Many Thanks to Organizing Committee for Invitation to HSQCD2008 Conference

Exclusive electroproduction of ρ^0 and ϕ mesons at HERMES

S. I. Manayenkov
on behalf of the HERMES collaboration,
Petersburg Nuclear Physics Institute

Hadron Structure and QCD,
June 30 - July 04, 2008, Gatchina, Russia

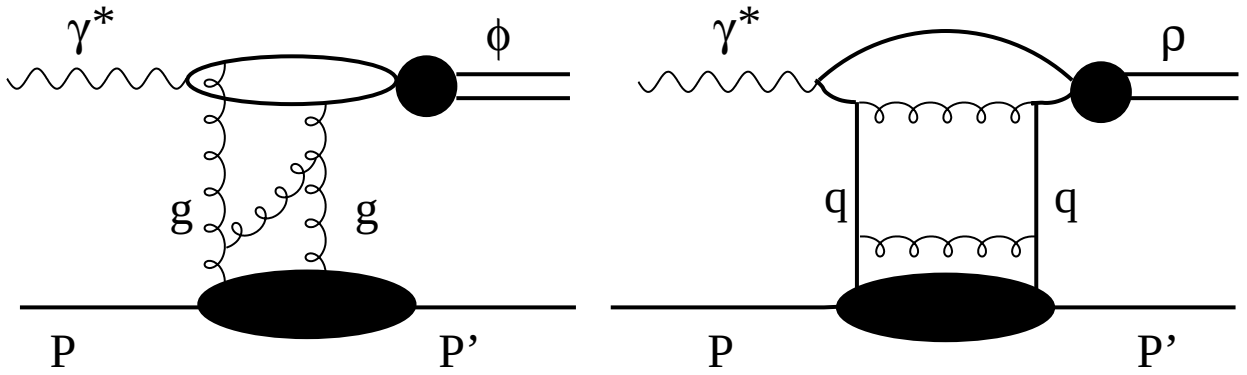
- Physics Motivation
- Reaction $e + N \rightarrow e + V + N$
- Kinematics of Exclusive ρ^0 and ϕ Production at HERMES
- Method of Data Processing

R e s u l t s:

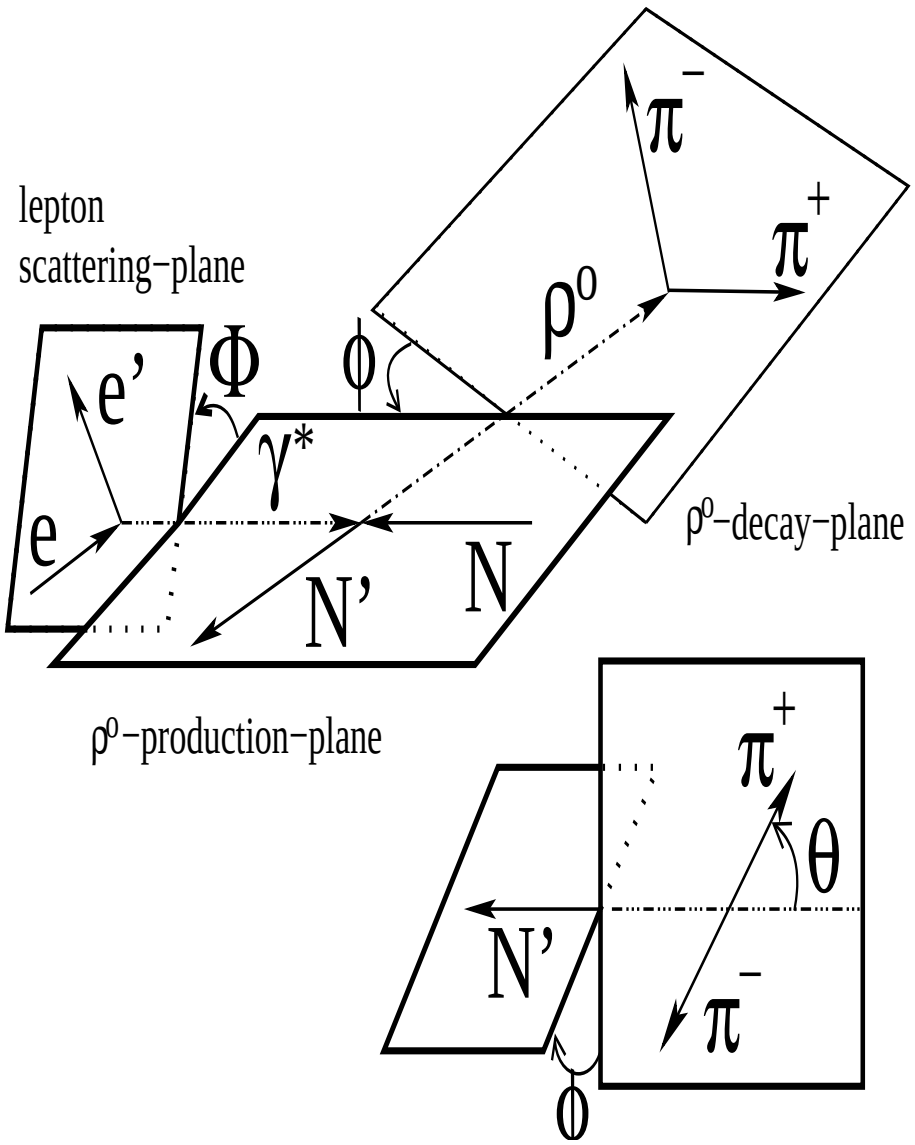
- Spin Density Matrix Elements $r^{\alpha}_{\lambda_\rho \lambda'_\rho}$
- Longitudinal-to-Transverse Cross-Section Ratio
- Kinematic Dependences of SDMEs
- Test of Unnatural-Parity Exchange
- Summary & Outlook

Physics Motivation

- $\gamma^* + N \rightarrow V + N$ is a perfect reaction to study vector-meson ($V = \rho^0,\ \phi$) production mechanism: spin state of γ^* is known from QED ; decays $\rho^0 \rightarrow \pi^+ + \pi^-$ and $\phi \rightarrow K^+ + K^-$ are self-analysing. The process provides information on Generalized Parton Distributions (GPD) of the nucleon.
- Measurement of s-channel helicity violation (SCHV) proves existence of spin-flip amplitudes $T_{01},\ T_{10},\ T_{-11}$. In the absence of quark Fermi-motion in vector mesons, $T_{01} = T_{10} = 0$.
- Hierarchy of amplitudes of diagonal $\lambda_\gamma \rightarrow \lambda_V$ transitions is measured via the cross section ratio ($R = \sigma_L/\sigma_T$) of production by photons with longitudinal (L) and transverse (T) polarization. The hierarchy for spin-flip amplitudes can be established by comparing values of different SCHV spin density matrix elements (SDMEs).
- Vector-meson production mechanisms can be tested both by comparing experimental SDMEs with theoretical calculations and via comparison of ρ^0 and ϕ production. Two gluon (Pomeron) and quark-antiquark (secondary reggeons) exchanges in the t-channel contribute to ρ^0 production while the dominant contribution to ϕ production is two gluon exchange.
- Measurement of SDMEs provides a possibility to distinguish between contributions of Natural Parity Exchange (NPE) amplitudes $T_{\lambda_V \lambda_\gamma}$ and Unnatural Parity Exchange (UPE) amplitudes $U_{\lambda_V \lambda_\gamma}$. In Regge phenomenology, NPE corresponds to Pomeron, $\rho,\ \omega,\ a_2,\ \ldots$ exchanges ($J^P = 0^+,\ 1^-,\ 2^+,\ \ldots$) and exchange with $\pi,\ a_1,\ b_1$,...($J^P = 0^-,\ 1^+,\ 2^-,\ \ldots$) is UPE.



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



- First: $e \to e + \gamma^*$ (QED)
  Spin-density matrix
  of the virtual photon $\rho(\gamma^*)$
- Second: $\gamma^* + N \to V + N$ (QCD)
  Helicity amplitudes in CMS of $\gamma^* N$
  $F_{\lambda_V \lambda'_N;\lambda_\gamma \lambda_N} = F_{\lambda_V \lambda_\gamma}$,
  Vector-meson spin-density matrix
  $r(V) = \frac{1}{2N} \mathrm{tr}_{\lambda_N \lambda'_N} \{\mathrm{F}\ \rho(\gamma^*)\ \mathrm{F}^+\}$.
  Free parameters $r^\alpha_{\lambda_V \lambda'_V}$ where
  $r^\alpha = \frac{1}{2N} \mathrm{tr}_{\lambda_N \lambda'_N} \{\mathrm{F}\ \Sigma^\alpha\ \mathrm{F}^+\}$
  with $\alpha = 0,\ 1, ...,\ 8$. If contributions of transverse and longitudinal photons are not separated, then $r^0_{\lambda_V \lambda'_V} + \epsilon r^4_{\lambda_V \lambda'_V} \Rightarrow r^{04}_{\lambda_V \lambda'_V}$.
- Third: $\rho^0 \Rightarrow \pi^+ \pi^-$ (conservation of $\vec{J}$)
  $|\rho^0; 1m> \ \to\ |\pi^+\pi^-; 1m> \ \Rightarrow\ Y_{1m}(\theta, \phi)$

Kinematics of Exclusive ρ^0 and ϕ Production at HERMES

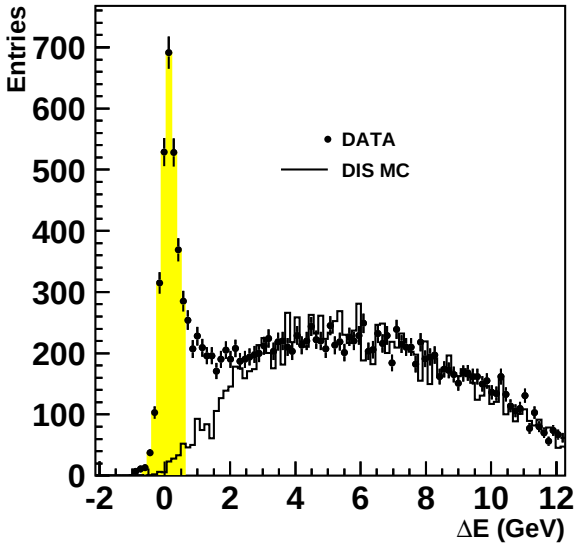
- $W = 3.0 \div 6.5$ GeV, $< W >= 4.9$ GeV
- $Q^2 = 1.0 \div 5.0$ GeV^2, $< Q^2 >= 2.3$ GeV^2
- $x_B = 0.01 \div 0.35$, $< x_B >= 0.07$
- $-t' =\leq 0.4$ GeV^2, $< -t' >= 0.13$ GeV^2 with $t' = t - t_{min}$

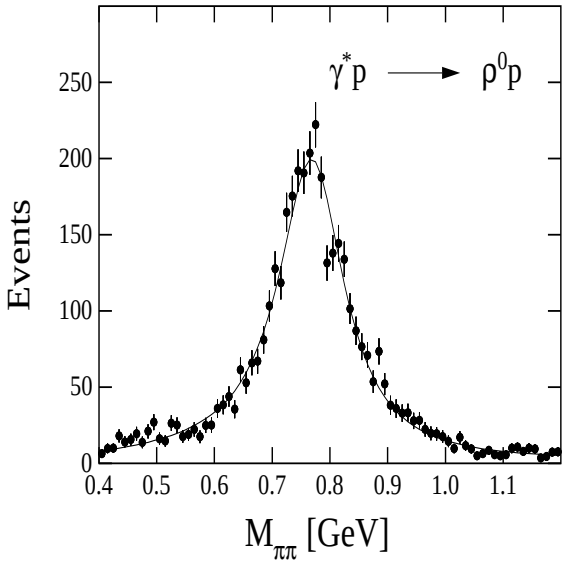
Total number of events (1996-2000)

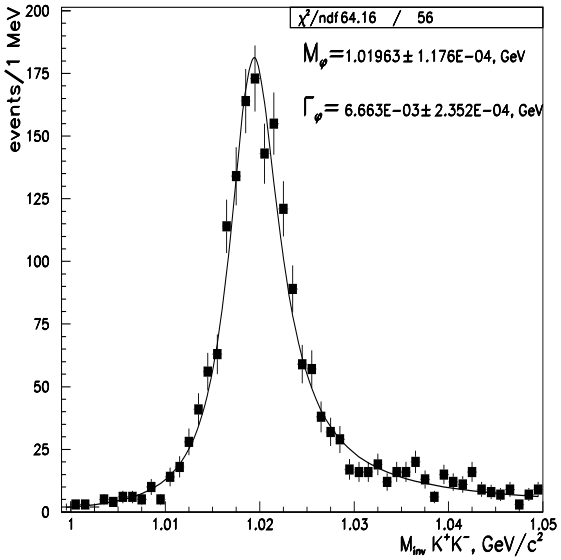
Deuteron: ρ^0 - 16388, ϕ - 1038

Hydrogen: ρ^0 - 9860, ϕ - 711

$\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$ with $M_X^2 = (p + q - v)^2$ and M_X being mass of recoil hadronic system





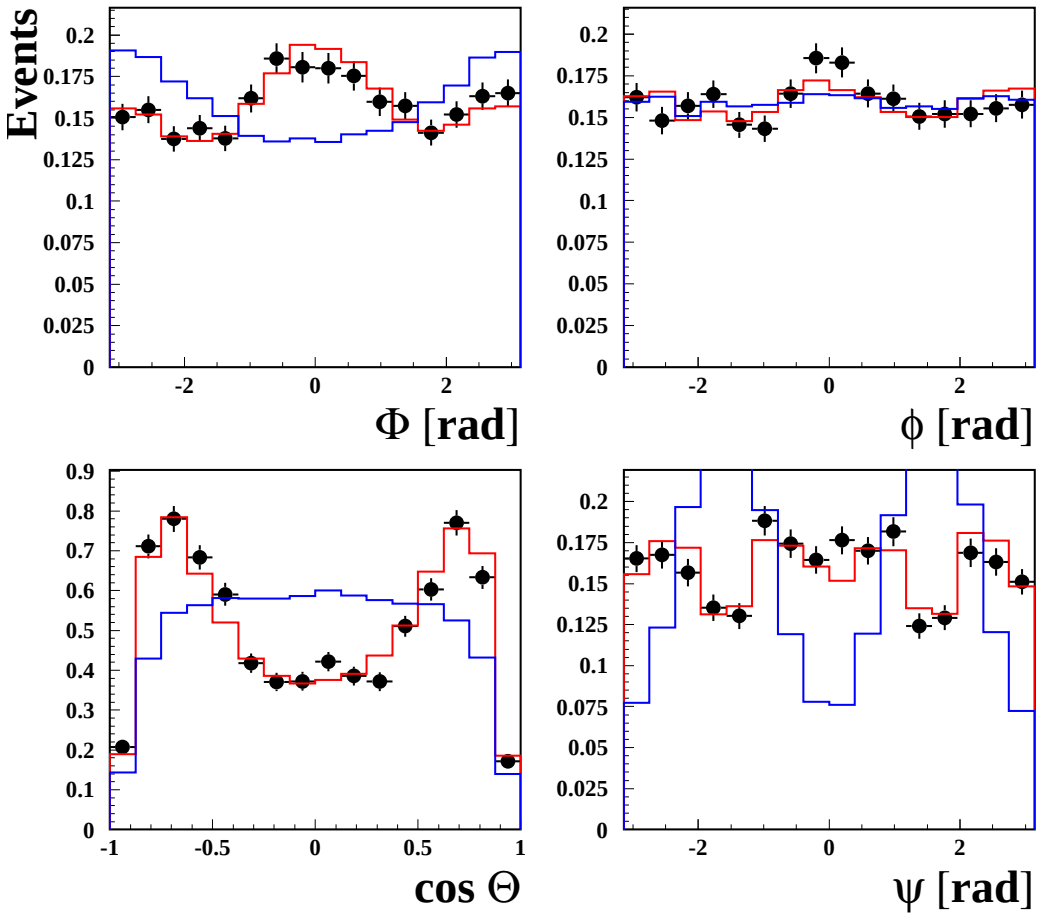


$-1.0 < \Delta E < 0.6$ GeV, $0.6 < M_{\pi\pi} < 1$ GeV, $1.01 < M_{KK} < 1.03$ GeV

Background is subtracted with the help of MC (PYTHIA)

Data Processing using Maximum Likelihood Method in MINUIT

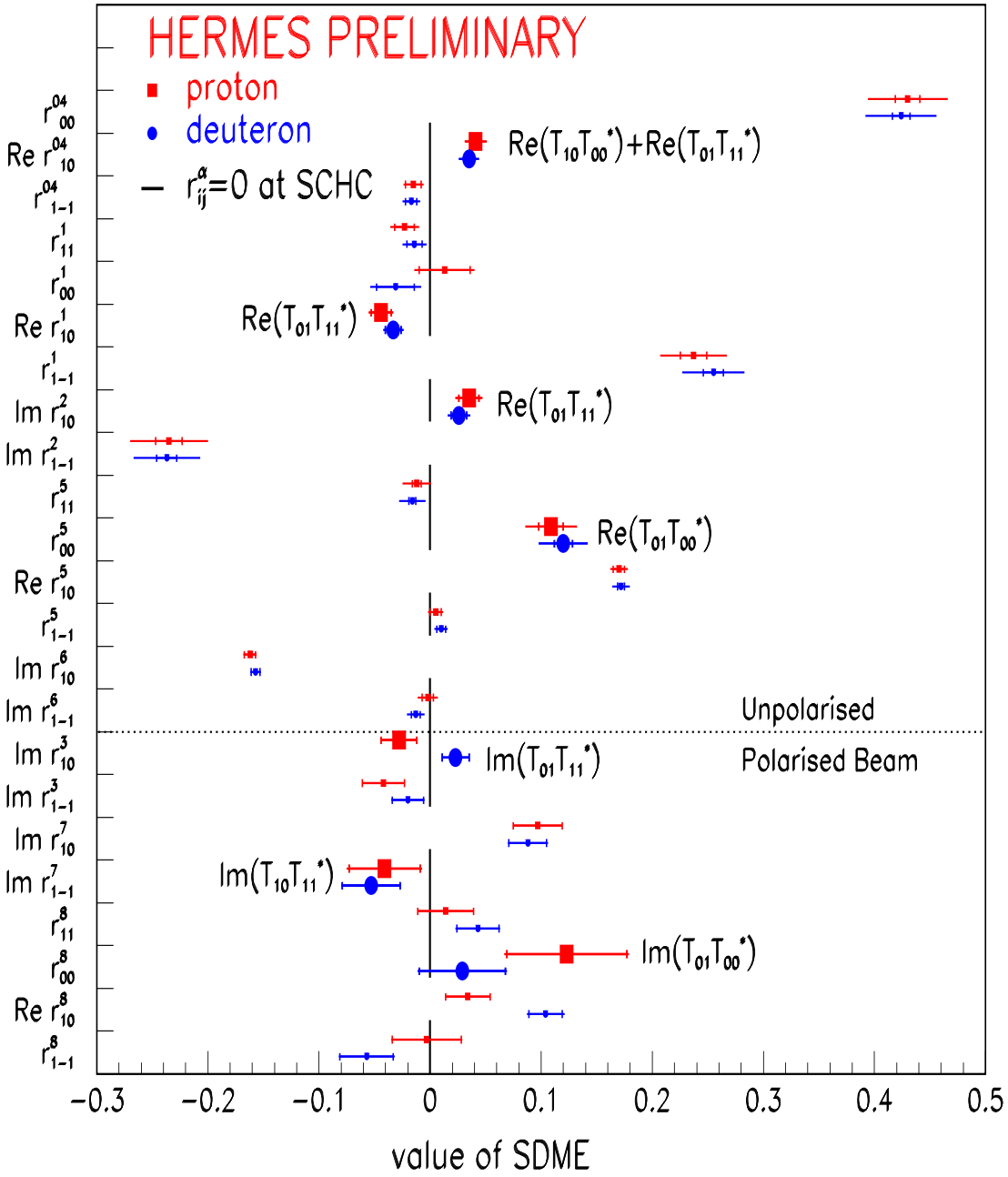
- Monte Carlo Events: 3-dimensional matrix of fully reconstructed MC events at initial uniform angular distribution.
- Binned Maximum Likelihood Method: $8 \times 8 \times 8$ bins of $\cos(\Theta), \phi, \Phi$. Simultaneous fit of 23 SDMEs for data with negative and positive beam helicity ($< P_b >=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



$\Psi = \phi - \Phi$

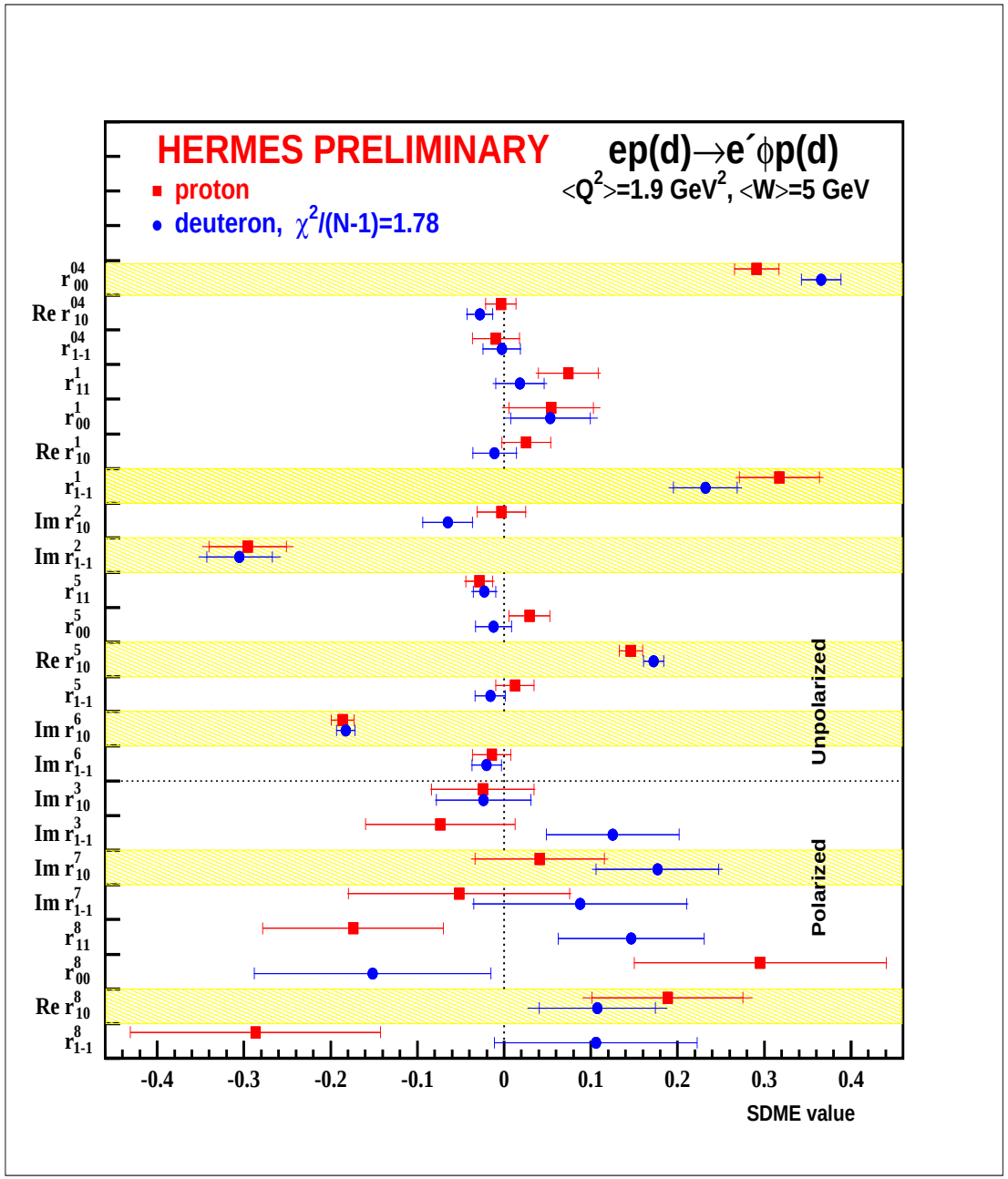
S-Channel Helicity Conservation (SCHC): helicity of γ^* = helicity of vector meson

Spin Density Matrix Elements $r^{\alpha}_{\lambda_\rho \lambda'_\rho}$ of ρ^0 meson



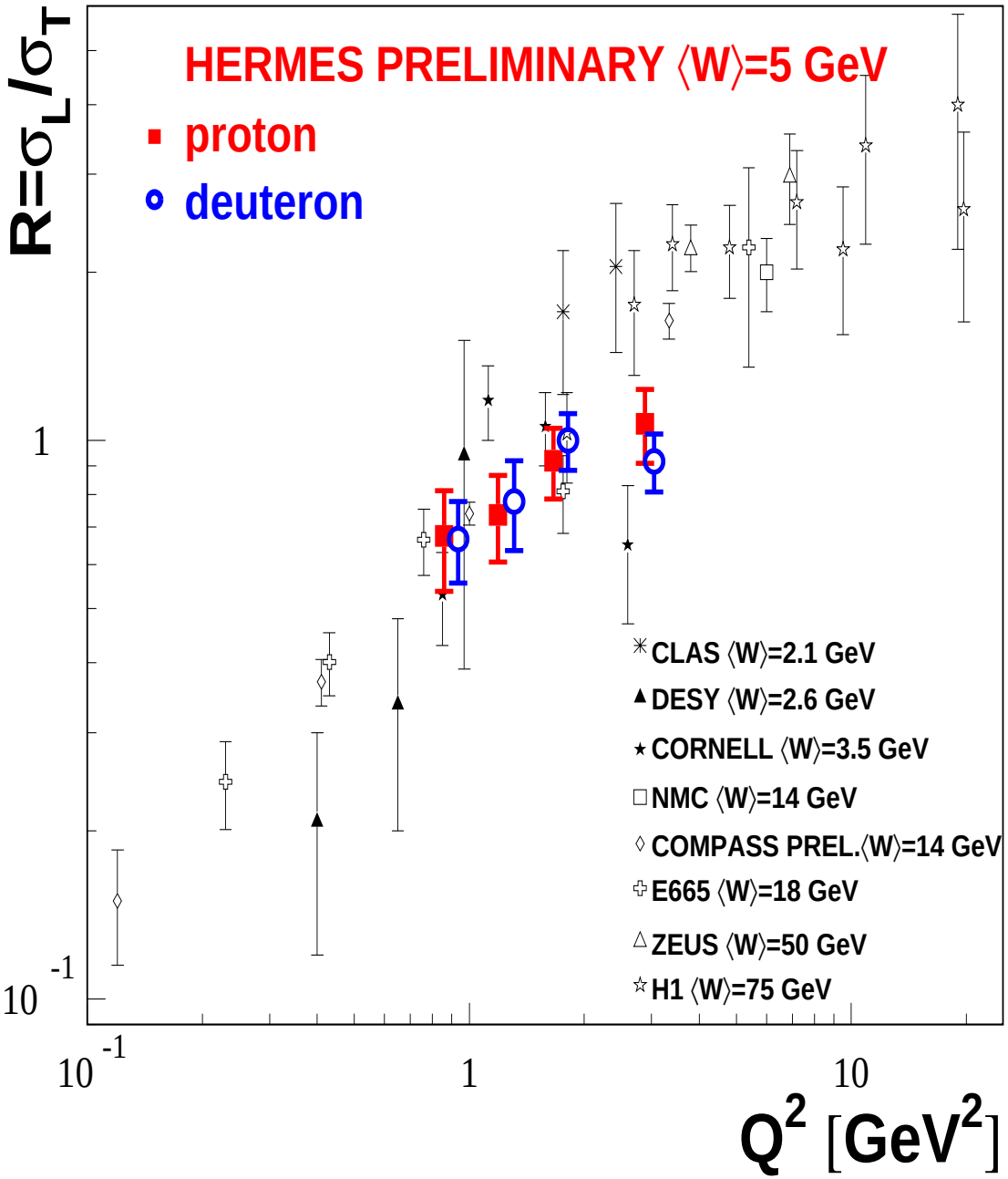
- Polarized SDMEs have been measured by HERMES for the first time
- No statistically significant difference between proton and deuteron.
- S-Channel Helicity Conservation.
  Non-zero amplitudes:
  NPE $T_{00} \equiv F_{00}$,
  $T_{11} = (F_{11} + F_{-1-1})/2$,
  UPE $U_{11} = (F_{11} - F_{-1-1})/2$.
- Violation of S-Channel Helicity: enlarged points $(2 \div 5\,\sigma)$.
  Linear contribution of NPE spin-flip amplitudes T_{01}, T_{10}, T_{-11}.
- Hierarchy of amplitudes at HERMES kinematics:
  $|T_{00}|^2 \sim |T_{11}|^2 \gg |U_{11}|^2 > |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2$

Spin Density Matrix Elements $r^{\alpha}_{\lambda_\rho \lambda'_\rho}$ of ϕ meson



- Polarized SDMEs have been measured by HERMES for the first time
- No statistically significant difference between proton and deuteron. $\Rightarrow$ No noticeable contribution of reggeon exchanges with natural parity and isospin $I = 1$ ($q\bar{q}$-pair exchanges)
- No violation of S-Channel Helicity: Non-zero NPE amplitudes: T_{00}, T_{11}.
- Hierarchy of amplitudes at HERMES kinematics;
  $|T_{00}| \sim |T_{11}|$,
  $|T_{01}| \approx |T_{10}| \approx |T_{-11}| \approx |U_{11}| \approx 0$.

Longitudinal-to-Transverse Cross-section Ratio for ρ^0 Meson



$$R = \sigma_L/\sigma_T = N_L/N_T,$$

$$N_L = \frac{1}{2}\sum_{\lambda_N\lambda'_N}\Big(|T_{00}|^2+2|T_{10}|^2+2|U_{10}|^2\Big),$$

$$N_T = \frac{1}{2}\sum_{\lambda_N\lambda'_N}\Big(|T_{11}|^2+|T_{01}|^2+|T_{-11}|^2$$

$$+|U_{11}|^2+|U_{01}|^2+|U_{-11}|^2\Big).$$

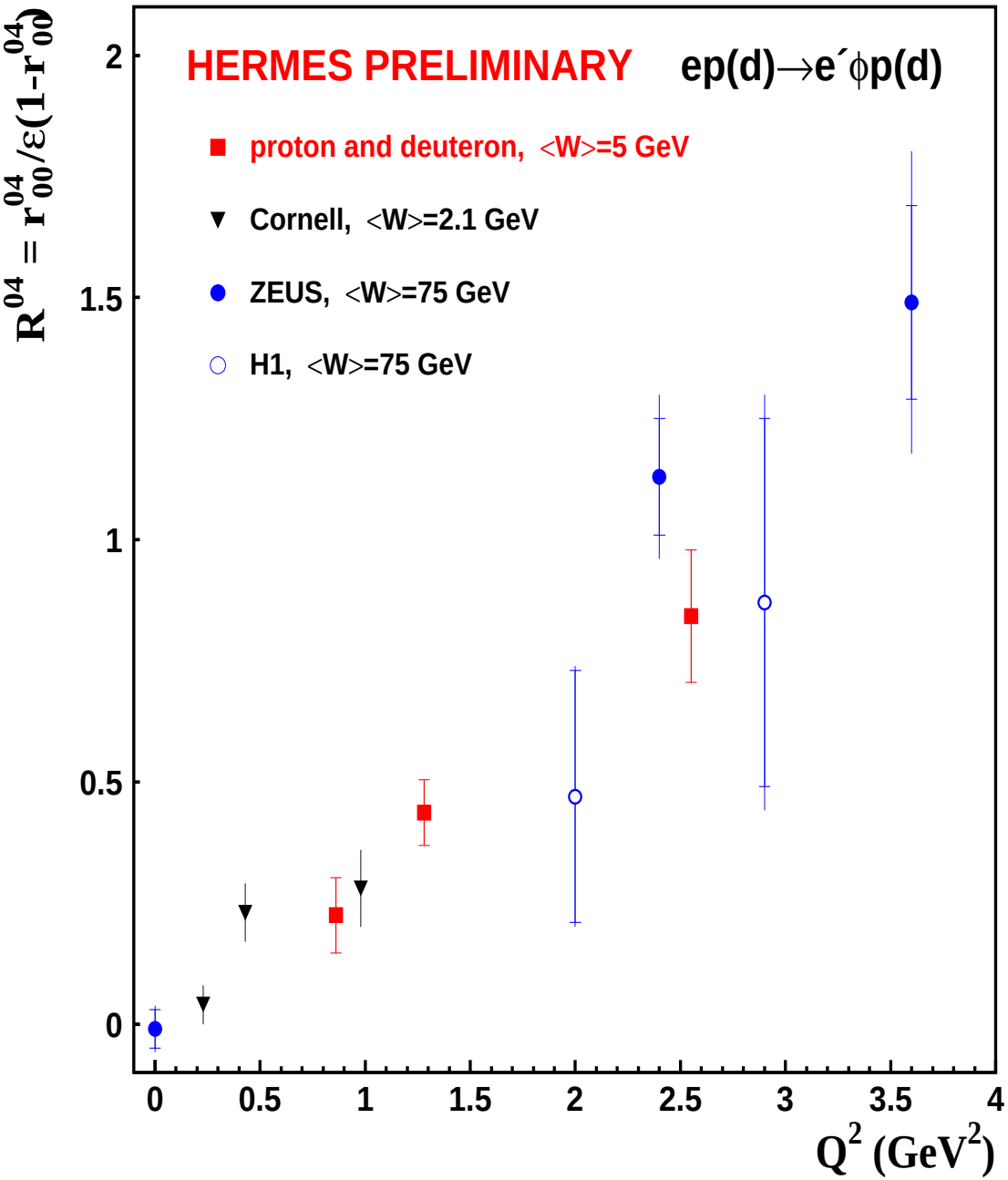
Second order contribution of spin-flip amplitudes (violating SCHC) to R.

SCHC approximation

$$R^{SCHC} = \frac{|T_{00}|^2}{|T_{11}|^2+|U_{11}|^2} \approx R^{04},$$

$$R^{04} = \frac{r^{04}_{00}}{\epsilon(1-r^{04}_{00})}.$$

Longitudinal-to-Transverse Cross-Section Ratio for ϕ Mesons



- SCHC approximation for $R = \sigma_L/\sigma_T$

$$R \approx R^{04} = \frac{r_{00}^{04}}{\epsilon(1 - r_{00}^{04})}$$

- Linear dependence of R^{04} on Q^2
- Agreement with world data

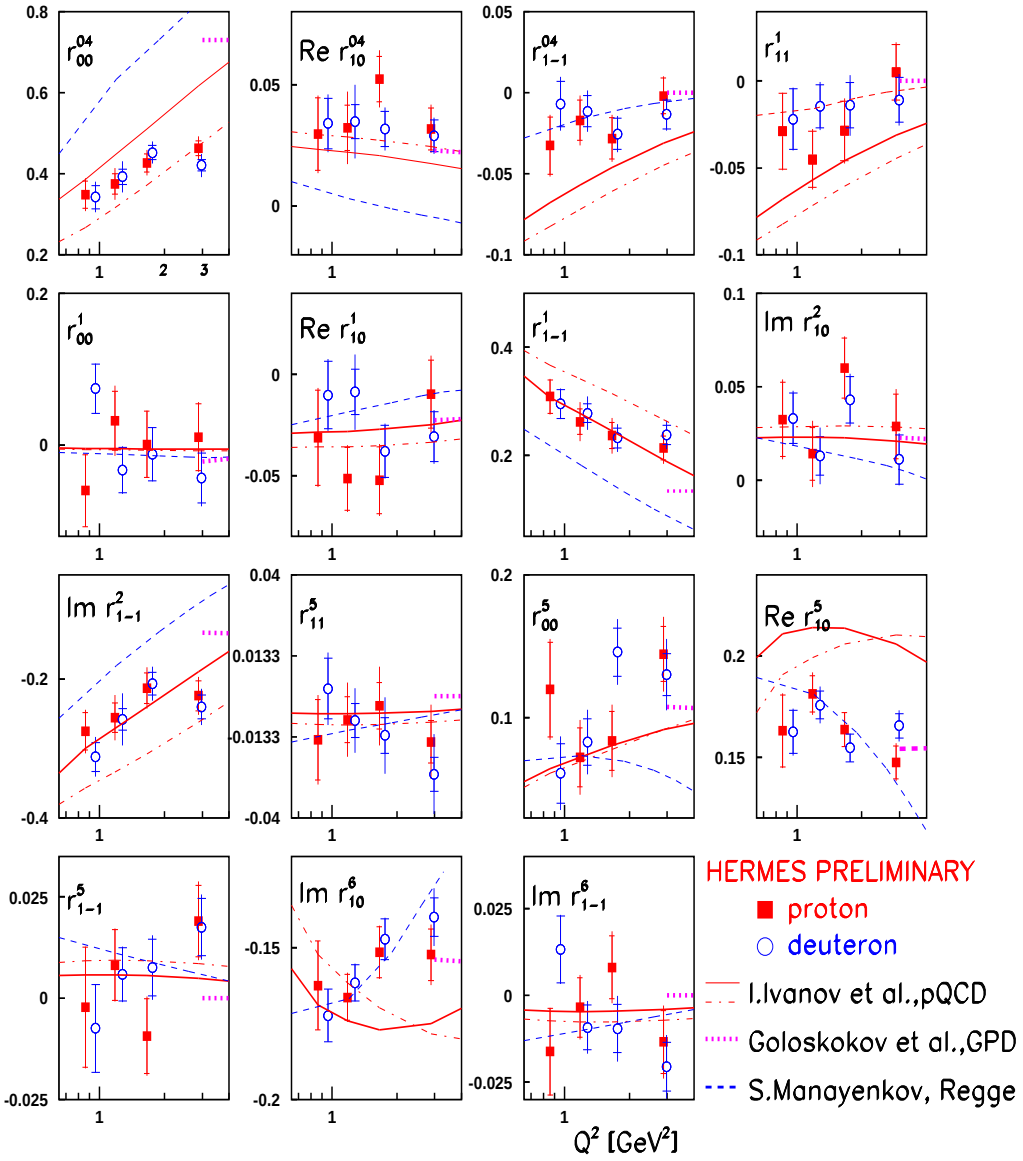
Kinematic Dependences of SDMEs

Theoretical Calculation of SDMEs

- Model 1. (I. P. Ivanov and N. N. Nikolaev, JETP Lett. **69** (1999) 294; I. P. Ivanov, PhD thesis, Bonn University, 2003, hep-ph/0303053)
  pQCD. Two-gluon (Pomeron) exchange, ρ-meson wave function with S- and D-waves (Coulomb-like and Gaussian functions). NPE amplitudes: T_{00}, T_{11}, T_{01}, T_{10}, T_{1-1}.
- Model 2. (S. V. Goloskokov and P. Kroll, Eur.Phys.J. C **42** (2005) 281; hep-ph/0501242)
  Generalized Parton Distributions (GPD), Gaussian ρ-meson wave function (S-wave).
  NPE amplitudes: T_{00}, T_{11}, T_{01}.
- Model 3. (S.Manayenkov, Eur.Phys.J. C **33** (2004) 397)
  Regge Phenomenology. Exchanges with Pomeron, ρ, ω, f, A_2. Parton-hadron duality.
  NPE amplitudes: T_{00}, T_{11}, T_{01}, T_{10}, T_{1-1}.

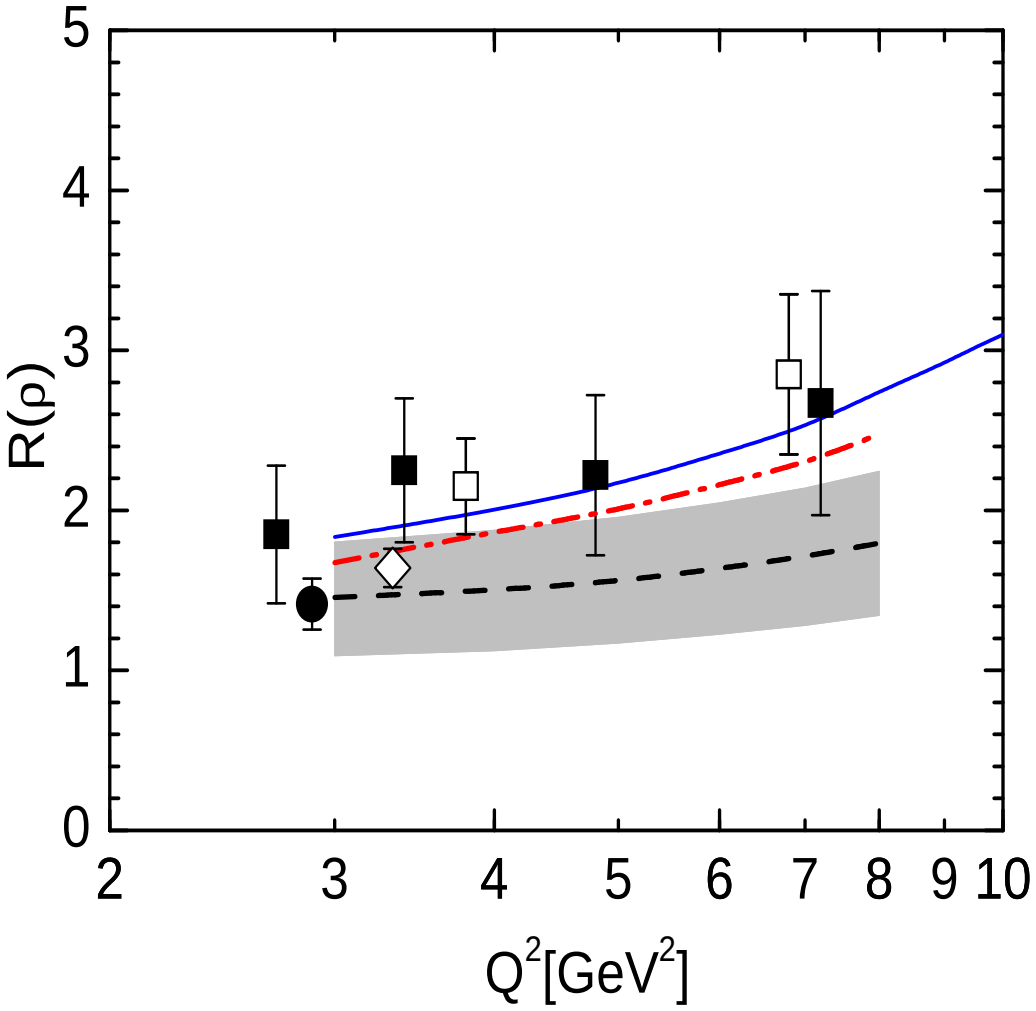
- Special calculations for the HERMES kinematics before data treatment.

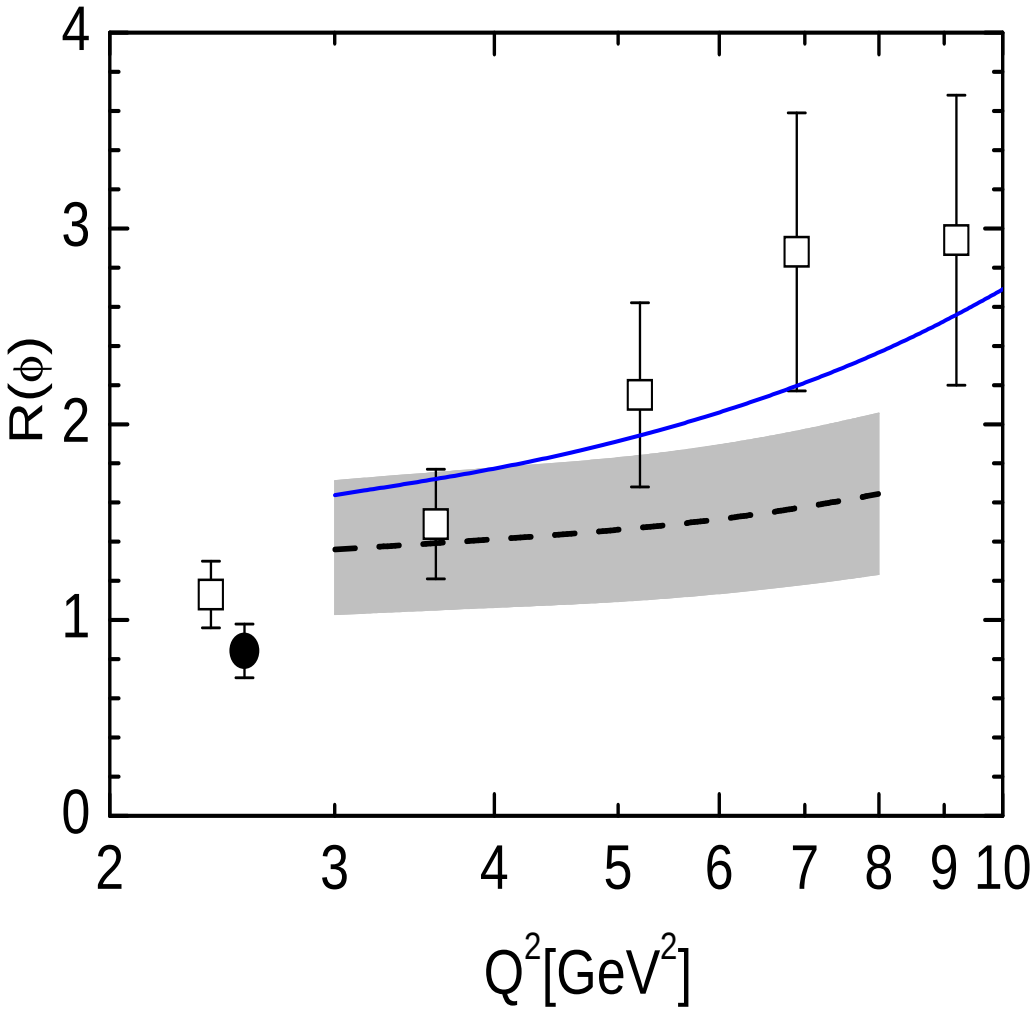
Q^2-Dependence of Spin Density Matrix Elements



- Calculations predict reasonably order of magnitude for a majority of SDMEs.
- The most crucial disagreement of calculations with data for
  Model 1 - r^{04}_{1-1}, $\mathrm{Re}\{r^{5}_{10}\}$, $\mathrm{Im}\{r^{6}_{10}\}$;
  Model 2 - r^{04}_{00}, r^{1}_{1-1}, $\mathrm{Im}\{r^{2}_{1-1}\}$;
  Model 3 - r^{04}_{00}, r^{04}_{10}, r^{1}_{1-1}, $\mathrm{Im}\{r^{2}_{1-1}\}$.
- No model describes well all unpolarized SDMEs.
- Exchanges of quark-antiquark pairs with natural and unnatural parity are probably important.
- HERMES data provides information for tuning theoretical models.

Comparison of R^{04} for ρ^0 and ϕ mesons with Calculations in GK Model

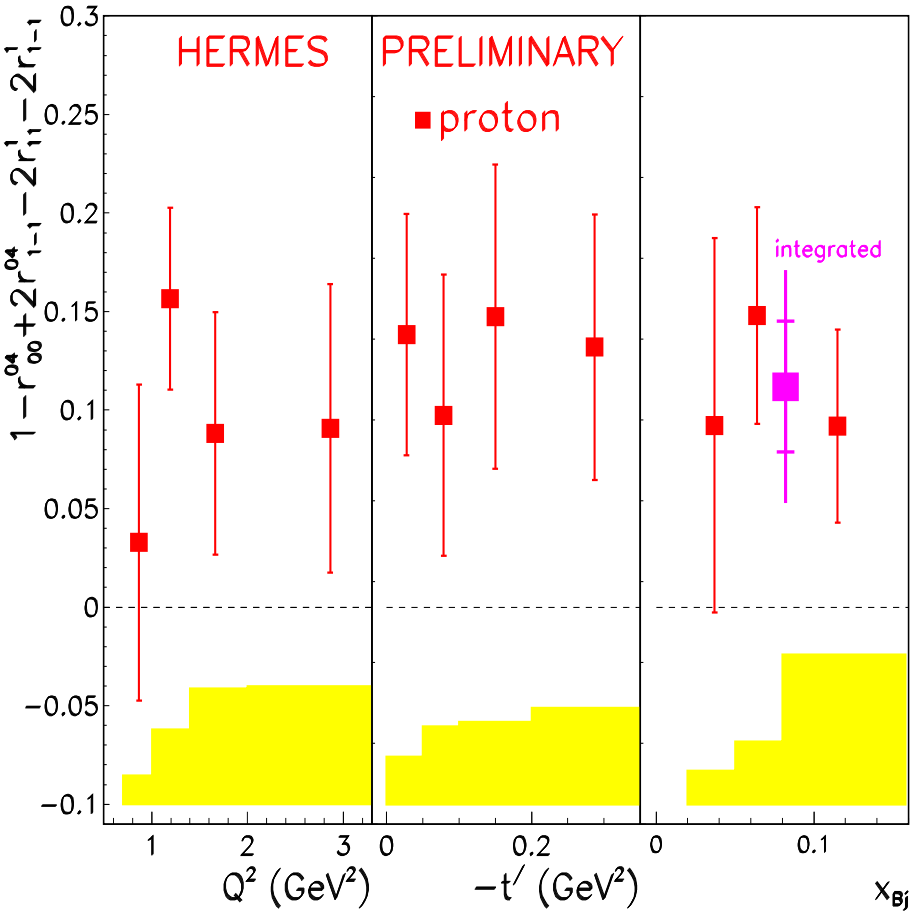




Calculations in the Goloskokov-Kroll (GK) model after tuning GPD parameters.
Blue line W=90 GeV, red line W=10 GeV, black line W=5 GeV.
Data: solid squares - H1, open squares - ZEUS, diamond - COMPASS,
circles - HERMES (without UPE contribution).

W-dependence of R^{04} is confirmed by calculations.

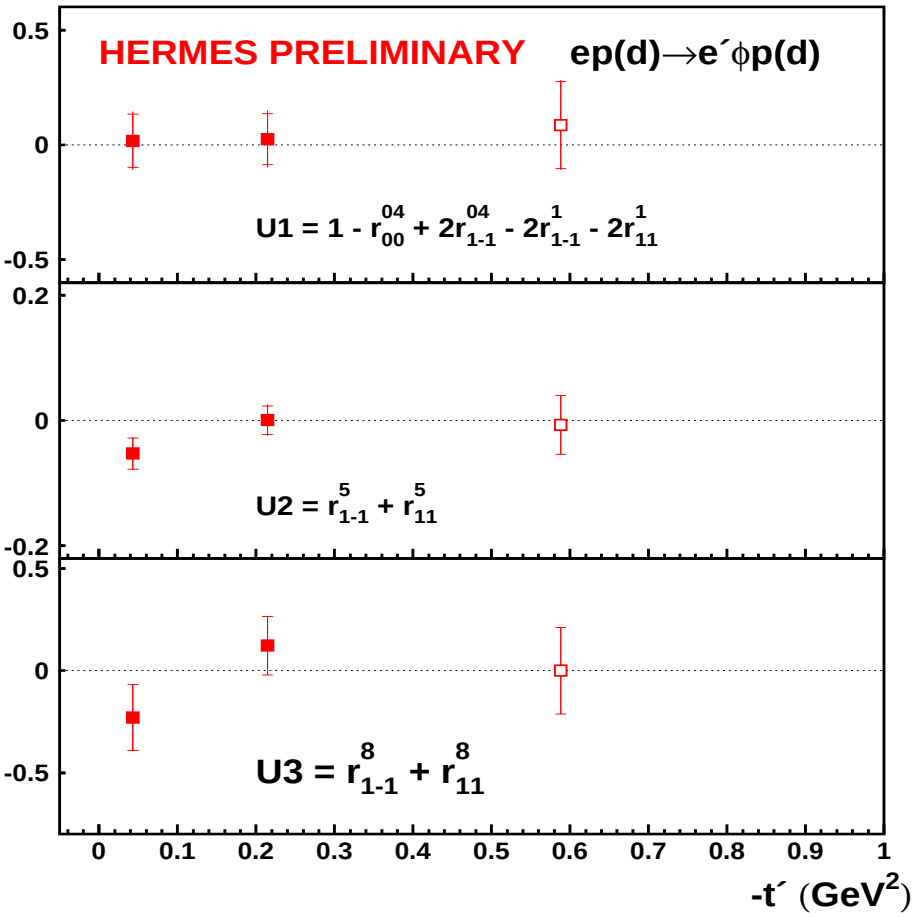
Test of Unnatural-Parity Exchange for ρ^0 meson

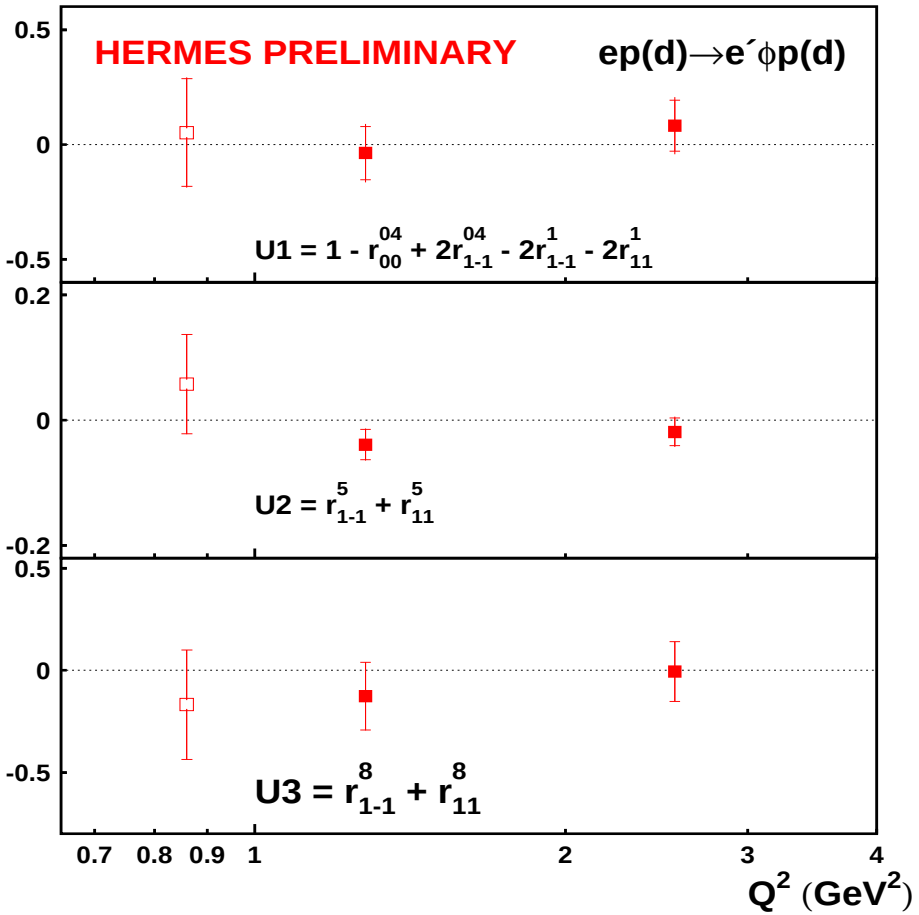


$u_1 = 0.132 \pm 0.026_{stat} \pm 0.053_{syst}$ (H),
$u_1 = 0.094 \pm 0.022_{stat} \pm 0.044_{syst}$ (D)
$u_1 = 0.109 \pm 0.037_{tot}$ (H+D)

- Natural and Unnatural Parity Exchanges in the t-channel
  NPE: $P = (-1)^J$; $T_{\lambda_\rho \lambda'_N;\lambda_\gamma \lambda_N}$
  UPE: $P = -(-1)^J$; $U_{\lambda_\rho \lambda'_N;\lambda_\gamma \lambda_N}$
  NPE (Pomeron, ρ, ω, f_2, a_2, ...) dominate and UPE (π, a_1, b_1...) are suppressed at high energies
- $F_{\lambda_\rho \lambda_\gamma} = T_{\lambda_\rho \lambda_\gamma} + U_{\lambda_\rho \lambda_\gamma}$
  where $T_{\lambda_\rho \lambda_\gamma} =$
  $(F_{\lambda_\rho \lambda_\gamma} + (-1)^{\lambda_\rho - \lambda_\gamma} F_{-\lambda_\rho -\lambda_\gamma})/2$
  No interference between NPE and UPE contributions to SDMEs $r^{\alpha}_{\lambda_\rho \lambda'_\rho}$ for **unpolarized** target
- $u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1}$,
  $u_1 = \sum_{\lambda_N \lambda'_N} (2\epsilon |U_{10}|^2$
  $+ |U_{11} + U_{-11}|^2)/(N_T + \epsilon N_L)$

Test of Unnatural-Parity Exchange for ϕ meson





$$u_1 = \ \ 0.02 \pm 0.07_{stat} \pm 0.16_{syst},$$
$$u_2 = -0.03 \pm 0.01_{stat} \pm 0.03_{syst},$$
$$u_3 = -0.05 \pm 0.12_{stat} \pm 0.07_{syst}.$$

No signal of unnatural parity exchange (as expected if it is due to pion exchange).

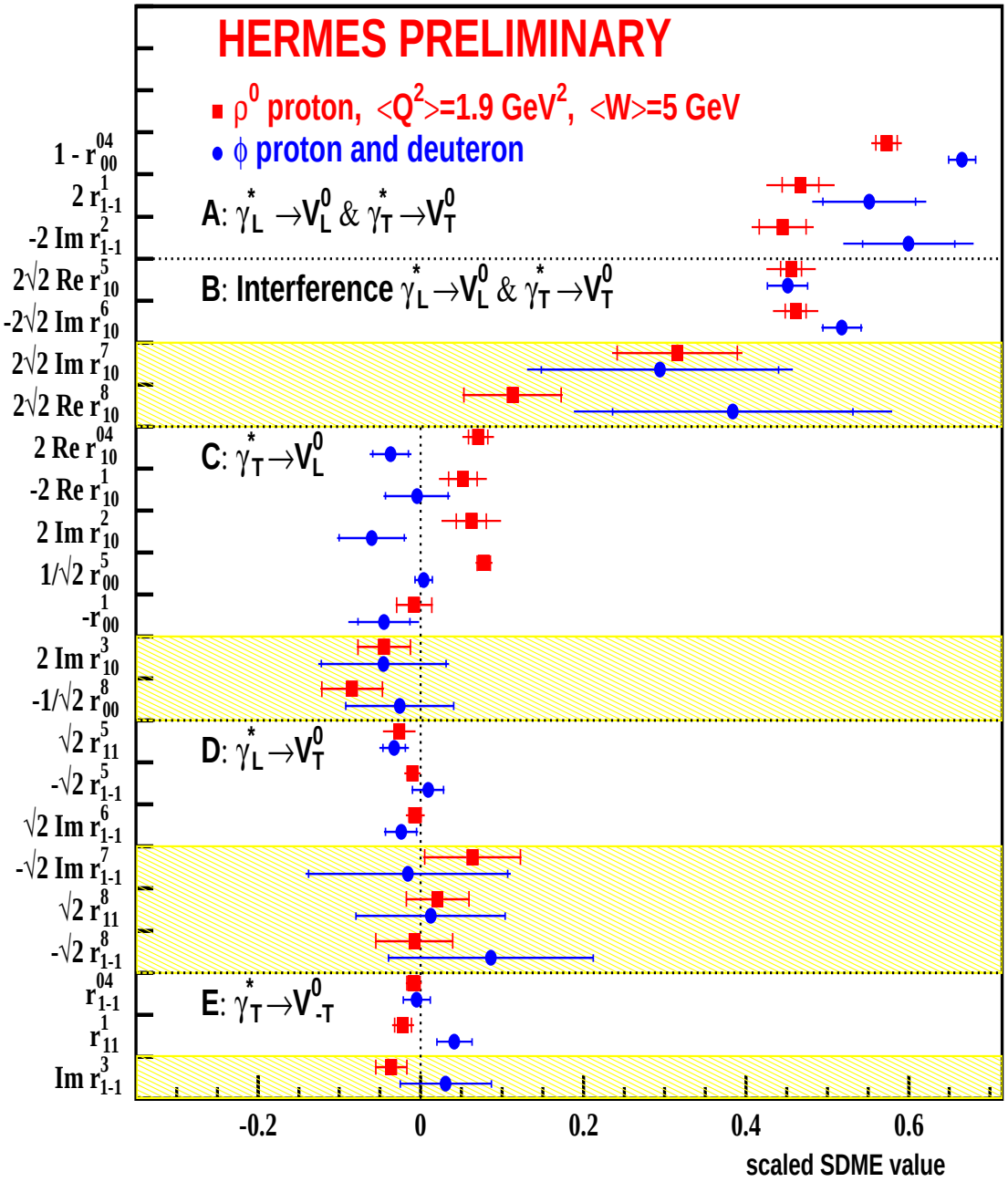
Summary

- 15 unpolarized and, for the first time, 8 polarized SDMEs are obtained for ρ^0 and ϕ.
- Violation of S-channel helicity is observed for several SDMEs in ρ^0 production both on proton and deuteron with $2 \div 5\ \sigma$. No signal of S-channel helicity violation is found for ϕ meson.
- No statistically significant difference between proton and deuteron data is observed.
- $R = \sigma_L/\sigma_T$ is obtained from r^{04}_{00} and is in agreement with world data.
- Kinematic dependences of SDMEs are measured for 4 bins in Q^2 and t' for ρ and for 3 bins for ϕ mesons. The dependences of SDMEs are compared to theoretical models which predict order of magnitude of SDMEs. No model without tuning describe well all SDMEs. HERMES data can be used for tuning model's parameters.
- Unnatural parity exchange contribution in ρ^0 production is seen for the combined data on the proton and deuteron with $3\ \sigma$. No UPE signal for ϕ mesons is found.

Outlook

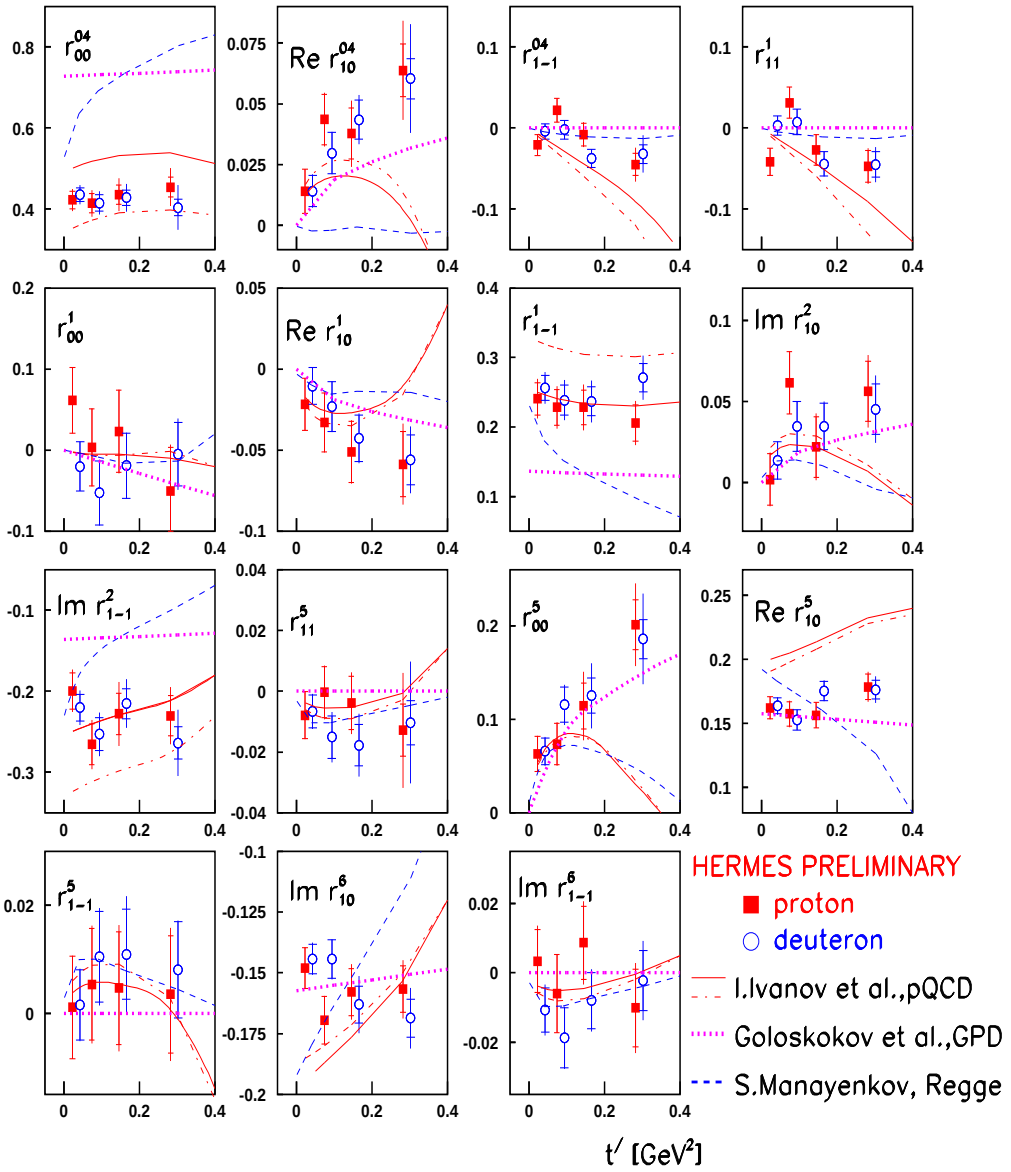
- Increasing statistics by factor ~ 4 is in progress (first step ~ 1.7).
- Study of SDMEs on polarized targets is also in progress.

Comparison of SDMEs for ρ^0 and ϕ mesons



- Class A. Main terms: $\propto |T_{00}|^2$ or $|T_{11}|^2$.
- Class B. $\mathrm{Re}\{T_{11}T_{00}^*\}$, $\mathrm{Im}\{T_{11}T_{00}^*\}$.
- Class C. $\mathrm{Re}\{T_{01}T_{00}^*\}$, $\mathrm{Im}\{T_{01}T_{00}^*\}$, $\mathrm{Re}\{T_{01}T_{11}^*\}$, $\mathrm{Im}\{T_{01}T_{11}^*\}$
- Class D. $\mathrm{Re}\{T_{10}T_{11}^*\}$, $\mathrm{Im}\{T_{10}T_{11}^*\}$
- Class E. $\mathrm{Re}\{T_{-11}T_{11}^*\}$, $\mathrm{Im}\{T_{-11}T_{11}^*\}$
- Class C. $T_{01} \sim (z - 1/2)$ where z is momentum fraction carried by quark in vector meson. Longitudinal motion of quark and antiquark is more intensive in ρ^0 rather than in ϕ mesons.

t'-Dependence of Spin Density Matrix Elements



- t' dependence of SDMEs is reproduced worse than Q^2 one especially for the highest measured transverse momenta.
- The most crucial disagreement of calculations with data for
  Model 1 - $\mathrm{Re}\{\mathrm{r}^5_{10}\}$, $\mathrm{Im}\{\mathrm{r}^6_{10}\}$
  Model 2 - r^{04}_{00}, r^{1}_{1-1}, $\mathrm{Im}\{\mathrm{r}^2_{1-1}\}$,
  Model 3 - r^{04}_{00}, r^{04}_{10}, r^{1}_{1-1}, $\mathrm{Im}\{\mathrm{r}^2_{1-1}\}$.
- No model describes well all unpolarized SDMEs.
- Quark-exchange or/and many-Pomeron exchanges are probably important.