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Transversity results from HERMES

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for the hermes collaboration

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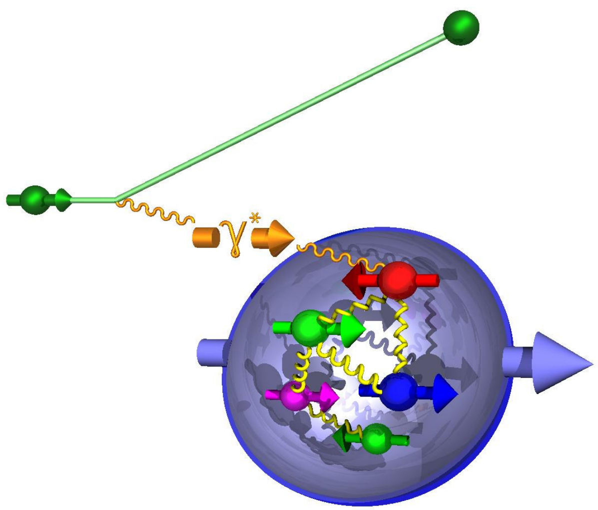
Outline

- The leading-twist distribution functions of the nucleon
- The chiral-odd transversity distribution
- The SIDIS cross section and the Collins and Sivers effects
- The HERMES experiment at HERA
- The Single Spin Asymmetry
- HERMES results on Collins and Sivers moments for $\pi^{\pm}$ and $K^{\pm}$
- Conclusions and outlook

The inner spin distribution of the nucleon

Spin distribution of the nucleon ➡ polarised DIS (polarised beam and/or target)



The relevant kinematical variables:

$$Q^2 = -q^2 \overset{lab}{=} 2EE'\,(1\text{-}\cos\theta)$$

$$x \overset{lab}{=} \frac{Q^2}{2M\nu} \qquad y \overset{lab}{=} \frac{\nu}{E} \qquad \nu \overset{lab}{=} E - E'$$

- Virtual photon can only couple to quarks of opposite spin
- Different targets give sensitivity to different quark flavors

⬇

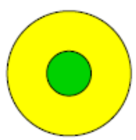
experiments at CERN, SLAC, DESY, JLAB

The three leading-twist distribution functions

All equally important for a complete description of momentum and spin distribution of the nucleon at leading-twist.

unpolarised DF

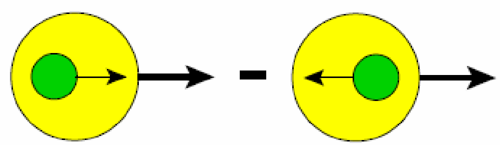
$q(x, Q^2)$



well known

Helicity

$\Delta q(x, Q^2)$

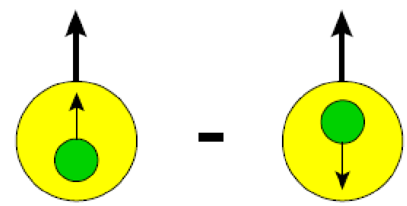


known

HERMES 1996-2000

Transversity

$\delta q(x, Q^2)$



unkown

HERMES 2002-2005

Positivity limit

$$|\delta q(x)| < q(x)$$

Soffer bound

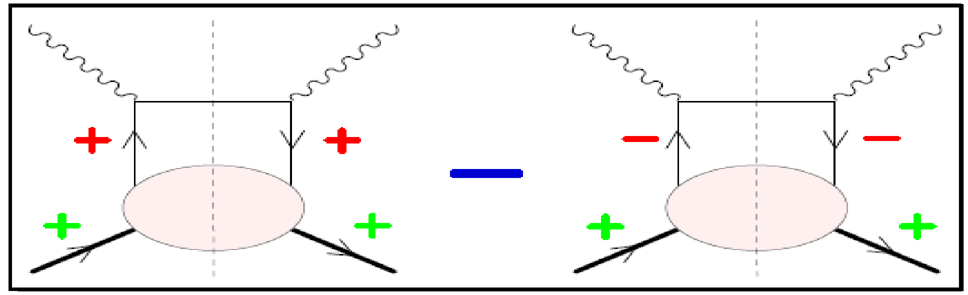
$$|\delta q(x)| < \frac{1}{2}\left(q(x) + \Delta q(x)\right)$$

$$\begin{cases} \delta q(x) = \Delta q(x) & \text{non-relativistic regime} \\ \delta q(x) \neq \Delta q(x) & \text{relativistic regime} \end{cases}$$

Probes relativistic nature of quarks

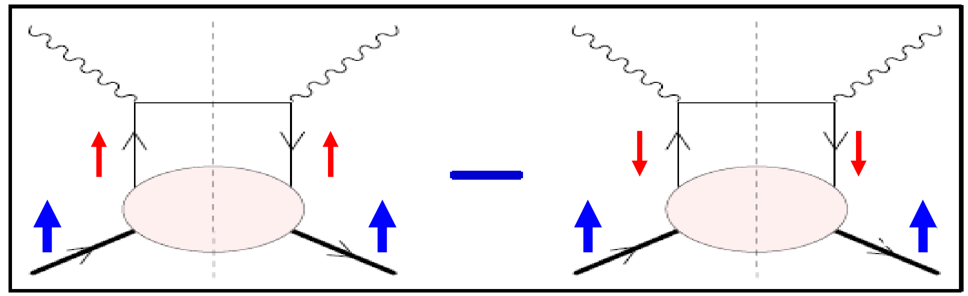
$$\Delta q(x, Q^2)$$

Helicity basis: $|+\rangle, |-\rangle$



$$\delta q(x, Q^2)$$

Transverse spin basis: $|\uparrow\rangle, |\downarrow\rangle$



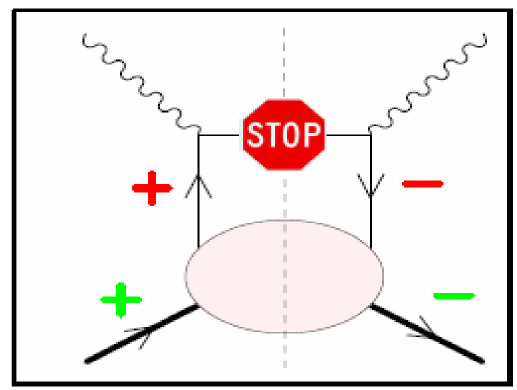
$$\int dx\left(\delta q(x) - \delta\bar{q}(x)\right) = \langle PS|\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi|PS\rangle$$

δq is chiral-odd object

associated with a helicity flip of the struck quark

δq in helicity basis:

$$\begin{cases} |+\rangle = \dfrac{1}{\sqrt{2}}\left(|\uparrow\rangle + |\downarrow\rangle\right) \\ |-\rangle = \dfrac{1}{\sqrt{2}i}\left(|\uparrow\rangle - |\downarrow\rangle\right) \end{cases}$$

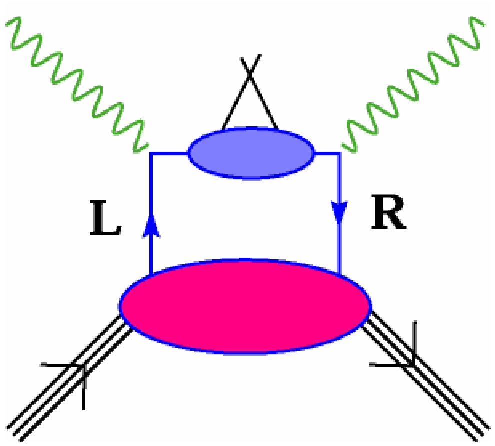


EM interactions cannot flip the chirality of the probed quark

Transversity Distribution is not measurable in inclusive DIS

How can one measure transversity?

Need another chiral-odd object! $\Rightarrow$ Semi-Inclusive DIS



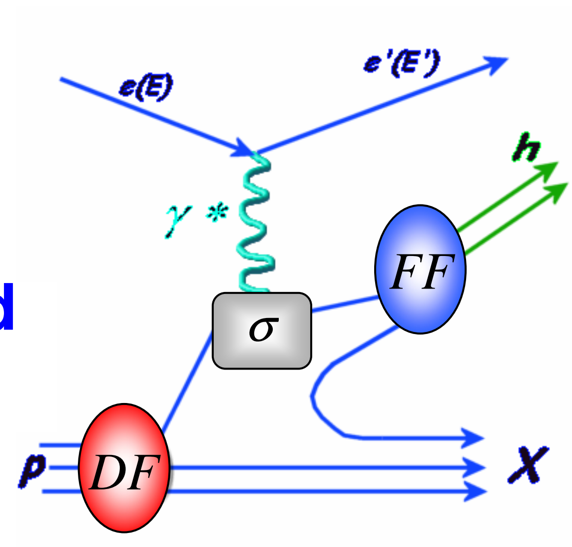
one hadron in the initial state and at least one in the final state (semi-inclusive leptoproduction)

$$\sigma^{ep\to ehX} = \sum_q \delta q \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}$$

$\Downarrow$ **chiral – odd DF**

$\Downarrow$ **chiral – odd FF**

CHIRAL EVEN

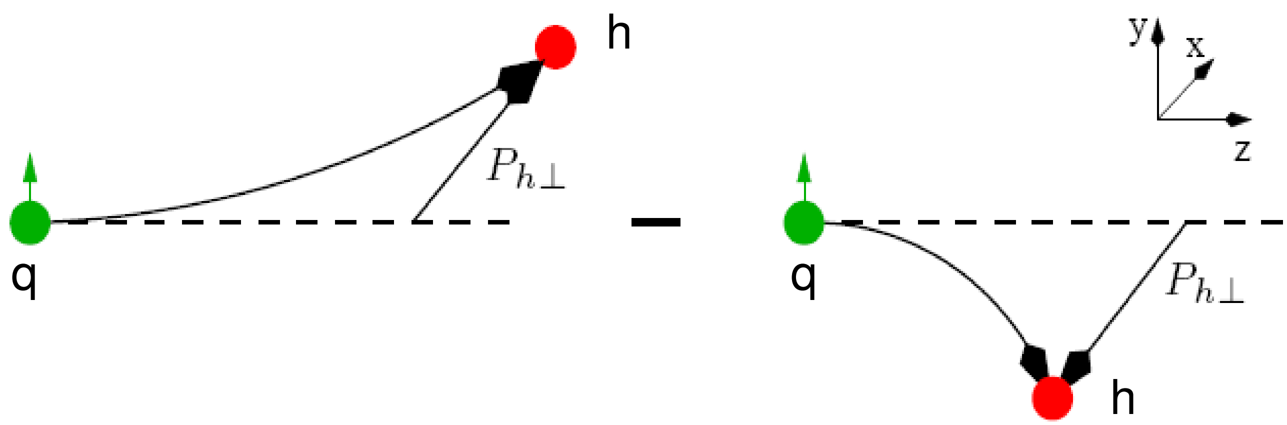


The "Collins effect"

Collins fragmentation function $H_1^{\perp}(z, k_T^2)$ carries out the correlation between the transverse spin of the fragmenting quark and $P_{h\perp}$.

Chiral – odd & naïve T – odd

produces left-right asymmetry in the direction of the outgoing hadron

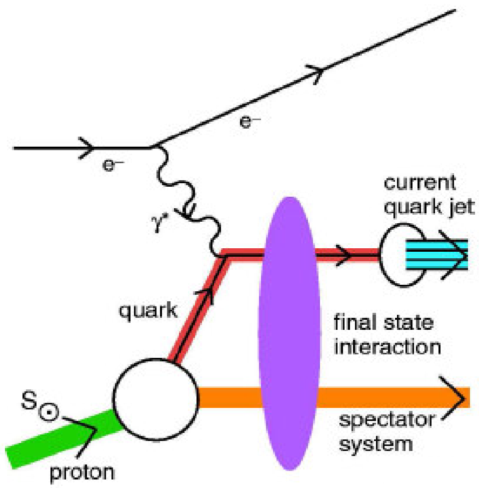


The "Sivers effect"

Correlation between p_T and transverse spin of the nucleon

Sivers distribution function $f_{1T}^{\perp q}(x, p_T^2)$ describes the probability to find an unpolarized quark with transverse momentum p_T in a transversely polarized nucleon

Chiral – even & naïve T – odd

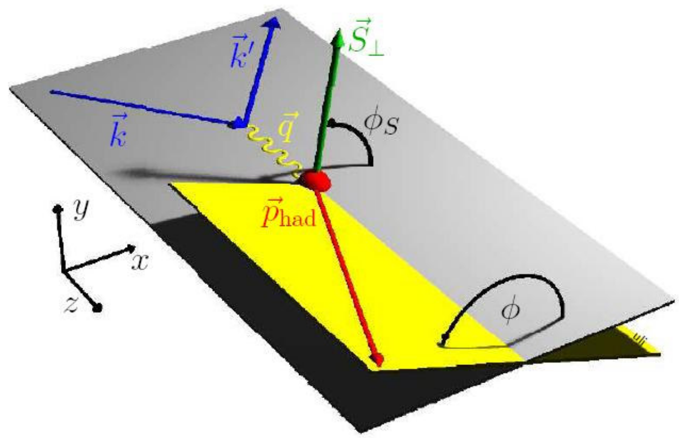


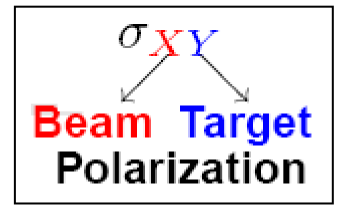
requires a quark rescattering via soft gluon exchange (gauge link)

(Brodsky, Hwang, Schmidt)

Non-zero Sivers function requires non-vanishing orbital angular momentum in the nucleon wave function (can contribute to nucleon spin!)

The SIDIS cross-section at leading order in 1/Q





$$d\sigma = d\sigma_{UU}^{(0)} + \cos 2\phi \, d\sigma_{UU}^{(1)} + S_L \left\{ \sin 2\phi \, d\sigma_{UL}^{(2)} + \lambda_e d\sigma_{LL}^{(3)} \right\} + \lambda_e \cos(\phi - \phi_S) \; d\sigma_{LT}^{(4)}$$

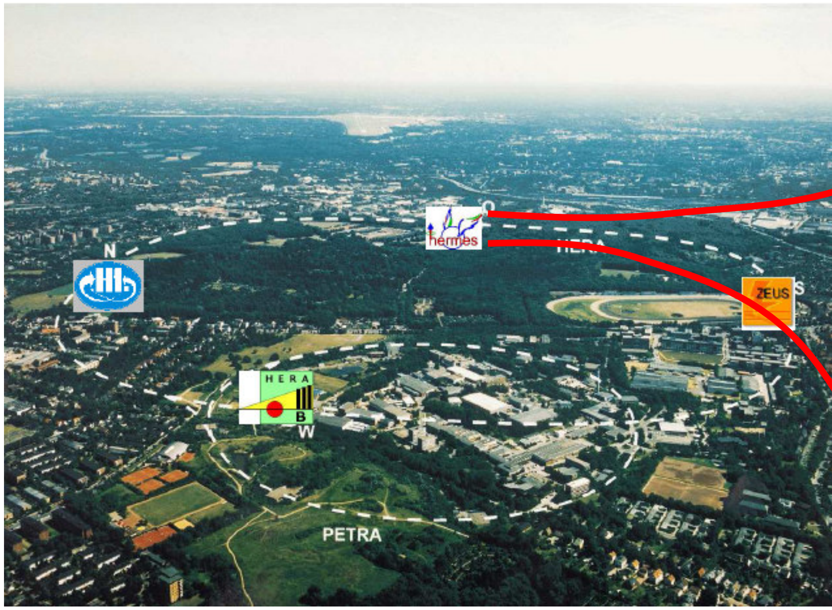
$$+ S_T \left\{ \underbrace{\sin(\phi+\phi_S) \; d\sigma_{UT}^{(5)}}_{\text{Collins}} + \underbrace{\sin(\phi-\phi_S) \; d\sigma_{UT}^{(6)}}_{\text{Sivers}} + \sin(3\phi-\phi_S) \; d\sigma_{UT}^{(7)} + \sin\phi_S d\sigma_{UT}^{(8)} \right\}$$

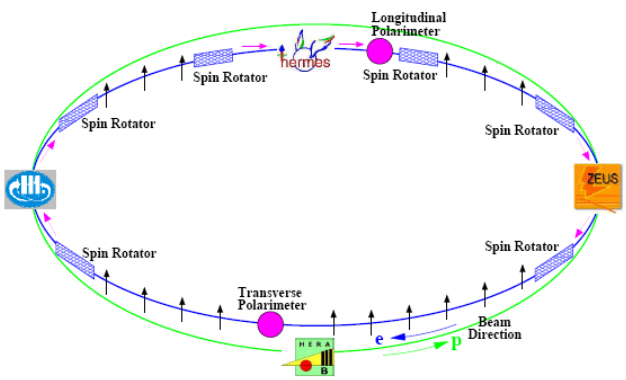
$$d\sigma_{UT}^{Collins} \propto |S_T| \sin(\phi+\phi_S) \cdot \sum_q e_q^2 I\left[\frac{\vec{k}_T \cdot \hat{P}_{h\perp}}{M_h} \boxed{\delta q(x, p_T^2)} \otimes \boxed{H_1^{\perp q}(z, k_T^2)} \right]$$

$$d\sigma_{UT}^{Sivers} \propto |S_T| \sin(\phi-\phi_S) \cdot \sum_q e_q^2 I\left[\frac{\vec{p}_T \cdot \hat{P}_{h\perp}}{M_h} \boxed{f_{1T}^{\perp q}(x, p_T^2)} \otimes \boxed{D_1^q(z, k_T^2)} \right]$$

$I[...] =$ convolution integral over initial $(\vec{p}_T)$ and final $(\vec{k}_T)$ quark transverse momenta

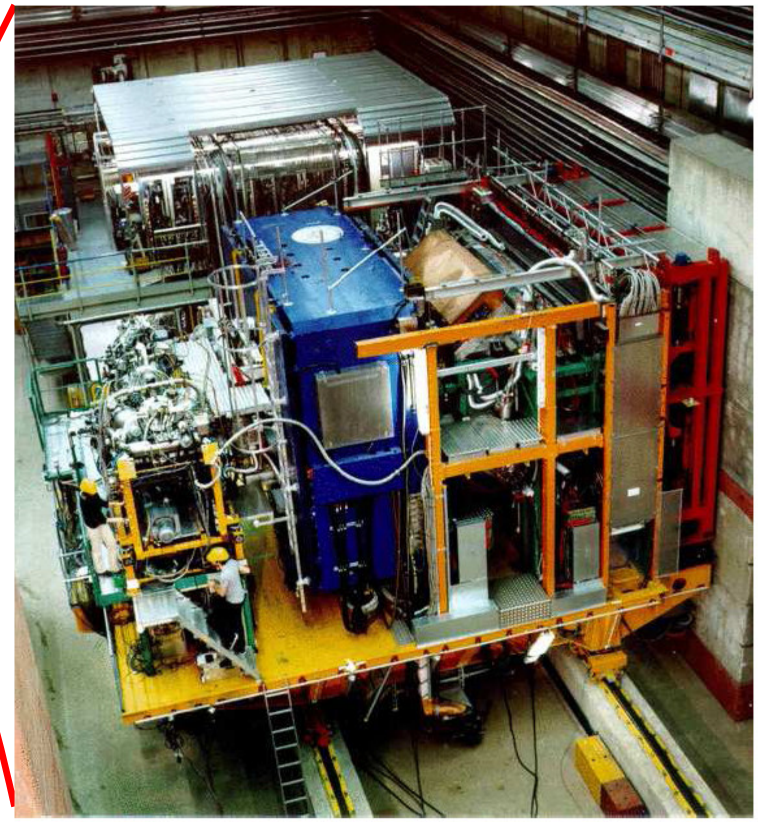
The HERA storage ring (DESY)





- 27.5 GeV e^+/e^- beam
- Self-polarizing through Sokolov-Ternov-Effect
- Average beam polarization of about 55%

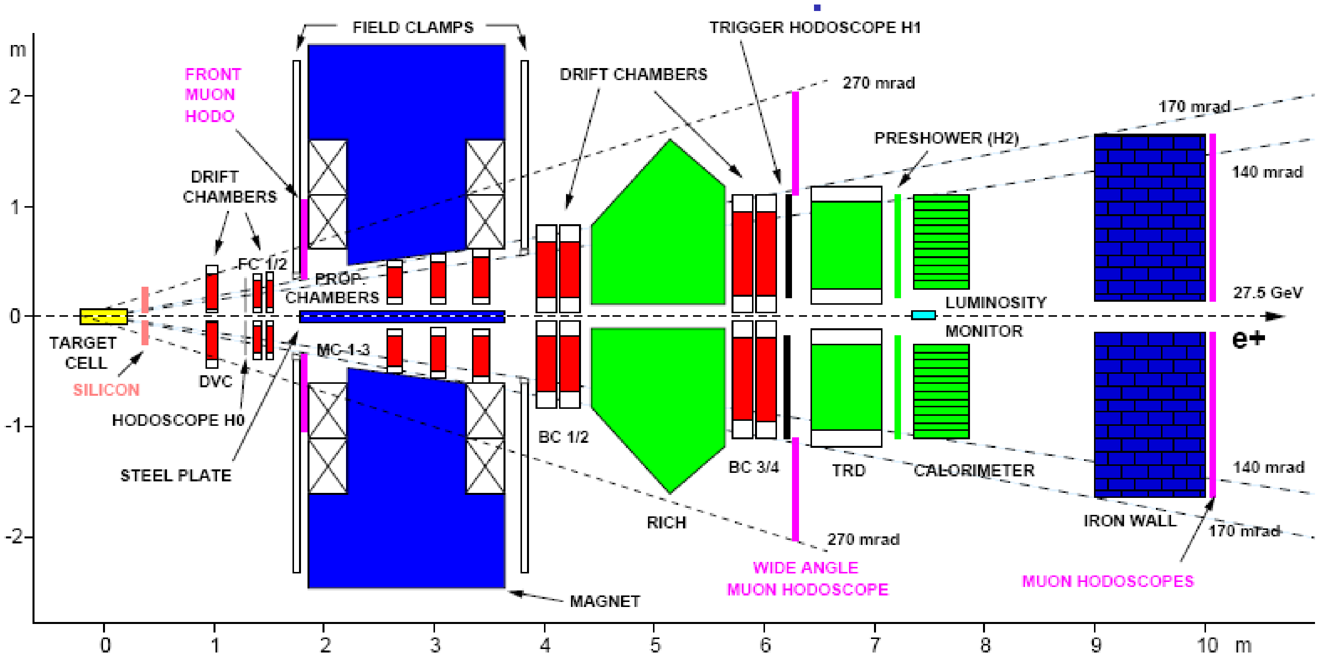
The HERMES Spectrometer

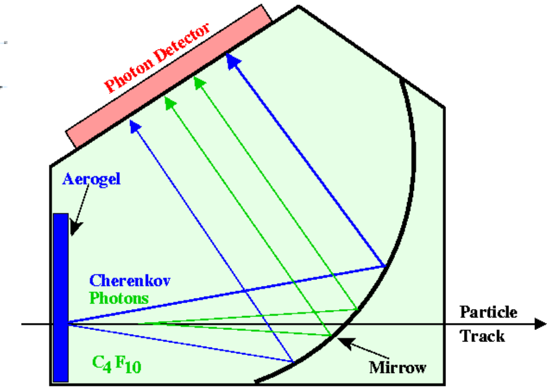


- Fixed target experiment
- forward spectrometer symmetric above and below the beampipe
- Polarized internal gas target
- Relatively large acceptance

Angular acceptance: $40\ mrad < |\theta_y| < 140\ mrad \quad |\theta_x| < 170\ mrad$

Resolution: $\delta p \leq 2.6\%$; $\delta\vartheta \leq 1\ mrad$





Dual radiator RICH

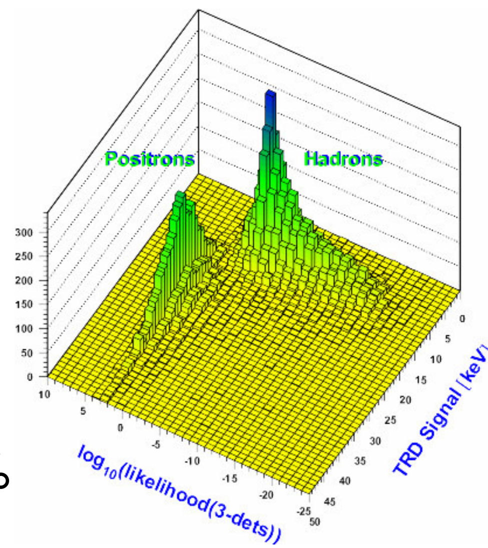
Particle Identification:

TRD, Calorimeter, preshower, RICH:

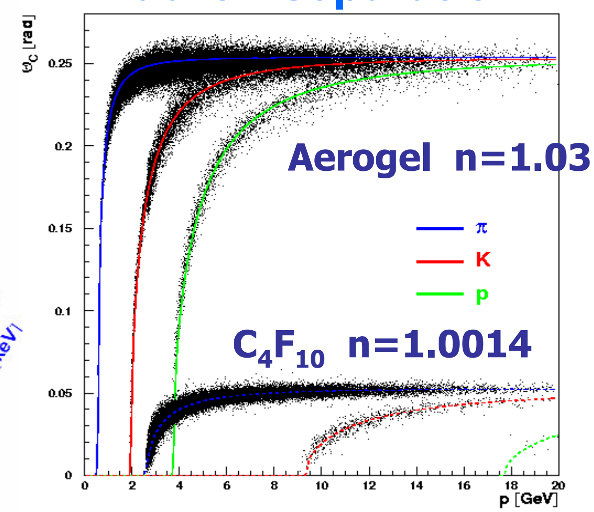
lepton-hadron > 98%

RICH:

Hadron: π ~ 98%, K ~ 88% , P ~ 85%



hadron separation



Data from running period 2002-2004 (transversely polarized hydrogen target)

$Q^2 > 1\ GeV^2$ $\quad$ $0.2 < z \overset{lab}{=} \frac{E_h}{\nu} < 0.7$ $\quad$ $0.023 < x < 0.4$

$2\ GeV < P_h < 15\ GeV$ $\quad$ $W^2 > 10\ GeV^2$ $\quad$ $0.1 < y \leq 0.85$

The Single Spin Asymmetry of the SIDIS cross-section

$$A_{UT}^h(\phi, \phi_S) = \frac{1}{|S_T|} \frac{N_h^{\uparrow}(\phi, \phi_S) - N_h^{\downarrow}(\phi, \phi_S)}{N_h^{\uparrow}(\phi, \phi_S) + N_h^{\downarrow}(\phi, \phi_S)}$$

$$\approx 2\langle \sin(\phi + \phi_S) \rangle_{UT}^h \sin(\phi + \phi_S) + 2\langle \sin(\phi - \phi_S) \rangle_{UT}^h \sin(\phi - \phi_S) + \cdots$$

Collins moment

$\propto \delta q(x) H_1^{\perp q}(z)$

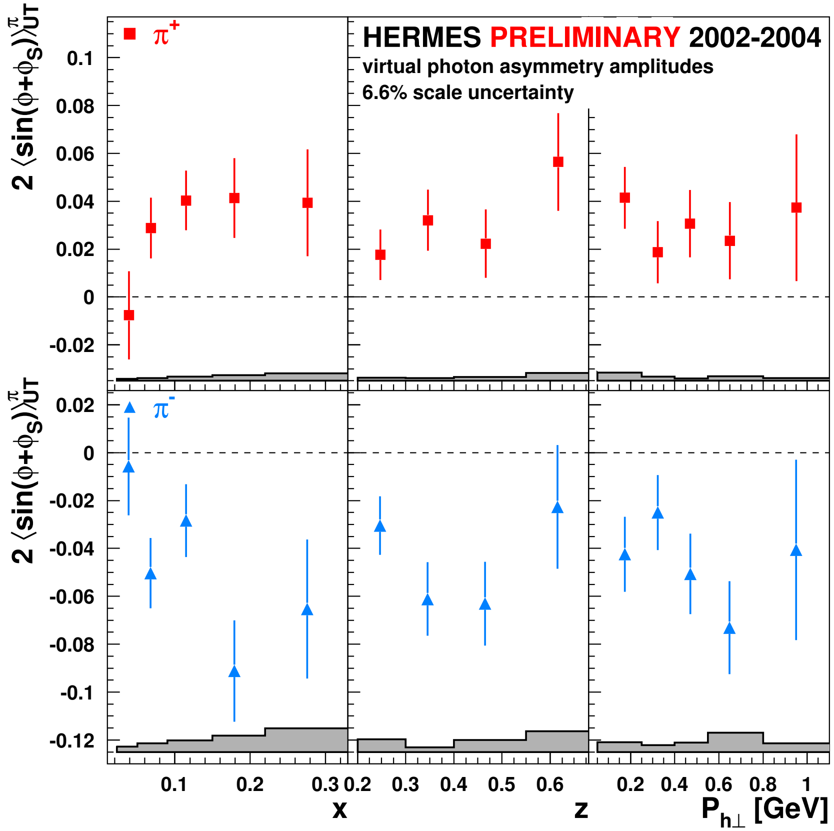
Sivers moment

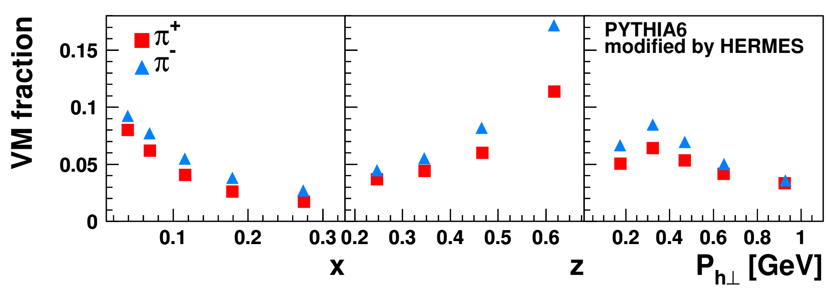
$\propto f_{1T}^{\perp q}(x) D_1^q(z)$

The Collins and Sivers moments are then extracted by fitting the asymmetry with:

$$A_{UT}^{Fit}(\phi, \phi_S) = P(1)\sin(\phi + \phi_S) + P(2)\sin(\phi - \phi_S) + P(3)\sin(\phi_S) + P(4)\sin(2\phi + \phi_S) + P(5)$$

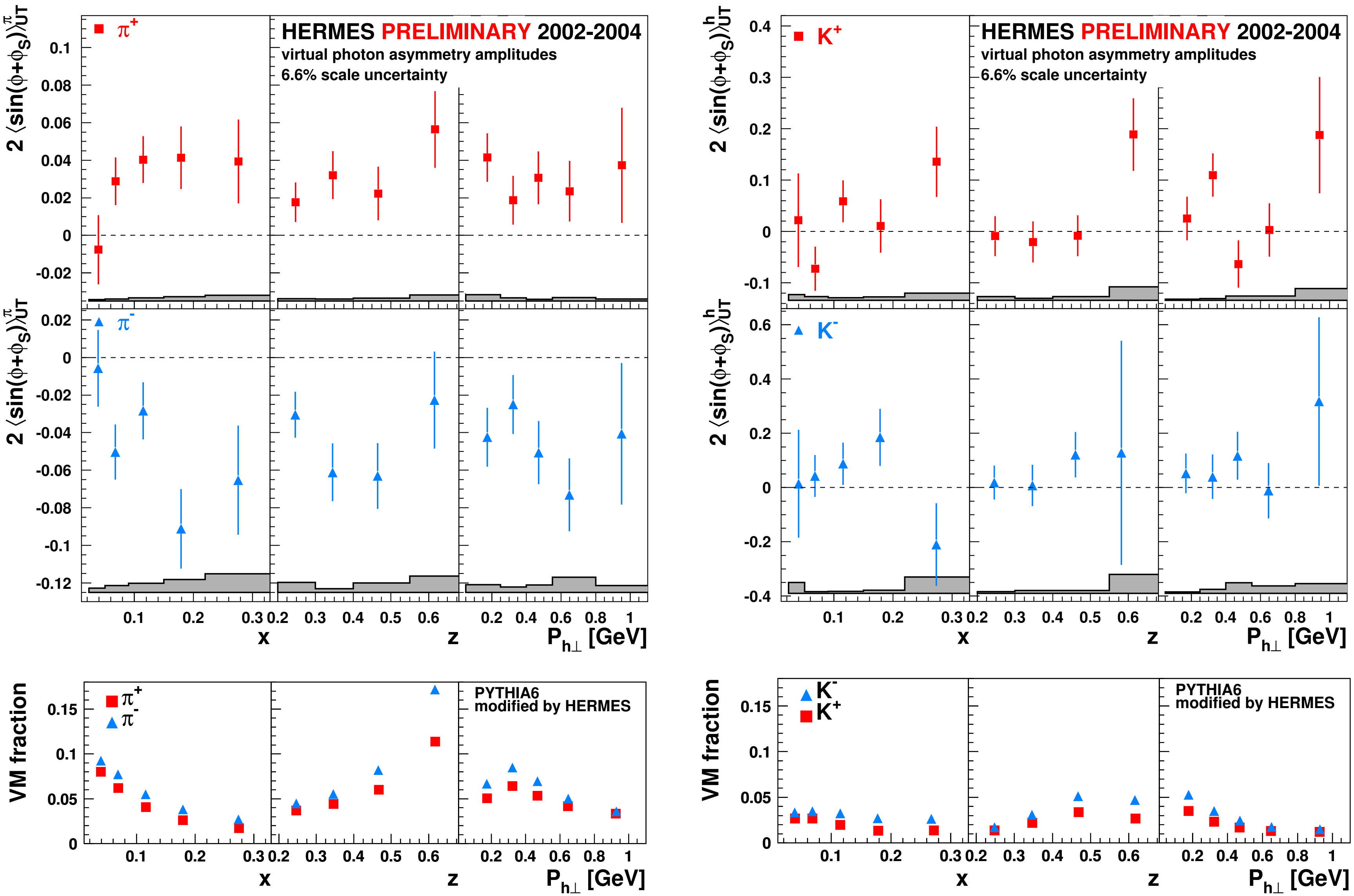
Collins moments for $\pi^{+/-}$ (2002-2004)



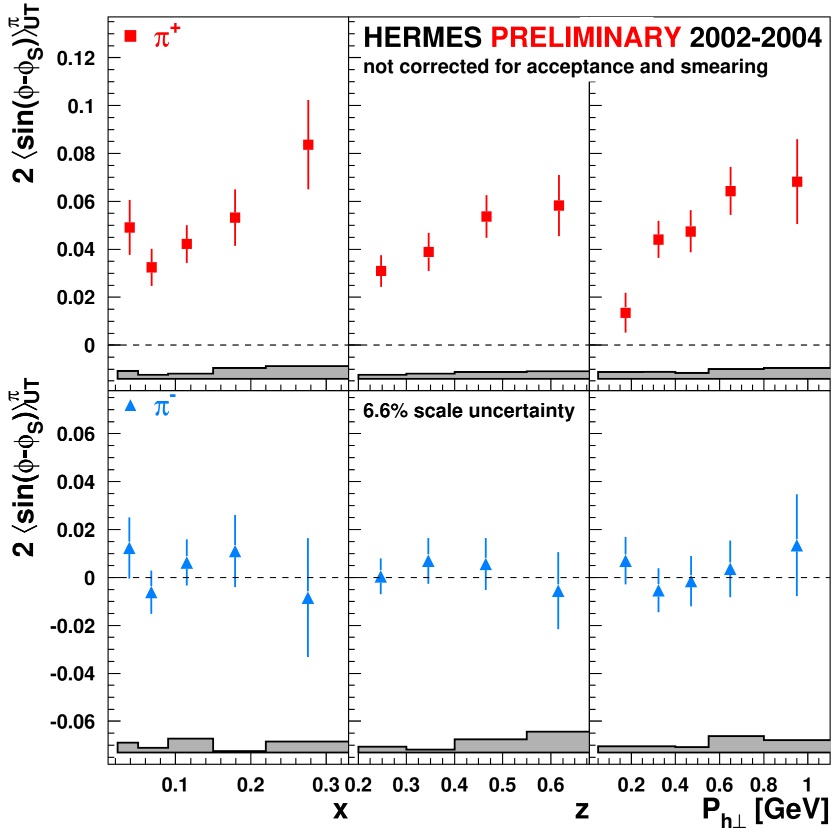


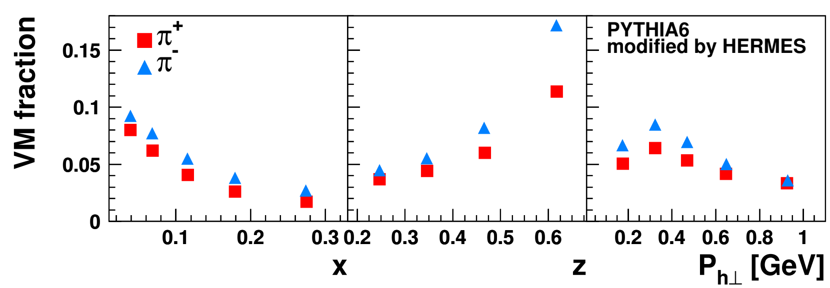
- $\propto \delta q(x) H_1^{\perp q}(z)$
- First evidence for non-zero Collins function
- Collins moment is positive for π^+
- Collins moment negative for π^-
- the large negative π^- amplitude suggests disfavored Collins function with opposite sign
- systematic errors (shaded bands) include acceptance and smearing effects and contributions from unpolarised $\langle\cos(2\varphi)\rangle$ and $\langle\cos(\varphi)\rangle$ moments

Collins moments for $\pi^{+/-}$ and $K^{+/-}$ (2002-2004)



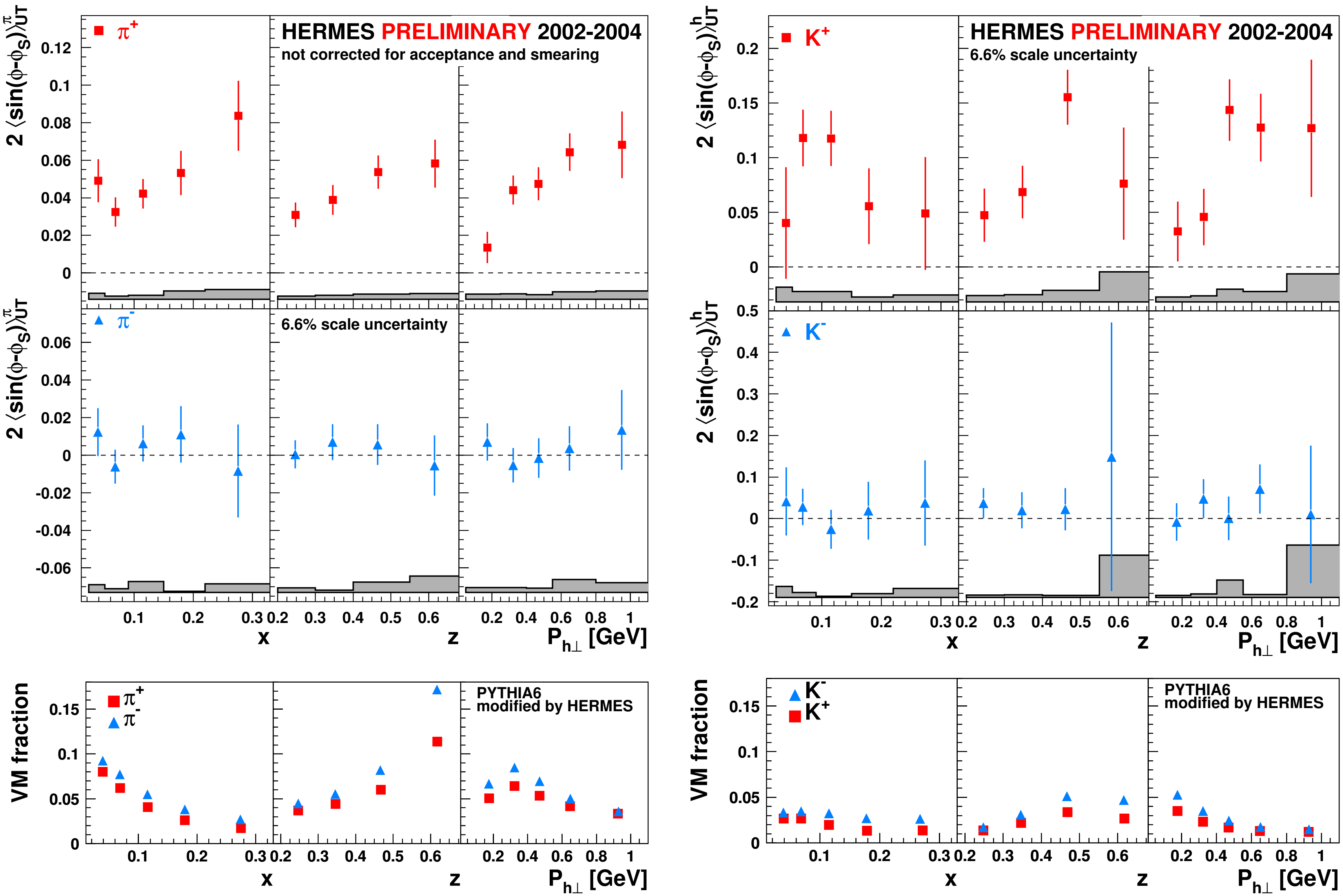
Sivers moments for $\pi^{+/-}$ (2002-2004)





- $\propto f_{1T}^{\perp q}(x) D_1^q(z)$
- Sivers moment is positive for π^+
- First evidence for non-zero Sivers function $\Rightarrow$ non-vanishing orbital angular momentum L_z^q
- Sivers moment consistent with zero for π^-
- systematic errors (shaded bands) include acceptance and smearing effects and contributions from unpolarised $\langle\cos(2\varphi)\rangle$ and $\langle\cos(\varphi)\rangle$ moments

Sivers moments for $\pi^{+/-}$ and $K^{+/-}$ (2002-2004)

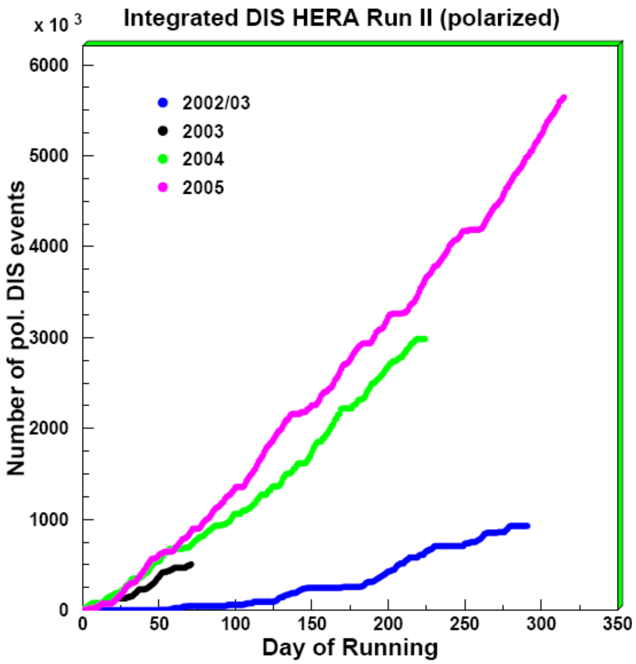


Conclusions

- Transverse Spin physics fast evolving (experimental and theoretical) field
- Single Spin Asymmetries powerful tool to access transversity at HERMES.
- Preliminary HERMES results on semi-inclusive pion and kaon leptoproduction support the existence of non-zero chiral-odd and T-odd structures that describe the transverse structures the nucleon.
- First measurements for kaons suggest that sea quarks may provide an important contribution to the Sivers function

Outlook

- 2005 data will double current statistics
- $P_{h\perp}$-weighted asymmetries are under study
- Sivers function likely to be extracted within the next few years at HERMES
- Collins function estimation will allow extraction of the Transversity distribution (first data from Belle supports a non-zero $H_1^{\perp}$)



Backup slides

The SIDIS cross-section (up to subleading order in 1/Q)

$$d\sigma = d\sigma^0_{UU} + \cos 2\phi \, d\sigma^1_{UU} + \frac{1}{Q}\cos\phi \, d\sigma^2_{UU} + \lambda_e \frac{1}{Q}\sin\phi \, d\sigma^3_{LU}$$

$$+S_L \left\{ \sin 2\phi \, d\sigma^4_{UL} + \frac{1}{Q}\sin\phi \, d\sigma^5_{UL} + \lambda_e \left[d\sigma^6_{LL} + \frac{1}{Q}\cos\phi \, d\sigma^7_{LL} \right] \right\}$$

$$+S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \sin(\phi + \phi_S) \, d\sigma^9_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \right.$$

$$+ \frac{1}{Q}\left(\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right)$$

$$\left. + \lambda_e \left[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q}\left(\cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \right\}$$

σ_{XY}: X = Beam, Y = Target

Beam Target Polarization

$$(d^6\sigma_{UT})_{Collins} \propto |S_T| \sin(\phi + \phi_S) \cdot \sum_q e_q^2 I\left[\frac{\vec{k}_T \cdot \hat{P}_{h\perp}}{M_h} h_1^q(x, p_T^2) \otimes H_1^{\perp q}(z, k_T^2) \right]$$

$$(d^6\sigma_{UT})_{Sivers} \propto |S_T| \sin(\phi - \phi_S) \cdot \sum_q e_q^2 I\left[\frac{\vec{p}_T \cdot \hat{P}_{h\perp}}{M_h} f_{1T}^{\perp q}(x, p_T^2) \otimes D_1^q(z, k_T^2) \right]$$

Once the convolution integral over the intrinsic momenta is solved (e.g. gaussian ansatz)

$$\left\langle \sin(\phi+\phi_S)\right\rangle_{UT}^{h} \propto \frac{\left|\vec{S}_T\right|}{\sqrt{1+z^2\left\langle p_T^2\right\rangle / \left\langle K_T^2\right\rangle}} \frac{\sum_{q,\bar{q}} e_q^2 \delta q(x) H_1^{\perp q}(z)}{\sum_{q,\bar{q}} e_q^2 \cdot q(x) \cdot D_1^q(z)}$$

$$\left\langle \sin(\phi-\phi_S)\right\rangle_{UT}^{h} \propto \frac{\left|\vec{S}_T\right|}{\sqrt{1+\left\langle K_T^2\right\rangle / \left(z^2\left\langle p_T^2\right\rangle\right)}} \frac{\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp q}(x) D_1^q(z)}{\sum_{q,\bar{q}} e_q^2 \cdot q(x) \cdot D_1^q(z)}$$

$P_{h\perp}$-weighted moments (no assumption on intrinsic transverse momenta distributions)

$$\left\langle \frac{P_{h\perp}}{zM_h} \sin(\phi+\phi_S)\right\rangle_{UT}^{h} \propto \left|\vec{S}_T\right| \frac{\sum_{q,\bar{q}} e_q^2 \delta q(x) H_1^{\perp q}(z)}{\sum_{q,\bar{q}} e_q^2 \cdot q(x) \cdot D_1^q(z)}$$

$$\left\langle \frac{p_{h\perp}}{zM_h} \sin(\phi-\phi_S)\right\rangle_{UT}^{h} \propto -\left|\vec{S}_T\right| \frac{\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp q}(x) D_1^q(z)}{\sum_{q,\bar{q}} e_q^2 \cdot q(x) \cdot D_1^q(z)}$$

The Maximum Likelihood unbinned fit

(Un)binned Maximum-Likelihood fits to azimuthal Fourier amplitudes are significantly superior to least-χ^2 fits for data sets with few events

The polarised event distribution and PDF for each target spin state is:

$$
\begin{aligned}
C\,N_{\uparrow(\downarrow)}(x,y,z,P_t,\phi,\phi_S) &= \varepsilon(x,y,z,P_{h\perp},\phi,\phi_S)\,\underline{\sigma}_{UU}(x,y,z,P_t)\times \\
&\quad \frac{1}{2}[1 + A_{UU}^{\cos\phi}(x,y,z,P_t)\cos\phi + A_{UU}^{\cos 2\phi}(x,y,z,P_t)\cos(2\phi) \\
&\quad +(-)\,A_C(\lambda_1,x,y,z,P_t)\sin(\phi+\phi_S) +(-)\,A_S(\lambda_2,x,y,z,P_t)\sin(\phi-\phi_S)] \\
&\equiv F_{\uparrow(\downarrow)}(\lambda_1,\lambda_2,x,y,z,P_t,\phi,\phi_S) \quad \text{(Probability Density Fun.)}
\end{aligned}
$$

Acceptance ε and azimuthally averaged cross section $\underline{\sigma}_{UU}$ do not depend on the fitting parameter sets λ_1 and λ_2

normalization integral

$$
\mathcal{N}_{\uparrow(\downarrow)}(\lambda_1,\lambda_2) = \sum_{i=1}^{N_\uparrow+N_\downarrow}\left[1 + \frac{[+(-)\,A_C(\lambda_1,x_i,y_i,z_i,P_{ti})\sin(\phi_i+\phi_{Si}) +(-)\,A_S(\lambda_2,x_i,y_i,z_i,P_{ti})\sin(\phi_i-\phi_{Si})]}{1 + A_{UU}^{\cos\phi}(x_i,y_i,z_i,P_{ti})\cos\phi + A_{UU}^{\cos 2\phi}(x_i,y_i,z_i,P_{ti})\cos(2\phi)}\right]
$$

Likelihood function

$$
\mathcal{L}(\lambda_1,\lambda_2) = \frac{\prod_{i=1}^{N_\uparrow} F_\uparrow(\lambda_1,\lambda_2,x_i,y_i,z_i,P_{ti},\phi_i,\phi_{Si})\ \prod_{i=1}^{N_\downarrow} F_\downarrow(\lambda_1,\lambda_2,x_i,y_i,z_i,P_{ti},\phi_i,\phi_{Si})}{\mathcal{N}_\uparrow^{N_\uparrow}(\lambda_1,\lambda_2)\ \mathcal{N}_\downarrow^{N_\downarrow}(\lambda_1,\lambda_2)}
$$

(to be maximized with respect to the parameter sets: λ_1, λ_2)