Exclusive meson production at hermes

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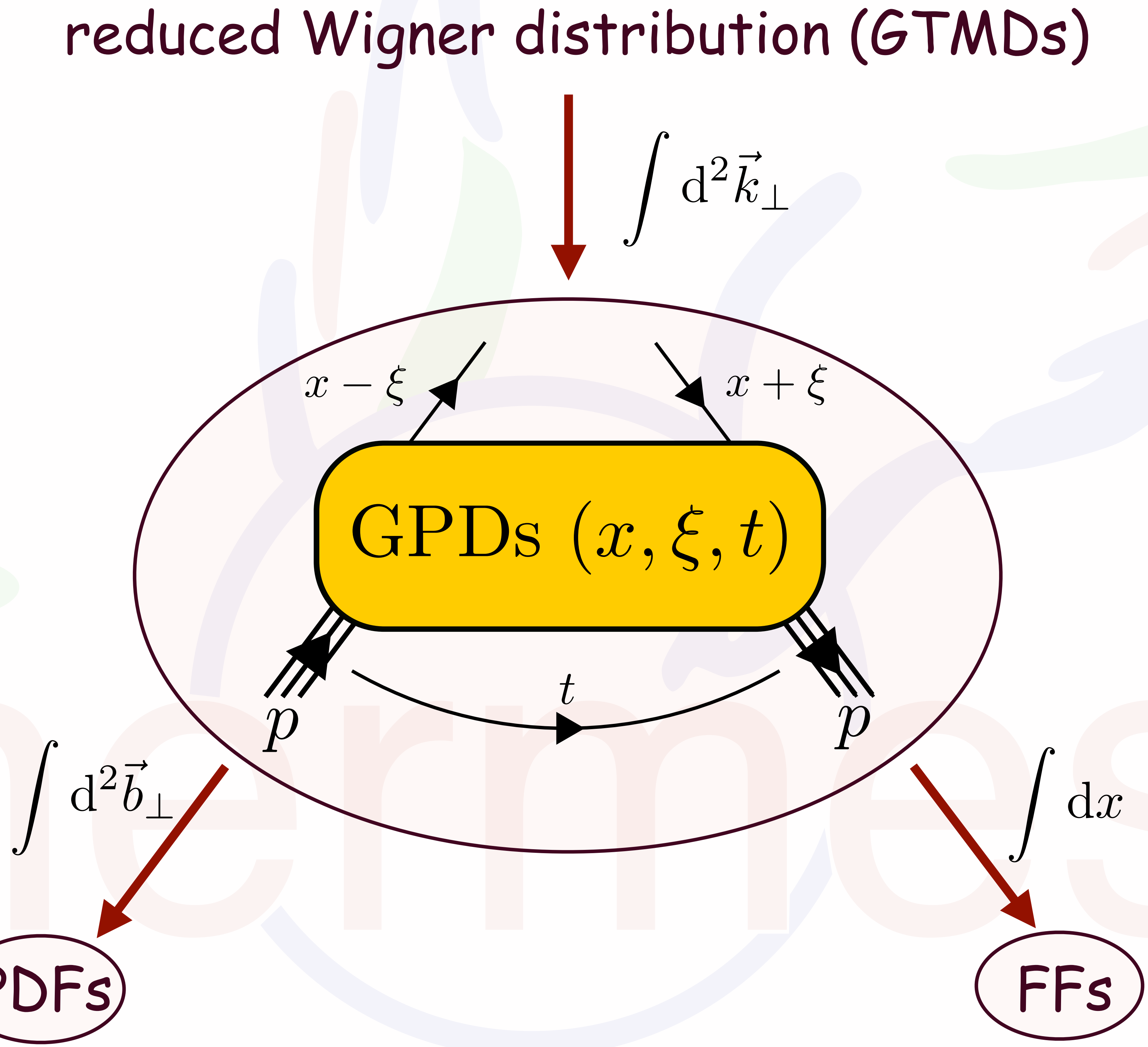
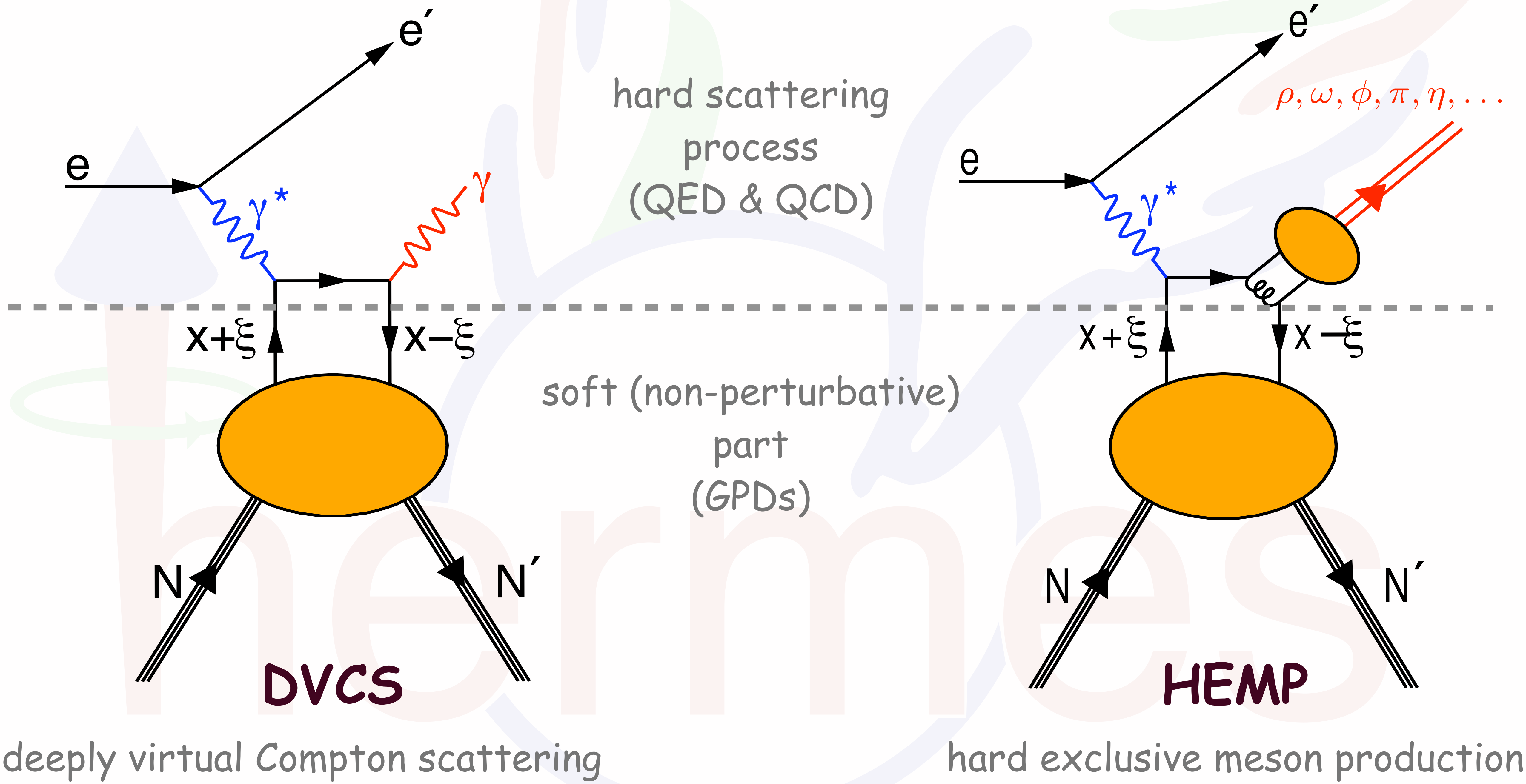
generalized parton distributions

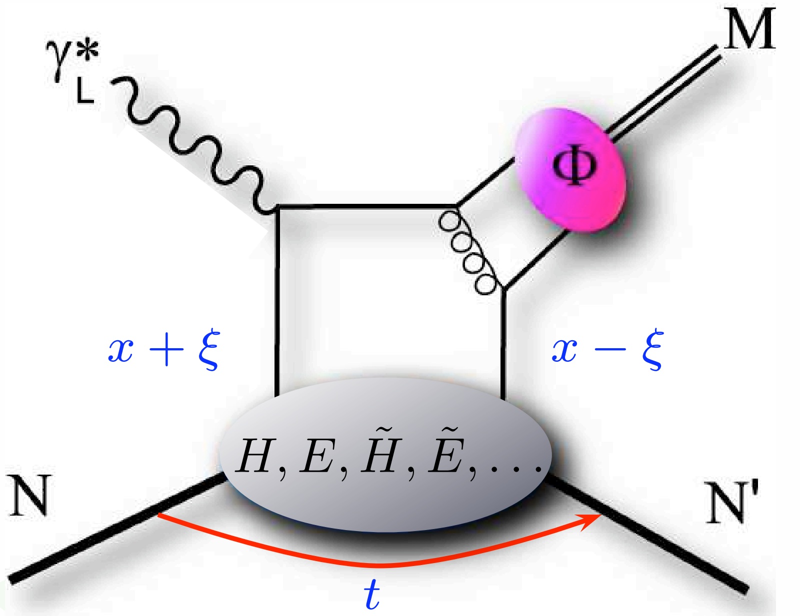


GPDs in exclusive reactions

GPDs can be accessed through
measurements of hard exclusive lepton-nucleon scattering processes.



exclusive meson production

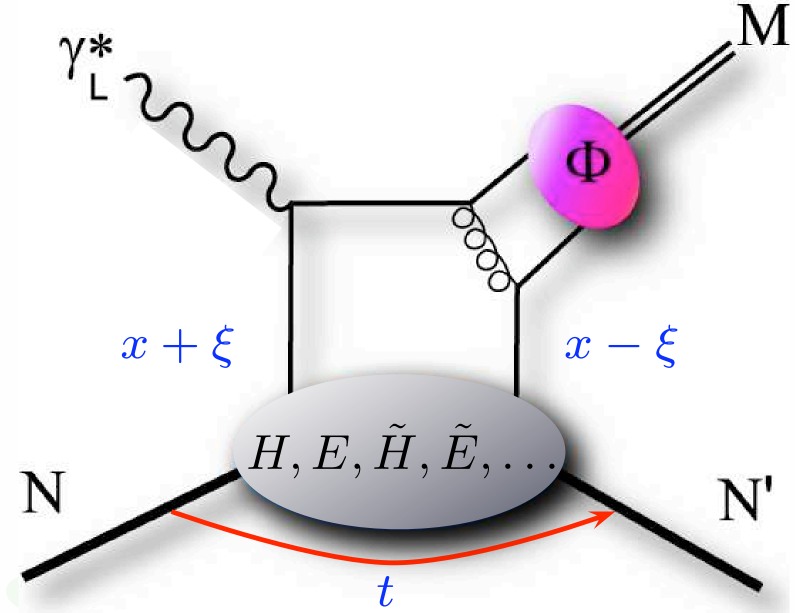


- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations
- factorization proven for longitudinal photons
- generalized to transverse photons in GK model

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$
ρ^0	2u+d, 9g/4
ω	2u−d, 3g/4
ϕ	s, g
ρ^+	u−d
J/ψ	g

GK ... S. Goloskokov & P. Kroll, e.g., EPJ C50 (2007) 829; C53 (2008) 367

exclusive meson production



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- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations
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- generalized to transverse photons in GK model
- vector-meson cross section:

$$\frac{d\sigma}{dx_B\, dQ^2\, dt\, d\phi_S\, d\phi\, d\cos\theta\, d\varphi} = \frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi_S, \phi, \cos\theta, \varphi)$$

$$W = W_{UU} + P_B W_{LU} + S_L W_{UL} + P_B S_L W_{LL} + S_T W_{UT} + P_B S_T W_{LT}$$

look at various angular (decay) distributions to study helicity transitions ("spin-density matrix elements", "amplitude ratios")

SDMEs from angular decay distribution

unpolarized beam   long. polarized beam

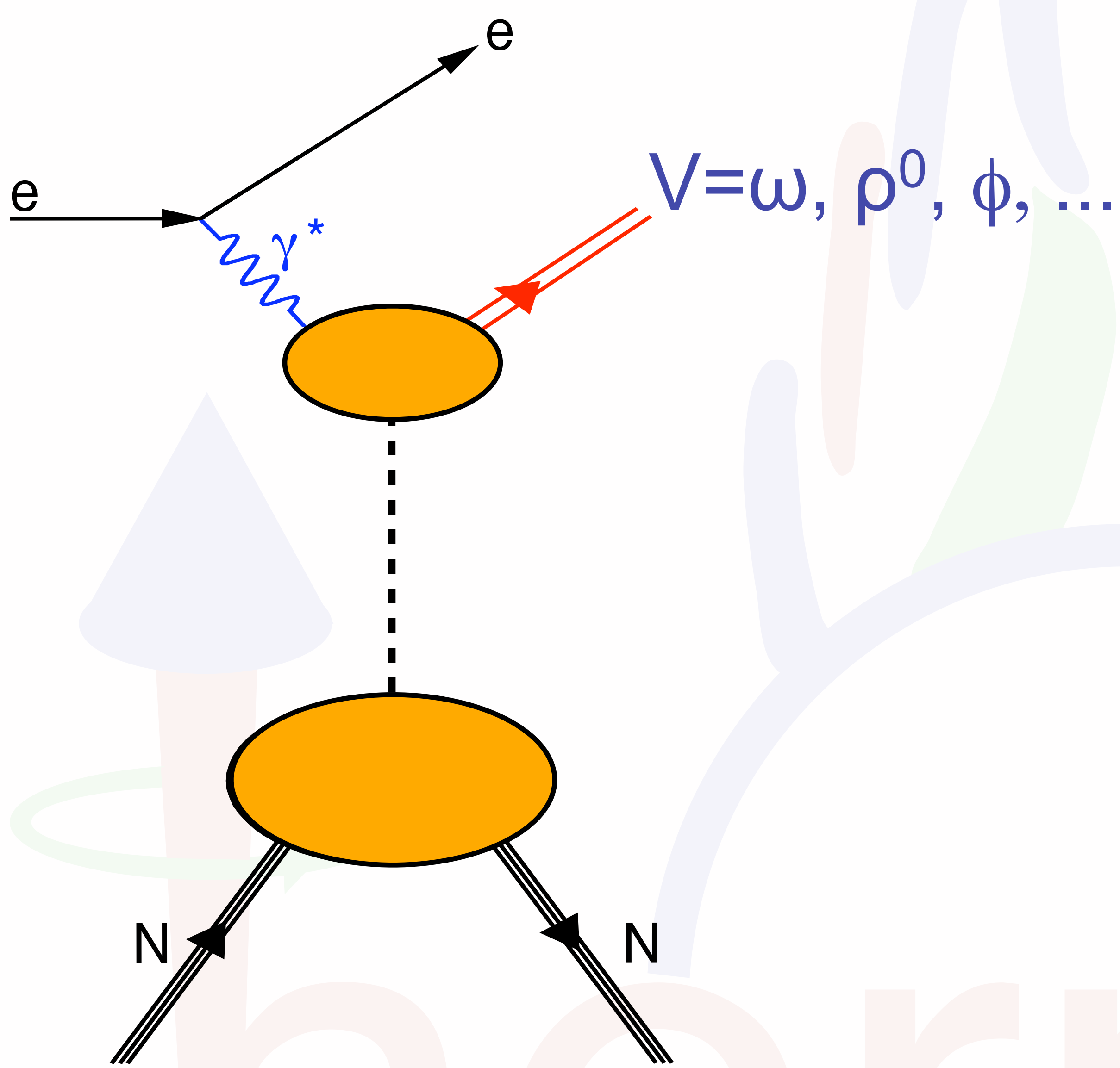
$$\mathcal{W}^{U+L}(\Phi,\phi,\cos\Theta) = \mathcal{W}^{U}(\Phi,\phi,\cos\Theta) + \mathcal{W}^{L}(\Phi,\phi,\cos\Theta),$$

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

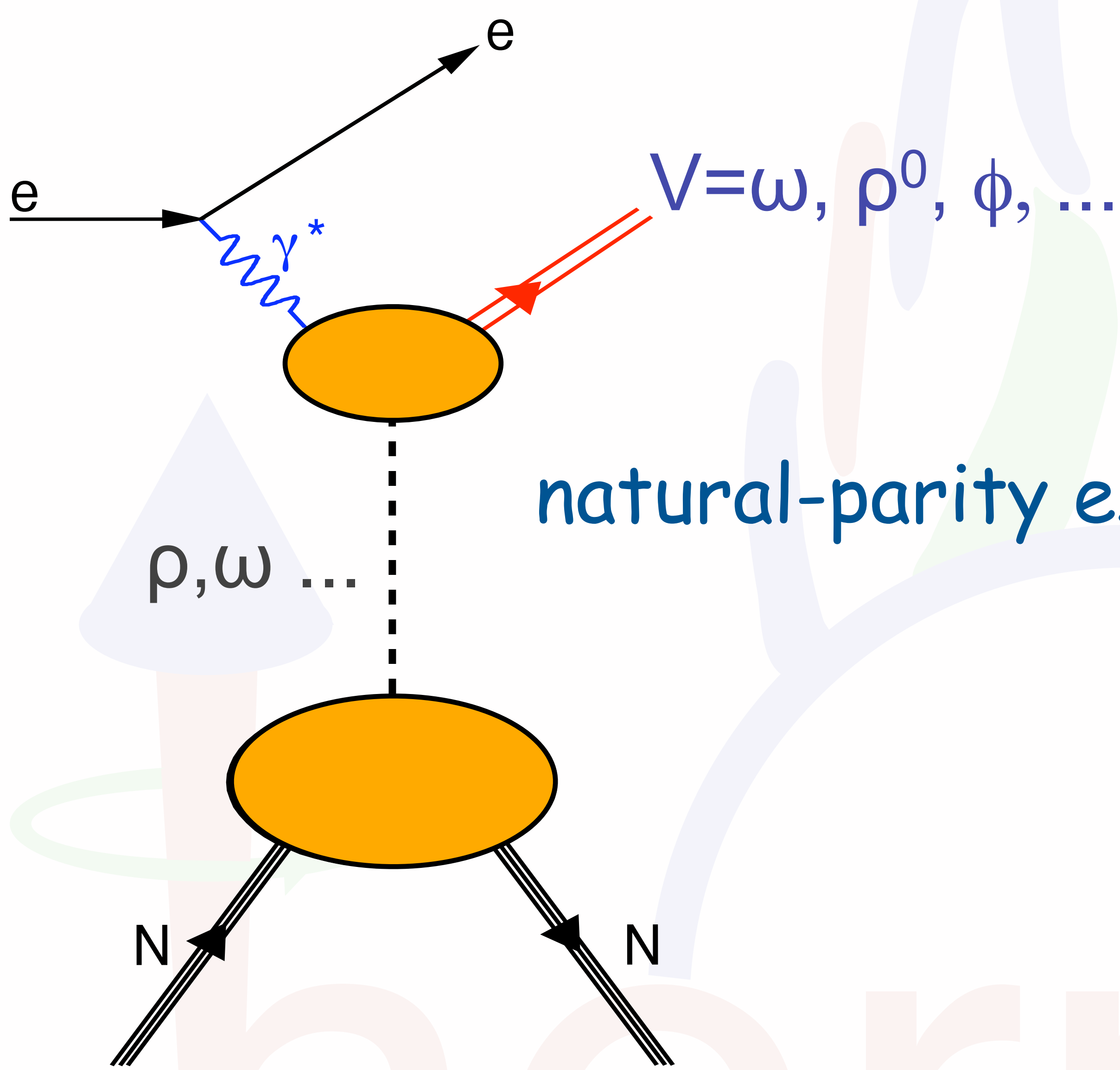
$$\begin{aligned}
\mathcal{W}^{L}(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}P_{\mathrm{beam}}\Bigg[& \sqrt{1-\epsilon^2}\big(\sqrt{2}\,\mathrm{Im}\{r^{3}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{3}_{1-1}\}\sin^2\Theta\sin 2\phi\big) \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos\Phi\big(\sqrt{2}\,\mathrm{Im}\{r^{7}_{10}\}\sin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

(angle definitions in backup)

vector-meson production

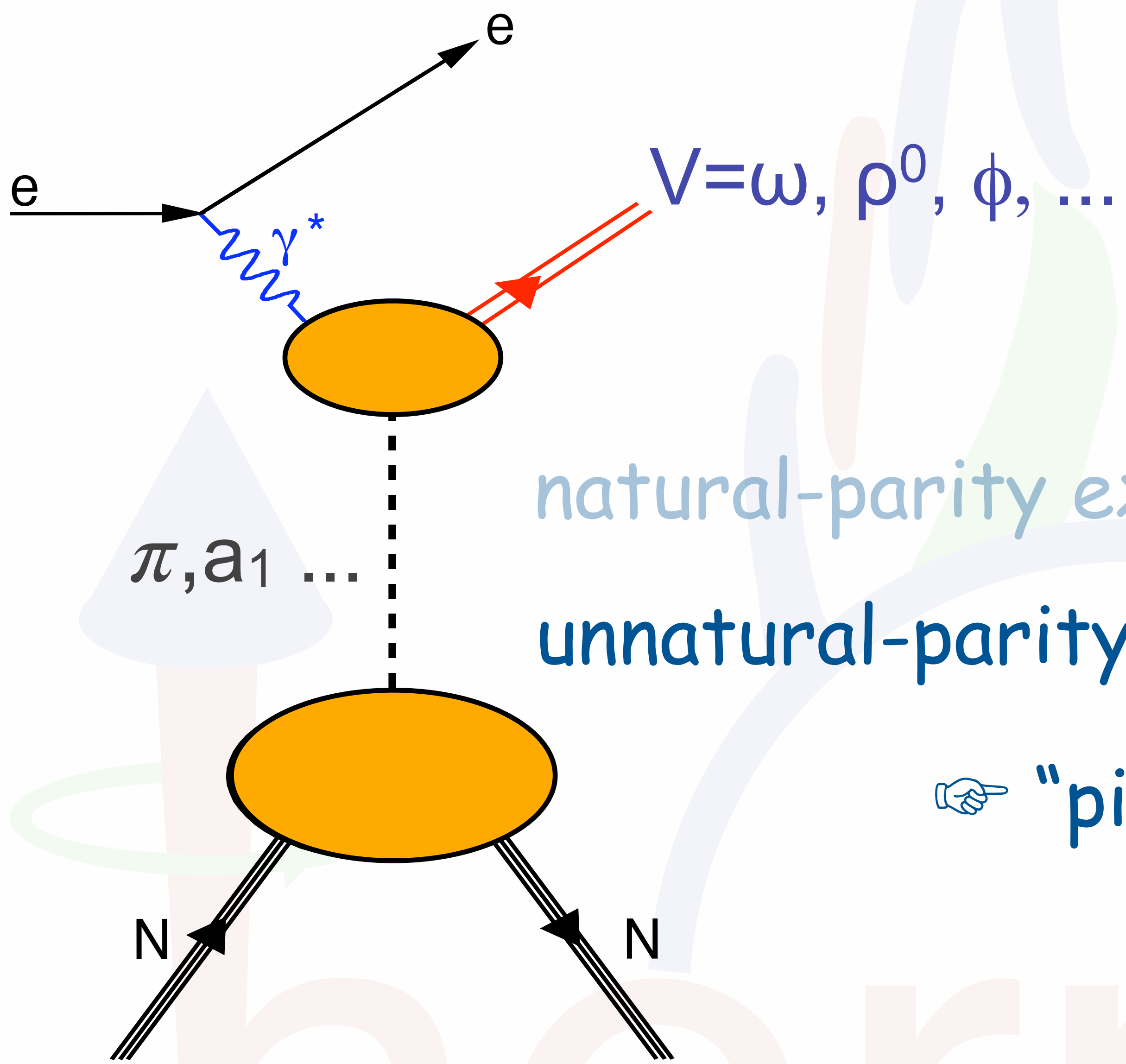


vector-meson production



natural-parity exchange $J^P = 0^+, 1^-, \ldots$ GPDs H&E

vector-meson production

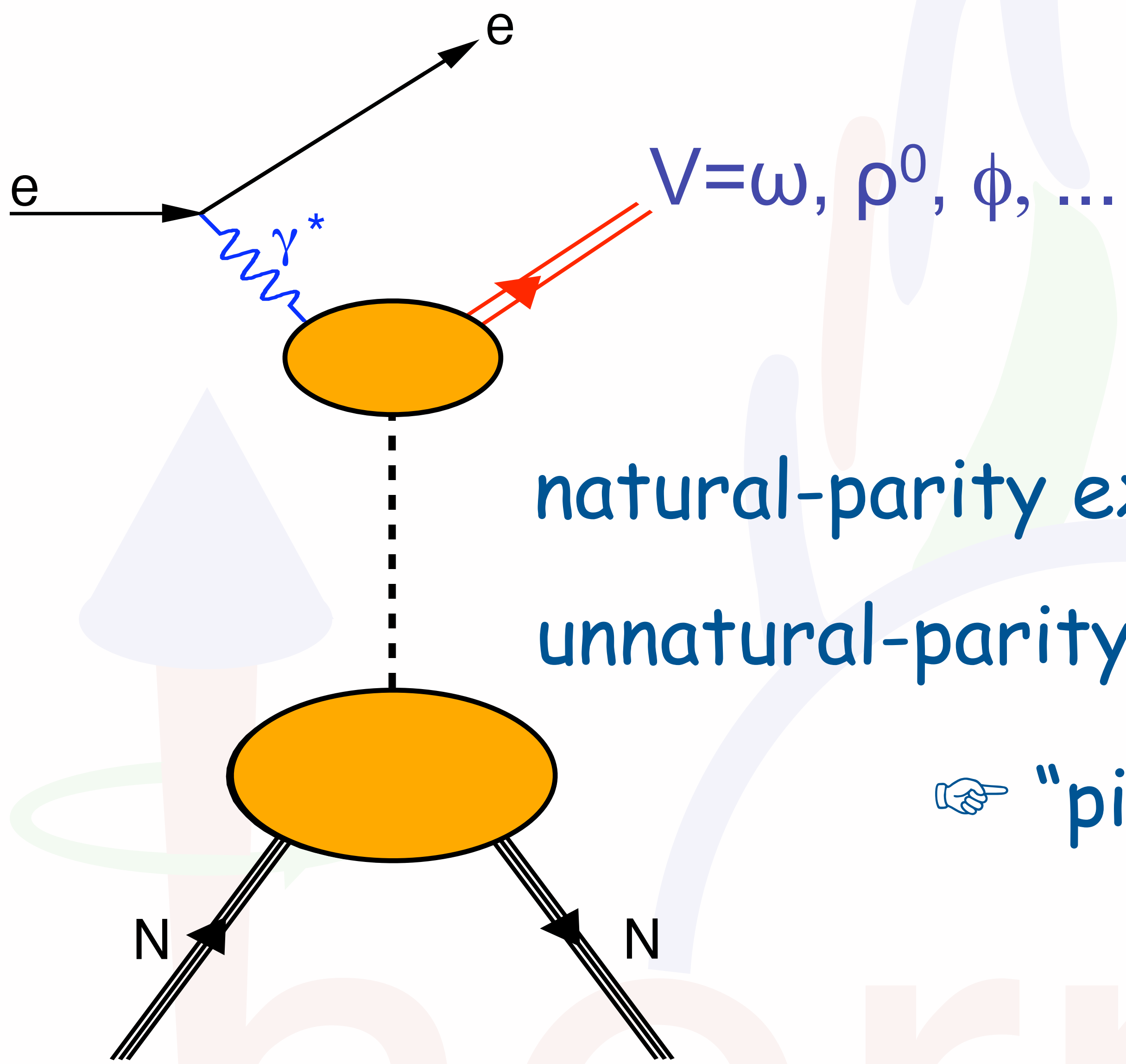


natural-parity exchange $J^P = 0^+, 1^-, \ldots$ GPDs H&E

unnatural-parity exchange $J^P = 0^-, 1^+, \ldots$ GPDs $\tilde{H}$&$\tilde{E}$

☞ “pion-pole contribution”

vector-meson production



natural-parity exchange $J^P = 0^+, 1^-, \ldots$ GPDs H&E

unnatural-parity exchange $J^P = 0^-, 1^+, \ldots$ GPDs $\tilde{H}$&$\tilde{E}$

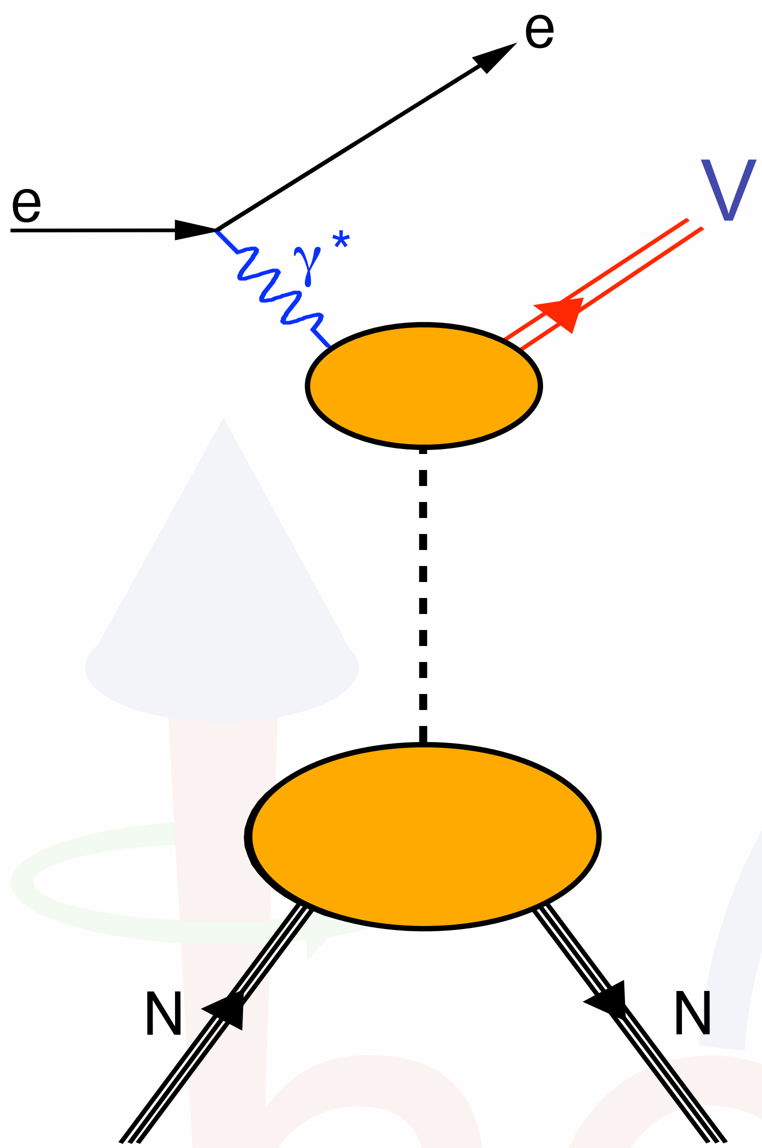
☞ "pion-pole contribution"

H: nucleon-helicity non-flip amplitudes

E: nucleon-helicity flip amplitudes

-> transverse target polarization

vector-meson production



V=ω, ρ^0, φ, ...

$$\gamma^*(\lambda_\gamma) + N(\lambda_N) \to V(\lambda_V) + N'(\Lambda'_N)$$

λ_i ... helicities

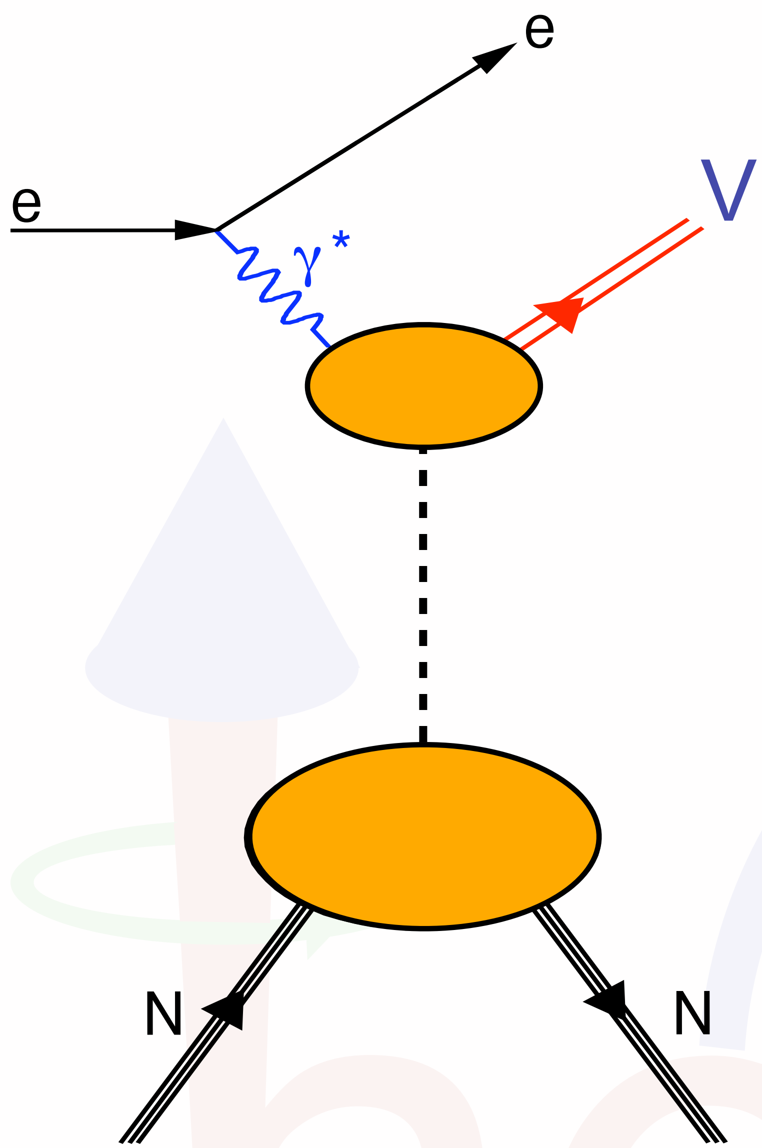
expressed in terms of helicity amplitudes:

$$F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$$

natural unnatural
parity exchange
(NPE) (UPE)

in total 10+8 complex helicity amplitudes

vector-meson production



$$\gamma^*(\lambda_\gamma) + N(\lambda_N) \to V(\lambda_V) + N'(\Lambda'_N)$$

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expressed in terms of helicity amplitudes:

$$F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$$

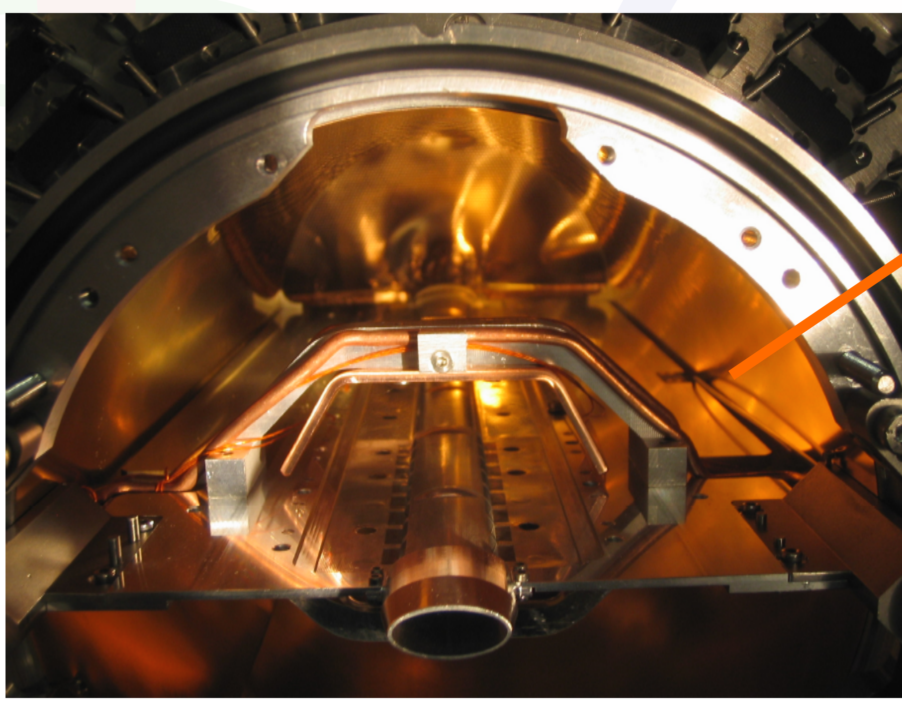
SDMEs: bilinear in helicity amplitudes

helicity-amplitude ratios: e.g., normalized to dominant $T_{0,\frac{1}{2},0,\frac{1}{2}}$

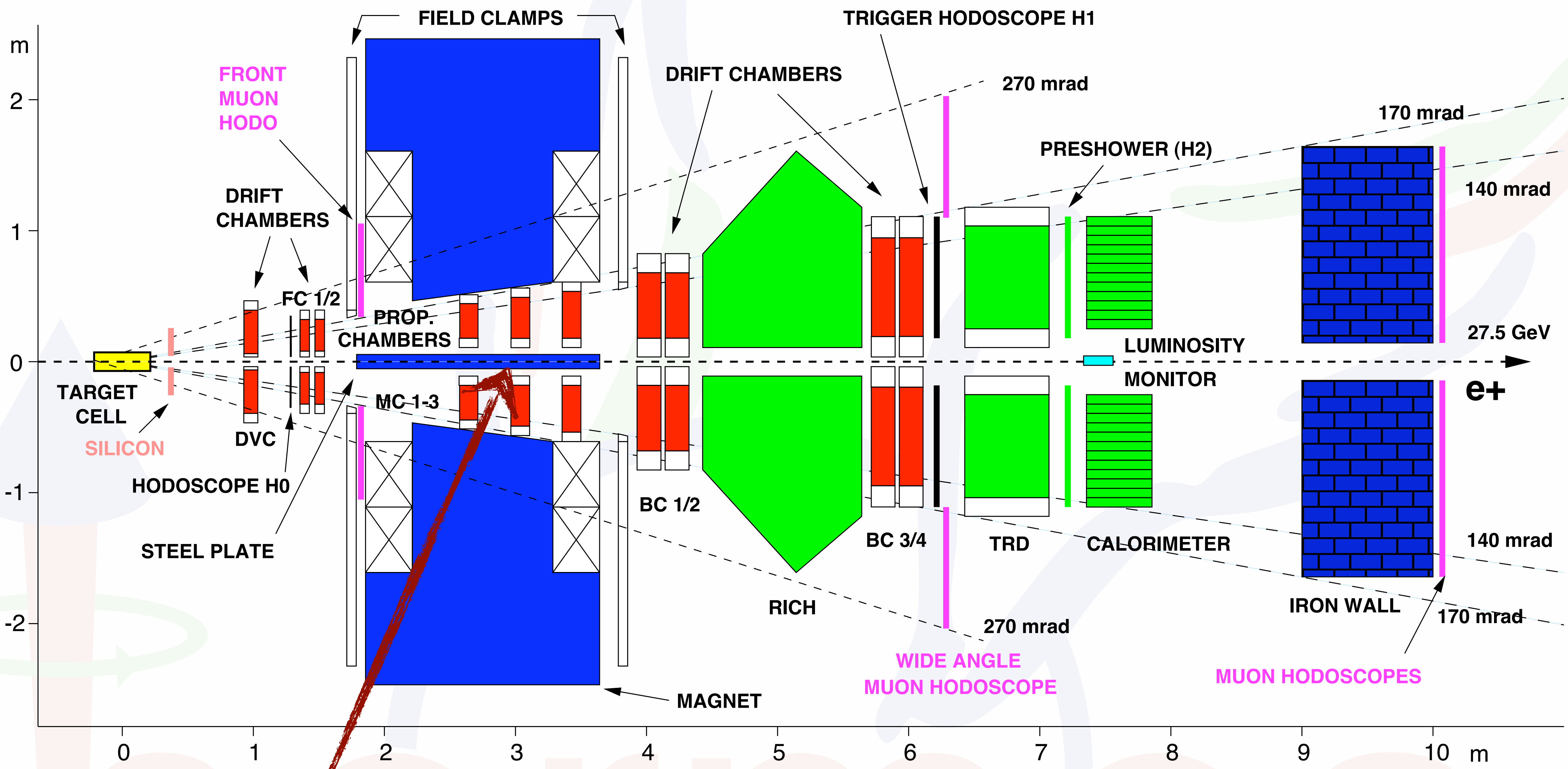
The HERMES experiment (1995-2007)

novel (pure) gas target:

- internal to HERA 27.6 GeV $e^{\pm}$ ring
- unpolarized (^{1}H … Xe)
- longitudinally polarized: ^{1}H, ^{2}H, ^{3}He
- transversely polarized: ^{1}H

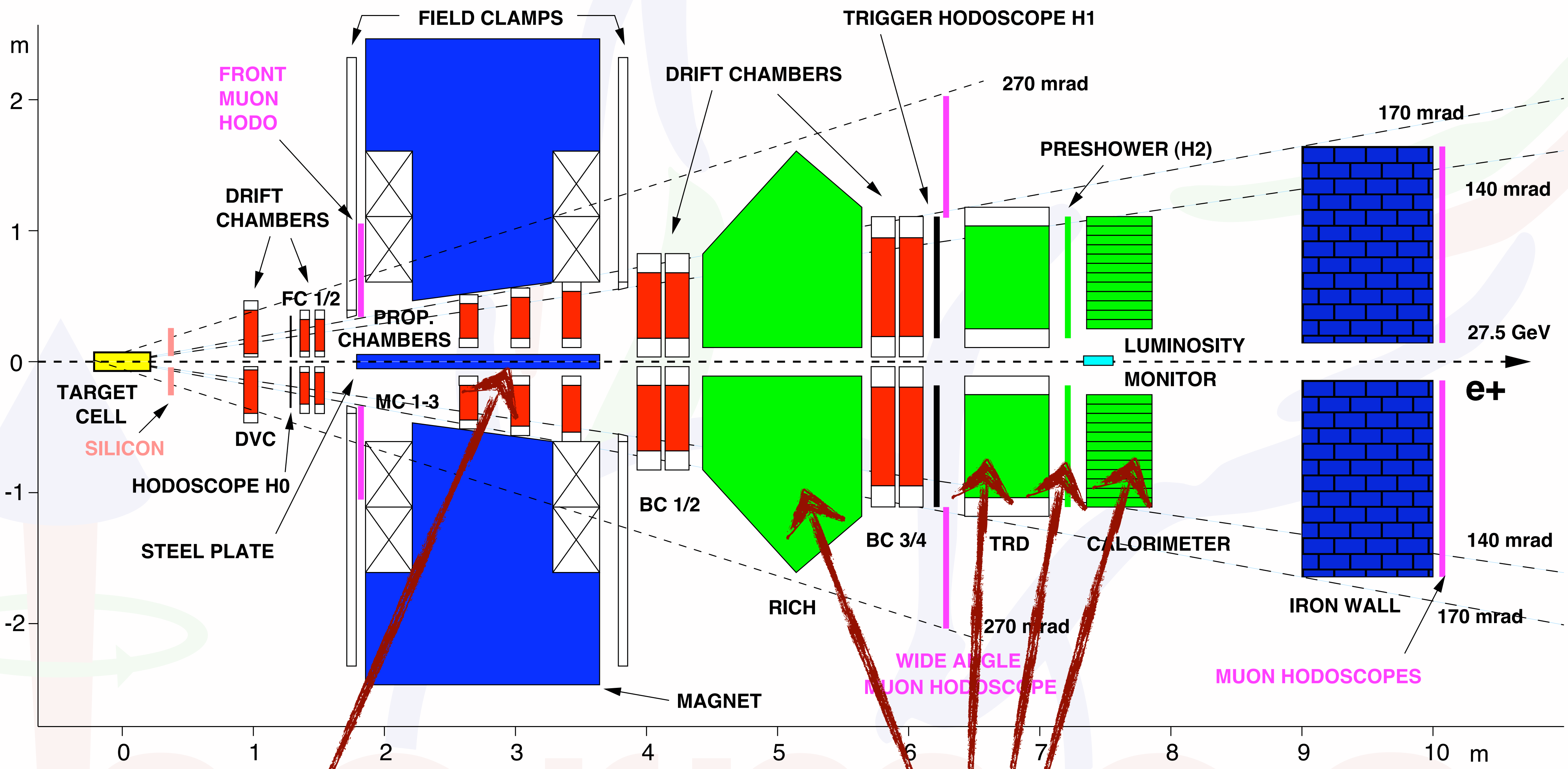


HERMES (1998-2005) schematically



two (mirror-symmetric) halves

HERMES (1998-2005) schematically



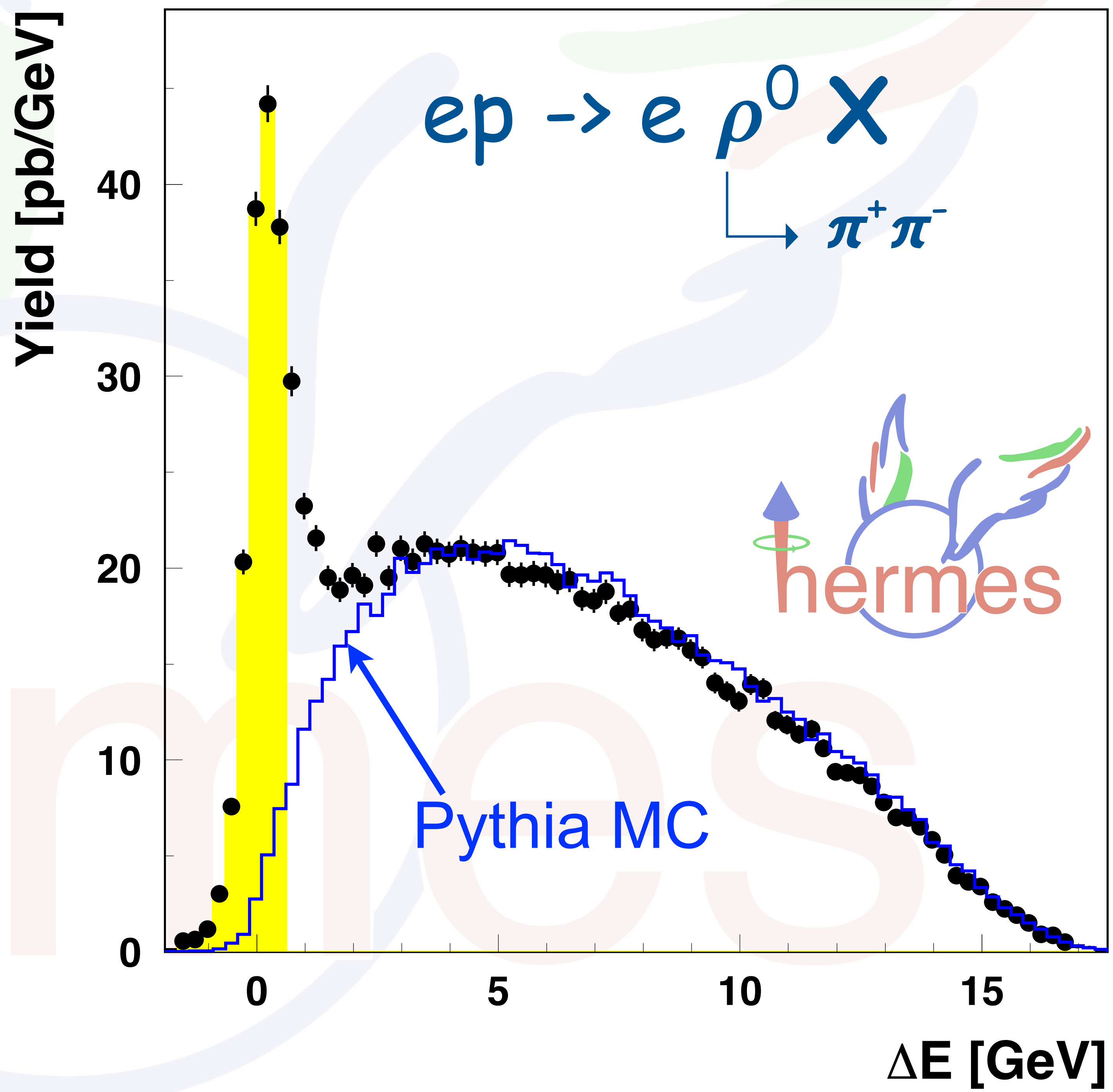
two (mirror-symmetric) halves

Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton discrimination 2GeV<p<15GeV

exclusivity: missing-energy technique

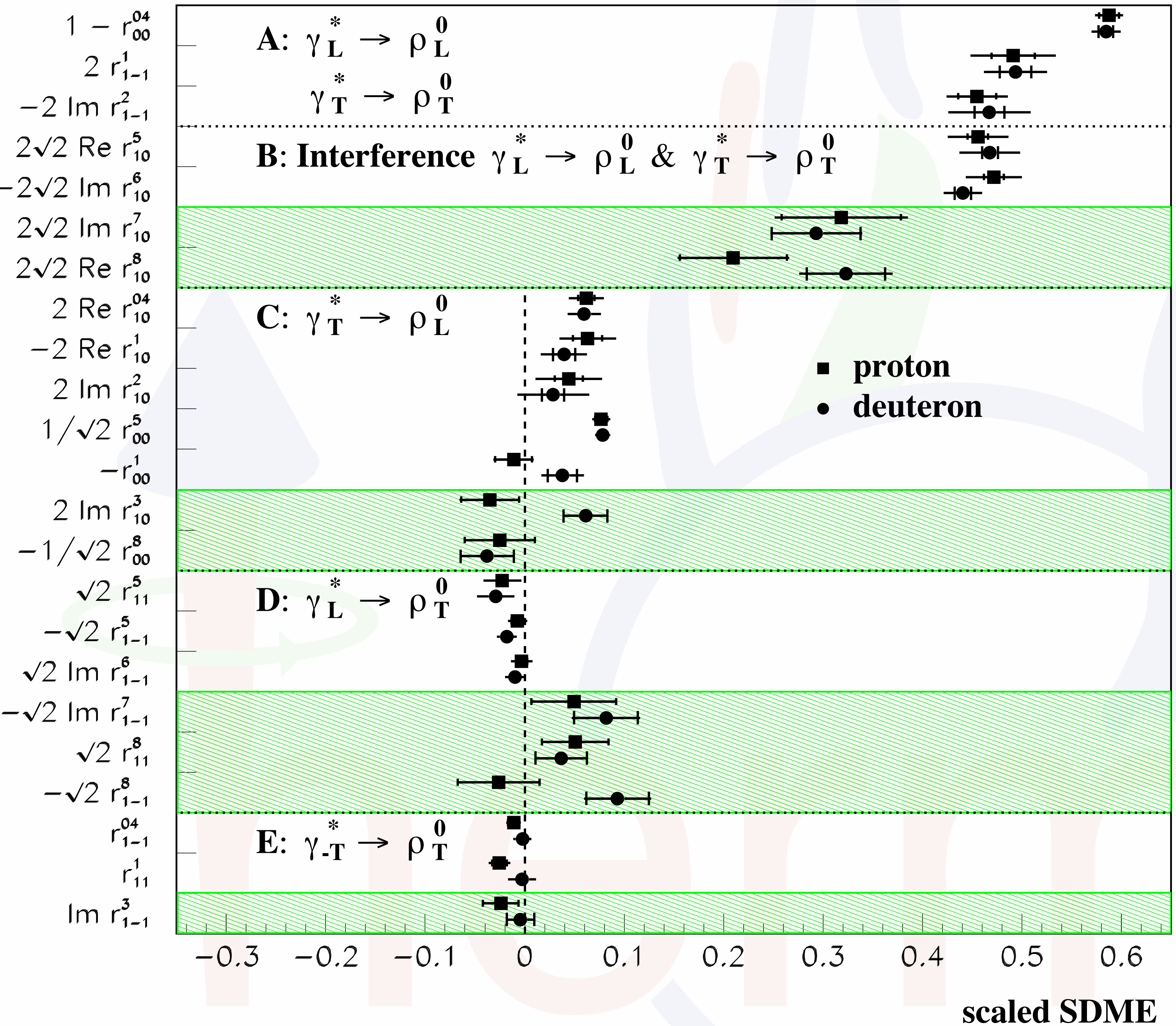
- recoiling proton not registered
- M_X ... mass of recoiling system
- missing energy vanishes when X=proton
- fraction of BG estimate based on PYTHIA MC tuned to HERMES
  ☞ subtracted
- 7% to 23% for increasing $t' = -(t-t_{min})$ in case of ρ^0

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



ρ^0 SDMEs from HERMES

[A. Airapetian et al., EPJ C62 (2009) 659]



target-polarization independent SDMEs

ρ^0 SDMEs from HERMES

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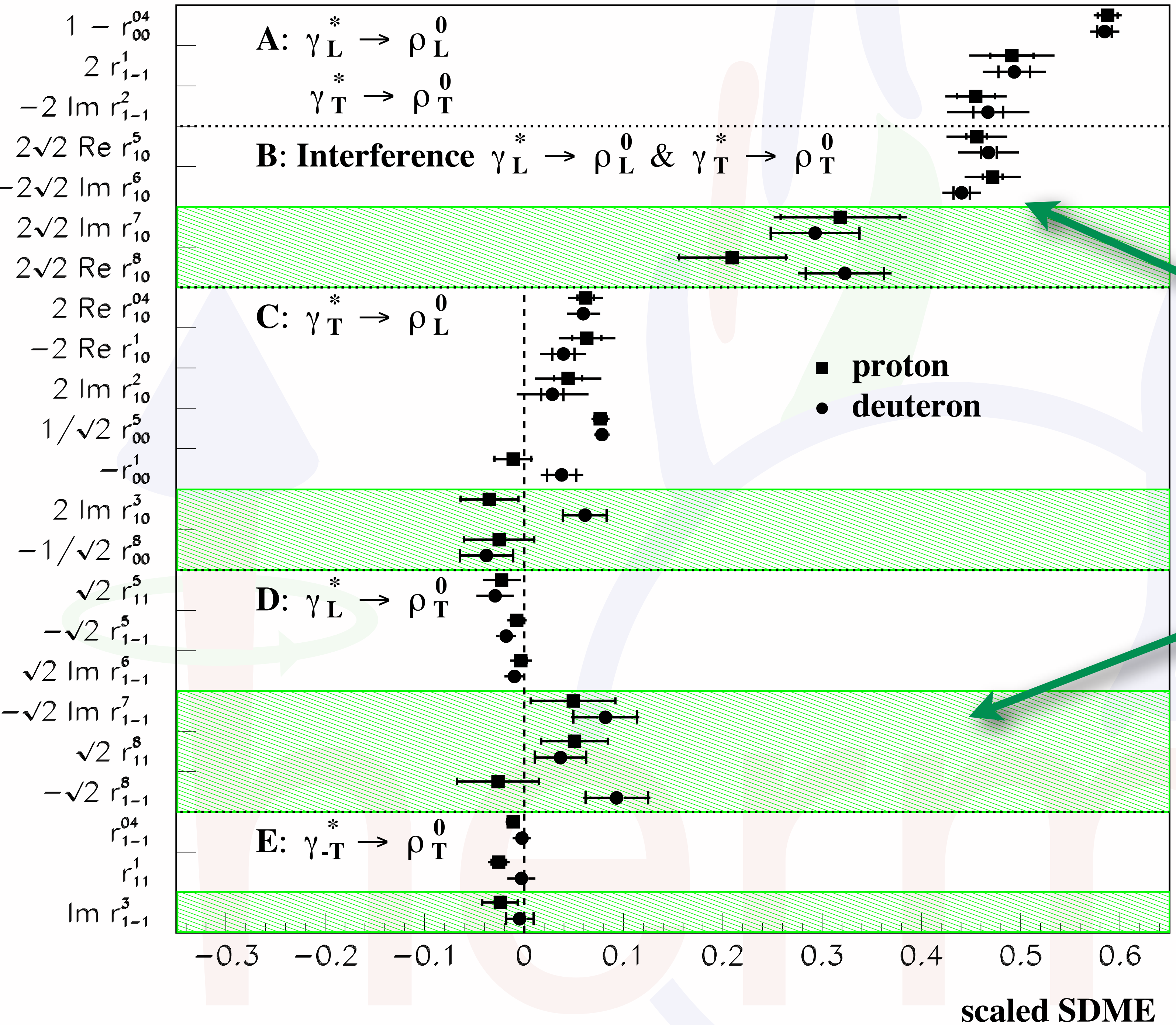

helicity non-flip much larger than helicity-flip and double helicity-flip

target-polarization independent SDMEs

ρ^0 SDMEs from HERMES

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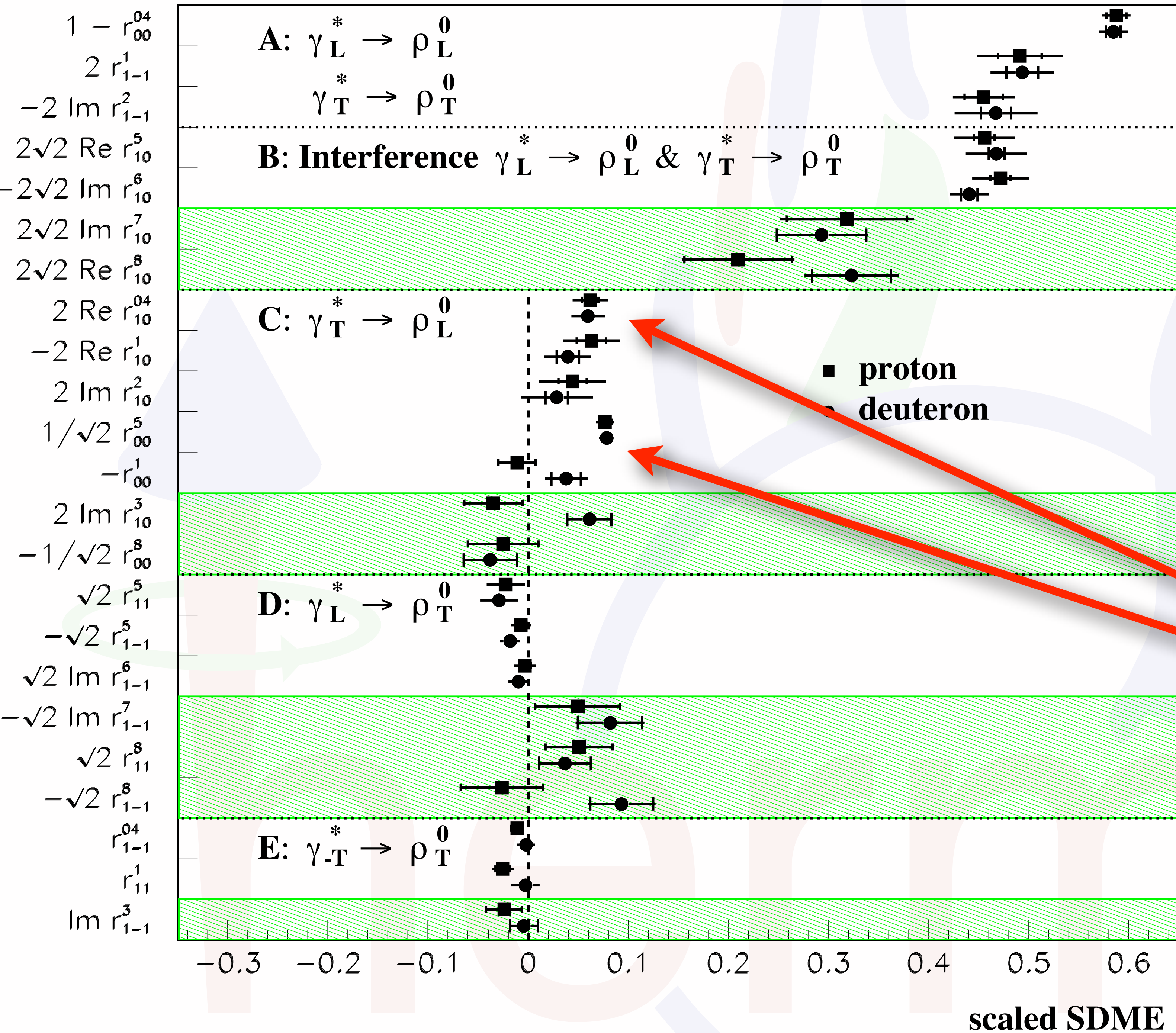

clear breaking of s-channel helicity conservation

target-polarization independent SDMEs

ρ^0 SDMEs from HERMES

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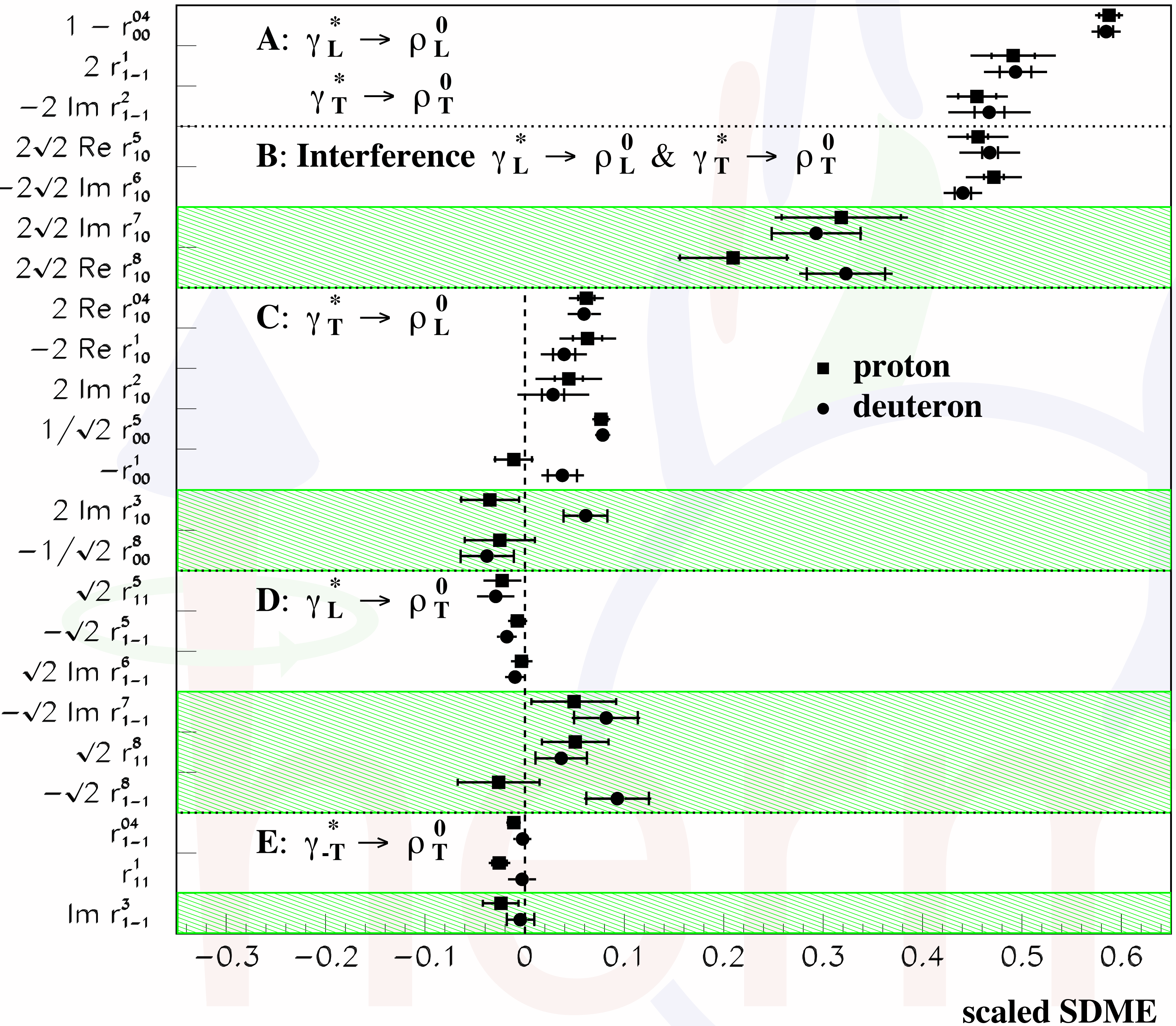
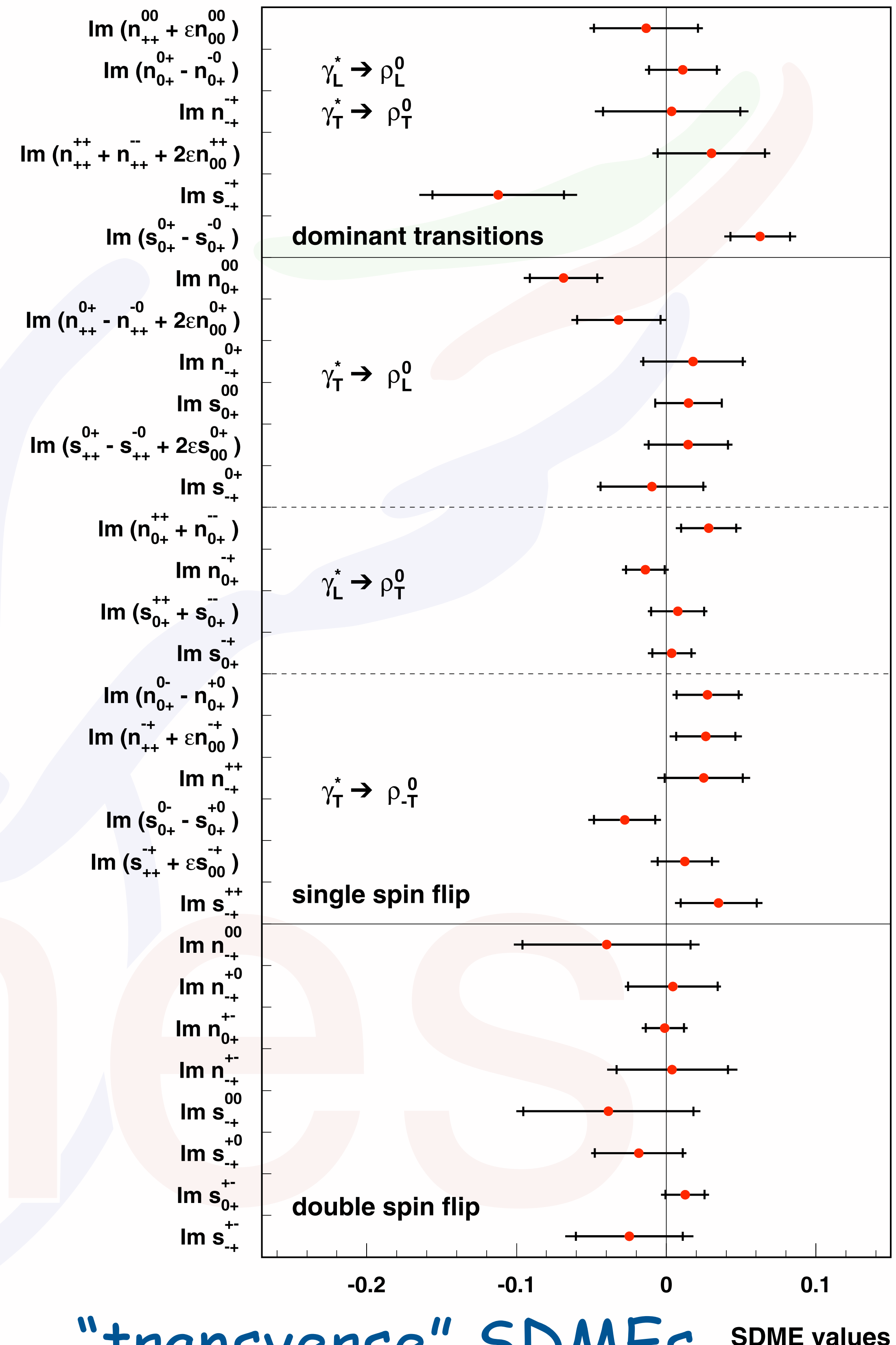


target-polarization independent SDMEs

[PLB 679 (2009) 100]



"transverse" SDMEs

ρ^0 SDMEs from HERMES

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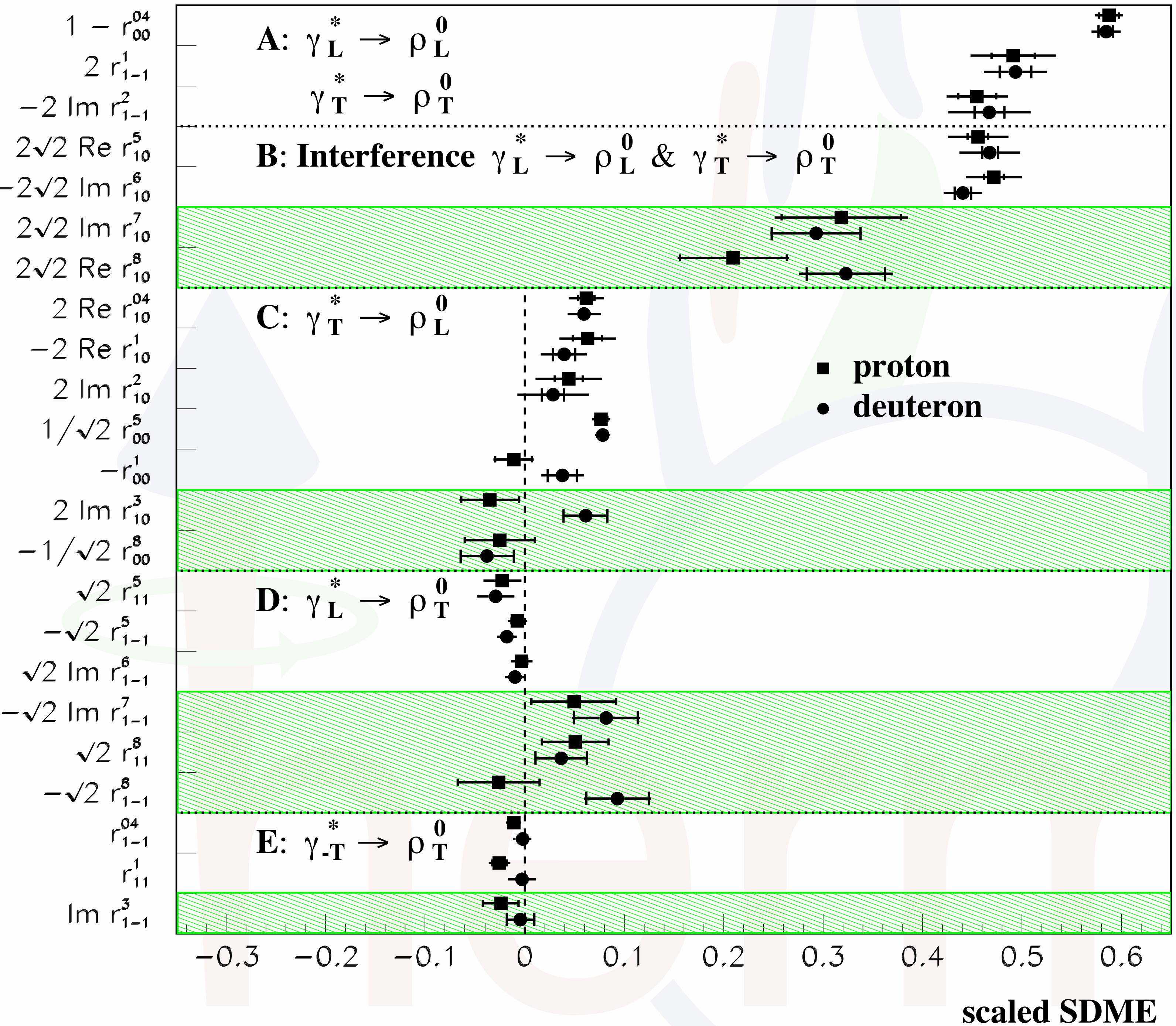

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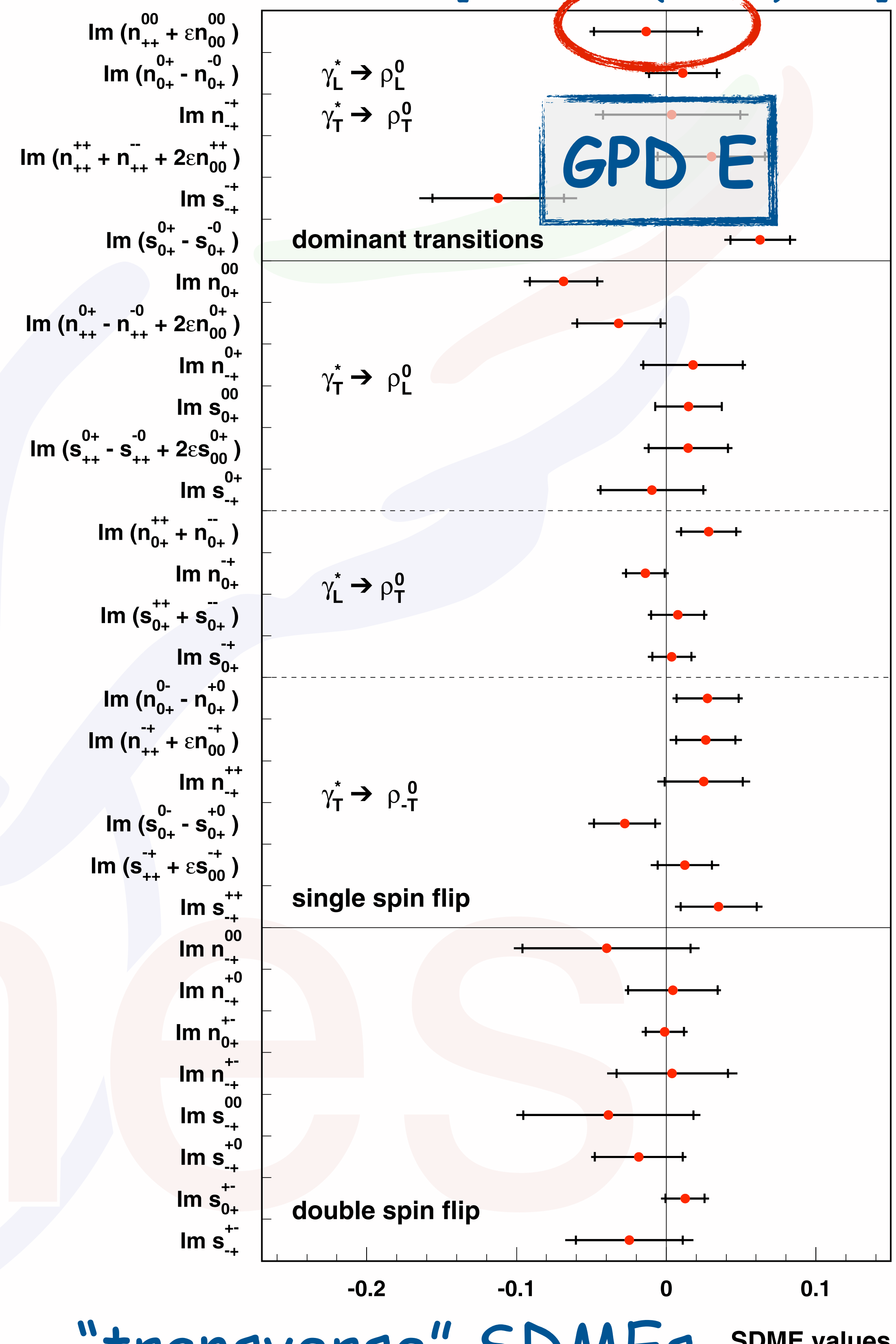

"transverse" SDMEs

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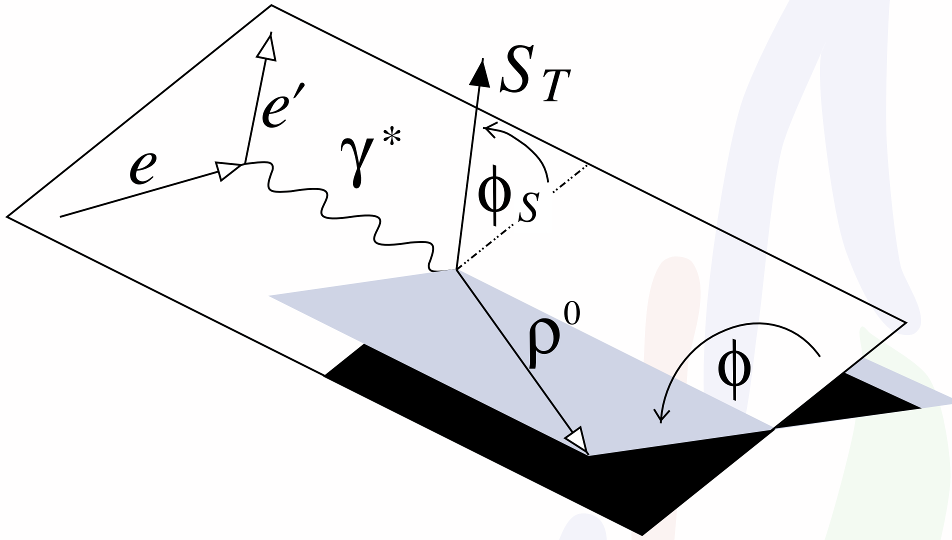
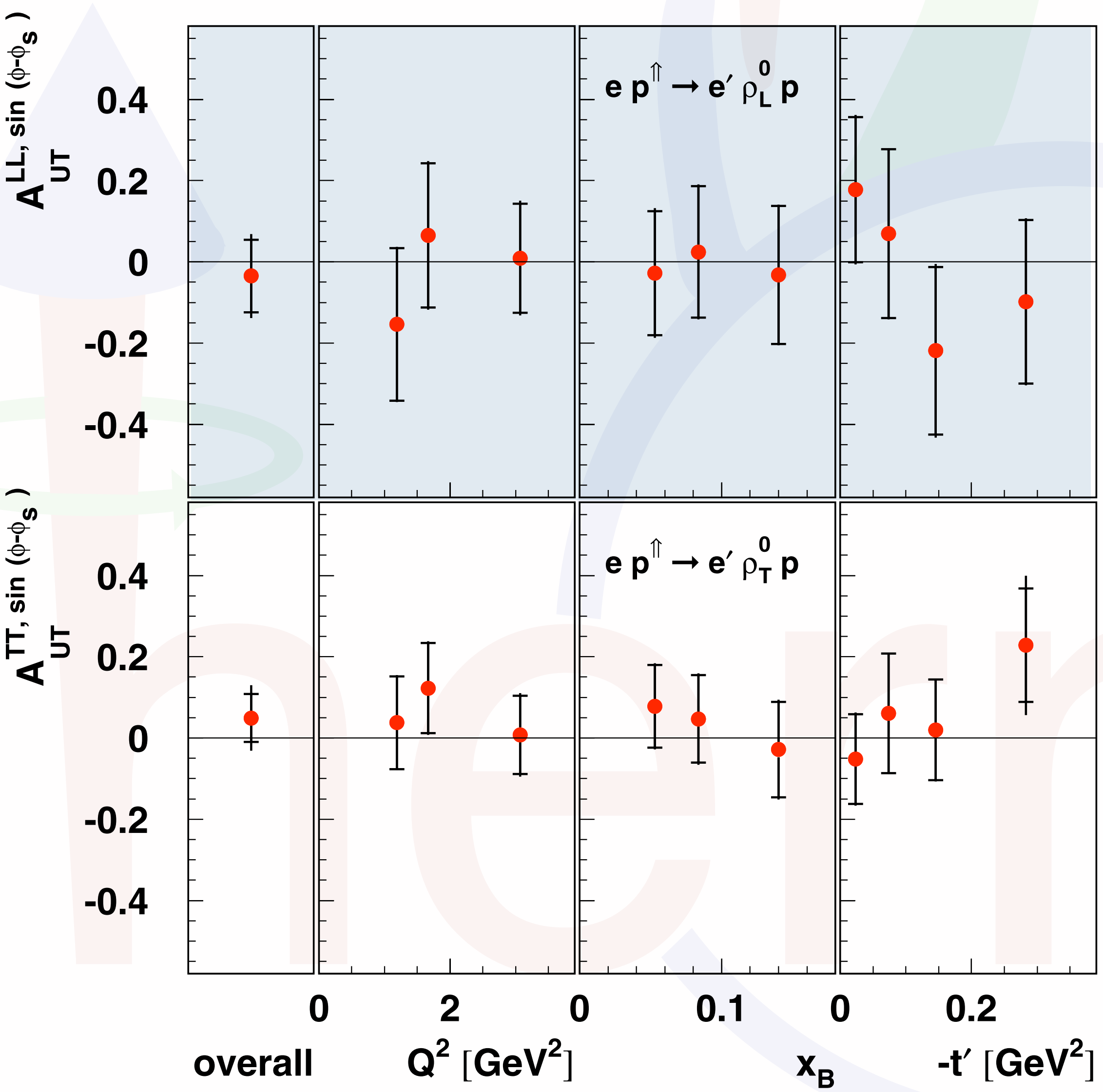


longitudinal ρ^0

transverse ρ^0



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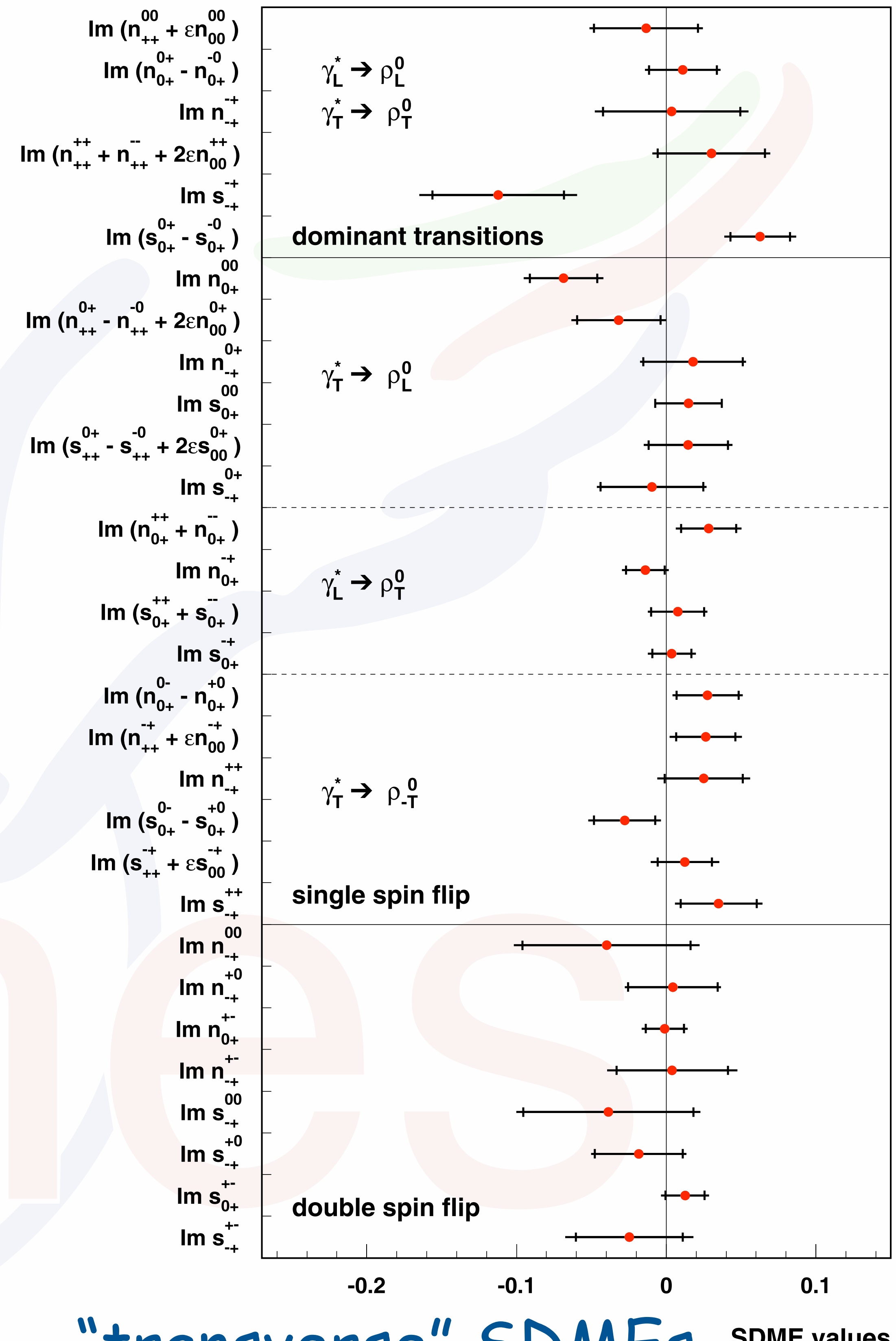
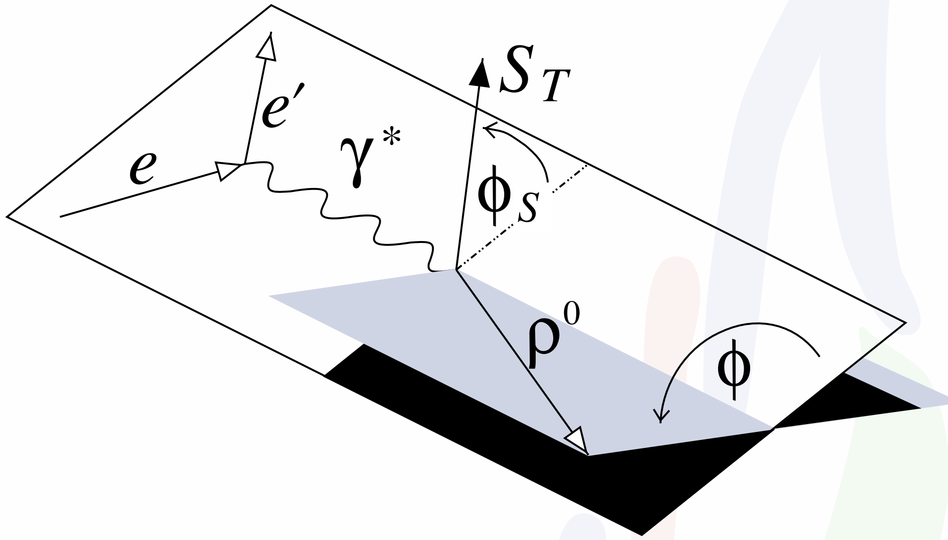


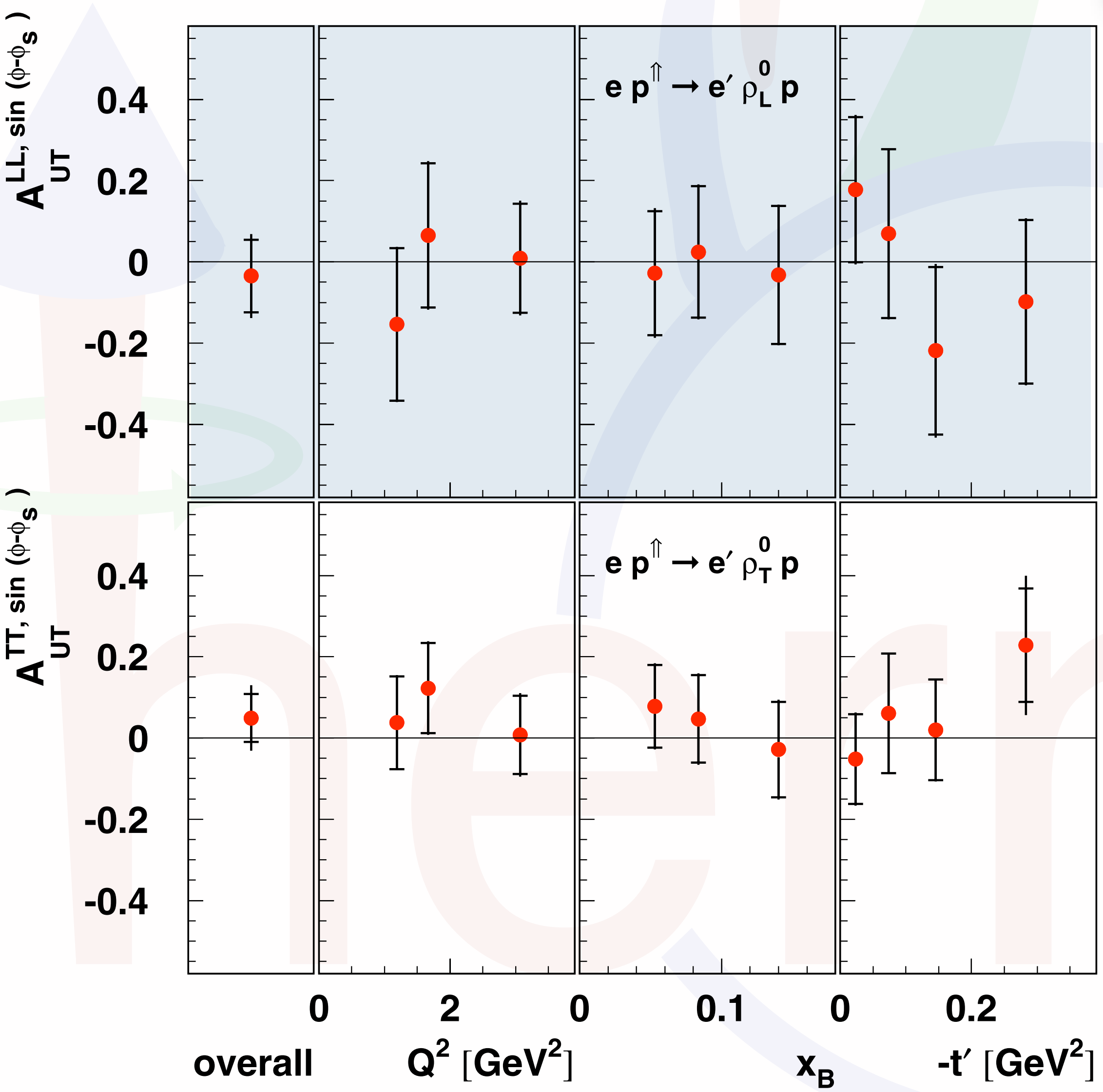
"transverse" SDMEs

ρ^0 SDMEs from HERMES



longitudinal ρ^0

transverse ρ^0



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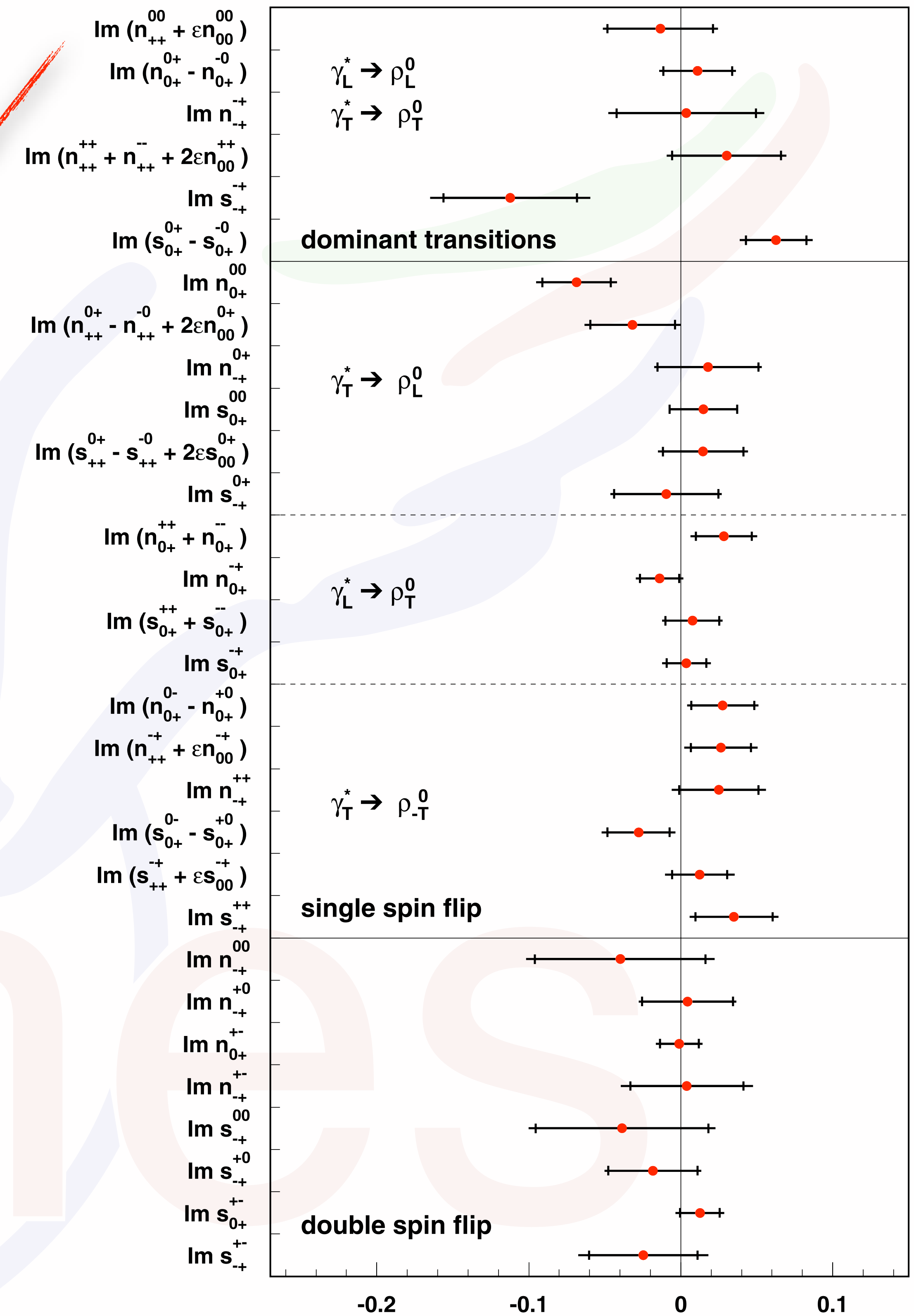
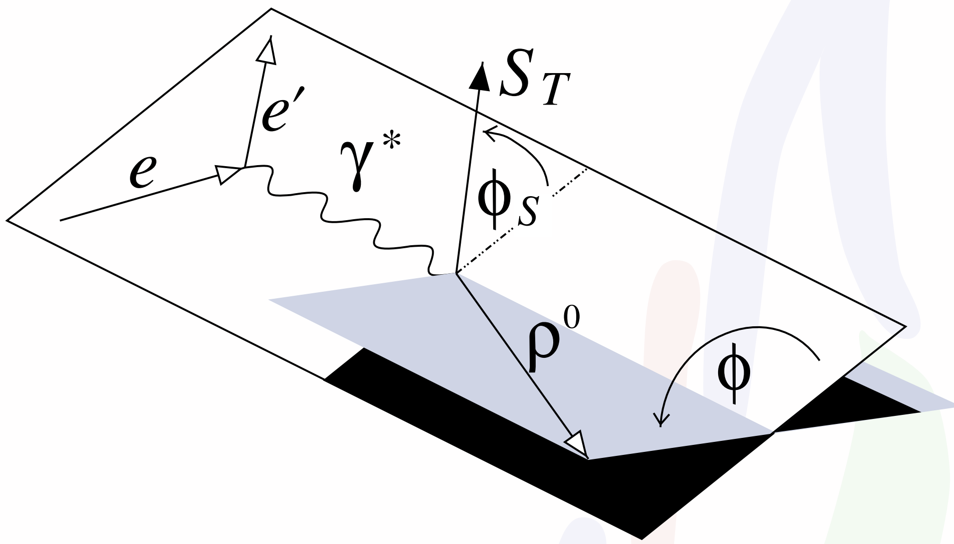
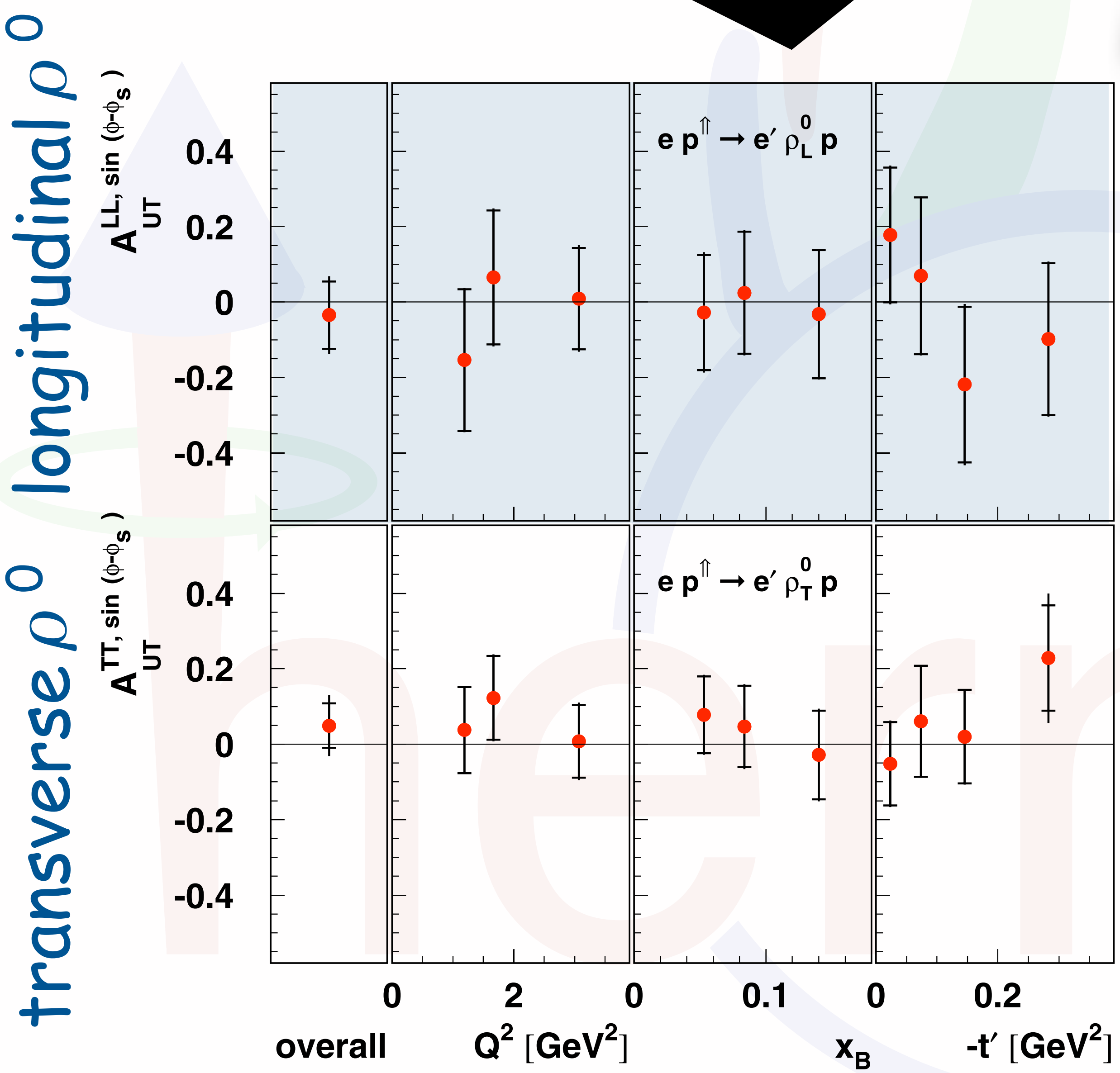


"transverse" SDMEs

ρ^0 SDMEs from HERMES





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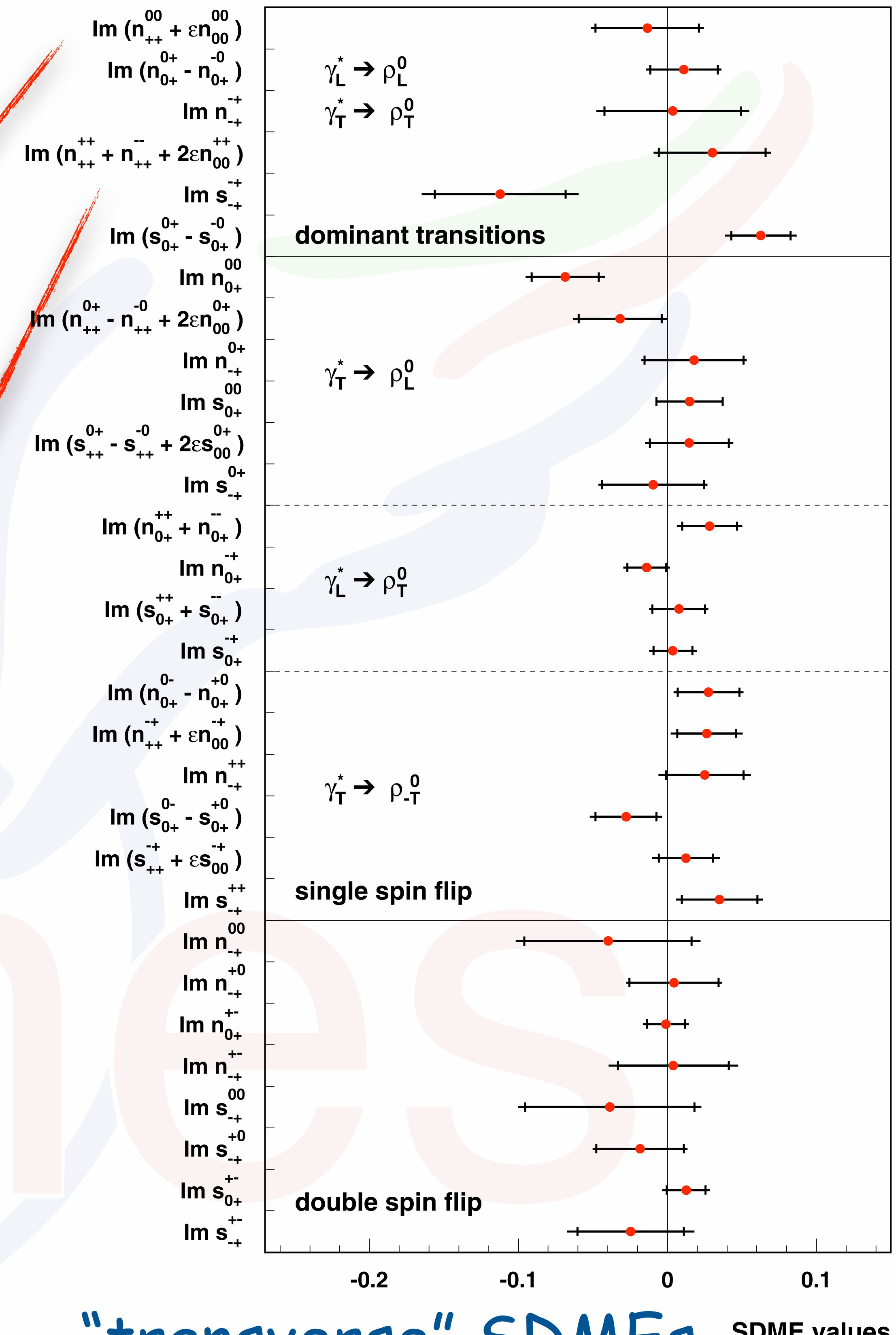
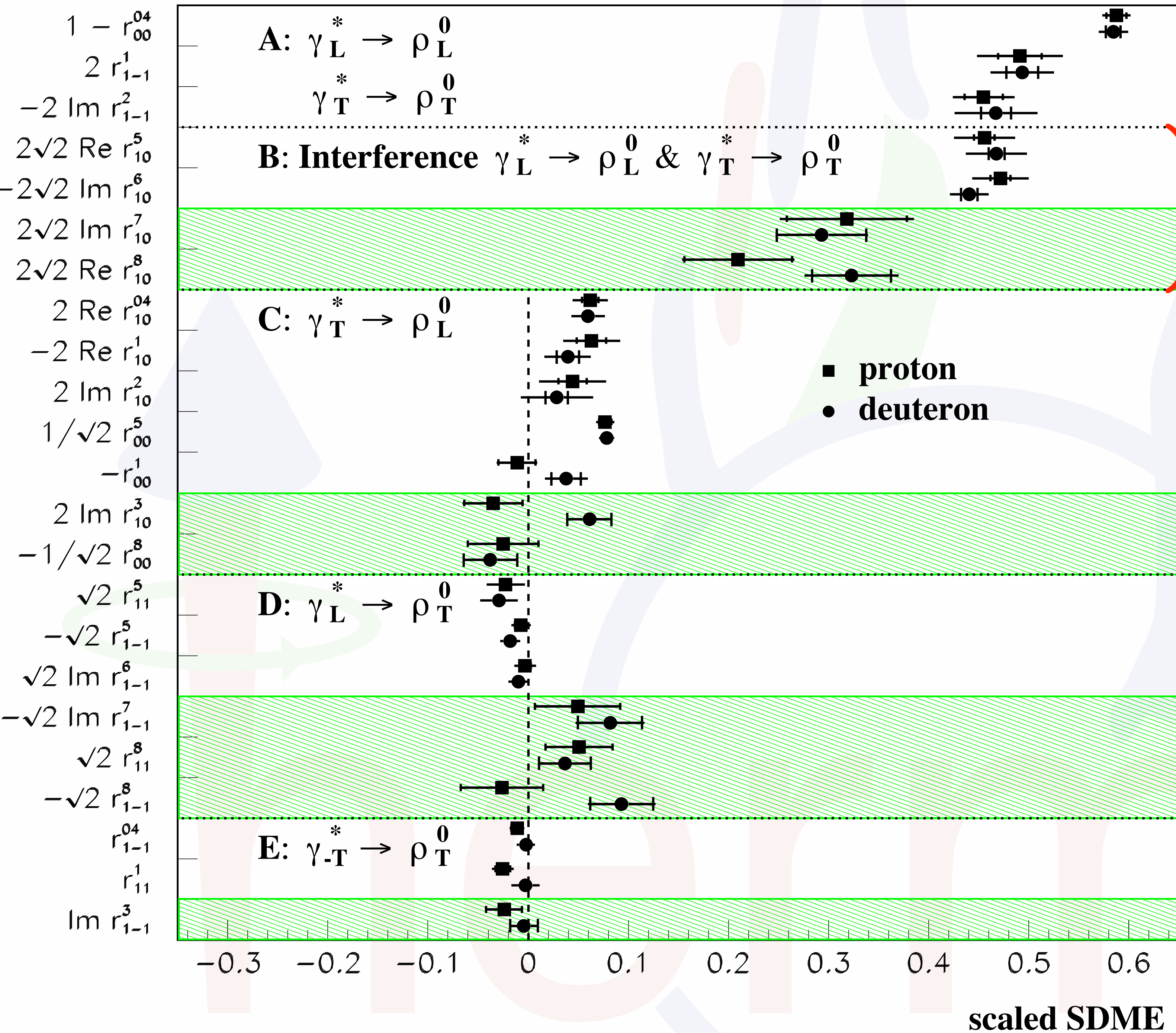


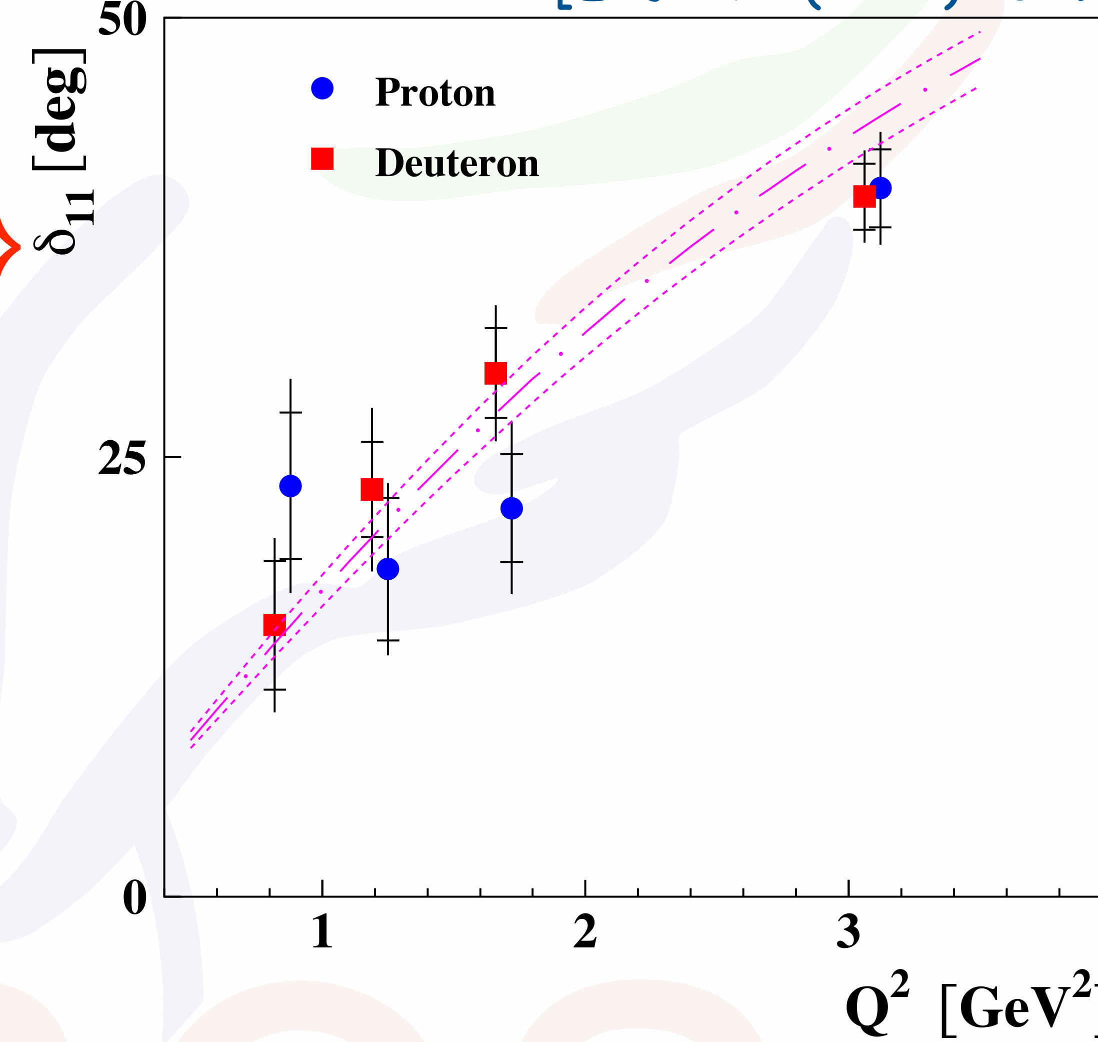
"transverse" SDMEs

ρ^0 SDMEs from HERMES: challenges

[A. Airapetian et al., EPJ C62 (2009) 659]



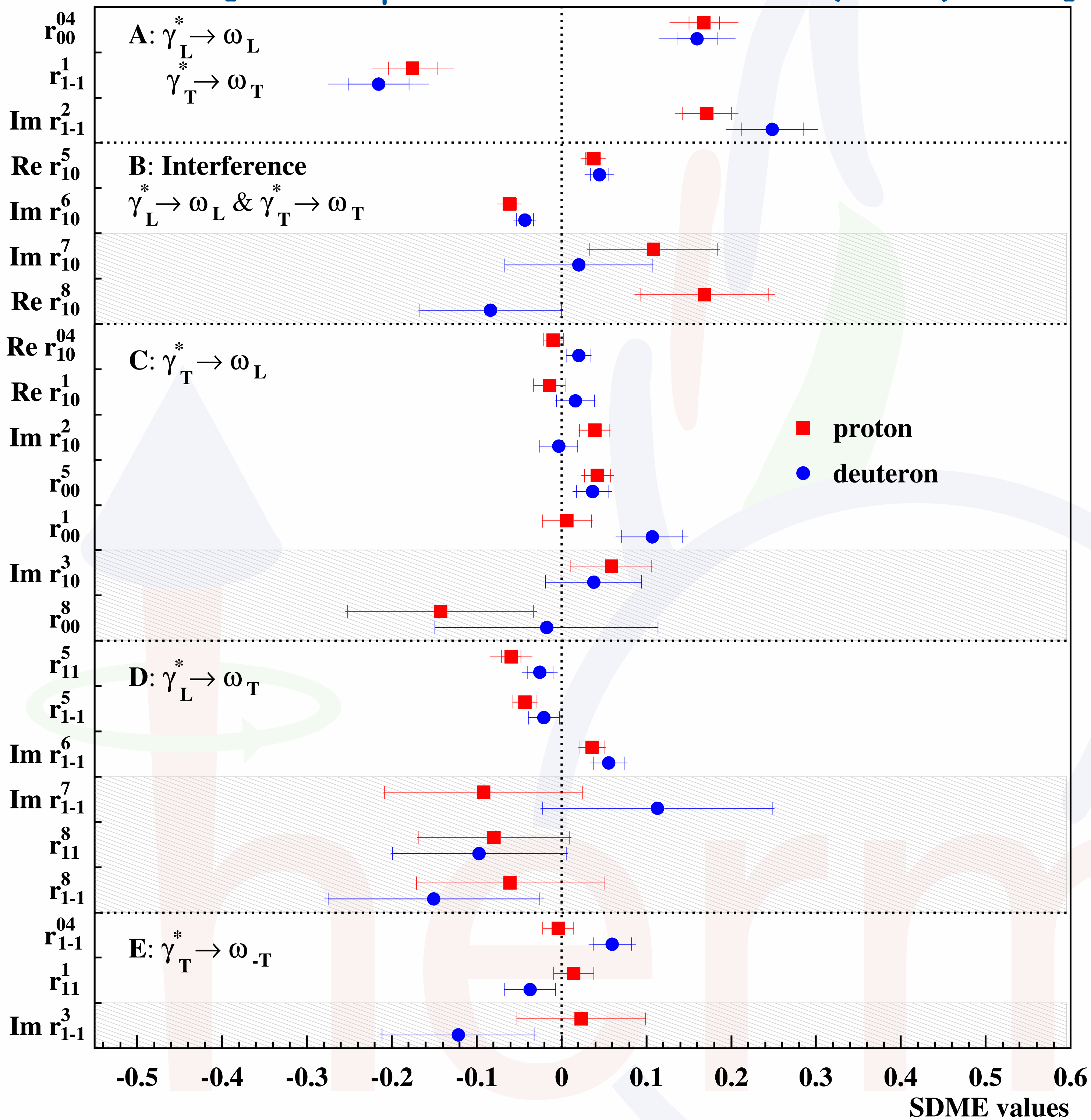
[EPJ C71 (2011) 1609]



Extraction of SDMEs and helicity amplitude ratios at HERMES for ρ mesons challenges GPD-based calculations (giving small values)

… ω production

[A. Airapetian et al., EPJ C74 (2014) 3110]



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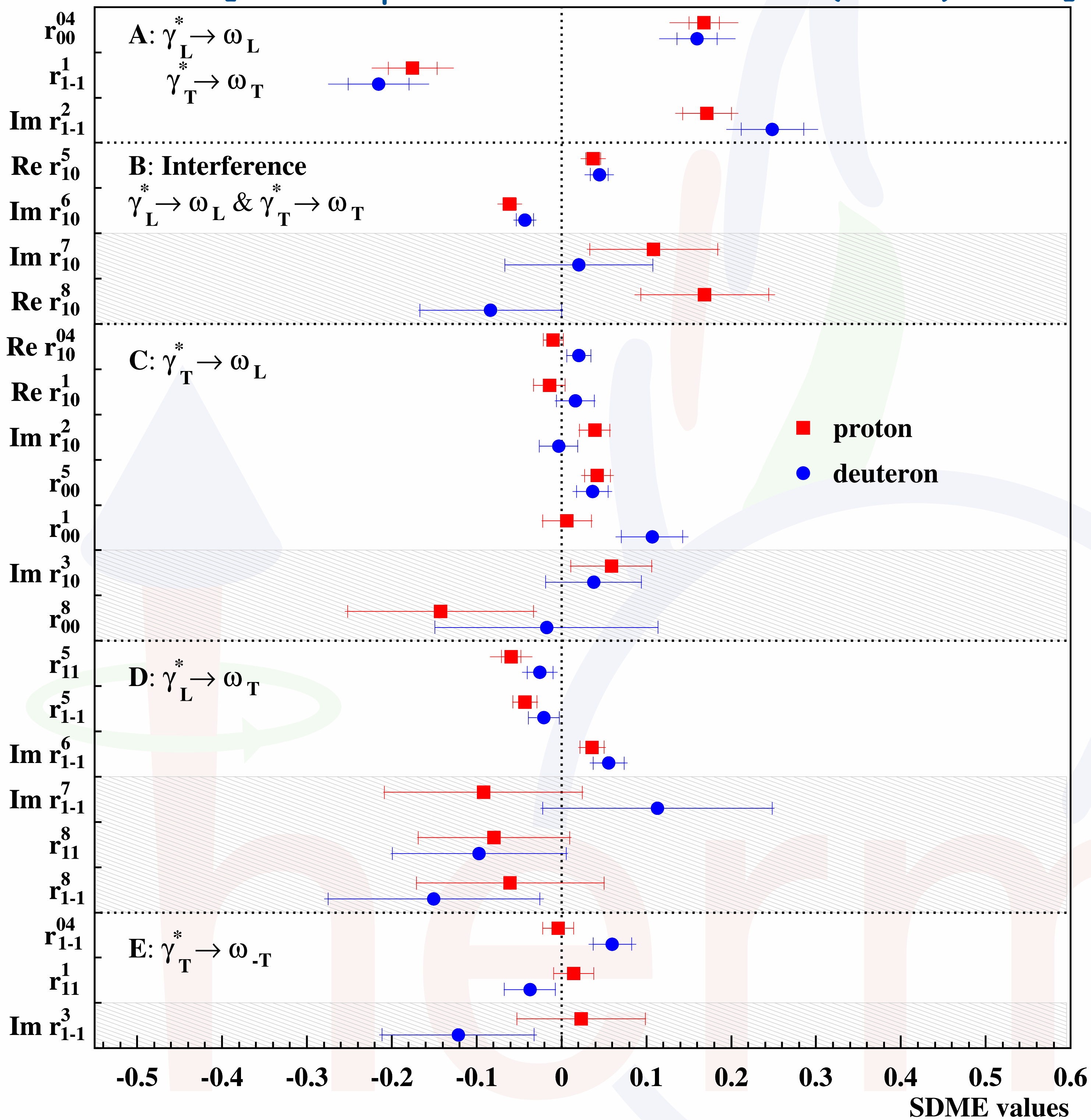
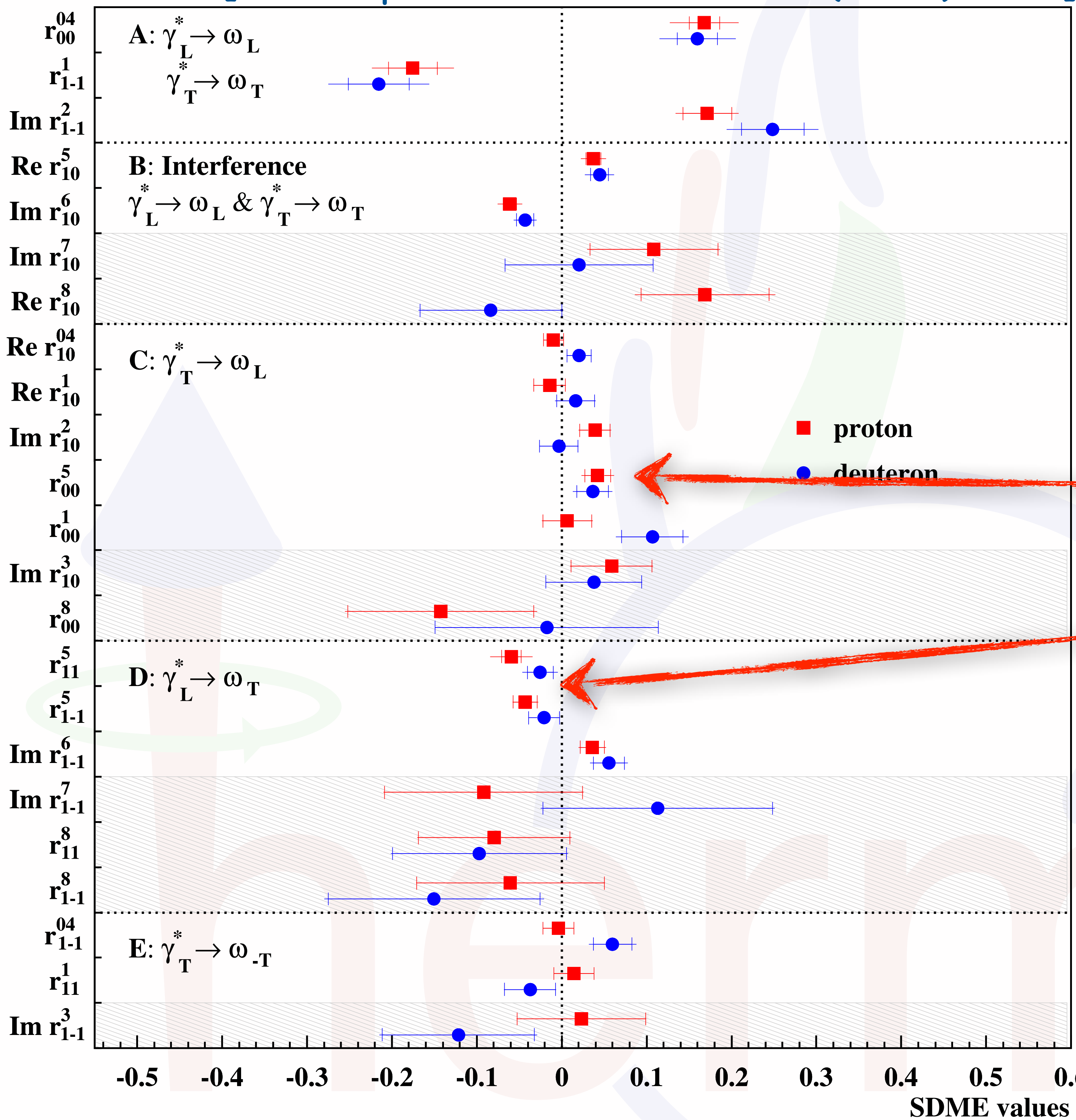


- helicity-conserving SDMEs dominate

… ω production

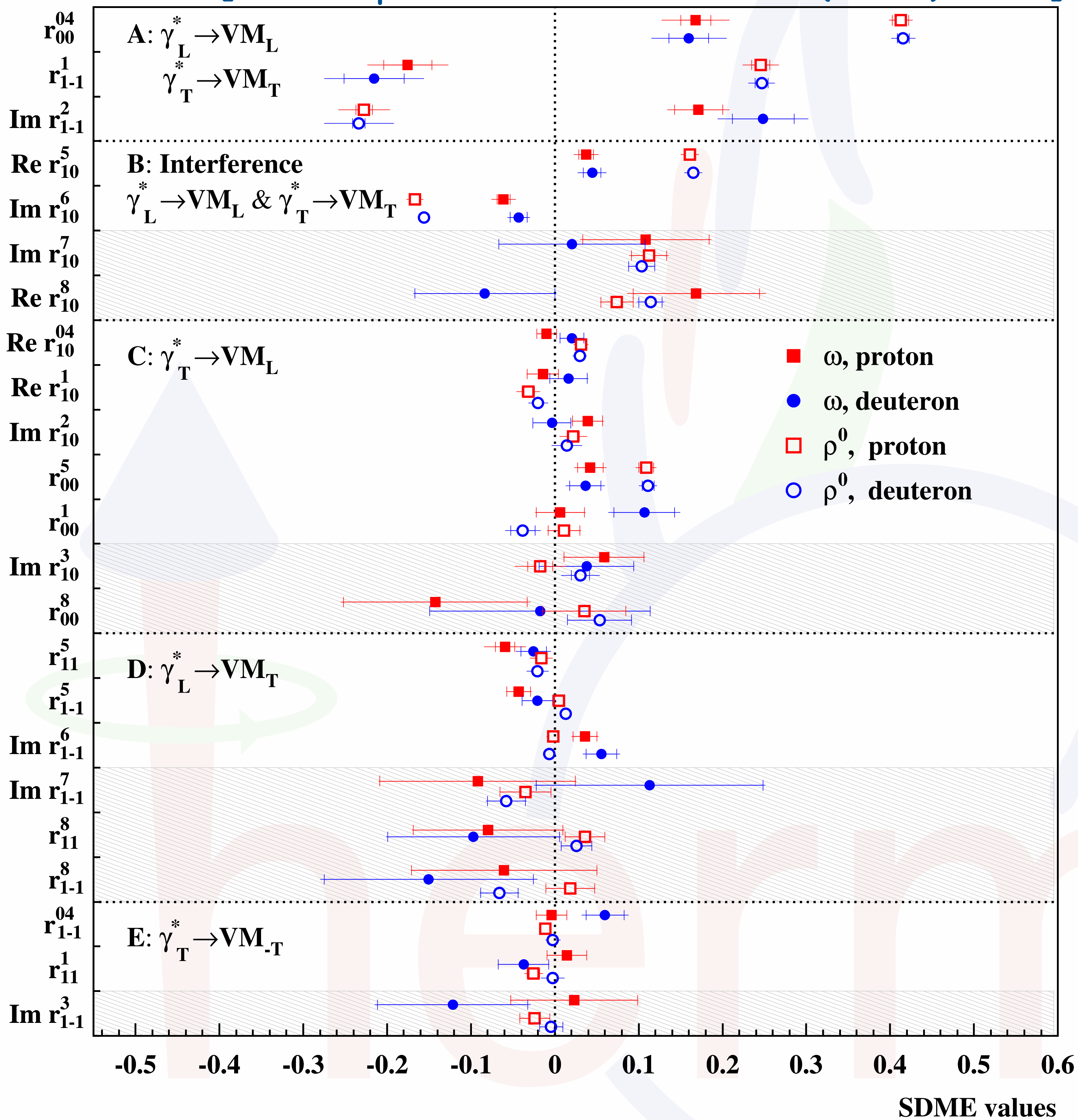
[A. Airapetian et al., EPJ C74 (2014) 3110]



- helicity-conserving SDMEs dominate
- hardly any violation of SCHC, except maybe for
  - r^5_{00}
  - $r^5_{11} + r^5_{1\text{-}1} - \Im r^6_{1\text{-}1}$

… ω production

[A. Airapetian et al., EPJ C74 (2014) 3110]



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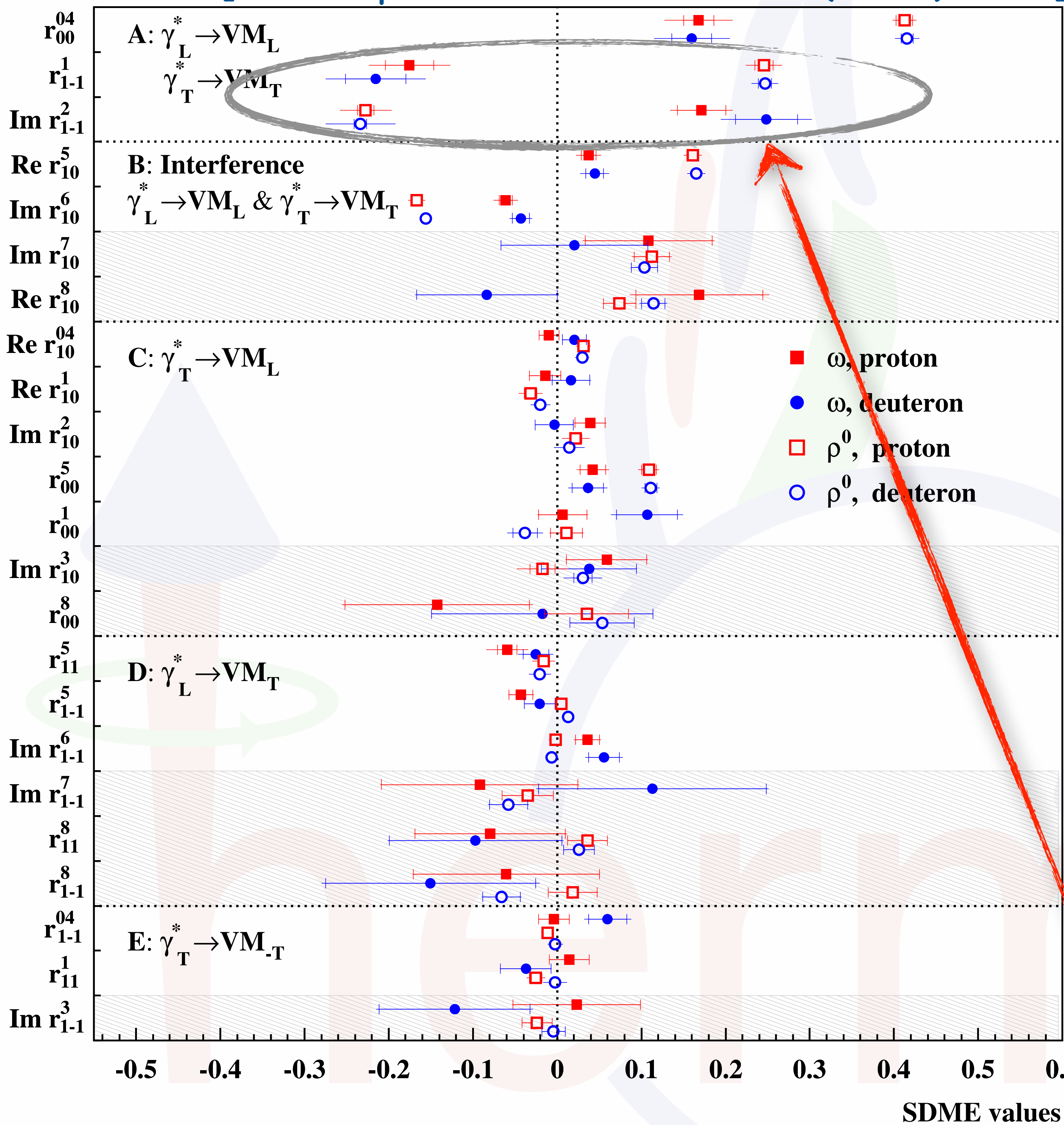

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  - r^5_{00}
  - $r^5_{11} + r^5_{1\text{-}1} - \Im r^6_{1\text{-}1}$
- interference smaller than for ρ^0 …
- … and opposite signs for $r^1_{1\text{-}1}$ & $\Im r^2_{1\text{-}1}$

(un)natural-parity exchange contributions

$$\Im\, r^2_{1-1} - r^1_{1-1} = \frac{1}{\mathcal{N}} \widetilde{\sum} (|U_{11}|^2 - |T_{11}|^2)$$

UPE contribution NPE contribution

- positive for omega -> large UPE contributions (unlike for rho)
- can construct various UPE quantities:

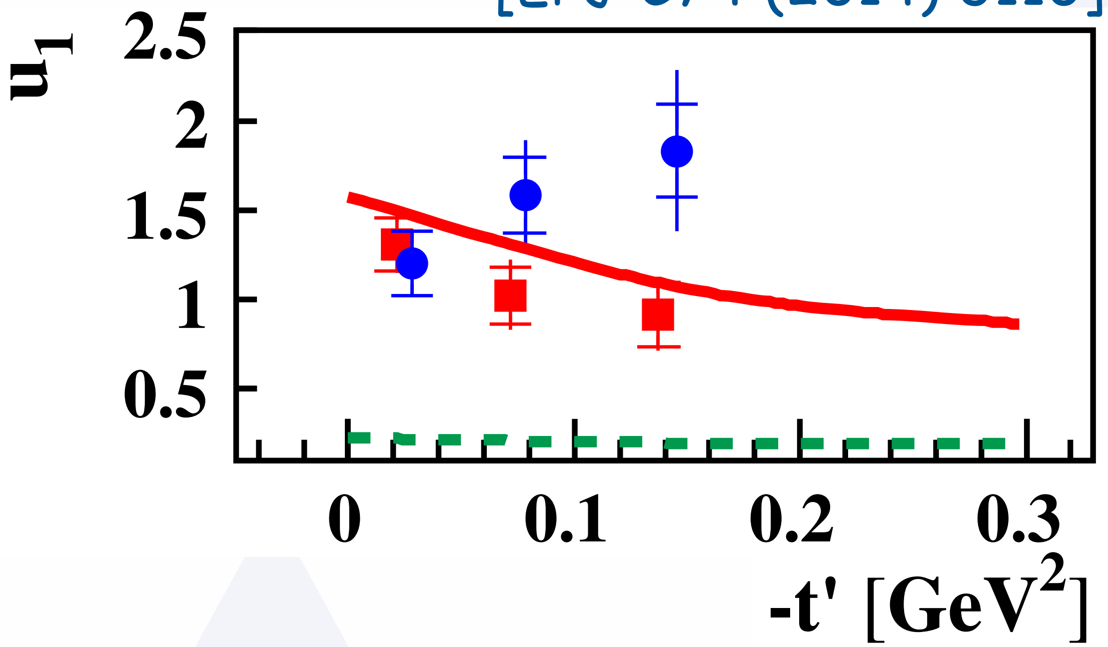
$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^1_{11} - 2r^1_{1-1}$$

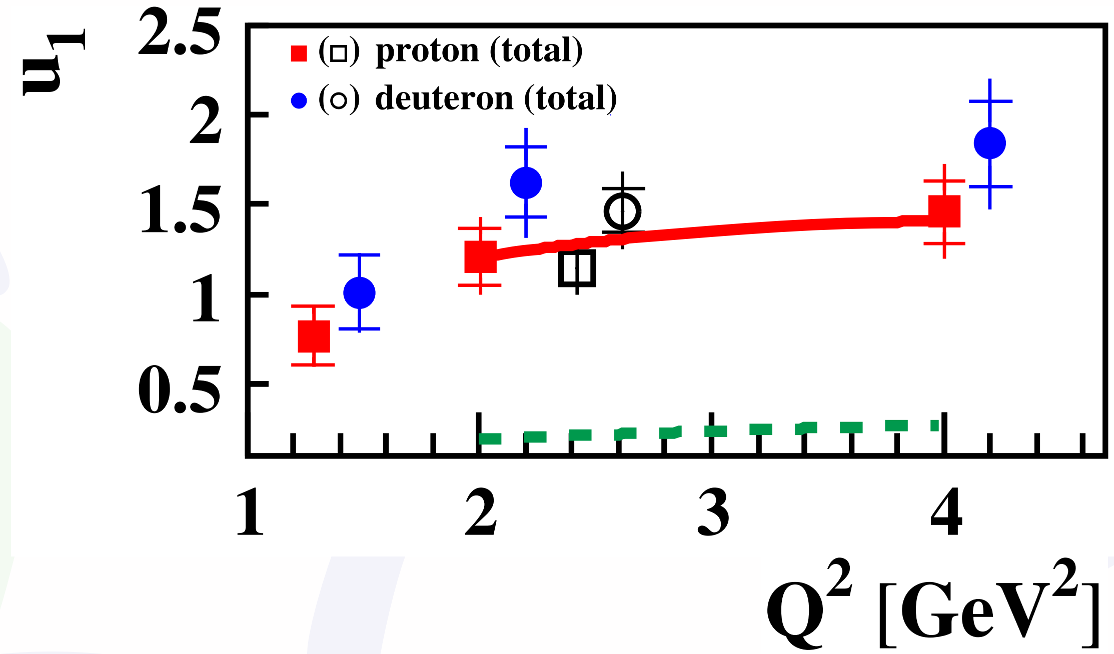
$$u_2 = r^5_{11} + r^5_{1-1}$$

$$u_3 = r^8_{11} + r^8_{1-1}$$

test of UPE

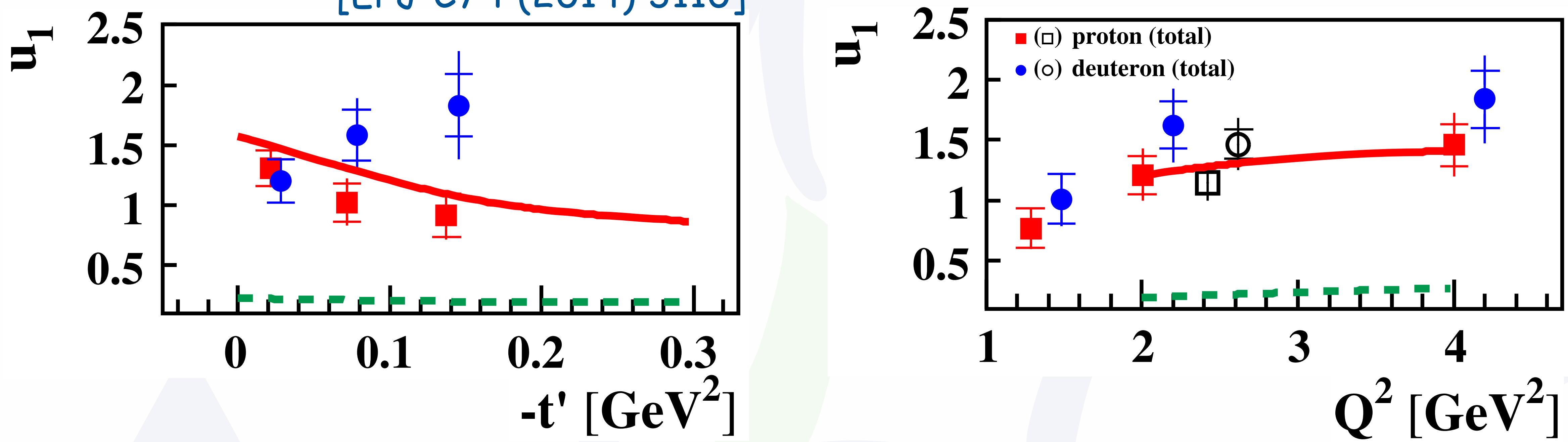
[EPJ C74 (2014) 3110]





test of UPE

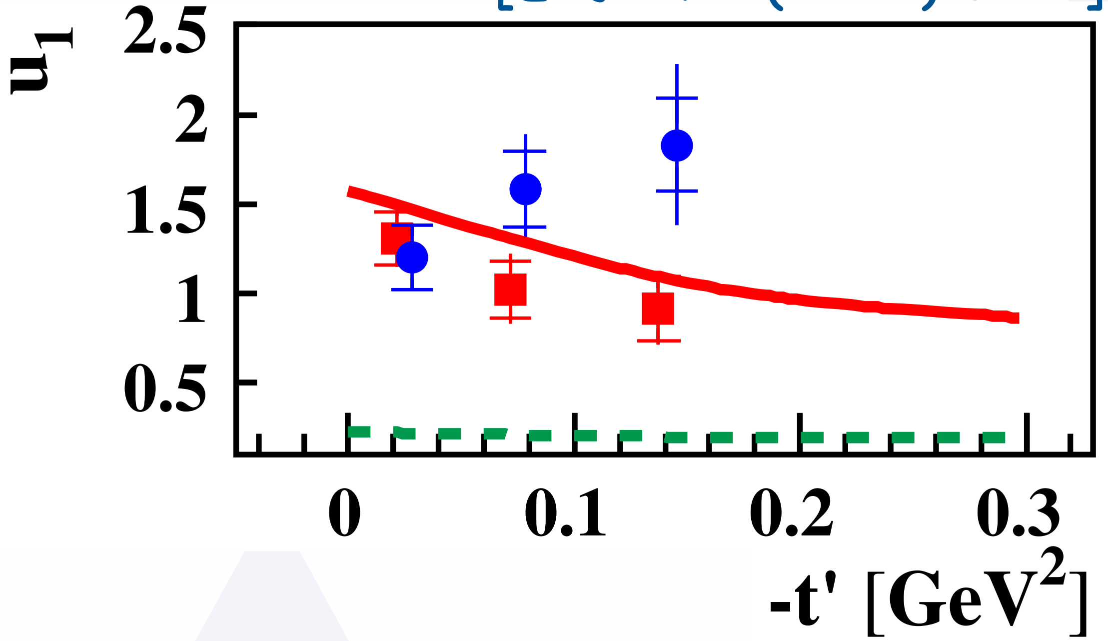
[EPJ C74 (2014) 3110]

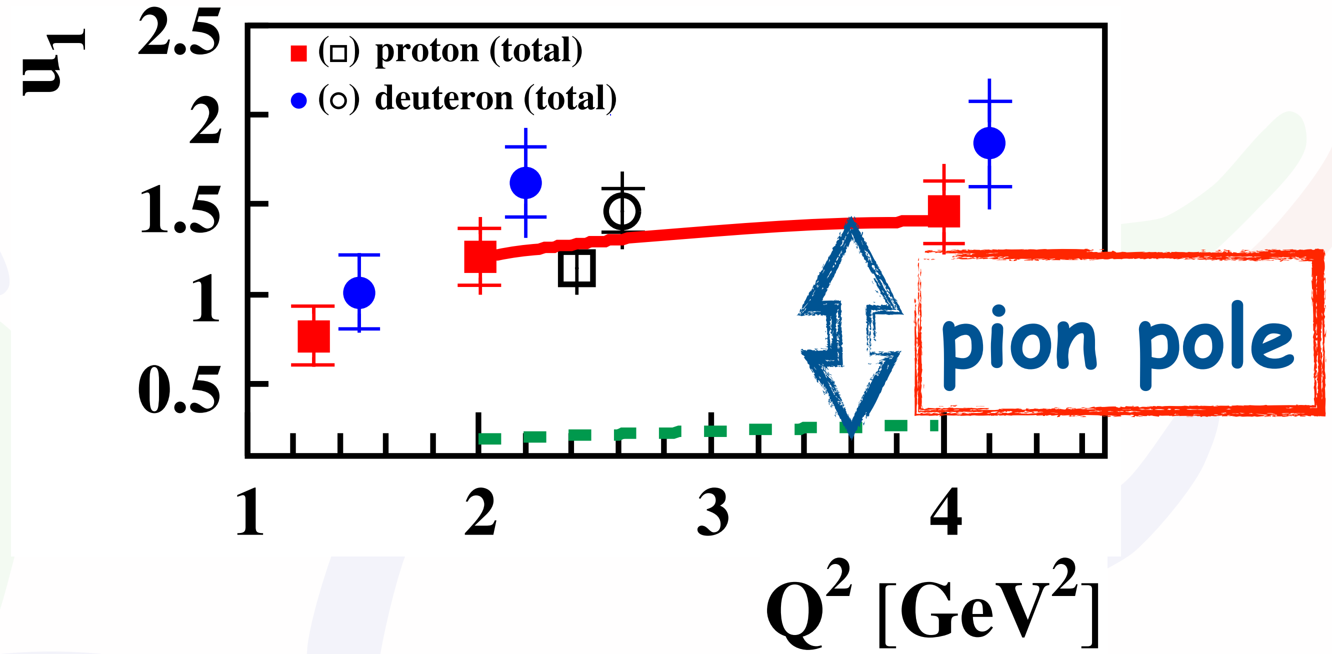


- large UPE contributions

test of UPE

[EPJ C74 (2014) 3110]



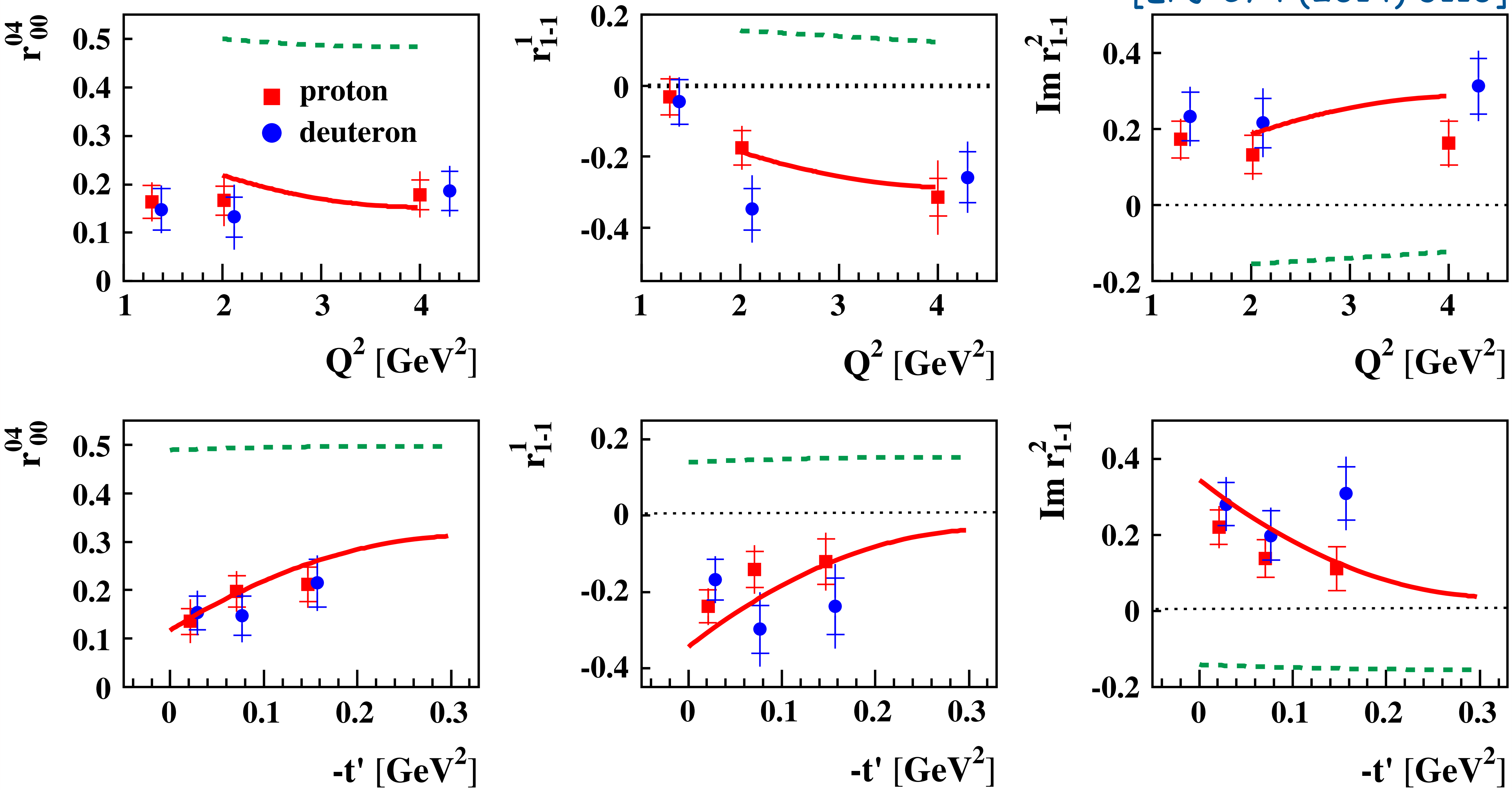


- large UPE contributions
- modified GK model [EPJ A50 (2014) 146] can describe data when including
  - pion pole contribution (red curve)
  - corresponding $\pi\omega$ transition form factor (fit to these data)

impact of pion-pole contr. on SDMEs

- "class-A" - helicity-conserving transitions

[EPJ C74 (2014) 3110]



impact of pion-pole contr. on SDMEs

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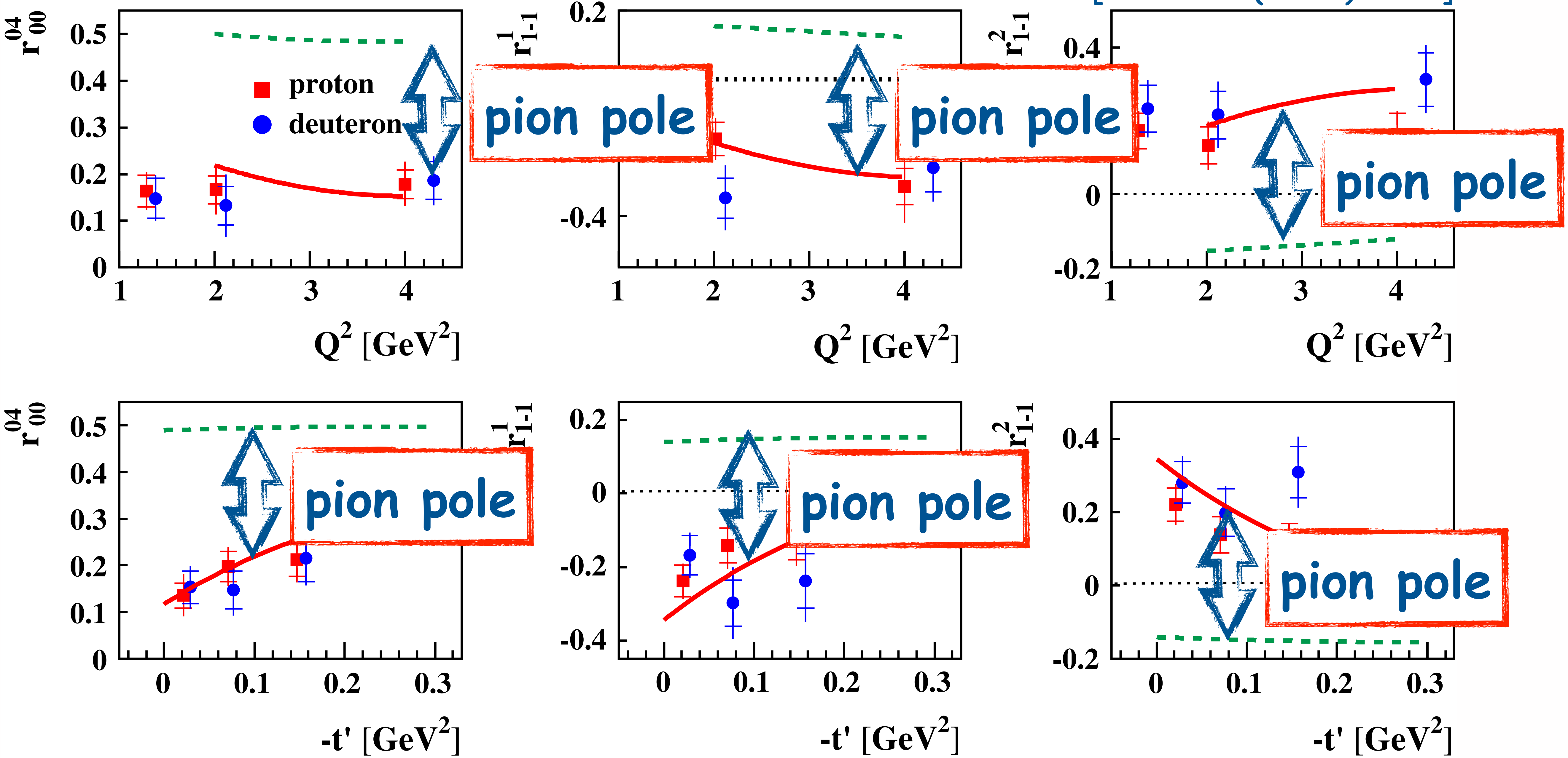
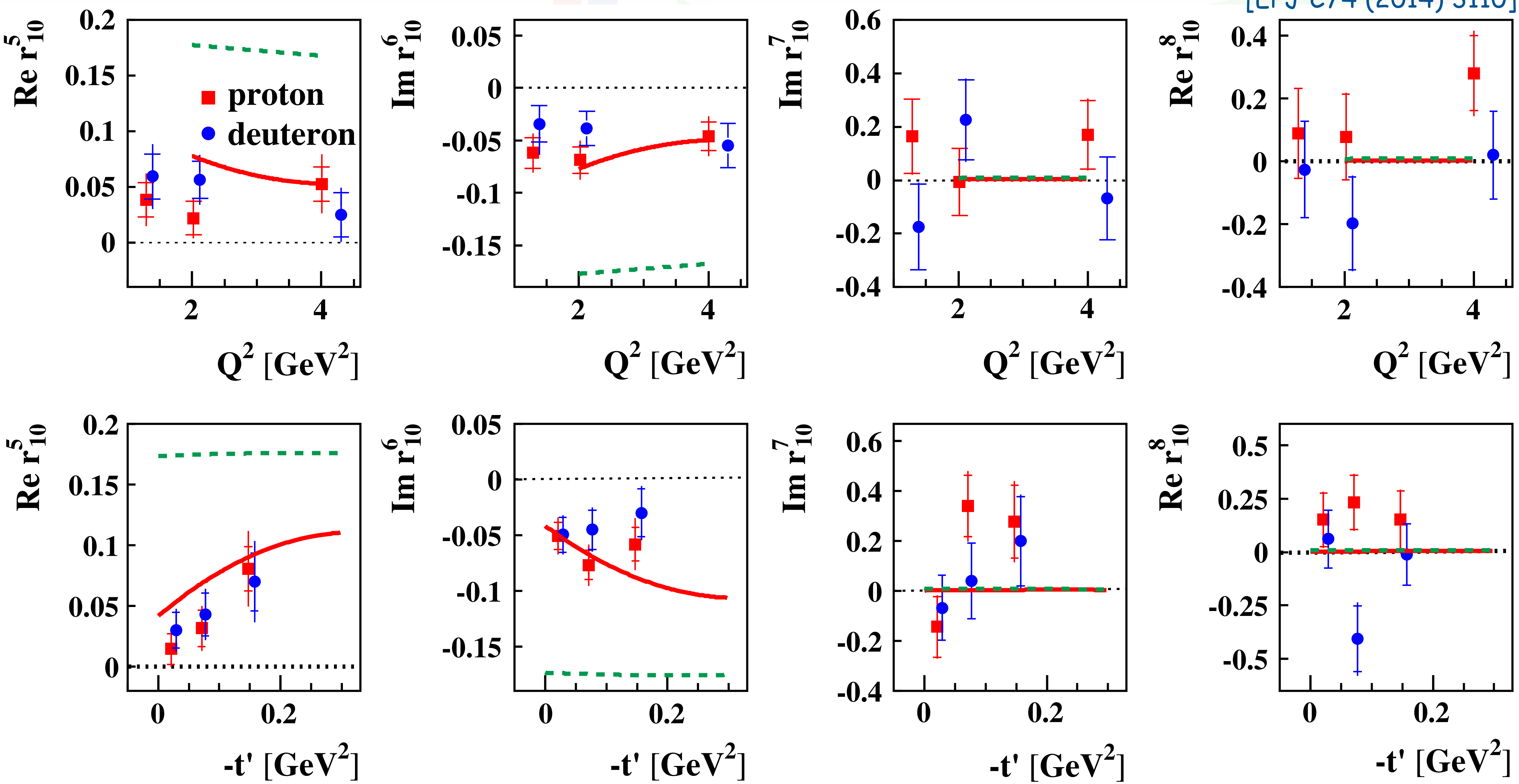


impact of pion-pole contr. on SDMEs

- "class-B" - interference of helicity-conserving transitions

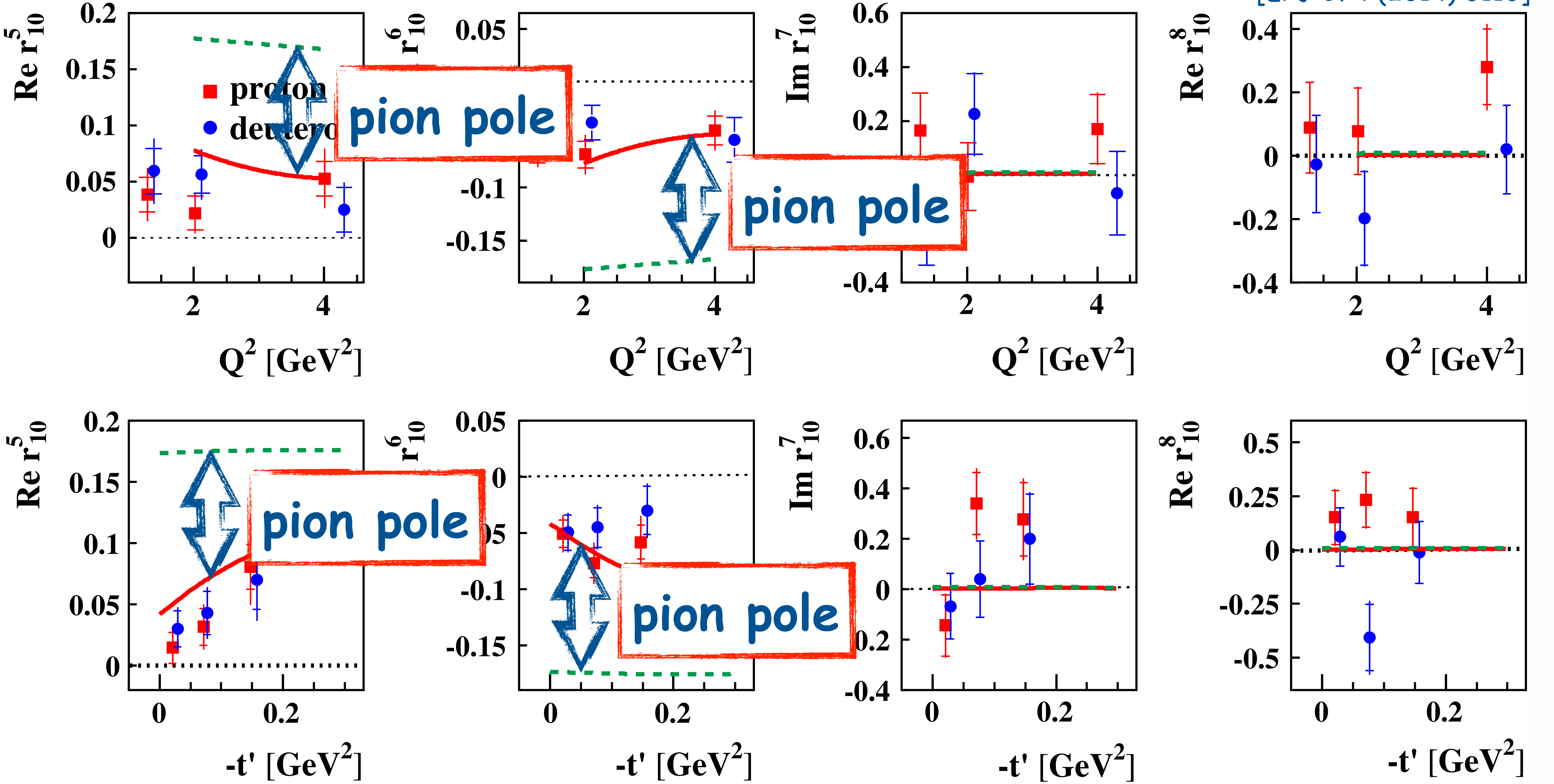
[EPJ C74 (2014) 3110]



impact of pion-pole contr. on SDMEs

- "class-B" - interference of helicity-conserving transitions

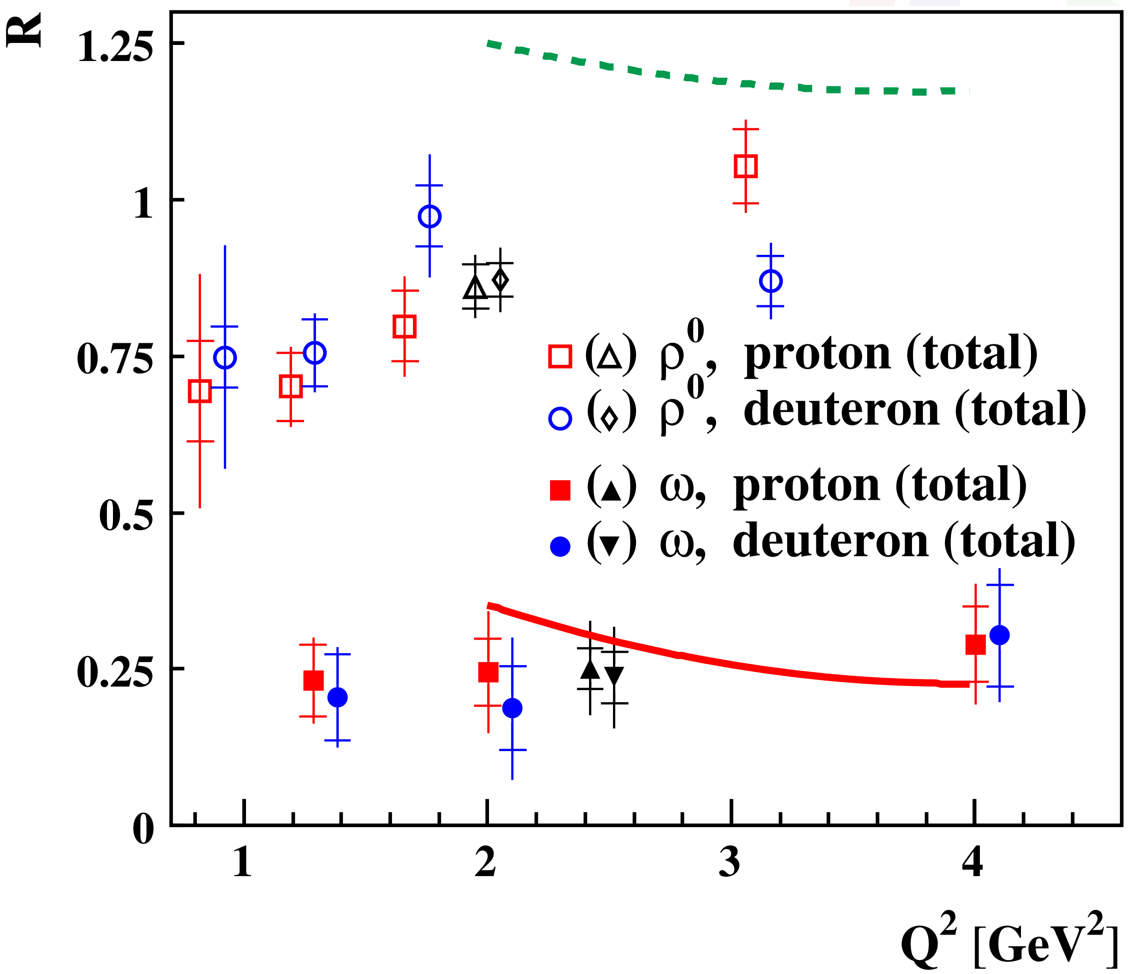
[EPJ C74 (2014) 3110]

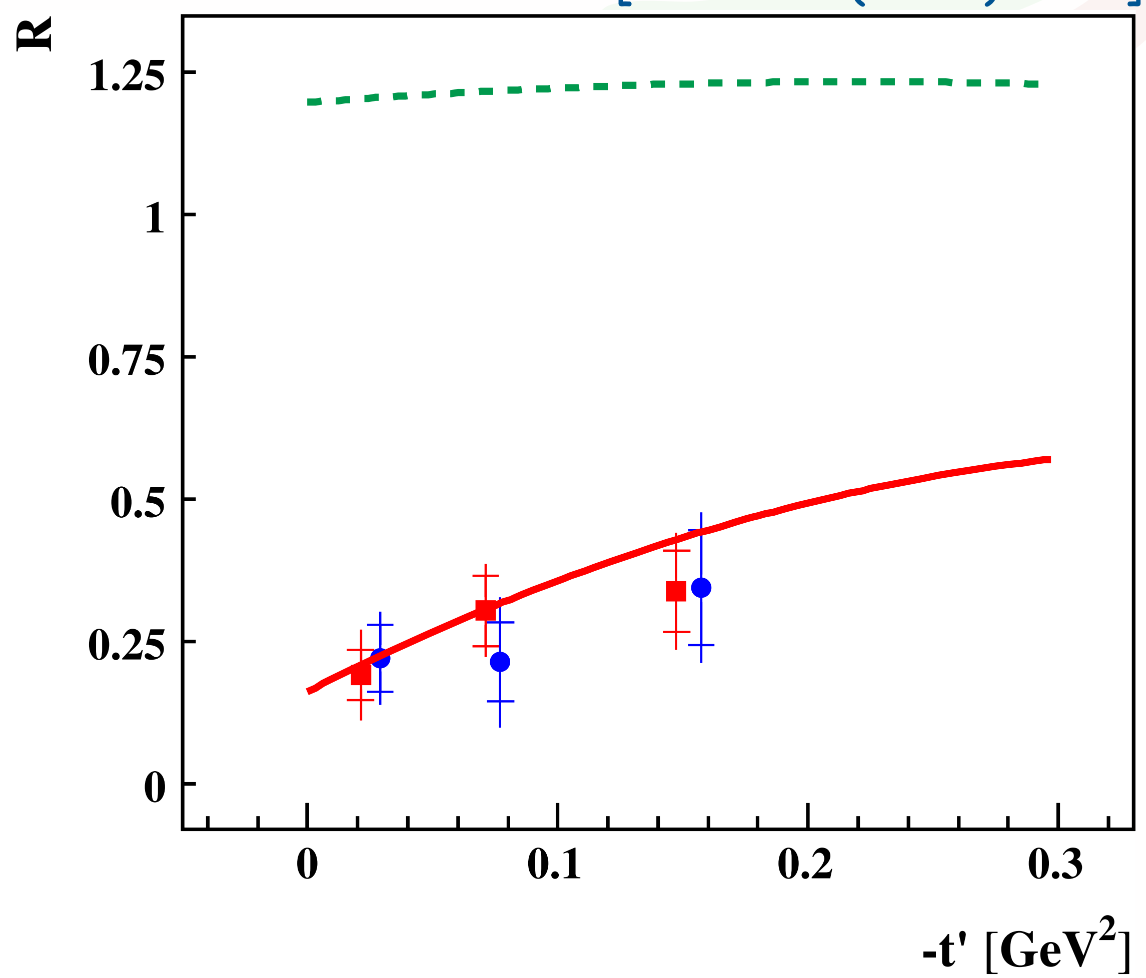


long.-to-transverse cross-section ratio

$$R = \frac{d\sigma(\gamma_L^* \to \omega)}{d\sigma(\gamma_T^* \to \omega)} \approx \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - r_{00}^{04}}$$

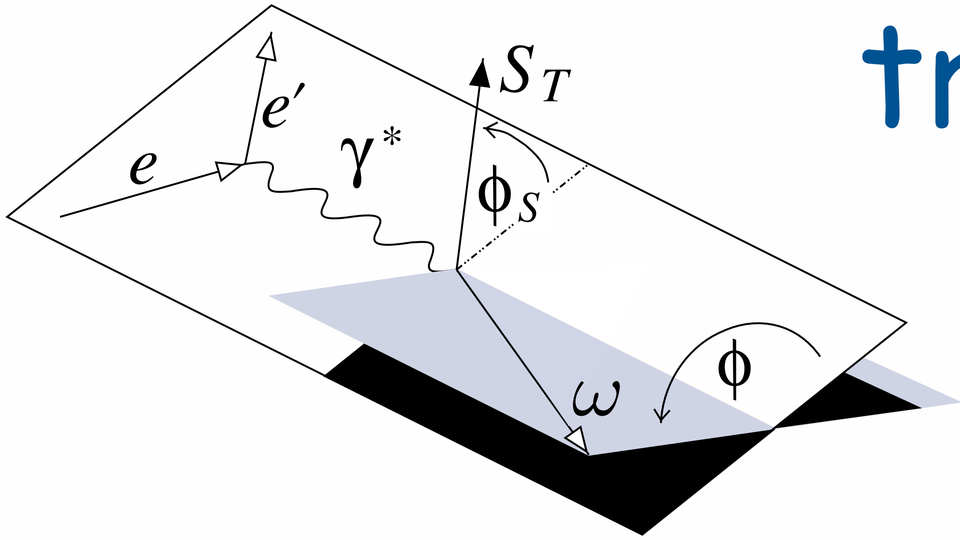
[EPJ C74 (2014) 3110]





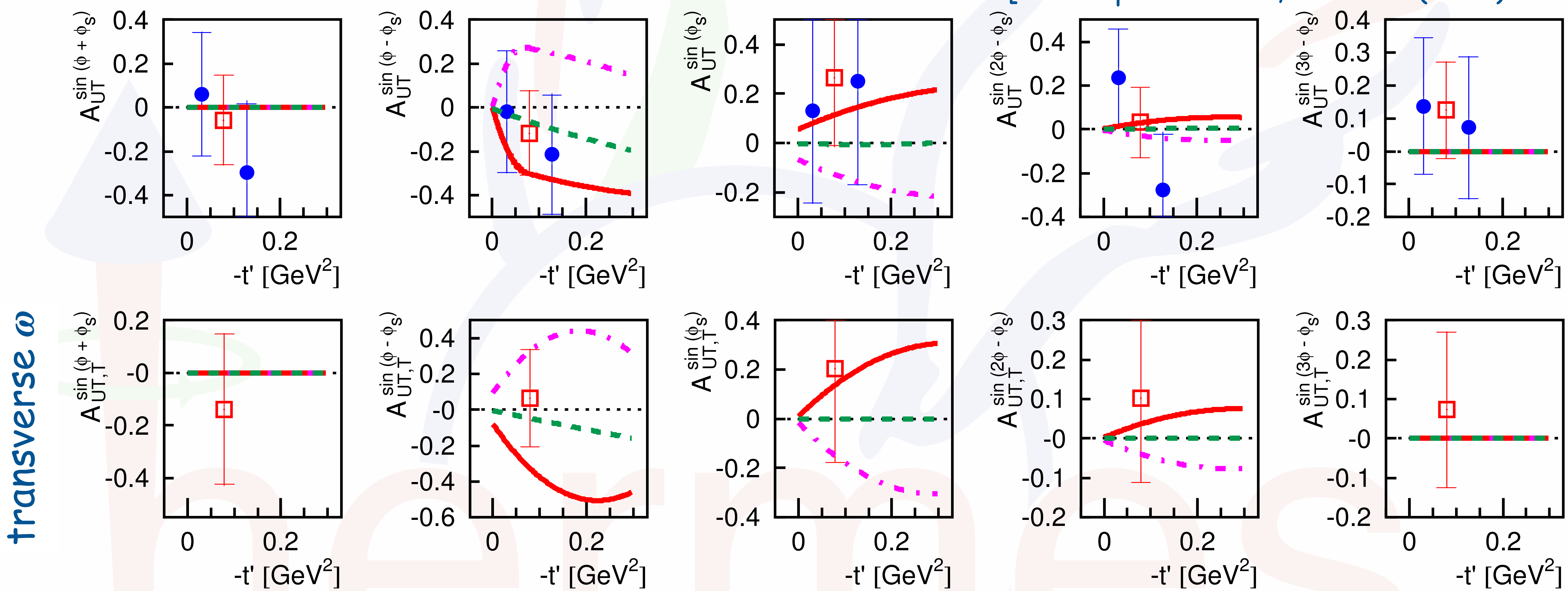
- significantly smaller for ω than for ρ
- again, data point to important contribution from pion pole

transverse-spin asymmetry



sensitive, in principle, to sign of $\pi\omega$ transition FF

[A. Airapetian et al., EPJ C75 (2015) 600]



slight preference for positive $\pi\omega$ transition FF (red/full line) vs. negative one (magenta/dash-dotted line)

helicity-amplitude ratios - formalism

- NPE: $T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = [F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + (-1)^{\lambda_\gamma - \lambda_V} F_{-\lambda_V \lambda'_N -\lambda_\gamma \lambda_N}]/2$
- UPE: $U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = [F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} - (-1)^{\lambda_\gamma - \lambda_V} F_{-\lambda_V \lambda'_N -\lambda_\gamma \lambda_N}]/2$
- nucleon-helicity non-flip / flip amplitudes:

$$T^{(1)}_{\lambda_V \lambda_\gamma} \equiv T_{\lambda_V \frac{1}{2} \lambda_\gamma \frac{1}{2}} = T_{\lambda_V -\frac{1}{2} \lambda_\gamma -\frac{1}{2}}, \quad U^{(1)}_{\lambda_V \lambda_\gamma} \equiv U_{\lambda_V \frac{1}{2} \lambda_\gamma \frac{1}{2}} = -U_{\lambda_V -\frac{1}{2} \lambda_\gamma -\frac{1}{2}}$$

$$T^{(2)}_{\lambda_V \lambda_\gamma} \equiv T_{\lambda_V \frac{1}{2} \lambda_\gamma -\frac{1}{2}} = -T_{\lambda_V -\frac{1}{2} \lambda_\gamma \frac{1}{2}}, \quad U^{(2)}_{\lambda_V \lambda_\gamma} \equiv U_{\lambda_V \frac{1}{2} \lambda_\gamma -\frac{1}{2}} = U_{\lambda_V -\frac{1}{2} \lambda_\gamma \frac{1}{2}}$$

- 17 (complex amplitude) ratios in total:

$$t^{(1)}_{\lambda_V \lambda_\gamma} = T^{(1)}_{\lambda_V \lambda_\gamma}/T^{(1)}_{00}, \; t^{(2)}_{\lambda_V \lambda_\gamma} = T^{(2)}_{\lambda_V \lambda_\gamma}/T^{(1)}_{00}, \; u^{(1)}_{\lambda_V \lambda_\gamma} = U^{(1)}_{\lambda_V \lambda_\gamma}/T^{(1)}_{00}, \; u^{(2)}_{\lambda_V \lambda_\gamma} = U^{(2)}_{\lambda_V \lambda_\gamma}/T^{(1)}_{00}$$

- for longitudinally polarized beam and transversely polarized target 25 parameters can be reliably extracted
- phase shifts of $T^{(1)}_{11}$ and $U^{(1)}_{11}$ are fixed from previous HERMES data
- amplitude ratios parametrized according to low-t behavior

[EPJ C77 (2017) 378]

fit results

(for reference ;-)

extracted using 2d binning in (t', Q^2)

3 GeV < W < 6.3 GeV

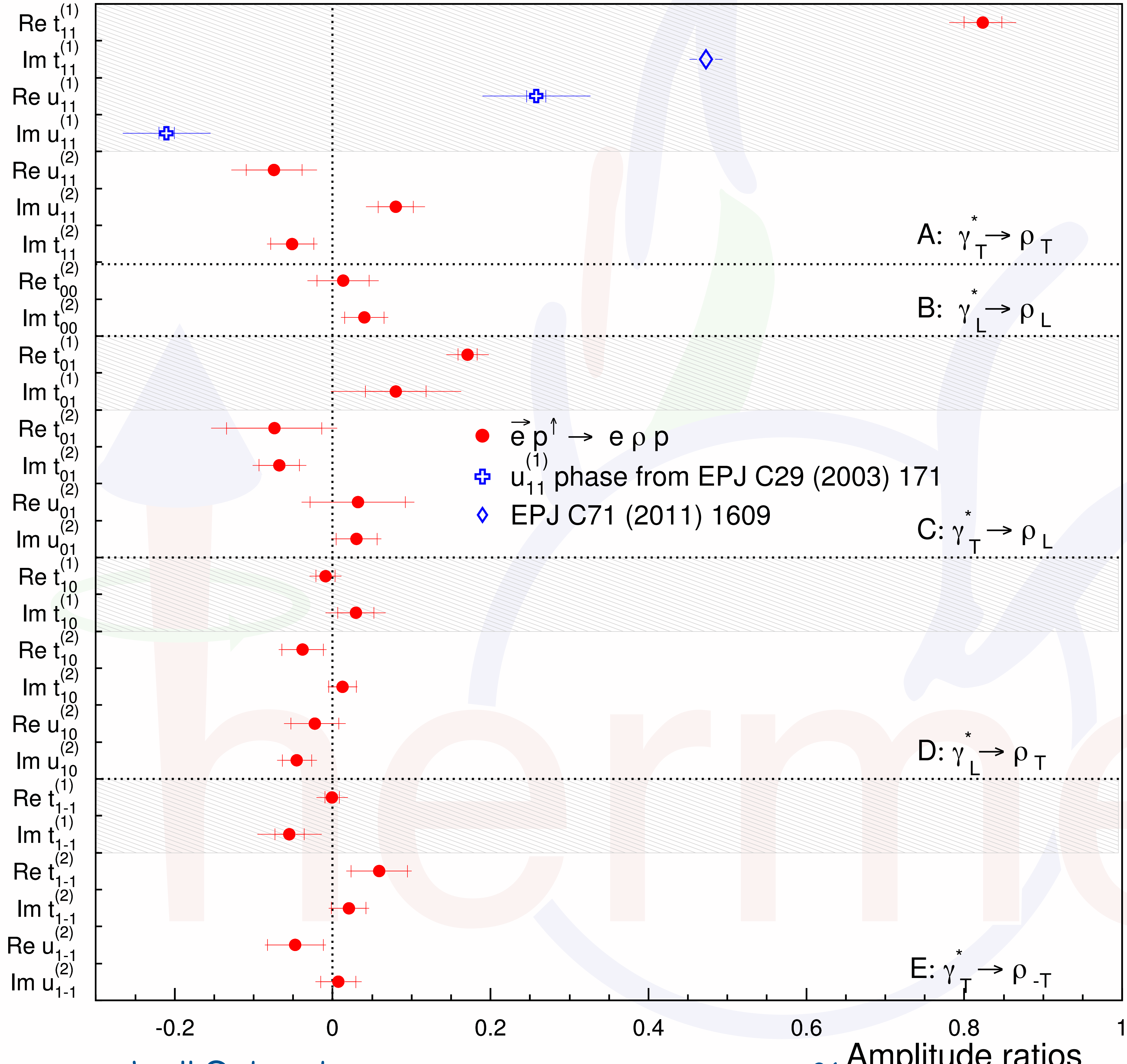
1 GeV^2 < Q^2 < 7 GeV^2

t' < 0.4 GeV^2

Parametrization	Value of parameter	Statistical uncertainty	Total uncertainty
$\mathrm{Re}\{t_{11}^{(1)}\} = b_1/Q$	$b_1 = 1.145$ GeV	0.033 GeV	0.081 GeV
$\lvert u_{11}^{(1)}\rvert = b_2$	$b_2 = 0.333$	0.016	0.088
$\mathrm{Re}\{u_{11}^{(2)}\} = b_3$	$b_3 = -0.074$	0.036	0.054
$\mathrm{Im}\{u_{11}^{(2)}\} = b_4$	$b_4 = 0.080$	0.022	0.037
$\xi = b_5$	$b_5 = -0.055$	0.027	0.029
$\zeta = b_6$	$b_6 = -0.013$	0.033	0.044
$\mathrm{Im}\{t_{00}^{(2)}\} = b_7$	$b_7 = 0.040$	0.025	0.030
$\mathrm{Re}\{t_{01}^{(1)}\} = b_8\sqrt{-t'}$	$b_8 = 0.471$ GeV^{-1}	0.033 GeV^{-1}	0.075 GeV^{-1}
$\mathrm{Im}\{t_{01}^{(1)}\} = b_9\frac{\sqrt{-t'}}{Q}$	$b_9 = 0.307$	0.148	0.354
$\mathrm{Re}\{t_{01}^{(2)}\} = b_{10}$	$b_{10} = -0.074$	0.060	0.080
$\mathrm{Im}\{t_{01}^{(2)}\} = b_{11}$	$b_{11} = -0.067$	0.026	0.036
$\mathrm{Re}\{u_{01}^{(2)}\} = b_{12}$	$b_{12} = 0.032$	0.060	0.072
$\mathrm{Im}\{u_{01}^{(2)}\} = b_{13}$	$b_{13} = 0.030$	0.026	0.033
$\mathrm{Re}\{t_{10}^{(1)}\} = b_{14}\sqrt{-t'}$	$b_{14} = -0.025$ GeV^{-1}	0.034 GeV^{-1}	0.063 GeV^{-1}
$\mathrm{Im}\{t_{10}^{(1)}\} = b_{15}\sqrt{-t'}$	$b_{15} = 0.080$ GeV^{-1}	0.063 GeV^{-1}	0.118 GeV^{-1}
$\mathrm{Re}\{t_{10}^{(2)}\} = b_{16}$	$b_{16} = -0.038$	0.026	0.030
$\mathrm{Im}\{t_{10}^{(2)}\} = b_{17}$	$b_{17} = 0.012$	0.018	0.019
$\mathrm{Re}\{u_{10}^{(2)}\} = b_{18}$	$b_{18} = -0.023$	0.030	0.039
$\mathrm{Im}\{u_{10}^{(2)}\} = b_{19}$	$b_{19} = -0.045$	0.018	0.026
$\mathrm{Re}\{t_{1-1}^{(1)}\} = b_{20}\frac{(-t')}{Q}$	$b_{20} = -0.008$ GeV^{-1}	0.096 GeV^{-1}	0.212 GeV^{-1}
$\mathrm{Im}\{t_{1-1}^{(1)}\} = b_{21}\frac{(-t')}{Q}$	$b_{21} = -0.577$ GeV^{-1}	0.196 GeV^{-1}	0.428 GeV^{-1}
$\mathrm{Re}\{t_{1-1}^{(2)}\} = b_{22}$	$b_{22} = 0.059$	0.036	0.047
$\mathrm{Im}\{t_{1-1}^{(2)}\} = b_{23}$	$b_{23} = 0.020$	0.022	0.026
$\mathrm{Re}\{u_{1-1}^{(2)}\} = b_{24}$	$b_{24} = -0.047$	0.035	0.039
$\mathrm{Im}\{u_{1-1}^{(2)}\} = b_{25}$	$b_{25} = 0.007$	0.022	0.029

helicity-amplitude ratios

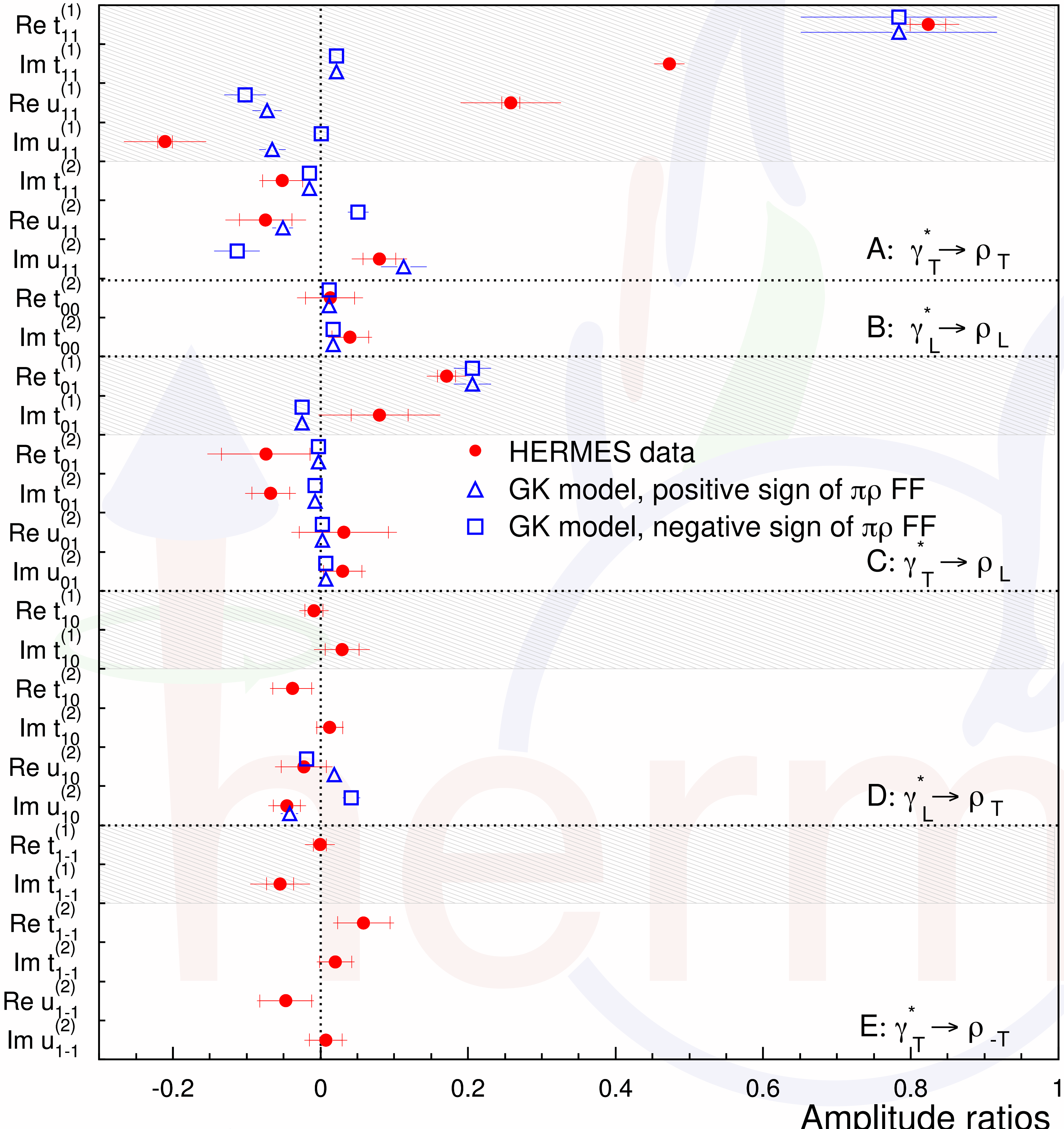
[EPJ C77 (2017) 378]



- shaded: without nucleon-helicity flip [previously already extracted and published in EPJ C71 (2011) 1609]
- blue points from or extracted using previous results
- most nucleon-helicity flip amplitudes small, consistent with zero
- indications of **non-vanishing** helicity-flip $\mathbf{t_{01}}$, $\mathbf{u_{10}}$ and $\mathbf{u_{11}}$

helicity-amplitude ratios

[EPJ C77 (2017) 378]

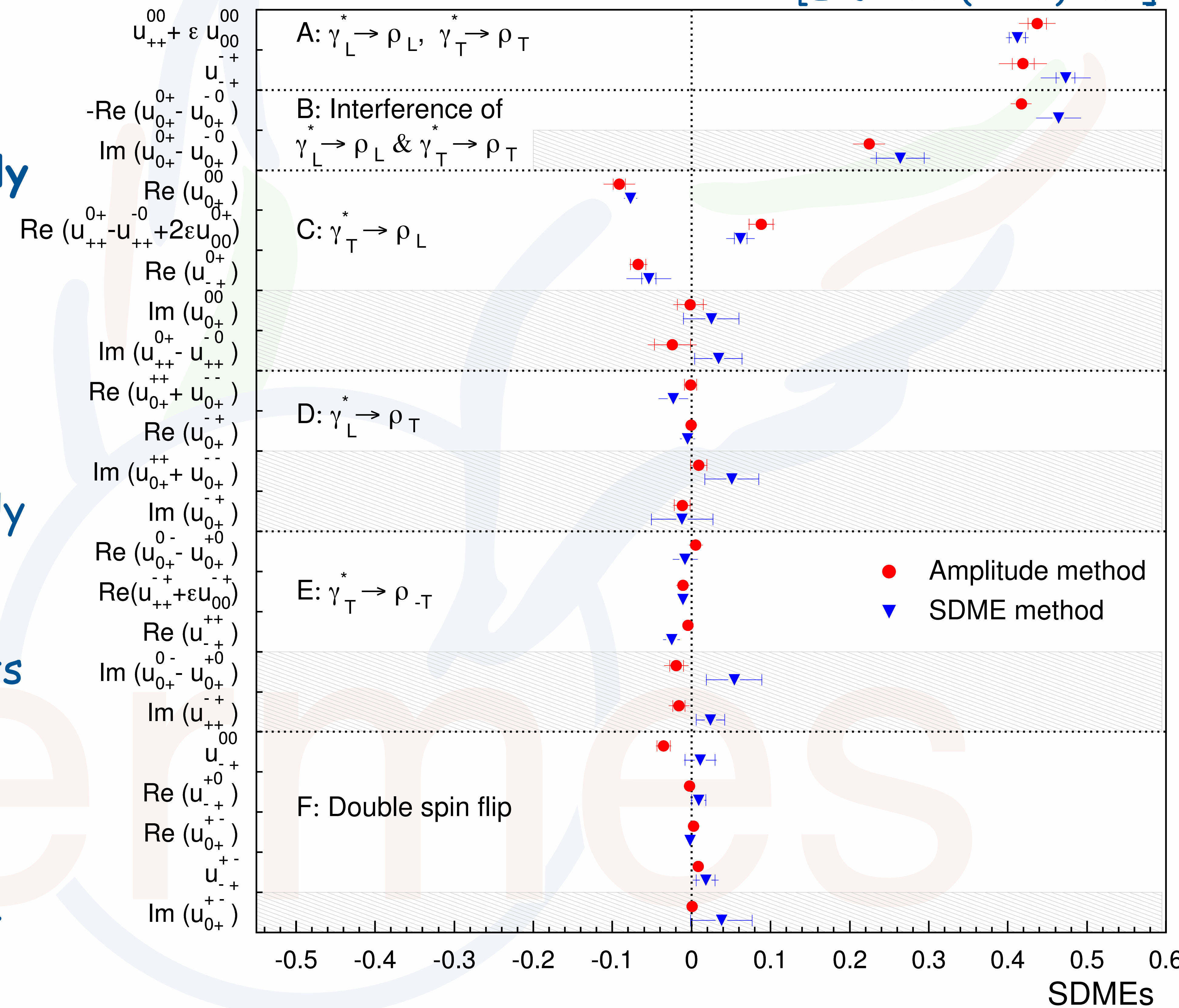


- comparison with GK model [EPJ C77 (2017) 378]
- where missing, set to zero in GK model
- two sets of calculations using opposite signs for $\pi\rho$ transition form factors
- data clearly favors positive sign
- good agreement for most ratios, but clearly off for some
  - problems with phases known already

comparison with SDMEs

- amplitude ratios used to calculate SDMEs
- compared to **directly extracted** SDMEs [EPJ C62 (2009) 659]
- **complimentary** extractions and fully **consistent**
- note that SDME fits can not take into account underlying correlations (e.g., when involving same amplitudes)

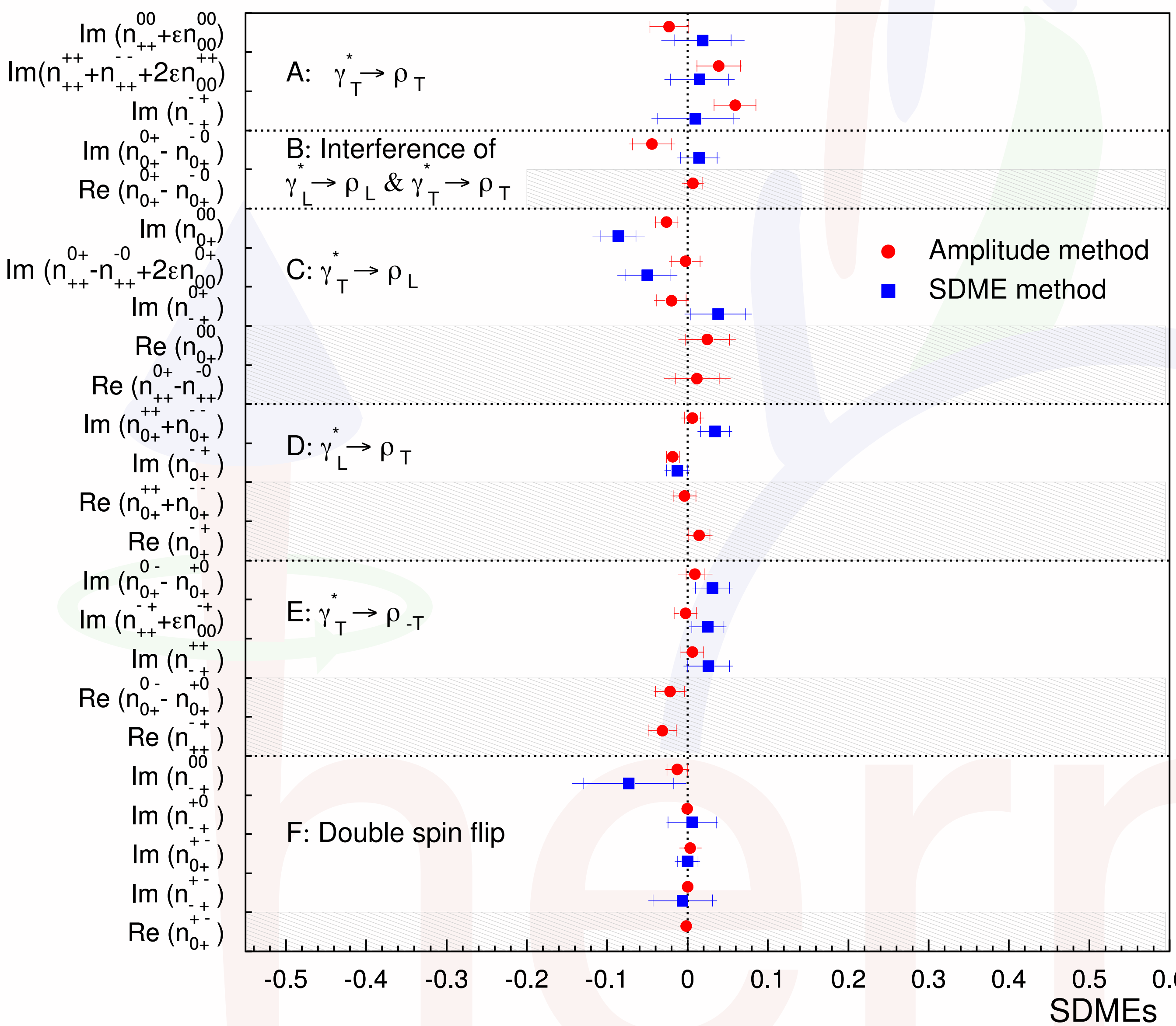
[EPJ C77 (2017) 378]

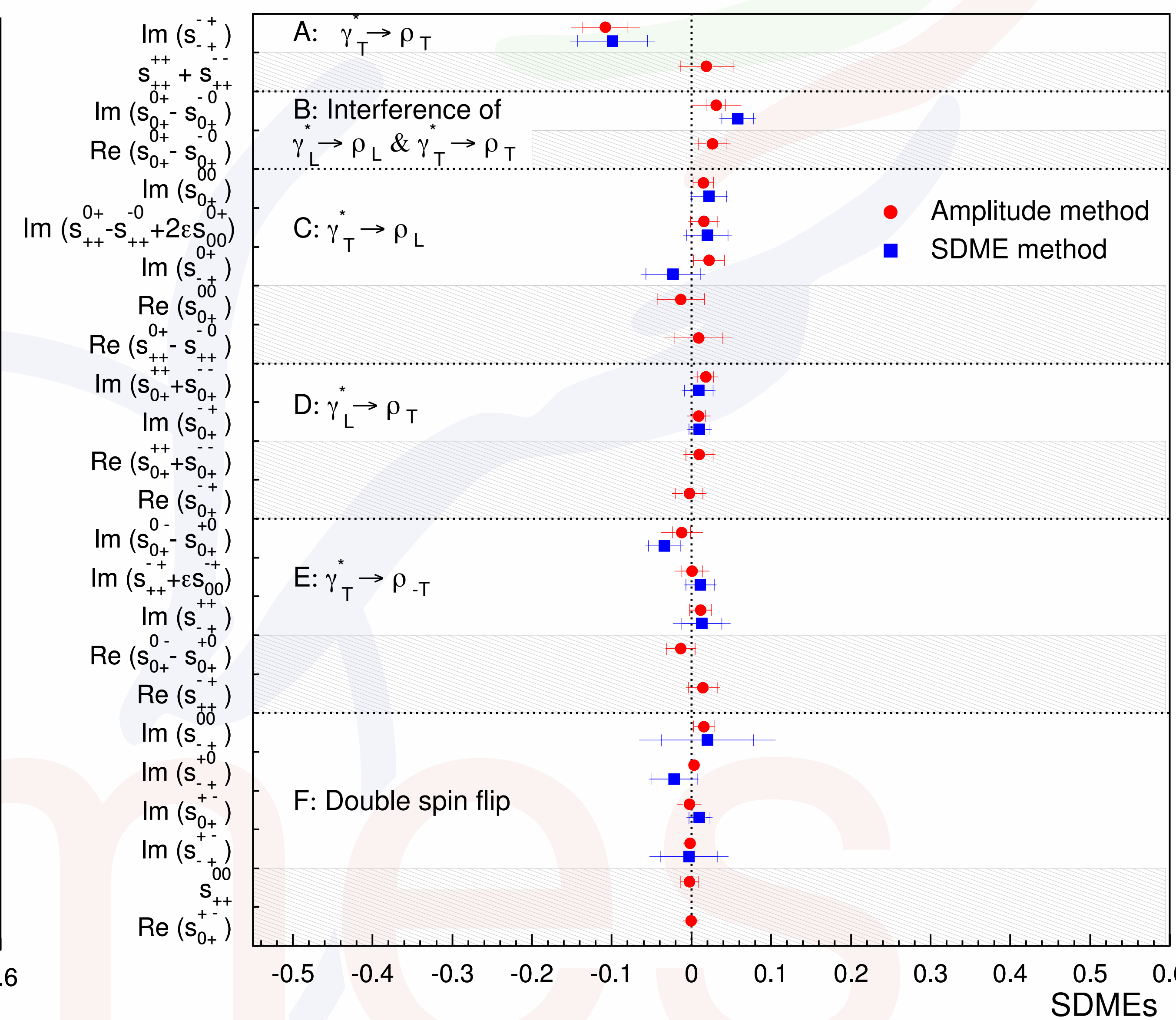


comparison with SDMEs

[EPJ C77 (2017) 378]

- transverse-target SDMEs [from Phys. Lett. B679 (2009) 100]



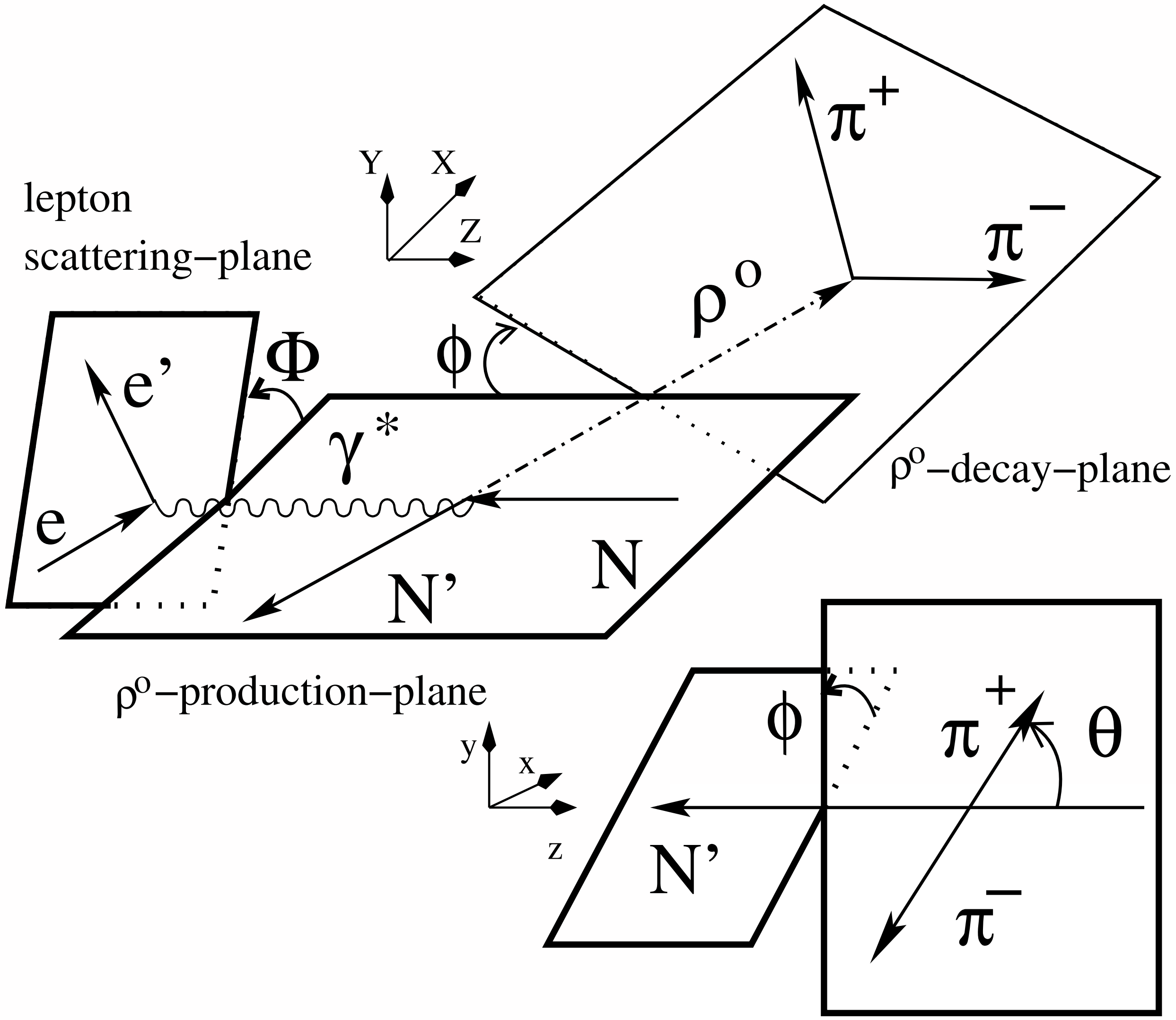


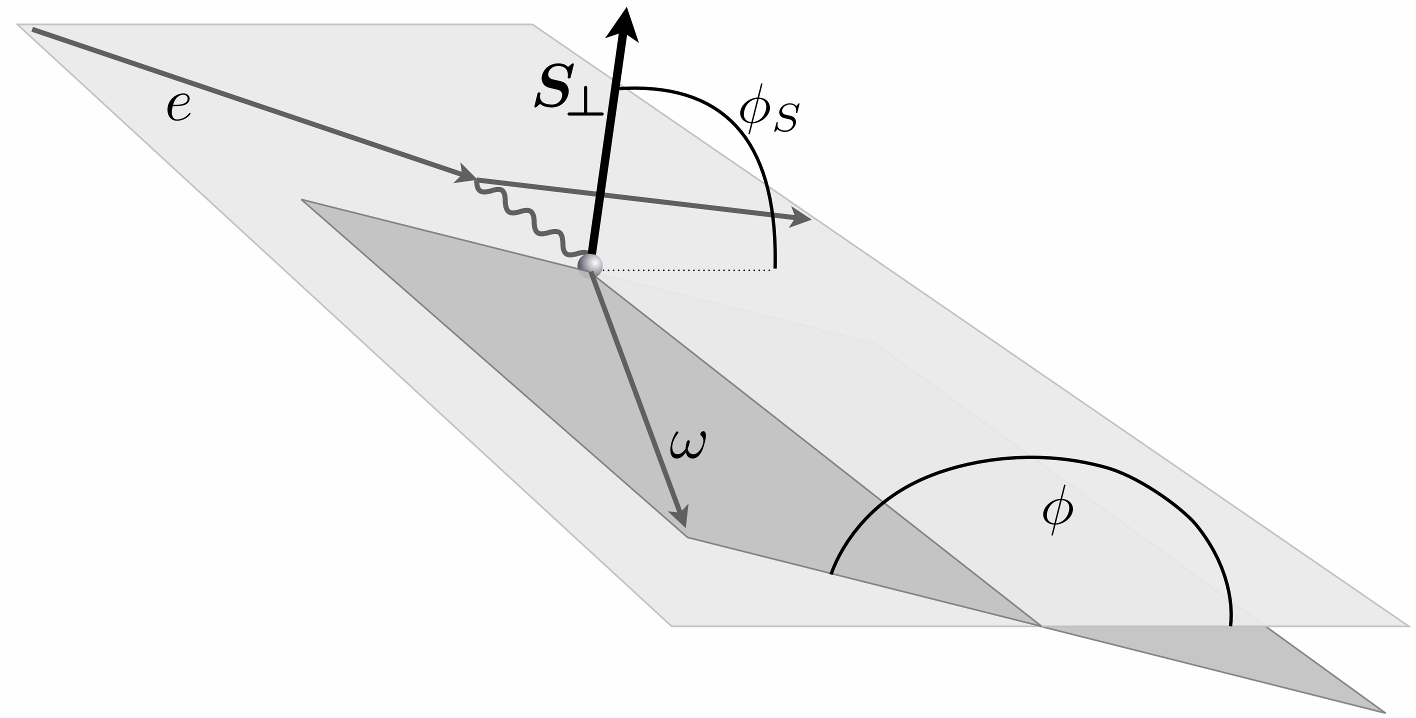
- "transverse SDMEs" involving beam polarization measured here for first time

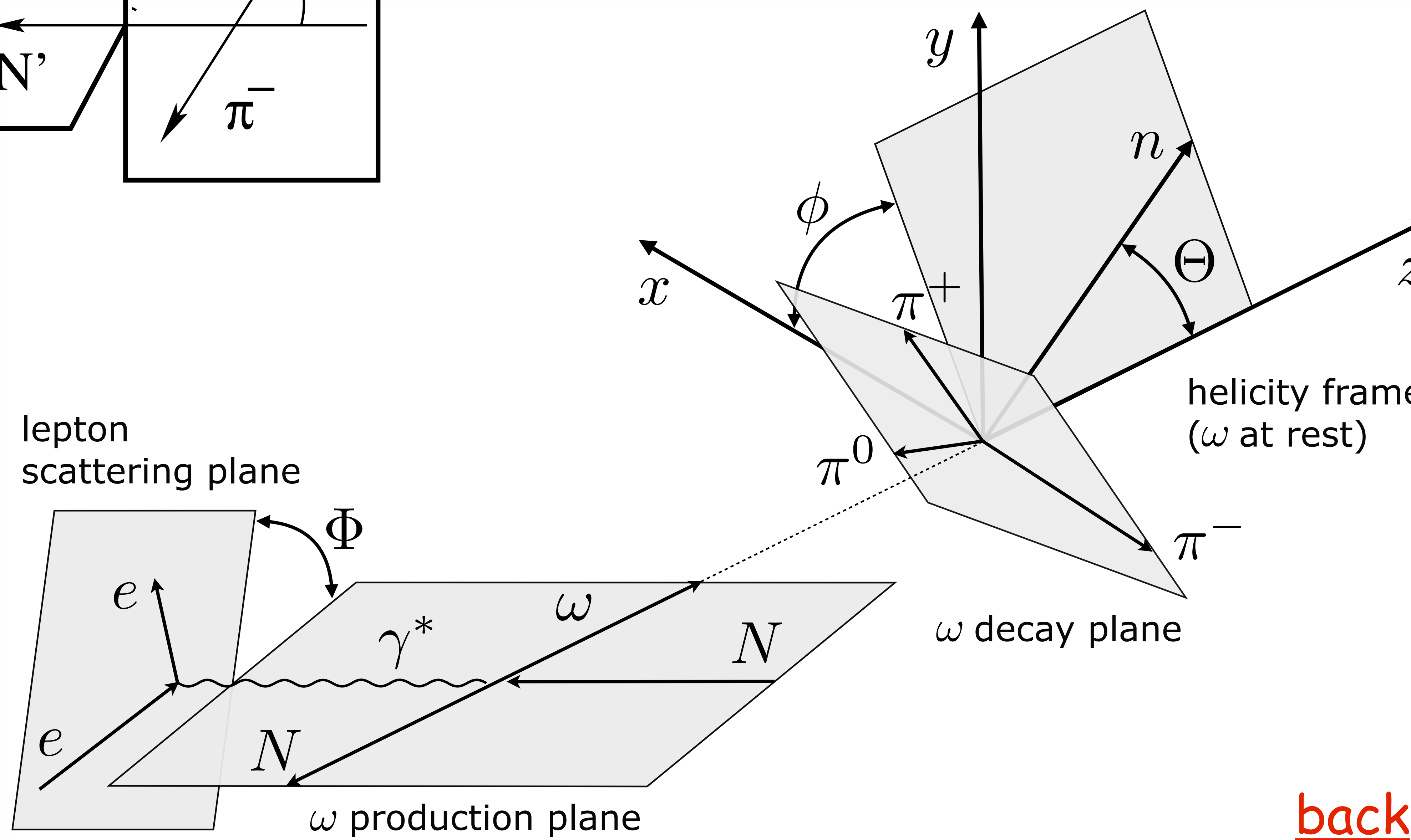
summary

- exclusive vector-meson electroproduction in DIS studied at HERMES using a longitudinally polarized 27.6 GeV $e^{\pm}$ beam and unpolarized p/d or transversely polarized p targets
- SDMEs for ρ^0 confirm dominance of NPE, while large UPE contributions for ω -> important role of pion pole
- A_{UT} for ω favors positive sign of $\pi\omega$ form factor
- for first time, amplitude analysis performed for ρ^0 electroproduction on transversely polarized protons
  - important role of pion pole for UPE amplitudes
  - positive sign of $\pi\rho$ form factor
  - re-calculated SDMEs in good agreement with those extracted directly

backup slides

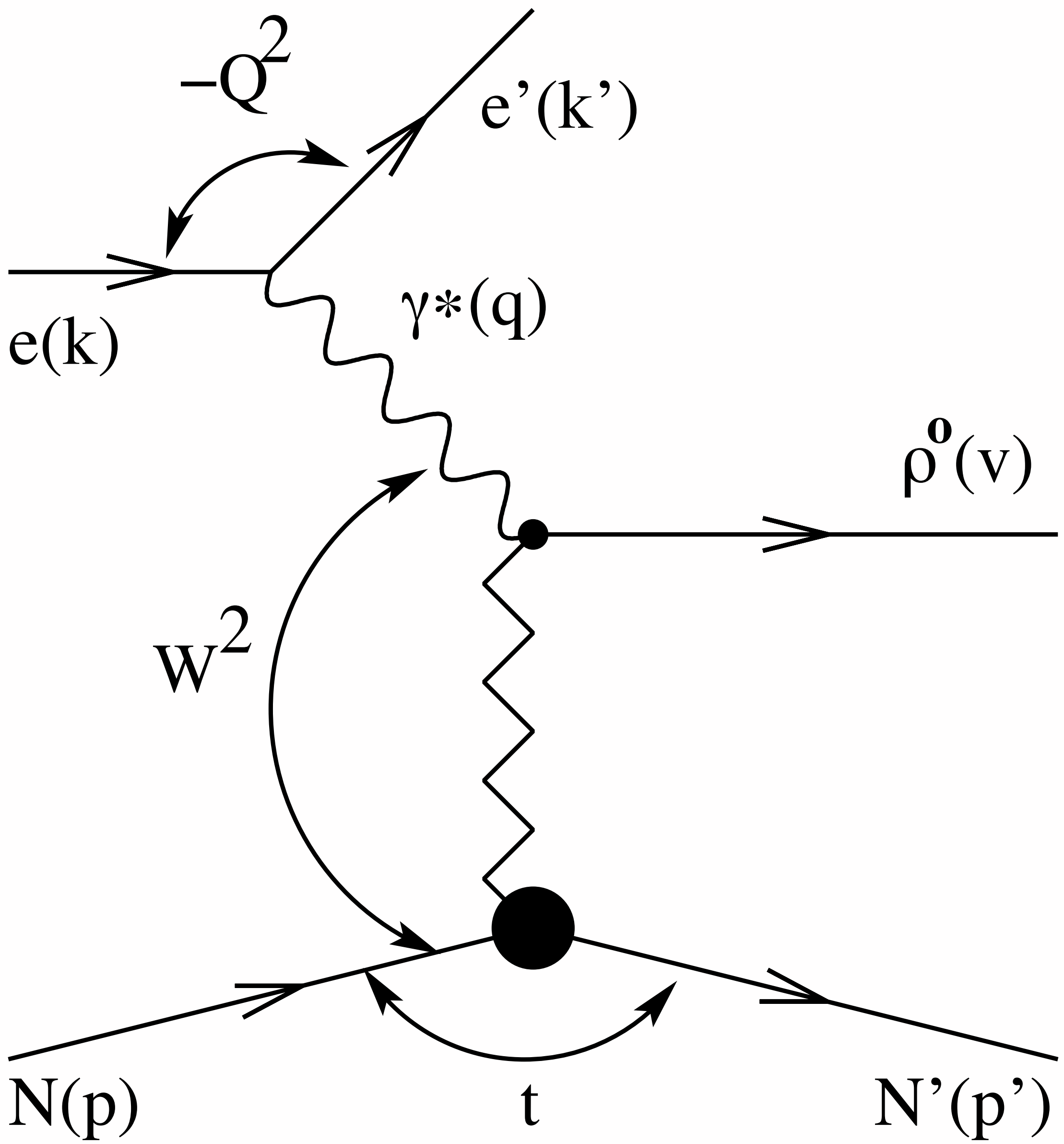

lepton
scattering–plane
Y
X
Z
Φ
e'
e
γ*
N'
N
φ
ρ°
π+
π−
ρ°–decay–plane
ρ°–production–plane
y
x
z
φ
π+
θ
N'
π−


e
$S_\perp$
ϕ_S
ω
ϕ


y
n
x
z
ϕ
Θ
π+
π0
π−
helicity frame
(ω at rest)
ω decay plane
lepton
scattering plane
Φ
e
e
γ*
ω
N
N
ω production plane

back

… going into the details



Courtesy S. Manaenkov

$$\mathrm{QED}: \quad \mathrm{e}(\lambda) \to \mathrm{e}'(\lambda') + \gamma^*(\lambda_\gamma),$$

$$\mathrm{QCD}: \gamma^*(\lambda_\gamma) + \mathrm{N}(\lambda_\mathrm{N}) \to \mathrm{V}(\lambda_\mathrm{V}) + \mathrm{N}'(\lambda'_\mathrm{N}).$$

The helicity amplitude of the reaction
$\gamma^* + N \to V + N$

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

$$= (-1)^{\lambda_\gamma} \langle v \lambda_V p' \lambda'_N | J^\sigma_{(h)} | p \lambda_N \rangle e^{(\lambda_\gamma)}_\sigma .$$

$J^\sigma_{(h)}$ is the electromagnetic current of hadrons;
$e^{(\lambda_\gamma)}_\sigma$ is the photon polarization four-vector;
$\lambda_\gamma = \pm 1$ transverse virtual photon,
$\lambda_\gamma = 0$ longitudinal virtual photon.
$E^{(\lambda_V)}_\sigma$ is the vecor meson polarization vector;
$\lambda_V = \pm 1$ transverse vector meson,
$\lambda_V = 0$ longitudinal vector meson.
Amplitude decomposition into Natural (NPE) and Unnatural Parity Exchange (UPE) Amplitudes (18=10+8)

$$F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$$