Spin Density Matrix Elements from diffractive ϕ vector meson production at HERMES

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on behalf of HERMES Collaboration

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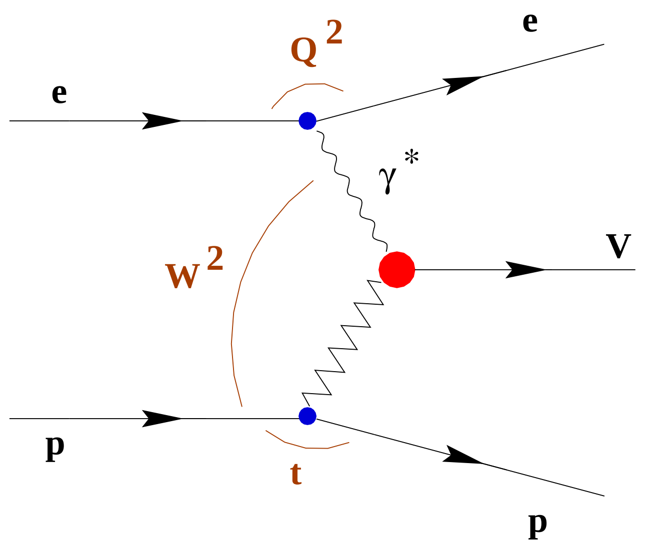
- **Rudiments**
- **Spin Density Matrix Elements (SDME's) : definitions and their determination**
- **The derived observables:**
  - **SDME's and Amplitudes vector mesons**
  - **Dependences of SDME's on Q^2 and t'**
  - $R = \frac{\sigma_L}{\sigma_T}$
  - **the signatures of the Natural or Unnatural Parity Exchange amplitudes**
  - **The Transverse Target Spin Asymmetry - A_{UT}**
- **Conclusions**

$e + p \rightarrow e' + p' + V$: Rudiments



Kinematics:

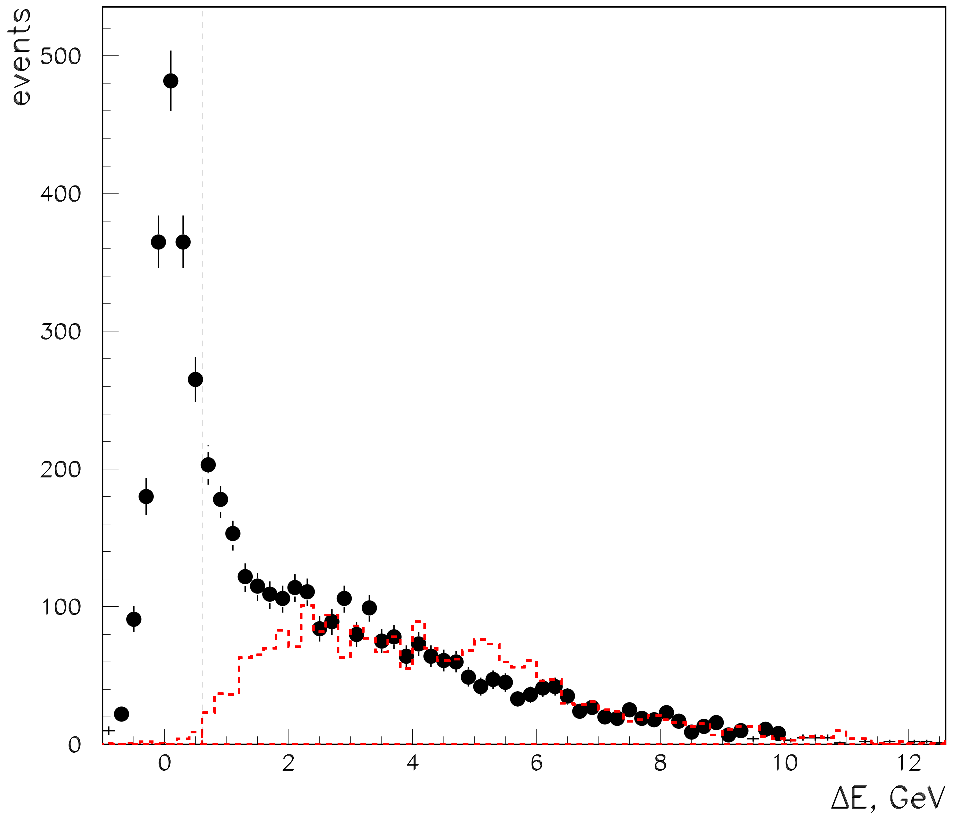
- $\nu = 5 \div 24$ **GeV,** $< \nu >= 13.3$ **GeV,**
- $Q^2 = 0.5 \div 7.0$ **GeV^2,** $< Q^2 >= 2.3$ **GeV^2**
- $W = 3.0 \div 6.5$ **GeV,** $< W >= 4.9$ **GeV,**
- $x_{Bj} = 0.01 \div 0.35, < x_{Bj} >= 0.07$
- $t' = (t - t_{min})$
  t$' = 0 \div 0.4$ **GeV^2,** $< t' >$ **= 0.13 GeV^2**

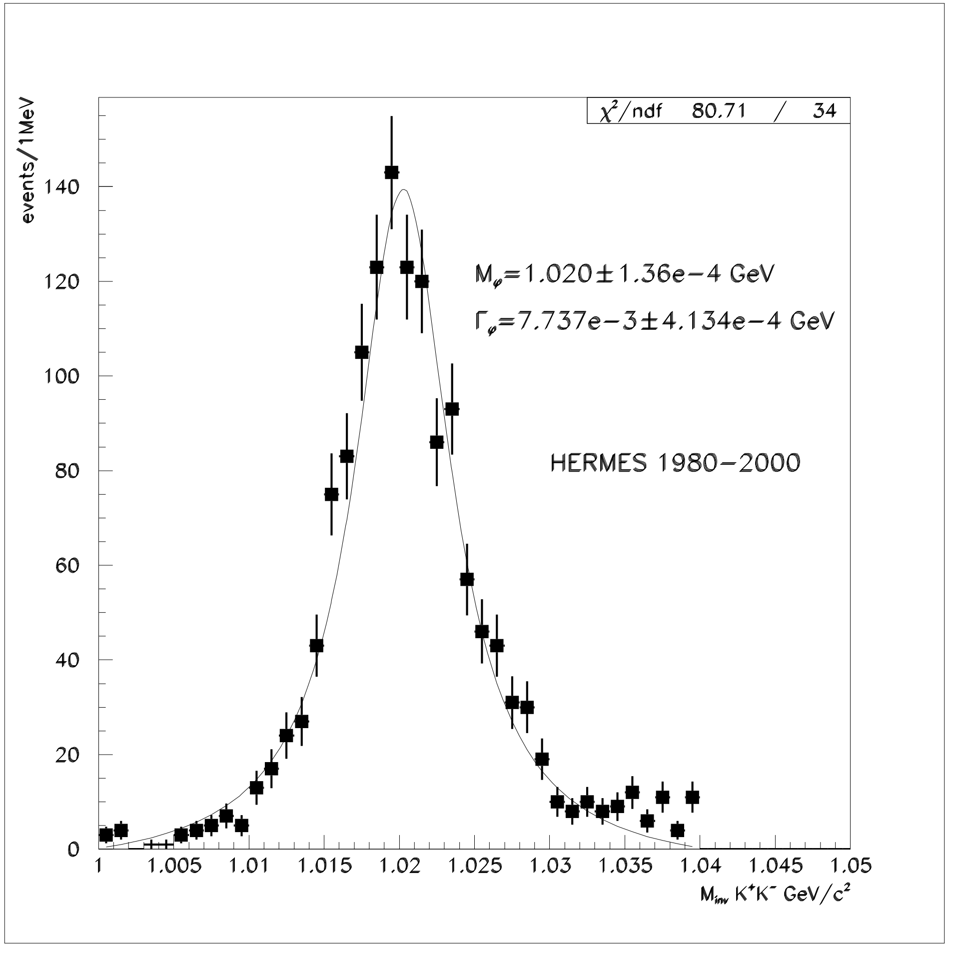
- In one photon approximation $\equiv \gamma^* + p \rightarrow p' + V$
- The amplitude of this process can be factorized: $A = \Phi^*_{\gamma^* \rightarrow q\bar{q}} \otimes A_{q\bar{q}+p \rightarrow q\bar{q}+p} \otimes \Phi_{q\bar{q} \rightarrow V}$. In these three steps the interaction time $(q\bar{q})$ with target is shorter than γ^* fluctuation and formation of VM. (Collins,Frankfurt and Strikman Phys.Rev D56(1997)2982)
- $\gamma^* + N \rightarrow \phi^0 + N'$ is good tool to study the helicity conservation:
  - helicity state of γ^* is easy to determine (QED)
  - $\phi^0 \rightarrow K^+K^-$ decay determines the helicity of ϕ^0

Exclusive ϕ Meson Production

$$e + p \rightarrow e' + p' + \phi \rightarrow K^+K^-$$

The exclusive events were selected from the missing energy spectra $\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$.



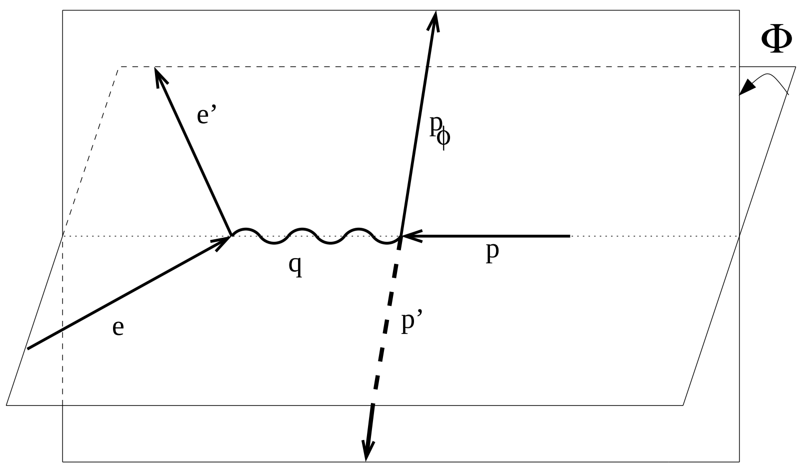


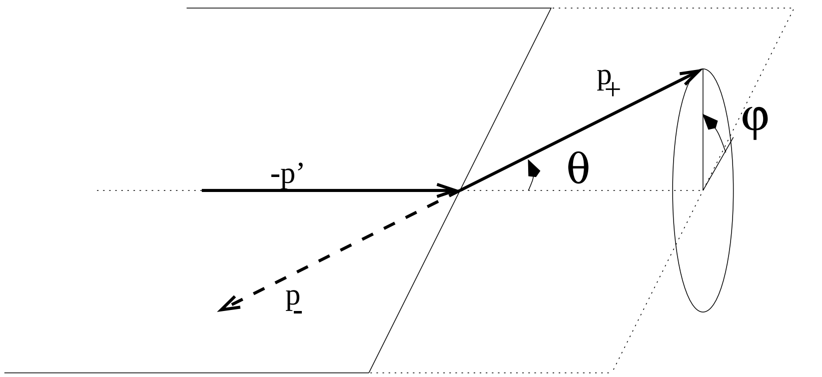
The background was simulated by code MC PYTHIA.

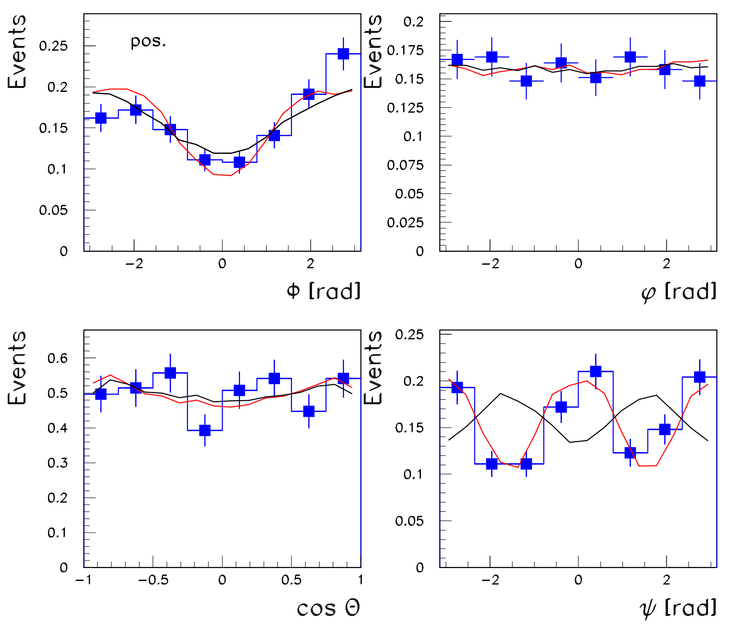
ϕ-meson Spin Density Matrix Elements (SDMEs)

- SDMEs: $r^{\alpha}_{\lambda_V \lambda'_V} \sim \rho(V) = \frac{1}{N} \sum_{\lambda'_\gamma, \lambda_\gamma} (T_{\lambda_V \lambda_\gamma} \rho(\gamma) T^{+}_{\lambda'_V \lambda'_\gamma})$
  spin-density matrix of the vector meson $\rho(V)$ in terms of the photon matrix $\rho(\gamma)$ and helicity amplitude $T_{\lambda_V \lambda_\gamma}$
- presented according to K.Schilling and G.Wolf (Nucl. Phys. B61 (1973) 381)
  $\alpha =$ 04 - long. or trans. photon with $\lambda_\phi = 0$; $\alpha =$ 1-2 - trans. with lin. pol. ;
  $\alpha =$ 3 - trans. with cir. pol.; $\alpha =$ 5-8 - interf. trans./long. terms.
- measured experimentally at $5 < W < 75$ GeV (HERMES,COMPASS,H1,ZEUS)
- provide access to helicity amplitudes $T_{\lambda_V \lambda_\gamma}$ and phases, which are:
  - extracted experimentally from SDMEs
  - calculated from GPDs:S.V.Goloskokov,P.Kroll arXiv:0708.3569 [hep-ph]27.08.07; Eur.Phys.J. C 50,829 (2007) hep-ph/0601290; Eur.Phys.J. C 42,281 (2005) hep-ph/0501242

Angular Distributions Fit: Likelihood Method in MINUIT







- Simulated Events: matrix of fully reconstructed MC events from 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 ($< |P_b| >= 53.5\%$, $\Psi = \Phi - \phi$)

$\Leftarrow$ red line after the fit MAX. Liklihood method, black one starting parameters

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

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

$$W^{unpol}(\cos\Theta,\phi,\Phi) =$$

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

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

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

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

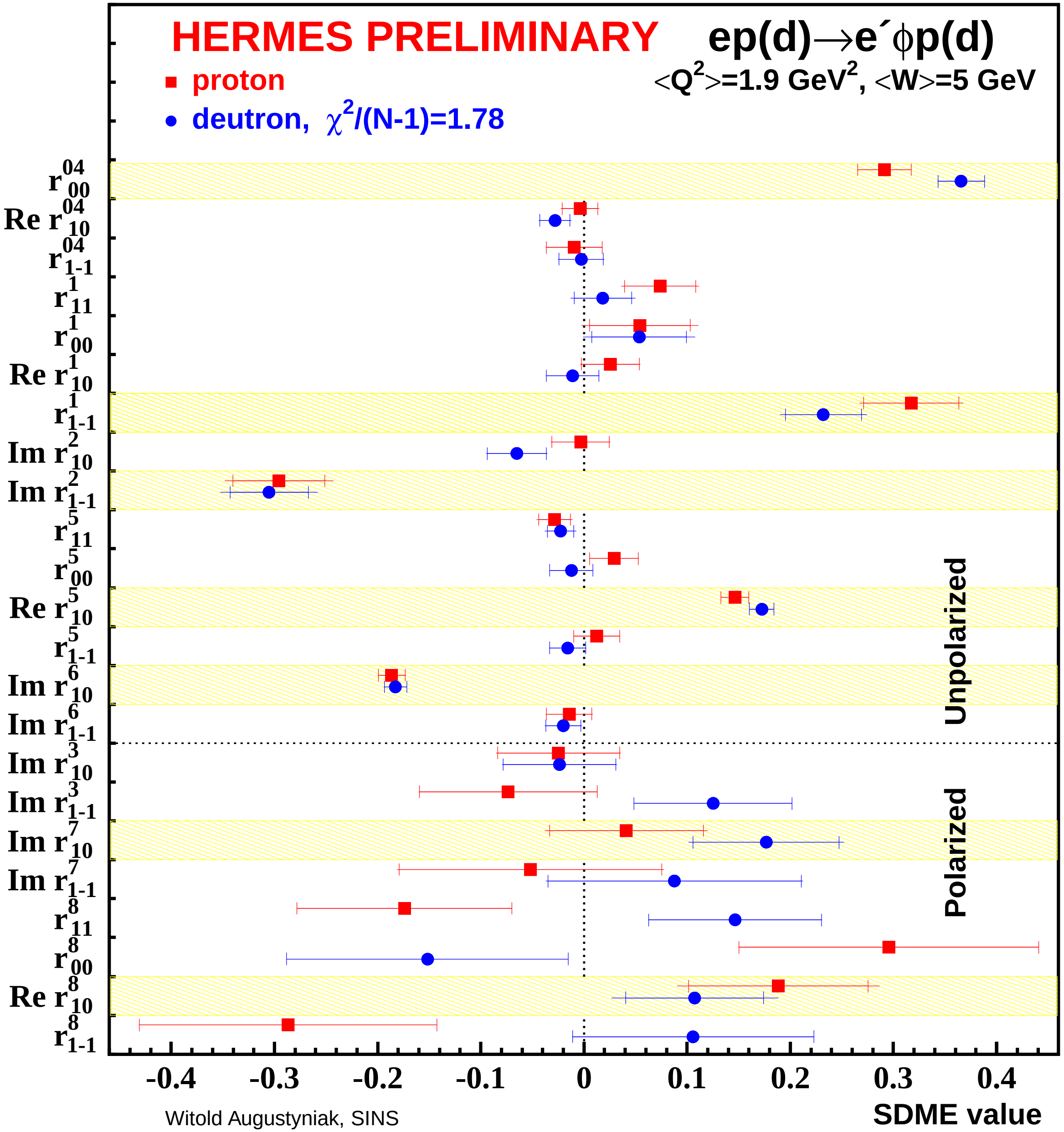
$$+\ \sqrt{2\epsilon(1+\epsilon)}\sin\Phi\Big(\sqrt{2}\mathrm{Im}\{\mathrm{r}^{6}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{\mathrm{r}^{6}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)\Bigg],$$

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

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

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

Sets of SDMEs for different targets



The SDME's for proton (red) and deuteron (blue) for 1.0$< Q^2 <$7.0 GeV^2.

SDMEs and Amplitudes

A- SCHC $\gamma^*_L \to \phi^0_L$ and $\gamma^*_T \to \phi^0_T$

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

B- Interference: γ^*_L, ϕ^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: $\gamma^*_T \to \phi^0_L$

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: $\gamma^*_L \to \phi^0_T$

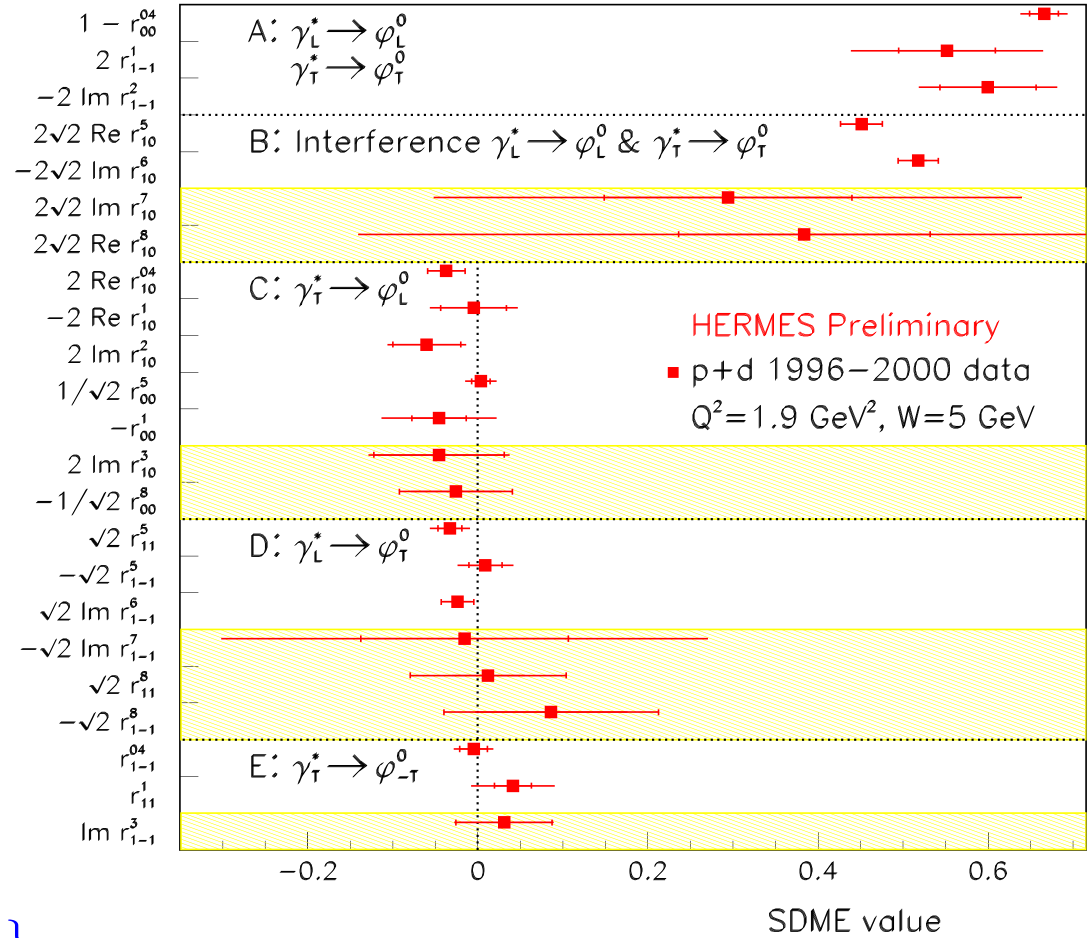
Re $\{T_{10}T^*_{11}\} \propto r^5_{11} \propto r^5_{1-1} \propto$ Im$\{r^6_{1-1}\}$

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

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

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

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



The phase difference δ^{ϕ}_{p+d} between transverse T_{11} and T_{00} amplitudes was determined:

$$tg(\delta^{\phi}) = \frac{Imr^7_{10} - Rer^8_{10}}{Rer^5_{10} - Imr^6_{10}}, \quad \delta^{\phi}_{p+d} = 33.0^0 \pm 7.4^0.$$

hermes

SDMEs and Amplitudes

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

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: $\gamma^*_L \to \phi^0_T$

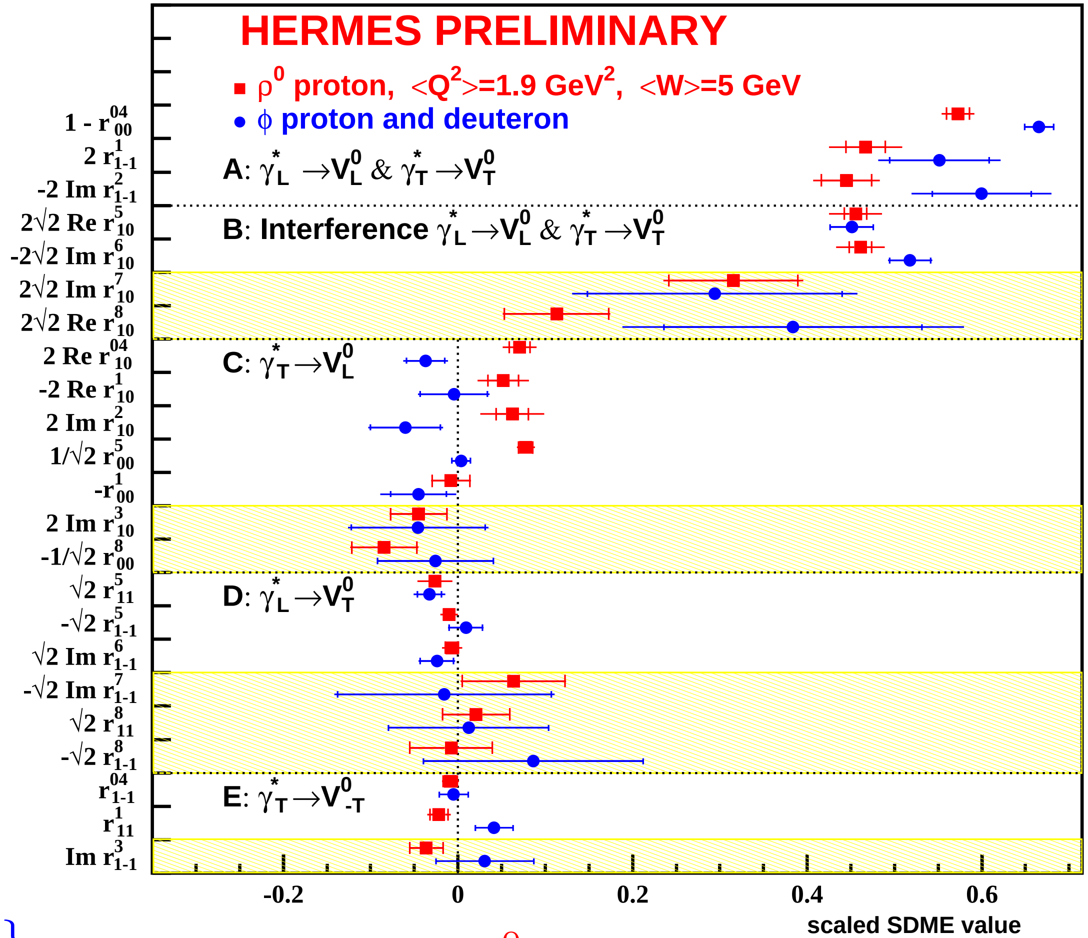
Re $\{T_{10}T^*_{11}\} \propto r^5_{11} \propto r^5_{1-1} \propto$ Im$\{r^6_{1-1}\}$

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

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

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

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

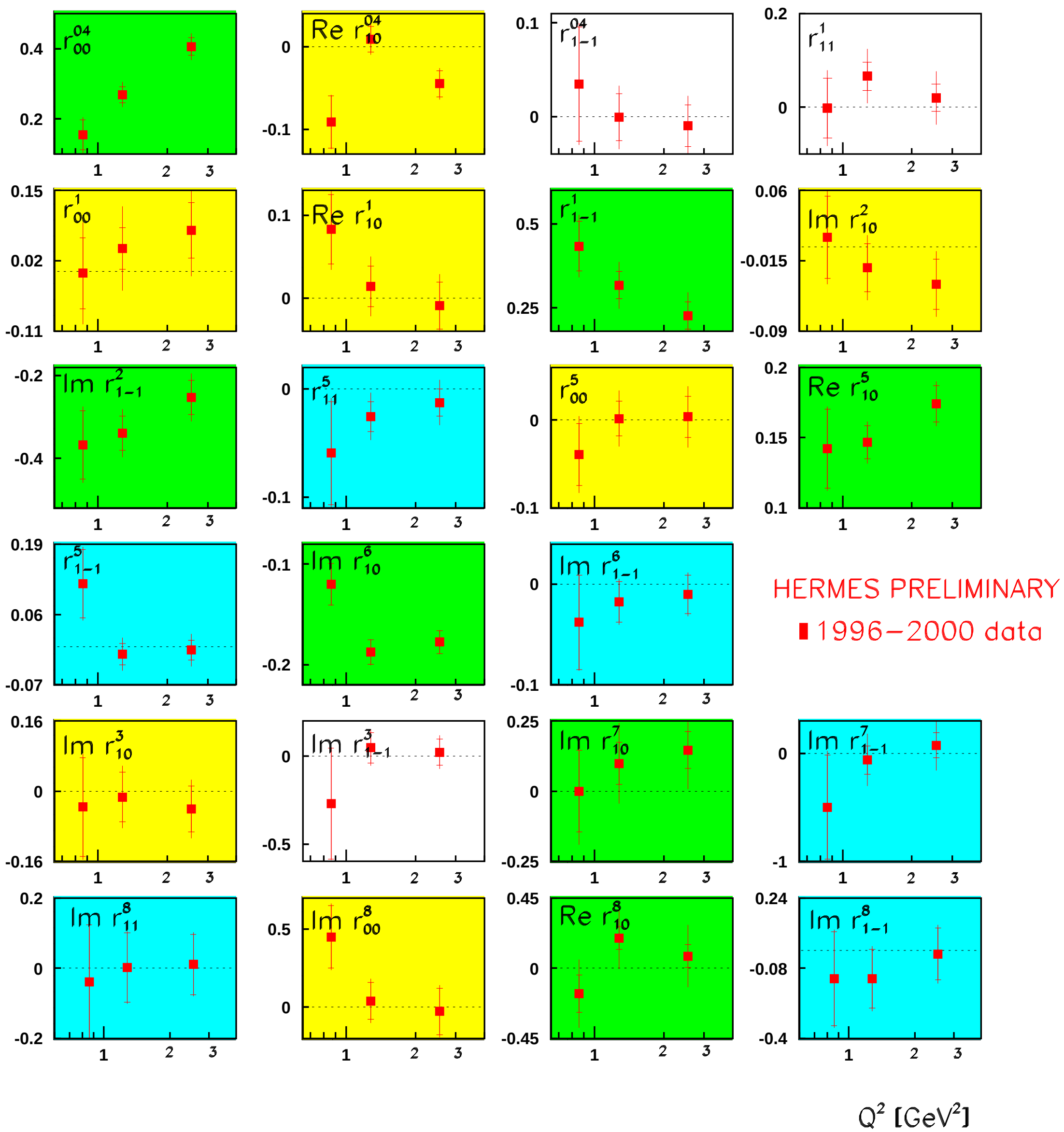


$\Longrightarrow$ **Hierarchy of ϕ^0 amplitudes:**

$|T_{00}| \sim |T_{11}| \gg |T_{01}| > |T_{10}| \gtrsim |T_{1-1}|$, $(0 \to L, 1 \to T)$

$\Longrightarrow$ ϕ meson SDMEs are consistent with SCHC, $|T_{00}| \sim |T_{11}|$

Dependences of ϕ meson SDME's on Q^2



The dependences of SDME's on Q^2 for proton and deuteron data. The outer bars represent the total, the inner ones the statistical errors.

INDICATIONS:

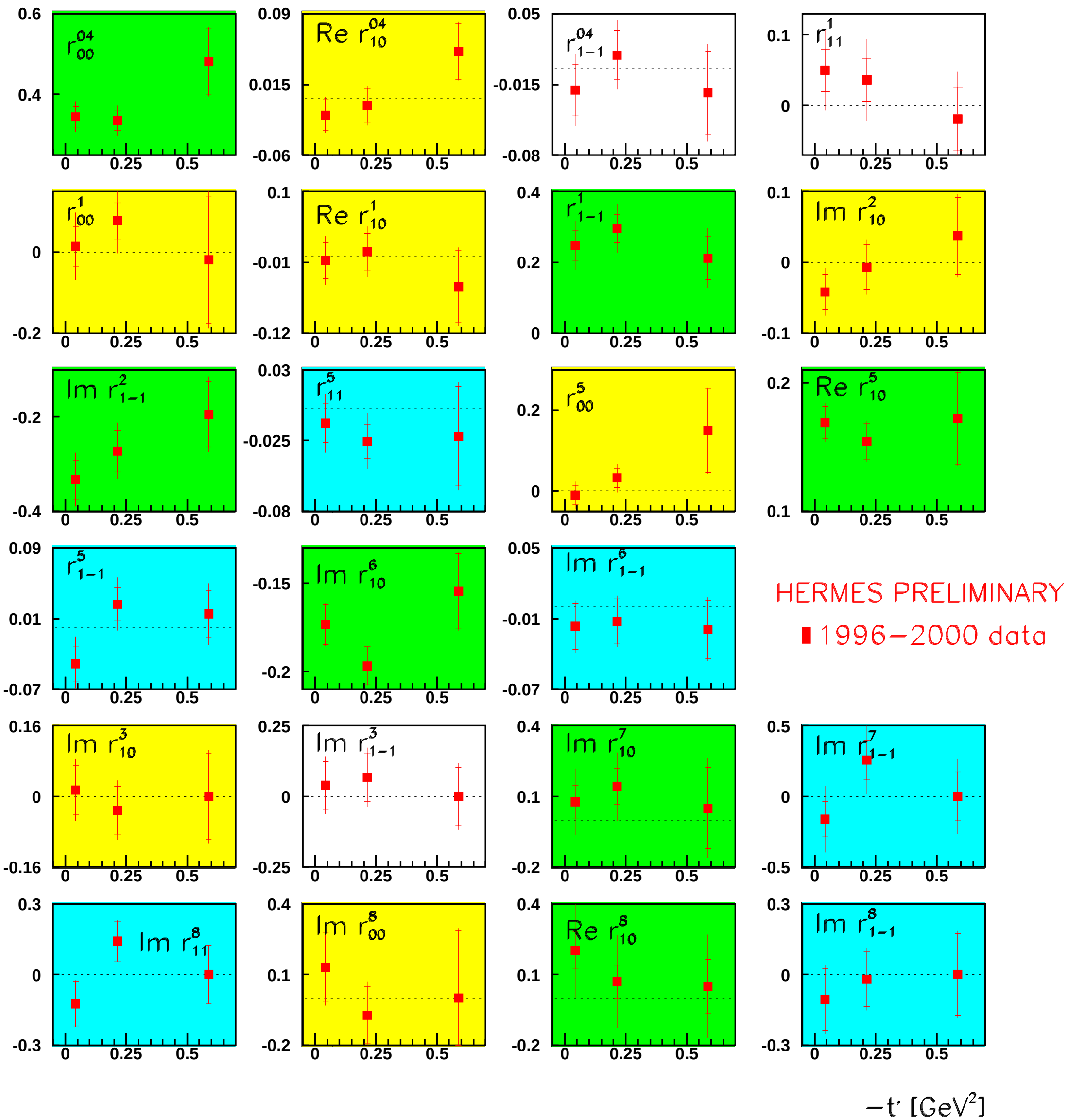
green: Helicity conserving transitions (SCHC) - $\gamma^*_L \longrightarrow V_L, \gamma^*_T \longrightarrow V_T$

yellow: Single Flip - $\gamma^*_T \longrightarrow V_L$

blue: Single Flip - $\gamma^*_L \longrightarrow V_T$

blank: Double Flip - $\gamma^*_T \longrightarrow V_{-T}$

Dependences of ϕ meson SDME's on t'



The dependences of SDME's on t' for proton and deuteron data. The outer bars represent the total, the inner ones the statistical errors.

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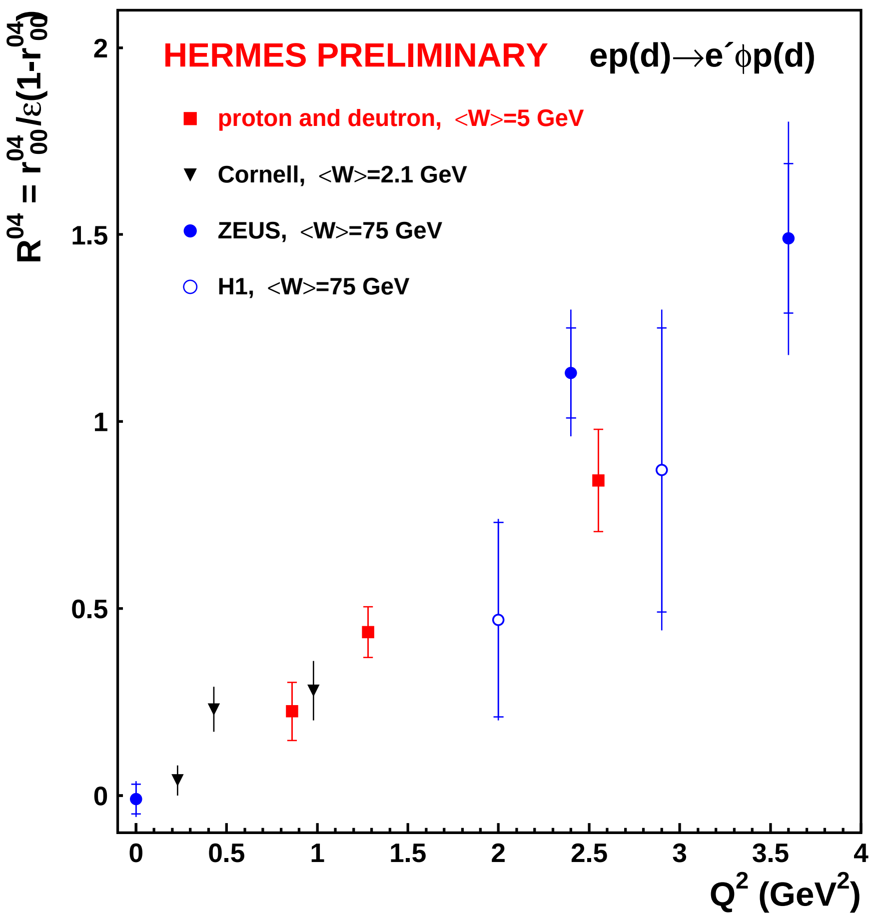
Longitudinal-to-Transverse Cross-Section Ratio



Comparison of commonly measured:

$$R^{04} = \frac{\sigma_L}{\sigma_T} = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}},$$

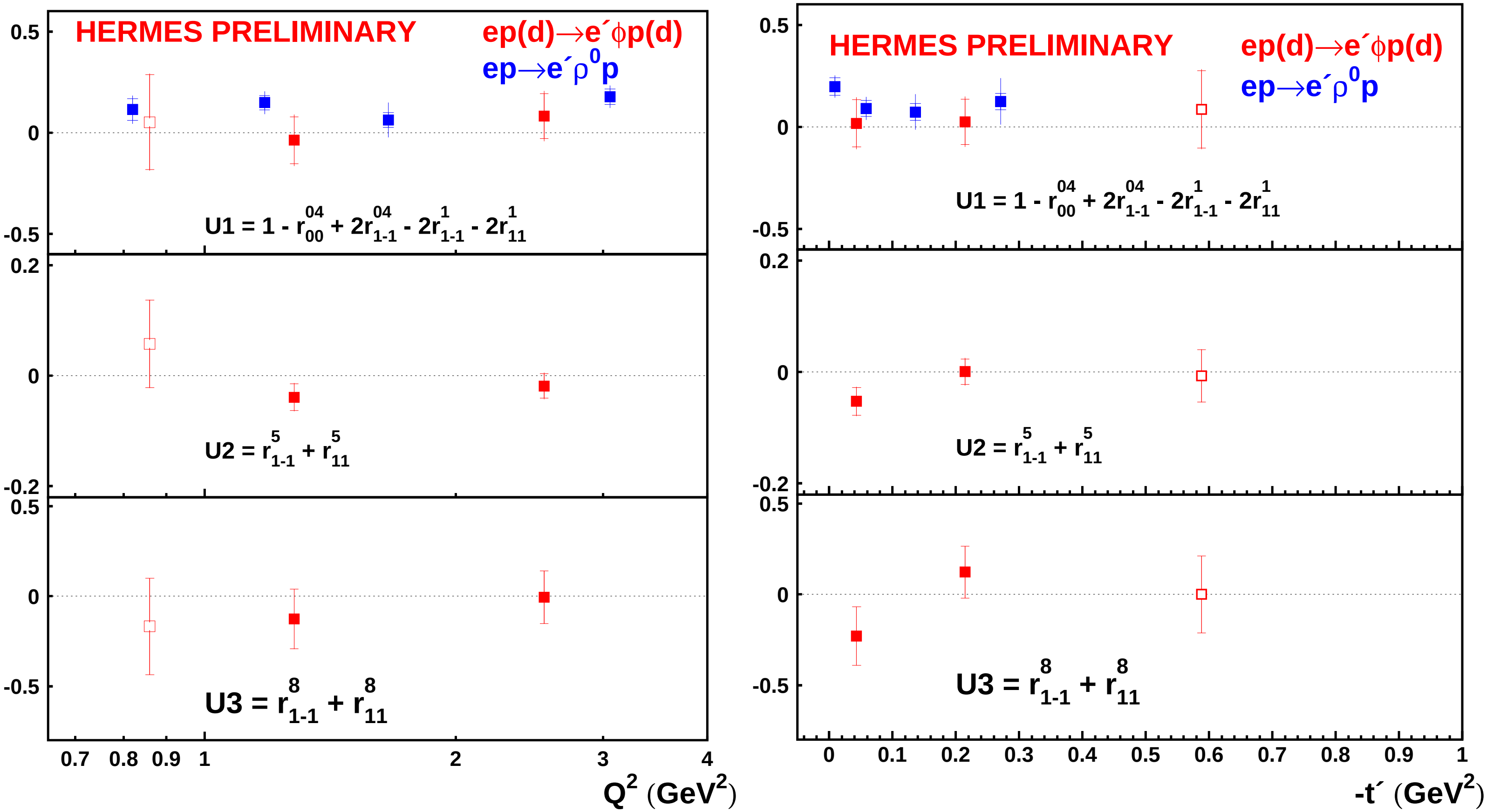
where:

$$r^{04}_{00} = \sum\{\epsilon|T_{00}|^2 + |T_{11}|^2\}/\sigma_{tot}$$

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

$\Longrightarrow$ R^{04} **for ϕ meson at HERMES is in good agreement with world data.**

Natural Parity Exchange in ϕ Meson Leptoproduction



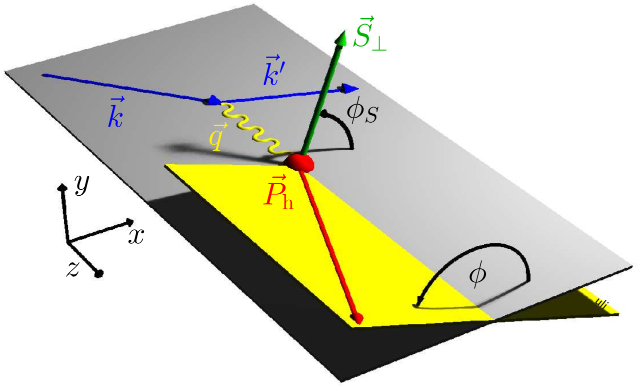
$U1 = 0.02 \pm 0.07_{stat} \pm 0.16_{syst}$

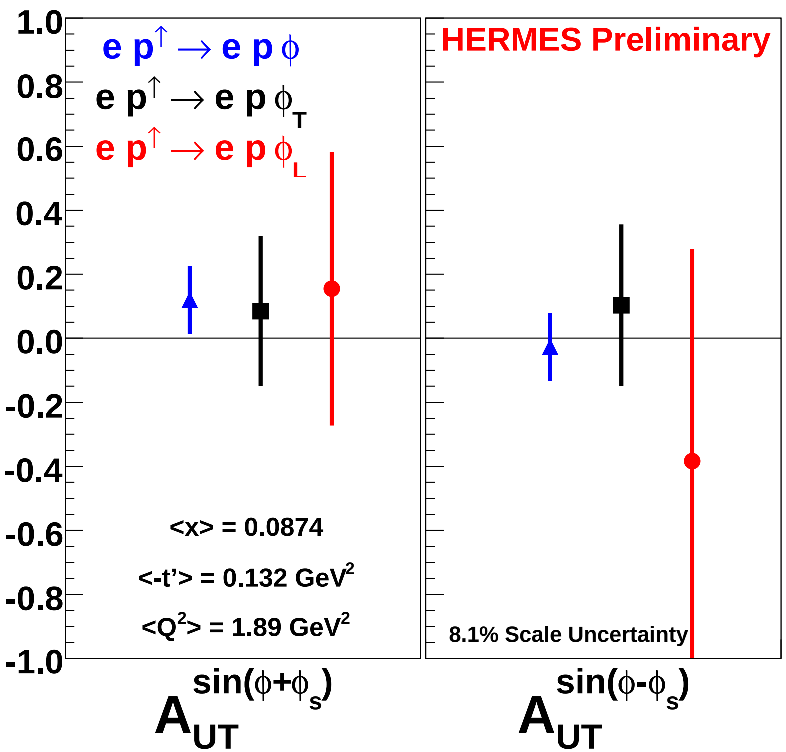
$U2 = -0.03 \pm 0.01_{stat} \pm 0.03_{syst}$

$U3 = -0.05 \pm 0.11_{stat} \pm 0.07_{syst}$

$\Longrightarrow$ **no UPE for ϕ meson production, as expected**

Transverse Target Spin Asymmetry (TTSA)





TTSA allows to separate, sensitive to helicity-flip E GPDs with different spin dependence which contain information about the orbital angular momentum.

Def: $A^{l}_{UT} = \frac{d\sigma(\phi_s)-d\sigma(\phi_s+\pi)}{d\sigma(\phi_s)+d\sigma(\phi_s+\pi)}$, for $P_T = 1, P_L = 0$

Def: $A^{\gamma^*}_{UT} = \frac{d\sigma(\phi_s)-d\sigma(\phi_s+\pi)}{d\sigma(\phi_s)+d\sigma(\phi_s+\pi)}$, for $S_T = 1, S_L = 0$

Determined following prescribtion of M.Diehl and S. Sapeta : hep-ph/0503023v1

from angular distribution $W(P_T, cos(\theta), \phi, \phi_s)$ as amplitudes of $sin(\phi \pm \phi_s)$.

Conclusions

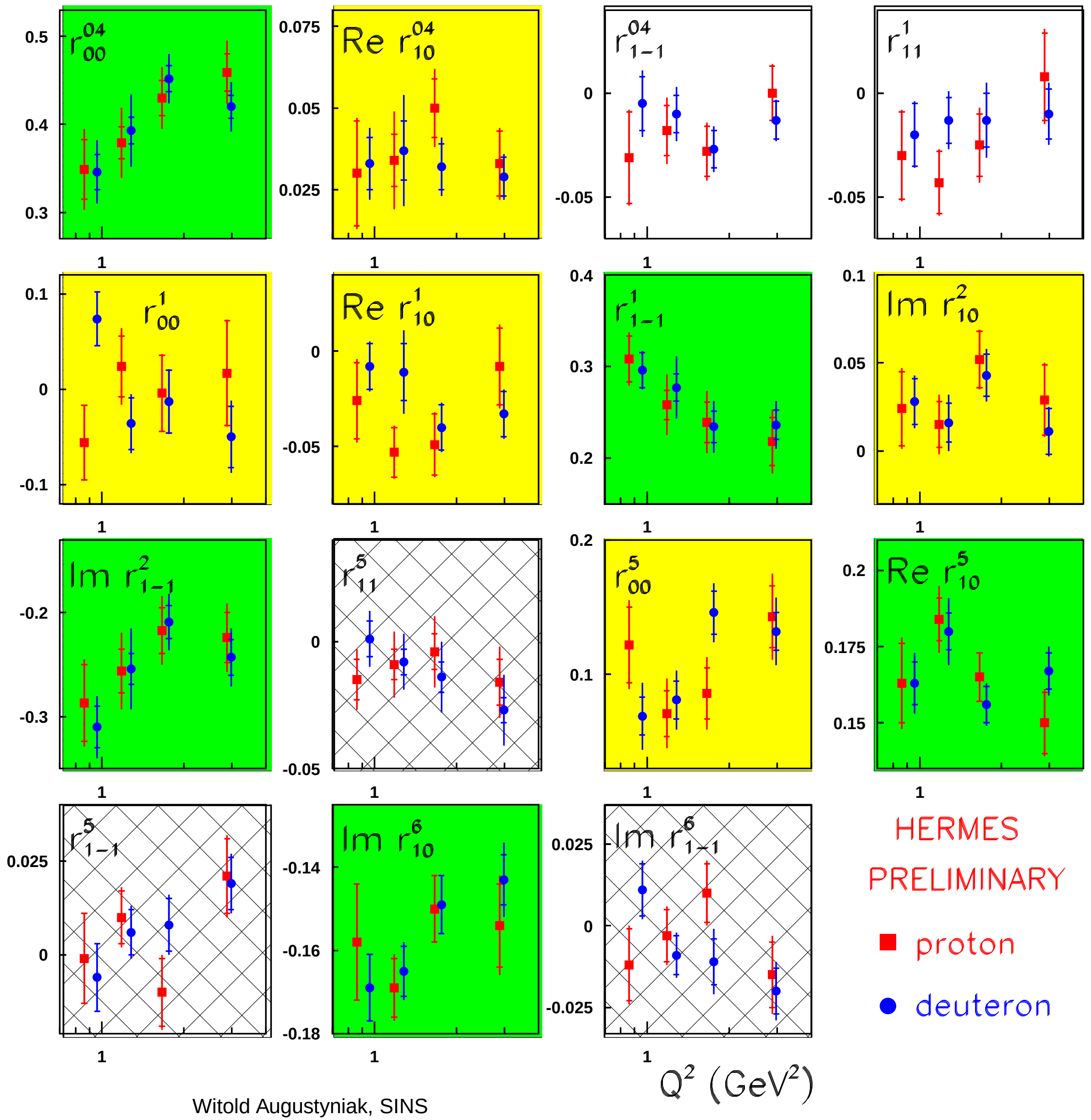
The first measurement of the complete set of SDMEs for ϕ mesons

- **The transitions $\gamma^*_L \to \phi^0_L$ and $\gamma^*_T \to \phi^0_T$ are dominant.**
  SDME's: $(1 - r^{04}_{00})$, r^1_{1-1}, Im r^2_{1-1}, depend on Q^2 i.e $\sim 1/(Q^2 + m_v^2)$
- **The determined value of the difference between phase transitions $\gamma^*_T \to \phi^0_T$ and $\gamma^*_L \to \phi^0_L$**
  $\delta^{\phi}_{p+d} = 33.0^0 \pm 7.4^0$.
- **The SDME's describing the single-helicity-flip transitions: $\gamma^*_T \to \phi^0_L$ and $\gamma^*_L \to \phi^0_T$ as well as the double-helicity-fip $\gamma^*_T \to \phi^0_{-T}$ fluctuate near zero values.**
- **Dependence on target (H, D): not observed.**
- **Only Natural-Parity Exchange was observed.**
- **The comparisons of the $\frac{\sigma_L}{\sigma_T}$ with other measurements: good agreement.**
- **Determination of TTSA with L,T separation**

The latest theoretical calculations in GPD model :S.V.Goloskokov,P.Kroll arXiv:0708.3569 [hep-ph]27.08.07, have been done for HERMES kinematics.

Additional slides

Dependencies of ρ^0 meson SDME's on Q^2



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grid: **Single Flip -** $\gamma^*_L \longrightarrow V_T$

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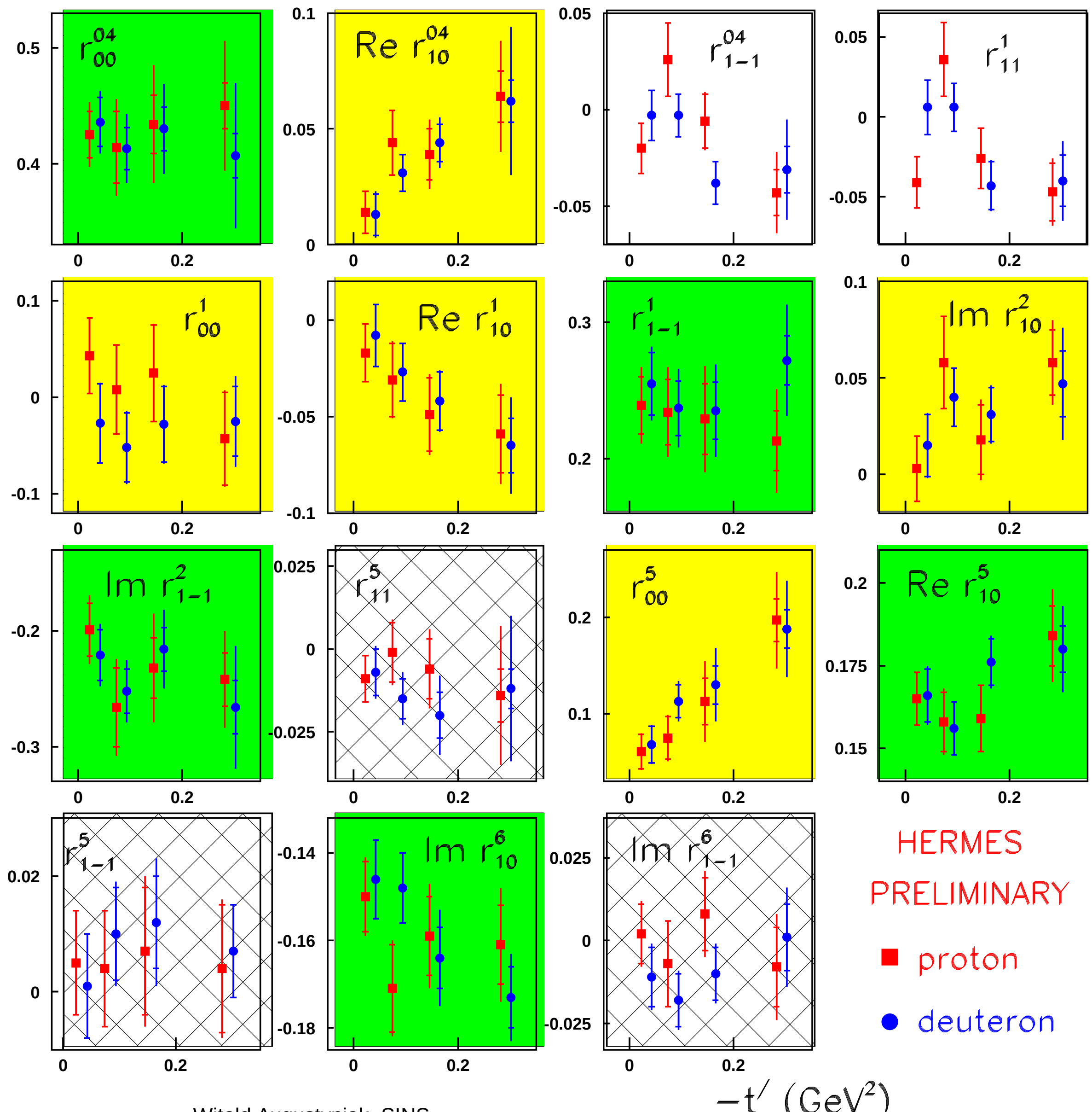
Dependencies of ρ^0 meson SDME's on t'



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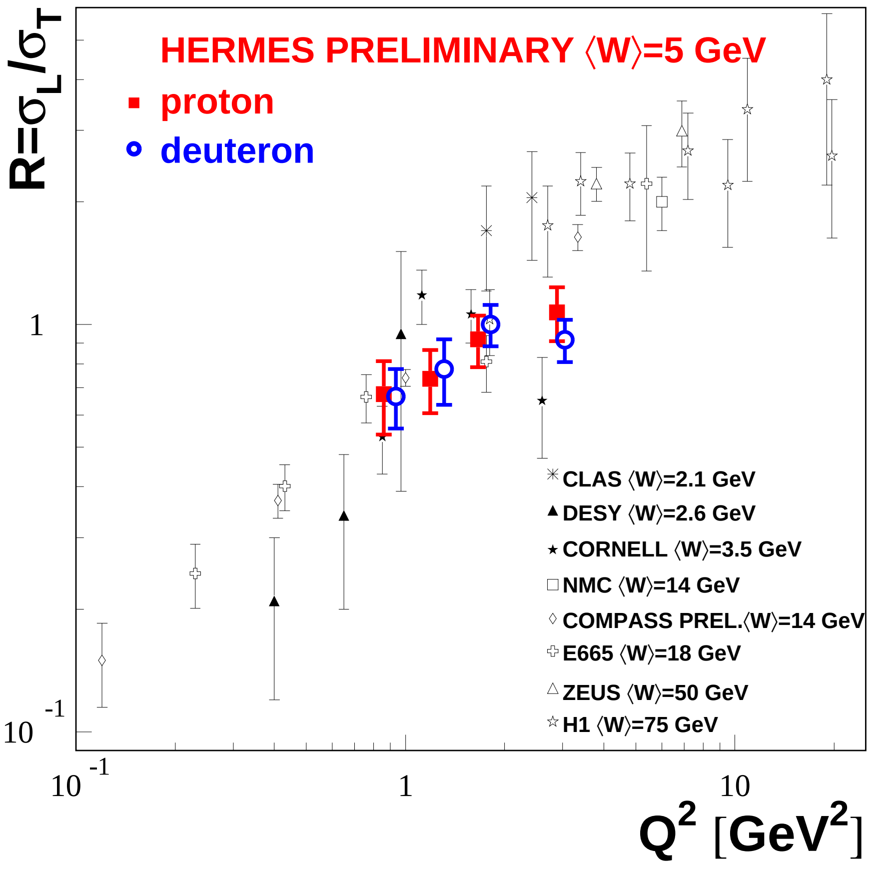
ρ^0 Longitudinal-to-Transverse Cross-Section Ratio



Comparison of commonly measured:

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

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

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

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

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

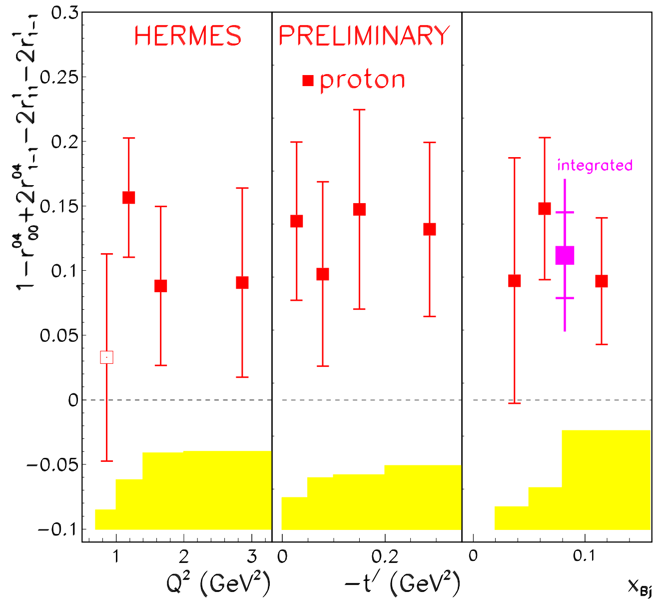
Due to the helicity-flip and unnatural parity amplitudes R^{04} depends on kinematic conditions, and is not identical to $R \equiv |T_{00}|^2/|T_{11}|^2$ at SCHC and NPE dominance.

$\Longrightarrow$ Second order contribution of spin-flip amplitudes to R^{04}

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

Unnatural Parity Exchange (UPE) in ρ^0 Leptoproduction

- Natural-parity exchange: interaction is mediated by a particle of 'natural' parity: vector or scalar meson:
  $J^P = 0^+, 1^-$ e.g. ρ^0, ω, a_2
- Unnatural parity exchange is mediated by pseudoscalar or axial meson:
  $J^P = 0^-, 1^+$, e.g. π, a_1, b_1 $\rightarrow$ only quark-exchange conribution
- No interference between NPE and UPE contributions on unpolarized target
- Extracted from SDMEs:
  $U2 + iU3 \propto (U_{11} + U_{1-1}) * U_{10}$
  $U2 = r^5_{11} + r^5_{1-1}$
  p: $U2 = -0.012 \pm 0.006_{stat} \pm 0.012_{syst}$
  d: $U2 = -0.008 \pm 0.0046_{stat} \pm 0.010_{syst}$
  $U3 = r^5_{11} + r^5_{1-1}$
  p: $U3 = -0.020 \pm 0.050_{stat} \pm 0.007_{syst}$
  d: $U3 = -0.021 \pm 0.038_{stat} \pm 0.011_{syst}$



- $U1 \propto \epsilon|U_{10}|^2 + 2|U_{11} + U_{1-1}|^2$
  $U1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^1_{11} - 2r^1_{1-1}$
  p: $U1 = 2|U_{11}|^2 =$
  $0.132 \pm 0.026_{st} \pm 0.053_{syst}$
  d: $U1 = 0.094 \pm 0.020_{st} \pm 0.044_{syst}$
  p+d: $U1 = 0.109 \pm 0.037_{tot}$

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