Recent HERMES Results on Inclusive Scattering and Exclusive Reactions

- $\Rightarrow$ Spin Asymmetries in Semi-inclusive Meson Production
- $\Rightarrow$ Measurement of b_1^d Structure Function
- $\Rightarrow$ Deeply Virtual Compton Scattering
- $\Rightarrow$ Exclusive π^+ Production
- $\Rightarrow$ Exclusive Vector Meson Production
- $\Rightarrow$ Hard Exclusive $\pi^+\pi^-$ Pair Production

Michael Tytgat
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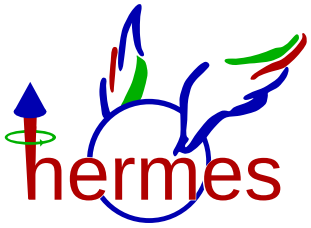
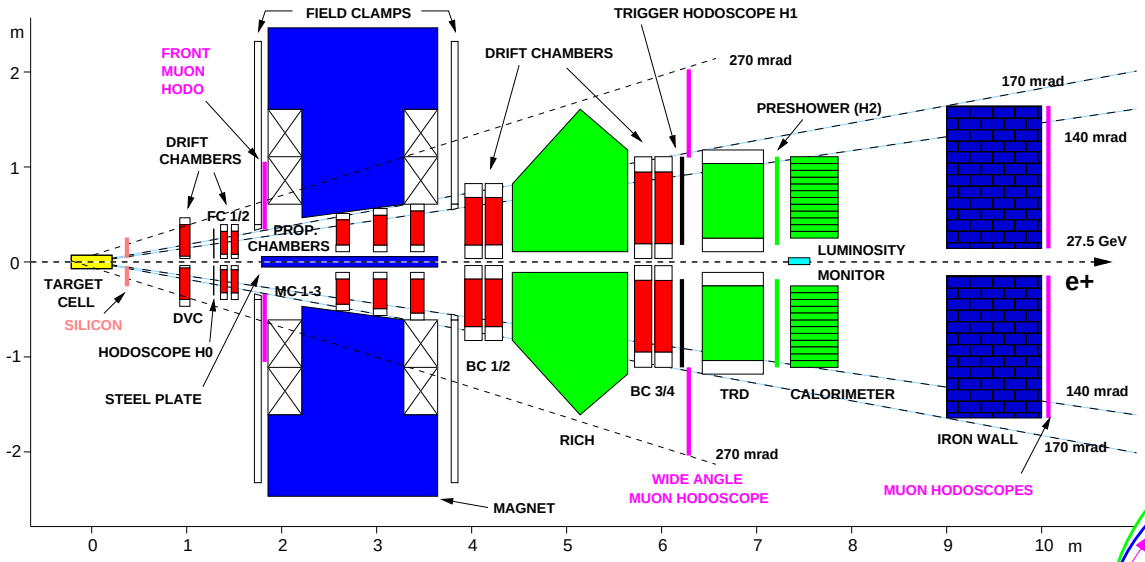
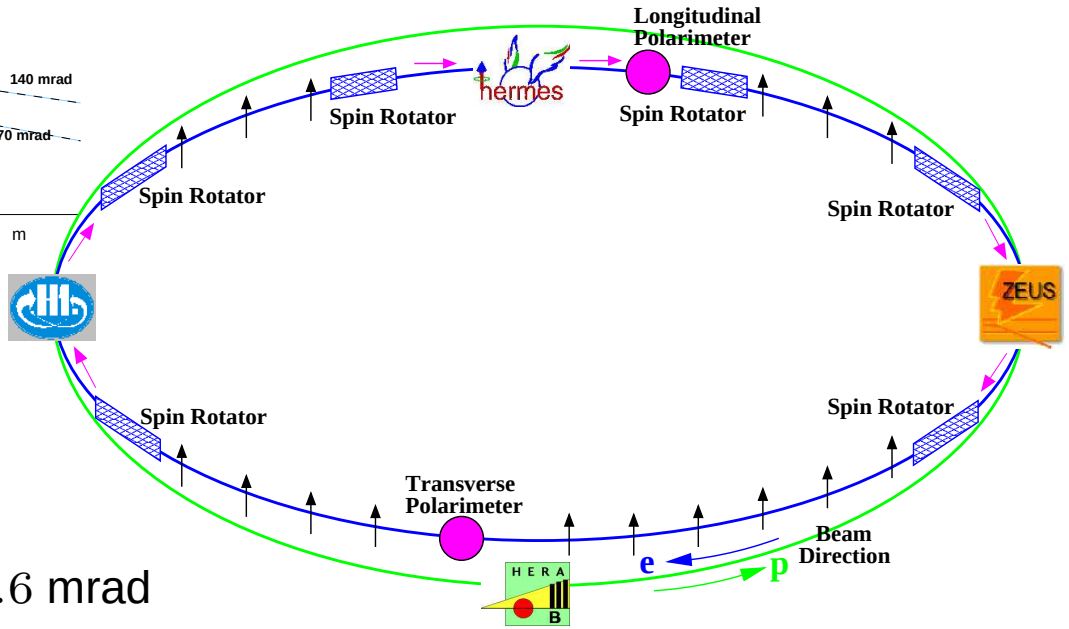
on behalf of the HERMES Collaboration



The HERMES Experiment @ DESY





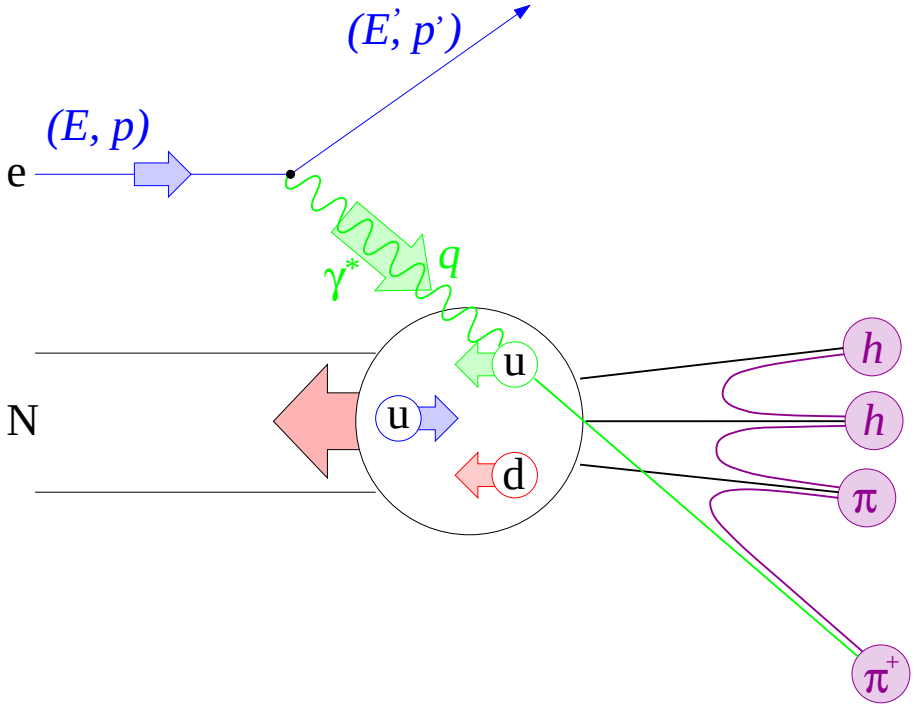
- 27.6 GeV HERA $\vec{e}$-beam
- Internal, pure gas target : $\vec{\text{He}}$, $\vec{\text{H}}$, $\vec{\text{D}}$, H$\uparrow$;
  unpol : H_2, D_2, He, N, Ne, Kr, Xe
- Resolution : $\Delta p/p = 1.4 - 2.5$ %, $\Delta\theta < 0.6$ mrad
- Lepton/hadron separation : TRD, Preshower, Calorimeter, Cherenkov (1995-97)
- Hadron ID : Cherenkov (1995-97) - RICH (1998- ...)
- Target polarization : longitudinal (1996-2000) $\langle P_t \rangle \sim 85$ %
  & transverse (2002-2005) $\langle P_t \rangle \sim 75$ % ; flipping every 90s
- HERA beam polarization $\langle P_b \rangle = 53$ % longitudinal

Semi-inclusive Deep Inelastic Scattering

HERMES $\rightarrow$ study nucleon spin structure in terms of quarks and gluons through polarized deep-inelastic scattering

$\Rightarrow$ HERMES-I (1995-2000) : longitudinally polarized beam and target

$\Rightarrow$ HERMES-II (2002-2005) : transversely polarized target



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

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

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

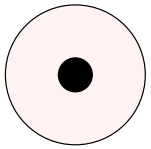
$$z \overset{\text{lab}}{=} \frac{E_h}{\nu}$$

$\Rightarrow$ Cross section contains quark distribution and fragmentation functions

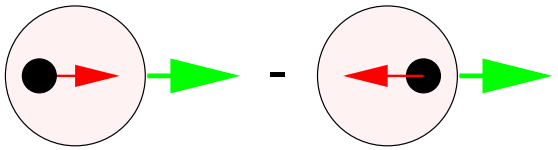
$$\sigma^{eN \rightarrow ehX} \sim \sum_q f^{N \rightarrow q} \otimes \sigma^{eq \rightarrow eq} \otimes D^{q \rightarrow h}$$

Distribution Functions

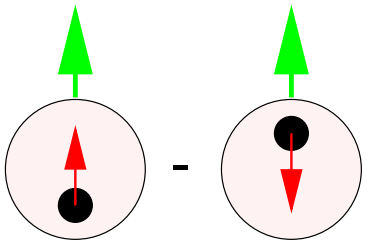
In leading twist, integrating over quark transverse momenta, 3 DFs :

f_1 =  : unpolarized quarks in unpolarized nucleons

$\Rightarrow$ Unpolarized DF $q(x)$: spin averaged, very well known

g_1 =  : longitudinally polarized quarks in longitudinal nucleons

$\Rightarrow$ Helicity DF $\Delta q(x) \equiv q^{\vec{\Rightarrow}}(x) - q^{\vec{\Leftarrow}}(x)$: helicity difference, well known (HERMES-I)

h_1 =  : transversely polarized quarks in transverse nucleons

$\Rightarrow$ Tranversity $\delta q = q^{\uparrow\Uparrow} - q^{\uparrow\Downarrow}$: helicity flip, unkwnown (HERMES-II)

Quark Helicity DF

HERMES-I : longitudinal (semi)-inclusive double spin asymmetries

$$A_1^h(x) = \sum_q \mathcal{P}_q^h(x) \frac{\Delta q(x)}{q(x)}$$

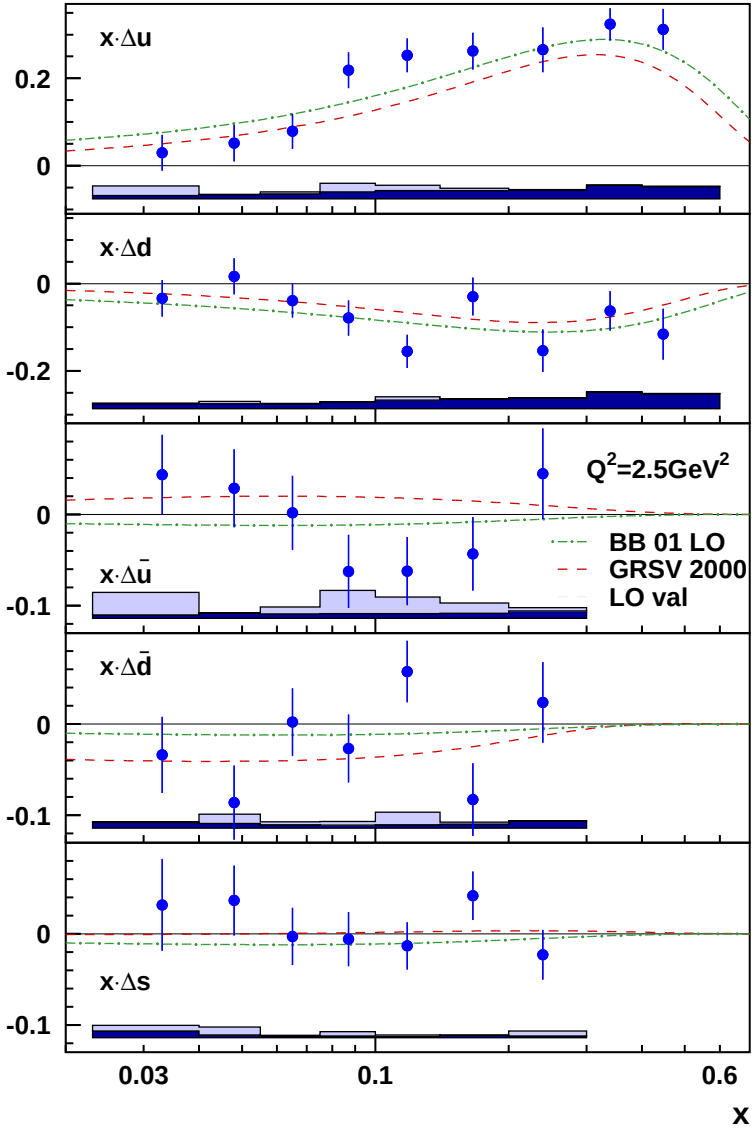
with purity $\mathcal{P}_q^h(x) = \dfrac{e_q^2 q(x) \int_{0.2}^{0.8} D_q^h(z)\mathrm{d}z}{\sum_{q'} e_{q'}^2 q'(x) \int_{0.2}^{0.8} D_{q'}^h(z)\mathrm{d}z}$

☞ Solve matrix equation :

$$\vec{A}_1(x) = \mathcal{P}(x) \cdot \vec{Q}(x)$$

with

$$\vec{A}_1(x) = (A_{1p}, A_{1p}^{\pi^+}, A_{1p}^{\pi^-}, A_{1d}, A_{1d}^{\pi^+}, A_{1d}^{\pi^-}, A_{1d}^{K^+}, A_{1d}^{K^-})$$



Strange Quark Polarization

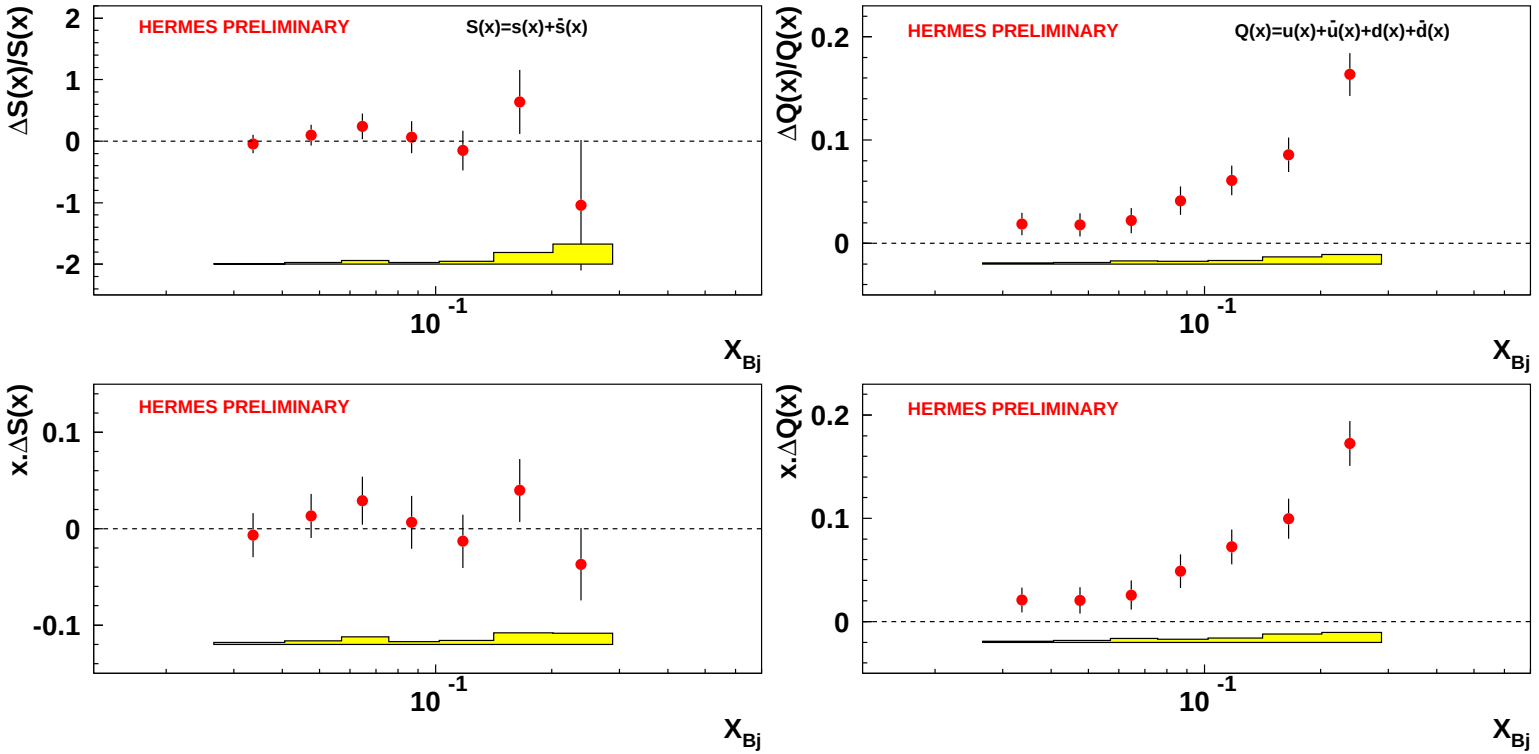
☞ Expect significant negative strange quark polarization

Extract $[\Delta Q/Q](x)$ and $[\Delta S/S](x)$ from $A_D(x, Q^2)$ and $A_D^{K^+ + K^-}$; assume only charge conjugation invariance for purities

$$\begin{pmatrix} A_d(x) \\ A_d^K(x) \end{pmatrix} = C_R \begin{pmatrix} P_q(x) & P_S(x) \\ P_q^K(x) & P_S^K(x) \end{pmatrix} \begin{pmatrix} \Delta Q(x)/Q(x) \\ \Delta S(x)/S(x) \end{pmatrix}$$

with $Q(x) \equiv u(x) + \bar{u}(x) + d(x) + \bar{d}(x)$ and $S(x) \equiv s(x) + \bar{s}(x)$

Determine K fragmentation functions from measured multiplicities

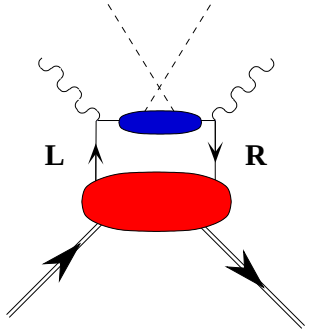


Transversity

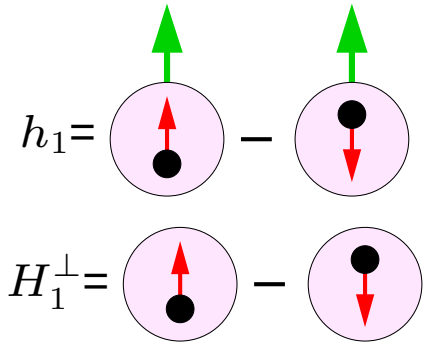
- $f_1(x)$ and $g_1(x)$ can be measured in inclusive DIS;
  $h_1(x)$ is chiral-odd $\rightarrow$ need another chiral-odd object to access transversity

$\Rightarrow$ Consider quark transverse momentum in distribution and fragmentation functions and measure transversity via single-spin azimuthal asymmetries in $e + p \rightarrow e + h + X$ on a polarized target

Collins effect : $A \sim h_1(x)\, H_1^{\perp}(z)$



h_1 combined with chiral-odd Collins FF $H_1^{\perp}$

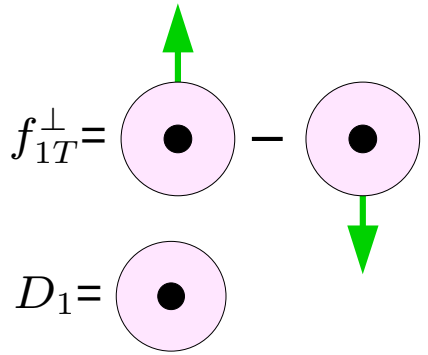


$\rightarrow$ Influence of quark's polarization on transverse momentum acquired in fragmentation process orthogonal to its transverse polarization

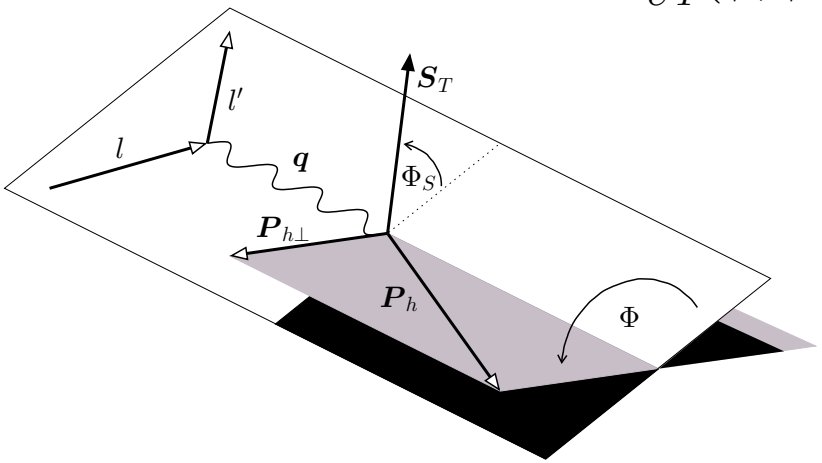
Sivers effect : $A \sim f_{1T}^{\perp}(x)\, D_1(z)$

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

$\rightarrow$ Struck quark "remembers" transverse momentum it had in the target and influences transverse momentum of produced hadrons; implies non-vanishing quark orbital angular momentum



Extracting Transverse Target Asymmetries

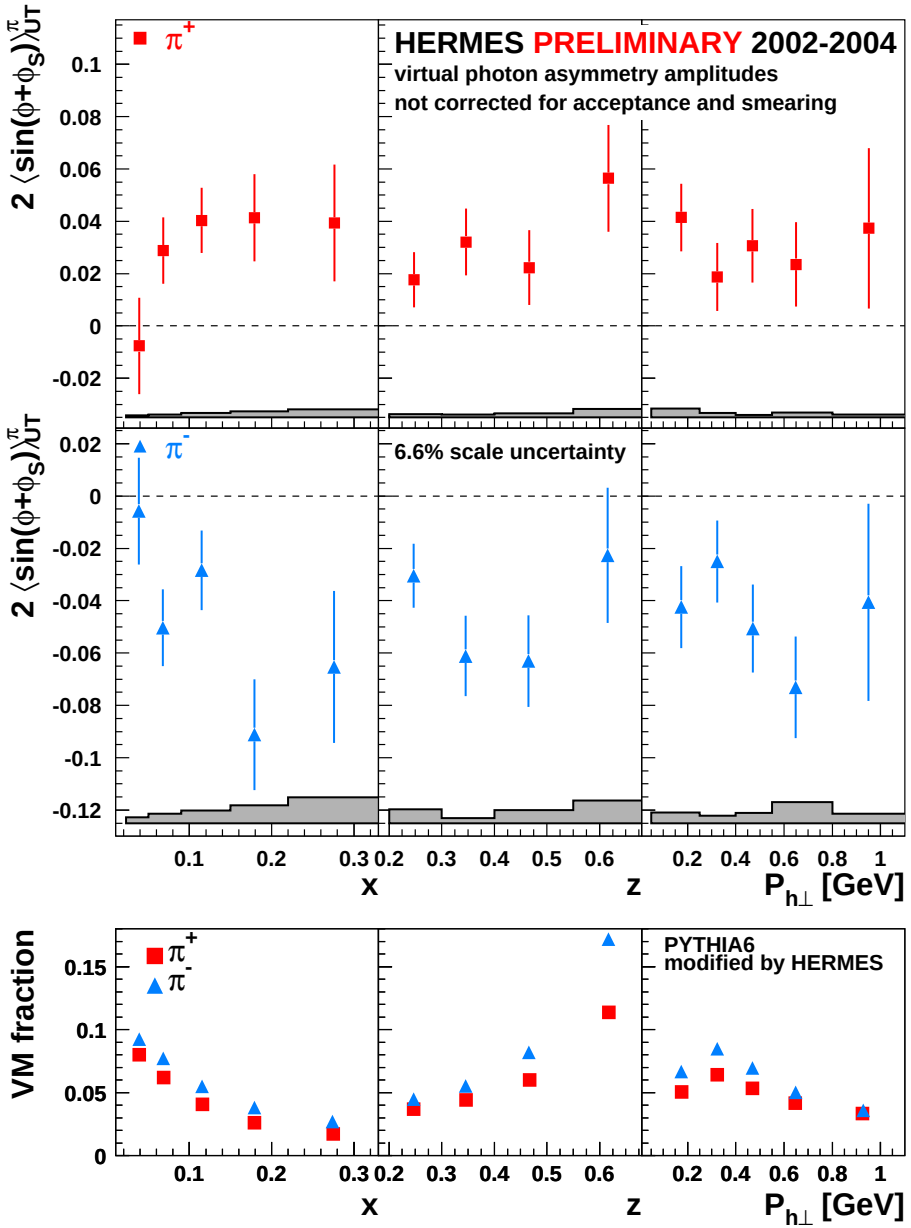


$$
\begin{aligned}
A_{UT}^{h}(\phi,\phi_S) &= \frac{1}{\langle P_z\rangle}\frac{N_h^{\uparrow}(\phi,\phi_S)-N_h^{\downarrow}(\phi,\phi_S)}{N_h^{\uparrow}(\phi,\phi_S)+N_h^{\downarrow}(\phi,\phi_S)} \\
&= 2\cdot\langle\sin(\phi-\phi_S)\rangle_{UT}^{h}\cdot\sin(\phi-\phi_S) \\
&\quad +2\cdot\langle\sin(\phi+\phi_S)\rangle_{UT}^{h}\cdot\frac{B(\langle y\rangle)}{A(\langle x\rangle,\langle y\rangle)}\cdot\sin(\phi+\phi_S) \\
&\propto sin(\phi+\phi_S)\frac{\sum_q e_q^2\delta q(x)H_1^{\perp}(z)}{\sum_q e_q^2 q(x)D_1(z)} \\
&\quad +sin(\phi-\phi_S)\frac{\sum_q e_q^2 f_{1T}^{\perp}(x)D_1(z)}{\sum_q e_q^2 q(x)D_1(z)}
\end{aligned}
$$

$\Rightarrow$ Extract Collins moment $\langle\sin(\phi+\phi_S)\rangle_{UT}^{h}$ and

Sivers moment $\langle\sin(\phi-\phi_S)\rangle_{UT}^{h}$ by 2-dimensional fit to $A_{UT}^{h}(\phi,\phi_S)$

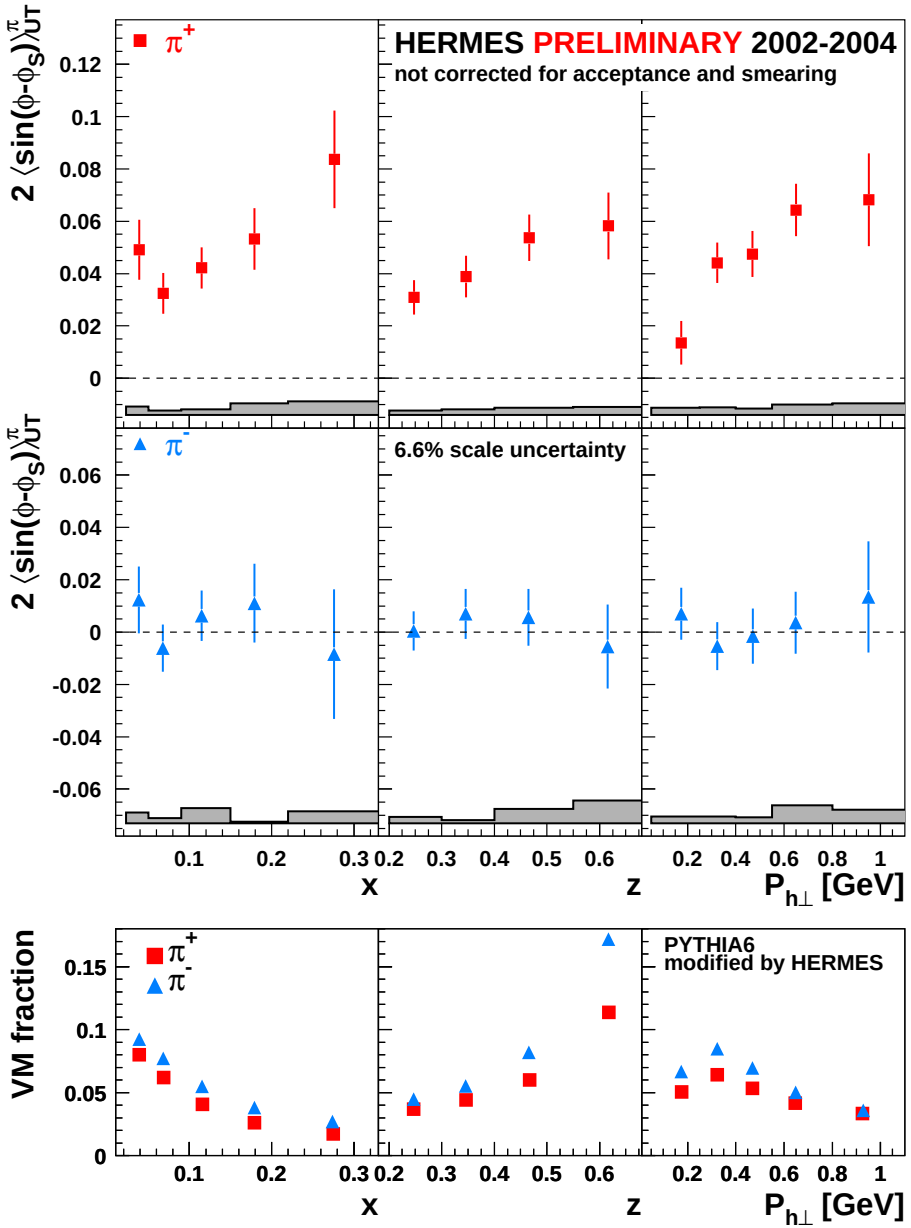
Extracted Collins Moments



[A. Airapetian *et al.*, Phys. Rev. Lett. 94 (2005) 012002]

- Collins moment positive for π^+; negative for π^-
- Expect $\delta u > 0$ and $\delta d < 0$
- Unexpected large absolute value for π^-; role of unfavoured FF ?
- Additional information on Collins FF needed to extract transversity distribution

Extracted Sivers Moments



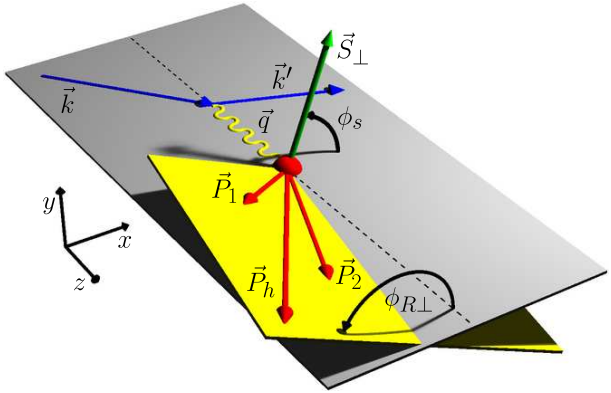
- Sivers moment significantly positive for π^+; requires a non-vanishing quark orbital angular momentum
- Sivers moment consistent with zero for π^-
- Extraction of Sivers function in principle possible (known unpolarized fragmentation function)

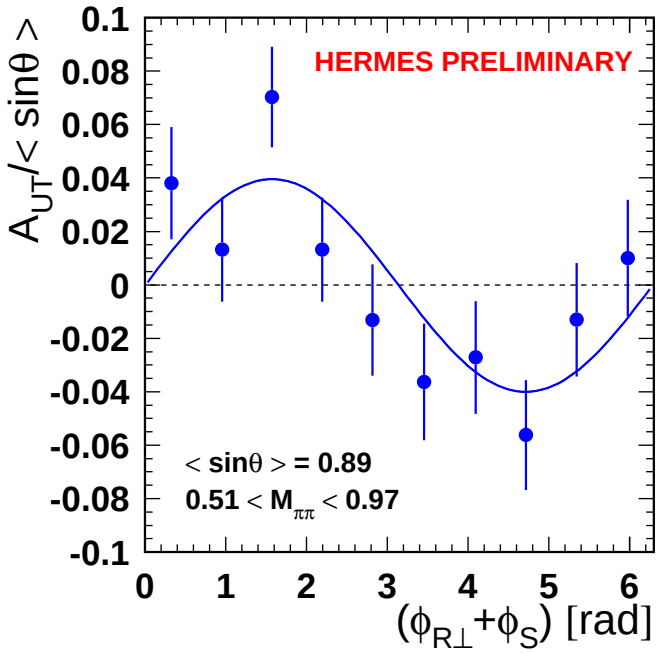
Interference Fragmentation on Transverse Target

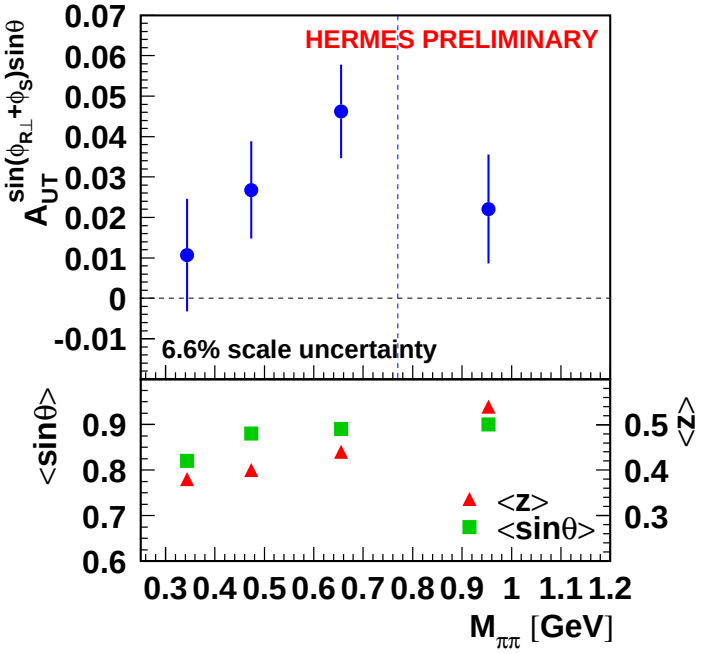
- Accessing transversity $h_1(x)$ in 2-pion production
- $A_{UT} \propto \sin(\phi_{R\perp} + \phi_S) \sin\theta h_1 H_1^{\sphericalangle}$ with interference FF

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

Jaffe *et al.*, PRL80 (1998) : predicted sign change around ρ^0 mass







☞ Evidence for non-zero interference fragmentation function; positive asymmetry vs. $M_{\pi\pi}$, no sign change observed

Tensor Structure Function b_1^d

Leading-twist structure functions in DIS :

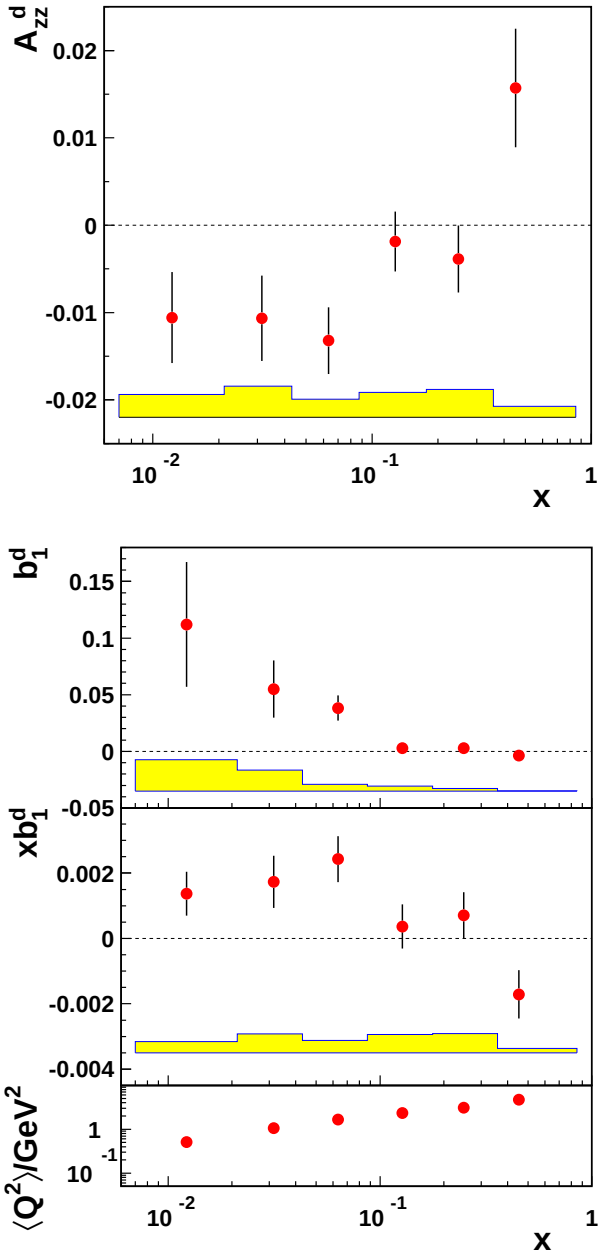
	Nucleon	Deuteron
F_1	$\frac{1}{2}\sum_q e_q^2[q_\uparrow^{\frac{1}{2}} + q_\uparrow^{-\frac{1}{2}}]$	$\frac{1}{3}\sum_q e_q^2[q_\uparrow^1 + q_\uparrow^{-1} + q_\uparrow^0]$
g_1	$\frac{1}{2}\sum_q e_q^2[q_\uparrow^{\frac{1}{2}} - q_\downarrow^{-\frac{1}{2}}]$	$\frac{1}{2}\sum_q e_q^2[q_\uparrow^1 - q_\downarrow^1]$
b_1	–	$\frac{1}{2}\sum_q e_q^2[2q_\uparrow^0 - (q_\uparrow^1 + q_\uparrow^{-1})]$

☞ $b_1(x)$ measures difference between parton densities in $m = 1$ and $m = 0$ deuteron states; vanishes in absence of nuclear effects

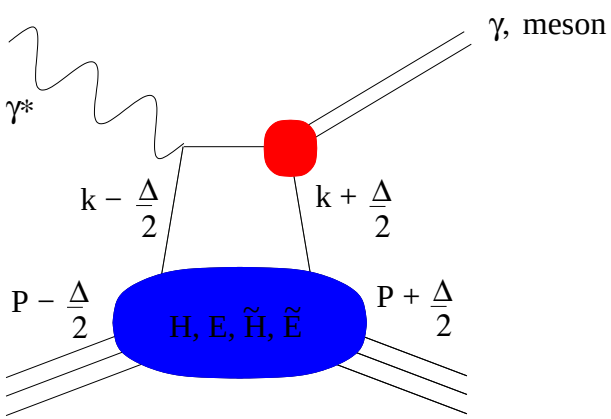
$$\mathrm{d}\sigma_{\mathrm{pol}} = \mathrm{d}\sigma_{\mathrm{unpol}}[1 - P_z P_B D A_1^d + \frac{1}{2} P_{zz} A_{zz}^d]$$

with $A_1^d \simeq \frac{g_1^d}{F_1^d}$ and $b_1^d = -\frac{3}{2} A_{zz}^d F_1^d$

$0.01 < \langle x \rangle < 0.45$ and 0.5 GeV^2 $< \langle Q^2 \rangle <$ 5 GeV^2



Generalized Parton Distributions



- For $Q^2 >>$ and $t << Q^2$, factorization for longitudinal photons in meson production
- 4 GPDs in leading twist :
  $H^q(x,\xi,t)$, $E^q(x,\xi,t)$ unpolarized;
  $\tilde{H}^q(x,\xi,t)$, $\tilde{E}^q(x,\xi,t)$ polarized

  H^q, $\tilde{H}^q$ conserve nucleon helicity;
  E^q, $\tilde{E}^q$ flip nucleon helicity

$\Rightarrow$ New observables in hard exclusive scattering; related to standard PDF and form factors :

$$H^q(x,0,0) = q(x), \qquad \tilde{H}^q(x,0,0) = \Delta q(x),$$
$$\int_{-1}^{+1} \mathrm{d}x\, H^q(x,\chi,t) = F_1^q(t), \qquad \int_{-1}^{+1} \mathrm{d}x\, E^q(x,\chi,t) = F_2^q(t), \qquad \ldots$$

- Ji's sum rule : $J_q = \frac{1}{2}\Delta q + L_q = \frac{1}{2}\int_{-1}^{+1} \mathrm{d}x\, x\, [H^q + E^q]$

  $\Rightarrow$ access to orbital angular momentum
- Unpolarized cross section contain quadratic combinations of GPDs;
  new information from polarized measurements

Accessing Generalized Parton Distributions

Final state quantum numbers select different GPDs :

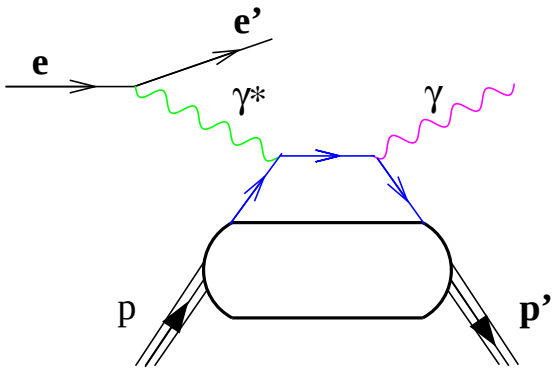
- Deeply Virtual Compton Scattering : H, E, $\tilde{H}$, $\tilde{E}$
  $\Rightarrow$ Beam charge asymmetry ($e^+ \leftrightarrow e^-$) : H
  $\Rightarrow$ Beam-spin Azimuthal Asymmetry : H [A. Airapetian *et al.*, Phys. Rev. Lett. 87 (2001) 182001]
  $\Rightarrow$ Longitudinal Target Spin Asymmetry : $\tilde{H}$
  $\Rightarrow$ Transverse Target Spin Asymmetry : E, J_q

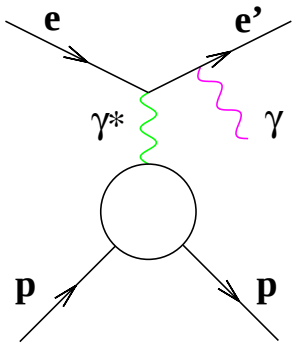
- Pseudoscalar meson production (π, η ...) : $\tilde{H}$, $\tilde{E}$
  $\Rightarrow$ Cross section exclusive π^+ production
  $\Rightarrow$ Transverse single spin asymmetries

- Vector meson production (ρ, ω, ϕ ...) : H, E
  $\Rightarrow$ Cross section exclusive ρ^0 (ω, ϕ) production [A. Airapetian *et al.*, Eur. Phys. J. C17 (2000) 389]
  $\Rightarrow$ Transverse single spin asymmetries

- Pion pair production : H, E
  $\Rightarrow$ Angular distributions [A. Airapetian *et al.*, Phys. Lett. B599 (2004) 212]

Deeply Virtual Compton Scattering

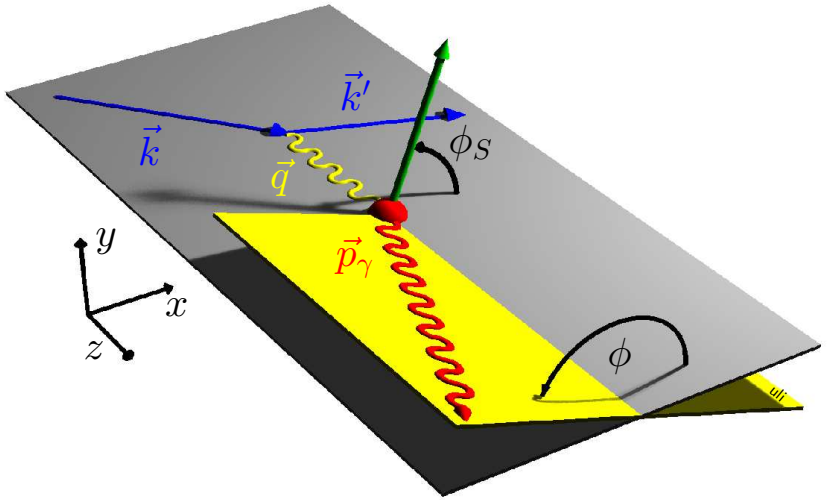




BH $\gg$ DVCS for HERMES kinematics

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

☞ Interference term gives rise to azimuthal asymmetries



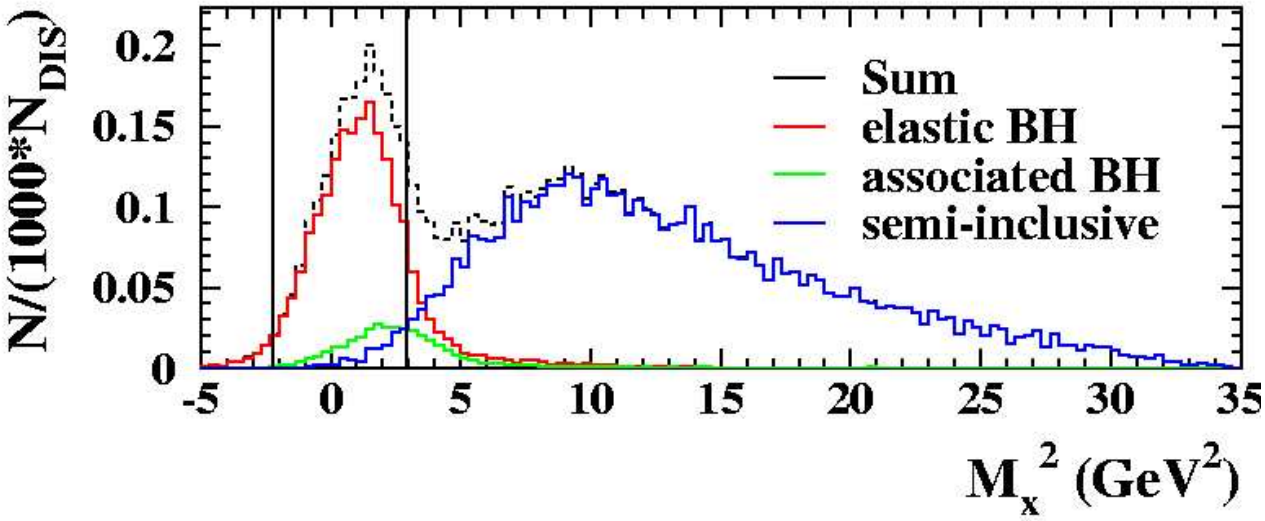
$$A(\phi) = \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$

Deeply Virtual Compton Scattering

- $ep \rightarrow e\gamma p$: no recoil detection so far; only e and γ detected

- Select exclusive events via missing mass cut

$$M_X^2 = (p + g - p_\gamma)^2$$

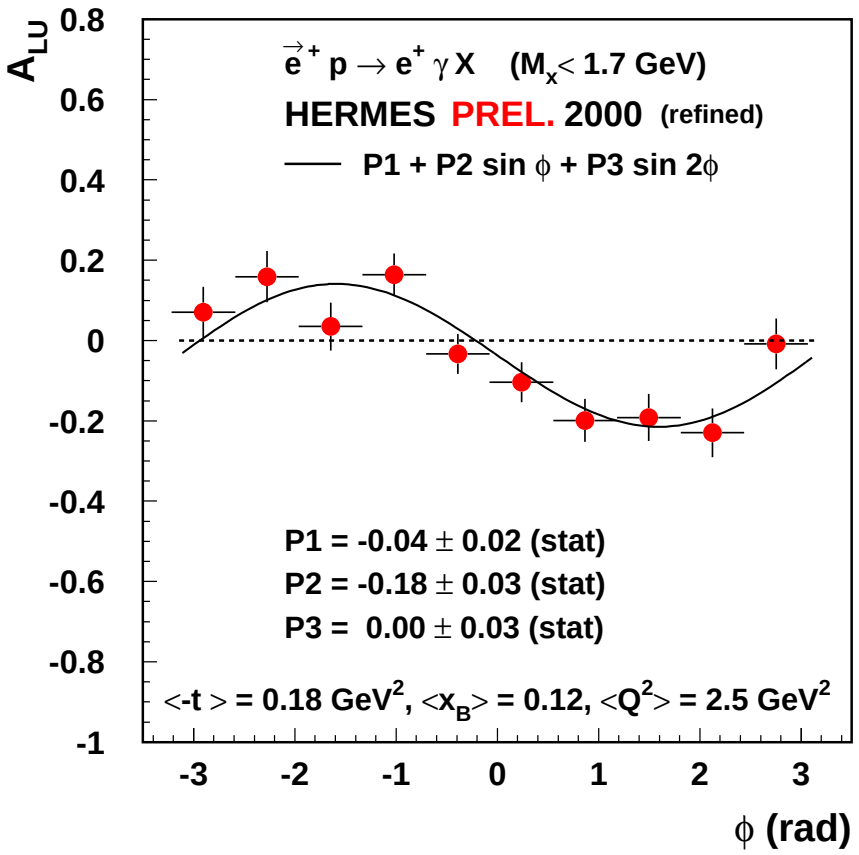


- No separation between elastic and associated DVCS; SIDIS background contamination estimated using Monte Carlo

DVCS : Beam Spin and Charge Asymmetry

Beam Spin Asymmetry A_{LU} :

$$d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi) \propto \sin\phi \cdot \mathrm{Im}(T_{BH}T_{DVCS})$$

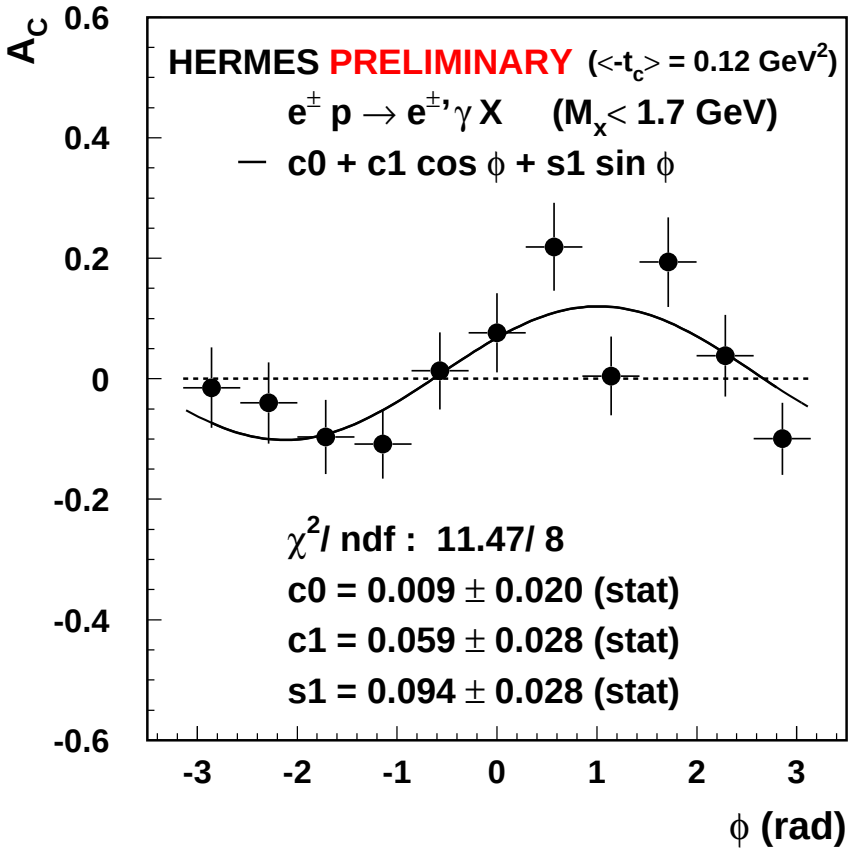


$$A_{LU} \propto \mathrm{Im}(F_1 H) \cdot \sin\phi$$

Beam Charge Asymmetry A_C :

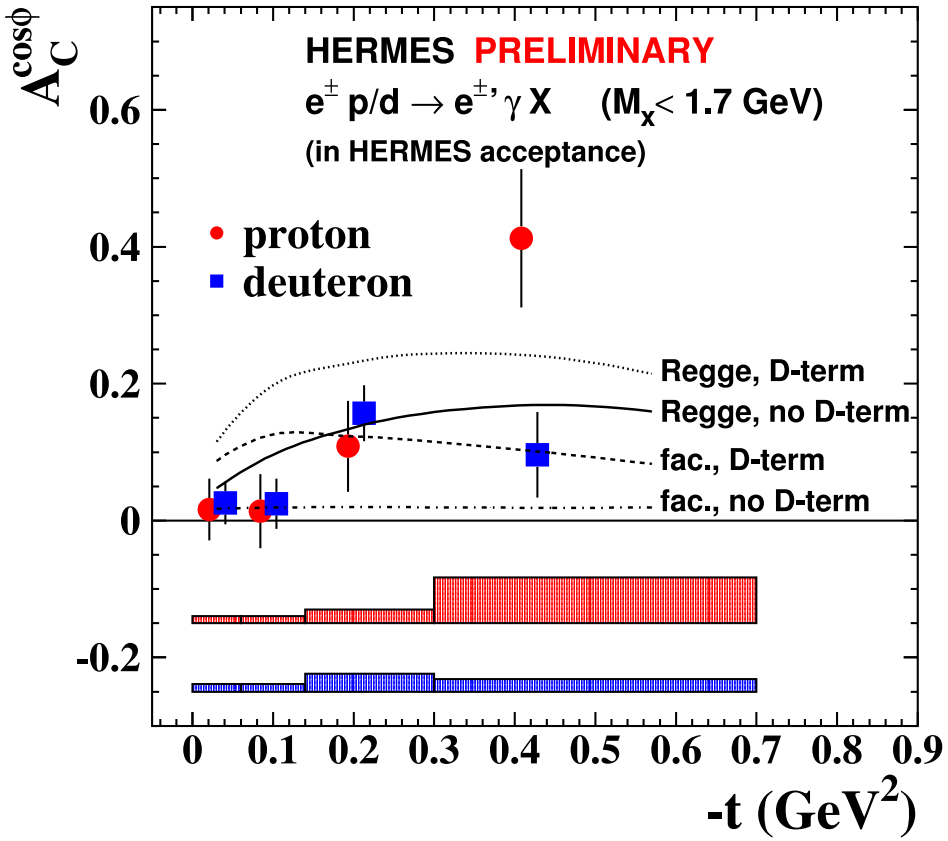
$$d\sigma(e^{+},\phi) - d\sigma(e^{-},\phi) \propto \cos\phi \cdot \mathrm{Re}(T_{BH}T_{DVCS})$$

Only @ HERA



$$A_C \propto \mathrm{Re}(F_1 H) \cdot \cos\phi$$

DVCS : Beam Charge Asymmetry t-Dependence



Proton $\leftrightarrow$ Deuteron

- Coherent contribution at low $-t \sim 40$ %
- Increasing neutron form factor at high $-t$

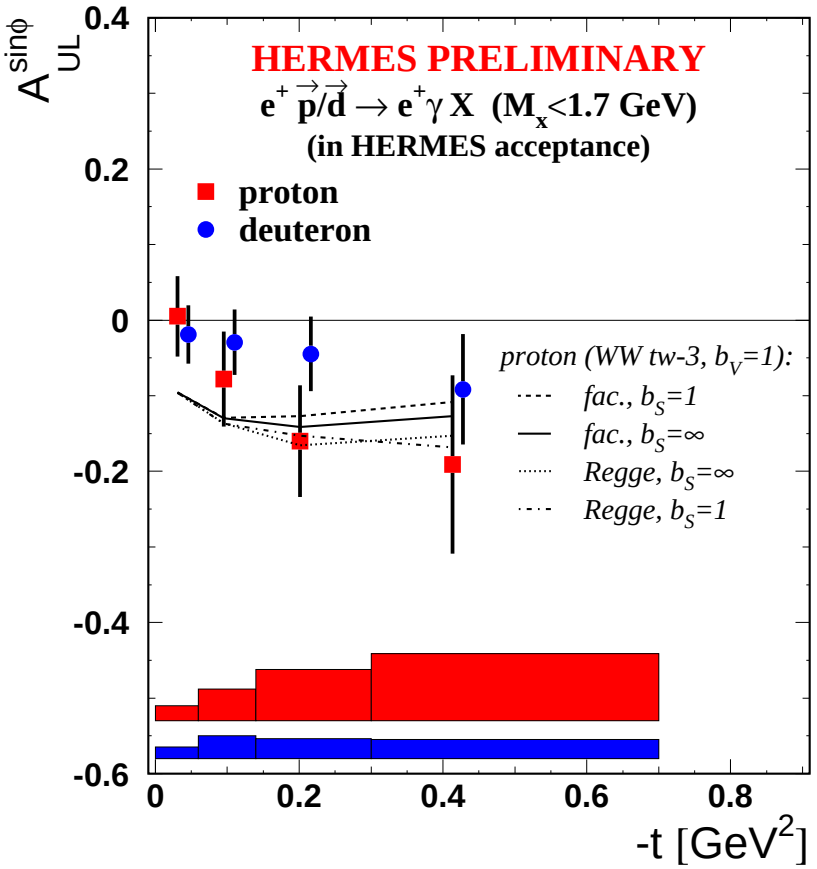
Tiny e^- data sample (only ~ 10 pb^{-1}), but all 2005 with e^- !

GPD model : M. Vanderhaeghen *et al.*, PRD 60 (1999) 094017

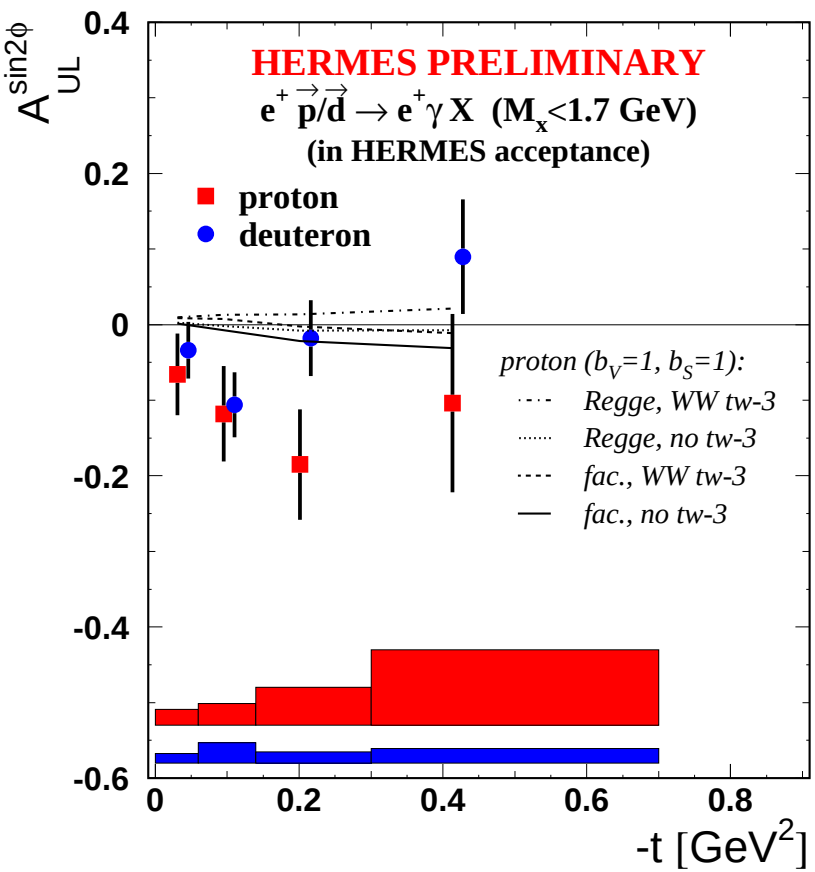
☞ t-dependence of BCA may constrain GPD models

DVCS : Longitudinal Target Spin Asymmetry

$$A_{UL} : \mathrm{d}\sigma(\overrightarrow{p},\phi) - \mathrm{d}\sigma(\overleftarrow{p},\phi) \propto A_{UL}^{\sin\phi}\sin\phi + A_{UL}^{\sin 2\phi}\sin 2\phi$$



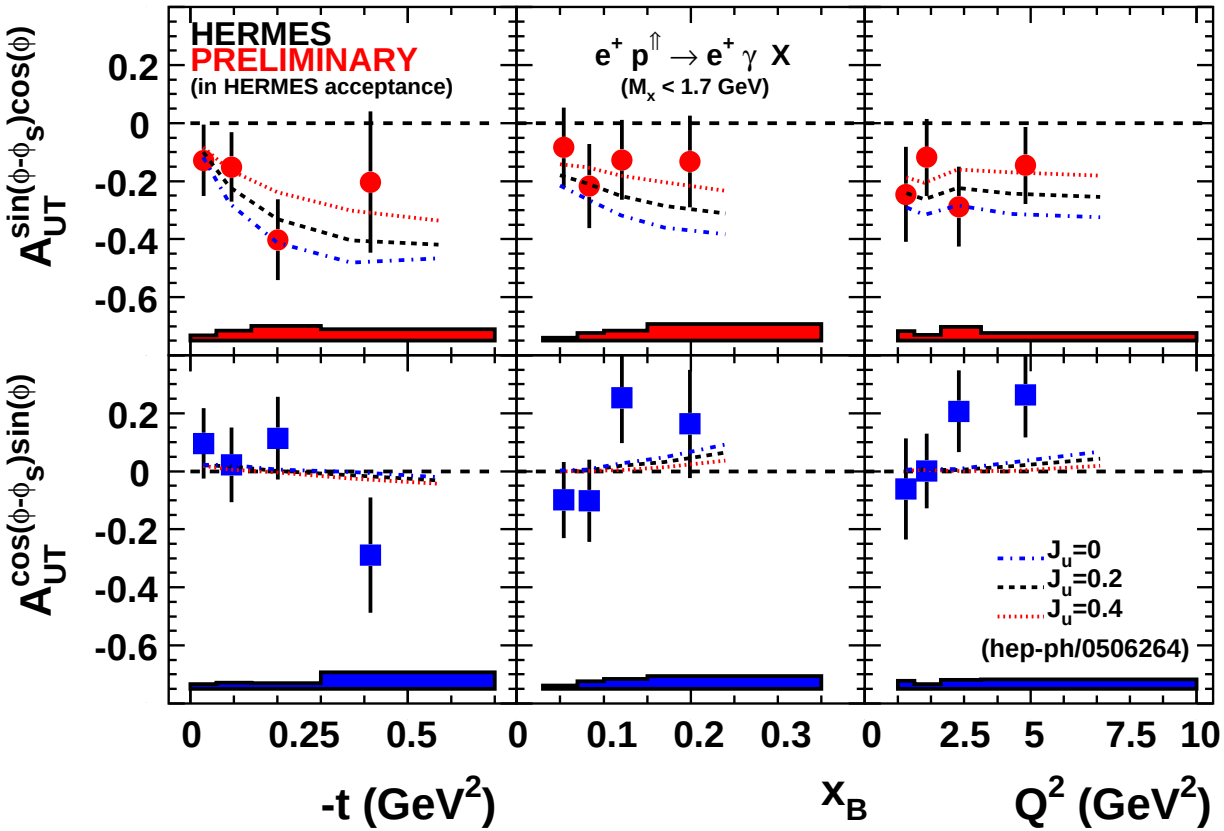
$A_{UL}^{\sin\phi} \propto \mathrm{Im}(F_1\tilde{H})$;
compatible with theory model



$A_{UL}^{\sin 2\phi}$ larger than theory expectation
$\longrightarrow$ twist-3 GPD ?

DVCS : Transverse Target Spin Asymmetry

$$A_{UT}(\phi,\phi_S) : \mathrm{d}\sigma(p^{\uparrow},\phi,\phi_S) - \mathrm{d}\sigma(p^{\downarrow},\phi,\phi_S)$$
$$\propto \mathrm{Im}(F_2 H - F_1 E)\cdot \sin(\phi-\phi_S)\cos\phi + \mathrm{Im}(F_2\tilde{H} - F_1\xi\tilde{E})\cdot\cos(\phi-\phi_S)\sin\phi$$



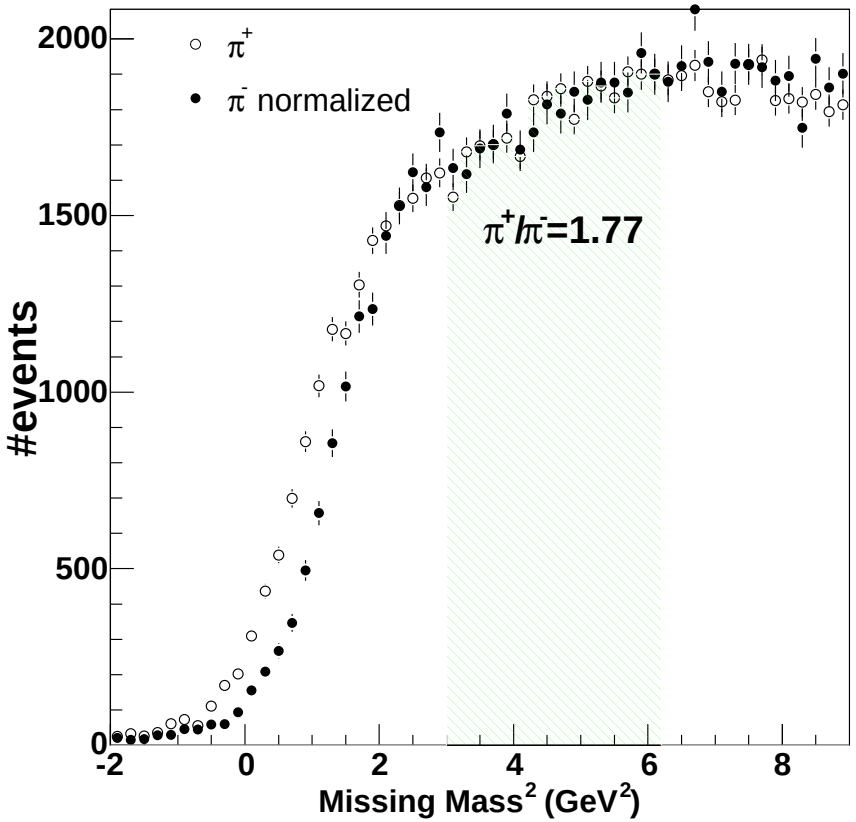
$\mathrm{Im}(F_2 H - F_1 E)$

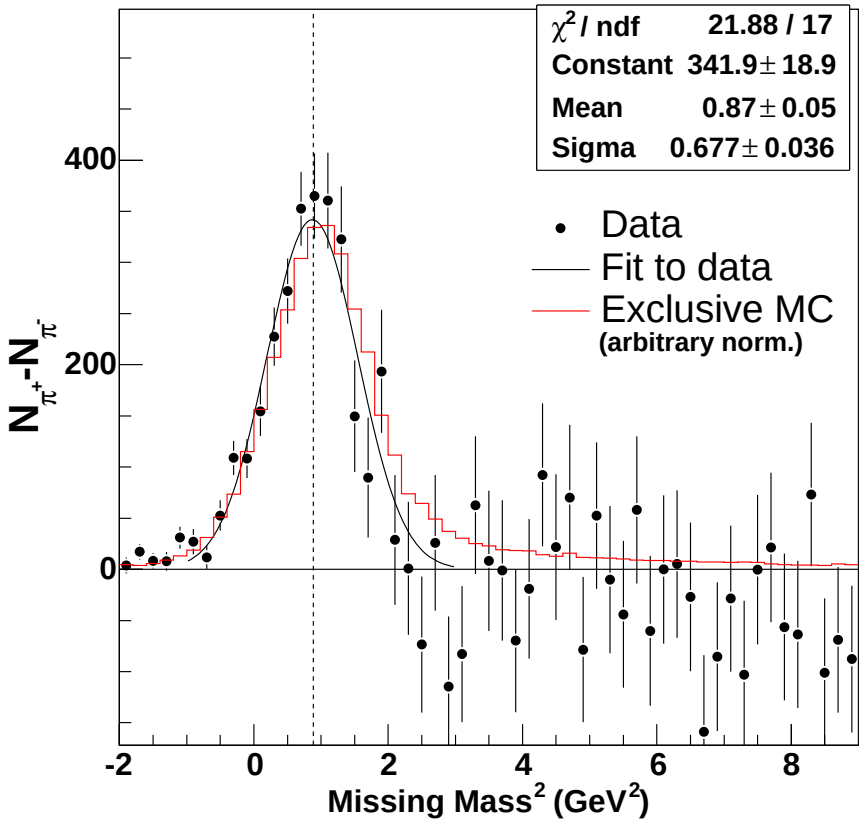
$\mathrm{Im}(F_2\tilde{H} - F_1\xi\tilde{E})$

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

Exclusive Pion Production

$$e + p \rightarrow e + n + \pi^+$$

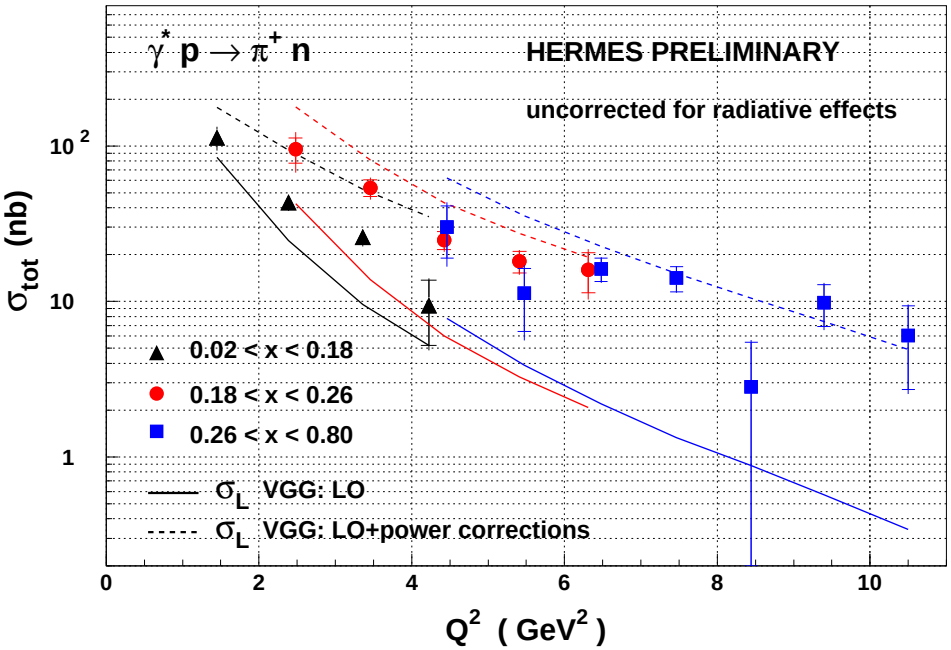


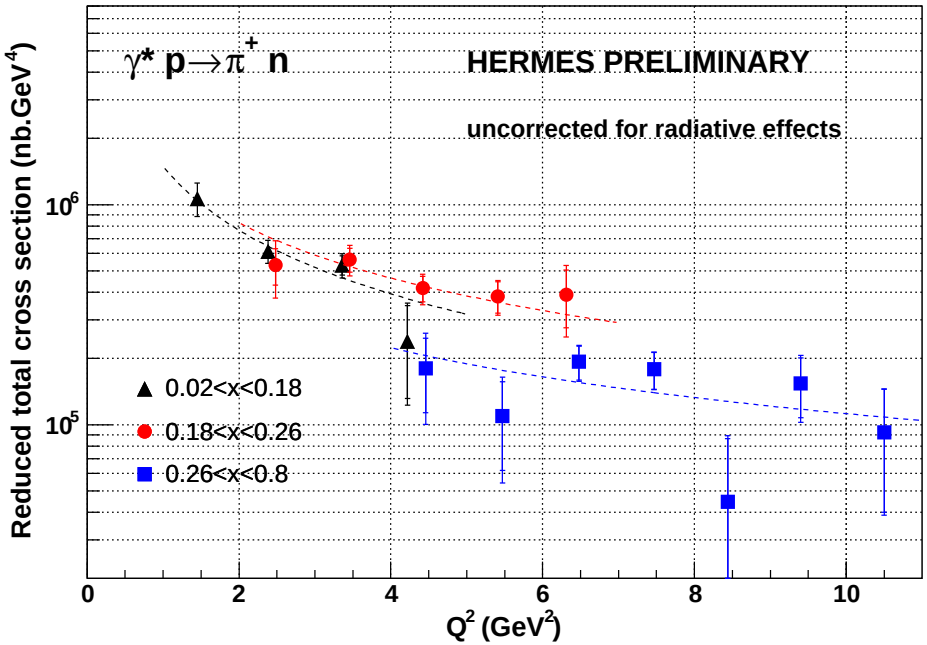


☞ Use missing mass for $e + p \rightarrow e + \pi^+ + X$;

Subtract non-exclusive background via π^- production;
method cross-checked with GPD based Monte Carlo

π^+ Cross Section Measurement



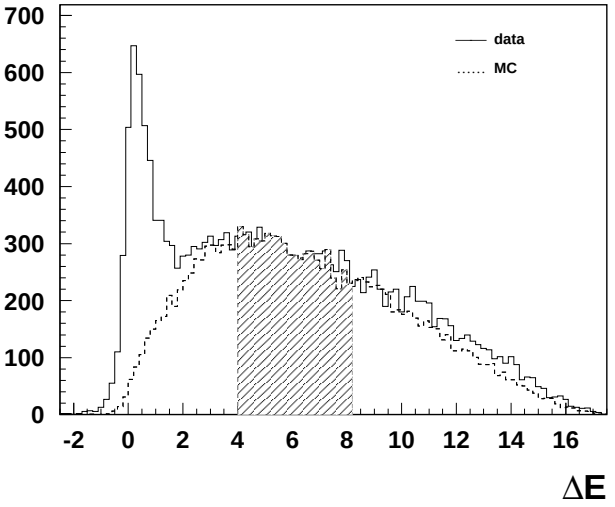


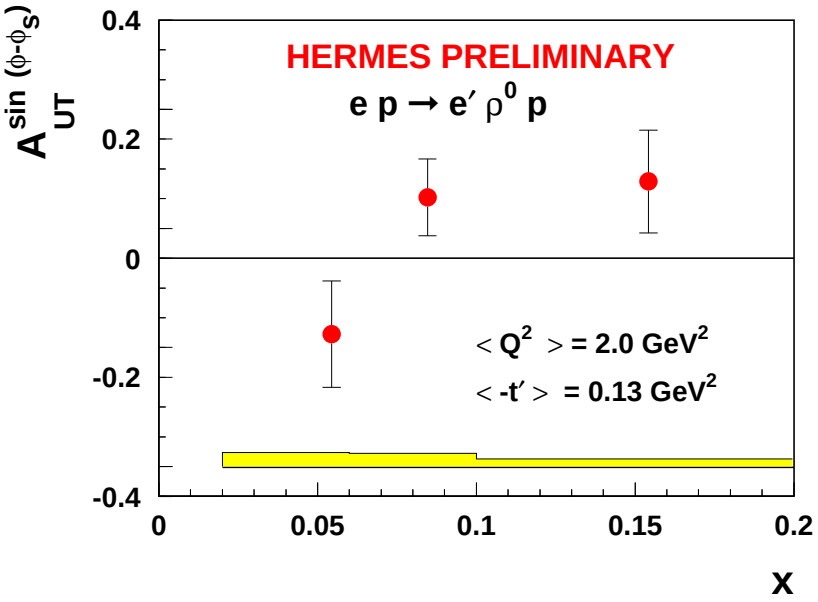
- GPD model : Vanderhaeghen, Guichon, Guidal
- $\sigma_{\text{tot}} = \sigma_T + \epsilon\sigma_L$
  no LT-separation, but σ_T suppressed by $1/Q^2$ and $0.80 < \epsilon < 0.96$ for HERMES
  ☞ Q^2 dependence consistent with LO expectations; power corrections ($k_\perp$ and soft overlap) overestimate data
- $\sigma_{\text{reduced}} \to 1/Q^2$ in agreement with data [$\sigma_L = K(x, Q^2) \cdot \sigma_{\text{reduced}}$ with $K \propto 1/Q^4$]

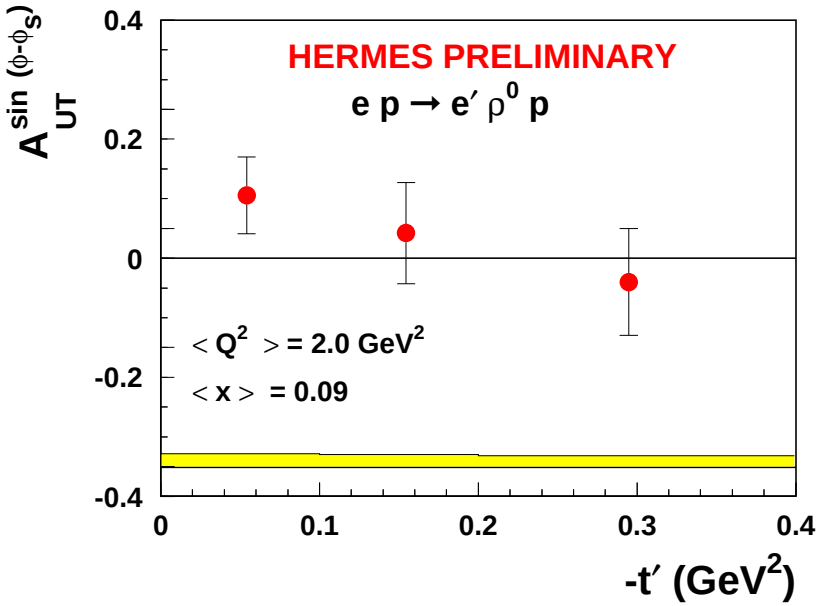
Target Single Spin Asymmetry in ρ^0 Production

$$e + p \rightarrow e + p + \rho^0$$

- Exclusivity through $\Delta E = \dfrac{(M_X^2 - M_p^2)}{2M_p}$ cut
- A_{UT} sensitive to interference of H and E and to total angular momentum of u-quarks

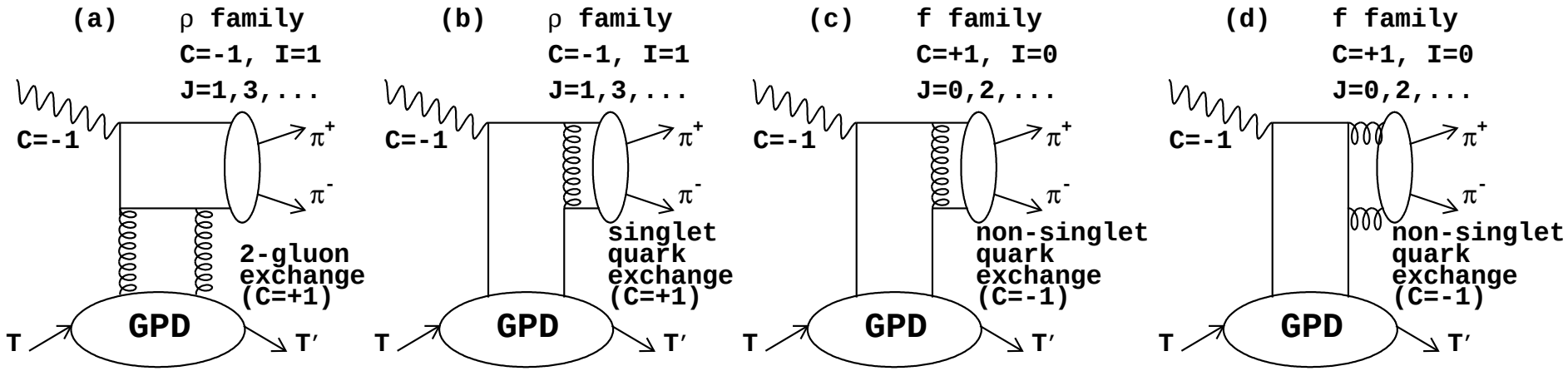






Data consistent with theory expectations

Hard Exclusive $\pi^+\pi^-$ Pair Production

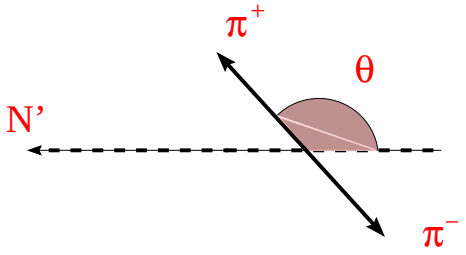


- pion pairs are formed by gluon exchange (isovector pairs) or quark exchange (isovector + isoscalar pairs)

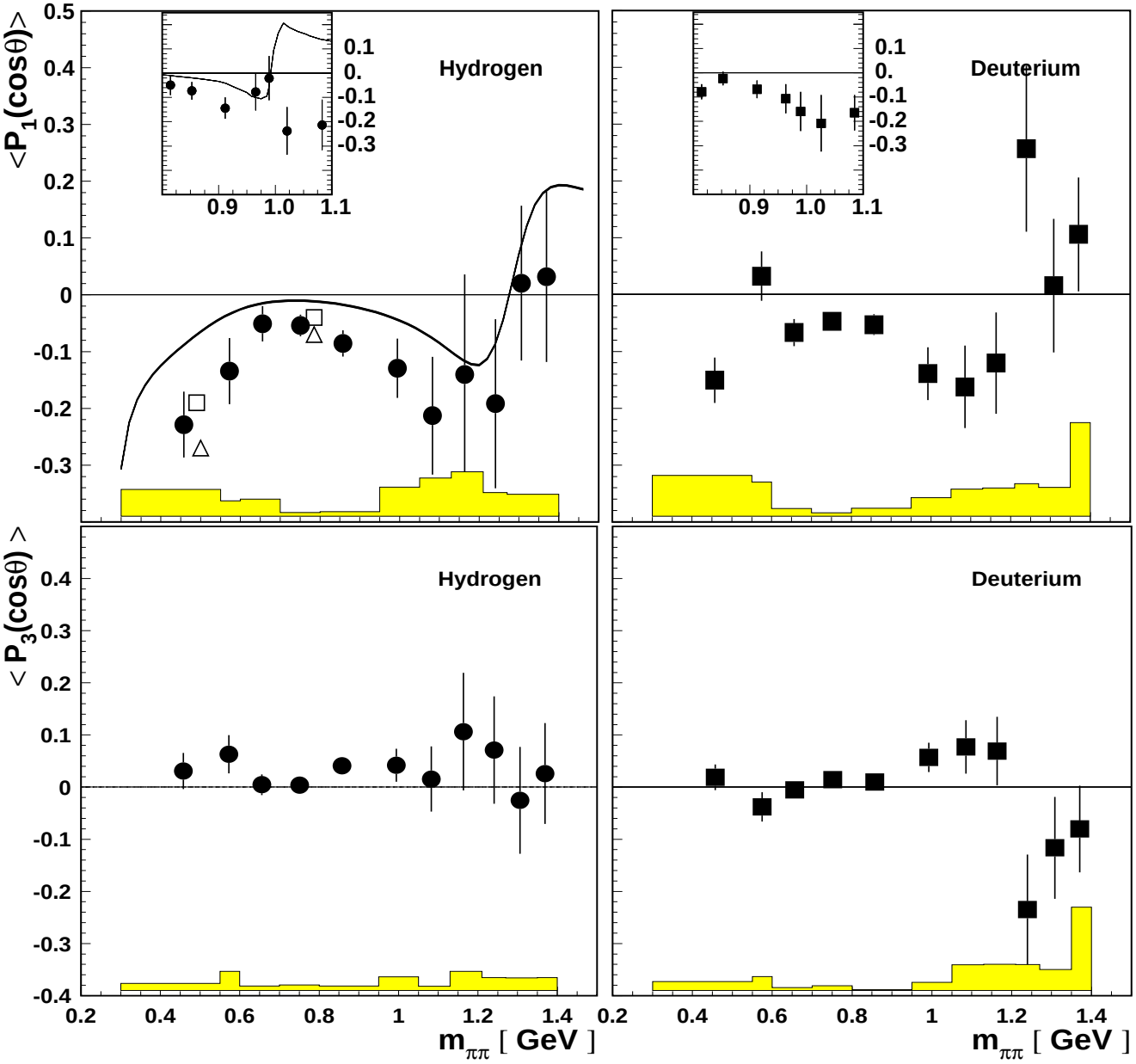
  $\Rightarrow$ study interference between $I = 1$ (ρ-family) and $I = 0$ (f-family) channels to get information on small isoscalar channel

  $\Rightarrow$ new constraints on certain combinations of GPDs
- HERMES : $ep \to ep\pi^+\pi^-$ and $ed \to ed\pi^+\pi^-$
- Intensity densities (Legendre moments) :

$$< P_l(\cos\theta) >^{\pi\pi} = \frac{\int_{-1}^{+1} \mathrm{d}\cos\theta \; P_l(\cos\theta) \frac{\mathrm{d}\sigma^{\pi\pi}}{\mathrm{d}\cos\theta}}{\int_{-1}^{+1} \mathrm{d}\cos\theta \frac{\mathrm{d}\sigma^{\pi\pi}}{\mathrm{d}\cos\theta}}$$



Hard Exclusive $\pi^+\pi^-$ Pair Production



$\langle P_1 \rangle$ sensitive to interference of P-wave with S and D-waves

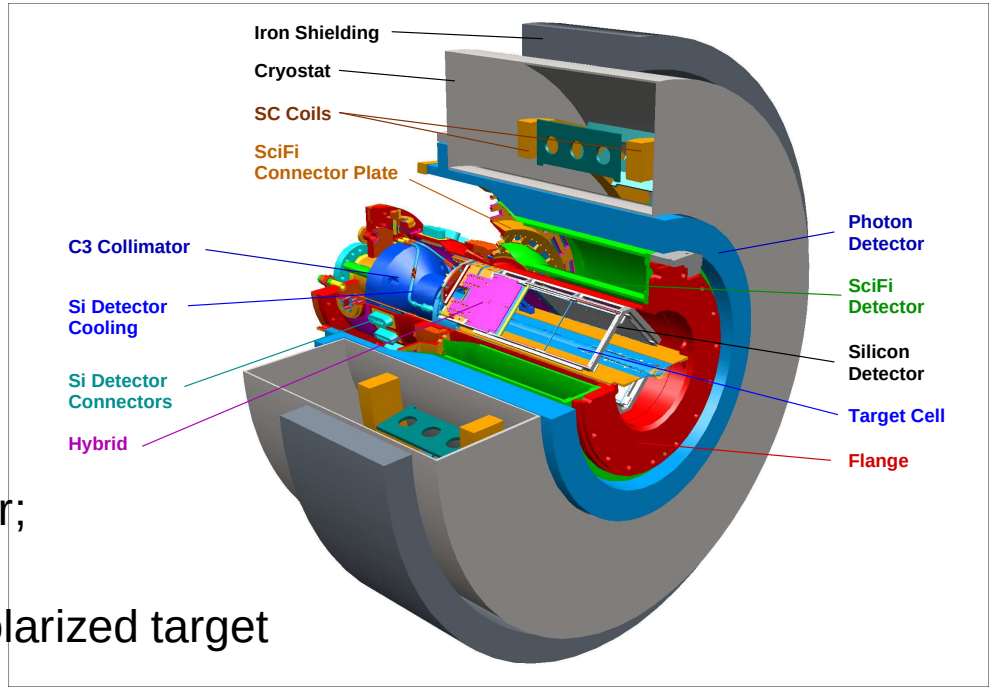
$\Rightarrow$ Interference of ρ^0 P-wave with non-resonant $\pi\pi$ S-wave, $f_0(980)$ S-wave and $f_2(1270)$ D-wave

$\langle P_3 \rangle$ sensitive to interference of P-wave with D-wave

GPD model : B. Lehmann-Dronke *et al.*

Summary & Outlook

- First measurements of transverse target asymmetries in DIS;
  first observation of Sivers effect;
  large Collins asymmetry for π^+ and π^-;
  evidence for non-zero interference fragmentation function in $\pi\pi$ production
  ☞ Expect double statistics for full transverse data set; with Belle Collins and interference FF extraction of h_1 could become feasible
- First measurement of b_1^d structure function
- Access to GPDs in deeply virtual Compton scattering and hard exclusive pseudo-scalar and vector meson production



☞ Installation of Recoil Detector end of this year;
HERMES will focus on exclusive reactions
during running for 2 years with high density unpolarized target