Exclusive Photon and Meson Production at HERMES

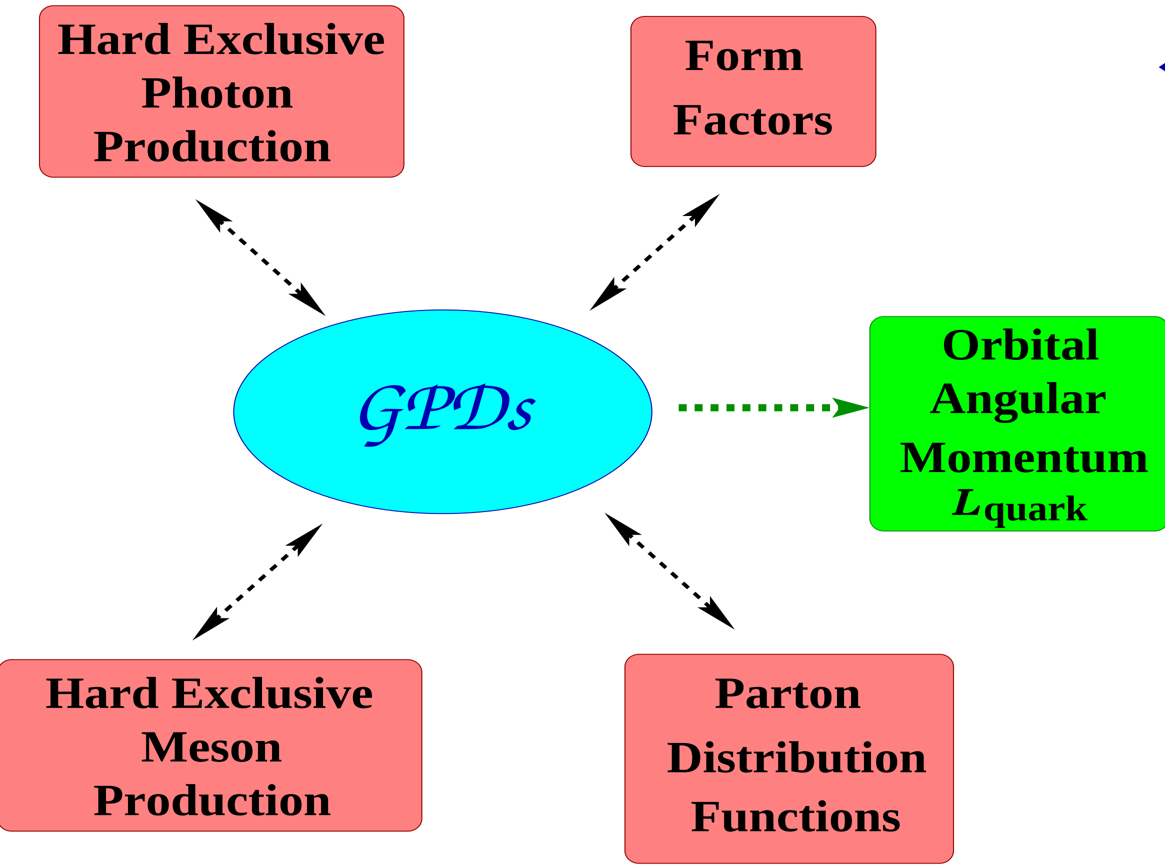
Riccardo Fabbri

on behalf of the *HERMES* Collaboration

EDS 2007 **_DESY_, 22 May 2007**

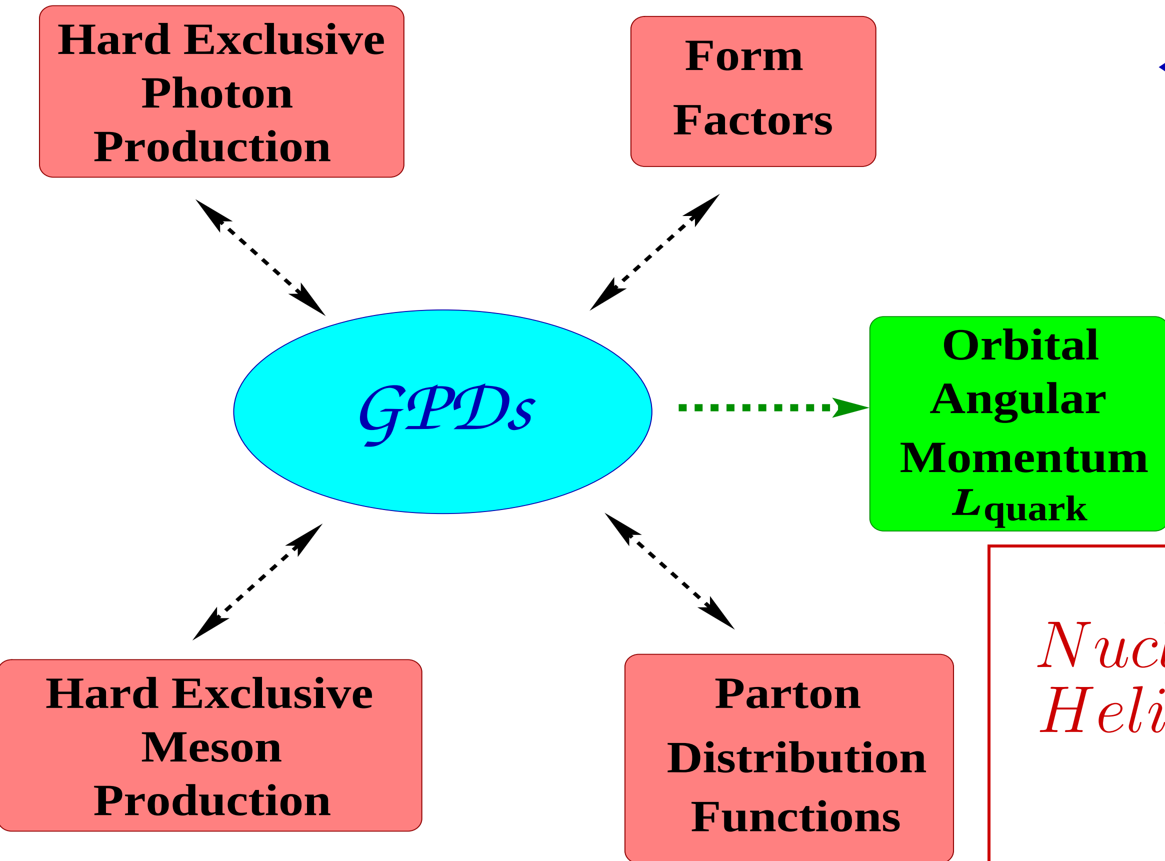
- **Exclusive Reactions and GPDs**
- **The HERMES Experiment**
- **Exclusive Photon Production (DVCS)**
- **Exclusive Meson Production**
- **Summary and Outlook**

Exclusive Reactions & GPDs



- GPDs offer most complete description of quark-gluon structure of hadrons

Exclusive Reactions & GPDs



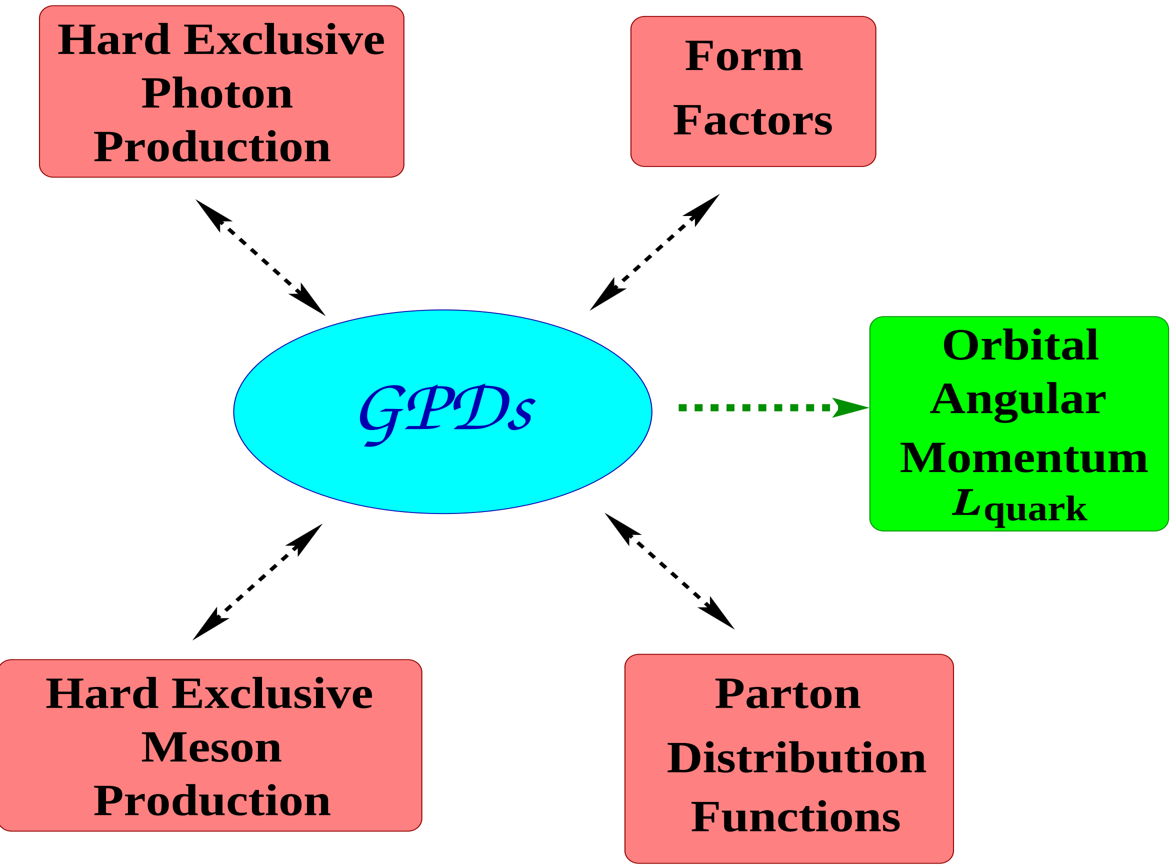
- GPDs offer most complete description of quark-gluon structure of hadrons

$$\mathit{Nucleon\ Helicity} = \underbrace{\frac{1}{2} \cdot \overbrace{\Delta\Sigma}^{30\%} + \overbrace{L_q}^{?}}_{J_q} + \overbrace{J_g}^{?}$$

Ji sum rule:

$$J_q = \lim_{t \to 0} \int_{-1}^{+1} x dx \left[H_q(x, \xi, t) + E_q(x, \xi, t) \right]$$

Exclusive Reactions & GPDs



- **Hard Exclusive Processes interpreted in GPD framework!**

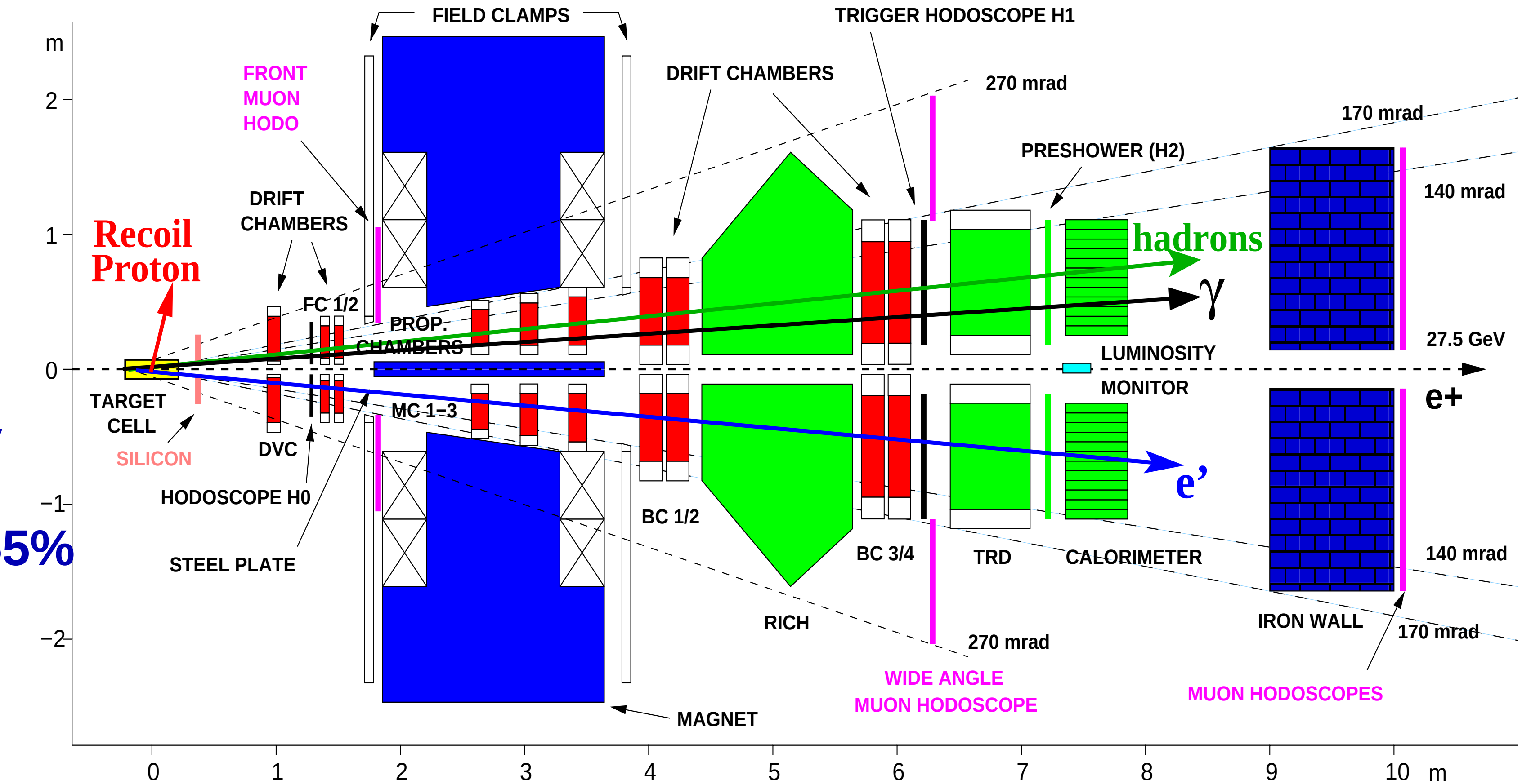
large Q^2, small t

The HERMES Experiment at DESY

$\vec{e}^{+}/\vec{e}^{-}$

27.6 GeV

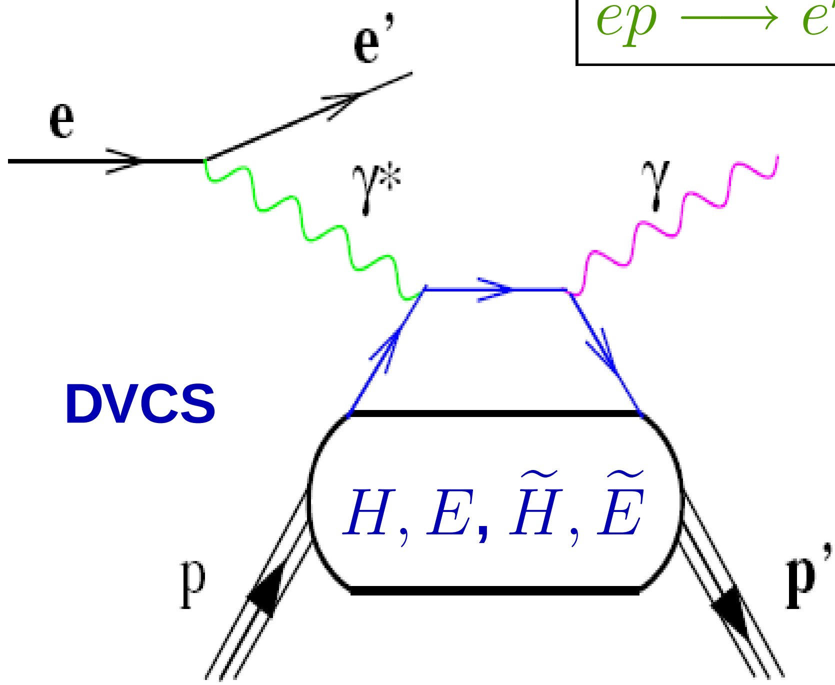
$P_b \approx$ **35-55%**



- **Gas storage target cell: Polarized/Unpolarized gas.** $P_T \approx$ **88-97%**
- **Forward spectrometer:** $40\ mrad < \theta < 220\ mrad$
- **Tracking chambers:** $\Longrightarrow \delta p/p \approx 2\%, \delta\theta \leq 1\ mrad$
- **PIDs:** e/h **separation efficiency** $> 98\%, \pi^{\pm}/K^{\pm}/p$ **ID:** $2 < p < 15$ **GeV**

Deeply Virtual Compton Scattering

$$ep \longrightarrow e'p'\gamma$$



- In principle, $H, E, \widetilde{H}, \widetilde{E}$ all participate in describing the target
- Final photon observables directly interpreted in terms of four $GPDs$

Deeply Virtual Compton Scattering

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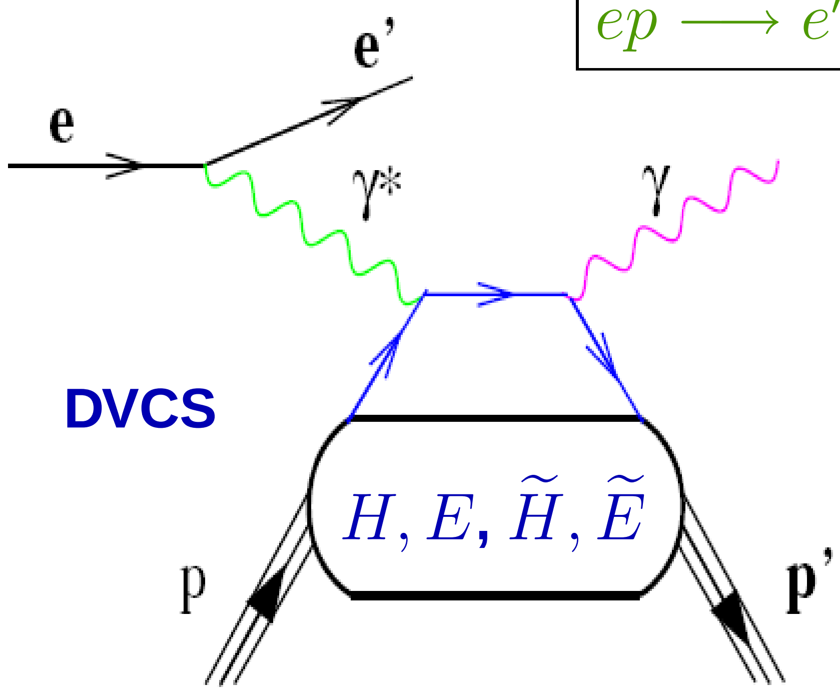
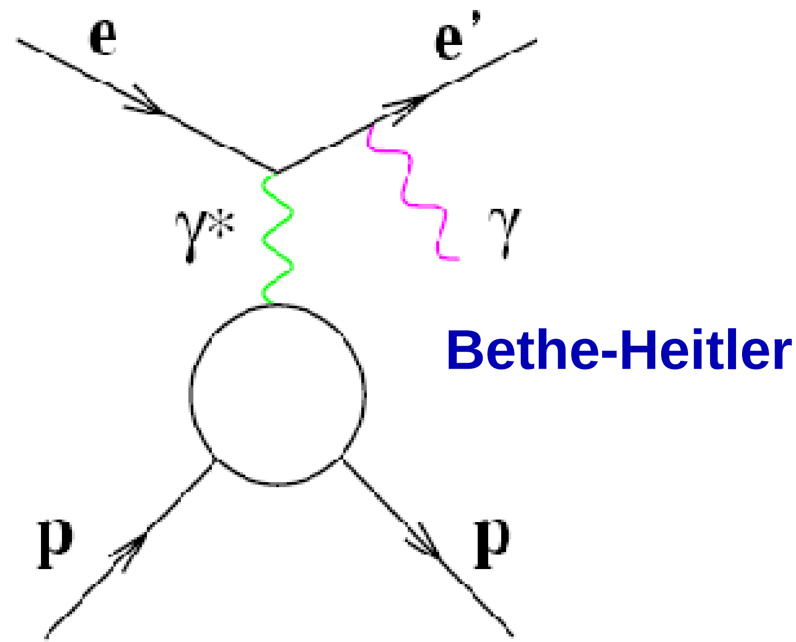


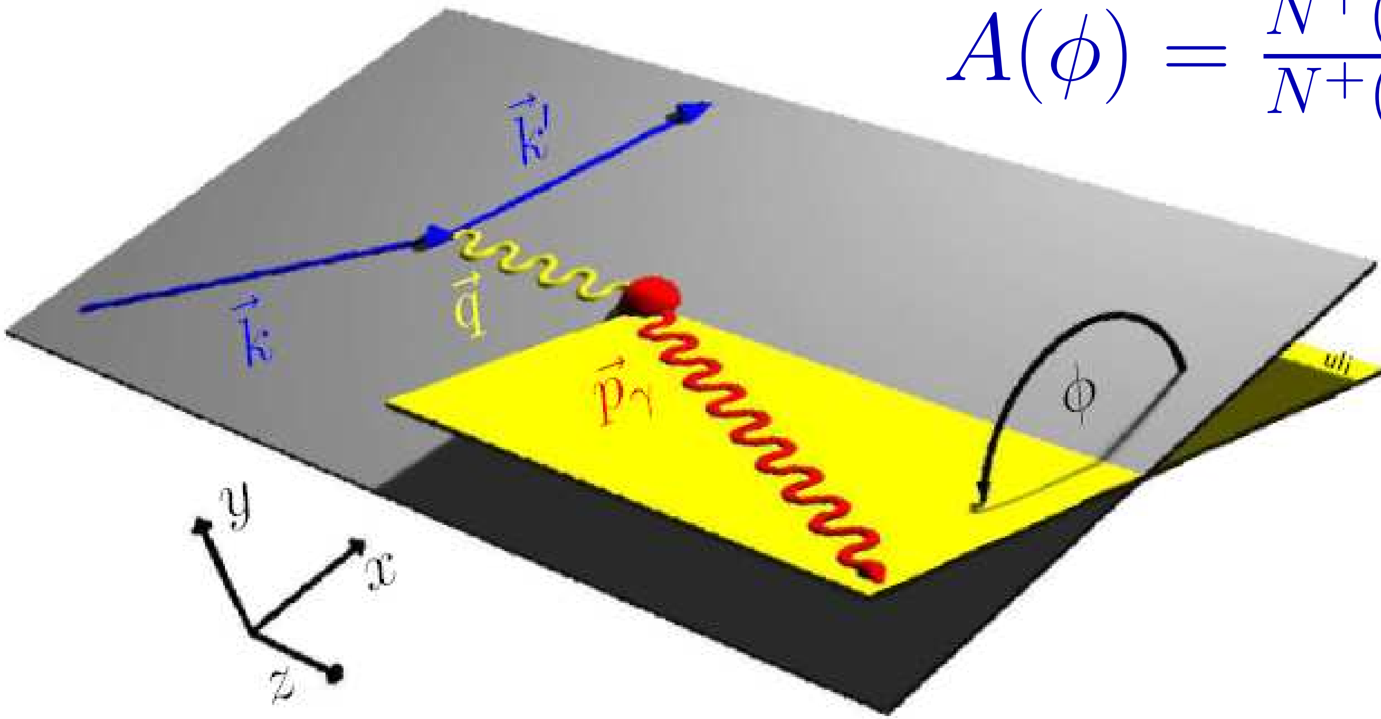


$$d\sigma \propto | A_{DVCS} |^2 + | A_{BH} |^2 + | A^\star_{DVCS} A_{BH} + A_{DVCS} A^\star_{BH} |^2$$

- **At HERMES kinematics BH contribution dominates**
- **DVCS-BH interference gives rise to non-zero azymuthal asymmetry**

  $\Longrightarrow$ **still possible to access quark information**

Deeply Virtual Compton Scattering



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

❖ **Choosing specific Beam/Target polarization asymmetries:**

$\Longrightarrow$ **gives access to different combinations of GPDs**

❖ **HERMES kinematics:** $\langle x_{Bj} \rangle \approx 0.1, \langle -t \rangle \approx 0.1$

$\Longrightarrow$ **inside the selected combination, certain GPDs suppressed**

DVCS: Asymmetries

- **Beam-charge asymmetry** $A_C(\phi)$ **(BCA):**

  $d\sigma(e^+;\phi) - d\sigma(e^-;\phi) \propto Re[\mathcal{H}] \cdot \cos(\phi)$

- **Beam-spin asymmetry** $A_{LU}(\phi)$ **(BSA):**

  $d\sigma(\overrightarrow{e};\phi) - d\sigma(\overleftarrow{e};\phi) \propto Im[\mathcal{H}] \cdot \sin(\phi)$

- **Longitudinal target-spin asymmetry** $A_{UL}(\phi)$ **(LTSA):**

  $d\sigma(\overset{\Rightarrow}{P};\phi) - d\sigma(\overset{\Leftarrow}{P};\phi) \propto Im[\widetilde{\mathcal{H}}] \cdot \sin(\phi)$

- **Observables sensitive to convolution of GPDs**

  with hard-scattering kernel (as for others hard exclusive processes):

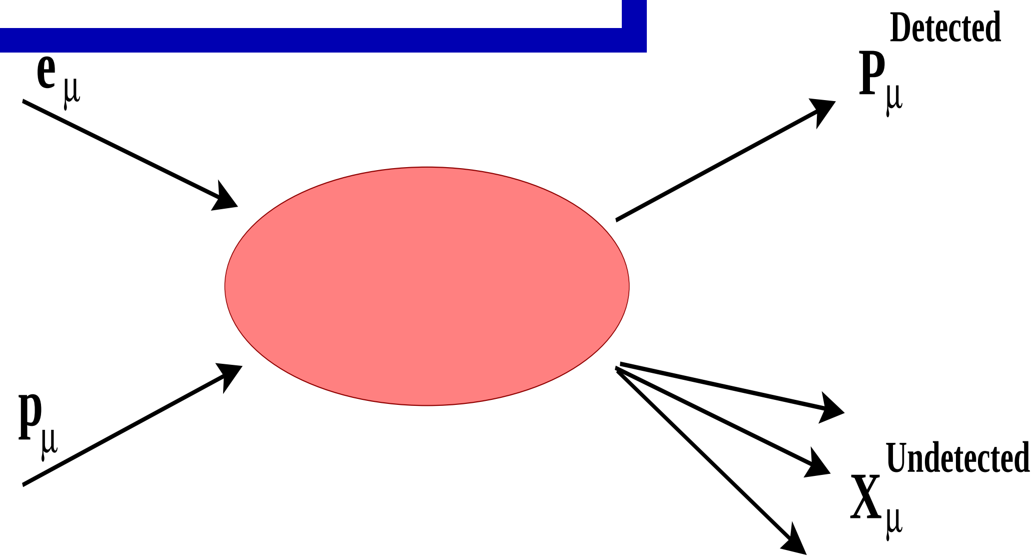
  - $H, E, \widetilde{H}, \widetilde{E} \longrightarrow \mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}$

(For simplicity: $F_1 \& F_2$ **FF from BH amplitude not shown)**

Background Subtraction

- Recoiling nucleon not detected
- Exclusive events selected via "missing mass" technique:

$$M_X^2 = (e_\mu + p_\mu - P_\mu^{detected})^2$$



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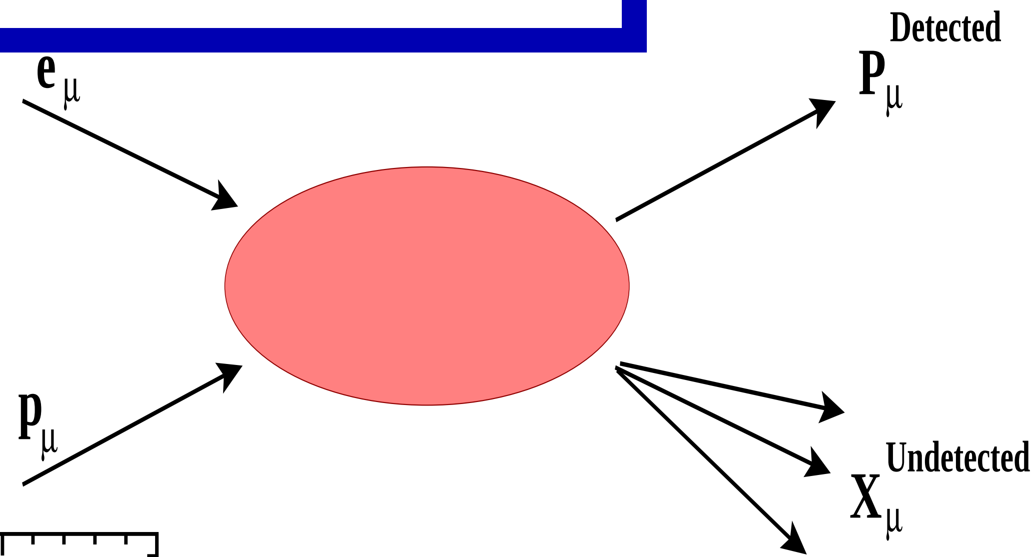
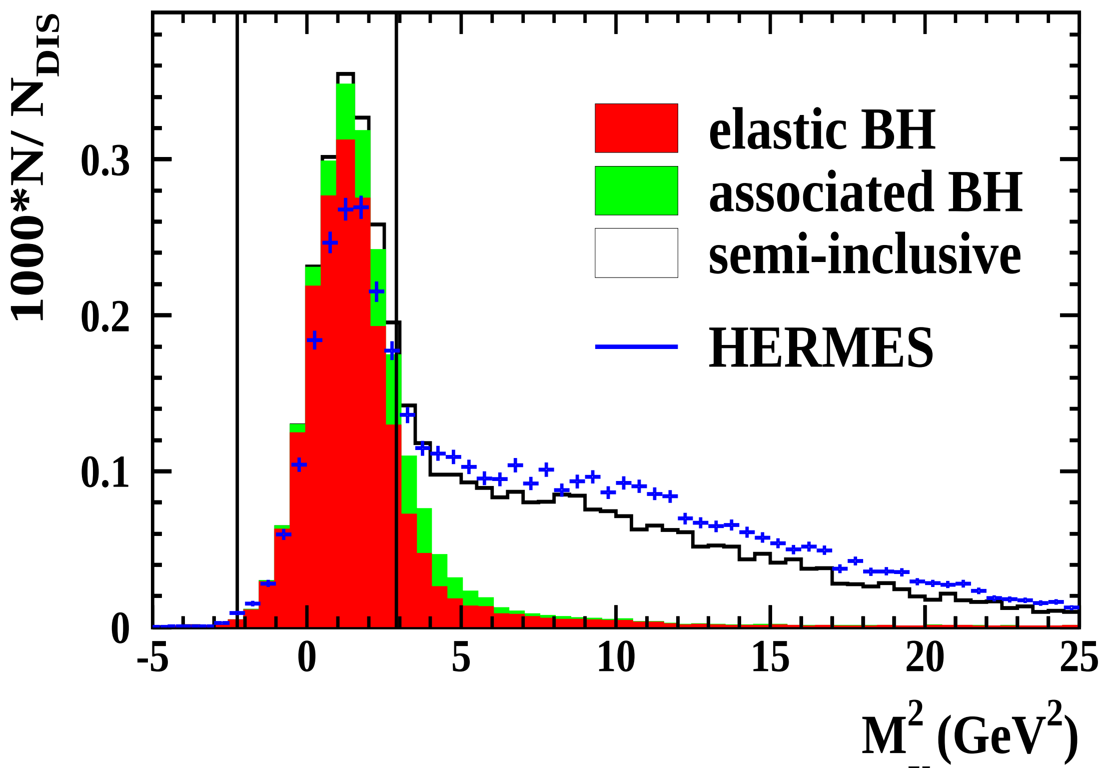
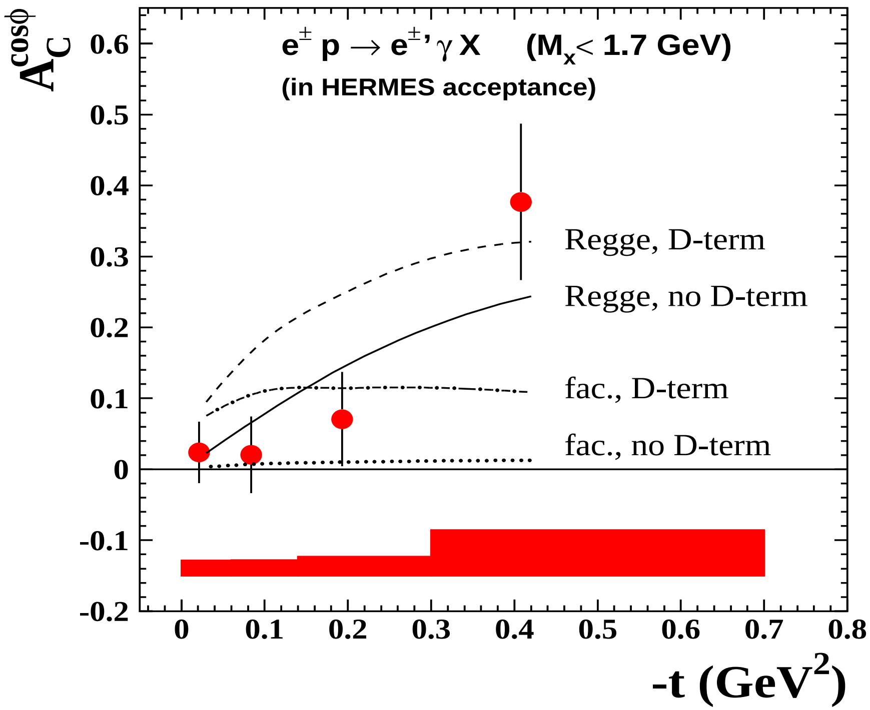




- Bg contamination estimated with non-exclusive MC (and data)

DVCS: sensitivity to $\mathcal{H}$ via BCA

- **BCA:** $A_C(\phi) \propto Re[\mathcal{H}] \cdot \cos(\phi)$



- **GPD calculations for H**
  [Vanderhaegen et. al. (1999)]
- **Different ways to model GPDs in non-forward region**
  D-term: included OR not-included
- **t-dependence:**
  Regge-inspired OR factorized (e.g. $F(t,x,\xi) = g(t) \cdot h(x,\xi)$)

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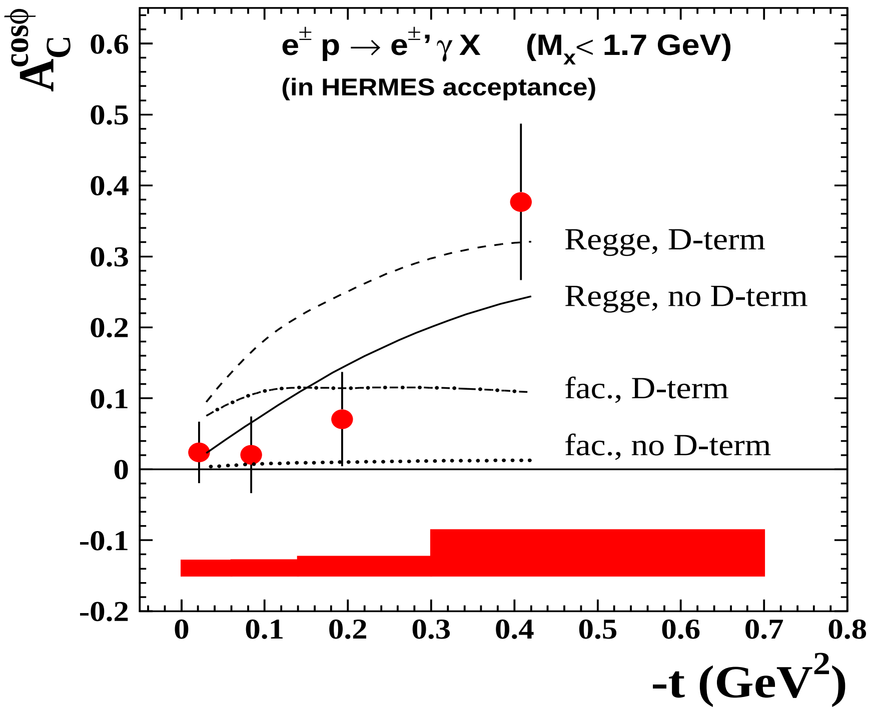

- **Unique measurement:**
  First kinematical dependence of DVCS
- **On publishing**
- **Analyzed data set: 1998/2000**
- **Additional data are being analyzed**

- **GPD calculations for H**
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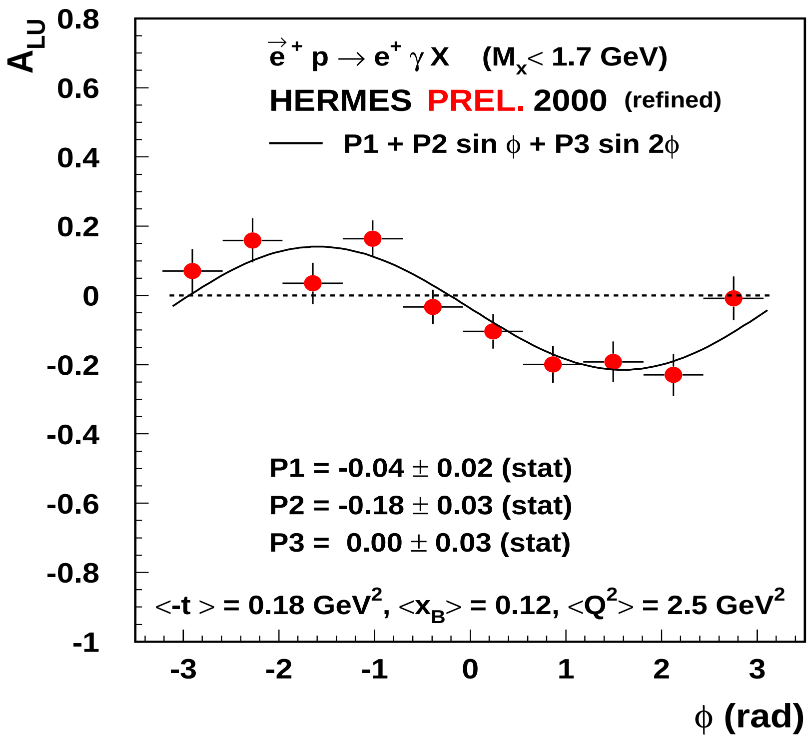

- **Non-zero** $\sin\phi$ **moment:**

...a $Im[\mathcal{H}]$ **signature**

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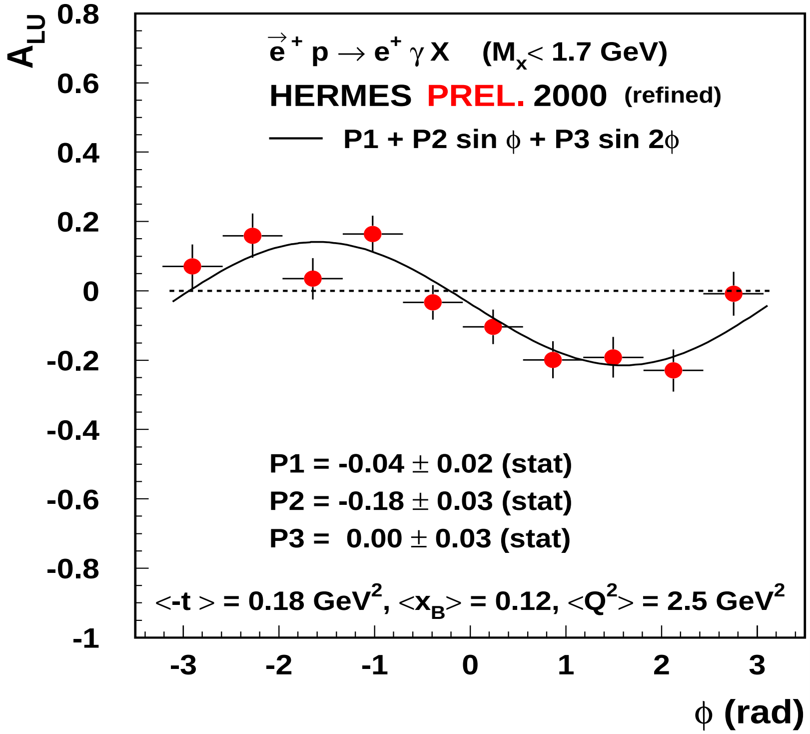
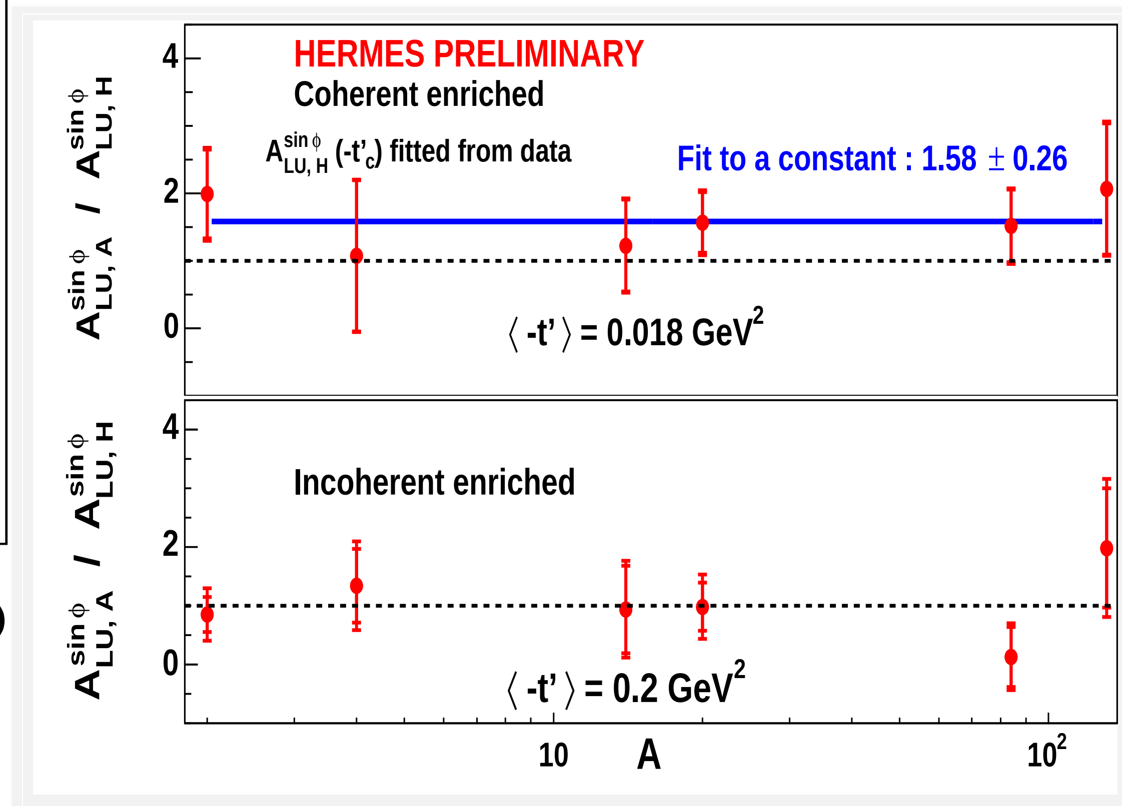


❖ **Non-zero** $\sin\phi$ **moment:**

...a $Im[\mathcal{H}]$ **signature**

❖ **Versatility of HERMES target:**

BSA off nuclei: H, D, He, N, Ne, Kr, Xe



❖ **In coherent region, ratio off unity:**

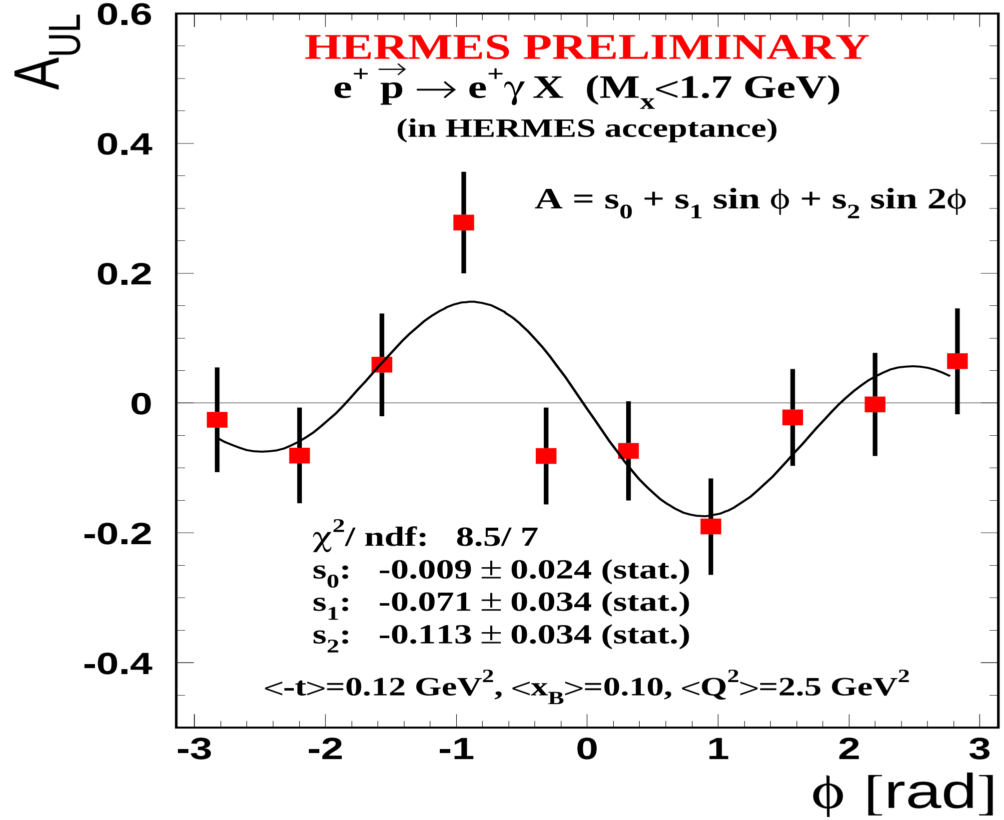
qualitatively in agreement with

Phys. Rev. C68 (2003) 015204

DVCS: sensitivity to $\widetilde{\mathcal{H}}$ via LTSA

- **LTSA:** $A_{UL}(\phi) \propto Im[\widetilde{\mathcal{H}}] \cdot \sin(\phi)$

- **Final statistics of H and D**



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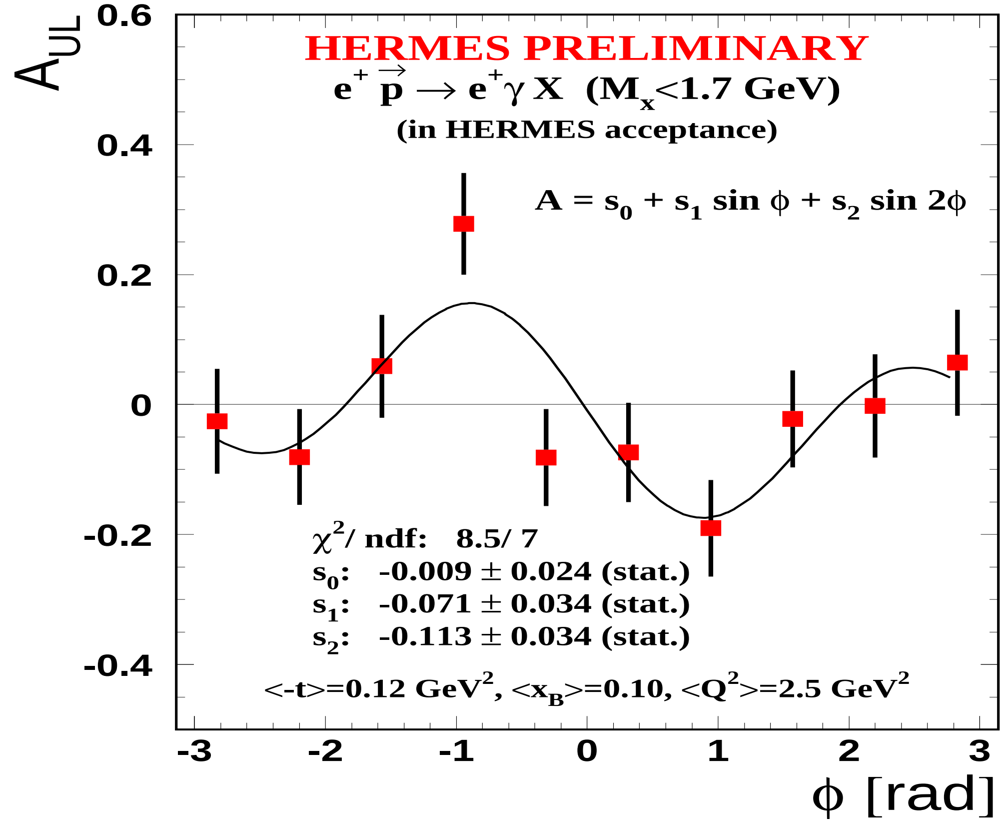


- **Final statistics of H and D**

- **expected $\sin\phi$ behaviour**

- **unexpected $\sin 2\phi$ moment**

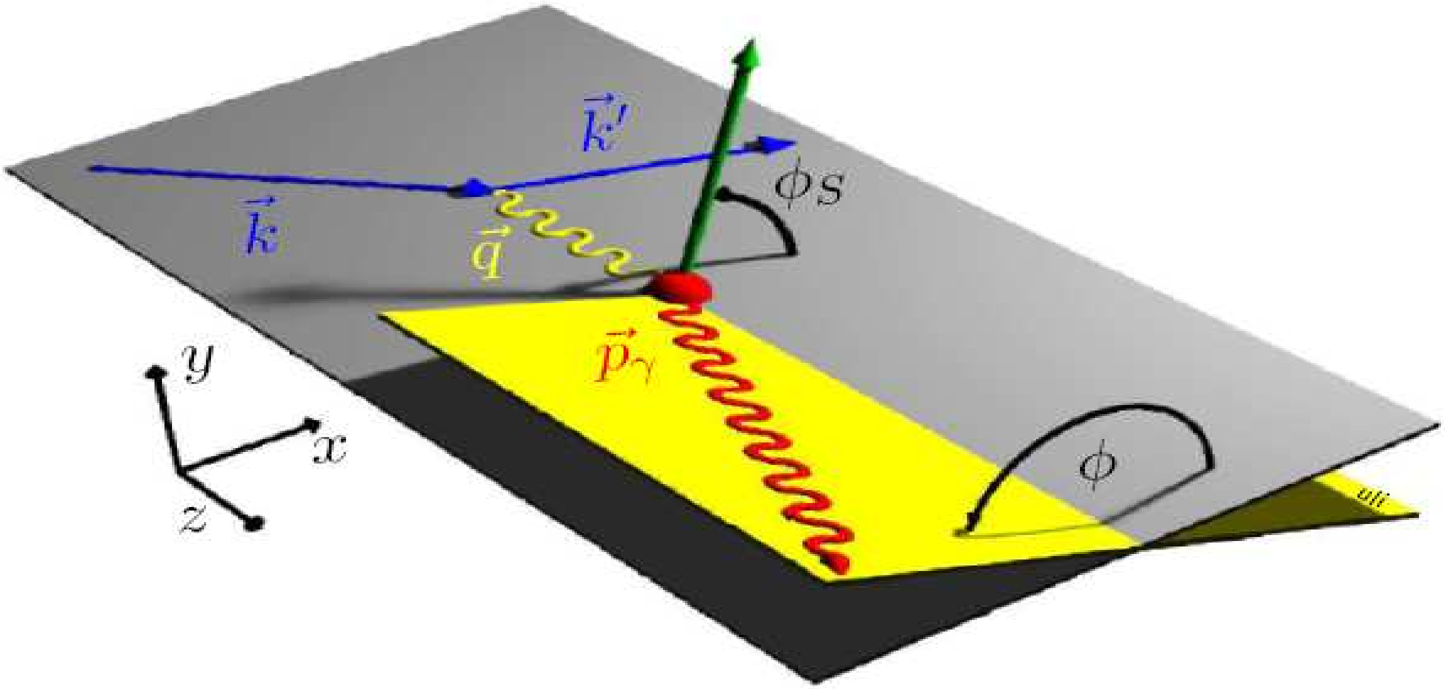
  $\Longrightarrow > 3\sigma$ (1.7σ) **on proton (deuteron)**

  Twist-3 effect?

DVCS: sensitivity to $\mathcal{E}, \mathcal{H}, \widetilde{\mathcal{H}}$ via TTSA

- **Sofar, measured asymmetries insensitive to GPD E, and $\widetilde{E}$ suppressed by HERMES kinematics!**

DVCS: sensitivity to $\mathcal{E}, \mathcal{H}, \widetilde{\mathcal{H}}$ via TTSA



- **Transverse target-spin asymmetry $A_{UT}(\phi, \phi_S)$:**

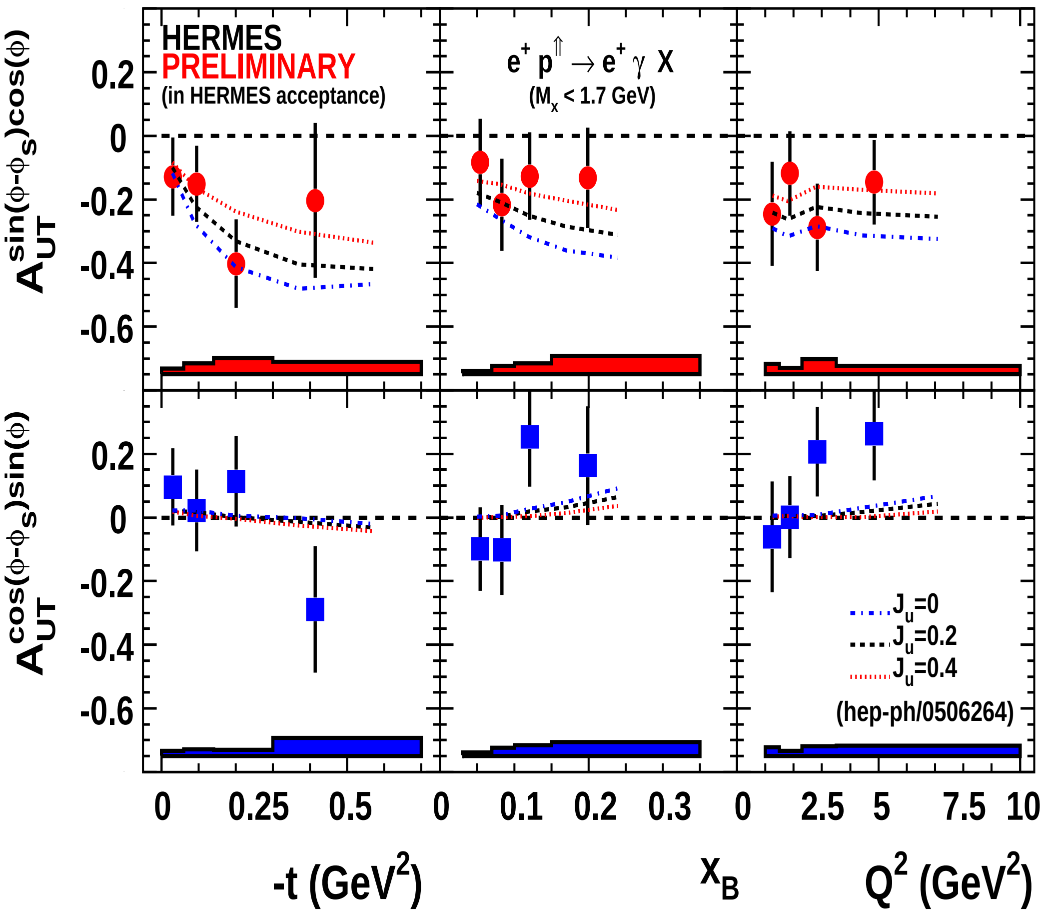
$$d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi) \propto Im[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi-\phi_S)\cdot\cos(\phi) +$$

$$\xi = \frac{x_{Bj}}{2-x_{Bj}} \qquad Im[F_2\widetilde{\mathcal{H}} - \xi F_1\widetilde{\mathcal{E}}] \cdot \cos(\phi-\phi_S)\cdot\sin(\phi)$$

- **Now we have sensitivity to $\mathcal{E}$**

DVCS: sensitivity to $\mathcal{E}, \mathcal{H}, \widetilde{\mathcal{H}}$ via TTSA

- **TTSA:** $A_{UT}(\phi) \propto A_{UT}^{\sin(\phi-\phi_S)\cdot\cos(\phi)} \cdot \sin(\phi-\phi_S)\cdot\cos(\phi) + A_{UT}^{\cos(\phi-\phi_S)\cdot\sin(\phi)} \cdot \cos(\phi-\phi_S)\cdot\sin(\phi)$



- **Analyzed data sample:** 50% **[2002-2004]**

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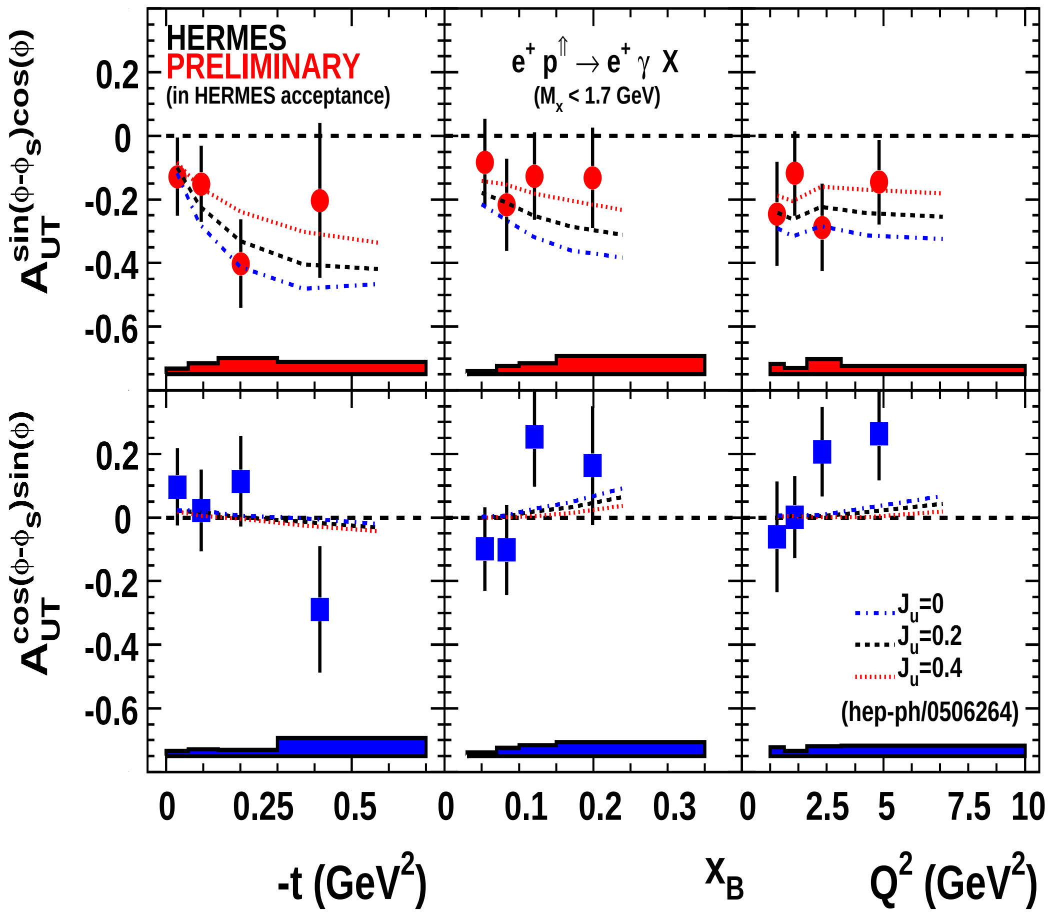


- **Analyzed data sample:** 50% **[2002-2004]**
- **Predictions:**
  Ellinghaus et al. (Eur.Phys.J. C46 (2006) 729-739) based on Goeke et al. (2001)
- **Model GPD E via unkown J**
- **$J_d = 0$ assumed here**
- **Sensitivity to J_u:**
  - **expected for $A_{UT}^{\sin(\phi-\phi_S)\cdot\cos(\phi)}$**
  - **NOT-expected for $A_{UT}^{\cos(\phi-\phi_S)\cdot\sin(\phi)}$**
- **Minor sensitivity found to other GPDs parameters:**
  - **profile / t-dependence**

TTSA: ...exploiting sensitivity to J_q

$$\chi^2_{exp}(J_u, J_d) = \sum_i^{kin\ bins} \frac{[A^{\sin(\phi-\phi_S)\cdot\cos(\phi)}_{UT,i}|_{exp} - A^{\sin(\phi-\phi_S)\cdot\cos(\phi)}_{UT,i}|_{VGG(J_u,J_d)}]^2}{\delta A^2_{stat,i} + \delta A^2_{syst,i} + \delta A^2_{accept,i}}$$

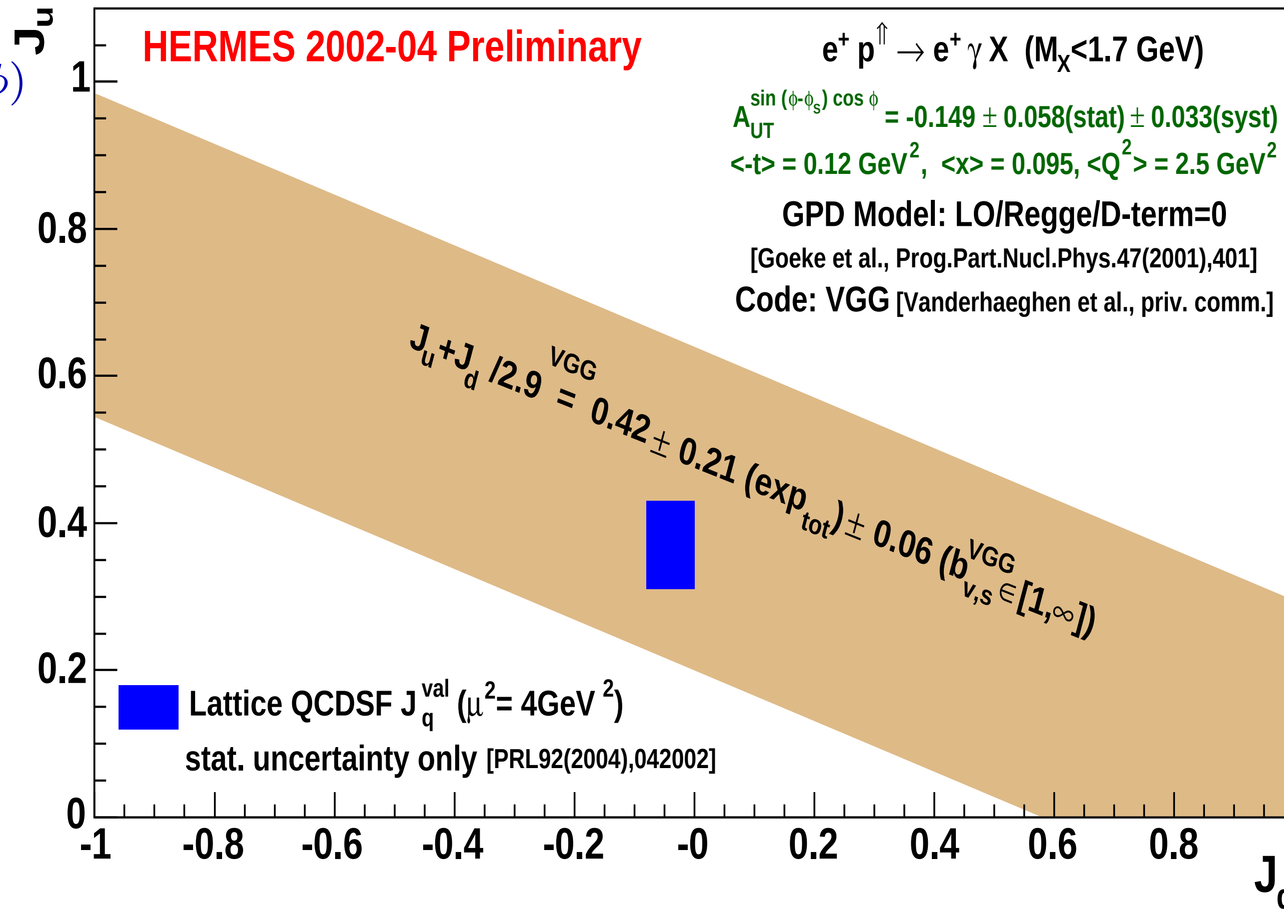
- **Calculate** $A^{\sin(\phi-\phi_S)\cdot\cos(\phi)}_{UT}$ **within VGG-based model**
- J_u, J_d **kept free in fit**
- **Via** χ^2 **minimization determine** 1σ **area for (**J_u, J_d**)**

TTSA: ...exploiting sensitivity to J_q

$$\chi^2_{exp}(J_u, J_d) = \sum_i^{kin\ bins} \frac{[A_{UT,i}^{\sin(\phi-\phi_S)\cdot\cos(\phi)}|_{exp} - A_{UT,i}^{\sin(\phi-\phi_S)\cdot\cos(\phi)}|_{VGG(J_u,J_d)}]^2}{\delta A^2_{stat,i} + \delta A^2_{syst,i} + \delta A^2_{accept,i}}$$

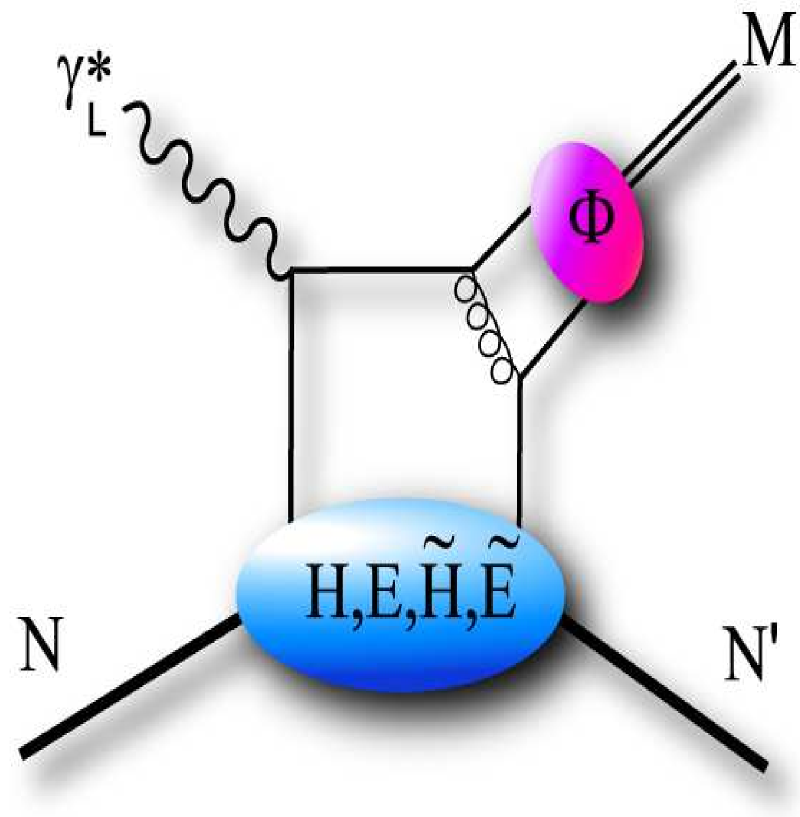
- **Calculate $A_{UT}^{\sin(\phi-\phi_S)\cdot\cos(\phi)}$ within VGG-based model**
- **J_u, J_d kept free in fit**
- **Via χ^2 minimization determine 1σ area for (J_u, J_d)**

More details in: Z. Ye et al., hep-ex/0606061



- **First contraint on J_u vs J_d, ALBEIT model-dependent**

Hard Exclusive Meson Production



- **More complex interpretation in terms of $GPDs$: include meson amplitude**
- **Quantum numbers of final meson state filter different contrib. of $GPDs$**

- **Vector mesons (ρ^o): $\mathcal{H}, \mathcal{E}$ (flavor singlet)**
- **f-meson family (f_0, f_2): $\mathcal{H}, \mathcal{E}$ (flavor non-singlet)**
- **Pseudoscalar mesons (π^+): $\widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}$**

ρ-meson Family

Sensitivity to $\mathcal{H}$ and $\mathcal{E}$
in flavour singlet state

Hard Exclusive ρ^o_L Production

TTSA: $A_{UT}(\phi - \phi_S) \propto \frac{N^{\uparrow}_{excl}(\phi-\phi_S)-N^{\downarrow}_{excl}(\phi-\phi_S)}{N^{\uparrow}_{excl}(\phi-\phi_S)+N^{\downarrow}_{excl}(\phi-\phi_S)}$

$$A_{UT}^{sin(\phi-\phi_S)} \sim \frac{\mathcal{E}}{\mathcal{H}} \sim \frac{\mathcal{E}_q+\mathcal{E}_g}{\mathcal{H}_q+\mathcal{H}_g}$$

Hard Exclusive ρ_L^o Production

TTSA: $A_{UT}(\phi - \phi_S) \propto \frac{N^{\uparrow}_{excl}(\phi-\phi_S) - N^{\downarrow}_{excl}(\phi-\phi_S)}{N^{\uparrow}_{excl}(\phi-\phi_S) + N^{\downarrow}_{excl}(\phi-\phi_S)}$

$$A_{UT}^{sin(\phi-\phi_S)} \sim \frac{\mathcal{E}}{\mathcal{H}} \sim \frac{\mathcal{E}_q+\mathcal{E}_g}{\mathcal{H}_q+\mathcal{H}_g}$$

Analysis strategy :

- $P_T \cdot A_{UT}^{beam} = S_T \cdot A_{UT}^{\gamma^\star} + S_L \cdot A_{UL}^{\gamma^\star}$

  $P_T \cdot A_{UT}^{beam} \sim S_T \cdot A_{UT}^{\gamma^\star}$ **at HERMES!**

- ρ_L^o / ρ_T^o **separation via angular distribution**

  $\Longrightarrow$ **from HERMES data**

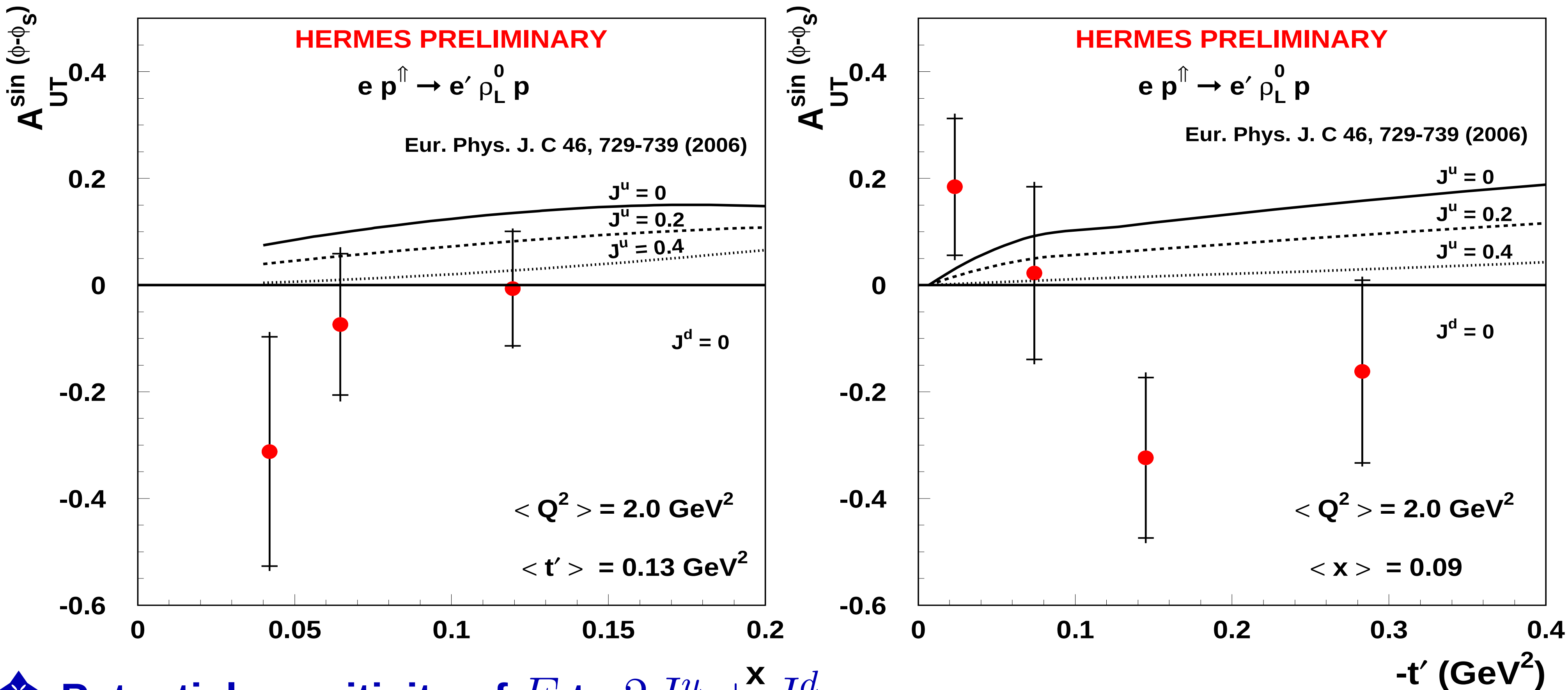
- **Because** sCH **is approximately conserved:**

  ρ_L^o / ρ_T^o **can be mapped into** $\gamma_L^\star / \gamma_T^\star$ **separation**

- **Asymmetry extracted with Unbinned Maximum Likelihood fit**

Hard Exclusive ρ_L^o Production

$$\gamma_L^\star p \longrightarrow p \rho_L^o$$



- **Potential sensitivity of E to $2J^u + J^d$**
- **all 2002-05 available data used!**
- **Combined statistical analysis in progress, to make statement concerning J**

Pion Pairs and f-meson Family

Sensitivity to $\mathcal{H}$ and $\mathcal{E}$
in flavour non-singlet state

Complementary to Vector Meson sensitivity
($\mathcal{H}$ and $\mathcal{E}$ in flavour singlet state)

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

$$\gamma_L^\star p \longrightarrow p\pi^+\pi^-$$

$$\gamma_L^\star d \longrightarrow d\pi^+\pi^-$$

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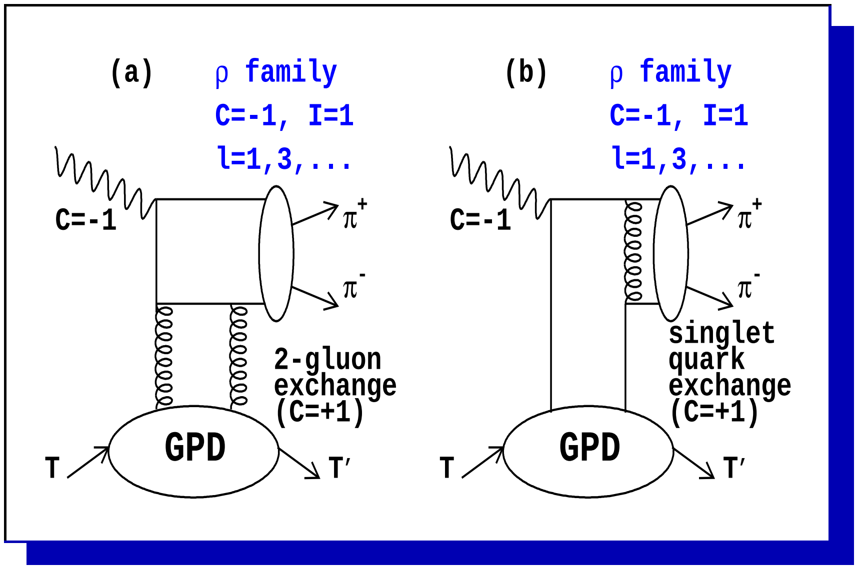
Which channels may contribute?



Example:

- ρ^0: $I(J^{PC})$=$1(1^{--})$

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

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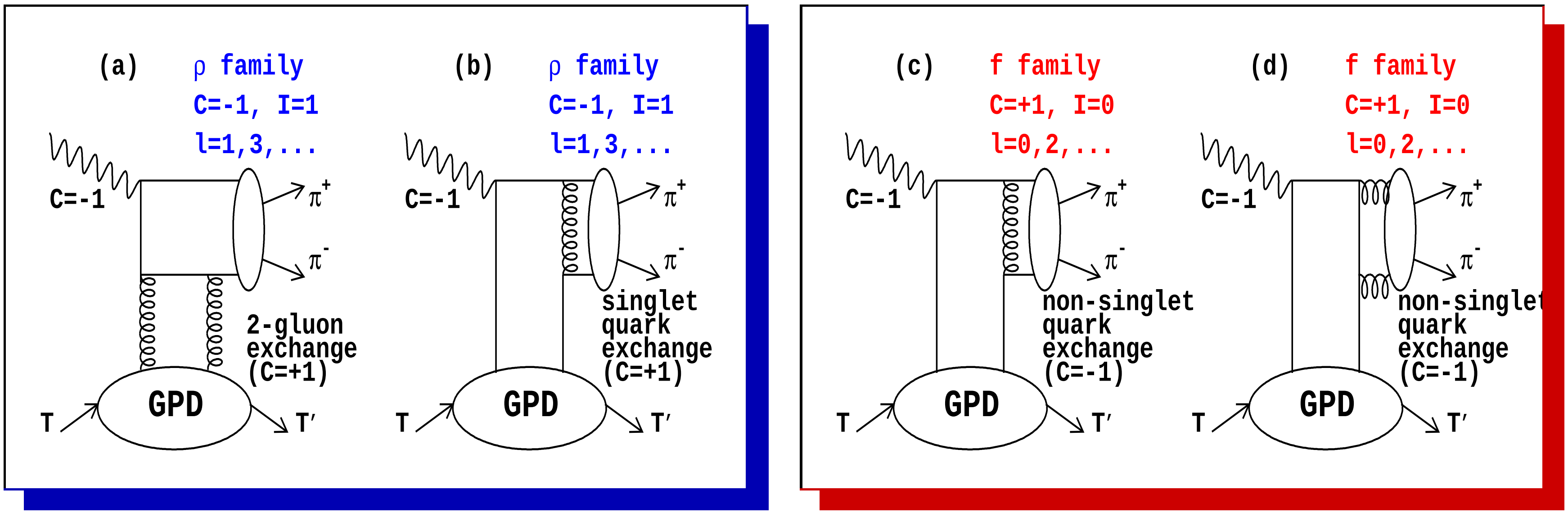

Example:

- ρ^0: $I(J^{PC})=1(1^{--})$

Example:

- non-resonant S-wave & f_0: $I(J^{PC})=0(0^{++})$
- f_2: $I(J^{PC})=0(2^{++})$

Legendre Moments

- **How to highlight the elusive *f*-meson family channel?**

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$$\frac{d\sigma^{\pi^+\pi^-}}{d\cos\theta} \propto \sum_{JJ'\lambda\lambda'} \rho^{JJ'}_{\lambda\lambda'} Y_{J\lambda}(\theta,\phi) Y^\star_{J'\lambda'}(\theta,\phi)$$

Spin Density Matrix:

$$\rho^{JJ'}_{\lambda\lambda'}$$

Legendre Moments

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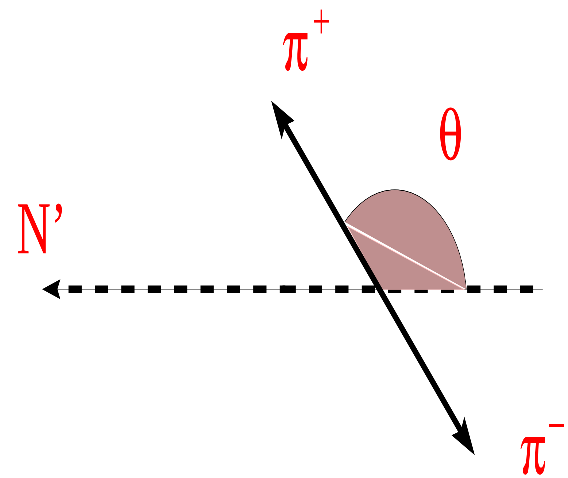

Legendre Moments:

$$\langle P_l(cos\theta)\rangle^{\pi^+\pi^-} = \frac{\int_{-1}^{1} dcos\theta \, P_l(cos\theta) \, \frac{d\sigma^{\pi^+\pi^-}}{dcos\theta}}{\int_{-1}^{1} dcos\theta \, \frac{d\sigma^{\pi^+\pi^-}}{dcos\theta}}$$

Legendre Moments

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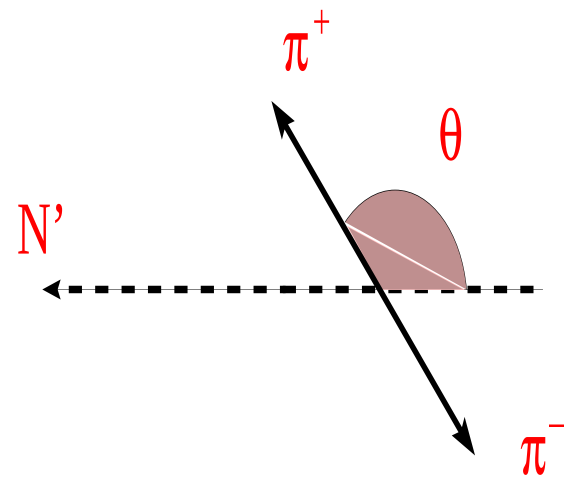

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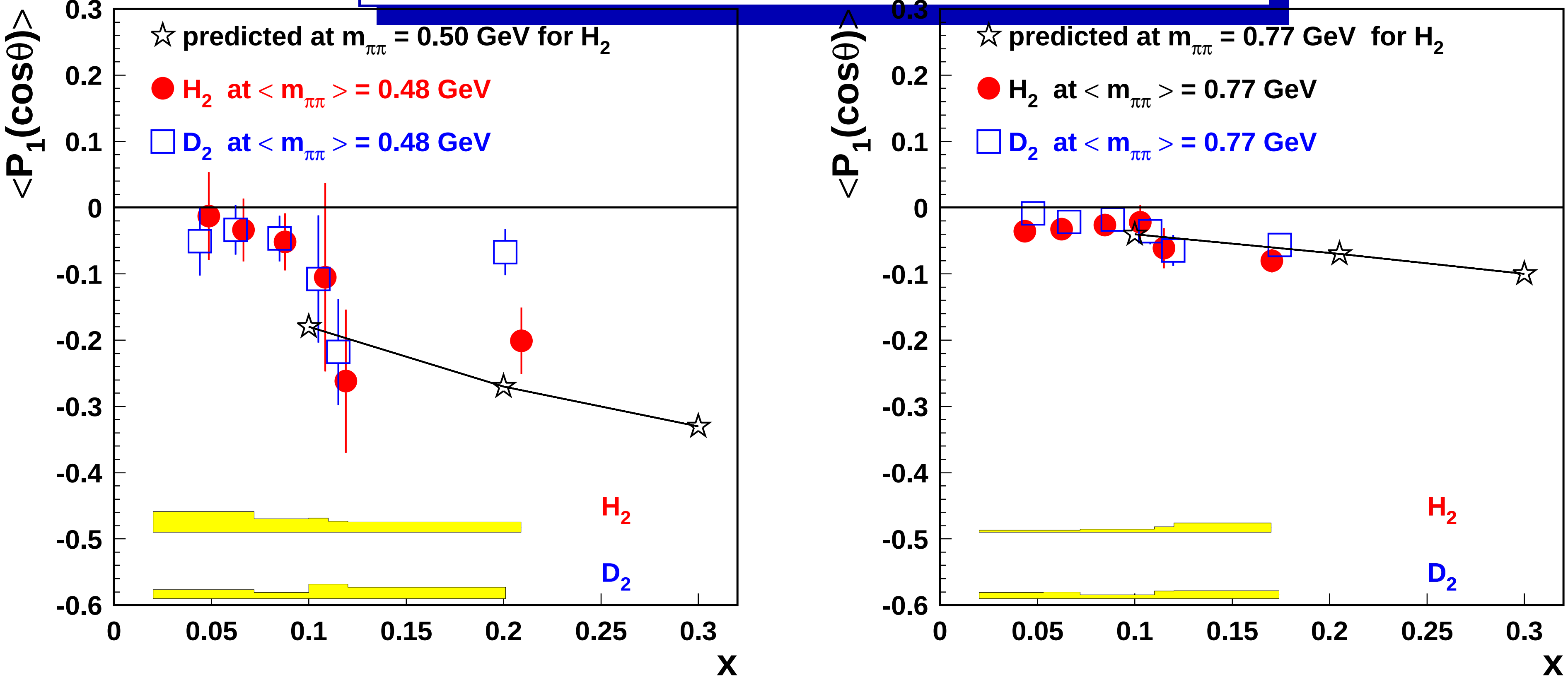
$$\langle P_1(\cos\theta)\rangle = \frac{1}{\sqrt{15}}\left[\underbrace{4\sqrt{3}\rho^{21}_{11} + 4\rho^{21}_{00}}_{tensor-vector}\ \overbrace{+2\sqrt{5}\rho^{10}_{00}}^{vector-scalar}\right]$$

❖ **highlighting elusive *f*-meson family channel through its interference with dominating ρ^{o}-meson**

❖ **Sensitivity to the interference by measuring $\langle P_1(\cos\theta)\rangle$**

x-dependence of $\langle P_1(cos\theta)\rangle$

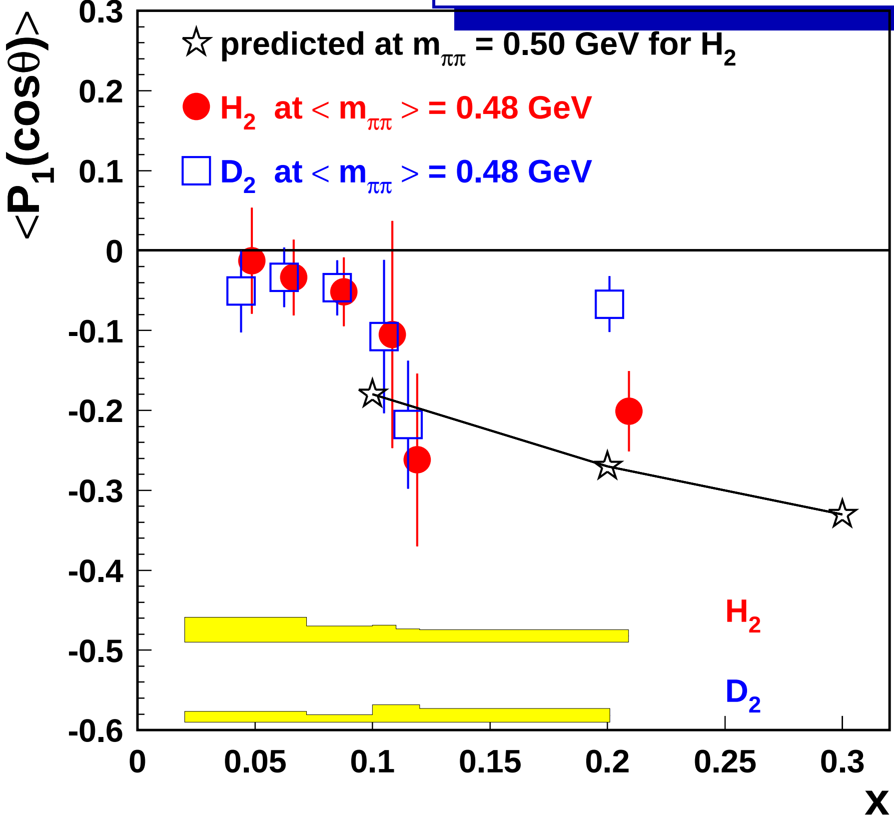


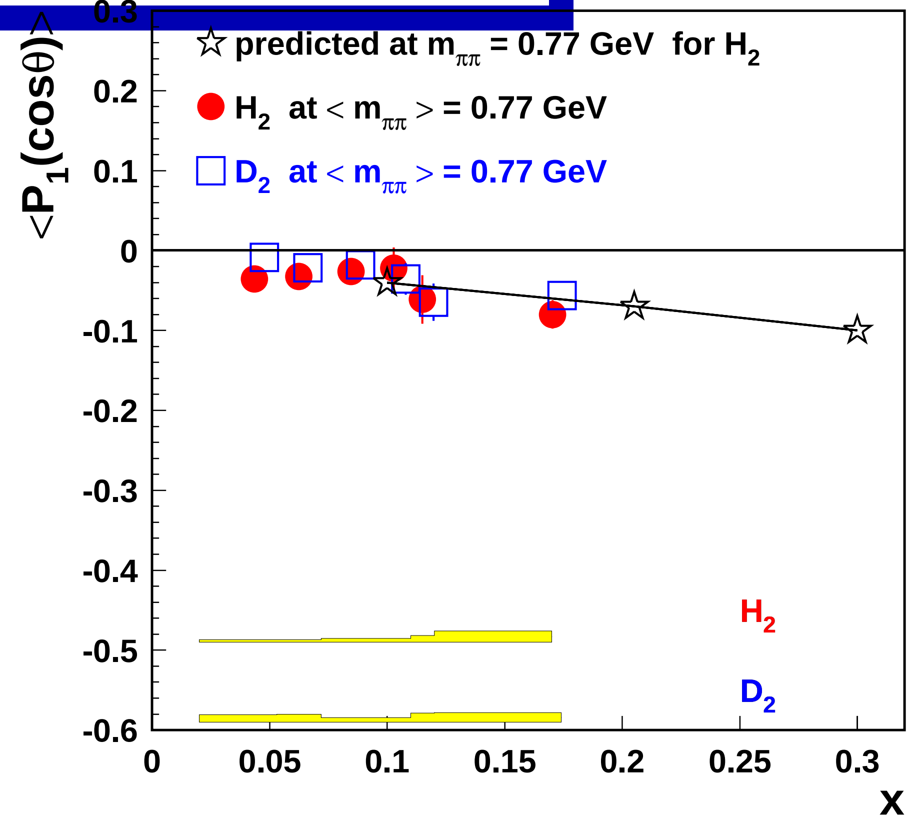
Increasing interference vs increasing x
between non-resonant S-wave and ρ^0
$\Rightarrow$ **increased contribution of non-singlet $q\bar{q}$ exchange**

Described by flavor non-singlet combinations of $\mathcal{H}_q$ & $\mathcal{E}_q$

- Potential sensitivity to J_u, J_d

x-dependence of $\langle P_1(cos\theta)\rangle$





Increasing interference vs increasing x
between non-resonant S-wave and ρ^0
$\Rightarrow$ **increased contribution of non-singlet $q\bar{q}$ exchange**

- B.Lehmann-Dronke, P.V.Pobylitsa, M.V.Polyakov, A.Schäfer, K.Goeke:
  - Phys. Lett. B **475**, (2000) 147

$\Rightarrow$ **gluon *GPD* neglected**

- **Reasonable agreement of theory with data**

Conclusions & Outlook

- **Several hard exclusive production channels measured**

  $\Longrightarrow$ **interpreted in the GPD framework**

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- **First model-dependent constraint on J_u & J_d**

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– exclusive ρ^o_L:

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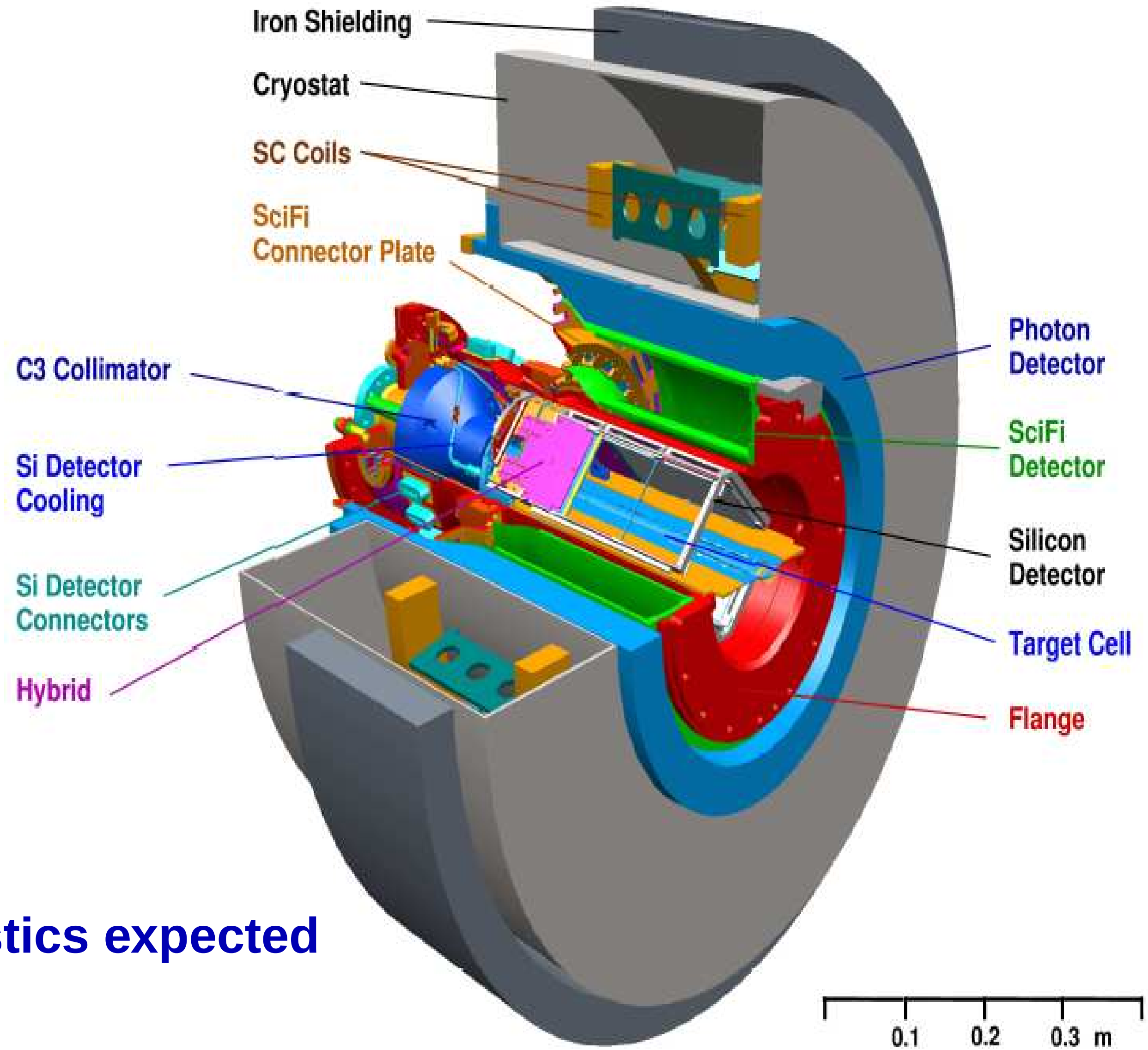
– exclusive $\pi^+\pi^-$:

- **Legendre moments measured: $\Longrightarrow$ agreement with GPDs predictions**
- $\langle P_1 \rangle$ **increase vs x: $\Longrightarrow$ relative increase with x of non-singlet H_q & E_q**

Conclusions & Outlook



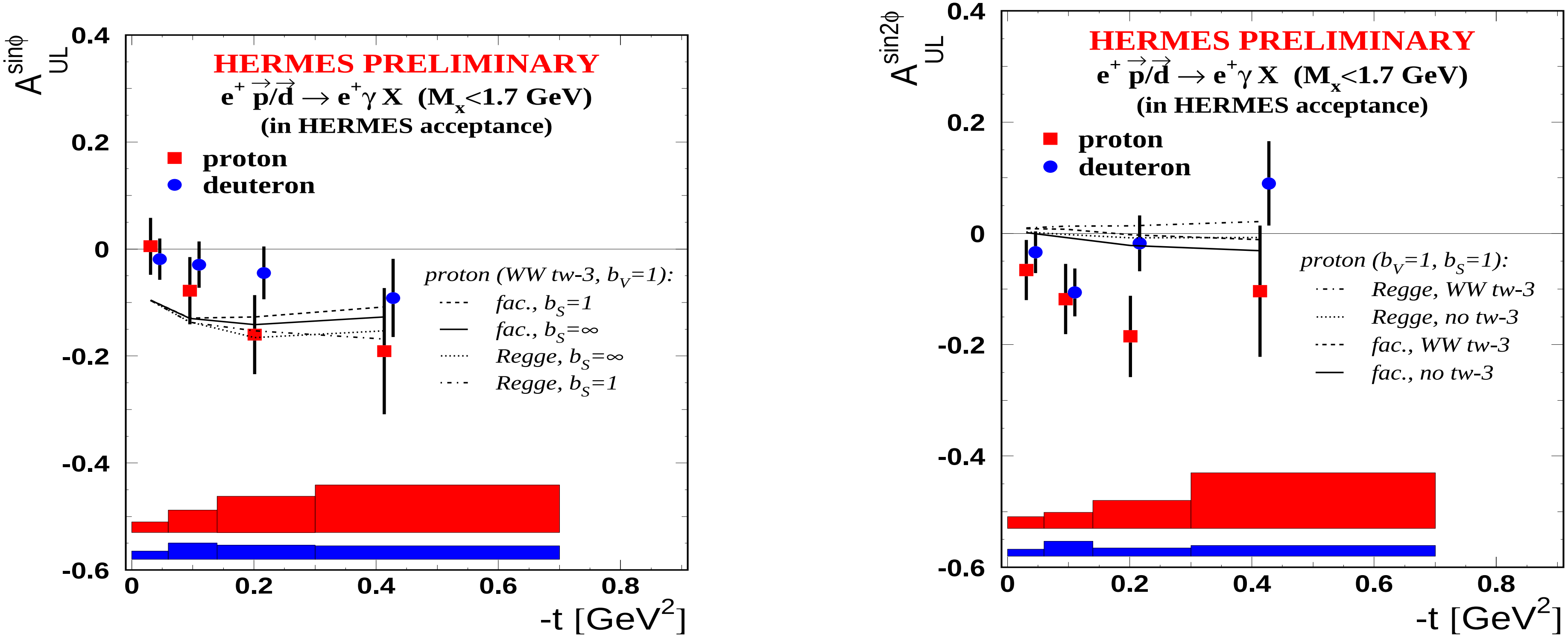
Near future:

- **Improved resolution/statistics expected with new RECOIL detector**
- **Expected total $47 \cdot 10^6$ unpol. DIS on H, $\sim 1 fb^{-1}$ (as in the proposal)**

Back Slides

DVCS: sensitivity to $\widetilde{\mathcal{H}}$ via LTSA

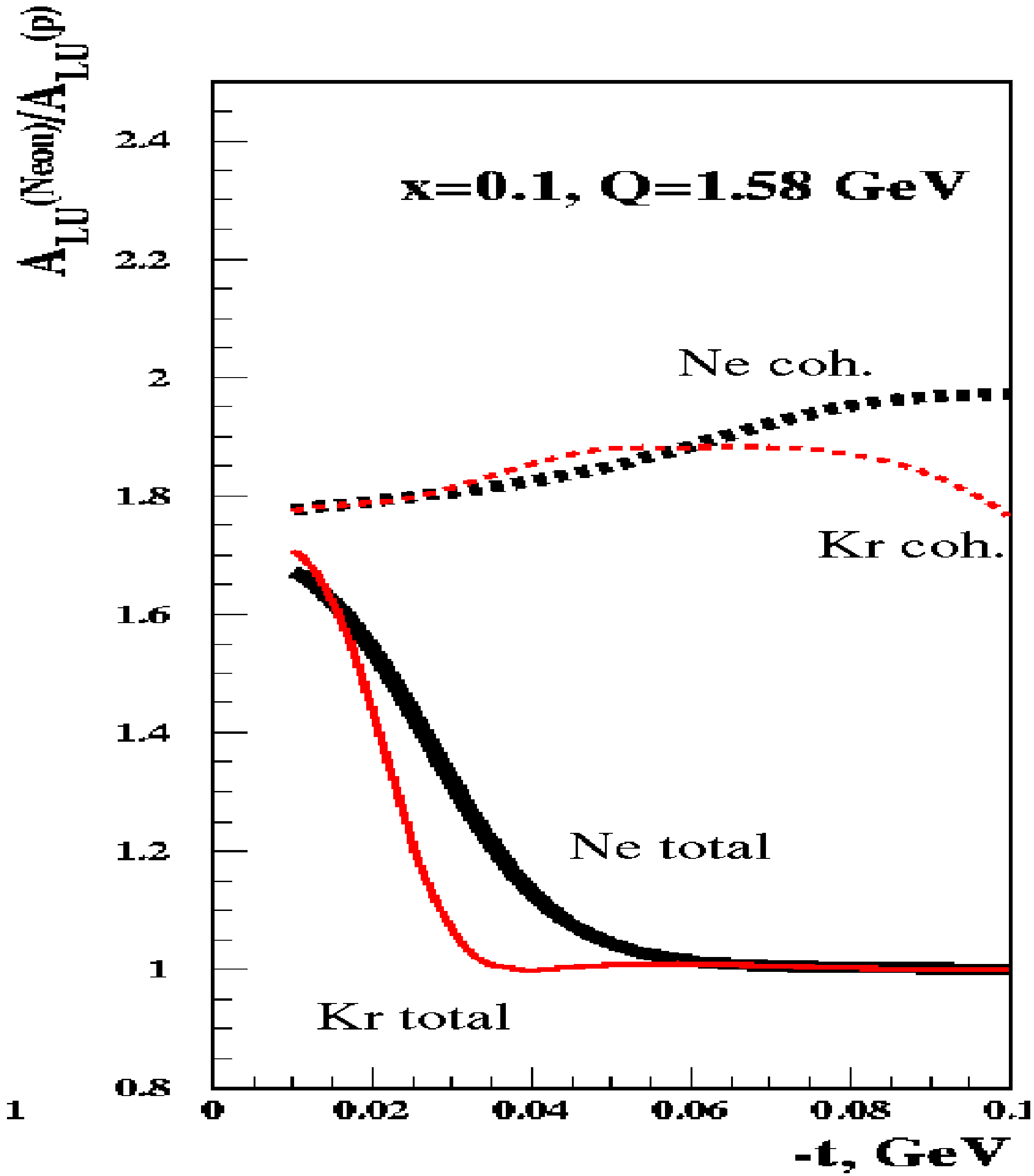
- **LTSA:** $A_{UL}(\phi) \propto Im[\widetilde{\mathcal{H}}] \cdot \sin(\phi) = A_{UL}^{\sin(\phi)} \cdot \sin(\phi)$ **at Lead.Twist**



- **Both targets consistent within uncertainties**
- **Only proton GPD predictions exist:**
  - ✘ $\sin\phi$ **in agreement with VGG model**
  - ✘ **VGG failure in reproduce** $\sin 2\phi$

But: only Twist-3 WW-term included → **Twist-3 qGq-term needed?** **(π^0 contamination negligible)**

BSA off nuclei



V. Guzey and M. Strikman:

Phys. Rev. C68 (2003) 015204

GPD-based

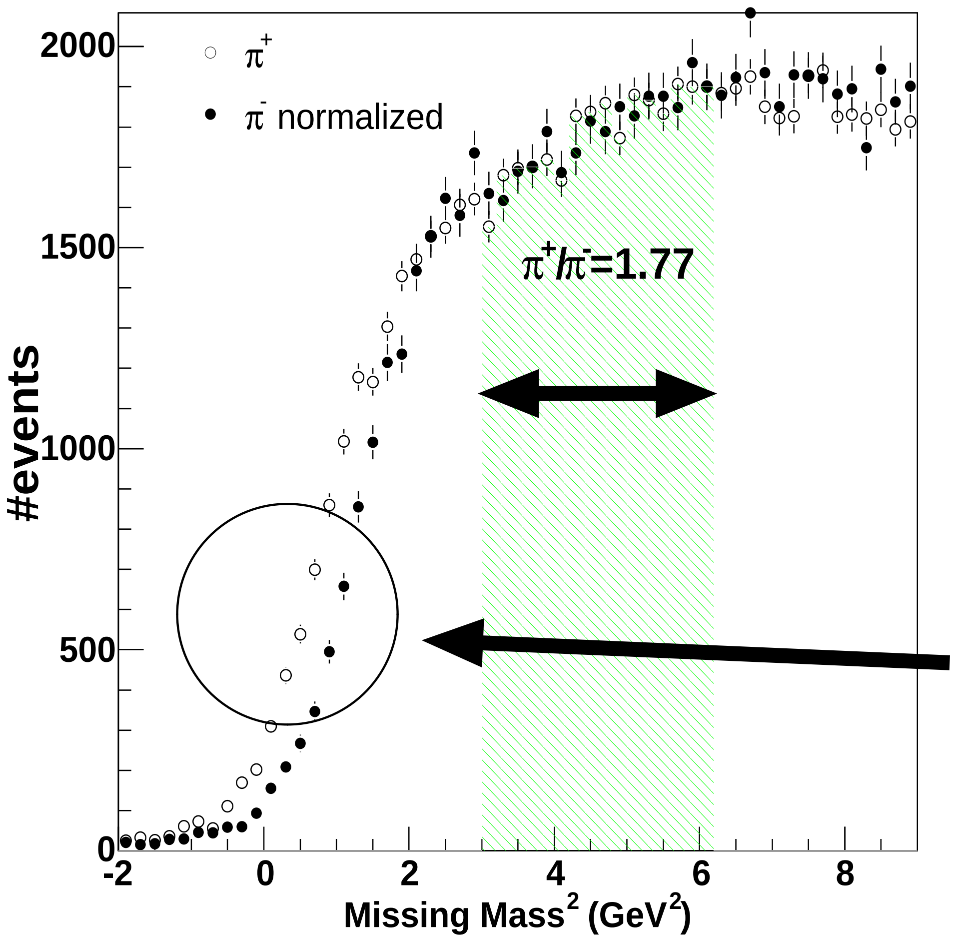
Pseudoscalar Mesons

Sensitivity to $\widetilde{\mathcal{H}}$ and $\widetilde{\mathcal{E}}$

Hard Exclusive π^+ Cross-section

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

Extraction of the exclusive sample



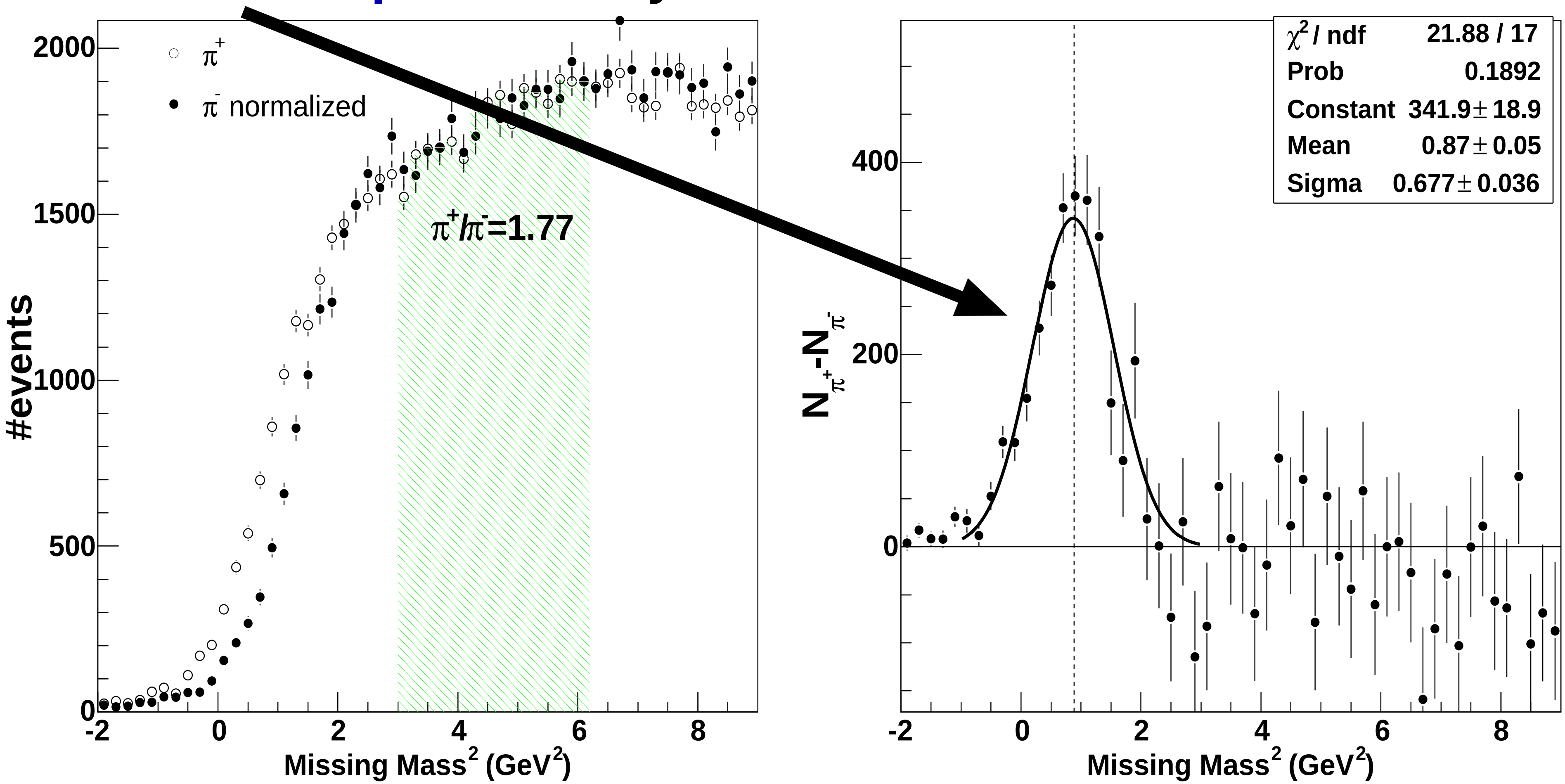
- **Detection:** e^+, π^+
- **Recoil neutron reconstructed via Missing Mass**
- **Use of π^- to subtract the non-exclusive bg**
- π^+ **enhancement**

Hard Exclusive π^+ Cross-section

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

Extraction of the exclusive sample

Exclusive peak clearly centered at the neutron mass



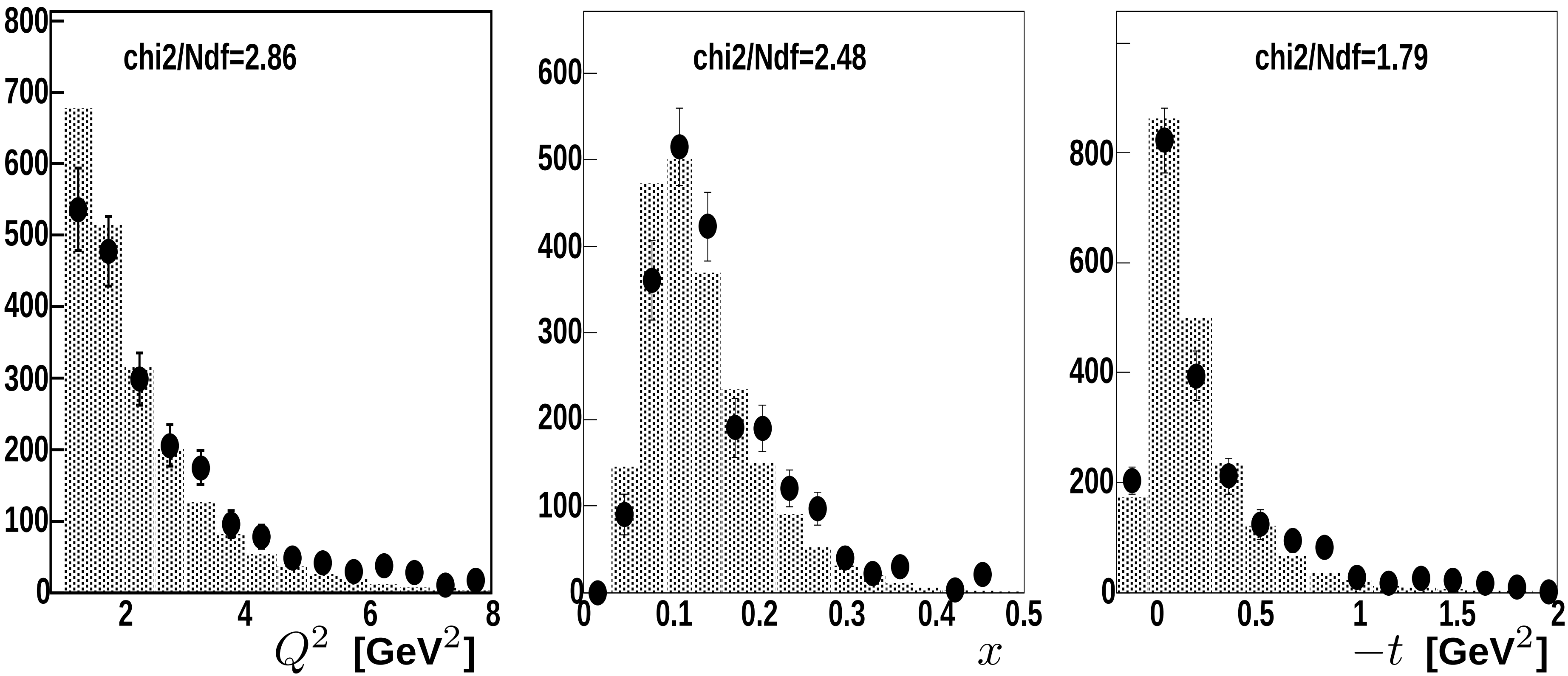
MC Tuning for Exclusive π^+ Cross-section

Cross-section: $\sim (\widetilde{\mathcal{H}} + \widetilde{\mathcal{E}})^2$

- **X_section extracted after proper tuning of exclusive MC in the HERMES acceptance**

$GPDs$ **framework in terms of:** $\widetilde{H}$ & $\widetilde{E}$

- Vanderhaeghen, Guichon & Guidal (1999) -



✔ **VGG_MC well reproduces data kin.distributions in the HERMES detector**

Hard Exclusive π^+ Cross-section

Cross-section: $\sim (\widetilde{\mathcal{H}} + \widetilde{\mathcal{E}})^2$

- X_section extracted after proper tuning of exclusive MC in the HERMES acceptance

  - Vanderhaeghen, Guichon & Guidal (1999) -

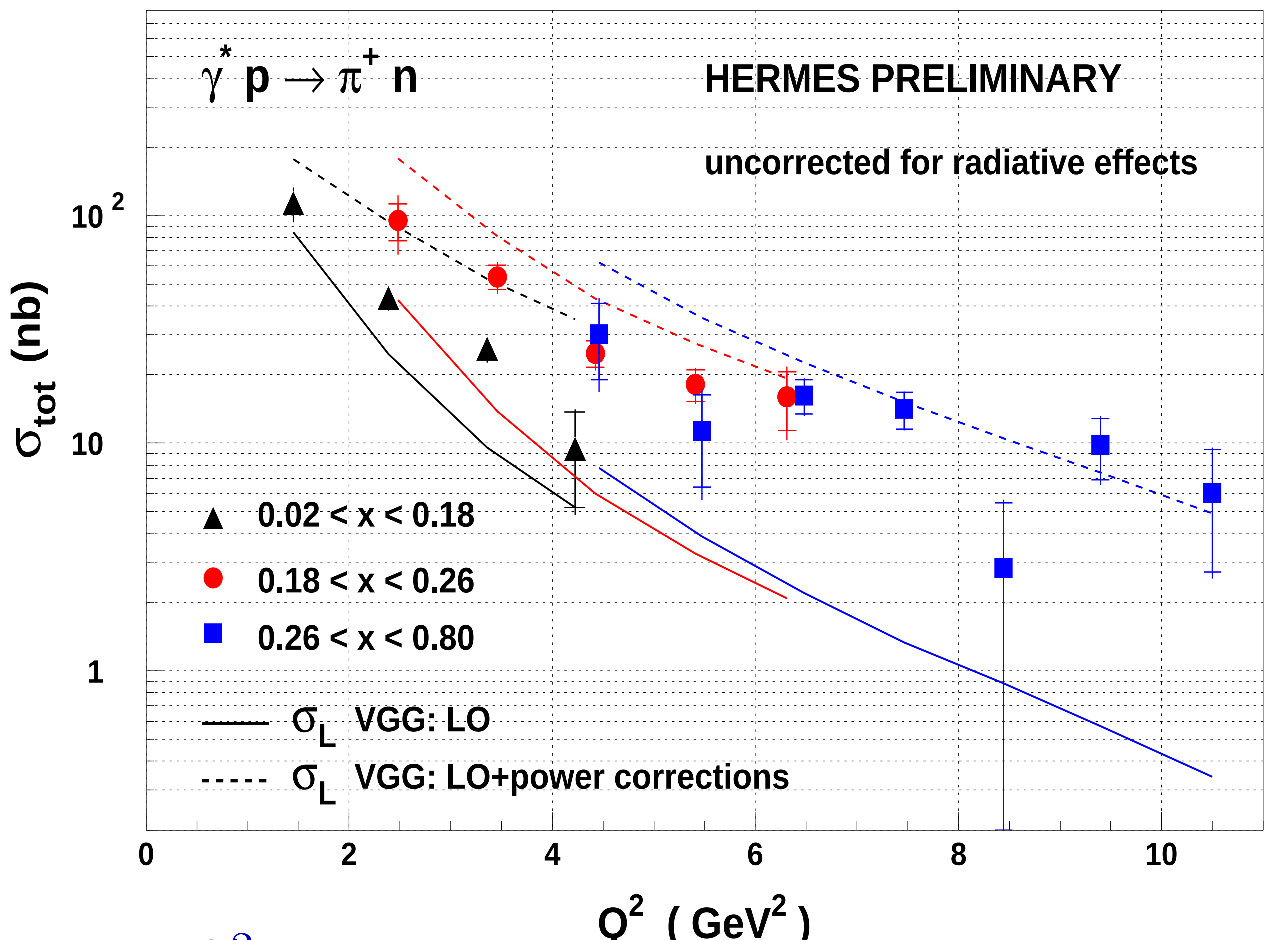
$GPDs$ **framework in terms of:**

$\widetilde{H}$ & $\widetilde{E}$

$$\sigma^{\gamma^\star p \longrightarrow \pi^+ n}(x, Q^2) = \frac{N_{\pi^+}^{excl}}{L \Delta x \Delta Q^2 \Gamma(x,Q^2) \kappa(x,Q^2)}$$

Hard Exclusive π^+ Cross-section

Cross-section: $\sim (\widetilde{\mathcal{H}} + \widetilde{\mathcal{E}})^2$

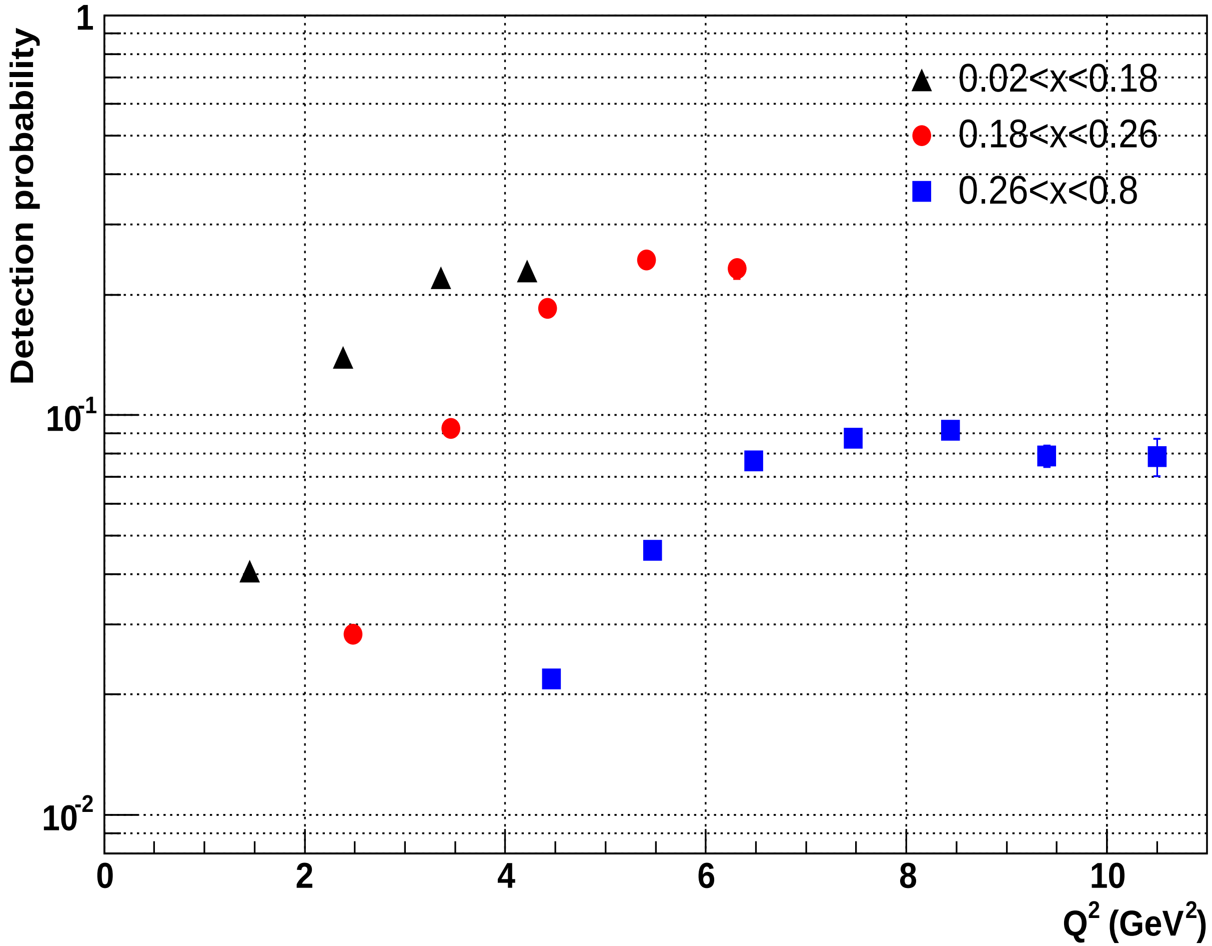


❖ No σ_L/σ_T separation

- ❖ VGG (1999): Q^2 dependence qualitatively in agreement with the data
- ❖ Leading order calculations underestimate the data
- ❖ Power correction calculations overestimate the data

Exclusive π^+: Acceptance Correction

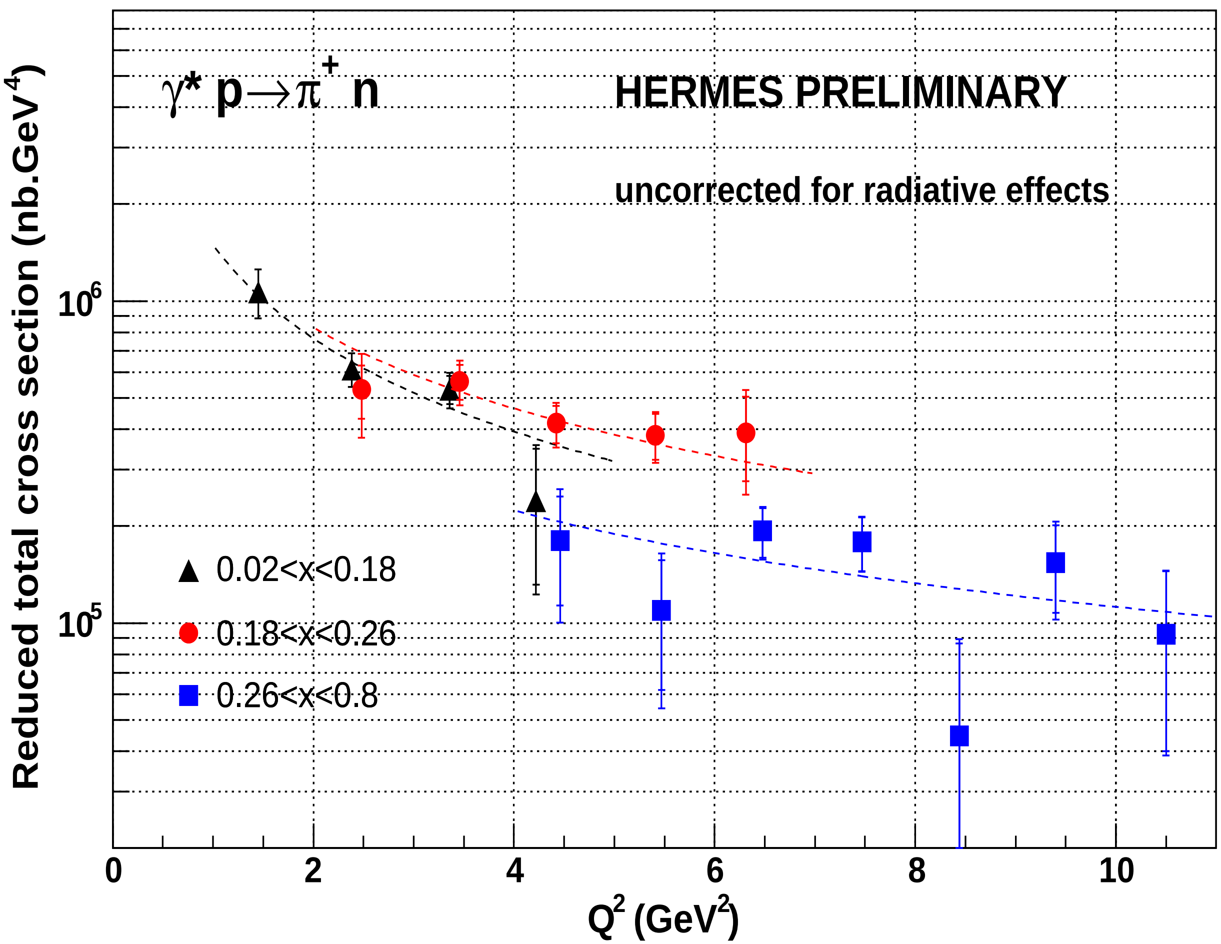
- Acceptance correction found to be model dependent
- Comparison with two different models made and included in the systematics



Exclusive π^+: Reduced X_section

- **Reduced X_section σ_{red} defined as**

$$\sigma_{tot} = \frac{1}{16\pi} \frac{x^2}{1-x} \frac{1}{Q^4} \frac{1}{\sqrt{(1+\frac{4x^2 M_p^2}{Q^2})}} \cdot \sigma_{red}$$



Fit of the form: $1/Q^p$**:**

$p = 1.9 \pm 0.5$

$p = 1.7 \pm 0.6$

$p = 1.5 \pm 1.0$

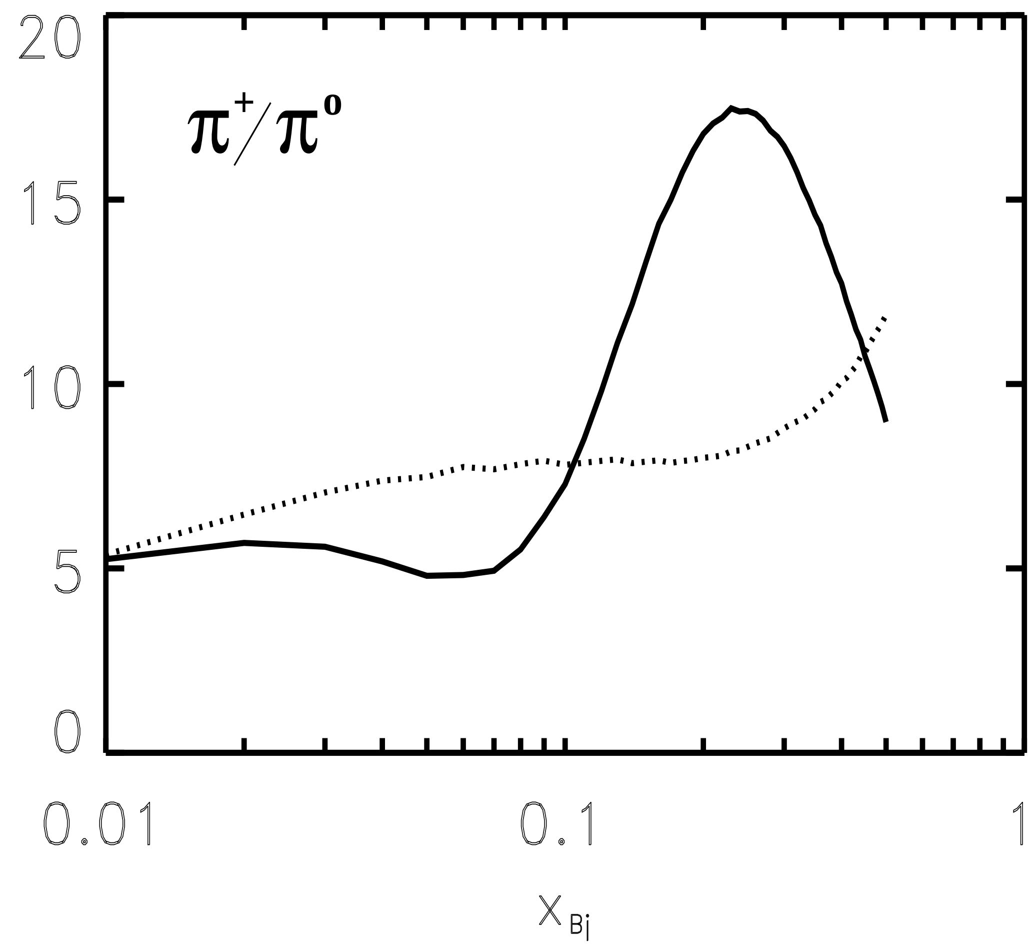
- agreement with theoretical expectation $1/Q^2$ at fixed x and t

Hard Exclusive π^o Production

- **Analysis of exclusive π^o on unpolarized proton target on going**

- **no pion-pole contribution in $\widetilde{E}$**
- **predicted sensitivity to $\widetilde{E}$**

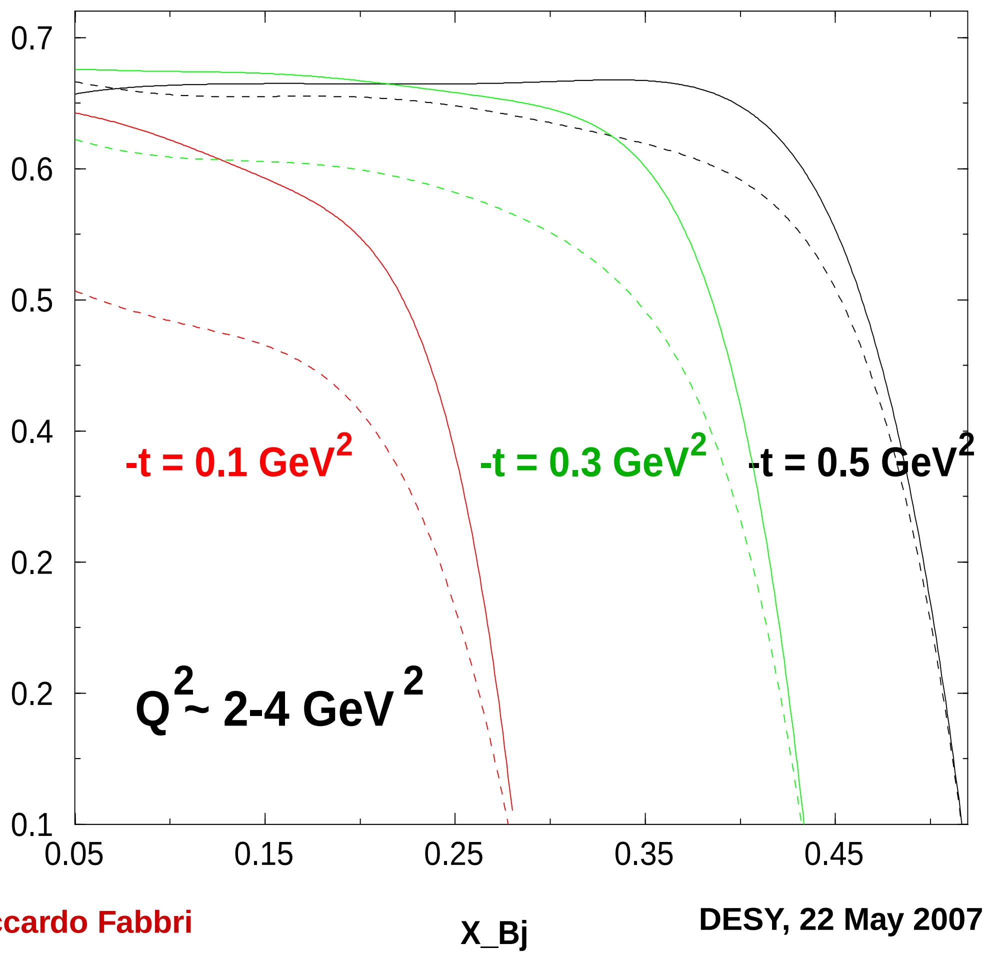
  - Mankiewicz et. al. (1999) -



Hard Exclusive ρ_L^o Production

Transverse Target Spin Asymmetry: $\sim \widetilde{\mathcal{E}} \cdot \widetilde{\mathcal{H}}$

$$A_{UT}(\phi - \phi_S) \propto \frac{N^{\uparrow}_{excl}(\phi{-}\phi_S) - N^{\downarrow}_{excl}((\phi{-}\phi_S)}{N^{\uparrow}_{excl}((\phi{-}\phi_S) + N^{\downarrow}_{excl}((\phi{-}\phi_S)}$$



- Frankfurt, Polybitsa,

Polyakov & Strikman (1999) -

$GPDs$ **framework**

❖ **Sizable asymmetry predicted!**