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Spin Density Matrix Elements (SDMEs) and Helicity Amplitude Ratios in Exclusive ρ^0 Electroproduction at

hermes

- Physics motivation
- ρ^0 SDMEs on unpolarized p and d data
  - Validity of S-channel helicity conservation approximation
  - Longitudinal-to-transverse cross-section ratios
  - Unnatural parity exchange
- Direct extraction of helicity amplitude ratios on unpolarized p and d data
- SDMEs and asymmetries on transversely polarized p data
- Summary

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Amplitudes and Spin Density Matrices for $e + N \to e' + \rho^0 + N$

1. $e \to e + \gamma^*$ (QED)

Spin-density matrix of the virtual photon is known: $\varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma} = \varrho^{U}_{\lambda_\gamma \lambda'_\gamma} + P_{beam}\, \varrho^{L}_{\lambda_\gamma \lambda'_\gamma},$

$$\varrho^{U}_{\lambda_\gamma \lambda'_\gamma}(\epsilon,\Phi) = \frac{1}{2}\begin{pmatrix} 1 & \sqrt{\epsilon(1+\epsilon)}e^{-i\Phi} & -\epsilon e^{-2i\Phi} \\ \sqrt{\epsilon(1+\epsilon)}e^{i\Phi} & 2\epsilon & -\sqrt{\epsilon(1+\epsilon)}e^{-i\Phi} \\ -\epsilon e^{2i\Phi} & -\sqrt{\epsilon(1+\epsilon)}e^{i\Phi} & 1 \end{pmatrix}, \varrho^{L}_{\lambda_\gamma \lambda'_\gamma}(\epsilon,\Phi) = \frac{\sqrt{1-\epsilon}}{2}\begin{pmatrix} \sqrt{1+\epsilon} & \sqrt{\epsilon}e^{-i\Phi} & 0 \\ \sqrt{\epsilon}e^{i\Phi} & 0 & \sqrt{\epsilon}e^{-i\Phi} \\ 0 & \sqrt{\epsilon}e^{i\Phi} & -\sqrt{1+\epsilon} \end{pmatrix}$$

2. $\gamma^* + N \to \rho^0 + N$ (QCD)

The spin density matrix $\rho_{\lambda_V \lambda'_V}$ of ρ^0 meson is related to $\varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma}$, through the von Neumann formula:

$$\rho_{\lambda_V \lambda'_V} = \frac{1}{2\mathcal{N}} \sum_{\lambda_\gamma \lambda'_\gamma \lambda_N \lambda'_N} F_{\lambda_V \lambda'_N;\lambda_\gamma \lambda_N}\, \varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma}\, F^*_{\lambda'_V \lambda'_N;\lambda'_\gamma \lambda_N},$$

where $F_{\lambda_V \lambda'_N;\lambda_\gamma \lambda_N}(W,Q^2,t') \equiv F_{\lambda_V \lambda_\gamma}$ are the helicity amplitude of the $\gamma^* N \to \rho^0 N$.

After decomposion of $\varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma}$ into the standard set of nine hermitian matrices Σ^α $(\alpha = 0,\ 1,\ \ldots,\ 8)$, without separation of transverse and longitudinal photons:

$$r^{04}_{\lambda_V \lambda'_V} = (\rho^0_{\lambda_V \lambda'_V} + \epsilon R \rho^4_{\lambda_V \lambda'_V})/(1+\epsilon R), \qquad r^{\alpha}_{\lambda_V \lambda'_V} = \begin{cases} \dfrac{\rho^\alpha_{\lambda_V \lambda'_V}}{(1+\epsilon R)}, & \alpha = 1,2,3, \\[2ex] \dfrac{\sqrt{R}\rho^\alpha_{\lambda_V \lambda'_V}}{(1+\epsilon R)}, & \alpha = 5,6,7,8. \end{cases}$$

On unpolarized target SDMEs are presented according K.Schilling and G.Wolf (Nucl. Phys. B61 (1973) 381), $\alpha = 04, 1 \div 3, 5 \div 8$ long. or trans. photon, $\lambda_\rho = -1, 0, 1$ - polarization of ρ^0.

3. $\rho^0 \;\Rightarrow\; \pi^+\pi^-$ (conservation of $\vec{J}$), $\quad |\rho^0; 1m > \to\ |\pi^+\pi^-; 1m > \Rightarrow\ Y_{1m}(\theta,\phi)$

General Properties of Amplitudes

- Total number of amplitudes.
  - Initial: 3 spin states of γ^* : $(\lambda_\gamma \equiv j = 1, 0, -1)$ and 2 nucleon helicities $(\lambda_N \equiv n = \frac{1}{2}, -\frac{1}{2})$,
    Final: the same for ρ^0: $(\lambda_\rho \equiv i)$ and nucleon $(\lambda'_N \equiv m)$ $\longrightarrow$ 36 amplitudes
  - Parity conservation: $T_{im;jn} = T_{-i-m;-j-n} \cdot (-1)^{i-j+m-n}$
    $\longrightarrow$ 18 independent amplitudes $T_{im;jn}$, 36 parameters to fit

- Natural-parity plus Unnatural-parity representation:
  $F_{\lambda_\rho \lambda_\gamma} = T_{\lambda_\rho \lambda_\gamma} + U_{\lambda_\rho \lambda_\gamma}$
  NPE: $T_{im;jn} = \frac{1}{2}\left[F_{im;jn} + (-1)^{i-j} \cdot F_{-im;-jn}\right]$, GPDs: no target spin-flip H, spin-flip E
  UPE: $U_{im;jn} = \frac{1}{2}\left[F_{im;jn} - (-1)^{i-j} \cdot F_{-im;-jn}\right]$, GPDs: no target spin-flip $\widetilde{H}$, spin-flip $\widetilde{E}$
  No interference between NPE and UPE contributions to SDMEs for unpolarized target (Schilling,Wolf,1978)
  $\longrightarrow$ 10 NPE plus 8 UPE amplitudes

- **On unpolarized target** contribution of NPE amplitudes with nucleon spin flip ($T_{\lambda_\rho -\frac{1}{2};\lambda_\gamma \frac{1}{2}}$ and $T_{\lambda_\rho \frac{1}{2};\lambda_\gamma -\frac{1}{2}}$) are to be neglected since no linear contributions to SDMEs.

  $\Longrightarrow$ Results to 5 NPE and 4 UPE amplitudes:
  - Five NPE amplitudes are T_{00}, $T_{11} = T_{-1-1}$, $T_{01} = -T_{0-1}$, $T_{10} = -T_{-10}$, $T_{1-1} = T_{-11}$
  - Four UPE amplitudes are $U_{11} = -U_{-1-1}$, $U_{01} = U_{0-1}$, $U_{10} = U_{-10}$, $U_{1-1} = -U_{-11}$, as $U_{00} \equiv 0$.

SDMEs versus Helicity Amplitudes

- SDMEs are measured experimentally at $2 < W < 100$ GeV (CLAS,HERMES,COMPASS,H1,ZEUS)
- calculated in GPD models from the helicity amplitudes, c.f. GK model for HERMES kinematics (S. V. Goloskokov and P. Kroll, Eur. Phys. J. C **59** (2009) 809; Eur. Phys. J. C **53** (2008) 367; Eur.Phys.J. C **50**,829 (2007); Eur.Phys.J. C **42**,281 (2005))

- Number of SDMEs depends on the beam and target polarization (M.Diehl, JHEP09 (2007) 064, arXiv:0704.1565v2)

Beam, Target	UU	UL	UT	LU	LL	LT
Number of SDMEs	15	14	30	8	10	18

U is denoted as Unpolarized, L as a Longitudinal and T as a Transverse polarization.

- Total number of fit parameters for amplitude ratios Re(Im)(F_{ij}/T_{00}) is 34. But due to the hierarchy, **nine** real parameters are extracted on unpolarized target instead of 23 $UU + LU$ SDMEs.

- In case of discrepancy between theoretical calculation and experimentally obtained SDME, it is not clear which particular amplitudes are not well predicted by a theoretical model.
- The SDMEs can be calculated from the extracted helicity amplitude ratios. The region of the directly extracted SDME values is greater than the region for SDME values calculated in the amplitudes.

$\Longrightarrow$ **The amplitude ratios are more advanced and representative than SDMEs!**

Transverse Target Polarization Asymmetry A_{UT} and/or UT-SDMEs

Goeke,Polyakov,Vanderhaeghen(2001): $A_{UT}^{\rho^0} \propto |S_T| \sin(\phi - \phi_s) E H$

$$A_{UT}(\phi, \phi_s) = \frac{\sigma_{UT}}{\sigma_{UU}} = \frac{[\sigma(\phi,\phi_S)-\sigma(\phi,\phi_S+\pi)]/P_T}{\int[\sigma(\phi,\phi_S)+\sigma(\phi,\phi_S+\pi)]d\phi/(2\pi)} \approx \frac{\sqrt{t_0-t}}{m_p} \frac{Im(E_V^* H_V)}{|H_V|^2} = \frac{\sqrt{t_0-t}}{m_p} \left|\frac{E_V}{H_V}\right| \sin\delta_V,$$

where $\delta_V = \arg(H_V/E_V)$, is relative phase between H_V and E_V

$\Longrightarrow$ Access to GPD function E which is sensitive to the angular momentum of quarks and gluons
Ji's sum rule: $J^a = \frac{1}{2}\int dx x[H^a(x,0,0) + E^a(x,0,0)]$, where $a = u,\ d,\ s$ quarks

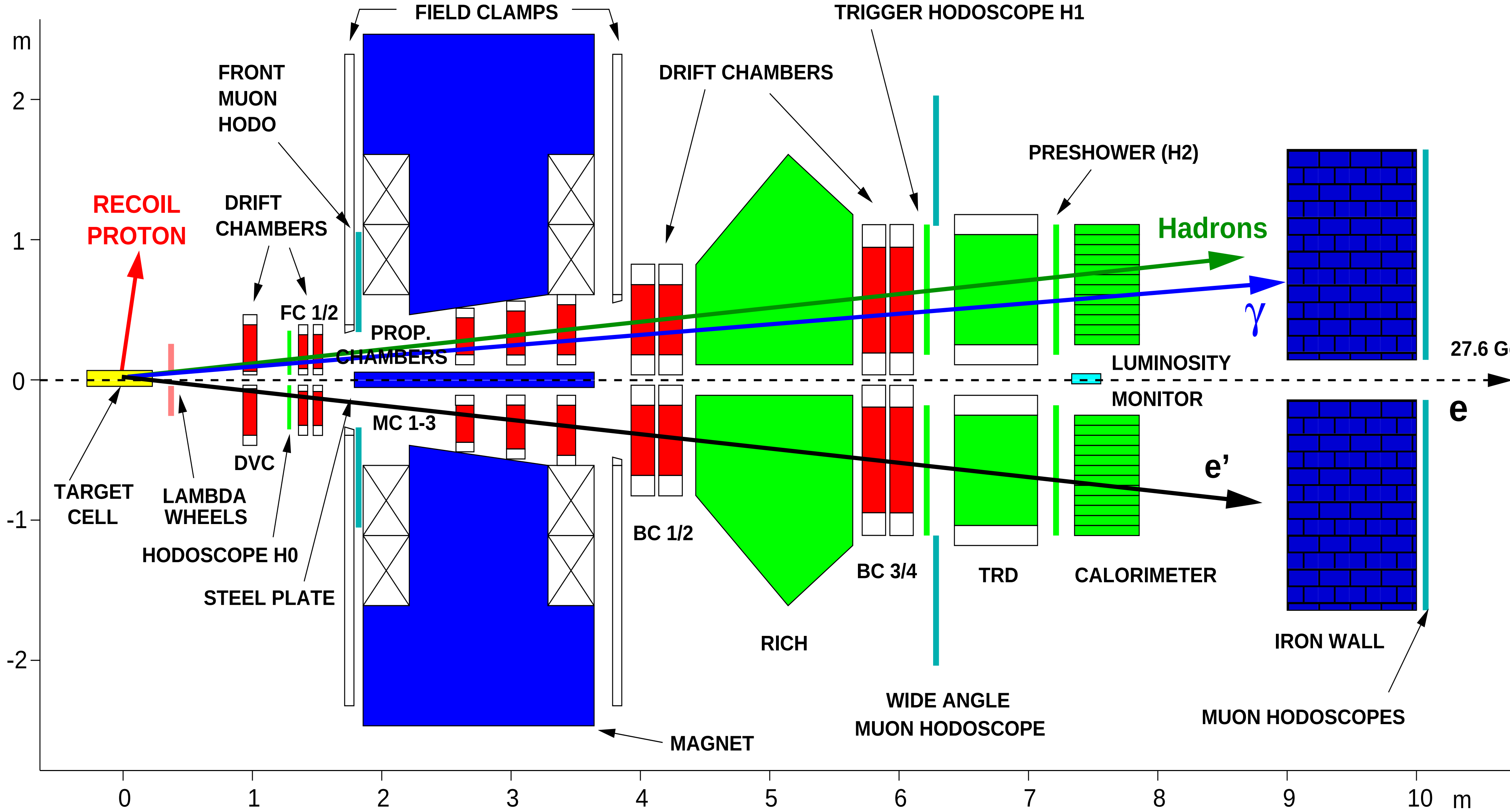
M.Diehl, S.Sapeta (Eur.Phys.J.C41:515-533,2005; arXiv:hep-ph/0503023): cross section decomposition in terms of 6 $\sin(m * \phi + n * \phi_s)$ moments, see talk of I.Hristova.
New formalism of SDMEs for L&T polarized targets (M.Diehl, JHEP09 (2007) 064, arXiv:0704.1565v2).

GPD based calculations of A_{UT}^V:

- M.Diehl, W.Kugler (Eur.Phys.J.C52:933-966,2007, arXiv:0708.1121, DESY-07-17) LO and NLO, at $Q^2 \geq 4$ GeV^2, $t = -0.4$ GeV^2, $V = \rho^0,\ \omega,\ \phi$
- D.Ivanov (arXiv:0712.3193, and HERMES seminar, DESY, 9.12.2008): stable results for a resummation of NLO amplitudes for vector mesons are presented for fixed target experiments only.
- S. V. Goloskokov, P. Kroll, (Eur. Phys. J. C 53(2008) 367; and arXiv:0809.4126) LO, at $W = 5$ GeV, $Q^2 \geq 3$ GeV^2, $0 < -t < 0.4$ GeV^2, i.e. at HERMES kinematic conditions, $V = \rho^0, \phi, \omega, \rho^+, K^{*0}$

$\Longrightarrow$ Comparison of HERMES data with the GPD based calculations

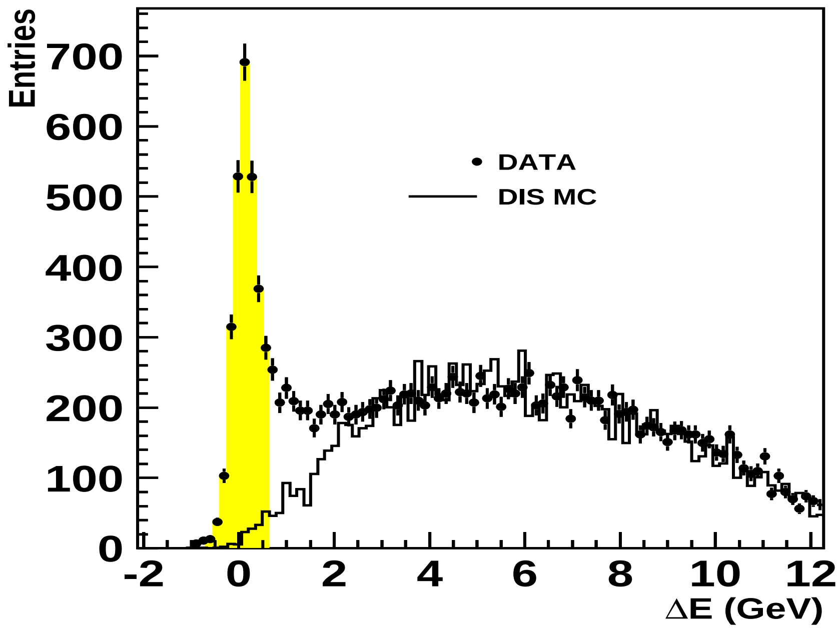
HERMES Detector *was* Two Identical Halves of Forward Spectrometer

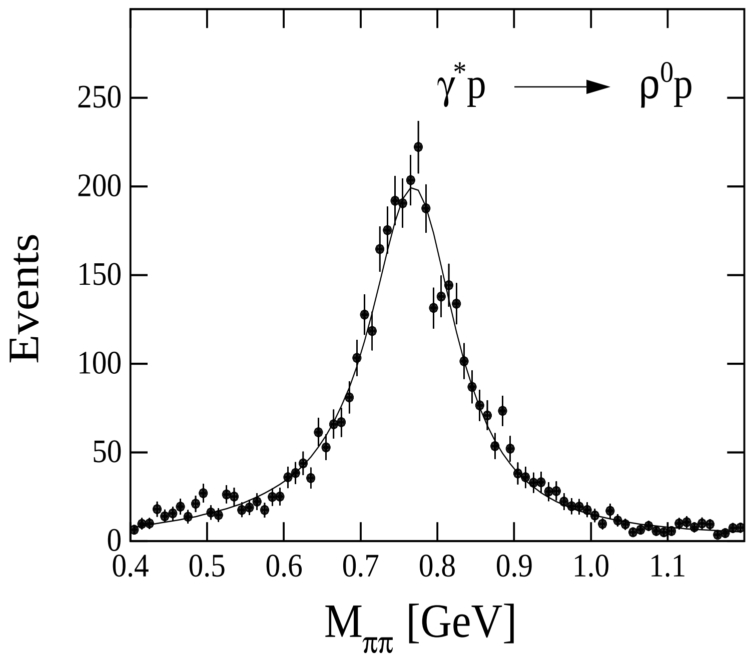


- $e^{\pm}$ beam, $P = 27.6$ GeV/c, longitudinal polarization $\sim 55\%$
- $\sim 80\%$ longitudinally, transversely polarized hydrogen, or unpolarized hydrogen or deuterium targets
- Acceptance: $40 < \Theta < 220$ mrad, $|\Theta_x| < 170$ mrad, $40 < |\Theta_y| < 140$ mrad
- Resolution: $\delta p/p \leq 1\%$, $\delta\Theta \leq 0.6$ mrad

Data on Exclusive ρ^0 Meson Production $e + p \to e' + p' + \rho^0 \to \pi^+\pi^-$

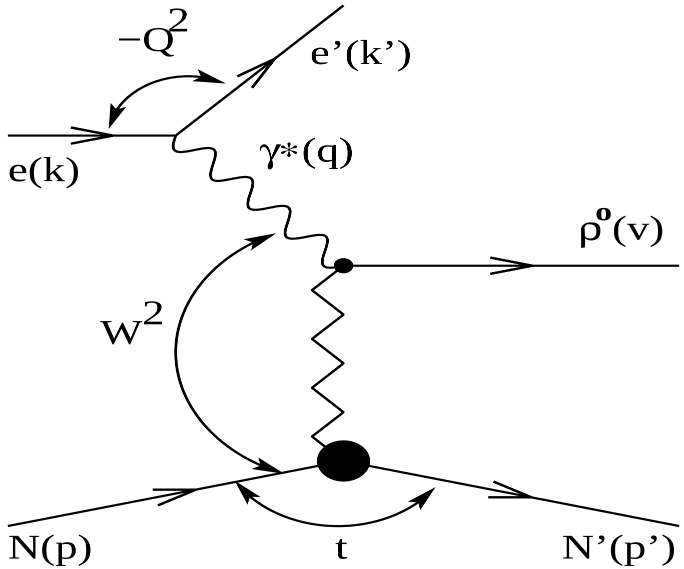
Clean exclusive peak of missing energy $\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$, background is subtracted using PYTHIA



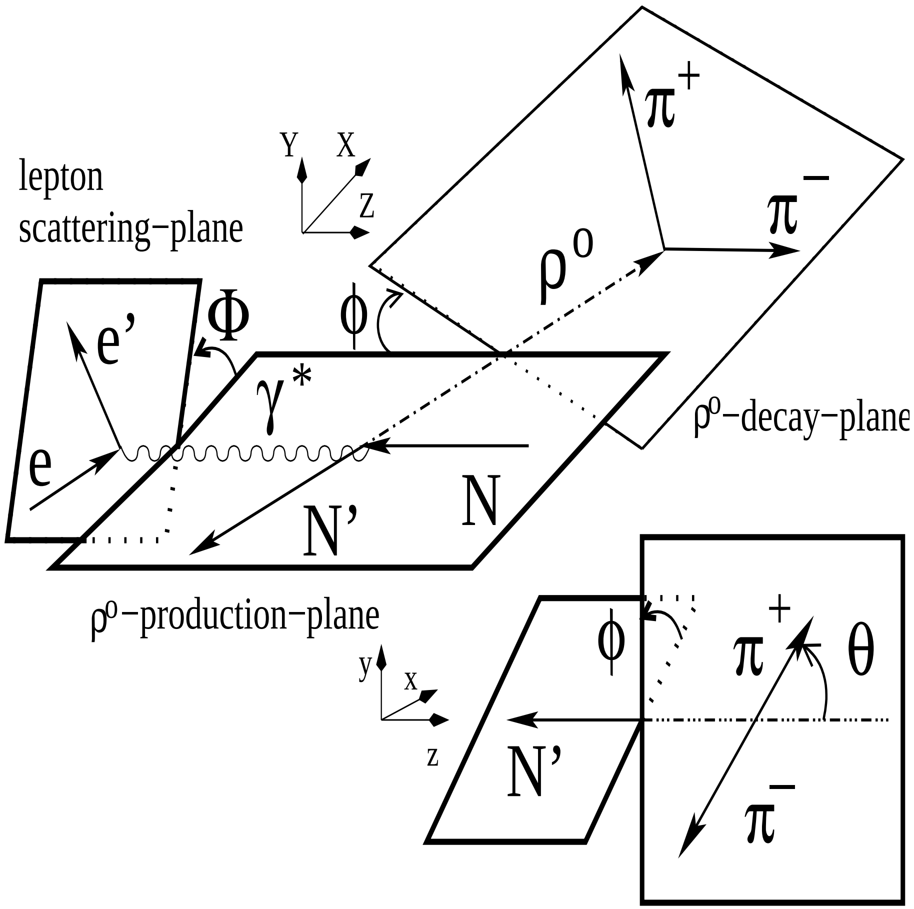


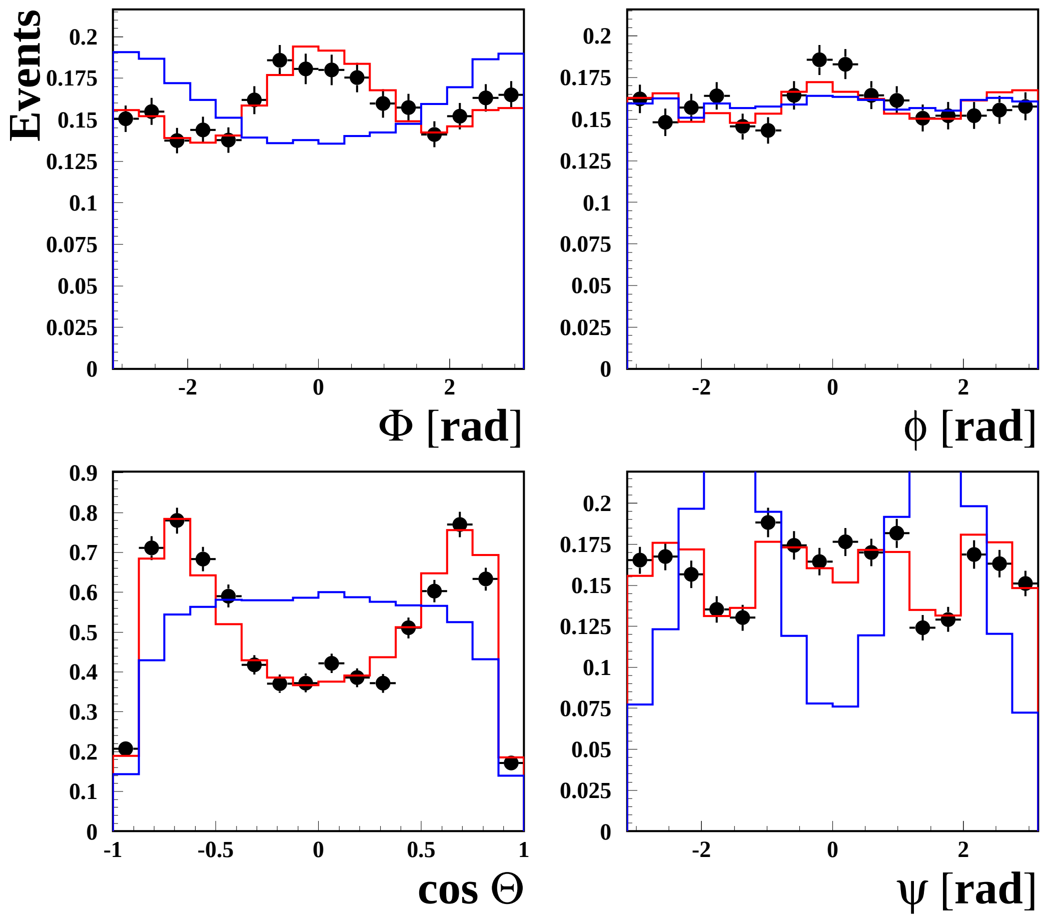
Kinematics:

- $Q^2 = 0.5 \div 7.0$ GeV^2, $\langle Q^2 \rangle = 2.3$ GeV^2
- $W = 3.0 \div 6.5$ GeV, $\langle W \rangle = 4.9$ GeV
- $x_{Bj} = 0.01 \div 0.35$, $\langle x_{Bj} \rangle = 0.07$
- $-t' = 0 \div 0.4$ GeV^2, $\langle -t' \rangle = 0.13$ GeV^2



Fit of Angular Distributions Using Max. Likelihood Method in MINUIT





Fit of 23 SDMEs after full detector simulation done using initial uniform angular distribution

- Binned Maximum Likelihood Method: $8 \times 8 \times 8$ bins of $\cos(\Theta), \phi, \Phi$.
- Simultaneous fit of 23 SDMEs: $r^{\alpha}_{ij} = W(\Phi, \phi, \cos\Theta)$for data with negative and positive beam helicity ($\langle|P_b|\rangle = 53.5\%$, $\Psi = \Phi - \phi$).
- 15 "unpolarized" plus, for the first time, 8 "polarized" SDMEs.

$\Longrightarrow$ **Full agreement of the fitted angular distributions with data**

Function for the Fit of 23 SDME r^{α}_{ij}

$$\mathrm{W}(\cos\Theta,\phi,\Phi) = W^{\mathrm{unpol}} + W^{\mathrm{long.pol}},$$

$$\mathrm{W}^{\mathrm{unpol}}(\cos\Theta,\phi,\Phi) = \frac{3}{8\pi^2}\Bigg[\frac{1}{2}(1 - r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00} - 1)\cos^2\Theta - \sqrt{2}\mathrm{Re}\{\mathrm{r}^{04}_{10}\}\sin 2\Theta\cos\phi -$$

$$\mathrm{r}^{04}_{1-1}\sin^2\Theta\cos 2\phi - \epsilon\cos 2\Phi\left(\mathrm{r}^{1}_{11}\sin^2\Theta + \mathrm{r}^{1}_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{\mathrm{r}^{1}_{10}\}\sin 2\Theta\cos\phi - \mathrm{r}^{1}_{1-1}\sin^2\Theta\cos 2\phi\right)$$

$$-\ \epsilon\sin 2\Phi\left(\sqrt{2}\mathrm{Im}\{\mathrm{r}^{2}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{\mathrm{r}^{2}_{1-1}\}\sin^2\Theta\sin 2\phi\right)$$

$$+\sqrt{2\epsilon(1+\epsilon)}\cos\Phi\left(\mathrm{r}^{5}_{11}\sin^2\Theta + \mathrm{r}^{5}_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{\mathrm{r}^{5}_{10}\}\sin 2\Theta\cos\phi - \mathrm{r}^{5}_{1-1}\sin^2\Theta\cos 2\phi\right)$$

$$+\sqrt{2\epsilon(1+\epsilon)}\sin\Phi\left(\sqrt{2}\mathrm{Im}\{\mathrm{r}^{6}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{\mathrm{r}^{6}_{1-1}\}\sin^2\Theta\sin 2\phi\right)\Bigg],$$

$$\mathrm{W}^{\mathrm{long.pol.}}(\cos\Theta,\phi,\Phi) = \frac{3}{8\pi^2}P_{\mathrm{beam}}\Bigg[\sqrt{1-\epsilon^2}\left(\sqrt{2}\mathrm{Im}\{\mathrm{r}^{3}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{\mathrm{r}^{3}_{1-1}\}\sin^2\Theta\sin 2\phi\right)$$

$$+\sqrt{2\epsilon(1-\epsilon)}\cos\Phi\left(\sqrt{2}\mathrm{Im}\{\mathrm{r}^{7}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{\mathrm{r}^{7}_{1-1}\}\sin^2\Theta\sin 2\phi\right)$$

$$+\sqrt{2\epsilon(1-\epsilon)}\sin\Phi\left(r^{8}_{11}\sin^2\Theta + r^{8}_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{\mathrm{r}^{8}_{10}\}\sin 2\Theta\cos\phi - \mathrm{r}^{8}_{1-1}\sin^2\Theta\cos 2\phi\right)\Bigg]$$

$\Longrightarrow$ **“Polarized” SDMEs are measurable with longitudinally polarized beam and** $\epsilon < 1$

ρ^0 SDMEs According to Hierarchy of Amplitudes with(out) Helicity Flip

- A, $\gamma^*_L \to \rho^0_L$ and $\gamma^*_T \to \rho^0_T$

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

- B, Interference: γ^*_L, ρ^0_T

  $Re\{T_{00}T^*_{11}\} \propto Re\ \{r^5_{10}\} \propto -Im\{r^6_{10}\}$

  $Im\{T_{11}T^*_{00}\} \propto Im\{r^7_{10}\} \propto Re\{r^8_{10}\}$

- C, Spin Flip: $\gamma^*_T \to \rho^0_L$

  $Re\{T_{11}T^*_{01}\} \propto Re\{r^{04}_{10}\} \propto Re\{r^1_{10}\} \propto Im\{r^2_{10}\}$

  $Re\{T_{01}T^*_{00}\} \propto r^5_{00}$

  $|T_{01}|^2 \propto r^1_{00}$

  $Im\{T_{01}T^*_{11}\} \propto Im\{r^3_{10}\}$

  $Im\{T_{01}T^*_{00}\} \propto r^8_{00}$

- D, Spin Flip: $\gamma^*_L \to \rho^0_T$

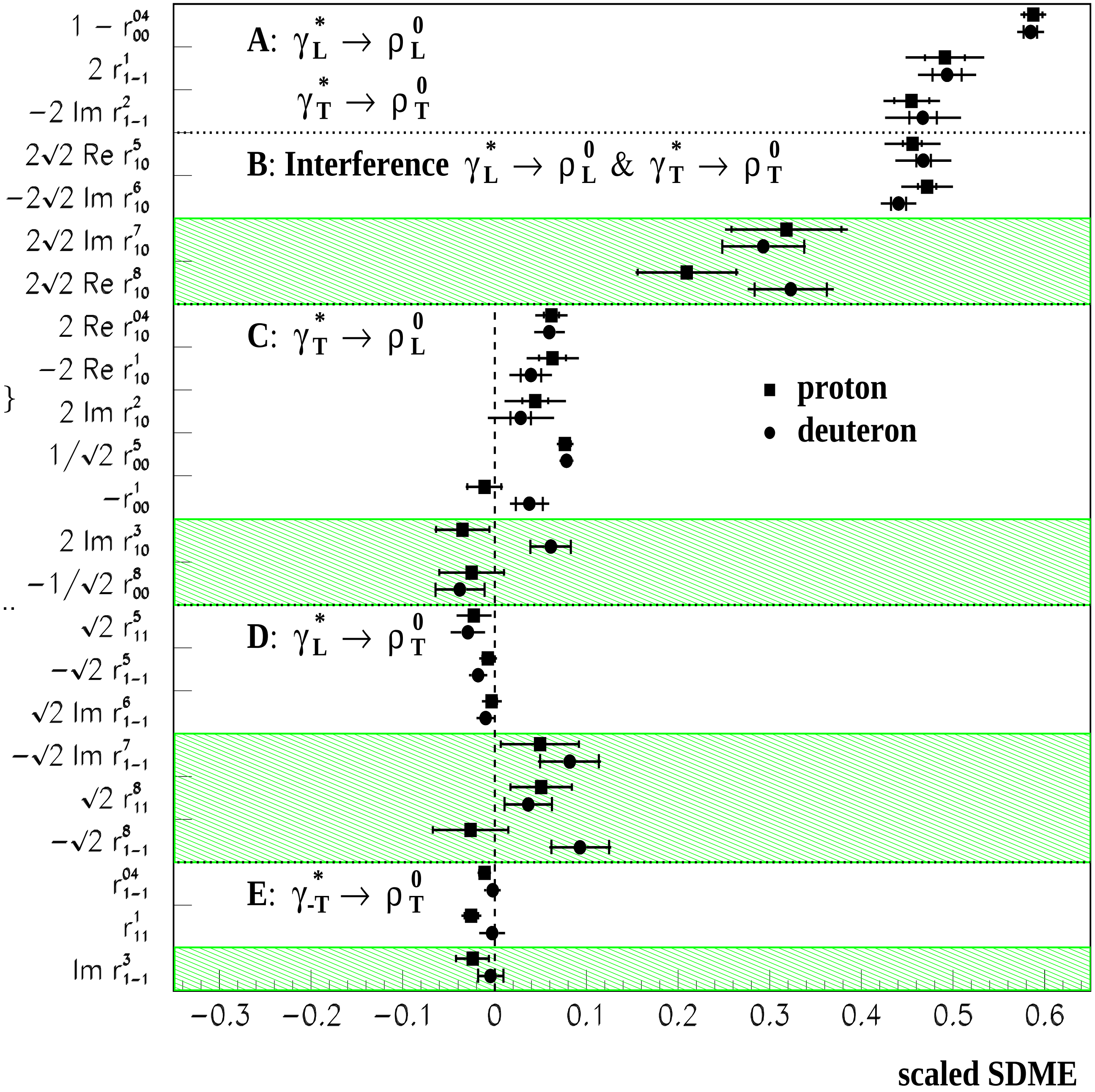
  $Re\{T_{10}T^*_{11}\} \propto r^5_{11} \propto r^5_{1-1} \propto Im\{r^6_{1-1}\}$

  $Im\{T_{10}T^*_{11}\} \propto Im\{r^7_{1-1}\} \propto r^8_{11} \propto r^8_{1-1}$

- E, Spin Flip: $\gamma^*_T \to \rho^0_{-T}$

  $Re\{T_{1-1}T^*_{11}\} \propto r^{04}_{1-1} \propto r^1_{11}$

  $Im\{T_{1-1}T^*_{11}\} \propto Im\{r^3_{1-1}\}$



$\Longrightarrow$ **Hierarchy of ρ^0 amplitudes:** $|T_{00}| \sim |T_{11}| \gg |T_{01}| > |T_{10}| \gtrsim |T_{1-1}|$, $(0 \to L, 1 \to T)$

(HERMES collab. EPJ C (in press); arXiv:0901.0701)

Observation of Unnatural Parity Exchange (UPE) in ρ^0 Leptoproduction

- Unnatural parity exchange is mediated by pseudoscalar or axial meson: $J^P = 0^-, 1^+$, e.g. π, a_1, b_1 $\longrightarrow$ only quark-exchange conribution

- No interference between NPE and UPE contributions on unpolarized target

- Extracted from SDMEs:

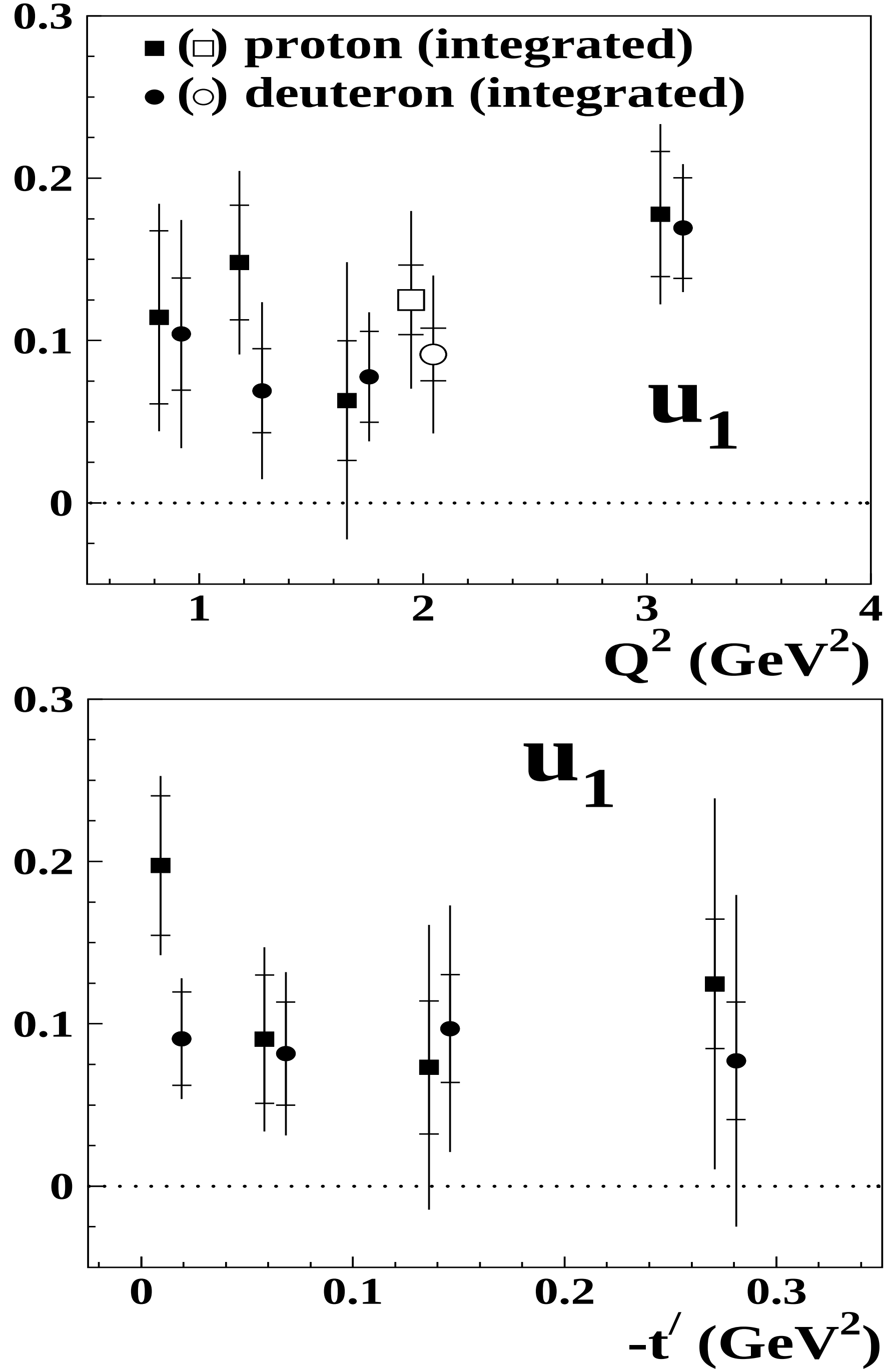
$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1}$$

$$u_1 \propto \epsilon|U_{10}|^2 + 2|U_{11} + U_{1-1}|^2 \approx 2|U_{11}|^2$$

p: $u_1 = 0.125 \pm 0.021_{stat} \pm 0.050_{syst}$

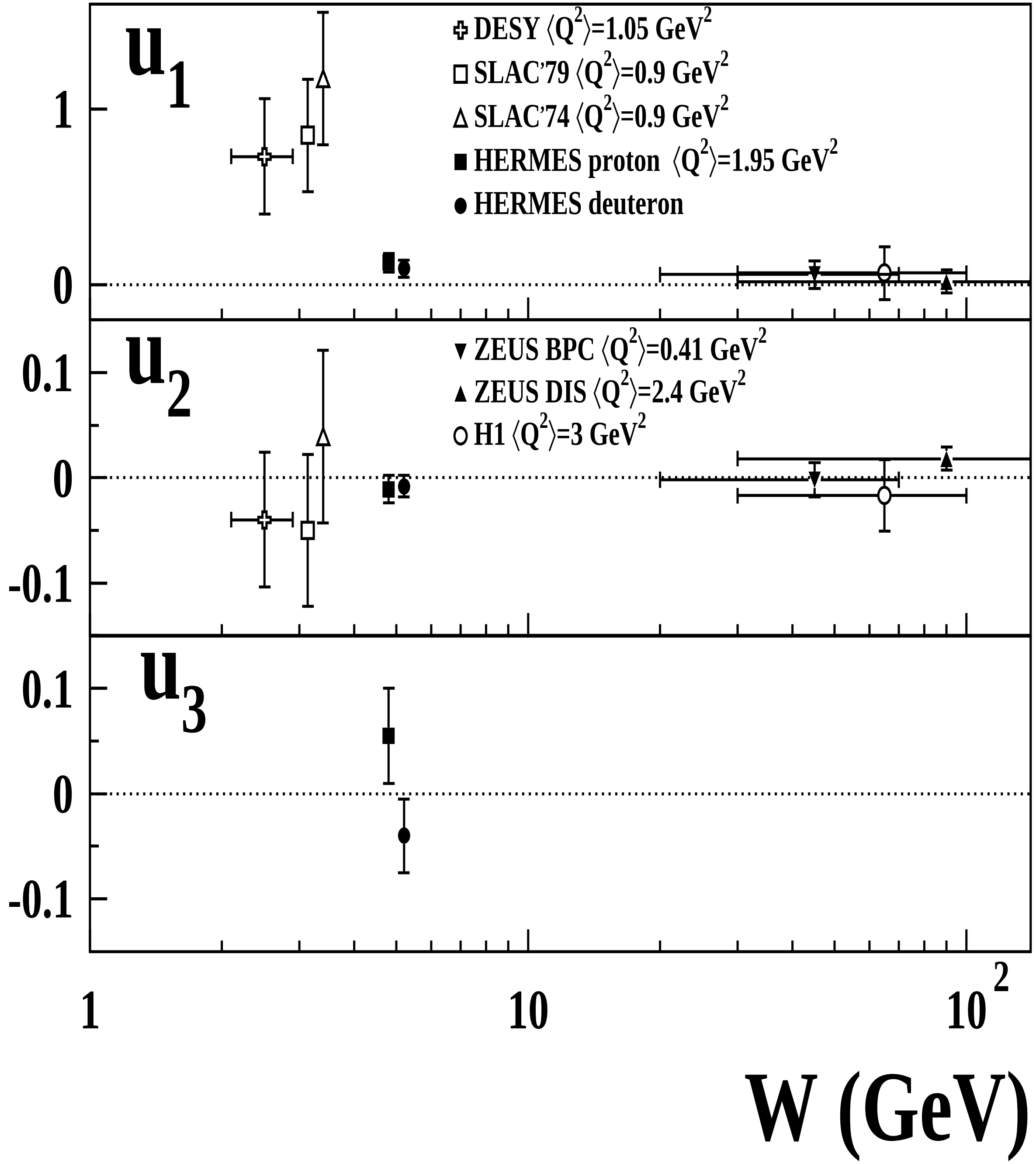
d: $u_1 = 0.091 \pm 0.016_{stat} \pm 0.046_{syst}$

p+d: $u_1 = 0.106 \pm 0.036$



$\Longrightarrow$ No Q^2 and t' dependences observed for u_1

World data on Unnatural Parity Exchange and Spin-Flip Contributions for ρ^0



- $\langle u_1^{\text{low}-W} \rangle = 0.70 \pm 0.16$

  $\Longrightarrow$ **W-dependence of u_1**

- $u_2 + i u_3 \propto (U_{11} + U_{1-1}) * U_{10}$

- $u_2 = r^5_{11} + r^5_{1-1}$
  p: $u_2 \approx -0.011 \pm 0.013$
  d: $u_2 \approx -0.008 \pm 0.011$

- $u_3 = r^8_{11} + r^8_{1-1}$
  p: $u_3 \approx 0.055 \pm 0.050$
  d: $u_3 \approx -0.040 \pm 0.040$

$\Longrightarrow$ **Indication on hierarchy of ρ^0 UPE amplitudes:**
$|U_{11}| \gg |U_{10}| \sim |U_{01}|$

ρ^0 Longitudinal-to-Transverse Cross-Section Ratio

Presented commonly measured $R^{04} = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}}$,

$$r^{04}_{00} = \sum\{\epsilon|T_{00}|^2 + |T_{01}|^2 + |U_{01}|^2\}/\sigma_{tot}$$

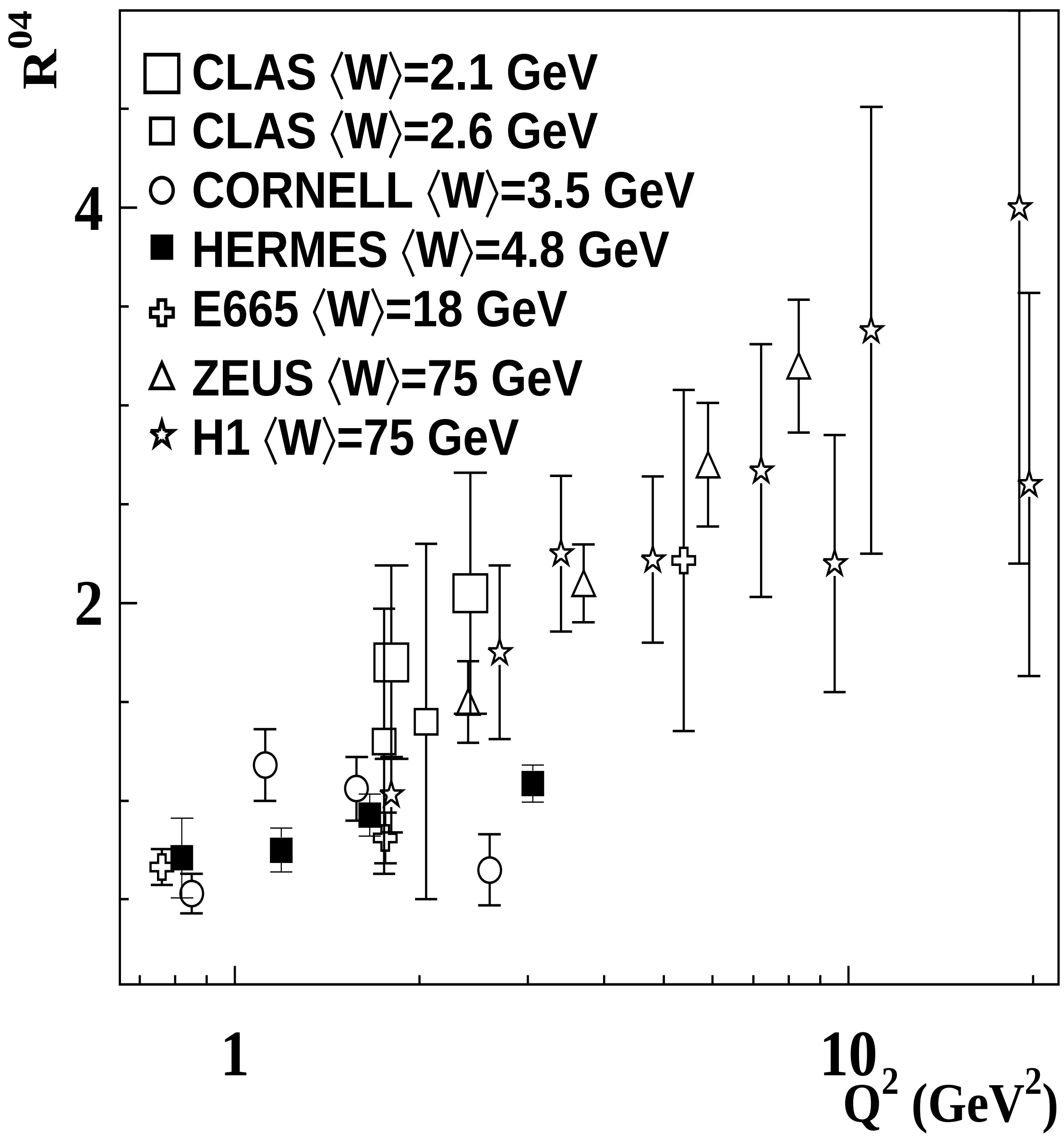
$$\sigma_{tot} = \epsilon\sigma_L + \sigma_T$$

$$\sigma_T = \sum\{|T_{11}|^2 + |T_{01}|^2 + |T_{1-1}|^2 + |U_{11}|^2\}$$

$$\sigma_L = \sum\{|T_{00}|^2 + 2|T_{10}|^2\}$$

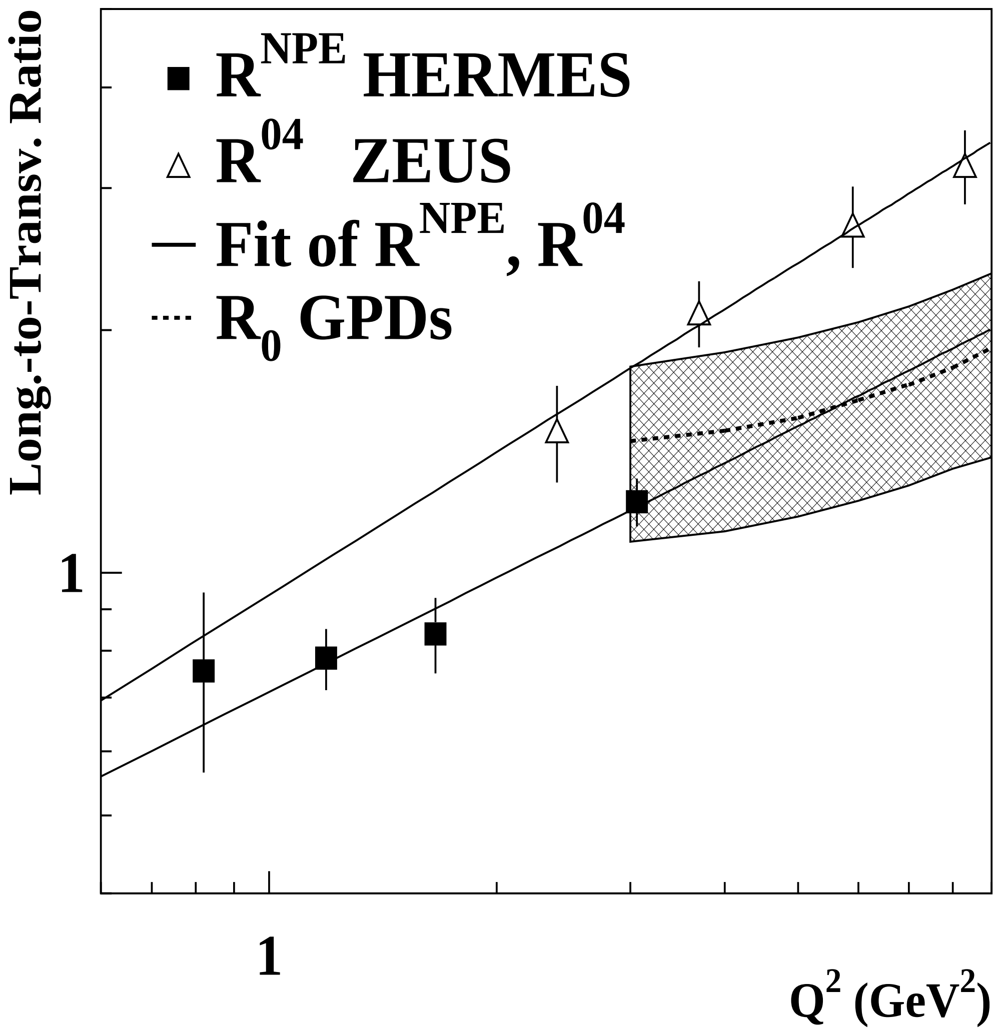
Due to the helicity-flip and unnatural parity amplitudes R^{04} depends on kinematic conditions, and is not identical to $R \equiv |T_{00}|^2/|T_{11}|^2$ for SCHC and NPE dominance.

$\Longrightarrow$ **HERMES ρ^0 data on R^{04} indicate R(W)-dependence**



(HERMES collab. EPJ C (in press); arXiv:0901.0701)

ρ^0 Longitudinal-to-Transverse Cross-Section Ratio



(HERMES collab. EPJ C (in press); arXiv:0901.0701)

$R_0 \equiv |T_{00}|^2/|T_{11}|^2$

without NPE contribution:
$R^{NPE} \approx R^{04}[1 + 0.5u_1(1 + \epsilon R^{04})]$

Fit of HERMES and ZEUS data:

$R(Q^2) = c_o(\frac{Q^2}{M_V^2})^{c_1}$

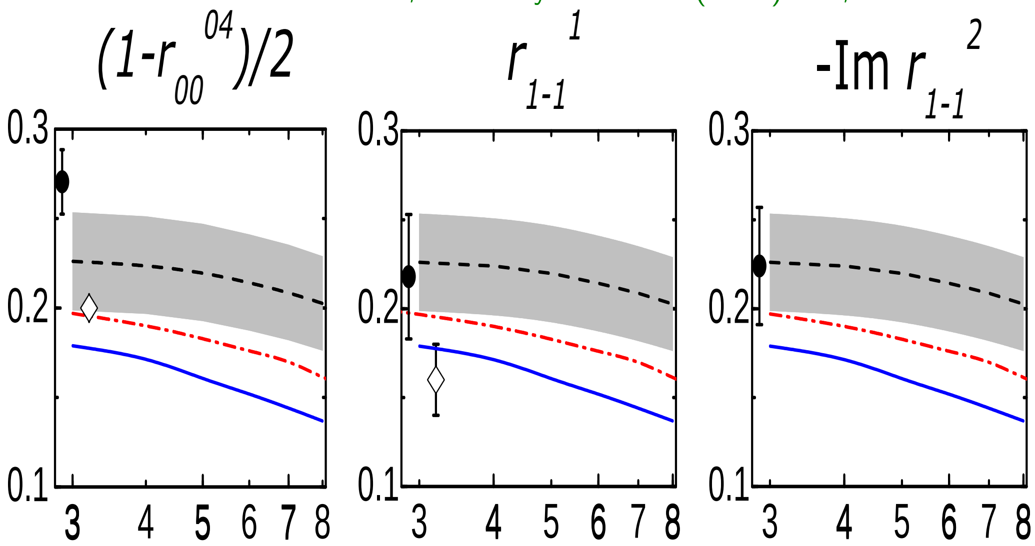
HERMES:
$c_0 = 0.56 \pm 0.08$, $c_1 = 0.47 \pm 0.12$, $\chi^2/d.o.f. = 0.45$

ZEUS:
$c_0 = 0.69 \pm 0.22$, $c_1 = 0.59 \pm 0.15$, $\chi^2/d.o.f. = 0.15$

$\Longrightarrow$ **W-dependence of c_0 and c_1**

ρ^0 SDMEs Compared to GK Model Calculations

S. V. Goloskokov and P. Kroll, Eur. Phys. J. C **53** (2008) 367;



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

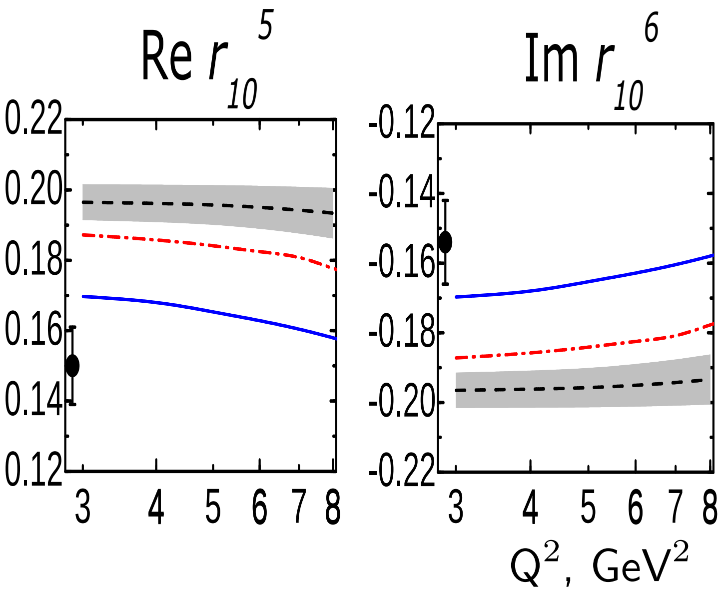
i.e. amplitudes for $\gamma^*_L \to \rho^0_L$, $\gamma^*_T \to \rho^0_T$

– W=90 GeV

– W=10 GeV, diamond: COMPASS

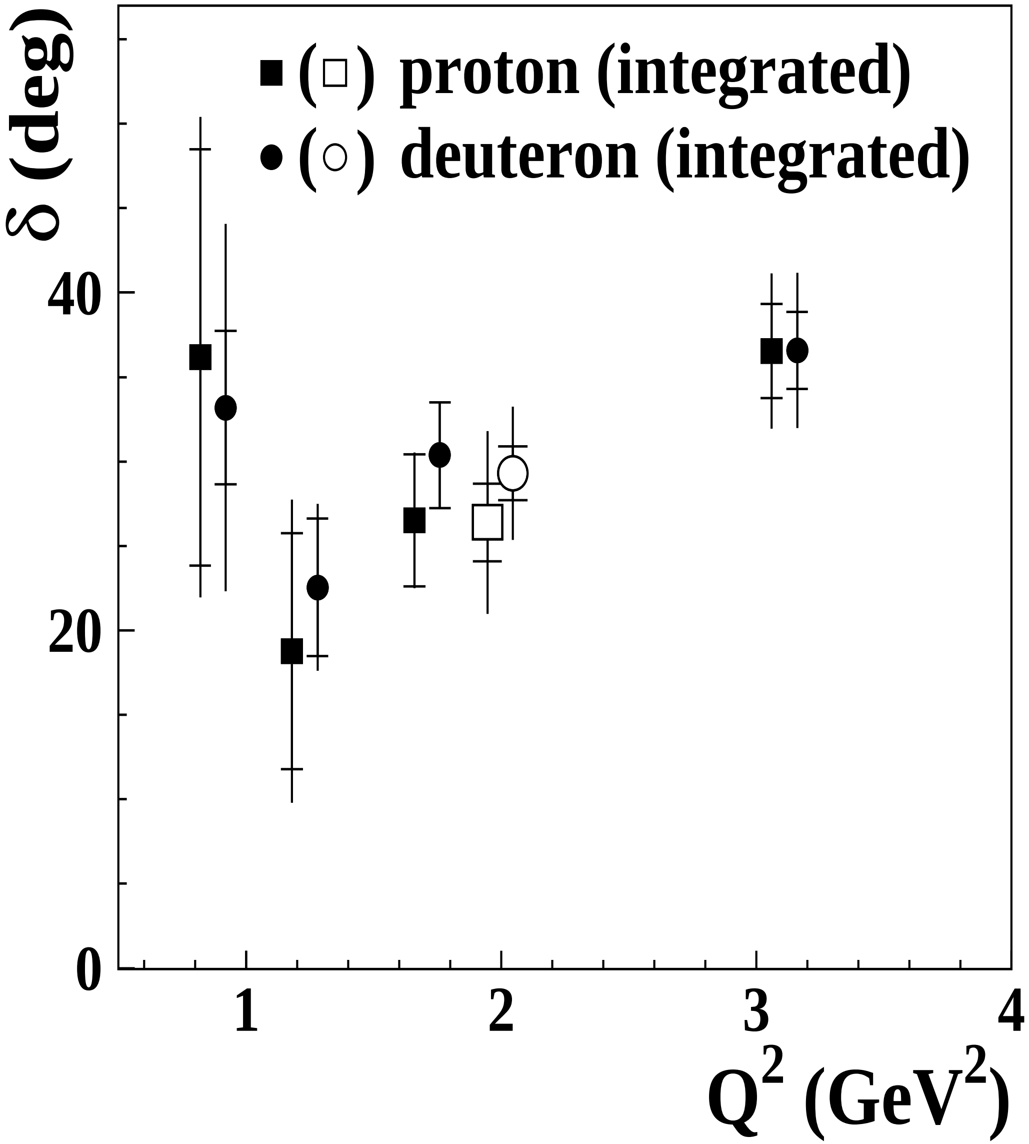
– W=5 GeV, circle: HERMES PRELIMINARY

$\Longrightarrow$ Fair agreement with data



Disagreement of calculations for SDMEs Re r^5_{10} and Im r^6_{10} corresponding to interference of γ^*_L, ρ^0_T amplitudes, i.e. phase difference between T_{11} and T_{00}

Phase Difference δ between T_{11} and T_{00} amplitudes



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

ρ^0 p: $\delta = 30.6 \pm 5.0_{stat} \pm 2.4_{syst}$ deg
ρ^0 d: $\delta = 36.3 \pm 3.9_{stat} \pm 1.7_{syst}$ deg

But in GK model $\delta = 3.1$ deg at W=5 GeV

$\Longrightarrow$ **Indication on Q^2 dependence of δ**

(HERMES collab. EPJ C (in press); arXiv:0901.0701)

Equations "SDMEs-from-Amplitudes"

A: $\gamma^*_L \longrightarrow \rho^0_L \mathrm{and} \gamma^*_T \longrightarrow \rho^0_T$

$r^{04}_{00} = \widetilde{\sum}\{\epsilon|T_{00}|^2 + |T_{01}|^2 + |U_{01}|^2/\}/N_{full}$,

$r^1_{1-1} = \frac{1}{2}\widetilde{\sum}\{|T_{11}|^2 + |T_{1-1}|^2 - |U_{11}|^2 - |U_{1-1}|^2\}/N_{full}$,

$\mathrm{Im}\{r^2_{1-1}\} = \frac{1}{2}\widetilde{\sum}\{-|T_{11}|^2 + |T_{1-1}|^2 + |U_{11}|^2 - |U_{1-1}|^2\}/N_{full}$,

B :interferenceof $\gamma^*_L \longrightarrow \rho^0_L \mathrm{and} \gamma^*_T \longrightarrow \rho^0_T$

$\mathrm{Re}\{r^5_{10}\} = \frac{1}{\sqrt{8}}\widetilde{\sum}\mathrm{Re}\{2T_{10}T^*_{01} + (T_{11} - T_{1-1})T^*_{00}\}/N_{full}$,

$\mathrm{Im}\{r^6_{10}\} = \frac{1}{\sqrt{8}}\widetilde{\sum}\mathrm{Re}\{2U_{10}U^*_{01} - (T_{11} + T_{1-1})T^*_{00}\}/N_{full}$,

$\mathrm{Im}\{r^7_{10}\} = \frac{1}{\sqrt{8}}\widetilde{\sum}\mathrm{Im}\{2U_{10}U^*_{01} + (T_{11} + T_{1-1})T^*_{00}\}/N_{full}$,

$\mathrm{Re}\{r^8_{10}\} = \frac{1}{\sqrt{8}}\widetilde{\sum}\mathrm{Im}\{-2T_{10}T^*_{01} + (T_{11} - T_{1-1})T^*_{00}\}/N_{full}$,

C :$\gamma^*_T \longrightarrow \rho^0_L$

$\mathrm{Re}\{r^{04}_{10}\} = \widetilde{\sum}\mathrm{Re}\{\epsilon T_{10}T^*_{00} + \frac{1}{2}T_{01}(T_{11} - T_{1-1})^* + \frac{1}{2}U_{01}(U_{11} + U_{1-1})^*\}/N_{full}$,

$\mathrm{Re}\{r^1_{10}\} = \frac{1}{2}\widetilde{\sum}\mathrm{Re}\{-T_{01}(T_{11} - T_{1-1})^* + U_{01}(U_{11} + U_{1-1})^*\}/N_{full}$,

$\mathrm{Im}\{r^2_{10}\} = \frac{1}{2}\widetilde{\sum}\mathrm{Re}\{T_{01}(T_{11} + T_{1-1})^* - U_{01}(U_{11} - U_{1-1})^*\}/N_{full}$,

$r^5_{00} = \sqrt{2}\widetilde{\sum}\mathrm{Re}\{T_{01}T^*_{00}\}/N_{full}$,

$r^1_{00} = \widetilde{\sum}\{-|T_{01}|^2 + |U_{01}|^2\}/N_{full}$,

$\mathrm{Im}\{r^3_{10}\} = -\frac{1}{2}\widetilde{\sum}\mathrm{Im}\{T_{01}(T_{11} + T_{1-1})^* + U_{01}(U_{11} - U_{1-1})^*\}/N_{full}$,

$r^8_{00} = \sqrt{2}\widetilde{\sum}\mathrm{Im}\{T_{01}T^*_{00}\}/N_{full}$,

D :$\gamma^*_L \longrightarrow \rho^0_T$

$r^5_{11} = \frac{1}{\sqrt{2}}\widetilde{\sum}\mathrm{Re}\{T_{10}(T_{11} - T_{1-1})^* + U_{10}(U_{11} - U_{1-1})^*\}/N_{full}$,

$r^5_{1-1} = \frac{1}{\sqrt{2}}\widetilde{\sum}\mathrm{Re}\{-T_{10}(T_{11} - T_{1-1})^* + U_{10}(U_{11} - U_{1-1})^*\}/N_{full}$,

$\mathrm{Im}\{r^6_{1-1}\} = \frac{1}{\sqrt{2}}\widetilde{\sum}\mathrm{Re}\{T_{10}(T_{11} + T_{1-1})^* - U_{10}(U_{11} + U_{1-1})^*\}/N_{full}$,

$\mathrm{Im}\{r^7_{1-1}\} = \frac{1}{\sqrt{2}}\widetilde{\sum}\mathrm{Im}\{T_{10}(T_{11} + T_{1-1})^* - U_{10}(U_{11} + U_{1-1})^*\}/N_{full}$,

$r^8_{11} = -\frac{1}{\sqrt{2}}\widetilde{\sum}\mathrm{Im}\{T_{10}(T_{11} - T_{1-1})^* + U_{10}(U_{11} - U_{1-1})^*\}/N_{full}$,

$r^8_{1-1} = \frac{1}{\sqrt{2}}\widetilde{\sum}\mathrm{Im}\{T_{10}(T_{11} - T_{1-1})^* - U_{10}(U_{11} - U_{1-1})^*\}/N_{full}$,

E :$\gamma^*_T \longrightarrow \rho^0_{-T}$

$r^{04}_{1-1} = \widetilde{\sum}\mathrm{Re}\{-\epsilon|T_{10}|^2 + \epsilon|U_{10}|^2 + T_{1-1}T^*_{11} - U_{1-1}U^*_{11}\}/N_{full}$,

$r^1_{11} = \widetilde{\sum}\mathrm{Re}\{T_{1-1}T^*_{11} + U_{1-1}U^*_{11}\}/N_{full}$,

$\mathrm{Im}\{r^3_{1-1}\} = -\widetilde{\sum}\mathrm{Im}\{T_{1-1}T^*_{11} - U_{1-1}U^*_{11}\}/N_{full}$,

where N_{full} is normalized total ρ^0 production cross section

Direct Extraction of Amplitude Ratios from Angular Distributions

- The SDMEs are expressed as the ratio of the sums of the bilinear products of helicity amplitudes.

- Dividing both the numerators and denominator of the equations "SDMEs-from-amplitudes" by $|T_{00}|^2$ formulas for the SDMEs expressed through the amplitude ratios.

- From the analysis of SDMEs, UPE SCHnC amplitudes are negligible: $U_{01} \approx U_{10} \approx U_{1-1} \approx 0$.

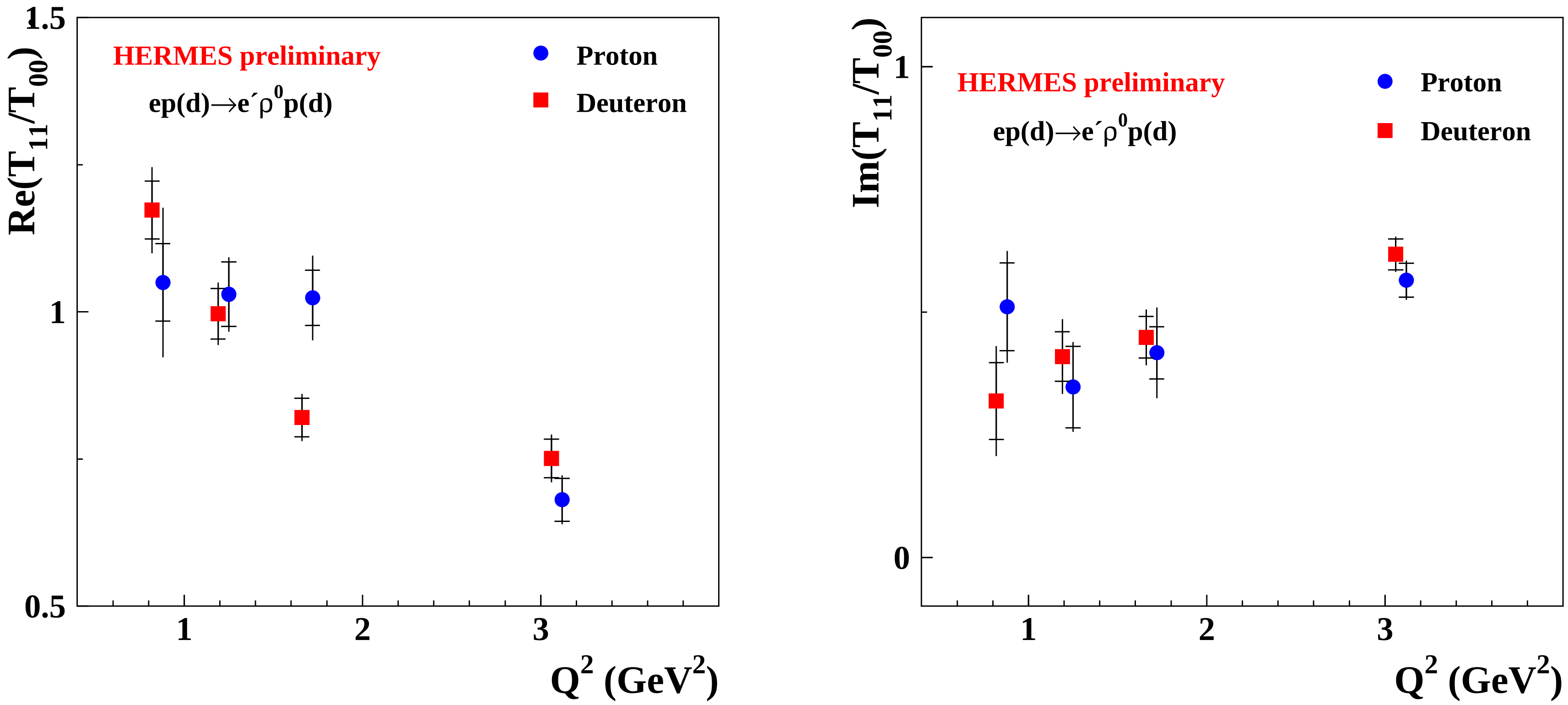
- Putting these expressions for the SDMEs into formulas "angular distributions-from-SDMEs" we fit the measured angular distribution considering **nine** amplitude ratios as free parameters:

$$A_1 = \mathrm{Re}\{\mathrm{T}_{11}/\mathrm{T}_{00}\}, \quad \mathrm{A}_2 = \mathrm{Im}\{\mathrm{T}_{11}/\mathrm{T}_{00}\},$$
$$A_3 = \mathrm{Re}\{\mathrm{T}_{01}/\mathrm{T}_{00}\}, \quad \mathrm{A}_4 = \mathrm{Im}\{\mathrm{T}_{01}/\mathrm{T}_{00}\},$$
$$A_5 = \mathrm{Re}\{\mathrm{T}_{10}/\mathrm{T}_{00}\}, \quad \mathrm{A}_6 = \mathrm{Im}\{\mathrm{T}_{10}/\mathrm{T}_{00}\},$$
$$A_7 = \mathrm{Re}\{\mathrm{T}_{1-1}/\mathrm{T}_{00}\}, \quad \mathrm{A}_8 = \mathrm{Im}\{\mathrm{T}_{1-1}/\mathrm{T}_{00}\},$$
$$A_9 = |U_{11}/T_{00}| \ ,$$

  where $|U_{11}|^2 = |U_{1\frac{1}{2};1\frac{1}{2}}|^2 + |U_{1\frac{1}{2};1-\frac{1}{2}}|^2$, i.e. UPE target-spin-flip amplitudes are not neglected.

- Q^2 and t'-dependences are studied $\longrightarrow$ 2-dimensional (Q^2, t') binning is used.
  Q^2 bins are the following: $0.5 \div 1.0 \div 1.4 \div 2.0 \div 7.0$ GeV^2,
  $-t'$ bins are: $0.0 \div 0.04 \div 0.10 \div 0.20 \div 0.40$ GeV^2.

Q^2 dependence of Amplitude Ratios Re(Im)(T_{11}/T_{00})

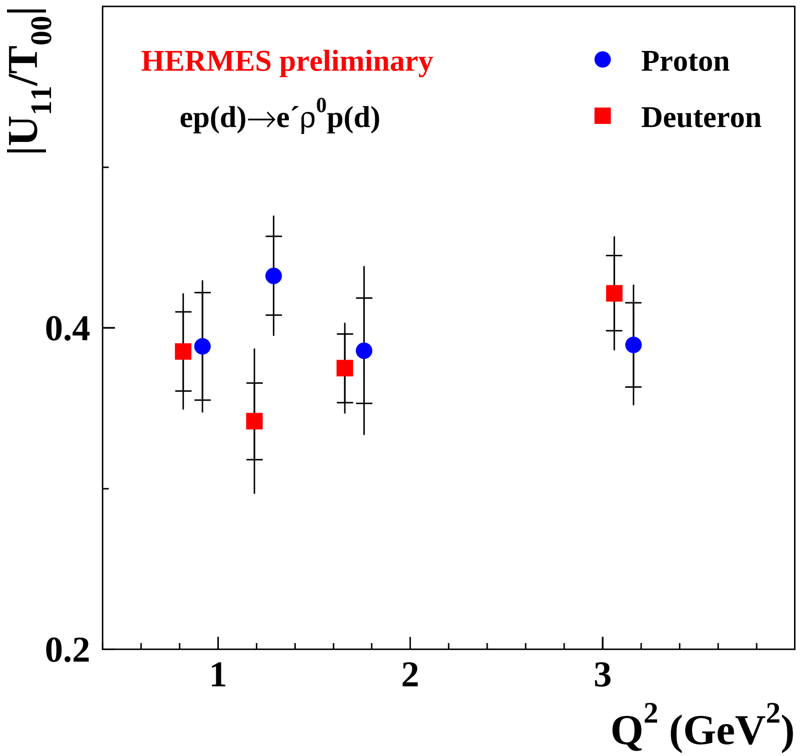


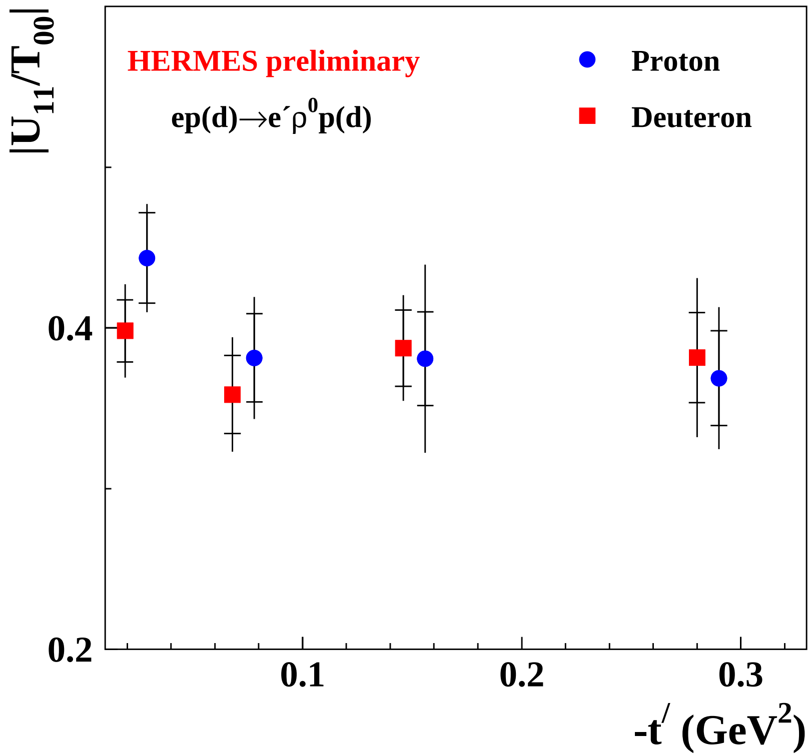
- pQCD prediction (Ivanov, Kirshner '98) and GPD GK model: $T_{11}/T_{00} \propto M_V/Q$

- Fits of Q dependence: $\mathrm{Re}\{\mathrm{T}_{11}/\mathrm{T}_{00}\} = \mathrm{a}/\mathrm{Q}$, $\mathrm{Im}\{\mathrm{T}_{11}/\mathrm{T}_{00}\} = \mathrm{b} \cdot \mathrm{Q}$
  Combined $p + d$ data: $a = 1.129 \pm 0.024$ GeV, $\chi^2/N_{df} = 1.02$
  $b = 0.344 \pm 0.014$ GeV^{-1}, $\chi^2/N_{df} = 0.87$

- Fit results are in full agreement with the another representation from the SDME analysis, where the phase difference $\delta_{11} \sim 30^\circ$ and grows with Q^2

Q^2 and t' dependence of Amplitude Ratios $|U_{11}/T_{00}|$

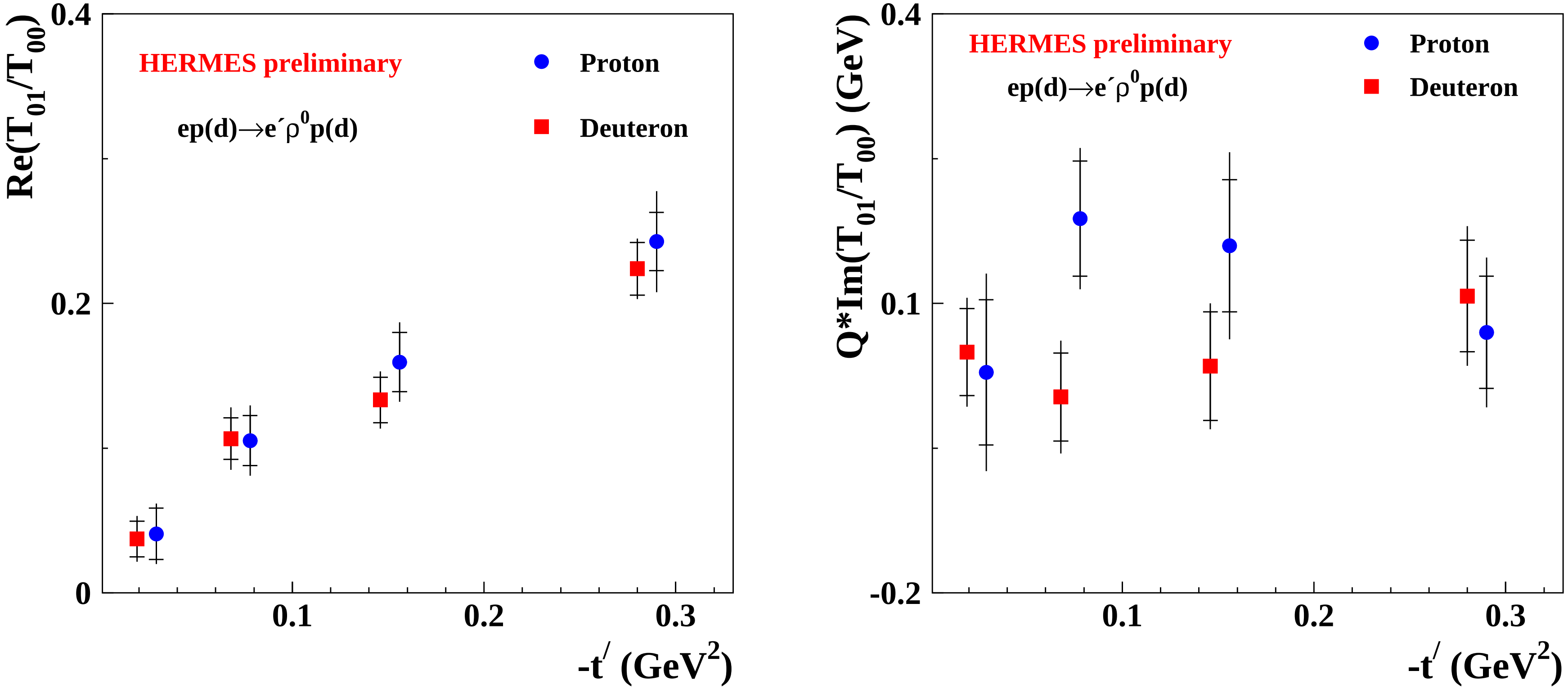




- pQCD prediction: $U_{11}/T_{00} \propto M_V/Q$
- Fit: $|U_{11}/T_{00}| = a, \quad a = 0.391 \pm 0.013, \quad \chi^2/N_{df} = 0.44$
- Contribution of Unnatural Parity Exchange is observed with much better accuracy than in SDME method

$\Longrightarrow$ Neither Q^2 nor t' dependence visible

t' dependence of Amplitude Ratios Re(Im)(T_{01}/T_{00})



- pQCD prediction (Ivanov, Kirshner'98) and GPD GK model: $T_{01}/T_{00} \propto \sqrt{-t'}/Q$

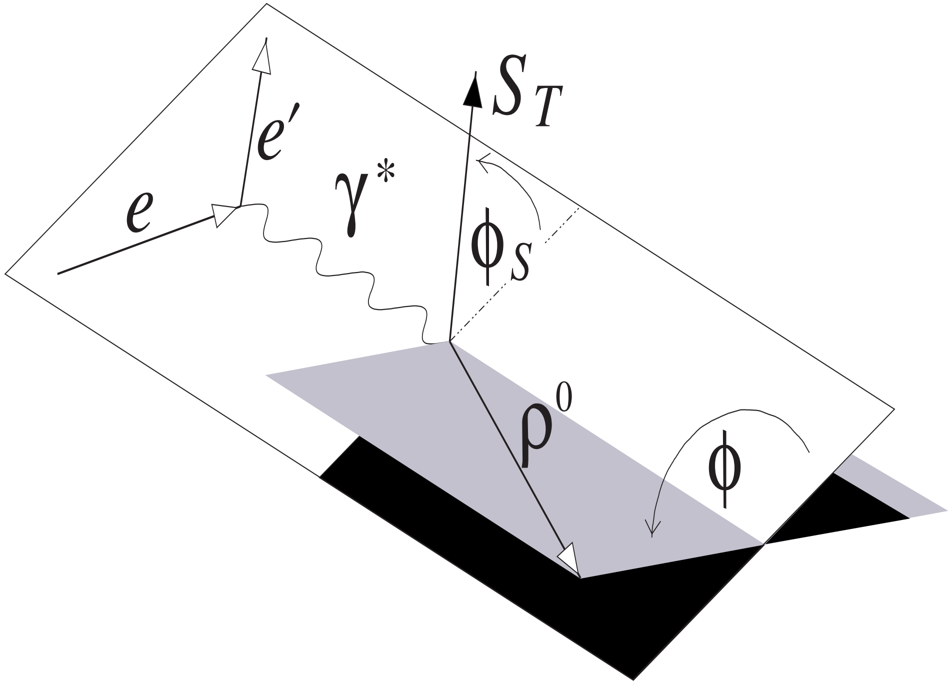
- Fit of t' dependence: $\mathrm{Re}\{\mathrm{T}_{01}/\mathrm{T}_{00}\} = \mathrm{a}\sqrt{-\mathrm{t}'}$, $\mathrm{Im}\{\mathrm{T}_{01}/\mathrm{T}_{00}\} = \mathrm{b}\sqrt{-\mathrm{t}'}/\mathrm{Q}$
  Combined $p+d$ data: $a = 0.399 \pm 0.023$ GeV^{-1}, $\chi^2/N_{df} = 0.72$;
  $b = 0.20 \pm 0.07$, $\chi^2/N_{df} = 1.09$.

$\Longrightarrow$ Re and Im parts of T_{01}/T_{00} have different slopes of t'.

- Correspondingly, phase difference δ_{01} decreases with Q^2 and $\delta_{01} = (29 \pm 9)^\circ$ at $Q^2 = 0.8$ GeV^2.

‘Transverse’ UT-SDMEs on Transversely Polarized Proton

New formalism for L&T polarized targets (M.Diehl, JHEP09 (2007) 064, arXiv:0704.1565v2), interference between NPE and UPE amplitudes accounted, $\phi \pm \phi_s$ distributions are in the fit function.



- Notation: $F^{\rho^0 p'}_{\gamma^* p} \equiv F^{\nu\sigma}_{\mu\lambda}$

$$\rho^{\nu\nu'}_{\mu\mu',\lambda\lambda'} = (N_T + \epsilon N_L)^{-1} \sum_\sigma F^{\nu\sigma}_{\mu\lambda} (F^{\nu'\sigma'}_{\mu'\lambda'})^*$$

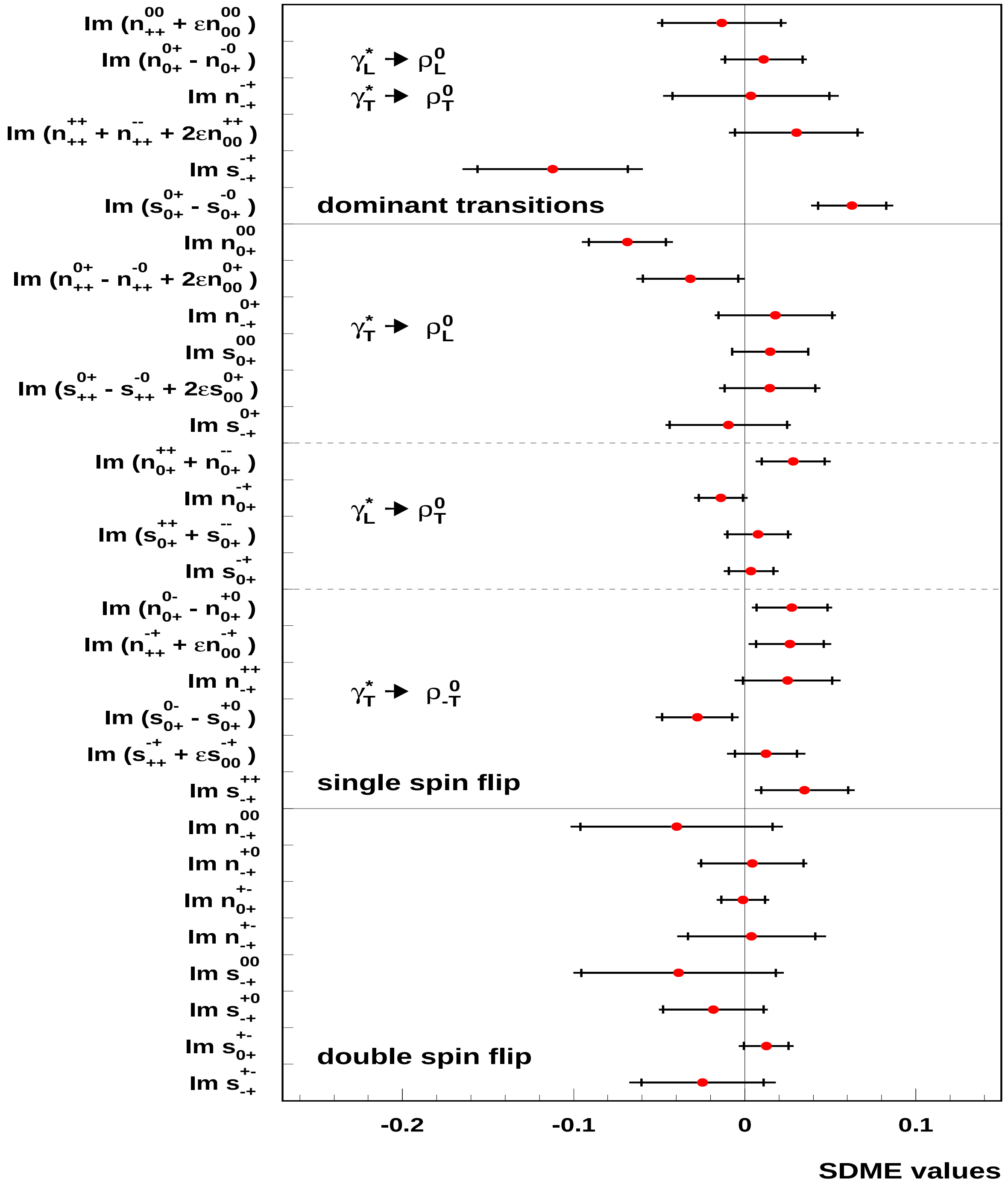
$$\mathrm{s}^{\nu\nu'}_{\mu\mu',\lambda\lambda'} = \tfrac{1}{2}(\rho^{\nu\nu'}_{\mu\mu',+-} + \rho^{\nu\nu'}_{\mu\mu',-+})$$

$$\mathrm{n}^{\nu\nu'}_{\mu\mu',\lambda\lambda'} = \tfrac{1}{2}(\rho^{\nu\nu'}_{\mu\mu',+-} - \rho^{\nu\nu'}_{\mu\mu',-+})$$

- n and s are for normal and sideways target polarization with respect to the direction of the virtual photon and electron scattering plane.

- Sub(super) scripts refer to the helicity of the virtual photon (ρ^0 meson) in the amplitudes that occur in the SDME.

ρ^0 SDMEs on Transversely Polarized Proton (HERMES collab. arXiv:0906.5160 DESY-09-094)

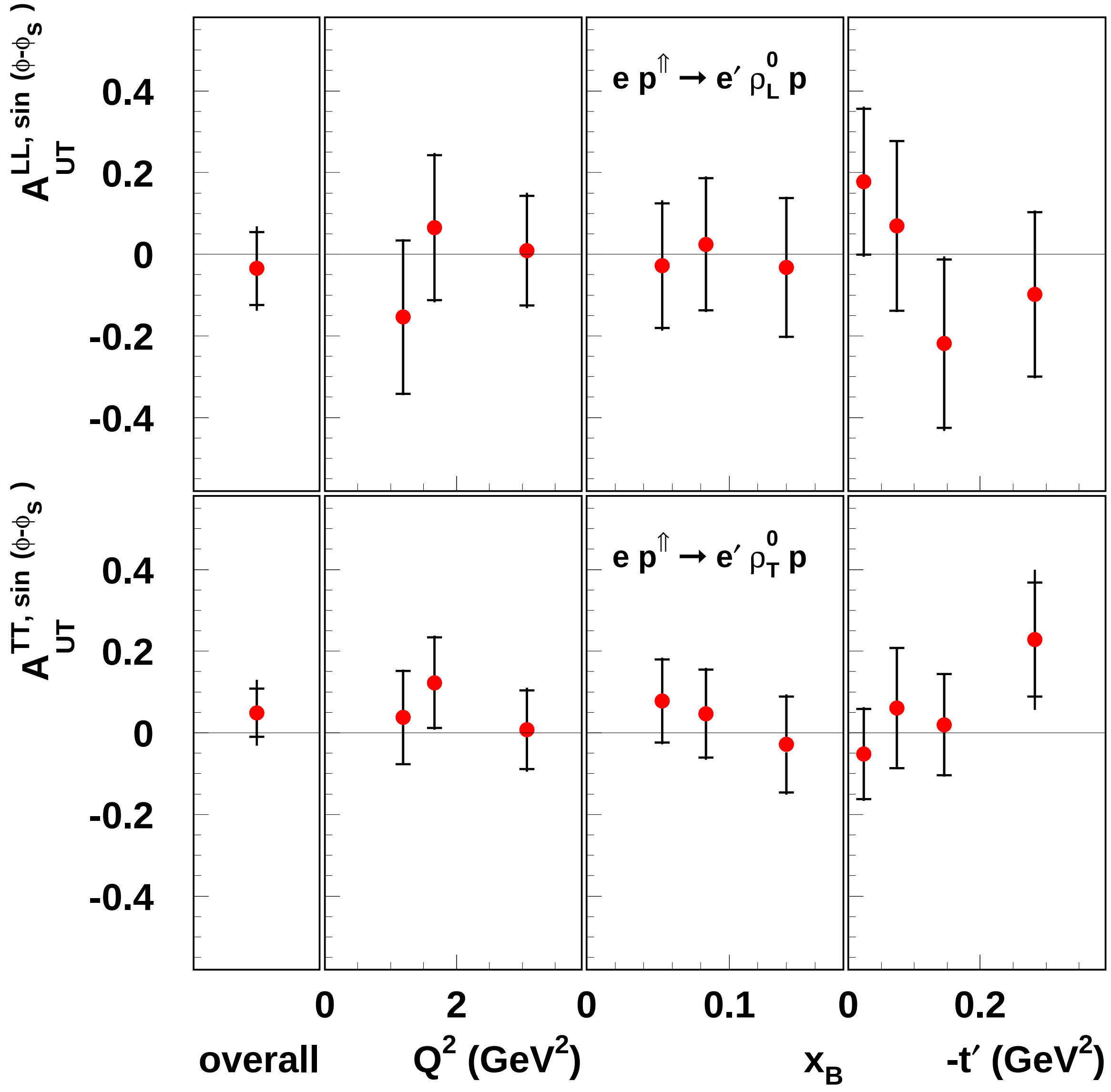


- $P_T = 0.724 \pm 0.059$ with scale uncertainty 8.1%

- Indication on nonzero SDMEs: $\mathrm{Im}(s^{-+}_{-+})$, $\mathrm{Im}(s^{0+}_{0+} - s^{-0}_{0+})$ due to the interference of NPE and UPE amplitudes on the trasversely polarized target, and $\mathrm{Im}(n^{00}_{0+})$ due to violation of SCHC.

- $\Longrightarrow$ Small values of all 30 SDMEs

ρ^0 Transverse Target Polarization Asymmetry (HERMES collab. arXiv:0906.5160 DESY-09-094)



- Average kinematics:
  $\langle -t' \rangle = 0.13$ GeV^2
  $\langle x_B \rangle = 0.08$
  $\langle Q^2 \rangle = 1.95$ GeV^2

- σ_L and σ_T separation
  done using the ρ^0 UT-SDMEs:

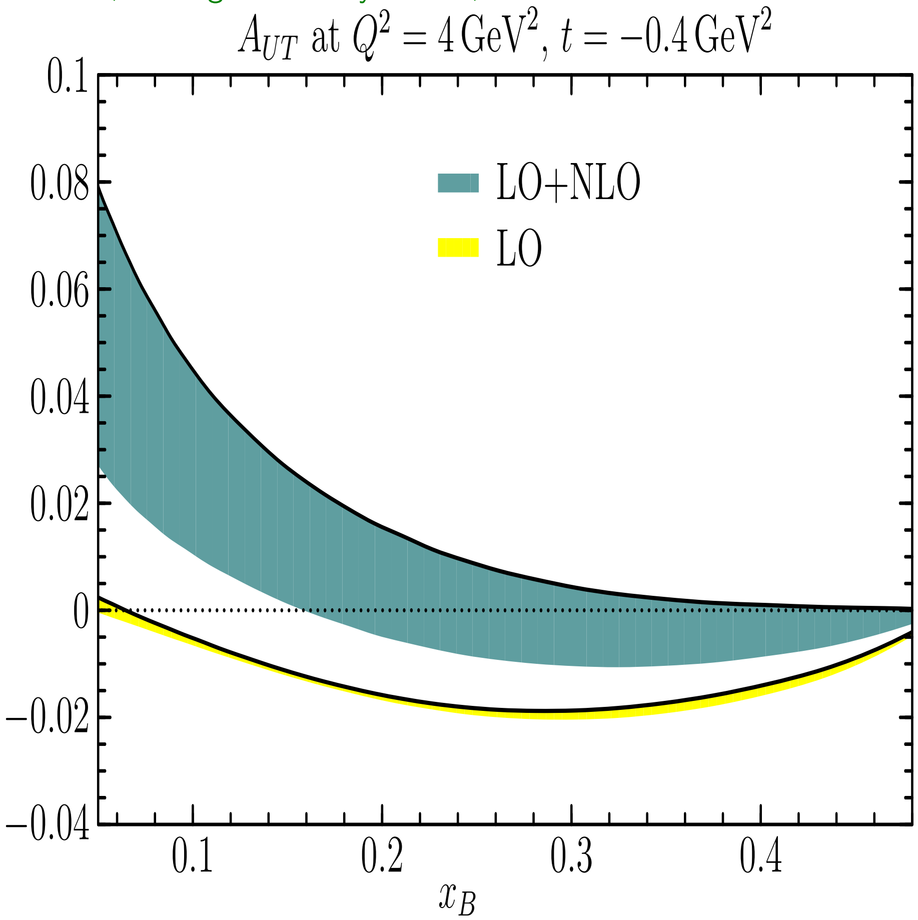
$$A_{UT}^{(\gamma^*_L \rightarrow \rho^0_L), sin(\phi-\phi_s)} = \frac{\mathrm{Im}(\mathrm{n}^{00}_{++} + \epsilon \mathrm{n}^{00}_{00})}{(u^{00}_{++} + \epsilon u^{00}_{00})}$$

$$A_{UT}^{(\gamma^*_T \rightarrow \rho^0_T), sin(\phi-\phi_s)} = \frac{\mathrm{Im}(\mathrm{n}^{++}_{++} + \mathrm{n}^{--}_{++} + 2\epsilon \mathrm{n}^{++}_{00})}{(1 - u^{00}_{++} + \epsilon u^{00}_{00})}$$

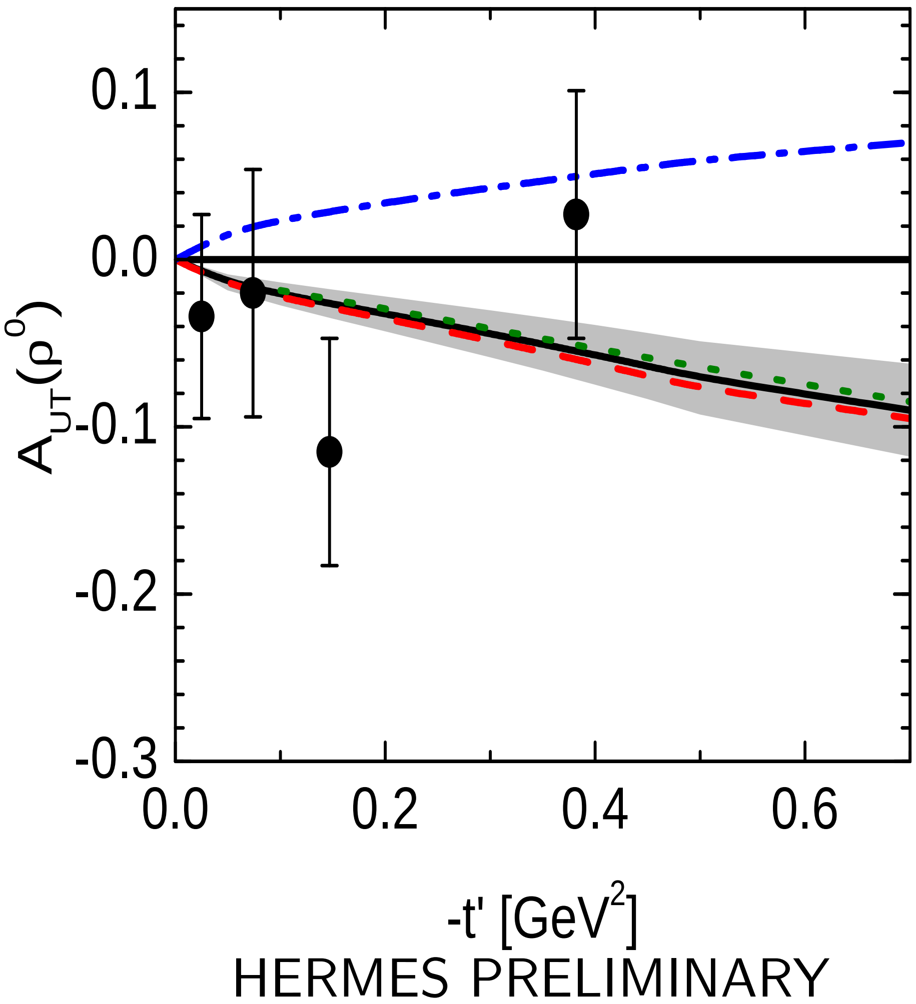
$\Longrightarrow$ Compartible with zero overall value for leading amplitude: $A_{UT}^{\rho^0} = -0.033 \pm 0.058$

Calculations of ρ^0 Transverse Target Polarization Asymmetry

M.Diehl, W.Kugler Eur.Phys.J.C52,2007

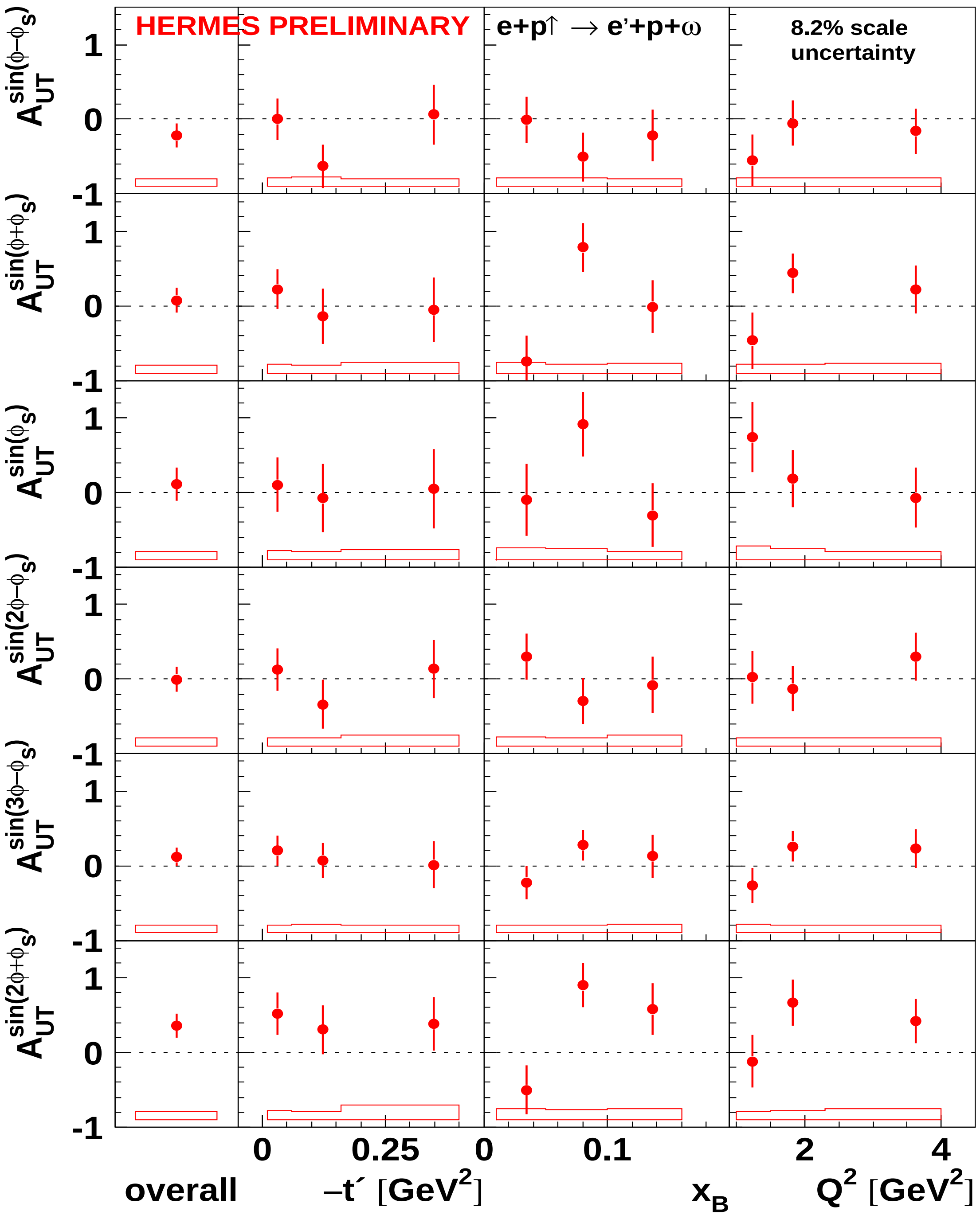


S. V. Goloskokov, P. Kroll arXiv:0809.4126



$\Longrightarrow$ $A_{UT}^{\rho^0}$ is also small in calculations

Asymmetries of ω Meson Produced on Transversely Polarized Proton



- In leading twist:

$$A_{UT}(\phi,\phi_S) = \frac{[\sigma(\phi,\phi_S) - \sigma(\phi,\phi_S+\pi)]/P_T}{\int[\sigma(\phi,\phi_S)+\sigma(\phi,\phi_S+\pi)]d\phi/(2\pi)}$$

$$= \sum_{m,n} A_{UT}^{\sin(m\phi+n\phi_S)} \sin(m\phi+n\phi_S)$$

- **First indication on negative A_{UT} in ω meson leptoproduction:**

$$A_{UT}^{\omega,\sin(\phi-\phi_S)} = -0.22 \pm 0.16_{st} \pm 0.11_{syst}$$

- No contradiction with small value of $A_{UT}^{\rho^0}$ due to different contributions of u and d quarks in GPD E:

$$A_{UT}^{\sin(\phi-\phi_S)}(\rho^0) \propto \frac{\sqrt{-t'}}{M}\mathrm{Im}\left\{\frac{2\mathrm{E^u}+\mathrm{E^d}}{2\mathrm{H^u}+\mathrm{H^d}}\right\}$$

$$A_{UT}^{\sin(\phi-\phi_S)}(\omega) \propto \frac{\sqrt{-t'}}{M}\mathrm{Im}\left\{\frac{2\mathrm{E^u}-\mathrm{E^d}}{2\mathrm{H^u}-\mathrm{H^d}}\right\}$$

- Note agreement with the calculated for HERMES $A_{UT}^{\omega} \approx -0.10$

(S. V. Goloskokov, P. Kroll arXiv:0809.4126)

and also predicted $A_{UT}^{\rho^+} \approx 0.40$.

Summary

- 15 unpolarized and, for the first time, **8 polarized ρ^0 SDMEs** are obtained on unpolarized proton and deuteron.
  - No statistically significant difference between proton and deuteron data is observed.
  - Violation of S-channel helicity is confirmed in ρ^0 electroproduction with high accuracy.
  - Various versions of $R = \sigma_L/\sigma_T$ are determined, indication is found for a W dependence of R.
  - Unnatural parity exchange contribution in ρ^0 production is seen for the combined data on the proton and deuteron SDMEs with $3\ \sigma_{tot}$.

- For the first time, Q^2 and t' dependences of the **Re&Im parts of the ratios of amplitudes:** T_{11}/T_{00}, T_{01}/T_{00}, and $|U_{11}/T_{00}|$ are measured for ρ^0 electroproduction.
  - Q^2 dependence of Im(T_{11}/T_{00}) differs from pQCD prediction and confirm **increase of phase difference with** Q^2, with better precision than at SDMEs approach
  - t' dependence of Im(T_{01}/T_{00}) also indicates **different phase** of T_{01} amplitude relative T_{00}.
  - **No** Q^2 **and** t' **dependences** of unnatural parity exchange amplitude in ρ^0 meson production is found.

- For the first time, HERMES measured 30 SDMEs for ρ^0 and single spin asymmetry for ρ^0 and ω on transversely polarized proton.
  - Small values of SDMEs and A_{UT} are observed for ρ^0 electroproduction.
  - **Indication on negative** A^{ω}_{UT} is obtained, which is in agreement with GK model GPD based calculations.

$\Longrightarrow$ **HERMES data provide tests and constrains on GPDs H, $\widetilde{H}$ and E.**