Recent results on exclusive processes at HERMES

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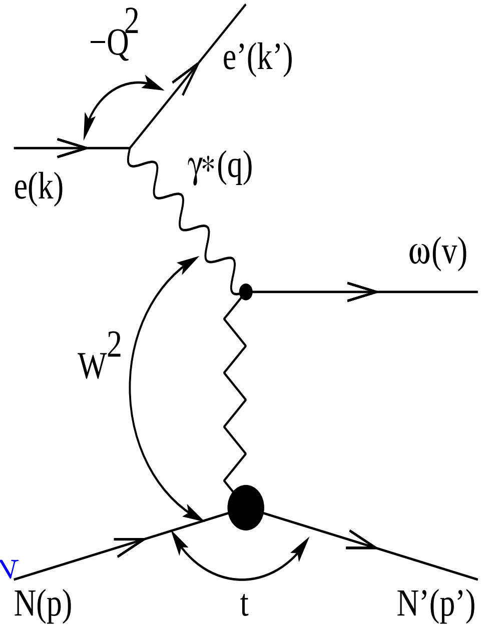
Hard exclusive vector meson production

$$e + N \to e + V + N$$

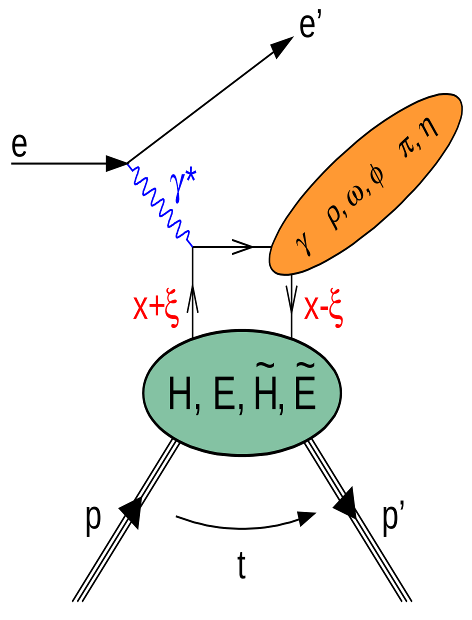


- Exclusive electroproduction of vector meson in the process $\gamma^* + N \to V + N'$ ($V = \rho^0$, ϕ, ω) provides information both on reaction mechanism and nucleon structure.
  - Test of S-channel Helicity Conservation (SCHC) hypothesis ($\lambda_\gamma = \lambda_V$).
  - Possibility to distinguish between contribution of Natural and Unnatural Parity Exchange contribution (NPE, UPE).
    NPE ($J^P = 0^+,\ 1^-, ...$) (pomeron, ρ, ω, a_2,...reggeons) $T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$
    UPE ($J^P = 0^-,\ 1^+, ...$)(π, a_1, b_1,...reggeons), $U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$
  - Determination of hierarchy of helicity amplitudes.
  - Determination of phase difference between helicity amplitudes.
  - Longitudinal-to-transverse cross-section ratio ($R = \frac{d\sigma_L(\gamma_L^* \to V)}{d\sigma_T(\gamma_T^* \to V)}$).

Hard exclusive vector meson production

$$e + N \rightarrow e + V + N$$

- Possibility of testing Generalized Parton Distribution (GPD) models.
  - Lepton-quark hard-scattering amplitude is convoluted with GPD.
  - The factorization is rigorously proven for longitudinal virtual photons only ($\gamma_L \rightarrow V_L$).
  - Quark(gluon) GPDs H$_{q(g)}$(x, ξ, t) and E$_{q(g)}$(x, ξ, t).
  - Ji's Sum Rules $\frac{1}{2}\int dx x[H^f + E^f] = \langle J^f \rangle$.
  - Access to various quark-flavor combination ρ(2u+d), ω(2u-d), ϕ(s)... .
  - Natural Parity Exchange (NPE) corespond to GPD H and E.
    Unnatural Parity Exchange (UPE) corespond to GPD $\tilde{H}$ and $\tilde{E}$.
  - Factorization applied also for transverse photons in phenomenological Goloskokov - Kroll (GK) model.



- Fiting of angular distribution as a function of SDMEs, helicity amplitude ratios, asymmetry amplitudes.

Spin Density Matrix Elements in Exclusive ω Electroproduction on ^{1}H and ^{2}H Targets at 27.5 GeV Beam Energy

A.Airapetian et al. (the HERMES Collaboration), Eur. Phys. J. C.74, (2014) 3110

Exclusive ω-meson production at HERMES $e + p \rightarrow e' + p' + \omega \rightarrow (\pi^+\pi^-\pi^0(\rightarrow 2\gamma))$

- $W = 3.0 \div 6.3$ GeV, $< W >= 4.8$ GeV
- $Q^2 = 1.0 \div 10.0$ GeV^2, $< Q^2 >= 1.9$ GeV^2
- $x_B = 0.01 \div 0.35$, $< x_B >= 0.08$
- $0 \le -t' \le 0.2$ GeV^2, $< -t' >= 0.08$ GeV^2 with $t' = t - t_{min}$

total number of events

Hydrogen: ω -2260

Deuterium: ω -1332

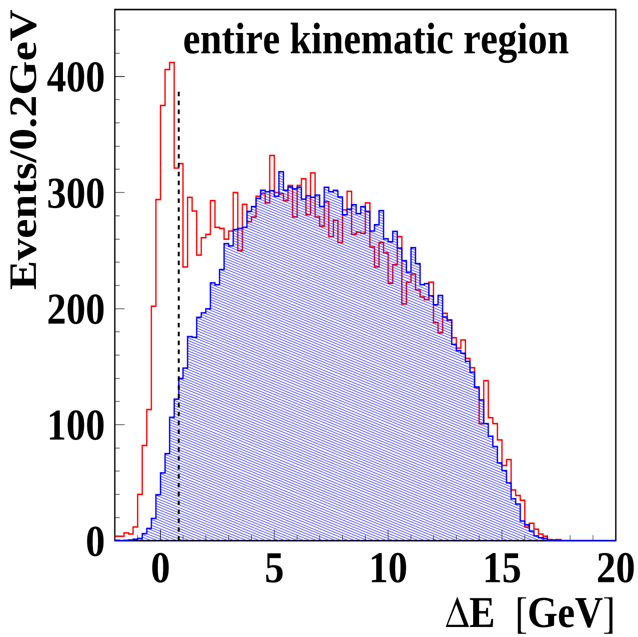
$W^2 = (q + p)^2$

$Q^2 = -(k - k')^2$

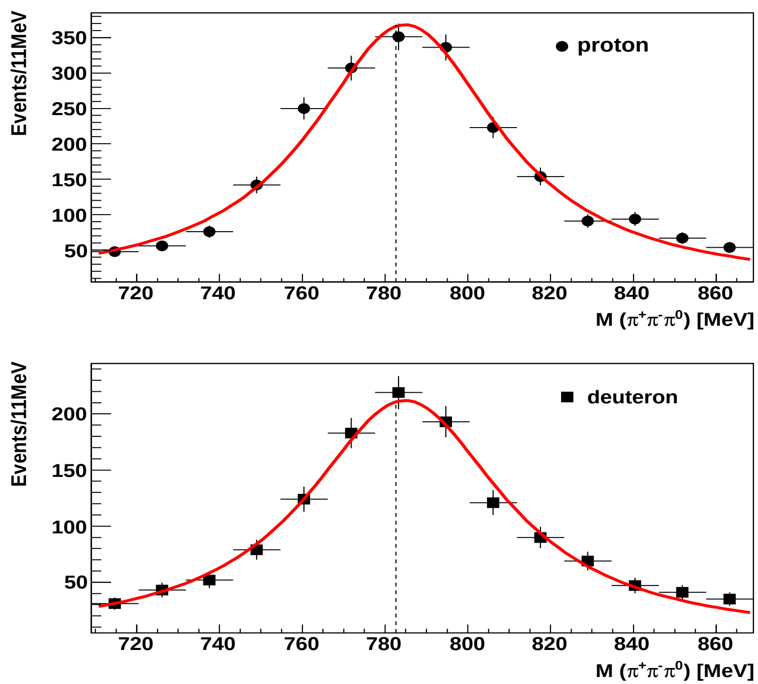
$x_B = \frac{Q^2}{2pq}$

$t = (q - v)^2$

$\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$ with $M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-} - p_{\pi^0})^2$ and M_X being missing mass, p, q, p_{π^+}, p_{π^-} p_{π^0} are 4-momenta of proton, γ^* and pions. Beam polarization $\approx 40\%$.

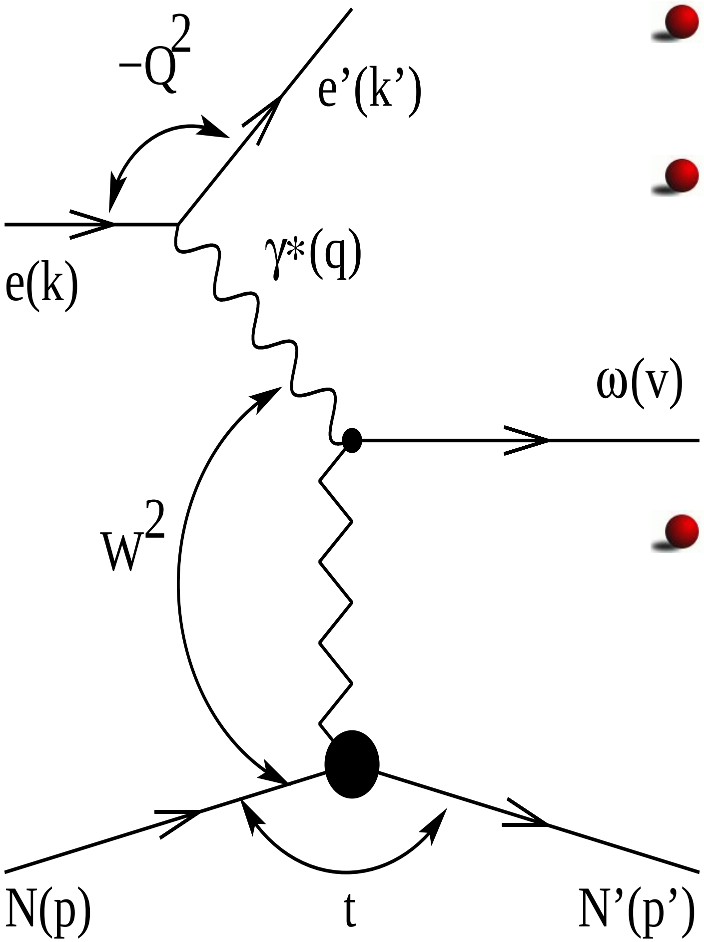


$-1.0 < \Delta E < 0.8$ GeV,



$0.71 < M(\pi^+\pi^-\pi^0) < 0.87$ GeV,

Spin Density Matrices, Schilling-Wolf representation



- $e \rightarrow e' + \gamma^*$ (QED). Spin-density matrix $\varrho(\gamma)$ of the virtual photon is known.
- $\gamma^* + N \rightarrow \omega + N \rightarrow \pi^+ + \pi^- + \pi^0 + N$ (QCD). Vector-meson spin-density matrix $\varrho(V)$ it is expressed by helicity amplitudes $F_{\lambda_V \lambda'_N; \lambda_\gamma \lambda_N}(W, Q^2, t')$. In CM frame of $\gamma^* N$ is given by the von Neumann formula: $\varrho(V) = \frac{F \varrho(\gamma) F^+}{\mathcal{N}}$
- $\varrho(\lambda)$ decomposes into the set of nine hermitian matrices(3×3) Σ^α (α=0÷3 - transv.,4 - long. 5÷8 - interf.), spin density matrix element is:

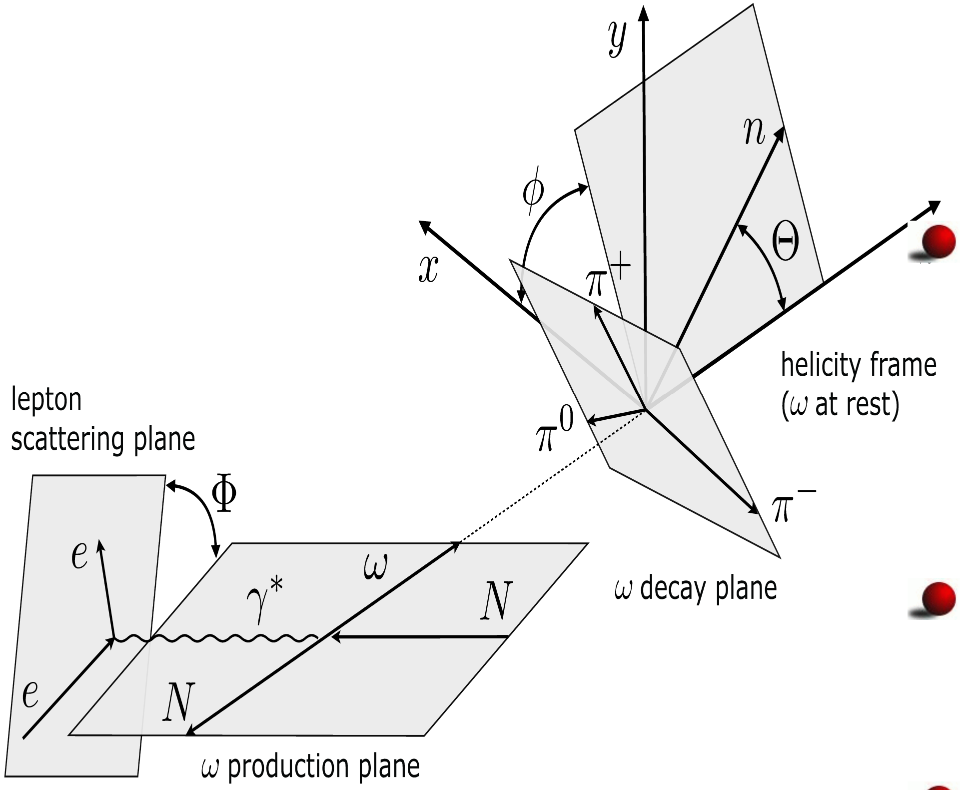
  $$r^\alpha_{\lambda_V \lambda'_V} = \frac{1}{2\mathcal{N}} \sum_{\lambda_\gamma \lambda'_\gamma \lambda_N \lambda'_N} F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \Sigma^\alpha_{\lambda_\gamma \lambda'_\gamma} F^*_{\lambda'_V \lambda'_N \lambda'_\gamma \lambda_N},$$

  where helicity amplitudes:

  $$F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = (-1)^{\lambda_\gamma} \langle v \lambda_V p' \lambda'_N | J^\kappa | p \lambda_N \rangle e^{(\lambda_\gamma)}_\kappa,$$

  J^κ - electromagnetic current of hadrons,
  $e^{(\lambda_\gamma)}_\kappa$ - photon polarization four-vector
- $F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$

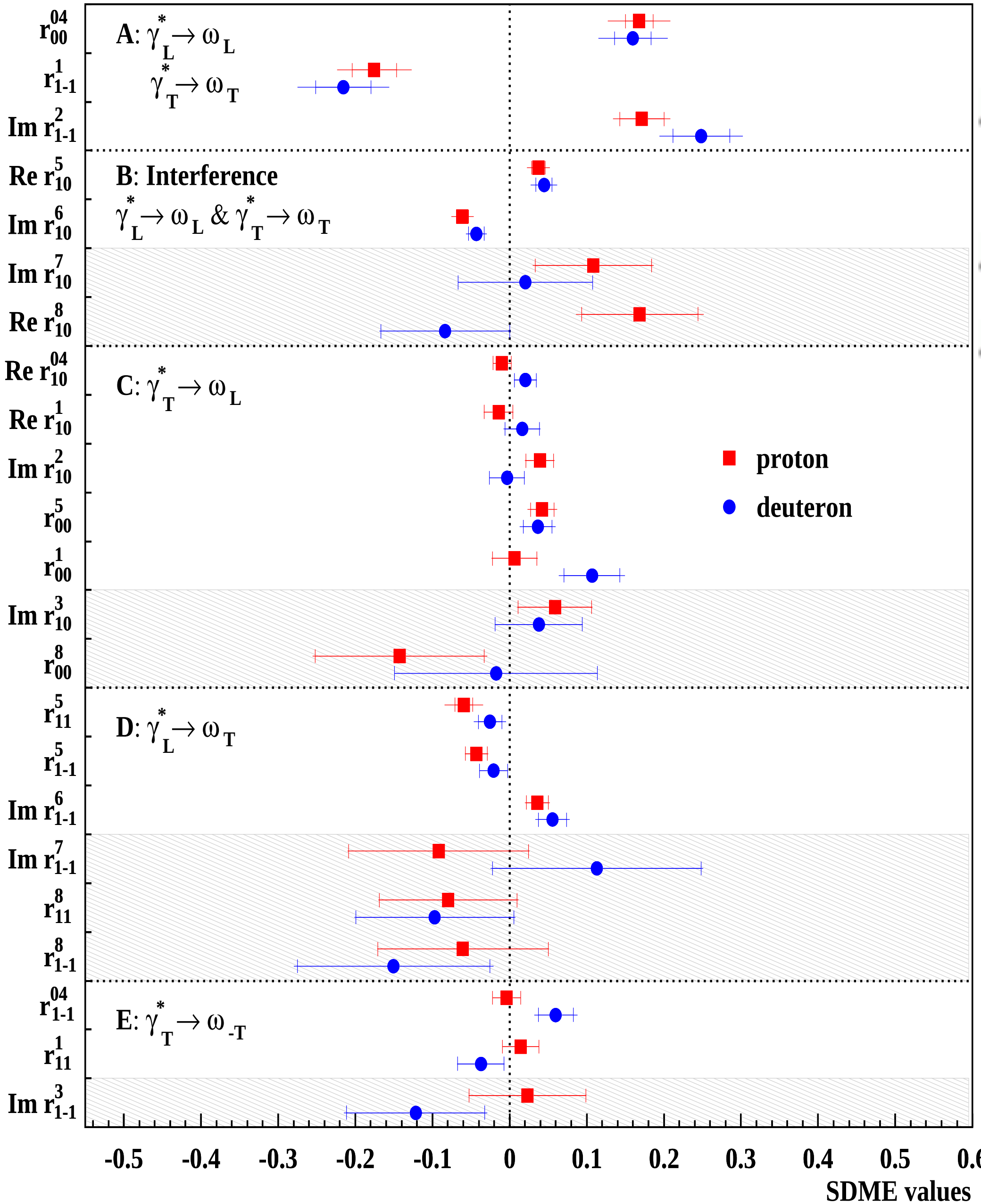
Extraction of SDMEs



In case of ρ^0 $\vec{n} = \frac{\vec{p}_{\pi^+}}{|\vec{p}_{\pi^+}|}$

- $\omega \Rightarrow \pi^+\pi^-\pi^0$ (conservation of $\vec{J}$) $|\omega; 1m > \rightarrow |\pi^+\pi^-\pi^0; 1m > \Rightarrow Y_{1m}(cos(\Theta), \phi)$, $(m = \pm 1, 0)$. Angular distribution $\mathcal{W}(r^{\alpha}_{\lambda_V \lambda'_V}, \Phi, cos\Theta, \phi)$ depends linearly on $r^{\alpha}_{\lambda_V \lambda'_V}$ and beam polariztion P_b.
- For longitudinally polarized beam and unpolarized target there are 23 SDMEs,(15 unpolarized and 8 polarized).
- The SDMEs are determined from the fit of angular distribution of pions from decay $\omega \Rightarrow \pi^+\pi^-\pi^0$, by angular distribution $\mathcal{W}(r^{\alpha}_{\lambda_V \lambda'_V}, \Phi, cos\Theta, \phi)$, with Maximum Likelihood method.

SDMEs of exclusive ω production for the entire kinematic region



- s-channel helicity concervation (SCHC)
  $\lambda_\gamma = \lambda_V$
- Similar SDMEs for proton and deuteron .
- if SCHC holds:
  $r^1_{1-1} = -Im\{r^2_{1-1}\}$
  $Re\ \{r^5_{10}\} = -Im\{r^6_{10}\}$
  $Im\{r^7_{10}\} = Re\{r^8_{10}\}$

These relation are well obeyed:

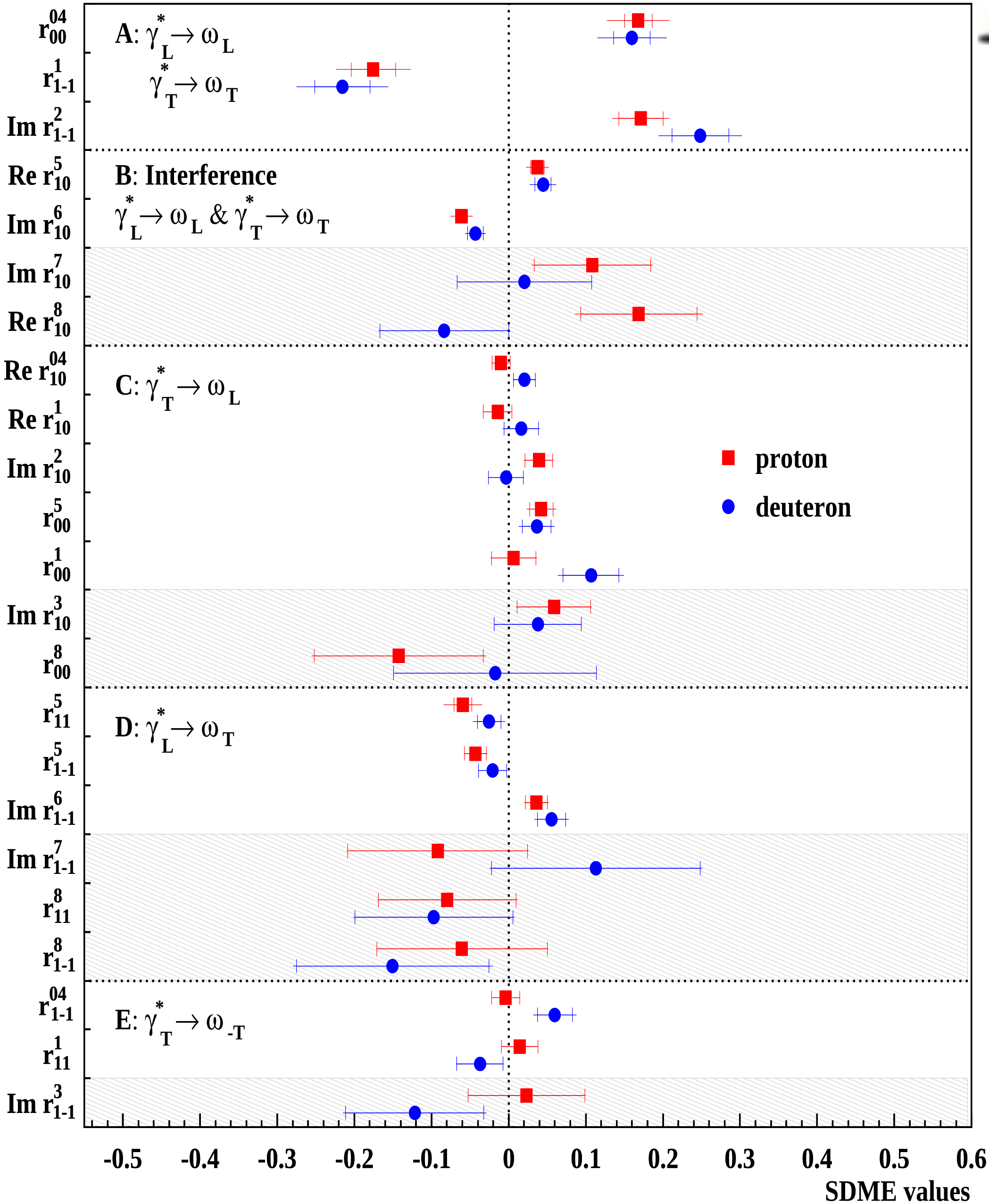
for hydrogen

$$r^1_{1-1} + Imr^2_{1-1} = -0.004 \pm 0.038 \pm 0.017,$$
$$Rer^5_{10} + Imr^6_{10} = -0.024 \pm 0.013 \pm 0.003,$$
$$Imr^7_{10} - Rer^8_{10} = -0.060 \pm 0.010 \pm 0.044,$$

for deuterium

$$r^1_{1-1} + Imr^2_{1-1} = 0.033 \pm 0.049 \pm 0.004$$
$$Rer^5_{10} + Imr^6_{10} = 0.001 \pm 0.016 \pm 0.015,$$
$$Imr^7_{10} - Rer^8_{10} = 0.10 \pm 0.11 \pm 0.17.$$

SDMEs of exclusive ω production for the integrated data



- Test of SCHC hypothesis.
  - CLASS C, Spin Flip: $\gamma^*_T \to \omega_L$
    SDME $r^5_{00} \neq 0$ by 3σ(proton), 2σ(deuteron
  - CLASS D, Spin Flip: $\gamma^*_L \to \omega_T$

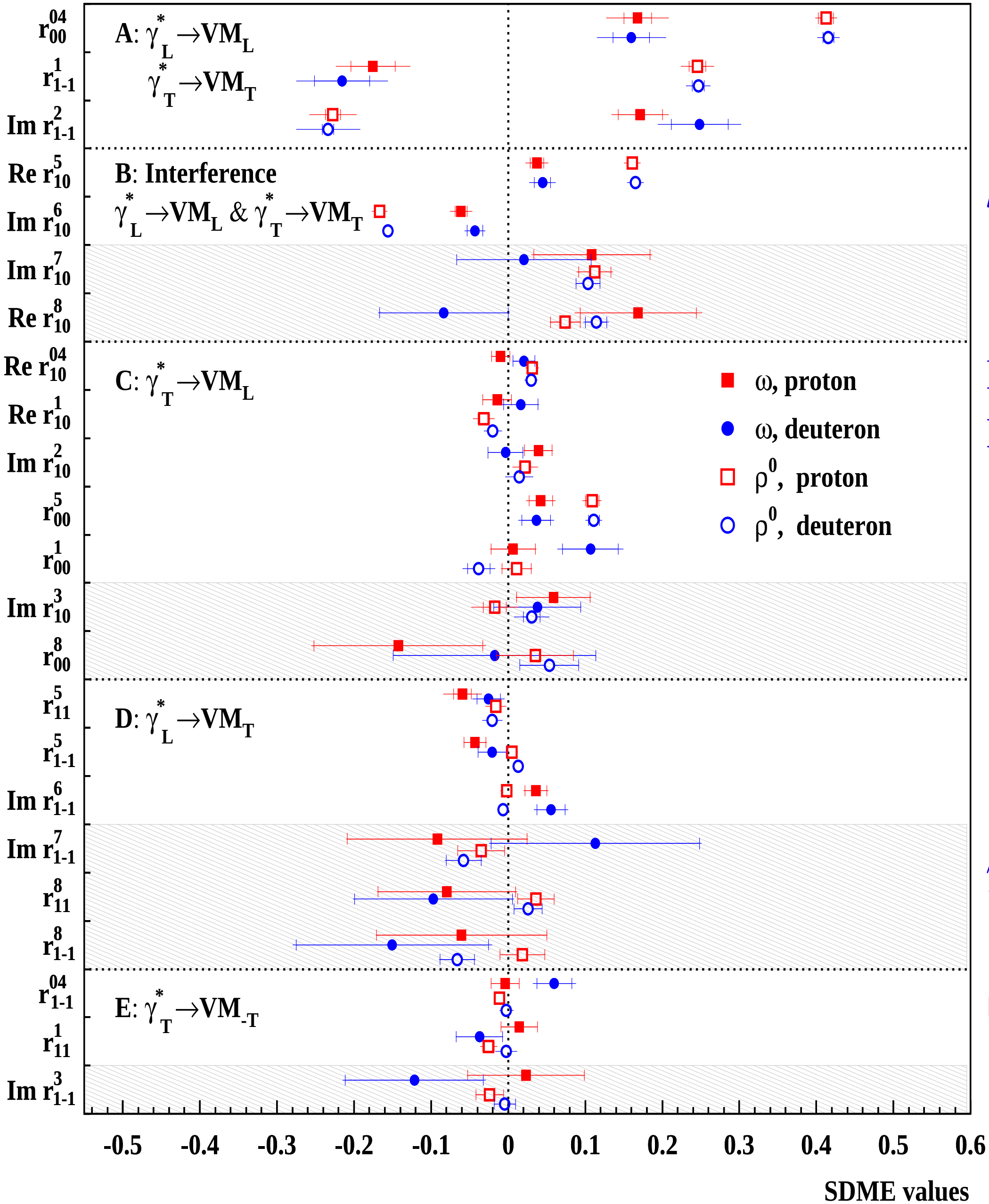
$r^5_{11} + r^5_{1-1} - Im\{r^6_{1-1}\}=$
$-0.14 \pm 0.02 \pm 0.04$ for hydrogen

$r^5_{11} + r^5_{1-1} - Im\{r^6_{1-1}\}=$
$-0.10 \pm 0.03 \pm 0.03$ for deuterium

$r^5_{11} \approx Re[U_{10}U^*_{11}]$
$r^5_{1-1} \approx Re[U_{10}U^*_{11}]$
$Im\{r^6_{1-1}\} \approx Re[-U_{10}U^*_{11}]$

  - SCHC Hypothesis seems to be violated.

Comparison of SDMEs in exclusive ω and ρ^0 production for the integrated data



ρ^0 SDMEs, HERMES, Eur. Phys. J. C62 (09) 659.

A, $\gamma^*_L \rightarrow \omega_L$ and $\gamma^*_T \rightarrow \omega_T$

$\mathrm{Im}\{r^2_{1-1}\} - r^1_{1-1} > 0$ for ω meson

$\mathrm{Im}\{r^2_{1-1}\} - r^1_{1-1} < 0$ for ρ^0 meson

$$\mathrm{Im}\{r^2_{1-1}\} - r^1_{1-1} = \frac{1}{\mathcal{N}}(-|T_{1\frac{1}{2}1\frac{1}{2}}|^2 - |T_{1-\frac{1}{2}1\frac{1}{2}}|^2 + |U_{1\frac{1}{2}1\frac{1}{2}}|^2 + |U_{1-\frac{1}{2}1\frac{1}{2}}|^2).$$

$T_{1-\frac{1}{2}1\frac{1}{2}} \approx U_{1-\frac{1}{2}1\frac{1}{2}} \approx 0$

$|U_{1\frac{1}{2}1\frac{1}{2}}|^2 > |T_{1\frac{1}{2}1\frac{1}{2}}|^2 \quad |U_{11}|^2 > |T_{11}|^2$

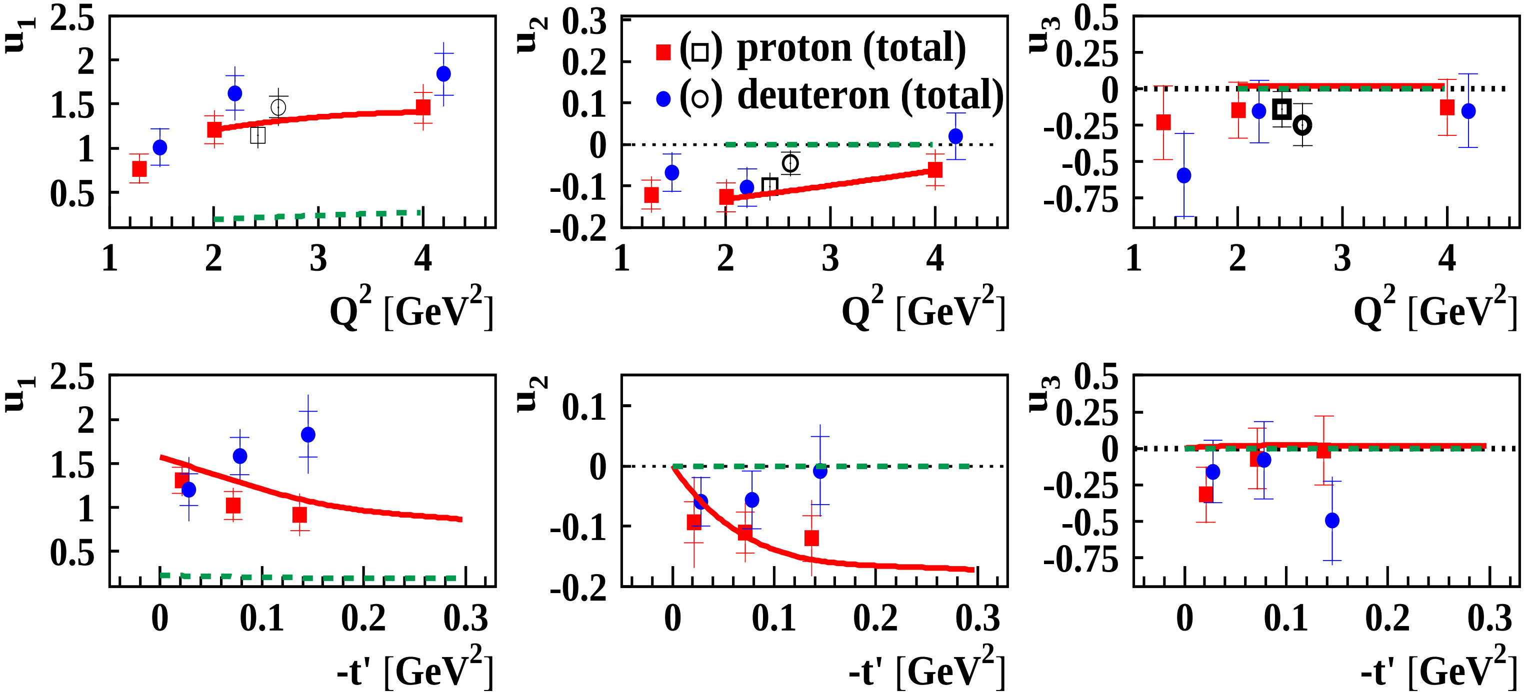
UPE dominate in exclusive ω meson

Test of Unnatural-Parity Exchange in exclusive ω meson production

Signal of UPE in the SDMEs

$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1}$, $u_1 = \widetilde{\sum} \frac{4\epsilon|U_{10}|^2 + 2|U_{11}+U_{-11}|^2}{\mathcal{N}}$ u1 > 0 UPE contribution

$u_2 = r^{5}_{11} + r^{5}_{1-1}$, $u_3 = r^{8}_{11} + r^{8}_{1-1}$, $u_2 + iu_3 = \sqrt{2}\widetilde{\sum} \frac{(U_{11}+U_{-11})U^{*}_{10}}{\mathcal{N}}$,

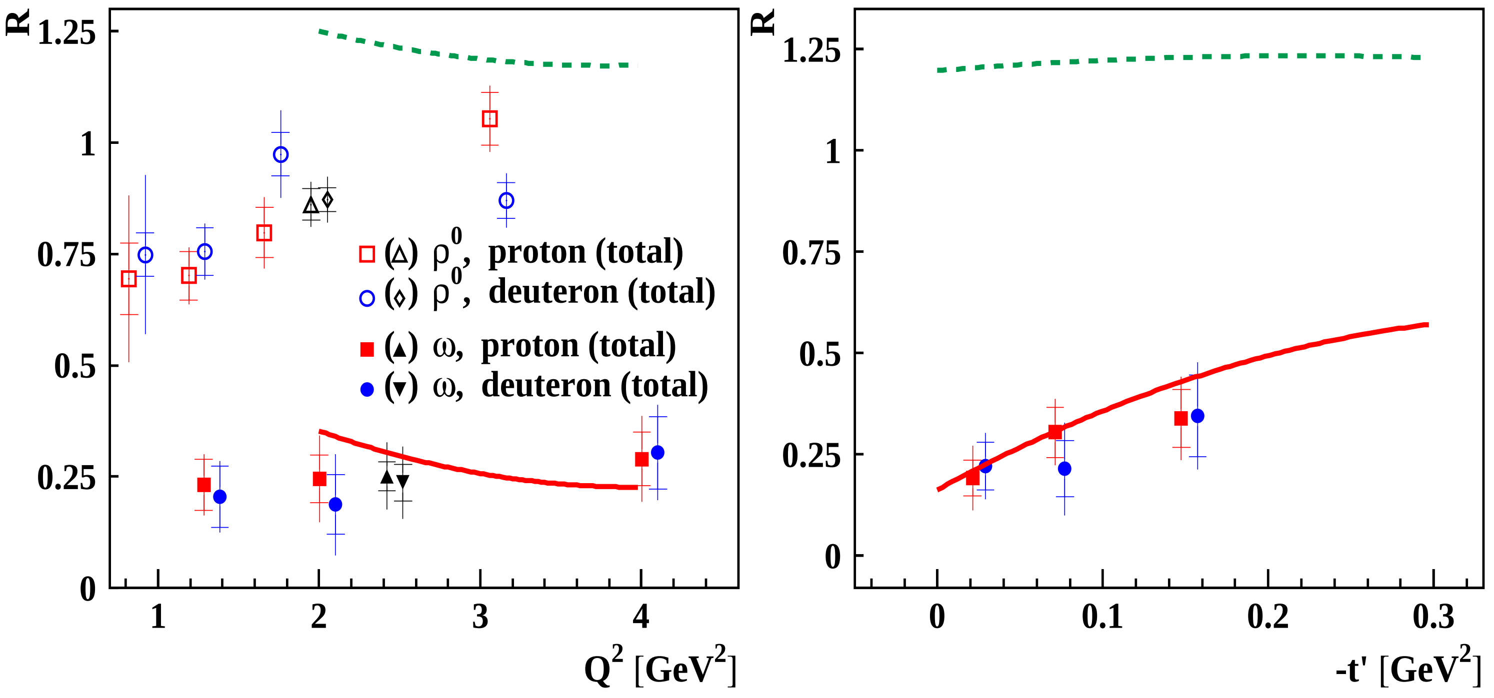


Solid (dashed) line denotes results with (without) pion-pole contribution of GK model.

S.V. Goloskokov and P. Kroll, Eur.Phys. J. A **50**, 146 (2014)

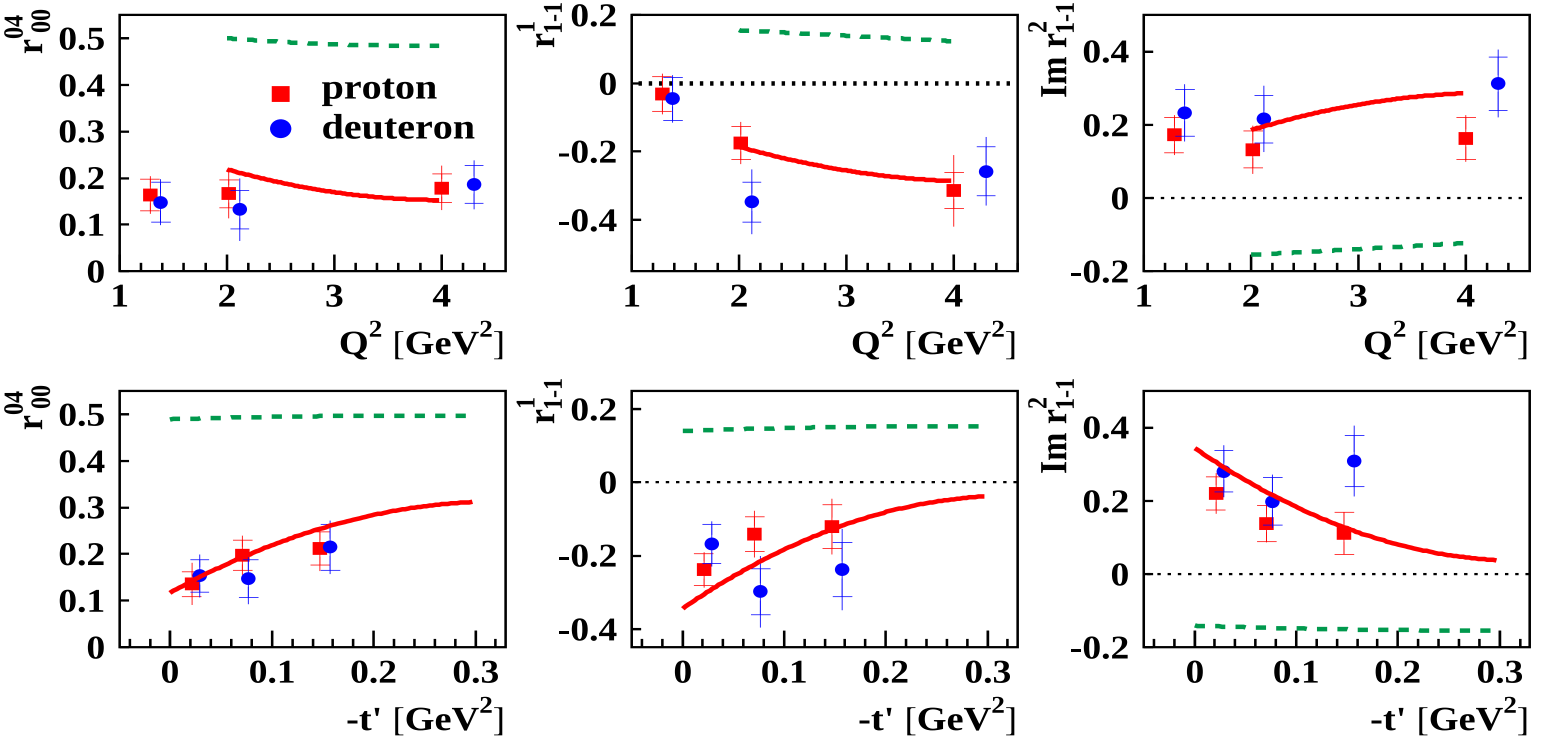
Longitudinal to Transverse cross section ratio for ω meson

$$R = \frac{d\sigma_L(\gamma_L^* \to V)}{d\sigma_T(\gamma_T^* \to V)} \qquad R \approx \frac{1}{\epsilon}\frac{r_{00}^{04}}{1-r_{00}^{04}}$$



The Q^2 (left) and $-t'$ (right) dependence of the longitudinal-to-transverse virtual-photon differential cross-section ratio for exclusive ω and ρ^0 electroproduction at HERMES, where the $-t'$ bin covers the interval [0.0-0.2] GeV^2 for ω meson and [0.0-0.4] GeV^2 for ρ^0 meson. The triangle symbols represent the value of R in the entire kinematic region. Solid (dashed) line denotes results with (without) pion-pole contribution of GK model.

Dependences of SDMEs on Q^2 end t'



Q^2 and $-t'$ dependences of class-A SDMEs. Proton data are denoted by squares and deuteron data by circles. The inner error bars represent the statistical uncertainties, while the outer ones indicate the statistical and systematic uncertainties added in quadrature. Solid (dashed) line denotes results with (without) pion-pole contribution of GK model.

Transverse-target-spin asymmetry in exclusive ω-meson electroproduction

A.Airapetian et al. (the HERMES Collaboration),Eur. Phys. J. C.75, (2015) 600

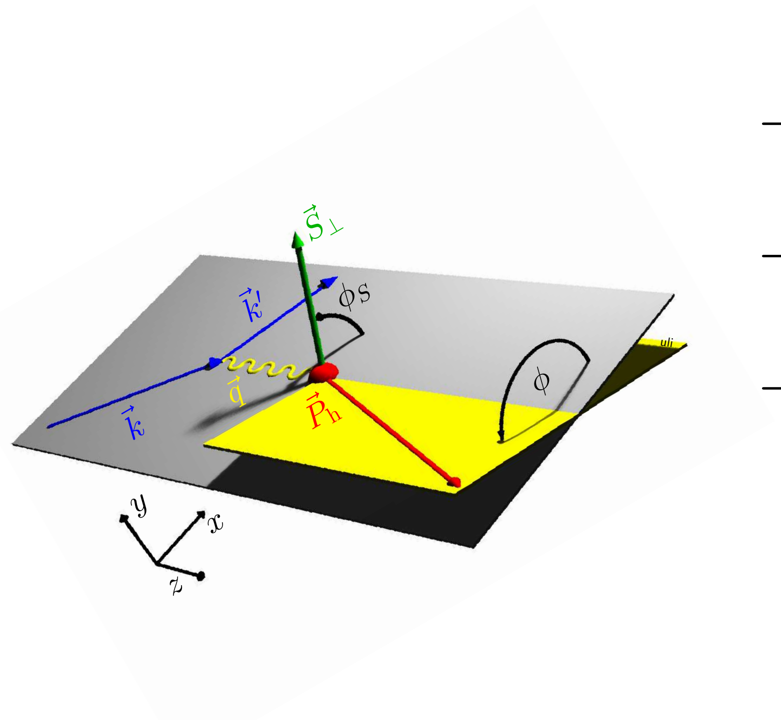
Kinematic constraints are the same as in omega SDMEs, 279 exclusive omegas,

$\langle|P_T|\rangle = 0.724 \pm 0.059$.

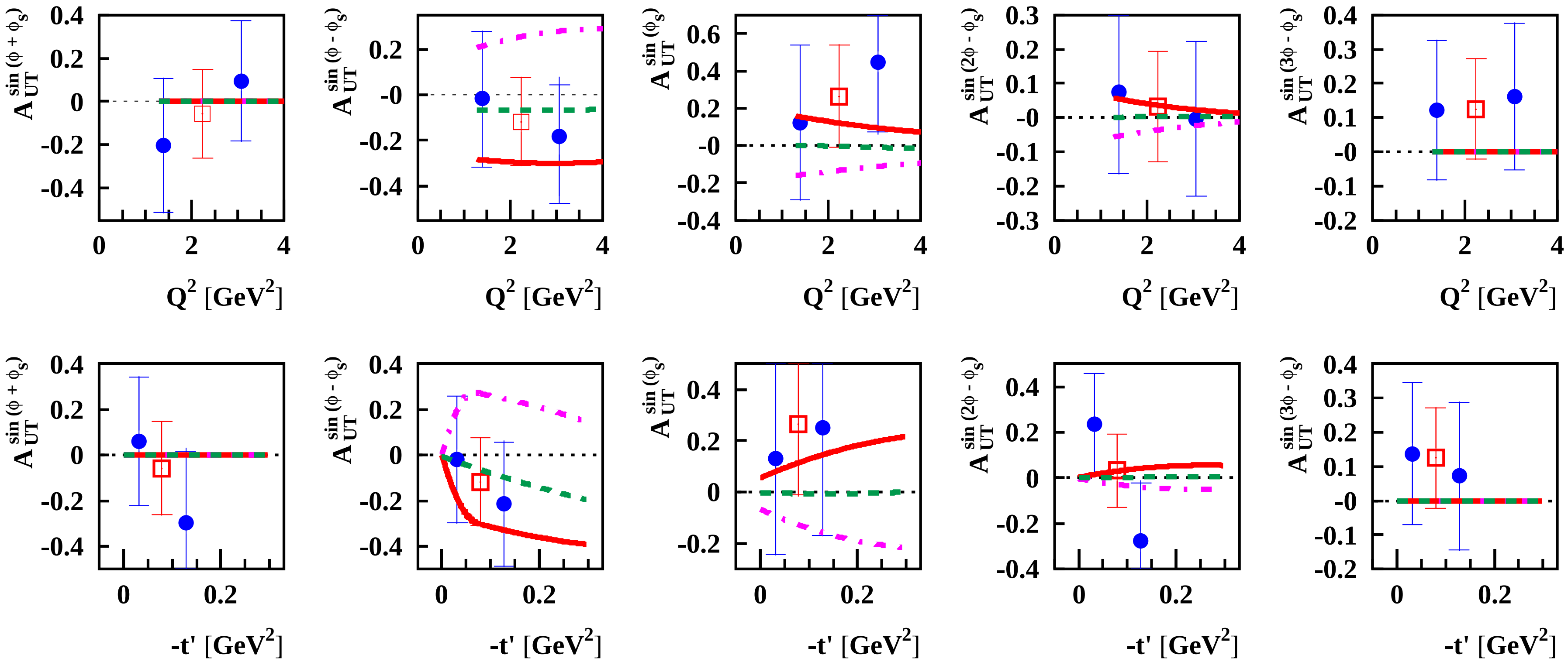
Transverse Target Spin Asymmetry

- Angular distribution for omegas produced from transversely polarized target

$$\begin{aligned}\mathcal{W}(\phi,\phi_S) = 1 &+ A_{UU}^{\cos(\phi)}\cos(\phi) + A_{UU}^{\cos(2\phi)}\cos(2\phi)\\ &+ S_\perp[A_{UT}^{\sin(\phi+\phi_S)}\sin(\phi+\phi_S)\\ &+ A_{UT}^{\sin(\phi-\phi_S)}\sin(\phi-\phi_S)\\ &+ A_{UT}^{\sin(\phi_S)}\sin(\phi_S)\\ &+ A_{UT}^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\\ &+ A_{UT}^{\sin(3\phi-\phi_S)}\sin(3\phi-\phi_S)].\end{aligned}$$



Comparison of Asymmetries amplitudes A_{UT} with GK model



The full circles show the data in two bins of Q^2 and t'. The open squares represent the entire kinematic region. The solid (dash-dotted) lines show the calculation of the phenomenological Goloskokov-Kroll model. Green line - calculation without pion pole. Red - with positive pion pole contribution included. Magenta - with negative pion pole contribution included.

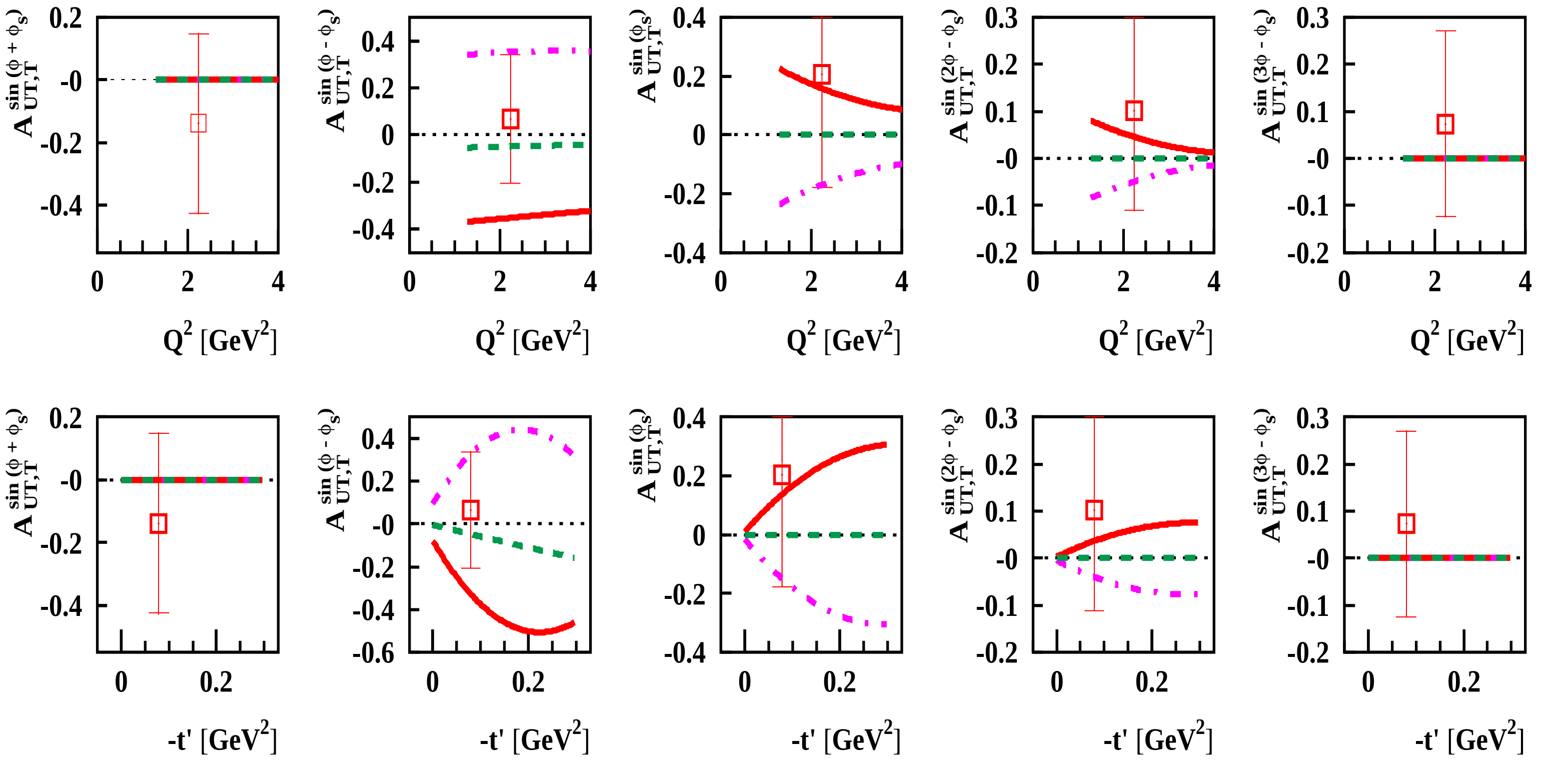
A_{UT} moments separated for L and T final states

- Angular distribution function for longitudinal (L) and transverse (T) ω meson.

$$W(\phi, \phi_s, \cos(\theta)) = \frac{3}{2}\, r_{00}^{04}\, \cos^2(\theta)\, w_L(\phi, \phi_s) + \frac{3}{4}\,(1 - r_{00}^{04})\, \sin^2(\theta)\, w_T(\phi, \phi_s).$$

$$w_L(\phi, \phi_s) = 1 + A_{UU,L}(\phi) + P_T A_{UT,L}(\phi, \phi_s)$$
$$w_T(\phi, \phi_s) = 1 + A_{UU,T}(\phi) + P_T\, A_{UT,T}(\phi, \phi_s).$$

Comparison of transverse components of Asymmetries A_{UT} with GK model



The Q^2 and t' dependences of the transverse components of the asymmetry amplitudes A_{UT}.The open squares represent the entire kinematic region. The solid (dash-dotted) lines show the calculation of the phenomenological GK model. Green line - calculation without pion pole. Red - with positive pion pole contribution included. Magenta - with negative pion pole contribution included.

Ratios of Helicity Amplitudes for Exclusive ρ^0 Electroproduction on Transversely Polarized Proton

in preparation

Ratio of Helicity amplitudes

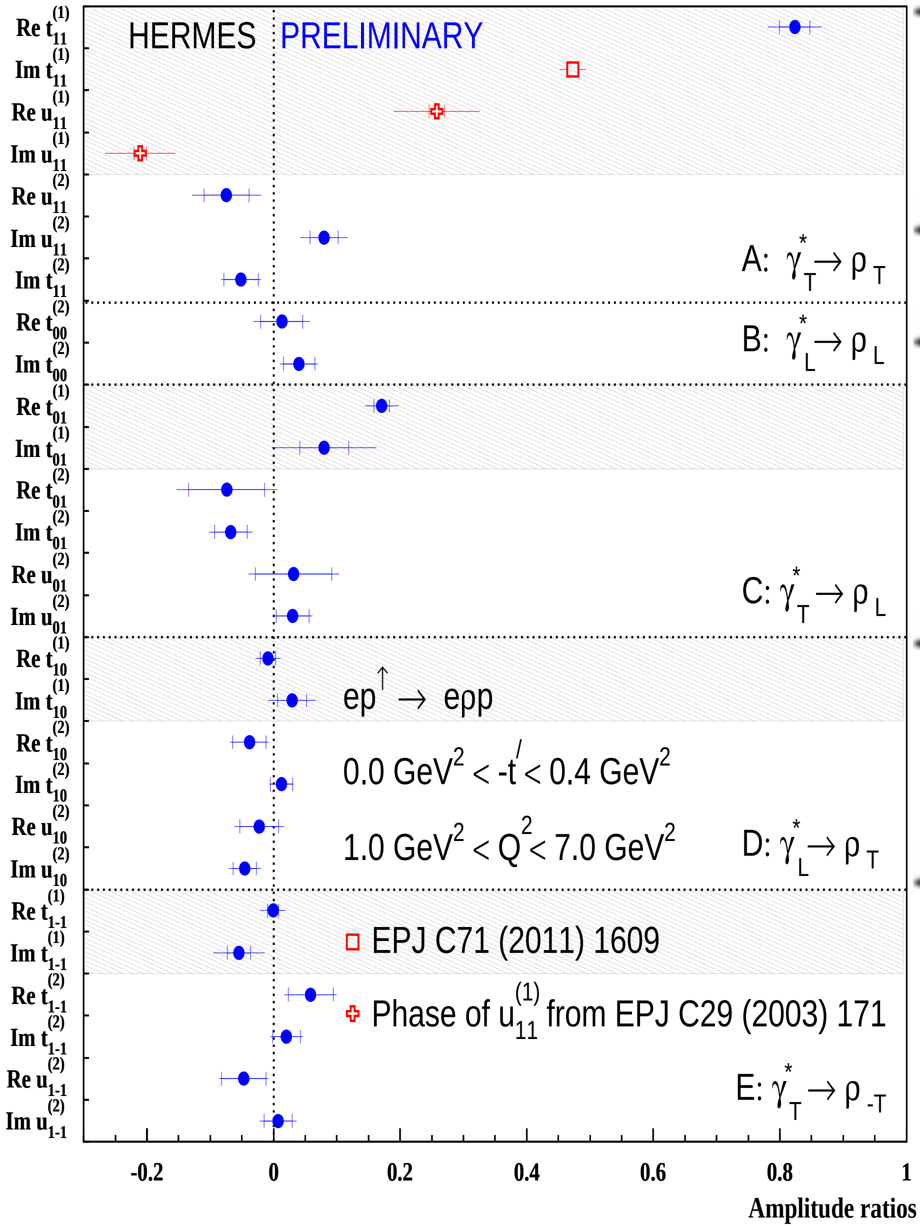
- Continuation of A.Airapetian et al., (HERMES Collaboration), Phys. Lett.679, 100 (2009)
  SDMEs for the electroproduction of ρ^0 meson on transversely polarized proton.
  30 SDMEs in Diehl representation.
- Mean value of target polarization $\langle|P_T|\rangle = 0.724 \pm 0.059$ for t' < 0.4 GeV^2.
  Mean value of beam polarization $|P_B|$ is about 0.3.
  8741 exclusive ρ^0-meson.
- SDMEs in Diehl representation.
  $u^{\lambda_V,\lambda_V^{'}}_{\lambda_\gamma,\lambda_\gamma^{'}}$ - describe production on unpolarized target.
  $n^{\lambda_V,\lambda_V^{'}}_{\lambda_\gamma,\lambda_\gamma^{'}}$, $s^{\lambda_V,\lambda_V^{'}}_{\lambda_\gamma,\lambda_\gamma^{'}}$ - describe production on transversely polarized target.
  $l^{\lambda_V,\lambda_V^{'}}_{\lambda_\gamma,\lambda_\gamma^{'}}$ - describe production on longitudinally polarized target.

Ratio of Helicity amplitudes

Angular distribution depends on SDMEs or alternatively on helicity amplitudes ratios.
Abbreviated notation for the amplitudes:

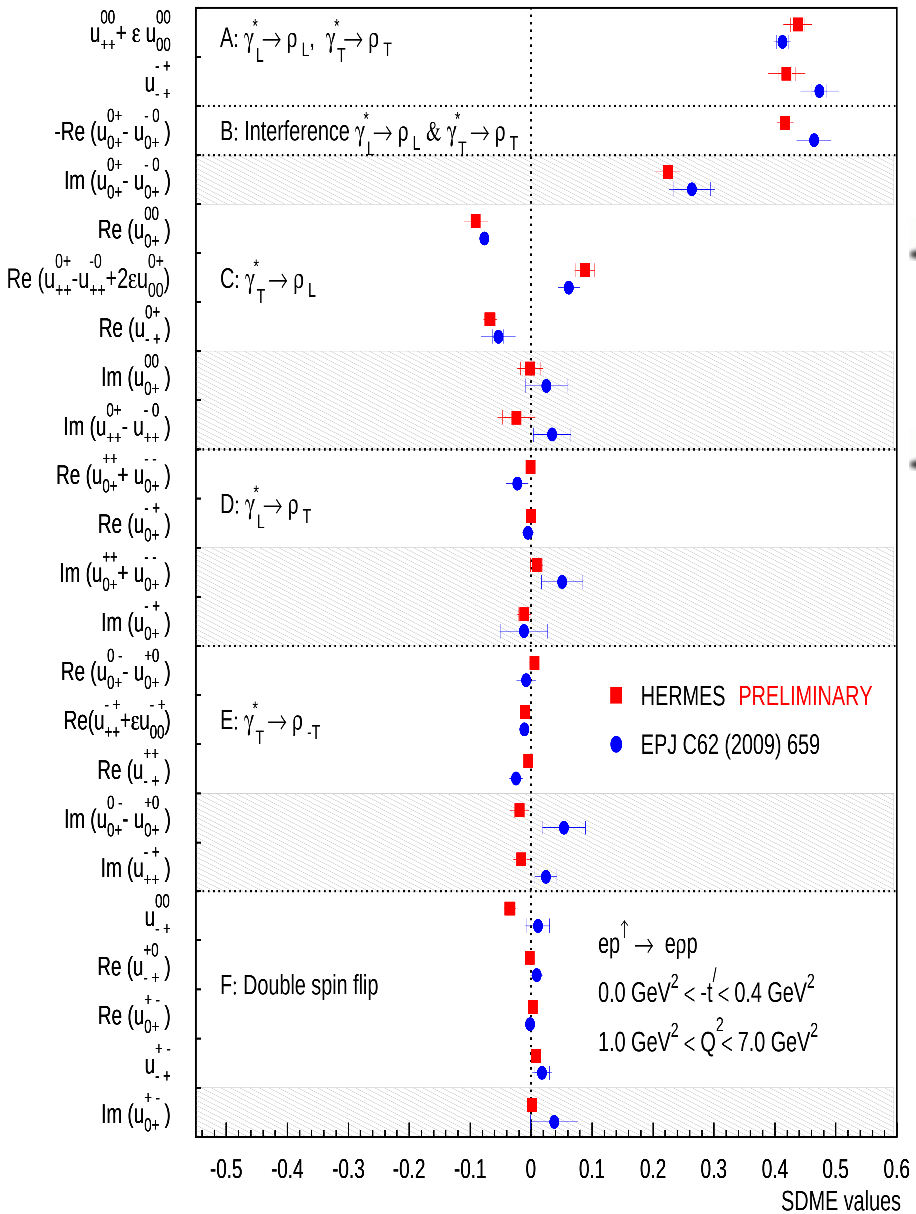
- without nucleon helicity flip,
  $T^{(1)}_{\lambda_V\lambda_\gamma} \equiv T_{\lambda_V\frac{1}{2}\lambda_\gamma\frac{1}{2}} = T_{\lambda_V-\frac{1}{2}\lambda_\gamma-\frac{1}{2}}, \quad U^{(1)}_{\lambda_V\lambda_\gamma} \equiv U_{\lambda_V\frac{1}{2}\lambda_\gamma\frac{1}{2}} = -U_{\lambda_V-\frac{1}{2}\lambda_\gamma-\frac{1}{2}},$
- with nucleon helicity flip,
  $T^{(2)}_{\lambda_V\lambda_\gamma} \equiv T_{\lambda_V\frac{1}{2}\lambda_\gamma-\frac{1}{2}} = -T_{\lambda_V-\frac{1}{2}\lambda_\gamma\frac{1}{2}}, \quad U^{(2)}_{\lambda_V\lambda_\gamma} \equiv U_{\lambda_V-\frac{1}{2}\lambda_\gamma-\frac{1}{2}} = U_{\lambda_V-\frac{1}{2}\lambda_\gamma\frac{1}{2}}$
- Amplitude ratios: $t^{(1)}_{\lambda_V\lambda_\gamma} = T^{(1)}_{\lambda_V\lambda_\gamma}/T^{(1)}_{00}, \quad t^{(2)}_{\lambda_V\lambda_\gamma} = T^{(2)}_{\lambda_V\lambda_\gamma}/T^{(1)}_{00},$
  $u^{(1)}_{\lambda_V\lambda_\gamma} = U^{(1)}_{\lambda_V\lambda_\gamma}/T^{(1)}_{00}, \quad u^{(2)}_{\lambda_V\lambda_\gamma} = U^{(2)}_{\lambda_V\lambda_\gamma}/T^{(1)}_{00}$
- Total number of amplitudes ratio is 17 (34 real functions).
- The largest amplitudes at $-t' \leq 0.4$ GeV^2 and $Q^2 \geq 1$ GeV^2 are $T^{(1)}_{00}$, $T^{(1)}_{11}$, $U^{(1)}_{11}$, and $T^{(1)}_{01}$. Small amplitudes can be extracted if they are multiplied by these amplitudes.
- Ratios $u^{(1)}_{10}$, $u^{(1)}_{01}$, $u^{(1)}_{1-1}$ are set equal to zero, since they are multiplied by small longitudinal component of the target polarization.
- The phase shift of amplitude $U^{(1)}_{11}$ and $\mathrm{Im}\{\mathrm{t}^{(1)}_{11}\}$ are fixed from earlier HERMES data.
- 25 parameters can be extracted for longitudinally polarized beam and transversely polarized target.

Ratio of Helicity amplitudes



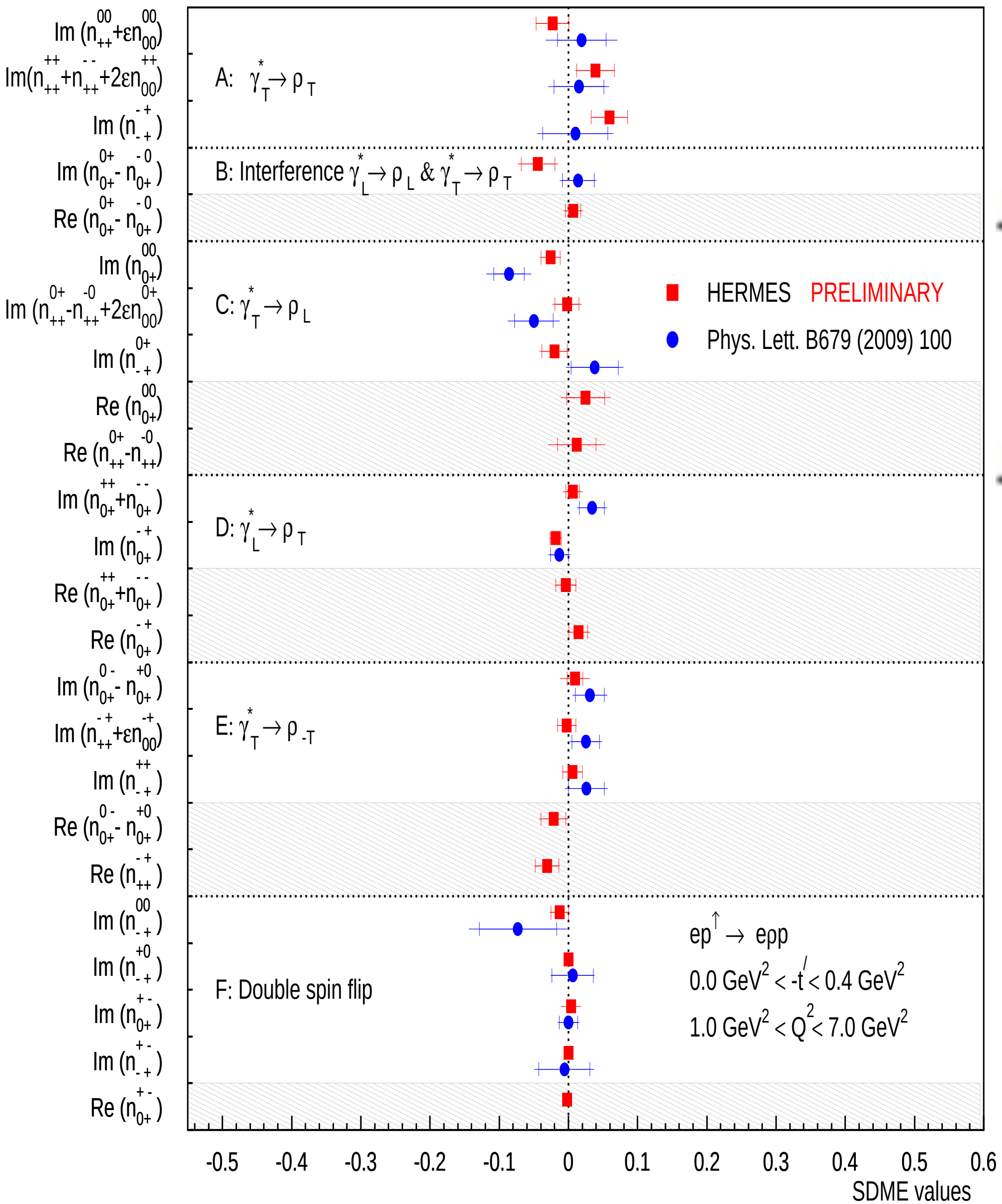
- Ratios of helicity amplitudes obtained from 25 parameter fit. The ratios without nucleon helicity flip are shown in the shaded area.
- $\mathrm{Re}\{u^{(1)}_{11}\} \neq 0$ and $\mathrm{Im}\{u^{(1)}_{11}\} \neq 0$
- The main contribution to $\sqrt{|u^{(1)}_{11}|^2 + |u^{(2)}_{11}|^2}$ comes from the amplitude $U^{(1)}_{11}$ without nucleon-helicity flip, and in particular that $|U^{(1)}_{11}|^2 \gg |U^{(2)}_{11}|^2$.
- The amplitude ratios $\mathrm{Im}\{t^{(2)}_{01}\}$, $\mathrm{Im}\{u^{(2)}_{11}\}$, and $\mathrm{Im}\{u^{(2)}_{10}\}$ deviate from zero by about two standard deviations
- Within the total experimental uncertainty, all determined amplitude ratios with nucleon-helicity flip are consistent with zero.

Ratio of Helicity amplitudes



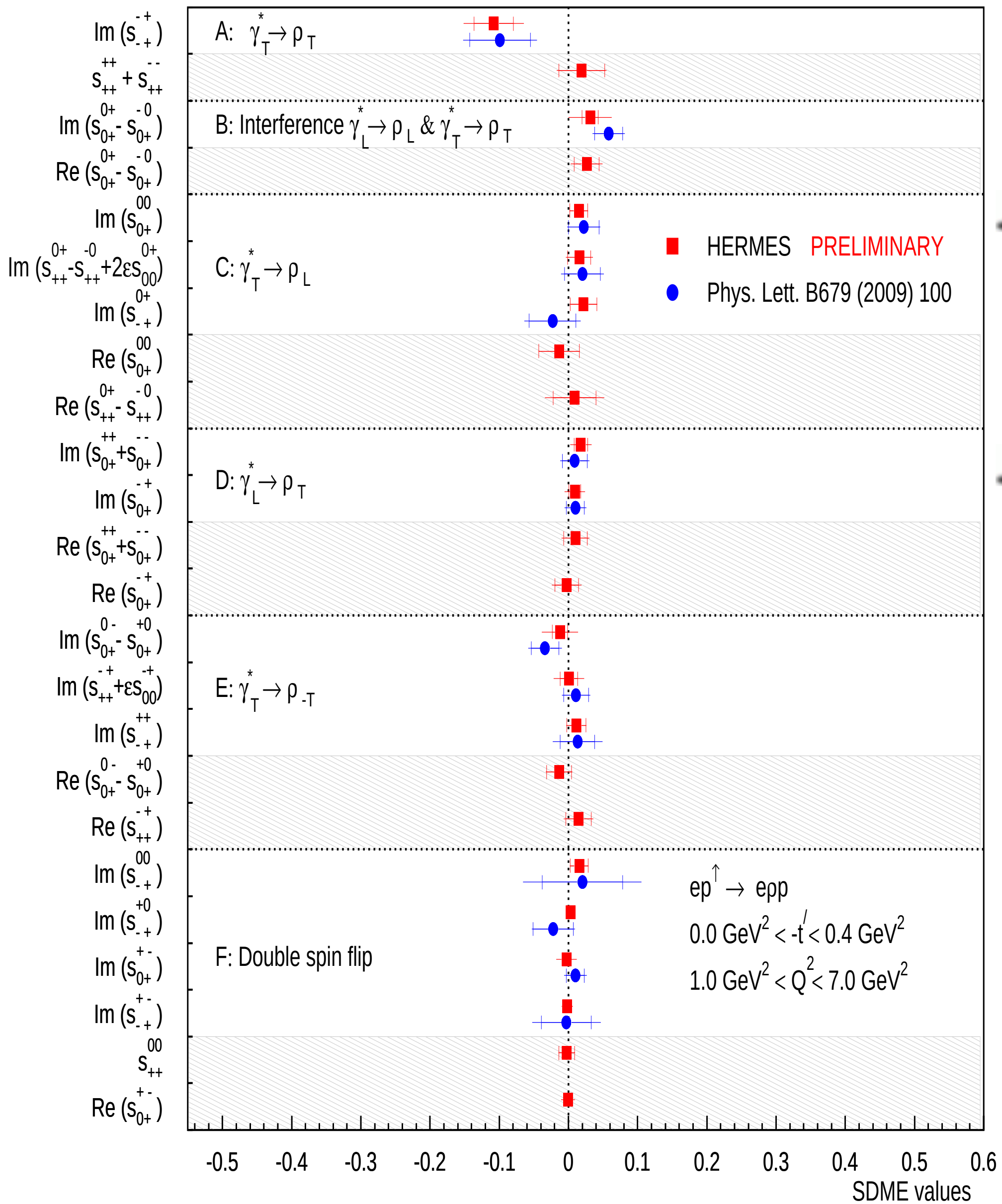
- Comparison of calculated (red points) and "direct" (blue) SDMEs $u^{\lambda_V,\lambda'_V}_{\lambda_\gamma,\lambda'_\gamma}$ in Diehl representation.
- SDMEs coresponding to longitudinally polarized beam are shown in shaded areas.

Ratio of Helicity amplitudes



- Comparison of calculated (red points) and "direct" (blue) SDMEs $n^{\lambda_V,\lambda'_V}_{\lambda_\gamma,\lambda'_\gamma}$ in Diehl representation.
- SDMEs coresponding to longitudinally polarized beam are shown in shaded areas.

Ratio of Helicity amplitudes



- Comparison of calculated (red points) and "direct" (blue) SDMEs $s^{\lambda_V,\lambda'_V}_{\lambda_\gamma,\lambda'_\gamma}$ in Diehl representation.
- SDMEs coresponding to longitudinally polarized beam are shown in shaded areas.

Summary

- Exclusive ω ρ^0 electroproduction is studied at HERMES using a longitudinally polarized lepton beam and unpolarized (polarized) hydrogen and deuterium targets in the kinematic region $Q^2 > 1.0$ GeV^2, 3.0 GeV $< W < 6.3$ GeV, and $-t' < 0.2$ GeV^2, $-t' < 0.4$ GeV^2.
- Using an unbinned maximum likelihood method, 15 unpolarized, and, for the first time, 8 polarized spin density matrix elements are extracted.
- No significant differences between proton and deuteron results are seen.
- Using the SDMEs r^1_{1-1} and $\mathrm{Im}\{r^2_{1-1}\}$, it is shown that for exclusive ω-meson production it is shown that $|U_{11}|^2 > |T_{11}|^2$.
- The UPE contribution seems to be very large (dominant) for ω meson production.
- Two cosine modulations for unpolarized target and five sine modulations for transversely polarized target are presented for the entire kinematic region.extracted asymmetry amplitudes favors a positive sign of the $\pi\omega$ form factor.
- For the first time 25 amplitudes ratio for the ρ-meson electroproduction on transversely polarized target is obtained.