Transverse Spin Physics at HERMES

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on behalf of the HERMES collaboration

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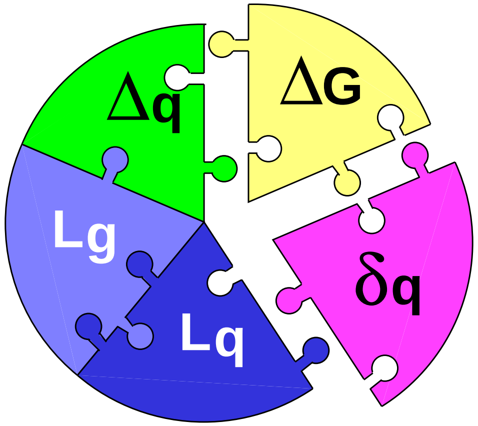
- Spin Puzzle
- HERMES Experiment
- TTSA in semi-inclusive meson production
- TTSA in exclusive reactions
- Summary

Spin Puzzle

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

$$J_q = \frac{1}{2}(\Delta u + \Delta d + \Delta s) + L_q$$

$$J_G = \Delta G + L_G$$



Δq - known from DIS (contribute about 30% to the nucleon spin only!)

ΔG - there are first measurements (small?)

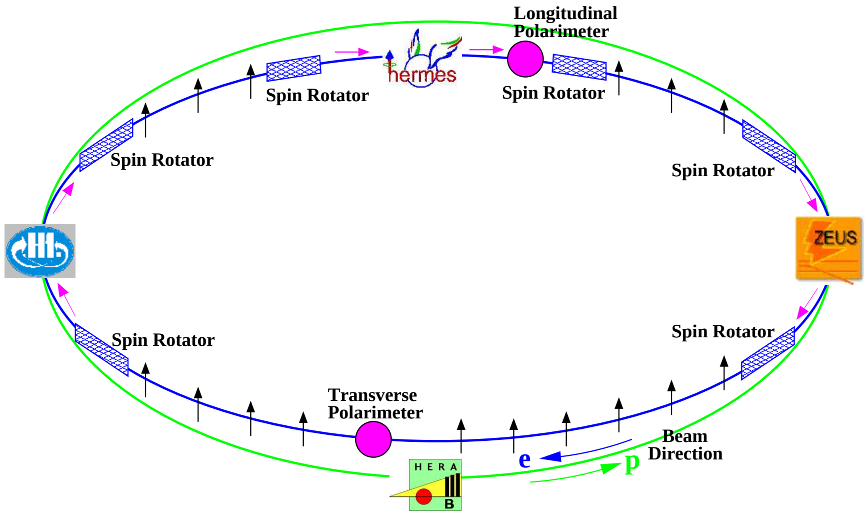
L_q and L_G - are unknown.

To clarify the nucleon spin structure one need to measure:

- orbital angular momenta L_q, L_G
- transversity distribution function $\delta q(x)$

HERMES Experiment

27.5 GeV polarized e^{+}/e^{-} beam of HERA



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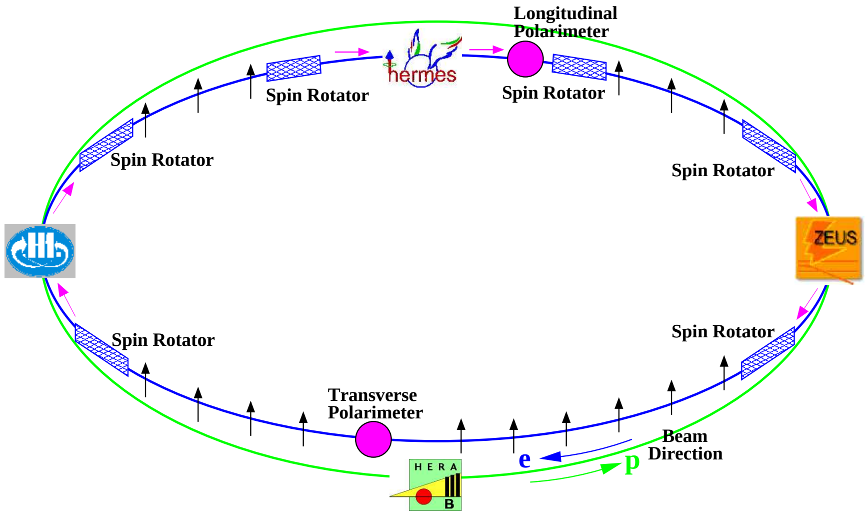
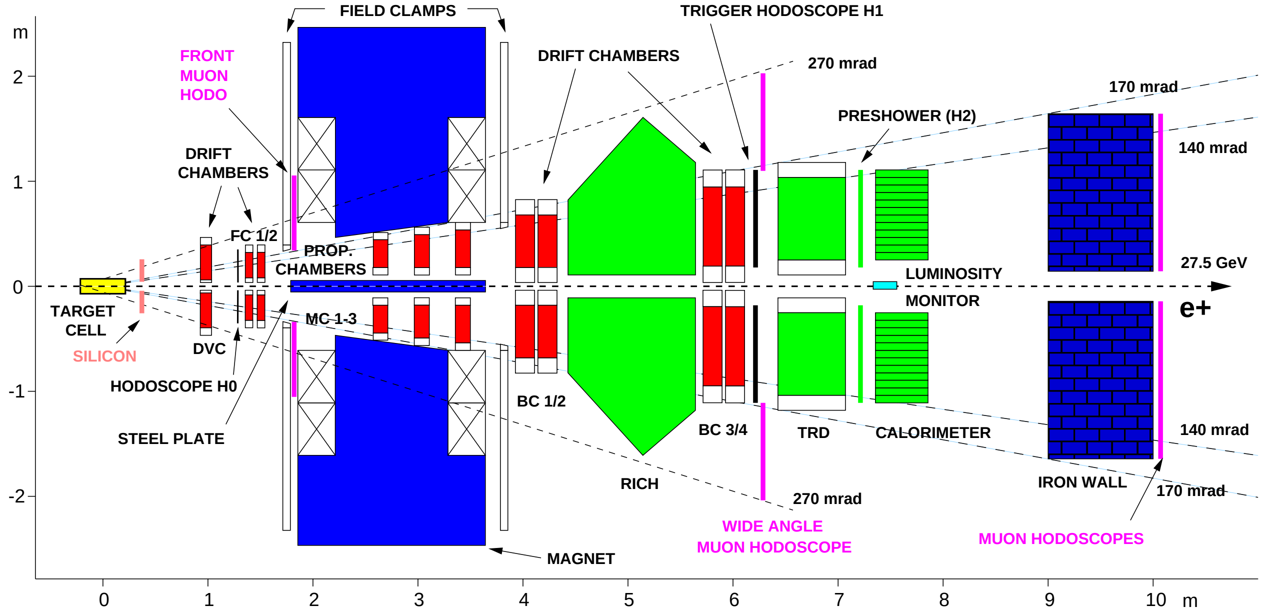
27.5 GeV polarized e^+/e^- beam of HERA





Internal gas Target:

polarized - $H^{\uparrow}$

Angular acceptance:

$40 < \theta < 220$ mrad

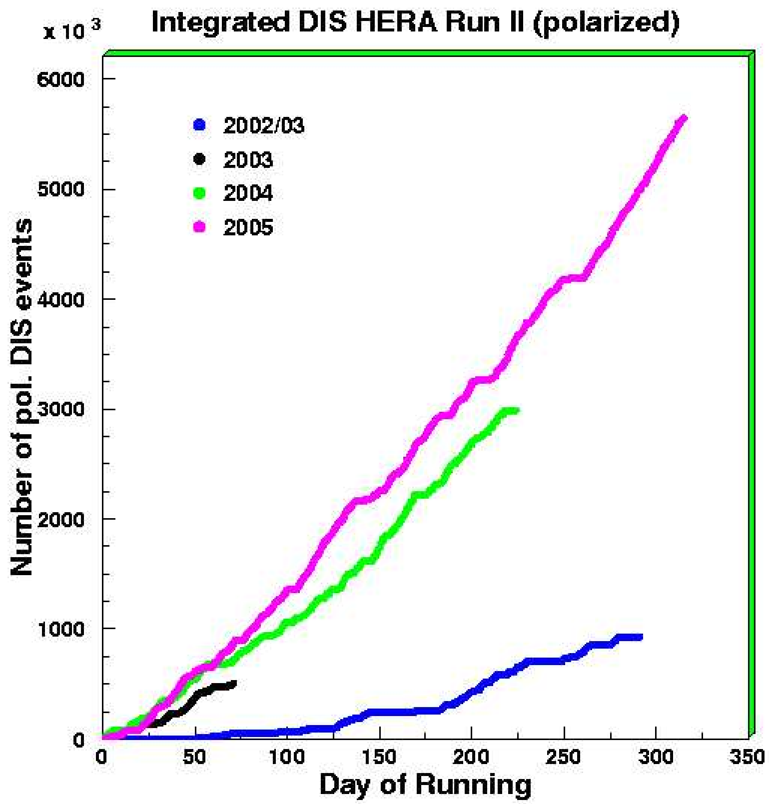
RICH: π / K / p

- e/h rejection: TRD, Preshower, Calorimeter, RICH
- magnetic spectrometer: $\Delta p/p < 2.5\%$ and $\Delta\theta < 0.6$ mrad

HERMES Experiment

2002 – 2005 data taking years:

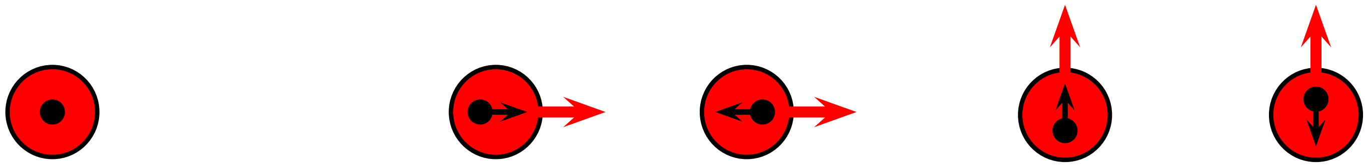
- transversely polarized atomic hydrogen ($P \sim 75\%$);
- flip of the polarisation direction every 90 sec in 0.5 sec;
- integrated luminosity about 170 pb^{-1}



Motivation: Transversity Distribution Function

Leading Twist: three quark distribution functions.

Unpolarized DF	Helicity DF	Transversity DF
$q(x) = \overrightarrow{q}(x) + \overleftarrow{q}(x)$	$\Delta q(x) = \overrightarrow{q}(x) - \overleftarrow{q}(x)$	$\delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$



well known	known	unknown

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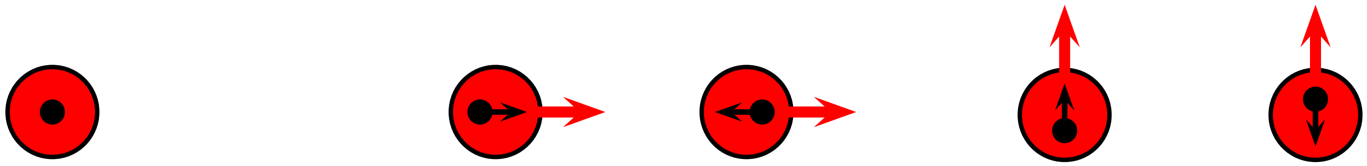

well known	known	unknown

- for non-relativistic quarks: $\delta q(x) = \Delta q(x)$.
- no gluon transversity for spin-1/2 nucleon
- $\delta q(x)$ doesn't contribute to inclusive DIS, $ep \to eX$, due to its chiral-odd nature.
- requires a combination with other chiral-odd object, e.g. Collins FF $\Longrightarrow$
  study of transverse target-spin asymmetries (TTSA) in SIDIS, $ep \to ehX$.

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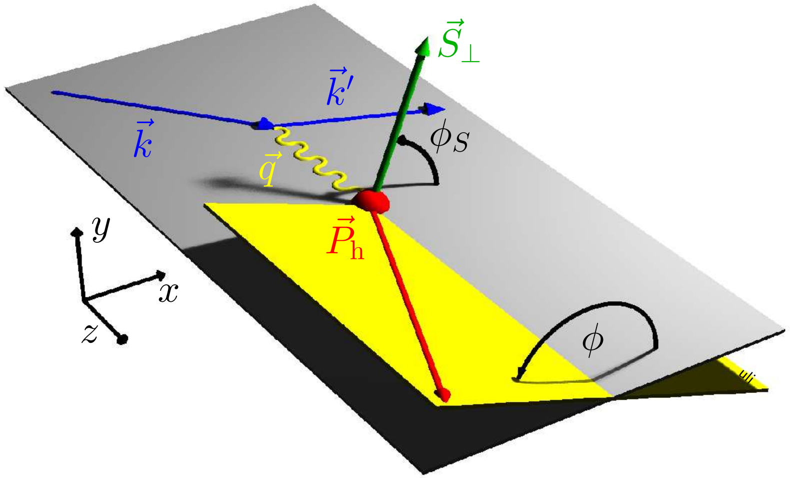
TTSA in SIDIS

- Collins FF $H_1^{\perp}$ describes an influence of the quark transverse polarization on the hadron transverse momentum $\vec{P}_{h\perp}$.
- A completely different possible mechanism for target-related SSA's is known. Sivers DF $f_{1T}^{\perp}$ describes a correlation of struck quark p_T with target polarization.
- Fortunately, two mechanisms produce different angular dependencies of the A_{UT}.



A_{XY}: X(Y) - Beam (Target) polarization.

$$A^h_{UT}(\phi,\phi_S) = \frac{1}{|S_T|}\frac{N_h^{\uparrow}(\phi,\phi_S) - N_h^{\downarrow}(\phi,\phi_S)}{N_h^{\uparrow}(\phi,\phi_S) + N_h^{\downarrow}(\phi,\phi_S)}$$

$$A^h_{UT}(\phi,\phi_S) \propto \sin(\phi+\phi_S) \sum_q e_q^2 \cdot \mathcal{I}[h_{1T}^q(x,P_T^2) \cdot H_1^{\perp q}(z,k_T^2)]$$ — "Collins"

$$A^h_{UT}(\phi,\phi_S) \propto \sin(\phi-\phi_S) \sum_q e_q^2 \cdot \mathcal{I}[f_{1T}^{\perp q}(x,P_T^2) \cdot D_1^q(z,k_T^2)]$$ — "Sivers"

$\mathcal{I}[\ldots]$ - convolution integral over initial (P_T^2) and final (k_T^2) quark transverse momenta.

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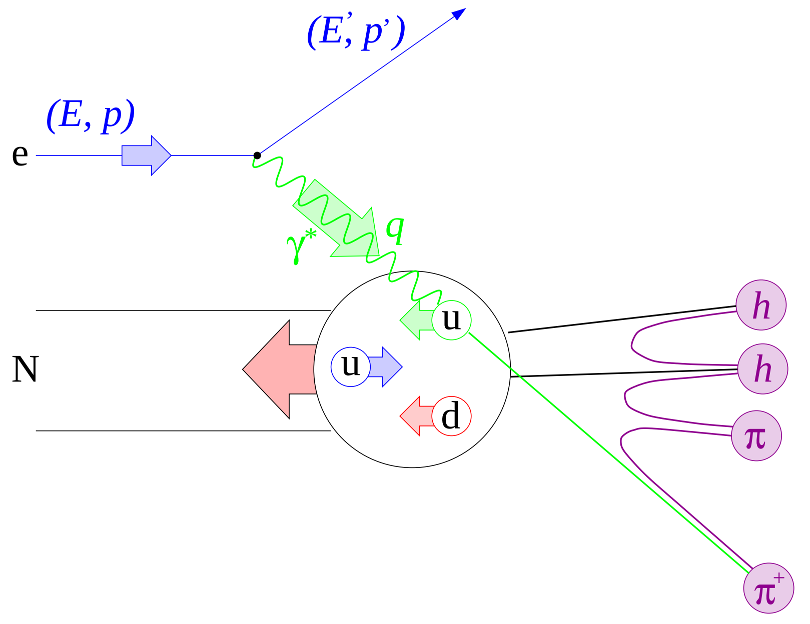
SIDIS Kinematics



$$e(k) + P(P) \longrightarrow e'(k') + h(P_h) + X(P_X)$$

$$Q^2 = -q^2 = -(k-k')^2,\ x_B = \frac{Q^2}{2P\cdot q},\ y = \frac{P\cdot q}{P\cdot k},\ W^2 = (P+q)^2,\ z = \frac{P\cdot P_h}{P\cdot q}$$

$$W^2 > 10\ \mathrm{GeV}^2,\quad 0.1 < y < 0.85,\quad Q^2 > 1\ \mathrm{GeV}^2,\quad 0.2 < z < 0.7$$

$$< Q^2 >= 2.4\ \mathrm{GeV}^2, < x >= 0.09, < y >= 0.54, < z >= 0.36, P_{h\perp} = 0.41\ \mathrm{GeV}^2$$

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Extraction of TTSA Amplitudes

- Unbinned maximum likelihood (ML) fits are used to extract simultaneously the Collins and Sivers amplitudes.

- Probability density function is defined as:

$$F(2 < \sin(\phi+\phi_S) >^h_{UT},\ 2 < \sin(\phi-\phi_S) >^h_{UT},\ \ldots,\ P,\ \phi,\ \phi_S) =$$

$$\frac{1}{2}\Big(1 + P\cdot\Big(2 < \sin(\phi+\phi_S) >^h_{UT} \cdot \sin(\phi+\phi_S) +$$

$$2 < \sin(\phi-\phi_S) >^h_{UT} \cdot \sin(\phi-\phi_S) +$$

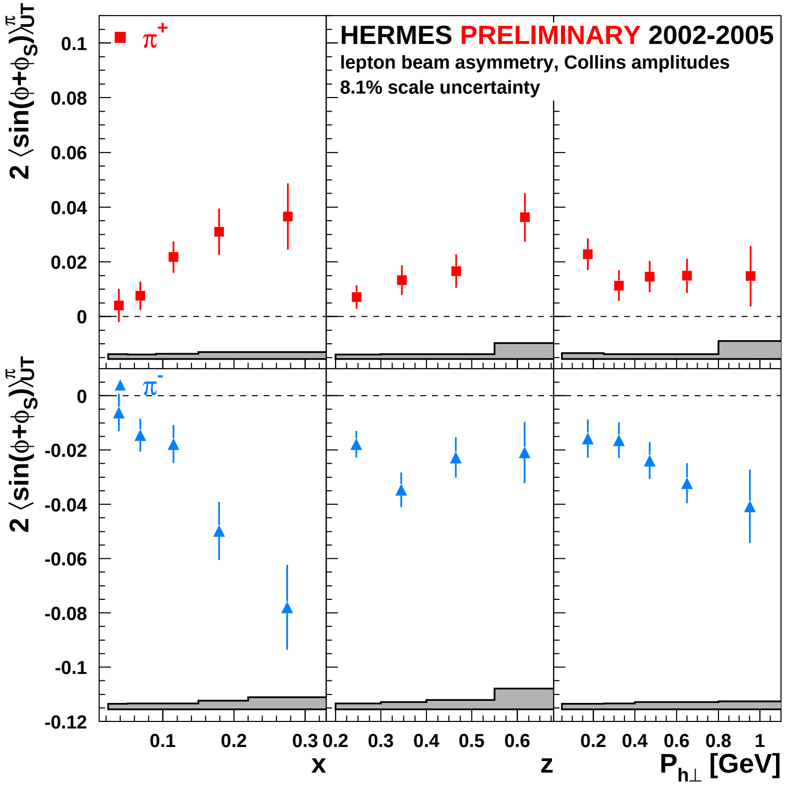
$$2 < \sin(3\phi-\phi_S) >^h_{UT} \cdot \sin(3\phi-\phi_S) +$$

$$2 < \sin(2\phi-\phi_S) >^h_{UT} \cdot \sin(2\phi-\phi_S) +$$

$$2 < \sin(\phi_S) >^h_{UT} \cdot \sin(\phi_S)\Big)\Big)$$

- The logarithm of the likelihood function $\mathcal{L} = \prod_i F_i^{w_i}$ is maximized wrt the TTSA amplitudes.

Collins amplitudes for charged pions

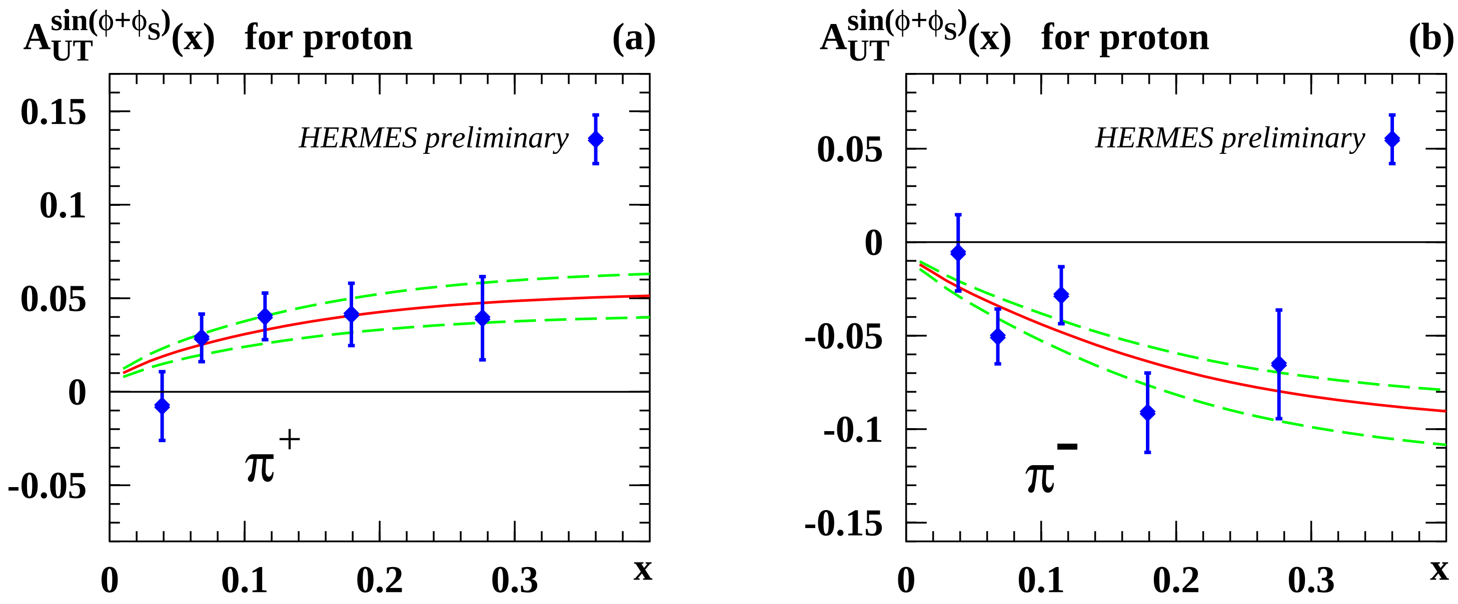


- all data (2002 - 2005) are used (PRL, 94 (2005) 012002)
- positive amplitudes for π^+
- negative amplitudes for π^-
- large negative amplitudes for π^- were unexpected
- $H_1^{\perp,unf}(z) \approx -H_1^{\perp,fav}(z)$

- $H_1{}^{fav} = H_1{}^{u\to\pi^+} = H_1{}^{d\to\pi^-} = H_1{}^{\bar{u}\to\pi^-} = H_1{}^{\bar{d}\to\pi^+}$
- $H_1{}^{unf} = H_1{}^{u\to\pi^-} = H_1{}^{d\to\pi^+} = H_1{}^{\bar{u}\to\pi^+} = H_1{}^{\bar{d}\to\pi^-}$

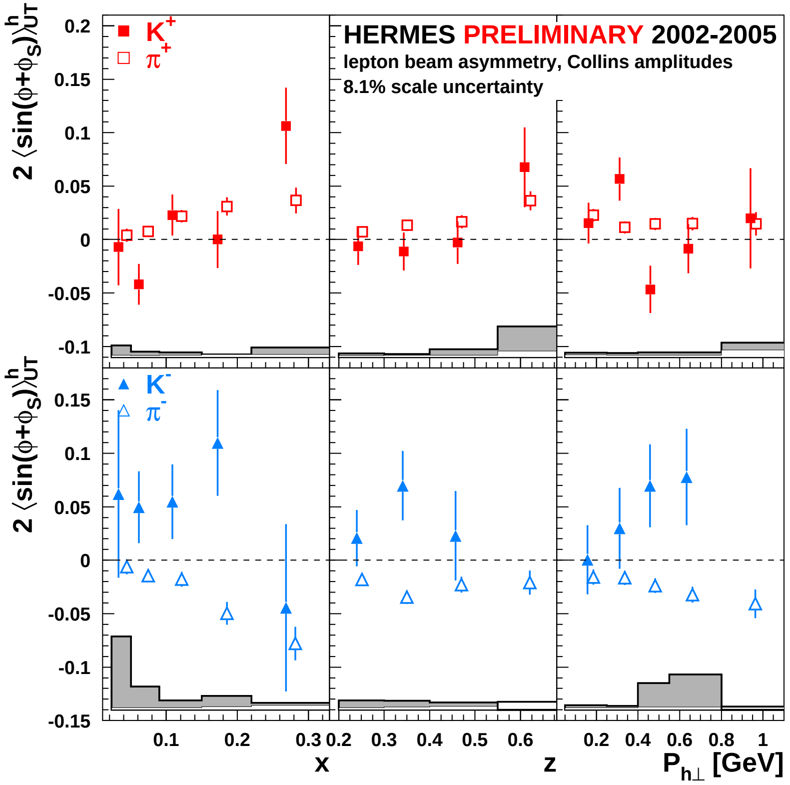
Collins amplitudes for charged pions

Efremov, Goeke, Schweitzer (Phys.Rev.D73,094025,2006)
Preliminary HERMES data 2002 - 2004.



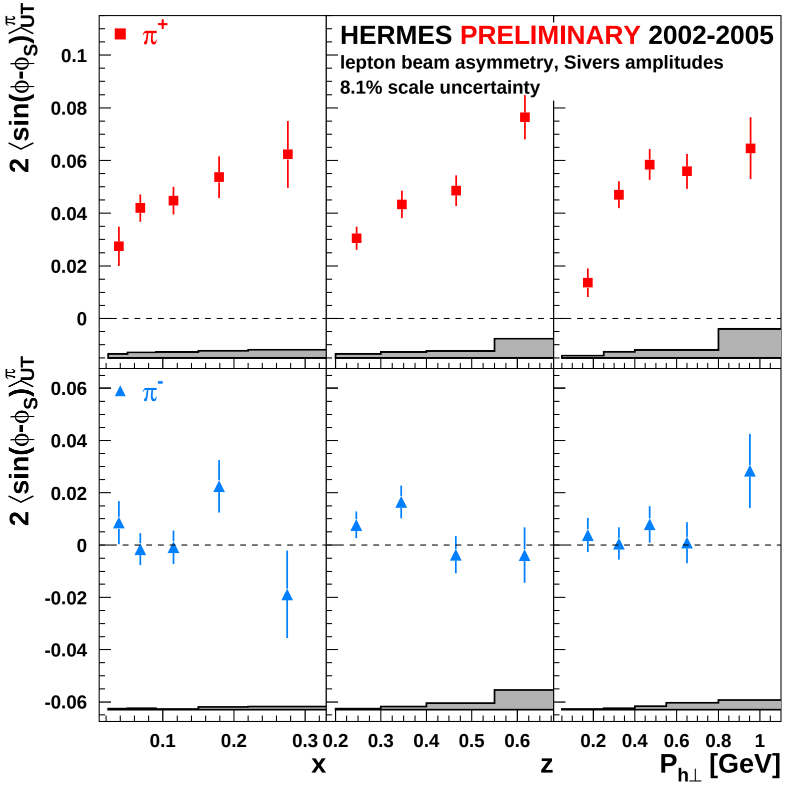
$$\langle 2B_{\text{Gauss}} H_1^{\perp(1/2)\text{fav}} \rangle = \quad (3.5 \pm 0.8)\%$$
$$\langle 2B_{\text{Gauss}} H_1^{\perp(1/2)\text{unf}} \rangle = -(3.8 \pm 0.7)\%$$

Collins amplitudes for charged kaons



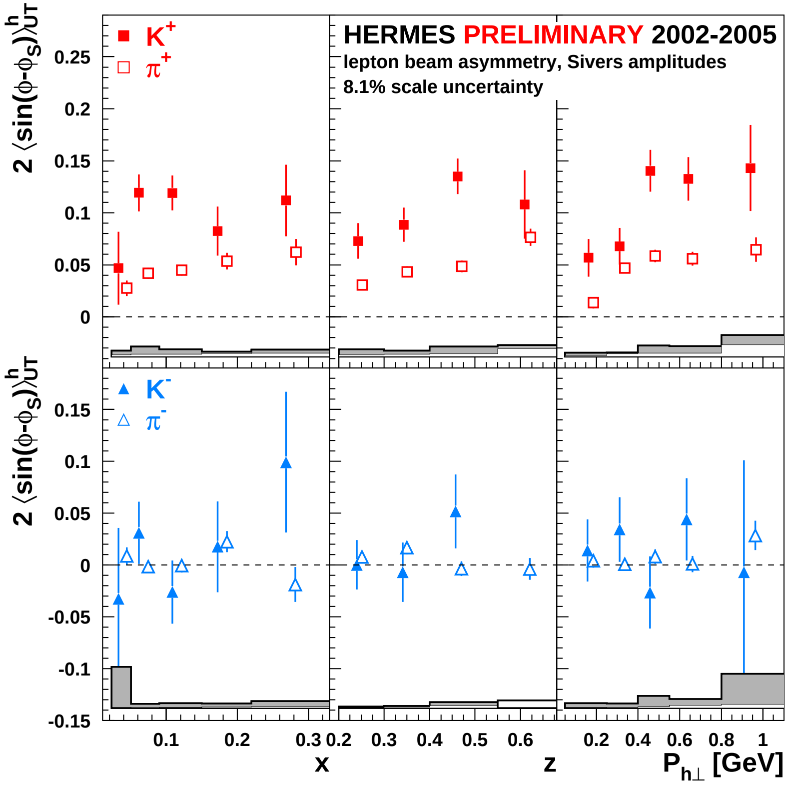
- K^+ amplitudes are consistent with π^+
- K^- may have the opposite sign from π^-

Sivers amplitudes for charged pions



- significantly positive for π^+
- a signiture of non-zero quark orbital angular momentum
- π^- amplitudes consistent with zero

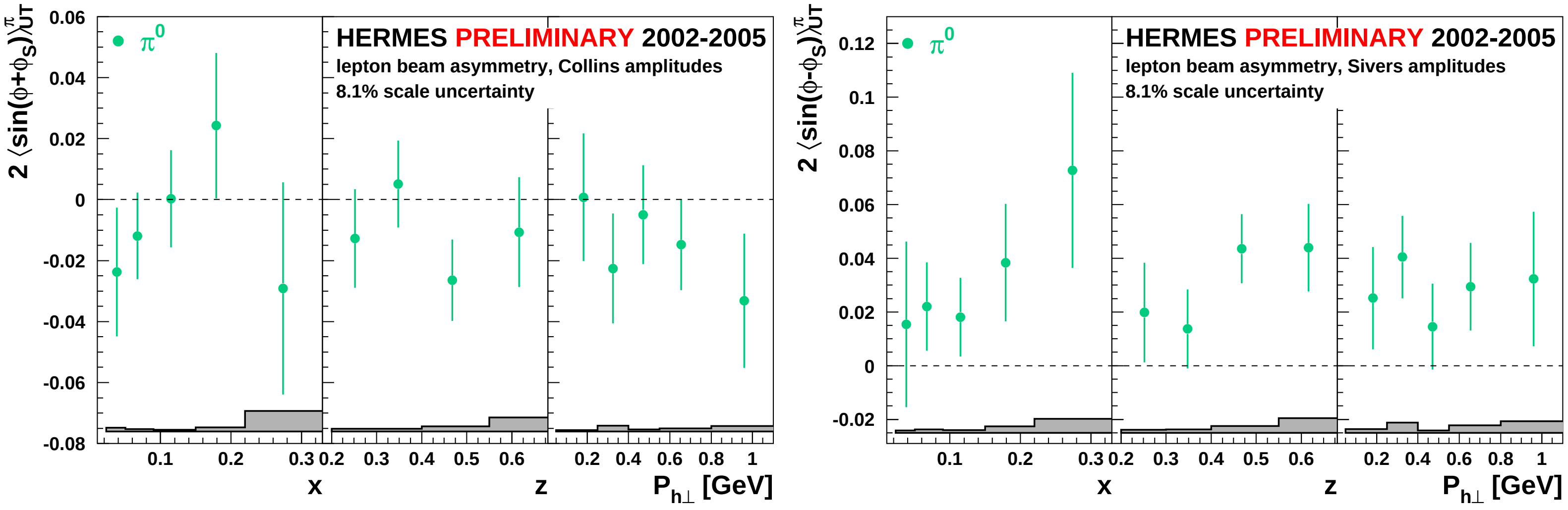
Sivers amplitudes for charged kaons



- significantly positive for K^+
- K^- amplitudes consistent with zero
- K^+ amplitude is 2.3 ± 0.3 times larger than for π^+

- $K^- = s\bar{u},\ \pi^- = d\bar{u}$ same antiquark
- $K^+ = u\bar{s},\ \pi^+ = u\bar{d}$ different antiquarks
- May suggest significant antiquark Sivers functions and strongly flavor-dependent.

Amplitudes for neutral pions



Using charge conjugation and isospin symmetry of the Collins fragmentation function π^+, π^-, and π^0 amplitudes can be related:

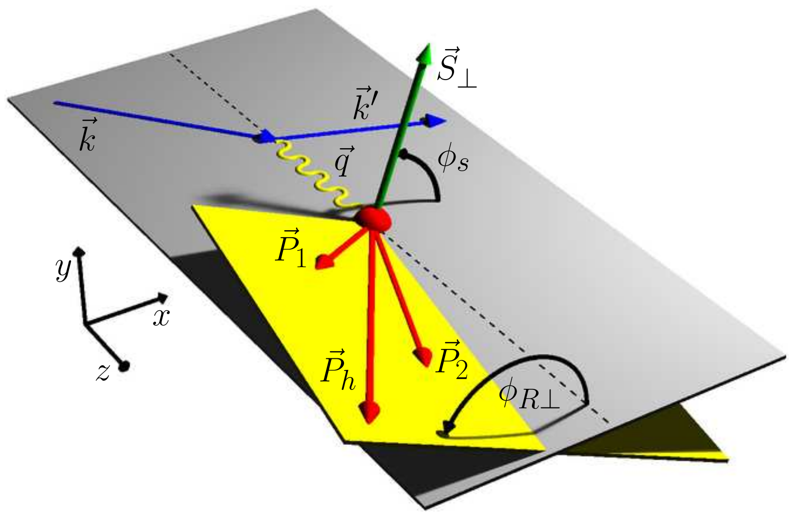
$$< \sin(\phi \pm \phi_S) >_{UT}^{\pi^+} + C\cdot < \sin(\phi \pm \phi_S) >_{UT}^{\pi^-} + (1-C)\cdot < \sin(\phi \pm \phi_S) >_{UT}^{\pi^0} = 0$$

Here, $C = \sigma_{UU}^{\pi^+} / \sigma_{UU}^{\pi^-}$

Hermes results for the extracted TTSA amplitudes fulfill the isospin symmetry relation.

Two-pion Asymmetry

$\underline{ep \to e\pi^+\pi^- X}$ (R.Jaffe et al., 1997; M.Radici et al., 2001)



$$\vec{P}_h = \vec{P}_1 + \vec{P}_1$$

$$A_{UT} \propto |S_\perp| \sin(\phi_{R\perp} + \phi_S) \frac{\sum_q e_q^2 \, h_1^q \, H_1^{\sphericalangle, sp}}{\sum_q e_q^2 \, f_1^q \, D_1^q}$$

$H_1^{\sphericalangle, sp}$ – interference fragmentation between pion pair in s- and p-wave.

Alternative access for Transversity

Advantages:

- direct product of h_1^q and FF (no convolution)

Disadvantages:

- less statistics
- cross-section depends on 9 variables (acceptance effects more complex)

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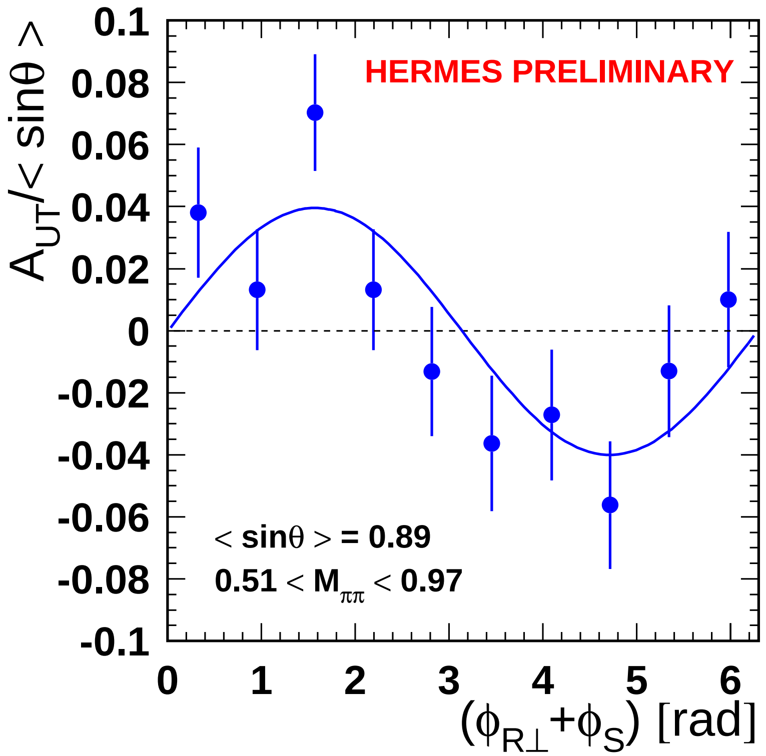
Two-pion Asymmetry



$$A_{UT}(\phi_{R\perp},\phi_S,\theta) =$$

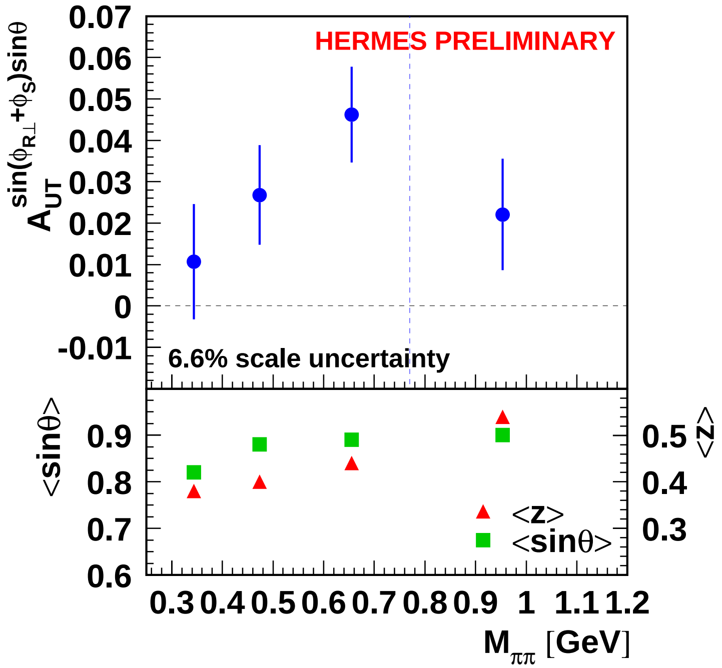
$$\frac{1}{|S_T|}\frac{\sigma^{\uparrow}(\phi_{R\perp},\phi_S,\theta)-\sigma^{\downarrow}(\phi_{R\perp},\phi_S,\theta)}{\sigma^{\uparrow}(\phi_{R\perp},\phi_S,\theta)+\sigma^{\downarrow}(\phi_{R\perp},\phi_S,\theta)}$$

Data of 2002–2004 years only.

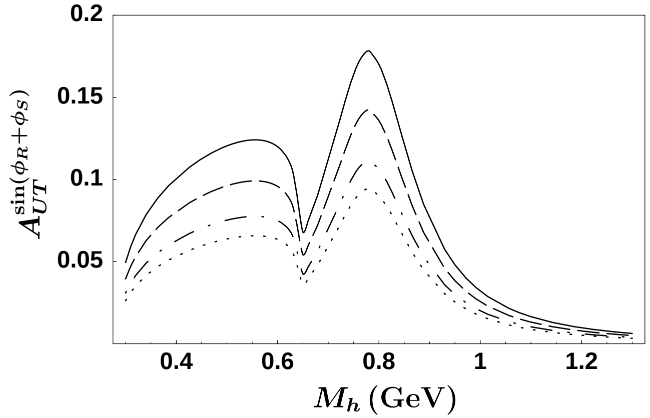
$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta} = 0.040 \pm 0.009(stat) \pm 0.003(syst)$$

Efforts to include data of 2005 are underway.

Two-pion Asymmetry

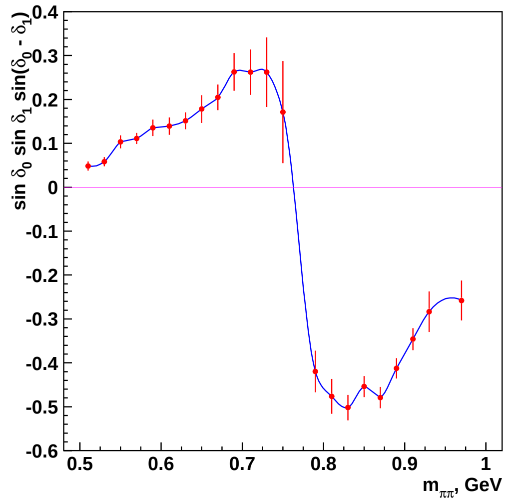


- result disfavors model of Jaffe, 1997;
- model of Bacchetta and Radici:
  - — overestimates amplitudes;
  - — no sign change.



Radici, Bacchetta, 2006

Jaffe et al, 1997



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Motivation: Total Angular Momentum of Quarks

Ji's relation (1996):

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

A measurement of Generalized Parton Distributions (GPD) H and E is required.

$\Longrightarrow$ Hard Exclusive reactions, e.g. DVCS, meson production

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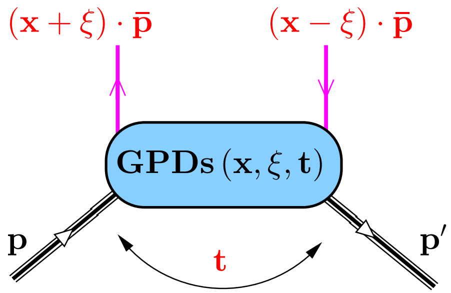
Motivation: Total Angular Momentum of Quarks

- 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 :

$$H_q\,(x, 0, 0) = q\,(x)$$

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

$$H_g\,(x, 0, 0) = g\,(x)$$

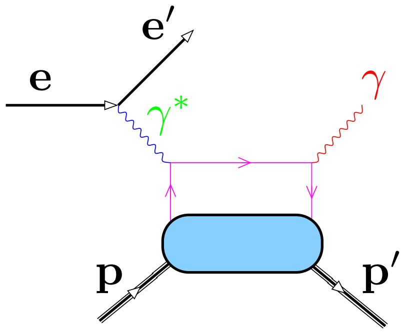
$$\tilde{H}_g\,(x, 0, 0) = \Delta g\,(x).$$

DVCS depends on four GPDs $H, E, \widetilde{H}, \widetilde{E}$.

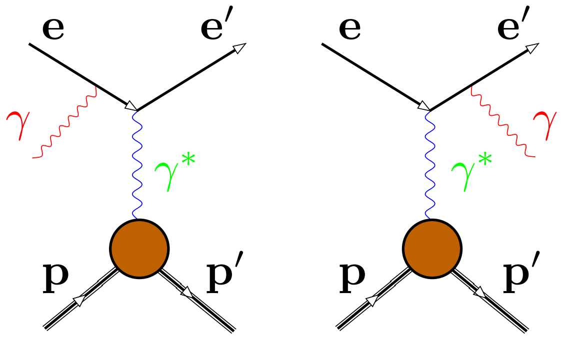
DVCS TTSA provides an access to GPD E without a kinematic suppression.

Exclusive production of vector mesons (ρ, ω, ϕ) depends on two GPDs, H and E.

Deeply Virtual Compton Scattering



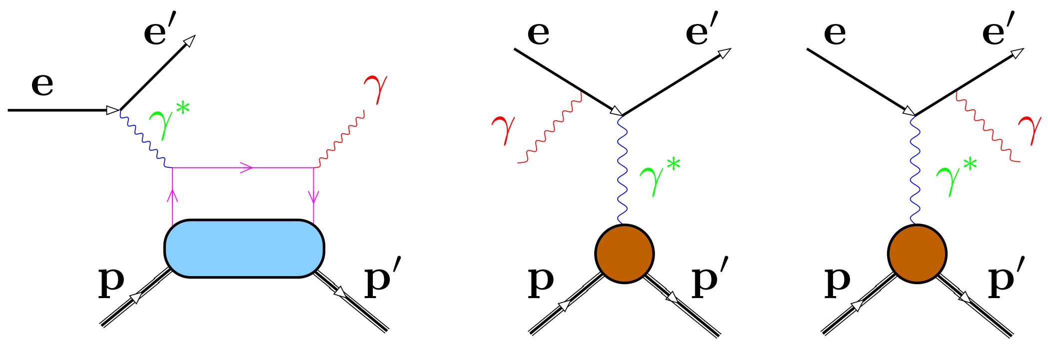
DVCS



BH

$$d\sigma \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{\mathcal{I}}$$

Deeply Virtual Compton Scattering

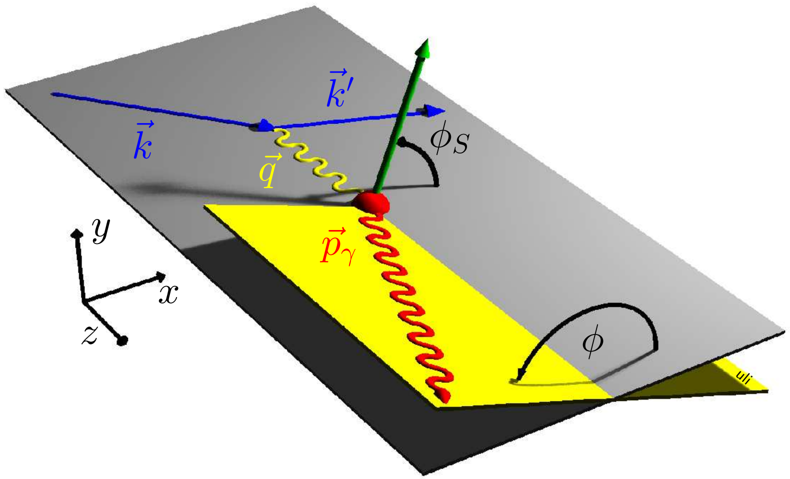


DVCS BH

$$d\sigma \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{\mathcal{I}}$$

- $\mathcal{T}_{BH}$ depends on known Dirac and Pauli FFs F_1, F_2
- $\mathcal{T}_{DVCS}$ depends on Compton FFs $\mathcal{H}$, $\mathcal{E}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{E}}$, which are convolutions of respective GPDs with hard-scattering kernels.
- At HERMES, $|\mathcal{T}_{BH}| \gg |\mathcal{T}_{DVCS}|$.
- $\mathcal{I}$ contains an information on the amplitudes and phases of the Compton FFs.

Transverse Target-Spin Asymmetry for DVCS



- $A_{UT}(\phi, \phi_s) = \frac{d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi)}{d\sigma(\phi,\phi_S) + d\sigma(\phi,\phi_S+\pi)} \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi - \phi_S)\cos\phi + \ldots$

- $\mathrm{A}_{\mathrm{UT}}^{\sin(\phi-\phi_{\mathrm{S}})\cos\phi}$ is sensitive to $\mathcal{E}$ and therefore to J_q.

- Previously measured A_{LU} (HERMES, 2001) is mainly sensitive to $\mathcal{H}$.

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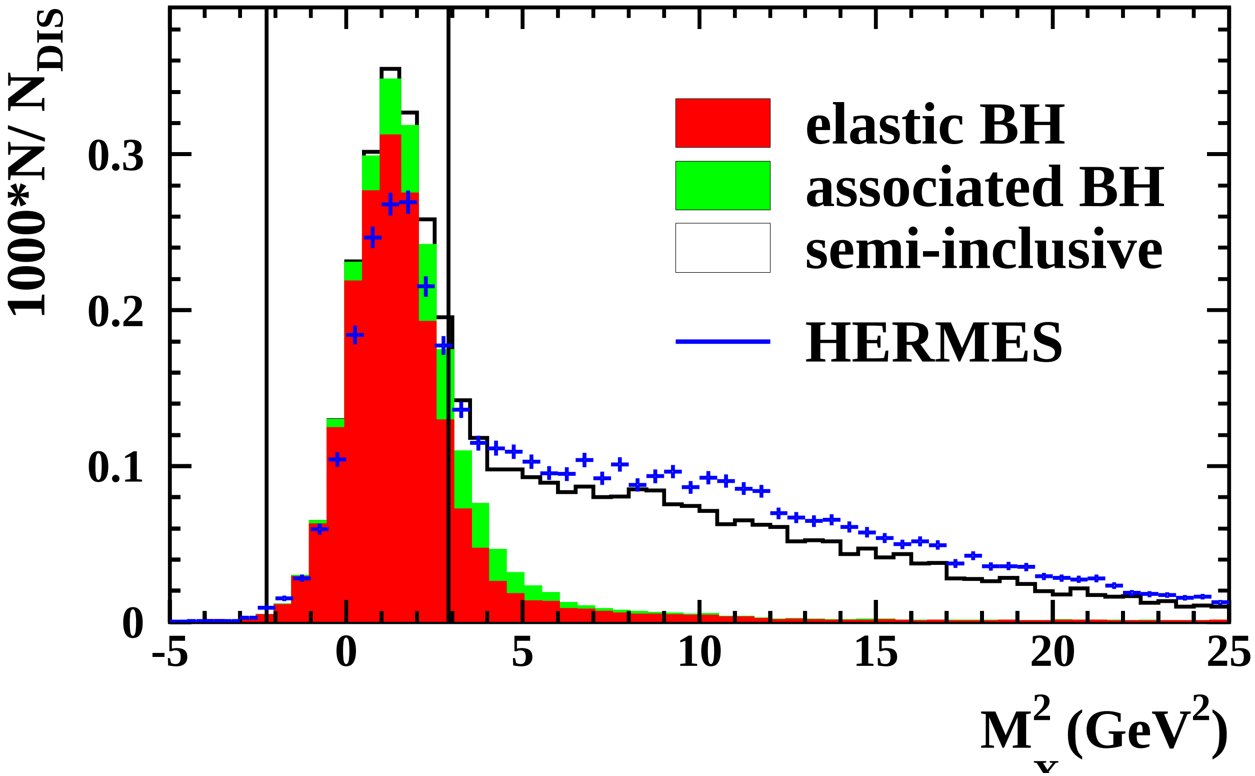
DVCS Measurements at HERMES

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

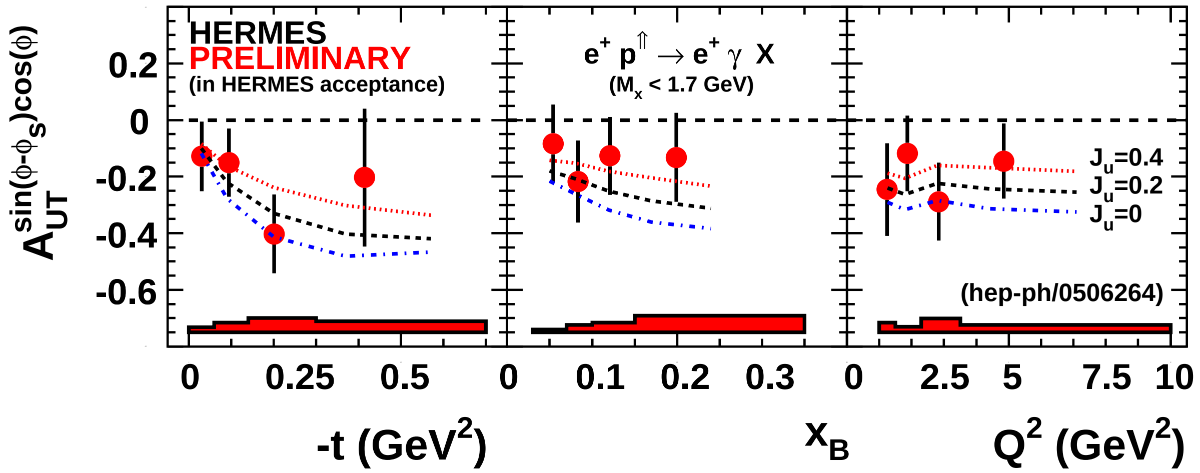
$$\mathrm{M_x^2 = (P_e + P_p - P_{e'} - P_\gamma)^2}$$

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



(Ignazio Vilardi talk)

TTSA at HERMES



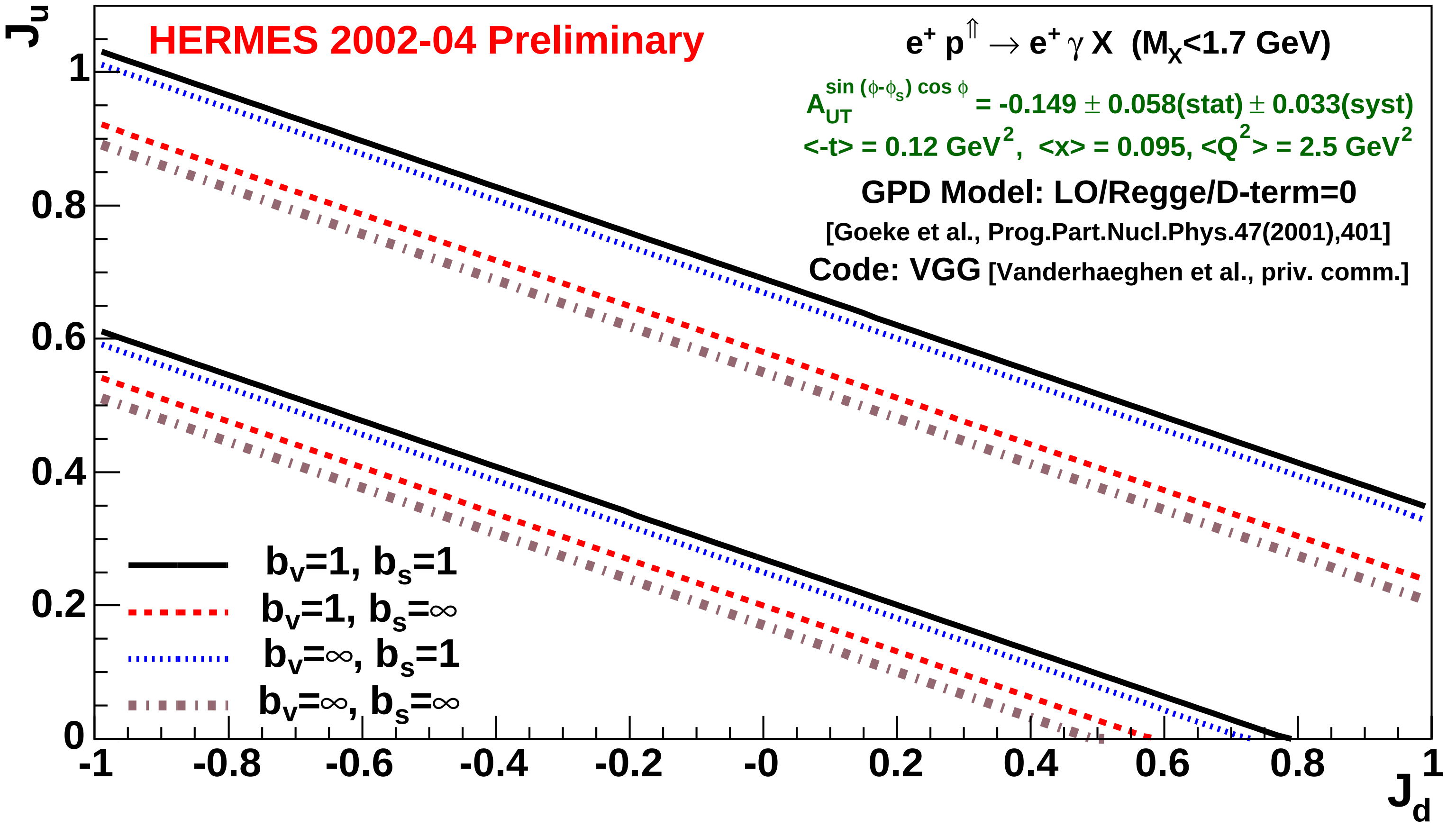
$\propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]$

- The nucleon helicity flip GPD E in the forward limit can be modelled as $e_q(x) = E_q(x,0,0) = A_q \cdot q_{val}(x) + B_q \cdot \delta(x)$.
  The values of A_q and B_q are related to J_q:
  $\frac{1}{2}\int dx\, x[q(x) + e_q(x)] = J_q$, $\int dx\, e_q(x) = F_2^q(0) = k^q$.
  Goeke et al., Prog.Part.Nucl.Phys. 47, 401 (2001)

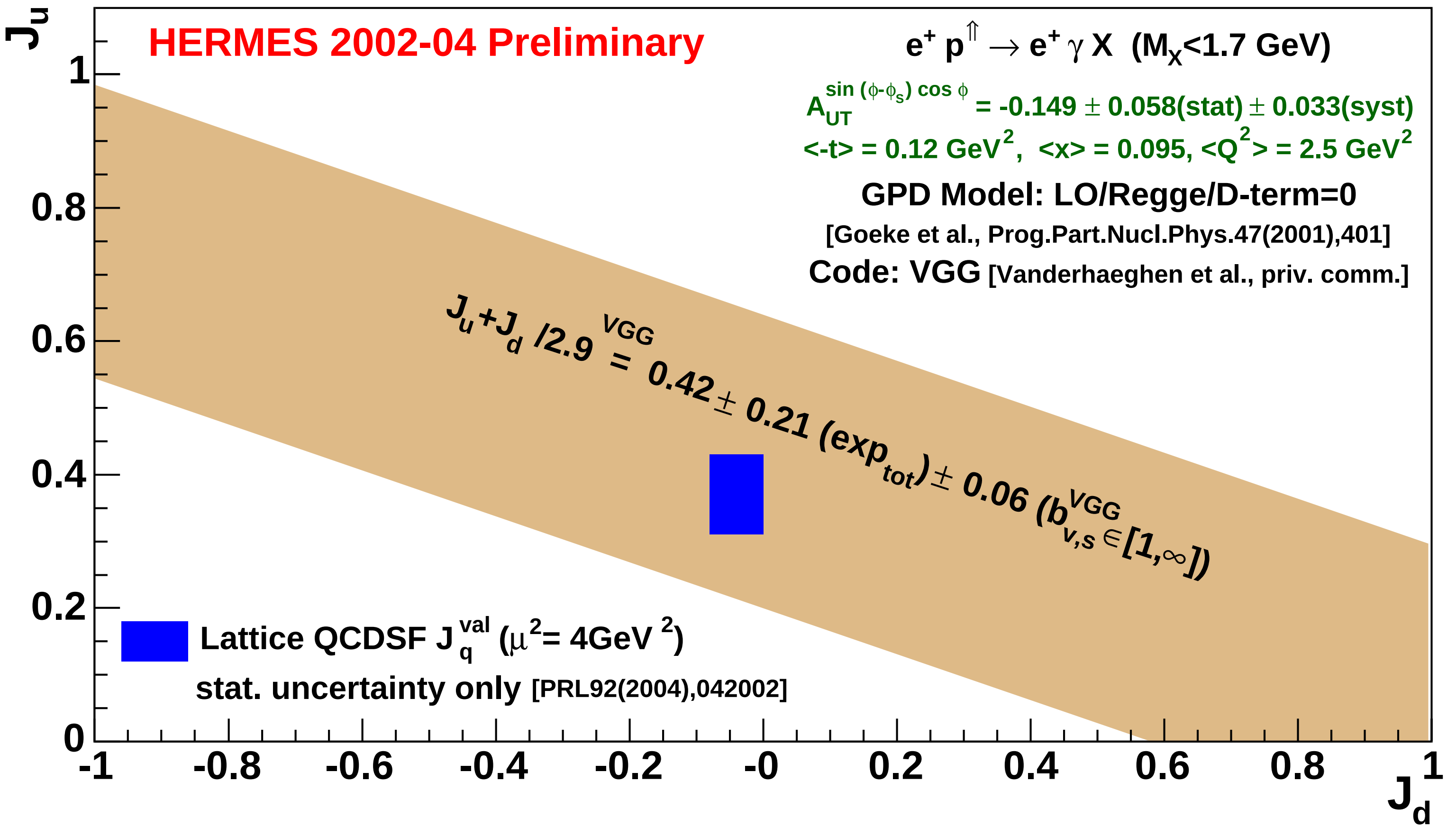
- $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ is sensitive to J_u and insensitive to other model parameters.
  Ellinghaus et al., Eur.Phys.J.C46(2006)729

A Model-Dependent Constraint on J_u vs J_d

- $\chi^2(J_u, J_d) = \frac{\left[A_{UT}^{\sin(\phi-\phi_S)\cos\phi}|_{exp} - A_{UT}^{\sin(\phi-\phi_S)\cos\phi}(J_u, J_d)|_{VGG}\right]^2}{\delta A_{stat}^2 + \delta A_{syst}^2}$
- 1-σ constraint on J_u versus J_d is determined by $\chi^2(J_u, J_d) \leq \chi^2_{min} + 1$

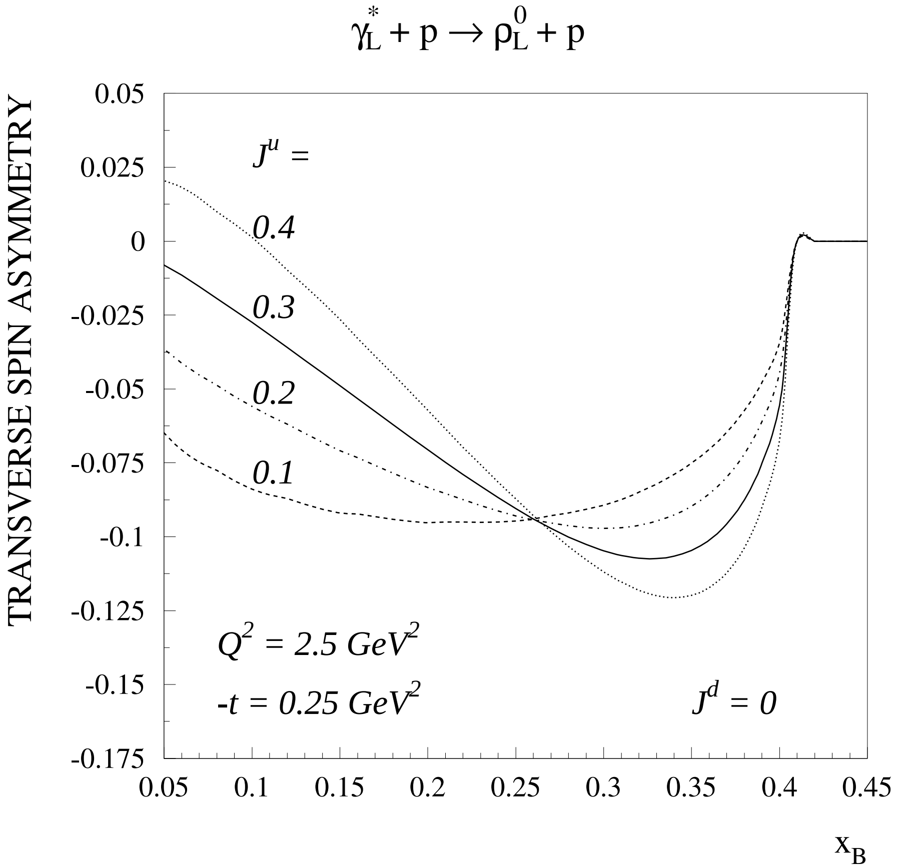


A Model-Dependent Constraint on J_u vs J_d



- First model dependent constraint on total quark angular momentum J_u, J_d.
- 2005 data still to be included.

TTSA for Exclusive ρ^0 Electroproduction



- cross-section for vector meson production depends on GPDs H and E
- GPV 2001 calculated TTSA for the HERMES kinematic
- TTSA is quite non-zero and depends (due to a model) on J_u, J_d
- factorization requires disentengling of ρ^0_L and ρ^0_T

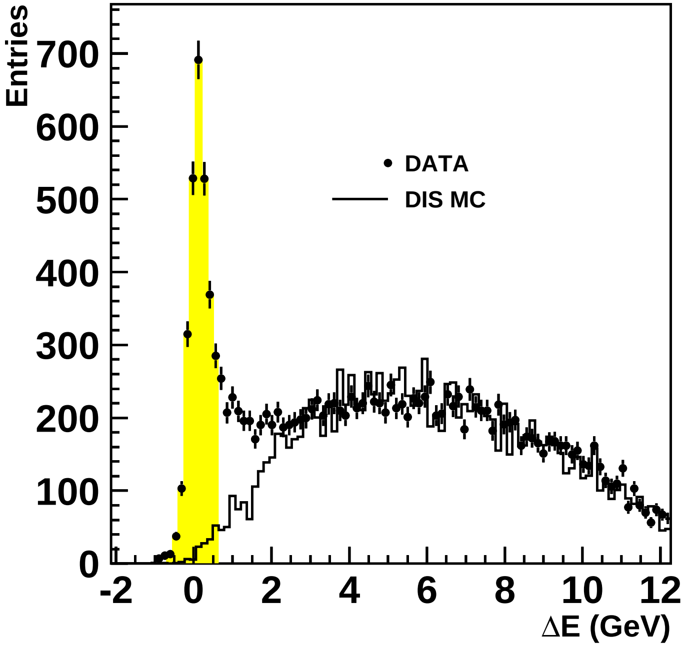
Exclusive ρ^0 Production at HERMES

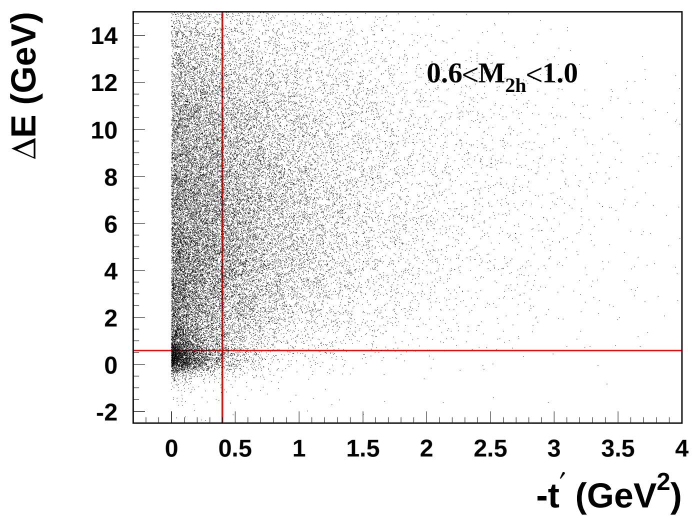
$$\rho^0 \rightarrow \pi^+\pi^-$$

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

$$\Delta E = \frac{M_x^2 - M_p^2}{2M_p} < 0.6 \text{ GeV}$$

$$-t' = t_0 - t < 0.4 \text{ GeV}^2$$





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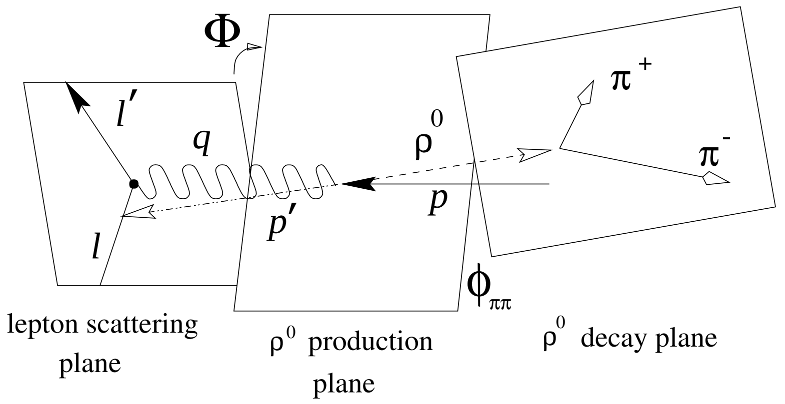
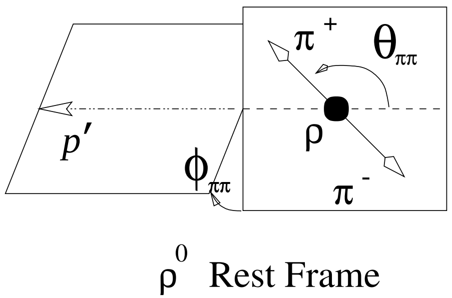
ρ^0_L, ρ^0_T Separation



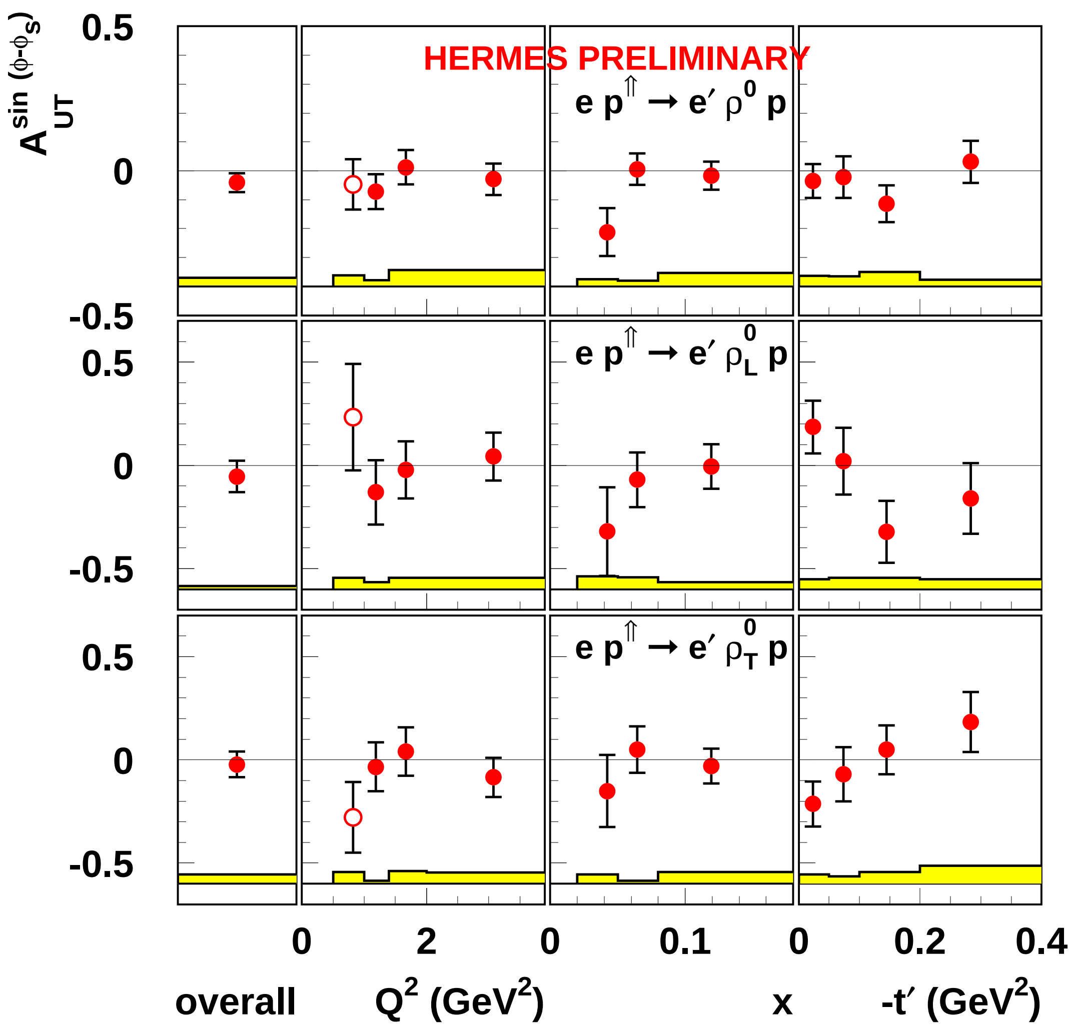


- each ρ^0 polarization state has a characteristic decay angular state
- one may use angle $\theta_{\pi\pi}$ to disentangle ρ^0_L, ρ^0_T
- under assumption of s-channel helicity conservation (SCHC) the results may be compared to GPD based calculations
- HERMES has measured spin density matrix elements (SDME) of exclusive ρ^0 production at unpolarized target
- the results mostly in agreement with SCHC hypothesis

$$W(\phi,\phi_S,\theta_{\pi\pi}) = \frac{3}{2}\left[r^{04}_{00}\cos^2\theta_{\pi\pi}(1+A_{UU,\rho_L}(\phi) + P_T A^l_{UT,\rho_L}(\phi,\phi_S)) + \right.$$
$$\left.(1-r^{04}_{00})\frac{1}{2}\sin^2\theta_{\pi\pi}(1+A_{UU,\rho_T}(\phi) + P_T A^l_{UT,\rho_T}(\phi,\phi_S))\right]$$

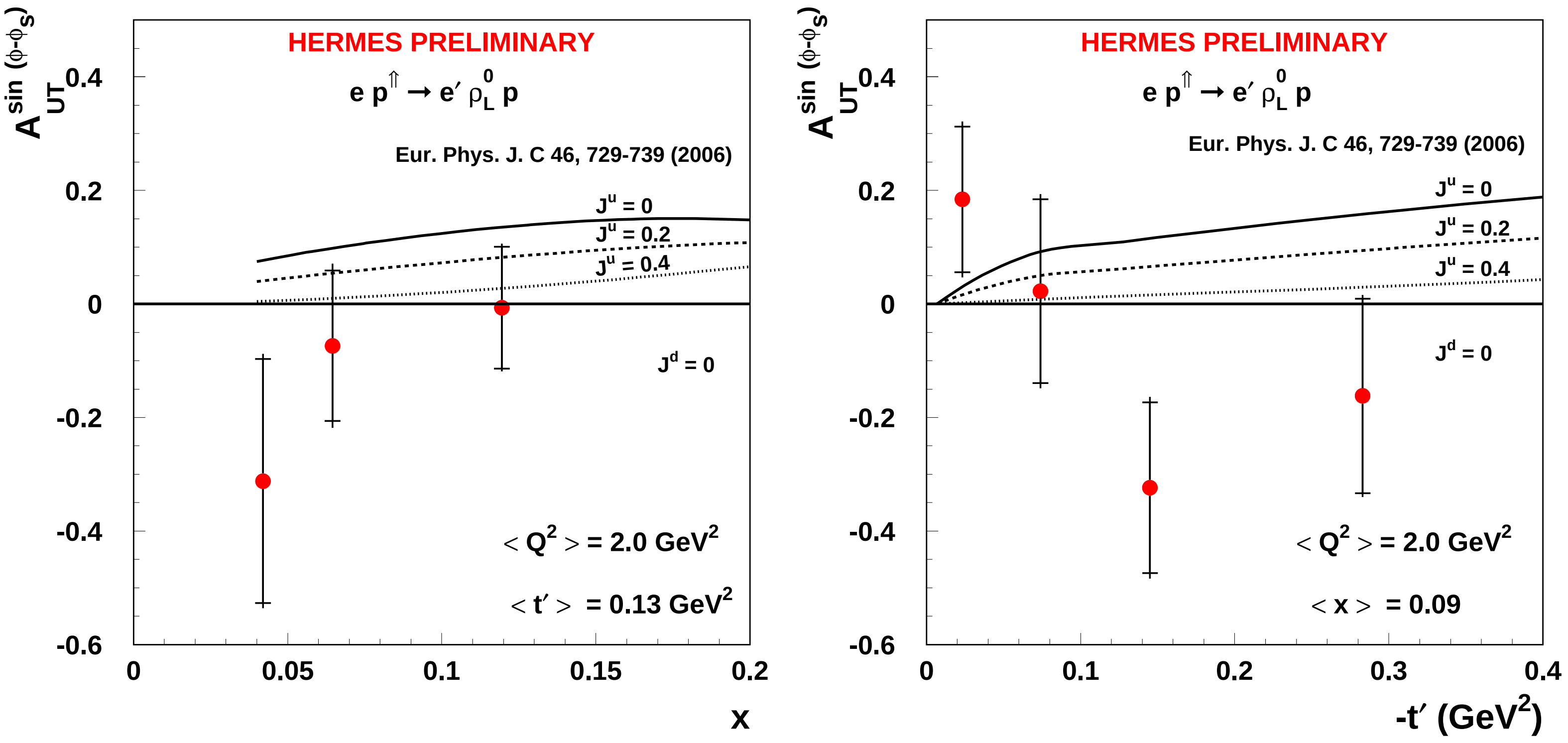
hermes

Exclusive ρ TTSA at HERMES



- assuming SCHC the results can be compared with a theory

Exclusive Production of Longitudinal ρ^0



- data in favor to positive J_u
- in agreement with HERMES DVCS result

Summary

- Non-vanishing Collins effect observed for $\pi^{\pm}$.
  Published data confirmed with much more high accuracy.
  Collins amplitudes for π^- have an opposite sign wrt to π^+ and unexpectedly large.
  An explanation: $H_1^{\perp,unf}(z) \approx -H_1^{\perp,fav}(z)$

- First evidence of Sivers distribution in DIS.

- Sivers amplitudes for K^+ by factor 2.3 ± 0.3 larger than for π^+. Sea quarks?

- First observation of transverse asymmetries in IFF.
  Final data will be based on 2.5 higher statistic.

- TTSA for DVCS provides a first model-dependent constraint on total angular momentum J_u vs J_d. Final data will be based on 2.5 higher statistic.

- First data on ρ^0_L in electroproduction. Under the SCHC the results in favor to positive J_u and in agreement with HERMES DVCS result.

- Polarized beam ($< P_B \cdot P_T > \approx 30\%$). Studies of g_2 and A_{LT} are underway.