Exclusive Reactions at hermes

Exclusive Reactions as Access to GPDs

DVCS Asymmetries

...with and without Recoil Detection
...on unpolarized, longitudinal and transversely polarized targets

Exclusive Meson Production

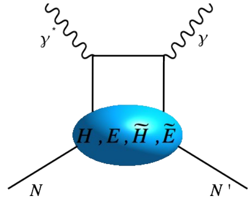
spin density matrix elements
natural and unnatural parity exchange

Eduard Avetisyan
PHOTON 2013, Paris
May 22

HELMHOLTZ ASSOCIATION

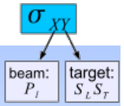
DESY

DVCS



$$\gamma^* \to \gamma : H, E, \widetilde{H}, \widetilde{E}$$

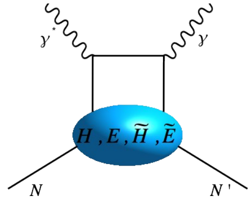
- The cleanest channel to access GPDs
  - Experimental access restricted to CFF
- Theoretically accurate at NNLO
- X-section decomposition w.r.t. Beam and target polarisation states:



$$\begin{aligned} d\sigma \sim d\sigma_{UU}^{BH} &+ e_\ell d\sigma_{UU}^{I} + d\sigma_{UU}^{DVCS} \\ &+ e_\ell P_\ell d\sigma_{LU}^{I} + P_\ell d\sigma_{LU}^{DVCS} \\ &+ e_\ell S_L d\sigma_{UL}^{I} + S_L d\sigma_{UL}^{DVCS} \\ &+ e_\ell S_T d\sigma_{UT}^{I} + S_T d\sigma_{UT}^{DVCS} \\ +P_\ell S_L d\sigma_{LL}^{BH} &+ e_\ell P_\ell S_L d\sigma_{LL}^{I} + P_\ell S_L d\sigma_{LL}^{DVCS} \\ +P_\ell S_T d\sigma_{LT}^{BH} &+ e_\ell P_\ell S_T d\sigma_{LT}^{I} + P_\ell S_T d\sigma_{LT}^{DVCS} \end{aligned}$$

- Unpolarized target: GPD H
- Longitudinal target: GPD $\widetilde{H}$
- Transverse target: GPD E

DVCS



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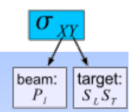

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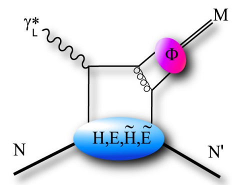
\end{aligned}
$$

> Unpolarized target: GPD H

> Longitudinal target: GPD $\widetilde{H}$

> Transverse target: GPD E

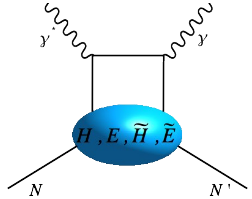
Meson Production



> Unlike γ: L and T states possible (VM)!
  - Factorization only proven in collinear approximation for $\gamma_L \to (\rho_L, \omega_L, \phi_L)$
  - $\gamma_L \to \rho_T$ suppressed by 1/Q
  - γ_T suppressed by 1/Q^2
  - $\gamma_T \to \rho_T$ transitions calculable

> Sensitive to H and E in twist-2
  - $\widetilde{H}$ and $\widetilde{E}$ in twist-3

DVCS



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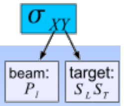

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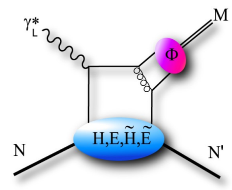

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> Sensitive to H and E in twist-2

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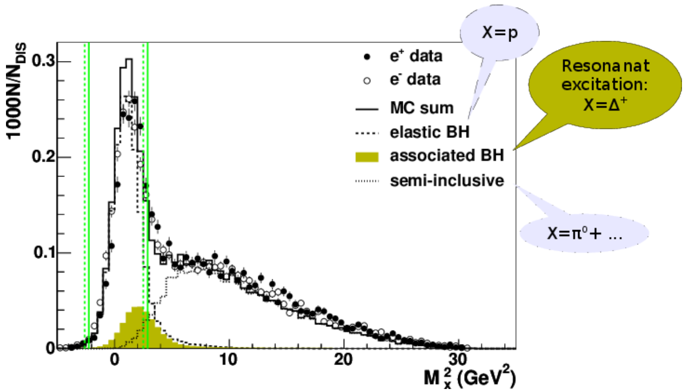
> Pseudoscalar mesons (π^+):

- Sensitive to $\widetilde{H}$ and $\widetilde{E}$ in twist-2
- H_T in twist-3

DVCS (no recoil) $ep \rightarrow e'\gamma X$

> Missing mass technique

$$M_X^2 = (p + e - e' - \gamma)^2$$



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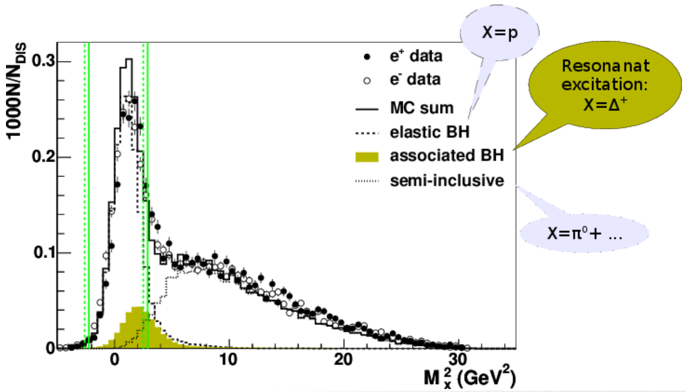
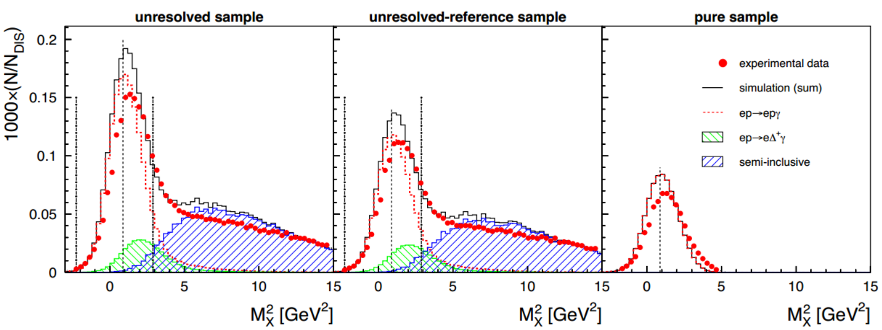


DVCS (with recoil detection)

- Kinematic fitting $ep \rightarrow e'\gamma p'$



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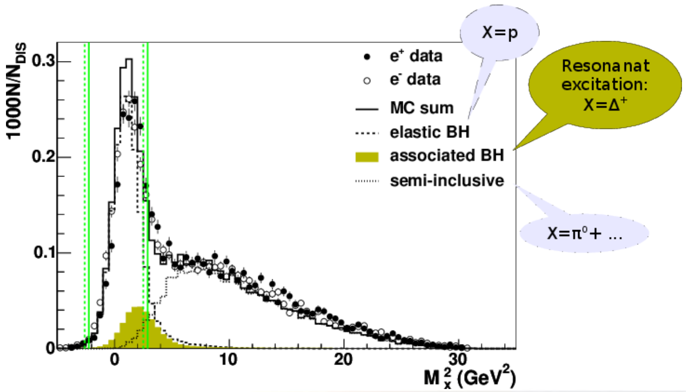

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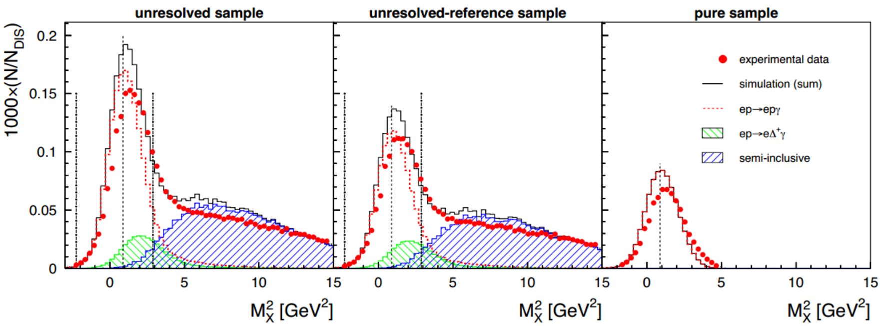


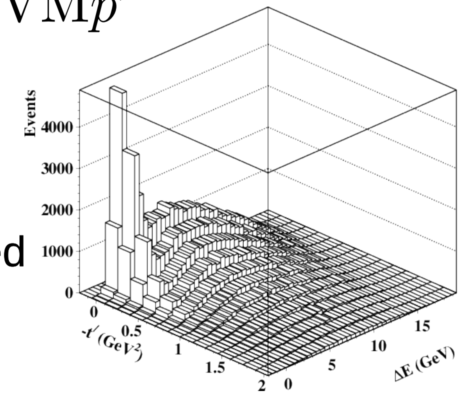
VM $ep \to e'\mathrm{VM}p'$

> Small missing energy
> Elastic scattering

$$\Delta E = \frac{M_X^2 - M^2}{2M} \approx 0$$

> Little energy transferred to the target

$$t = (\mathrm{q} - \mathrm{v})^2$$



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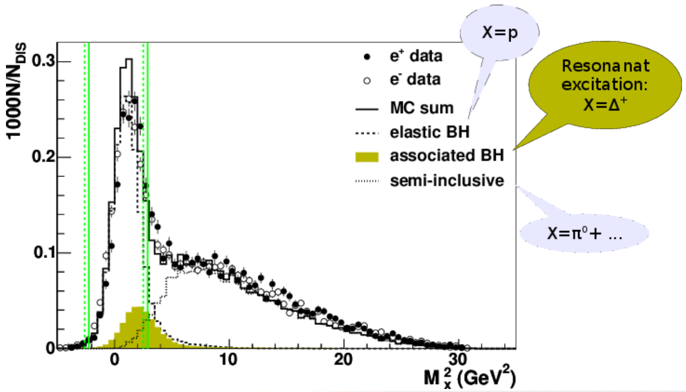

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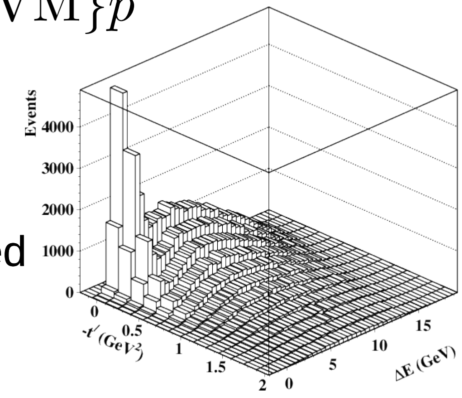

DVCS (with recoil detection)

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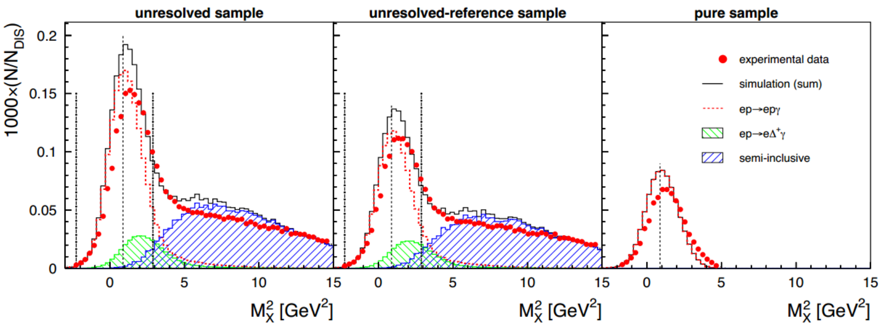


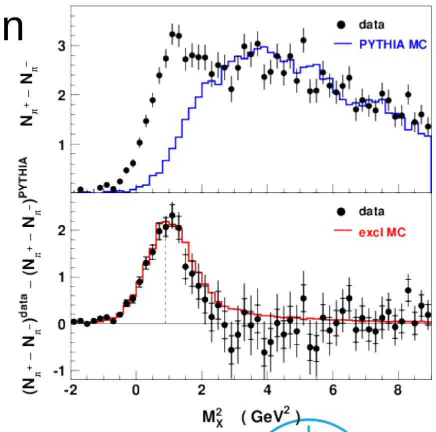
π^+ (no neutron detection) $ep \to e'\pi^+ n$

$$N^{excl} = (\pi^+ - \pi^-)^{data} - (\pi^+ - \pi^-)^{MC}$$

> π^+-π^- yield difference used for background subtraction

> Missing mass technique

$$M_X^2 = (p + e - e' - \pi^+)^2$$



GPD H: DVCS on Unpolarized Target

$ep \to e'\gamma X$ hermes

Pre-recoil data

[JHEP 11 (2009) 083]

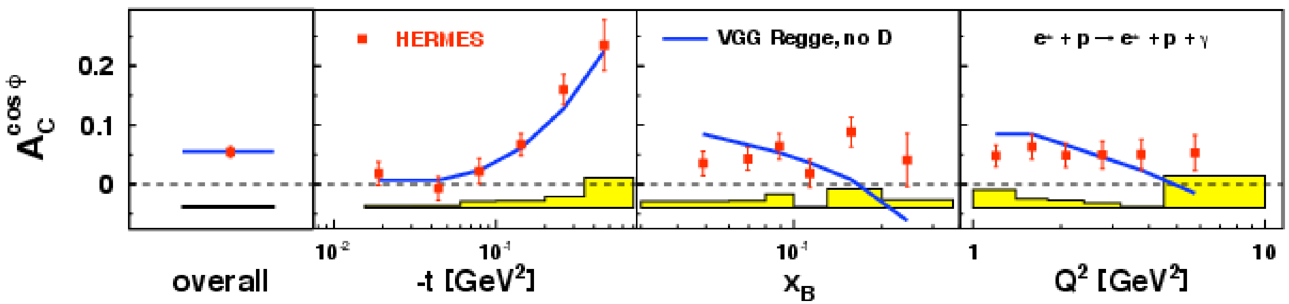
$$\sigma(\phi, P_l, e_l) = \sigma_{UU}(\phi)[1 + P_l \mathcal{A}_{LU}^{DVCS}(\phi) + e_l P_l \mathcal{A}_{LU}^{I}(\phi) + e_l \mathcal{A}_C(\phi)]$$

$$\mathcal{A}_C(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) - (\sigma^{-\rightarrow} + \sigma^{+\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{+\leftarrow})}$$

$$\mathcal{A}_C^{\cos\phi} \propto \mathrm{Re}[F_1 \mathcal{H}]$$

$$\mathcal{A}_C(\phi) = \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi)$$

$$\mathcal{A}_{LU}^{I}(\phi) = \sum_{n=0}^{2} A_{LU,\mathrm{I}}^{\sin(n\phi)} \sin(n\phi)$$



Beam-charge asymmetry

- Large signal
- Strong t-dependence
- No Q2-dependence

DESY

Pre-recoil data

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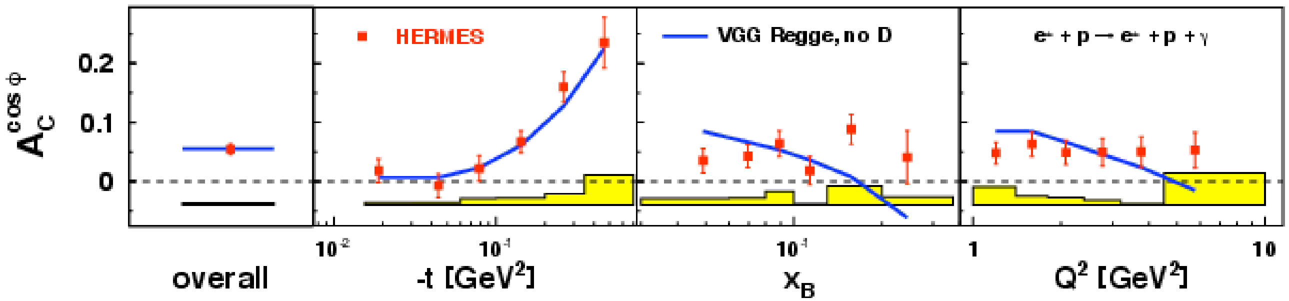

Beam-charge asymmetry

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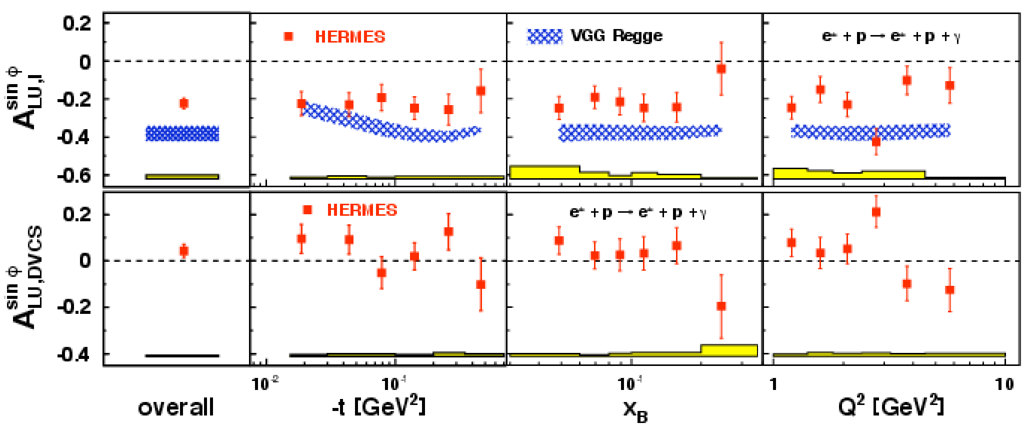
$$A_{LU}^{I,DVCS}(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) \overset{+}{-} (\sigma^{-\rightarrow} - \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})}$$

$$\mathcal{A}_{LU,\mathrm{I}}^{\sin\phi} \propto \mathrm{Im}[F_1 \mathcal{H}]$$



Charge-difference beam helicity asymmetry

- Large signal
- No kinematic dependences

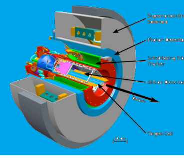
Charge-averaged beam helicity asymmetry

- Consistent with zero

$$A_{LU,\mathrm{DVCS}}^{\sin\phi} \propto \mathrm{Im}[\mathcal{H}\mathcal{H}^* - \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*]$$

DESY

GPD H: DVCS with Recoil Detector



$ep \to e'\gamma p'$

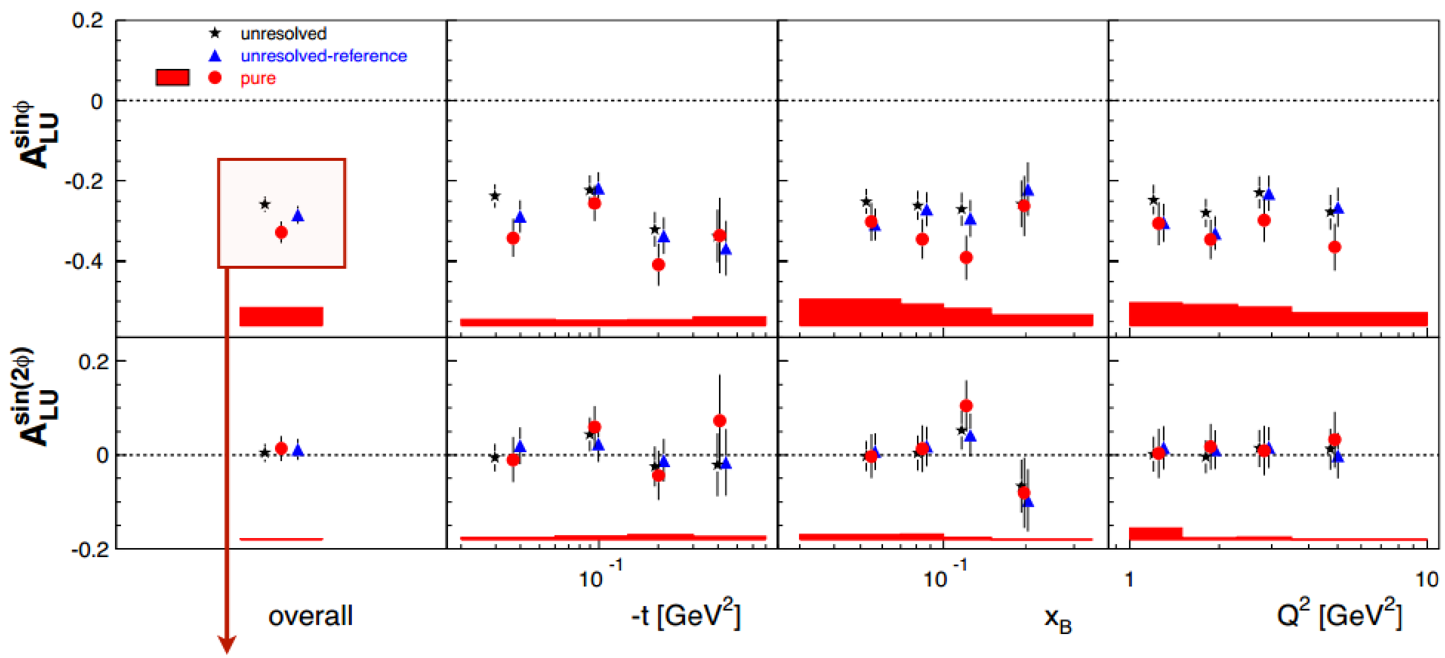
hermes

Single-charge (+) beam helicity asymmetry

[JHEP 10 (2012) 042]

$$\sigma(\phi, P_l, e_l) = \sigma_{UU}(\phi)[1 + P_l \mathcal{A}_{LU}^{DVCS}(\phi) + e_l P_l \mathcal{A}_{LU}^{I}(\phi) + e_l \mathcal{A}_C(\phi)]$$

$$\mathcal{A}_{LU}(\phi) \simeq \sum_{n=0}^{2} A_{LU}^{\sin(n\phi)} \sin(n\phi)$$



twist-2

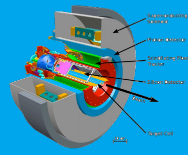
twist-3

Magnitude of the leading asymmetry has increased by 0.054 ± 0.016

All sets are strongly correlated but the unresolved samples contain an average contribution of 12 -14 % of associated processes

DESY

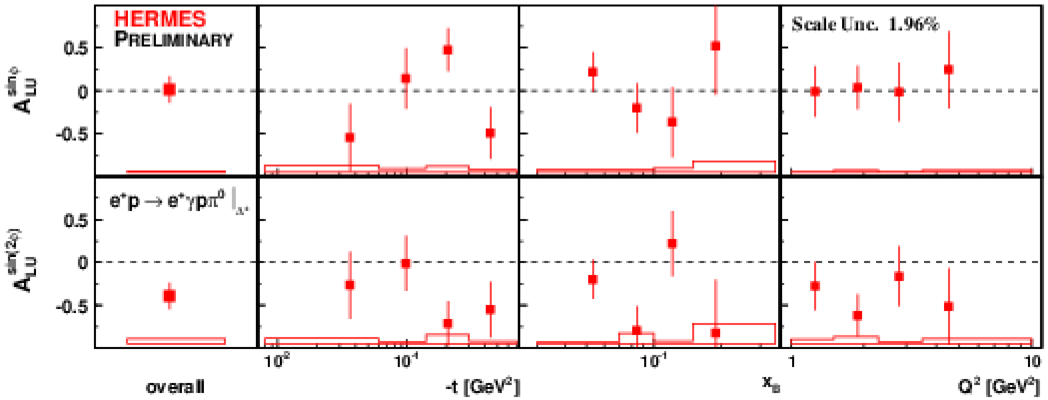
GPD H: DVCS with Recoil Detector



$ep \to e'\gamma\Delta^+$

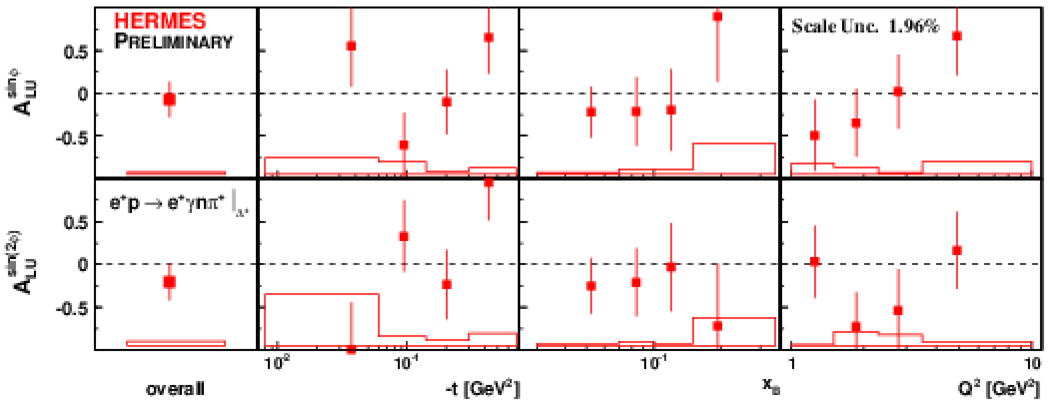
Single-charge (+) beam helicity asymmetry in associated DVCS

$$\Delta^+ \to p\pi^0$$



Fractional purity:
Associated DVCS/BH 85.7 ± 1.8
Elastic DVCS/BH ($ep \to e\gamma p$) 1.1 ± 0.1
SIDIS 13.2 ± 1.9

$$\Delta^+ \to n\pi^+$$



Fractional purity:
Associated DVCS/BH 75.6 ± 2.6
Elastic DVCS/BH ($ep \to e\gamma p$) 0.1 ± 0.1
SIDIS 24.4 ± 3.4

Pre-recoil data

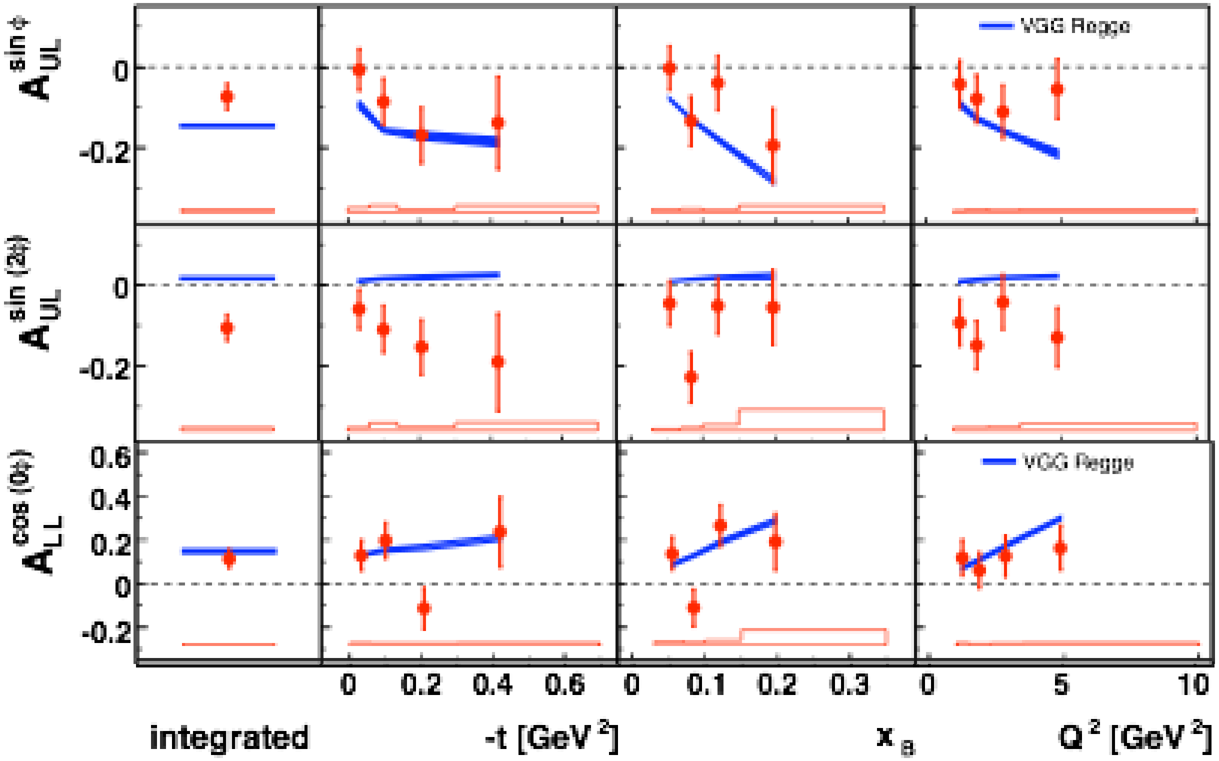
[Nucl.Phys.B842 (2011) 265]

$$\sigma(\phi, P_z, P_l, e_l) = \sigma_{UU}(\phi, e_l)[1 + P_z \mathcal{A}_{UL}(\phi) + P_l P_z \mathcal{A}_{LL}^{I}(\phi)]$$

> No separate access to DVCS and Interference terms possible

$$\mathcal{A}_{UL}(\phi) \simeq \sum_{n=0}^{3} A_{UL}^{\sin(n\phi)} \sin(n\phi)$$

$$\mathcal{A}_{LL}(\phi) = \sum_{n=0}^{2} A_{LL}^{\cos(n\phi)} \sin(n\phi)$$



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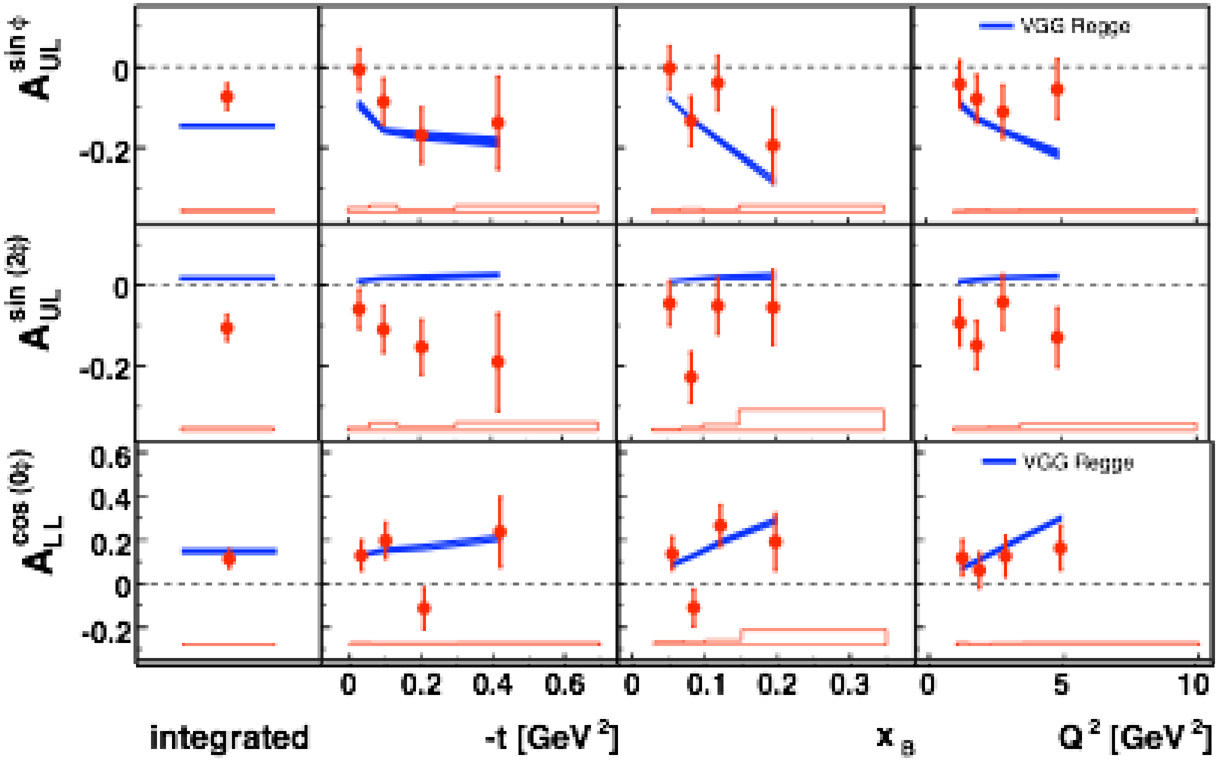

$$A_{UL}^{\sin\phi} \propto \begin{cases} \text{DVCS : twist} - 3 \\ \text{I : twist} - 2 \end{cases}$$

$$\mathcal{A}_{UL}^{\sin\phi} \propto F_1 \mathrm{Im}\widetilde{\mathcal{H}}$$

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[Nucl.Phys.B842 (2011) 265]

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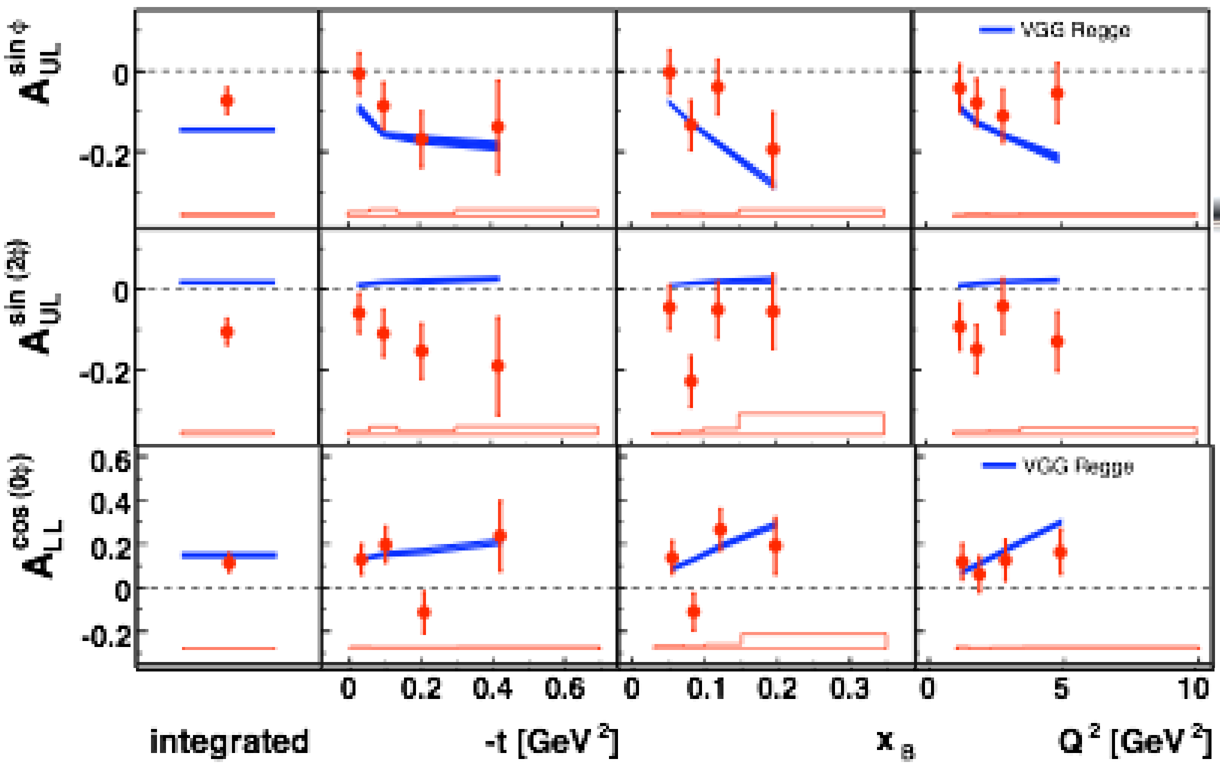

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$$A_{UL}^{\sin 2\phi} \propto \begin{cases} \text{I : quark twist} - 3 \\ \quad \text{or gluon twist} - 2 \\ \text{DVCS : twist} - 4 \end{cases}$$

Unexpectedly large value

Pre-recoil data

[Nucl.Phys.B842 (2011) 265]

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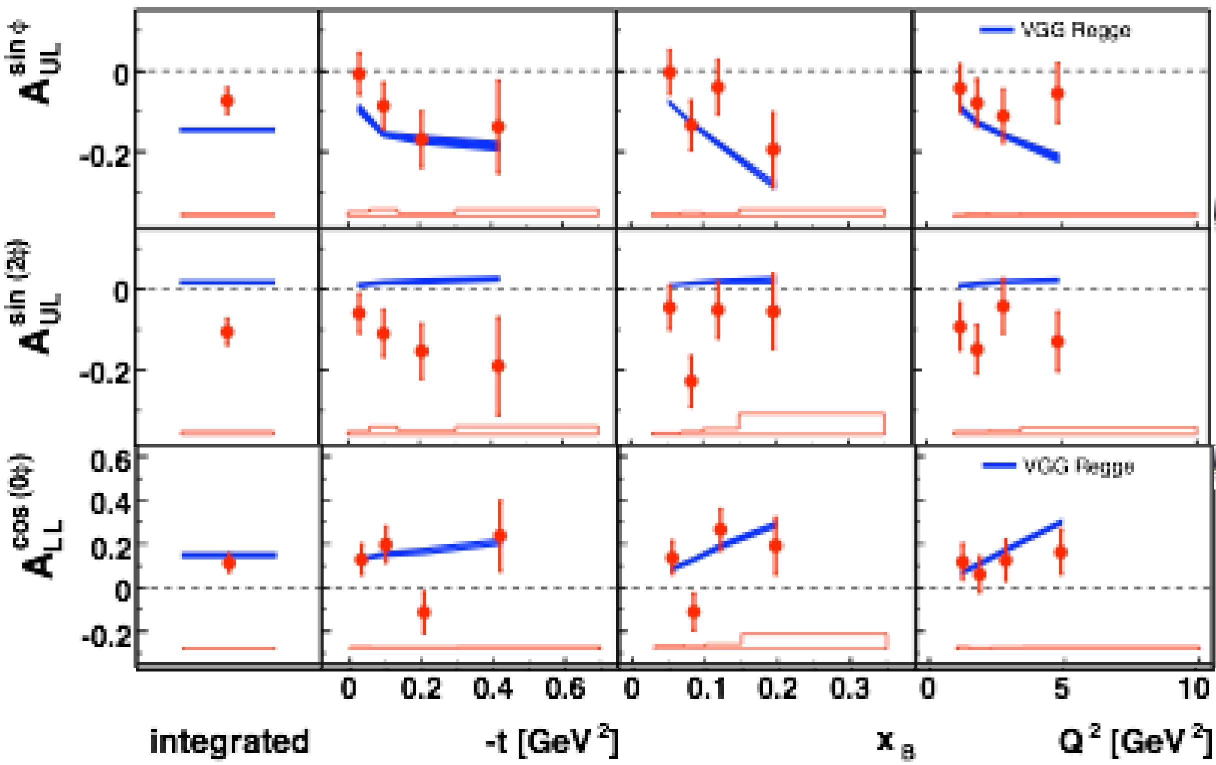

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Unexpectedly large value

$$A_{LL}^{\cos 0\phi} \propto \begin{cases} \text{DVCS : twist} - 2 \\ \text{I : twist} - 2 \end{cases}$$

$$\mathcal{A}_{LL}^{\cos 0\phi} \propto F_1 \mathrm{Re}\widetilde{\mathcal{H}}$$

GPD E: with Transversely Polarized Target

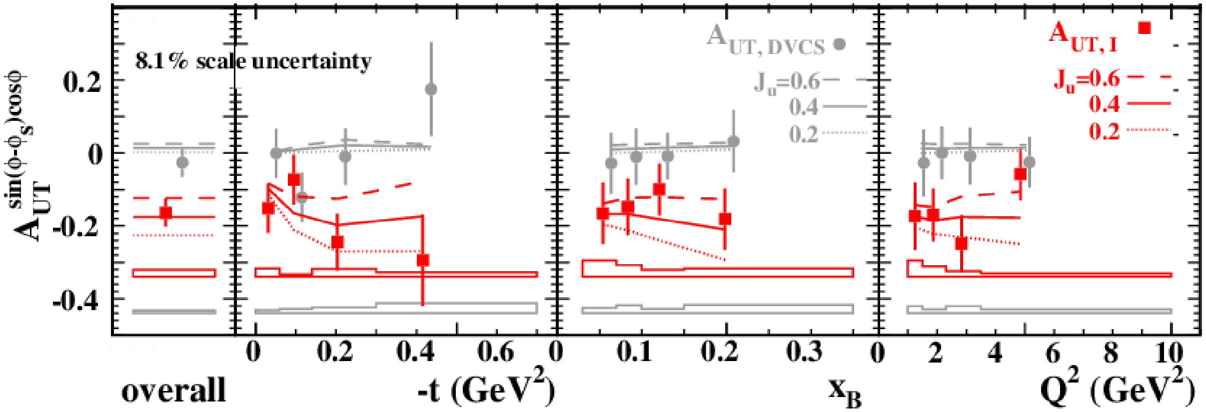
$ep^{\uparrow} \rightarrow e'\gamma X$ hermes

Pre-recoil data

[JHEP 06 (2008) 066, 24]

$$\sigma(\phi, \phi_S, e_l, S_\perp, \lambda) = \sigma_{UU}(\phi)\{1 + e_l\mathcal{A}_C(\phi) + \lambda\mathcal{A}_{LU}^{\mathrm{DVCS}}(\phi) + e_l\lambda\mathcal{A}_{LU}^{\mathrm{I}}(\phi)$$
$$+S_\perp\mathcal{A}_{UT}^{\mathrm{DVCS}}(\phi, \phi_S) + e_l S_\perp\mathcal{A}_{UT}^{\mathrm{I}}(\phi, \phi_S)$$
$$+S_\perp\lambda\mathcal{A}_{LT}^{\mathrm{BH+DVCS}}(\phi, \phi_S) + e_l\lambda S_\perp\mathcal{A}_{LT}^{\mathrm{I}}(\phi, \phi_S)\}$$

$$\mathcal{A}_{UT}^{I,DVCS}(\phi, \phi_S) = \frac{(\sigma^{+\Uparrow} - \sigma^{+\Downarrow}) \pm (\sigma^{-\Uparrow} - \sigma^{-\Downarrow})}{(\sigma^{+\Uparrow} + \sigma^{+\Downarrow}) + (\sigma^{-\Uparrow} + \sigma^{-\Downarrow})}$$



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

$\propto \mathrm{Im}[\mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^* + \xi\widetilde{\mathcal{E}}\widetilde{\mathcal{H}}^* - \widetilde{H}\xi\widetilde{E}^*]$

- ✔ $A_{\mathrm{UT,I}}^{\sin(\phi-\phi_S)\cos\phi}$ has the highest sensitivity to GPD E and, through **Ji** formalism, to J_u total orbital angular momentum of quarks
- ✔ With a good model allows a model-dependent constraint

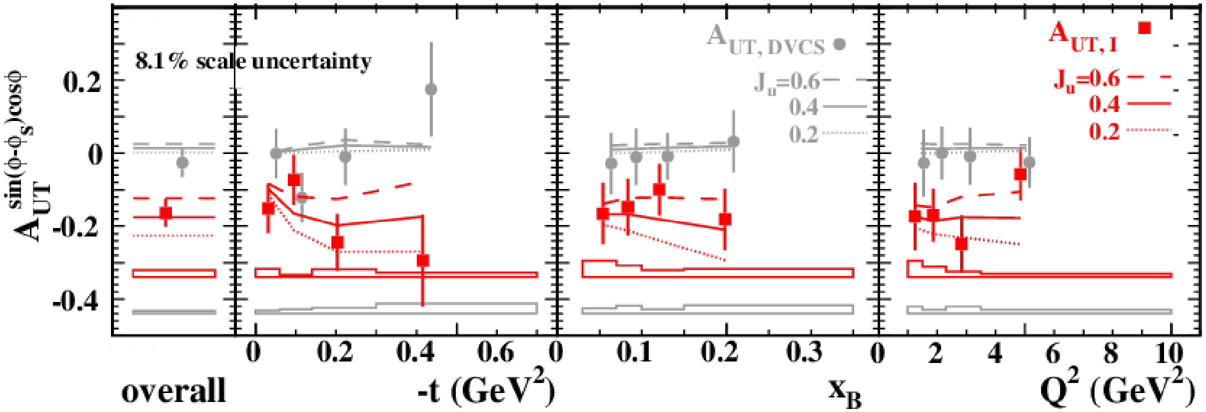
DESY

Pre-recoil data

[JHEP 06 (2008) 066, 24]

$$\sigma(\phi,\phi_S,e_l,S_\perp,\lambda) = \sigma_{UU}(\phi)\{1+e_l\mathcal{A}_C(\phi)+\lambda\mathcal{A}_{LU}^{\rm DVCS}(\phi)+e_l\lambda\mathcal{A}_{LU}^{\rm I}(\phi) + S_\perp\mathcal{A}_{UT}^{\rm DVCS}(\phi,\phi_S)+e_lS_\perp\mathcal{A}_{UT}^{\rm I}(\phi,\phi_S) + S_\perp\lambda\mathcal{A}_{LT}^{\rm BH+DVCS}(\phi,\phi_S)+e_l\lambda S_\perp\mathcal{A}_{LT}^{\rm I}(\phi,\phi_S)\}$$

$$\mathcal{A}_{UT}^{I,DVCS}(\phi,\phi_S) = \frac{(\sigma^{+\Uparrow}-\sigma^{+\Downarrow}) \pm (\sigma^{-\Uparrow}-\sigma^{-\Downarrow})}{(\sigma^{+\Uparrow}+\sigma^{+\Downarrow})+(\sigma^{-\Uparrow}+\sigma^{-\Downarrow})}$$



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

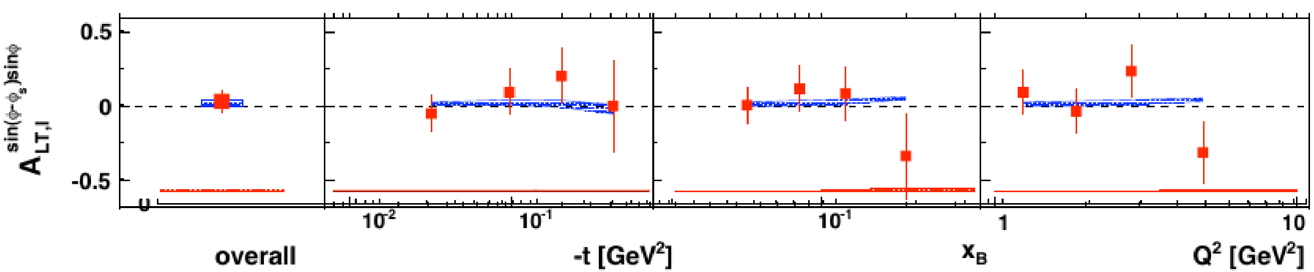
$\propto \mathrm{Im}[\mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^* + \xi\widetilde{\mathcal{E}}\widetilde{\mathcal{H}}^* - \widetilde{H}\xi\widetilde{E}^*]$

- ✔ $A_{\rm UT,I}^{\sin(\phi-\phi_S)\cos\phi}$ has the highest sensitivity to GPD E and, through **Ji** formalism, to J_u total orbital angular momentum of quarks
- ✔ With a good model allows a model-dependent constraint

[Phys.Lett.B 704 (2011) 15-23]

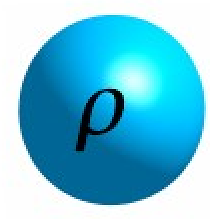
$$\mathcal{A}_{LT}^{I,BH+DVCS}(\phi,\phi_S) = \frac{(\overrightarrow{\sigma}^{+\Uparrow}+\overleftarrow{\sigma}^{+\Downarrow}-\overrightarrow{\sigma}^{+\Downarrow}-\overleftarrow{\sigma}^{+\Uparrow}) \pm (\overrightarrow{\sigma}^{-\Uparrow}+\overleftarrow{\sigma}^{-\Downarrow}-\overrightarrow{\sigma}^{-\Downarrow}-\overleftarrow{\sigma}^{-\Uparrow})}{(\overrightarrow{\sigma}^{+\Uparrow}+\overleftarrow{\sigma}^{+\Downarrow}+\overrightarrow{\sigma}^{+\Downarrow}+\overleftarrow{\sigma}^{+\Uparrow})+(\overrightarrow{\sigma}^{+\Uparrow}+\overleftarrow{\sigma}^{+\Downarrow}+\overrightarrow{\sigma}^{+\Downarrow}+\overleftarrow{\sigma}^{+\Uparrow})}$$

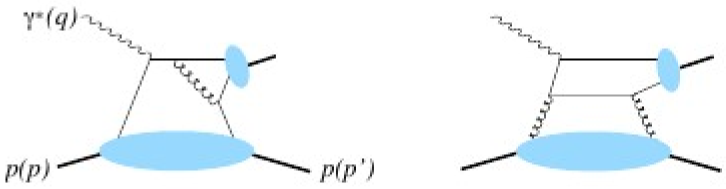
$\propto \mathrm{Re}[F_2\mathcal{H} - F_1\mathcal{E}]$

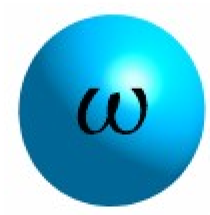


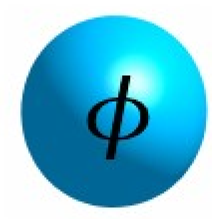
- ✔ $A_{\rm LT,I}^{\sin(\phi-\phi_S)\sin\phi}$ sensitive to the real part of GPD E
- ✔ could provide an independent constraint
- ✔ suppressed kinematically

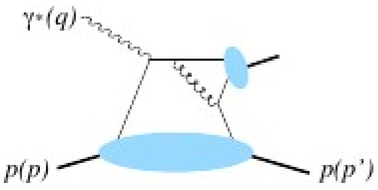
DESY

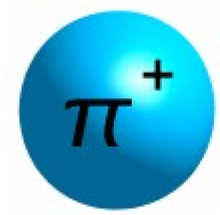

ρ

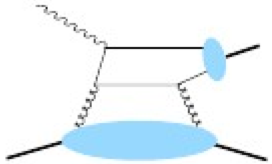

γ*(q)
p(p)
p(p')


ω


φ


γ*(q)
p(p)
p(p')


π+

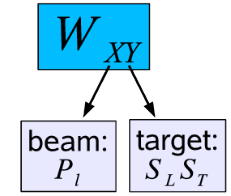


Vector Meson cross-section decompositions

- Fully differential cross-section

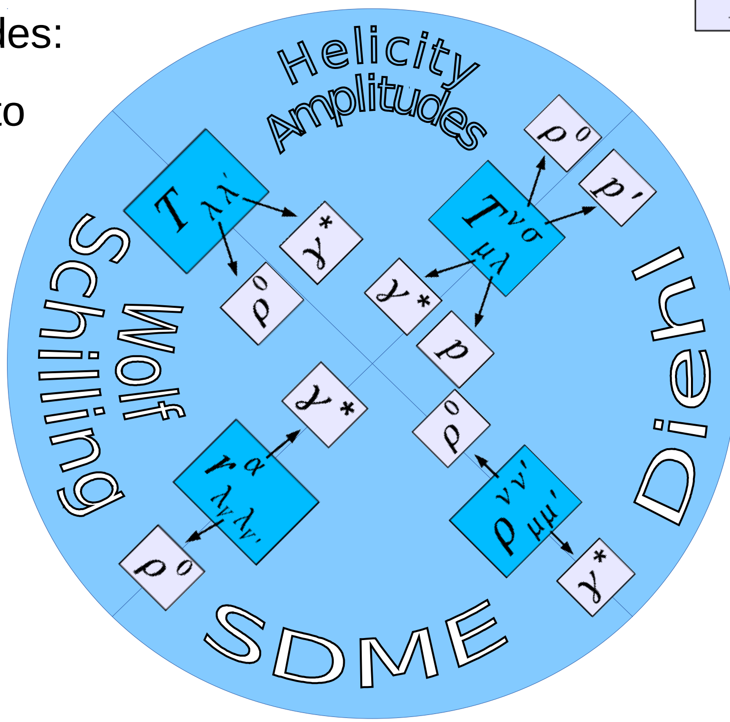
$$\frac{d\sigma}{dx_B\, dQ^2\, dt\, d\phi_s\, d\phi\, d\cos\vartheta\, d\varphi} \sim \frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi_s, \phi, \cos\vartheta, \varphi)$$

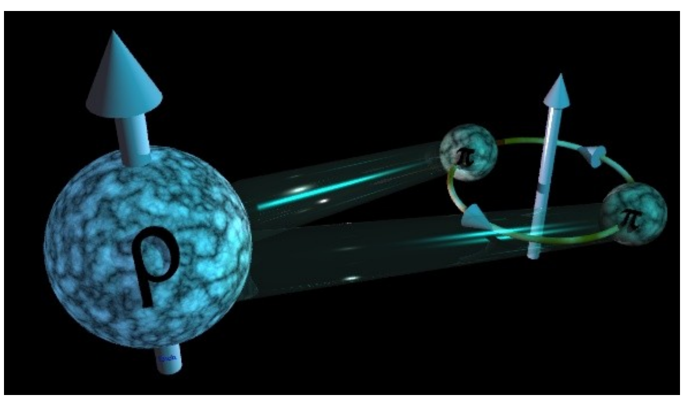
- Decomposed through production and decay angular distributions **W**



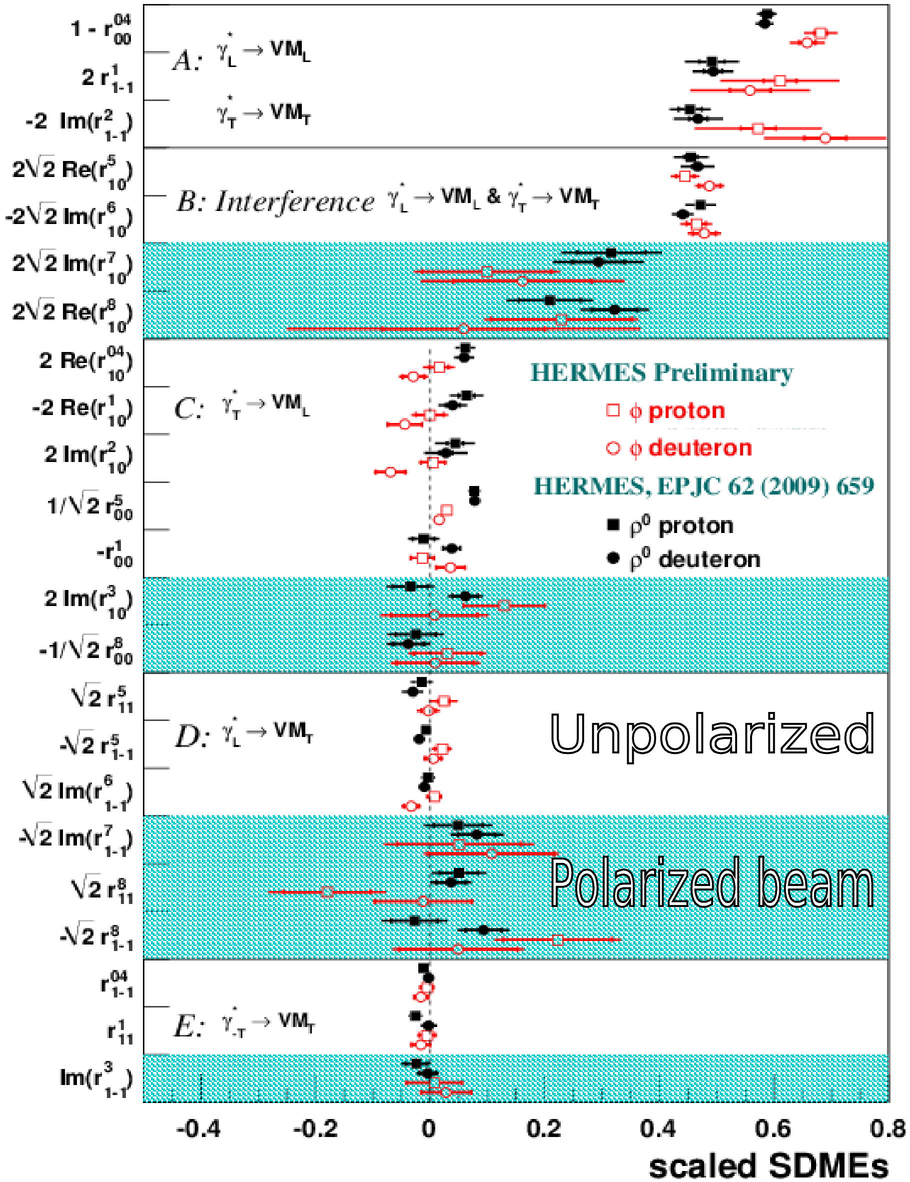
$$W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT}$$

- Parametrized through SDMEs or helicity amplitudes:
- Describe the helicity transfer from virtual photon to the produced meson
- and the parity of the exchange process:
  - Natural parity (vacuum quantum numbers) related to H and E
  - Unnatural parity related to $\widetilde{H}$ and $\widetilde{E}$





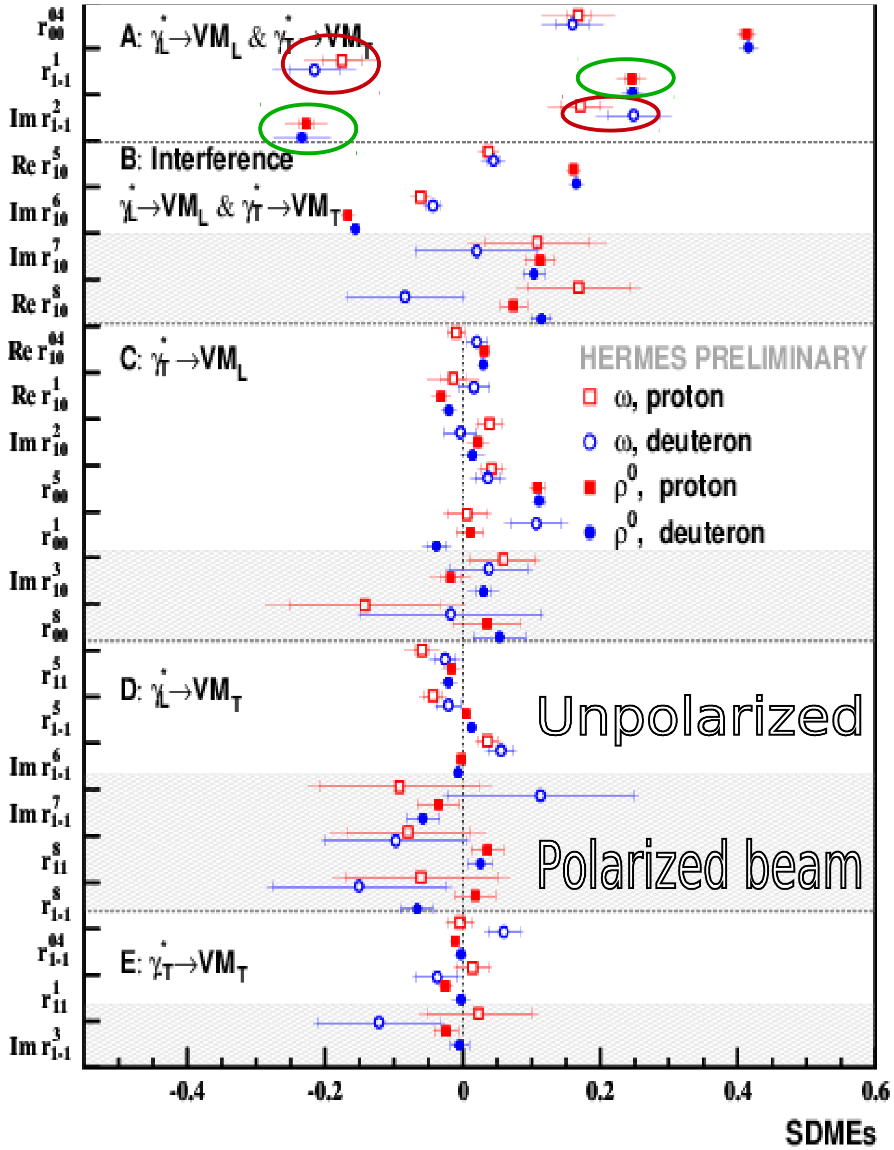
SDMEs on Unpolarized Target(s) $ep \to e'\rho^0 p'$ $ep \to e'\phi^0 p'$



23 SDMEs in 5 classes:

- **A:** leading class, helicity transfer conforms SCHC
  - ϕ SDMEs are 10% larger than ρ
- **B:** similar values for L/T interference SDME
- **C:** pronounced differences between ϕ/ρ
  - Hints of smaller longitudinal quark motion in ϕ meson
- **D, E:** mainly compatible with zero
- Proton and Deuterium results compatible

SDMEs on Unpolarized Target(s) $ep \to e'\rho^0 p'$ $ep \to e'\omega^0 p'$



23 SDMEs in 5 classes:

- **A:** different sign of leading twist SDMEs compared to ρ
  - indication of unnatural parity exchange!

- **D:** Some SDMEs indicate SCHC violation

Unnatural Parity Exchange Observations (ρ,ω,ϕ)

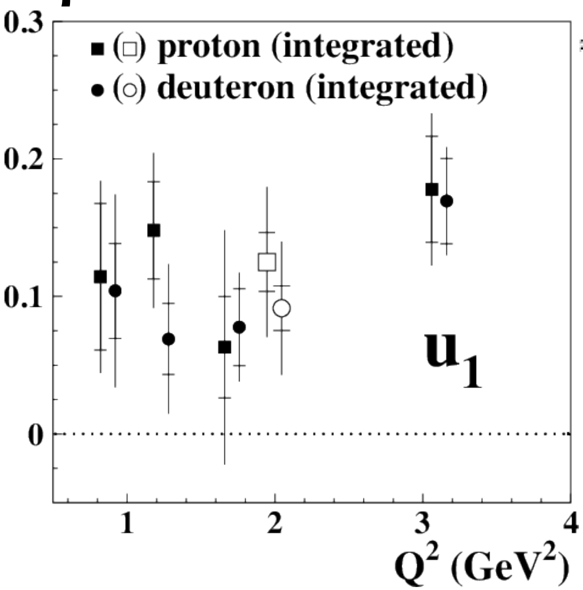
- At large Q^2 and W the **unnatural** parity exchange should be suppressed by M_V/Q
- The combinations of SDMEs expected to be zero in case of natural parity exchange dominance:

$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^1_{11} - 2r^1_{1-1} \qquad u_2 = r^5_{11} + r^5_{1-1} \qquad u_3 = r^8_{11} + r^8_{1-1}$$

(Wolf-Schilling notation)

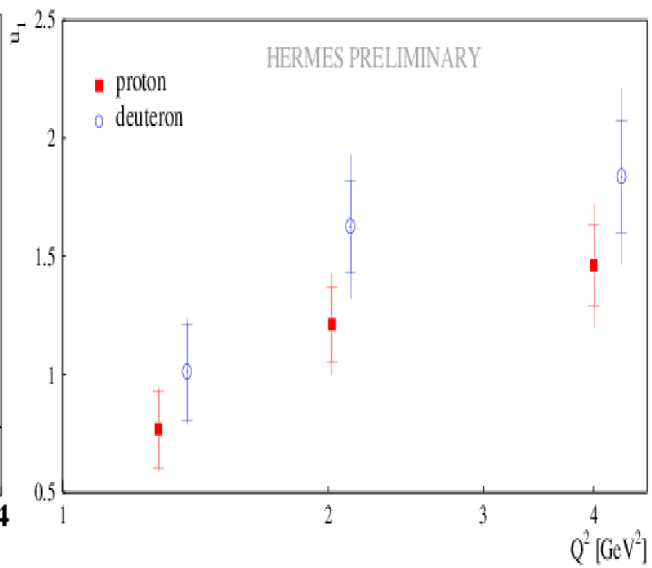
[EPJC 62 (2009) 659]

ρ: non-zero UPE (3σ)

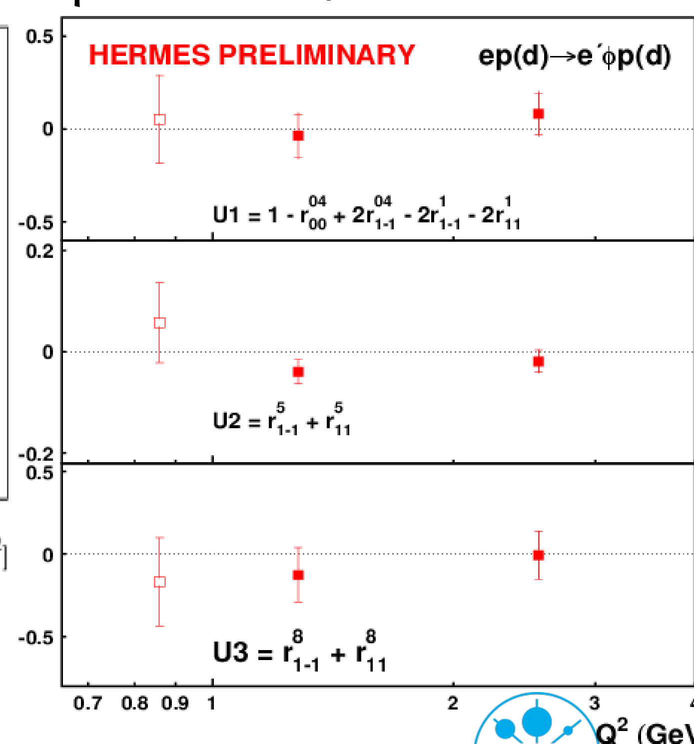


Possible access to GPD $\widetilde{H}$

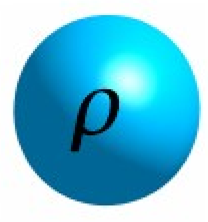
ω: Dominant UPE signal!

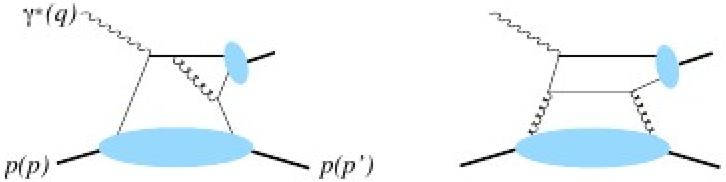


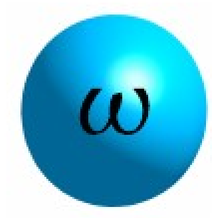
ϕ: UPE compatible with zero

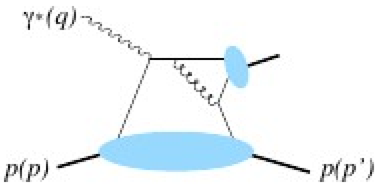


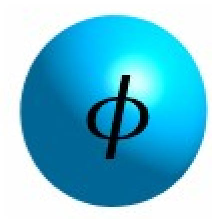
Unnatural Parity Exchange Observations (ρ,ω,ϕ)

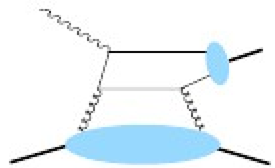












SDMEs on a Transversely Polarized Target $ep^{\uparrow} \rightarrow e'\rho^0 p'$

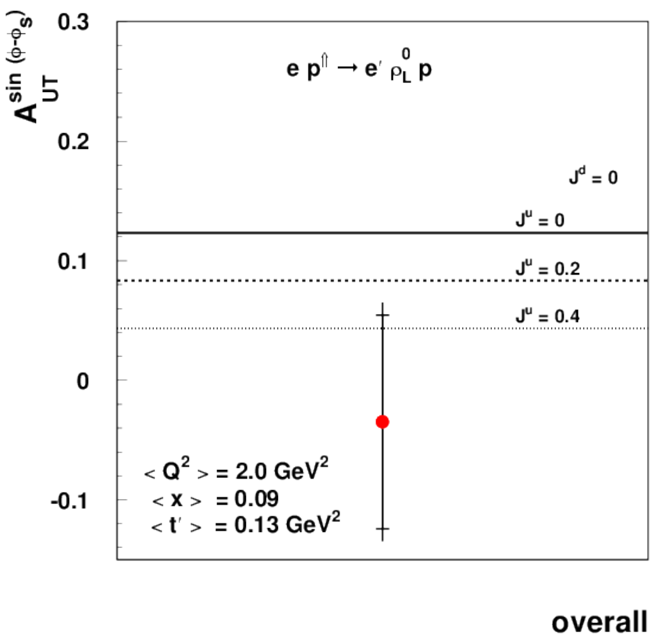
[Phys. Lett. B679 (2009) 100-105]

- Suppressed by factor $\sqrt{-t}/2M_p$
- Out of 30 SDMEs only one sensitive to GPD E

$$A_{UT}^{\sin(\phi-\phi_s)} = \frac{\mathrm{Im} n_{00}^{00}}{u_{00}^{00}} \propto \frac{\mathrm{Im}(\mathcal{E}_V{}^*\mathcal{H}_V)}{|\mathcal{H}_V|^2} \propto \left|\frac{\mathcal{E}_V}{\mathcal{H}_V}\right| \sin\delta$$

(Diehl notation)

[Ellinghaus,Nowak,Vinnikov, Ye (2004)]

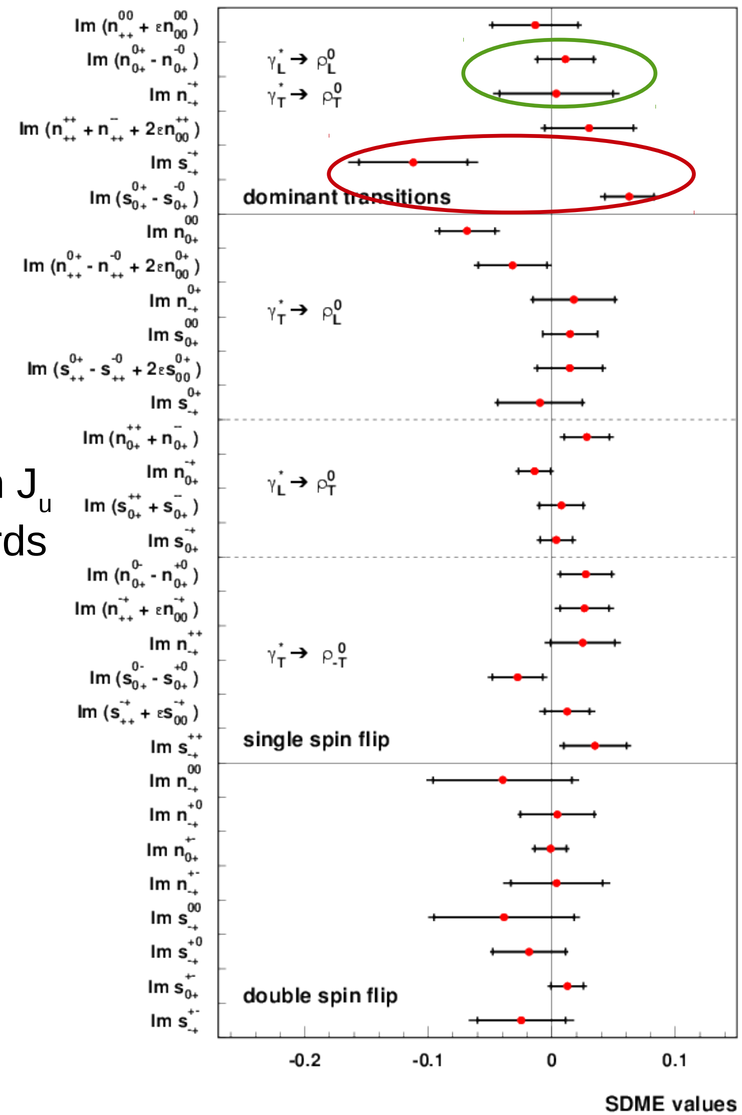


Model-based constraint on J_u indicates preference towards positive values

- UPE signature:

$$s_{\mu\mu'}^{\nu\nu'} > n_{\mu\mu'}^{\nu\nu'}$$

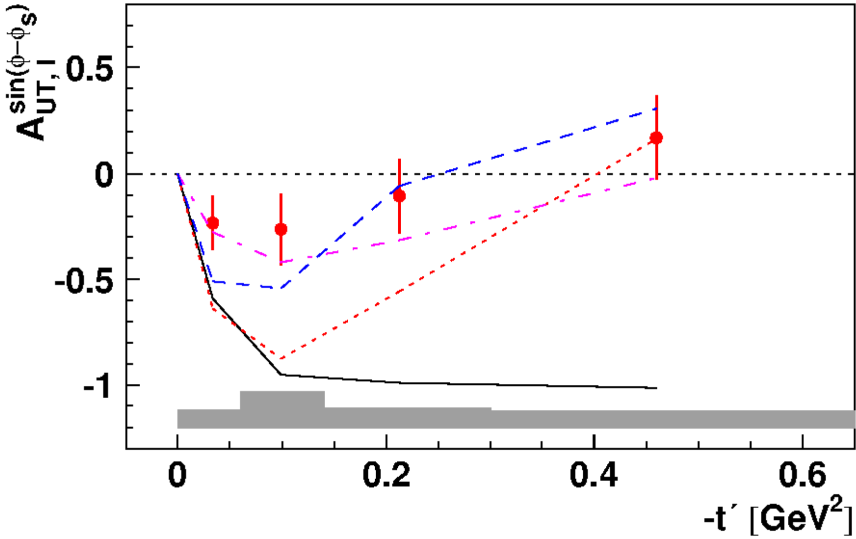
- Access GPD $\widetilde{H}, \widetilde{E}$



π^+ on a Transversely Polarized Target

$ep^\uparrow \rightarrow e'\pi^+ n$

[Phys. Lett. B 682 (2010) 345-350]



> No σ_L/σ_T separation

> Small overall asymmetry with possible sign change

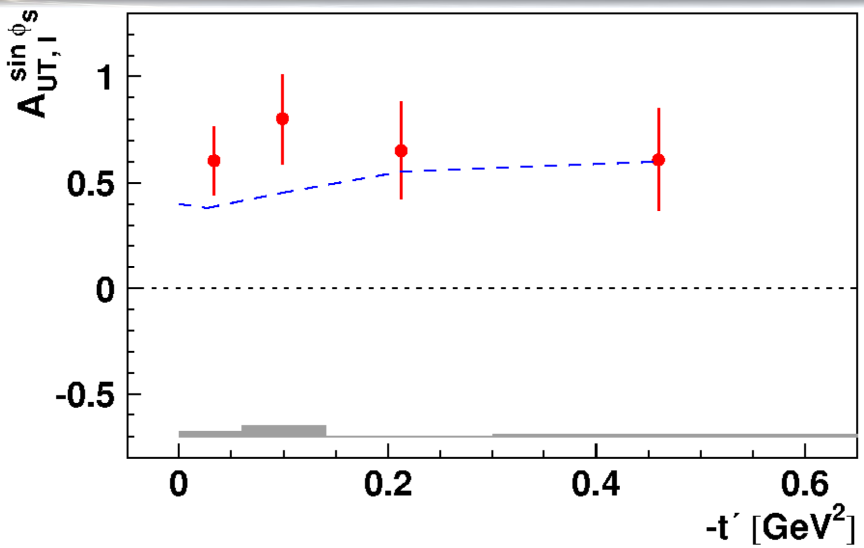
$$A_{UT}^{\sin(\phi-\phi_S)} \propto \frac{\mathrm{Im}(\widetilde{\mathcal{H}} * \widetilde{\mathcal{E}})}{|\widetilde{\mathcal{H}}|^2} \propto |\frac{\widetilde{\mathcal{E}}}{\widetilde{\mathcal{H}}}| \sin\delta$$

> Theoretical expectations – suppression by $\sqrt{-t}$

-Frankfurt et al. (2001)- -Belitsky, Muller (2001)-

-Goloskokov, Kroll (2009)- -Bechler, Muller (2009)-

> Evidence of contribution from γ^*_T



> Unexpectedly large signal for subleading twist

> No turnover towards 0 at t'→0

> Can be explained by σ_L/σ_T interference

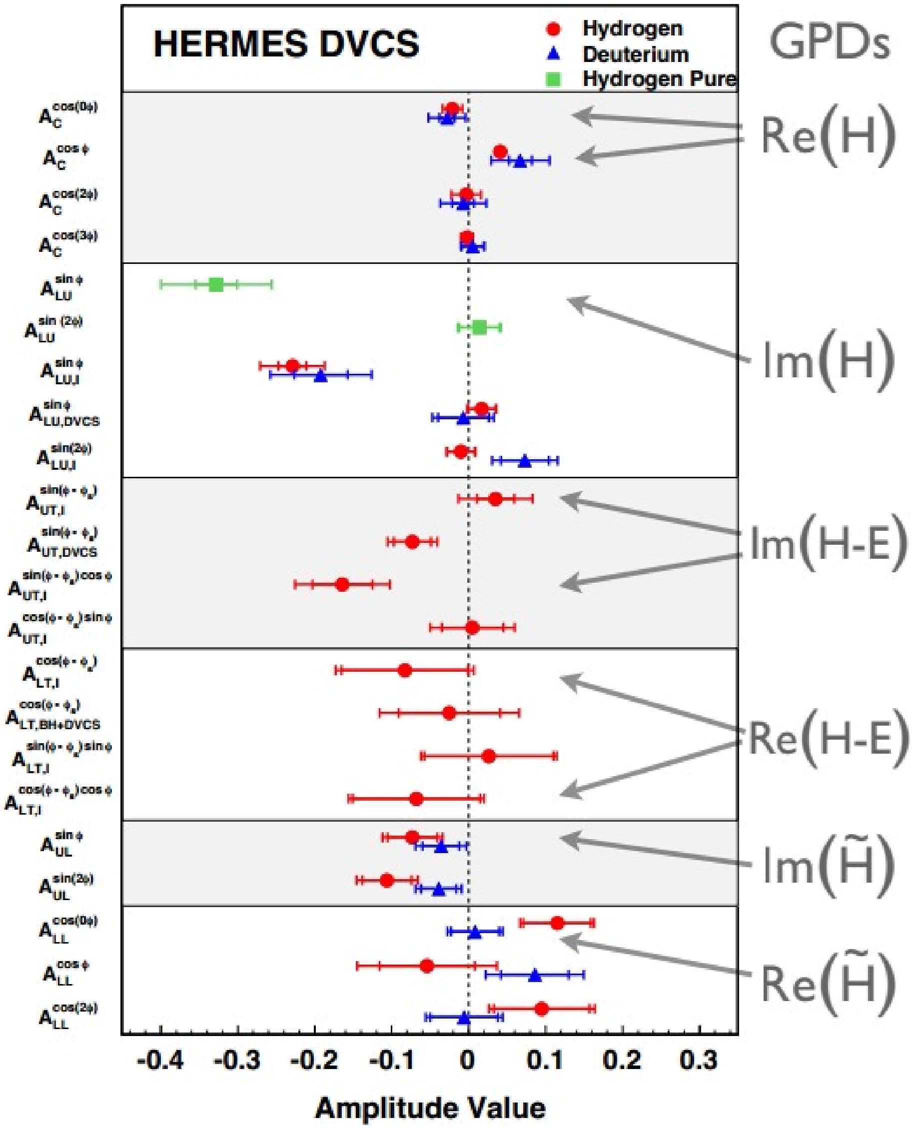
> In good agreement with model prediction

  – Goloskokov, Kroll (2009)

> Sensitive to H_T GPD

> Evidence of contribution from γ^*_T

Summary – DVCS



A. Airapetian et al, JHEP 06 (2008) 066

A. Airapetian et al, Nucl. Phys. B 829 (2010) 1-27

A. Airapetian et al, JHEP 06 (2010) 019

A. Airapetian et al, Nucl. Phys. B 842 (2011) 265-298

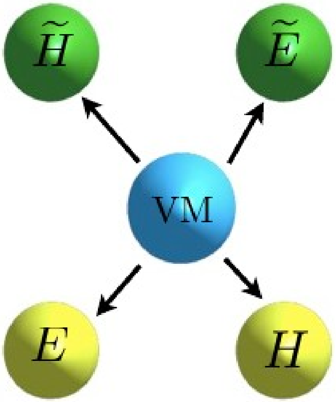
A. Airapetian et al, JHEP 07 (2012) 032

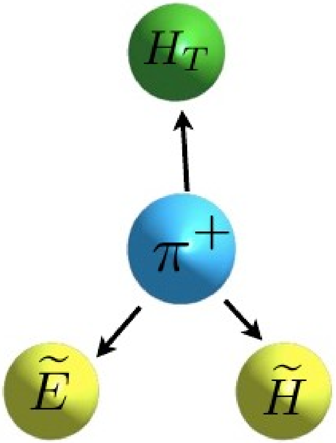
A. Airapetian et al, Phys. Lett. B 704 (2011) 15-23

A. Airapetian et al, JHEP 10 (2012) 042

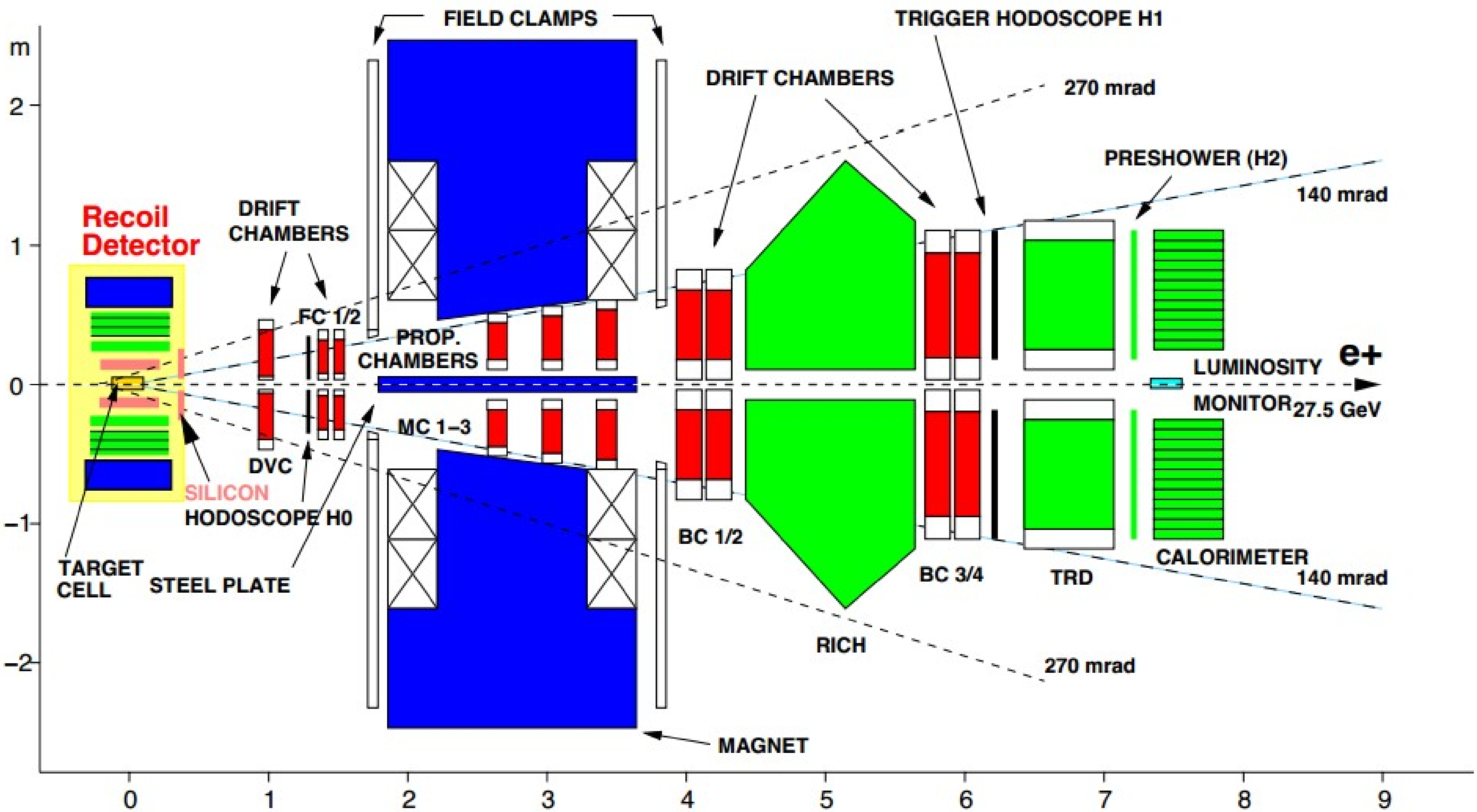
Summary – Mesons

- Single- and double-spin azimuthal asymmetries in meson production provide access to GPDs
- Transverse target asymmetries give model-based predictions/constraints for quark total orbital angular momentum (Ji framework)
- Significant signal of unnatural parity exchange observed in w meson production provides access to spin-flip GPD $\widetilde{H}$
- π^+ production allows access to subleading twist "transverse" GPD H_T





Backup slides



GPD E and J_u Constraint