# Status of transversity studies at HERMES

Luciano Pappalardo
pappalardo@fe.infn.it

for the hermes collaboration

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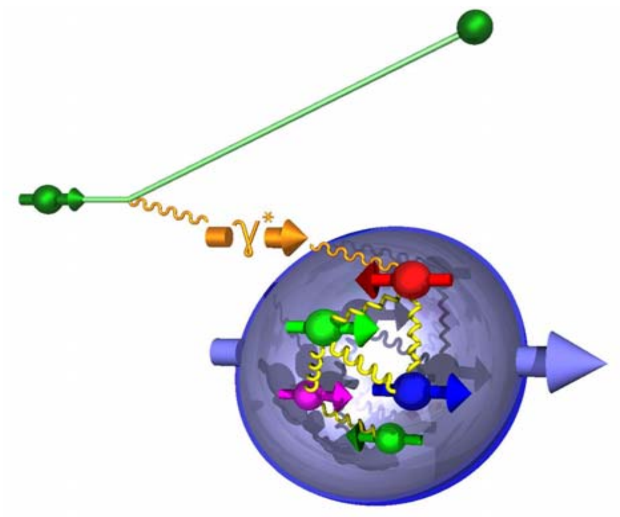
# Outline

- Polarized DIS and the HERMES experiment at HERA
- The leading-twist distribution functions of the nucleon
- The chiral-odd Transversity distribution
- The one-hadron SIDIS cross section and the Collins and Sivers effects
- HERMES results on Collins and Sivers moments for $\pi^{\pm}$ & $K^{\pm}$
- The two-hadron SIDIS cross section and the Interference Fragmentation Function
- Conclusions

# The inner spin distribution of the nucleon

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




The relevant kinematical variables:

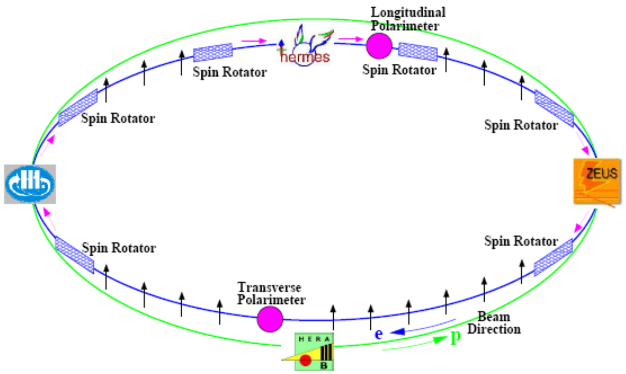
$$Q^2 = -q^2 \overset{\text{lab}}{=} 2EE'(1\text{-}\cos\theta)$$

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

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

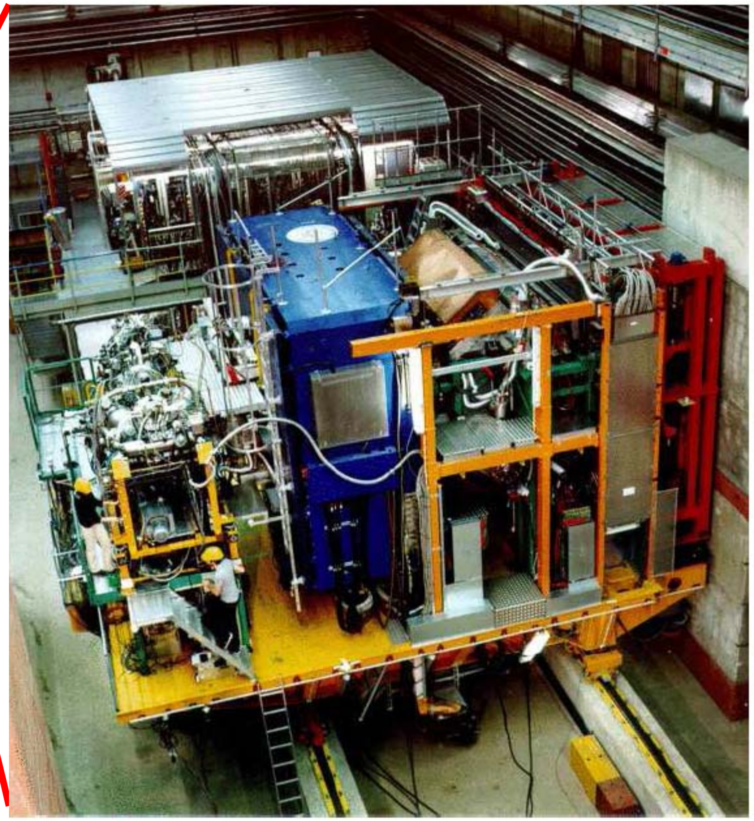
experiments at CERN, SLAC, JLAB, DESY ➡ hermes

The HERA storage ring (DESY)


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

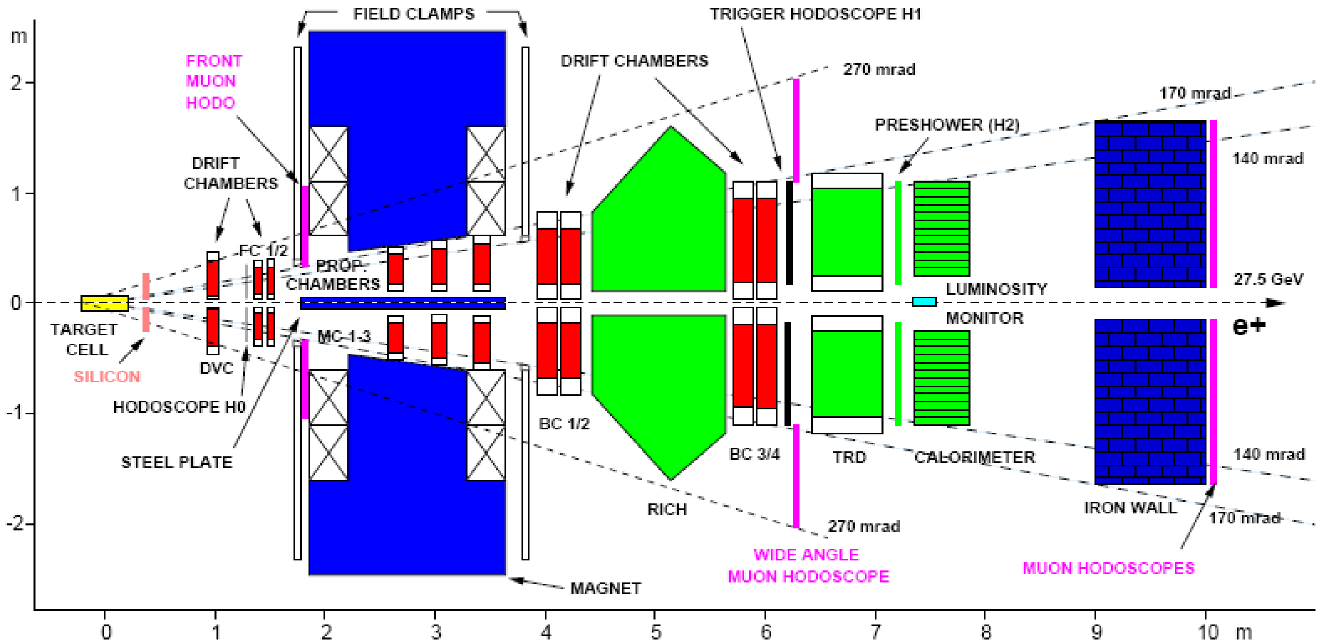
The HERMES Spectrometer

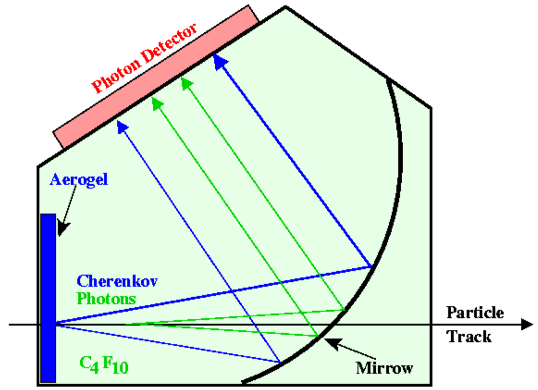


- Fixed target experiment
- forward spectrometer symmetric above and below the beampipe
- Polarized internal gas target
- Relatively large acceptance

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

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




**Dual radiator RICH**

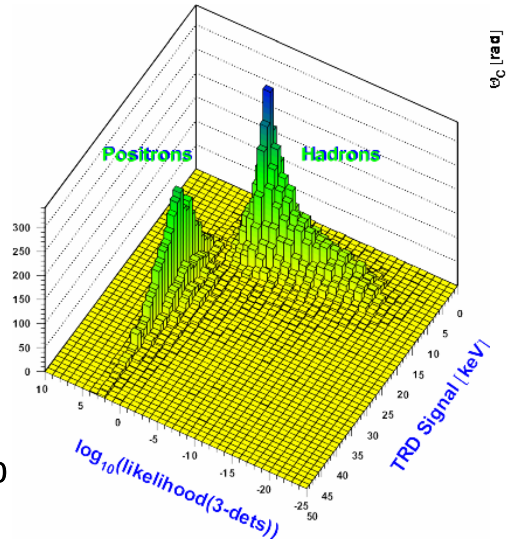
## Particle Identification:

TRD, Calorimeter, preshower, RICH:

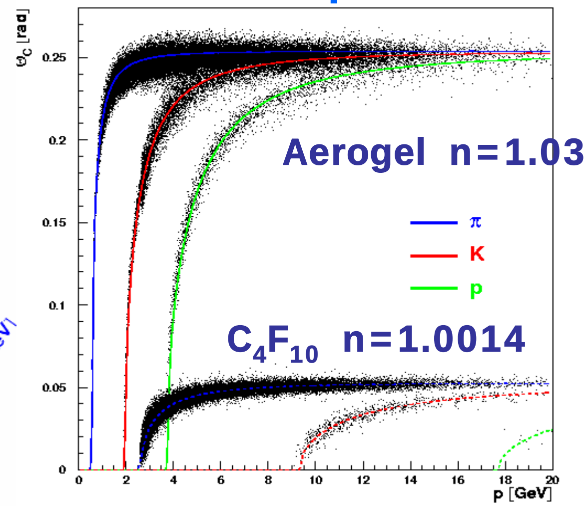
lepton-hadron > 98%

RICH:

Hadron: π ~ 98%, K ~ 88% , P ~ 85%

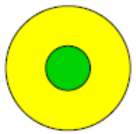
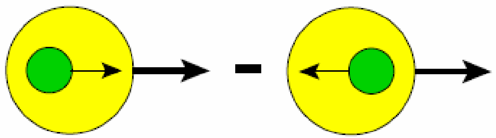
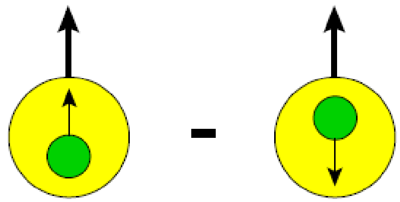



**hadron separation**



# 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 | Helicity | Transversity |
|---|---|---|
| $q(x, Q^2)$ | $\Delta q(x, Q^2)$ | $\delta q(x, Q^2)$ |
|  |  |  |
| well known | known | unkown |
| | HERMES 1996-2000 | HERMES 2002-2005 |

**Positivity limit**

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

**Soffer bound**

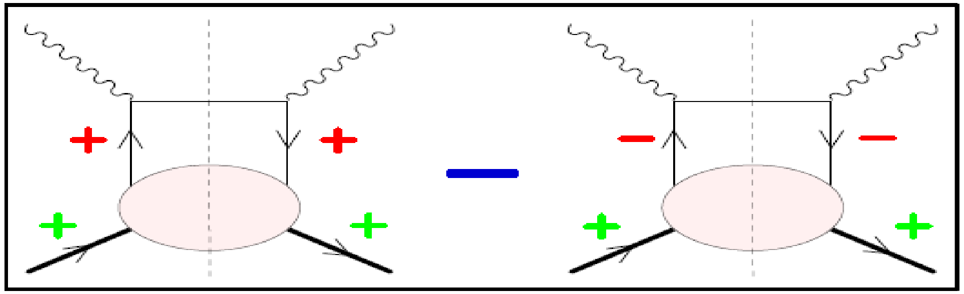
$$|\delta q(x)| < \frac{1}{2}\left(q(x) + \Delta q(x)\right)$$

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

Probes relativistic nature of quarks

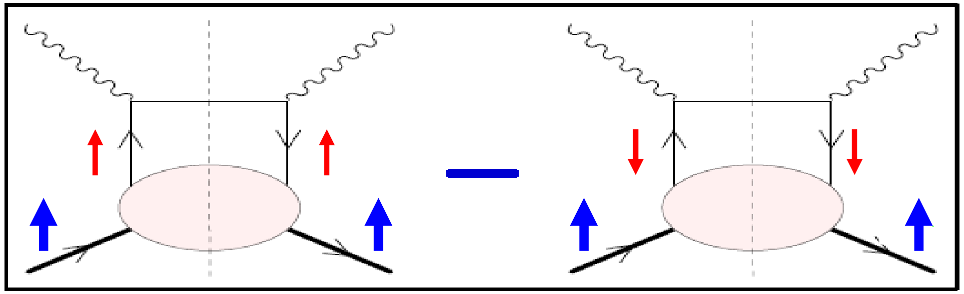
$$\Delta q(x,Q^2)$$

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



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

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



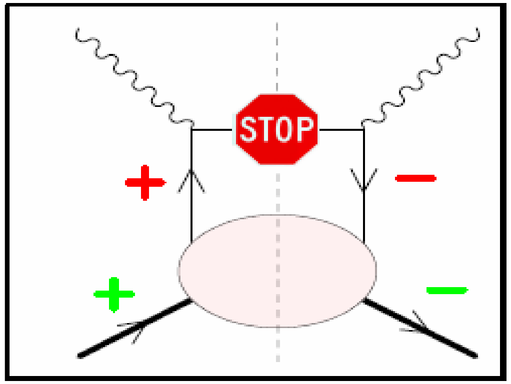
$$\int dx\left(\delta q(x) - \delta\bar{q}(x)\right) = \langle PS|\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi|PS\rangle$$

$\delta q$ is chiral-odd object

associated with a helicity flip of the struck quark

$\delta q$ in helicity basis:

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

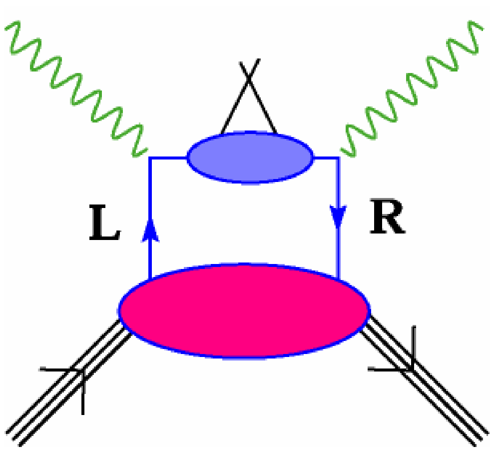



EM interactions cannot flip the chirality of the probed quark

Transversity Distribution is not measurable in inclusive DIS

# How can one measure transversity?

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



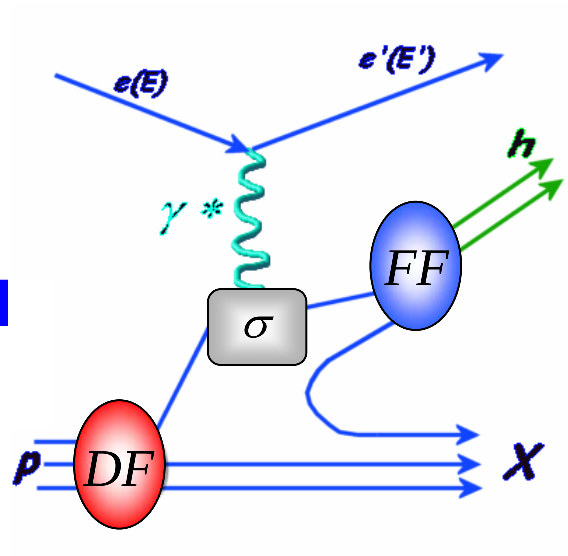

one hadron in the initial state and at least one in the final state (semi-inclusive leptoproduction)

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

$\Downarrow$ chiral – odd DF

$\Downarrow$ chiral – odd FF

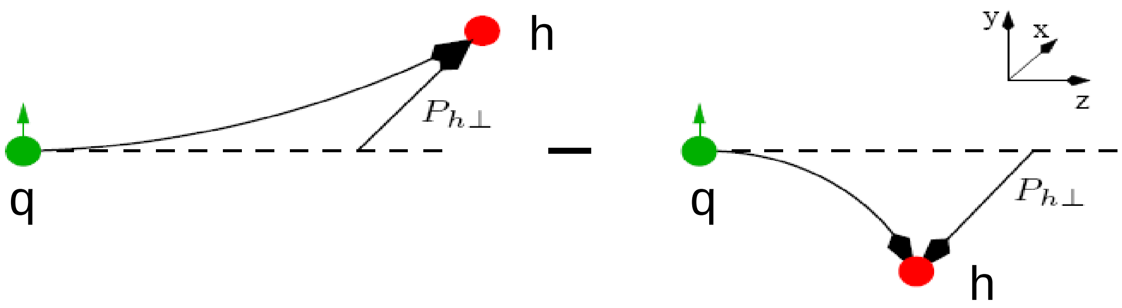
CHIRAL EVEN



# One-hadron case

# 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 $P_{h\perp}$.



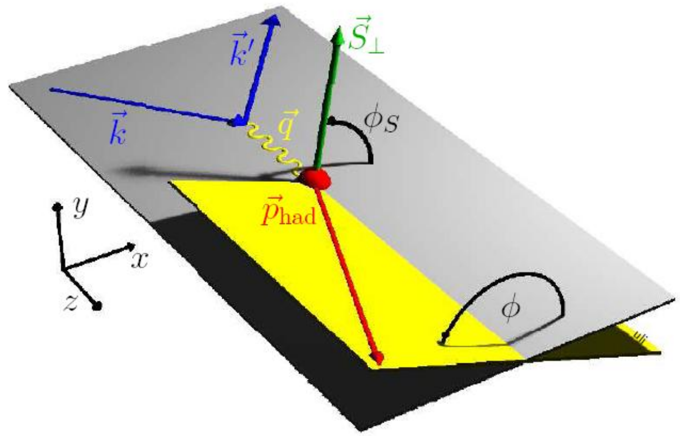

# The "Sivers effect"

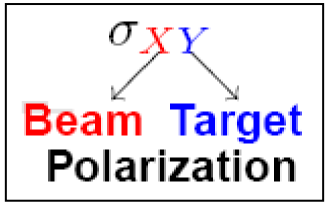
Correlation between $p_T$ and transverse spin of the nucleon

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

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

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

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

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

## The Single Spin Asymmetry of the SIDIS cross-section

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

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

Collins moment

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

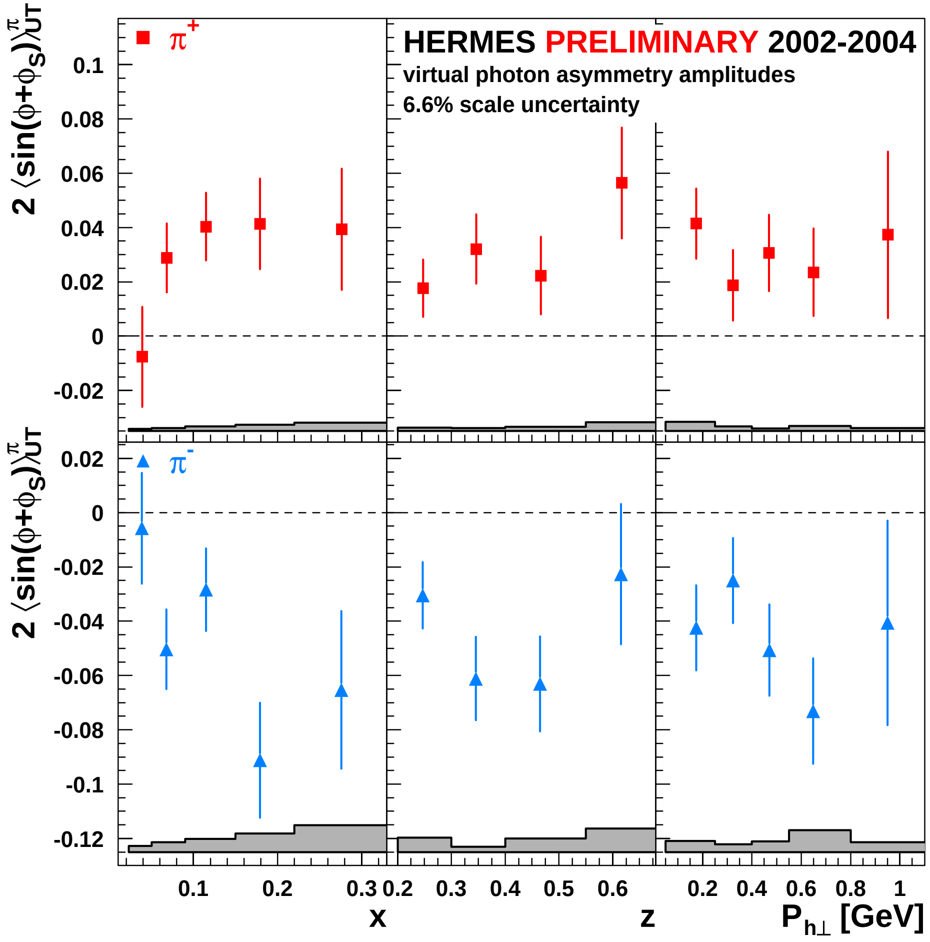
Sivers moment

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

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

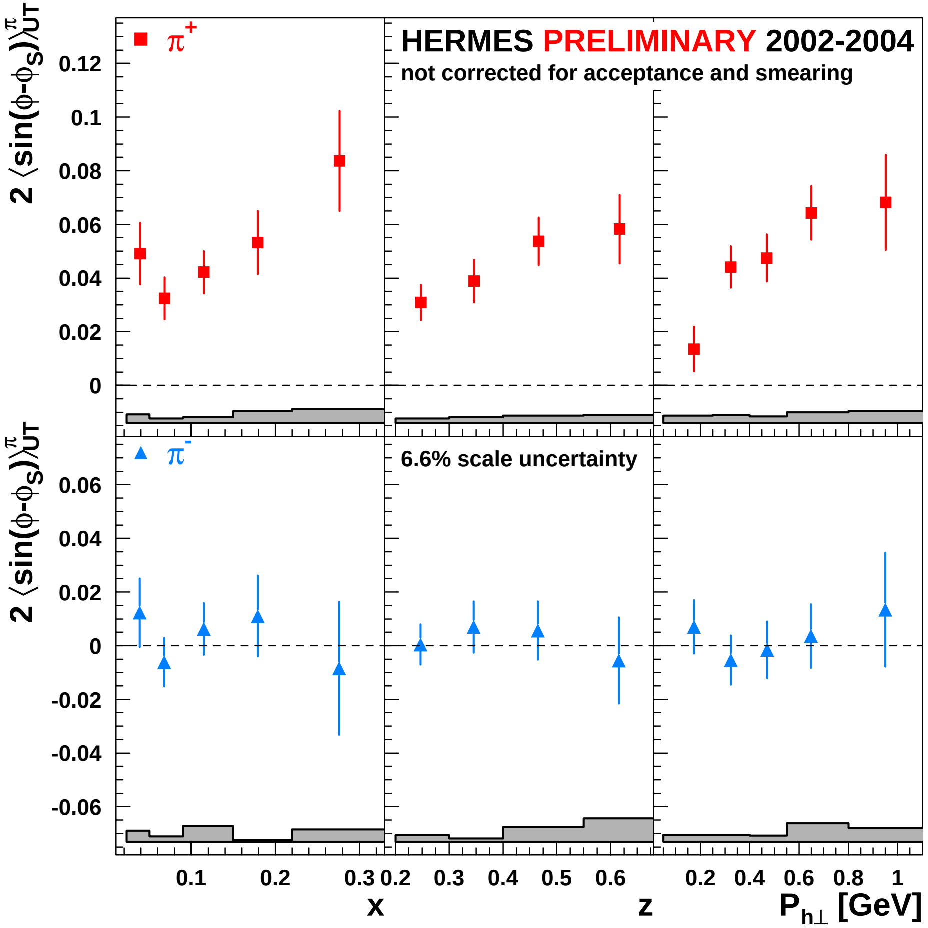
$$A_{UT}^{Fit}(\phi,\phi_S) = P(1)\sin(\phi+\phi_S) + P(2)\sin(\phi-\phi_S) + P(3)\sin(\phi_S) + P(4)\sin(2\phi-\phi_S) + P(5)$$

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




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

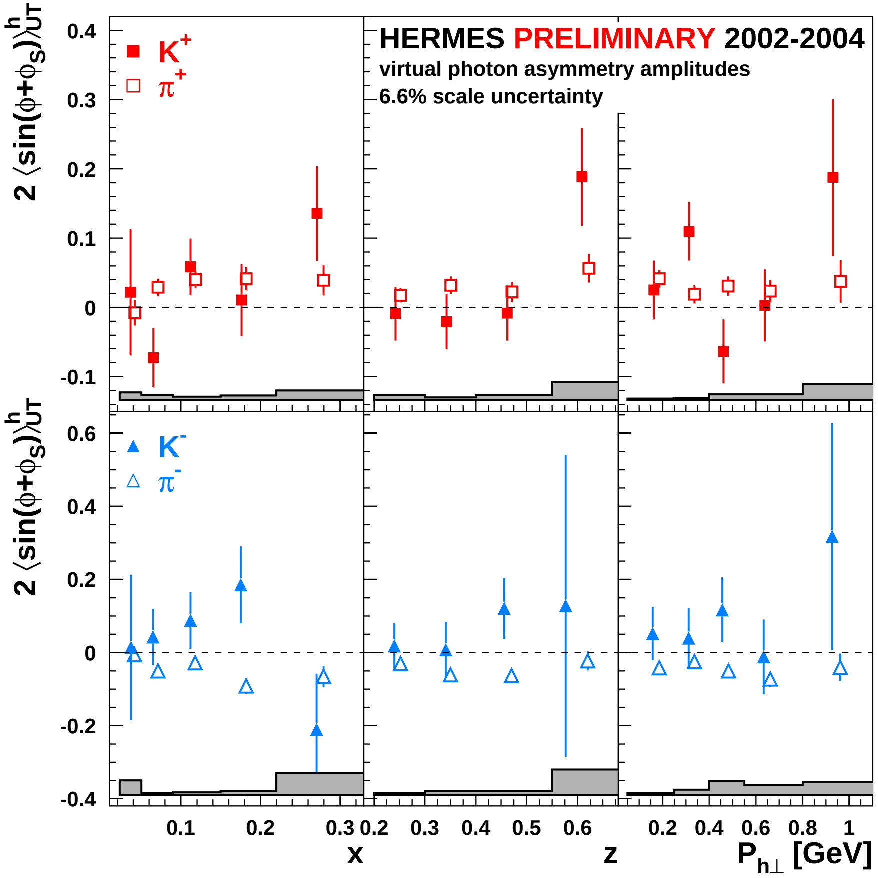
# Sivers moments for $\pi^{+/-}$ (2002-2004)



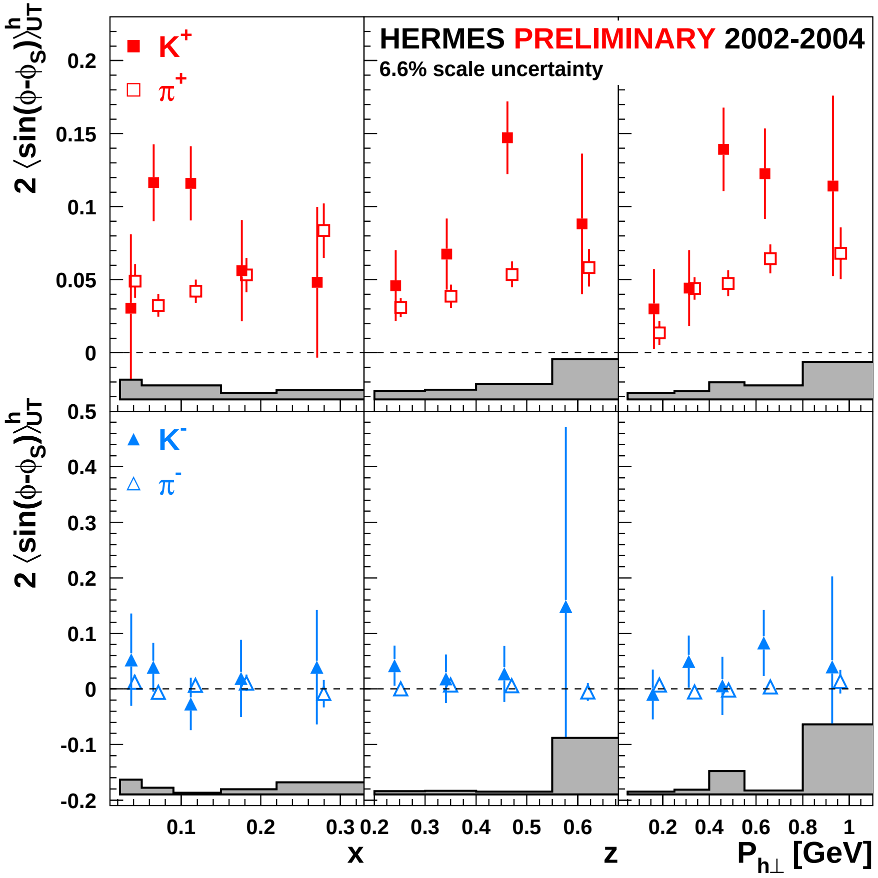

- $\propto I[f_{1T}^{\perp q}(x) D_1^q(z)]$
- Sivers moment is positive for $\pi^+$
- First evidence for non-zero Sivers function $\Rightarrow$ non-vanishing orbital angular momentum $L_z^q$
- Sivers moment consistent with zero for $\pi^-$
- systematic errors (shaded bands) include acceptance and smearing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

# Pion-Kaon comparison plots

## Collins moments



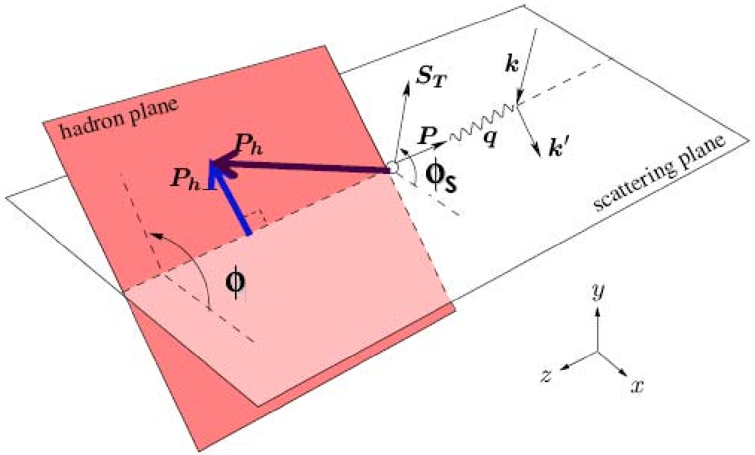

## Sivers moments



# Two-hadron case

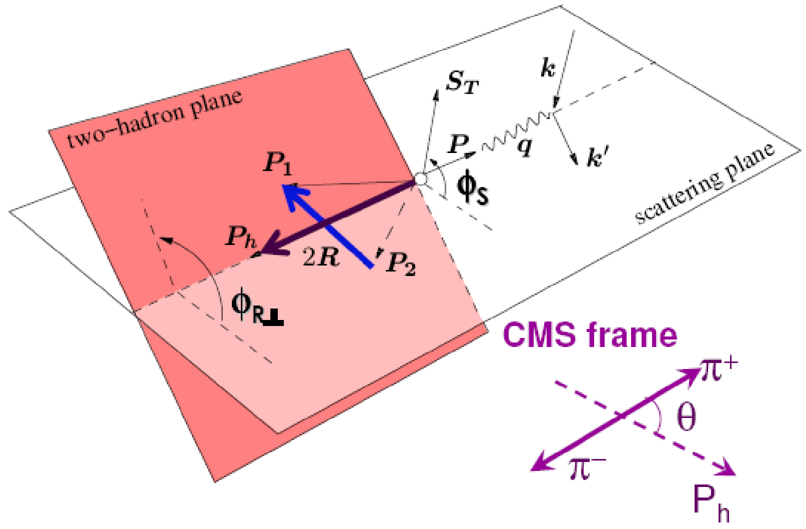
# The two-hadron SIDIS cross section

**One-hadron case**




$$\sigma_{UT} \propto S_T \sin(\phi + \phi_S) \sum_q e_q^2 I\left[ \frac{k_T \cdot \hat{P}_{h\perp}}{M} \delta q \; H_{1,q}^{\perp} \right]$$

**Two-hadron case**




$$\sigma_{UT} \propto S_T \sin\theta \sin(\phi_{R\perp} + \phi_S) \sum_q e_q^2 \delta q \; H_{1,q}^{\sphericalangle}$$

The measured asymmetries are based on events integrated over the transverse momentum of the two pion system, therefore $\delta q$ and the IFF appear in simple direct product in the cross-section (no convolution integral involved!).

- A completely independent method to extract transversity
- …but affected by a poor statistics!

# The two-hadron cross section asymmetry

• all possible combinations of detected pions to make $\pi^+\pi^-$ pairs were included for each event

• contributions from exclusive channels were suppressed using the cut on the missing energy:

$$\Delta E = (M_x^2 - M_P^2)/2M_P > 2\ GeV$$

$$A_{UT}(\phi_{R\perp}+\phi_S,\theta) \equiv \frac{\sigma_{UT}}{\sigma_{UU}} = \frac{1}{|S_T|}\frac{N^{\uparrow}_{SIDIS}(\phi_{R\perp}+\phi_S,\theta) - N^{\downarrow}_{SIDIS}(\phi_{R\perp}+\phi_S,\theta)}{N^{\uparrow}_{SIDIS}(\phi_{R\perp}+\phi_S,\theta) + N^{\downarrow}_{SIDIS}(\phi_{R\perp}+\phi_S,\theta)}$$

$$A_{UT} \propto \frac{\sum_q \sin(\phi_{R\perp}+\phi_S)\sin\theta\ \delta q\ H_{1,q}^{\triangleleft}}{\sum_q f_{1,q} D_{1,q}}$$

… different partial waves may contribute to the final 2-π state

partial wave expansion

$$A_{UT} \propto \frac{\sum_q \sin(\phi_{R\perp}+\phi_S)\ \delta q\ (\sin\theta\ H_{1,q}^{\triangleleft,sp} + \sin\theta\cos\theta\ H_{1,q}^{\triangleleft,pp})}{\sum_q f_{1,q}(D_{1,q}^{ss,pp} + \cos\theta\ D_{1,q}^{sp} + 1/4\,(3\cos^2\theta - 1) D_{1,q}^{pp})}$$

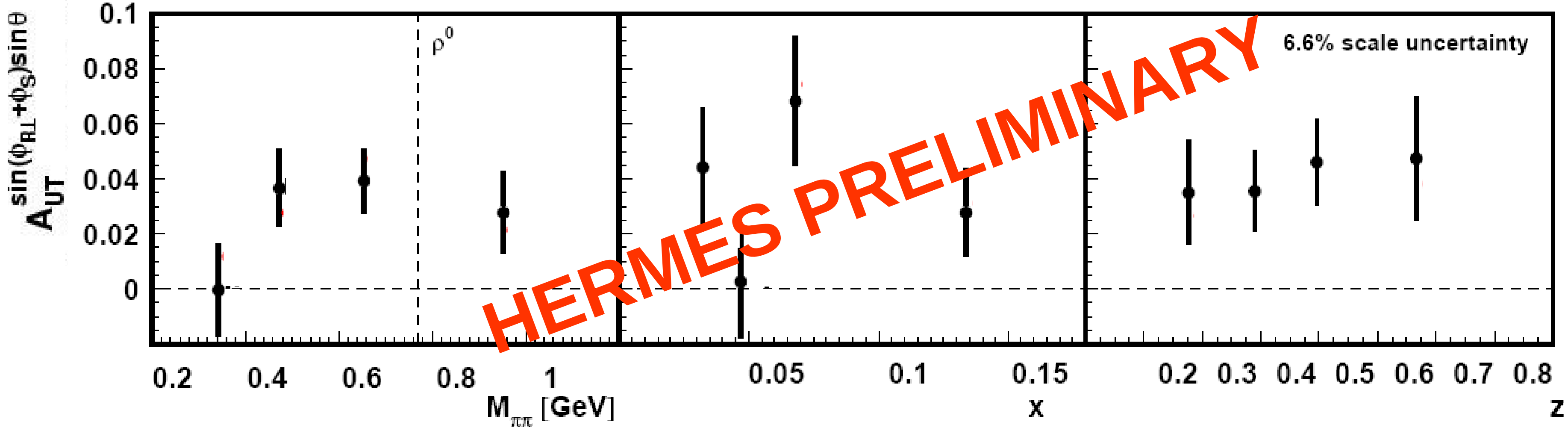
# The azimuthal moments

$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S)\ \delta q\ \frac{H_{1,UT}^{\sphericalangle,sp} \sin\theta + \frac{1}{2} H_{1,LT}^{\sphericalangle,pp} \sin(2\theta)}{D_{1,UU} + \cos\theta D_{1,UL}^{sp} + \frac{1}{4}(3\cos^2\theta - 1) D_{1,LL}^{pp}}$$

2-Dim NON LINEAR FIT

$$A_{UT} = \sin(\phi_{R\perp} + \phi_S) \frac{a \sin(\theta) + b \sin(2\theta)}{1 + c \cos\theta + d \cos^2\theta}$$

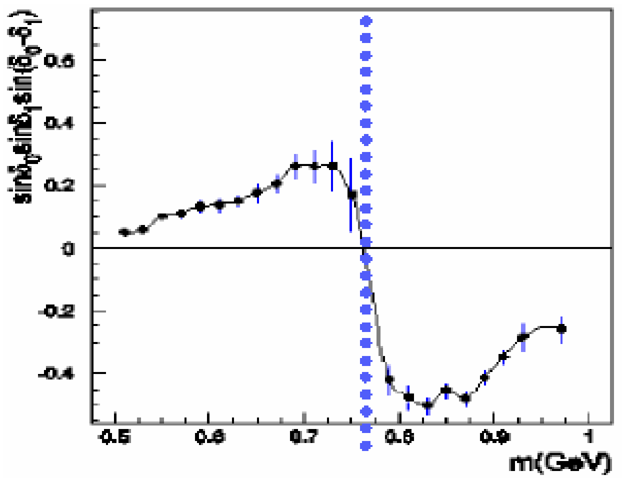
$$A_{UT}^{\sin(\phi_{R\perp} + \phi_S)\sin\theta} \propto \frac{\sum_q e_q^2 \delta q\ H_{1,q}^{\sphericalangle,sp}}{\sum_q e_q^2 f_{1,q} (D_{1,q}^{ss,pp} - 1/4\, D_{1,q}^{pp})}$$




**Significantly positive amplitude in the whole ranges of $M_{\pi\pi}$, $x$ and $z$.**

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\ \sin\theta} = 0.040 \pm 0.009\ (stat) \pm 0.003\ (syst)$$

**First evidence of a chiral-odd di-hadron fragmentation function!**




No evidence of the sign-change at the $\rho^0$ mass predicted by **Jaffe et al.**
*(Phys.Rev.Lett.80,1166(1998))*

# Conclusions

- Single Spin Asymmetries powerful tool to access transversity at HERMES

## One hadron

- Preliminary HERMES results on semi-inclusive pion and kaon leptoproduction support the existence of non-zero chiral-odd structures relevant for the understanding of the transverse spin phenomena of the nucleon.

- The Sivers moments for charged kaons suggest that sea quarks may carry a significant fraction of orbital angular momentum of the nucleon.

## Two hadron

- For the first time a non-zero SSA is measured in two-pion SIDIS

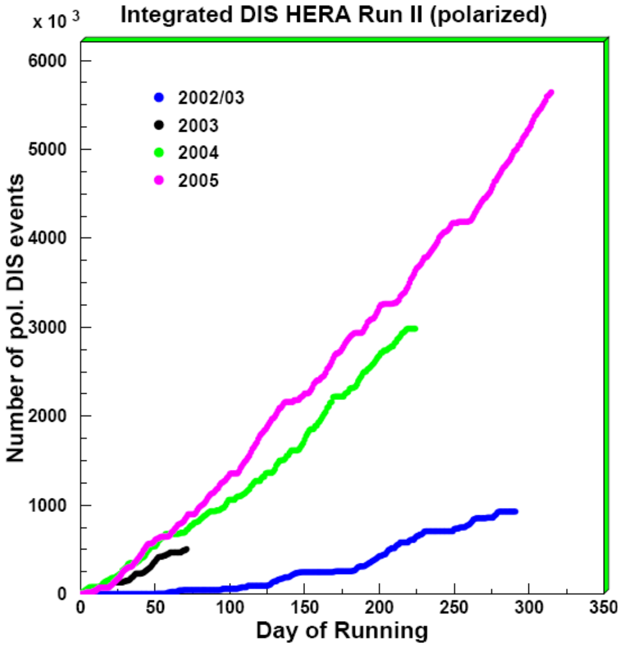
- These measurements provided the first evidence for a non-zero chiral-odd IFF and allow the extraction of the transversity in a completely independent way.

- No evidence of a sign change of SSA at $\rho_o$ mass (Jaffe et. al.)

# Backup slides

# Outlook

- 2005 data will double current statistics for both single and double hadron SIDIS analises




## Single hadron

- $P_{h\perp}$-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 $H_1^\perp$)

## Double hadron

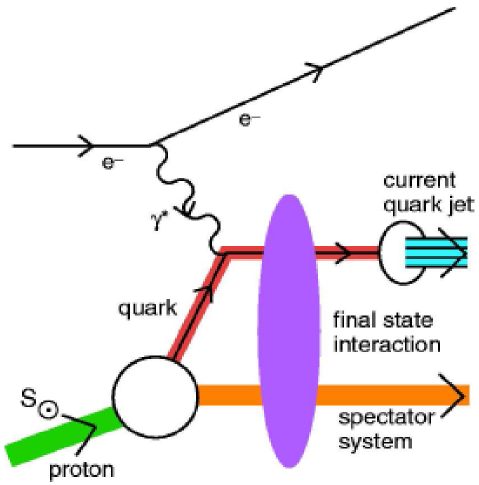
- The non-linear fit is in progress

# 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 (up to subleading order in 1/Q)

$$
\begin{aligned}
d\sigma = \;& d\sigma^0_{UU} + \cos 2\phi \, d\sigma^1_{UU} + \frac{1}{Q}\cos\phi \, d\sigma^2_{UU} + \lambda_e \frac{1}{Q}\sin\phi \, d\sigma^3_{LU} \\
&+ S_L \left\{ \sin 2\phi \, d\sigma^4_{UL} + \frac{1}{Q}\sin\phi \, d\sigma^5_{UL} + \lambda_e \left[ d\sigma^6_{LL} + \frac{1}{Q}\cos\phi \, d\sigma^7_{LL} \right] \right\} \\
&+ S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \sin(\phi + \phi_S) \, d\sigma^9_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \right. \\
&\qquad + \frac{1}{Q}\left( \sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right) \\
&\qquad \left. + \lambda_e \left[ \cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q}\left( \cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \right\}
\end{aligned}
$$

$\sigma_{XY}$: 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)

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

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

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

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

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

# The Maximum Likelihood unbinned fit

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

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

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

Acceptance $\epsilon$ and azimuthally averaged cross section $\underline{\sigma}_{UU}$ do not depend on the fitting parameter sets $\lambda_1$ and $\lambda_2$

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: $\lambda_1, \lambda_2$ )

# Data selection

- Data from running period: 2002-2004 (transversely polarized hydrogen target) (2005 data will be included soon)
- We select both the DIS and the SIDIS events
- We use the RICH for the PID of charged pions and kaons
- We use the ECAL for the reconstruction of neutral pions
- We use the following kinematical cuts:

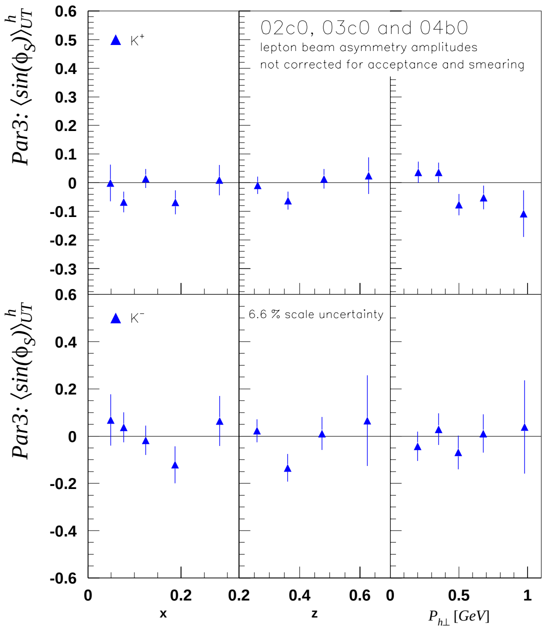
$Q^2 > 1\ GeV^2$ To access the perturbative QCD regime

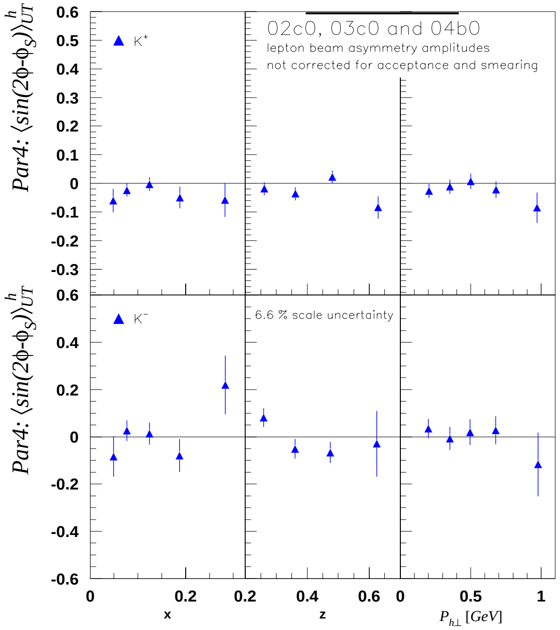
$2\ GeV < P_h < 15\ GeV$ To allow an unambiguous hadronic PID from the RICH

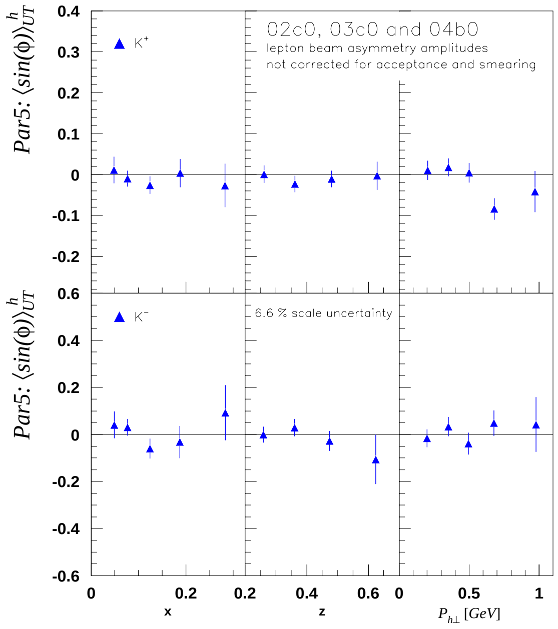
$0.2 < z < 0.7$ To reduce the background from vector mesons decays $(\rho_0)$

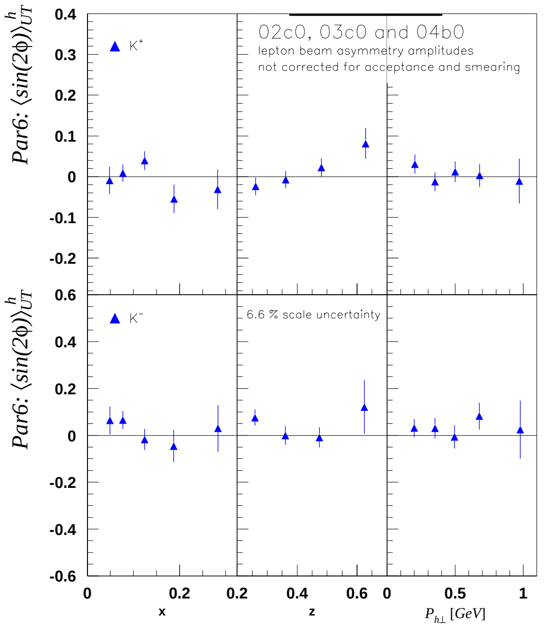
$W^2 > 10\ GeV^2$ To exclude nuclear resonances (like $\Delta$ resonances)

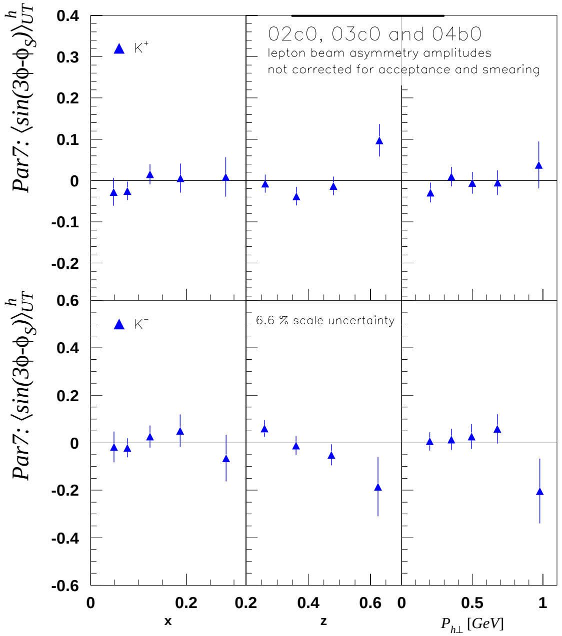
$$\left.\begin{array}{l} 0.023 < x < 0.4 \\ 0.1 < y \leq 0.85 \end{array}\right\}$$ Are a consequence of the detector limited acceptance

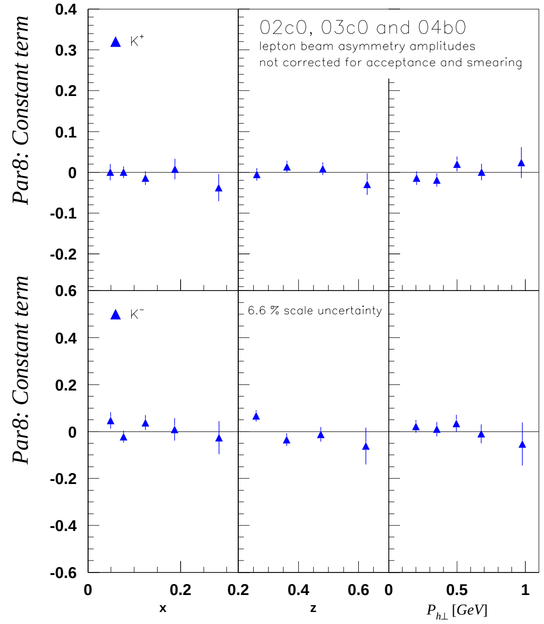

Par3: $\langle sin(\phi_S)\rangle^h_{UT}$
K⁺
K⁻
02c0, 03c0 and 04b0
lepton beam asymmetry amplitudes
not corrected for acceptance and smearing
6.6 % scale uncertainty
x
z
$P_{h\perp}$ [GeV]


Par4: $\langle sin(2\phi-\phi_S)\rangle^h_{UT}$
K⁺
K⁻
02c0, 03c0 and 04b0
lepton beam asymmetry amplitudes
not corrected for acceptance and smearing
6.6 % scale uncertainty
x
z
$P_{h\perp}$ [GeV]

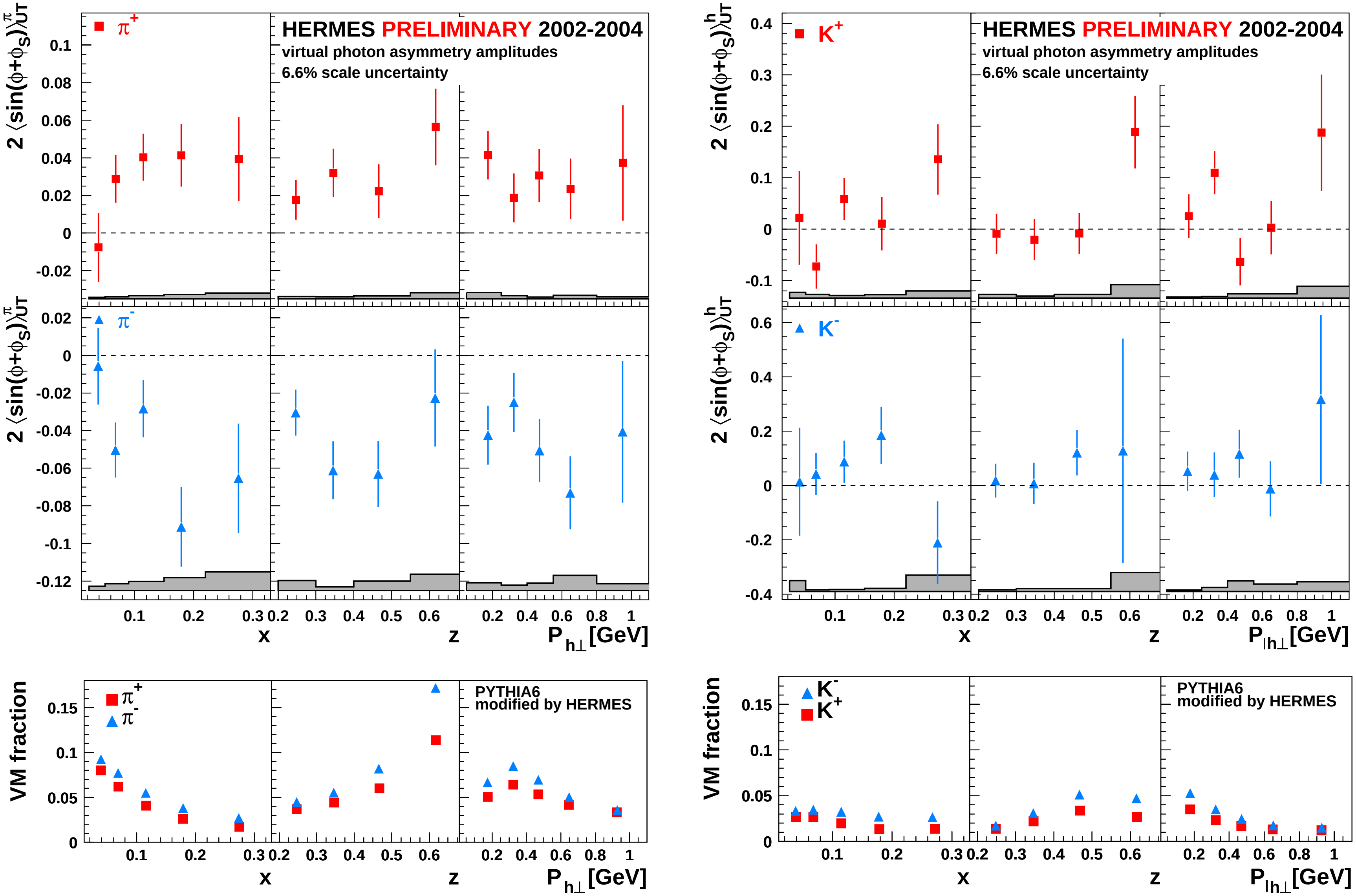

Par5: $\langle sin(\phi)\rangle^h_{UT}$
K⁺
K⁻
02c0, 03c0 and 04b0
lepton beam asymmetry amplitudes
not corrected for acceptance and smearing
6.6 % scale uncertainty
x
z
$P_{h\perp}$ [GeV]


Par6: $\langle sin(2\phi)\rangle^h_{UT}$
K⁺
K⁻
02c0, 03c0 and 04b0
lepton beam asymmetry amplitudes
not corrected for acceptance and smearing
6.6 % scale uncertainty
x
z
$P_{h\perp}$ [GeV]

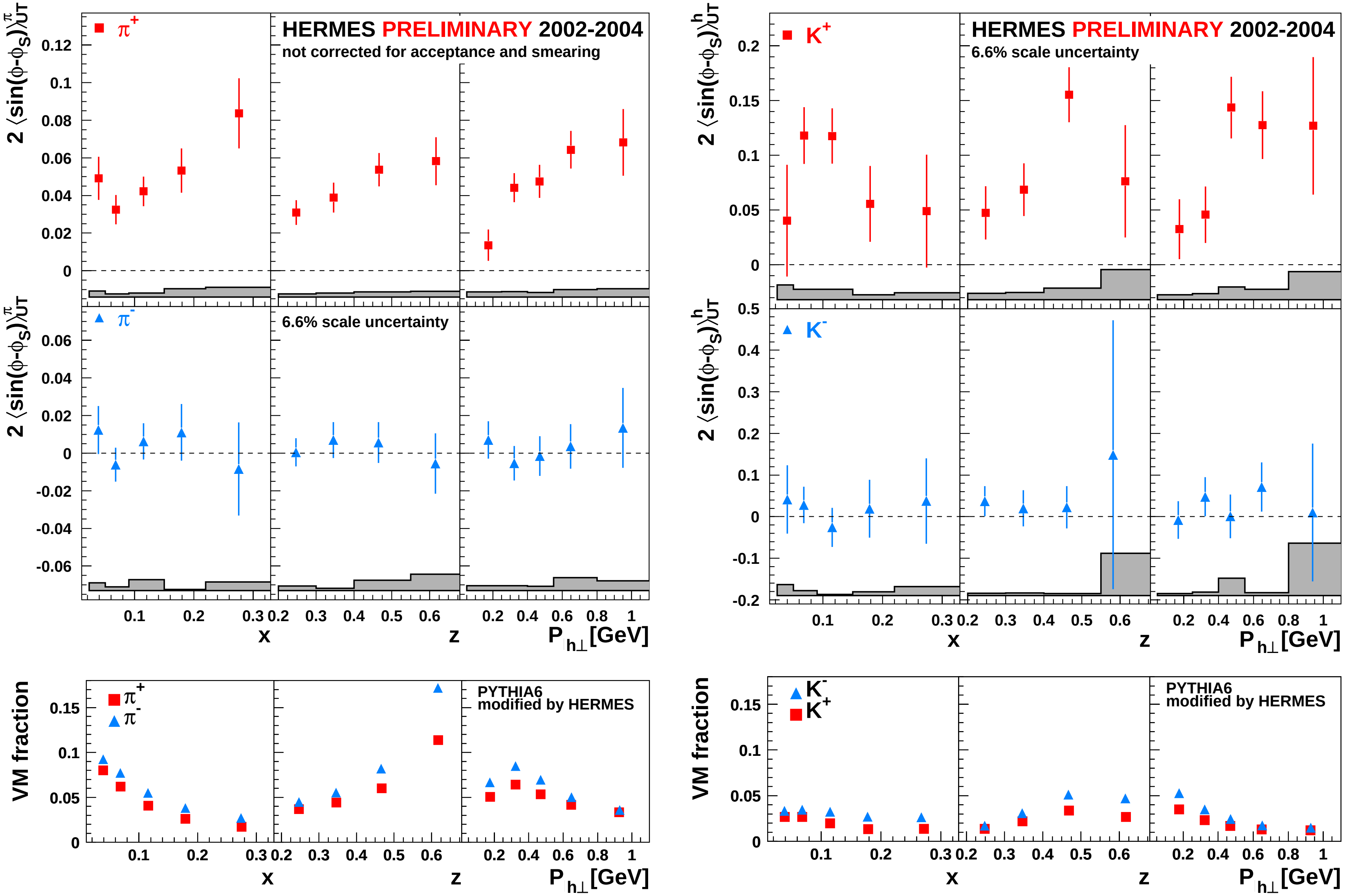

Par7: $\langle sin(3\phi-\phi_S)\rangle^h_{UT}$
K⁺
K⁻
02c0, 03c0 and 04b0
lepton beam asymmetry amplitudes
not corrected for acceptance and smearing
6.6 % scale uncertainty
x
z
$P_{h\perp}$ [GeV]


Par8: Constant term
K⁺
K⁻
02c0, 03c0 and 04b0
lepton beam asymmetry amplitudes
not corrected for acceptance and smearing
6.6 % scale uncertainty
x
z
$P_{h\perp}$ [GeV]

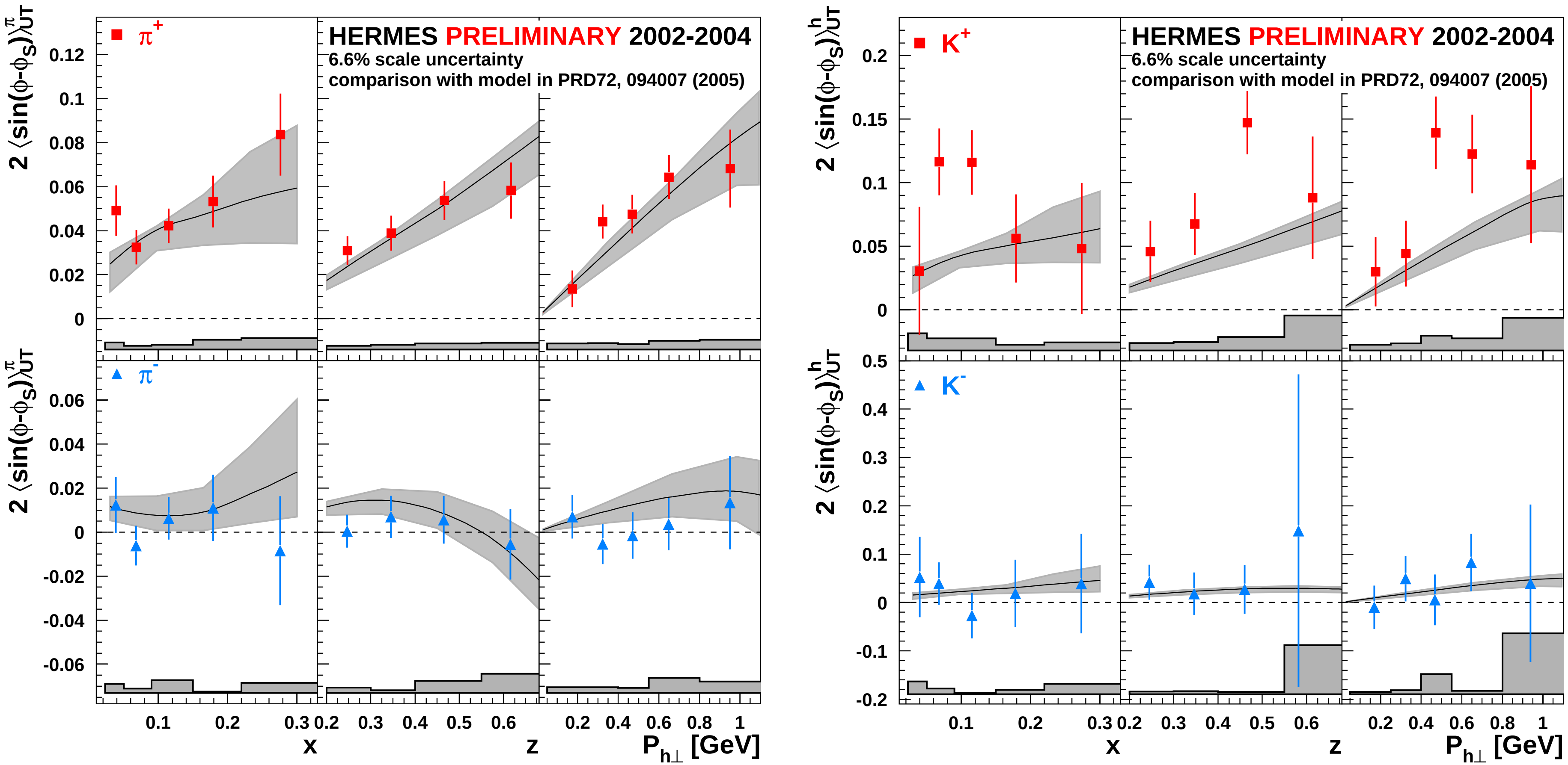
# Collins moments for $\pi^{+/-}$ and $K^{+/-}$ (2002-2004)



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

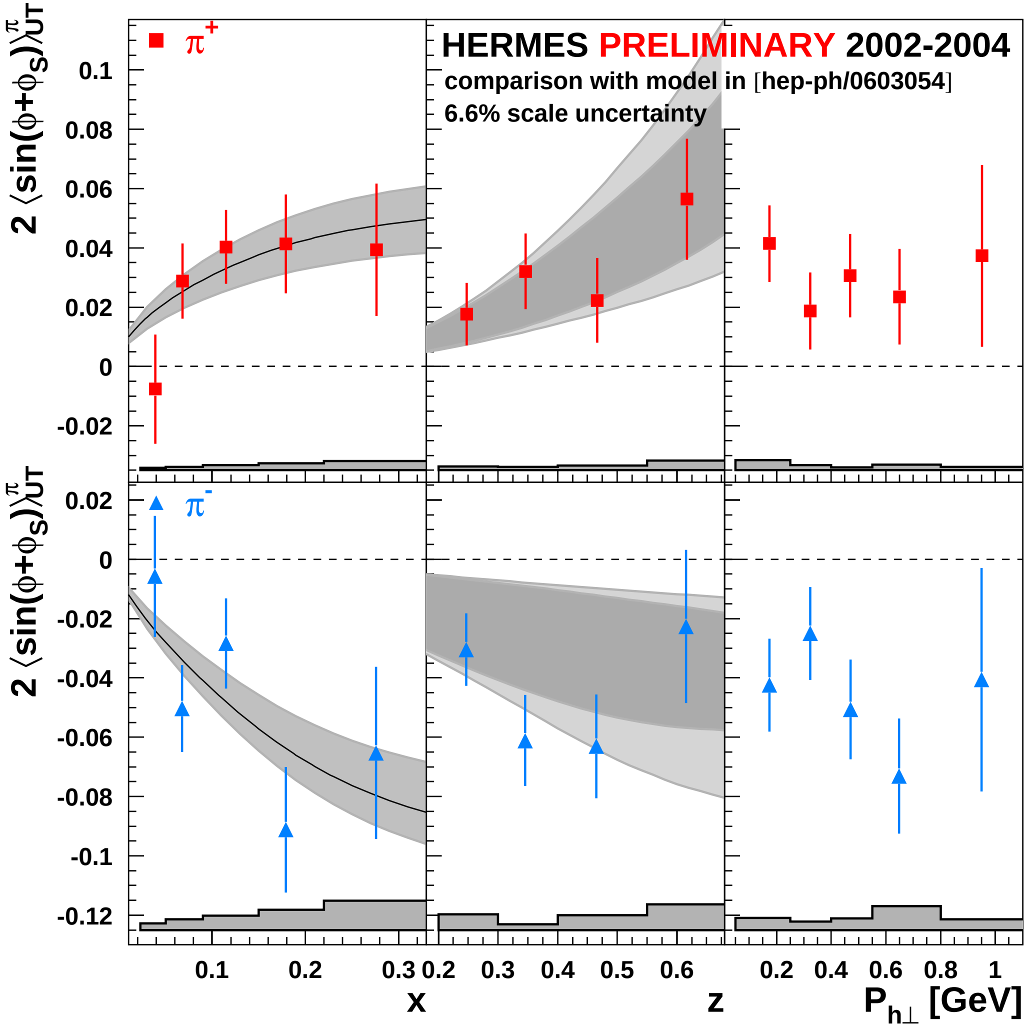


# Comparison with Anselmino's fit (Sivers)



# Comparison with model in hep-ph/0603054

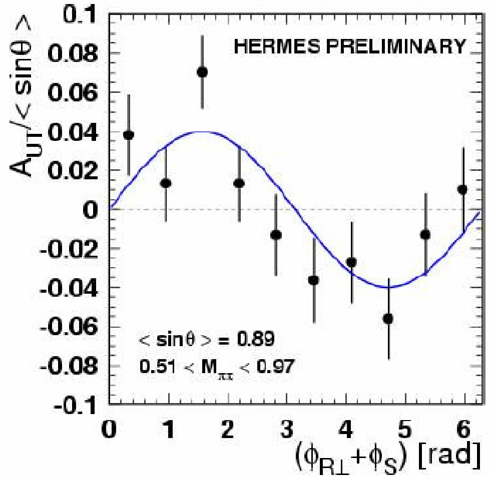
## (A.V.Efremov, K.Goeke, P.Schweitzer)



# The first method: 2-dimensional linear $\chi^2$ fit

neglecting denominator
partial wave expansion

$$A_{UT} \propto \frac{\sum_q \sin(\phi_{R\perp}+\phi_S)\, \delta q\, (\sin\theta\, H_{1,q}^{\sphericalangle,sp} + \sin 2\theta\, H_{1,q}^{\sphericalangle,pp})}{\sum_q f_{1,q} D_{1,q}}$$




*Linear fit: The azimuthal moments are extracted from $A_{UT}$ using a 2-dimensional $\chi^2$ fit*

$$f(\theta,(\phi_{R\perp}+\phi_S)) = \sin(\phi_{R\perp}+\phi_S)\left[a\sin\theta + \frac{b}{2}\sin(2\theta)\right]$$

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta} \propto \frac{\sum_q e_q^2\, \delta q\, H_{1,q}^{\sphericalangle,sp}}{\sum_q e_q^2 f_{1,q} D_{1,q}}$$

The extracted values of the moments are not affected by the presence of this term and other extra terms like $\sin\phi_S$ and $\cos\phi_{R\perp}\sin\theta$

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\ \sin\theta} = 0.040 \pm 0.009\,(stat) \pm 0.003\,(syst)$$

**First evidence of a T-odd and chiral-odd dihadron fragmentation function!**

# The second method: 1-dimensional linear $\chi^2$ fit

$$A_{UT} \propto \frac{\sum_q \sin(\phi_{R\perp} + \phi_S)\ \delta q\ (\sin\theta\ H_{1,q}^{\sphericalangle,sp} + \sin\theta\cos\theta\ H_{1,q}^{\sphericalangle,pp})}{\sum_q f_{1,q}(D_{1,q}^{ss,pp} + \cos\theta\ D_{1,q}^{sp} + 1/4\,(3\cos^2\theta - 1)D_{1,q}^{pp})}$$

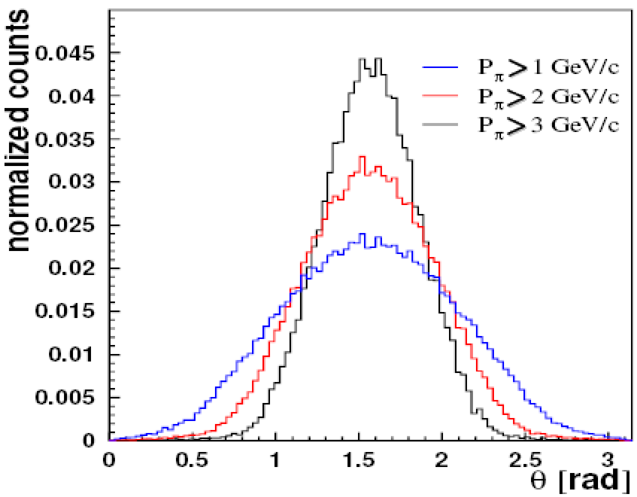
integrating over θ…

$$A_{UT} = \frac{\int \mathrm{d}\theta\ \mathrm{d}\sigma_{UT}}{\int \mathrm{d}\theta\ \mathrm{d}\sigma_{UU}} \sim \sin(\phi_{R\perp} + \phi_S)\ \frac{\delta q\ H_{1,UT}^{\sphericalangle,sp}}{f_1\ D_{1,UU}}$$

linear fit function: $A_{UT} = a\sin(\phi_{R\perp} + \phi_S) + b$

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)} \propto \frac{\sum_q e_q^2\,\delta q\ H_{1,q}^{\sphericalangle,sp}}{\sum_q e_q^2\, f_{1,q} D_{1,q}^{ss,pp}}$$

If 2-π pairs are isotropically distributed in the phase-space, θ-distribution is proportional to sinθ




But…

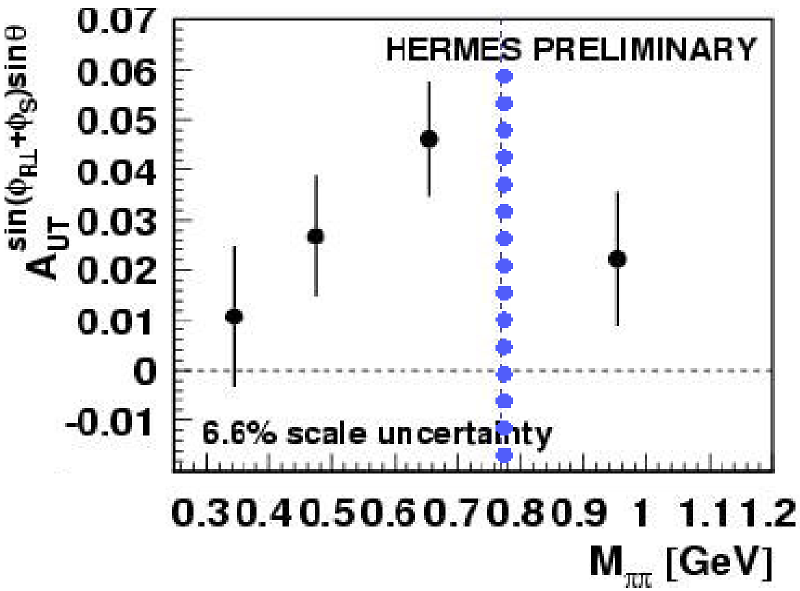
a cut on the pion momentum significantly biases the θ distribution

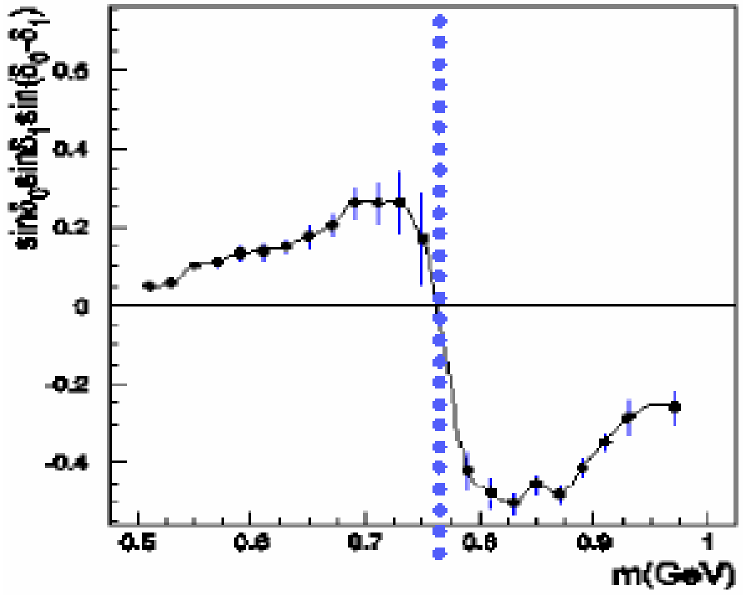
Integration over θ is NOT practicable!

# The $M_{\pi\pi}$ dependence

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta} \propto \frac{\sum_q e_q^2 \delta q \; H_{1,q}^{\triangleleft,sp}}{\sum_q e_q^2 f_{1,q} (D_{1,q}^{ss,pp} - 1/4 \, D_{1,q}^{pp})}$$

No evidence of the sign-change at the $\rho^0$ mass predicted by **Jaffe et al.** *(Phys.Rev.Lett.80,1166(1998))*



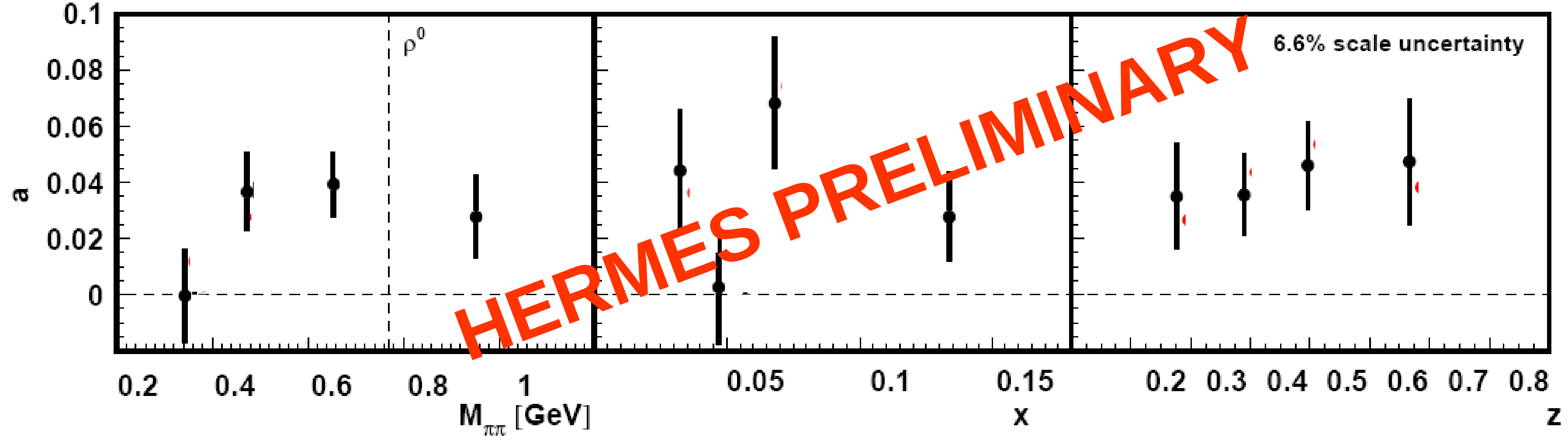




**Positive amplitude** in the whole range

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\ \sin\theta} = 0.040 \pm 0.009\ (stat) \pm 0.003\ (syst)$$

**First evidence of a chiral-odd di-hadron fragmentation function!**

# Fit method comparison: results are consistent




- using a fit with $f(\phi_{R\perp}+\phi_S,\theta) = \sin(\phi_{R\perp}+\phi_S)*(a*\sin\theta + b*\sin2\theta)$
- using a fit with $f(\sin(\phi_{R\perp}+\phi_S)) = a*\langle\sin\theta\rangle*\sin(\phi_{R\perp}+\phi_S)$
- using a fit with $f(\phi_{R\perp}+\phi_S,\theta) = \sin(\phi_{R\perp}+\phi_S)*(a*\sin\theta + b*\sin2\theta)/(1 + c*\cos\theta + d*\cos^2\theta)$