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# Elastic Production of Vector Mesons at HERA

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## Outline

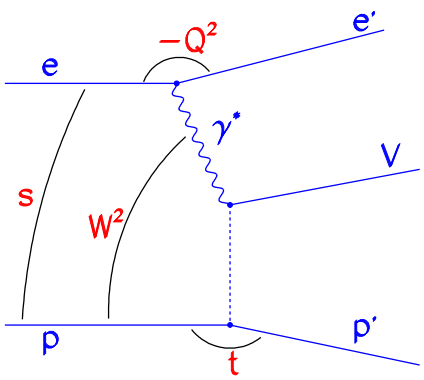
- Photoproduction
- Intermediate and high $Q^2$ region
- Helicity studies
- Summary

# Diffractive Vector Meson Production at HERA

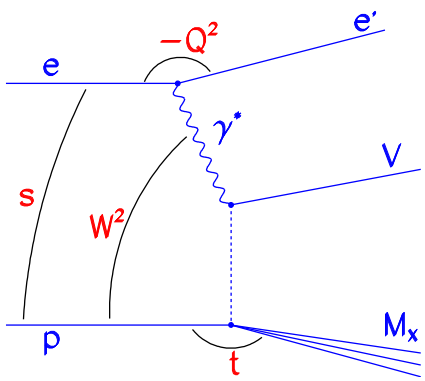
$e^{\pm}$ 27.5 GeV  p 820 GeV

CMS energy $\simeq$ 300 GeV

Exclusive (or Elastic)
$\gamma p \to Vp$




Proton Dissociative
$\gamma p \to VY$




$W_{\gamma p}$ center of mass energy of $\gamma^*$–p system : 20 – 240 GeV

$Q^2$ photon virtuality: $10^{-11}$ – 60 GeV$^2$

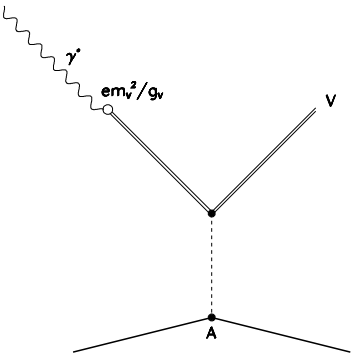
$|t|$ square of 4–momentum transfer at the proton vertex : 0 – 10 GeV$^2$

$M_V$ meson mass : 0.77 – 10 GeV

- Physics whith several large scales which can be varied in wide ranges

# Theoretical Status - Non Pert. Model

Non-perturbative description based on
Regge theory and Vector Dominance Model




$\Rightarrow$ exchange of a $soft$ $\mathbb{P}$ trajectory:

$$\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} \cdot t = 1.08 + 0.25\, t$$

- slow rise of cross section with energy

$$\sigma(W) \propto \frac{W^{4(\alpha_{\mathbb{P}}(0)-1)}}{b} \sim W_{\gamma p}^{0.22}$$

- shrinkage of the forward peak $\frac{d\sigma}{dt} \propto e^{-b\ |t|}$

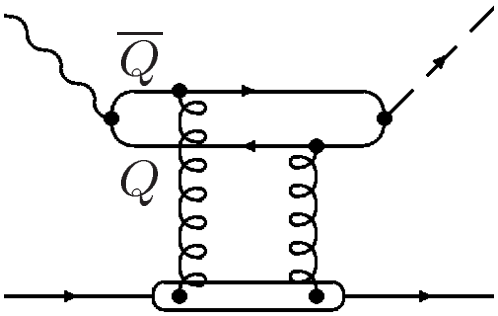
$\Rightarrow$ $b$ increasing with energy $b = b_0 + \alpha'_{\mathbb{P}} \cdot \ln(W_{\gamma p})$

- $R = \sigma_L/\sigma_T = \epsilon Q^2/M_V^2$

- s-channel helicity conservation (SCHC)

# Theoretical status - QCD

When a hard scale is provided, by $Q^2$, $M_V$ or $|t|$, perturbative QCD can be applied




Colourless exchange described in terms of gluon ladders

- fast increase of the cross-section with $W_{\gamma p}$ related to the evolution of the gluon density in the proton

$$\sigma(W) \propto \left[\alpha_s(\bar{q}^2)\bar{x}g(\bar{x},\bar{q}^2)\right]^2 \quad \bar{x} \propto \frac{Q^2+M_V^2}{W_{\gamma p}}$$

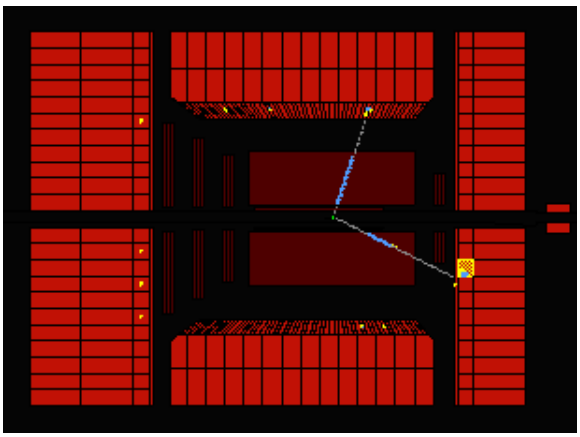
- universal shape of the t distribution, flavor and energy independent (almost no shrinkage)
- $Q^2$ and $W$ dependence of $R = \sigma_L/\sigma_T$
- violation of the s-channel helicity conservation

▶ Use all available scale to understand transition from *soft* to *hard* regime

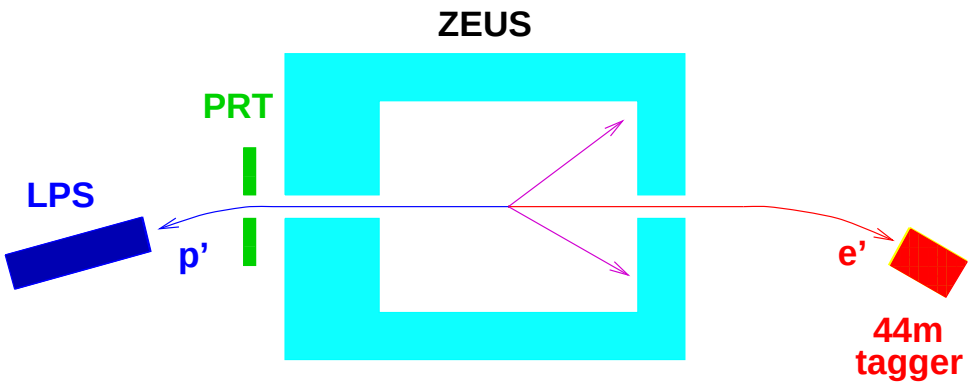
# Event Selection in Photoproduction

- VM reconstructed by its decay particles using central tracking detectors
- elastic selection: no energy deposits in the main detector other than decay particles
- forward detectors allow to tag proton dissociative events

$e'$ not observed $\Rightarrow$ $Q^2 \sim 10^{-6}$ GeV$^2$

$e \rightarrow$  $\leftarrow p$

$e'$ observed in 44m tagger $\Rightarrow$ $Q^2 < 10^{-2}$GeV$^2$, high $|t|$

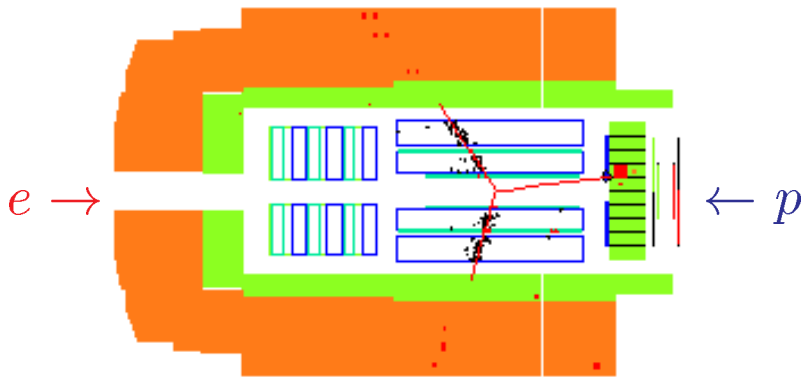


# Event Selection in Electroproduction

$e'$ observed in Beam Pipe Calorimeter
$\Rightarrow$ 0.25 GeV$^2$ $< Q^2 <$ 0.85 GeV$^2$, intermediate $Q^2$ region

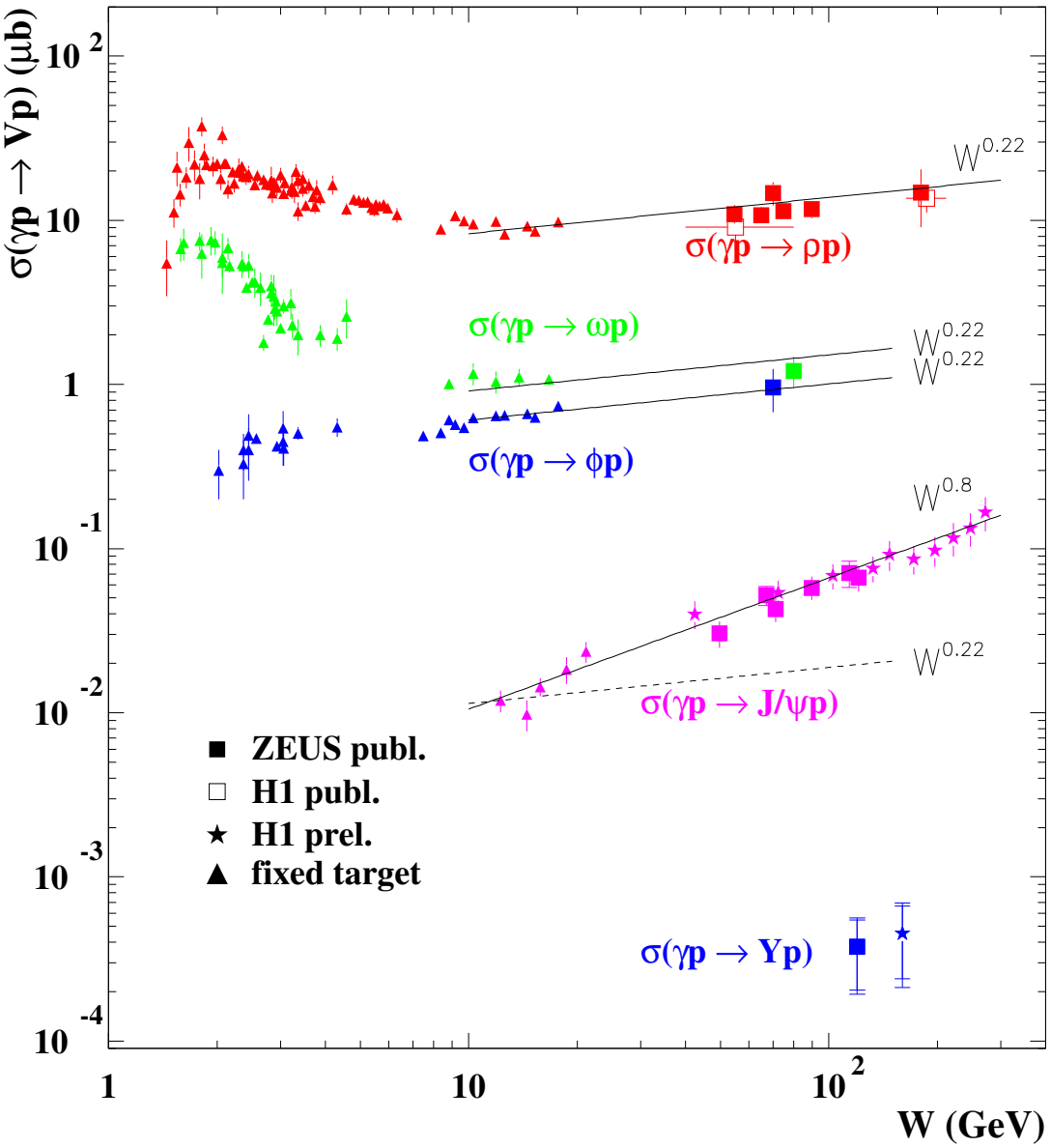
or $e'$ observed in main detector

$\Rightarrow$ 1 GeV$^2$ $< Q^2 <$ 60 GeV$^2$, electroproduction



# Photoproduction

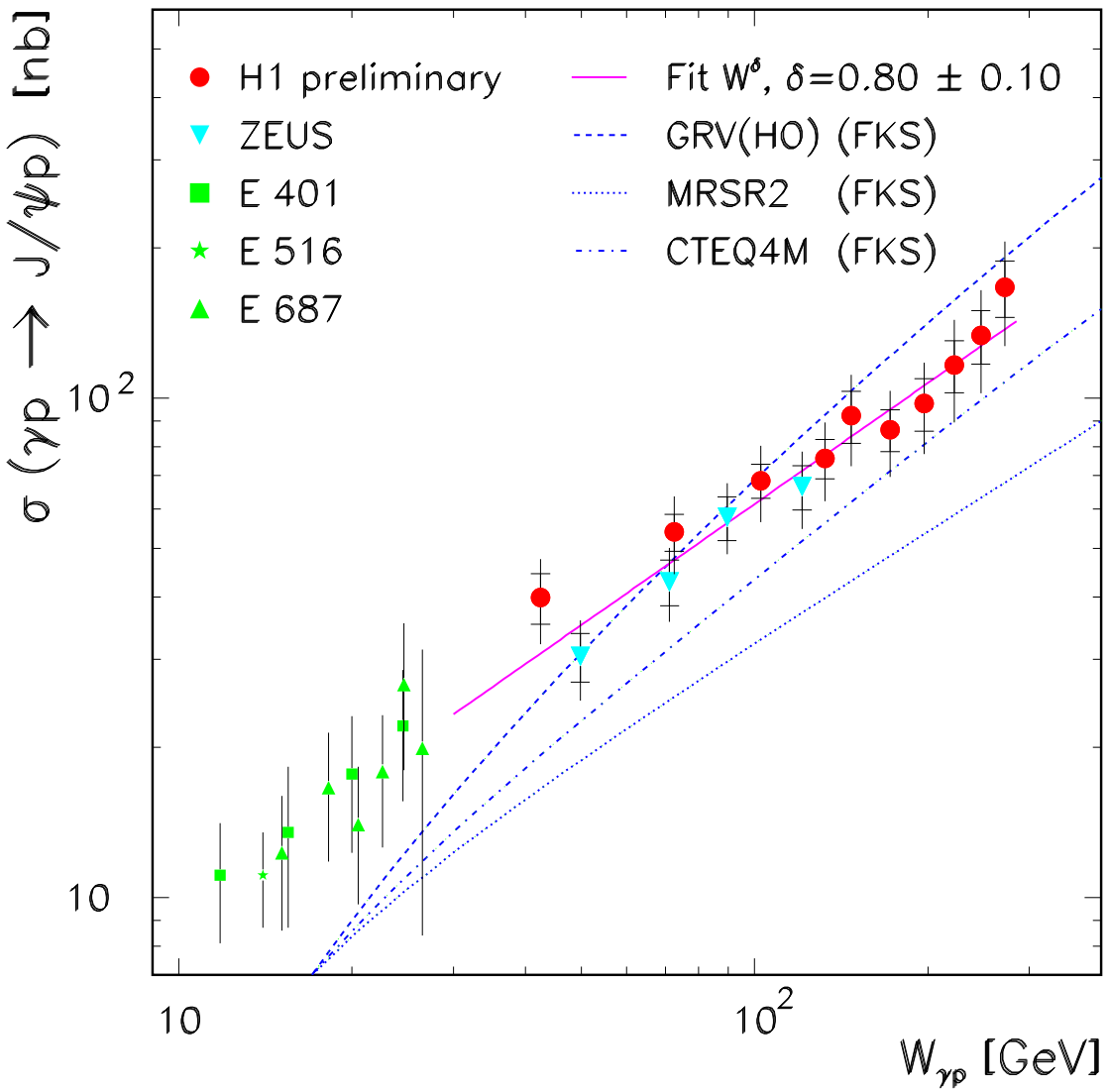
- VM cross section vs energy




- $\rho$, $\omega$ and $\phi$ have a Regge behaviour: $\sigma_{\gamma p \to Vp} \propto W^{0.22}$
- J/$\psi$ is not described by Regge: much stronger dependence on $W$

## Photoproduction

- J/$\psi$ cross section vs energy



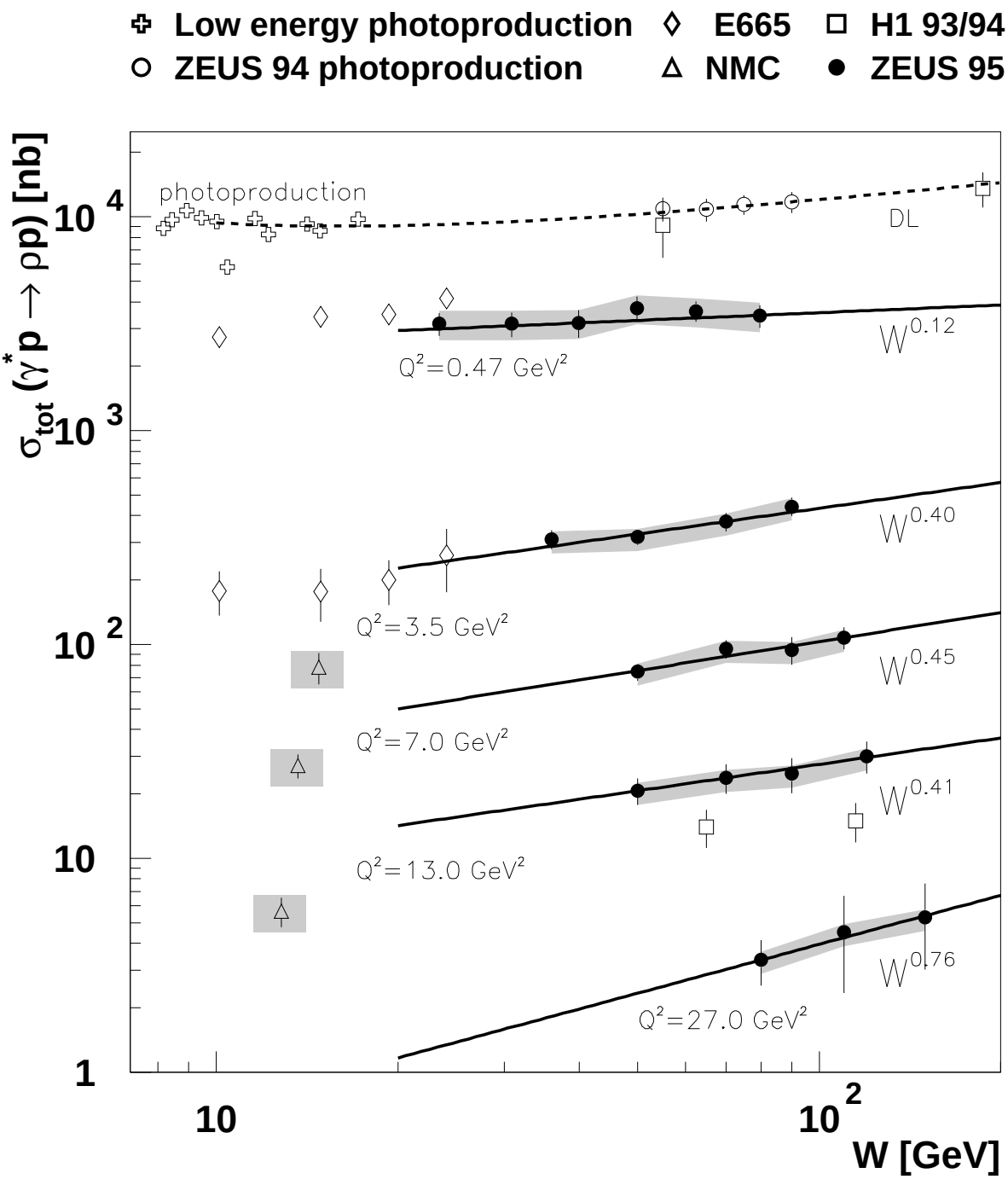

• The rise of the cross section with the energy can be described by pQCD model:

$$\sigma(W) \propto [xg(x, Q^2)]^2$$

- Sensitivity to parameterizations of $xg(x)$

# Intermediate and High $Q^2$ Region

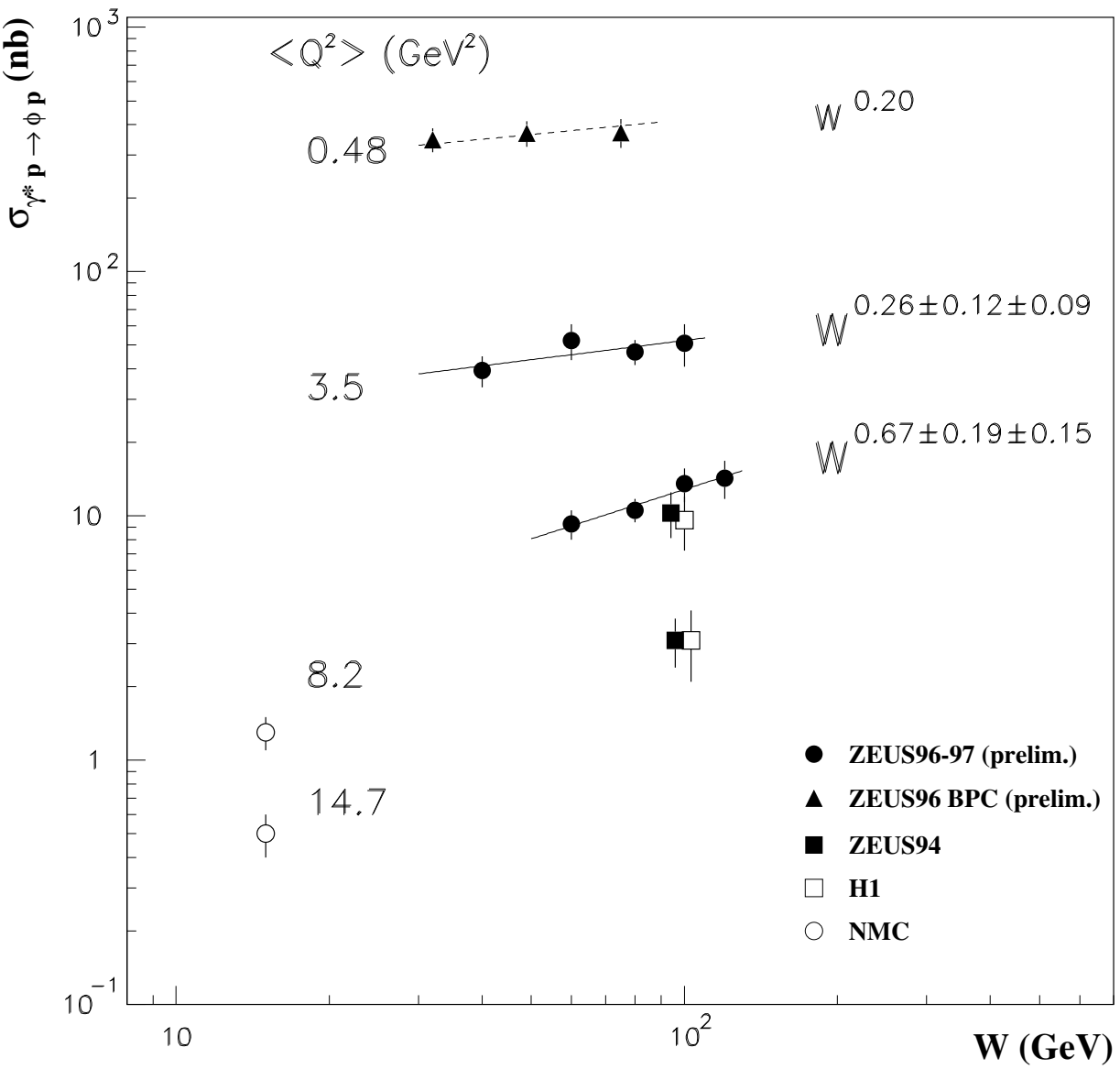
- $\rho$ cross section vs energy for different $Q^2$




- The rise of the cross section with the energy becomes faster with increasing $Q^2$ as expected in pQCD

## Intermediate and high $Q^2$ region

- $\phi$ cross section vs. energy for different $Q^2$



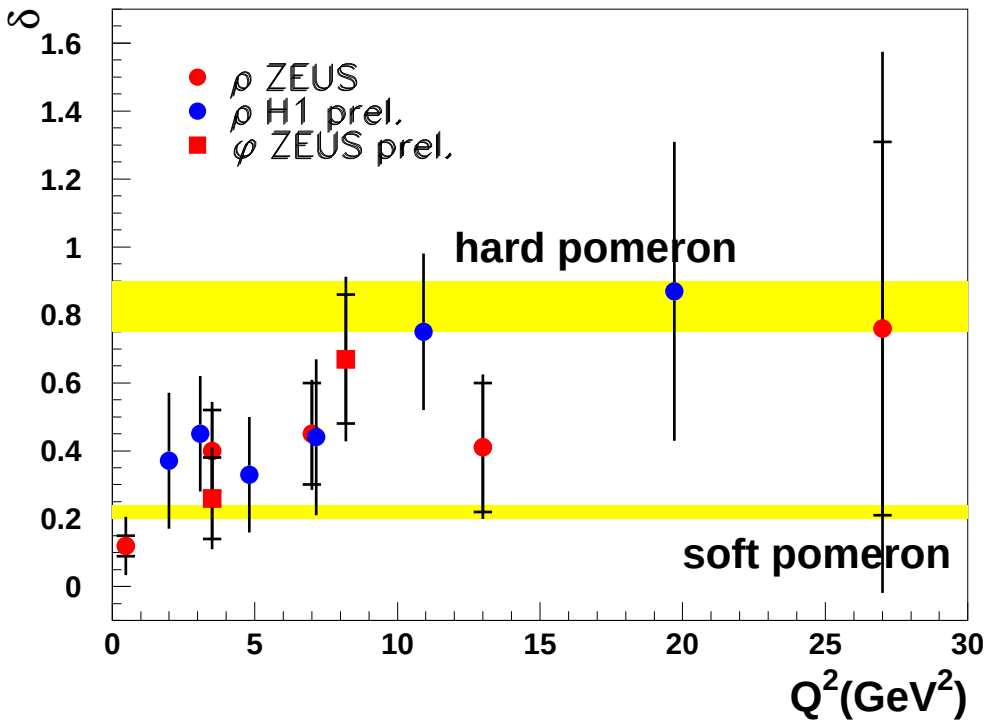

- W dependence consistent with that observed in exclusive $\rho$ electroproduction

## Intermediate and High $Q^2$ Region

- $\rho$ cross section vs. energy for different $Q^2$

ZEUS and H1: measure of the energy dependence of the cross section within one experiment

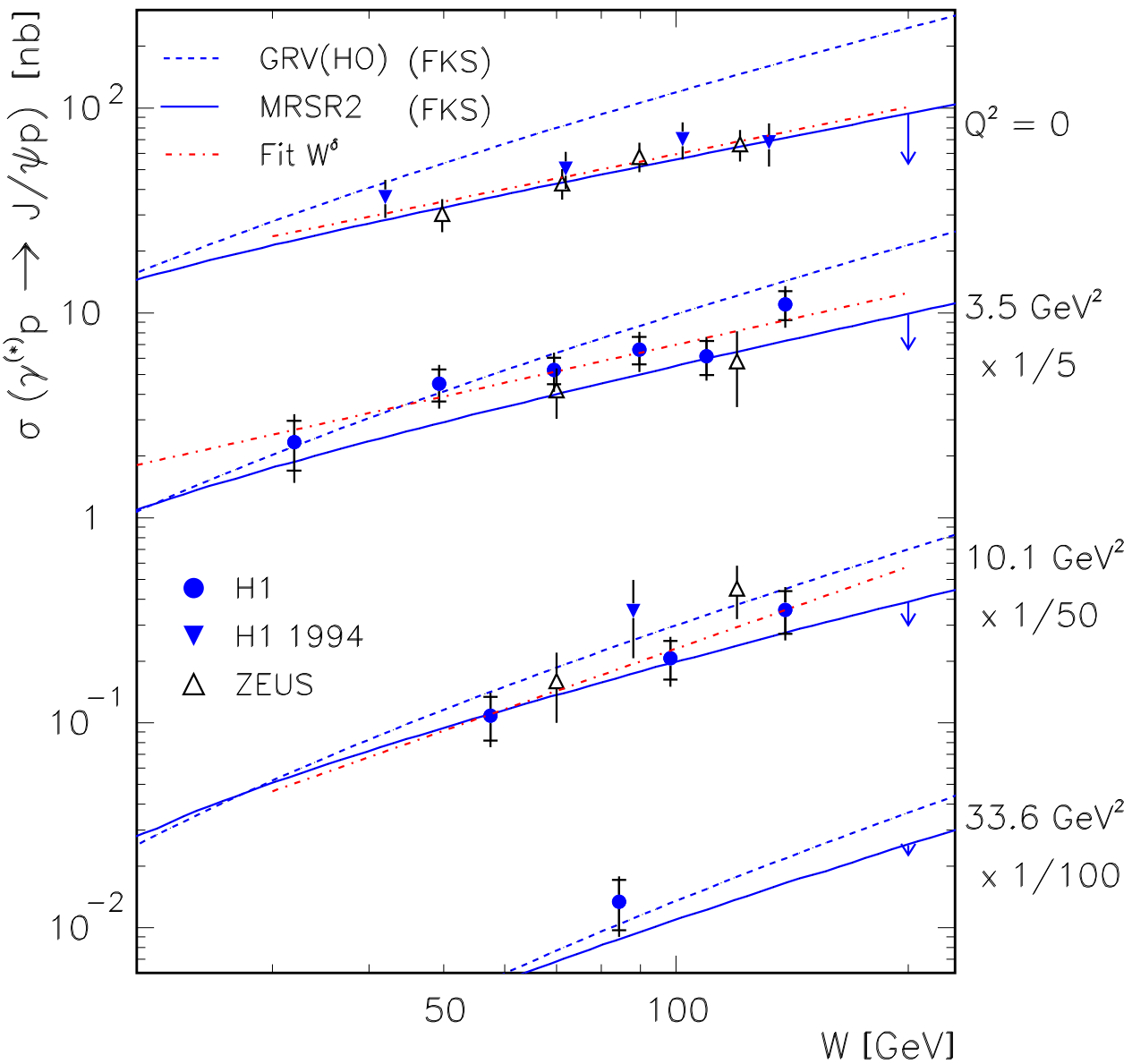
Fit: $\sigma_{\gamma^* p \to \rho p} \propto W^{\delta}$




- At high $Q^2$ the rise of the cross section with the energy is compatible with an *hard pomeron* exchange as seen in $J/\psi$ photoproduction

# Electroproduction

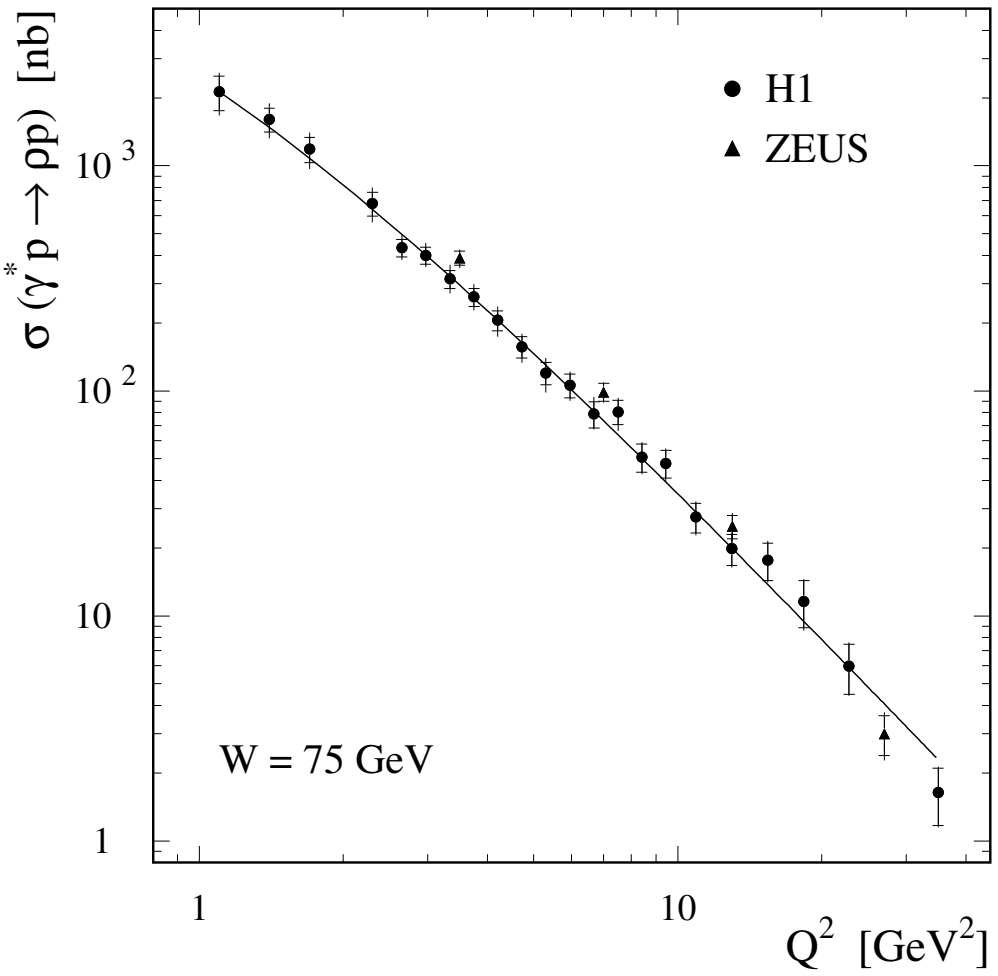
- J/$\psi$ cross section vs energy for different $Q^2$




- The $W$ dependence at fixed $Q^2$ is found to be similar to that at $Q^2 = 0$ GeV$^2$ as expected in pQCD

# Electroproduction

- $\rho$ cross section vs $Q^2$ for fixed $W$ value




- Cross-section dependence on $Q^2$ described by:

$$\sigma_{\gamma^* p \to \rho p} \propto 1/(Q^2 + M_\rho^2)^n$$

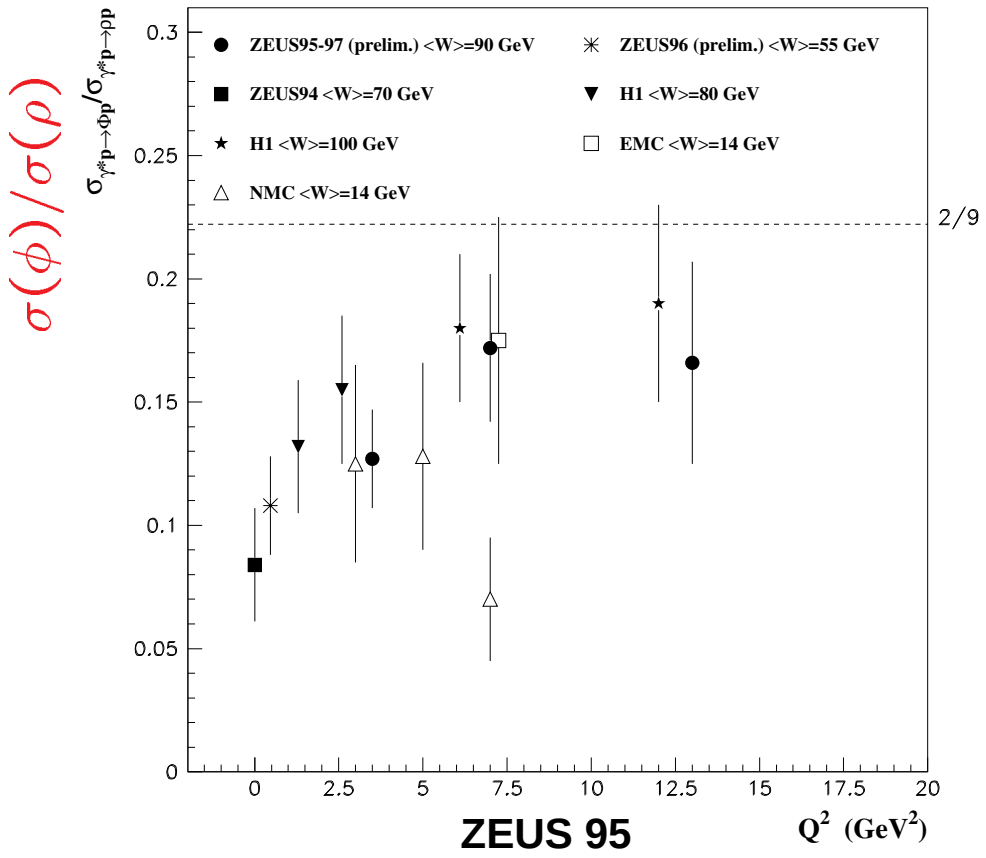
The fit yelds $n = 2.24 \pm 0.09$

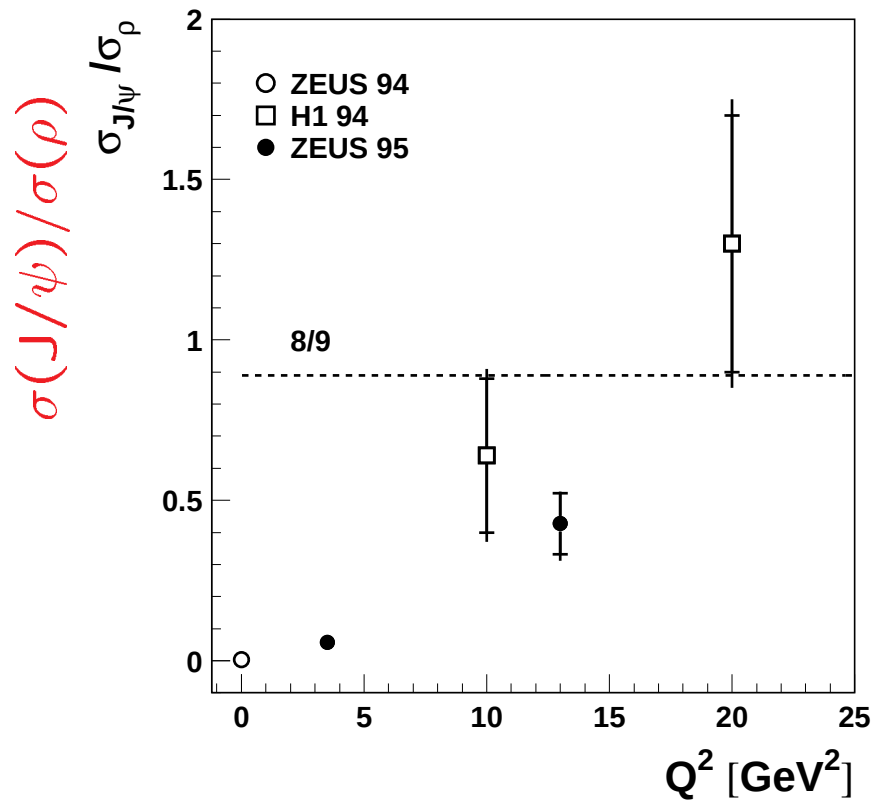
- Similar results for $\phi$ and for $J/\psi$

## VM Production Ratios vs $Q^2$

If direct EM coupling of $\gamma$ to quarks without form factor

$$\rho \ : \ \phi \ : \ J/\psi \ = \ 9 \ : \ 2 \ : \ 8$$



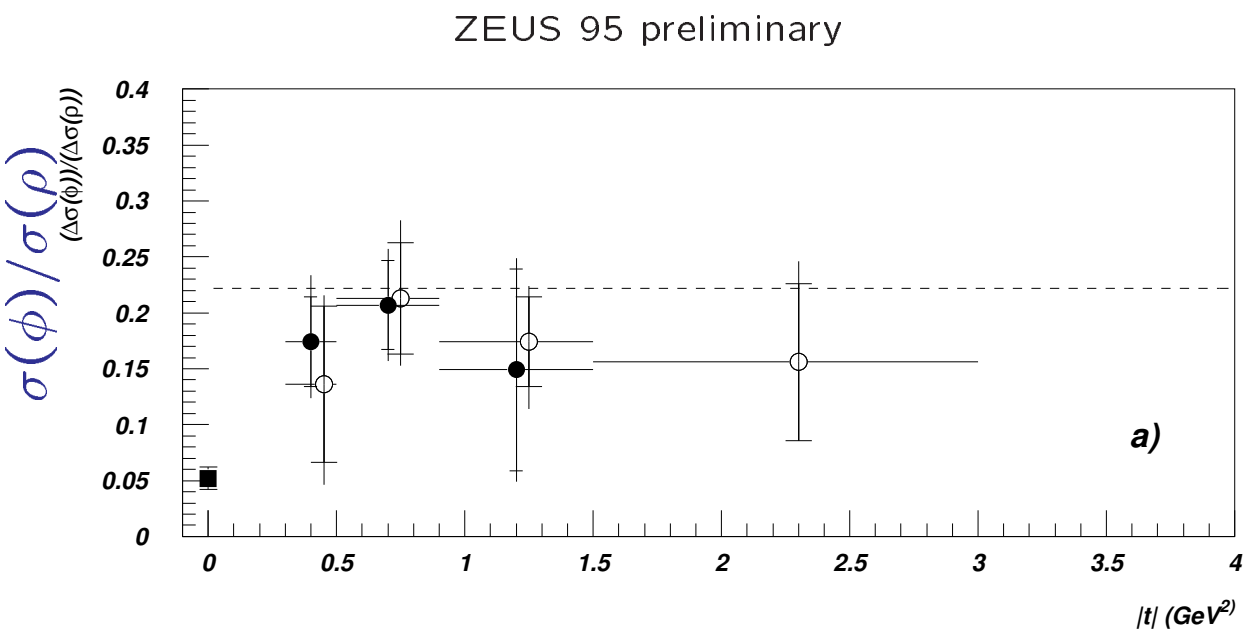



# High $|t|$ Photoproduction

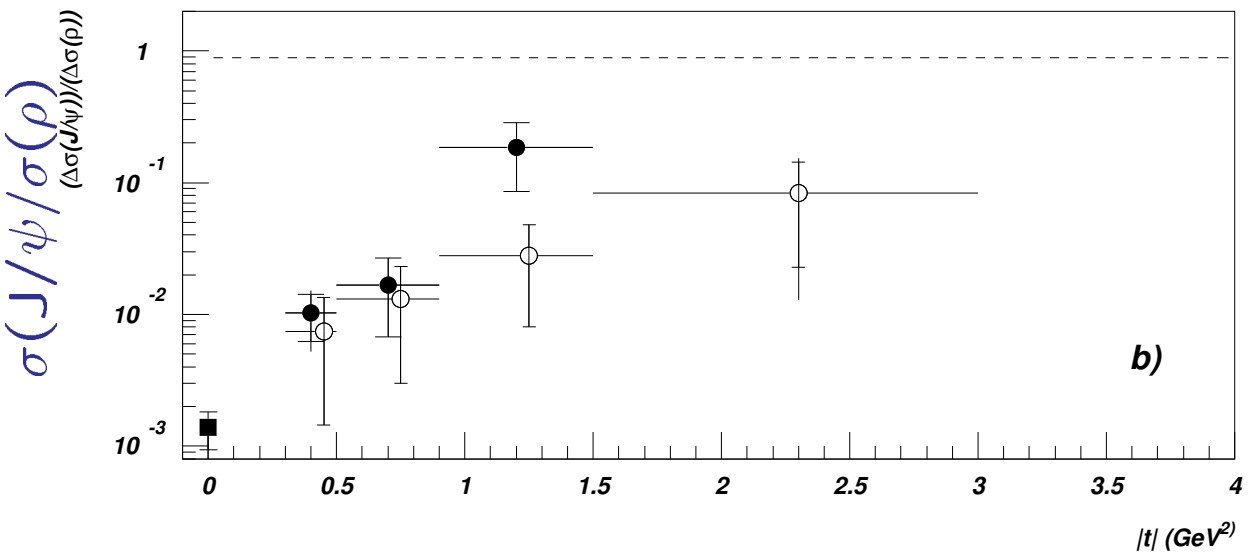
- VM production ratios

If direct EM coupling of $\gamma$ to quarks without form factor

$$\rho \ : \ \phi \ : \ J/\psi \ = \ 9 \ : \ 2 \ : \ 8$$




$\Rightarrow$ 2/9



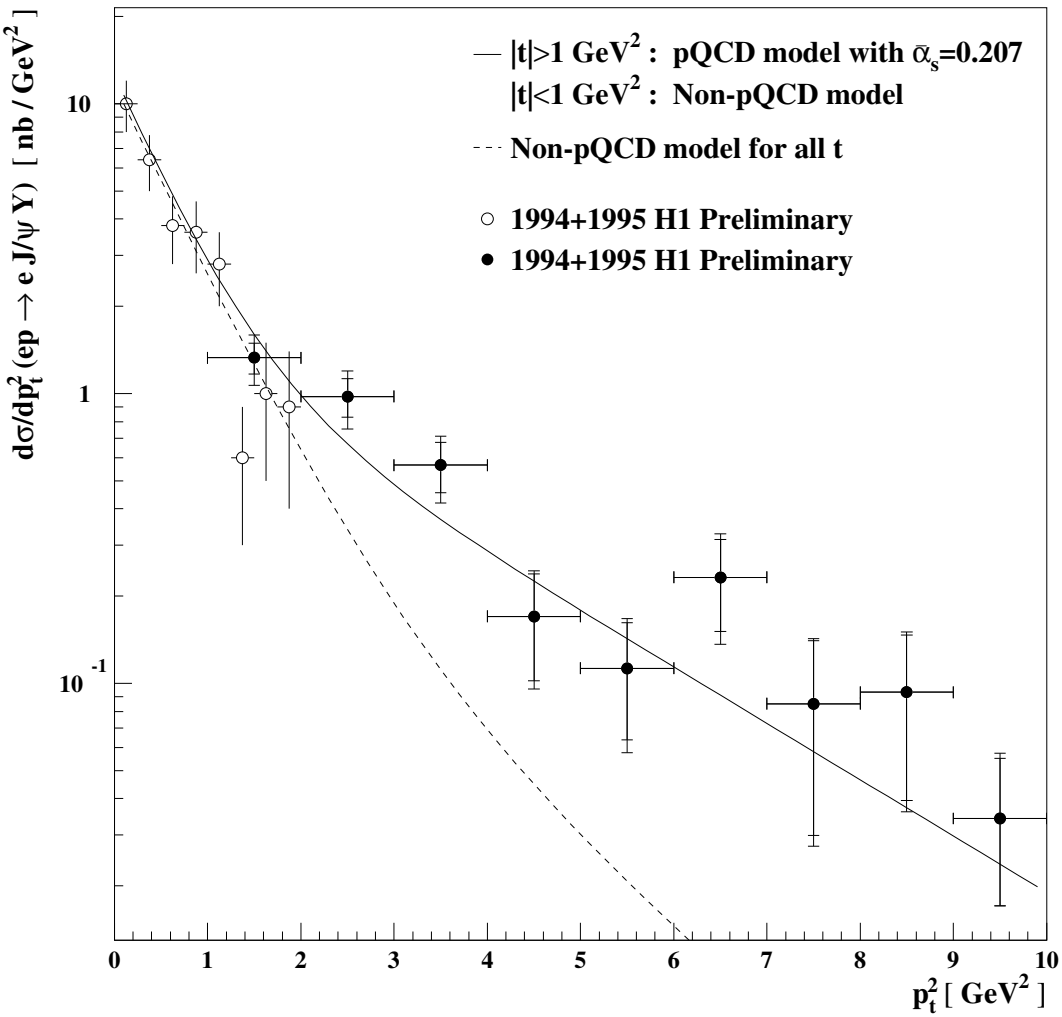

$\Rightarrow$ 8/9

Evidence for $|t|$ providing a hard scale approach flavour independent values

$\Rightarrow$ pQCD expectations

# High $|t|$ Photoproduction

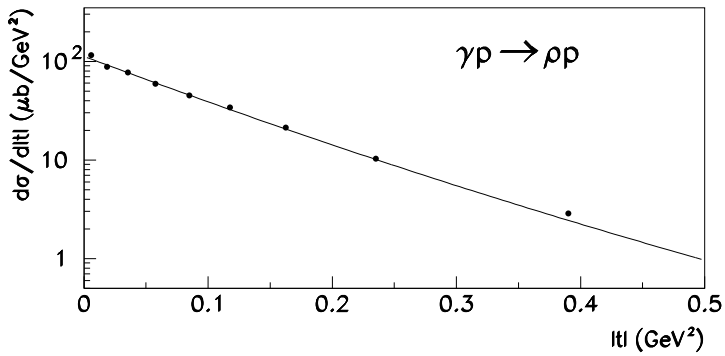
- $J/\psi$ cross section vs $t$




- pQCD model (Bartels et al.) describes well $t$ dependence

## $t$-slope vs $M^2_{VM}$

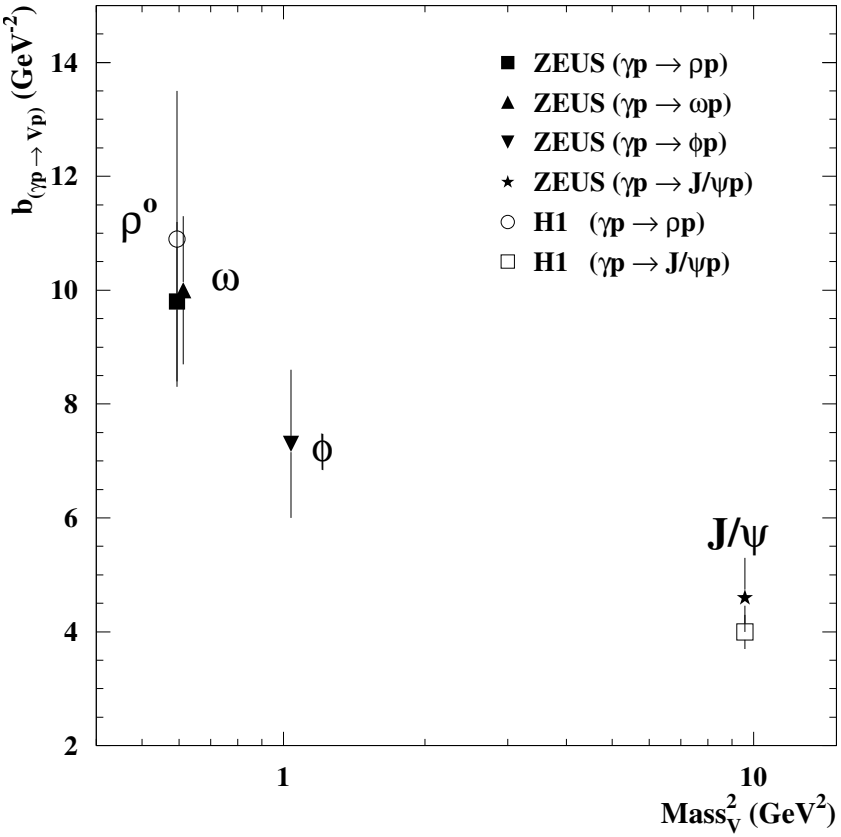
Exponential fall characteristic of diffractive processes




$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

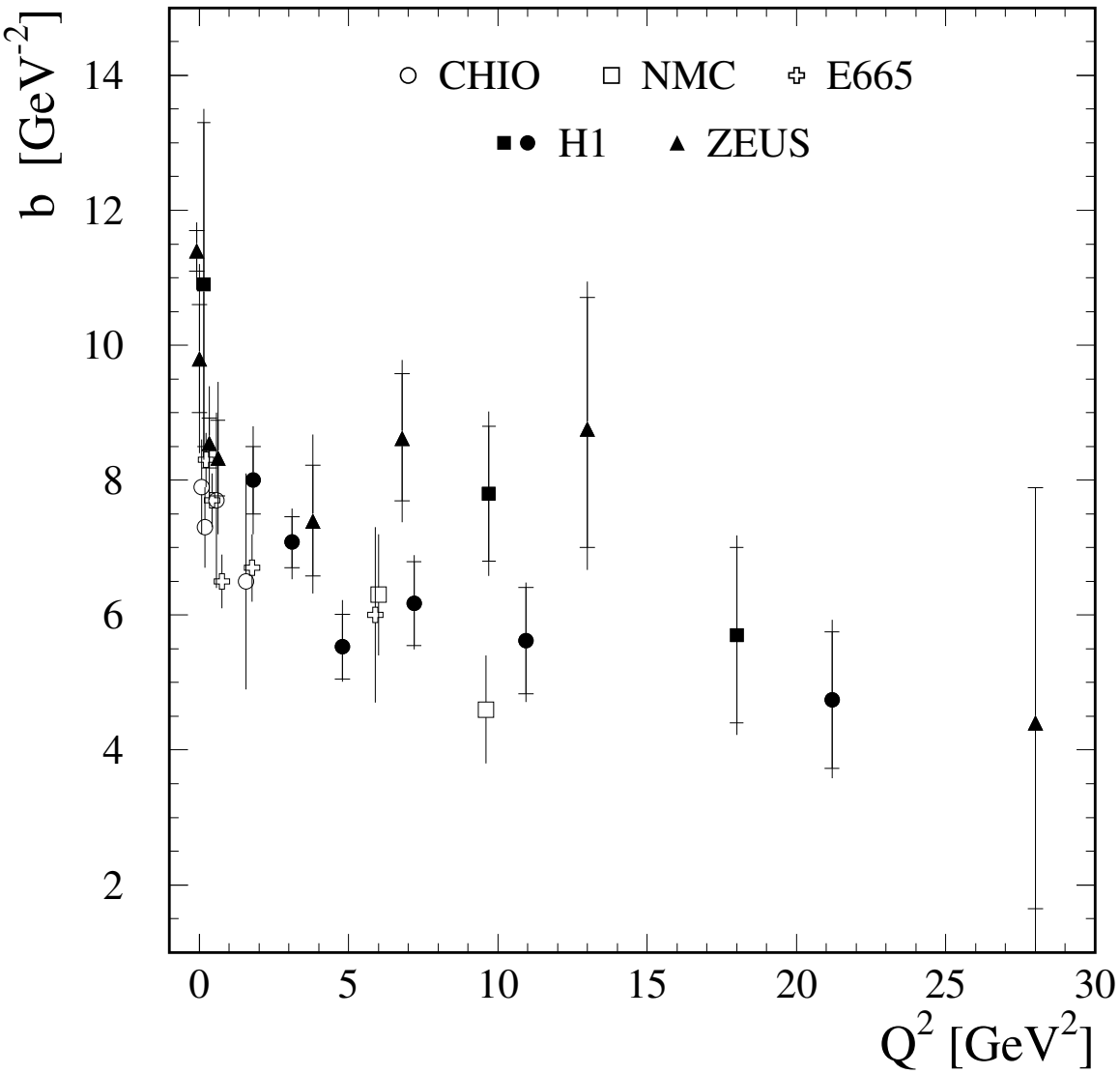
similarity with diffraction of light by a circular aperture $\rightarrow b \propto R^2$

$b$ related to transverse size of the interaction




- J/$\psi$ radius smaller than $\rho$, $\omega$ and $\phi$ radius

## $t$-slope for $\rho$ Mesons vs $Q^2$




$\Rightarrow$ $\rho$: $b$ decreases with increasing $Q^2$

No strong dependence on $Q^2$ for J/$\psi$

# Energy Dependence of the $t$-Slope

- QCD: the $t$ distribution is energy independent

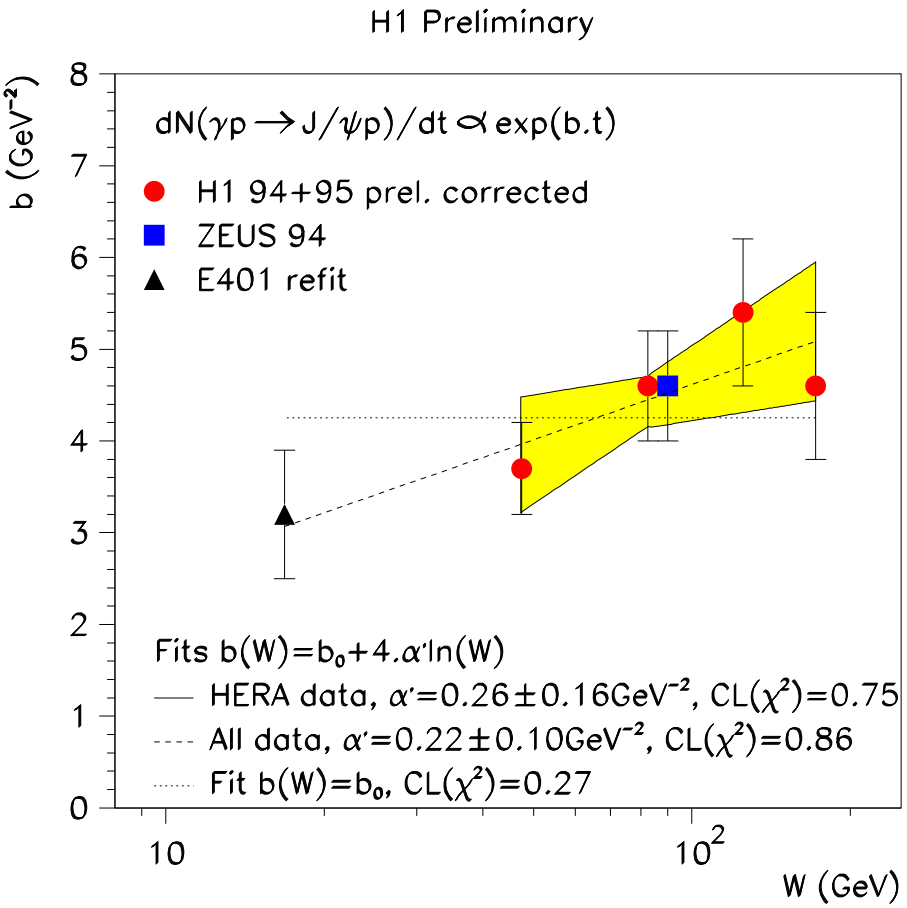
$\Rightarrow$ almost no shrinkage of the forward diffractive peak

- Regge phenomenology: $\frac{d\sigma}{dt} \sim f(t) \cdot W^{2\cdot(2\alpha(t)-2)}$

Assuming $f(t) \sim e^{-b|t|}$ and $\alpha(t) = \alpha_0 + \alpha\prime \cdot t$

$$\frac{d\sigma}{dt} \sim e^{-b|t|}, \quad b = b_0 + 2\alpha\prime \cdot \log(\frac{W}{W_0})^2$$

$\alpha(t) = 1.08 + 0.25 \cdot t$ (DL) $\Rightarrow$ shrinkage




$\Leftarrow$ J/$\psi$

Fit to the

H1+ZEUS+E401 data:

$b = b_0 + 2\alpha'_{I\!P} ln W^2$

$\alpha'_{I\!P} = 0.22 \pm 0.10$ GeV$^{-2}$

- The data indicate that shrinkage may be present but are not conclusive

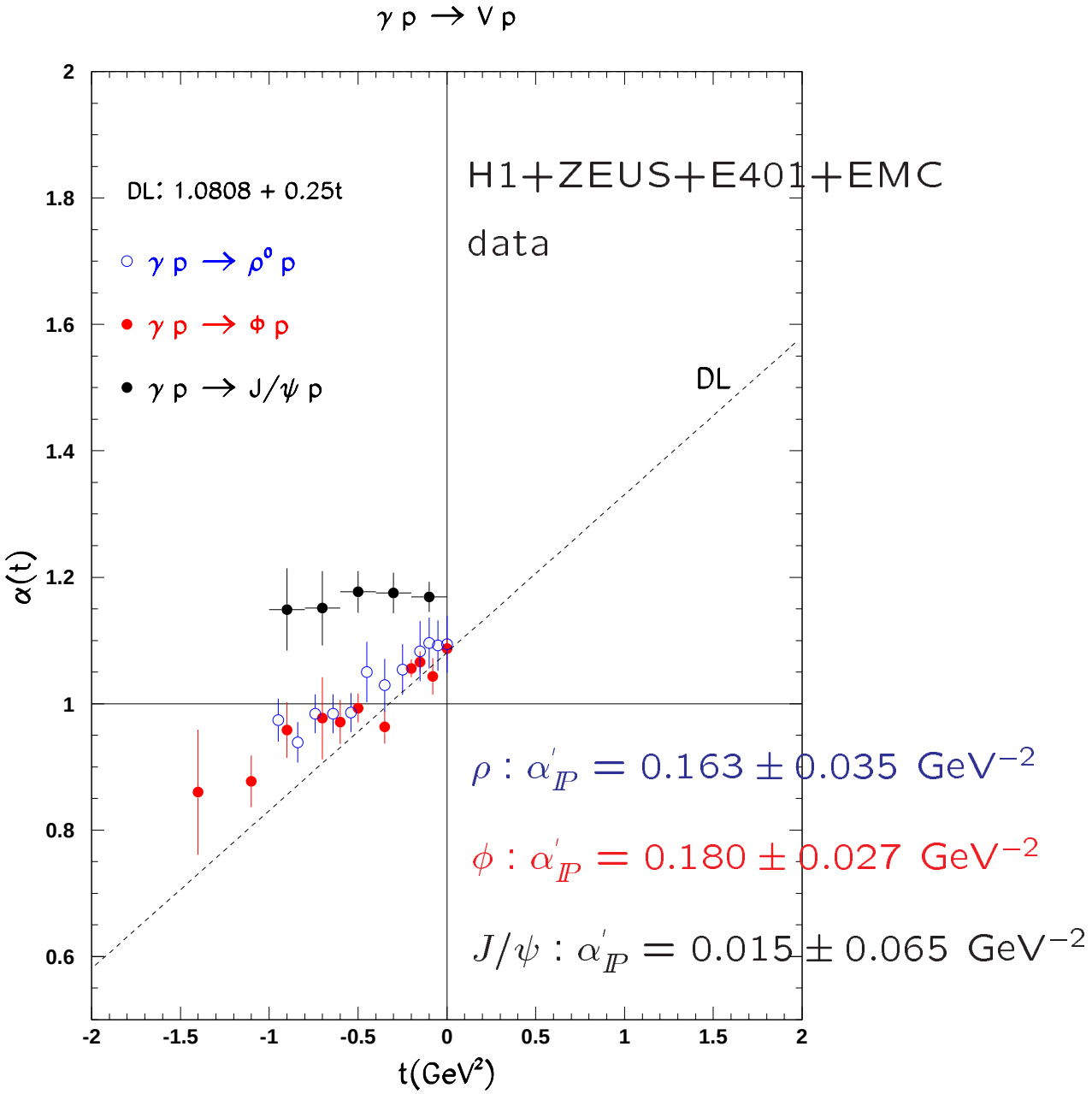
# Energy Dependence of the $t$-Slope

Determination of the trajectory (A.Levy):

Study the $W$ dependence of $d\sigma/dt$ at fixed $t$

$$d\sigma/dt = f(t)(W^2)^{[2\alpha_{I\!P}(t)-2]}$$

fit a linear trajectory $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} \cdot t$

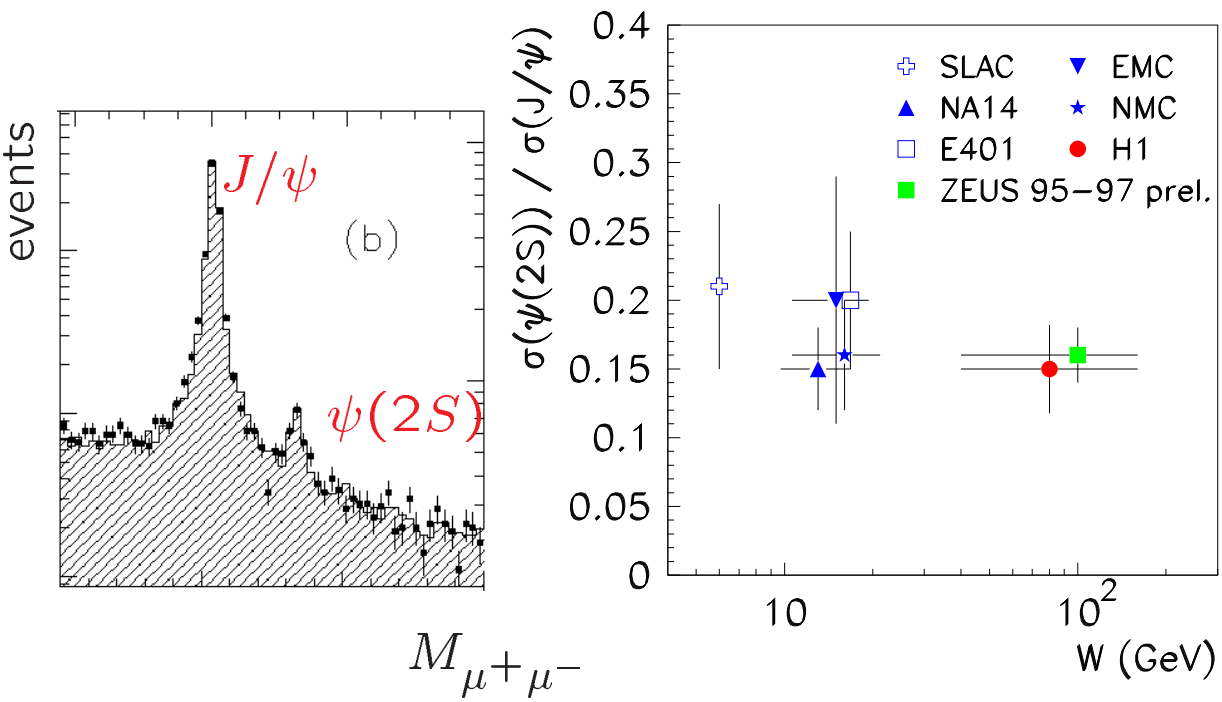



▶ The data indicate that the Pomeron trajectory is not universal

## Elastic $\psi(2S)$ Photoproduction

The ratio $R = \frac{\sigma_{\gamma p}(\psi(2S))}{\sigma_{\gamma p}(J/\psi)}$ is sensitive to the radial wave function of the charmonium

QCD prediction: $R = 0.17$

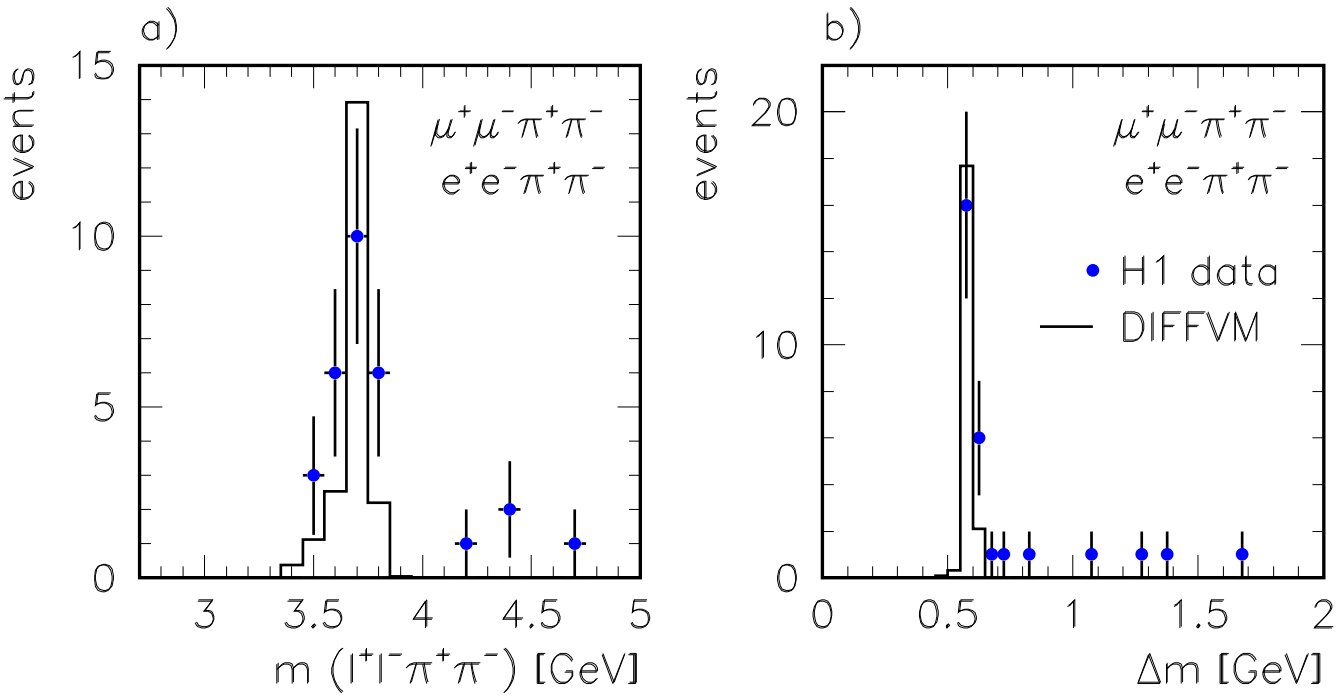


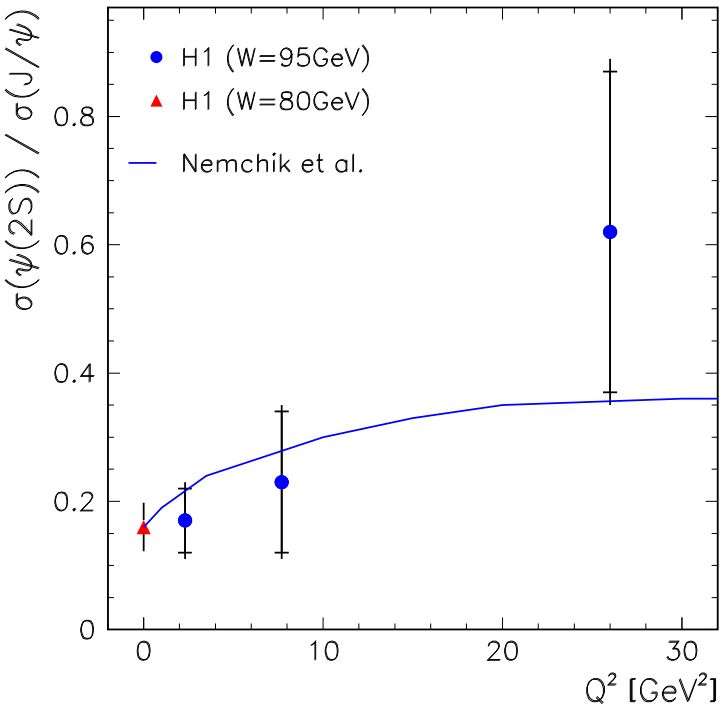

$R = 0.16 \pm 0.02 \pm 0.04 \quad 40 < W_{\gamma p} < 160$ GeV

- No significant dependence on $W_{\gamma p}$

# Elastic $\psi(2S)$ Electroproduction

$\psi(2S) \to J/\psi\pi^+\pi^-$ $\quad BR = (32.4 \pm 2.6)\%$

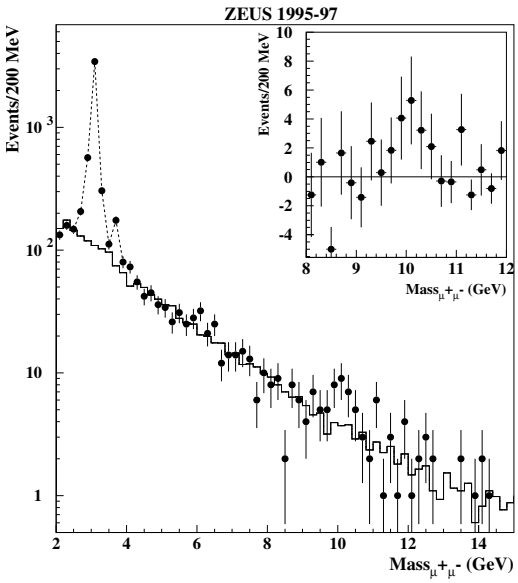


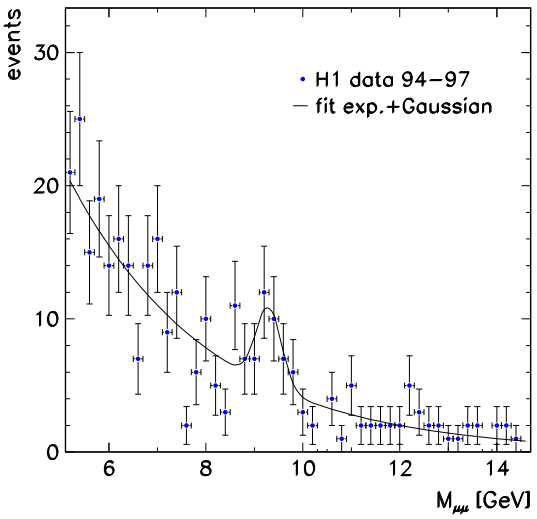




- Agreement between photoproduction (H1 and ZEUS prel.) and result at low $Q^2$
- Indication for a rise with $Q^2$, compatible with QCD

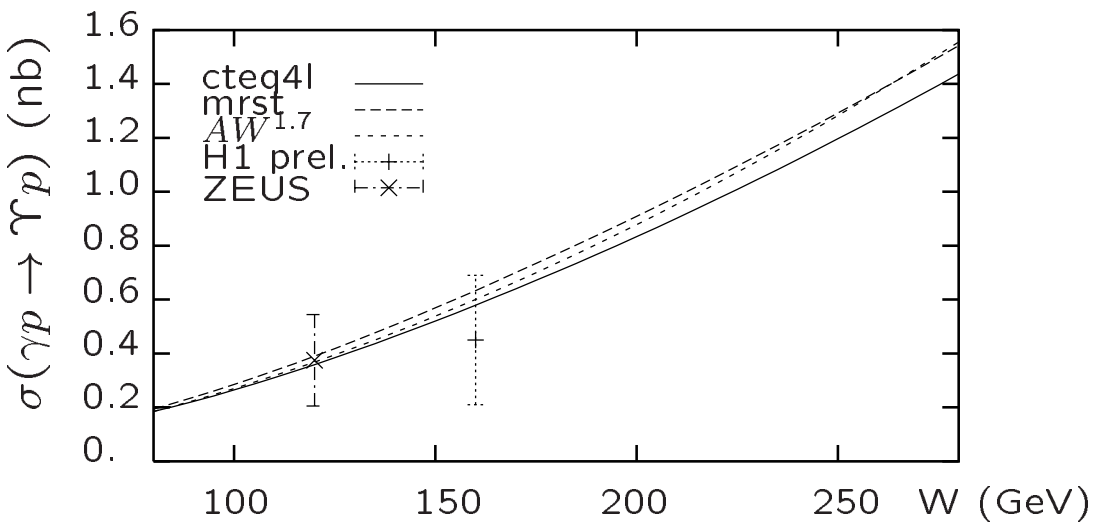
# Elastic $\Upsilon$ Photoproduction

ZEUS $\int \mathcal{L} \simeq 43\ pb^{-1}$ H1 $\int \mathcal{L} \simeq 35\ pb^{-1}$



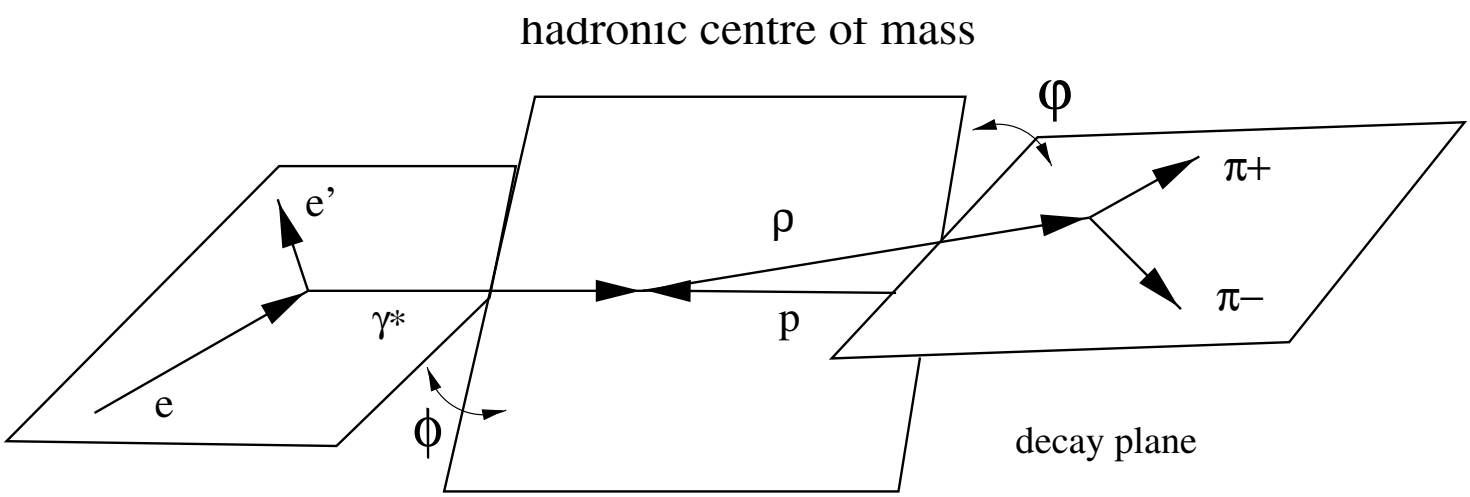



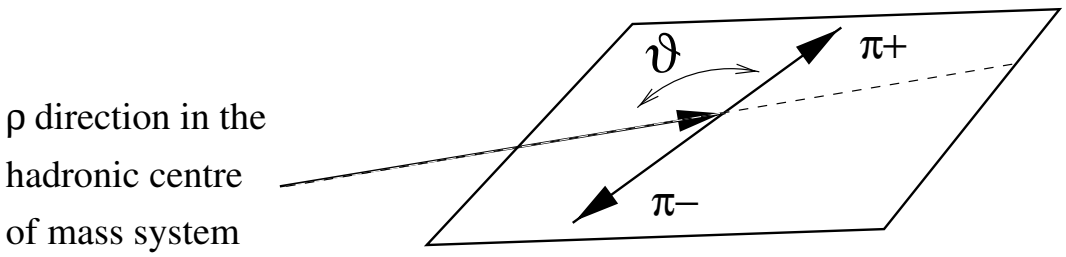

- $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$ cannot be resolved
- Observed mass spectrum consistent with $\simeq 70\%$ contribution from $\Upsilon(1S)$ as observed elsewhere
- Background from $\gamma\gamma \to \mu^+\mu^-$ subtract using MC (ZEUS) or fit (H1)




- Described by pQCD models

# Decay Angular Distribution




Helicity angles:

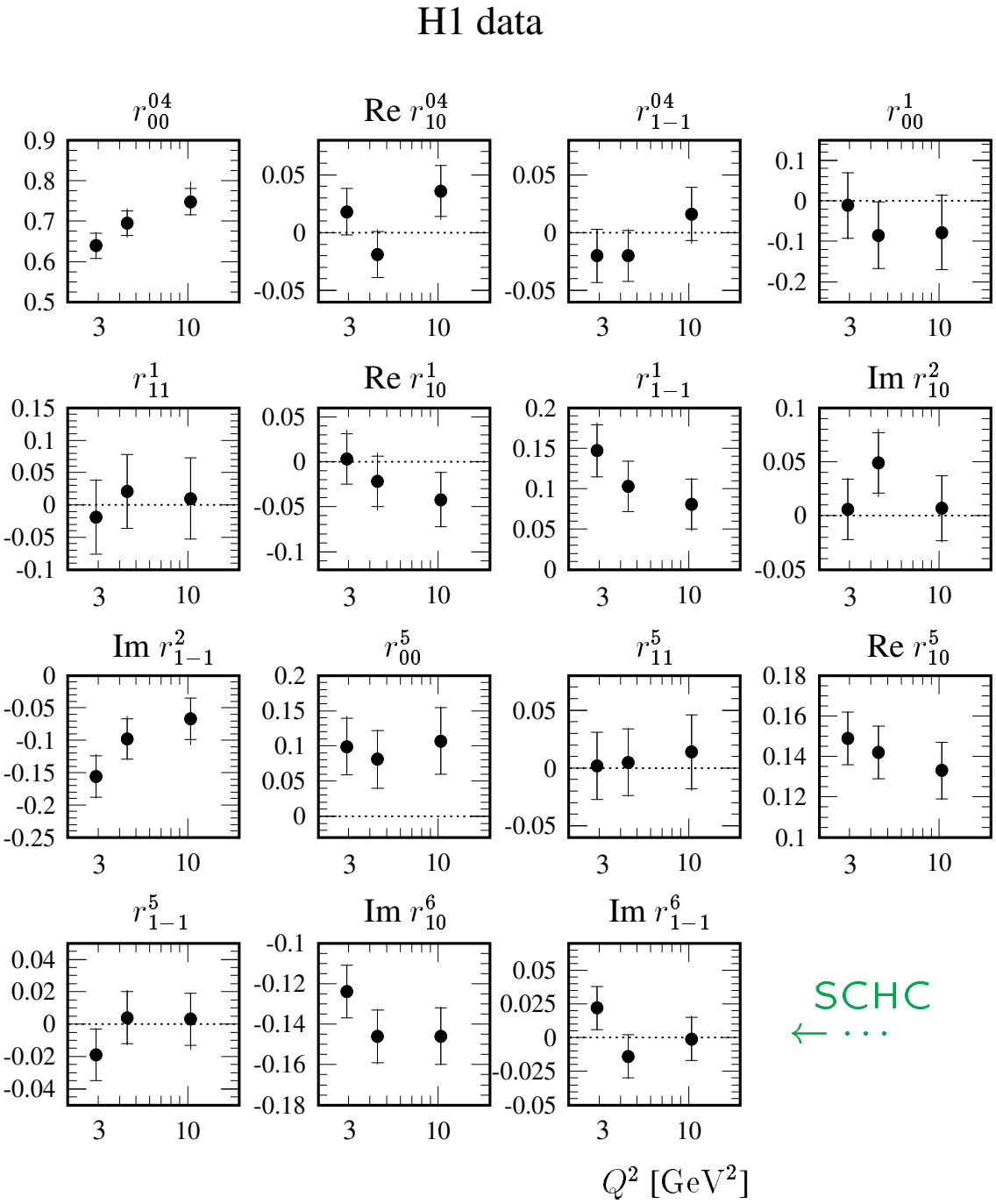
$(\theta_h, \phi_h)$ - polar and azimuthal angles of decay particle in the helicity frame (meson rest frame)

$\Phi$ - angle between scattering and production plane

Analysis of the helicity angles $\rightarrow$ information on $\gamma^*$ and meson helicity states

# Electroproduction of $\rho$

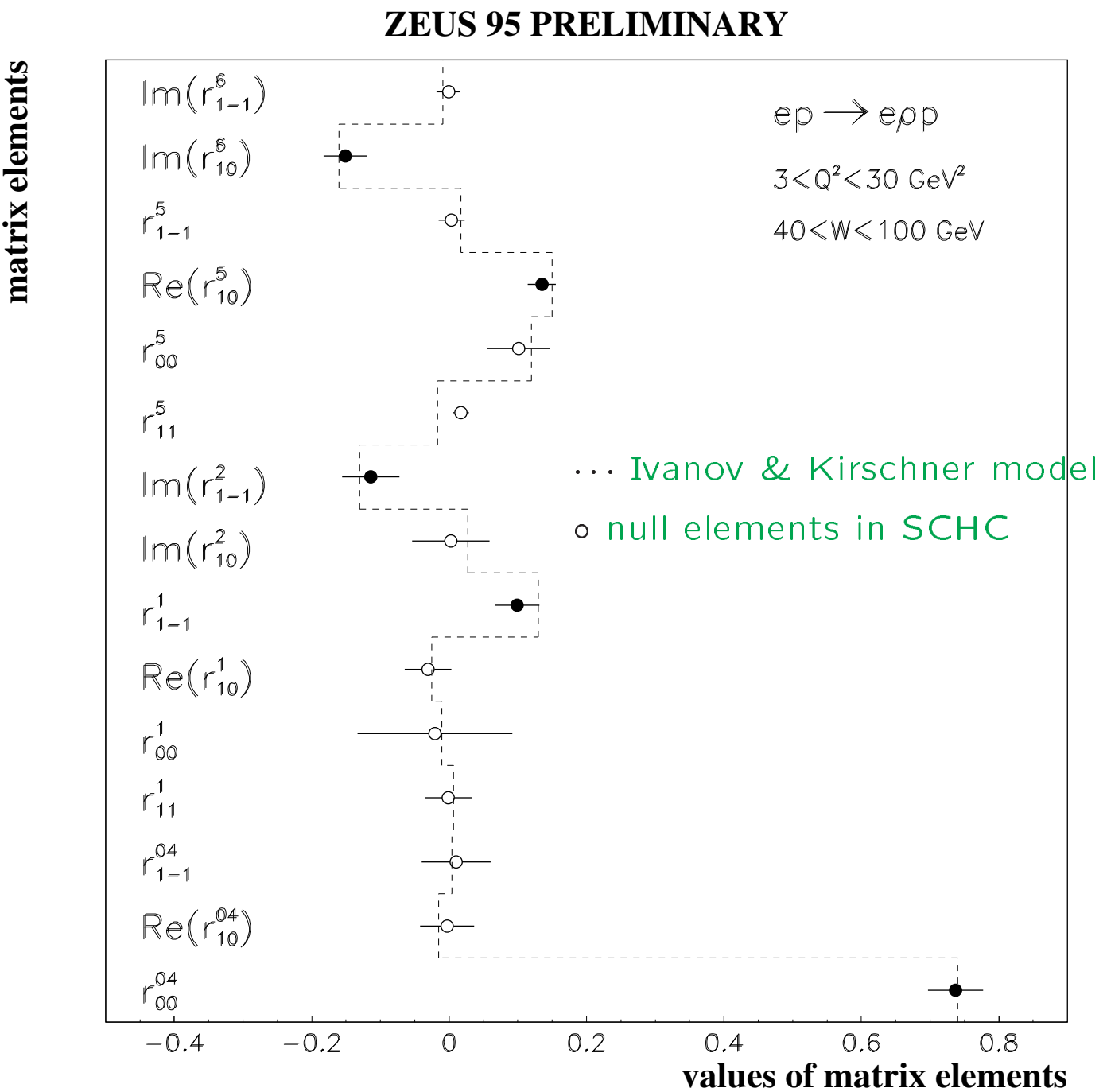
- Spin density matrix elements




- Deviation from SCHC on $r^5_{00}$

# Electroproduction of $\rho$

- Spin density matrix elements

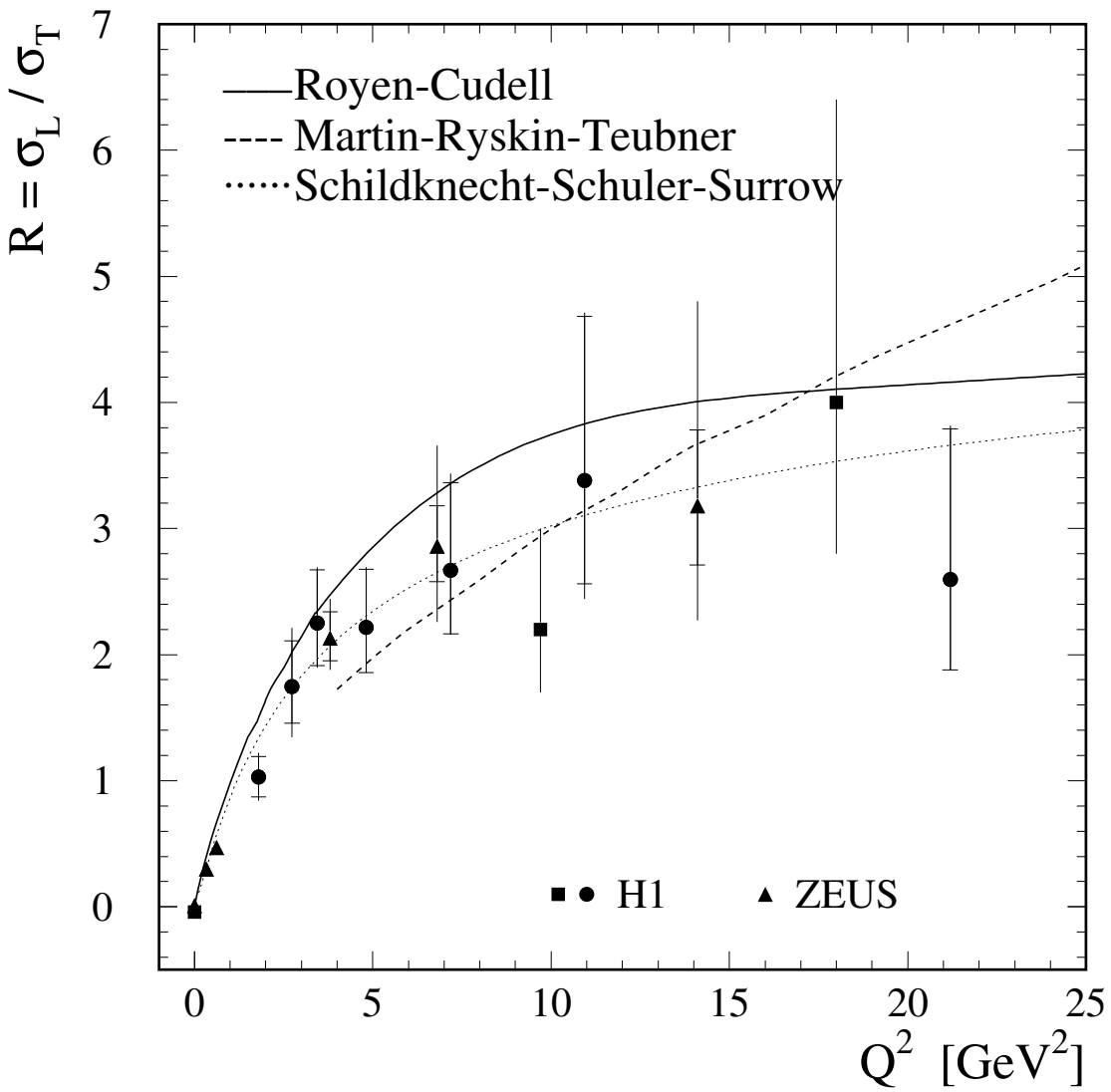



- Deviation from SCHC on $r^5_{00}$
- Good agreement between data and QCD calculation

# R from Decay Angular Distribution

- $R = \sigma_L/\sigma_T$ vs $Q^2$

Assume SCHC: $R = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}}$




- the increase of $R$ with $Q^2$ is not described by *conventional* VDM ($R = \xi_V Q^2/M_V^2$)
- QCD or GVDM models describe the data

## Summary

Wealth of precise and interesting data spanning between soft and hard regimes of diffraction

- Evidence increase that indeed for the diffractive meson production at HERA the hard scale can be given either by meson mass, or by $Q^2$ or $|t|$. At these large scales the meson diffraction seems to proceed in similar, approximately flavour independent fashion, in accord with expectations of pQCD.

$\Rightarrow$ Coherent picture of diffraction is emerging and may provide valuable information on the proton and on the meson structure.