HERMES RUN II - Physics Program

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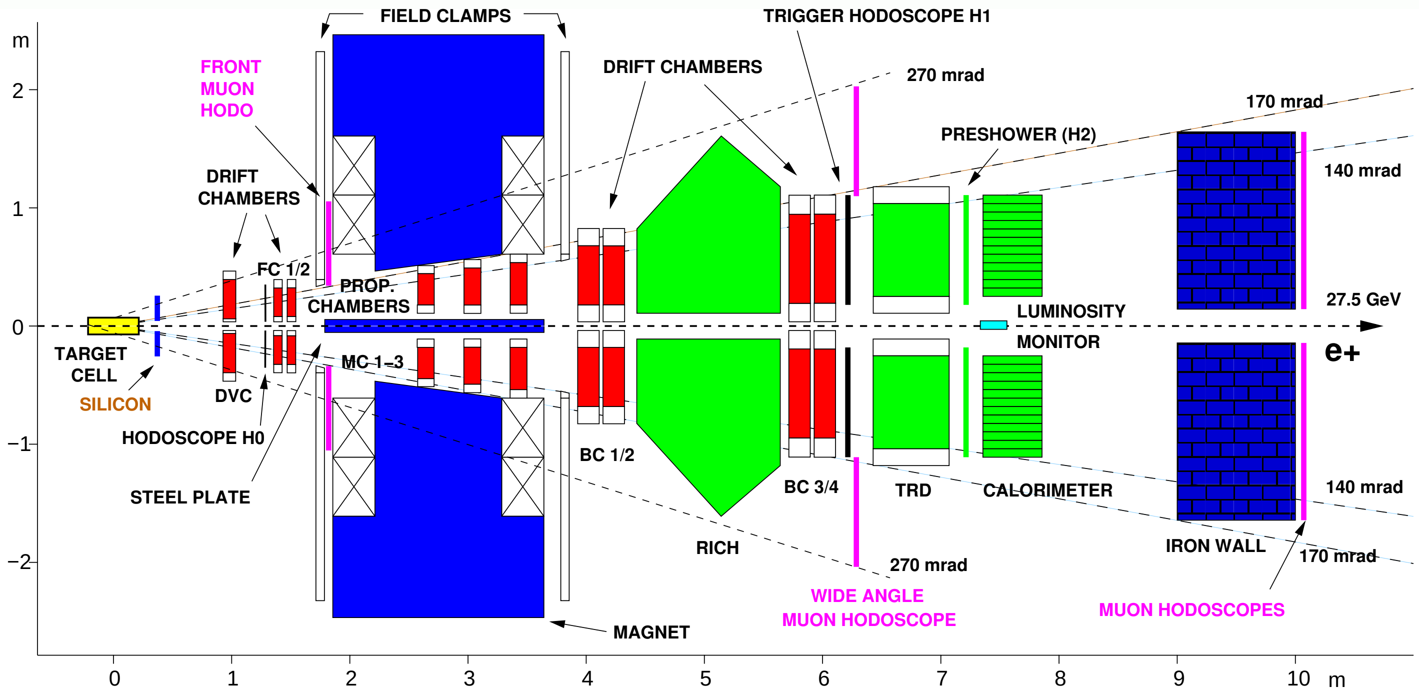
DESY-ZEUTHEN

on behalf of the hermes Collaboration

- What can a transverse polarized target tell us
  - Transversity
  - GPDs
    The Hermes Recoil Detector
- Summary

The HERMES Experiment at HERA



Kinematic Range: 0.02 $\leq$ x $\leq$ 0.8 at $Q^2 \geq 1GeV^2$ and W $\geq$ 2GeV

Reconstruction: δp/p 0.7 - 1.3%, $\delta\Theta \leq$ 0.6mrad

Internal Gas Target: $\overrightarrow{\mathrm{H}e}$,$\overrightarrow{\mathrm{D}}$, $\overrightarrow{\mathrm{H}}$,$H^{\uparrow}$ unpol: H_2, D_2, He, N_2, Ne, Ar, Kr

Particle ID: TRD, Preshower, Calorimeter

$\longrightarrow$ 1997: $\check{C}$erenkov 1998 $\longrightarrow$: RICH + Muon-ID

DIS - Cross Section:

$$\frac{d^2\sigma}{d\Omega dE^2} = \frac{\alpha^2 E'}{Q^2 E} L_{\mu\nu} W^{\mu\nu}$$

$L_{\mu\nu}$ **=** $2[k_\mu k'_\nu + k_\nu k'_\mu - \left(k \cdot k' - m_e^2\right) g_{\mu\nu} + i m_e \epsilon_{\mu\nu\alpha\beta} S^\alpha \left(k - k'\right)^\beta]$

Where: $S^\alpha = \frac{1}{2}\overline{u}\left(k, s\right)\gamma^\alpha \gamma_5 u\left(k, s\right)$

$W^{\mu\nu}$ **=** $-g^{\mu\nu} F_1\left(x, Q^2\right) + \frac{p^\mu p^\nu}{\nu} F_2\left(x, Q^2\right)$

$+\frac{i}{\nu}\epsilon^{\mu\nu\lambda\sigma} q_\lambda S_\sigma g_1\left(x, Q^2\right) + \frac{i}{\nu^2}\epsilon^{\mu\nu\lambda\sigma} q_\lambda \left(p \cdot q S_\sigma - S \cdot q p_\sigma\right) g_2\left(x, Q^2\right)$

(for spin 1) **+ quadrapole terms** (b_1, b_2, b_3, b_4)

F_1, F_2 g_1, g_2 $\Longrightarrow$ **Un- / Polarized Structure Functions**

BUT

Quarks are relativistic, have intrinsic k_T, masses and correlations

DIS and SIDIS Cross Section

$$d\sigma = d\sigma^0_{UU} + \frac{p_T}{Q}\cos\phi\, d\sigma^1_{UU} + \lambda\frac{1}{Q}\sin\phi\, d\sigma^2_{LU}$$

$$\searrow f_1$$

$$+S_L[\sin 2\phi\, d\sigma^3_{UL} + \frac{1}{Q}\sin\phi\, d\sigma^4_{UL}] + \lambda S_L[d\sigma^5_{LL} + \frac{1}{Q}\cos\phi\, d\sigma^6_{LL}]$$

$$\searrow h^{\perp}_{1L} \qquad\qquad \searrow g_{1L}$$

$$+S_T[\sin(\phi+\phi_S)\, d\sigma^7_{UT} + \sin(3\phi-\phi_S)\, d\sigma^8_{UT} + \frac{1}{Q}\sin(2\phi-\phi_S)\, d\sigma^9_{UT}]$$

$$\searrow h_1 \qquad\qquad \searrow h^{\perp}_{1T}$$

$$+\lambda S_T[\cos(\phi-\phi_S)\, d\sigma^{10}_{LT} + \frac{1}{Q}\cos(2\phi-\phi_S)\, d\sigma^{11}_{LT}]$$

$$\searrow g_{1T}$$

σ_{LT} $\Longrightarrow$ **non zero Single Spin Asymmetries**

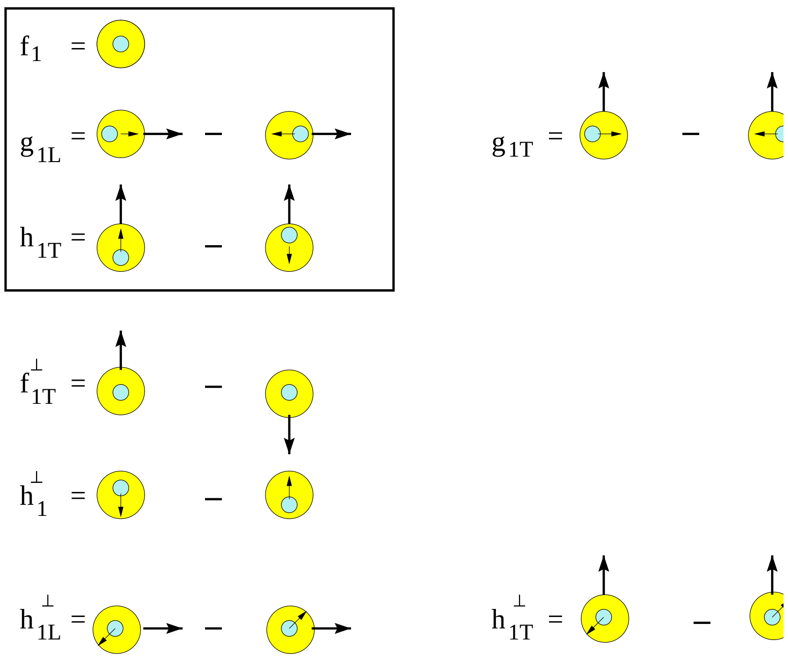
$\swarrow \searrow$

Beam Target polarization

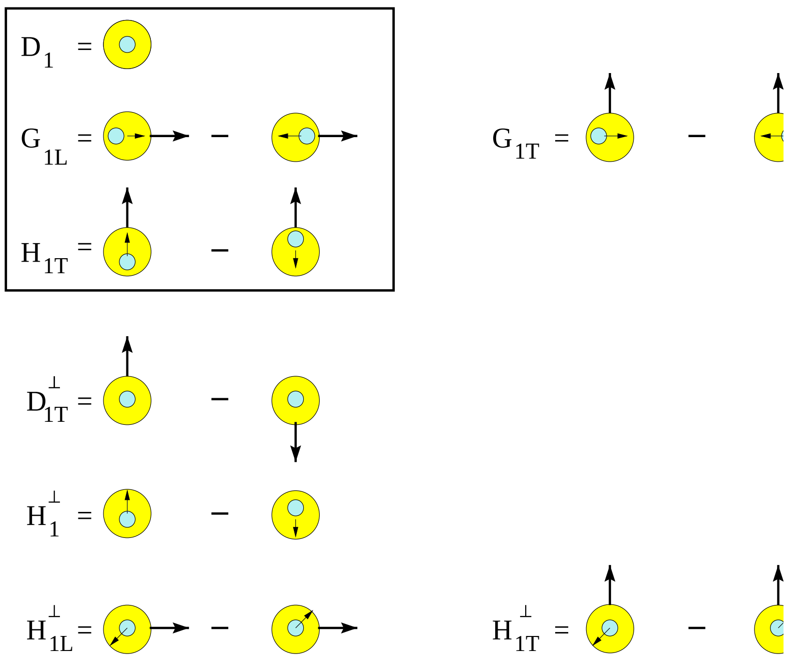
Mulders and Tangermann (NP B 461 (1996) 197)

Twist-2 Quark Distribution Functions

Distribution Functions



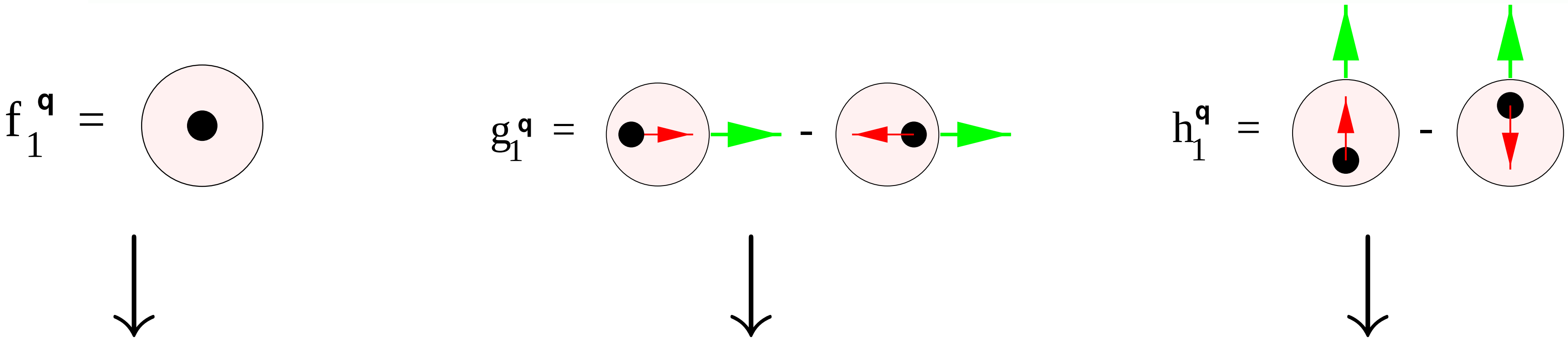
Fragmentation Functions



☐ **Functions Surviving Integration over Transverse Momenta**

The others are sensitive to intrinsic $< k_t >$ in the nucleon & in the fragmentation process

... surviving $k_\perp$ integration



Unpolarized
quarks and nucleons

vector charge:

$< PS|\bar{\psi}\gamma^{\mu}\psi|PS >=$
$\int_0^1 dx q(x) - \bar{q}(x)$

q(x): spin averaged
well known

Longitudinally polarized
quarks and nucleons

axial charge:

$< PS|\bar{\psi}\gamma^{\mu}\gamma_5\psi|PS >=$
$\int_0^1 dx \Delta q(x) + \Delta\bar{q}(x)$

Δq(x): helicity difference
known

HERMES 1995-2000

Transversely polarized
quarks and nucleons

tensor charge :

$< PS|\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi|PS >=$
$\int_0^1 dx \delta q(x) - \delta\bar{q}(x)$

δq(x): helicity flip
unmeasured

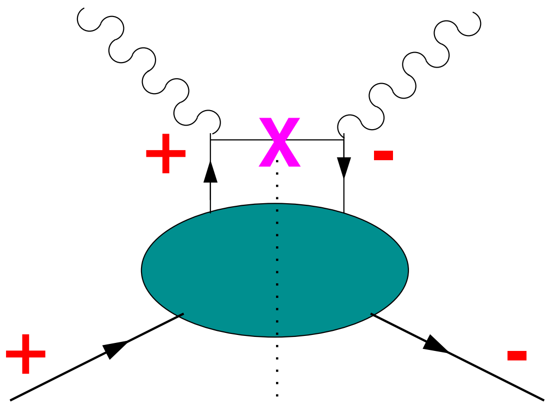
HERMES 2002...

Characteristics of Transversity

- **Non-relativistic quarks:** $\Delta q(x) = \delta q(x)$
  $\Rightarrow$ δq **probes relativistic nature of quarks**
- **Angular momentum conservation**
  $\Rightarrow$ **Transversity has no gluon component**
  $\Rightarrow$ **different** Q^2 **evolution than** $\Delta q(x)$
- q **and** $\bar{q}$ **contribute with opposite sign to** $\delta q(x)$
  $\Rightarrow$ **predominantly sensitive to valence quark polarization**
- **Bounds:**
  $\Rightarrow$ $|\delta q(x)| \leq q(x)$
  $\Rightarrow$ **Soffer bound:** $|\delta q(x)| \leq \frac{1}{2}[q(x) + \Delta q(x)]$

- **Transversity distribution CHIRAL ODD**

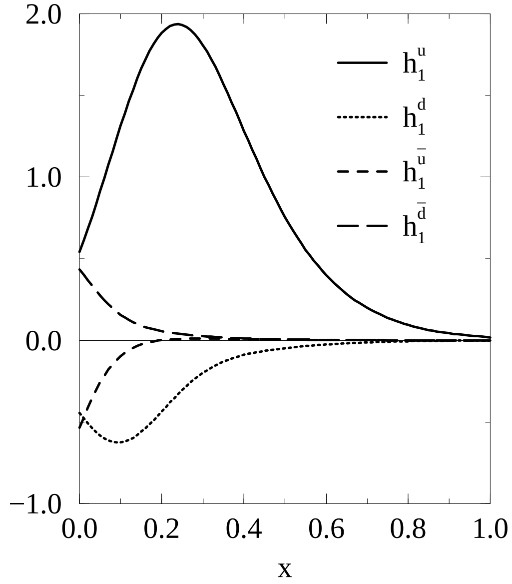
$\Rightarrow$ **No Access In Inclusive DIS**

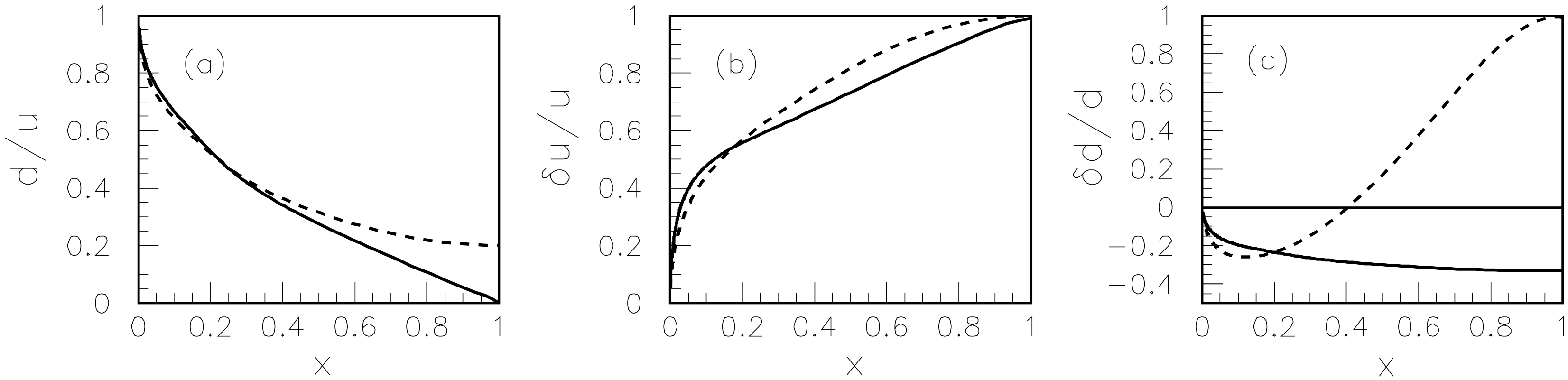


Transversity Phenomenology

- a number of model calculations
  But lack of experimental data
- h_1 must satisfy Soffer inequality
- in common: h_1 behaves more valence-like

χQSM (A.V. Efremov et al)





Quark-Diquark (solid), pQCD based model (dashed) (B.Q. Ma et al)

How can one measure Transversity?

Need another chiral-odd object!

δq(x) accessible in semi-inclusive DIS

$$\sigma^{ep\rightarrow ehX} = \sum_q f^{H\rightarrow q} \otimes \sigma^{eq\rightarrow eq} \otimes D^{q\rightarrow h}$$

$$\Downarrow \qquad\qquad \Downarrow$$

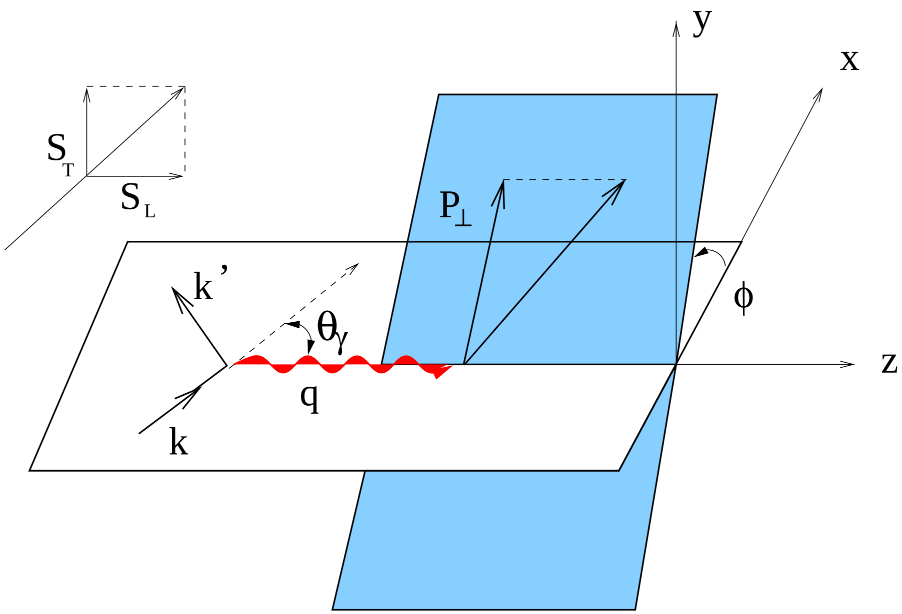
chiral-odd DF   **chiral-odd FF**

Study SSA with a transversely polarized target at HERMES

1. $ep^{\uparrow} \longrightarrow e'\pi X$ $\Leftarrow$ **Favored Process**
   Collins,93, Kotzinian,95, Mulders et al,96
2. $ep^{\uparrow} \longrightarrow e'\Lambda^{\uparrow} X$ **Baldracchini,82, Jaffe,96**
3. $ep^{\uparrow} \longrightarrow e'\pi\pi X$ **Jaffe et al,97**

Single Spin Asymmetries

$$ep^{\uparrow} \longrightarrow e'\pi X$$



$\Phi = \phi + \phi_s^l$ **Collins angle**

$\phi_s^l \ldots$ **angle between target spin vector and scattering plane**

study azimuthal distribution of π's:

$$A^{\sin\Phi} \propto \frac{\sum_{i=1}^{N^+} \sin\Phi_i - \sum_{i=1}^{N^-} \sin\Phi_i}{\frac{1}{2}(N^+ + N^-)}$$

Transversely polarized target:

$$A_T^{\sin\Phi} \propto \frac{\sum_q e_q^2 \delta q(x) H_1^{\perp,q}(z)}{\sum_q e_q^2 q(x) D_1^q(z)}$$

$H_1^\perp(z)$ **Collins fragmentation function**

Hydrogen Target

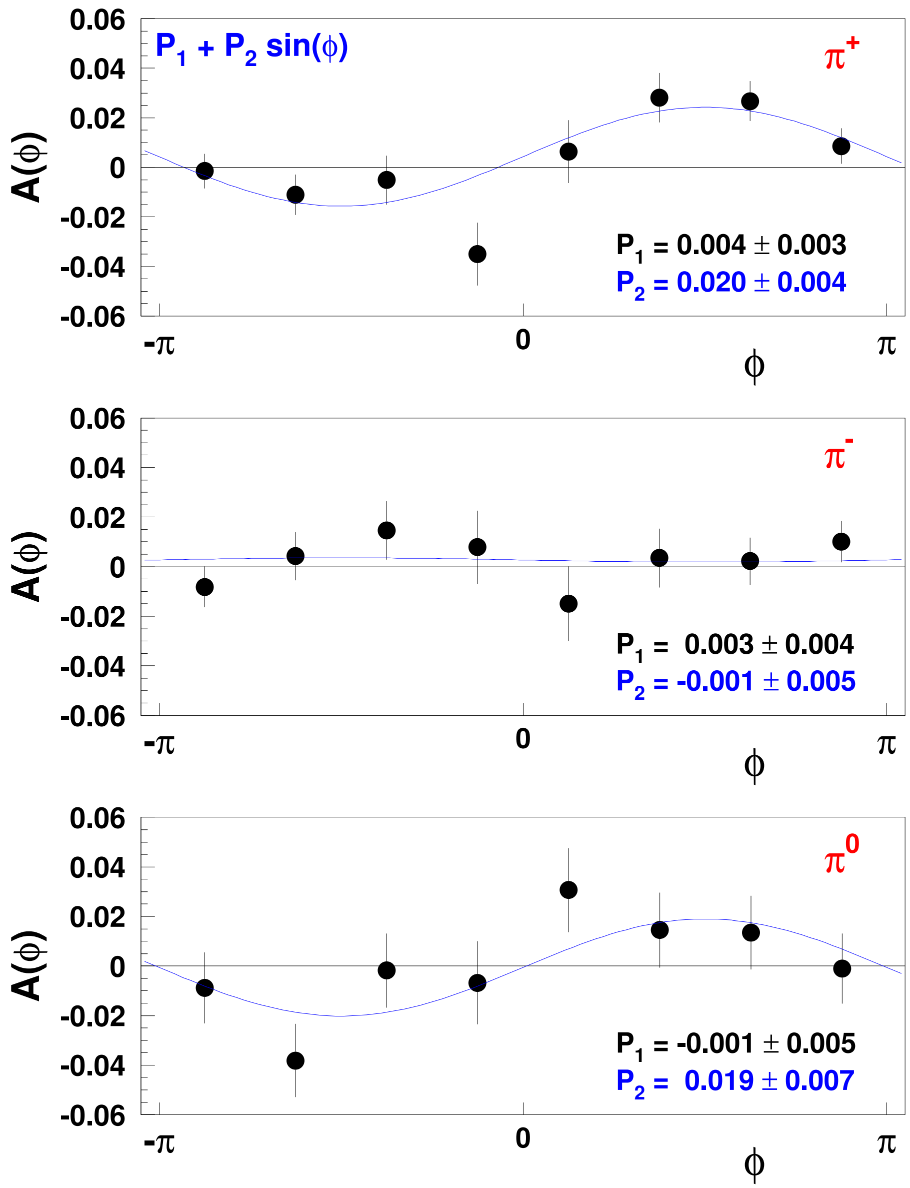
First glimpse on Transversity?!

$$A_{UL}(\phi) = \frac{1}{\langle P \rangle} \cdot \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$

S_T **transverse component of target spin w.r.t. virtual photon:**

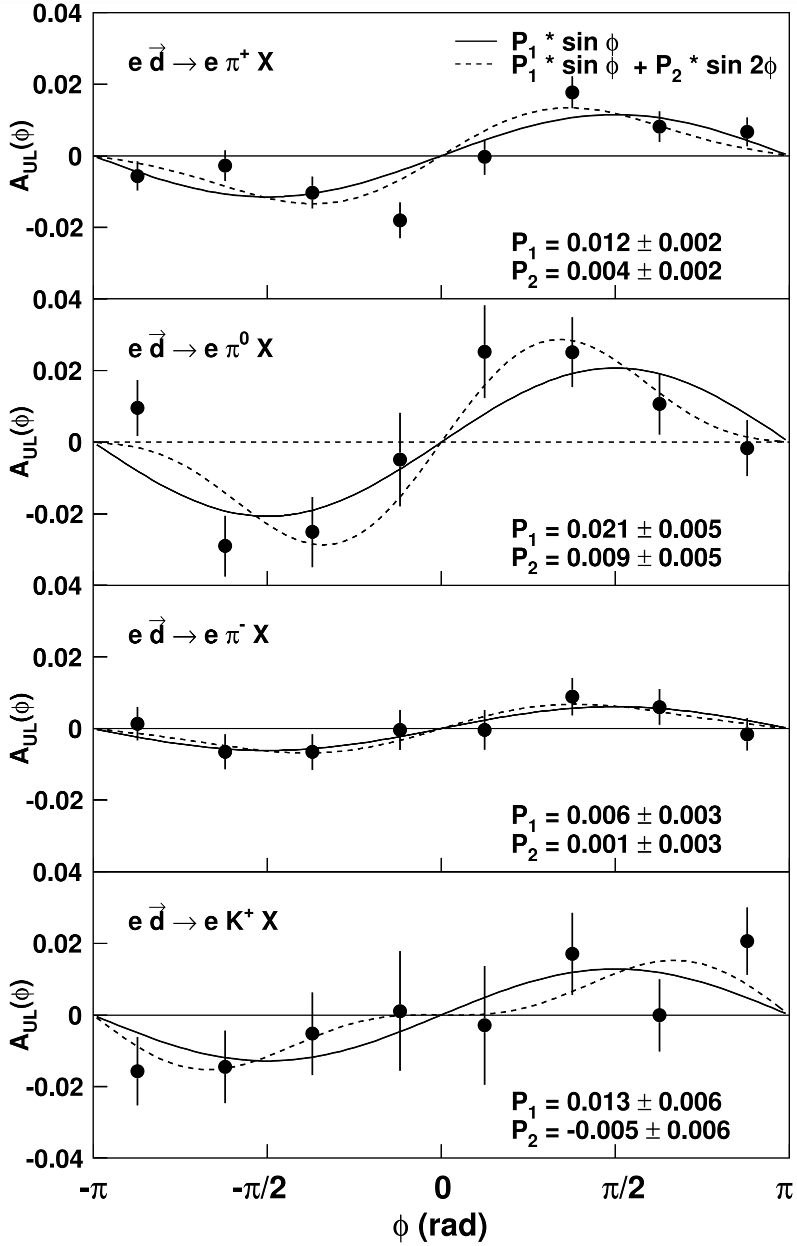
$$S_T \propto \sin\Theta_\gamma \simeq \frac{2Mx}{Q}\sqrt{1-y} \sim \mathbf{0.15}$$

π^0: hep-ex/0104005, $\pi^{\pm}$: hep-ex/9910062



Deuteron Target

- Longitudinal polarized deuteron target
- High statistics: ~8 Million DIS
- Very good hadron identification due to RICH
- First measurement of Kaon SSA



Attempt of Interpretation

- **observe non-vanishing $\langle \sin\phi \rangle$-moments**
- $\langle \sin 2\phi \rangle$**-moment small (consistent with zero)**

Attribute asymmetry to Collins fragmentation and Transversity:

$$A^{\sin\phi}_{UL} \sim S_L \langle \sin\phi \rangle_{UL} - S_T \langle \sin\phi \rangle_{UT}$$

L**ongitudinally polarized in experiment (along beam direction)**

L/T **polarized in theory (along virtual gamma direction**

$$\langle \sin\phi \rangle_{UL} \sim \frac{1}{Q} \sum_q e_q^2 \left(h_L^q(x) H_1^{\perp(1),q}(z) - \frac{1}{z} h_{1L}^{\perp(1),q}(x) \tilde{H}(z) \right)$$

$$\langle \sin\phi \rangle_{UT} \sim \sum_q e_q^2 x h_1^q(x) H_1^{\perp(1),q}(z)$$ **but** $S_T \sim \frac{1}{Q}$ **like twist-3**

$$\langle \sin 2\phi \rangle_{UL} \sim \sum_q e_q^2 x h_{1L}^{\perp(1),q}(x) H_1^{\perp(1),q}(z)$$

Distribution functions are related:

$$h_L(x) = \frac{m_q}{M}\frac{h_1(x)}{x} - \frac{2}{x}h_{1L}^{\perp(1)}(x) + \tilde{h}_L(x)$$

Lorentz covariance:

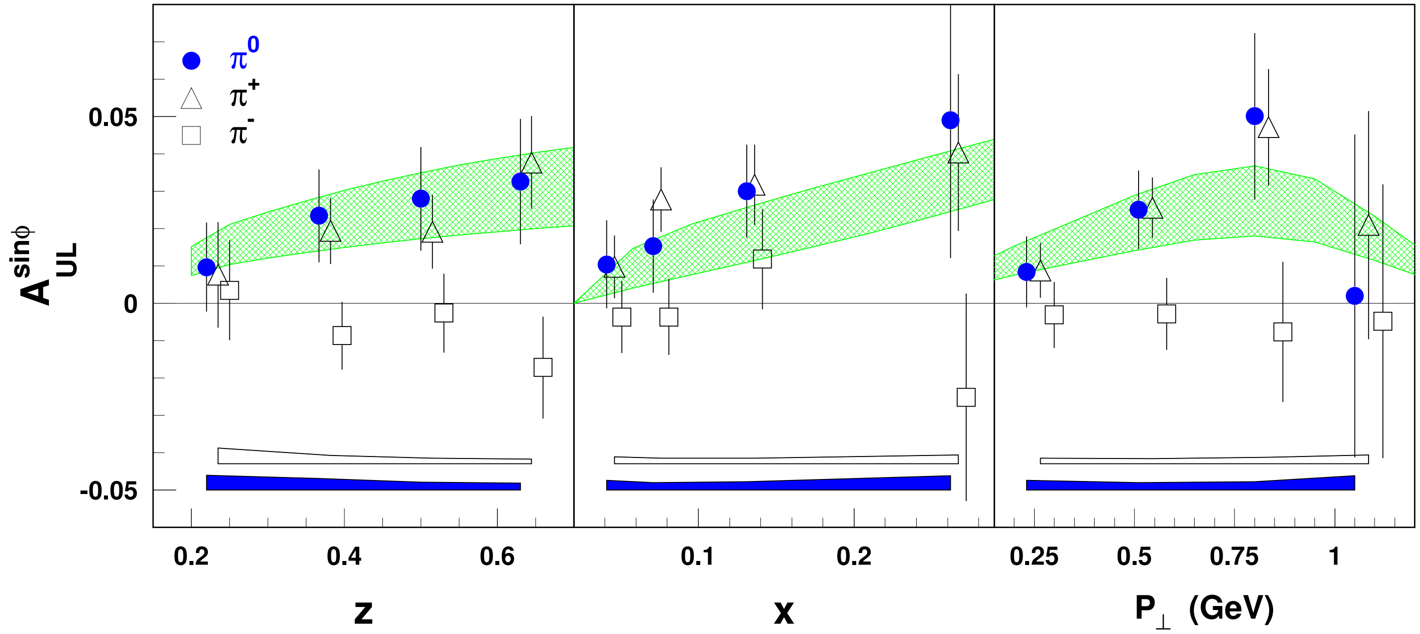
$$h_L(x) = h_1(x) - \frac{d}{dx}h_{1L}^{\perp(1)}(x)$$

$$h_L(x) = \tilde{h}_L(x) + 2x\int_x^1 \frac{dy}{y^2}\left[h_1(y) - \tilde{h}_L(y)\right]$$

set $\tilde{h}_L$ **= 0** $\rightarrow$ **"Reduced Twist-3"**

$$h_L(x) = -\frac{2}{x}h_{1L}^{\perp(1)}(x) = 2x\int_x^1 \frac{dy}{y^2}h_1(y)$$

Let's assume Collins



Proton Target

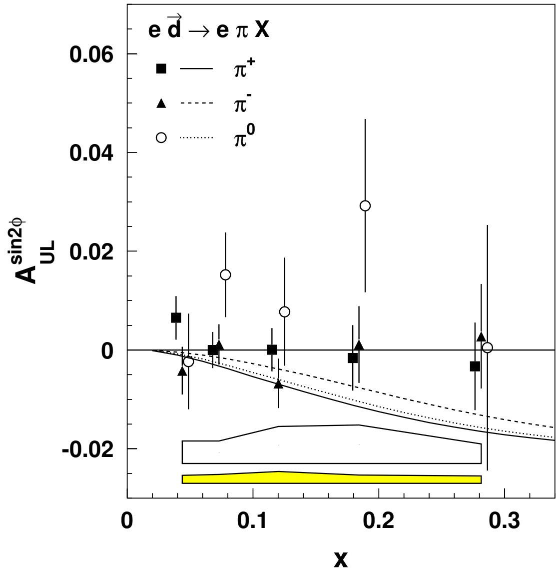
$$A_{UL}^{sin(\phi)} \sim \frac{\sum_{i=1}^{N^+} sin(\phi_i^+) - \sum_{i=1}^{N^-} sin(\phi_i^-)}{|P| \cdot \frac{1}{2}(N^+ + N^-)}$$

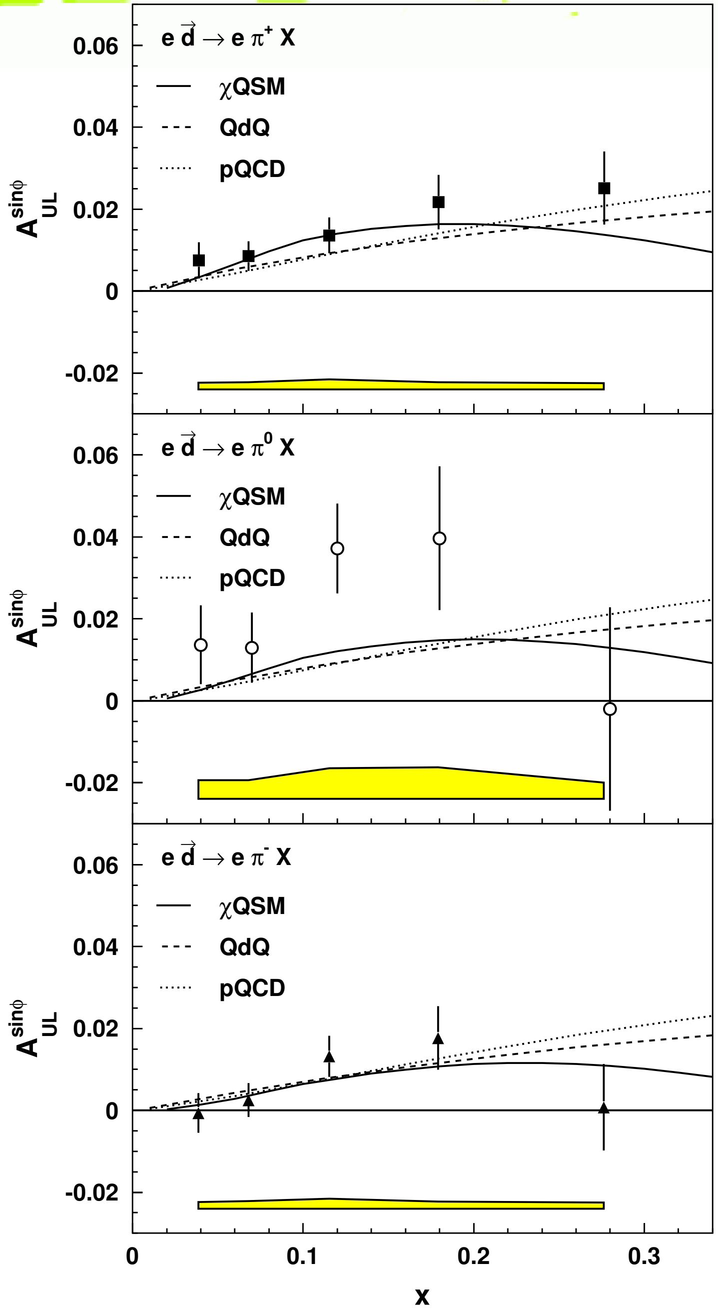
Original predictions by Collins:

- **Larger for π^+, π^0 than for π^- (u-quark dominance)**
- **Peak around $x = 0.3$ (valence quark dominance)**
- **Grow with $p_\perp$ and peak around 1 GeV ($\frac{H_1^\perp}{D_1} \propto \frac{M_c M_h}{M_c^2 + p_\perp^2}$ with $M_c \simeq$1 GeV)**

Deuteron Results

- h_1 **from**
  χ**QSM, quark-diquark and pQCD model**
- **assume reduced twist-3**
- $H_1^{\perp}$ **: Collins Ansatz or fit to DELPHI data**
- $\sin 2\phi$ **using** χ**QSM model**





Challenges in Interpretation

Attribute asymmetry to Sivers effect:

- Initial state interactions (Brodsky et al.)
- Sivers function (Sivers, Mulders et al) $\langle \sin\phi \rangle_{UL} \sim f_{1T}^{\perp(1)} D_1$

longitudinally polarized target $\Rightarrow$ Sivers and Collins effect indistinguishable

Transversely polarized target

- $\langle \sin\phi \rangle_{UT}$ becomes dominant
- Sivers and Collins distinguishable

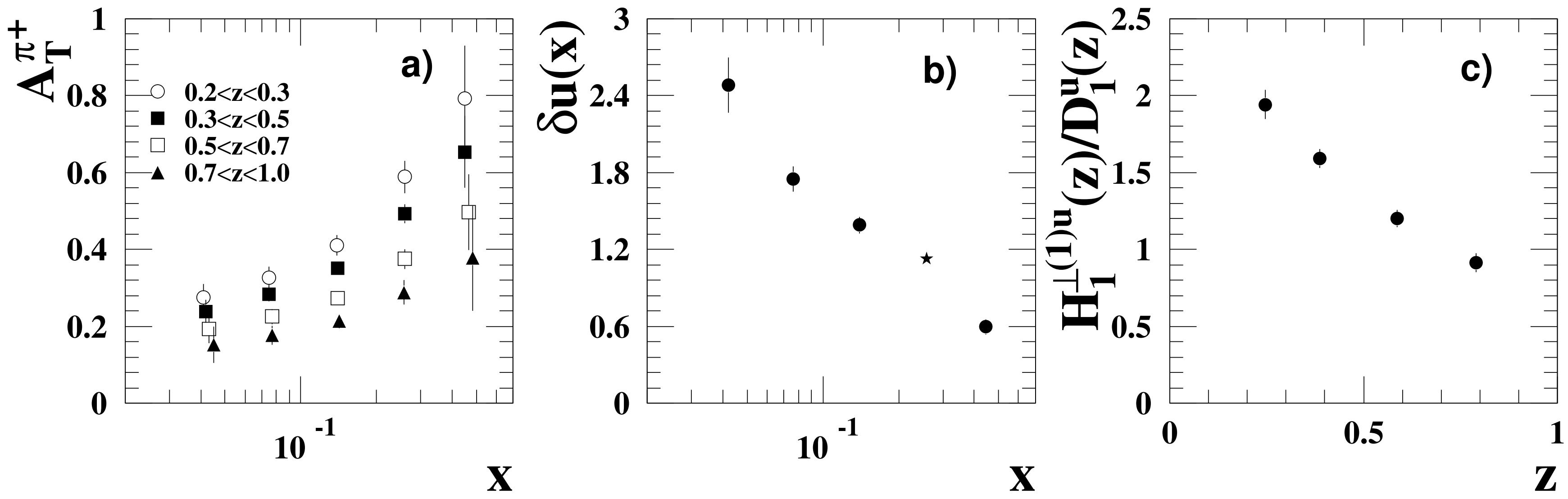
$\swarrow$ $\searrow$

$\langle \sin(\phi_h^l - \phi_s^l) \rangle$ moment $\langle \sin(\phi_h^l + \phi_s^l) \rangle$ moment

Expected Accuracy

$$A_p^{\pi^+}(x,y,z) = P_T \cdot D_{nn} \cdot \frac{\delta u(x)}{u(x)} \cdot \frac{H_1^{\perp(1)}(z)}{D_1(z)}$$

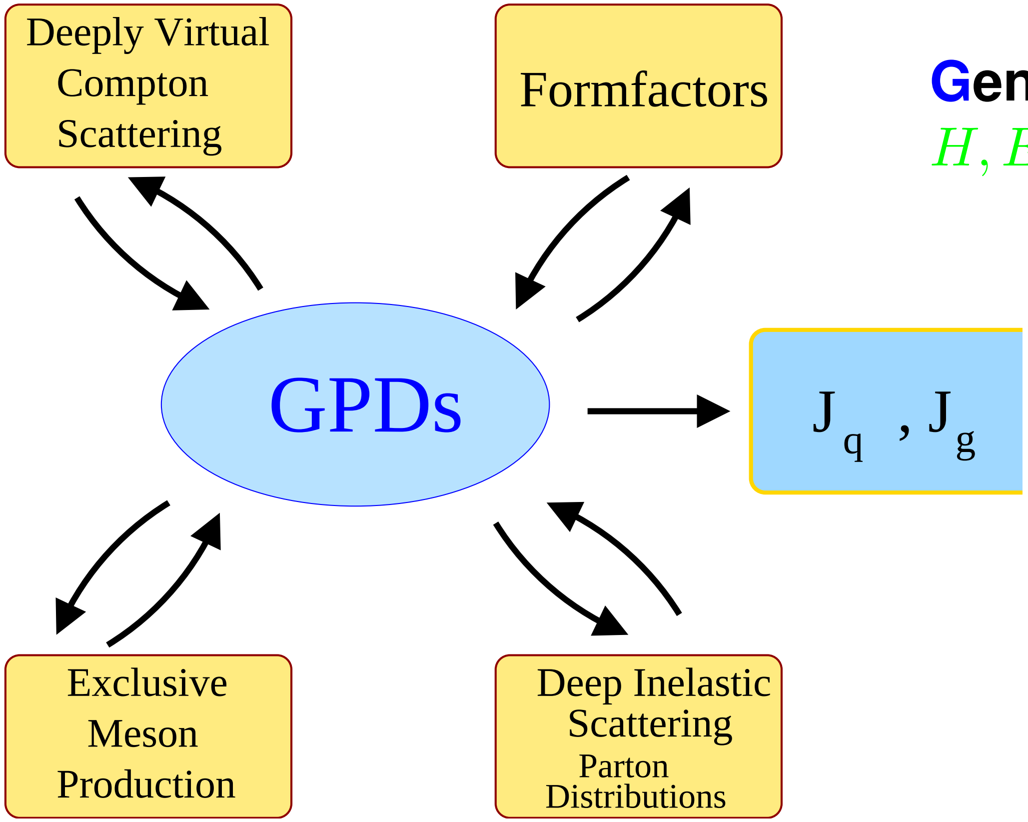
Statistics: 7 Million DIS collected with a transverse polarized proton target



$\delta u(x) + \delta d(x)$: $\longrightarrow$ **transverse polarized deuterium target**

$H_1^{\perp(1)q}(z)$ **can be measured at e^+e^- (LEP, BELLE)**

GPDs Introduction



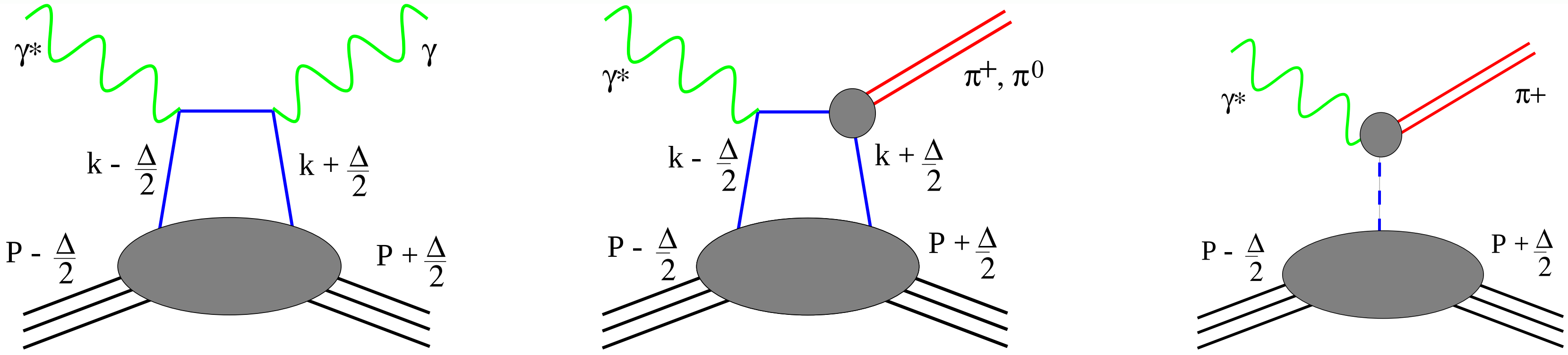
new observables in hard exclusive processes

Genaralised **P**arton **D**istributions

$H, E, \tilde{H}, \tilde{E}$

$\Rightarrow$ **access to orbital angular momentum**

$$\boxed{\int x \mathrm{d}x \,(H + E) \; = \; J_q}$$



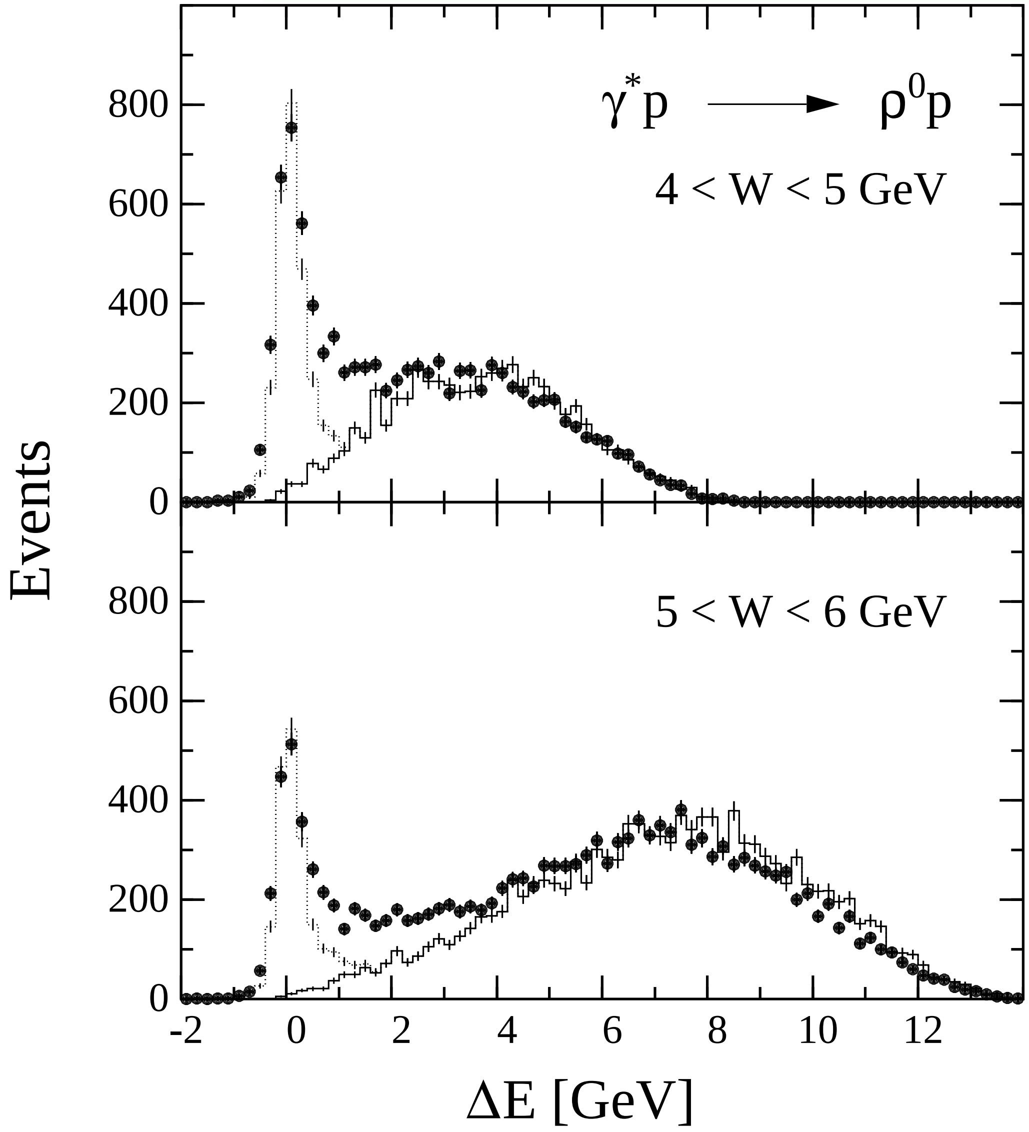
quantum numbers of final state $\longrightarrow$ select different GPDs

DVCS: $\tilde{H}, \tilde{E}$ $H, E,$
vector mesons: H, E
pseudo-scalar mesons: $\tilde{H}, \tilde{E}$

quadratic combination of GPDs appear in unpolarized cross section

$\longrightarrow$ **polarization provides new observables**

Exclusive VM-production $ep \to e'\rho^0(\phi,\omega)p$



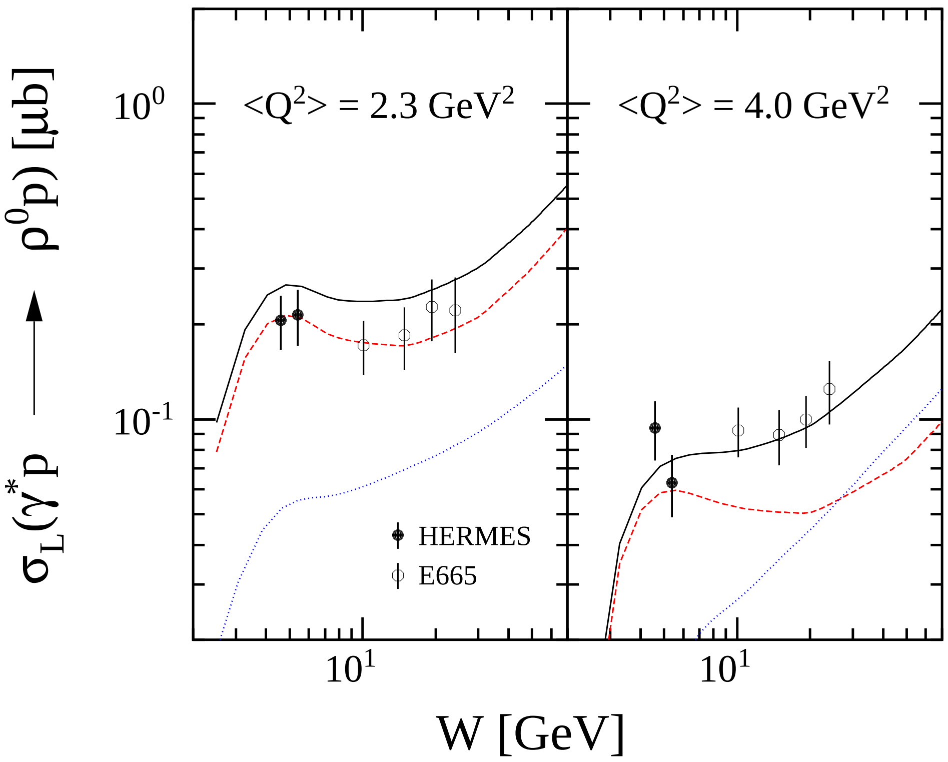
$$\rho^0 \to \pi^+\pi^-$$
$$\phi \to K^+K-$$
$$\omega \to \pi^+\pi^-\pi^0$$

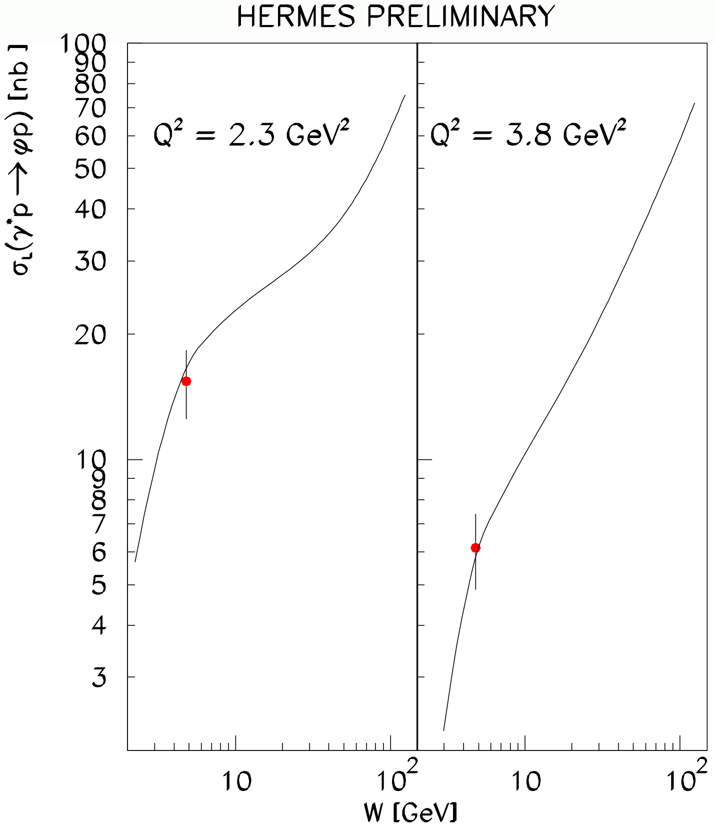
$\Rightarrow$ **good determination of exclusive channel**

$\to$ **DIS-‘background‘ well described by Monte Carlo**

$\Rightarrow$ **deduce longitudinal cross section from decay angular distributions**

Exclusive $\rho^0, \phi\, \sigma_L$



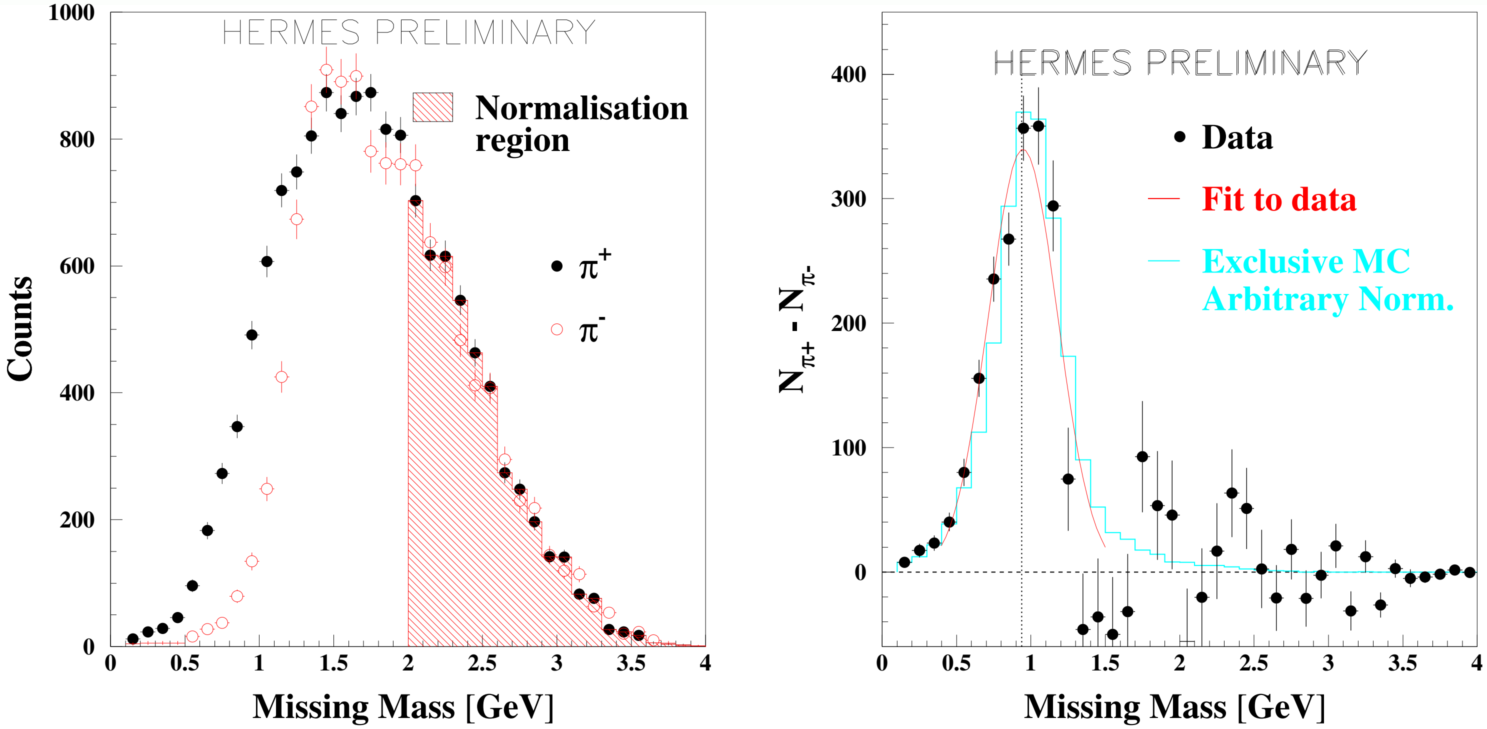


[Guichon, Guidal, Vanderhaegen, Phys. Rev. D 60 (1999), 094017; private communication 2001]

GPD calculations:
- ○ **quark exchange mechanism dominates** $\sigma_L(\gamma^* \mathbf{p} \rightarrow \rho^0 \mathbf{p})$
- ○ **2-gluon exchange mechanism dominates** $\sigma_L(\gamma^* \mathbf{p} \rightarrow \phi \mathbf{p})$

transverse polarised target: higher sensitivity to GPD E

Exclusive PS meson production $e\,\vec{\mathrm{p}} \rightarrow e'\,n\,\pi^+$

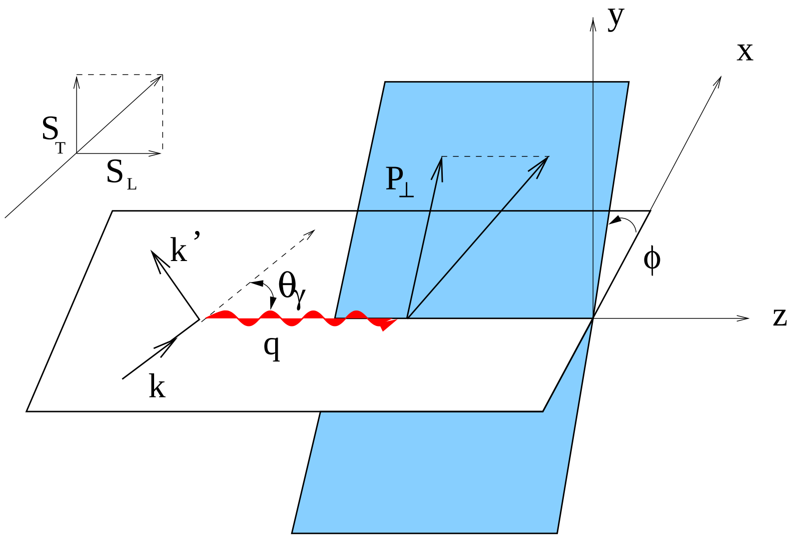


clear peak at missing mass $\approx \mathrm{M_n}$

position and width in agreement with MC based on GPD model for $\sigma_L(Q^2, x, t)$
Mankiewicz et al. Eur. Phys. J. C10 (1999), 307]

$\rightarrow$ **Problematic: difference in relative contribution of resonant and non-resonant channels to π^+, π^- yield**

Exclusive π^+ target - SSA



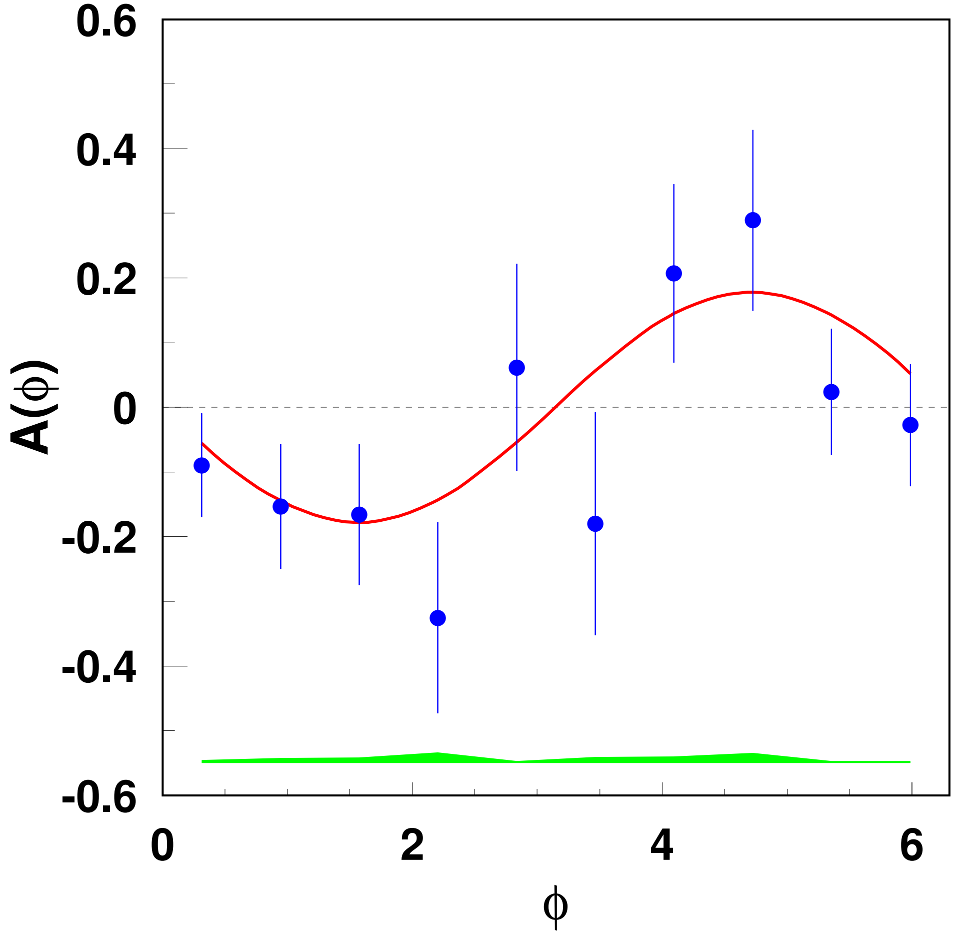
transverse component in γ^* frame:

$$\boxed{\sigma_S \sim [S_\perp \sigma_L + S_\parallel \sigma_{LT}] \cdot A_{UL}^{\sin\phi} \sin\phi}$$

σ_{LT} **suppressed by** $1/Q \cdots$ **but** $S_\parallel > S_\perp$

HERMES in 1997: $\boxed{S_\perp / S \sim 0.17}$

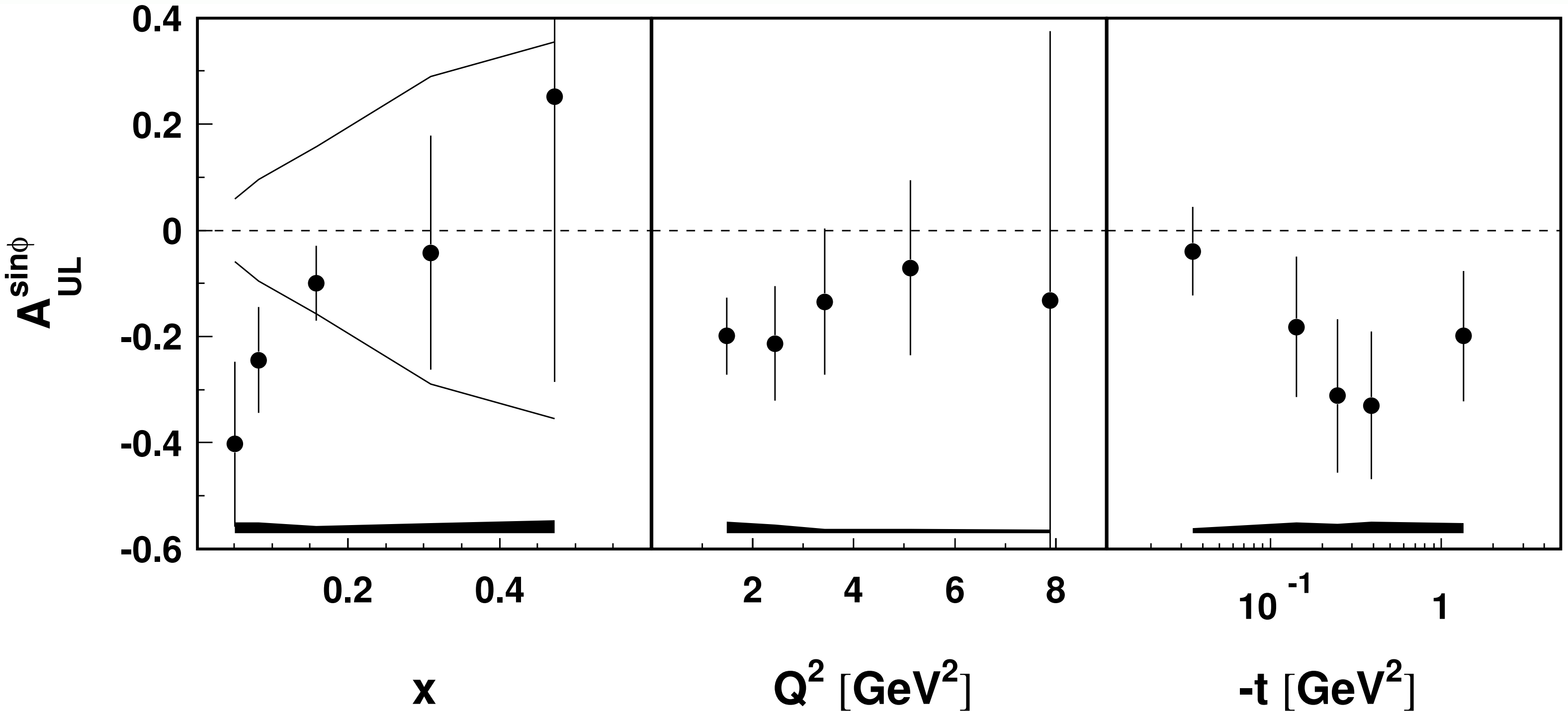
$$A_{UL}(\phi) = \frac{1}{\langle |P_t| \rangle} \cdot \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$



$$A_{UL}^{\sin\phi} = -0.18 \pm 0.05 \pm 0.02$$

[hep-ex/0112002]

Exclusive π^+ target - SSA II



$$\sigma_P \sim [S_\perp(x,Q^2)\sigma_L + S_\parallel(x,Q^2)\sigma_{LT}]$$

— lines indicate limits for any asymmetry from a transverse target component

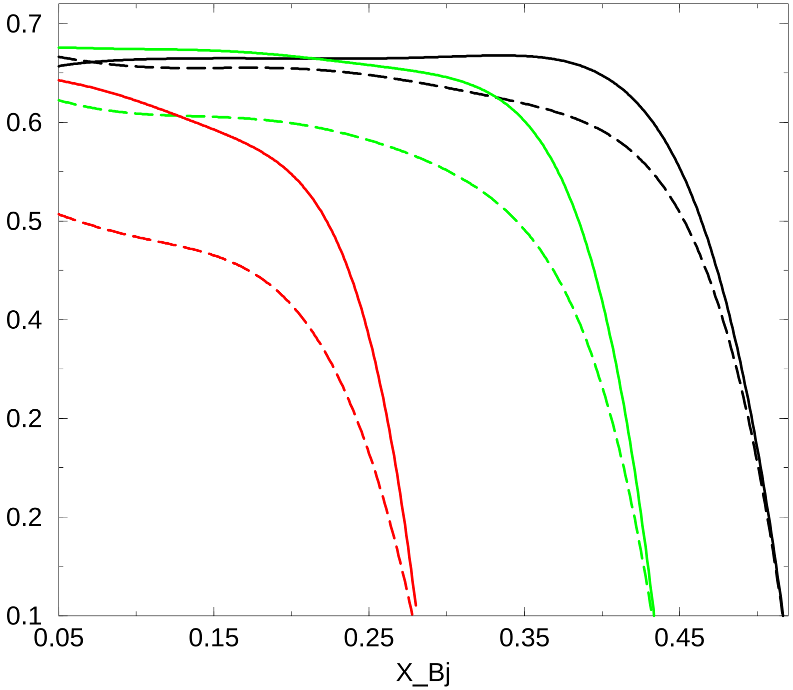
$\Rightarrow$ asymmetry at low x arises from longitudinal target component $S_\parallel$

HERMES run II transverse target

large transverse π^+ SSA expected
$\longrightarrow$ due to interference between pole and non-pole amplitudes:

$$\sigma \propto |S_{\mathrm{T}}| \sin\phi \; \tilde{E} \cdot \tilde{H}$$

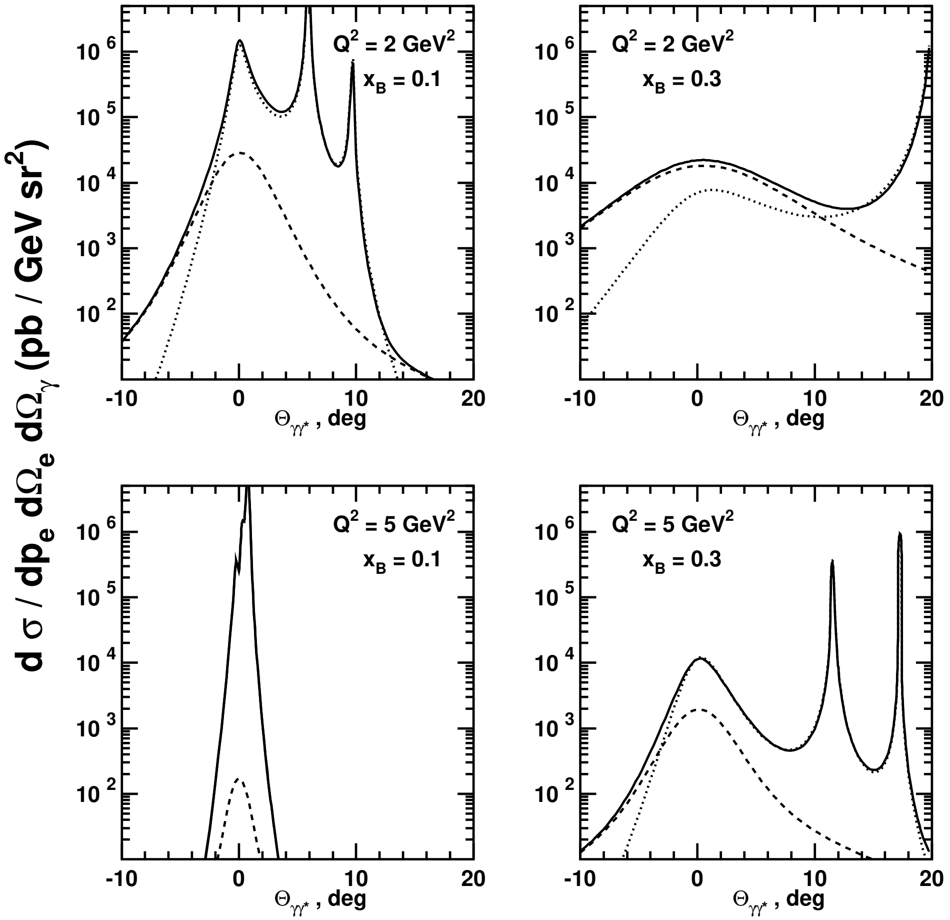
transverse spin asymmetry

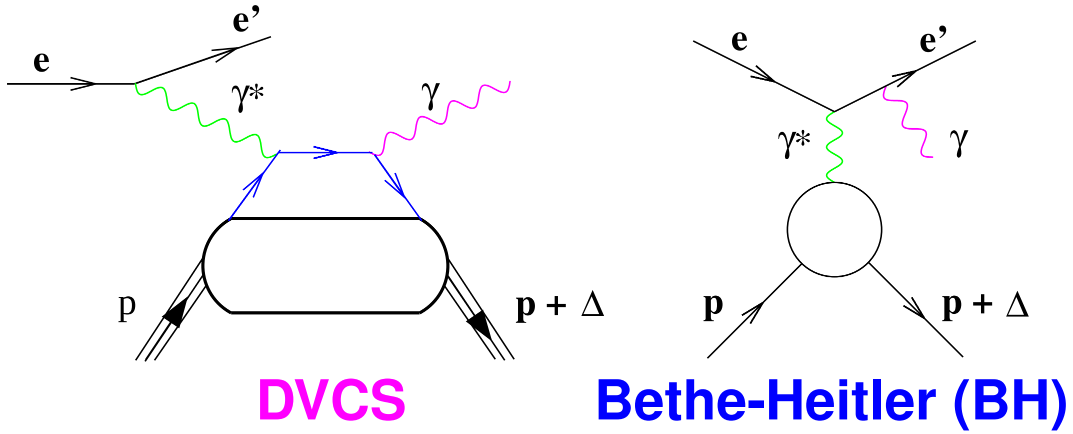


size of asymmetry depends on pion FF.:
1- asymptotic pion distribution amplitude
2- Chernyak-Zhitnitsky pion DA
for t = -0.1, -0.3, -0.5

[Frankfurt,Pobylitsa,Polyakov,Strikman PRD60(1999),014010]

HERMES kinematics:
BH process larger than DVCS





$$d\sigma \quad \propto \quad |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2$$
$$+ \quad (\mathcal{T}^*_{BH}\mathcal{T}_{DVCS} + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH})$$

DVCS-BH interference:

$\longrightarrow$ **use BH as a vehicle to study DVCS**

[Korotkov, Nowak, hep-ph/0108077]

DVCS azimuthal asymmetries

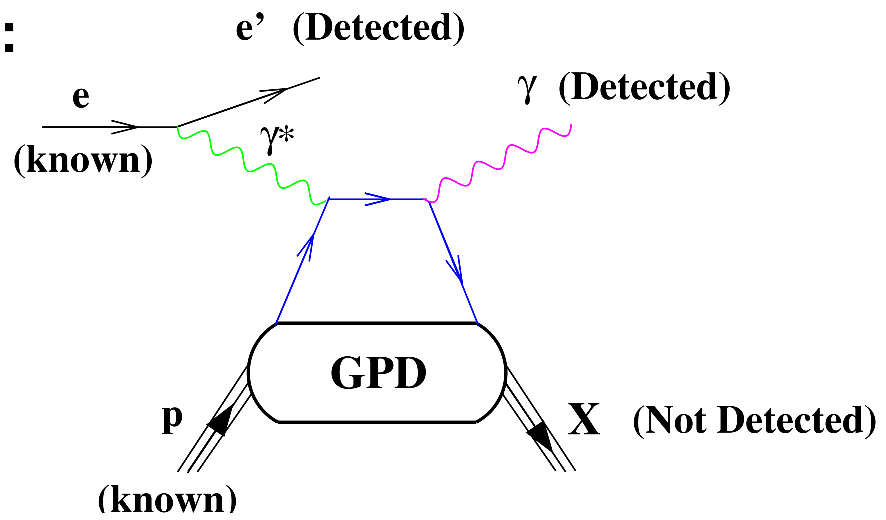
isolate BH-DVCS interference term:

- **imaginary part $\propto$ beam helicity asymmetry:**

$$d\sigma_{\overleftarrow{e^+}} - d\sigma_{\overrightarrow{e^+}} \propto \mathrm{Im}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS}) \propto \sin\phi$$

- **real part $\propto$ beam charge asymmetry:**

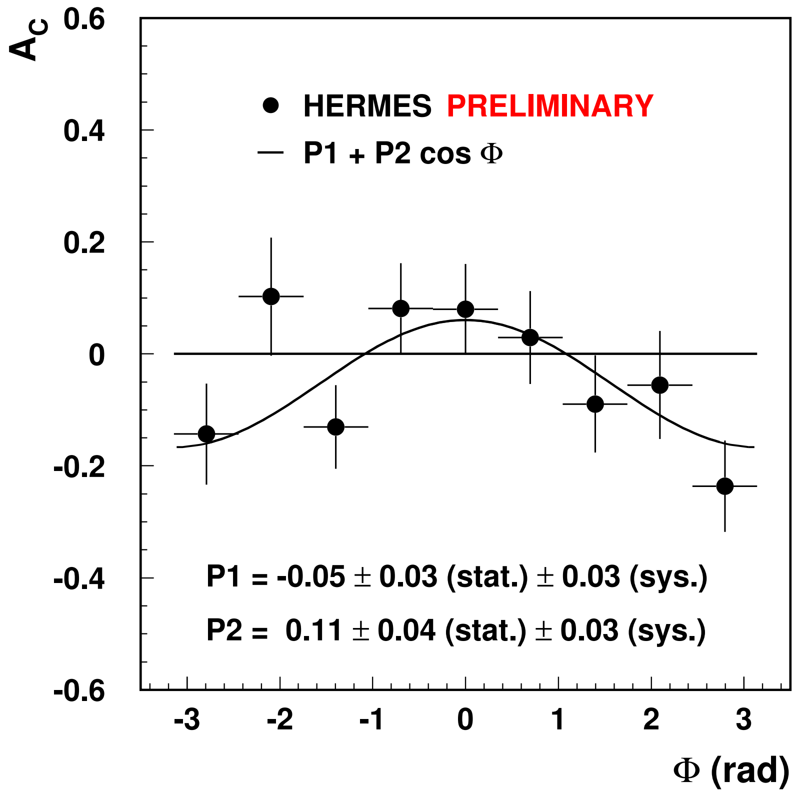
$$d\sigma_{e^+} - d\sigma_{e^-} \propto \mathrm{Re}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS}) \propto \cos\phi$$

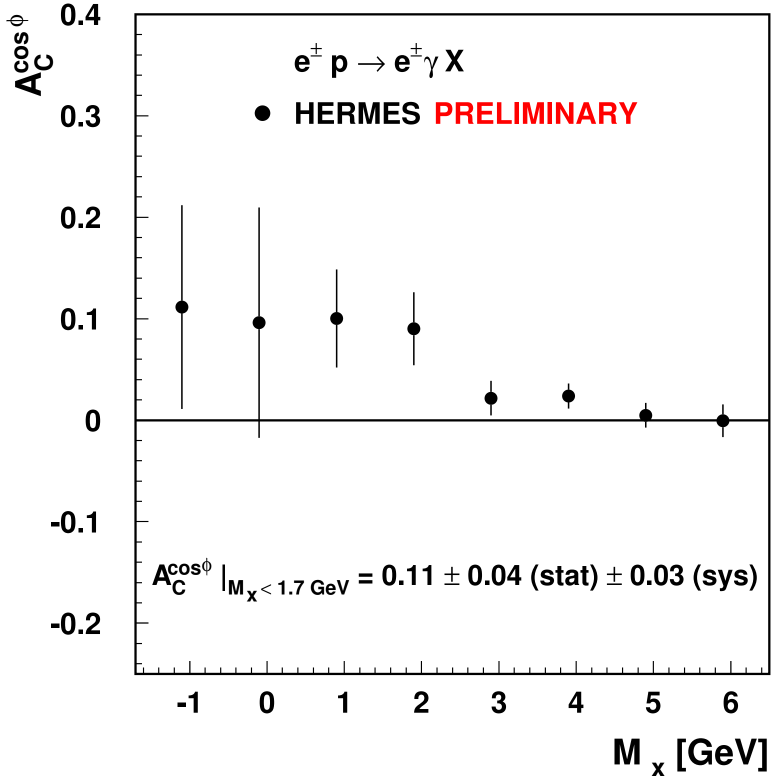


$\Rightarrow$ **both asymmetries measured by HERMES**

ϕ: azimuthal angle between lepton scattering plane and the $\gamma^*\gamma$ - plane

DVCS beam charge asymmetry (BCA)





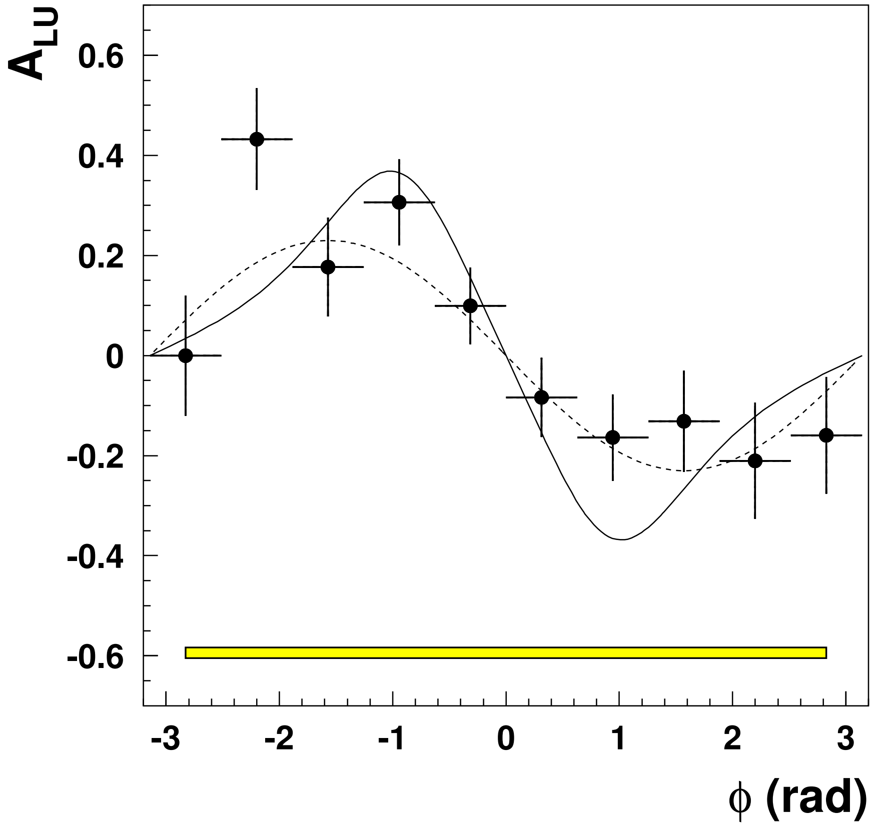
$$A_C(\phi) = \frac{N_{e^+}(\phi) - N_{e^-}(\phi)}{N_{e^+}(\phi) + N_{e^-}(\phi)}$$

$$A_C^{cos\phi} = \frac{1}{N^{e+}} \sum_{i=1}^{N^{e+}} cos(\phi_i) - \frac{1}{N^{e-}} \sum_{i=1}^{N^{e-}} cos(\phi_i)$$

exclusive region: -1.5 < M_x < 1.7 GeV

DVCS single beam-spin asymmetry (SSA)

exclusive region: -1.5 $<$ M$_x$ $<$ 1.7 GeV



$$A_{LU}(\phi) = \frac{1}{\langle|P_l|\rangle} \cdot \frac{N^+(\phi)-N^-(\phi)}{N^+(\phi)+N^-(\phi)}$$

$$A_{LU}^{\sin\phi}(\phi) = -0.23 \pm 0.04 \pm 0.03$$

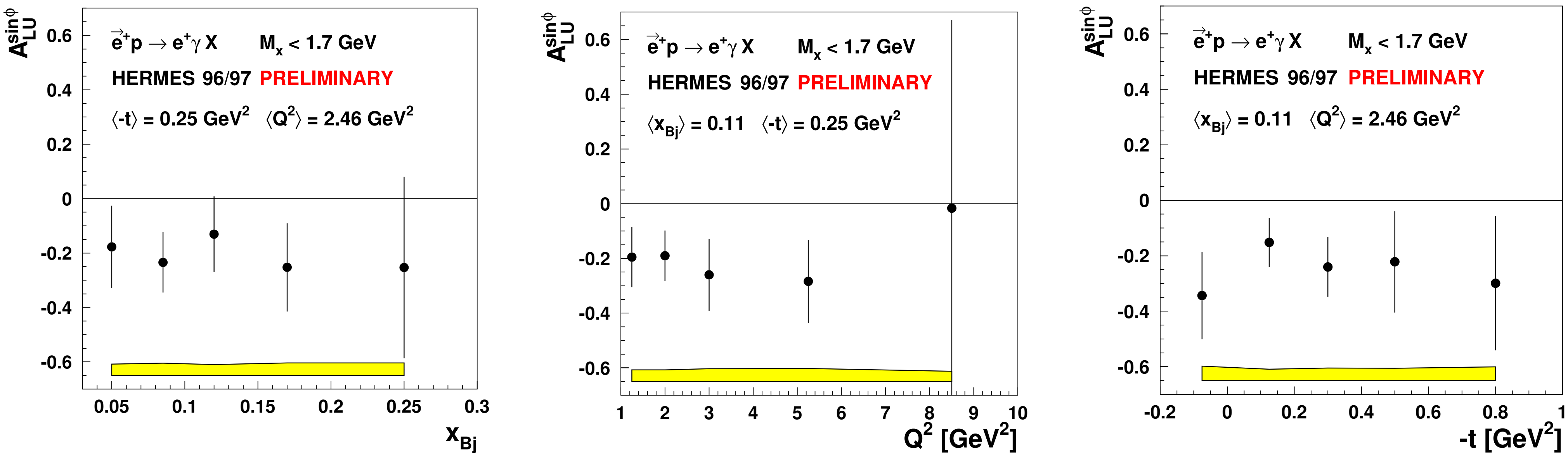
at $\langle x \rangle = 0.11$ $\langle Q^2 \rangle = 2.5$ **GeV**^{2} $\langle -t \rangle = 0.27$ **GeV**^{2}

— **GPD based calculation including twist-3 contributions**

[Kivel et al. Phys. Rev. D 63 (2001), 114014]

[Phys. Rev. Lett. 87 (2001), 182001]

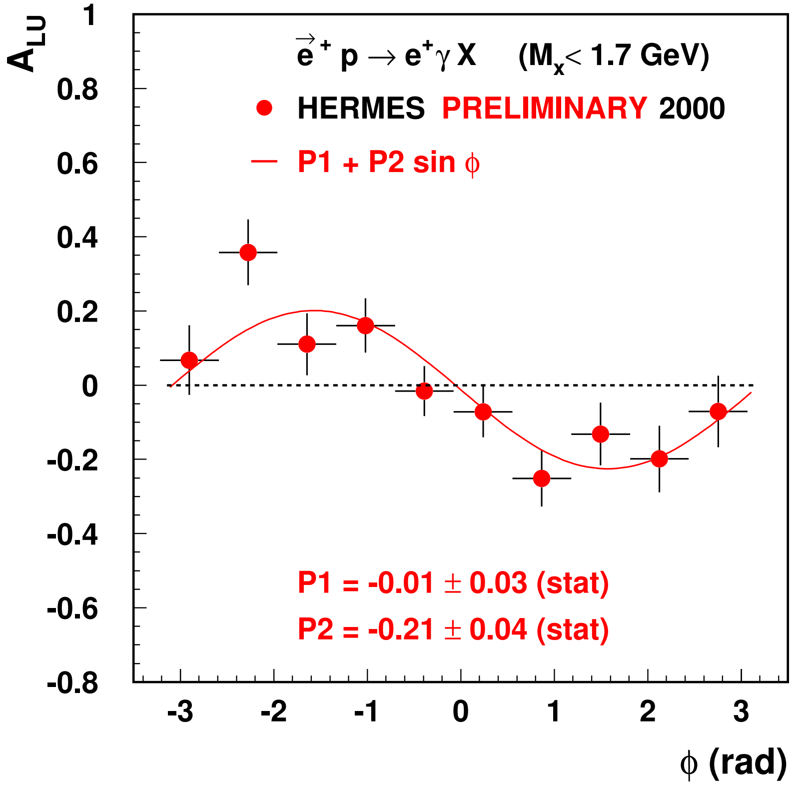
DVCS SSA kinematic dependences

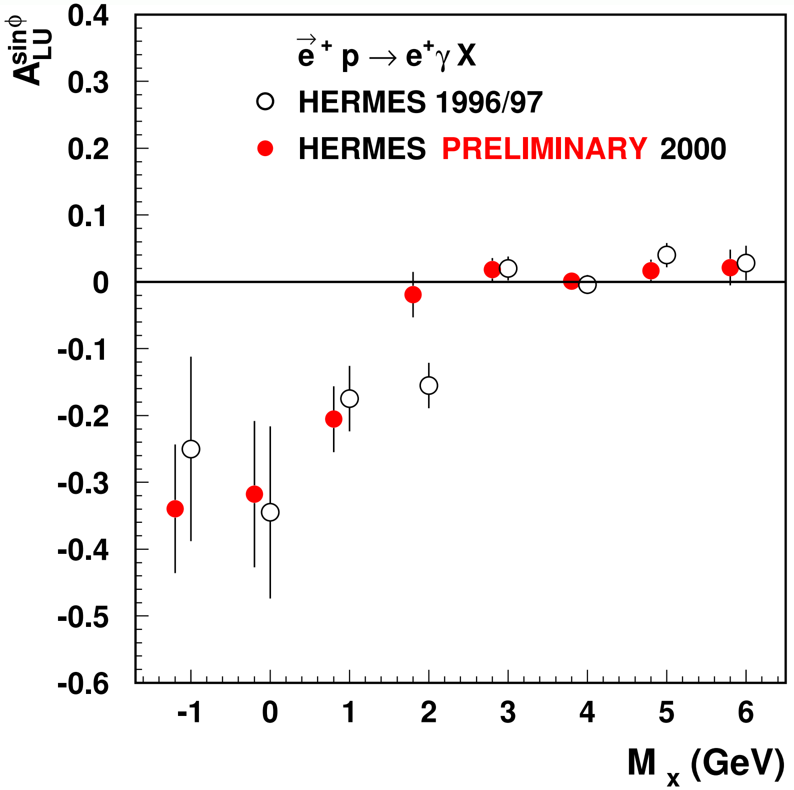


dependences on x, Q^2, and $-t$ consistent with a MC simulation based on a twist-2 GPD model

[Guichon, Guidal, Vanderhaegen, Phys. Rev. D 60 (1999), 094017]

DVCS ongoing analysis 2000 data



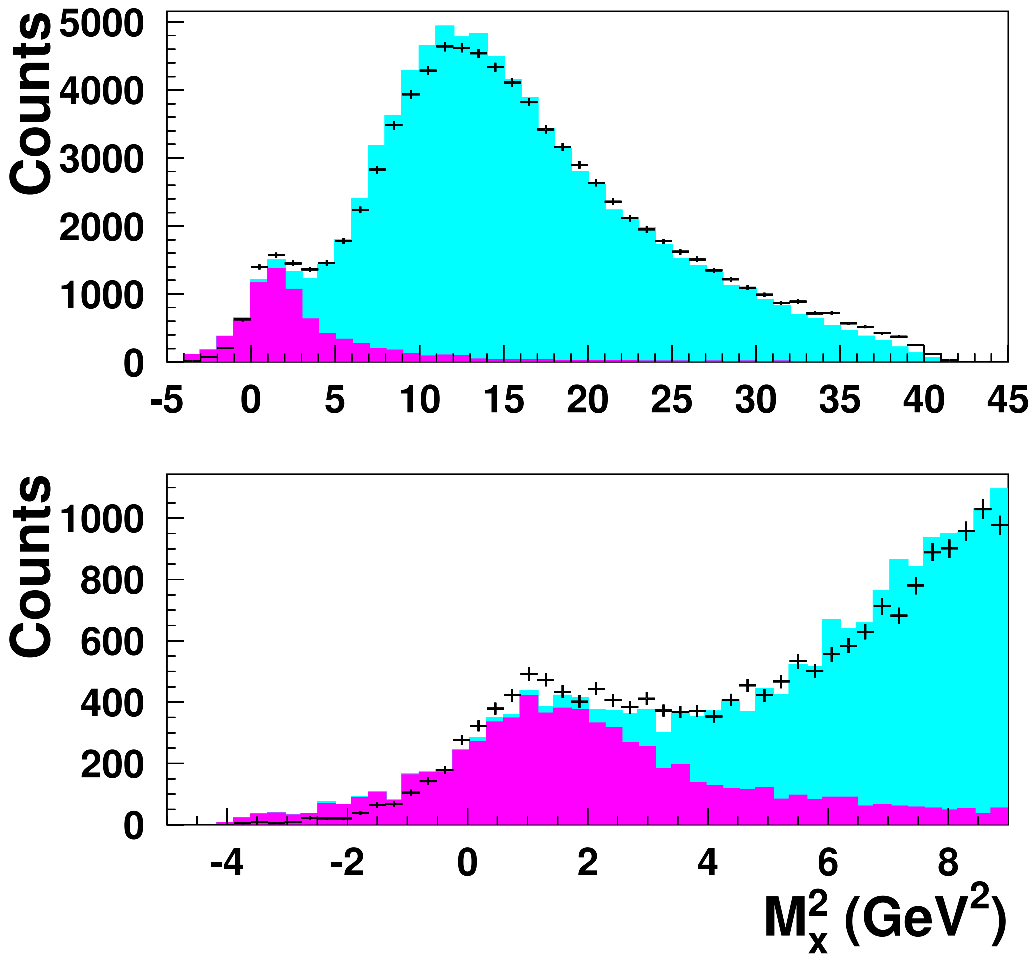


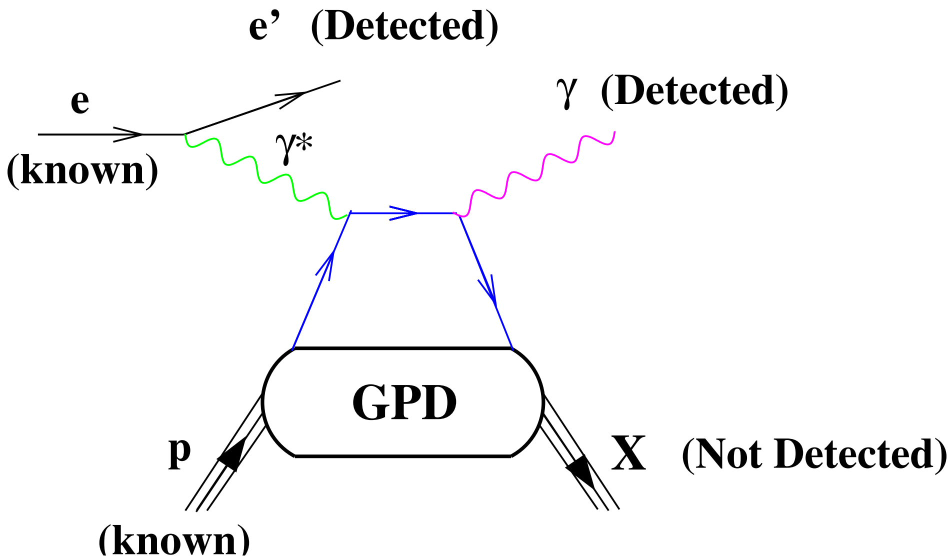
$\longrightarrow$ combine 96/97 + 2000 hydrogen data set

$\longrightarrow$ SSA from 2000 Deuterium and Neon data

$\longrightarrow$ target-spin asymmetry from 96/97 hydrogen and 2000 deuterium

$\longrightarrow$ take more data with different targets 2002 - 2004





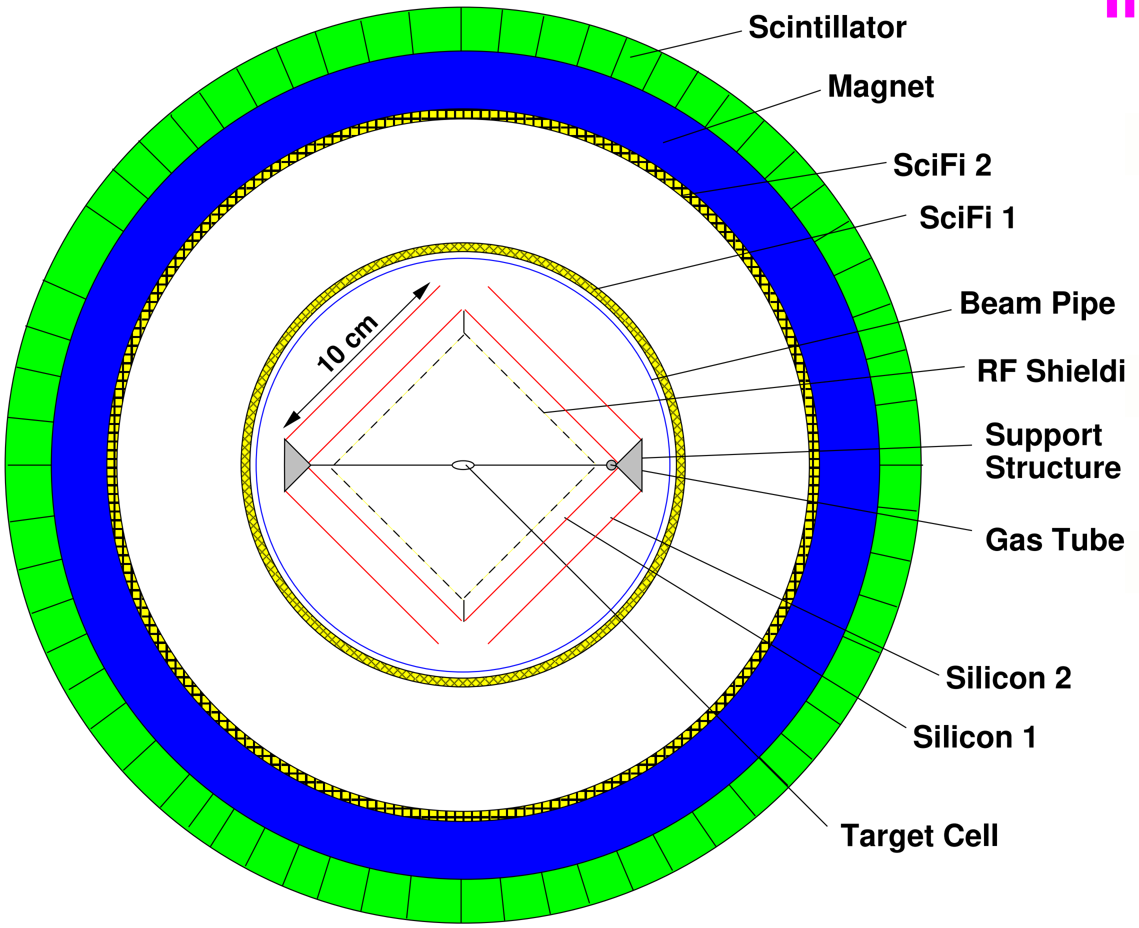
Energy resolution in exclusive region:

$$\mathbf{M}_\mathrm{x}^2 = (q + p - p_\gamma)^2 = M_p^2$$

$$\longrightarrow \sigma(\mathrm{M_x}) \approx \mathbf{0.8\ GeV}$$

Improve Exclusivity: detect recoil proton

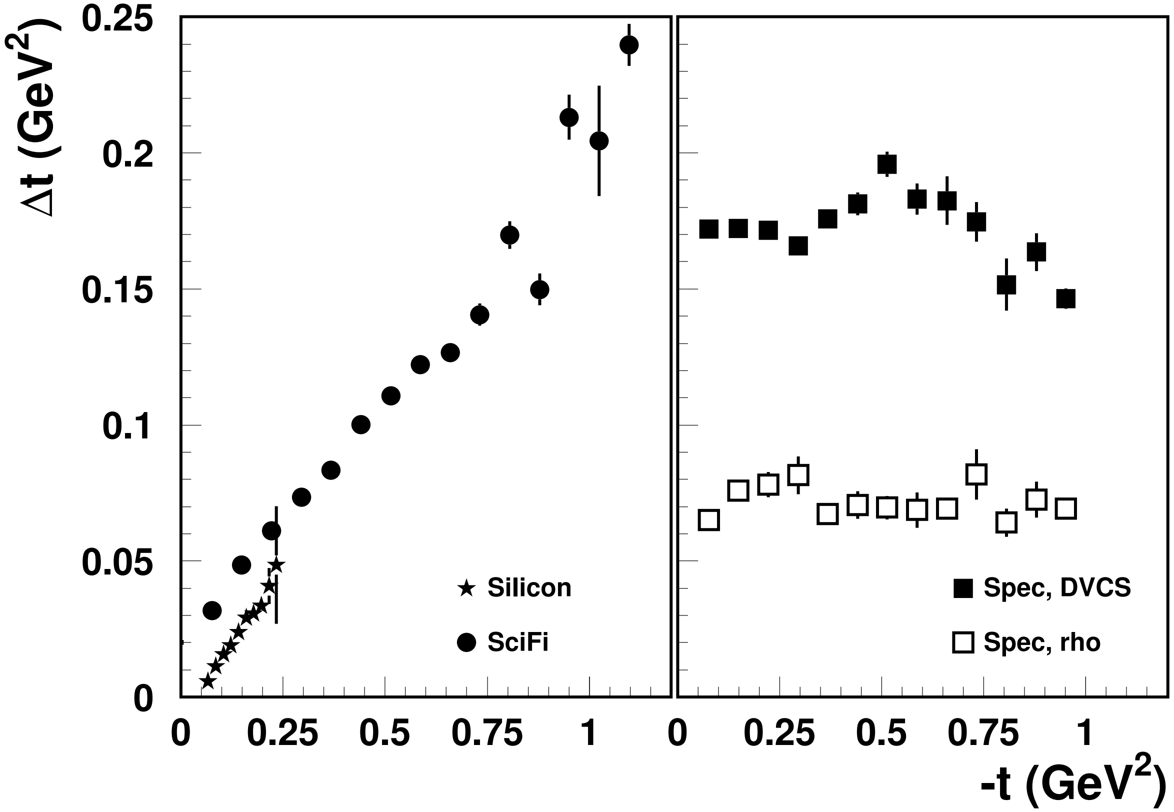
HERMES run II upgrade: recoil detector



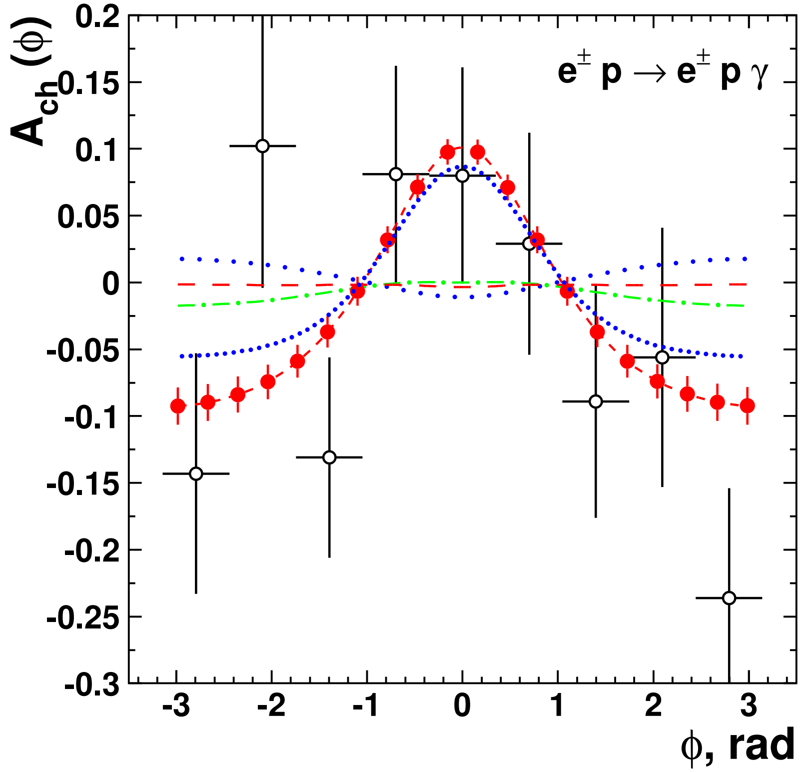
Improvements

- detection of the recoiling proton
  $\rightarrow$ improved exclusivity
  $\rightarrow$ suppress Δ contribution
- improve t-resolution
  $\rightarrow$ study kinematical dependences
- run with unpol. target
  $\rightarrow$ 2 fb^{-1} per year of data taking

HERMES run II upgrade: recoil detector II



Expected t-resolution



Expected statistical accuracy for 2 fb^{-1}

Summary

- **2002/2003 transverse polarized proton running**
  - $\longrightarrow$ **first measurement of δu**
  - $\longrightarrow$ **exclusive $\pi^+\pi^0$ and VM - production**
    - $\longrightarrow$ **Input for GPDs**
- **2004 longitudinal polarized proton running**
  - $\longrightarrow$ **improve statistical accuracy of Δq**
- **2002 - 2004:**
  - $+$ **longitudinal polarized and helicity balanced beam**
  - $+$ **different beam charges**
  - $+$ **Running with unpolarized targets**
  - $\longrightarrow$ **Measurements of : g_2, DVCS, Λ-polarization, Fragmentation F., ...**
- **2005/2006 Running with the Recoil Detector and unpolarized targets**
  - $\longrightarrow$ **DVCS and exclusive $\pi^+\pi^-\pi^0$ and VM - production**