Exclusive vector mesons at HERA

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Next-generation GPD studies with exclusive meson production at EIC
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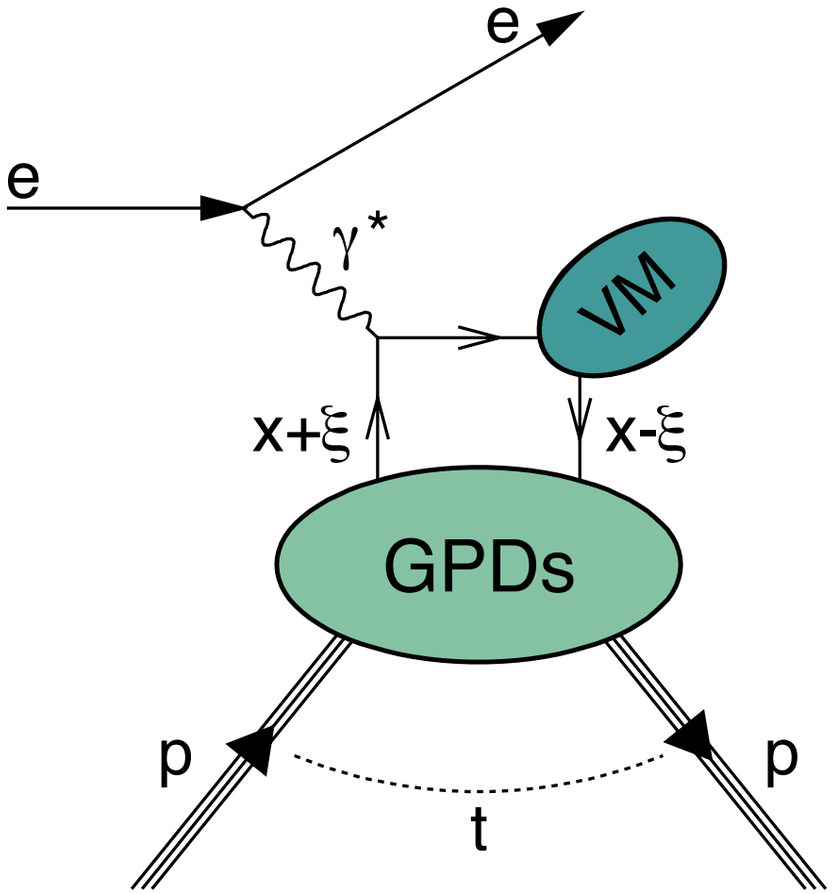
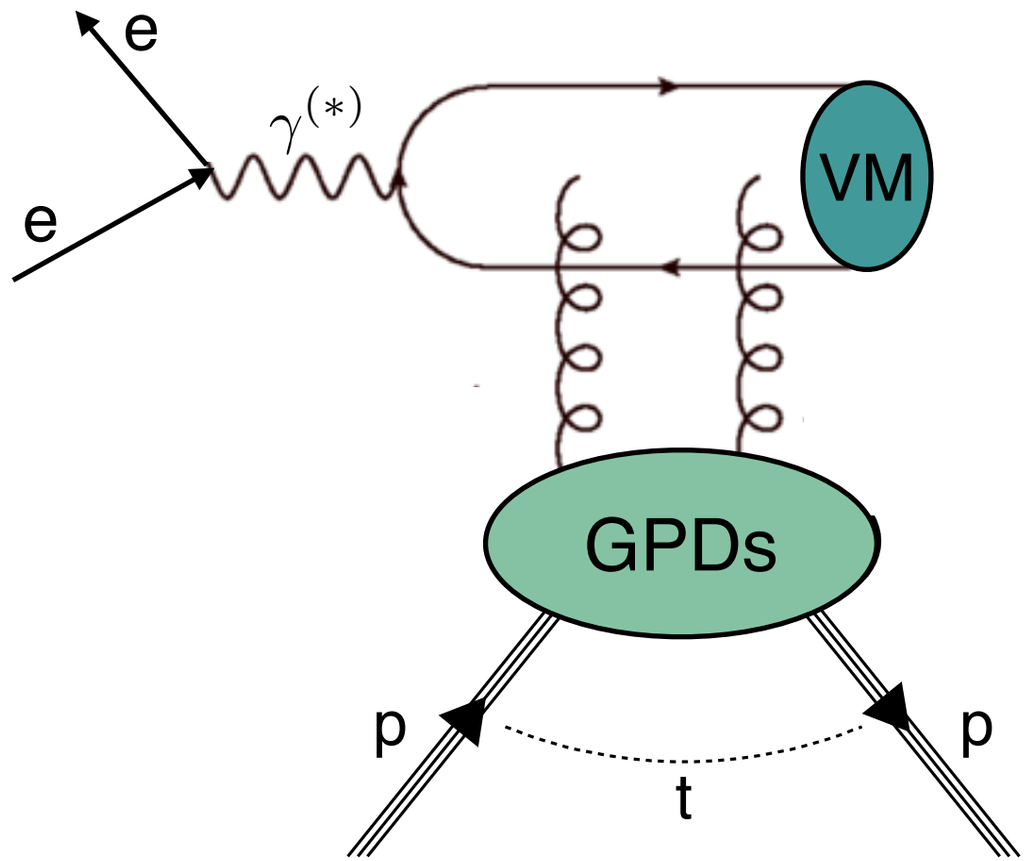
CFNS, Stony Brook

Exclusive vector-meson production at HERA



HERMES:

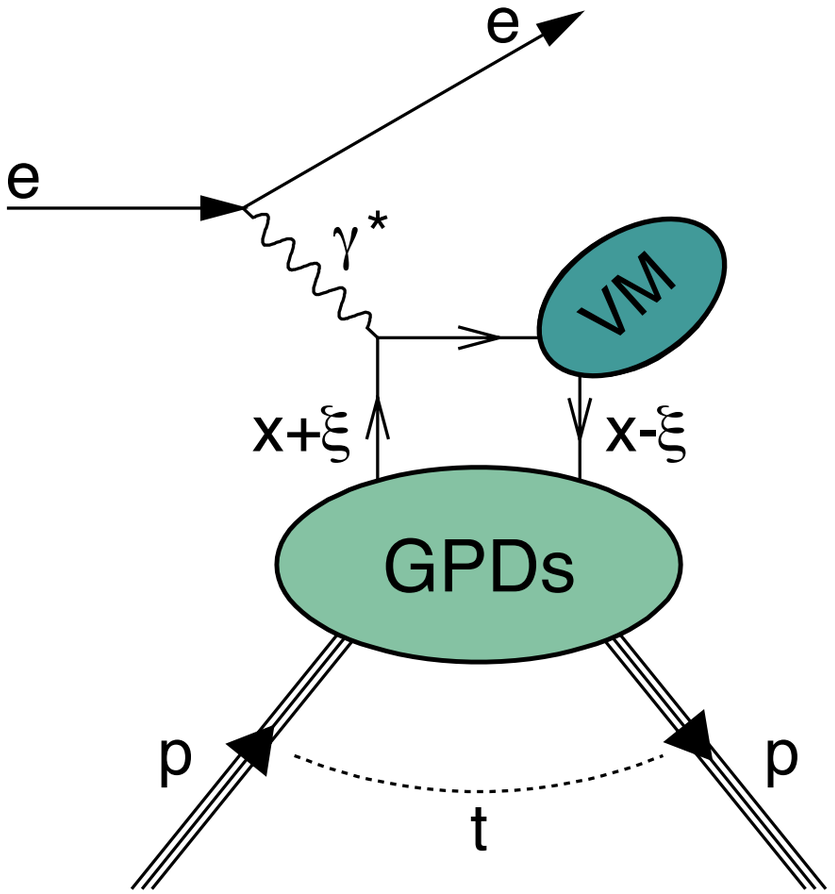
- exclusive electroproduction of ρ and ω
- quark GPDs
- target:
  - unpolarized protons and deuterons
  - transversely polarized protons
- longitudinally polarized lepton beam

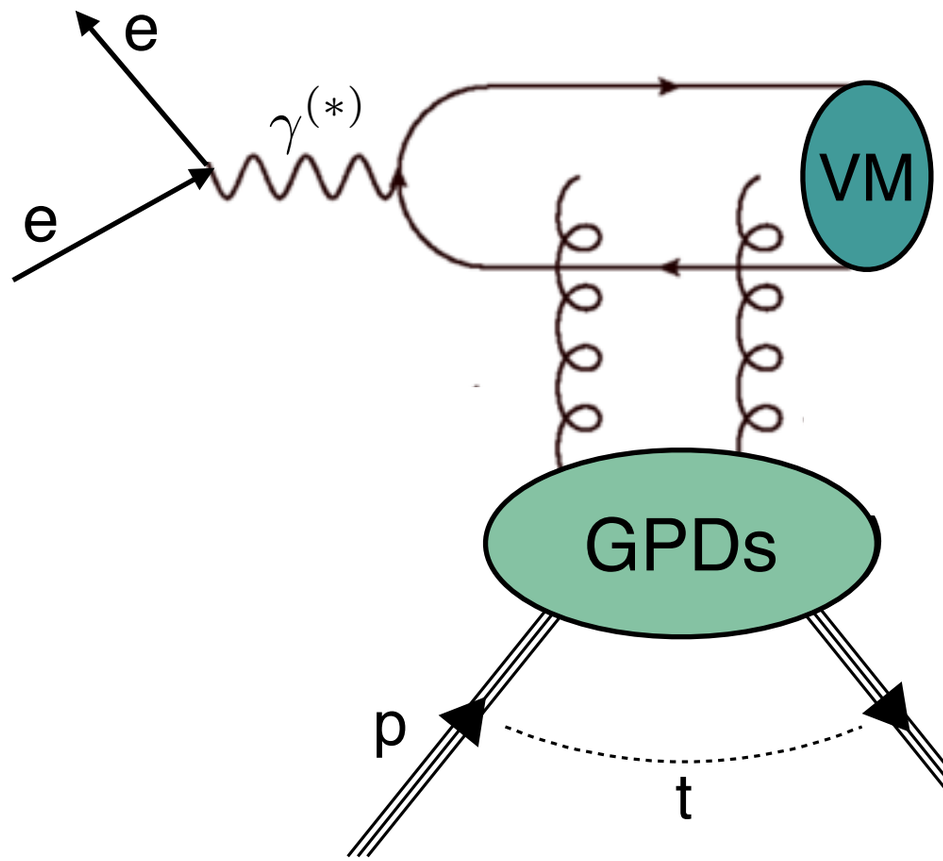


H1 and ZEUS:

- exclusive electroproduction of $\rho,\ \omega,\ \phi,\ J/\psi,\ \psi(2s),\ \Upsilon$
- exclusive photoproduction of $J/\psi,\ \psi(2s),\ \Upsilon$
- gluon GPDs
- unpolarized proton beam

Exclusive vector-meson production at HERA





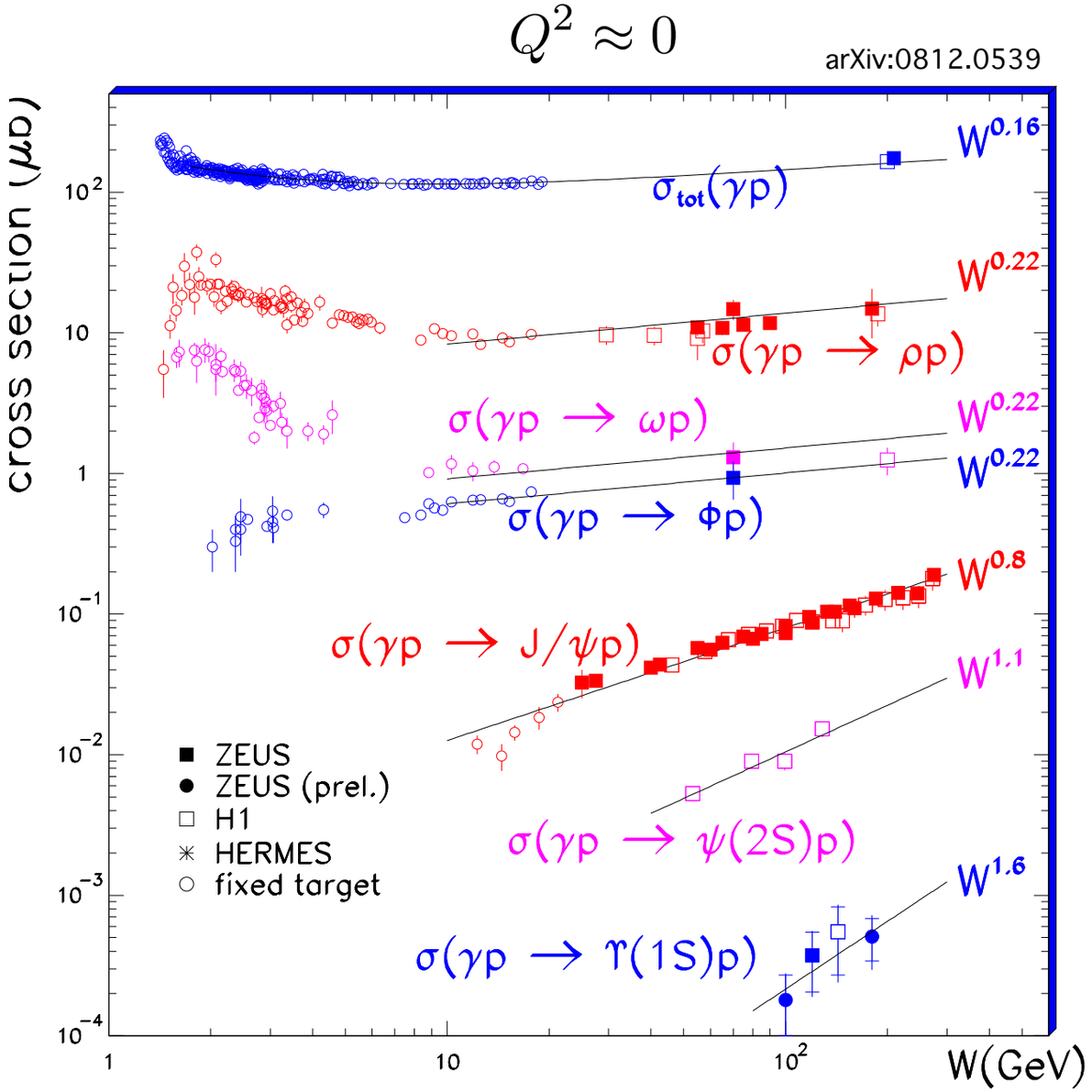
HERMES:

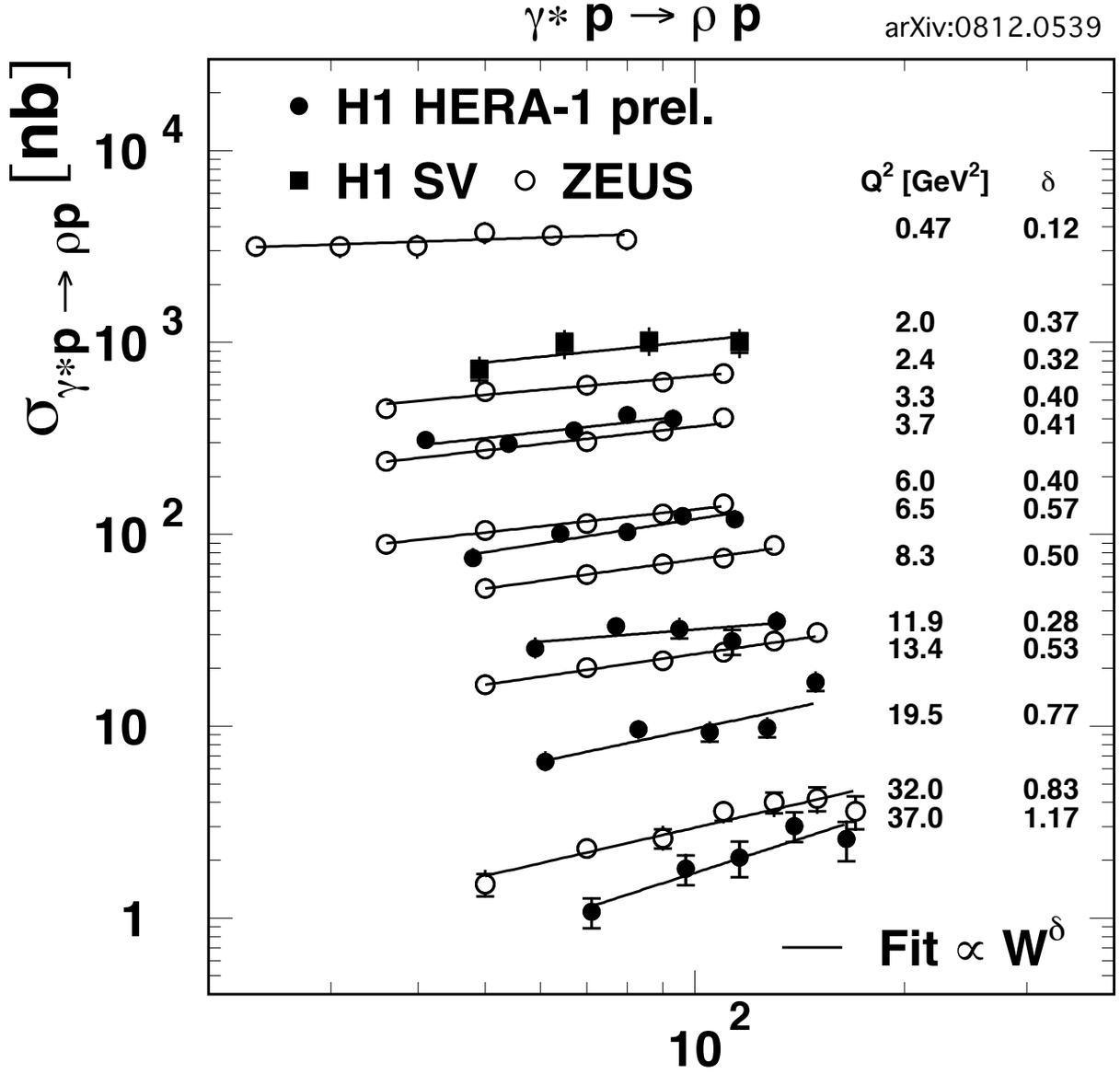
$$10^{-2} \leq x_B \leq 0.5$$
$$1\ \mathrm{GeV}^2 < Q^2 < 10\ \mathrm{GeV}^2$$
$$3.0\ \mathrm{GeV} \leq W \leq 6.3\ \mathrm{GeV}$$

H1 and ZEUS:

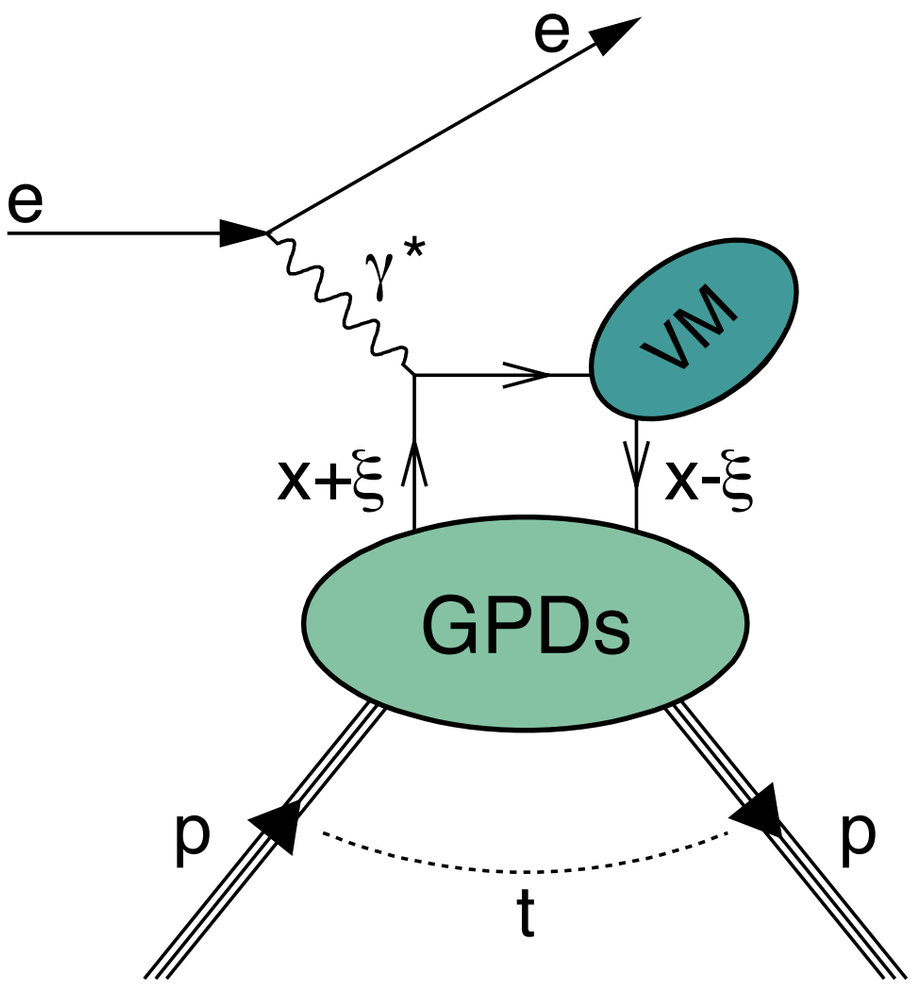
$$10^{-4} \leq x_B \leq 10^{-2}$$
$$2\ \mathrm{GeV}^2 \leq Q^2 \leq 100\ \mathrm{GeV}^2 \text{ (DIS)}$$
$$30\ \mathrm{GeV} \leq W \leq 300\ \mathrm{GeV}$$

W dependence





Exclusive vector-meson production



Target polarization state

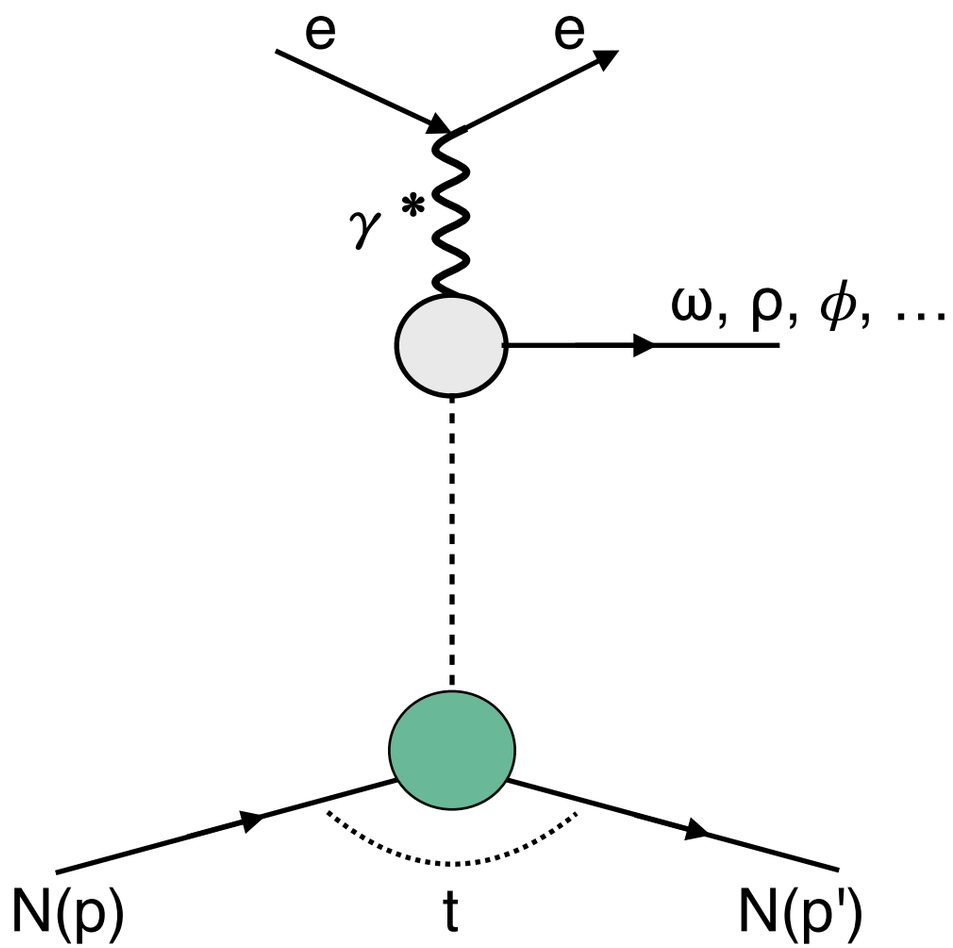
- unpolarized target:

  nucleon-helicity-non-flip GPDs H, $\tilde{H}$ and $\overline{E}_T=2H_T+\tilde{E}_T$.

- transversely polarized target:

  nucleon-helicity-flip GPDs E, $\tilde{E}$ and H_T.

Exclusive vector-meson production



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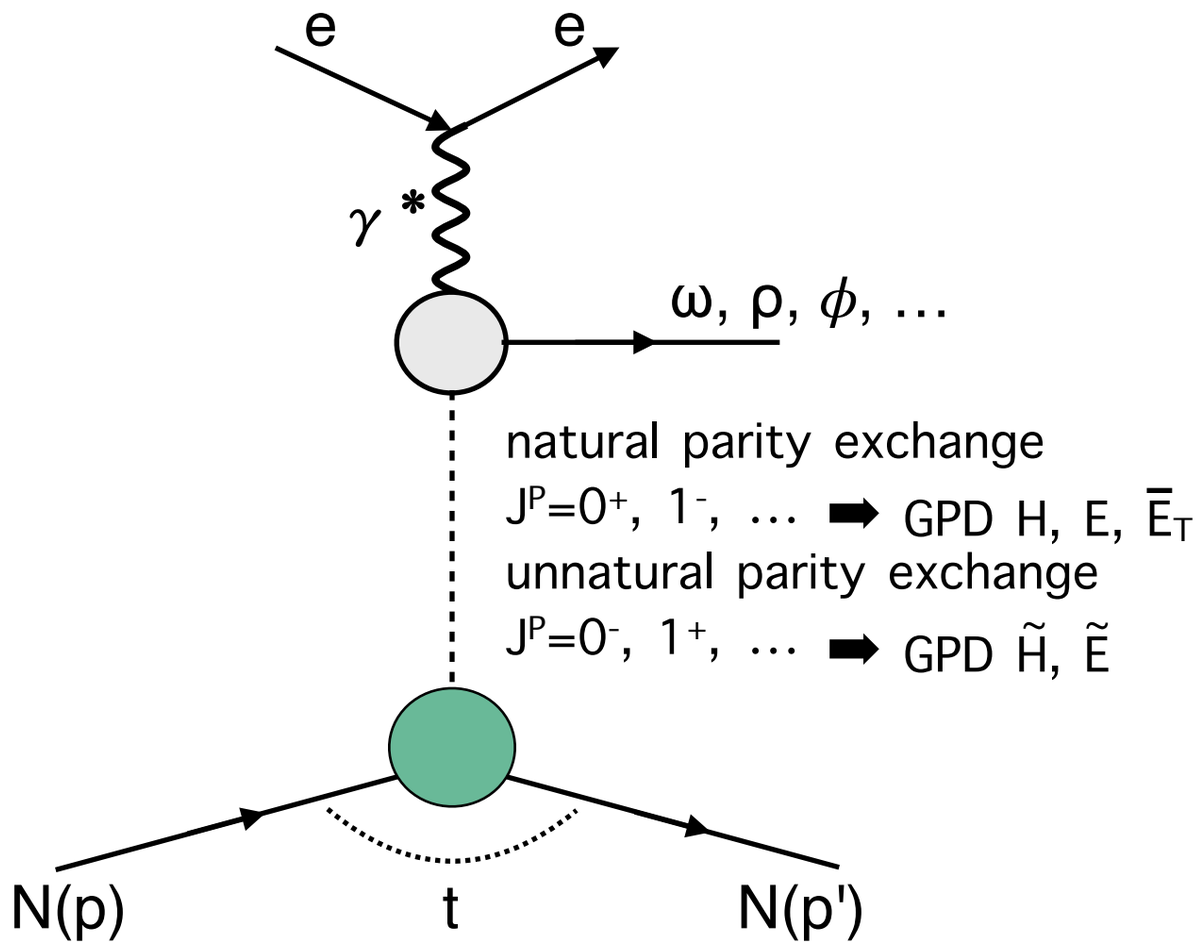

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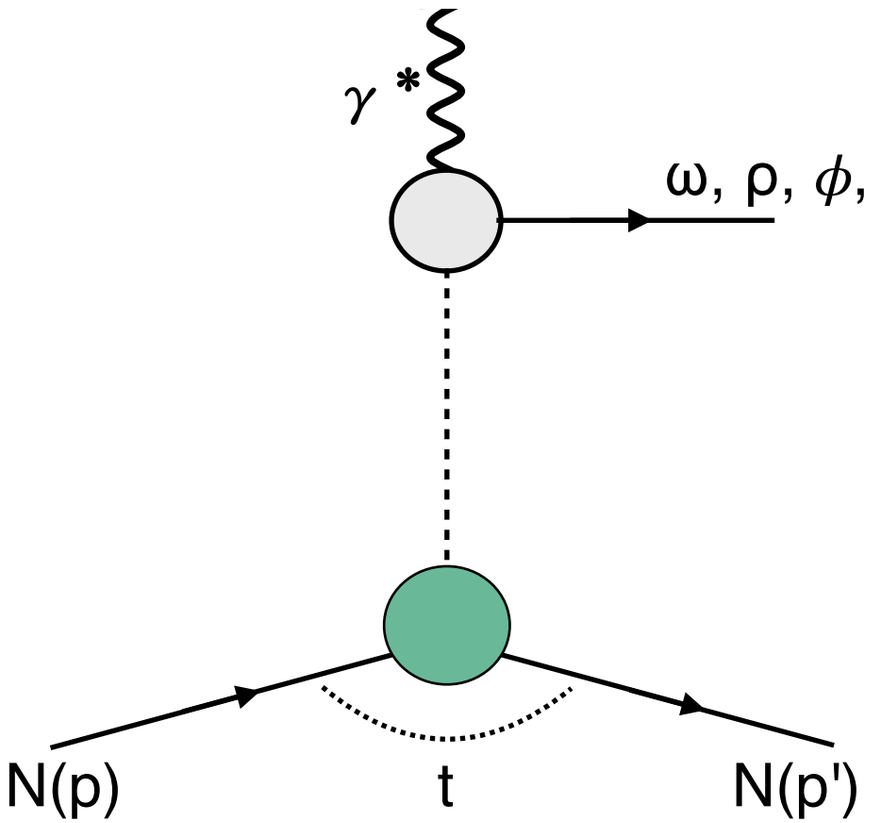
Helicity amplitude ratios and SDMEs

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

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



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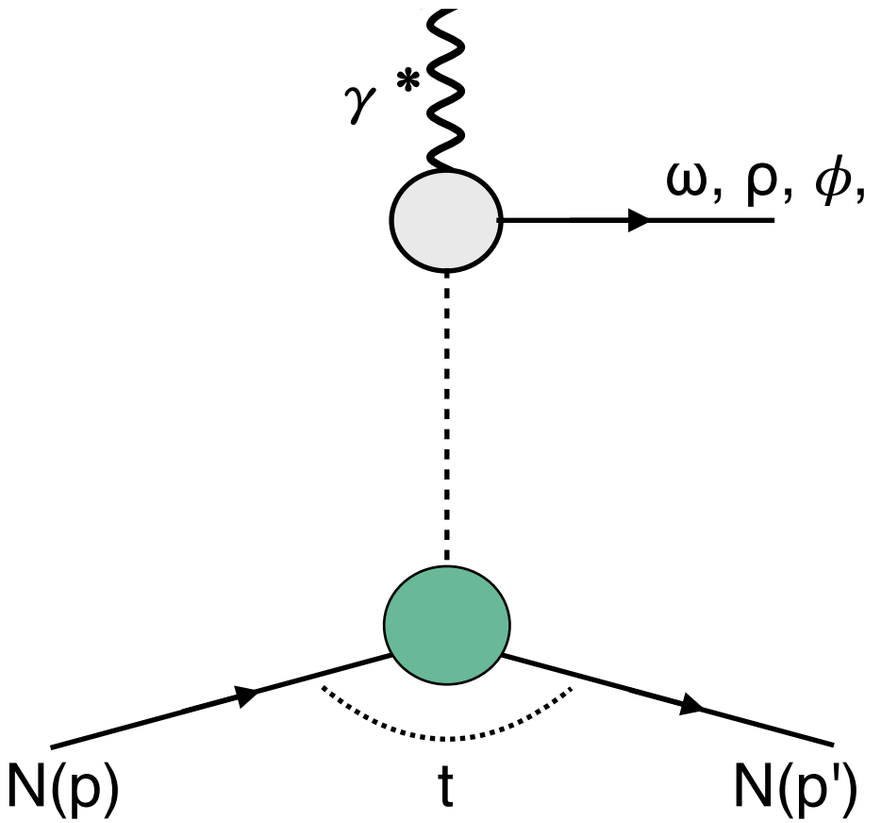

- Helicity amplitude $F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$

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

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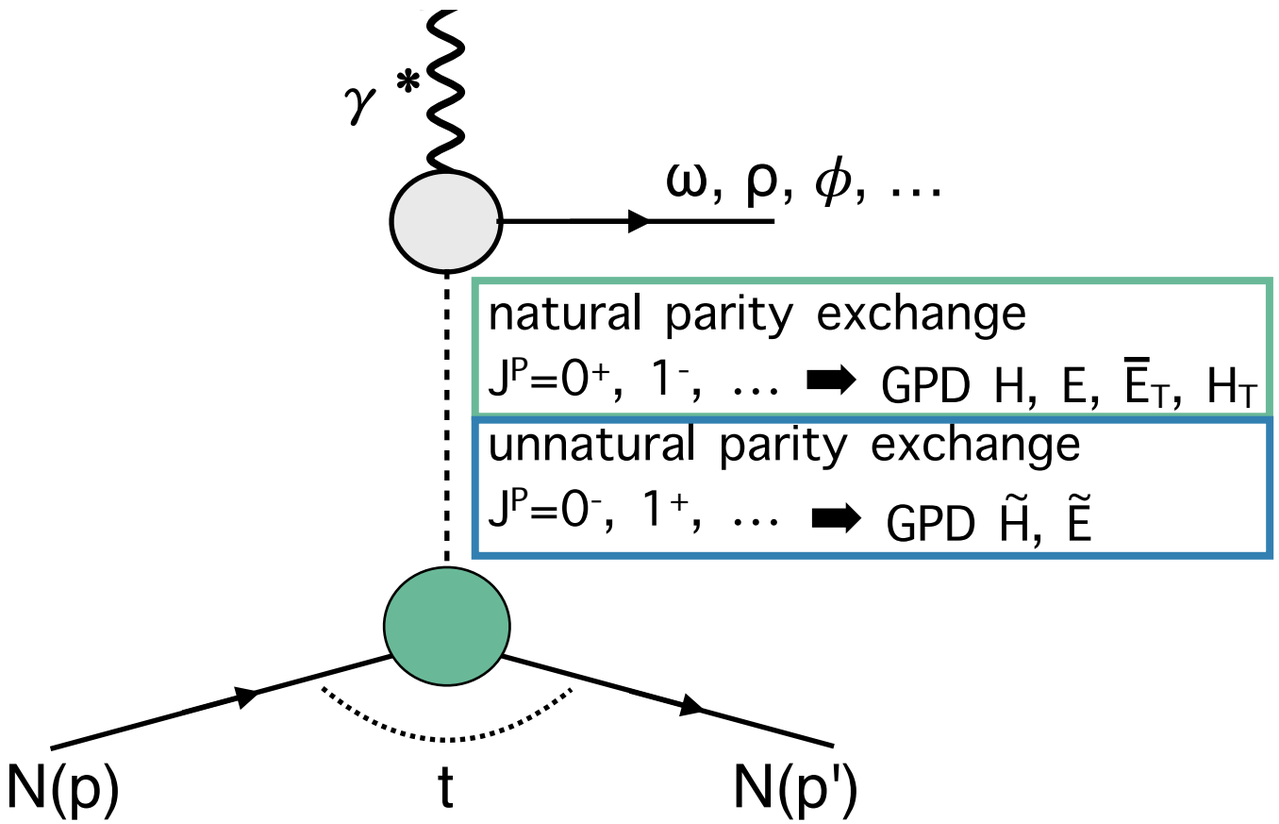

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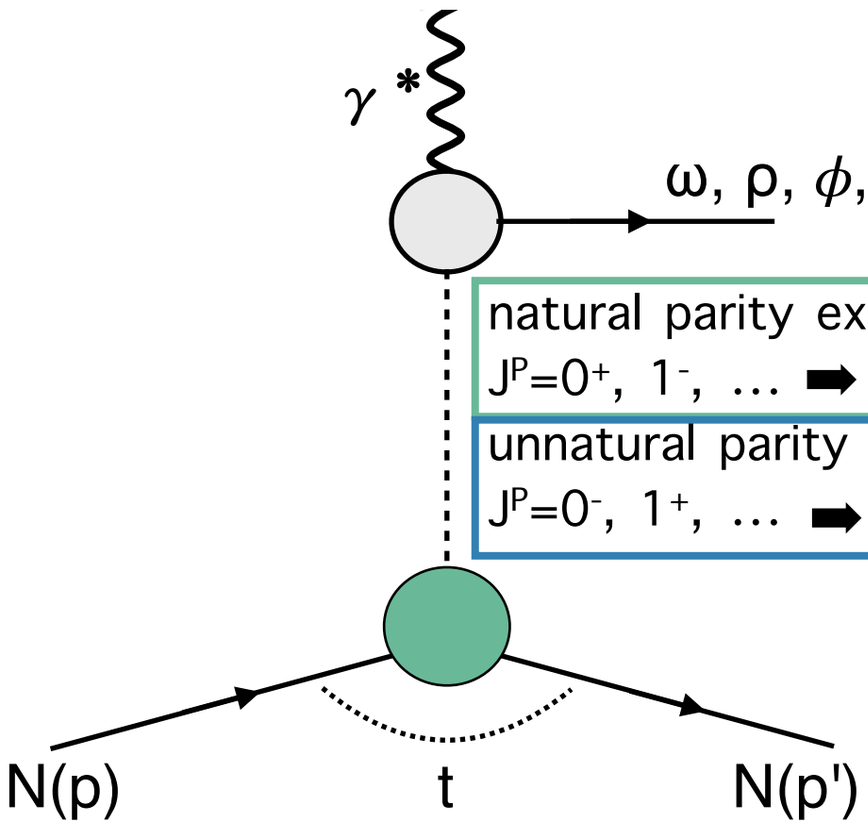

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- Helicity amplitude ratios

$$t^{(n)}_{\lambda_V \lambda_\gamma} = T^{(n)}_{\lambda_V \lambda_\gamma} / T_{0\frac{1}{2}0\frac{1}{2}}$$

$$u^{(n)}_{\lambda_V \lambda_\gamma} = U^{(n)}_{\lambda_V \lambda_\gamma} / T_{0\frac{1}{2}0\frac{1}{2}}$$

$$n = 1 \quad \lambda_N = \lambda'_N$$
$$n = 2 \quad \lambda_N \neq \lambda'_N$$

Helicity amplitude ratios and SDMEs

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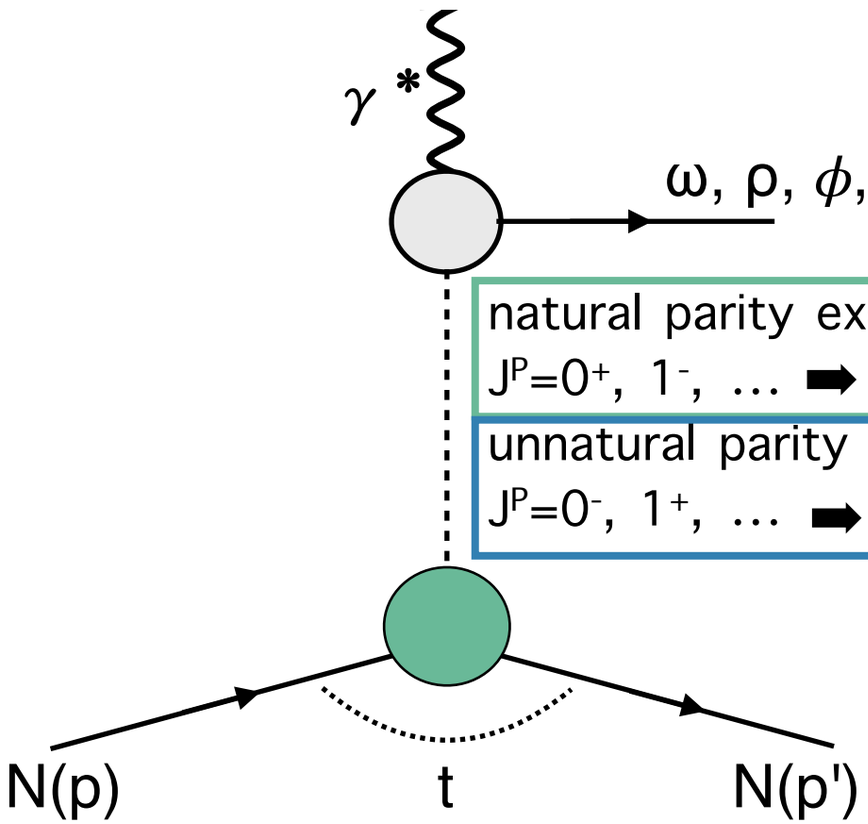

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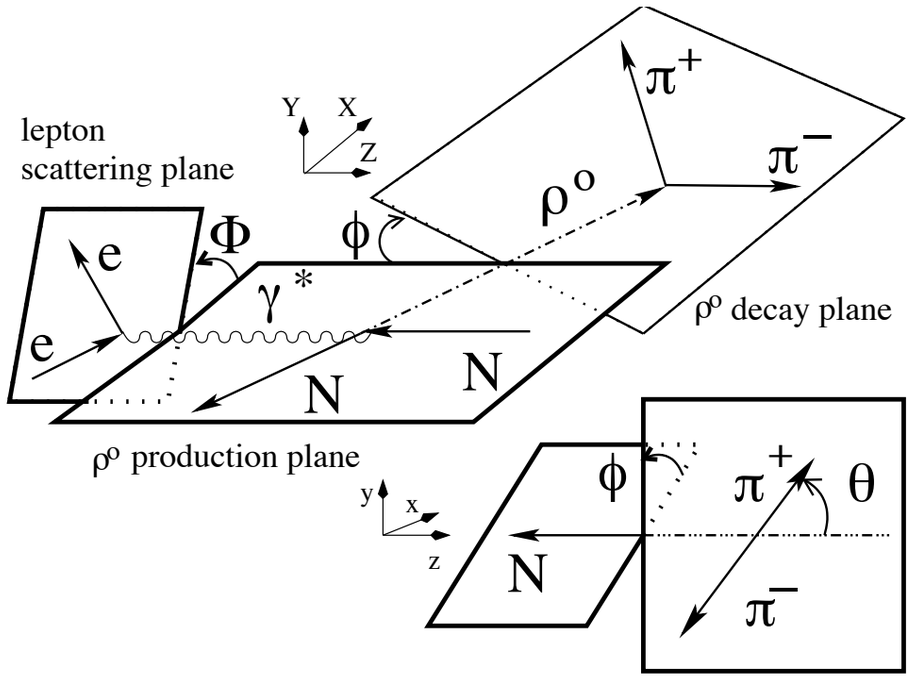
- SDMEs

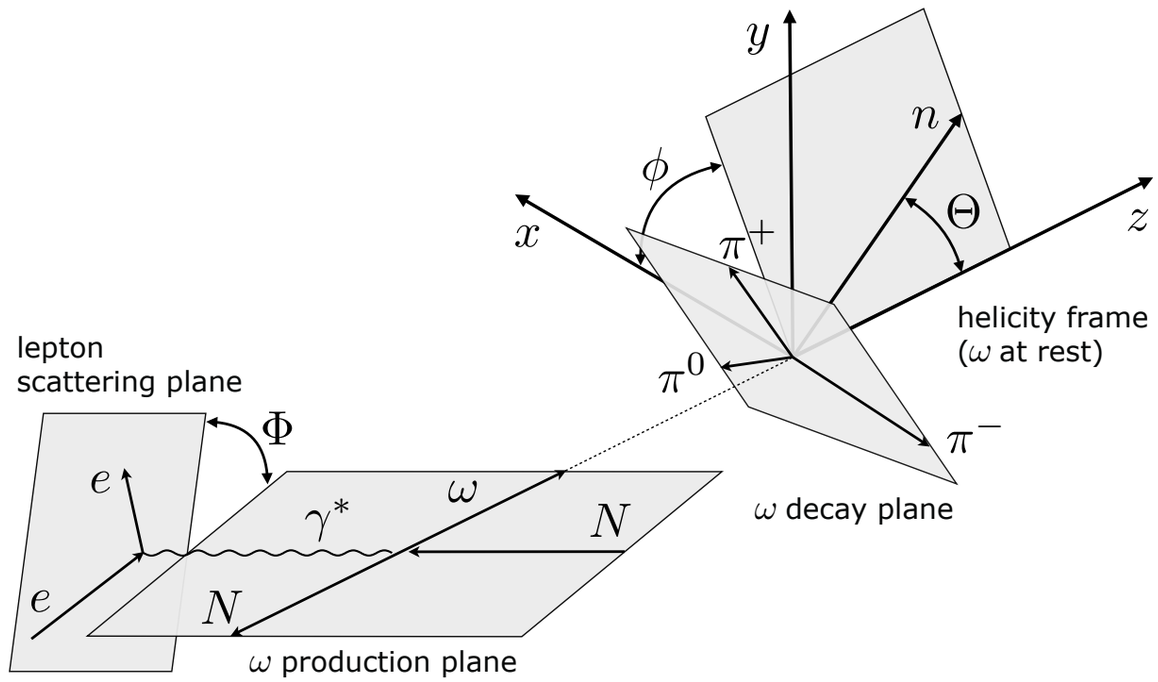
$$\propto F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \Sigma^\alpha_{\lambda_\gamma \lambda'_\gamma} F^*_{\lambda'_V \lambda'_N \lambda'_\gamma \lambda_N}$$

Angular distributions

$$e + N \to e + N + \rho^0$$
$$\rho^0 \to \pi^+ + \pi^-$$



$$e + N \to e + N + \omega$$
$$\omega \to \pi^+ + \pi^- + \pi^0(2\gamma)$$



Fit angular distribution of decay particles $\mathcal{W}(\Phi, \phi, \Theta)$ and extract either Spin Density Matrix Elements (SDMEs) or helicity amplitude ratios

Angular distributions

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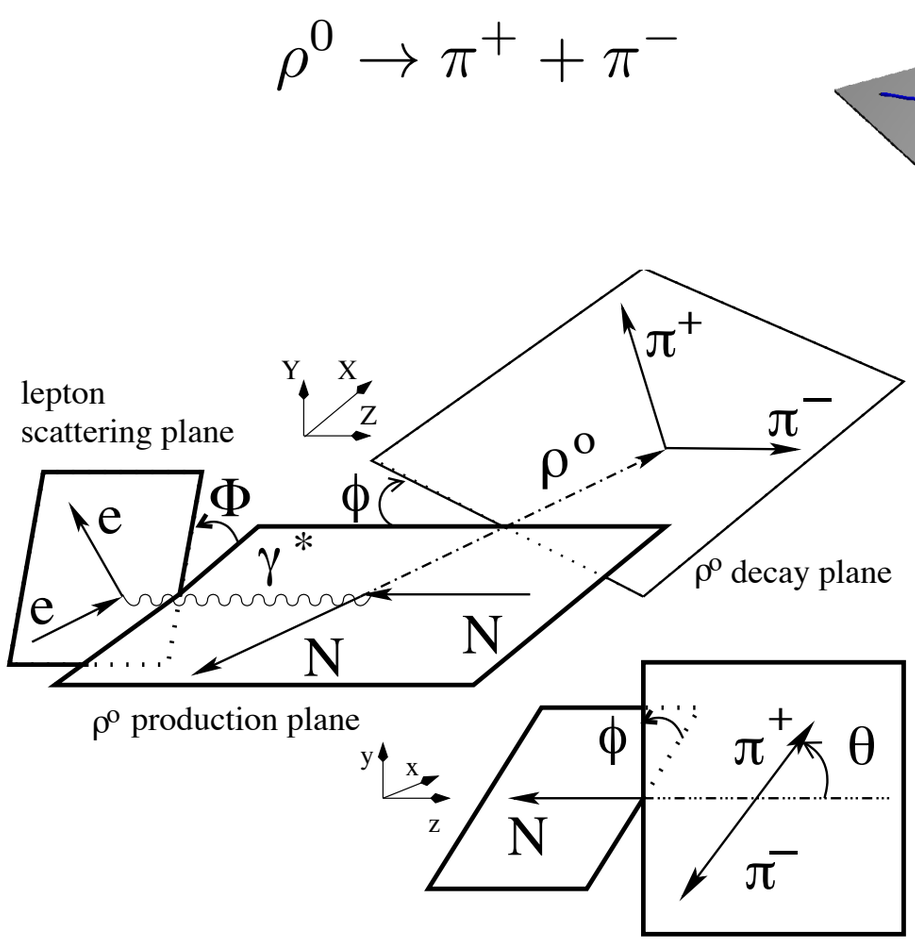

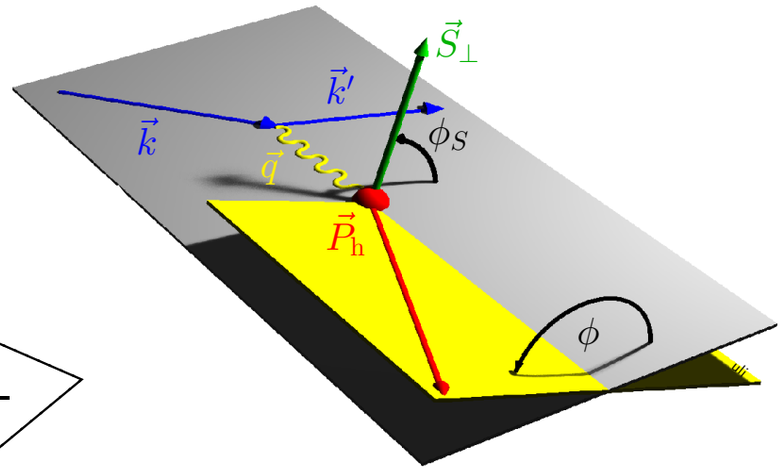

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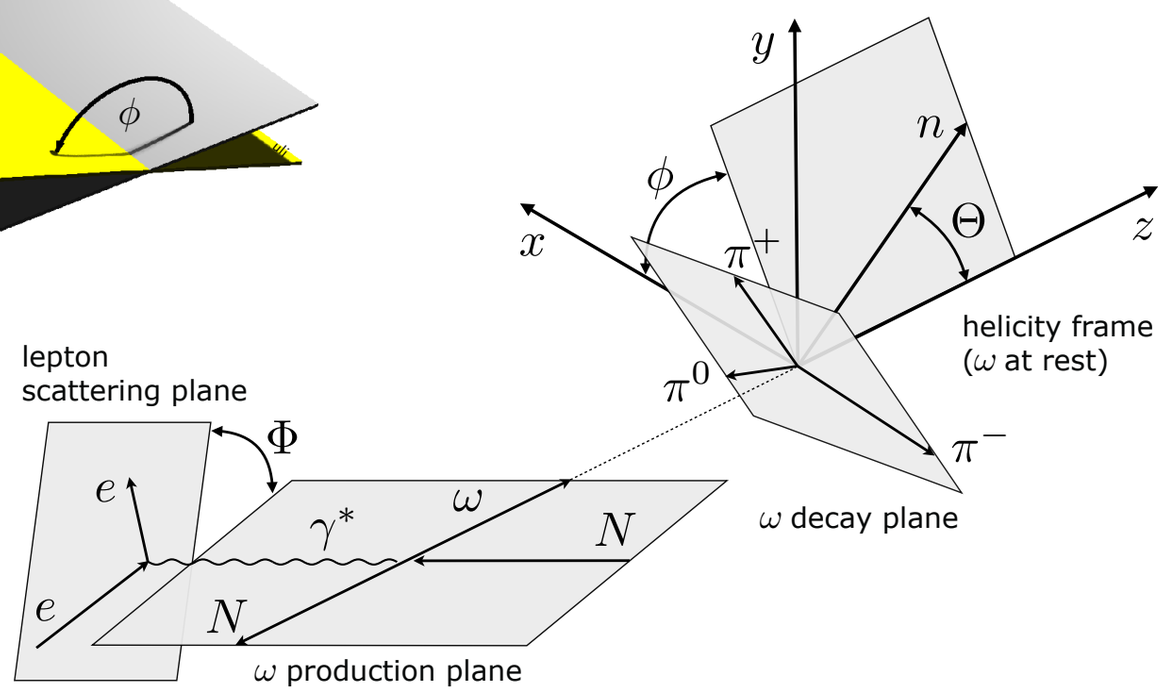
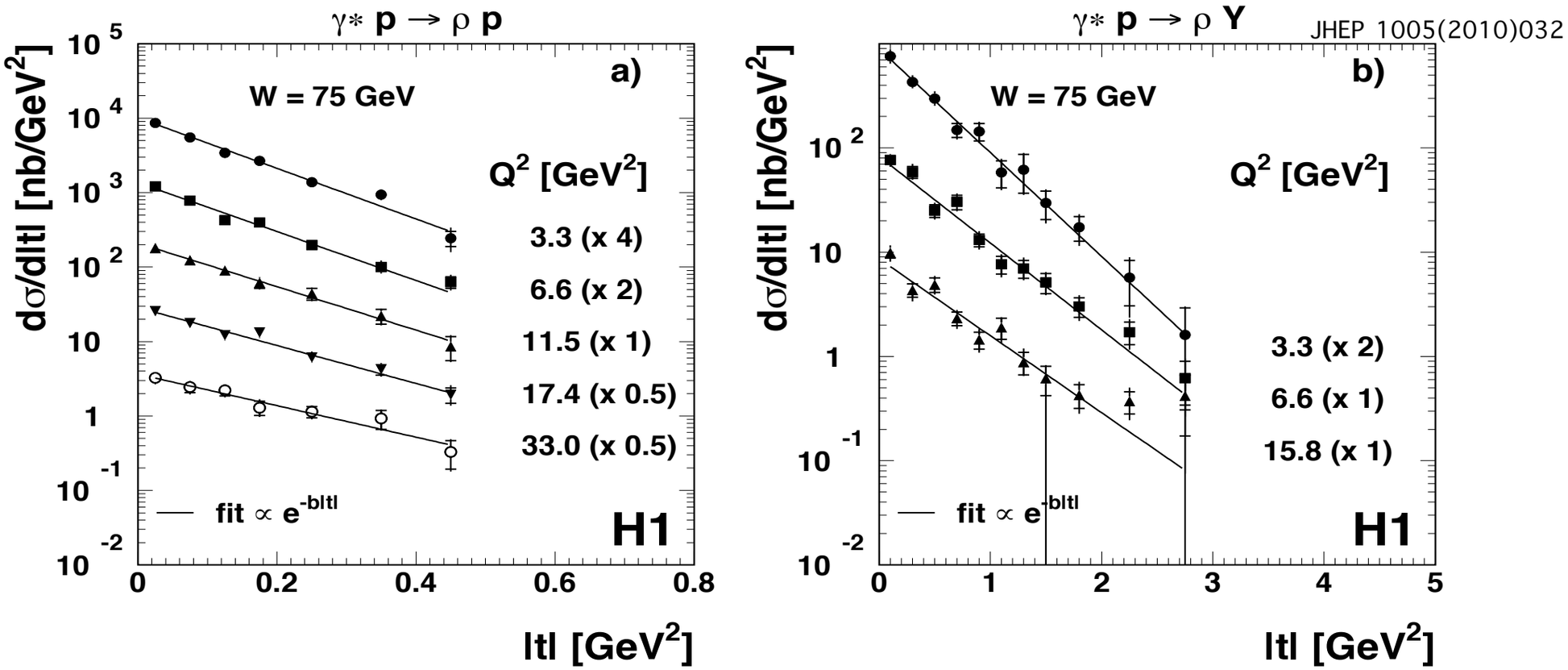


Fit angular distribution of decay particles $\mathcal{W}(\Phi, \phi, \Theta, \phi_S)$ and extract either Spin Density Matrix Elements (SDMEs) or helicity amplitude ratios

Exclusive ρ^0

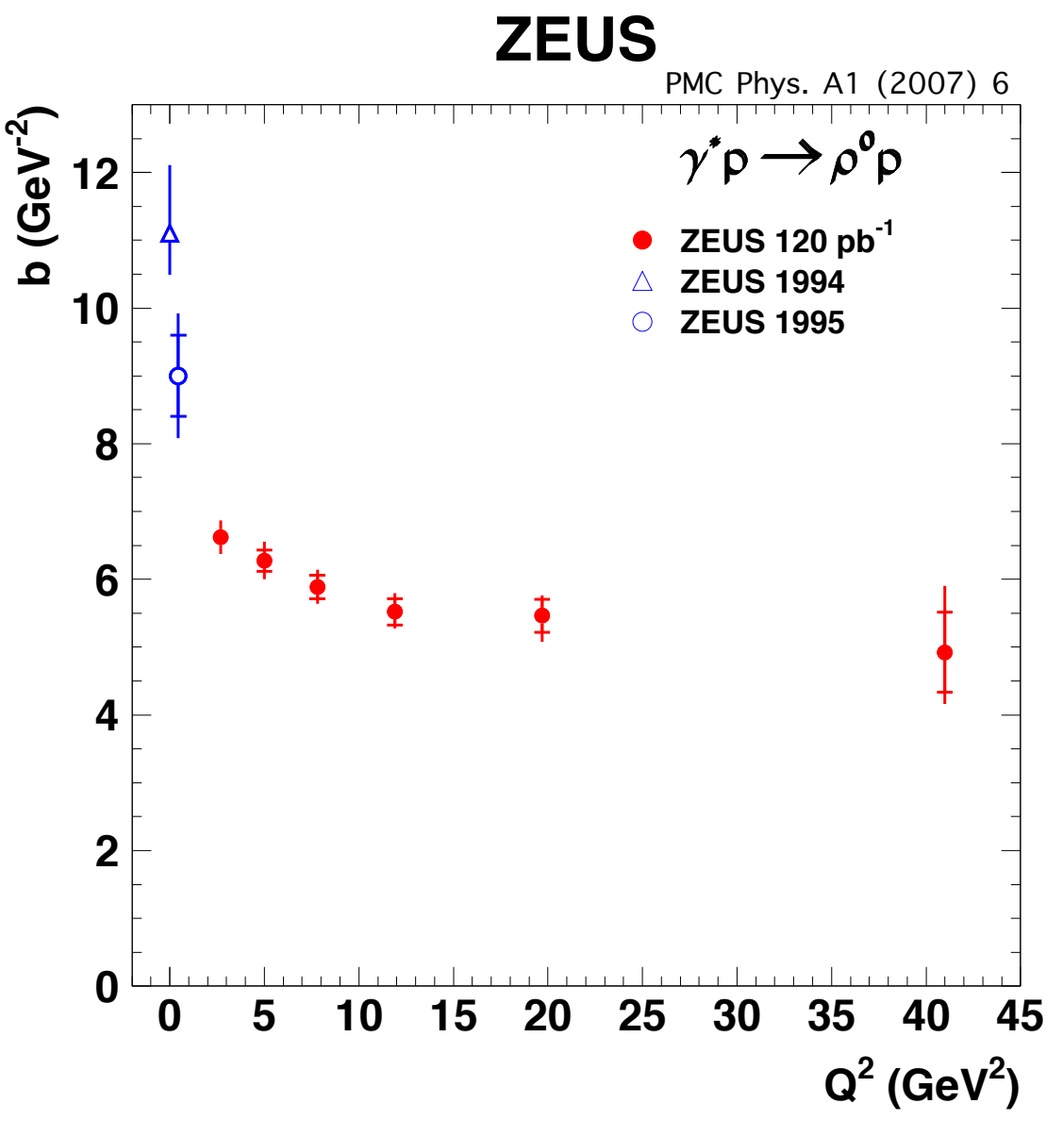
- unpolarized H and D targets
- transversely polarized H target

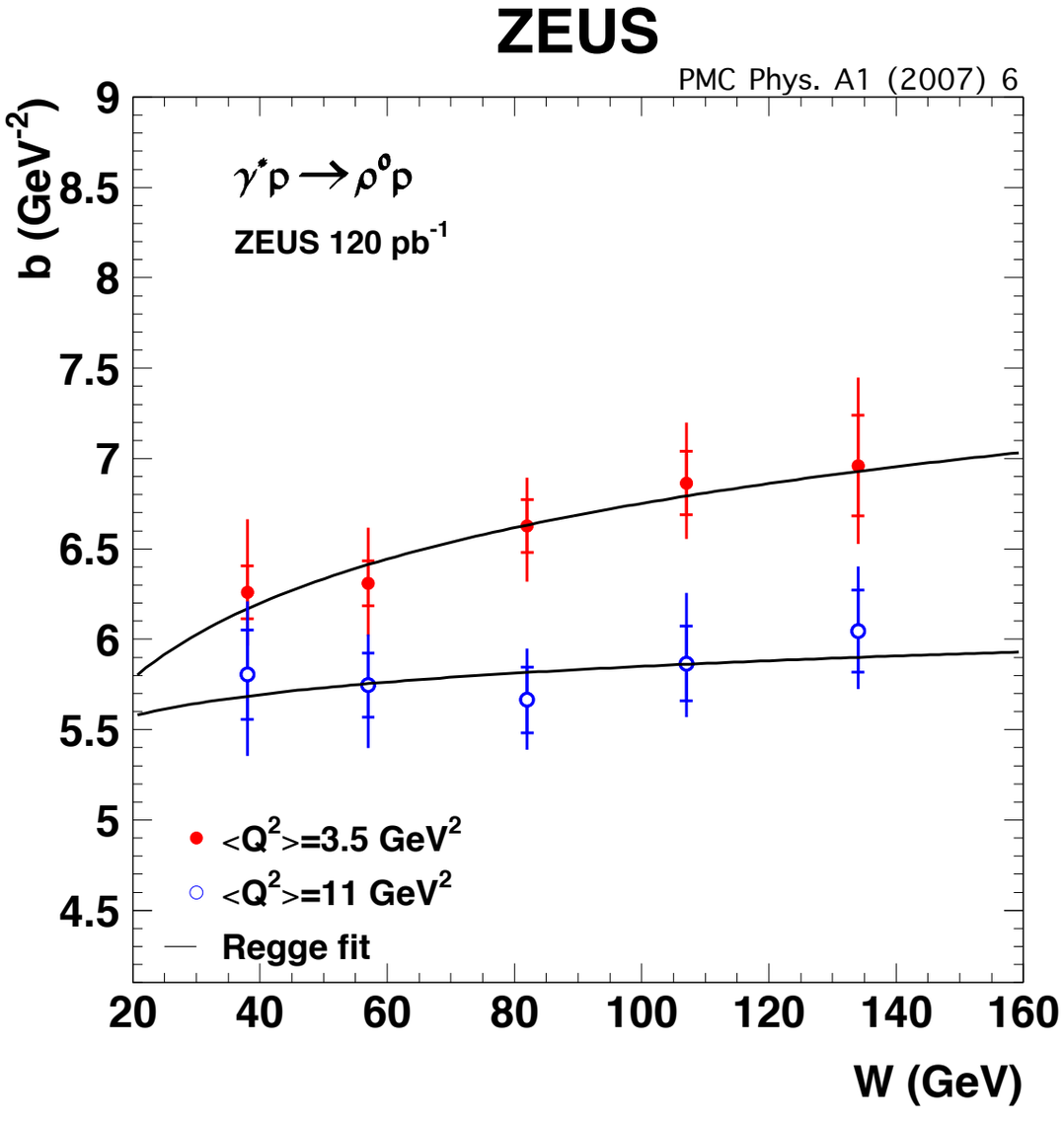
t dependence



$$b = b_Y + b_{q\bar{q}} + b_{\mathbb{P}}(+b_V)$$

b slope





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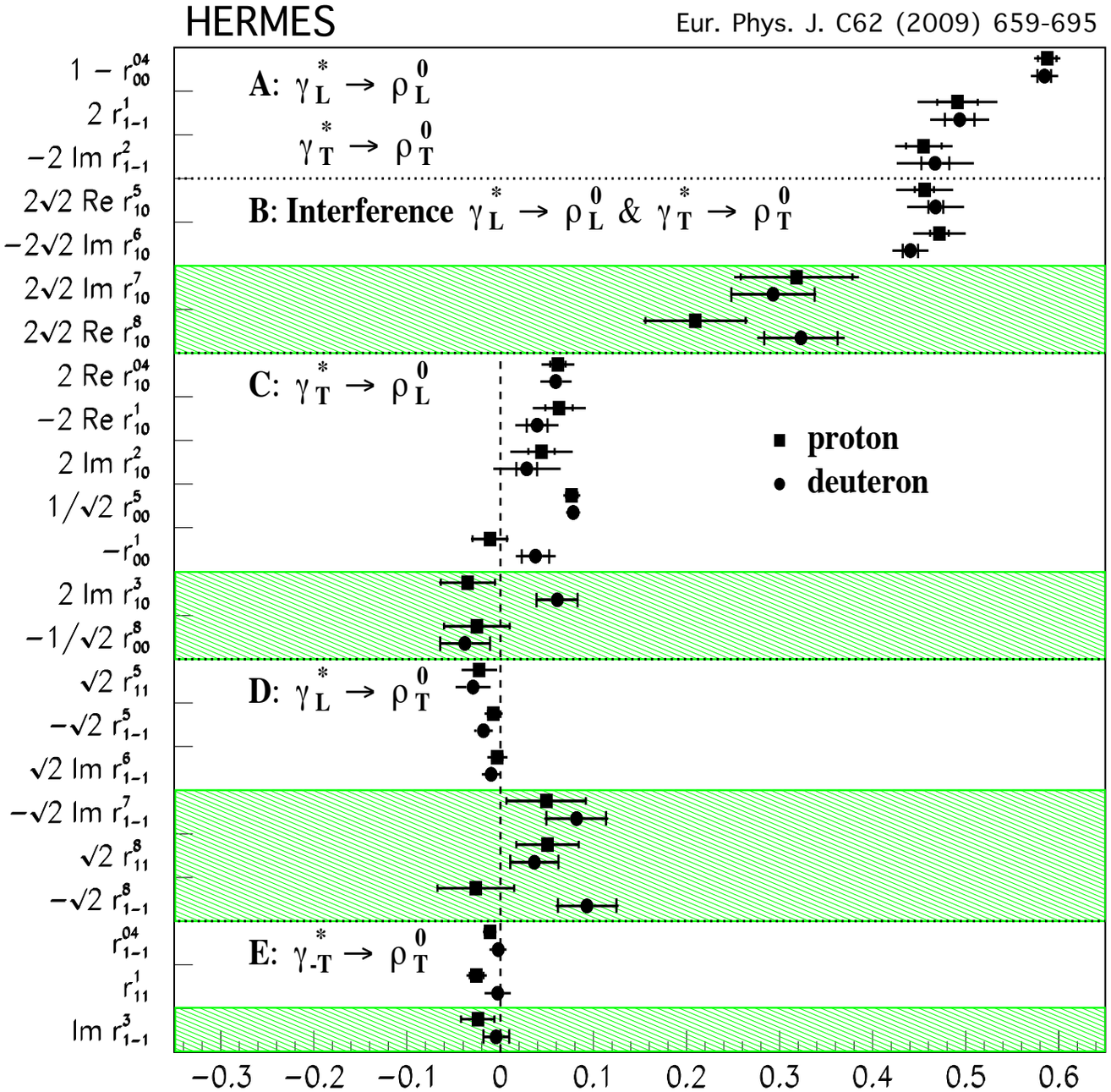
Results ρ SDMEs

longitudinally polarized beam
unpolarized p and d target



- 5 classes of SDMEs
- unpolarized and polarized SDMEs
- proton & deuteron similar

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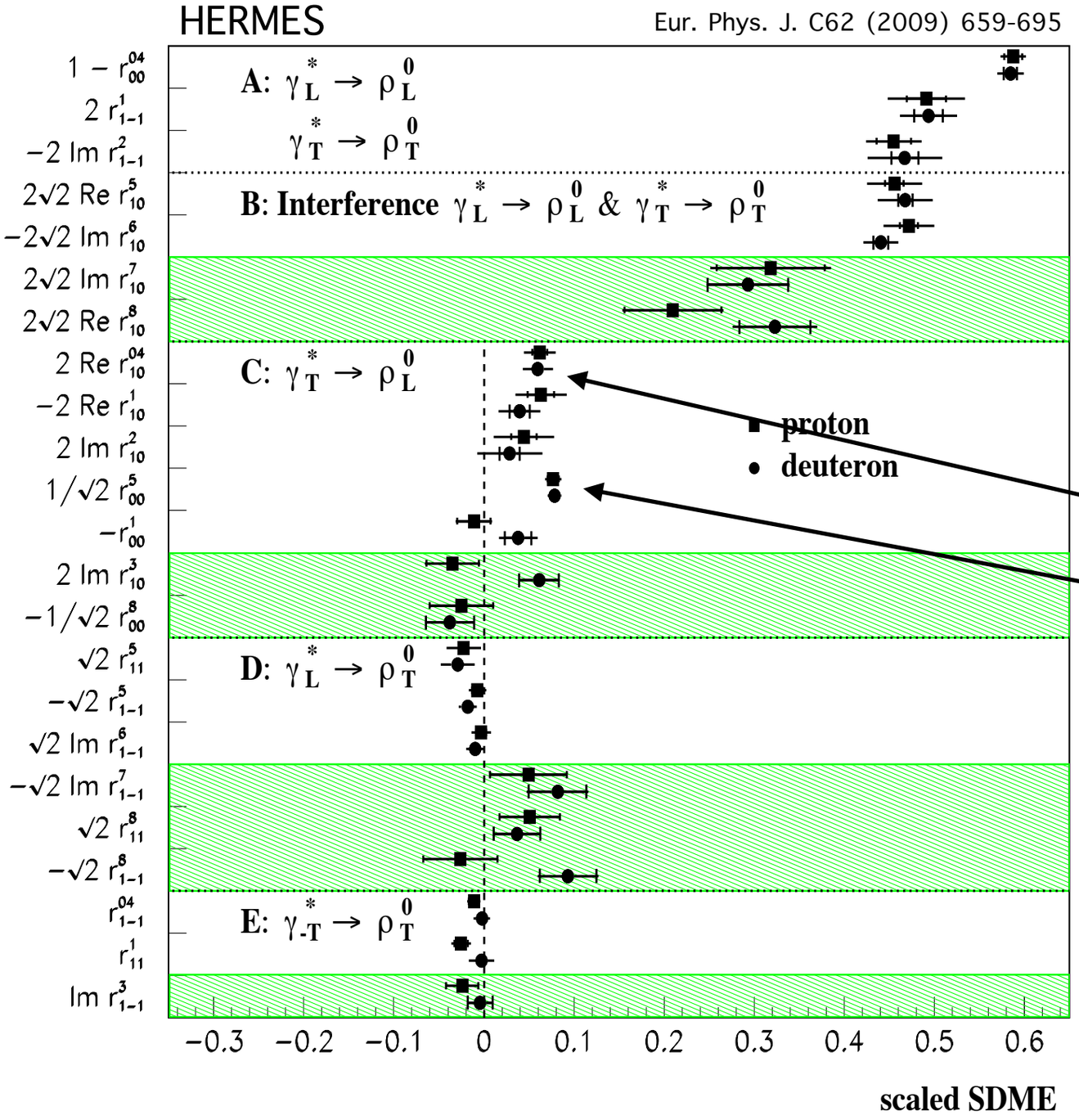

- 5 classes of SDMEs
- unpolarized and polarized SDMEs
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- s-channel helicity conservation ($\lambda_{\gamma*} = \lambda_\omega$):
  - fulfilled for class A & B
  - class C - strong violation:

$\Re\, r^{04}_{10} \neq 0$ by $4(4)\sigma$ for p(d)

$r^5_{00} \neq 0$ by $9(10)\sigma$ for p(d)

Results ρ SDMEs

longitudinally polarized beam
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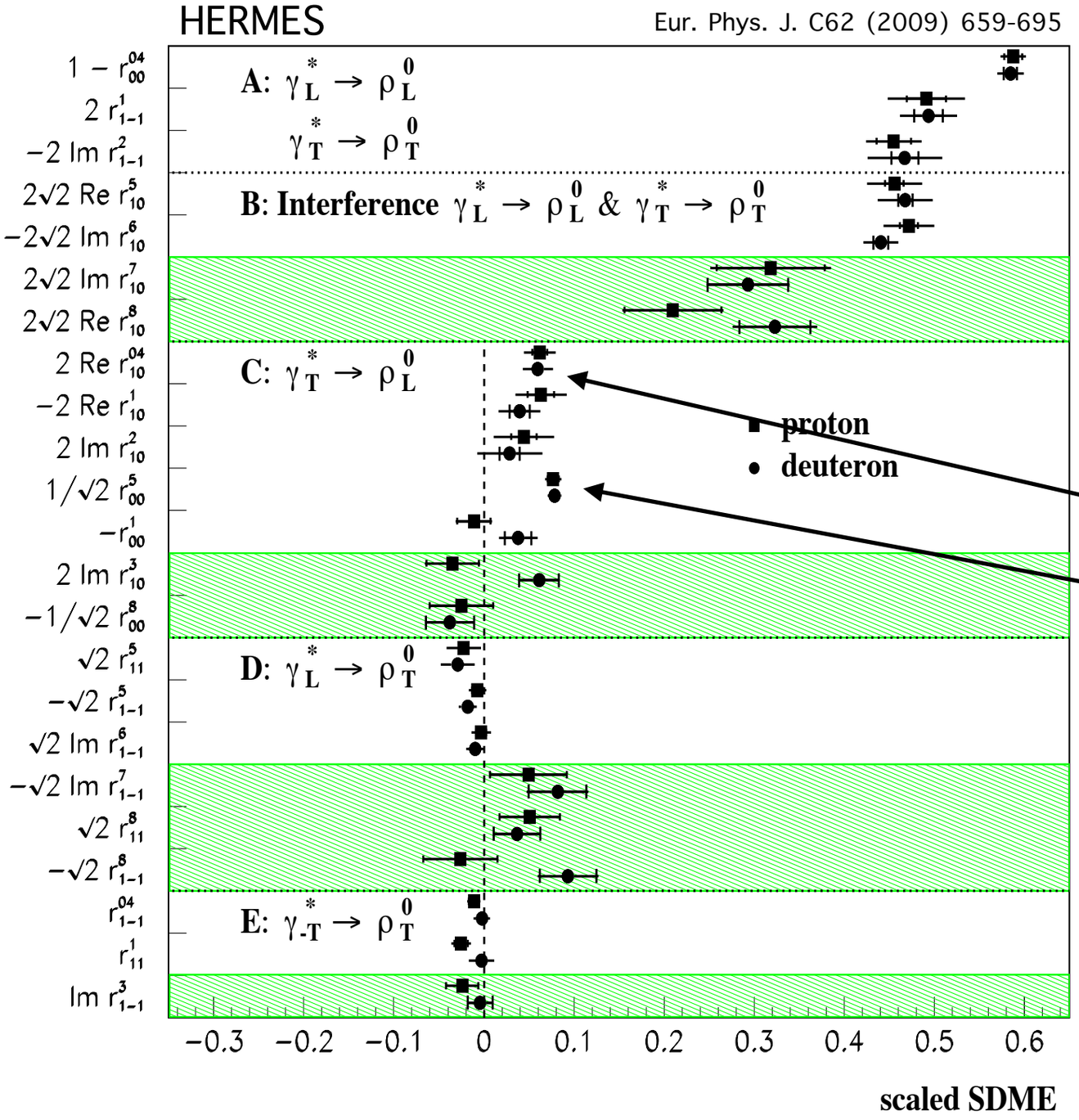

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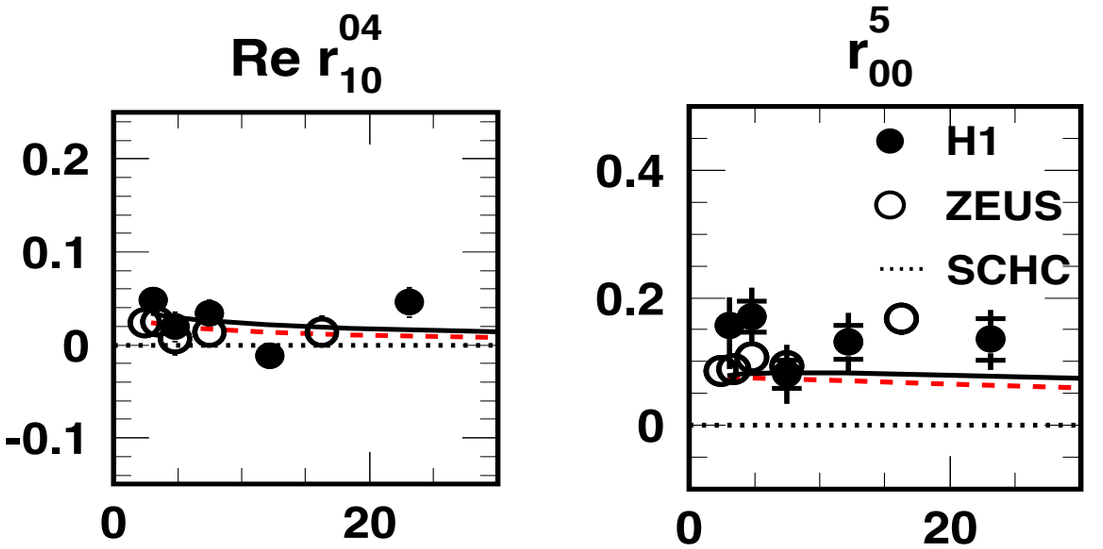
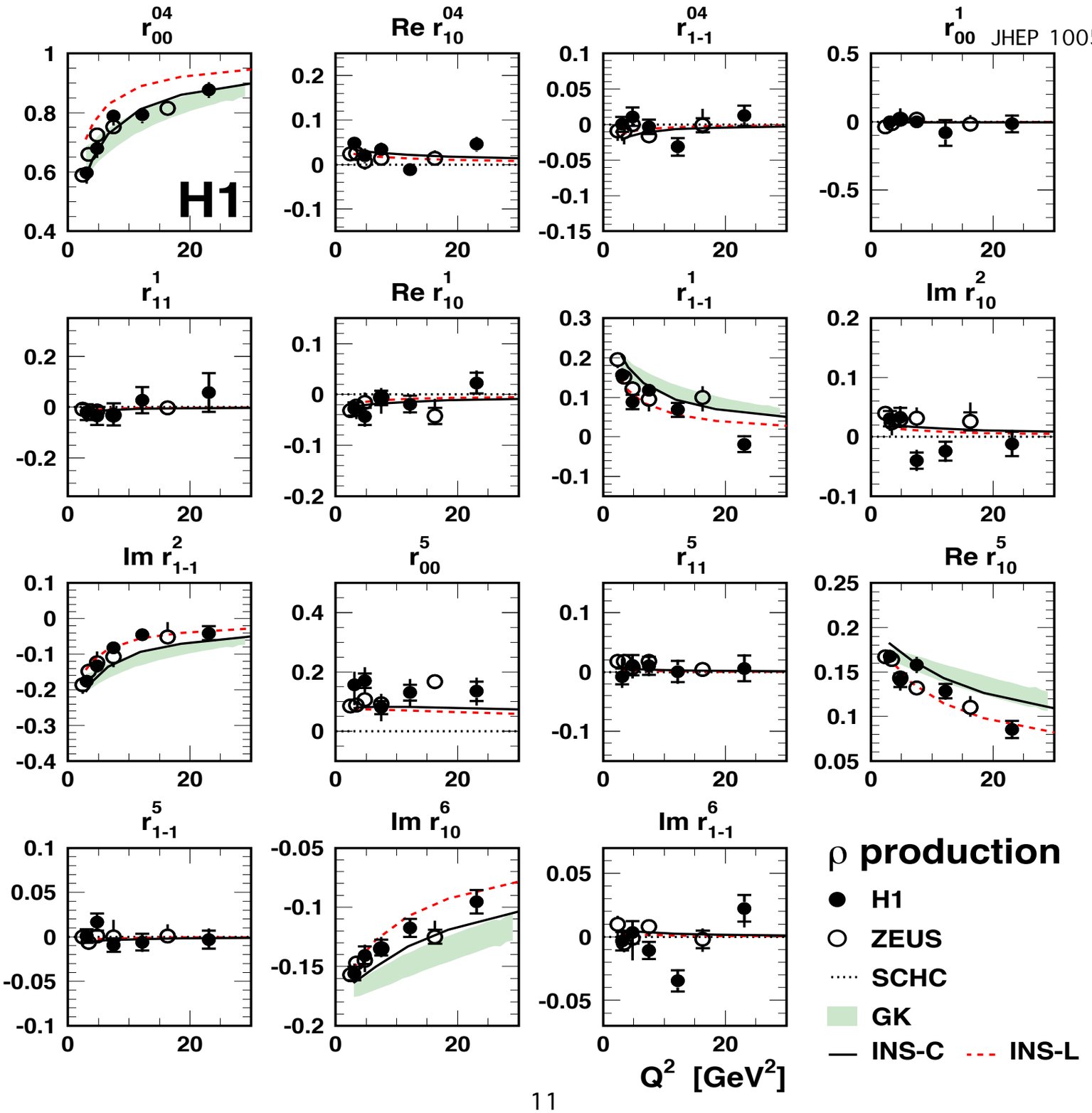


JHEP 1005(2010)032

Q^2 dependence



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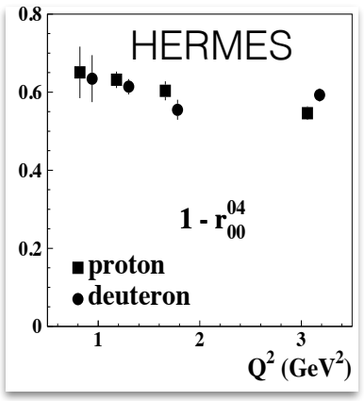
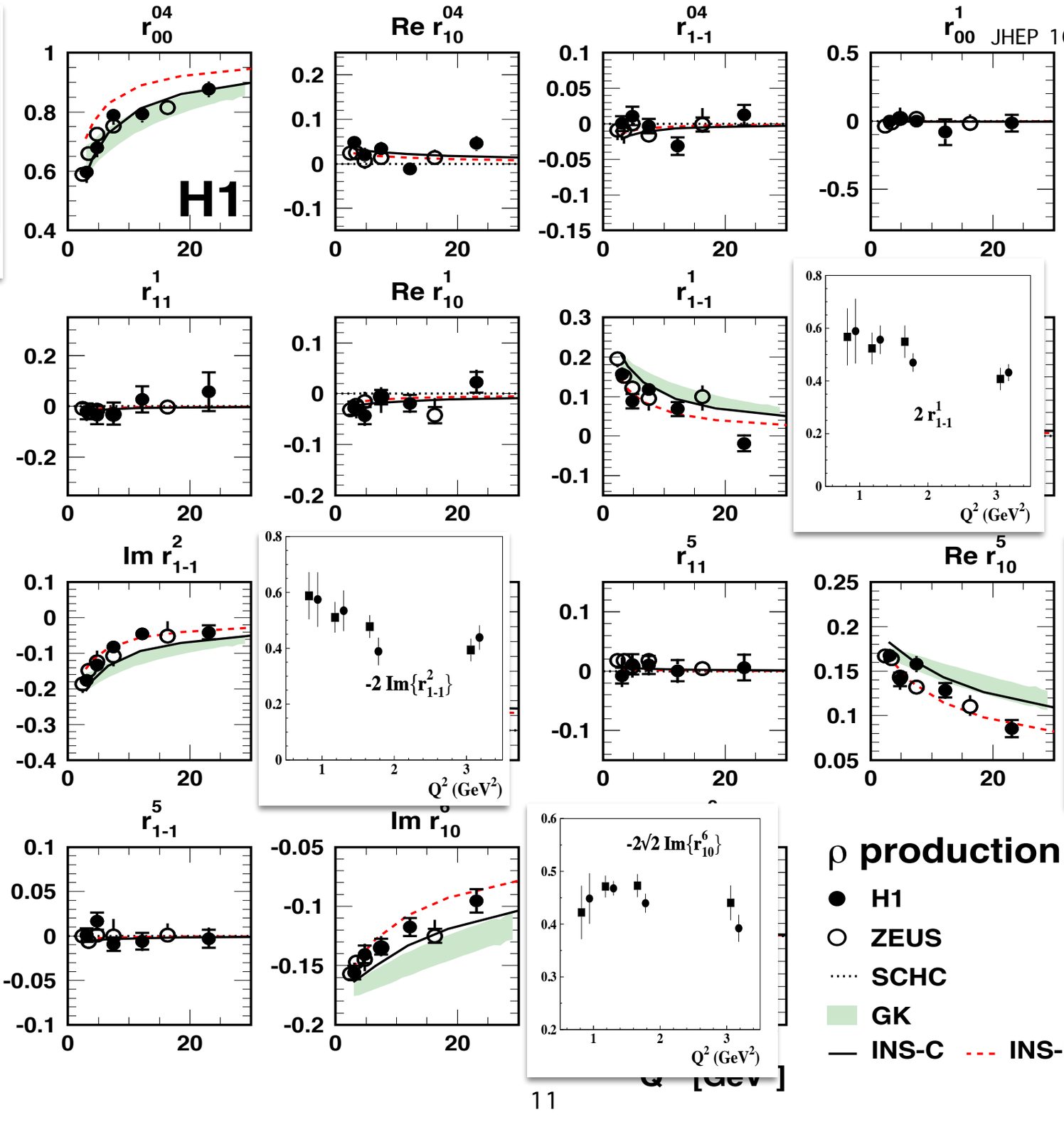
Q^2 dependence

Eur. Phys. J. C62 (2009) 659-695



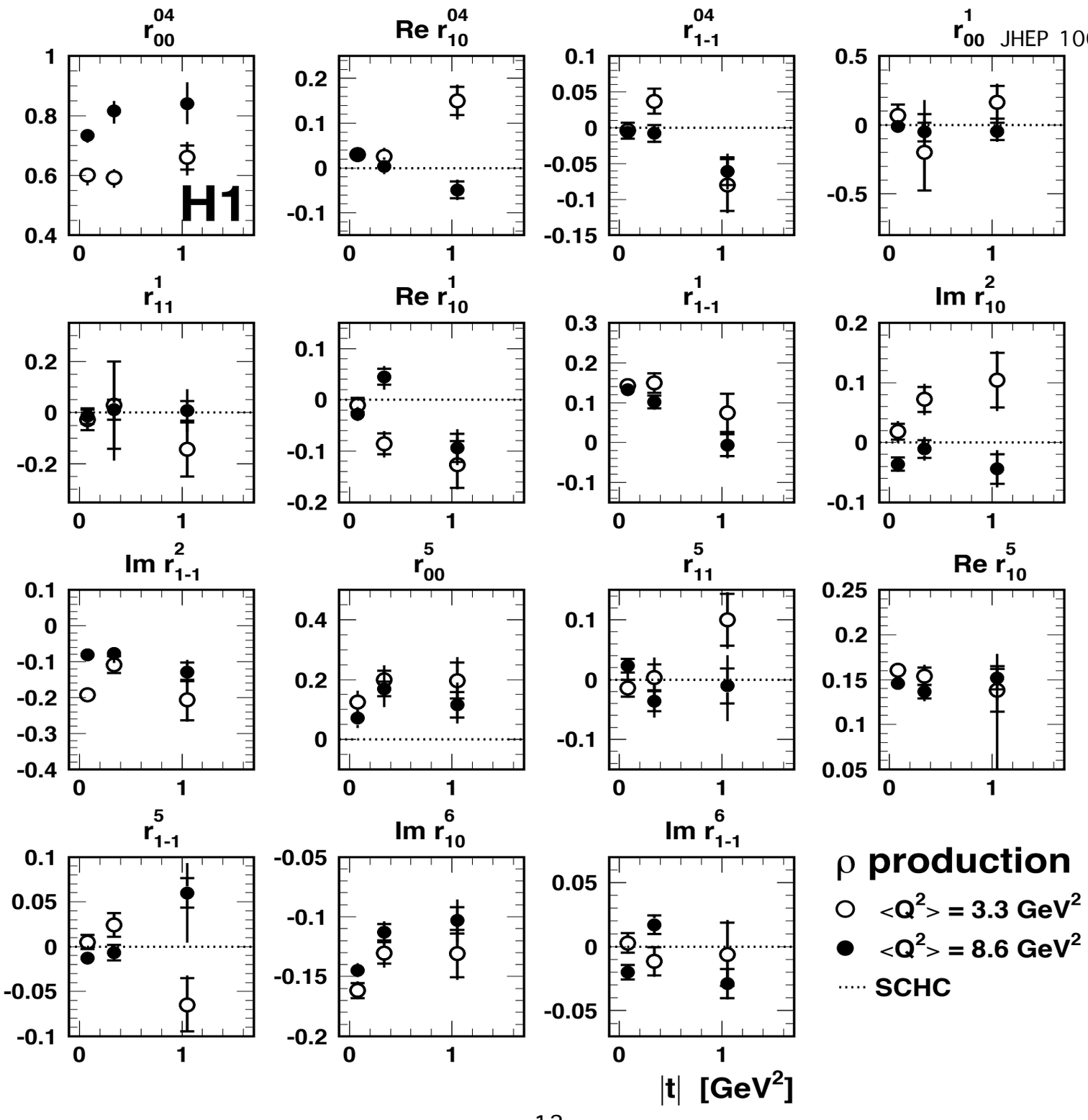


JHEP 1005(2010)032

ρ production

- H1
- ZEUS
- SCHC
- GK
- INS-C
- INS-L

t dependence



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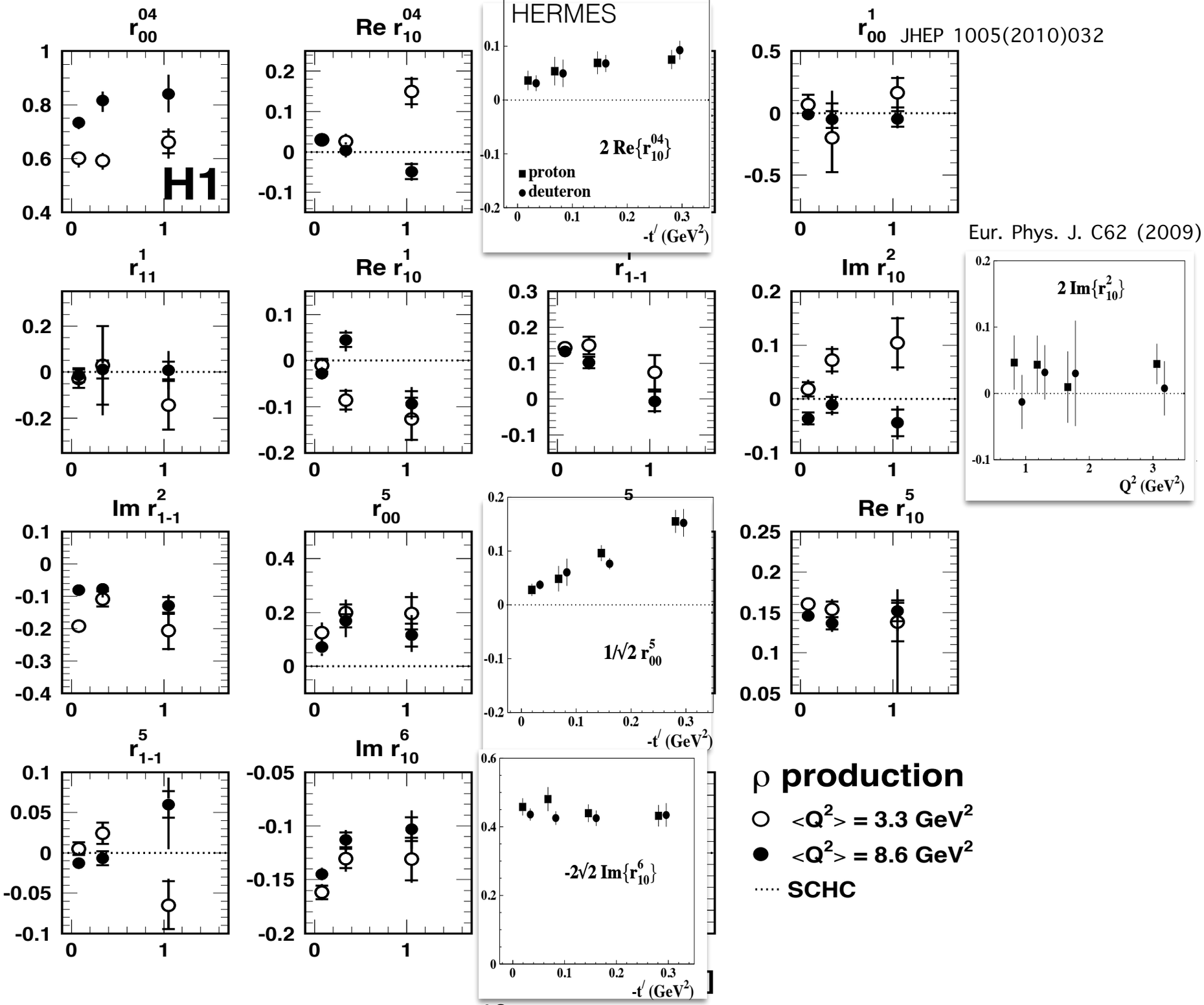

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Eur. Phys. J. C62 (2009) 659-695

ρ production

○ $\langle Q^2 \rangle$ = 3.3 GeV^2

● $\langle Q^2 \rangle$ = 8.6 GeV^2

····· SCHC

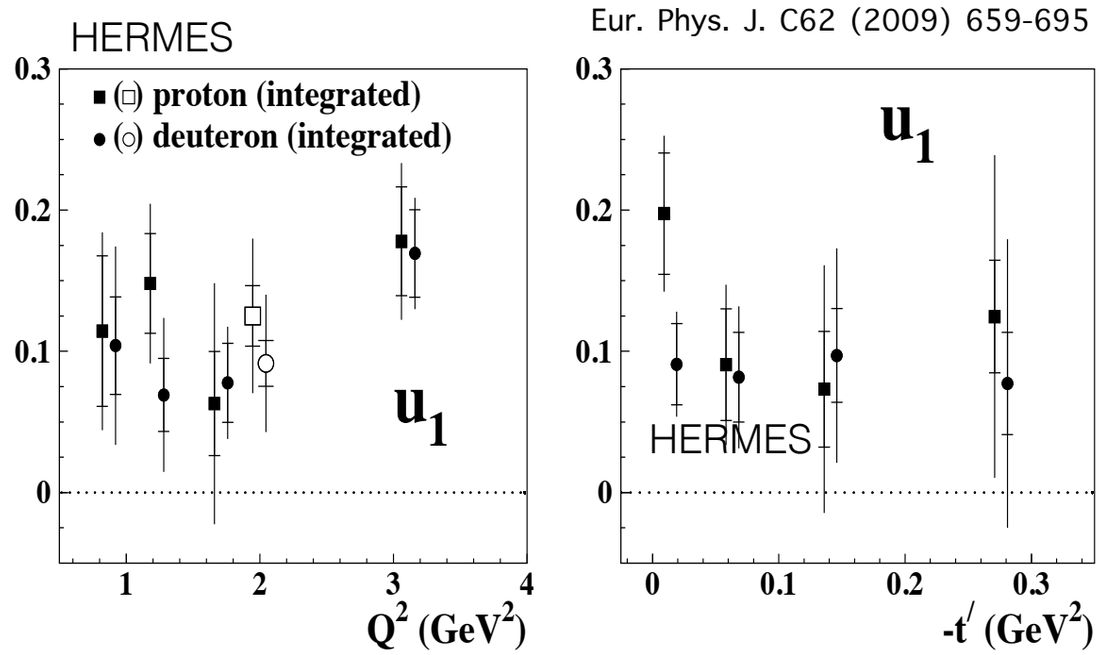
Test of unnatural parity exchange

SDMEs – HERMES

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

$$\propto 2\epsilon|U_{10}|^2 + |U_{11} + U_{-11}|^2$$

- ≠ 0 by 2σ for proton data
- UPE for deuteron expected to be smaller because of absence of UPE for coherent scattering



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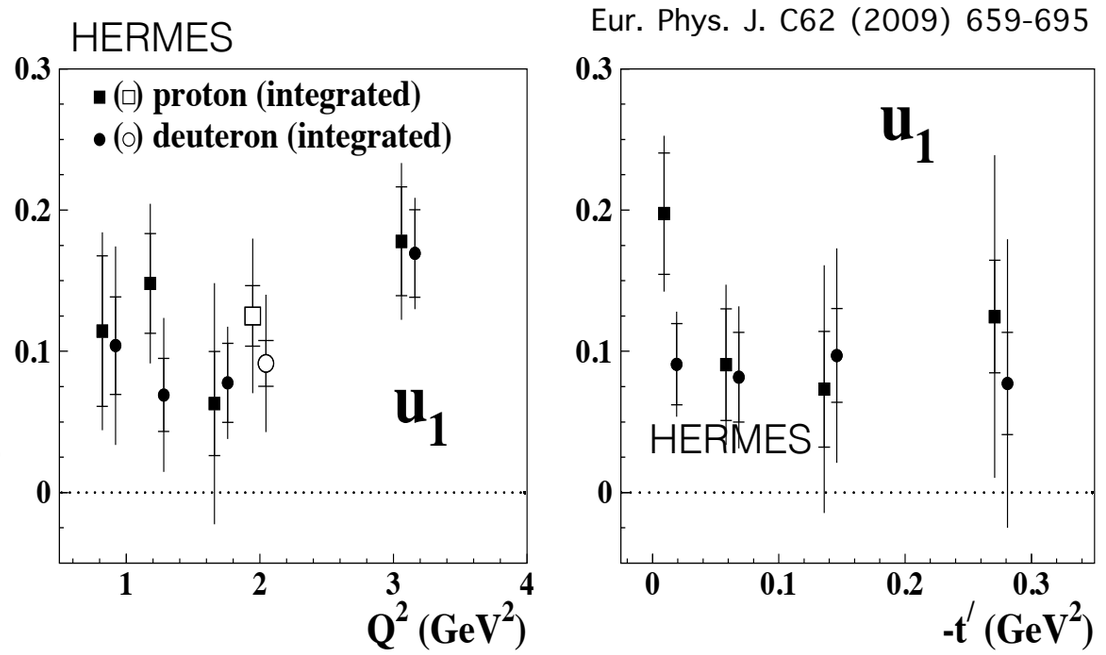
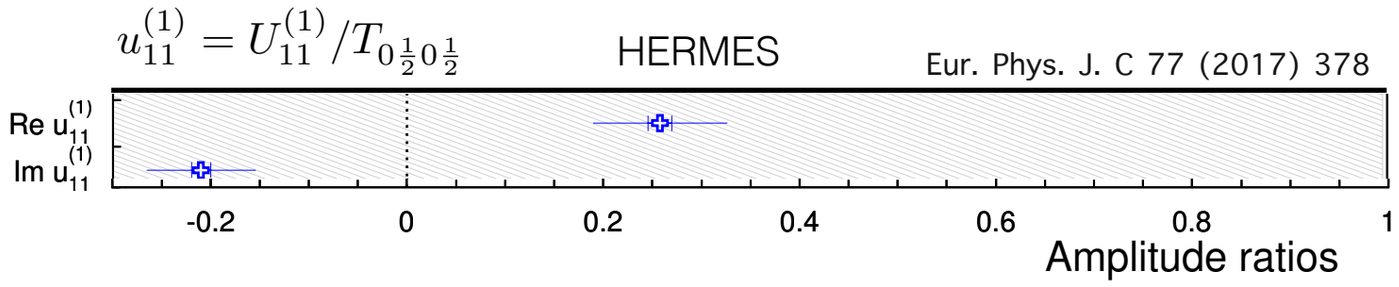


Eur. Phys. J. C62 (2009) 659-695

helicity amplitude ratio – HERMES

- unnatural parity nucleon-helicity non-flip

  ≠ 0 by 4σ



Eur. Phys. J. C 77 (2017) 378

Test of unnatural parity exchange

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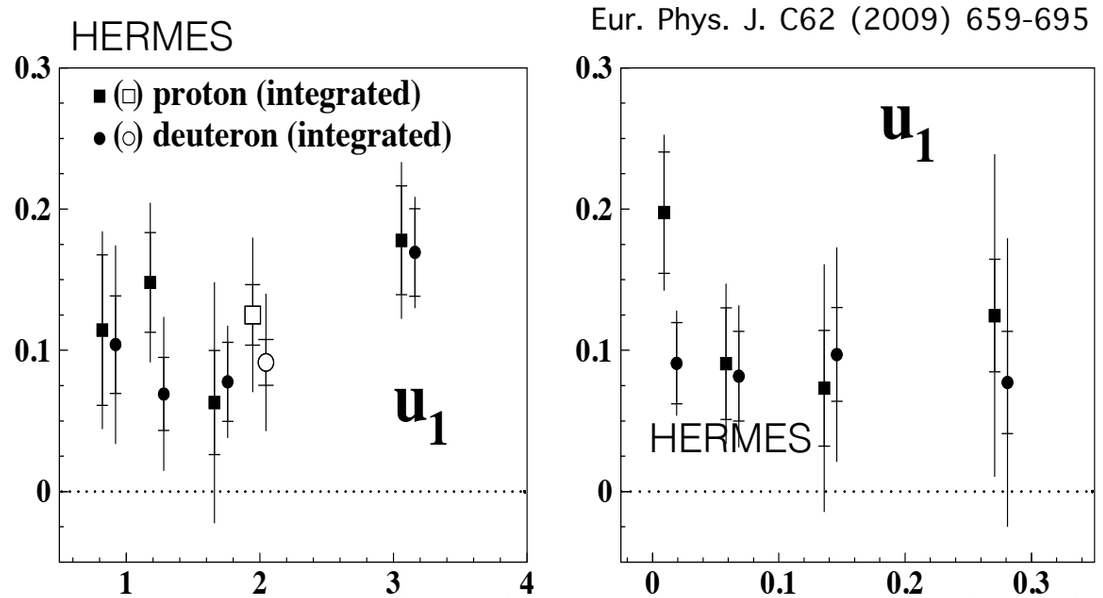

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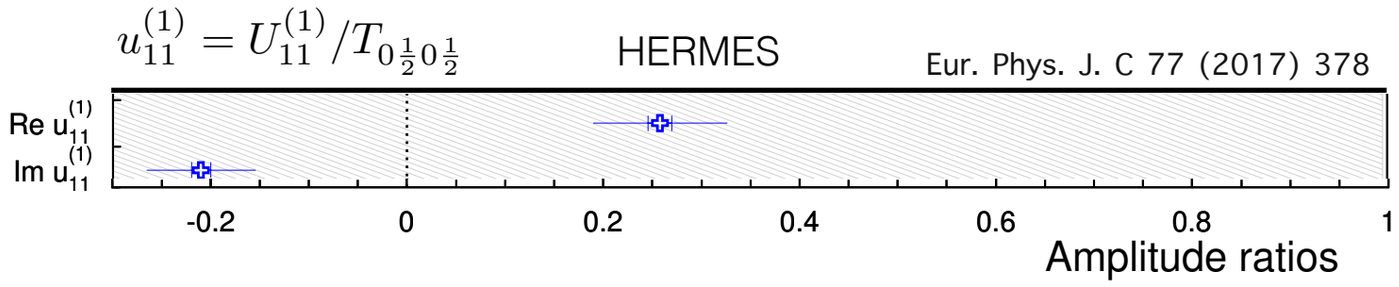
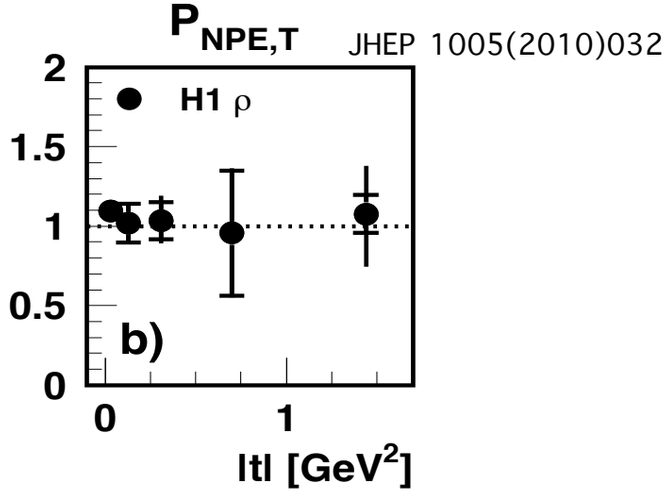


asymmetry – H1

$$P_{NPE,T} = \frac{\sigma^N_T - \sigma^U_T}{\sigma^N_T + \sigma^U_T}$$



Longitudinal-to-transverse cross-section ratios

$$R = \frac{1}{\epsilon}\frac{r_{00}^{04}}{1 - r_{00}^{04}} = \frac{d\sigma(\gamma_L^* \to V_L) + \frac{1}{\epsilon}\, d\sigma(\gamma_T^* \to V_L)}{d\sigma(\gamma_T^* \to V_T) + \epsilon\, d\sigma(\gamma_L^* \to V_T)}$$

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$$R^{\gamma^*} = \frac{d\sigma(\gamma_L^*)}{d\sigma(\gamma_T^*)}$$

$$R^{\gamma^*} = R - \frac{\eta(1+\epsilon\, R)}{\epsilon(1+\eta)} \qquad \text{with} \quad \eta = \eta(T_{01}, T_{10}, U_{01}, U_{10})$$

$$\eta = 0 \quad \text{for SCHC}$$

Longitudinal-to-transverse cross-section ratios

$$R = \frac{1}{\epsilon}\frac{r_{00}^{04}}{1-r_{00}^{04}} = \frac{d\sigma(\gamma_L^* \to V_L) + \frac{1}{\epsilon}\, d\sigma(\gamma_T^* \to V_L)}{d\sigma(\gamma_T^* \to V_T) + \epsilon\, d\sigma(\gamma_L^* \to V_T)}$$

$$R^{\gamma^*} = \frac{d\sigma(\gamma_L^*)}{d\sigma(\gamma_T^*)}$$

$$R^{\gamma^*} = R - \frac{\eta(1+\epsilon\, R)}{\epsilon(1+\eta)} \quad \text{with} \quad \eta = \eta(T_{01}, T_{10}, U_{01}, U_{10})$$

$$\eta = 0 \ \text{ for SCHC}$$

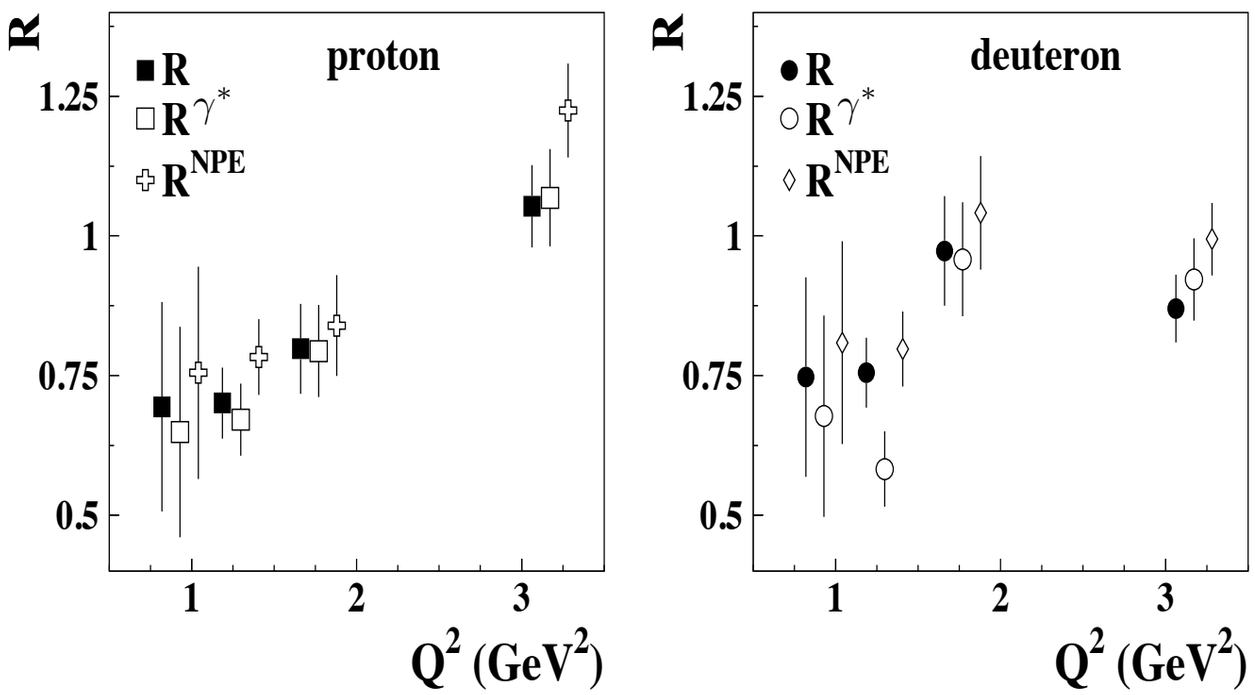
$$R^{NPE} \approx R\left[1 + \frac{u_1}{2}(1+\epsilon R)\right] \ \text{with} \ u_1 = u_1(U_{10}, U_{11}, U_{-11})$$

subtraction of all UPE amplitudes

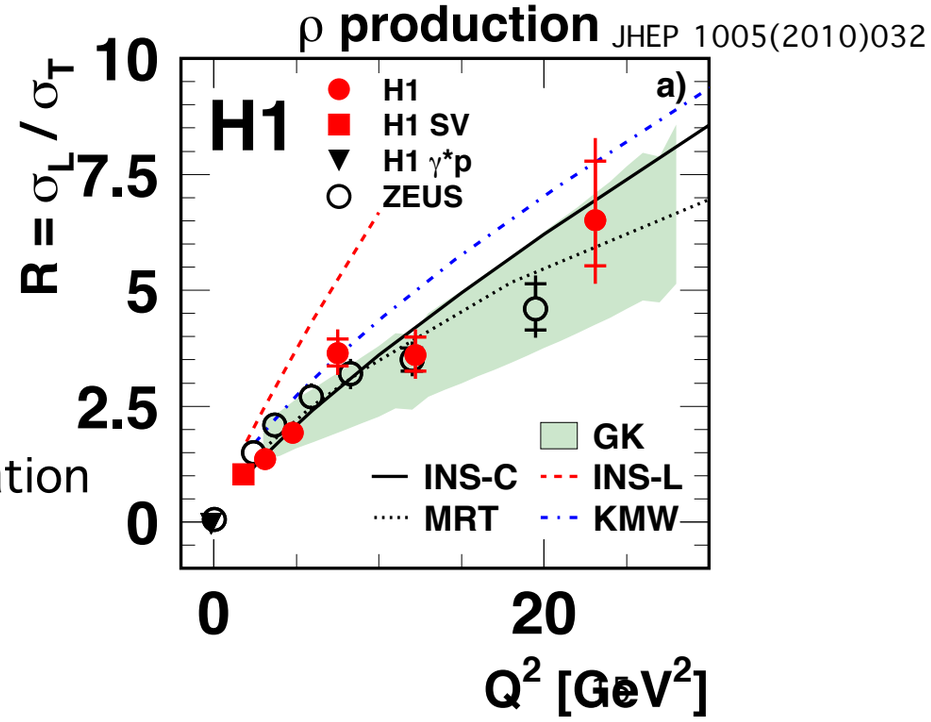
Longitudinal-to-transverse cross-section ratios

HERMES

Eur. Phys. J. C62 (2009) 659-695

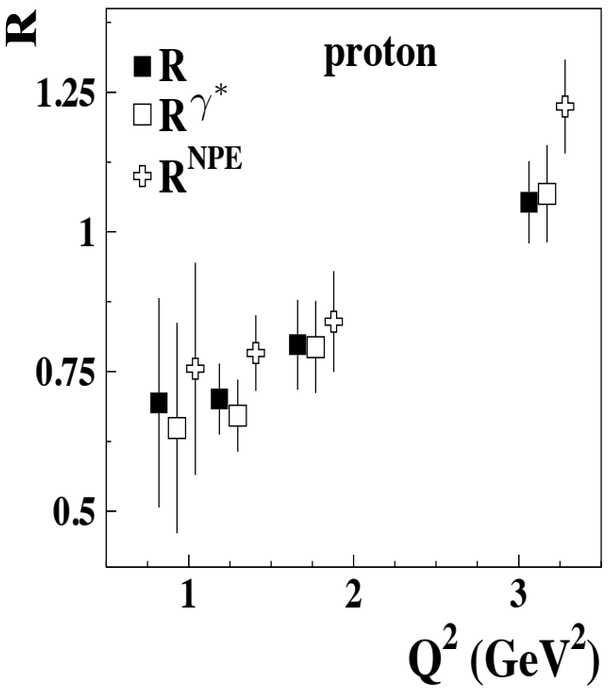


- corrected for SCHC violation seen in r^5_{00} and r^{04}_{00}

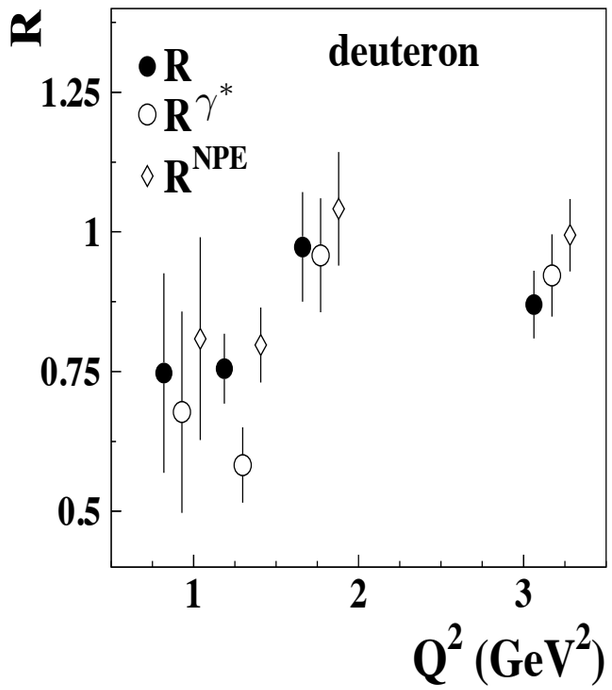


Longitudinal-to-transverse cross-section ratios

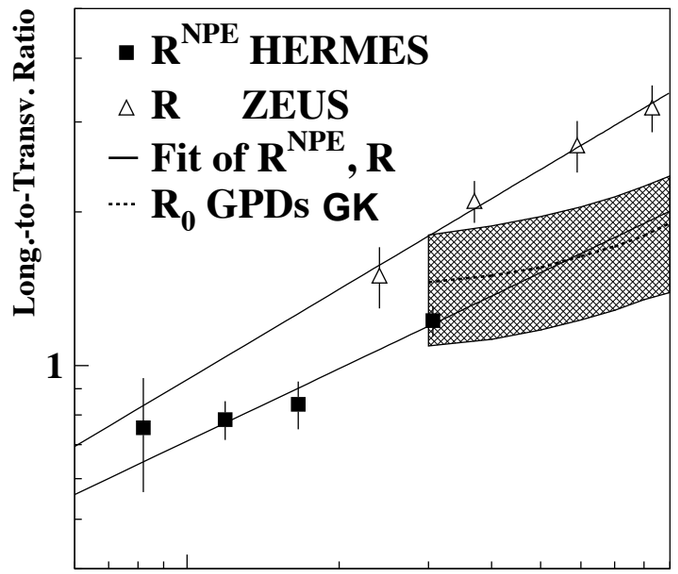
HERMES



Eur. Phys. J. C62 (2009) 659-695



Eur. Phys. J. C62 (2009) 659-695



$$R(Q^2) = c_0 \left(\frac{Q^2}{M_V^2} \right)^{c_1}$$

$$c_0^{\mathrm{HERMES}} = 0.56 \pm 0.08$$

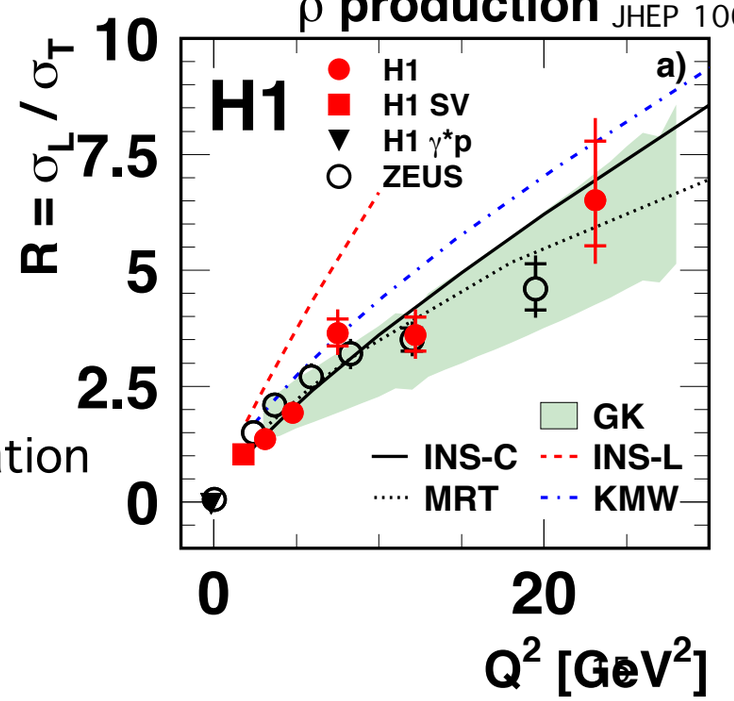
$$c_1^{\mathrm{HERMES}} = 0.47 \pm 0.12$$

$$c_0^{\mathrm{ZEUS}} = 0.69 \pm 0.22$$

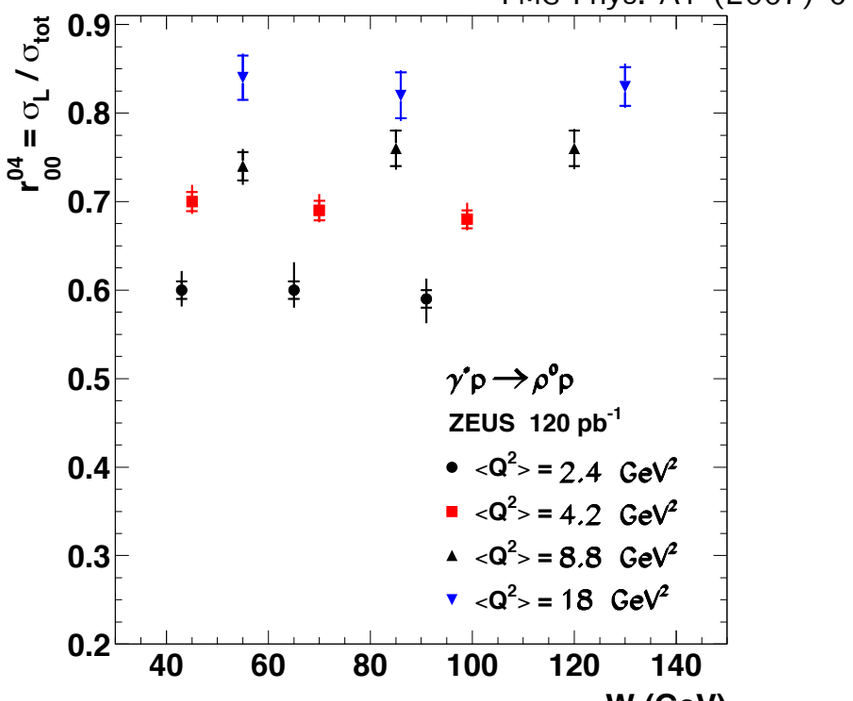
$$c_1^{\mathrm{ZEUS}} = 0.59 \pm 0.15$$

- corrected for SCHC violation seen in r_{00}^5 and r_{00}^{04}

ρ production JHEP 1005(2010)032

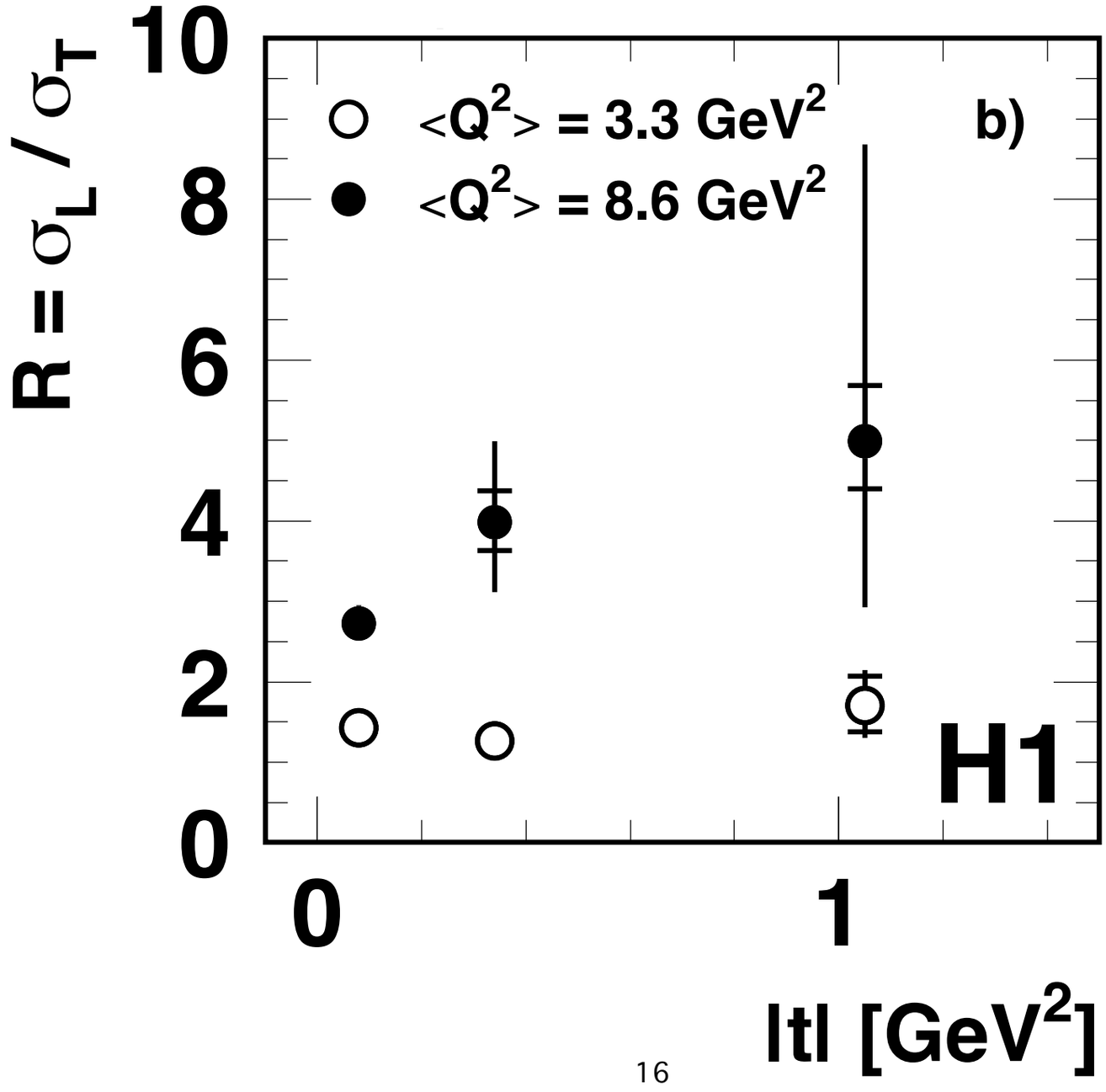


ZEUS PMC Phys. A1 (2007) 6



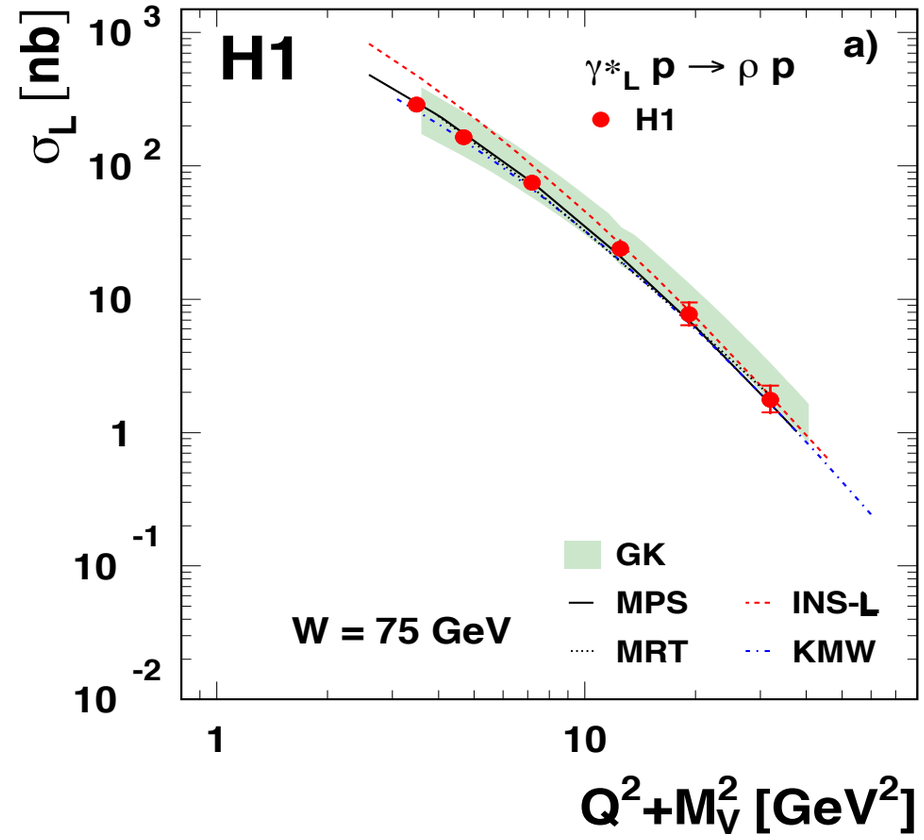
Longitudinal-to-transverse cross-section ratios

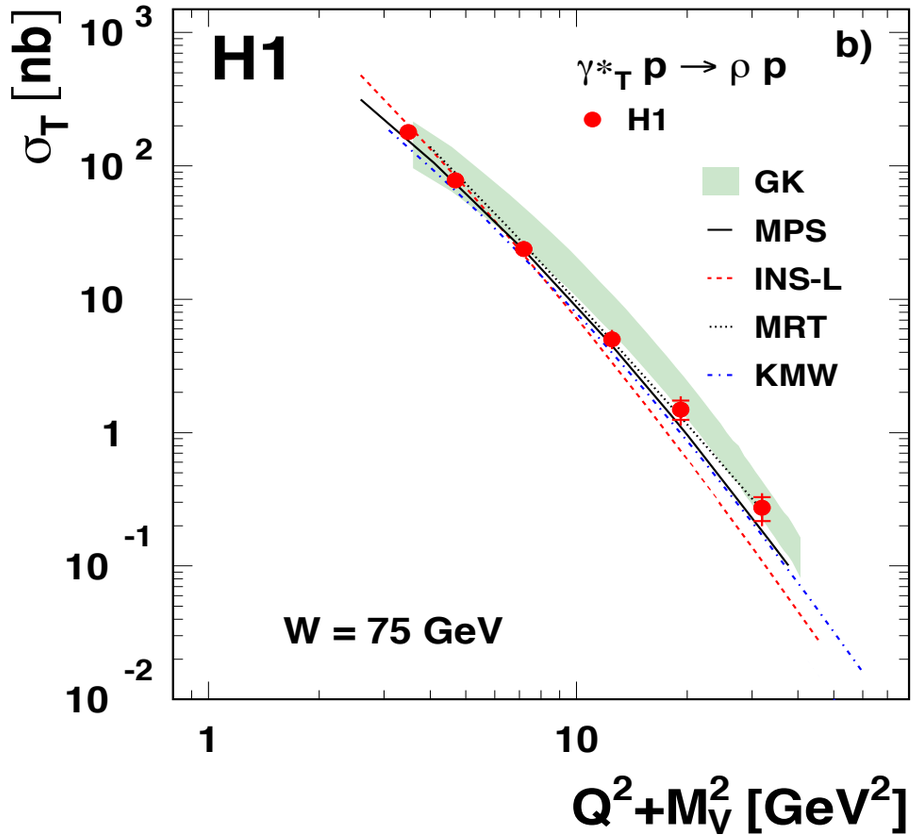
$$R(t) \propto e^{-(b_L - b_T)|t|}$$



Longitudinal and transverse cross sections

JHEP 1005(2010)032



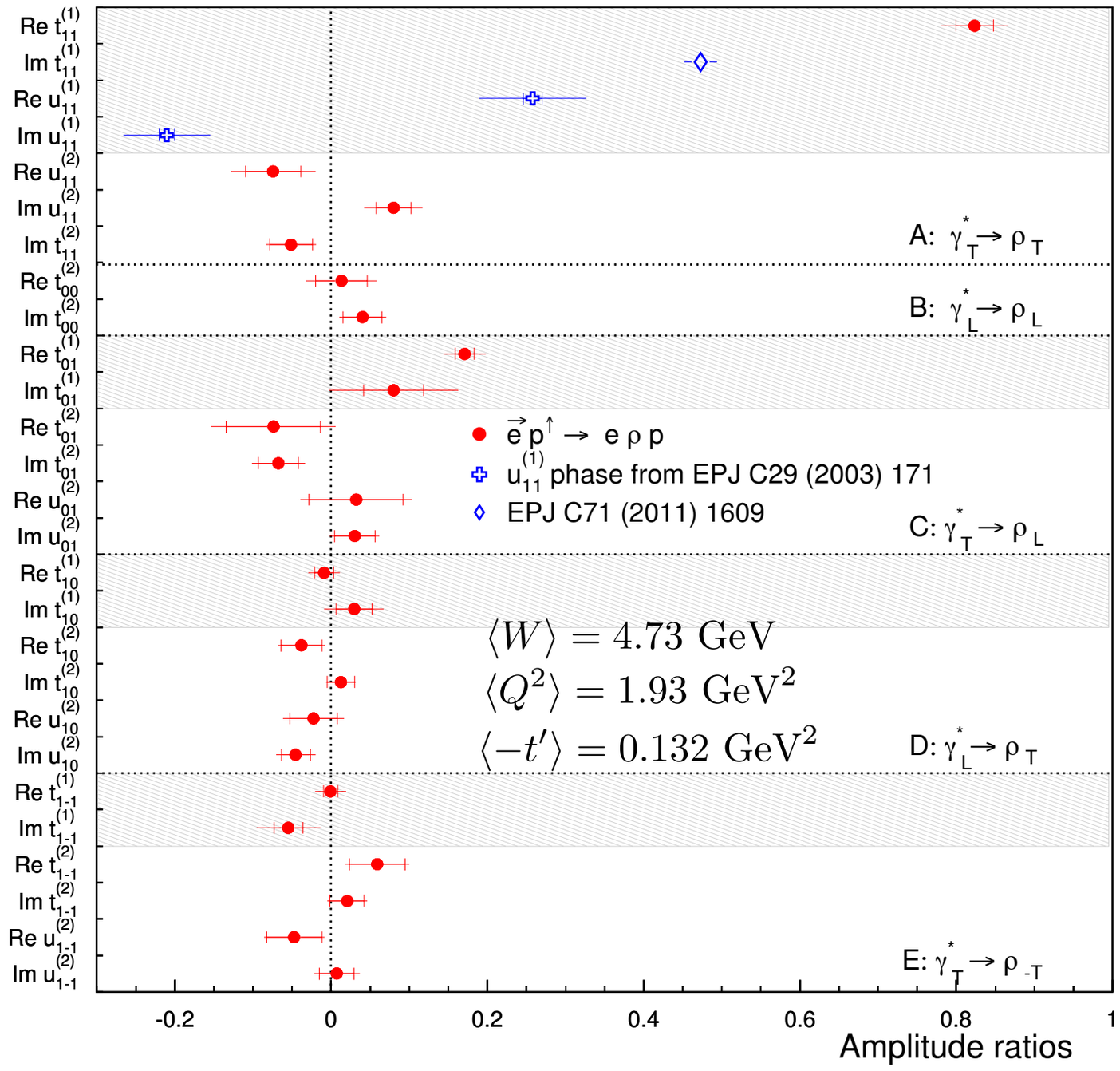


fit $1/(Q^2 + M_V^2)^n$

n	
$\sigma_L(\rho)$	$\sigma_T(\rho)$
$2.17 \pm 0.09^{+0.07}_{-0.07}$	$2.86 \pm 0.07^{+0.11}_{-0.12}$

Transversely polarized target: ρ^0 helicity amplitude ratios

Eur. Phys. J. C 77 (2017) 378



8% uncertainty target polarization
2% uncertainty beam polarization

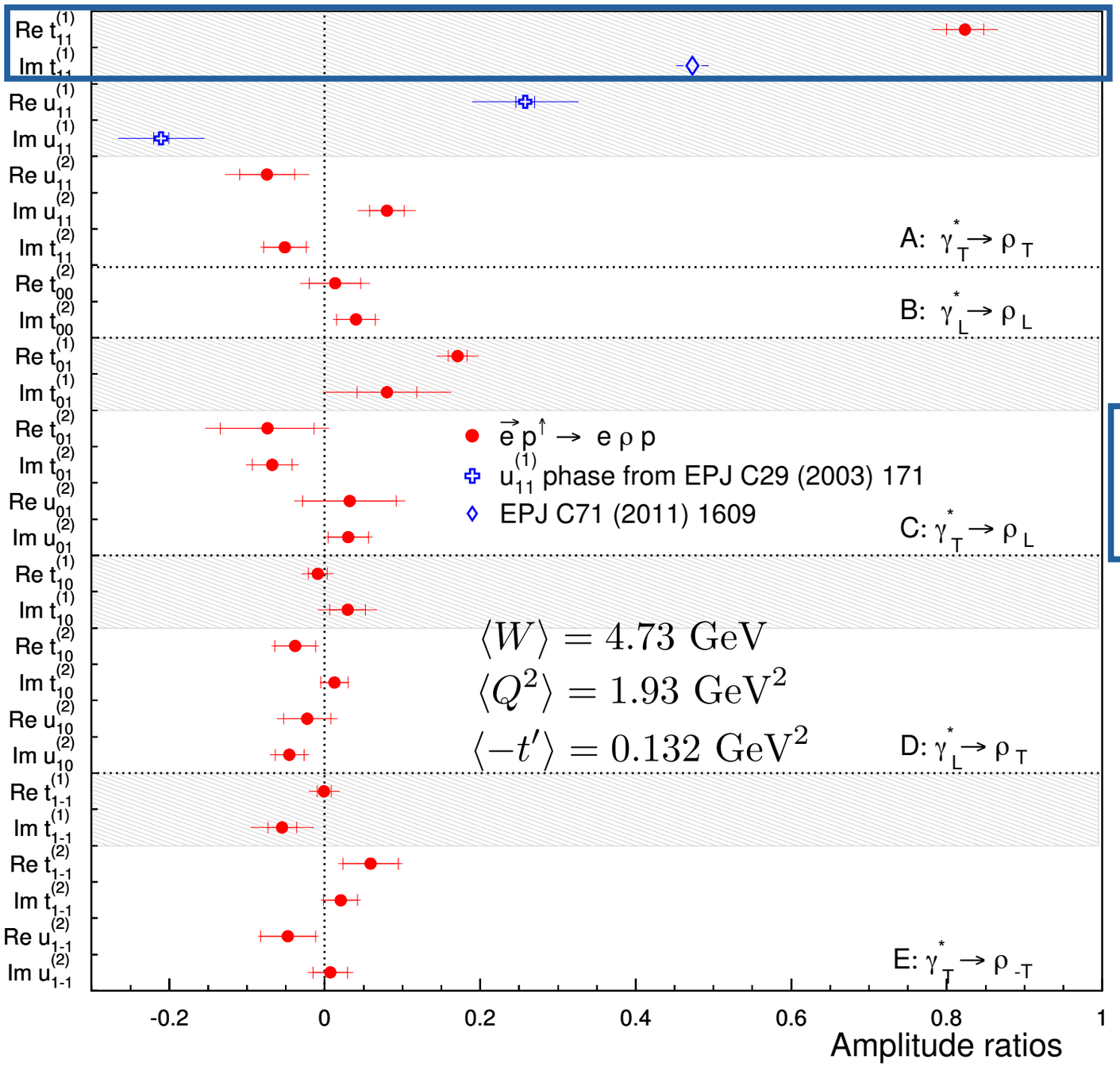
accessible via unpolarized target

accessible via transversely polarized target

- 5 classes of helicity amplitude ratios

Transversely polarized target: ρ^0 helicity amplitude ratios

Eur. Phys. J. C 77 (2017) 378



8% uncertainty target polarization
2% uncertainty beam polarization

accessible via unpolarized target

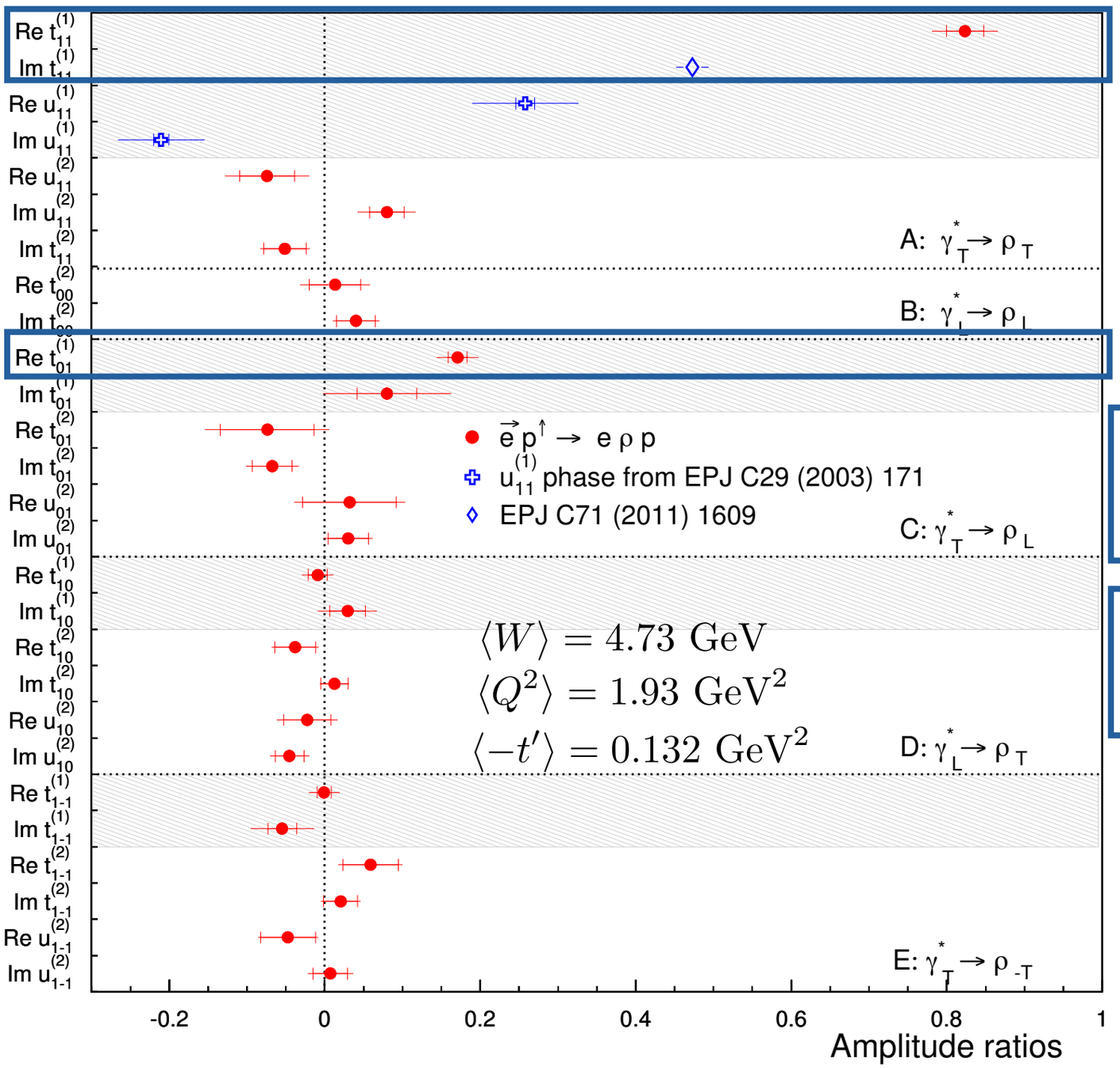
accessible via transversely polarized target

- 5 classes of helicity amplitude ratios

- dominant amplitude: natural parity nucleon-helicity non-flip $t_{11}^{(1)}$ ($\neq 0$ by $>5\sigma$)

Transversely polarized target: ρ^0 helicity amplitude ratios

Eur. Phys. J. C 77 (2017) 378



8% uncertainty target polarization
2% uncertainty beam polarization

accessible via unpolarized target

accessible via transversely polarized target

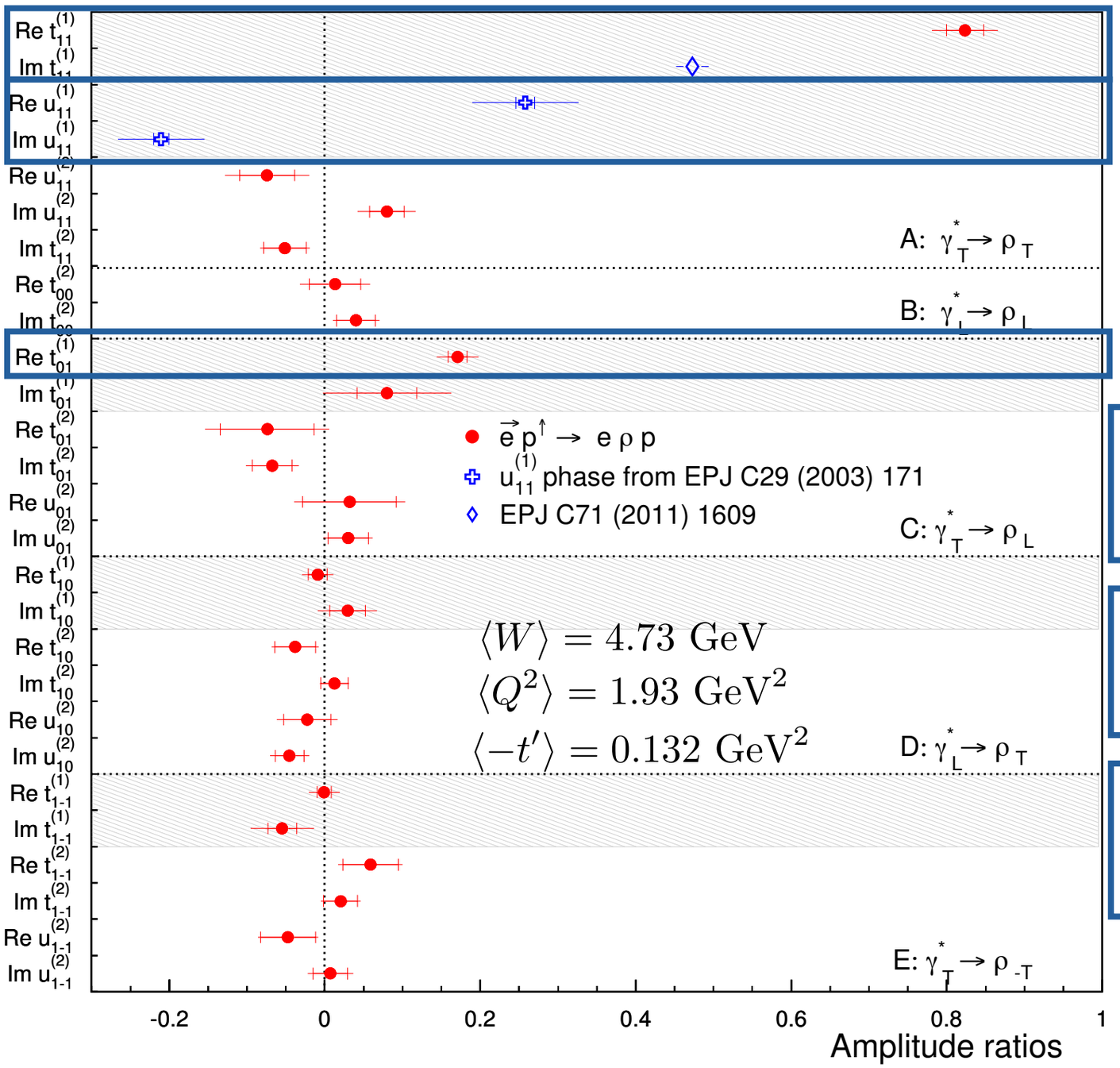
- 5 classes of helicity amplitude ratios

- dominant amplitude: natural parity nucleon-helicity non-flip $t_{11}^{(1)}$ (≠0 by >5σ)

- Significant nucleon-helicity non-flip $\Re\, t_{01}^{(1)}$ (≠0 by 5σ)

Transversely polarized target: ρ^0 helicity amplitude ratios

Eur. Phys. J. C 77 (2017) 378



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accessible via unpolarized target

accessible via transversely polarized target

- 5 classes of helicity amplitude ratios

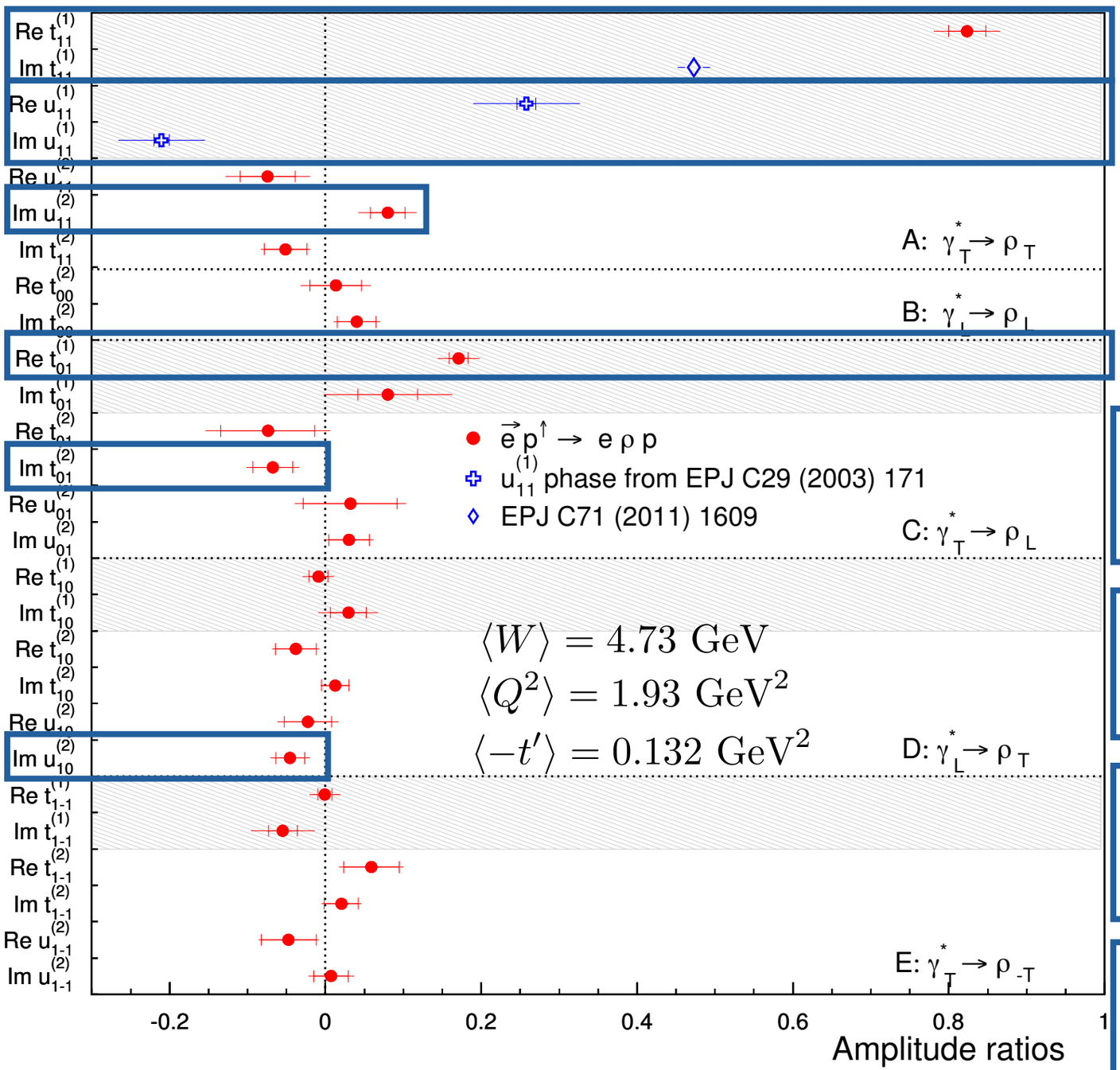
- dominant amplitude: natural parity nucleon-helicity non-flip $t_{11}^{(1)}$ (≠0 by >5σ)

- Significant nucleon-helicity non-flip $\Re\, t_{01}^{(1)}$ (≠0 by 5σ)

- unnatural parity nucleon-helicity non-flip $u_{11}^{(1)}$ ≠ 0 by 4σ

Transversely polarized target: ρ^0 helicity amplitude ratios

Eur. Phys. J. C 77 (2017) 378



8% uncertainty target polarization
2% uncertainty beam polarization

accessible via unpolarized target

accessible via transversely polarized target

- 5 classes of helicity amplitude ratios

- dominant amplitude: natural parity nucleon-helicity non-flip $t_{11}^{(1)}$ (≠0 by >5σ)

- Significant nucleon-helicity non-flip $\Re\, t_{01}^{(1)}$ (≠0 by 5σ)

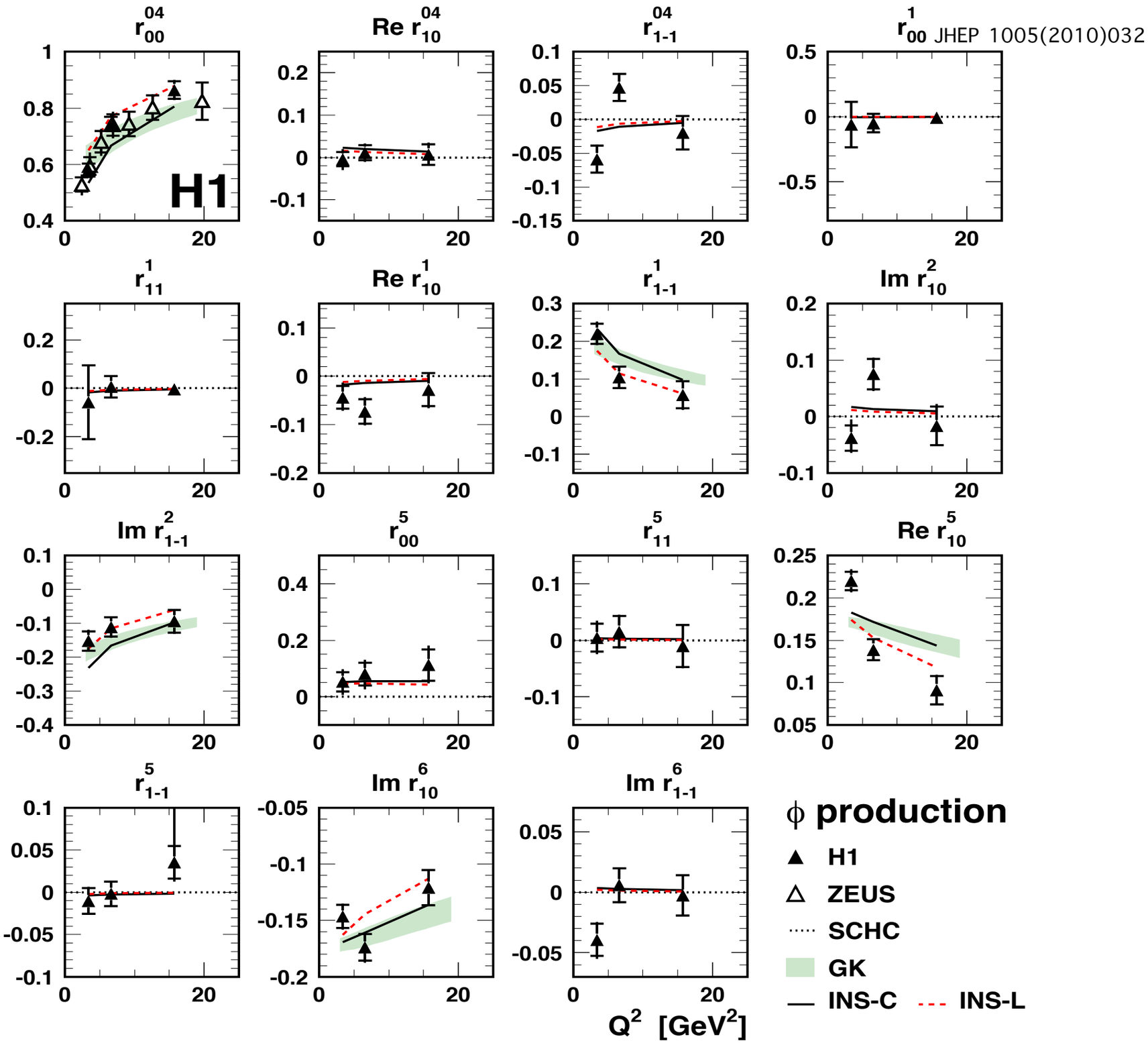
- unnatural parity nucleon-helicity non-flip $u_{11}^{(1)}$ ≠ 0 by 4σ

- nucleon-helicity flip $\Im\, t_{01}^{(2)}$, $\Im\, u_{11}^{(2)}$, $\Im\, u_{10}^{(2)}$ ≠ 0 by 2σ

Exclusive ϕ

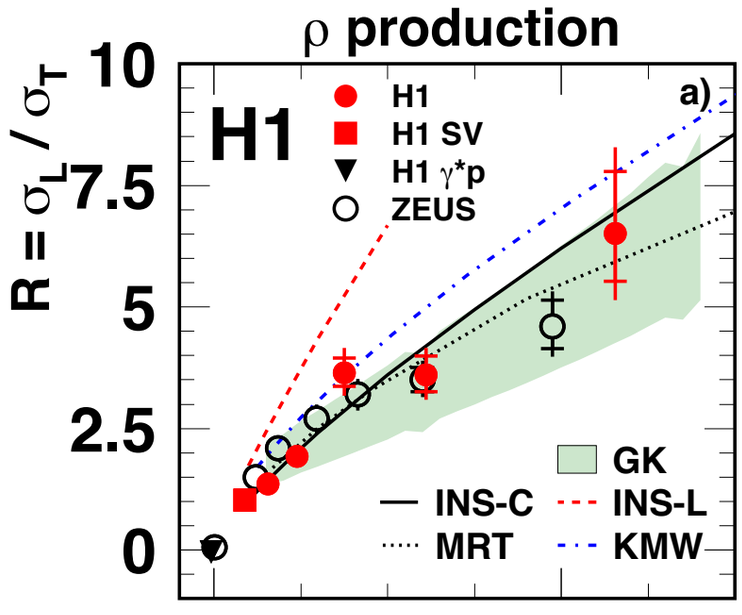
- unpolarized H target

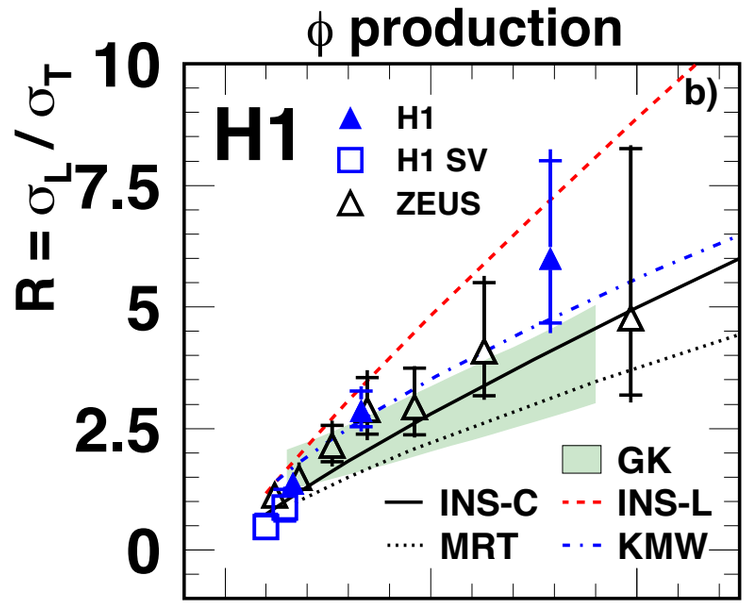
Q^2 dependence



JHEP 1005(2010)032

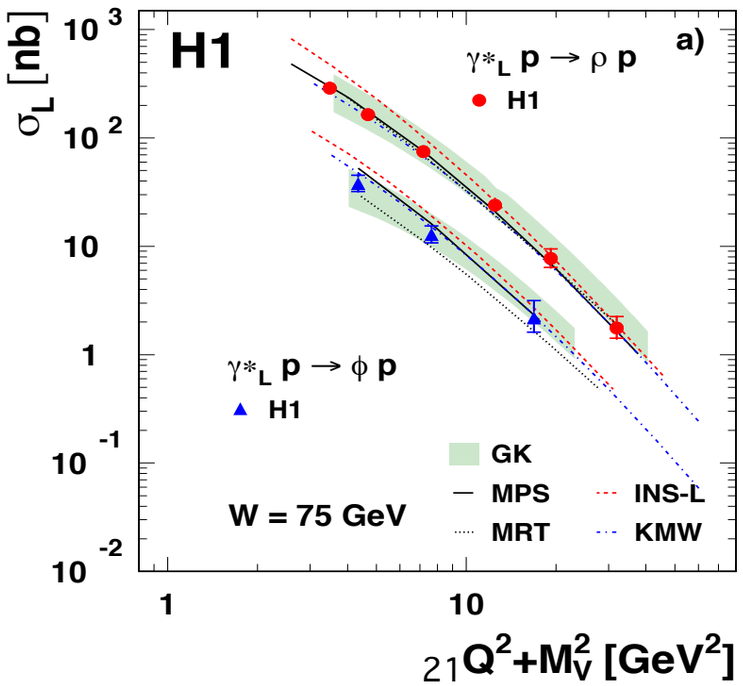
Longitudinal and transverse cross sections

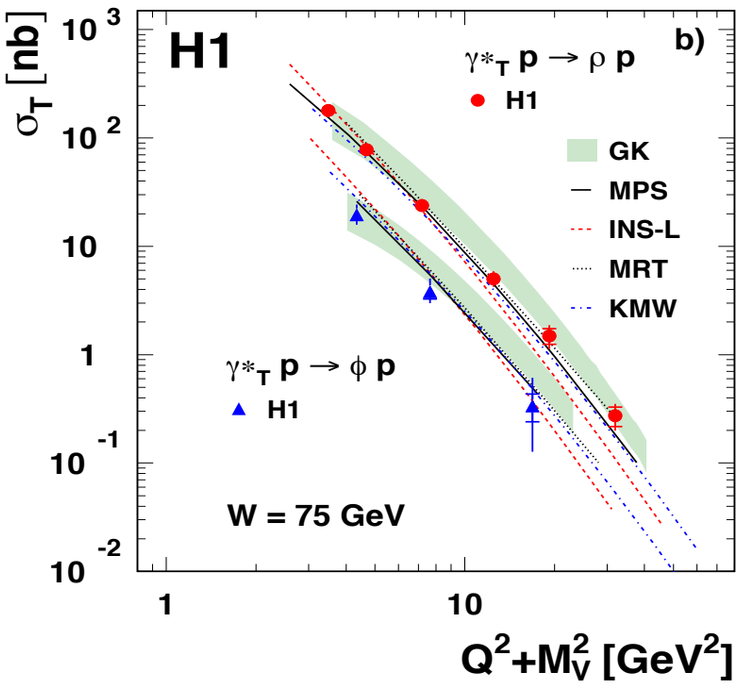




fit $1/(Q^2+M_V^2)^n$

n	
$\sigma_L(\rho)$	$\sigma_T(\rho)$
$2.17 \pm 0.09^{+0.07}_{-0.07}$	$2.86 \pm 0.07^{+0.11}_{-0.12}$
$\sigma_L(\phi)$	$\sigma_T(\phi)$
$2.06 \pm 0.49^{+0.09}_{-0.09}$	$2.97 \pm 0.52^{+0.14}_{-0.16}$

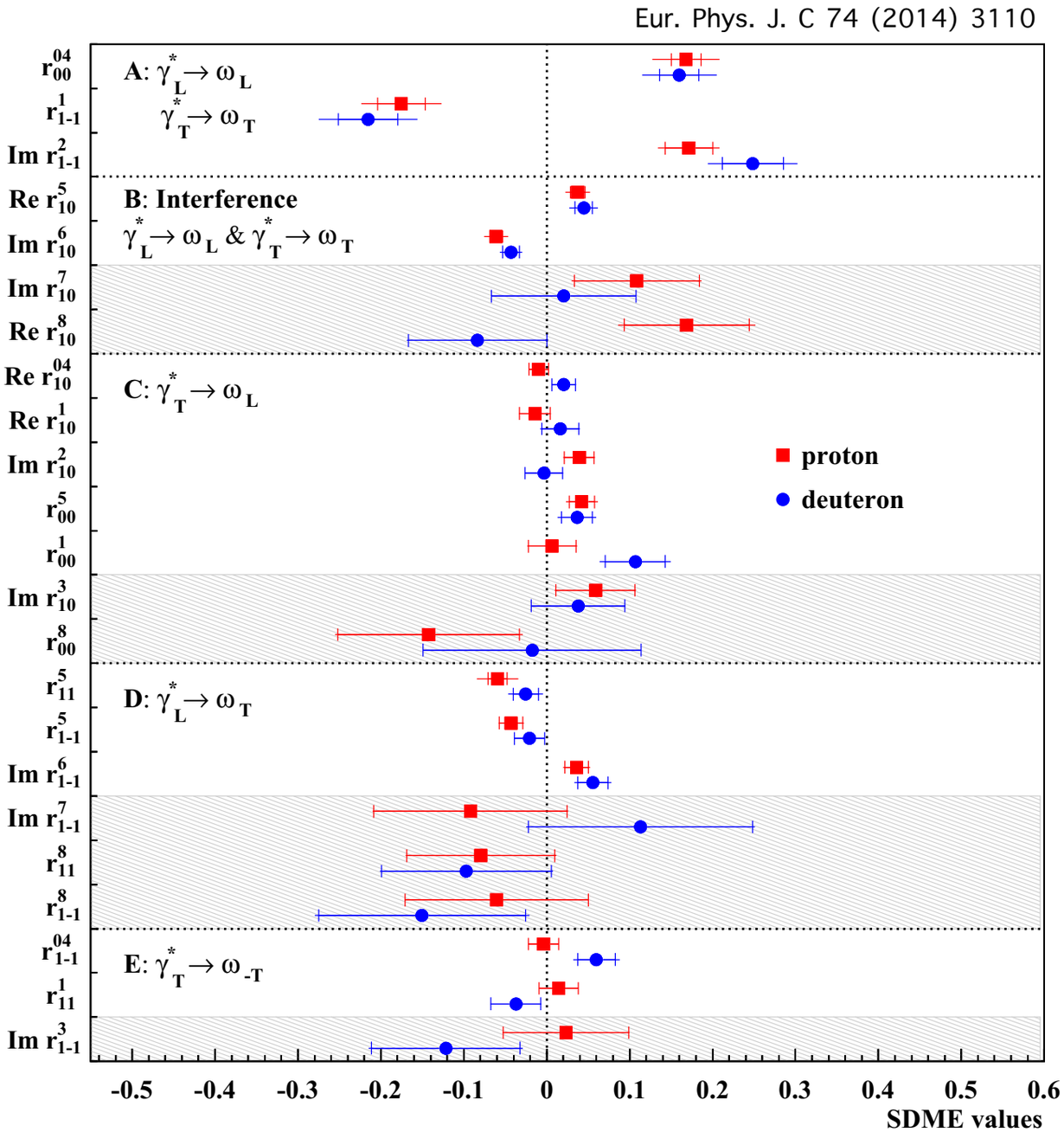




Exclusive ω

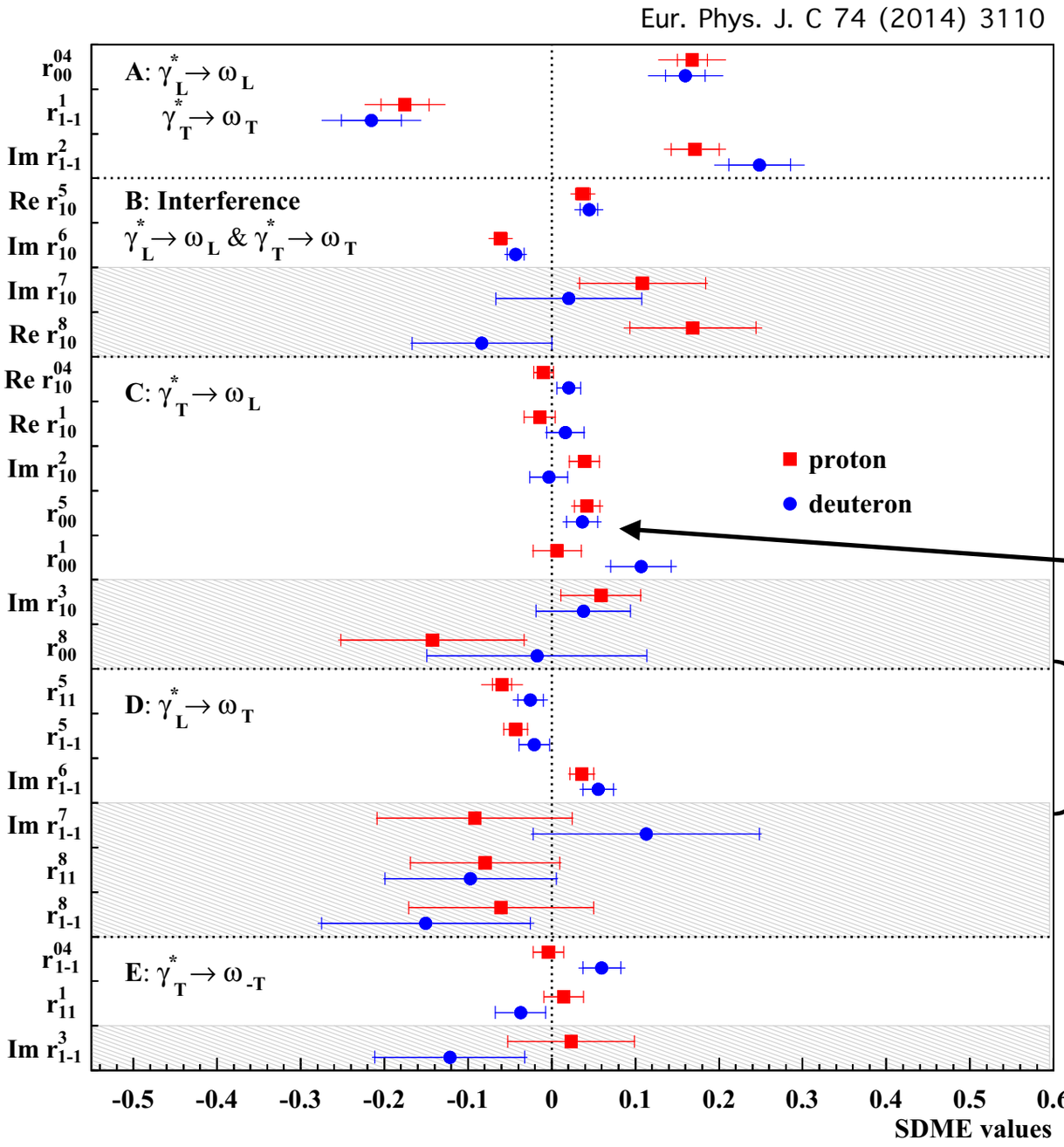
- unpolarized H and D targets
- transversely polarized H target

Results ω SDMEs



- 5 classes of SDMEs
- unpolarized and polarized SDMEs
- proton & deuteron similar

Results ω SDMEs



- 5 classes of SDMEs
- unpolarized and polarized SDMEs
- proton & deuteron similar

- s-channel helicity conservation ($\lambda_{\gamma*} = \lambda_\omega$):
  - fulfilled for class A & B
  - class C - slight violation:

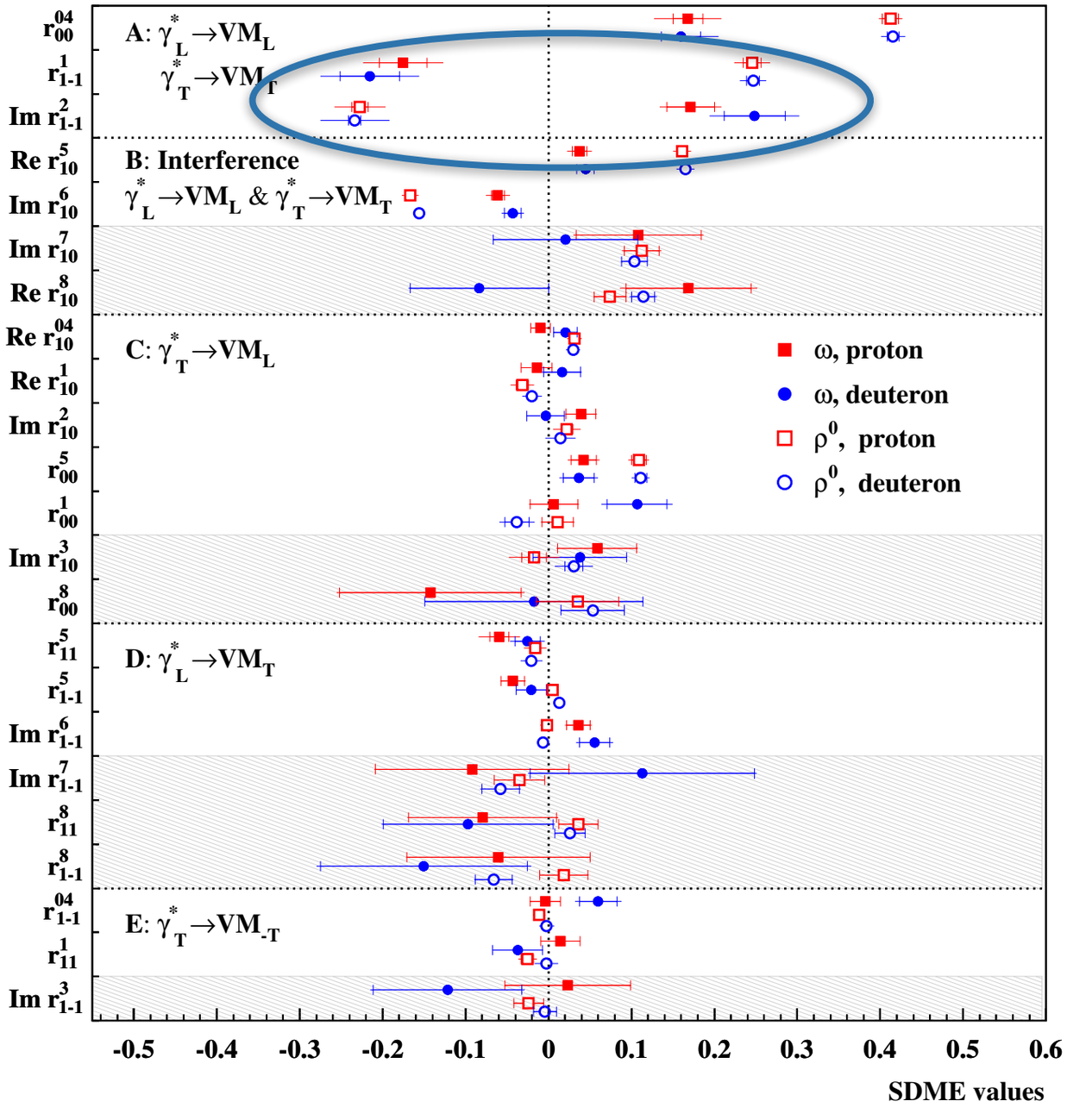
$r^5_{00} \neq 0$ by $3(2)\sigma$ for p(d)

  - class D - slight violation:

$r^5_{11} + r^5_{1-1} - \Im r^6_{1-1} \neq 0$
by $3(2.5)\sigma$ for p(d)

Results ω and ρ^0 SDMEs

Eur. Phys. J. C 74 (2014) 3110



exclusive ρ^0: Eur. Phys. J. C 62 (2009) 659

- ω: $r^1_{1-1} < 0$ and $\Im r^2_{1-1} > 0$
- ρ: $r^1_{1-1} > 0$ and $\Im r^2_{1-1} < 0$

⇩

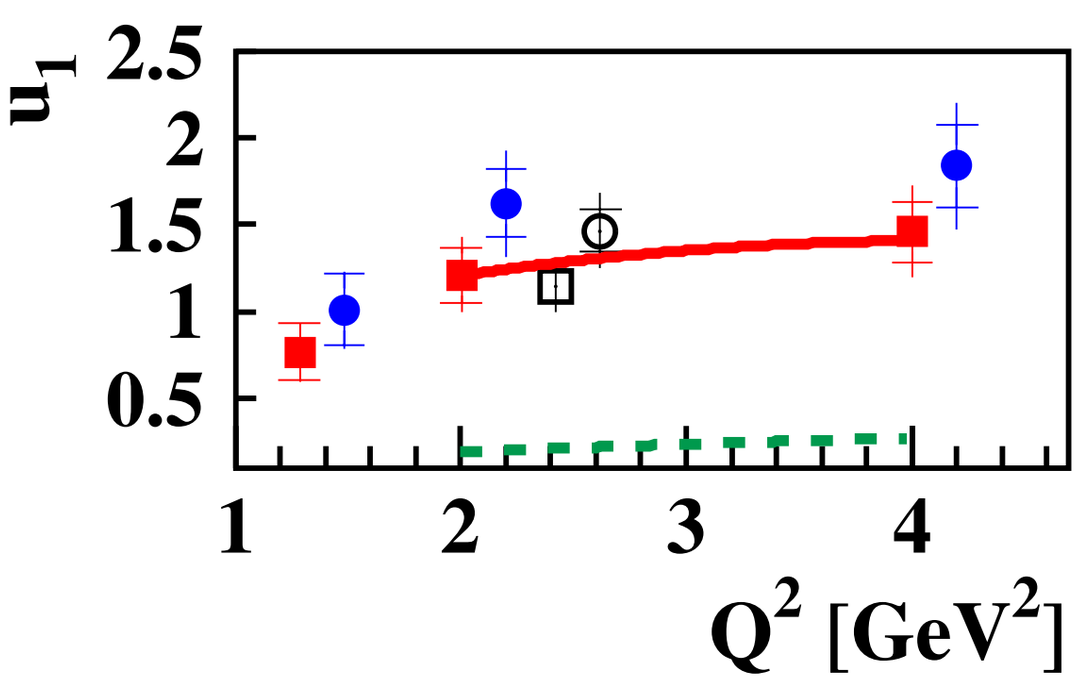
- ω: large unnatural parity exchange
- ρ: large natural parity exchange

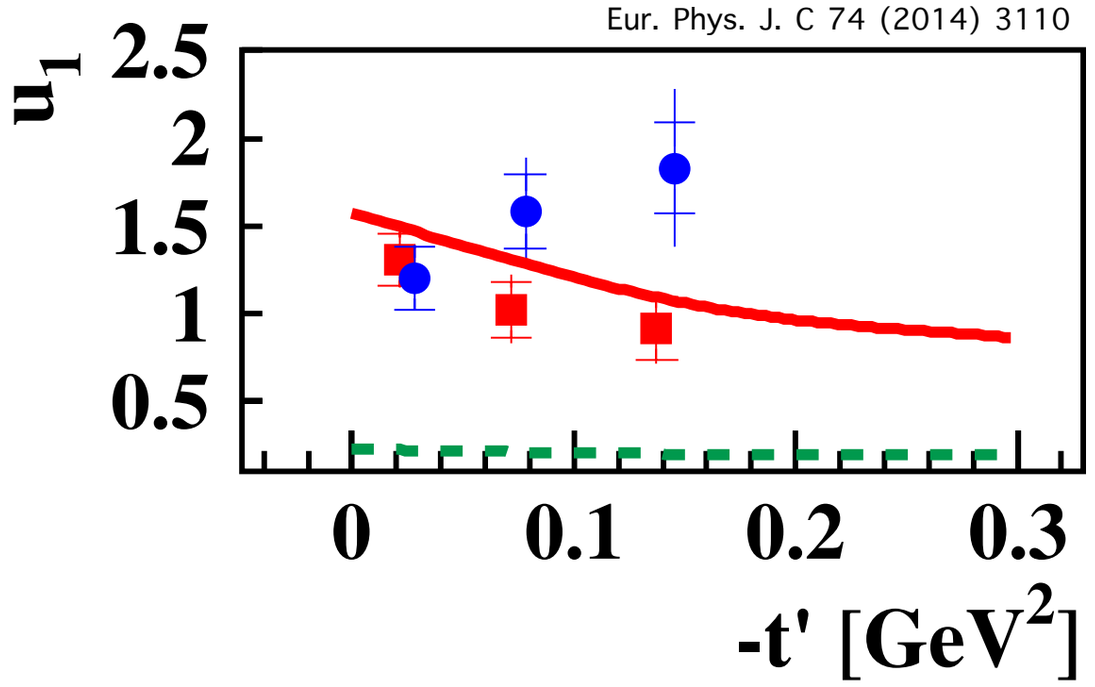
Test of unnatural parity exchange

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

$$\propto 2\epsilon|U_{10}|^2 + |U_{11} + U_{-11}|^2$$

(U=unnatural-parity amplitude)





- large unnatural parity exchange seen

GK model

model for protons - S. Goloskokov and P. Kroll,
Eur. Phys. J. C 50 (2007) 829; 53 (2008) 367, Eur. Phys. J. A 50 (2014) 146

$$F_{\lambda_V \frac{1}{2} \lambda_\gamma = \lambda_V \frac{1}{2}} \propto \sum_{q,g} \mathcal{I} \left[\mathcal{A} \times \left(H^a, \frac{\xi^2}{1-\xi^2} E^a \right) + \mathcal{A}' \times \left(\tilde{H}^a, \frac{\xi^2}{1-\xi^2} \tilde{E}^a \right) \right]$$

$$F_{\lambda_V -\frac{1}{2} \lambda_\gamma = \lambda_V \frac{1}{2}} \propto \sum_{q,g} \mathcal{I} \left[\mathcal{A} \times E^a + \mathcal{A}' \times \xi \tilde{E}^a \right]$$

GK model

model for protons - S. Goloskokov and P. Kroll,
Eur. Phys. J. C 50 (2007) 829; 53 (2008) 367, Eur. Phys. J. A 50 (2014) 146

$$F_{\lambda_V \frac{1}{2} \lambda_\gamma = \lambda_V \frac{1}{2}} \propto \sum_{q,g} \mathcal{I} \left[\mathcal{A} \times \left(H^a, \frac{\xi^2}{1-\xi^2} E^a \right) + \mathcal{A}' \times \left(\tilde{H}^a, \frac{\xi^2}{1-\xi^2} \tilde{E}^a \right) \right]$$

$$F_{\lambda_V -\frac{1}{2} \lambda_\gamma = \lambda_V \frac{1}{2}} \propto \sum_{q,g} \mathcal{I} \left[\mathcal{A} \times E^a + \mathcal{A}' \times \xi \tilde{E}^a \right]$$

natural parity

unnatural parity

GK model

model for protons - S. Goloskokov and P. Kroll,
Eur. Phys. J. C 50 (2007) 829; 53 (2008) 367, Eur. Phys. J. A 50 (2014) 146

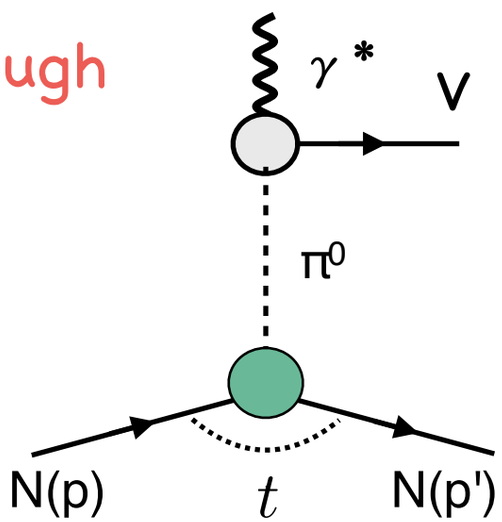
$$F_{\lambda_V \frac{1}{2} \lambda_\gamma = \lambda_V \frac{1}{2}} \propto \sum_{q,g} \mathcal{I} \left[\mathcal{A} \times \left(H^a, \frac{\xi^2}{1-\xi^2} E^a \right) + \mathcal{A}' \times \left(\tilde{H}^a, \frac{\xi^2}{1-\xi^2} \tilde{E}^a \right) \right]$$

$$F_{\lambda_V -\frac{1}{2} \lambda_\gamma = \lambda_V \frac{1}{2}} \propto \sum_{q,g} \mathcal{I} \left[\mathcal{A} \times E^a + \mathcal{A}' \times \xi \tilde{E}^a \right]$$

natural parity
unnatural parity

Factorization only proven for $\gamma_L^* \to V_L$.
Assumed for other transitions.
IR singularities regularised by modified perturbative approach.

Pion pole $\left(\propto \frac{1}{t - m_\pi^2} \right)$ through one-particle exchange

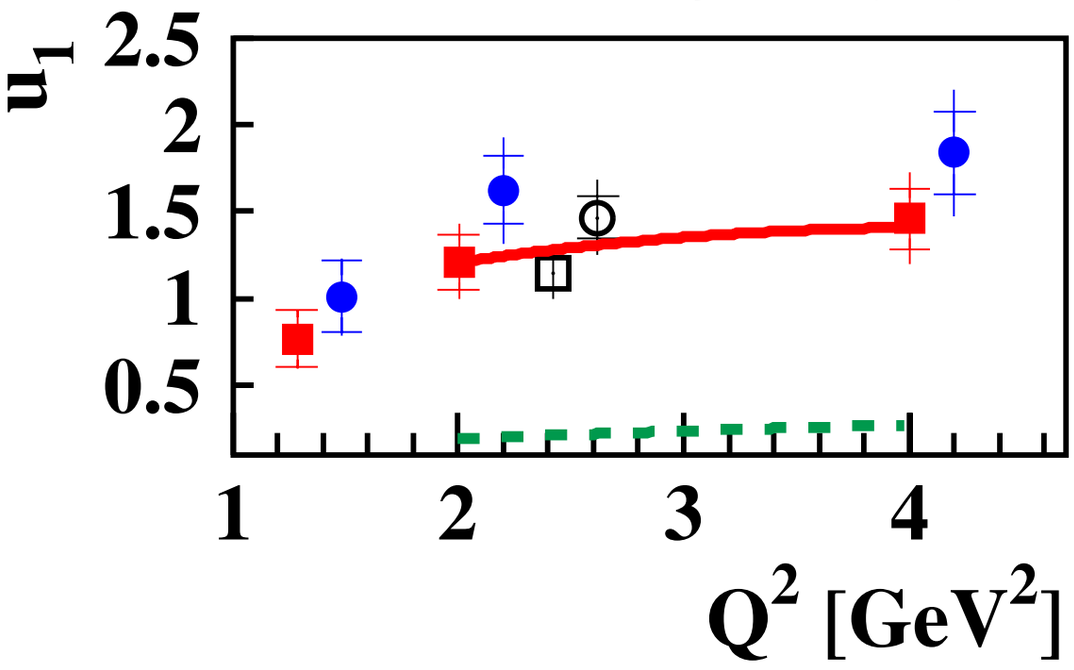


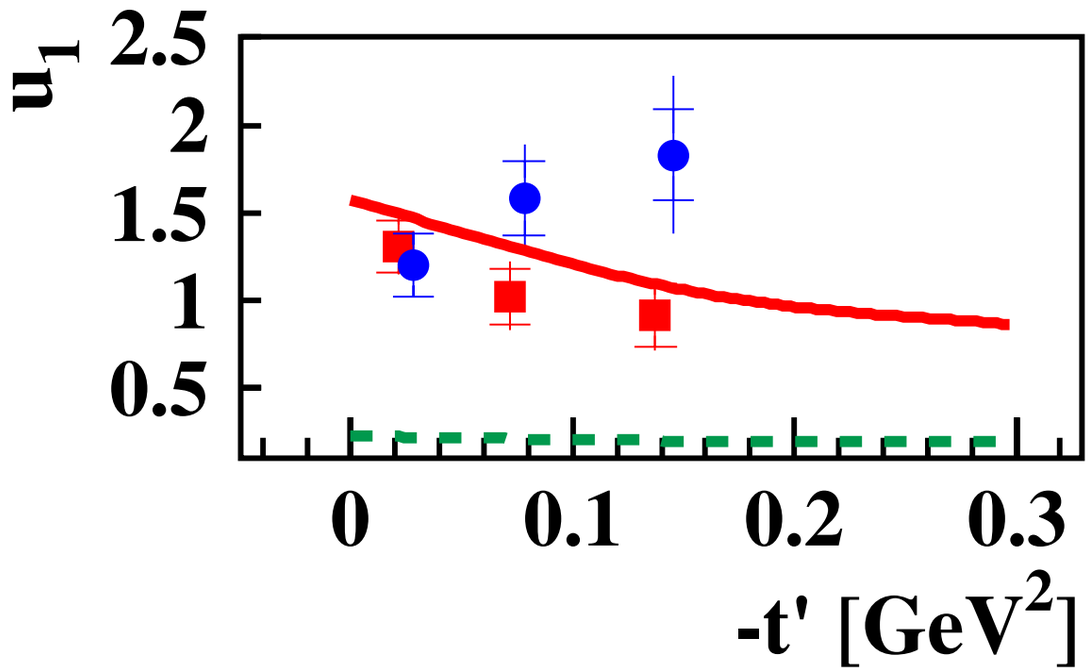
$g_{\gamma^* \pi V}(Q^2, t) \simeq g_{\pi V}(Q^2)$
at small t

πω transition form factor extracted from ω SDMEs

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

GK, Eur. Phys. J. A 50 (2014) 146
HERMES, Eur. Phys. J. C 74 (2014) 3110



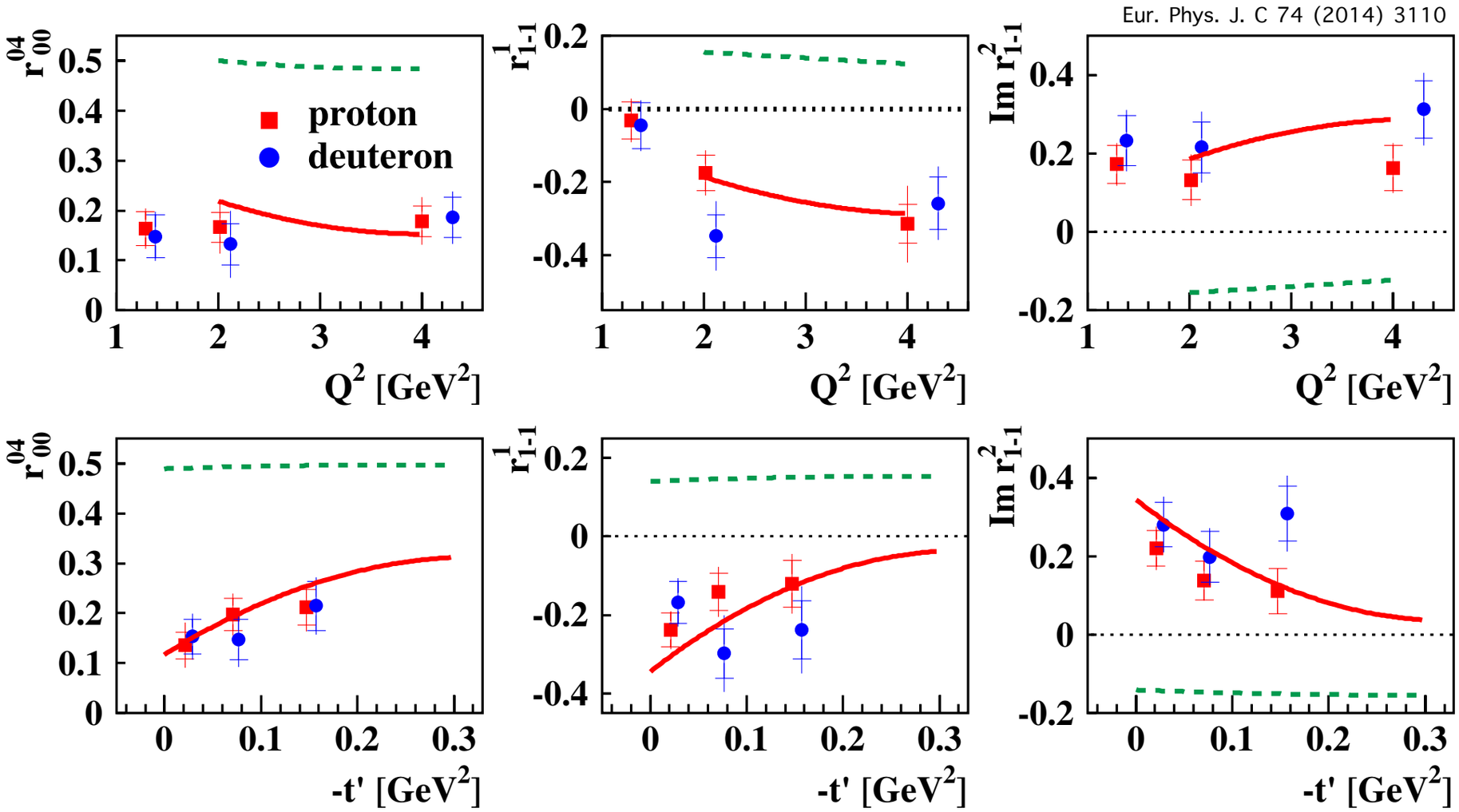


without pion-pole contribution
with pion-pole contribution

Only magnitude of transition form factor, not sign

Kinematic dependencies

class A: $\gamma_L^* \to \omega_L$ and $\gamma_T^* \to \omega_T$

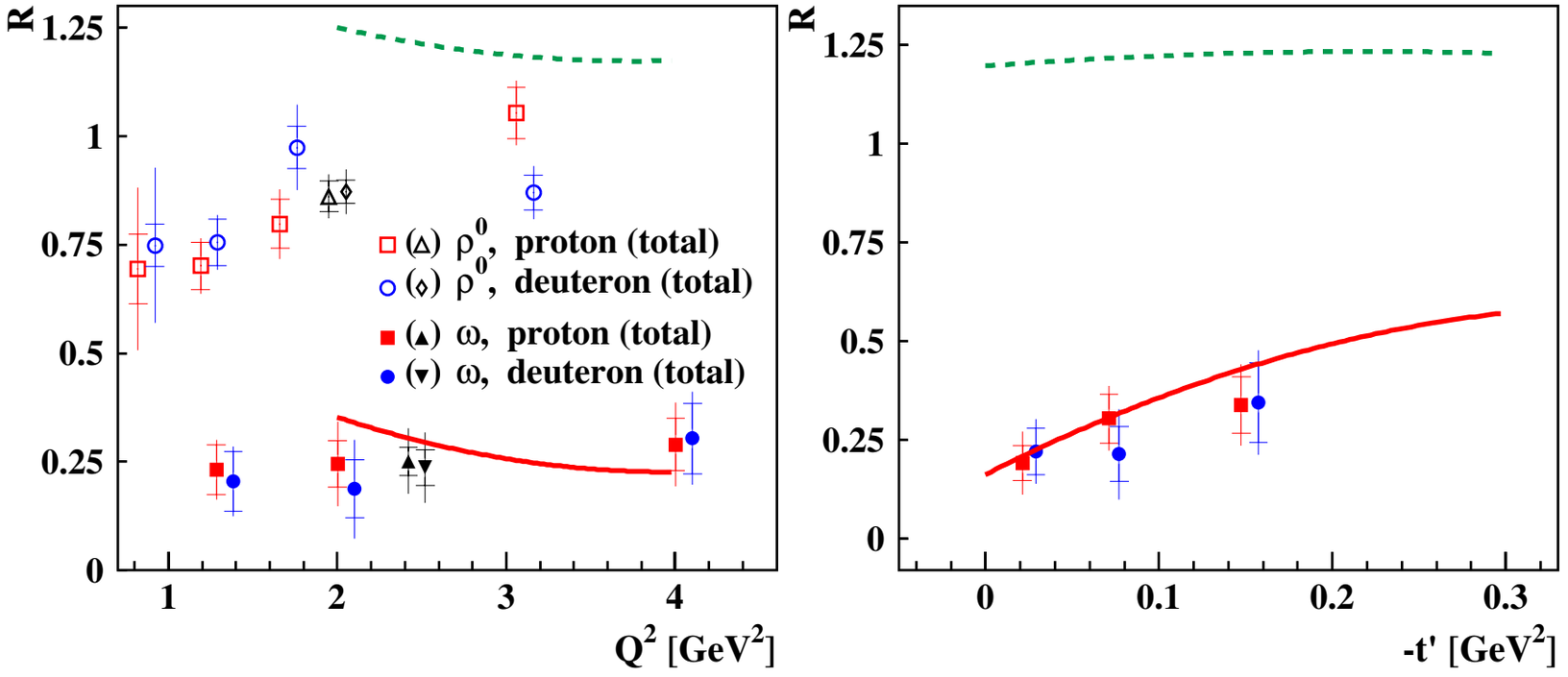


- no pronounced kinematic dependence observed
- again, need for pion-pole contribution observed

Longitudinal-to-transverse cross-section ratio

$$R = \frac{1}{\epsilon}\frac{r_{00}^{04}}{1 - r_{00}^{04}} = \frac{d\sigma(\gamma_L^* \to V_L) + \frac{1}{\epsilon}\, d\sigma(\gamma_T^* \to V_L)}{d\sigma(\gamma_T^* \to V_T) + \epsilon\, d\sigma(\gamma_L^* \to V_T)}$$

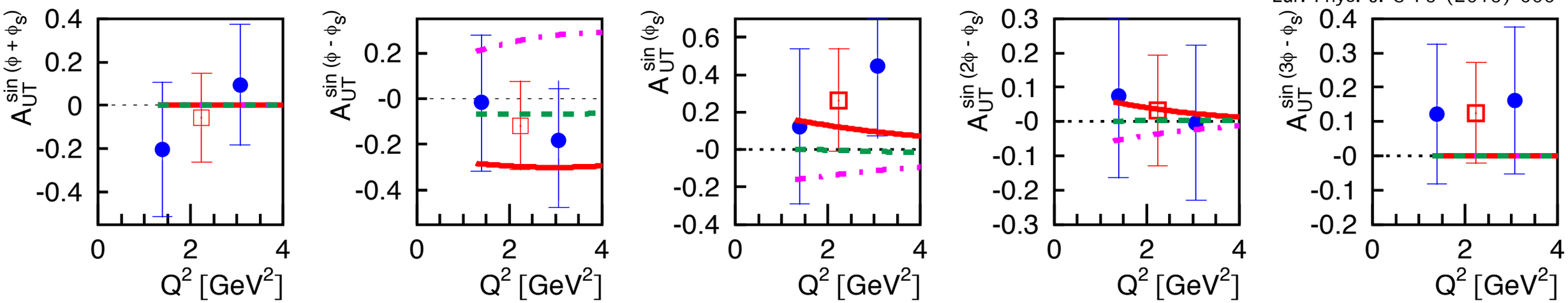
Eur. Phys. J. C 74 (2014) 3110



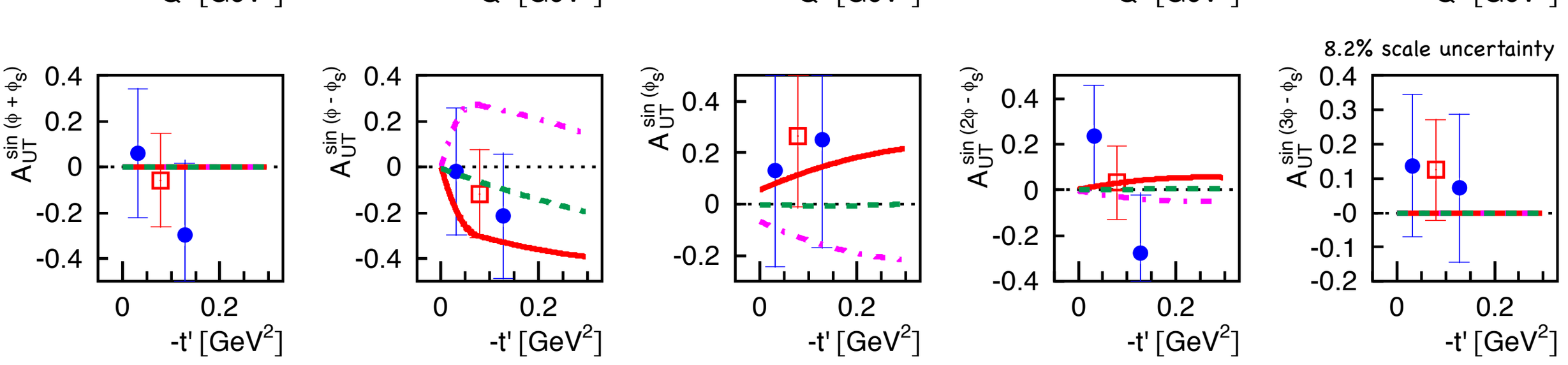
- R(ω) 4 times smaller than R(ρ)
- no pronounced kinematic dependence observed

Transversely polarized target: ω A_{UT}

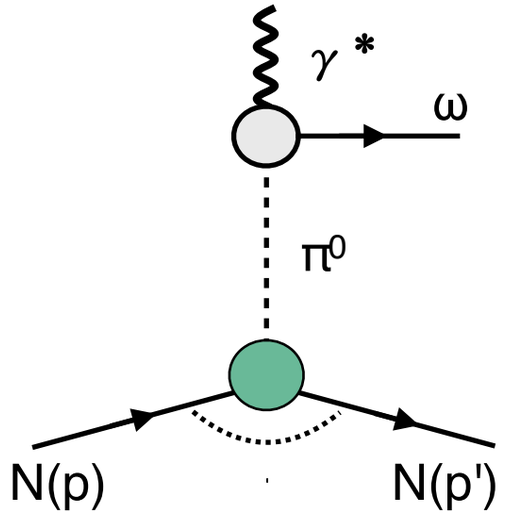
Eur. Phys. J. C 75 (2015) 600



8.2% scale uncertainty



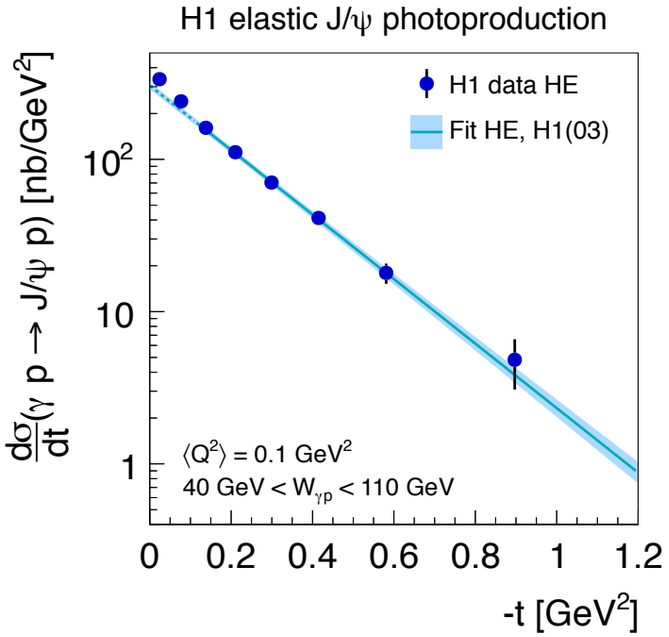
- Model S. Goloskokov and P. Kroll, Eur. Phys. J A 50 146 (2014)
  without pion-pole contribution
  with pion-pole contribution: πω transition FF > 0
  with pion-pole contribution: πω transition FF < 0
- Positive πω transition FF favoured



Exclusive J/ψ

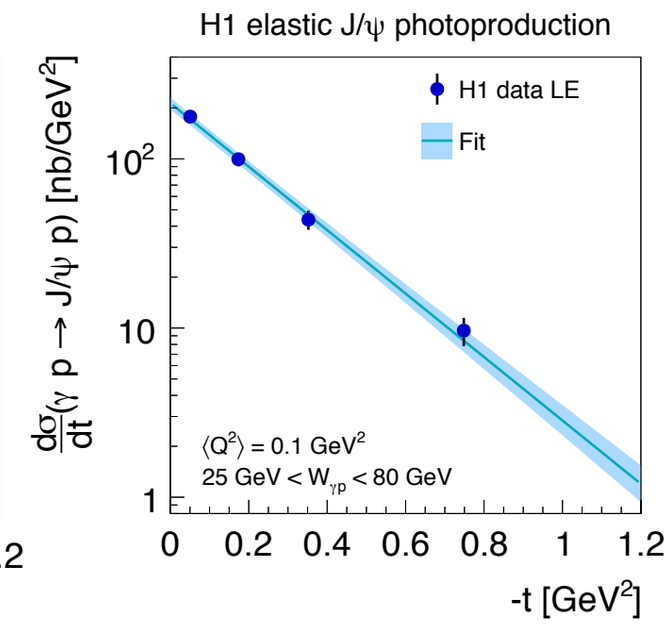
t slope

elastic



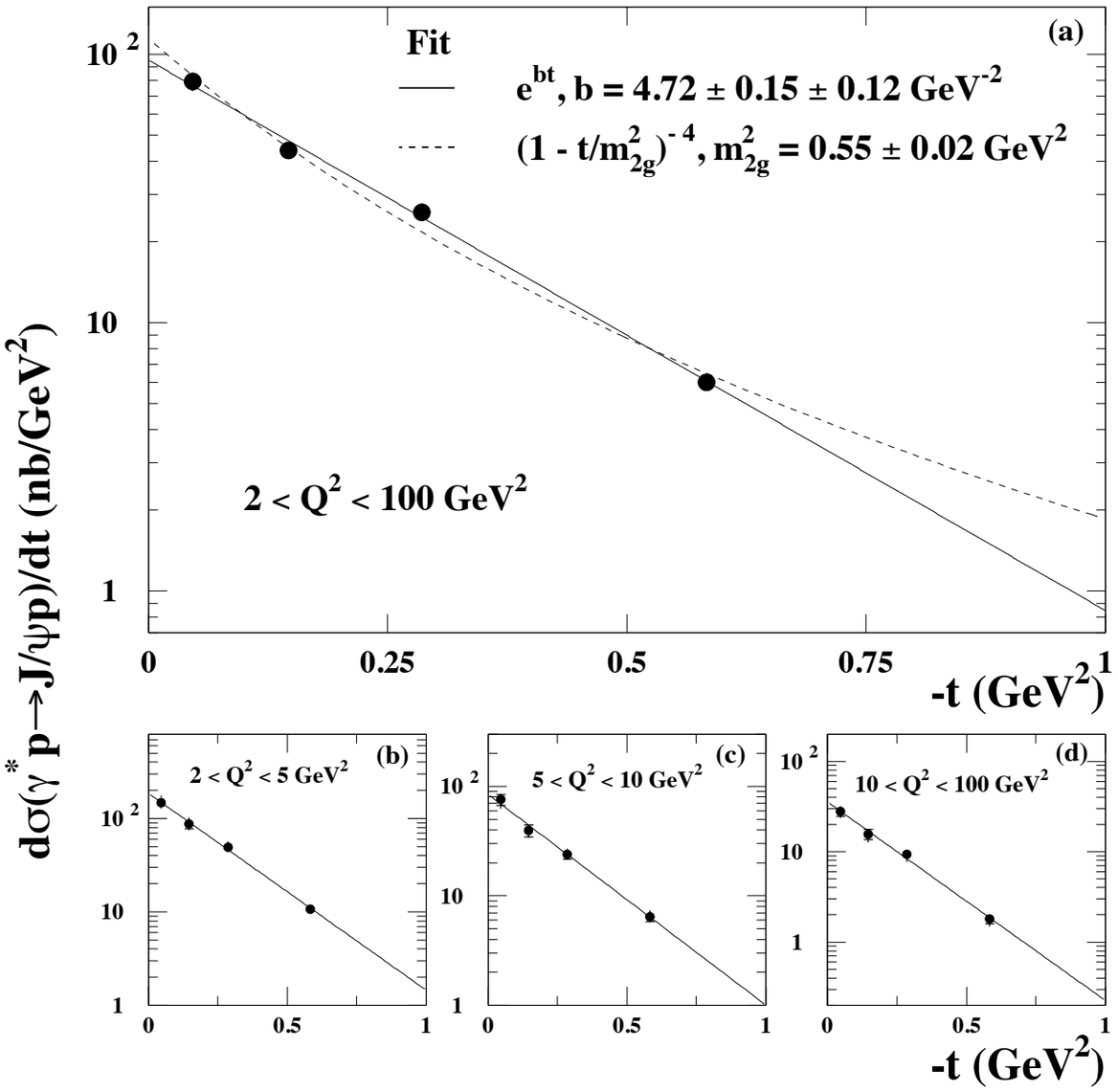
$b = 4.88 \pm 0.15 \text{ GeV}^{-2}$

Eur. Phys. J. C73 (2013) 2466



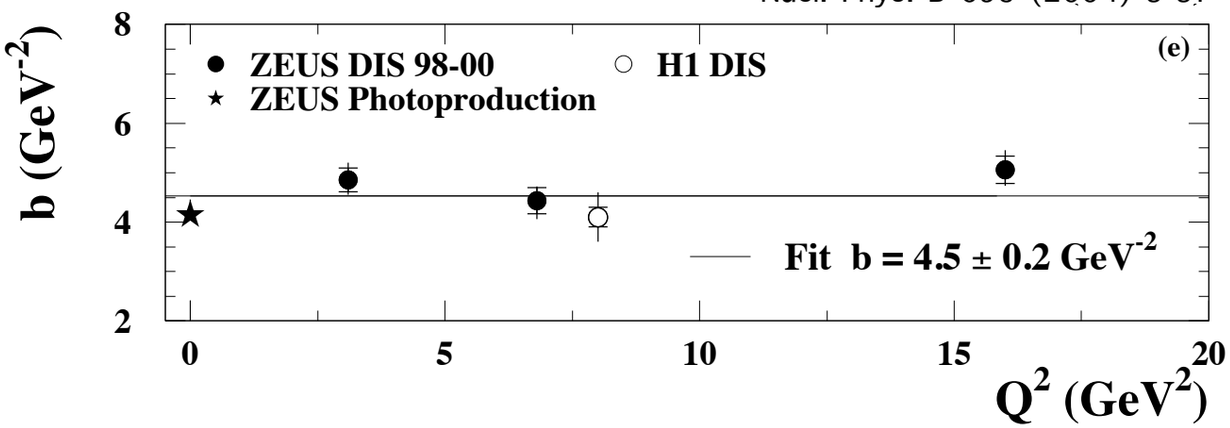
$b = 4.30 \pm 0.20 \text{ GeV}^{-2}$

ZEUS Nucl. Phys. B 695 (2004) 3-37

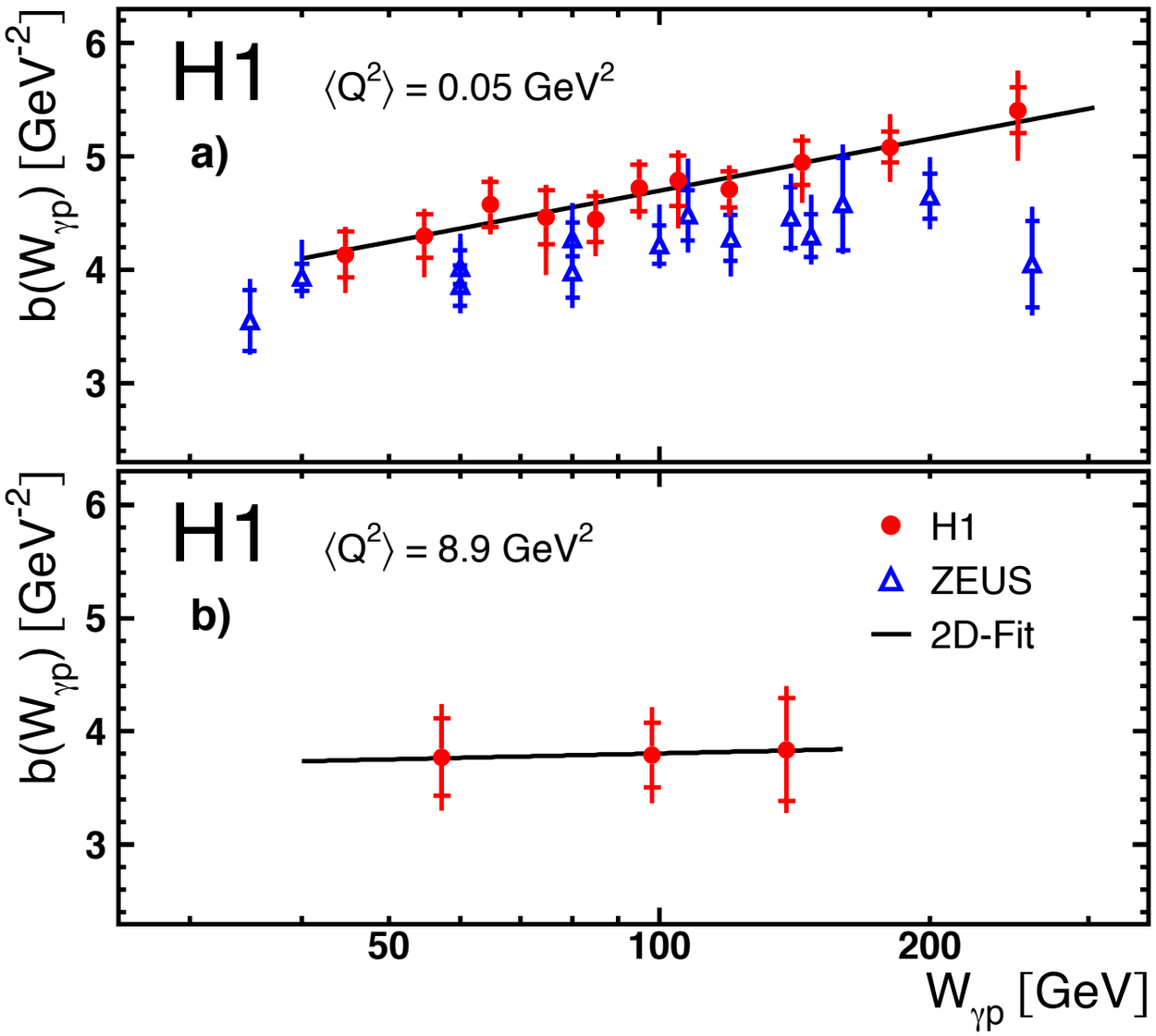


t slope Q^2 and W dependence

Nucl. Phys. B 695 (2004) 3-37

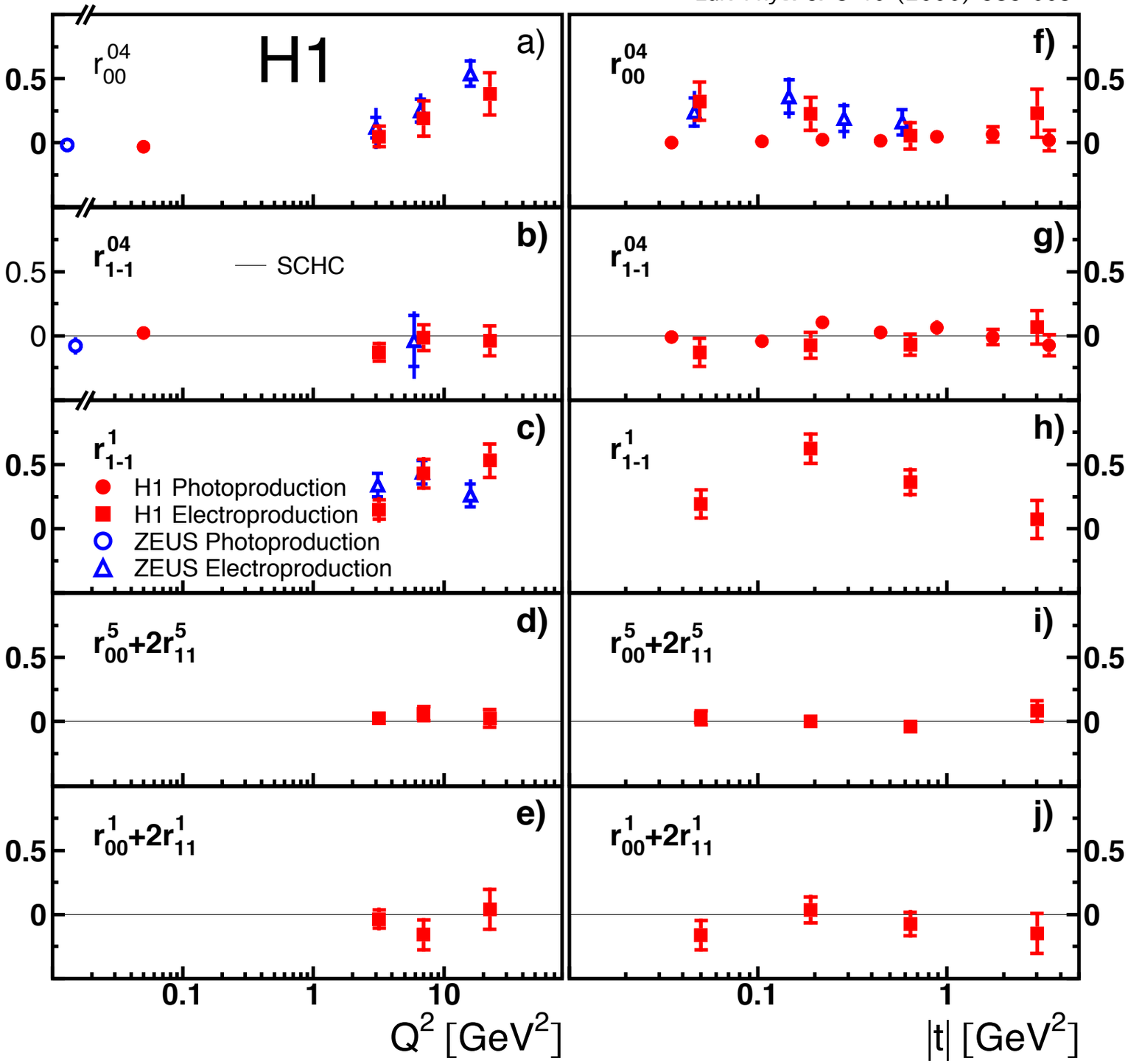


Eur. Phys. J. C 46 (2006) 585-603



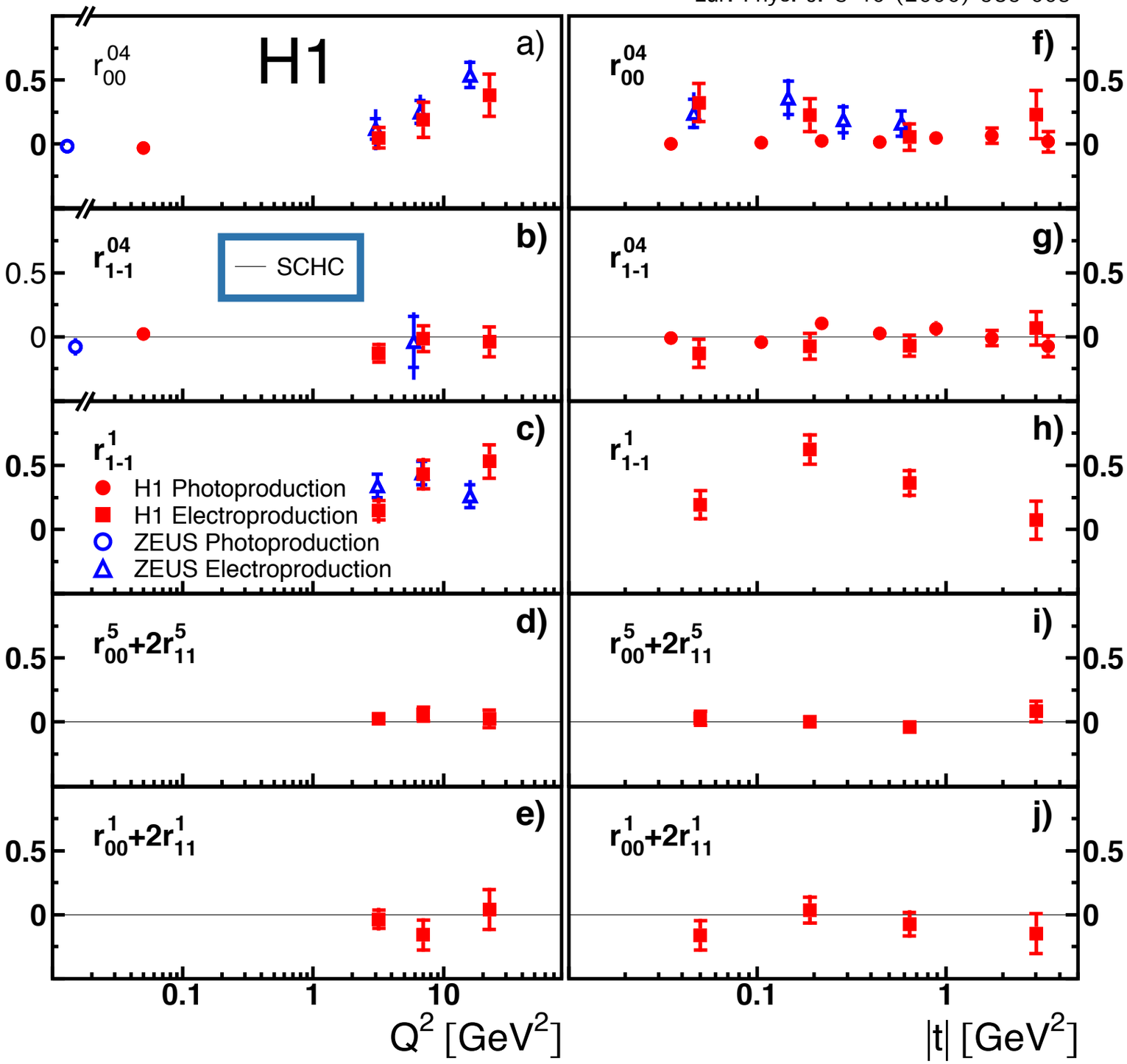
SDMEs

Eur. Phys. J. C 46 (2006) 585-603



SDMEs

Eur. Phys. J. C 46 (2006) 585-603



SCHC and NPE:

$$r^1_{1-1} = \frac{1}{2}\left(1 - r^{04}_{00}\right)$$

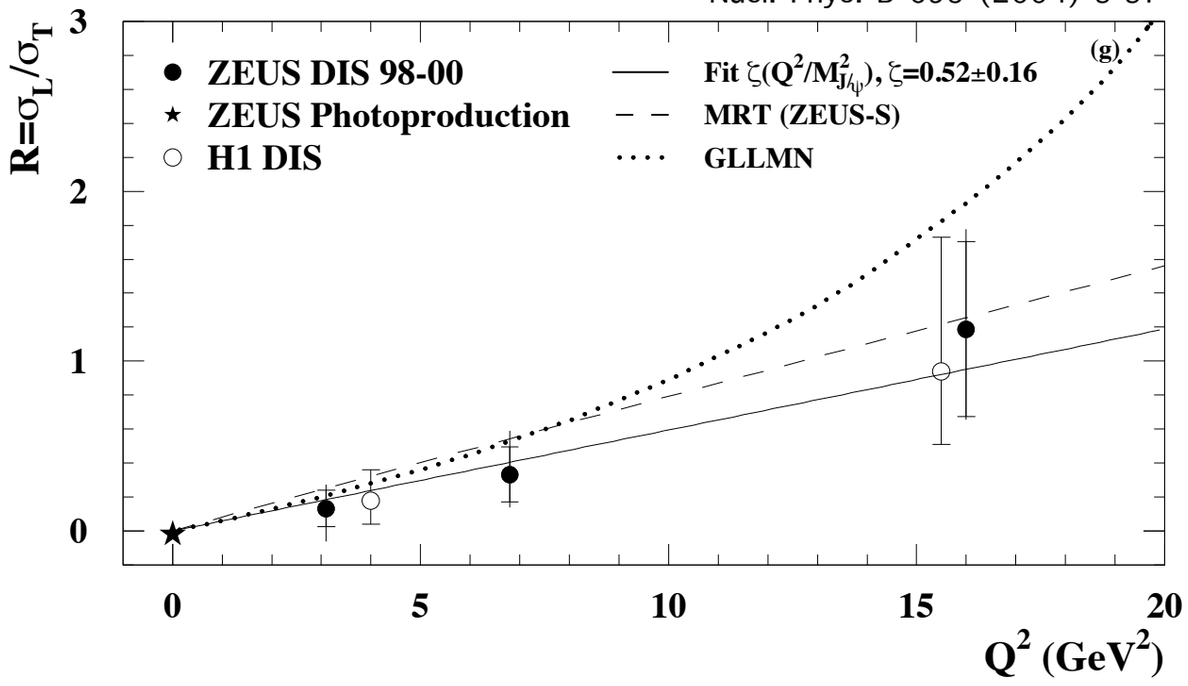
$r^1_{1-1} - \frac{1}{2}\left(1 - r^{04}_{00}\right)$
$-0.10 \pm 0.09^{+0.08}_{-0.06}$
$0.06 \pm 0.10^{+0.08}_{-0.06}$
$0.03 \pm 0.11^{+0.07}_{-0.02}$

Nucl. Phys. B 695 (2004) 3-37

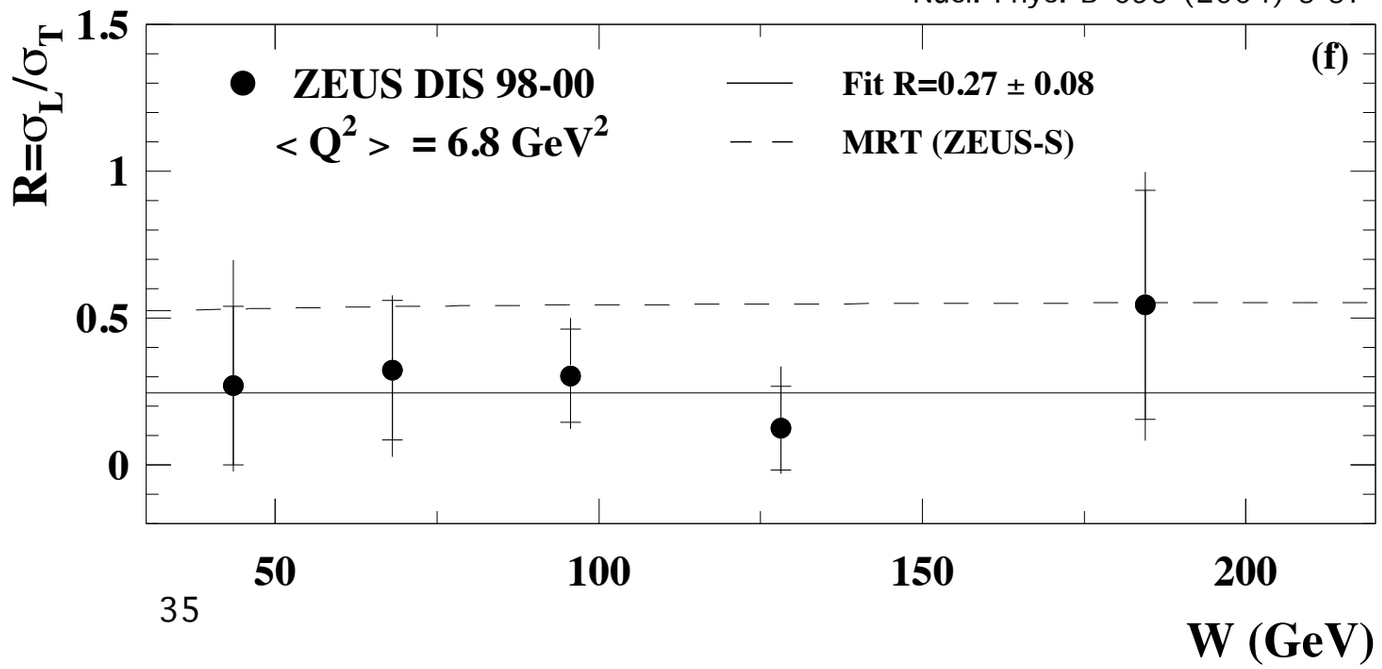
$R=\sigma_L/\sigma_T$

$$R = \frac{1}{\epsilon}\frac{r_{00}^{04}}{1-r_{00}^{04}}\Bigg|_{\text{SCHC}}$$

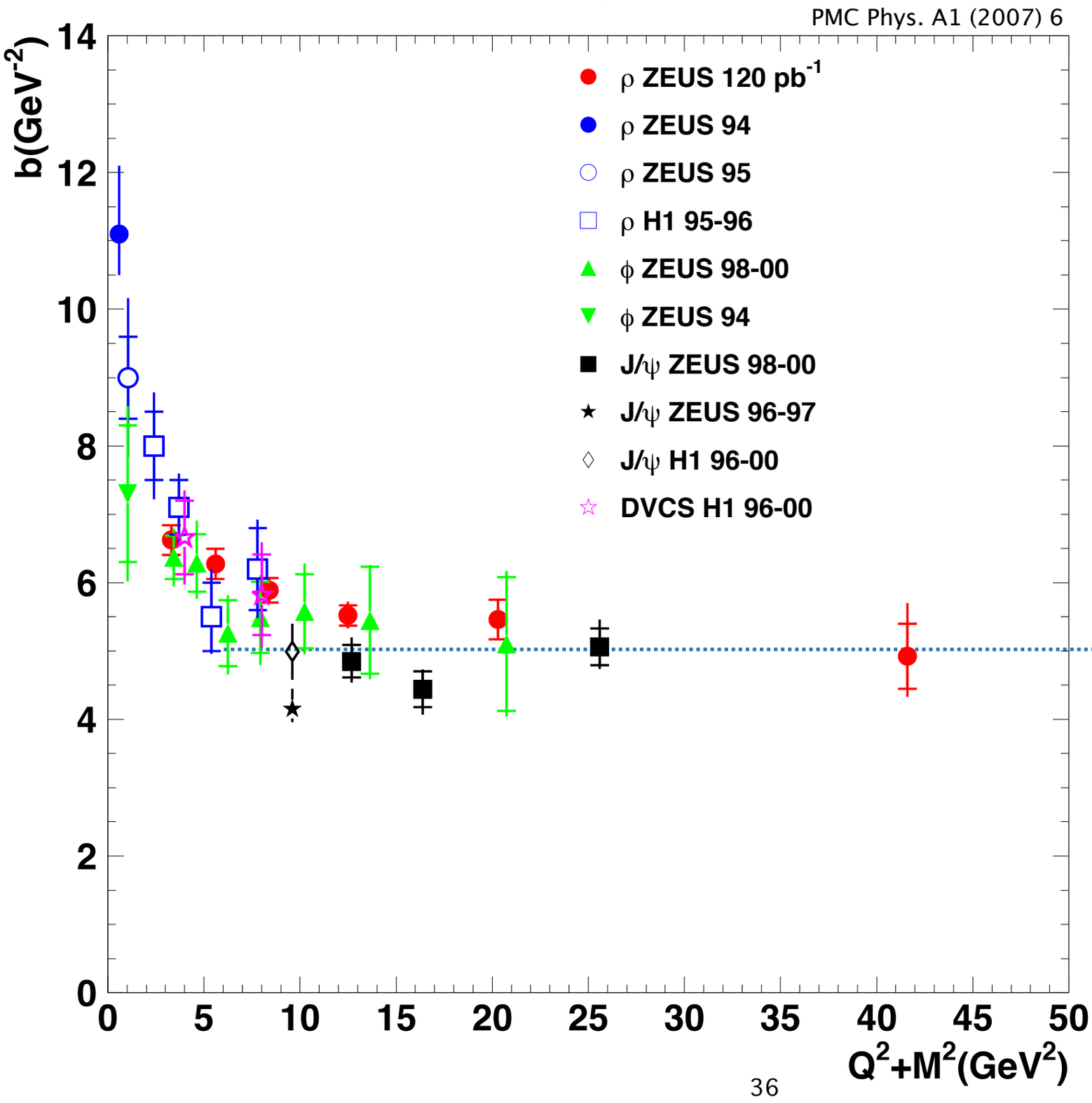
Nucl. Phys. B 695 (2004) 3-37



Nucl. Phys. B 695 (2004) 3-37



Q^2+M^2 dependence of b



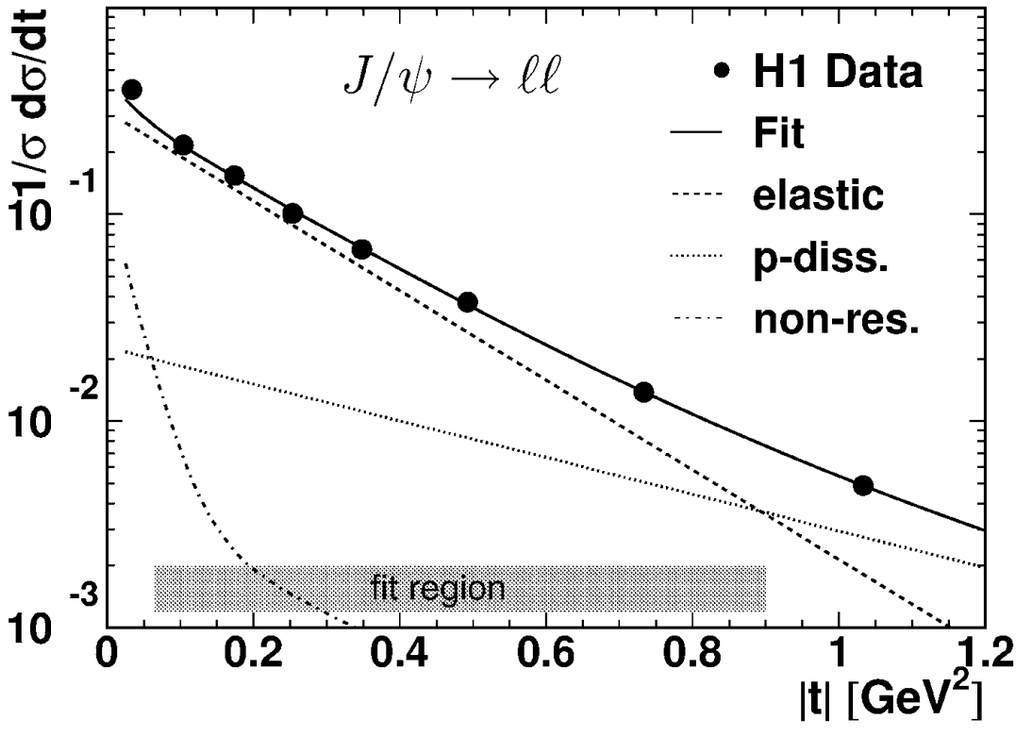
$$b = b_Y + b_{q\bar{q}} + b_{\mathbb{P}}(+b_V)$$

$5\ \mathrm{GeV}^2 :\ \langle r \rangle_g \sim 0.6\ \mathrm{fm}$

Exclusive $\psi(2S)$

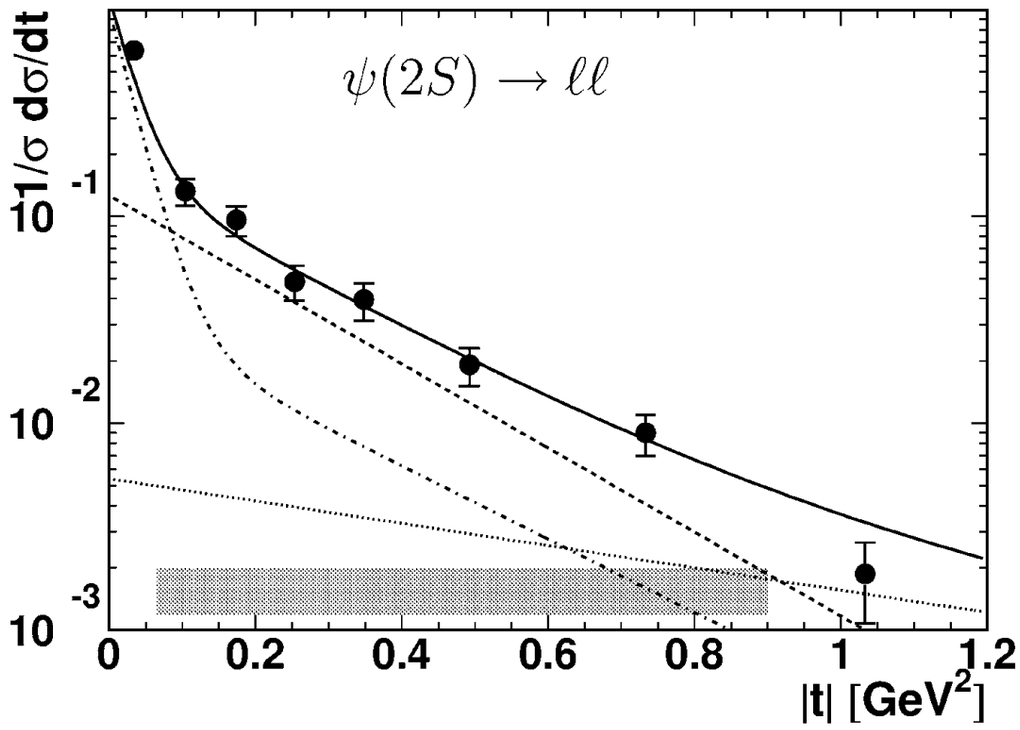
t slope

$Q^2 \approx 0$



$$b^{J/\psi} = 4.99 \pm 0.13 \pm 0.39 \text{ GeV}^{-2}$$

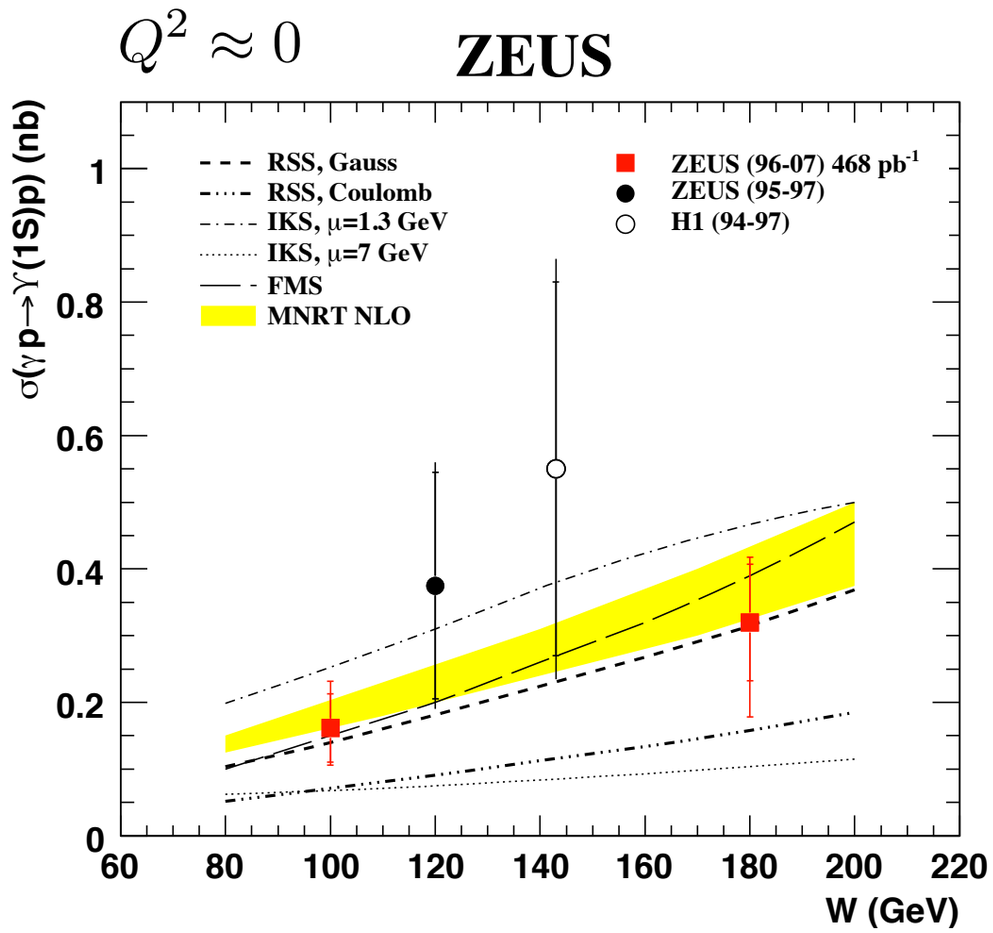
Phys. Lett. B 541 (2002) 251–264



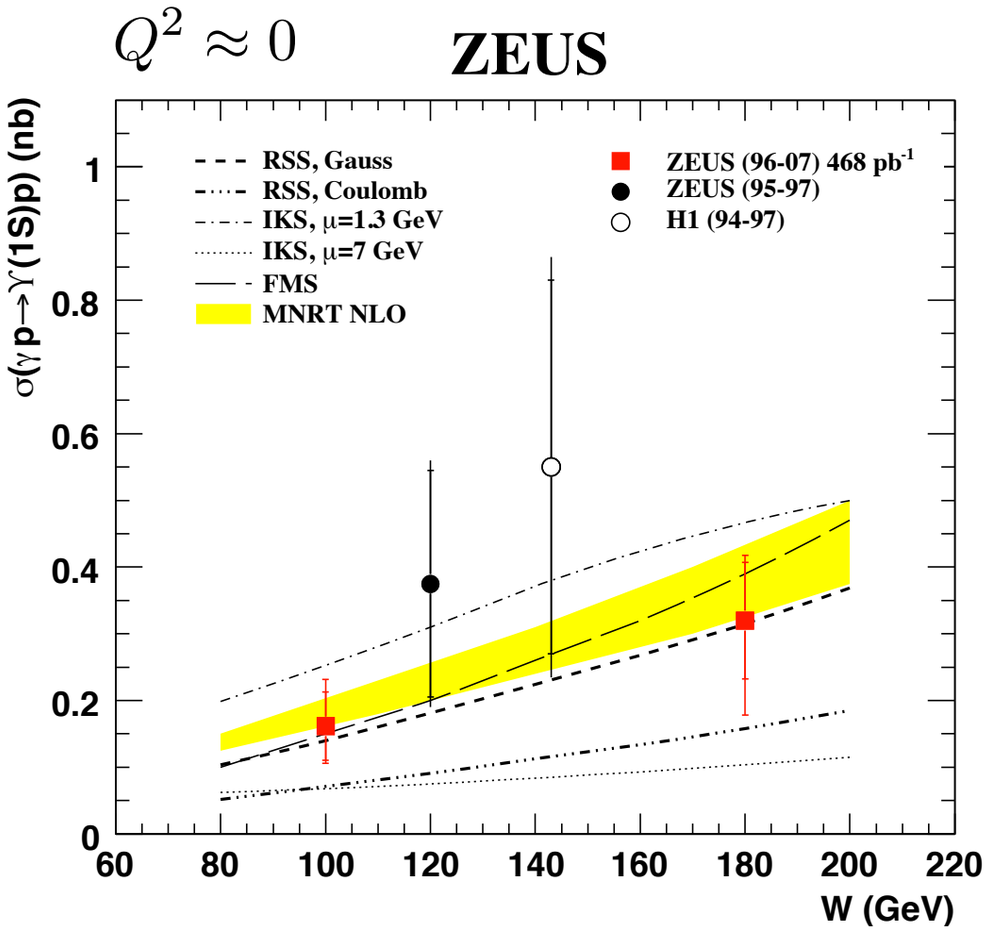
$$b^{\psi(2S)} = 4.31 \pm 0.57 \pm 0.46 \text{ GeV}^{-2}$$

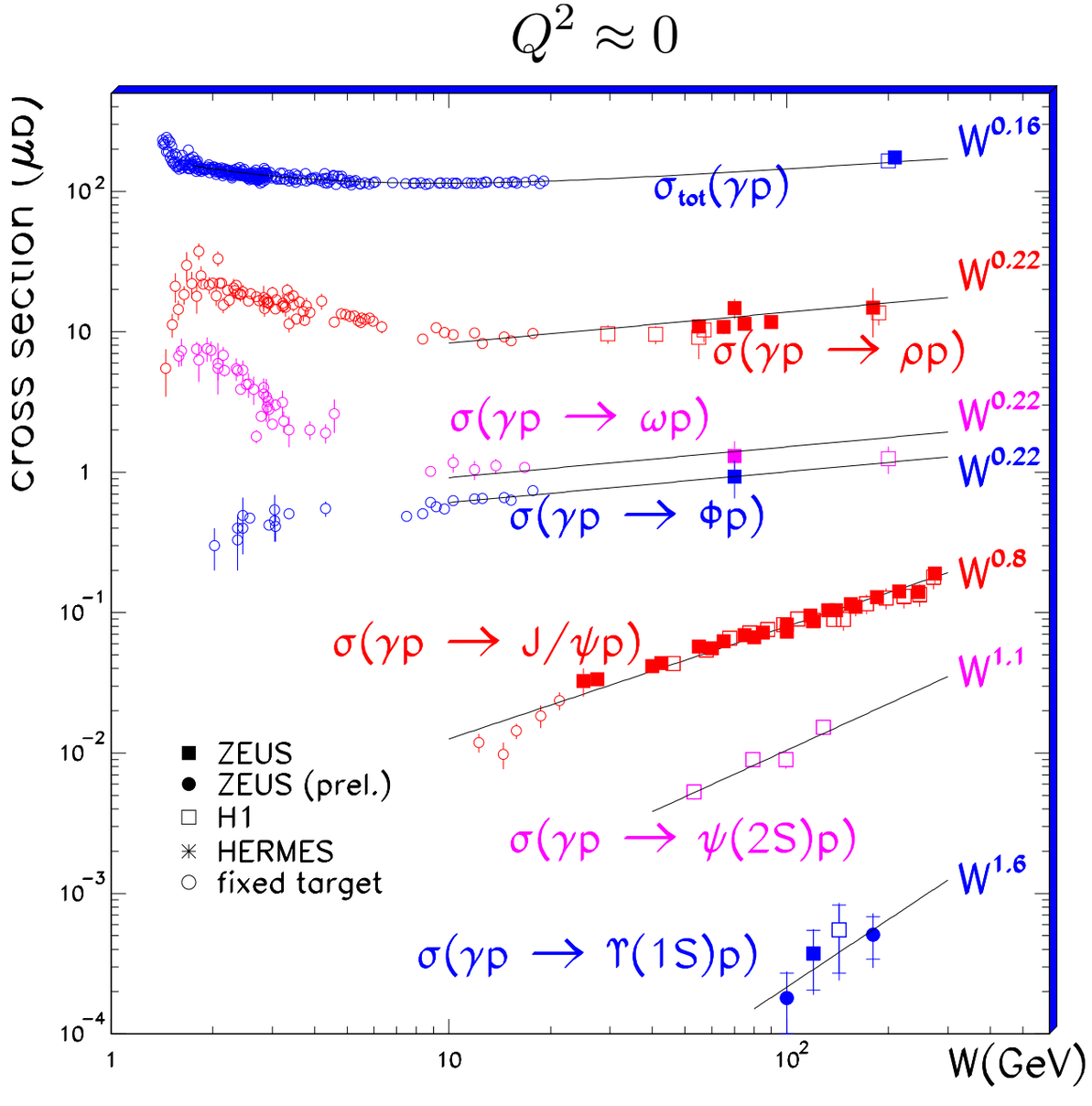
Exclusive ♈

W dependence



W dependence





Summary

- Exclusive measurements in electroproduction and photoproduction of $\rho,\ \phi,\ \omega,\ J/\psi,\ \psi(2S)$, and Υ
- W dependence: soft and hard interactions
- 71 SDMEs; 17 helicity amplitude ratios:
  unpolarized and transversely polarized target, beam polarization
- Disentanglement of longitudinal and transverse cross section
- t dependence: size of interacting systems, color distribution in hadron
- Natural and unnatural parity exchange
- $Q^2+M_V^2$ comparison of vector mesons

Back up

Helicity amplitude ratios

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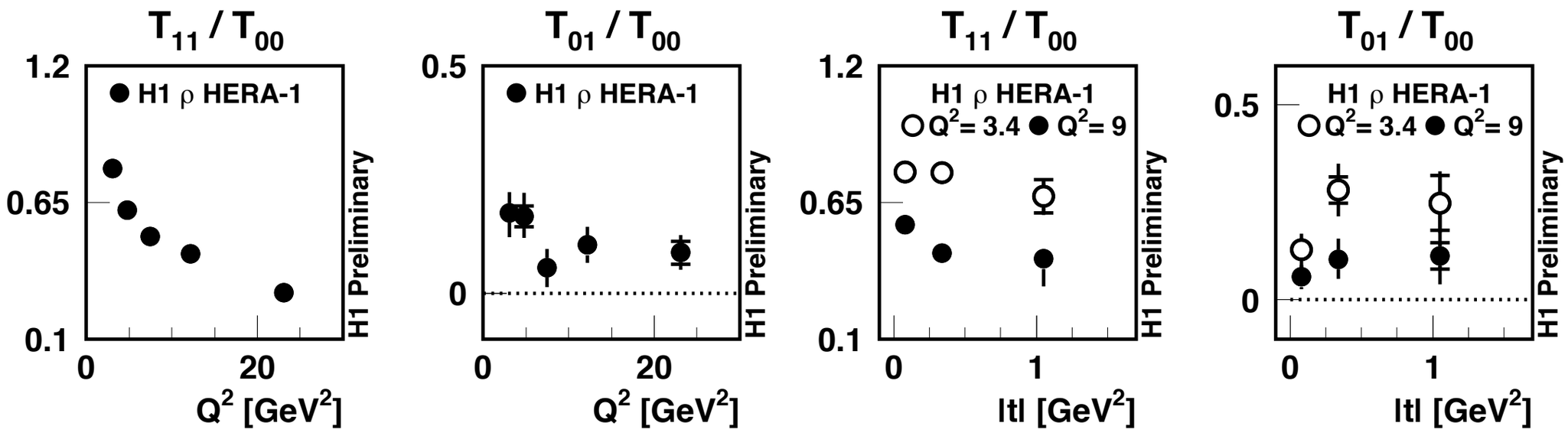
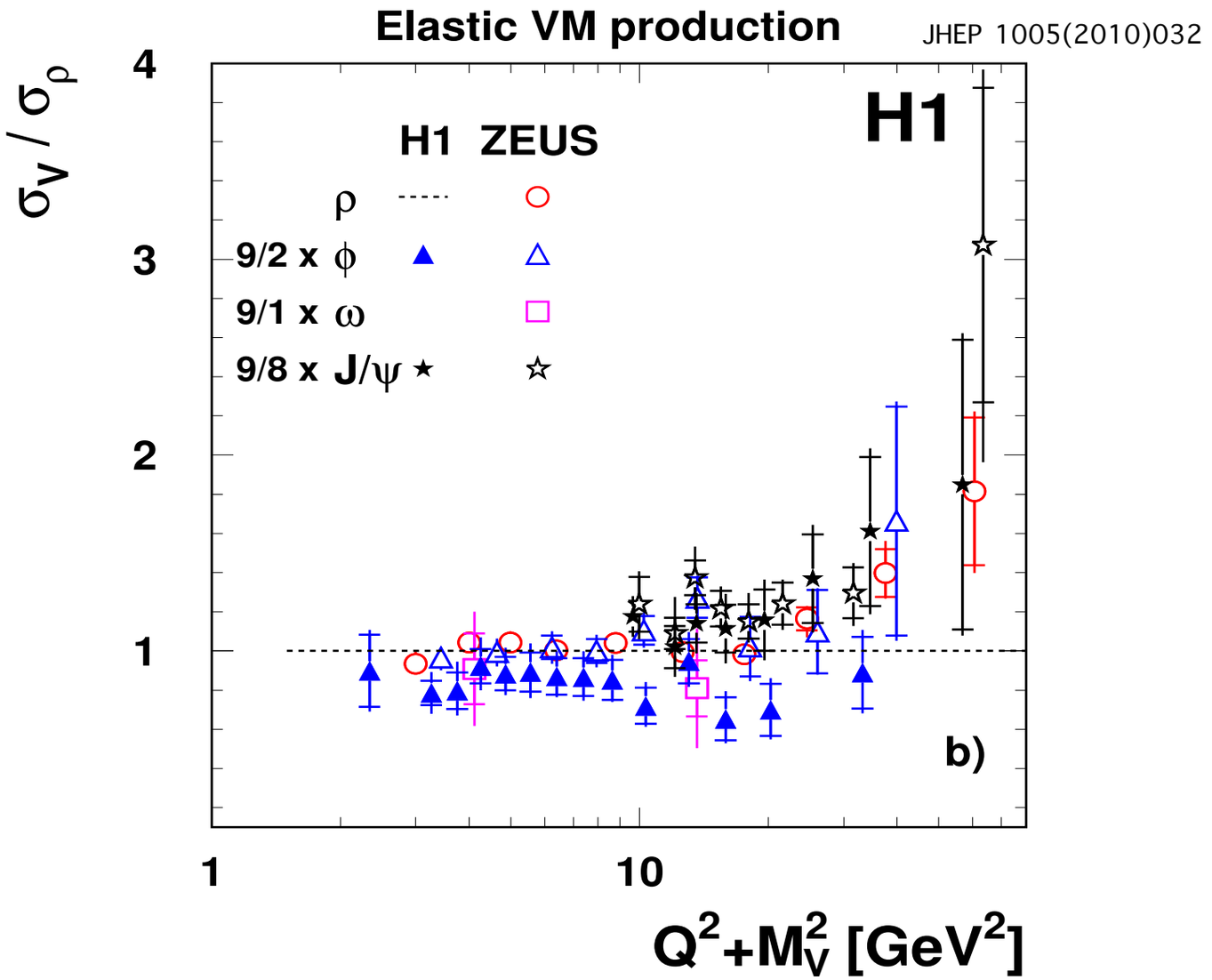
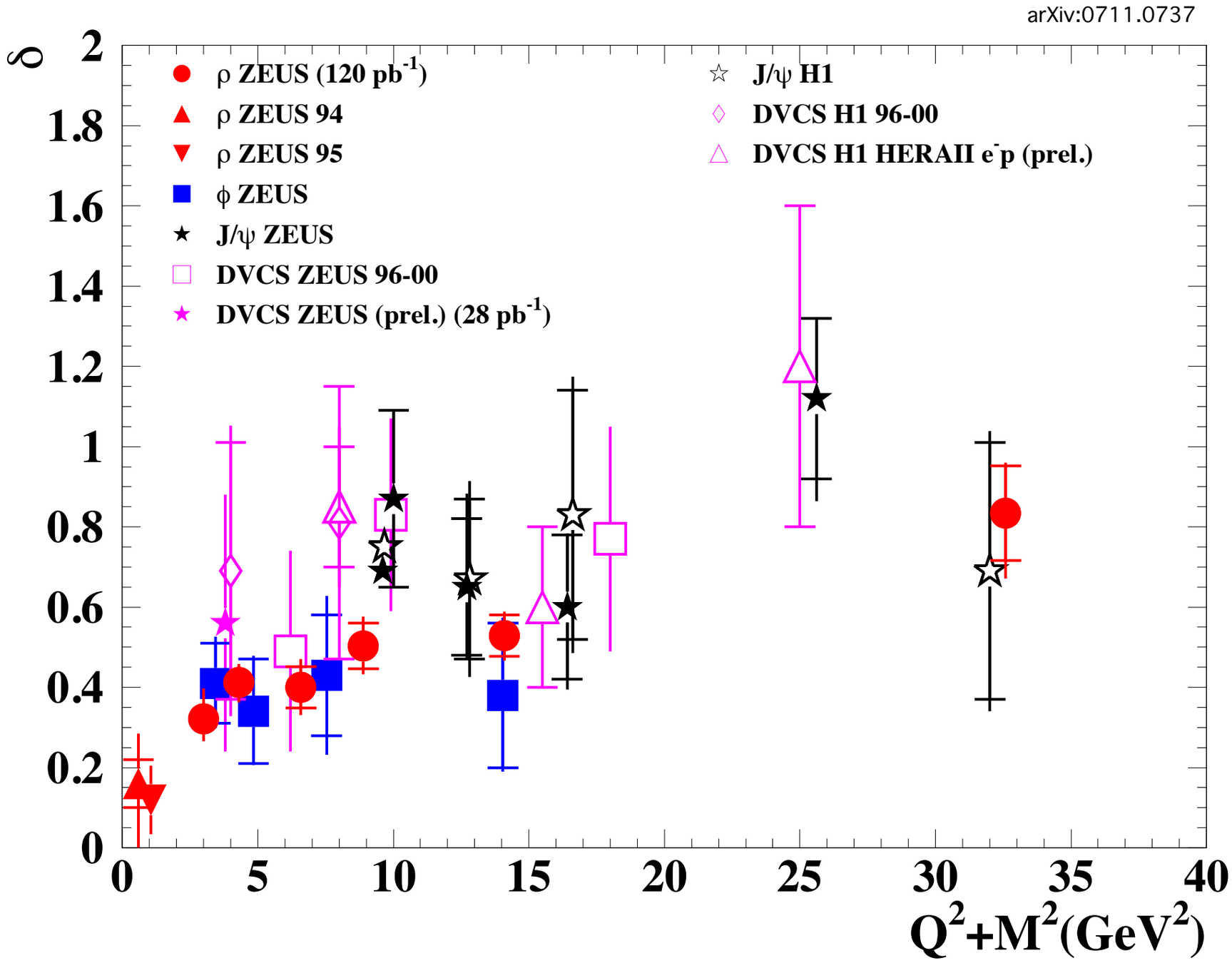


Cross section ratios

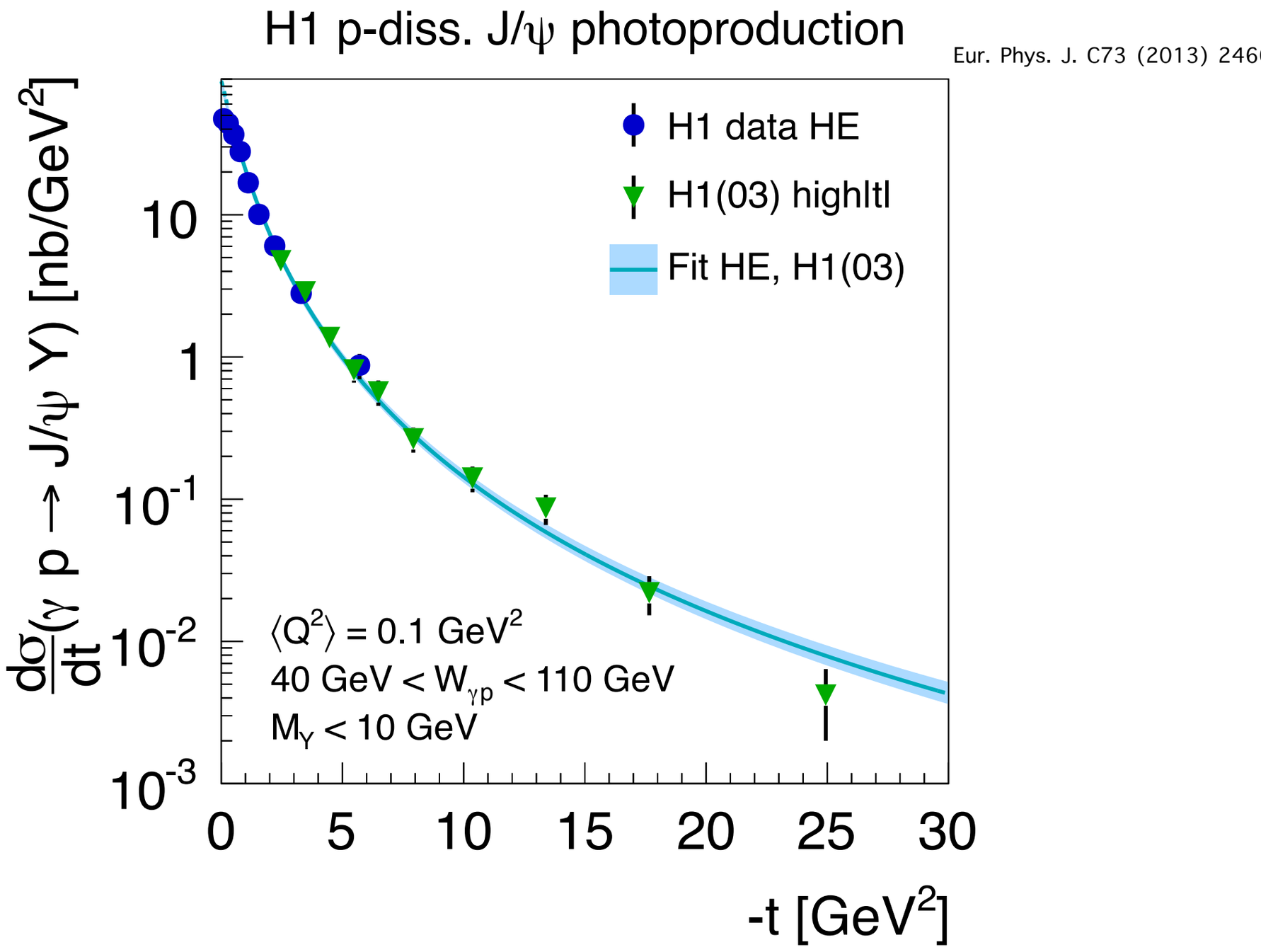


$\sigma \propto W_{\gamma p}^{\delta}$

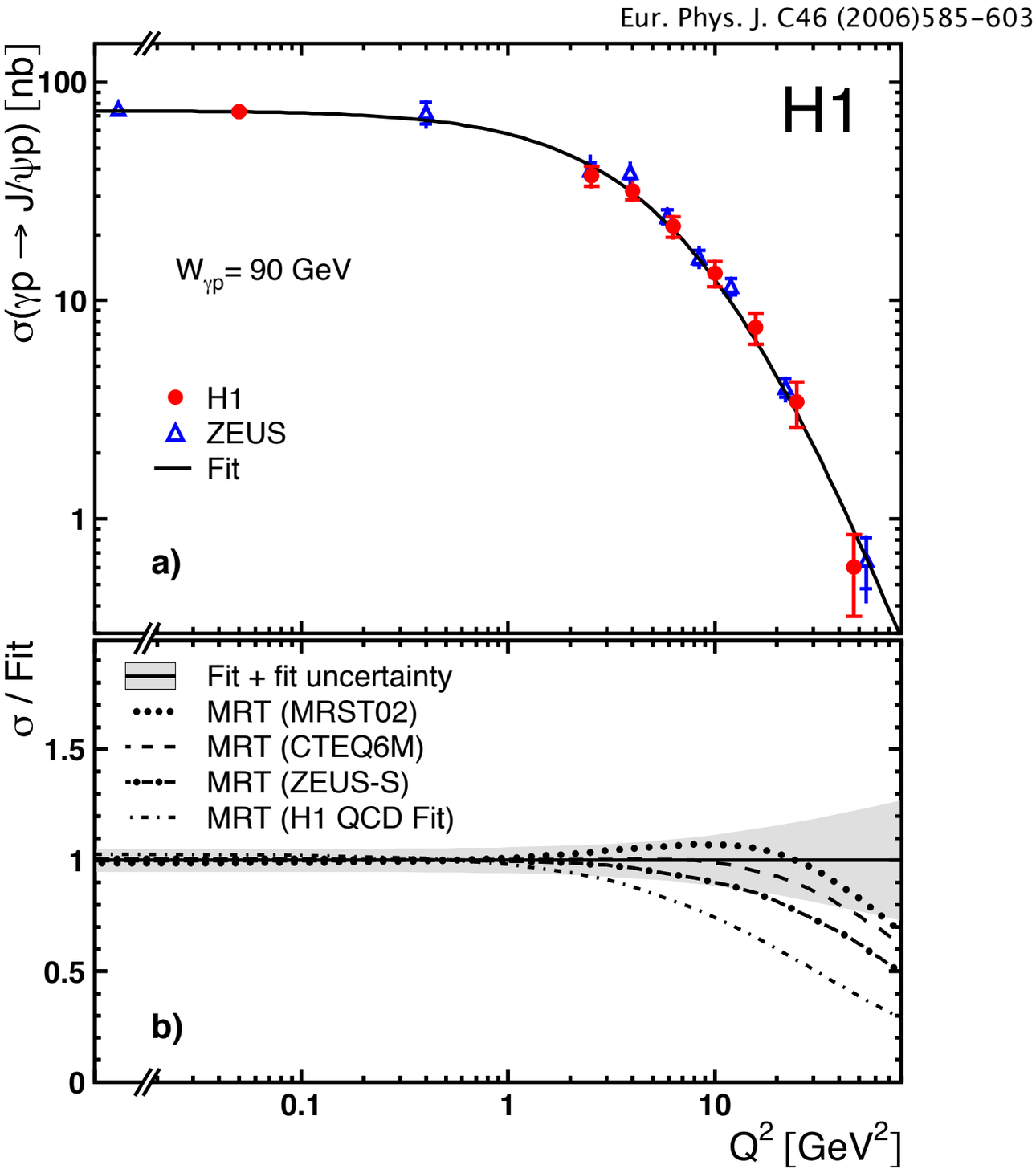
δ



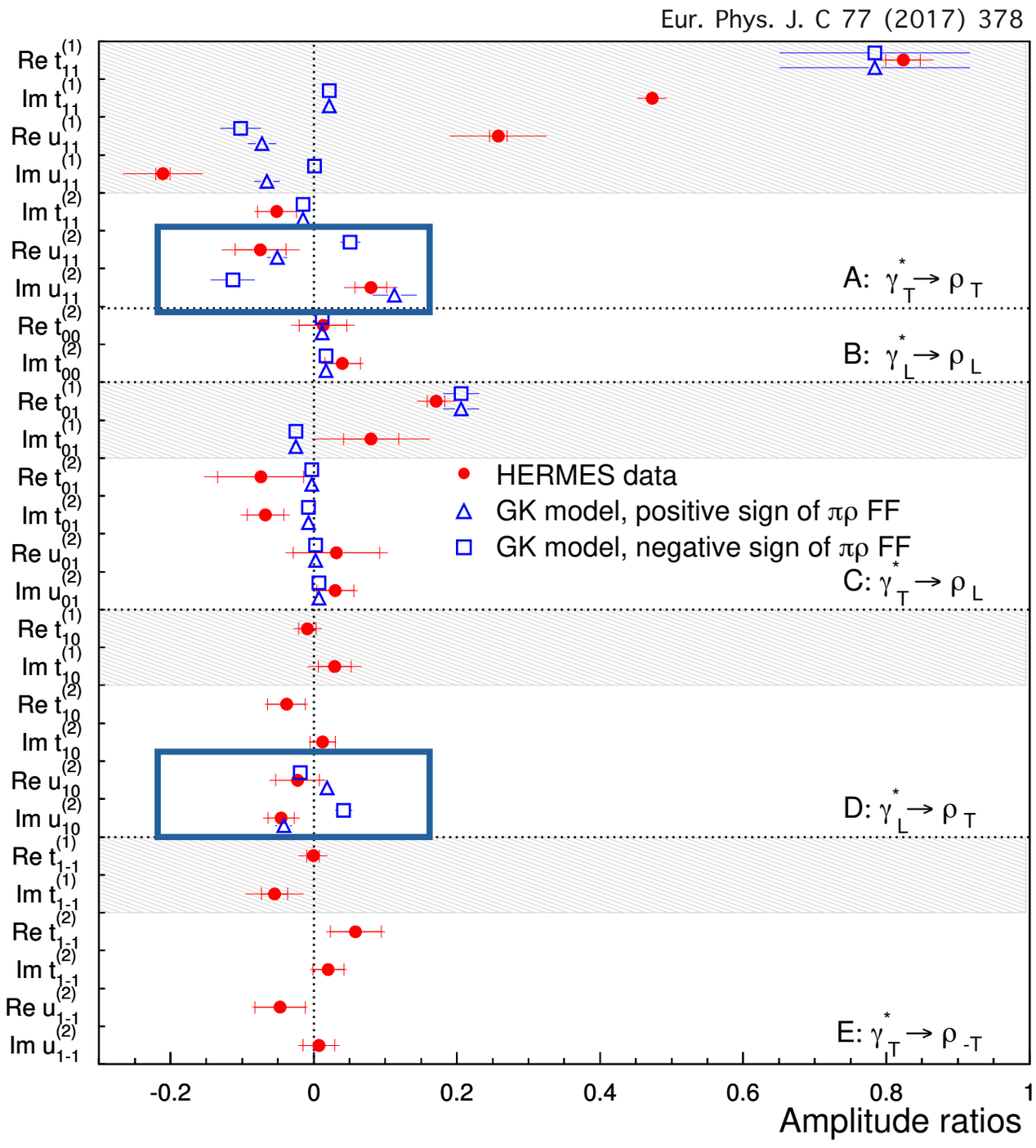
t slope low and high |t|



Q^2 dependence

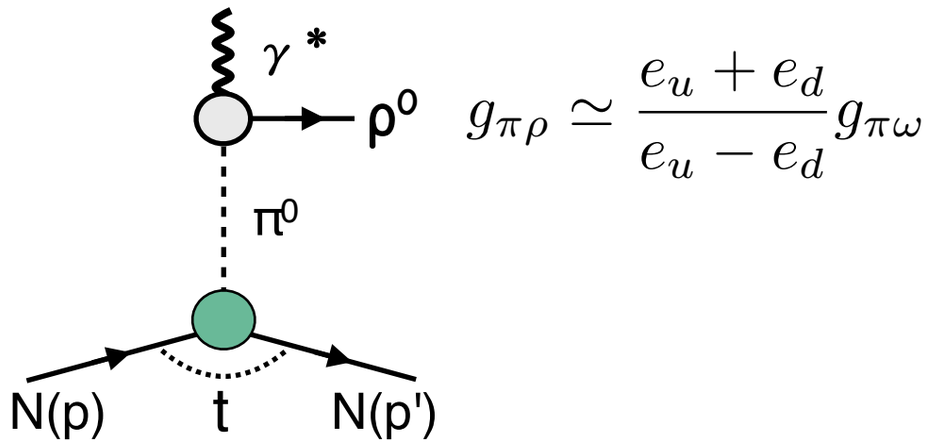


Comparison ρ^0 helicity amplitude ratios with GK model



- GPD H.
- GPD H.
- GPD $\widetilde{H}$ + pion pole.
- GPD E.
- Only pion pole. Positive form factor.
- GPD E.
- GPD $\overline{E}_T$.
- GPD H_T.

- Only pion pole. Positive form factor.



$$g_{\pi\rho} \simeq \frac{e_u + e_d}{e_u - e_d} g_{\pi\omega}$$