Single-spin asymmetries in SIDIS off transversely polarized protons at HERMES

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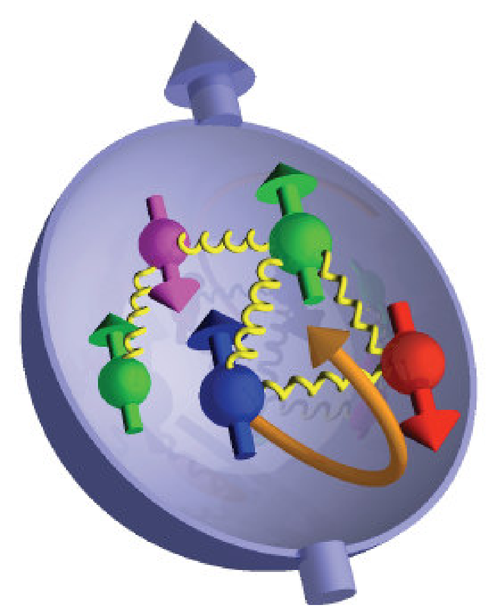
The nucleon spin structure



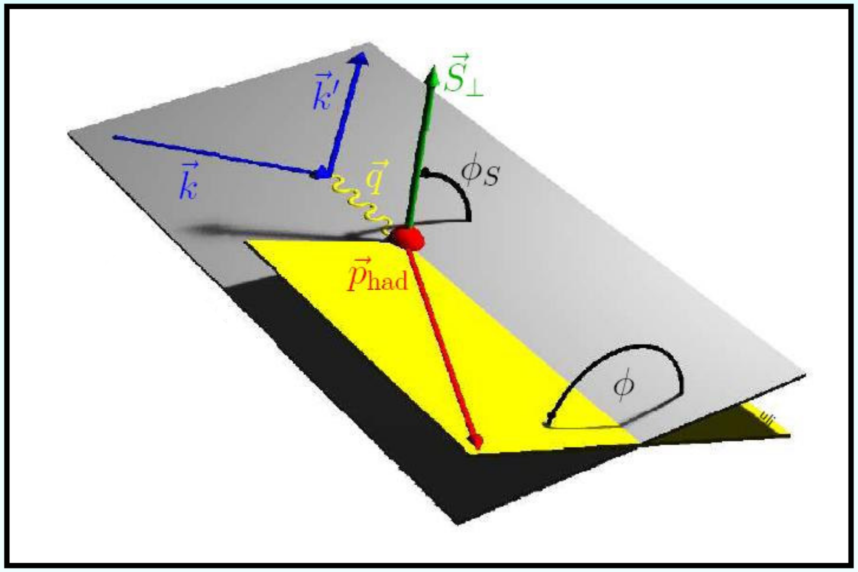
The nucleon spin structure

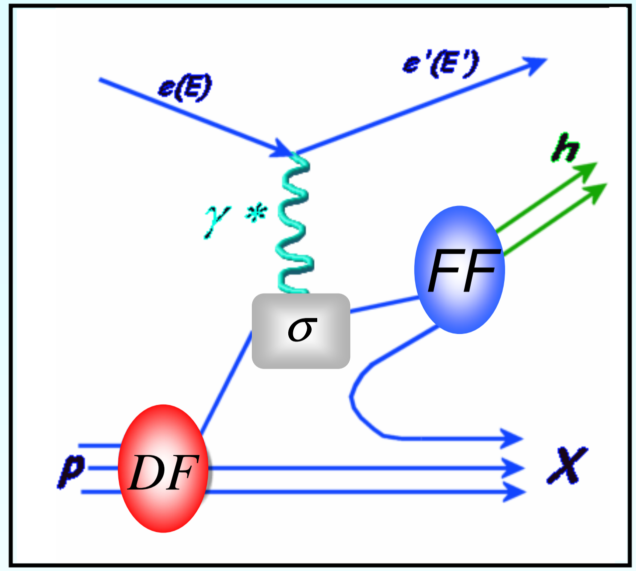
		quark		
		U	**L**	**T**
nucleon	**U**	f_1		
	L		g_1 -	
	T			h_1 -

The nucleon spin structure

		quark		
		U	L	T
nucleon	U	f_1		$h_1^{\perp}$
	L		g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1 $h_{1T}^{\perp}$

Can be studied by measuring azimuthal asymmetries in SIDIS

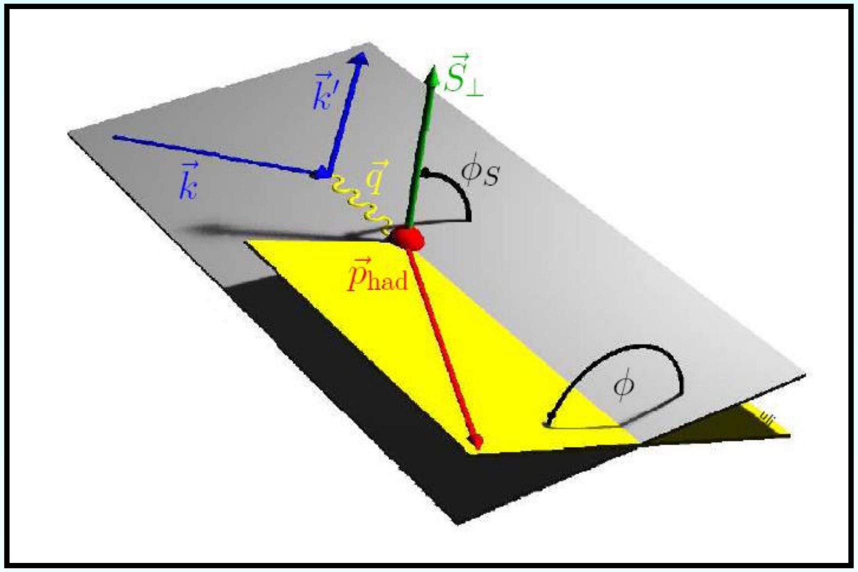


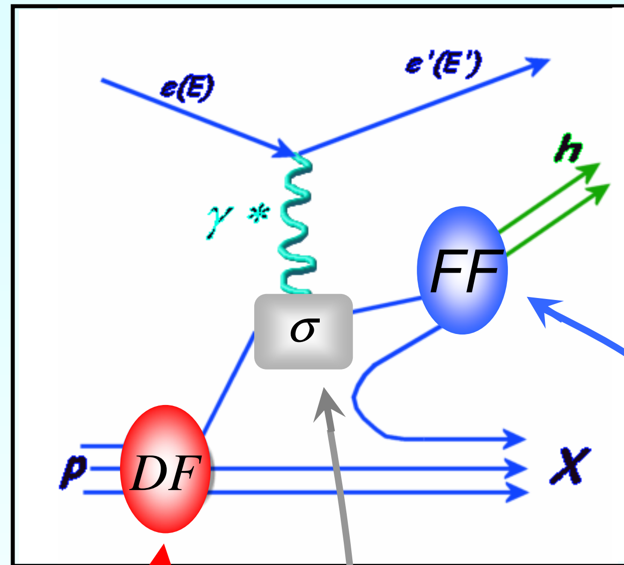


$$\sigma^{ep\rightarrow ehX}$$

↓

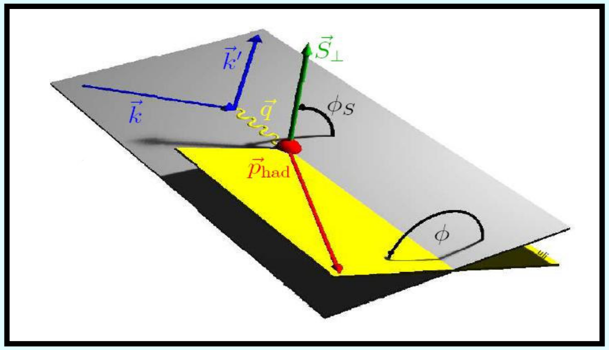
exhibits asymmetries in the azimuthal angles ϕ and ϕ_S

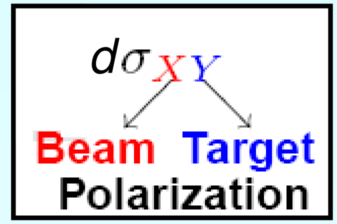




Factorization theorem: $$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

exhibits asymmetries in the azimuthal angles ϕ and ϕ_S





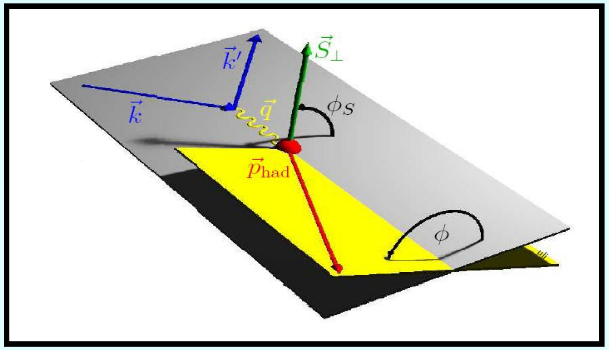
$$d\sigma = d\sigma_{UU}^{0} + \cos 2\phi \, d\sigma_{UU}^{1} + \frac{1}{Q}\cos\phi \, d\sigma_{UU}^{2} + \lambda_e \frac{1}{Q}\sin\phi \, d\sigma_{LU}^{3}$$

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

$$+ S_T \Big\{ \sin(\phi - \phi_S) \; d\sigma_{UT}^{8} + \sin(\phi + \phi_S) \; d\sigma_{UT}^{9} + \sin(3\phi - \phi_S) \; d\sigma_{UT}^{10}$$

$$+ \frac{1}{Q}\sin(2\phi - \phi_S) \; d\sigma_{UT}^{11} + \frac{1}{Q}\sin\phi_S d\sigma_{UT}^{12}$$

$$+ \lambda_e \left[\cos(\phi - \phi_S) \; d\sigma_{LT}^{13} + \frac{1}{Q}\cos\phi_S d\sigma_{LT}^{14} + \frac{1}{Q}\cos(2\phi - \phi_S) d\sigma_{LT}^{15} \right] \Big\}$$



8 leading-twist terms

$d\sigma_{XY}$

Beam Target Polarization

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

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

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

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

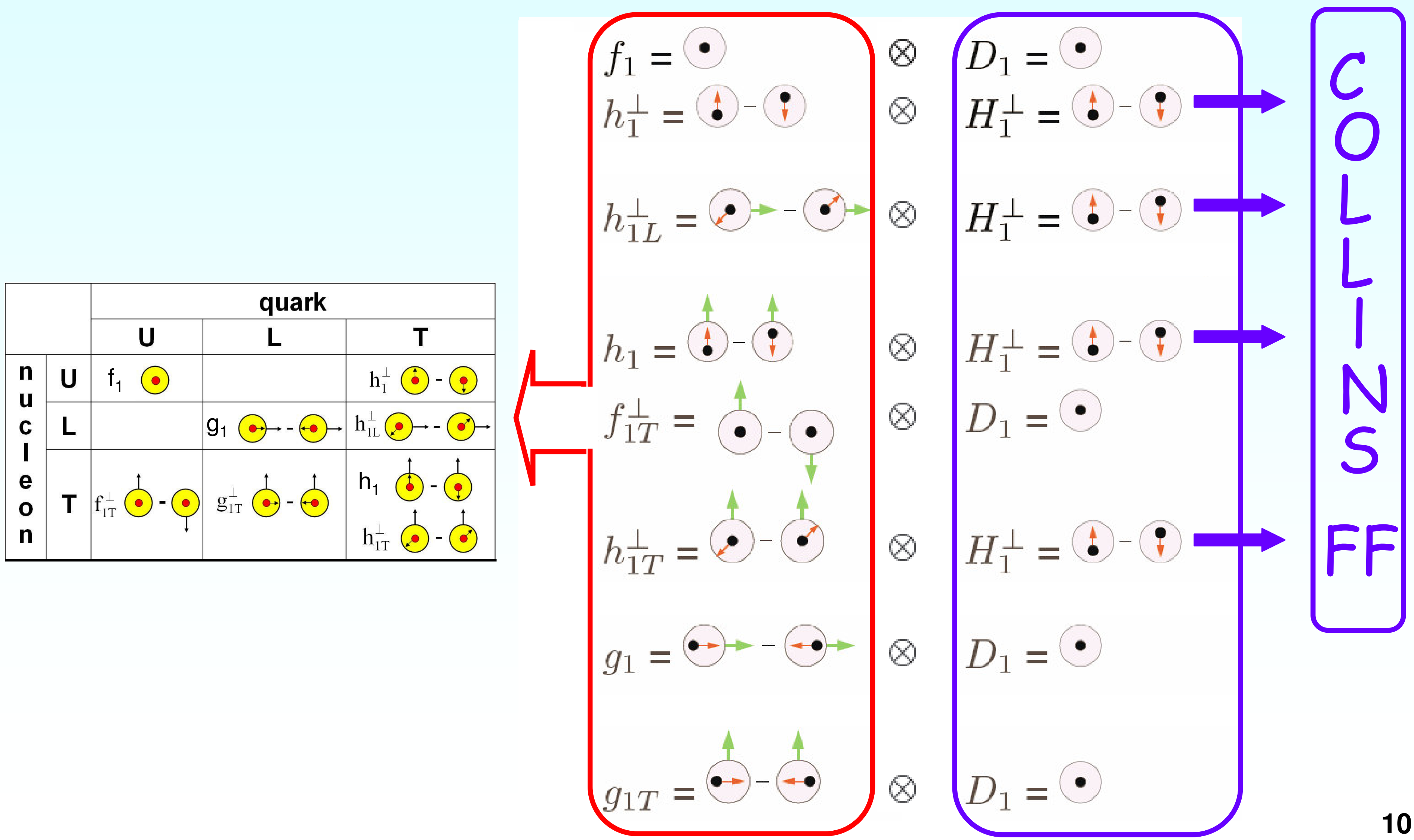
$$\left. +\lambda_e\left[\boxed{\cos(\phi-\phi_S)\ d\sigma^{13}_{LT}} + \frac{1}{Q}\cos\phi_S d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi-\phi_S) d\sigma^{15}_{LT}\right]\right\}$$

$$\sigma_{\text{BT}}^{ep\rightarrow ehX} = \sum_q \text{DF} \otimes \sigma^{eq\rightarrow eq} \otimes FF$$

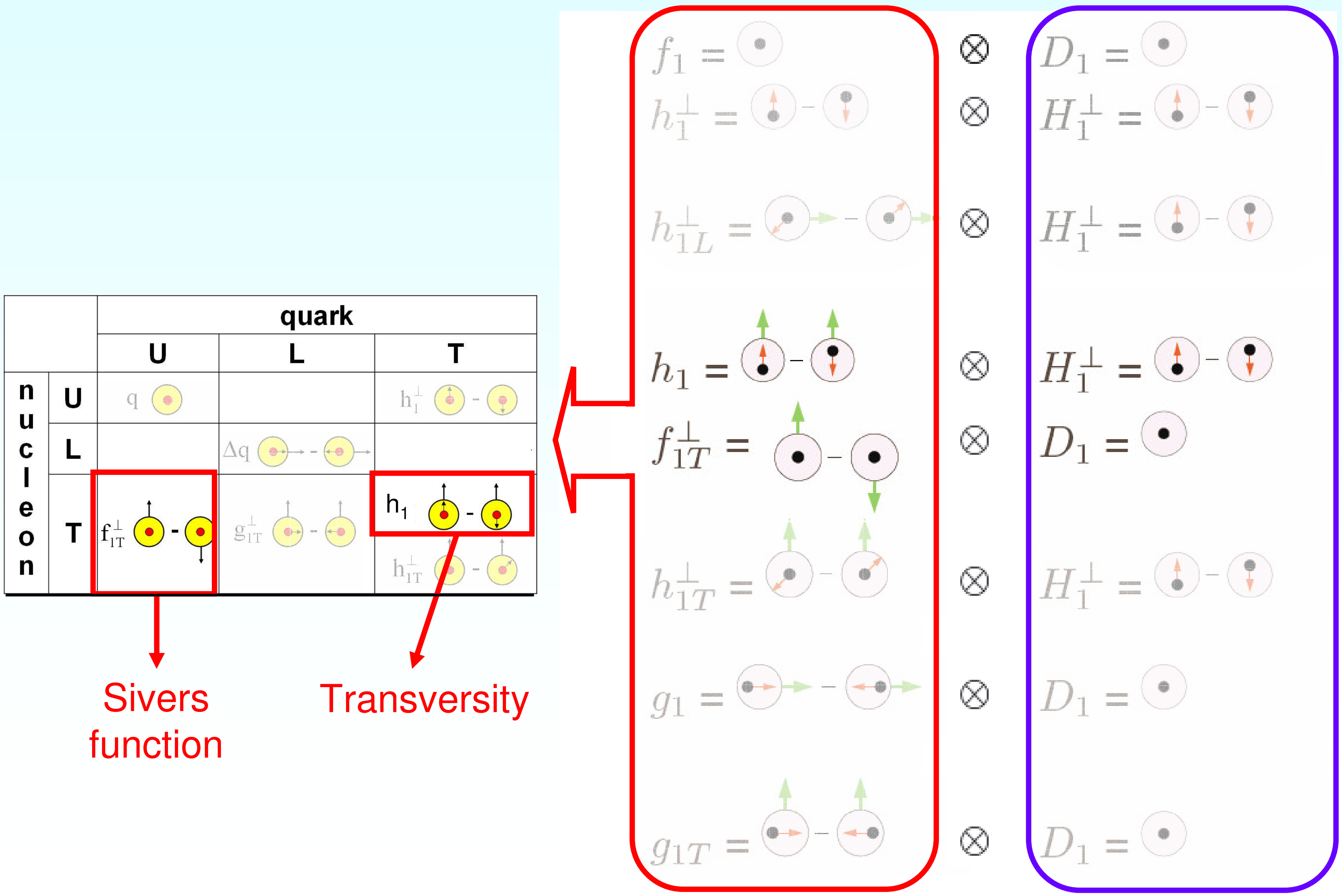
BT: **Beam pol.** **Target pol.**

	BT		DF		FF
1	UU	1	$f_1 =$	$\otimes$	$D_1 =$
2		$\cos(2\phi_h^l)$	$h_1^\perp =$	$\otimes$	$H_1^\perp =$
3	UL	$\sin(2\phi_h^l)$	$h_{1L}^\perp =$	$\otimes$	$H_1^\perp =$
4	UT	$\sin(\phi_h^l + \phi_S^l)$	$h_1 =$	$\otimes$	$H_1^\perp =$
5		$\sin(\phi_h^l - \phi_S^l)$	$f_{1T}^\perp =$	$\otimes$	$D_1 =$
6		$\sin(3\phi_h^l - \phi_S^l)$	$h_{1T}^\perp =$	$\otimes$	$H_1^\perp =$
7	LL	1	$g_1 =$	$\otimes$	$D_1 =$
8	LT	$\cos(\phi_h^l - \phi_S^l)$	$g_{1T} =$	$\otimes$	$D_1 =$

$$\sigma_{\mathbf{BT}}^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

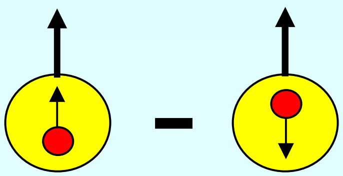


$$\sigma_{\mathbf{BT}}^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$



Transversity

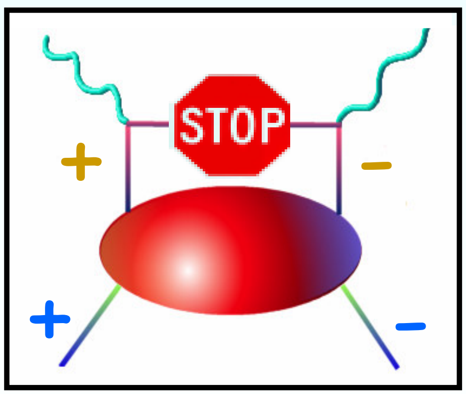
$$\delta q(x, Q^2) = q^{\uparrow} - q^{\downarrow}$$



Difference of probabilities to find quarks with spin aligned or anti-aligned to the nucleon transverse spin

Chiral-odd

requires spin flip of the quark



Not measurable in inclusive DIS

Unmeasured for long time!

Transversity

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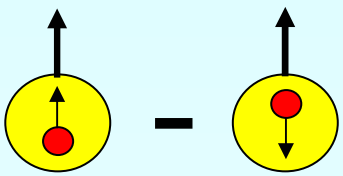

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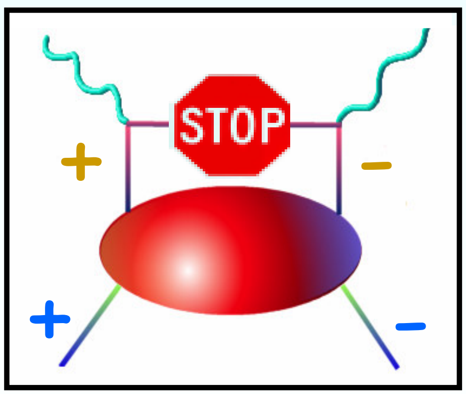

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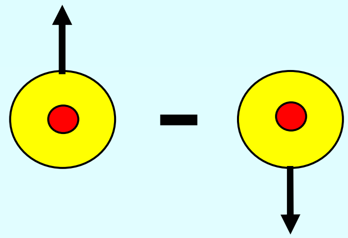
Sivers function

$f_{1T}^{\perp q}(x, p_T^2)$



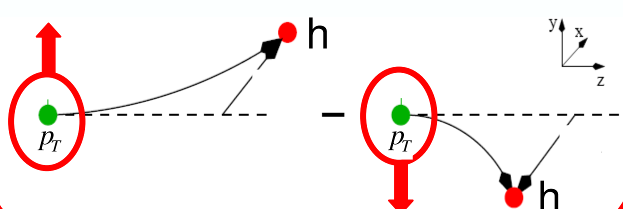
Chiral-even   T- odd

Probability to find unpolarized quarks with transverse momentum p_T in a transversely pol. nucleon.

describes spin-orbit correlation in the nucleon

Requires **non-zero orbital angular momentum!**

azimuthal asymmetries in the direction of the outgoing hadrons.



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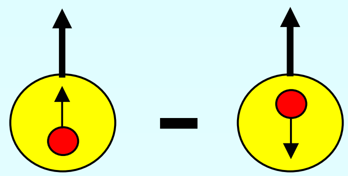
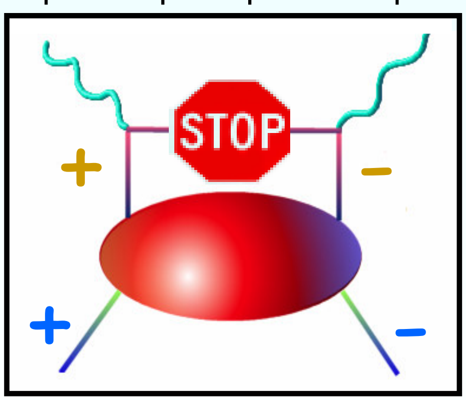
$$\delta q(x,Q^2) = q^\uparrow - q^\downarrow$$



Difference of probabilities to find quarks with spin aligned or anti-aligned to the nucleon transverse spin

Chiral-odd

requires spin flip of the quark



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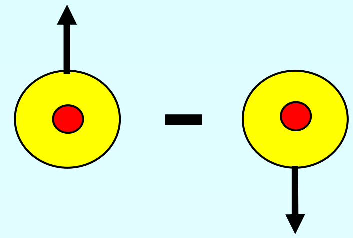

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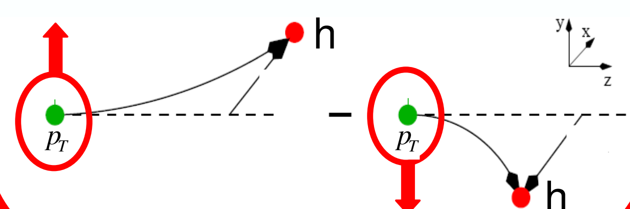
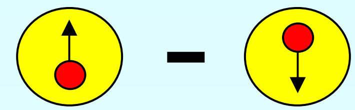


Collins function

$$H_1^\perp(z, k_T^2)$$



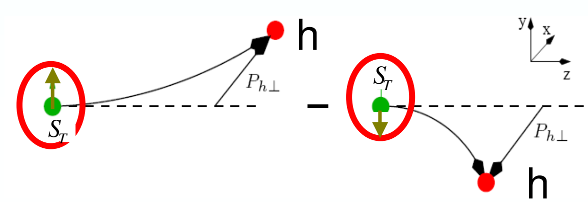
Chiral-odd T- odd

Correlation between transverse spin of the fragmenting quark and transverse momentum of the produced hadron

describes spin-orbit correlation in fragmentation

Analyzer of fragmenting quark's transv. polarization

azimuthal asymmetries in the direction of the outgoing hadrons.



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

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

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

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

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

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

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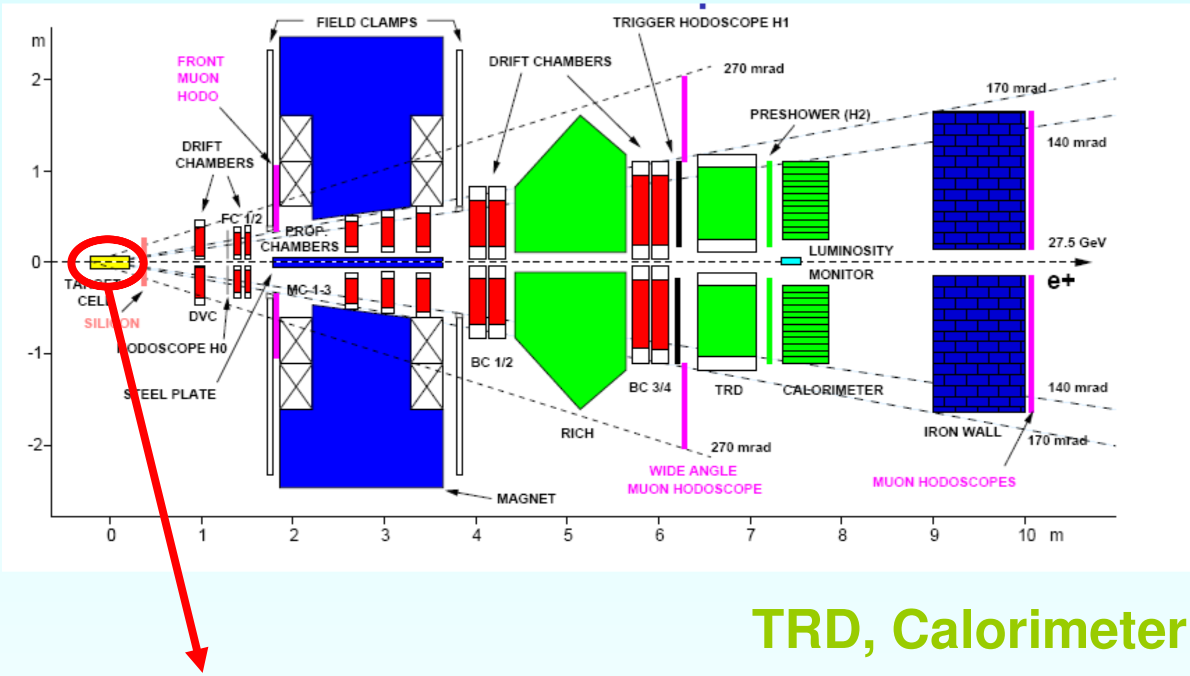
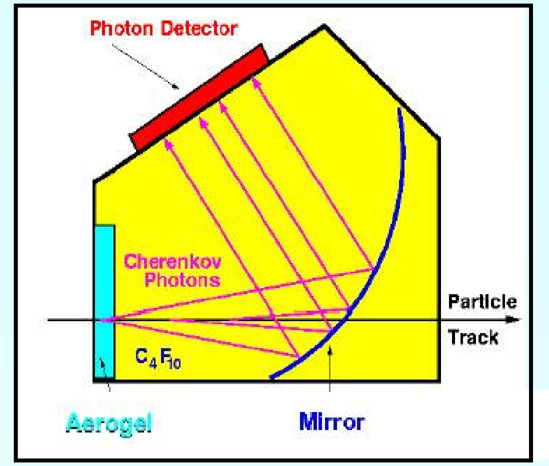
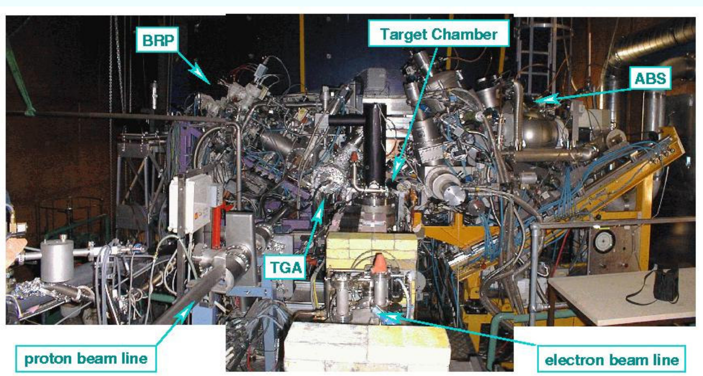
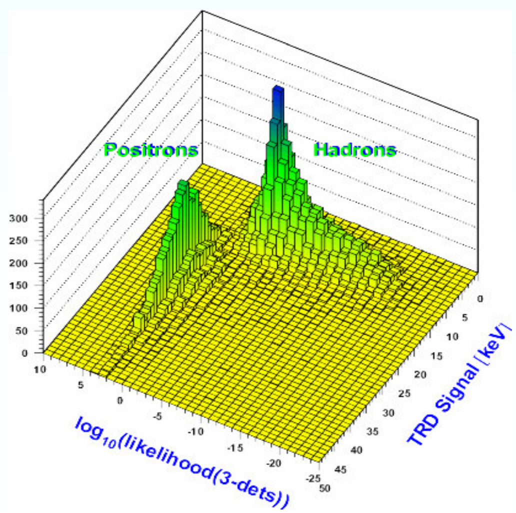




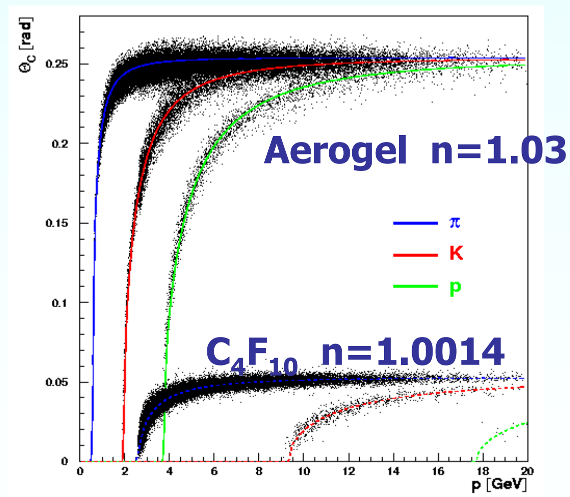


TRD, Calorimeter, preshower, RICH:

lepton-hadron > 98%



hadron separation



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 final hadronic 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		$0.2 < z < 0.7$

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

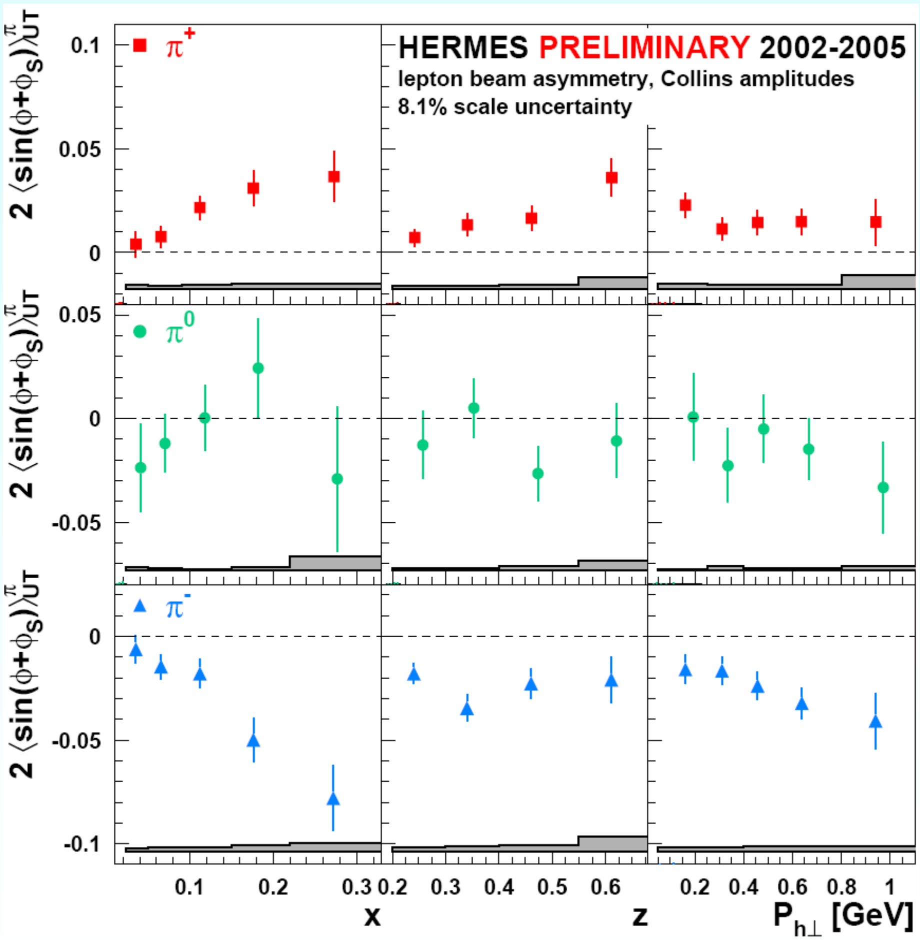
$$L = \prod_i (F_i)^{w_i}$$

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

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

Results and interpretation

Collins moments for pions (2002-2005)



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

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

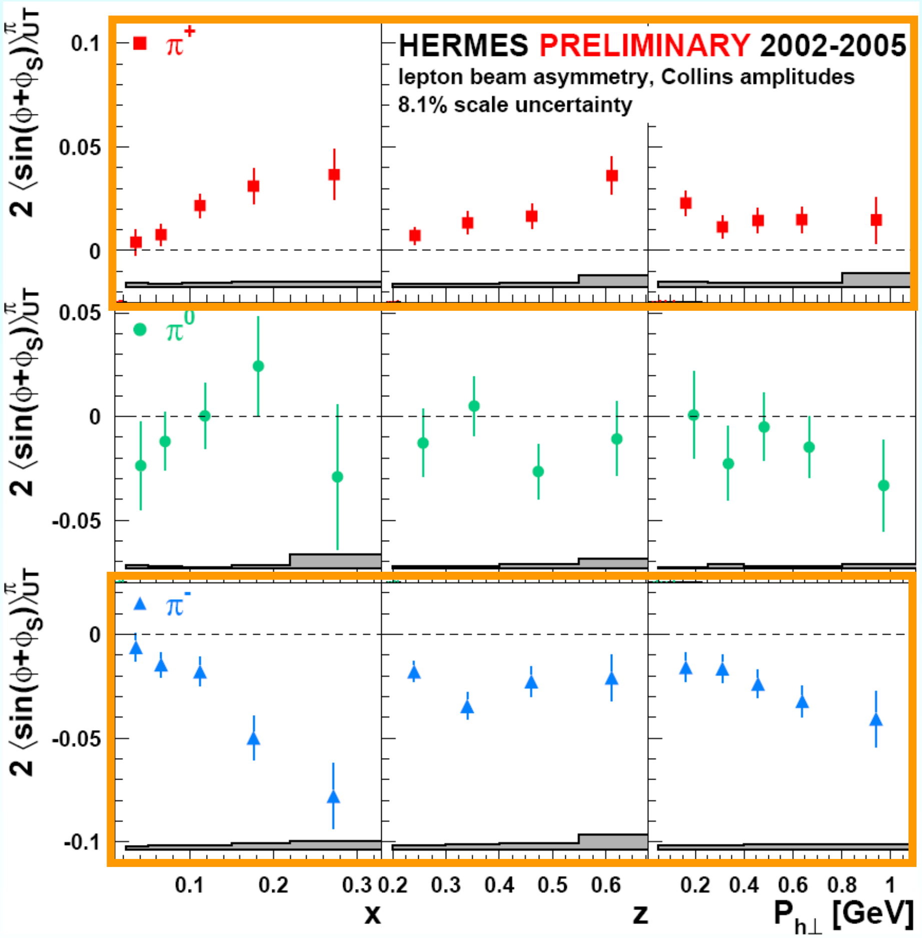
the large negative π^- amplitude suggests disfavored Collins function with opposite sign:

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

→ measurement at e^+e^- collider machines

$$\propto I[h_1(x) H_1^{\perp q}(z)]$$

Collins moments for pions (2002-2005)



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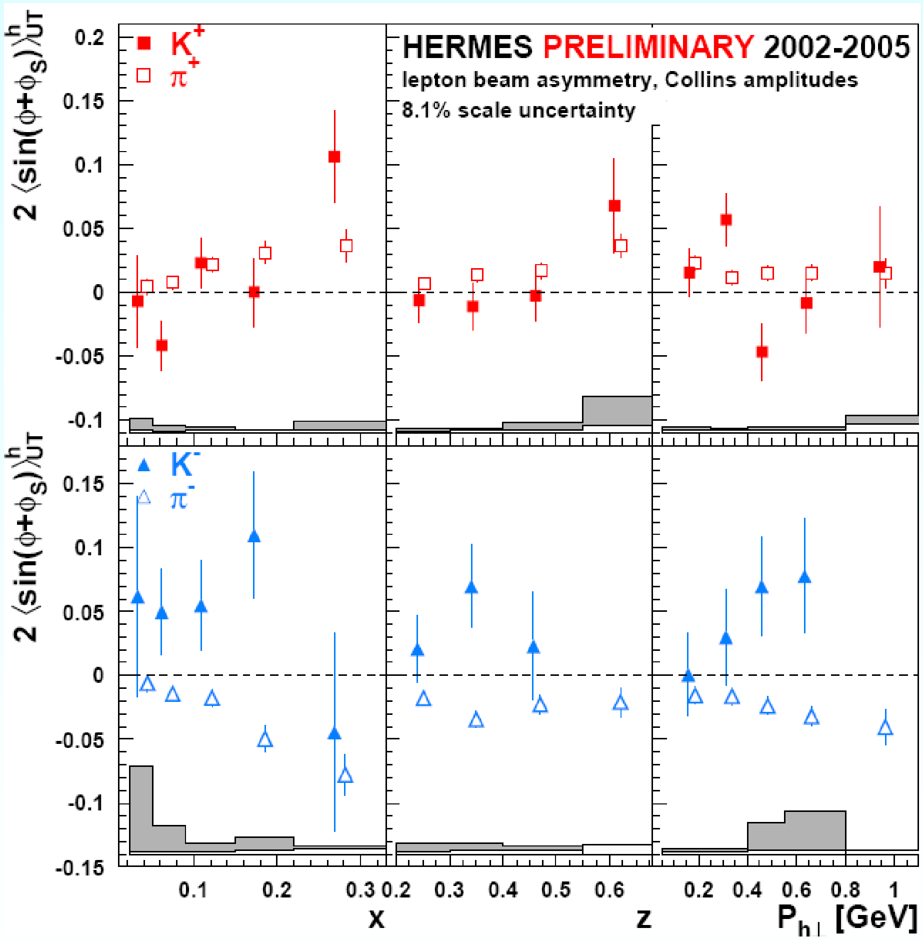
→ measurement at e^+e^- collider machines

$$\propto I[h_1(x) H_1^{\perp q}(z)] \neq 0$$

Transversity & Collins FF ≠ 0

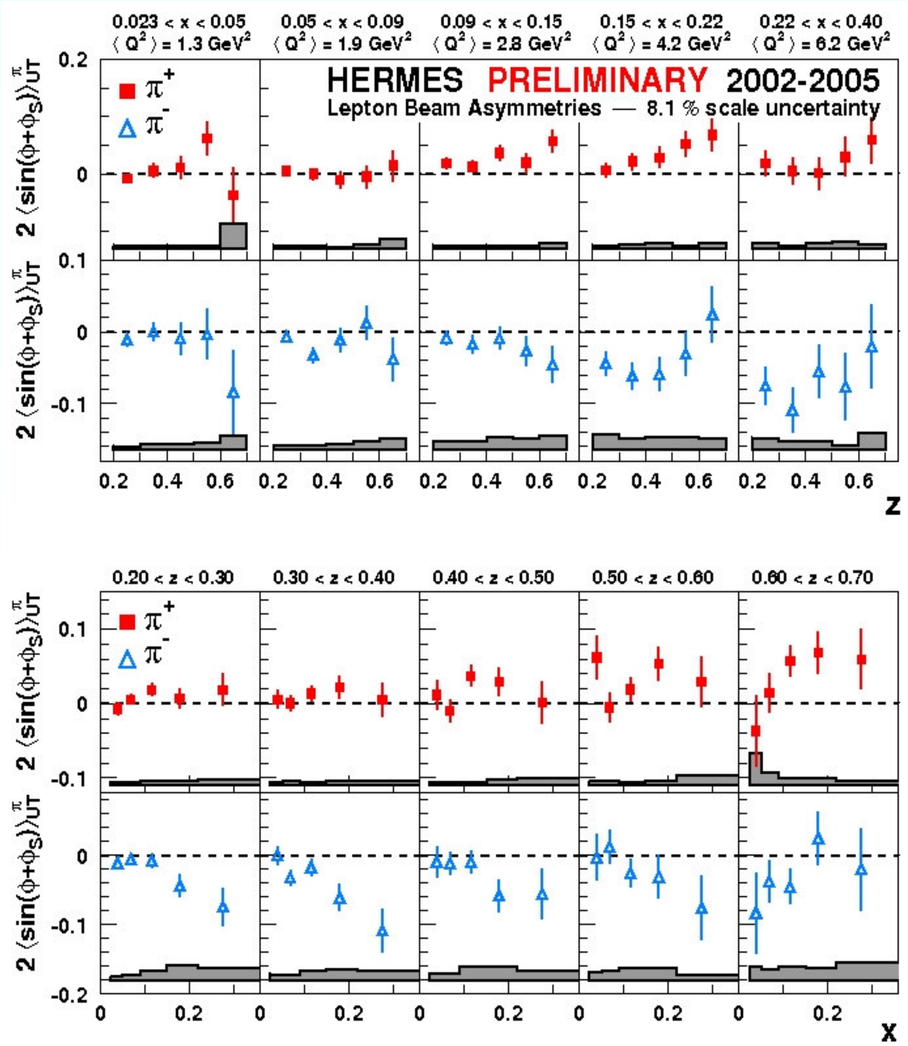
Collins moments: Pion-kaon comparison



- 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)

2-D Collins moments for $\pi^{\pm}$

X vs. Z



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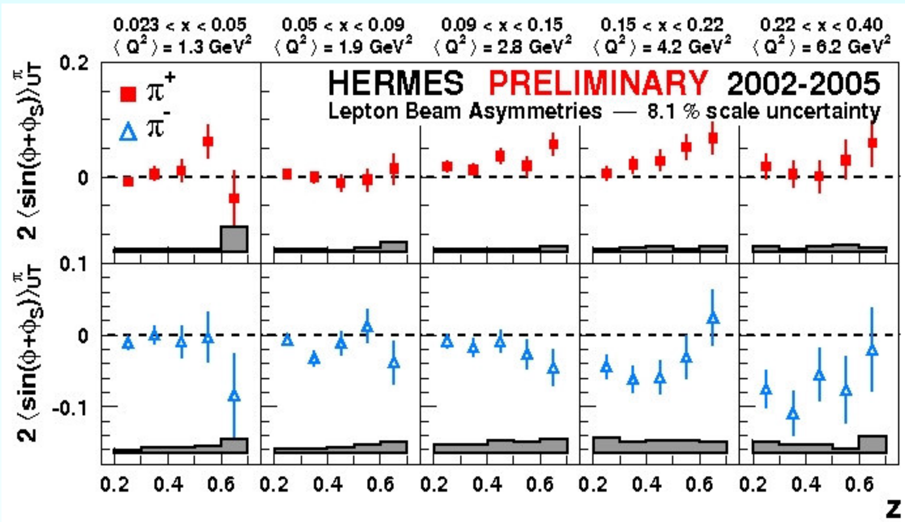
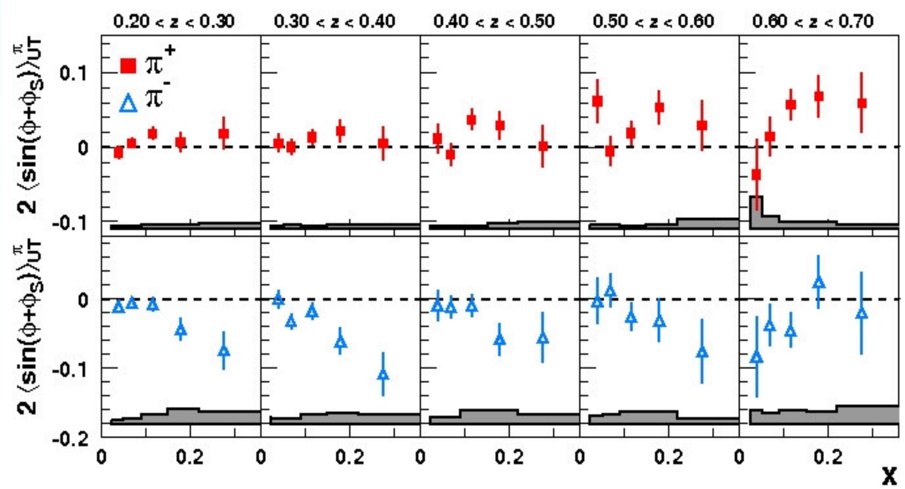
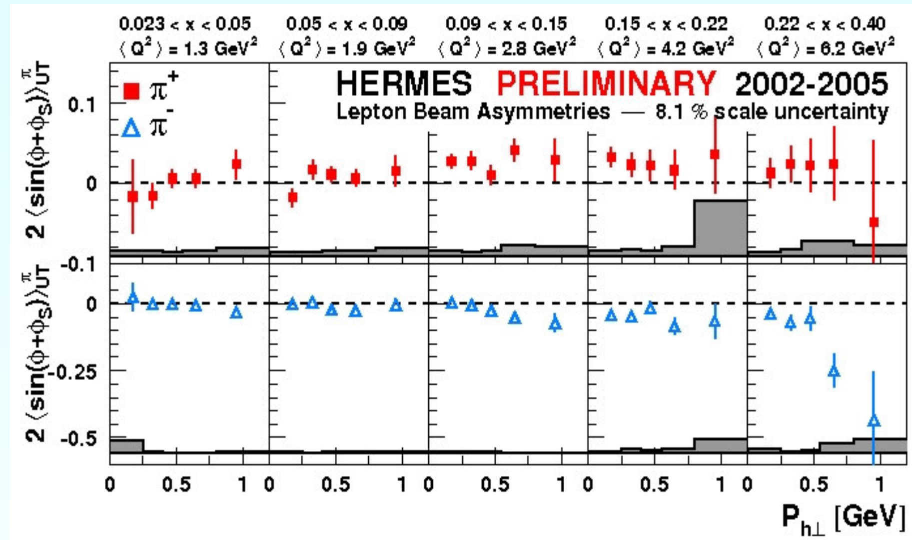
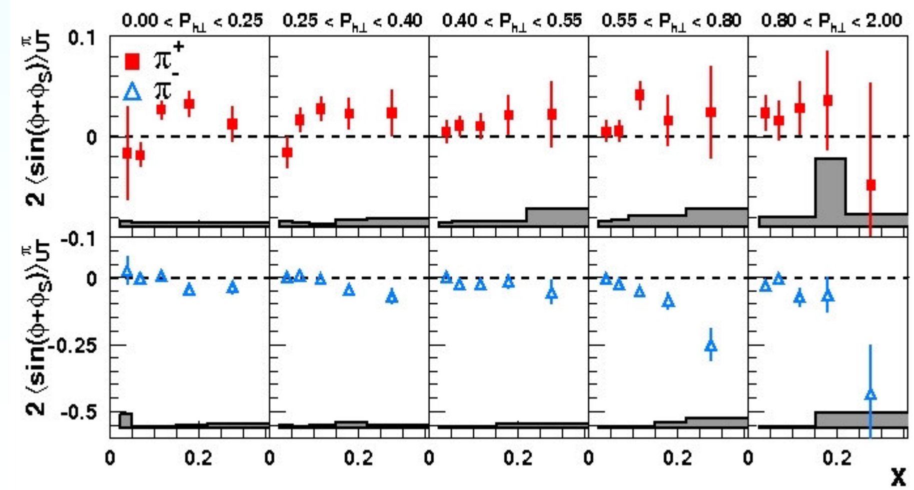


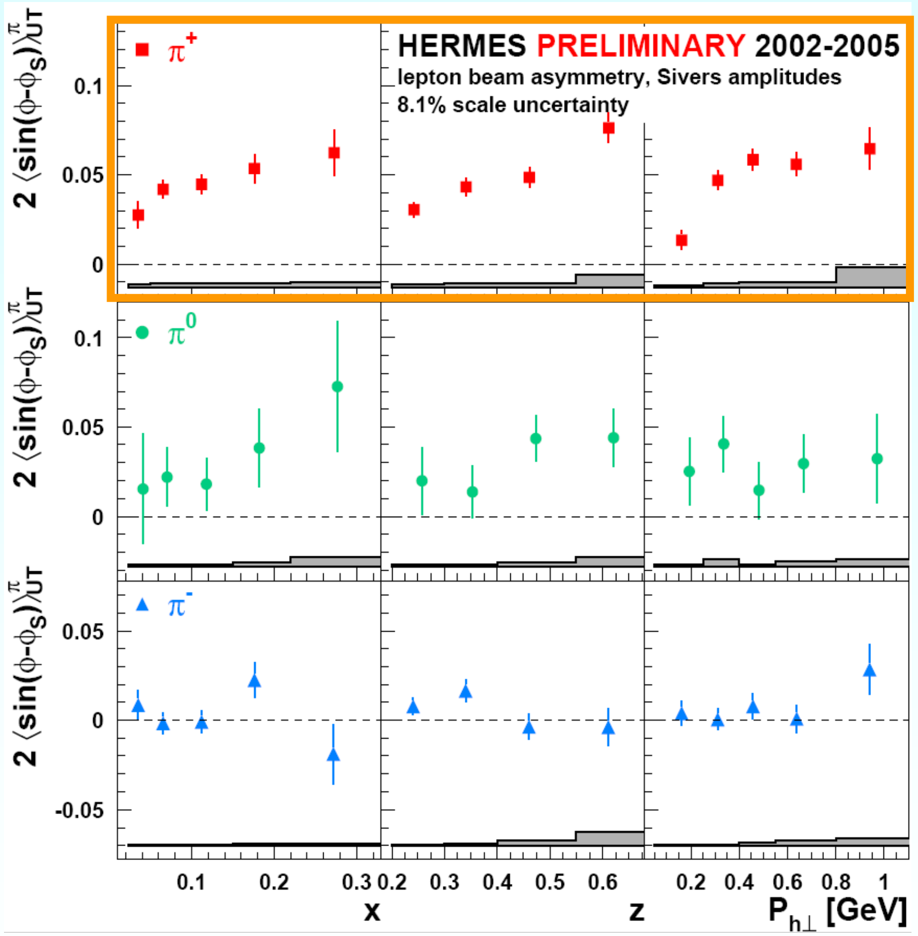


X vs. $P_{h\perp}$





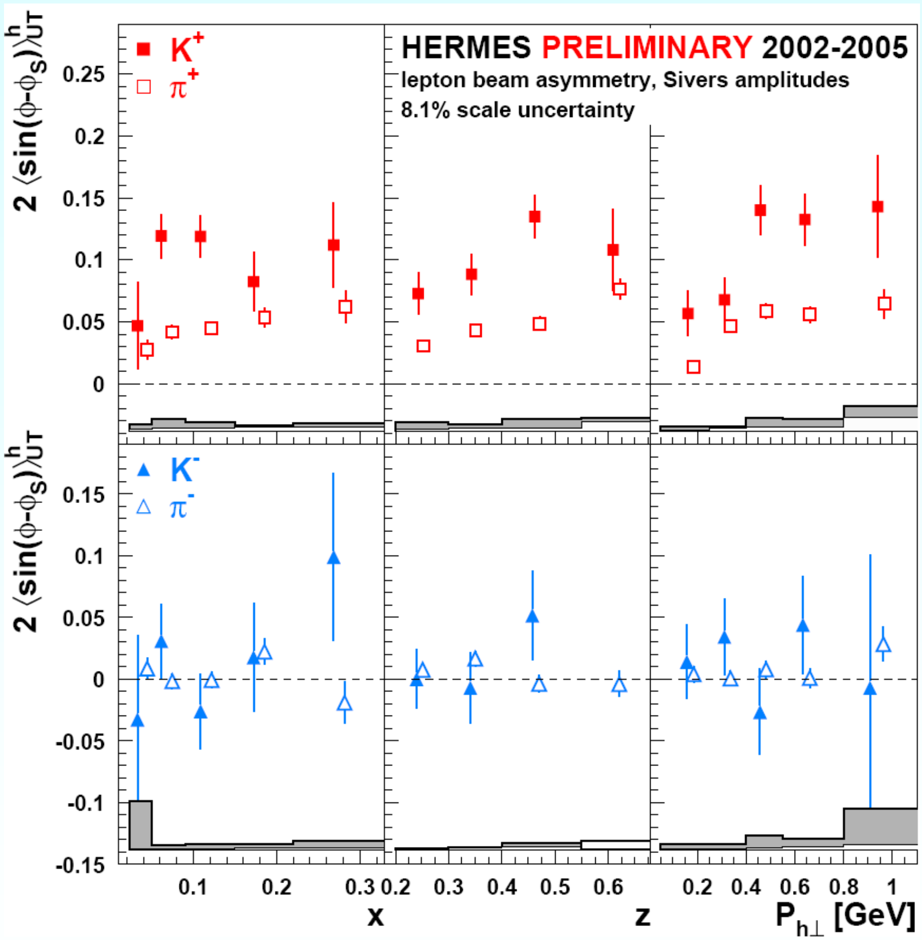
Sivers moments for pions (2002-2005)



- 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** ⇒ $L_q \neq 0$

Sivers moments: Pion-kaon comparison



- **K^+ amplitude is larger than for π^+** conflicts with usual expectations based on u-quark dominance

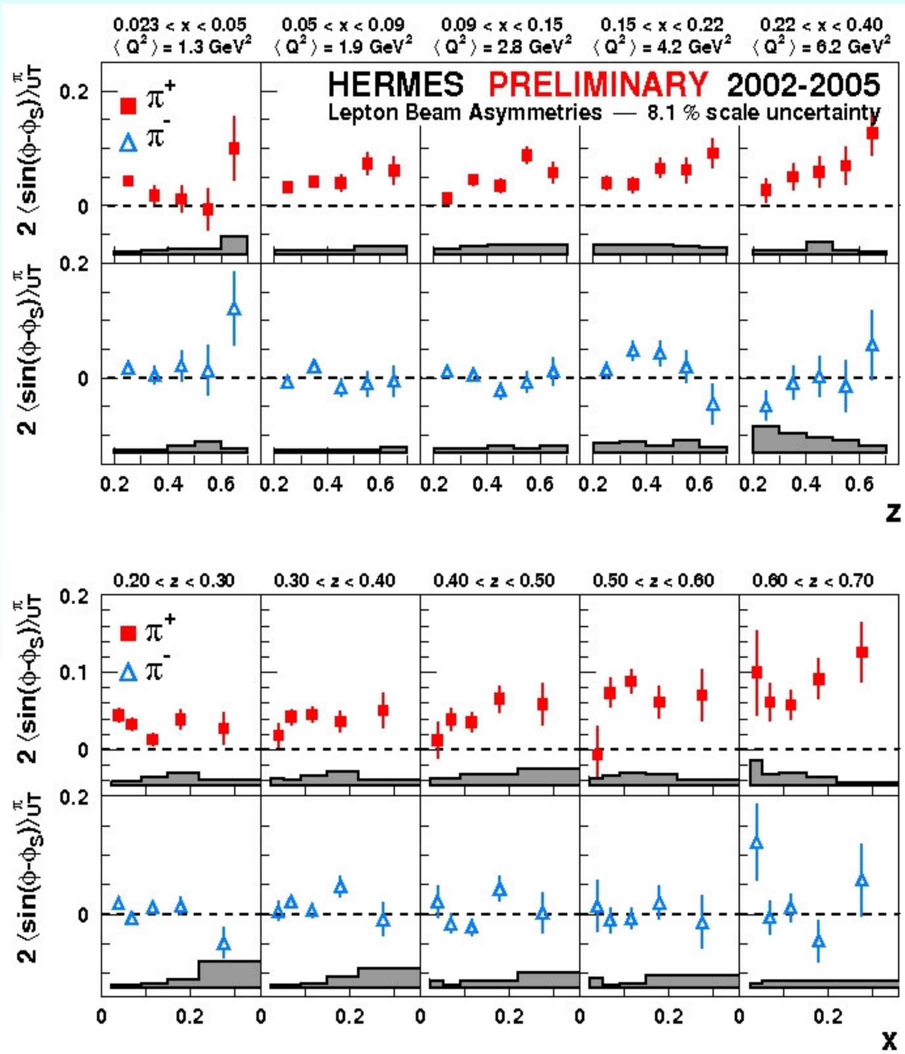
$$\pi^+ \equiv (u,\bar{d}) \qquad K^+ \equiv (u,\bar{s})$$

suggests substantial magnitudes of the Sivers function for the sea quarks

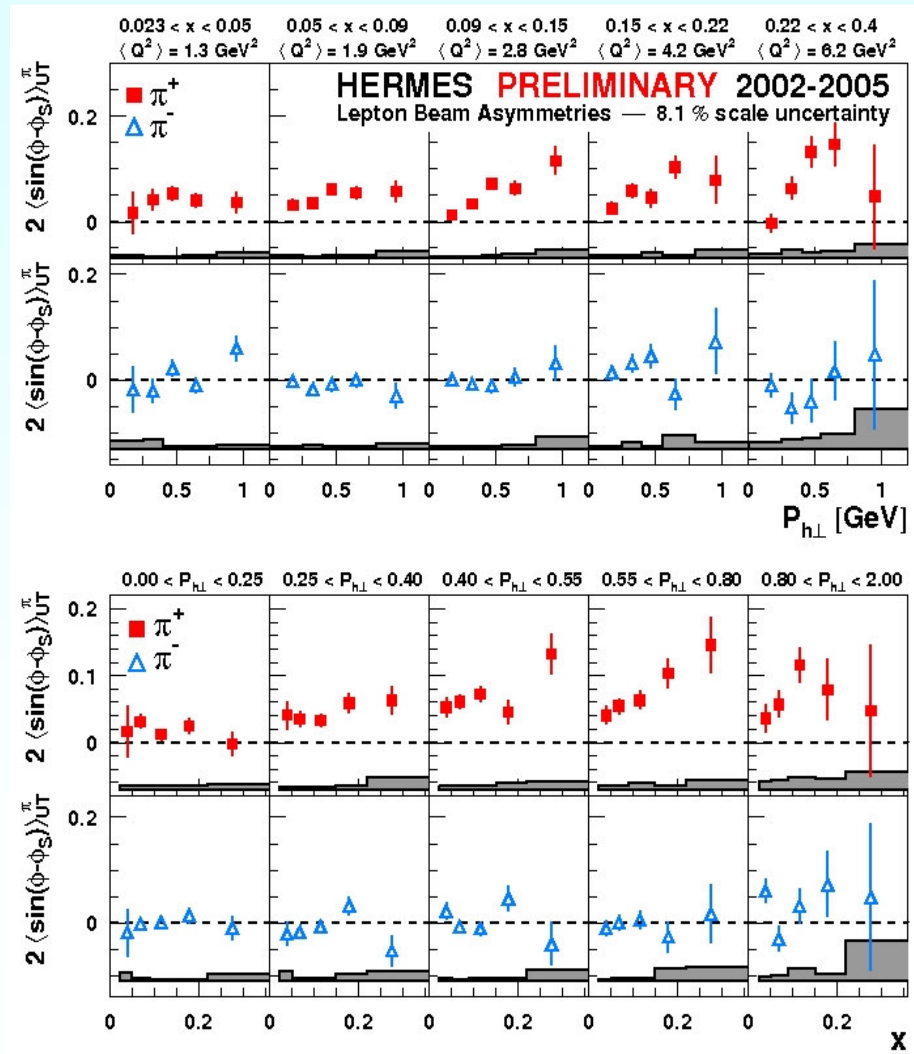
- Both K^- and π^- amplitudes are consistent with zero

2-D Sivers moments for $\pi^{\pm}$

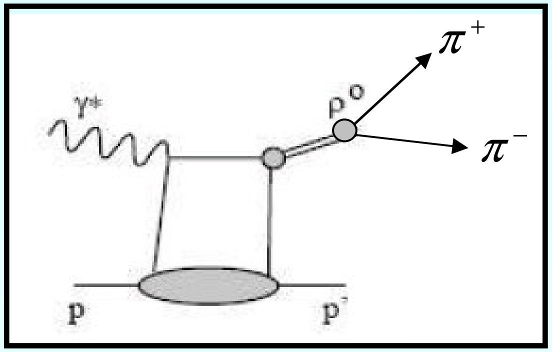
X vs. Z

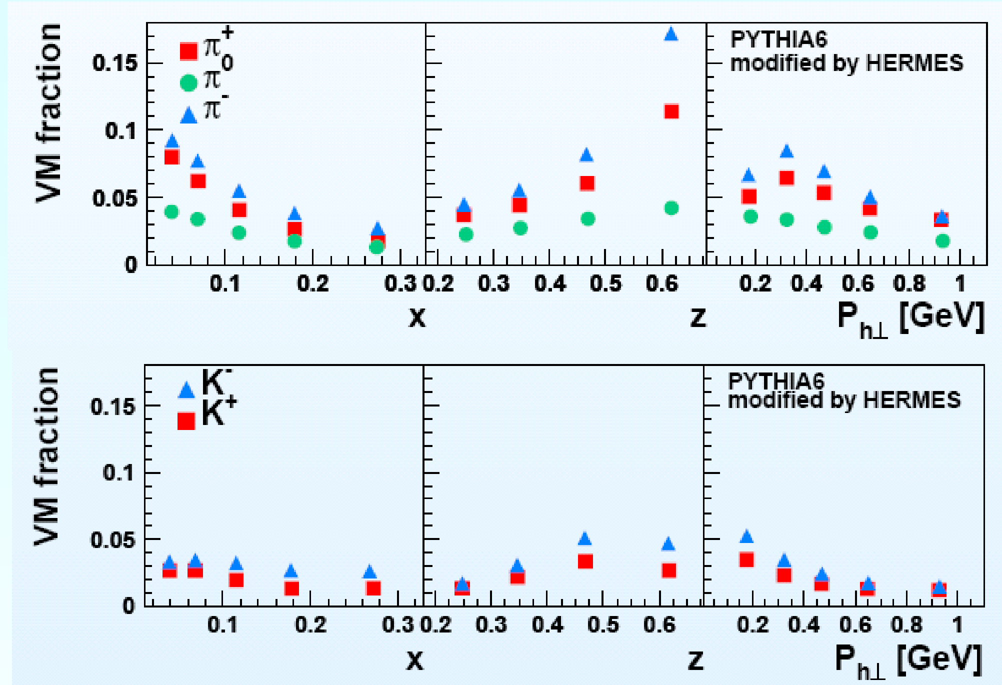


X vs. $P_{h\perp}$



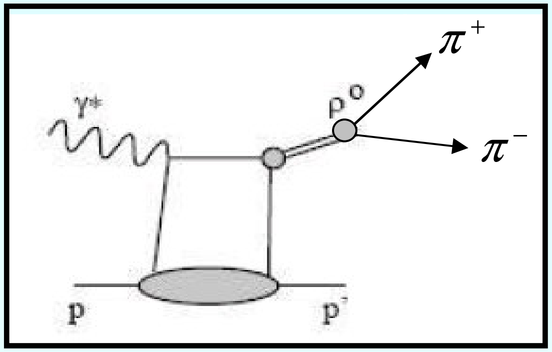
Exclusive Vector Meson contribution

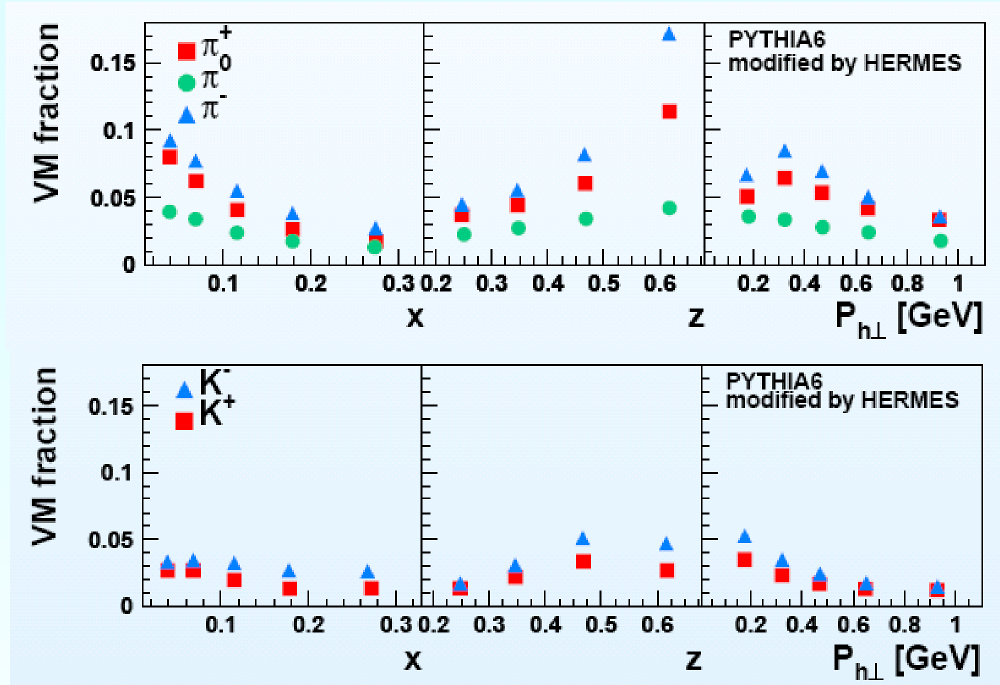




Contribution by decay of exclusively produced vector mesons is not negligible

Exclusive Vector Meson contribution





Contribution by decay of exclusively produced vector mesons is not negligible

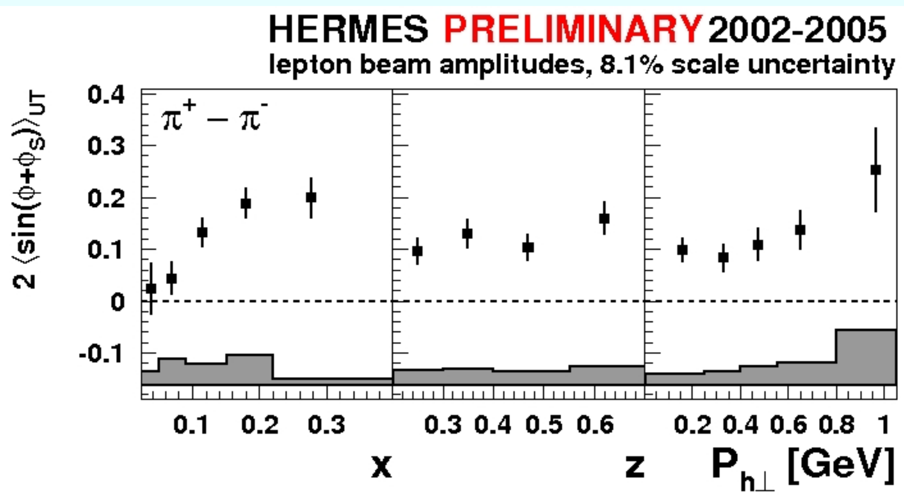
To evaluate the impact of this contribution on the extracted azimuthal moments, a new observable was regarded which does not experience contributions from the ρ^0: the **pion-difference target-spin asymmetry**

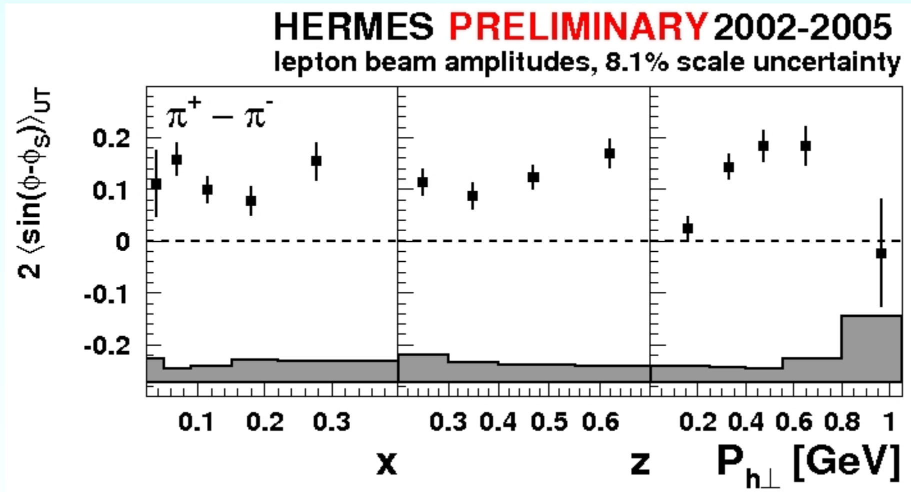
$$A_{UT}^{\pi^+-\pi^-}(\phi,\phi_S) \equiv \frac{1}{S_T}\frac{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})-(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})+(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}$$

Pion-difference asymmetry

$$A_{UT}^{\pi^+-\pi^-}(\phi,\phi_S) \equiv \frac{1}{S_T}\frac{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})-(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})+(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}$$

Contribution from exclusive ρ^0 largely cancels out





Significantly positive amplitudes are obtained as a function of $x, z, P_{h\perp}$.

the underlying (Collins and Sivers) asymmetry amplitudes are not generated by vector meson contribution.

Pion-difference asymmetry

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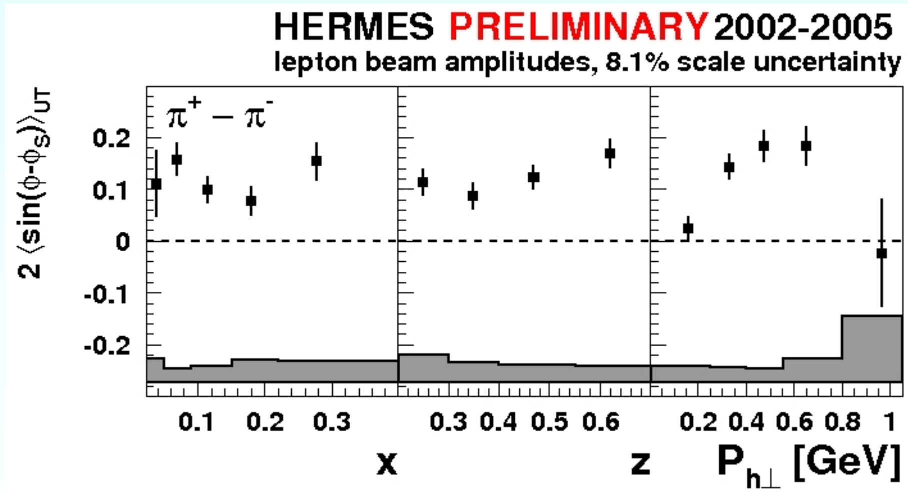
Contribution from exclusive ρ^0 largely cancels out

$$A_{\mathrm{UT}}^{\pi^+-\pi^-} = -\frac{4f_{1T}^{\perp,u_v}-f_{1T}^{\perp,d_v}}{4f_1^{u_v}-f_1^{d_v}}$$

(assuming charge-conjugation and isospin symmetry amongst the pion fragmentation functions)



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the underlying (Collins and Sivers) asymmetry amplitudes are not generated by vector meson contribution.

$$A_{UT}^{\sin(\phi+\phi_S)} \propto h_1(x) \otimes H_1^{\perp q}(z)$$

(H)

$lp \to l' hX$

(D)

$ld \to l' hX$

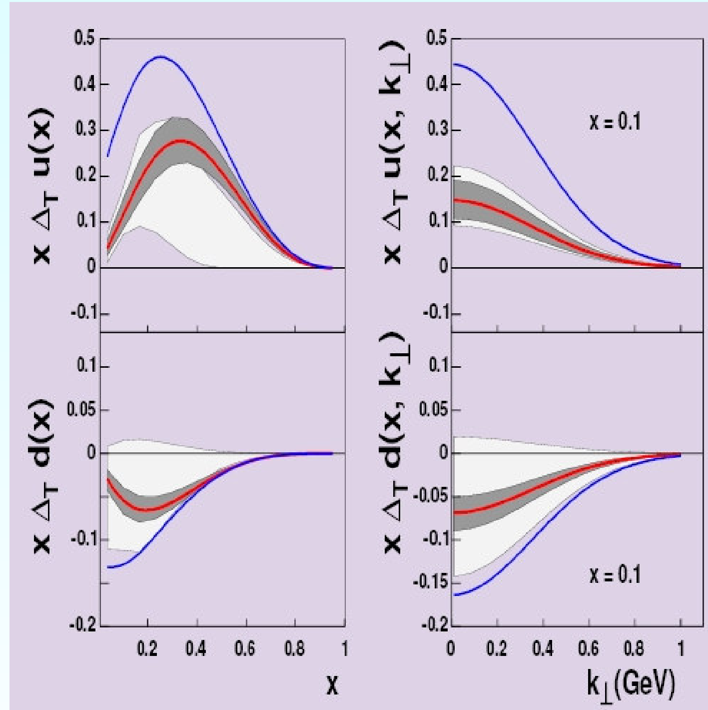
First extraction of transversity distribution

$$A_{UT}^{\sin(\phi+\phi_S)} \propto h_1(x) \otimes H_1^{\perp q}(z)$$

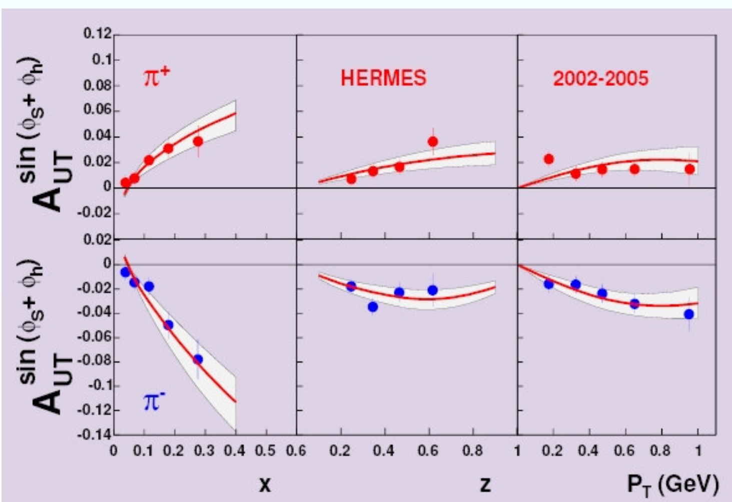
hermes (H) $lp \rightarrow l'hX$

COMPASS (D) $ld \rightarrow l'hX$

BELLE



A. Prokudin at Transversity 2008

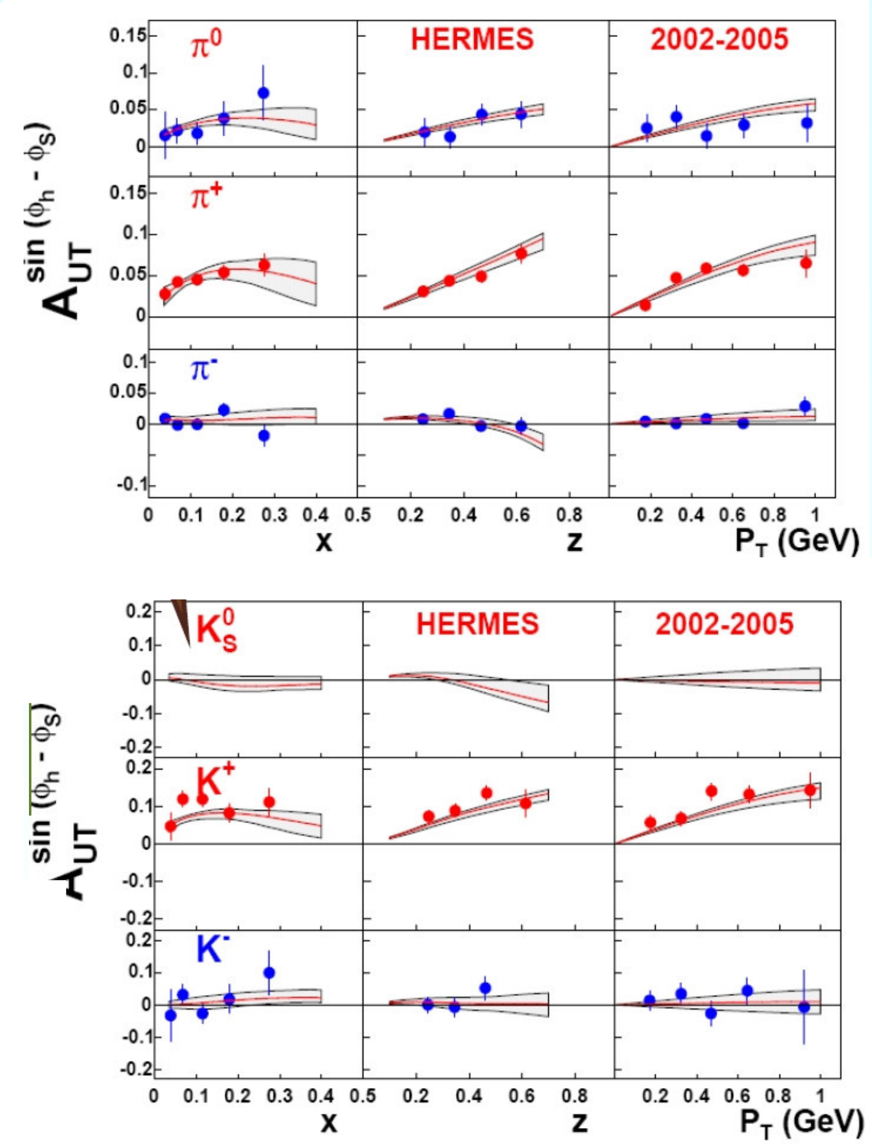


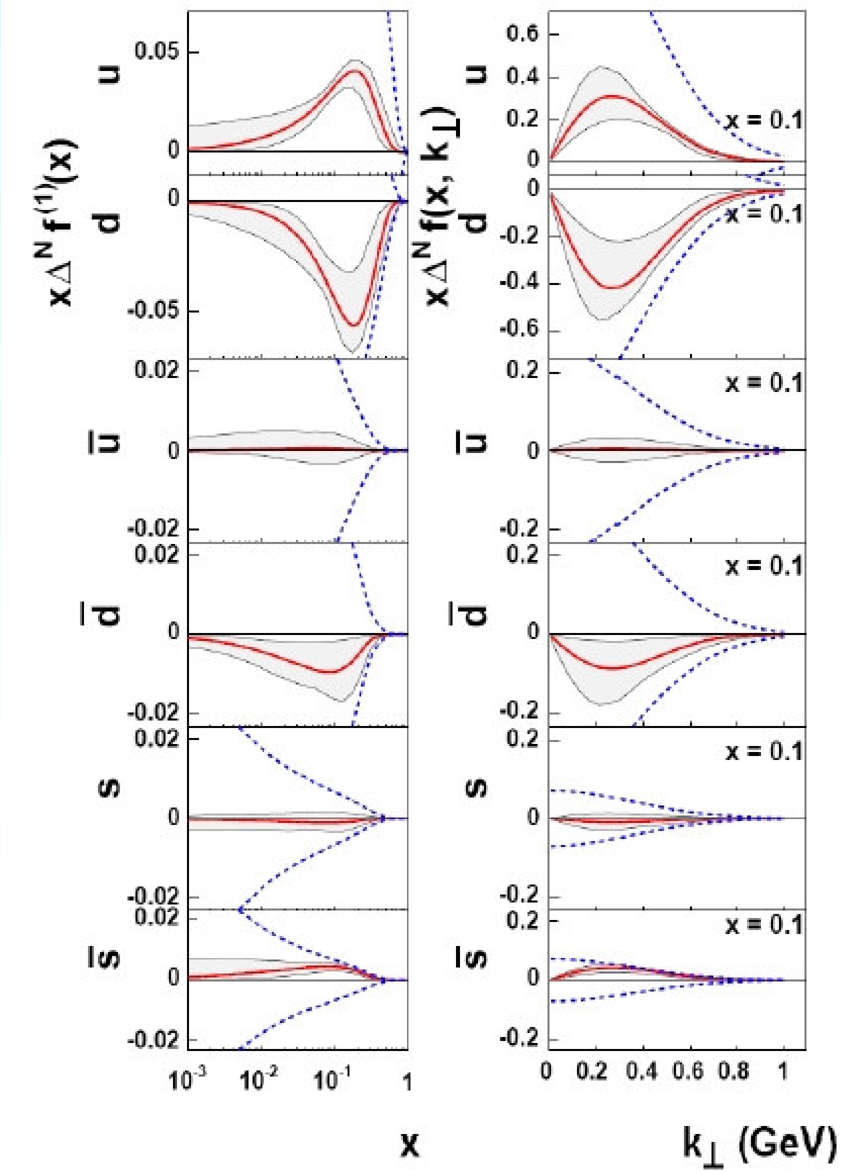
Consistent picture

Also with new proton
data from COMPASS

(based on Gaussian ansatz)

Extraction of Sivers function

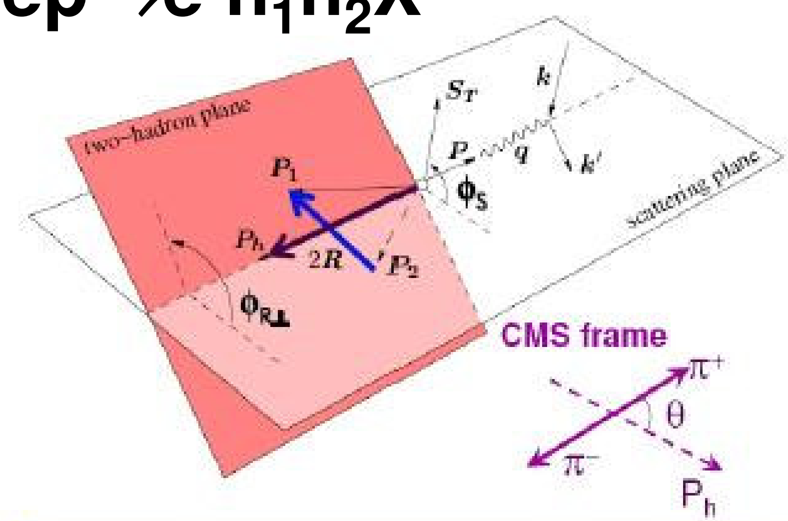




E. Boglione at Transversity 2008

An alternative way to access transversity: the di-hadron SSA

$ep \to e'h_1h_2X$



$$\sigma_{UT} \propto S_T \sin\theta \sin(\phi_{R\perp} + \phi_S) \sum_q e_q^2 \, h_1 H_{1,q}^{\triangleleft}$$

Interference FF

$$H_{1,q}^{\perp\triangleleft}(z, M_{\pi\pi}, \cos(\vartheta))$$

(does not depend on quark transv. momentum)

Chiral-odd T- odd

Correlation between transverse spin of the fragmenting quark and the relative orbital angular momentum of the hadron pair.

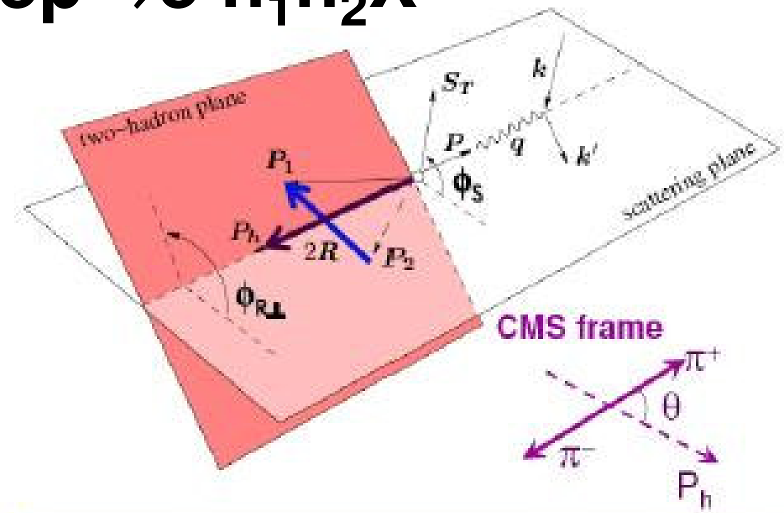
Describes Spin-orbit correlation in fragmentation

⇓

azimuthal asymmetries in the direction of the outgoing hadron pairs.

An alternative way to access transversity: the di-hadron SSA

$ep \rightarrow e' h_1 h_2 X$



$$\sigma_{UT} \propto S_T \sin\theta \sin(\phi_{R\perp} + \phi_S) \sum_q e_q^2 h_1 H_{1,q}^{\triangleleft}$$

Events are integrated over the transverse momentum of the 2-pion system. Therefore h_1 and IFF appear in the cross section in simple direct product

Interference FF

$$H_{1,q}^{\perp\triangleleft}(z, M_{\pi\pi}, \cos(\vartheta))$$

(does not depend on quark transv. momentum)

Chiral-odd T- odd

Correlation between transverse spin of the fragmenting quark and the relative orbital angular momentum of the hadron pair.

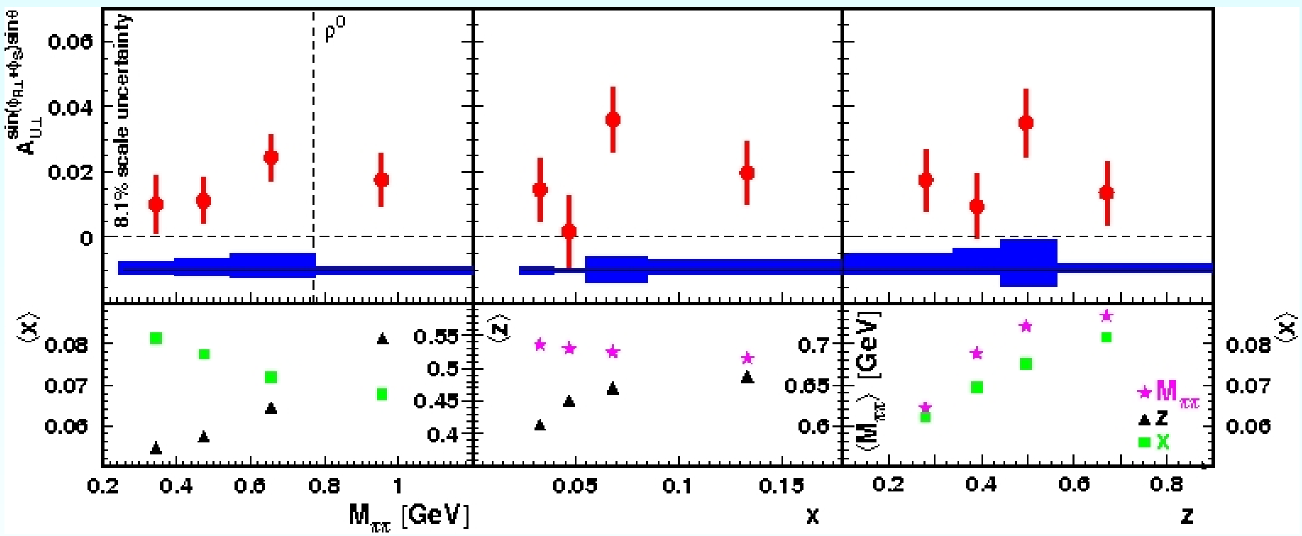
Describes Spin-orbit correlation in fragmentation

azimuthal asymmetries in the direction of the outgoing hadron pairs.

No convolution integral over transverse momentum involved!

Di-hadron amplitudes

- Independent way to access transversity
- No complications due to convolution integral
- ...but limited statistical power (v.r.t. 1-hadron SSAs)



$$\propto h_{1,q}(x) H_{1,q}^{\perp\triangleleft}(z) \neq 0$$

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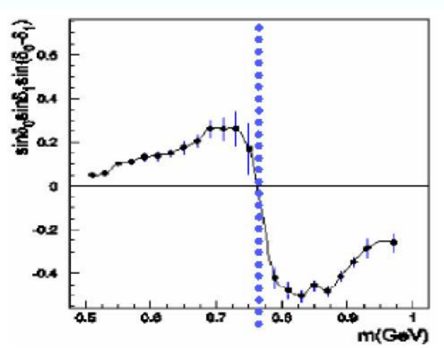
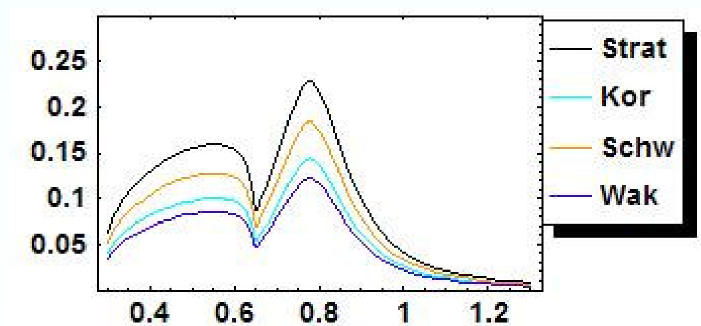
Evidence of a T-odd and chiral-odd Interference FF !

No evidence of the sign-change at the ρ^0 mass



Jaffe et al.
Phys.Rev.Lett.80,1166(1998)



Bacchetta and Radici
hep-ph/0608037

Conclusions

• **significant Collins amplitudes observed for π-mesons**
→ enabled first extraction of transversity

• **significant Sivers amplitudes observed for π^+ and K^+**
→ clear evidence of non-zero Sivers function
→ (indirect) evidence for non-zero quark orbital angular momentum

• Non vanishing pion-difference amplitudes demonstrates that **measured asymmetries do not arise from (only) exclusive vector meson contamination**

• Current extractions of transversity and Sivers function based on unweighted moments (need Gaussian ansatz)

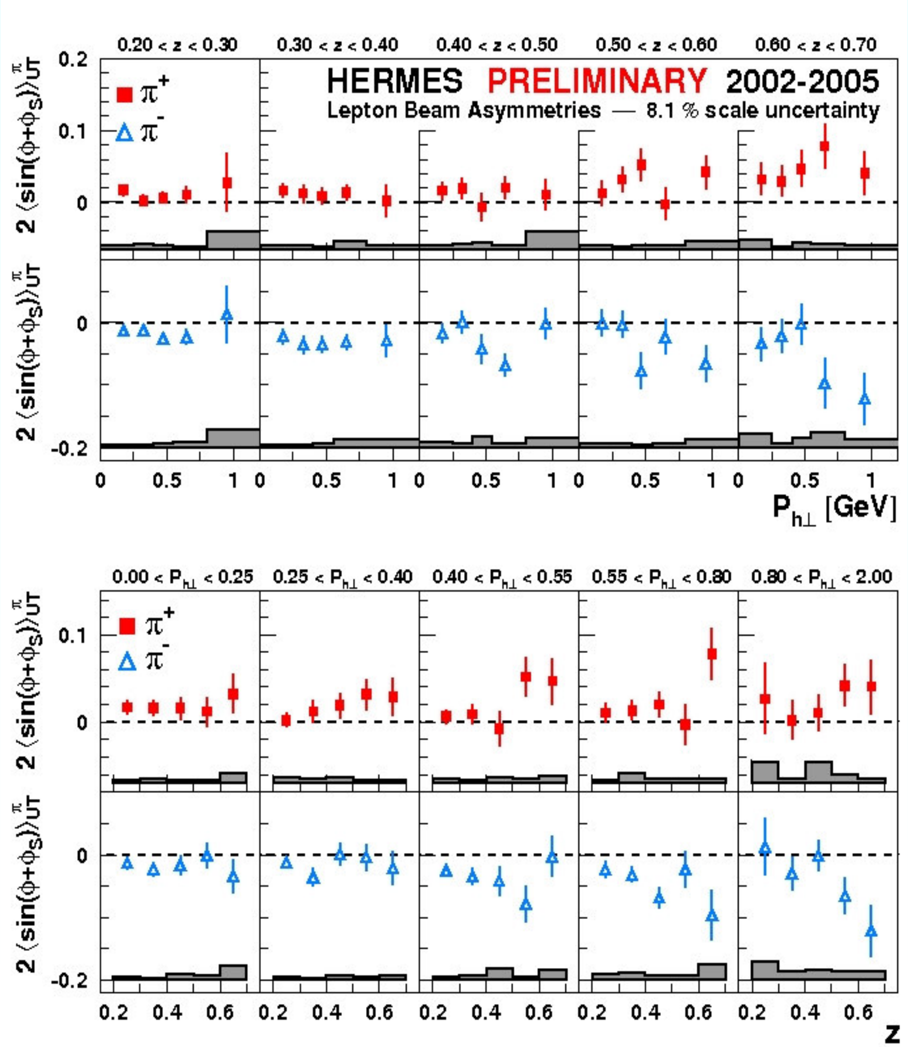
• Assumpion-free extractions can be achieved in the future from $P_{h\perp}$-weighted moments.

• **significant di-hadron amplitudes observed**
→ clear evidence of non-zero Interference Fragmentation Function
→ more transparent interpretation in terms of DF and FF (no convol. integral)

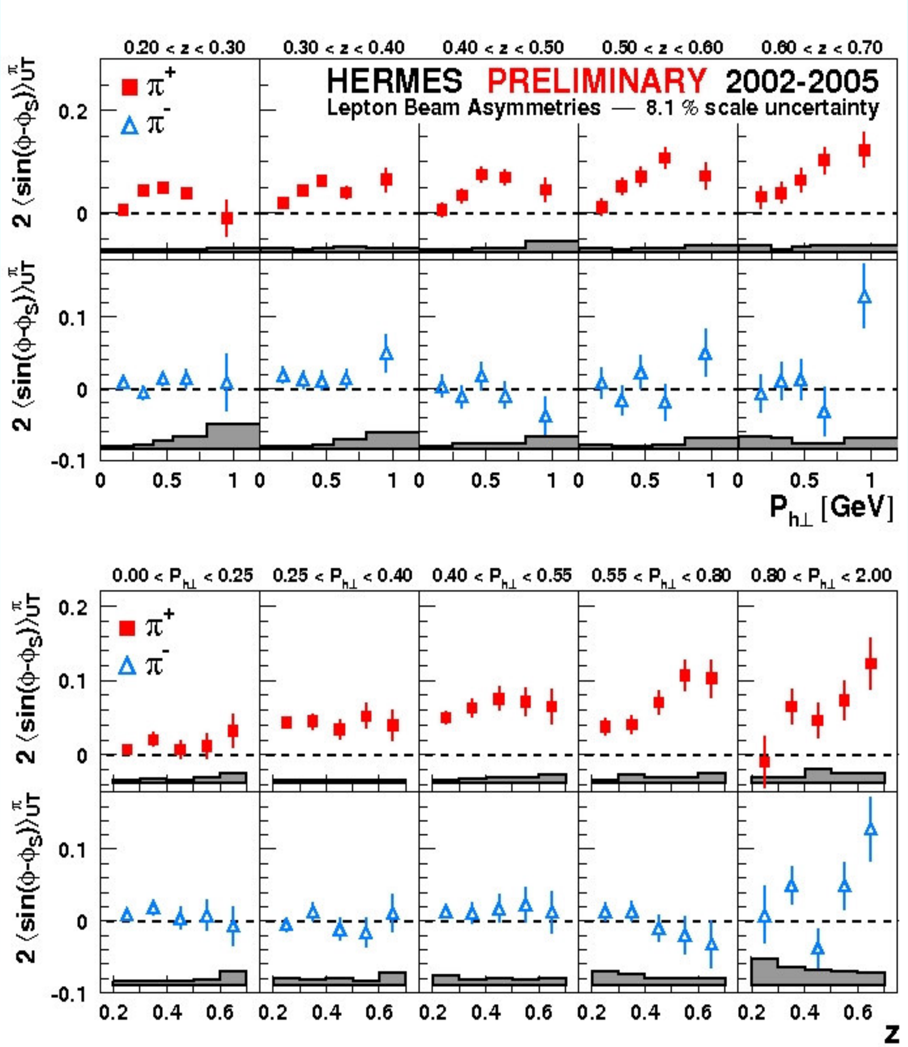
Back-up slides

2-D moments for $\pi^{\pm}$: z vs. $P_{h\perp}$

Collins



Sivers



The extraction of the Distribution Functions

$$\left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{h} = \frac{\int d\phi_S d^2\vec{P}_{h\perp} \sin(\phi+\phi_S)\ d\sigma_{UT}}{\int d\phi_S d^2\vec{P}_{h\perp} d\sigma_{UU}} \propto \mathbf{I}\left[\frac{\vec{k}_T \cdot \hat{P}_{h\perp}}{M_h} h_1(x, p_T^2) H_1^{\perp q}(z, k_T^2)\right]$$

Convolution integral on transverse momenta p_T and k_T

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

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

Theory: difficult to solve ⟹ Gaussian ansatz

$$h_1(x, p_T^2) \approx \frac{h_1(x)}{\pi\left\langle p_T^2(x)\right\rangle} e^{-\frac{p_T^2}{\left\langle p_T^2(x)\right\rangle}} \qquad H_1^{\perp q}(z, k_T^2) \approx \frac{H_1^{\perp q}(z)}{\pi\left\langle k_T^2(z)\right\rangle} e^{-\frac{k_T^2}{\left\langle k_T^2(z)\right\rangle}}$$

(extraction assumption-dependent)

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

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

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

P_{hT}-weighted Sivers moments (measured)

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.