Recent ZEUS results on Vector Mesons

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on behalf of

ZEUS

Collaboration

DIFFRACTION 2004
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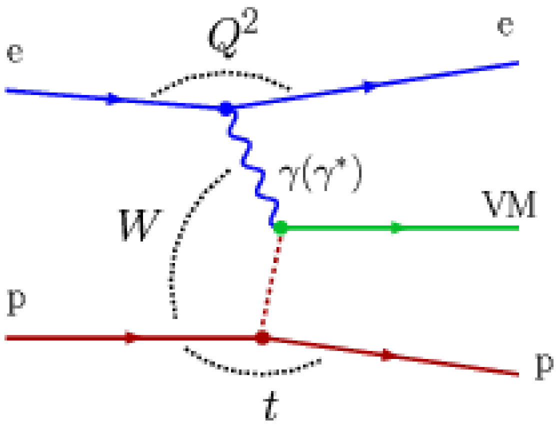
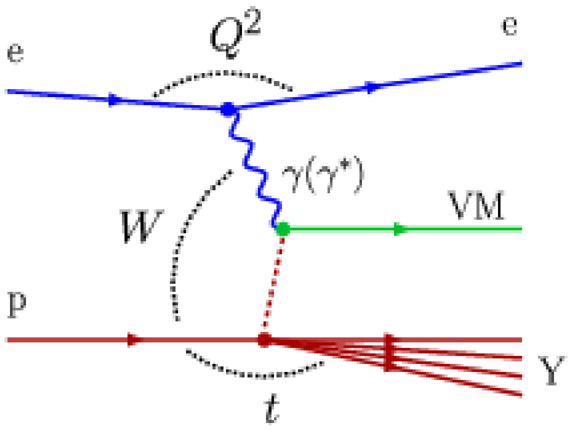
Diffractive Vector Meson production at HERA

HERA (DESY): collisions of 27.5 GeV e with 920 GeV p $(\sqrt{s} = 318 \text{ GeV})$



$\gamma^* p \to V\ p$

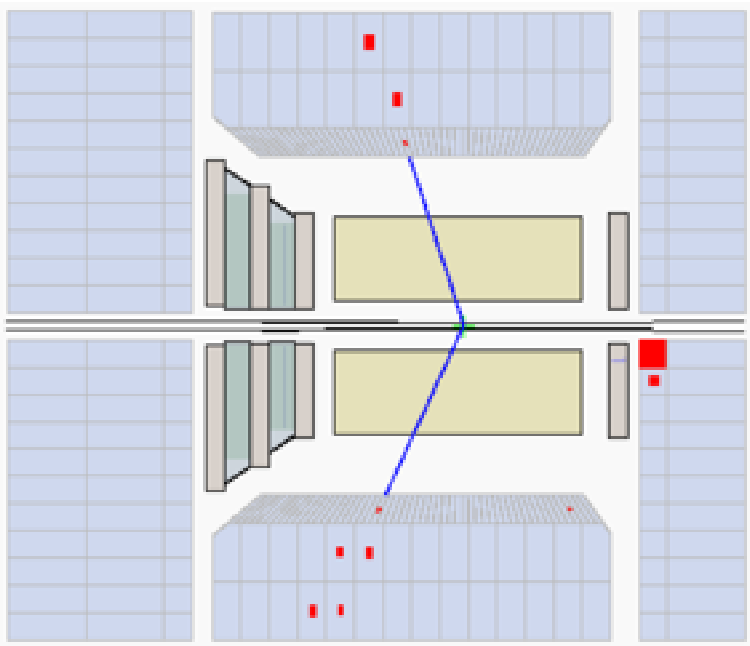
exclusive



$\gamma^* p \to V\ Y$

proton dissociative

VM:	Vector Meson	$\rho,\ \omega,\ \phi,\ J/\psi,\ \psi(2S),\ \Upsilon$
Q^2:	(4-mom transfer)^2 at the electron vertex (photon virtuality)	$0 < Q^2 < 100$ GeV^2
W:	CM energy of the $\gamma^* p$ system $(x = Q^2/W^2)$	$20 < W < 290$ GeV
t:	(4-mom. transfer)^2 at the proton vertex	$0 < \lvert t\rvert < 30$ GeV^2



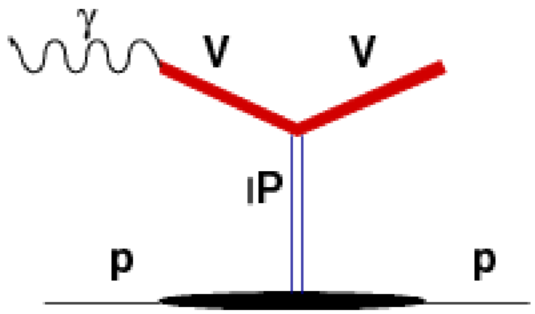
Experimentally clean process in a wide kinematic range

Motivation

Increased precision of recent data allows to:

- Study the VM dynamics within QCD
  - ⇒ Test QCD in the transition region: soft → hard
  - ⇒ Given factorisation:
    - ∗ Test pQCD
    - ∗ Measure non-perturbative quantites (gluon PDFs)

Soft production mechanism



Phenomenological description (hadron level):

- Photon fluctuates into the Vector Meson ($\gamma^* \to V$)
- VM interacts with the proton by the soft Pomeron exchange ($Vp \to Vp$, elastic interaction)

VDM+Regge Theory

soft Pomeron: $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} \cdot t$

$\alpha_{I\!P}(0) = 1.08, \alpha'_{I\!P} = 0.25$ GeV^{-2}

$$d\sigma/dt \propto e^{b_0 t}(W/W_0)^{4(\alpha_{I\!P}(t)-1)}$$

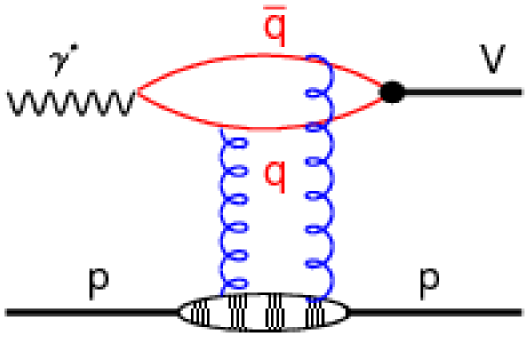
Expectations:

- Slow rise of the cross section with energy: $\sigma(W) \simeq W^{\delta}$, $\delta \simeq 0.22$
- Shrinkage of the diffractive peak with energy ($b \propto R_p^2 + R_V^2$):

$$d\sigma/d|t| \propto e^{-b(W)|t|} \qquad b(W) = b(W_0) + 4\,\alpha'_{I\!P} \ln(W/W_0) \qquad b(W_0) \approx 10 \text{ GeV}^{-2}$$

- s-channel helicity conservation (SCHC): $\gamma^*_L \to V_L$, $\gamma^*_T \to V_T$

Hard production mechanism



Two-gluon exchange (LO)

(for small size of $q\bar{q}$ pair : γ^* or $V = c\bar{c}$ or $b\bar{b}$)

QCD picture (parton level):

- Photon fluctuates into $q\bar{q}$ pair ($\gamma^* \to q\bar{q}$)
- $q\bar{q}$ pair interacts with the proton by the two-gluon exchange ($q\bar{q} - p$)
- $q\bar{q}$ pair forms the vector meson ($q\bar{q} \to V$)

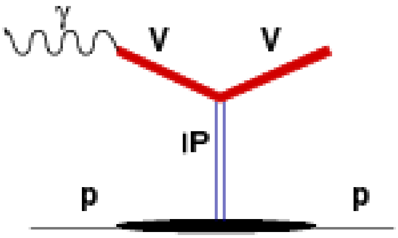
$$\sigma_L \propto \alpha_S(\bar{q}^2)[xg(x, \bar{q}^2)]^2/Q^6$$

Expectations:

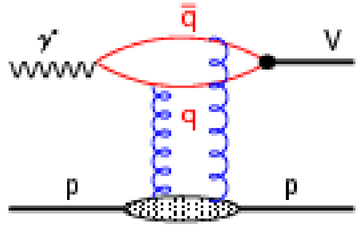
- Steep rise of the cross section with energy: $\sigma(W) \simeq W^\delta, \delta \simeq 0.7$ (gluon density rises at low x)
- Universal t dependence: $d\sigma/d|t| \propto e^{-b|t|}$, $b_{2g} \approx 4 - 5$ GeV^{-2} (gluon cloud of the proton)
- Little shrinkage (b dependence on W): $\alpha'_{\mathbb{P}} \simeq 0$
- Restoration of SU(4) flavour symmetry: $\sigma_\rho : \sigma_\omega : \sigma_\phi : \sigma_{J/\psi} = 9:1:2:8$

Hard scale provided by $Q^2,\ M_V^2,\ t$ $\qquad f(Q^2, M_V^2, t)$?

Transition from soft to hard at HERA



$\Rightarrow$

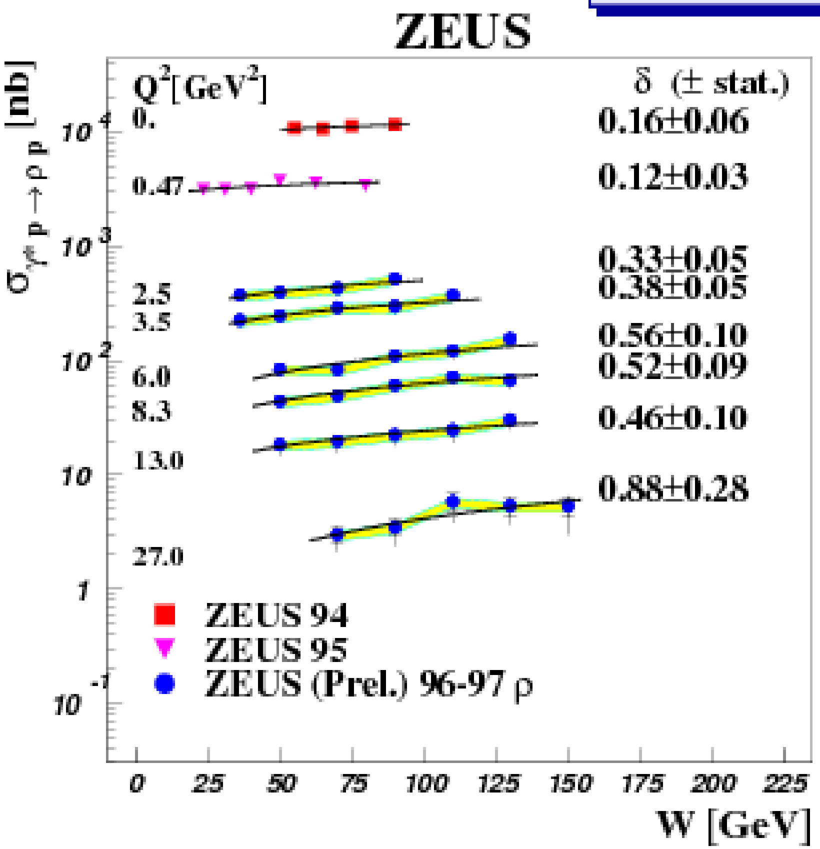


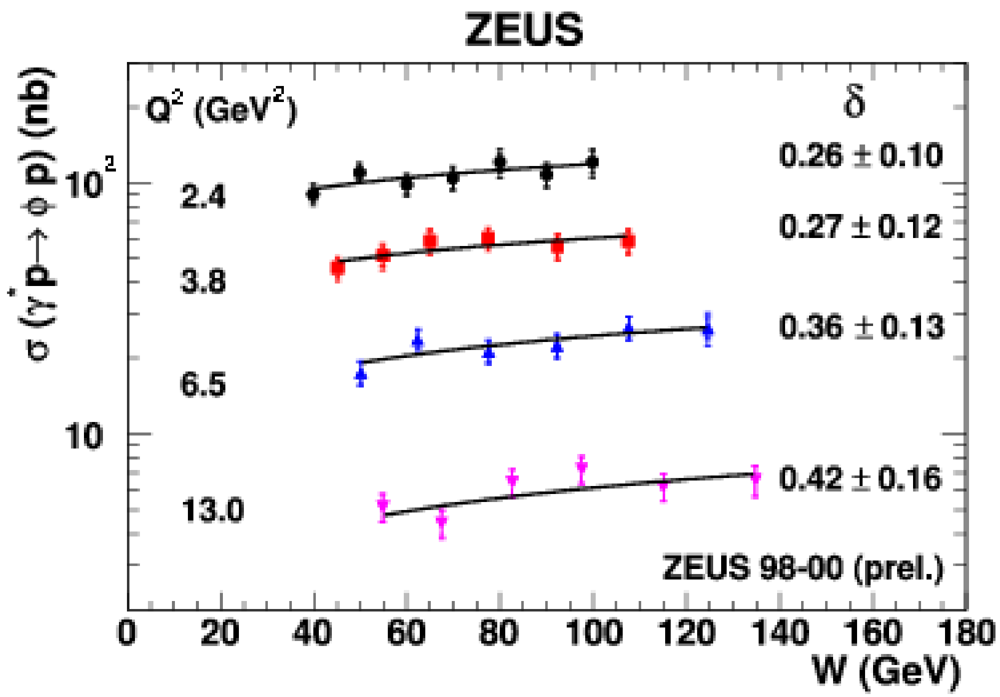
Soft		Scale:	Hard	
VDM+Regge			pQCD	
$\sigma \propto W^{\delta}$	$\delta \approx 0.2$		$\sigma \propto W^{\delta}$	$\delta \approx 0.7$
$\frac{d\sigma}{d\|t\|} \propto e^{-b\|t\|}$	$b \approx 10$ GeV^{-2}		$\frac{d\sigma}{d\|t\|} \propto e^{-b\|t\|}$	$b \approx 4-5$ GeV^{-2}
$\alpha_{I\!P}(t), b(W)$	$\alpha'_{I\!P} \approx 0.25$ GeV^{-2}		$\alpha_{I\!P}(t), b(W)$	$\alpha'_{I\!P} \ll 0.25$ GeV^{-2}
light VM	$(\rho,\ \omega,\ \phi)$	M_V	heavy VM	$(J/\psi, \psi(2S),\ \Upsilon)$
$Q^2 \approx 0$	(photoproduction)	Q^2	high Q^2	(DIS, electroproduction)
low $\|t\|$	$(\gamma p \to Vp)$	t	high $\|t\|$	$(\gamma p \to V\ Y)$

Exclusive VM production

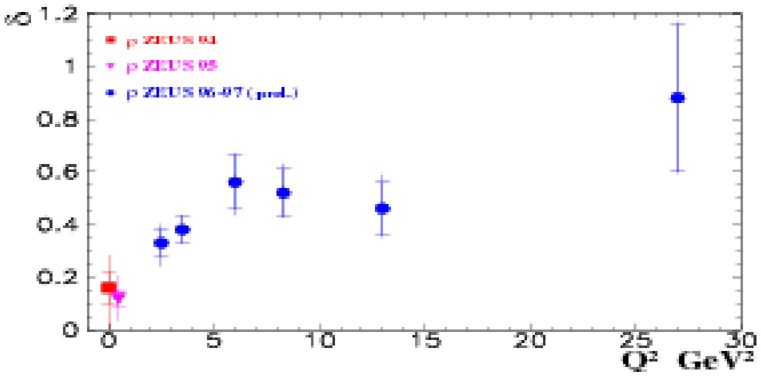
- Transition (soft $\rightarrow$ hard) with Q^2 and M_V^2
- Comparison with pQCD models (J/ψ electroproduction: σ vs W, Q^2)
- Transverse size of the interaction (σ vs t)
- Pomeron trajectory
- Universality of VM production
- Transverse and longitudinal cross sections ($R = \sigma_L/\sigma_T$)

ρ, ϕ electroproduction (scale: Q^2)





$\Leftarrow$ $\gamma^* p \to \rho\, p$ $\qquad$ $\gamma^* p \to \phi\, p$



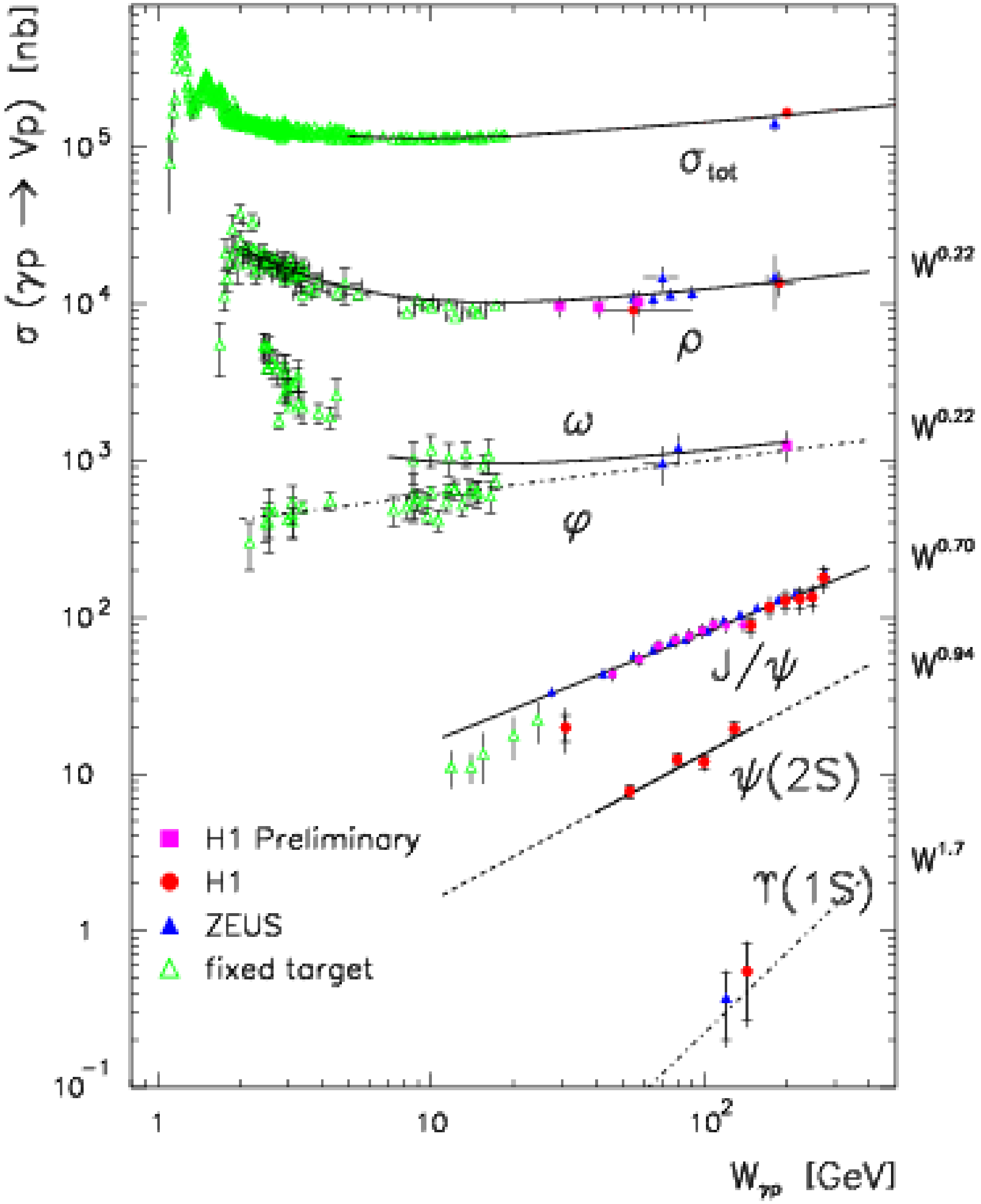
Fits with W^δ at different values of Q^2

- δ rises with Q^2 (transition 'soft' $\to$ 'hard')

  $\Rightarrow$ Q^2 provides hard scale

(pQCD: $\sigma \propto |xg(x,Q^2)|^2,\ x \propto 1/W^2$)

VM photoproduction (scale: M^2)



Fits with W^{δ}

$\Leftarrow$ ρ, ω, ϕ:

$\delta \approx 0.22$

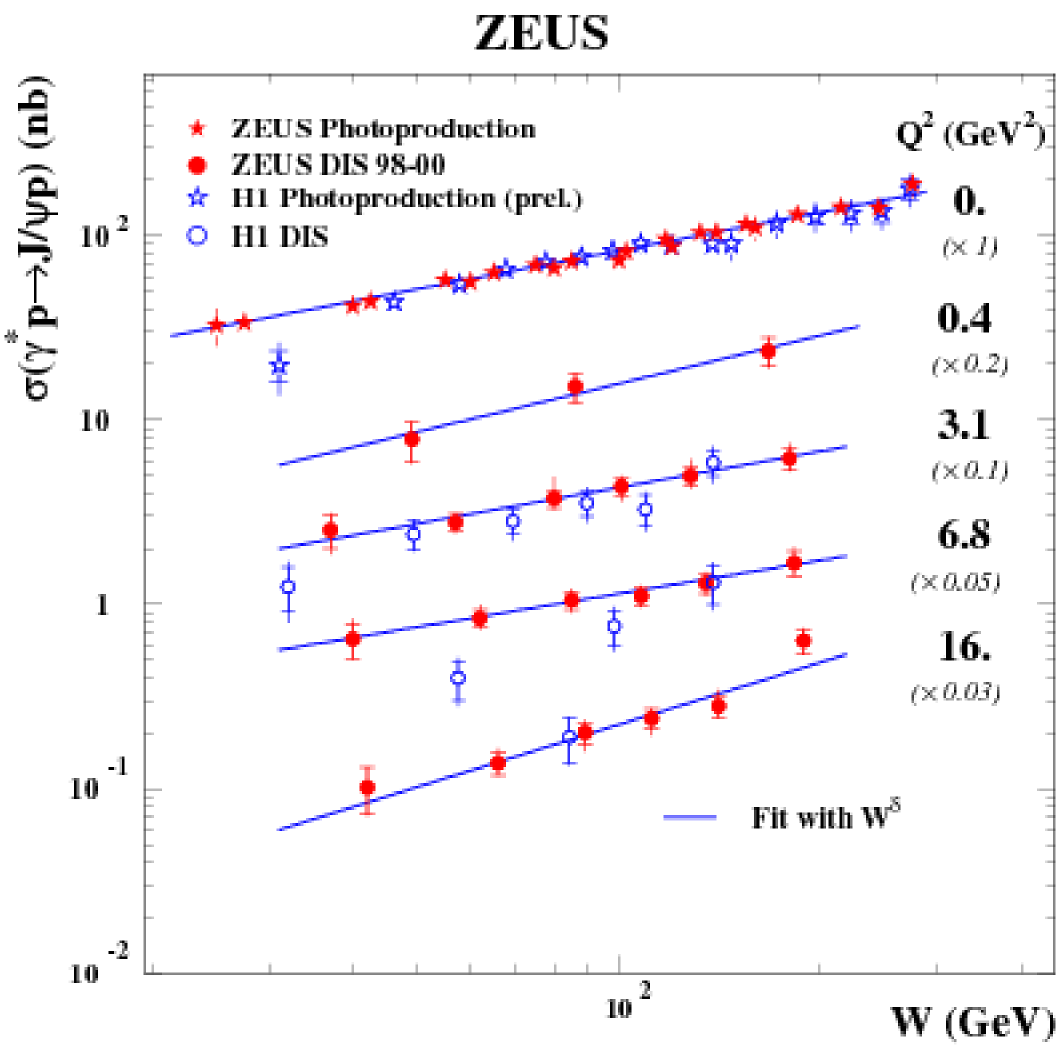
$\Leftarrow$ J/ψ:

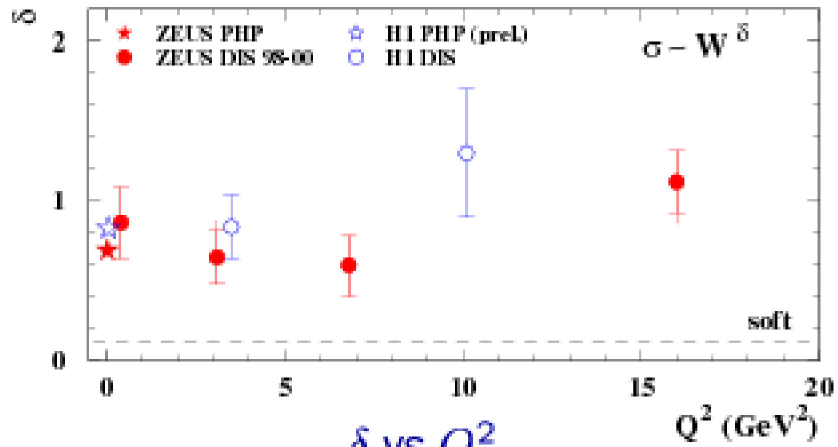
$\delta = 0.69 \pm 0.02 \pm 0.03$

- Steeper W dependence for heavy VMs.

$\Rightarrow$ M_V provides hard scale

J/ψ electroproduction (scales: Q^2, M^2)



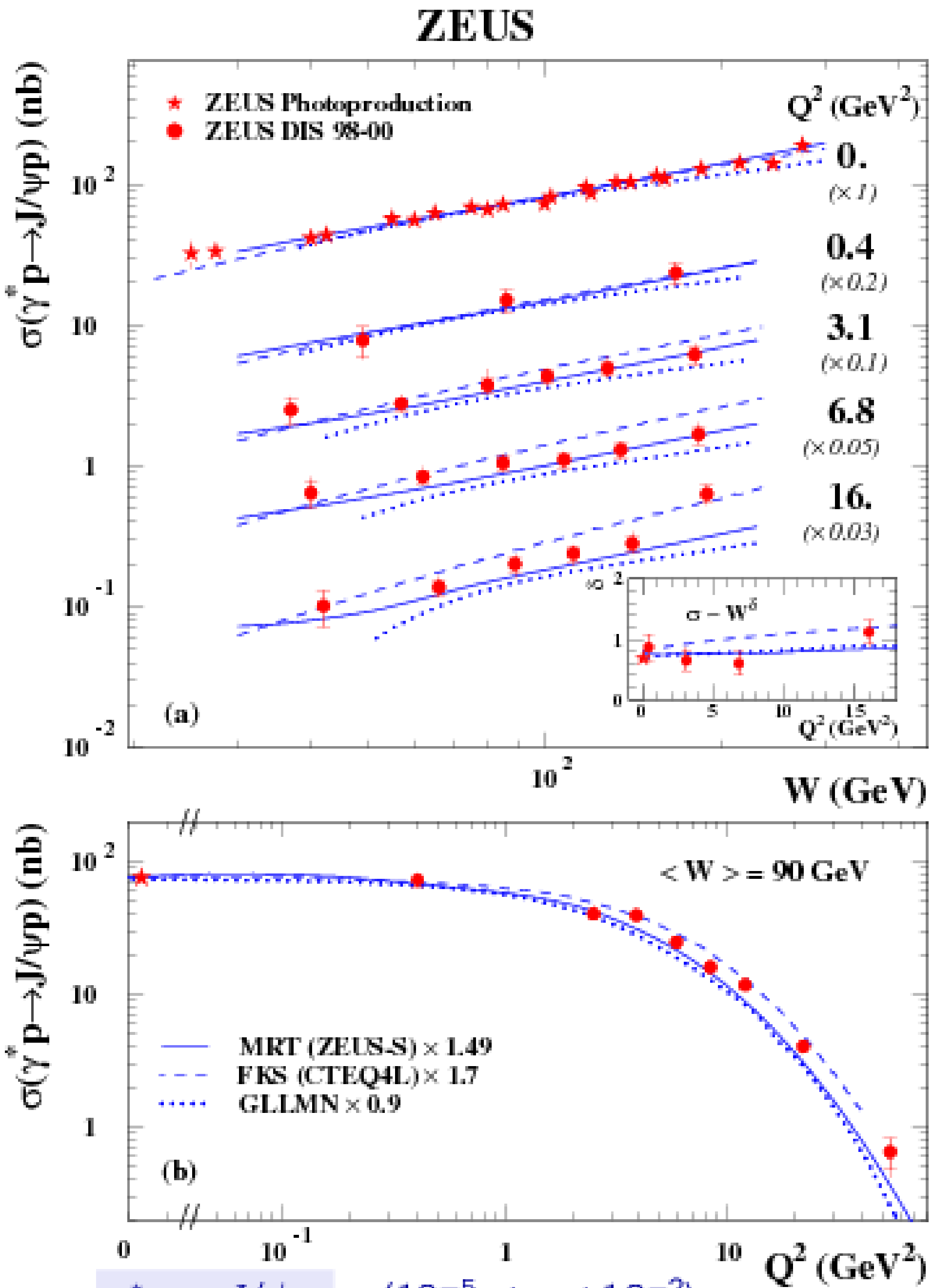


δ vs Q^2

$\sigma \propto W^\delta$ $\delta \approx 0.7$

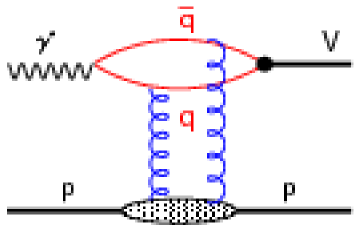
- No change of W dependence with Q^2

⇒ Hard regime in photoproduction and DIS



$\gamma^* p \to J/\psi\, p$ $(10^{-5} < x < 10^{-2})$

Comparison with theoretical models (LO pQCD)



$$A \propto \psi^{\gamma^*}_{q\bar{q}} \otimes \sigma_{(q\bar{q})p} \otimes \psi^{V}_{q\bar{q}}$$

models differ for $\psi^{V}_{q\bar{q}}$ and $\sigma_{(q\bar{q})p}$

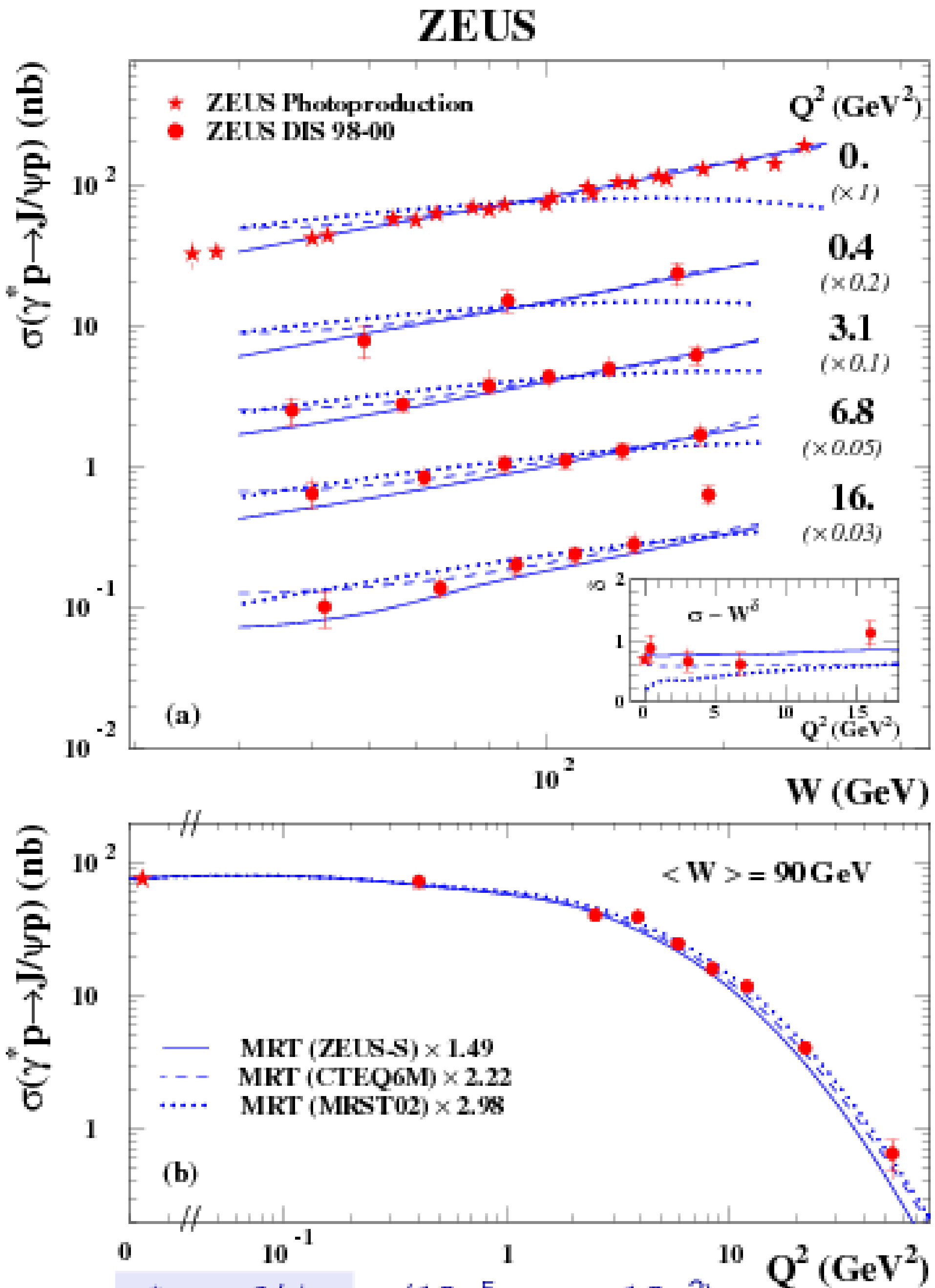
MRT - Martin, Ryskin, Teubner

FKS - Frankfurt, Koepf, Strikman

GLLMN - Gotsman, Levin, Lubisky, Maon, Naftali

- Good qualitative description
- Large normalisation uncertainty

(normalised to σ at $Q^2 = 0$ and $W = 90$ GeV)



$\gamma^* p \to J/\psi\, p$ $(10^{-5} < x < 10^{-2})$

Uncertainties of theoretical models $\Rightarrow$

uncertainties of gluons PDFs

$$\sigma \propto |xg(x, \bar{q}^2)|^2$$

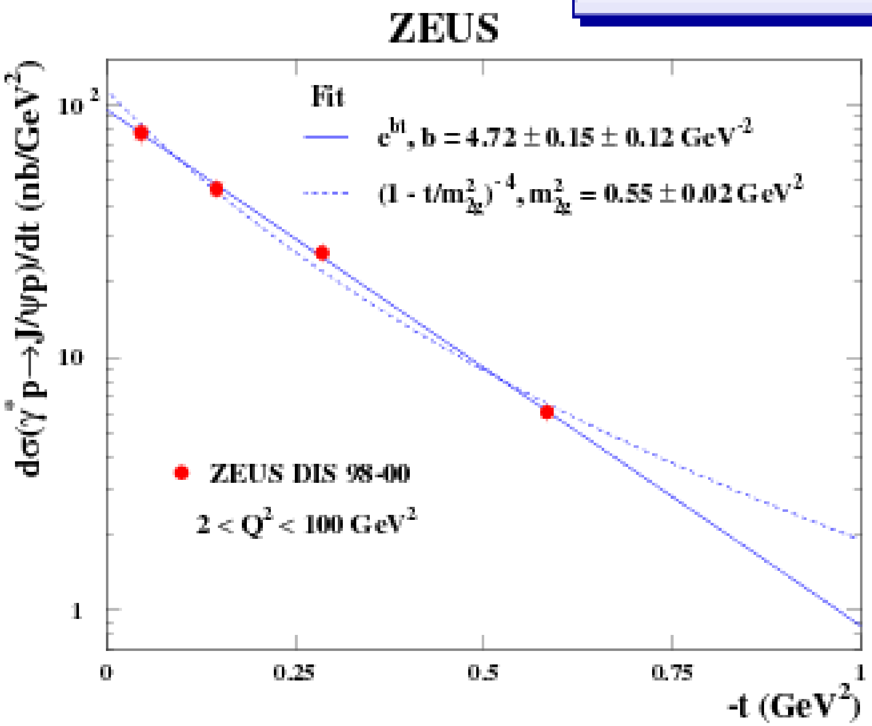
Comparison with MRT model for different gluon PDFs

- ZEUS-S and CTEQ6M describe the data
- MRST02 fails at low Q^2 and high W
- Data exibit potential to constrain PDFs

  $\Rightarrow$ Full NLO calculations needed

  (recently available for J/ψ PHP, Ivanov *et al.*)

t dependence of the cross section



$$\frac{d\sigma}{dt} \propto e^{-b|t|} \qquad b \propto R_p^2 + R_{q\bar{q}}^2$$

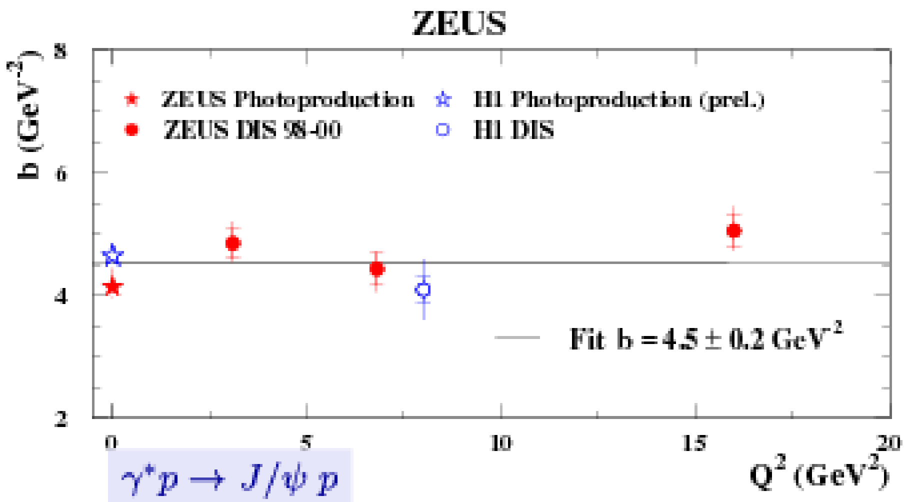
- J/ψ: b independent of Q^2 (pQCD)

point-like interaction dominanted by the gluon cloud of the proton

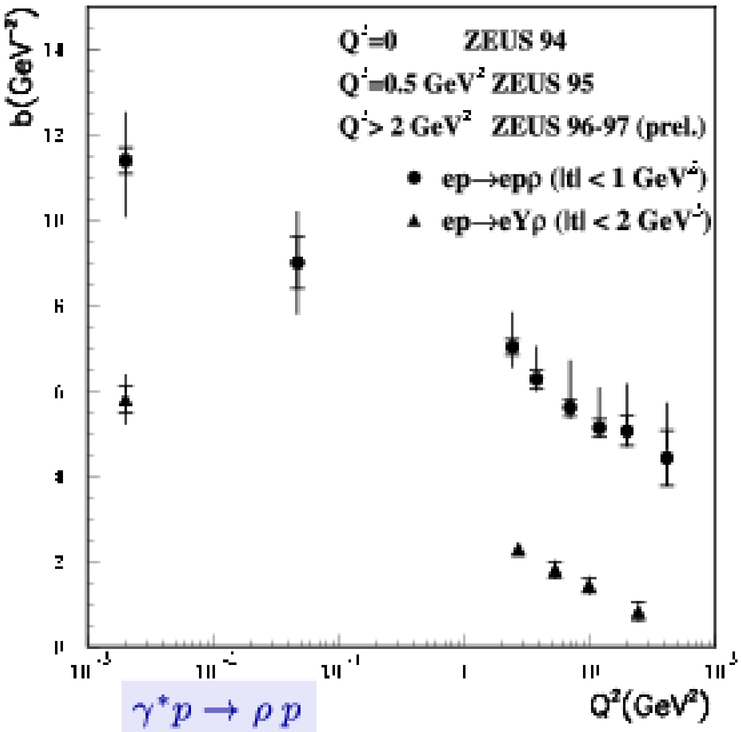
- ρ: b decreases with Q^2

$$b_{\rho,\phi}(Q^2 \gg 0) \rightarrow b_{J/\psi}(Q^2 = 0)$$

the size of the meson decreases with Q^2

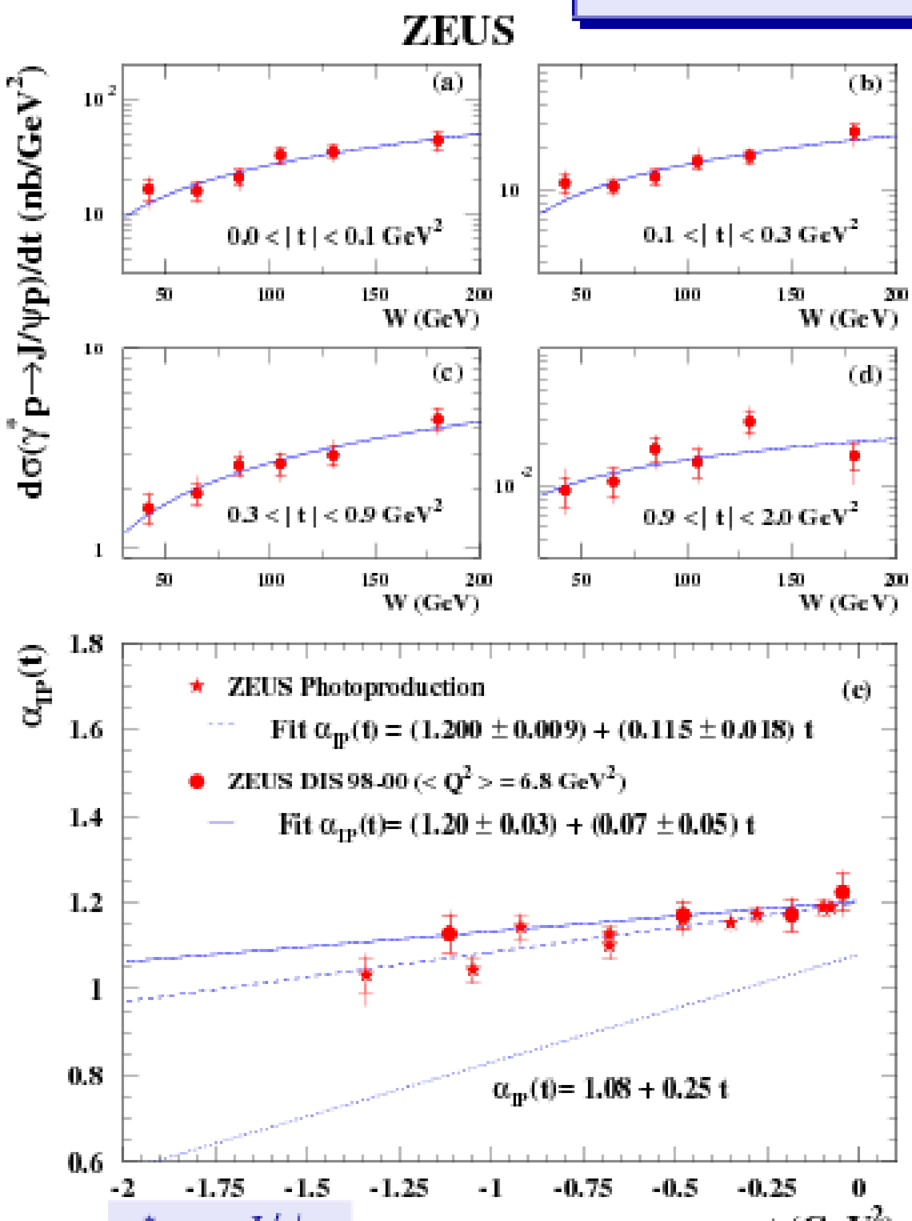


$\gamma^* p \rightarrow J/\psi\, p$



$\gamma^* p \rightarrow \rho\, p$

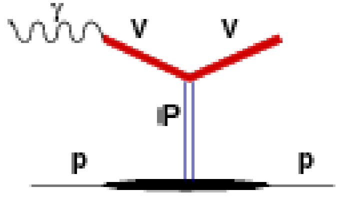
Pomeron trajectory for J/ψ: $\alpha_{I\!P}(t)$



$\gamma^* p \to J/\psi\ p$

Measure W dependence in bins of t

$$\frac{d\sigma}{dt} \propto W^{4(\alpha_{I\!P}(t)-1)}$$

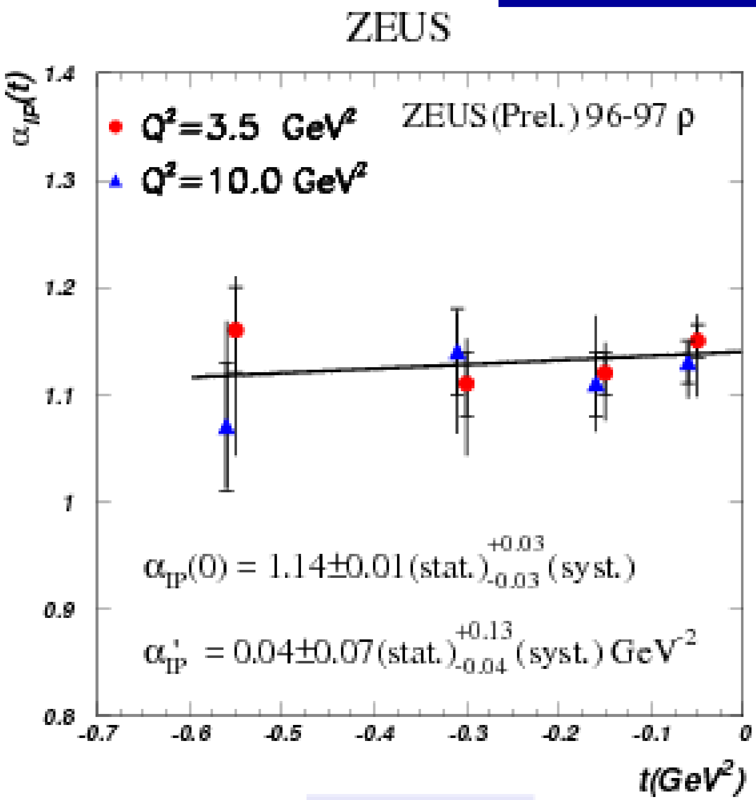


Linear fit with: $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} \cdot t$:

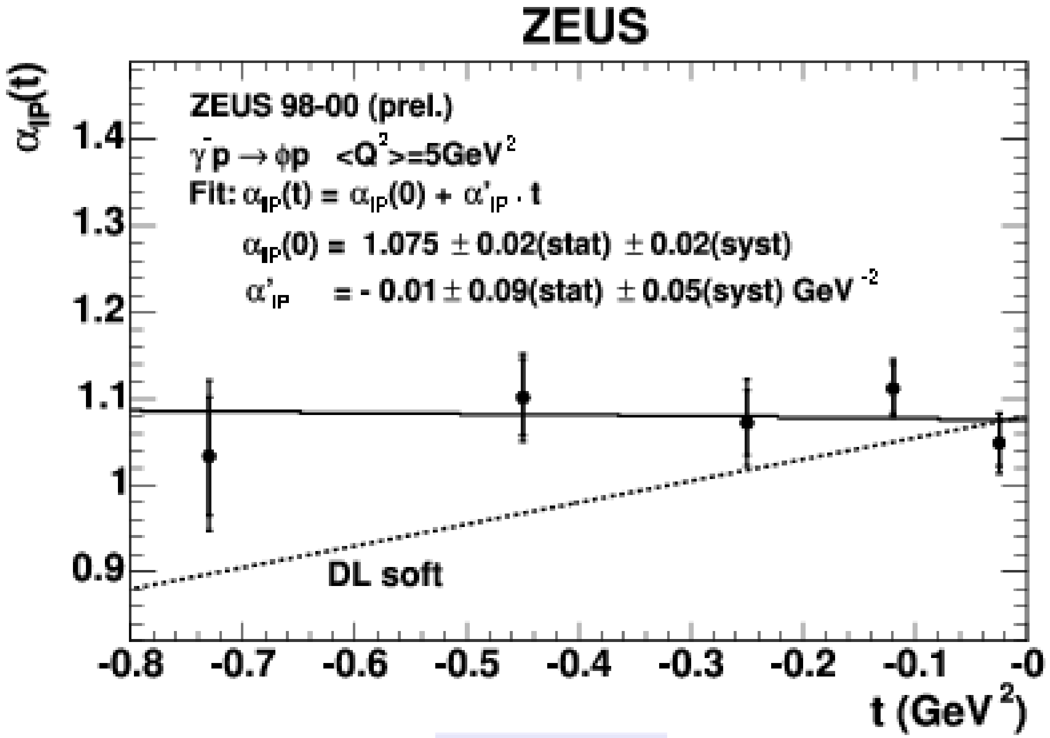
$$\alpha_{I\!P}(t) = (1.20 \pm 0.03) + (0.07 \pm 0.05) \cdot t$$

- In agreement with the measurement at $Q^2 = 0$
- Not in agreement with soft Pomeron trajectory:
  $$\alpha_{I\!P}(t) = 1.08 + 0.25 \cdot t$$
- $\alpha_{I\!P}(0)$ in agreement with NLO BFKL
- $\alpha'_{I\!P} = 0.07 \pm 0.05$ GeV^{-2} $<$ 0.25 GeV^{-2}
  $\Rightarrow$ Less shrinkage (pQCD)

Pomeron trajectory for light VM: $\alpha_{I\!P}(t)$



$\gamma^* p \to \rho\, p$



$\gamma^* p \to \phi\, p$

- Not in agreement with the soft Pomeron
- $\alpha_{I\!P}(0)^{\rho,\,\phi} < \alpha_{I\!P}(0)^{J/\psi}$ at $Q^2 \approx 5 - 7$ GeV^2
- $\alpha'_{I\!P}{}^{\rho,\,\phi} \approx \alpha'_{I\!P}{}^{J/\psi}$ within uncertainties

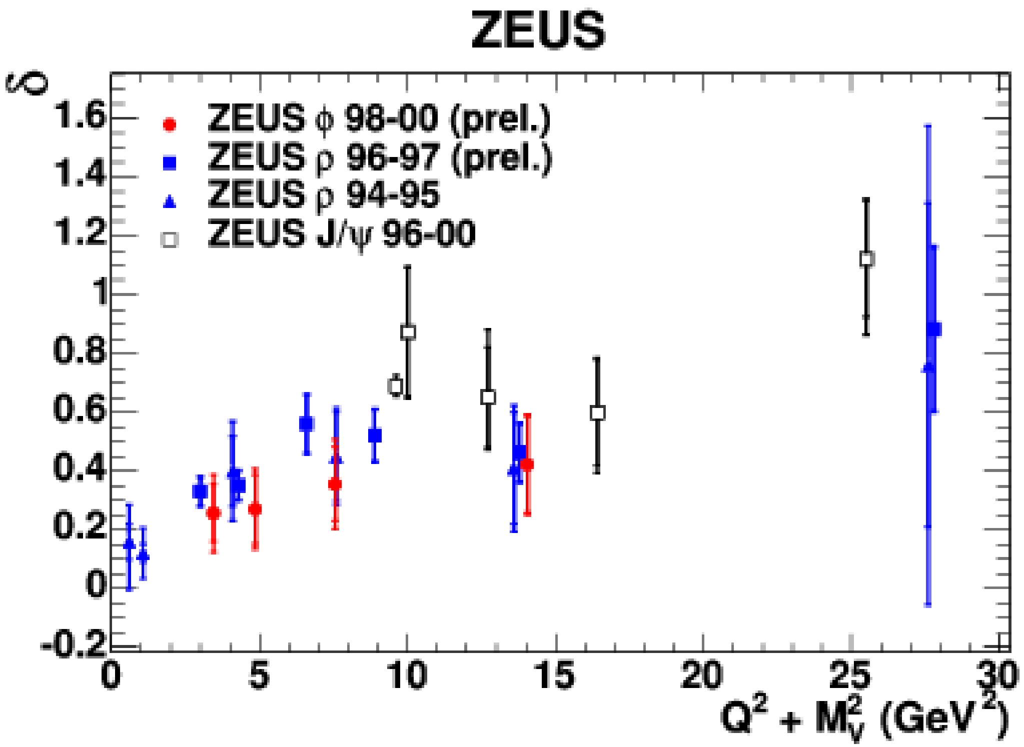
$\Rightarrow$ No universal Pomeron

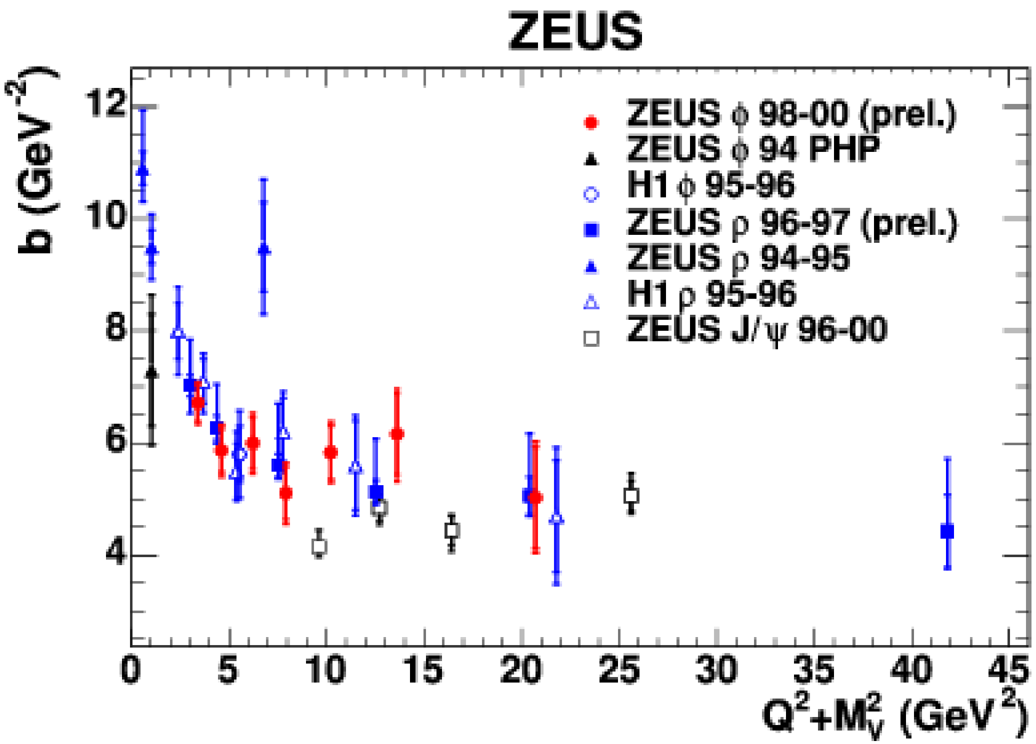
Searching for universality of VM production: ρ, ϕ, J/ψ

W and $|t|$ dependence of the cross section:

ρ,ϕ at higher Q^2 $\approx$ J/ψ at $Q^2 = 0$

$\Rightarrow$ data suggest scaling with $Q^2 + M_V^2$



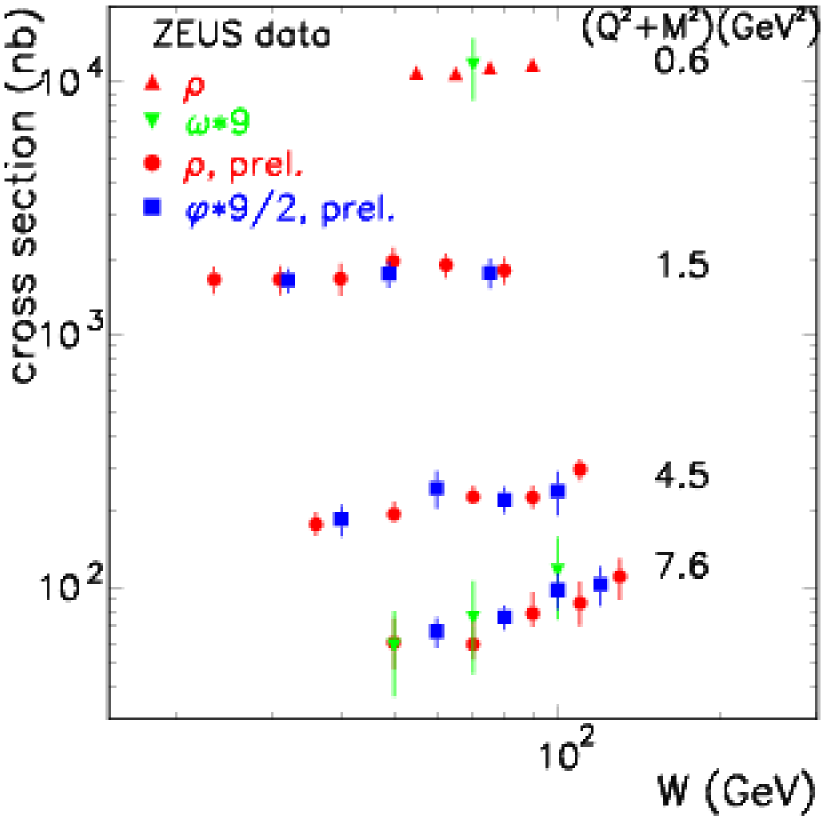


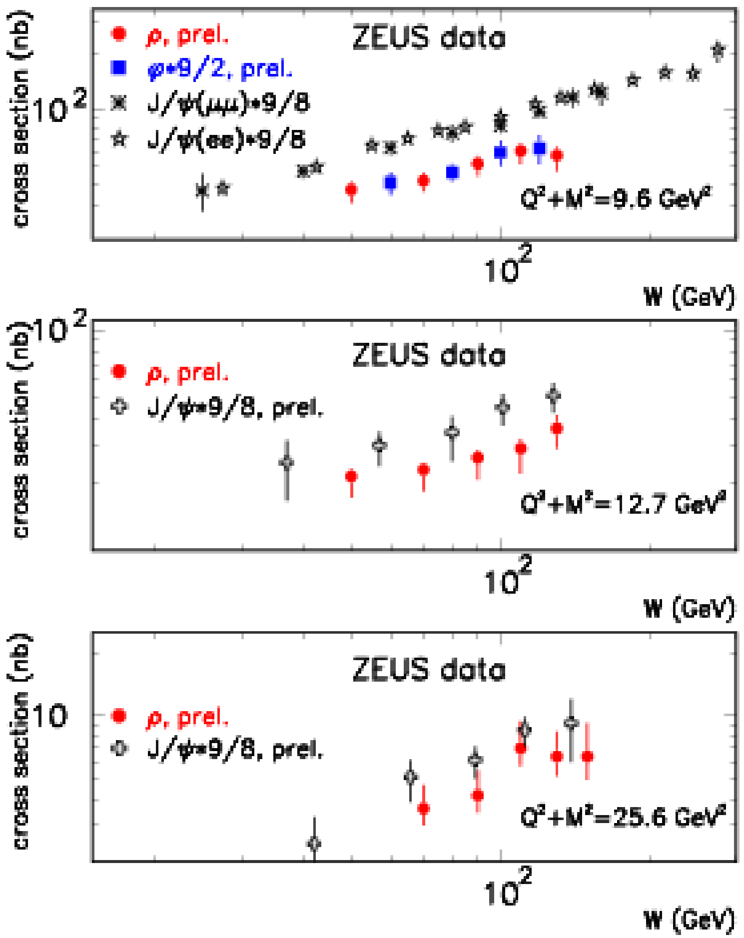
$\sigma \propto W^{\delta}$, δ vs $Q^2 + M_V^2$ $d\sigma/d|t| \propto e^{-b|t|}$, b vs $Q^2 + M_V^2$

Universality of VM production ? (scale $Q^2 + M_V^2$)

SU(4) flavour symmetry $\Rightarrow \sigma_\rho : \sigma_\omega : \sigma_\phi : \sigma_{J/\psi} = 9 : 1 : 2 : 8$

After correction for $\gamma^* q$ coupling:





SU(3) – restored with the scale $Q^2 + M^2$

SU(4) – not (fails for J/ψ)

Scaling works for light quarks (u,d,s), but not for heavy (c,b) (VM wave function effects?)

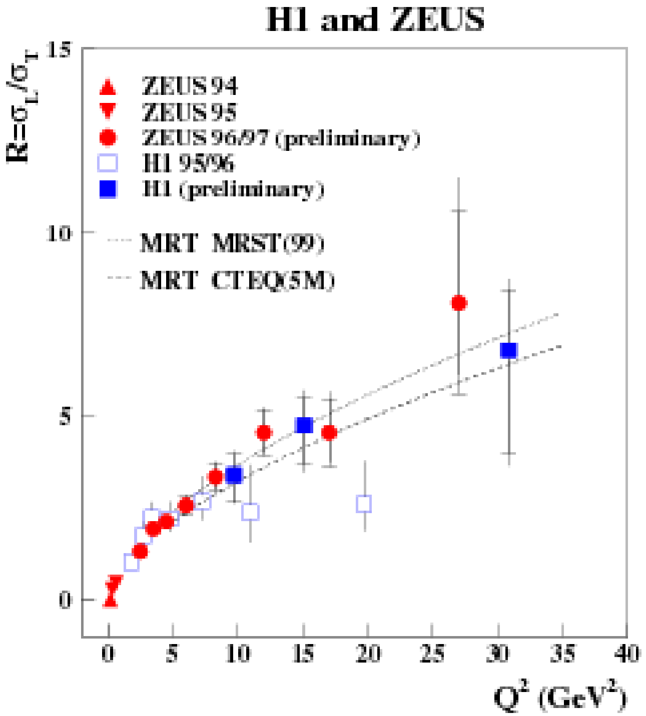
Transverse and longitudinal cross sections, $R = \sigma_L/\sigma_T$

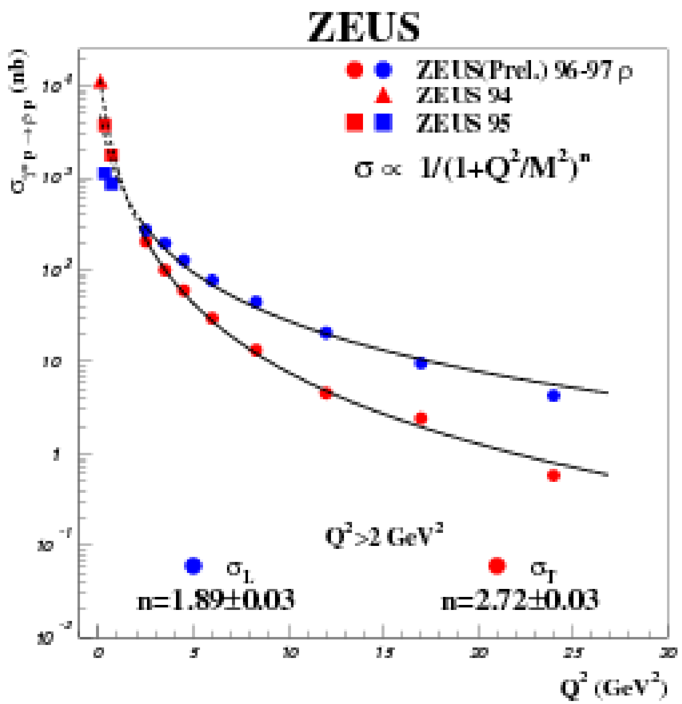
VM production processes $\Rightarrow$ unique opportunity to extract $R = \sigma_L/\sigma_T$

R measured through angular distributions of the final state particles

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_h} = f(\cos^2\theta_h, r_{00}^{04}) \quad \Rightarrow \quad r_{00}^{04} = \frac{\sigma_L}{\sigma_{TOT}} \quad \Rightarrow \quad R = \sigma_L/\sigma_T \simeq \frac{r_{00}^{04}}{\epsilon(1-r_{00}^{04})}$$

SCHC approximation $\epsilon \simeq 0.99$



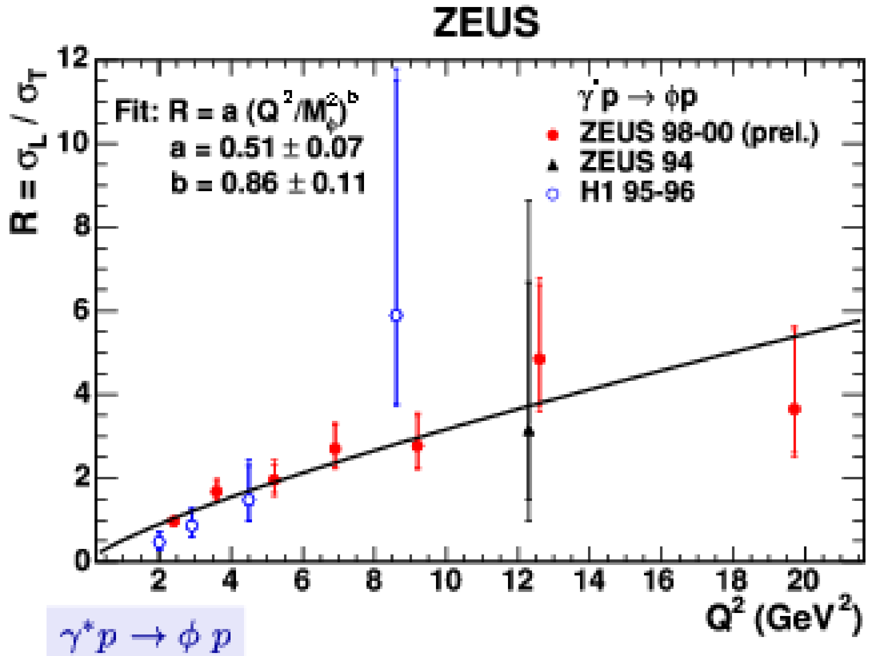


$\gamma^* p \to \rho\, p$

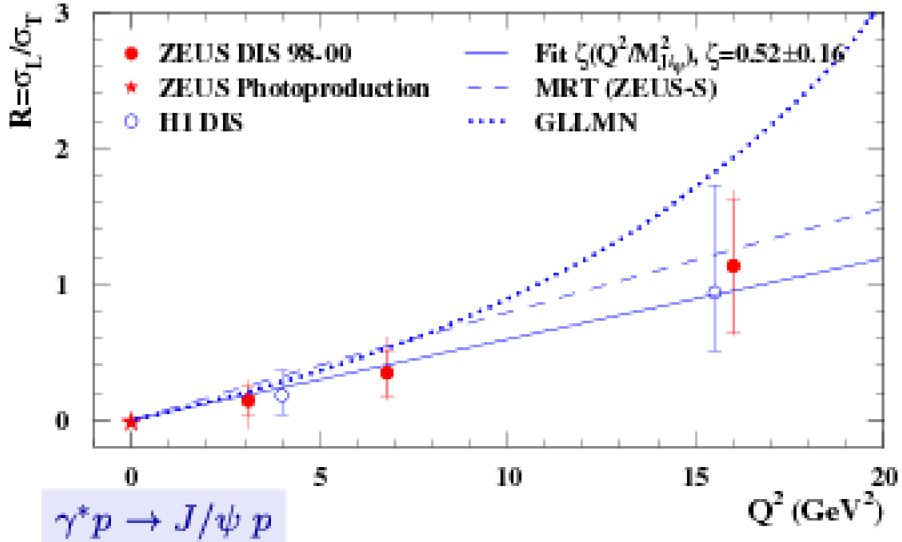
- $R = \sigma_L/\sigma_T$ rises with Q^2
  (expected from pQCD)

  $\Rightarrow$ σ_T and σ_L have different Q^2 dependence

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

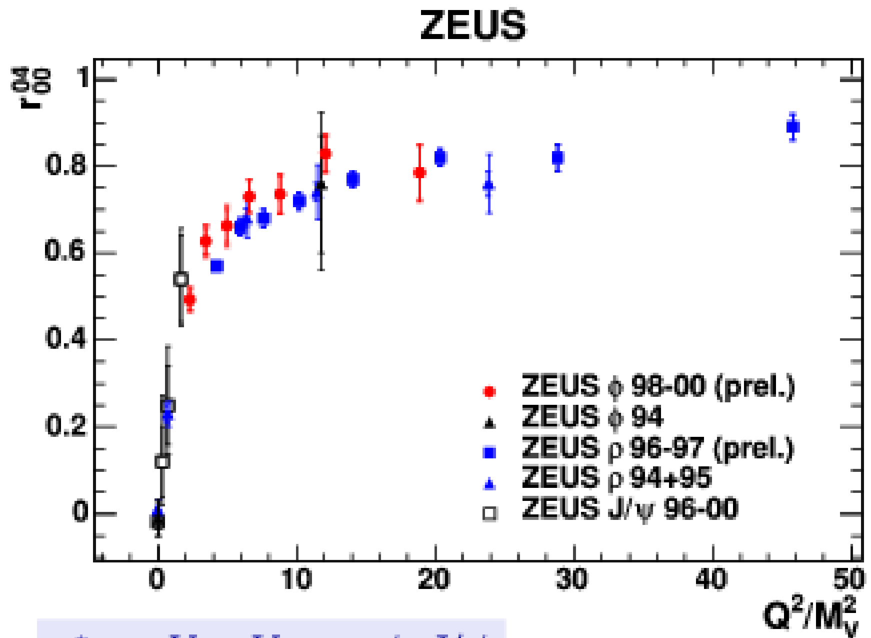


$\gamma^* p \to \phi\ p$



$\gamma^* p \to J/\psi\ p$

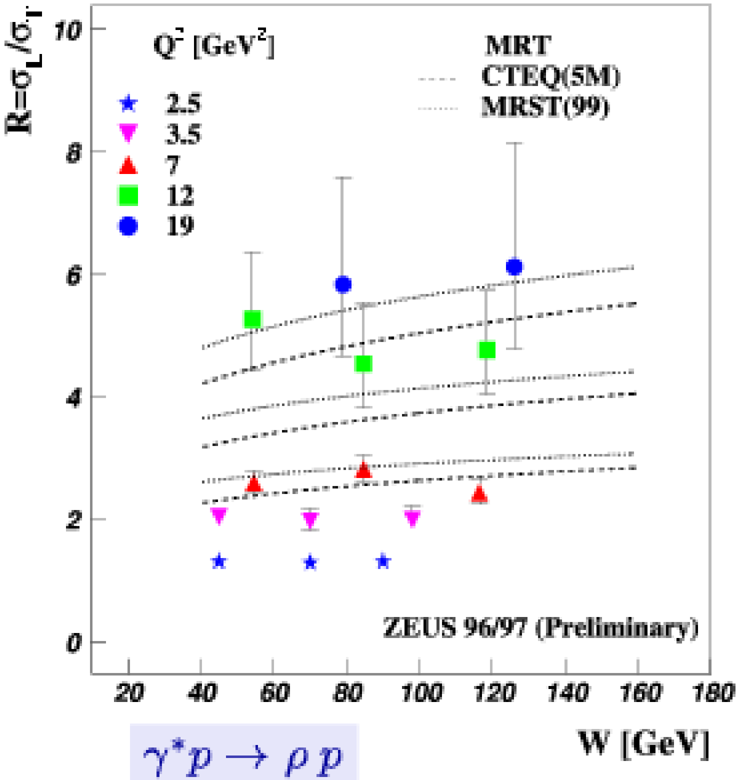
- Data suggest scaling of R (and r_{00}^{04}) with Q^2/M_V^2



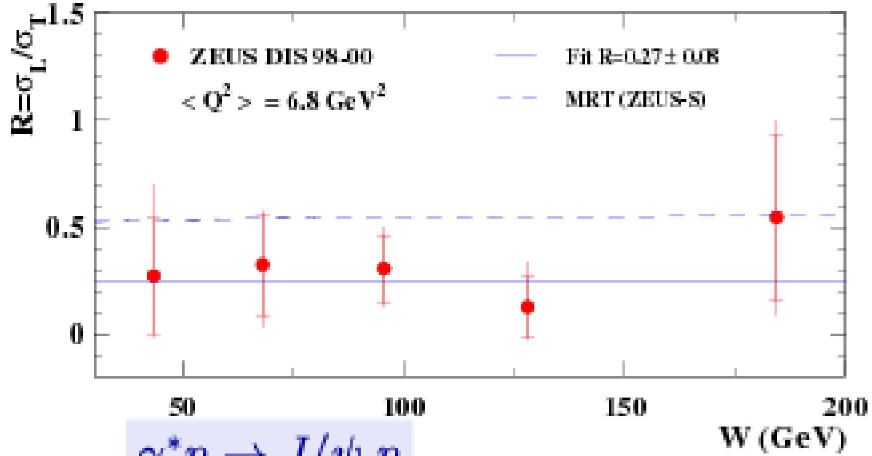
$\gamma^* p \to V\ p,\ V = \rho,\ \phi,\ J/\psi$

r_{00}^{04} vs Q^2/M_V^2

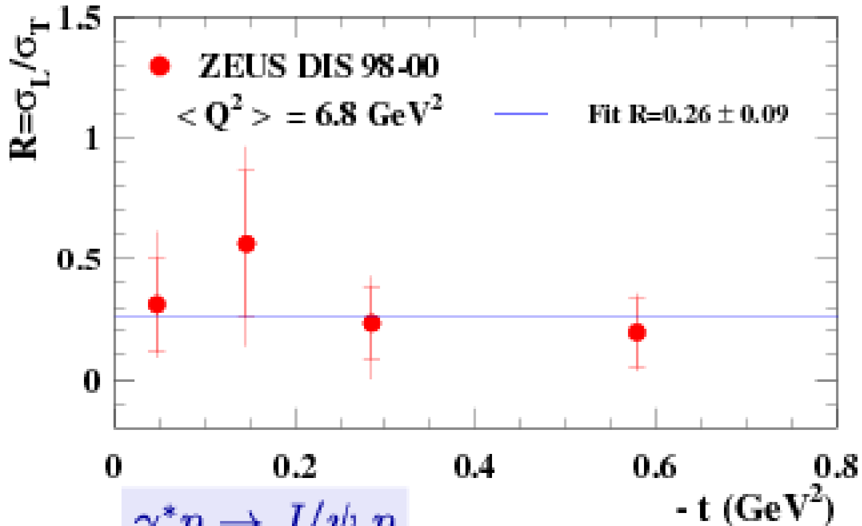
$R = \sigma_L/\sigma_T$ vs W, $|t|$



$\gamma^* p \to \rho\, p$



$\gamma^* p \to J/\psi\ p$

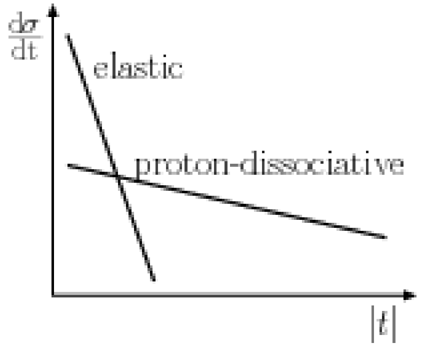


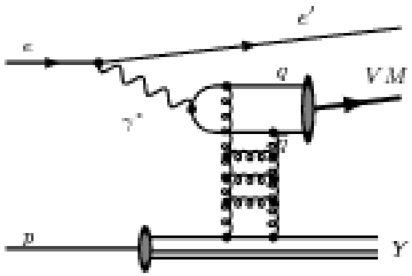
$\gamma^* p \to J/\psi\ p$

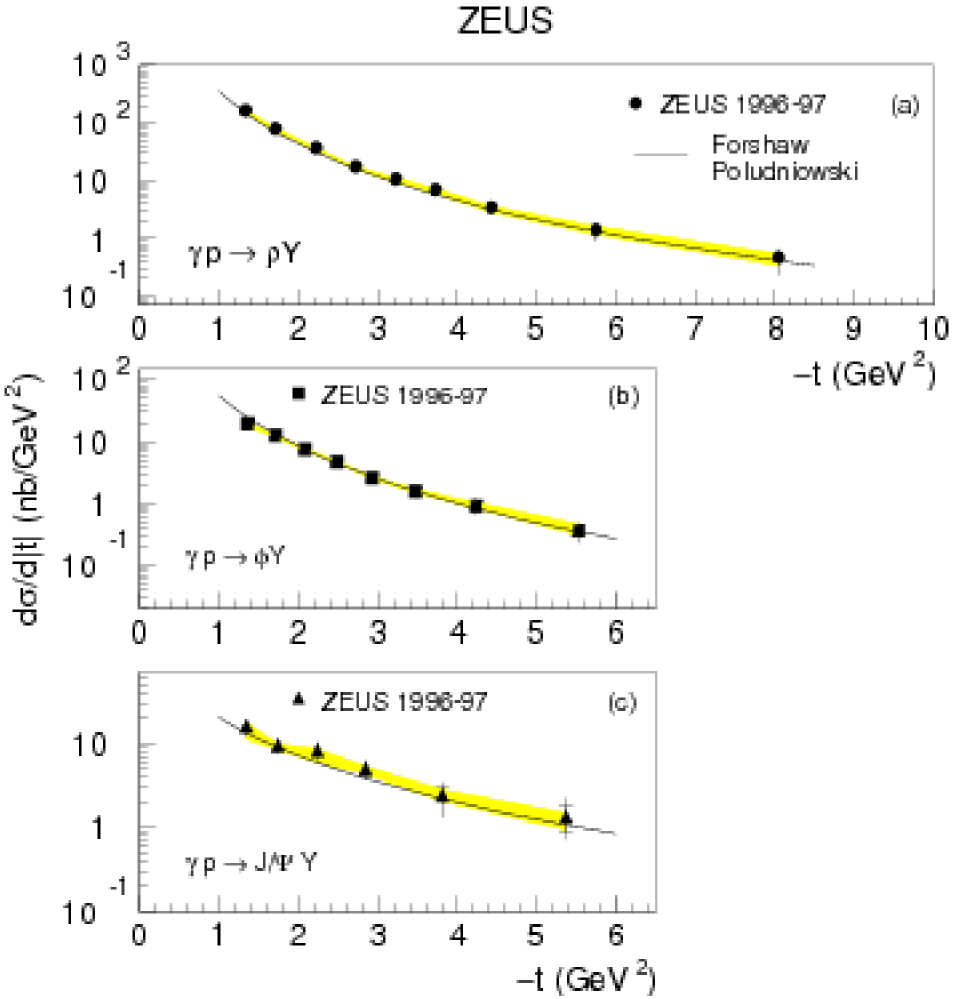
- same W dependence for σ_T and σ_L (ρ, J/ψ)
- same $|t|$ dependence for σ_T and σ_L (J/ψ)
  (the same transverse size of the interaction)

Proton dissociative VM production

- Energy dependence of the cross section (J/ψ)







Proton dissociative production dominates at high $|t|$

$\Rightarrow$ $|t|$ serves as a hard scale

$\Rightarrow$ search for sign of BFKL dynamics

Expectations:

- power-law dependence (not exponential)

$$d\sigma/dt \propto |t|^{-n}$$

- steep rise of the cross section with W

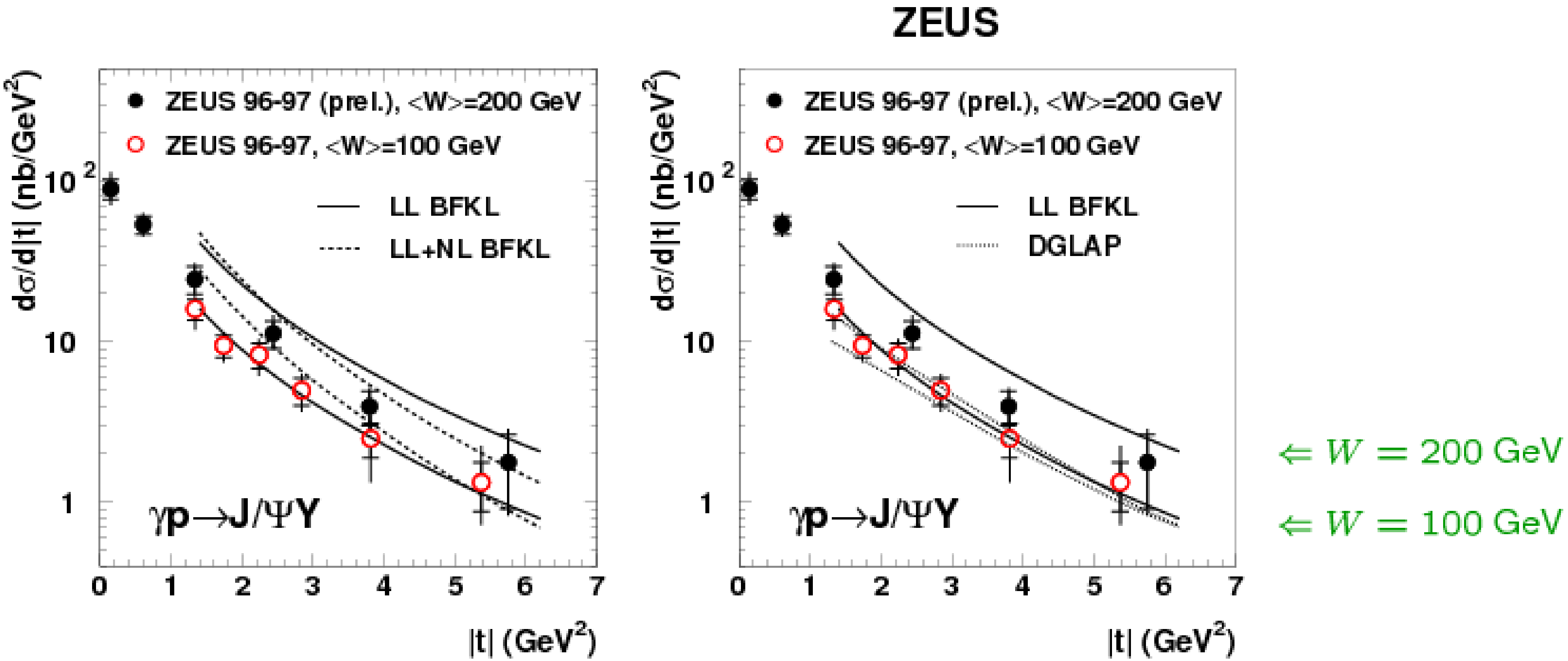
ρ, ϕ, J/ψ

LL BFKL (Forshaw, Poludniowski) predictions describe well the data at $W = 100$ GeV

What happens at higher W?

J/ψ photoproduction at high W

Tuned at W=100 GeV, BFKL and DGLAP calculations give predictions for W=200 GeV



- LL BFKL (Engberg *et al*) describes $d\sigma/d|t|$, but overestimates the rise with W
- LL+NL BFKL describes the rise with W, but predicts steeper $d\sigma/d|t|$
- LL DGLAP (Gotsman *et al.*) does not reproduce the rise of the cross section with W

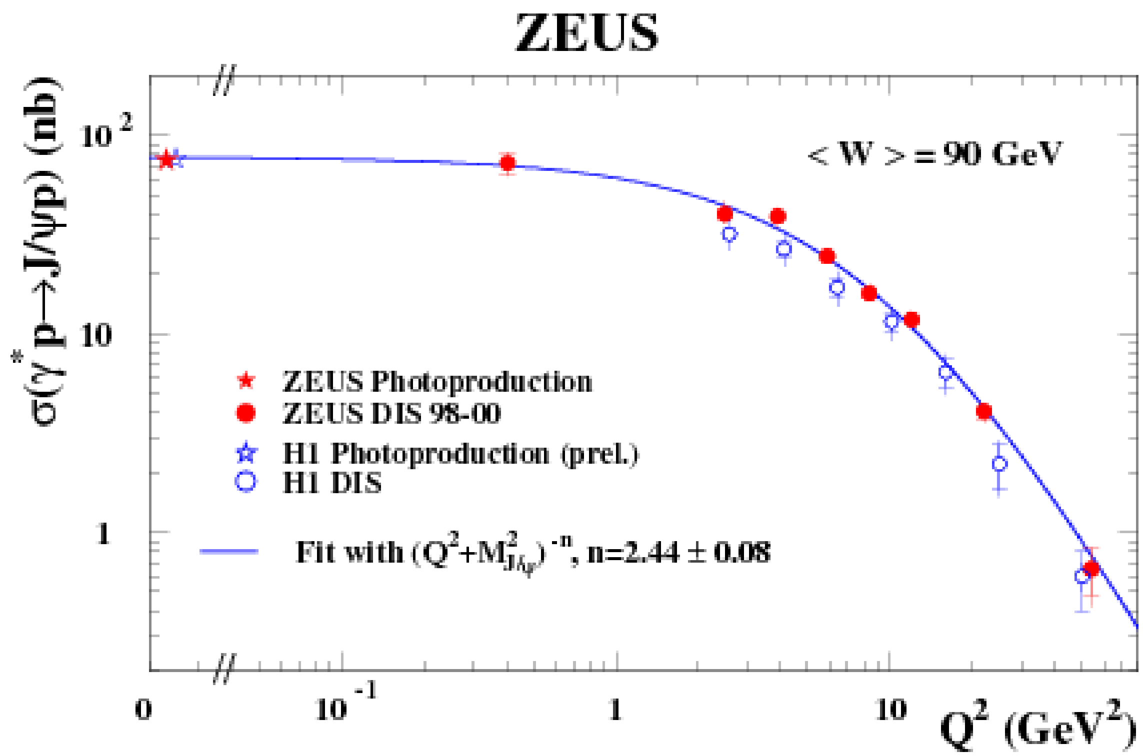
Summary

- High precision data in the wide kinematic range
  - ⇒ ρ, ϕ show the transition from soft to hard regime as Q^2 increases
  - ⇒ J/ψ has all characteristics of hard process already for $Q^2 = 0$
  - ⇒ Universality of VMs with the scale $Q^2 + M_V^2$ $(R = \sigma_L/\sigma_T$ with $Q^2/M_V^2)$
    - ⇒ SU(3) flavour symmetry restored with $Q^2 + M_V^2$ (SU(4) not)

- Vector meson production processes succesfully described by pQCD models
  - ⇒ data exhibit potential to extract gluon distributions in the proton
  - ⇒ need full NLO calculations (recently available for J/ψ at $Q^2 = 0$)

- Energy dependence observed for the proton dissociative J/ψ photoproduction described only qualitatively by the BFKL evolution (unlike DGLAP)

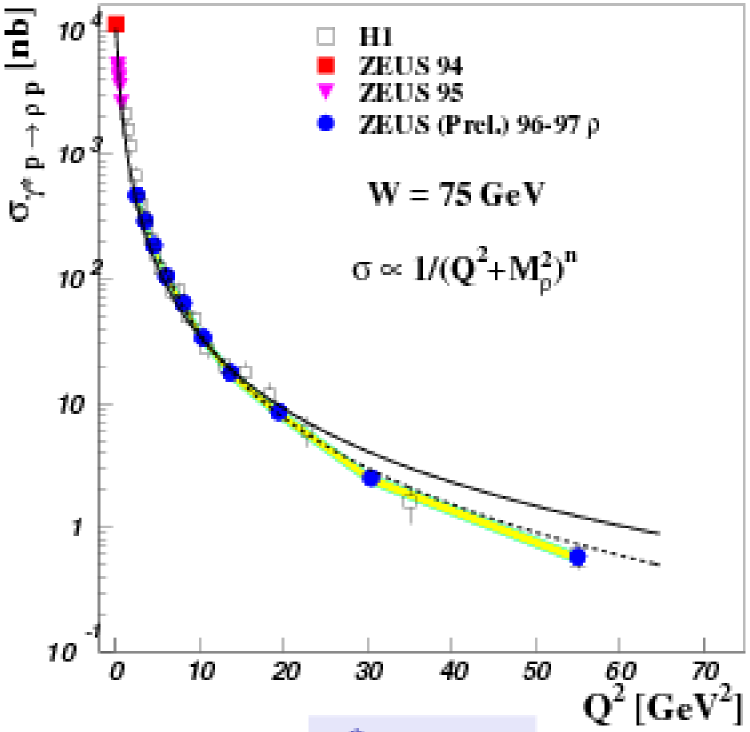
Exclusive J/ψ electroproduction (Q^2 dependence)



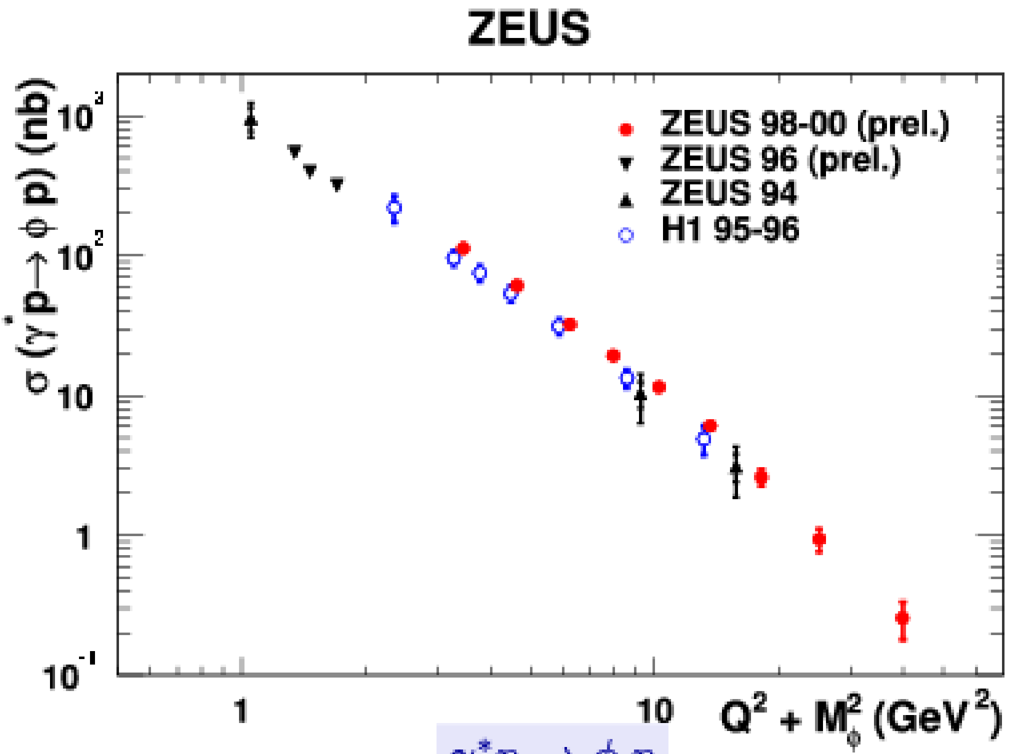
$\sigma \propto (Q^2 + M_V^2)^{-n}$ $\quad n = 2.44 \pm 0.08$

- Fit describes data in the entire Q^2 range
- Fit for $Q^2 > 2$ GeV^2 reproduced the cross section at $Q^2 = 0$

Exclusive ρ, ϕ electroproduction (Q^2 dependence)



$\gamma^* p \to \rho\, p$



$\gamma^* p \to \phi\, p$

$\sigma \propto (Q^2 + M_V^2)^{-n}$

For light VM cross sections can not be desribed with one function in the entire Q^2 range

$n = 1.85 \pm 0.06$ for $Q^2 > 0$ GeV^2

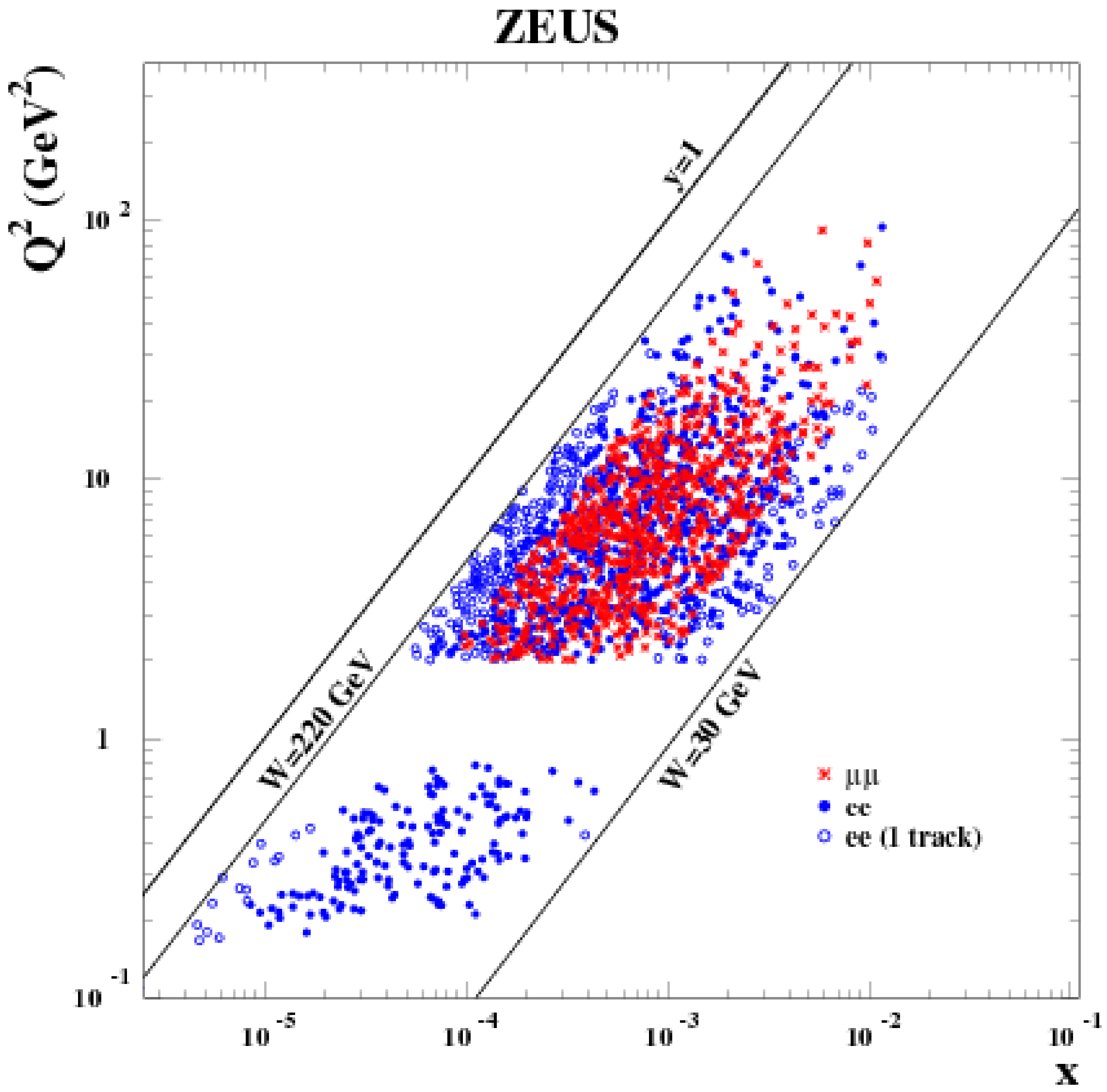
$n = 2.36 \pm 0.04$ for $Q^2 > 5$ GeV^2

$n = 2.10 \pm 0.05$ for $2.4 < Q^2 < 9.2$ GeV^2

$n = 2.75 \pm 0.05$ for $9.2 < Q^2 < 70$ GeV^2

Data suggest that n rises with Q^2

Exclusive J/ψ electroproduction



Kinematic range

- $0.15 < Q^2 < 0.8$ GeV^2
  $2 < Q^2 < 100$ GeV^2
- $30 < W < 220$ GeV
- $|t| < 1$ GeV^2

$10^{-5} < x < 10^{-2}$