Pioneering TMD measurements at the HERMES experiment

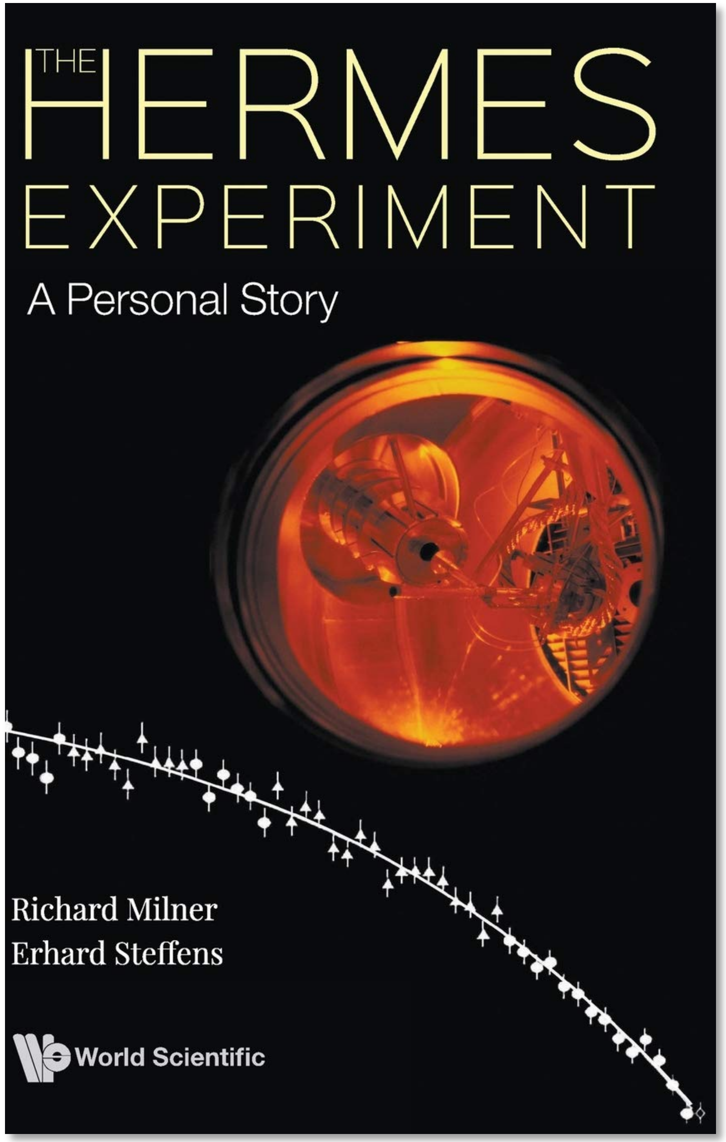
Member of HERMES collaboration and its TMD Working Group

EIC²

EIC Center at Jefferson Lab

Markus Diefenthaler

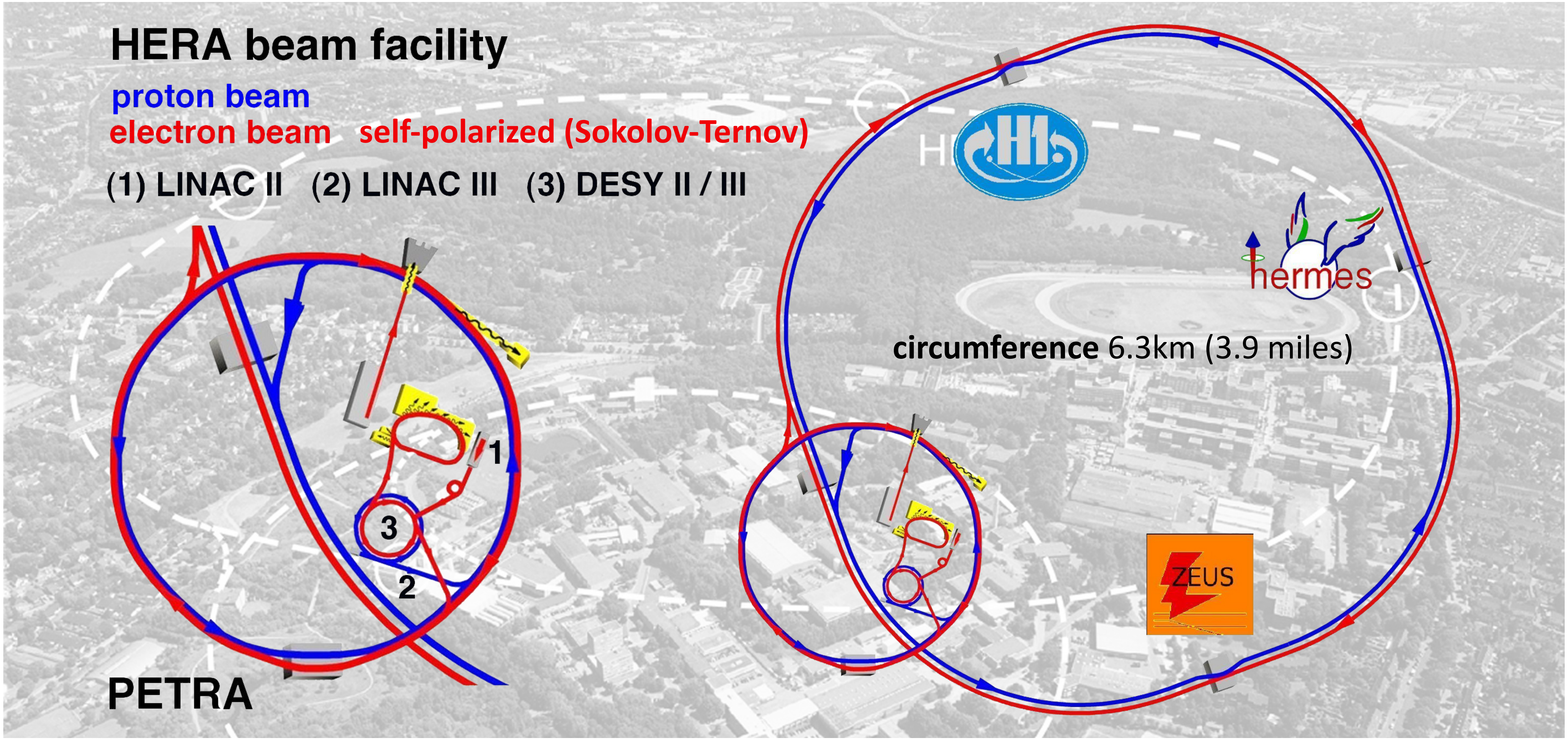
A reminiscence on the HERMES experiment



This book describes the story of how a collaboration of several hundred physicists from Europe and North America formed in 1988 to design, construct, install, commission and operate, for the years 1995-2007 the technically innovative HERMES experiment at the DESY laboratory in Hamburg, Germany to **study the spin structure** of the fundamental structure of matter.

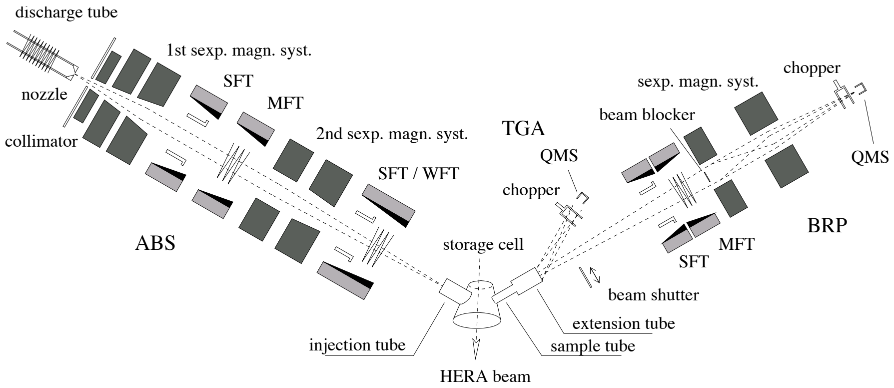
The book describes the HERMES scientific results, their **considerable impact**, how HERMES shaped an entire generation of young people into scientific leaders, and ends with a description of the twenty-first century picture of the proton that has subsequently been developed.

The first Electron-Ion Collider: HERA (1992 – 2007)

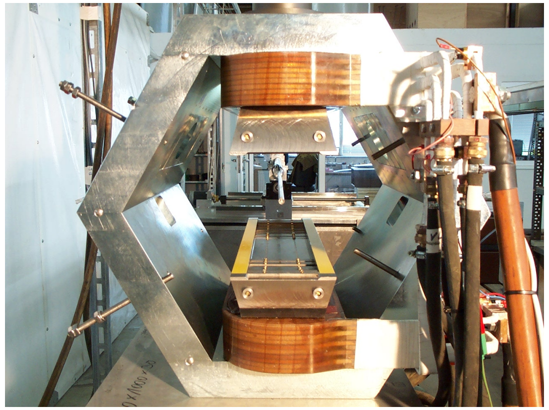


HERMES experiment

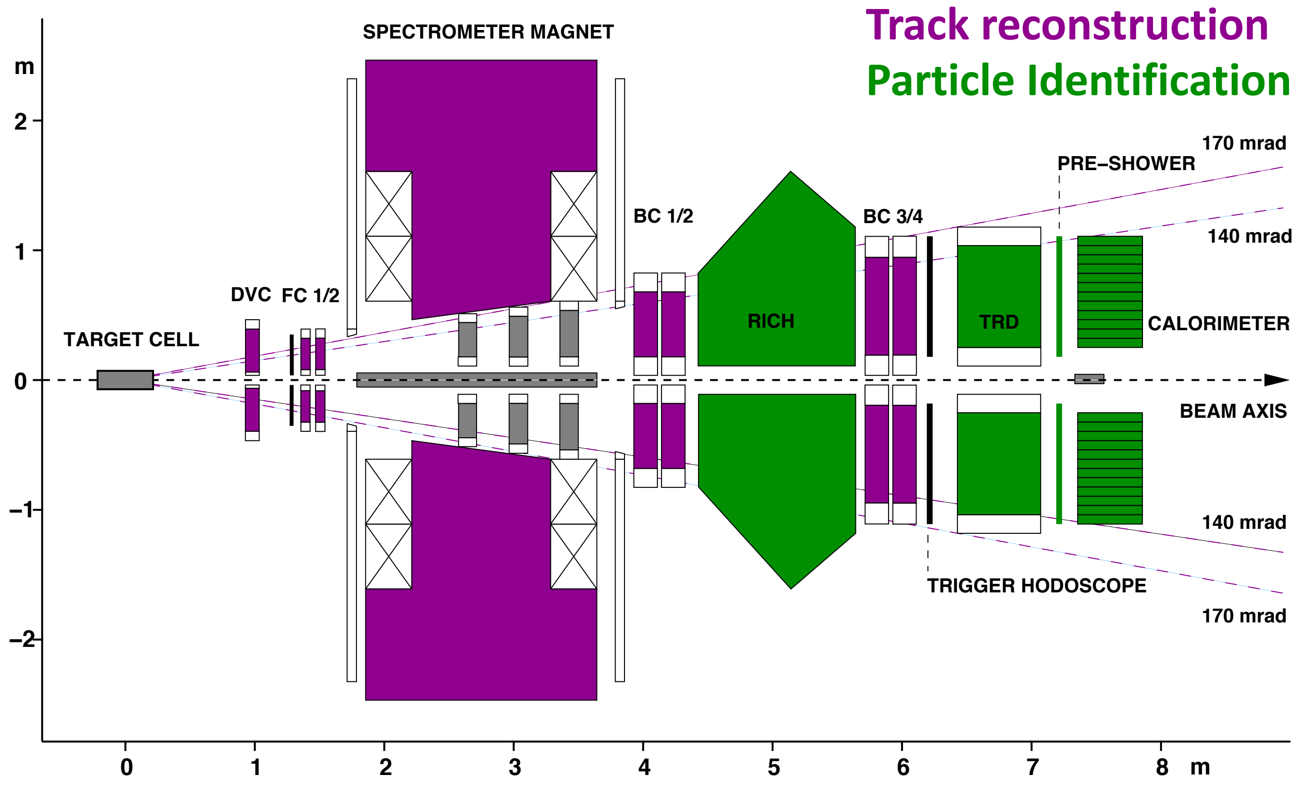
Internal gas target



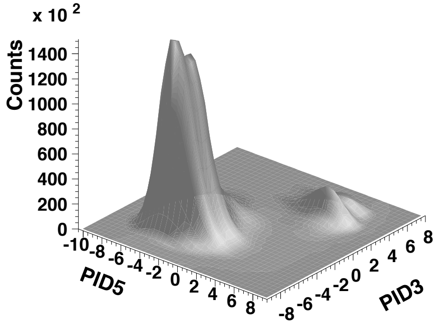
Transverse target magnet

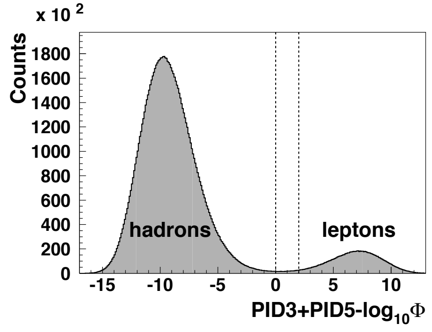


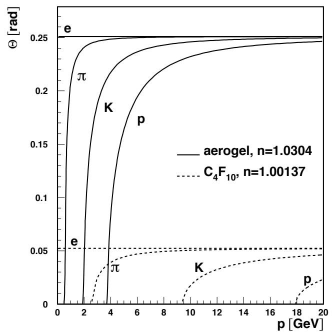
Spectrometer



PID



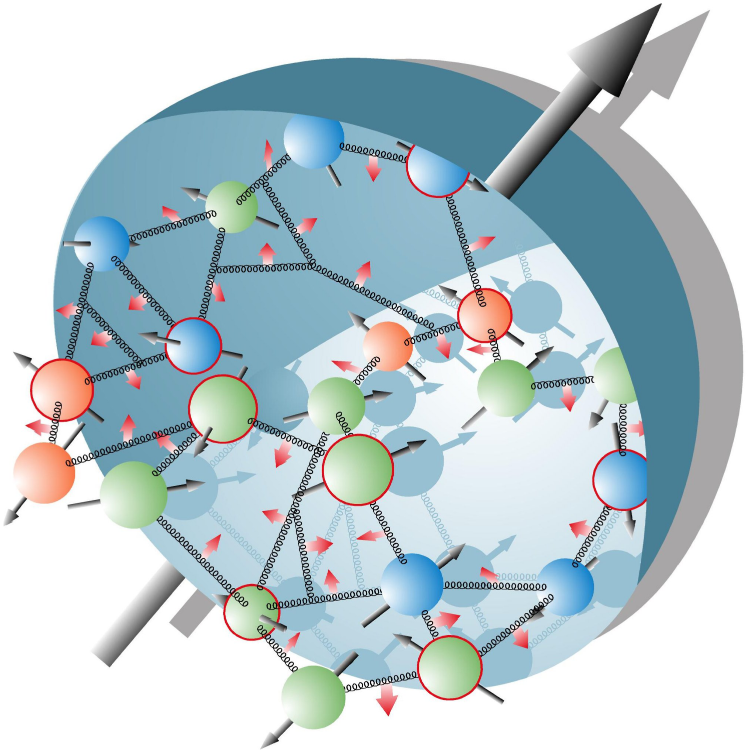




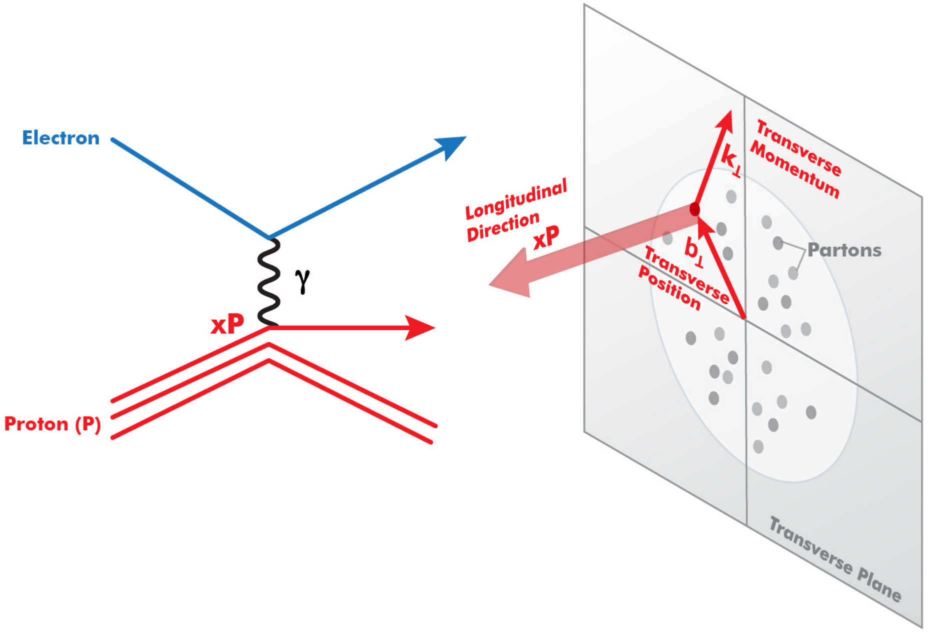
Jefferson Lab

Polarized DIS measurements

hermes Polarization



Novel QCD phenomena



3D imaging in space and momentum

longitudinal structure (PDF)
+ transverse position Information (GPDs)
+ transverse momentum information (TMDs)

order of a few hundred MeV

Nucleon structure and transverse-momentum dependent PDFs

Dirac decomposition of the quark-quark correlator

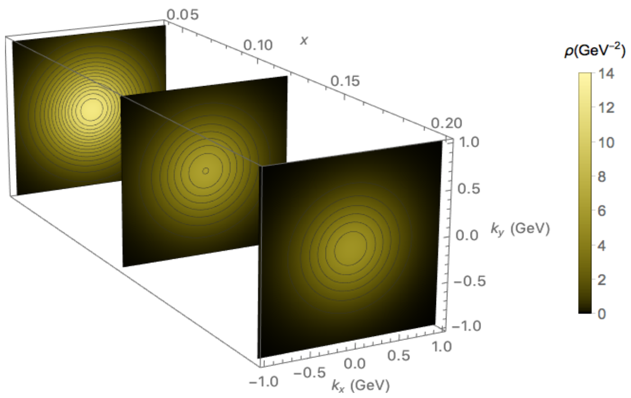
$$\frac{1}{2}\mathrm{Tr}\left[(\gamma^+ + \lambda\gamma^+\gamma_5)\,\Phi(x,\mathbf{p}_T)\right] = \frac{1}{2}\Big[f_1^q(x,\mathbf{p}_T^2) + S_T^i\varepsilon^{ij}p_T^j\frac{1}{M}f_{1T}^{\perp,q}(x,\mathbf{p}_T^2) + \lambda\Lambda\, g_1^q(x,\mathbf{p}_T^2) + \lambda S_T^i p_T^i\frac{1}{M}g_{1T}^{\perp,q}(x,\mathbf{p}_T^2)\Big],$$

$$\frac{1}{2}\mathrm{Tr}\left[\left(\gamma^+ - s_T^j i\sigma^{+j}\gamma_5\right)\Phi(x,\mathbf{p}_T)\right] = \frac{1}{2}\Big[f_1^q(x,\mathbf{p}_T^2) + S_T^i\varepsilon^{ij}p_T^j\frac{1}{M}f_{1T}^{\perp,q}(x,\mathbf{p}_T^2) + s_T^i\varepsilon^{ij}p_T^j\frac{1}{M}h_1^{\perp,q}(x,\mathbf{p}_T^2) + s_T^iS_T^i\,h_1^q(x,\mathbf{p}_T^2) + s_T^i\left(2p_T^ip_T^j - \mathbf{p}_T^2\delta^{ij}\right)S_T^j\frac{1}{2M^2}h_{1T}^{\perp,q}(x,\mathbf{p}_T^2) + \Lambda s_T^ip_T^i\frac{1}{M}h_{1L}^{\perp,q}(x,\mathbf{p}_T^2)\Big].$$

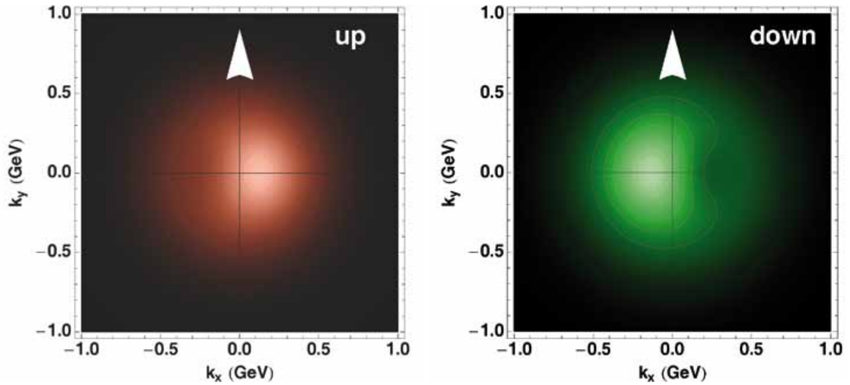
TMD	probabilistic interpretation	chiral properties	naive-T properties
$f_{1T}^{\perp,q}(x,\mathbf{p}_T^2)$		chiral-even	naive-T-odd
$h_1^{\perp,q}(x,\mathbf{p}_T^2)$		chiral-odd	naive-T-odd
$h_{1T}^{\perp,q}(x,\mathbf{p}_T^2)$		chiral-odd	naive-T-even
$h_{1L}^{\perp,q}(x,\mathbf{p}_T^2)$		chiral-odd	naive-T-even
$g_{1T}^{\perp,q}(x,\mathbf{p}_T^2)$		chiral-even	naive-T-even
legend		transverse and longitudinal nucleon polarisation	
		transverse and longitudinal quark polarisation	

Unpolarized nucleon

JHEP 1706 (2017) 081



Transversely polarized nucleon

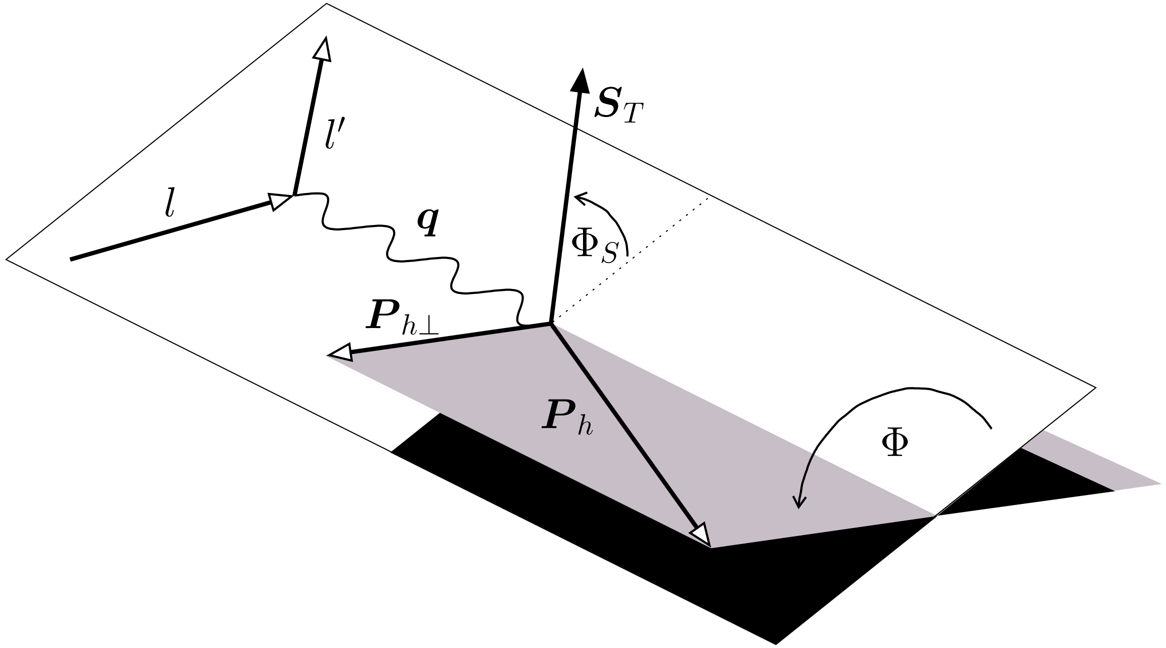


SSA in SIDIS measurements at HERMES

SSA in QCD

- spin-orbit correlations

  $\mathbf{S} \cdot (\mathbf{p}_1 \times \mathbf{p}_2)$ **E704** $\vec{S}_{\text{beam}} \cdot (\vec{p}_{\text{beam}} \times \vec{p}_{\pi})$
- **Brodsky, Hwang, Schmidt [BHS02]** caused by the interference of scattering amplitudes with different complex phases coupling to the same final state
- **Transverse SSA** related to the interference of scattering amplitudes with different hadron helicities:
  - **[KPR78]** suppressed in hard scattering processes
  - **[BHS02]** caused by initial- or final-state interactions
- **naive-*T*-odd** function with the property to induce SSA



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

Cross section decomposition in terms of structure functions

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

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

Sivers effect

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

Collins effect

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

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

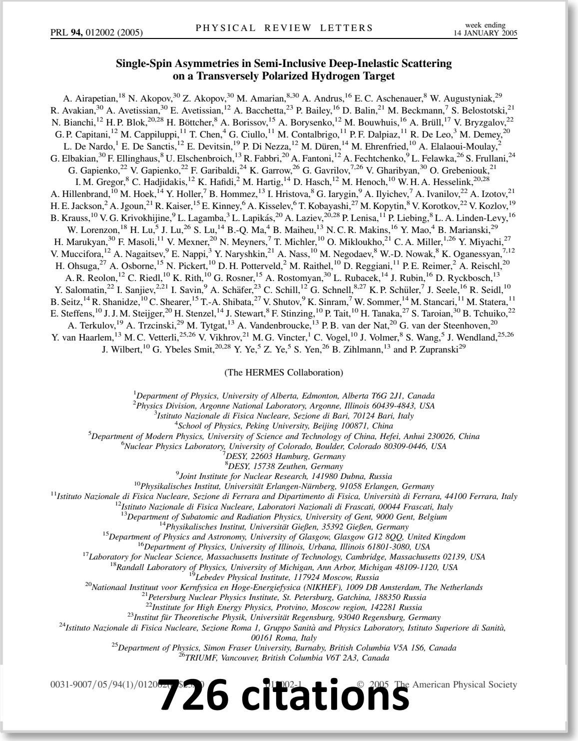
Sivers TMD and spin-independent FF

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

Transversity PDF and Collins FF

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

First measurement of SSA for SIDIS with transverse target polarization


PRL **94,** 012002 (2005) PHYSICAL REVIEW LETTERS week ending 14 JANUARY 2005

Single-Spin Asymmetries in Semi-Inclusive Deep-Inelastic Scattering on a Transversely Polarized Hydrogen Target

A. Airapetian,[18] N. Akopov,[30] Z. Akopov,[30] M. Amarian,[8,30] A. Andrus,[16] E. C. Aschenauer,[8] W. Augustyniak,[29] R. Avakian,[30] A. Avetissian,[30] E. Avetissian,[12] A. Bacchetta,[23] P. Bailey,[16] D. Balin,[21] M. Beckmann,[7] S. Belostotski,[21] N. Bianchi,[12] H. P. Blok,[20,28] H. Böttcher,[8] A. Borissov,[15] A. Borysenko,[12] M. Bouwhuis,[16] A. Brüll,[17] V. Bryzgalov,[22] G. P. Capitani,[12] M. Cappiluppi,[11] T. Chen,[4] G. Ciullo,[11] M. Contalbrigo,[11] P. F. Dalpiaz,[11] R. De Leo,[3] M. Demey,[20] L. De Nardo,[1] E. De Sanctis,[12] E. Devitsin,[19] P. Di Nezza,[12] M. Düren,[14] M. Ehrenfried,[10] A. Elalaoui-Moulay,[2] G. Elbakian,[30] F. Ellinghaus,[8] U. Elschenbroich,[13] R. Fabbri,[20] A. Fantoni,[12] A. Fechtchenko,[9] L. Felawka,[26] S. Frullani,[24] G. Gapienko,[22] V. Gapienko,[22] F. Garibaldi,[24] K. Garrow,[26] G. Gavrilov,[7,26] V. Gharibyan,[30] O. Grebeniouk,[21] I. M. Gregor,[8] C. Hadjidakis,[12] K. Hafidi,[2] M. Hartig,[14] D. Hasch,[12] M. Henoch,[10] W. H. A. Hesselink,[20,28] A. Hillenbrand,[10] M. Hoek,[14] Y. Holler,[7] B. Hommez,[13] I. Hristova,[8] G. Iarygin,[9] A. Ilyichev,[7] A. Ivanilov,[22] A. Izotov,[21] H. E. Jackson,[2] A. Jgoun,[21] R. Kaiser,[15] E. Kinney,[6] A. Kisselev,[6] T. Kobayashi,[27] M. Kopytin,[8] V. Korotkov,[22] V. Kozlov,[19] B. Krauss,[10] V. G. Krivokhijine,[9] L. Lagamba,[3] L. Lapikás,[20] A. Laziev,[20,28] P. Lenisa,[11] P. Liebing,[8] L. A. Linden-Levy,[16] W. Lorenzon,[18] H. Lu,[5] J. Lu,[26] S. Lu,[14] B.-Q. Ma,[4] B. Maiheu,[13] N. C. R. Makins,[16] Y. Mao,[4] B. Marianski,[29] H. Marukyan,[30] F. Masoli,[11] V. Mexner,[20] N. Meyners,[7] T. Michler,[10] O. Mikloukho,[21] C. A. Miller,[1,26] Y. Miyachi,[27] V. Muccifora,[12] A. Nagaitsev,[9] E. Nappi,[3] Y. Naryshkin,[21] A. Nass,[10] M. Negodaev,[8] W.-D. Nowak,[8] K. Oganessyan,[7,12] H. Ohsuga,[27] A. Osborne,[15] N. Pickert,[10] D. H. Potterveld,[2] M. Raithel,[10] D. Reggiani,[11] P. E. Reimer,[2] A. Reischl,[20] A. R. Reolon,[12] C. Riedl,[10] K. Rith,[10] G. Rosner,[15] A. Rostomyan,[30] L. Rubacek,[14] J. Rubin,[16] D. Ryckbosch,[13] Y. Salomatin,[22] I. Sanjiev,[2,21] I. Savin,[9] A. Schäfer,[23] C. Schill,[12] G. Schnell,[8,27] K. P. Schüler,[7] J. Seele,[16] R. Seidl,[10] B. Seitz,[14] R. Shanidze,[10] C. Shearer,[15] T.-A. Shibata,[27] V. Shutov,[9] K. Sinram,[7] W. Sommer,[14] M. Stancari,[11] M. Statera,[11] E. Steffens,[10] J. J. M. Steijger,[20] H. Stenzel,[14] J. Stewart,[8] F. Stinzing,[10] P. Tait,[10] H. Tanaka,[27] S. Taroian,[30] B. Tchuiko,[22] A. Terkulov,[19] A. Trzcinski,[29] M. Tytgat,[13] A. Vandenbroucke,[13] P. B. van der Nat,[20] G. van der Steenhoven,[20] Y. van Haarlem,[13] M. C. Vetterli,[25,26] V. Vikhrov,[21] M. G. Vincter,[1] C. Vogel,[10] J. Volmer,[8] S. Wang,[5] J. Wendland,[25,26] J. Wilbert,[10] G. Ybeles Smit,[20,28] Y. Ye,[5] Z. Ye,[5] S. Yen,[26] B. Zihlmann,[13] and P. Zupranski[29]

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0031-9007/05/94(1)/01200 012002-1

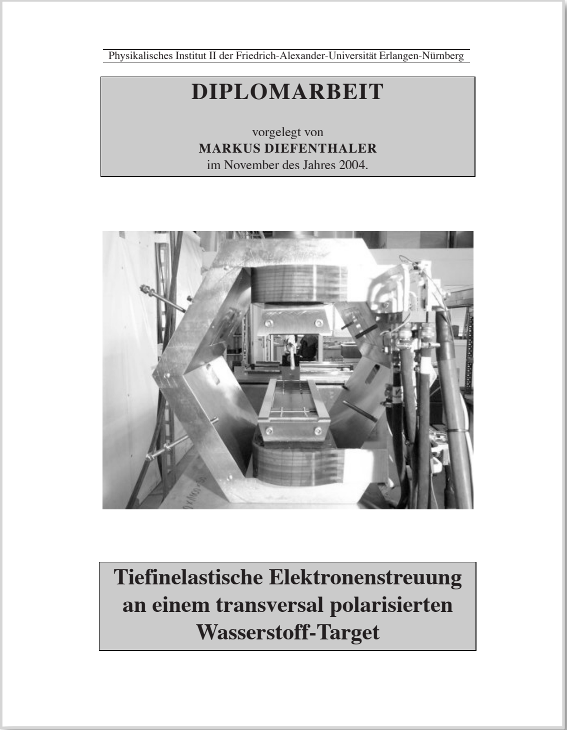
726 citations

HERMES Collaboration

- worked on paper based on 2002-2003 data

MD

- in parallel first look at 2002-2004 data
- analysis documented in diploma thesis


Physikalisches Institut II der Friedrich-Alexander-Universität Erlangen-Nürnberg

DIPLOMARBEIT

vorgelegt von
MARKUS DIEFENTHALER
im November des Jahres 2004.

Tiefinelastische Elektronenstreuung an einem transversal polarisierten Wasserstoff-Target

HERMES data on SIDIS off transversely polarized hydrogen target

2002–2003	
2002–2004	**x5**
2002–2005	**x13**

Jefferson Lab

Updated and extended analysis

DIS 2005

arXiv:hep-ex/0507013v1 2 Jul 2005

Transversity measurements at HERMES

Markus Diefenthaler (on behalf of the HERMES collaboration)

Physikalisches Institut II, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erwin-Rommel-Straße 1, 91058 Erlangen, Germany

Abstract. Azimuthal single-spin asymmetries (SSA) in semi-inclusive electroproduction of charged pions in deep-inelastic scattering (DIS) of positrons on a transversely polarised hydrogen target are presented. Azimuthal moments for both the Collins and the Sivers mechanism are extracted. In addition the subleading-twist contribution due to the transverse spin component from SSA on a longitudinally polarised hydrogen target is evaluated.

Recently the HERMES collaboration published first evidence for azimuthal single-spin asymmetries (SSA) in the semi-inclusive production of charged pions on a transversely polarised target [1]. Significant signals for both the Collins and Sivers mechanisms were observed in data recorded during the 2002–2003 running period of the HERMES experiment. Below we present a preliminary analysis of these data combined with additional data taken in the years 2003 and 2004. All data was recorded at a beam energy of 27.6 GeV using a transversely nuclear-polarised hydrogen-target internal to the HERA positron storage ring at DESY.

At leading twist, the momentum and spin of the quarks inside the nucleon are described by three parton distribution functions: the well-known momentum distribution $q(x,Q^2)$, the known helicity distribution $\Delta q(x,Q^2)$ [2] and the unknown *transversity distribution* $\delta q(x,Q^2)$ [3, 4, 5, 6]. In the helicity basis, transversity is related to a quark-nucleon forward scattering amplitude involving helicity flip of both nucleon and quark ($N^{\Rightarrow}q^{\leftarrow} \to N^{\Leftarrow}q^{\rightarrow}$). As it is chiral-odd, transversity cannot be probed in inclusive measurements. At HERMES transversity in conjunction with the chiral-odd Collins fragmentation function [7] is accessible in SSA in semi-inclusive DIS on a transversely polarised target (*Collins mechanism*). The Collins fragmentation function describes the correlation between the transverse polarisation of the struck quark and the transverse momentum $P_{h\perp}$ of the produced hadron. As it is also odd under naive time reversal (T-odd) it can produce a SSA, i.e. a left-right asymmetry in the momentum distribution of the produced hadrons in the directions transverse to the nucleon spin [8].

The *Sivers mechanism* can also cause a SSA: The T-odd Sivers distribution function [9] describes the correlation between the transverse polarisation of the nucleon and the transverse momentum k_T of the quarks within. A non-zero Sivers mechanism provides a non-zero Compton amplitude involving nucleon helicity flip without quark helicity flip ($N^{\Rightarrow}q^{\leftarrow} \to N^{\Leftarrow}q^{\leftarrow}$), which must therefore involve orbital angular momentum of the quark inside the nucleon [8, 10].

With a transversely polarised target, the azimuthal angle ϕ_S of the target spin direction in the "⇑" state is observable in addition to the azimuthal angle ϕ of the detected

82 citations

2002–2004 data

SPIN 2006

arXiv:hep-ex/0612010v1 6 Dec 2006

Azimuthal single-spin asymmetries in semi-inclusive deep-inelastic scattering on a transversely polarised hydrogen target

Markus Diefenthaler (on behalf of the HERMES collaboration)

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Abstract. Azimuthal single-spin asymmetries (SSA) in semi-inclusive electroproduction of charged pions and kaons in deep-inelastic scattering of positrons on a transversely polarised hydrogen target were observed. SSA amplitudes for both the Collins and the Sivers mechanism are presented.

Keywords: transversity distribution, azimuthal single-spin asymmetries, Collins mechanism, Sivers mechanism
PACS: 13.60.-r,13.88.+e,14.20.Dh,14.65.-q

In 2005 the HERMES collaboration published first evidence for azimuthal single-spin asymmetries (SSA) in the semi-inclusive production of charged pions on a transversely polarised target [1]. Significant signals for both the Collins and Sivers mechanisms were observed in data recorded during the 2002–2003 running period of the HERMES experiment. Below we present a preliminary analysis of these data combined with additional data taken in the years 2003 and 2004. All data were recorded at a beam energy of 27.6 GeV using a transversely nuclear-polarised hydrogen-target internal to the HERA positron storage ring at DESY. The HERMES dual radiator ring-imaging Čerenkov counter allows full $\pi^{\pm}$, $K^{\pm}$, p separation for all selected particle momenta. Therefore, a preliminary analysis of SSA in the electroproduction of charged kaons on a transversely polarised target is also presented.

At leading twist, the momentum and spin of the quarks inside the nucleon are described by three parton distribution functions: the well-known momentum distribution $q(x,Q^2)$, the known helicity distribution $\Delta q(x,Q^2)$ [2] and the unknown *transversity distribution* $\delta q(x,Q^2)$ [3, 4, 5, 6]. In the helicity basis, transversity is related to a quark-nucleon forward scattering amplitude involving helicity flip of both nucleon and quark ($N^{\Rightarrow}q^{\leftarrow} \to N^{\Leftarrow}q^{\rightarrow}$). As it is chiral-odd, transversity cannot be probed in inclusive measurements. At HERMES transversity in conjunction with the chiral-odd Collins fragmentation function [7] is accessible in SSA in semi-inclusive DIS on a transversely polarised target (*Collins mechanism*). The Collins fragmentation function describes the correlation between the transverse polarisation of the struck quark and the transverse momentum $P_{h\perp}$ of the hadron produced. As it is also odd under naive time reversal (T-odd) it can produce a SSA, i.e. a left-right asymmetry in the momentum distribution of the produced hadrons in the directions transverse to the nucleon spin [8].

The *Sivers mechanism* can also cause a SSA: The T-odd Sivers distribution function

15 citations

2002–2004 data
kaons

DIS 2007

arXiv:0706.2242v2 [hep-ex] 19 Jun 2007

HERMES Measurements of Collins and Sivers Asymmetries from a transversely polarised Hydrogen Target

Markus Diefenthaler (on behalf of the HERMES collaboration)

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Erwin-Rommel-Straße 1, 91058 Erlangen - Germany

Azimuthal single-spin asymmetries (SSA) in semi-inclusive electroproduction of π-mesons and charged K-mesons in deep-inelastic scattering of positrons and electrons on a transversely polarised hydrogen target were observed. Significant SSA amplitudes for both the Collins and the Sivers mechanism are presented for the full data set recorded with transverse target polarisation at the HERMES experiment.

1 Contribution

In 2005 the HERMES collaboration published first evidence for azimuthal single-spin asymmetries (SSA) in the semi-inclusive production of charged pions on a transversely polarised hydrogen target [2]. Significant signals for both the Collins [3] and Sivers mechanisms [4] were observed in data recorded during the 2002–2003 running period of the HERMES experiment. Below we present a preliminary analysis of these data combined with additional data taken in the years 2003–2005; i.e. an preliminary analysis of the full data set with transverse target polarisation [1]. All data were recorded at a beam energy of 27.6 GeV using a transversely nuclear-polarised hydrogen-target internal to the HERA storage ring at DESY. The HERMES dual-radiator ring-imaging Čerenkov counter allows full $\pi^{\pm}$, $K^{\pm}$, p separation for all particle momenta within the range $2\,\mathrm{GeV} < P_h < 15\,\mathrm{GeV}$. Therefore, a preliminary analysis of SSA in the electroproduction of charged kaons on a transversely polarised target is also presented. In addition the measurement is accompanied by an preliminary analysis of reconstructed neutral-pion events.

At leading twist, the longitudinal momentum and spin of the quarks inside the nucleon are described by three parton distribution functions: the well-known momentum distribution $q(x,Q^2)$, the known helicity distribution $\Delta q(x,Q^2)$ [5] and the (experimentally) unknown transversity distribution $\delta q(x,Q^2)$ [6, 7, 8, 9]. In the helicity basis, transversity is related to a quark-nucleon forward scattering amplitude involving helicity flip of both nucleon and quark ($N^{\Rightarrow}q^{\leftarrow} \to N^{\Leftarrow}q^{\rightarrow}$). As it is chiral-odd, transversity cannot be probed in inclusive deep-inelastic scattering (DIS). At HERMES transversity in conjunction with the chiral-odd Collins fragmentation function [3] is accessible in SSA in semi-inclusive DIS on a transversely polarised target (*Collins mechanism*). The Collins fragmentation function describes the correlation between the transverse polarisation of the struck quark and the transverse momentum $\boldsymbol{P}_{h\perp}$ of the hadron produced. As it is also odd under naive time reversal (T-odd) it can produce a SSA, i.e. a left-right asymmetry in the momentum distribution of the produced hadrons in the plane transverse to the virtual photon direction.

The *Sivers mechanism* can also cause a SSA: The T-odd Sivers distribution function [4] describes the correlation between the transverse polarisation of the nucleon and the transverse momentum $\boldsymbol{p}_{\perp}$ of the quarks within. A non-zero Sivers mechanism provides

DIS 2007

82 citations

2002–2005 data
neutral pions
improved analysis

2002–2003

2002–2004 x5

2002–2005 x13

Completed SSA analysis and first DSA analysis

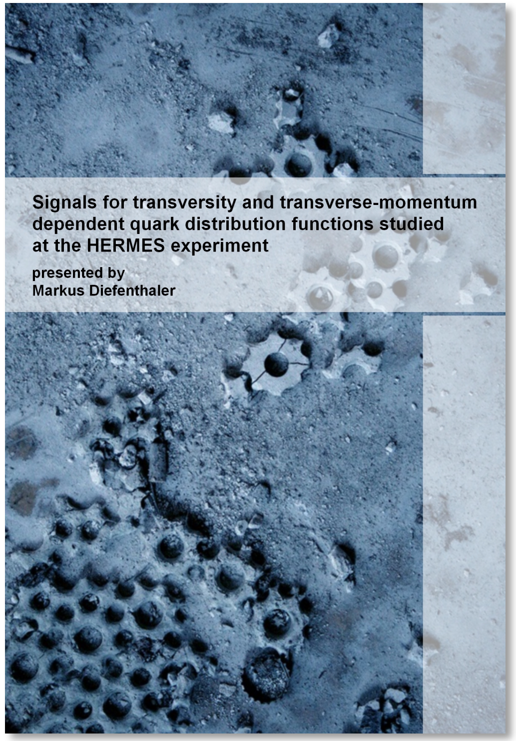
2009

362 citations

2010

223 citations

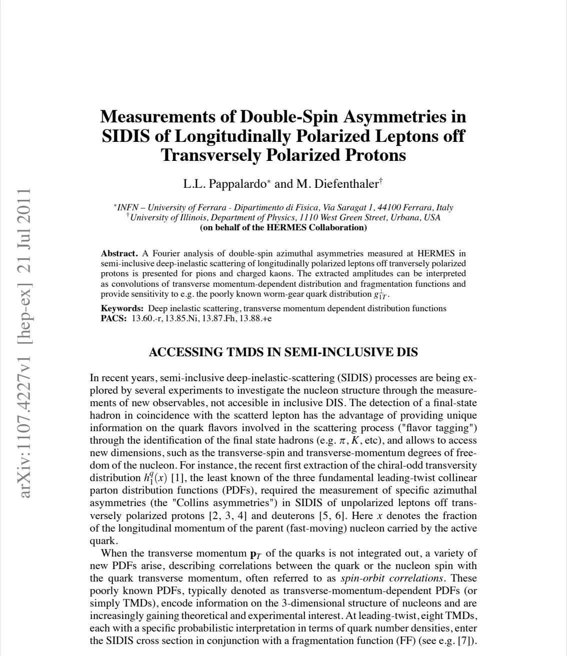
2010



Published SSA analysis and first DSA analysis

Final SSA and DSA analysis

2011



arXiv:1107.4227v1 [hep-ex] 21 Jul 2011

Measurements of Double-Spin Asymmetries in SIDIS of Longitudinally Polarized Leptons off Transversely Polarized Protons

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(on behalf of the HERMES Collaboration)

Abstract. A Fourier analysis of double-spin azimuthal asymmetries measured at HERMES in semi-inclusive deep-inelastic scattering of longitudinally polarized leptons off tranversely polarized protons is presented for pions and charged kaons. The extracted amplitudes can be interpreted as convolutions of transverse momentum-dependent distribution and fragmentation functions and provide sensitivity to e.g. the poorly known worm-gear quark distribution $g_{1T}^{\perp}$.

Keywords: Deep inelastic scattering, transverse momentum dependent distribution functions
PACS: 13.60.-r, 13.85.Ni, 13.87.Fh, 13.88.+e

ACCESSING TMDS IN SEMI-INCLUSIVE DIS

In recent years, semi-inclusive deep-inelastic-scattering (SIDIS) processes are being explored by several experiments to investigate the nucleon structure through the measurements of new observables, not accesible in inclusive DIS. The detection of a final-state hadron in coincidence with the scatterd lepton has the advantage of providing unique information on the quark flavors involved in the scattering process ("flavor tagging") through the identification of the final state hadrons (e.g. π, K, etc), and allows to access new dimensions, such as the transverse-spin and transverse-momentum degrees of freedom of the nucleon. For instance, the recent first extraction of the chiral-odd transversity distribution $h_1^q(x)$ [1], the least known of the three fundamental leading-twist collinear parton distribution functions (PDFs), required the measurement of specific azimuthal asymmetries (the "Collins asymmetries") in SIDIS of unpolarized leptons off transversely polarized protons [2, 3, 4] and deuterons [5, 6]. Here x denotes the fraction of the longitudinal momentum of the parent (fast-moving) nucleon carried by the active quark.

When the transverse momentum $\mathbf{p}_T$ of the quarks is not integrated out, a variety of new PDFs arise, describing correlations between the quark or the nucleon spin with the quark transverse momentum, often referred to as *spin-orbit correlations*. These poorly known PDFs, typically denoted as transverse-momentum-dependent PDFs (or simply TMDs), encode information on the 3-dimensional structure of nucleons and are increasingly gaining theoretical and experimental interest. At leading-twist, eight TMDs, each with a specific probabilistic interpretation in terms of quark number densities, enter the SIDIS cross section in conjunction with a fragmentation function (FF) (see e.g. [7]).

6 citations

DSA

2020

arXiv:2007.07755v1 [hep-ex] 15 Jul 2020

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

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[a] Deceased.

9 citations

Final analysis

To Be Continued

JLab 12 GeV

EIC

The HERMES compendium on TMD analysis

JHEP 12 (2020) 010

PREPARED FOR SUBMISSION TO JHEP
DESY REPORT 20-119

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

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
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Supplemental material
118 pages, 23 figures, 118 tables

New

10 type of asymmetries

- 6 SSA
- **4 DSA**

7 hadron types

- π^+, π^0, π^-
- K^+, K^-
- **protons and antiprotons**

3D projections and optimized 1D projections

- ***x*** $0.023 < x < 0.6$ (before $x < 0.4$)
- ***z*** $0.2 < z < 1.2$ (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

Example amplitude for more detailed discussion

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]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

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

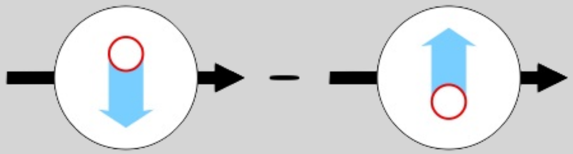
HERMES results on Sivers effect

PRL103 (2009) 152002

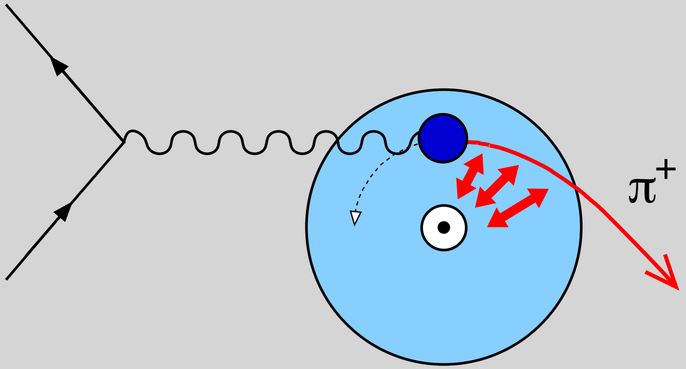
SSA amplitude

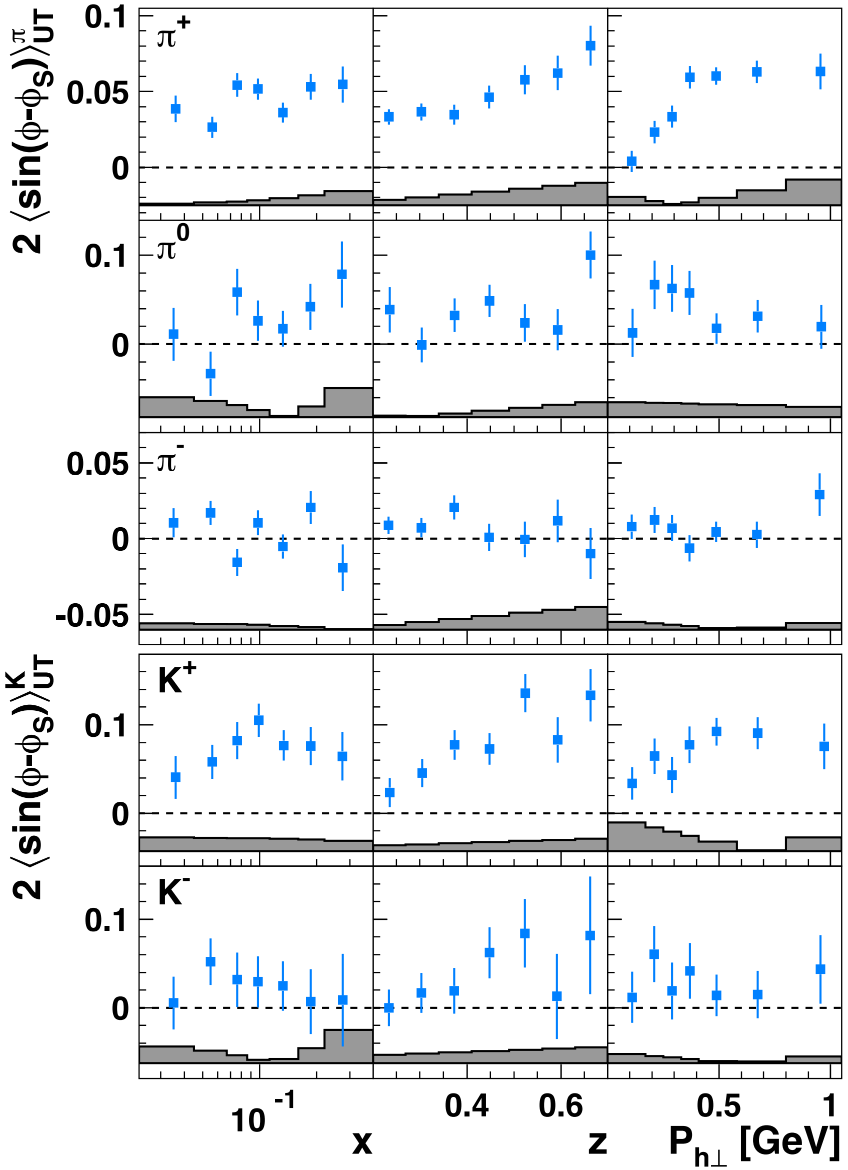
$$2\langle\sin(\phi-\phi_S)\rangle^h_{UT} = -\frac{\mathscr{C}\left[\frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M} f_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right) D_1^q\left(z,z^2\mathbf{k}_T^2\right)\right]}{\mathscr{C}\left[f_1^q\left(x,\mathbf{p}_T^2\right) D_1^q\left(z,z^2\mathbf{k}_T^2\right)\right]}$$

Sivers TMD

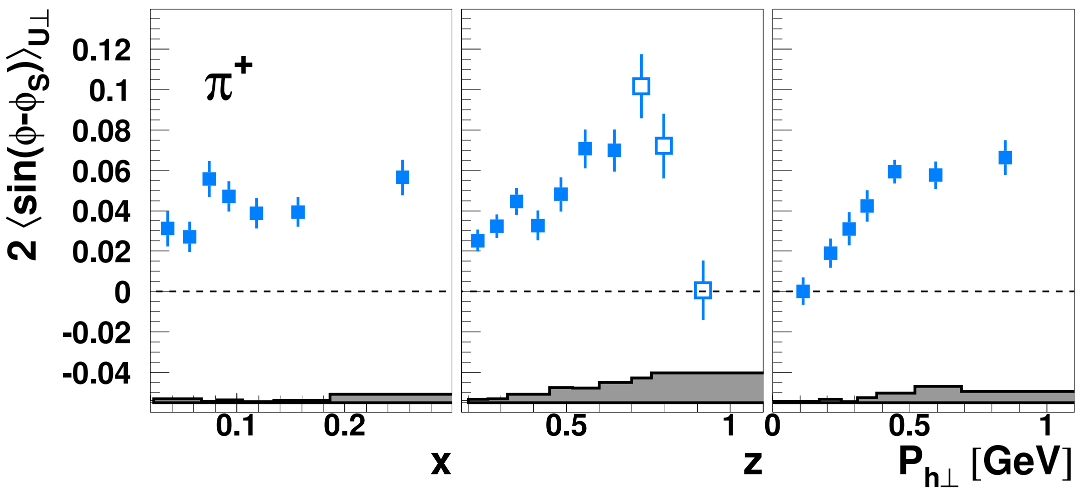


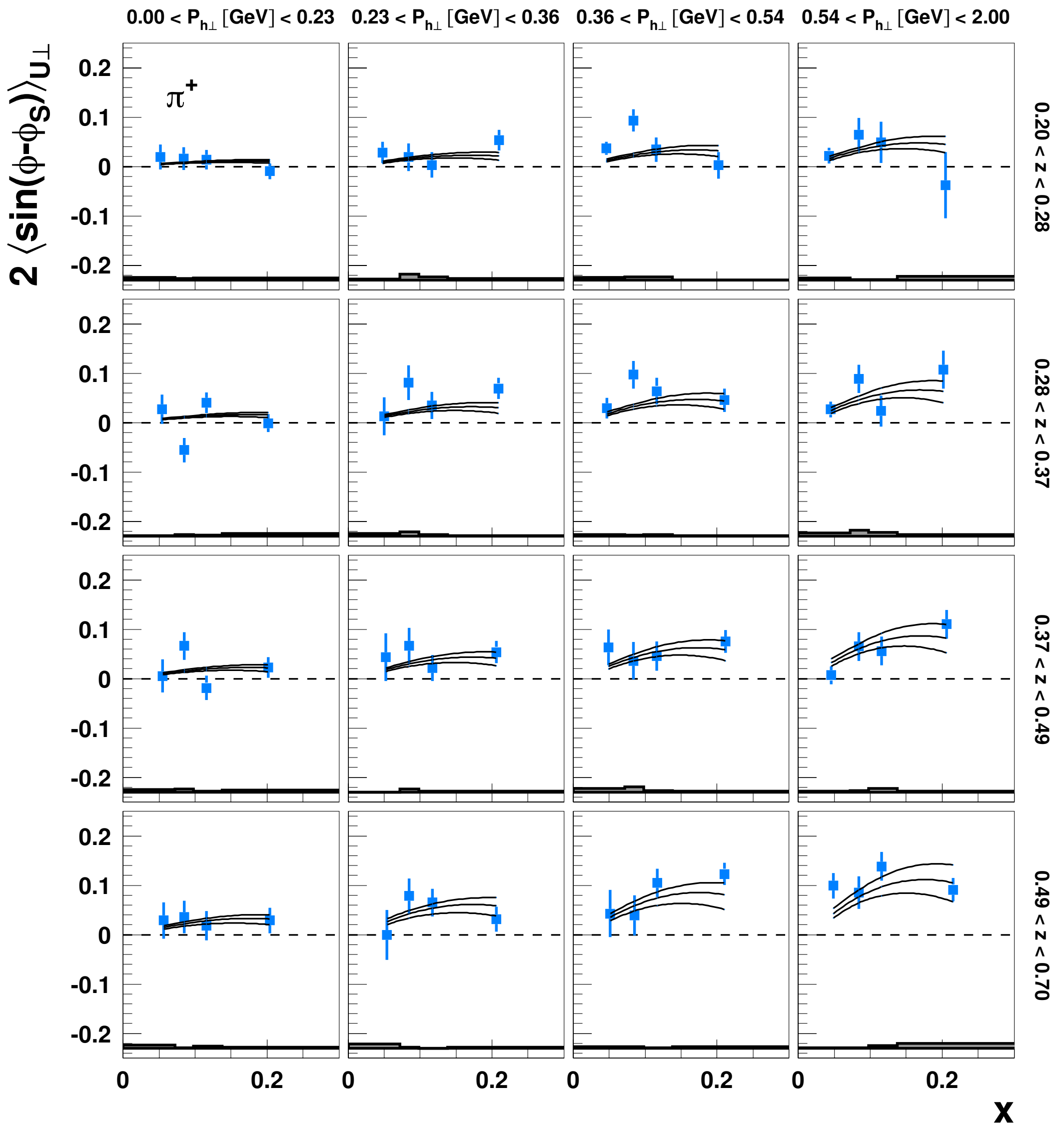
Semi-classical picture





Multi-dimensional analysis

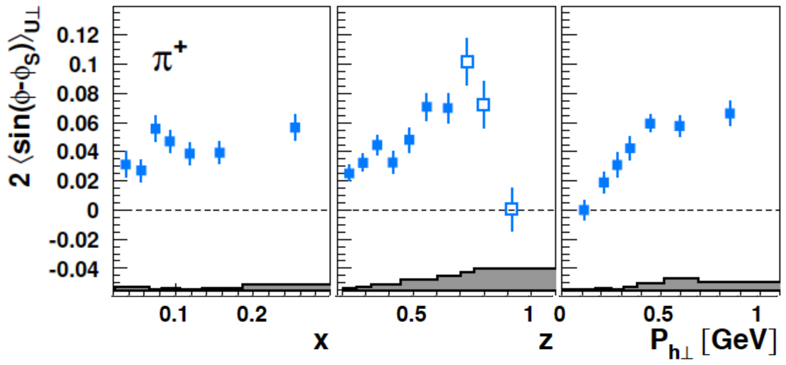




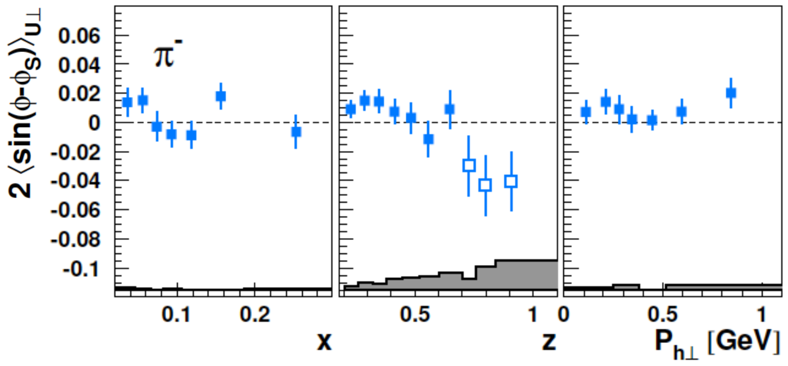
Goal: Fully differential approach with small bin-sizes (similar to this analysis):

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

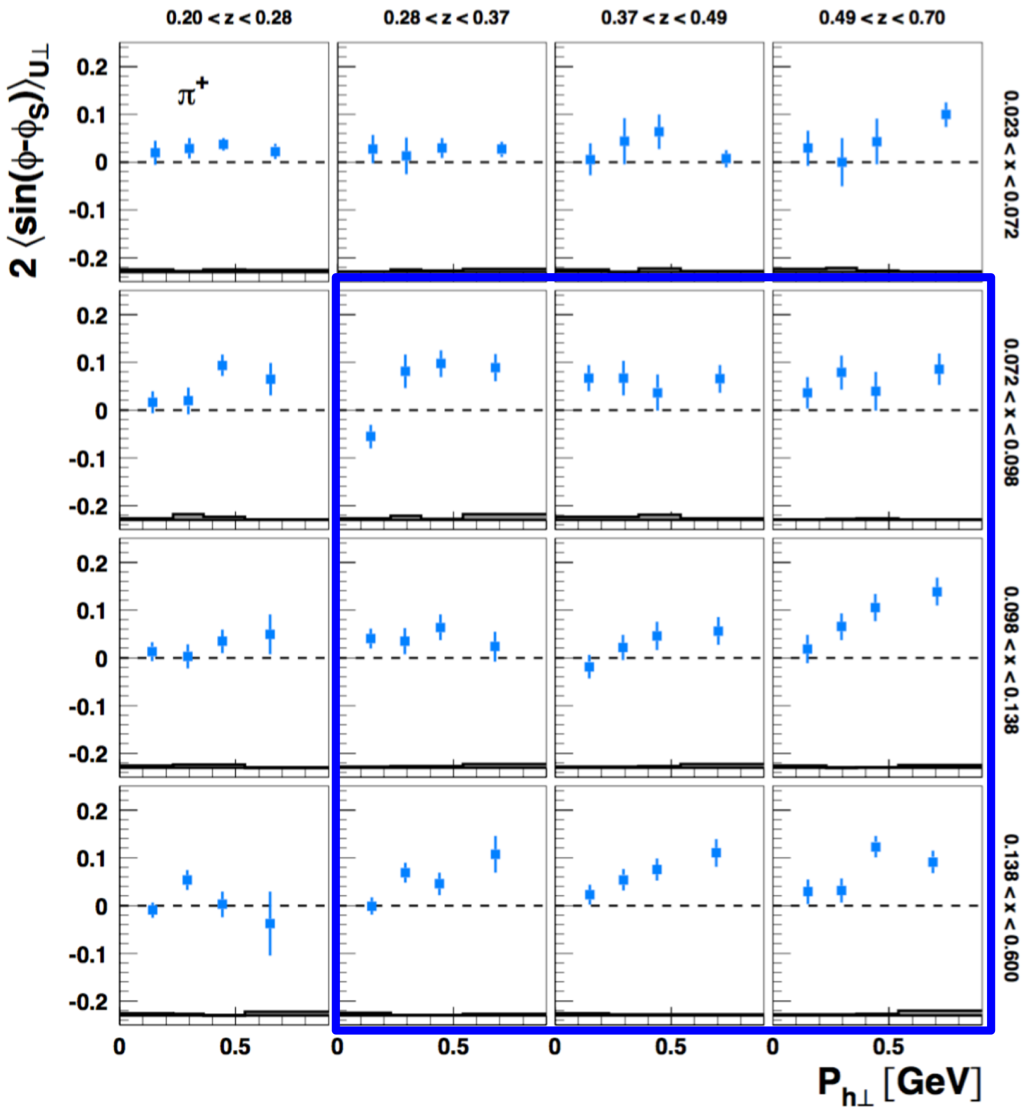
Sivers amplitudes for charged pions



- 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 $P_{h\perp}$

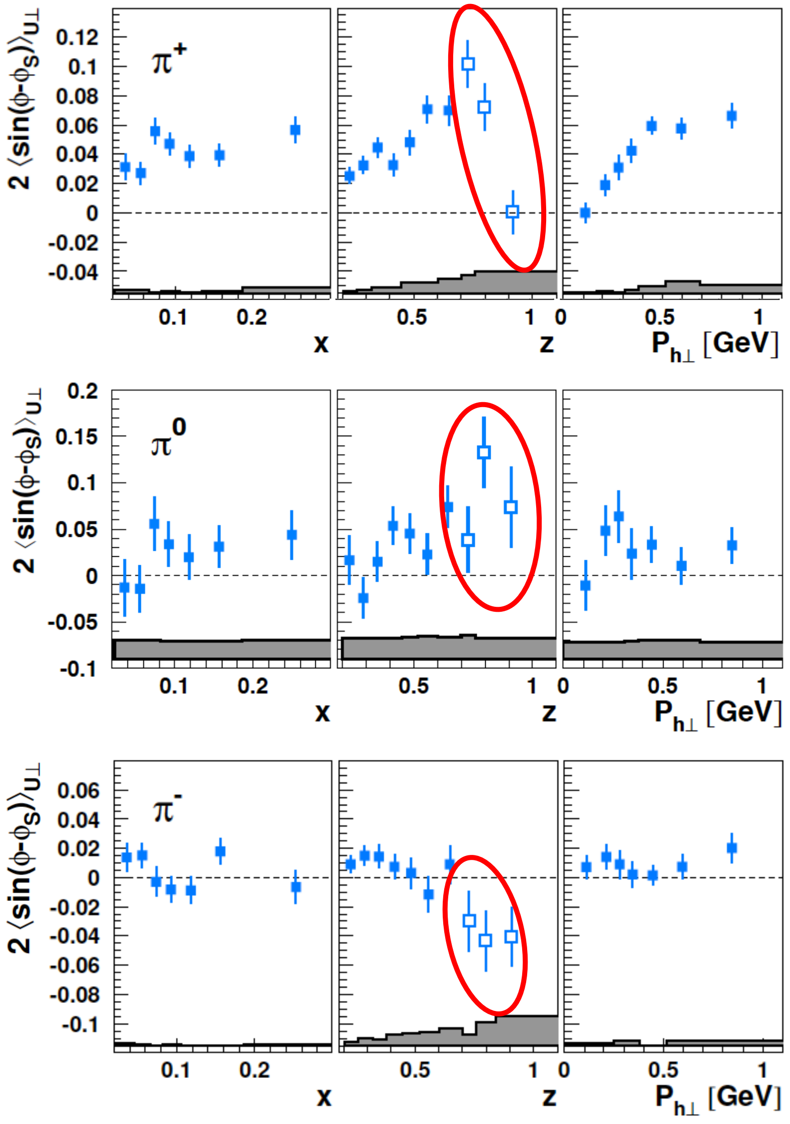


Vanishing due to the cancellation of the opposite Sivers effect for *u* and *d* quarks

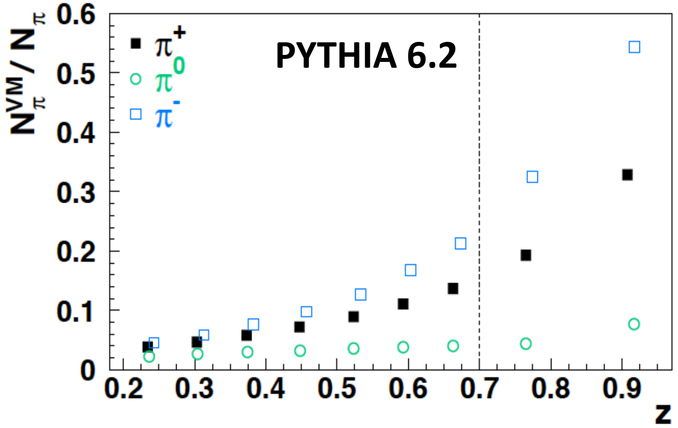


Jefferson Lab

Sivers amplitudes for pions

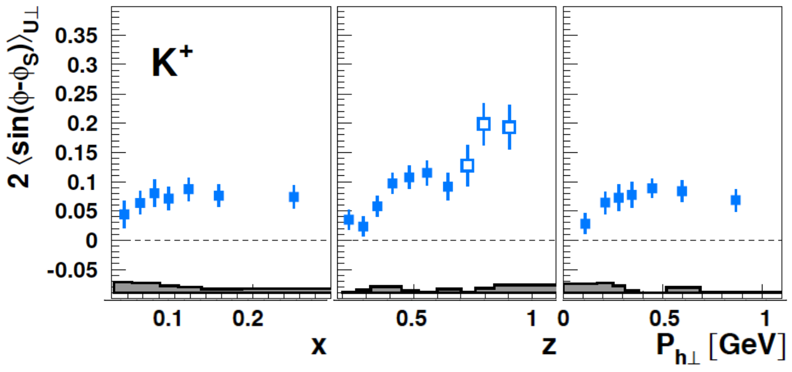


- Sudden drop at large-z (> 0.7) reveals a change of mechanism in this **semi-exclusive region**
- Contributions from decays of exclusively produced ρ^0 into $\pi^+\pi^-$ are large in this region!

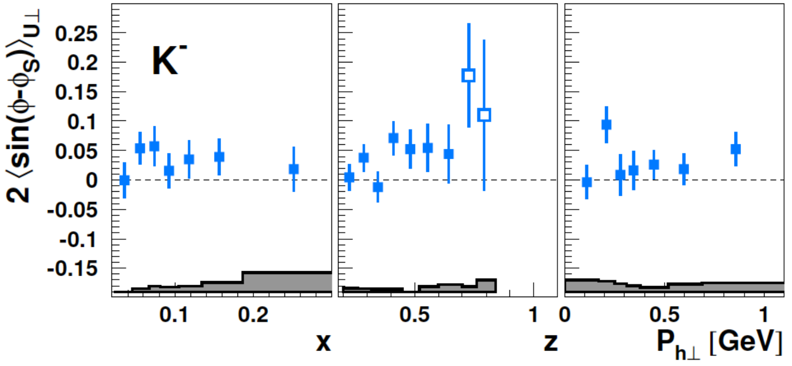


- intermediate size between those of π^+ and π^- reflects isospin symmetry at the amplitude level
- π^0 amplitude is much less susceptible to VM decays and no sudden change is observed at large z → observed positive signal cannot be attributed solely to contributions from VM
- An alternative (concurrent?) explanation: at large z, favored fragmentation ($d \to \pi^-$) prevails over the disfavored one ($u \to \pi^-$) → no cancellation and a non-zero amplitude opposite to that of π^+ is observed.

Sivers amplitudes for charged kaons

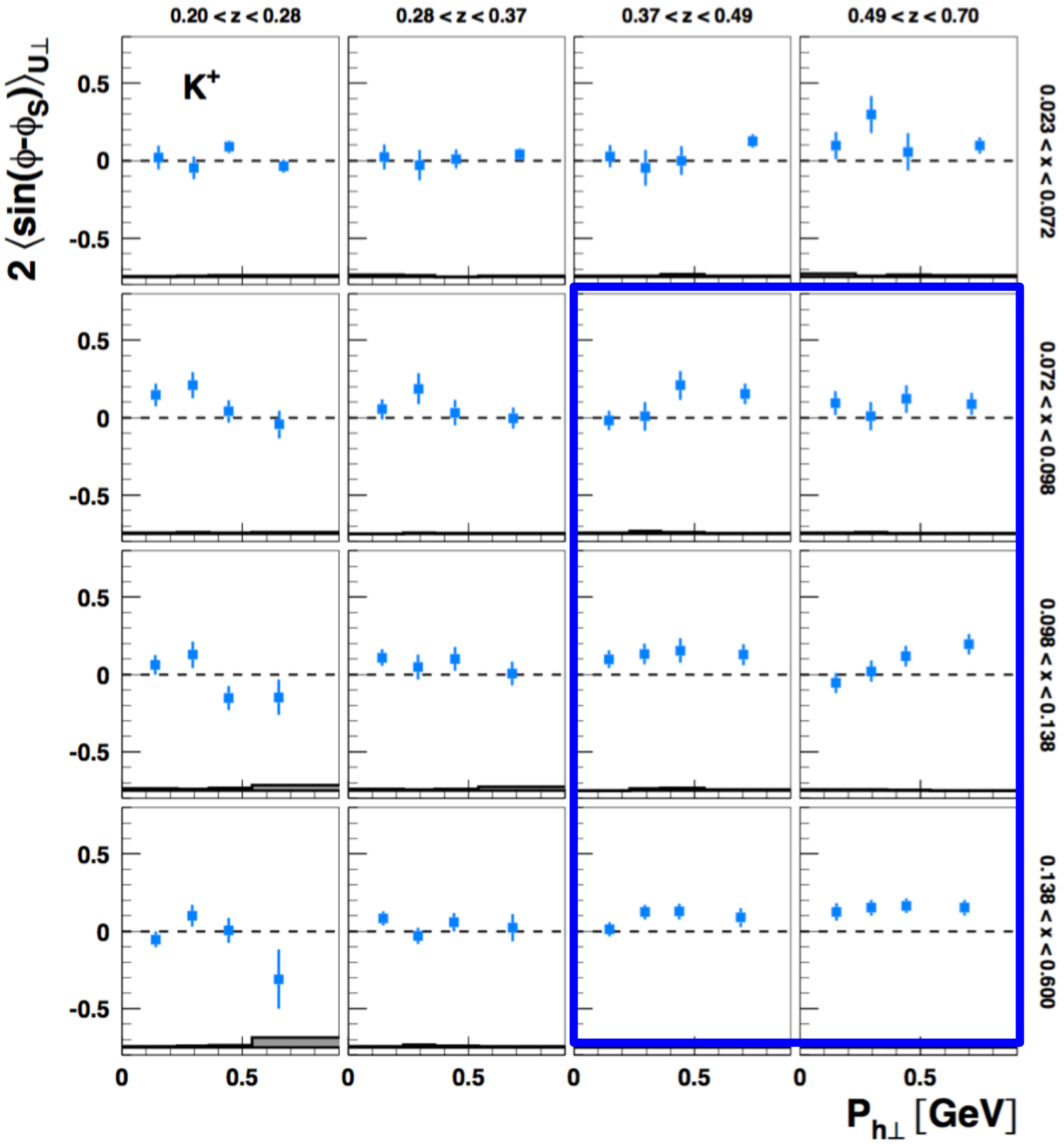


Large positive amplitude, similar kinematic dep. of π^+



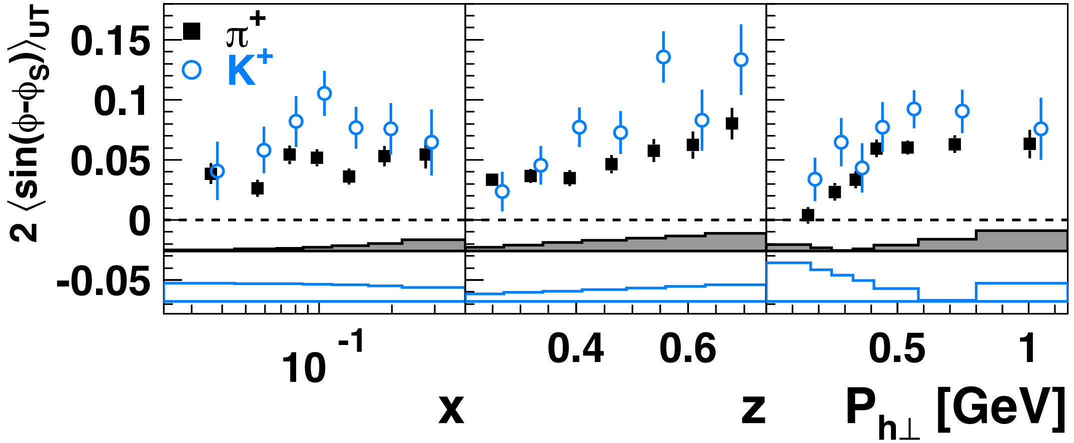
Positive amplitude, different than π^-

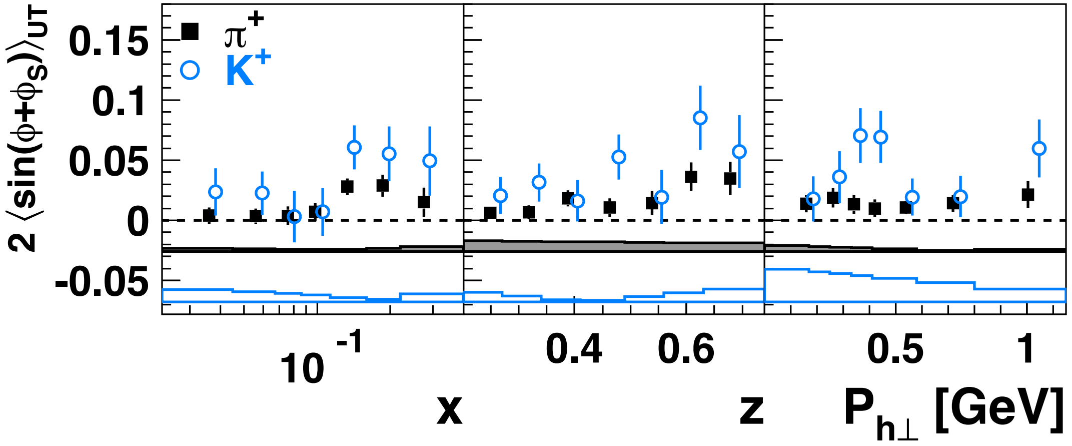
K^- is a pure sea object with no valence quarks in common with target proton

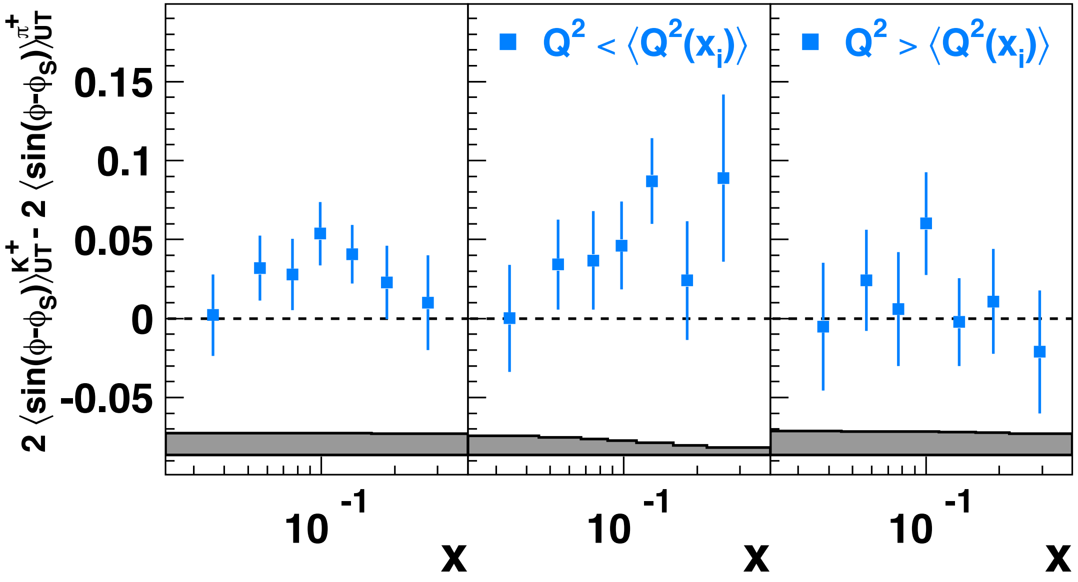


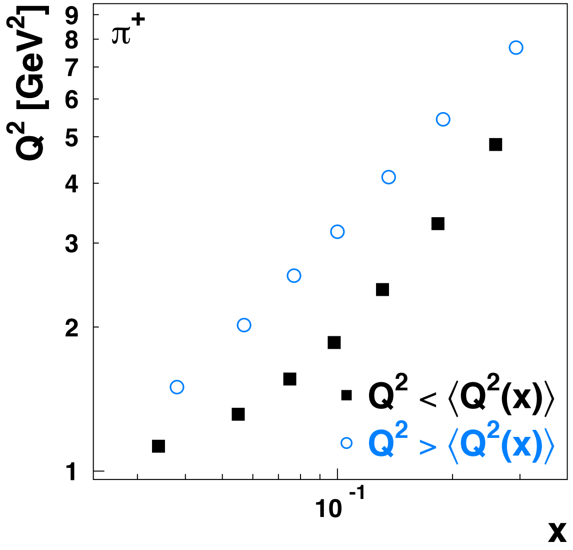
u-quark dominance and the role of higher twist

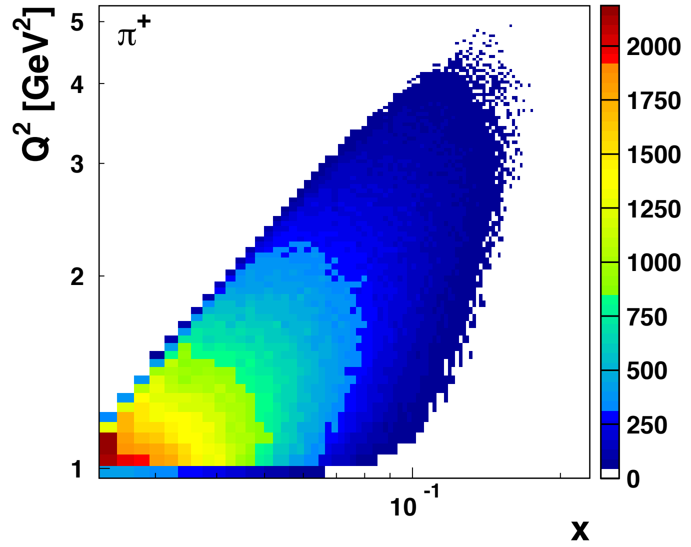
PRL103 (2009) 152002



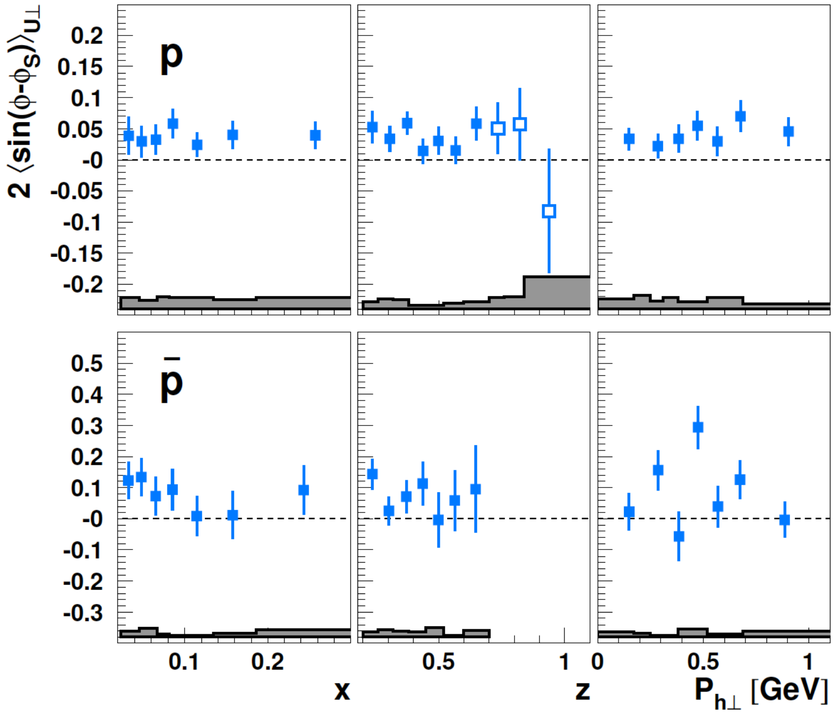






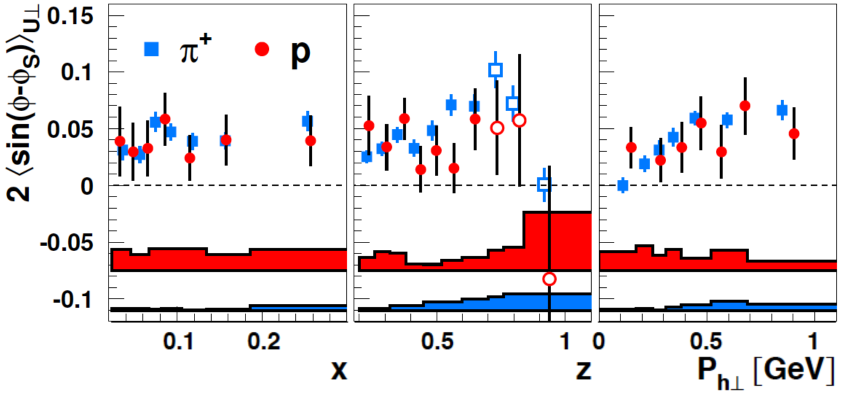


Sivers amplitudes for protons



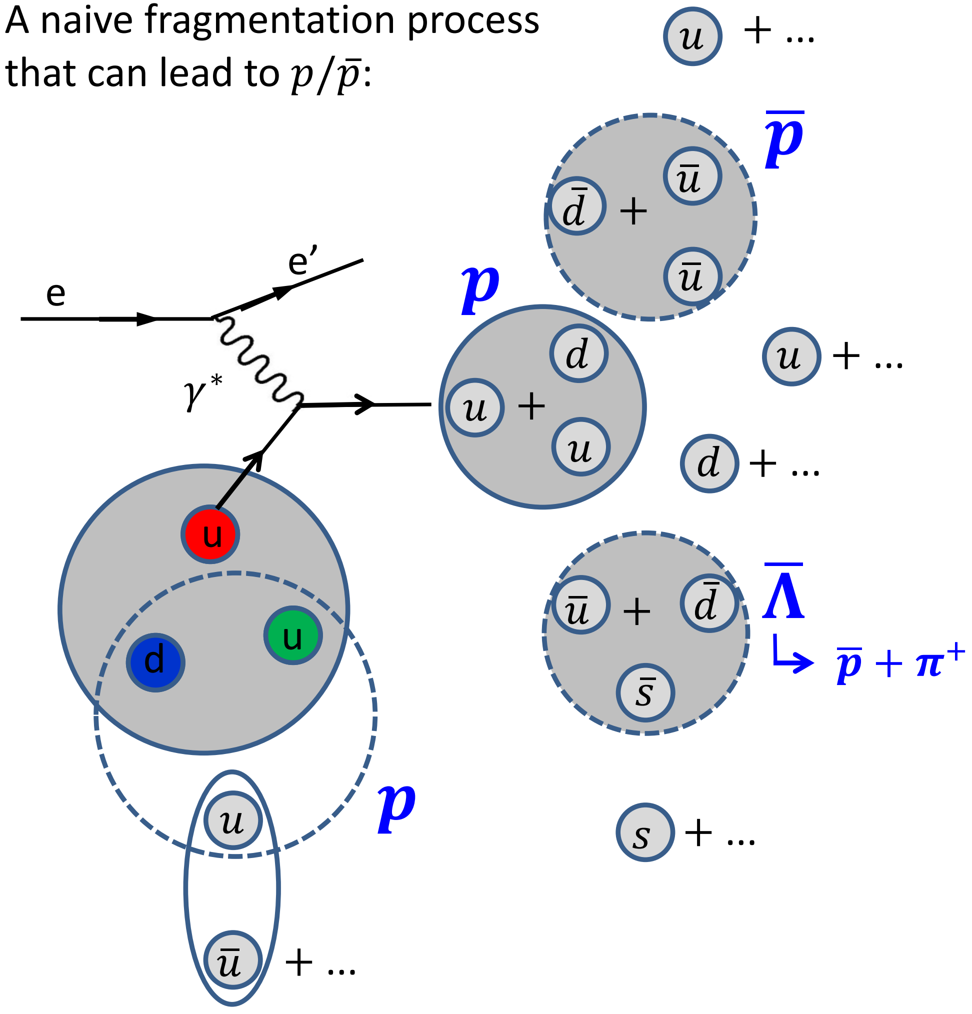
First measurement of Sivers asymmetries for $p, \bar{p}$ in SIDIS

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 $p/\bar{p}$:

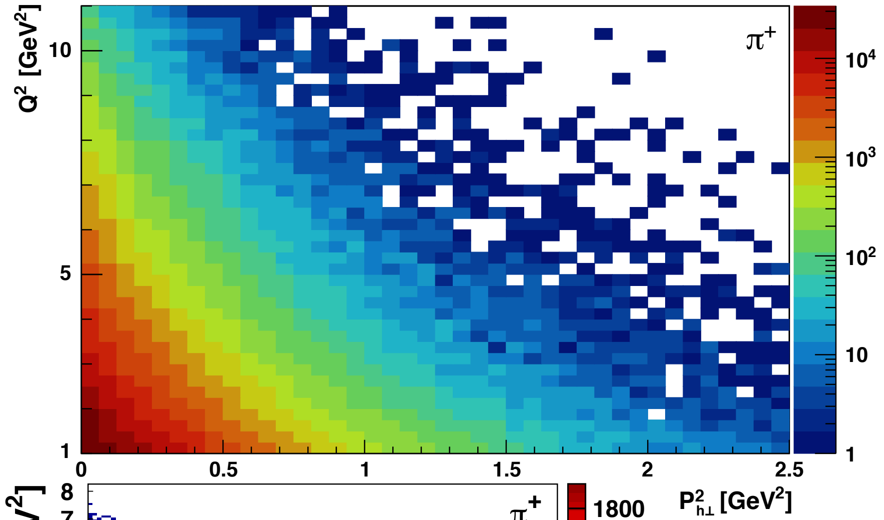


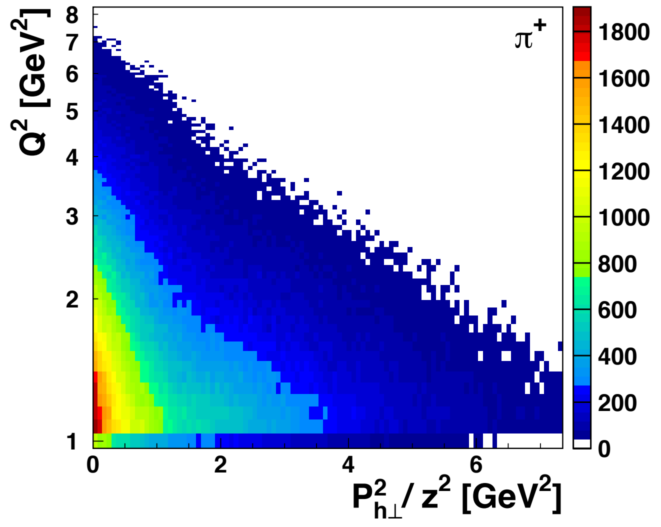
...also from TFR (low z, high $P_{h\perp}$)

Jefferson Lab

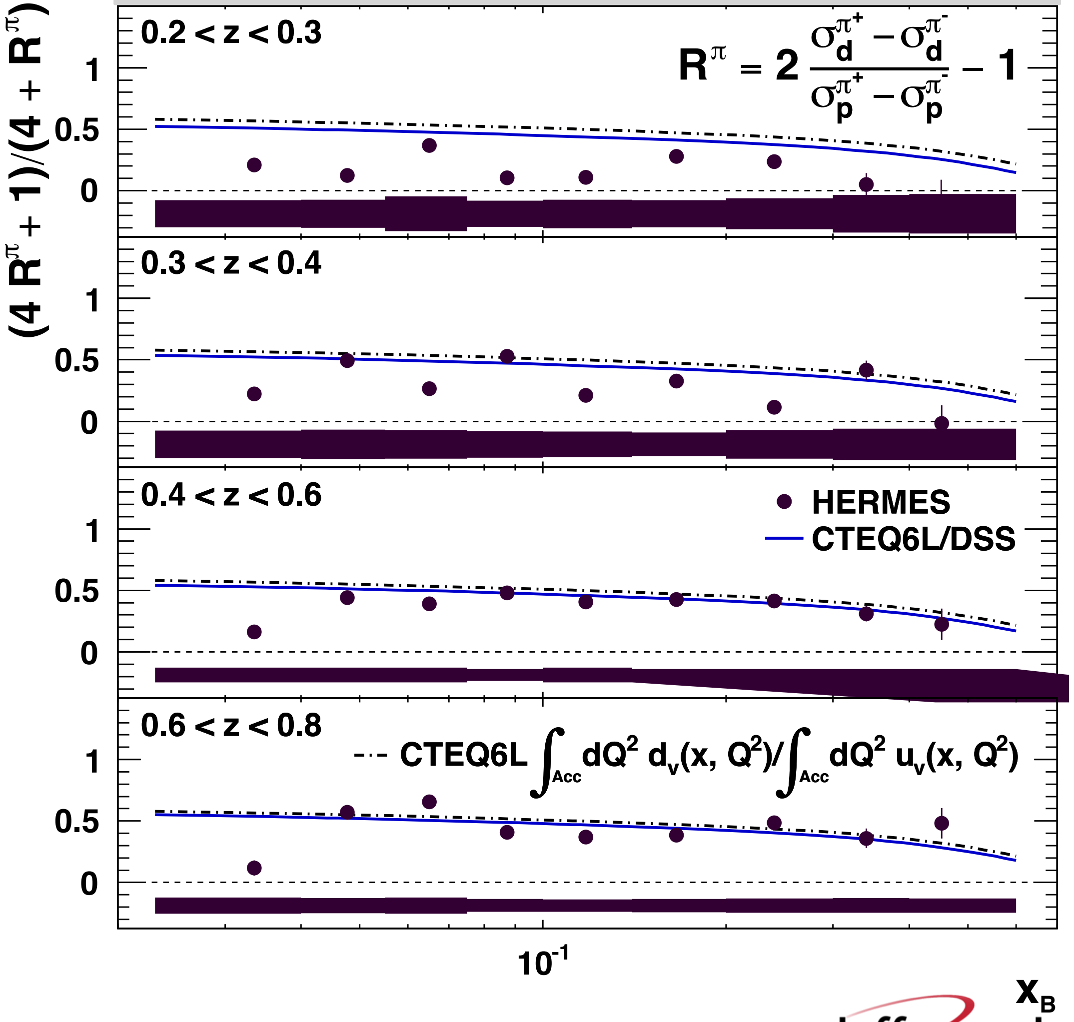
Factorization scales and breaking

TMD factorization
partonic scale << hard-scattering scale

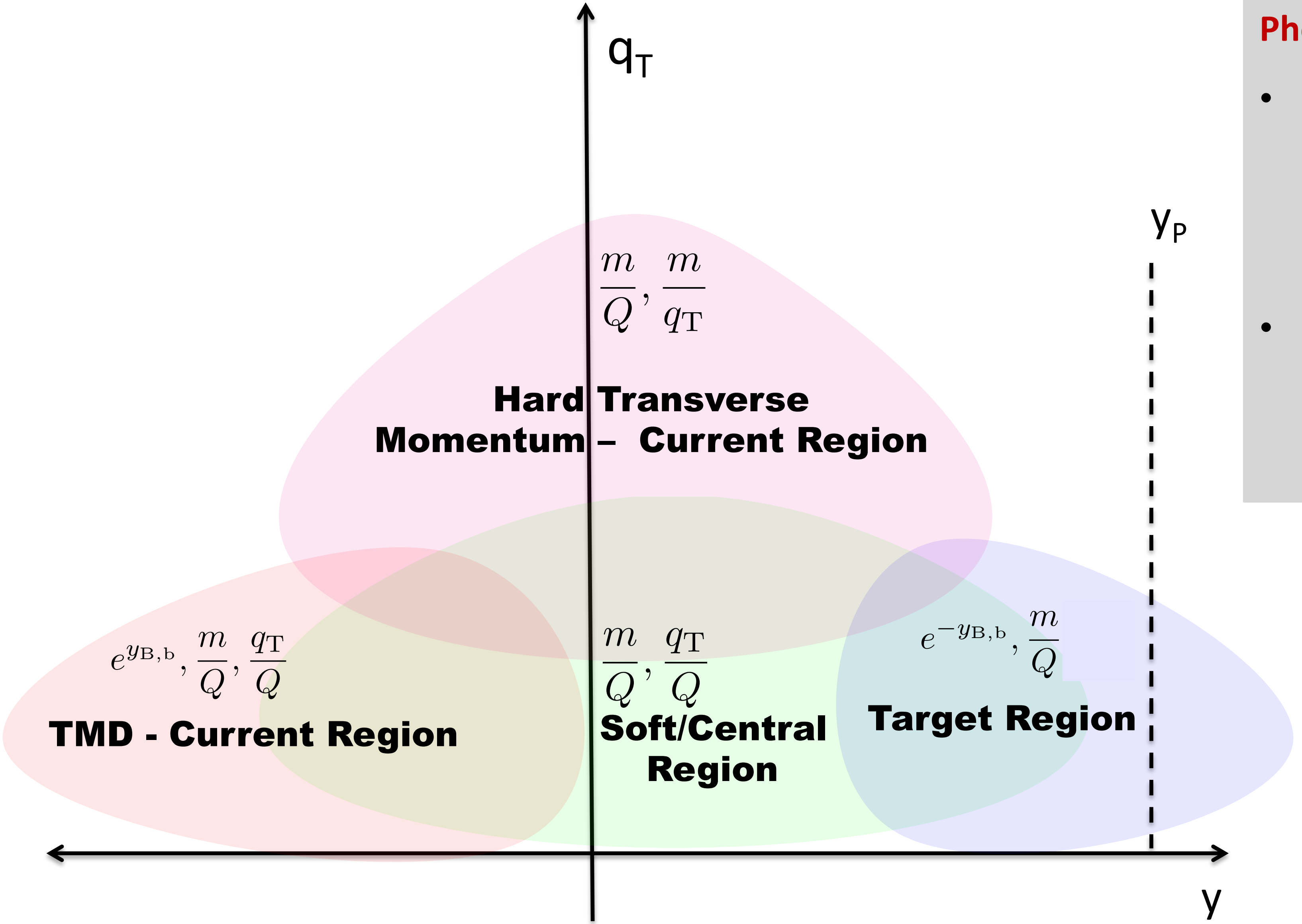




HERMES multiplicities from unpolarized SIDIS sample



Exploring SIDIS regions



Phenomenologicial studies

- Boglione et al., **Kinematics of Current Region Fragmentation in Semi-Inclusive Deeply Inelastic Scattering**, *Phys.Lett.B* 766 (2017) 245-253
- Boglione et al., **Mapping the Kinematical Regimes of Semi-Inclusive Deep Inelastic Scattering**, *JHEP* 10 (2019) 122

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TMDs Imaging quarks and gluons within the nucleon.

- **HERMES** Pioneering TMD measurements at the first Electron-Ion Collider.
- ***JHEP* 12 (2020) 010** Compendium on TMD analysis:
  - Final HERMES analysis on SSA and DSA in SIDIS off transversely polarized proton target.
  - HERMES results for pions, charged kaons, and **now** protons have revealed first information about TMDs for valence and sea quarks.
  - **New** HERMES results in 3D binning maximize information for QCD analysis.
  - Detailed description of the HERMES analysis to guide future measurements (204 pages, 70 figures, 118 tables).
- **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.