
# GPDs and diffraction at the HERA collider experiments

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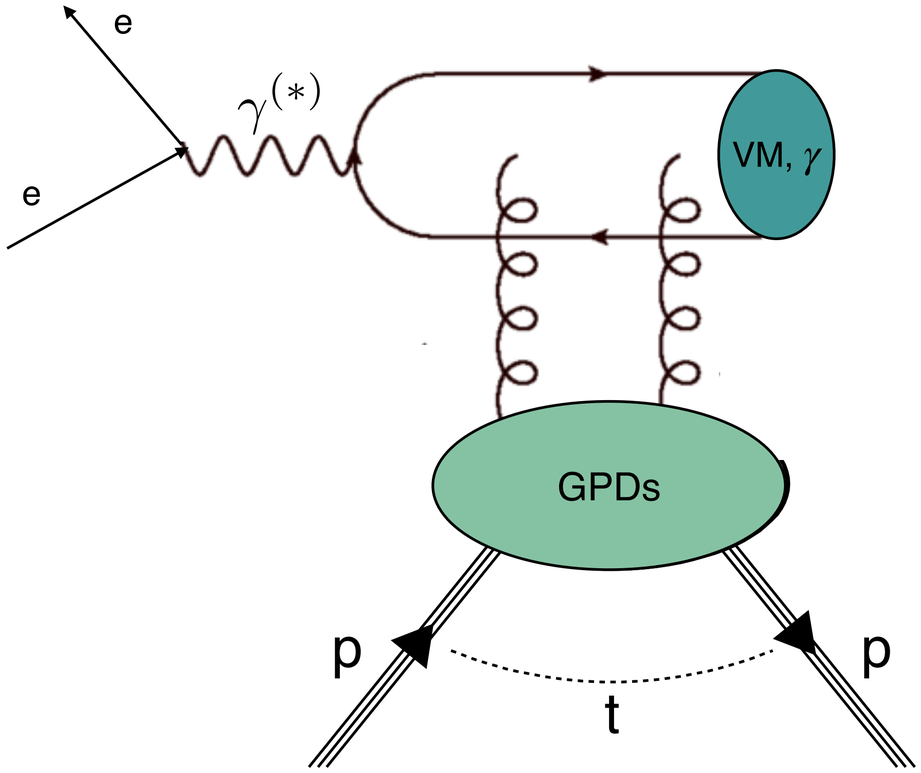
ECT*-APCTP Joint Workshop:
Exploring resonance structure with transition GPDs
Trento, Italy
21–25 August 2023

# Measurements at H1 and ZEUS




- unpolarised 920 GeV proton beam
- effectively unpolarised 27 GeV lepton beam
- exclusive production of

  $\gamma,\ \rho,\ \omega,\ \phi,\ J/\psi,\ \psi(2S),\ \Upsilon$
- dissociative diffraction of $\rho,\ \omega,\ \phi,\ J/\psi,\ \psi(2S),\ \Upsilon$

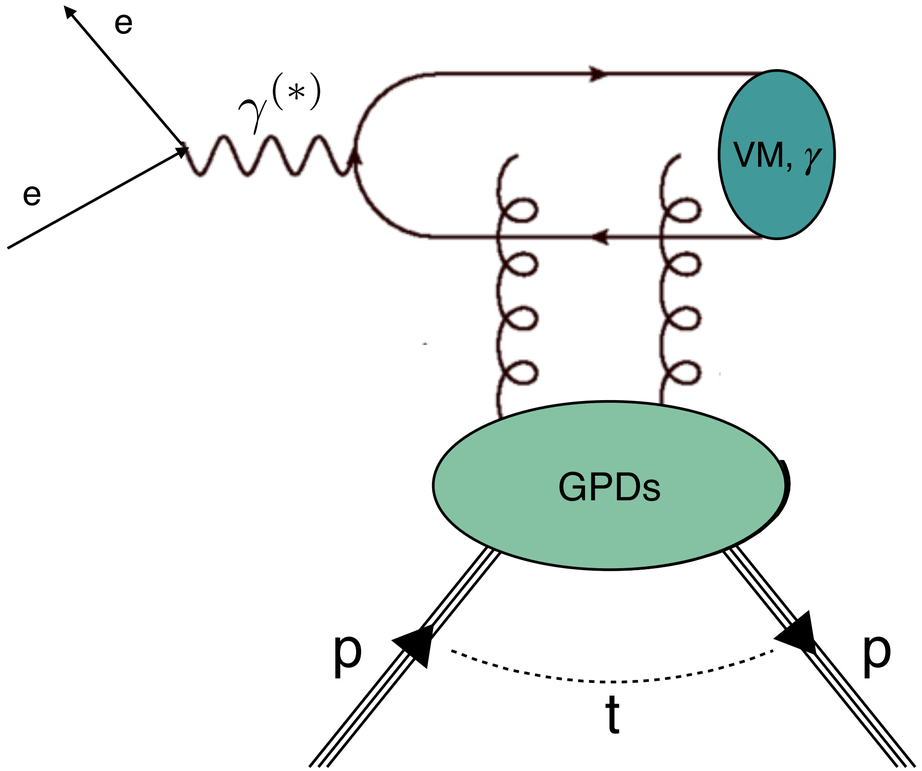
- far-forward tiggers and calorimeters:
  separation elastic and dissociative events
- far-forward proton spectrometers:
  detection of scattered proton with few % acceptance
  for elastic events

$$10^{-4} \leq x_B \leq 10^{-2}$$

$$25\ \text{GeV} \leq W \leq 305\ \text{GeV}$$

$$2\ \text{GeV}^2 \leq Q^2 \leq 100\ \text{GeV}^2\ \text{(DIS)}$$

# Exclusive vector-meson production




Target polarization state

- unpolarized target:
  nucleon-helicity-non-flip GPDs H, $\tilde{H}$ and $\bar{E}_T=2H_T+\tilde{E}_T$.
- transversely polarised target:
  nucleon-helicity-flip GPDs E, $\tilde{E}$ and $H_T$.

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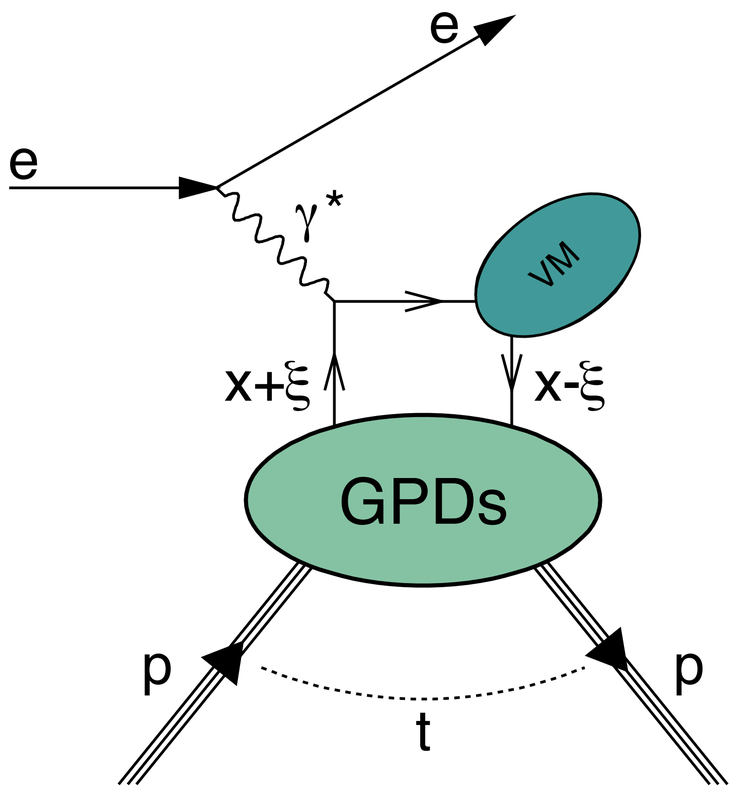


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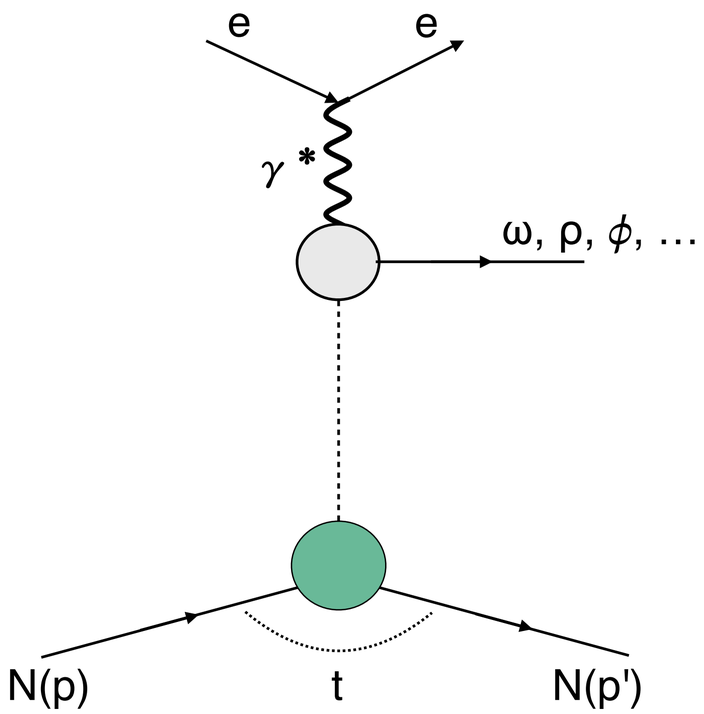


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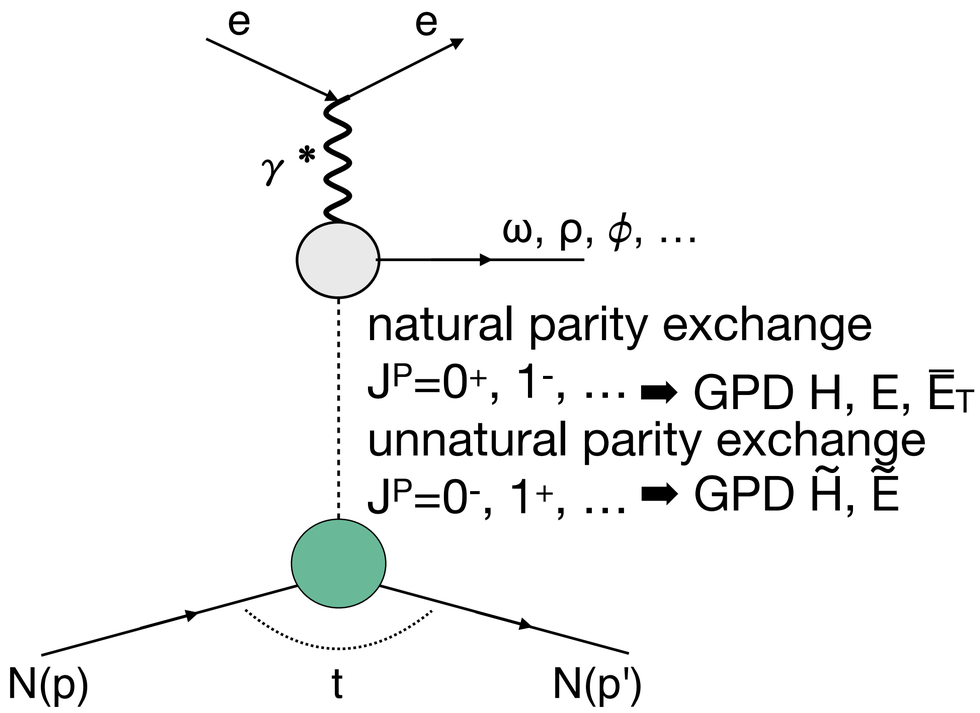


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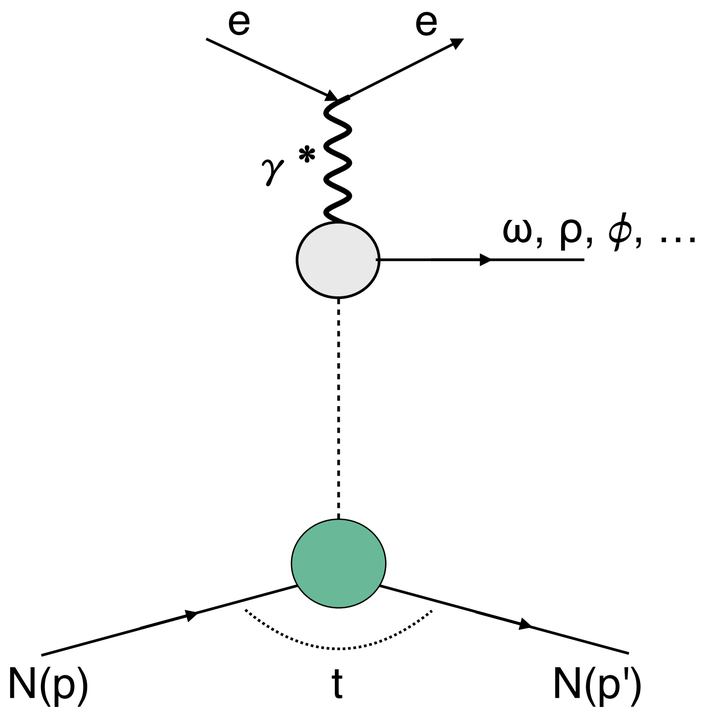
# Helicity amplitude ratios and spin-density matrix elements (SDMEs)

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




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

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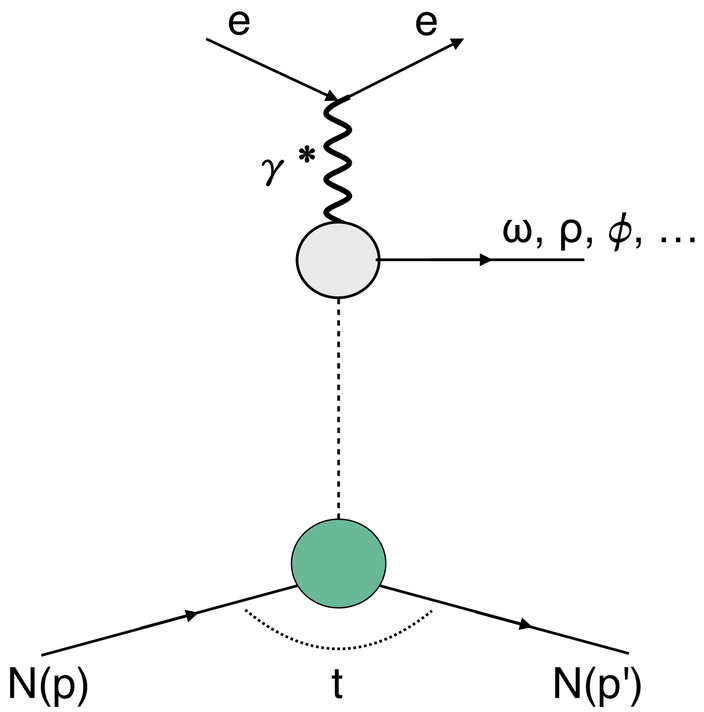


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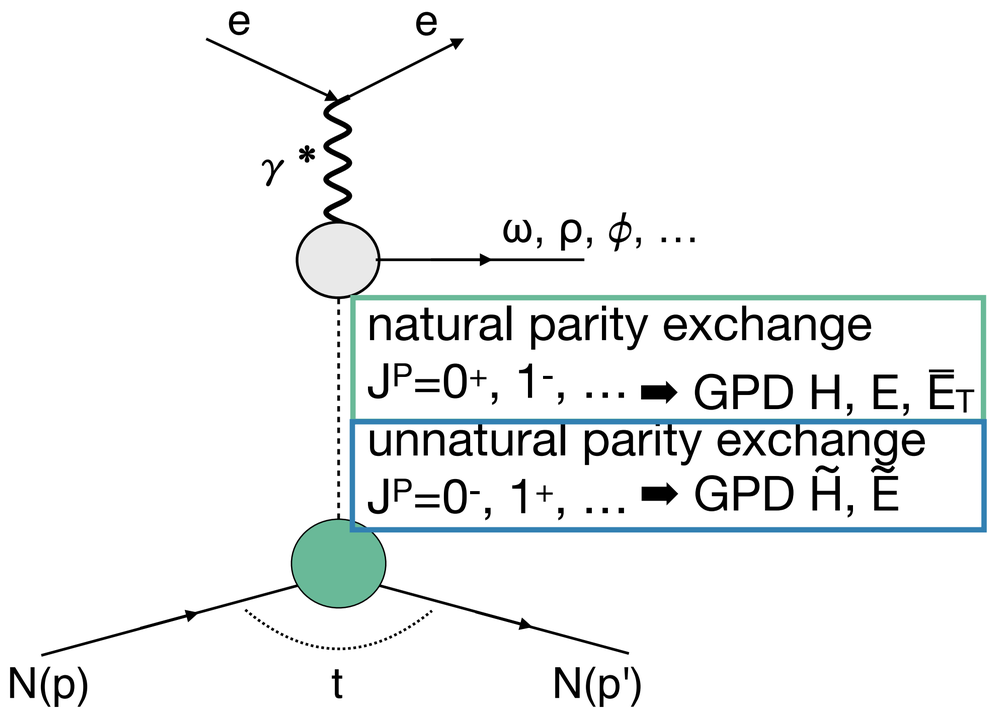


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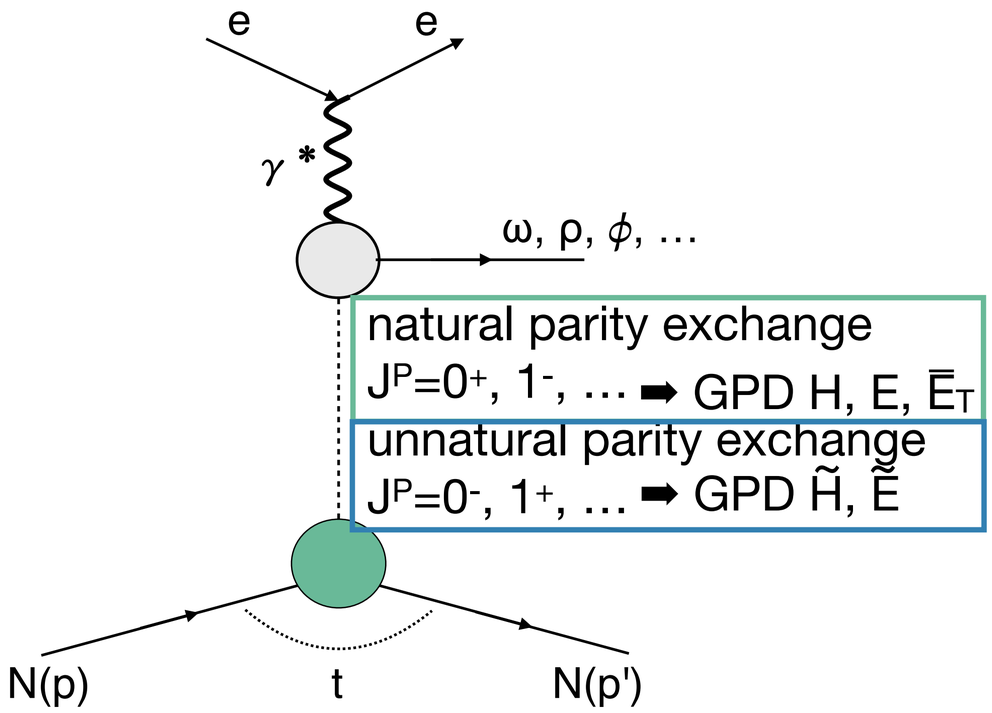


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$$n = 1 \quad \lambda_N = \lambda'_N$$
$$n = 2 \quad \lambda_N \neq \lambda'_N$$

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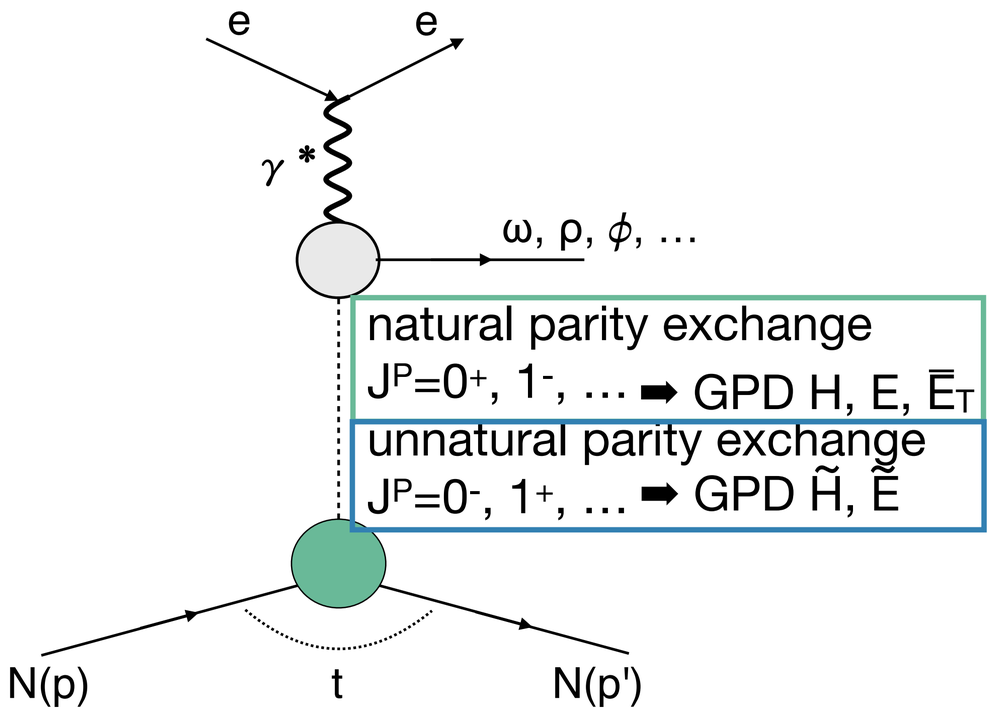


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- SDMEs

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

# Dissociative production

$$\sigma_{\rm tot} \sim \langle |A|^2 \rangle$$

average cross section

$$\sigma_{\rm el} \sim |\langle A \rangle|^2$$

average amplitude over target configurations:
probes average distributions

$$\sigma_{\rm diss} \sim \sum_{f \neq i} |\langle f|A|i\rangle|^2$$

$$= \sum_f \langle i|A|f\rangle^\dagger \langle f|A|i\rangle - \langle i|A|i\rangle^\dagger \langle i|A|i\rangle$$

$$= \left( \langle |A|^2 \rangle - |\langle A \rangle|^2 \right)$$

Incoherent
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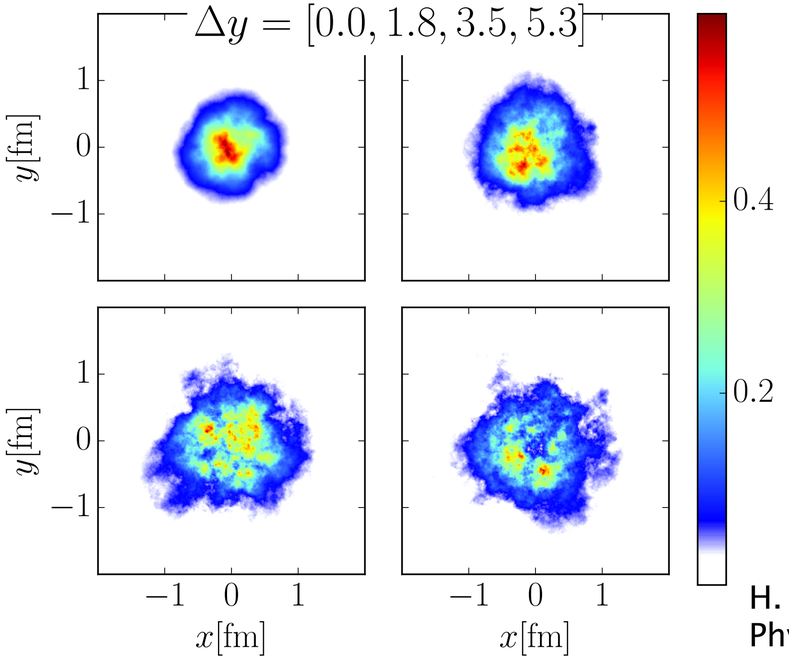


H. Mäntysaari and B. Schenke.
Phys. Rev. D 98, 034013 (2018)

# Dissociative production

See Michael Winn's talk

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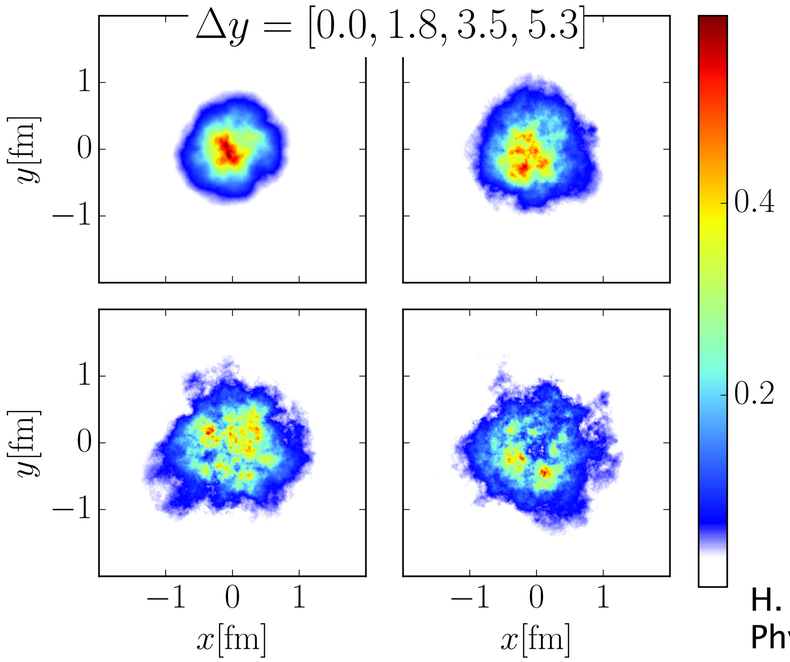


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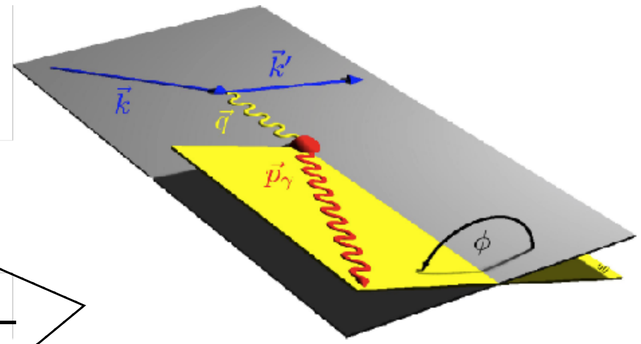
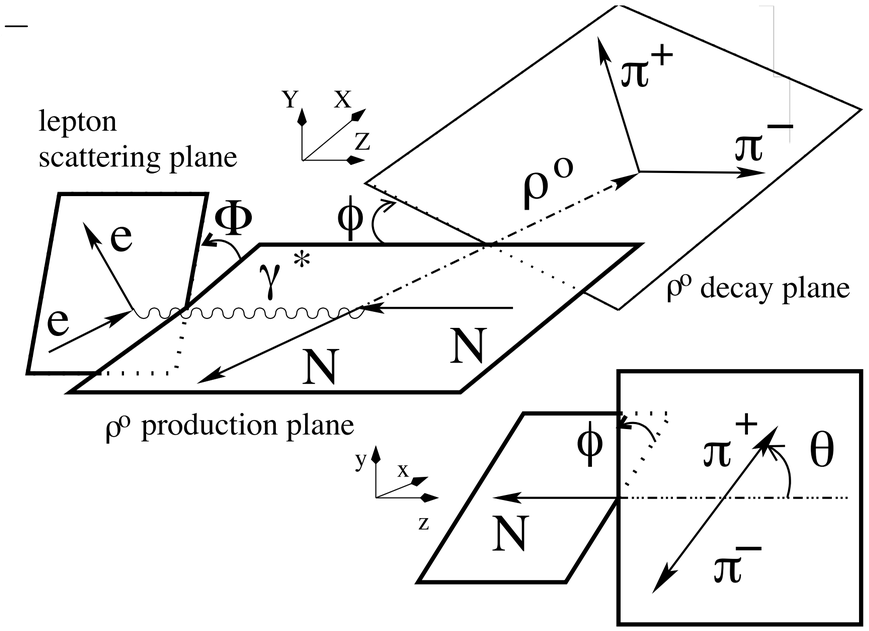
# Angular distributions

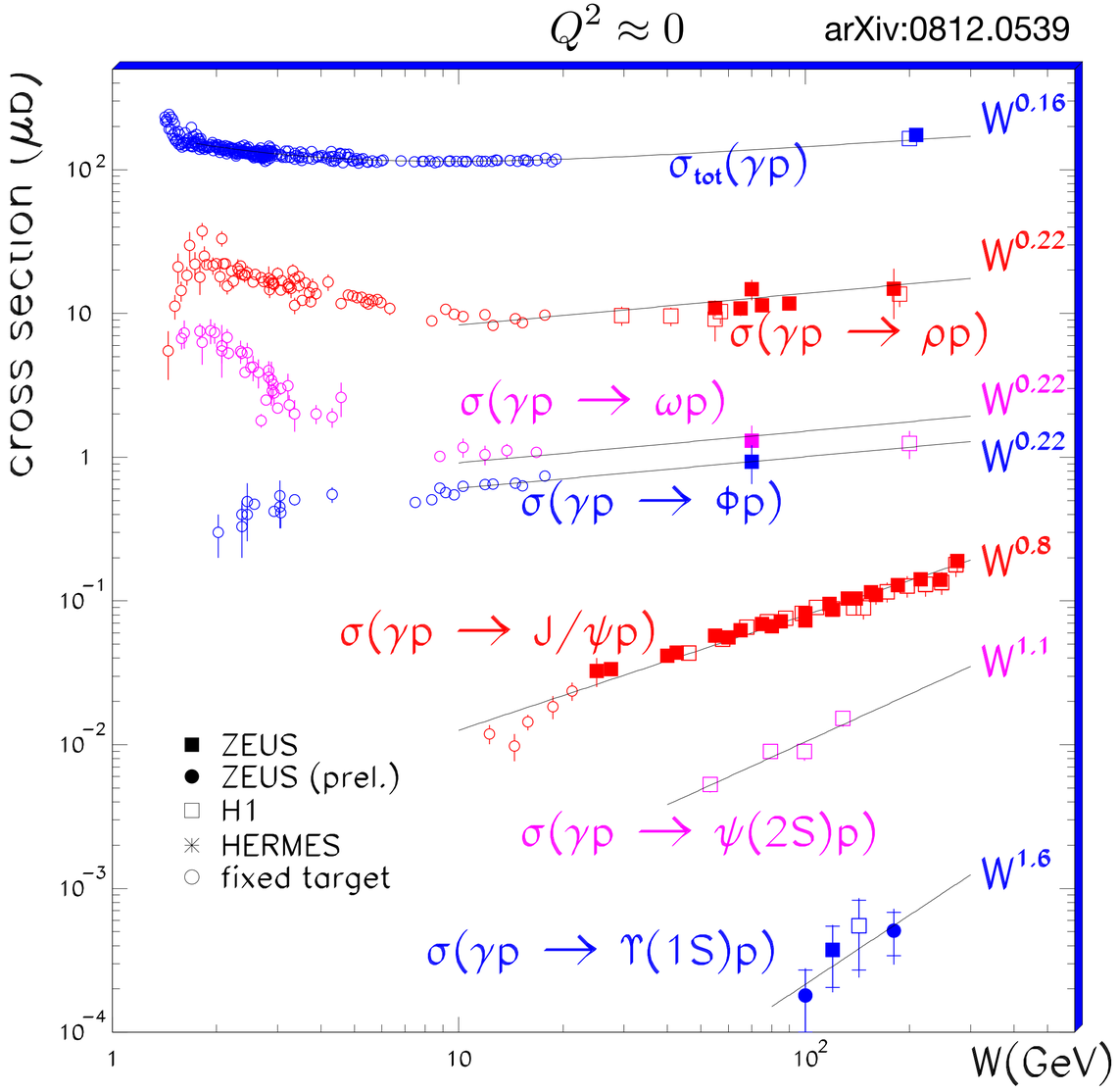
$$e + N \to e + N + \rho^0$$
$$\rho^0 \to \pi^+ + \pi^-$$

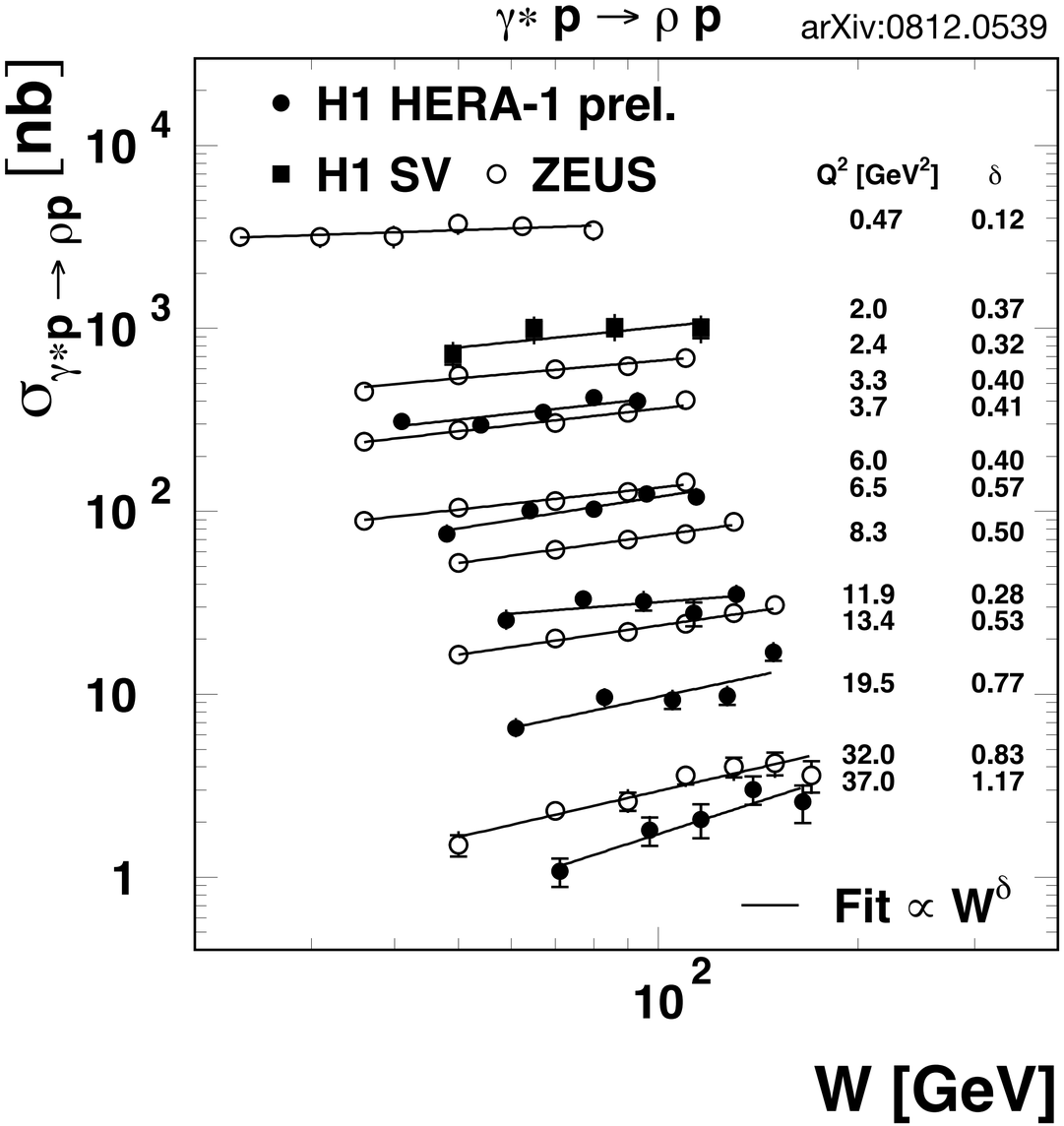



Fit angular distribution of decay pions/muons $\mathcal{W}(\Phi, \phi, \Theta)$ and extract either Spin Density Matrix Elements (SDMEs) or helicity amplitude ratios

# W dependence of elastic production

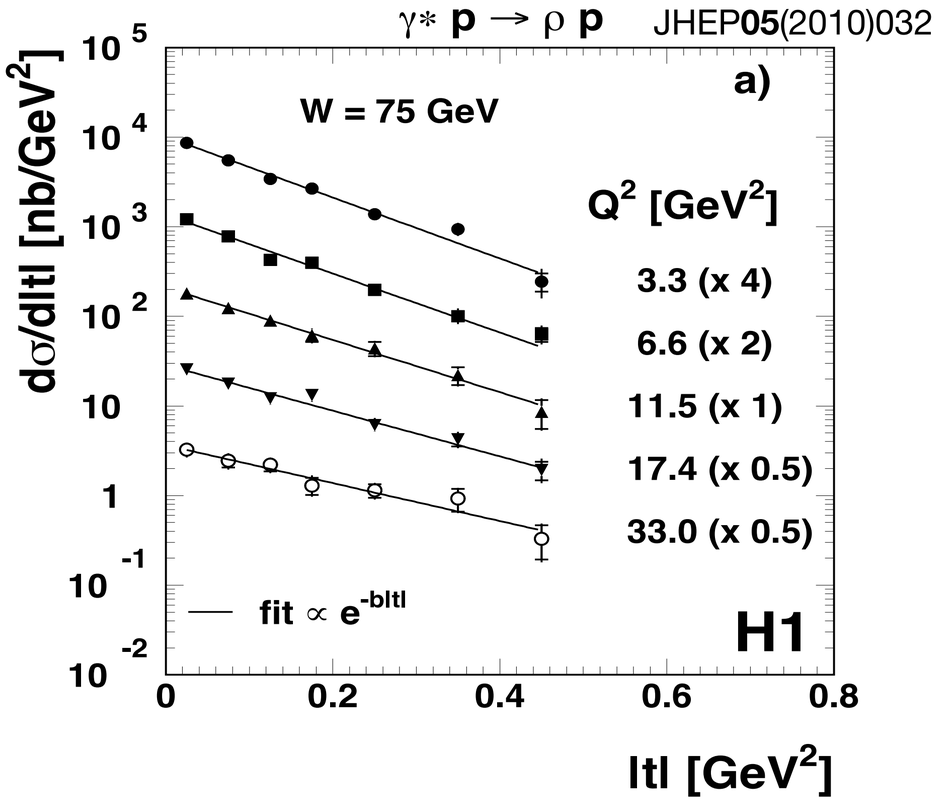


# Light-meson production

# t dependence

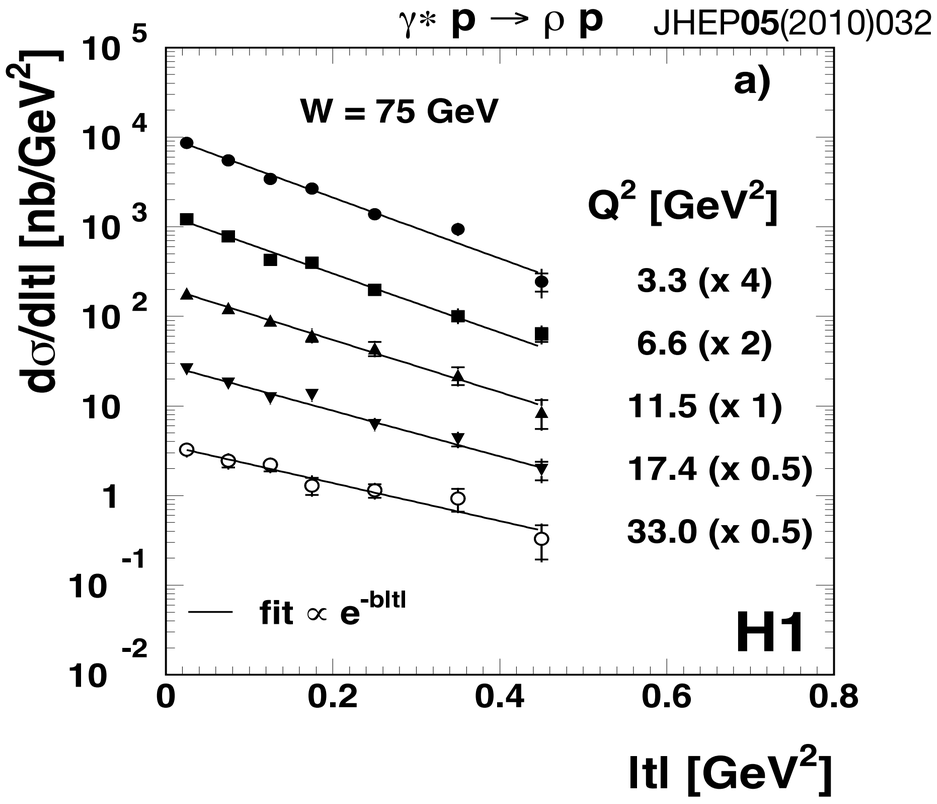
elastic

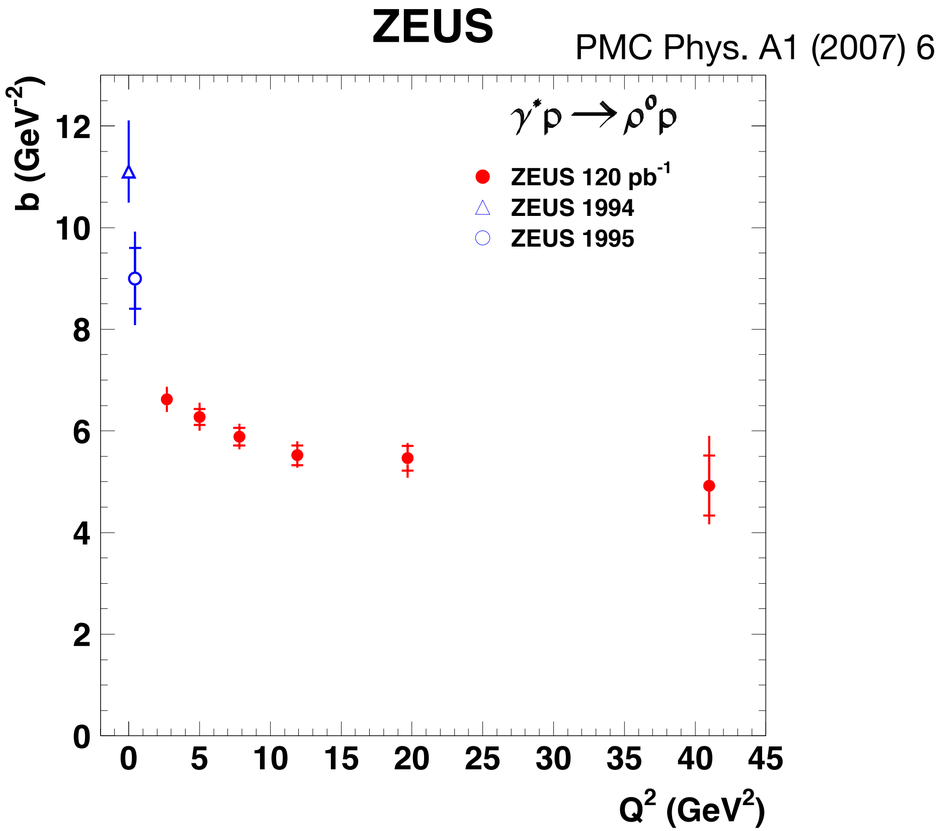



$$b = b_{VM} + b_p$$

# t dependence

elastic

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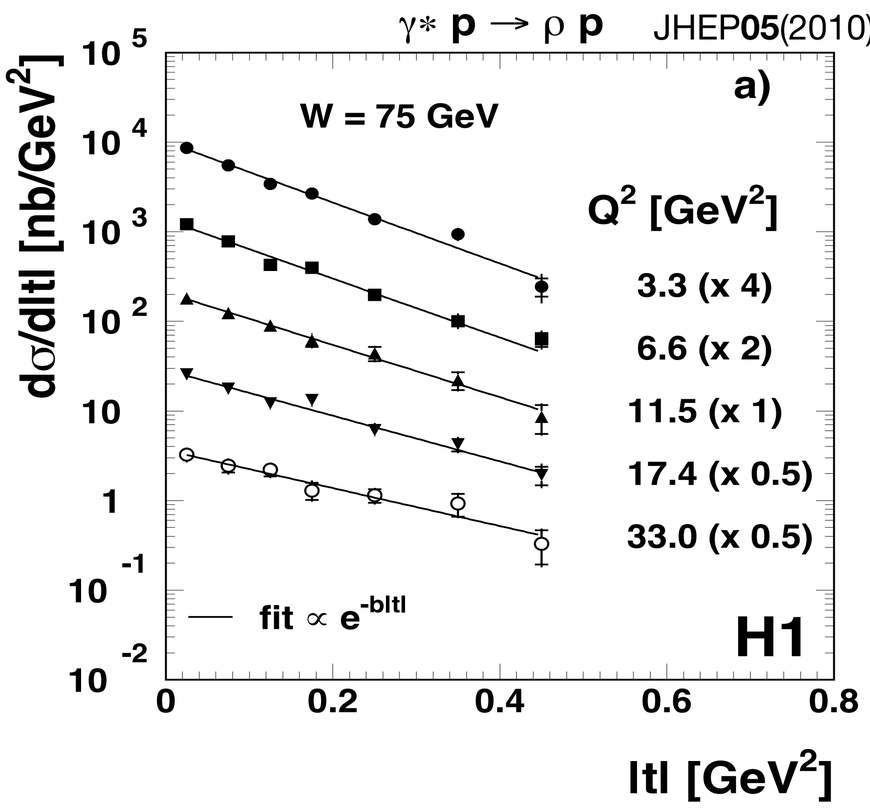


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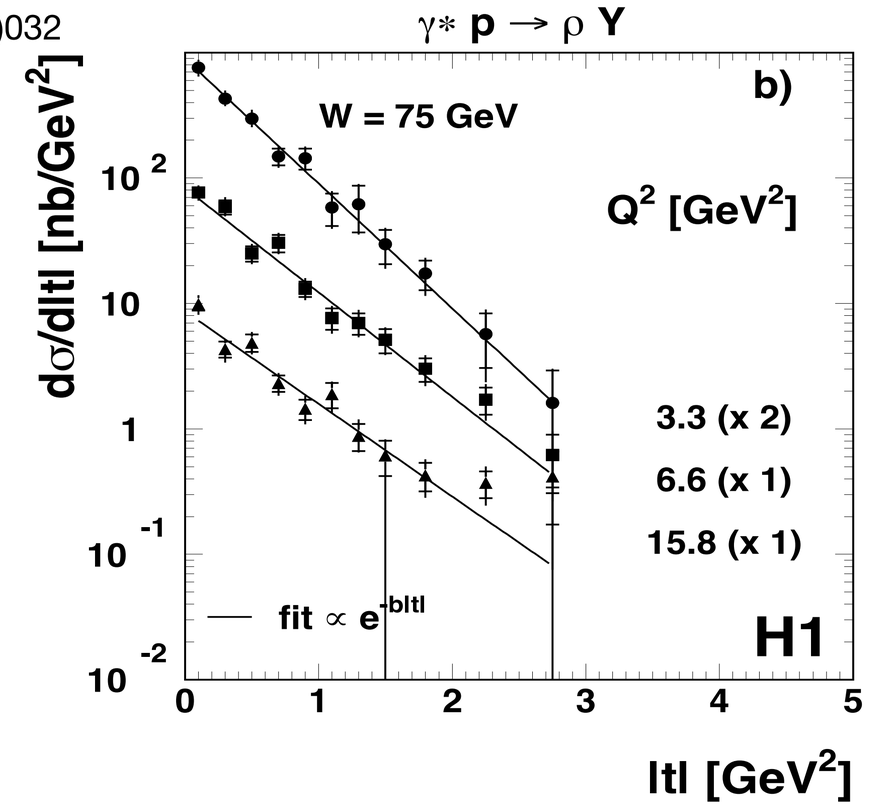
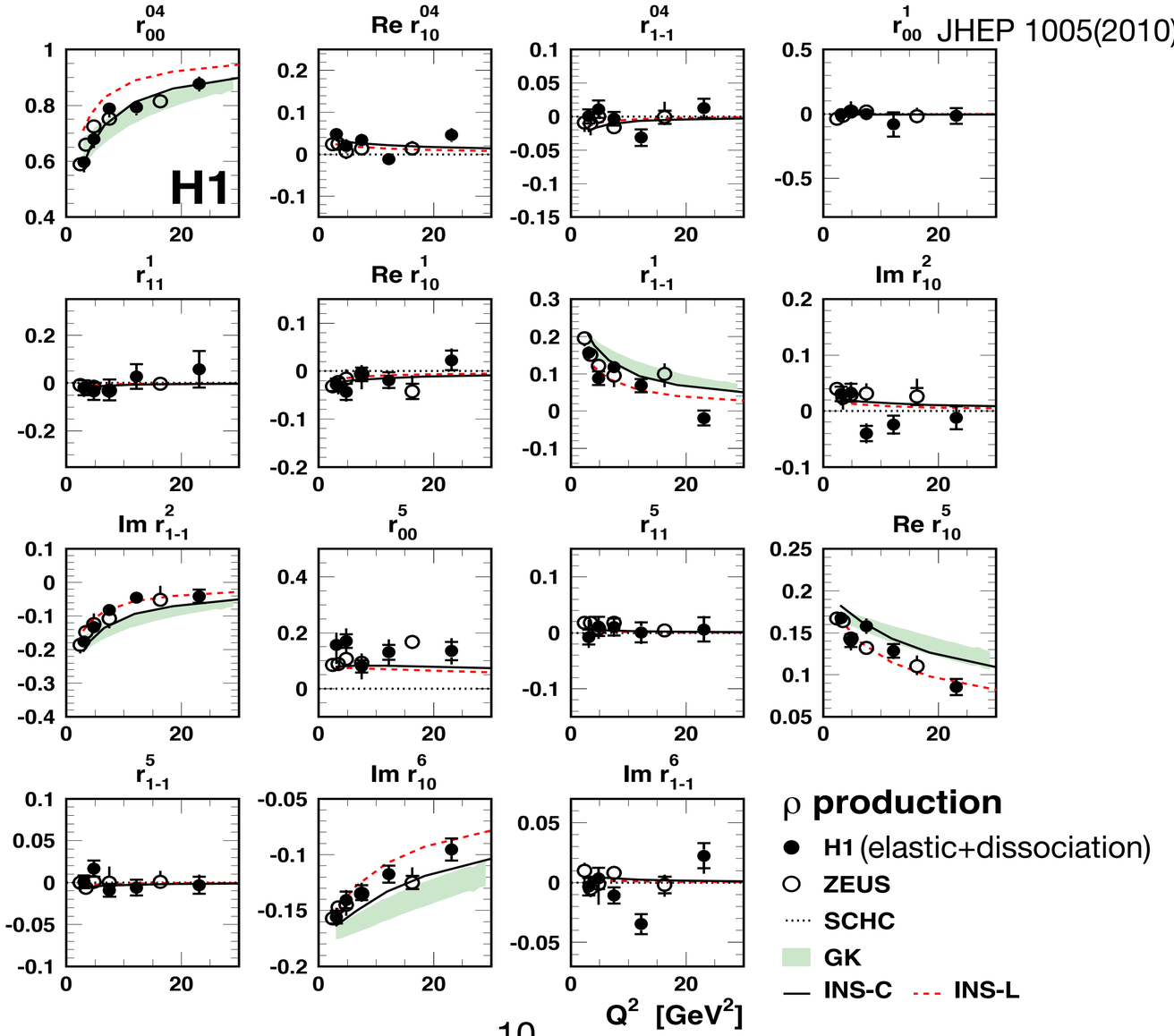
dissociative




$$b = b_{VM} + b_Y$$

# $\rho^0$ SDMEs




JHEP 1005(2010)032

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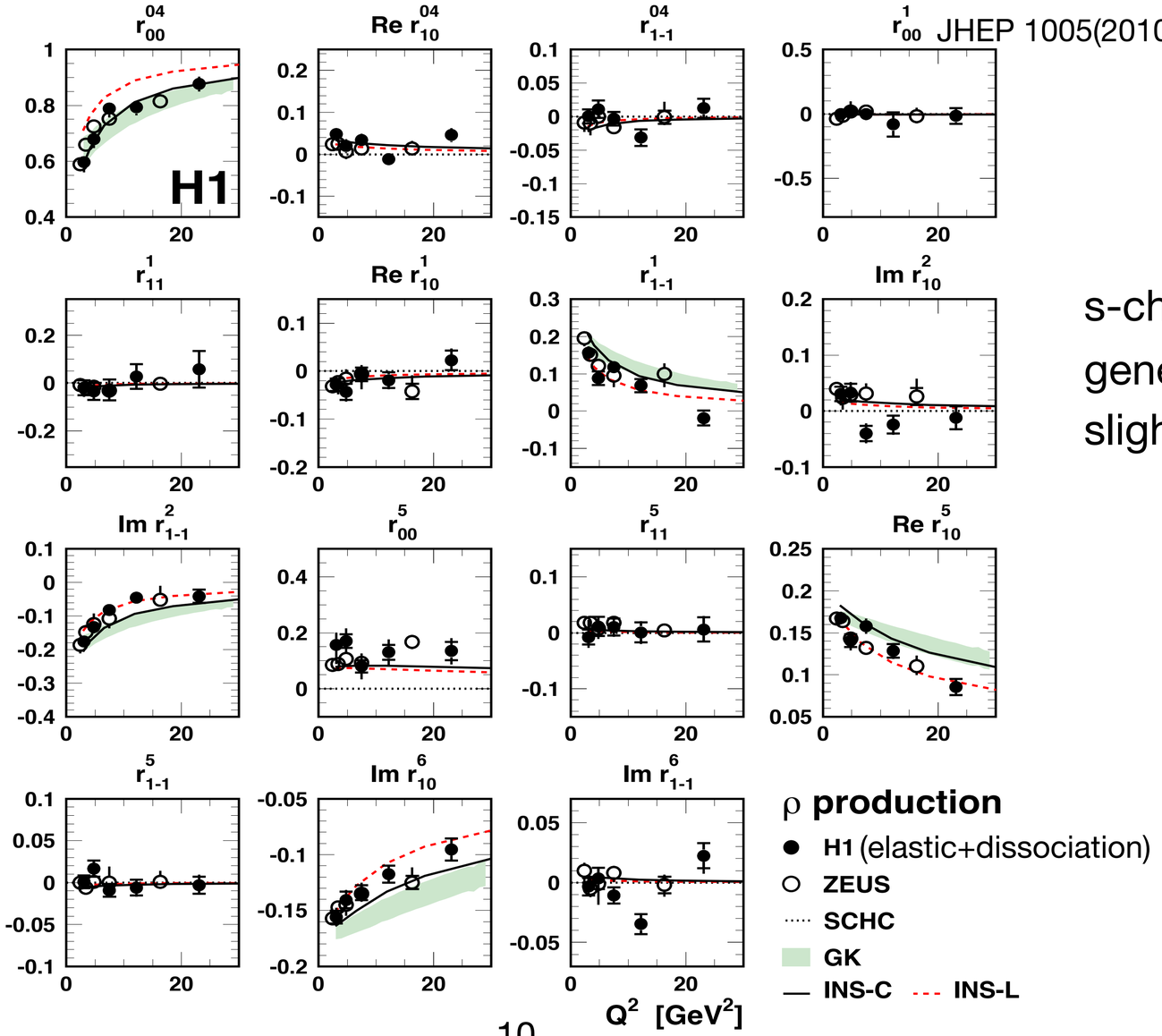



JHEP 1005(2010)032

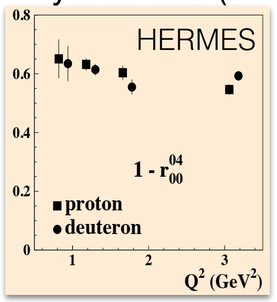
s-channel helicity conservation ( $\lambda_{\gamma^*} = \lambda_\rho$):

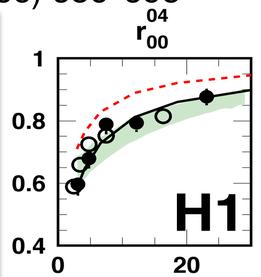
generally fulfilled;

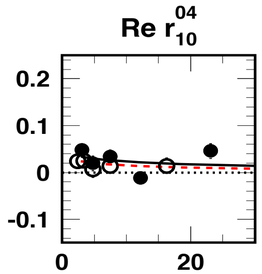
slight deviation from 0 fro $r^5_{00}$

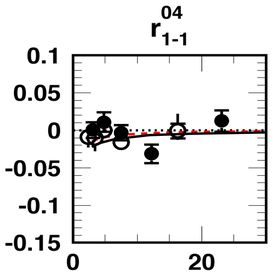
# $\rho^0$ SDMEs

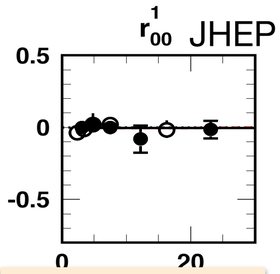
Eur. Phys. J. C62 (2009) 659-695

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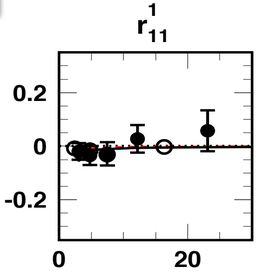


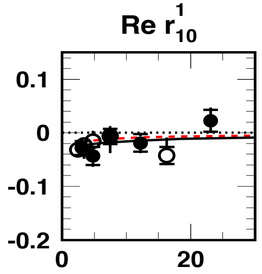


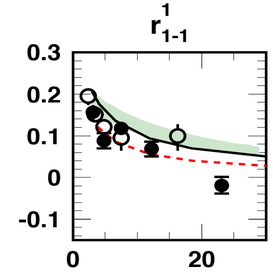


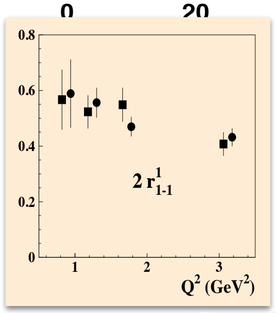


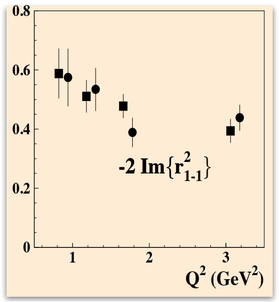


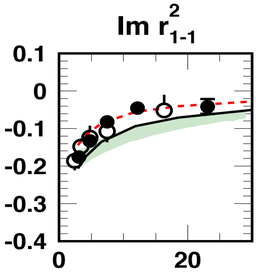


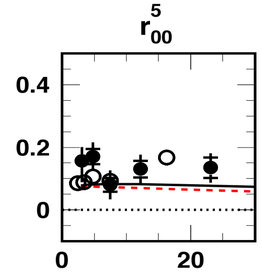


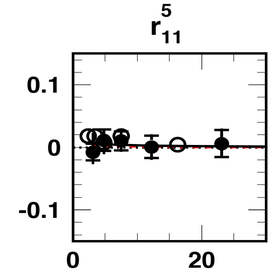


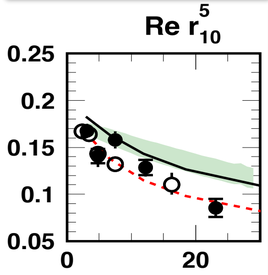


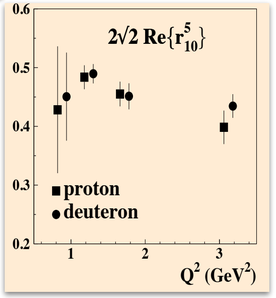


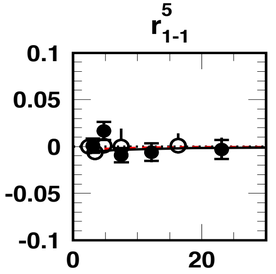


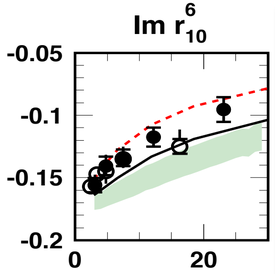


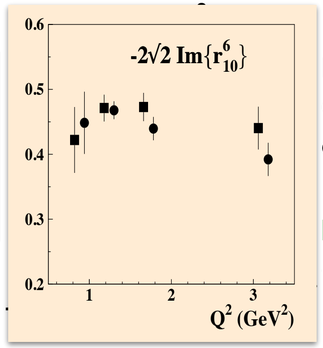


**ρ production**

- **H1** (elastic+dissociation)
- **ZEUS**
- **SCHC**
- **GK**
- **INS-C** **INS-L**

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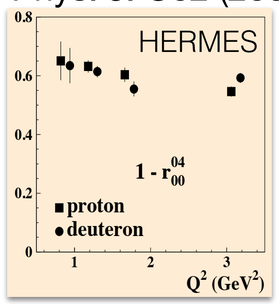
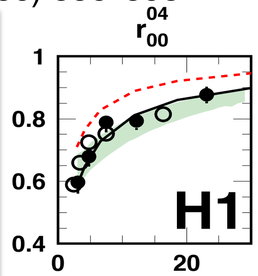
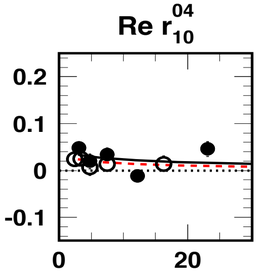
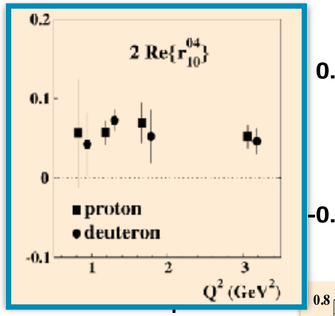
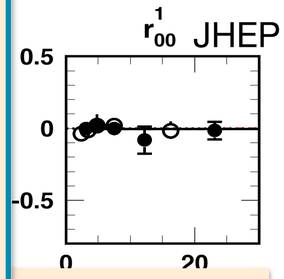
Eur. Phys. J. C62 (2009) 659-695

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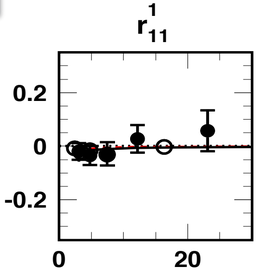
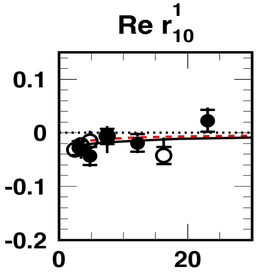
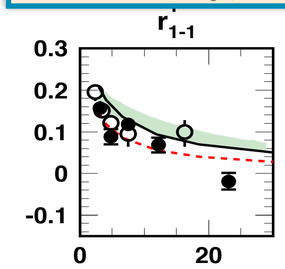
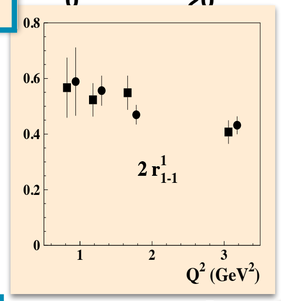
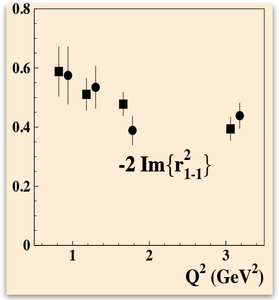
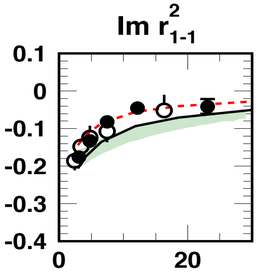


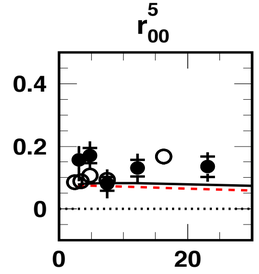



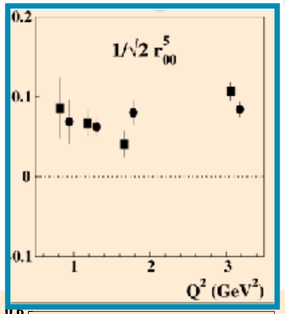



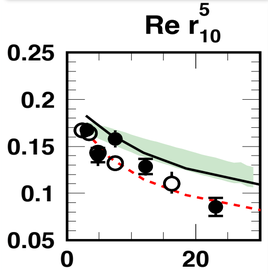



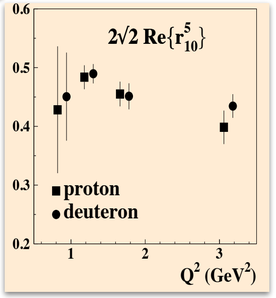



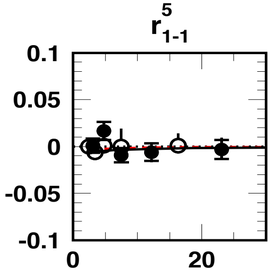



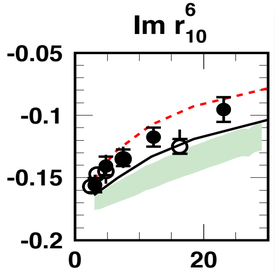



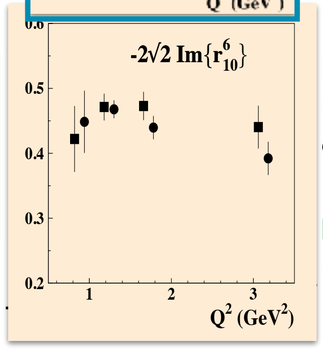




ρ **production**

- **H1** (elastic+dissociation)
- **ZEUS**
- **SCHC**
- **GK**
- **INS-C** **INS-L**

s-channel helicity conservation ( $\lambda_{\gamma^*} = \lambda_\rho$):

generally fulfilled;

slight deviation from 0 fro $r^5_{00}$

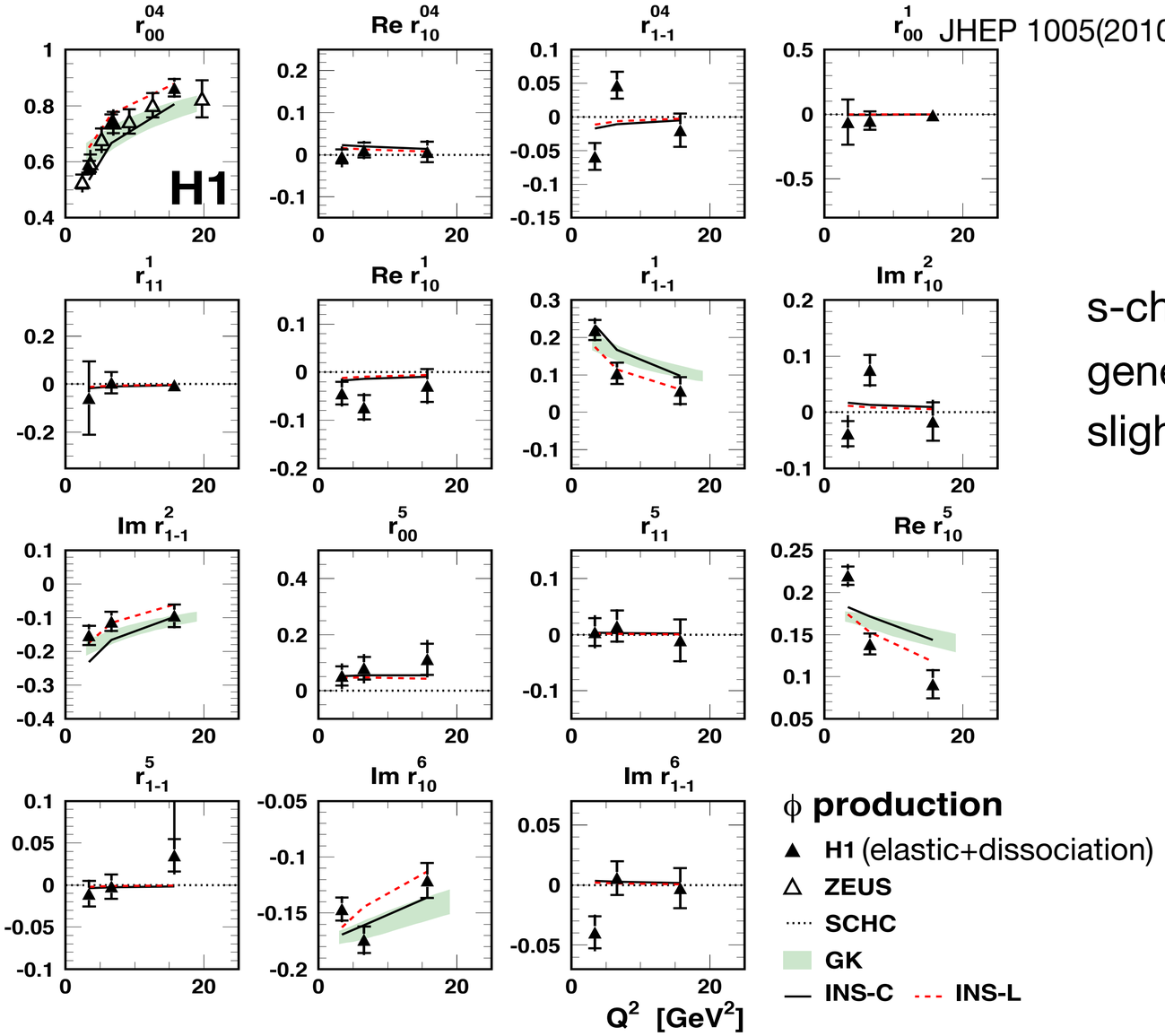
HERMES: strong violation of s-channel helicity conservation for some SDMEs:

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

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

$\gamma^*_T \rightarrow \rho_L$

# $\phi$ SDMEs

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s-channel helicity conservation ( $\lambda_{\gamma^*} = \lambda_\phi$):

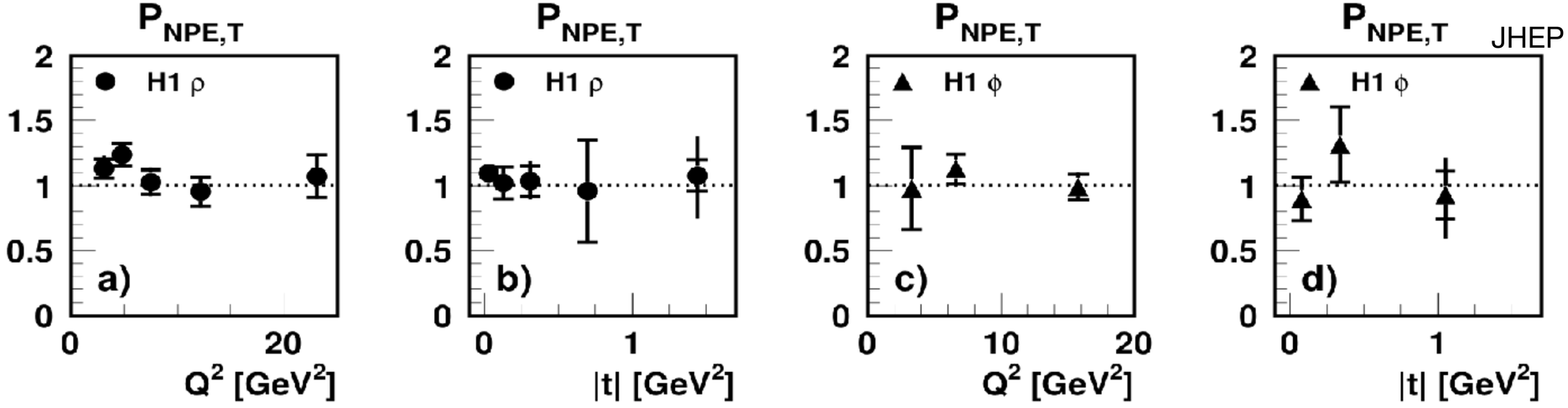
generally fulfilled;

slight deviation from 0 fro $r_{00}^{5}$

# Parity exchange for $\rho^0$ and $\phi$

- Asymmetry between natural and unnatural parity exchange

$$P_{NPE,T} = \frac{\sigma_T^N - \sigma_T^U}{\sigma_T^N + \sigma_T^U} = 2 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^1 - 2r_{1-1}^1$$

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diffraction ~ 2 gluon exchange → NPE

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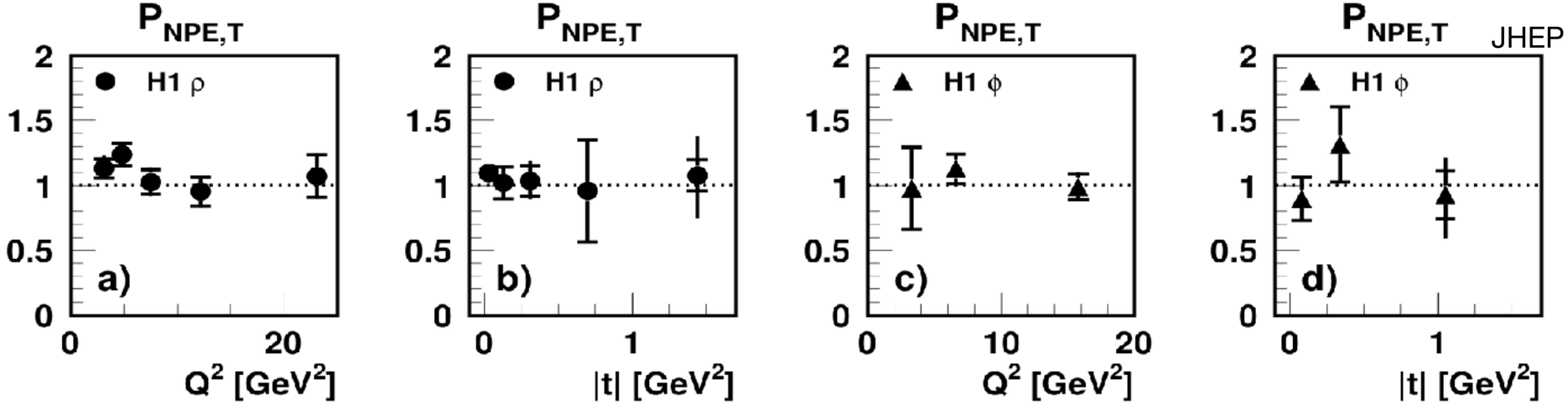


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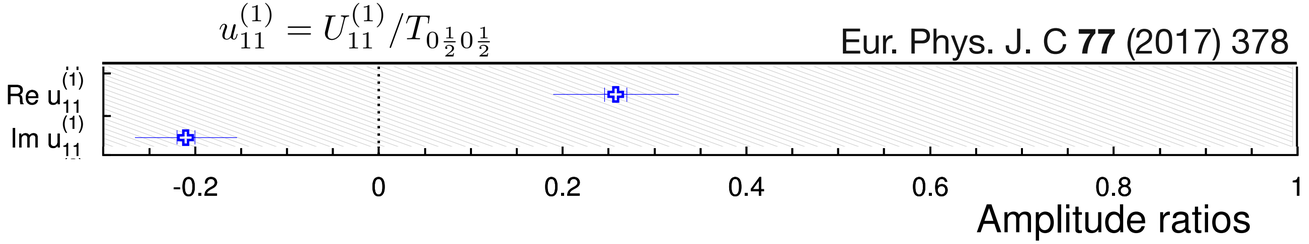
diffraction ~ 2 gluon exchange → NPE

- helicity amplitude ratio – HERMES

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unnatural parity nucleon-helicity non-flip $\neq 0$ by $4\sigma$

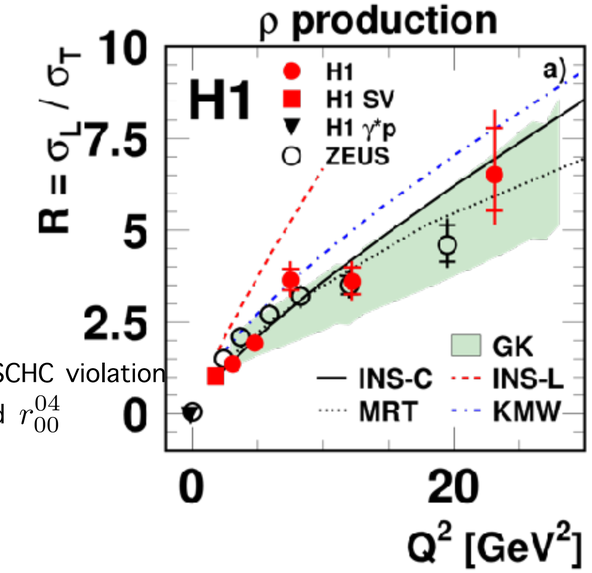
cf. quark exchange

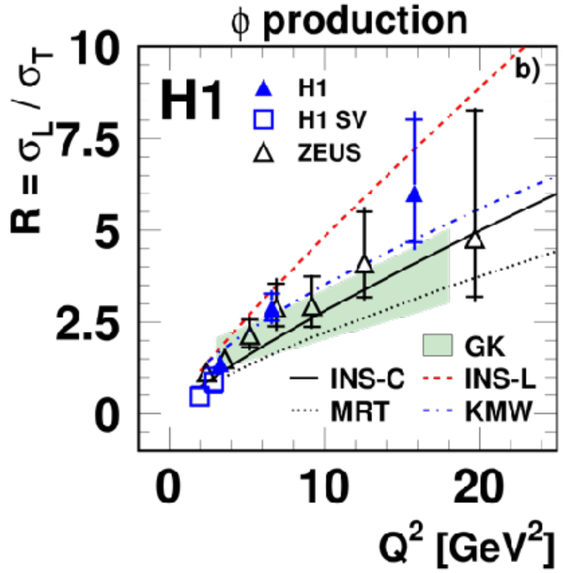
# Longitudinal-to-cross section ratio

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

$$\overset{\text{SCHC}}{=} \frac{d\sigma(\gamma^*{}_L)}{d\sigma(\gamma^*{}_T)}$$

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

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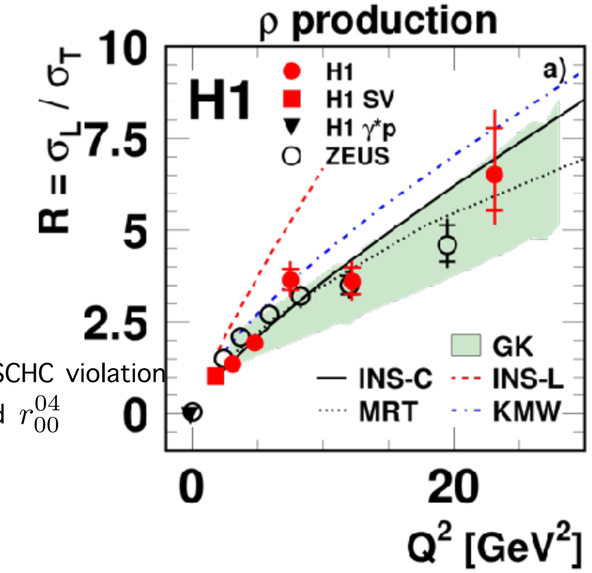


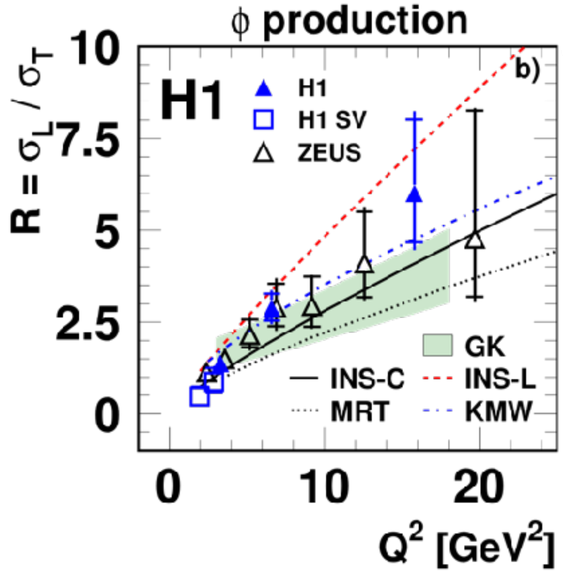


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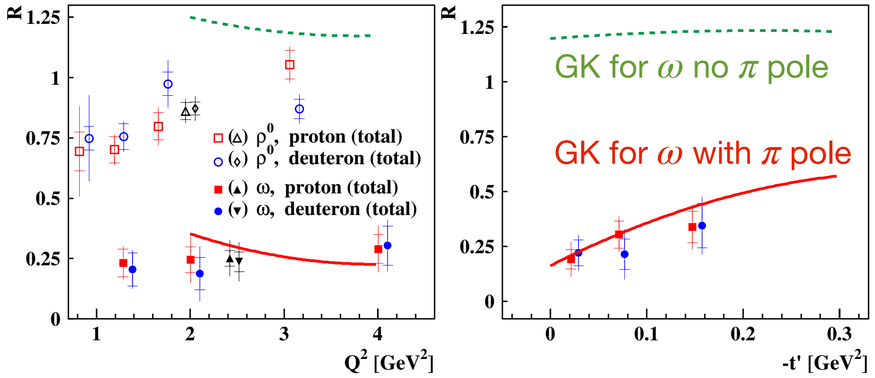

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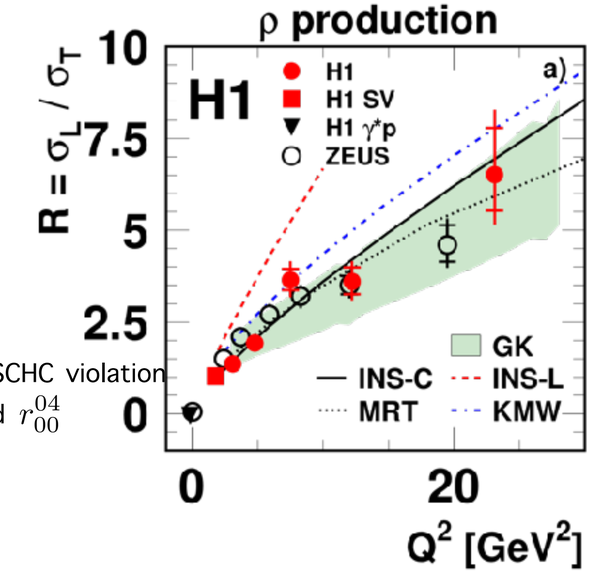


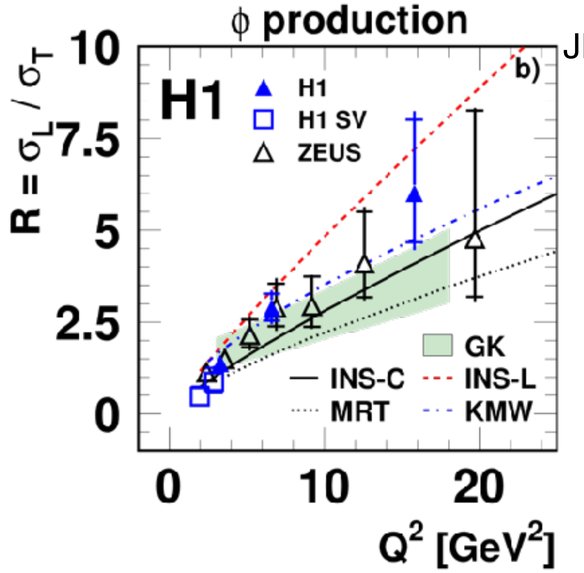


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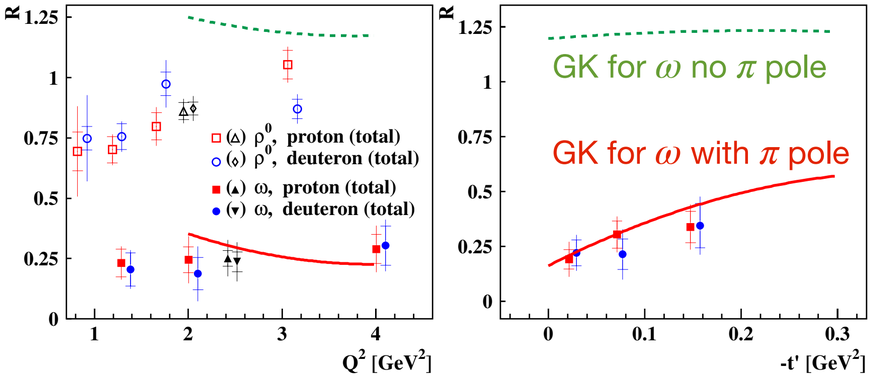
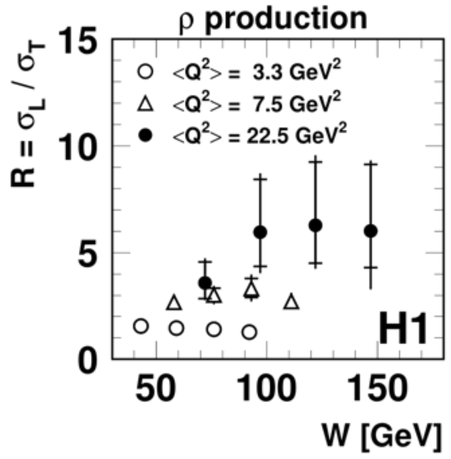
Eur. Phys. J. C **74** (2014) 3110

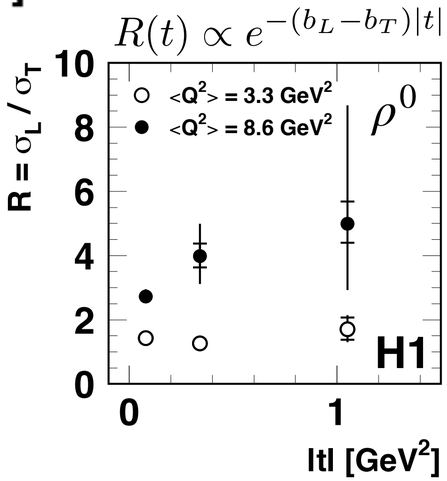









$R(t) \propto e^{-(b_L - b_T)|t|}$

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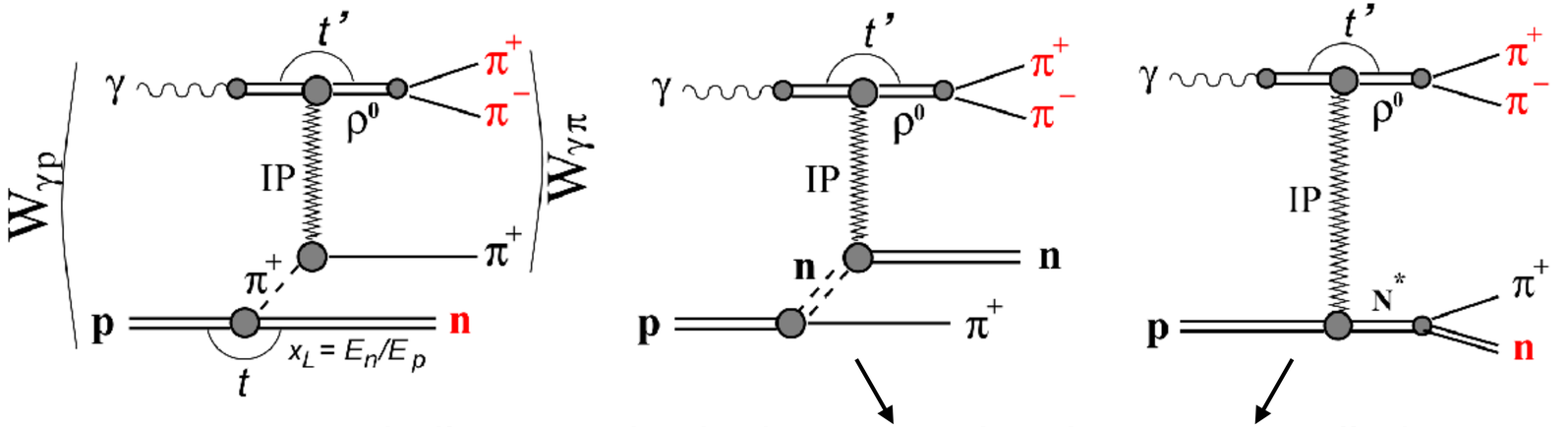
# $\rho$ photoproduction with leading neutron




similar magnitude, but opposite sign → cancellation, especially for $t \to 0$

V.A. Tsarev, PRD **11** (1975) 1864

L.A. Ponomarev, Proceedings XVIII Intern. Conf. High-Energy Physics, C76-07-15 (1976), pp. A1-A24

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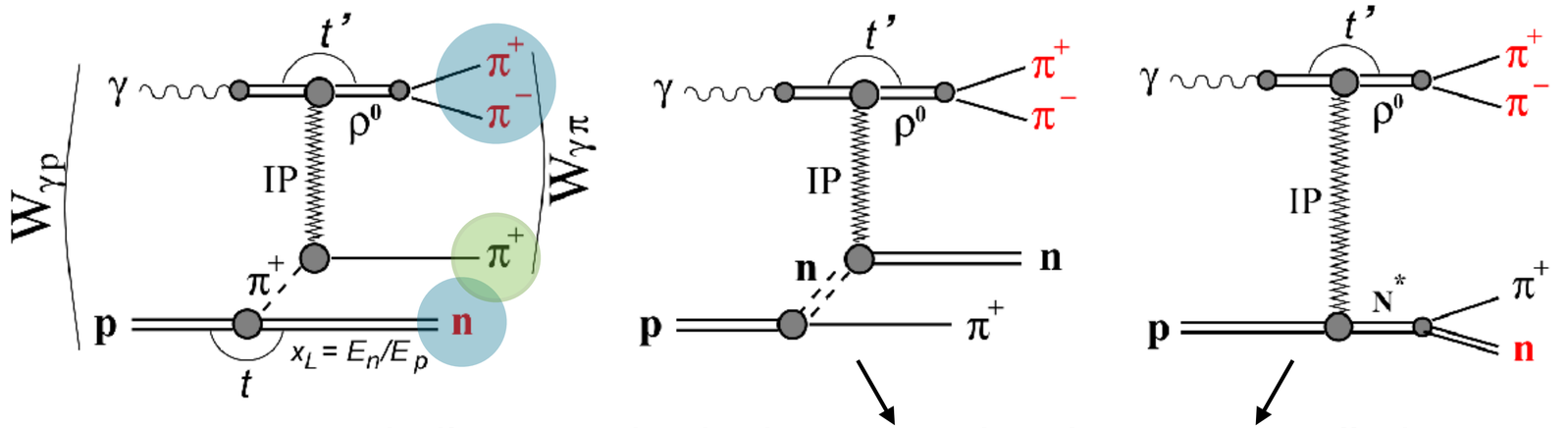


detected

escapes along beam line

similar magnitude, but opposite sign → cancellation, especially for $t \to 0$

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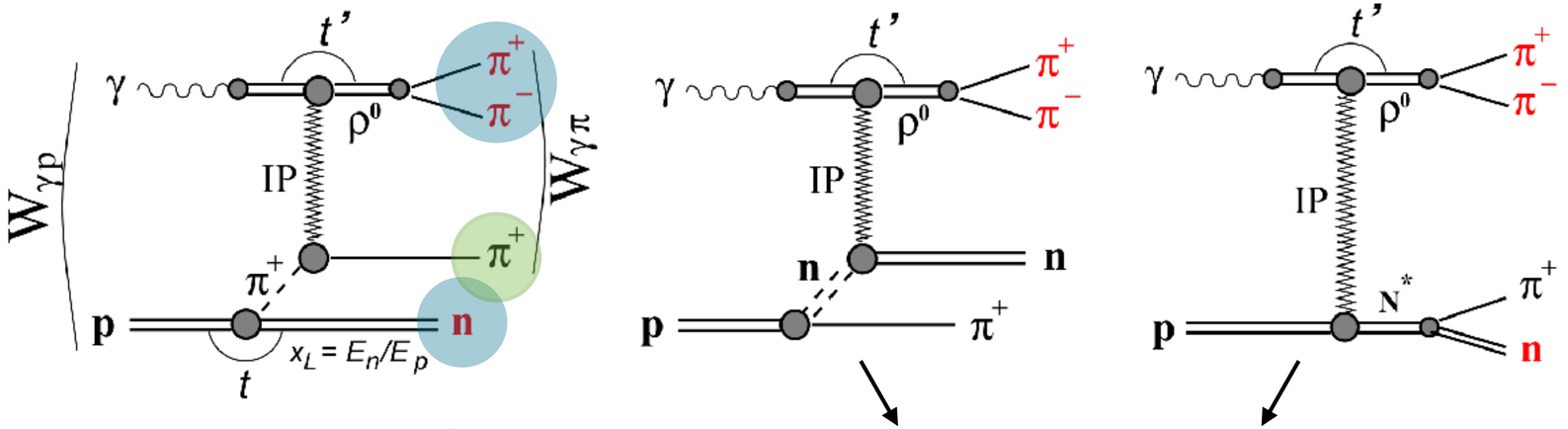


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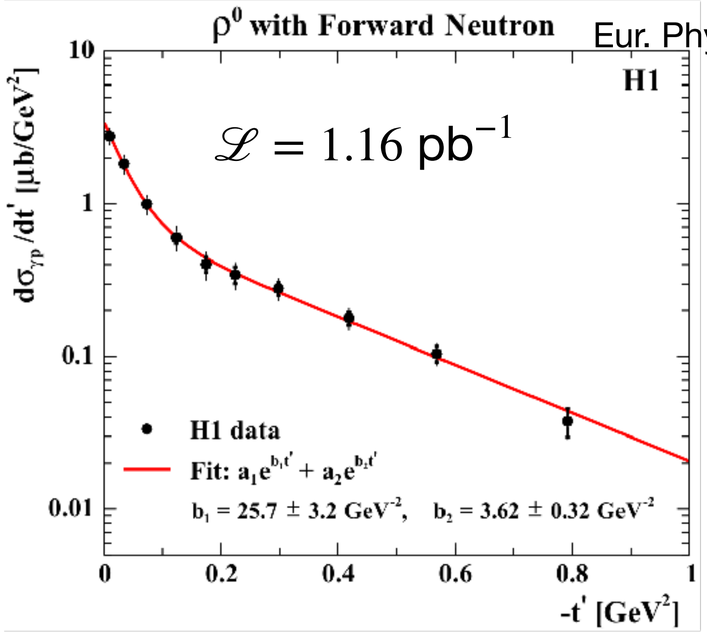


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<u>geometric picture</u>:

large b1 → large impact parameter $\langle r^2 \rangle \approx (1.6 R_p)^2$

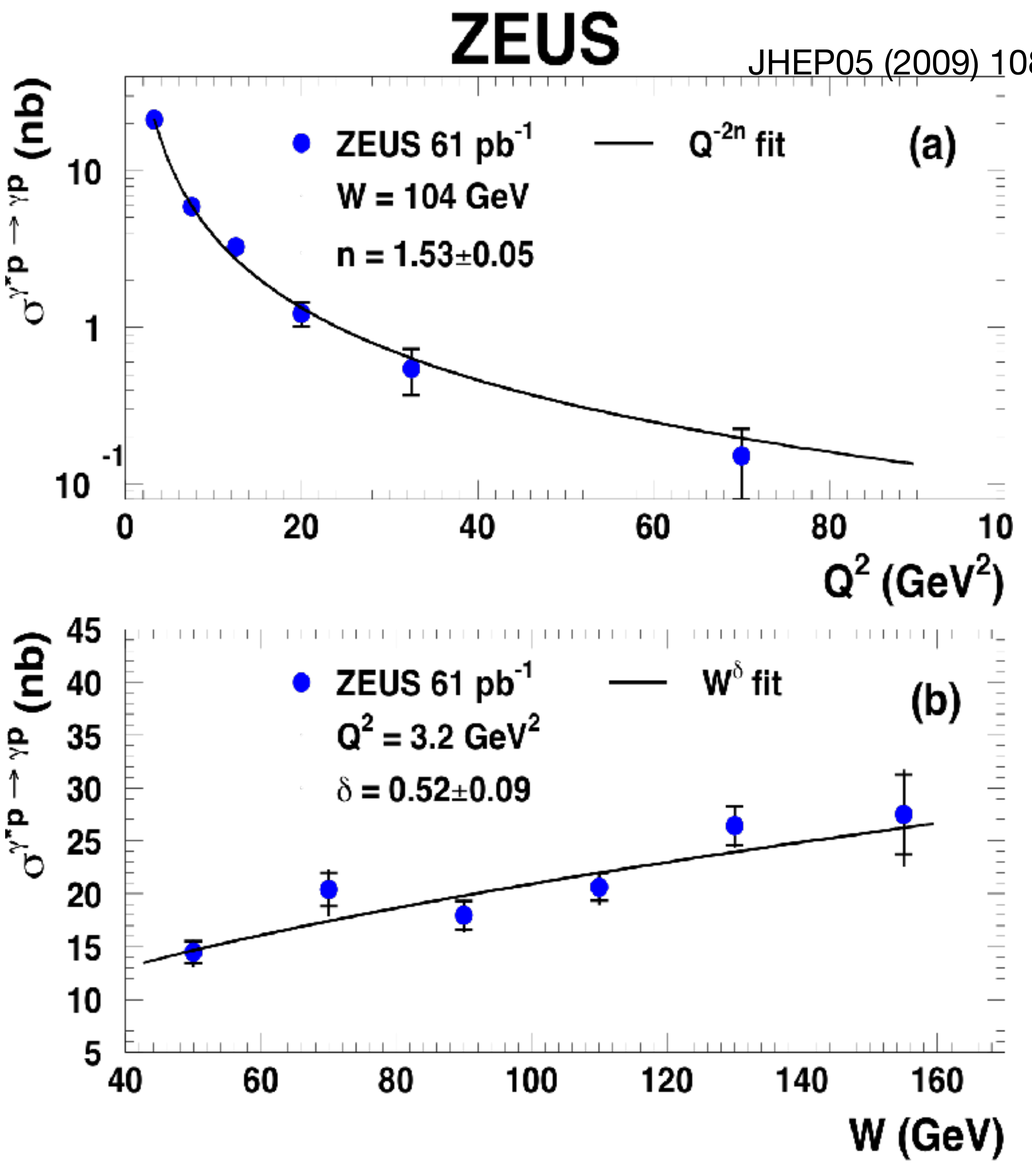
b2 → $\langle r^2 \rangle \approx (0.5 \text{ fm})^2$

<u>double peripheral process:</u>

interference of three diagrams

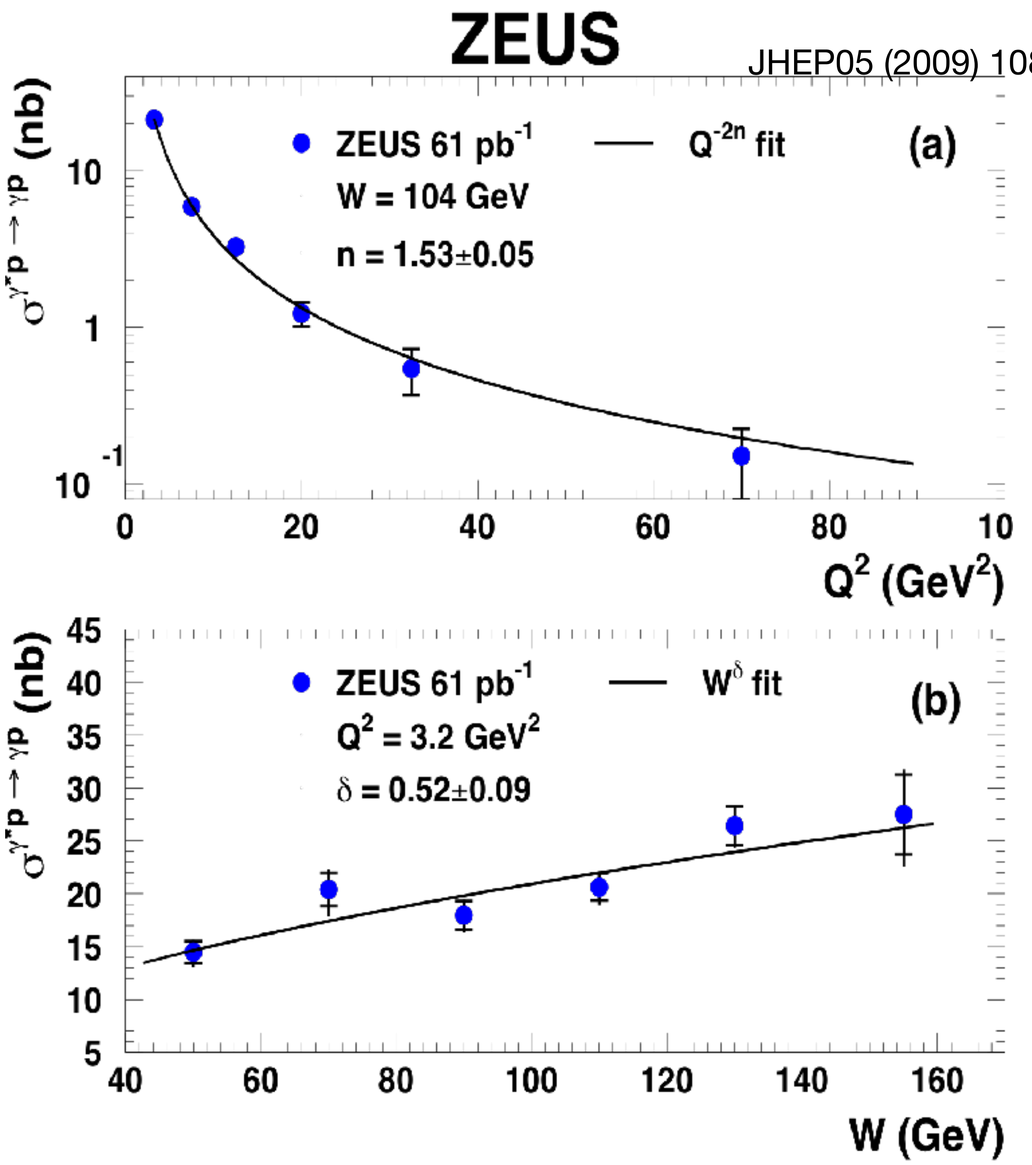
# Deeply virtual Compton scattering

# $Q^2$ and W of cross section



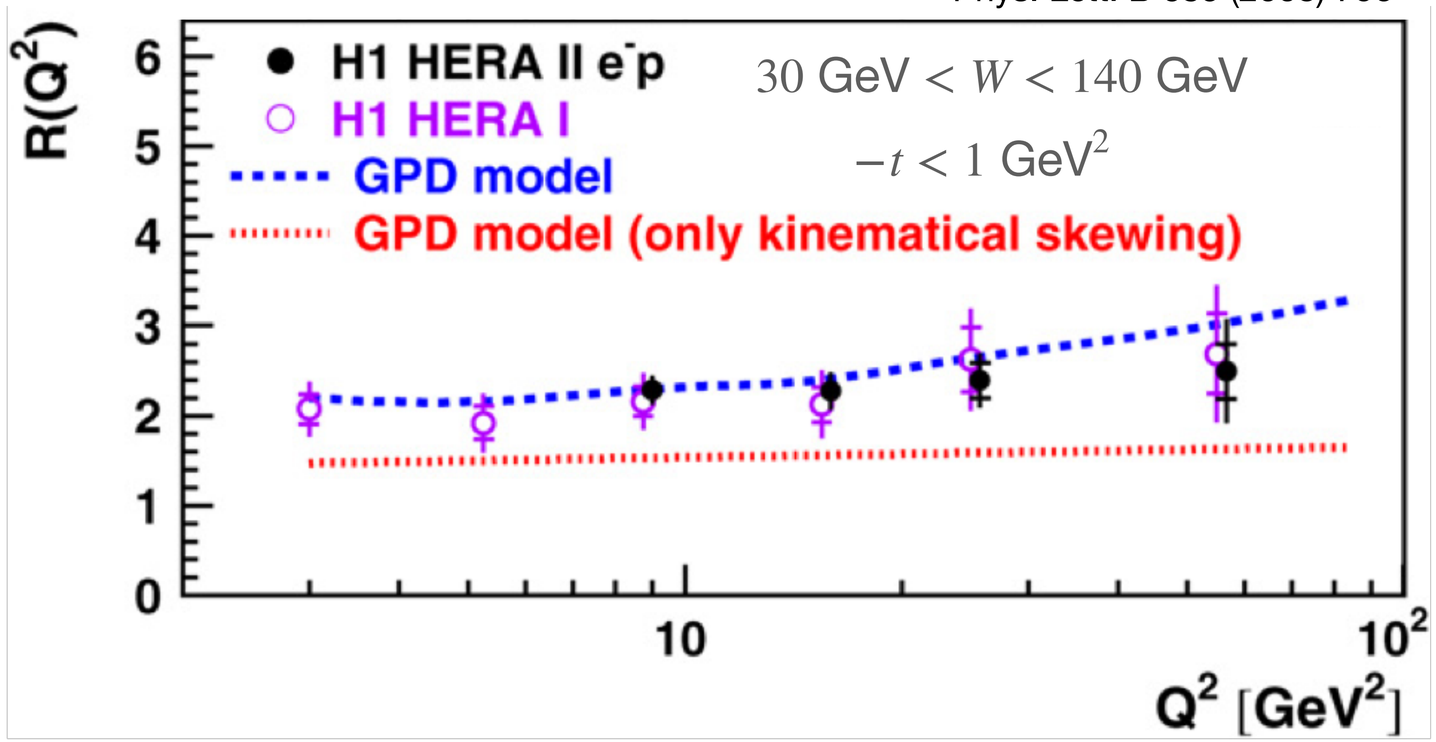

JHEP05 (2009) 108

# $Q^2$ and W of cross section




JHEP05 (2009) 108

Phys. Lett. B **659** (2008) 796



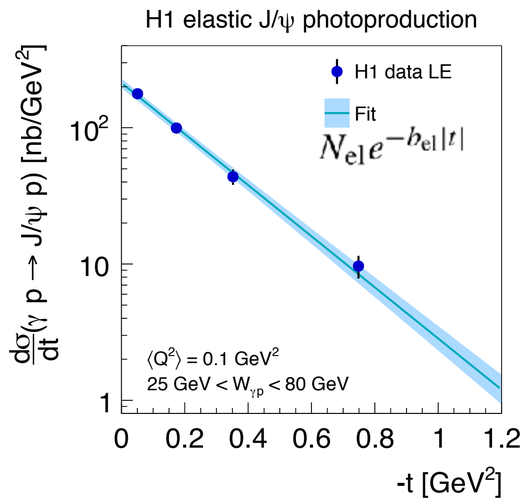

$$R = \frac{4\sqrt{\pi\sigma_{\mathrm{DVCS}}b(Q^2)}}{\sigma_T(\gamma^* p \to X)\sqrt{(1+\rho^2)}} \overset{\mathrm{LO}}{\sim} \frac{\mathrm{GPD}}{\mathrm{PDF}}$$

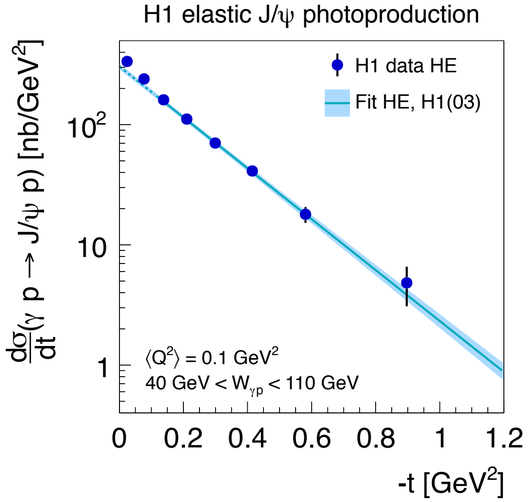
# Quarkonium production

# t slope

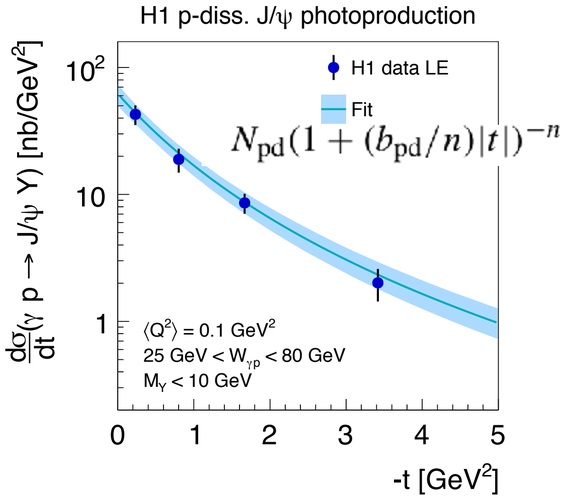
## elastic

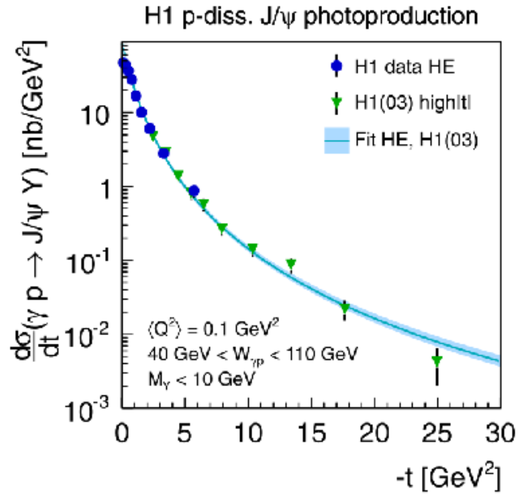
Eur. Phys. J. C73 (2013) 2466



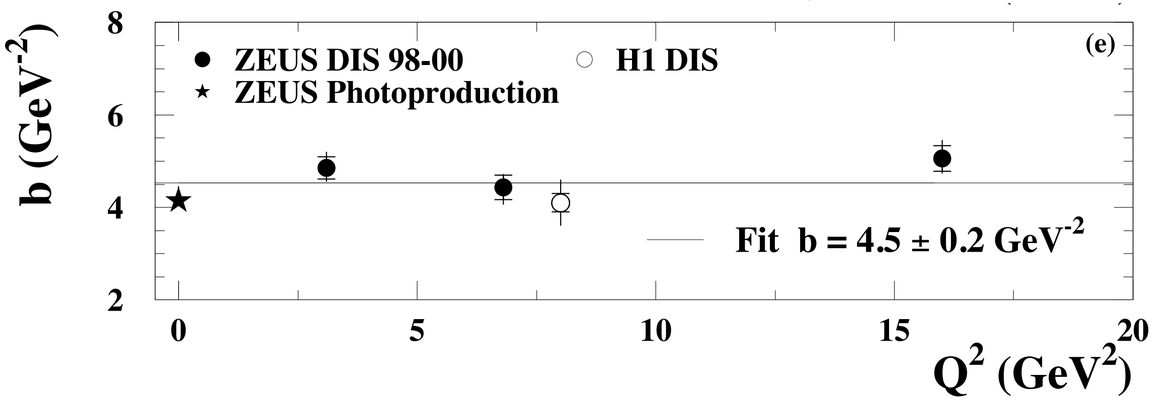

## dissociative



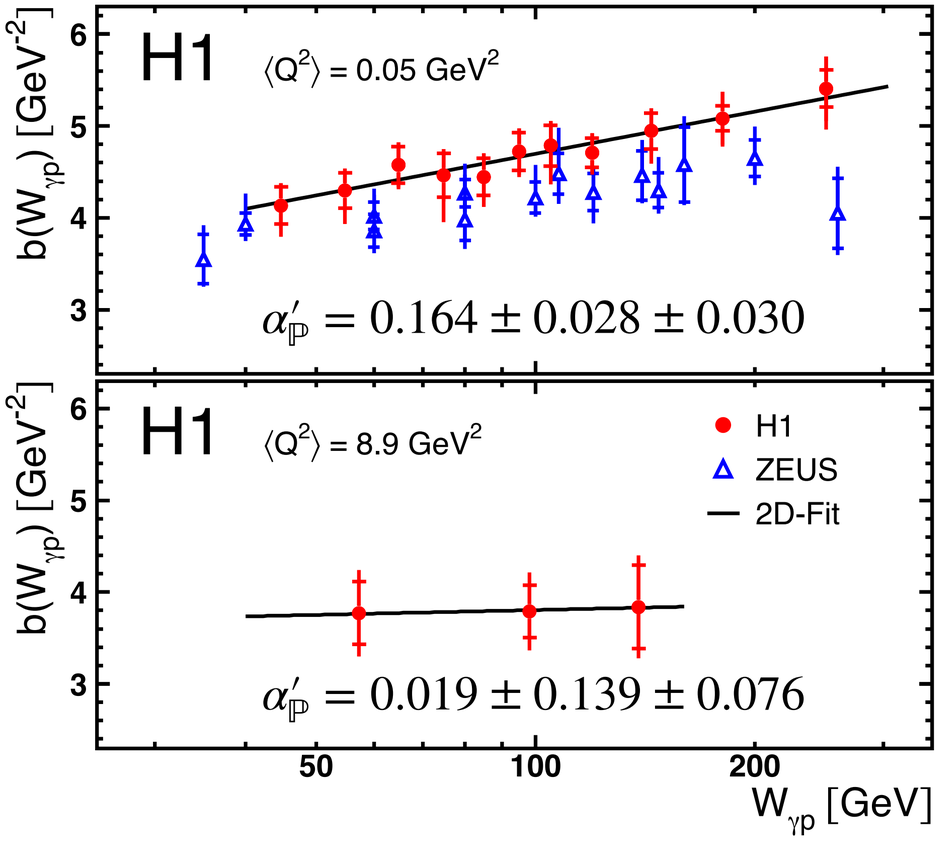



# $Q^2$ and W dependence of t slope

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



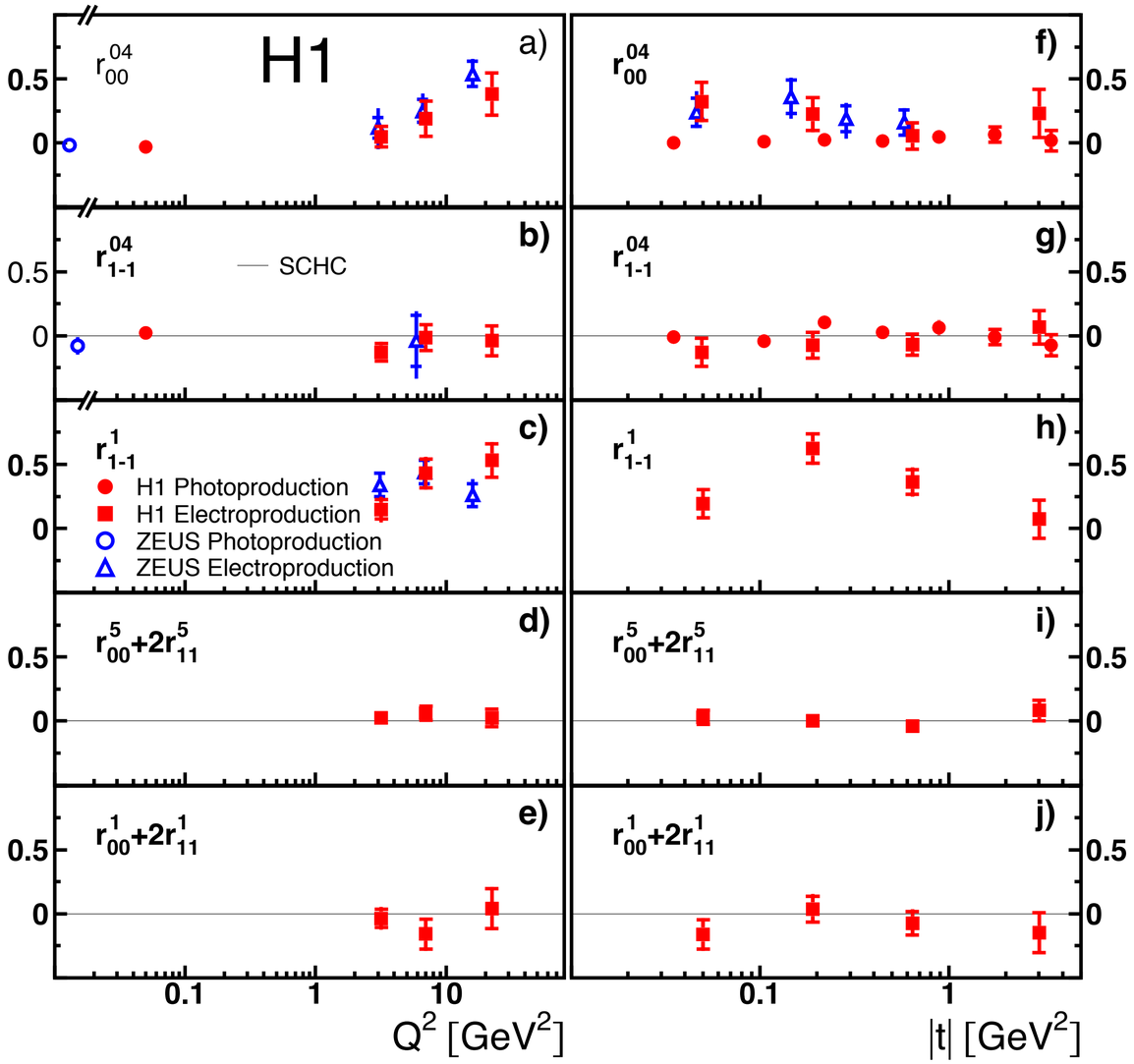

Eur. Phys. J. C 46 (2006) 585-603




Fit: $b = b_0 + 4\alpha'_{\mathbb{P}} \ln \frac{W}{W_0}$

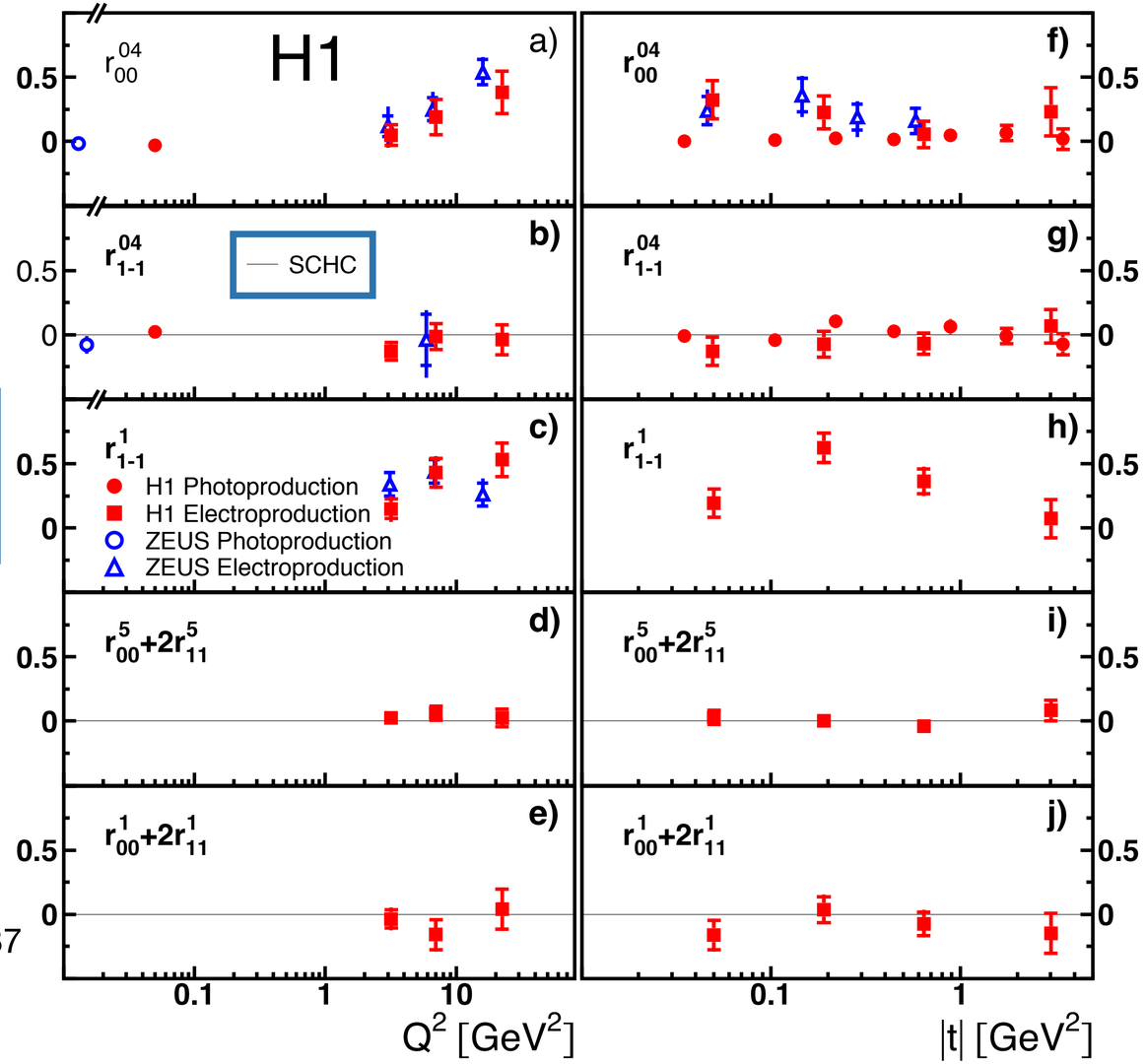
# SDMEs

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



# SDMEs

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




SCHC and NPE:

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

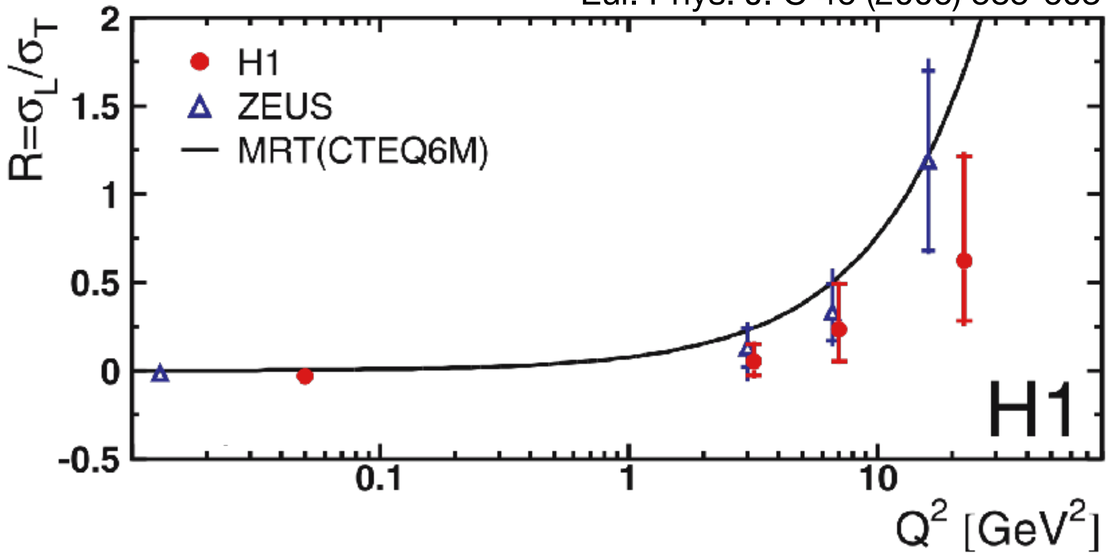
| $r^1_{1-1} - \frac{1}{2}\left(1 - r^{04}_{00}\right)$ |
|---|
| $-0.10 \pm 0.09^{+0.08}_{-0.06}$ |
| $0.06 \pm 0.10^{+0.08}_{-0.06}$ |
| $0.03 \pm 0.11^{+0.07}_{-0.02}$ |

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

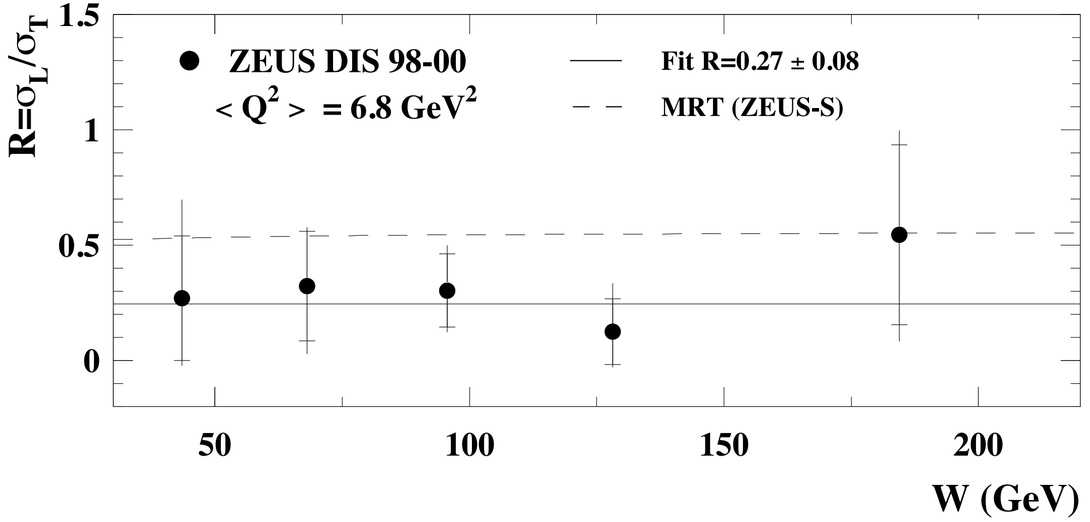
# $R=\sigma_L/\sigma_T$

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

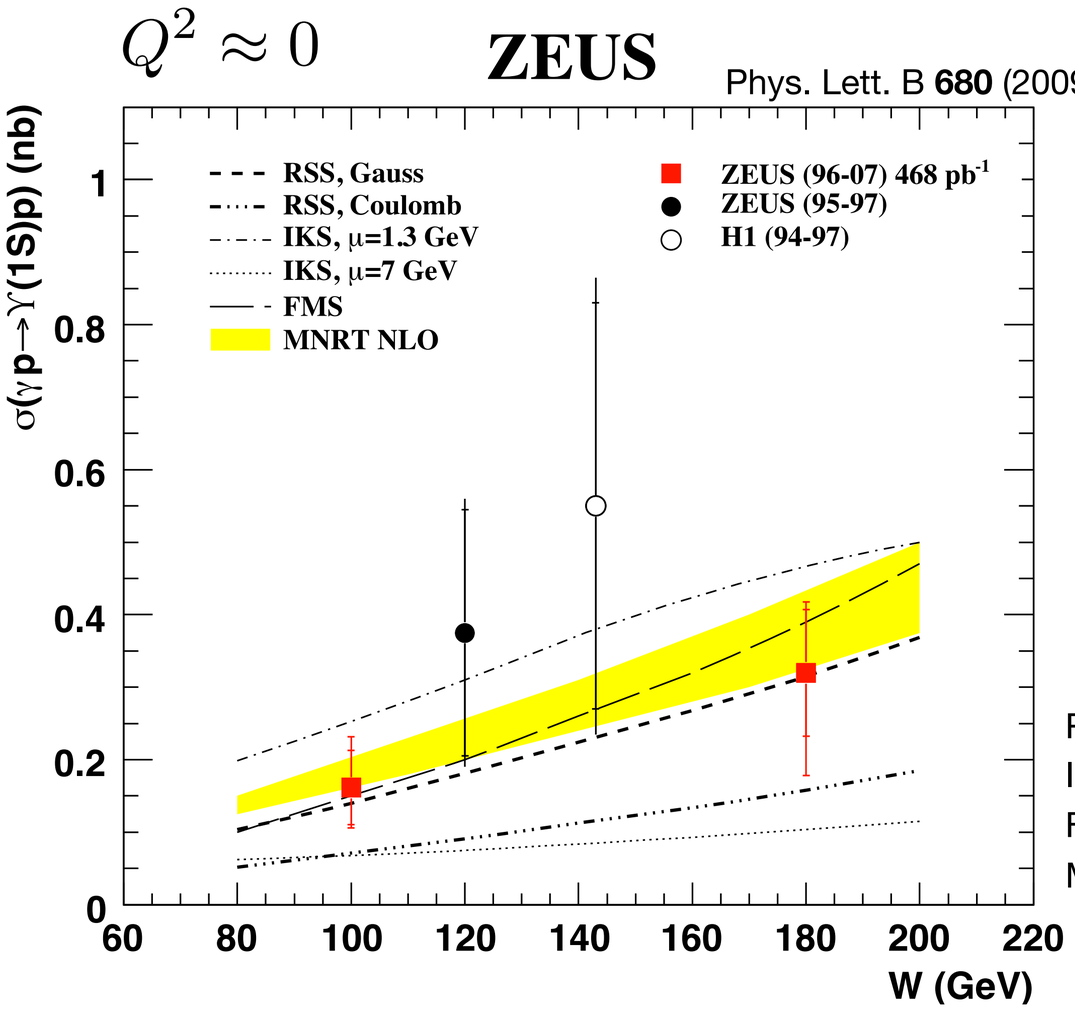
Eur. Phys. J. C 46 (2006) 585-603




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



# $\Upsilon$ : $W$ dependence




RSS: kT factorisation + LCWF Gaussian- or Couloumb-like

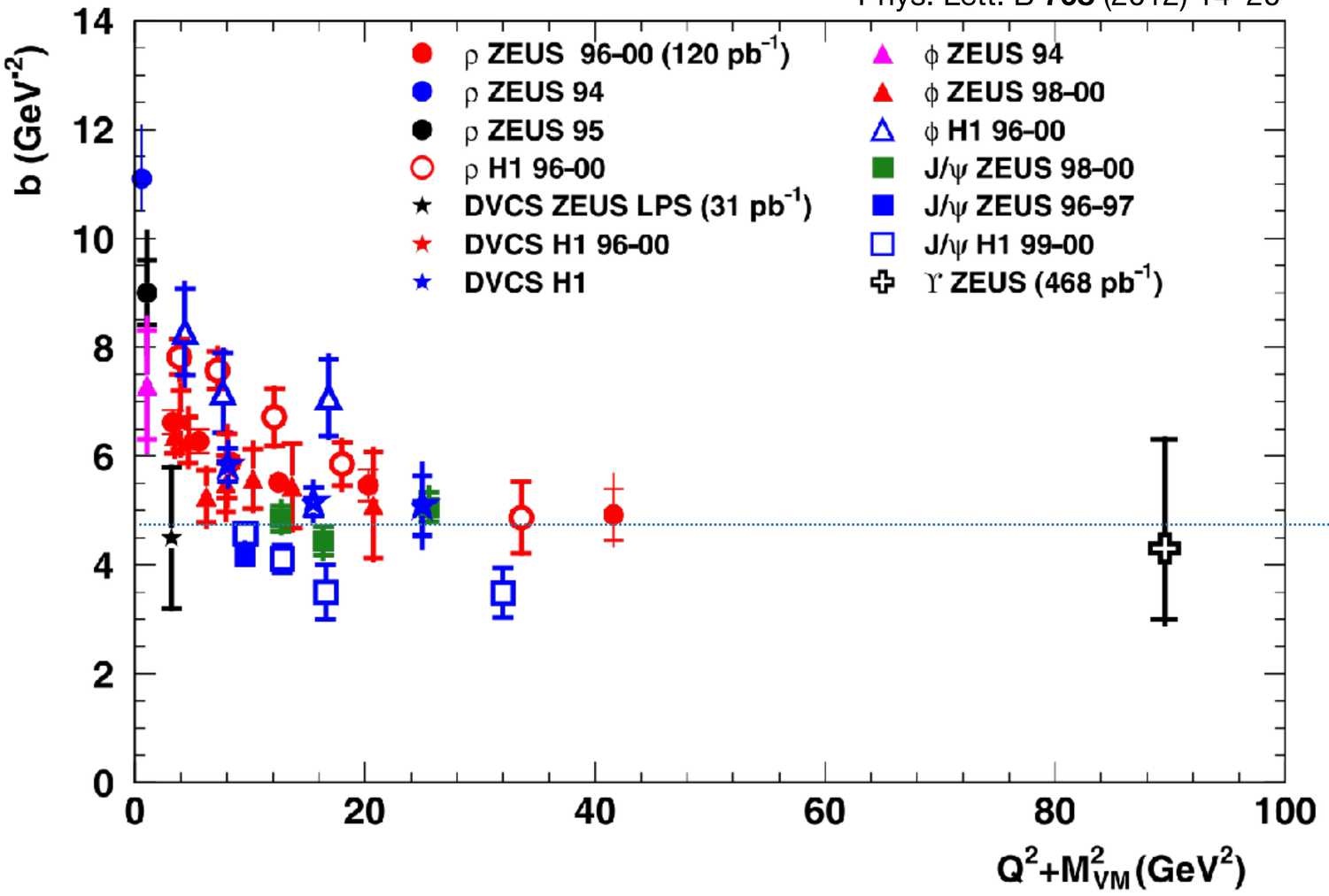
IKS: NLO W=f($\mu$)

FMS: $q\bar{q}$ dipole+2-gluon exchange (CTEQ4L)

MNRT NLO+gPDF from HERA $J/\psi$

# $Q^2+M^2$ dependence of b: elastic

Phys. Lett. B **708** (2012) 14–20




$$b = b_{VM} + b_p$$

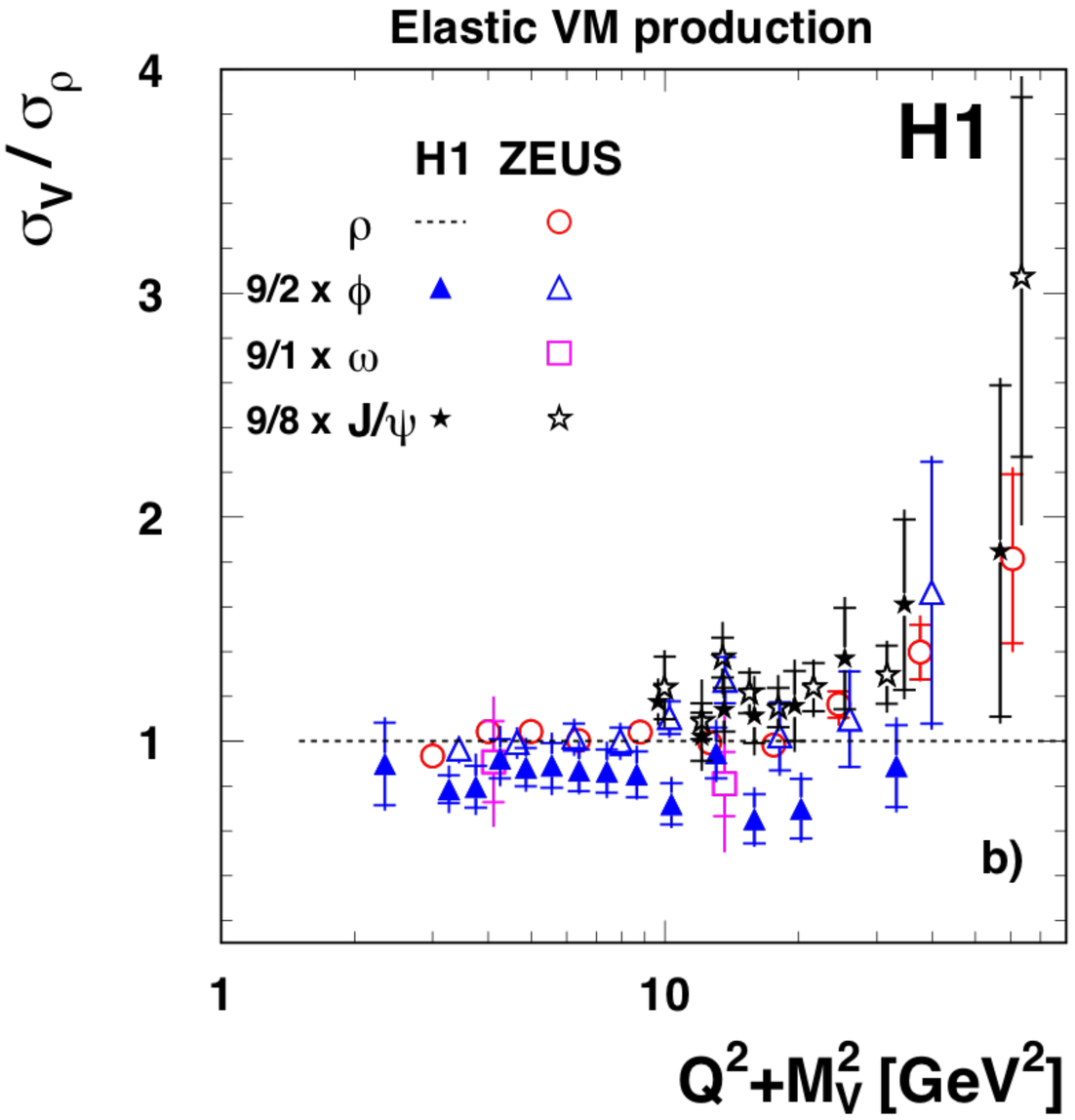
$$b_{VM} \sim \frac{1}{Q^2 + M^2_{VM}}$$

$b_p \rightarrow$ size of gluon area $\langle r \rangle_g$

$\langle r_g \rangle \approx 0.6$ fm

< proton radius (0.84 fm)

# Flavour dependence: universality



# Summary

- W dependence: soft and hard interactions
- Diffractive electroproduction of $\rho$, $\omega$ $\phi$, $J/\psi$, $\psi(2S)$, and $\Upsilon$: NPE and global SCHC
- Disentanglement of longitudinal and transverse cross section:
  rise of longitudinal cross section with $Q^2$
- $Q^2 + M_V^2$ evolution of vector mesons:
  towards sole sensitivity of proton size with increasing $Q^2 + M_V^2$