Transverse Spin Physics at HERMES

- Azimuthal asymmetries in semi-inclusive deep inelastic scattering
- Results of the HERMES experiment
- Subleading twist terms for longitudinally polarised target
- Two pion semi-inclusive deep inelastic scattering
- Summary and outlook

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Nuclear Dynamics Workshop
Breckenridge, Colorado
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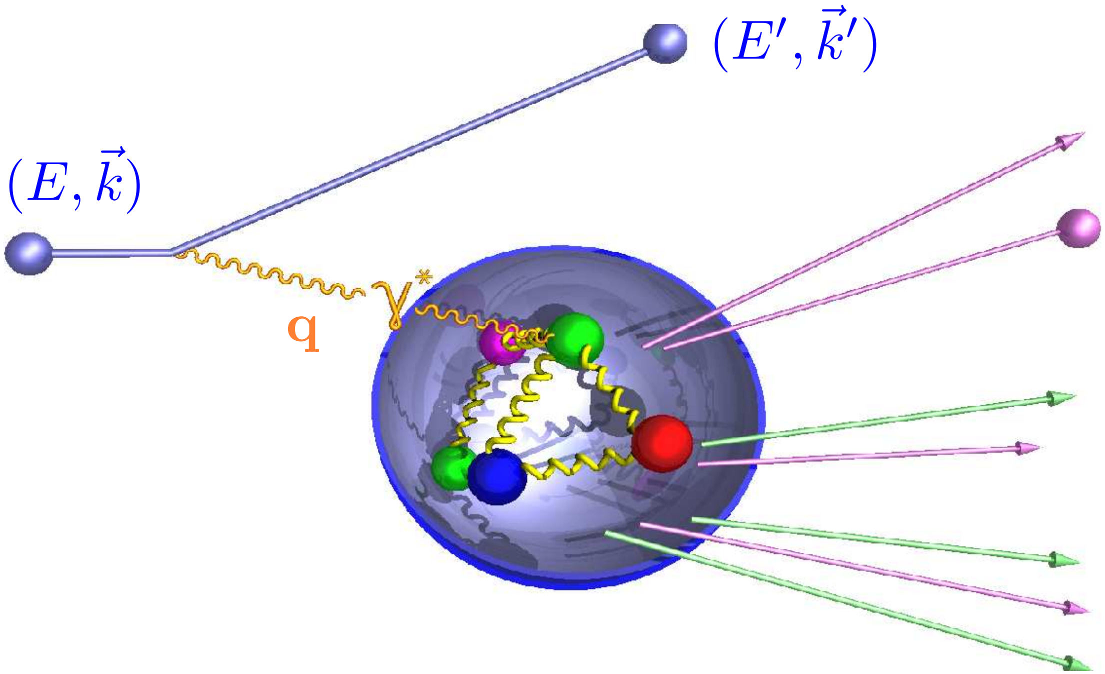
Semi-inclusive Deep Inelastic Scattering



$$Q^2 = -\mathbf{q}^2 = -(\mathbf{k} - \mathbf{k}')^2$$

$$\nu \overset{\text{Lab}}{=} E - E'$$

$$x = \frac{Q^2}{2M\nu}$$

$$z \overset{\text{Lab}}{=} \frac{E_{had}}{\nu}$$

evaluation of the cross section contains
quark distribution and fragmentation functions

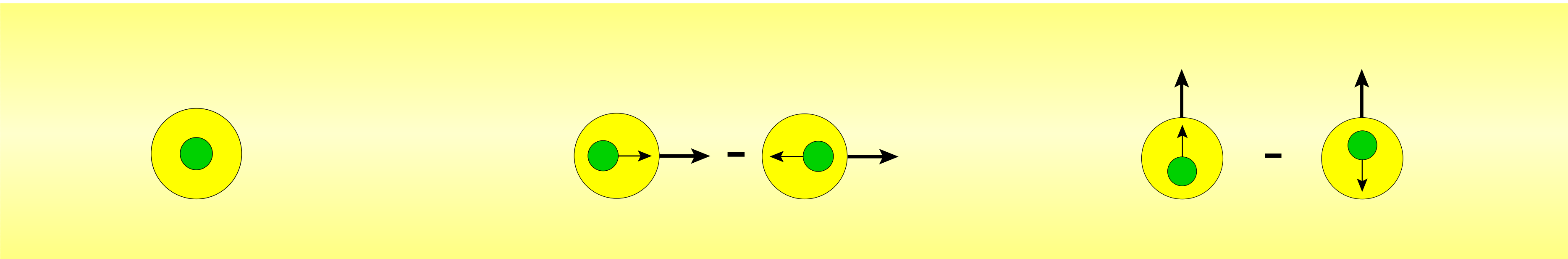
$$\sigma^{ep\to eh} \sim \sum_q \mathbf{DF}^{p\to q} \otimes \sigma^{eq\to eq} \otimes \mathbf{FF}^{q\to h}$$

Distribution Functions

Leading twist:

3 DFs survive the integration over transverse quark momenta

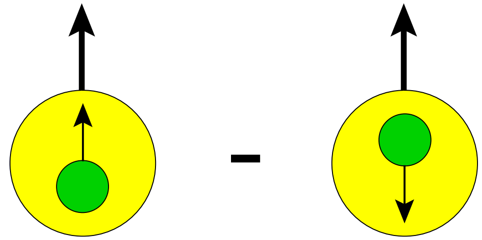
unpolarised DF	Helicity	Transversity



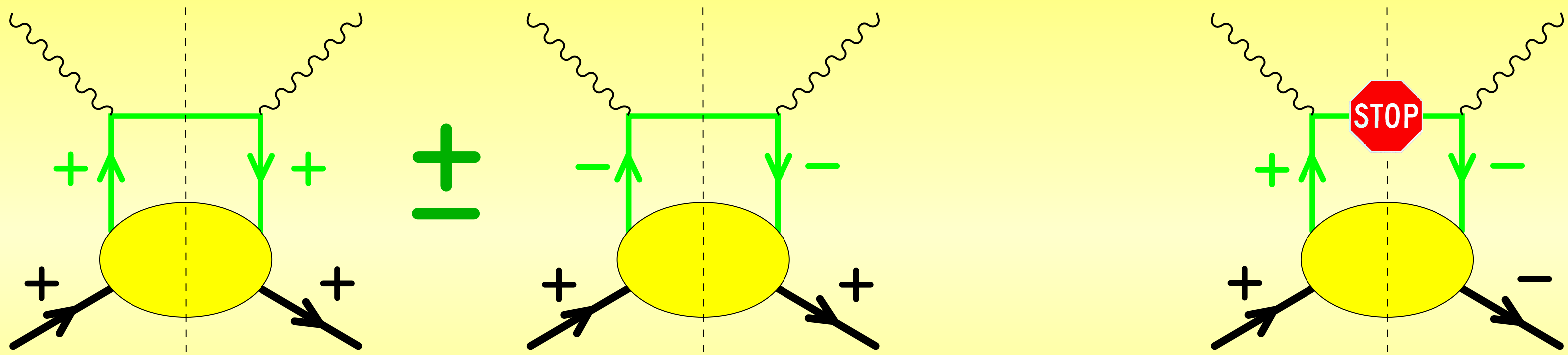
$q(x, Q^2)$	$\Delta q(x, Q^2)$	$\delta q(x, Q^2)$
well known	known	unknown
	HERMES 1996-2000	HERMES > 2002

Transversity δq

- non-relativistic quarks ➜ transversity = helicity



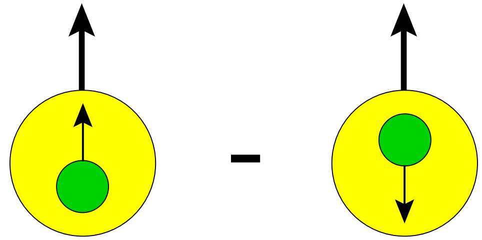
- chiral-odd ➜ helicity flip



+ ➜ $q(x)$ **−** ➜ $\Delta q(x)$

Transversity δq

- non-relativistic quarks ➜ transversity = helicity



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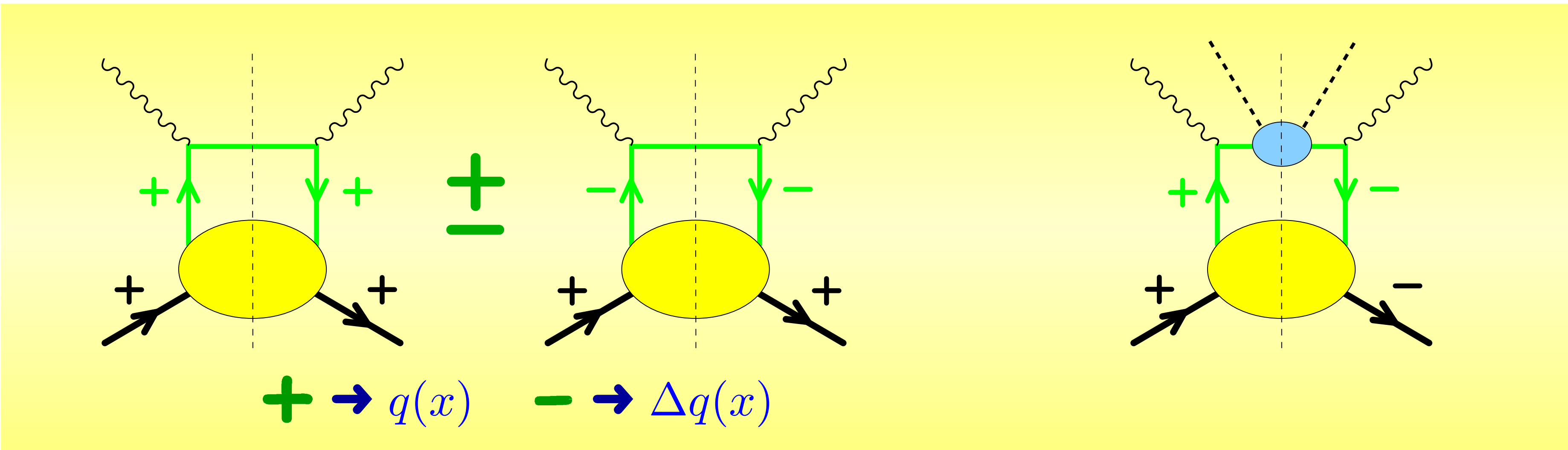
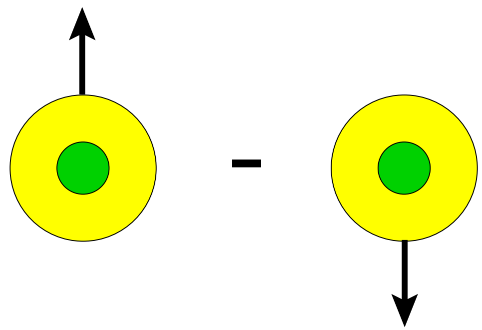


- access of δq in combination with other chiral-odd object
  ➜ χ-odd fragmentation function $H_1^{\perp}(z)$ (Collins function)

Sivers Function $f_{1T}^{\perp}$



- describes correlation between intrinsic transverse quark momentum $\vec{p}_T$ and transverse nucleon spin

- chiral-even function

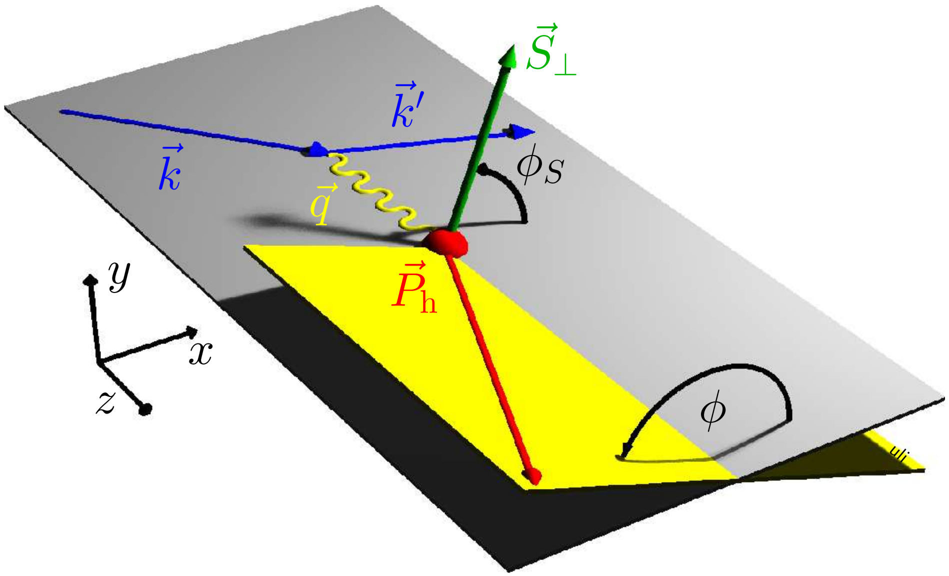
- naïve T-odd: reverse everything except initial and final state
  $f_{1T}^{\perp}$ allowed due to final state interactions (FSI):
  quark rescattering via a soft gluon

- non-zero Sivers function requires non-vanishing quark orbital angular momentum (contributing to nucleon spin)

Azimuthal Asymmetries

Measurement of cross section asymmetries depending on the azimuthal angles ϕ and ϕ_S

$$A_{\mathrm{UT}}(\phi,\phi_S) = \frac{1}{S_\perp}\frac{N^\uparrow(\phi,\phi_S) - N^\downarrow(\phi,\phi_S)}{N^\uparrow(\phi,\phi_S) + N^\downarrow(\phi,\phi_S)}$$



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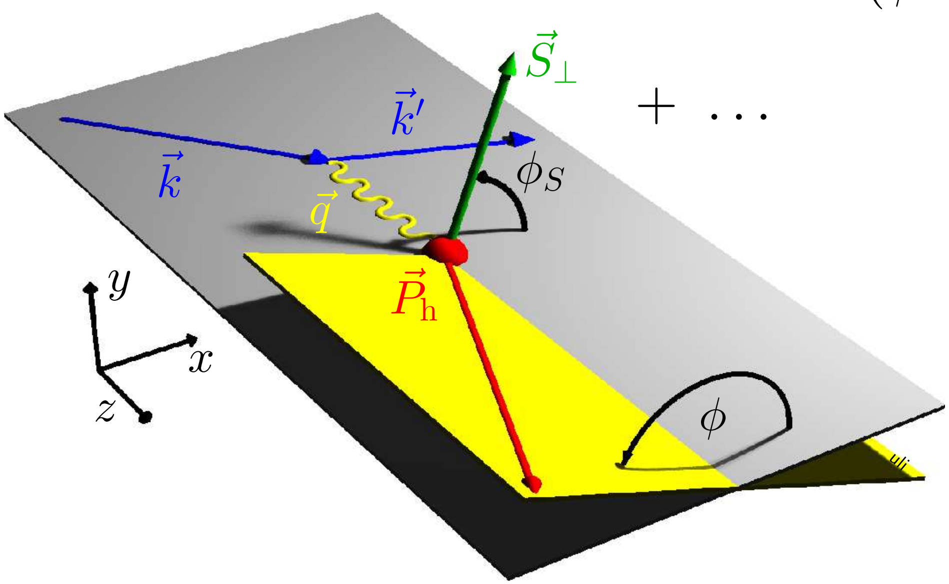
$$\sim \ldots \sin(\phi+\phi_S)\frac{\sum_q e_q^2\, \mathcal{I}\left[\ldots \delta q(x,\vec{p}_T^{\,2}) \cdot H_1^{\perp q}(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\, q(x)\cdot D_1^q(z)}$$

$$+ \ \ldots \sin(\phi-\phi_S)\frac{\sum_q e_q^2\, \mathcal{I}\left[\ldots f_{1T}^{\perp q}(x,\vec{p}_T^{\,2}) \cdot D_1^q(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\, q(x)\cdot D_1^q(z)}$$

$$+ \ \ldots$$



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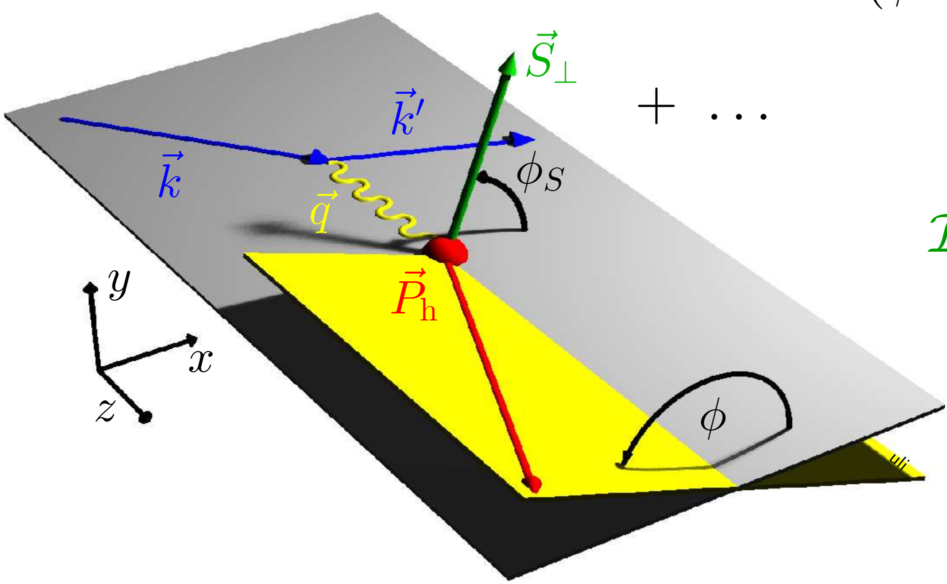
$$+ \ \ldots$$



$\mathcal{I}\,[\ldots]$: convolution integral over initial ($\vec{p}_T$) and final ($\vec{k}_T$) quark transverse momenta

How to Disentangle . . .

. . . distribution and fragmentation functions?

Assume a Gaussian distribution for $\vec{p}_T$ and $\vec{k}_T$ dependence:

$$A_{\rm UT}(\phi,\phi_S) \;\sim\; \ldots \sin(\phi+\phi_S) \sum_q e_q^2 \cdot \delta q(x) \cdot H_1^{\perp(1/2)\,q}(z) + \ldots \sin(\phi-\phi_S) \sum_q e_q^2 \cdot f_{1T}^{\perp(1/2)\,q}(x) \cdot D_1^q(z)$$

(1/2): $|\vec{p}_T|$, $|\vec{k}_T|$ moment of
distribution / fragmentation function

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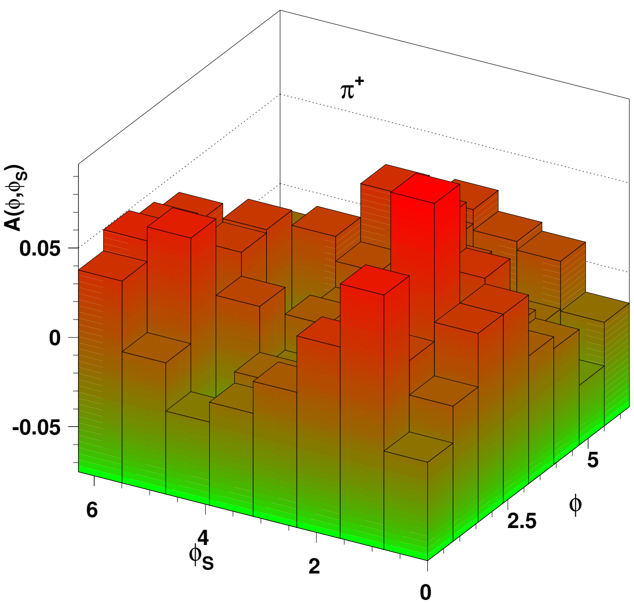
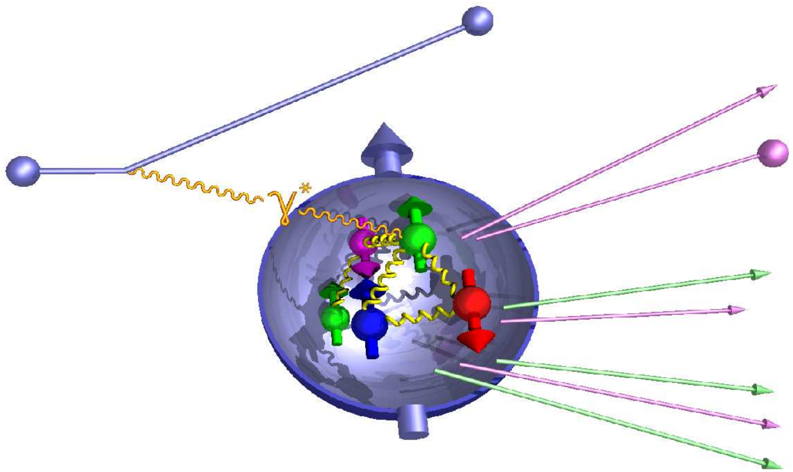
$$+ \;\ldots \sin(\phi-\phi_S)\underbrace{\sum_q e_q^2 \cdot f_{1T}^{\perp(1/2)\,q}(x) \cdot D_1^q(z)}$$

asymmetry amplitudes $A_{\mathrm{UT}}^{\sin(\phi+\phi_S)}$ and $A_{\mathrm{UT}}^{\sin(\phi-\phi_S)}$



bin $A_{\mathrm{UT}}(\phi,\phi_S)$ in 8×8 bins,
perform two dimensional fit

The HERMES Experiment at HERA



The HERMES Experiment at HERA

HERA positron beam 27.5 GeV

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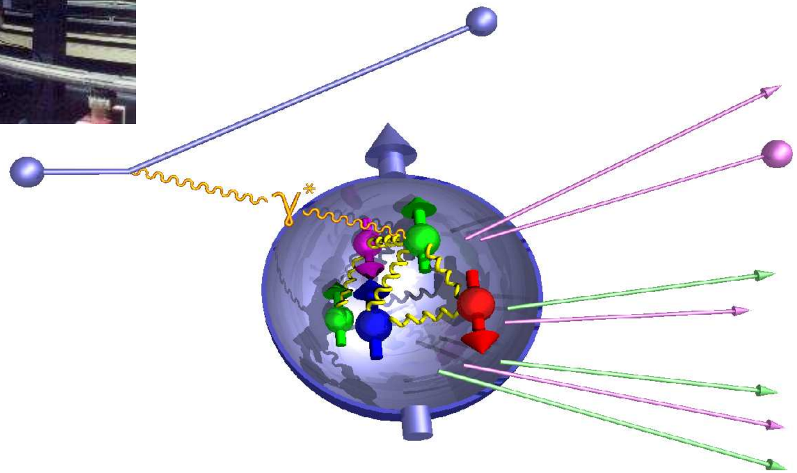

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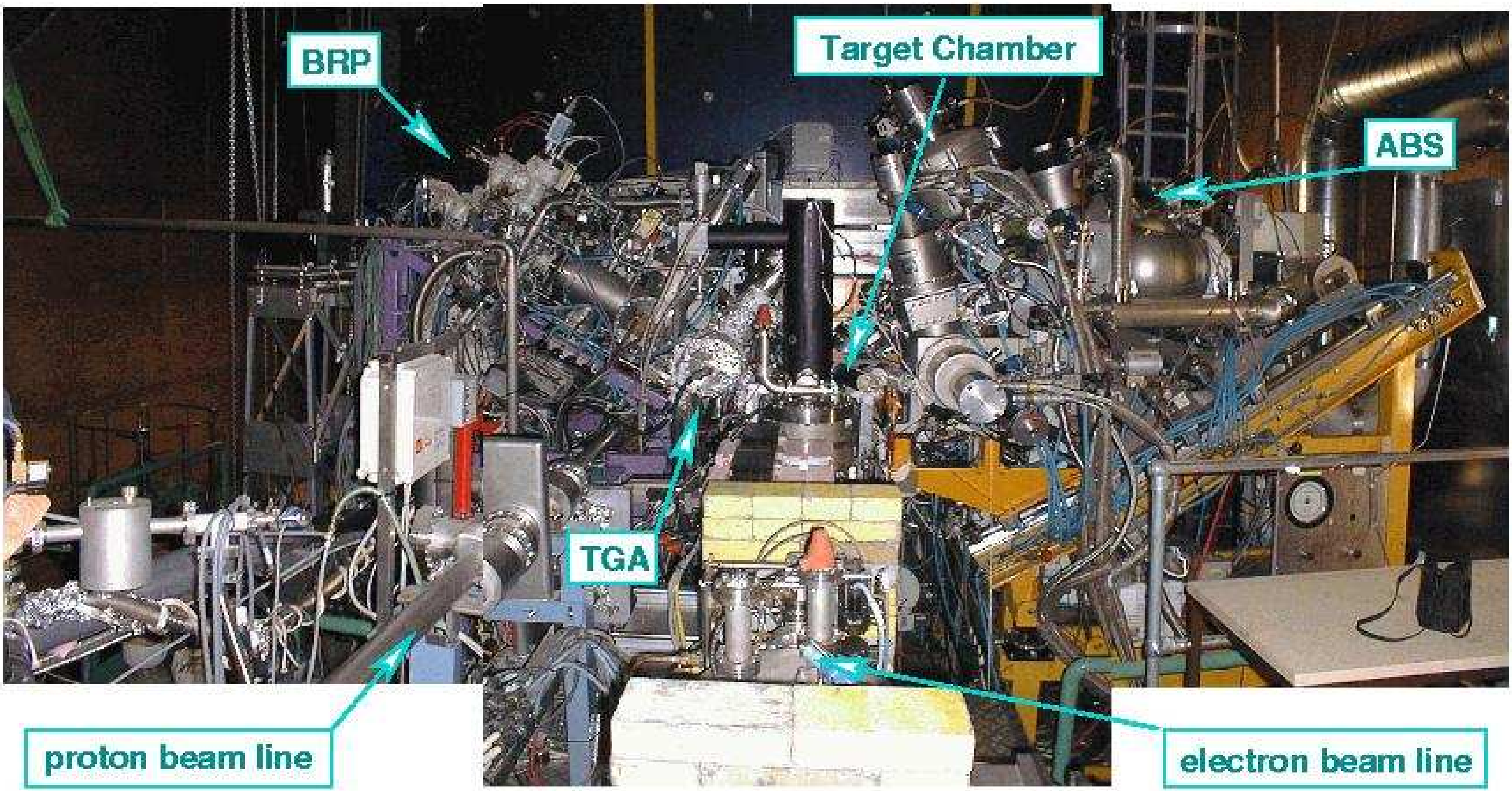
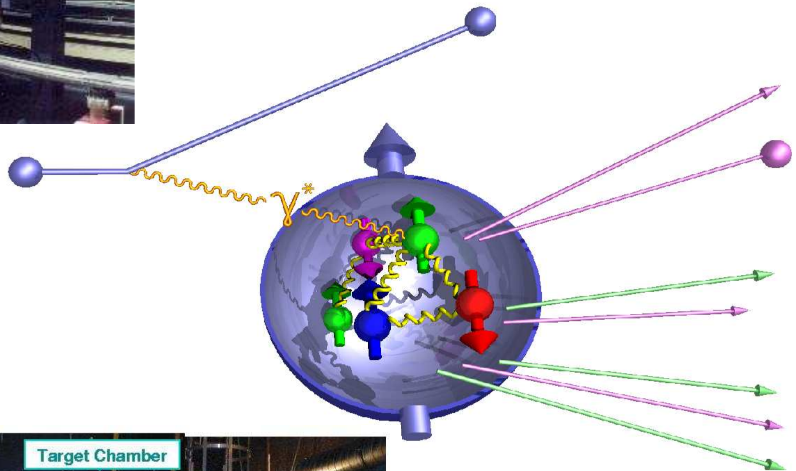
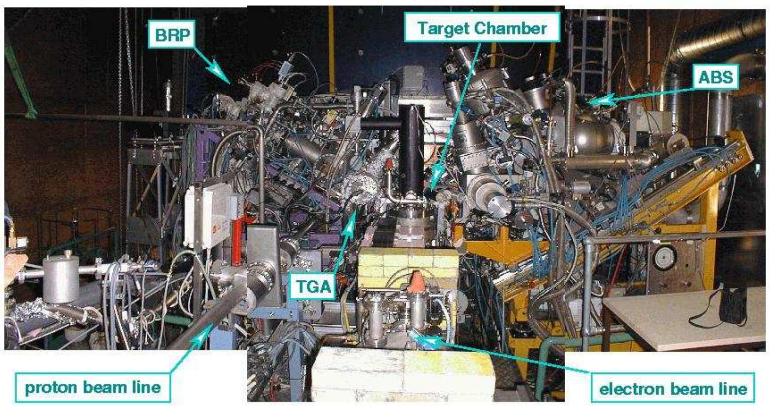


transversely polarised atomic Hydrogen $\langle P \rangle \approx 80$ %

The HERMES Experiment at HERA

HERA positron beam 27.5 GeV





since 2002

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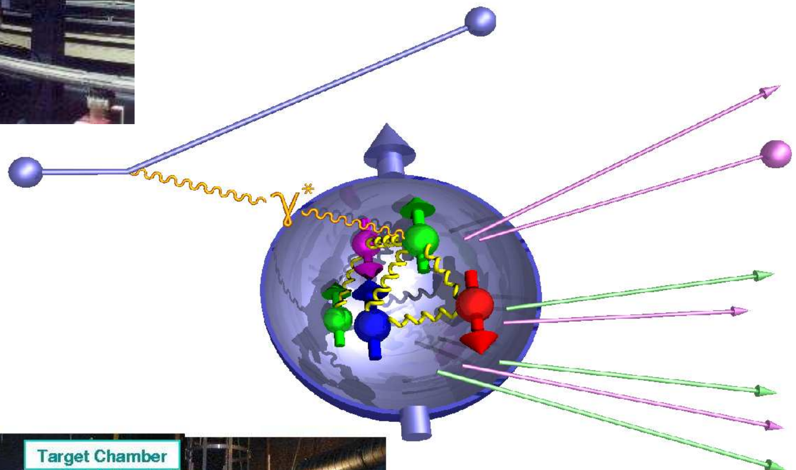
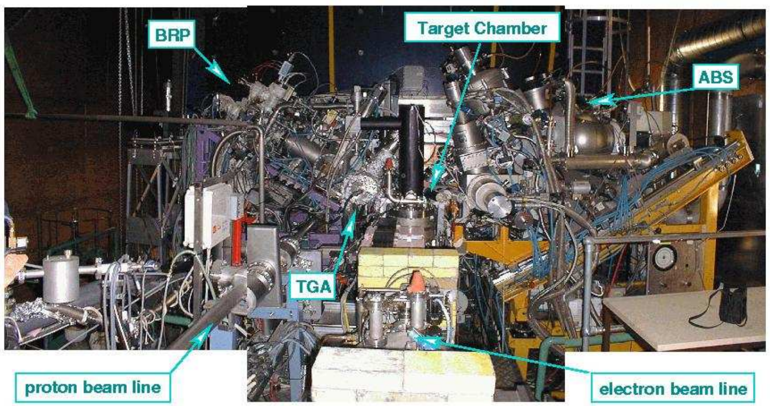
The HERMES Experiment at HERA

The HERMES Experiment at HERA

HERA positron beam 27.5 GeV

HERMES spectrometer





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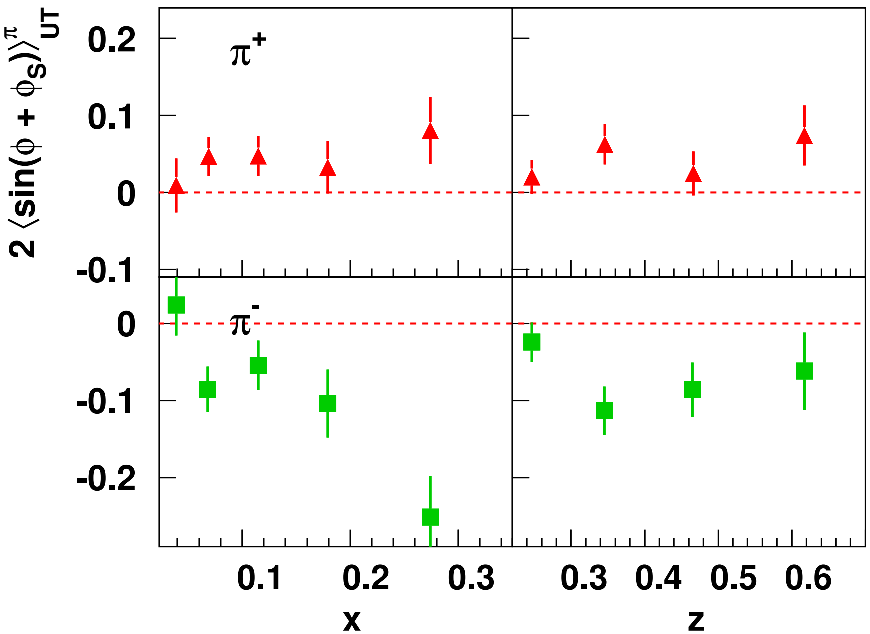
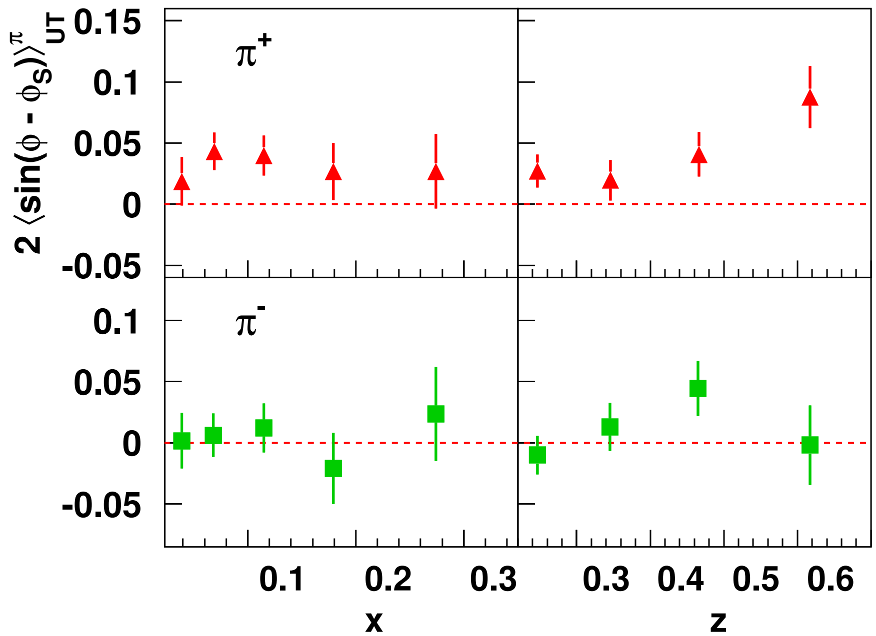
Results for the Asymmetry Amplitudes

$$A_{\mathrm{UT}}^{\sin(\phi+\phi_S)} \sim \delta q(x) \cdot H_1^{\perp(1/2)}(z)$$



$$A_{\mathrm{UT}}^{\sin(\phi-\phi_S)} \sim f_{1T}^{\perp(1/2)}(x) \cdot D_1(z)$$



overall scale uncertainty 8%

[Phys. Rev. Lett. 94 (2005) 012002]

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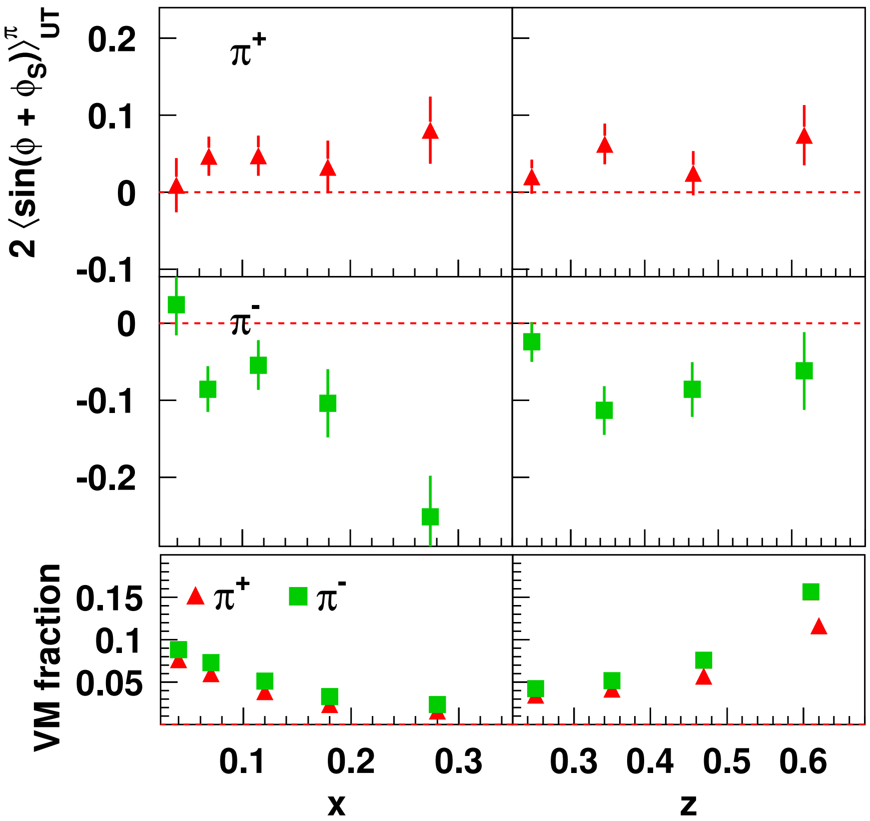


- positive for π^+, negative for π^- expectations: δu > 0, δd < 0
- unexpected large absolute value for π^-
- contribution to pion sample from exclusively produced vector mesons (PYTHIA)

[Phys. Rev. Lett. 94 (2005) 012002]

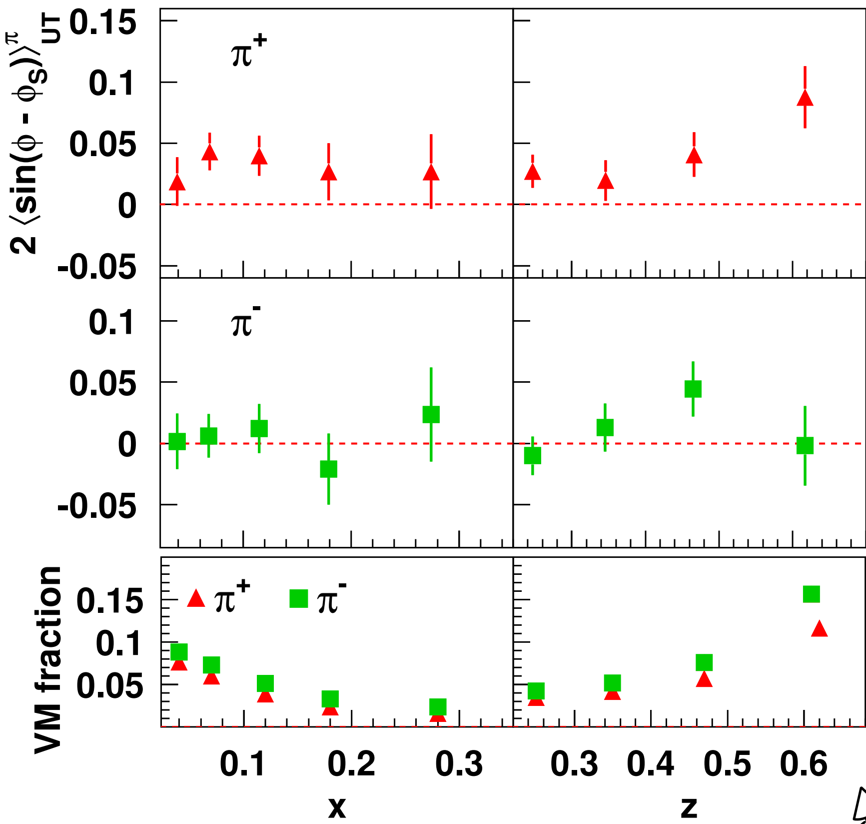
Results for the Asymmetry Amplitudes

$$A_{\mathrm{UT}}^{\sin(\phi-\phi_S)} \sim f_{1T}^{\perp(1/2)}(x) \cdot D_1(z)$$

- π^- asymmetry consistent with zero
- significantly positive for π^+

→ first hint of naïve T-odd DF from DIS

- contribution to pion sample from exclusively produced vector mesons (PYTHIA)

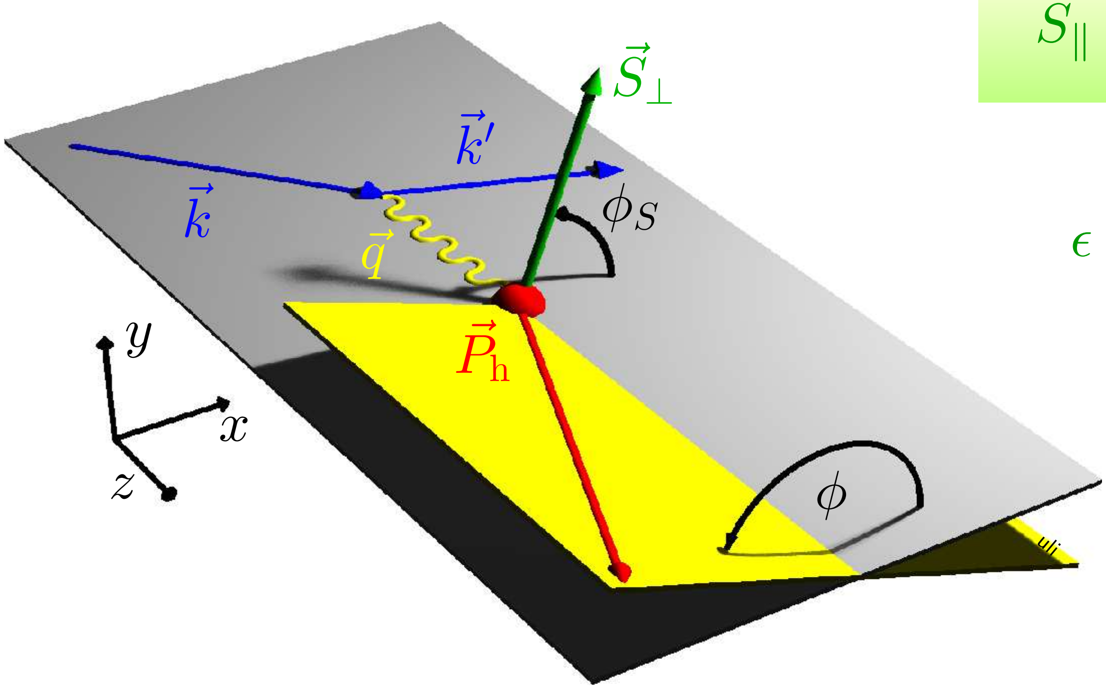


[Phys. Rev. Lett. 94 (2005) 012002]

Transversely Polarised Target

Theory: polarisation w.r.t. the virtual photon ➜ $A_{\mathrm{UT},\gamma^*}^{\sin(\phi\pm\phi_S)}$

Experiment: polarisation w.r.t. the lepton beam ➜ $A_{\mathrm{UT},l}^{\sin(\phi\pm\phi_S)}$



$$S_\perp = \epsilon \cos\theta_{\gamma^*}$$
$$S_\parallel = \epsilon \sin\theta_{\gamma^*} \cos\phi_S$$

$$\epsilon = 1\Big/\sqrt{1-\sin^2\phi_S \sin^2\theta_{\gamma^*}} \approx 1$$

Transversely Polarised Target

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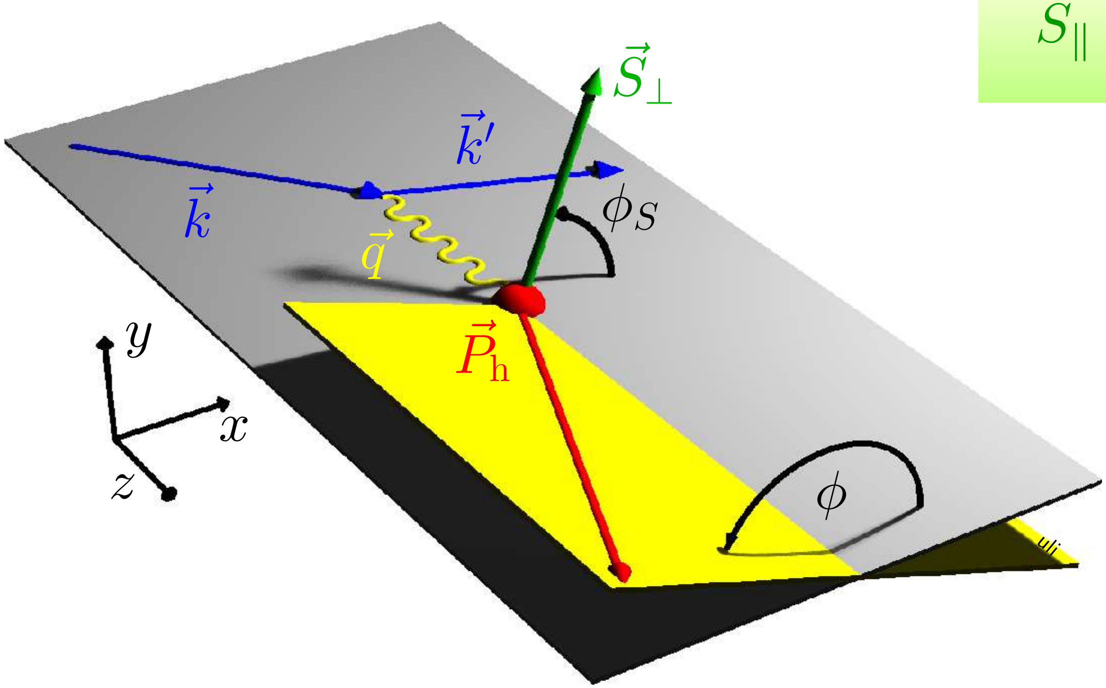


$$S_\perp = \epsilon \cos\theta_{\gamma^*}$$

$$S_\parallel = \epsilon \sin\theta_{\gamma^*} \cos\phi_S$$

➜ $\langle S_\parallel \rangle = 0$

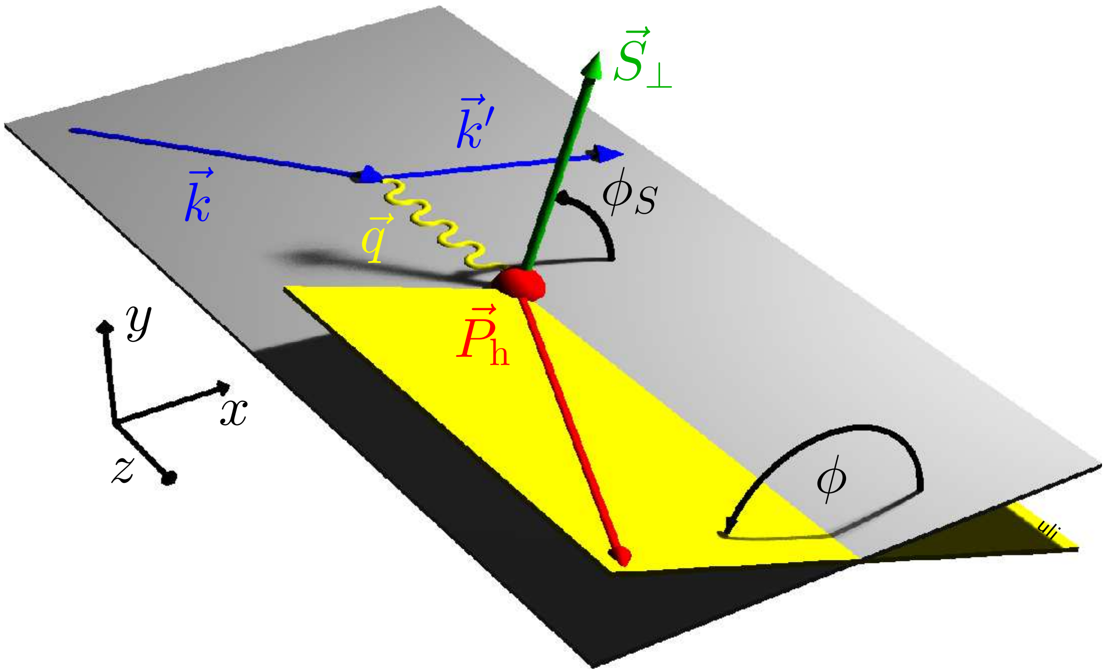
➜ $A_{UT,\gamma^*}^{\sin(\phi\pm\phi_S)} \approx \cos\theta_{\gamma^*}\, A_{UT,l}^{\sin(\phi\pm\phi_S)}$

$A_{UT,\gamma^*}^{\sin(\phi\pm\phi_S)} \approx A_{UT,l}^{\sin(\phi\pm\phi_S)}$

Transversely Polarised Target

BUT: If A_{UL,γ^*} contains $\sin\phi$ modulation

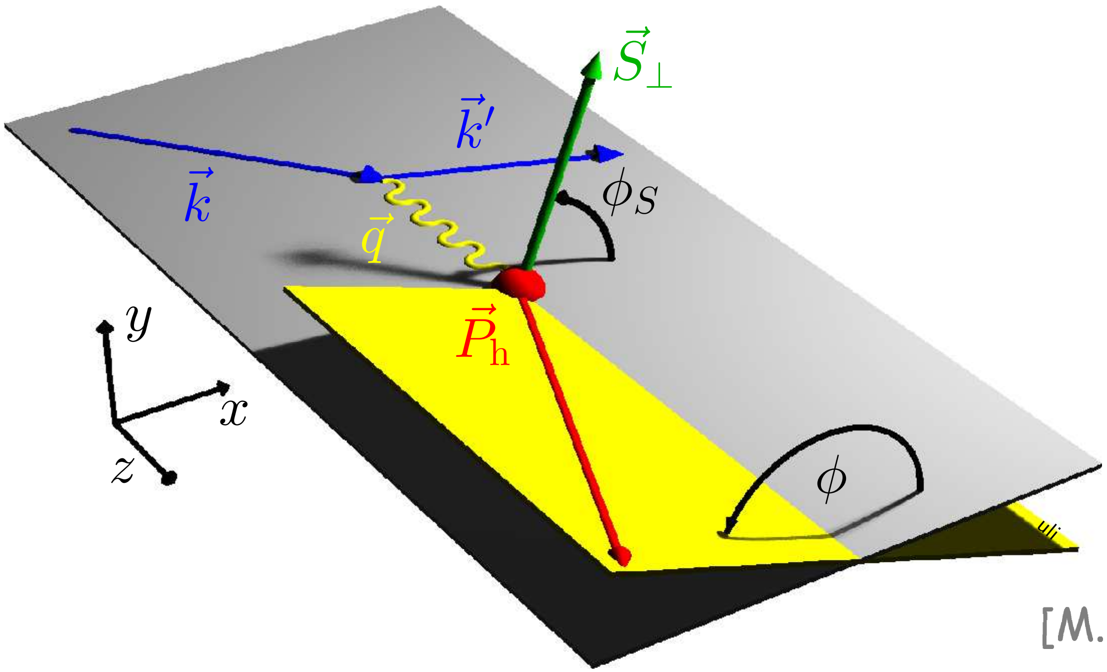
➜ $$\cos\phi_S \sin\phi = \frac{1}{2}\left[\,\sin(\phi+\phi_S)+\sin(\phi-\phi_S)\right]$$



Transversely Polarised Target

$$A_{\mathrm{UT},l}^{\sin(\phi+\phi_S)} = \cos\theta_{\gamma^*}\, A_{\mathrm{UT},\gamma^*}^{\sin(\phi+\phi_S)} + \frac{1}{2}\sin\theta_{\gamma^*}\, A_{\mathrm{UL},\gamma^*}^{\sin\phi}$$

$$A_{\mathrm{UT},l}^{\sin(\phi-\phi_S)} = \cos\theta_{\gamma^*}\, A_{\mathrm{UT},\gamma^*}^{\sin(\phi-\phi_S)} + \frac{1}{2}\sin\theta_{\gamma^*}\, A_{\mathrm{UL},\gamma^*}^{\sin\phi}$$



$$\cos\theta_{\gamma^*} \approx 1$$

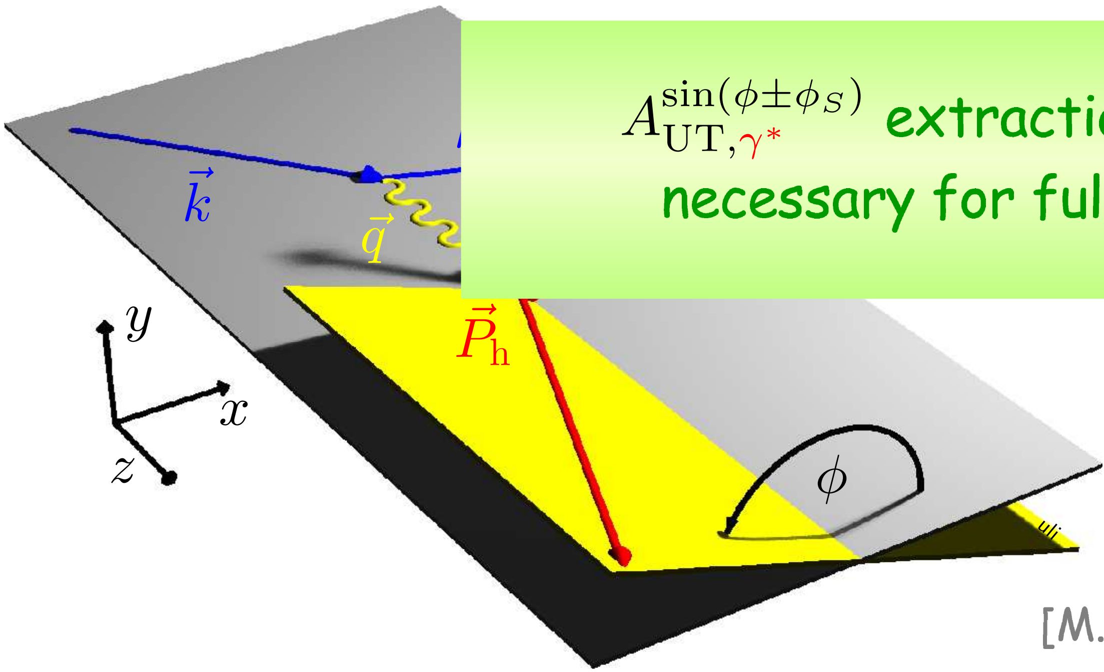
$$\sin\theta_{\gamma^*} = 4\ldots15\%$$

[M. Diehl, S. Sapeta, in preparation]

Transversely Polarised Target

$$A_{\mathrm{UT},\gamma^*}^{\sin(\phi+\phi_S)} \approx A_{\mathrm{UT},l}^{\sin(\phi+\phi_S)} - \frac{1}{2}\sin\theta_{\gamma^*}\, A_{\mathrm{UL},l}^{\sin\phi}$$

$$A_{\mathrm{UT},\gamma^*}^{\sin(\phi-\phi_S)} \approx A_{\mathrm{UT},l}^{\sin(\phi-\phi_S)} - \frac{1}{2}\sin\theta_{\gamma^*}\, A_{\mathrm{UL},l}^{\sin\phi}$$



$A_{\mathrm{UT},\gamma^*}^{\sin(\phi\pm\phi_S)}$ extraction possible!
necessary for full data set

[M. Diehl, S. Sapeta, in preparation]

Longitudinally Polarised Target

$$A_{\mathrm{UL},\gamma^*}^{\sin\phi} \sim \ldots \frac{1}{Q} \frac{\sum_q e_q^2\, \mathcal{I}\left[\ldots h_L(x,\vec{p}_T^{\,2}) \cdot H_1^{\perp q}(z,\vec{k}_T^{\,2})\right.}{\sum_q e_q^2\, q(x) \cdot D_1^q(z)}$$

$$\frac{+\ldots \Delta q(x,\vec{p}_T^{\,2}) \cdot G^{\perp q}(z,\vec{k}_T^{\,2})}{\sum_q e_q^2\, q(x) \cdot D_1^q(z)}$$

Subleading twist!

➜ no probabilistic interpretation

$$\frac{+\ldots h_{1L}^{\perp}(x,\vec{p}_T^{\,2}) \cdot \tilde{H}^q(z,\vec{k}_T^{\,2})}{\sum_q e_q^2\, q(x) \cdot D_1^q(z)}$$

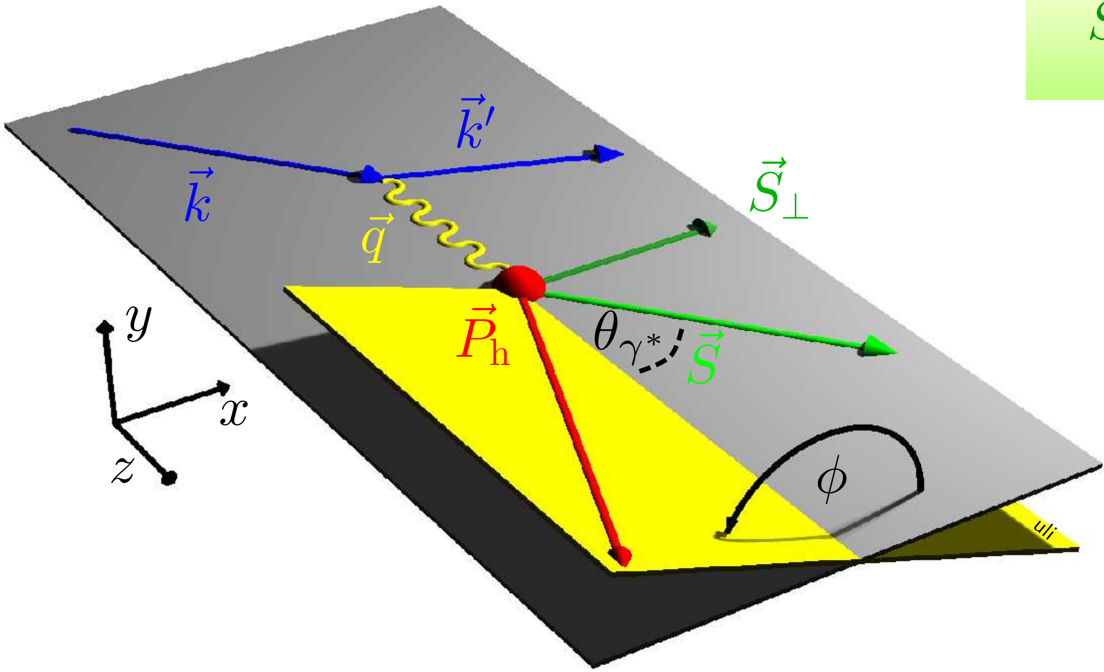
$$\frac{\left. +\ldots f_L^{\perp}(x,\vec{p}_T^{\,2}) \cdot D_1^q(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\, q(x) \cdot D_1^q(z)}$$

Measurement with longitudinally polarised Hydrogen available!

Longitudinally Polarised Target

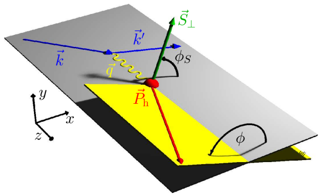
$$A_{\mathrm{UL},l}^{\sin\phi} = \cos\theta_{\gamma^*}\, A_{\mathrm{UL},\gamma^*}^{\sin\phi} - \sin\theta_{\gamma^*}\, A_{\mathrm{UT},\gamma^*}^{\sin(\phi+\phi_S)} - \sin\theta_{\gamma^*}\, A_{\mathrm{UT},\gamma^*}^{\sin(\phi-\phi_S)}$$

$$S_\perp = \sin\theta_{\gamma^*}$$
$$S_\parallel = \cos\theta_{\gamma^*}$$

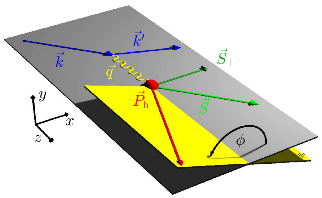


Subleading Twist Component

Combine measurements with



transversely polarised Hydrogen: $A_{\mathrm{UT},l}^{\sin(\phi+\phi_S)}$ and $A_{\mathrm{UT},l}^{\sin(\phi-\phi_S)}$

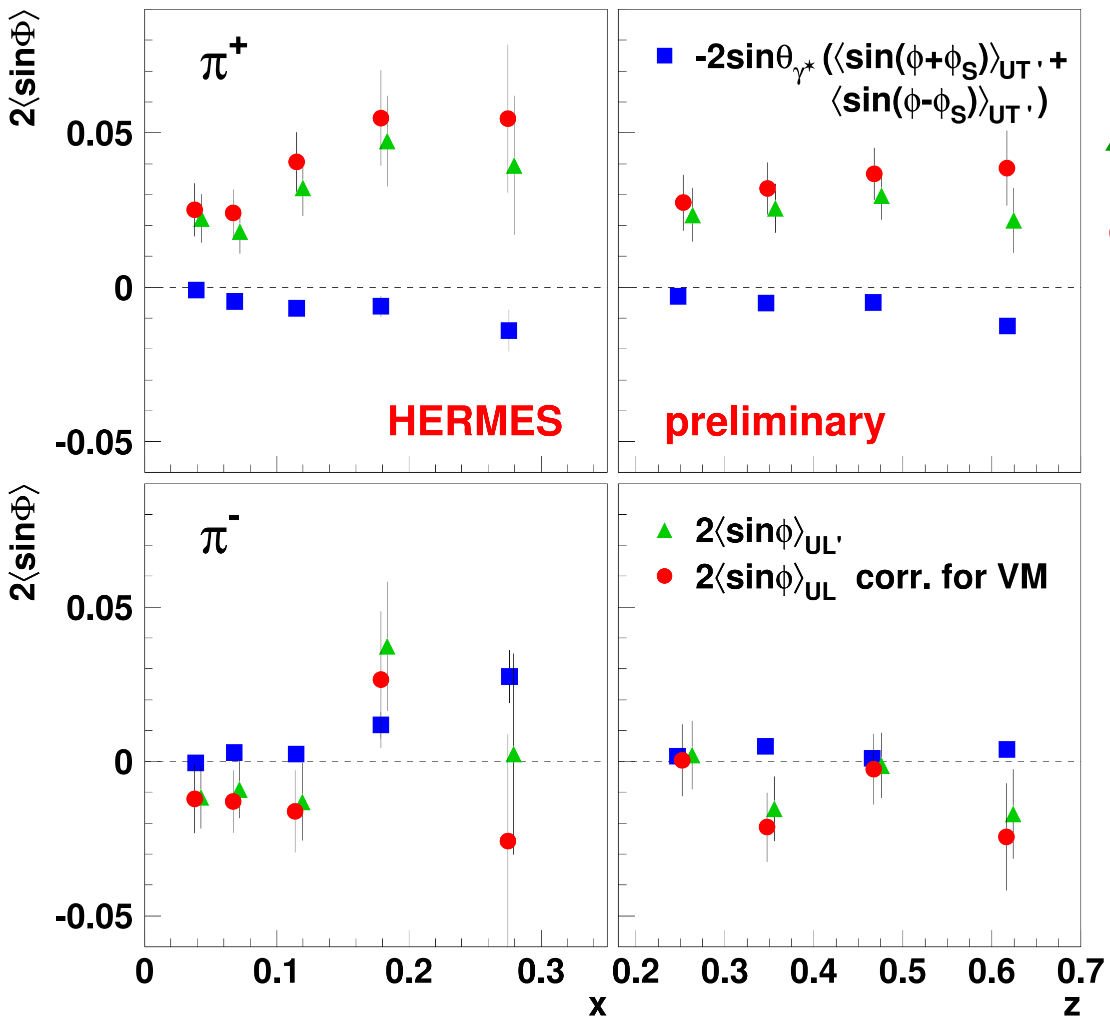


longitudinally polarised Hydrogen: $A_{\mathrm{UL},l}^{\sin\phi}$

$$\rightarrow \quad A_{\mathrm{UL},\gamma^*}^{\sin\phi} = \cos\theta_{\gamma^*} A_{\mathrm{UL},l}^{\sin\phi} + \sin\theta_{\gamma^*}\left(A_{\mathrm{UT},l}^{\sin(\phi-\phi_S)} + A_{\mathrm{UT},l}^{\sin(\phi+\phi_S)}\right)$$

$$\cos\theta_{\gamma^*} \approx 1 \qquad \sin\theta_{\gamma^*} = \frac{2xM}{Q}\sqrt{\frac{1-\frac{\nu}{E}-\frac{\nu^2x^2M^2}{E^2Q^2}}{1+\frac{4x^2M^2}{Q^2}}}$$

Results of $A_{\mathrm{UL},\gamma^*}^{\sin\phi}$



■ $-\sin\theta_{\gamma^*}\left(A_{\mathrm{UT},l}^{\sin(\phi-\phi_S)} + A_{\mathrm{UT},l}^{\sin(\phi+\phi_S)}\right)$

▲ $A_{\mathrm{UL},l}^{\sin\phi}$

● $A_{\mathrm{UL},\gamma^*}^{\sin\phi}$

- systematic uncertainty less than 0.003
- π^+: $A_{\mathrm{UL},\gamma^*}^{\sin\phi}$ = 2 . . . 5 %
  π^-: $A_{\mathrm{UL},\gamma^*}^{\sin\phi} \sim 0$
- measurement of $A_{\mathrm{UL},l}^{\sin\phi}$ dominated by $A_{\mathrm{UL},\gamma^*}^{\sin\phi}$

Extraction of the Distribution Functions

$$\sum_q \mathbf{DF}^q(x) \cdot \mathbf{FF}^q(z)$$

- measure $A^{\sin(\phi \pm \phi_S)}$ in many (x, z) bins
  → large statistics necessary
- information about fragmentation functions

Extraction of the Distribution Functions

$$\sum_q \mathbf{DF}^q(x) \cdot \mathbf{FF}^q(z)$$

$$\sum_q f_{1T}^{\perp q}(x) \cdot D_1^q(z)$$

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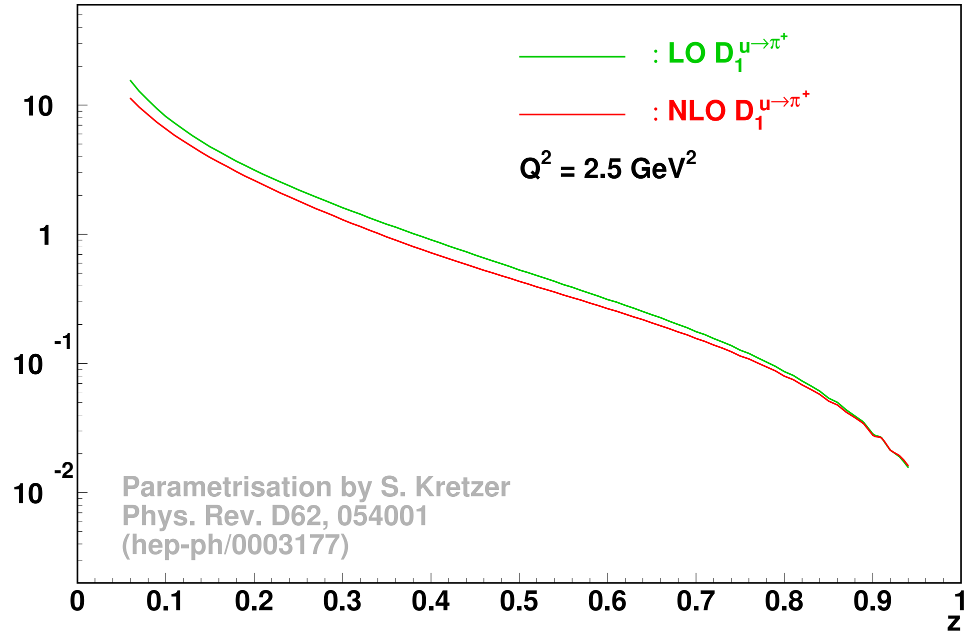
  ➜ large statistics necessary
- information about fragmentation functions
  - $D_1^{q \to h}(z)$ for some hadrons h sufficiently known



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    universality violated?
    basic expectation of QCD:
    sign opposite in Drell-Yan

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$$\sum_q f_{1T}^{\perp q}(x) \cdot D_1^q(z)$$

$$\sum_q \delta q(x) \cdot H_1^{\perp q}(z)$$

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  - $H_1^{\perp q \to h}(z)$: results of different asymmetries from other experiments,
    for example e^+e^- annihilation: BABAR, BELLE
    will make Transversity extraction possible

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$\sum_q \mathbf{DF}^q(x) \cdot \mathbf{FF}^q(z)$

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    for example e^+e^- annihilation: BABAR, BELLE
    will make Transversity extraction possible

$\mathbf{DF}^q(x)$

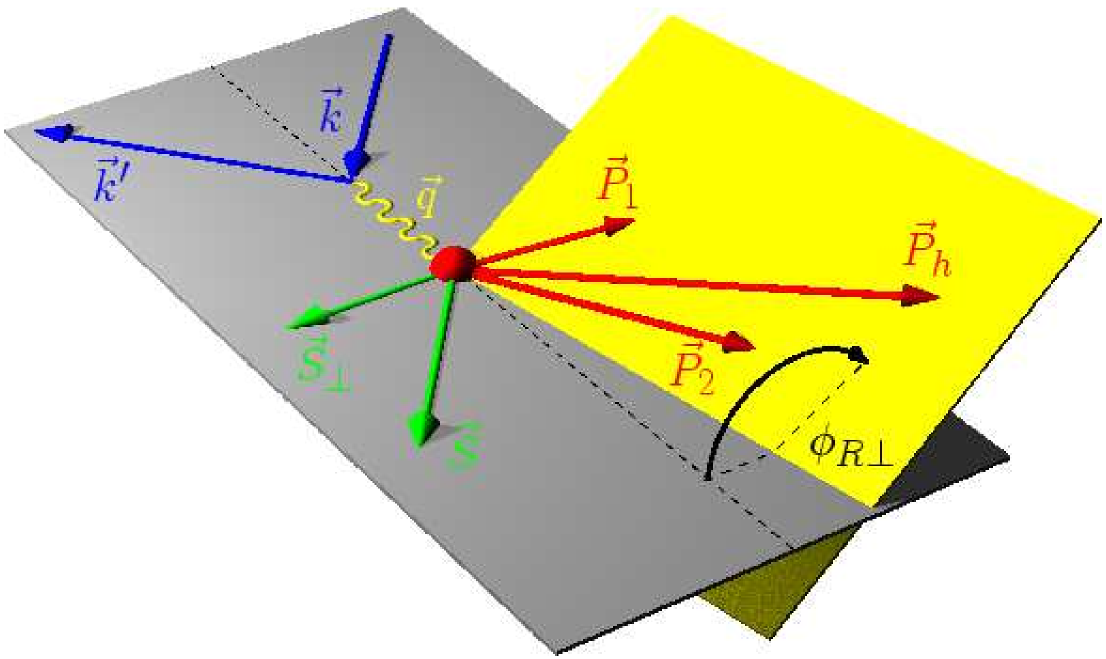
combination of $A^{\sin(\phi \pm \phi_S)}$ of various hadrons
➜ quark flavour decomposition

Two Pion Production in Semi-inclusive DIS

Detection of two final state pions:

$$A_{\mathrm{UL},\gamma^*} \sim \ \ldots \ \sin\phi_{R\perp} \frac{1}{Q} \left(h_L \cdot H_1^{\sphericalangle} + \Delta q \cdot \tilde{G}^{\sphericalangle} \right) + \ \ldots$$

$$A_{\mathrm{UT},\gamma^*} \sim \ \ldots \ \sin(\phi_{R\perp} + \phi_S)\ \delta q \cdot H_1^{\sphericalangle} + \ \ldots$$



$H_1^{\sphericalangle}$ and $\tilde{G}^{\sphericalangle}$: two pion fragmentation functions

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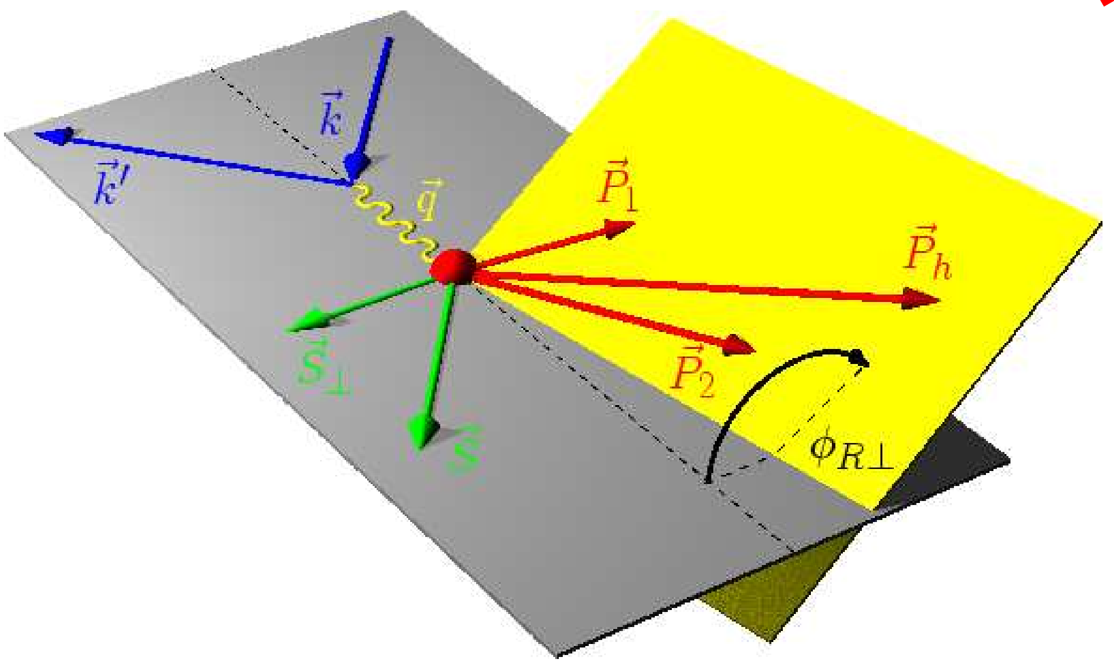
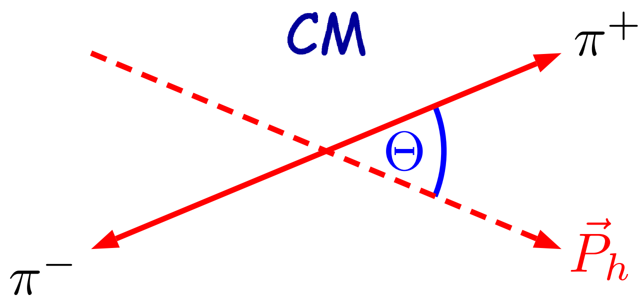


$H_1^{\sphericalangle}$ and $\tilde{G}^{\sphericalangle}$: two pion fragmentation functions

Interference Fragmentation Function $H_1^{\sphericalangle,sp}$

Partial wave expansion:

$$H_1^{\sphericalangle}(z, \cos\Theta, M_{\pi\pi}^2) = H_1^{\sphericalangle,sp}(z, M_{\pi\pi}^2) + \cos\Theta\ H_1^{\sphericalangle,pp}(z, M_{\pi\pi}^2)$$



integration over Θ

➜ $H_1^{\sphericalangle,pp}(z, M_{\pi\pi}^2)$ drops out

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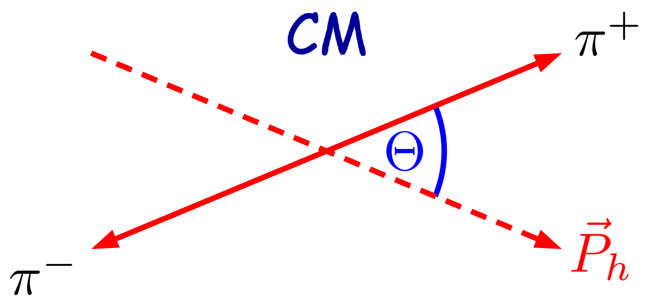
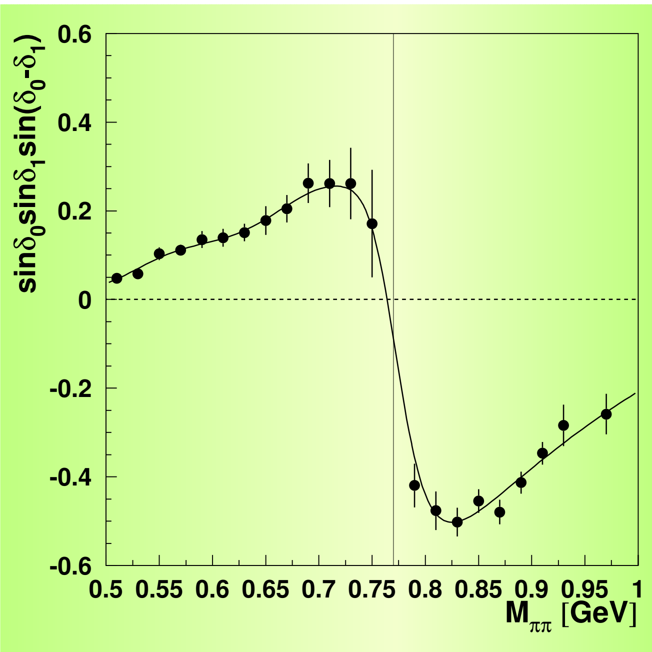


integration over Θ

→ $H_1^{\sphericalangle,pp}(z,M_{\pi\pi}^2)$ drops out



$$H_1^{\sphericalangle,sp}(z,M_{\pi\pi}^2) = \sin\delta_0\sin\delta_1\sin(\delta_0-\delta_1)H_1^{\sphericalangle,sp\prime}(z)$$

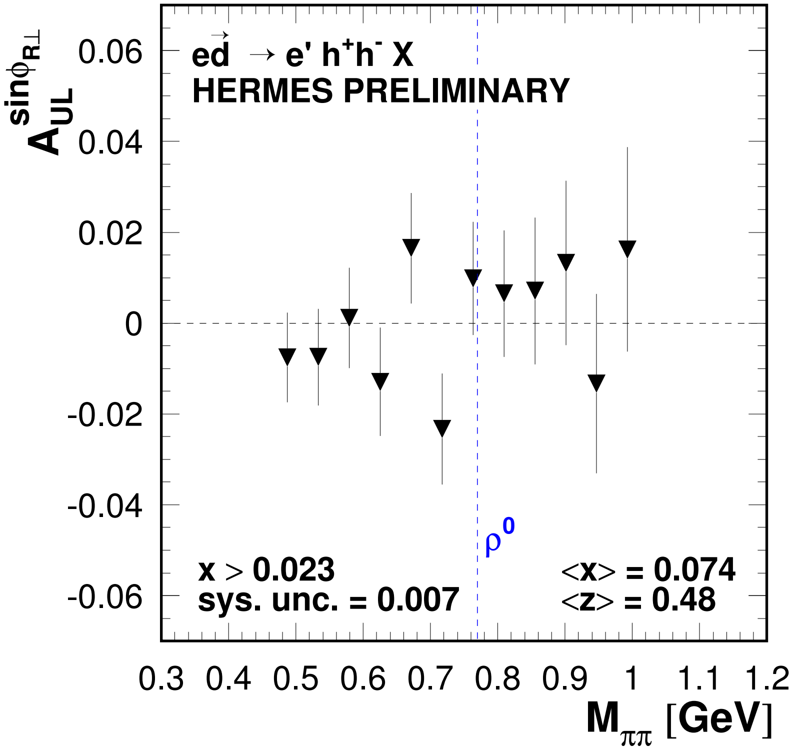
$$= \mathcal{P}(M_{\pi\pi}^2)\cdot H_1^{\sphericalangle,sp\prime}(z)$$

δ_0 : s-wave
δ_1 : p-wave } phase shifts

[Jaffe, Jin, Tang; Phys. Rev. Lett. 80 (1998) 1166]

Results for Longitudinally Polarised Deuterium

$$A_{\mathrm{UL},l}^{\sin\phi_{R\perp}} \approx A_{\mathrm{UL},\gamma^*}^{\sin\phi_{R\perp}} + \sin\theta_{\gamma^*} A_{\mathrm{UT},\gamma^*}^{\sin\phi_{R\perp}}$$

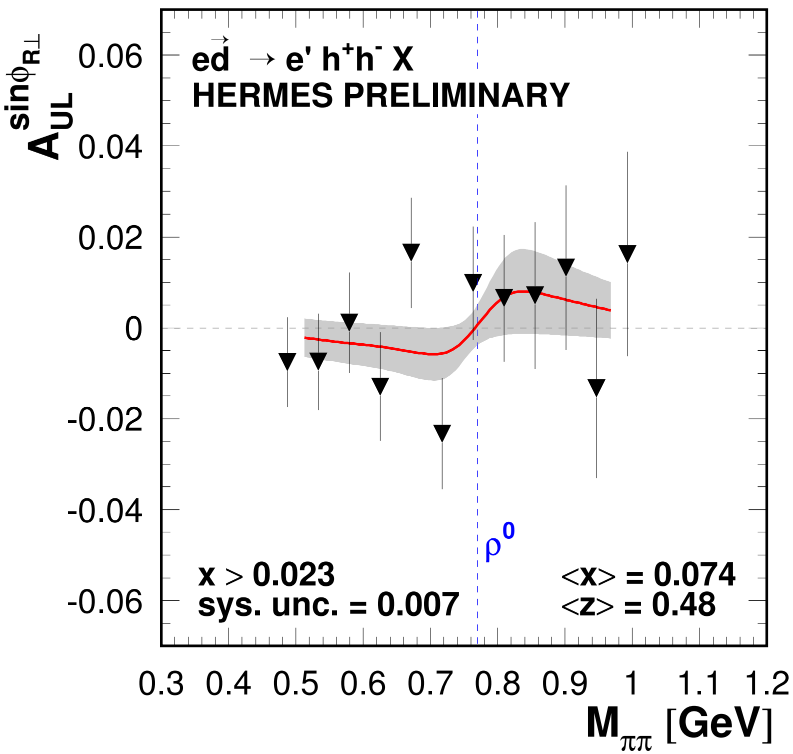


- first measurement of $A_{\mathrm{UL},l}^{\sin\phi_{R\perp}}$
- hadrons assumed to be pions
- small asymmetries

Results for Longitudinally Polarised Deuterium

$$A_{\mathrm{UL},l}^{\sin\phi_{R\perp}} \approx A_{\mathrm{UL},\gamma^*}^{\sin\phi_{R\perp}} + \sin\theta_{\gamma^*} A_{\mathrm{UT},\gamma^*}^{\sin\phi_{R\perp}}$$

$$\approx \ldots \frac{1}{Q}\Delta q \cdot \tilde{G}^{\sphericalangle}(M_{\pi\pi}^2) + \ldots \left(\frac{1}{Q}h_L + \frac{1}{Q}\delta q\right)\mathcal{P}(M_{\pi\pi}^2) \cdot H_1^{\sphericalangle,sp'}$$



- fit $A_{\mathrm{UL},l}^{\sin\phi_{R\perp}}$ with $c_1 \cdot \mathcal{P}(M_{\pi\pi}^2) + c_2$

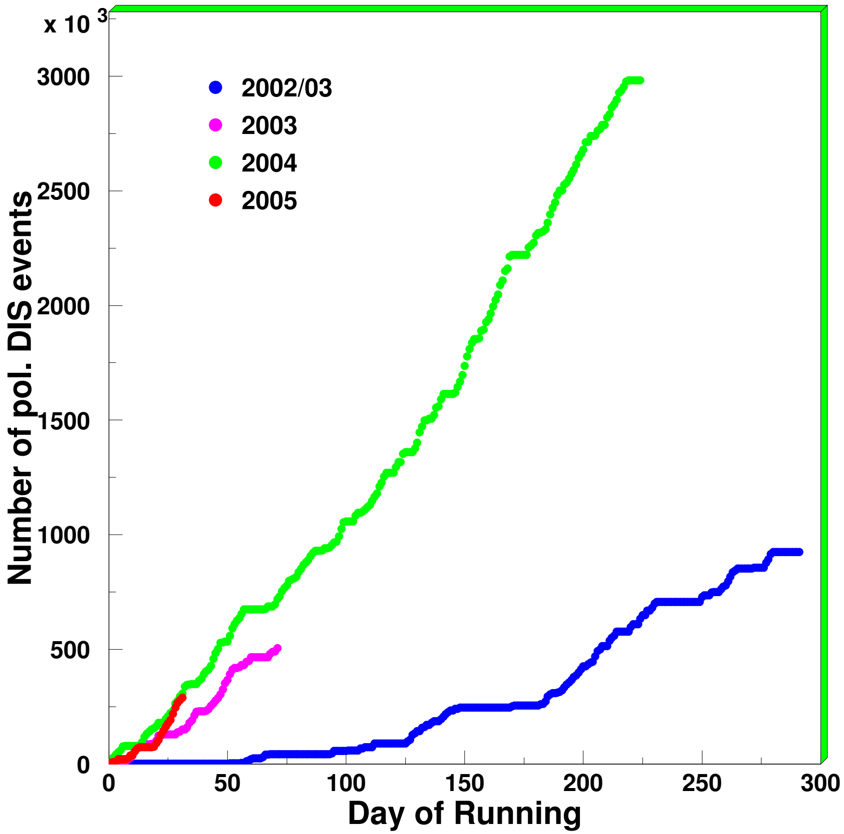
→ c_1 = 0.040±0.036
c_2 = -0.001±0.004

- hint of a sign change at ρ^0 mass

Summary and Outlook

- First measurement of transverse target spin asymmetries in DIS.
- First evidence for non-zero Sivers function.
- Subleading twist terms dominate measurement with longitudinally polarised target.
- Two pion semi-inclusive DIS can also probe transversity.
  No $\frac{1}{Q}$ suppression with transversely polarised target.

Summary and utlook



- Number of DIS events:
  2002+2003+2004 = 5·2002
  2005: HERMES continues data taking

- Sivers function extraction possible ➜ work in progress.

- $A_{\mathrm{UT},l}^{\sin(\phi_{R\perp}+\phi_S)}$: statistics of $H^{\Uparrow}$ data ≈ 60 % $D^{\Rightarrow}$ data

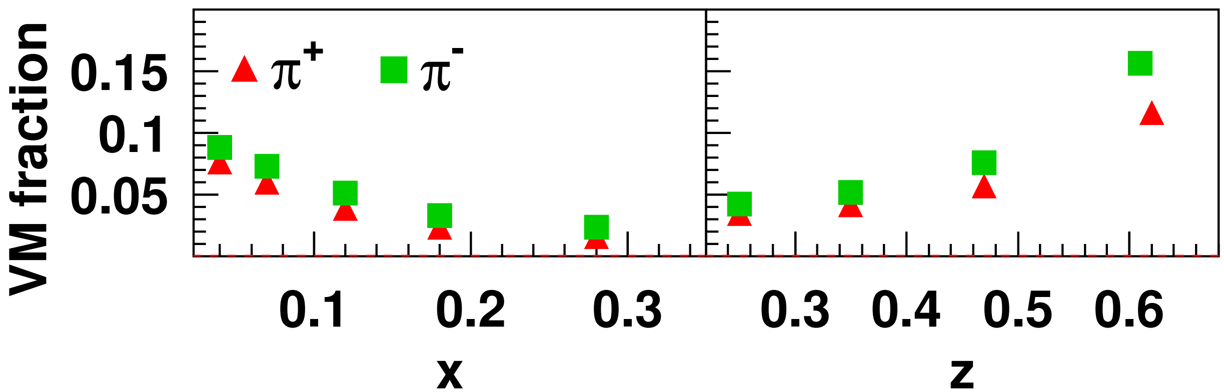
Backup Transparencies

Exclusive Vector Meson Background

- exclusive vector meson background of A_{UT,γ^*}:
  same contribution to $A_{UT,l}$ and $A_{UL,l}$ ➜ cancellation

- no background asymmetry A^{VM}_{UL,γ^*} due to vector meson production or decay distribution ➜ only dilution

$$A^{corr}_{UL,\gamma^*} = \frac{1}{1 - \text{VM fraction}} A^{extracted}_{UL,\gamma^*}$$



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