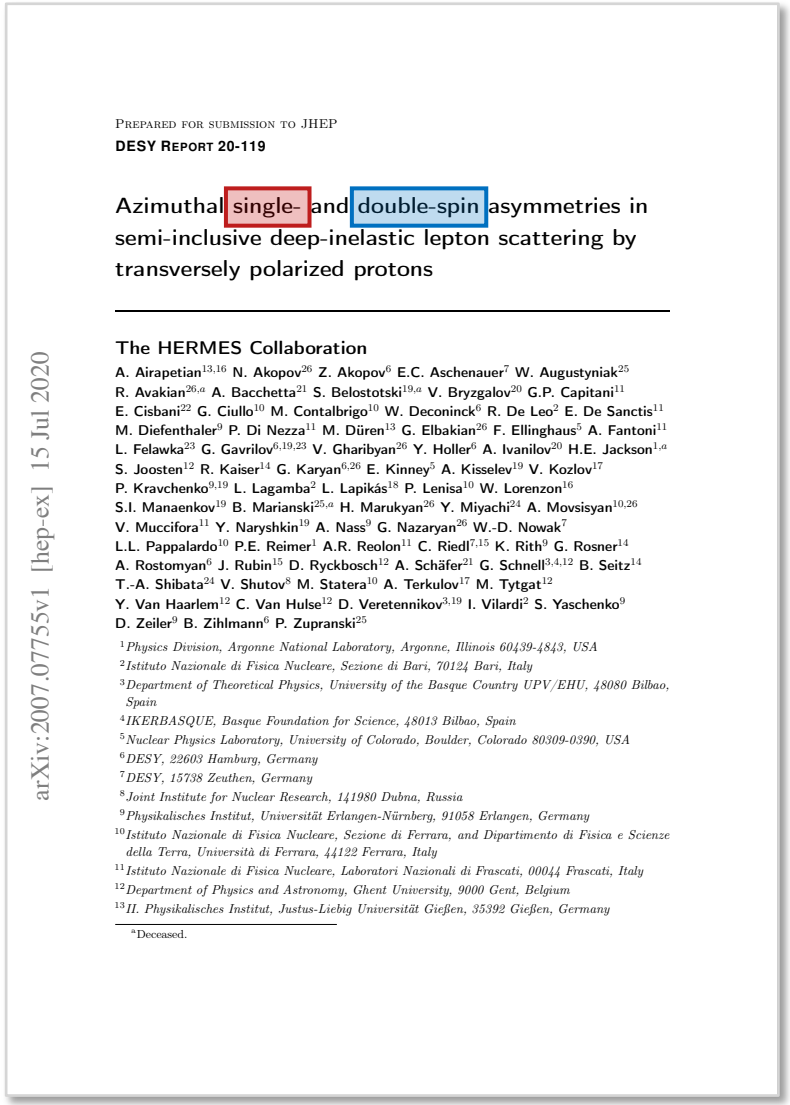
$$F_{UT,T}^{\sin(\phi-\phi_S)} = \mathscr{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M} f_{1T}^{\perp} D_1\right]$$

Transversity PDF and Collins FF

$$F_{UT}^{\sin(\phi+\phi_S)} = \mathscr{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h} h_1 H_1^{\perp}\right]$$

The HERMES compendium on TMD analysis

JHEP 12 (2020) 010



Prepared for submission to JHEP

DESY Report 20-119

Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering by transversely polarized protons

The HERMES Collaboration

A. Airapetian[13,16] N. Akopov[26] Z. Akopov[6] E.C. Aschenauer[7] W. Augustyniak[25] R. Avakian[26,a] A. Bacchetta[21] S. Belostotski[19,a] V. Bryzgalov[20] G.P. Capitani[11] E. Cisbani[22] G. Ciullo[10] M. Contalbrigo[10] W. Deconinck[6] R. De Leo[2] E. De Sanctis[11] M. Diefenthaler[9] P. Di Nezza[11] M. Düren[13] G. Elbakian[26] F. Ellinghaus[5] A. Fantoni[11] L. Felawka[23] G. Gavrilov[6,19,23] V. Gharibyan[26] Y. Holler[6] A. Ivanilov[20] H.E. Jackson[1,a] S. Joosten[12] R. Kaiser[14] G. Karyan[6,26] E. Kinney[5] A. Kisselev[19] V. Kozlov[17] P. Kravchenko[9,19] L. Lagamba[2] L. Lapikás[18] P. Lenisa[10] W. Lorenzon[16] S.I. Manaenkov[19] B. Marianski[25,a] H. Marukyan[26] Y. Miyachi[24] A. Movsisyan[10,26] V. Muccifora[11] Y. Naryshkin[19] A. Nass[9] G. Nazaryan[26] W.-D. Nowak[7] L.L. Pappalardo[10] P.E. Reimer[1] A.R. Reolon[11] C. Riedl[7,15] K. Rith[9] G. Rosner[14] A. Rostomyan[6] J. Rubin[15] D. Ryckbosch[12] A. Schäfer[21] G. Schnell[3,4,12] B. Seitz[14] T.-A. Shibata[24] V. Shutov[8] M. Statera[10] A. Terkulov[17] M. Tytgat[12] Y. Van Haarlem[12] C. Van Hulse[12] D. Veretennikov[3,19] I. Vilardi[2] S. Yaschenko[9] D. Zeiler[9] B. Zihlmann[6] P. Zupranski[25]

[1] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439-4843, USA*
[2] *Istituto Nazionale di Fisica Nucleare, Sezione di Bari, 70124 Bari, Italy*
[3] *Department of Theoretical Physics, University of the Basque Country UPV/EHU, 48080 Bilbao, Spain*
[4] *IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain*
[5] *Nuclear Physics Laboratory, University of Colorado, Boulder, Colorado 80309-0390, USA*
[6] *DESY, 22603 Hamburg, Germany*
[7] *DESY, 15738 Zeuthen, Germany*
[8] *Joint Institute for Nuclear Research, 141980 Dubna, Russia*
[9] *Physikalisches Institut, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany*
[10] *Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, and Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, 44122 Ferrara, Italy*
[11] *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, 00044 Frascati, Italy*
[12] *Department of Physics and Astronomy, Ghent University, 9000 Gent, Belgium*
[13] *II. Physikalisches Institut, Justus-Liebig Universität Gießen, 35392 Gießen, Germany*

[a] Deceased.

$$
\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right) \Bigg\{ & \\
& \Big[F_{UU,T} + \varepsilon F_{UU,L} \\
& + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \varepsilon\cos(2\phi) F_{UU}^{\cos(2\phi)}\Big] \\
+ \quad \lambda_l & \Big[\sqrt{2\varepsilon(1-\varepsilon)}\sin(\phi) F_{LU}^{\sin(\phi)}\Big] \\
+ \quad S_L & \Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi) F_{UL}^{\sin(\phi)} + \varepsilon\sin(2\phi) F_{UL}^{\sin(2\phi)}\Big] \\
+ \quad S_L \quad \lambda_l & \Big[\sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos(\phi) F_{LL}^{\cos(\phi)}\Big] \\
+ \quad S_T & \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) \\
& + \varepsilon\sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)} \\
& + \sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} \\
& + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\Big] \\
+ \quad S_T \quad \lambda_l & \Big[\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} \\
& + \sqrt{2\varepsilon(1-\varepsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)} \\
& + \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\Big] \\
\Big\} &
\end{aligned}
$$

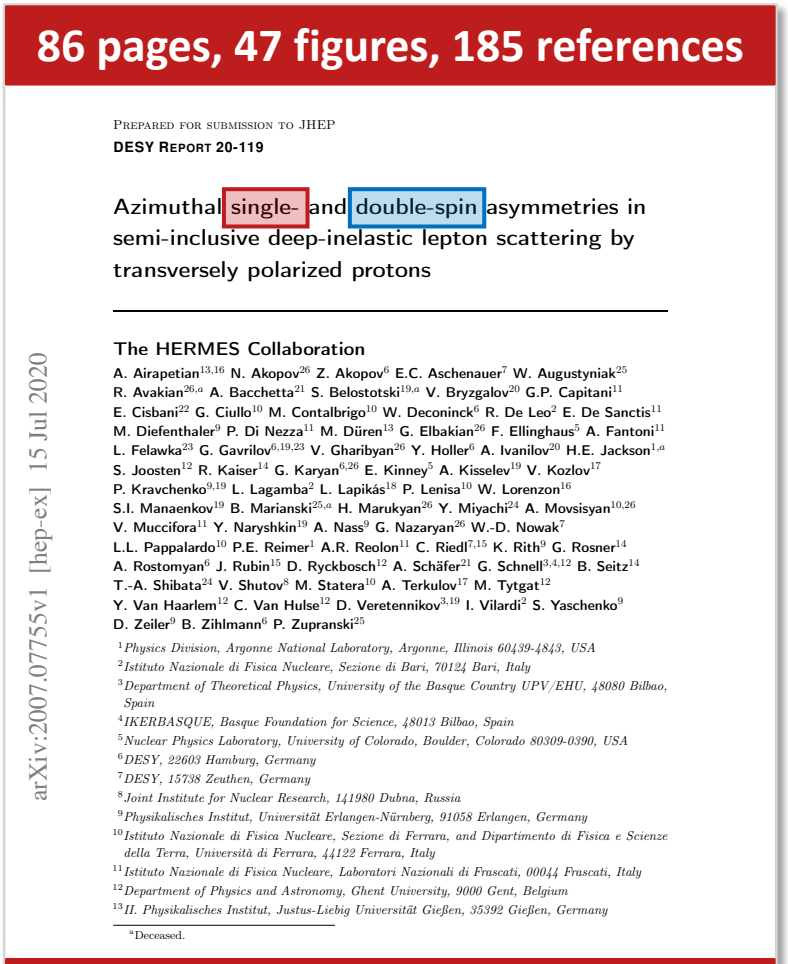
Single-Spin Asymmetries (SSA)

Double-Spin Asymmetries (DSA)

The HERMES compendium on TMD analysis

JHEP 12 (2020) 010

86 pages, 47 figures, 185 references



Prepared for submission to JHEP
DESY Report 20-119

Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering by transversely polarized protons

The HERMES Collaboration

A. Airapetian[13,16] N. Akopov[26] Z. Akopov[6] E.C. Aschenauer[7] W. Augustyniak[25] R. Avakian[26,a] A. Bacchetta[21] S. Belostotski[19,a] V. Bryzgalov[20] G.P. Capitani[11] E. Cisbani[22] G. Ciullo[10] M. Contalbrigo[10] W. Deconinck[6] R. De Leo[2] E. De Sanctis[11] M. Diefenthaler[9] P. Di Nezza[11] M. Düren[13] G. Elbakian[26] F. Ellinghaus[5] A. Fantoni[11] L. Felawka[23] G. Gavrilov[6,19,23] V. Gharibyan[26] Y. Holler[6] A. Ivanilov[20] H.E. Jackson[1,a] S. Joosten[12] R. Kaiser[14] G. Karyan[6,26] E. Kinney[5] A. Kisselev[19] V. Kozlov[17] P. Kravchenko[9,19] L. Lagamba[2] L. Lapikás[18] P. Lenisa[10] W. Lorenzon[16] S.I. Manaenkov[19] B. Marianski[25,a] H. Marukyan[26] Y. Miyachi[24] A. Movsisyan[10,26] V. Muccifora[11] Y. Naryshkin[19] A. Nass[9] G. Nazaryan[26] W.-D. Nowak[7] L.L. Pappalardo[10] P.E. Reimer[1] A.R. Reolon[11] C. Riedl[7,15] K. Rith[9] G. Rosner[14] A. Rostomyan[6] J. Rubin[15] D. Ryckbosch[12] A. Schäfer[21] G. Schnell[3,4,12] B. Seitz[14] T.-A. Shibata[24] V. Shutov[8] M. Statera[10] A. Terkulov[17] M. Tytgat[12] Y. Van Haarlem[12] C. Van Hulse[12] D. Veretennikov[3,19] I. Vilardi[2] S. Yaschenko[9] D. Zeiler[9] B. Zihlmann[6] P. Zupranski[25]

[1] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439-4843, USA*
[2] *Istituto Nazionale di Fisica Nucleare, Sezione di Bari, 70124 Bari, Italy*
[3] *Department of Theoretical Physics, University of the Basque Country UPV/EHU, 48080 Bilbao, Spain*
[4] *IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain*
[5] *Nuclear Physics Laboratory, University of Colorado, Boulder, Colorado 80309-0390, USA*
[6] *DESY, 22603 Hamburg, Germany*
[7] *DESY, 15738 Zeuthen, Germany*
[8] *Joint Institute for Nuclear Research, 141980 Dubna, Russia*
[9] *Physikalisches Institut, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany*
[10] *Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, and Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, 44122 Ferrara, Italy*
[11] *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, 00044 Frascati, Italy*
[12] *Department of Physics and Astronomy, Ghent University, 9000 Gent, Belgium*
[13] *II. Physikalisches Institut, Justus-Liebig Universität Gießen, 35392 Gießen, Germany*

[a] Deceased.

Supplemental material
118 pages, 23 figures, 118 tables

10 type of asymmetries
- 6 SSA
- **4 DSA**

New

7 hadron types
- π^+, π^0, π^-
- K^+, K^-
- **protons and antiprotons**

3D projections and **optimized 1D projections**
- x $0.023 < x < \mathbf{0.6}$ (before $x < 0.4$)
- z $0.2 < z < \mathbf{1.2}$ (before $z < 0.7$)
- $P_{h\perp}$

2 types of extractions
- **Cross-Section Asymmetries (CSA)** entire Fourier amplitude of each cross-section contribution.
- **Structure-Function Asymmetries (SFA)** pure ratios of structure functions, including correction for ε-dependent kinematic prefactors.

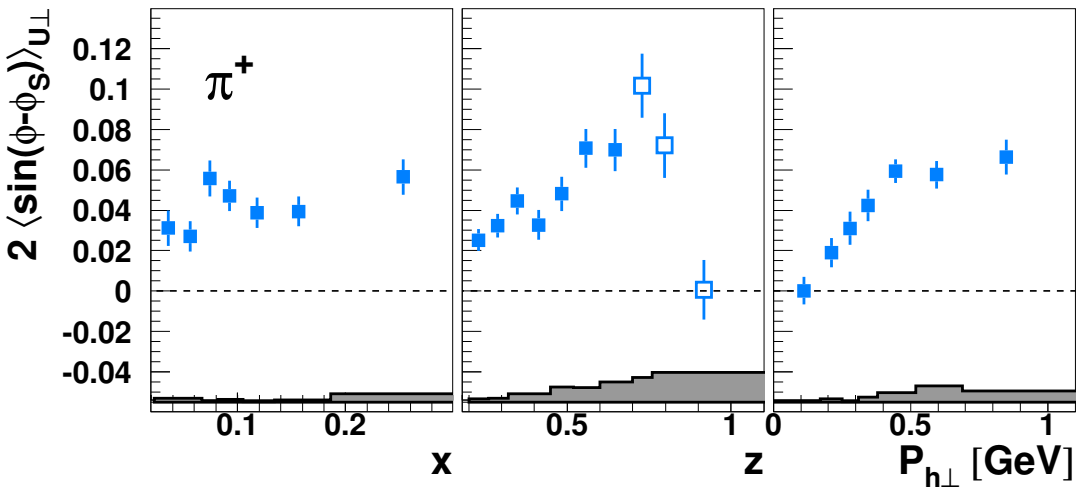
SSA and DSA summary

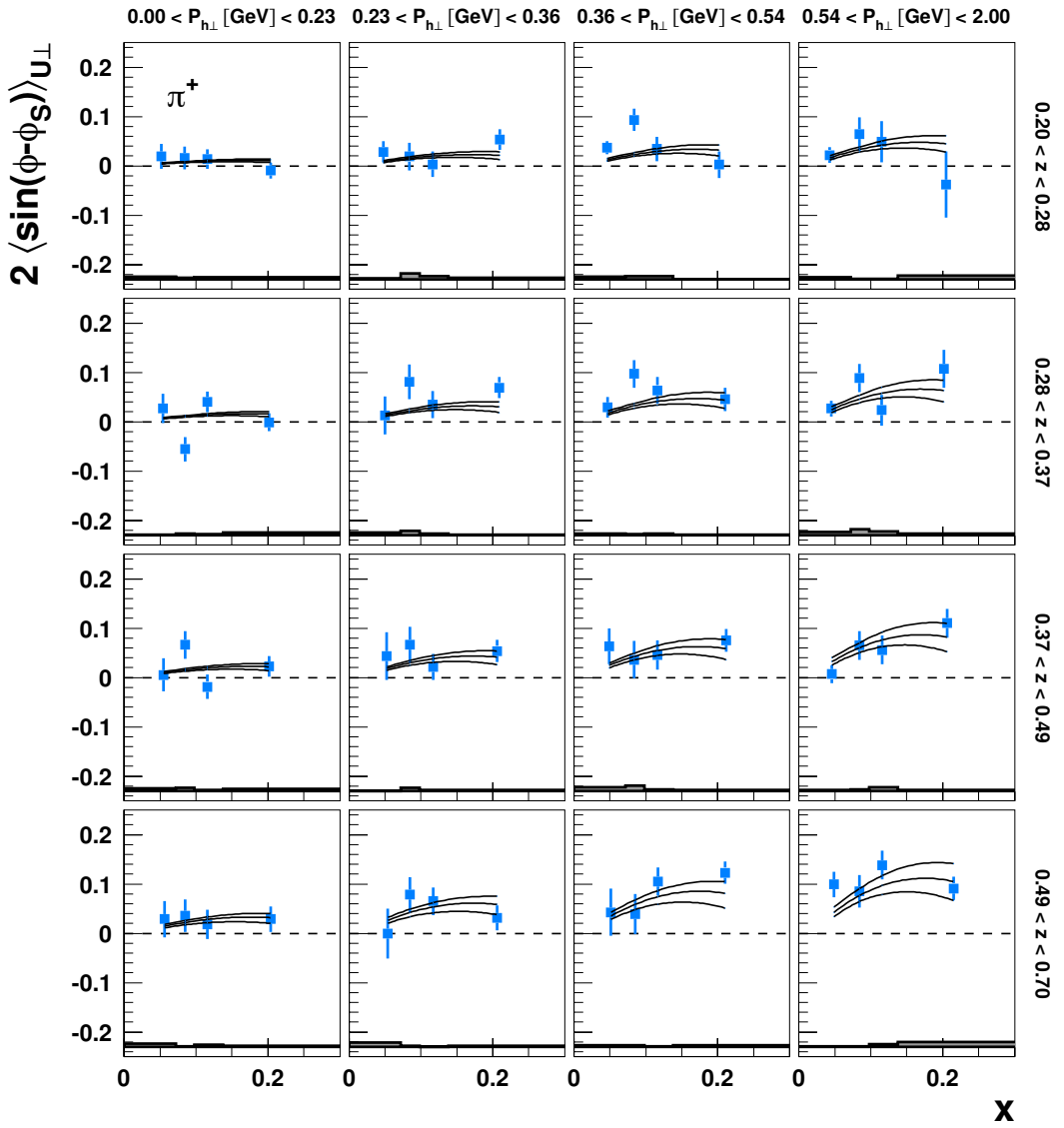
✓ := incompatible with NULL hypothesis at 95% CL (✓) := incompatible with NULL hypothesis at 90% CL

Azimuthal modulation		Significant non-vanishing Fourier amplitude						
		π^+	π^-	K^+	K^-	p	π^0	$\bar{p}$
$\sin(\phi+\phi_S)$	[Collins]	✓	✓	✓		✓		
$\sin(\phi-\phi_S)$	[Sivers]	✓		✓	✓	✓	(✓)	✓
$\sin(3\phi-\phi_S)$	[Pretzelosity]							
$\sin(\phi_S)$		(✓)	✓		✓			
$\sin(2\phi-\phi_S)$								(✓)
$\sin(2\phi+\phi_S)$				✓				
$\cos(\phi-\phi_S)$	[Worm-gear]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

Next slides Discussion of the Sivers amplitudes, expanding on the earlier publication, PRL103 (2009) 152002, where HERMES reported clear evidence for the Sivers effect in SIDIS.

Multi-dimensional analysis

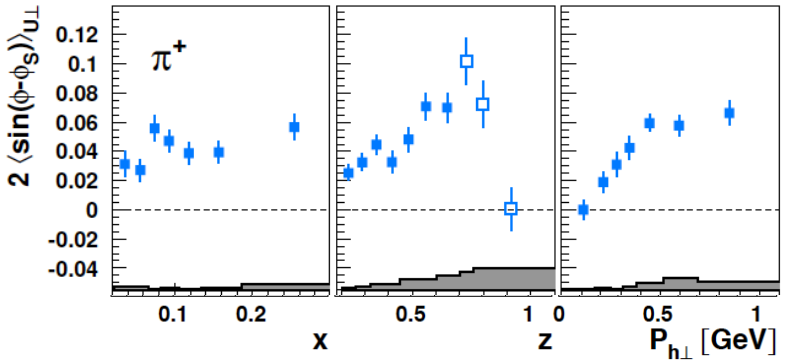




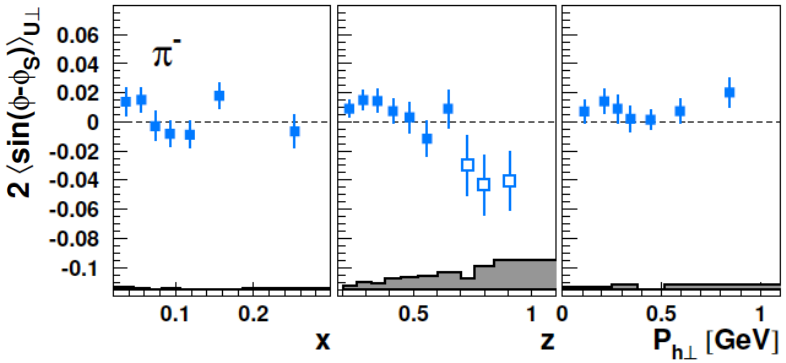
Fully differential approach with small bin-sizes

- minimizes the dominant contributions to the systematic uncertainty, and therefore maximizes the attainable experimental precision
- maximize information for QCD analysis

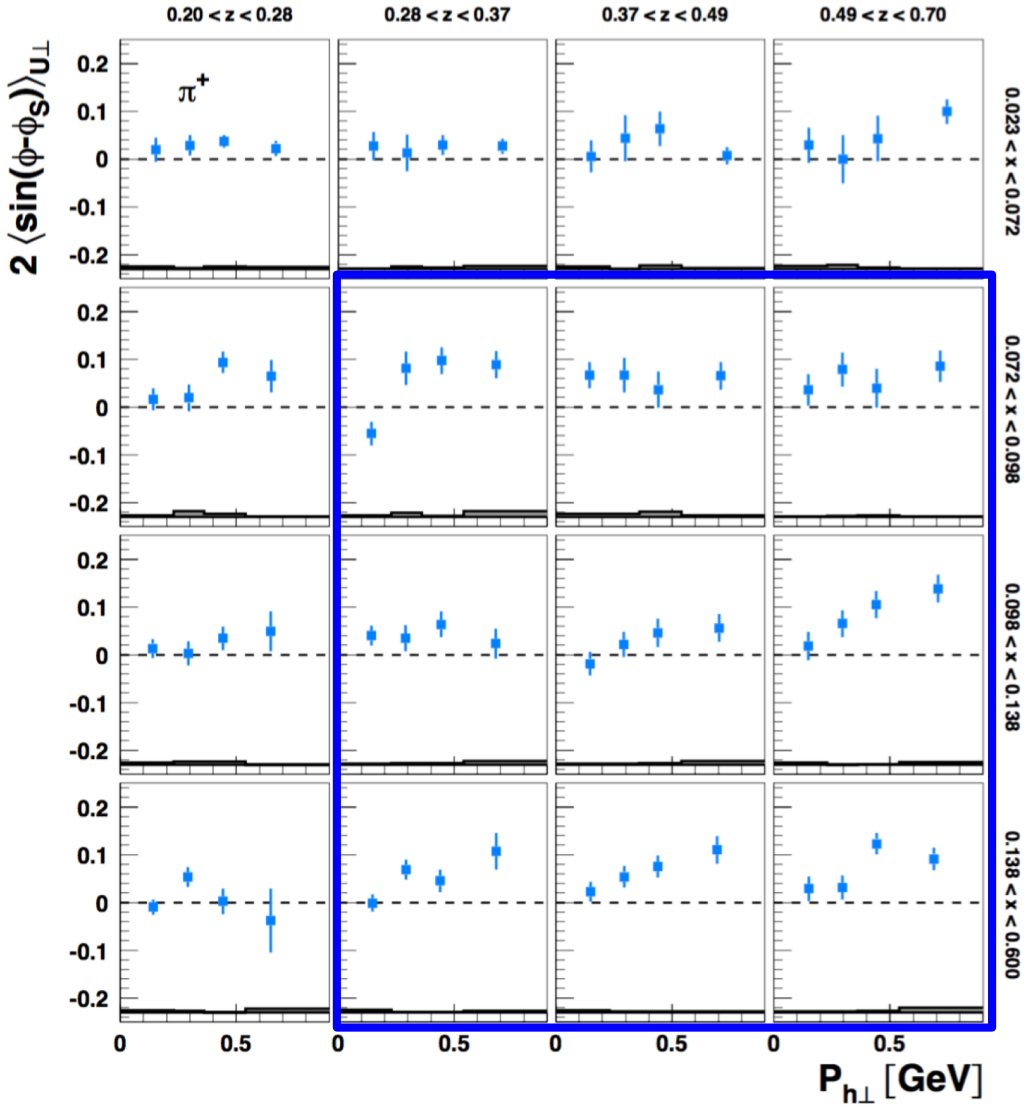
Sivers amplitudes for charged pions



- large positive amplitude → clear evidence of non-zero $f_{1T}^{\perp,u}$
- signal rises with x, z and $P_{h\perp}$ in SIDIS region ($0.2 < z < 0.7$)
- More informative 3D projections confirm and further detail the rise of the amplitude at large x, z and $P_{h\perp}$

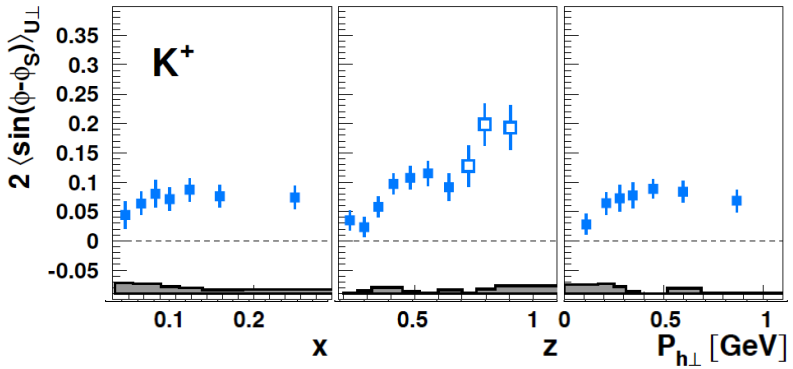


Vanishing due to the cancellation of the opposite Sivers effect for *u* and *d* quarks

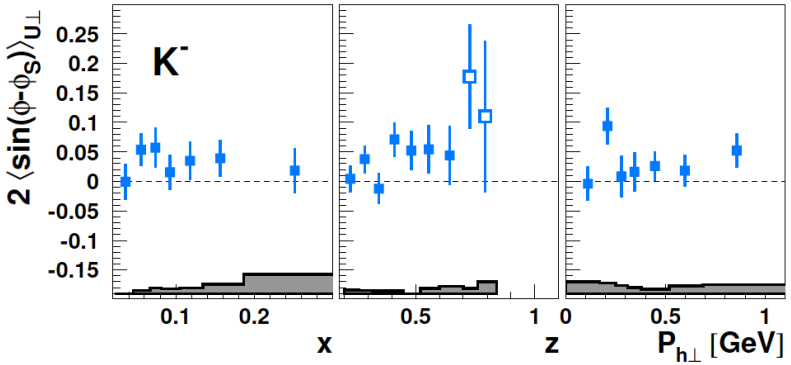


Jefferson Lab

Sivers amplitudes for charged kaons

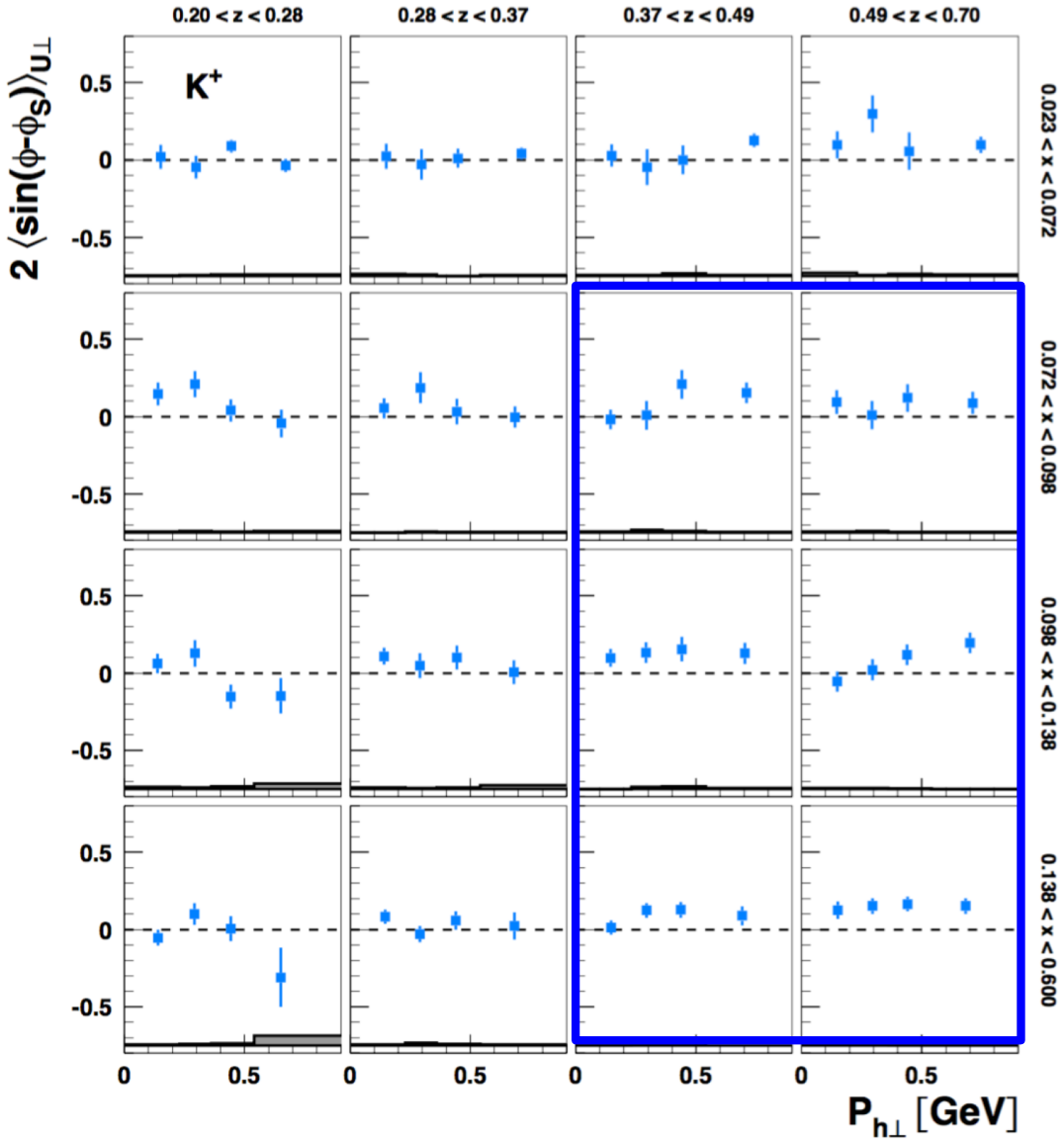


Large positive amplitude, similar kinematic dep. of π^+



Positive amplitude, different than π^-

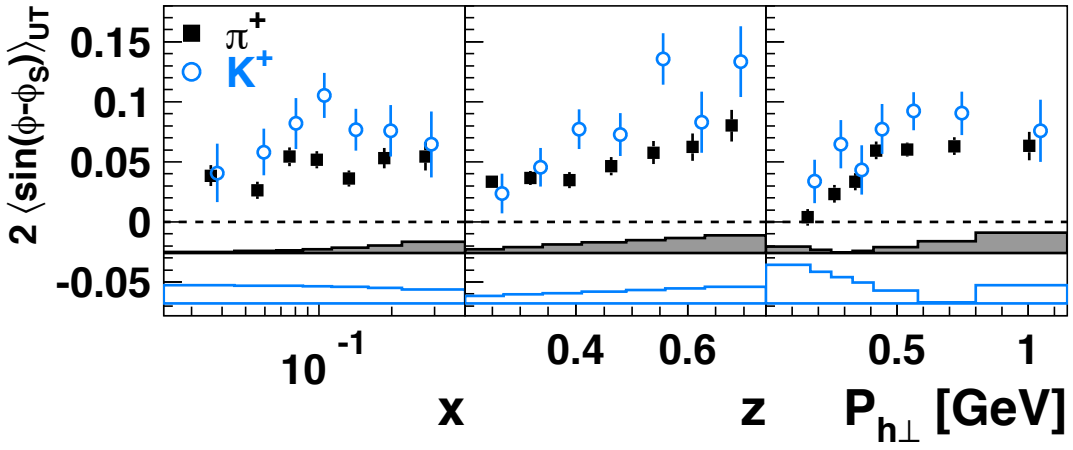
K^- is a pure sea object with no valence quarks in common with target proton

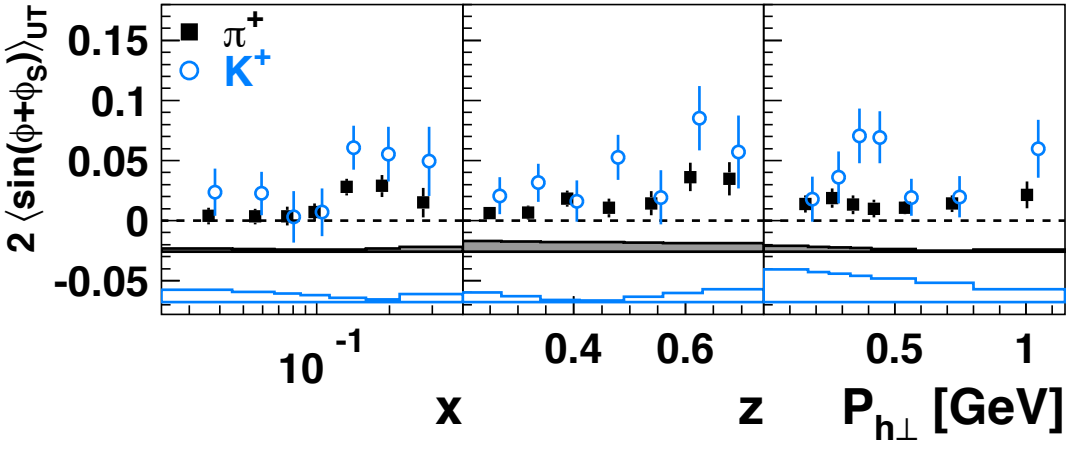


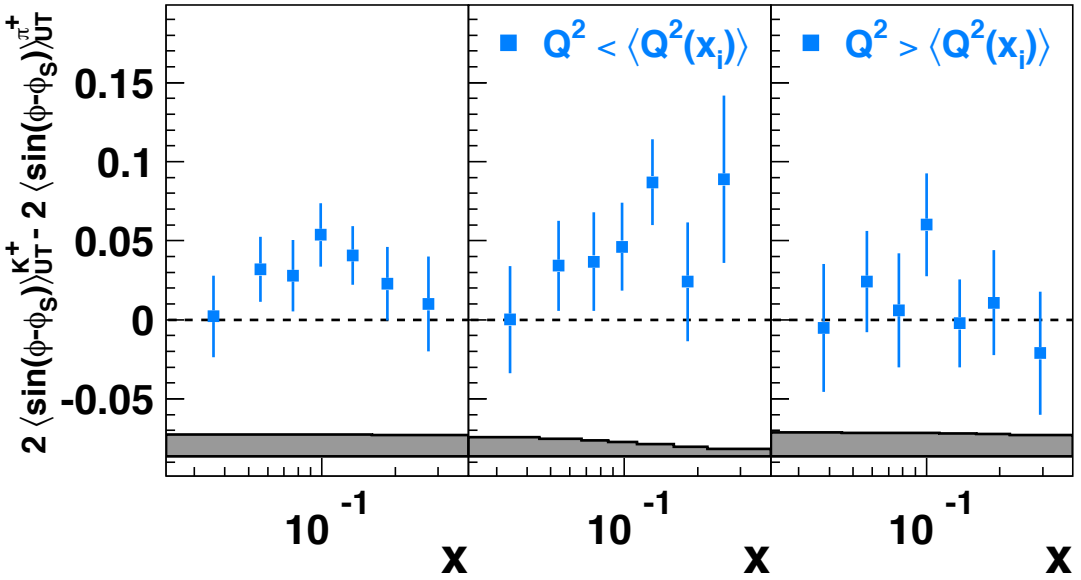
Jefferson Lab

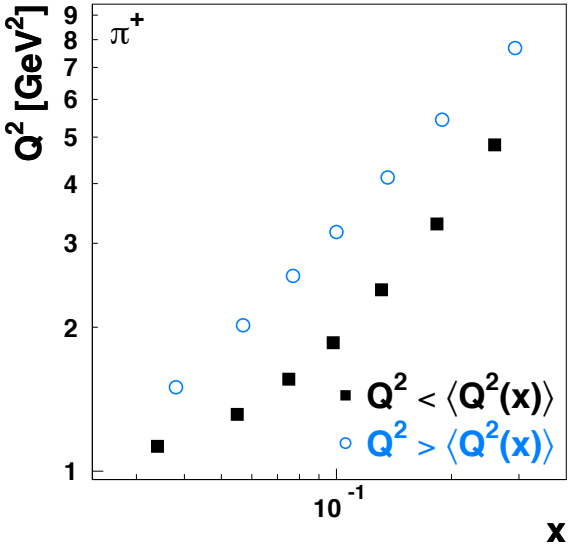
u-quark dominance and the role of higher twist

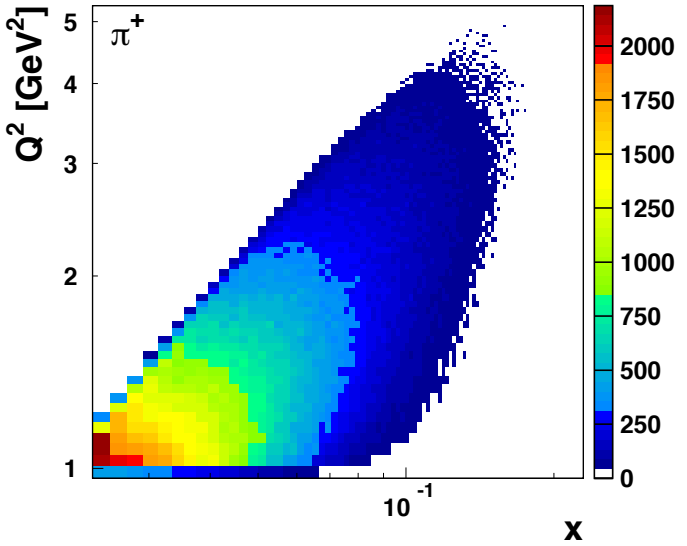
PRL103 (2009) 152002



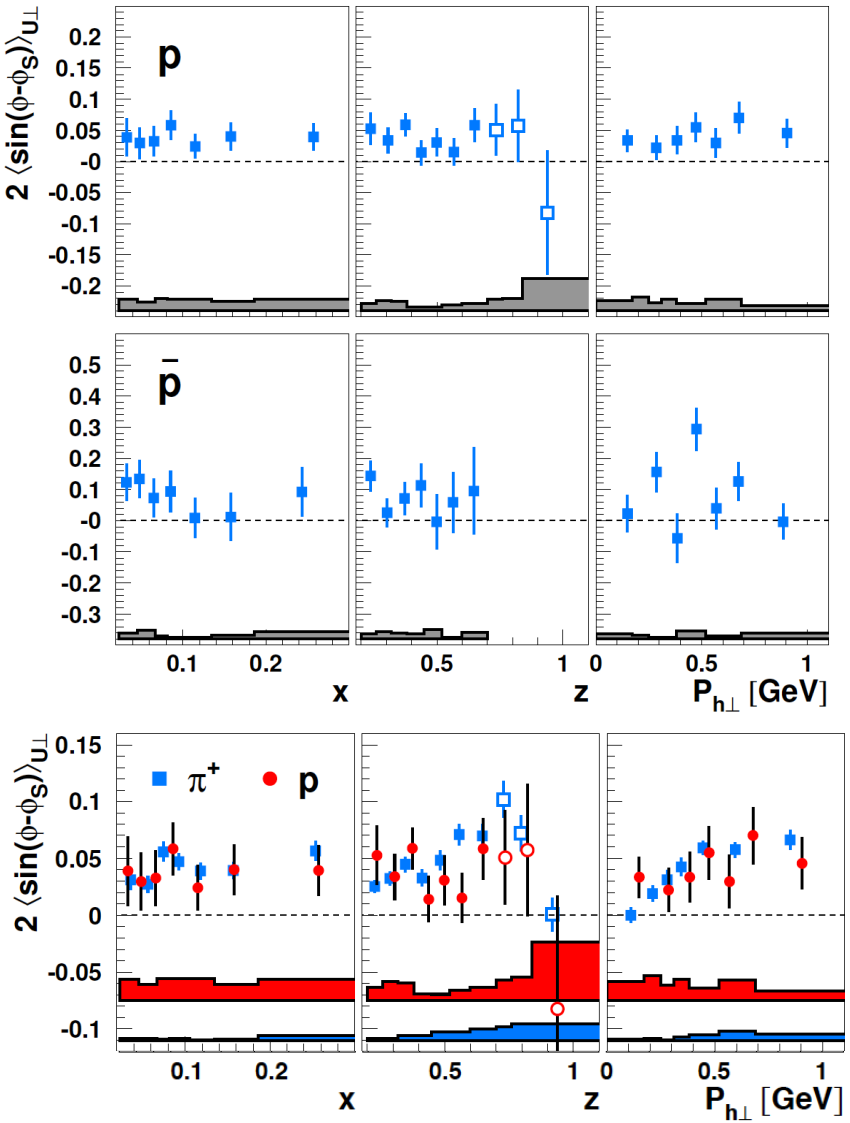








Sivers amplitudes for protons

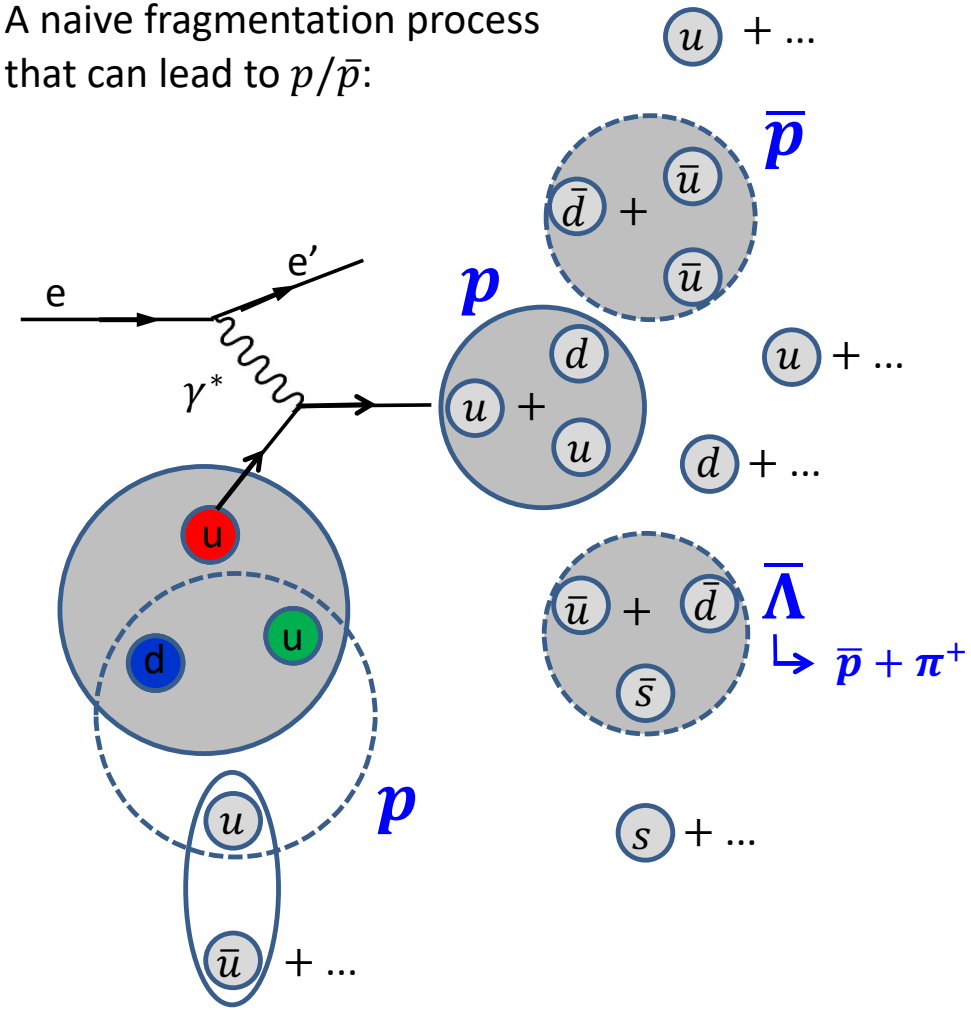


First measurement of Sivers asymmetries for $p, \bar{p}$ in SIDIS

Both amplitudes are non-zero and positive

Similar agreement between $\bar{p}$ and π^+ (but with larger statistical errors)

A naive fragmentation process that can lead to $p/\bar{p}$:

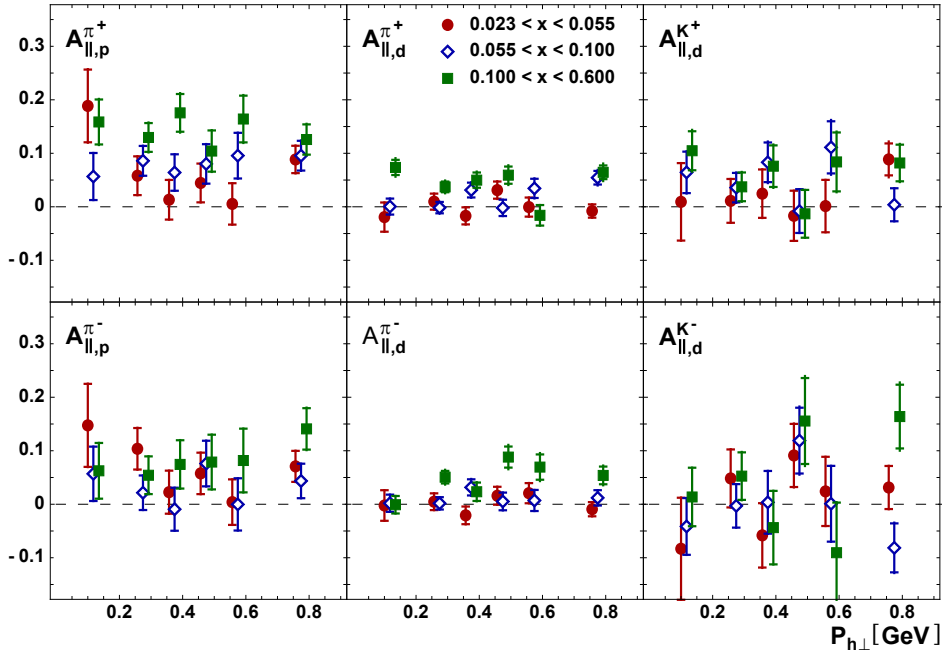


...also from TFR (low z, high $P_{h\perp}$)

Additional HERMES results on DSA and SSA

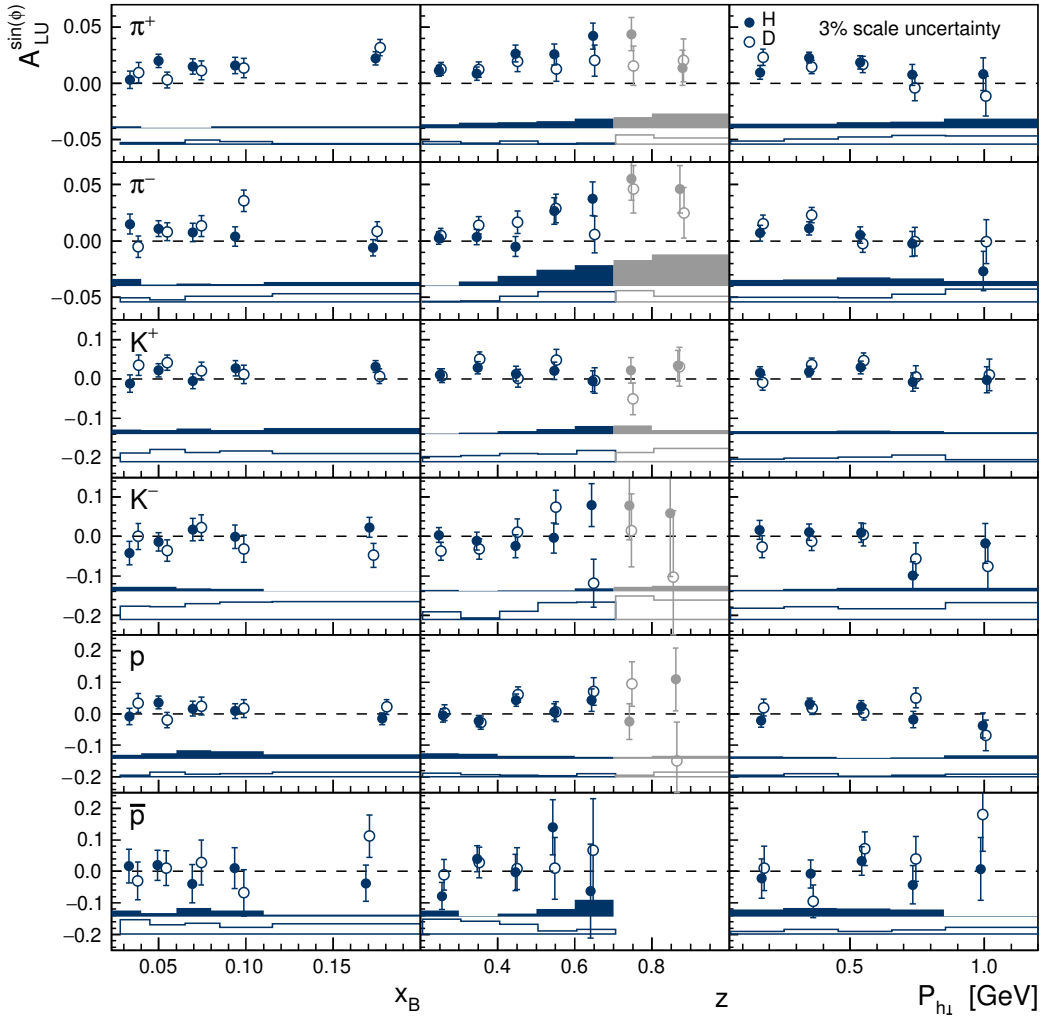
Multidimensional analysis of longitudinal DSA $A_{\parallel}$ in SIDIS, including transverse dependence

Phys.Rev.D 99 (2019) 11, 112001



Multidimensional analysis of beam-helicity asymmetries for single-hadron production in SIDIS

Phys.Lett.B 797 (2019) 134886



Jefferson Lab

Markus Diefenthaler

mdiefent@jlab.org

- **TMDs** Imaging quarks and gluons within the nucleon.
- **HERMES** Pioneering TMD measurements
  - **Recent** HERMES results in 3D binning maximize information for QCD analysis.
- **Important guidance for**
  - **The 12 GeV Science Program at Jefferson Lab** Precision TMD studies for valence quarks.
  - **Electron-Ion Collider** Precision TMD studies for sea quarks and gluons.