# Spin Density Matrix Elements in Exclusive $\rho^0$ Electroproduction on H and D Targets at HERMES

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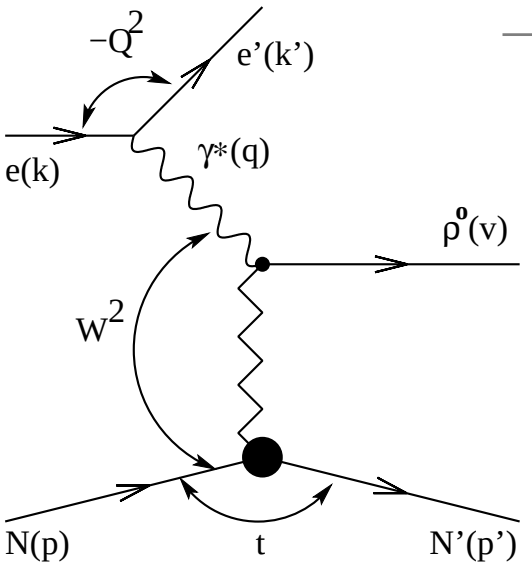
# Descriptions of Exclusive Vector Meson Electroproduction

For studying vector meson production mechanisms use exclusive electroproduction, $\gamma^* + N \to V + N$:

i) Spin state of $\gamma^*$ is known from QED

ii) $\rho^0 \to \pi^+\pi^-$ decay is self-analyzing.




TWO COMPLEMENTARY DESCRIPTIONS:

I) Vector Meson Dominance: $\gamma^* \to V$, with $V + N$ interaction described by (e.g.) Regge phenomenology

II) pQCD: $\gamma^* \to q\bar{q}$ dissociation, followed by $q + N$ (and/or $\bar{q} + N$) interaction

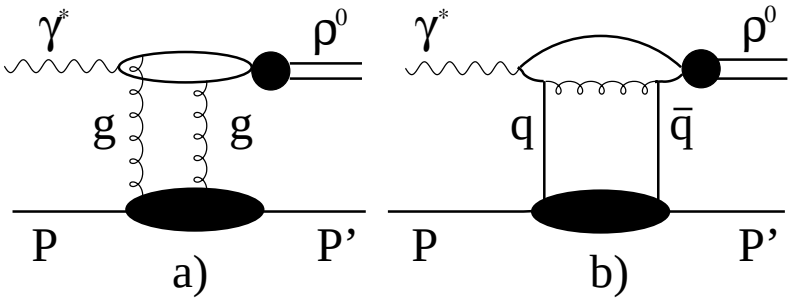
$\Longrightarrow$ One way to constrain Generalized Parton Distributions of the nucleon

- $s$-channel helicity conserved ? (do spin-flip amplitudes contribute )?
- spin-parity ($J^P$) exchange only 'natural' (NPE) or also 'unnatural' (UPE) ?

$J^P = 0^+, 1^-, ...$ NPE:

(Pomeron, $\rho$, ...) $\Rightarrow$

(GPDs $H, E$) $\Rightarrow$




UPE: $J^P = 0^-, 1^+, ...$

$\Leftarrow$ $(\pi, a_1, ...)$

$\Leftarrow$ (GPDs $\widetilde{H}, \widetilde{E}$)

# Exclusive $\rho^0$ Production: $e + N \to e + V + N$

**K.Schilling & G.Wolf, Nucl.Phys.B61,381(1973): Formalism for longitudinal polarized beam, unpolarized target**

I) $e \to e + \gamma^*$ (QED)

Spin-density matrix of virtual photon: $\rho(\gamma^*)$

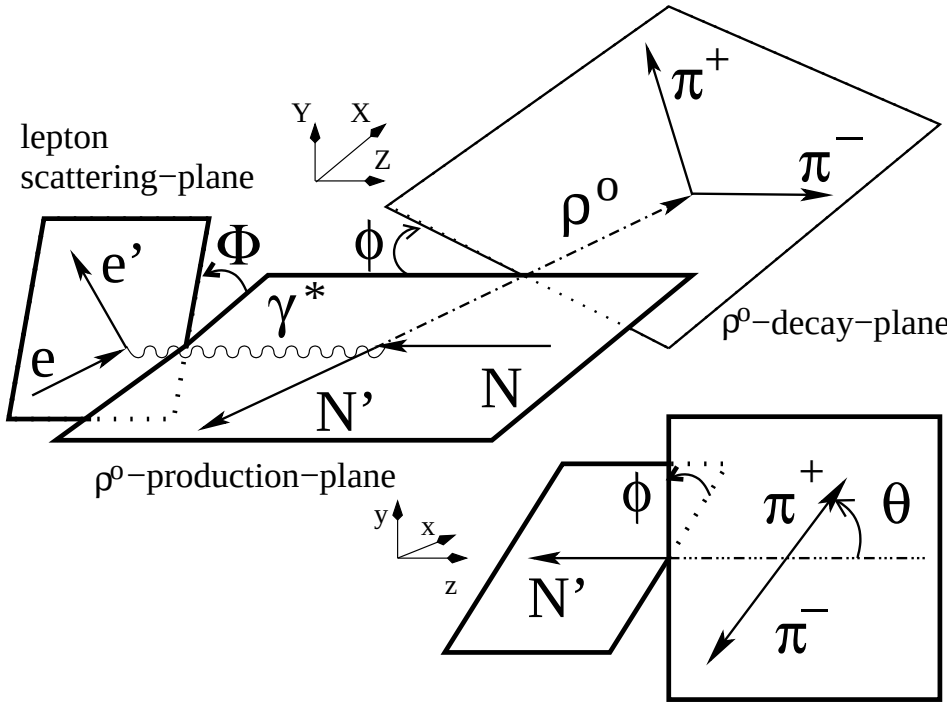
II) $\gamma^* + N \to V + N$ (QCD)

Helicity amplitudes in c.m.s. of $\gamma^* N$:

$F_{\lambda_V \lambda'_N;\lambda_\gamma \lambda_N}$

Vector-meson spin-density matrix:

$r(V) = \frac{1}{2N} \mathrm{tr}_{\lambda_N \lambda'_N} \{F\ \rho(\gamma^*)\ F^*\}$




Define here $\rho^0$ Spin Density Matrix Elements (SDMEs) to be:

Free parameters $r^\alpha_{\lambda_V \lambda'_V}$ where $r^\alpha = \frac{1}{2N} \mathrm{tr}_{\lambda_N \lambda'_N} \{F\ \Sigma^\alpha\ F^*\}$ with $\alpha = 0,\ 1, ...,\ 8$.

If no transverse-longitudinal $\gamma^*$ separation: $r^0_{\lambda_V \lambda'_V} + \epsilon r^4_{\lambda_V \lambda'_V} \Rightarrow r^{04}_{\lambda_V \lambda'_V}$.

$\Longrightarrow$ 15 'unpolarized' SDMEs & 8 'polarized' SDMEs can be extracted

III) $\rho^0 \ \Rightarrow\ \pi^+\pi^-$ (Conservation of $\vec{J}$) $\Rightarrow\ Y_{1m}(\theta, \phi)$ (Decay pion angular distribution)

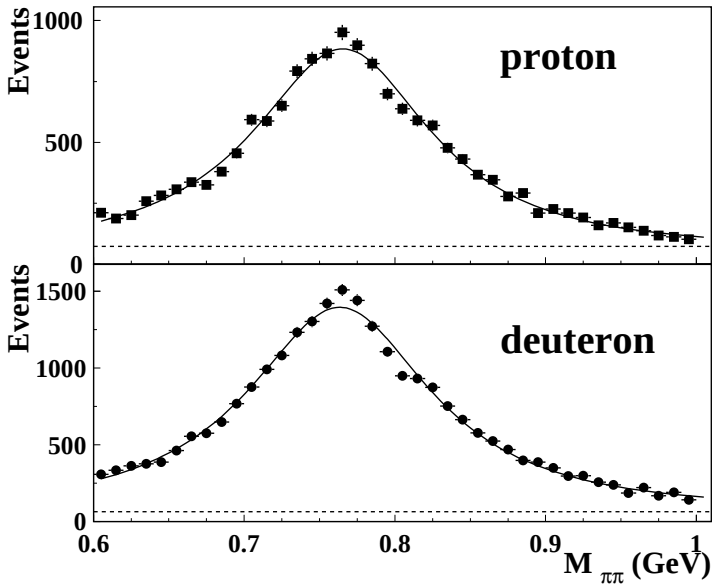
# Kinematic Requirements

- $W = 3.0 \div 6.5$ GeV, $\langle W \rangle = 4.9$ GeV
- $Q^2 = 1.0 \div 7.0$ GeV$^2$, $\langle Q^2 \rangle = 2.3$ GeV$^2$
- $x_B = 0.01 \div 0.35$, $\langle x_B \rangle = 0.07$
- $-t' =\leq 0.4$ GeV$^2$, $\langle -t' \rangle = 0.13$ GeV$^2$ with $t' = t - t_{min}$

Total no. of events (1996-2005)

Hydrogen Target: 16362

Deuterium target: 25940



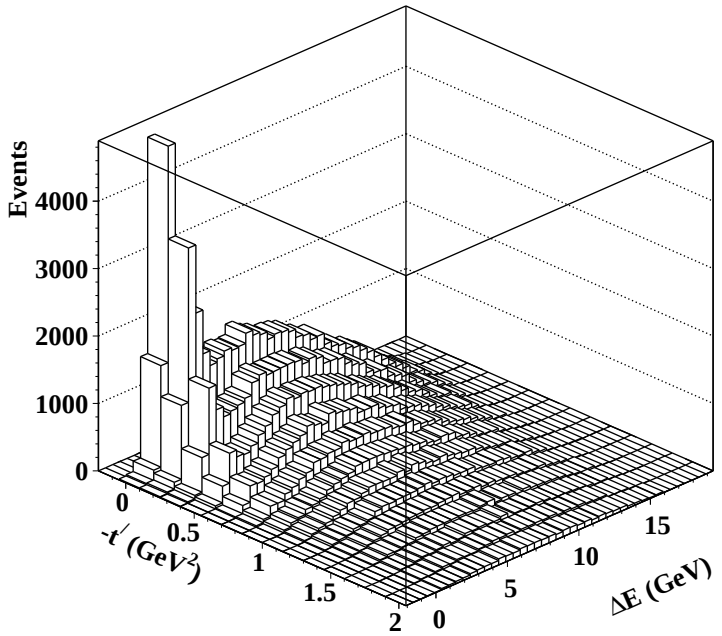

$0.6 < M_{\pi\pi} < 1.0$ GeV

Missing mass:

$$M_X^2 = (p+q-v)^2$$

Missing energy:

$$\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$$

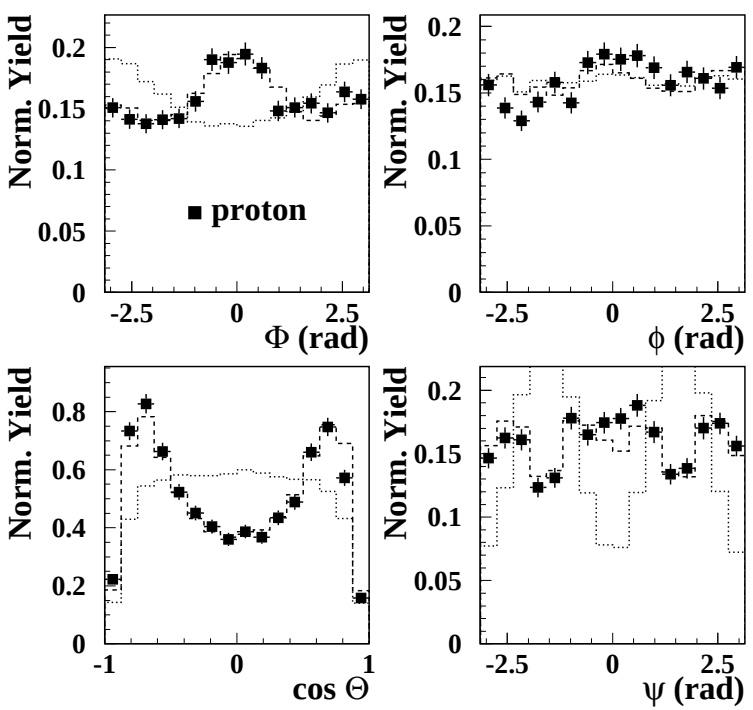


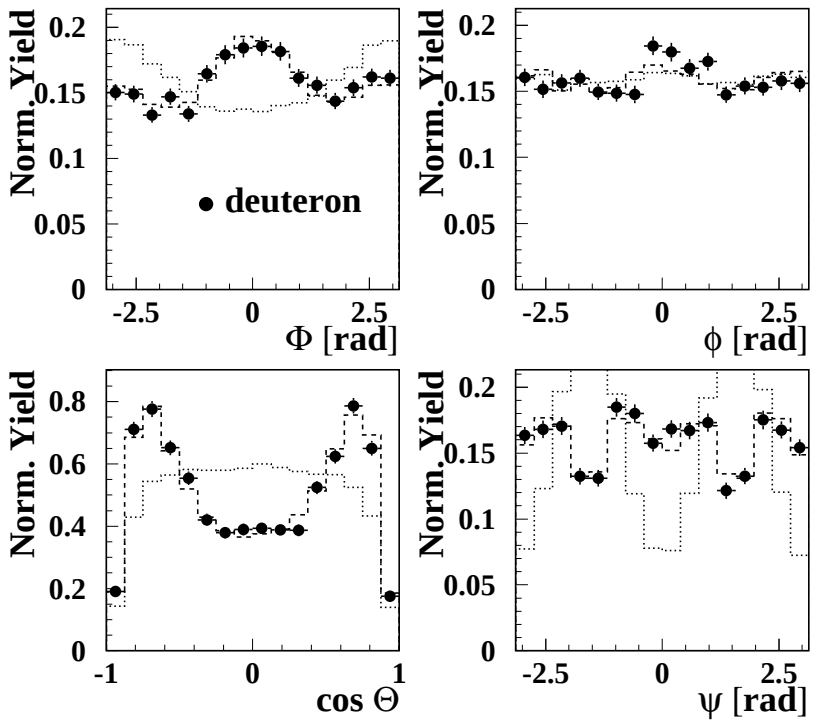

$-1.0 < \Delta E < 0.6$ GeV

SIDIS background simulated by PYTHIA and subtracted per kinematic bin.

# Determination of Spin-density Matrix Elements

- Proton and deuteron data sets treated separately ($\langle |P_{beam}| \rangle = 53.5\%$).
- $(8 \times 8 \times 8)$ binning used for 3-dimensional angular distribution in $(\cos\Theta, \phi, \Phi)$.
- Start from uniform ('fully reconstructed') MC angular distribution **[dotted lines]**.
  By comparing it to experimental angular distribution, fit simultaneously
  15 'unpolarized' SDMEs plus, for the first time, 8 'polarized' SDMEs .
- Good agreement of fitted MC angular distribution **[dashed lines]** and data **[points]**:

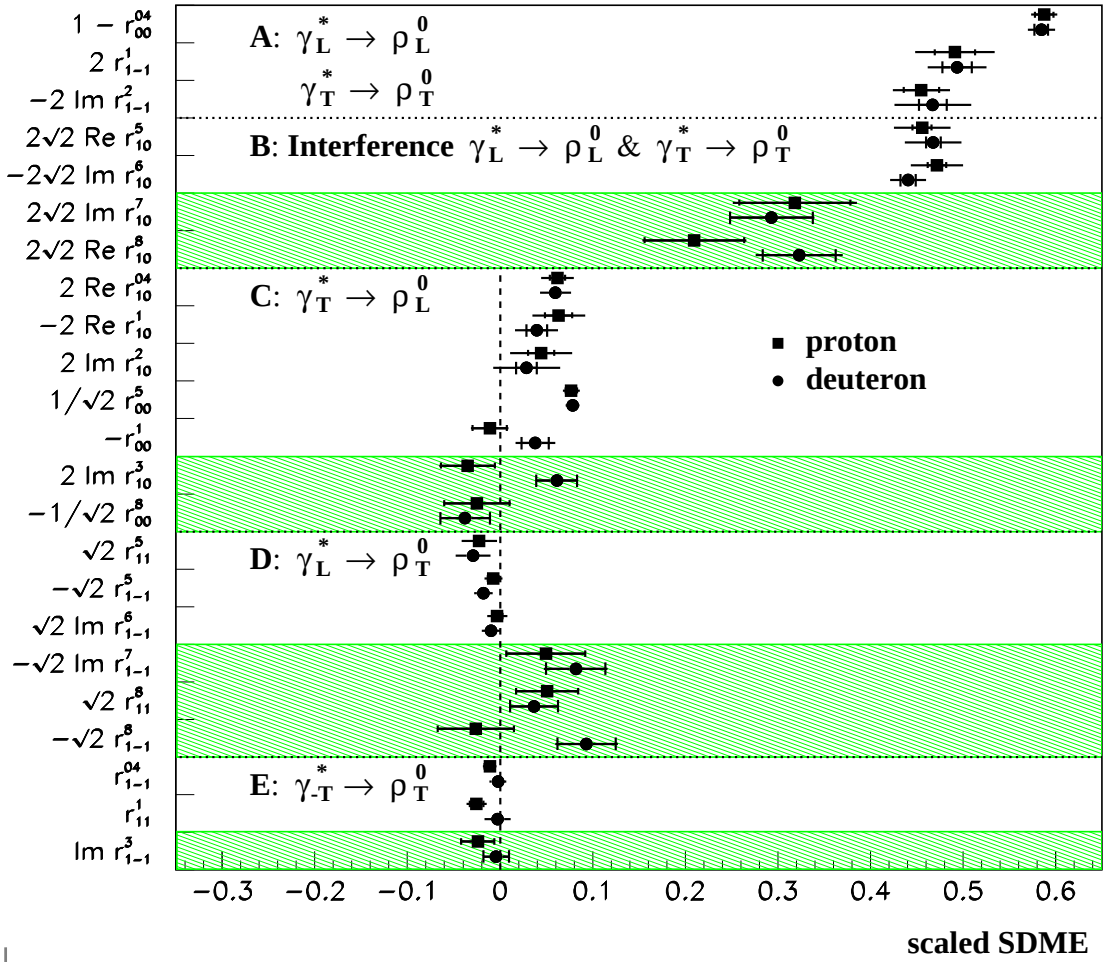


# Results on $\rho^0$ Meson SDMEs $r^{\alpha}_{\lambda_\rho \lambda'_\rho}$ at Average Kinematics

Resulting SDMEs shown according to suggested hierarchy of helicity amplitudes:

$$|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2$$




($T_{\lambda_\rho \lambda_\gamma}$ NPE amplitude,
L: $\lambda_i = 0$, T: $\lambda_i = \pm 1$)

$\Rightarrow$ hierarchy 'confirmed'

- p and d data consistent
- **vertical line:** SCHC
  ($s$-channel helicity conservation)

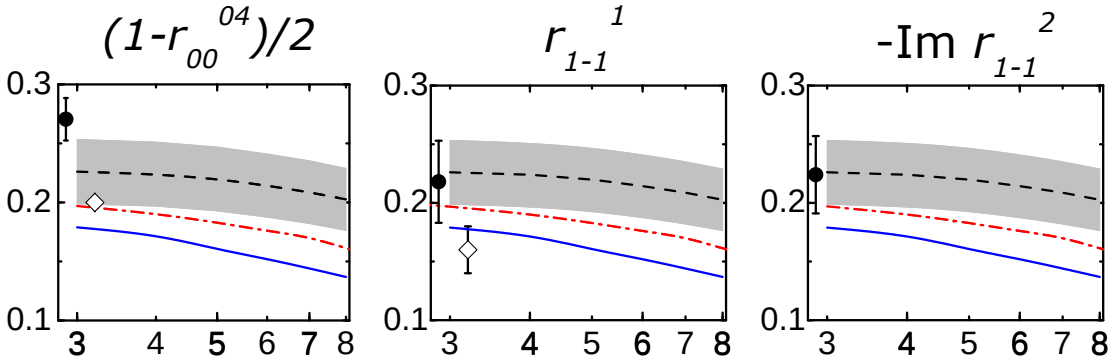
$\Rightarrow$ is violated on $2 \div 10\sigma$ level

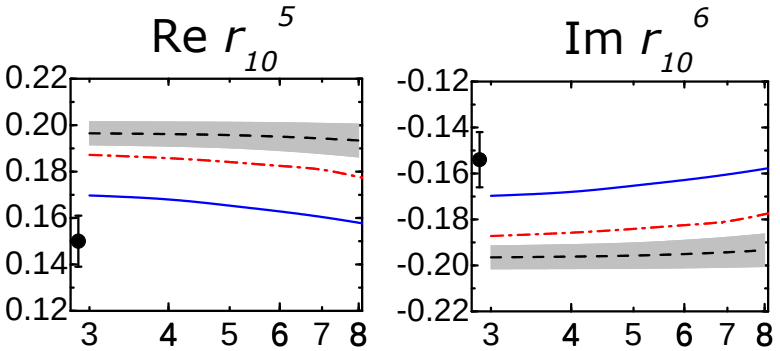
- this data can/will be used to constrain helicity amplitudes

$Q^2$ and $t$ depend. measured for all 23 SDMEs; arXiv:0901.0701[hep-ex], acc. by EPJC

# Comparison with a GPD Model

S.V.Goloskokov & P.Kroll, EPJ C53, 367 (2008):




$Q^2$ dep. of SDMEs calculated for 3 different values of $W$:

$W = 5$ GeV (dashed) – HERMES (prel.!)

$W = 10$ GeV (dash-dotted) –COMPASS

$W = 90$ GeV (solid) – collider

($Q^2 > 3$ GeV$^2$ to reduce HO corrections)

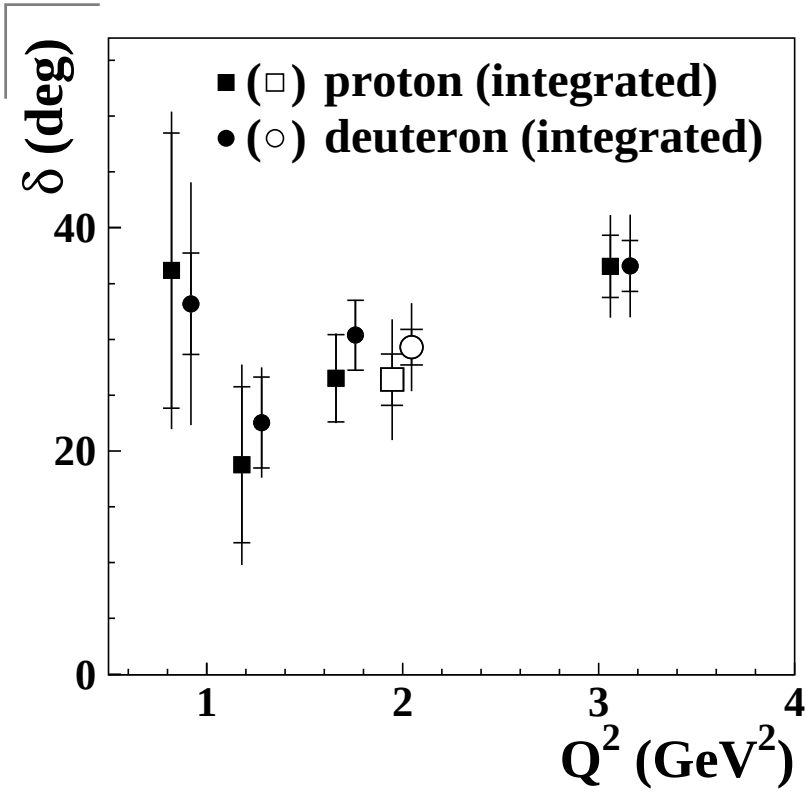
$\Uparrow\Uparrow\Uparrow\Uparrow$ Class-A SDMEs, for $\gamma^*_L \to \rho^0_L$ and $\gamma^*_T \to \rho^0_T$:

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

$\Leftarrow$ Class-B SDMEs, for interference of $\gamma^*_L \to \rho^0_L$ and $\gamma^*_T \to \rho^0_T \Rightarrow$ phase diff. between $T_{00}$ and $T_{11}$

- Class-A SDMEs well described, also $W$ dependence
- Class-B SDMEs not well described (as also phase difference between $T_{00}$ and $T_{11}$, see next slide)

# Phase Difference $\delta$ between Amplitudes $T_{00}$ and $T_{11}$




Neglecting spin-flip amplitudes,

- $|\delta|$ obtained from unpolarized SDMES:

$$\cos\delta = \frac{2\sqrt{\epsilon}(\mathrm{Re}\{r^5_{10}\}-\mathrm{Im}\{r^6_{10}\})}{\sqrt{r^{04}_{00}(1-r^{04}_{00}+r^1_{1-1}-\mathrm{Im}\{r^2_{1-1}\})}},$$

- sign of $\delta$ obtained, for the first time, from polarized SDMES:

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

- $\delta$ shows possible $Q^2$ dependence

- HERMES results on $\delta$ (in degrees):

▷ Proton: $|\delta| = 26.4 \pm 2.3_{\mathrm{stat}} \pm 4.9_{\mathrm{syst}}$; $\delta = +30.6 \pm 5.0_{\mathrm{stat}} \pm 2.4_{\mathrm{syst}}$

▷ Deuteron: $|\delta| = 29.3 \pm 1.6_{\mathrm{stat}} \pm 3.6_{\mathrm{syst}}$; $\delta = +36.3 \pm 3.9_{\mathrm{stat}} \pm 1.7_{\mathrm{syst}}$

$\Rightarrow$ consistent with H1 result: $|\delta| = 21.5^{+4.3}_{-5.3}$ [EPJ C13, 371 (2000)]

!!! GPD model [EPJC53,367(2008)]: $\delta = 3.1$ deg. (at $W = 5$ GeV) $\Rightarrow$ can't describe data !!!

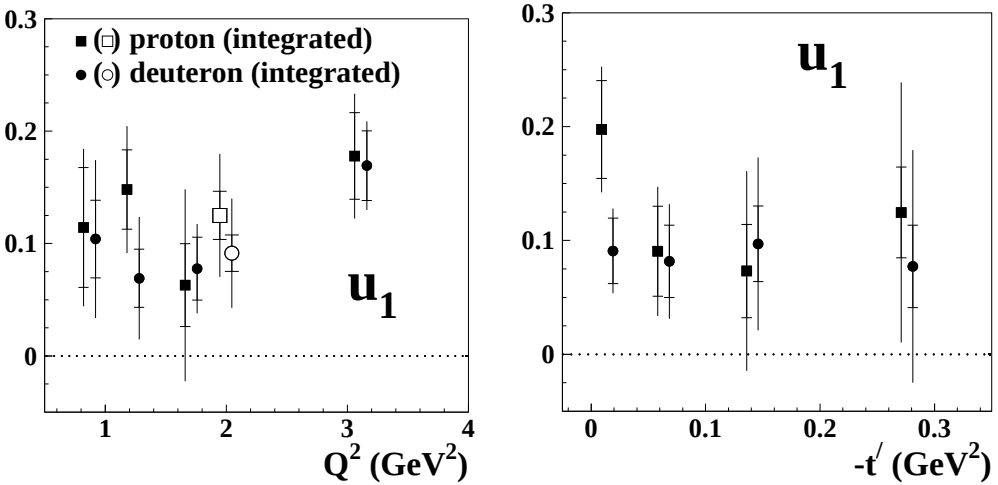
# Observation of Unnatural-Parity Exchange

- No interference between NPE and UPE contributions for unpolarized target
- UPE contributions measured from SDMEs:

$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1}, \quad u_2 = r^{5}_{11} + r^{5}_{1-1}, \quad u_3 = r^{8}_{11} + r^{8}_{1-1}$$

- UPE contributions expressed through amplitudes:

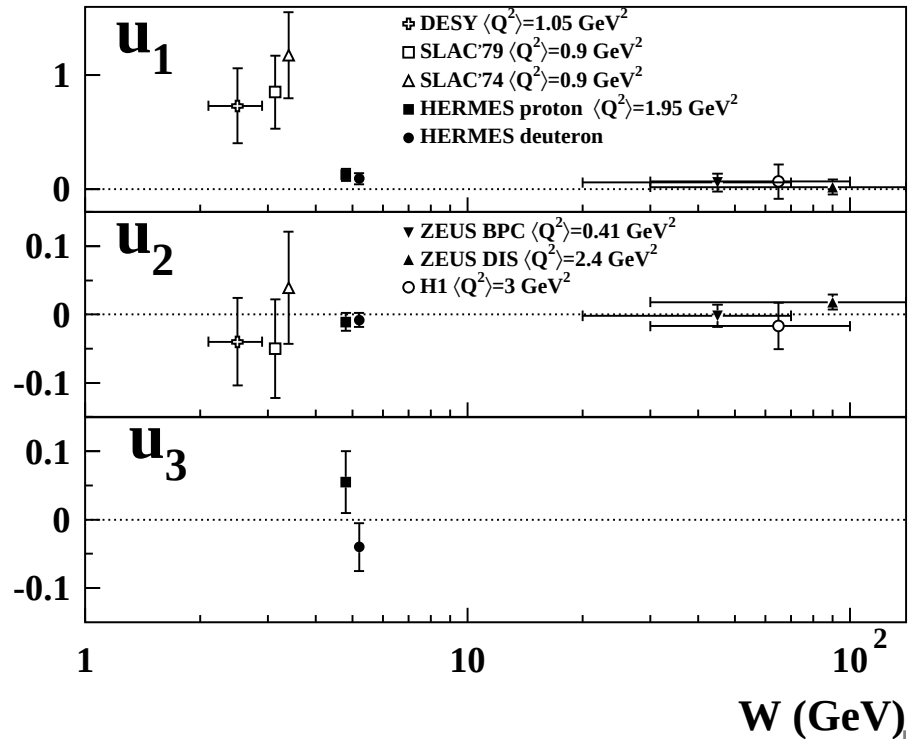
$$u_1 \propto \epsilon|U_{10}|^2 + 2|U_{11} + U_{1-1}|^2, \quad u_2 + iu_3 \propto (U_{11} + U_{1-1}) * U_{10}$$




- $u_1^{\mathrm{p}} = 0.125 \pm 0.021_{stat} \pm 0.050_{syst}$,
- $u_1^{\mathrm{d}} = 0.091 \pm 0.016_{stat} \pm 0.046_{syst}$

$$\Rightarrow \quad u_1^{\mathrm{p+d}} = 0.106 \pm 0.036$$

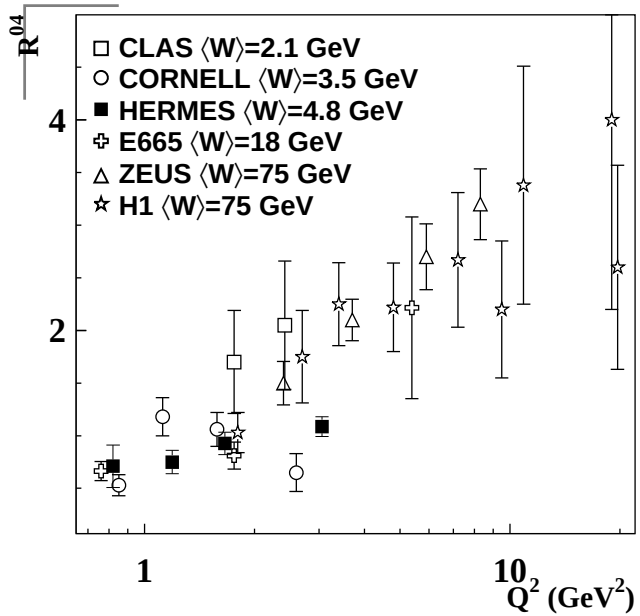
⇒ Hierarchy of UPE amplitudes (?):
$|U_{11}| \gg |U_{10}| \sim |U_{01}| \sim |U_{1-1}|$

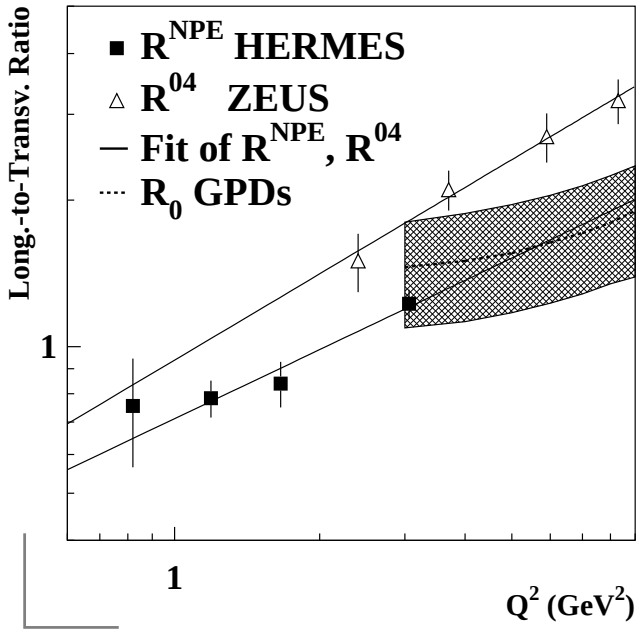



- $\langle u_1^{\mathrm{low-W}} \rangle = 0.70 \pm 0.16, \quad u_1^{\mathrm{high-W}} \approx 0$

⇒ UPE contribution is $W$ dependent

# Longitudinal-to-transverse Cross Section Ratio R




$\Longleftarrow$ Precise data of Hermes and Zeus show different $Q^2$ slopes:

origin: $W$ dependence of $R$ and/or UPE contribution at low $W$.

- True $R$ defi ned with respect to $\gamma^*$ polarization:

$$R(W,Q^2,t) = \frac{d\sigma_L}{dt} / \frac{d\sigma_T}{dt} = \mathcal{N}_L/\mathcal{N}_T,$$

with $\mathcal{N}_L = \frac{1}{2}\sum_{\lambda_N\lambda'_N}\left(|T_{00}|^2 + 2|T_{10}|^2 + 2|U_{10}|^2\right),$

and $\mathcal{N}_T = \frac{1}{2}\sum_{\lambda_N\lambda'_N}\left(|T_{11}|^2 + |T_{01}|^2 + |T_{-11}|^2 + |U_{11}|^2 + |U_{01}|^2 + |U_{-11}|^2\right).$

- Commonly measured R defi ned with respect to $\rho$ polarization:

$R^{04} = \frac{r^{04}_{00}}{\epsilon(1-r^{04}_{00})} \approx \frac{|T_{00}|^2}{|T_{11}|^2+|U_{11}|^2}$; theorists use $R_0 = \frac{|T_{00}|^2}{|T_{11}|^2}$

$\Rightarrow$ in both (SCHC-violating) spin-flip amplitudes are neglected.

- UPE contribution can be 'taken out' of $R^{04}$:

$R^{\rm NPE} \approx R^{04}[1 + \frac{u_1}{2}(1+\epsilon R^{04})]$ $\epsilon$: $\frac{\gamma^*_L}{\gamma^*_T}$ flux ratio

$\Rightarrow$ comparison of $R^{04}_{\rm ZEUS}$ and $R^{\rm NPE}_{\rm HERMES}$: $W$ dependence of $R$

# Summary

- Exclusive $\rho^0$ production was studied by HERMES at $\langle W \rangle \simeq 5$ GeV using polarized $e^+/e^-$ beams and unpolarized hydrogen and deuterium targets
- Measured were 15 'unpolarized' and, for the first time, 8 'polarized' SDMEs
- Kinematic dependences on $Q^2$ and $t$ were measured for all 23 SDMEs
- No statistically significant difference seen between proton and deuteron data
- $s$-channel helicity not conserved on 10$\sigma$ level (for $r^5_{00}$), 3.5$\sigma$ (for Re $r^{04}_{10}$)
- Signal for unnatural-parity exchange seen for the first time (on 3$\sigma$ level), for combined p and d data
- Sign of phase between 2 spin non-flip amplitudes measured for the first time
- Longitudinal-to-transverse cross section ratio R determined, experimental indication found for a $W$ dependence of the $Q^2$ slope of $R$, for the first time