Direct Extraction of Helicity Amplitude Ratios in Exclusive ρ^0 Electroproduction

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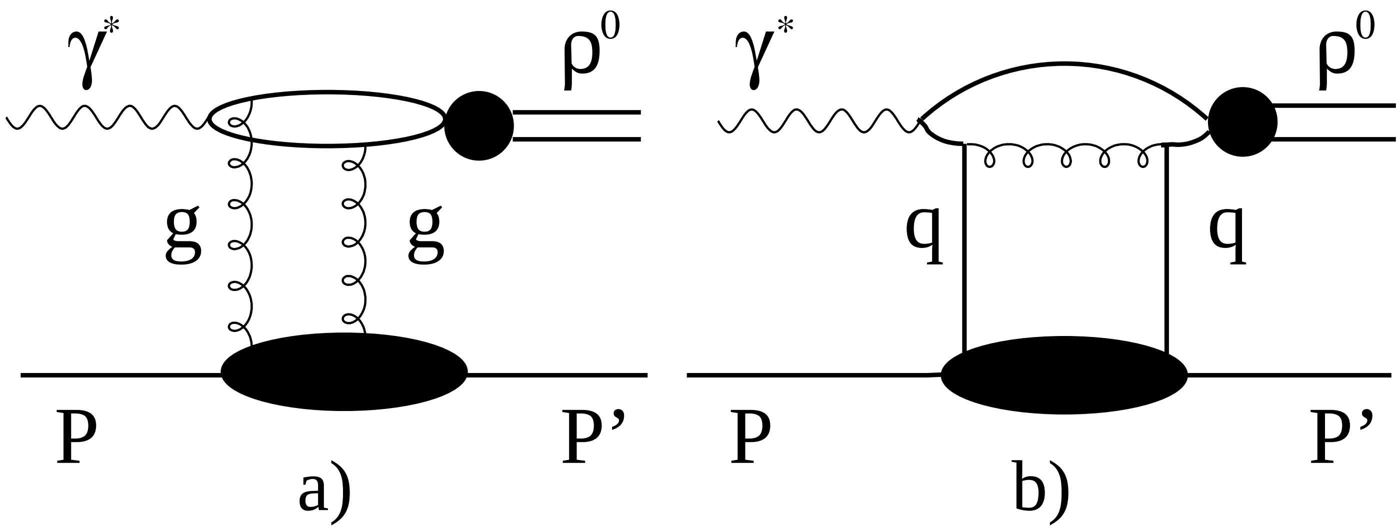
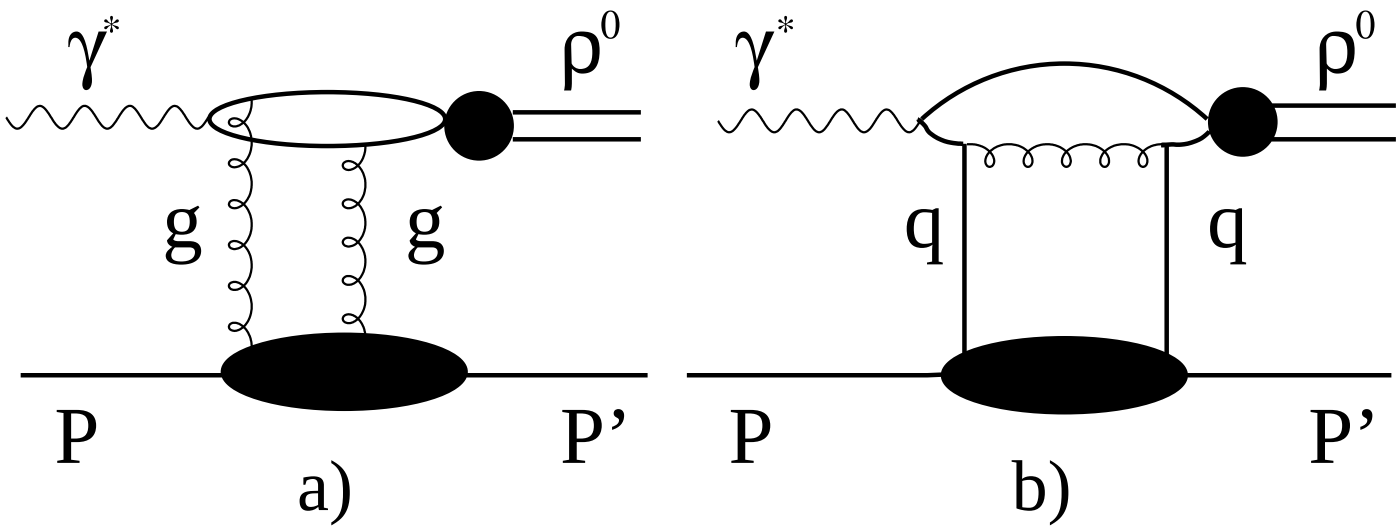
Physics Motivation



- $\gamma^* + N \to V + N$ is a perfect reaction to study both vector-meson production mechanism and hadron structure. Spin Density Matrix Elements (SDMEs) of ρ^0 at HERMES: EPJ C62 (2009) 659. SDMEs are expressible in terms of ratios of helicity amplitudes, hence ratios can be extracted from angular distribution of decay $\pi^+\pi^-$.
- Data on $d\sigma/dt = \sum |F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}|^2$ additional to SDMEs gives a possibility to extract moduli of all the helicity amplitudes and phase differences between them.
- Generalized Parton Distributions (GPDs) of the nucleon can be obtained from the amplitude $F_{00} \equiv F_{0\frac{1}{2}0\frac{1}{2}}$ ($\gamma_L \to V_L$) for which factorization theorem is proved. Extraction of amplitude ratios is a first step to get F_{00} and GPDs.
- Difference between proton and deuteron results would points out contribution of $q\bar{q}$-exchange with isospin $I = 1$ and natural parity $P = (-1)^J$ (ρ, a_0, a_2 reggeons).

Physics Motivation



- Extraction of amplitude ratios provides a possibility to distinguish between contributions of Natural Parity Exchange (NPE, $J^P = 0^+,\ 1^-, \ldots$) amplitudes $T_{\lambda_V \lambda_\gamma}$ (Pomeron = two-gluon exchange, ρ, ω, a_2,... reggeons = $q\bar{q}$ exchange) and Unnatural Parity Exchange (UPE, $J^P = 0^-,\ 1^+, \ldots$) amplitudes (π, a_1, b_1,...reggeons = $q\bar{q}$ exchange) $U_{\lambda_V \lambda_\gamma}$ better than in SDME method.

- Violation of s-channel helicity ($\lambda_V \neq \lambda_\gamma$) can be studied more reliably on the language of amplitude ratios rather than in SDME analysis. Spin-flip amplitudes T_{01}, T_{10} provide information on vector-meson structure. They are zero in the absence of quark motion in vector mesons (if quark carries momentum fraction $z = \frac{1}{2}$).

Kinematics of Exclusive ρ^0-Meson Production at HERMES

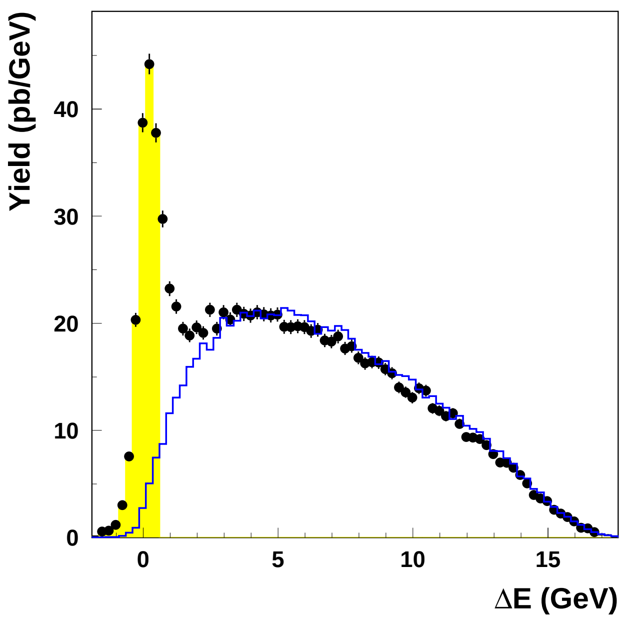
- $W = 3.0 \div 6.5$ GeV, $< W >= 4.9$ GeV
- $Q^2 = 0.5 \div 7.0$ GeV^2, $< Q^2 >= 1.95$ GeV^2
- $x_B = 0.01 \div 0.35$, $< x_B >= 0.08$
- $0 \leq -t' \leq 0.4$ GeV^2, $< -t' >= 0.13$ GeV^2 with $t' = t - t_{min}$

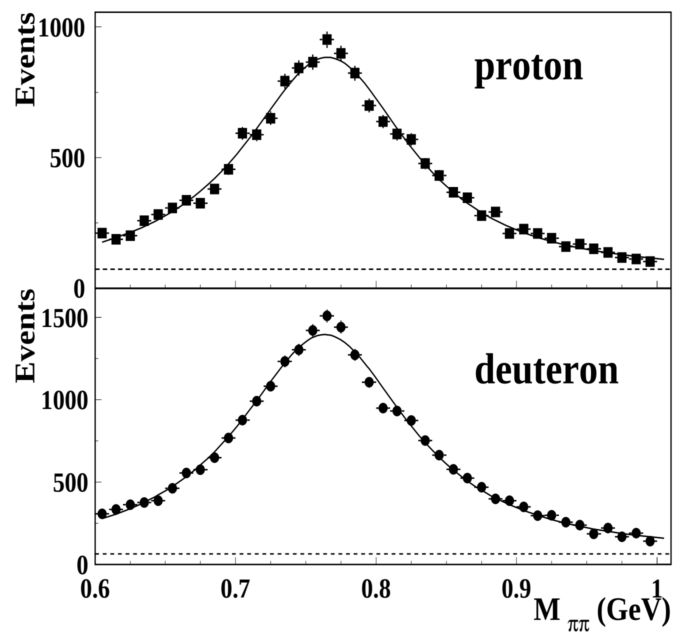
Total number of events (1996-2005)

Deuteron: ρ^0 - 16388

Hydrogen: ρ^0 - 9860

$\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$ with $M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-})^2$ and M_X being missing mass

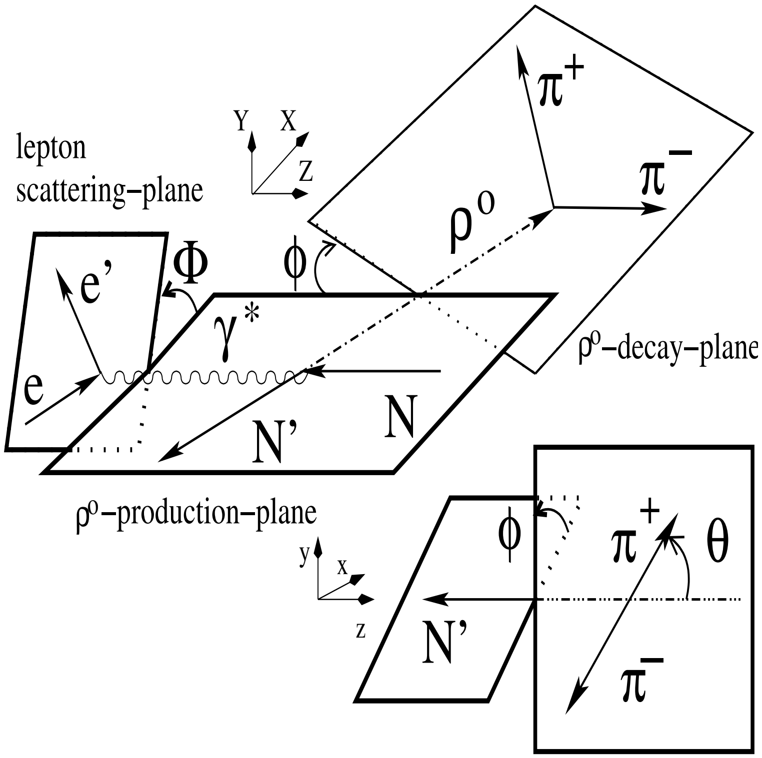


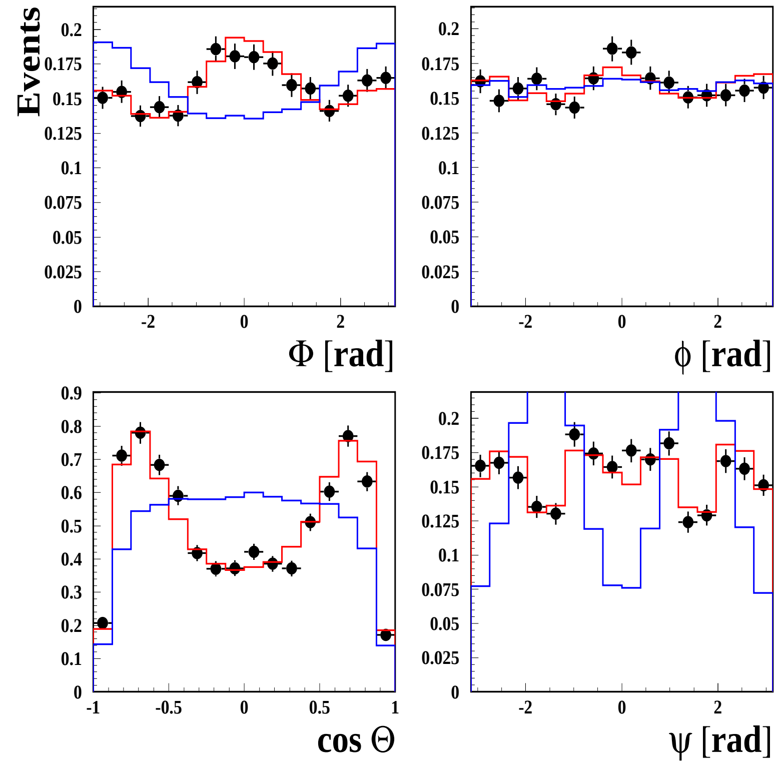


$-1.0 < \Delta E < 0.6$ GeV, $0.6 < M_{\pi\pi} < 1$ GeV,

SIDIS background is subtracted with the help of MC (PYTHIA)

Data Processing using Maximum Likelihood Method in MINUIT





$\Psi = \phi - \Phi$ (in S-Channel Helicity Conservation (SCHC) approximation)

- Monte Carlo Events: 3-dimensional matrix of fully reconstructed MC events at initial uniform angular distribution.
- Binned Maximum Likelihood (BML) Method: $8 \times 8 \times 8$ bins of $\cos(\Theta), \phi, \Phi$. Simultaneous fit of 23 SDMEs (5 ratios of helicity amplitudes) for data with negative and positive beam helicity ($< P_b >= \pm 53.5\%$) and unpolarized target.
  Agreement of fitted angular distributions with the HERMES data

Amplitude Method and Spin-Density Matrix Element Method

- First: $e \to e + \gamma^*$ (QED)
  Spin-Density Matrix (SDM) of the virtual photon $\rho(\Phi, \epsilon)$
- Second: $\gamma^* + N \to V + N$ (QCD)
  Helicity amplitudes in CM system of $\gamma^* N$ $F_{\lambda_V \lambda'_N ; \lambda_\gamma \lambda_N}(W, Q^2, t')$
  Vector-meson spin-density matrix
  $r = \frac{1}{2N} \mathrm{tr}_{\lambda_N \lambda'_N} \{\mathrm{F}\, \rho\, \mathrm{F}^+\}$,
  $N = \mathrm{Tr}_{\lambda_V \lambda'_V \lambda_N \lambda'_N} \{\mathrm{F}\, \rho\, \mathrm{F}^+\}$.
  If SDM of γ^* is decomposed into set of nine matrices Σ^α then SDMEs are
  $r^\alpha_{\lambda_V \lambda'_V} = \frac{1}{2N} \mathrm{tr}_{\lambda_N \lambda'_N} \{\mathrm{F}\, \Sigma^\alpha\, \mathrm{F}^+\}_{\lambda_V \lambda'_V}$.
- Third: $\rho^0 \Rightarrow \pi^+\pi^-$ (conservation of $\vec{J}$)
  $|\rho^0; 1m > \to |\pi^+\pi^-; 1m > \Rightarrow Y_{1m}(\theta, \phi)$
  Angular distribution $\mathcal{W}(\Phi, \phi, \cos\Theta)$ depends linearly on $r^\alpha_{\lambda_V \lambda'_V}$ and P_b.

SDME method

- 23 LU SDMEs (for Longitudinally polarized beam and Unpolarized target) are considered as free parameters in fit of angular distribution of pions from decay $\rho^0 \to \pi^+ + \pi^-$ in any small bin of kinematic variables (Q^2, t' etc.).
- Relation of SDMEs and helicity amplitudes is ignored.

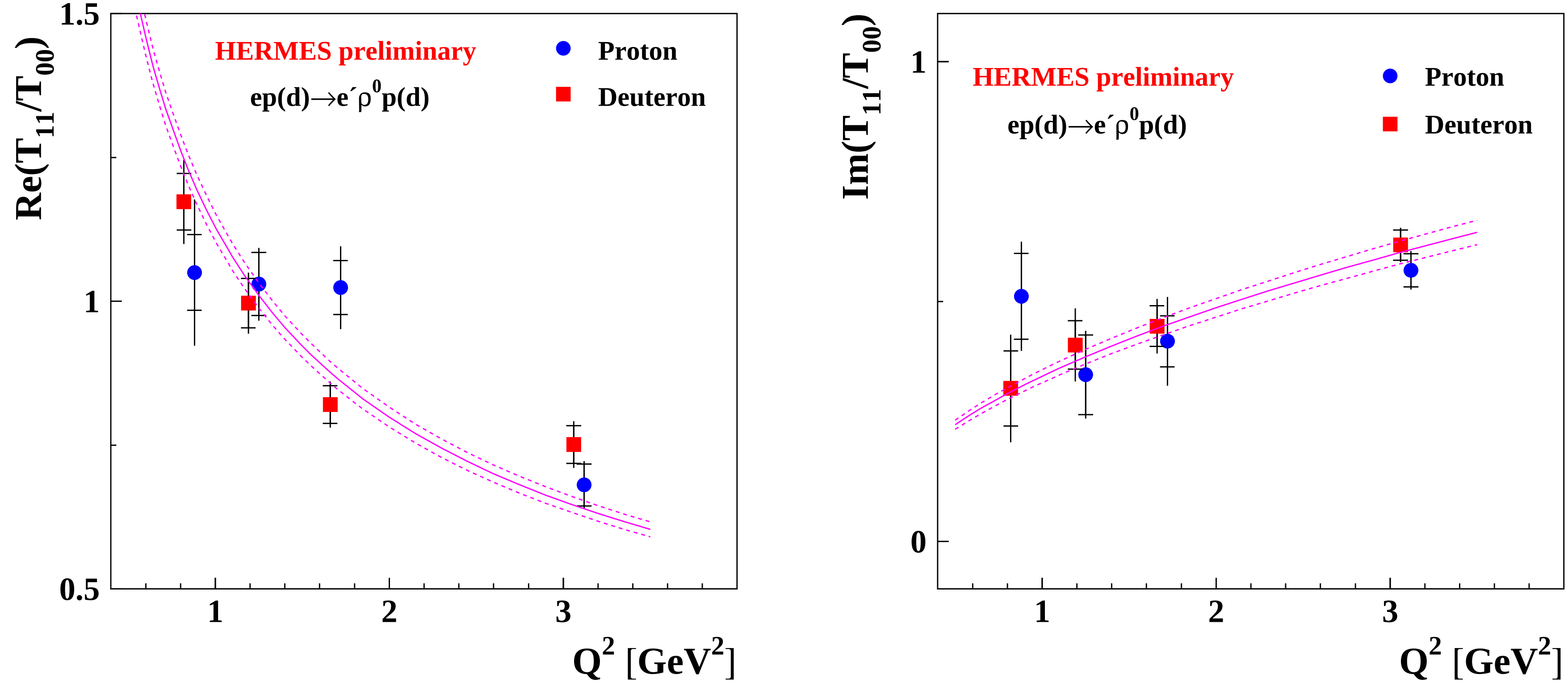
Amplitude method

- SDMEs are expressed in terms of ratios of helicity amplitudes.
- Helicity amplitude ratios are free parameters in fit of angular distribution in any small bin.
- Binning 4×4 of Q^2 and $-t'$.

Amplitude Method

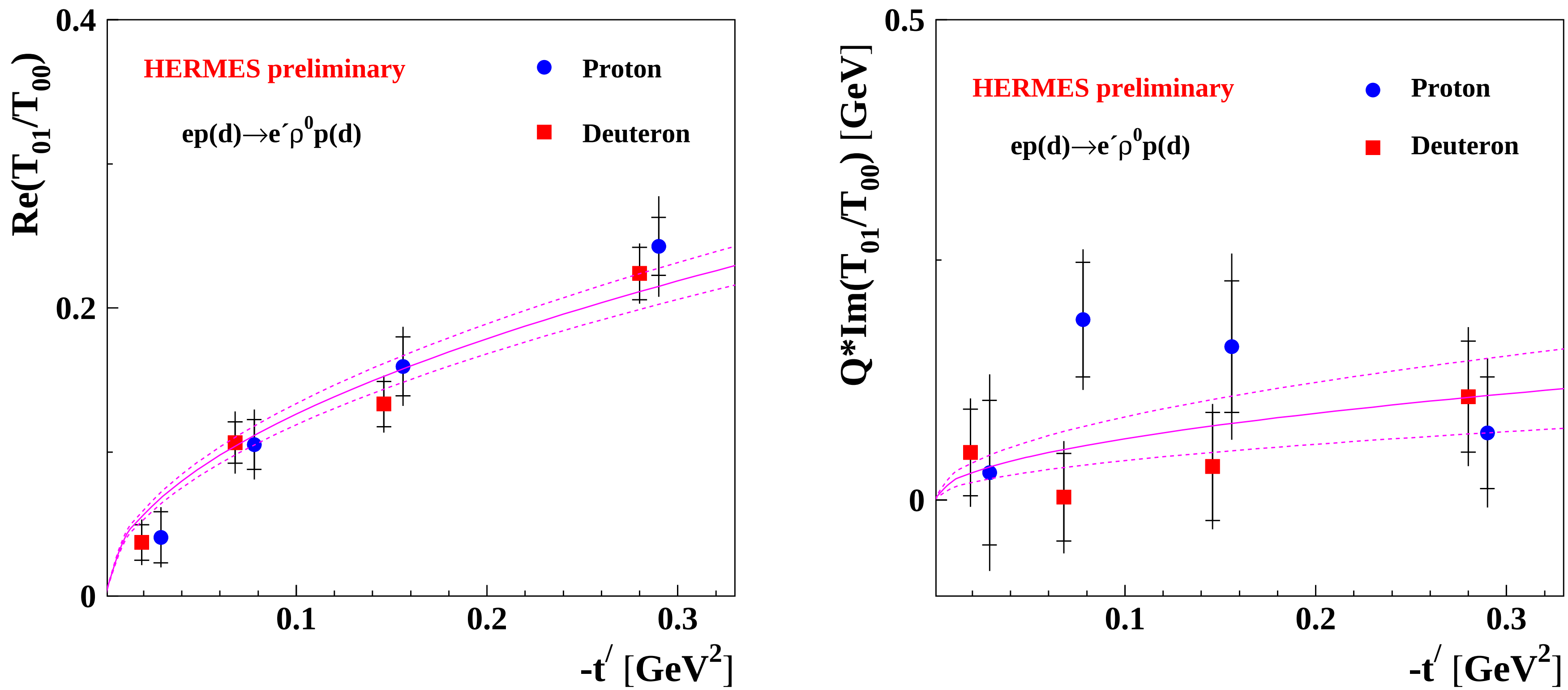
- 18 independent amplitudes
  34 real free parameters (functions)
- 23 LU SDMEs (< 34)
- Hierarchy of amplitudes at small t' and high Q^2.
  Neglect small amplitudes.
- NPE ($T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$) and UPE ($U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$) helicity amplitudes.
  $F = T + U$,
  $T/U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = \frac{1}{2}(F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$
  $\pm(-1)^{\lambda_N - \lambda'_N} F_{\lambda_V -\lambda'_N \lambda_\gamma -\lambda_N})$
  Shorthand notation:
  $T_{\lambda_V \lambda_\gamma} = T_{\lambda_V \frac{1}{2} \lambda_\gamma \frac{1}{2}}$
- No interference between NPE and UPE amplitudes for LU SDMEs
- UPE are suppressed at high W.
  Neglect all UPE amplitudes?
- No interference between amplitudes with and without nucleon spin flip.
- $T_{\lambda'_N \neq \lambda_N}/T_{\lambda'_N = \lambda_N} \sim \alpha = v_T/(2M)$.
  Fractional contribution of NPE amplitudes with $\lambda'_N \neq \lambda_N$ to LU SDMEs $\sim \alpha^2 <$ experimental uncertainty.
- Neglect with NPE nucleon spin-flip amplitudes retains T_{11}/T_{00}, T_{01}/T_{00}, T_{10}/T_{00}, T_{1-1}/T_{00} (8 parameters).
- SDME analysis: S-channel helicity conservation (SCHC) at small t'.
  $|U_{01}|, |U_{10}|, |U_{1-1}| \ll |U_{11}|$ retains only $|U_{11}| = \sqrt{|U_{1\frac{1}{2}1\frac{1}{2}}|^2 + |U_{1-\frac{1}{2}1\frac{1}{2}}|^2}$
  9th parameter: $|U_{11}|/|T_{00}|$.
- Hierarchy of extracted amplitudes at HERMES kinematic region
  $|T_{00}|^2 \sim |T_{11}|^2 \gg |U_{11}|^2 > |T_{01}|^2 > |T_{10}|^2 \sim |T_{1-1}|^2$

Kinematic Dependences of Ratios of Helicity Amplitudes



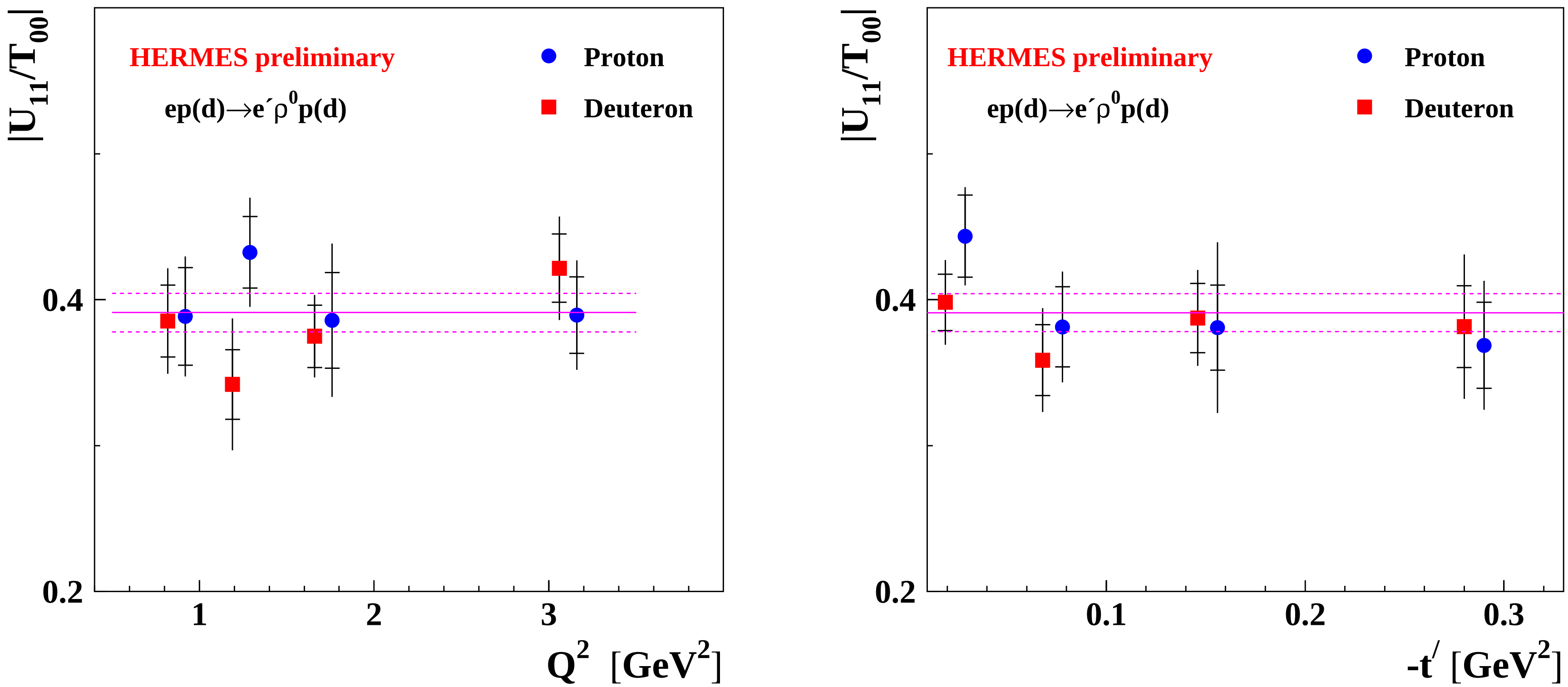
- No difference between proton and deuteron results for amplitude ratio T_{11}/T_{00}.
- pCQD prediction (Ivanov, Kirshner; Kuraev, Nikolaev, Zakharov): $T_{11}/T_{00} \propto M_\rho/Q$.
- Fit of Q dependence: $\mathrm{Re(T_{11}/T_{00}) = a/Q}$, $\mathrm{Im(T_{11}/T_{00}) = b \cdot Q}$.
  Combined data on proton and deuteron: $a = 1.129 \pm 0.024$ GeV, $\chi^2/N_{df} = 1.02$;
  $b = 0.344 \pm 0.014$ GeV^{-1}, $\chi^2/N_{df} = 0.87$.
- Behaviour of $\mathrm{Im(T_{11}/T_{00})}$ is in a contradiction with high-Q asymptotic in pQCD.
  Phase difference $\delta_{11} \sim 30^\circ$ and grows with Q^2 in disagreement with pQCD calculation
- No t dependence: difference of slopes $\beta_L - \beta_T = -0.6 \pm 0.4$ GeV^{-2}.

Kinematic Dependences of Ratios of Helicity Amplitudes



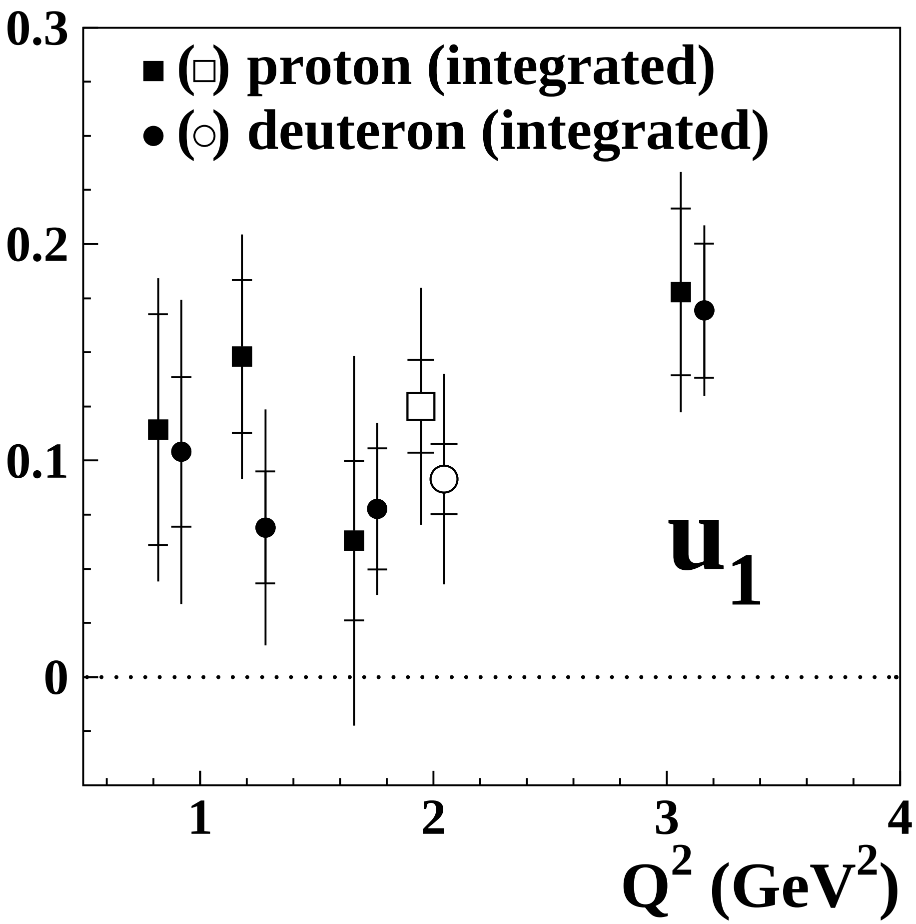
- Violation of S-Channel Helicity $(\lambda_V \neq \lambda_\gamma)$: $T_{01} \neq 0$.
- No difference between proton and deuteron results for amplitude ratio T_{01}/T_{00}.
- pQCD prediction (Ivanov, Kirshner; Kuraev, Nikolaev, Zakharov): $\frac{T_{01}}{T_{00}} \propto \frac{\sqrt{-t'}}{Q}$.
- Fit of 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 proton and deuteron data: $a = 0.399 \pm 0.023$ GeV^{-1}, $\chi^2/N_{df} = 0.72$; $b = 0.20 \pm 0.07$, $\chi^2/N_{df} = 1.09$.

Kinematic Dependences of Ratios of Helicity Amplitudes



- No difference between proton and deuteron results for amplitude ratio $|U_{11}/T_{00}|$.
- pQCD prediction: $U_{11}/T_{00} \propto M_\rho/Q$.
- Neither Q^2 nor t' dependence: $|U_{11}|/|T_{00}| = a$, $a = 0.391 \pm 0.013$, $\chi^2/N_{df} = 0.44$ where $|U_{11}|^2 \equiv |U_{1\frac{1}{2}1\frac{1}{2}}|^2 + |U_{1\frac{1}{2}1-\frac{1}{2}}|^2$.
- Unnatural Parity Exchange is seen much better than in SDME method.
- Contradiction both with high-Q asymptotic and one-pion-exchange dominance.

Test of Unnatural-Parity Exchange for ρ^0 Meson



$u_1 = 0.125 \pm 0.021_{stat} \pm 0.050_{syst}$ (H),
$u_1 = 0.091 \pm 0.016_{stat} \pm 0.046_{syst}$ (D)
$u_1 = 0.106 \pm 0.036_{tot}$ (H+D)

HERMES, Eur. Phys. J. C62 (09) 659.

- Natural and Unnatural Parity Exchanges in the t-channel
  NPE: GPD H, E ; $T_{\lambda_\rho \lambda_\gamma}$
  UPE: GPD $\tilde{H}$, $\tilde{E}$; $U_{\lambda_\rho \lambda_\gamma}$
  NPE (Pomeron, ρ, ω, f_2, a_2, ...) dominate and UPE (π, a_1, b_1...) are suppressed at high energies
- Signal of UPE in SDME method

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

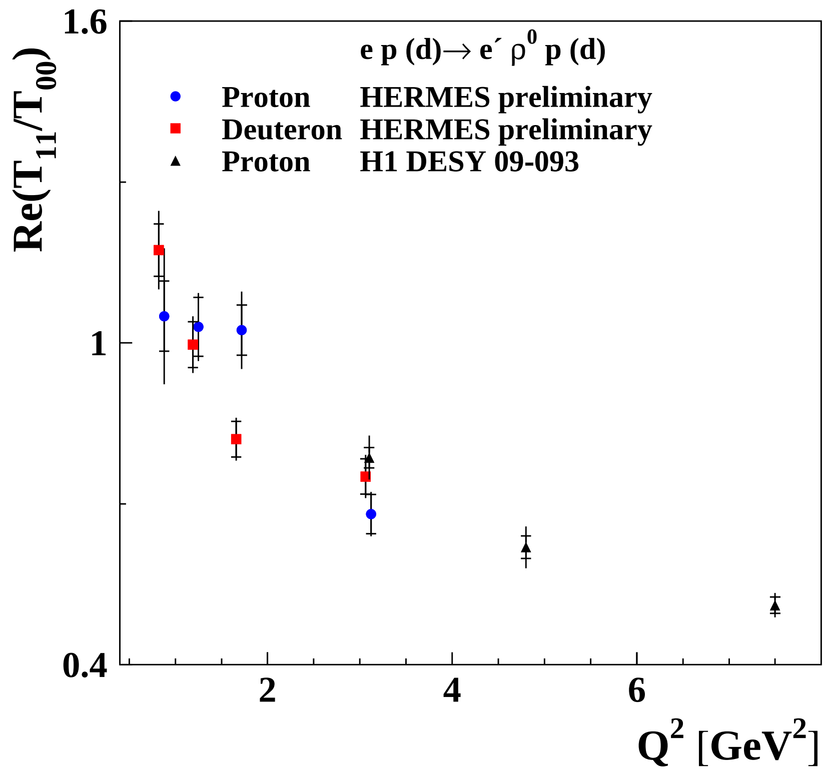
$$u_1 = \sum_{\lambda_N \lambda'_N} \frac{2\epsilon |U_{10}|^2 + |U_{11} + U_{-11}|^2}{N}$$

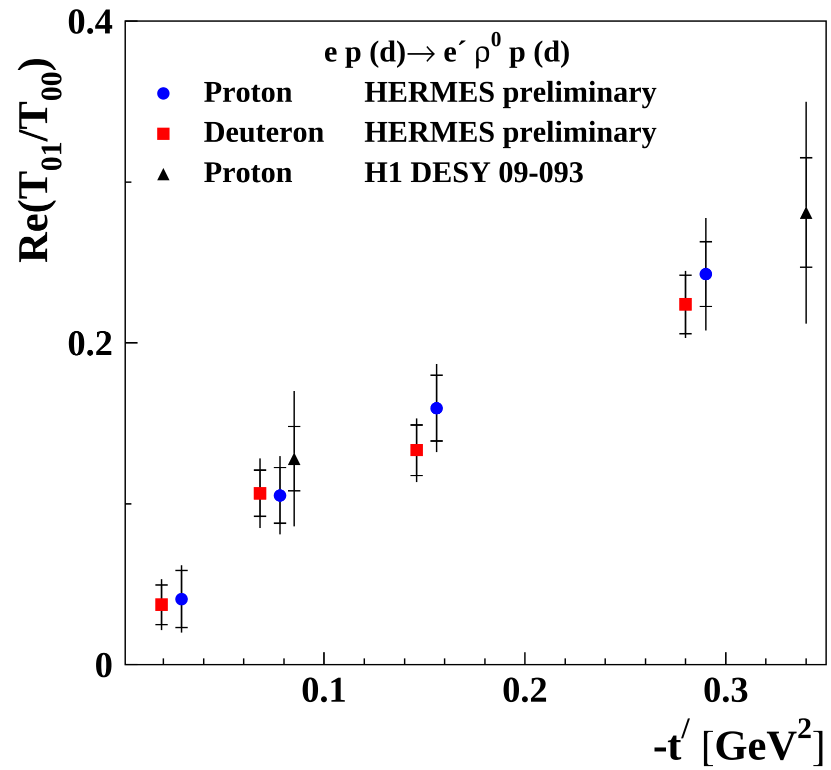
where $N = N_T + \epsilon N_L$,

$$N_T = \sum_{\lambda_N \lambda'_N} (|T_{11}|^2 + |T_{01}|^2 + |T_{-11}|^2 + |U_{11}|^2 + |U_{01}|^2 + |U_{-11}|^2),$$

$$N_L = \sum_{\lambda_N \lambda'_N} (|T_{00}|^2 + |T_{10}|^2 + |T_{-10}|^2 + |U_{10}|^2 + |U_{-10}|^2).$$

World Results on Ratios of Helicity Amplitudes





- H1: Unpolarized beam and unpolarized target (15 SDMEs), $< Q^2 >= 3.3$ GeV^2.
- Additional assumption: all amplitudes are imaginary, all amplitude ratios are real.
- HERMES: Longitudinally polarized beam and unpolarized target (23 SDMEs). Both real and imaginary parts of ratios of helicity amplitudes are extracted.
- Excellent agreement of amplitude ratios extracted by H1 and HERMES.

Summary

- Measurement of ρ^0-meson production by longitudinally polarized electron/positron beam on unpolarized proton and deuteron in the HERMES experiment permits to extract both real and imaginary parts of T_{11}/T_{00}, T_{01}/T_{00}, T_{10}/T_{00}, T_{1-1}/T_{00}, and $|U_{11}/T_{00}|$.
- Dependences of the most reliably obtained ratios T_{11}/T_{00}, T_{01}/T_{00}, $|U_{11}/T_{00}|$ on Q^2 and t' is studied. The observed dependences of $\mathrm{Im}(\mathrm{T}_{11}/\mathrm{T}_{00})$ and $|U_{11}/T_{00}|$ are in contradiction with high-Q asymptotic behaviour predicted in pQCD while dependences of $\mathrm{Re}(\mathrm{T}_{11}/\mathrm{T}_{00})$ and $\mathrm{Im}(\mathrm{T}_{01}/\mathrm{T}_{00})$ are in agreement with pQCD prediction.
- No statistically significant difference between proton and deuteron results for amplitude ratios T_{11}/T_{00}, T_{01}/T_{00}, $|U_{11}/T_{00}|$ is found.
- Violation of S-channel helicity is observed in amplitude method with higher accuracy than in SDME method.
- Contribution of unnatural parity exchange amplitude U_{11} of ρ^0-meson production is found in amplitude method with much higher accuracy than in SDME analysis.

Outlook

- To decrease background contribution by measuring recoil nucleon.
- Include data on transversely polarized target into amplitude analysis.