Latest HERMES Results on Transverse Spin in Hadron Structure and Formation

Riccardo Fabbri

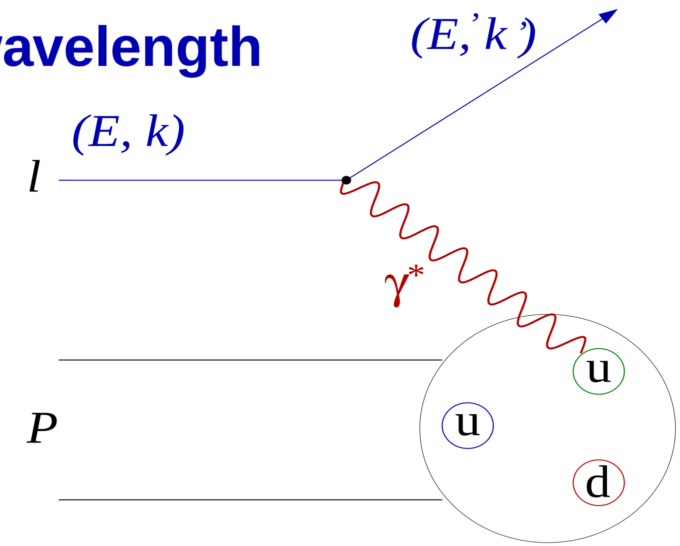
on behalf of the *HERMES* Collaboration

*MENU*2007 **Jülich, 11 Sept. 2007**

- **Proton Structure and Transversity**
- **The HERMES Experiment**
- **Single-Hadron SIDIS Production**
- **Two-Pions SIDIS Production**
- **Summary and Outlook**

Proton Structure in HEP

- Proton structure investigated via short-wavelength virtual photons emitted by impinging high energetic leptons: inclusive Deep Inelastic Scattering ($lP \rightarrow l'X$)



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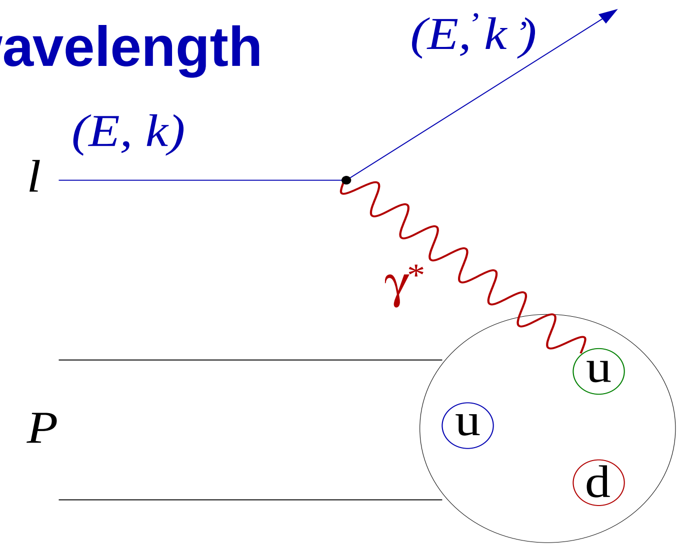
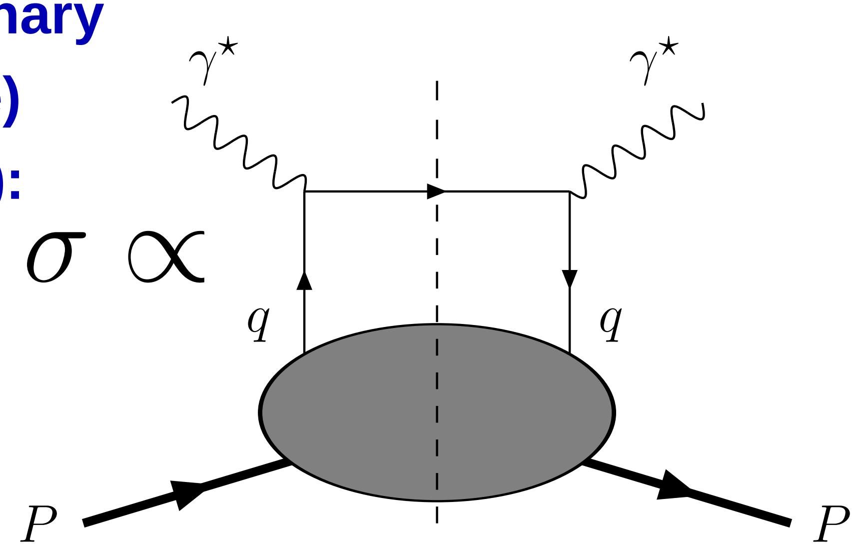


- **The cross-section is related to imaginary part of forward (zero scattering angle) transition amplitude $\mathcal{A}$ ($\gamma^\star P \rightarrow \gamma^\star P$):**



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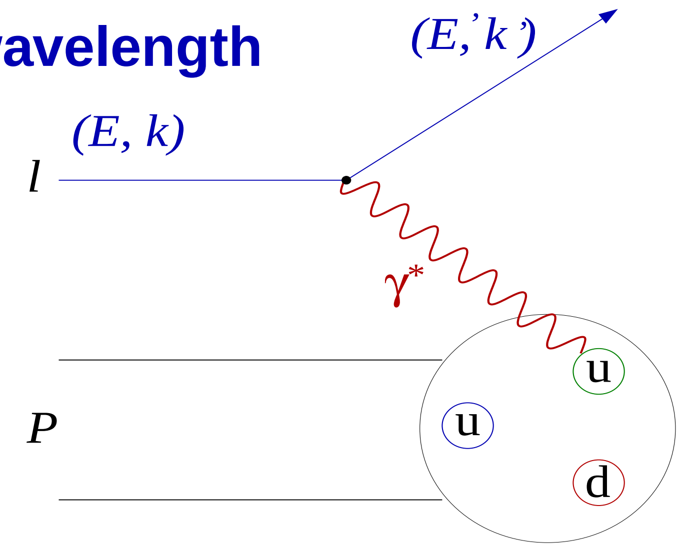

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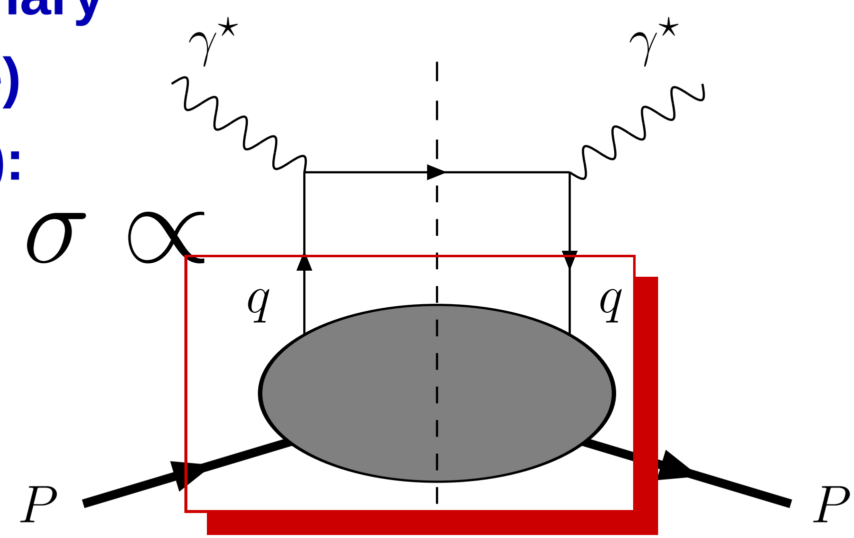
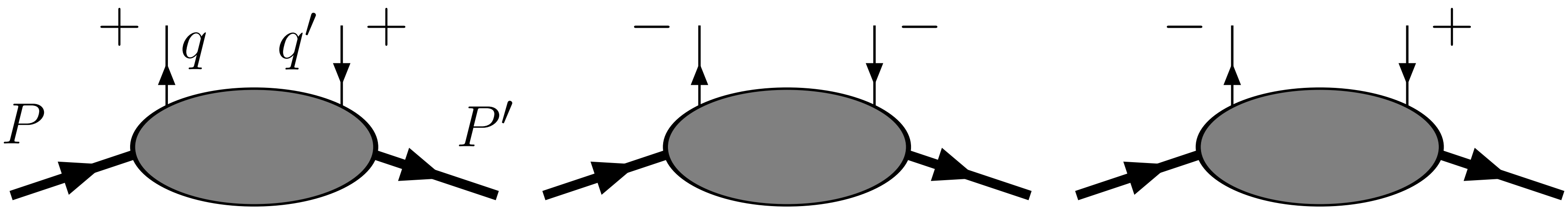


- Quarks configuration inside the proton can be accessed

Proton Structure and Transversity

- **At leading order & twist we have only these helicity amplitudes (neglecting over transverse quark momentum):**

chiral-even **chiral-even** **chiral-odd**



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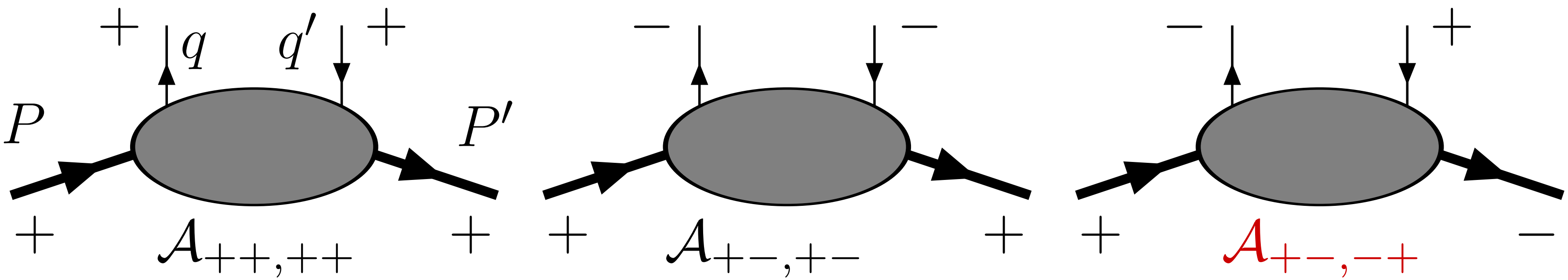

- ...describing the following quark probability distributions:

Momentum:	$\sim Im(\mathcal{A}_{++,++} + \mathcal{A}_{+-,+-})$	$q(x) = q^{\overset{\rightarrow}{\Rightarrow}}(x) + q^{\overset{\rightarrow}{\Leftarrow}}(x)$
Helicity:	$\sim Im(\mathcal{A}_{++,++} - \mathcal{A}_{+-,+-})$	$\Delta q(x) = q^{\overset{\rightarrow}{\Rightarrow}}(x) - q^{\overset{\rightarrow}{\Leftarrow}}(x)$
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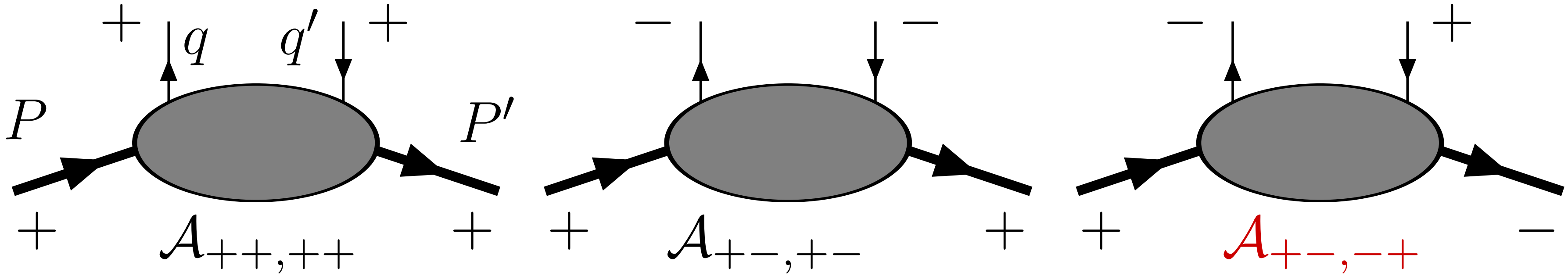

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- **Transversity poorly known! Comparison of $\Delta q(x)$ & $h_1(x)$ gives sensitivity to relativistic effects inside proton (different Q^2 evolution)**

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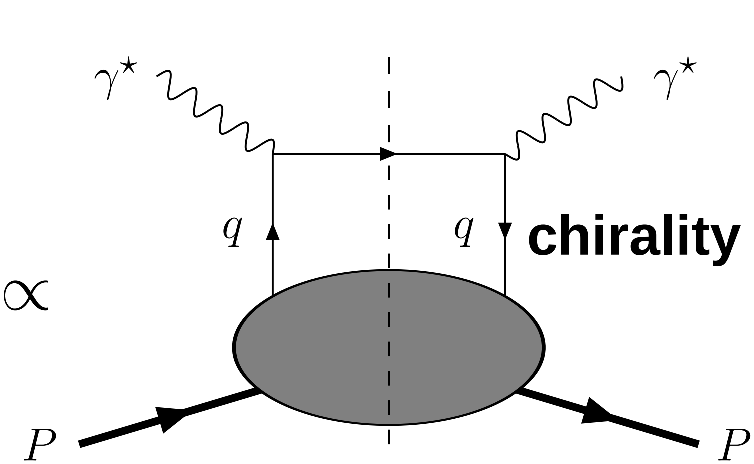
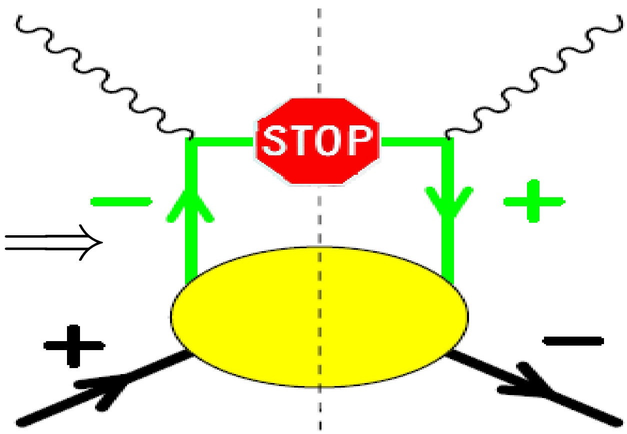


chirality conservation $\Longrightarrow$



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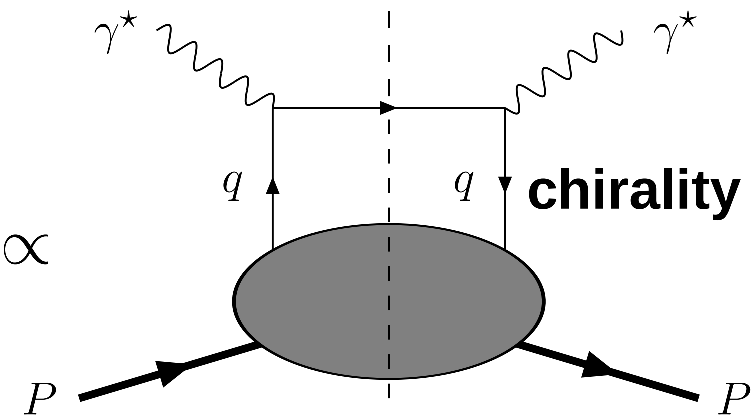

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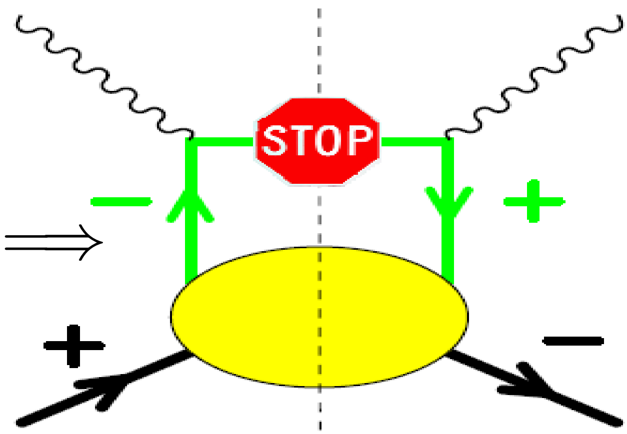

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- **We need processes where odd chirality in proton transition can be 'compensated'**

  $\Longrightarrow$ **to conserve chirality in the scattering process as a whole**

How to Measure Transversity

- **Single-hadron semi-inclusive DIS**

$\longrightarrow Q^2 = -q^2 = -(k - k')^2$

$\longrightarrow \nu \overset{lab}{=} E - E'$

$\longrightarrow x \overset{lab}{=} \frac{Q^2}{2m_P \cdot \nu}$

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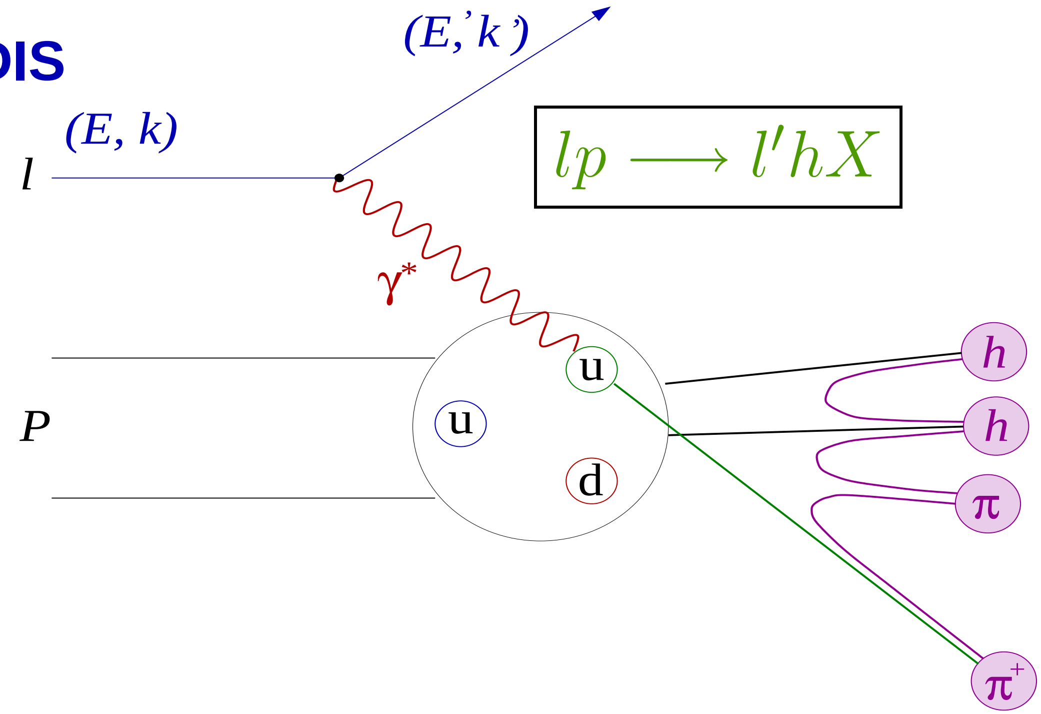

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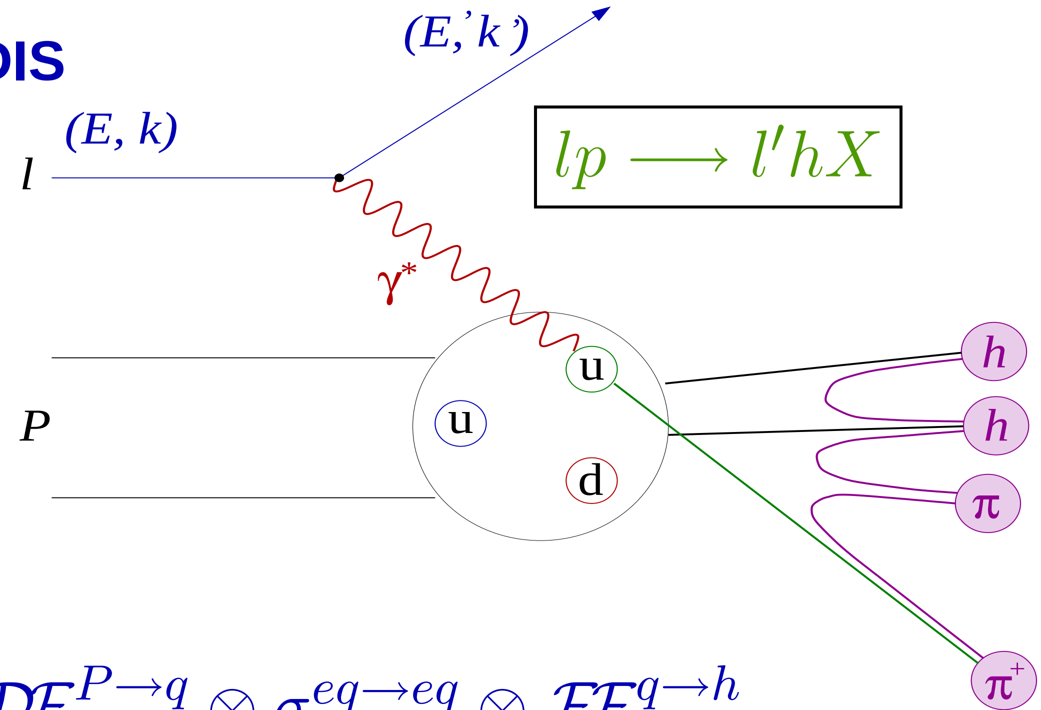

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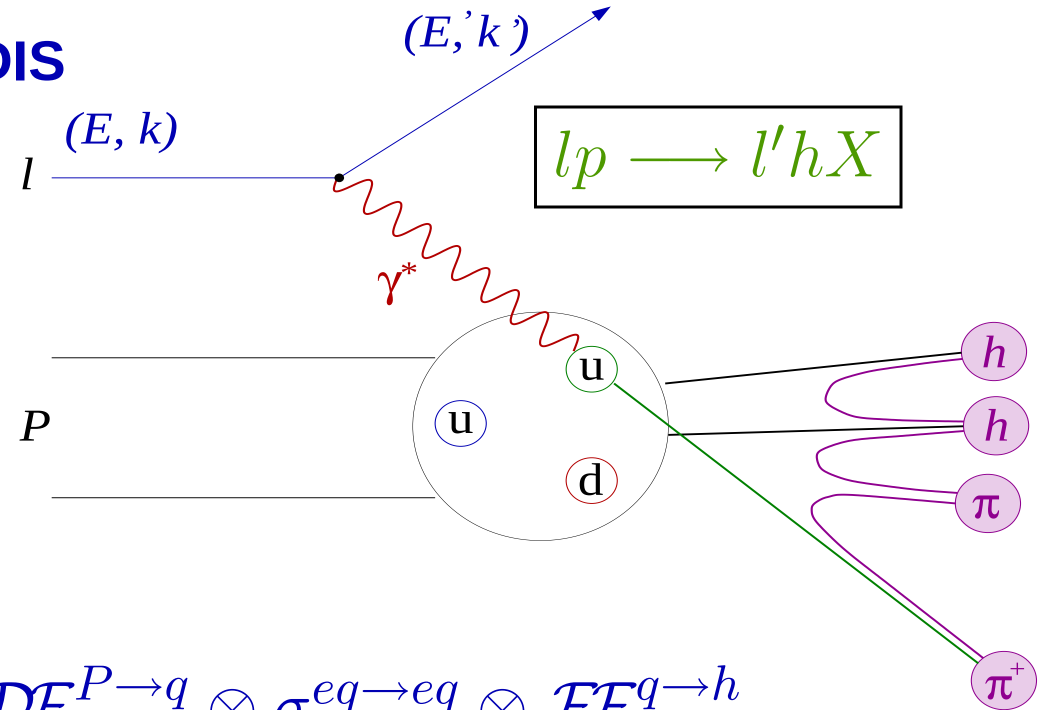

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$\rightarrow \mathcal{DF}$ $(\mathcal{FF})$ **denotes a distribution (fragmentation) function**

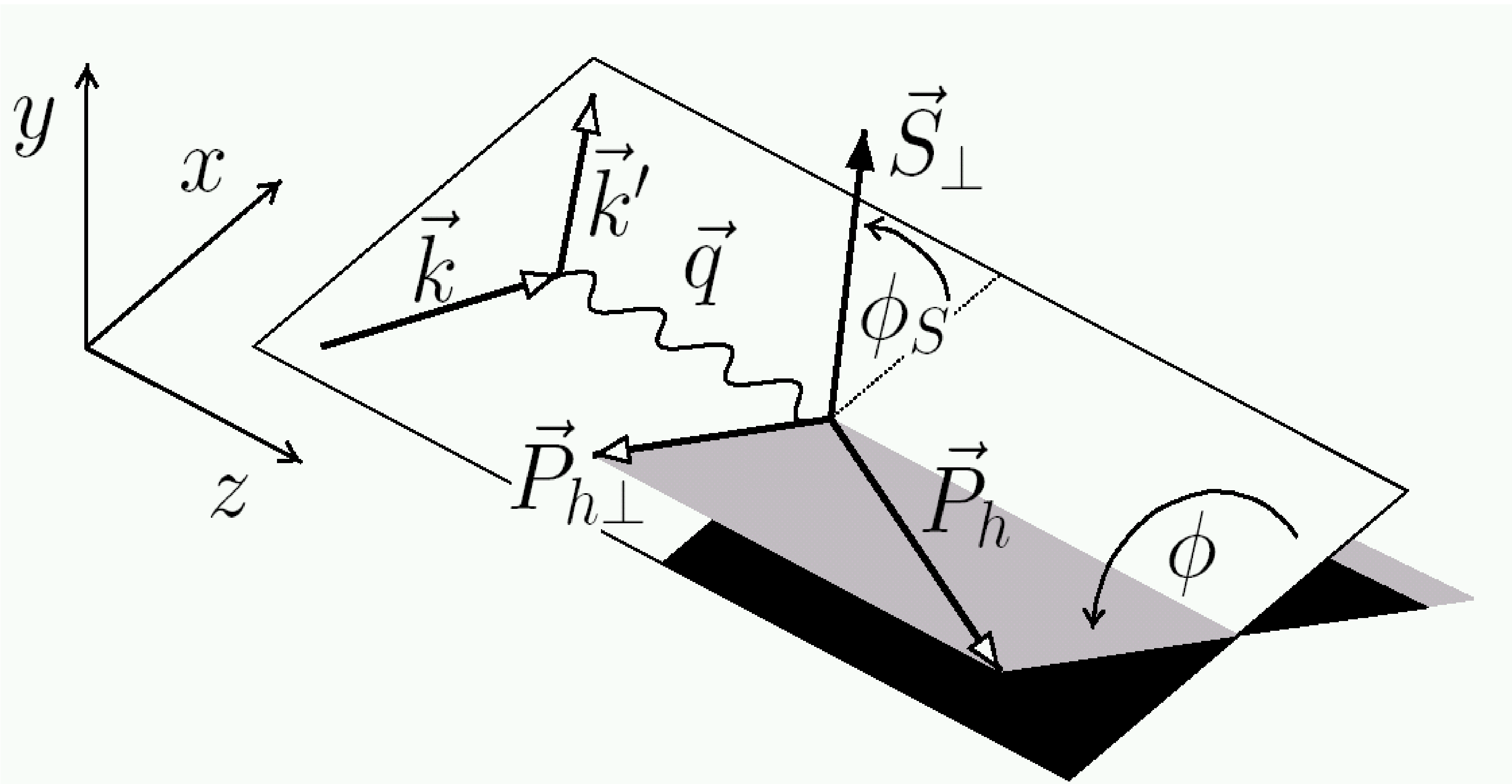
- **Chirality of the process assured if both $\mathcal{DF}$ and $\mathcal{FF}$ are chiral-odd**

$\rightarrow$ **to get sensitivity to transversity, a suitable process/observable is needed involving a chiral-odd fragmentation function**

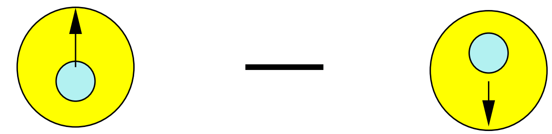
Single-Spin Azimuthal Asymmetry

- Consider the asymmetry in the azimuthal angles ϕ, ϕ_S with a transversely polarized target and unpolarized lepton beam:

$$A_{UT}(\phi,\phi_S) = \frac{1}{\langle S_T \rangle} \frac{\sigma_h^{\Uparrow}(\phi,\phi_S) - \sigma_h^{\Downarrow}(\phi,\phi_S)}{\sigma_h^{\Uparrow}(\phi,\phi_S) + \sigma_h^{\Downarrow}(\phi,\phi_S)}$$



The Collins Fragmentation Function

- **Collins** $\mathcal{FF} : H_1^{\perp} = \mathcal{P}_{h/q'\uparrow} - \mathcal{P}_{h/q'\downarrow} =$ 

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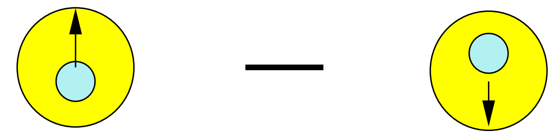
- **Collins** $\mathcal{FF}$: $H_1^{\perp} = \mathcal{P}_{h/q'\uparrow} - \mathcal{P}_{h/q'\downarrow} =$ 

chiral odd

- $A_{UT}(\phi, \phi_S) \sim \sin(\phi + \phi_S) \sum_q e_q^2 \ \mathcal{I}\left[h_1^q(x, k_T) H_1^{\perp,q}(z, k'_T)\right] + \ldots$

  $\rightarrow \mathcal{I}[\ldots]$: **convolution integral over initial quark (**k_T**) and final hadron (**k'_T**) transverse momenta**

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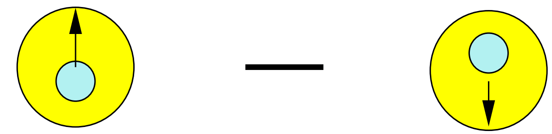

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- **If Collins $H_1^{\perp}$ is not zero:**

  $\longrightarrow$ **sensitivity to transversity appears**

  $\longrightarrow$ **although cannot directly extract transverse-momentum-dependent distribution function (due to the convolution)**

- **Additionally, other mechanisms contribute to A_{UT}**

  $\longrightarrow$ **with a different ϕ, ϕ_S modulation**

The Sivers Distribution Function

- **Consider the additional terms in azymuthal asymmetry:**

$$A_{UT}(\phi,\phi_S) \sim \sin(\phi+\phi_S)\sum_q e_q^2\ \mathcal{I}\left[h_1^q(x,k_T^2)H_1^{\perp,q}(z,k_T'^2)\right]+$$

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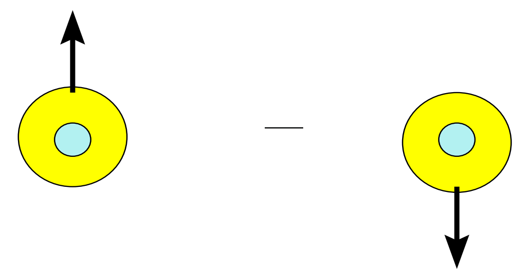

NOTE: $f_{1,T}^{\perp}$ not measured yet!

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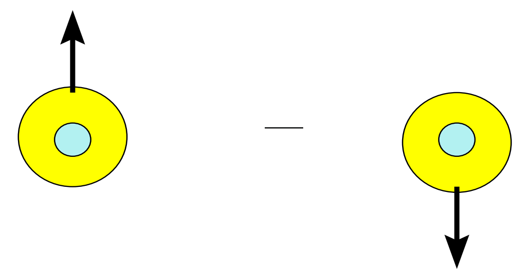

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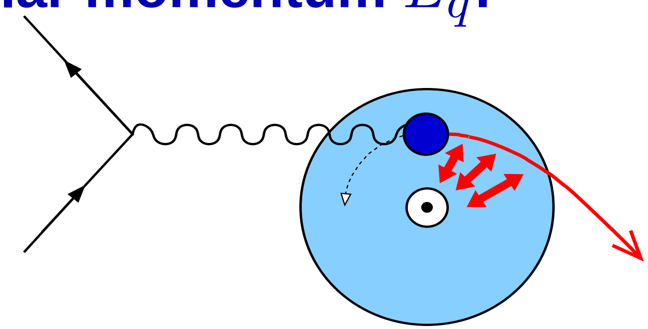
$\longrightarrow$ **M.Burkardt model**

$\longrightarrow$ **A non-zero L_q should be reflected in a non-zero Sivers $\mathcal{DF}$ $f_{1,T}^{\perp}$**



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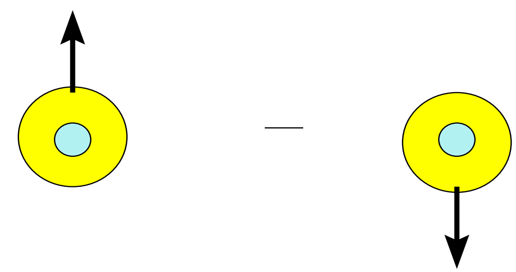

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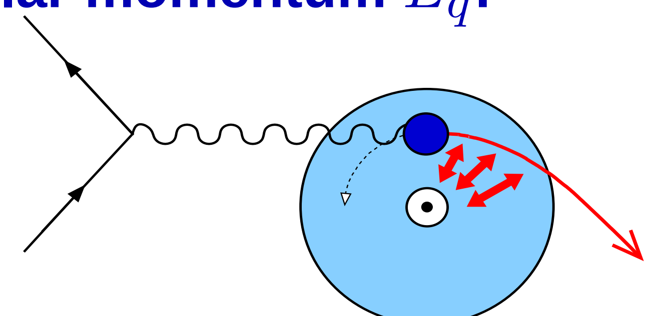
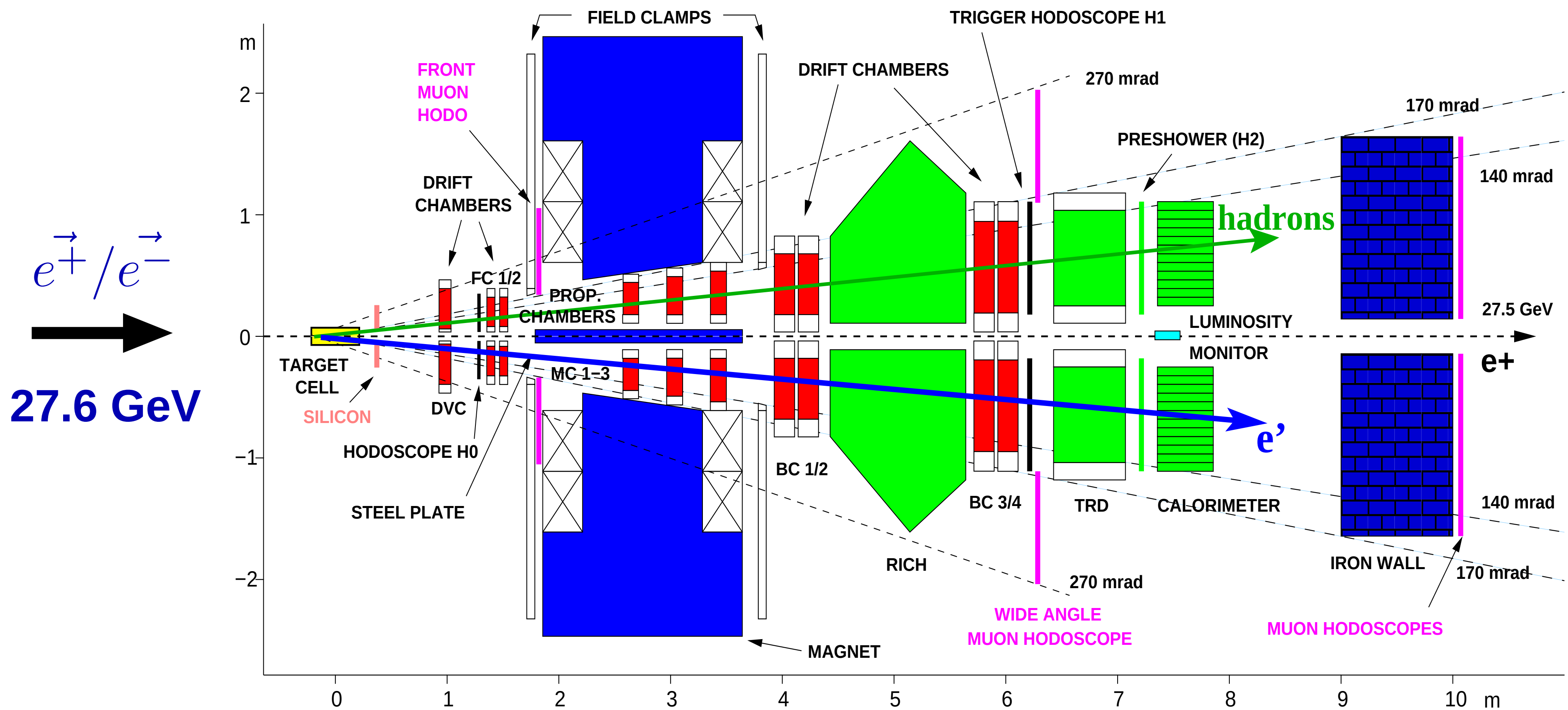


- **Collins and Sivers convoluted integrals have unique ϕ,ϕ_S signature**
  - $\longrightarrow$ **can be simultaneously extracted through a fit**

The HERMES Experiment at DESY



- **Gas storage target cell: Transversely Polarized H with $P_T \approx 80\%$**
- **Forward spectrometer:** $40\ mrad < \theta < 220\ mrad$
- **Tracking chambers:** $\Longrightarrow \delta p/p \approx 2\%$, $\delta\theta \leq 1\ mrad$
- **PIDs:** e/h **separation efficiency** $> 98\%$, $\pi^{\pm}/K^{\pm}/p$ **ID:** $2 < p < 15$ **GeV**

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$$e^{\pm} p^{\Uparrow} \longrightarrow e^{\pm} h X$$

- **Data Selection: All data with transverse (T) target used (2002-05)**

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Collins Amplitudes for Charged π

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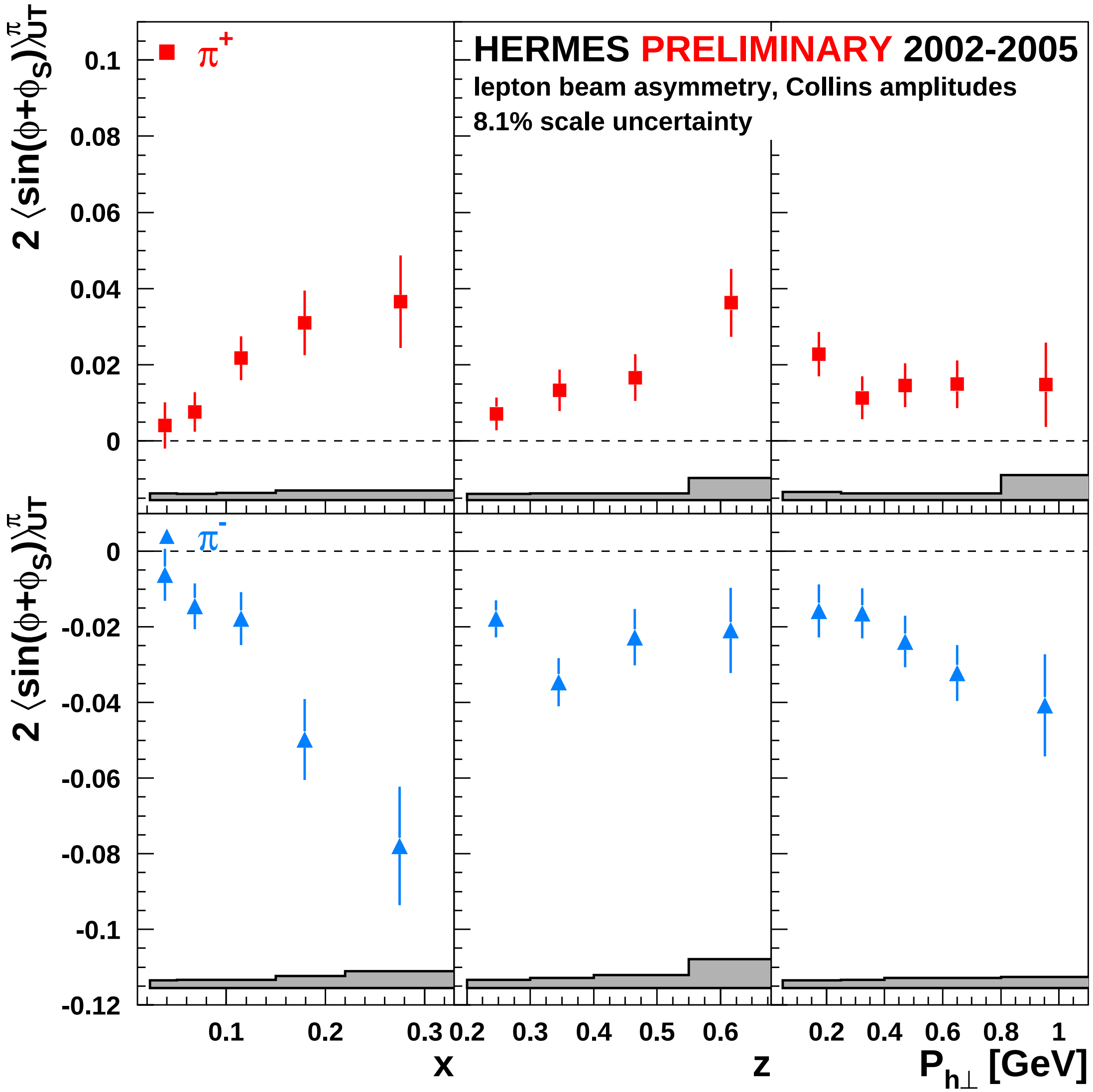

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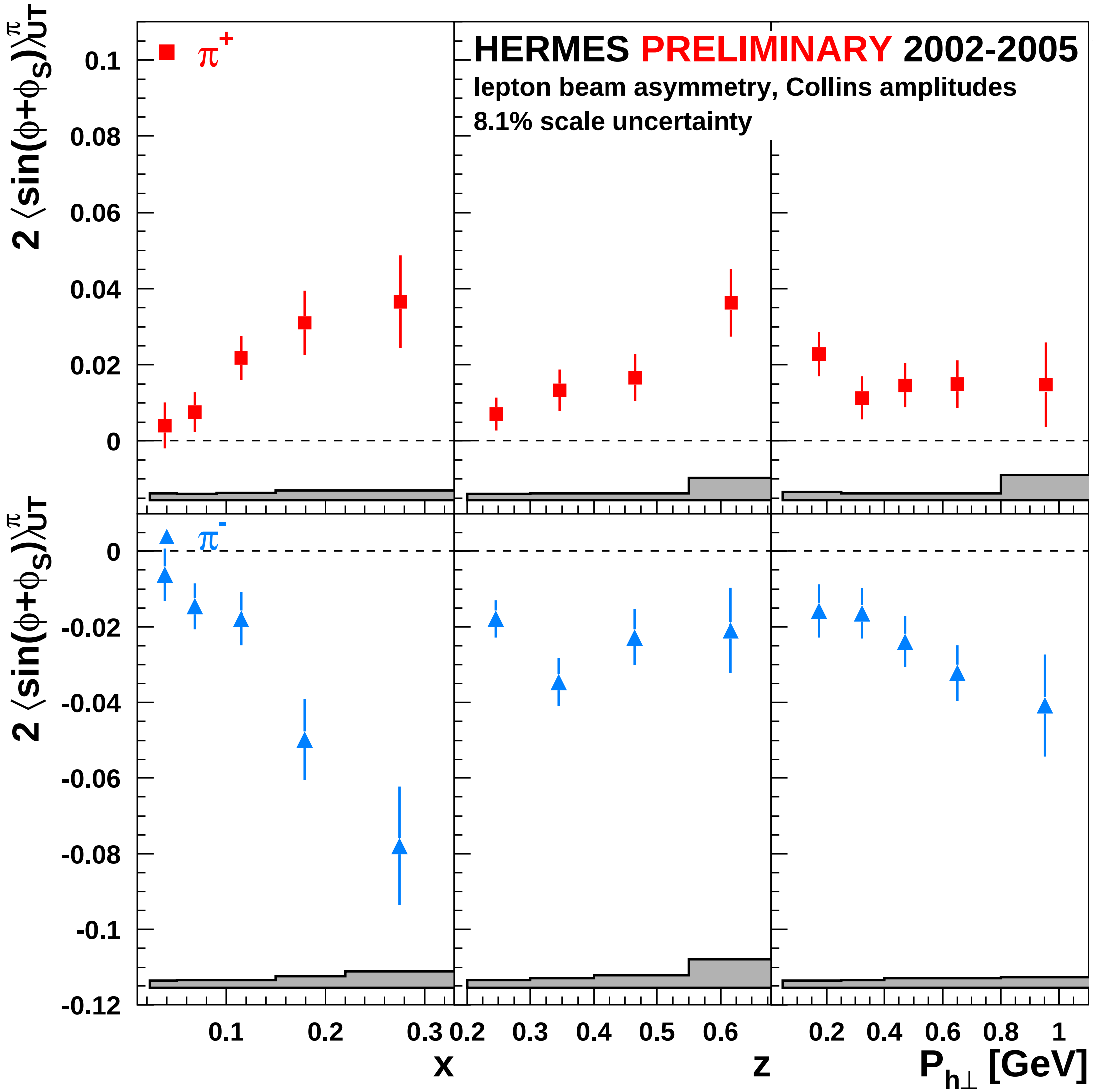

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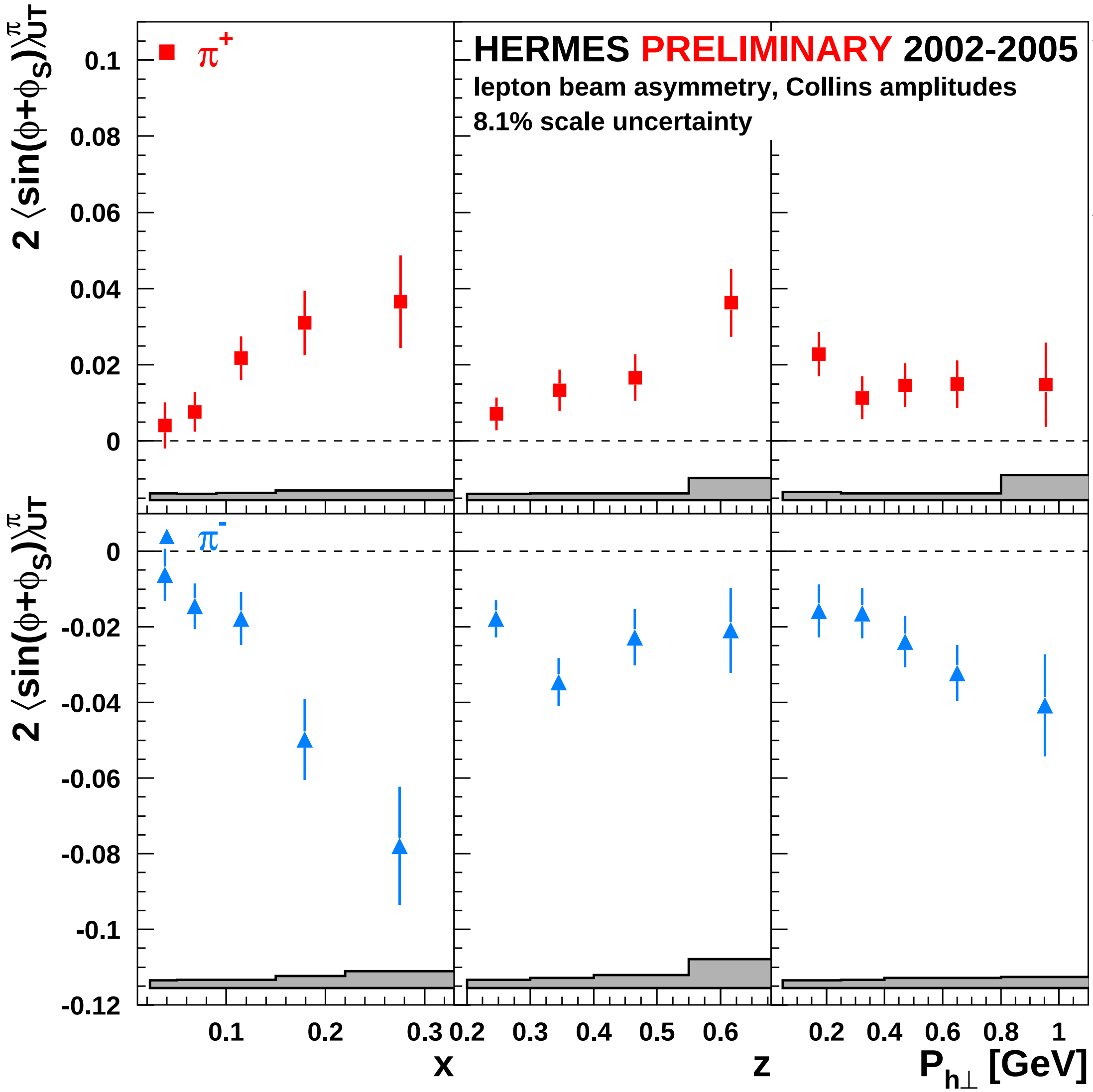

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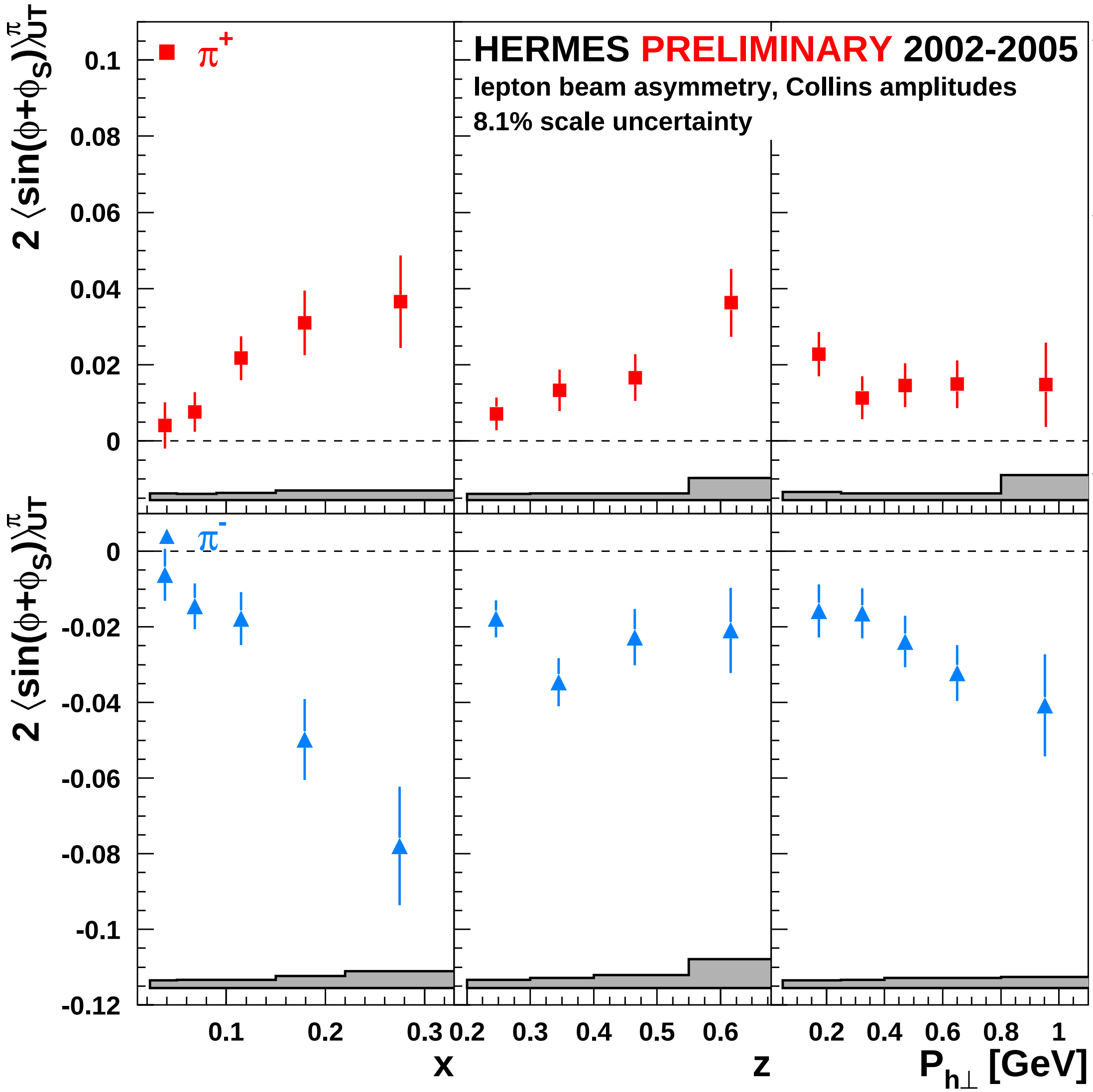

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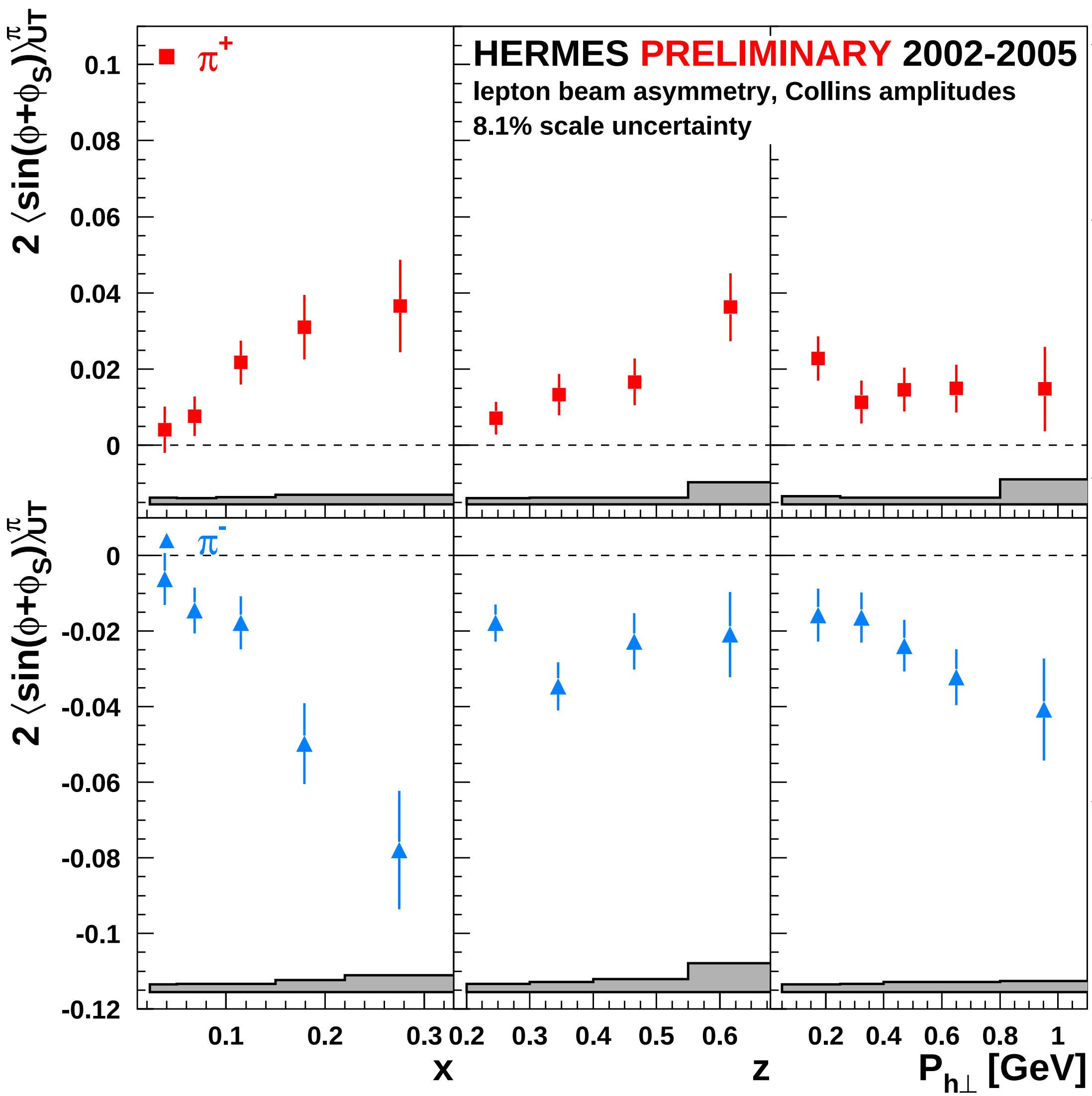

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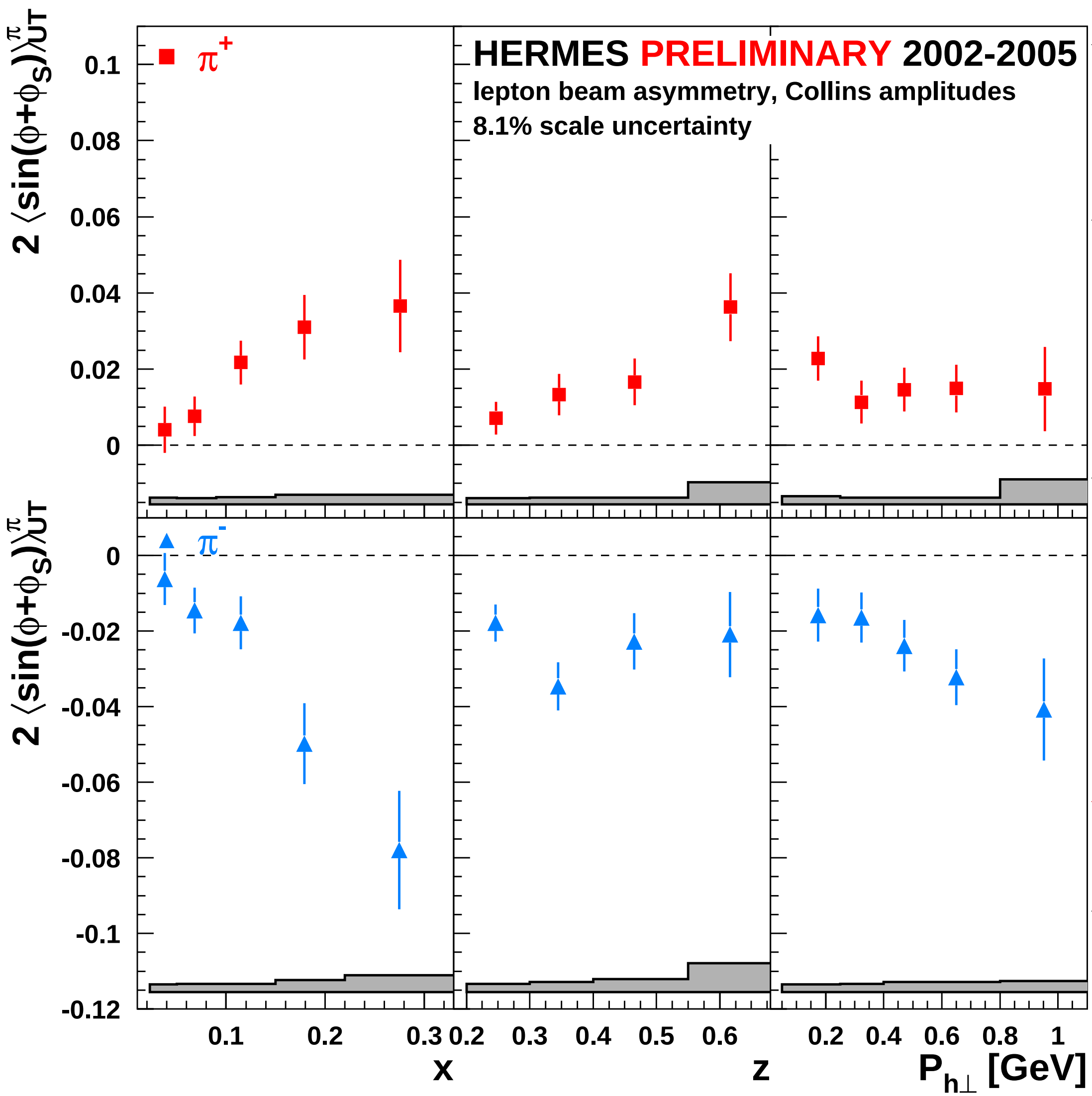
- **Both h_1 and $H_1^{\perp}$ not zero!**

Collins Amplitudes for Charged π

Sensitivity to $h_1 \otimes H_1^{\perp}$



- Collins amplitude **positive** **(negative)** for π^+ (π^-)
- Amplitudes sign: similar behaviour as for helicity distributions
- Large π^- amplitudes size:
  - — not expected
  - — due to role of disfavoured Collins $\mathcal{FF}$ $H_1^{\perp}$?
- **Both h_1 and $H_1^{\perp}$ not zero!**
- Info on $H_1^{\perp}$ needed to extract h_1 out of measured amplitudes

Fit Extraction of $h_1(x)$

- **Global analysis of experimental data on azimuthal asymmetries in:**

  —- SIDIS: HERMES+COMPASS

  —- $e^+e^- \to h_1 h_2 X$: Belle

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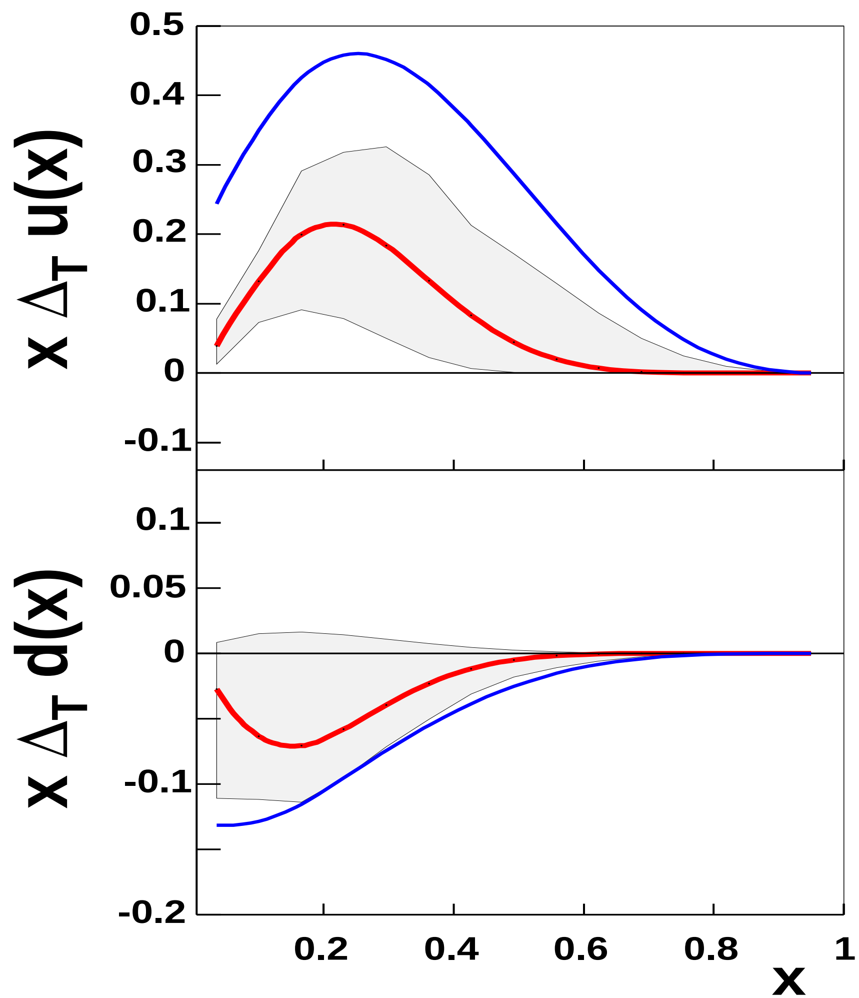
Anselmino et al.:

Phys.Rev. D75 054032 (2007)

First time ever fit-extraction of $h_1(x)$

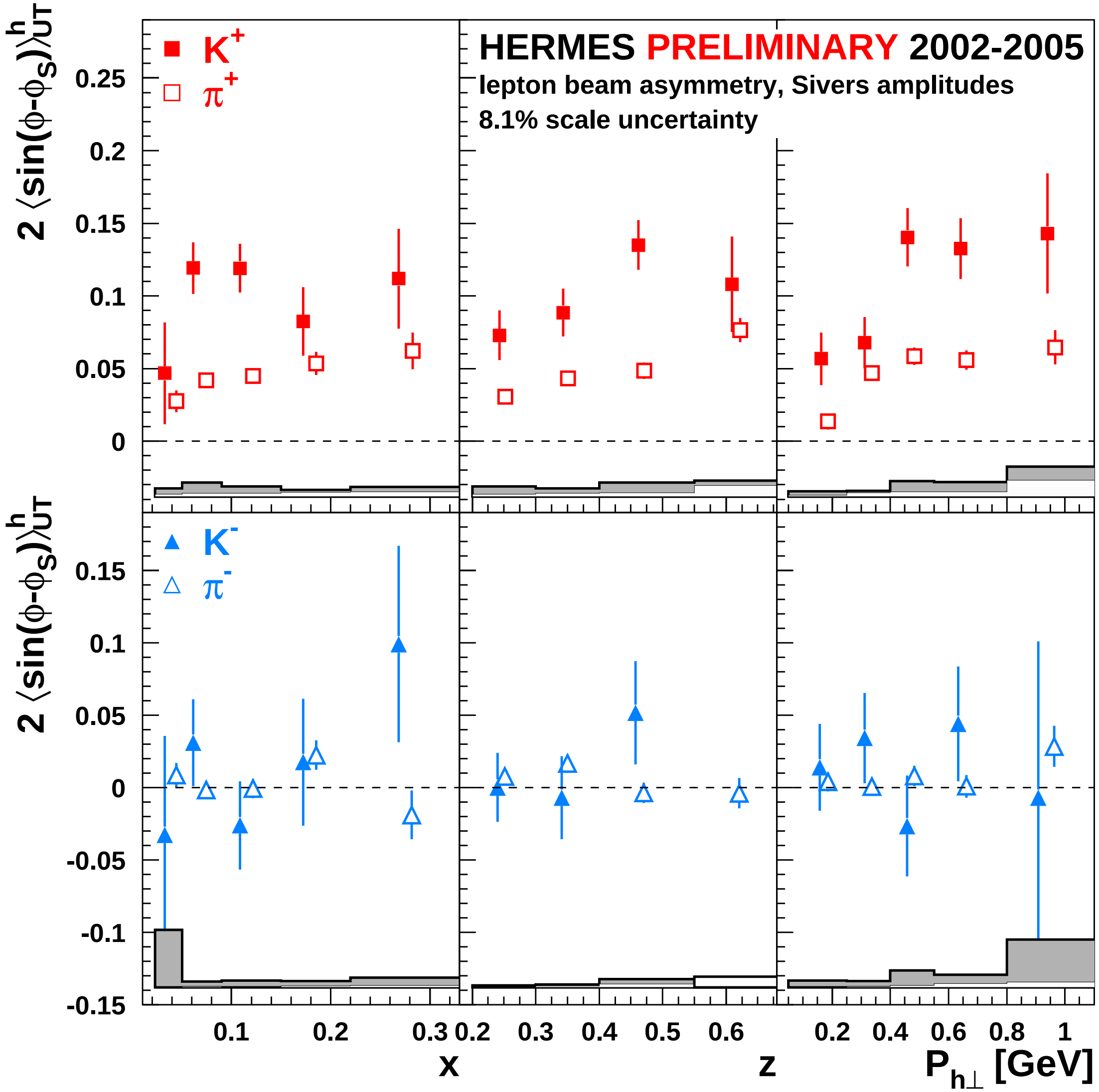
For more see: A. Drago (soon after) &

M. Anselmino (Friday)



Sivers Amplitudes for Charged π/K

Sensitivity to $f_{1T}^{\perp} \otimes D$



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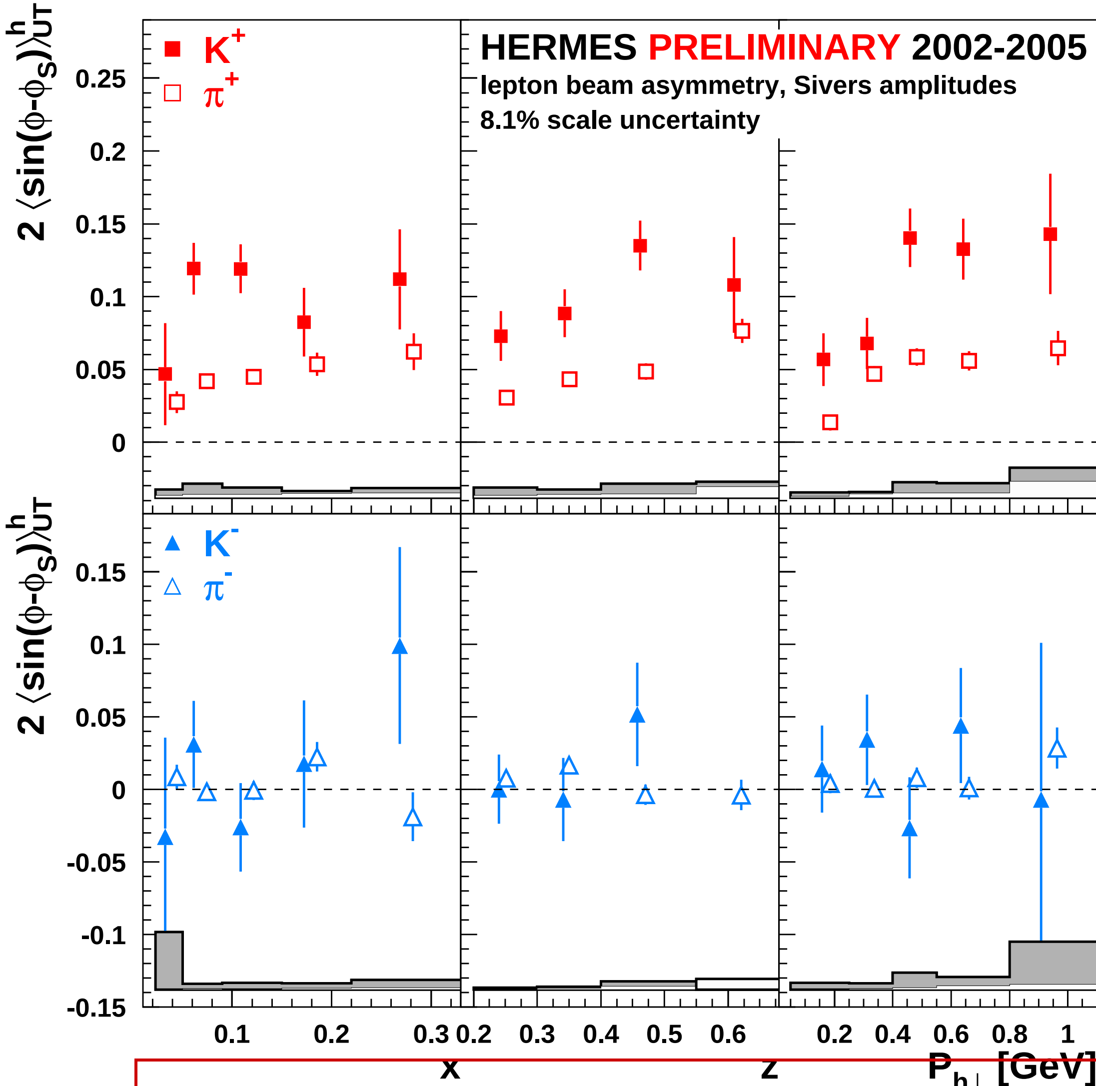


- Significantly non-zero and positive for π^+ and K^+ $\longrightarrow$ non-zero L_z^q
- K^+ amplitude size larger than π^+ case
  — does sea quarks play important role in Sivers mechanism? ($\pi^+ = |u\bar{d}\rangle, K^+ = |u\bar{s}\rangle$)
- π^- and K^- amplitudes consistent with zero

First indication of non-zero Sivers $\mathcal{DF}$

SIDIS Production of Two-Pions

SIDIS Production of Two-Pions

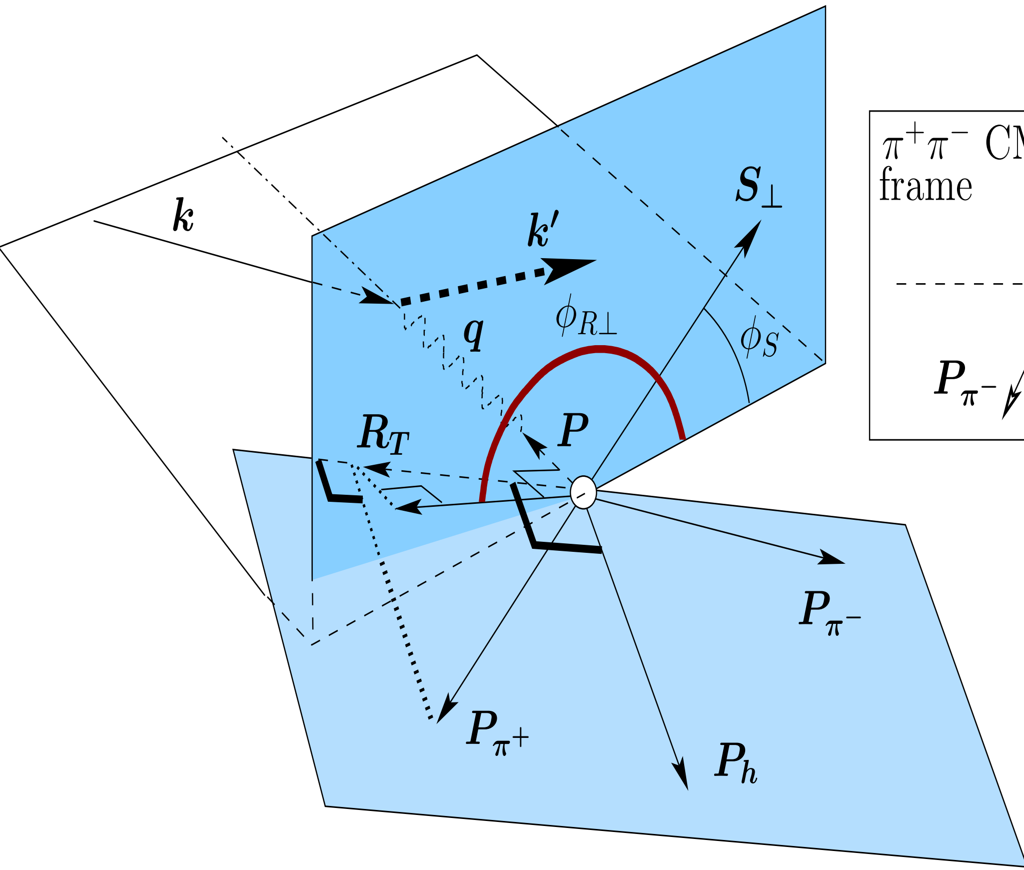
- **Complementary analysis to get sensitivity to transversity**

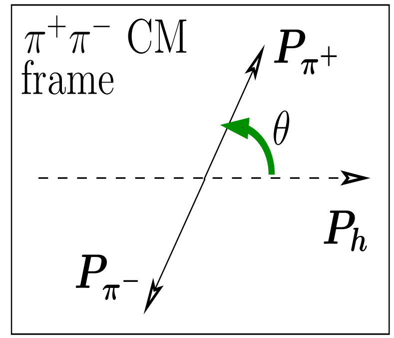
- **Advantages (compared to single-hadron analysis):**
  $\longrightarrow$ **Cross-section asymmetry directly proportional to** $h_1(x)$
  (no convolution involved!)
  $\longrightarrow$ **No Collins/Sivers 'entanglement'**
  $\longrightarrow$ **Completely independent from** $1h$ **analysis**

- **Disadvantages (compared to single-hadron analysis):**
  $\longrightarrow$ **Less statistics**
  $\longrightarrow$ **Additional unknown** $\mathcal{FF}$ **involved**
  (describing quark fragmentation into two pions)
  — But it can measured at Belle & Babar

SIDIS Production of Two-Pions

$$e^+ p^{\Uparrow\Downarrow} \longrightarrow e^+ \pi^+ \pi^- X$$





Two new angles ϕ_{R_T}, θ involved

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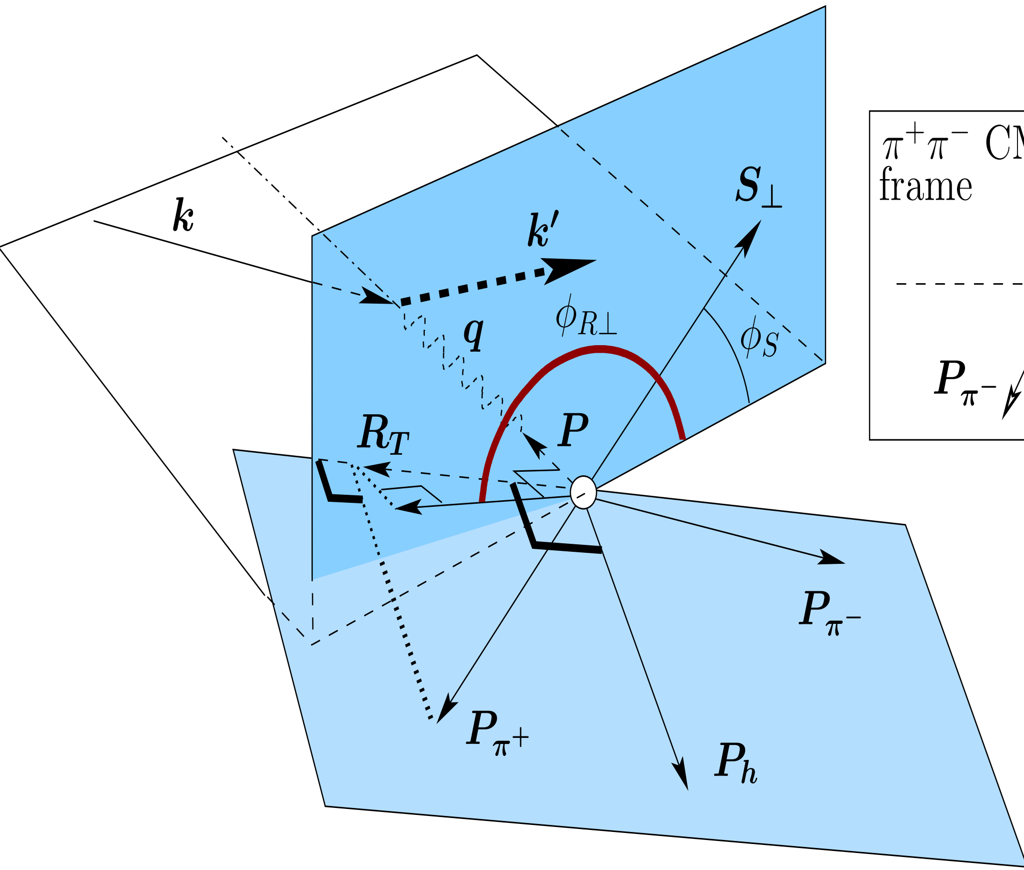

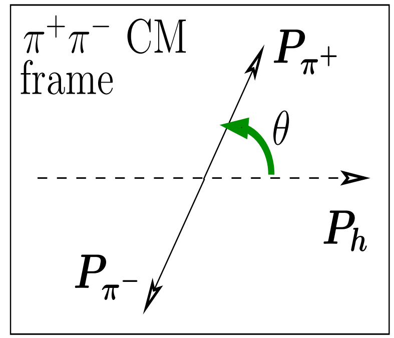

Two new angles ϕ_{R_T}, θ involved

$$A_{UT} = \frac{1}{S_T} \cdot \frac{d^7\sigma_{U\Uparrow} - d^7\sigma_{U\Downarrow}}{d^7\sigma_{U\Uparrow} + d^7\sigma_{U\Downarrow}}$$

where $d^7\sigma_{U\Uparrow(\Downarrow)} \stackrel{def}{=} \dfrac{d^7\sigma_{U\Uparrow(\Downarrow)}}{dx\,dy\,dz\,d\phi_S\,d\phi_{R\perp}\,d\cos\theta\,dm_{\pi\pi}}$

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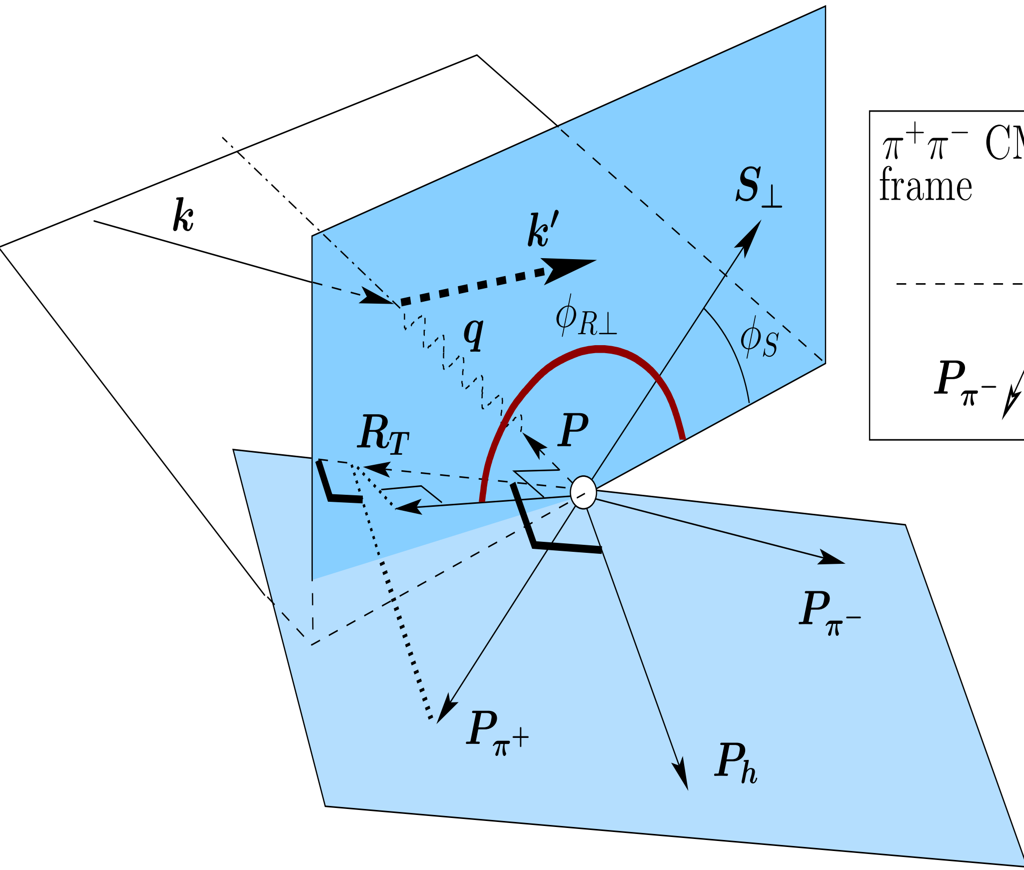

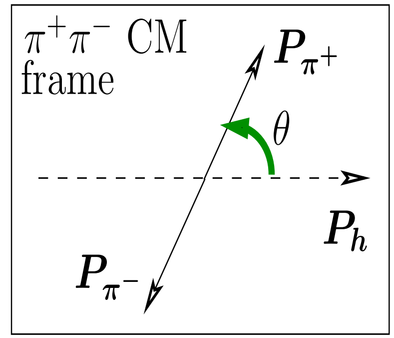

Two new angles ϕ_{R_T}, θ involved

At leading order & leading twist:

$$A_{UT} = \frac{1}{S_T} \cdot \frac{d^7\sigma_{U\Uparrow} - d^7\sigma_{U\Downarrow}}{d^7\sigma_{U\Uparrow} + d^7\sigma_{U\Downarrow}} \quad \sim$$

$$\sim \sum_q e_q^2 \left[\sin(\phi_{R\perp} + \phi_S) \sin\theta \right] \cdot h_1^q(x) H_{1,q}^{\sphericalangle, sp}(z, m_{\pi\pi}, \cos\theta)$$

where $d^7\sigma_{U\Uparrow(\Downarrow)} \stackrel{def}{=} \frac{d^7\sigma_{U\Uparrow(\Downarrow)}}{dx\,dy\,dz\,d\phi_S\,d\phi_{R\perp}\,d\cos\theta\,dm_{\pi\pi}}$

SIDIS Production of Two-Pions

- **Potential sensitivity to** $h_1(x)$
- **New, unknown, non-perturbative object appears:** $H_1^{\sphericalangle,sp}(z, m_{\pi\pi}, \cos\theta)$

  $\Rightarrow$ **interference between two-pions in relative** S**- and** P**-waves**

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- **First results released:**

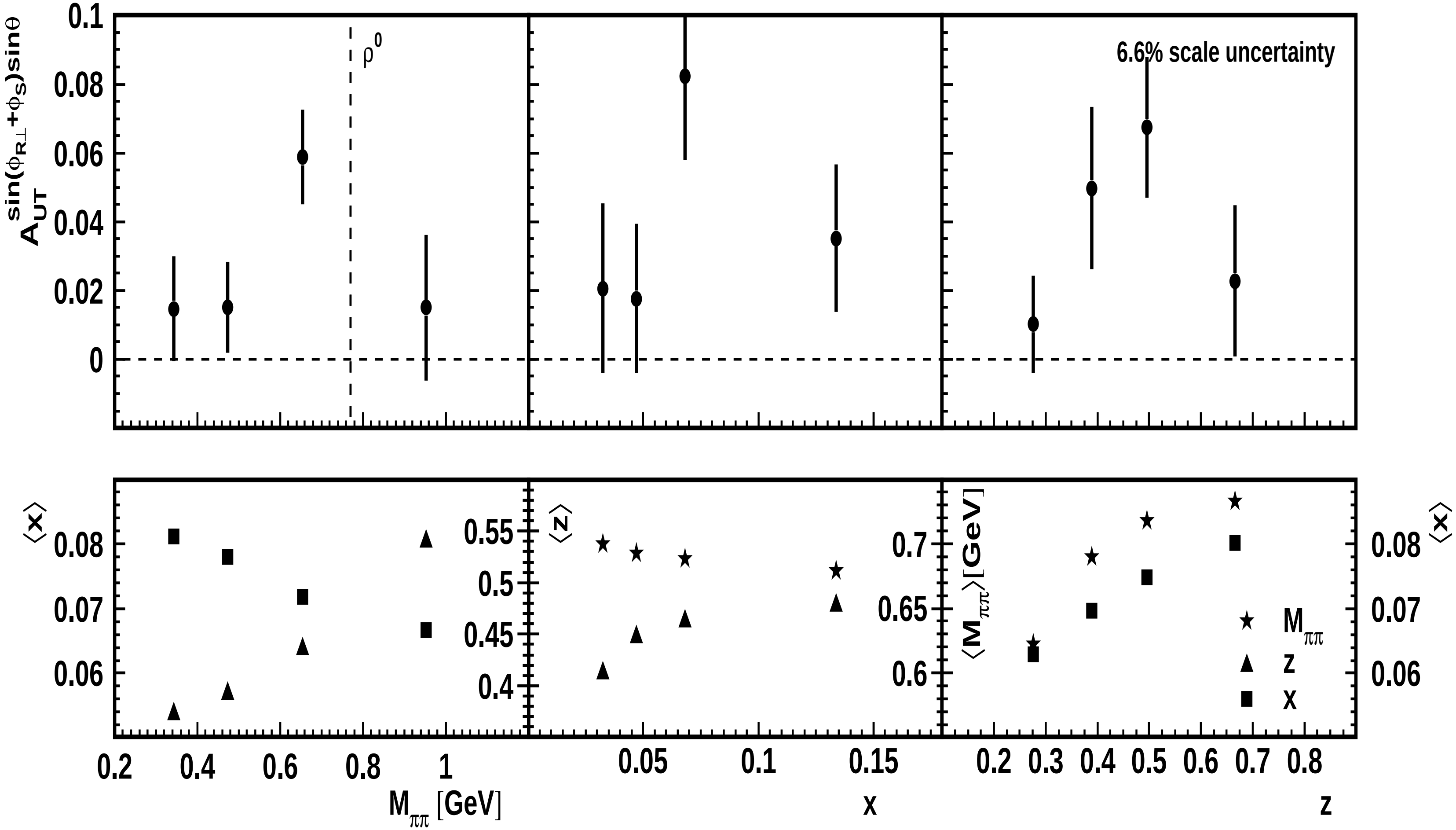
  $\Rightarrow$ **Data: 2002-2004 with H target (half of available statistics)**

  $\Rightarrow$ **Event Selection: $e^+ p^{\Uparrow\Downarrow} \longrightarrow e^+ \pi^+ \pi^- X$**

  $\Rightarrow$ **Experimental measured quantity: $A_{UT} = \frac{1}{\langle S_T \rangle} \frac{N^{\Uparrow}_{\pi^+\pi^-} - N^{\Downarrow}_{\pi^+\pi^-}}{N^{\Uparrow}_{\pi^+\pi^-} + N^{\Downarrow}_{\pi^+\pi^-}}$**

  $\Rightarrow$ **Amplitude of $\sin(\phi_{R\perp} + \phi_S) \sin\theta$ modulation extracted via χ^2 fit**

Two-Pions: Preliminary Results



- **Non-zero extracted amplitude** $\Rightarrow h_1(x) \cdot H_1^{\sphericalangle,sp}$ **not zero**
- **Main effect around $\rho^0 \Rightarrow$ contribution from interf. of 2π in S-P wave**

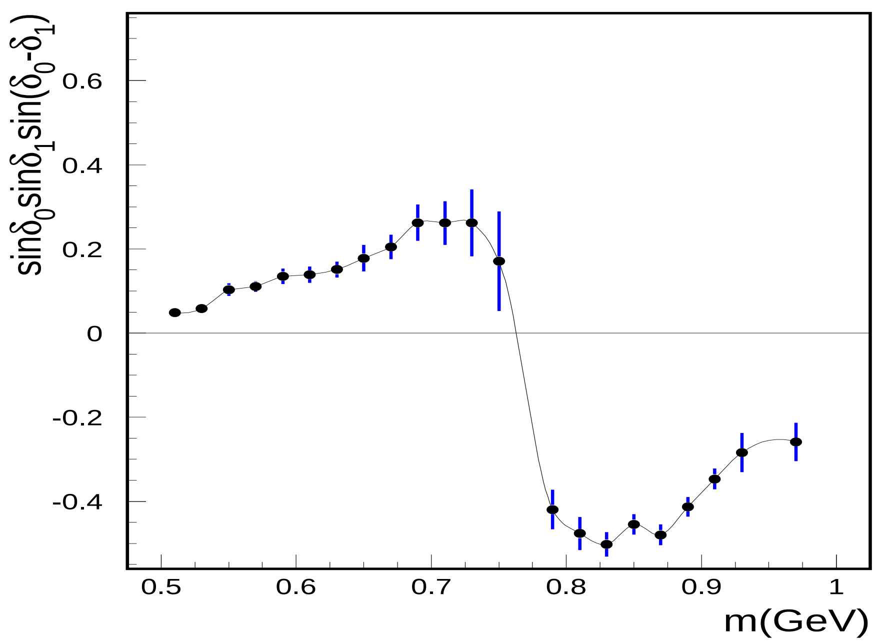
Two-Pions: Comparison with Theory

Two model predictions on 2π formation available

— Fragmentation into 2π modeled via:

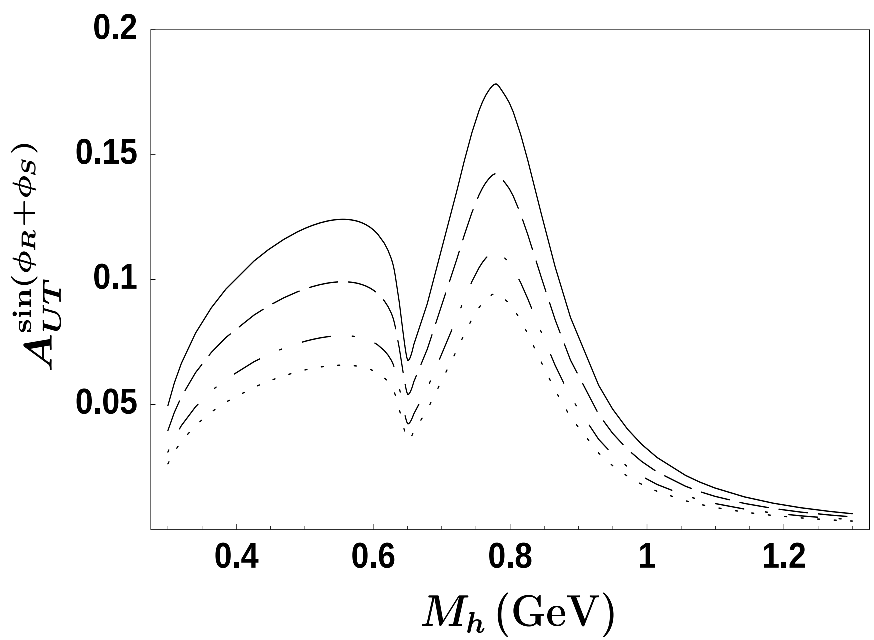
S- & P-wave phase shifts from elastic scattering via σ/ρ^0 resonances

Jaffe et al.: PRL 80 (1998) 1166



Non-res S-wave; more P-wave chan's Spectator $q \rightarrow \pi^+\pi^- X$ contrib. included

Radici et el.: PR D74 (2006) 114007



- **Preliminary results seem to favour Radici's model (no sign change)**
- **More precise statement might come after analyzing all available data**

Conclusions & Outlook

- Several observables related to internal structure of protons shown
  $\Longrightarrow$ first measurements were provided by HERMES

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  $\Longrightarrow$ **sofar, the remaining still unknown LO quark distribution**
- **First indication of non-zero Sivers** $\mathcal{DF}$ $f_{1,T}^{\perp}$
  $\Longrightarrow$ **evidence of non-zero** L_z^q **(a completely unknown quantity)**

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- Finalization of the analyses for publication is on-going

Back Slides

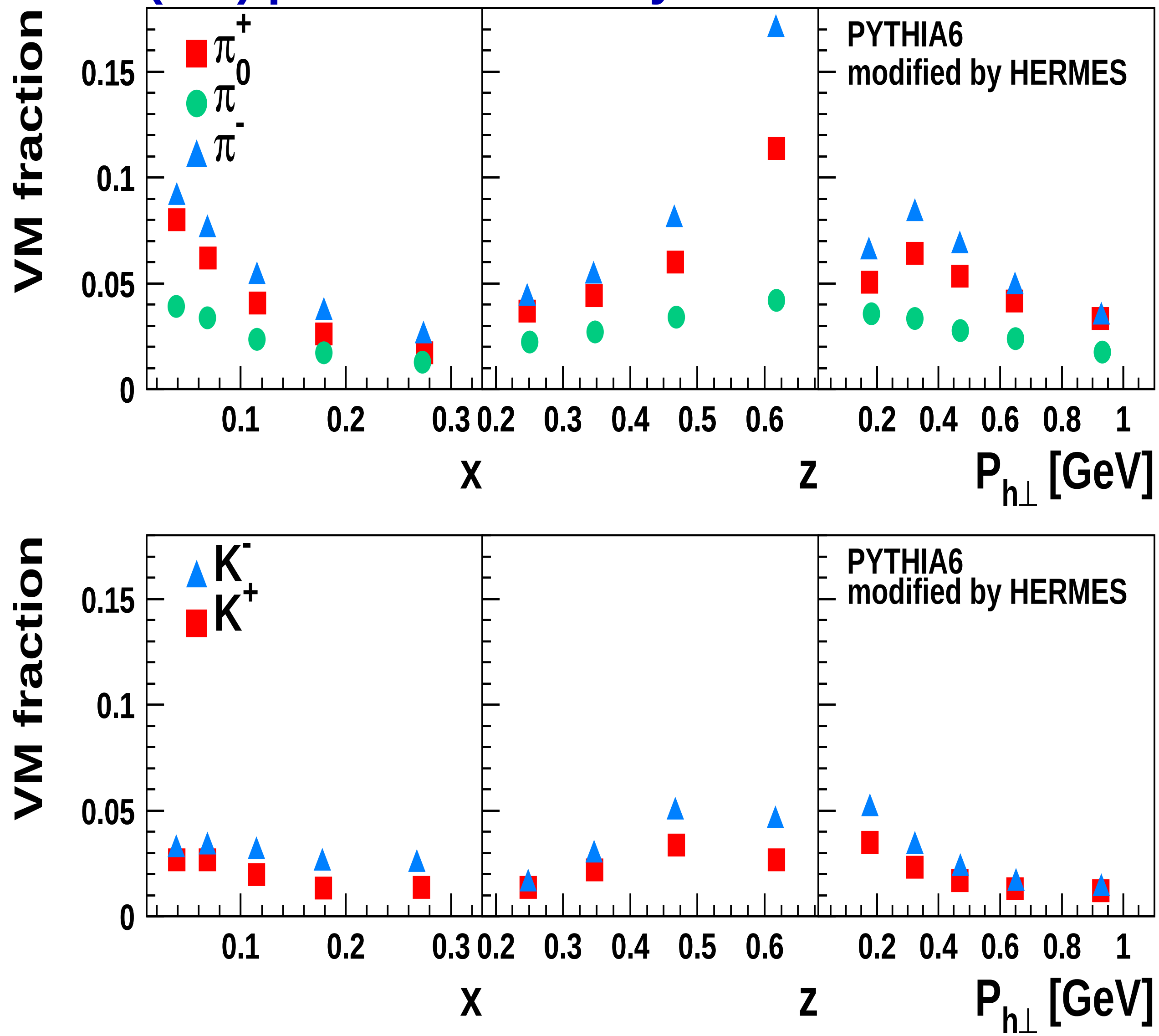
Vector Meson Contamination in $1h$ Analysis

- Possible contribution to asymmetry measured A_{UT} from exclusive vector meson (VM) production decay not known

Fraction

of contamination

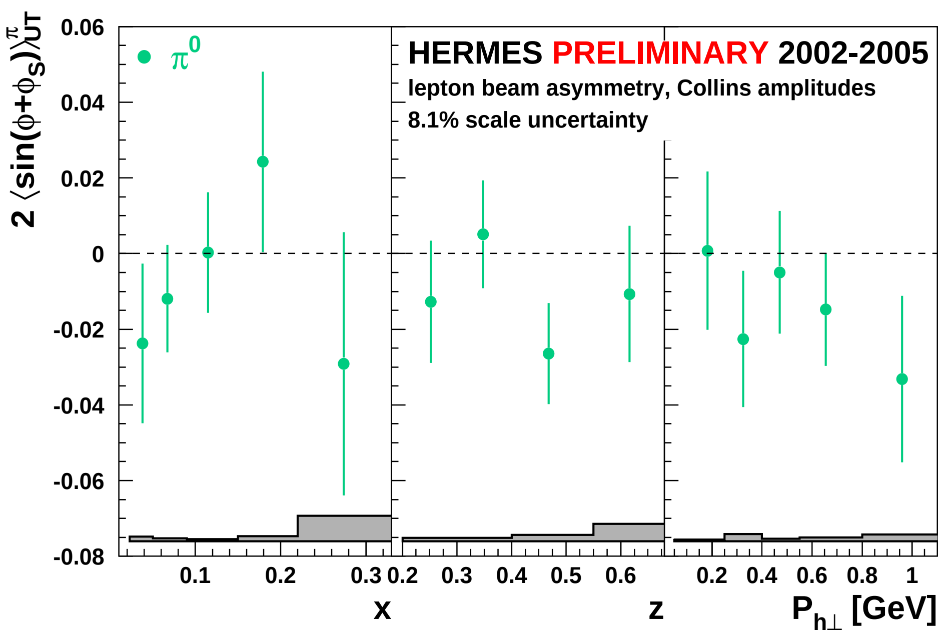
from VMs simulated

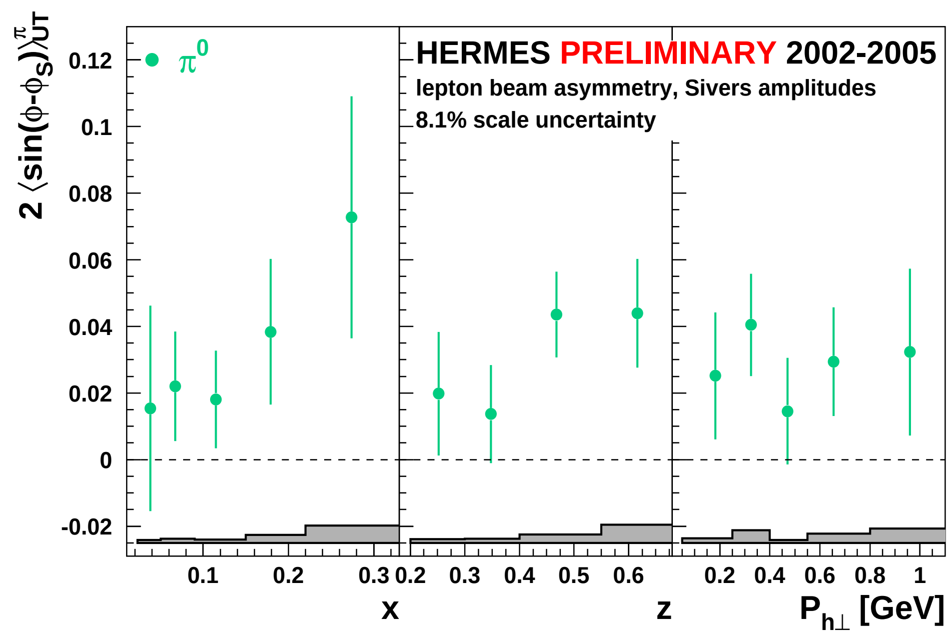


Isospin Symmetry for π Production

- **Assuming π strong isospin symmetry holds at HERMES**
  $\rightarrow H_1^{\perp}(u \rightarrow \pi^+) \approx H_1^{\perp}(d \rightarrow \pi^-)$; $H_1^{\perp}(d \rightarrow \pi^+) \approx H_1^{\perp}(u \rightarrow \pi^-)$
  $\rightarrow \pi$ **Collins/Sivers amplitudes should be related to each other:**

$$\mathcal{R} = A_{UT}^{\pi^+} + C A_{UT}^{\pi^-} - (1+C) A_{UT}^{\pi^0} = 0 \qquad C = \sigma_{unpol}^{\pi^-} / \sigma_{unpol}^{\pi^+}$$

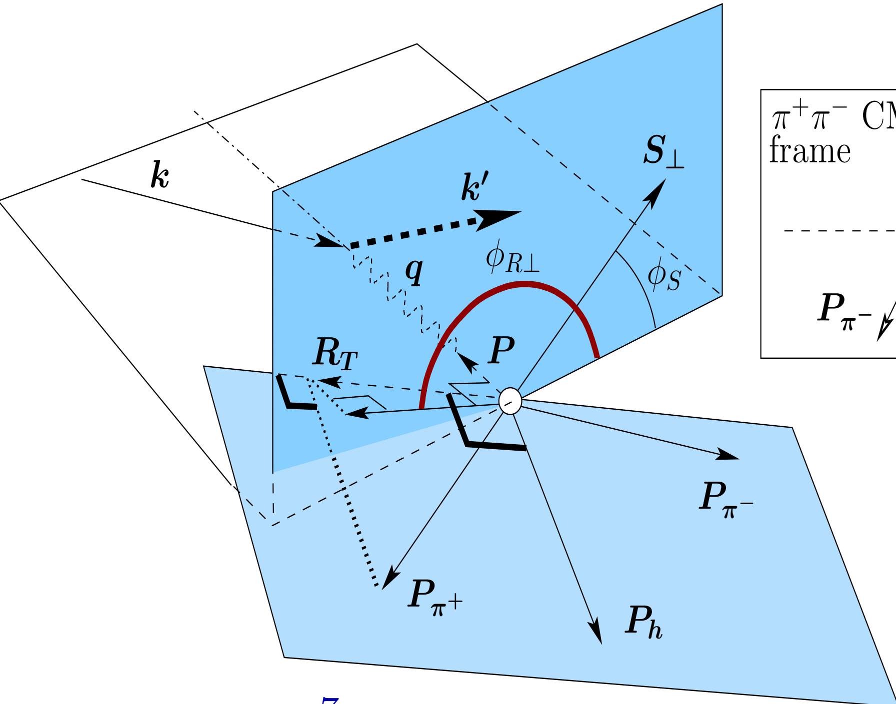


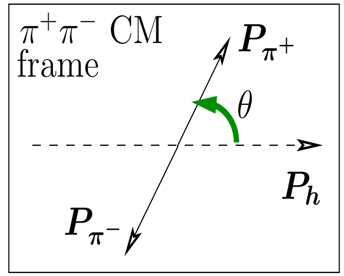


- $\mathcal{R}_{Collins} = 0.0173 \pm 0.0139$
- $\mathcal{R}_{Sivers} = -0.0022 \pm 0.0141$

- **Internal consistency verified within 1.3σ**

Two-Pions Analysis: Complete Cross-section





$$e^+ p^{\Uparrow\Downarrow} \longrightarrow e^+ \pi^+ \pi^- X$$

$$A_{UT} = \frac{1}{S_T} \cdot \frac{d^7\sigma_{UT}}{d^7\sigma_{UU}}$$

$$\sigma = \sigma_{UU}(1 + S_T \cdot A_{UT})$$

At leading twist and leading order:

- $$\frac{d^7\sigma_{UU}}{dx\,dy\,dz\,d\phi_S\,d\phi_{R\perp}\,d\cos\theta\,dm_{\pi\pi}} =$$
$$\sum_q \frac{\alpha_S^2 e_q^2}{2\pi s x y^2}\,(1 - y + y^2/2)\,q^q(x)\,D_q(z, m_{\pi\pi}, \cos\theta)$$

- $$\frac{d^7\sigma_{UT}}{dx\,dy\,dz\,d\phi_S\,d\phi_{R\perp}\,d\cos\theta\,dm_{\pi\pi}} \stackrel{\text{def}}{=} d^7\sigma_{U\Uparrow} - d^7\sigma_{U\Downarrow} =$$
$$-\|\vec{S_\perp}\| \sum_q \frac{\alpha_S^2 e_q^2}{2\pi s x y^2}\,(1-y)\sqrt{1 - 4\frac{m_\pi^2}{m_{\pi\pi}^2}}\,\sin(\phi_{R\perp} + \phi_S)\,\sin\theta\, h_1^q(x)\, H_{1,q}^{\sphericalangle}(z, m_{\pi\pi}, \cos\theta)$$

Two-Pions Analysis: Legendre Decomposition

- $\cos\theta$**-dependence factorized out**

$$H_1^{\triangleleft}(z, m_{\pi\pi}, \cos\theta) = H_{1,UT}^{\triangleleft,sp}(z, m_{\pi\pi}) + H_{1,LT}^{\triangleleft,pp}(z, m_{\pi\pi})\frac{1}{4}\cos\theta ...$$

$$D(z, m_{\pi\pi}, \cos\theta) = D_{UU}(z, m_{\pi\pi}) + D_{UL}^{sp}(z, m_{\pi\pi})\cos\theta + D_{LL}^{pp}(z, m_{\pi\pi})\frac{1}{4}(3\cos\theta^2 - 1)...$$

- **Decomposition plugged into** A_{UT} **expression**

$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S)\frac{h_1(x)}{q(x)} \cdot \frac{H_{1,UT}^{\triangleleft,sp}(z,m_{\pi\pi})\sin\theta + \frac{1}{2}H_{1,LT}^{\triangleleft,pp}(z,m_{\pi\pi})\sin 2\theta}{D_{UU}(z,m_{\pi\pi}) + D_{UL}^{sp}(z,m_{\pi\pi})\cos\theta + D_{LL}^{pp}(z,m_{\pi\pi})\frac{1}{4}(3\cos\theta^2 - 1)}$$