Study of spin-density matrix in exclusive electroproduction of ω meson at HERMES

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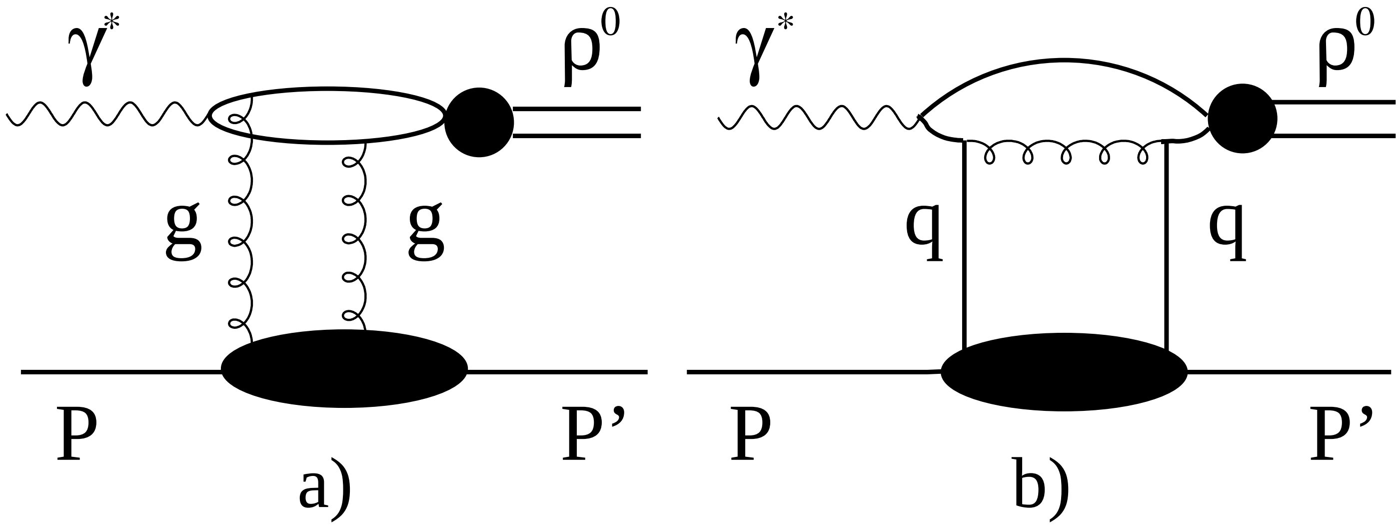
Physics Motivation



- $\gamma^* + N \to V + N$ is a perfect reaction to study both vector-meson $(V = \rho^0,\ \phi,\ \omega)$ production mechanism and hadron structure.
- Properties of Spin Density Matrix Elements (SDMEs).
  SDMEs are coefficients in the angular distribution of final hadrons and therefore can be extracted from data.
  SDMEs are expressible in terms of ratios of helicity amplitudes of $\gamma^* + N \to V + N$ reaction, hence ratios can be extracted from angular distribution of final hadrons.
  Data on $d\sigma/dt = \sum |F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}|^2$ additional to SDMEs gives a possibility to extract moduli of all the helicity amplitudes and phase differences between them.
- Generalized Parton Distributions (GPDs) of the nucleon can be obtained from the amplitude $F_{00} \equiv F_{0\frac{1}{2}0\frac{1}{2}}$ $(\gamma_L \to V_L\ )$ for which factorization theorem is proved.
  GPDs permit to calculate the contribution of the total angular momentum of a quark of some flavour or gluon to the nucleon spin (Ji's sum rule).

Phenomenological description of reaction $e + N \to e' + \omega^0 + N$

- First process $e \to e' + \gamma^*$ (QED). Spin-density matrix of virtual photon $\rho_{\lambda_\gamma \lambda'_\gamma}$.
- Second process $\gamma^* + N \to \omega + N$ (QCD). Helicity amplitudes $F_{\lambda_\omega \lambda'_N \lambda_\gamma \lambda_N}$.
  Spin-Density Matrix of ω: $r = F \rho F^+$. $\rho = \sum \left(c_\alpha \Sigma^\alpha \right)$, $r^\alpha = F \Sigma^\alpha F^+$, $r = \sum c_\alpha r^\alpha$.
- Third process $\omega \to \pi^+ + \pi^- + \pi^0 (\to \gamma + \gamma)$ (Quantum mechanics).
  ω: $J^P = 1^-$. P(3π) $= -1$, $Y_{1\lambda_\omega}(\vec{n})$, $\vec{n}$ unit normal to ω-decay plane.
- Spin-Density Matrix Elements (SDMEs) $r_{\lambda_\omega \lambda'_\omega}$ of the ω meson are extracted from the angular distribution of decay pions. $W(\Phi, \Theta, \phi) = \sum_{\lambda_\omega, \lambda'_\omega} Y_{1\lambda_\omega}(\vec{n}) r_{\lambda_\omega \lambda'_\omega} Y^*_{1\lambda'_\omega}(\vec{n})$.
- Quantities (SDMEs) $r^\alpha_{\lambda_\omega \lambda'_\omega}$ can be calculated from the relation
  $r^\alpha_{\lambda_\omega \lambda'_\omega} = \frac{1}{2N_\alpha} \sum F_{\lambda_\omega \lambda'_N; \lambda_\gamma \lambda_N} \, \Sigma^\alpha_{\lambda_\gamma \lambda'_\gamma} \, F^*_{\lambda'_\omega \lambda'_N; \lambda'_\gamma \lambda_N}$, where Σ^α is a set of 9 matrixes:

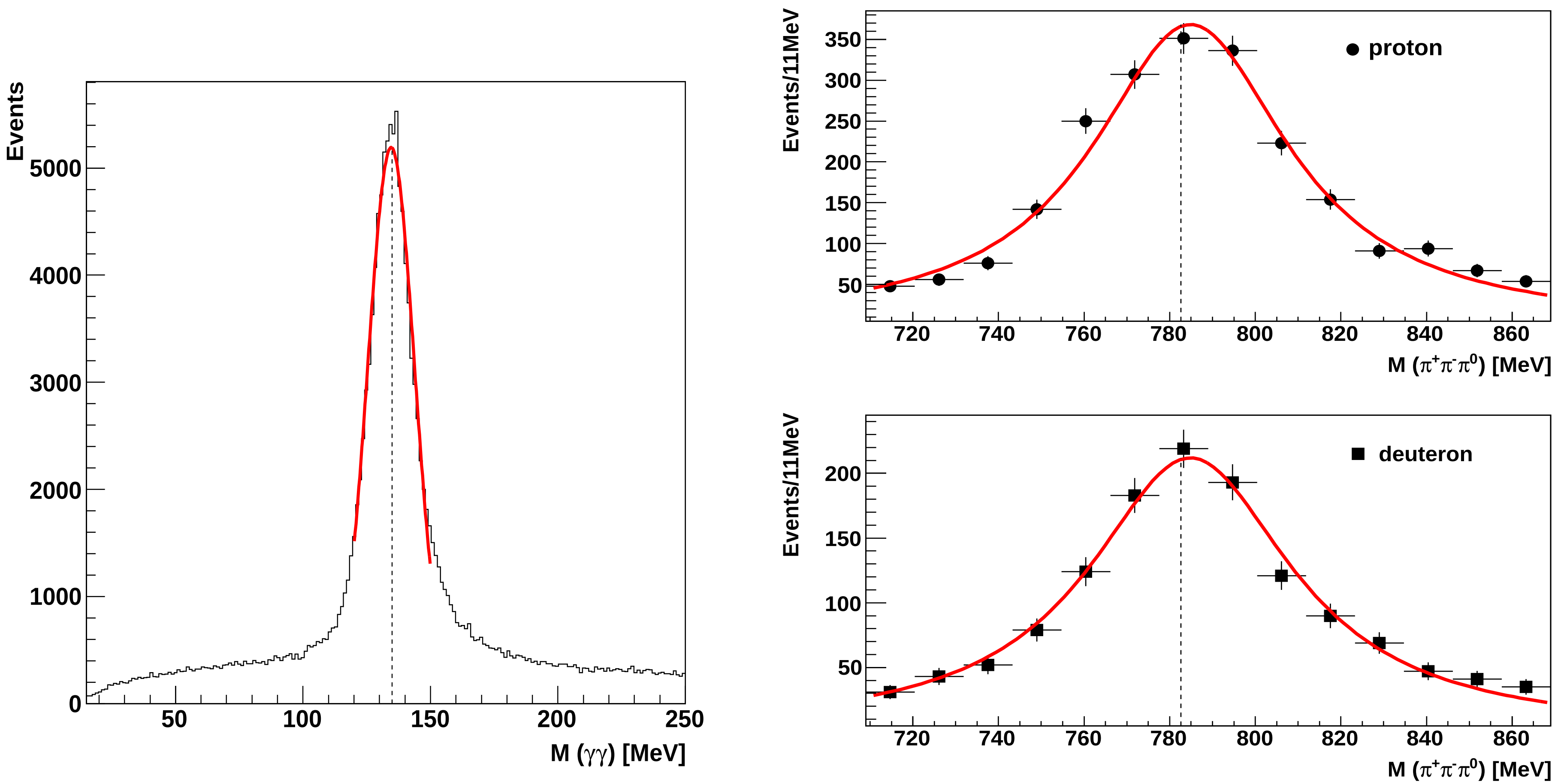
$$\Sigma^0 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \Sigma^1 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\Sigma^4 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \Sigma^5 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & -1 \\ 0 & -1 & 0 \end{pmatrix}$$

The HERMES Experiment

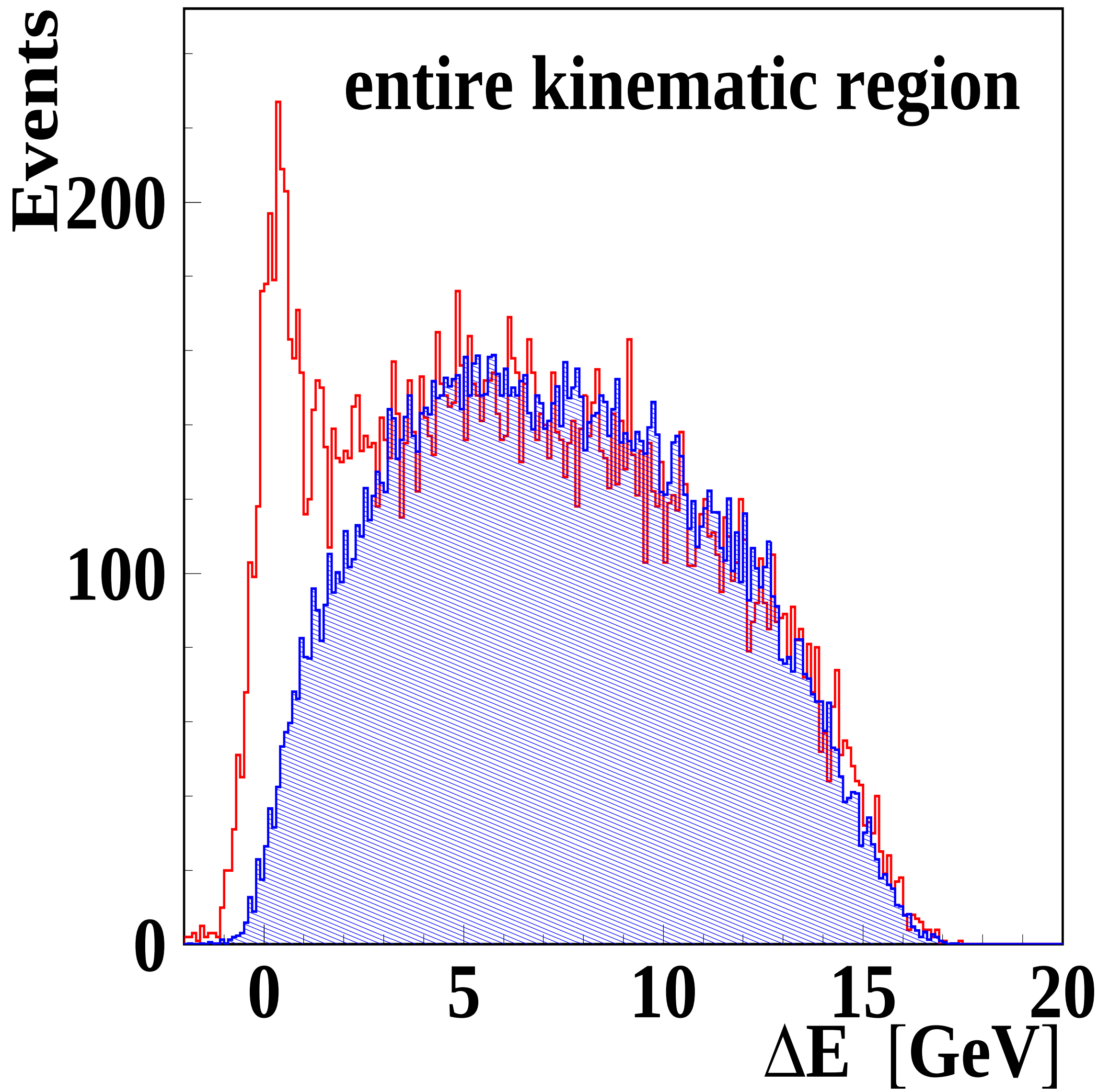
- Longitudinally polarized electron/positron beam with energy of 27.6 GeV.
- $\Delta P/P < 1.5\%$. Efficiency of electron identification 98%.
- Only three tracks of charged particles in any event, two calorimeter clusters (γ, γ).
- Energy of scattered electron $E'_e > 3.5$ GeV.
- $W > 3.0$ GeV, $Q^2 > 1$ GeV^2, $-t' = -(t - t_{max}) < 0.2$ GeV^2.
- Recoil nucleon was not measured. Missing mass criterion was used.
  $\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$; $-1.0 < \Delta E < 0.8$ GeV; M_X (M_p) mass of recoil system (proton).
- $0.11 < M(\gamma\gamma) < 0.16$ GeV; $0.71 < M(\pi^+\pi^-\pi^0) < 0.87$ GeV.
- $16\% <$ fraction of background $< 26\%$ for increasing $-t'$.
- 2260 events with exclusive ω meson produced on proton and 1332 on deuteron were accumulated in 1996 - 2007 years.

- Mass distributions for π^0 and ω decays



Left panel: $\gamma\gamma$ mass distribution for π^0 decay ($m_{\pi^0} = 134.7 \pm 19.9$ MeV).
Right panel: π^+, π^-, π^0 mass distribution for ω decay.

ΔE distribution for ω meson production



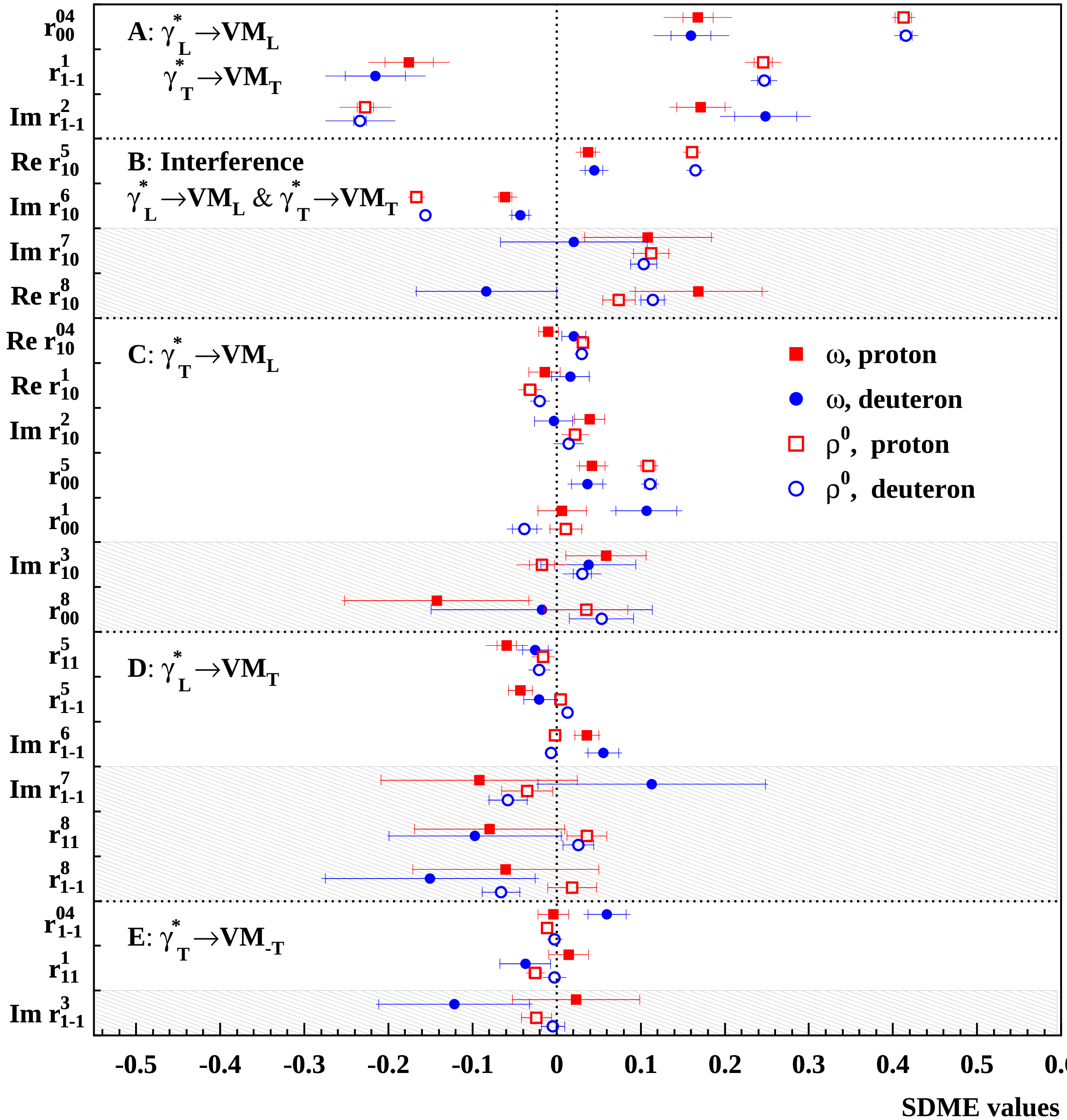
$\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$. M_X and M_p are masses of recoil system and proton, respectively.

Results on Spin-Density Matrix Elements

- S-Channel Helicity Conservation (SCHC):
  helicity amplitudes with $\lambda_V = \lambda_\gamma$ are dominant (T_{00}, T_{11}, U_{11}).
  $T_{\lambda_V \mu_N \lambda_\gamma \lambda_N}$ is Natural Parity Exchange (NPE) amplitude.
  $U_{\lambda_V \mu_N \lambda_\gamma \lambda_N}$ is Unnatural Parity Exchange (UPE) amplitude.
  $$T_{\lambda_V \mu_N \lambda_\gamma \lambda_N} = \left[F_{\lambda_V \mu_N \lambda_\gamma \lambda_N} + (-1)^{\mu_N - \lambda_N} F_{\lambda_V -\mu_N \lambda_\gamma -\lambda_N}\right]/2,$$
  $$U_{\lambda_V \mu_N \lambda_\gamma \lambda_N} = \left[F_{\lambda_V \mu_N \lambda_\gamma \lambda_N} - (-1)^{\mu_N - \lambda_N} F_{\lambda_V -\mu_N \lambda_\gamma -\lambda_N}\right]/2,$$
- Class A of SDMEs: Main terms proportional to $|T_{00}|^2$ or $|T_{11}|^2$.
  Class B: Main terms proportional to $\mathrm{Re}[T_{00}T_{11}^*]$ or $\mathrm{Im}[T_{00}T_{11}^*]$.
  Class C: Main terms proportional to T_{01} ($\sim \sqrt{-t'}/M_p$ at small $-t'$).
  Class D: Main terms proportional to T_{10} ($\sim \sqrt{-t'}/M_p$ at small $-t'$).
  Class E: Main terms proportional to T_{1-1} ($-t'/M_p^2$ at small $-t'$).
  If SCHC is valid all elements of classes C, D, E are zero.
- Check of SCHC relations for Class-A and B SDMEs for the proton
  $r^1_{1-1} + \mathrm{Im}[r^2_{1-1}] = -0.004 \pm 0.038 \pm 0.015,$
  $\mathrm{Re}[r^5_{10}] + \mathrm{Im}[r^6_{10}] = -0.024 \pm 0.013 \pm 0.004,$
  $\mathrm{Im}[r^7_{10}] - \mathrm{Re}[r^8_{10}] = -0.060 \pm 0.100 \pm 0.018,$
  and deuteron
  $r^1_{1-1} + \mathrm{Im}[r^2_{1-1}] = 0.033 \pm 0.049 \pm 0.016,$
  $\mathrm{Re}[r^5_{10}] + \mathrm{Im}[r^6_{10}] = 0.001 \pm 0.016 \pm 0.005,$
  $\mathrm{Im}[r^7_{10}] - \mathrm{Re}[r^8_{10}] = 0.104 \pm 0.110 \pm 0.023.$

Results on Spin-Density Matrix Elements

- Comparison of results for ω and ρ^0 mesons



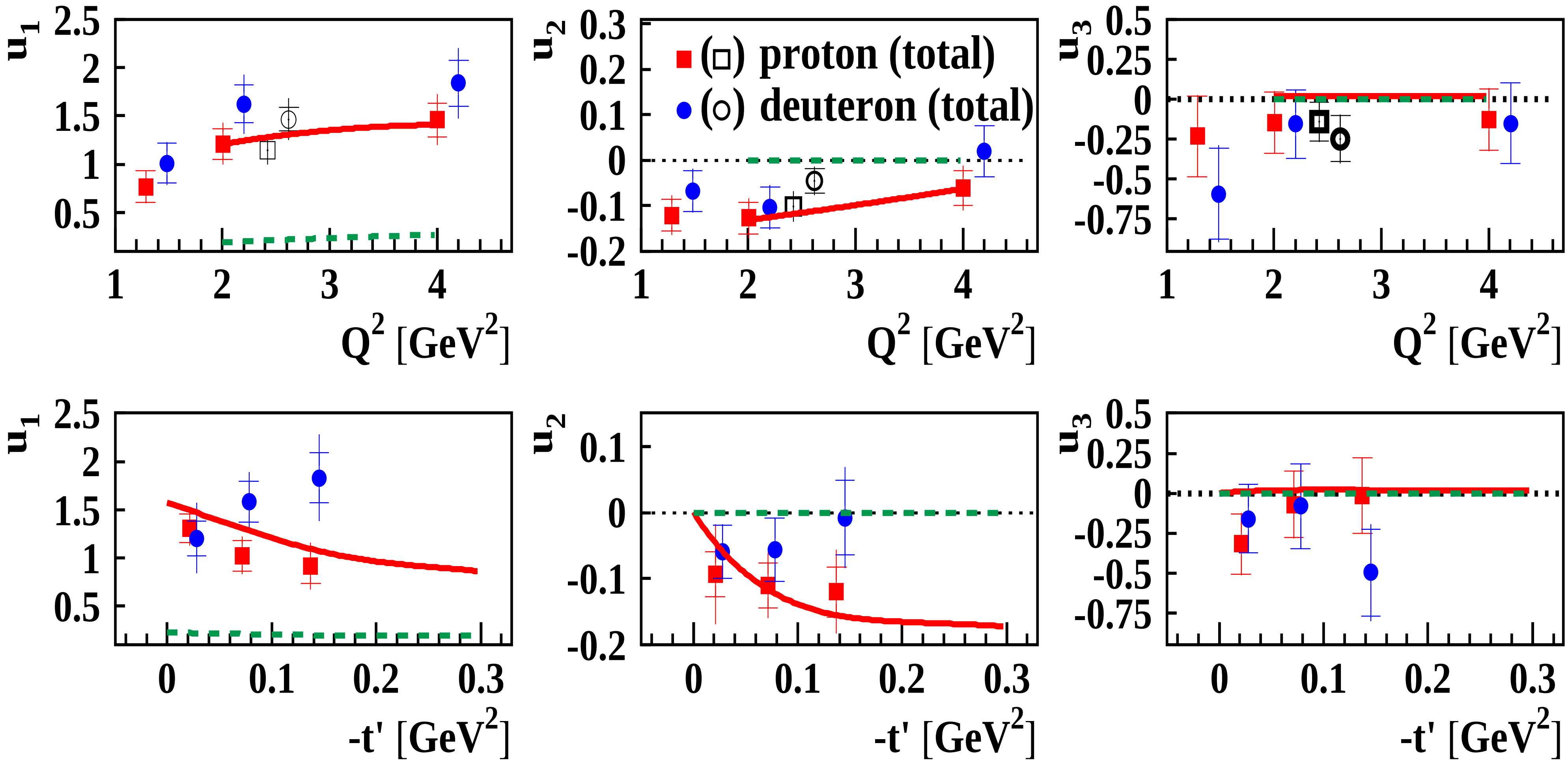
Results on Spin-Density Matrix Elements

- Enigma of the $\rho - \omega$ difference for class A SDMEs
  $\mathrm{Im}\{r^2_{1-1}\} - r^1_{1-1} = \frac{1}{N}(-|T_{1\frac{1}{2}1\frac{1}{2}}|^2 - |T_{1-\frac{1}{2}1\frac{1}{2}}|^2 + |U_{1\frac{1}{2}1\frac{1}{2}}|^2 + |U_{1-\frac{1}{2}1\frac{1}{2}}|^2) > 0.???$
  $T_{\lambda_V \mu_N \lambda_\gamma \lambda_N}$ is Natural Parity Exchange (NPE) amplitude.
  $U_{\lambda_V \mu_N \lambda_\gamma \lambda_N}$ is Unnatural Parity Exchange (UPE) amplitude.
  In Regge Phenomenology, NPE amplitudes are due to exchanges of Pomeron, ρ, ω, f_2, a_2, ... reggeons ($J^P = 0^+,\ 1^-,\ 2^+, ...$).
  UPE amplitudes are due to exchanges of π, a_1, ... reggeons ($J^P = 0^-,\ 1^+,\ 2^-, ...$).

- How to make the U_{11} amplitude dominant?
  First: hard ρ^0 production.
  Modulus of amplitude $|T_{11}(\gamma + N \to \rho^0 + N)| > |T_{11}(\gamma + N \to \omega + N)|$.
  Second: pion exchange in final state $\rho^0 + N \to \omega + N$.
  $\rho^0 \to \omega + \pi^0$, $\pi^0 + N \to N$. Vertices $\rho^0\omega\pi$ and πNN are big.
  Peripherical pion exchange (soft) is combined with hard ρ^0 production at high Q^2.

- Factorization theorem
  FT is proved for T_{00} ($\gamma_L \to V_L$) only. $U_{00} \equiv 0$.
  Ivanov-Kirshner: $|F_{00}/F_{11}| \propto Q$ at $Q \to \infty$. $F_{00} = T_{00}$, $F_{11} = T_{11} + U_{11}$.
  It is true for the "direct" amplitudes without final state interaction.
  Fractional contribution of pion exchange goes to zero at $W \to \infty$.

Test of Unnatural-Parity Exchange



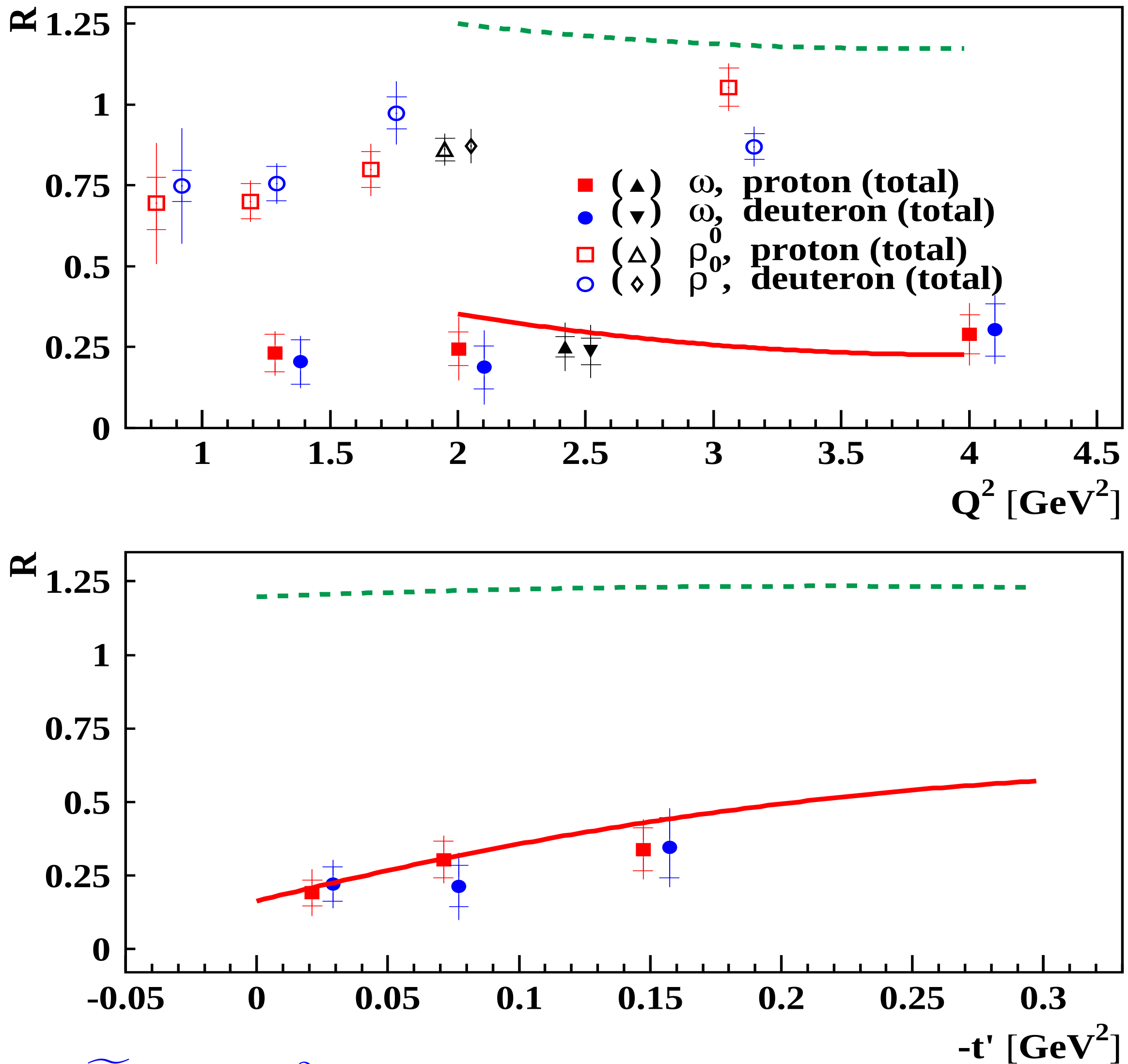
$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1}$, $\quad u_1 = \widetilde{\sum} \frac{4\epsilon|U_{10}|^2 + 2|U_{11}+U_{-11}|^2}{\mathcal{N}}$, $\epsilon = \frac{N_L^\gamma}{N_T^\gamma} \approx 0.8$,

$u_2 = r^{5}_{11} + r^{5}_{1-1}$, $u_3 = r^{8}_{11} + r^{8}_{1-1}$, $\quad u_2 + iu_3 = \sqrt{2}\widetilde{\sum}\frac{(U_{11}+U_{-11})U^*_{10}}{\mathcal{N}}$.

Curves show result of Goloskokov-Kroll calculations.

Longitudinal-to-Transverse Cross-Section Ratio

Kinematic dependence of $R = d\sigma_L/d\sigma_T$



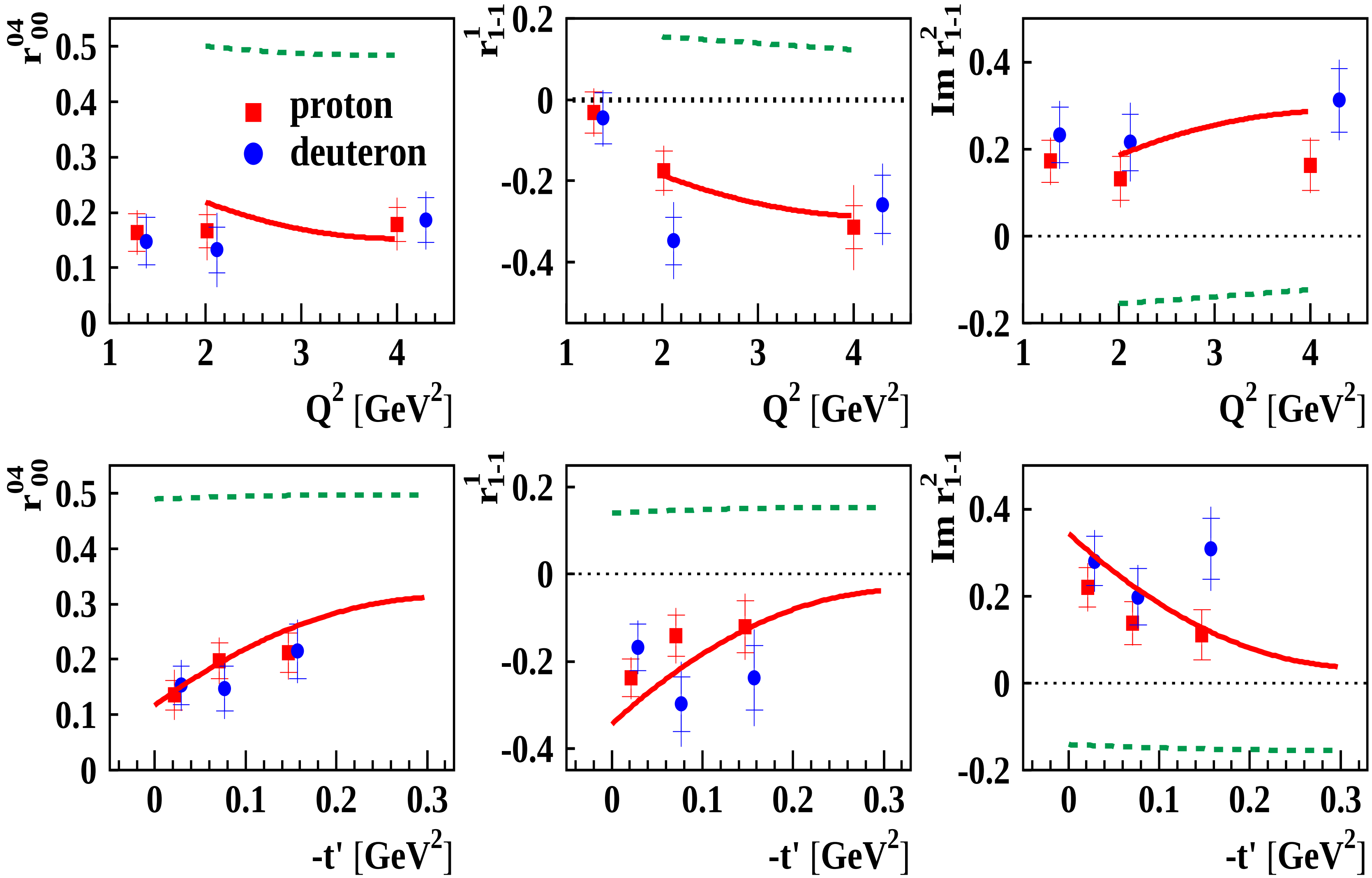
$$R = \frac{\widetilde{\sum}_{\lambda_\omega} |F_{\lambda_\omega 0}|^2}{\widetilde{\sum}_{\lambda_\omega} |F_{\lambda_\omega 1}|^2} \approx \frac{1}{\epsilon} \frac{r^{04}_{00}}{1 - r^{04}_{00}} \approx |T_{00}|^2 / [|T_{11}|^2 + |U_{11}|^2].$$

Curves show result of Goloskokov-Kroll calculations.

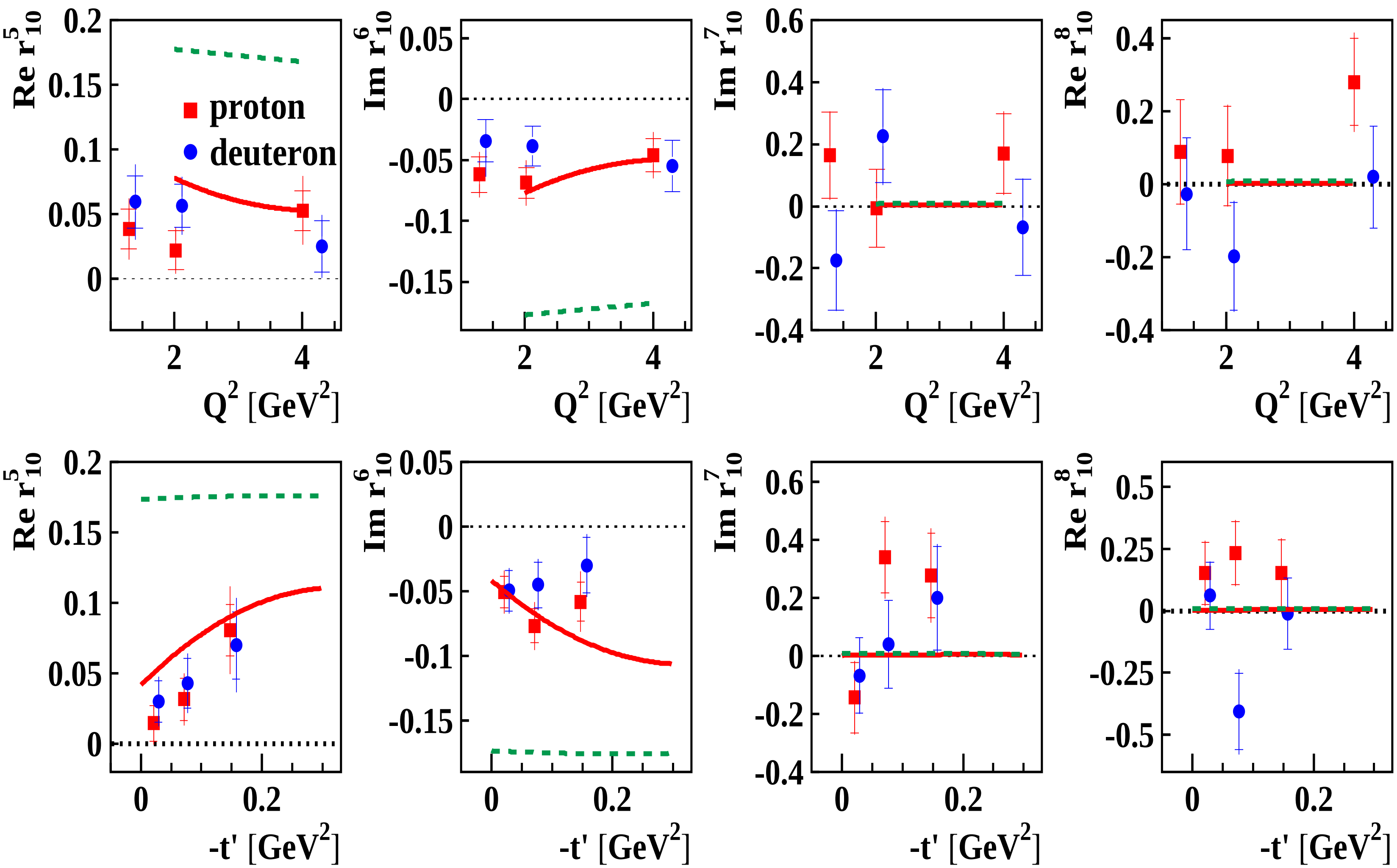
Summary

- Exclusive ω electroproduction is studied at HERMES using a longitudinally polarized electron/positron beam and unpolarized hydrogen and deuterium targets in the kinematic region $Q^2 > 1.0$ GeV^2, 3.0 GeV $< W < 6.3$ GeV, and $-t' < 0.2$ GeV^2.
- Using an unbinned maximum likelihood method, 15 unpolarized, and, for the first time, 8 polarized spin density matrix elements are extracted.
- No significant differences between proton and deuteron results are seen.
- While the values of class-A and B SDMEs agree with the hypothesis of s-channel helicity conservation, the class-C SDME r^5_{00} indicates a violation of this hypothesis.
- Using the SDMEs r^1_{1-1} and $\mathrm{Im}\{r^2_{1-1}\}$ it is shown that $|U_{11}|^2 > |T_{11}|^2$.
- The importance of UPE transitions is also shown by considering u_1, u_2, u_3. This suggests that at HERMES energies π^0, a_1... exchanges play a significant role.
- The ratio $R = d\sigma_L/d\sigma_T$ between longitudinal and transverse virtual-photon cross-sections is determined to be $R = 0.25 \pm 0.03 \pm 0.07$ for the ω meson.
- Two possible hierachies of amplitudes are shown to correspond to the obtained SDME values. The most probable hierachy is $|U_{11}|^2 > |T_{00}|^2 \sim |T_{11}|^2 \gg |U_{10}|^2 \sim |T_{01}|^2 \sim |U_{01}|^2 \gg |T_{10}|^2, |T_{1-1}|^2, |U_{1-1}|^2$.

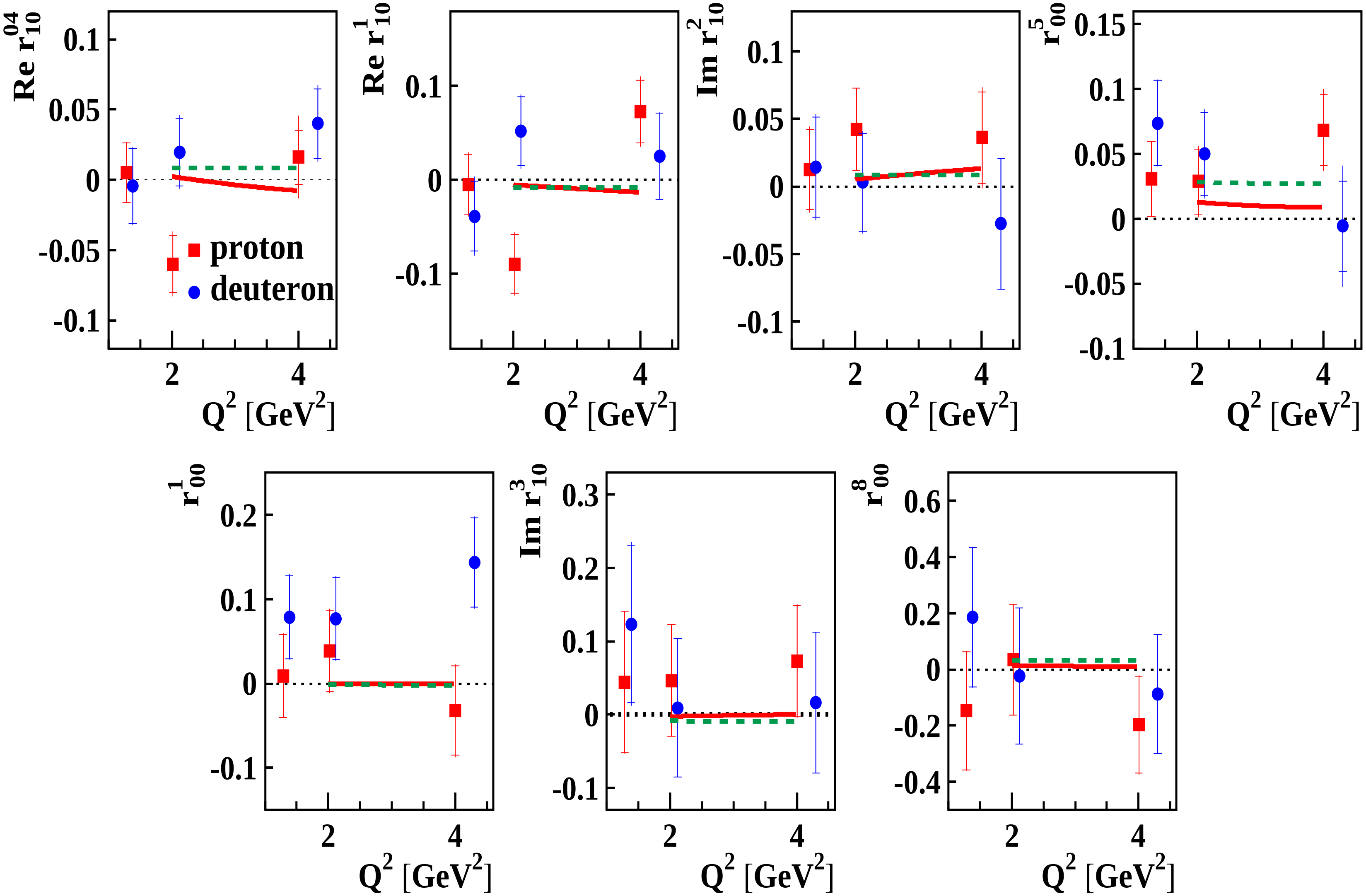
- Kinematic dependences of clas-A SDMEs



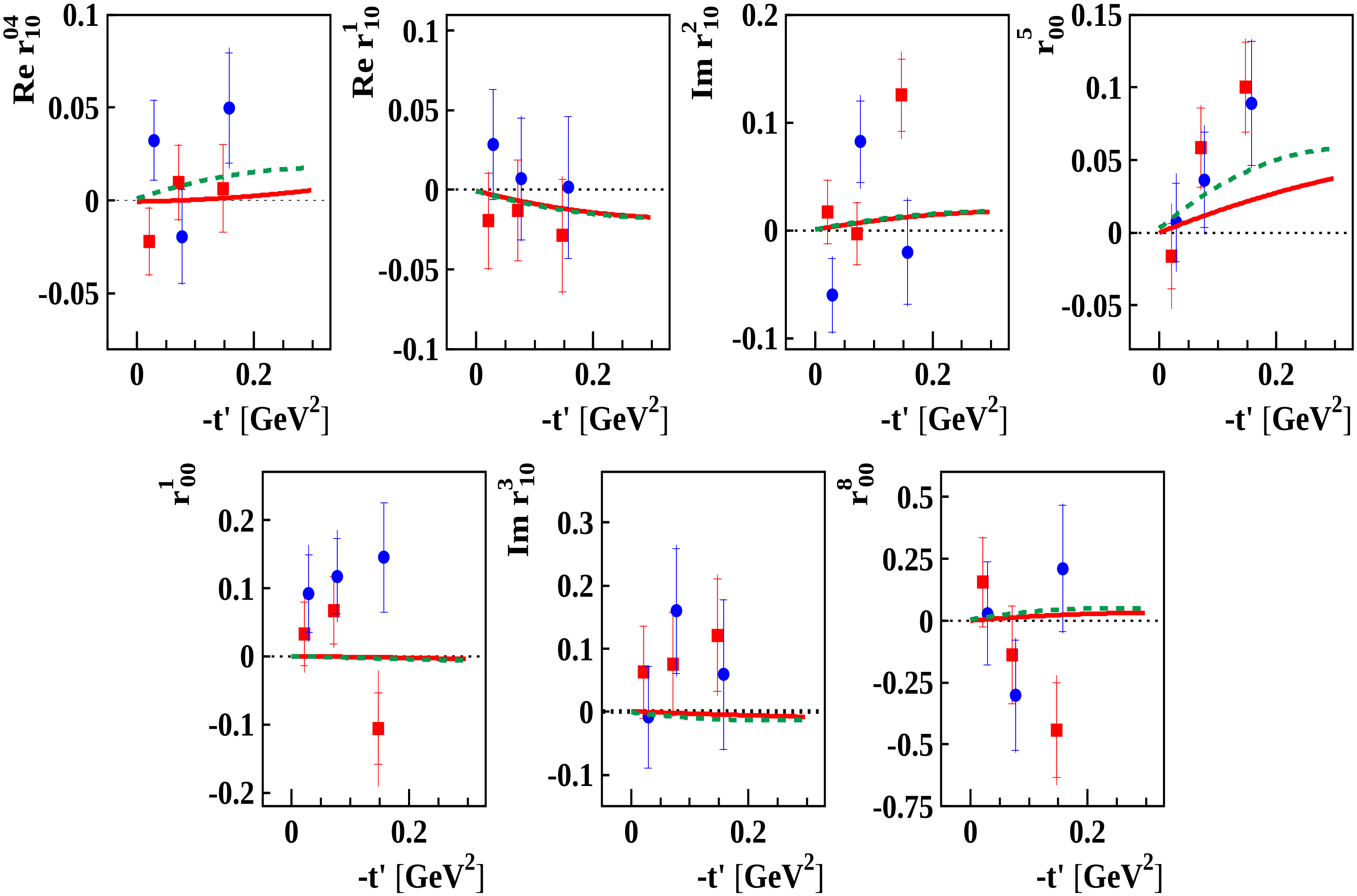
- Kinematic dependences of clas-B SDMEs



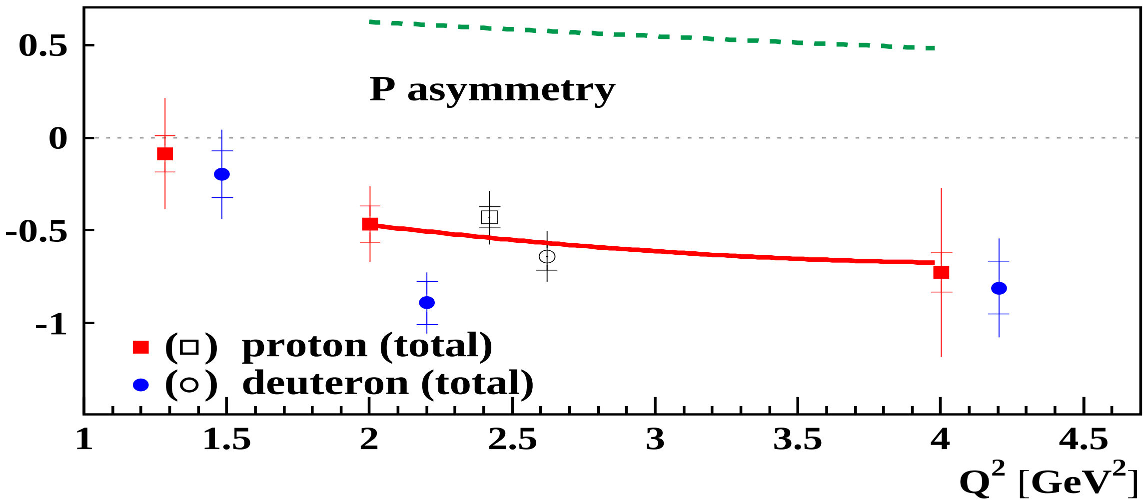
- Kinematic dependences of clas-C SDMEs

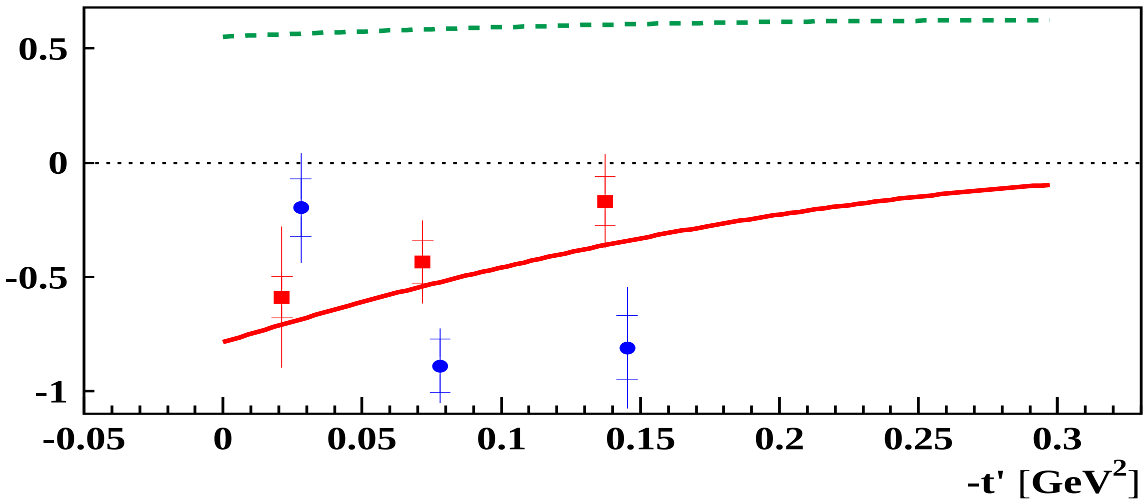


- Kinematic dependences of clas-C SDMEs



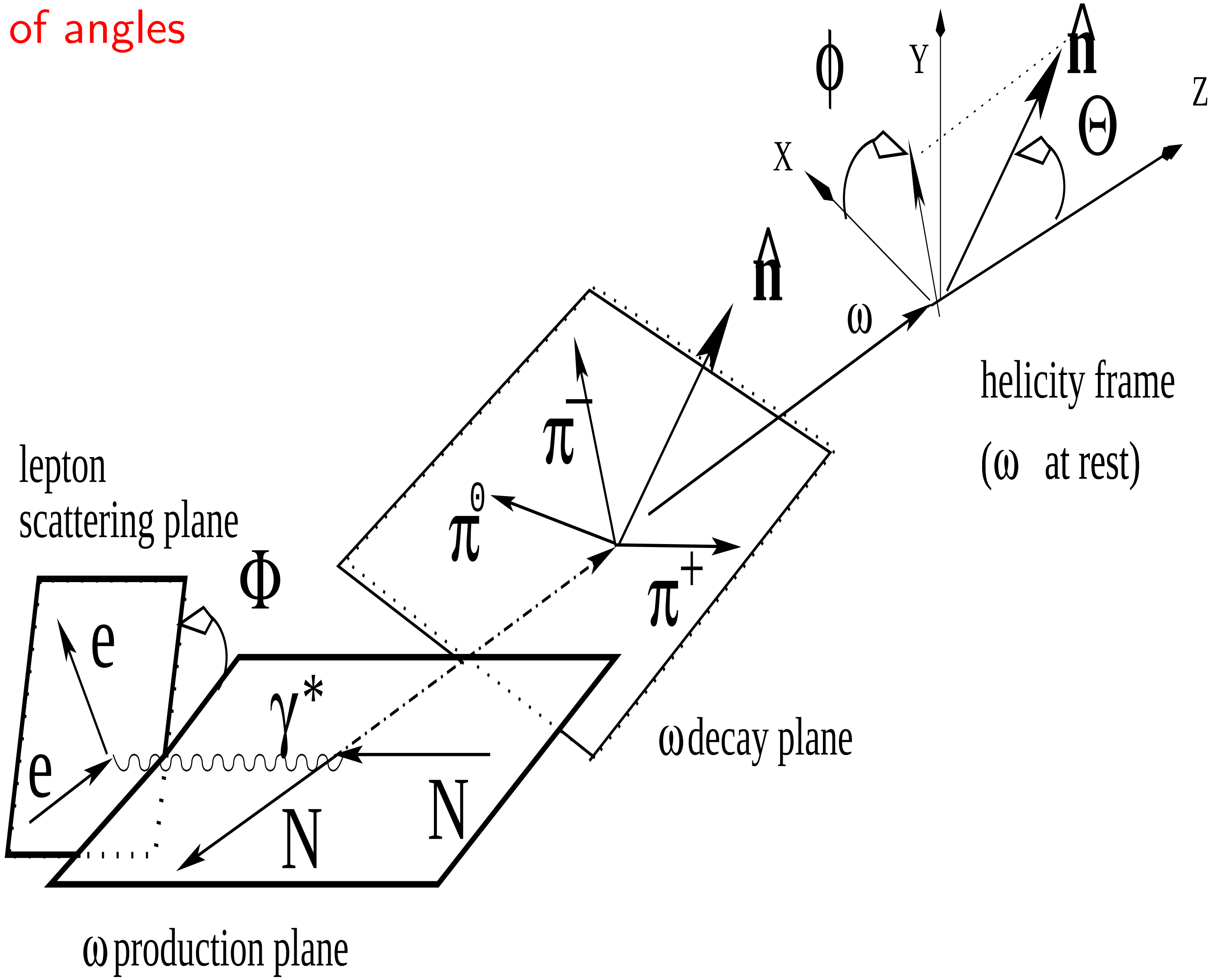
UPE-to-NPE asymmetry





$$P = \frac{d\sigma_T^N - d\sigma_T^U}{d\sigma_T^N + d\sigma_T^U} \approx \frac{2r^1_{1-1} - r^1_{00}}{1 - r^{04}_{00}}$$

- Definition of angles



- Dependence of angular distribution on SDMEs

$$\mathcal{W}^{U+L}(\Phi,\phi,\cos\Theta)=\mathcal{W}^{U}(\Phi,\phi,\cos\Theta)+P_b\mathcal{W}^{L}(\Phi,\phi,\cos\Theta)$$

$$\mathcal{W}^{U}(\Phi,\phi,\cos\Theta)=$$
$$\frac{3}{8\pi^2}\Big[\frac{1}{2}(1-r^{04}_{00})+\frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta-\sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi-r^{04}_{1-1}\sin^2\Theta\cos 2\phi$$
$$-\ \epsilon\cos 2\Phi\Big(r^{1}_{11}\sin^2\Theta+r^{1}_{00}\cos^2\Theta-\sqrt{2}\mathrm{Re}\{r^{1}_{10}\}\sin 2\Theta\cos\phi-r^{1}_{1-1}\sin^2\Theta\cos 2\phi\Big)$$
$$-\ \epsilon\sin 2\Phi\Big(\sqrt{2}\mathrm{Im}\{r^{2}_{10}\}\sin 2\Theta\sin\phi+\mathrm{Im}\{r^{2}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$
$$+$$
$$\sqrt{2\epsilon(1+\epsilon)}\cos\Phi\Big(r^{5}_{11}\sin^2\Theta+r^{5}_{00}\cos^2\Theta-\sqrt{2}\mathrm{Re}\{r^{5}_{10}\}\sin 2\Theta\cos\phi-r^{5}_{1-1}\sin^2\Theta\cos 2\phi\Big)$$
$$+\ \sqrt{2\epsilon(1+\epsilon)}\sin\Phi\Big(\sqrt{2}\mathrm{Im}\{r^{6}_{10}\}\sin 2\Theta\sin\phi+\mathrm{Im}\{r^{6}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)\Big],$$

$$\mathcal{W}^{L}(\Phi,\phi,\cos\Theta)=\frac{3}{8\pi^2}\Big[\sqrt{1-\epsilon^2}\Big(\sqrt{2}\mathrm{Im}\{r^{3}_{10}\}\sin 2\Theta\sin\phi+\mathrm{Im}\{r^{3}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$
$$+\ \sqrt{2\epsilon(1-\epsilon)}\cos\Phi\Big(\sqrt{2}\mathrm{Im}\{r^{7}_{10}\}\sin 2\Theta\sin\phi+\mathrm{Im}\{r^{7}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$
$$+\ \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r^{8}_{11}\sin^2\Theta+r^{8}_{00}\cos^2\Theta-\sqrt{2}\mathrm{Re}\{r^{8}_{10}\}\sin 2\Theta\cos\phi-$$
$$r^{8}_{1-1}\sin^2\Theta\cos 2\phi\Big)\Big].$$

Unbinned Maximum Likelihood Method

- No background corrections

$\ln \mathcal{L} = \sum_i^I \ln[\mathcal{W}(\mathcal{R}, (P_b)_i, (P_T)_i, \Phi_i, \Psi_i, \theta_i, \varphi_i))/N_i]$,

$N_i = K_1 + K_2(P_b)_i + K_3(P_T)_i + K_4(P_b)_i(P_T)_i$

$(P_b)_i$ beam polarization, $(P_T)_i$ target polarization for i-th event,
$\mathcal{R}$ set of amplitude ratios.

$N_{++} = \frac{1}{L}\sum_{m=1}^L \mathcal{W}(\mathcal{R}, (P_b = 1), (P_T = 1), \Phi_m, \Psi_m, \theta_m, \varphi_m)$

N_{+-} corresponds to $P_b = 1$, $P_T = -1$, N_{-+} to $P_b = -1$, $P_T = 1$ etc.
K_1, K_2, K_3, and K_4 are linear combinations of N_{++}, N_{+-}, N_{-+}, and N_{--}.

- Likelihood function with background corrections

$\ln \mathcal{L}_{tot} = \sum_i^I \ln\Big[(1 - f_{bg})\frac{\mathcal{W}(\mathcal{R},(P_b)_i,(P_T)_i,\Phi_i,\Psi_i,\theta_i,\varphi_i)}{N_i} + f_{bg}\frac{\mathcal{W}_{bg}((P_b)_i,(P_T)_i,\Phi_i,\Psi_i,\theta_i,\varphi_i)}{N_i^{bg}}\Big]$

Angular distribution, $\mathcal{W}_{bg}$ of background events is assumed to be independent of polarizations P_b and P_T, f_{bg} fraction of reconstructed background events.

$N_i^{bg} = \frac{1}{L}\sum_{m=1}^L \mathcal{W}_{bg}((P_b = 0), (P_T = 0), \Phi_m, \Psi_m, \theta_m, \varphi_m)$

$\ln \mathcal{L}_{tot} = \sum_i^I \ln\Big[\frac{(1-g_{bg})\mathcal{W}(\mathcal{R},(P_b)_i,(P_T)_i,\Phi_i,\Psi_i,\theta_i,\varphi_i)N_i + g_{bg}\mathcal{W}_{bg}((P_b)_i,(P_T)_i,\Phi_i,\Psi_i,\theta_i,\varphi_i)}{(1-g_{bg})N_i + g_{bg}N_i^{bg}}\Big]$

g_{bg} is the fraction of background in 4π (before interaction of particles with detector)