Exclusive mesons at HERMES

ECT* workshop on hard photon and meson production

Trento, Italy

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Ami Rostomyan

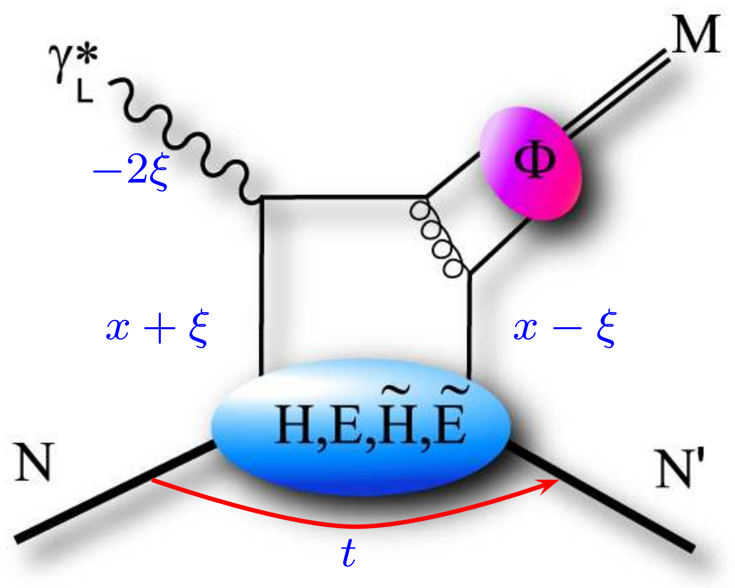
presented by Wolf-Dieter Nowak

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

- 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)-*

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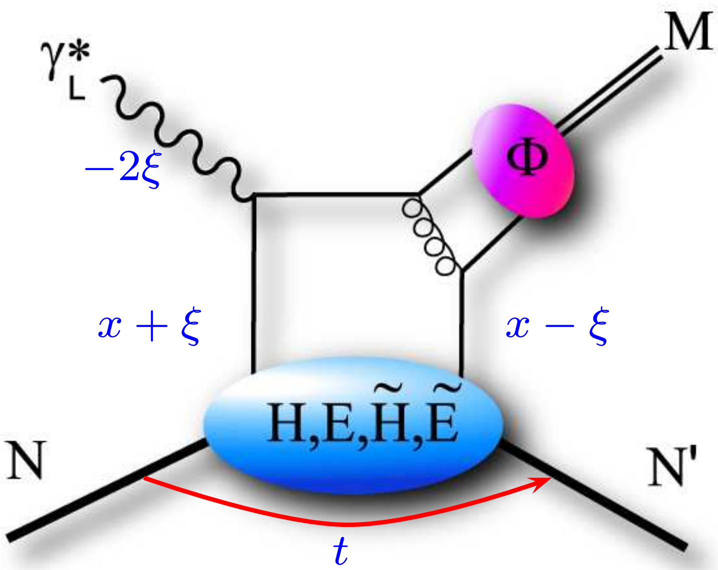

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power corrections: $k_\perp$ is not neglected

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

exclusive meson production

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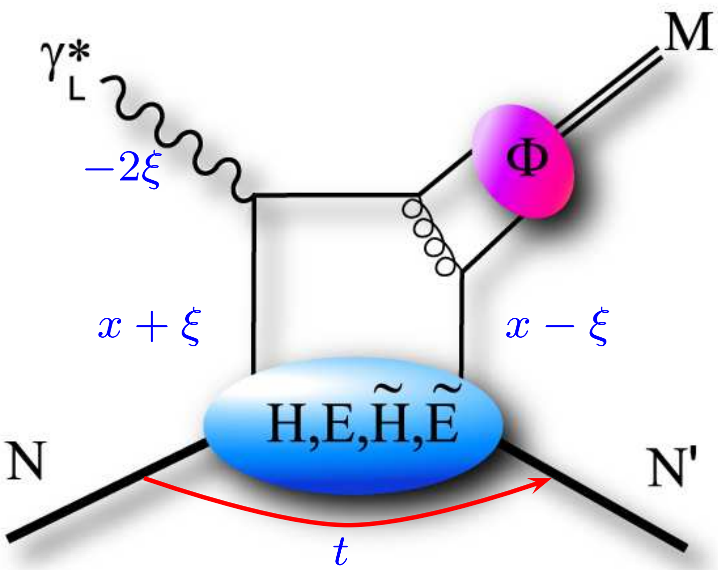

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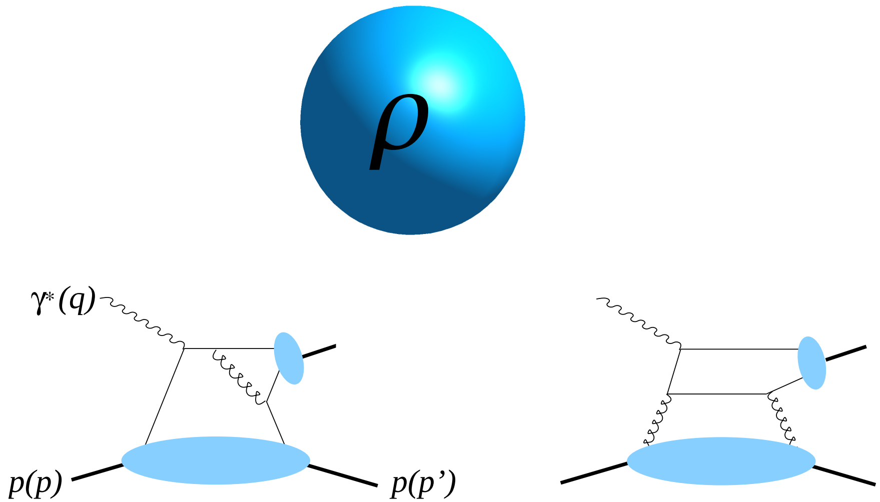
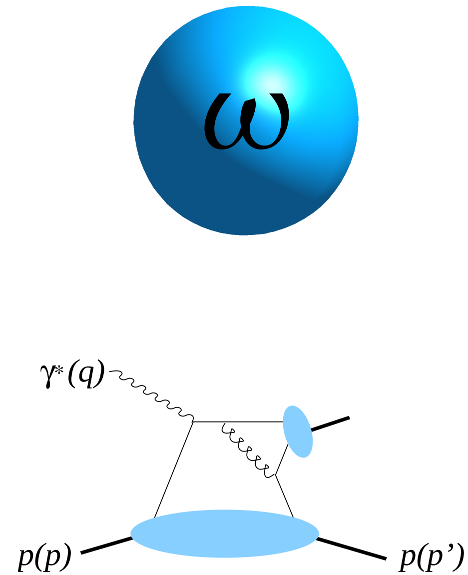
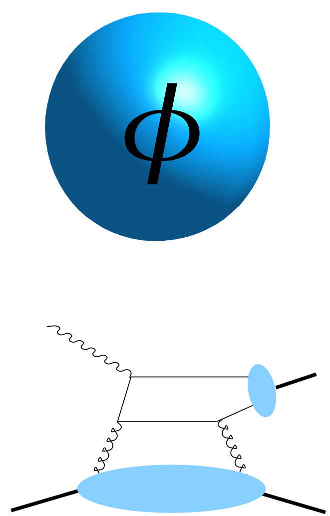
power corrections: $k_\perp$ is not neglected

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

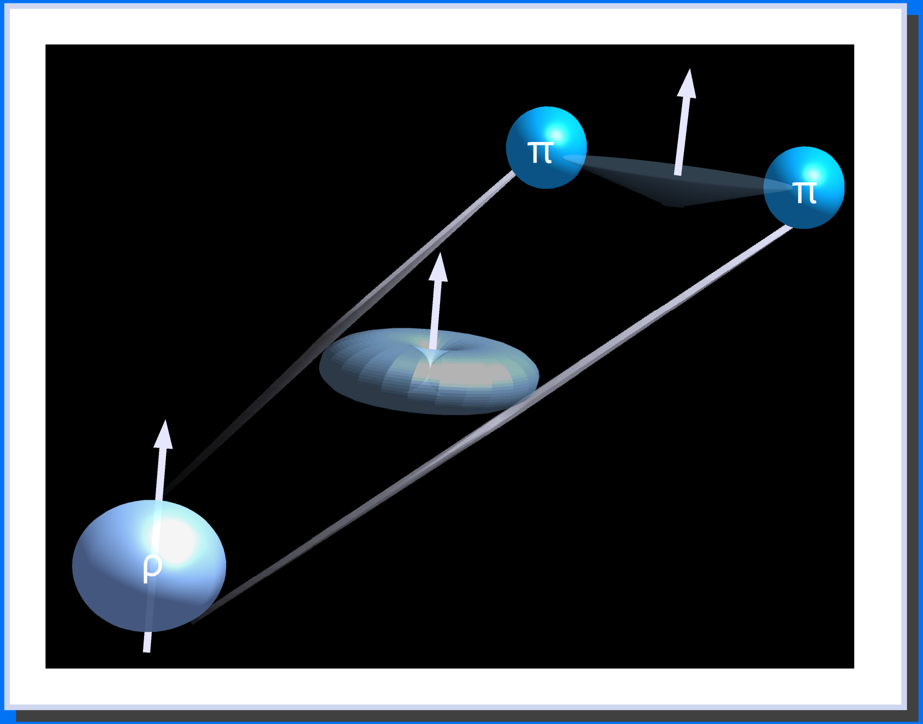

ρ
γ*(q)
p(p)
p(p')


ω
γ*(q)
p(p)
p(p')


φ

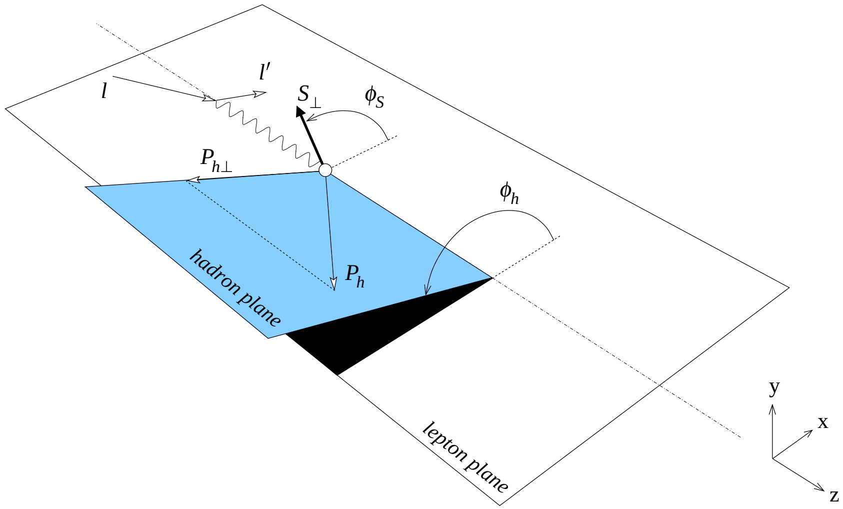
vector meson polarization

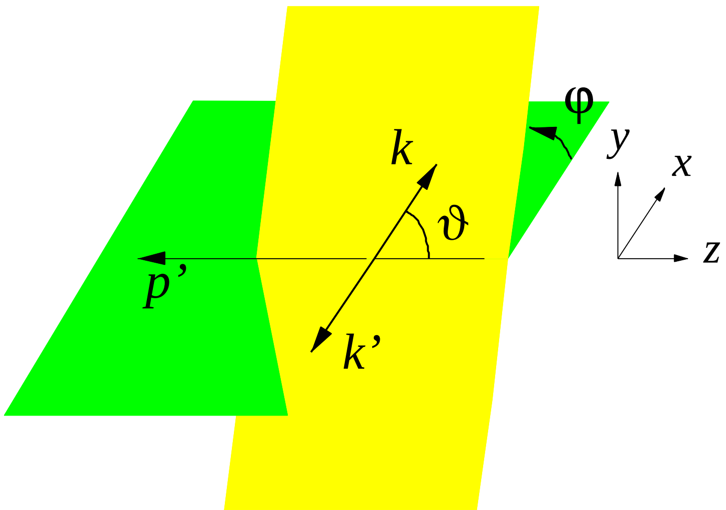
- γ^* and ρ^0, ϕ, ω have the same quantum numbers
  - helicity transfer $\gamma^* \rightarrow \rho^0, \phi, \omega$
    - signature: ρ^0, ϕ, ω production angular distribution
- the spin-state of the ρ^0, ϕ, ω is reflected in the orbital angular momentum of decay particles
  - ρ^0, ϕ, ω (in the rest frame):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



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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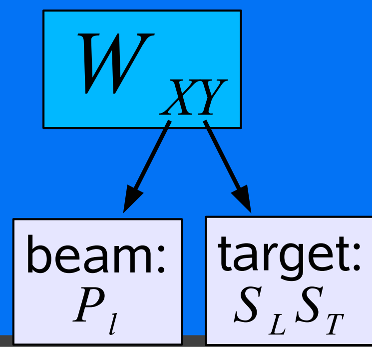
- production and decay angular distributions W decomposed:

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



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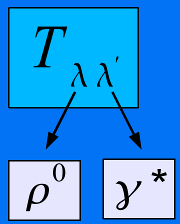
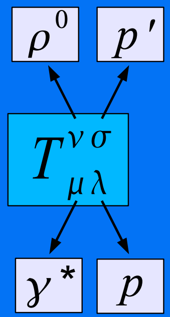
- parametrized by helicity amplitudes $T_{\lambda\lambda'}$ or $T^{\nu\sigma}_{\mu\lambda}$:

-Schilling, Wolf (1973)- *-Diehl notation (2007)-*





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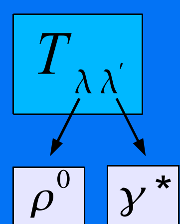
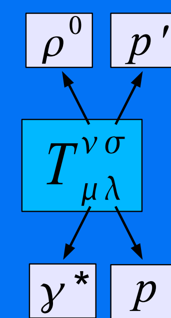
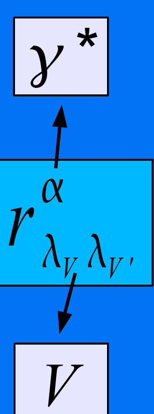
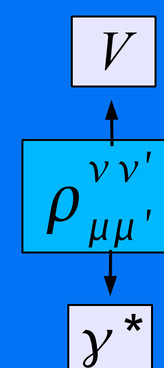


-Diehl notation (2007)-



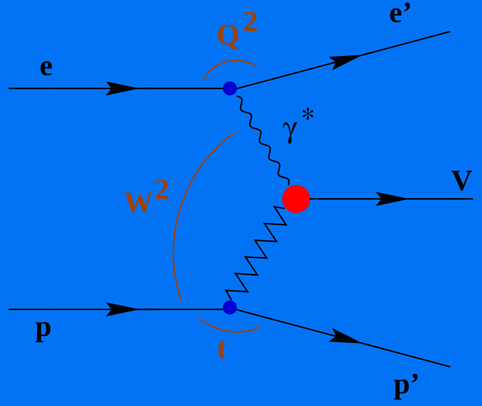
- or alternatively by spin-density matrix elements (SDMEs):





(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

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- 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 $\widetilde{E}$

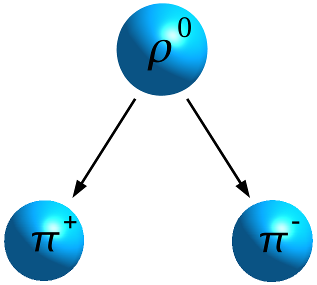
pomeron exchange $\Rightarrow$ gluon exchange

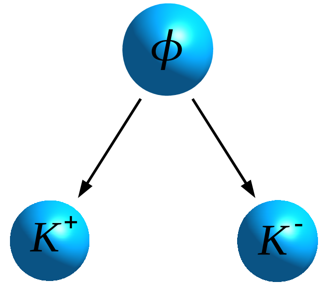
- only NPE

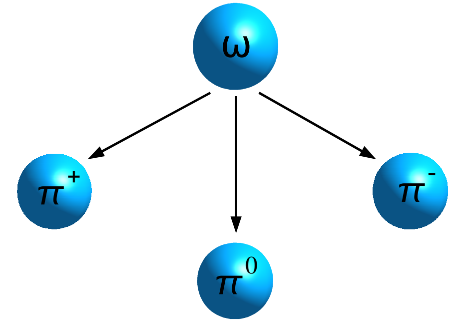
reggeon exchange $\Rightarrow$ quark exchange

- 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

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

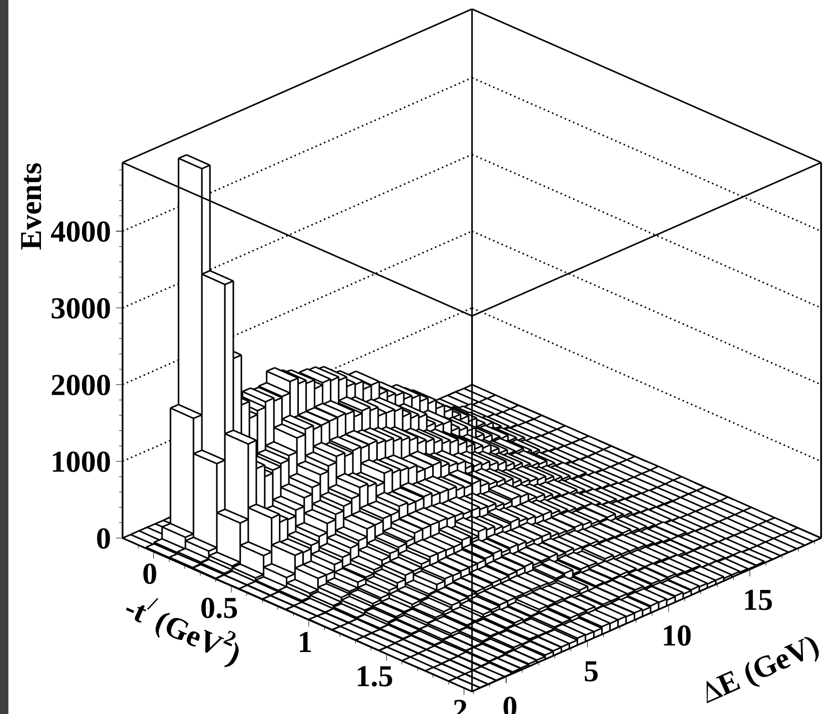
- transverse four-momentum transfer is used

$$t' = t - t_0$$

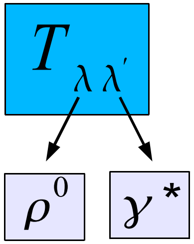
- main contribution at small values of ΔE and t'
- non-exclusive events:

$$\Delta E > 0$$

- SIDIS background estimated by PYTHIA MC



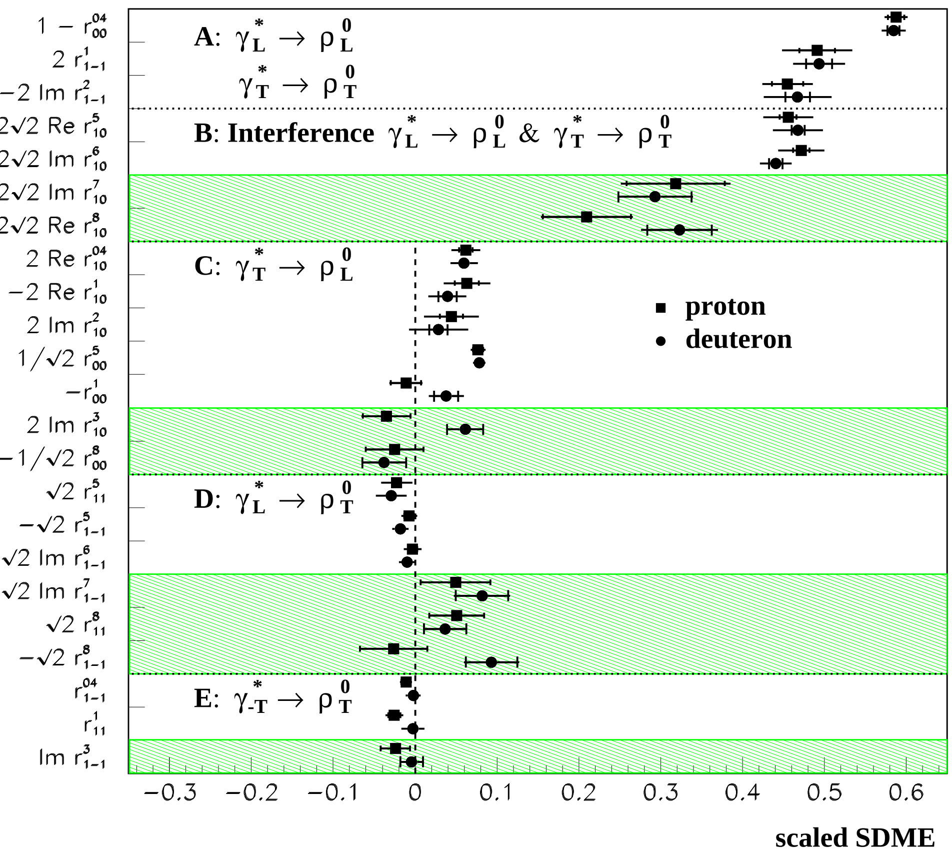
ρ^0: unpolarized & beam-polarized SDMEs



SDMEs shown according to hierarchy of NPE helicity amplitudes:

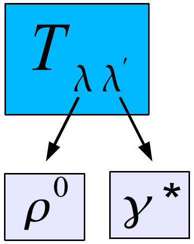
$$|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2$$

-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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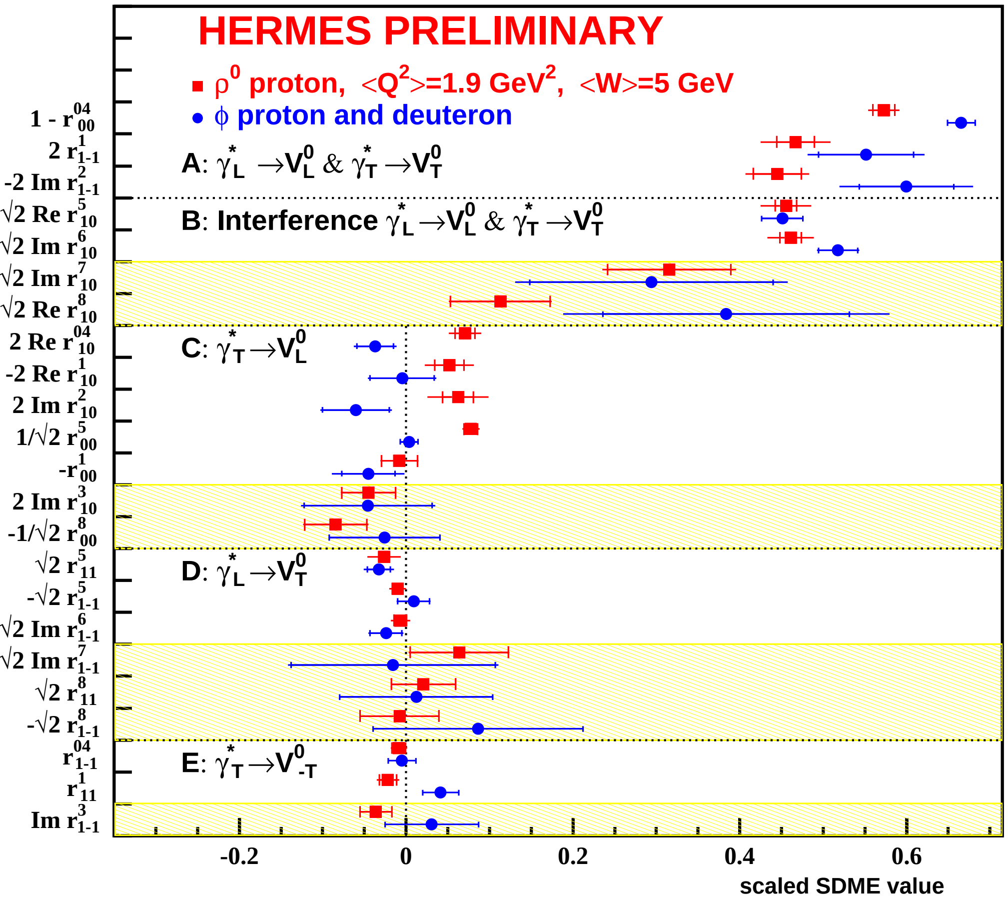
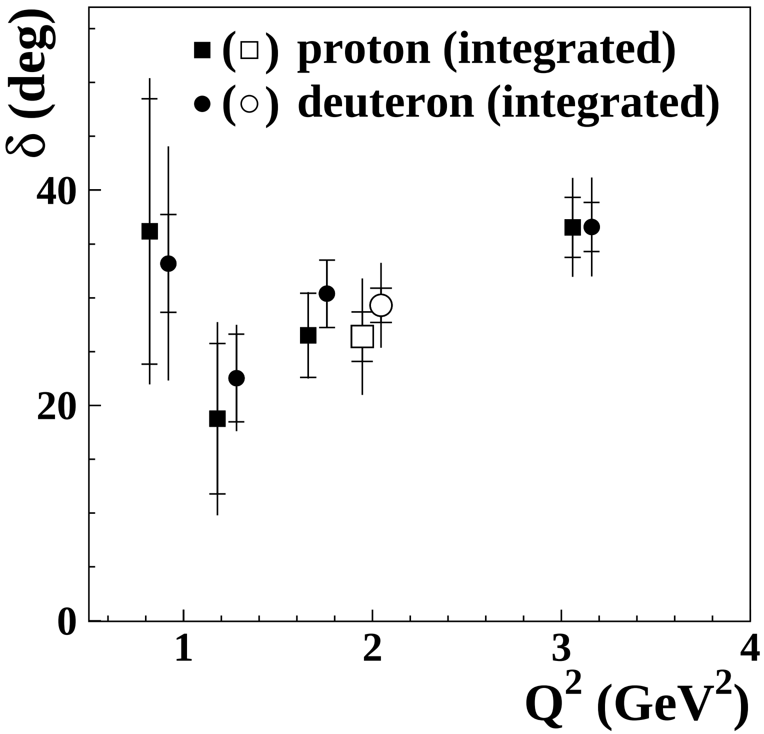


- unpolarized SDMEs: W_{UU}
- beam-polarized SDMEs: W_{UL}
- polarized SDMEs have been measured by HERMES for the first time
- no statistically significant difference between proton and deuteron
- no s-channel helicity violation
- hierarchy of amplitudes:
  $T_{00} \sim T_{11}$
  $T_{01} \approx T_{10}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

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



-HERMES Collaboration: arXiv:0901.0701 (2009)-

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

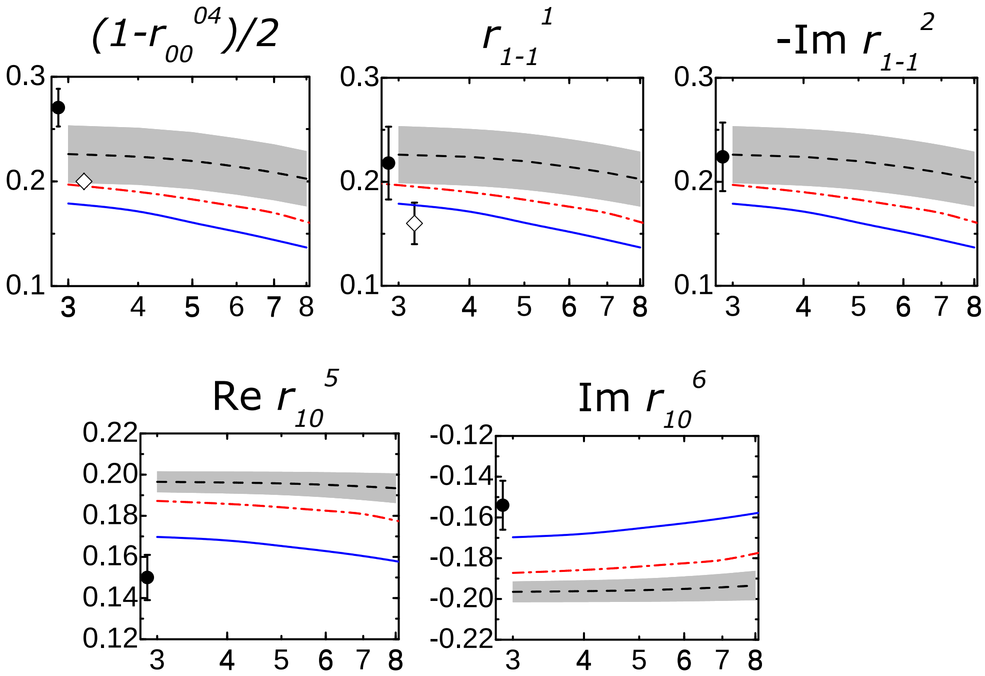
$$\cos\delta = \frac{2\sqrt{\epsilon}(\Re r^5_{10} - \Im r^6_{10})}{\sqrt{r^{04}_{00}(1 - r^{04}_{00} + r^1_{1-1} - \Im r^2_{1-1})}}$$

- 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:

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

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

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

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

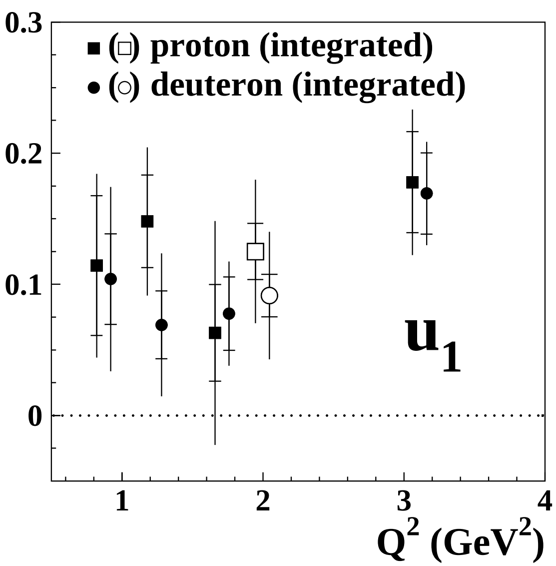
- $r_{10}^5 \propto -\Im r_{10}^6 \propto T_{00}$ and T_{11} interference
- model does not describe the data
- model uses phase difference $\delta = 3.1$ degree between T_{00} and T_{11}
- HERMES result: $\delta \approx 30$ degree

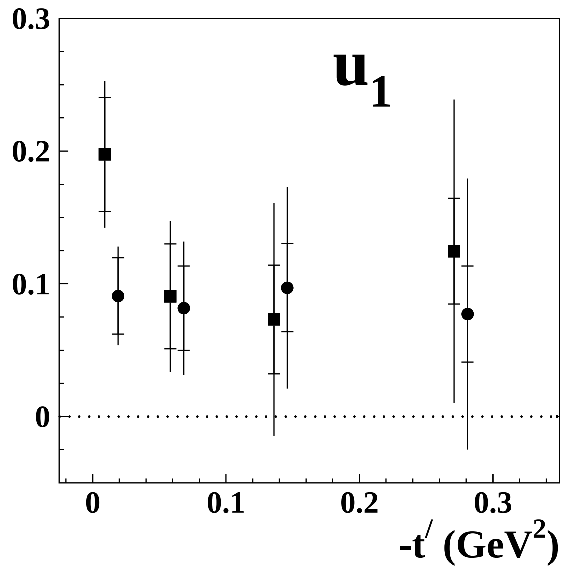
ρ^0: observation of unnatural-parity exchange

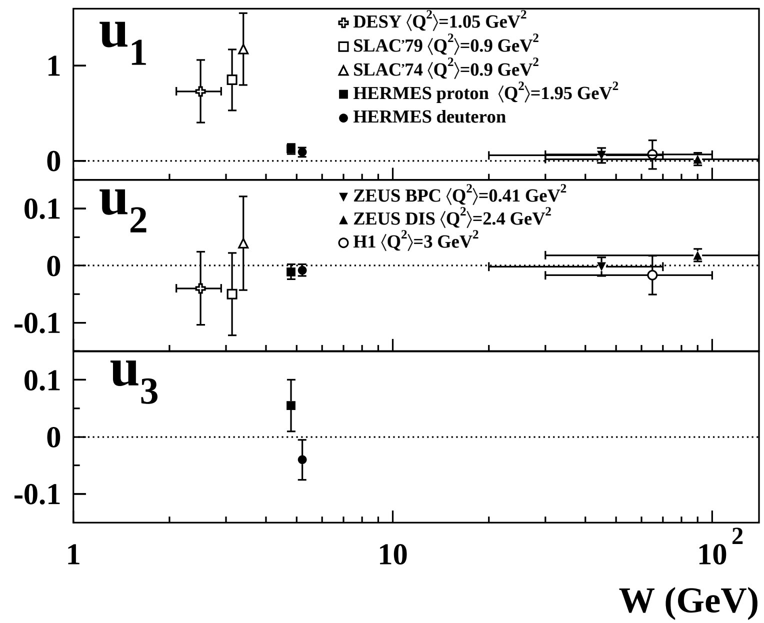
- UPE contributions measured from SDMEs: *-HERMES Collaboration: arXiv:0901.0701 (2009)-*

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

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







- proton:

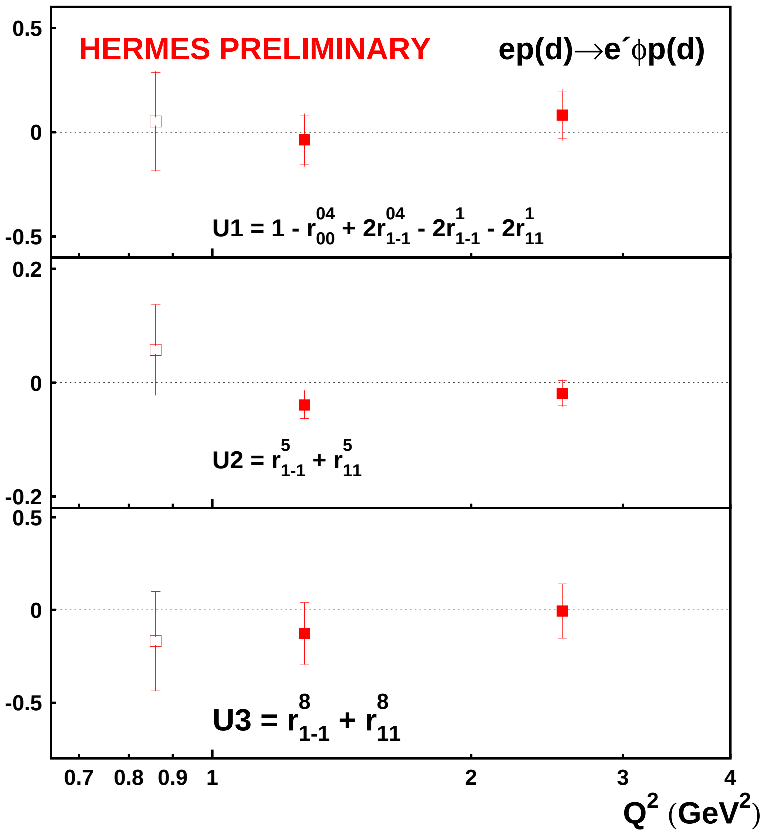
  $u_1 = 0.125 \pm 0.021_{stat} \pm 0.050_{sys}$

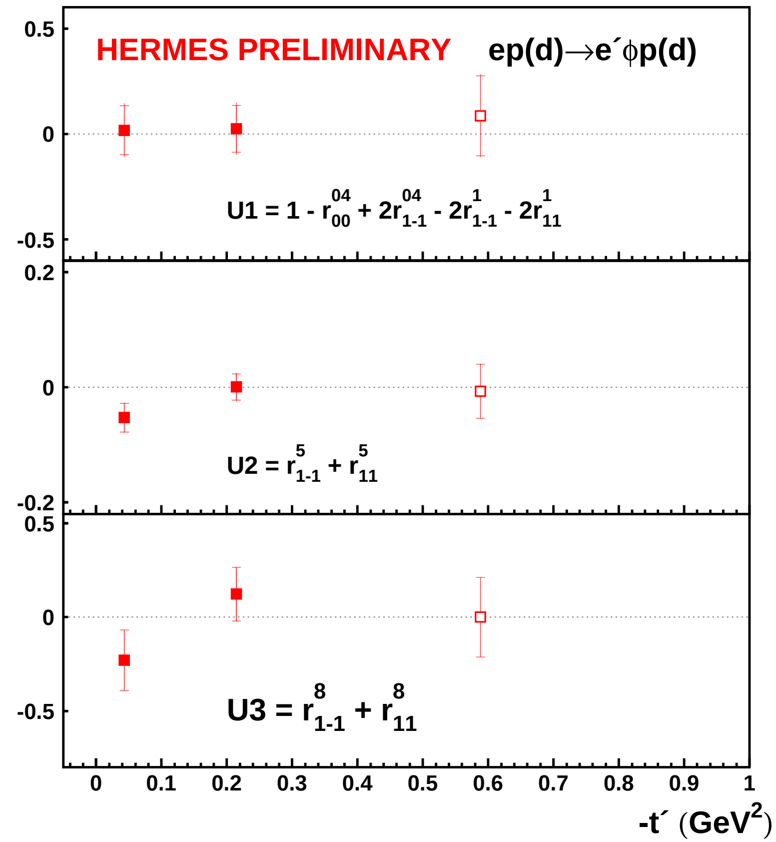
- deuteron:

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

UPE contribution is W-dependent

ϕ: observation of unnatural-parity exchange

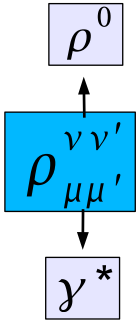




- $u_1 = 0.02 \pm 0.07_{stat} \pm 0.16_{sys}$
- $u_2 = -0.03 \pm 0.01_{stat} \pm 0.03_{sys}$
- $u_3 = -0.05 \pm 0.12_{stat} \pm 0.07_{sys}$
- no signal of unnatural-parity exchange

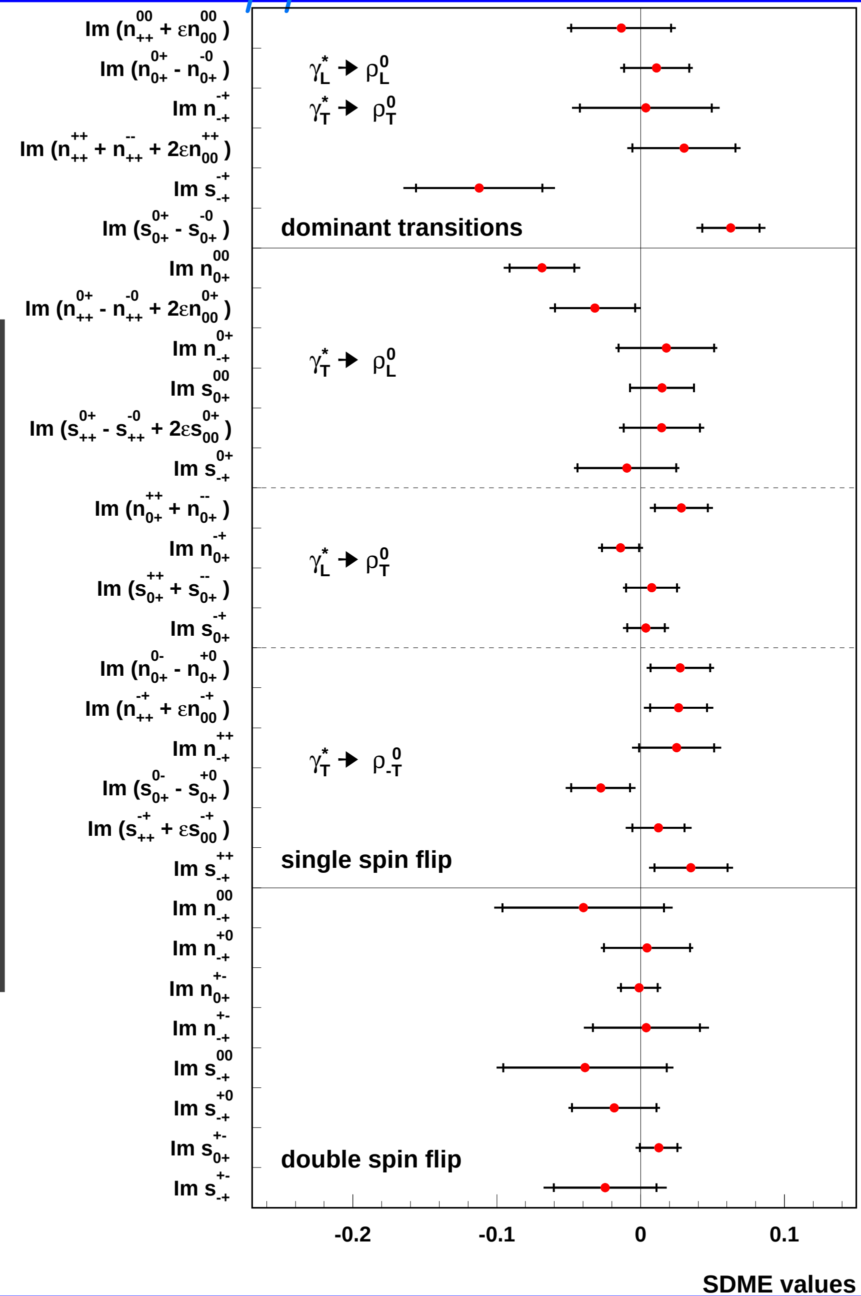
expected since dominant contribution to the production is from two gluon exchange

'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 $\sqrt{-t}/2M_p$



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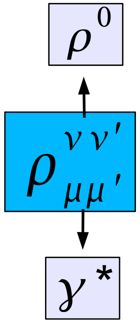


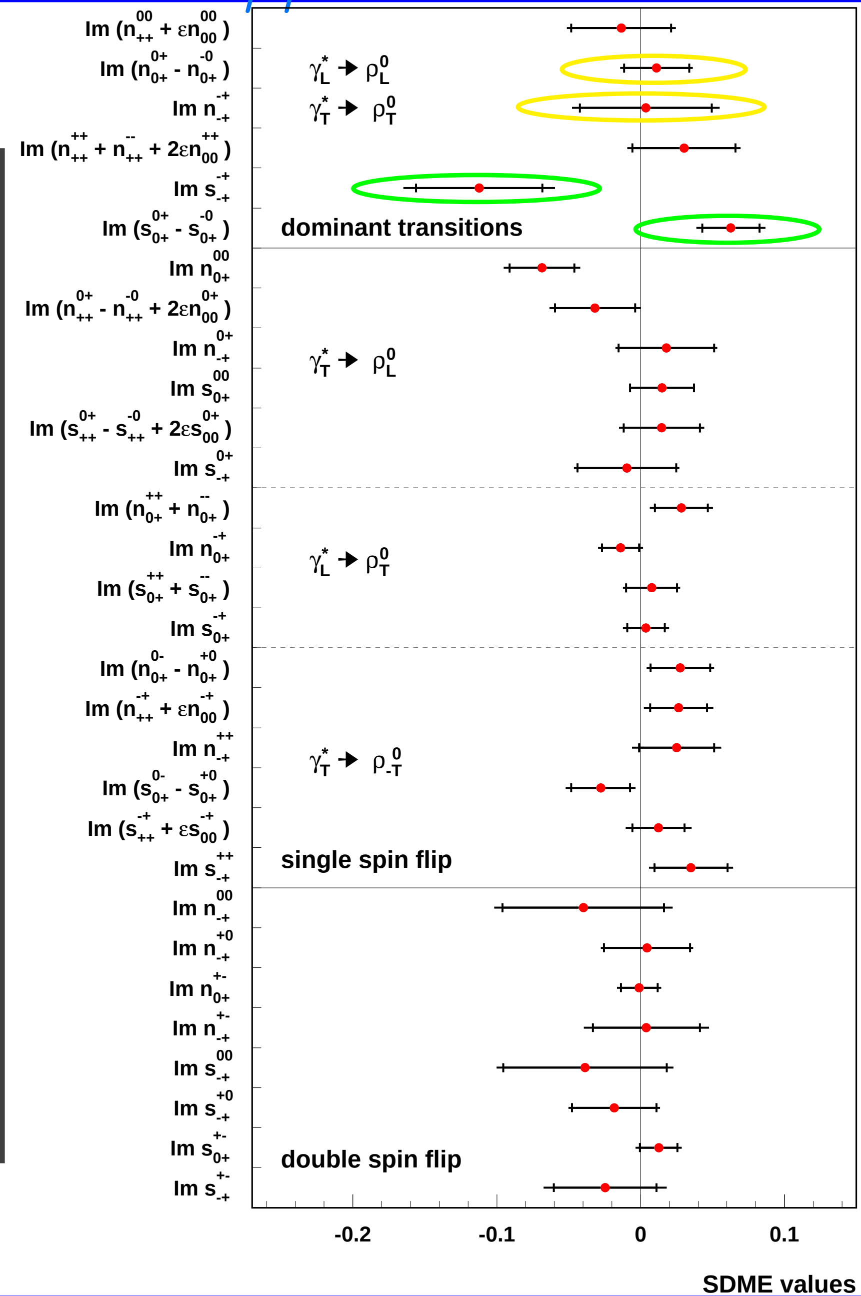
-HERMES Collaboration: arXiv:0906.5160 (2009)-

$\gamma^*_L \to \rho^0_L$ 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 $\widetilde{E}$



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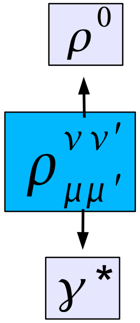


-HERMES Collaboration: arXiv:0906.5160 (2009)-

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

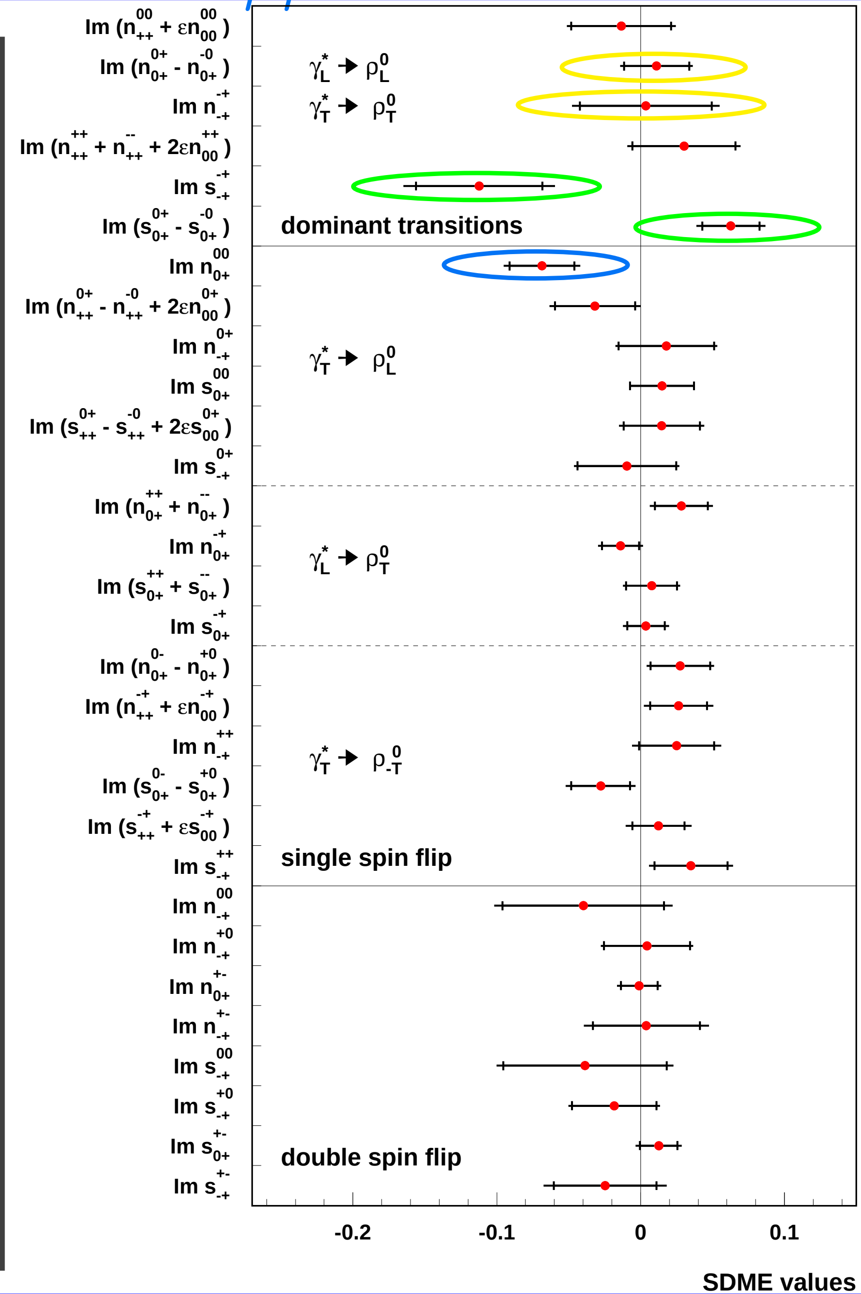
- $\mathrm{Im}\, s^{-+}_{-+}$ and $\mathrm{Im}(s^{0+}_{0+} - s^{-0}_{0+})$: deviate from 0 by 2.5σ
- expected $s^{\nu\nu'}_{\mu\mu'} < n^{\nu\nu'}_{\mu\mu'}$ (if identical indices)
- s^{-+}_{-+} and $\mathrm{Im}\, s^{0+}_{0+}$ involve

  -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 $\widetilde{E}$

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

- $\mathrm{Im}\, n^{00}_{0+}$: 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

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

  - 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:

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

- u_{++}^{00} and n_{++}^{00} are expected to be negligible
- similarly, $\gamma_T^* \rightarrow \rho_T^0$:

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

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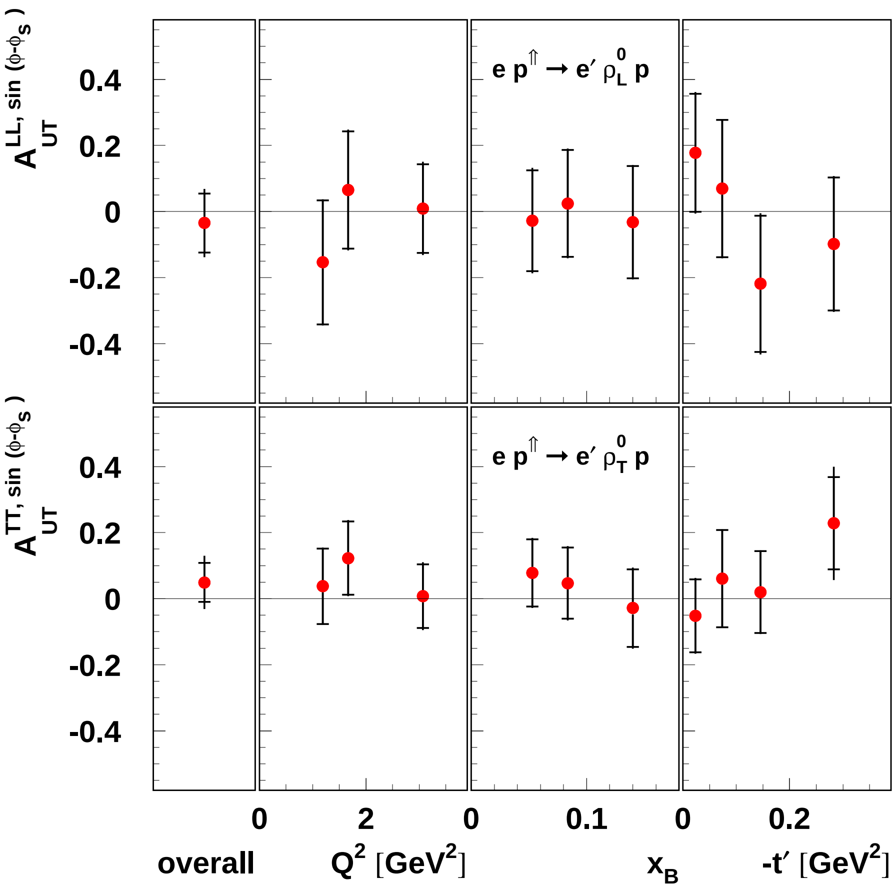
-HERMES Collaboration: arXiv:0906.5160 (2009)-



compatible with 0 overall value:

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

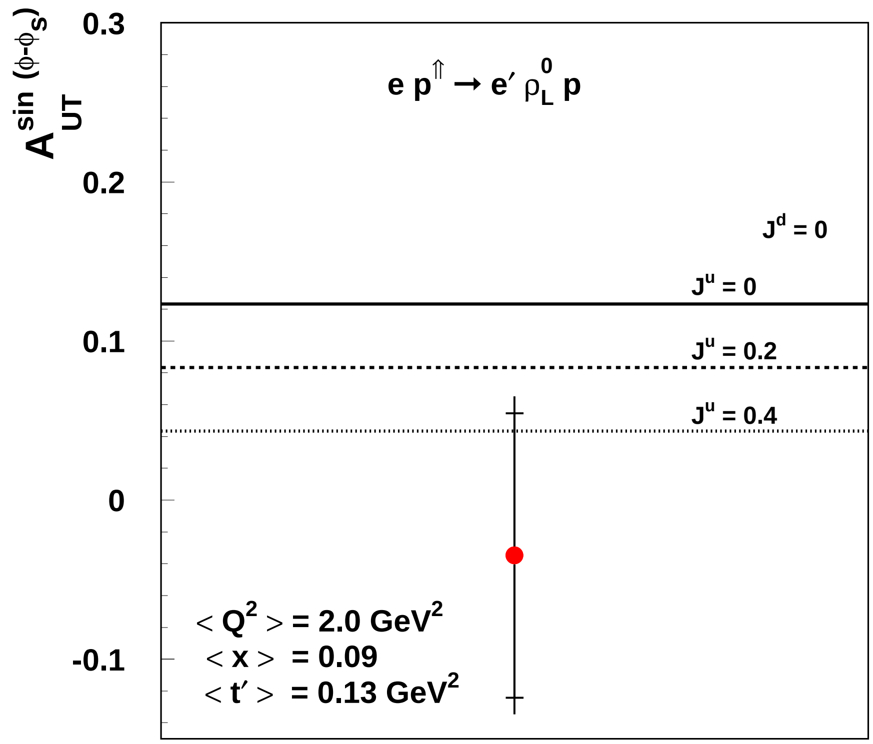
ρ^0: comparison with GPD models

- 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

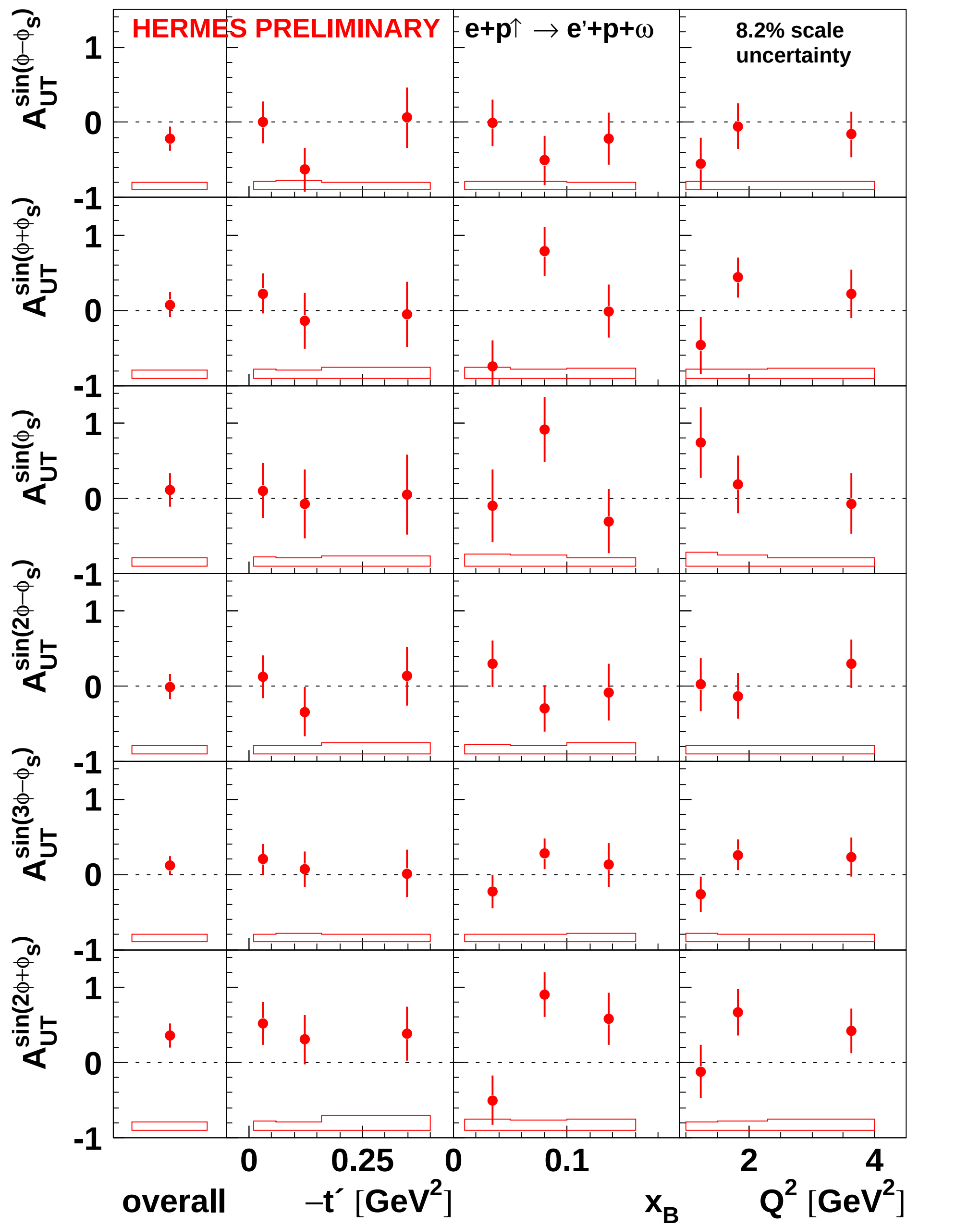
- Goeke, Polyakov, Vanderhaeghen (1999)-

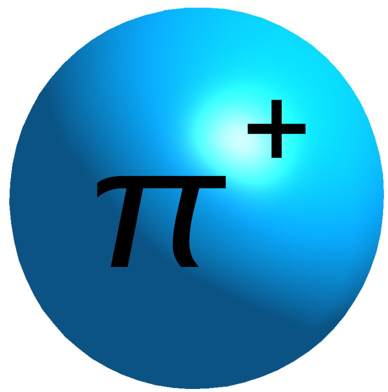
-Goloskokov, Kroll (2007)-

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



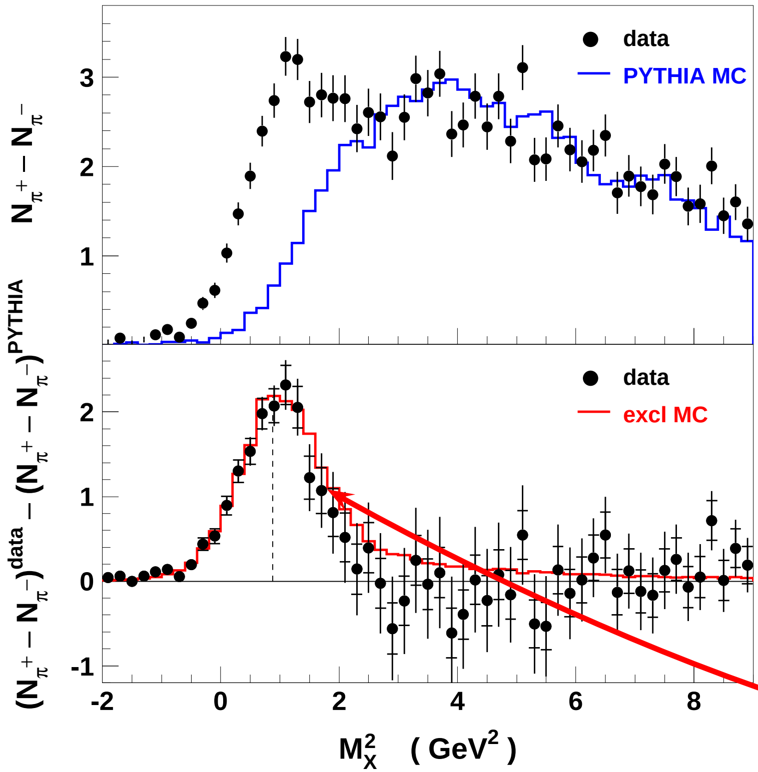

π+

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

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

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

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

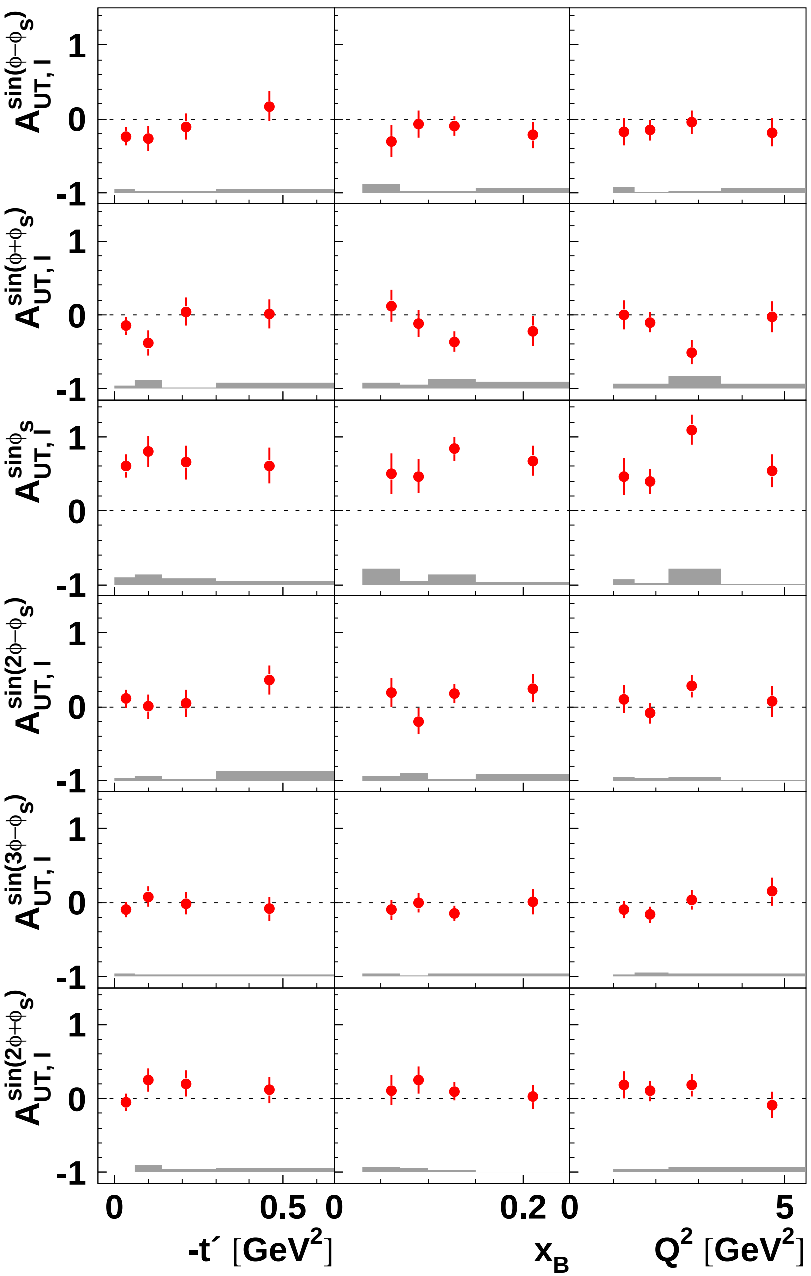


-HERMES collaboration arXiv:0707.0222 (2007)-

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 $A_{UT}^{\pi^+}$

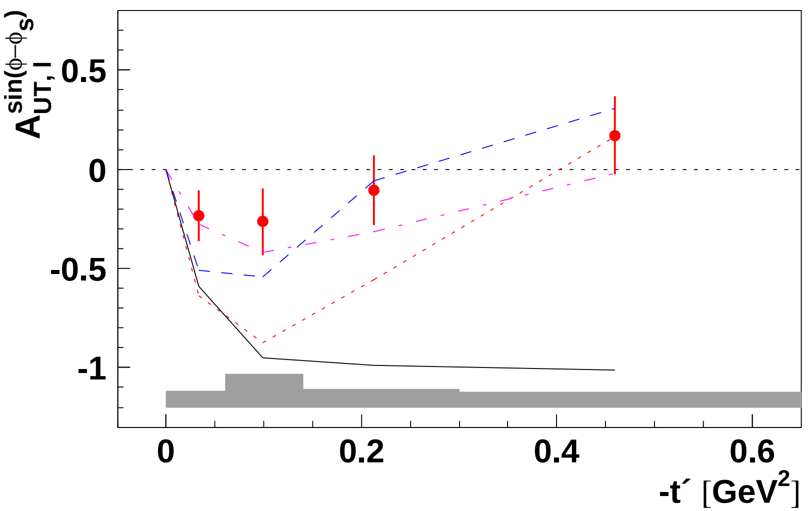
leading azimuthal amplitude $A_{UT}^{\sin(\phi-\phi_s)}$

- 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)-

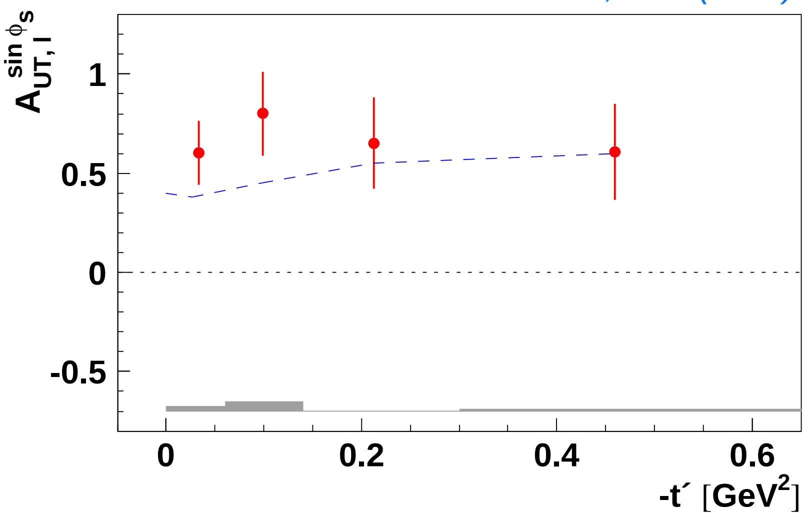
  -Bechler, Muller (2009)-



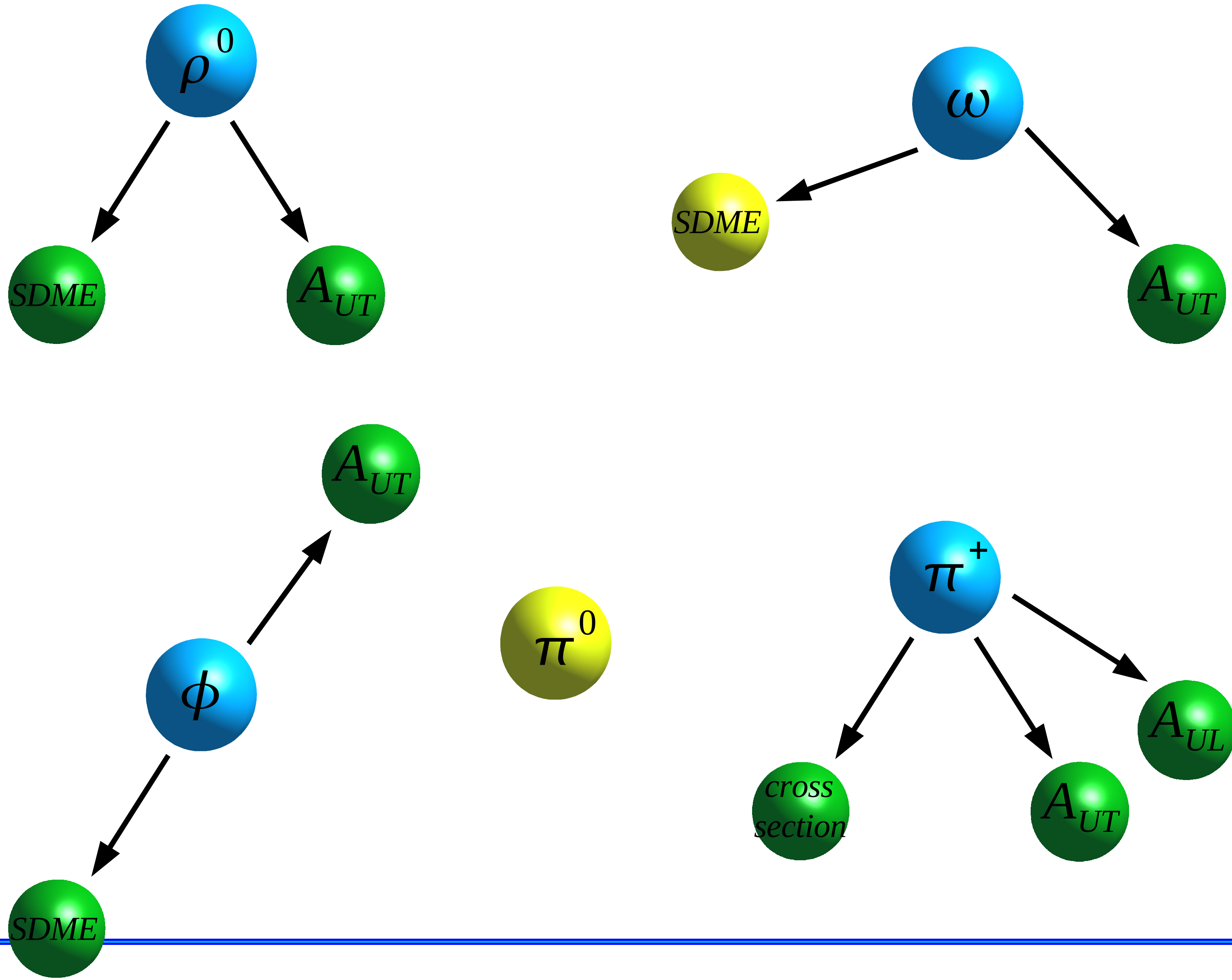
azimuthal amplitude $A_{UT}^{\sin\phi_s}$

- 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)-



HERMES and GPDs



ρ^0: observation of unnatural-parity exchange

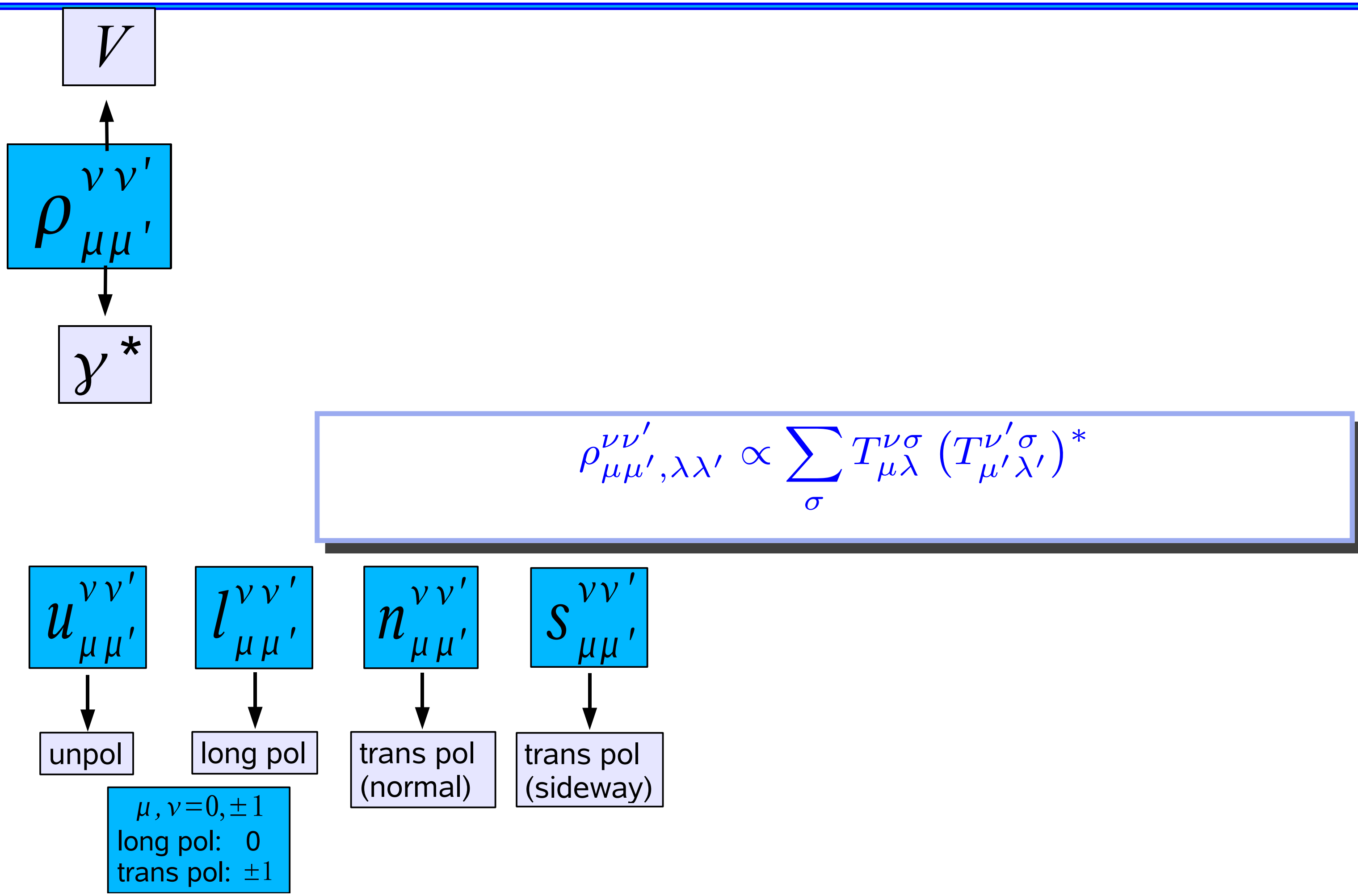
- UPE contributions measured from SDMEs:

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

- 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:



$$\rho^{\nu\nu'}_{\mu\mu',\lambda\lambda'} \propto \sum_{\sigma} T^{\nu\sigma}_{\mu\lambda} \left(T^{\nu'\sigma}_{\mu'\lambda'}\right)^*$$