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HERMES Measurements of Hard-Exclusive Processes

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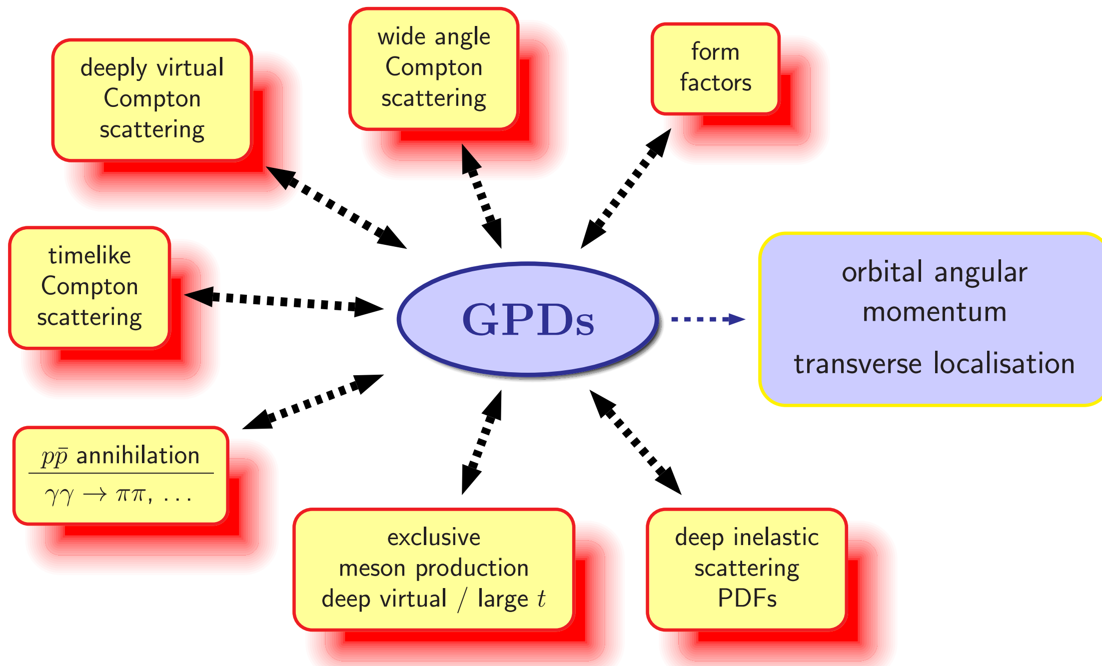
- Objectives: Generalized Parton Distribution
- HERMES Experiment
- Exclusive ρ^0 and ϕ vector meson selection
  - ρ^0 and ϕ Meson Spin Density Matrix Elements (SDMEs)
  - Transverse target-spin asymmetry in exclusive ρ^0production
- DVCS
- Summary

Probing GPD experimentally



- GPDs are accessable in hard exlusive processes:

- Exclusive meson production

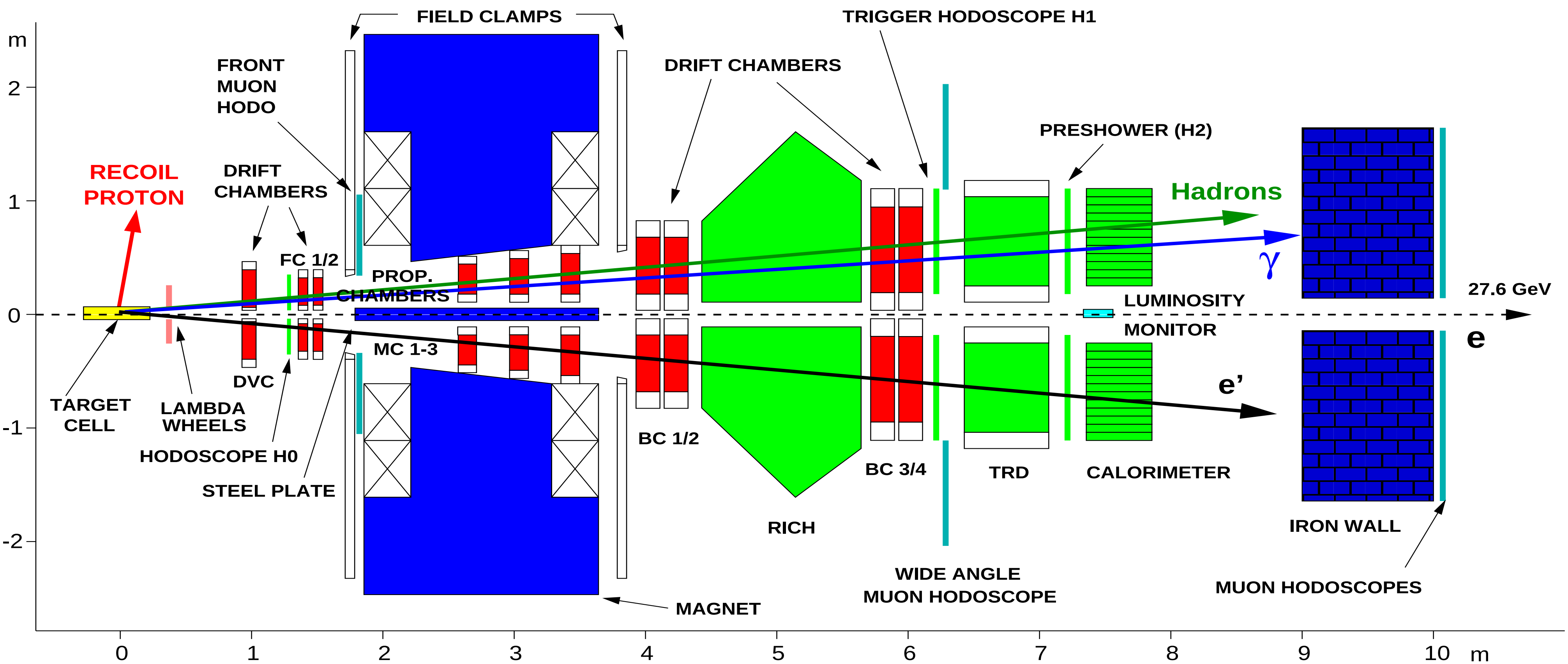
- longitudinally polarized vector meson - E, H
- pseudoscalar or the axial-vector meson - $\tilde{E}, \tilde{H}$

- DVCS -E, H, $\tilde{E}, \tilde{H}$
- Observables: cross sections, SDMEs, asymetries

HERMES Detector is Two Identical Halves of Forward Spectrometer

- Beam: $P = 27.56$ GeV/c, $50 ... 100$ mA, longitudinal polarization $\sim 55\%$, accuracy of 2%

- Target: ^{1}H, ^{2}H gases, unpolarized, polarized



- Acceptance: $40 < \Theta < 220$ mrad, $|\Theta_x| < 170$ mrad, $40 < |\Theta_y| < 140$ mrad

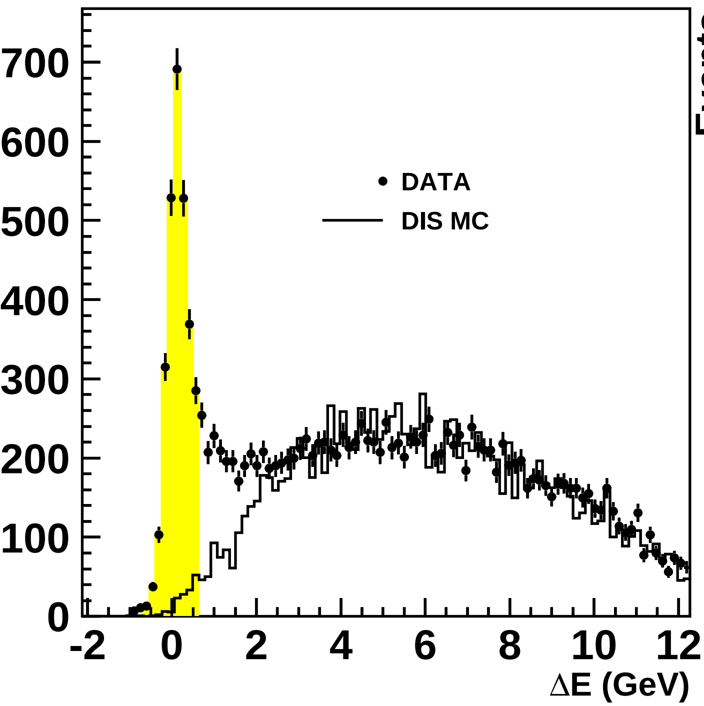
- Resolution: $\delta p/p < 1\%$, $\delta\Theta < 0.6$ mrad

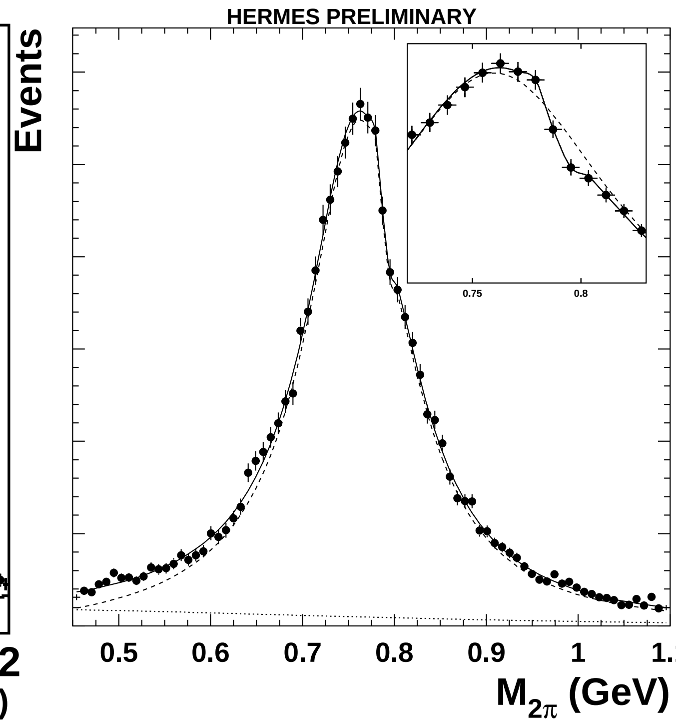
Selection of exclusive ρ^0 and ϕ meson production

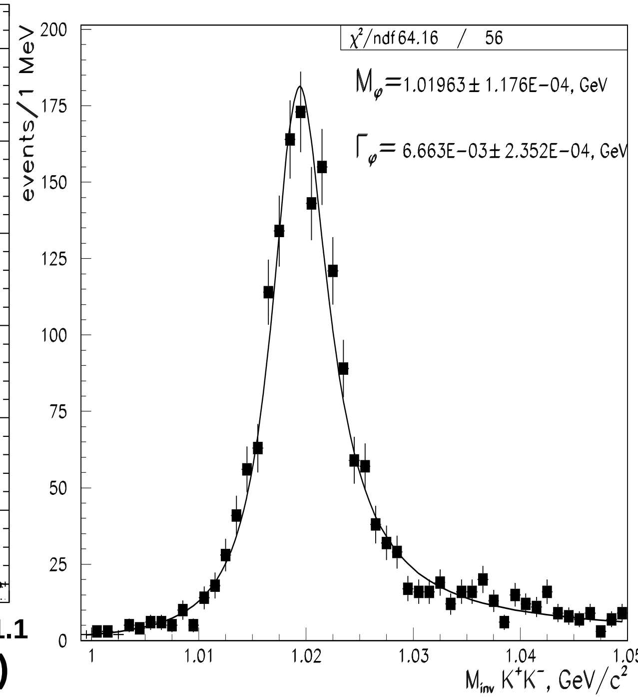
$e + p \rightarrow e' + p' + \rho^0 \rightarrow \pi^+\pi^-$ $\qquad$ $e + p \rightarrow e' + p' + \phi \rightarrow K^+K^-$

Clean ρ^0 exclusivity peak

$\Delta E = \frac{M_X^2 - M_p^2}{2M_p} = \nu + \frac{t}{2M_p} - E_h, \nu = E - E'$, $\qquad$ M$_{inv}$:$\rho^0 \rightarrow \pi^+\pi^-$ $\qquad$ $\phi \rightarrow K^+K^-$



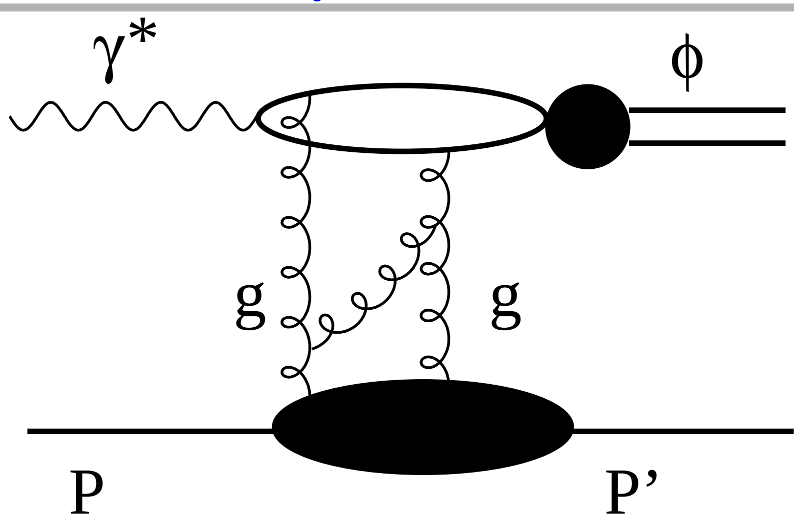


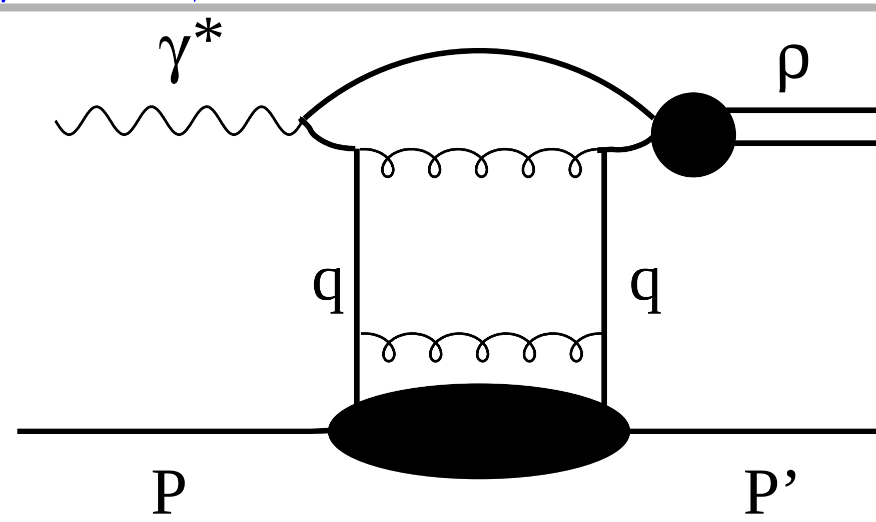


- SIDIS Background is subtracted using MC (PYTHIA)

- $\nu = 5 \div 24$ GeV, $<\nu> = 13.3$ GeV, $\qquad$ $Q^2 = 1.0 \div 5.0$ GeV^2,$<Q^2> = 2.3$ GeV^2
- $W = 3.0 \div 6.5$ GeV, $<W> = 4.9$ GeV, $\quad$ $x_{Bj} = 0.01 \div 0.35$,$<x_{Bj}> = 0.07$

Comparison of Exclusive ρ^0 and ϕ Meson Production





Properties of ρ^0 and ϕ meson data:

- different pQCD production mechanisms:
  - only two-gluon exchange for ϕ,
  - both two-gluon and quark exchanges for ρ^0

  $\Longrightarrow$ GPDs as a flavor filter

- quark exchange mediated by
  - vector or scalar meson: ρ^0, ω, a_2 (natural parity: $J^P = 0^+, 1^-$)

    $\Longrightarrow$ unpolarized GPDs: H, E
  - pseudoscalar or axial meson: π, a_1, b_1 (unnatural parity $J^P = 0^-, 1^+$)

    $\Longrightarrow$ polarized GPDs: $\tilde{H}$, $\tilde{E}$

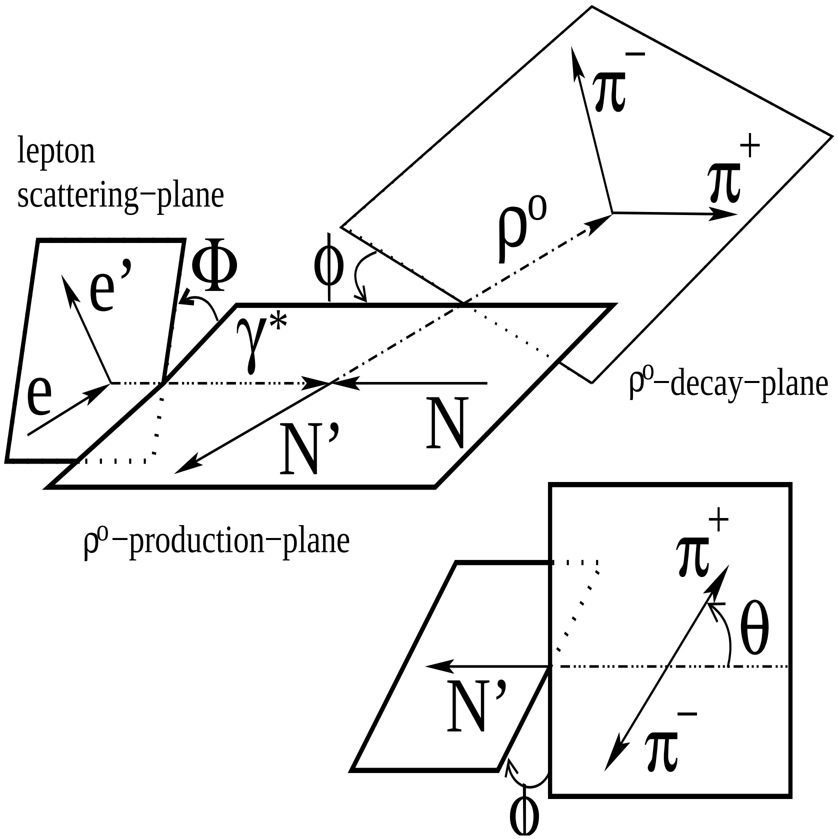
Experimental observables:

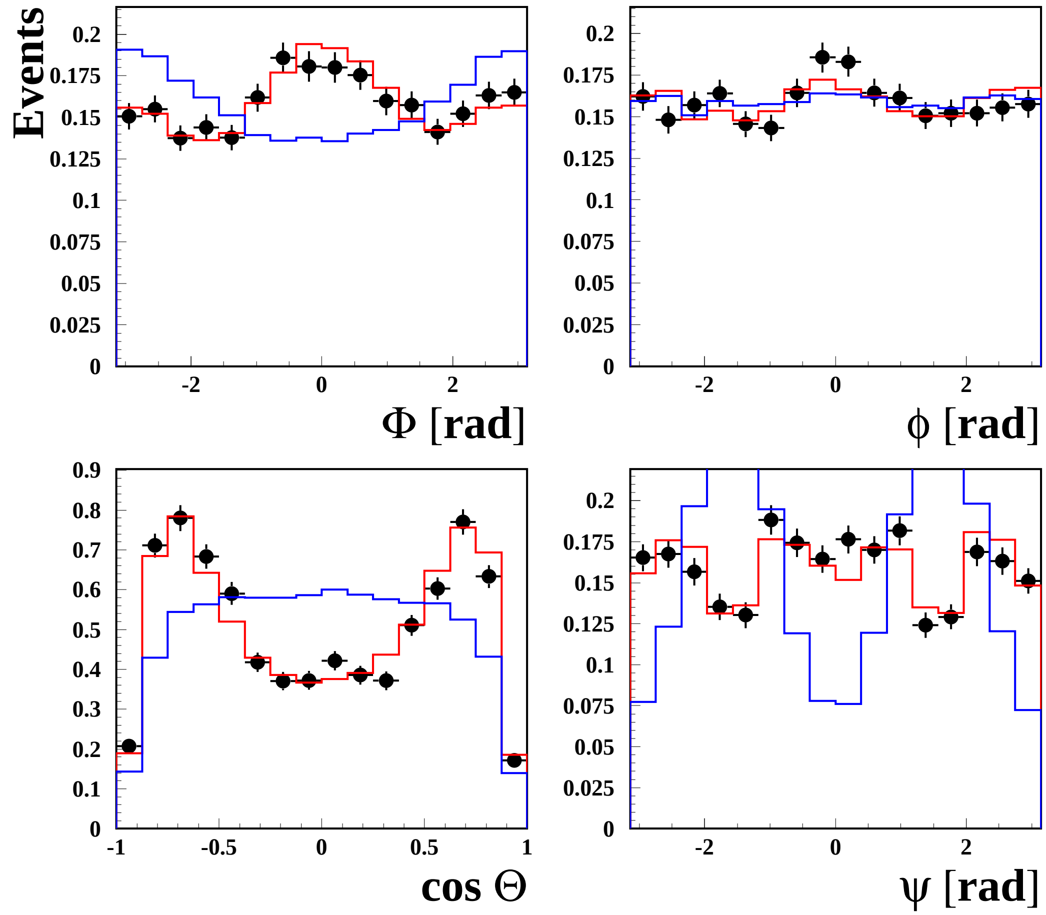
- Spin Density Matrix Elements (SDMEs): $r^{\alpha}_{\lambda_\rho \lambda'_\rho} \sim \rho(V) = \frac{1}{2} T \rho(\gamma) T^+$
  Vector meson spin-density matrix $\rho(V)$ in terms of the photon matrix $\rho(\gamma)$ and helicity amplitude $T_{\lambda_V \lambda_\gamma}$

- SCHC: helicity of γ^* = helicity of ρ^0, any violation?

- Determination of the contribution of the Natural (NPE,$P = (-1)^J$) and Unnatural(UPE,$P = -(-1)^J$) Parity Helicity Amplitudes

Fit of Angular Distributions Using Max. Likelihood Method in MINUIT



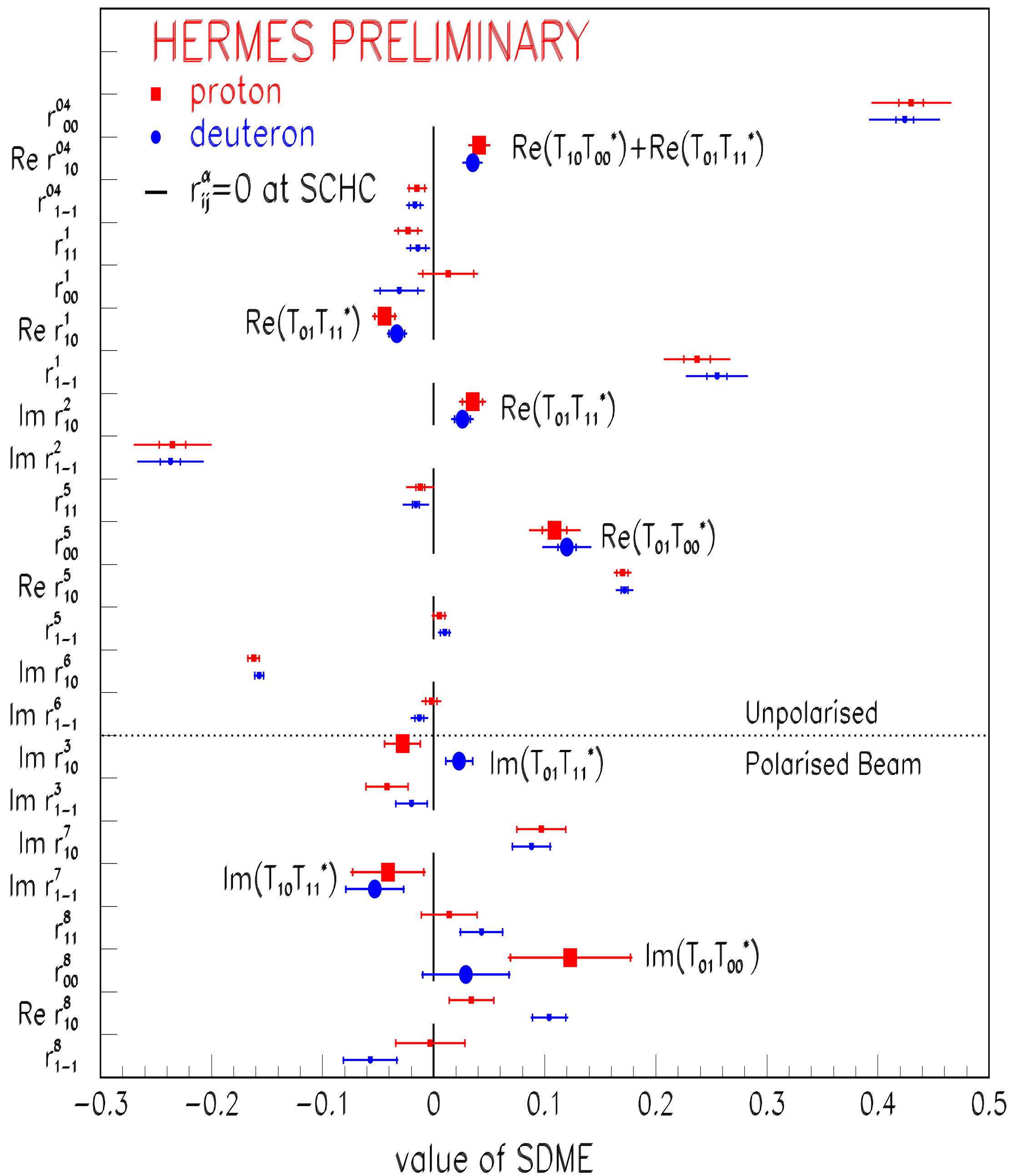


- Simulated Events: matrix of fully reconstructed MC events at initial uniform angular distribution
- Binned Maximum Likelihood Method: $8 \times 8 \times 8$ bins of $\cos(\Theta), \phi, \Phi$. Simultaneous fit of theoretical angular distribution W($\mathrm{r}_{ij}^{\alpha}, \Phi, \phi, \cos\Theta$)to data with negative and positive beam helicity ($< P_b >= 53.5\%$)

$\Longrightarrow$ **Full agreement of fitted angular distributions with data**

23 Spin Density Matrix Elements $r^{\alpha}_{\lambda_\rho \lambda'_\rho}$ from $\gamma^* + N \to \rho^0 + N'$

at $0 < t' < 0.4$ GeV^2 and $1 < Q^2 < 5$ GeV^2



- SDMEs: $r^{\alpha}_{\lambda_\rho \lambda'_\rho} \sim \rho(V) = \frac{1}{2} T \rho(\gamma) T^{+}$ in terms of the photon matrix $\rho(\gamma)$ and helicity amplitude $T_{\lambda_V \lambda_\gamma}$

  $\Longrightarrow$ Beam-polarization dependent SDMEs, for the first time

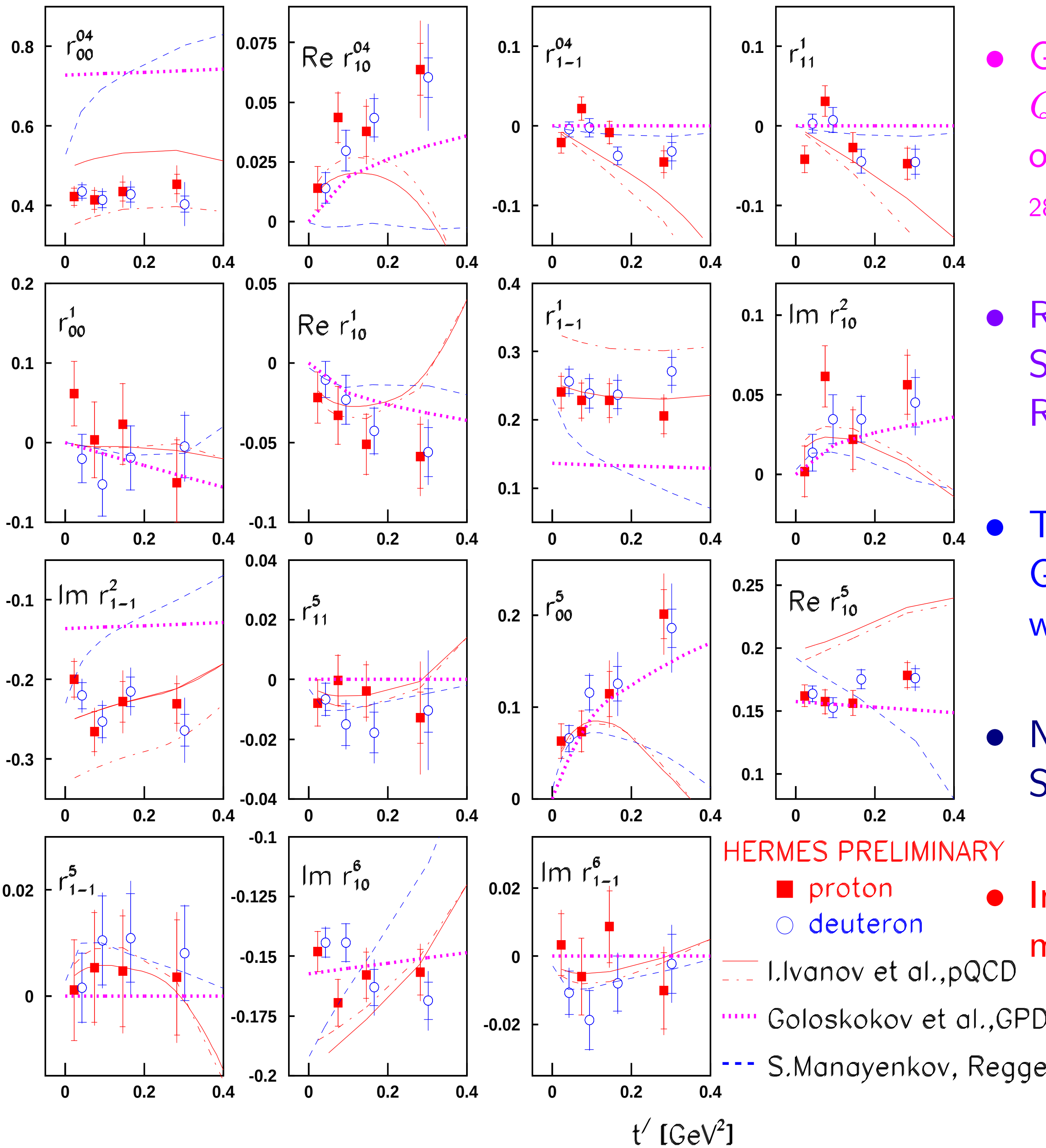
- SCHC?

  $\Longrightarrow$ enlarged SDMEs violating SCHC $(2 \div 5\ \ \sigma)$, indicating non-zero spin-flip amplitudes: T_{01}, T_{10}, T_{1-1}

- $q\bar{q}$-exchange with isospin 1 can be observed in case of difference between proton and deuteron data

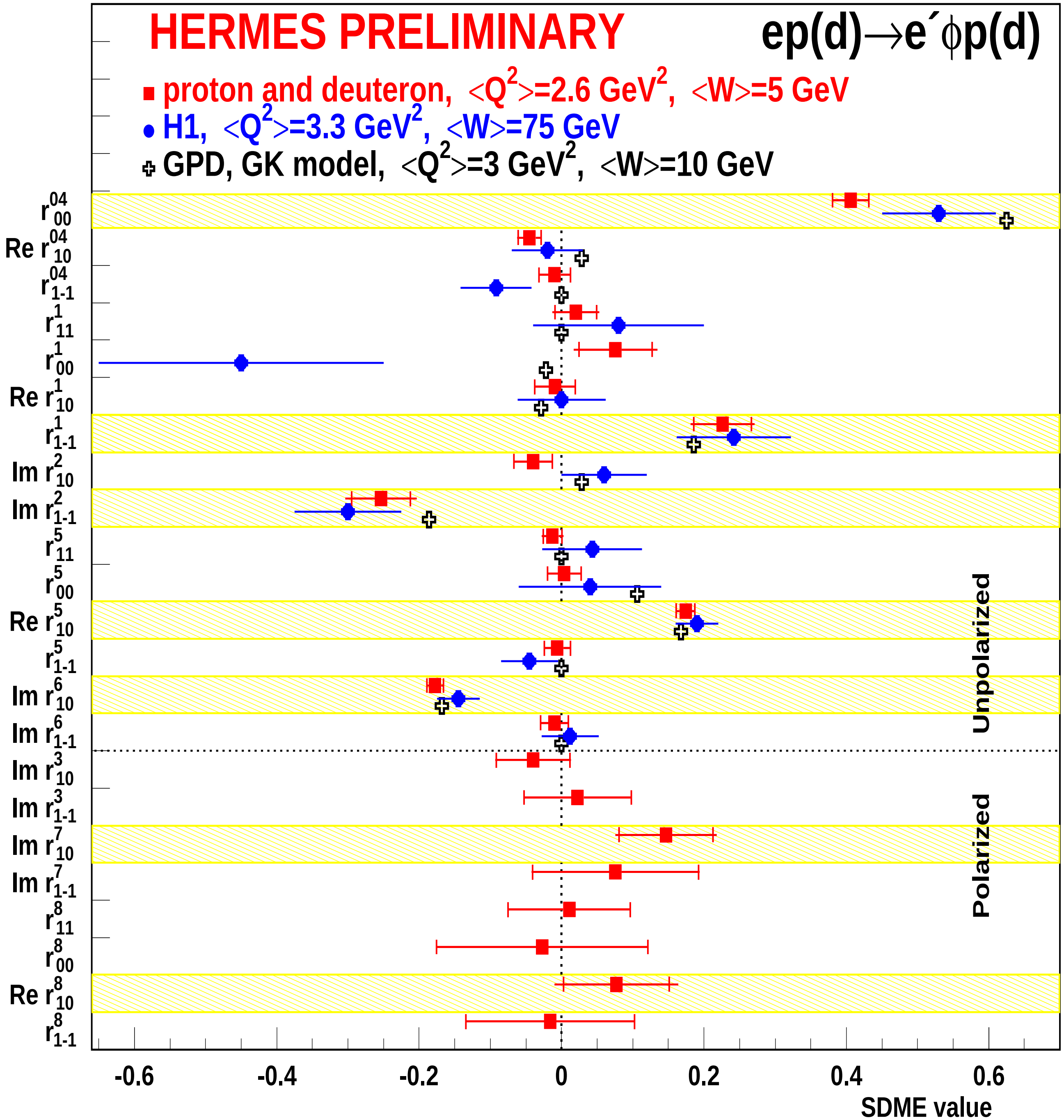
  $\Longrightarrow$ No significant difference between proton and deuteron

t'-Dependence of ρ^0 SDMEs Compared with Calculations



- GK model calculations done for $Q^2 > 3.0$ GeV^2 for two-gluon exchange only (S.V.Goloskokov and P.Kroll, Eur.Phys.J. C **42** (2005) 281)
- Reasonable agreement for a majority of SDMEs (12 elements) at low t': Re r^{04}_{10}, r^{5}_{00}...
- The most crucial disagreement with data for GK model: r^{04}_{00}, r^{1}_{1-1}, $\mathrm{Im}\{\mathrm{r}^2_{1-1}\}$ connected with σ_L/σ_T ratio
- No model describes well all unpolarized SDMEs.
- Incorporation of quark-exchange into GK model is under development

ϕ Meson SDMEs Compared with Calculations and High Energy Data



- Note: GK model calculations done for $Q^2 = 3.0$ GeV^2 and two-gluon exchange

  $\Longrightarrow$ Reasonable agreement for a majority of SDMEs

- Disagreement with data for GK Model:
  - $r^{04}_{00} \longrightarrow \sigma_L/\sigma_T$ ratio
  - $r^{5}_{00} \longrightarrow$ SCHC in data, but not in the model

$\Longrightarrow$ Further development of GK model

SDMEs According to Hierarchy of Amplitudes without&with Helicity Flip: ρ^0, ϕ

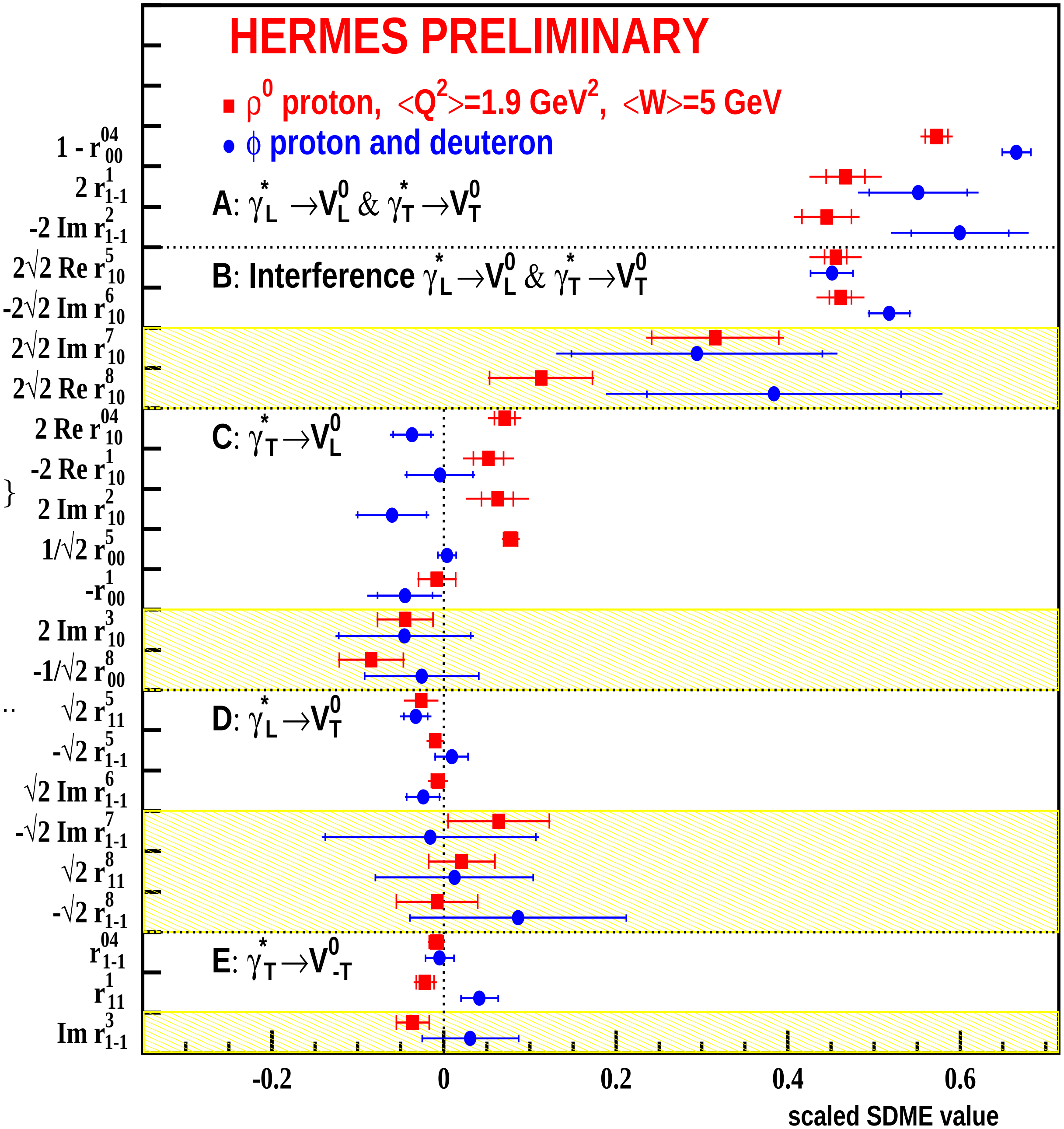
- A, $\gamma^*_L \to \rho^0_L$ and $\gamma^*_T \to \rho^0_T$
  $|T_{11}|^2 \propto 1 - r^{04}_{00} \propto r^1_{1-1} \propto -Im\{r^2_{1-1}\}$

- B, Interference: γ^*_L, ρ^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: $\gamma^*_T \to \rho^0_L$
  $Re\{T_{11}T^*_{01}\} \propto Re\{r^{04}_{10}\} \propto Re\{r^1_{10}\} \propto Im\{r^2_{10}\}$
  $Re\{T_{01}T^*_{00}\} \propto r^5_{00}$
  $|T_{01}|^2 \propto r^1_{00}$
  $Im\{T_{01}T^*_{11}\} \propto Im\{r^3_{10}\}$
  $Im\{T_{01}T^*_{00}\} \propto r^8_{00}$

- D, Spin Flip: $\gamma^*_L \to \rho^0_T$
  $Re\{T_{10}T^*_{11}\} \propto r^5_{11} \propto r^5_{1-1} \propto Im\{r^6_{1-1}\}$
  $Im\{T_{10}T^*_{11}\} \propto Im\{r^7_{1-1}\} \propto r^8_{11} \propto r^8_{1-1}$

- E, Spin Flip: $\gamma^*_T \to \rho^0_{-T}$
  $Re\{T_{1-1}T^*_{11}\} \propto r^{04}_{1-1} \propto r^1_{11}$
  $Im\{T_{1-1}T^*_{11}\} \propto Im\{r^3_{1-1}\}$

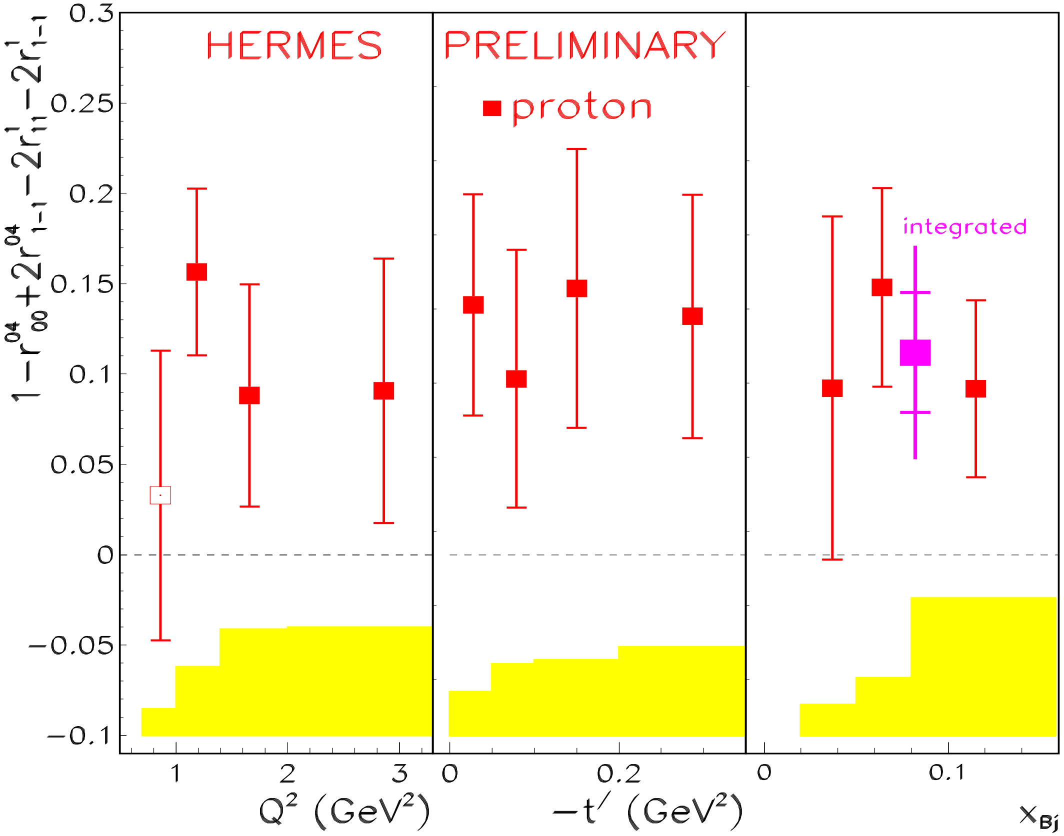


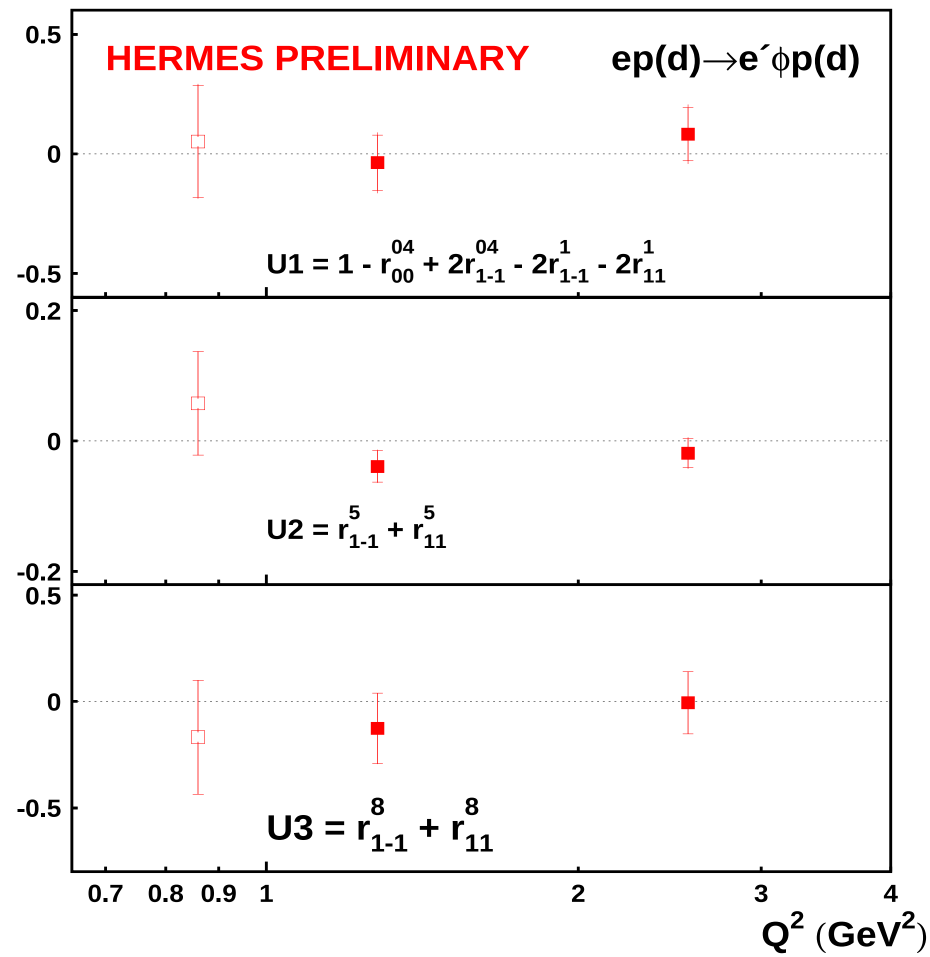
$\Longrightarrow$ **Hierarchy of ρ^0 amplitudes:** $|T_{00}| \sim |T_{11}| \gg |T_{01}| > |T_{10}| \gtrsim |T_{1-1}|$,

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

Observation of 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
- UPE amplitudes correspond to the contributions of polarized GPDs: $\tilde{H}$, $\tilde{E}$





p: $U1 = 2|U_{11}|^2 = 0.132 \pm 0.026_{st} \pm 0.053_{syst}$

d: $U1 = 0.094 \pm 0.020_{st} \pm 0.044_{syst}$

$U2 \propto |U_{10}|^2 = 0$, $U3 \propto |U_{01}|^2 = 0$

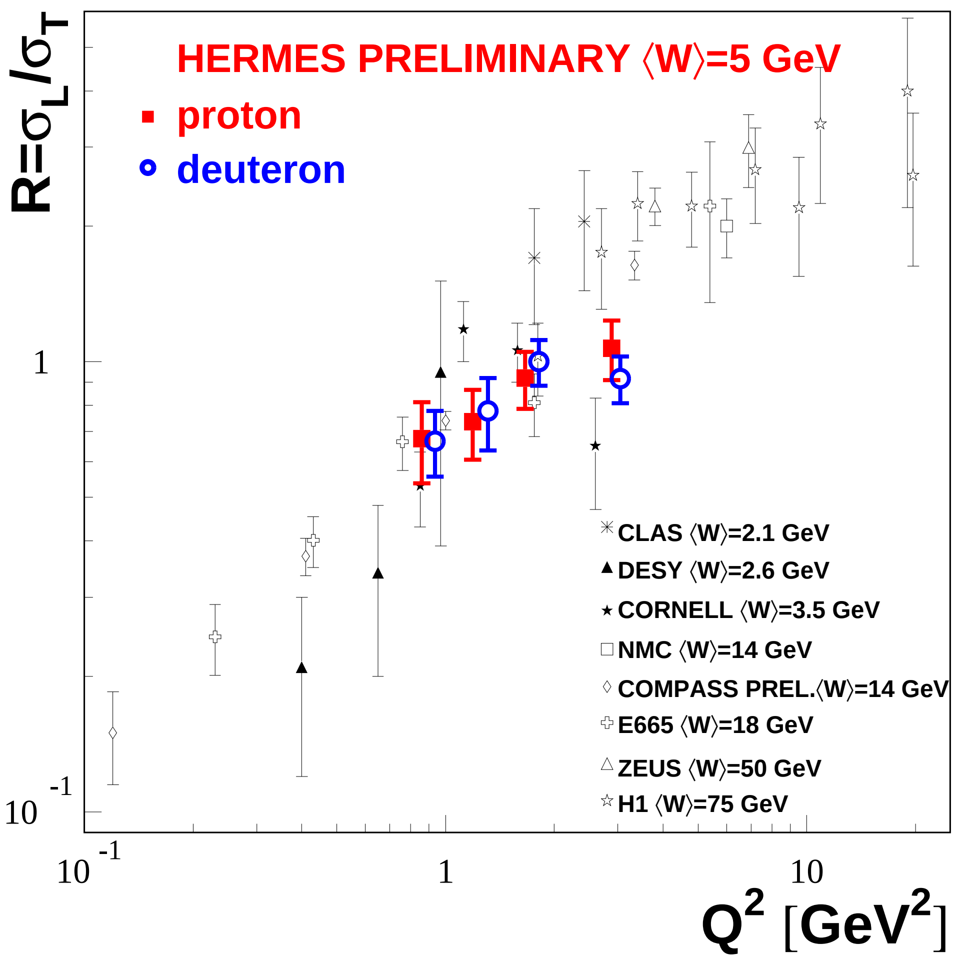
$\Longrightarrow$ **no UPE for ϕ meson production**

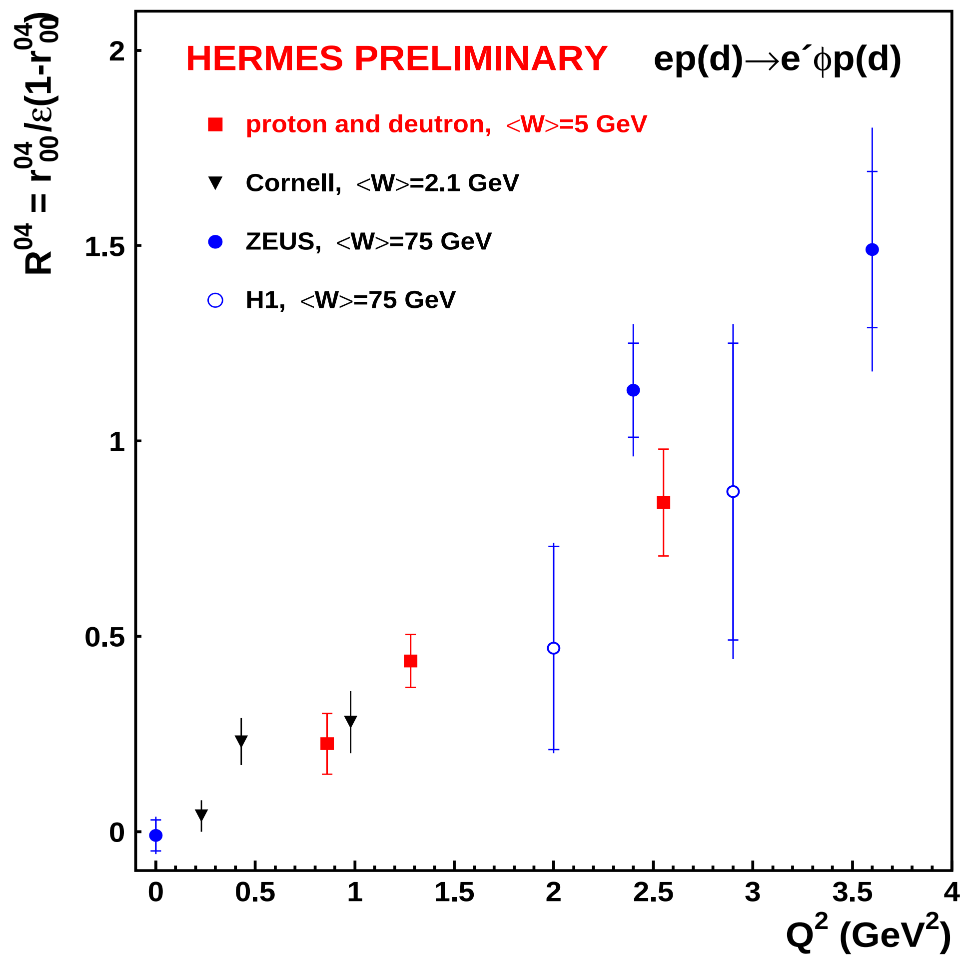
$\Longrightarrow$ **Indication on hierarchy of ρ^0 UPE amplitudes: $|U_{11}| \gg |U_{10}| \sim |U_{01}|$**

ρ^0 and ϕ Longitudinal-to-Transverse Cross-Section Ratio $R^{04} = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}}$,

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

$\sigma_T = \sum\{|T_{11}|^2 + |T_{01}|^2 + |T_{1-1}|^2 + |U_{11}|^2\}$, $\quad \sigma_L = \sum\{|T_{00}|^2 + 2|T_{10}|^2\}$



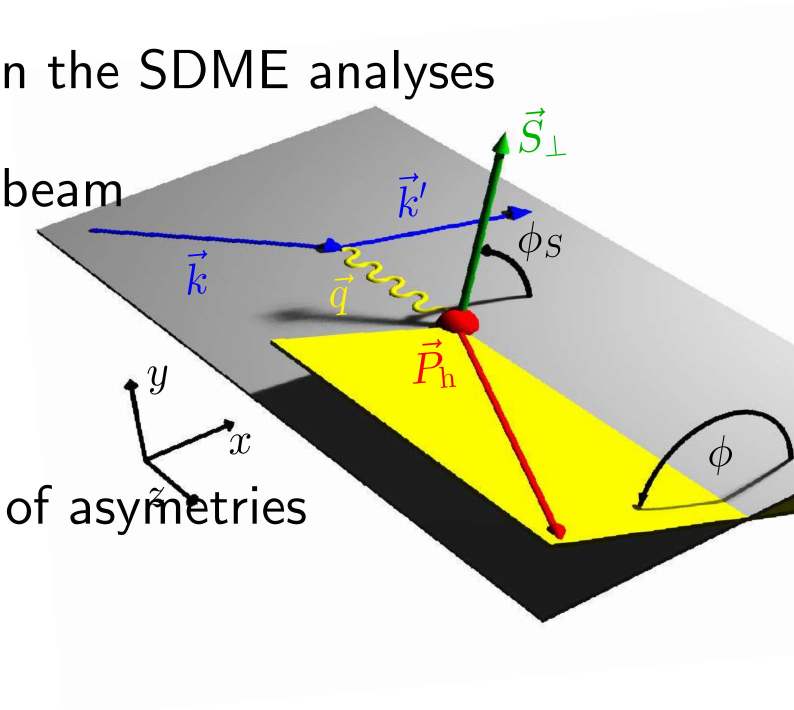


$\Longrightarrow$ Due to the helicity-flip and unnatural parity amplitudes R^{04} depends on kinematic conditions, and is not identical to $R \equiv |T_{00}|^2/|T_{11}|^2$ at SCHC and NPE dominance

$\Longrightarrow$ **HERMES data suggests an R(W)-dependence**

Transverse Target Spin Asymmetry in Exclusive ρ_0 production

- Data taken with a transversely polarized Hydrogen target
- Selection of exclusive ρ_0 vector meson the same as in the SDME analyses
- Transverse target polarization relative to the lepton beam direction



$$A^l_{UT}(\phi, \phi_s) = \frac{1}{P_T}\frac{d\sigma(\phi,\phi_s) - d\sigma(\phi,\phi_s+\pi)}{d\sigma(\phi,\phi_s) + d\sigma(\phi,\phi_s+\pi)}$$

- Angular (ϕ, ϕ_s) distribution can be written in terms of asymmetries

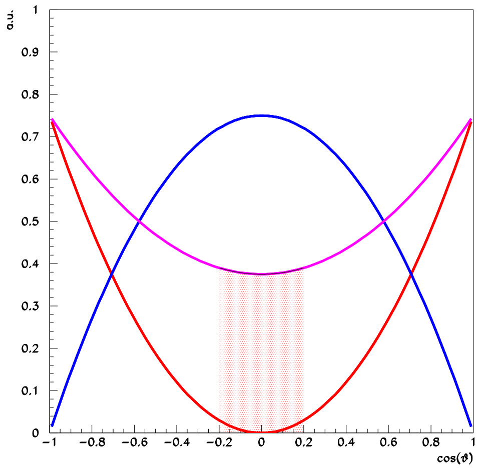
$$W(P_T, \phi, \phi_s) \propto (1 + A_{UU}(\phi) + \mathrm{P}_T A^l_{UT}(\phi, \phi_s))$$

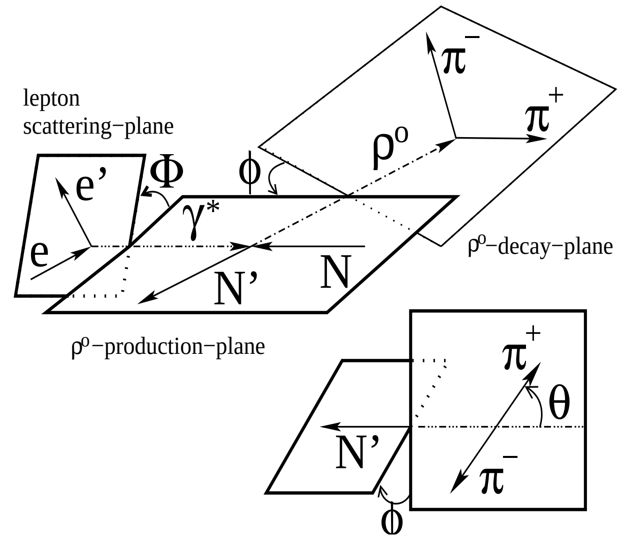
Where $A_{UU}(\phi), A^l_{UT}(\phi, \phi_s)$ are parametrized as:

$$A_{UU}(\phi) = A_{UU}^{cos(\phi_s)} cos(\phi_s) + A_{UU}^{cos(2\phi_s)} cos(\phi_s$$

$$A^l_{UT}(\phi, \phi_s) = A_{UT}^{sin(\phi_s)} sin(\phi_s) + A_{UT}^{sin(\phi-\phi_s)} sin(\phi - \phi_s) + A_{UT}^{sin(\phi+\phi_s)} sin(\phi + \phi_s) + A_{UT}^{sin(2\phi+\phi_s)} sin(2\phi - \phi_s) + A_{UT}^{sin(2\phi+\phi_s)} sin(2\phi + \phi_s) + A_{UT}^{sin(3\phi+\phi_s)} sin(3\phi - \phi_s)$$

Method of Asymetry Extraction





- Each ρ^0 polarization state has a characteristic decay angular distribution

- Assuming SCHC hypothesis we can separate ρ^0_L, ρ^0_L wchich is equivalent to γ^*_L, γ^*_T separation, $\sigma_L = \frac{R}{1+\epsilon R}\sigma_{tot}$, where $R = \sigma_L/\sigma_T = \frac{r^{04}_{00}}{\epsilon(1-r^{04}_{00})}$

- Angular $(cos\theta, \phi, \phi_s)$ distribution can be written as: (Diel,Sapeta:hep-ph/0503023)

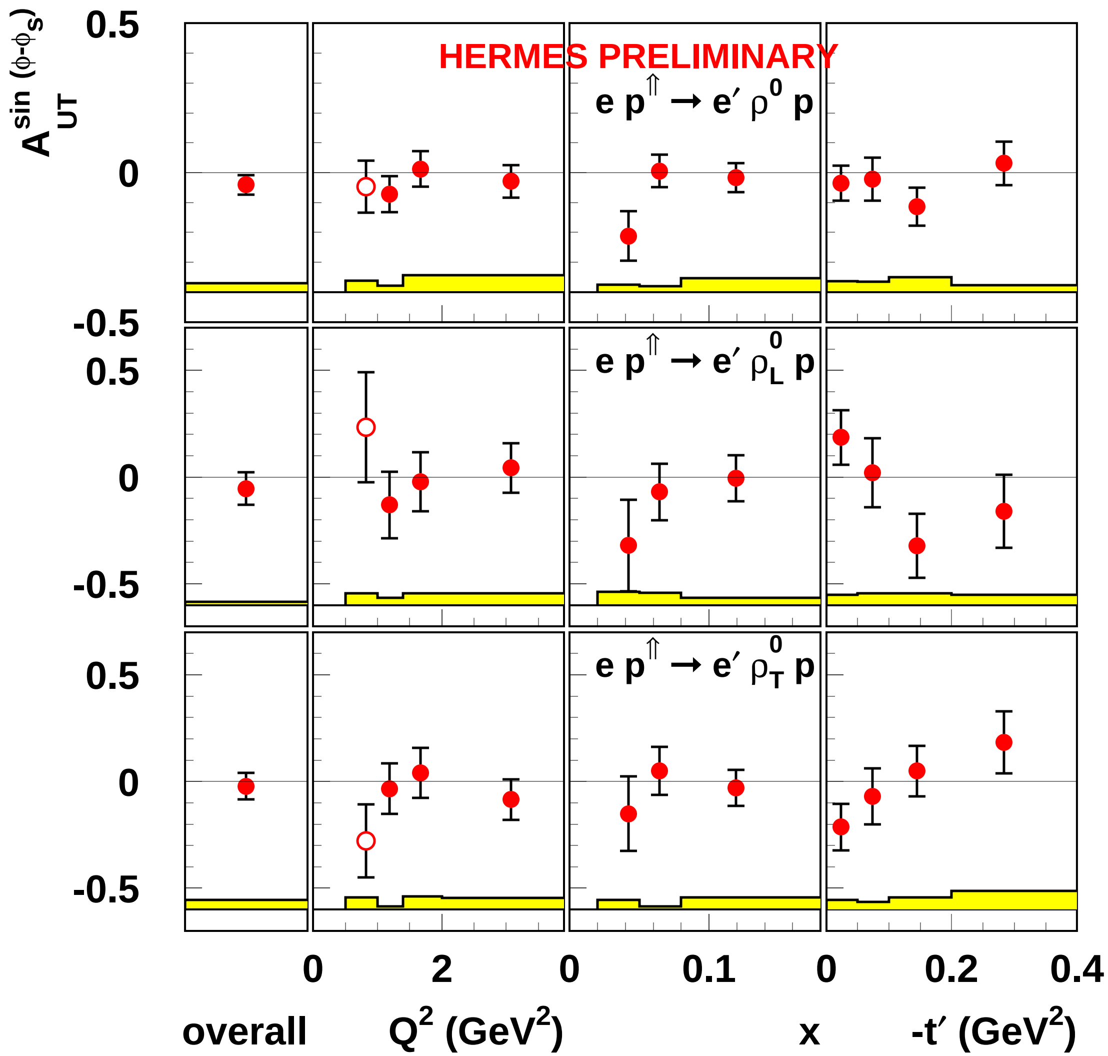
$$W(P_T, cos\theta_{\pi\pi}, \phi, \phi_s) \propto$$

$$[cos^2\theta r^{04}_{00}(1 + P_T A^l_{UT,\rho_L}(\phi, \phi_s)) + A_{UU,\rho_L}(\phi)) +$$

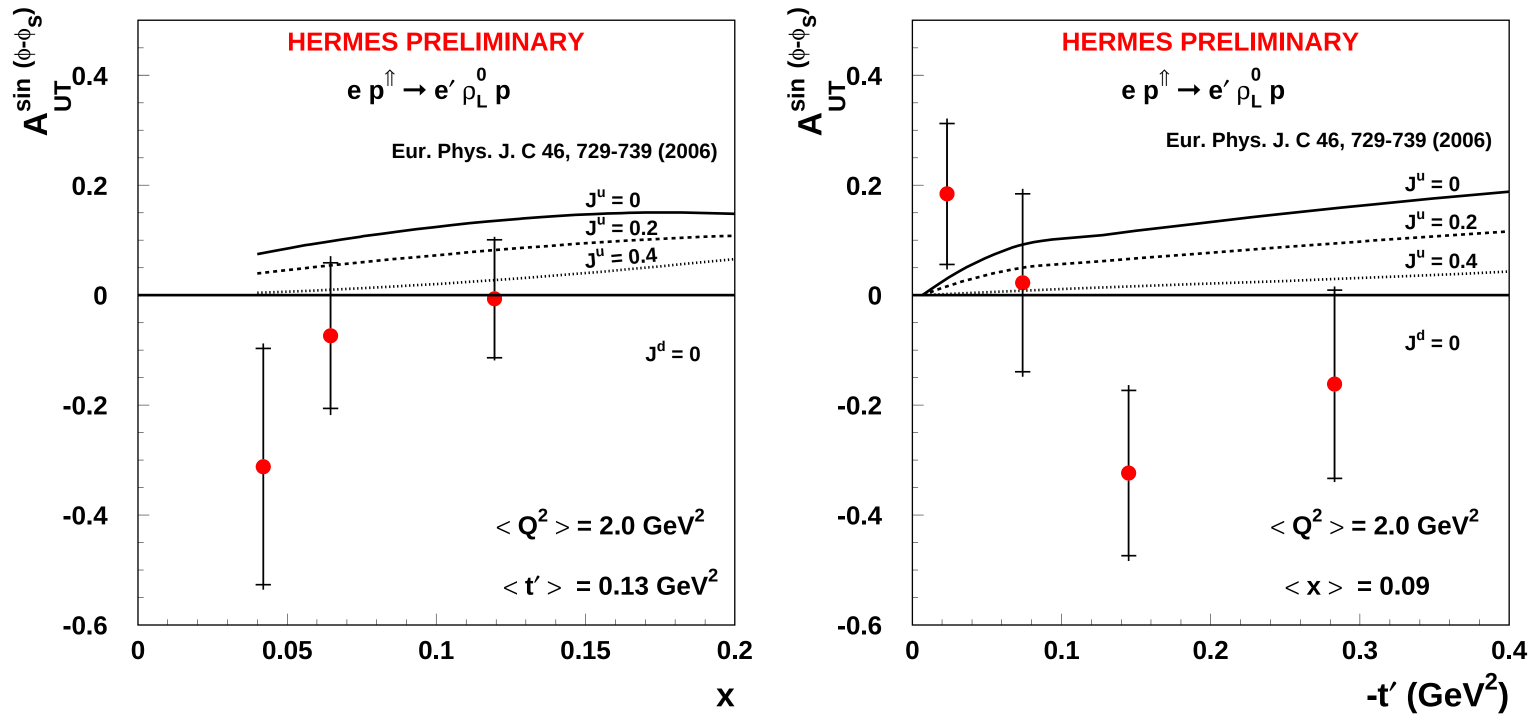
$$\frac{1}{2}sin^2\theta(1 - r^{04}_{00})(1 + P_T, A^l_{UT,\rho_T}(\phi, \phi_s)) + A_{UU,\rho_T}(\phi))]$$

- Assymetries extracted with Unbinned Max Likelihood fit to Yields
- $A_{UU}, _{\rho_L/\rho_T}$ terms are obtained from SDME

$A_{UT}^{sin(\phi-\phi s)}$ for q^2,x,t' bins



Comparison with Theory.



- Data hints positive J^u
- In agreement with HERMES DVCS result

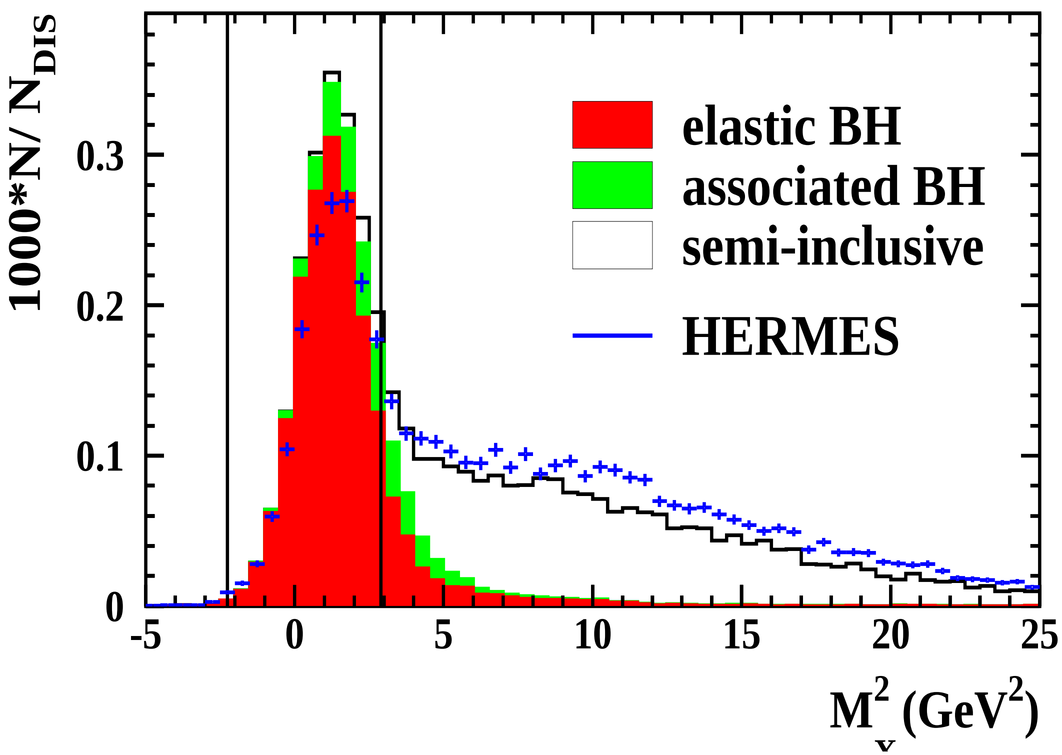
DVCS Event selection

- Exactly one DIS lepton and one trackless cluster (photon) in the calorimeter
- Recoiling proton undetected

$$t = (p - p')^2 = -Q^2 - 2E_\gamma(\nu - \sqrt{\nu^2 + Q^2} \cdot cos\theta_{\gamma,\gamma^*})$$

Exclusivity via Missing Mass: $M_x^2 = (q + p + q')^2$

$-(1.5)^2 < M_x^2 < 1.7^2 GeV^2$



$ep \rightarrow e'p\gamma$: Elastic BH

$ep \rightarrow e'\Delta^+\gamma$: Associate BH

$ep \rightarrow e'\pi X$: Semi- Inclusive

Overall background contribution $\approx 15\%$

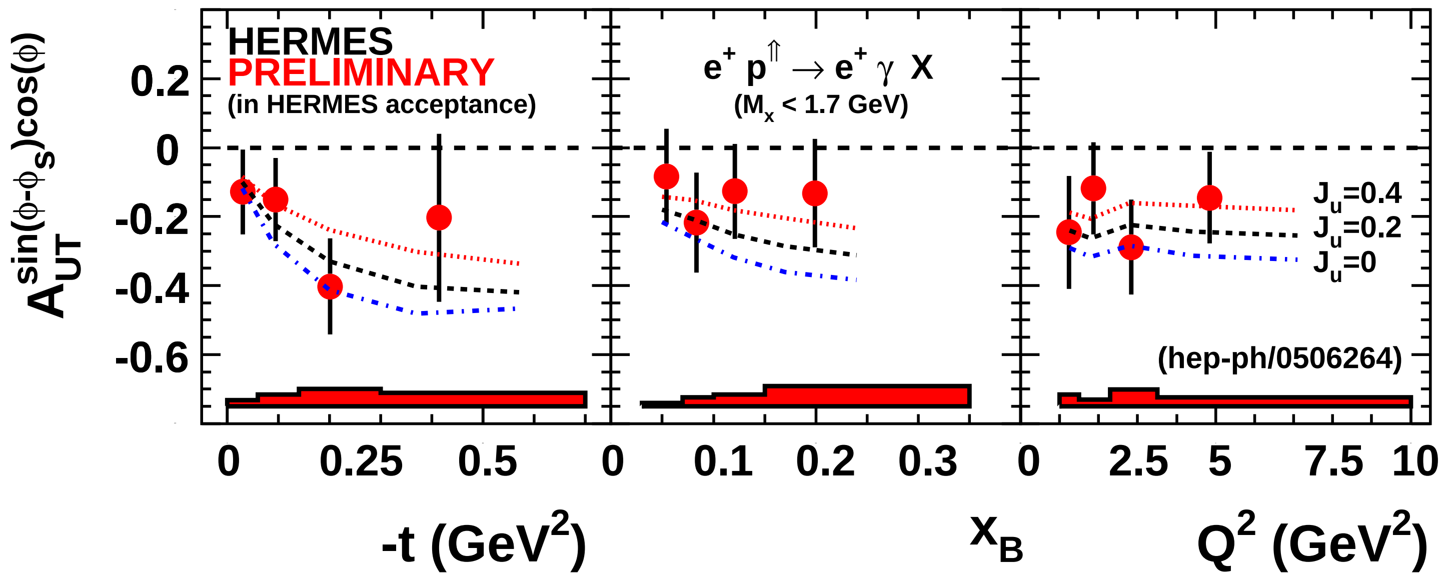
DVCS Transverse Target-Spin Asymetry

$$d\sigma(e^+, p^\uparrow) - d\sigma(e^+, p^\downarrow) \propto Im[F_2\mathcal{H} - F_1\mathcal{E}] \cdot sin(\phi - \phi s) \cdot cos(\phi - \phi s)...$$

only asymmetry with GPD E entering in leading order

$J_q = lim_{t\to 0}\frac{1}{2}\int_{-1}^{1} dx x[H_q(x,\xi,t) + E_q(x,\xi,t)] \Rightarrow$ Access total angular momentum

$$A_{UT}(\phi,\phi_s) = A_{UT}^{sin(\phi-\phi_s)cos\phi} \cdot sin(\phi-\phi_s)cos\phi + A_{UT}^{cos(\phi-\phi_s)sin\phi} \cdot cos(\phi-\phi_s)sin\phi$$



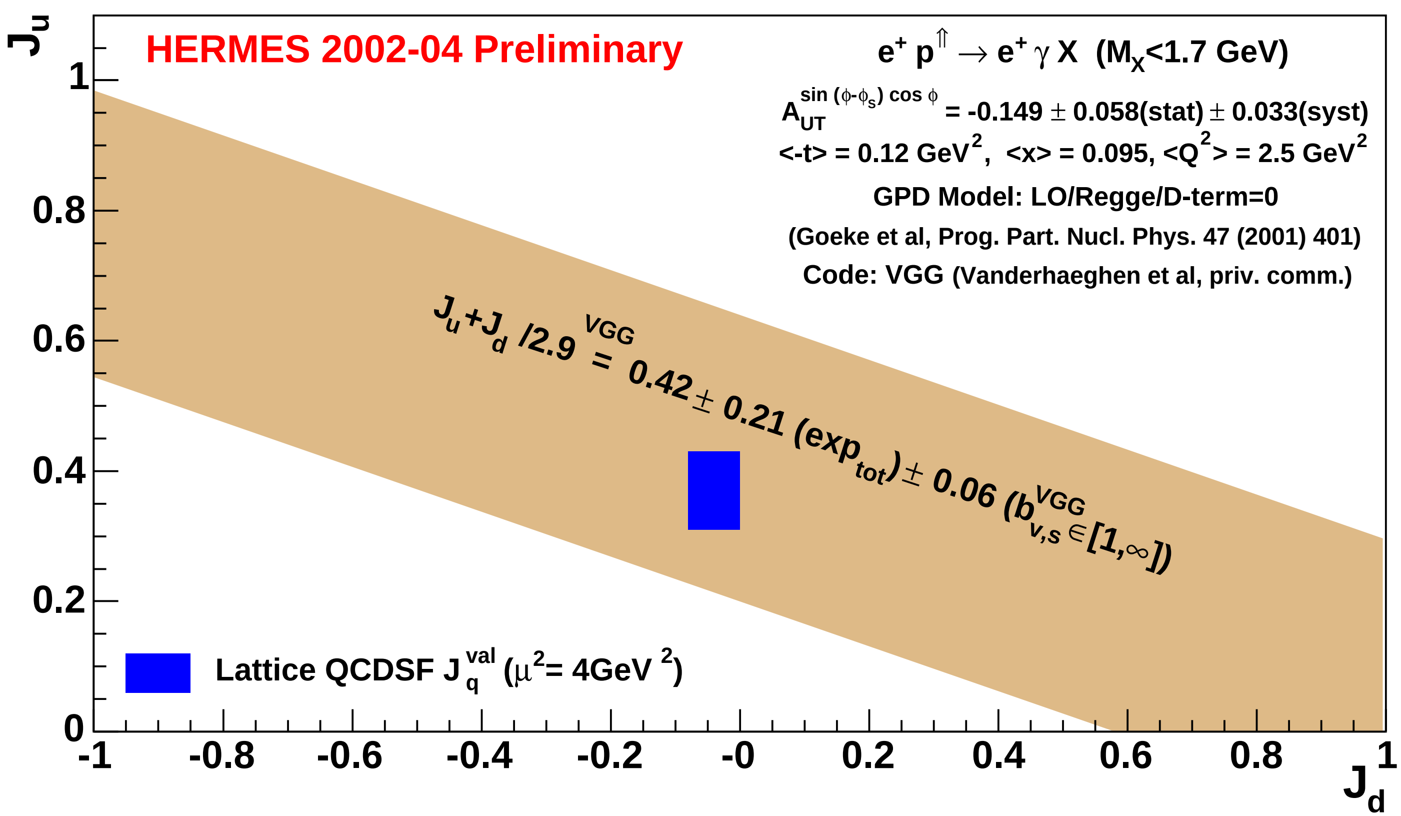
$A_{UT}^{sin(\phi-\phi_s)cos\phi}$ sensitive to J_u under assumption $J_d = 0$

First Model-Depndent Constraint on J_u and J_d

$$\chi^2(J_u, J_d) = \frac{[A_{UT}^{sin(\phi-\phi_S)cos\phi}|_{exp.} - A_{UT}^{sin(\phi-\phi_S)cos\phi}|_{VGG(J_u,J_d)}]^2}{\delta A^2_{stat.} + \delta A^2_{sys.}}$$

J_u and J_d free parameters i GPD-Model (VGG)

$1-\sigma = 0$ constraint onJ_u vs J_u given by $\chi^2(J_u, J_d) \leqslant \chi^2_{min} + 1$



Large 2005 data sample yet to be added

Summary

- 15 beam-polarization-independent SDMEs and plus,for the first time, 8 beam-polarization-dependent SDMEs for the ρ^0 ϕ, are obtained

- Deviation from SCHC for ρ^0 and holds of SCHC hypothesis for ϕ is observed

- Indication of UNP processes for ρ^0 and dominace of NP processes for ϕ is observed

- Hierarchy of helicity transfer amplitudes is established

- $R \equiv \sigma_L/\sigma_T$ ratio is suggests a W-dependence for ρ^0

- First measurement of $A_{UT}^{sin(\phi-\phi s)}$ seperately for ρ^L and ρ^T

- First Model-Dependent Constraint on J_u and J_d is made

The HERMES recoil counter and the 2006-2007 Data