



# Diffraction electroproduction of $\rho$ and $\phi$ mesons at HERA

[arXiv:0910.5831]

**Xavier Janssen**

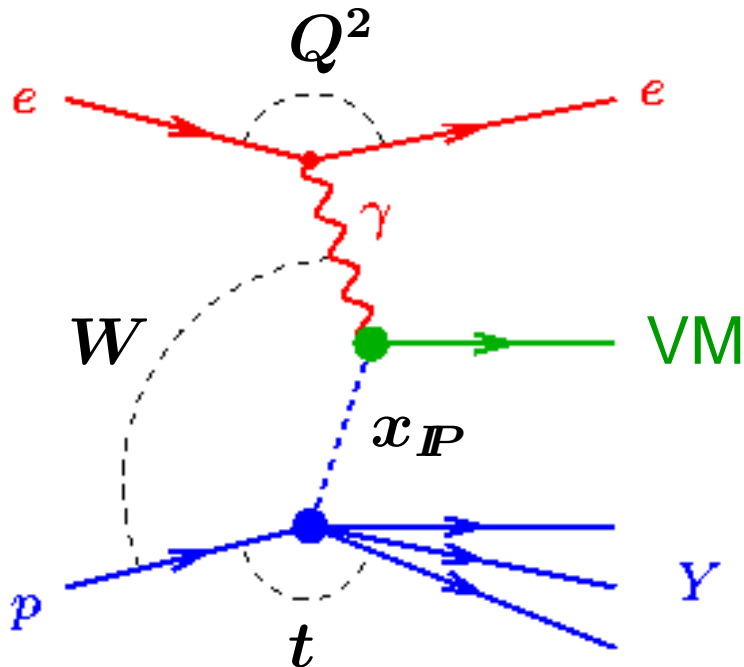


**DIS 2010**

**19-23 April 2010, Firenze, Italy**

# Diffractive Vector Meson Production

$$e + p \rightarrow e + VM (= \rho, \phi, J/\psi, \dots, \text{or } \gamma) + Y (\text{or } p)$$



- $Q^2$  Photon Virtuality  
Photoproduction:  $Q^2 \sim 0$
- $W$   $\gamma p$  CMS energy
- $t$  4-momentum transfer squared
- $x_{\mathbb{P}}$  Momentum fraction of the colour singlet exchange

## Regge Theory

= Soft  $\mathbb{P}$ omeron exchange

$$\sigma \propto \left(\frac{W}{W_0}\right)^{4(\alpha_{\mathbb{P}}(t)-1)}$$

$$\alpha_{\mathbb{P}}(t) = 1.08 + 0.25 t \text{ (DL)}$$

Light VM at low  $Q^2$  and low  $|t|$

$\implies$  Investigate transition between soft and hard regimes

## pQCD Models

Exchange of  $\geq 2$  gluons

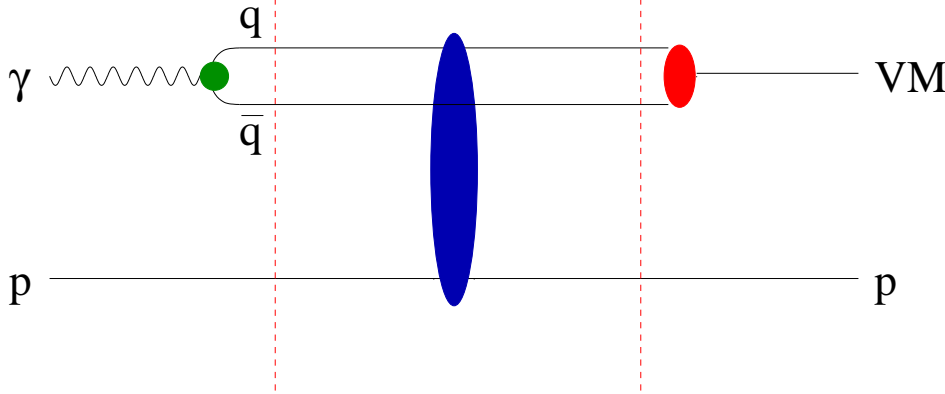
$$\sigma \propto (xG(x, Q^2))^2$$

Steep rise of  $xG(x, Q^2)$

Requires hard scale:  $Q^2, t$  or  $m_q$

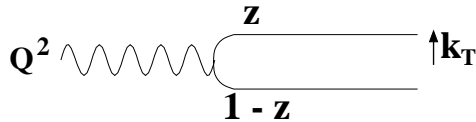
# VM theory: Perturbative QCD approaches

## Dipole approach ( $k_t$ factorisation)



$$\mathcal{A} = \Psi_{q\bar{q}}^\gamma \otimes \sigma_{q\bar{q}-p} \otimes \Psi_{q\bar{q}}^V$$

Scanning radius decrease with increasing  $Q^2$  or  $M_V^2 \rightarrow \mu^2 = z(1-z)(Q^2 + M_V^2)$



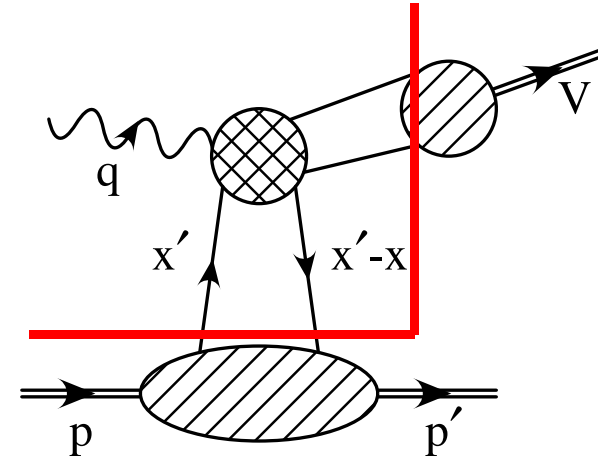
$$\rightarrow \sigma_L \propto \frac{Q^2/M_V^2}{(Q^2 + M_V^2)^4} [\alpha_s(\mu^2) G(x, \mu^2)]^2$$

with  $z \simeq 1/2 \rightarrow \mu^2 \simeq 1/4(Q^2 + M_V^2)$

$$\rightarrow \sigma_T \propto \frac{1}{(Q^2 + M_V^2)^4} [\alpha_s(\mu^2) G(x, \mu^2)]^2$$

with  $z = 0, 1$  endpoints contributions  
 $\rightarrow$  hard scale damped

## Collinear factorisation theorem



$$\mathcal{A}_L = f(x, x', t, \mu) \otimes H \otimes \Psi^V$$

where  $f_i$ : non-forward PDF ( $x' \neq x$ )  
 $\rightarrow$  Generalized Parton Density

Theorem proven for  $\sigma_L$ ; often assumed for  $\sigma_T$   
 Collins, Frankfurt & Strikman [hep-ph/9611433]

### Dipole - Saturation:

Kowalski, Motyka, Watt (KMW) [hep-ph/0606272]  
 Marquet, Peschanski, Soyez (MPS) [hep-ph/0702171]

### Dipole - $k_T$ factorisation:

Ivanov, Nikolaev, Savin (INS) [hep-ph/0501034]

### Collinear - GPD:

Goloskokov, Kroll (GK) [hep-ph/07083569]

### Parton hadron duality:

Martin, Ryskin, Teubner (MRT) [hep-ph/9609448]

# VM theory: Main features / expectations

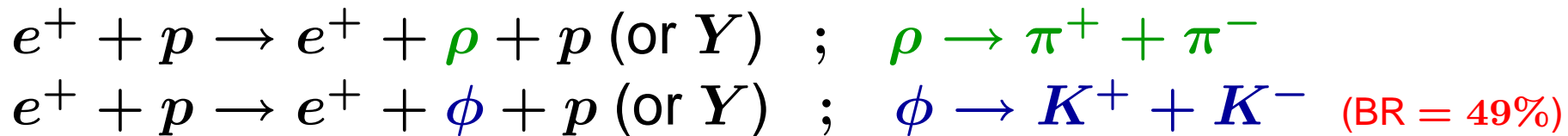
$\sigma(Q^2)$ :  $\sigma_L \propto Q^{-6}$ ;  $\sigma_T \propto Q^{-8}$  but modified by gluon pdf  $Q^2$  depend., quark Fermi motion and virtuality,  $\alpha_s(Q^2)$ , higher order.  
→ Naive  $R = \sigma_L/\sigma_T \propto Q^2/M_V^2$  also modified.

$\sigma(W)$ : ● For  $\sigma_L$  at high  $Q^2$  and heavy VM, hard (universal)  $W$  depend. expected from  $1/x$  hard gluon pdf evolution.  
● For light VM, delayed approach to hard pQCD regime ( $\sigma_T$ ).

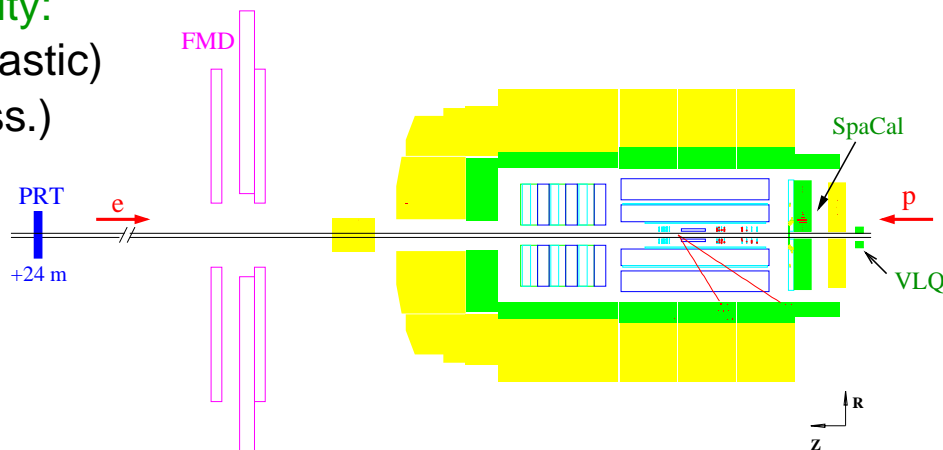
$d\sigma/dt$ :  $\propto \exp(-b|t|)$  for low  $|t|$ , where  $b = b_{q\bar{q}} \otimes b_{\mathbf{P}} \otimes b_p$   
● Expect common  $b$  for  $\sigma_L$  at high  $Q^2$  and heavy VM.  
→ Naive universality of  $b$  vs.  $\mu^2 = 1/4(Q^2 + M_V^2)$   
● Larger dipole in  $\sigma_T$  than in  $\sigma_L$  → expect  $b_T > b_L$   
→ Delayed universality of  $b$  vs.  $\mu^2$

Helicity amplitudes: see later

# Data Selection



Forward activity:  
 NOTAG ( $\simeq$  elastic)  
 TAG ( $\simeq$  p diss.)



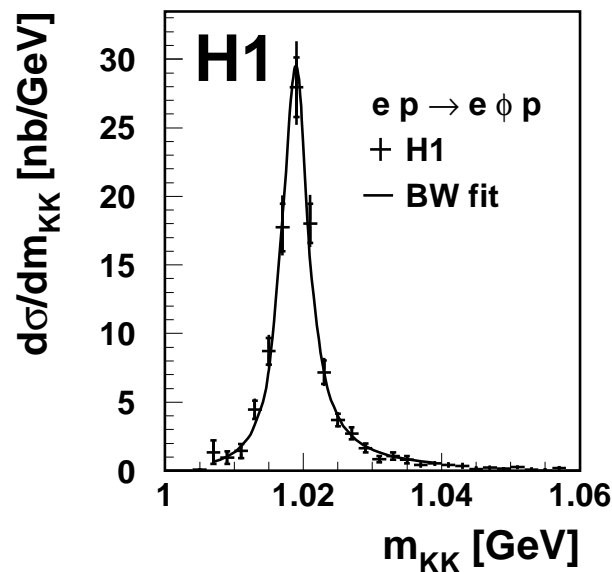
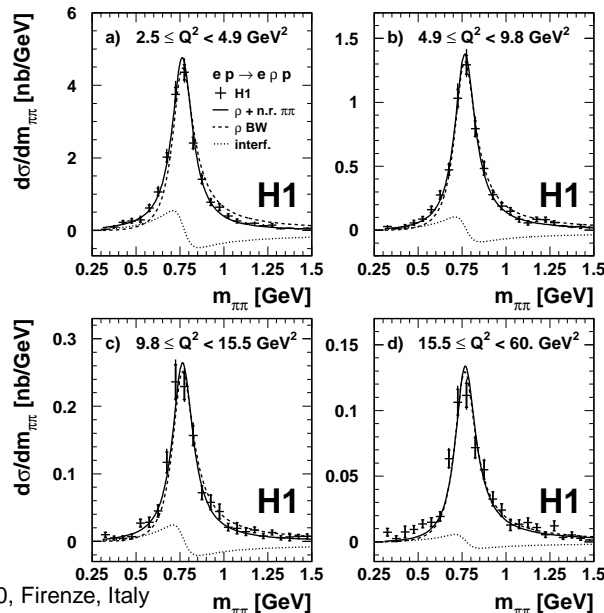
$$2.5 < Q^2 < 60 \text{ GeV}^2$$

$$35 < W < 180 \text{ GeV}$$

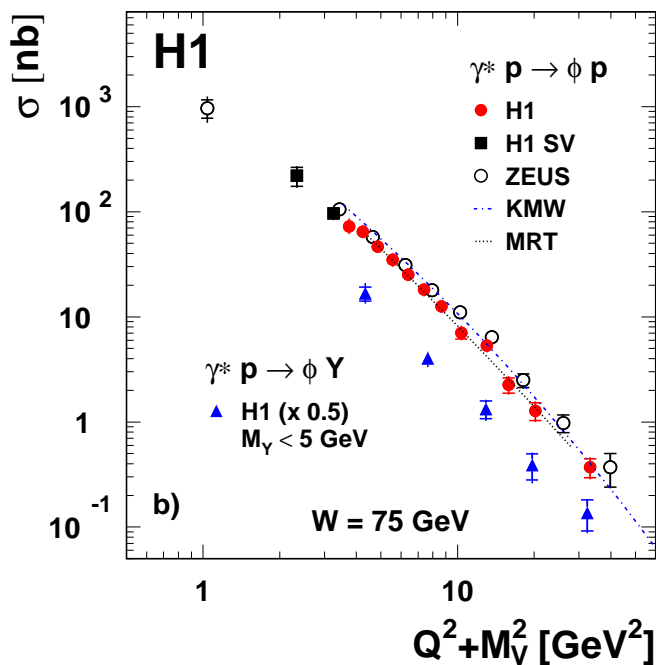
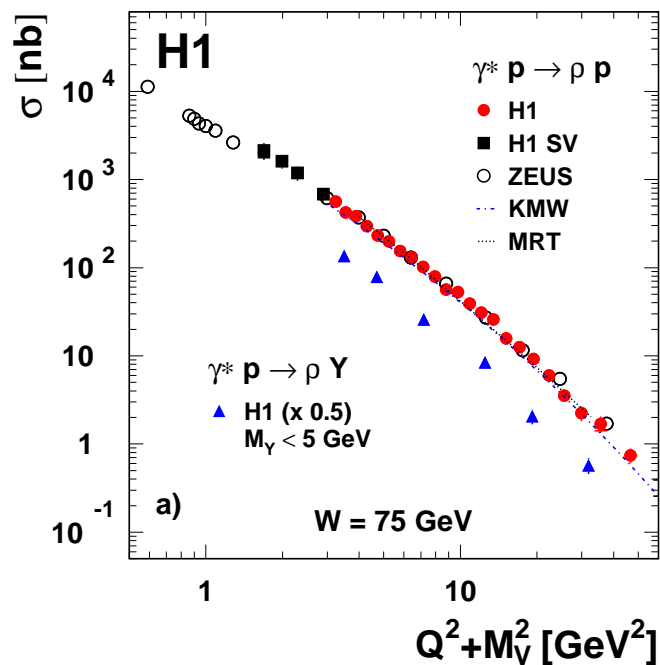
$$\text{elastic: } |t| < 0.5 \text{ GeV}^2$$

$$\text{p diss.: } |t| < 3 \text{ GeV}^2$$

$$M_Y < 5 \text{ GeV}$$

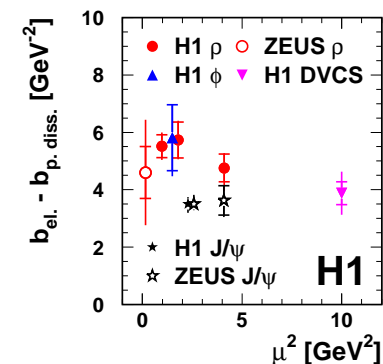
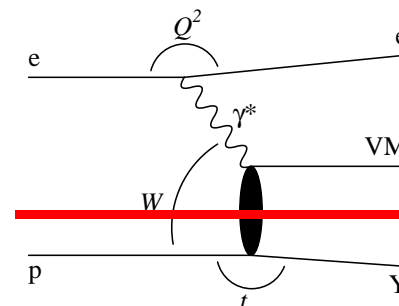
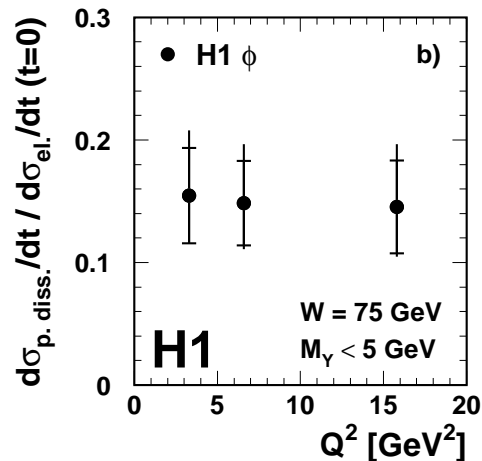
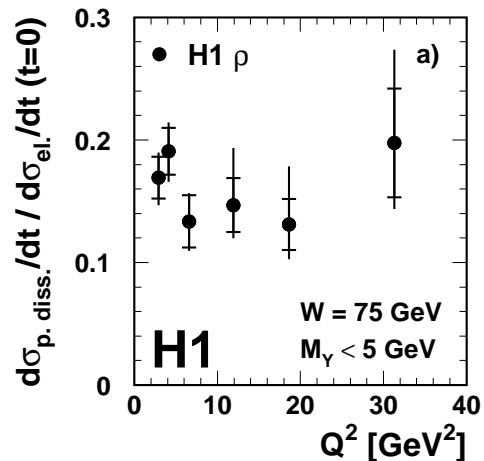


# $Q^2$ dependence



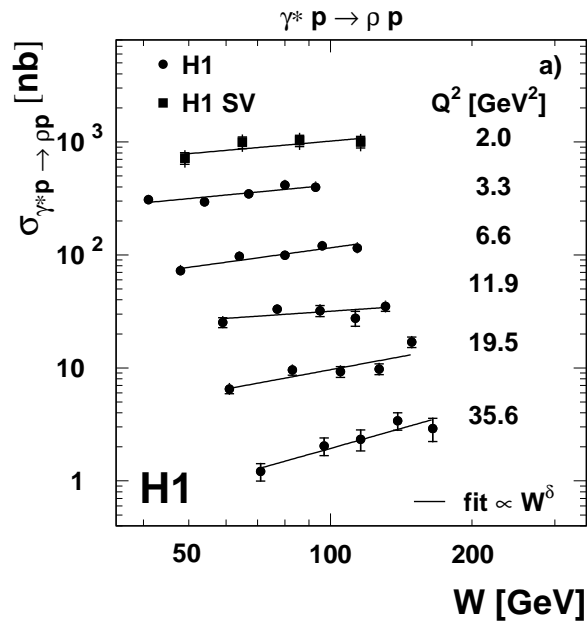
- High precision for elastic cross-sections
- First  $\phi$  p-diss. cross-section
- H1 Zeus relative agreement

## Test of vertex ("Regge") factorisation:



- p.diss/el : no  $Q^2$  dep.
- $t$ -depend. : no  $Q^2$  dep.
- vertex factorisation

# Soft to hard transition - $\sigma(W)$



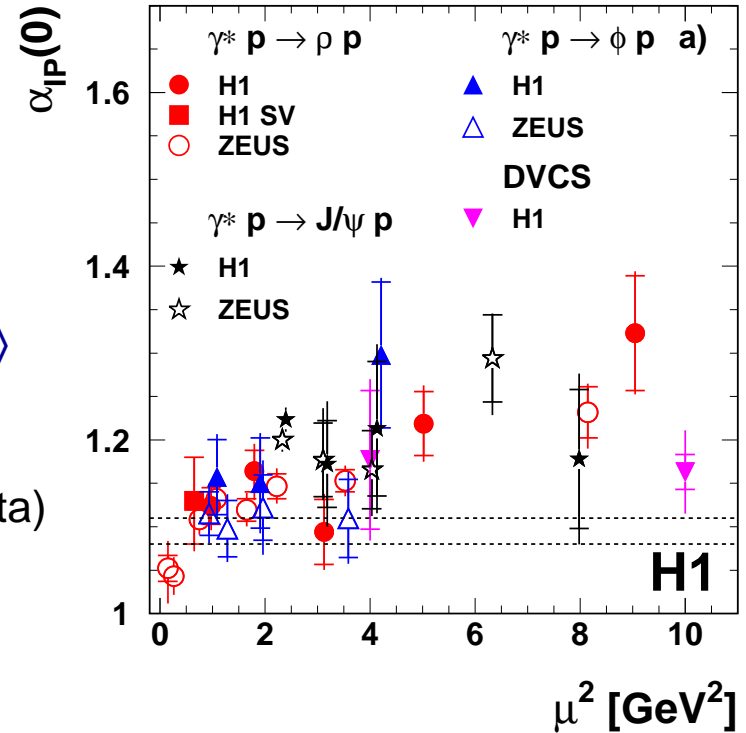
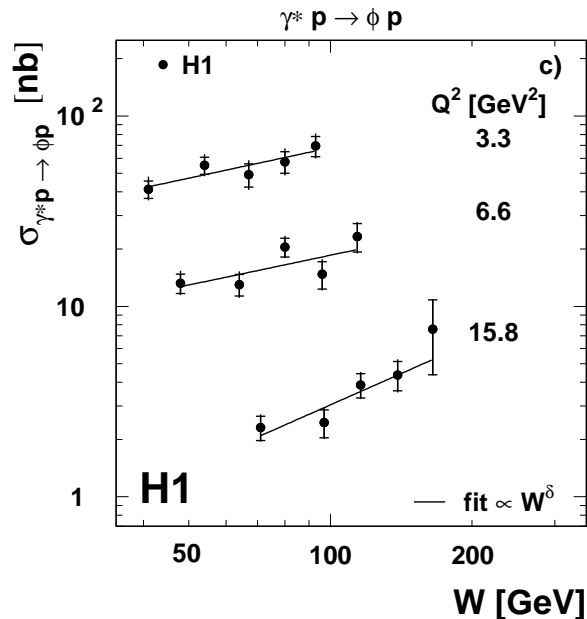
$$\sigma(W) \propto W^\delta$$

$$\alpha_P(0) = 1 + \delta/4$$

$$+ \alpha'_P / \langle |t| \rangle$$

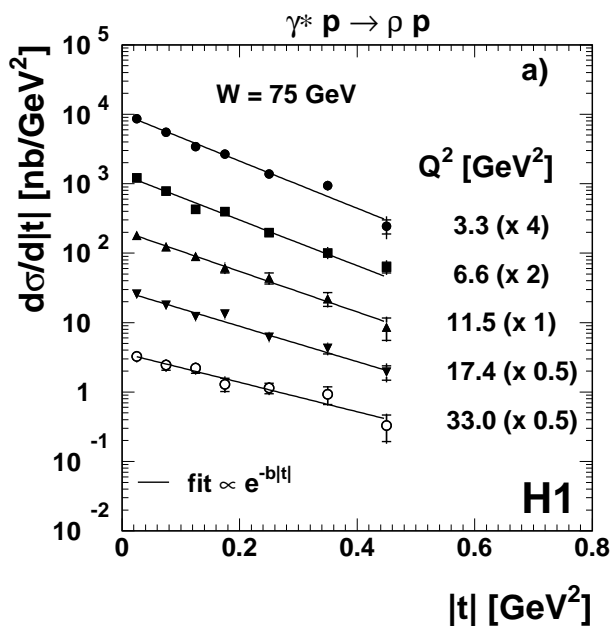
$$\alpha'_P: 0-0.25 \text{ (} \rightarrow \text{data)}$$

$$\langle |t| \rangle: \text{b-slopes (} \rightarrow \text{data)}$$



- Common hardening of  $\alpha_P(0)$  with  $Q^2 + M^2$  for all VM and DVCS  
 $\Rightarrow$  Transition from soft to hard regime with  $\mu^2 = (Q^2 + M^2)/4$
- Soft contributions (in  $\sigma_L$  ?) up to  $\mu^2 \sim 5 \text{ GeV}^2$  for  $\rho$  and  $\phi$

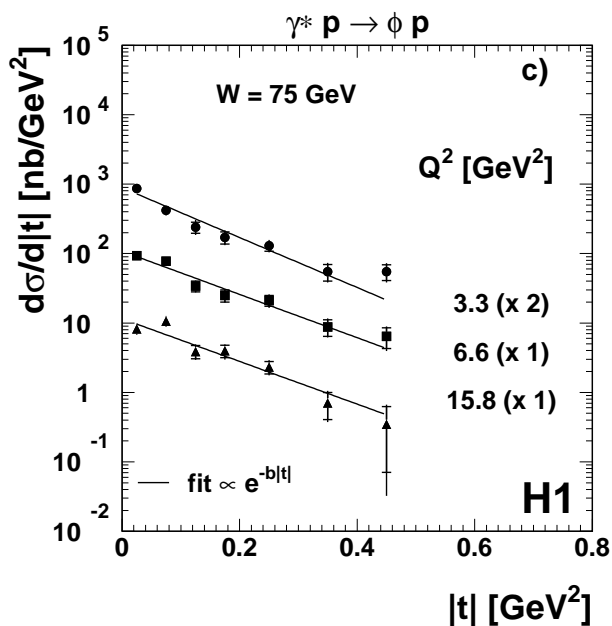
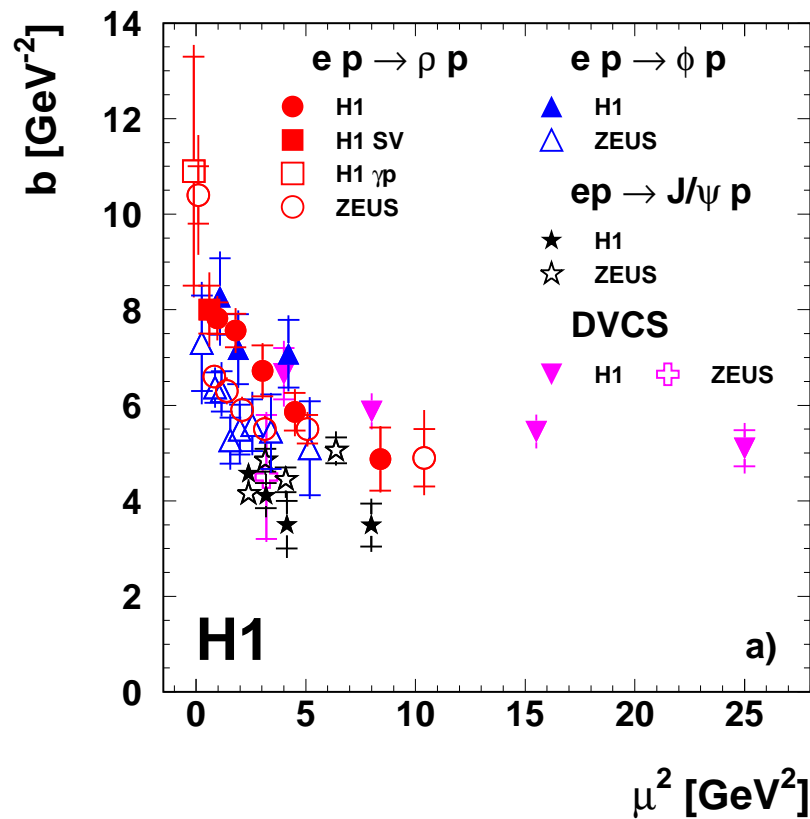
# Soft to hard transition - $t$ dependences



fit  $e^{-b|t|}$

$$b = b_p \otimes b_{q\bar{q}} \otimes b_{\mathbb{P}}$$

$\rightarrow b \propto q\bar{q}$  dipole size



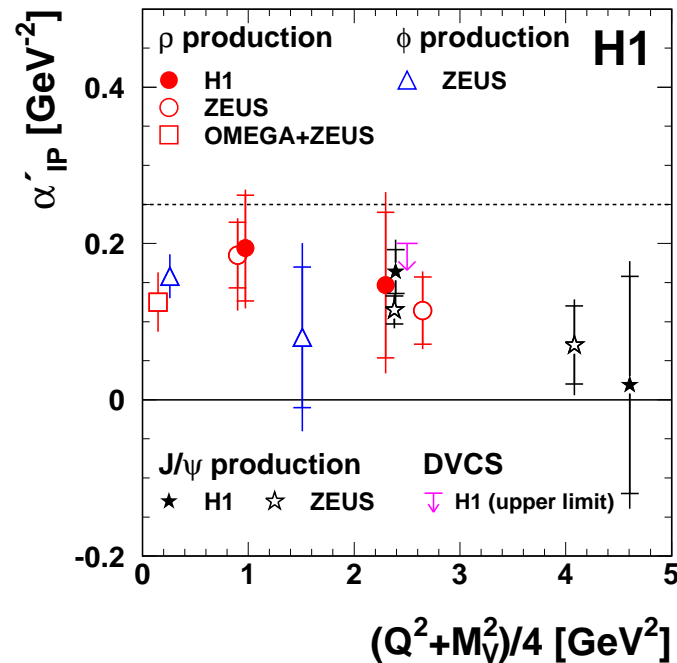
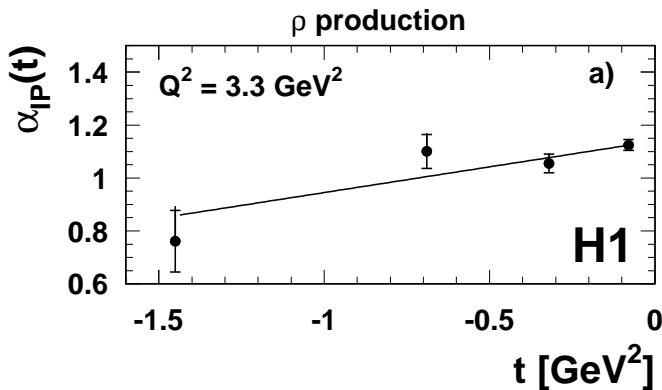
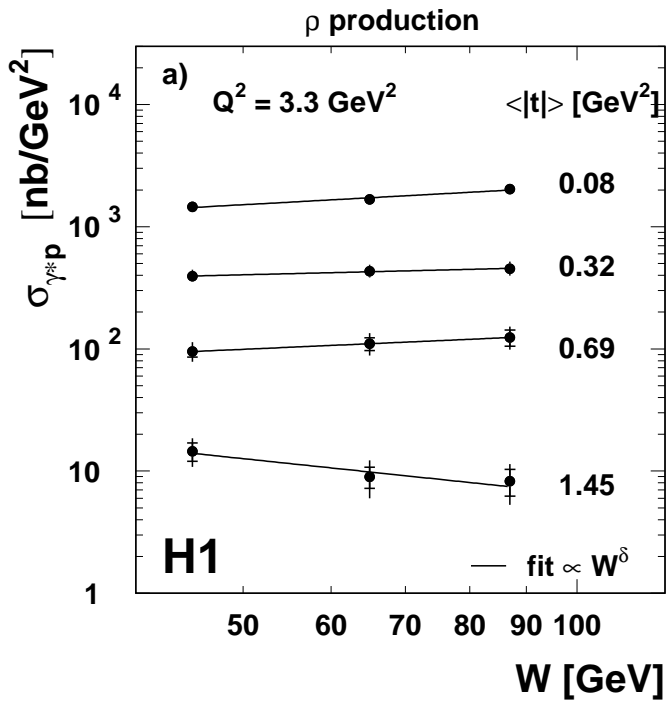
- $b_\rho$  and  $b_\phi$  decrease with  $\mu^2$
  - Common value with  $J/\psi$  for  $\mu^2 > 5$  GeV $^2$
  - Large dipole for light VM at low  $Q^2$
- $\Rightarrow$  Transition from soft to hard regime with  $\mu^2$



# Shrinkage : $\alpha'_{\mathbb{P}}$ measurements

$$\frac{d\sigma}{dt}(W) \propto e^{b_0 t} W^{4(\alpha_{\mathbb{P}}(t)-1)}$$

1. Study  $W$  depend. in bins of  $t$ :  
 $\rightarrow$  Fit:  $W^\delta \rightarrow \alpha_{\mathbb{P}}(t) = 1 + \delta/4$
2. Study  $\alpha_{\mathbb{P}}(t)$  trajectories:  
 $\rightarrow$  Fit:  $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} t$

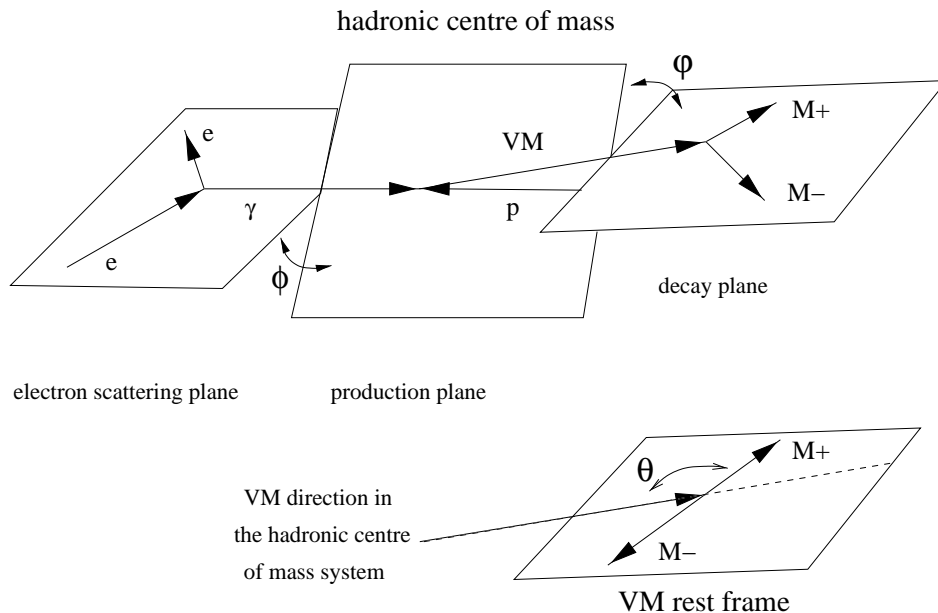


$\Rightarrow$  For all VM,  $\alpha'_{\mathbb{P}}$  smaller than 0.25 (DL,  $p\bar{p}$ )  
 (cf BFKL, multiple  $\mathbb{P}$  exchange)

# SPIN DENSITY MATRIX ELEMENTS

$$\theta^*, \Phi, \varphi \iff 15 \text{ SDMEs} : r_{kl}^{ij} \propto T_{\lambda'_\rho \lambda'_\gamma} T_{\lambda_\rho \lambda_\gamma}$$

$T_{\lambda_\rho \lambda_\gamma}$  : helicity amplitudes



No helicity flip:  $T_{00} : \gamma_L \rightarrow \rho_L$

$T_{11} : \gamma_T \rightarrow \rho_T$

Single flip:  $T_{01} : \gamma_T \rightarrow \rho_L$

$T_{10} : \gamma_L \rightarrow \rho_T$

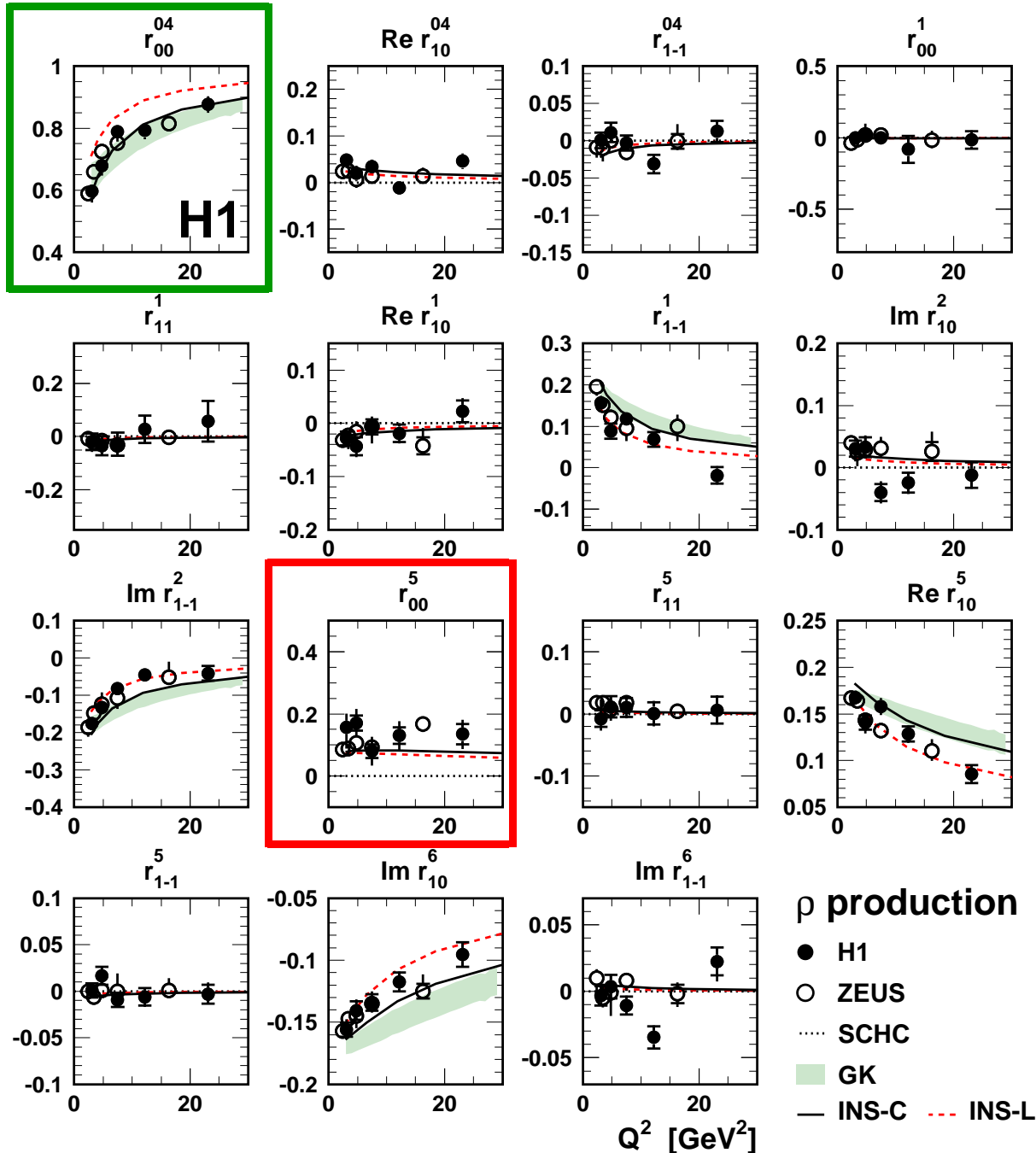
Double flip:  $T_{1-1} : \gamma_T \rightarrow \rho_T$

$s$ -Channel Helicity Conservation (SCHC):  $T_{01} = T_{10} = T_{1-1} = 0$

- pQCD models:**
- SCHC violation ( single flip  $\propto \sqrt{|t|}$ , double  $\propto |t|$  )
  - Hierarchy:  $|T_{00}| > |T_{11}| > |T_{01}| > |T_{10}| > |T_{1-1}|$

D. Yu Ivanov and  
R. Kirschner  
[hep-ph/9807324]

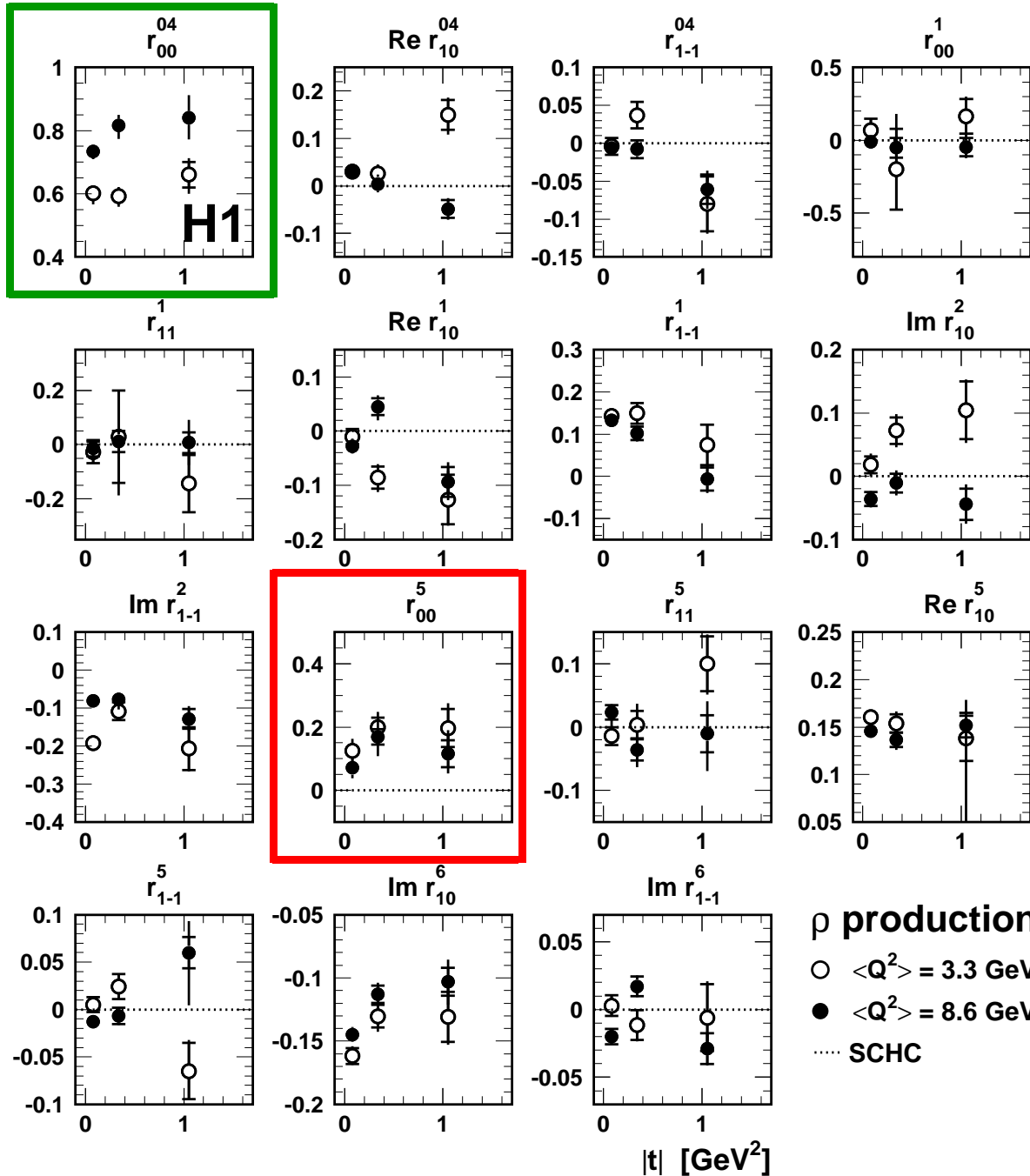
# $\rho$ Polarisation - SDMEs vs. $Q^2$



- $r_{00}^{04}$  increases with  $Q^2$
- ↔ similar effects for  $r_{1-1}^1$ ,  $\text{Im } r_{1-1}^2$ ,  $\text{Re } r_{10}^5$  and  $\text{Im } r_{10}^6$  (in SCHC)
- ↔ Fair description by GK (GPD) model

- $r_{00}^5$  violates SCHC
- Other SDME  $\simeq 0$

# $\rho$ Polarisation - SDMEs vs. $|t|$



- $r_{00}^5$  increases with  $|t|$
- ↔ SCHC violation increases with  $|t|$

- $r_{00}^{04}$  increases with  $|t|$
- ↔ similar effects for  $r_{1-1}^1$ ,  $\text{Im } r_{1-1}^2$ ,  $\text{Re } r_{10}^5$  and  $\text{Im } r_{10}^6$  (in SCHC)

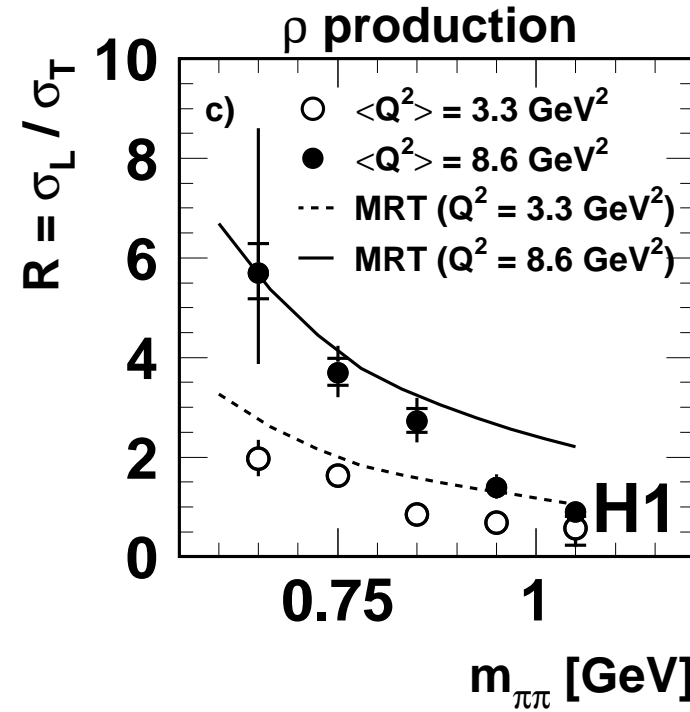
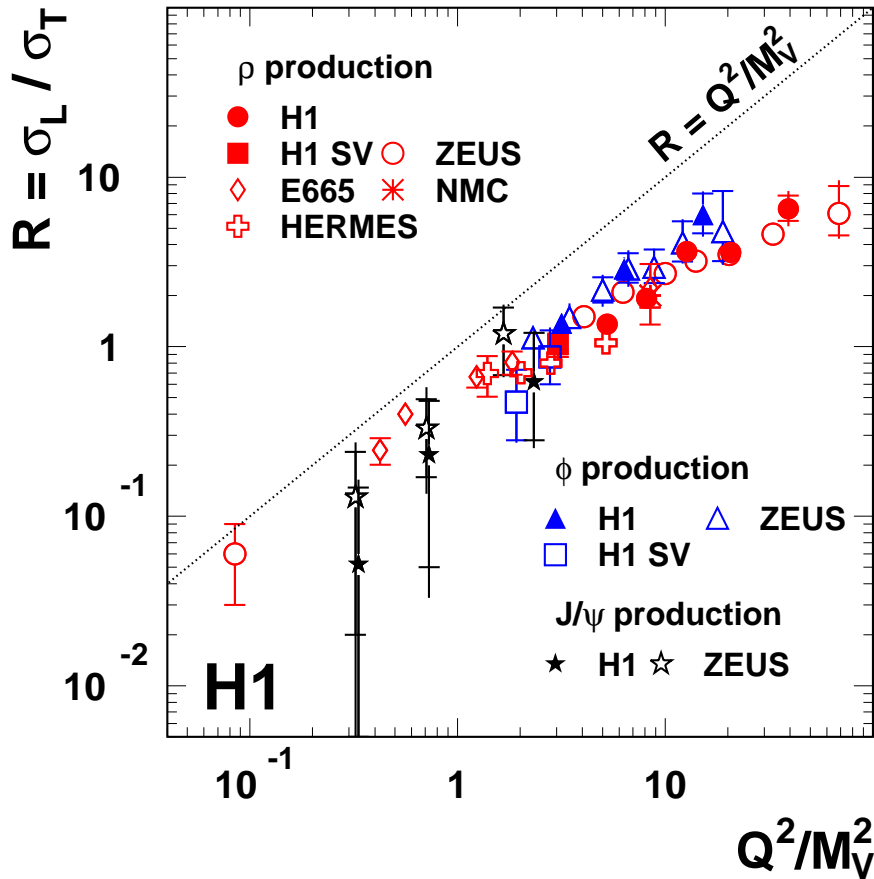
## $\rho$ production

- $\langle Q^2 \rangle = 3.3 \text{ GeV}^2$
- $\langle Q^2 \rangle = 8.6 \text{ GeV}^2$
- ..... SCHC

# $\rho$ and $\phi$ Polarisation - $R = \sigma_L / \sigma_T$

$$R_{SCHC} = \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - \epsilon r_{00}^{04}} = \frac{|T_{00}|^2}{|T_{11}|^2} + \text{non SCHC corrections from } T_{01}$$

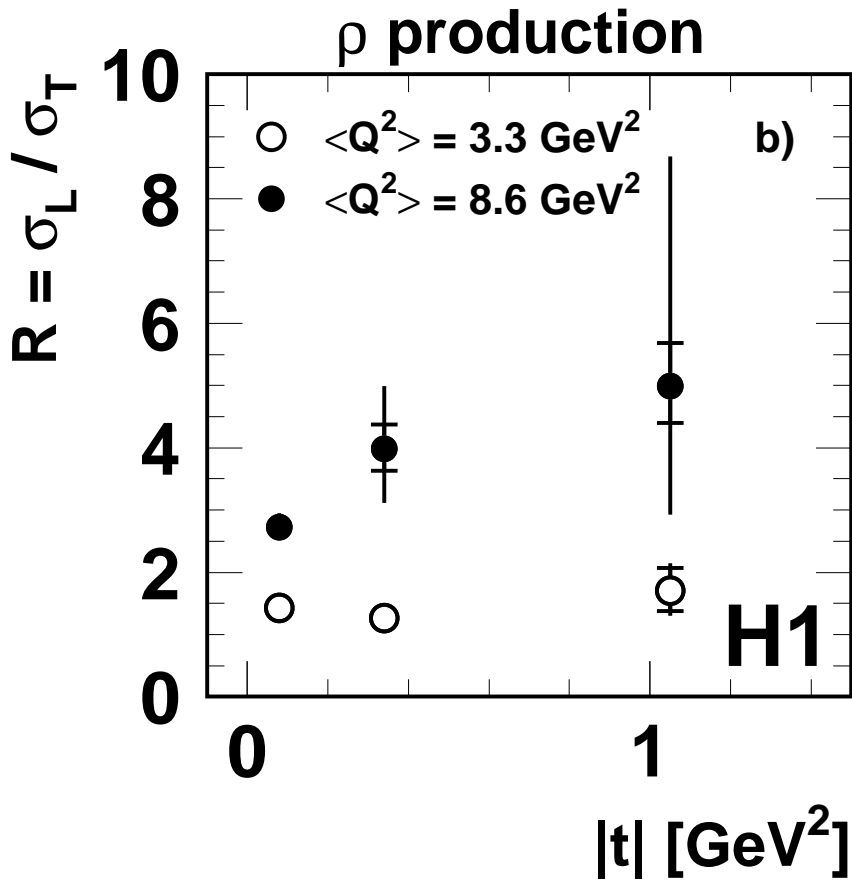
VM production



- Formal pQCD:  $R \propto Q^2 / M^2$
- Scaling for all VM with  $Q^2 / M_V^2$
- Damping at large  $Q^2$

- Strong invariant mass dependence in  $\rho$  case
- formal pQCD:  $R \propto Q^2 / M^2$  but M being diquark mass cf Martin, Ryskin, Teubner calculation

# $\rho$ and $\phi$ Polarisation - $R(t)$ and $b_L - b_T$



$$R(t) \propto \frac{\sigma_L}{\sigma_T} \exp(-(b_L - b_T)|t|)$$

@  $Q^2 = 3.3 \text{ GeV}^2$ :

$$b_L - b_T = -0.03 \pm 0.27^{+0.19}_{-0.17}$$

@  $Q^2 = 8.6 \text{ GeV}^2$ :

$$b_L - b_T = -0.65 \pm 0.14^{+0.41}_{-0.51}$$

- $(b_L - b_T) < 0$  by  $1.5\sigma$  for  $Q^2 > 5 \text{ GeV}^2$
- also a  $t$  dependance of  $T_{11}/T_{00}$  - see later
  - Small difference of transverse size of  $q\bar{q}$  dipoles from transverse and longitudinal photons
  - large dipole in  $\sigma_L$  at low  $Q^2$

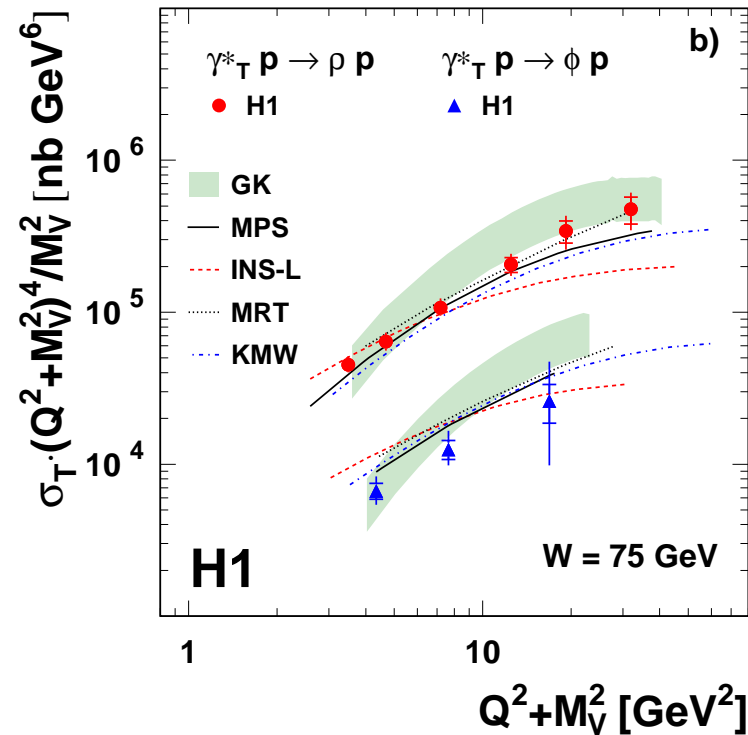
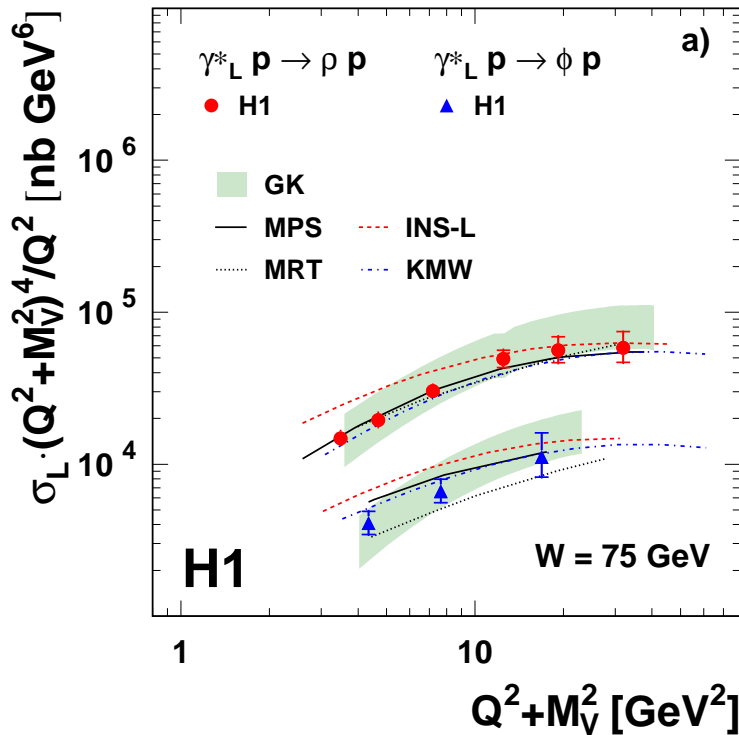
# $\rho$ and $\phi$ Polarisation - Cross-sections

## Longitudinal

$$\sigma_L \propto \frac{Q^2/M_V^2}{(Q^2+M_V^2)^4} [\alpha_s(\mu^2) G(x, \mu^2)]^2$$

## Transverse

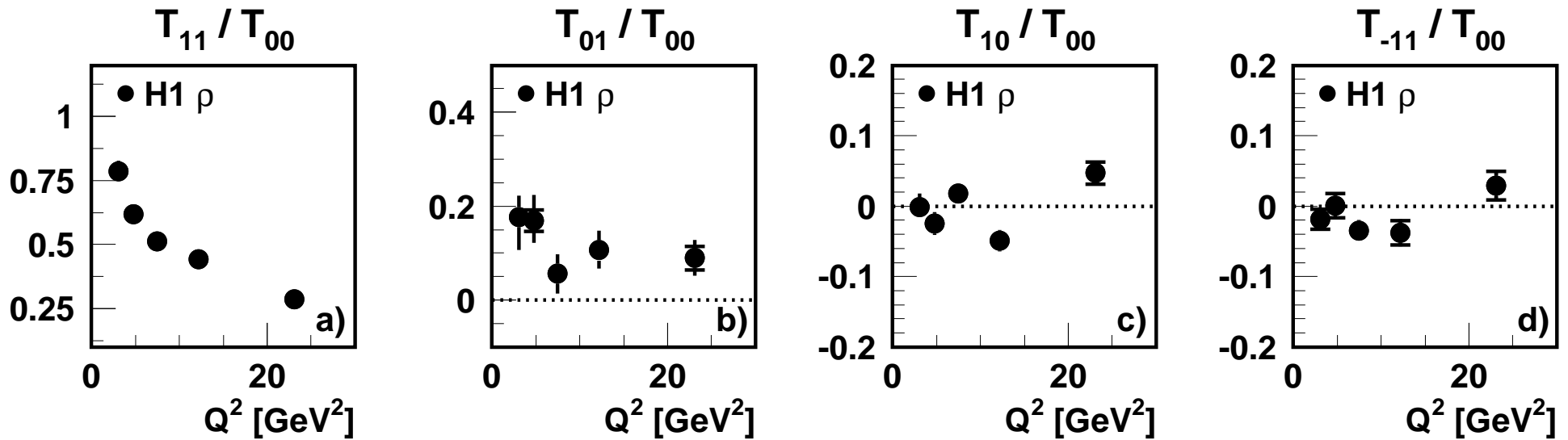
$$\sigma_T \propto \frac{1}{(Q^2+M_V^2)^4} [\alpha_s(\mu^2) G(x, \mu^2)]^2$$



- Different  $Q^2 + M^2$  dependences of  $\sigma_L$  and  $\sigma_T$  ( $\sigma_L = 0$  at  $Q^2 = 0$ )
  - Good description by models with some differences
  - Effect of  $Q^2$  dependences of  $[\alpha_s(\mu^2) G(x, \mu^2)]^2$  visible
- N.B.: data at fixed  $W \rightarrow$  varying  $x$  with  $Q^2 + M_V^2$

# Polarisation - Amplitude ratios vs. $Q^2$

- pQCD (IK):
- $T_{11}/T_{00} \propto \frac{M}{Q} \frac{1+\gamma}{\gamma}$
  - $T_{10}/T_{00} \propto -\frac{M \sqrt{|t|}}{Q^2} \frac{\sqrt{2}}{\gamma}$
  - $T_{01}/T_{00} \propto \frac{\sqrt{|t|}}{Q} \frac{1}{\sqrt{2}\gamma}$
  - $\gamma$ : gluon anomalous dim.

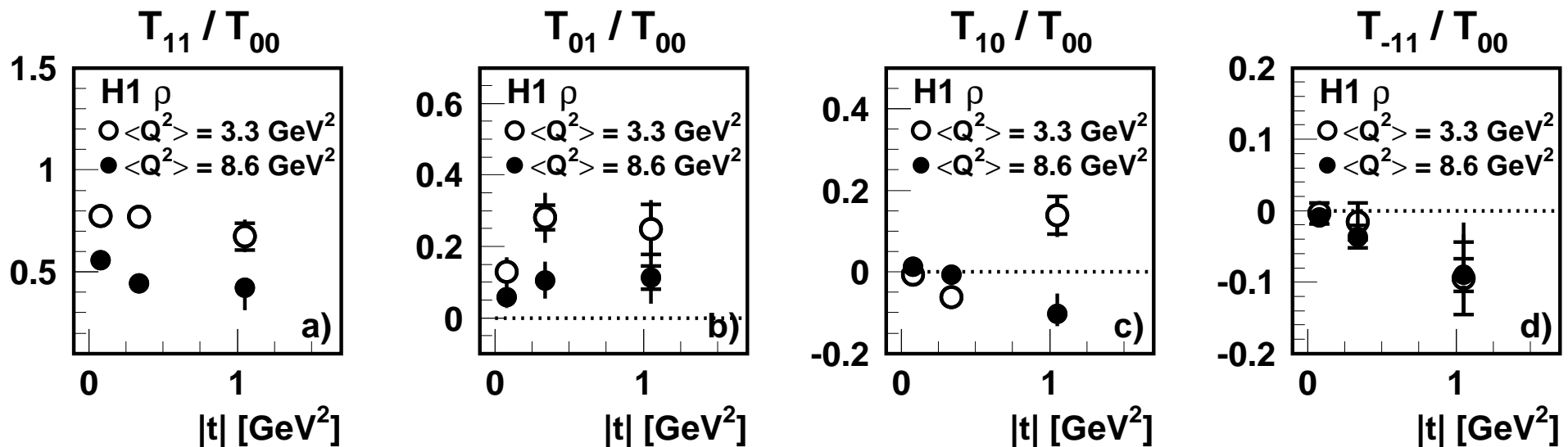


- $T_{11}/T_{00}$  decreases with  $Q^2 \leftrightarrow \sigma_L/\sigma_T$  increases with  $Q^2$
- $T_{01}/T_{00} > 0 \leftrightarrow$  SCHC violation
- $T_{10}/T_{00}$  and  $T_{-11}/T_{00}$  are small
- $\Rightarrow |T_{00}| > |T_{11}| > |T_{01}| > |T_{10}|, |T_{-11}| \leftrightarrow$  hierarchy observed



# Polarisation - Amplitude ratios vs. $|t|$

- pQCD (IK):
- $T_{11}/T_{00} \propto \frac{M}{Q} \frac{1+\gamma}{\gamma}$
  - $T_{10}/T_{00} \propto -\frac{M}{Q^2} \frac{\sqrt{|t|}}{\gamma} \frac{\sqrt{2}}{\gamma}$
  - $T_{01}/T_{00} \propto \frac{\sqrt{|t|}}{Q} \frac{1}{\sqrt{2}\gamma}$
  - $\gamma$ : gluon anomalous dim.



- $T_{11}/T_{00}$  decreases with  $|t|$  (cf.  $b_L - b_T$ )
- $T_{01}/T_{00}$  increases with  $|t| \leftrightarrow$  SCHC violation increases with  $|t|$
- $T_{10}/T_{00}$  and  $T_{-11}/T_{00}$  are small but some  $|t|$  dependence

# CONCLUSIONS

---

## VM cross-section measurements:

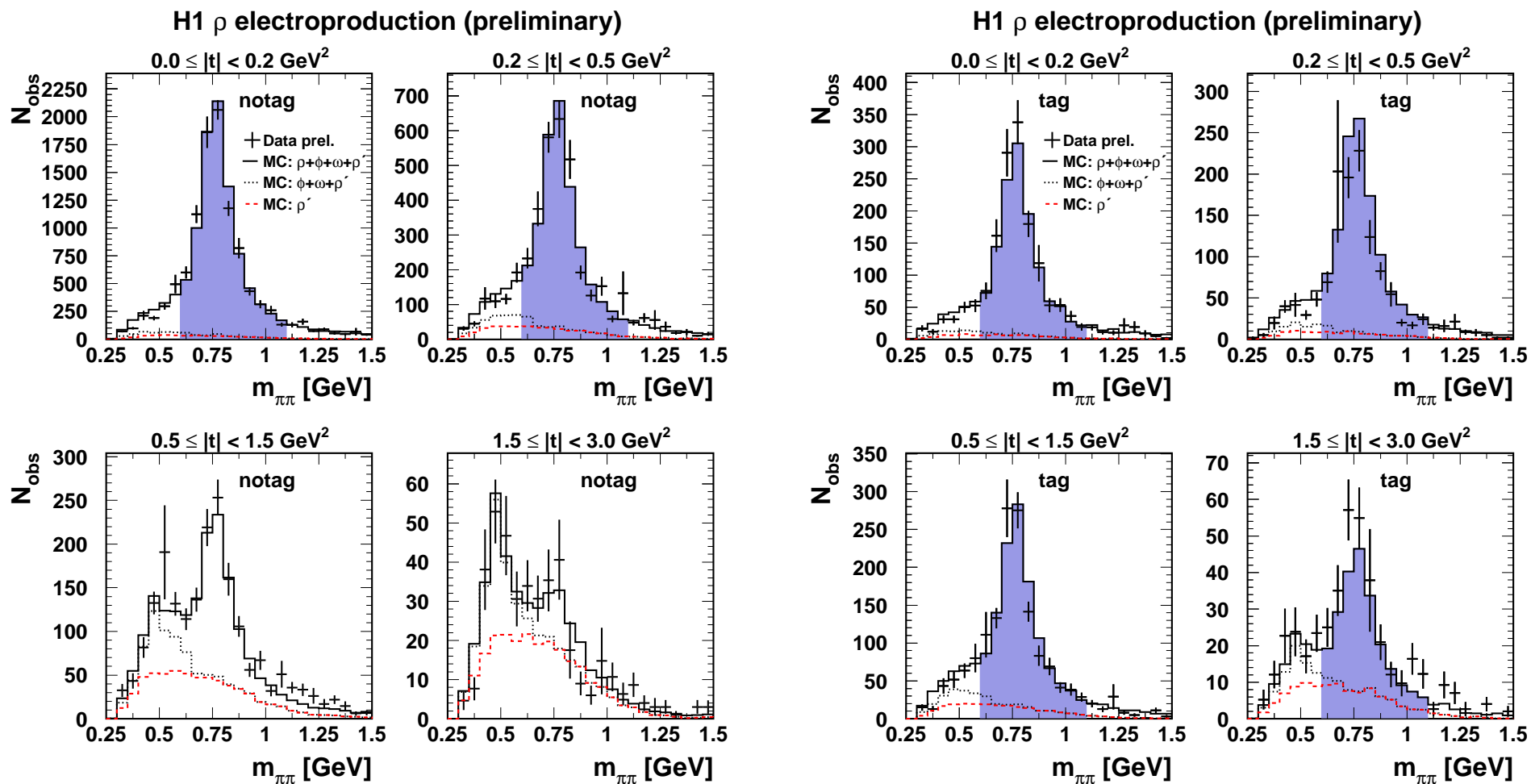
- Hard regime reached only around  $\mu^2 = \frac{Q^2 + M^2}{4} = 5 \text{ GeV}^2$  as observed in measurements of  $\alpha_{\mathbb{P}}(0)$  and  $b$ -slopes.
  - Possible soft component in  $\sigma_L$  up to "high"  $Q^2$  for light VM.
- p diss. / elastic ratio: proton vertex factorisation observed

## VM polarisation properties:

- Polarised cross-section and amplitude ratios have been extracted
- $\sigma_L/\sigma_T$  increases with  $Q^2$  and maybe with  $|t|$  at high  $Q^2$ 
  - ↔  $|t|$  depend. expected in pQCD from  $\neq$  dipole in  $\sigma_L$  and  $\sigma_T$ .
- Violation of SCHC: significant  $T_{01}/T_{00}$  increases with  $|t|$
- $\sigma_L/\sigma_T$  decreases with  $\rho$  invariant mass
  - ↔ Predicted by MRT / limited influence of VM wave function.

**pQCD models:** GPD and dipole ones describe main features, but differences in details

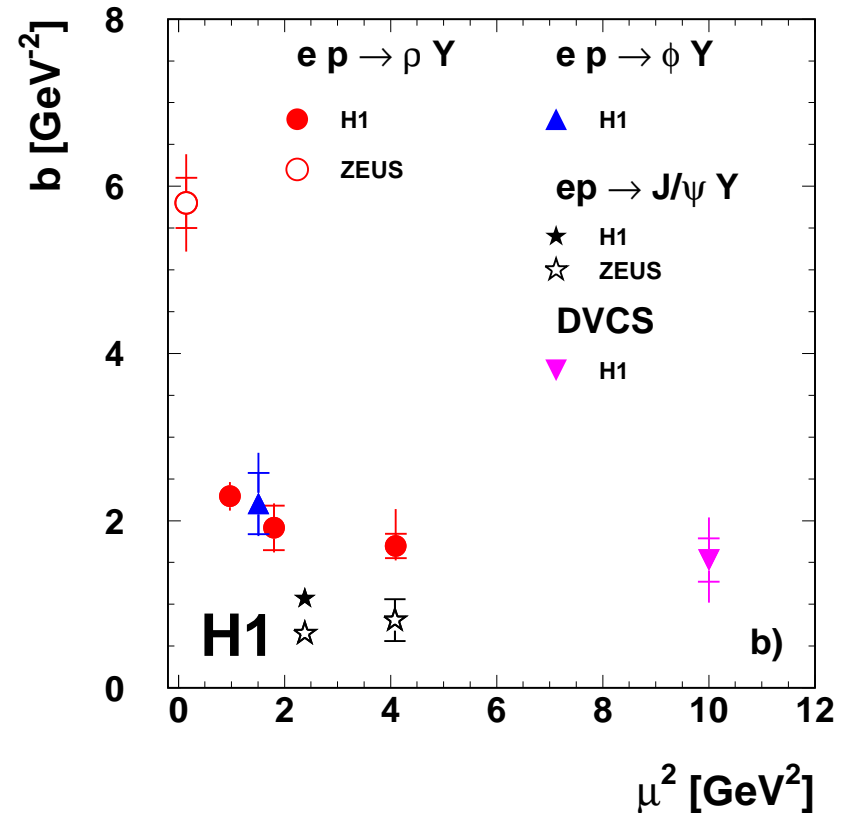
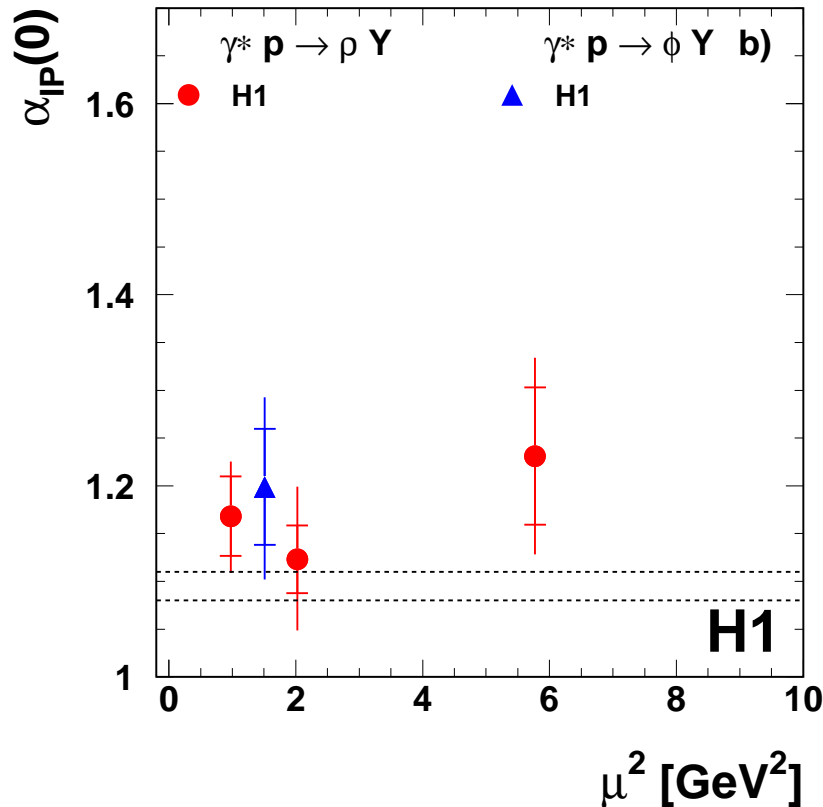
# H1 background subtraction



# Soft to hard transition - proton dissociation

$$\sigma(W) \propto W^\delta$$

$$d\sigma/dt \propto \exp(-bt)$$



- First measurements of  $\alpha_{IP}(0)$  and  $b$ -slopes for  $\rho$  and  $\phi$  in electroproduction at HERA.
- Smaller values but similar features as for elastic channel

# **Polarisation - Retrieving Amplitude ratios**

Assume purely imaginary amplitudes  $\longrightarrow$  phase =  $\pm 1$  !

$\longrightarrow$  Extract  $|T_{11}|/|T_{00}|$ ,  $|T_{01}|/|T_{00}|$ ,  $|T_{10}|/|T_{00}|$  and  $|T_{-11}|/|T_{00}|$  from fit to the 15 SDMEs:

$$\begin{aligned}
 r_{00}^{04} &= B (\varepsilon + \beta^2) \\
 \text{Re } r_{10}^{04} &= B/2 (2\varepsilon\delta + \beta\alpha - \beta\eta) \\
 r_{1-1}^{04} &= B (\alpha\eta - \varepsilon\delta^2) \\
 r_{00}^1 &= -B \beta^2 \\
 r_{11}^1 &= B \alpha\eta \\
 \text{Re } r_{10}^1 &= B/2 \beta(\eta - \alpha) \\
 r_{1-1}^1 &= B/2 (\alpha^2 + \eta^2) \\
 \text{Im } r_{10}^2 &= B/2 \beta(\alpha + \eta) \\
 \text{Im } r_{1-\Gamma}^2 &= B/2 (\eta^2 - \alpha^2) \\
 r_{00}^5 &= \sqrt{2} B \beta \\
 r_{11}^5 &= B/\sqrt{2} \delta(\alpha - \eta) \\
 \text{Re } r_{10}^5 &= B/(2\sqrt{2}) (2\beta\delta + \alpha - \eta) \\
 r_{1-1}^5 &= B/\sqrt{2} \delta(\eta - \alpha) \\
 \text{Im } r_{10}^6 &= -B/(2\sqrt{2}) (\alpha + \eta) \\
 \text{Im } r_{1-\Gamma}^6 &= B/\sqrt{2} \delta(\alpha + \eta)
 \end{aligned}$$

$$\begin{aligned}
 \alpha &= |T_{11}|/|T_{00}| \\
 \beta &= |T_{01}|/|T_{00}| \\
 \delta &= |T_{10}|/|T_{00}| \\
 \eta &= |T_{-11}|/|T_{00}|
 \end{aligned}$$

$$\begin{aligned}
 B &= \frac{1}{N_T + \varepsilon N_L} = \frac{R}{1 + \varepsilon R} \\
 N_T &= \alpha^2 + \beta^2 + \eta^2 \\
 N_L &= 1 + 2\delta^2
 \end{aligned}$$