Diffractive Production of Vector Mesons at HERA

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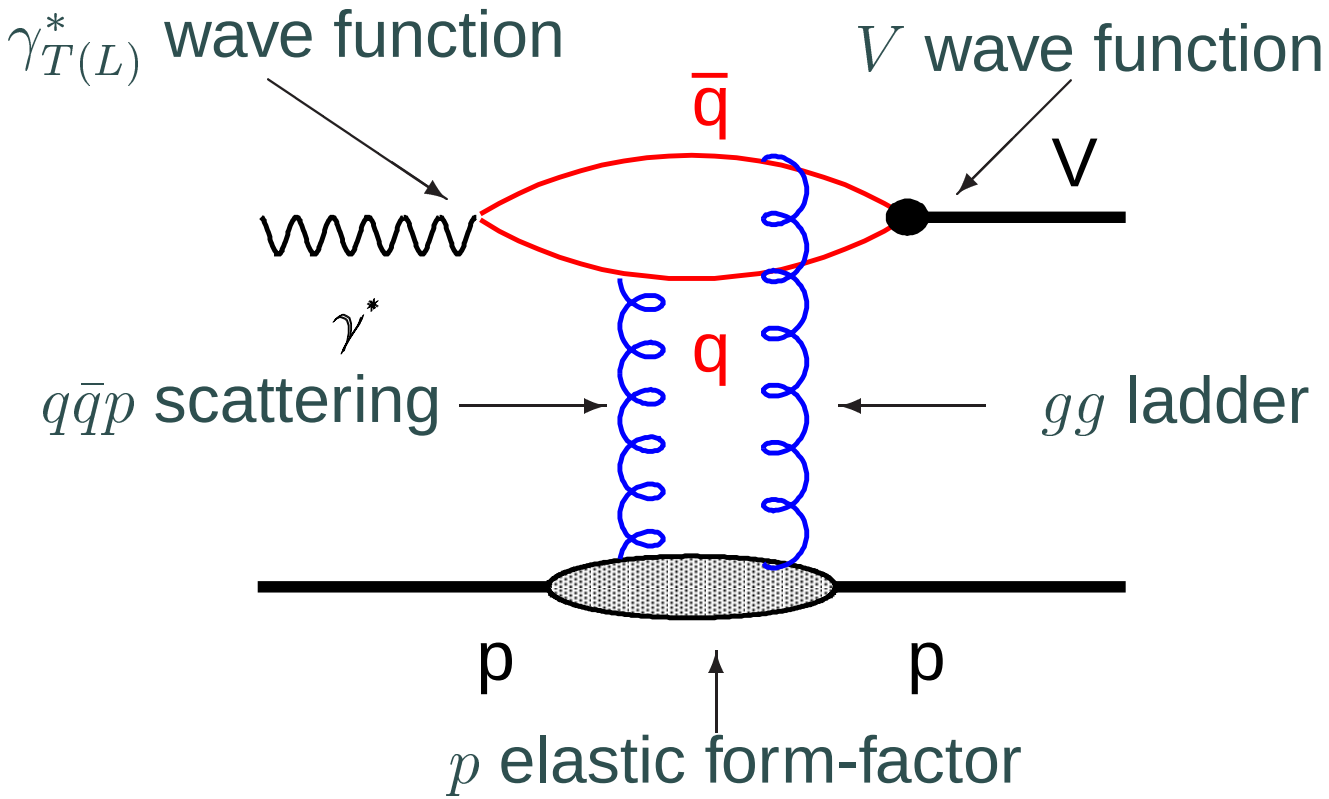
OUTLINE

- **Introduction**
- **Motivation**
- **Experimental results:** ρ^0, ϕ, J/ψ, $\psi(2S)$

  different kinematic regimes: photoproduction, high Q^2, high t
- **Summary and Outlook**

INTRODUCTION

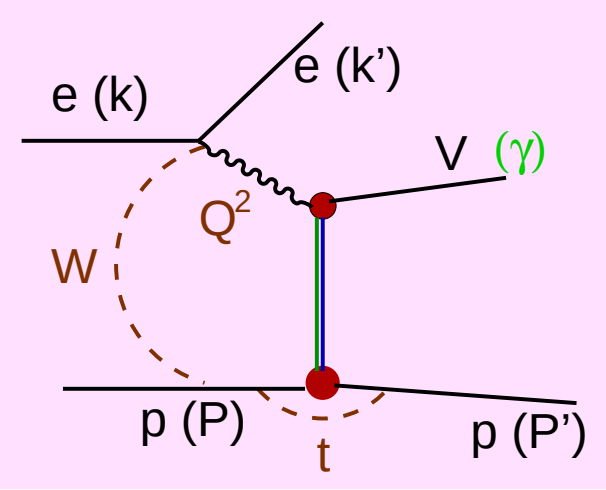
Aim is understand VM in QCD



$\Rightarrow$ understand dynamics of high energy scattering

- test pQCD in transition regime soft-hard
- measure non-perturbative quantities (generalised) pdfs

KINEMATICS



- Q^2 - virtuality of exchanged γ^*

$$Q^2 = -q^2 = -(k - k')^2$$

- W - $\gamma^* p$ centre of mass energy

$$W = (q + p)^2$$

- t - 4-momentum transfer squared at the p vertex

$$t = (P - P')^2$$

- x - Bjorken variable

$$x = \frac{Q^2}{P \cdot q} = \frac{Q^2}{Q^2 + W^2}$$

MOTIVATION

HERA regime: collisions of 27.5 GeV e with 820 (920) GeV p

$0 < Q^2 < 50\ \mathrm{GeV}^2$ and $30 < W < 300\,\mathrm{GeV}$

- Large W, large Q^2, but $Q^2 \ll W^2$

$\Rightarrow$ strong interactions in the presence of a large scale (unitarity limit?)

- Small x

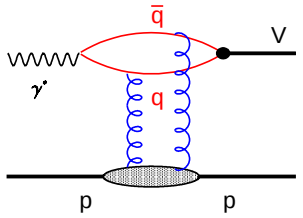
$\Rightarrow$ large density of partons, expect coherent effects

- Transition from soft to hard interactions

$\Rightarrow$ transition from a hadron to a state of partons (confinement?)

EXCLUSIVE VECTOR MESON IN ep

Candidate for a Hard process



small $q\bar{q} \Rightarrow$ either γ^*_L or

$V = c\bar{c}$ or $b\bar{b}$

$$\sigma_L \sim \frac{\alpha_S^2}{Q^6} \mid xG(x,Q^2) \mid^2$$

$\Rightarrow$ fast increase of σ_L with W^2

$\Rightarrow$ Q^2 dependence slower than $1/Q^6$

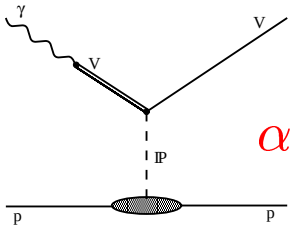
$\Rightarrow$ universal t dependence $\sim e^{b_{2g}t}$

$b_{2g} \simeq 4$ GeV^{-2} and $\alpha'_{I\!P} \simeq 0$

$\Rightarrow$ $\rho : \omega : \Phi : J/\psi = 9 : 1 : 2 : 8$

In the soft Pomeron picture

based on Regge phen. and VDM



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

$$\sigma_{\rm tot} \sim s^{\alpha_{I\!P}(0)-1}$$

$$\frac{d\sigma_{\rm el}}{dt} \sim \frac{\sigma^2_{\rm tot}}{16\pi} e^{2(b_0^{\rm el} + \alpha'_{I\!P} \ln s)t}$$

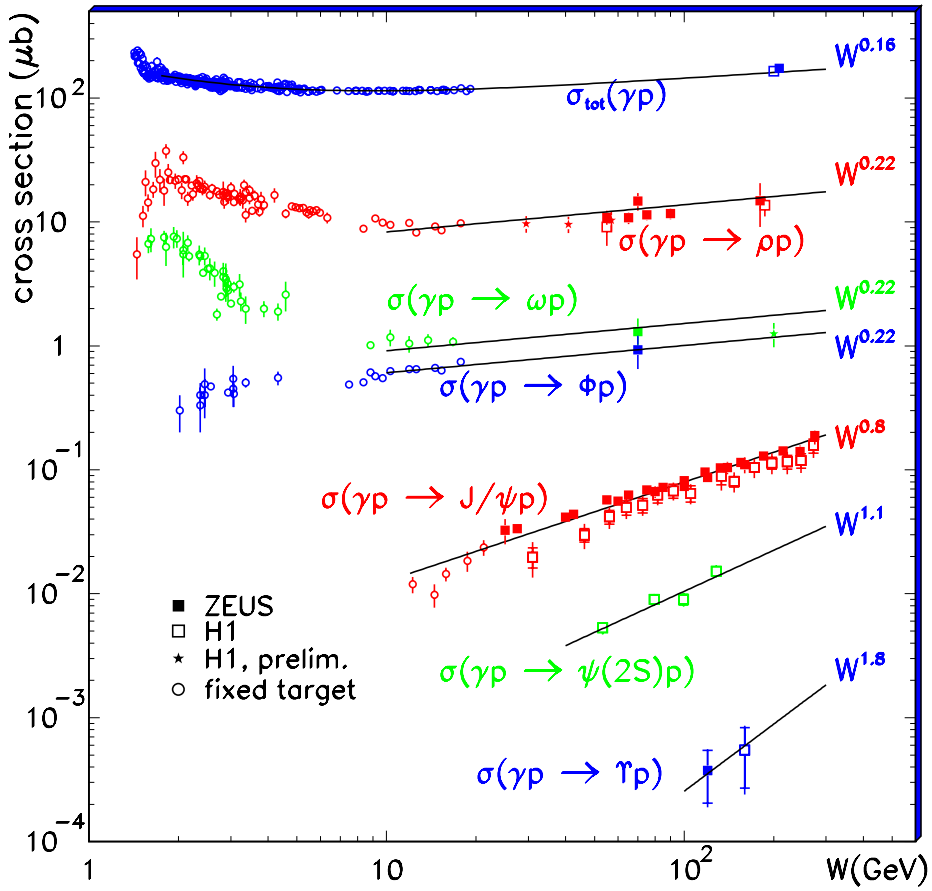
$\Rightarrow$ $\alpha_{I\!P}(0) = 1 + \epsilon \simeq 1.10$

and $\alpha'_{I\!P} = 0.25$ GeV^{-2}

$\Rightarrow$ $\frac{\sigma_{\rm el,D}}{\sigma_{\rm tot}} \sim s^{\epsilon}$

$\Rightarrow$ shrinkage of the t slope

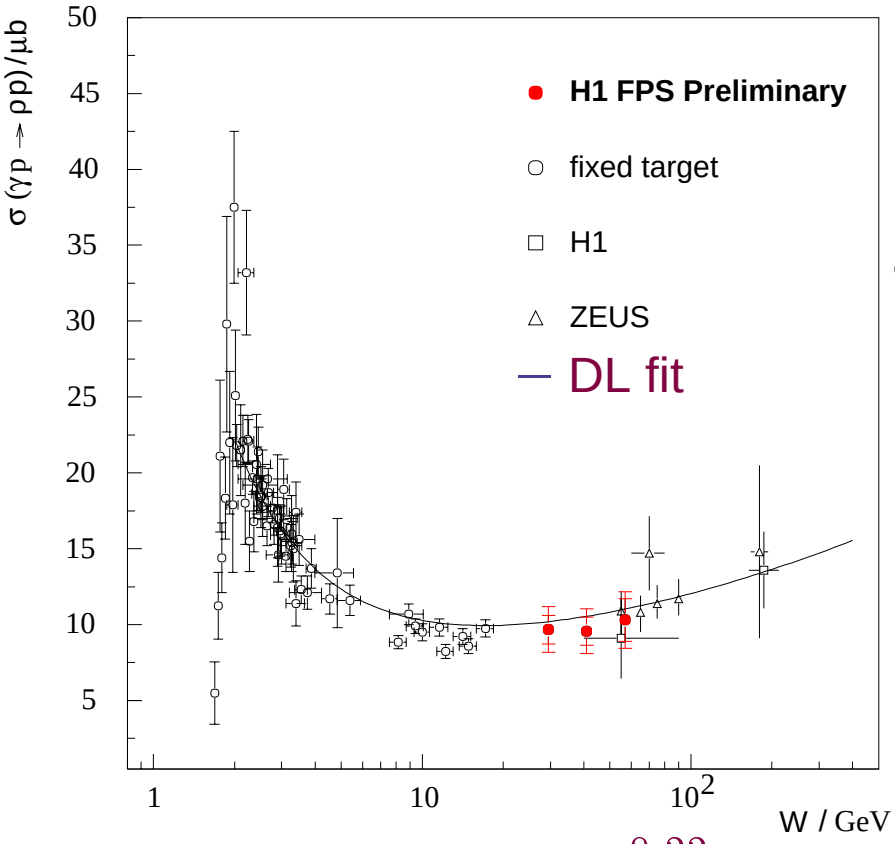
EXCLUSIVE VECTOR MESON IN γp



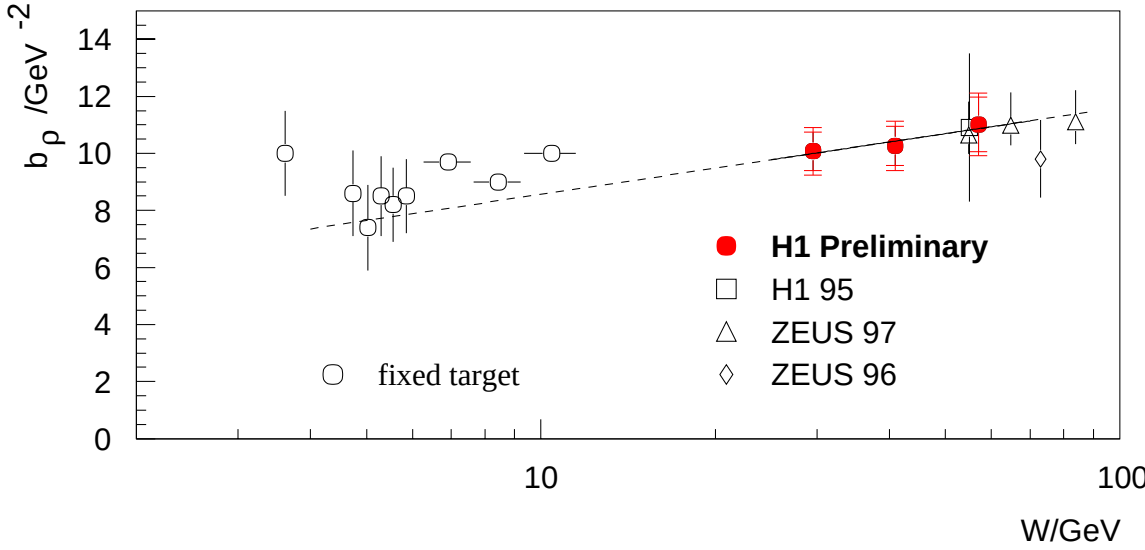
$\Rightarrow$ at $Q^2 = 0$, change of regime with mass

EXCLUSIVE ρ^0 MESON IN γp

p measured in forward proton spectrometer



Fit $\frac{d\sigma}{dt} \propto e^{b \cdot t}$

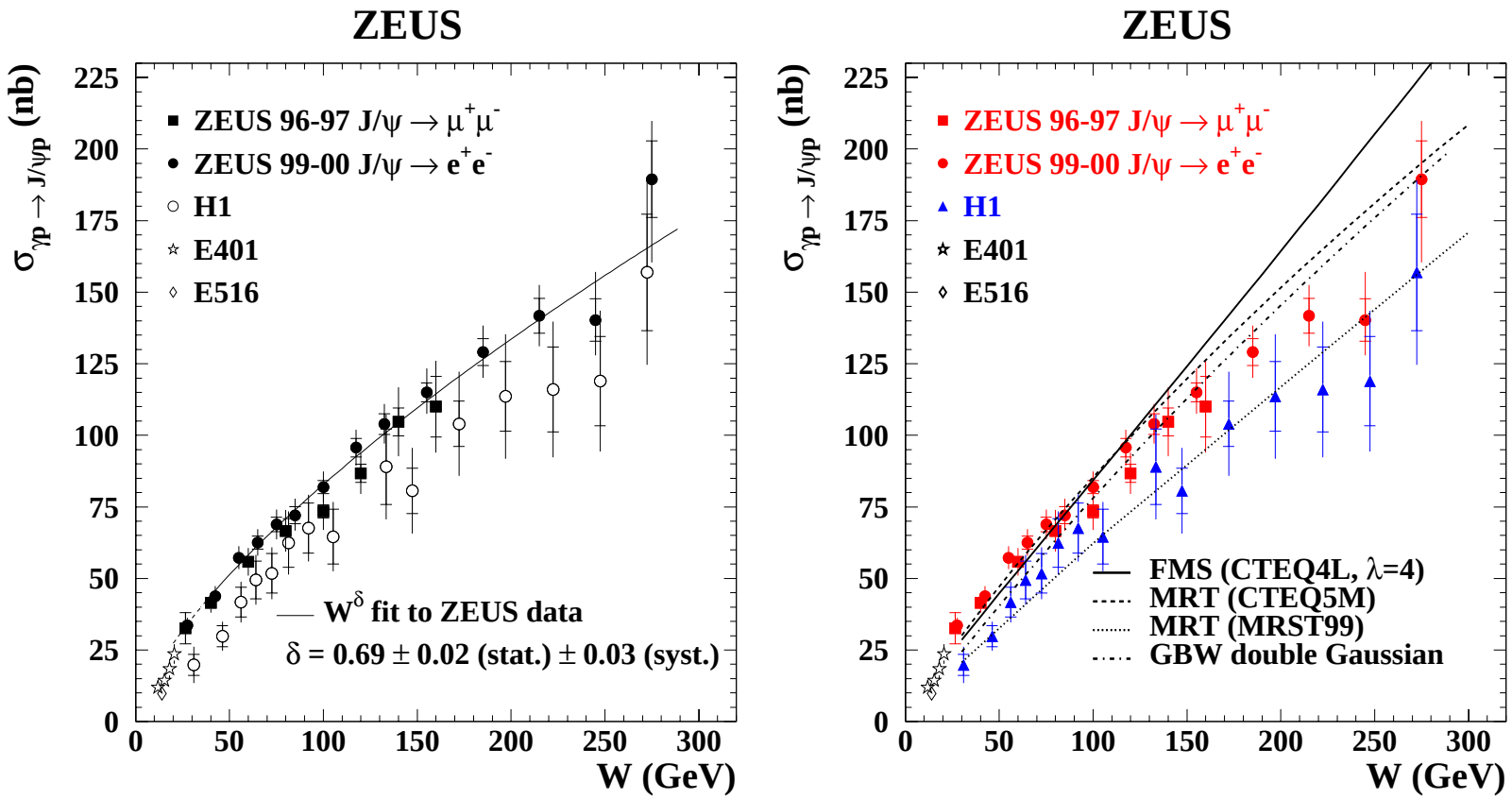


$\sigma_{\gamma p \to \rho p} \propto W^{0.22}$ $b_\rho \propto ln(W)$

$\Rightarrow$ consistent with Regge phenomenology

EXCLUSIVE J/ψ IN γp

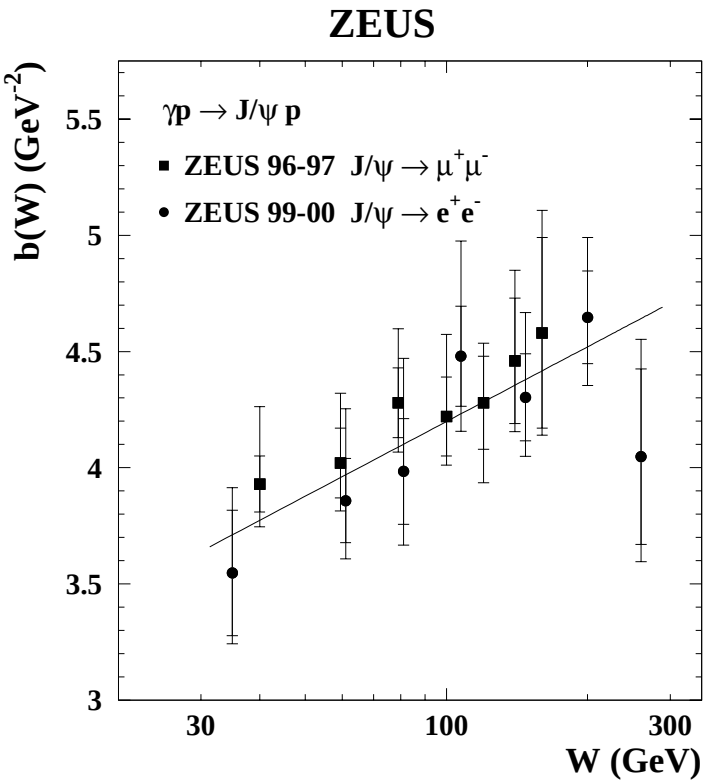
$\sigma(\gamma p \to J/\psi p)$

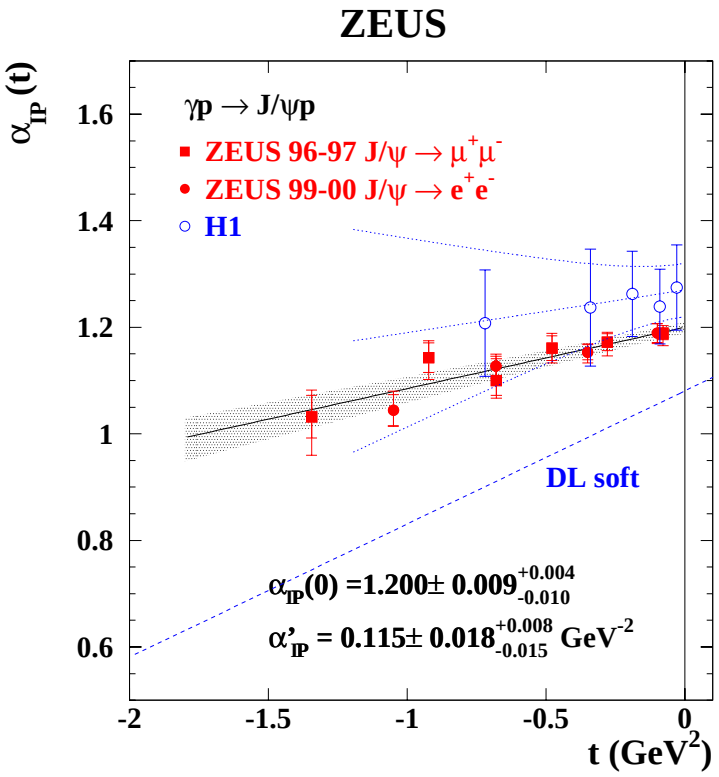


- Fast rise with W, compatible with pQCD calculations
- Deconvolution of $xg(x, Q^2)$ from data still not possible

EXCLUSIVE J/ψ IN γp

b slopes and $I\!P$ trajectory

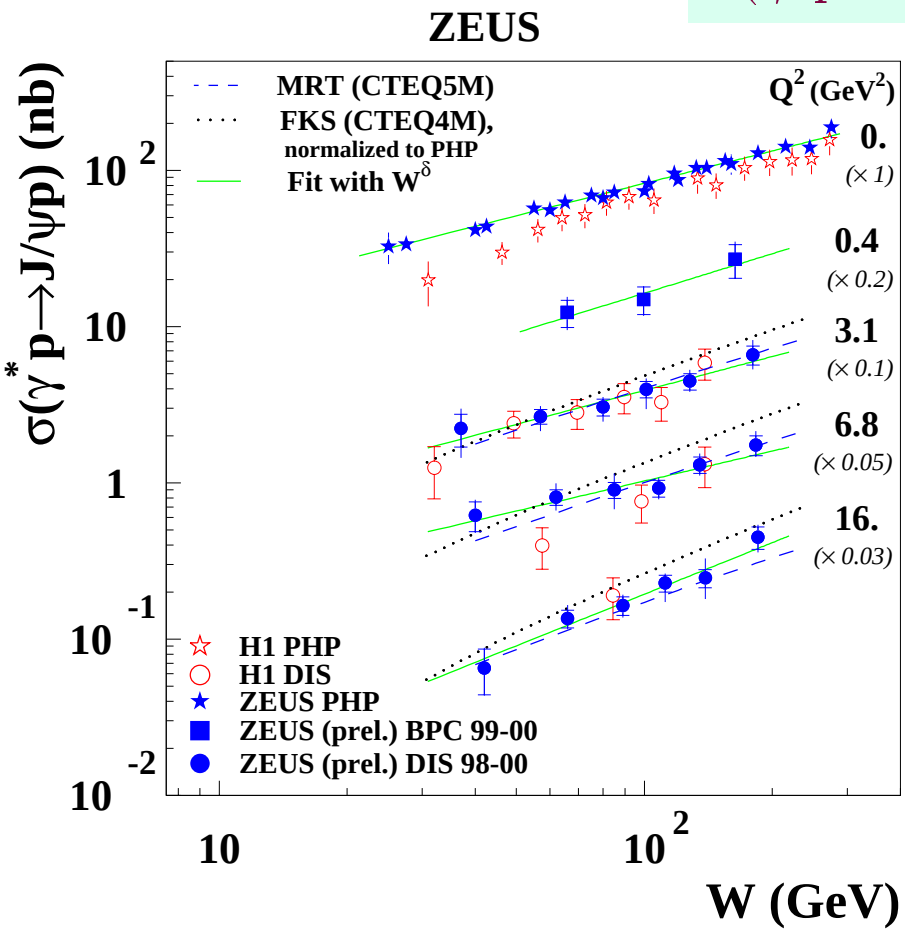




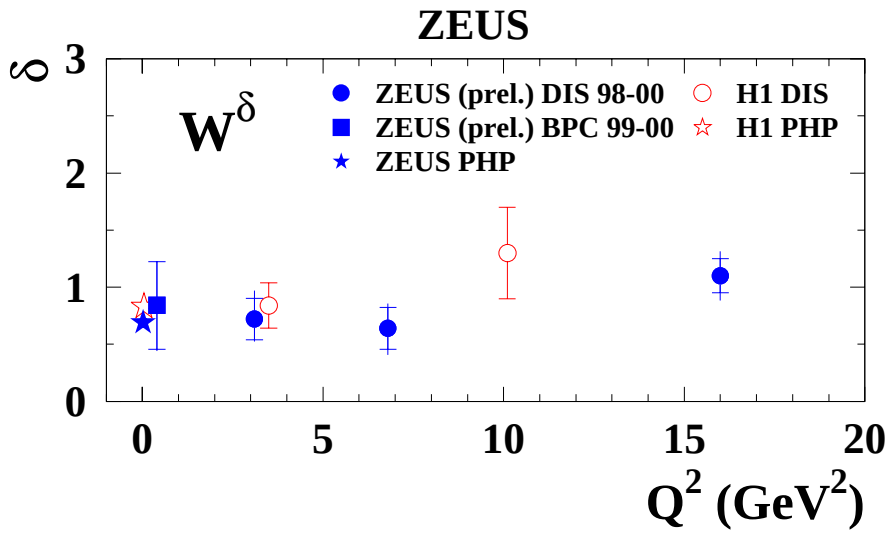
- $b \simeq 4$ GeV^2 $\Rightarrow$ point-like interaction
- Slight rise of b with W

EXCLUSIVE J/ψ IN $\gamma^* p$

$\sigma(\gamma^* p \to J/\psi p)$



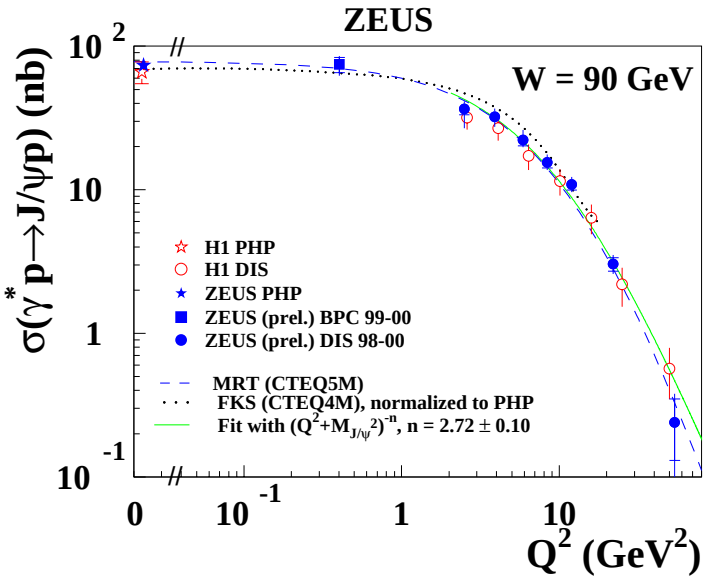
$\sigma_{\gamma^* p \to J/\psi p} \propto W^{\delta}$ at different Q^2

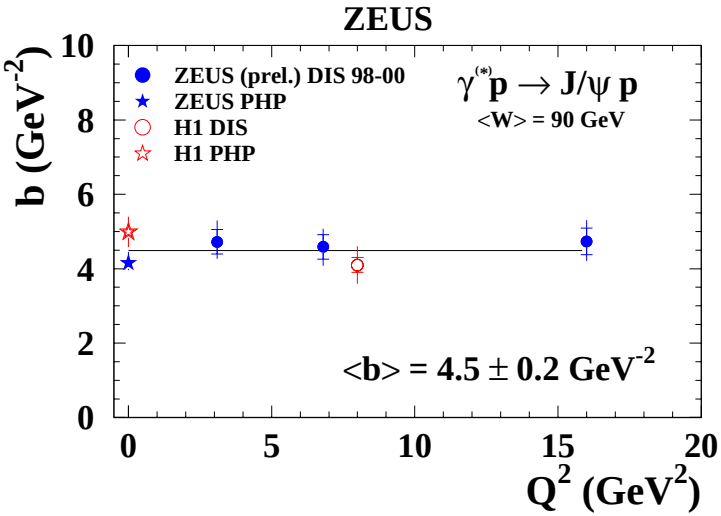


- $\delta \sim$ flat with Q^2

EXCLUSIVE J/ψ IN $\gamma^* p$

$\sigma(\gamma^* p \to J/\psi p)$ and b vs Q^2

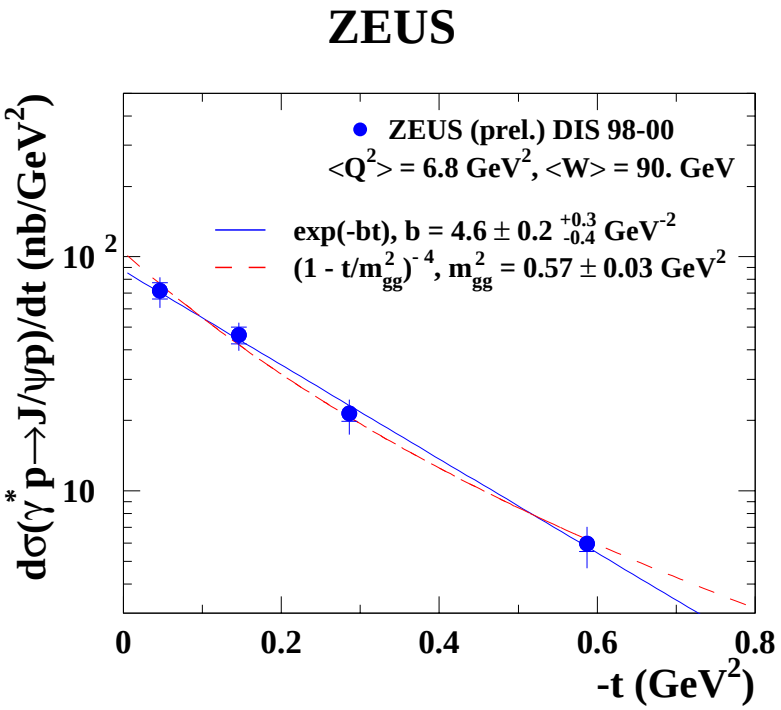




$\Rightarrow$ J/ψ production has all the characteristics of a hard process

EXCLUSIVE J/ψ IN $\gamma^* p$

"Proton elastic form-factor"

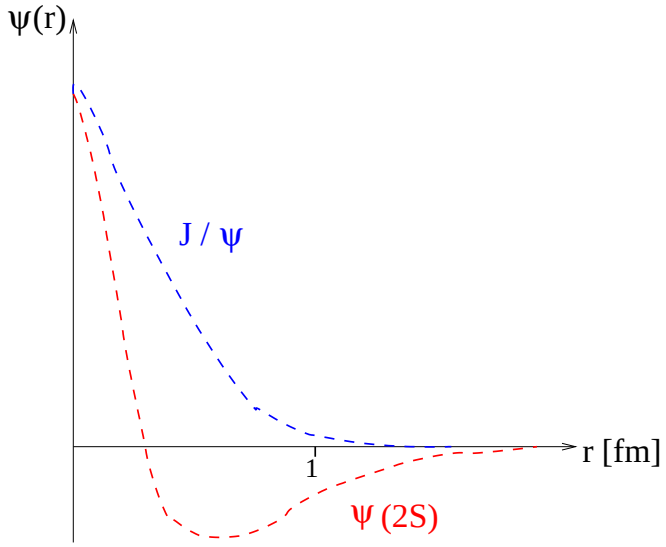


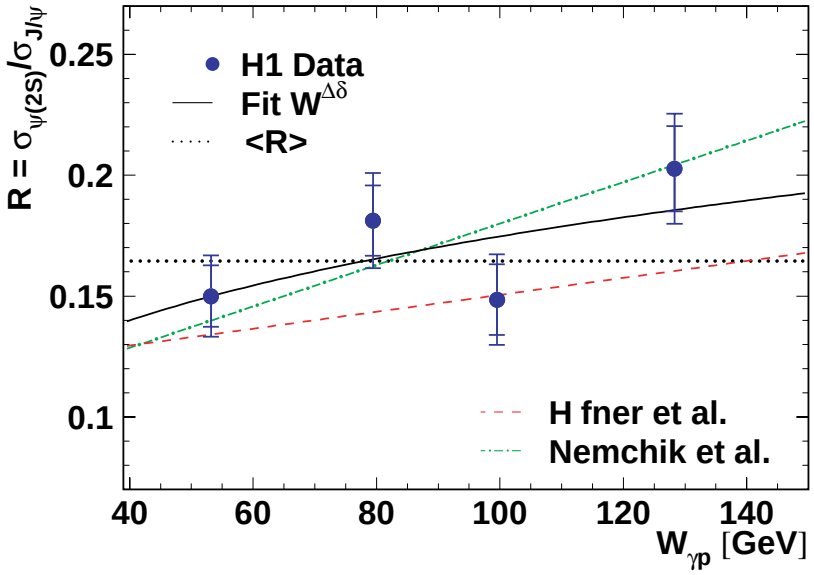
- In QCD, at high Q^2, b related to transverse gluon distribution
- Form $(1 - t/m_{2g}^2)^{-4}$ suggested as elastic form-factor of $2g$ exchange by Frankfurt and Strikman

DIFFRACTIVE $\psi(2S)$ IN γp

Ratio $R = \frac{\sigma(\psi(2S)p)}{\sigma(J/\psi p)}$ sensitive to the radial wave function of charmonium

QCD prediction $R \simeq 0.17$

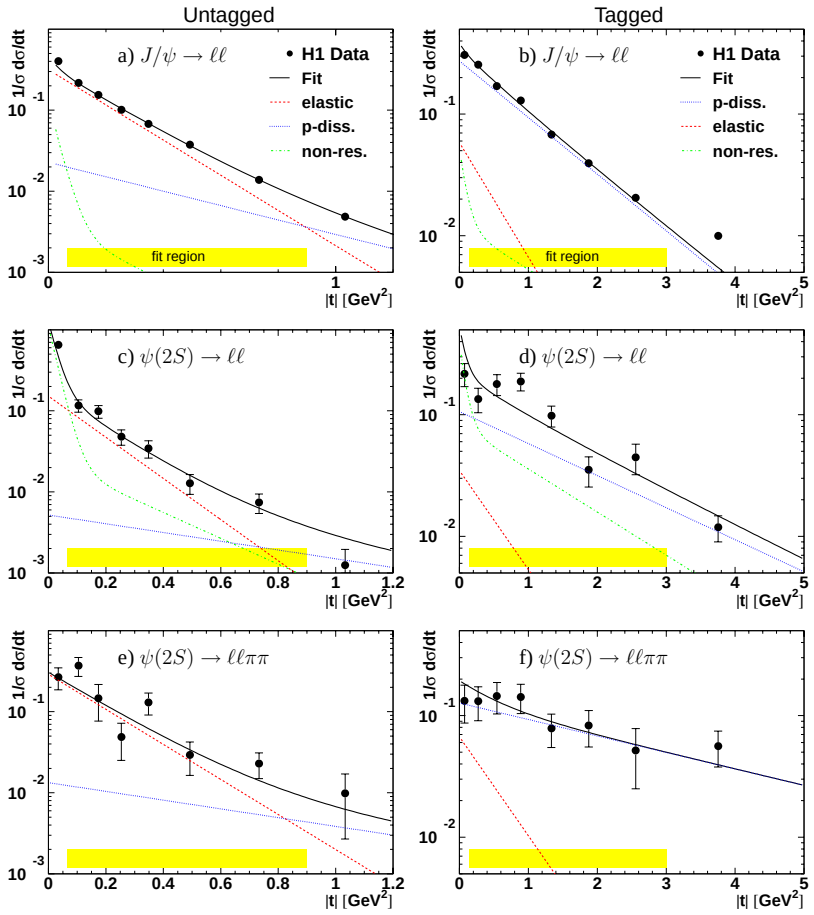




- $\psi(2S)$ production suppressed
- Energy dependence similar to J/ψ

DIFFRACTIVE $\psi(2S)$ IN γp

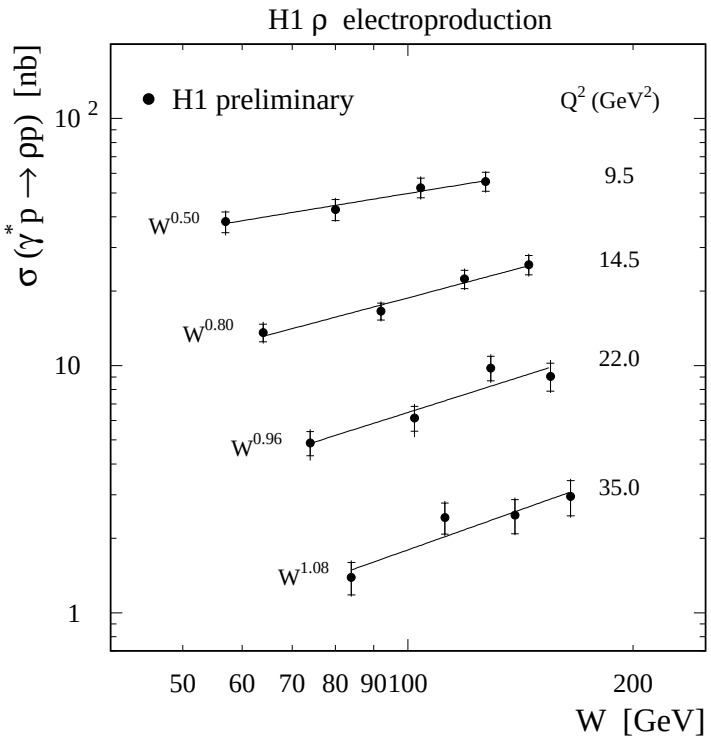
$d\sigma/dt(\gamma p \to \psi p)$ $d\sigma/dt(\gamma p \to \psi Y)$

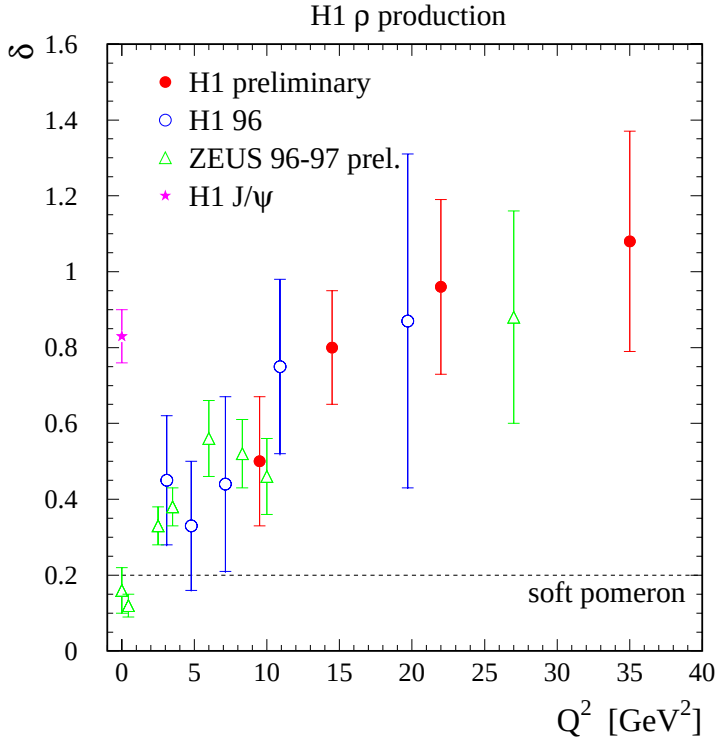


- t-dependence of J/ψ and $\psi(2S)$ is similar

EXCLUSIVE ρ^0 MESON IN $\gamma^* p$

W dependence of $\sigma(\gamma^* p \to \rho^0 p)$

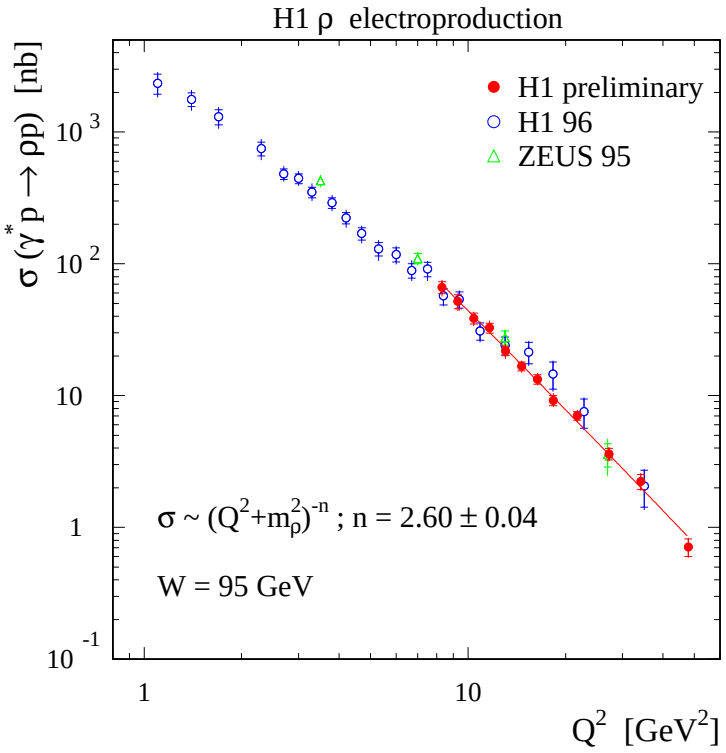




$\sigma_{\gamma^* p \to \rho p} \propto W^{\delta}$ at different Q^2, $\Rightarrow$ δ increases with Q^2

EXCLUSIVE ρ^0 MESON IN $\gamma^* p$

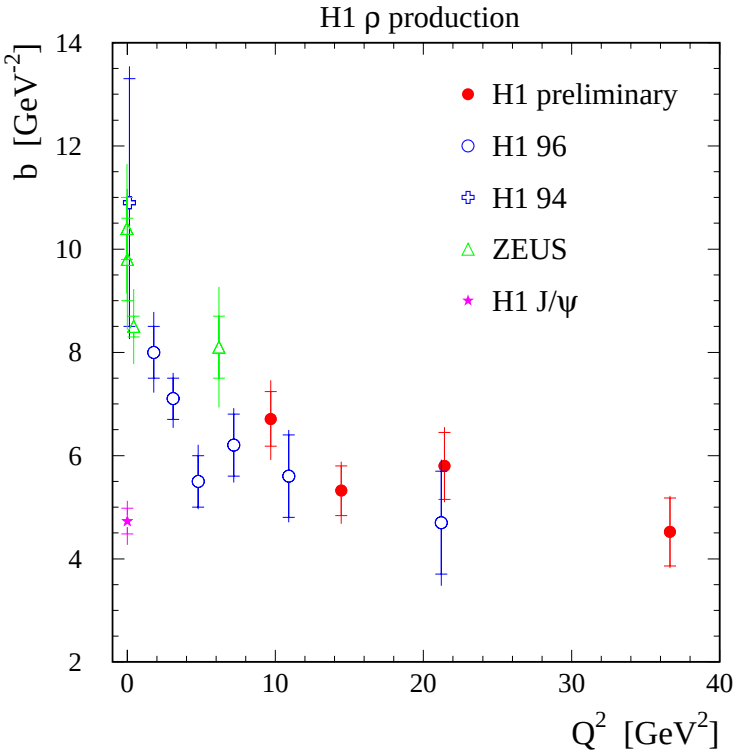
Q^2 dependence of $\sigma(\gamma^* p \to \rho^0 p)$

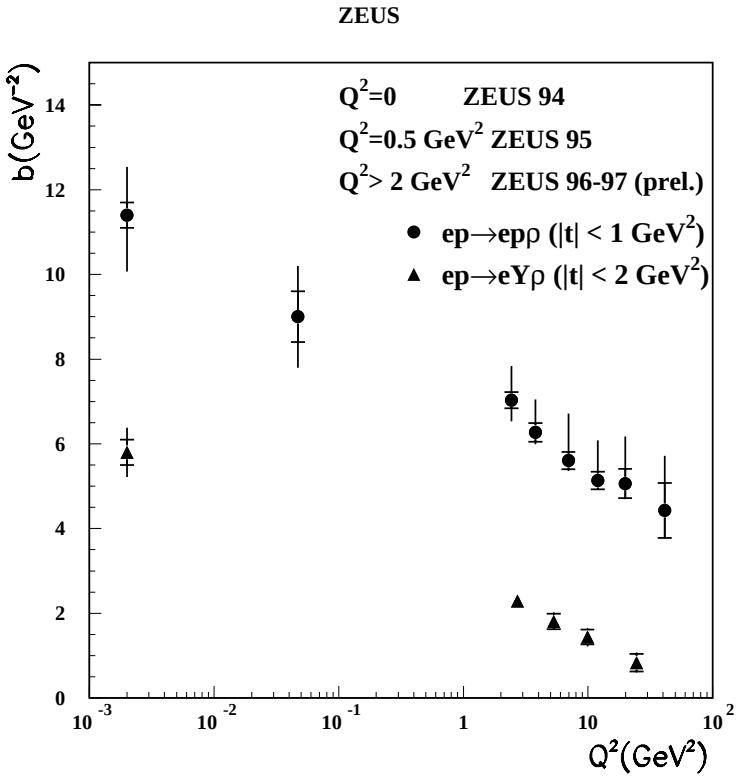


$\Rightarrow$ pQCD: $\sigma_L \sim \frac{\alpha_S^2}{Q^6} \mid xG(x,Q^2) \mid^2$

ρ^0 MESON IN $\gamma^* p \to \rho^0 p$ AND $\gamma^* p \to \rho^0 Y$

Q^2 dependence of b

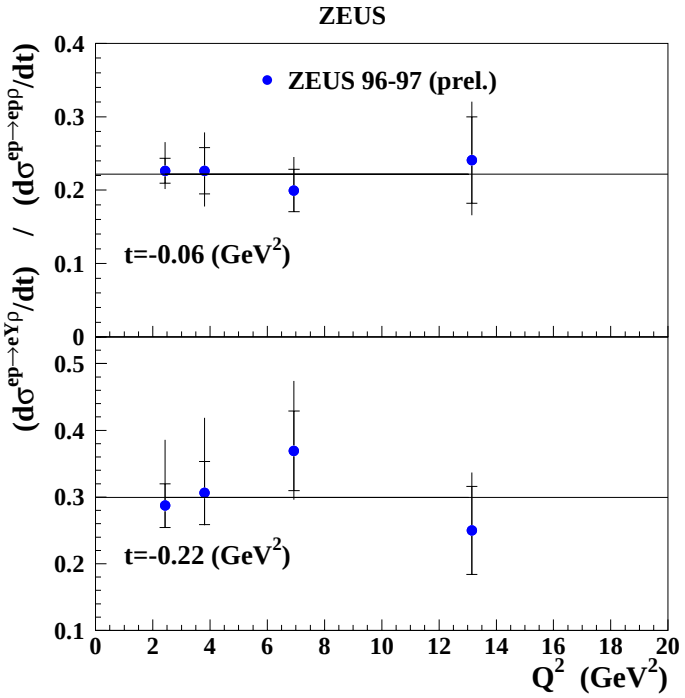




$\Rightarrow$ b decreases with Q^2 for both exclusive and p-diss. reaction

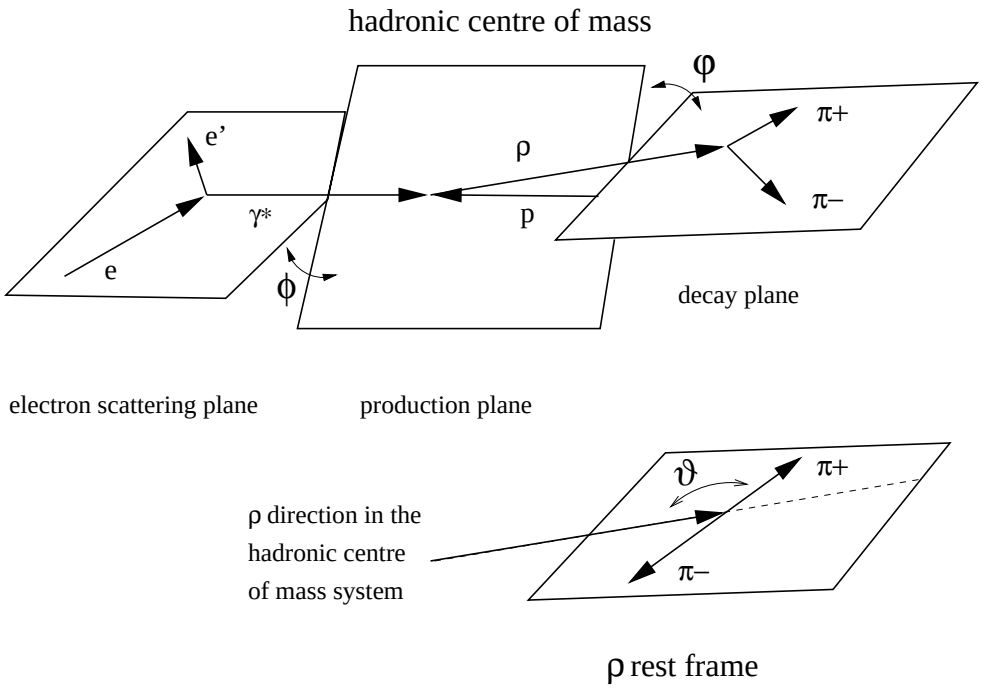
ρ^0 MESON IN $\gamma^* p \to \rho^0 p$ AND $\gamma^* p \to \rho^0 Y$

Q^2 dependence of $d\sigma/dt$



$\Rightarrow$ Vertex factorization holds: probability of proton dissociation is independent of the projectile

DECAY ANGULAR DISTRIBUTIONS



Helicity angles

θ_h, ϕ_h - angles of decay particle in the meson rest frame

Φ - angle between scattering and production plane

- Angular distributions are related to the spin of γ^* and meson

Angular distr. $\rightarrow$ spin density matrix elements $r_{ij}^{kl} \rightarrow$ helicity amplitudes $T_{\lambda_V M \lambda_\gamma}$

Decay Angular Distributions

Spin Matrix Elements

s-channel helicity conservation (SCHC):

- the VM retains the γ^* helicity. $R = \sigma_L/\sigma_T$ is related to the spin density matrix elements r^{04}_{00} (good approximation).

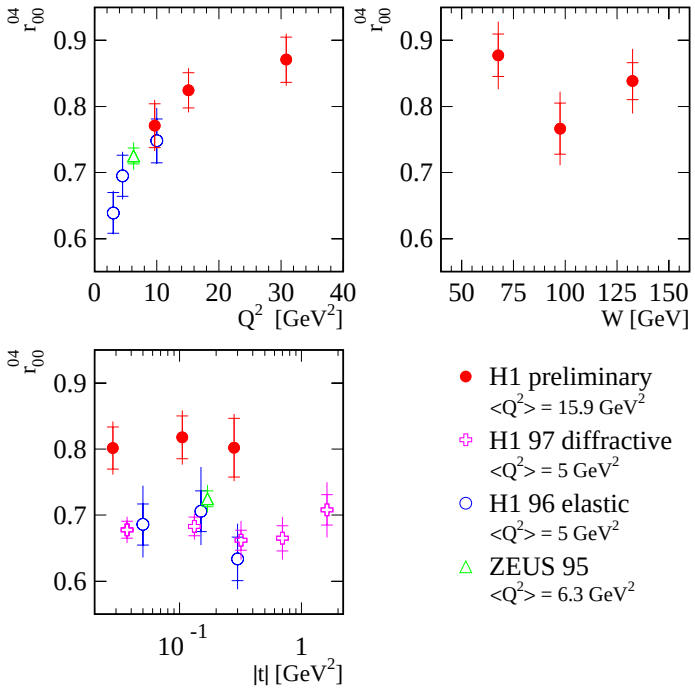
pQCD:

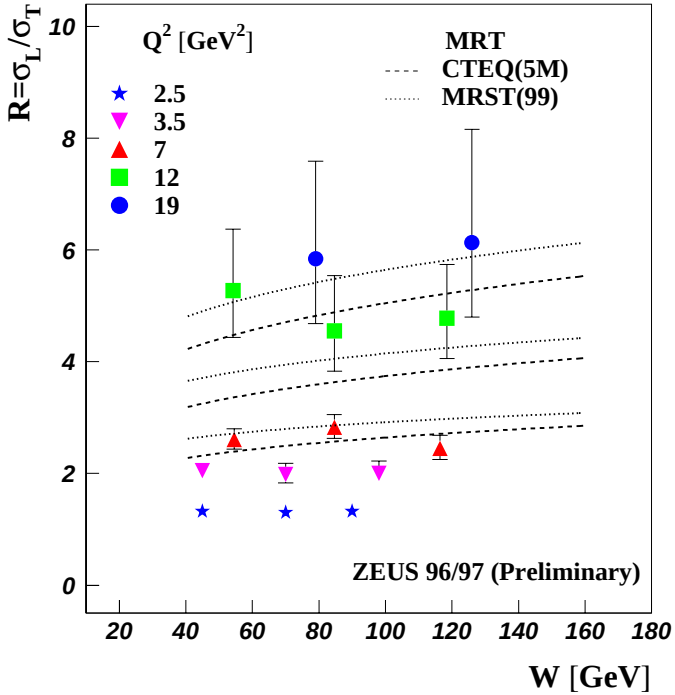
- during the interaction, the orbital angular momentum of the $q\overline{q}$ can be modified through the transfer of transverse momentum carried by gluons;
- the helicity of the outgoing vector meson can be different from that of the incoming photon, helicity flip between photon and meson is possible.

EXCLUSIVE ρ^0 MESON IN $\gamma^* p$

Spin Matrix Elements $\sigma(cos(\theta)) \rightarrow r_{00}^{04}$

$$R = \sigma_L/\sigma_T \simeq \frac{r_{00}^{04}}{\epsilon(1-r_{00}^{04})}$$

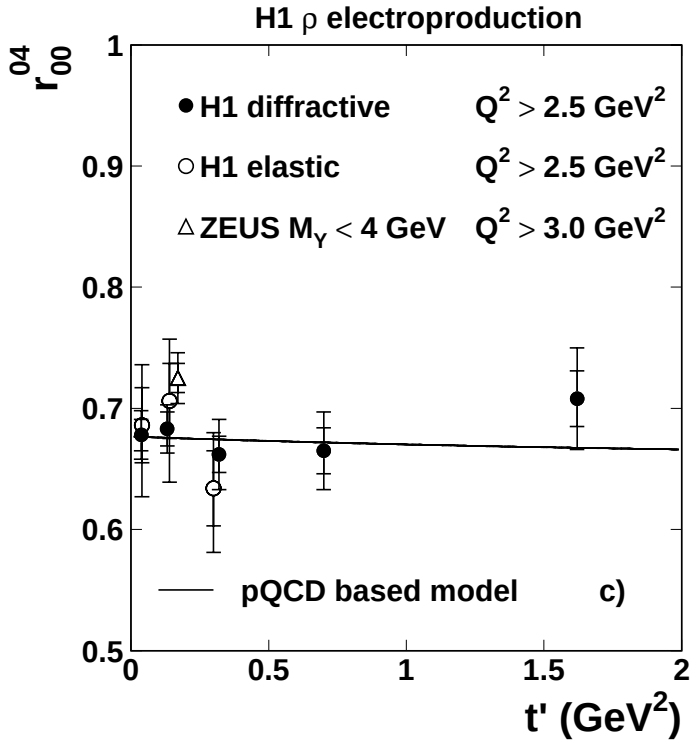




- σ_L and σ_T have the same W and t dependence

ρ^0 MESON IN $\gamma^* p \to \rho^0 Y$

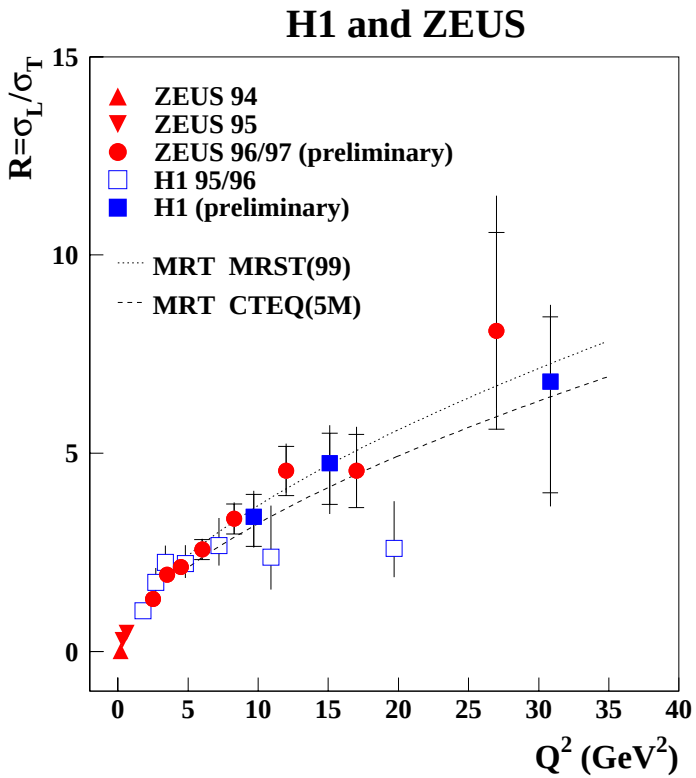
Spin Matrix Elements, $\sigma(cos(\theta)) \to r_{00}^{04}$



- σ_L and σ_T have the same t dependence

EXCLUSIVE ρ^0 MESON IN $\gamma^* p$

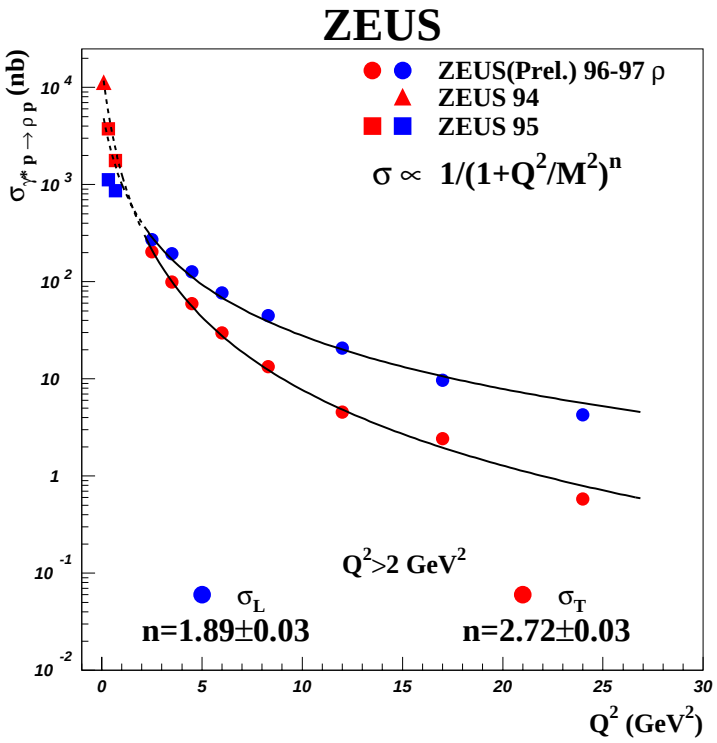
$$R = \sigma_L/\sigma_T \simeq \frac{r_{00}^{04}}{\epsilon(1-r_{00}^{04})}$$



$\Rightarrow$ Continuous rise of R with Q^2

EXCLUSIVE ρ^0 MESON IN $\gamma^* p$

Q^2 dependence of $\sigma(\gamma^* p \to \rho^0 p)$

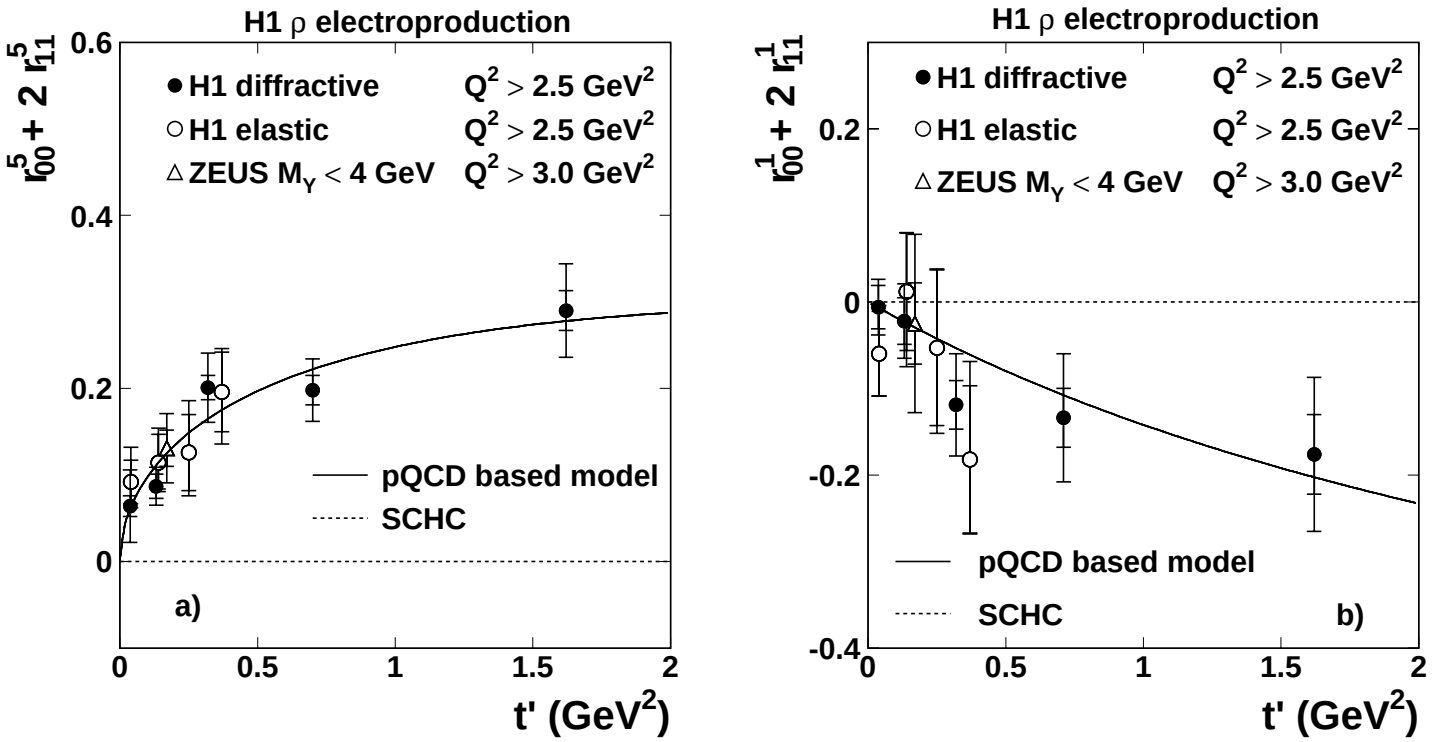


$\Rightarrow$ As expected different n for σ_L and σ_T

ρ^0 MESON IN $\gamma^* p \to \rho^0 Y$

$\sigma(cos(\Phi)) \to r^5_{00} + 2r^5_{11}$, sensitive to single flip

$\sigma(cos(2\Phi)) \to r^1_{00} + 2r^1_{11}$, sensitive to double flip

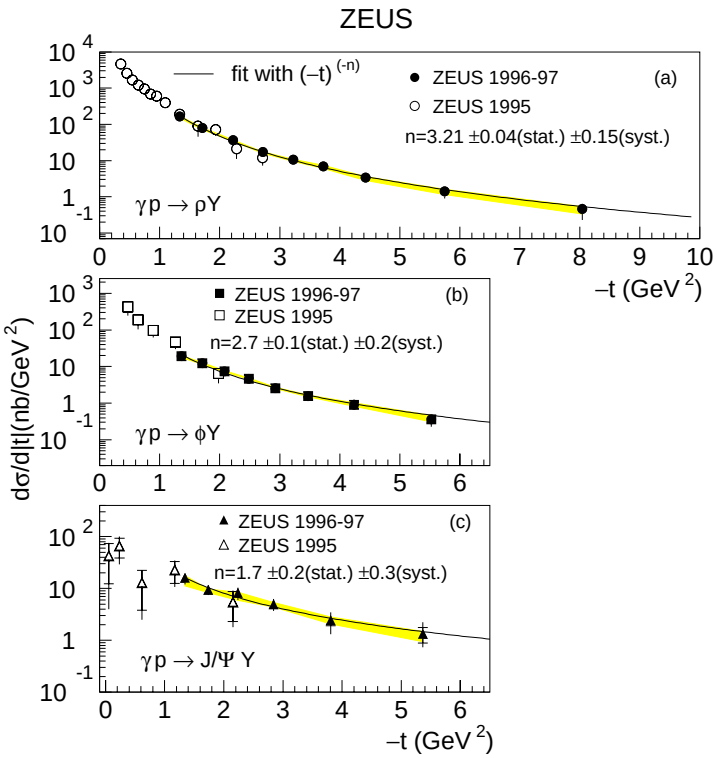


- Ratio of single flip to non flip amplitudes increases with t'

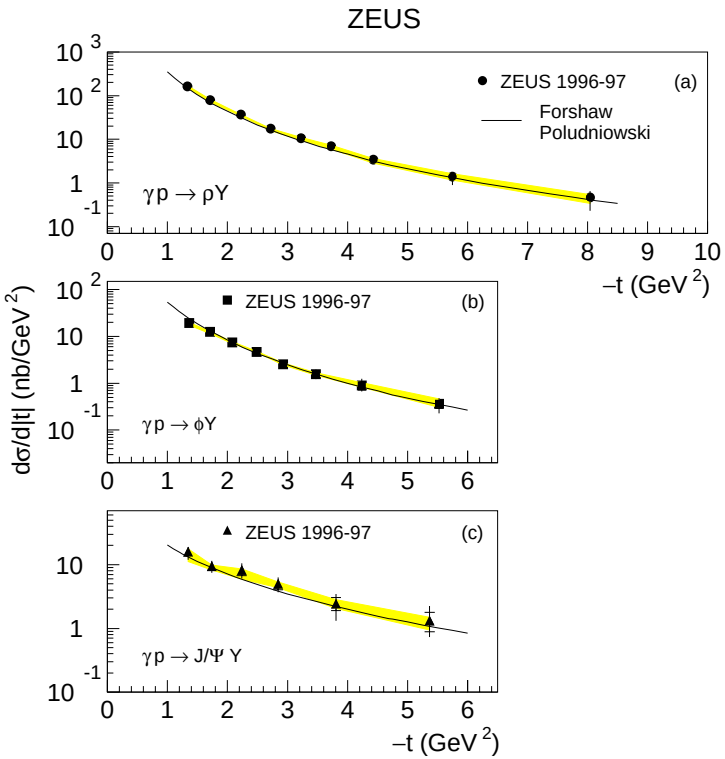
Probability of double flip is still small in this t-kinematic domain

HIGH-t ρ^0, ϕ AND J/ψ IN γp

t dependence of $\sigma(\gamma p \to VY)$



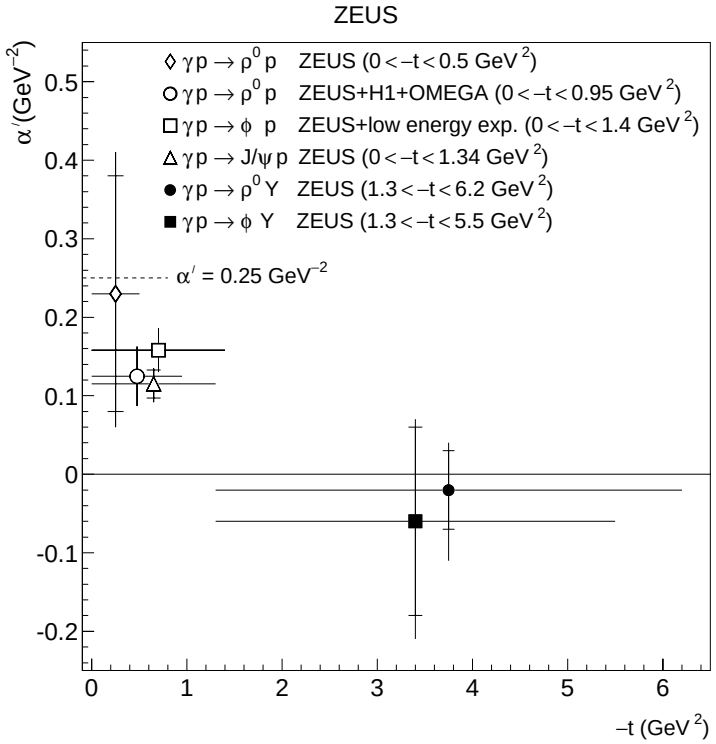
⇒ power-like behavior

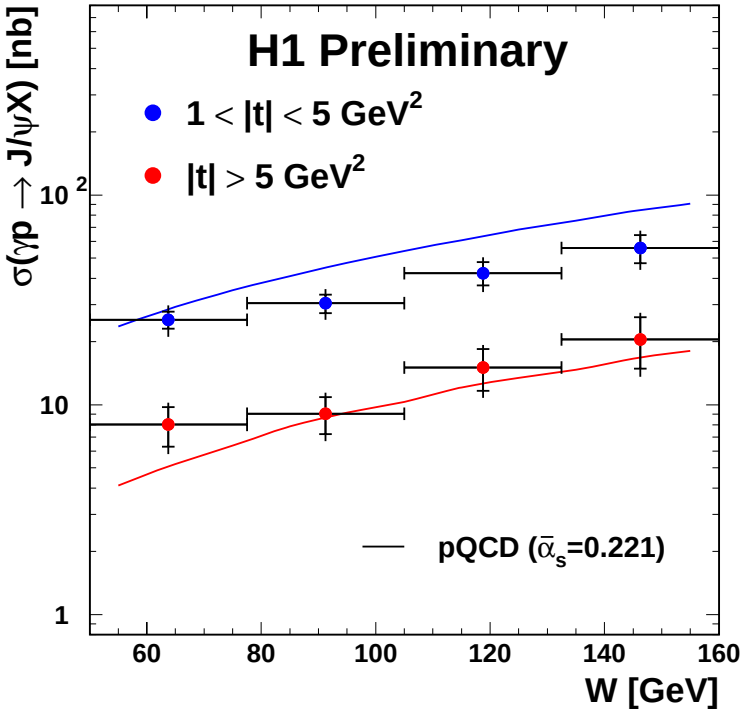


⇒ BFKL-type behavior

HIGH-t ρ^0, ϕ AND J/ψ IN γp

t dependence of $\alpha'_{I\!P}$ and W



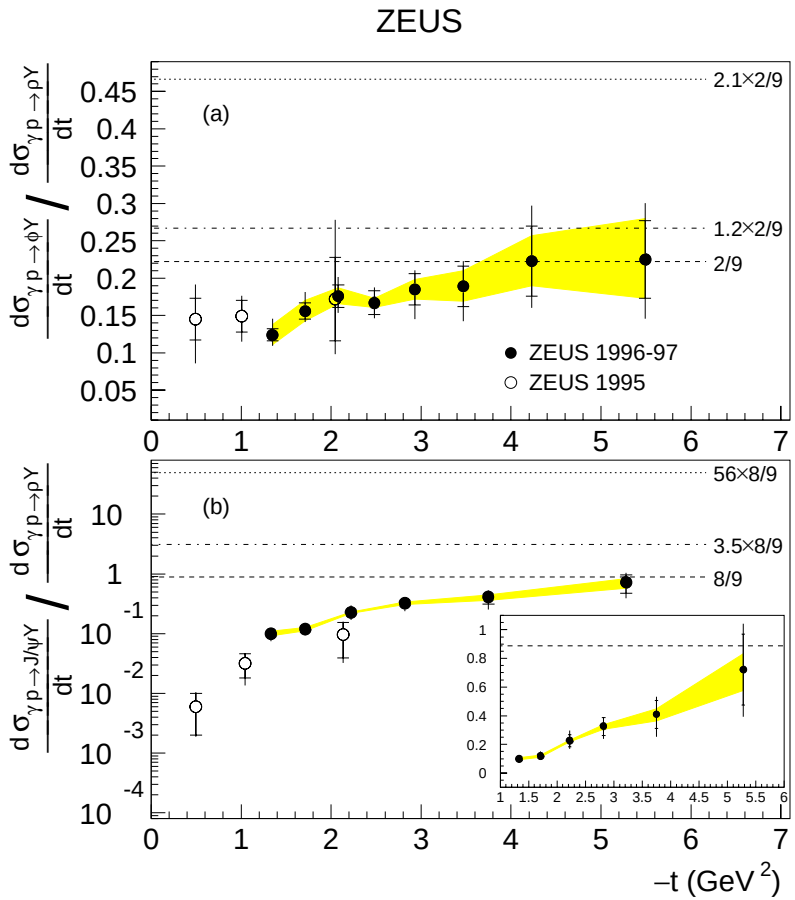


$\alpha'_{I\!P}$ small $\equiv$ W dependence not change with t, described by pQCD

$\Rightarrow$ t provides an hard scale; $\alpha_{I\!P}(t)$ is not linear in t

HIGH-t ρ^0, ϕ AND J/ψ IN γp

$\sigma_{\phi,J/\psi}/\sigma_\rho$ ratios at high t and $SU(4)$

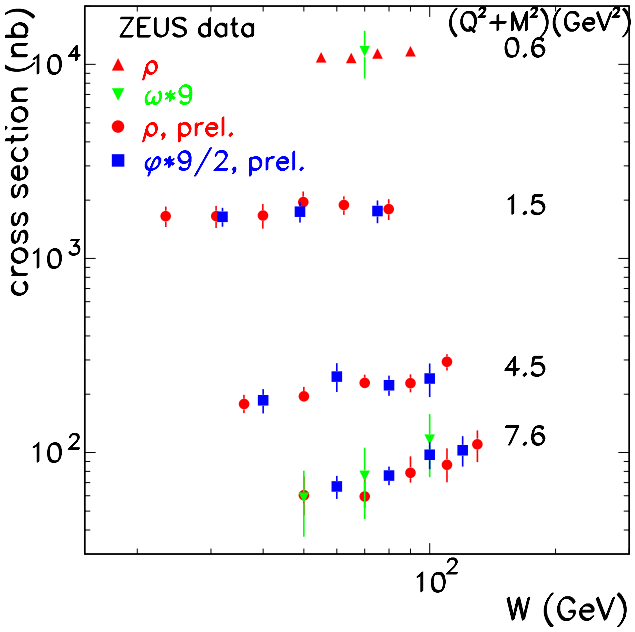


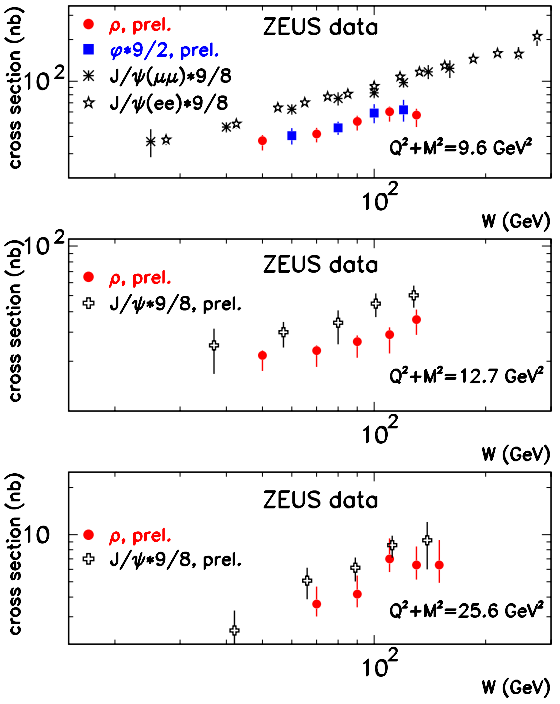
- Indication of VM production flavour independent at high t

OVERVIEW OF VECTOR MESON PRODUCTION

$SU(4)$?

- Scaling of $\sigma(\gamma^* p \rightarrow Vp)$ $\Rightarrow$ does not work for J/ψ in $Q^2 + M_V^2$ proposed by H1



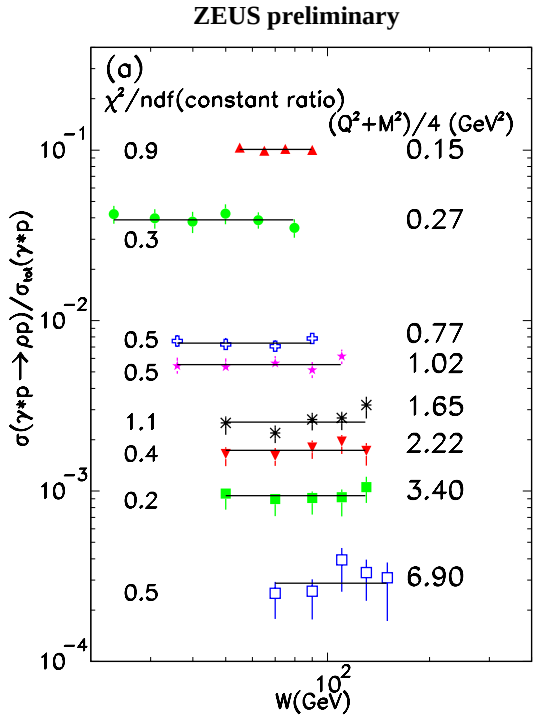


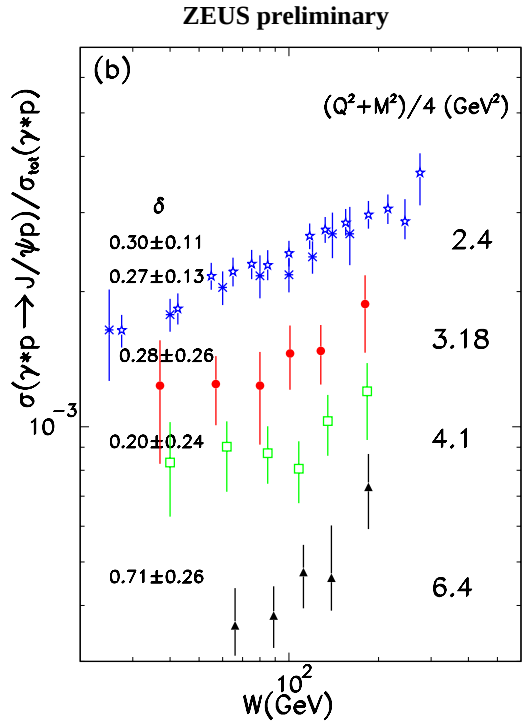
- No simple universality for VM if $Q^2 + M^2$ is used as a scale
- Naive $SU(4)$ may be altered by VM wave function effects

OVERVIEW OF VECTOR MESON PRODUCTION

$$r_V = \frac{\sigma(\gamma^* p \to V p)}{\sigma_{\rm tot}(\gamma^* p)} \text{ vs } W$$

Expectation: $\sigma_{\rm tot}(\gamma^* p) \propto W^{\delta}$, $\sigma(\gamma^* p \to V p) \propto W^{2\delta} \Rightarrow r_V \propto W^{\delta}$



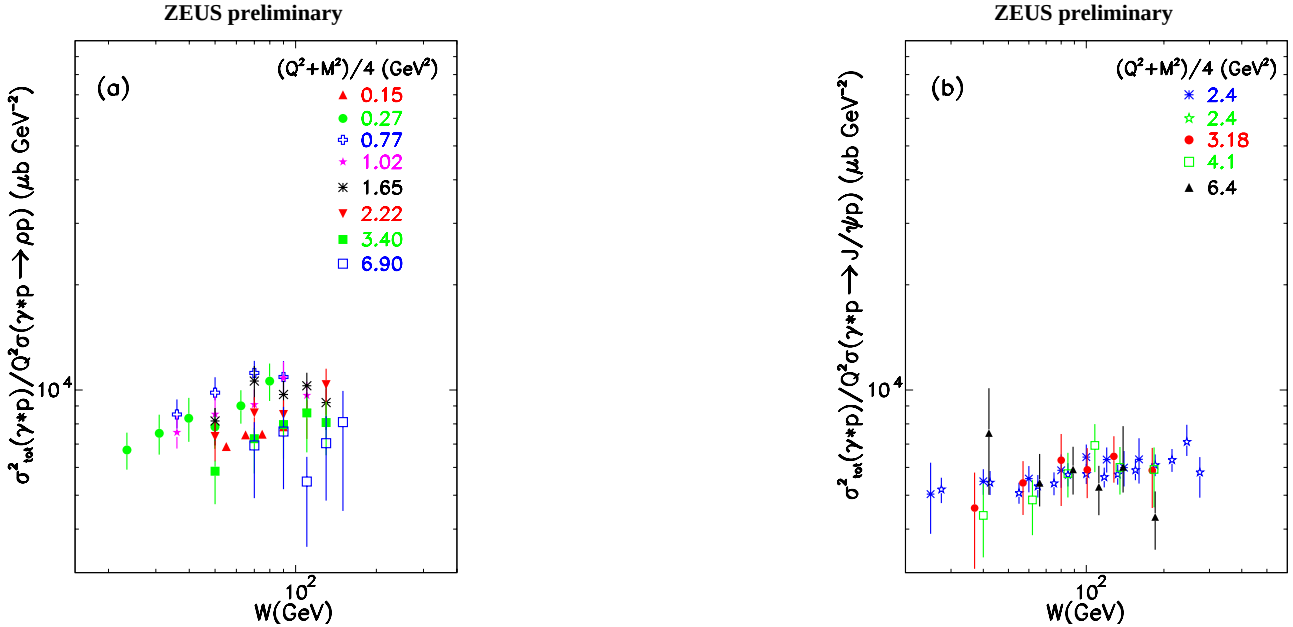


- W independence of r_V for ρ^0 can not be explained by pQCD or Regge; it is similar to inclusive diffraction

OVERVIEW OF VECTOR MESON PRODUCTION

$$\frac{\sigma^2_{\rm tot}(\gamma^* p)}{\sigma(\gamma^* p \to V p)} \text{ vs } W$$

Typical for $2g$ exchange: $\frac{\sigma^2_{\rm tot}(\gamma^* p)}{\sigma(\gamma^* p \to V p)} \propto \frac{1/(\alpha_S^2(Q^2)Q^4)}{1/(Q^6 \cdot b)} \propto Q^2 \cdot b$



- Confirms the perturbative/non-perturbative $2g$ exchange as opposed to VDM mechanism

Summary and Outlook

- Experimentally much progress has been achieved,
  - high precision in large kinematic region
- Theoretically the overall picture looks correct,
  - large uncertainties
  - full NLO calculations are missing
- For the near future:
  - increased statistics at high Q^2 will help (HERA II),
  - Υ remains to be investigated (HERA II)