Spin Density Matrix Elements in exclusive production of omega mesons at HERMES

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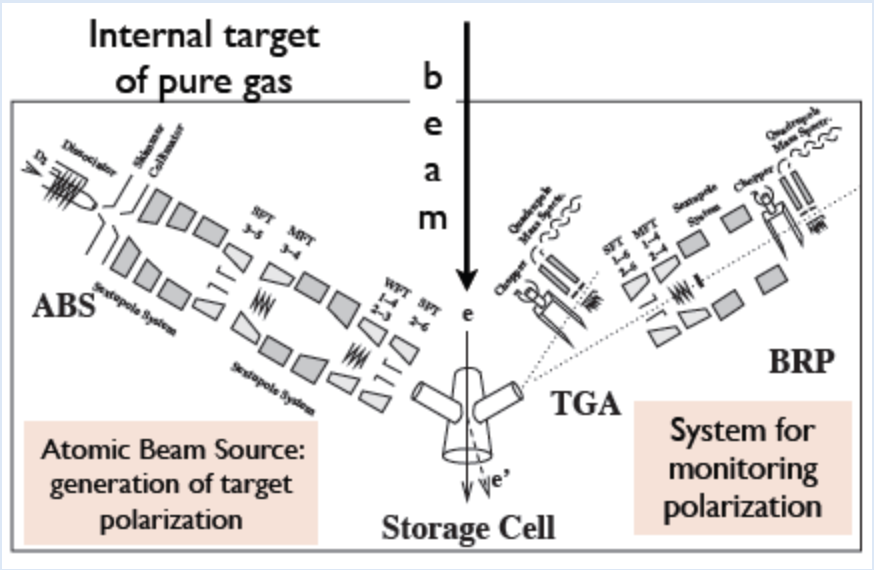
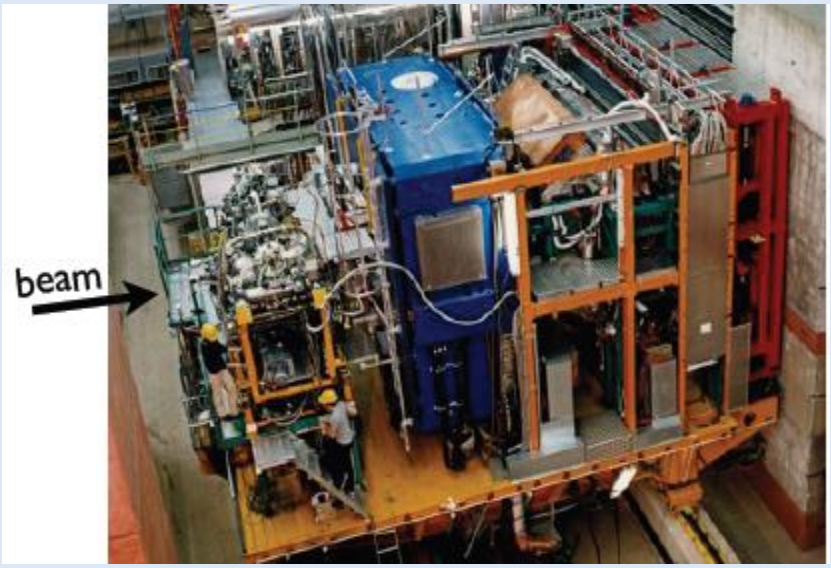
- HERMES experiment at HERA and exclusive ω meson production
- Helicity amplitudes and SDMEs
- Results:
  - SDME values
  - Unnatural –Parity Exchange for ω mesons
  - Longitudinal to Transverse cross section ratio for ω mesons
- Summary

HERMES at DESY

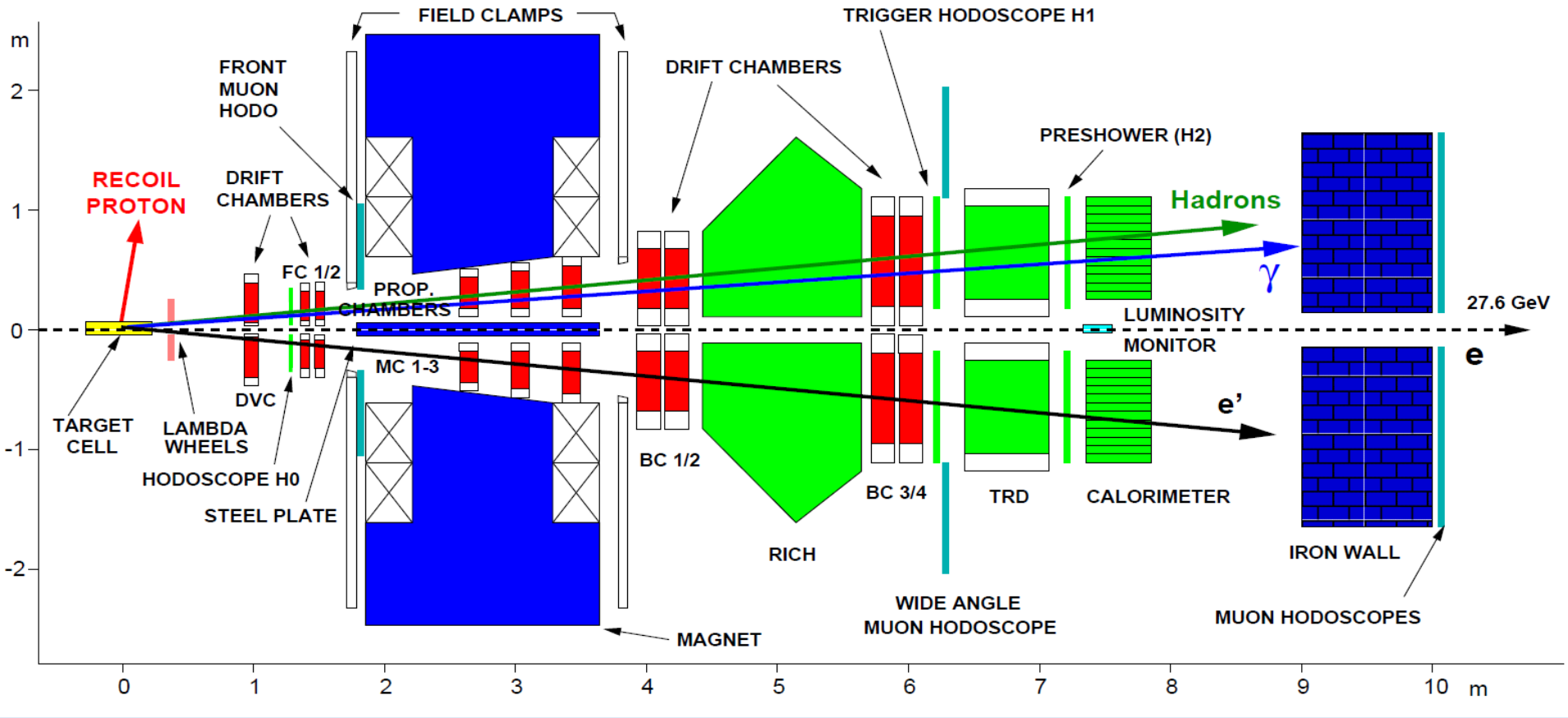
Self-polarized e^+ and e^- beams
27.6 GeV
Helicity switched every few months





Polarized hydrogen (Long.,Trans.), deuterium (Long.)
Polarization flipped at 60-180 s time intervals

The HERMES Spectrometer



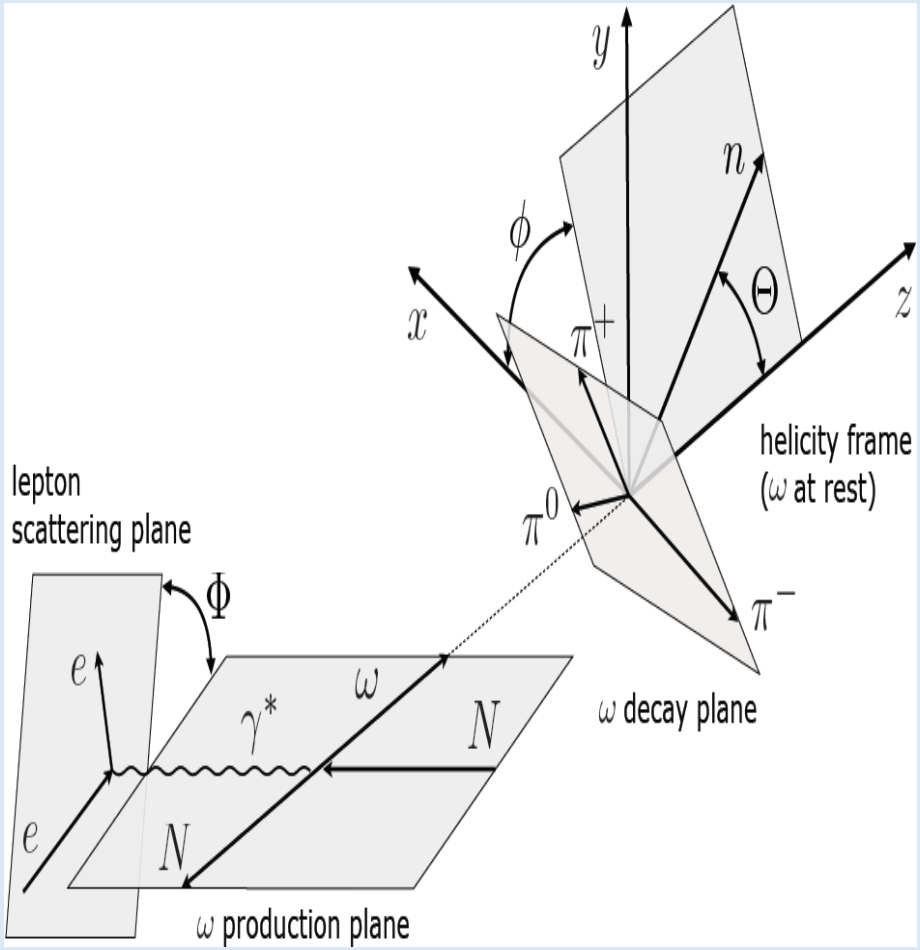
Data taking:1996-2007

- PID: RICH, TRD. Preshower and Calorimeter
- Momentum resolution of charged particles: $\delta \mathrm{P}/\mathrm{P} \simeq 1.5\%$

Exclusive ω - meson production at HERMES

$e(k) + N(p) \rightarrow e(k') + N(p') + \omega$

$\omega \rightarrow \pi^+ \pi^- \pi^0$, $\pi^0 \rightarrow 2\gamma$



Kinematic conditions:

$1\ \text{GeV}^2 < Q^2 < 10\ \text{GeV}^2$,

$0.01 < x_B < 0.35$,

$3.0\ \text{GeV} < W < 6.3\ \text{GeV}$,

$0 \leq -t' = -(t - t_{min}) < 0.2\ \text{GeV}^2$

Two photon invariant mass:

$0.11\ \text{GeV} < M(\gamma\gamma) < 0.16\ \text{GeV}$

Three-pion invariant mass:

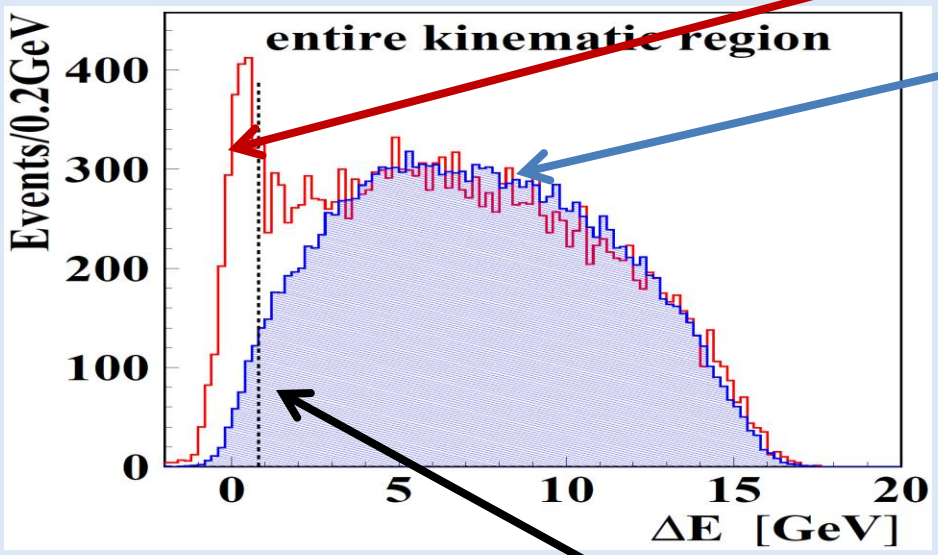
$0.71\ \text{GeV} < M(\pi^+ \pi^- \pi^0) < 0.87\ \text{GeV}$

Missing energy:

$$\Delta E = \frac{M_X^2 - M_p^2}{2M_p}, M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-} - p_{\pi^0})^2$$

Exclusive ω - meson production at HERMES

$\omega \rightarrow \pi^+ \pi^- \pi^0$, $\pi^0 \rightarrow 2\gamma$



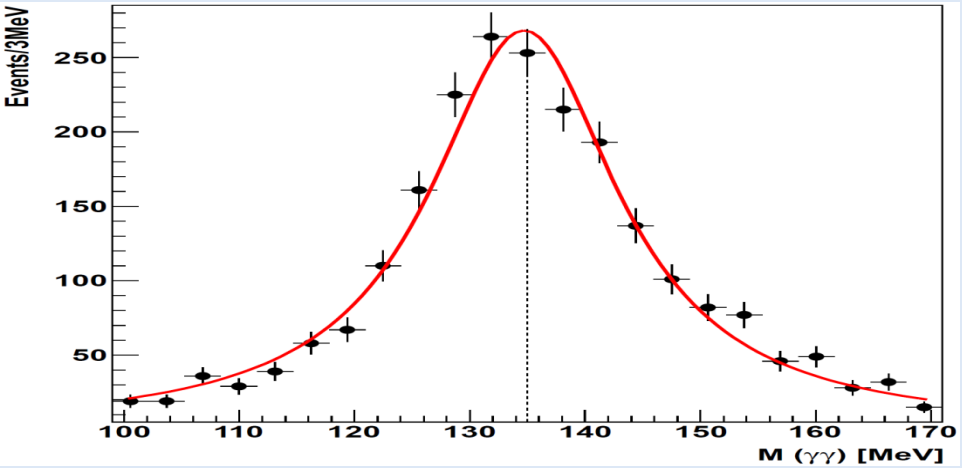
SIDIS background from PYTHIA

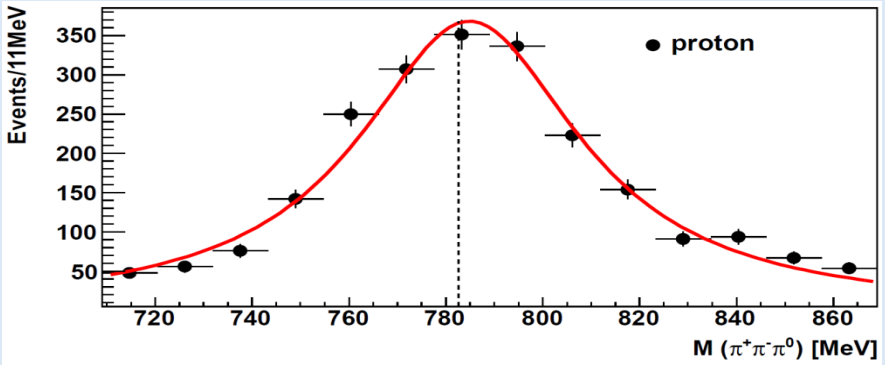
Number of ω events:

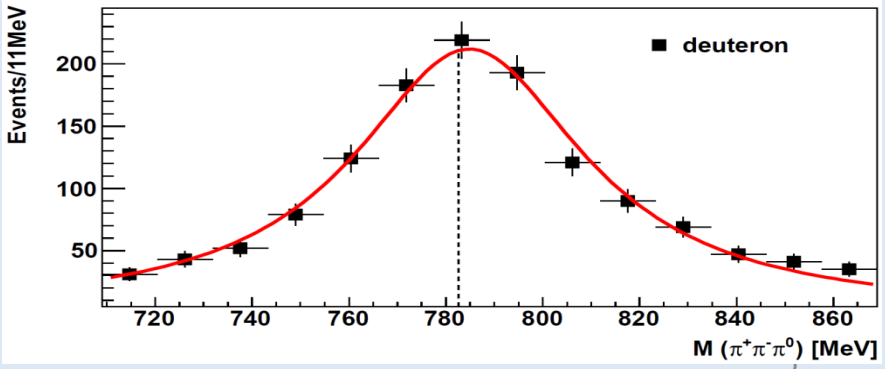
Hydrogen – 2260

Deuterium – 1332

$-1.0\ \text{GeV} < \Delta E < 0.8\ \text{GeV}$







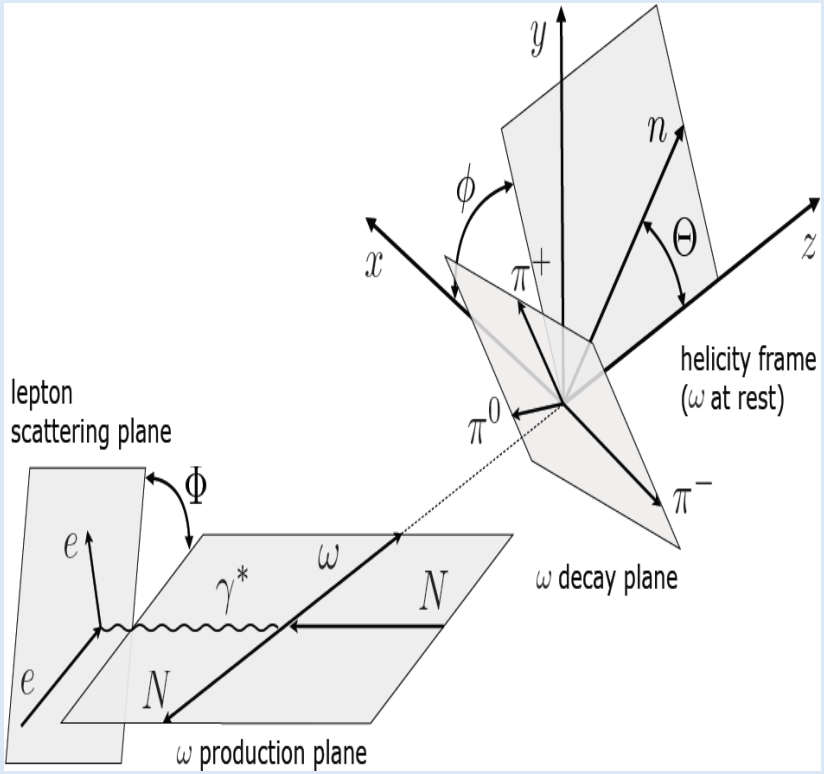
Angular distribution and extraction of SDMEs

Three-dimensional angular distribution $W^{U+L}(\Phi, \phi, \cos\Theta)$ depends linearly on SDMEs – $r^{\alpha}_{\lambda_V \lambda'_V}$ and beam polarization P_b

$$r^{\alpha}_{\lambda_V \lambda'_V} \sim \rho_{\lambda_V \lambda'_V} = \frac{1}{2N} \sum_{\lambda_\gamma \lambda'_\gamma \lambda_N \lambda'_N} F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \rho^{U+L}_{\lambda_\gamma \mu_\gamma} F^{*}_{\lambda'_V \lambda'_N \lambda'_\gamma \lambda_N}$$

Photon SDMEs

Helicity amplitudes



- Helicity amplitudes are the fundamental quantities to be compared with theory.
- They form a basis for the SDMEs.
- For longitudinally polarized beam and unpolarized target there are 23 SDMEs: 15 unpolarized and 8 polarized.
- The SDMEs are extracted by fitting the angular distribution $W^{U+L}(\Phi, \phi, \cos\Theta)$ to the experimental angular distribution of pions from ω - decay using unbinned Maximum Likelihood method.

Spin Density Matrix Elements

- SDMEs – $r^{\alpha}_{\lambda_V \lambda'_V}$ are expressed through $F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}(W, Q^2, t')$.
- In CM frame of γ*N they are given by the von Neumann formula:

$$r^{\alpha}_{\lambda_V \lambda'_V} \sim \rho_{\lambda_V \lambda'_V} = \frac{1}{2N} \sum_{\lambda_\gamma \lambda'_\gamma \lambda_N \lambda'_N} F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \rho^{U+L}_{\lambda_\gamma \mu_\gamma} F^{*}_{\lambda'_V \lambda'_N \lambda'_\gamma \lambda_N}$$

λ_γ (λ_V) – is the photon (meson) helicity,
$\alpha = 0,\ldots,3$ transversely polarized photon, $\alpha = 4$ longitudinally polarized photon,
$\alpha = 5,\ldots,8$ transverse/longitudinal interference.

- $F_{\lambda_V \lambda_\gamma} = T_{\lambda_V \lambda_\gamma} + U_{\lambda_V \lambda_\gamma}$; unplarized target, nucleon-helicity indices omitted.

T – Natural-Parity Exchange (NPE) ($P = (-1)^J$),
U – Unnatural-Parity Exchange (UPE) ($P = -(-1)^J$)

- Unpolarized target: nucleon helicity-flip amplitudes are suppressed.

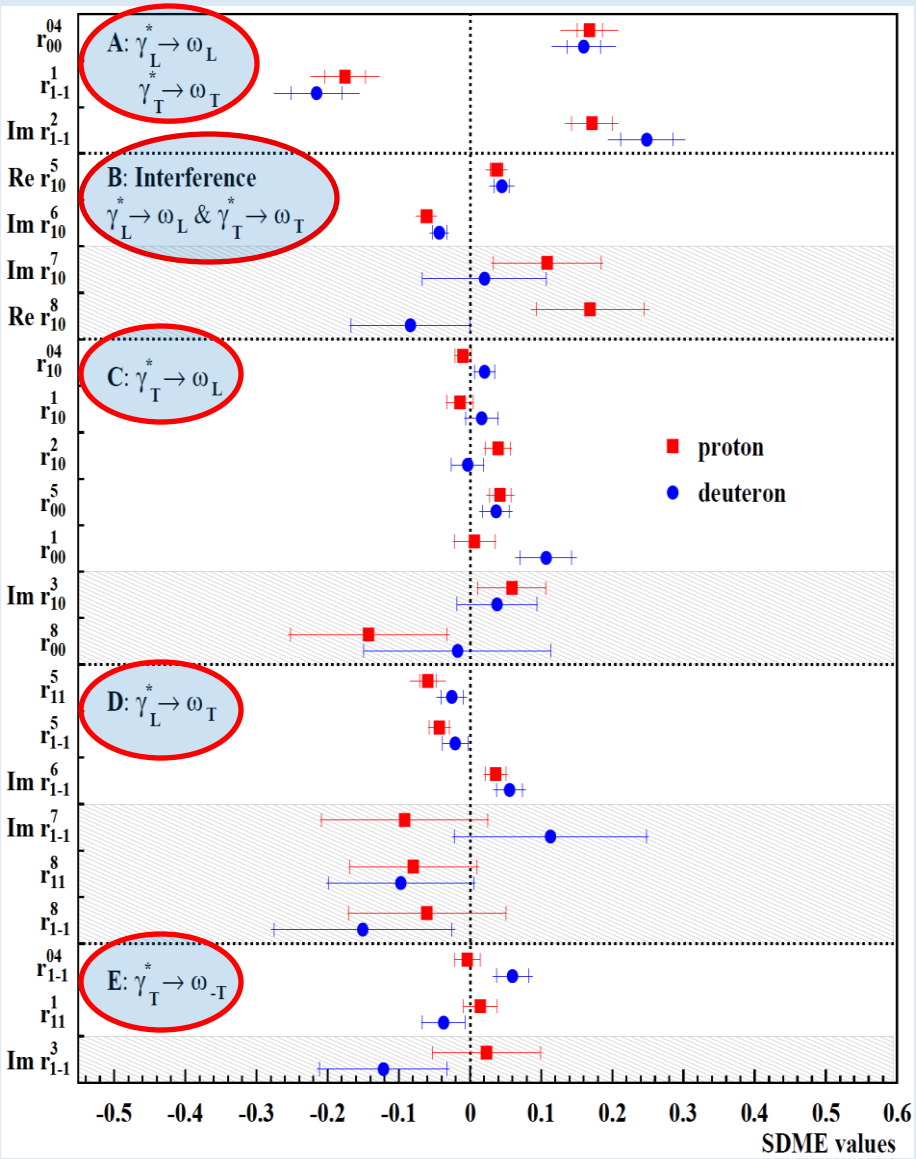
T_{00}, T_{11}, U_{11} conserve the photon helicity,
T_{01}, T_{10}, T_{1-1}, U_{01}, U_{10}, U_{1-1} not.

- Dominance of diagonal transitions is called:

s-channel helicity conservation (SCHC).

SDMEs of exclusive ω production : SCHC hypothesis

E-Print: arXiv:1407.2119



- Similar magnitudes of SDMEs on proton & deuteron
- SCHC holds for class – A & class – B SDMEs:

$$\begin{cases} r^1_{1-1} = -\mathrm{Im}\, r^2_{1-1} \\ \mathrm{Re}\, r^5_{10} = -\mathrm{Im}\, r^6_{10} \\ \mathrm{Im}\, r^7_{10} = \mathrm{Re}\, r^8_{10} \end{cases}$$

For proton:

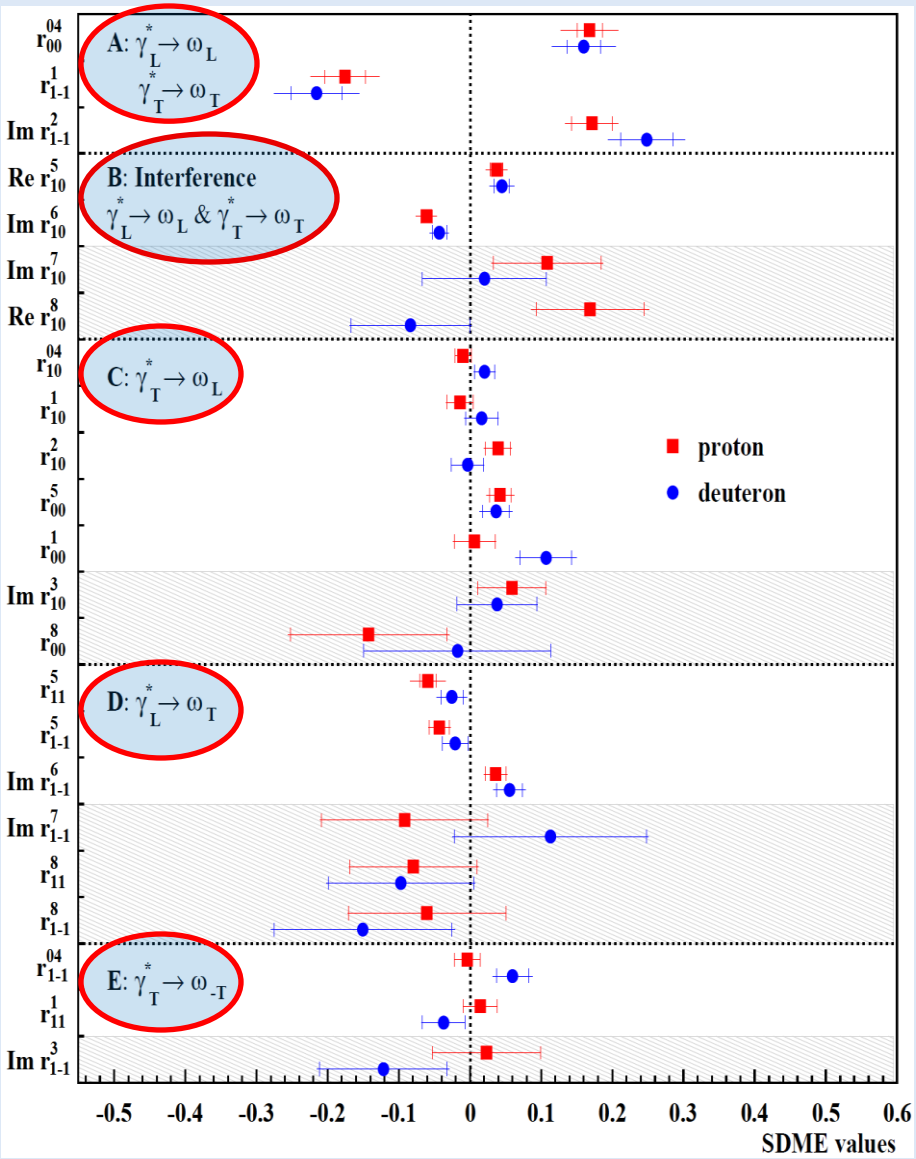
$$\begin{cases} r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = -0.004 \pm 0.038 \pm 0.015, \\ \mathrm{Re}\, r^5_{10} + \mathrm{Im}\, r^6_{10} = -0.024 \pm 0.013 \pm 0.004, \\ \mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = -0.060 \pm 0.100 \pm 0.018. \end{cases}$$

For deuteron:

$$\begin{cases} r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = 0.033 \pm 0.049 \pm 0.016, \\ \mathrm{Re}\, r^5_{10} + \mathrm{Im}\, r^6_{10} = 0.001 \pm 0.016 \pm 0.005, \\ \mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0.104 \pm 0.110 \pm 0.023. \end{cases}$$

SDMEs of exclusive ω production : SCHC hypothesis

e-Print: arXiv:1407.2119 [hep-ex]



- If SCHC holds: all SDMEs class –C to –E =0.
- The class – C SDME r^5_{00} deviates from zero: 3σ – for proton; 2σ – for deutron.
- The class – D SDMEs: r^5_{11}, r^5_{1-1} & r^6_{1-1} ≠0.

$$\rightarrow \begin{cases} r^5_{11} \approx \mathrm{Re}\left[U_{10}U^*_{11}\right], \\ r^5_{1-1} \approx \mathrm{Re}\left[U_{10}U^*_{11}\right], \\ \mathrm{Im}\left\{r^6_{1-1}\right\} \approx -\mathrm{Re}\left[U_{10}U^*_{11}\right]. \end{cases}$$

For proton:

$$r^5_{11}+r^5_{1-1}-\mathrm{Im}\left\{r^6_{1-1}\right\} = -0.14 \pm 0.02 \pm 0.04$$

For deuteron:

$$r^5_{11}+r^5_{1-1}-\mathrm{Im}\left\{r^6_{1-1}\right\} = -0.10 \pm 0.03 \pm 0.03$$

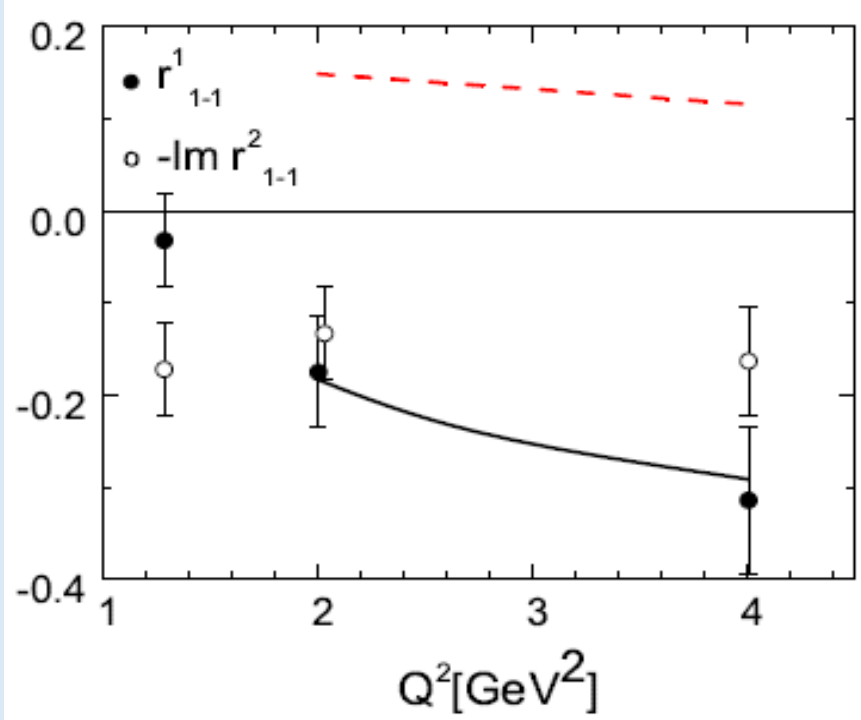
SCHC hypothesis slightly violated.

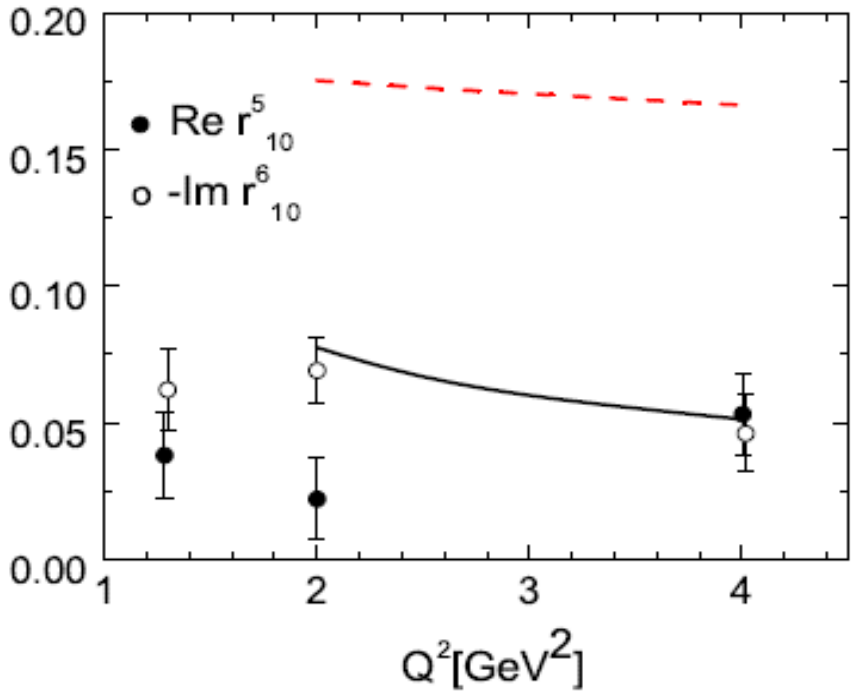
Comparison of ω SDMEs to GK model

Handbag approach with (without) inclusion of pion-pole contribution

Data:e-Print: arXiv:1407.2119 [hep-ex]

S.V. Goloskokov,P. Kroll: EPJ A 50 (2014)146

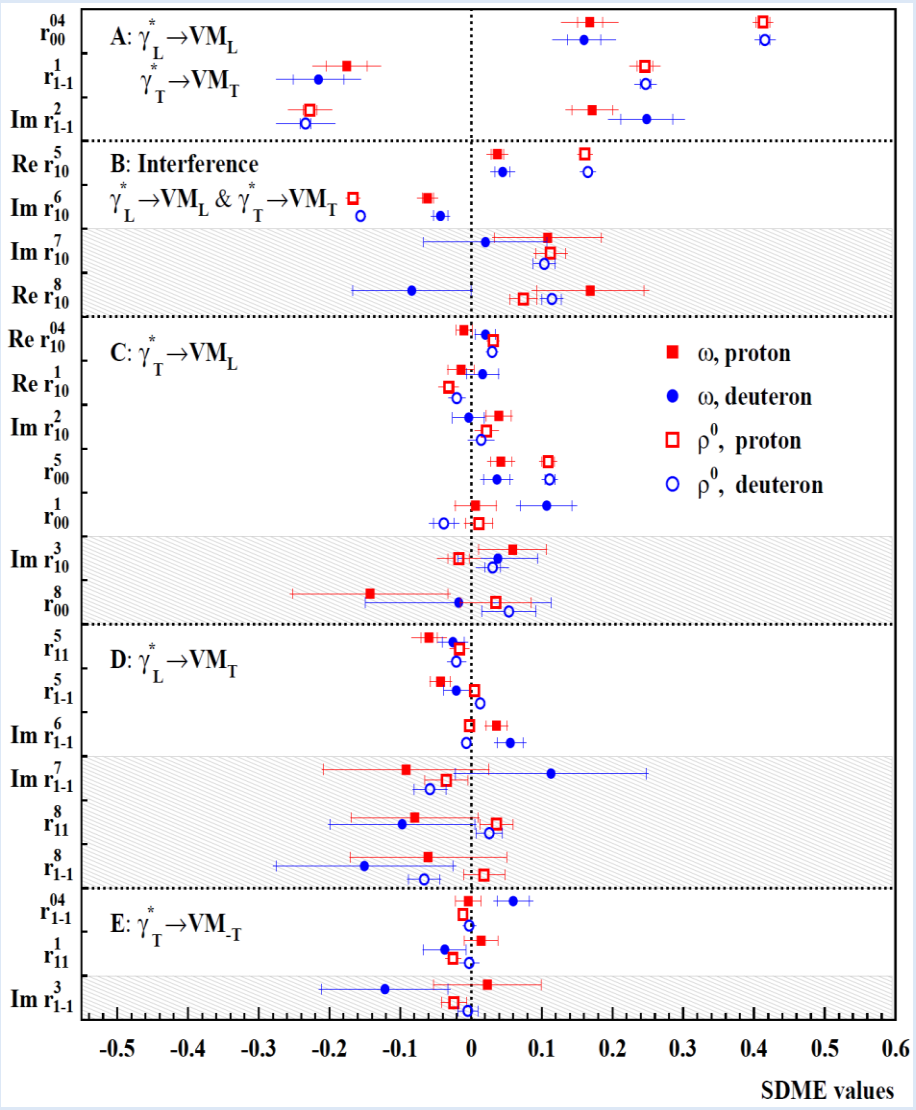




- Well agreement between measured SDME values and theoretical calculations

Comparison of SDMEs in exclusive ω and ρ^0 productions

e-Print: arXiv:1407.2119 [hep-ex]



ρ^0 **SDMEs HERMES,** EPJ C 62 (2009) 659.

- The class – A SDMEs: r^1_{1-1} & Im $\{r^2_{1-1}\}$ have opposite sign for ω and ρ^0 .
- Large UPE contribution for ω:

$$r^1_{1-1} = \tilde{\Sigma}\left\{|T_{11}|^2 + |T_{1-1}|^2 - |U_{11}|^2 - |U_{1-1}|^2\right\}/2N,$$

$$\text{Im}\left\{r^2_{1-1}\right\} = \tilde{\Sigma}\left\{-|T_{11}|^2 + |T_{1-1}|^2 + |U_{11}|^2 - |U_{1-1}|^2\right\}/2N.$$

For ω meson

$$\text{Im}\left\{r^2_{1-1}\right\} - r^1_{1-1} = \tilde{\Sigma}\left\{-|T_{1-1}|^2 + |U_{11}|^2\right\}/N > 0$$

$$\tilde{\Sigma}|U_{11}|^2 > \tilde{\Sigma}|T_{1-1}|^2$$

For ρ^0 meson

$$\text{Im}\left\{r^2_{1-1}\right\} - r^1_{1-1} = \tilde{\Sigma}\left\{-|T_{1-1}|^2 + |U_{11}|^2\right\}/N < 0$$

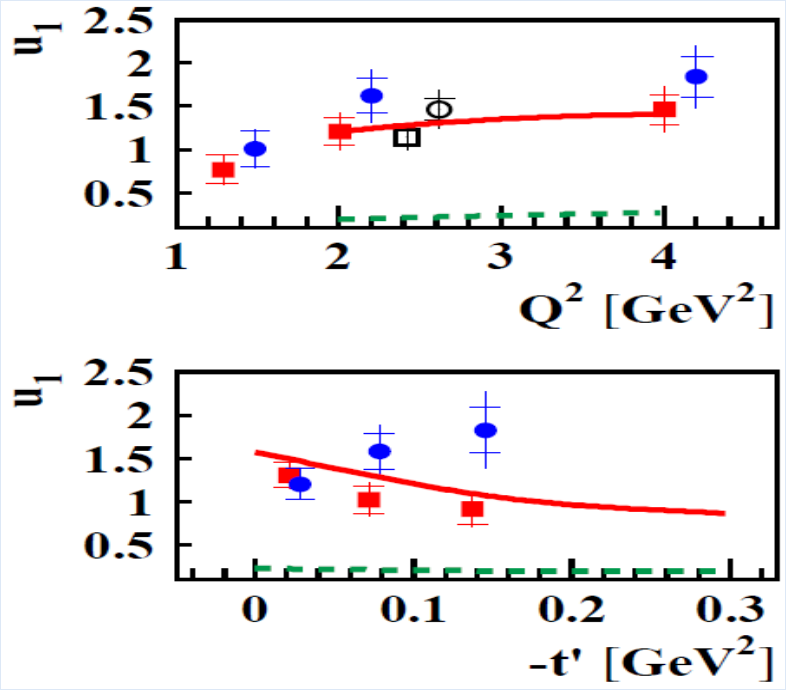
$$\tilde{\Sigma}|U_{11}|^2 < \tilde{\Sigma}|T_{1-1}|^2$$

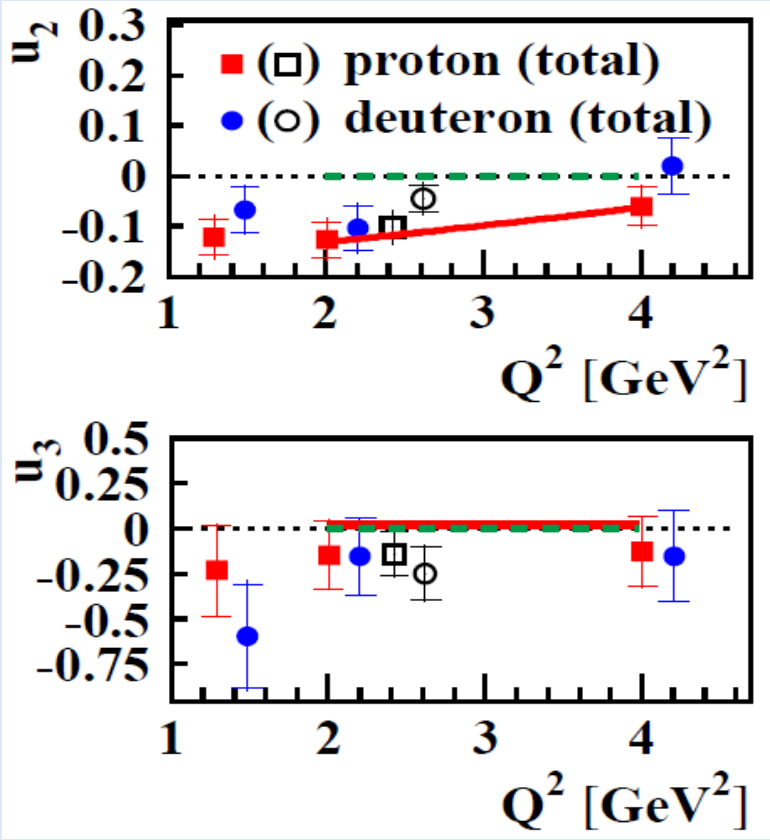
Observation of Unnatural Parity Exchange for ω meson

- The combinations of these SDMEs are expected to be zero in case of NPE:

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

e-Print: arXiv:1407.2119 [hep-ex]





- Large UPE contribution:

  $u_1(p) = 1.15 \pm 0.09 \pm 0.12$;

  $u_1(d) = 1.47 \pm 0.12 \pm 0.18$.

S.V. Goloskokov,P. Kroll: EPJ A 50 (2014)146

Inclusion of pion-pole accounts for UPE

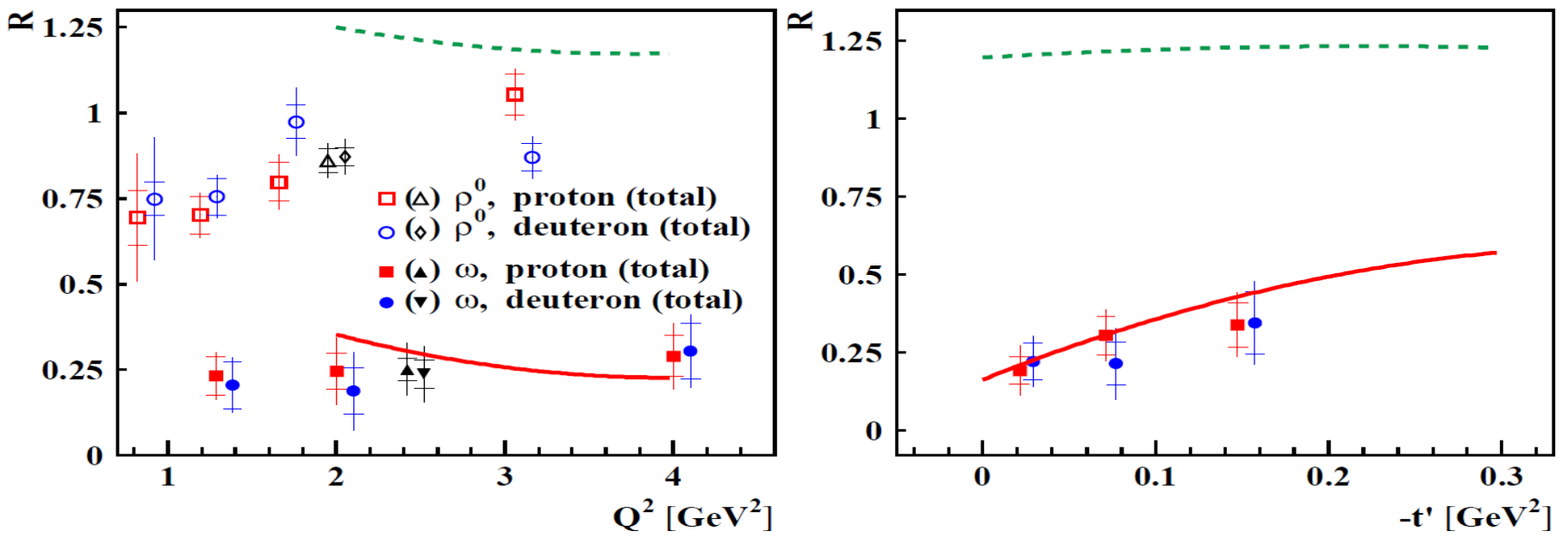
- u_2 is definitely nonzero for proton for ω

  u_2 & u_3 are compatible with zero for ρ^0

Longitudinal to transverse crosss section ratio for ω & ρ^0

$$R = \frac{d\sigma_L\left(\gamma_L^* \to V\right)}{d\sigma_T\left(\gamma_T^* \to V\right)} \approx \frac{1}{\varepsilon}\frac{r_{00}^{04}}{1-r_{00}^{04}}$$

e-Print: arXiv:1407.2119 [hep-ex]

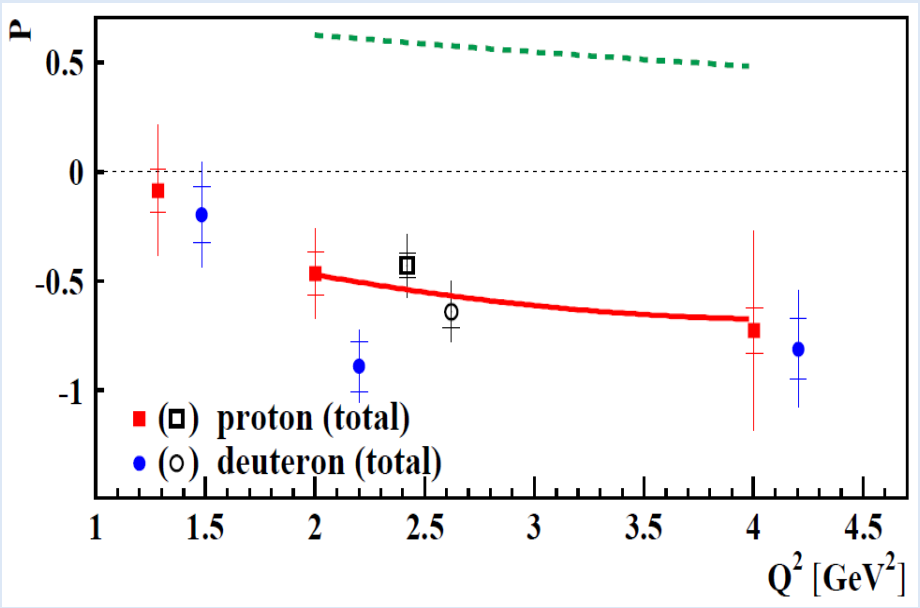


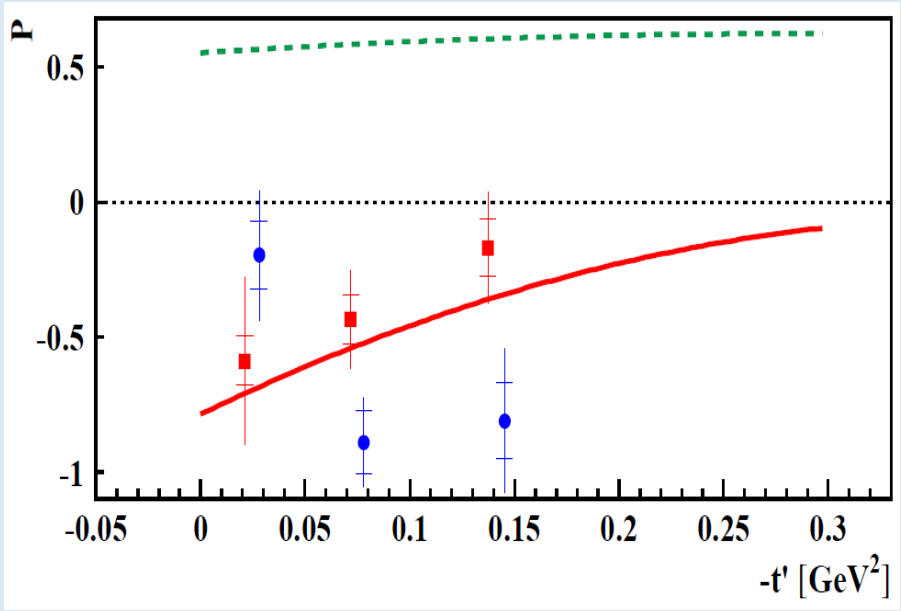
- Entire kinematic region: for ω – R(p) = 0.25 ± 0.03 ± 0.07 R(d) = 0.24 ± 0.04 ± 0.07
- For ω R is about 4 times smaller than for ρ^0 & almost independent of Q^2
- Curves are calculations of GK model with & without pion-pole inclusion

UPE-to-NPE asymmetry of the ω transverse cross section

$$P = \frac{d\sigma_T^N - d\sigma_T^U}{d\sigma_T^N + d\sigma_T^U} \equiv \frac{d\sigma_T^N / d\sigma_T^U - 1}{d\sigma_T^N / d\sigma_T^U + 1} = (1+\varepsilon R)\left(2r^1_{1-1} - r^1_{00}\right) \approx \frac{2r^1_{1-1} - r^1_{00}}{1 - r^{04}_{00}}$$

e-Print: arXiv:1407.2119 [hep-ex]





- Entire kinematic region: P(p) = – 0.42 ± 0.06 ± 0.08 P(d) = – 0.64 ± 0.07 ± 0.12
- Curves are calculations of GK model with & without pion-pole inclusion
- GK model appears to fully account for UPE , agreement in shape & magnitude

Summary

- The SDMEs are extracted for exclusive electroproduction of ω meson on proton and deuteron at HERMES.
- The SDMEs are divided into five classes according to the helicity transitions in the reaction.
- The SCHC hypothesis in ω meson production seems slightly violated.
- The UPE contribution seems to be very large (dominant) for ω meson.
- Longitudinal to Transverse cross section ratio R for ω meson is smaller than for ρ^0 .
- The SDME values, R & P asymmetry for ω meson production agree well with pQCD-inspired phenomenological model including pion-pole (unnatural parity) contribution.

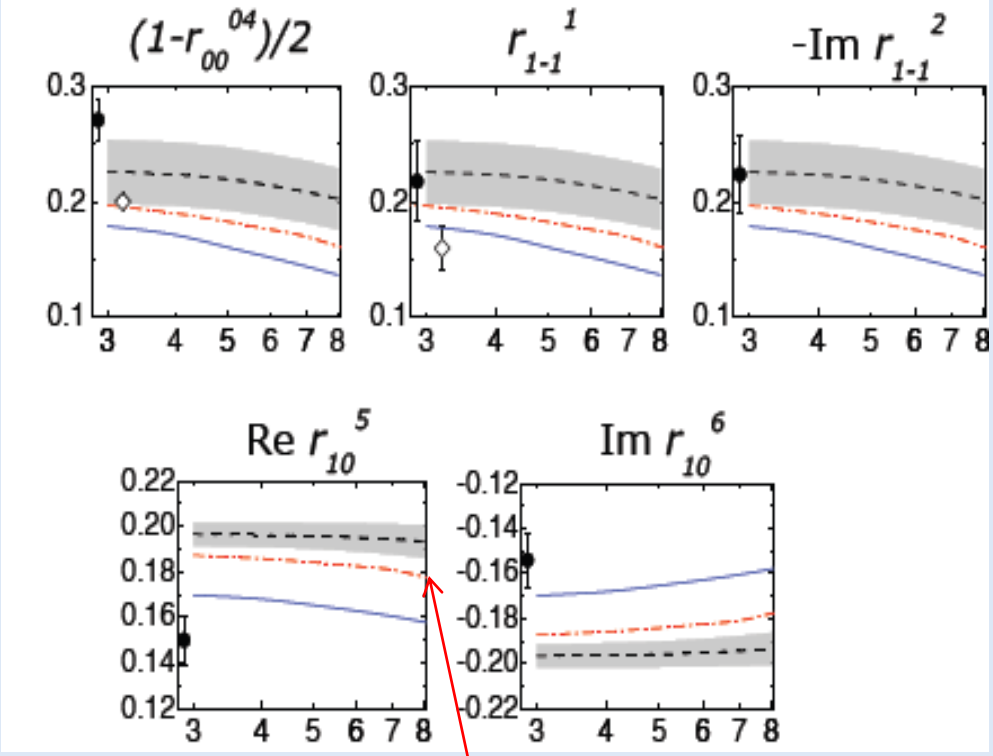
Backup Slides

Comparison of ρ^0 SDMEs to GK model

$\gamma^*_L \to \rho^0_L$ & $\gamma^*_T \to \rho^0_T$

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

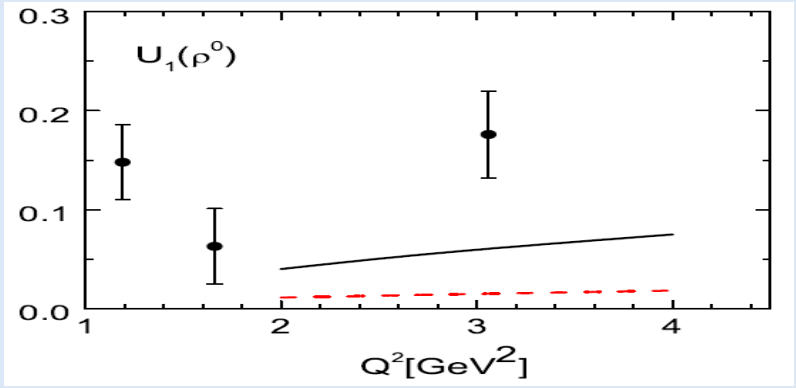
GPD model: S. Goloskokov, P. Kroll (2007)

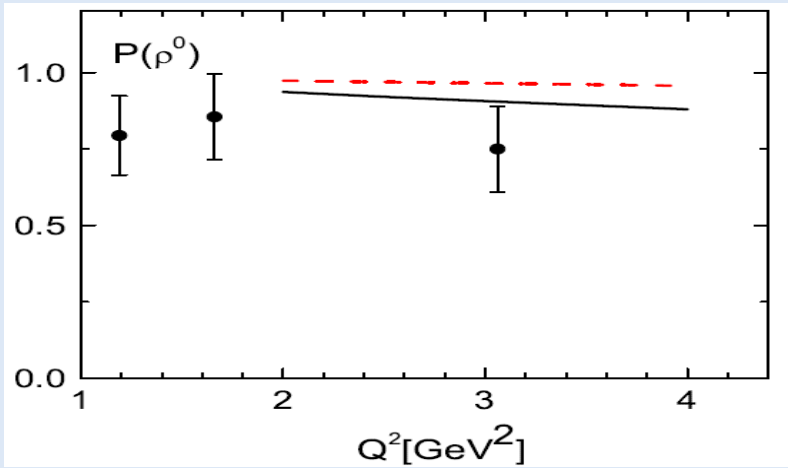


W = 5 GeV, 10 GeV and 75 GeV

Model is in an agreement with data

Handbag approach with (without) inclusion of pion-pole contribution





The difference is very small

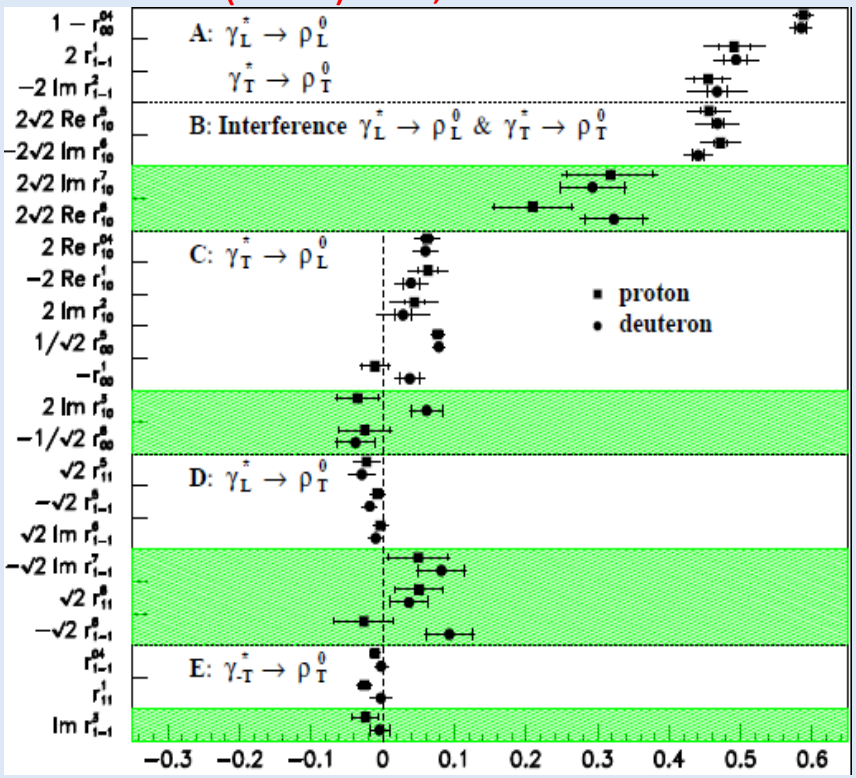
SDMEs on unpolarized targets: ρ^0 & ϕ productions

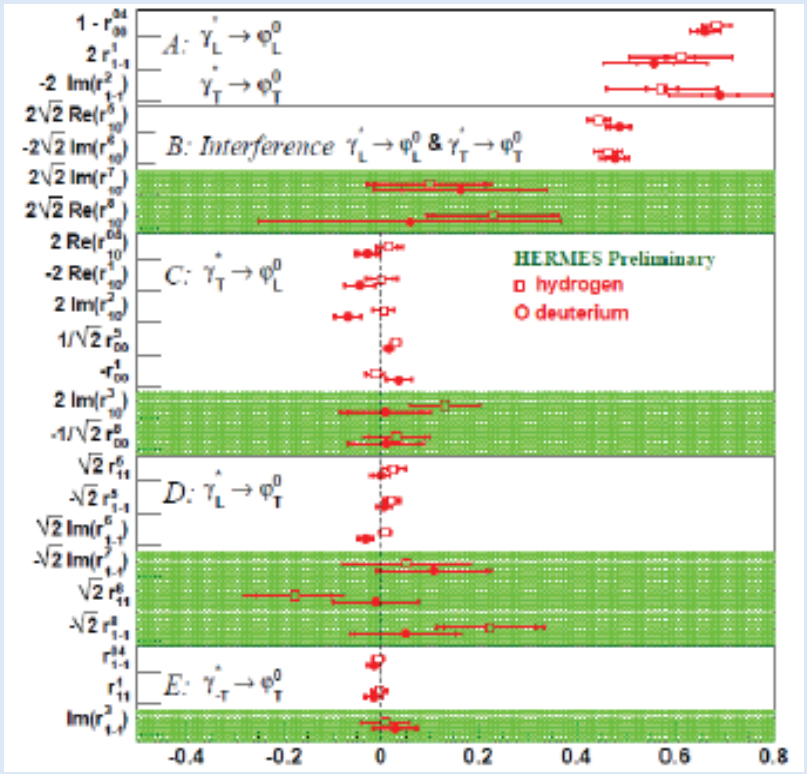
Hierarchy predicted by theory: confirmed by HERMES

$$|T_{00}|^2 \approx |T_{11}|^2 >> |U_{11}|^2 > |T_{01}|^2 >> |T_{10}|^2 \ldots$$

$\gamma^*_L \to V_L$ $\gamma^*_T \to V_T$ $\gamma^*_T \to V_L$ $\gamma^*_L \to V_T$

EPJ C 62 (2009) 659, arXiv:0901.0701





$\gamma^*_L \to V_L$ & $\gamma^*_T \to V_T$:
10-20% difference between ρ^0 & ϕ

$\gamma^*_T \to V_L$:
pronounced difference between ρ^0 & ϕ