

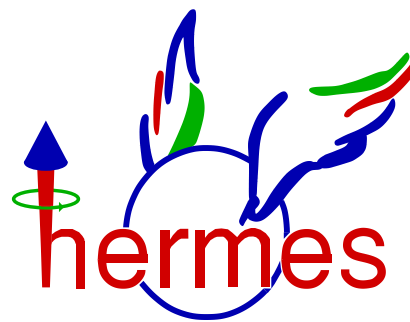
Exclusive Meson Production

at HERMES

*Quarks and Nuclear Physics 2009,
Beijing, China*

Eduard Avetisyan

(on behalf of the HERMES collaboration)

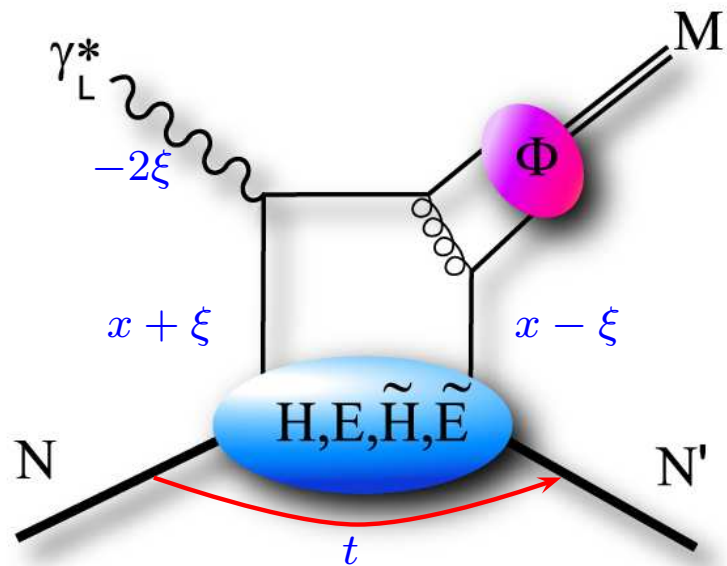


exclusive meson production

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

$\bullet$ H and $\tilde{H}$ conserve the nucleon helicity

$\bullet$ E and $\tilde{E}$ describe the nucleon helicity flip

quantum numbers of final state selects different GPDs

$\bullet$ **vector mesons** ($\gamma_L^* \rightarrow \rho_L, \omega_L, \phi_L$): H, E

$\bullet$ **pseudoscalar mesons** ($\gamma_L^* \rightarrow \pi, \eta$): $\tilde{H}, \tilde{E}$

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

$\bullet$ $\sigma_L - \sigma_T$ suppressed by $1/Q$

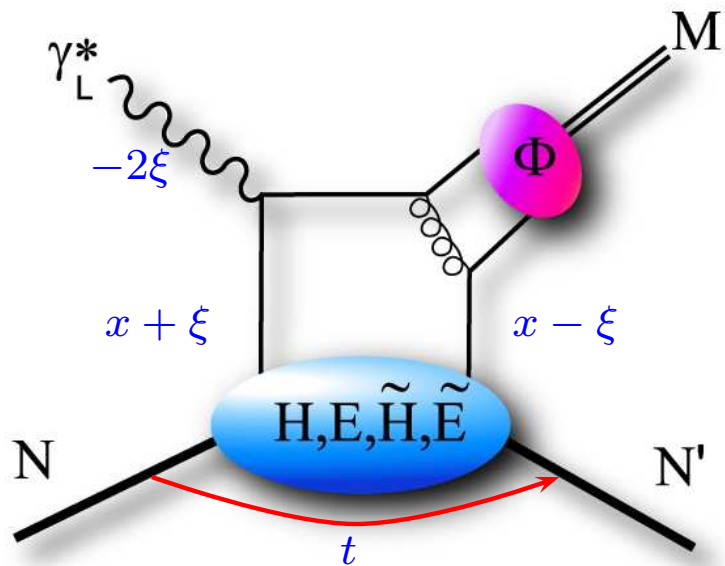
$\bullet$ σ_T suppressed by $1/Q^2$

exclusive meson production

modified perturbative approach

-Goloskokov, Kroll (2006)-

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$\bullet$ $\sigma_L - \sigma_T$ suppressed by $1/Q$

$\bullet$ σ_T suppressed by $1/Q^2$

power corrections: $k_\perp$ is not neglected

$\bullet$ regulate the singularity in the transverse amplitude

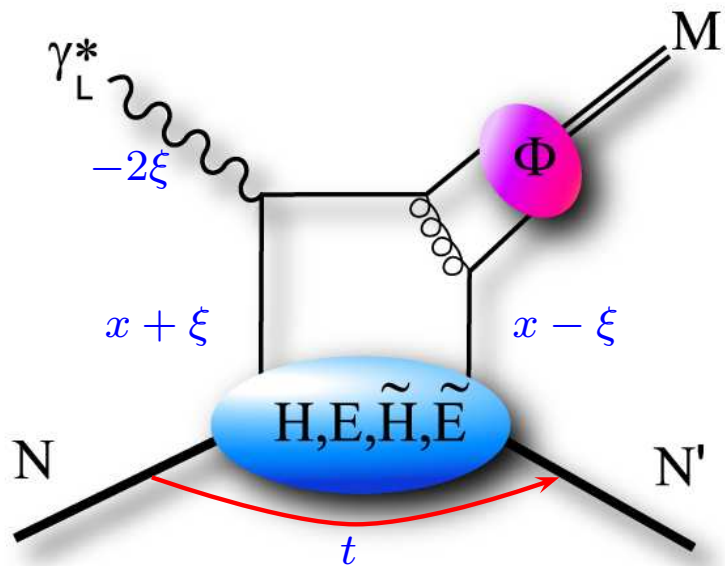
$\bullet$ $\gamma_T^* \rightarrow \rho_T^0$ transitions can be calculated (model dependent)

exclusive meson production

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-Goloskokov, Kroll (2006)-

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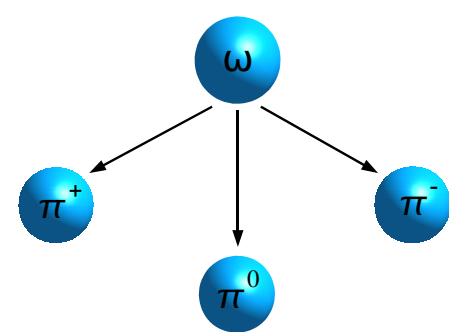
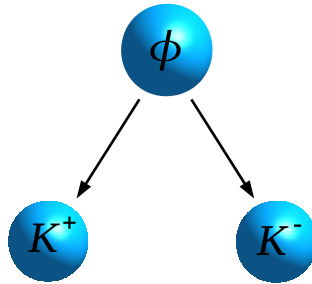
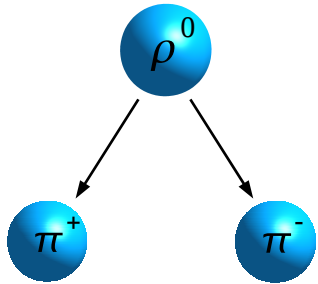
power corrections: $k_\perp$ is not neglected

$\bullet$ $\gamma_T^* \rightarrow \rho_T^0$ transitions can be calculated (model dependent)

$\blacksquare$ ρ^0 : contributions from $\tilde{H}$ and $\tilde{E}$

$\blacksquare$ $\pi^\pm$: contributions from H_T and $\tilde{H}_T$

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

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

- transverse four-momentum transfer is used

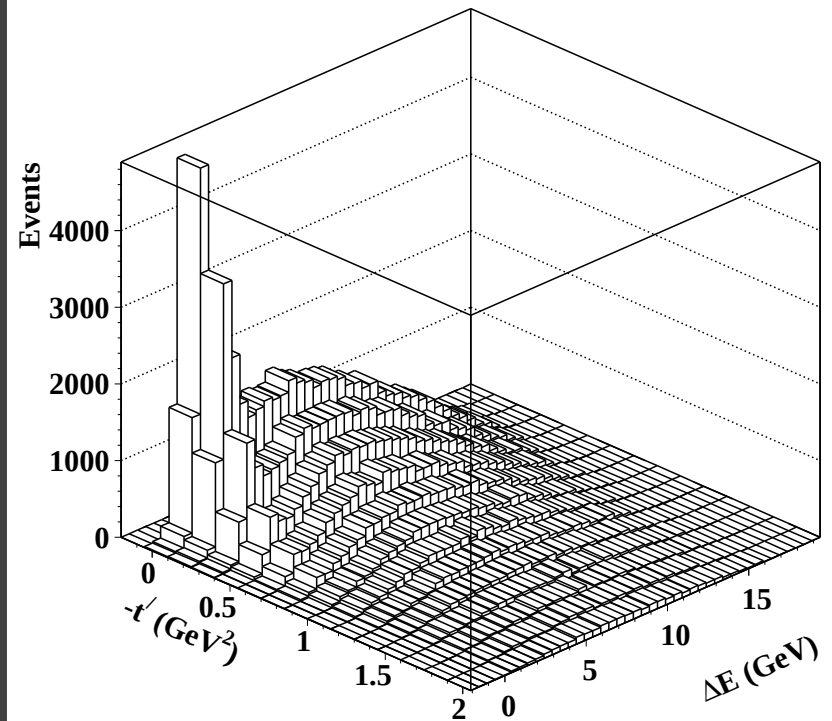
$$t' = t - t_0$$

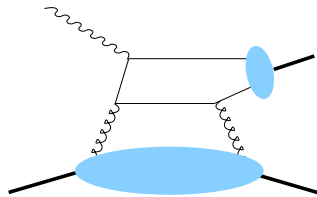
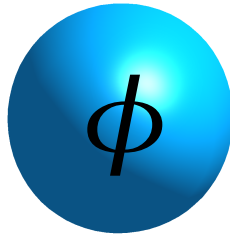
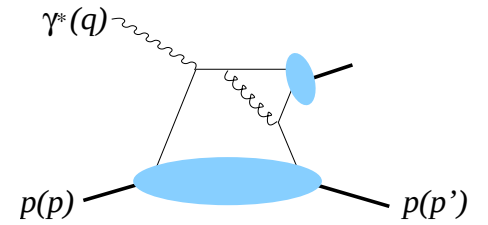
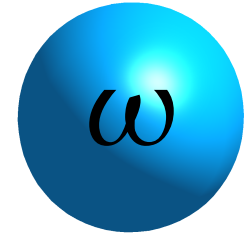
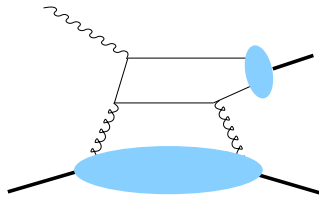
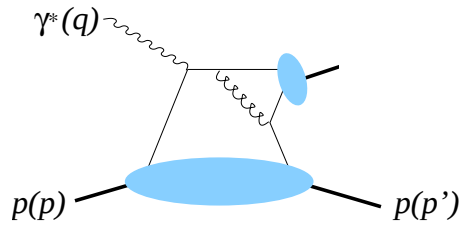
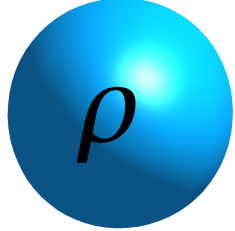
- main contribution at small values of ΔE and t'

- non-exclusive events:

$$\Delta E > 0$$

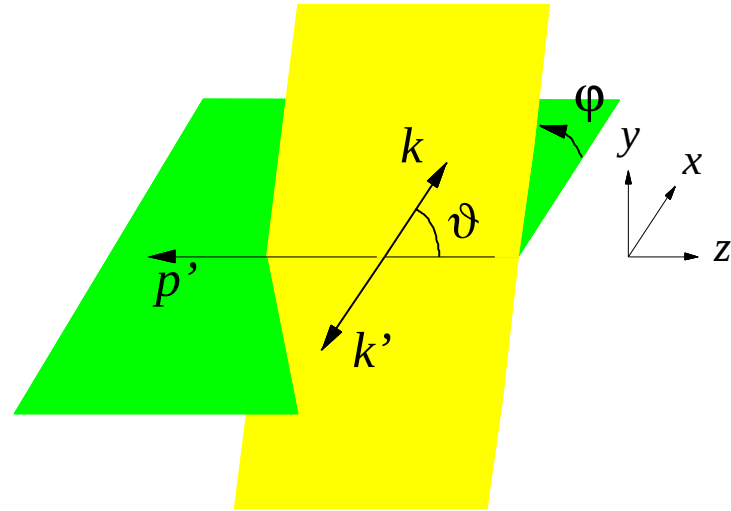
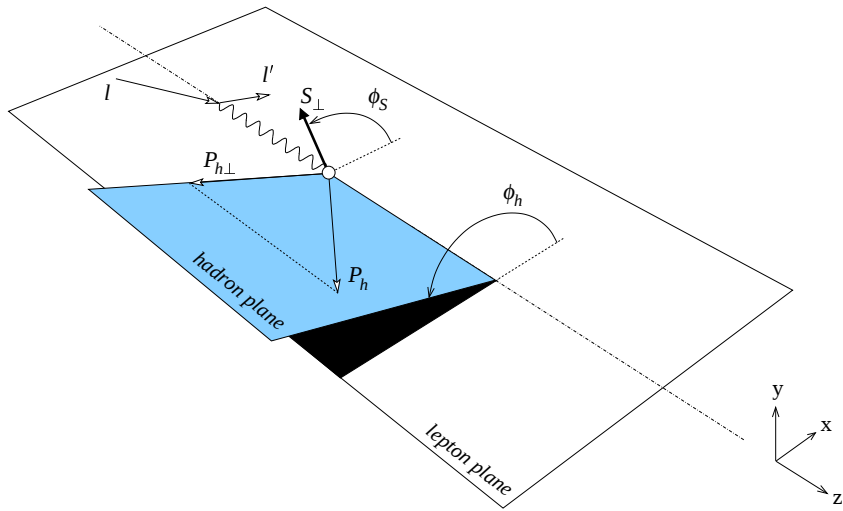
- SIDIS background estimated by PYTHIA MC





vector meson cross section

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

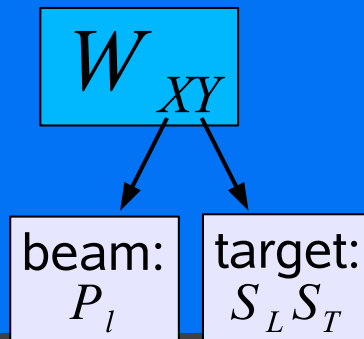


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 production and decay angular distributions W decomposed:

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



vector meson cross section

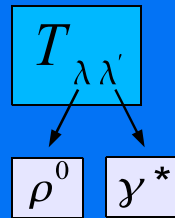
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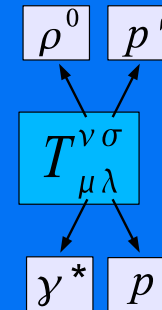
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parametrized by helicity amplitudes $T_{\lambda\lambda'}$ or $T_{\mu\lambda}^{\nu\sigma}$:

-Schilling, Wolf (1973)-



-Diehl notation (2007)-



vector meson cross section

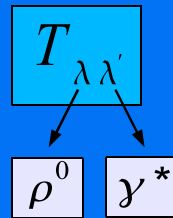
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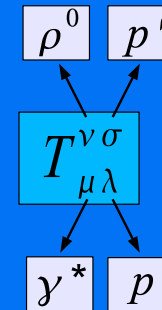
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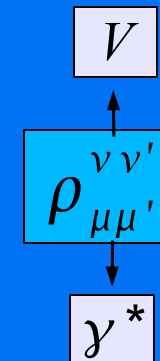
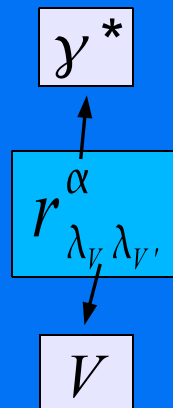
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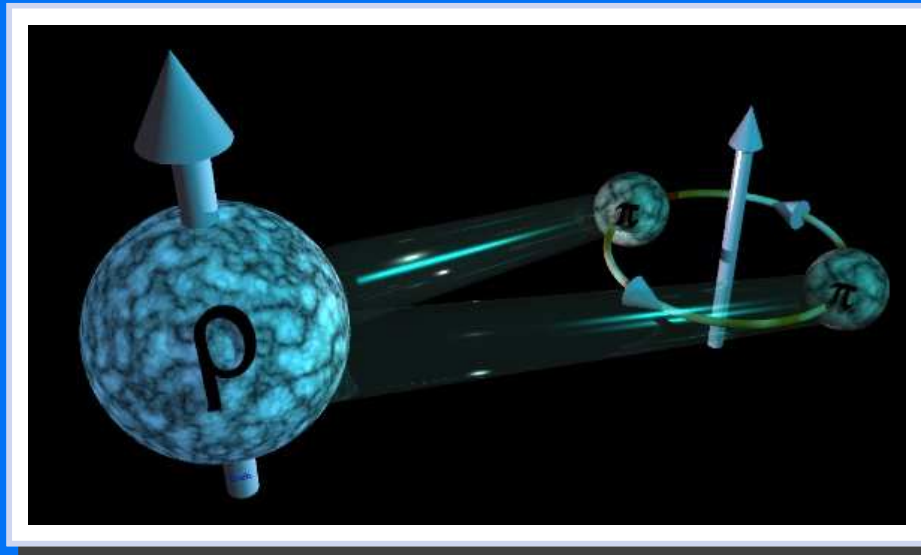


or alternatively by spin-density matrix elements (SDMEs):

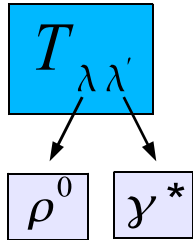


vector meson polarization

- 🌐 γ^* and ρ^0, ϕ, ω have the same quantum numbers
 - ▣ helicity transfer $\gamma^* \rightarrow \rho^0, \phi, \omega$
 - 🌐 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



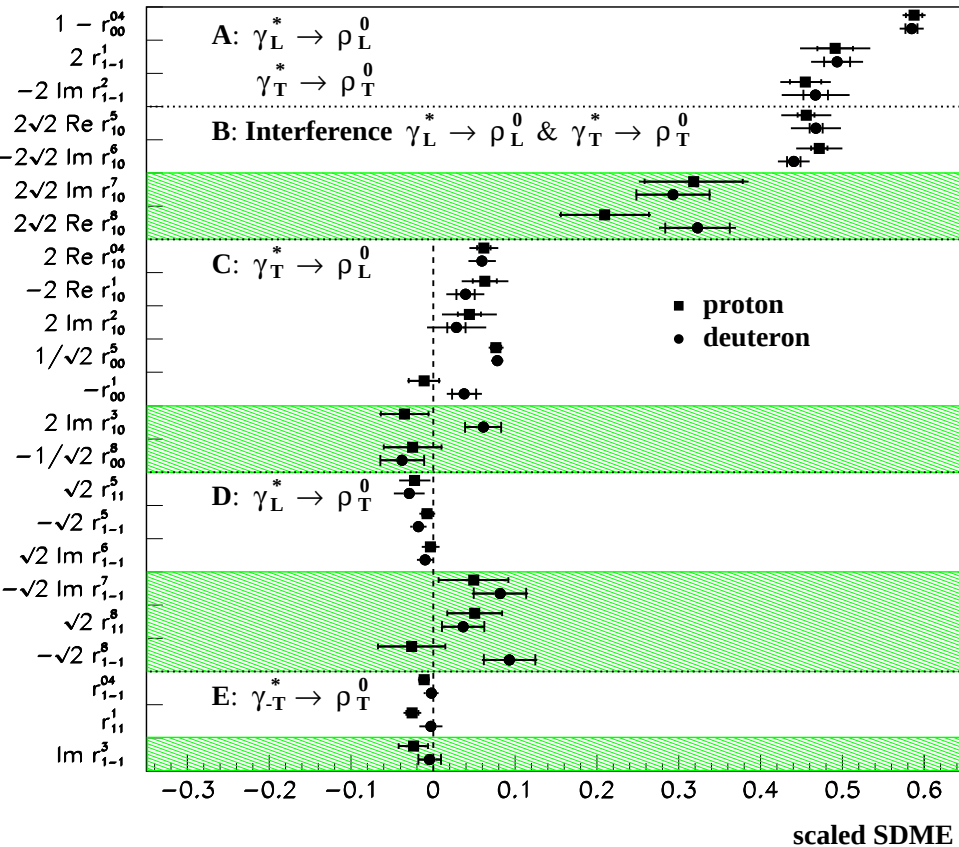
ρ^0 : unpolarized & beam-polarized SDMEs



SDMEs shown according to hierarchy of NPE helicity amplitudes:

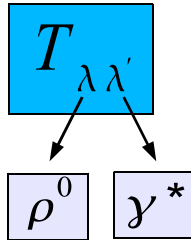
$$|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2$$

-HERMES Collaboration: arXiv:0901.0701 (2009)-



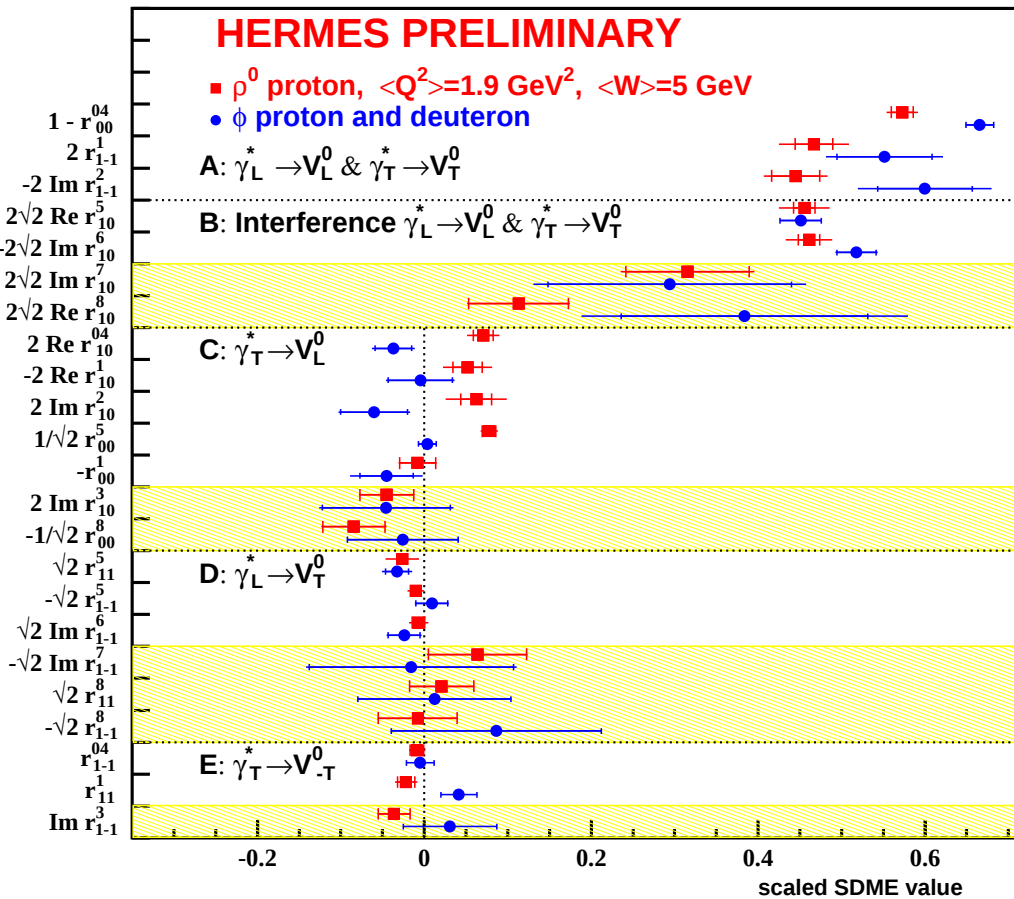
- unpolarized SDMEs: W_{UU}
- beam-polarized SDMEs: W_{LU}
- hierarchy confirmed experimentally
- proton and deuteron data consistent
- s-channel helicity conservation: (ρ^0 conserves the helicity of γ^*)
 - significant $\gamma_L^* \rightarrow \rho_L^0$ and $\gamma_T^* \rightarrow \rho_T^0$
 - a substantial interference
- s-channel helicity violation (vertical line corresponds to SCHC)
 - significant $\gamma_T^* \rightarrow \rho_L^0$
 - smaller $\gamma_L^* \rightarrow \rho_T^0$ and $\gamma_{-T}^* \rightarrow \rho_T^0$
 - 2 – 10 σ level violation

$\rho^0 - \phi$: comparison



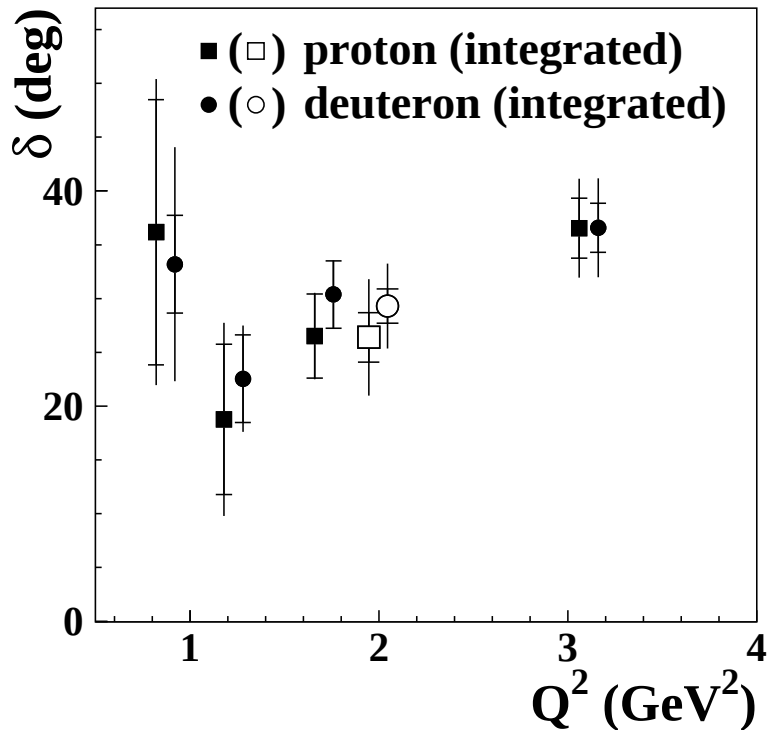
SDMEs shown according to hierarchy of NPE helicity amplitudes:

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



- unpolarized SDMEs: W_{UU}
- beam-polarized SDMEs: W_{LU}
- 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 : phase difference δ between T_{00} and T_{11}



neglecting spin-flip amplitudes

 $|\delta|$ obtained from unpolarized SDMEs:

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

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

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

 results on δ (in degrees):

 proton: $|\delta| = 26.4 \pm 2.3_{stat} \pm 4.9_{sys}$; $\delta = 30.6 \pm 5.0_{stat} \pm 2.4_{sys}$

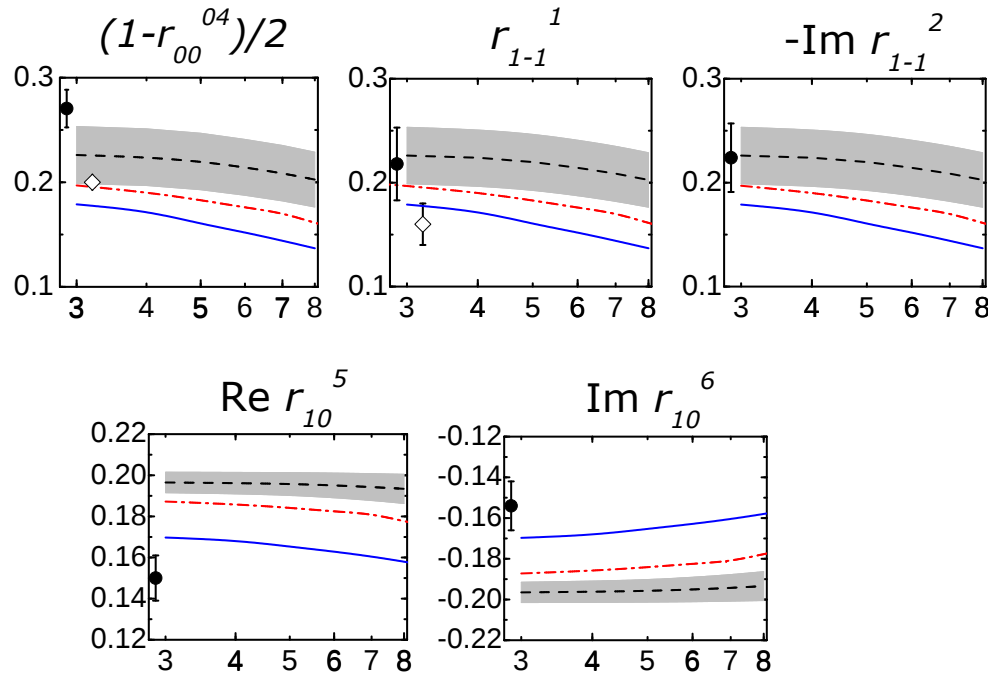
 deuteron: $|\delta| = 29.3 \pm 1.6_{stat} \pm 3.6_{sys}$; $\delta = 36.3 \pm 3.9_{stat} \pm 1.7_{sys}$

 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:

$W = 5 \text{ GeV (HERMES)}$

$W = 10 \text{ GeV (COMPASS)}$

$W = 90 \text{ GeV (H1, ZEUS)}$

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

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

describe data for various W -ranges

interference of $\gamma_L^* \rightarrow \rho_L^0$ and $\gamma_T^* \rightarrow \rho_T^0$

$r_{10}^5 \propto -\Im r_{10}^6 \propto T_{00}$ and T_{11} interference

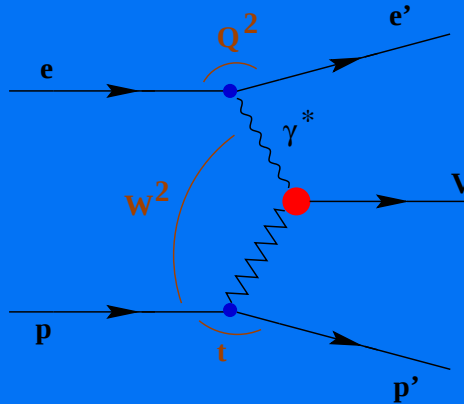
model does not describe the data

model uses phase difference $\delta = 3.1$ degree between T_{00} and T_{11}

HERMES result: $\delta \approx 30$ degree

(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

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 $P = -(-1)^J$: exchange of π, a_1, b_1

 $\propto (M/W)^2$

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

 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 $\tilde{H}$ and $\tilde{E}$

pomeron exchange $\Rightarrow$ gluon exchange

 only **NPE**

reggeon exchange $\Rightarrow$ quark exchange

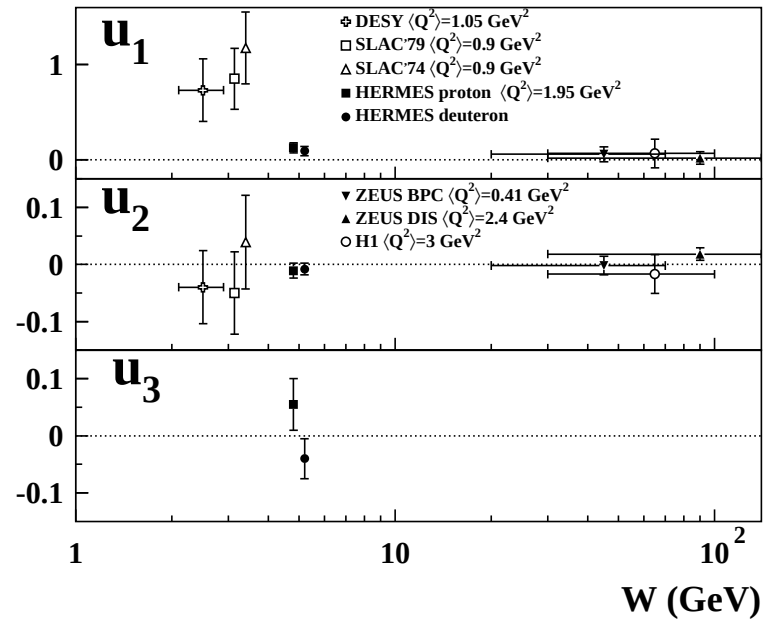
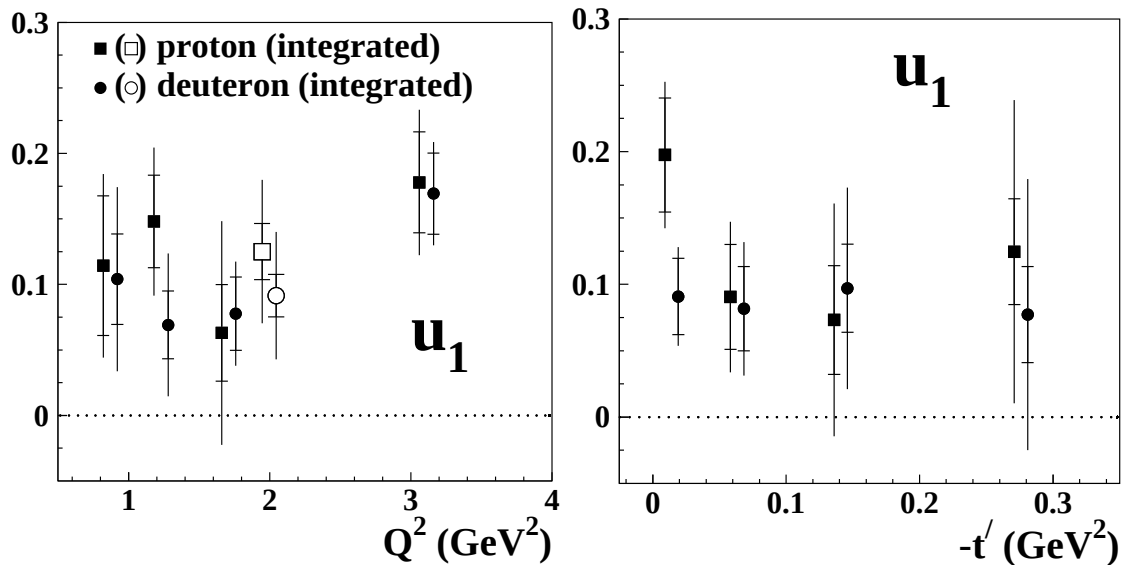
 **NPE** and **UPE**

ρ^0 : observation of unnatural-parity exchange

☉ UPE contributions measured from SDMEs:

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

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



UPE contribution is W -dependent

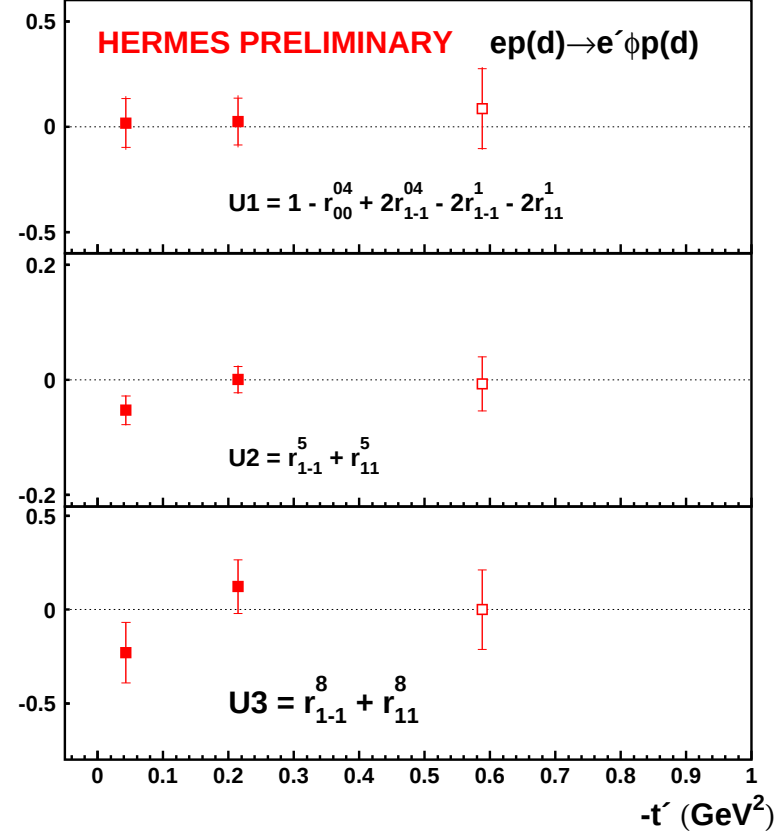
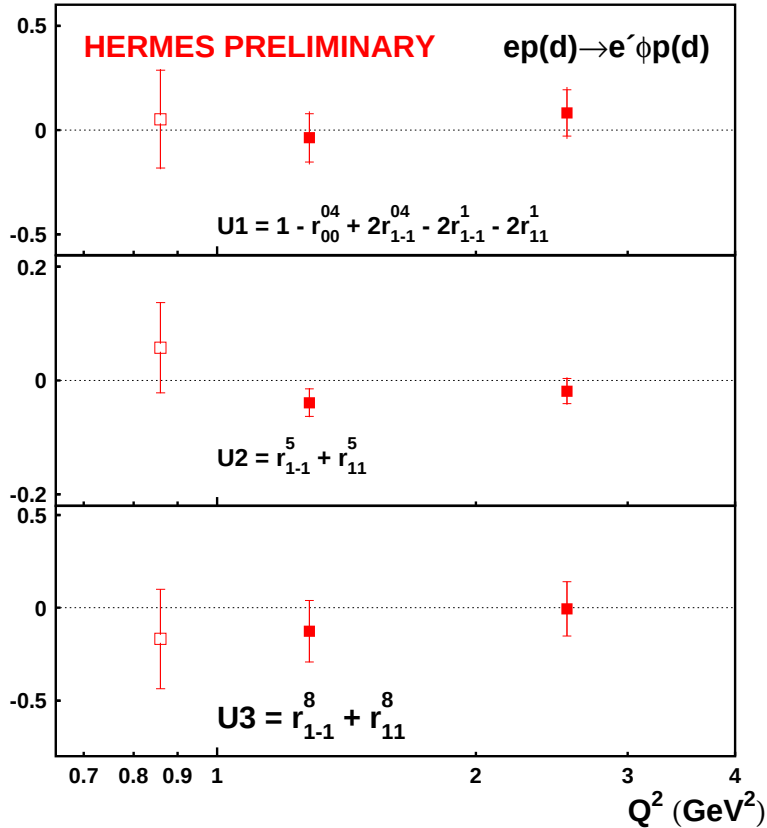
☉ proton:

$$u_1 = 0.125 \pm 0.021_{stat} \pm 0.050_{sys}$$

☉ deuteron:

$$u_1 = 0.091 \pm 0.016_{stat} \pm 0.046_{sys}$$

ϕ : observation of unnatural-parity exchange



$$u_1 = 0.02 \pm 0.07_{stat} \pm 0.16_{sys}$$



$$u_2 = -0.03 \pm 0.01_{stat} \pm 0.03_{sys}$$



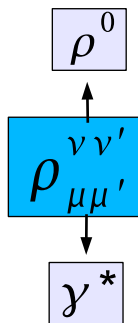
$$u_3 = -0.05 \pm 0.12_{stat} \pm 0.07_{sys}$$



no signal of unnatural-parity exchange

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

'transverse' SDMEs: $n_{\mu\mu'}^{\nu\nu'}$ and $s_{\mu\mu'}^{\nu\nu'}$



 -HERMES Collaboration: arXiv:0906.5160 (2009)-
transverse SDMEs: W_{UT}

 measured for the first time

 average kinematics:

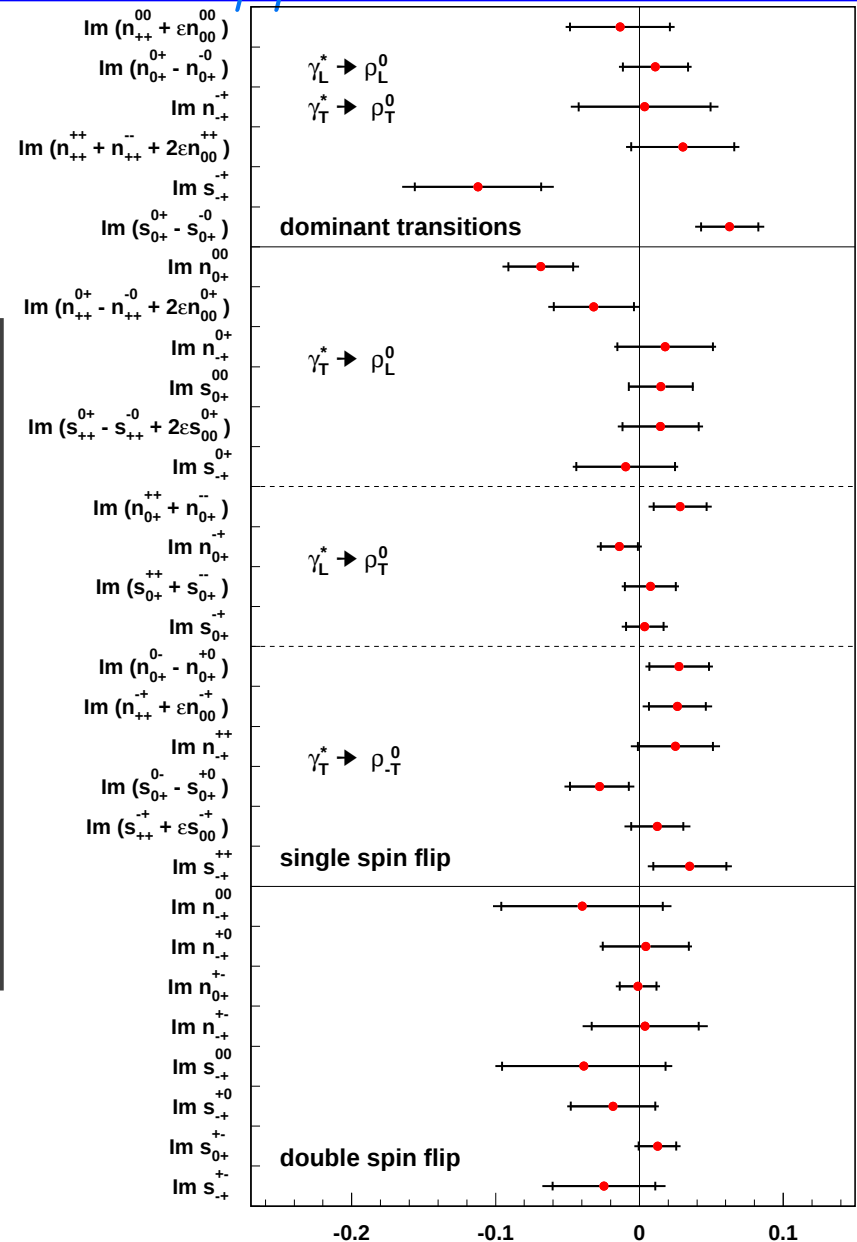
$$\langle -t' \rangle = 0.13 \text{ GeV}^2$$

$$\langle x_B \rangle = 0.09$$

$$\langle Q^2 \rangle = 2.0 \text{ GeV}^2$$

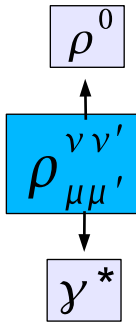
 related to the proton helicity-flip
amplitude

 suppressed by a factor $\sqrt{-t'}/2M_p$



SDME values

'transverse' SDMEs: $n_{\mu\mu'}^{\nu\nu'}$ and $s_{\mu\mu'}^{\nu\nu'}$



-HERMES Collaboration: arXiv:0906.5160 (2009)-
 $\gamma_L^* \rightarrow \rho_L^0$ and $\gamma_T^* \rightarrow \rho_T^0$

$\text{Im } s_{-+}^{0+}$ and $\text{Im}(s_{0+}^{0+} - s_{0+}^{-0})$:
deviate from 0 by 2.5σ

expected $s_{\mu\mu'}^{\nu\nu'} < n_{\mu\mu'}^{\nu\nu'}$
(if identical indices)

$\text{Im } s_{-+}^{0+}$ and $\text{Im } s_{0+}^{0+}$ involve

-Manaenkov (2008)-

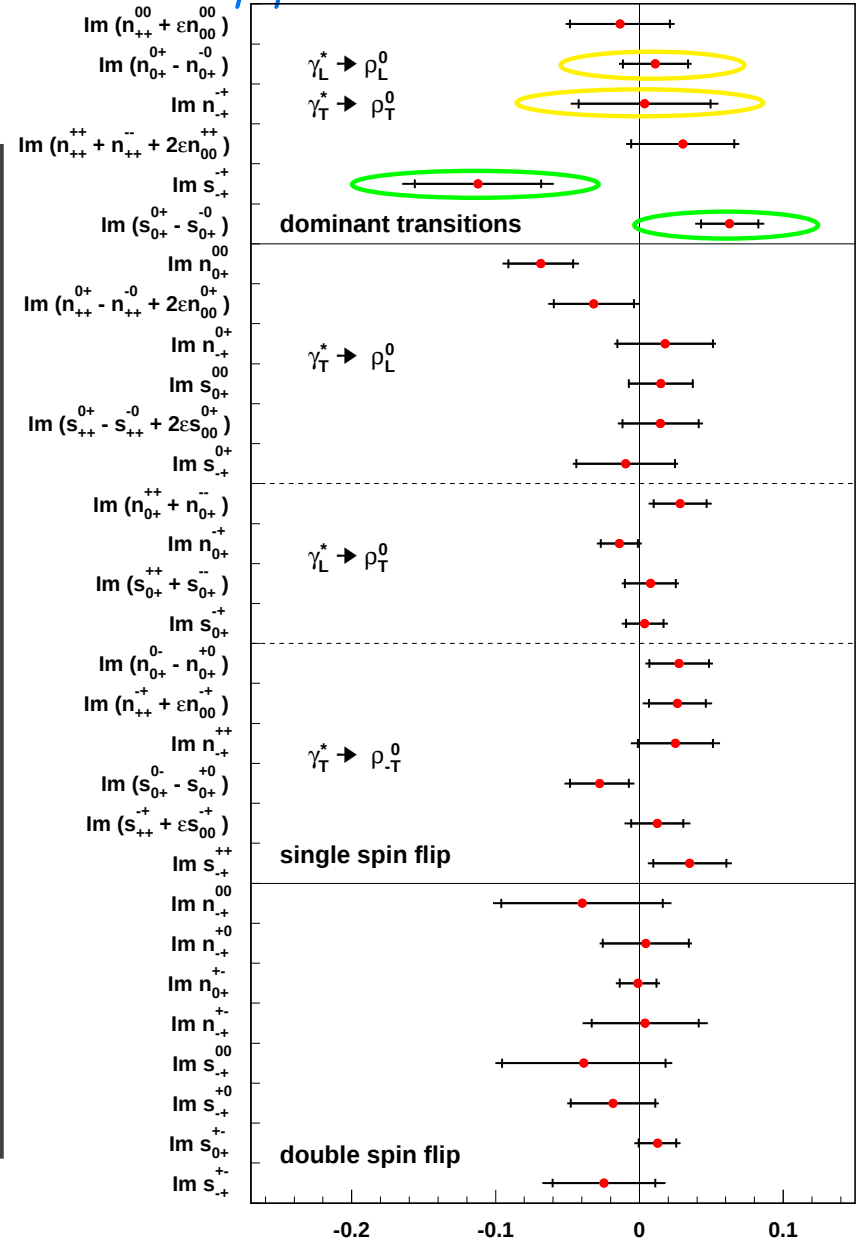
the biggest NPE
amplitudes

N_{-+}^{0+} or N_{0+}^{0+}

the biggest UPE amplitude
 U_{+-}^{++}

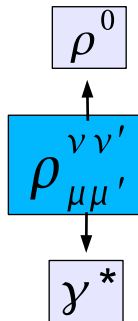
signal for unnatural-parity
exchange

related to GPDs $\tilde{H}$ and $\tilde{E}$



SDME values

'transverse' SDMEs: $n_{\mu\mu'}^{\nu\nu'}$ and $s_{\mu\mu'}^{\nu\nu'}$



-HERMES Collaboration: arXiv:0906.5160 (2009)-
 $\gamma_L^* \rightarrow \rho_L^0$ and $\gamma_T^* \rightarrow \rho_T^0$

$\text{Im } s_{-+}^{0+}$ and $\text{Im}(s_{0+}^{0+} - s_{0+}^{-0})$:
deviate from 0 by 2.5σ

expected $s_{\mu\mu'}^{\nu\nu'} < n_{\mu\mu'}^{\nu\nu'}$
(if identical indices)

$\text{Im } s_{-+}^{0+}$ and $\text{Im } s_{0+}^{0+}$ involve

-Manaenkov (2008)-

the biggest **NPE**
amplitudes

N_{-+}^{0+} or N_{0+}^{0+}

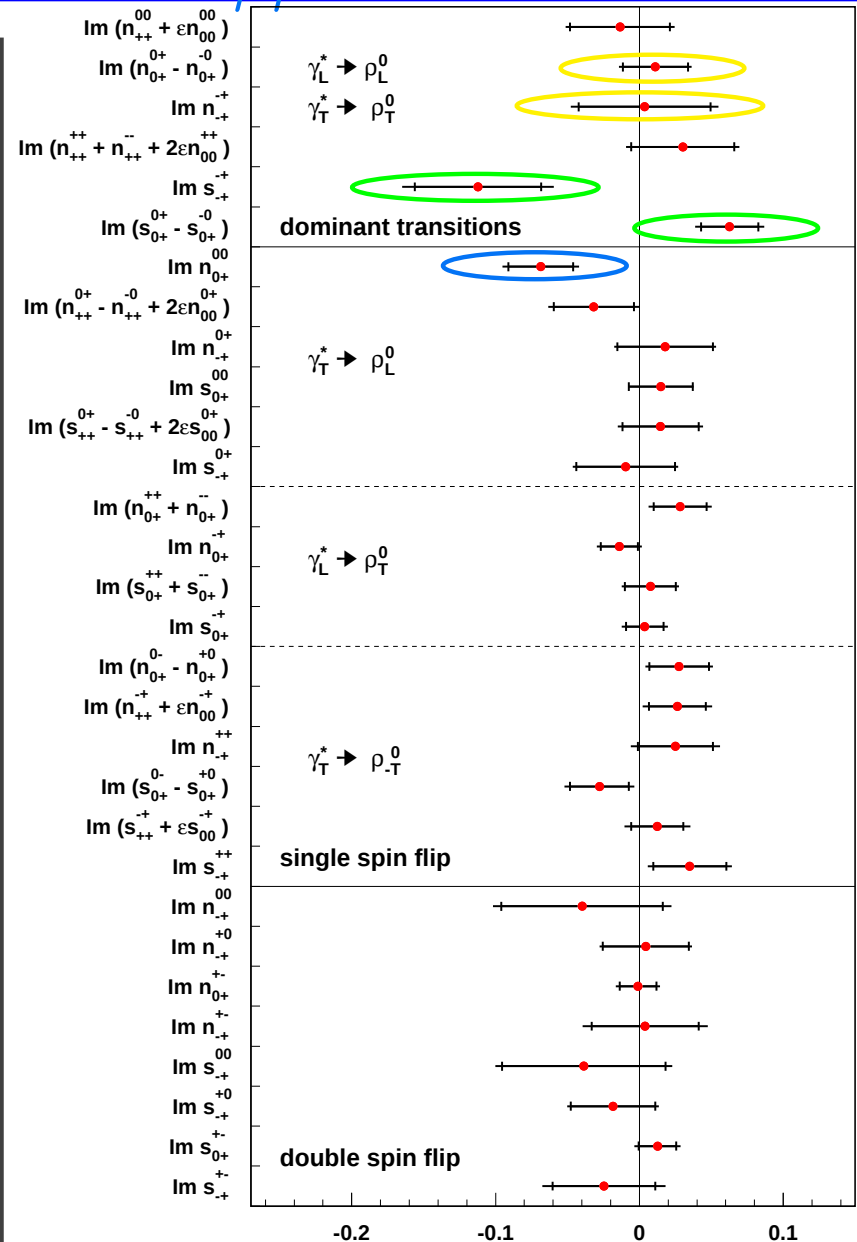
the biggest **UPE** amplitude
 U_{+-}^{++}

signal for **unnatural-parity**
exchange

related to GPDs $\tilde{H}$ and $\tilde{E}$

$\gamma_T^* \rightarrow \rho_L^0$

$\text{Im } n_{0+}^{00}$: 2.5σ deviation from 0



SDME values

ρ^0 : transverse target-spin asymmetry

 theoretically at leading order in $1/Q$
($\gamma_L^* \rightarrow \rho_L^0$):

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

 asymmetry in terms of GPDs

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

-  depends linearly on the helicity-flip GPDs $E^{q,g}$
-  no kinematic suppression $E^{q,g}$ with respect to $H^{q,g}$

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- experimentally:

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

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

- similarly, $\gamma_T^* \rightarrow \rho_T^0$:

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

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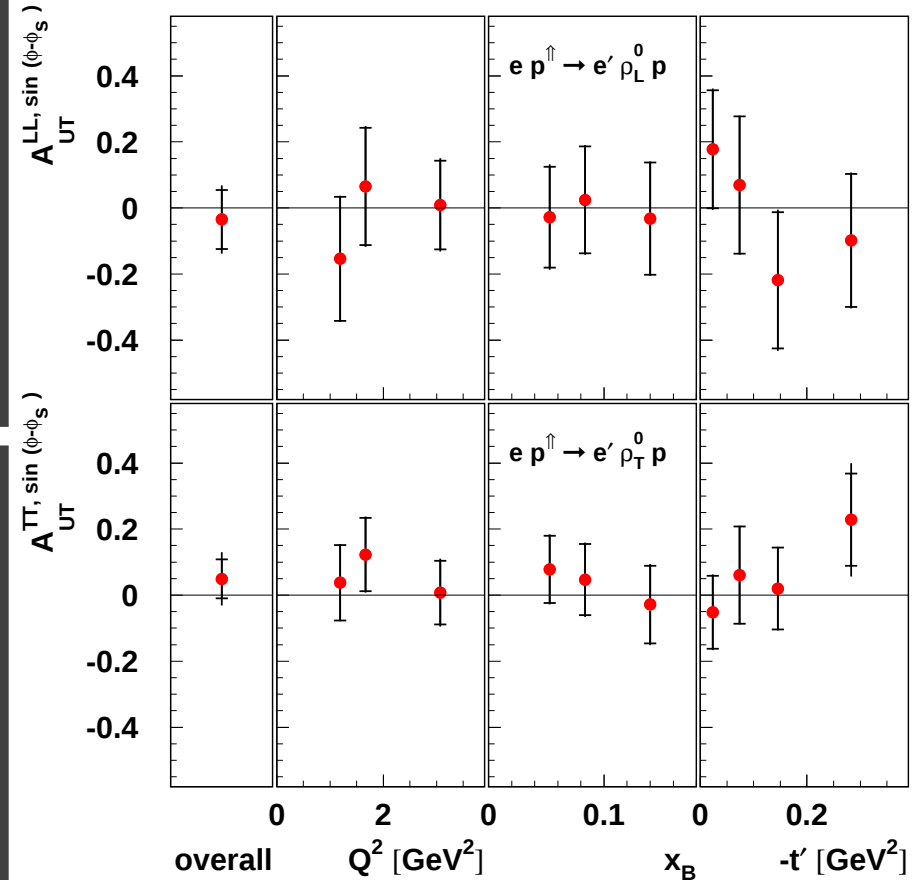
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-HERMES Collaboration: arXiv:0906.5160 (2009)-



compatible with 0 overall value:

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

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 $J^d = 0$

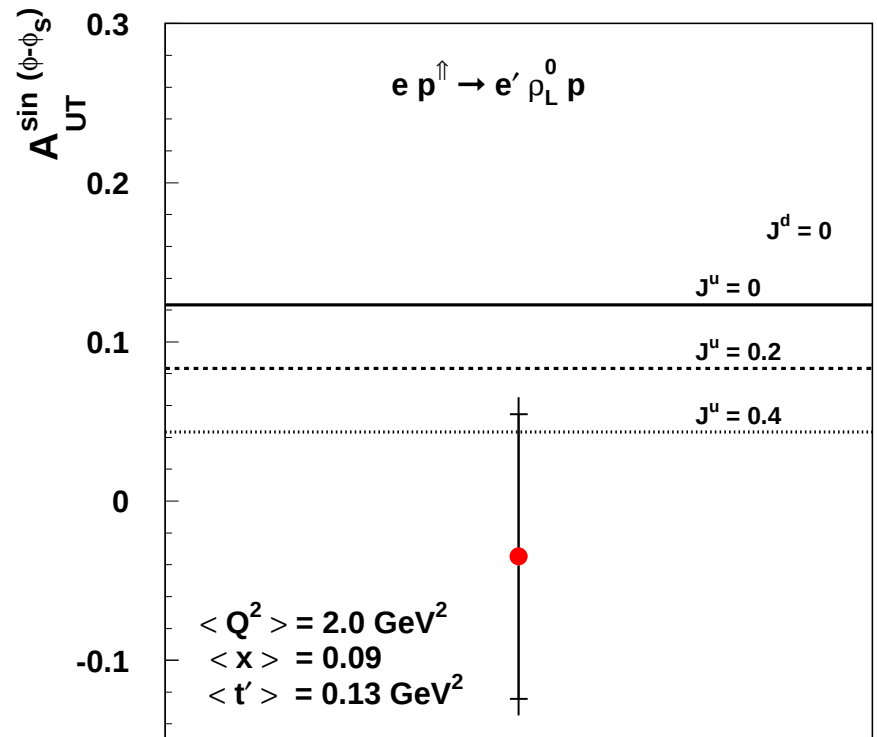
$E^{\bar{q}}$ and E^g are neglected

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 $E^{\bar{q}}$?



overall

other GPD model calculations

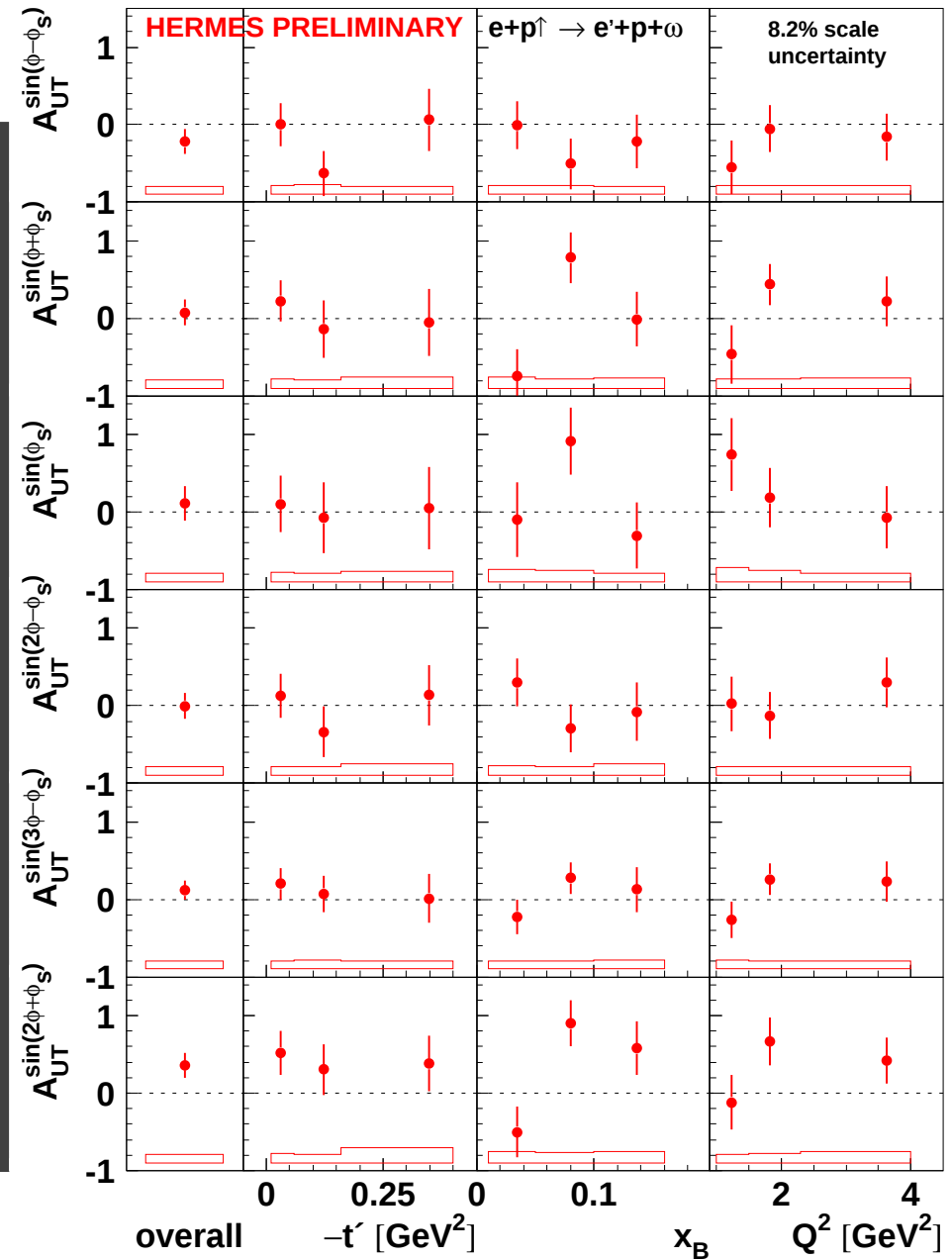
- Goeke, Polyakov, Vanderhaeghen (1999)-

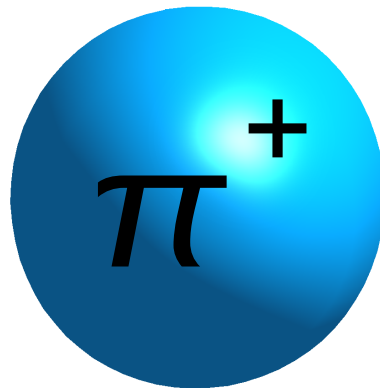
-Goloskokov, Kroll (2007)-

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





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



no recoil nucleon detection



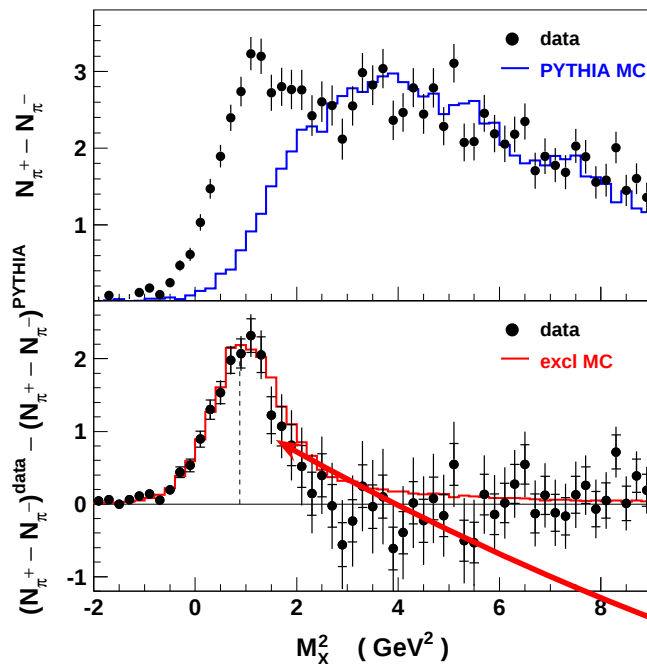
select exclusive π^+ reaction through the missing mass technique:

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

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

-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

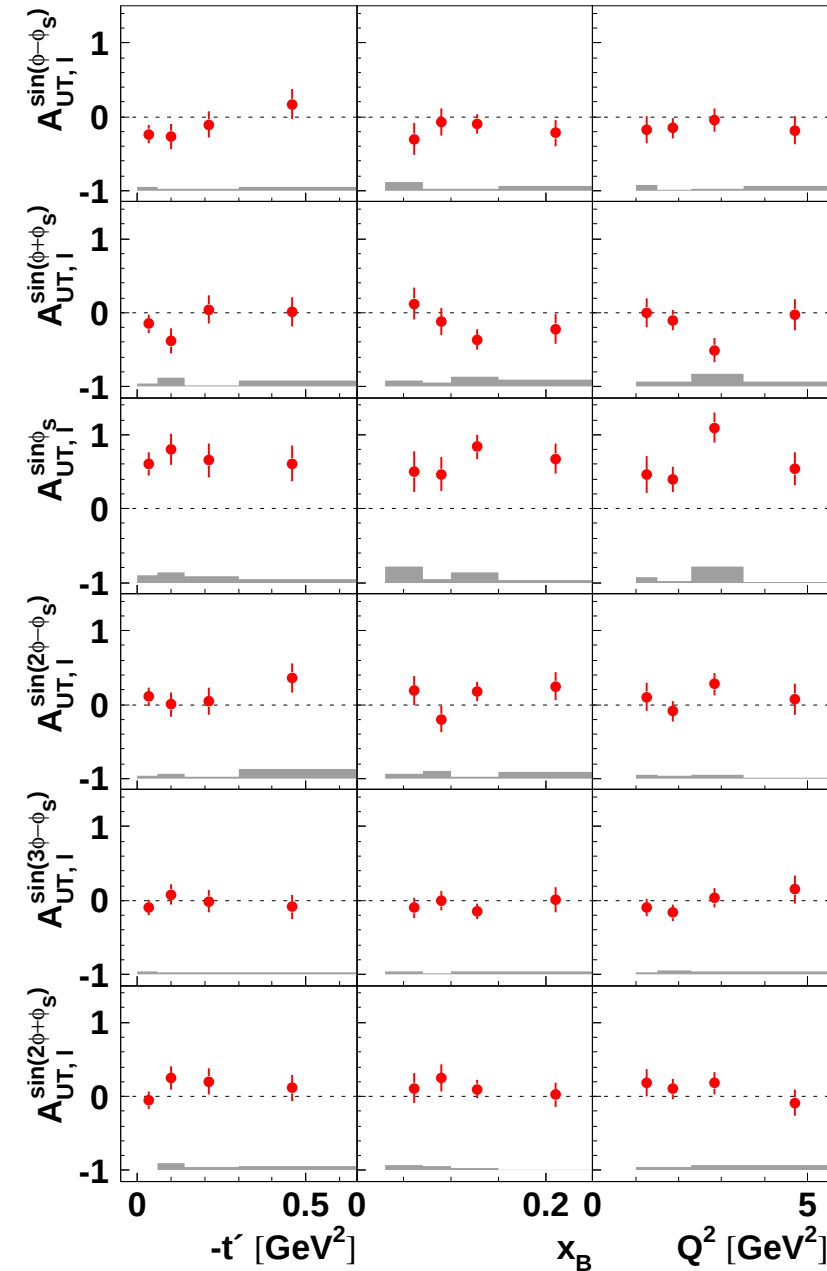


exclusive peak centered at the nucleon mass



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:

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

$$\langle x_B \rangle = 0.13$$

$$\langle Q^2 \rangle = 2.38 \text{ GeV}^2$$

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

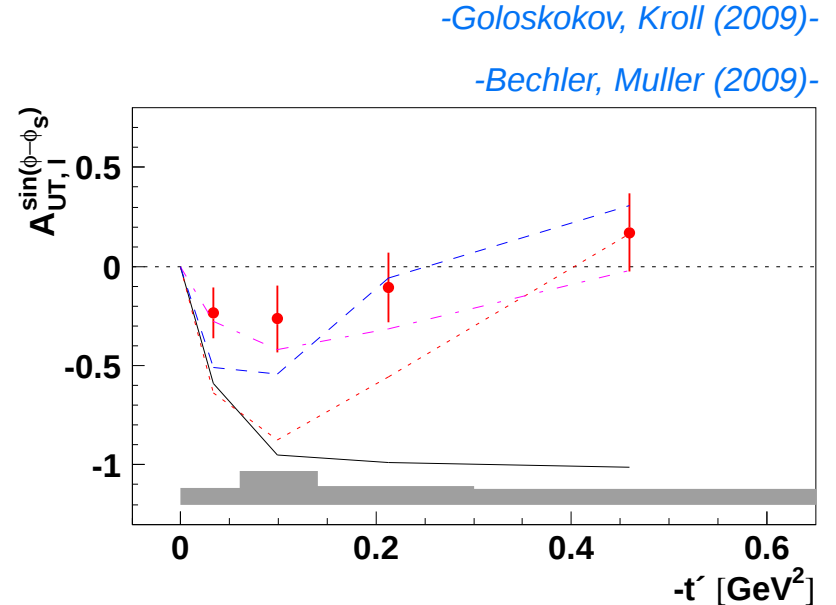
other moments: consistent with 0

evidence of contributions from transversely polarized photons

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

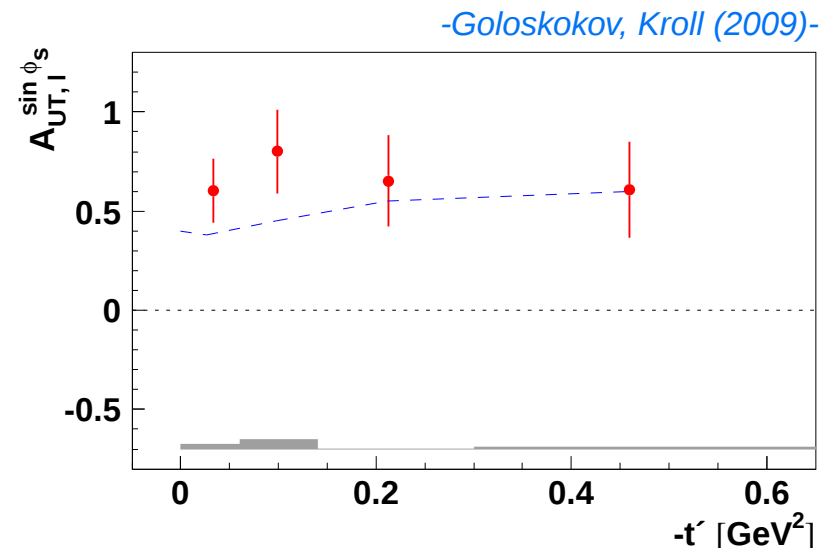
leading azimuthal amplitude $A_{UT}^{\sin(\phi-\phi_s)}$

- theoretical expectation: large negative asymmetry
- $A_{UT}^{\sin(\phi-\phi_s)} \propto \sqrt{-t'}$ -Frankfurt et al. (2001)-
-Belitsky, Muller (2001)-
- not large asymmetry with possible sign change
- calculations for γ_L^* and for γ_L^*/γ_T^* Contributions

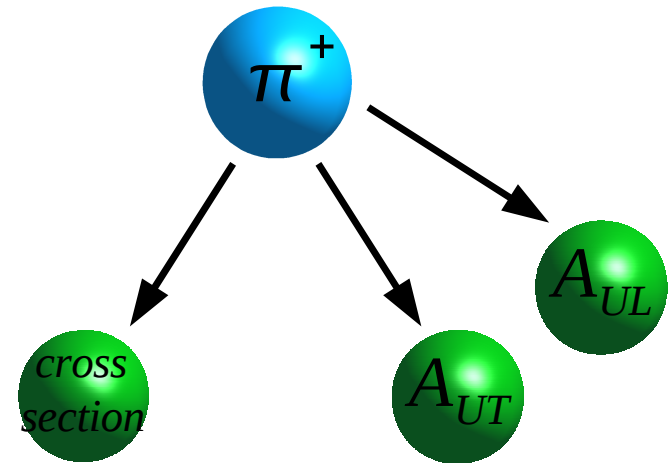
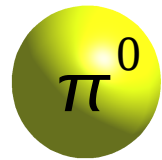
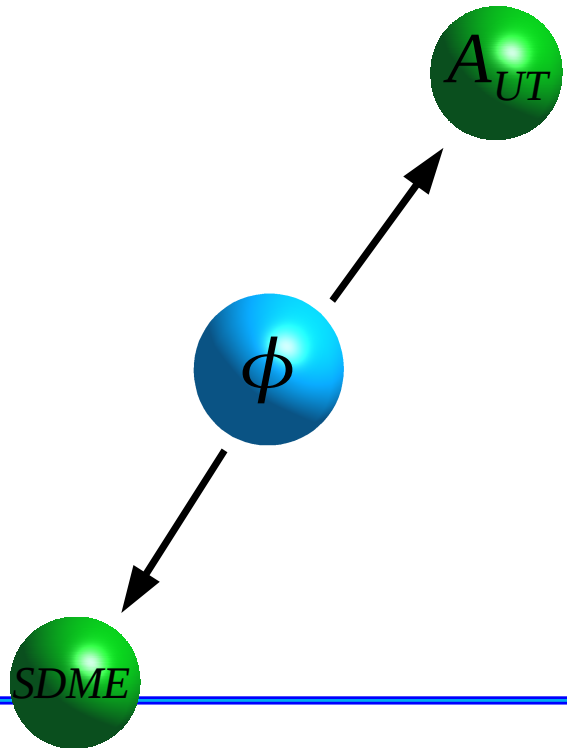
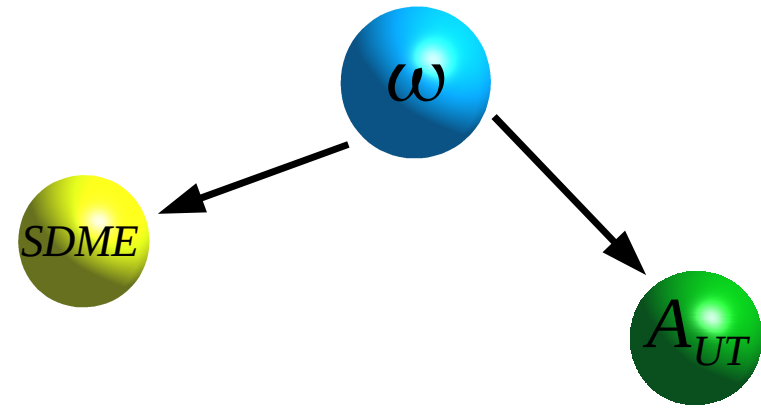
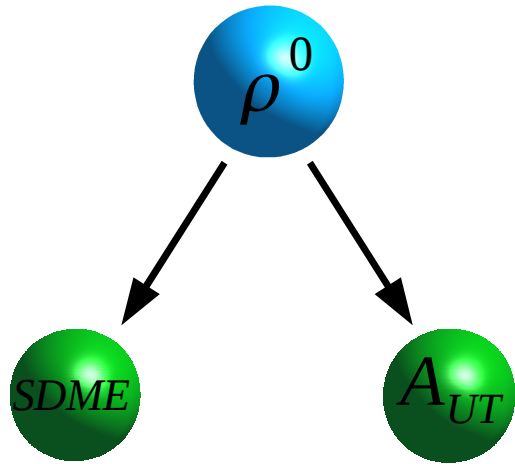


azimuthal amplitude $A_{UT}^{\sin \phi_s}$

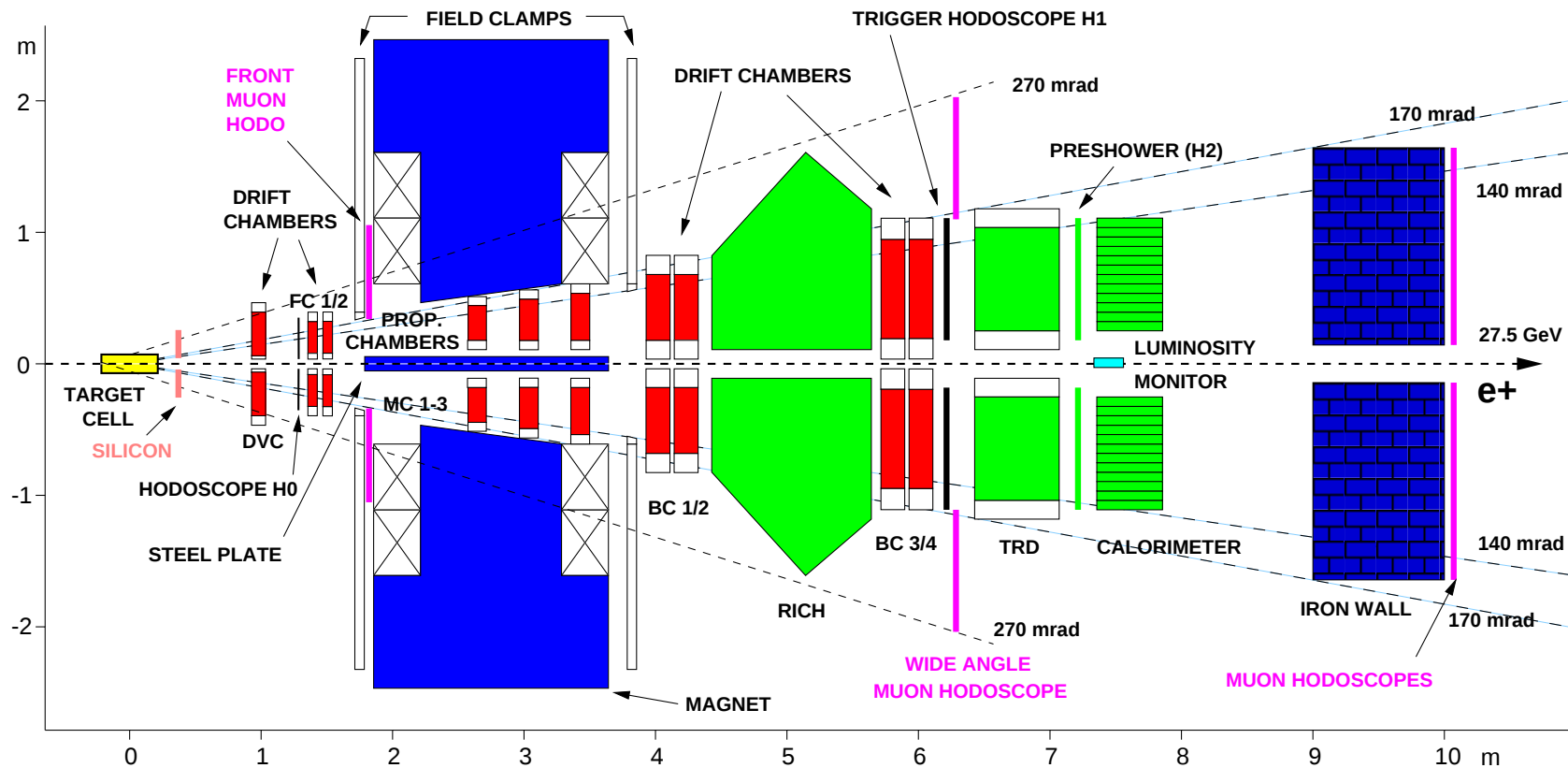
- no turnover against 0 for $t' \rightarrow 0$
- mild t -dependence
- can be explained only by γ_L^*/γ_T^* interference
- predictions $A_{UT}^{\sin \phi_s} \approx const$
- non-vanishing model predictions: contributions H_T and $\tilde{H}_T$



HERMES and GPDs



HERMES Spectrometer



ρ^0 : observation of unnatural-parity exchange

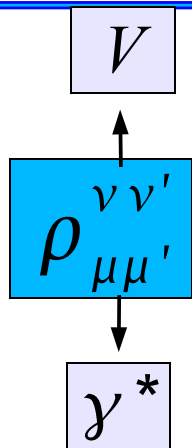
☉ UPE contributions measured from SDMEs:

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

☉ 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:



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

