Measurement of Collins and Sivers asymmetries at HERMES

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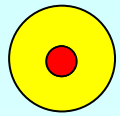
Transversity 2008   Ferrara, 28-31 March 2008

The nucleon structure at leading-twist

Momentum DF

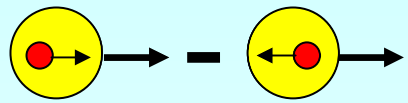
$$q(x,Q^2) = q^+ + q^-$$



WELL KNOWN

Helicity DF

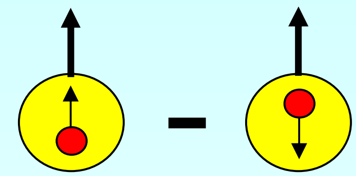
$$\Delta q(x,Q^2) = q^+ - q^-$$



KNOWN

Transversity DF

$$\delta q(x,Q^2) = q^\uparrow - q^\downarrow$$



Unmeasured for long time!

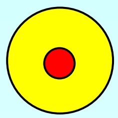
All equally important for a complete description of momentum and spin distribution of the nucleon!

… but not all equally known

The nucleon structure at leading-twist

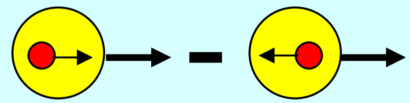
Momentum DF

$$q(x,Q^2) = q^+ + q^-$$



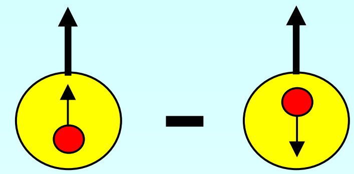
Helicity DF

$$\Delta q(x,Q^2) = q^+ - q^-$$



Transversity DF

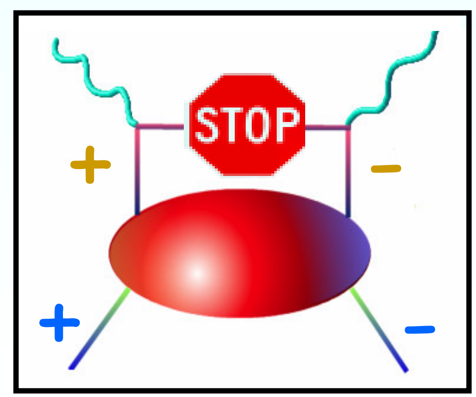
$$\delta q(x,Q^2) = q^\uparrow - q^\downarrow$$



Unmeasured for long time!

EM and strong interactions cannot flip the chirality of the probed quark

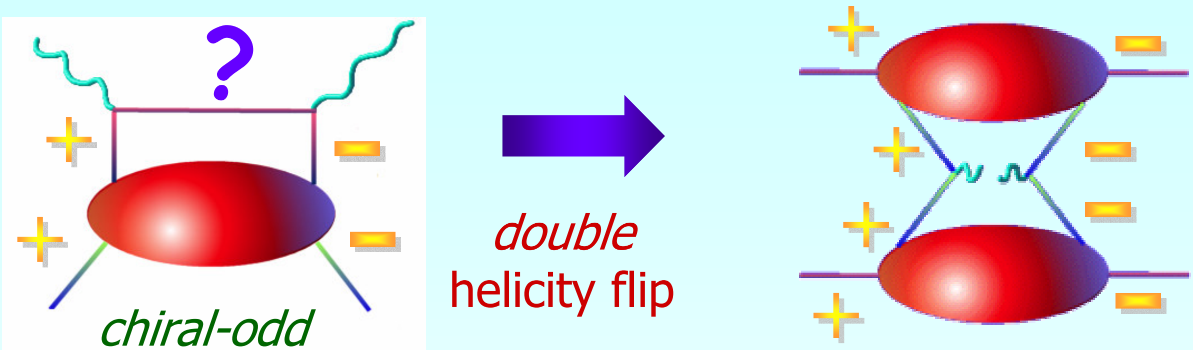
Chiral-odd: requires spin flip of the quark



Transversity not measurable in inclusive DIS

How can one measure transversity?

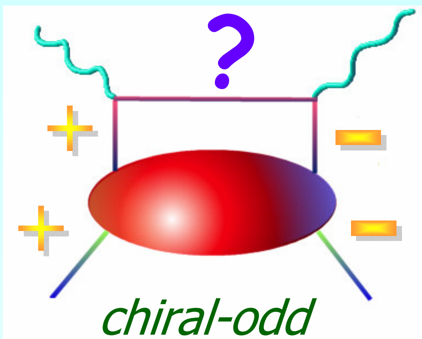
Need another chiral-odd object!



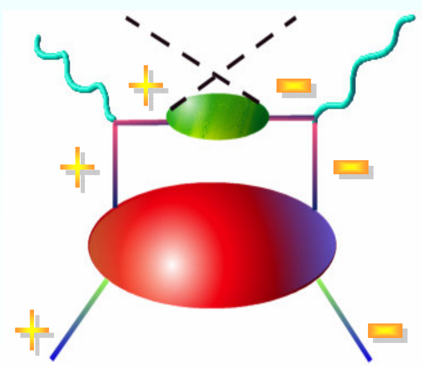
Drell-Yan: $p^{\uparrow}p^{\uparrow} \rightarrow ll\ X$

How can one measure transversity?

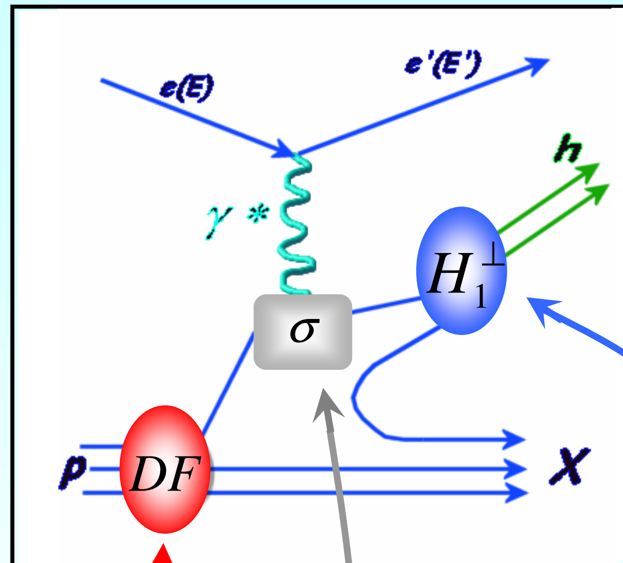
Need another chiral-odd object!



chiral odd fragmentation function



SIDIS: $l\, N^{\uparrow} \to l'\, h\, X$



$$\sigma^{ep\to ehX} = \sum_q \delta q \otimes \sigma^{eq\to eq} \otimes H_1^{\perp}$$

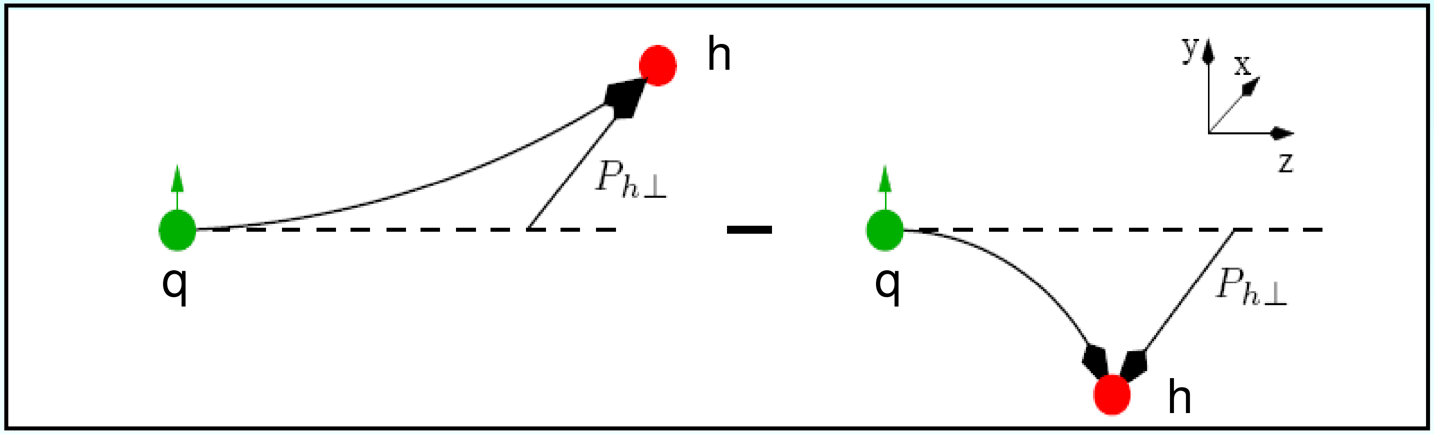
chiral even!

Transversity

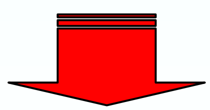
Collins FF

The "Collins effect"

The **Collins FF** $H_1^{\perp}(z, k_T^2)$ accounts for the correlation between the transverse spin of the fragmenting quark and the transverse momentum $P_{h\perp}$ of the produced (unpolarized) hadron



…and generates **left-right (azimuthal) asymmetries** in the direction of the outgoing hadrons



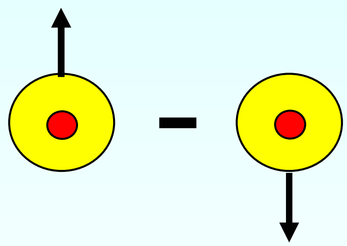
We have an observable to look at!!!

Is this observable unique?

The "Sivers effect":

"Correlation between p_T and transverse spin of the nucleon"

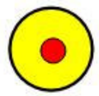
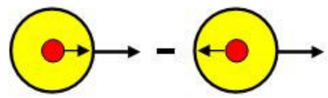
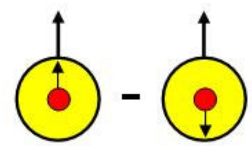
Sivers distribution function $f_{1T}^{\perp q}(x, p_T^2)$ describes the probability to find an unpolarized quark with transverse momentum p_T in a transversely polarized nucleon.



…and (also!) generates **left-right (azimuthal) asymmetries** in the direction of the outgoing hadrons.

Sivers function requires **non-zero orbital angular momentum**

[M. Burkardt, *Physical Review* **D66**, 114005 (2002)]

		quark		
		U	**L**	**T**
nucleon	**U**	q 		
	L		Δq 	
	T			δq 

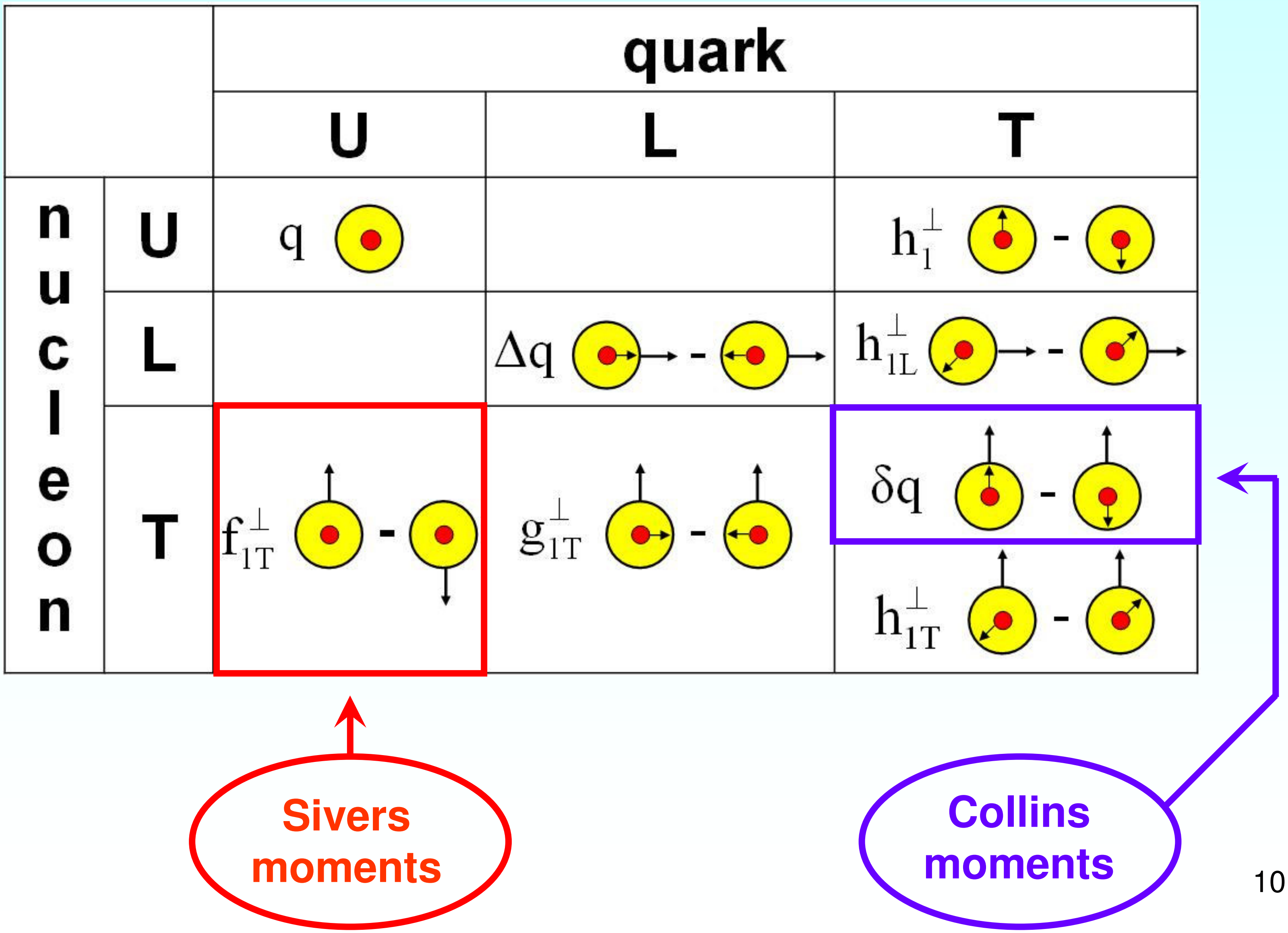
The TMD Distribution Functions

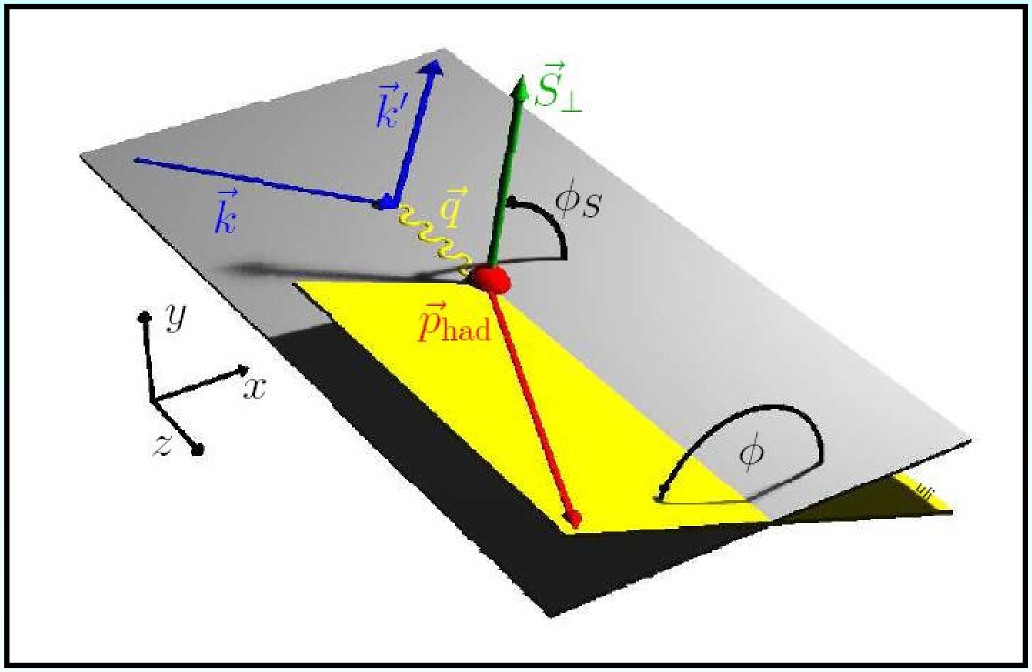
		quark		
		U	L	T
nucleon	U	q		$h_1^\perp$
	L		Δq	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	δq $h_{1T}^\perp$

Incredible amount of information on the nucleon structure!!!

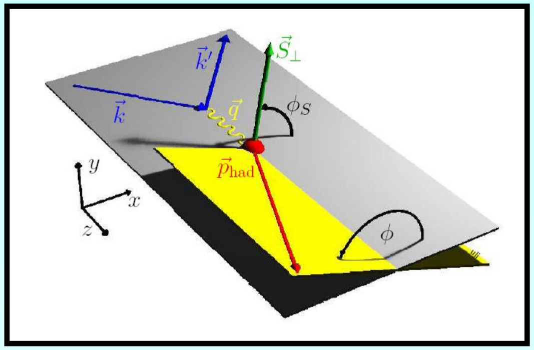
Exciting time for the new generation experiments!

The TMD Distribution Functions




$\vec{k}'$
$\vec{S}_\perp$
$\vec{k}$
$\vec{q}$
ϕ_S
$\vec{p}_{\text{had}}$
y
x
z
ϕ

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



$d\sigma_{XY}$ — X: Beam, Y: Target — Polarization

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

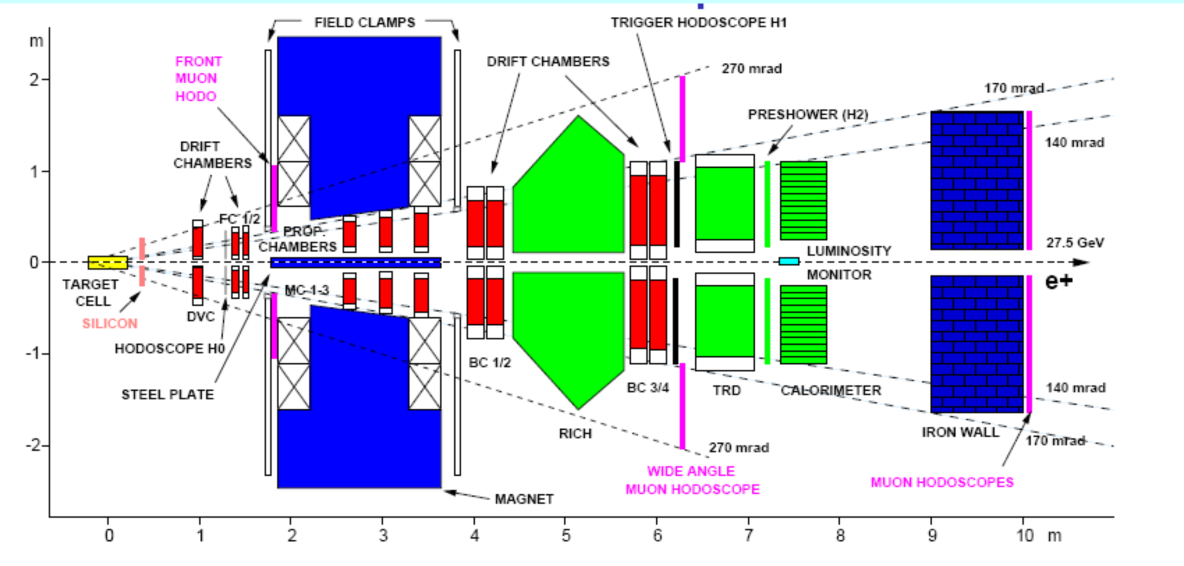
$$+ S_T \Big\{ \underbrace{\sin(\phi + \phi_S) \; d\sigma_{UT}^{(5)}}_{\text{Collins}} + \underbrace{\sin(\phi - \phi_S) \; d\sigma_{UT}^{(6)}}_{\text{Sivers}} + \sin(3\phi - \phi_S) \; d\sigma_{UT}^{(7)} + \sin \phi_S d\sigma_{UT}^{(8)} \Big\}$$

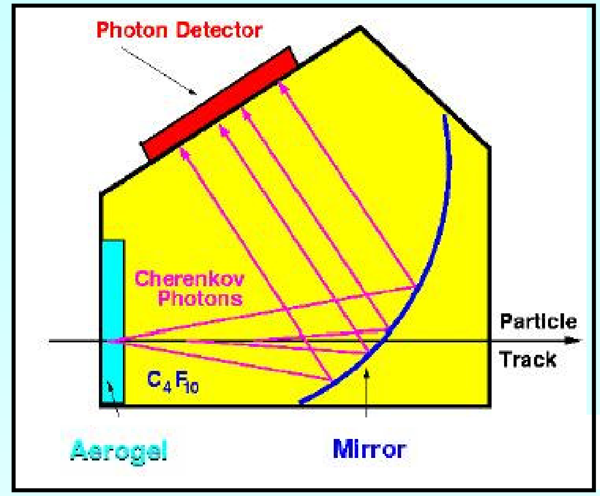
$$d\sigma_{UT}^{Collins} \propto |S_T| \sin(\phi + \phi_S) \cdot \sum_q e_q^2 I \left[\frac{\vec{k}_T \cdot \hat{P}_{h\perp}}{M_h} \delta q(x, p_T^2) \otimes H_1^{\perp q}(z, k_T^2) \right]$$

Two distinctive signatures if $\phi_S \neq 0$ (transversely polarized target)

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

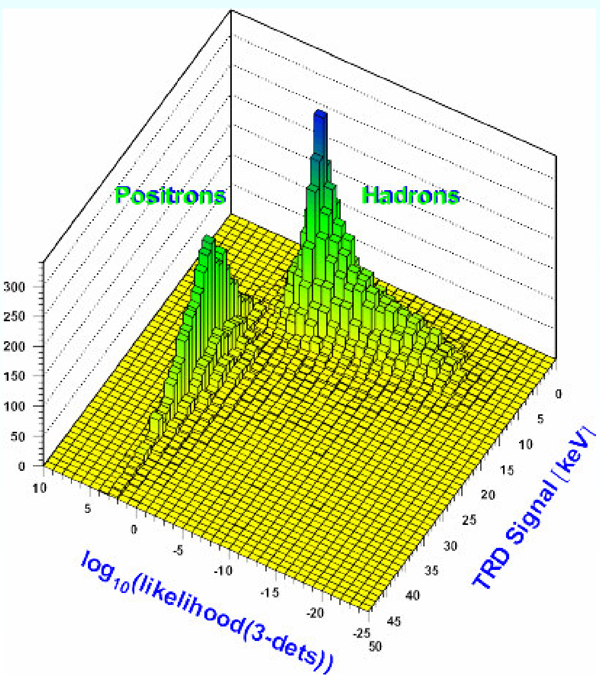
$I[...]$ =convolution integral over intrinsic ($\vec{p}_T$) and fragmentation ($\vec{k}_T$) transverse momenta





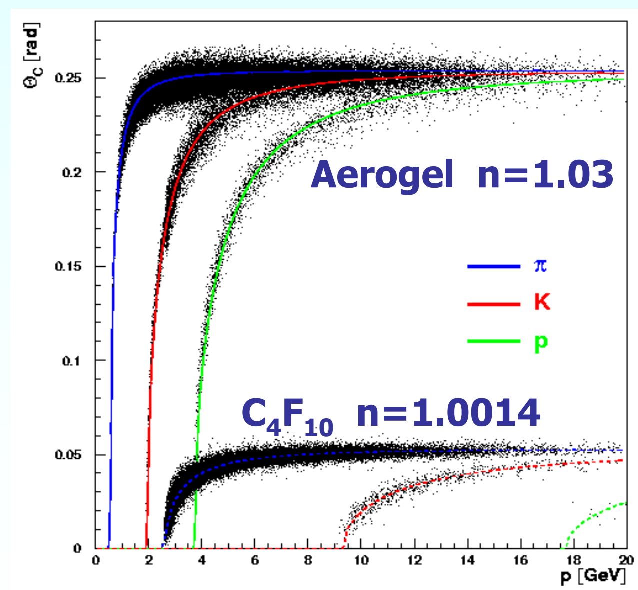
hadron separation

Particle Identification:



TRD, Calorimeter, preshower, RICH:

lepton-hadron > 98%



Hadron: π ~ 98%, K ~ 88% , P ~ 85%

Full HERMES transverse data set (2002-2005)

(transversely polarized hydrogen target: $\langle P \rangle \approx 73\,\%$)

	inclusive DIS	semi-inclusive DIS
four momentum transfer	$Q^2 > 1\,\mathrm{GeV}^2$	$Q^2 > 1\,\mathrm{GeV}^2$
squared mass of the final state	$W^2 > 4\,\mathrm{GeV}^2$	$W^2 > 10\,\mathrm{GeV}^2$
fractional energy transfer	$0.1 < y < 0.95$	$y < 0.95$
Bjorken scaling variable	$0.023 < x < 0.4$	$0.023 < x < 0.4$
virtual photon – hadron angle		$\theta_{\gamma^* h} > 0.02\,\mathrm{rad}$
hadron momentum		$2\,\mathrm{GeV} < P_h < 15\,\mathrm{GeV}$
energy fraction (extended range)		$0.2 < z < 0.7$

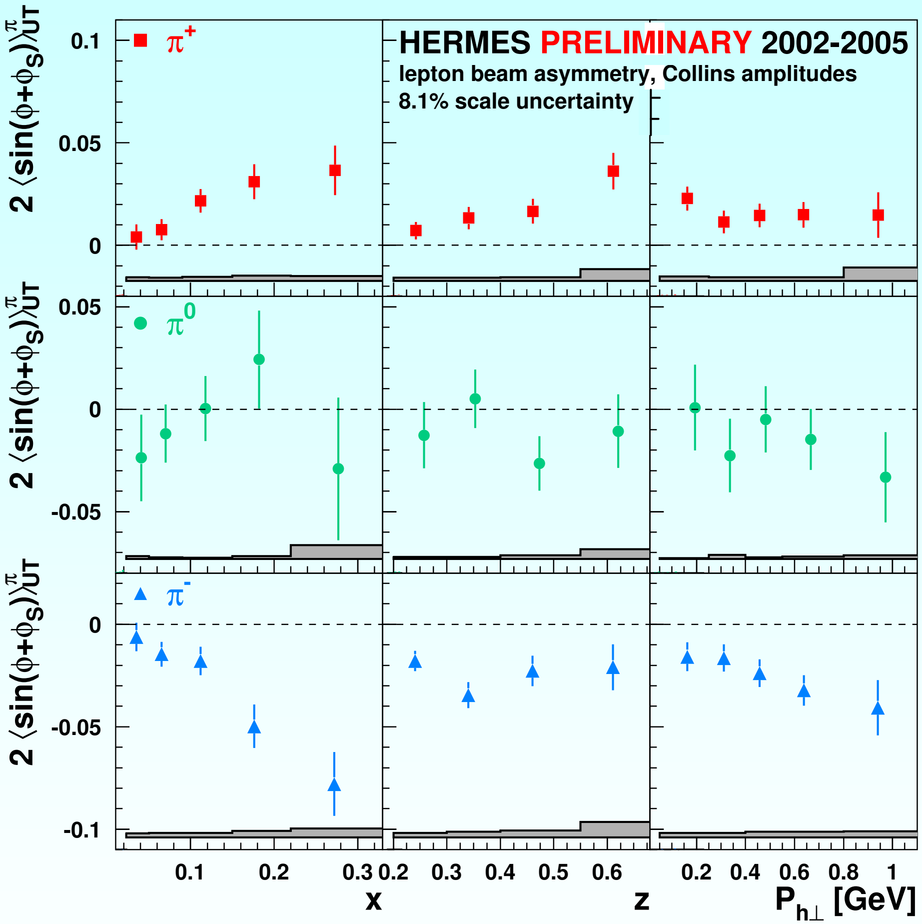
The selected SIDIS events are used to extract the Collins and Sivers amplitudes through a Maximum Likelihood fit using the PDF:

$$L = \prod_i (F_i)^{w_i}$$

$$F_i\left(\langle\sin(\phi\pm\phi_S)\rangle^h_{UT}, P_t, \phi, \phi_S\right) \propto 1 + P_t\Big[2\langle\sin(\phi+\phi_S)\rangle^h_{UT}\sin(\phi+\phi_S) + 2\langle\sin(\phi-\phi_S)\rangle^h_{UT}\sin(\phi-\phi_S)$$

$$+ 2\langle\sin(\phi_S)\rangle^h_{UT}\sin(\phi_S) + 2\langle\sin(3\phi-\phi_S)\rangle^h_{UT}\sin(3\phi-\phi_S) + 2\langle\sin(2\phi-\phi_S)\rangle^h_{UT}\sin(2\phi-\phi_S)\Big]$$

Collins moments for pions (2002-2005)



- positive amplitude for π^+
- ~ 0 amplitude for π^0
- negative amplitude for π^-

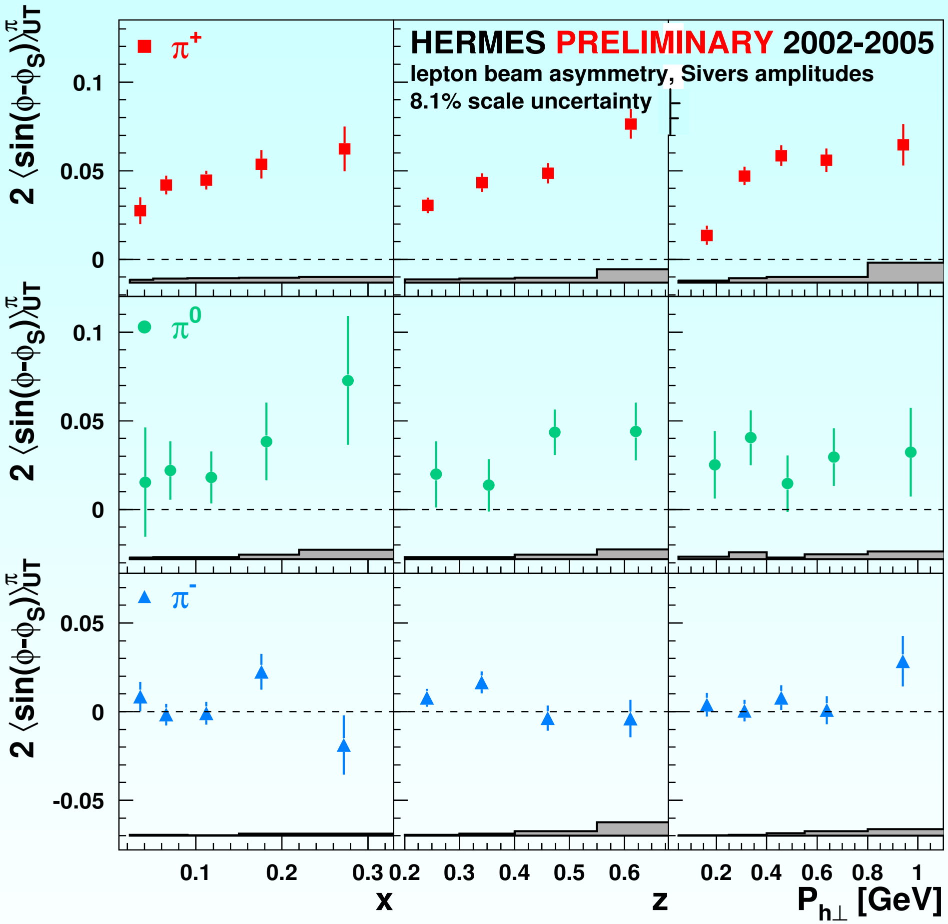
$$\begin{cases} u \Rightarrow \pi^+ \;;\; d \Rightarrow \pi^- \; (fav) \\ u \Rightarrow \pi^- \;;\; d \Rightarrow \pi^+ \; (unfav) \end{cases}$$

the large negative π^- amplitude suggests disfavored Collins function with opposite sign:

$$H_1^{\perp,\text{unfav}}(z) \approx -H_1^{\perp,\text{fav}}(z)$$

$\propto I[\delta q(x) H_1^{\perp q}(z)] \neq 0$ ⇒ **Transversity & Collins FF ≠ 0**

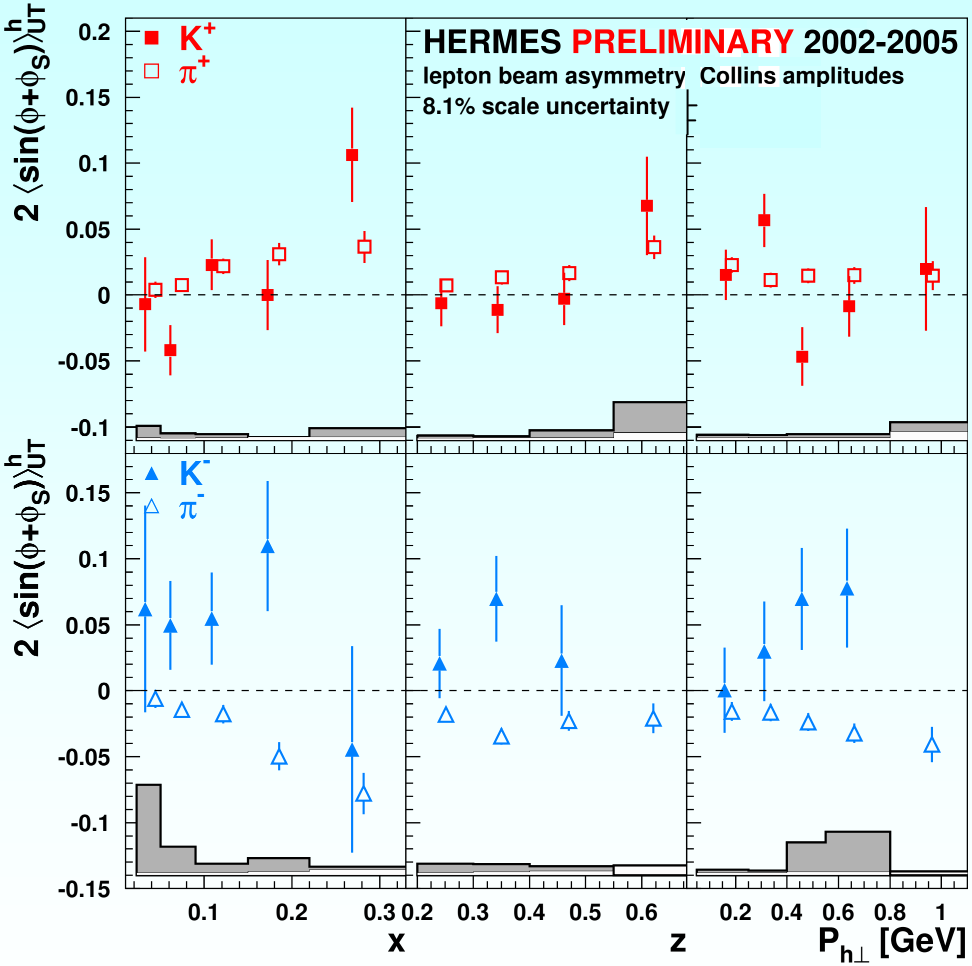
Sivers moments for pions (2002-2005)



- positive amplitude for π^+
- positive amplitude for π^0
- amplitude ~ 0 for π^-

$\propto I[f_{1T}^{\perp q}(x) D_1^q(z)] \neq 0$ ⇒ **Sivers function ≠ 0** ⇒ $L_q \neq 0$

Pions-Kaons comparison: Collins moments

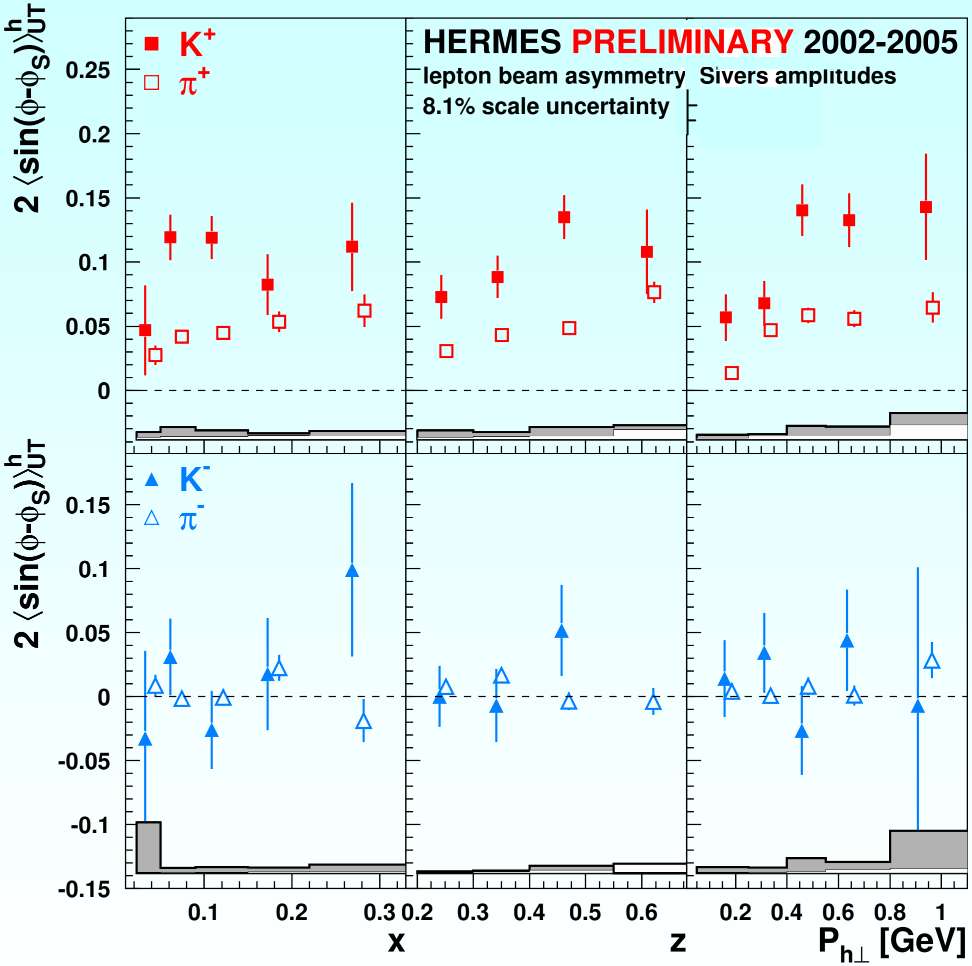


- K^+ and π^+ amplitudes consistent (u-quark dominance)

- K^- and π^- amplitudes with opposite sign

(but $K^-(\bar{u}s)$ originates from fragmentation of sea quarks)

Pions-Kaons comparison: Sivers moments



- **K⁺ amplitude is ~2 times larger than for π⁺:** conflicts with usual expectations based on u-quark dominance

$$\pi^+ \equiv (u, \bar{d}) \qquad K^+ \equiv (u, \bar{s})$$

suggests substantial magnitudes of the Sivers function for the sea quarks

- Both K^- and π^- amplitudes are consistent with zero

The extraction of the Distribution Functions

		quark		
		U	L	T
nucleon	U	q		$h_1^\perp$ -
	L		Δq -	$h_{1L}^\perp$ -
	T	$f_{1T}^\perp$ -	$g_{1T}^\perp$ -	δq - $h_{1T}^\perp$ -

Exciting physics

...but challenging

$$\left\langle \sin(\phi+\phi_S)\right\rangle_{UT}^{h} = \frac{\int d\phi_S d^2\vec{P}_{h\perp} \sin(\phi+\phi_S)\ d\sigma_{UT}}{\int d\phi_S d^2\vec{P}_{h\perp} d\sigma_{UU}} \propto \mathbf{I}\left[\frac{\vec{k}_T\cdot\hat{P}_{h\perp}}{M_h}\delta q(x,p_T^2) H_1^{\perp q}(z,k_T^2)\right]$$

Convolution integral on transverse momenta p_T and k_T

Experiment: only partial coverage of the full $P_{h\perp}$ range

Theory: difficult to solve ⟹ Gaussian ansatz

$$\delta q(x,p_T^2) \approx \frac{\delta q(x)}{\pi\left\langle p_T^2(x)\right\rangle} e^{-\frac{p_T^2}{\left\langle p_T^2(x)\right\rangle}} \qquad H_1^{\perp q}(z,k_T^2) \approx \frac{H_1^{\perp q}(z)}{\pi\left\langle k_T^2(z)\right\rangle} e^{-\frac{k_T^2}{\left\langle k_T^2(z)\right\rangle}}$$

(extraction assumption-dependent)

Extraction of transversity

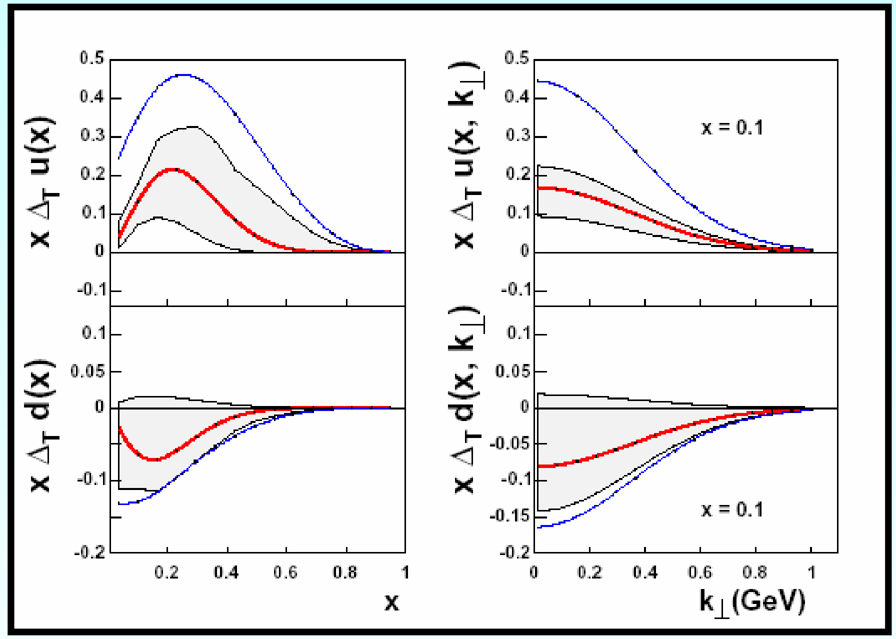
$$A_{UT}^{\sin(\phi+\phi_S)} \propto \delta q(x) \otimes H_1^{\perp q}(z)$$

(H) $lp \to l' hX$

(D) $ld \to l' hX$

BELLE

[Anselmino et al. PRD75 (2007)]



Extraction based on:

- "unweighted" Collins amplitudes
- Gaussian ansatz

New extraction : **don't miss Alexei's talk!!!**

...similarly for the Sivers function

$$\langle \sin(\phi-\phi_S)\rangle^h_{UT} = \frac{\int d\phi_S d^2\vec{P}_{h\perp} \sin(\phi-\phi_S)\; d\sigma_{UT}}{\int d\phi_S d^2\vec{P}_{h\perp} d\sigma_{UU}} \propto \mathbf{I}\left[\frac{\vec{p}_T\cdot\hat{P}_{h\perp}}{M} f_{1T}^{\perp q}(x,p_T^2) D_1^q(z,k_T^2)\right]$$

Convolution integral on transverse momenta p_T and k_T

...again, one needs gaussian ansatz

$$f_{1T}^{\perp q}(x,p_T^2) \approx \frac{f_{1T}^{\perp q}(x)}{\pi\langle p_T^2(x)\rangle} e^{-\frac{p_T^2}{\langle p_T^2(x)\rangle}} \qquad D_1^q(z,k_T^2) \approx \frac{D_1^q(z)}{\pi\langle k_T^2(z)\rangle} e^{-\frac{k_T^2}{\langle k_T^2(z)\rangle}}$$

⇓

extraction assumption-dependent

Alternatively one can use the so-called $P_{h\perp}$ -weighted moments (don't require any assumption on transverse momenta distributions)

$$\left\langle \frac{P_{h\perp}}{zM}\sin(\phi-\phi_S)\right\rangle_{UT}^{h} \equiv \frac{\int d\phi_S d^2\vec{P}_{h\perp}\sin(\phi-\phi_S)\frac{P_{h\perp}}{zM}d^6\sigma_{UT}}{\int d\phi_S d^2\vec{P}_{h\perp}d^6\sigma_{UU}}$$

P_{hT}-weighted Sivers moments (measured)

$$\propto -\left|\vec{S}_T\right|\sum_{q\bar{q}}\mathbf{P}_q^h(x,z)\, f_{1T}^{\perp(1)q}(x)$$

Sivers function

$$\mathbf{P}_q^h(x,z) \equiv \frac{e_q^2 q(x) D_1^{q\to h}(z)}{\sum_{q'\bar{q}'} e_{q'}^2 q'(x) D_1^{q'\to h}(z)}$$

purities (based on known quantities)

Extraction above requires, in principle, a full integration over $P_{h\perp}$ (from 0 to ∞)

Due to the partial experimental coverage in $P_{h\perp}$ the evaluation of acceptance effects is of crucial importance (preliminary MC studies at HERMES show big acceptance effects on $P_{h\perp}$ -weighted moments).

Evaluation of the acceptance effects

(a possible method under investigation)

The idea of underneath the method in 3 steps

1. The full kinematic dependence of the Collins and Sivers moments on $\bar{x} \equiv (x, Q^2, z, P_{h\perp})$ is evaluated from the real data through a fit of the full set of SIDIS events based on a Taylor expansion on $\bar{x}$:

$$f(\bar{x}, P_t; c) = 1 + P_t \cdot [A_{Collins}(\bar{x}; c_i) \cdot \sin(\phi + \phi_S) + A_{Sivers}(\bar{x}; c_i) \cdot \sin(\phi - \phi_S)]$$

e.g.: $A_{Collins}(\bar{x}, c) = c_0 + c_1 \cdot x + c_2 \cdot z + c_3 \cdot Q^2 + c_4 \cdot P_{h\perp} + c_5 \cdot x^2 + \ldots + c_{22} \cdot x^2 \cdot z \cdot P_{h\perp}$

2. The extracted azimuthal moments $A_{Collins}(\bar{x}; c_i)$ and $A_{Sivers}(\bar{x}; c_i)$ are folded with the spin-independent cross section (known!) in 4π $(\sigma_{UU}^{4\pi})$ and within the HERMES acceptance $(\sigma_{UU}^{acc.})$:

$$\left\langle \frac{P_{h\perp}}{zM} \sin(\phi \pm \phi_S) \right\rangle_{UT}^{acc,4\pi}(x) = \frac{\int P_{h\perp}/(zM)\ \sigma_{UU}^{acc,4\pi}(\bar{x})\ A_{Collins,Sivers}(\bar{x}; c_i)}{\int \sigma_{UU}^{acc,4\pi}(\bar{x})}$$

3. **Acceptance effects:** difference between asymmetry amplitudes **folded in 4π** and those **folded within the acceptance**.

The main advantage of the method

The kinematic dependence of Collins and Sivers is extracted from the data

no need to rely on a model for Collins and Sivers

The limits of the method

- kinematic dependence of azimuthal moments outside the acceptance is assumed to be the same as inside
- truncation of the Taylor expansion
- need a model for the spin-independent cross section (e.g. PYTHIA) (use of different models to test stability and estimate a systematic error)

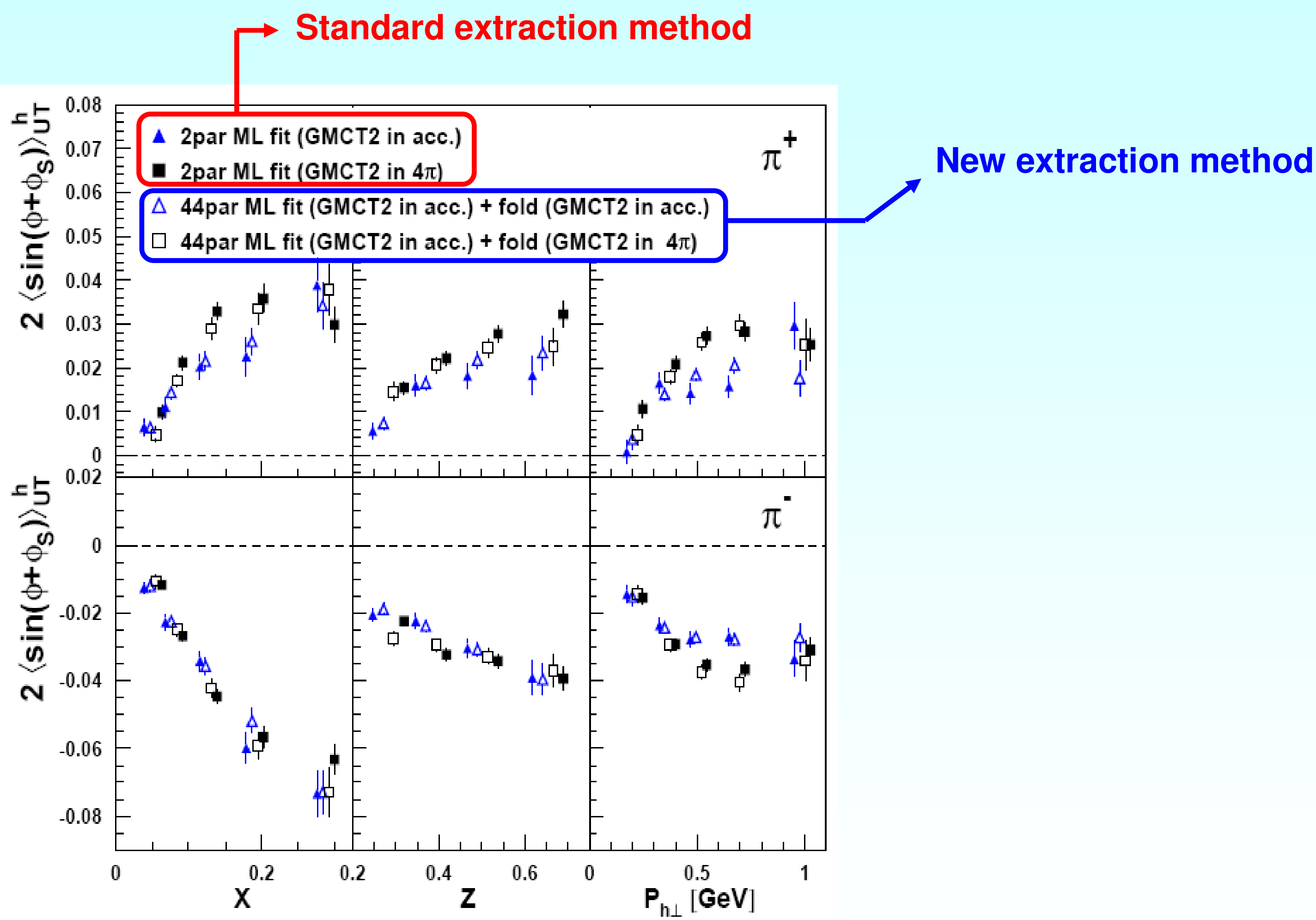
Testing the method with a MC simulation

(GMC_TRANS MC generator ⟹ see Gunar's talk)

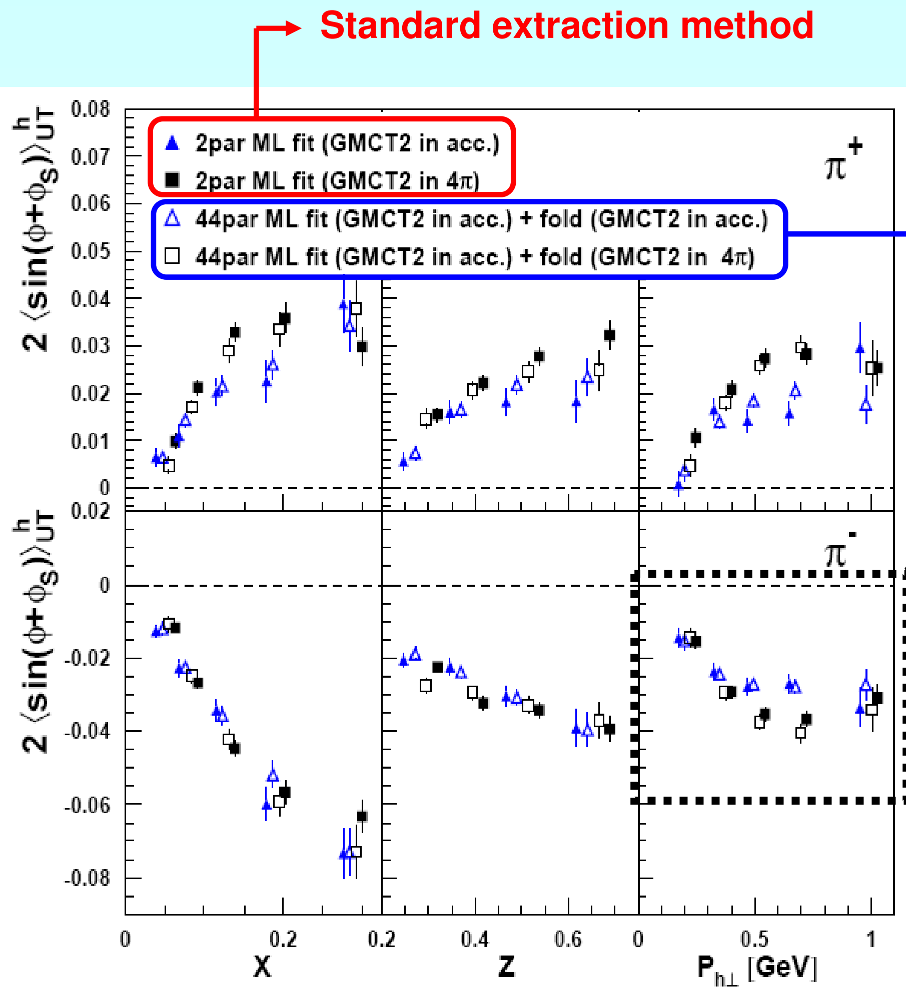
- physics generator for SIDIS pion production
- include transverse-momentum dependence, in particular simulate Collins and Sivers effects
- start from 1-hadron SIDIS expressions of Mulders & Tangerman (Nucl.Phys.B461:197-237,1996)
- use Gaussian Ansatz for all transverse-momentum dependencies of DFs and FFs
- unpolarized DFs (as well as helicity distribution) and FFs from fits/parametrizations (e.g., Kretzer FFs etc.)

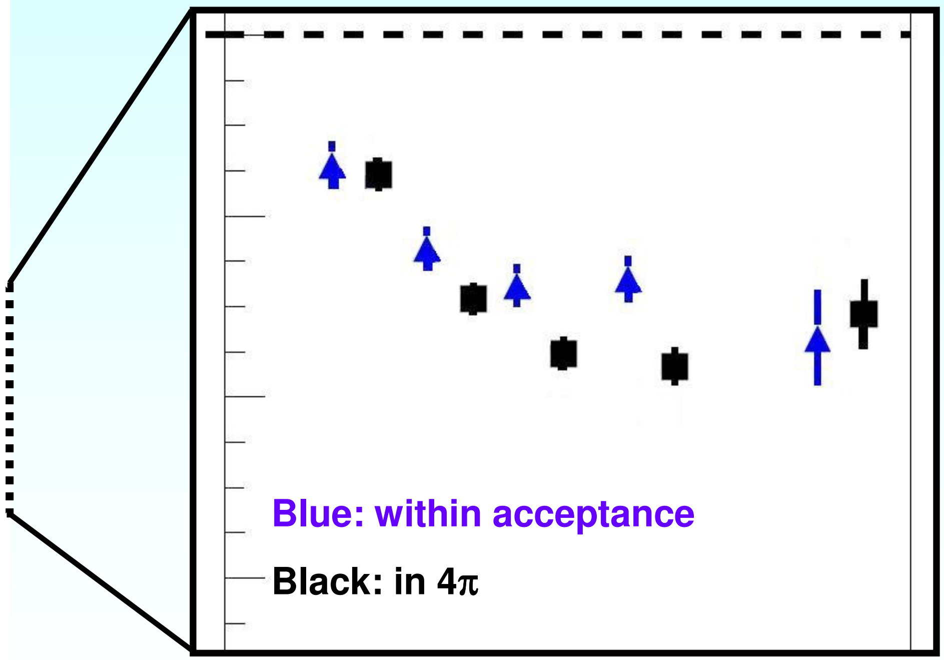
- ***generated events***: events generated in 4π with original kinematics
- **reconstructed events**: events generated within the HERMES acceptance with smeared kinematics (simulated detector smearing)

Applying the method on GMC_TRANS data

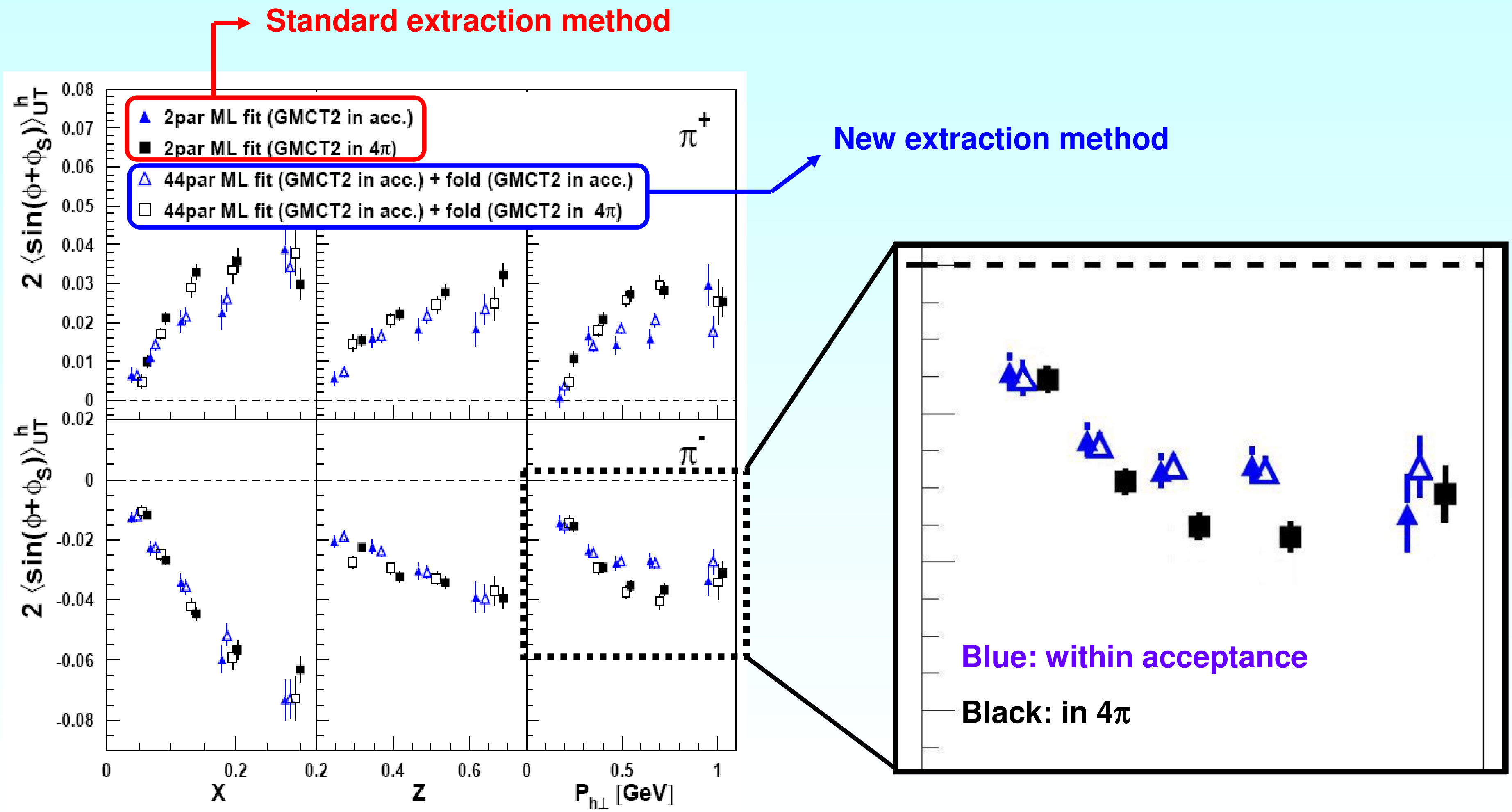


Applying the method on GMC_TRANS data

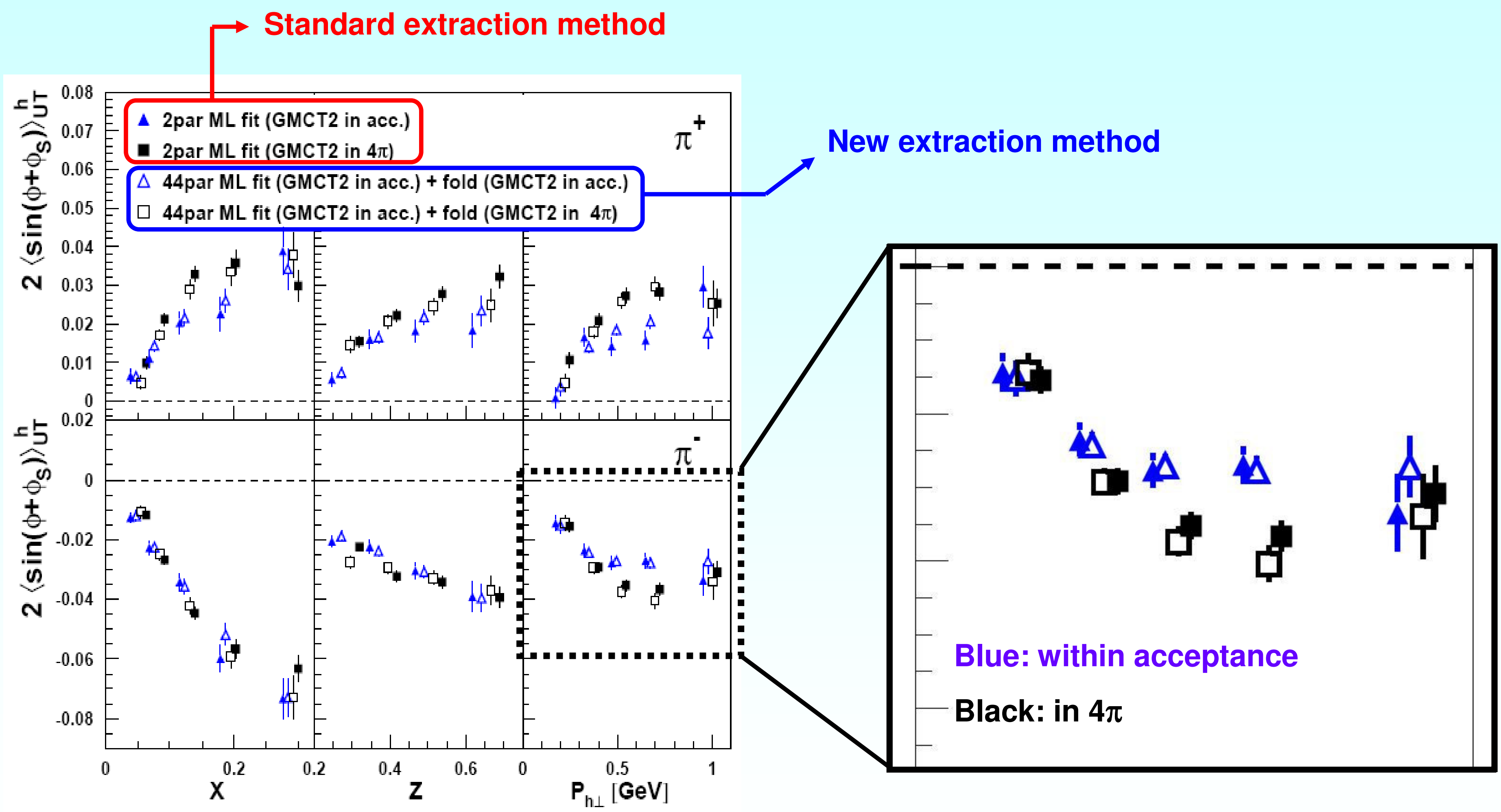




Applying the method on GMC_TRANS data



Applying the method on GMC_TRANS data



The method works nicely at MC level!

Conclusions

- **significant Collins amplitudes observed for π-mesons**

$\rightarrow$ enabled first extraction of transversity distribution

- **significant Sivers amplitudes observed for π^+ and K^+**

$\rightarrow$ clear evidence of non-zero Sivers function

$\rightarrow$ (indirect) evidence for non-zero quark orbital angular momentum

- Current extractions of transversity and Sivers function based on unweighted moments ($\rightarrow$ need Gaussian ansatz)
- Assumpion-free extractions can be done in the future from $P_{h\perp}$-weighted moments.
- Evaluation of acceptance effects becomes crucial
- A method to evaluate acceptance effects is currently under study at HERMES.
- Promising results at MC level!

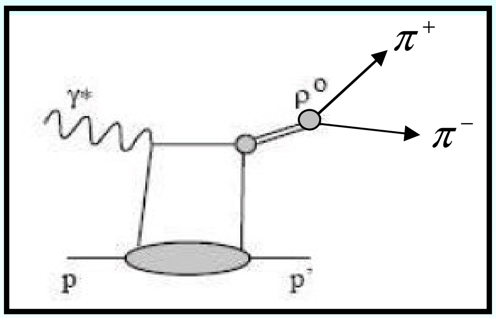
Back-up slides

The isospin triplet of π-mesons is reflected in a relation for any SSA amplitudes:

$$2\langle\sin(\phi\pm\phi_S)\rangle_{UT}^{\pi^+} + \left(\frac{\sigma^{\pi^-}}{\sigma^{\pi^+}}\right)\cdot 2\langle\sin(\phi\pm\phi_S)\rangle_{UT}^{\pi^-} - \left(1+\frac{\sigma^{\pi^-}}{\sigma^{\pi^+}}\right)\cdot\langle\sin(\phi\pm\phi_S)\rangle_{UT}^{\pi^0} = 0$$

fulfilled by the extracted amplitudes !!

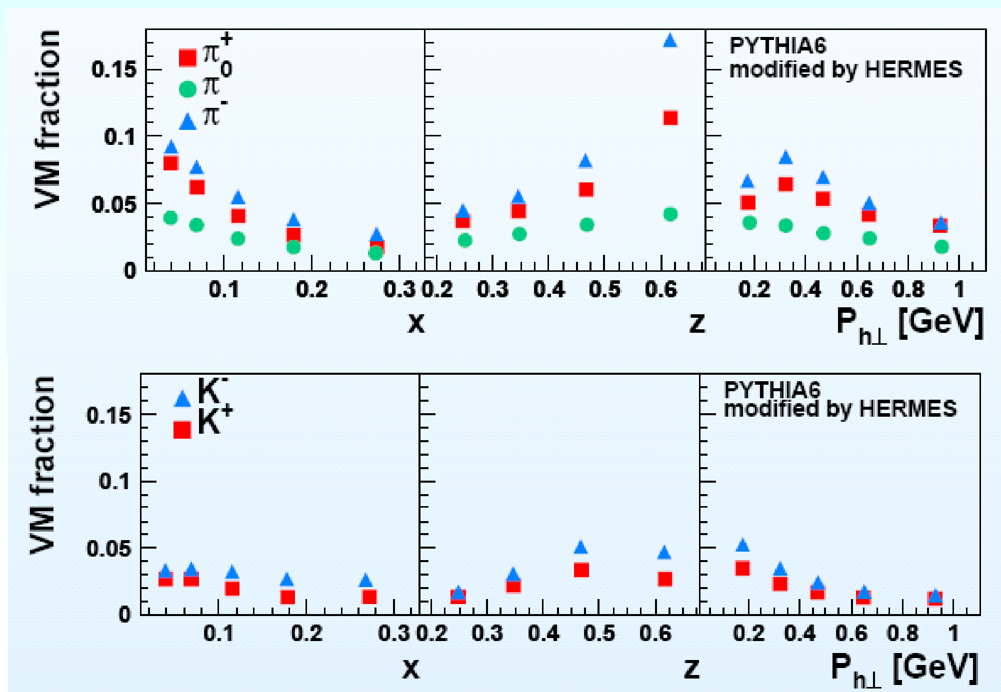
"Contamination" by decay of exclusively produced vector mesons is not negligible



up to 16% for pions

What about the kaons?

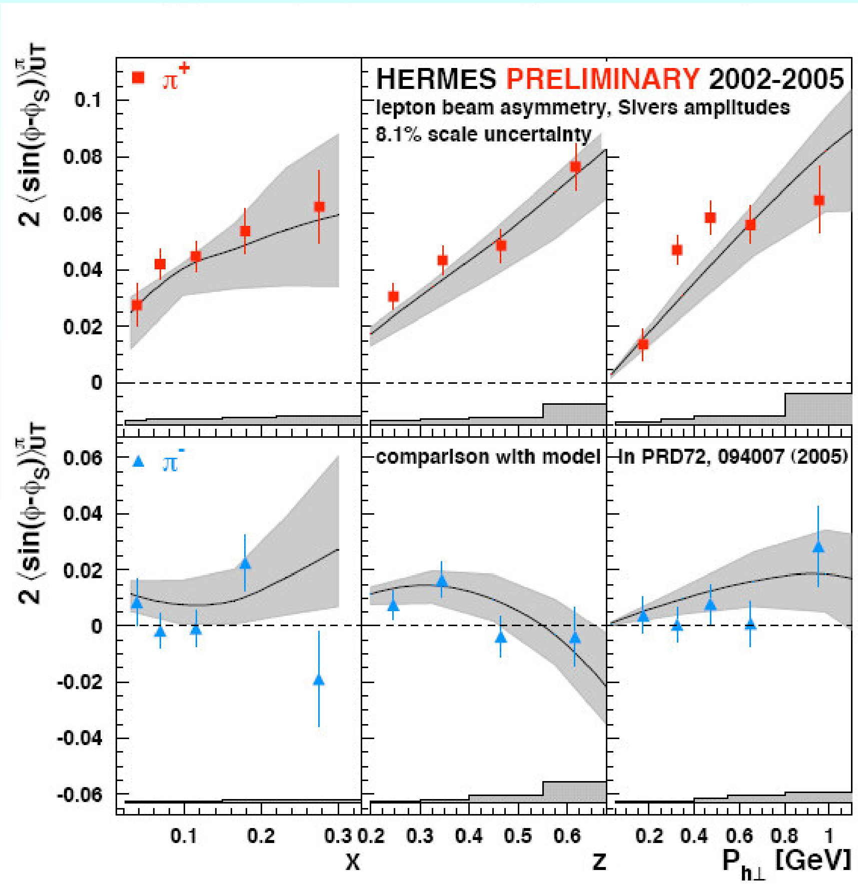
...below 5%!!!

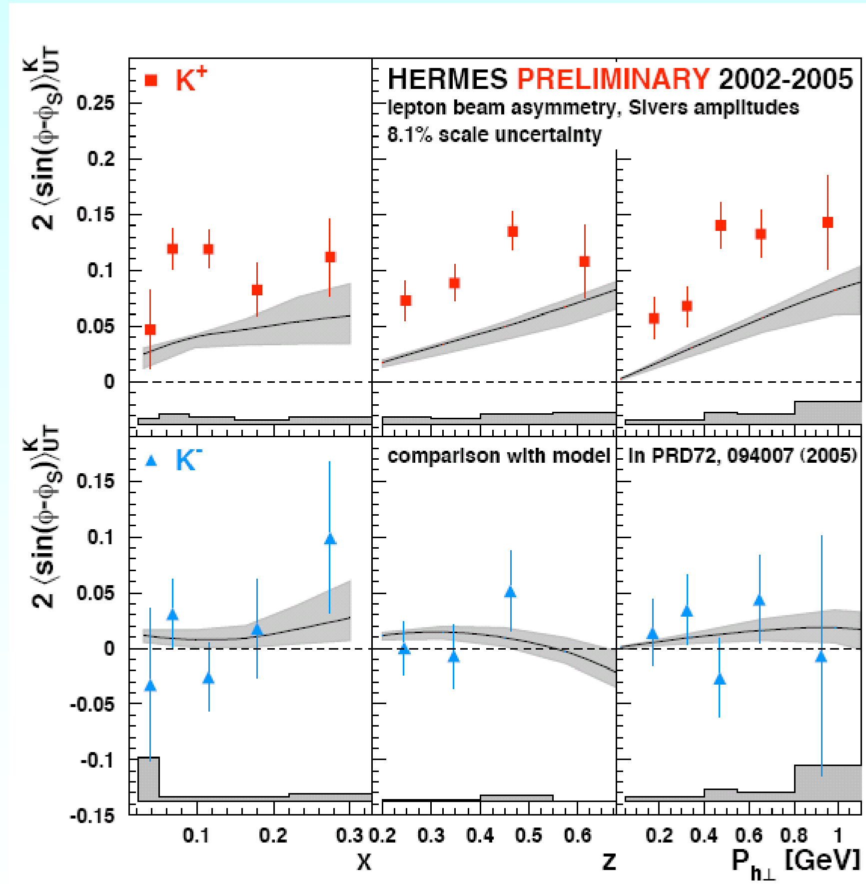


Sivers amplitudes vs. Anselmino's fit/predictions

[Anselmino et al., Phys. Rev. D72, 094007]

- using Gaussian widths for intrinsic p_T
- using Kretzer fragmentation functions

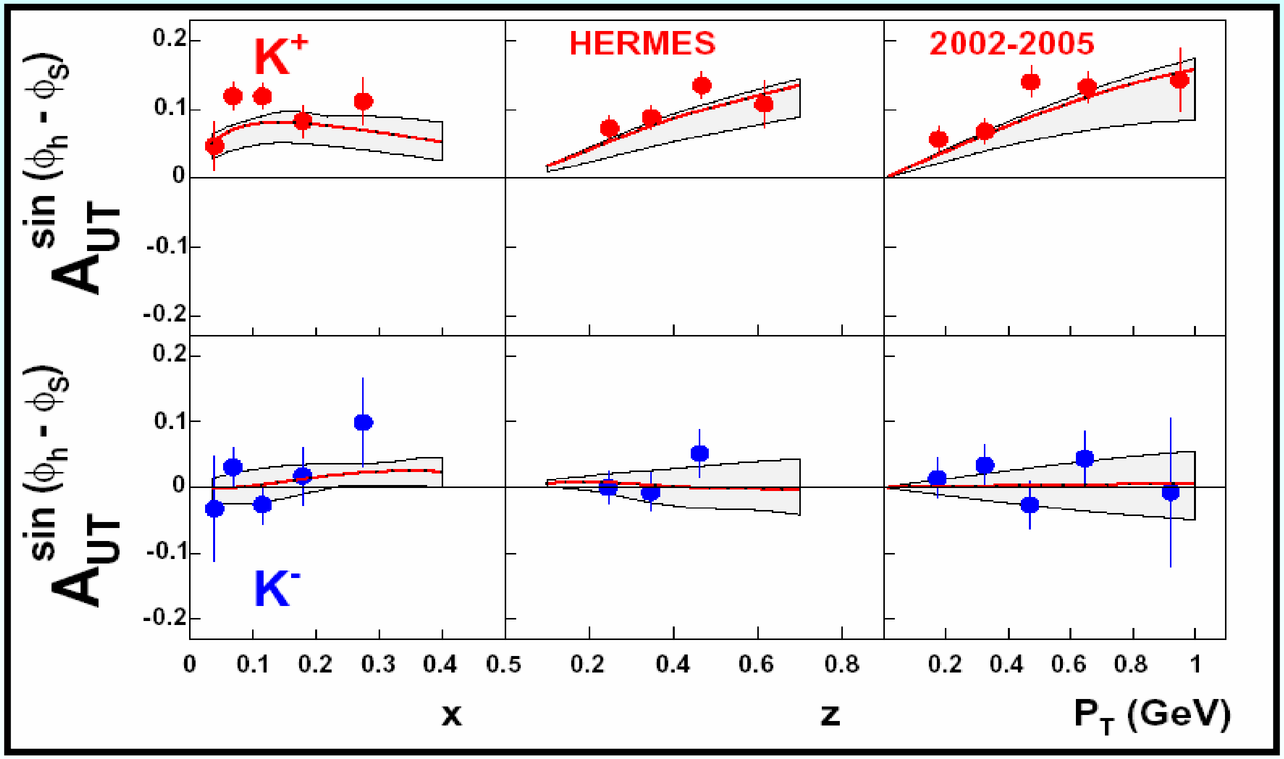




pions don't constrain sea quarks ⟹ predictions for K+ fail to reproduce our data

… and using de Florian, Sassot, Stratmann fragmentation functions

[arXiv:hep-ph/0703242v1 22 Mar 2007]



(...from Anselmino's talk @

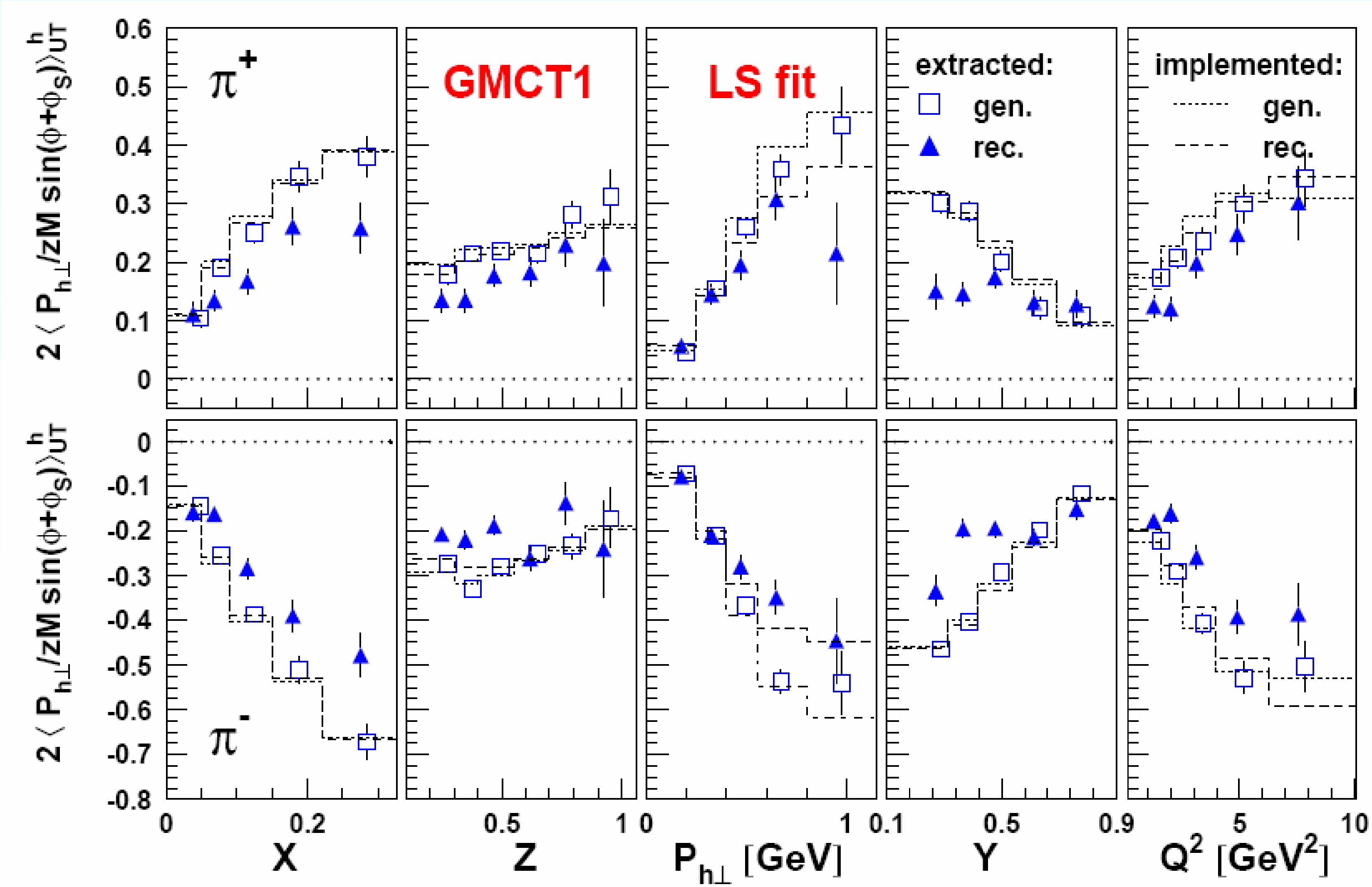
The 6th Circum-Pan-Pacific Symposium on High Energy Spin Physics
July 30 - August 2 2007
Vancouver BC)

The GMC_TRANS Monte Carlo generator

- physics generator for SIDIS pion production
- simulates Collins and Sivers effects
- uses *gaussian ansatz* for all TMD DFs and FFs.

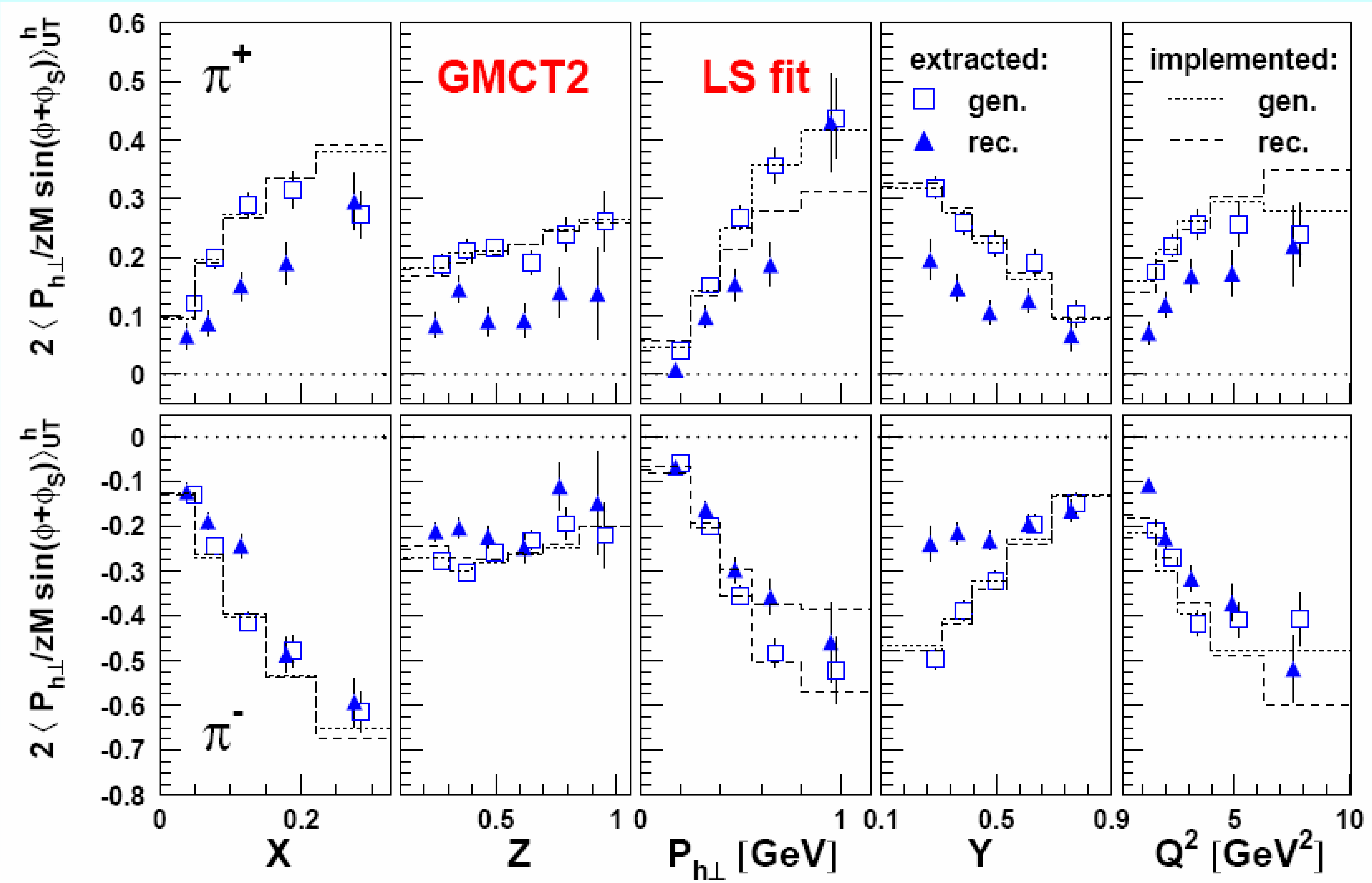
GMC_TRANS settings	
Version **GMCT1**	Version **GMCT2**
Distribution Functions $(q_{sea} = \bar{u}, \bar{d}, s, \bar{s})$	
$\delta u(x) = 0.7 \cdot \Delta u(x)$	$\delta u(x) = 0.7 \cdot \Delta u(x)$
$\delta d(x) = 0.7 \cdot \Delta d(x)$	$\delta d(x) = 0.7 \cdot \Delta d(x)$
$\delta q_{sea}(x) = 0.7 \cdot \Delta q_{sea}(x)$	$\delta q_{sea}(x) = 0.7 \cdot \Delta q_{sea}(x)$
$f_{1T}^{\perp u}(x) = -0.3 \cdot u(x)$	$f_{1T}^{\perp u}(x) = -0.6 \cdot u(x)$
$f_{1T}^{\perp d}(x) = 0.9 \cdot d(x)$	$f_{1T}^{\perp d}(x) = 1.05 \cdot d(x)$
$f_{1T}^{\perp q_{sea}}(x) = 0.0$	$f_{1T}^{\perp q_{sea}}(x) = 0.3 \cdot q_{sea}(x)$
Fragmentation Functions	
$H_{1,fav}^{\perp(1)}(z) = 0.65 \cdot D_{1,fav}(z)$	$H_{1,fav}^{\perp(1)}(z) = 0.65 \cdot D_{1,fav}(z)$
$H_{1,unfav}^{\perp(1)}(z) = -1.30 \cdot D_{1,unfav}(z)$	$H_{1,unfav}^{\perp(1)}(z) = -1.30 \cdot D_{1,unfav}(z)$
Transverse momentum mean values	
$\langle P_{h\perp}^2(z)\rangle = z^2\langle p_T^2\rangle + \langle K_T^2\rangle$	$\langle P_{h\perp}^2(z)\rangle = z^2\langle p_T^2\rangle + \langle K_T^2(z)\rangle$
$(\langle p_T^2\rangle = \langle K_T^2\rangle = 0.18\ \mathrm{GeV}^2$	$\langle K_T^2\rangle$ z-dependent
kinematic ranges	
$Q^2 > 1\ \mathrm{GeV}^2$	$Q^2 > 0.9\ \mathrm{GeV}^2$
$0.023 < x_{Bj} < 0.4$	$0.02 < x_{Bj} < 0.5$
$y < 0.85$	$y < 0.99$
$W^2 > 10\ \mathrm{GeV}^2$	$W^2 > 4\ \mathrm{GeV}^2$
$z > 0.2$	$z > 0.18$

$P_{h\perp}$-weighted Collins moments (GMCT1)



Huge acceptance effects at MC level

$P_{h\perp}$-weighted Collins moments (GMCT2)



…even worse with the new GMC_TRANS version