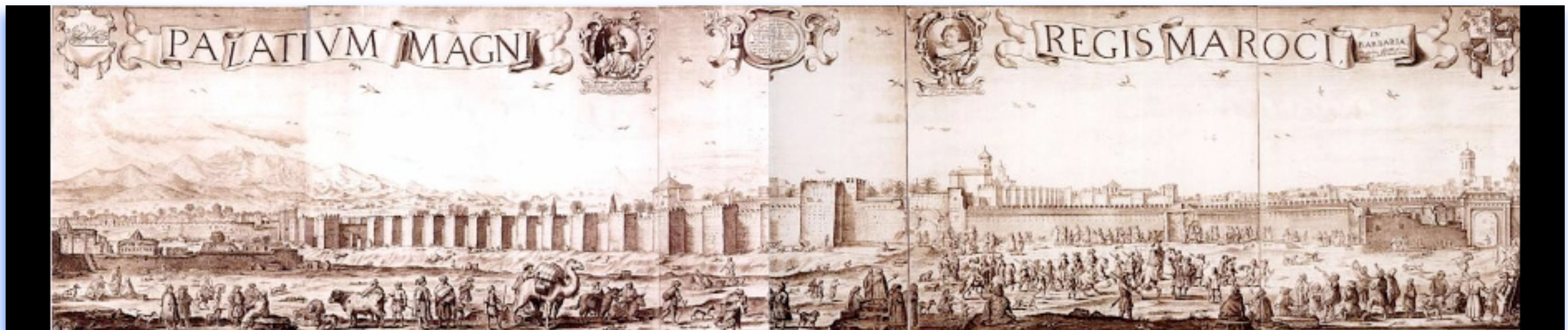
Exclusive hard processes at HERMES

Ami Rostomyan

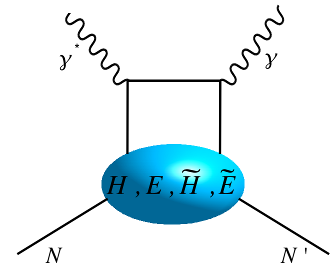


Partons in nucleons and nuclei

Marrakech, Morocco

2011

DVCS



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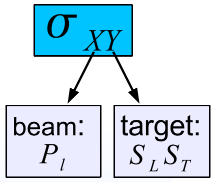
$$\gamma^* \to \gamma : H, E, \widetilde{H}, \widetilde{E}$$

- experimentally probing Compton form factors
- theoretical accuracy at NNLO



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d\sigma \sim d\sigma^{BH}_{UU} \quad &+ \quad e_\ell d\sigma^{I}_{UU} + d\sigma^{DVCS}_{UU} \\
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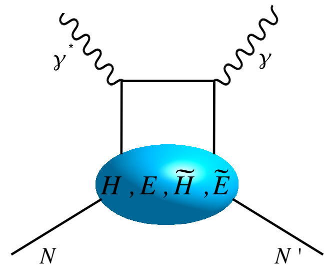

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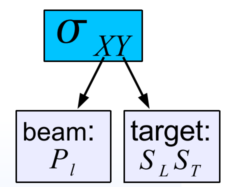

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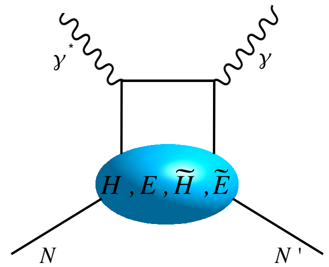
single spin terms:

- no pure Bethe-Heitler contribution
- project imaginary parts of Compton form factors

unpolarized and double-spin terms:

- project real parts of Compton form factors

DVCS



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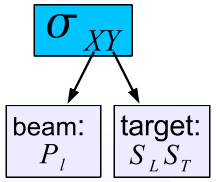

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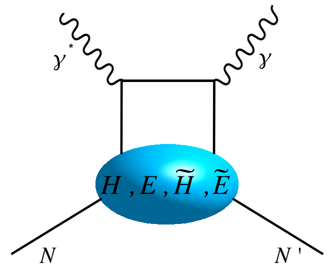

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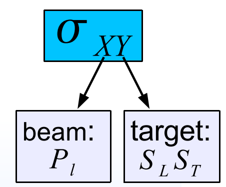

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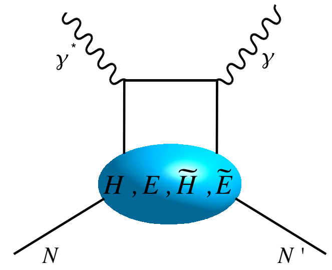
- Fourier expansion in azimuthal angle

interference term:

azimuthal modulation	$\gamma^*(\mu) \to \gamma(\mu')$	relative order
constant	$1 \to +1$	$1/Q$
$\cos\phi, \sin\phi$	$1 \to +1$	1
$\cos 2\phi, \sin 2\phi$	$0 \to +1$	$1/Q$
$\cos 3\phi, \sin 3\phi$	$-1 \to +1$	$1/Q^2$ *or* α_s

DVCS



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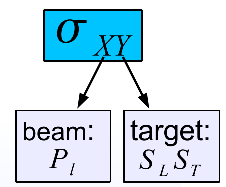

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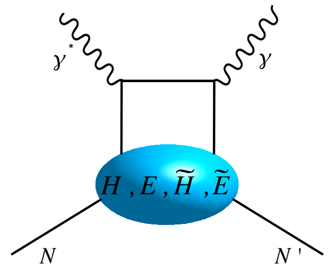

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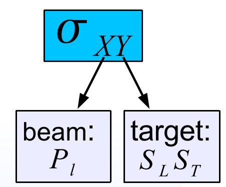

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- unpolarized target

$$F_1 \mathcal{H} + \frac{x_B}{2 - x_B}(F_1 + F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}$$

- longitudinally polarized target

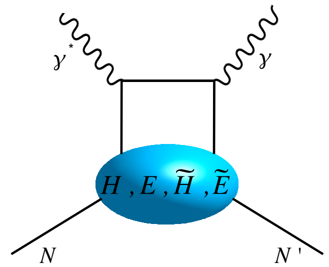
$$\frac{x_B}{2 - x_B}(F_1 + F_2)\left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right)$$

$$+F_1 \widetilde{\mathcal{H}} - \frac{x_B}{2 - x_B}\left(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2\right)\widetilde{\mathcal{E}}$$

- transversely polarized target

$$\frac{t}{4M^2}\left[(2 - x_B)F_1 \mathcal{E} - 4\frac{1 - x_B}{2 - x_B}F_2 \mathcal{H}\right]$$

DVCS



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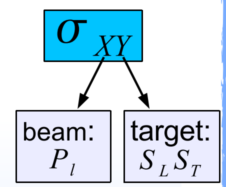

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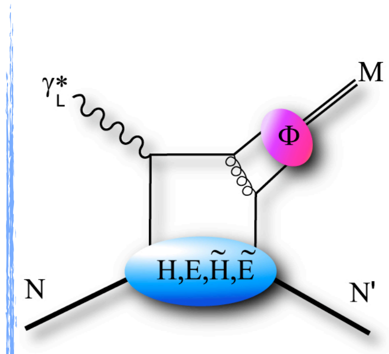
meson production



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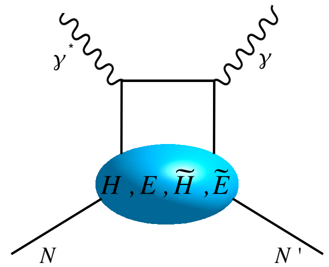

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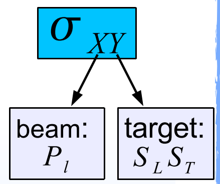

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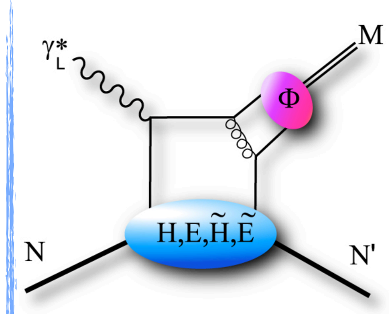

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-Goloskokov, Kroll (2006)-

- power corrections: $k_\perp$ is not neglected}
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- $\gamma^*_T \to \rho^0_T$ transitions can be calculated

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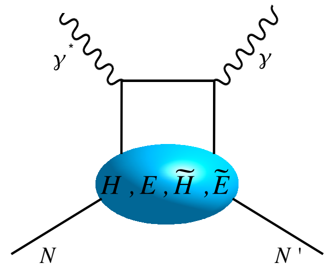

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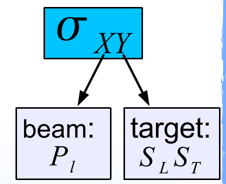

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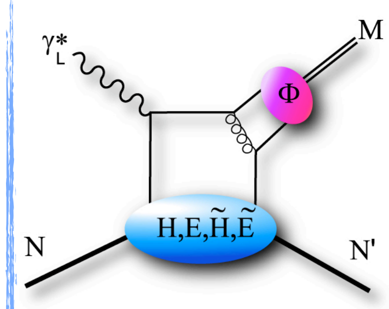

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<u>vector mesons</u>

at leading twist: H and E
higher twist: $\widetilde{H}$ and $\widetilde{E}$

unpolarized target

transversely polarized target

<u>pseudoscalar mesons</u>

at leading twist: $\widetilde{H}$ and $\widetilde{E}$
higher twist: H_T

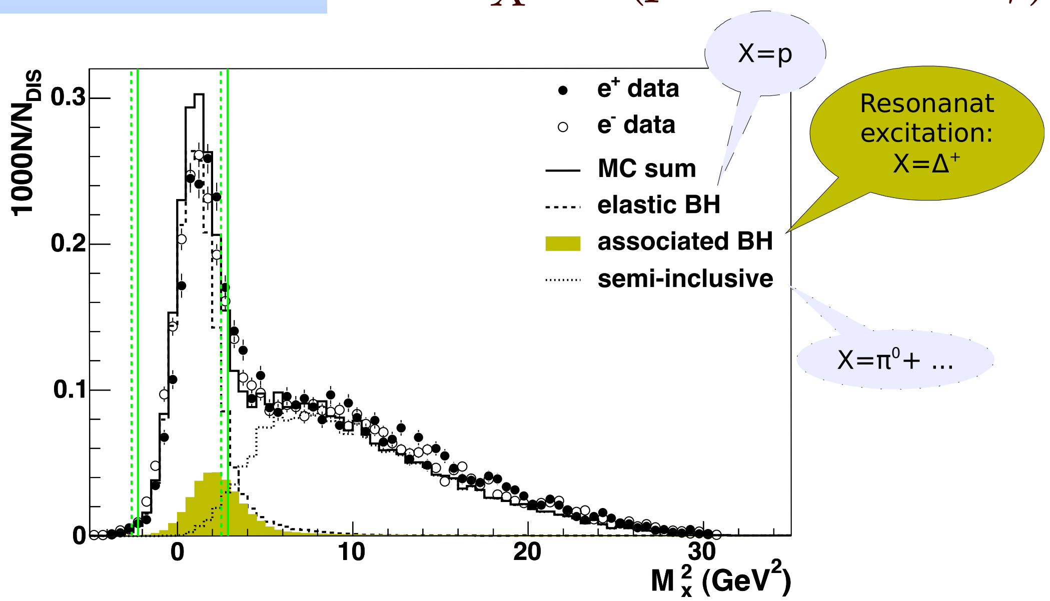
hard processes at HERMES

$ep \to e'\gamma X$

(pre-recoil data)

☛ missing mass technique

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



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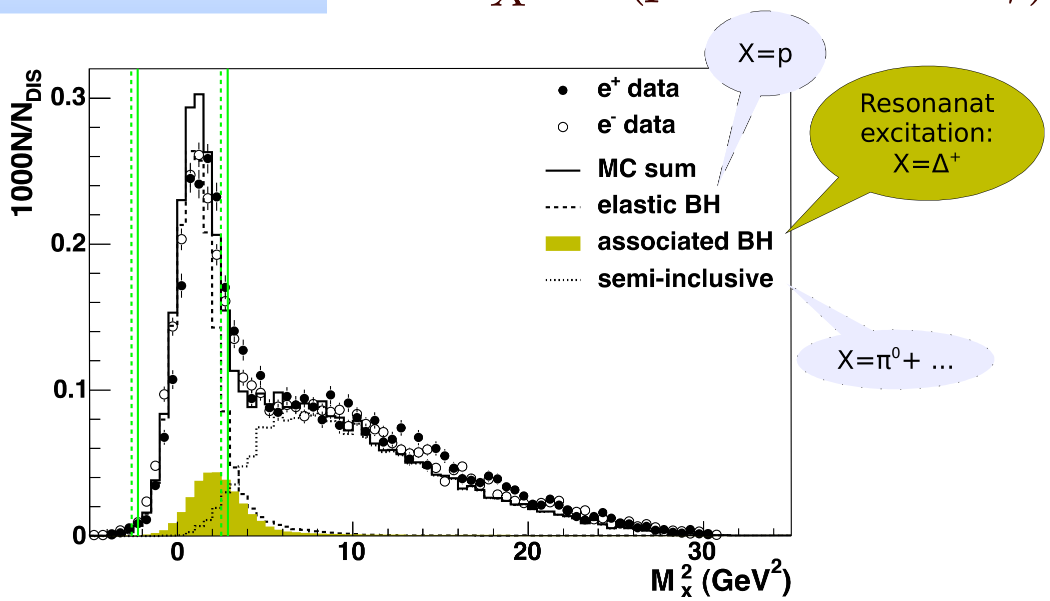
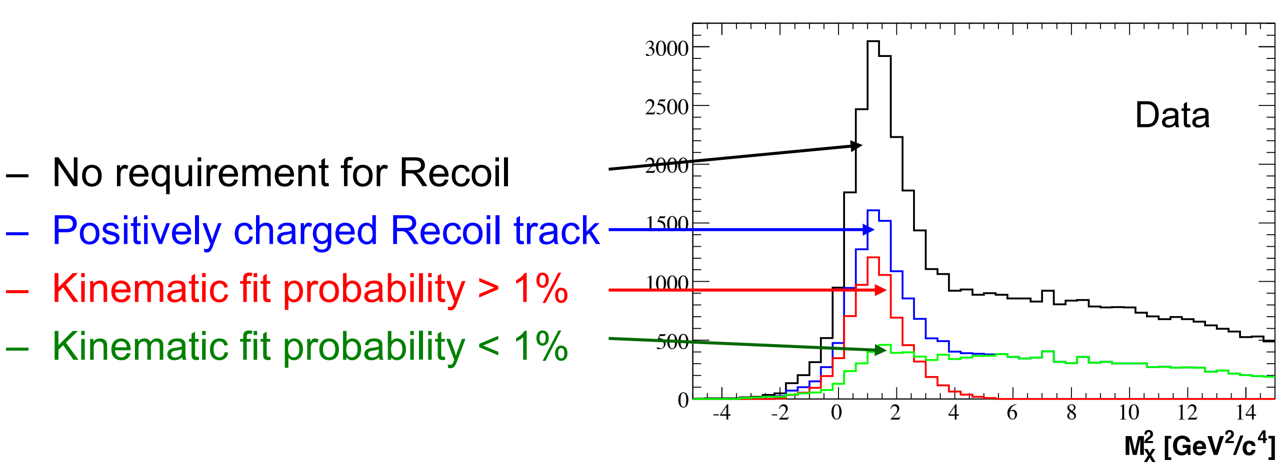


$ep \to e'\gamma p'$ (recoil data)

☛ suppression of background from associated and semi-inclusive processes to a negligible level (~0.1%)



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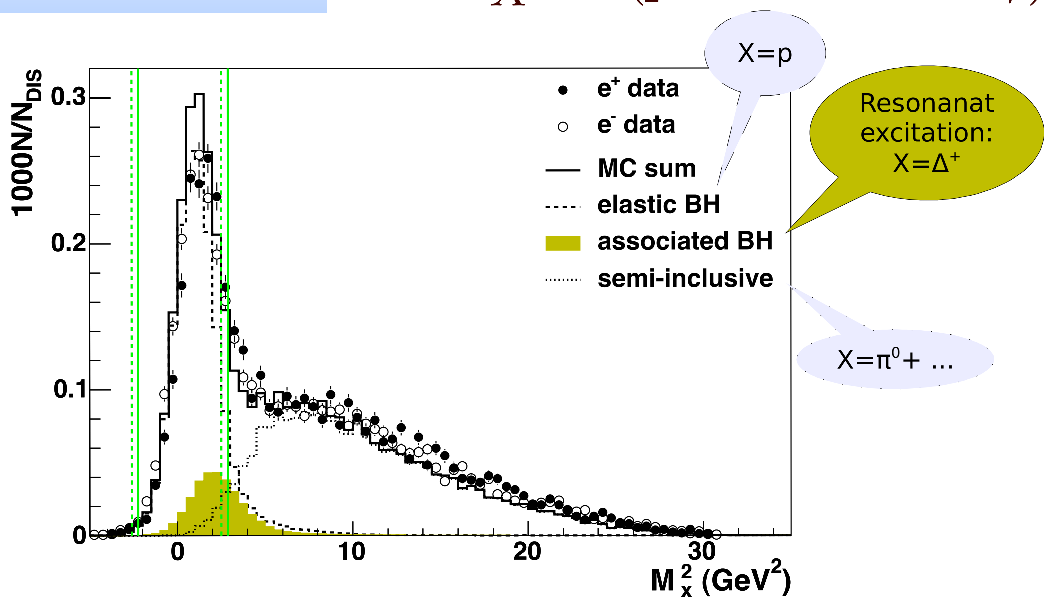

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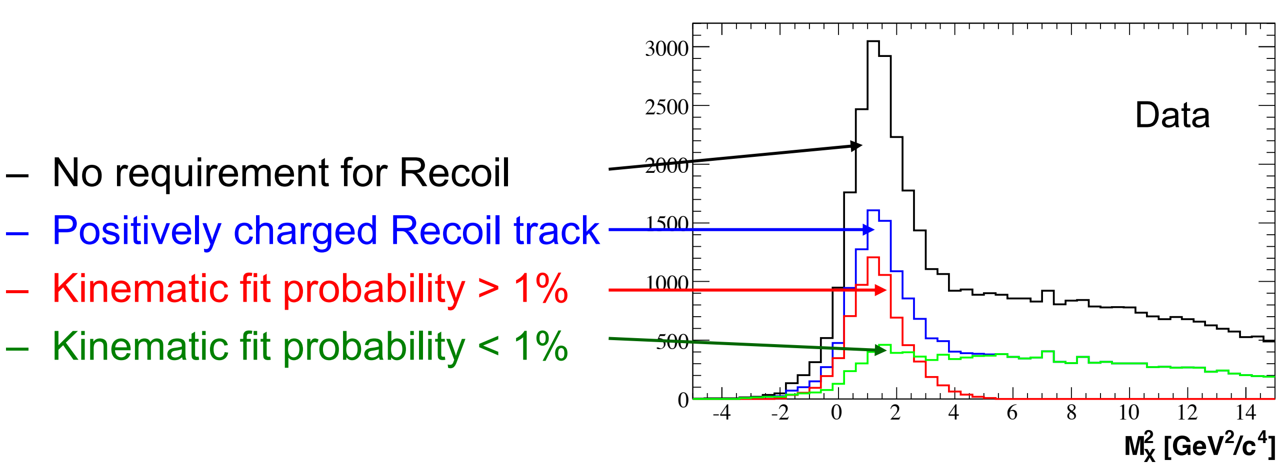
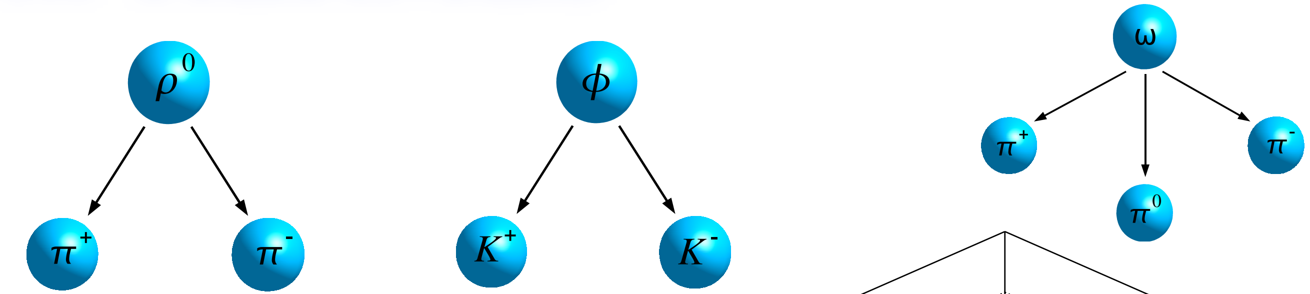


$ep \to e'$ VM p'

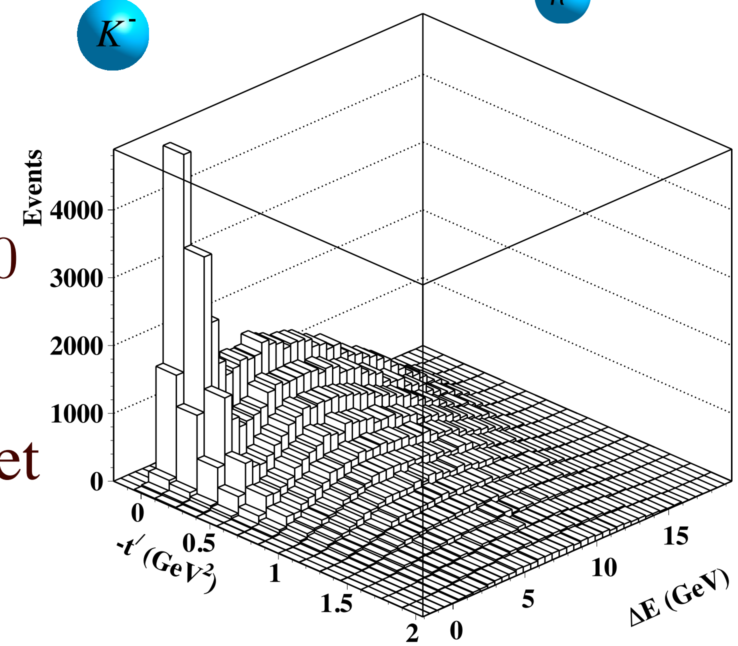


☛ elastic scattering

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

☛ only little energy transferred to the target

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



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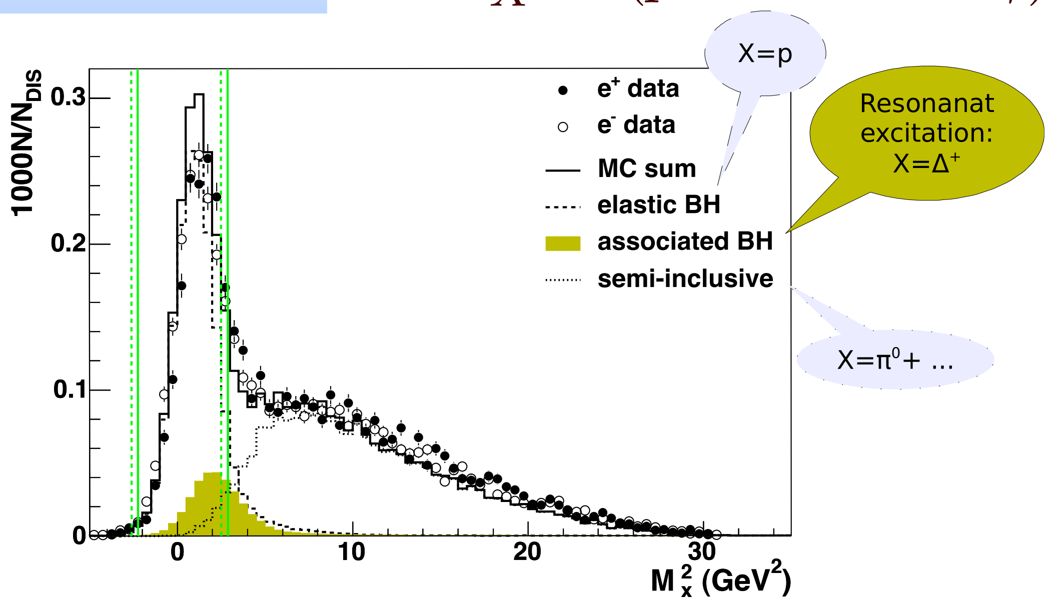
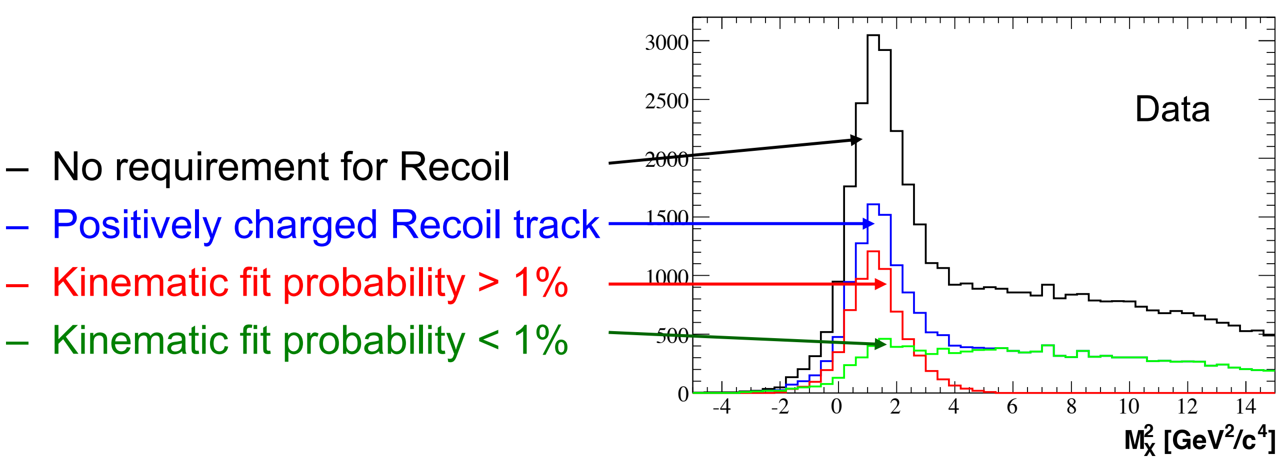
☛ missing mass technique

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

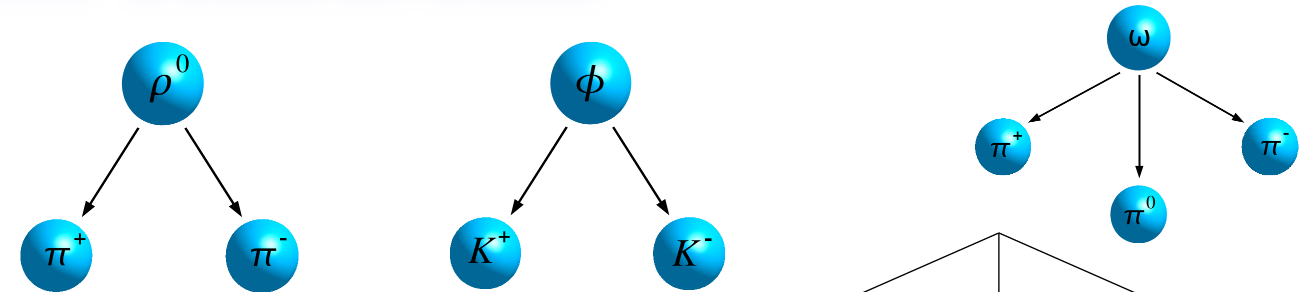


$ep \to e'\gamma p'$ (recoil data)

☛ suppression of background from associated and semi-inclusive processes to a negligible level (~0.1%)



$ep \to e'$ VM p'

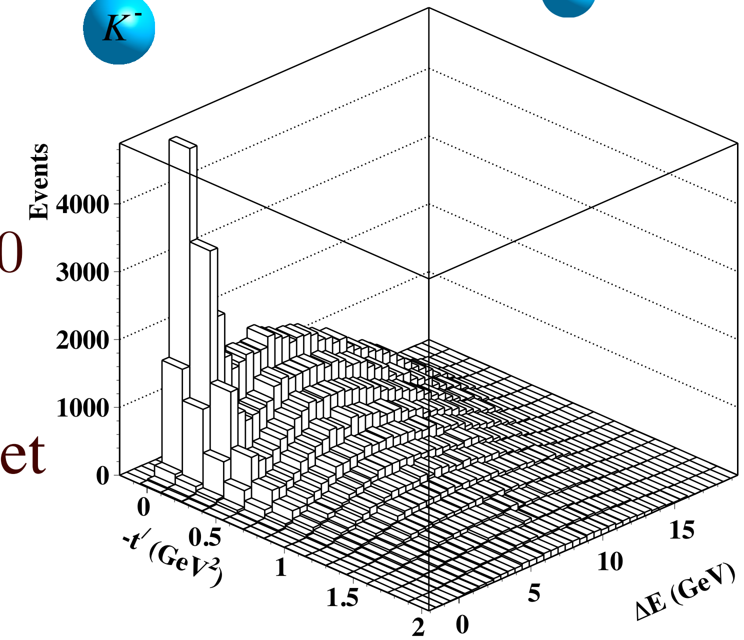


☛ elastic scattering

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

☛ only little energy transferred to the target

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



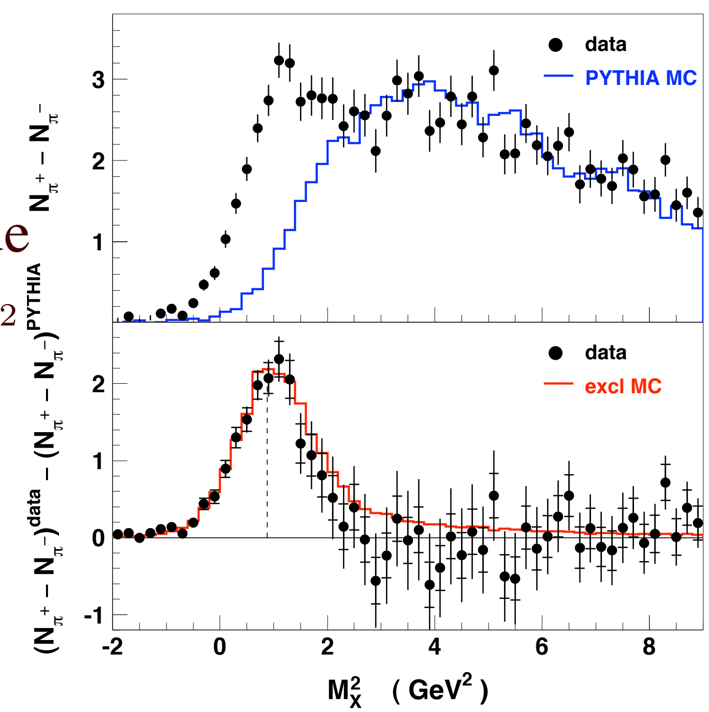
$$N^{excl} = (\pi^+ - \pi^-)^{data} - (\pi^+ - \pi^-)^{MC}$$

$ep \to e'\pi^+(n)$

☛ missing mass technique

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

☛ charged pion yield difference was used to subtract the non exclusive background



GPD H: *unpolarized hydrogen target*

γ

$ep \rightarrow e'\gamma X$

(pre-recoil data)

-HERMES Collaboration- : JHEP 11 (2009) 083

$$\sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[1 + P_\ell \mathcal{A}_{LU}^{DVCS}(\phi) + e_\ell P_\ell \mathcal{A}_{LU}^{I}(\phi) + e_\ell \mathcal{A}_C(\phi)\right]$$

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

$$\mathcal{A}_{LU}^{I}(\phi) = \sum_{n=1}^{2} A_{LU,\mathrm{I}}^{\sin(n\phi)} \sin(n\phi)$$

GPD H: *unpolarized hydrogen target*

$ep \to e'\gamma X$

(pre-recoil data)

-HERMES Collaboration- : JHEP 11 (2009) 083

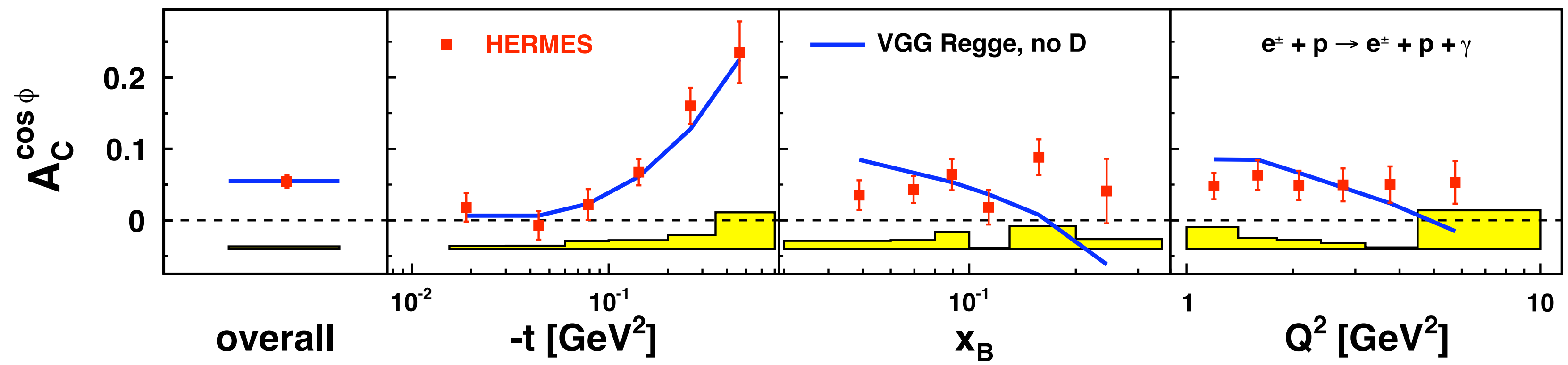
$$\sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[1 + P_\ell \mathcal{A}_{LU}^{DVCS}(\phi) + e_\ell P_\ell \mathcal{A}_{LU}^{I}(\phi) + e_\ell \mathcal{A}_C(\phi)\right]$$

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

$$\mathcal{A}_{LU}^{I}(\phi) = \sum_{n=1}^{2} A_{LU,\mathrm{I}}^{\sin(n\phi)} \sin(n\phi)$$

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

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



beam charge asymmetry

☛ strong t-dependence

☛ no x_B or Q^2 dependences

GPD H: *unpolarized hydrogen target*

$ep \to e'\gamma X$

(pre-recoil data)

-HERMES Collaboration- : JHEP 11 (2009) 083

$$\sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[1 + P_\ell \mathcal{A}_{LU}^{DVCS}(\phi) + e_\ell P_\ell \mathcal{A}_{LU}^{I}(\phi) + e_\ell \mathcal{A}_C(\phi)\right]$$

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

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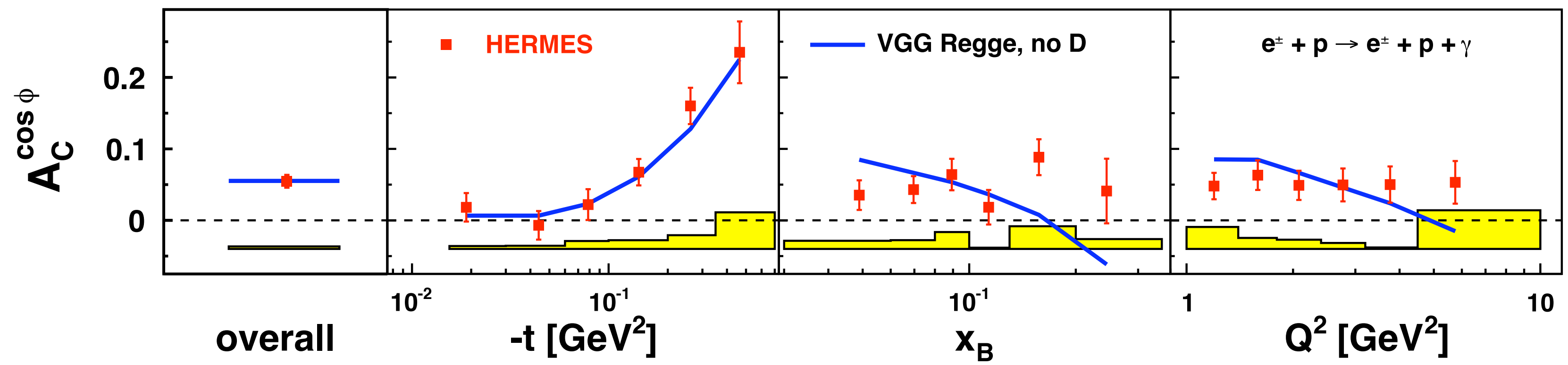
$$\mathcal{A}_C(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) - (\sigma^{-\rightarrow} + \sigma^{+\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{+\leftarrow})}$$

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

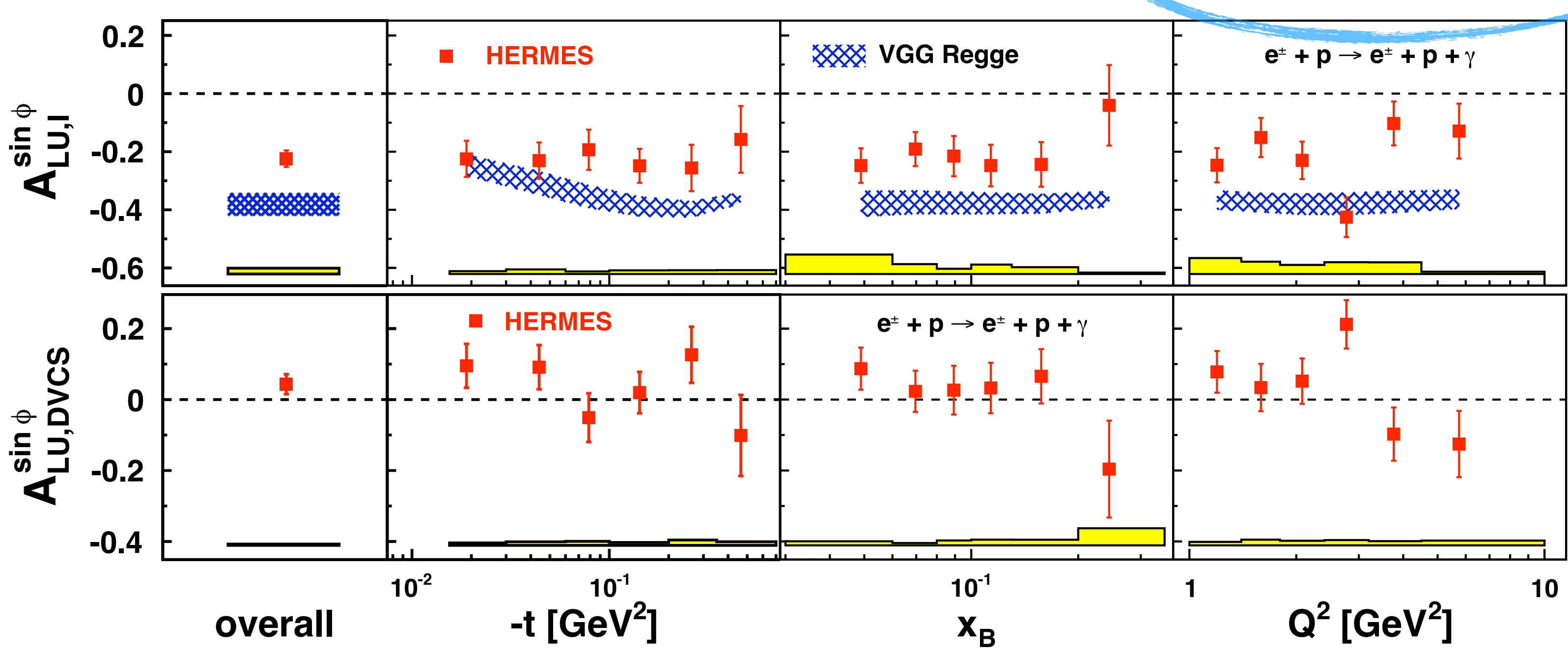


beam charge asymmetry

- ☛ strong t-dependence
- ☛ no x_B or Q^2 dependences

$$\mathcal{A}_{LU}^{I,DVCS}(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) \pm (\sigma^{-\rightarrow} - \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})}$$

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



charge-difference beam helicity asymmetry

- ☛ large overall value
- ☛ no kin. dependencies

charge-averaged beam helicity asymmetry

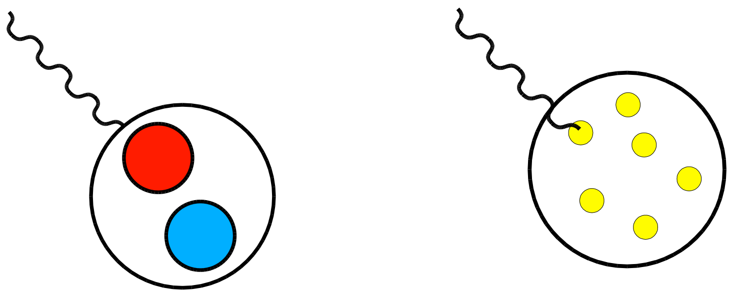
- ☛ consistent with zero

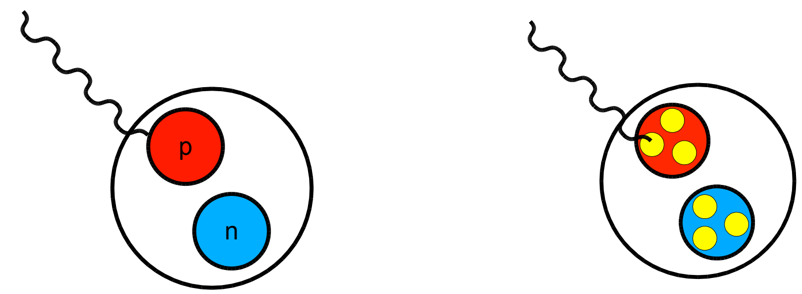
$$A_{LU,\mathrm{DVCS}}^{\sin\phi} \propto \mathrm{Im}[\mathcal{H}\mathcal{H}^* - \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*]$$

unpolarized deuterium target

☛ coherent: $e^{\pm}d \rightarrow e^{\pm}d\gamma$

☛ incoherent: $e^{\pm}d \rightarrow e^{\pm}pn\gamma$





☛ target stays intact

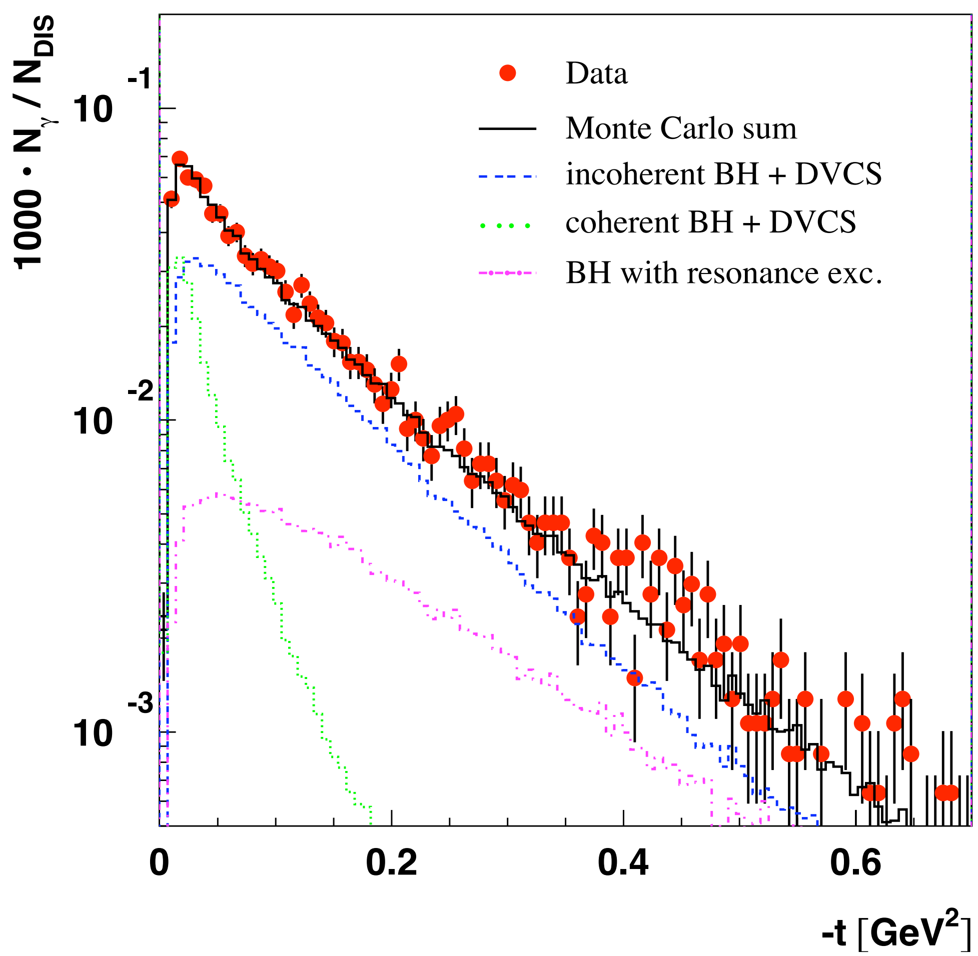
☛ spin-1 targets described by 9 GPDs:

$H_1^q, H_2^q, H_3^q, H_4^q, H_5^q, \widetilde{H}_1^q, \widetilde{H}_2^q, \widetilde{H}_3^q, \widetilde{H}_4^q$

☛ target brakes up

☛ spin-1/2 targets described by 4 GPDs:

$H, E, \widetilde{H}, \widetilde{E}$



coherent:

☛ contribution at small *-t*

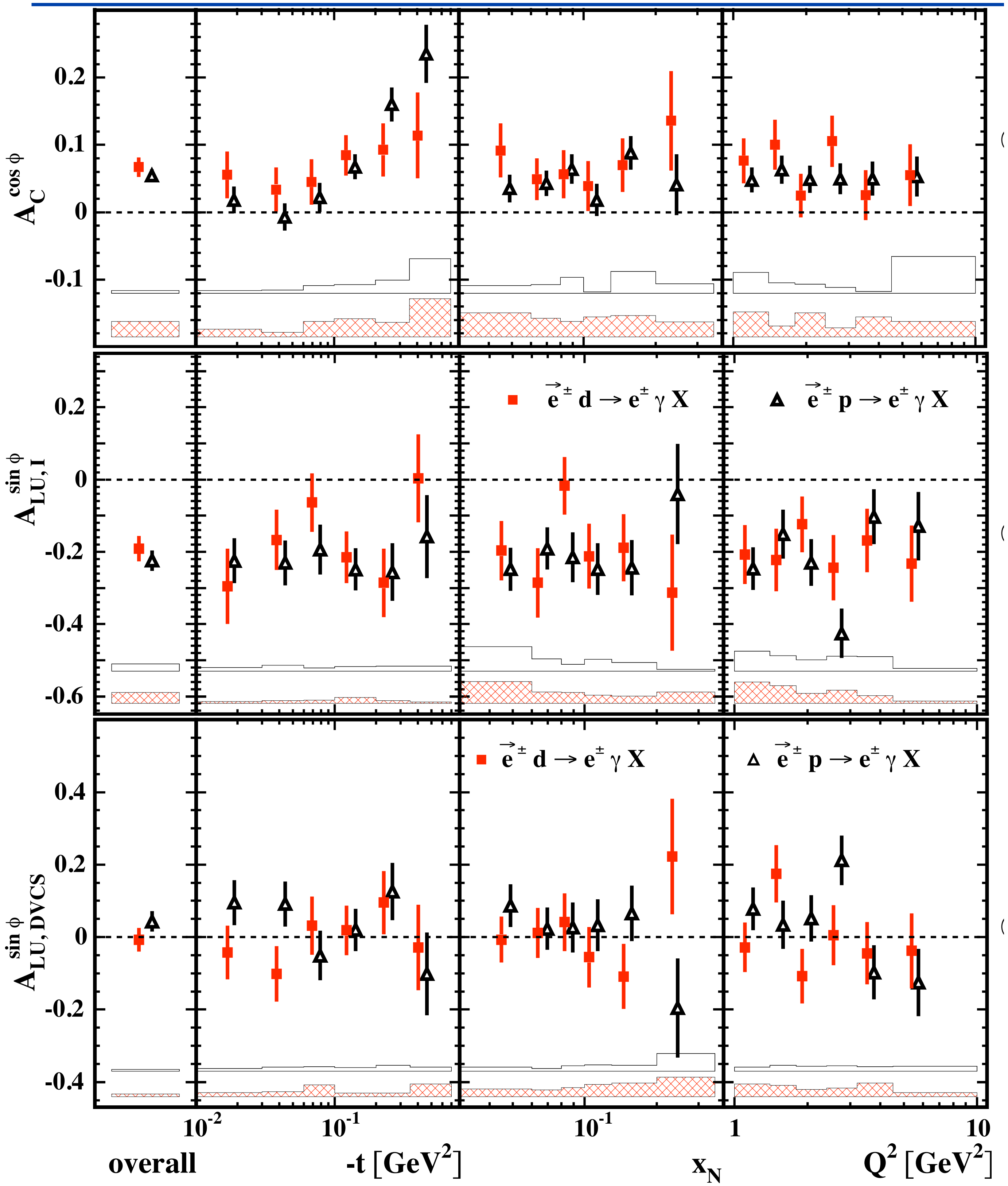
incoherent:

☛ contribution at larger *-t*

☛ contribution from coherent [0.06:0.7] GeV^2 is 20 %

GPD H: *unpolarized deuterium target*

-HERMES Collaboration-: Nucl. Phys. B 829 (2010) 1-27



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

$$\mathcal{A}_{LU}^{I}(\phi) = \sum_{n=1}^{2} A_{LU,\mathrm{I}}^{\sin(n\phi)} \sin(n\phi)$$

$$A_{C,incoh}^{\cos\phi} \propto \mathrm{Re}[F_1 \mathcal{H}]$$
$$A_{C,coh}^{\cos\phi} \propto \mathrm{Re}[G_1 \mathcal{H}_1]$$

$$A_{LU,\mathrm{I,incoh}}^{\sin\phi} \propto \mathrm{IM}[F_1 \mathcal{H}]$$
$$A_{LU,\mathrm{I,coh}}^{\sin\phi} \propto \mathrm{IM}[G_1 \mathcal{H}_1]$$

- ☛ d and p results consistent
- ☛ no clear signatures of coherent contribution at low -t

GPD H: *unpolarized hydrogen target*

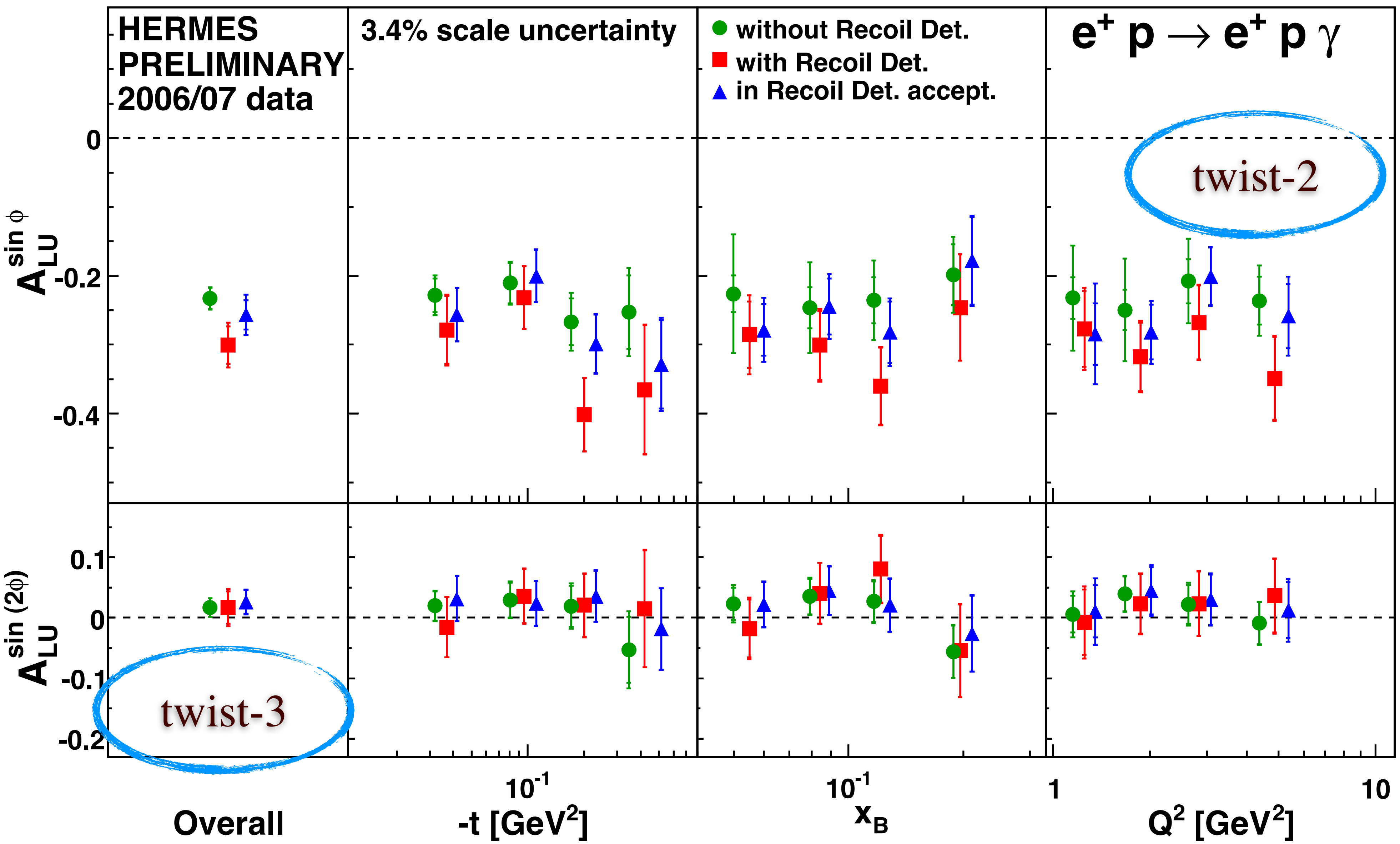
$ep \to e'\gamma p'$

(recoil data)

$$\sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[1 + P_\ell \mathcal{A}_{LU}^{DVCS}(\phi) + e_\ell P_\ell \mathcal{A}_{LU}^{I}(\phi) + e_\ell \mathcal{A}_C(\phi)\right]$$

$$\mathcal{A}_{\mathrm{LU}}(\phi) \simeq \sum_{n=1}^{2} A_{\mathrm{UL}}^{\sin(n\phi)} \sin(n\phi)$$

☛ extraction of single-charge beam-helicity asymmetry amplitudes for elastic data sample (background < 0.1%)



☛ indication for slightly larger magnitude of the leading amplitude for elastic process compared the one in the recoil detector acceptance

GPD $\widetilde{H}$: longitudinally polarized hydrogen target

$ep \to e'\gamma X$

(pre-recoil data)

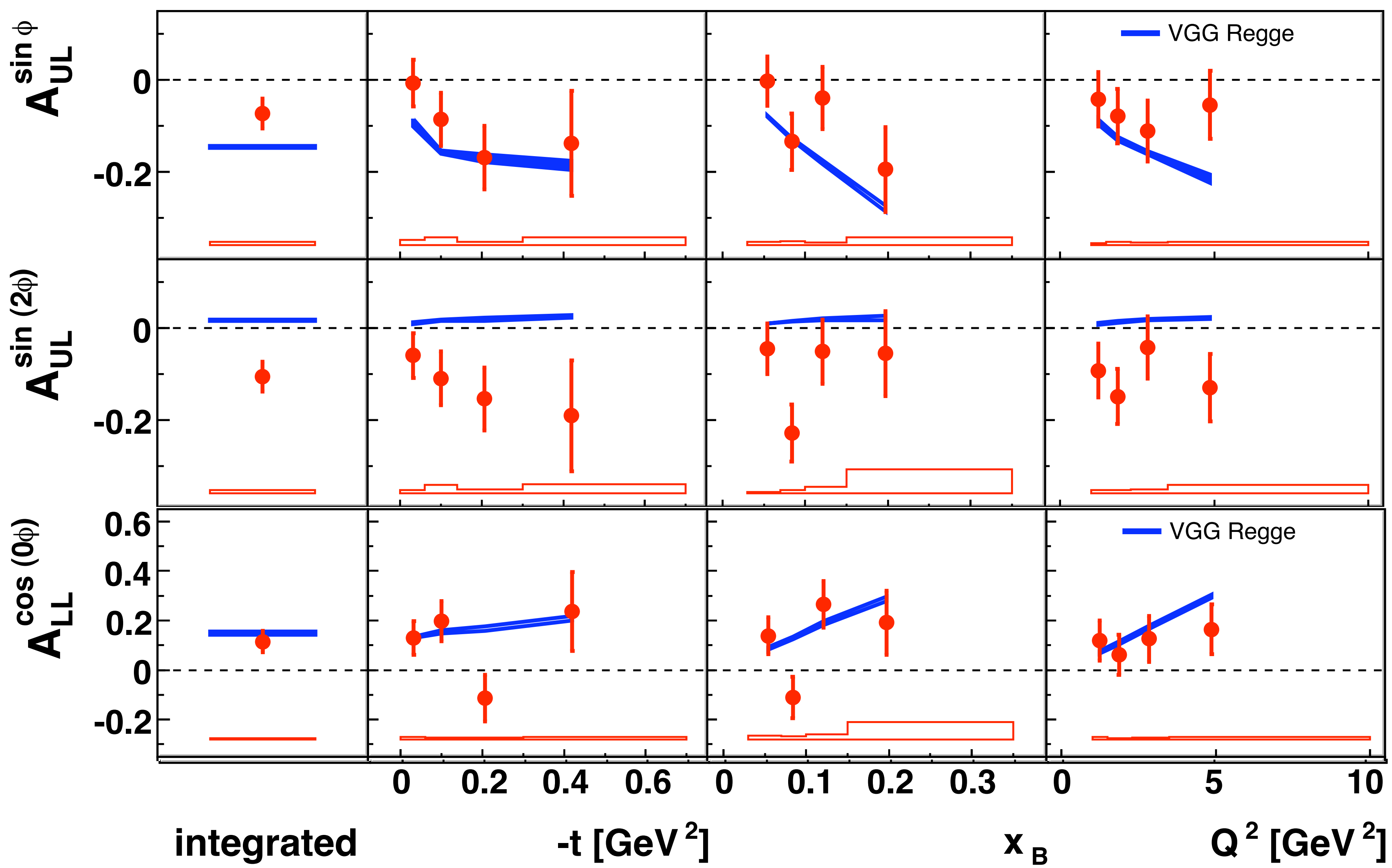
- HERMES Collaboration- Nucl. Phys. B842 (2011) 265

$$\sigma\,(P_\ell,\,P_z,\,\phi,e_\ell) = \sigma_{\rm UU}(\phi,e_\ell)\,[1 + P_z\,\mathcal{A}_{\rm UL}(\phi) + P_\ell\,P_z\,\mathcal{A}_{\rm LL}(\phi) + P_\ell\,\mathcal{A}_{\rm LU}(\phi)]$$

☛ no separate access to DVCS and interference terms

$$\mathcal{A}_{\rm UL}(\phi) \simeq \sum_{n=1}^{3} A_{\rm UL}^{\sin(n\phi)}\,\sin(n\phi)$$

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



GPD $\widetilde{H}$: longitudinally polarized hydrogen target

$ep \to e'\gamma X$

(pre-recoil data)

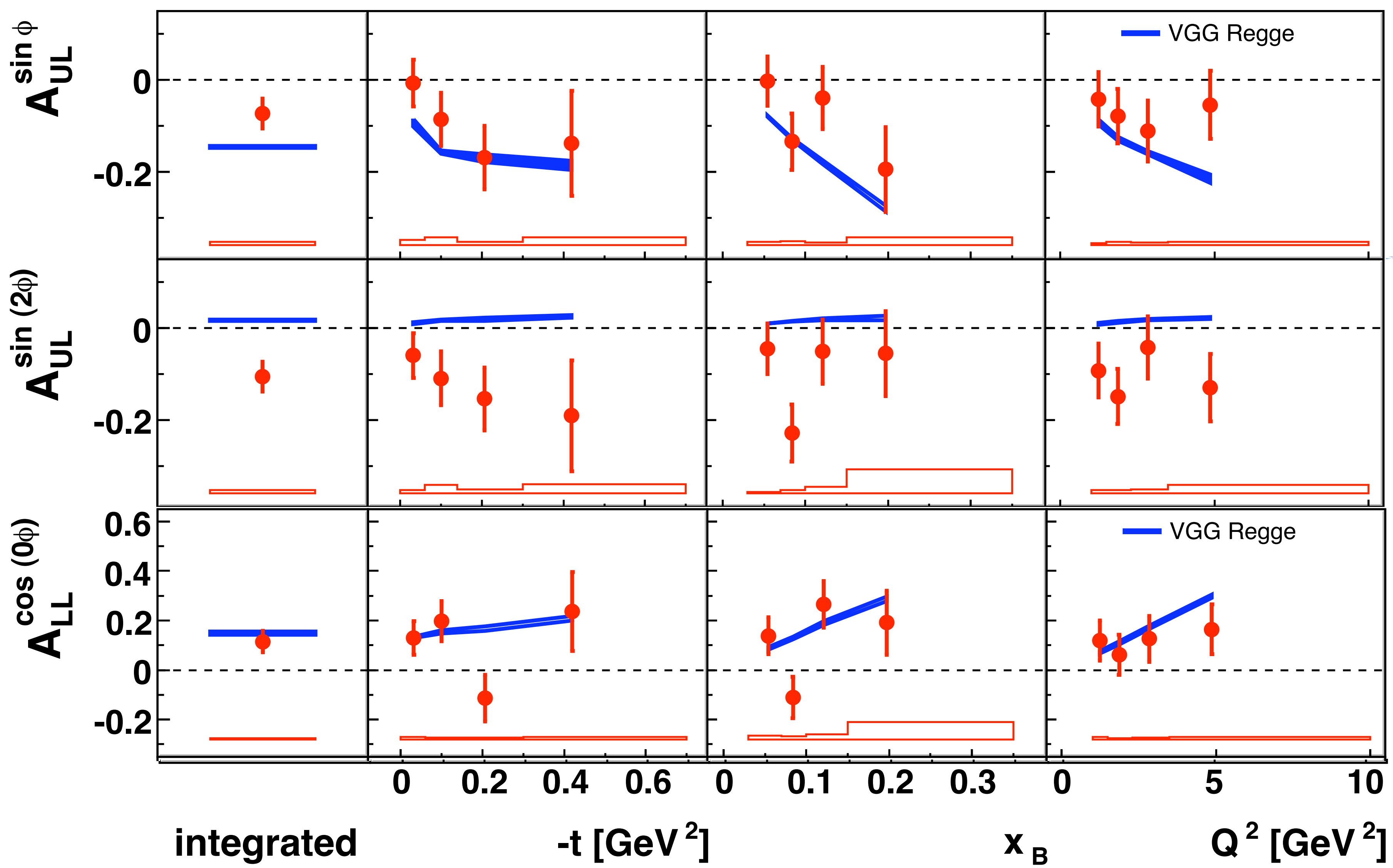
- HERMES Collaboration- Nucl. Phys. B842 (2011) 265

$$\sigma(P_\ell,\, P_z,\, \phi, e_\ell) = \sigma_{\mathrm{UU}}(\phi, e_\ell)\,[1 + P_z\, \mathcal{A}_{\mathrm{UL}}(\phi) + P_\ell\, P_z\, \mathcal{A}_{\mathrm{LL}}(\phi) + P_\ell\, \mathcal{A}_{\mathrm{LU}}(\phi)]$$

☛ no separate access to DVCS and interference terms

$$\mathcal{A}_{\mathrm{UL}}(\phi) \simeq \sum_{n=1}^{3} A_{\mathrm{UL}}^{\sin(n\phi)} \sin(n\phi)$$

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



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

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

GPD $\widetilde{H}$: longitudinally polarized hydrogen target

$ep \to e'\gamma X$

(pre-recoil data)

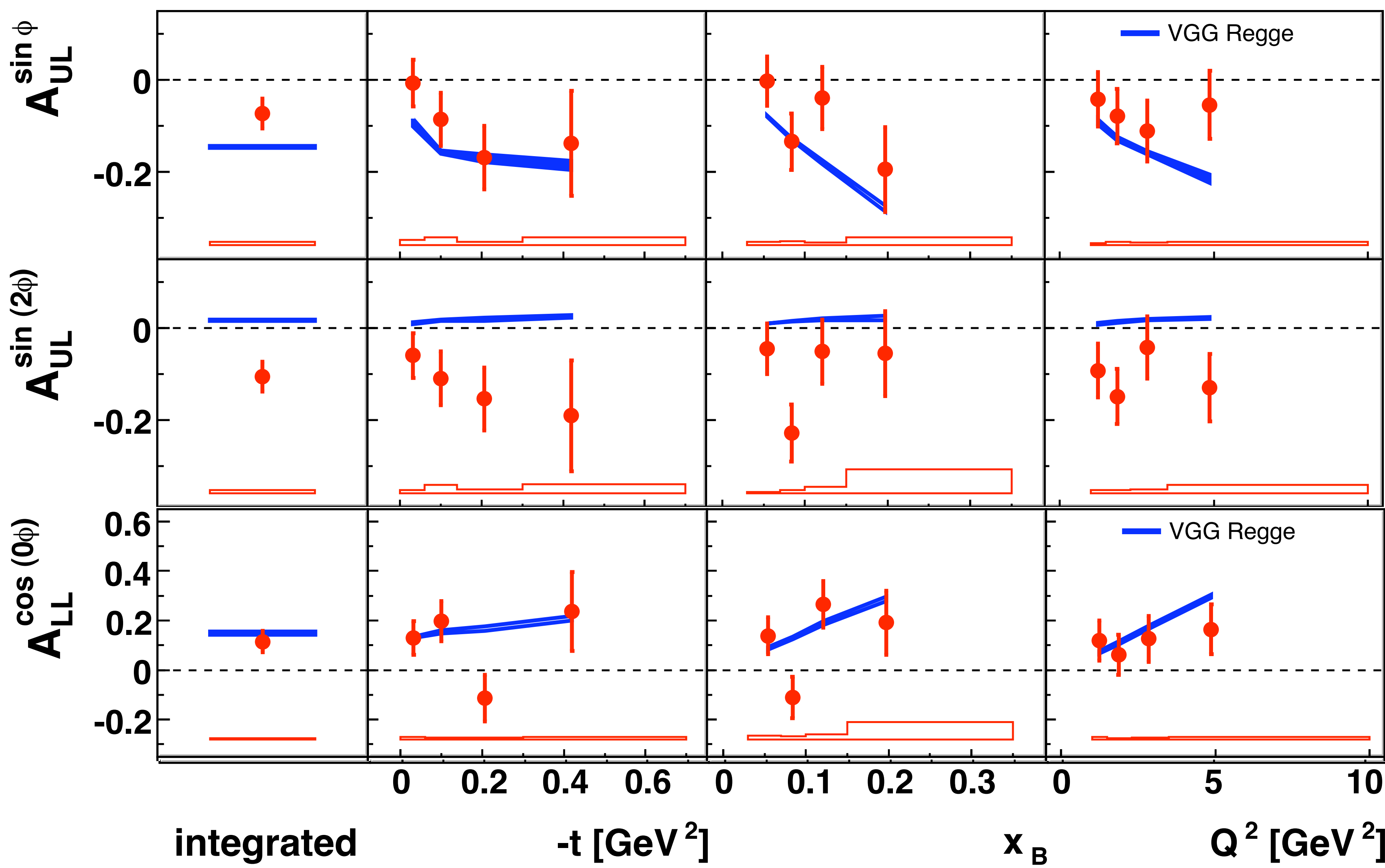
- HERMES Collaboration- Nucl. Phys. B842 (2011) 265

$$\sigma(P_\ell, P_z, \phi, e_\ell) = \sigma_{UU}(\phi, e_\ell)\left[1 + P_z\,\mathcal{A}_{UL}(\phi) + P_\ell\,P_z\,\mathcal{A}_{LL}(\phi) + P_\ell\,\mathcal{A}_{LU}(\phi)\right]$$

☛ no separate access to DVCS and interference terms

$$\mathcal{A}_{UL}(\phi) \simeq \sum_{n=1}^{3} A_{UL}^{\sin(n\phi)} \sin(n\phi)$$

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



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

$$A_{UL}^{\sin\phi} \propto F_1 \text{Im}\widetilde{\mathcal{H}}$$

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

☛ unexpected large value

GPD $\widetilde{H}$: longitudinally polarized hydrogen target

$ep \to e'\gamma X$

(pre-recoil data)

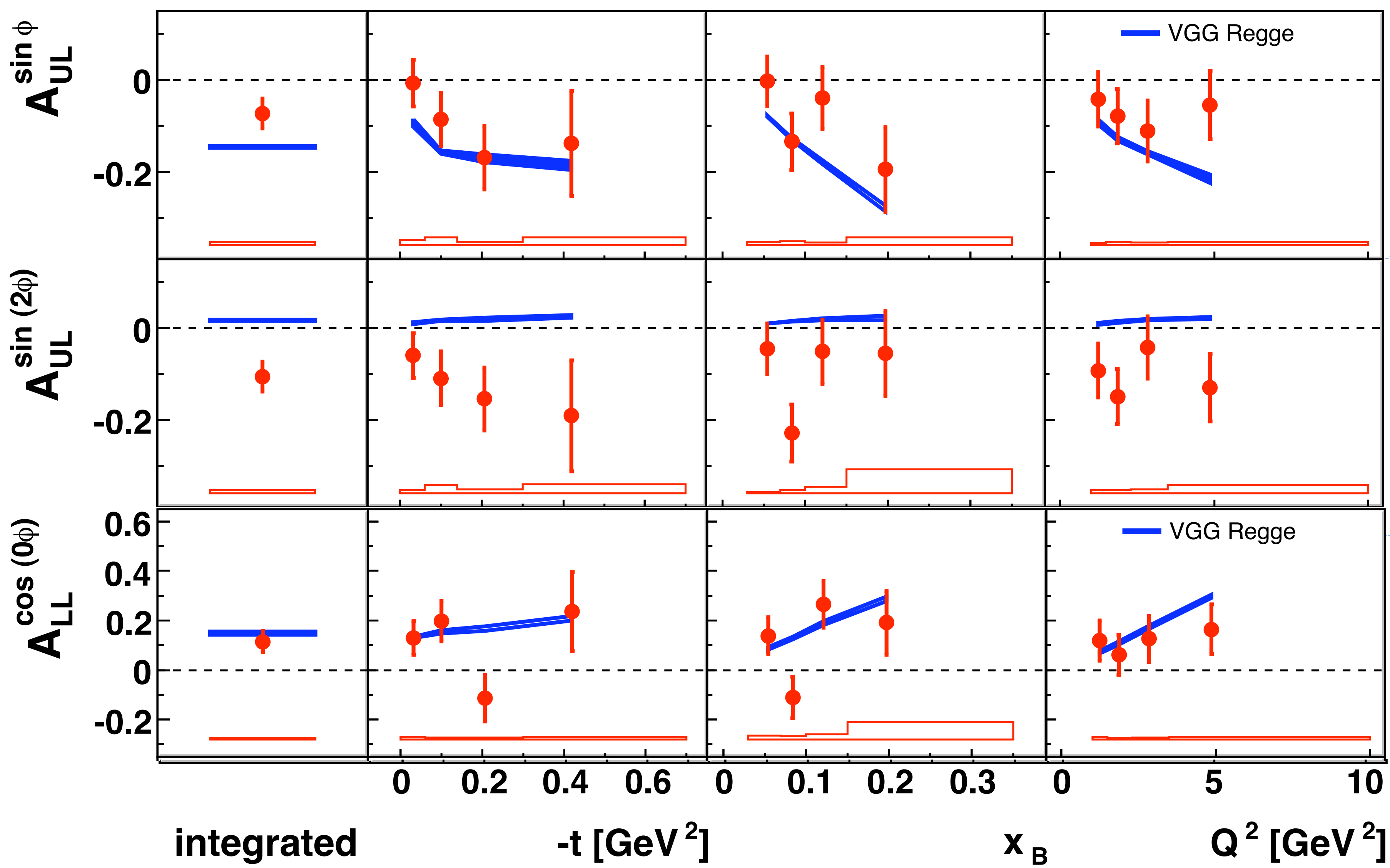
- HERMES Collaboration- Nucl. Phys. B842 (2011) 265

$$\sigma(P_\ell, P_z, \phi, e_\ell) = \sigma_{UU}(\phi, e_\ell)\,[1 + P_z\,\mathcal{A}_{UL}(\phi) + P_\ell\,P_z\,\mathcal{A}_{LL}(\phi) + P_\ell\,\mathcal{A}_{LU}(\phi)]$$

☛ no separate access to DVCS and interference terms

$$\mathcal{A}_{UL}(\phi) \simeq \sum_{n=1}^{3} A_{UL}^{\sin(n\phi)} \sin(n\phi)$$

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



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

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

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

☛ unexpected large value

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

$$A_{LL}^{cos0\phi} \propto F_1 \mathrm{Re}\widetilde{\mathcal{H}}$$

GPD E: *transversely polarized hydrogen target*

$ep \to e'\gamma X$

(pre-recoil data)

- HERMES Collaboration- : JHEP 06 (2008) 066, 24

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

GPD E: *transversely polarized hydrogen target*

$ep \to e'\gamma X$

(pre-recoil data)

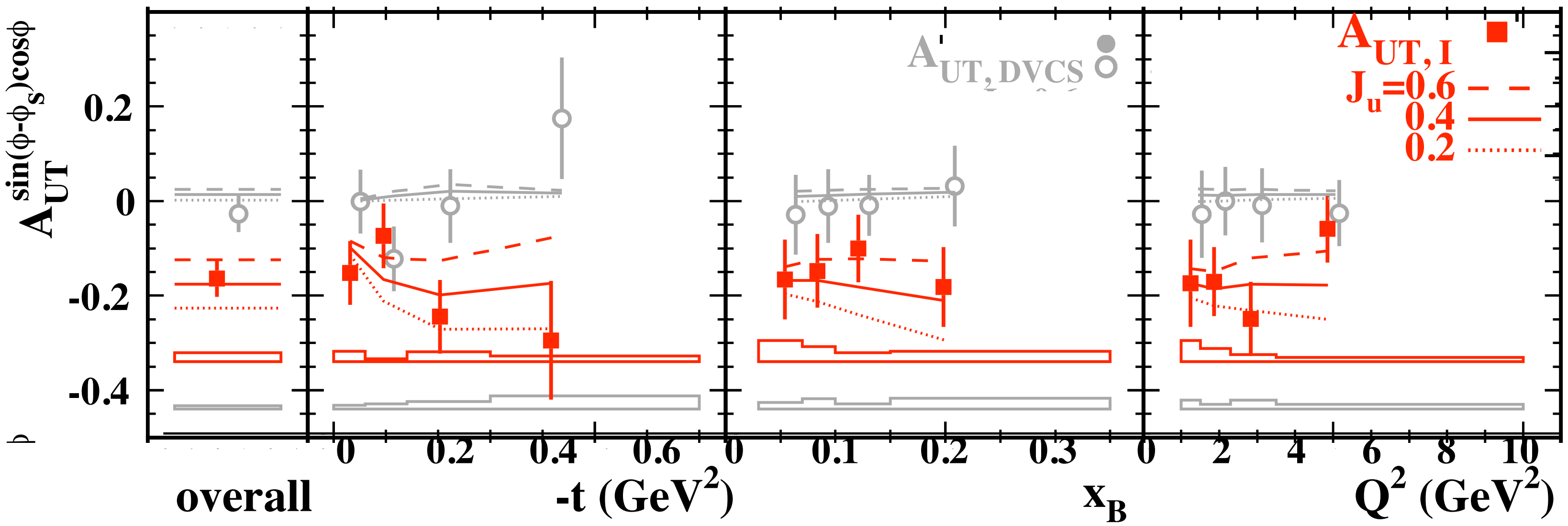
- HERMES Collaboration- : JHEP 06 (2008) 066, 24

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

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

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

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



- ☛ $A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi}$ found much more sensitive to GPD E than others, and thus to J_u
- ☛ with a good model, allows a model-dependent constraint

GPD E: transversely polarized hydrogen target

$ep \to e'\gamma X$

(pre-recoil data)

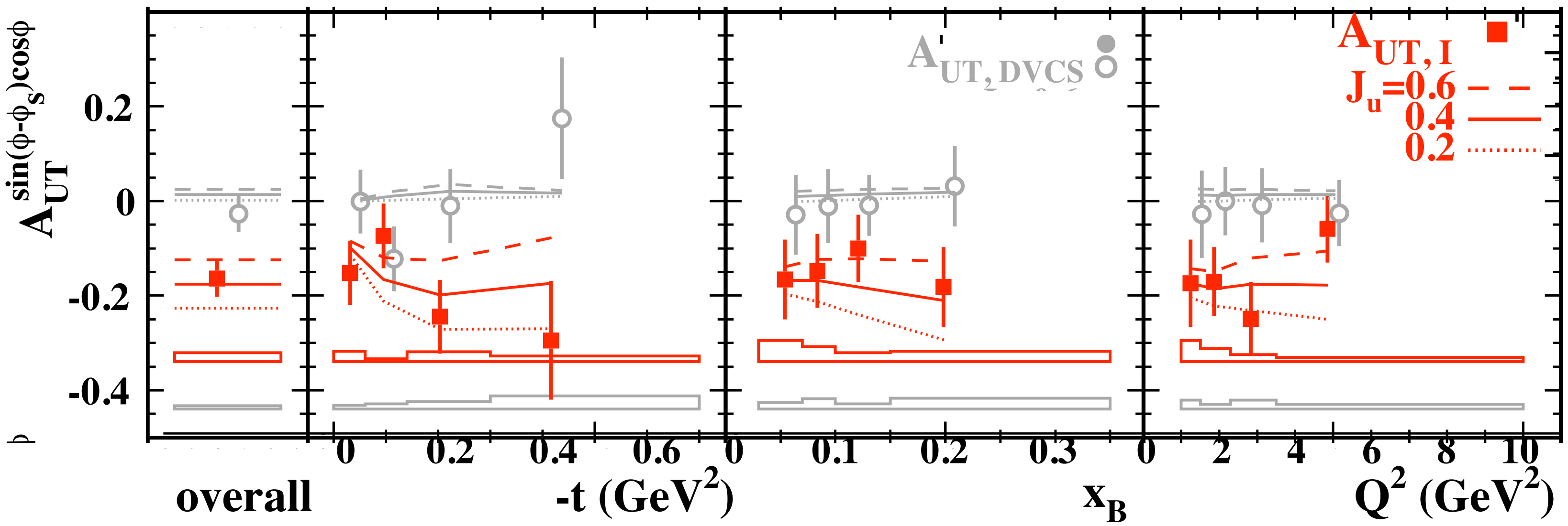
- HERMES Collaboration- : JHEP 06 (2008) 066, 24

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

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

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

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

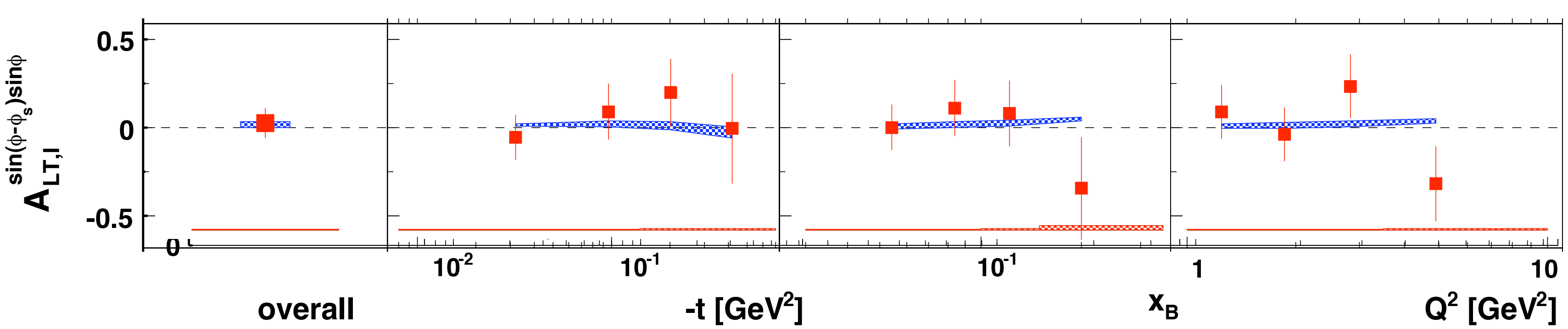


- ☛ $A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi}$ found much more sensitive to GPD E than others, and thus to J_u
- ☛ with a good model, allows a model-dependent constraint

- HERMES Collaboration- Phys. Lett. B 704 (2011) 15-23

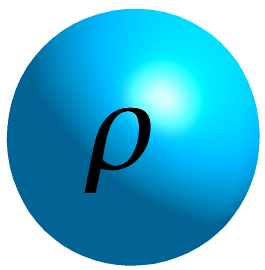
$\propto \mathrm{Re}[F_2\mathcal{H} - F_1\mathcal{E}]$

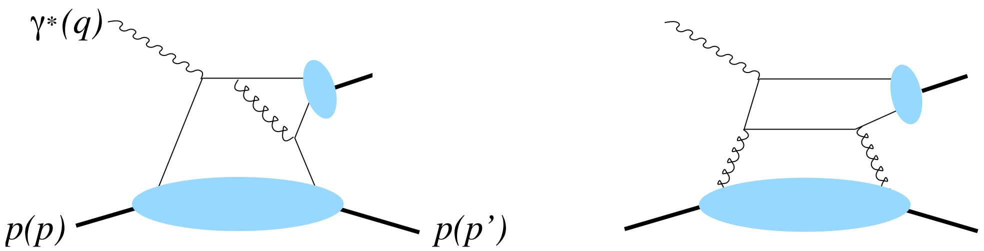
$$\mathcal{A}_{LT}^{I,BH+DVCS}(\phi,\phi_S) = \frac{(\overrightarrow{\sigma}^{+\Uparrow} + \overleftarrow{\sigma}^{+\Downarrow} - \overrightarrow{\sigma}^{+\Downarrow} - \overleftarrow{\sigma}^{+\Uparrow}) \pm (\overrightarrow{\sigma}^{-\Uparrow} + \overleftarrow{\sigma}^{-\Downarrow} - \overrightarrow{\sigma}^{-\Downarrow}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

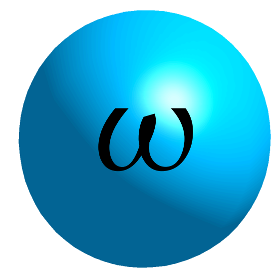


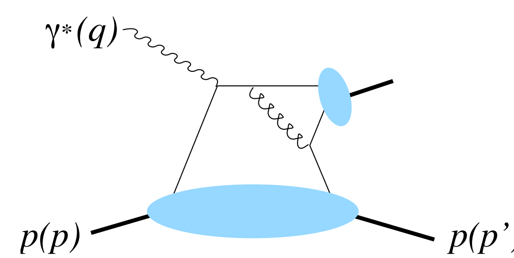
- ☛ $A_{UT,I}^{\sin(\phi-\phi_s)\sin\phi}$ could provide a similar constraint to the real part
- ☛ due to different kinematic pre-factors, this amplitude is suppressed

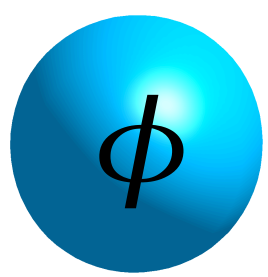
given channel probes specific **GPD** *flavor*

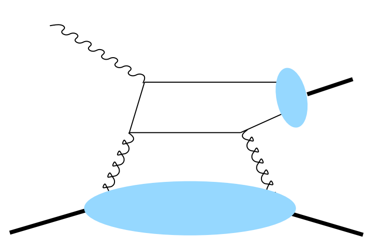


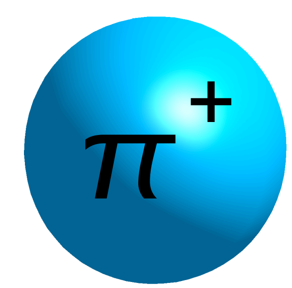












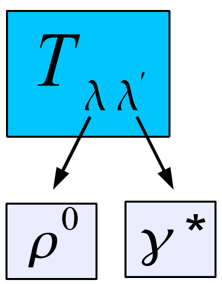
vector meson cross section

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

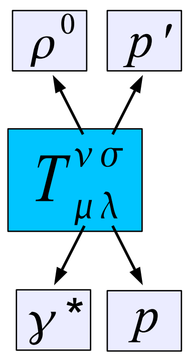
☛ production and decay angular distributions W decomposed:

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

☛ parametrized by helicity amplitudes



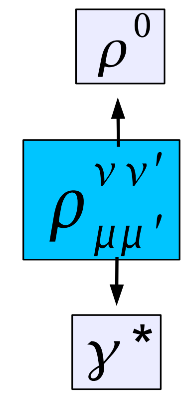
-Schilling, Wolf (1973)-



-Diehl (2007)-

☛ or alternatively by SDMEs:

-Schilling, Wolf (1973)-



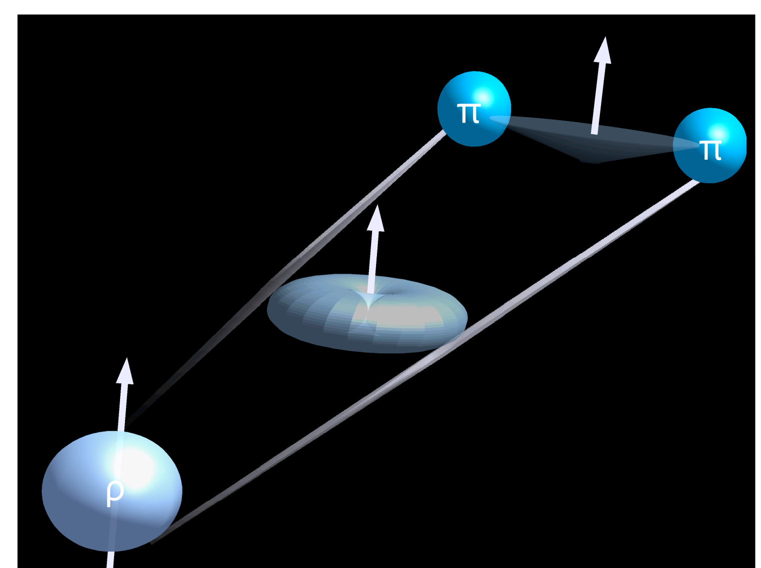
-Diehl (2007)-

helicity amplitudes or SDMEs describe

☛ the helicity transfer from virtual photon to the vector meson

☛ the parity of the diffractive exchange process

- ☛ natural parity is related to H and E
- ☛ unnatural parity is related to $\widetilde{H}$ and $\widetilde{E}$



ρ^0 ϕ

SDMEs *on an unpolarized target*

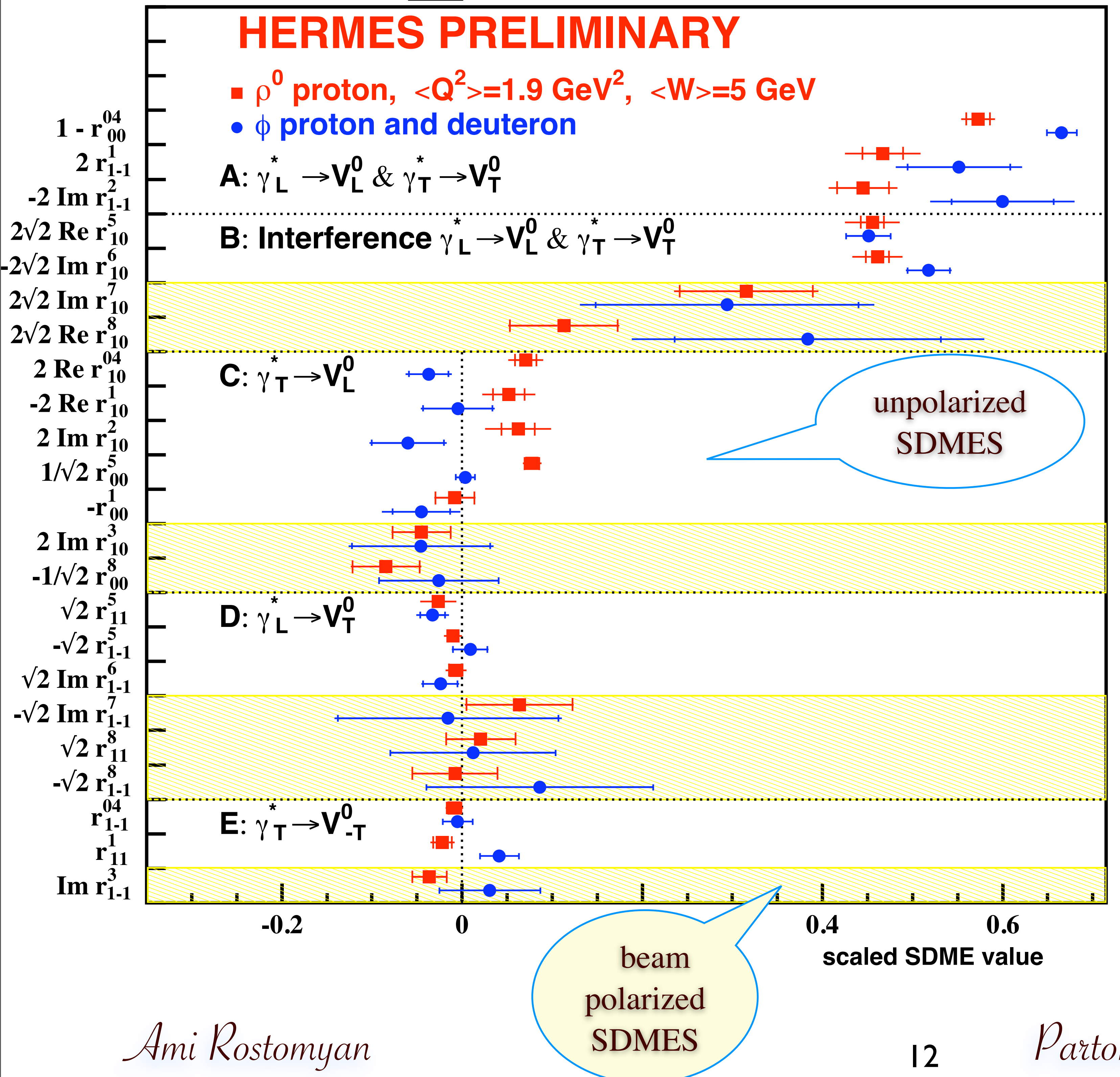
$ep \to e' \; \rho^0 \; p'$

$T_{\lambda\lambda'}$ → ρ^0, γ^*

$$|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2$$

$ep \to e' \; \phi \; p'$

-HERMES Collaboration-:
EPJC 62 (2009) 659-694



$\gamma_L^* \to \rho_L^0 \qquad \gamma_T^* \to \rho_T^0$

☛ SDMEs are significantly different from zero

☛ the magnitude of ϕ meson SDMEs is 10-20% larger

$$|T_{11}/T_{00}|_\phi > |T_{11}/T_{00}|_{\rho^0}$$

$\gamma_T^* \to \rho_L^0$

☛ pronounced differences between ϕ and ρ⁰ mesons.

$$r^5_{00} \quad \propto \quad \mathrm{Re}(T_{01}T_{00}) = |T_{01}||T_{00}|\cos\delta_{01}$$
$$r^8_{00} \quad \propto \quad \mathrm{Im}(T_{01}T_{00}) = |T_{01}||T_{00}|\sin\delta_{01}$$

$$|T_{01}|_\phi < |T_{01}|_{\rho^0}$$

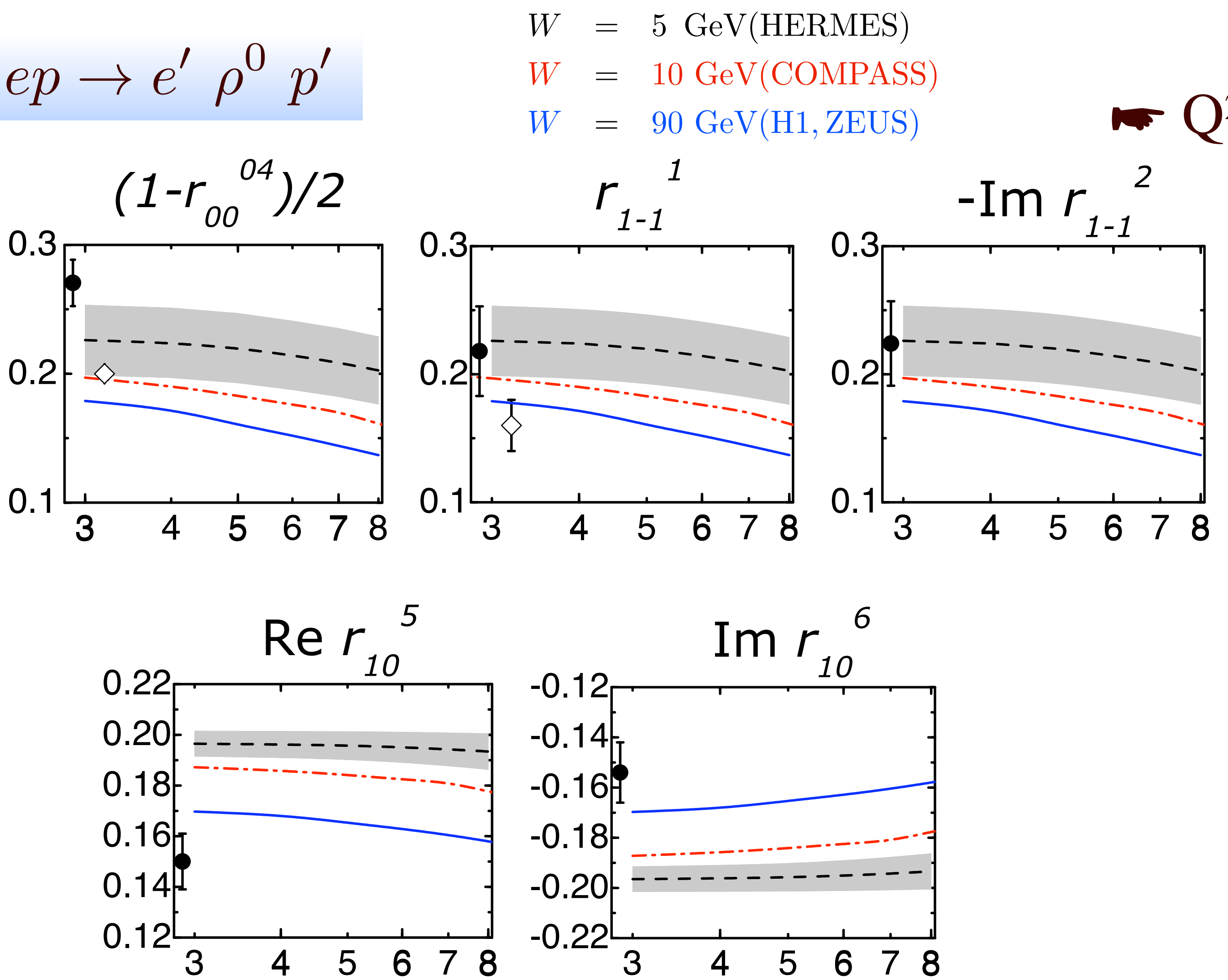
☛ T_{01} is related to the longitudinal quark motion in the meson

☛ smaller longitudinal quark motion in the ϕ meson as compared to the ρ⁰

comparison to GPD model

ρ^0

$ep \to e' \rho^0 p'$



-Goloskokov, Kroll (2007)-

☛ Q^2-dependence calculated using models for GPD H, neglecting GPD $\widetilde{H}$

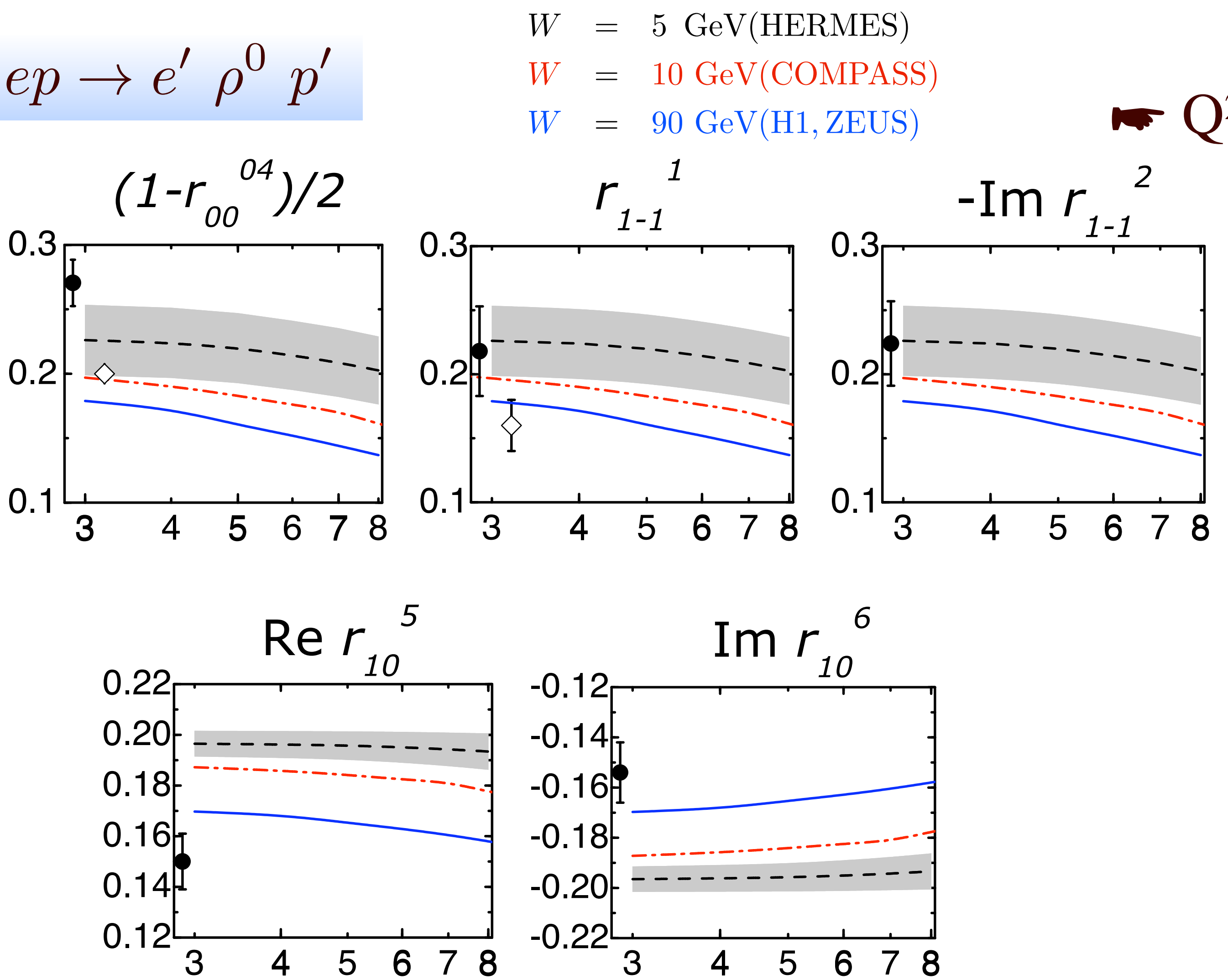
$\gamma_L^* \to \rho_L^0$ and $\gamma_T^* \to \rho_T^0$

☛ $1 - r_{00}^{04} \propto r_{1-1}^1 \propto -\mathrm{Im} r_{1-1}^2 \propto T_{11}$

☛ model describe the data

comparison to GPD model

$ep \to e' \rho^0 p'$



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☛ $1 - r_{00}^{04} \propto r_{1-1}^1 \propto -\mathrm{Im} r_{1-1}^2 \propto T_{11}$

☛ model describe the data

interference between $\gamma_L^* \to \rho_L^0$ and $\gamma_T^* \to \rho_T^0$

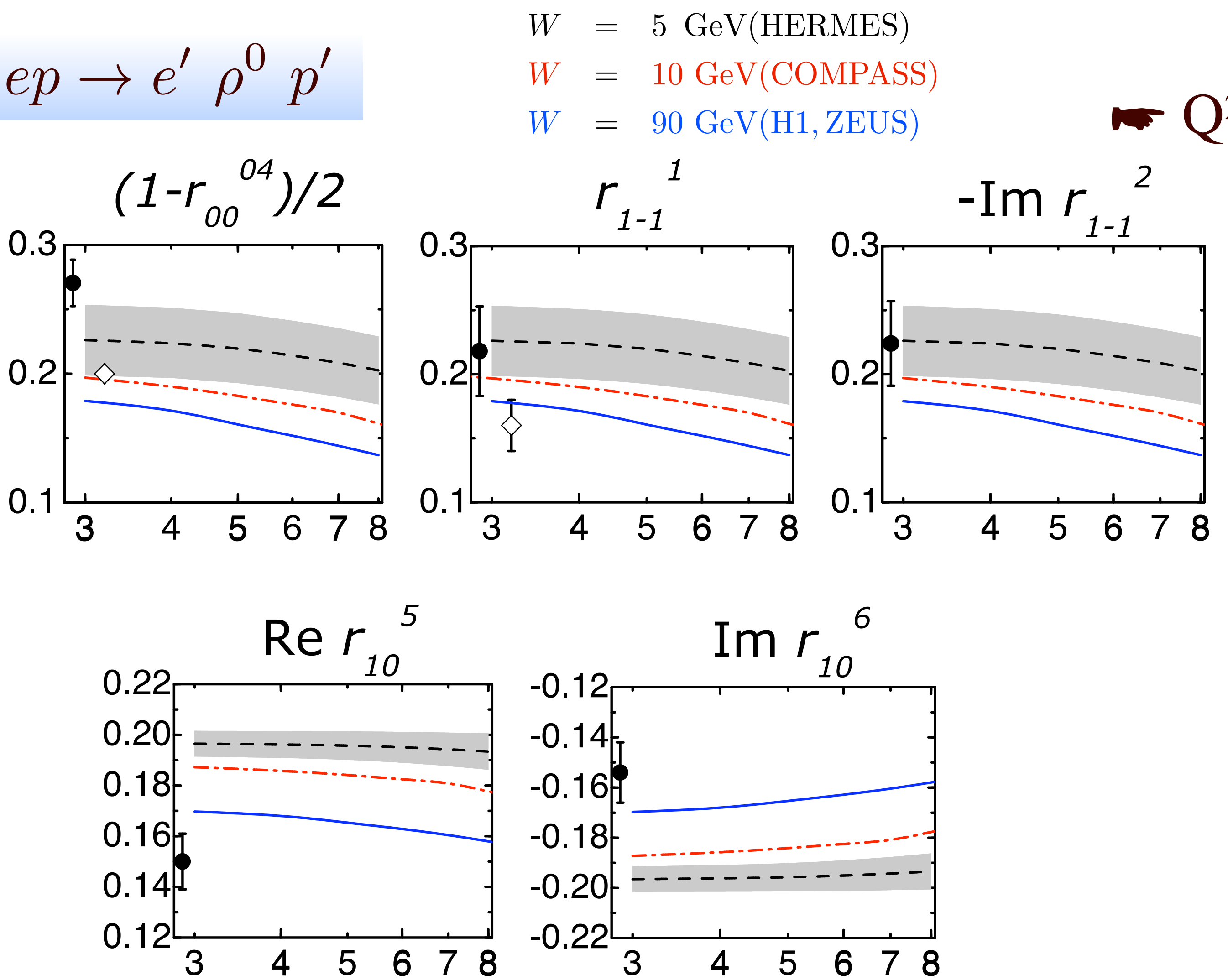
$r_{10}^5 \propto -\mathrm{Im} r_{10}^6$

☛ model does not describe the data

☛ model uses phase δ_{11}=3.1 degree difference between T_{00} and T_{11}

comparison to GPD model

$ep \rightarrow e' \; \rho^0 \; p'$



-Goloskokov, Kroll (2007)-

☛ Q^2-dependence calculated using models for GPD H, neglecting GPD $\widetilde{H}$

$\gamma^*_L \rightarrow \rho^0_L$ and $\gamma^*_T \rightarrow \rho^0_T$

☛ $1 - r^{04}_{00} \propto r^1_{1-1} \propto -\mathrm{Im} r^2_{1-1} \propto T_{11}$

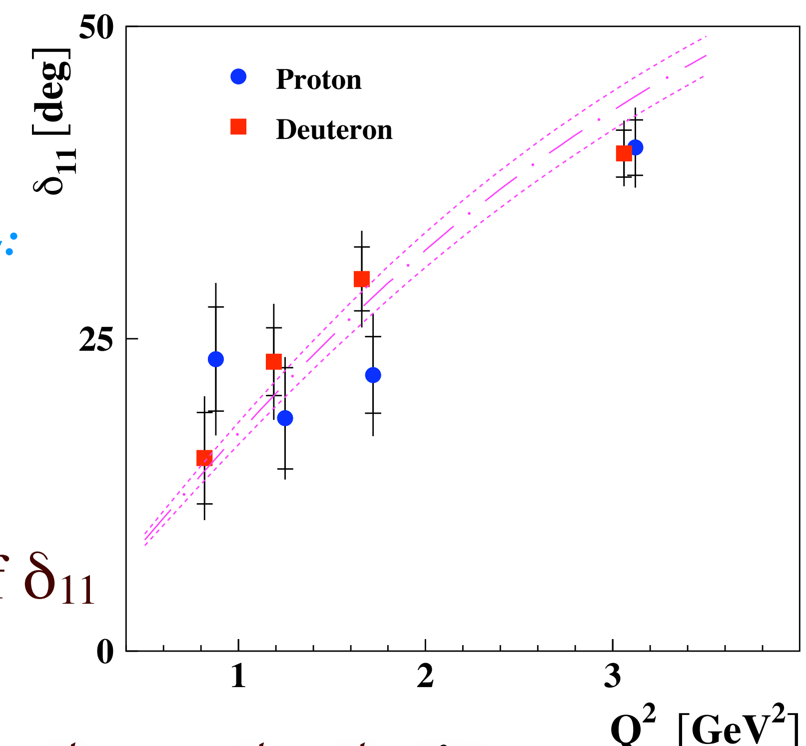
☛ model describe the data

interference between $\gamma^*_L \rightarrow \rho^0_L$ and $\gamma^*_T \rightarrow \rho^0_T$

$r^5_{10} \propto -\mathrm{Im} r^6_{10}$

☛ model does not describe the data

☛ model uses phase δ_{11}=3.1 degree difference between T_{00} and T_{11}



☛ HERMES result: δ_{11}~31.5 ± 1.4 degree

$$\tan\delta_{11} = \frac{\mathrm{Im}(T_{11}/T_{00})}{\mathrm{Re}(T_{11}/T_{00})}$$

-HERMES Collaboration-: EPJ C 71 (2011) 1609

☛ large phase difference δ_{11}=20 was measured by H1 collaboration

☛ no model capable of explaining the value and Q^2 dependence of δ_{11}

observation of unnatural-parity exchange

ρ^0 ϕ

at large W and Q^2, this transition should be suppressed by a factor of M_V/Q

- ☛ direct helicity amplitude ratio analysis: U_{11}/T_{00}
- ☛ the combinations of SDMEs expected to be zero in case of natural parity exchange dominance

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

observation of unnatural-parity exchange

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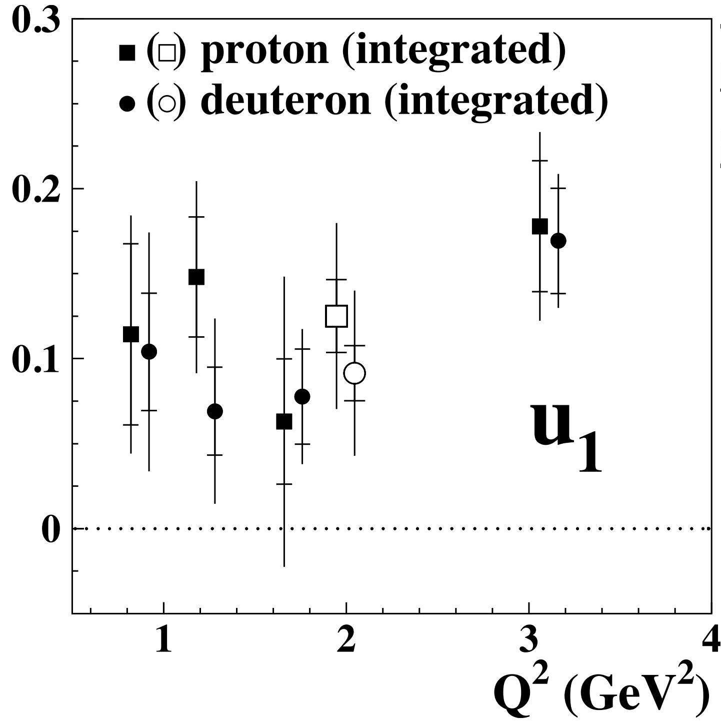
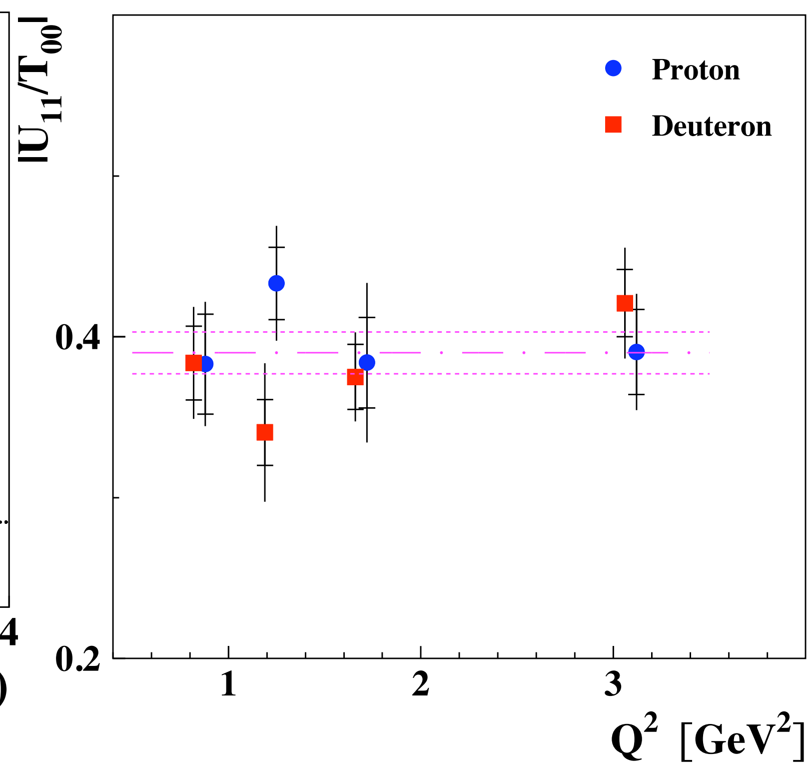
-HERMES Collaboration-:
EPJC 62 (2009) 659-694

-HERMES Collaboration-:
EPJ C 71 (2011) 1609

SDME method



helicity amplitude ratio method



- ☛ significance of 3σ
- ☛ significance of 20σ

- ☛ give information about $\widetilde{H}$

observation of unnatural-parity exchange

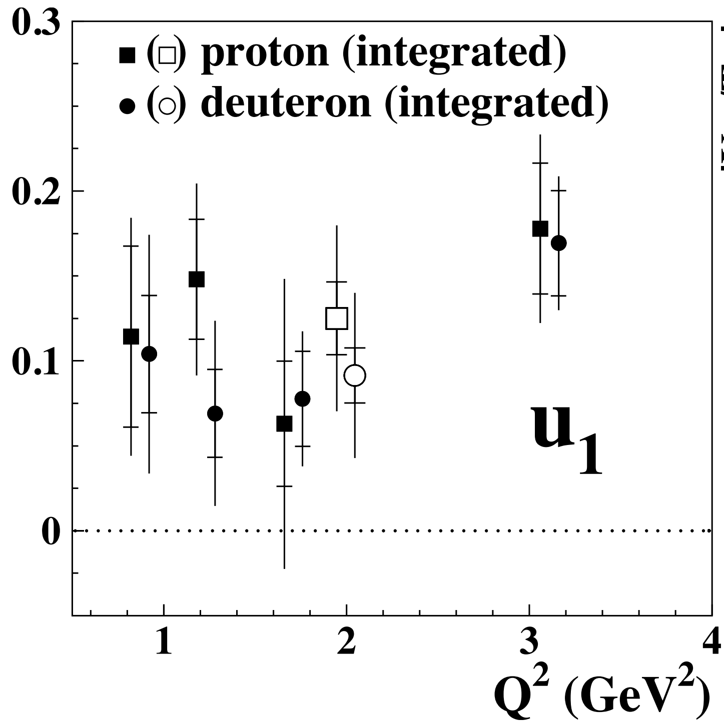
at large W and Q^2, this transition should be suppressed by a factor of M_V/Q

- direct helicity amplitude ratio analysis: U_{11}/T_{00}
- the combinations of SDMEs expected to be zero in case of natural parity exchange dominance

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

-HERMES Collaboration-:
EPJC 62 (2009) 659-694

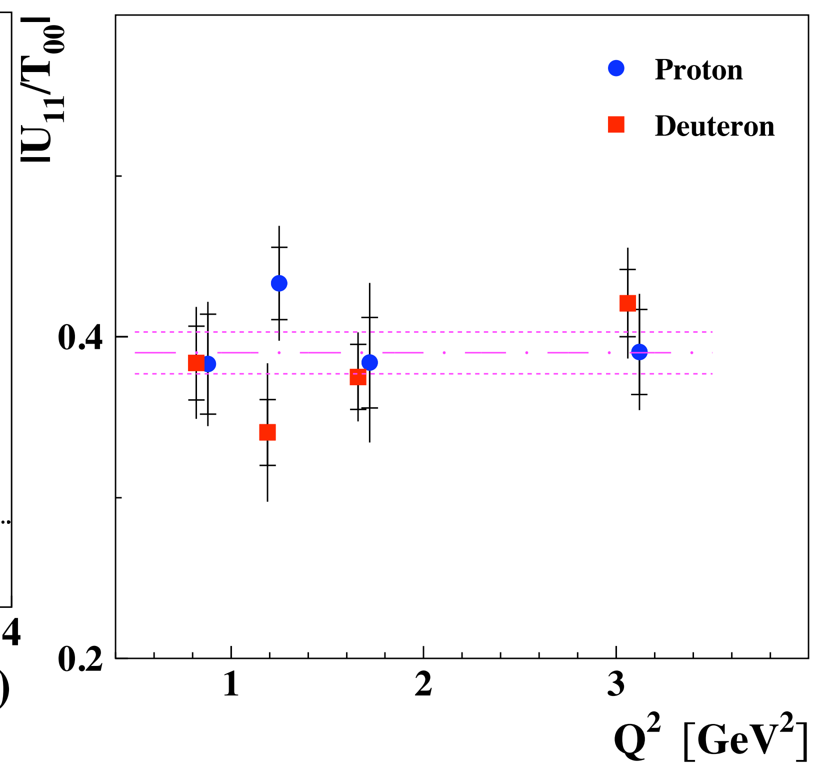
SDME method



- significance of 3σ

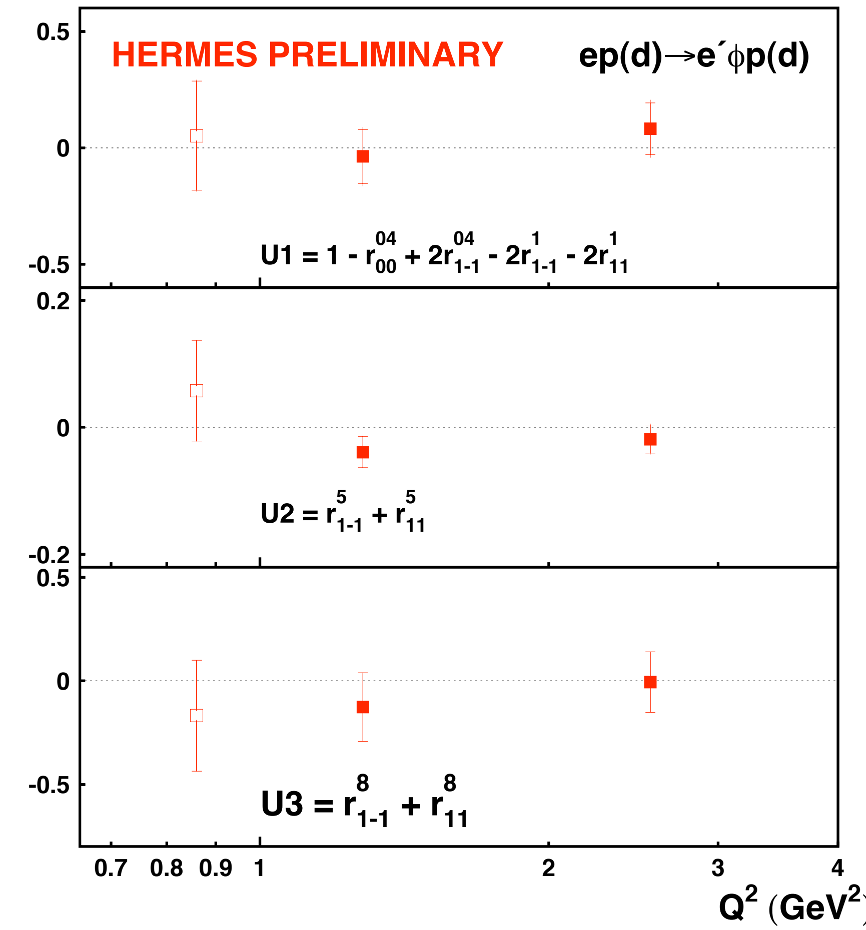
-HERMES Collaboration-:
EPJ C 71 (2011) 1609

helicity amplitude ratio method



- significance of 20σ

SDME method



- no signal of unnatural parity exchange
- expected since dominant contribution to the production is from two gluon exchange

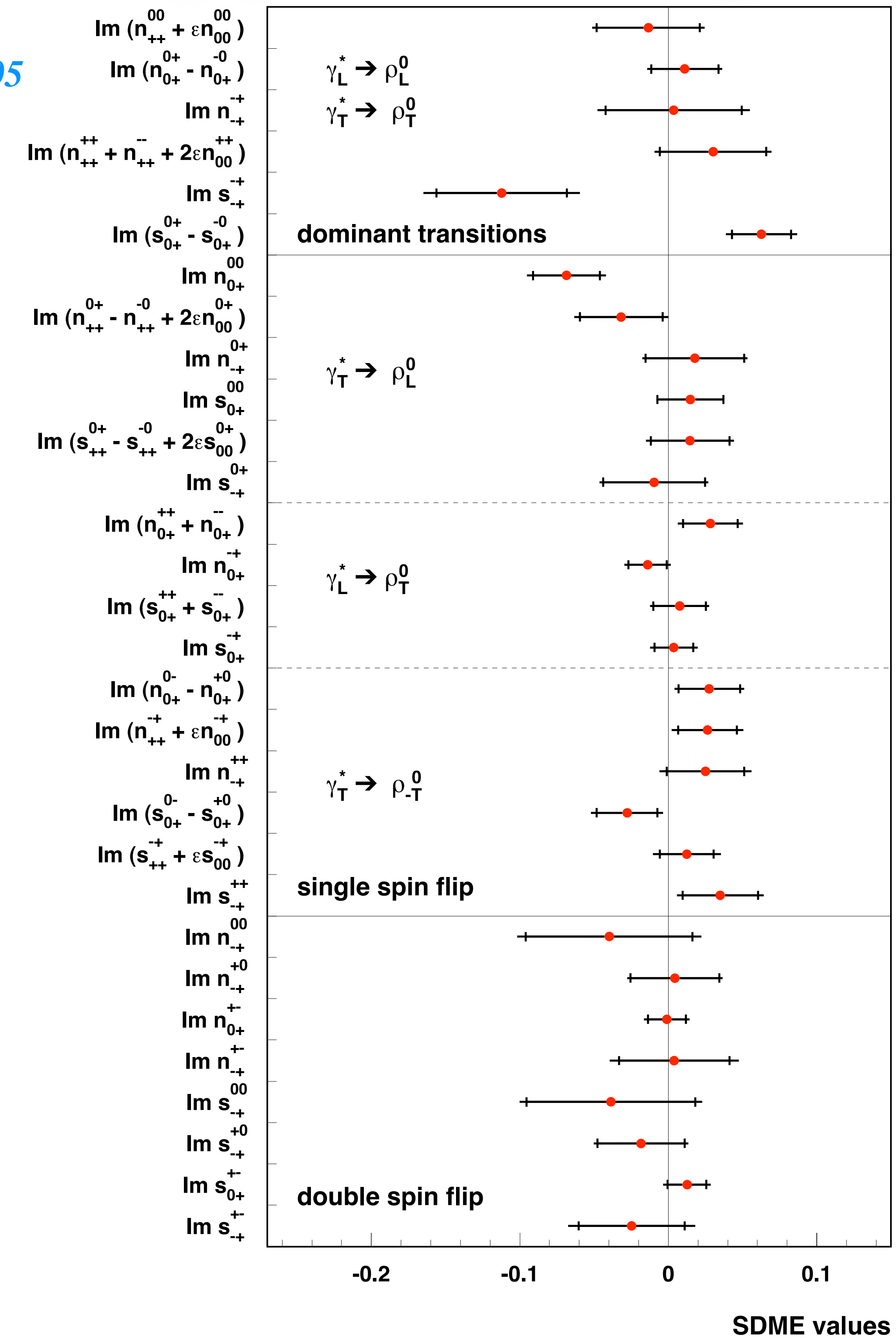
- give information about $\widetilde{H}$

SDMEs *on a transversely polarized target*

$ep \to e' \rho^0 p'$

-HERMES Collaboration-:
Phys. Lett. B679 (2009) 100-105

☛ suppressed by a factor $\sqrt{-t}/2M_p$



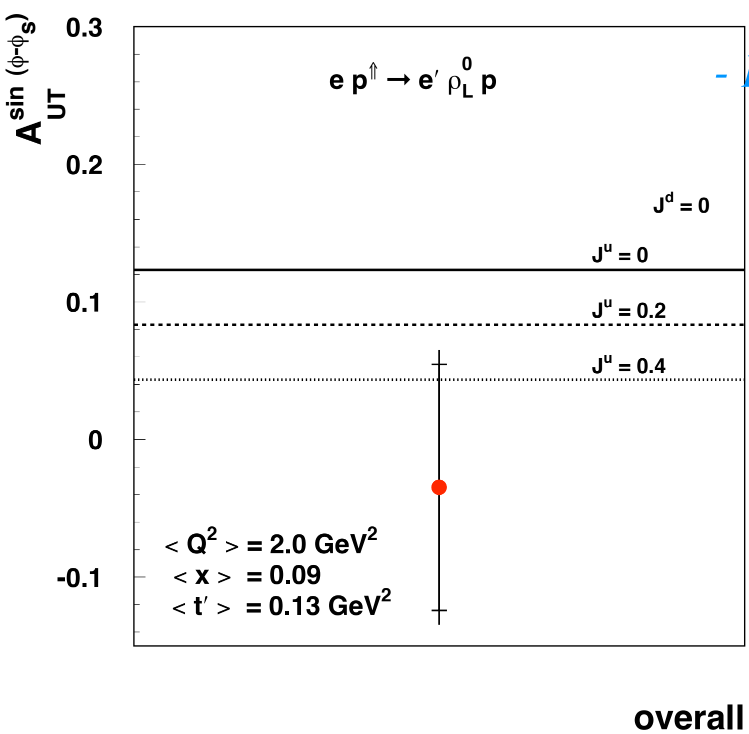
SDMEs *on a transversely polarized target*

$ep \to e' \rho^0 p'$

-HERMES Collaboration-:
Phys. Lett. B679 (2009) 100-105

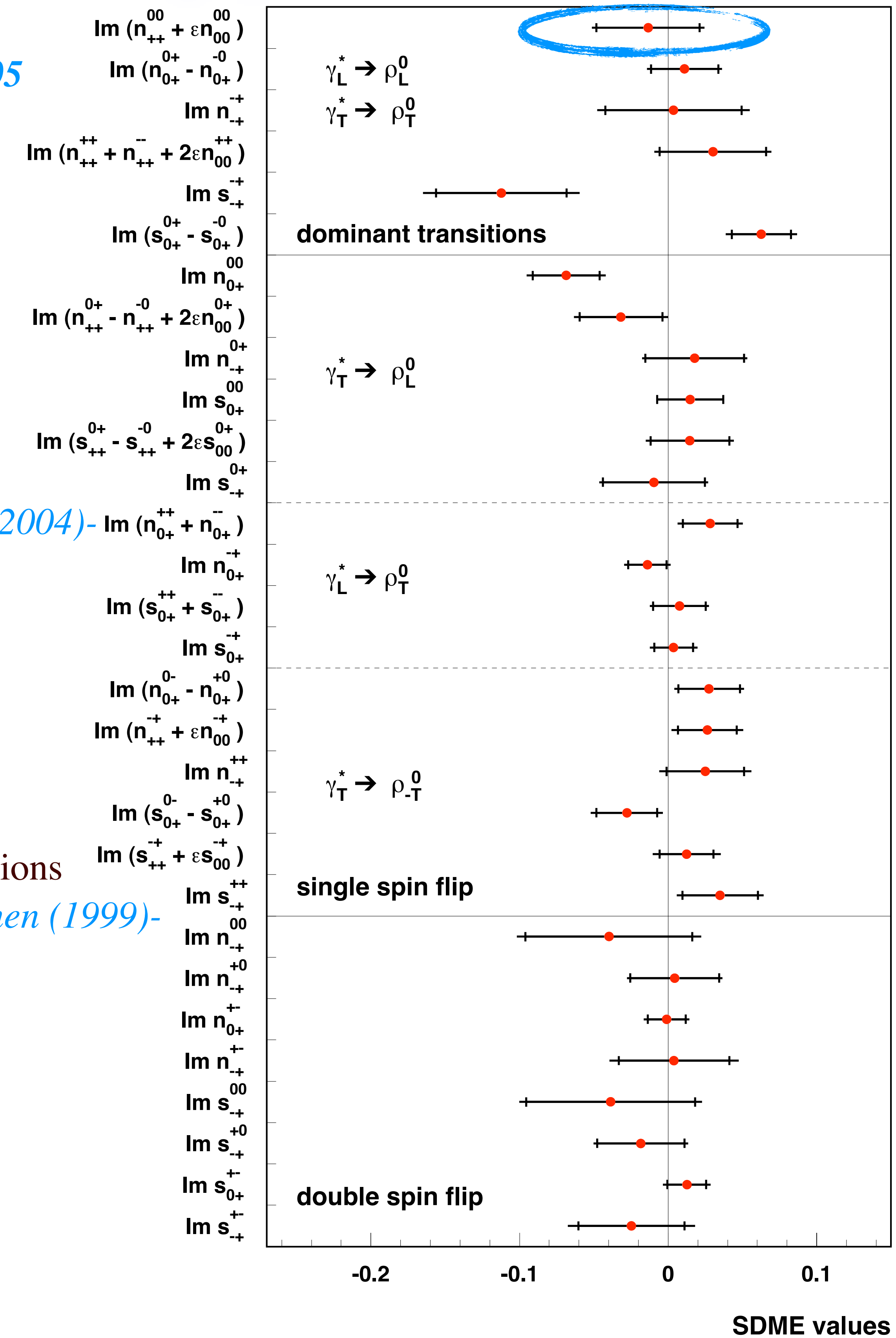
- suppressed by a factor $\sqrt{-t}/2M_p$
- only one out of 30 is related to asymmetry that can give an access to GPD E

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



- Ellinghaus, Nowak, Vinnikov, Ye (2004)-

other GPD model based calculations
- Goeke, Polyakov, Vanderhaeghen (1999)-
-Goloskokov, Kroll (2007)-
-Diehl, Kugler (2008)-



ρ^0 SDMEs *on a transversely polarized target*

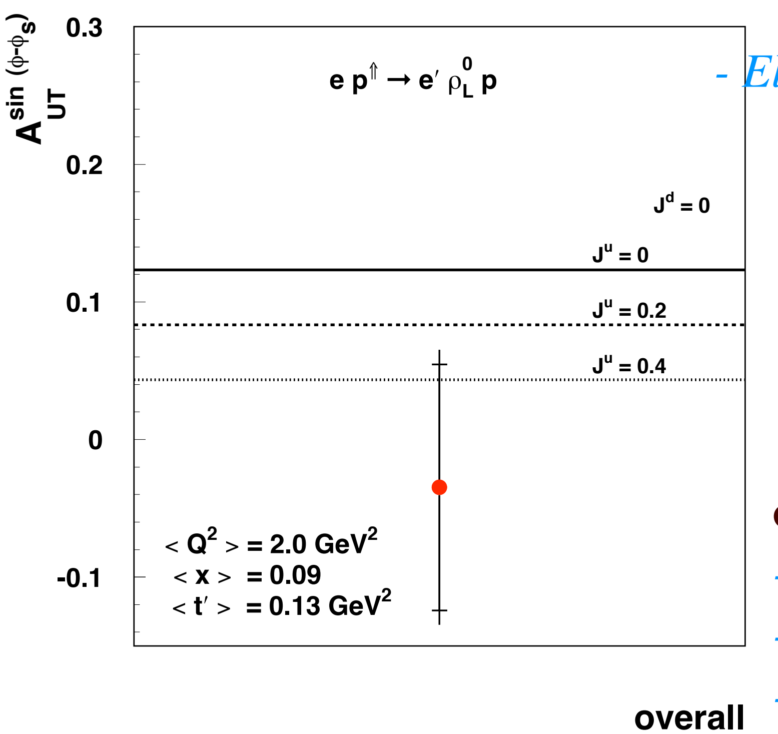
$ep \rightarrow e' \rho^0 p'$

-HERMES Collaboration-:
Phys. Lett. B679 (2009) 100-105

☛ suppressed by a factor $\sqrt{-t}/2M_p$

☛ only one out of 30 is related to asymmetry that can give an access to GPD E

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



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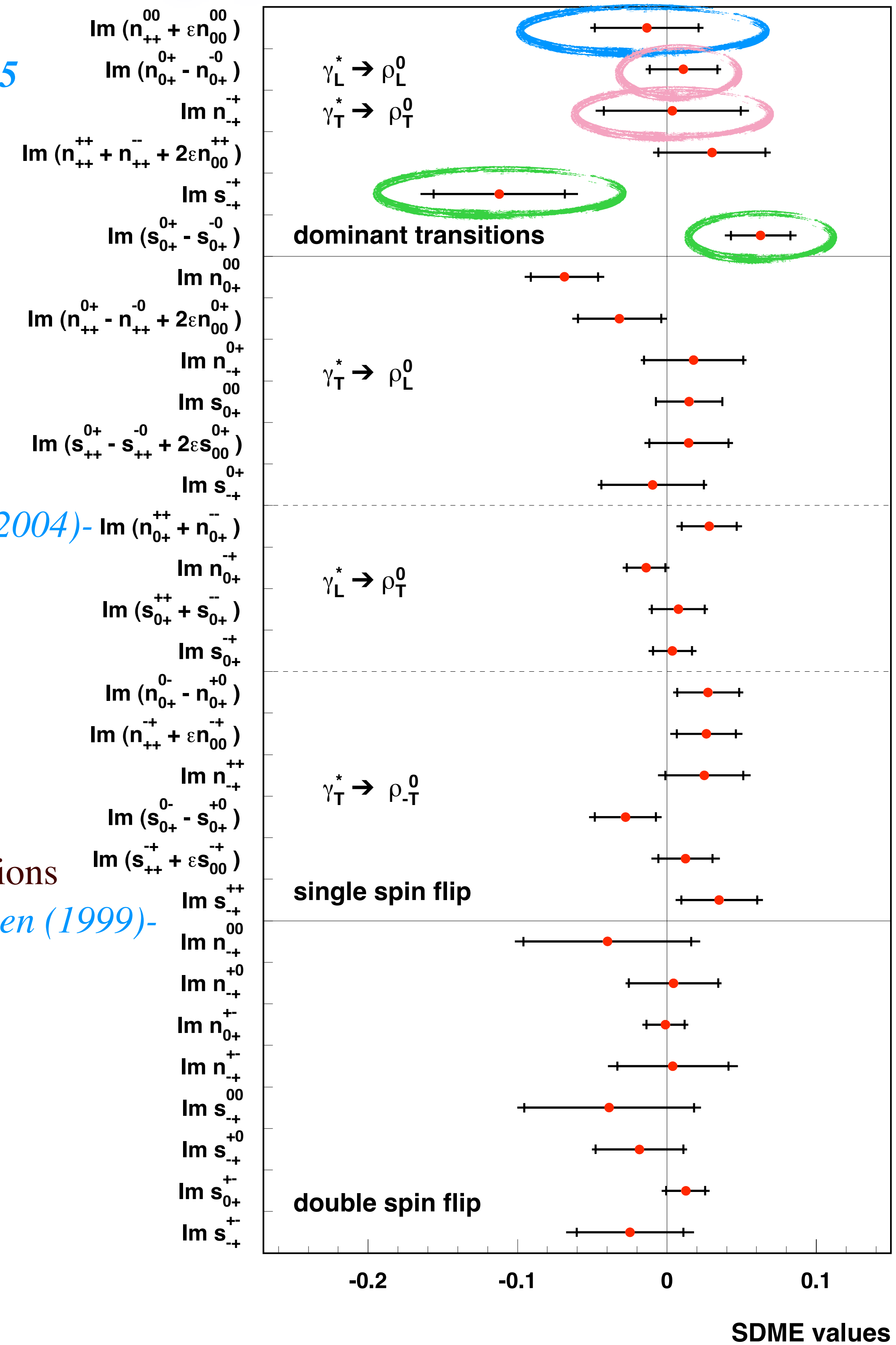


☛ in case of natural parity exchange dominance, expected $s_{\mu\mu'}^{\nu\nu'} < n_{\mu\mu'}^{\nu\nu'}$ (if identical indices)

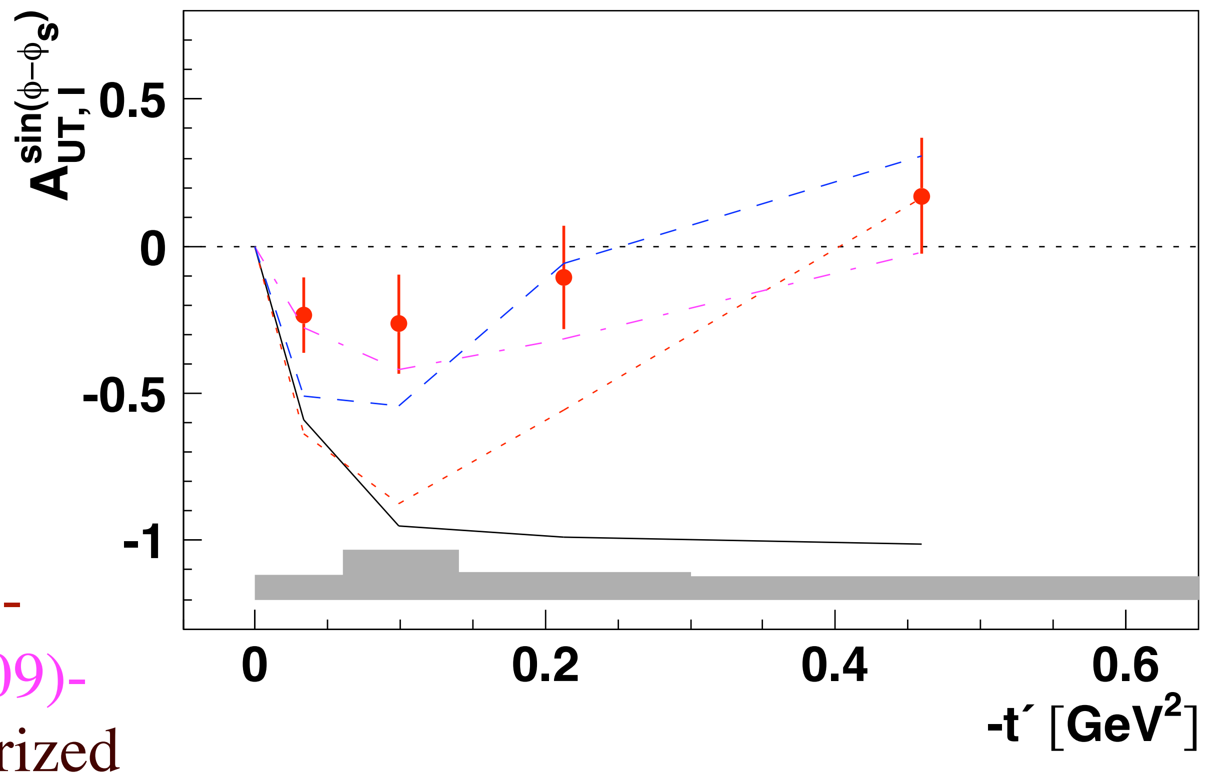
☛ signal for unnatural-parity exchange

☛ related to GPDs $\widetilde{H}$ and $\widetilde{E}$

π^+ production: transversely polarized hydrogen target

$ep \to e'\pi^+(n)$

-HERMES Collaboration-: Phys. Lett. B 682 (2010) 345-350



☛ no σ_L / σ_T separation

☛ small overall value for leading asymmetry amplitude with possible sign change

$$A_{UT}^{\sin(\phi-\phi_s)} \propto \frac{\text{Im}(\widetilde{\mathcal{E}}^*\widetilde{\mathcal{H}})}{|\widetilde{\mathcal{H}}|^2} \propto \left|\frac{\widetilde{\mathcal{E}}}{\widetilde{\mathcal{H}}}\right| \sin\delta$$

☛ theoretical expectation: $A_{UT}^{\sin(\phi-\phi_s)} \propto \sqrt{-t'}$

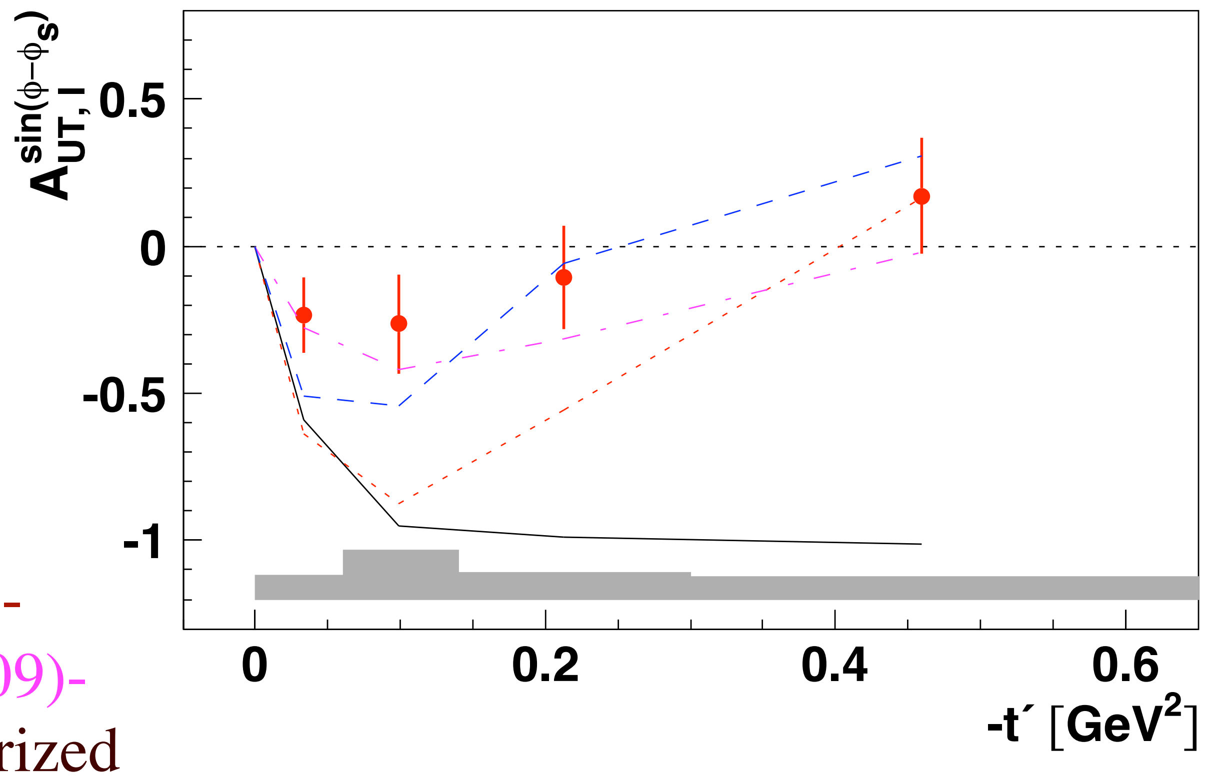
-Frankfurt et al. (2001)- -Belitsky, Muller (2001)-
-Goloskokov, Kroll (2009)- -Bechler, Muller (2009)-

☛ evidence of contributions from transversely polarized photons

π^+ production: transversely polarized hydrogen target

$ep \to e'\pi^+(n)$

-HERMES Collaboration-: Phys. Lett. B 682 (2010) 345-350

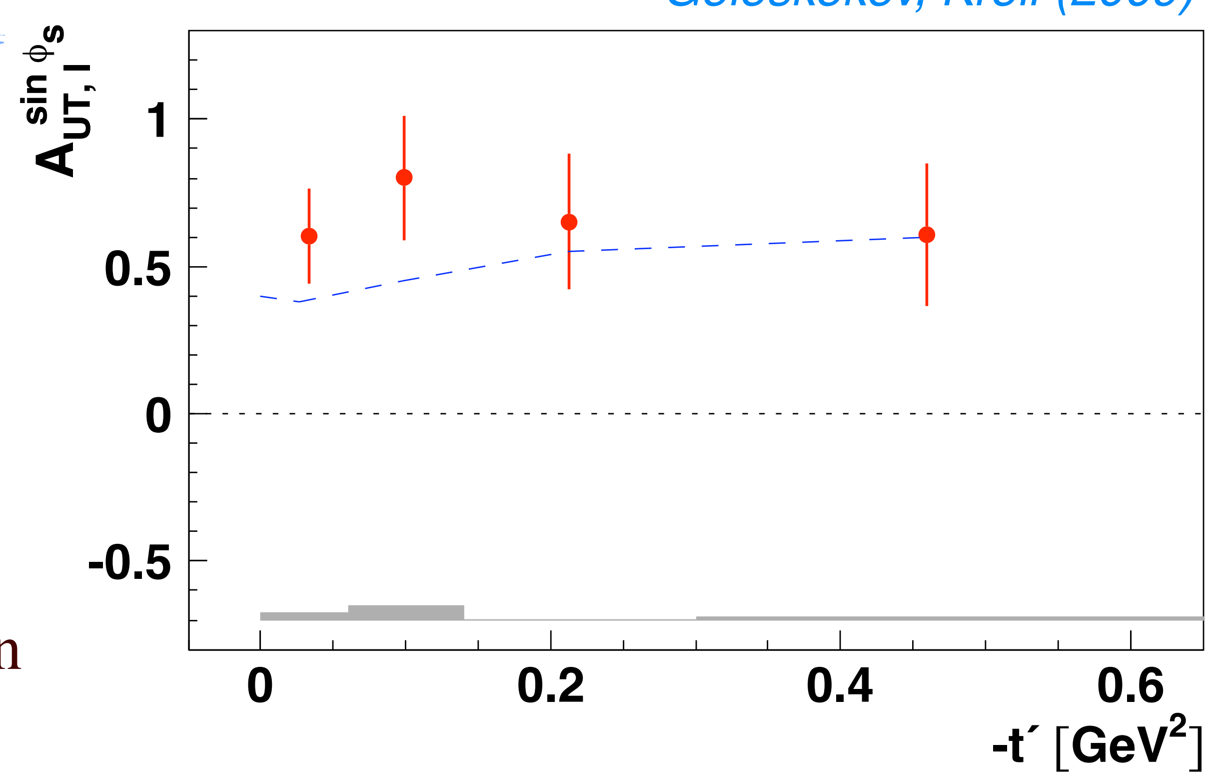


- ☛ no σ_L / σ_T separation
- ☛ small overall value for leading asymmetry amplitude with possible sign change

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

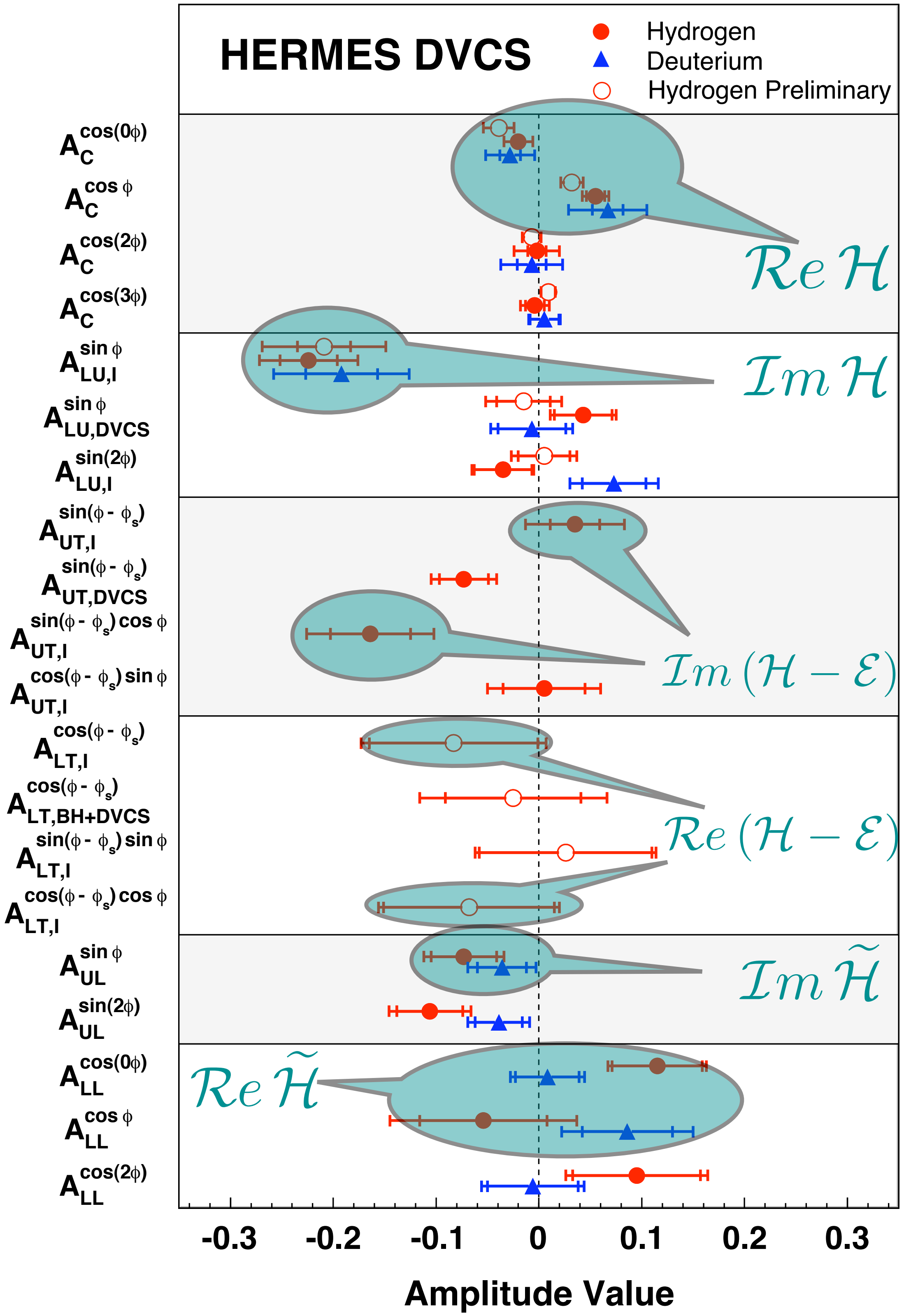
- ☛ theoretical expectation: $A_{UT}^{\sin(\phi-\phi_s)} \propto \sqrt{-t'}$
  - -Frankfurt et al. (2001)- -Belitsky, Muller (2001)-
  - -Goloskokov, Kroll (2009)- -Bechler, Muller (2009)-
- ☛ evidence of contributions from transversely polarized photons

-Goloskokov, Kroll (2009)-

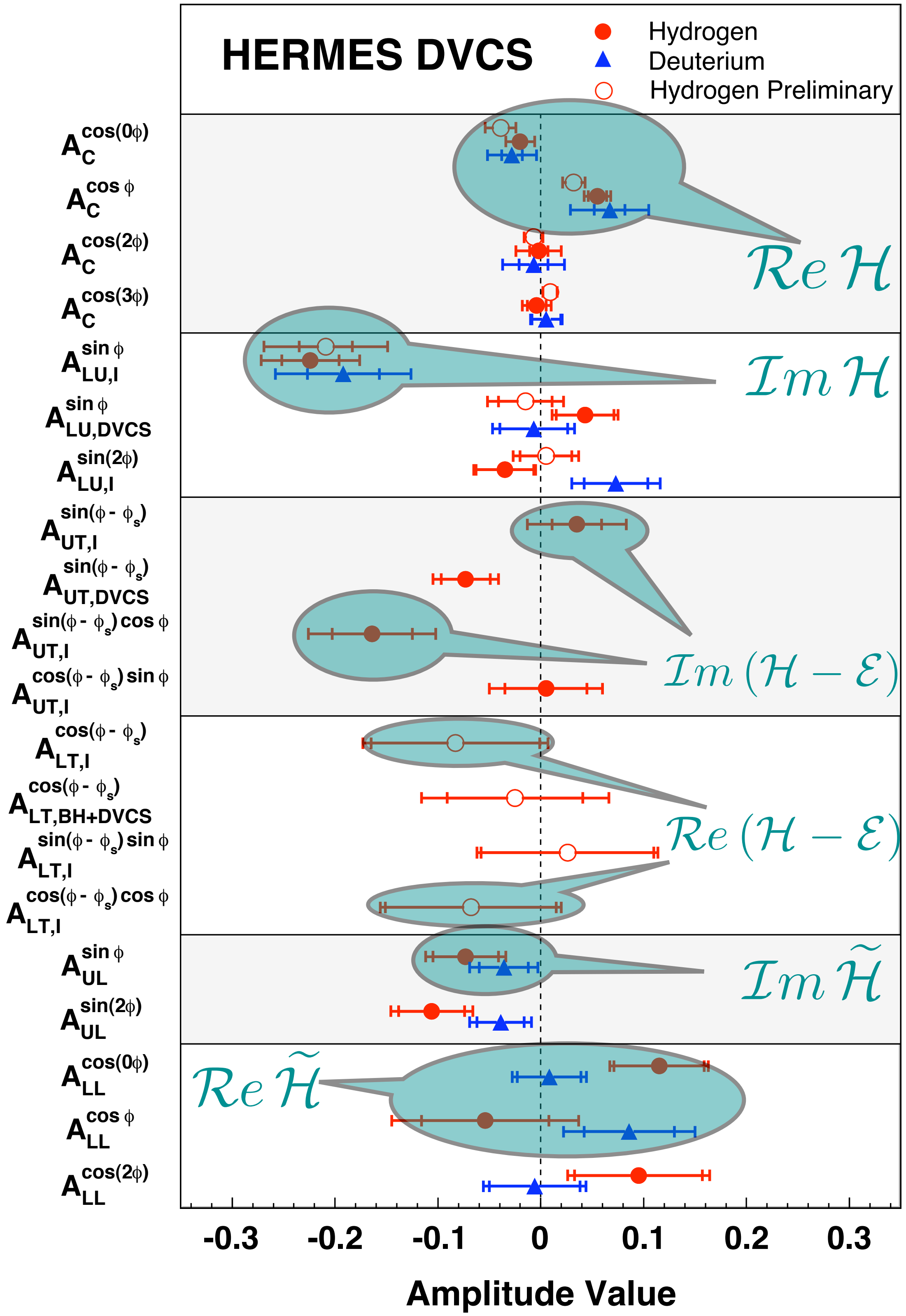


- ☛ unexpected large overall value for asymmetry amplitude $A_{UT}^{\sin\phi_s}$
- ☛ no turnover towards 0 for $t' \to 0$
- ☛ mild t-dependence
- ☛ can be explained only by σ_L / σ_T interference
- ☛ prediction is approximately constant
- ☛ non-vanishing model predictions with contribution from H_T

summary


HERMES DVCS
Hydrogen
Deuterium
Hydrogen Preliminary
$A_C^{\cos(0\phi)}$
$A_C^{\cos\phi}$
$A_C^{\cos(2\phi)}$
$A_C^{\cos(3\phi)}$
$A_{LU,I}^{\sin\phi}$
$A_{LU,DVCS}^{\sin\phi}$
$A_{LU,I}^{\sin(2\phi)}$
$A_{UT,I}^{\sin(\phi-\phi_s)}$
$A_{UT,DVCS}^{\sin(\phi-\phi_s)}$
$A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi}$
$A_{UT,I}^{\cos(\phi-\phi_s)\sin\phi}$
$A_{LT,I}^{\cos(\phi-\phi_s)}$
$A_{LT,BH+DVCS}^{\cos(\phi-\phi_s)}$
$A_{LT,I}^{\sin(\phi-\phi_s)\sin\phi}$
$A_{LT,I}^{\cos(\phi-\phi_s)\cos\phi}$
$A_{UL}^{\sin\phi}$
$A_{UL}^{\sin(2\phi)}$
$A_{LL}^{\cos(0\phi)}$
$A_{LL}^{\cos\phi}$
$A_{LL}^{\cos(2\phi)}$
$\mathcal{R}e\,\mathcal{H}$
$\mathcal{I}m\,\mathcal{H}$
$\mathcal{I}m\,(\mathcal{H}-\mathcal{E})$
$\mathcal{R}e\,(\mathcal{H}-\mathcal{E})$
$\mathcal{I}m\,\widetilde{\mathcal{H}}$
$\mathcal{R}e\,\widetilde{\mathcal{H}}$
-0.3 -0.2 -0.1 0 0.1 0.2 0.3
Amplitude Value

summary


HERMES DVCS
Hydrogen
Deuterium
Hydrogen Preliminary
$A_C^{\cos(0\phi)}$
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$A_C^{\cos(3\phi)}$
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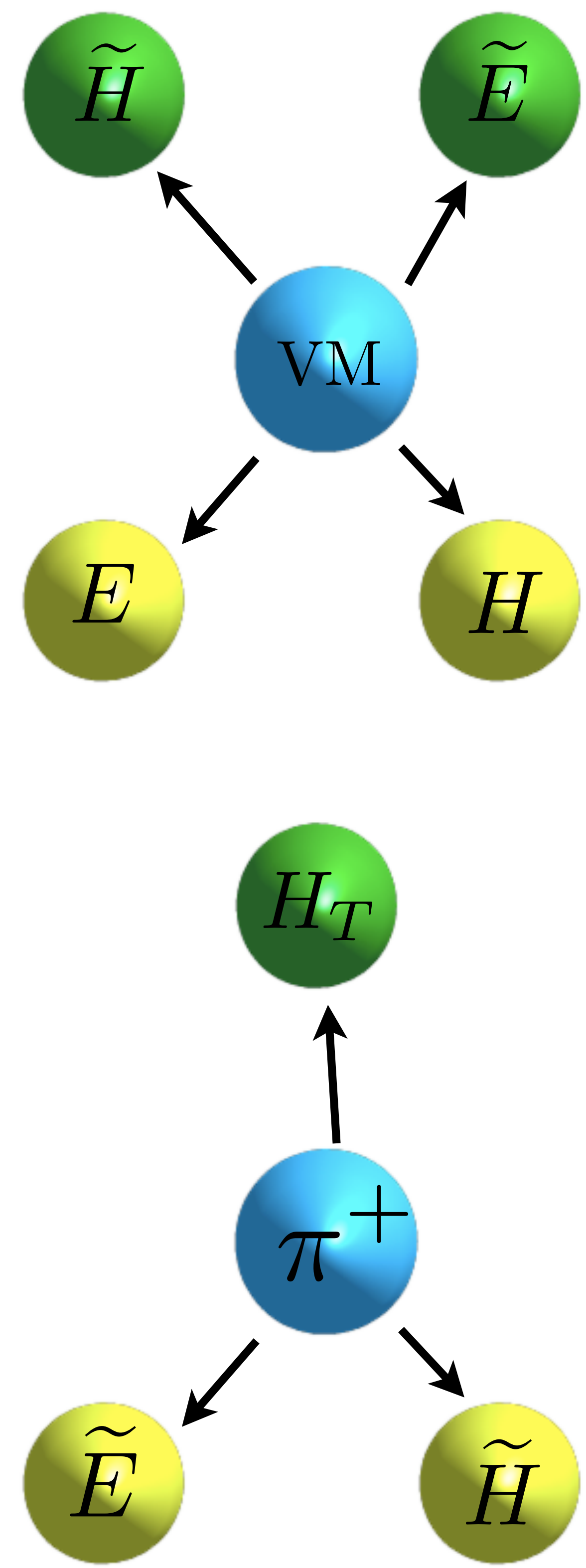
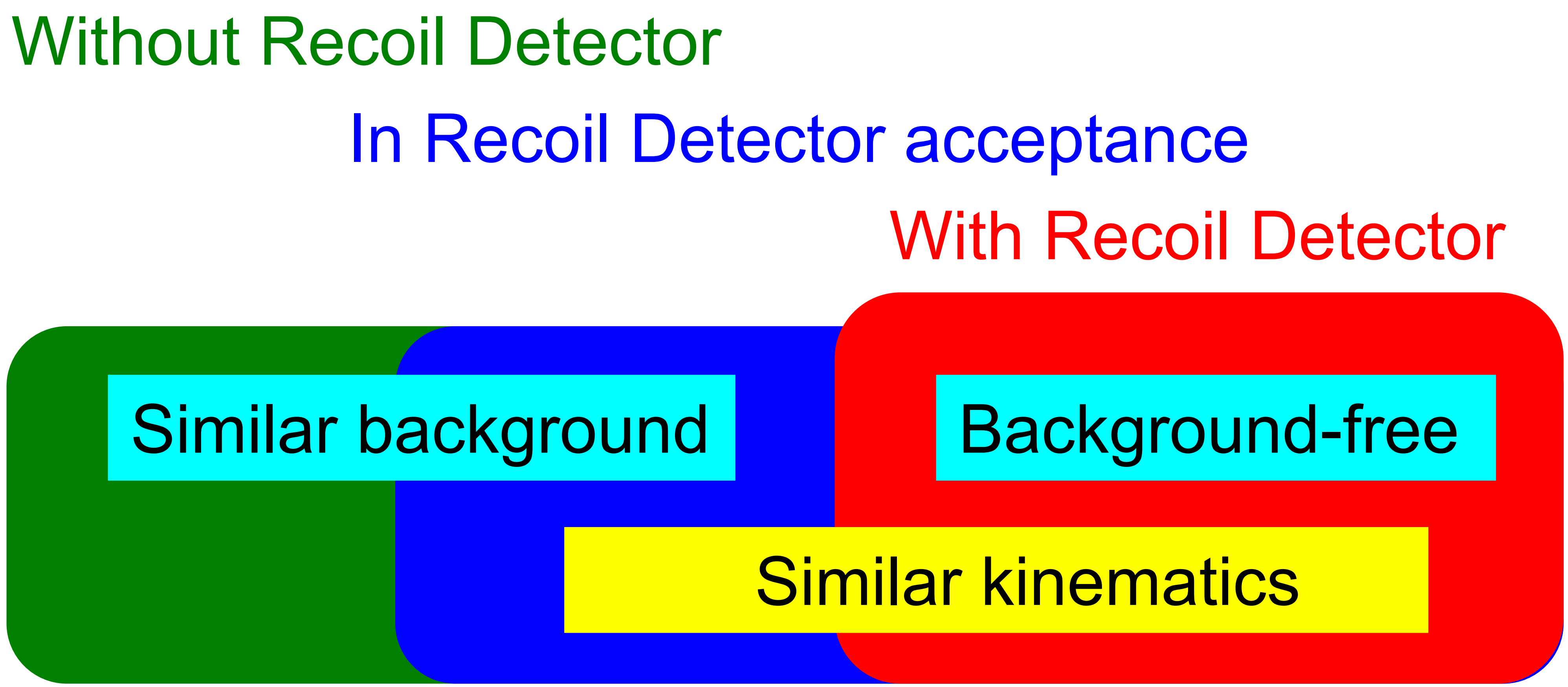
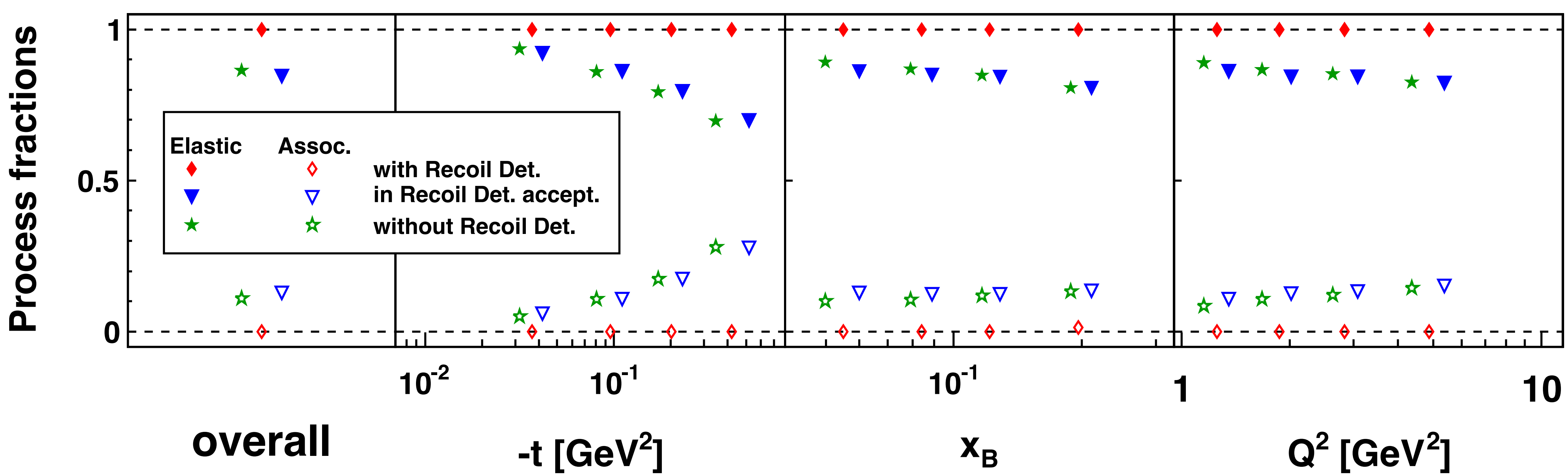
$A_{LU,DVCS}^{\sin\phi}$
$A_{LU,I}^{\sin(2\phi)}$
$A_{UT,I}^{\sin(\phi-\phi_s)}$
$A_{UT,DVCS}^{\sin(\phi-\phi_s)}$
$A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi}$
$A_{UT,I}^{\cos(\phi-\phi_s)\sin\phi}$
$A_{LT,I}^{\cos(\phi-\phi_s)}$
$A_{LT,BH+DVCS}^{\cos(\phi-\phi_s)}$
$A_{LT,I}^{\sin(\phi-\phi_s)\sin\phi}$
$A_{LT,I}^{\cos(\phi-\phi_s)\cos\phi}$
$A_{UL}^{\sin\phi}$
$A_{UL}^{\sin(2\phi)}$
$A_{LL}^{\cos(0\phi)}$
$A_{LL}^{\cos\phi}$
$A_{LL}^{\cos(2\phi)}$
$\mathcal{R}e\,\mathcal{H}$
$\mathcal{I}m\,\mathcal{H}$
$\mathcal{I}m\,(\mathcal{H}-\mathcal{E})$
$\mathcal{R}e\,(\mathcal{H}-\mathcal{E})$
$\mathcal{I}m\,\widetilde{\mathcal{H}}$
$\mathcal{R}e\,\widetilde{\mathcal{H}}$
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Amplitude Value


$\widetilde{H}$
$\widetilde{E}$
VM
E
H
H_T
π^+
$\widetilde{E}$
$\widetilde{H}$

backup slides


Without Recoil Detector
In Recoil Detector acceptance
With Recoil Detector
Similar background
Background-free
Similar kinematics


Process fractions
1
0.5
0
Elastic
Assoc.
with Recoil Det.
in Recoil Det. accept.
without Recoil Det.
10^-2
10^-1
10^-1
1
10
overall
-t [GeV^2]
x_B
Q^2 [GeV^2]