Transverse Spin Physics at HERMES

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on behalf of the hermes Collaboration

- Motivation
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- Semi-Inclusive Pion Production
  - Collins and Sivers Types of Asymmetries
  - 2-pion Fragmentation
- Exclusive Reactions
  - DVCS
  - ρ^0 Production
- Coming Statistics
- Summary

SPIN-05, Dubna, 29.09.2005

Motivation

Parton Distribution Functions at Leading Twist:

$q(x, Q^2)$ - unpolarized DF - quite well known.

$\Delta q(x, Q^2)$ - helicity DF - known.

$\delta q(x, Q^2)$ - transversity DF - absolutely unknown.

Transversity

For non-relativistic quarks: $\delta q(x) = \Delta q(x)$.
Doesn't contribute to inclusive cross-section $ep \to eX$ due to its chiral-odd nature.
Requires a combination with other chiral-odd object, e.g. Collins FF $\Longrightarrow$
a study of single-spin target azimuthal asymmetries.

Motivation

Proton Spin Composition

$$\frac{1}{2} = J_q + J_G$$

$$J_q = \frac{1}{2}(\Delta u + \Delta d + \Delta s) + L_q, \qquad J_G = \Delta G + L_G$$

Δq - known from DIS

ΔG - 1st measurements in DIS

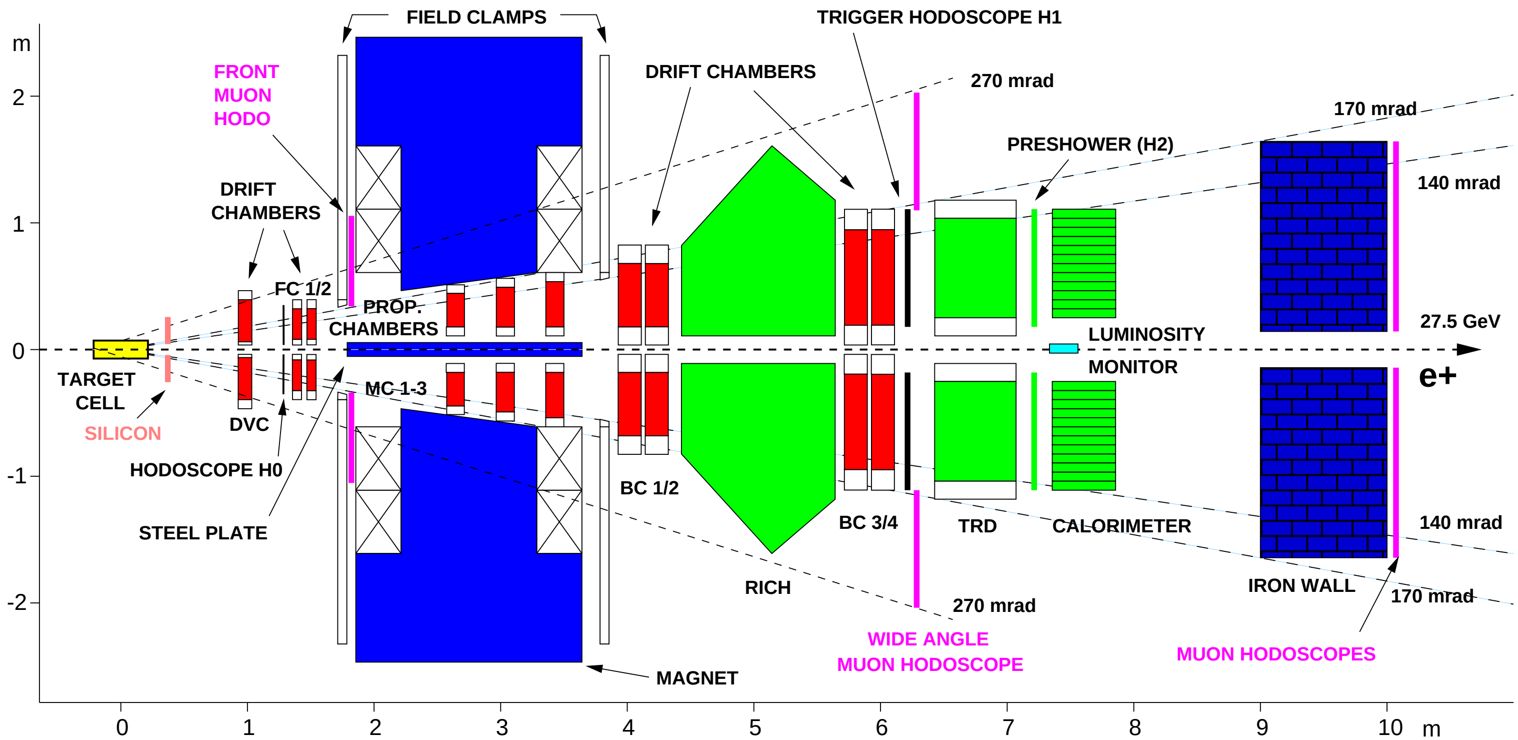
L_q and L_G - are unknown.

Ji's Sum Rule:

$$J_{q,g} = \frac{1}{2}\int_{-1}^{1} dx \cdot x[H_{q,g}(x,\xi,0) + E_{q,g}(x,\xi,0)]$$

A measurement of the Generalized Parton Distributions is required.

HERMES experiment



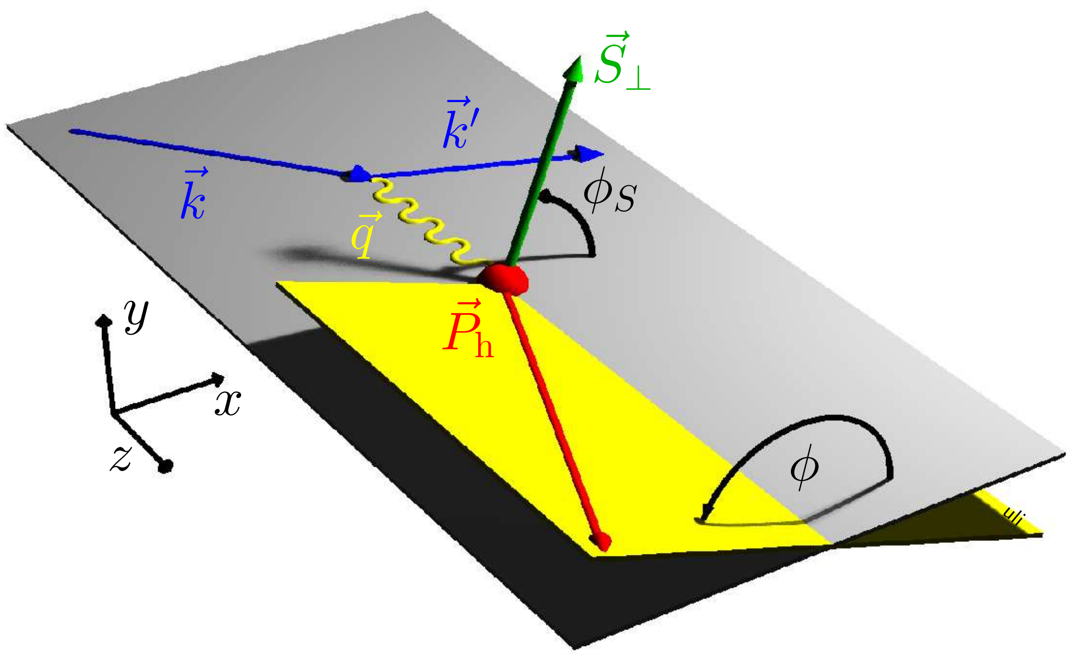
- longitudinally polarized electron beam of 27.5 GeV
- transversely polarized hydrogen gas target, $P_T = 75\%$
- forward magnetic spectrometer with precise momentum ($\Delta p/p < 2.5\%$) and angular ($\Delta\theta < 0.6$ mrad) resolution.
- particle ID: TRD, Preshower, Calorimeter, RICH
- kinematic range: $\theta < 220$ mrad, $0.02 < x_{Bj} < 0.80$, $Q^2 > 1$ Gev^2, $W > 2$ GeV.

Semi-Inclusive Pion Production

- Collins and Sivers Types of Asymmetries

- 2-pion fragmentation

Transverse Spin Asymmetries



$$A^h_{UT}(\phi, \phi_S) = \frac{1}{|S_T|} \frac{N^\uparrow_h(\phi, \phi_S) - N^\downarrow_h(\phi, \phi_S)}{N^\uparrow_h(\phi, \phi_S) + N^\downarrow_h(\phi, \phi_S)}$$

where $N_h^{\uparrow,\downarrow}(\phi, \phi_S)$ - is the semi-inclusive luminosity-normalized yield.

Transverse Spin Asymmetries

A completely different possible mechanism for target-related SSA's is known.

The Sivers DF $f_{1T}^{\perp}$ describes a correlation of p_T with target polarization.

Fortunately, two mechanisms produce different angular dependencies of the A_{UT}.

$A_{UT}^{h}(\phi,\phi_S) \propto \sin(\phi+\phi_S)\sum_q e_q^2 \cdot \delta q(x) \cdot H_1^{\perp(1/2)q}(z)$ - "Collins"

$A_{UT}^{h}(\phi,\phi_S) \propto \sin(\phi-\phi_S)\sum_q e_q^2 \cdot f_{1T}^{\perp(1/2)q}(x) \cdot D_1^q(z)$ - "Sivers"

Transverse Spin Asymmetries

The Collins azimuthal moment $< \sin(\phi + \phi_S) >^h_{UT}$ and Sivers moment $< \sin(\phi - \phi_S) >^h_{UT}$ of the virtual-photon asymmetry are extracted in the fit:

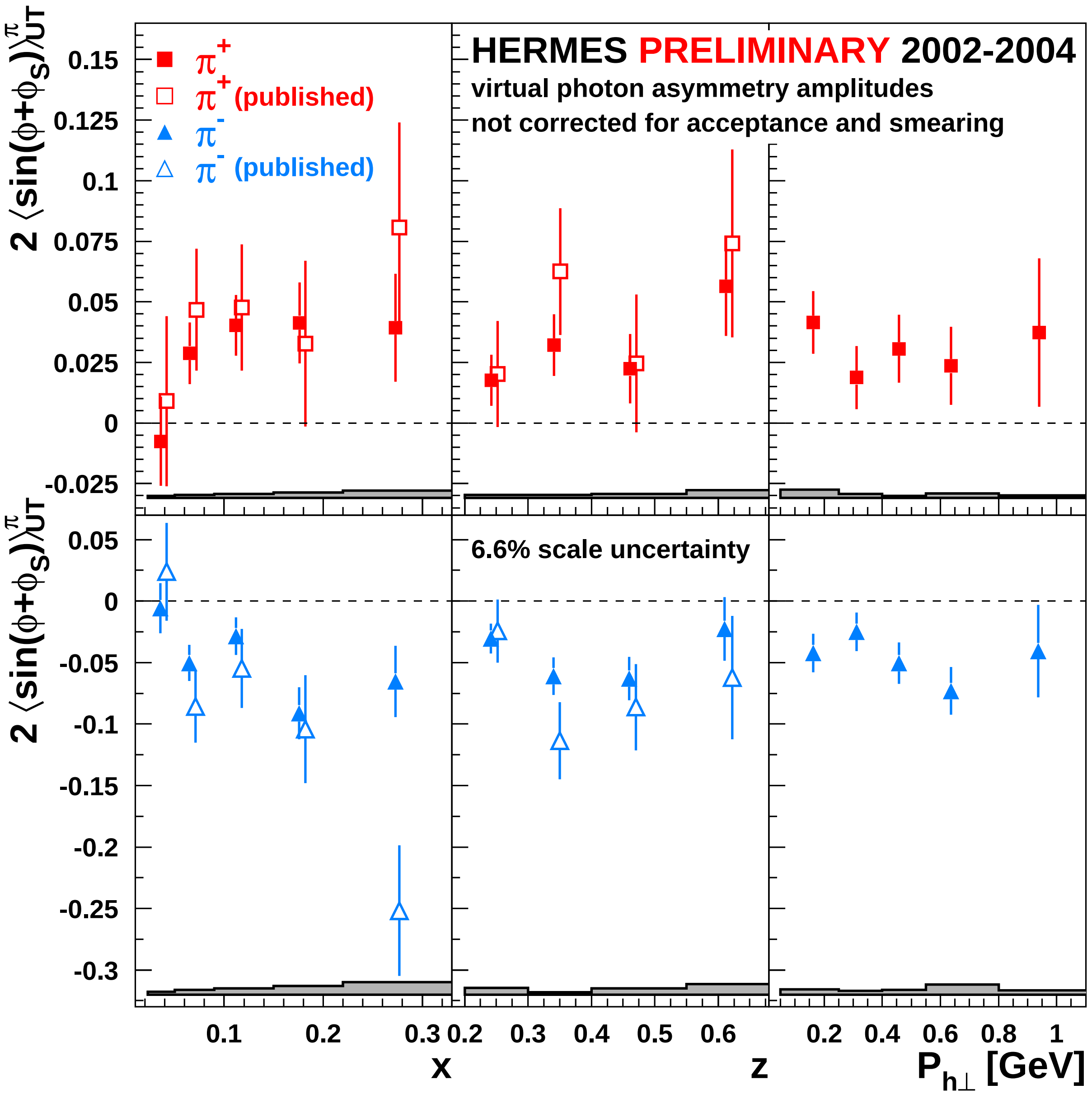
$$\begin{aligned} \frac{A^h_{UT}(\phi, \phi_S)}{2} &= < \sin(\phi + \phi_S) >^h_{UT} \frac{B(< y >)}{A(< x >, < y >)} \sin(\phi + \phi_S) \\ &+ < \sin(\phi - \phi_S) >^h_{UT} \sin(\phi - \phi_S) \end{aligned}$$

An (12x12) grid is used for (ϕ, ϕ_S) bins.

The addition of terms for $\sin(3\phi - \phi_S)$, $\sin \phi_S$, and $\sin(2\phi - \phi_S)$ produces negligible changes.

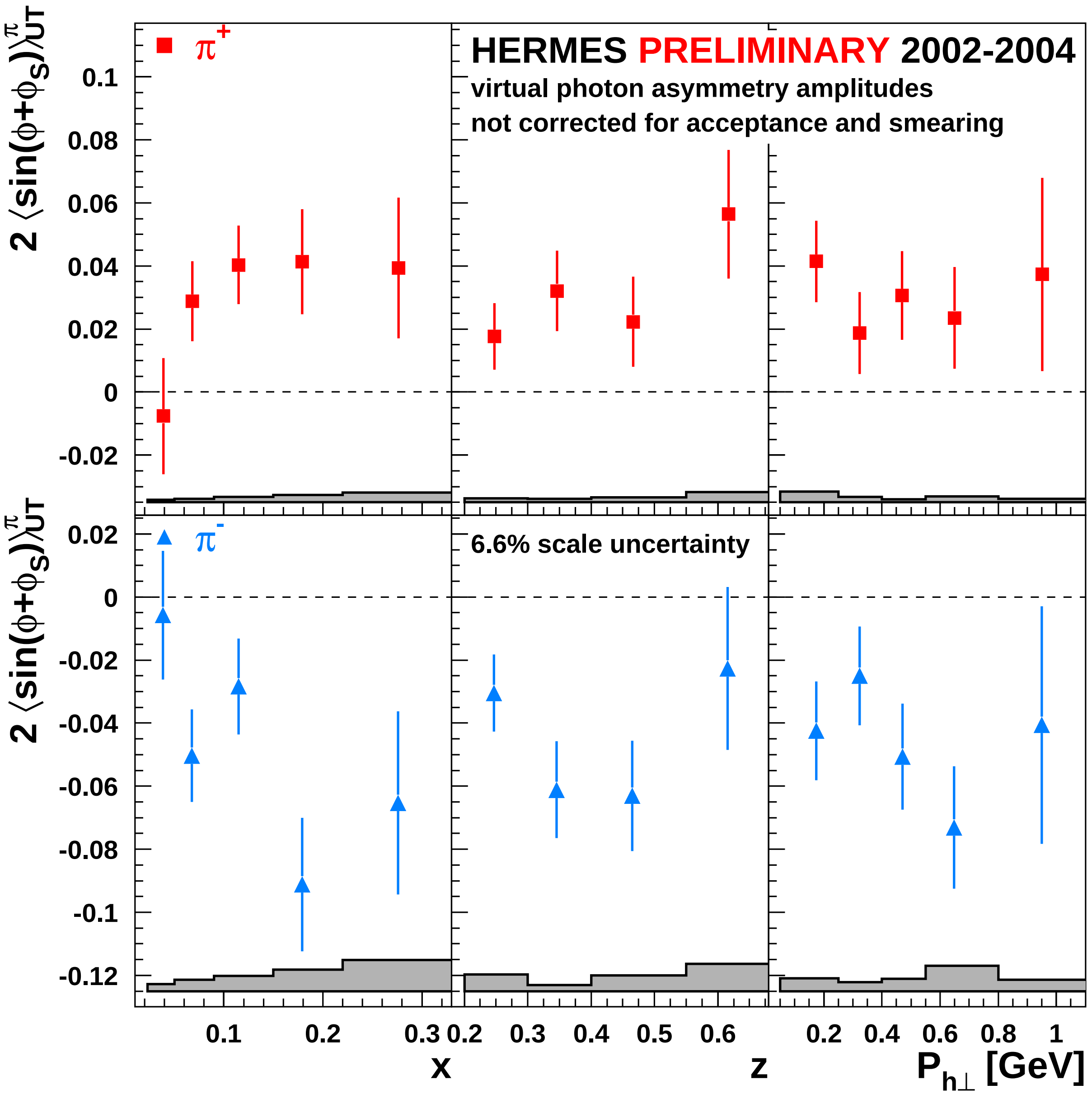
Mean values of the kinematic parameters are:
$< x >= 0.09$, $< y >= 0.54$, $< Q^2 >= 2.41$ GeV^2, $< z >= 0.36$, and $< P_{\pi\perp} = 0.41$ GeV.

Collins moments

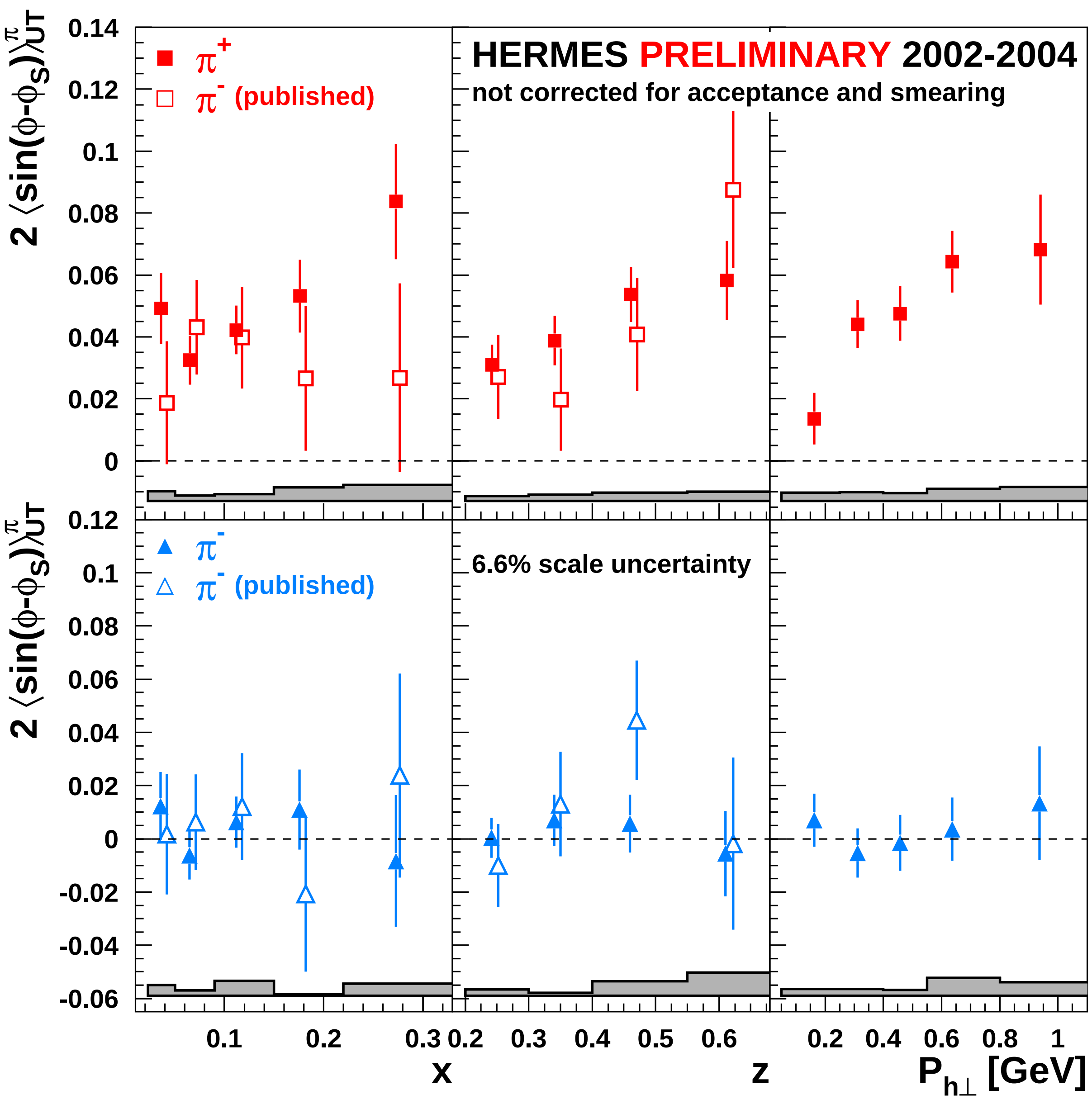


Results are consistent with previously published: PRL 94, 012002 (2005).

Collins moments



Sivers moments



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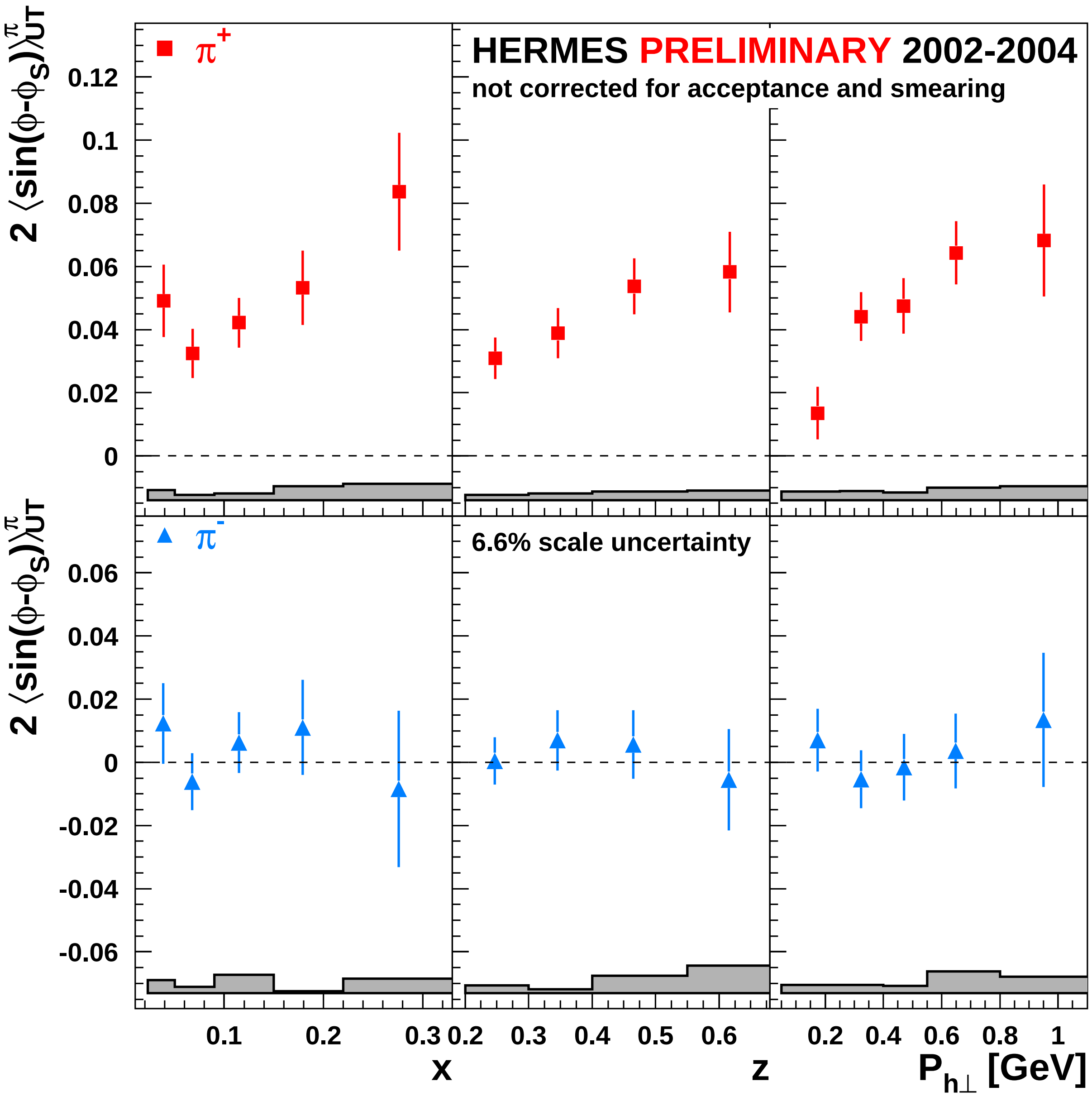
Sivers moments



Results for the Collins/Sivers Moments

The Collins moment for π^+ is positive while it is negative for π^-.

Expectation - δu is positive and δd is negative as for the helicity densities.

However, the magnitude of the negative π^- moment looks to be as large as for π^+.

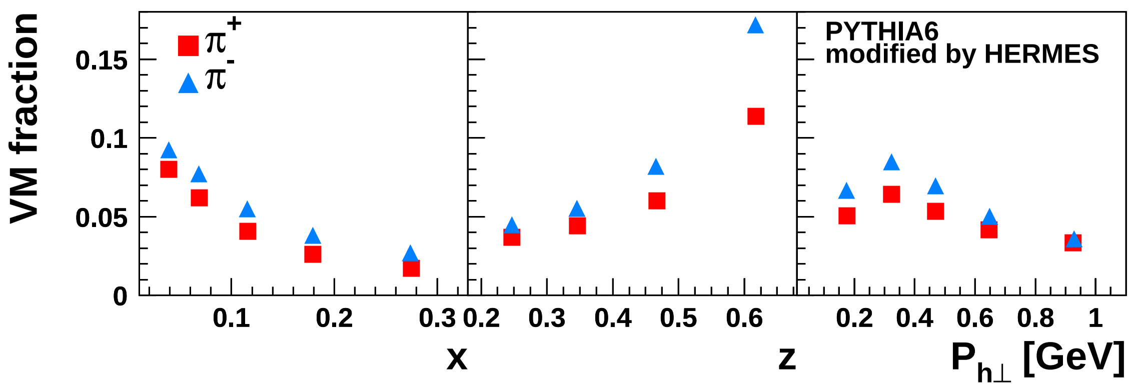
An explanation could be a substantial magnitude for the disfavored Collins FF ($u \to \pi^-$).

In principle, it might be understood in the string model of fragmentation.

The Sivers moment is positive for π^+ while it is compatible with zero for π^-.

The positive value for π^+ moment implies a negative value for the Sivers function of u-quark.

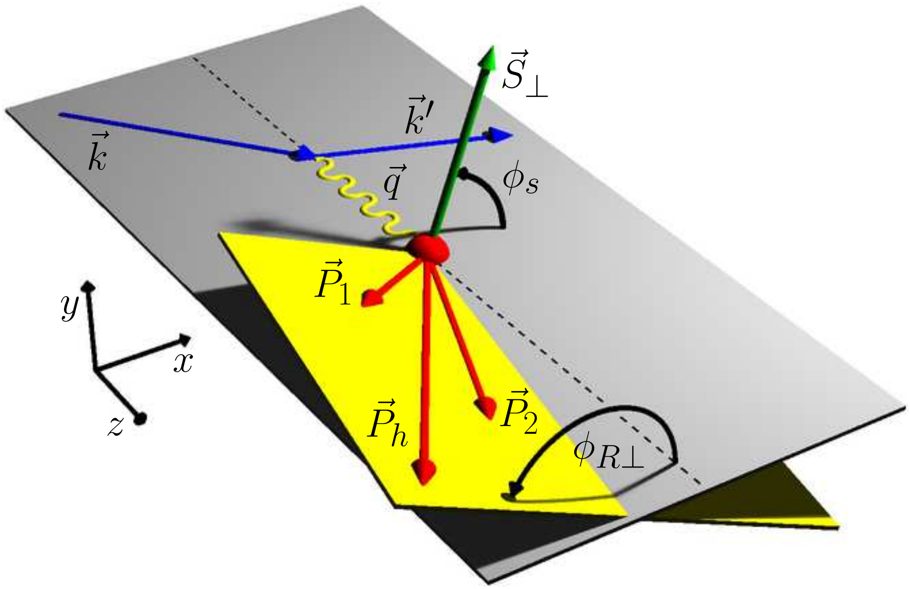
The relative contributions to the data from simulated exclusive vector meson production.



2-pion Fragmentation

Jaffe et al., hep-ph/9709322
Radici et al., hep-ph/0110252

$$ep \to e\pi\pi X$$



After integration over $P_{h\perp}$:

$$\sigma_{UT} \propto \sum_q e_q^2 \sin(\phi_{R\perp} + \phi_S)\, h_1\, H_1^{\triangleleft}$$

$$H_1^{\triangleleft} = H_1^{\triangleleft}(z, \xi, M_h^2)$$

$$\xi \propto z1/(z1 + z2)$$

+ asymmetry directly proportional to $h_1\, H_1^{\triangleleft}$

+ no Collins/Sivers mixing

- less statistics

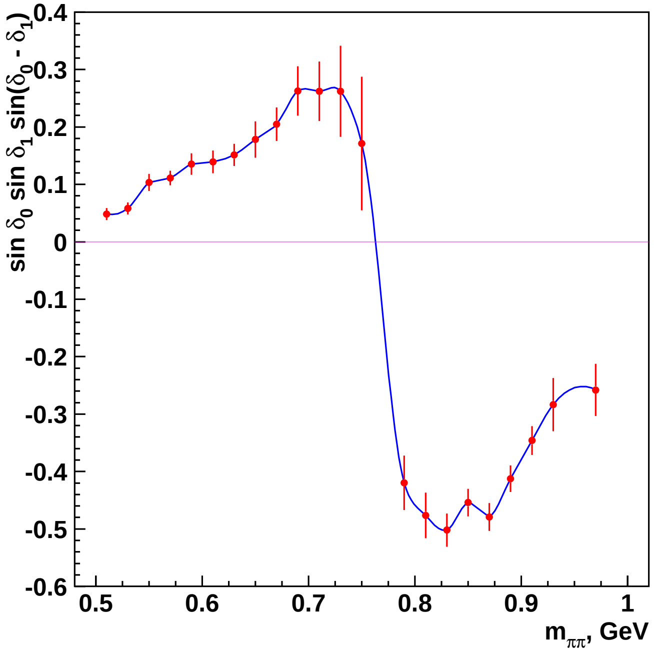
- $H_1^{\triangleleft}$ is unknown

Interference FF

The partial-wave expansion gives:

$$H_1^{\sphericalangle}(z, \cos\theta, M_h^2) \approx H_1^{\sphericalangle,sp}(z, M_h^2) + H_1^{\sphericalangle,pp}(z, M_h^2)\cos\theta$$

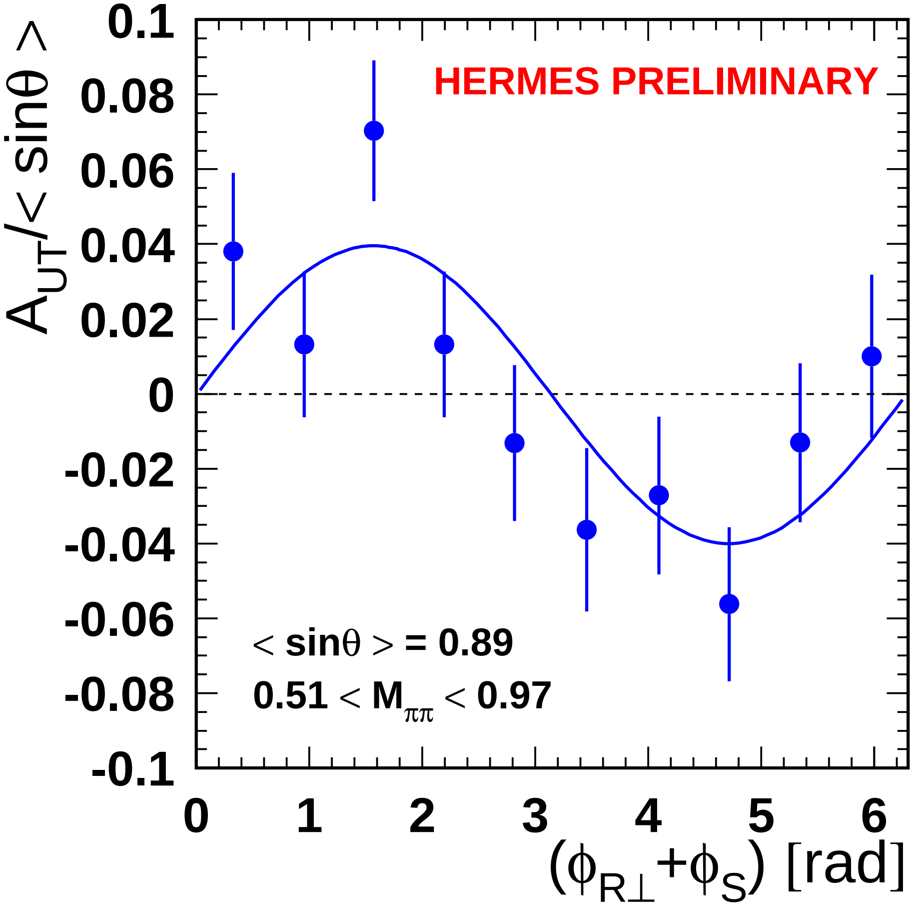
In Jaffe's model (hep-ph/9709322): $H_1^{\sphericalangle,sp}(z, M_h^2) = \sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1)\, H_1^{\sphericalangle,sp'}(z, M_h^2)$



Radici et al. (hep-ph/01110252) doesn't predict a sign change of the asymmetry.

Transverse Spin Asymmetry

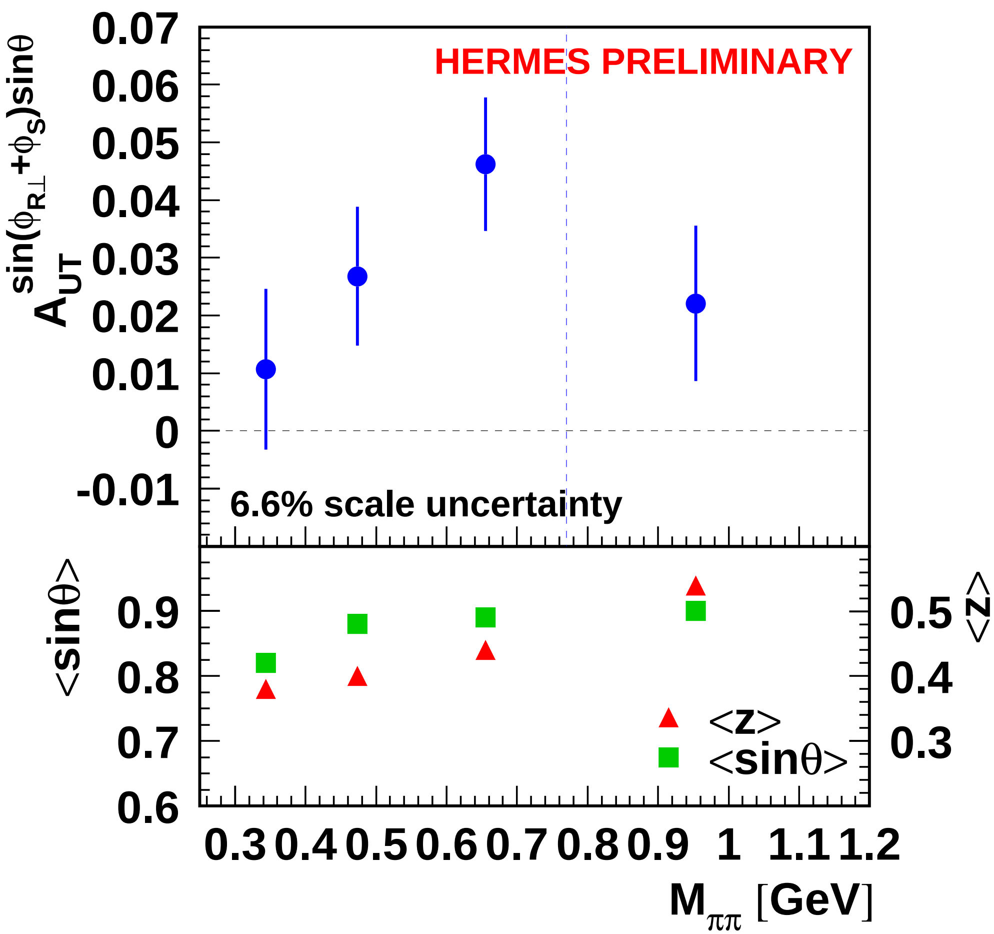
$$A_{UT}(\phi_{R\perp},\phi_S,\theta) = \frac{1}{|S_T|}\frac{N^{\uparrow}(\phi_{R\perp},\phi_S,\theta)/N^{\uparrow}_{DIS} - N^{\downarrow}(\phi_{R\perp},\phi_S,\theta)/N^{\downarrow}_{DIS}}{N^{\uparrow}(\phi_{R\perp},\phi_S,\theta)/N^{\uparrow}_{DIS} + N^{\downarrow}(\phi_{R\perp},\phi_S,\theta)/N^{\downarrow}_{DIS}}$$



significant $\sin(\phi_{R\perp}+\phi_S)$ behaviour

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

Invariant Mass Dependence



- positive asymmetry moment for all masses
- result rules out a sign change at the ρ^0 mass

Exclusive Reactions

- Generalized Parton Distributions

- Deeply Virtual Compton Scattering

- Exclusive ρ^0 Production

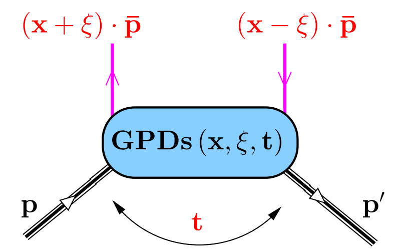
Generalized Parton Distributions

- twist-2 GPDs $H, E, \widetilde{H}, \widetilde{E}\,(x,\xi,t)$ for spin 1/2 hadron

$x \pm \xi$: longitudinal momentum fractions of the partons,

ξ: fraction of the momentum transfer, $\xi \simeq \frac{x_B}{2-x_B}$,

t: invariant momentum transfer, $t \equiv (p-p')^2$.



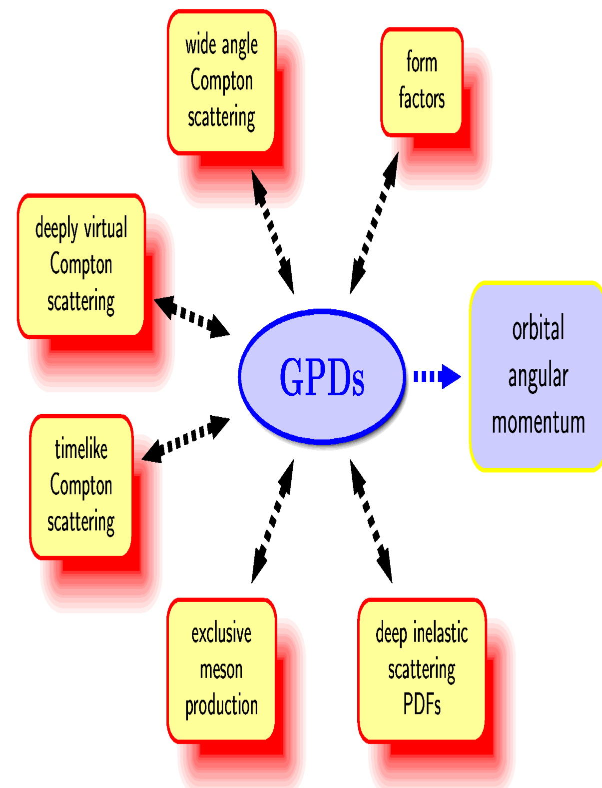
- GPDs $\Rightarrow$ Form Factors:

$$\int_{-1}^{1} dx \cdot H_q\,(x,\xi,t) = F_1^q\,(t),$$

$$\int_{-1}^{1} dx \cdot E_q\,(x,\xi,t) = F_2^q\,(t),$$

$$\int_{-1}^{1} dx \cdot \tilde{H}_q\,(x,\xi,t) = G_A^q\,(t),$$

$$\int_{-1}^{1} dx \cdot \tilde{E}_q\,(x,\xi,t) = G_P^q\,(t).$$



- GPDs $\Rightarrow$ PDFs :

$$H_q\,(x,0,0) = q\,(x),\ \tilde{H}_q\,(x,0,0) = \Delta q\,(x).$$

$$H_g\,(x,0,0) = g\,(x),\ \tilde{H}_g\,(x,0,0) = \Delta g\,(x).$$

- GPDs $\Rightarrow$ Total Angular Momentum of Partons

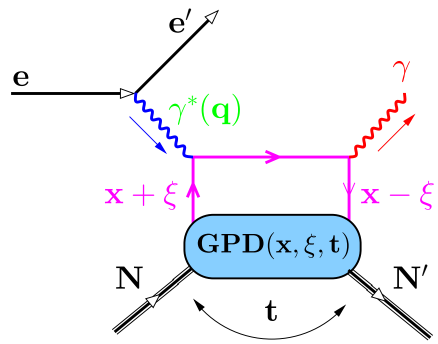
$$J_{q,g} = \frac{1}{2}\int_{-1}^{1} dx \cdot x[H_{q,g}(x,\xi,0) + E_{q,g}(x,\xi,0)]$$

How to Access GPDs?

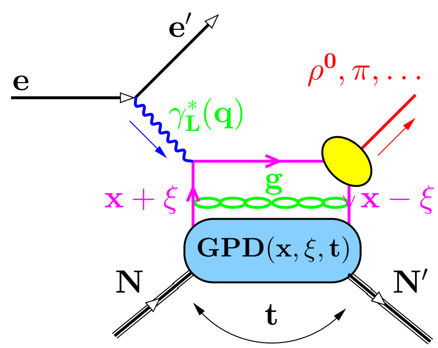
- GPDs constrained by known quantities (FFs, PDFs, . . .) and accessible in exclusive processes.

- At large Q^2 and small t, exclusive electroproduction of real photons or mesons can be factorized into a hard, perturbative part and a soft, non-perturbative part (GPDs).

- Deeply Virtual Compton Scattering $e + N \to e' + N' + \gamma$
  - described by GPDs $H, E, \widetilde{H}, \widetilde{E}$,
  - simplest process, gluons absent in the leading order.

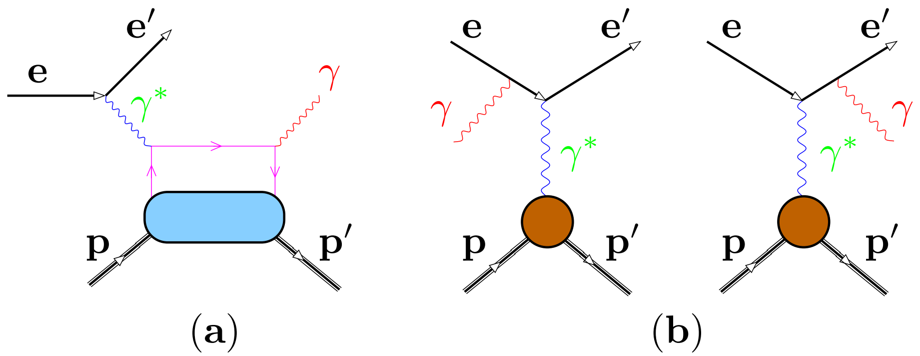


- Exclusive Meson Production $e + N \to e' + N' + \left(\rho^0, \pi, \dots\right)$
  - vector mesons (ρ^0, ω, ϕ): H, E,
  - pseudoscalar mesons (π, η): $\widetilde{H}, \widetilde{E}$,
  - pion pairs $(\pi^+\pi^-)$: H, E,



Deeply Virtual Compton Scattering

- DVCS (a) and Bethe-Heithler (b) processes have the same initial and final states:



- Interference between DVCS and Bethe-Heitler:
$d\sigma(\mathrm{eN} \to \mathrm{eN}\gamma) \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{\mathcal{I}}$

- $\mathcal{T}_{BH}$ is parameterized in terms of Dirac and Pauli Form Factors F_1, F_2.

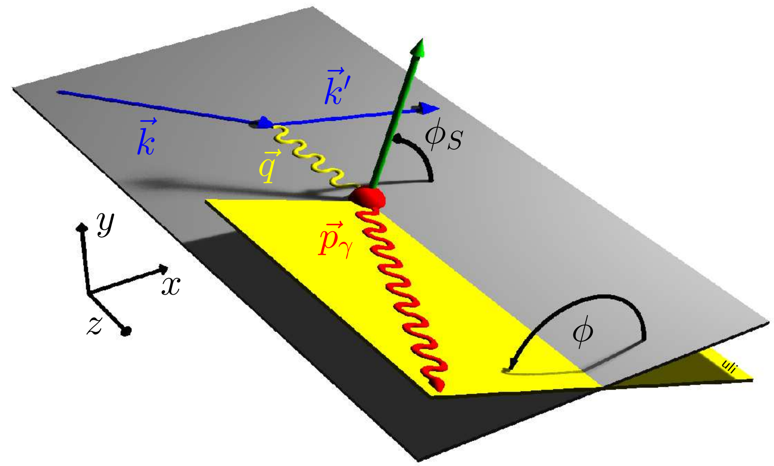
- $\mathcal{T}_{DVCS}$ is parameterized in terms of Compton form factors (convolution of GPDs) $\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}$.

- At HERMES kinematics, $\mathcal{T}^{BH} \gg \mathcal{T}^{DVCS}$, $\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}$ are accessed through $\mathcal{I}$.

Azimuthal Asymmetries in DVCS

$$d\sigma(\mathrm{eN} \to \mathrm{eN}\gamma) \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{\mathcal{I}}$$

- $\mathcal{I}$ induces azimuthal asymmetries in the cross-section:
  - Beam-charge asymmetry $A_C(\phi)$:
    $d\sigma(e^+, \phi) - d\sigma(e^-, \phi) \propto \mathrm{Re}[F_1\mathcal{H}] \cdot \cos\phi$
  - Beam-spin asymmetry $A_{LU}(\phi)$:
    $d\sigma(\overrightarrow{e}, \phi) - d\sigma(\overleftarrow{e}, \phi) \propto \mathrm{Im}[F_1\mathcal{H}] \cdot \sin\phi$
  - Longitudinal target-spin asymmetry $A_{UL}(\phi)$:
    $d\sigma(\overset{\Leftarrow}{P}, \phi) - d\sigma(\overset{\Rightarrow}{P}, \phi) \propto \mathrm{Im}[F_1\widetilde{\mathcal{H}}] \cdot \sin\phi$
  - Transverse target-spin asymmetry $A_{UT}(\phi, \phi_s)$:
    $d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi)$
    $\propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi - \phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\widetilde{\mathcal{E}}] \cdot \cos(\phi - \phi_S)\sin\phi$



$\Longrightarrow$ the only place $\mathcal{E}$ enters in the leading order $\Longrightarrow$ $\mathrm{A}_{\mathrm{UT}}^{\sin(\phi-\phi_S)\cos\phi}$ sensitive to J_q

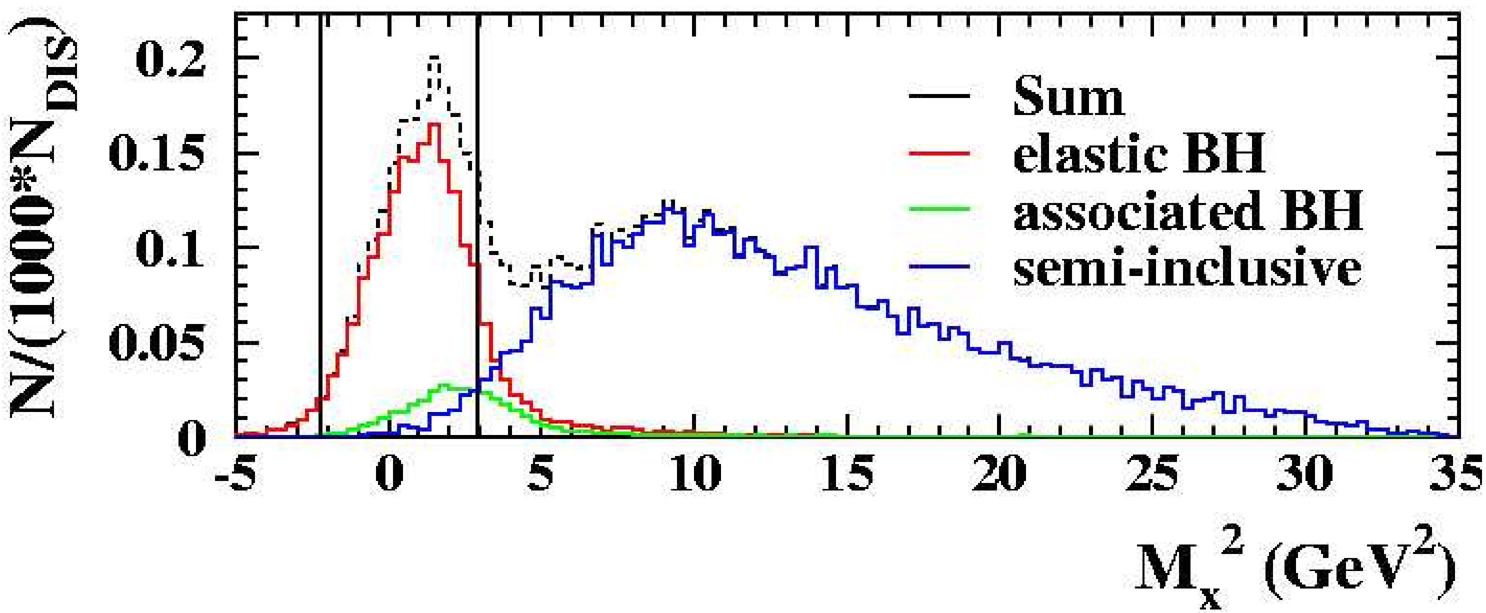
$$J_{q,g} = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx \cdot x \cdot [H_{q,g}(x,\xi,t) + E_{q,g}(x,\xi,t)]$$

DVCS Measurements at HERMES

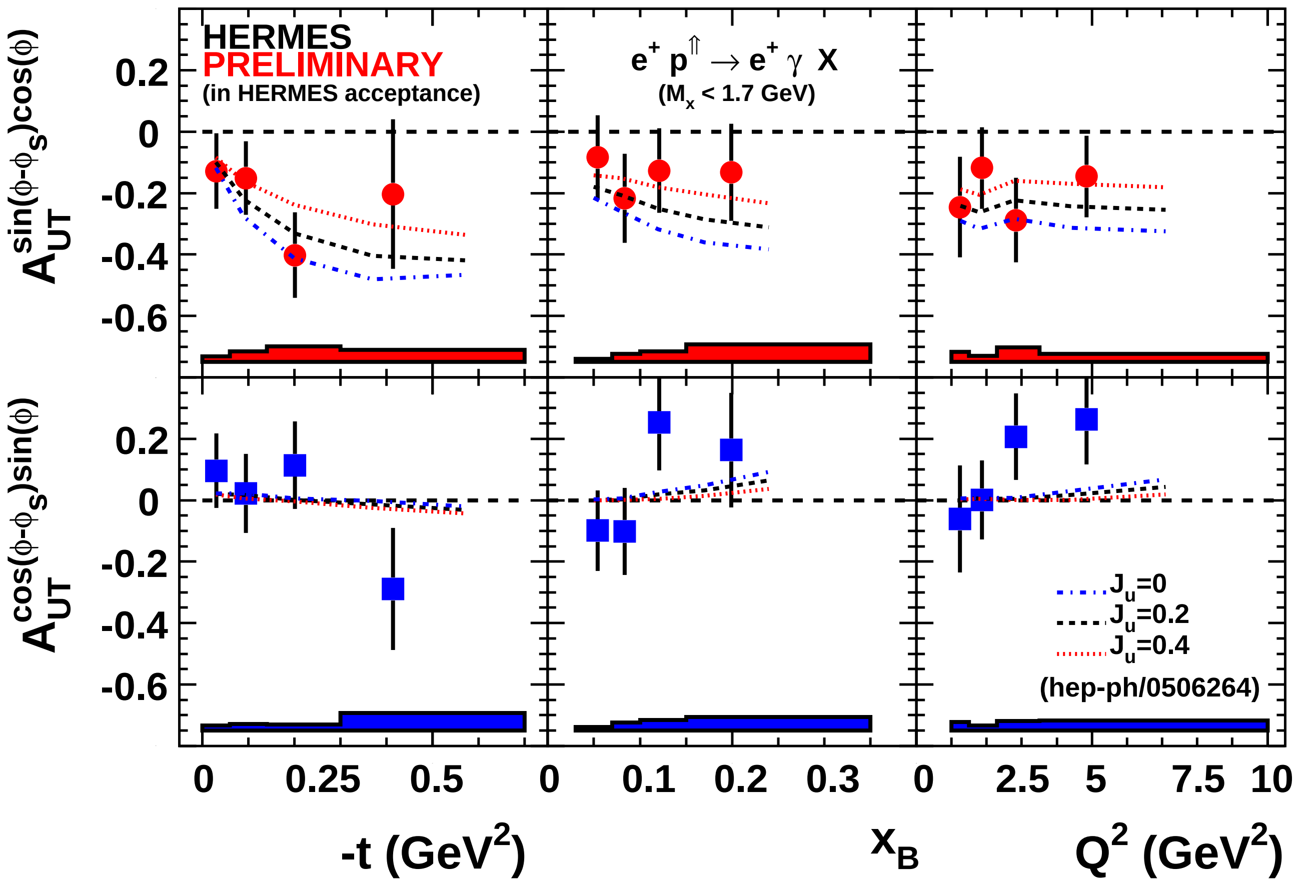
- Photons: calorimeter $\delta E_\gamma / E_\gamma \sim 5\%$
- Recoiling protons not detected $\Rightarrow$ missing mass technique ($ep \rightarrow e'p\gamma$)

$$\mathrm{M_x^2} = (\mathrm{P_e} + \mathrm{P_p} - \mathrm{P_{e'}} - \mathrm{P_\gamma})^2$$

- Background contribution $\sim 5\%$ is determined from MC and corrected.



Transverse Target-Spin Asymmetry



$$A_{UT}(\phi,\phi_s) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}] \cdot \cos(\phi-\phi_S)\sin\phi$$

- $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ sensitive to J_u and not to GPD model parameters (F.Ellinghaus et al, hep-ph/0506264)

$\Longrightarrow$ allows extraction of J_u within these GPD models

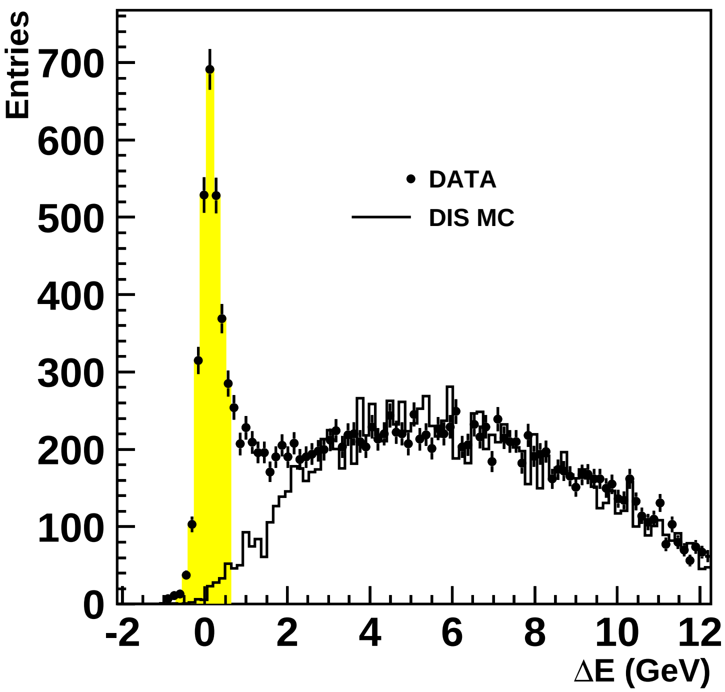
Exclusive ρ^0 Production

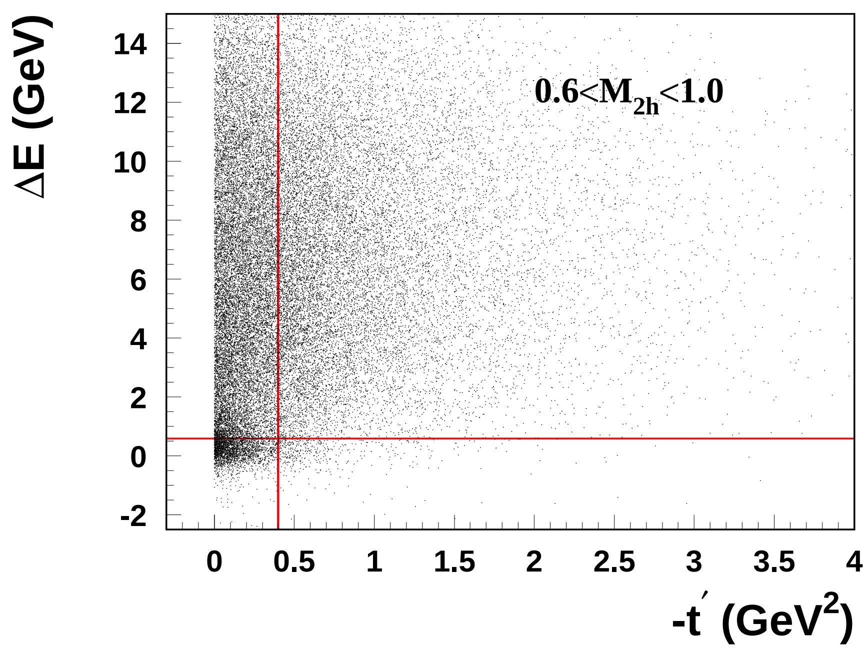
$\boxed{\rho^0 \to \pi^+\pi^-}$

- no recoil detection
- exclusive ρ^0 reaction through the energy and momentum transfer:

$$\boxed{\Delta E = \frac{M_x^2 - M_p^2}{2M_p}}$$

$$\boxed{t' = t - t_0}$$

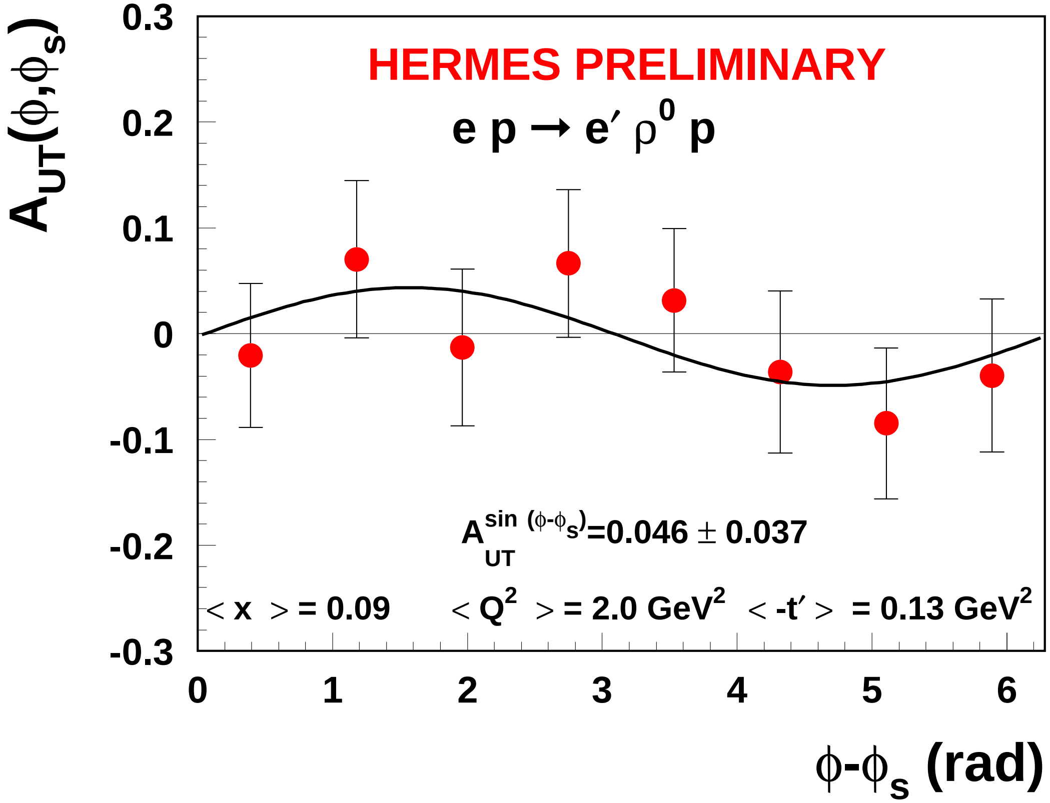




Transverse Spin Asymmetry for Exclusive ρ^0

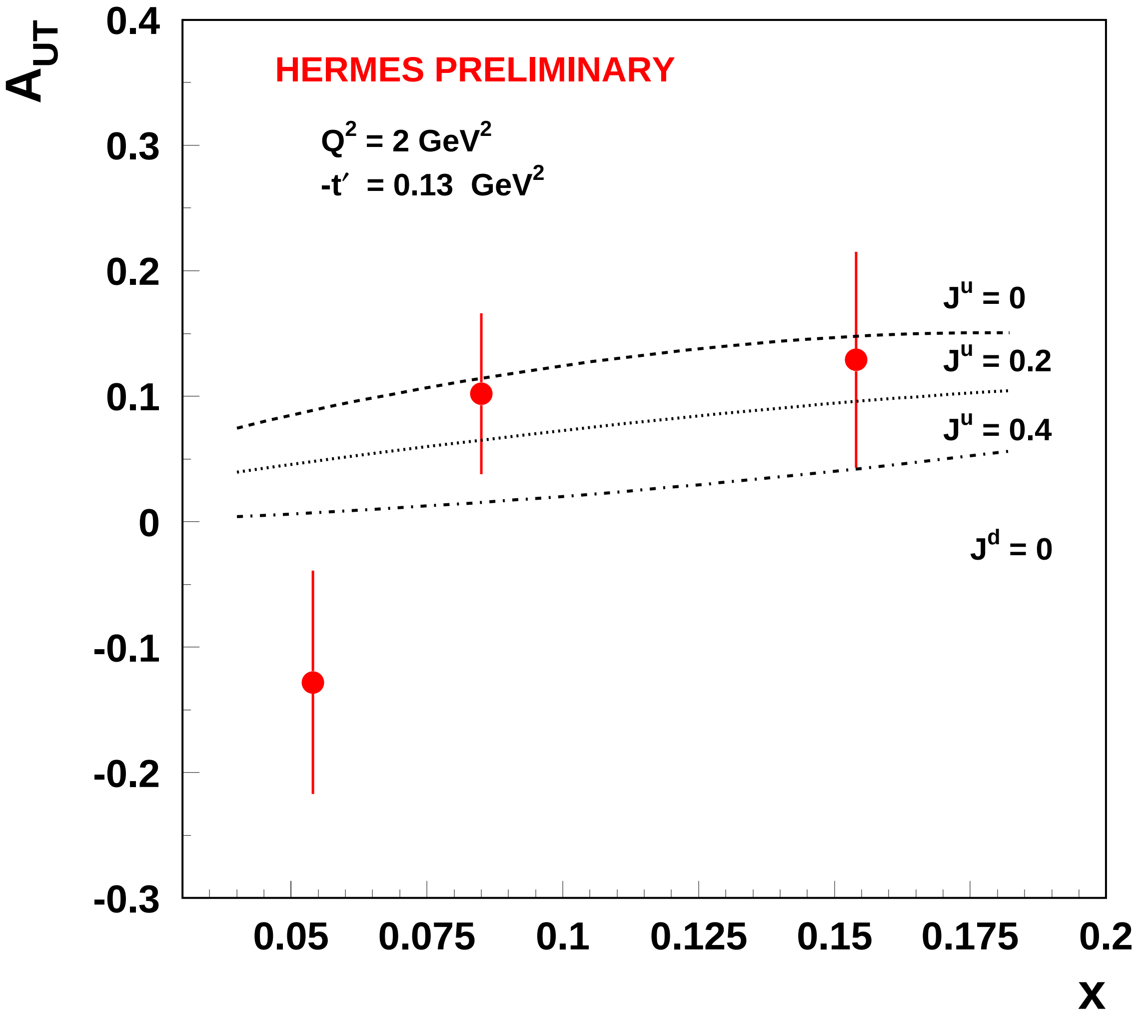
$$A_{UT}(\phi-\phi_s) = \frac{1}{|P_T|}\frac{N^{\uparrow}(\phi-\phi_s) - N^{\downarrow}(\phi-\phi_s)}{N^{\uparrow}(\phi-\phi_s) + N^{\downarrow}(\phi-\phi_s)},$$

$$A_{UT}(\phi-\phi_S) = A_{UT}^{\sin(\phi-\phi_S)} \cdot \sin(\phi-\phi_S) + \text{constant}$$



$$A_{UT}^{\sin(\phi-\phi_s)} = 0.046 \pm 0.037$$

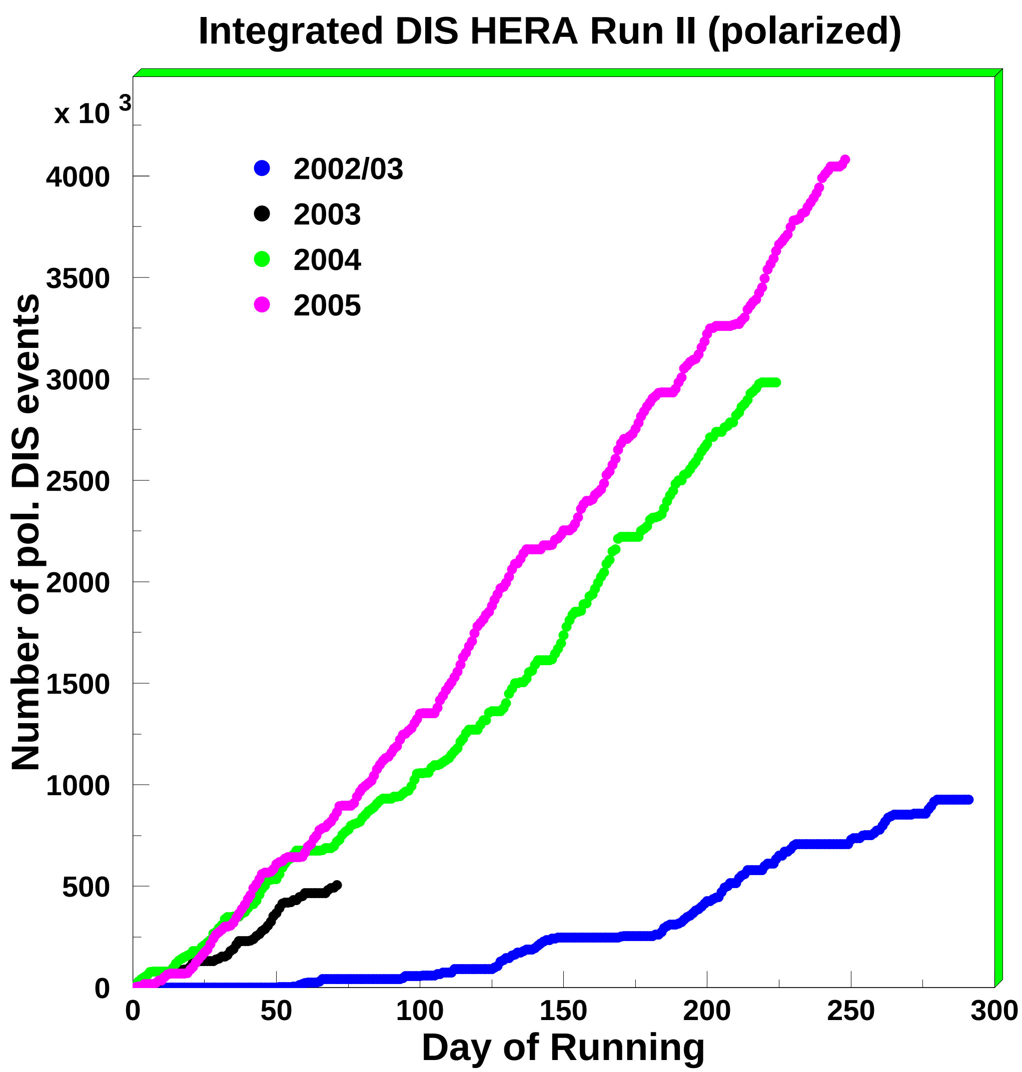
Kinematic Dependence



F.Ellinghaus et al., hep-ph/0506264

- within the statistical errors in agreement with theoretical calculations
- the statistics is not enough yet to make conclusive statement about J^u

Coming Statistics



Present analysis: 2002-2004 years
About 4 **M** DIS events

Still running with transversely
polarized hydrogen target

Summary

- A measurement of SSA's for semi-inclusive electroproduction of charged π's with transversely polarized hydrogen target disentangled two different mechanisms. The Collins moment for π^+ is found to be positive while for π^- it is negative. A magnitude of the moment for π^- is found to be unexpectedly large. An independent measurement of the Collins FF is required for an extraction of the transversity distribution.

- A significant positive Sivers moment for π^+ has been measured. This corresponds to a negative value of the f_{1T}^{u}.

- A significant non-zero transverse spin asymmetry moment for 2-pion fragmentation has been measured providing evidence for a non-zero interference fragmentation function. The result rules out the invariant mass dependence of the asymmetry predicted in Jaffe et al. model. The result implies that the method may be useful for the transversity study.

- Transverse spin target asymmetry for the DVCS process has been measured. With better statistics the asymmetry can be used for extraction of the quark total angular moment.

- Transverse spin target asymmetry for exclusive ρ^0 production has been measured. Within the statistical errors the asymmetry in agreement with theoretical estimation (F.Ellinghaus et al., hep-ph/0506264). The asymmetry can be used for extraction of the quark total angular moment.

- HERMES still running with the transversely polarized hydrogen target. A final statistics is expected to be by factor two high w.r.t. present one.

- Analysis of the inclusive and semi-inclusive asymmetries with a longitudinally polarized beam and transversely polarized target is on the way.