Exclusive hard processes at HERMES

10th international workshop on hadron structure and spectroscopy Venice, Italy, 2010

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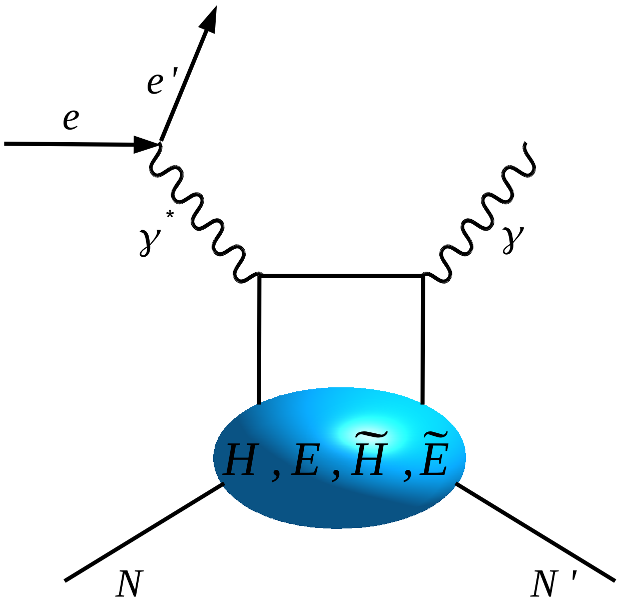
(on behalf of the HERMES collaboration)

deeply virtual Compton scattering



($\gamma^* \to \gamma$): H, E, $\widetilde{H}$, $\widetilde{E}$ (twist-2, chiral even)

- H and $\widetilde{H}$ conserve the nucleon helicity
- E and $\widetilde{E}$ describe the nucleon helicity flip
- Ji relation

$$J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx\, x\, [H_q(x,\xi,t) + E_q(x,\xi,t)]$$
$$= \frac{1}{2} \Delta\Sigma_q + L_q$$

why DVCS?

- the cleanest probe of GPDs
- theoretical accuracy at NNLO
- no gluons in the LO

Compton form factors

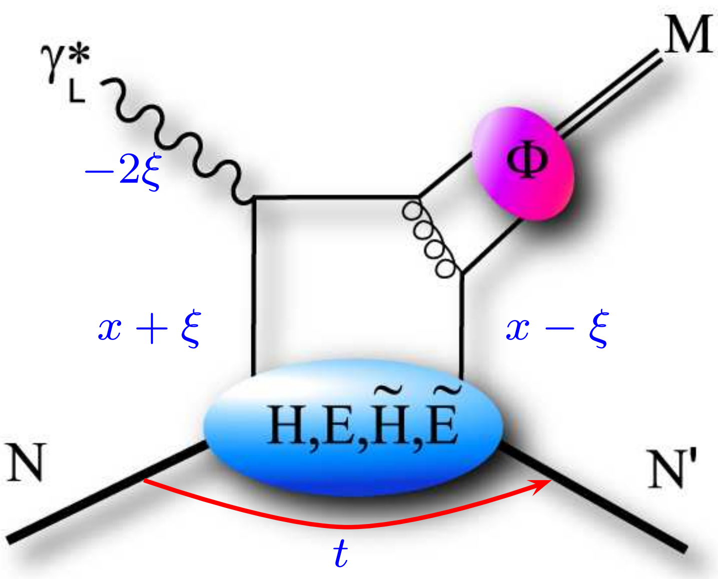
- convolutions of GPDs ($F : H, E, \widetilde{H}, \widetilde{E}$) and hard scattering functions

$$\mathcal{F}(\xi,t) = \sum_q \int_{-1}^{1} dx\, C_q(\xi,x)\, F^q(x,\xi,t)$$

exclusive meson production

factorization in collinear approximation *-Collins, Frankfurt, Strikman (1997)-*

$$\mathcal{A} \propto F(x,\xi,t;\mu^2) \otimes K(x,\xi,z;\log(Q^2/\mu^2) \otimes \Phi(z;\mu^2)$$



at leading-twist: H, E, $\widetilde{H}$, $\widetilde{E}$

- H and $\widetilde{H}$ conserve the nucleon helicity
- E and $\widetilde{E}$ describe the nucleon helicity flip

quantum numbers of final state selects different GPDs

- vector mesons ($\gamma^*_L \to \rho_L, \omega_L, \phi_L$): H, E
- pseudoscalar mesons ($\gamma^*_L \to \pi, \eta$): $\widetilde{H}$, $\widetilde{E}$

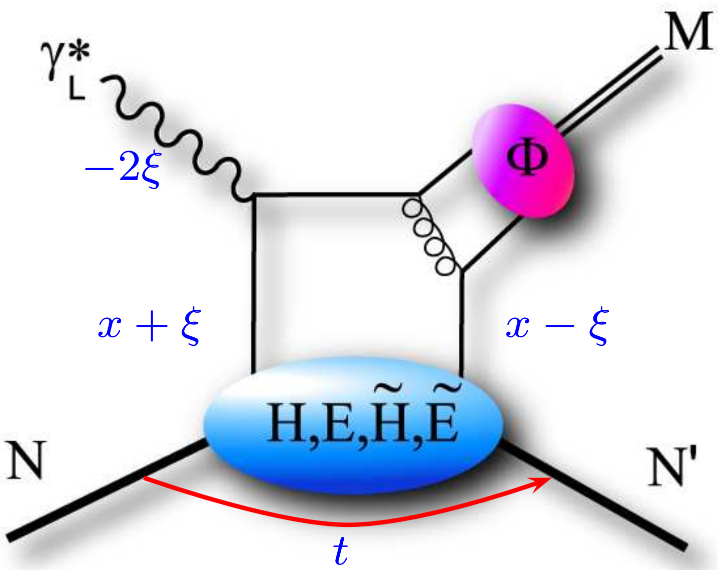
factorization for σ_L (and ρ_L, ω_L, ϕ_L) only

- $\sigma_L - \sigma_T$ suppressed by $1/Q$
- σ_T suppressed by $1/Q^2$

exclusive meson production

modified perturbative approach *-Goloskokov, Kroll (2006)-*

$$\mathcal{A} \propto F(x,\xi,t;\mu^2) \otimes K(x,\xi,z;\log(Q^2/\mu^2) \otimes \Phi(z,k_\perp;\mu^2)$$



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- $\sigma_L - \sigma_T$ suppressed by $1/Q$
- σ_T suppressed by $1/Q^2$

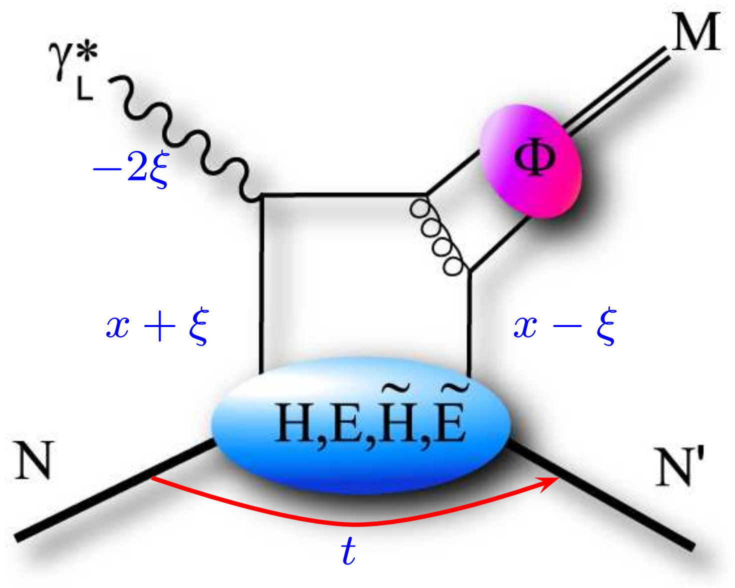
power corrections: $k_\perp$ is not neglected

- regulate the singularity in the transverse amplitude
- $\gamma^*_T \to \rho^0_T$ transitions can be calculated (model dependent)

exclusive meson production

modified perturbative approach *-Goloskokov, Kroll (2006)-*

$$\mathcal{A} \propto F(x,\xi,t;\mu^2) \otimes K(x,\xi,z;\log(Q^2/\mu^2)) \otimes \Phi(z,k_\perp;\mu^2)$$



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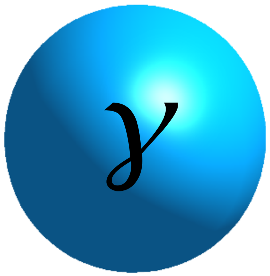
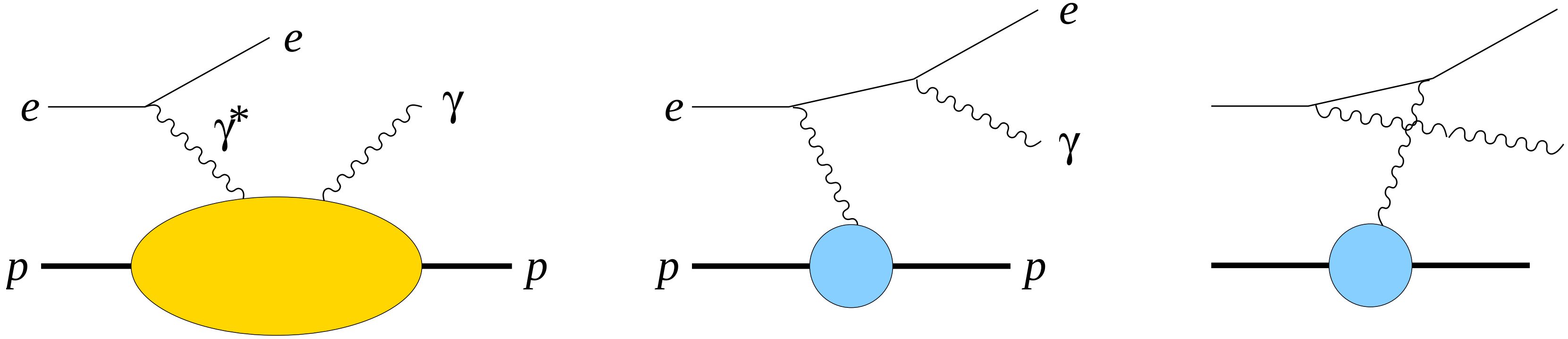
- $\sigma_L - \sigma_T$ suppressed by $1/Q$
- σ_T suppressed by $1/Q^2$

power corrections: $k_\perp$ is not neglected

- $\gamma^*_T \to \rho^0_T$ transitions can be calculated (model dependent)
  - ρ^0: contributions from $\widetilde{H}$ and $\widetilde{E}$
  - π^+: contributions from H_T


γ

Deeply Virtual Compton Scattering (DVCS)



same initial and final states in DVCS and Bethe-Heitler ⇒ Interference!

$$\sigma_{ep} \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{\mathcal{I}}$$

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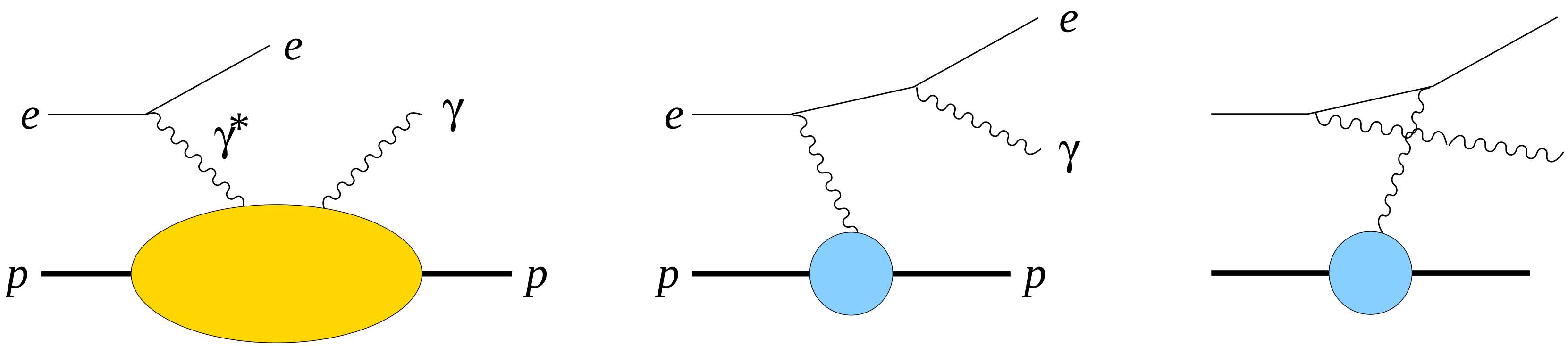

σ_{XY}

beam: P_l

target: $S_L S_T$

same initial and final states in DVCS and Bethe-Heitler ⇒ Interference!

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

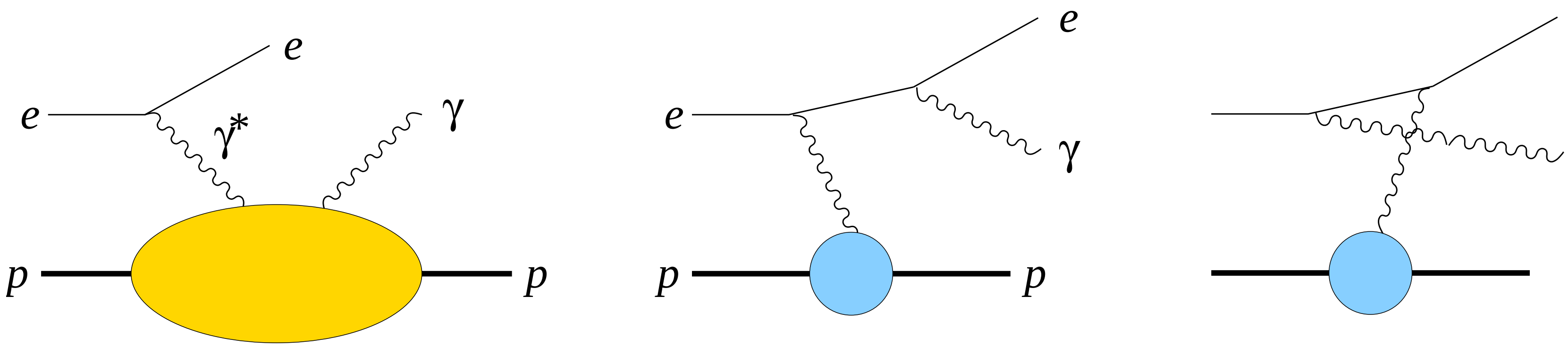
single spin terms: LU, UL, UT

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

unpolarized and double-spin terms: UU, LL, LT

- project real parts of Compton form factors

Deeply Virtual Compton Scattering (DVCS)



σ_{XY} → beam: P_l ; target: $S_L S_T$

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&+ \quad e_\ell S_L d\sigma^{I}_{UL} + S_L d\sigma^{DVCS}_{UL} \\
&+ \quad e_\ell S_T d\sigma^{I}_{UT} + S_T d\sigma^{DVCS}_{UT} \\
+P_\ell S_L d\sigma^{BH}_{LL} \quad &+ \quad e_\ell P_\ell S_L d\sigma^{I}_{LL} + P_\ell S_L d\sigma^{DVCS}_{LL} \\
+P_\ell S_T d\sigma^{BH}_{LT} \quad &+ \quad e_\ell P_\ell S_T d\sigma^{I}_{LT} + P_\ell S_T d\sigma^{DVCS}_{LT}
\end{aligned}$$

Bethe-Heitler contribution:

- calculated at QED

DVCS contribution:

- HERMES: $|\mathcal{T}_{DVCS}|^2 << |\mathcal{T}_{BH}|^2$

interference term:

- depend on a linear combination of Compton form factors
- access to GPD combinations through azimuthal asymmetries

express asymmetries in terms of Fourier coefficients

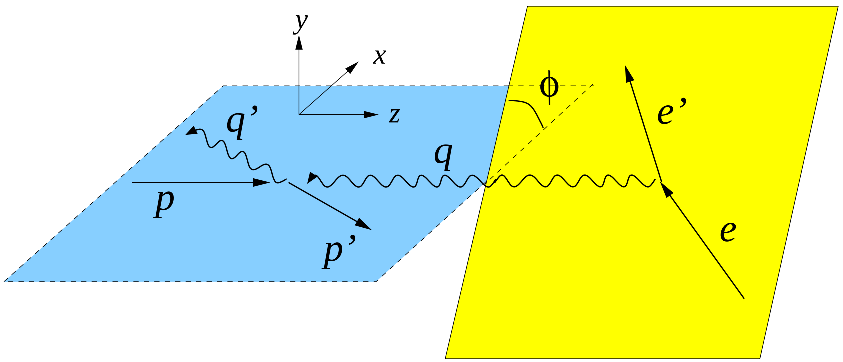
$$\sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[1 + P_\ell A_{LU}^{DVCS}(\phi) + e_\ell P_\ell A_{LU}^{I}(\phi) + e_\ell A_C(\phi)\right]$$

Fourier expansion in azimuthal angle ϕ

$$|\tau_{\mathrm{BH}}|^2 \propto \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi)$$

$$|\tau_{\mathrm{DVCS}}|^2 \propto \sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi) + P_\ell\, s_1^{\mathrm{DVCS}} \sin\phi$$

$$\mathrm{I} \propto \sum_{n=0}^{3} c_n^{\mathrm{I}} \cos(n\phi) + \sum_{n=1}^{2} P_\ell\, s_n^{\mathrm{I}} \sin(n\phi)$$



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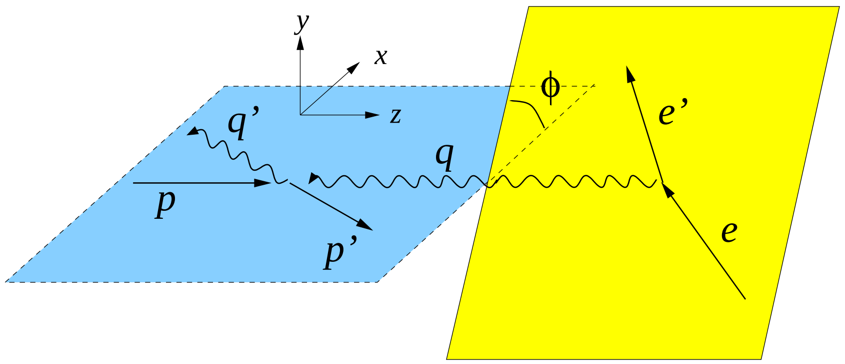

$$c_1^{\mathrm{I}} \propto F_1 \mathrm{Re}\mathcal{H}$$

$$c_0^{\mathrm{I}} \propto -\frac{-t}{Q} c_1^{\mathrm{I}}$$

$$s_1^{\mathrm{I}} \propto F_1 \mathrm{Im}\mathcal{H}$$

express asymmetries in terms of Fourier coefficients

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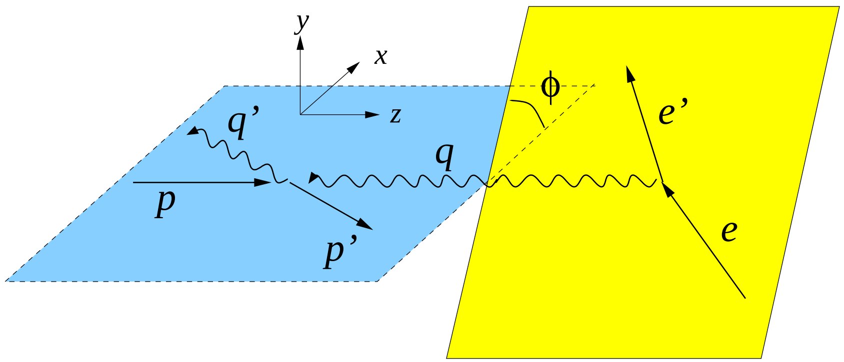

DVCS term:

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

$$c_1^{\text{I}} \propto F_1 \text{Re}\mathcal{H}$$

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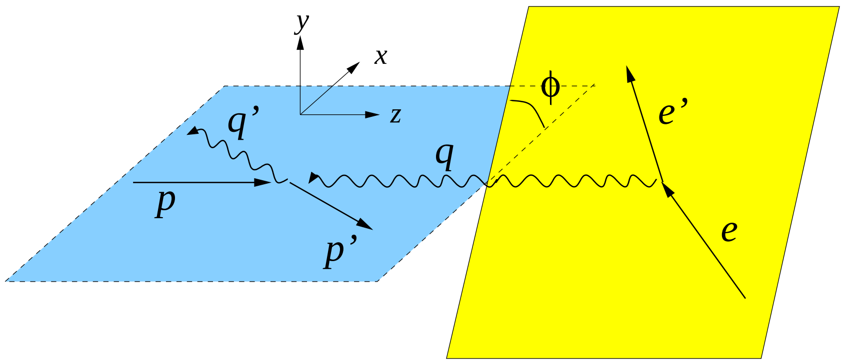

interference term:

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

$$c_1^{\mathrm{I}} \propto F_1 \mathrm{Re}\mathcal{H}$$

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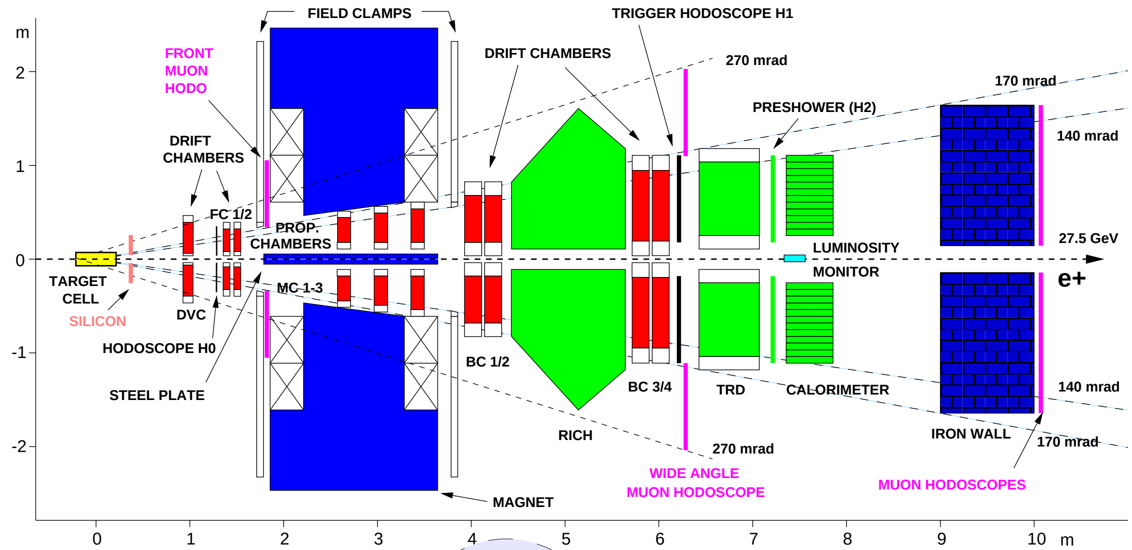
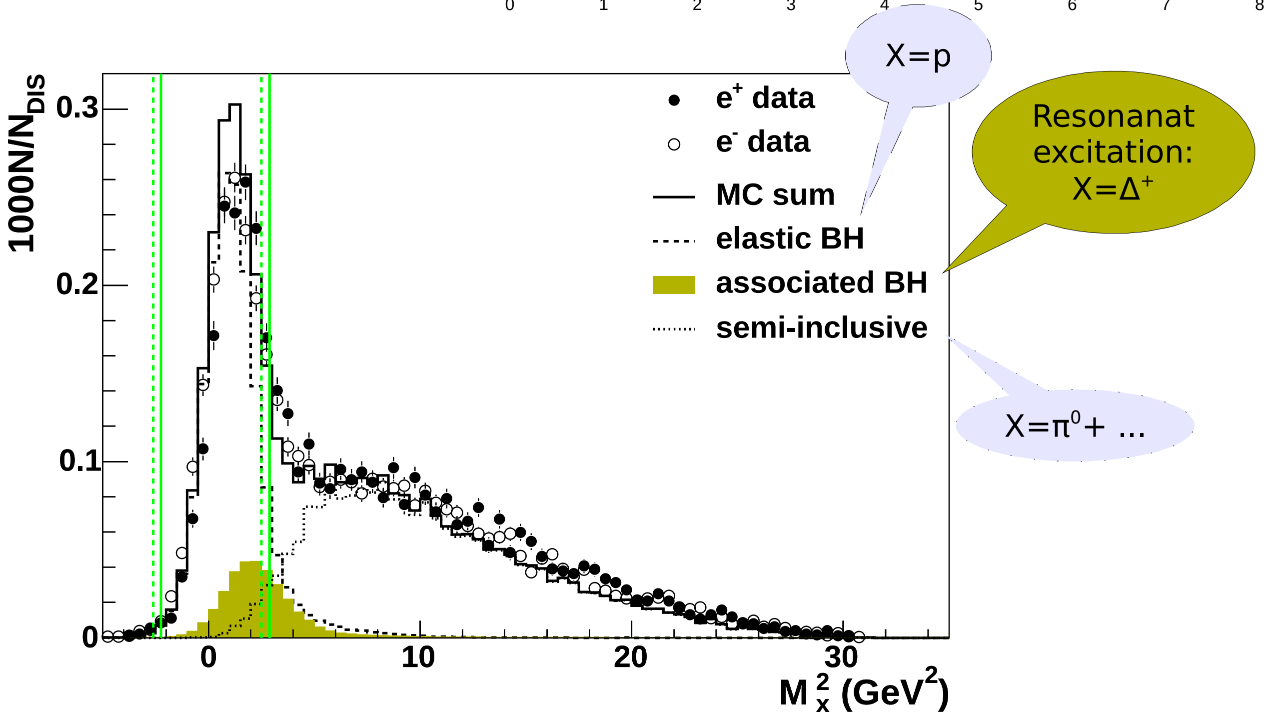
$$s_1^{\mathrm{I}} \propto F_1 \mathrm{Im}\mathcal{H}$$

DVCS at HERMES (pre-recoil data)

$$e + p \rightarrow e' + \gamma + p'$$

- detected particles: lepton and photon
- missing mass technique for $ep \rightarrow e'\gamma X$: $M_X^2 = (p + e - e' - \gamma)^2$





unpolarized-target asymmetries

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

beam-helicity asymmetry (single charge):

$$\mathcal{A}_{LU}(\phi) \equiv \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}}$$

- projects the imaginary part of τ_{DVCS}
- no separate access to s_1^{DVCS} and s_1^I

beam-helicity asymmetry (new approach):

- charge-difference beam-helicity asymmetry

$$\mathcal{A}_{LU}^{I}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) - (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

- charge-averaged beam-helicity asymmetry

$$\mathcal{A}_{LU}^{DVCS}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

- s_1^{DVCS} and s_1^I can be disentangled

beam-charge asymmetry:

$$\mathcal{A}_C(\phi) \equiv \frac{d\sigma^{+} - d\sigma^{-}}{d\sigma^{+} + d\sigma^{-}}$$

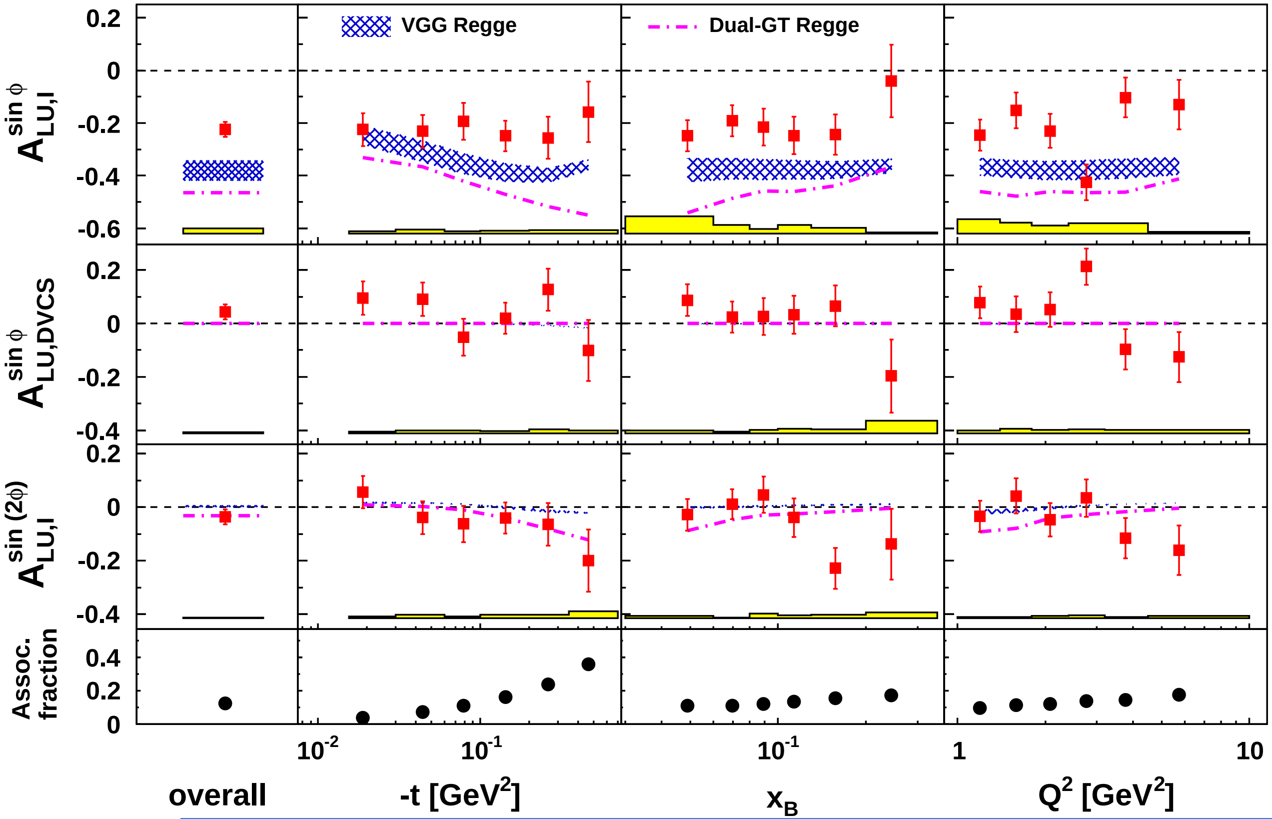
- projects the real part of τ_{DVCS}

beam helicity asymmetry

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

$$A^{\sin\phi}_{LU,\mathrm{DVCS}} \propto s^{\mathrm{DVCS}}_{1} \sin\phi$$

-HERMES Collaboration: arXiv:0909.3587 (2009)-



$A^{\sin\phi}_{LU,\mathrm{I}}$

- twist-2: $\propto F_1 \mathrm{Im}\mathcal{H}$
- large overall value
- no kin. dependencies

$A^{\sin\phi}_{LU,\mathrm{DVCS}}$, $A^{\sin 2\phi}_{LU,\mathrm{I}}$

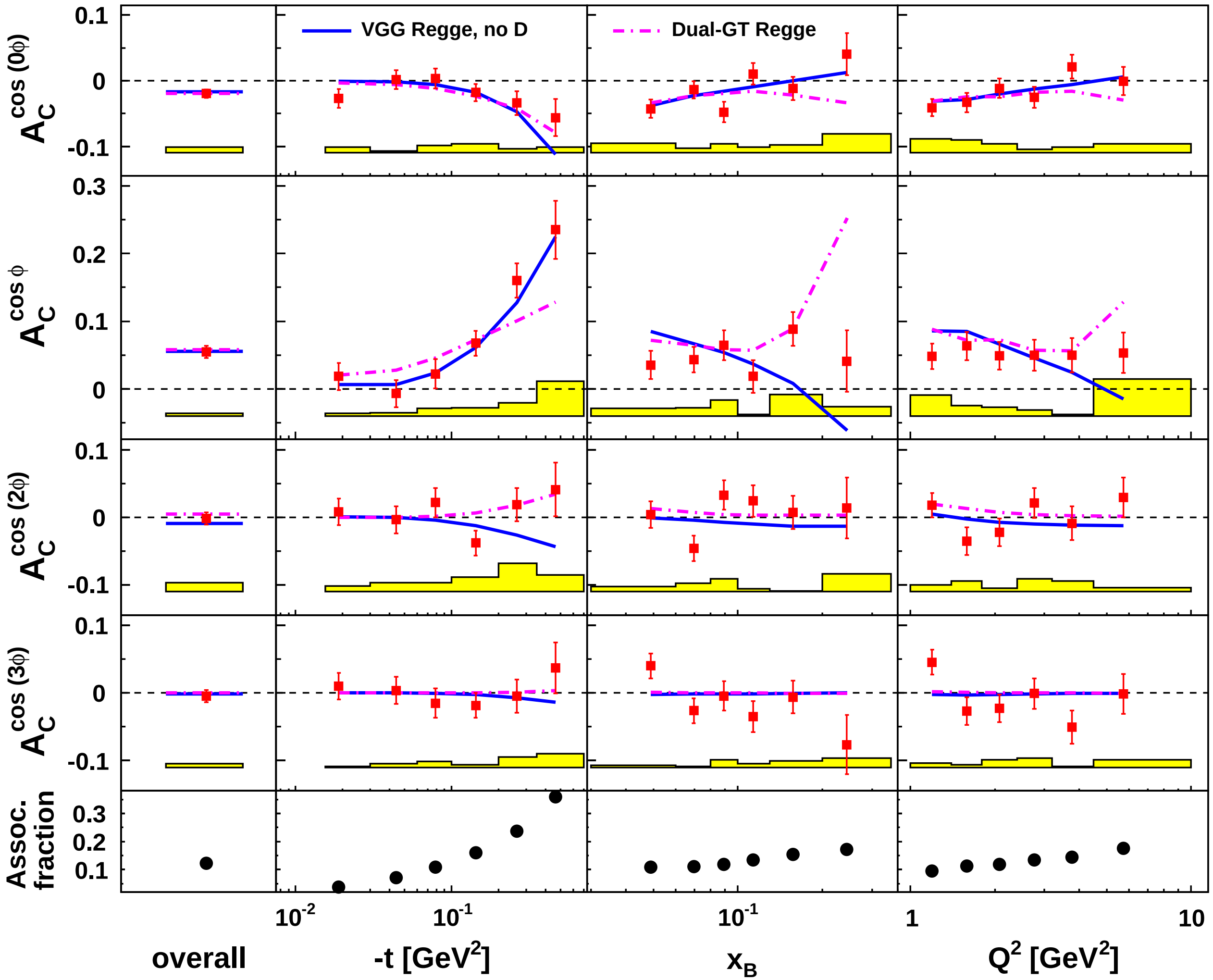
- twist-3
- overall value compatible with 0
- no kin. dependencies

- overshoot the magnitude of $A^{\sin\phi}_{LU,\mathrm{I}}$ by a factor of 2
- describe the shape of kin dependencies on x_B and Q^2, but not on t
- overestimation is not due to the associated production

beam charge asymmetry

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

-HERMES Collaboration: arXiv:0909.3587 (2009)-



twist-2 GPDs: $A_C^{\cos\phi}$, $A_C^{\cos 0\phi}$

- strong t-dependence
- no x_B, Q^2 dependencies

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

$$A_C^{\cos 0\phi} \propto -\frac{t}{Q} A_C^{\cos\phi}$$

$A_C^{\cos(2\phi)} \approx 0$: twist-3 GPDs
$A_C^{\cos(3\phi)} \approx 0$: gluon helicity-flip GPDs

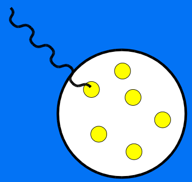
theoretical predictions:

- does not describe the beam-helicity data, but in good agreement with this data

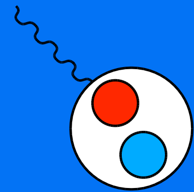
unpolarized deuterium targets

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

- DVCS



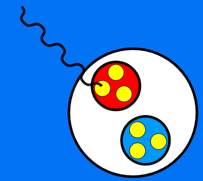
- Bethe-Heitler



- target stays intact
- spin-1 targets described by 9 GPDs:
  $H_1^q, H_2^q, H_3^q, H_4^q, H_5^q, \widetilde{H}_1^q, \widetilde{H}_2^q, \widetilde{H}_3^q, \widetilde{H}_4^q$

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

- DVCS



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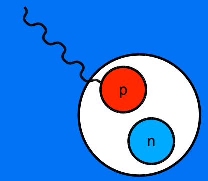
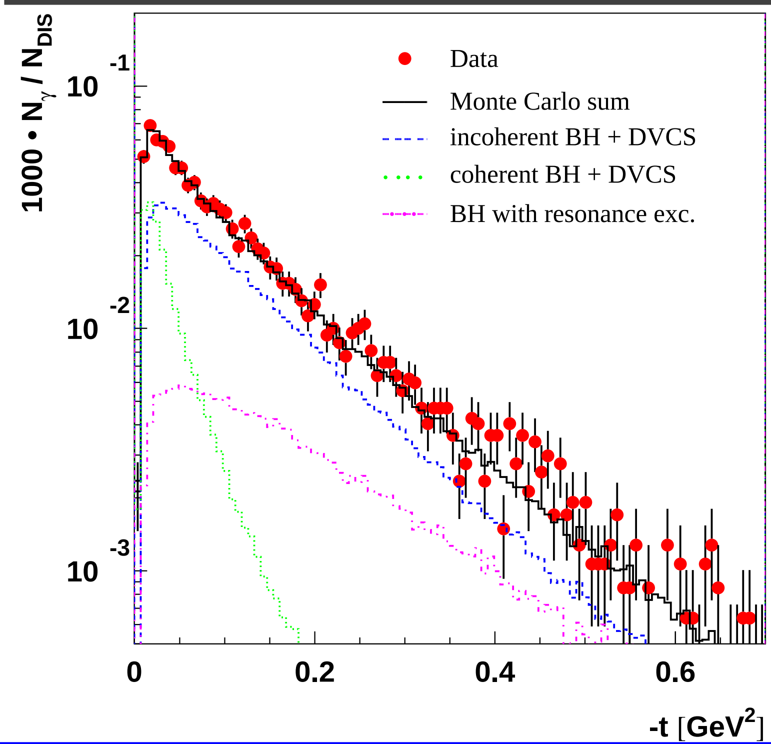


- target brakes up
- spin$-\frac{1}{2}$ targets described by 4 GPDs:
  $H, E, \widetilde{H}, \widetilde{E}$



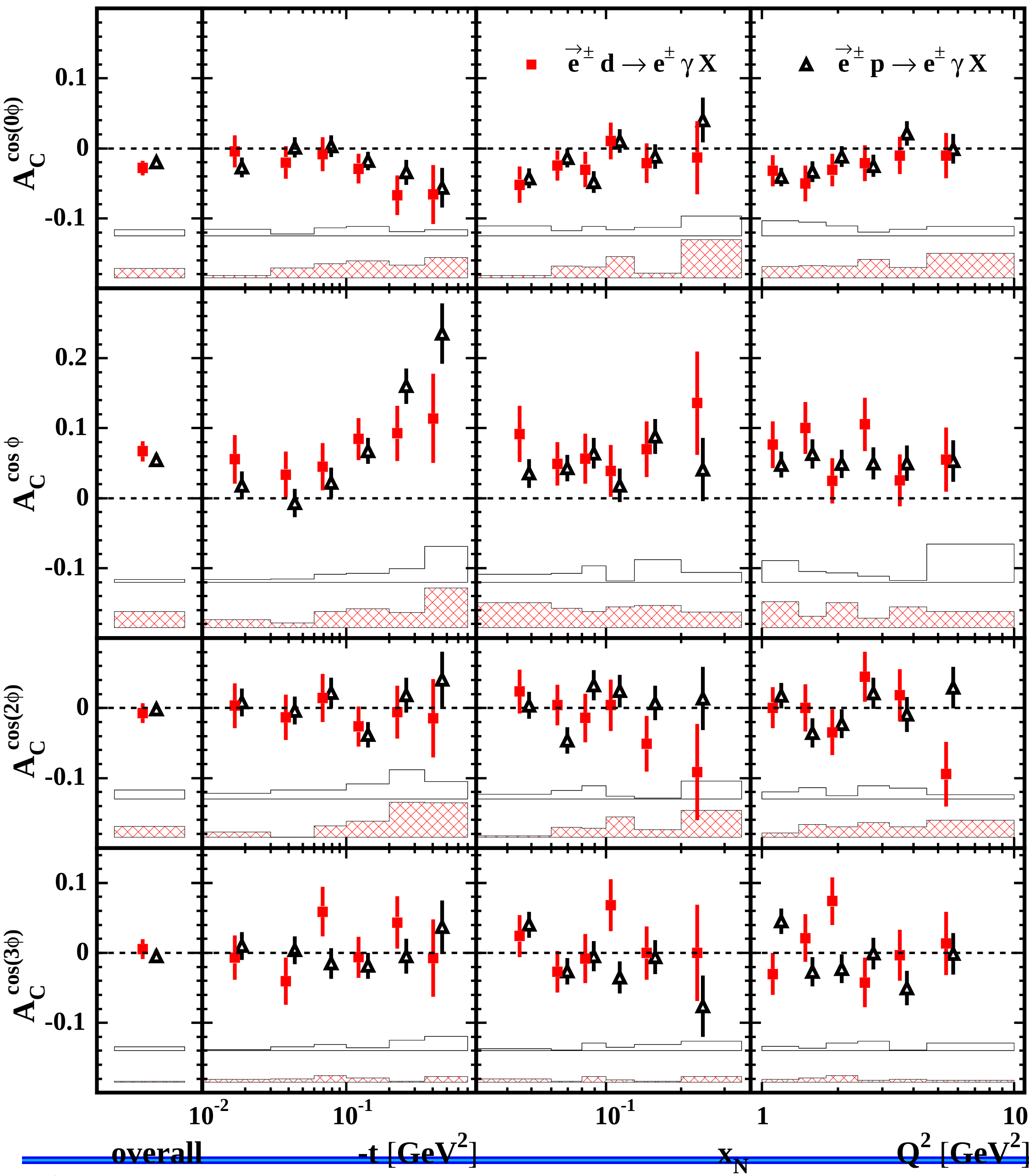
coherent:

- contribution at small $-t$

incoherent:

- contribution at larger $-t$
- contribution from coherent $[0.06 : 0.7]$ GeV^2: 20%

beam-charge asymmetry



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

-HERMES Collaboration: arXiv:0911.0091 (2009)-

twist-2:

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

$$A_{C,incoh}^{\cos\phi} \propto F_1 \mathrm{Re}\mathcal{H}$$

$$A_C^{\cos 0\phi} \propto -\frac{t}{Q} A_C^{\cos\phi}$$

higher twist :

$$A_C^{\cos(2\phi)} \approx 0$$

$$A_C^{\cos(3\phi)} \approx 0$$

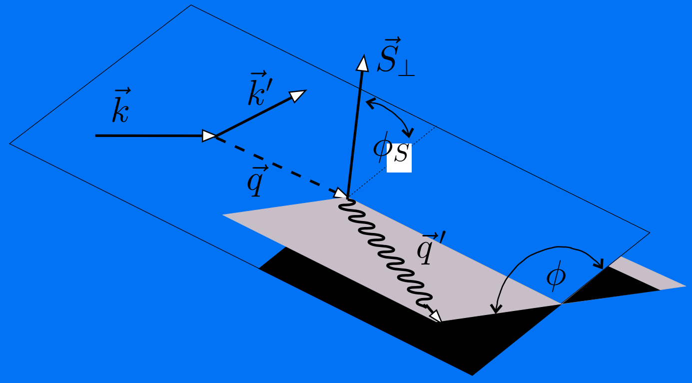
- d and p results consistent
- small values of $-t$: differences due to coherent contribution
- larger values of $-t$: differences due to neutron contribution

transversely polarized target

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

transverse target-spin asymmetry:

$$\mathcal{A}_{UT}(\phi,\phi_S) = \frac{1}{S_T} \cdot \frac{d\sigma^{\Uparrow}(\phi,\phi_S) - d\sigma^{\Downarrow}(\phi,\phi_S)}{d\sigma^{\Uparrow}(\phi,\phi_S) + d\sigma^{\Downarrow}(\phi,\phi_S)}$$



beam-charge asymmetry:

$$\mathcal{A}_C(\phi) \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

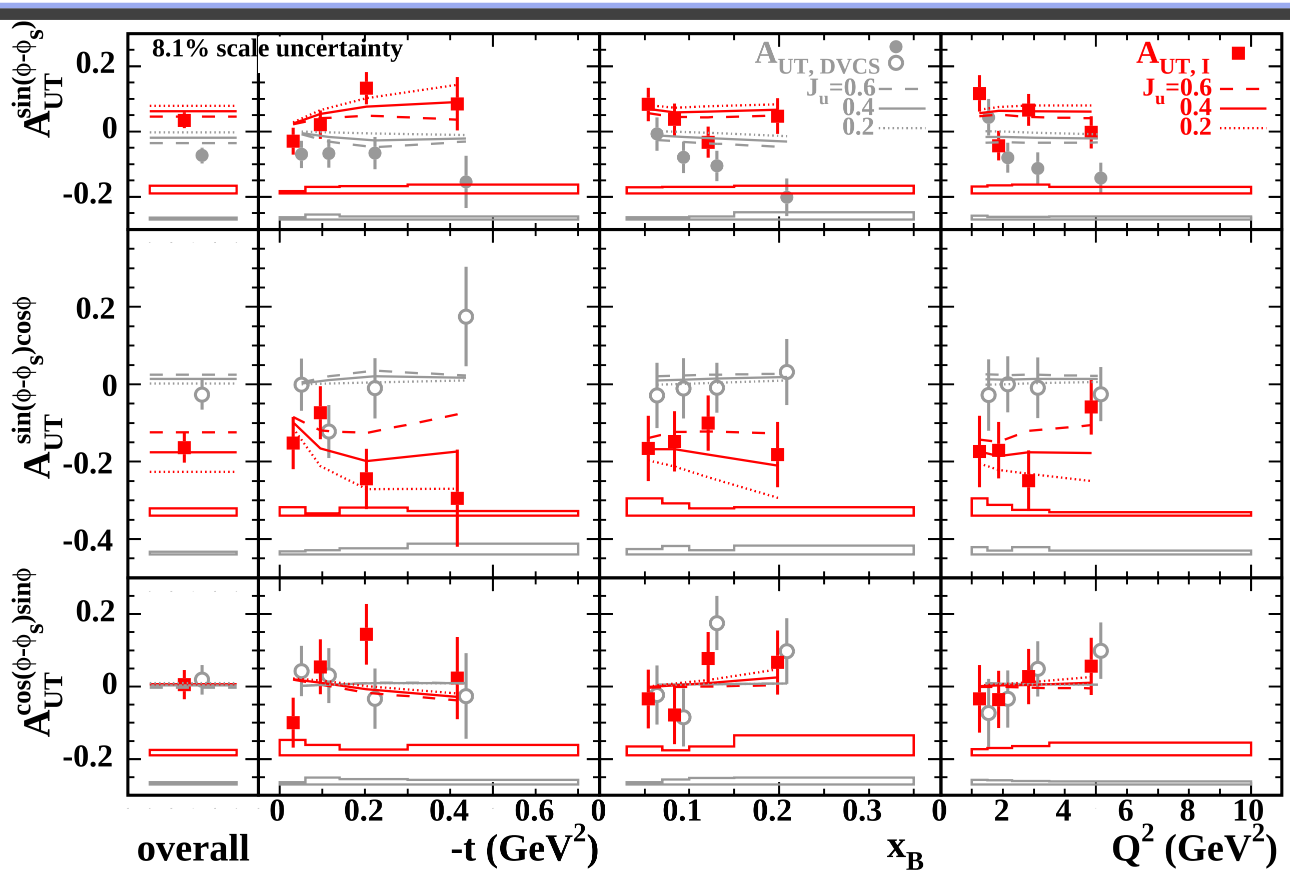
$$\mathcal{A}_{UT}^{\mathrm{DVCS}}(\phi,\phi_S) \equiv \frac{1}{S_T} \cdot \frac{d\sigma^{+\Uparrow}(\phi,\phi_S) - d\sigma^{+\Downarrow}(\phi,\phi_S) + d\sigma^{-\Uparrow}(\phi,\phi_S) - d\sigma^{-\Downarrow}(\phi,\phi_S)}{d\sigma^{+\Uparrow}(\phi,\phi_S) + d\sigma^{+\Downarrow}(\phi,\phi_S) + d\sigma^{-\Uparrow}(\phi,\phi_S) + d\sigma^{-\Downarrow}(\phi,\phi_S)}$$

$$\mathcal{A}_{UT}^{\mathrm{I}}(\phi,\phi_S) \equiv \frac{1}{S_T} \cdot \frac{d\sigma^{+\Uparrow}(\phi,\phi_S) - d\sigma^{+\Downarrow}(\phi,\phi_S) - d\sigma^{-\Uparrow}(\phi,\phi_S) + d\sigma^{-\Downarrow}(\phi,\phi_S)}{d\sigma^{+\Uparrow}(\phi,\phi_S) + d\sigma^{+\Downarrow}(\phi,\phi_S) + d\sigma^{-\Uparrow}(\phi,\phi_S) + d\sigma^{-\Downarrow}(\phi,\phi_S)}$$

- separation of s_i^{DVCS}, c_i^{DVCS} and s_i^{I}, c_i^{I} terms with same harmonic signatures
- projects the imaginary part of τ_{DVCS}

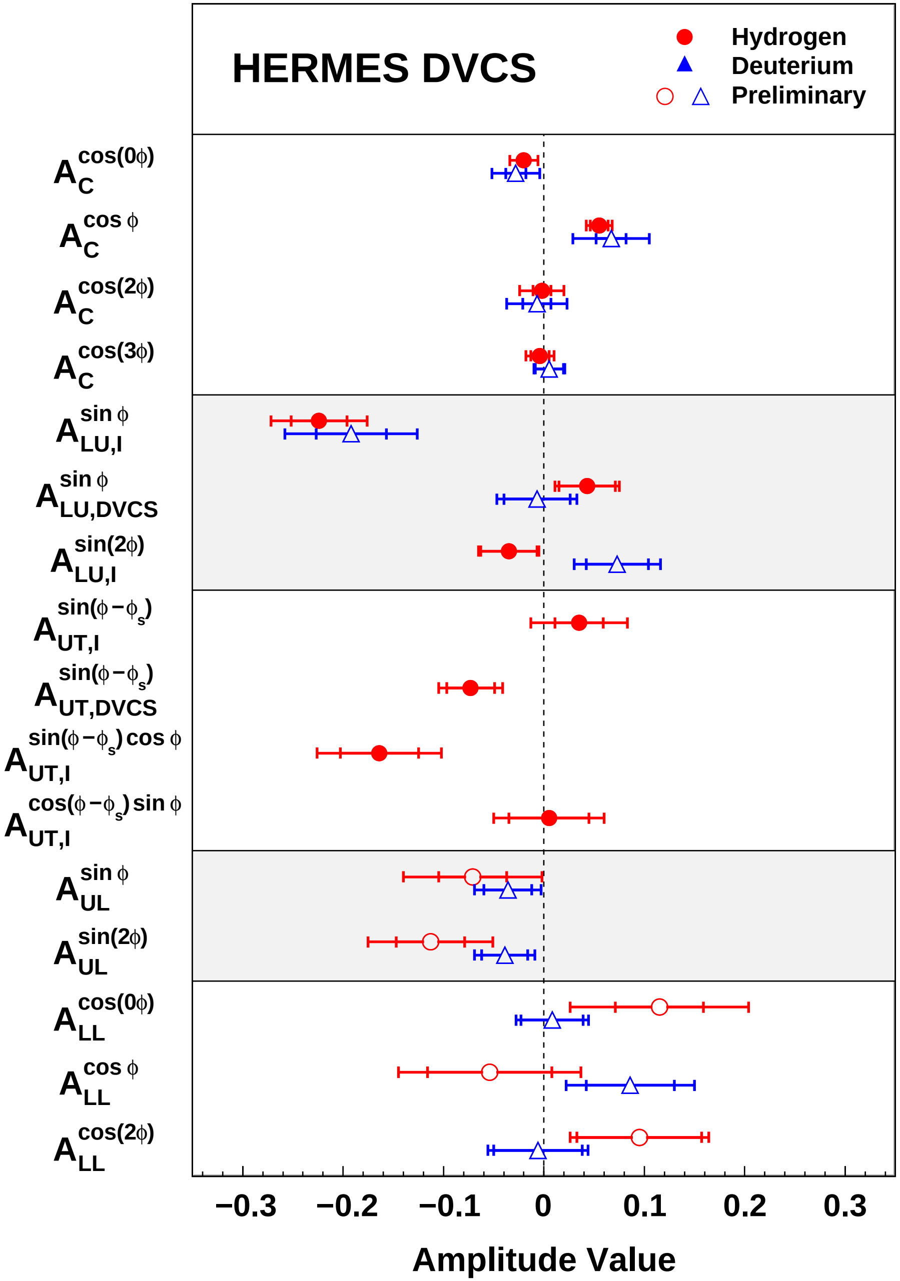
transverse target-spin asymmetry

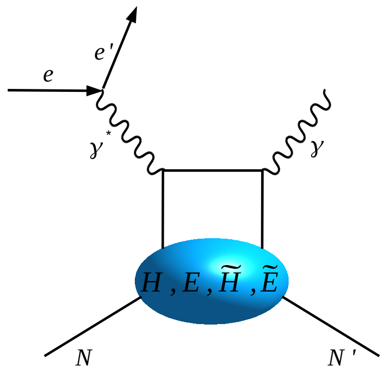
$$\mathcal{A}_{UT}(\phi,\phi_S) \quad \propto \quad \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]\sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]\sin(\phi-\phi_S)$$
$$+ \quad \mathrm{Im}[\mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^* + \xi\widetilde{\mathcal{E}}\,\widetilde{\mathcal{H}}^* - \widetilde{\mathcal{H}}\,\xi\widetilde{\mathcal{E}}^*]\sin(\phi-\phi_S) + \ldots$$



- $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ found much more sensitive to J_u than others
- insensitive to J_d, assumed $J_d = 0$ (supported by lattice QCD)
- with a good model, allows a model-dependent constraint

GPDs, DVCS and HERMES





beam-charge asymmetry:
- $\mathrm{Re}\mathcal{H}$

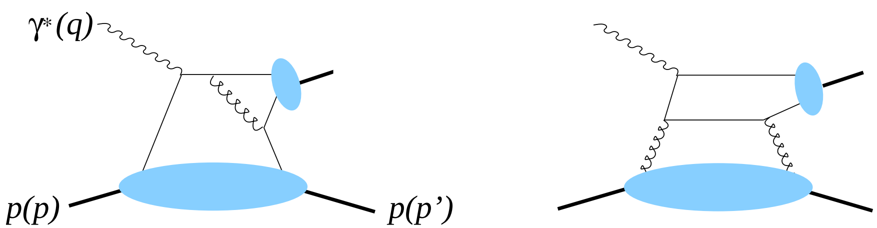
beam-helicity asymmetry:
- $\mathrm{Im}\mathcal{H}$

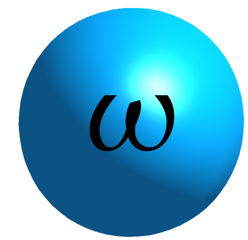
transverse target-spin asymmetry:
- $\mathrm{Im}(\mathcal{H}\,\mathcal{E})$

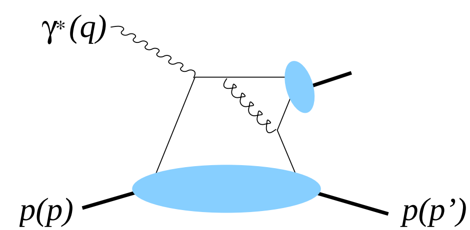
longitudinal target-spin asymmetry:
- $\mathrm{Im}\widetilde{\mathcal{H}}$

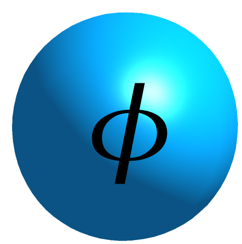
double-spin asymmetry:
- $\mathrm{Re}\widetilde{\mathcal{H}}$

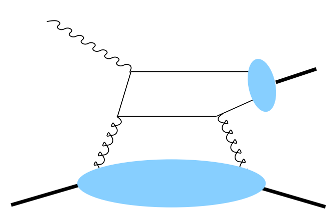

ρ


γ*(q)
p(p)
p(p')


ω

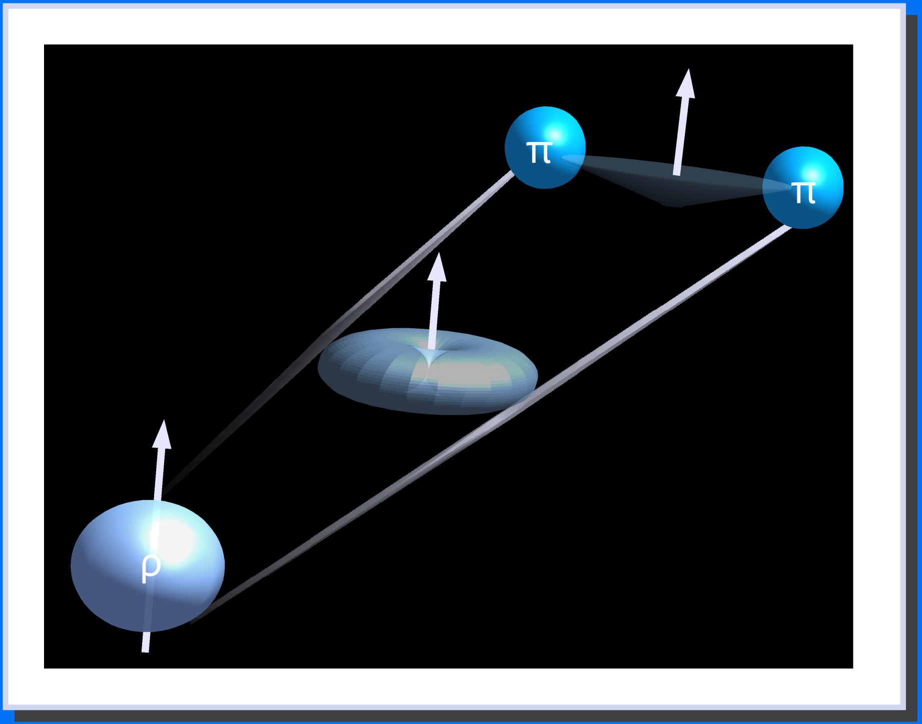

γ*(q)
p(p)
p(p')


φ



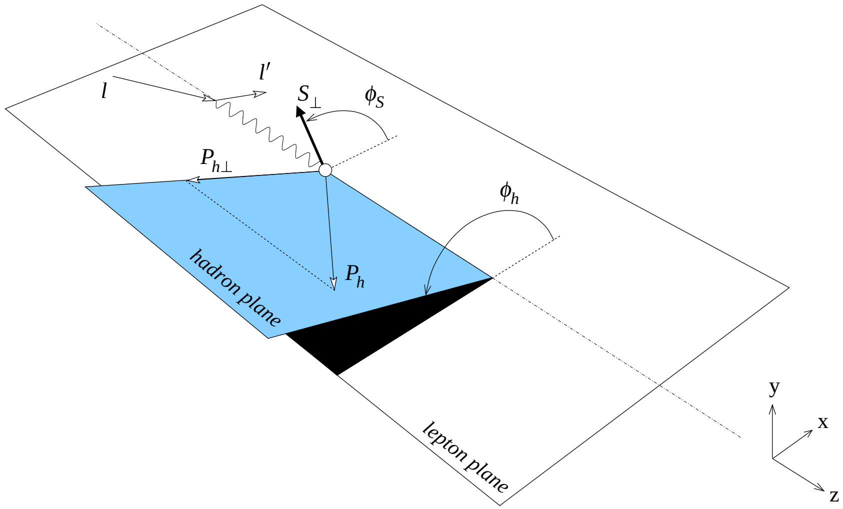
vector meson polarization

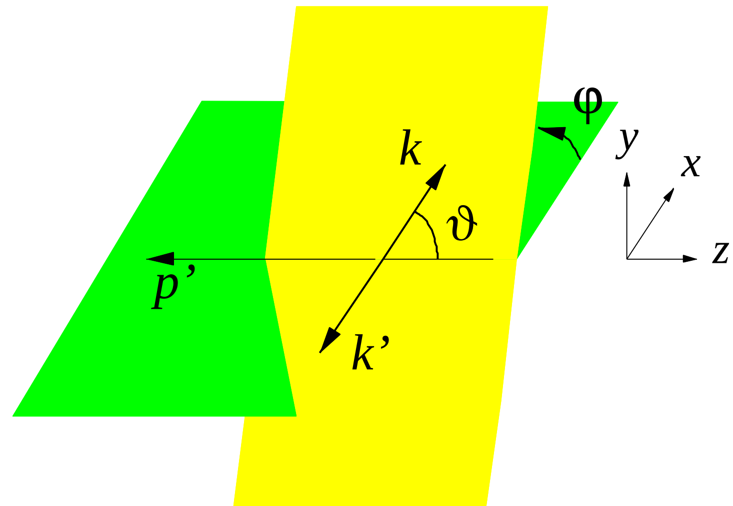
- γ^* and ρ^0, ϕ, ω have the same quantum numbers
  - helicity transfer $\gamma^* \to \rho^0, \phi, \omega$
    - signature: ρ^0, ϕ, ω production angular distribution
- the spin-state of the ρ^0, ϕ, ω is reflected in the orbital angular momentum of decay particles
  - ρ^0, ϕ, ω (in the rest frame): $J = L + S = 1$
  - $\pi, K : S = 0,\ L = 1$
    - signature: decay angular distribution



vector meson cross section

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





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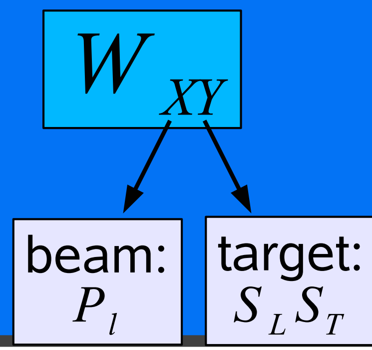
- production and decay angular distributions W decomposed:

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



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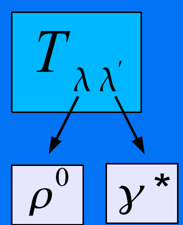
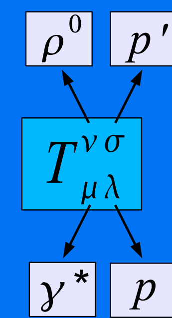
- parametrized by helicity amplitudes $T_{\lambda\lambda'}$ or $T^{\nu\sigma}_{\mu\lambda}$:

-Schilling, Wolf (1973)-



-Diehl notation (2007)-



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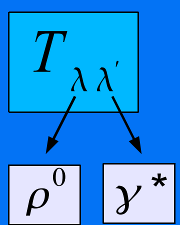

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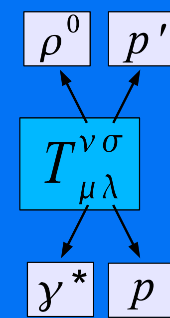
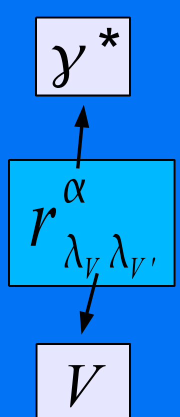
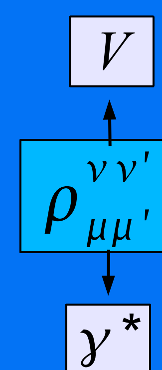


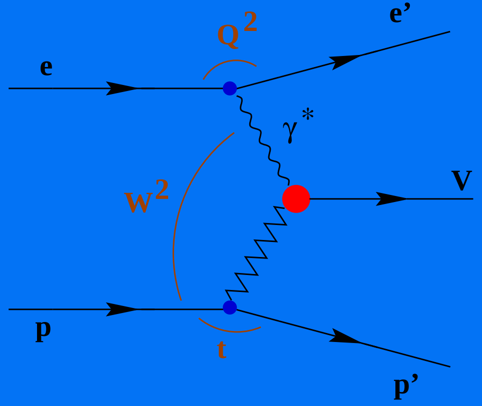
- or alternatively by spin-density matrix elements (SDMEs):





(un)natural-parity exchange

- Regge theory: the diffractive production of vector meson via an exchange of a particle



natural parity

- $P = (-1)^J$: exchange of ρ, ω, f_2, a_2 or pomeron
- $\propto M/W$

unnatural parity

- $P = -(-1)^J$: exchange of π, a_1, b_1
- $\propto (M/W)^2$

- unnatural-parity exchange contribution is expected only at lower values of W

(un)natural-parity exchange

- Regge theory: the diffractive production of vector meson via an exchange of a particle

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- $\propto (M/W)^2$

- unnatural-parity exchange contribution is expected only at lower values of W

- GPD formalism: generalized to characterize the symmetry properties of amplitudes under the helicity reversal of the γ^* and ρ^0

natural parity

- related to GPDs H and E

unnatural parity

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

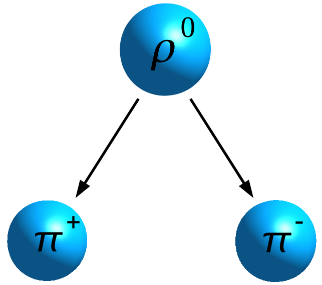
pomeron exchange $\Rightarrow$ gluon exchange

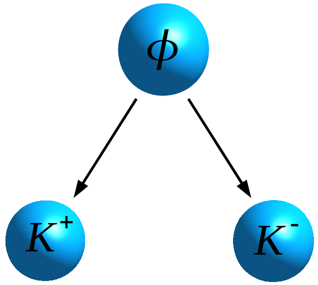
- only NPE

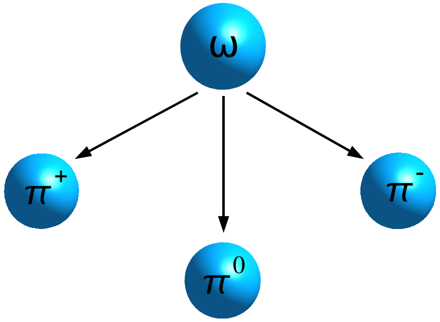
reggeon exchange $\Rightarrow$ quark exchange

- NPE and UPE

exclusive vector meson sample







- no recoil proton detection
- elastic scattering:

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

- only little energy transferred to the target

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

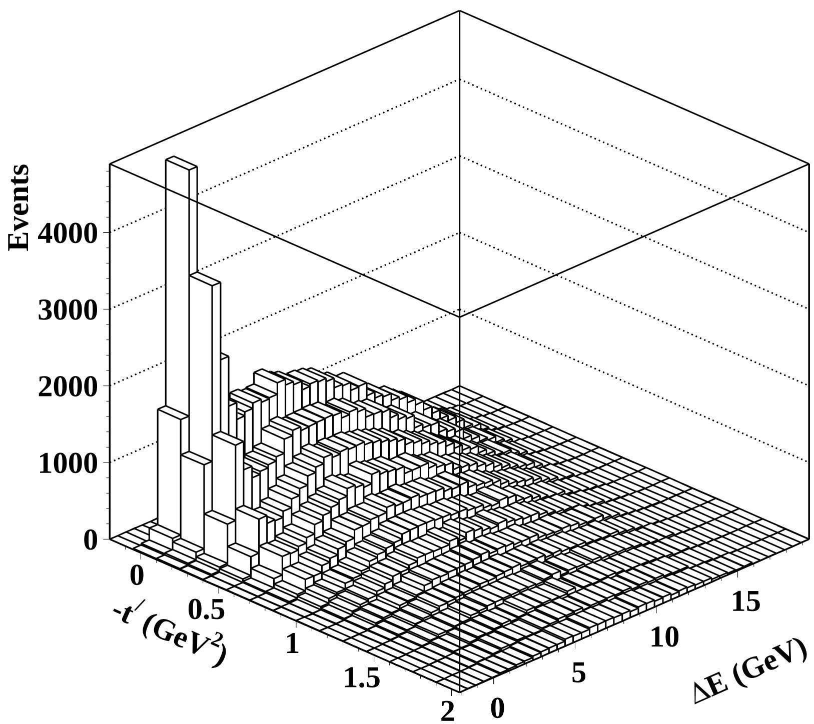
- transverse four-momentum transfer is used

$$t' = t - t_0$$

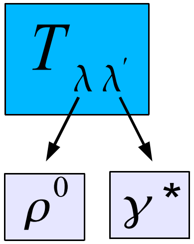
- main contribution at small values of ΔE and t'
- non-exclusive events:

$$\Delta E > 0$$

- SIDIS background estimated by PYTHIA MC



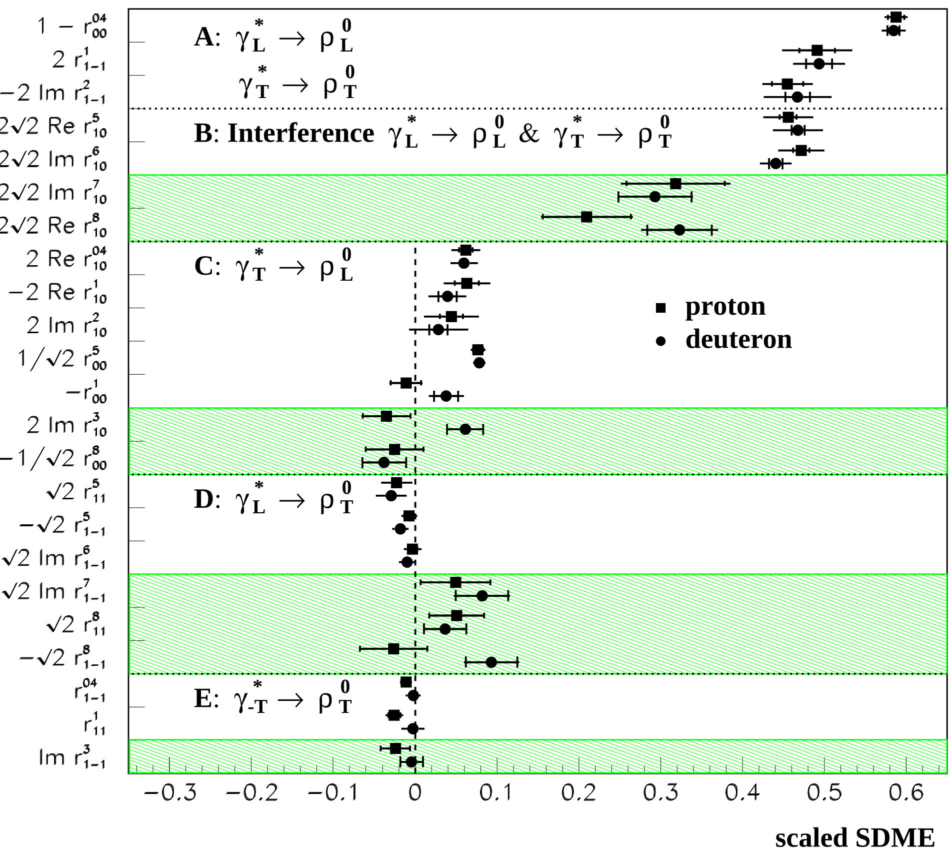
ρ^0: unpolarized & beam-polarized SDMEs



SDMEs shown according to hierarchy of NPE helicity amplitudes:

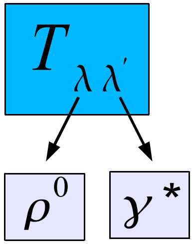
$$|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2$$

-HERMES Collaboration: arXiv:0901.0701 (2009)-



- unpolarized SDMEs: W_{UU}
- beam-polarized SDMEs: W_{UL}
- hierarchy confirmed experimentally
- proton and deuteron data consistent
- s-channel helicity conservation:
  (ρ^0 conserves the helicity of γ^*)
  - significant $\gamma^*_L \to \rho^0_L$ and $\gamma^*_T \to \rho^0_T$
  - a substantial interference
- s-channel helicity violation
  (vertical line corresponds to SCHC)
  - significant $\gamma^*_T \to \rho^0_L$
  - smaller $\gamma^*_L \to \rho^0_T$ and $\gamma^*_{-T} \to \rho^0_T$
  - $2 - 10\sigma$ level violation

$\rho^0 - \phi$: comparison



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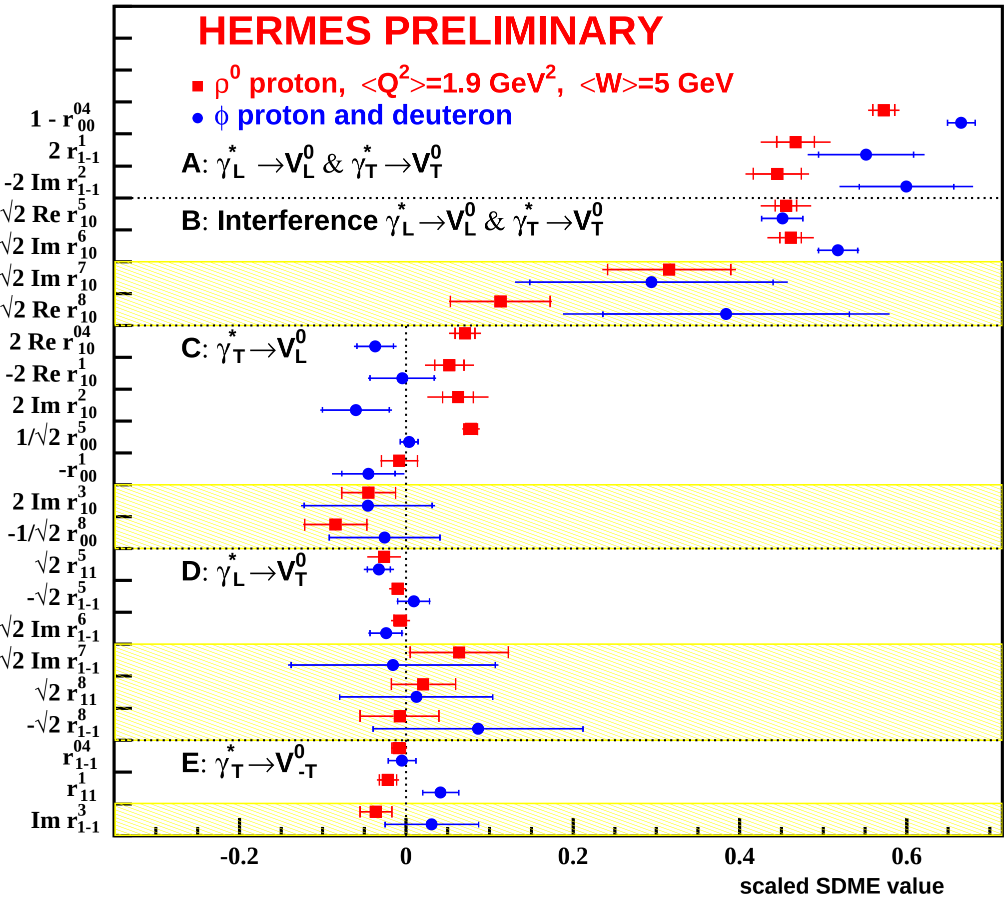


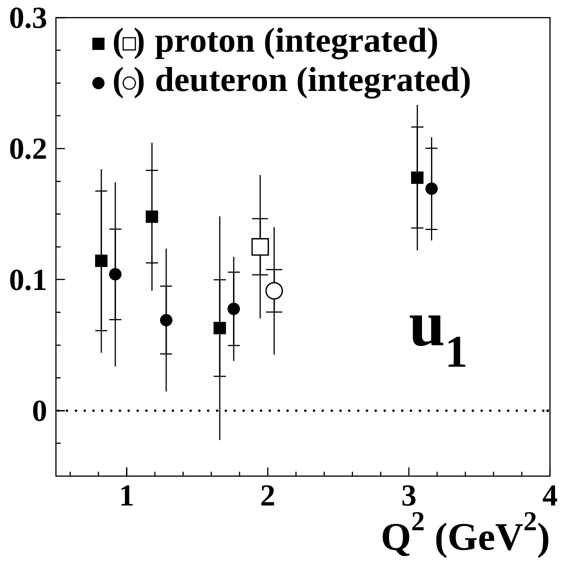
- unpolarized SDMEs: W_{UU}
- beam-polarized SDMEs: W_{UL}
- polarized SDMEs have been measured by HERMES for the first time
- no statistically significant difference between proton and deuteron
- no s-channel helicity violation
- hierarchy of amplitudes:
  $T_{00} \sim T_{11}$
  $T_{01} \approx T_{10} \approx T_{-11} \approx 0$

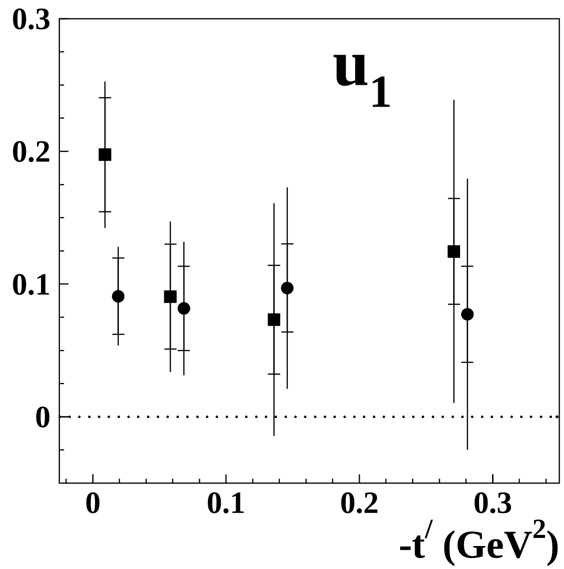
ρ^0: observation of unnatural-parity exchange

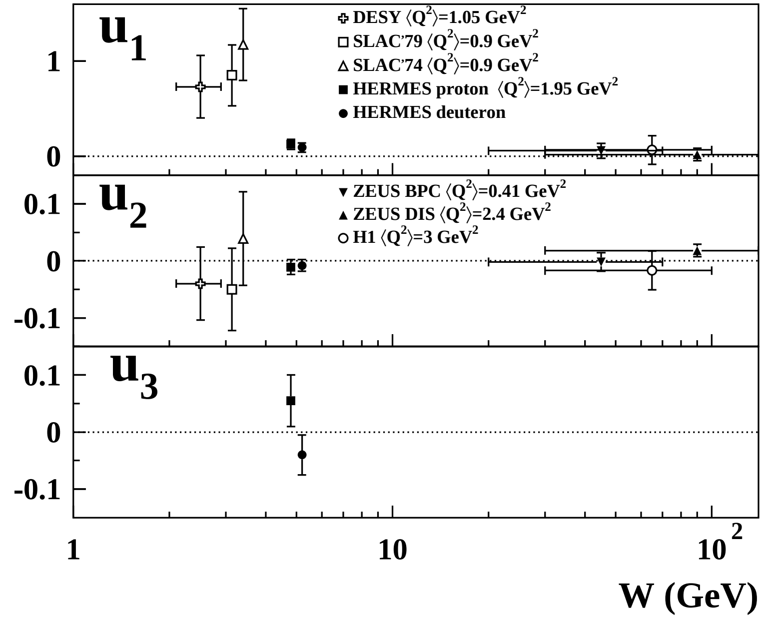
- UPE contributions measured from SDMEs: *-HERMES Collaboration: arXiv:0901.0701 (2009)-*

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

- the combinations of SDMEs expected to be the zero in case of NPE dominance



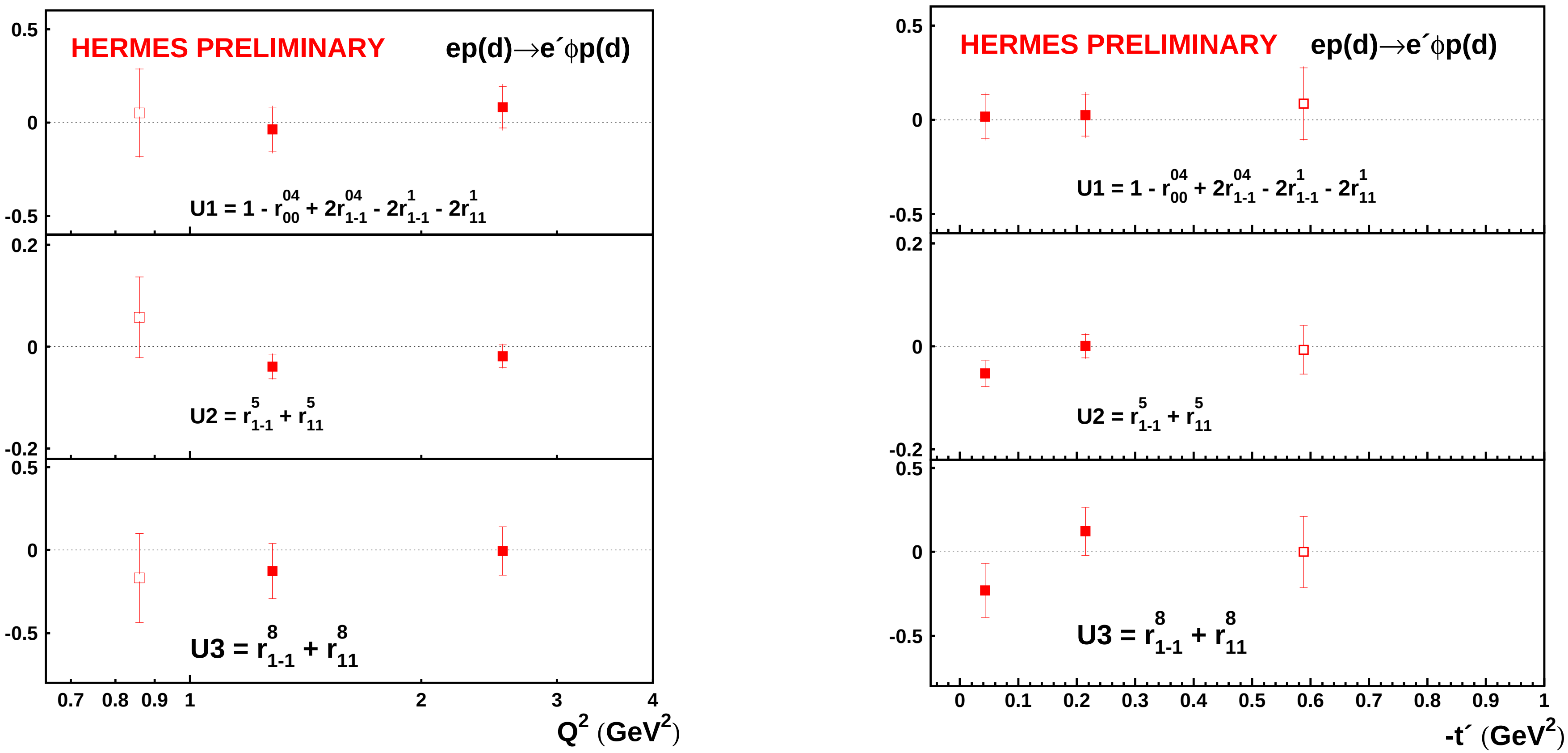




- proton:
  $u_1 = 0.125 \pm 0.021_{stat} \pm 0.050_{sys}$
- deuteron:
  $u_1 = 0.091 \pm 0.016_{stat} \pm 0.046_{sys}$

UPE contribution is W-dependent

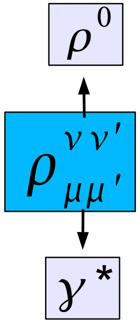
ϕ: observation of unnatural-parity exchange



- $u_1 = 0.02 \pm 0.07_{stat} \pm 0.16_{sys}$
- $u_2 = -0.03 \pm 0.01_{stat} \pm 0.03_{sys}$
- $u_3 = -0.05 \pm 0.12_{stat} \pm 0.07_{sys}$
- no signal of unnatural-parity exchange

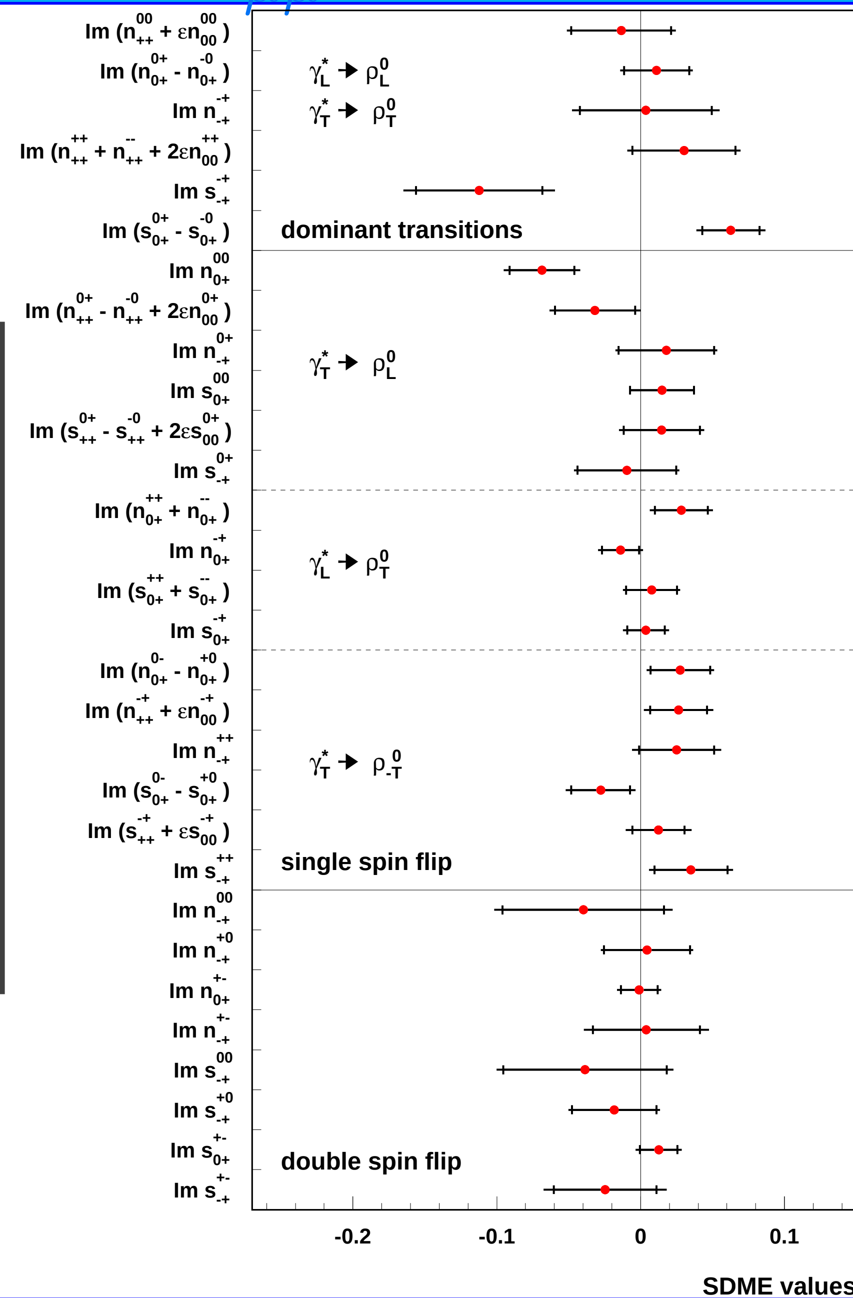
expected since dominant contribution to the production is from two gluon exchange

'transverse' SDMEs: $n^{\nu\nu'}_{\mu\mu'}$ and $s^{\nu\nu'}_{\mu\mu'}$

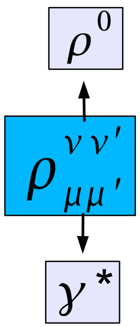


-HERMES Collaboration: arXiv:0906.5160 (2009)-

- transverse SDMEs: W_{UT}
- measured for the first time
  - average kinematics:
    $\langle -t' \rangle = 0.13$ GeV^2
    $\langle x_B \rangle = 0.09$
    $\langle Q^2 \rangle = 2.0$ GeV^2
- related to the proton helicity-flip amplitude
- suppressed by a factor $\sqrt{-t}/2M_p$



'transverse' SDMEs: $n^{\nu\nu'}_{\mu\mu'}$ and $s^{\nu\nu'}_{\mu\mu'}$



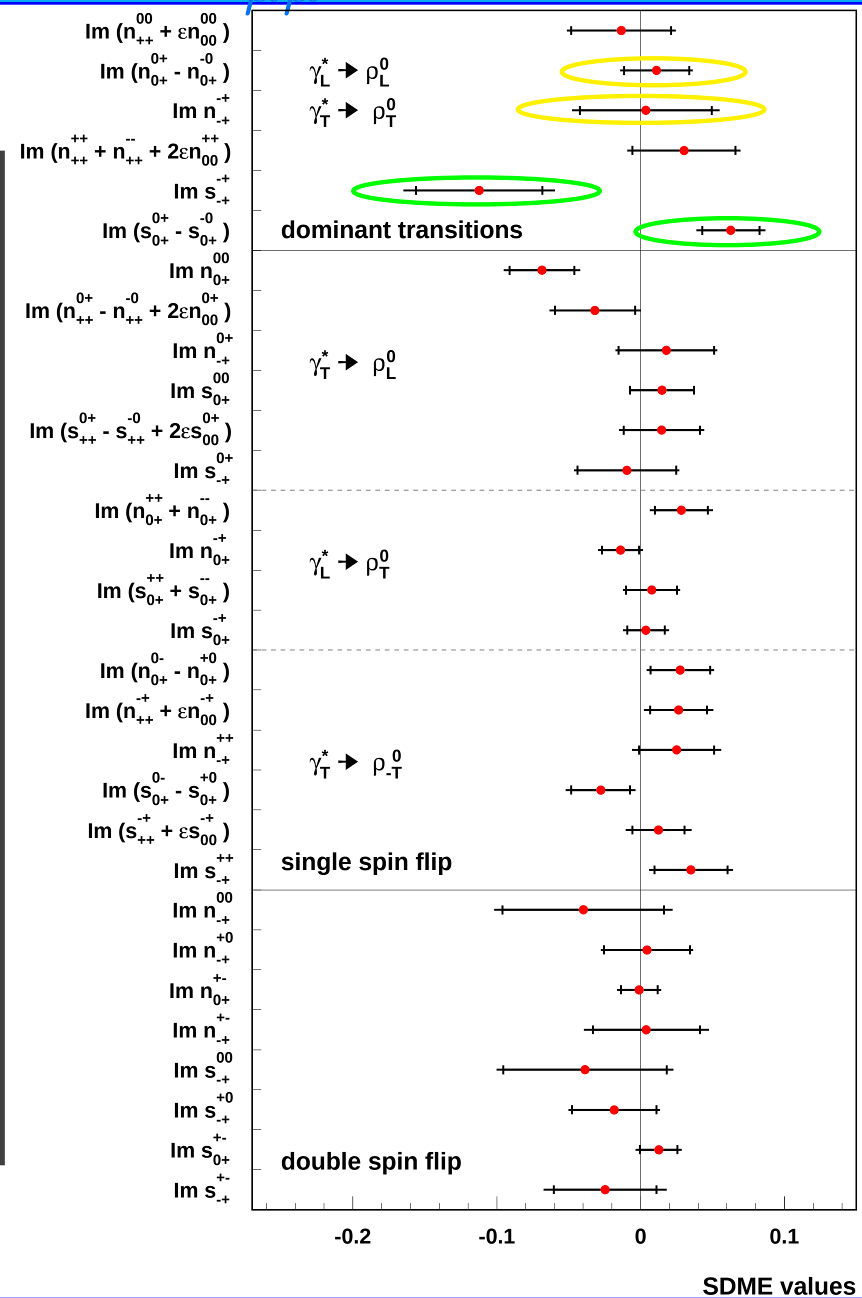
-HERMES Collaboration: arXiv:0906.5160 (2009)-

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

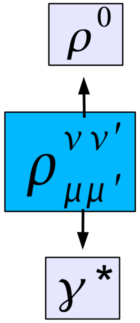
- $\mathrm{Im}\, s^{-+}_{-+}$ and $\mathrm{Im}(s^{0+}_{0+} - s^{-0}_{0+})$: deviate from 0 by 2.5σ
- expected $s^{\nu\nu'}_{\mu\mu'} < n^{\nu\nu'}_{\mu\mu'}$ (if identical indices)
- s^{-+}_{-+} and $\mathrm{Im}\, s^{0+}_{0+}$ involve

-Manaenkov (2008)-

  - the biggest NPE amplitudes N^{-+}_{-+} or N^{0+}_{0+}
  - the biggest UPE amplitude U^{++}_{+-}
- signal for unnatural-parity exchange
  - related to GPDs $\widetilde{H}$ and $\widetilde{E}$



'transverse' SDMEs: $n^{\nu\nu'}_{\mu\mu'}$ and $s^{\nu\nu'}_{\mu\mu'}$



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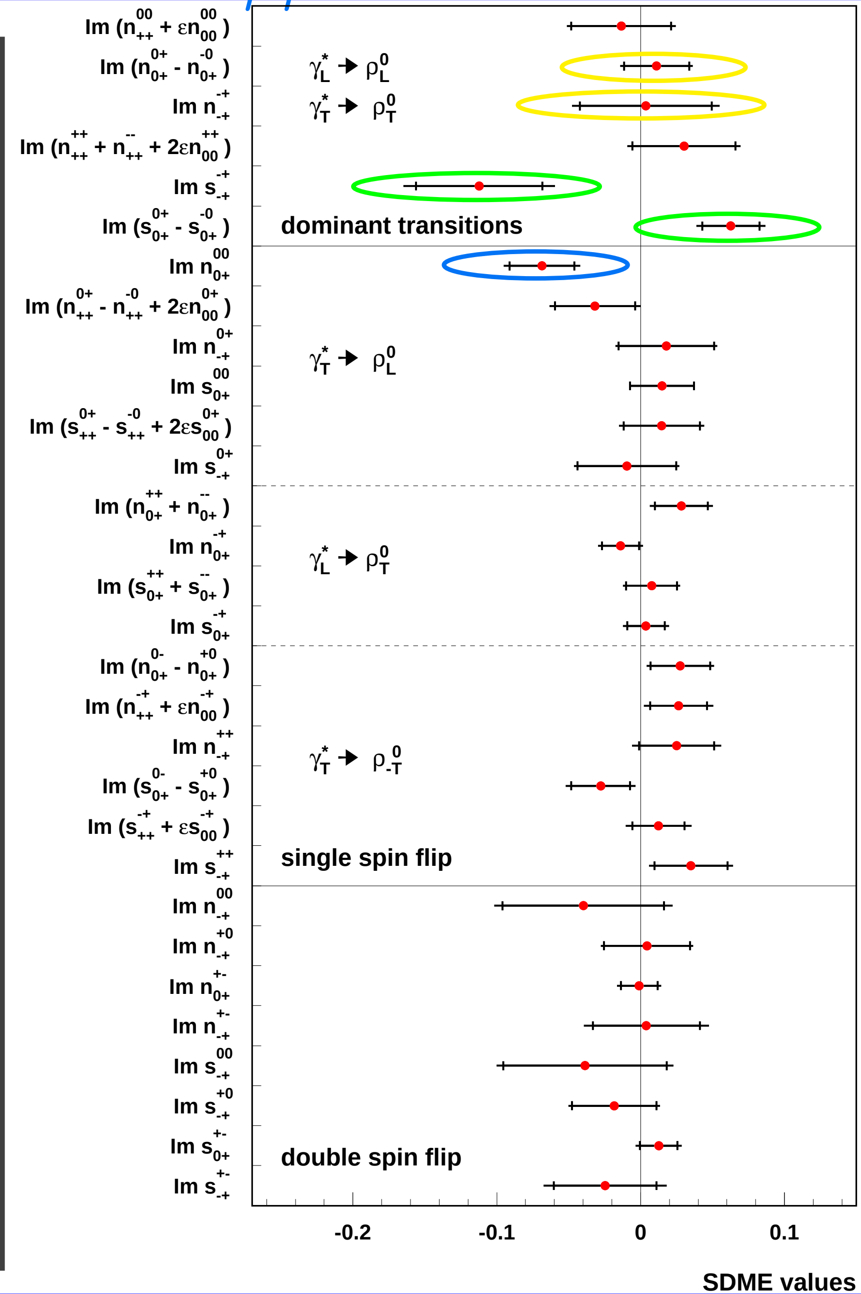
- signal for unnatural-parity exchange
  - related to GPDs $\widetilde{H}$ and $\widetilde{E}$

$\gamma^*_T \to \rho^0_L$

- $\mathrm{Im}\, n^{00}_{0+}$: 2.5σ deviation from 0



ρ^0: transverse target-spin asymmetry

- theoretically at leading order in $1/Q$ ($\gamma^*_L \to \rho^0_L$):

$$A_{UT}^{\sin(\phi-\phi_s)} = \frac{\mathrm{Im}\, n_{00}^{00}}{u_{00}^{00}}$$

- asymmetry in terms of GPDs

$$A_{UT}^{\sin(\phi-\phi_s)} \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g}$$

- experimentally:

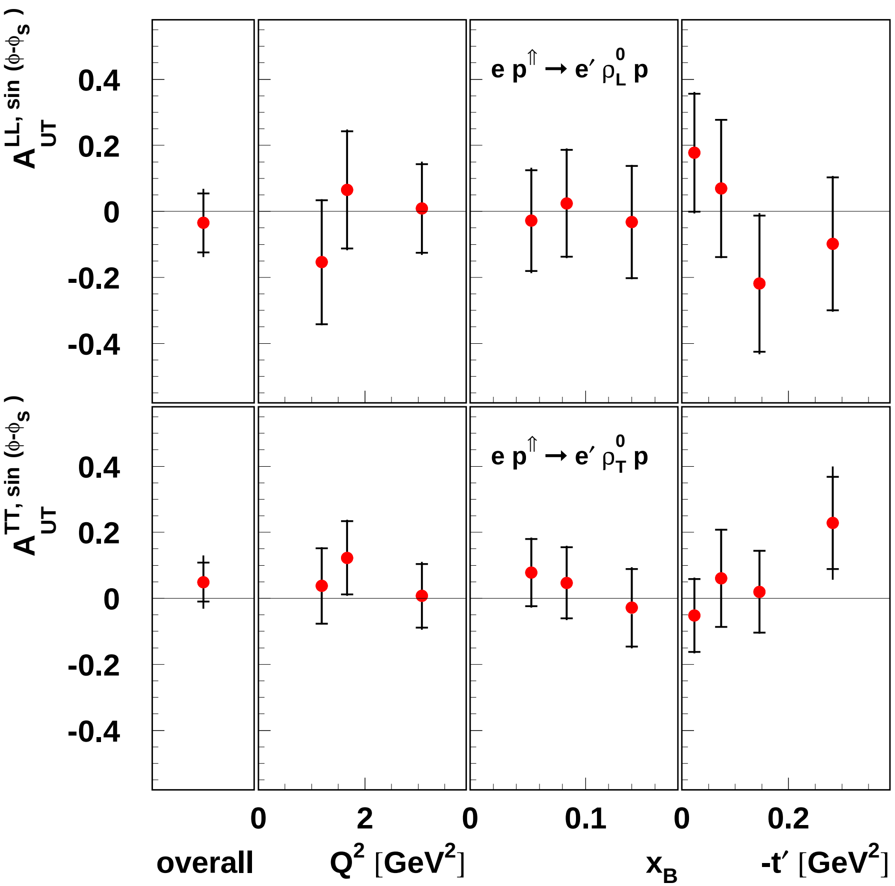
$$A_{UT}^{\gamma^*}(\phi,\phi_s) = \frac{\mathrm{Im}\left(n_{++}^{00} + \epsilon n_{00}^{00}\right)}{u_{++}^{00} + \epsilon u_{00}^{00}}$$

- u_{++}^{00} and n_{++}^{00} are expected to be negligible

- similarly, $\gamma^*_T \to \rho^0_T$:

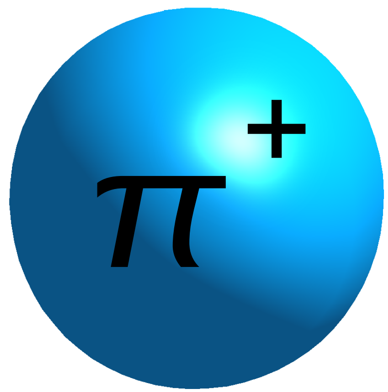
$$A_{UT}^{\gamma^*}(\phi,\phi_s) = \frac{\mathrm{Im}\,(n_{++}^{++} + n_{++}^{--} + 2\epsilon n_{00}^{++})}{u_{++}^{++} + u_{++}^{--} + 2\epsilon u_{00}^{++}}$$

-HERMES Collaboration: arXiv:0906.5160 (2009)-



compatible with 0 overall value:

$$A_{UT}^{\rho^0_L, \sin(\phi-\phi_s)} = -0.033 \pm 0.058$$

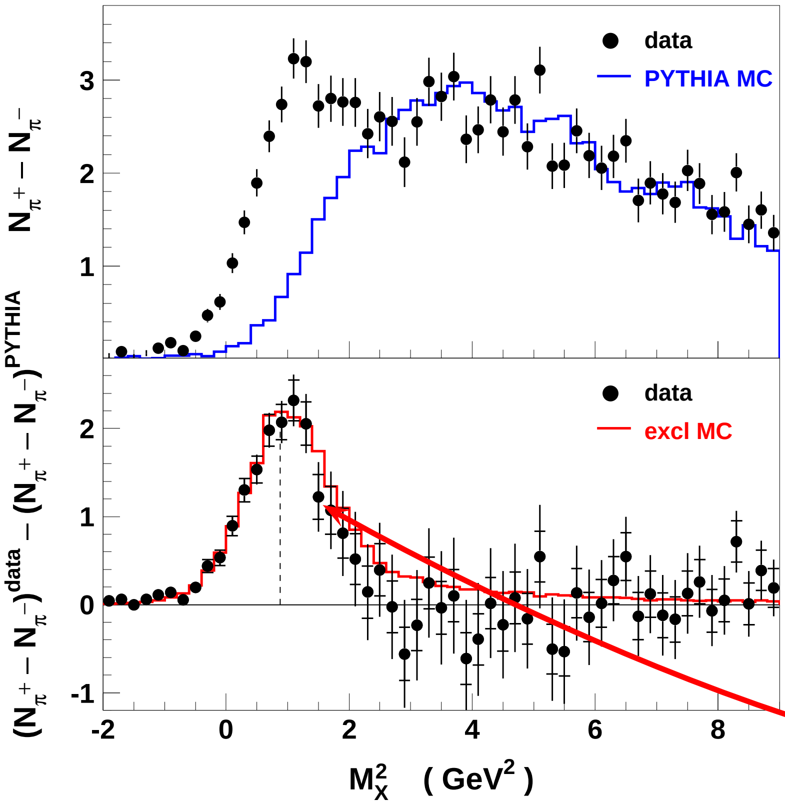

π^+

exclusive π^+ production: $ep \rightarrow e'\pi^+(n)$

- no recoil nucleon detection
- select exclusive π^+ reaction through the missing mass technique:

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

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

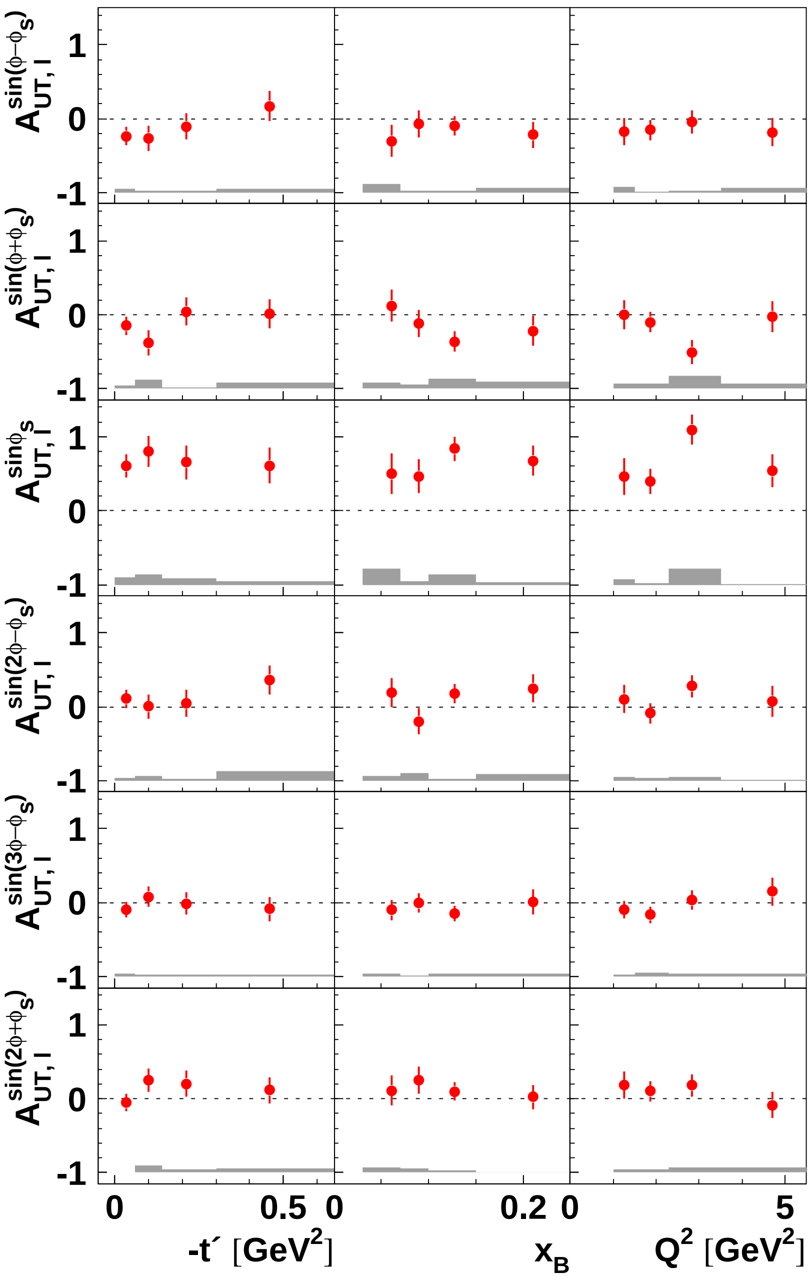


-HERMES collaboration arXiv:0707.0222 (2007)-

π^+	exclusive π^+	VM_{π^+}	SIDIS
π^-		VM_{π^-}	SIDIS

- $\pi^+ - \pi^-$ yield difference was used to subtract the non exclusive background
- exclusive peak centered at the nucleon mass
- exclusive MC based on GPD model

kinematic dependences of $A_{UT}^{\pi^+}$



-HERMES Collaboration: arXiv:0907.2596 (2009)-

- 6 azimuthal moments extracted according to

  -Diehl, Sapeta (2005)-

- average kinematics:

  $\langle -t' \rangle = 0.18$ GeV^2

  $\langle x_B \rangle = 0.13$

  $\langle Q^2 \rangle = 2.38$ GeV^2
- no γ_L^* / γ_T^* separation
- small overall value for leading asymmetry amplitude $A_{UT}^{\sin(\phi-\phi_s)}$
- unexpected large overall value for asymmetry amplitude $A_{UT}^{\sin\phi_s}$
- other moments: consistent with 0
- evidence of contributions from transversely polarized photons

theoretical interpretation of $A_{UT}^{\pi^+}$

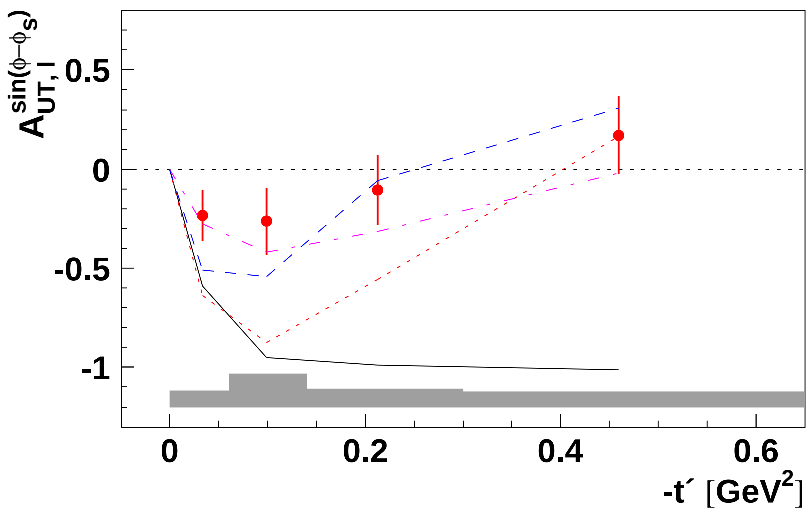
leading azimuthal amplitude $A_{UT}^{\sin(\phi-\phi_s)}$

- not large asymmetry with possible sign change
- theoretical expectation: $A_{UT}^{\sin(\phi-\phi_s)} \propto \sqrt{-t'}$
- large negative asymmetry *-Frankfurt et al. (2001)-*

  -Belitsky, Muller (2001)-
- are the differences due to γ_T^*?

  -Goloskokov, Kroll (2009)-

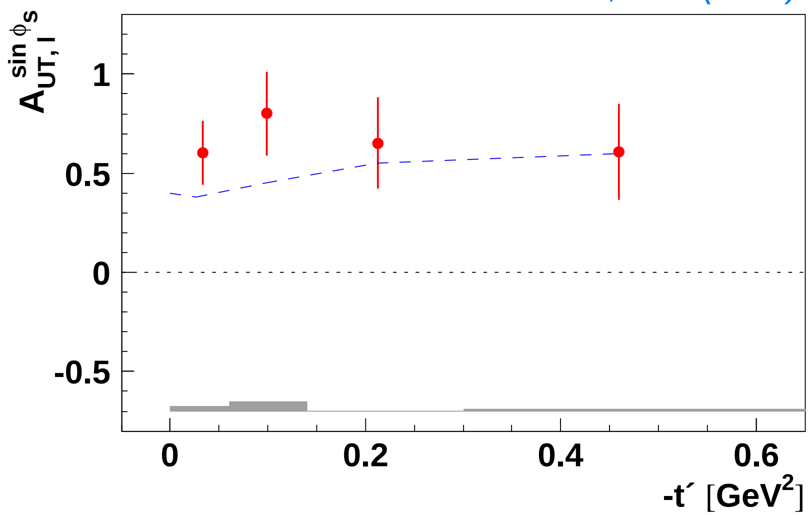
  -Bechler, Muller (2009)-



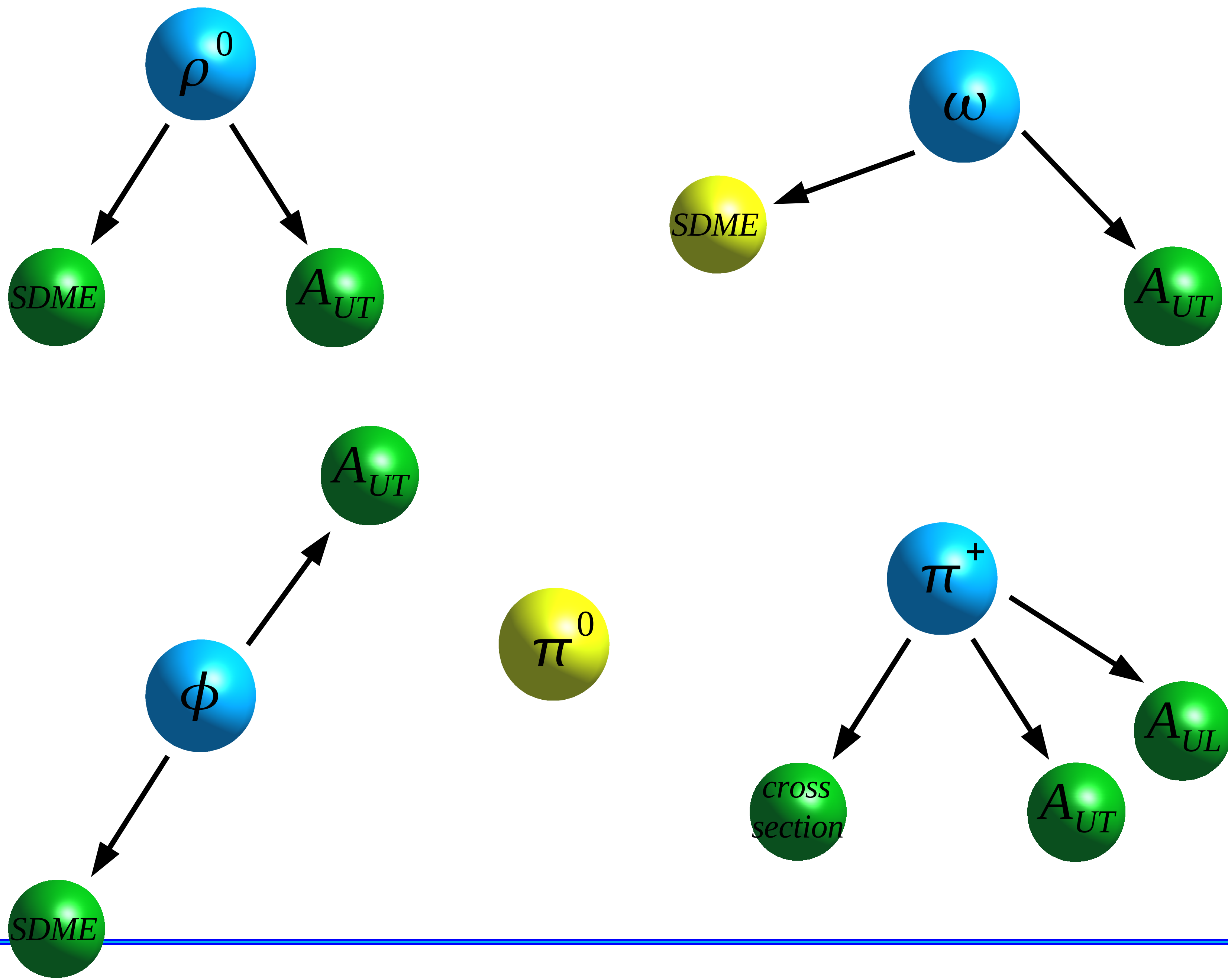
azimuthal amplitude $A_{UT}^{\sin\phi_s}$

- no turnover towards 0 for $t' \to 0$
- milde t-dependence
- can be explained only by γ_L^*/γ_T^* interference
- predictions $A_{UT}^{\sin\phi_s} \approx const$
- non-vanishing model predictions: contribution from H_T

-Goloskokov, Kroll (2009)-



GPDs, Meson Production and HERMES



backup slides

transverse target-spin asymmetry

$$\mathcal{A}_{UT}^{\mathrm{DVCS}}(\phi,\phi_S) = \sum_{n=0}^{2} A_{UT\,DVCS}^{\sin(\phi-\phi_S)\cos(n\phi)} \sin(\phi-\phi_S)\cos(n\phi) + \sum_{n=1}^{2} A_{UT,\,DVCS}^{\cos(\phi-\phi_S)\sin(n\phi)} \cos(\phi-\phi_S)\sin(n\phi)$$

$$\mathcal{A}_{UT}^{\mathrm{I}}(\phi,\phi_S) = \sum_{n=0}^{2} A_{UT,\,I}^{\sin(\phi-\phi_S)\cos(n\phi)} \sin(\phi-\phi_S)\cos(n\phi) + \sum_{n=1}^{2} A_{UT,\,I}^{\cos(\phi-\phi_S)\sin(n\phi)} \cos(\phi-\phi_S)\sin(n\phi)$$

longitudinal target polarization

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

beam helicity asymmetry:

$$\mathcal{A}_{LU}(\phi) \equiv \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}}$$

- projects the imaginary part of τ_{DVCS}
- no separate access to s_1^{DVCS} and s_1^I

longitudinal target-spin asymmetry:

$$\mathcal{A}_{UL}(\phi) \equiv \frac{(d\sigma^{\rightarrow\Rightarrow} + d\sigma^{\leftarrow\Rightarrow}) - (d\sigma^{\rightarrow\Leftarrow} + d\sigma^{\leftarrow\Leftarrow})}{(d\sigma^{\rightarrow\Rightarrow} + d\sigma^{\leftarrow\Rightarrow}) + (d\sigma^{\rightarrow\Leftarrow} + d\sigma^{\leftarrow\Leftarrow})}$$

- projects the imaginary part of τ_{DVCS}

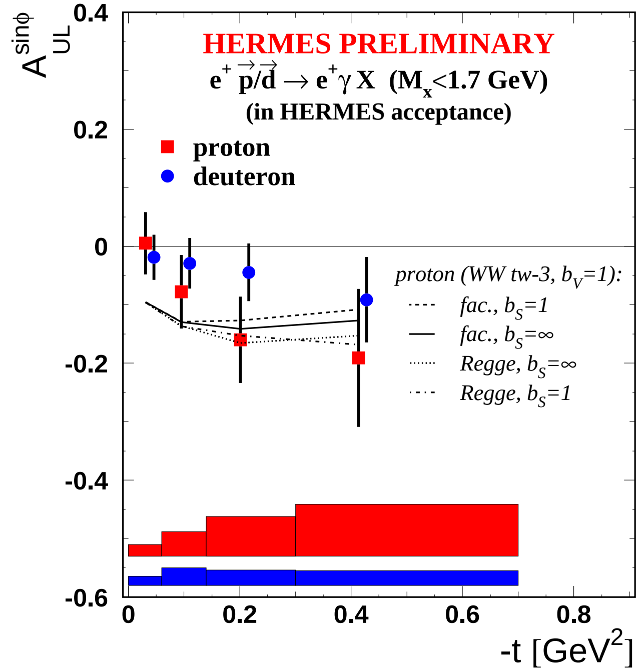
double-spin asymmetry:

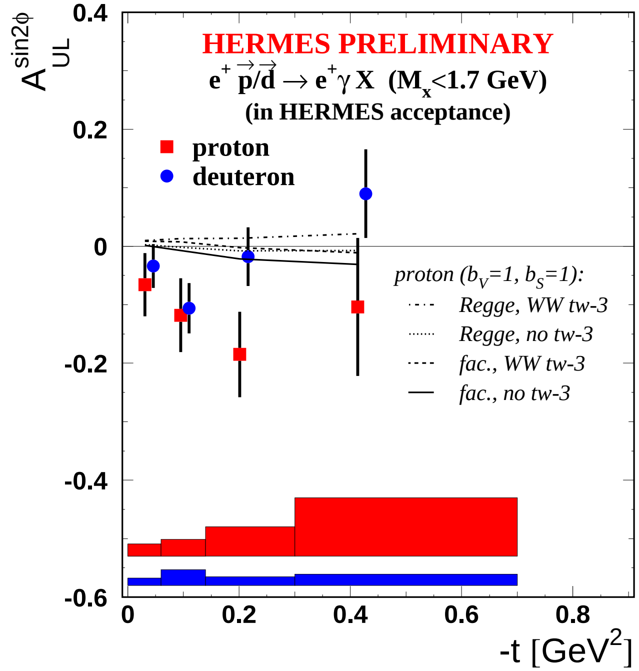
$$\mathcal{A}_{LL}(\phi) \equiv \frac{(d\sigma^{\rightarrow\Rightarrow} + d\sigma^{\leftarrow\Leftarrow}) - (d\sigma^{\leftarrow\Rightarrow} + d\sigma^{\rightarrow\Leftarrow})}{(d\sigma^{\rightarrow\Rightarrow} + d\sigma^{\leftarrow\Leftarrow}) + (d\sigma^{\leftarrow\Rightarrow} + d\sigma^{\rightarrow\Leftarrow})}$$

- projects the real part of τ_{DVCS}

longitudinal target-spin asymmetry

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





- s_1^{I}: twist-2

$$A_{UL}^{\sin\phi} \propto s_1^{\mathrm{I}} \propto F_1 \mathrm{Im}\widetilde{\mathcal{H}}$$

- s_1^{DVCS}: twist-3

model in good agreement with data

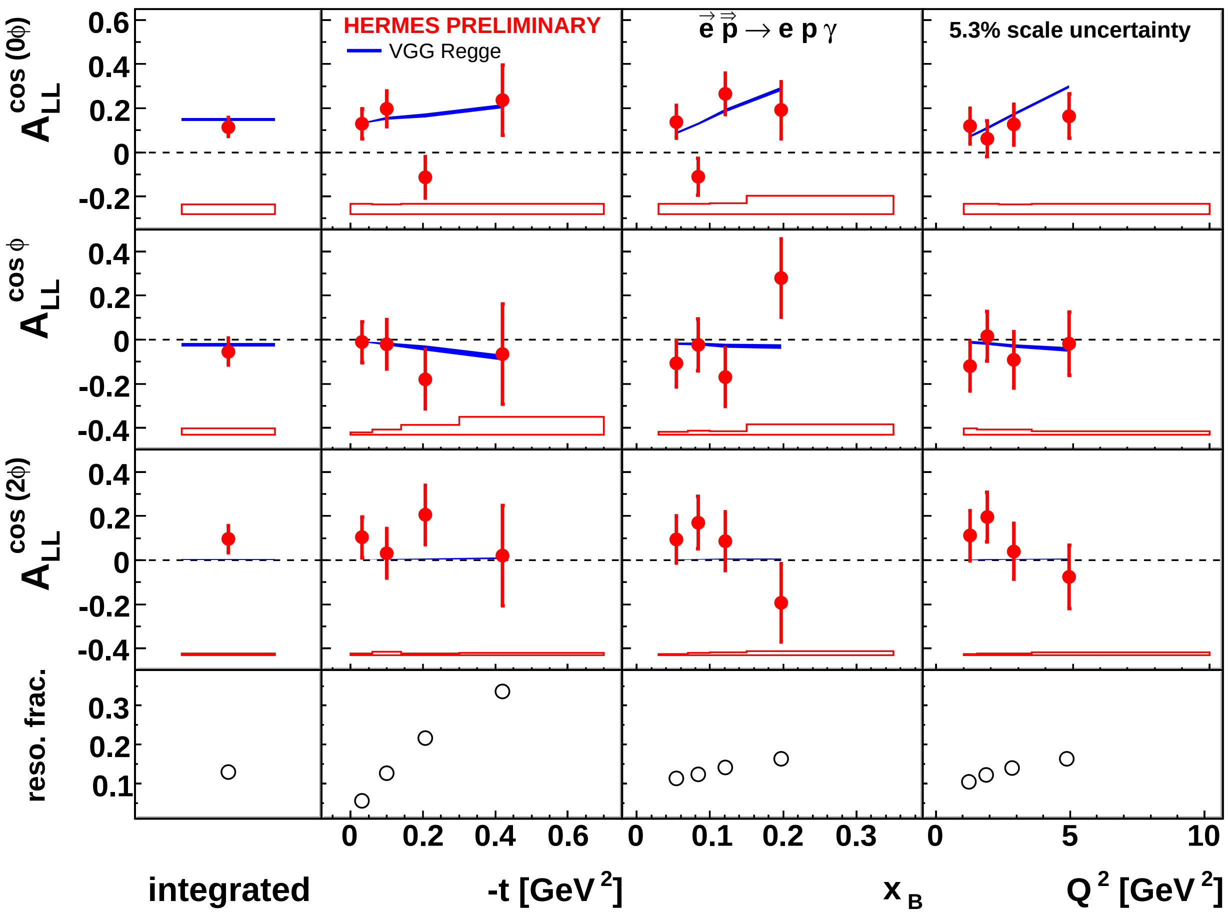
unexpected large value

- s_2^{I}: quark twist-3 or gluon twist-2
- s_2^{DVCS}: twist-4

model does not describe the data

double-spin asymmetry

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



twist-2: $\propto F_1 {\rm Re}\widetilde{\mathcal{H}}$

$$A_{LL}^{\cos 0\phi} \propto \begin{cases} c_0^{\rm DVCS} \\ c_0^{\rm I} \end{cases}$$

twist-2 / twist-3:

$$A_{LL}^{\cos\phi} \propto \begin{cases} c_1^{\rm DVCS} \\ c_1^{\rm I} \end{cases}$$

twist-3:

$$A_{LL}^{\cos 2\phi} \propto \{\ c_2^{\rm I}$$

model predictions:

- the same model, as for BCA and BHA
- in good agreement with data

ρ^0: observation of unnatural-parity exchange

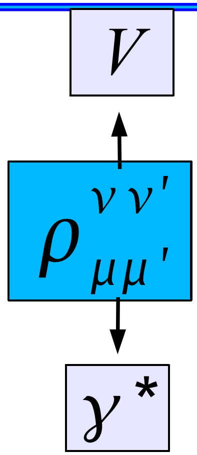
- UPE contributions measured from SDMEs:

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

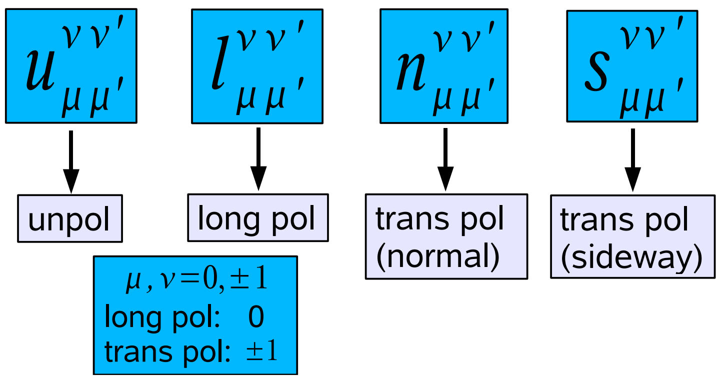
- UPE contributions expressed through amplitudes:

$$u_1 \propto \epsilon |U_{10}|^2 + 2|U_{11} + U_{1-1}|^2, \quad u_2 + iu_3 \propto (U_{11} + U_{1-1}) * U_{10}$$

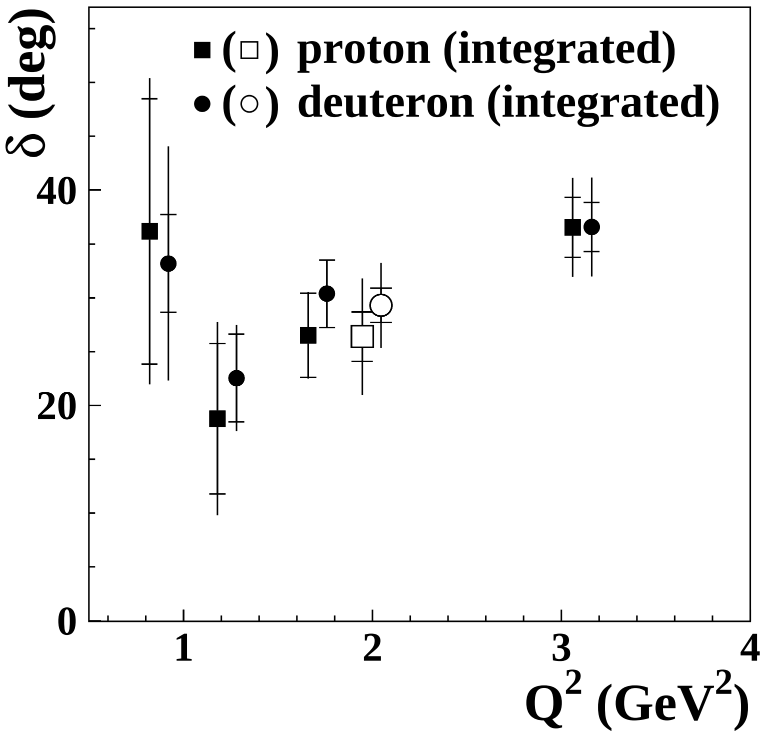
- the combinations of SDMEs expected to be the zero in case of NPE dominance:



$$\rho_{\mu\mu',\lambda\lambda'}^{\nu\nu'} \propto \sum_{\sigma} T_{\mu\lambda}^{\nu\sigma} \left(T_{\mu'\lambda'}^{\nu'\sigma}\right)^*$$



ρ^0: phase difference δ between T_{00} and T_{11}



-HERMES Collaboration: arXiv:0901.0701 (2009)-

- $|\delta|$ obtained from unpolarizes SDMEs:

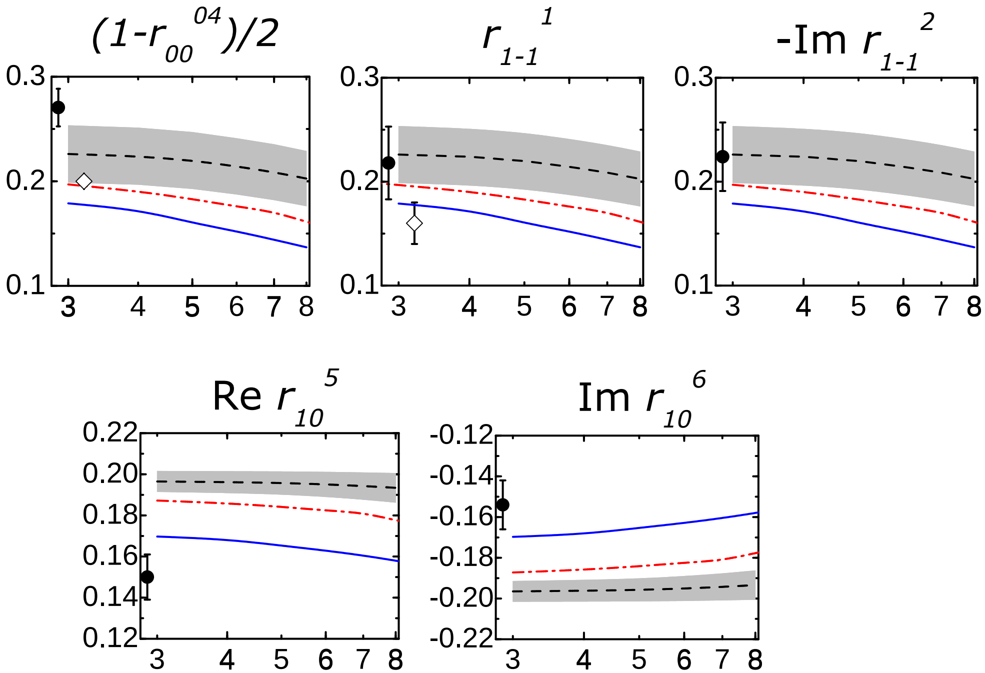
$$\cos\delta = \frac{2\sqrt{\epsilon}(\Re r^5_{10} - \Im r^6_{10})}{\sqrt{r^{04}_{00}(1 - r^{04}_{00} + r^1_{1-1} - \Im r^2_{1-1})}}$$

- sign of δ obtained from polarizes SDMEs: (for the first time)

$$\sin\delta = \frac{2\sqrt{\epsilon}(\Re r^8_{10} - \Im r^7_{10})}{\sqrt{r^{04}_{00}(1 - r^{04}_{00} + r^1_{1-1} - \Im r^2_{1-1})}}$$

- results on δ (in degrees):
  - proton: $|\delta| = 26.4 \pm 2.3_{stat} \pm 4.9_{sys}$; $\delta = 30.6 \pm 5.0_{stat} \pm 2.4_{sys}$
  - deuteron: $|\delta| = 29.3 \pm 1.6_{stat} \pm 3.6_{sys}$; $\delta = 36.3 \pm 3.9_{stat} \pm 1.7_{sys}$
- values are consistent
  - with each other
  - with H1 results: $|\delta| = 21.5 \pm 4.3_{stat} \pm 5.3_{sys}$

comparison with a GPD model



-Goloskokov, Kroll (2007)-

Q^2-dependence calculated for 3 different W values:

$$W = 5\ \mathrm{GeV(HERMES)}$$
$$W = 10\ \mathrm{GeV(COMPASS)}$$
$$W = 90\ \mathrm{GeV(H1, ZEUS)}$$

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

- $1 - r^{04}_{00} \propto r^1_{1-1} \propto -\Im r^2_{1-1} \propto T_{11}$
- describe data for various W-ranges

interference of $\gamma^*_L \to \rho^0_L$ and $\gamma^*_T \to \rho^0_T$

- $r^5_{10} \propto -\Im r^6_{10} \propto T_{00}$ and T_{11} interference
- model does not describe the data
- model uses phase difference $\delta = 3.1$ degree between T_{00} and T_{11}
- HERMES result: $\delta \approx 30$ degree

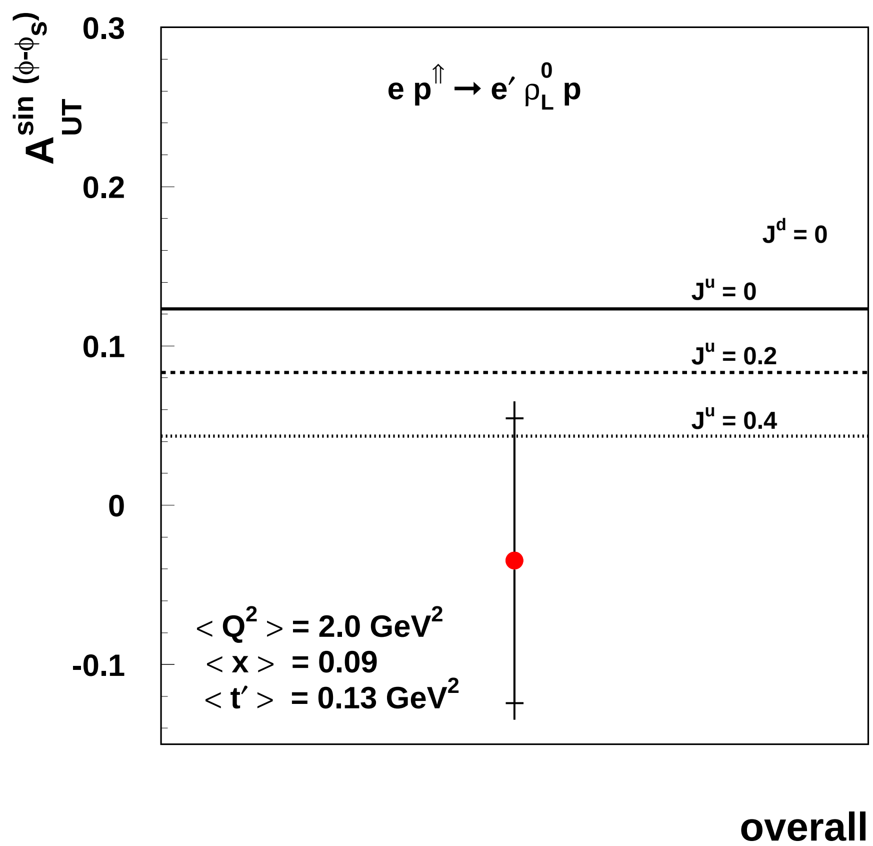
ρ^0: comparison with GPD models

- asymmetry in terms of GPDs

$$A_{UT}^{\sin(\phi-\phi_s)} \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g}$$

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

- parametrization for H^q, $H^{\bar{q}}$, H^g
- E^q is related to the total angular momenta J^u and J^d
  - predictions for $J^d = 0$
- $E^{\bar{q}}$ and E^g are neglected
- data favors positive J^u
  - statistics too low to reliably determine the value of J^u and its uncertainty
- within the statistical uncertainty in agreement with theoretical calculations
  - indication of small E^g and $E^{\bar{q}}$?



other GPD model calculations

- Goeke, Polyakov, Vanderhaeghen (1999)-

-Goloskokov, Kroll (2007)-

-Diehl, Kugler (2008)-

ω: transverse target-spin asymmetry

- 6 azimuthal moments extracted using integrated angular distributions
- due to low statistics no ω_L/ω_T separation
- predictions for large asymmetry $A_{UT}^{\sin(\phi-\phi_s)} \approx -0.10$
- indication of negative $\sin(\phi-\phi_s)$ amplitude $A_{UT}^{\sin(\phi-\phi_s)} = -0.22 \pm 0.16_{stat} \pm 0.11_{sys}$
- no contradiction with ρ^0 predictions

$$A_{UT}^{\rho^0,\sin(\phi-\phi_s)} \propto \Im\left\{\frac{2E^u + E^d}{2H^u + H^d + H^g}\right\}$$

$$A_{UT}^{\omega,\sin(\phi-\phi_s)} \propto \Im\left\{\frac{2E^u - E^d}{2H^u - H^d}\right\}$$