Spin structure of nucleons (session 2b) —

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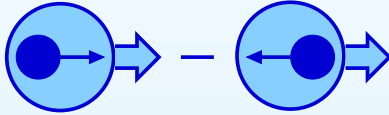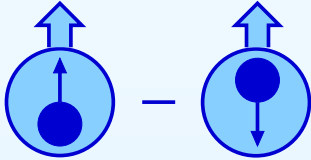
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hermes -collaboration

The spin structure of the nucleon:

The complete description of quark momentum and spin at leading twist:

momentum distribution $q\left(x, Q^2\right)$	helicity distribution $\Delta q\left(x, Q^2\right)$	transversity distribution $\delta q\left(x, Q^2\right)$
forward quark-nucleon amplitudes: (in helicity basis)		
$\sim \operatorname{Im}\left(A_{++,++} + A_{+-,+-}\right)$ measures spin average	$\sim \operatorname{Im}\left(A_{++,++} - A_{+-,+-}\right)$ measures helicity difference	$\sim \operatorname{Im}\left(A_{+-,-+}\right)$ measures helicity flip
probabilistic interpretation:		
(in helicity basis)	(in helicity basis)	(in basis of transverse spin eigenstates)

Some properties of the transversity distribution:

- The difference between helicity and the transversity distribution provides measurement of the relativistic nature of the quarks inside the nucleon.

- There is no gluon transversity at a nucleon target (i.e. pure valence quark object).
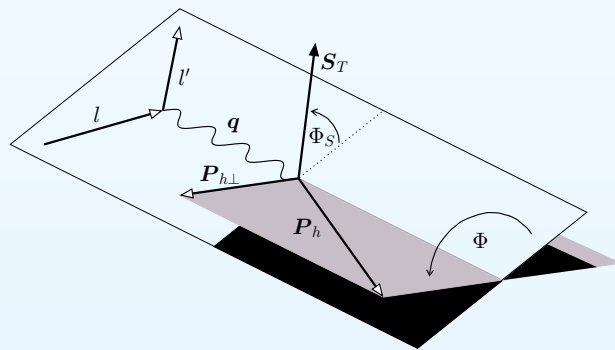
Chirality of the transversity distribution:

- The forward scattering amplitude, that defines $\delta q\left(x, Q^2\right)$. flips chirality of the quark, i.e. the transversity distribution is a **chiral-odd** function.

- Perturbative QCD (pQCD) processes and all interactions with external electroweak currents conserve chirality (for almost massless quarks); i.e. helicity flips are suppressed in pQCD processes.

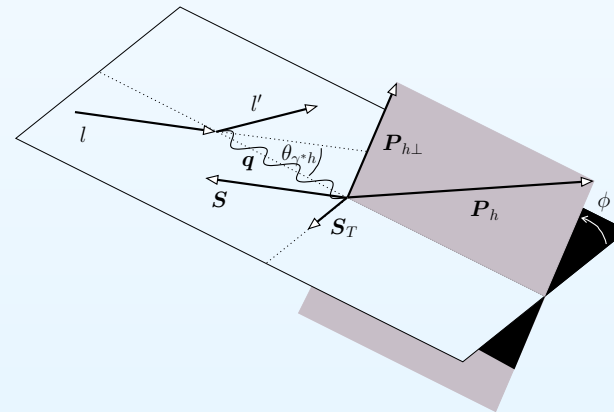- Transversity cannot be determined in inclusive DIS ($lp \to l'X$):

- Another chiral-odd function is needed.

- The transversity distribution can be measured in experiments with two hadrons in the initial state or one hadron both in initial and final state. Thereby at least one hadron has to be transversely polarised.

Measurement of transversity at HERMES:

- Transversity in conjunction with the chiral-odd Collins fragmentation function is accessible in SSA in semi-inclusive DIS on a transversely polarised target.

- **Azimuthal single-spin asymmetries (SSA)** are left-right asymmetries in the momentum distribution of the produced hadrons in the directions transverse to the nucleon spin.

- **Kinematics of semi-inclusive DIS on a transversely polarised target**:

(transversely polarised target)   (for comparison: longitudinally polarised target)

- In addition to the azimuthal angle ϕ the azimuthal angle ϕ_S is observable.
- At HERMES kinematics non-vanishing $P_{h\perp}$ is caused by intrinsic transverse momenta p_T (distribution part) and k_T (fragmentation part).
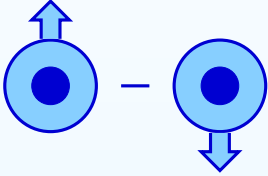
The Collins and Sivers mechanisms:

Collins function $H_1^\perp \left(z, (-z\boldsymbol{k}_T)^2 \right)$	
• fragmentation function • correlation between transverse polarisation of the fragmenting quark and the transverse momentum $P_{h\perp}$ of the produced (spinless) hadron • chiral-odd • naive time reversal odd $\Leftrightarrow$ final state interactions $\Rightarrow$ single-spin asymmetries	

The Collins and Sivers mechanisms:

Collins function $H_1^\perp\left(z,(-z\boldsymbol{k}_T)^2\right)$	**Sivers function** $f_{1T}^\perp\left(x,\boldsymbol{p}_T^2\right)$
 • fragmentation function • correlation between transverse polarisation of the fragmenting quark and the transverse momentum $P_{h\perp}$ of the produced (spin-less) hadron • chiral-odd • naive time reversal odd $\Leftrightarrow$ final state interactions $\Rightarrow$ single-spin asymmetries	 • distribution function • correlation between transverse polarisation of nucleon and the transverse momentum $\boldsymbol{p}_T$ of the quarks within • non-zero Compton amplitude $(N^{\Uparrow}q^{\downarrow} \to N^{\Downarrow}q^{\downarrow}) \Rightarrow$ involves orbital angular momentum of quarks • chiral-even • naive time reversal odd $\Leftrightarrow$ final state interactions $\Rightarrow$ single-spin asymmetries

Collins and Sivers amplitudes:

- The transverse target cross section contains a convolution integral over intrinsic transverse momenta $\boldsymbol{p}_T$ and $\boldsymbol{k}_T$.

- Assuming a Gaussian dependence one can disentangle the convolution integral.

- The count-rate asymmetry A^h_{UT} (for each hadron type h, unpolarised beam (U) and transversely polarised target (T)) becomes ($\boldsymbol{S}_T$ states target polarisation vector):

$$
A^h_{\mathrm{UT}} = \frac{\sigma^{\Downarrow\uparrow} - \sigma^{\Uparrow\downarrow}}{\sigma^{\Downarrow\uparrow} + \sigma^{\Uparrow\downarrow}}
$$

Collins amplitude

$$
\approx \quad 2\,|\boldsymbol{S}_T|\sin\left(\phi + \phi_S\right) \frac{\sum\limits_q \left(e_q^2\, \boldsymbol{\delta q}\left(x\right)\, \boldsymbol{H}_1^{\perp(1/2)q}\left(z\right) \right) \Big/ \sqrt{\langle p_T^2 \rangle + \langle k_T^2 \rangle}}{\sum\limits_q q\left(x\right)\, D_1^q\left(z\right)}
$$

$\uparrow$

distinctive

Sivers amplitude

signature

$\downarrow$

$$
- \quad 2\,|\boldsymbol{S}_T|\sin\left(\phi - \phi_S\right) \frac{\sum\limits_q \left(e_q^2\, \boldsymbol{f}_{1T}^{\perp(1/2)q}\left(x\right)\, \boldsymbol{D}_1^{\perp q}\left(z\right) \right) \Big/ \sqrt{\langle p_T^2 \rangle + \langle k_T^2 \rangle}}{\sum\limits_q q\left(x\right)\, D_1^q\left(z\right)}
$$

Extraction of Collins and Sivers amplitudes:

- Determination of unweighted, normalised asymmetries for charged pions:

$$A_{\mathrm{UT}}^{\pi^\pm}(\phi,\phi_S) = \frac{1}{\langle P_z \rangle} \cdot \frac{N_{\pi^\pm}^{\Uparrow}(\phi,\phi_S) - N_{\pi^\pm}^{\Downarrow}(\phi,\phi_S)}{N_{\pi^\pm}^{\Uparrow}(\phi,\phi_S) + N_{\pi^\pm}^{\Downarrow}(\phi,\phi_S)}$$

$\langle P_z \rangle = 0.754 \pm 0.050$ (average target polarisation)

- **Asymmetry amplitudes for charged pions** are extracted in a two-dimensional least-squares fit to avoid cross-contamination (reconstruction method was selected in Monte Carlo studies):
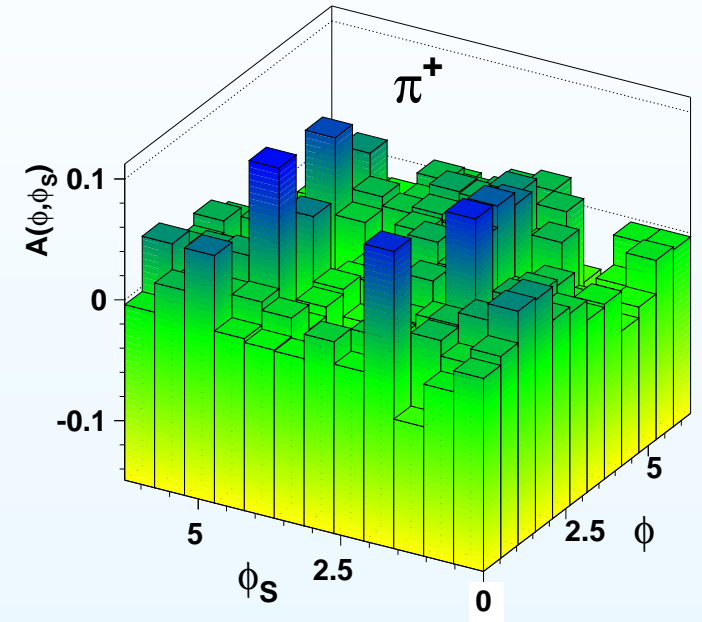
$$
\begin{aligned}
A_{\mathrm{UT}}^{\pi^\pm}(\phi,\phi_S) \quad = \quad & \textbf{Sivers amplitude} \\
& 2 \cdot \langle \sin(\phi - \phi_S) \rangle_{\mathrm{UT}}^{\pi^\pm} \cdot \sin(\phi - \phi_S) + \\
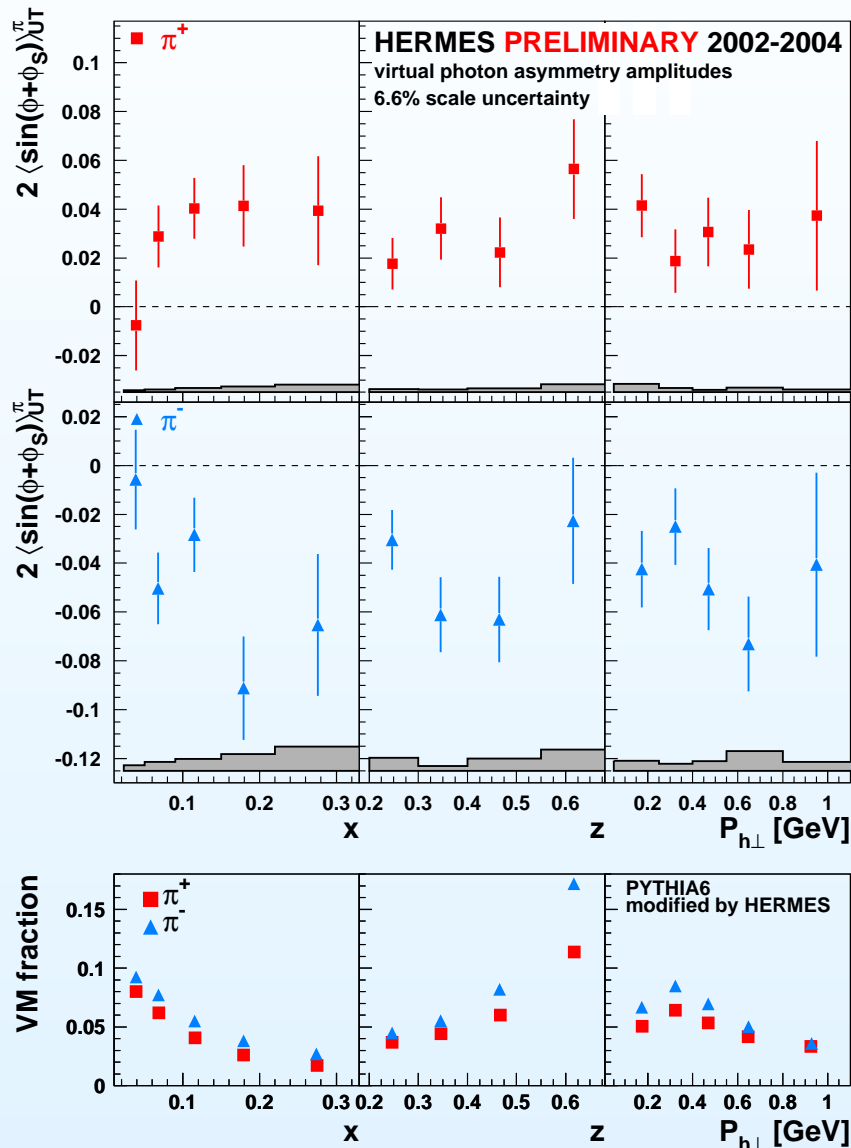& \textbf{Collins amplitude} \\
& 2 \cdot \langle \sin(\phi + \phi_S) \rangle_{\mathrm{UT}}^{\pi^\pm} \cdot \sin(\phi + \phi_S) + \\
& 2 \cdot \langle \sin(2\phi - \phi_S) \rangle_{\mathrm{UT}}^{\pi^\pm} \cdot \sin(2\phi - \phi_S) + 2 \cdot \langle \sin\phi_S \rangle_{\mathrm{UT}}^{\pi^\pm} \cdot \sin\phi_S + c
\end{aligned}
$$

Collins amplitudes for charged pions:

Collins amplitude is proportional to

$$\delta q\left(x\right) \otimes H_1^{\perp}\left(z\right).$$
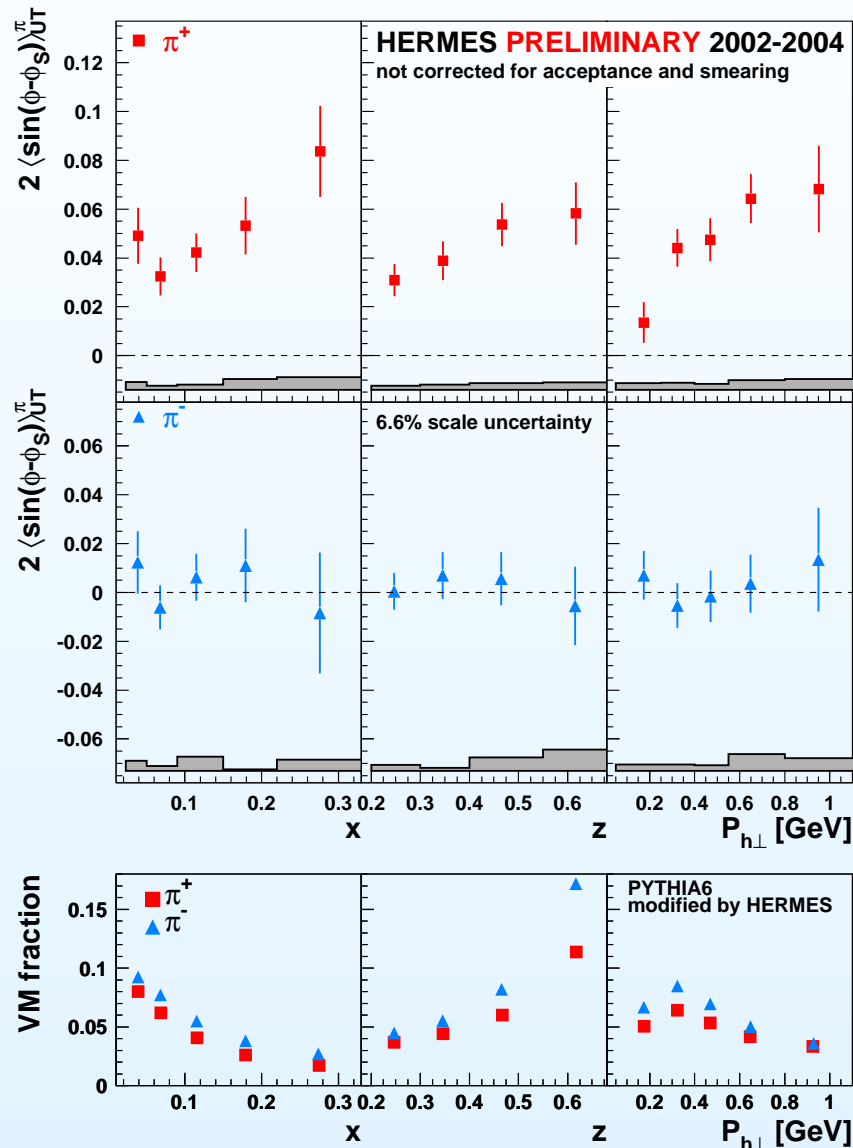
Results of 2002–2004 data:

- Collins amplitude is positive for π^+ and negative for π^-.

- The large negative π^- amplitude is unexpected; one explanation could be the role of the disfavoured Collins FF: $H_1^{\perp,\text{disfav}}\left(z\right) \approx -H_1^{\perp,\text{fav}}\left(z\right)$

- Additional information on the Collins fragmentation function is needed in order to extract transversity.

Systematic uncertainties:

- Common scale uncertainty of 6.6% in the amplitudes.

- Background asymmetry of diffractive vector mesons.

Sivers amplitudes for charged pions:

Sivers amplitude is proportional to
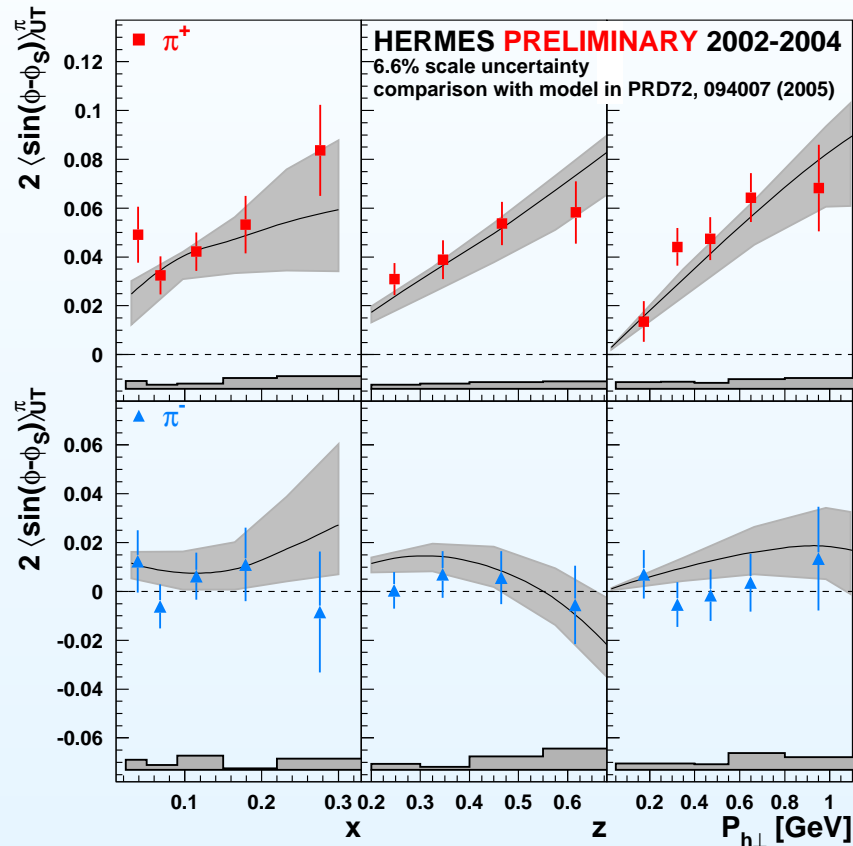$$f_{1T}^{\perp q}(x) \otimes D_1^{\perp q}(z).$$

Results of 2002–2004 data:

- Sivers amplitude is significantly positive for π^+ and implies a non-vanishing orbital angular momentum L_z^q.

- Sivers amplitude for π^- is consistent with zero.

- Since spin independent fragmentation function is known, extraction of Sivers function is possible.

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Sivers amplitudes for charged pions:

comparison with model in
Physical Review **D72**, 094007 (2005)

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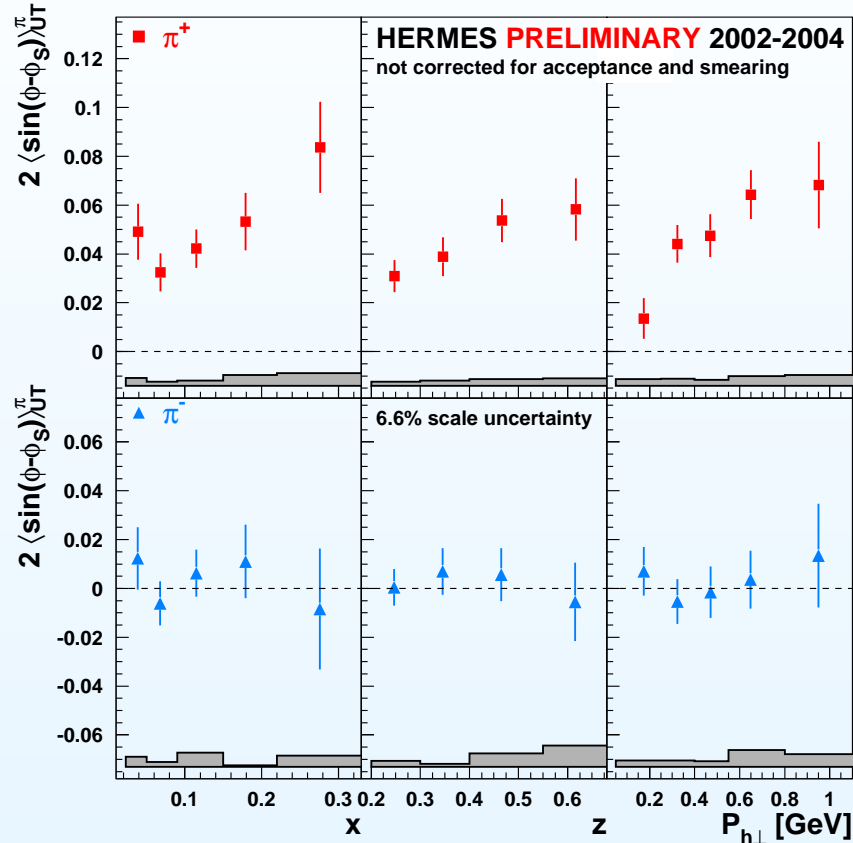$$f_{1T}^{\perp q}(x) \otimes D_1^{\perp q}(z).$$

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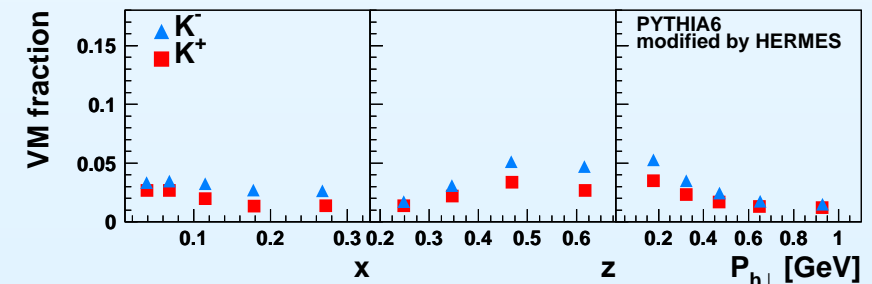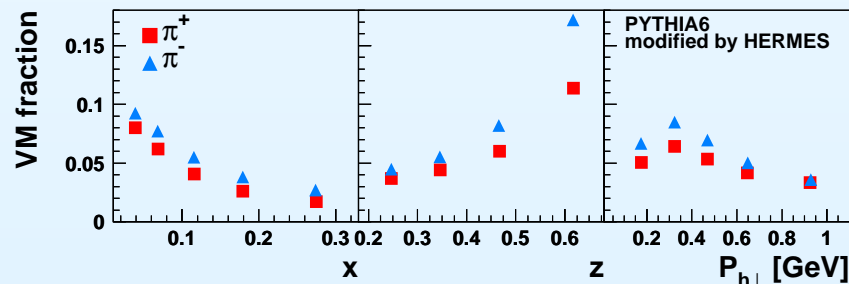# Sivers amplitudes for charged pions:

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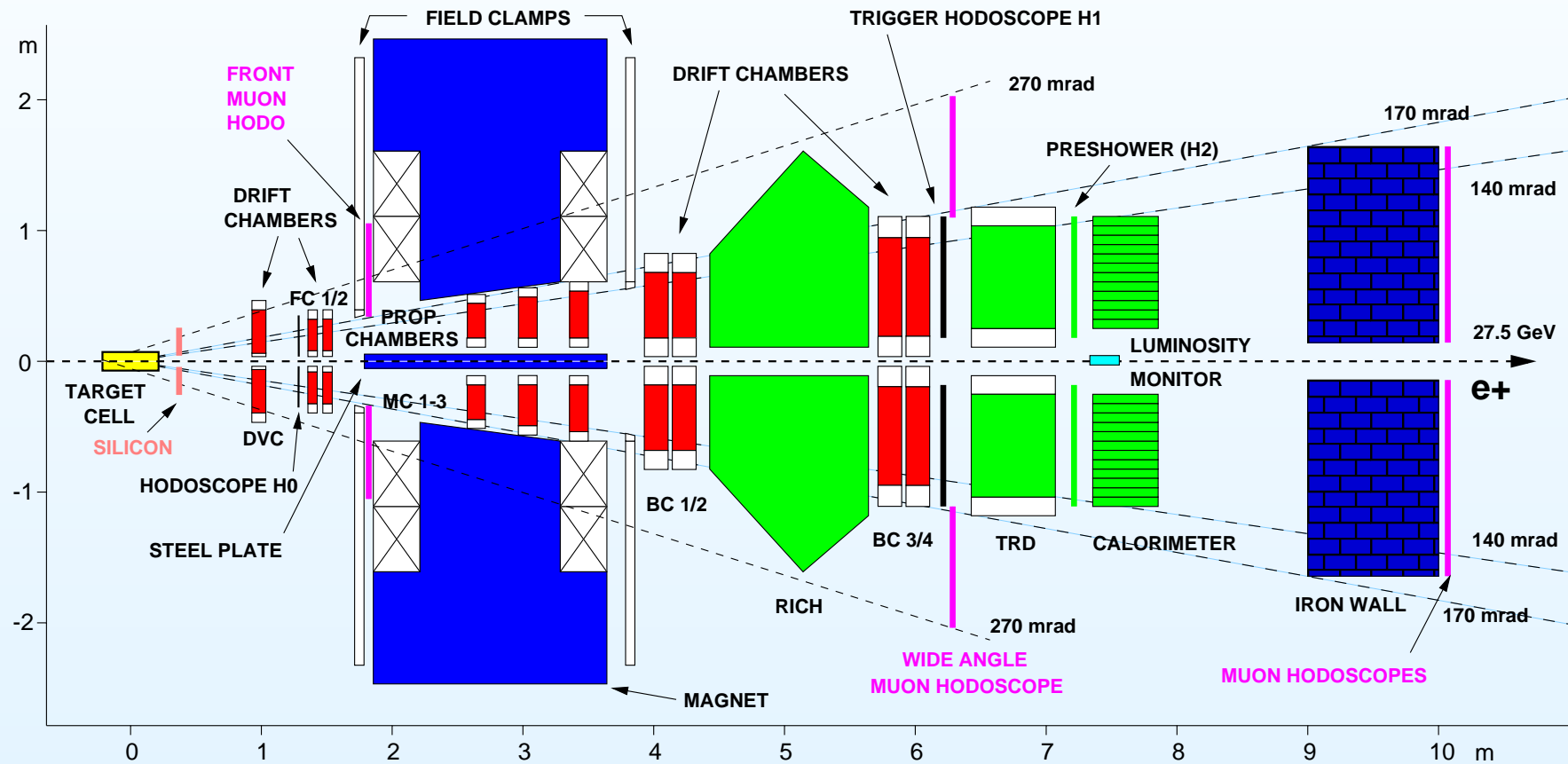$$f_{1T}^{\perp q}(x) \otimes D_1^{\perp q}(z).$$

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Vector meson contribution for $K^\pm$:

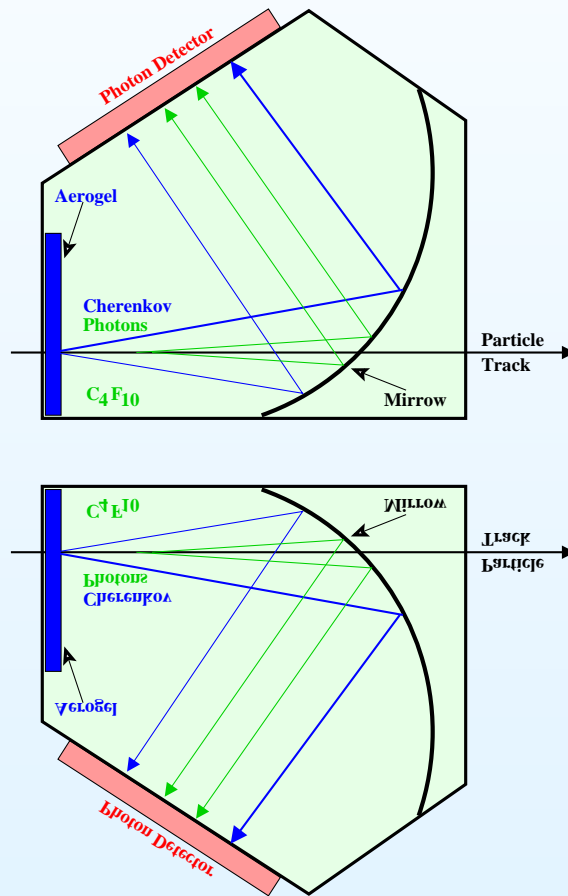# Hadron identification with the RICH:

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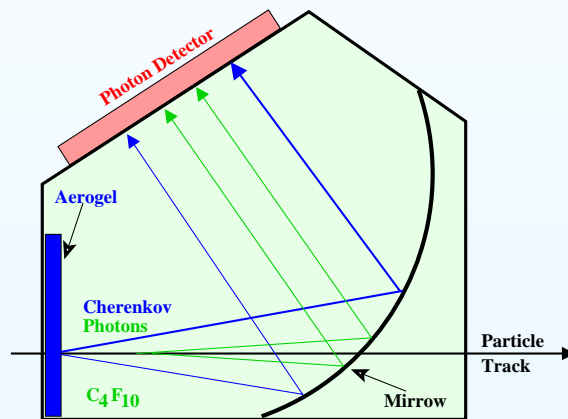
schematic of RICH:

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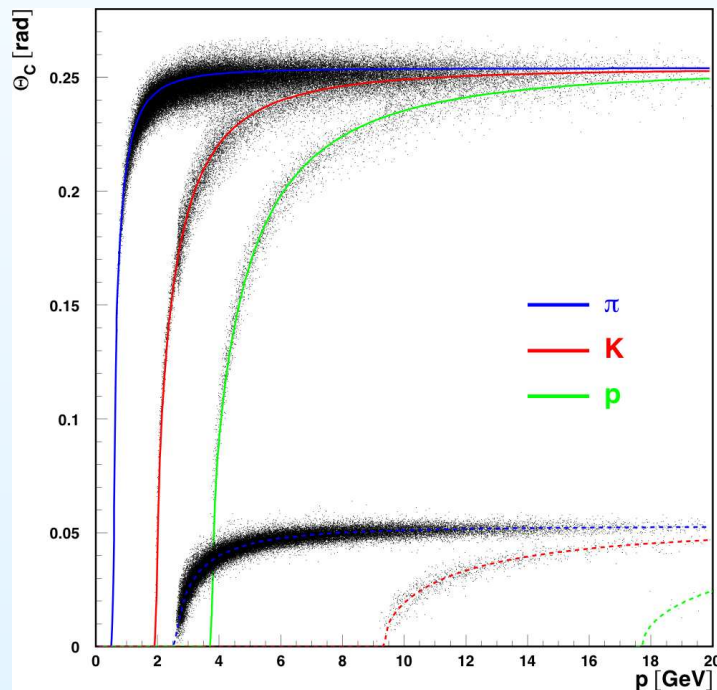schematic of RICH:

Aerogel: $n = 1.03$

C_4F_{10}: $n = 1.0014$
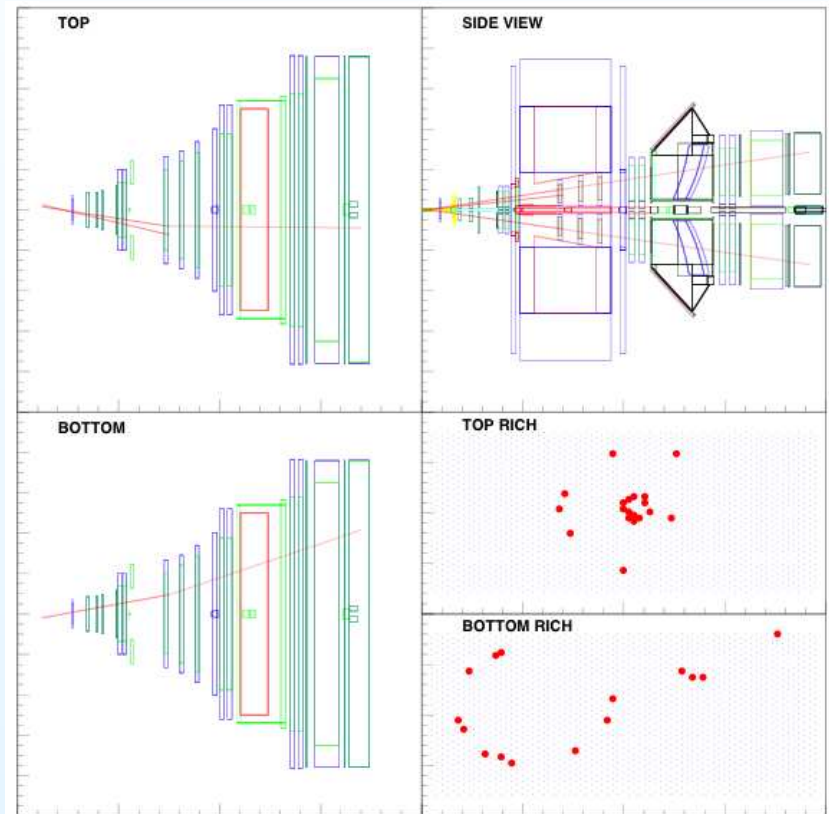
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The cone angle θ of the Čerenkov radiation is related to the refraction index n of the medium:

$$\theta = \arccos \frac{1}{\beta n}$$

$$p < p_{\text{thres}} = \frac{m}{\sqrt{n^2 - 1}}$$

RICH event display showing πK-event

Azimuthal amplitudes for charged kaons:

- In case of charged pions least squares are good maximum likelihood estimator; in case of charged kaons maximum likelihood fits have to be applied.

- Thus there is no azimuthal binning for charged kaons.

- The probability density function is defined as:

$$F_{\Uparrow(\Downarrow)}\left(2\left\langle\sin\left(\phi\pm\phi_S\right)\right\rangle_{\mathsf{UT}}^{K^\pm},\ldots,\phi,\phi_S\right)=$$

$$\frac{1}{2}\left(1+(-)\left\langle\sin\left(\phi\pm\phi_S\right)\right\rangle_{\mathsf{UT}}^{K^\pm}\cdot\sin\left(\phi\pm\phi_S\right)+(-)\ldots\right)$$
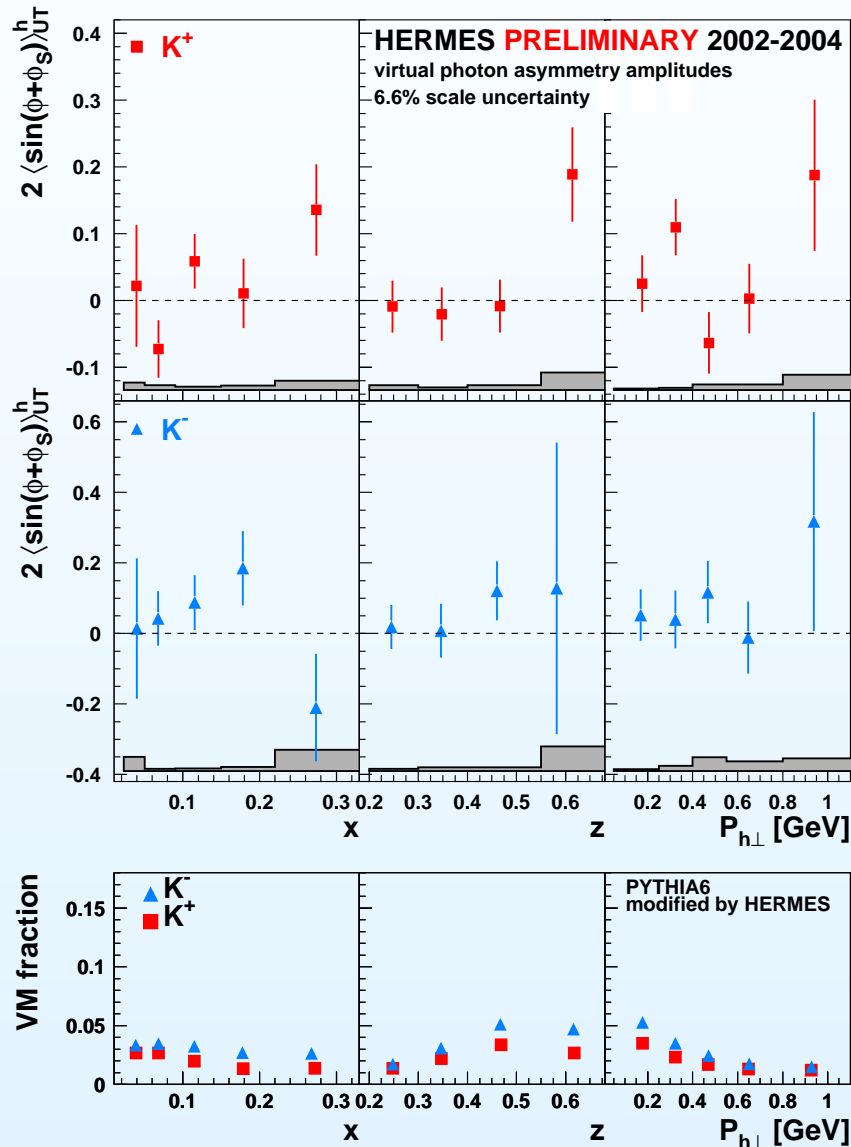
The acceptance ϵ and the spin-independent cross section σ_{UU} are independent of the set of parameters $\left\langle2\sin\left(\phi\pm\phi_S\right)\right\rangle_{\mathsf{UT}}^{K^\pm}$.

- The logarithm of the likelihood function:

$$\mathcal{L}=\frac{1}{\mathcal{N}}\prod_{i=1}^{N^\Uparrow}F_{\Uparrow,i}\prod_{i=1}^{N^\Downarrow}F_{\Downarrow,i}$$

is maximised with respect to the Collins and Sivers amplitudes (i.e. the fhe fit parameters; $\mathcal{N}$ states the normalisation function).

Collins amplitudes for charged kaons:

Collins amplitude is proportional to
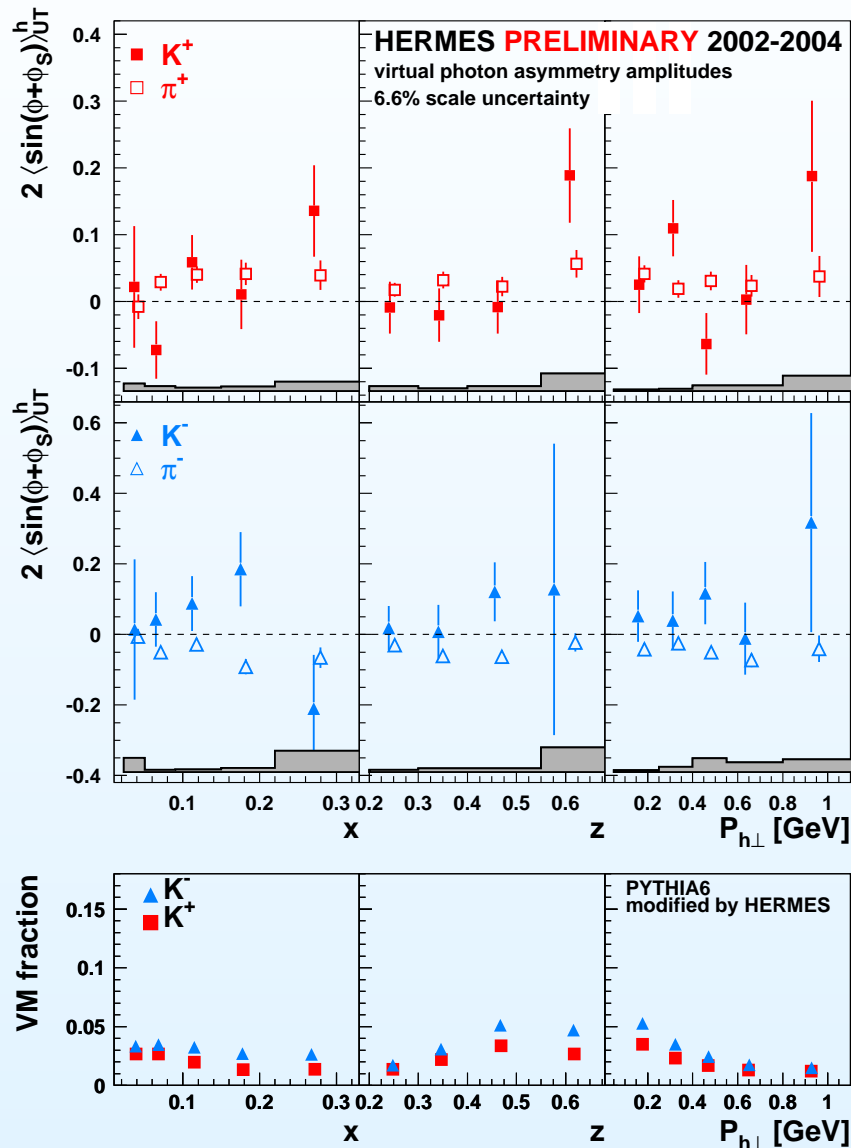
$$\delta q\,(x) \otimes H_1^\perp\,(z).$$

Results of 2002–2004 data:

- No significant non-zero Collins amplitudes for both K^+ and K^-.

Systematic uncertainties:

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Collins amplitudes for charged kaons:

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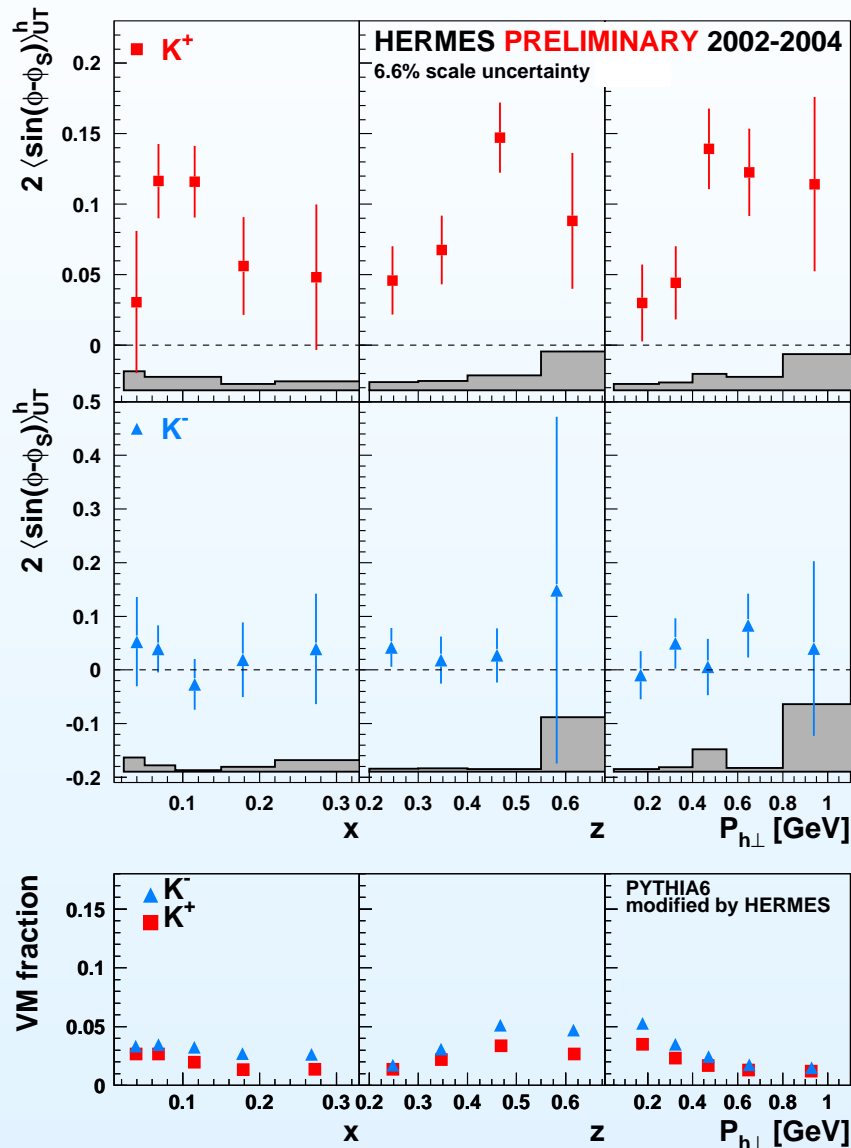$$\delta q\left(x\right) \otimes H_1^{\perp}\left(z\right).$$

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- The Collins amplitudes for K^+ are consistent to π^+ amplitudes.

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Sivers amplitudes for charged kaons:

Sivers amplitude is proportional to
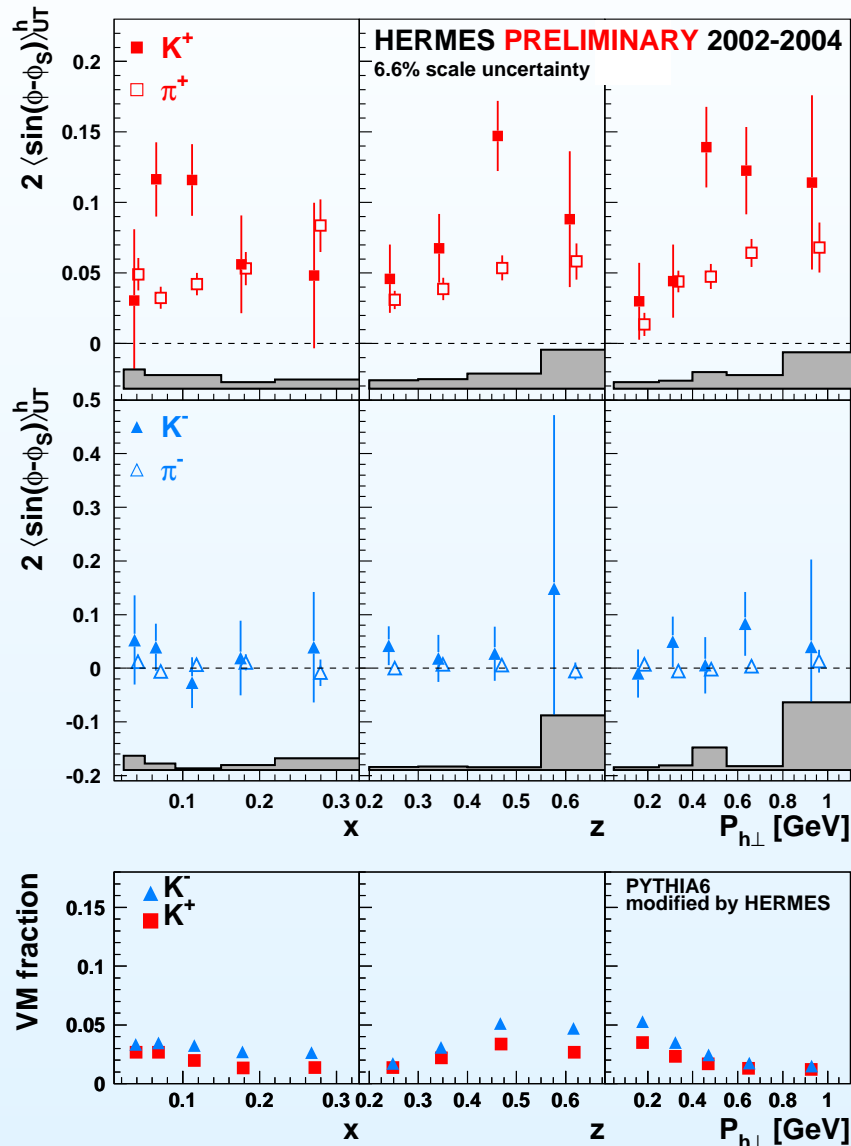
$$f_{1T}^{\perp q}(x) \otimes D_1^{\perp q}(z).$$

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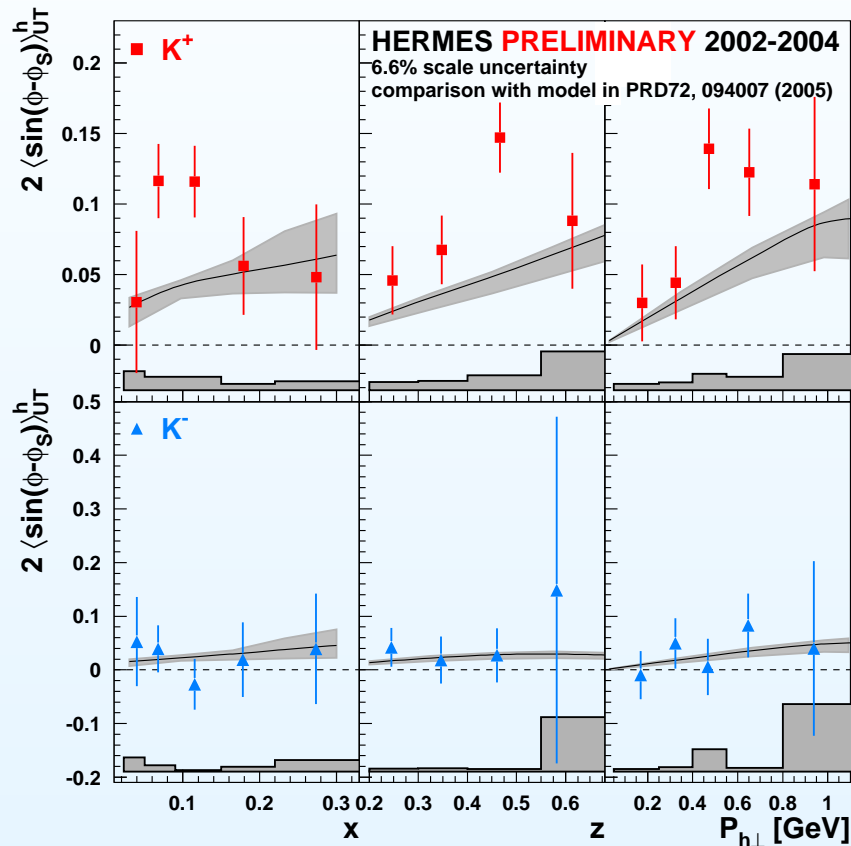
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- Sivers amplitude for K^+ is in some bins larger than the one for π^+. $\Rightarrow$ Sea quark contribution to Sivers mechanism may be important ($K^+ = |u\bar{s}\rangle$).

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Summary and outlook:

- The HERMES results provide first global evidence for both Collins and Sivers mechanism in semi-inclusive DIS.

- Non-zero Sivers amplitudes for both π^+ and K^+ imply non-vanishing orbital momentum of partons inside the nucleon.

- Flavour decomposition of the Sivers function is in progress.

- Data recorded in 2005 will double the amount of statistics.