Transverse Spin Effects in Single and Double Hadron Production at HERMES

- Azimuthal asymmetries in semi-inclusive deep-inelastic scattering
- Results of the HERMES experiment for single pion production
- Double pion production in semi-inclusive deep-inelastic scattering
- Summary and outlook

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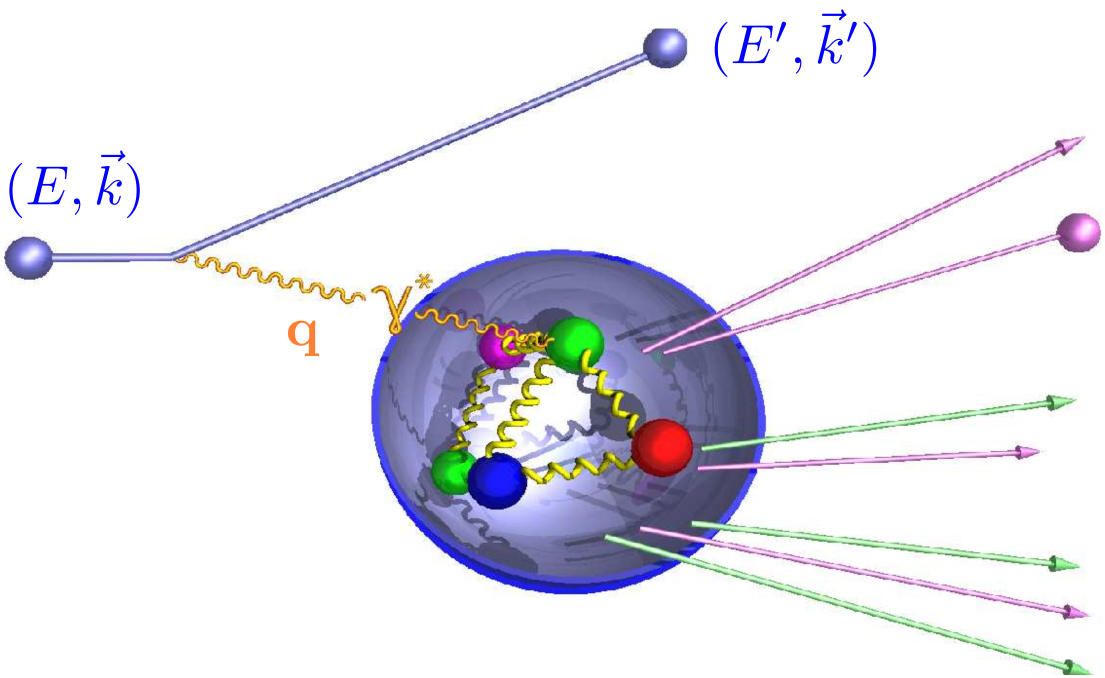
Semi-inclusive Deep-Inelastic Scattering



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

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

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

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

evaluation of the cross section contains
quark distribution and fragmentation functions

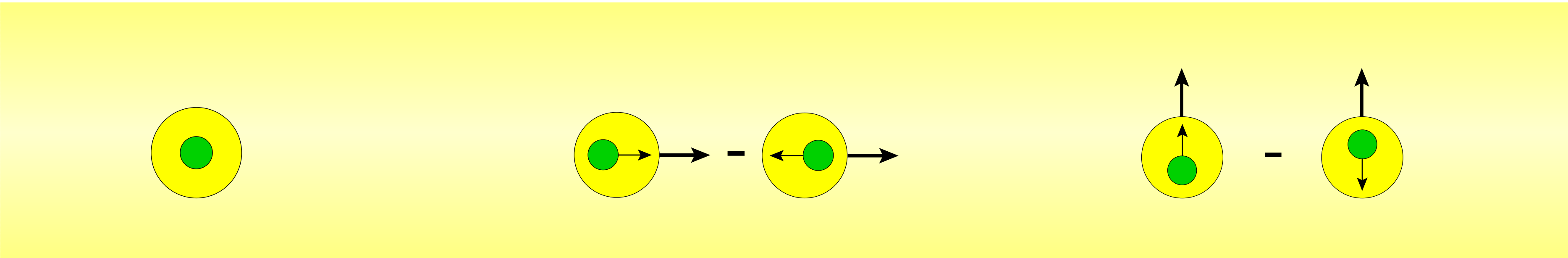
$$\sigma^{ep \to eh} \sim \sum_q \mathbf{DF}^{p \to q} \otimes \sigma^{eq \to eq} \otimes \mathbf{FF}^{q \to h}$$

Distribution Functions

Leading twist:

3 DFs survive the integration over transverse quark momenta

unpolarised DF | **Helicity** | **Transversity**



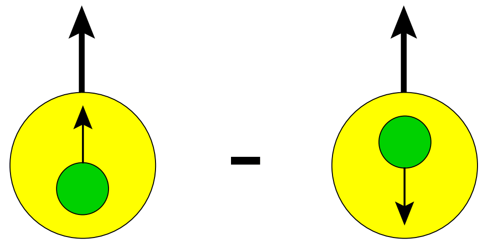
$q(x, Q^2)$ | $\Delta q(x, Q^2)$ | $\delta q(x, Q^2)$

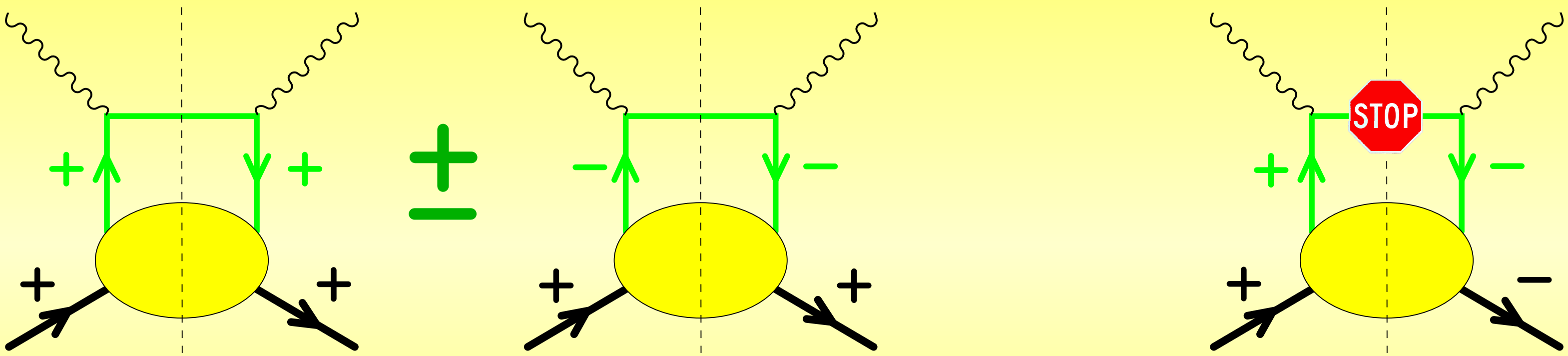
well known | known | unknown

HERMES 1996-2000 | HERMES > 2002

Transversity δq

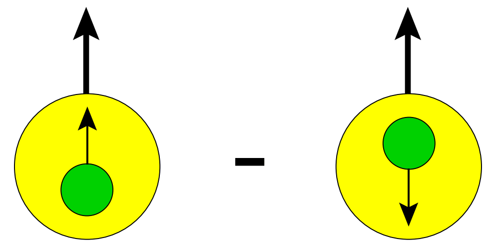
- non-relativistic quarks ➜ transversity = helicity
- chiral-odd ➜ helicity flip





$+$ ➜ $q(x)$ $\quad$ $-$ ➜ $\Delta q(x)$

Transversity δq



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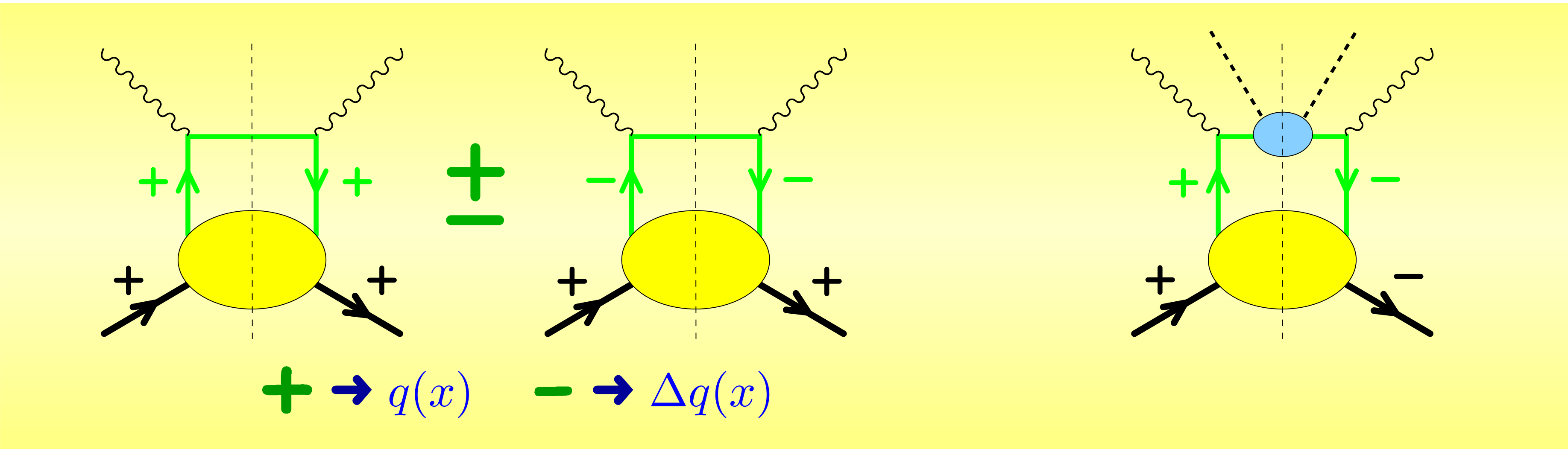


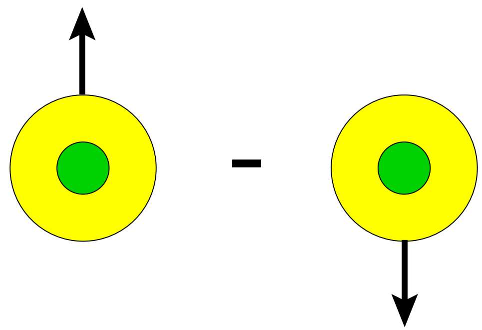
- access of δq in combination with other chiral-odd object
  ➜ χ-odd fragmentation function

single hadron production or double hadron production or...

Collins $H_1^\perp$ IFF $H_1^{\sphericalangle,sp}, H_1^{\sphericalangle,pp}$

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

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



- chiral-even function
- T-odd ➜ forbids its existence?

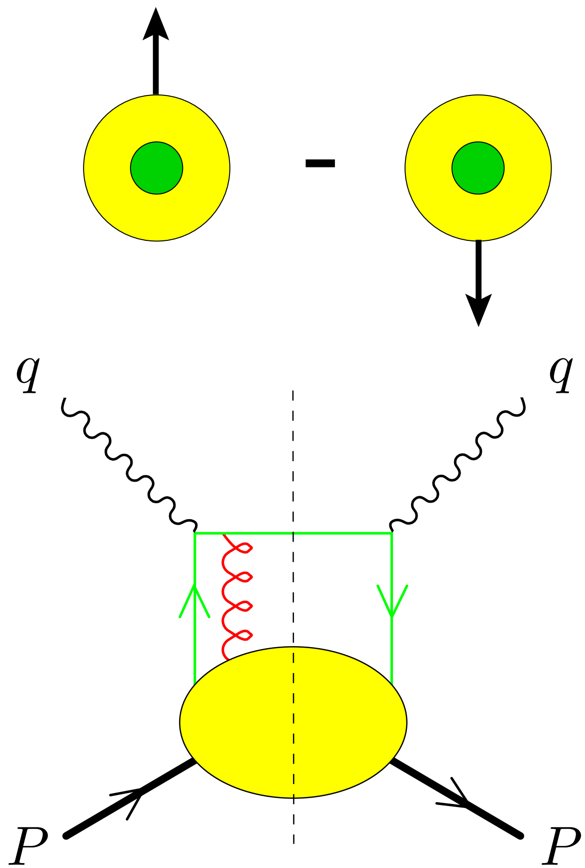
Sivers Function $f_{1T}^{\perp}$

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

- chiral-even function

- T-odd functions allowed due to final state interactions (FSI): quark rescattering via a soft gluon

  time-reversal invariance condition change ➜ naïve T-odd

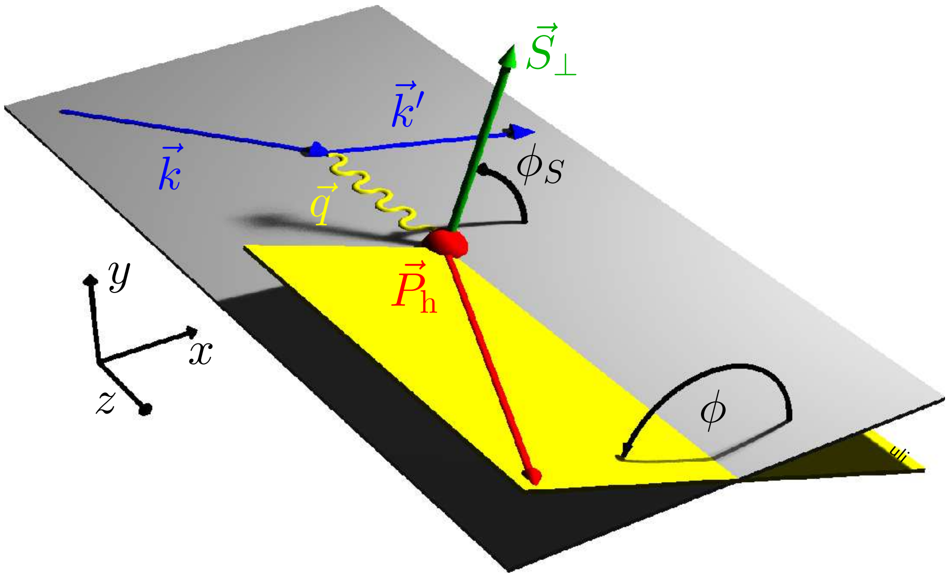


- non-zero Sivers function requires non-vanishing quark orbital angular momentum (contributing to nucleon spin)

Azimuthal Asymmetries

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

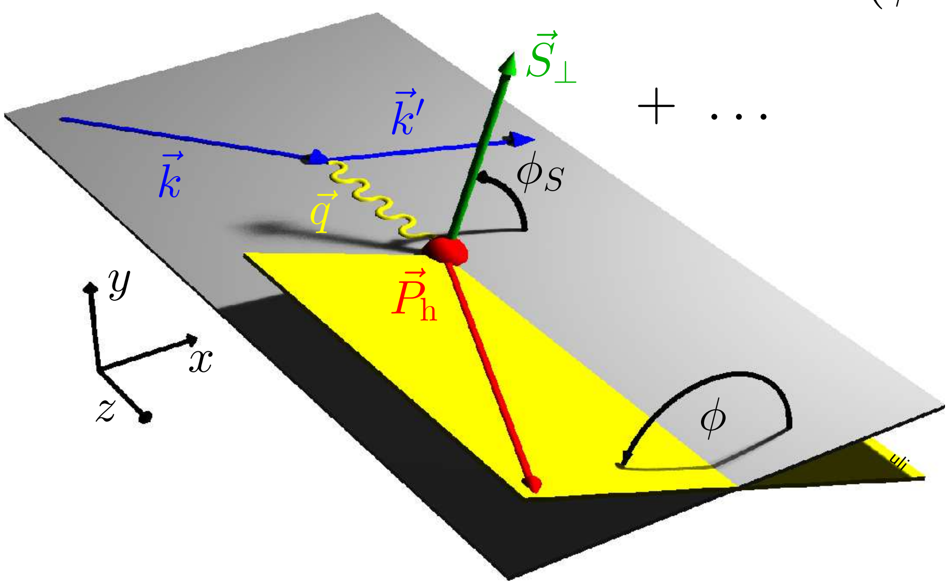
$$A_{\mathrm{UT}}(\phi, \phi_S) = \frac{1}{S_\perp} \frac{N^\uparrow(\phi, \phi_S) - N^\downarrow(\phi, \phi_S)}{N^\uparrow(\phi, \phi_S) + N^\downarrow(\phi, \phi_S)}$$



Azimuthal Asymmetries

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

$$
\begin{aligned}
A_{\mathrm{UT}}(\phi,\phi_S) &= \frac{1}{S_\perp}\,\frac{N^\uparrow(\phi,\phi_S)-N^\downarrow(\phi,\phi_S)}{N^\uparrow(\phi,\phi_S)+N^\downarrow(\phi,\phi_S)} \\
&\sim \ldots\ \sin(\phi+\phi_S)\,\frac{\sum_q e_q^2\,\mathcal{I}\left[\ldots\delta q(x,\vec{p}_T^{\,2})\cdot H_1^{\perp q}(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\ q(x)\cdot D_1^q(z)} \\
&+\ \ldots\ \sin(\phi-\phi_S)\,\frac{\sum_q e_q^2\,\mathcal{I}\left[\ldots f_{1T}^{\perp q}(x,\vec{p}_T^{\,2})\cdot D_1^q(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\ q(x)\cdot D_1^q(z)} \\
&+\ \ldots
\end{aligned}
$$



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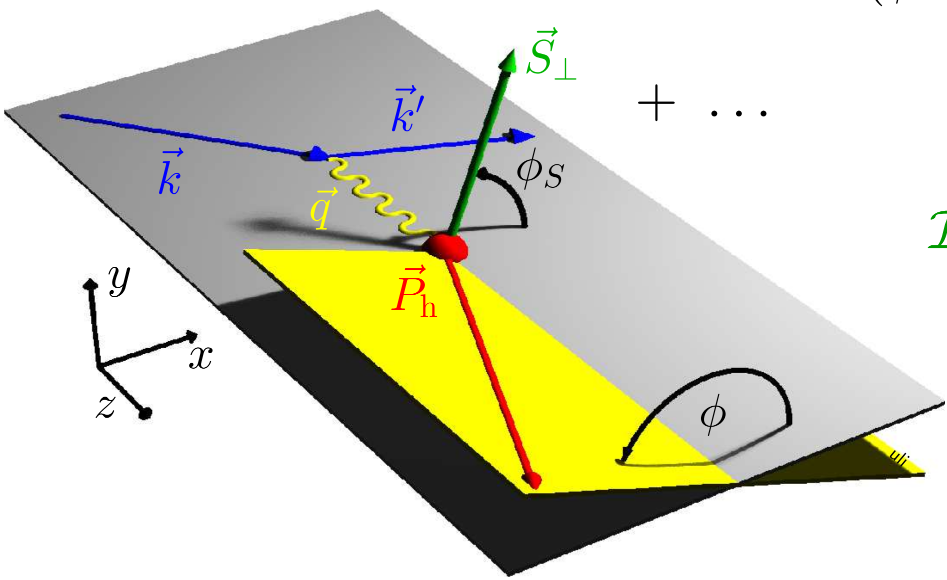
$$+\ \ldots \sin(\phi-\phi_S)\frac{\sum_q e_q^2\,\mathcal{I}\left[\ldots f_{1T}^{\perp q}(x,\vec{p}_T^{\,2})\cdot D_1^q(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\; q(x)\cdot D_1^q(z)}$$

$$+\ \ldots$$



$\mathcal{I}[\ldots]$: 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:

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

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

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

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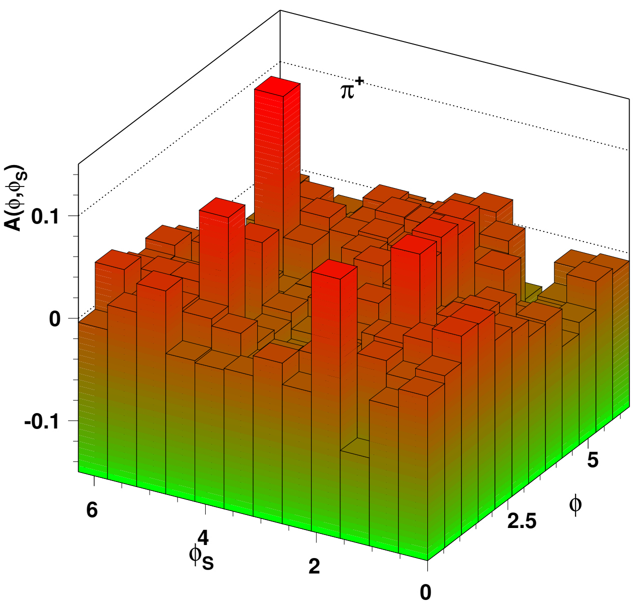
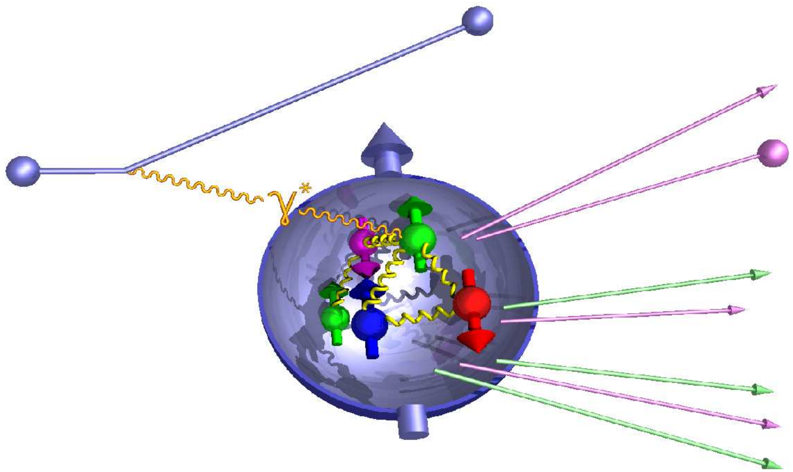
$$+ \ldots \sin(\phi - \phi_S) \sum_q e_q^2 \cdot f_{1T}^{\perp(1/2)\,q}(x) \cdot D_1^q(z)$$

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 12×12 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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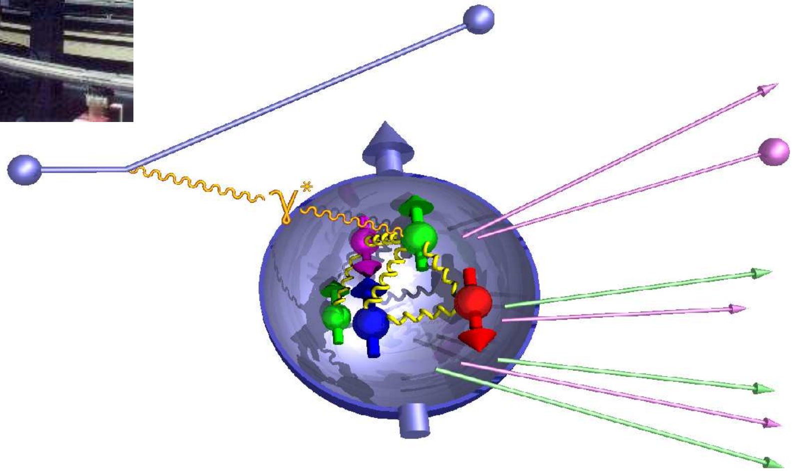

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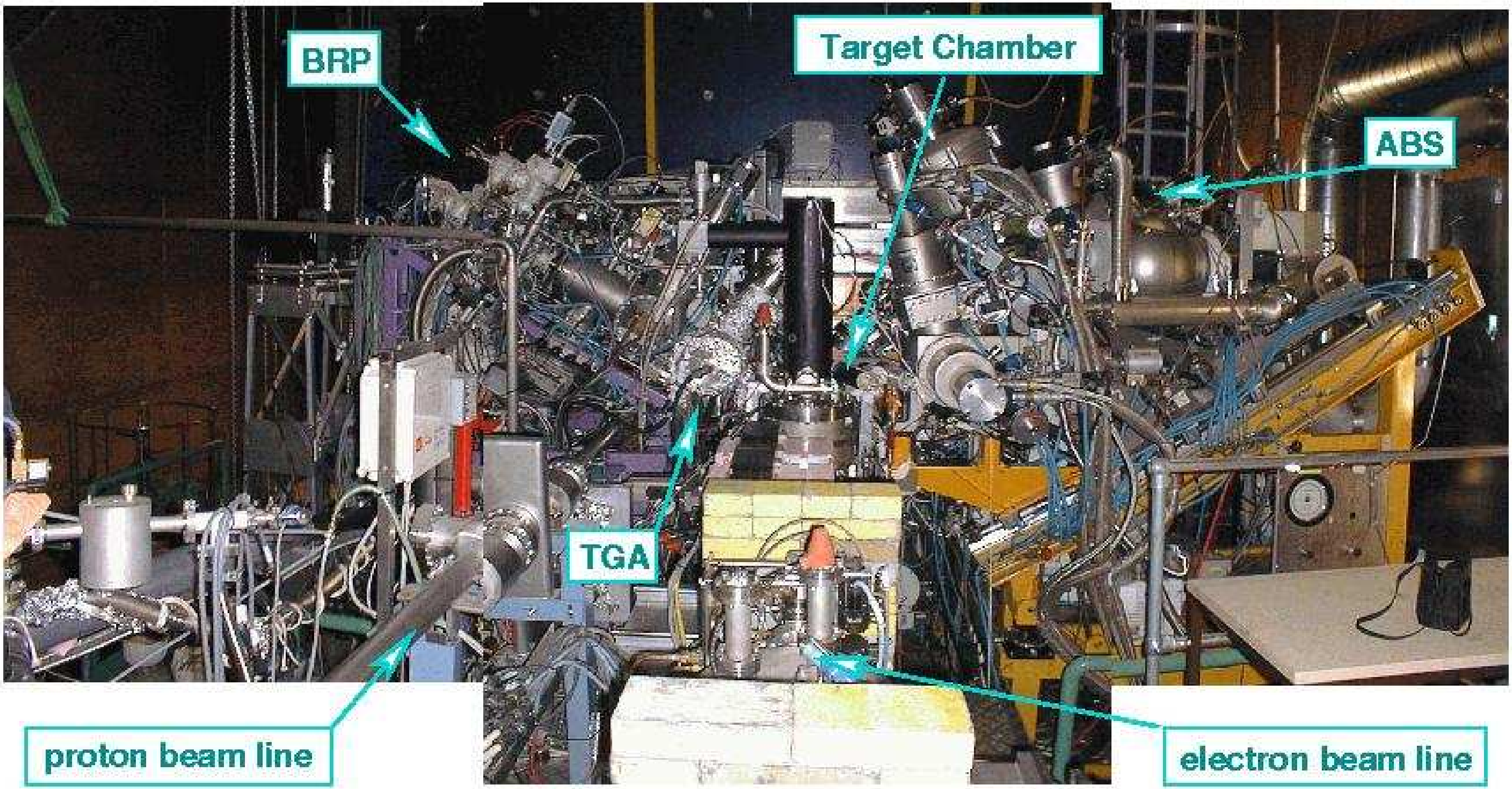

transversely polarised atomic Hydrogen $\langle P \rangle \approx 80$ %

The HERMES Experiment at HERA

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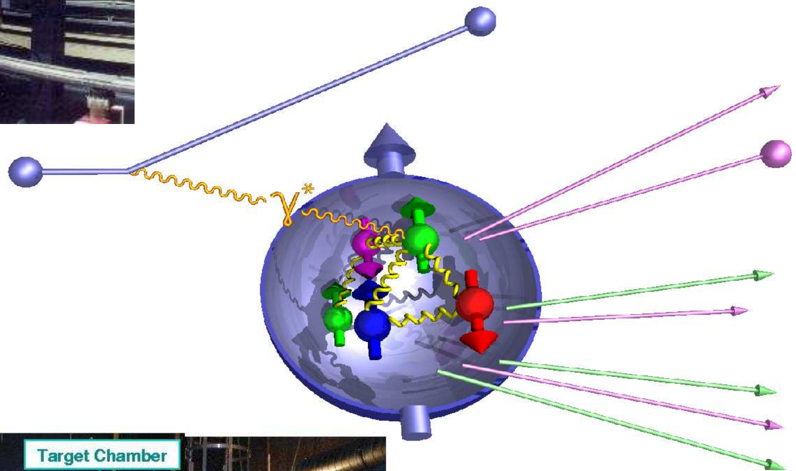

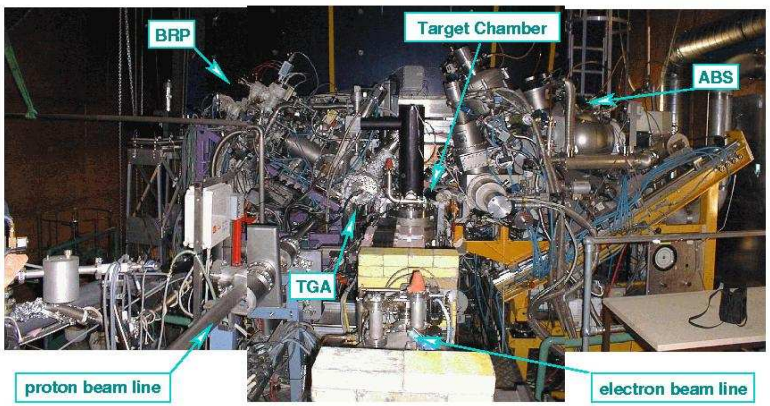

since 2002

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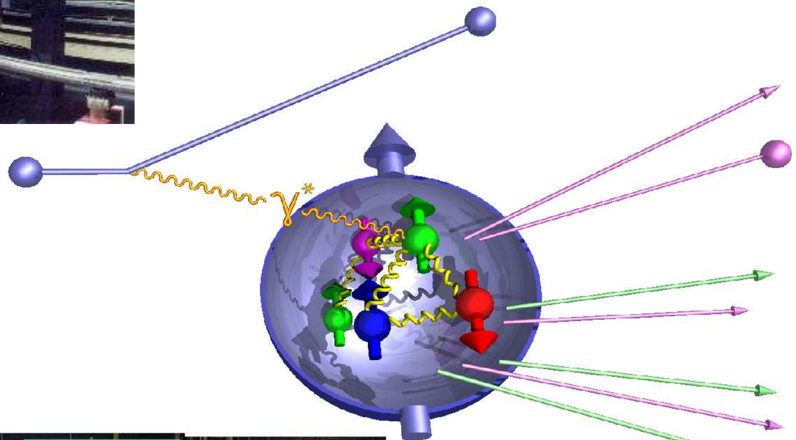
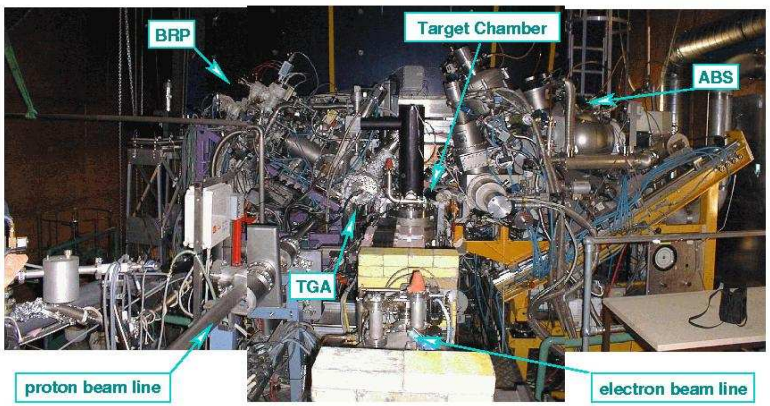
The HERMES Experiment at HERA

The HERMES Experiment at HERA

HERA positron beam 27.5 GeV

HERMES spectrometer





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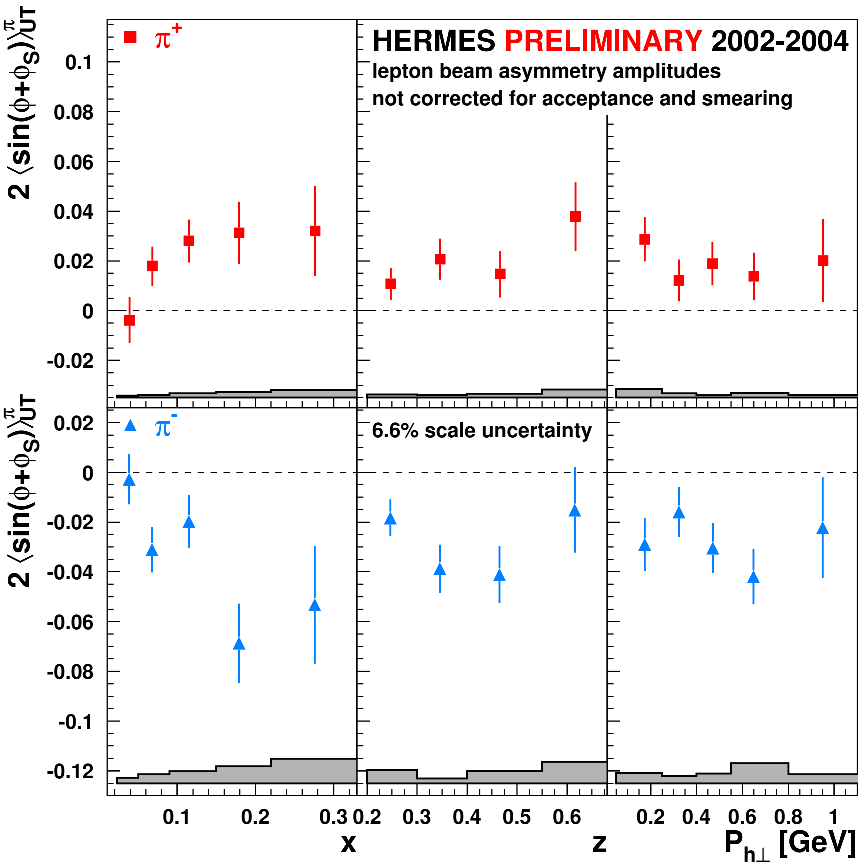
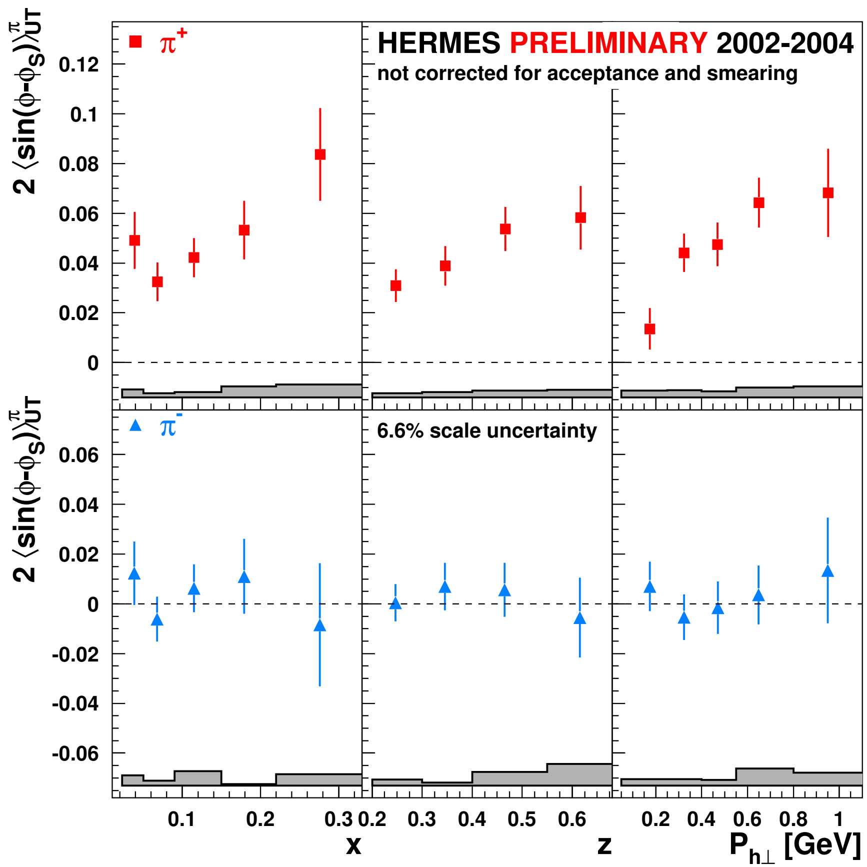
Results for the Asymmetry Amplitudes

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



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



overall scale uncertainty 6.6%

Results for the Asymmetry Amplitudes

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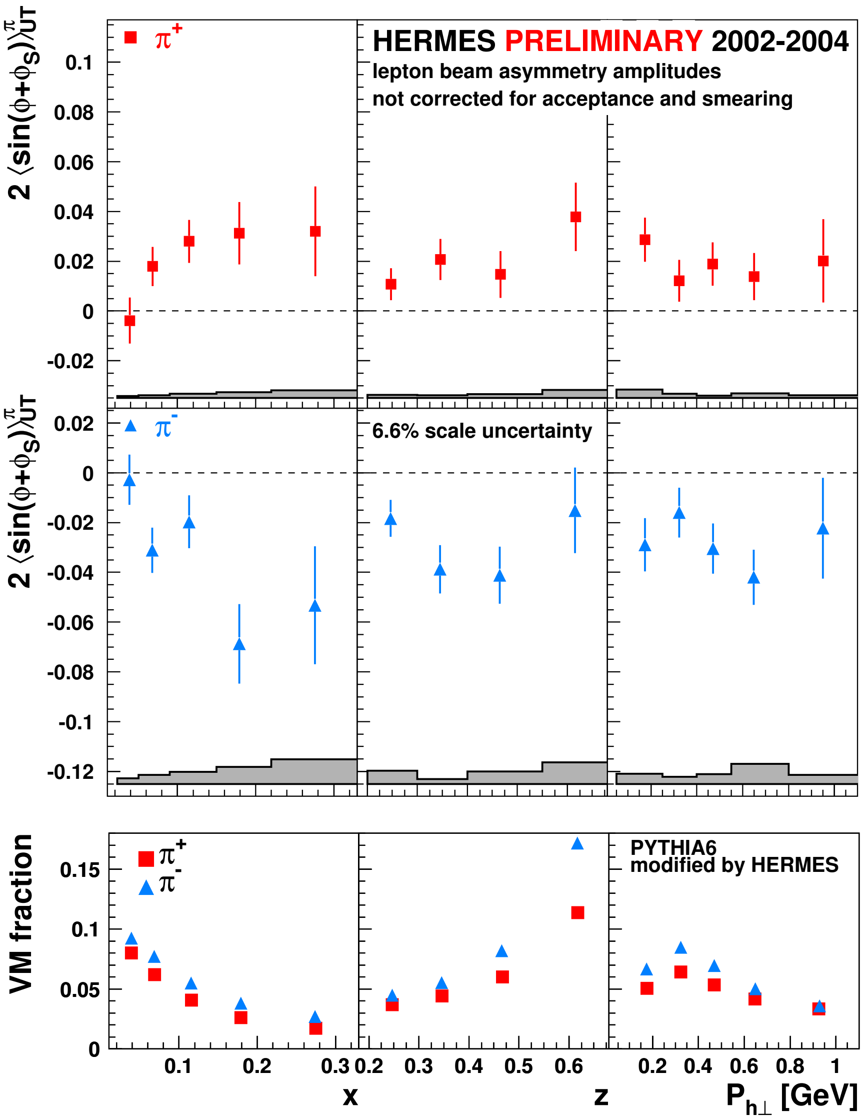


- positive for π^+, negative for π^-
  expectations: δu > 0, δd < 0
- unexpected large absolute value for π^-
- contribution to pion sample from exclusively produced vector mesons (PYTHIA)

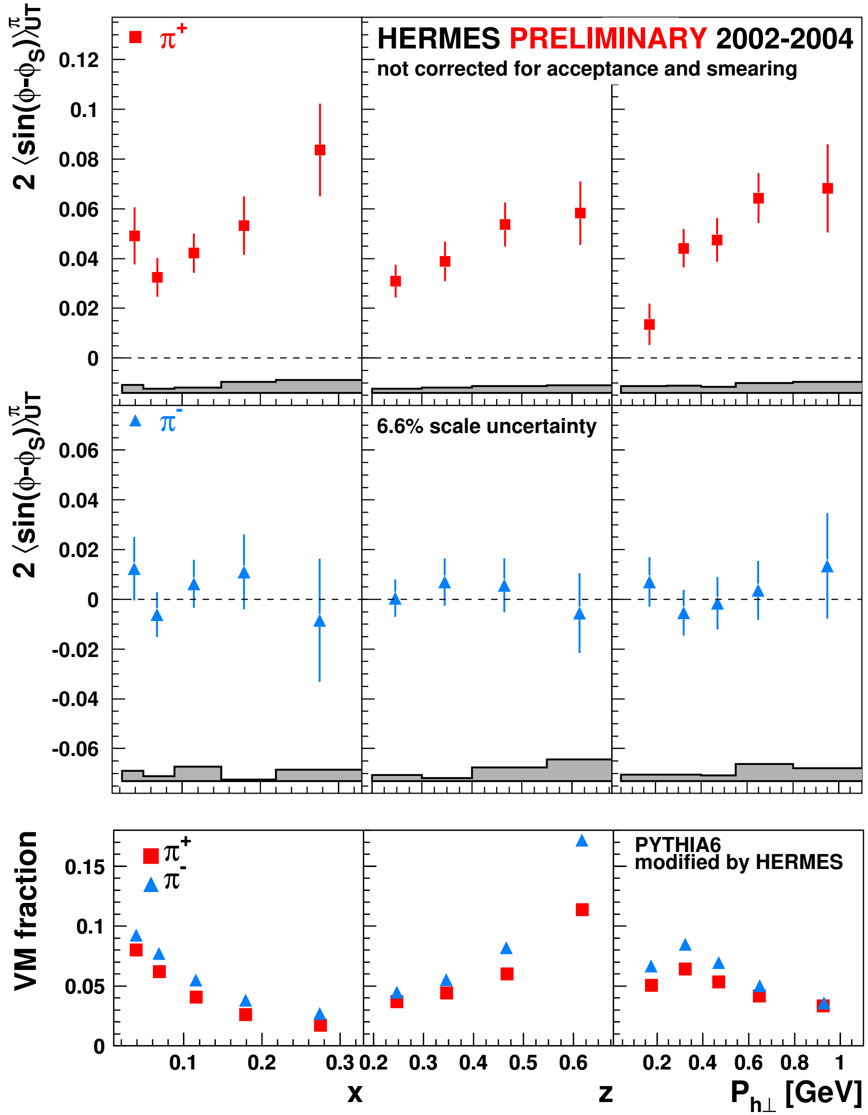
Results for the Asymmetry Amplitudes

- 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)

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



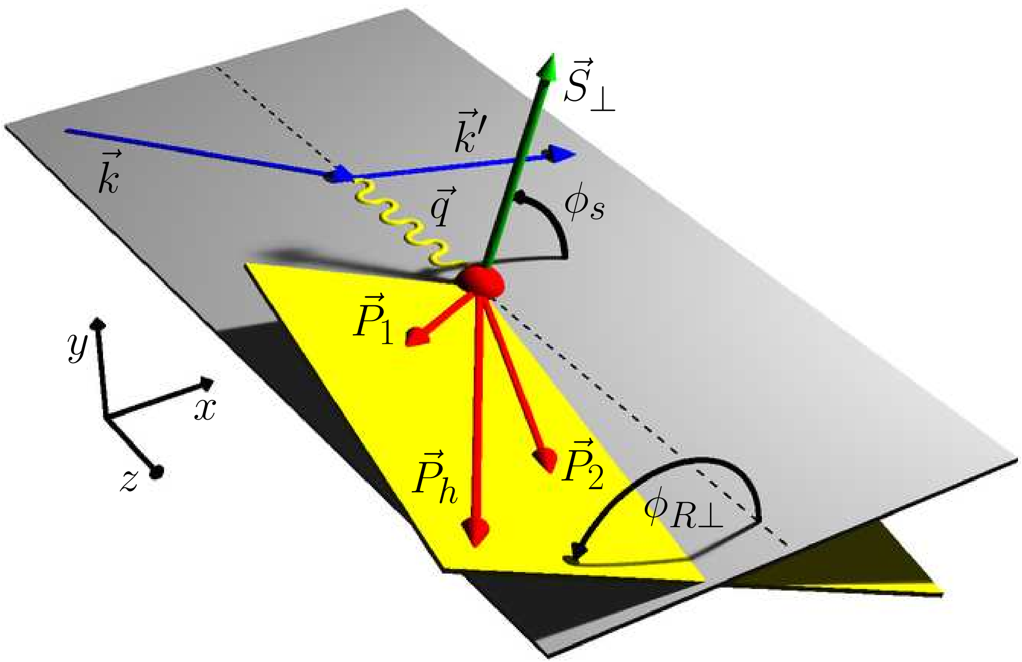
Double Pion Production in Semi-inclusive DIS

Detection of two final state pions with opposite charge:

$$A_{\mathrm{UT}}(\phi_{R\perp}, \phi_S) \quad \sim \quad \ldots \sin(\phi_{R\perp} + \phi_S) \, \frac{\sum_q e_q^2 \, \delta q(x) \cdot H_1^{\sphericalangle q}(z, M_{\pi\pi}^2)}{\sum_q e_q^2 \, q(x) \cdot D_1^q(z, M_{\pi\pi}^2)}$$

$$+ \ldots$$

$H_1^{\sphericalangle}(z, M_{\pi\pi}^2)$, $D_1(z, M_{\pi\pi}^2)$: two pion fragmentation functions

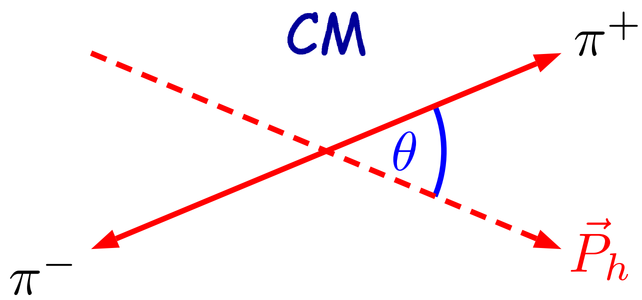


- no assumptions for $\vec{p}_T$ and $\vec{k}_T$ distributions necessary
- completely independent from single pion analysis
- less statistics

Interference Fragmentation Functions $H_1^{\sphericalangle,sp}$, $H_1^{\sphericalangle,pp}$

Partial wave expansion:

$$H_1^{\sphericalangle}(z, \cos\theta, M_{\pi\pi}^2) = \sin\theta \left[H_1^{\sphericalangle,sp}(z, M_{\pi\pi}^2) + \cos\theta \; H_1^{\sphericalangle,pp}(z, M_{\pi\pi}^2)\right]$$



integration over $0 < \theta < \pi$

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

IFF $H_1^{\sphericalangle,sp}$ and $H_1^{\sphericalangle,pp}$ describe interference between two pion pairs coming from different production channels

Interference Fragmentation Functions $H_1^{\sphericalangle,sp}, H_1^{\sphericalangle,pp}$

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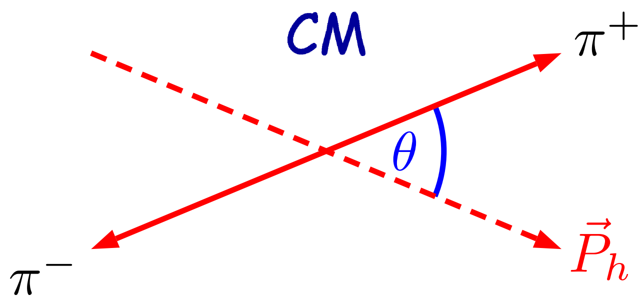

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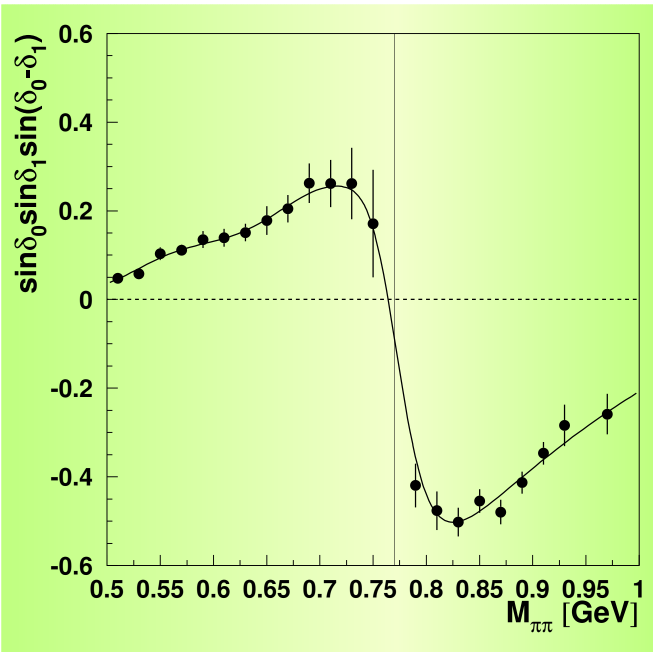

$$H_1^{\sphericalangle,sp}(z, M_{\pi\pi}^2) = \sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1) H_1^{\sphericalangle,sp'}(z)$$

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

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

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

Interference Fragmentation Functions $H_1^{\sphericalangle,sp}$, $H_1^{\sphericalangle,pp}$

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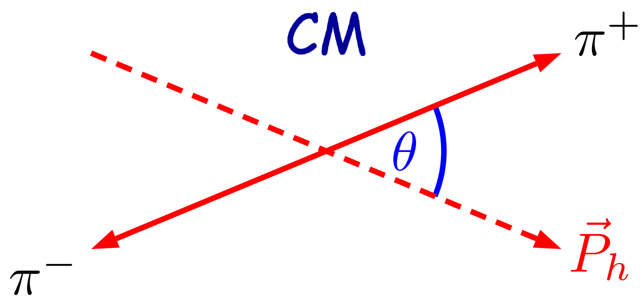
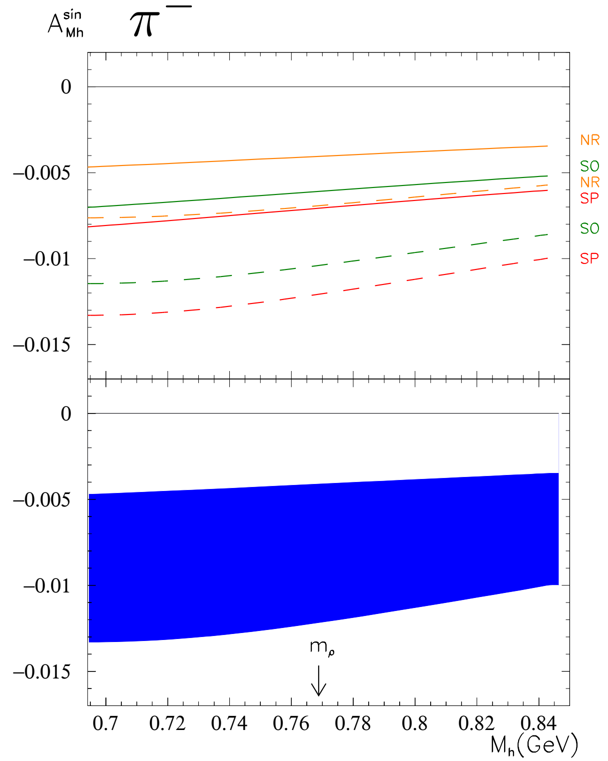


integration over $0 < \theta < \pi$

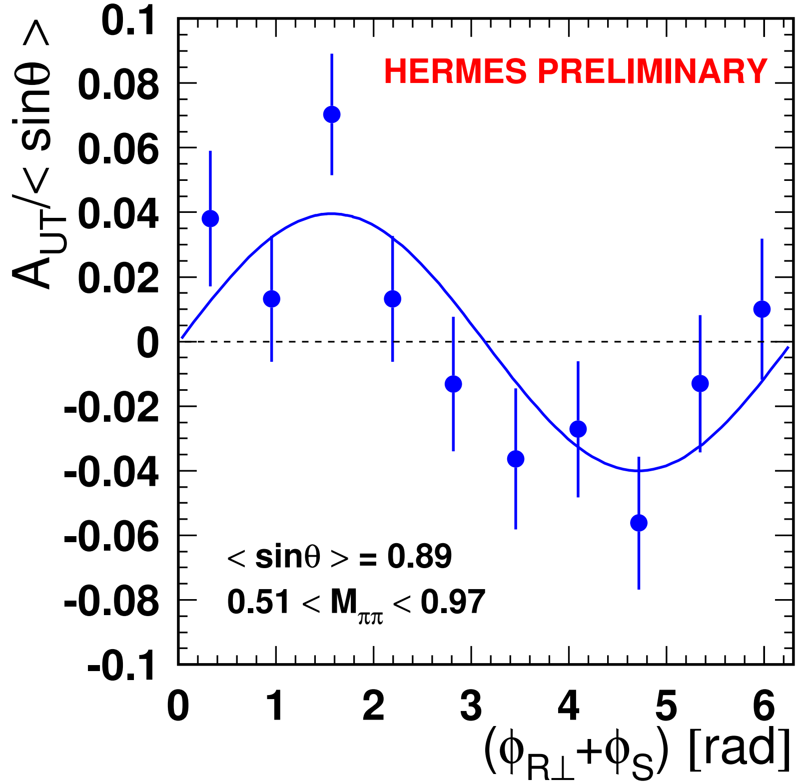
→ $H_1^{\sphericalangle,pp}(z,M_{\pi\pi}^2)$ drops out



- completely different model for $H_1^{\sphericalangle,sp}$
- no sign change at m_{ρ^0} predicted

[Radici, Jakob, Bianconi; Phys. Rev. D65 (2002) 074031]

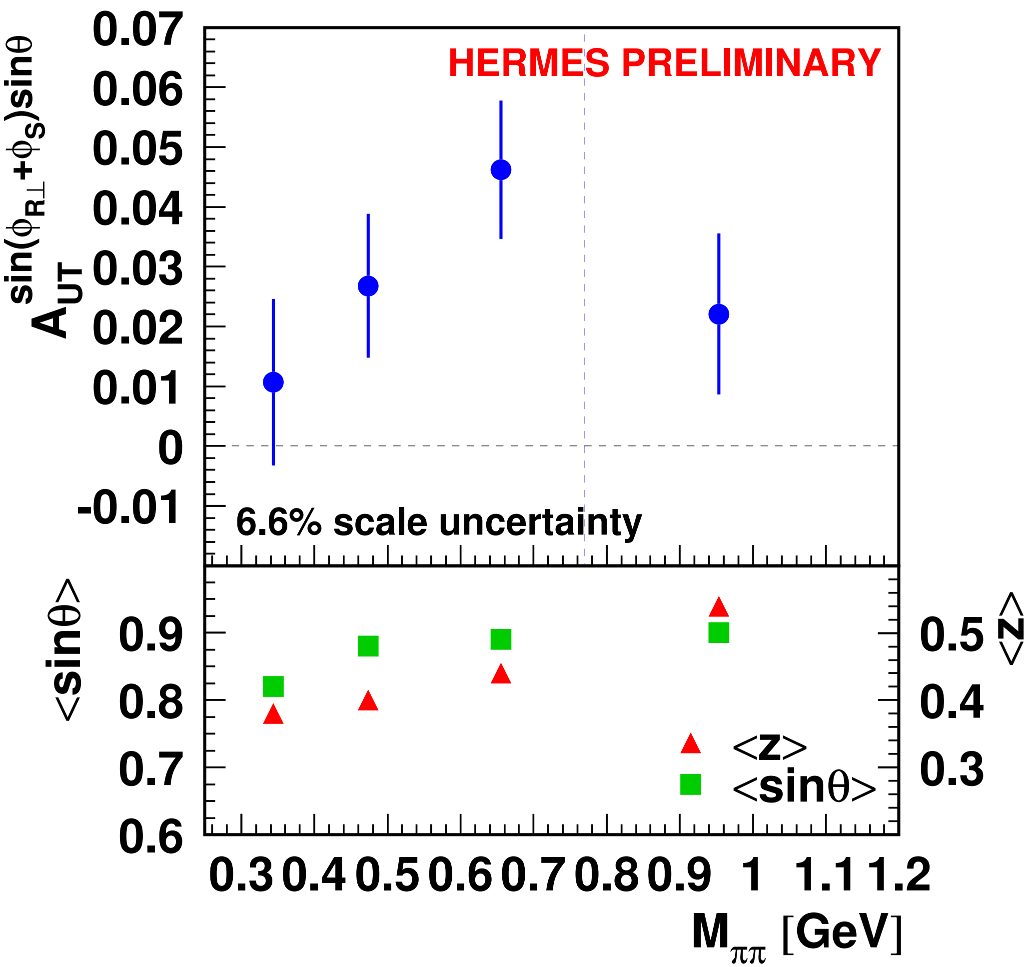
Azimuthal Asymmetry Results



- hadrons assumed to be pions
- fit $A_{\mathrm{UT}}(\phi_{R\perp}+\phi_S)/\langle\sin\theta\rangle$ with $p_1 + p_2 \sin(\phi_{R\perp}+\phi_S)$
- significant $\sin(\phi_{R\perp}+\phi_S)$ behaviour!
- extract $A_{\mathrm{UT}}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$ from $A_{\mathrm{UT}}(\phi_{R\perp},\phi_S,\theta)$ by three dimensional fit

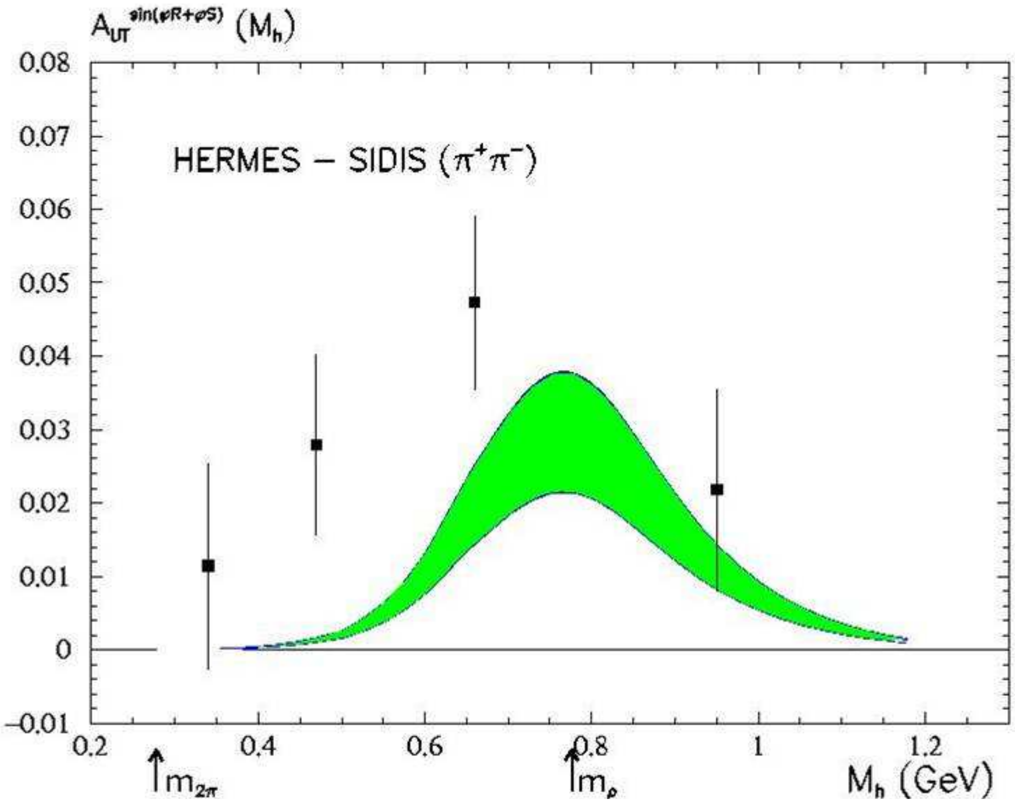
$A_{\mathrm{UT}}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$ = 0.040 $\pm$ 0.009 (stat) $\pm$ 0.003 (syst)

Invariant Mass Dependence



- positive asymmetry amplitudes in all bins
- no sign change at m_{ρ^0}!
- significant result for $A_{\mathrm{UT}}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$
  ➜ non-zero IFF!

Invariant Mass Dependence



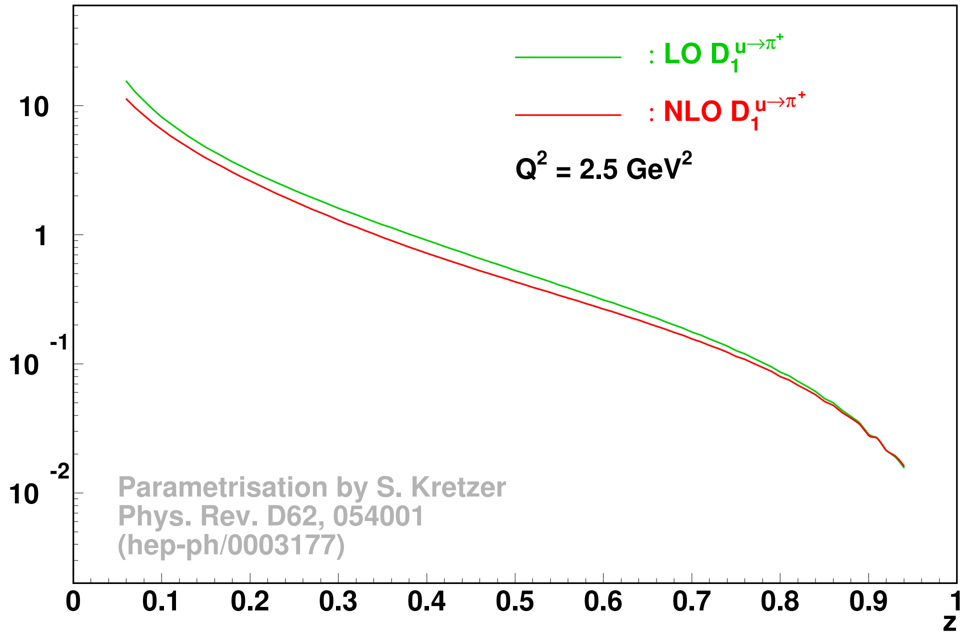
M. Radici at SIR 2005 (JLab)

- positive asymmetry amplitudes in all bins
- no sign change at m_{ρ^0}!
- significant result for $A_{\rm UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$
  ➜ non-zero IFF!
- qualitative agreement with model calculation of Bacchetta and Radici

Extraction of the Distribution Functions

Information about fragmentation functions necessary:

$f_{1T}^{\perp q}(x) \cdot D_1^q(z)$ $\quad D_1^{q\to h}(z)$ for some hadrons h sufficiently known



Extraction of the Distribution Functions

Information about fragmentation functions necessary:

$f_{1T}^{\perp q}(x) \cdot D_1^q(z)$ $D_1^{q \to h}(z)$ for some hadrons h sufficiently known

➜ Sivers function extraction possible

universality violated?

basic expectation of QCD: sign opposite in Drell-Yan

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$\delta q(x) \cdot H_1^{\perp q}(z)$ $H_1^{\perp q \to h}(z)$: First measurements of transverse spin asymmetries for double hadron production in e^+e^- annihilation at BELLE!

➜ sensitive to Collins function

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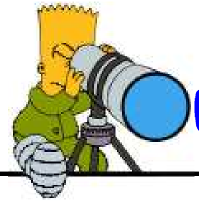
$\delta q(x) \cdot H_1^{\perp q}(z)$

$H_1^{\perp q \to h}(z)$: First measurements of transverse spin asymmetries for double hadron production in e^+e^- annihilation at BELLE!

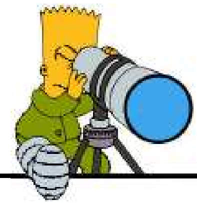
➜ sensitive to Collins function

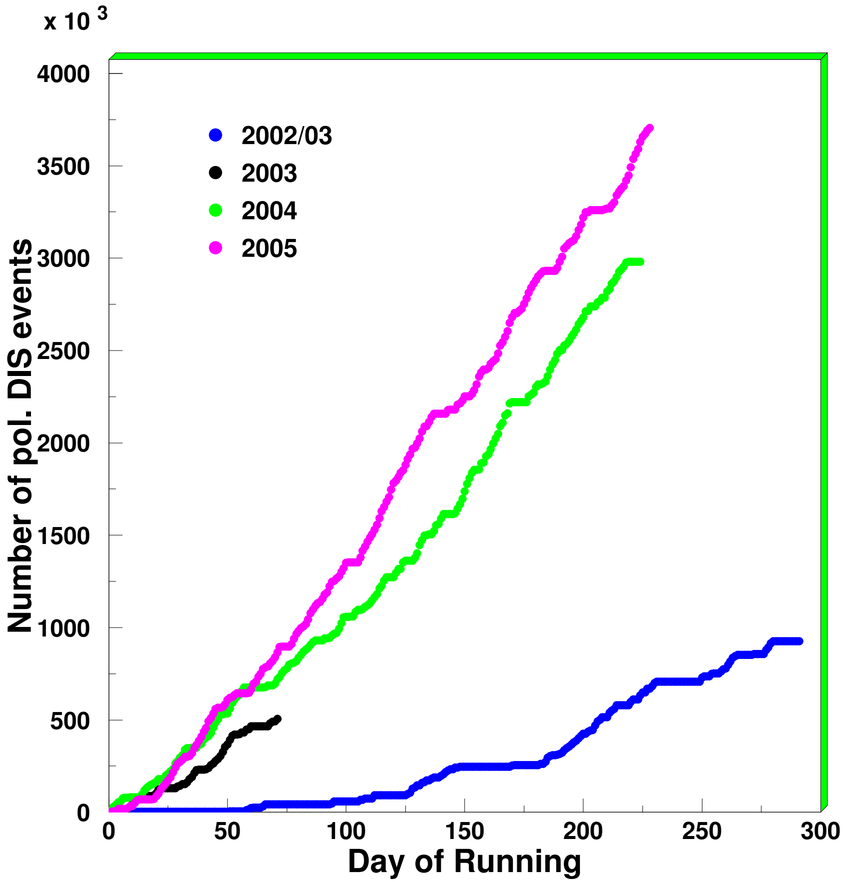
$\delta q(x) \cdot H_1^{\sphericalangle q}(z)$

IFF can also be measured at BELLE, BABAR

Summary and utlook

- Transversity is accessible in single and double pion production in semi-inclusive DIS.
- Sivers DF can be measured in single pion production. Transverse spin asymmetries show first evidence for non-zero Sivers function.
- In double pion production, transversity is coupled to IFF. Measurement of transverse spin asymmetry gives first evidence for non-zero IFF.

Summary and utlook



- 2005: Number of DIS events already almost doubled
  HERMES continues data taking
- Sivers function extraction possible ➜ work in progress.
- Neutral pion and charged kaon asymmetries will be presented soon.