Exclusive mesons at HERMES

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(on behalf of the HERMES collaboration)
exclusive meson production

factorization in collinear approximation

\[ \mathcal{A} \propto F(x, \xi, t; \mu^2) \otimes K(x, \xi, z; \log(Q^2/\mu^2) \otimes \Phi(z; \mu^2) \]

at leading-twist: \( H, E, \tilde{H}, \tilde{E} \)

- \( H \) and \( \tilde{H} \) conserve the nucleon helicity
- \( E \) and \( \tilde{E} \) describe the nucleon helicity flip

quantum numbers of final state selects different GPDs

- vector mesons \((\gamma^*_L \rightarrow \rho_L, \omega_L, \phi_L)\): \( H, E \)
- pseudoscalar mesons \((\gamma^*_L \rightarrow \pi, \eta)\): \( \tilde{H}, \tilde{E} \)

factorization for \( \sigma_L \) (and \( \rho_L, \omega_L, \phi_L \)) only

- \( \sigma_L - \sigma_T \) suppressed by \( 1/Q \)
- \( \sigma_T \) suppressed by \( 1/Q^2 \)
exclusive meson production

modified perturbative approach

\[ A \propto F(x, \xi, t; \mu^2) \otimes K(x, \xi, z; \log(Q^2/\mu^2)) \otimes \Phi(z, k_\perp; \mu^2) \]

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- \( \sigma_L - \sigma_T \) suppressed by \( 1/Q \)
- \( \sigma_T \) suppressed by \( 1/Q^2 \)

power corrections: \( k_\perp \) is not neglected
- regulate the singularity in the transverse amplitude
- \( \gamma^*_T \to \rho^0_T \) transitions can be calculated (model dependent)
exclusive meson production

modified perturbative approach

\[ \mathcal{A} \propto F(x, \xi, t; \mu^2) \otimes K(x, \xi, z; \log(Q^2/\mu^2)) \otimes \Phi(z, k_\perp; \mu^2) \]

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quantum numbers of final state selects different GPDs

- vector mesons \((\gamma^*_L \rightarrow \rho_L, \omega_L, \phi_L)\): \( H, E \)
- pseudoscalar mesons \((\gamma^*_L \rightarrow \pi, \eta)\): \( \tilde{H}, \tilde{E} \)

factorization for \( \sigma_L \) (and \( \rho_L, \omega_L, \phi_L \)) only

- \( \sigma_L - \sigma_T \) suppressed by \( 1/Q \)
- \( \sigma_T \) suppressed by \( 1/Q^2 \)

power corrections: \( k_\perp \) is not neglected

- \( \gamma^*_T \rightarrow \rho^0_T \) transitions can be calculated (model dependent)
- \( \rho^0 \): contributions from \( \tilde{H} \) and \( \tilde{E} \)
- \( \pi^+ \): contributions from \( H_T \)
vector meson polarization

\( \gamma^* \) and \( \rho^0, \phi, \omega \) have the same quantum numbers

- helicity transfer \( \gamma^* \rightarrow \rho^0, \phi, \omega \)
  - signature: \( \rho^0, \phi, \omega \) production angular distribution

- the spin-state of the \( \rho^0, \phi, \omega \) is reflected in the orbital angular momentum of decay particles
  - \( \rho^0, \phi, \omega \) (in the rest frame): \( J = L + S = 1 \)
  - \( \pi, K : S = 0, \ L = 1 \)
  - signature: decay angular distribution
vector meson cross section

\[ \frac{d\sigma}{dx_B dQ^2 dt d\phi_s d\phi d\cos \vartheta d\varphi} \sim \frac{d\sigma}{dx_B dQ^2 dt} W(x_B, Q^2, t, \phi_s, \phi, \cos \vartheta, \varphi) \]
vector meson cross section

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production and decay angular distributions $W$ decomposed:

\[ W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT} \]
vector meson cross section

\[
\frac{d\sigma}{dx_B dQ^2 dt d\phi_s d\phi d\cos \vartheta d\varphi} \sim \frac{d\sigma}{dx_B dQ^2 dt} W(x_B, Q^2, t, \phi_s, \phi, \cos \vartheta, \varphi)
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W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT}
\]

parametrized by helicity amplitudes \(T_{\lambda \lambda'}\) or \(T^{\nu \sigma}_{\mu \lambda}\):

\begin{align*}
T_{\lambda \lambda'} & : & \text{Schilling, Wolf (1973)} \\
T^{\nu \sigma}_{\mu \lambda} & : & \text{Diehl notation (2007)}
\end{align*}
vector meson cross section

\[
\frac{d\sigma}{dx_B \, dQ^2 \, dt \, d\phi_s \, d\phi \, d\cos \theta \, d\varphi} \sim \frac{d\sigma}{dx_B \, dQ^2 \, dt} \, W(x_B, Q^2, t, \phi_s, \phi, \cos \theta, \varphi)
\]

production and decay angular distributions \( W \) decomposed:

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\]

parametrized by helicity amplitudes \( T_{\lambda \lambda'} \) or \( T^{\nu \sigma}_{\mu \lambda} \):

- Schilling, Wolf (1973)

or alternatively by spin-density matrix elements (SDMEs):

- Diehl notation (2007)
(un)natural-parity exchange

Regge theory: the diffractive production of vector meson via an exchange of a particle

\[ e \rightarrow e' \]

\[ p \rightarrow p' \]

\[ Q^2 \]

\[ W^2 \]

\[ t \]

\[ \gamma^* \]

\[ V \]

natural parity

\[ P = (-1)^J \]: exchange of \( \rho, \omega, f_2, a_2 \)

or pomeron

\[ \propto M/W \]

unnatural parity

\[ P = -(-1)^J \]: exchange of \( \pi, a_1, b_1 \)

\[ \propto (M/W)^2 \]

unnatural-parity exchange contribution is expected only at lower values of \( W \)
**Regge theory:** the diffractive production of vector meson via an exchange of a particle

- **natural parity**
  
  \[ P = (-1)^J : \text{exchange of } \rho, \omega, f_2, a_2 \]

- **unnatural parity**
  
  \[ P = -(1)^J : \text{exchange of } \pi, a_1, b_1 \]

\[ \propto \frac{M}{W} \]

- unnatural-parity exchange contribution is expected only at lower values of \( W \)

**GPD formalism:** generalized to characterize the symmetry properties of amplitudes under

- **natural parity**
  
  \[ \text{related to GPDs } H \text{ and } E \]

- **unnatural parity**
  
  \[ \text{related to GPDs } \tilde{H} \text{ and } \tilde{E} \]

- **pomeron exchange** \( \Rightarrow \) **gluon exchange**

  - only **NPE**

- **reggeon exchange** \( \Rightarrow \) **quark exchange**

  - **NPE and UPE**
exclusive vector meson sample

- no recoil proton detection
- elastic scattering:
  \[ \Delta E = \frac{M_{x}^2 - M^2}{2M} \approx 0 \]
- only little energy transferred to the target
  \[ t = (q - v)^2 \]
- transverse four-momentum transfer is used
  \[ t' = t - t_0 \]
- main contribution at small values of \( \Delta E \) and \( t' \)
- non-exclusive events:
  \[ \Delta E > 0 \]
- SIDIS background estimated by PYTHIA MC
$\rho^0$: unpolarized & beam-polarized SDMEs

SDMEs shown according to hierarchy of NPE helicity amplitudes:

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

\( \rho^0 - \phi: \) comparison

SDMEs shown according to hierarchy of NPE helicity amplitudes:

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

HERMES PRELIMINARY

- \( \rho^0 \) proton, \( \langle Q^2 \rangle = 1.9 \text{ GeV}^2, \langle W \rangle = 5 \text{ GeV} \)
- \( \phi \) proton and deuteron

A: \( \gamma_L \rightarrow V_L^0 \) & \( \gamma_T \rightarrow V_T^0 \)

B: Interference \( \gamma_L \rightarrow V_L^0 \) & \( \gamma_T \rightarrow V_T^0 \)

C: \( \gamma_T \rightarrow V_L^0 \)

D: \( \gamma_L \rightarrow V_T^0 \)

E: \( \gamma_T \rightarrow V_{0-T}^0 \)

- unpolarized SDMEs: \( W_{UU} \)
- beam-polarized SDMEs: \( W_{UL} \)
- polarized SDMEs have been measured by HERMES for the first time
  - no statistically significant difference between proton and deuteron
  - no s-channel helicity violation
- hierarchy of amplitudes:
  \( T_{00} \sim T_{11} \)
  \( T_{01} \approx T_{10} \approx T_{-11} \approx 0 \)
$\rho^0$: phase difference $\delta$ between $T_{00}$ and $T_{11}$

\begin{align*}
\delta (\text{deg}) & \begin{cases} 
\square & \text{(□) proton (integrated)} \\
\bullet & \text{(○) deuteron (integrated)} 
\end{cases} \\
\end{align*}

\[ \cos \delta = \frac{2\sqrt{\epsilon (\Re r_{10}^7 - \Im r_{10}^6)}}{\sqrt{r_{00}^{04} (1 - r_{00}^{04} + r_{1-1}^{1} - \Im r_{1-1}^{2})}} \]

\[ \sin \delta = \frac{2\sqrt{\epsilon (\Re r_{10}^8 - \Im r_{10}^7)}}{\sqrt{r_{00}^{04} (1 - r_{00}^{04} + r_{1-1}^{1} - \Im r_{1-1}^{2})}} \]

\[ |\delta| \text{ obtained from unpolarized SDMEs:} \]

\[ \text{sign of } \delta \text{ obtained from polarized SDMEs:} \]
\[(\text{for the first time)}\]

\[ \text{results on } \delta \text{ (in degrees):} \]
- proton: $|\delta| = 26.4 \pm 2.3_{\text{stat}} \pm 4.9_{\text{sys}}$; $\delta = 30.6 \pm 5.0_{\text{stat}} \pm 2.4_{\text{sys}}$
- deuteron: $|\delta| = 29.3 \pm 1.6_{\text{stat}} \pm 3.6_{\text{sys}}$; $\delta = 36.3 \pm 3.9_{\text{stat}} \pm 1.7_{\text{sys}}$

\[ \text{values are consistent} \]
- with each other
- with H1 results: $|\delta| = 21.5 \pm 4.3_{\text{stat}} \pm 5.3_{\text{sys}}$
comparison with a GPD model

$\frac{1-r_{00}}{2}$  $r_{1-1}^1$  $-\text{Im } r_{1-1}^2$

$\text{Re } r_{10}^5$  $\text{Im } r_{10}^6$

$Q^2$-dependence calculated for 3 different $W$ values:

$W = 5 \text{ GeV (HERMES)}$

$W = 10 \text{ GeV (COMPASS)}$

$W = 90 \text{ GeV (H1, ZEUS)}$

$\gamma_L^* \to \rho_L^0$ and $\gamma_T^* \to \rho_T^0$

$1 - r_{00}^{04} \propto r_{1-1}^1 \propto -\text{Im } r_{1-1}^2 \propto T_{11}$

describe data for various $W$-ranges

interference of $\gamma_L^* \to \rho_L^0$ and $\gamma_T^* \to \rho_T^0$

$r_{10}^5 \propto -\text{Im } r_{10}^6 \propto T_{00}$ and $T_{11}$ interference

model does not describe the data

model uses phase difference $\delta = 3.1$ degree between $T_{00}$ and $T_{11}$

HERMES result: $\delta \approx 30$ degree
### Observation of Unnatural-Parity Exchange

**UPE contributions measured from SDMEs:**

\[
u_1 = 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{1} - 2r_{1-1}^{1}, \quad u_2 = r_{11}^{5} + r_{1-1}^{5}, \quad u_3 = r_{11}^{8} + r_{1-1}^{8}
\]

The combinations of SDMEs expected to be the zero in case of NPE dominance.

**Proton:**

\[
u_1 = 0.125 \pm 0.021_{\text{stat}} \pm 0.050_{\text{sys}}
\]

**Deuteron:**

\[
u_1 = 0.091 \pm 0.016_{\text{stat}} \pm 0.046_{\text{sys}}
\]

The UPE contribution is \(W\)-dependent.
$\phi$: observation of unnatural-parity exchange

\[ U_1 = 1 - r_{00} + 2r_{1-1}^0 - 2r_{1-1} - 2r_{11}^1 \]

\[ U_2 = r_{1-1}^5 + r_{11}^5 \]

\[ U_3 = r_{1-1}^8 + r_{11}^8 \]

\[ Q^2 (\text{GeV}^2) \]

\[ -t' (\text{GeV}^2) \]

- $u_1 = 0.02 \pm 0.07_{\text{stat}} \pm 0.16_{\text{sys}}$
- $u_2 = -0.03 \pm 0.01_{\text{stat}} \pm 0.03_{\text{sys}}$
- $u_3 = -0.05 \pm 0.12_{\text{stat}} \pm 0.07_{\text{sys}}$

no signal of unnatural-parity exchange

Expected since dominant contribution to the production is from two gluon exchange
transverse SDMEs: $n_{\mu\mu}'$ and $s_{\mu\mu}'$


- measured for the first time

  - average kinematics:
    - $\langle -t' \rangle = 0.13$ GeV$^2$
    - $\langle x_B \rangle = 0.09$
    - $\langle Q^2 \rangle = 2.0$ GeV$^2$

- related to the proton helicity-flip amplitude

- suppressed by a factor $\sqrt{-t}/2M_p$

### SDME values

- **Im (n$^{++}_L + n^{00}_T$)**
- **Im (n$^{0+}_L - n^{+0}_T$)**
- **Im n$^{--}_T$**
- **Im n$^{00}_L$**
- **Im (s$^{++}_L + s^{00}_T$)**
- **Im (s$^{0+}_L - s^{+0}_T$)**
- **Im n$^{+0}_L$**
- **Im n$^{0+}_L$**
- **Im s$^{00}_L$**
- **Im s$^{++}_L$**

**Dominant transitions**

- $\gamma^* \rightarrow \rho^0_L$
- $\gamma^* \rightarrow \rho^0_T$

**Single spin flip**

- $\gamma^* \rightarrow \rho^1_T$

**Double spin flip**

- $\gamma^* \rightarrow \rho^2_T$
'transverse' SDMEs: $n_{\mu\mu}'$ and $s_{\mu\mu}'$

\[ \gamma_L^* \rightarrow \rho_L^0 \text{ and } \gamma_T^* \rightarrow \rho_T^0 \]


Im $s_{--}^-$ and Im($s_{0+}^0 - s_{0+}^0$): deviate from 0 by 2.5\(\sigma\)

expected $s_{\mu\mu}' < n_{\mu\mu}'$ (if identical indices)

$s_{--}^-$ and Im $s_{0+}^0$ involve

-Manaenkov (2008)-

the biggest NPE amplitudes

$N_{--}^-$ or $N_{0+}^0$

the biggest UPE amplitude

$U_{++}^+$

signal for unnatural-parity exchange

related to GPDs $\bar{H}$ and $\bar{E}$

- Ami Rostomyan - p. 14
'transverse' SDMEs: $n_{\mu\mu'}^{\nu\nu'}$ and $s_{\mu\mu'}^{\nu\nu'}$

\[ \gamma_L^* \rightarrow \rho_L^0 \quad \text{and} \quad \gamma_T^* \rightarrow \rho_T^0 \]

- Im $s_{--}^{0+}$ and Im $(s_{0+}^{00} - s_{0+}^{00})$: deviate from 0 by $2.5\sigma$
- expected $s_{\mu\mu'}^{\nu\nu'} < n_{\mu\mu'}^{\nu\nu'}$ (if identical indices)
- Im $n_{-0}^{++}$: involve
  - the biggest NPE amplitudes $N_{--}$ or $N_{00}^{0+}$
  - the biggest UPE amplitude $U_{--}^{++}$
- signal for unnatural-parity exchange
  - related to GPDs $\vec{H}$ and $\vec{E}$
- Im $n_{00}^{00}$: $2.5\sigma$ deviation from 0

-Manaenkov (2008)-
\(\rho^0\): transverse target-spin asymmetry

Theoretically at leading order in \(1/Q\)

\((\gamma^*_L \rightarrow \rho^0_L)\):

\[A_{UT}^{\sin(\phi-\phi_s)} = \frac{\text{Im} n_{00}^{00}}{u_{00}}\]

Asymmetry in terms of GPDs

\[A_{UT}^{\sin(\phi-\phi_s)} \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g}\]

Depends linearly on the helicity-flip GPDs \(E^q, g\)

No kinematic suppression \(E^q, g\) with respect to \(H^q, g\)
$\rho^0$: transverse target-spin asymmetry

- Theoretically, at leading order in $1/Q$ ($\gamma^*_L \to \rho^0_L$):

$$A^\text{sin}(\phi - \phi_s)_{UT} = \frac{\text{Im } n_{00}^{00}}{u_{00}^{00}}$$

- Asymmetry in terms of GPDs:

$$A^\text{sin}(\phi - \phi_s)_{UT} \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g}$$

- Experimentally:

$$A^{\gamma^*_L}(\phi, \phi_s)_{UT} = \frac{\text{Im } (n_{++}^{00} + \epsilon n_{00}^{00})}{u_{++}^{00} + \epsilon u_{00}^{00}}$$

- $u_{++}^{00}$ and $n_{++}^{00}$ are expected to be negligible.

- Similarly, $\gamma^*_T \to \rho^0_T$:

$$A^{\gamma^*_T}(\phi, \phi_s)_{UT} = \frac{\text{Im } (n_{++}^{++} + n_{--}^{++} + 2\epsilon n_{00}^{++})}{u_{++}^{++} + u_{--}^{++} + 2\epsilon u_{00}^{++}}$$
$$\rho^0 : \text{transverse target-spin asymmetry}$$

- theoretically at leading order in $1/Q$ ($\gamma^*_L \to \rho^0_L$):
  
  $$A_{UT}^{\sin(\phi-\phi_s)} = \frac{\text{Im } n_{00}^{00}}{u_{00}^{00}}$$

- asymmetry in terms of GPDs
  
  $$A_{UT}^{\sin(\phi-\phi_s)} \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g}$$

- experimentally:
  
  $$A_{UT}^{\gamma^*_L}(\phi, \phi_s) = \frac{\text{Im}(n_{++}^{00} + \epsilon n_{00}^{00})}{u_{++}^{00} + \epsilon u_{00}^{00}}$$

- $u_{++}^{00}$ and $n_{++}^{00}$ are expected to be negligible

- similarly, $\gamma^*_T \to \rho^0_T$:
  
  $$A_{UT}^{\gamma^*_T}(\phi, \phi_s) = \frac{\text{Im}(n_{++}^{++} + n_{+0}^{00} + 2\epsilon n_{00}^{++})}{u_{++}^{++} + \epsilon u_{00}^{++} + 2\epsilon u_{00}^{++}}$$


- overall
  
  $A_{UT}^{\rho^0_L, \sin(\phi-\phi_s)} = -0.033 \pm 0.058$
\( \rho^0 \): comparison with GPD models

asymmetry in terms of GPDs

\[ A_{UT}^{\sin(\phi - \phi_s)} \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g} \]


parametrization for \( H^q, \ H^\bar{q}, \ H^g \)

\( E^q \) is related to the total angular momenta \( J^u \) and \( J^d \)

predictions for \( J^d = 0 \)

\( E^\bar{q} \) and \( E^g \) are neglected

data favors positive \( J^u \)

statistics too low to reliably determine the value of \( J^u \) and its uncertainty

within the statistical uncertainty in agreement with theoretical calculations

indication of small \( E^g \) and \( E^\bar{q} \)?

other GPD model calculations

- Goeke, Polyakov, Vanderhaeghen (1999)-
- Goloskokov, Kroll (2007)-
- Diehl, Kugler (2008)-
ω: transverse target-spin asymmetry

6 azimuthal moments extracted using integrated angular distributions

due to low statistics no \( \omega_L/\omega_T \) separation

predictions for large asymmetry
\[ A_{\sin(\phi-\phi_s)}^{\omega T} \approx -0.10 \]

indication of negative \( \sin(\phi - \phi_s) \) amplitude
\[ A_{\sin(\phi-\phi_s)}^{\omega UT} = -0.22 \pm 0.16_{\text{stat}} \pm 0.11_{\text{sys}} \]

no contradiction with \( \rho^0 \) predictions
\[ A_{\sin(\phi-\phi_s)}^{\rho^0 UT} \propto \Im \left\{ \frac{2E^u + E^d}{2H^u + H^d + H^g} \right\} \]
\[ A_{\sin(\phi-\phi_s)}^{\omega UT} \propto \Im \left\{ \frac{2E^u - E^d}{2H^u - H^d} \right\} \]
exclusive $\pi^+$ production: $ep \rightarrow e' \pi^+(n)$

- no recoil nucleon detection
- select exclusive $\pi^+$ reaction through the missing mass technique:

$$M_x^2 = (P_e + P_p - P_{e'} - P_{\pi^+})^2$$

$$N_{excl} = (\pi^+ - \pi^-)_{data} - (\pi^+ - \pi^-)_{MC}$$


| $\pi^+$ | exclusive $\pi^+$ | $VM_{\pi^+}$ | SIDIS |
| $\pi^-$ | $VM_{\pi^-}$ | SIDIS |

$\pi^+ - \pi^-$ yield difference was used to subtract the non exclusive background

- exclusive peak centered at the nucleon mass
- exclusive MC based on GPD model
kinematic dependences of $A_{UT}^{\pi^+}$

6 azimuthal moments extracted according to


average kinematics:
$\langle -t' \rangle = 0.18$ GeV$^2$
$\langle x_B \rangle = 0.13$
$\langle Q^2 \rangle = 2.38$ GeV$^2$

no $\gamma^*_L/\gamma^*_T$ separation

small overall value for leading asymmetry amplitude $A_{UT}^{\sin(\phi-\phi_s)}$

unexpected large overall value for asymmetry amplitude $A_{UT}^{\sin \phi_s}$

other moments: consistent with 0

evidence of contributions from transversely polarized photons

- Diehl, Sapeta (2005)-
theoretical interpretation of $A_{UT}^{\pi^+}$

leading azimuthal amplitude $A_{UT}^{\sin(\phi - \phi_s)}$
- not large asymmetry with possible sign change
- theoretical expectation: $A_{UT}^{\sin(\phi - \phi_s)} \propto \sqrt{-t'}$
- large negative asymmetry
  - Frankfurt et al. (2001)
  - Belitsky, Muller (2001)
- are the differences due to $\gamma_T^*$?
  - Goloskokov, Kroll (2009)
  - Bechler, Muller (2009)

azimuthal amplitude $A_{UT}^{\sin \phi_s}$
- no turnover towards 0 for $t' \to 0$
- milde $t$-dependence
- can be explained only by $\gamma_L^* / \gamma_T^*$ interference
- predictions $A_{UT}^{\sin \phi_s} \approx \text{const}$
- non-vanishing model predictions: contribution from $H_T$

-Goloskokov, Kroll (2009)-
HERMES and GPDs

\[
\begin{align*}
\rho^0 & \rightarrow \pi^+ \\
\phi & \rightarrow \pi^0 \\
\omega & \rightarrow SDME \\
A_{UT} & \rightarrow SDME
\end{align*}
\]
$\rho^0$: observation of unnatural-parity exchange

UPE contributions measured from SDMEs:

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

UPE contributions expressed through amplitudes:

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

the combinations of SDMEs expected to be the zero in case of NPE dominance:
\[ \rho_{\mu \nu', \lambda \lambda'} \propto \sum_{\sigma} T_{\mu \lambda}^{\nu \sigma} (T_{\mu' \lambda'}^{\nu' \sigma})^* \]