

Vector Meson Production at HERA

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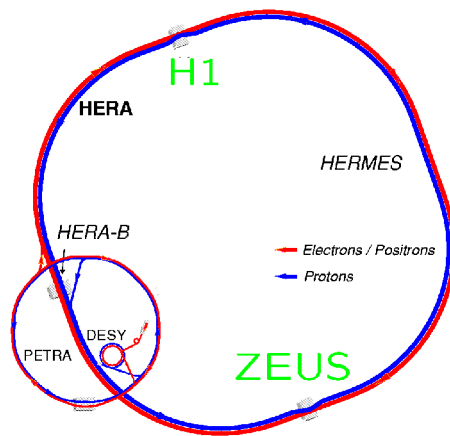
On behalf of ZEUS and H1 collaborations



- Introduction
- New results on elastic photo- and electroproduction
- Pomeron trajectory
- Looking for universality in VM production
- Proton-dissociative electro- and photoproduction
- Helicity studies
- Summary and Outlook

Hadron Structure 02, Herlany, Slovakia, September 22 - 27, 2002

HERA ep collider

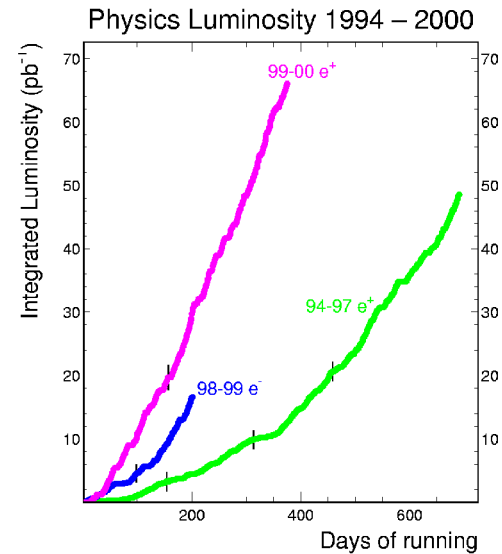


H1, ZEUS:

$$e^{\pm} \Rightarrow \Leftarrow p$$

27.5 GeV 920 GeV

$$\sqrt{s} = 320 \text{ GeV}$$



1994 – 1997

e^+p at $\sqrt{s} = 300 \text{ GeV}$
45 pb^{-1}

1998 – 1999

e^-p at $\sqrt{s} = 320 \text{ GeV}$
16 pb^{-1}

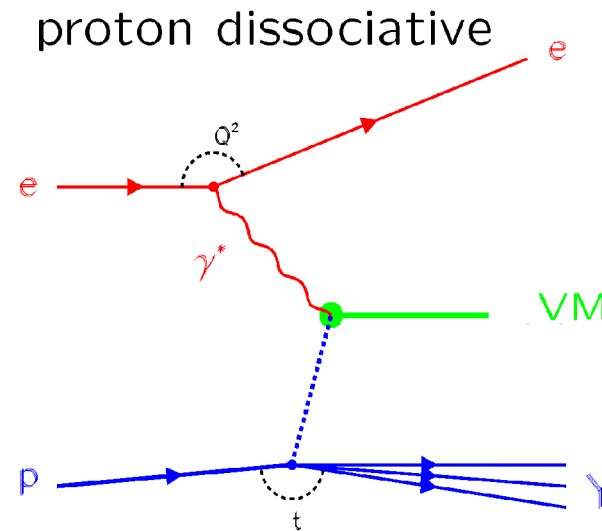
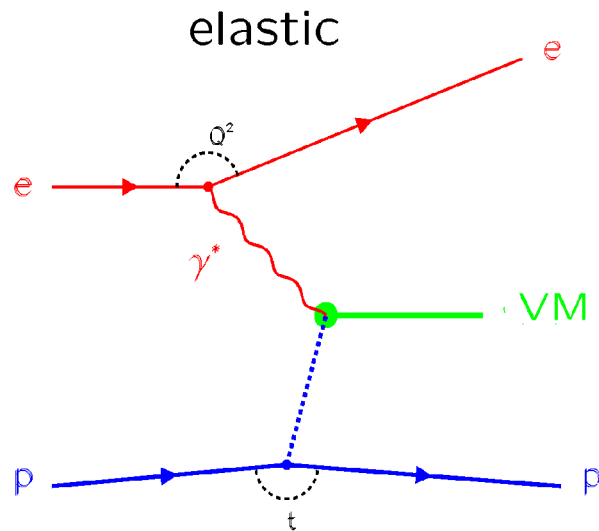
1999 – 2000

e^+p at $\sqrt{s} = 320 \text{ GeV}$
68 pb^{-1}

Half of the HERA I luminosity collected in 1999 - 2000 !

Only part of the data analysed so far!

Diffractive vector meson production at HERA



VM Vector Meson

$\rho^0, \omega, \phi, J/\psi, \psi', \Upsilon$

Q^2 γ^* virtuality

$0 < Q^2 < 70 \text{ GeV}^2$

W CM energy of $\gamma^* p$ system

$20 < W < 290 \text{ GeV}$

t (4-mom. transfer)²

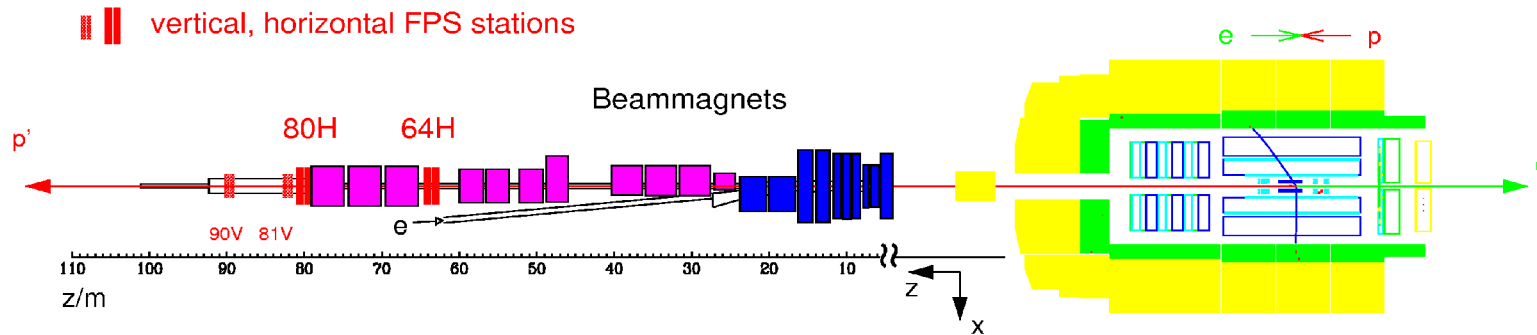
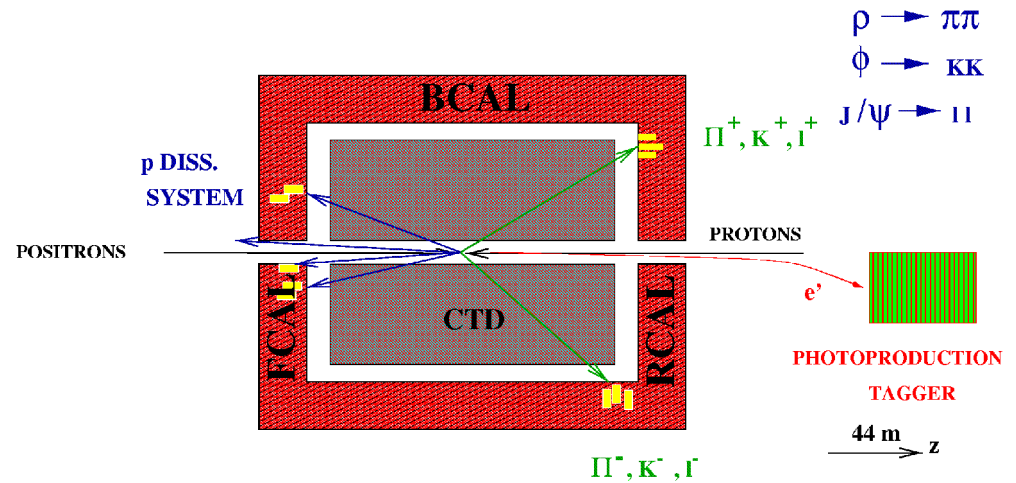
$0 < |t| < 20 \text{ GeV}^2$

At HERA we control all these variables!

Vector Meson Detection

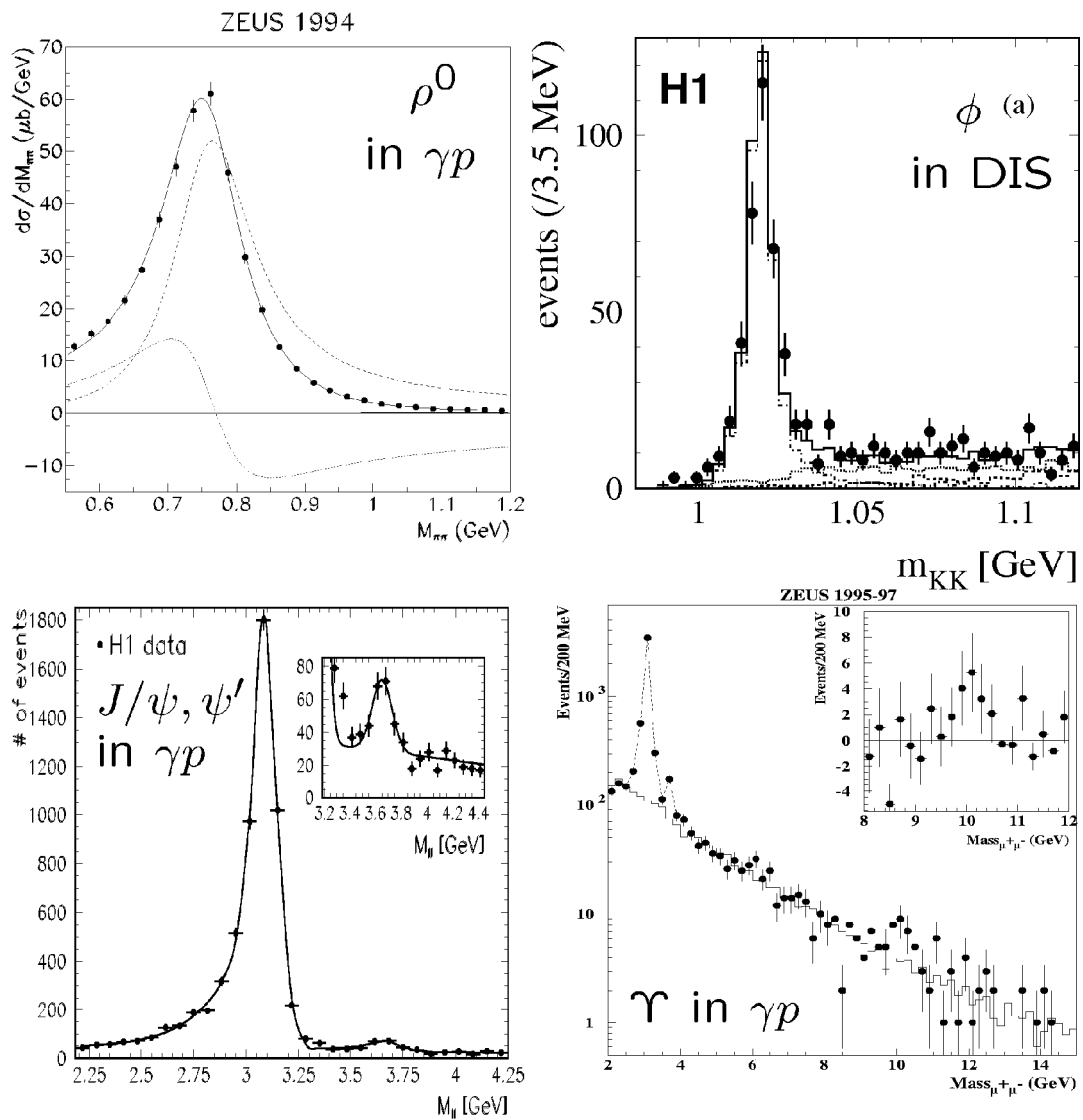
Schematic view of the **ZEUS** detector:

- charged tracks - VM (+positron in DIS)
- energy deposits in calorimeters
- extra detectors:
for protons,
proton remnants,
photoproduction tagger

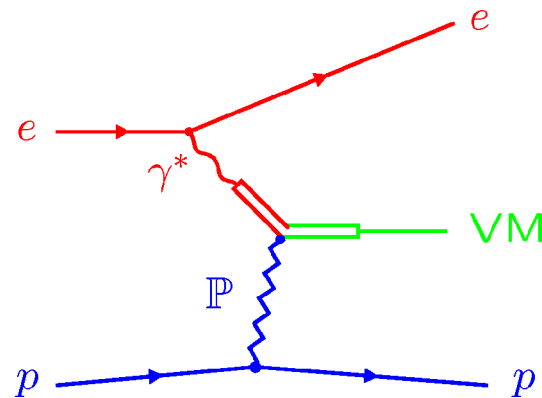


Elastic ρ^0 photoproduction in **H1** detector with a leading proton detected in the **Forward Proton Spectrometer**

Vector Meson Signals



Diffraction Vector Meson Production Models



VMD + Regge: $\gamma^* p \rightarrow Vp = (\gamma^* \rightarrow V) \times (Vp \rightarrow Vp)$

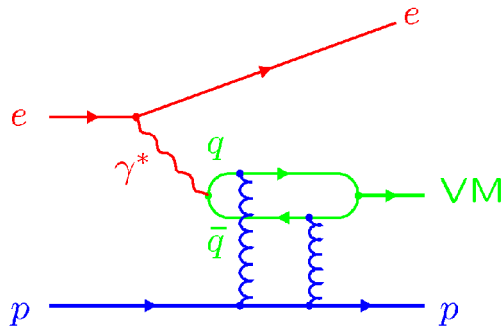
- $Vp \rightarrow Vp =$ “soft” interaction \Rightarrow Pomeron exchange
- $\alpha_P(t) = \alpha_0 + \alpha' t = 1.08 + 0.25 t$ (Donnachie-Landshoff)
- $d\sigma/dt \sim e^{b(W)t}$, $b \sim R_{int}^2$
- $b(W) = 2(b_{VM} + b_p + \alpha' \ln(W^2)) \Rightarrow$ shrinkage
- $\sigma_{Vp} \sim W^{4(\alpha_0 - 1)}/b(W) \sim W^\delta$, $\delta \approx 0.22 \Rightarrow$ weak energy dependence
- **S Channel Helicity Conservation** - VM retains γ^* helicity

Diffraction Vector Meson Production Models

BUT: “large” Q^2 , M_{VM} or $|t|$ = “small” VM and interaction size \Rightarrow “hard” interaction

\Rightarrow perturbative QCD applicable:

VM = qq dipol, exchange of ≥ 2 gluons (color singlet - QCD Pomeron)



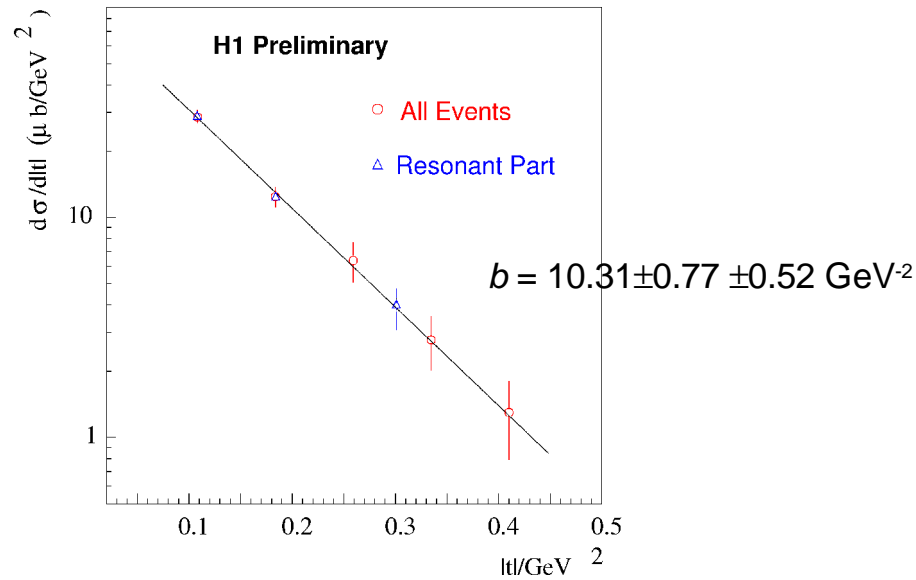
- Steeper rise of σ_{vp} with W , ($\sigma_{vp} \sim [x g(x, Q^2)]^2$, $x \approx Q^2/W^2$)
- Weaker t dependence, less shrinkage with W
- dominant longitudinal γ^* polarisation
- possible SCHC violation

VM at HERA: transition between soft and hard regime \Rightarrow testbed for pQCD scales:

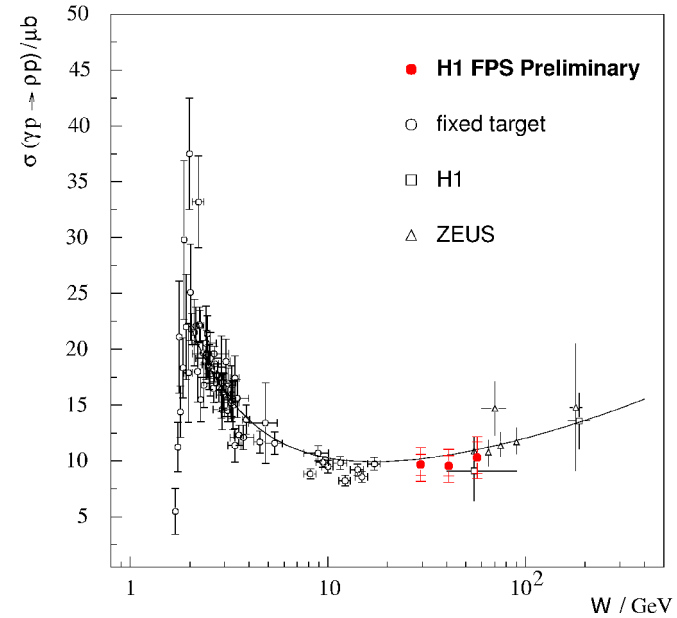
$$M_{VM}^2, \quad Q^2, \quad |t|$$

Elastic ρ^0 photoproduction with a leading p

Diffractive slope

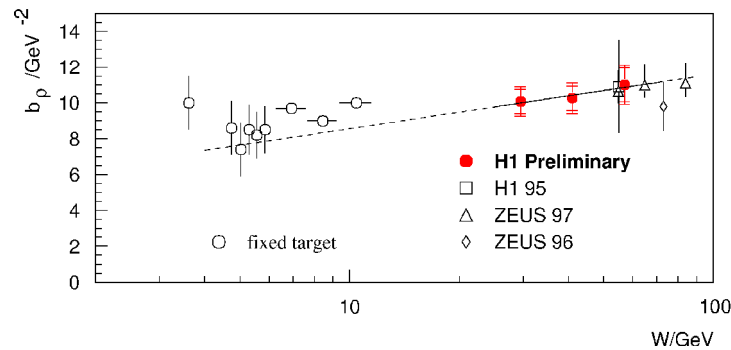


Energy dependence



$$\sigma(\gamma p \rightarrow \rho p) \sim W^{0.22}$$

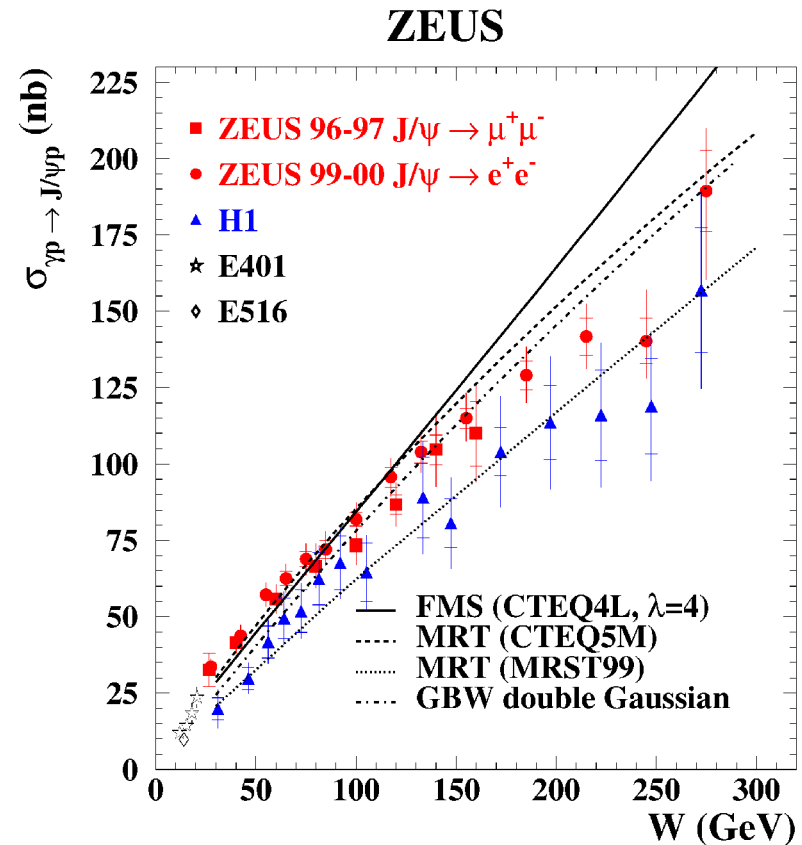
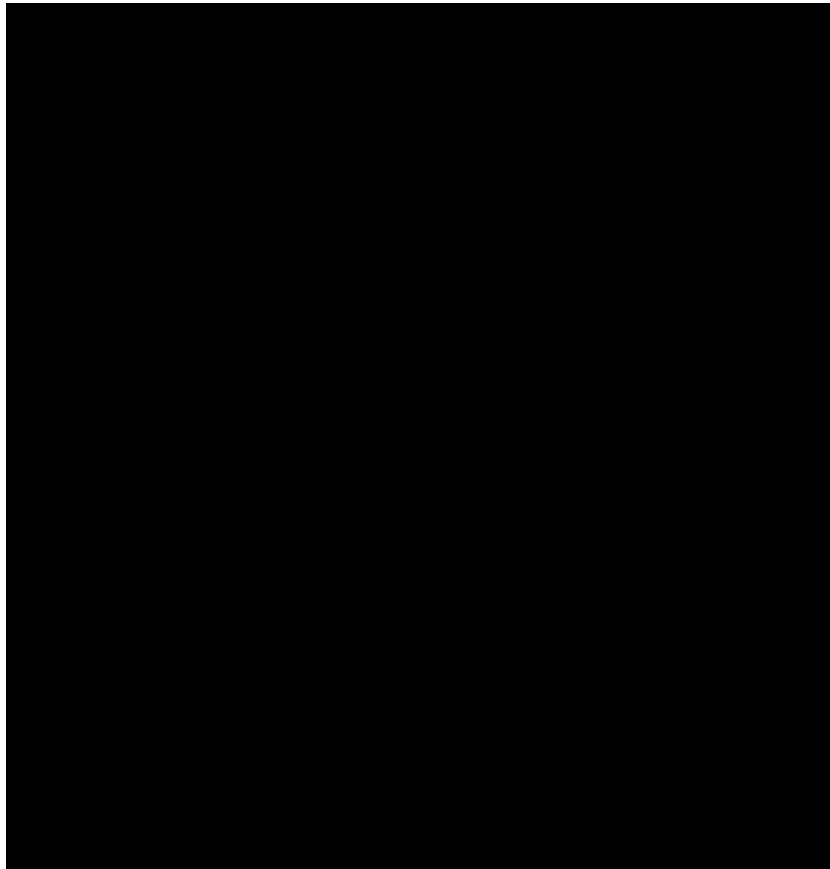
Pomeron trajectory



$$b(W) = b_0 + 4 \cdot 0.25 \cdot \ln(W)$$

ρ^0 photoproduction is “soft”

Elastic J/ψ photoproduction



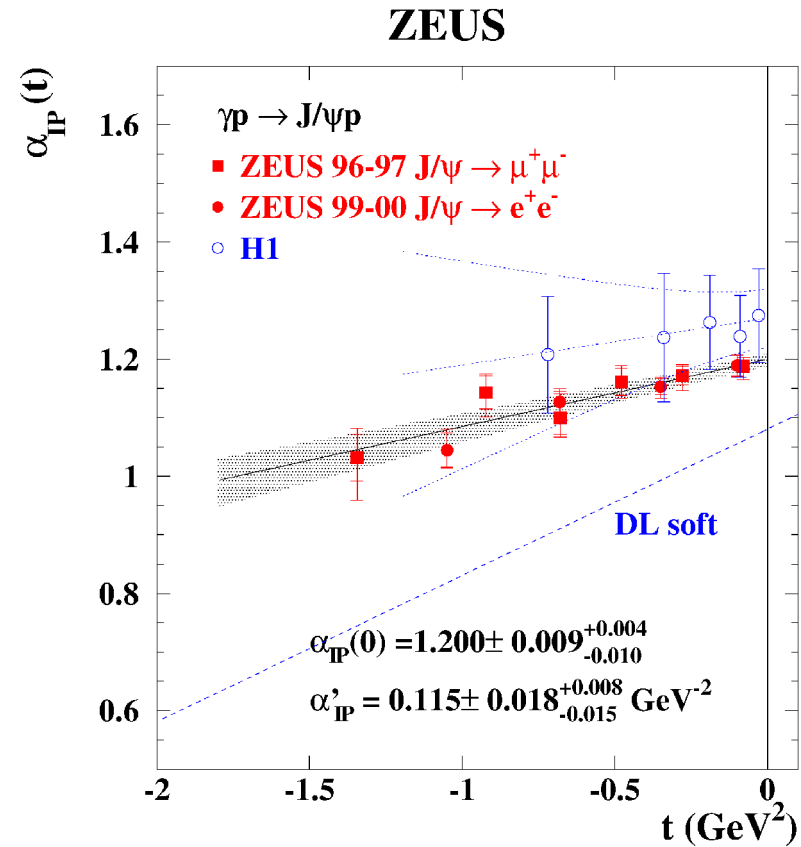
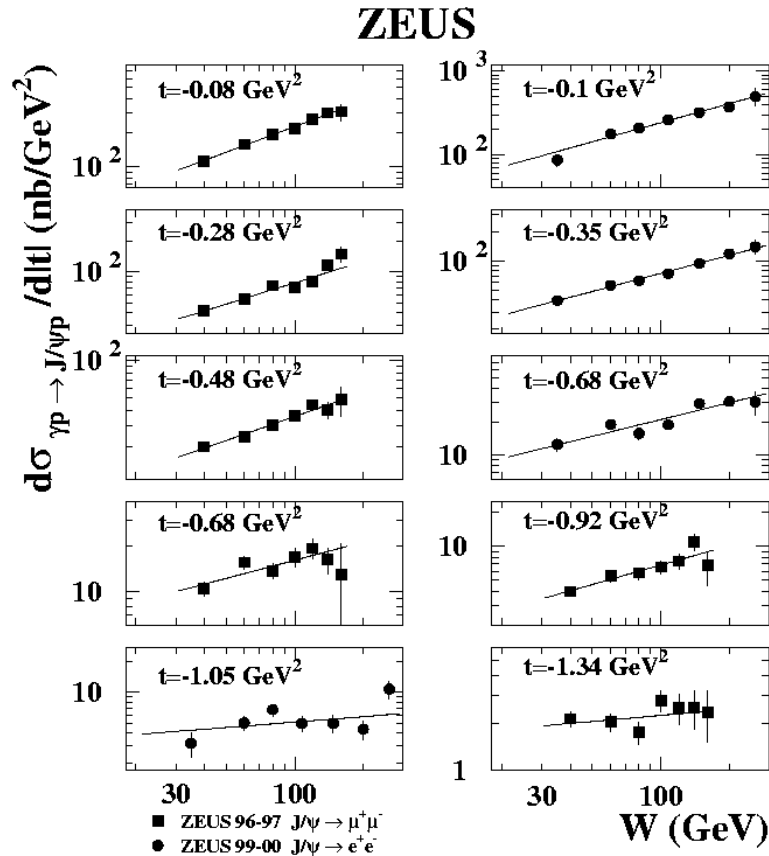
Large M_ψ is a **hard** scale: **pQCD** in action \Rightarrow steep rise of cross section with W .

The pQCD-based models reproduce the data.

J/ψ photoproduction is “**hard**”!

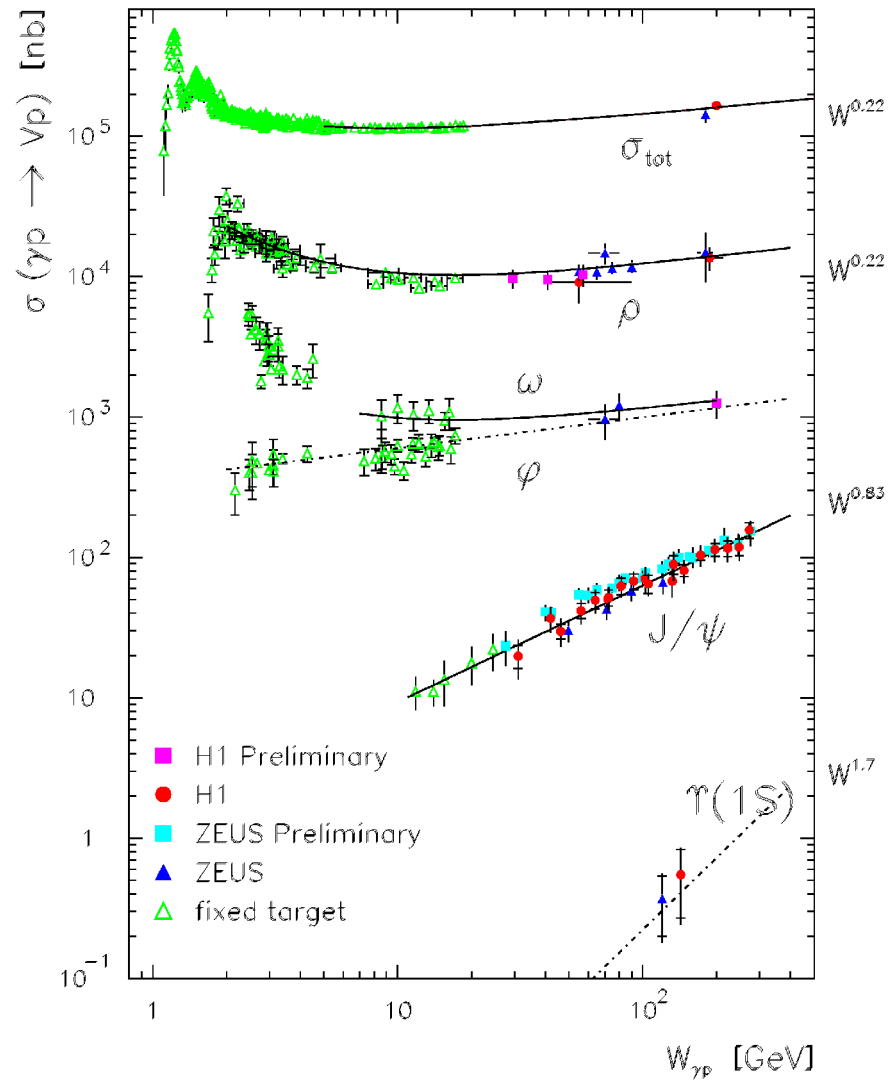
Elastic J/ψ photoproduction

Simultaneous W and t dependence $d\sigma/dt \sim (W^2)^{2\alpha(t)-2} \Rightarrow$ effective “Pomeron” trajectory



“Soft” Pomeron alone is excluded by the data!

VM cross sections in photoproduction



Increasing M_{VM} : transition from soft to hard regime.

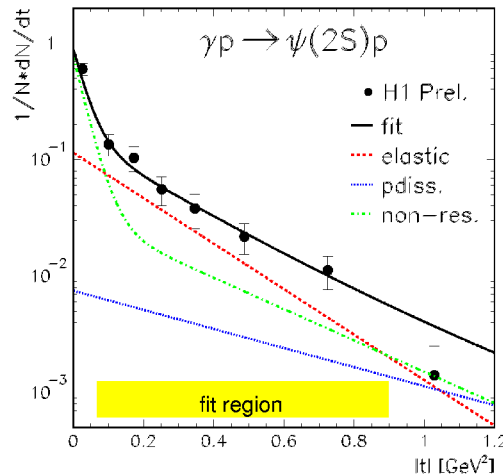
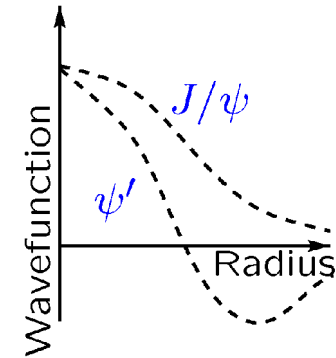
Elastic $\psi(2s)$ photoproduction

cc radial excitation; optical interpretation $\Rightarrow b_{\psi(2s)} > b_{J/\psi}$

BUT: QCD + $\psi(2s)$ wave function (with node) \Rightarrow

- $b_{\psi(2s)} \leq b_{J/\psi}$

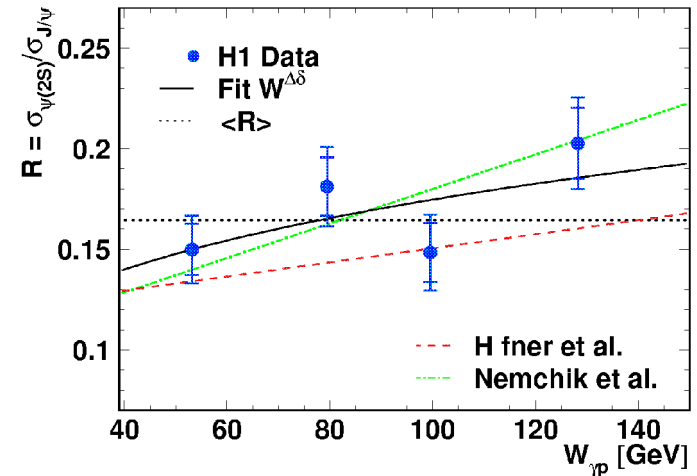
- $\sigma_{\psi(2s)} / \sigma_{J/\psi} < 1$



$$b_{\psi(2s)} = 4.31 \pm 0.57 \pm 0.46$$

$$b_{J/\psi} = 4.99 \pm 0.13 \pm 0.39$$

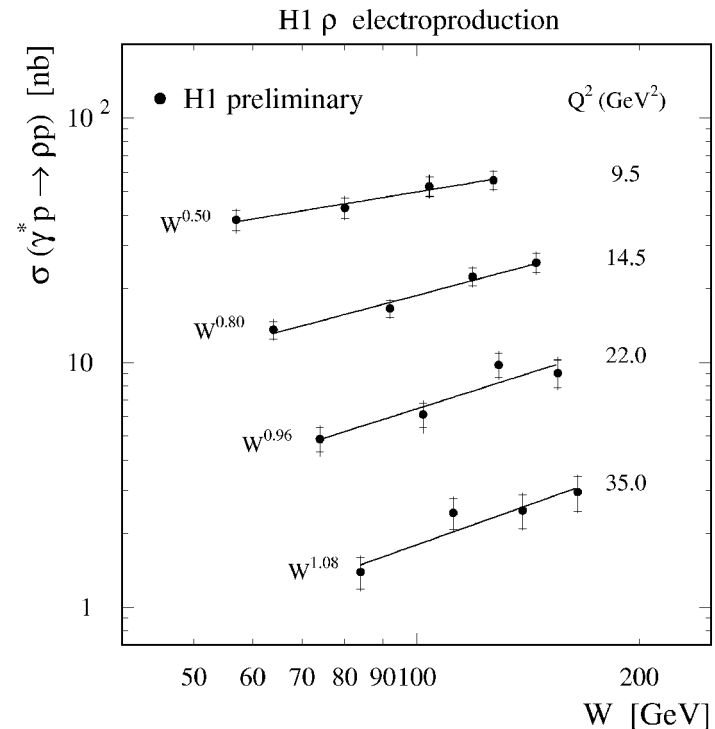
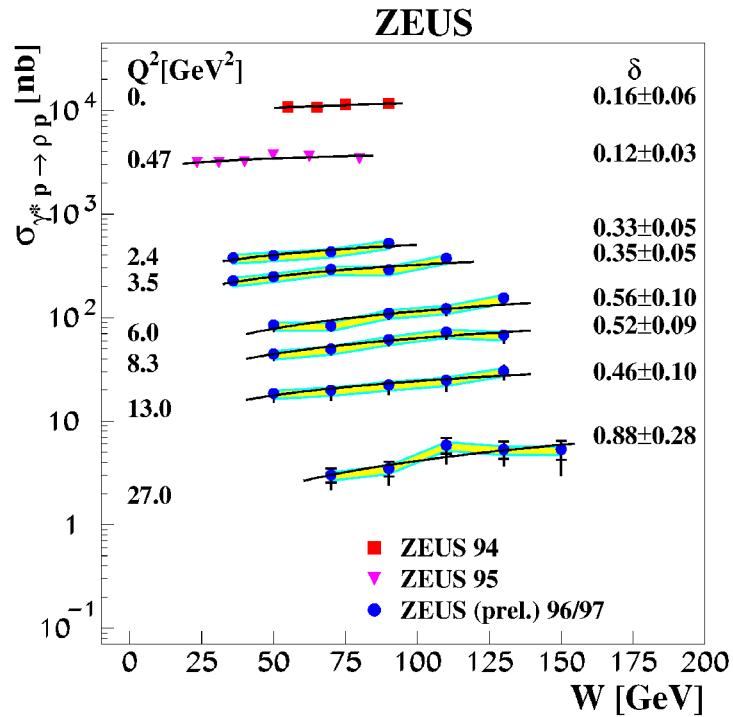
$$\sigma_{\psi(2s)} / \sigma_{J/\psi} \approx 0.17$$



QCD + wave function \Rightarrow OK!

Elastic ρ^0 electroproduction

Cross section $\sim W^6$ in Q^2 intervals

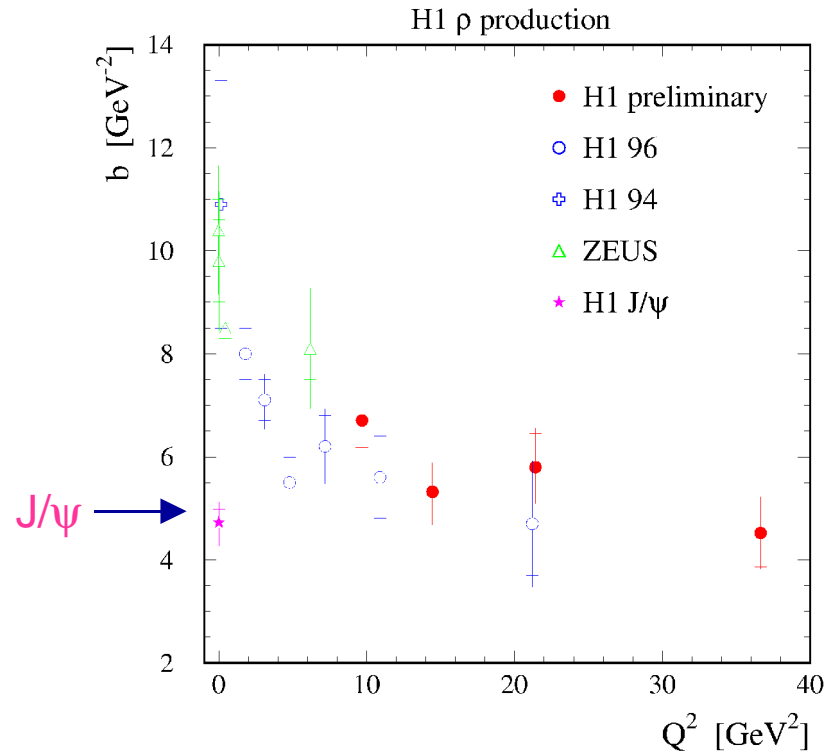
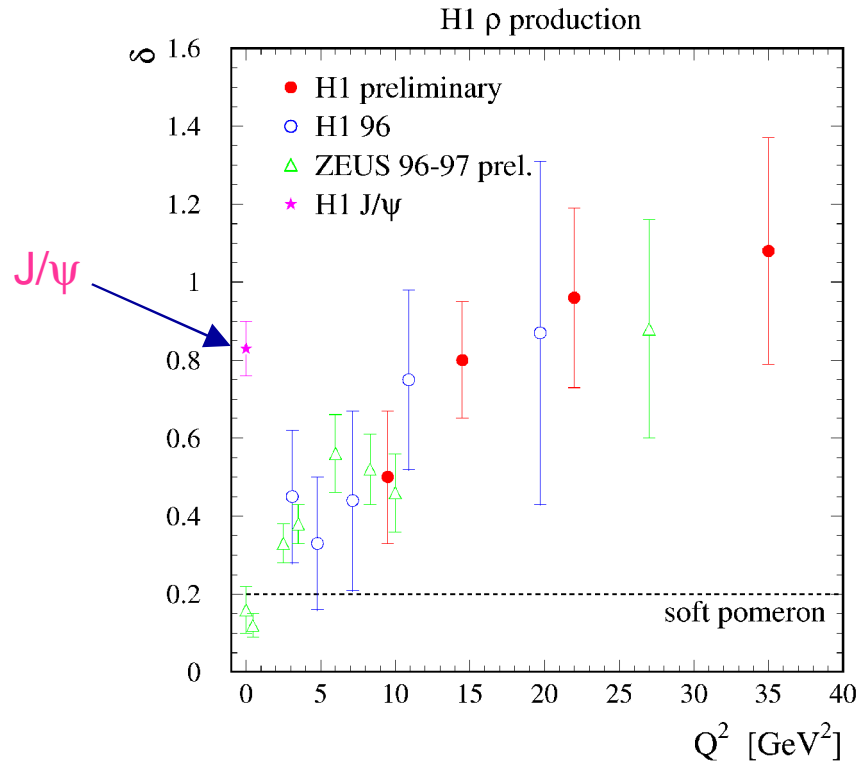


- $Q^2 \approx 0$: $\delta \approx 0.2$, weak W dependence - **soft** regime
- Large Q^2 is **hard** scale: large δ - steeper W dependence, as expected from color singlet exchange!

Elastic ρ^0 electroproduction

Cross section $\sim W^{\delta}$ in Q^2 intervals

slope b : $d\sigma/dt \sim \exp(-b/|t|)$

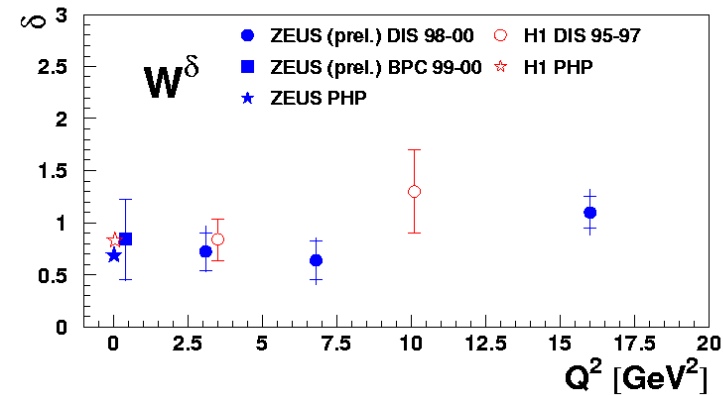
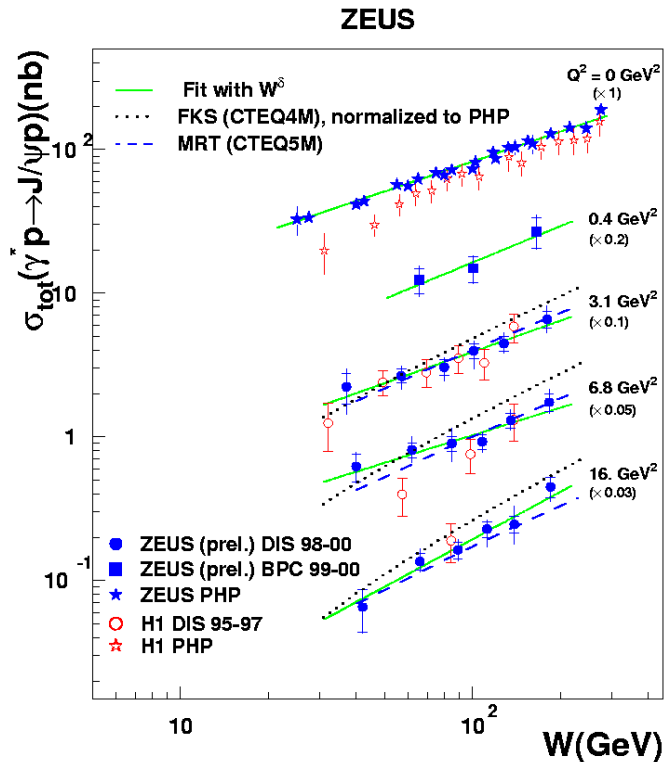


- power δ increases and slope b (\Rightarrow transverse size of qq pair!) decreases with Q^2

Q^2 controls soft - hard regime transition!

Elastic J/ψ electroproduction

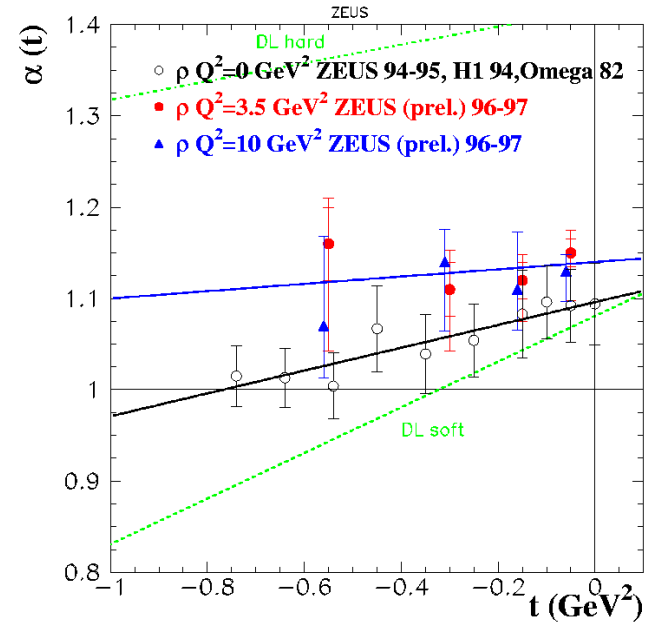
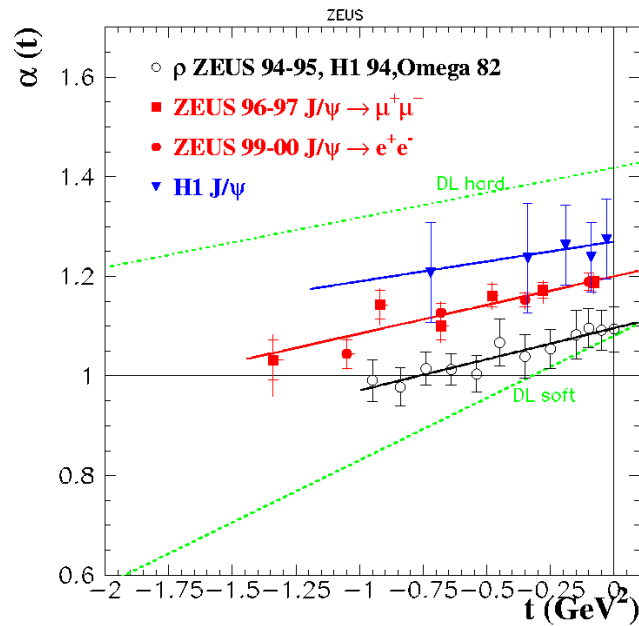
Cross section $\sigma_{J/\psi} \sim W^\delta$ in Q^2 intervals



- Steep rise of $\sigma_{J/\psi}$ ($\delta \geq 0.65$) depends weakly on Q^2 , large M_ψ is sufficient **hard** scale
- pQCD models using gluon densities are ~OK.

Pomeron trajectory...

J/ψ , ρ^0 photoproduction, ρ^0 electroproduction



V	$\alpha_P(0)$	α'_P (GeV^{-2})
ρ^0 , ($Q^2 \simeq 0$)	1.096 ± 0.021	0.125 ± 0.038
J/ψ (H1)	1.27 ± 0.05	0.08 ± 0.017
J/ψ (ZEUS)	$1.200 \pm 0.009^{+0.004}_{-0.010}$	$0.115 \pm 0.018^{+0.008}_{-0.015}$
ρ^0 (ZEUS, DIS)	$1.14 \pm 0.01^{+0.03}_{-0.03}$	$0.04 \pm 0.07^{+0.13}_{-0.04}$

$\alpha_P(0)$ increases with M_V (Q^2 ?)
 $\alpha'_P < 0.25 \text{ GeV}^{-2}$ ("soft" Pomeron)

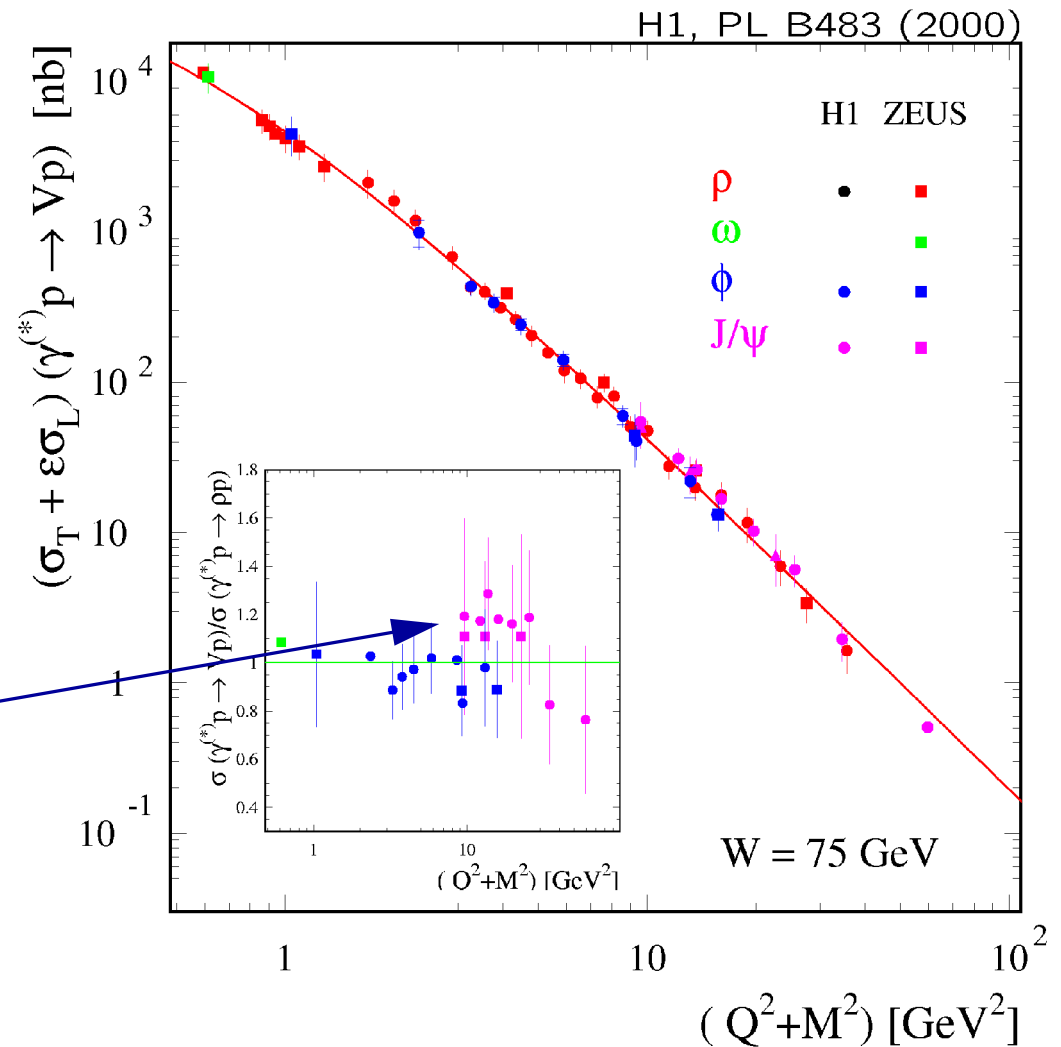
Looking for universality in VM production...

- Combined scale: $Q^2 + M^2$
- VM elastic cross sections “scaled” by SU(4) factors (assuming flavour independence and ignoring mass and wave function differences):

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

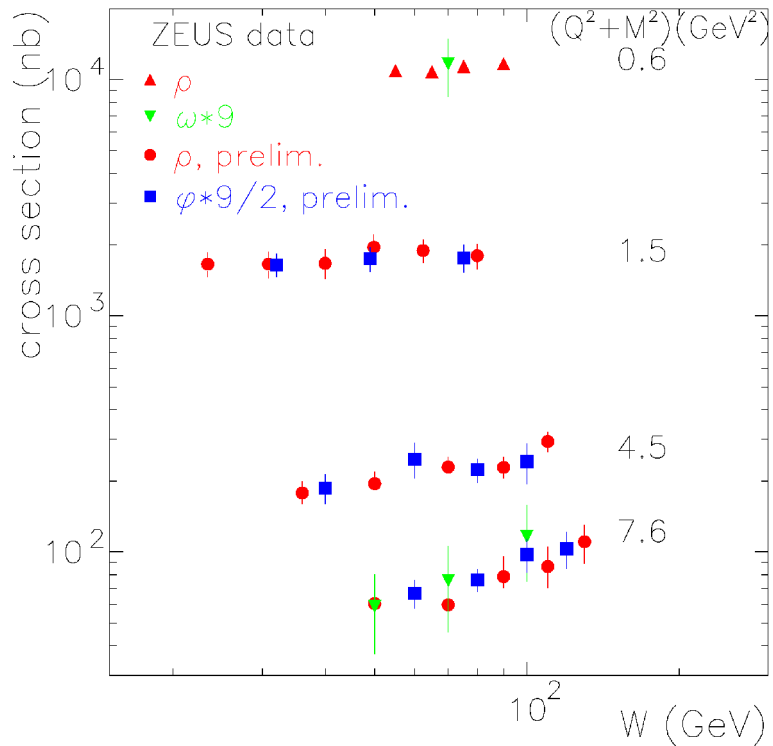
Looks good for light mesons

but J/ψ ...?



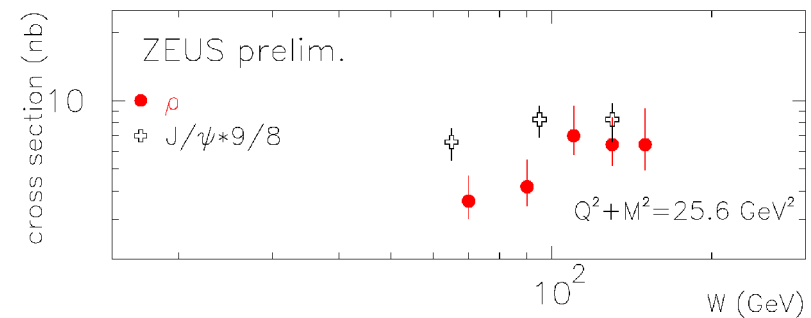
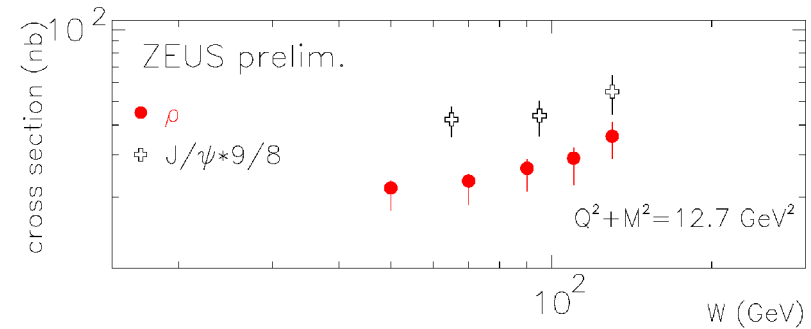
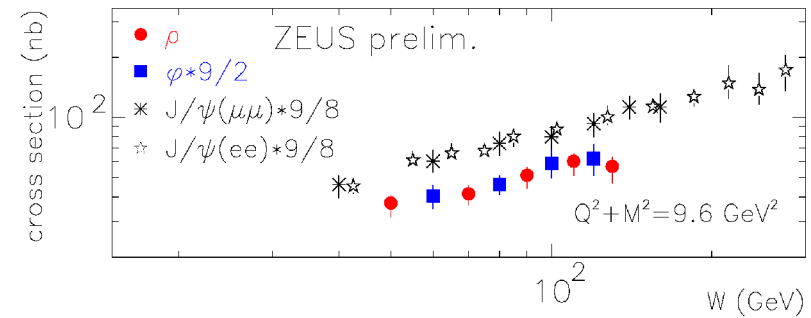
Looking for universality in VM production...

“Scaled” cross sections



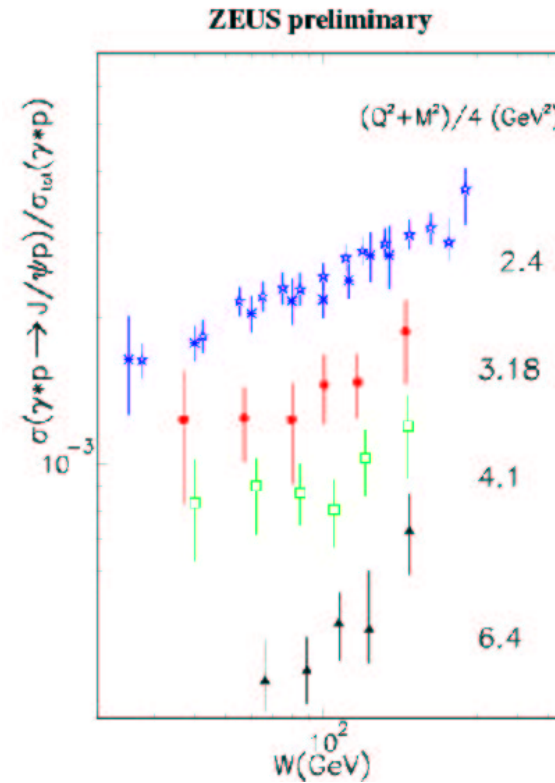
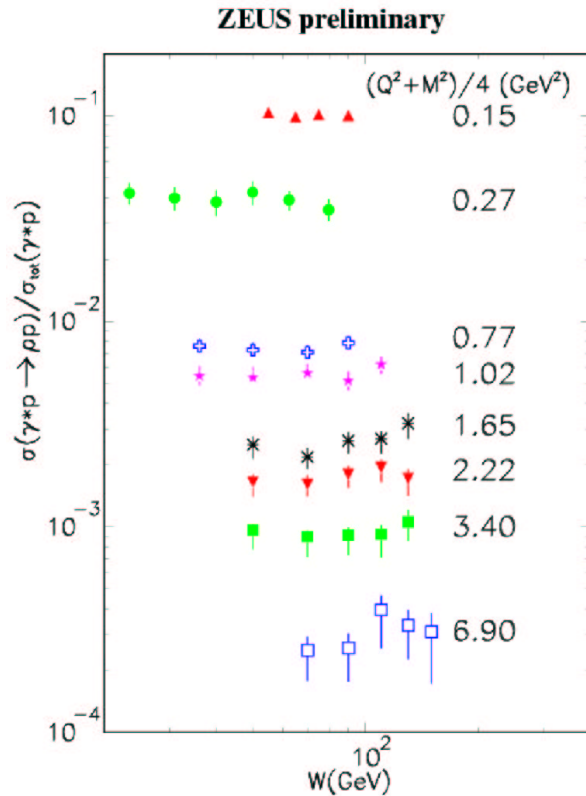
Recent data:

- universality for light VM
- J/ψ clearly enhanced above ρ and ϕ (???)



Looking for universality in VM production...

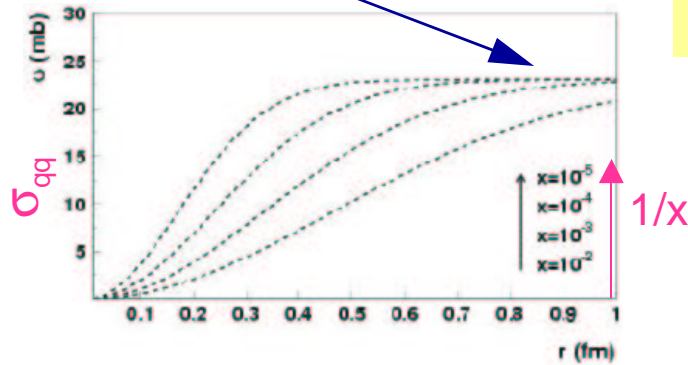
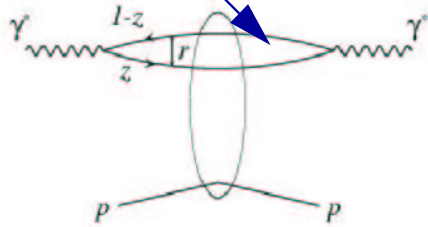
VDM+Regge: ratio: $\sigma_{\text{VM}}/\sigma_{\text{tot}}(\gamma^*p) \sim W^{2\alpha(0)-1}/b = W^{2\alpha(0)-1}/(b_0 + 4\alpha'\ln W) \Rightarrow ???$



- $\sigma_{\rho}/\sigma_{\text{tot}}$ does not depend on $W \dots(?)$
- $\sigma_{\psi}/\sigma_{\text{tot}}$ clearly rises with $W \dots(?)$

Looking for universality in VM production...

Dipol (saturation) model (GB-W):



$$\sigma_{\text{tot}} \sim \int d^2r \dots \Psi_{\gamma}^* \sigma_{\text{qq}}(x,r) \Psi_{\gamma}$$

$$\sigma_{\text{VM}} \sim \left| \int d^2r \dots \Psi_{\text{VM}}^* \sigma_{\text{qq}}(x,r) \Psi_{\gamma} \right|^2$$

$$\sigma_{\text{diff}} \sim \int d^2r \dots |\Psi_{\gamma}|^2 (\sigma_{\text{qq}}(x,r))^2$$

Qualitative (up to now) considerations:

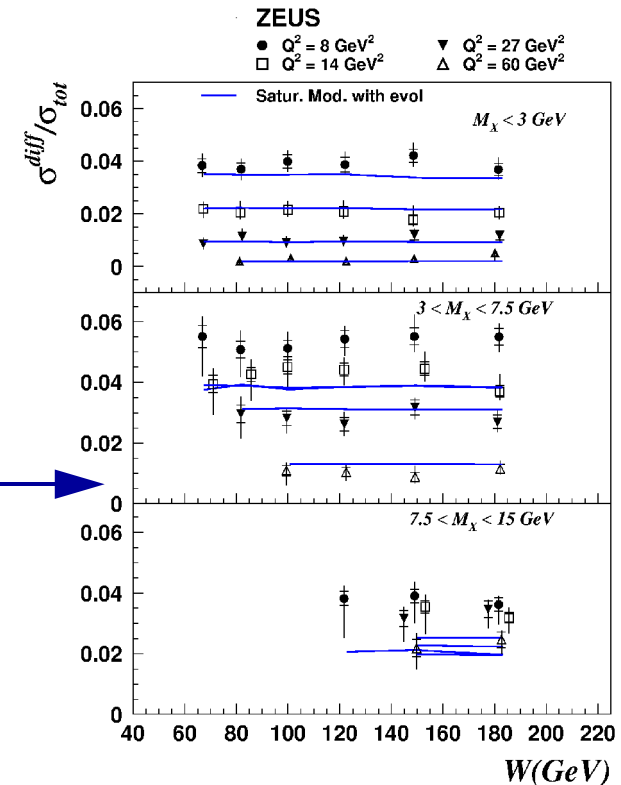
Interplay $\sigma_{\text{qq}}(x,r) \Leftrightarrow$ qq dipol size (Q^2, M_q^2)

$\Rightarrow \sigma_{\text{diff}}/\sigma_{\text{tot}} \approx \text{const}(W)$ (also quantitatively)

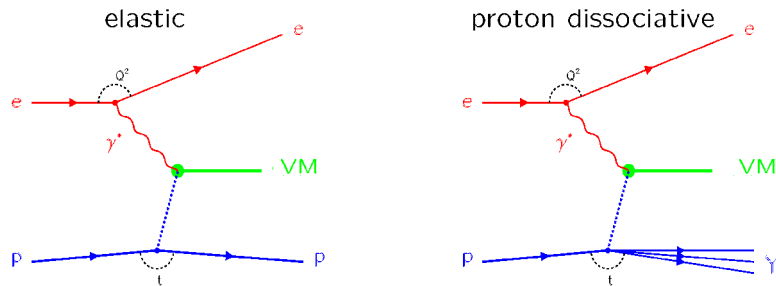
$\Rightarrow \sigma_p/\sigma_{\text{tot}} \approx \text{const}(W)$ (?)

$\Rightarrow \sigma_{\psi}/\sigma_{\text{tot}}$ rises with W (?)

Saturation model has great potential!



Proton-dissociative ρ^0 electroproduction

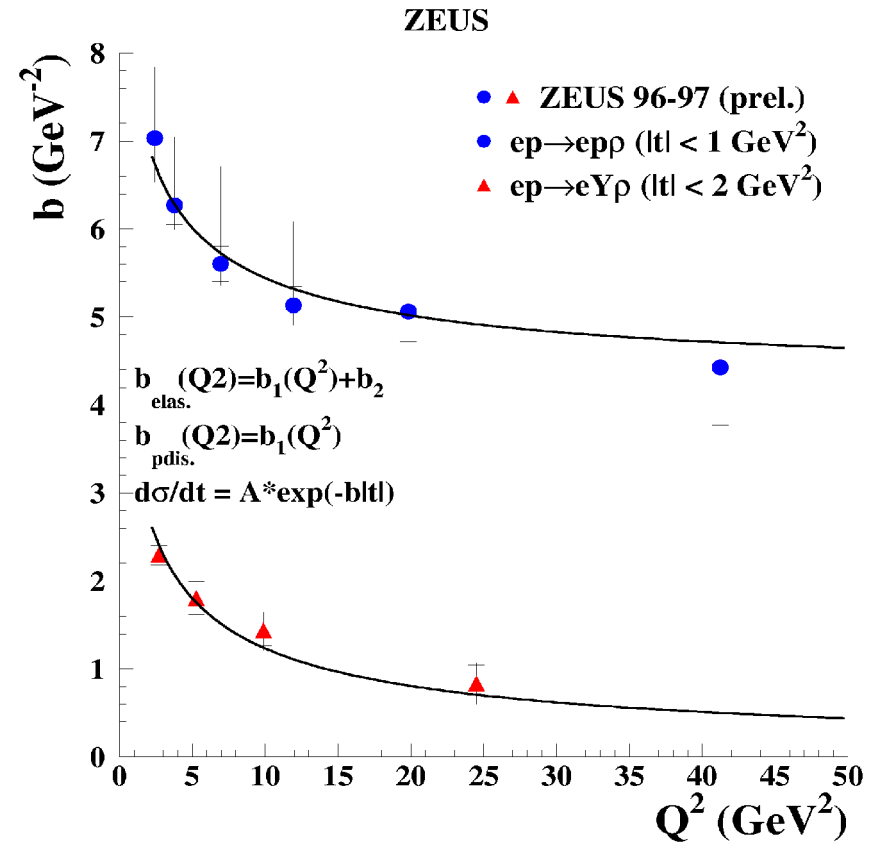
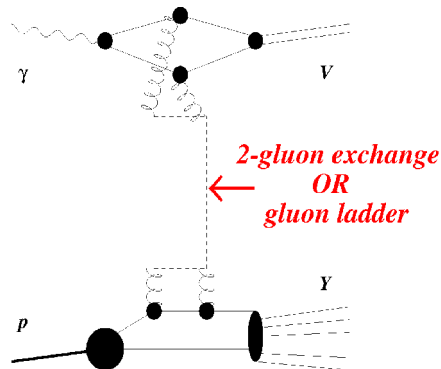


At “small” $|t|$: $d\sigma/dt \sim \exp(-b|t|)$

slope $b \sim (\text{interaction size})^2$

$$b_{\text{pdiss.}} < b_{\text{el.}} \Rightarrow$$

proton-dissociative interaction -
scattering off **parton!**



Proton-dissociative VM photoproduction at large $|t|$

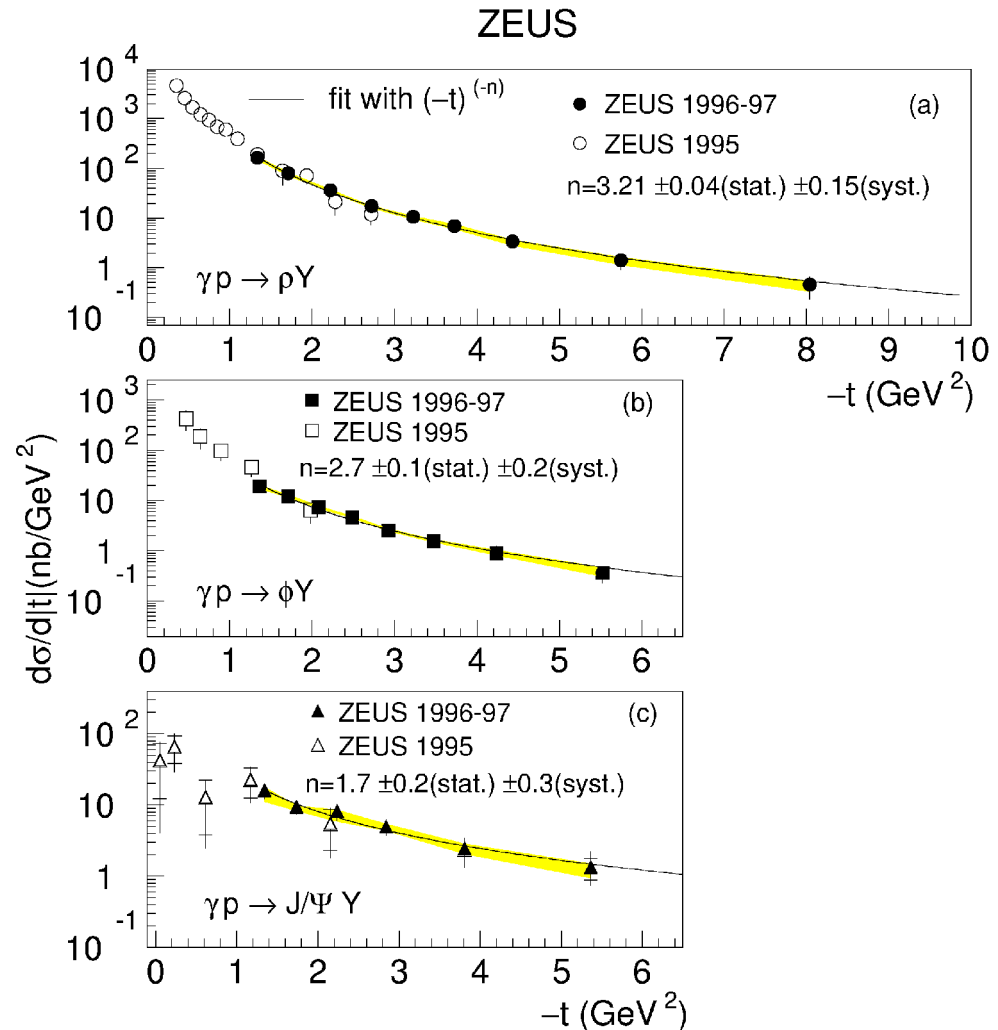
Does t provide **hard** pQCD scale?

VM = $\rho, \phi, J/\psi$

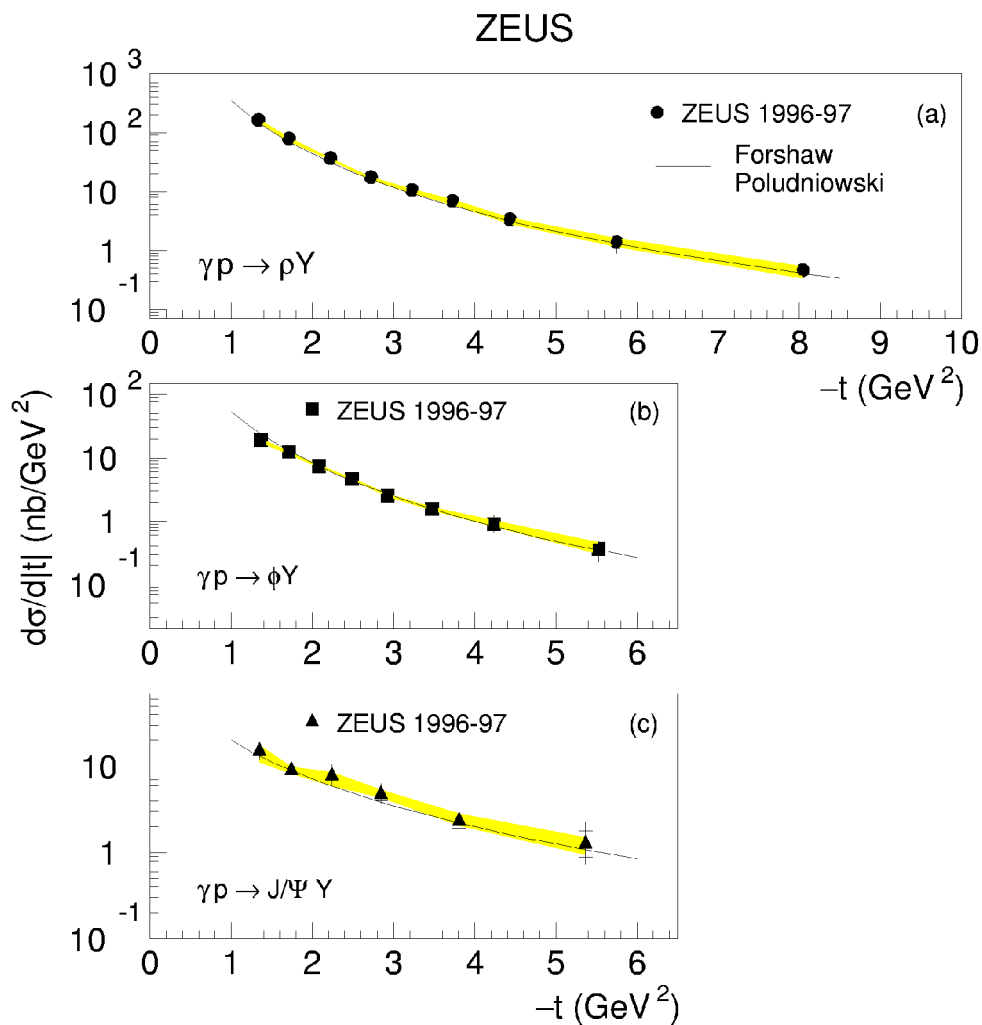
- $Q^2 < 0.02 \text{ GeV}^2$
- $1.2 < |t| < 10 \text{ GeV}^2$
- $80 < W < 120 \text{ GeV}$

pQCD: $d\sigma/dt \sim |t|^{-n}$

- the heavier VM -
the harder t distribution



Proton-dissociative VM photoproduction at large $|t|$



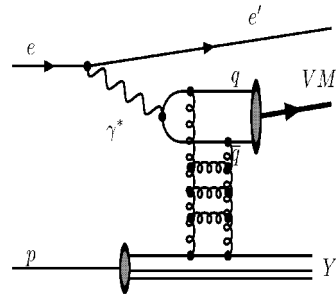
Forshaw & Poludniowski model:

- BFKL Pomeron
- coupling to single parton
- non-relativistic VM wave function (not proper for light VM)
- 3 parameters fitted to ZEUS data

BFKL exchange describes the data well

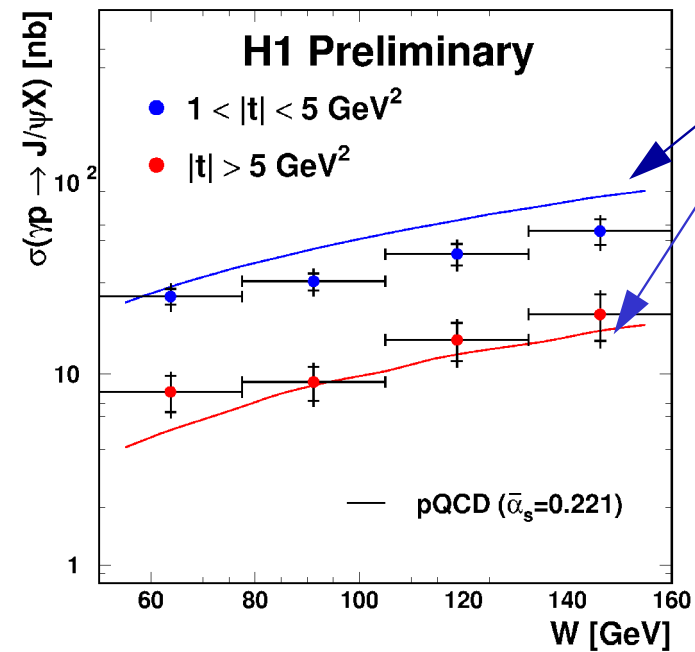
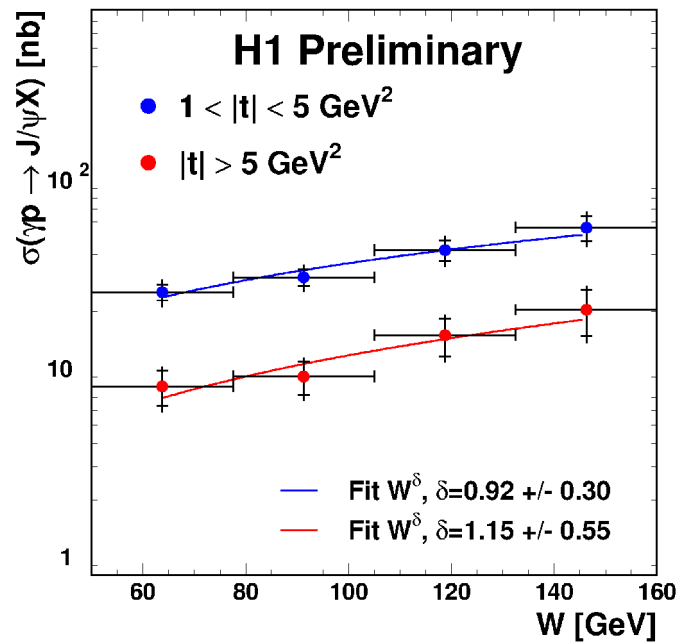
t is a hard scale...

Proton-dissociative J/ψ photoproduction at large $|t|$



$$\gamma p \rightarrow J/\psi Y, \quad |t| < 20 \text{ GeV}^2 \text{ (!)}$$

BFKL exchange: rise of $d\sigma/dt$ with energy (in contrast with 2-gluon exchange!)



Bartels *et al.*

Indication of BFKL ?!

Proton-dissociative VM photoproduction at large $|t|$

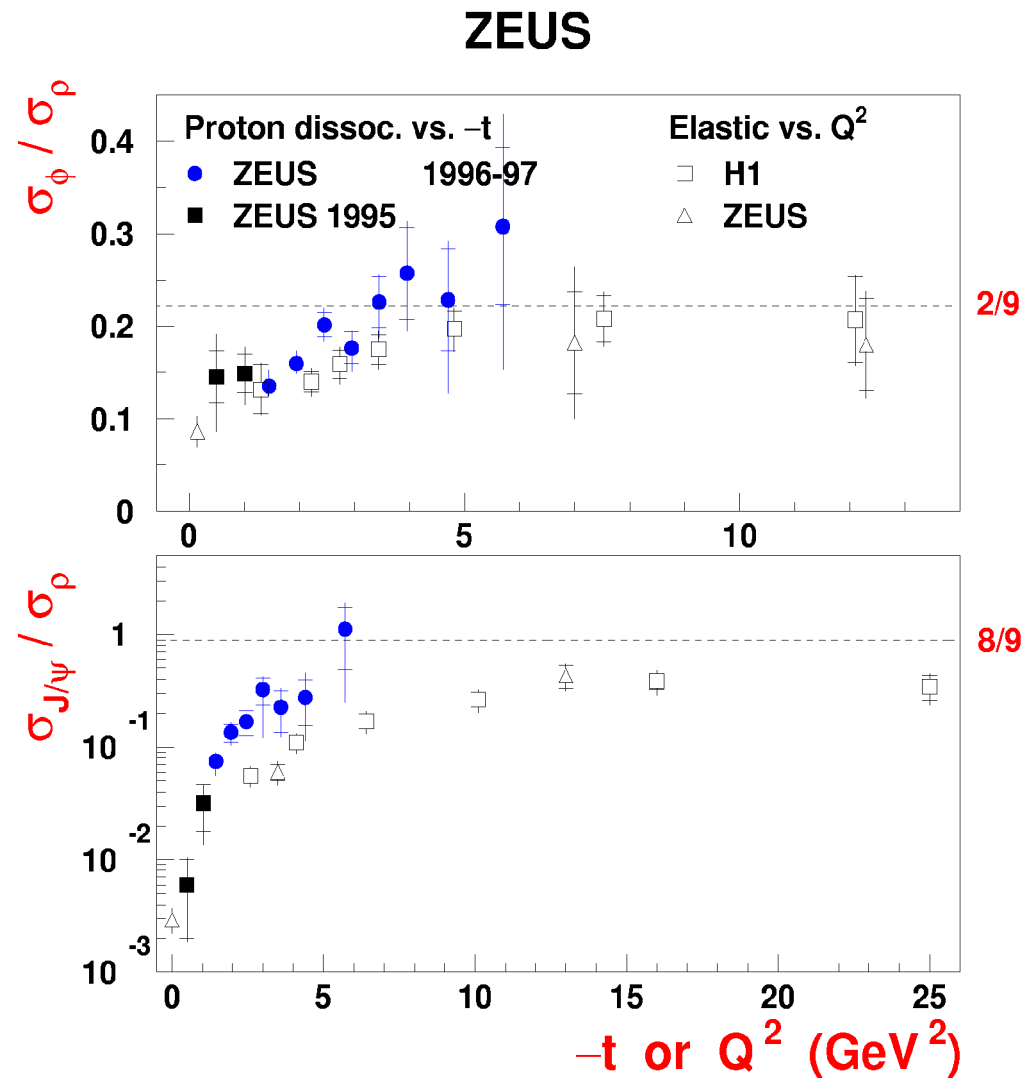
Cross section ratios in function of of:

- $-t$ for p-diss. photoproduction
- Q^2 for elastic electroproduction

The ϕ/ρ ratios approach SU(4) value, as well as ψ/ρ in photoproduction

The cross section ratios rise faster with $-t$ than with Q^2

$|t|$ and Q^2 are NOT equivalent scales!



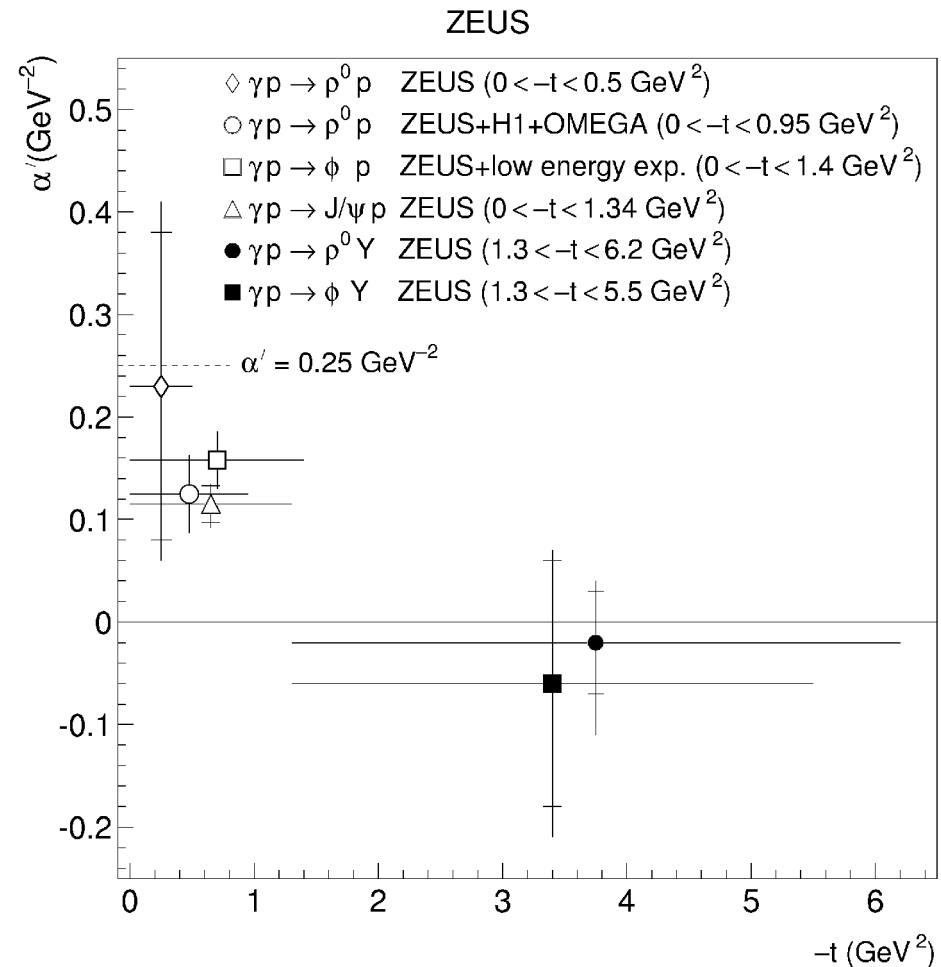
Proton-dissociative VM photoproduction at large $|t|$

Effective slope of Pomeron trajectory α'

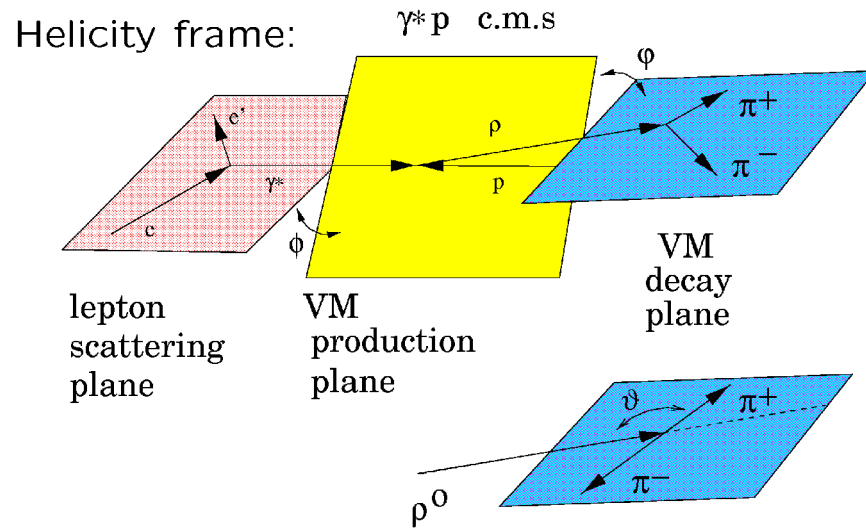
To avoid large correlated systematic errors “normalized” (W,t) distribution:

$$d\sigma/dt / d\sigma/dt(t=t_0) = W^{4\alpha'(t-t_0)}$$

With rising $-t$ transition from **soft** to **hard** regime...



Helicity studies



Decay angular distributions: $W(\vartheta, \varphi, \Phi)$

Helicity amplitudes $T_{\lambda_{VM} \lambda_{\gamma}}$

15 spin density matrix elements:

$$r_{ij}^{\alpha\beta} \sim T_{\lambda_1' \lambda_2'} T_{\lambda_1 \lambda_2}$$

T_{00}, T_{11} : no helicity flip

T_{01}, T_{10} : single flip

T_{1-1} : double flip

VMD legacy: S-Channel Helicity Conservation

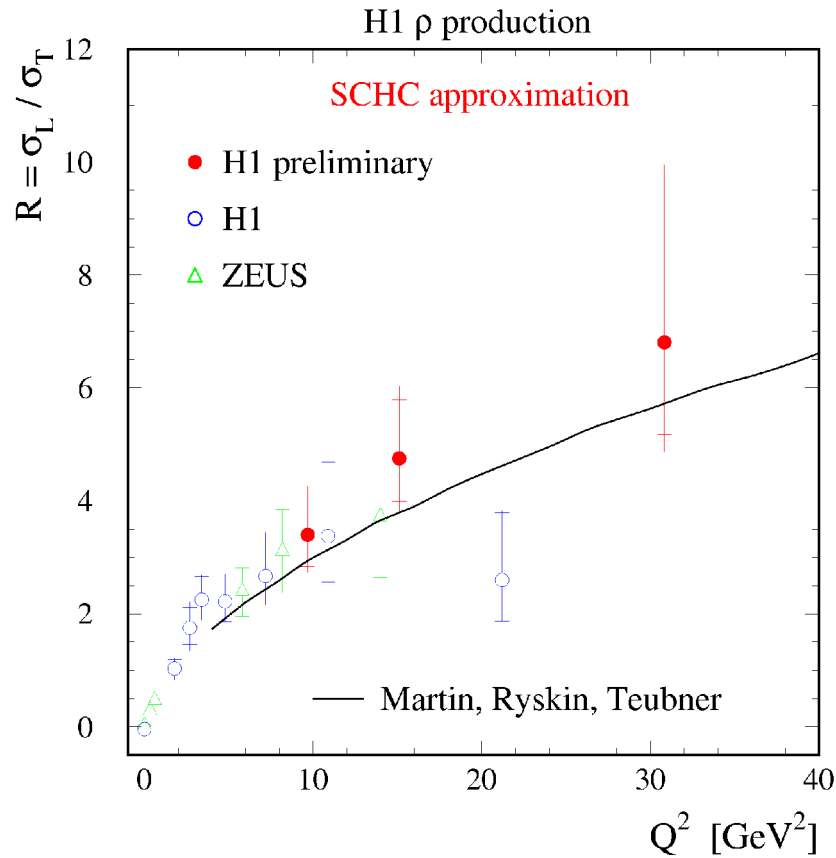
pQCD: quantitative predictions on transitions between γ^* and VM helicity states,

in particular dominance of longitudinal γ^* polarisation and small SCHC breaking

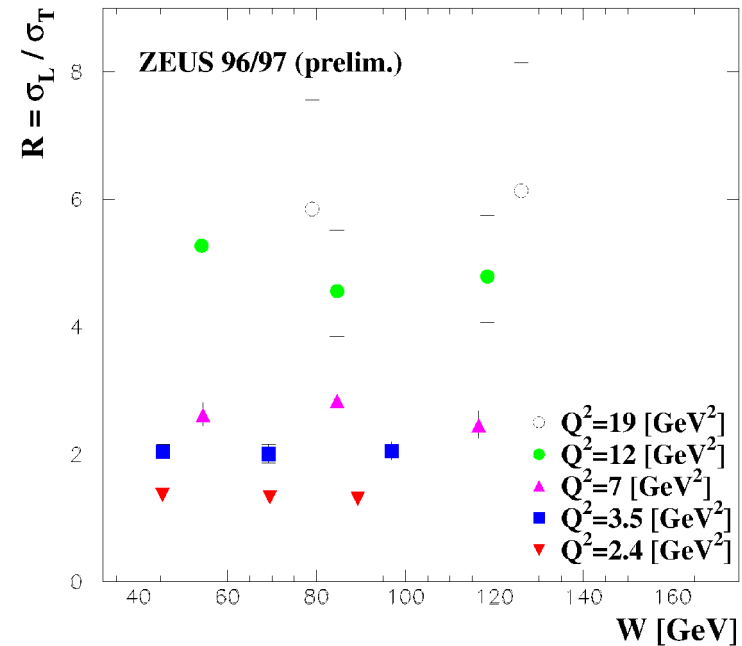
Experiment: approximate SCHC (small breaking)

Helicity studies

Elastic ρ^0 electroproduction:



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

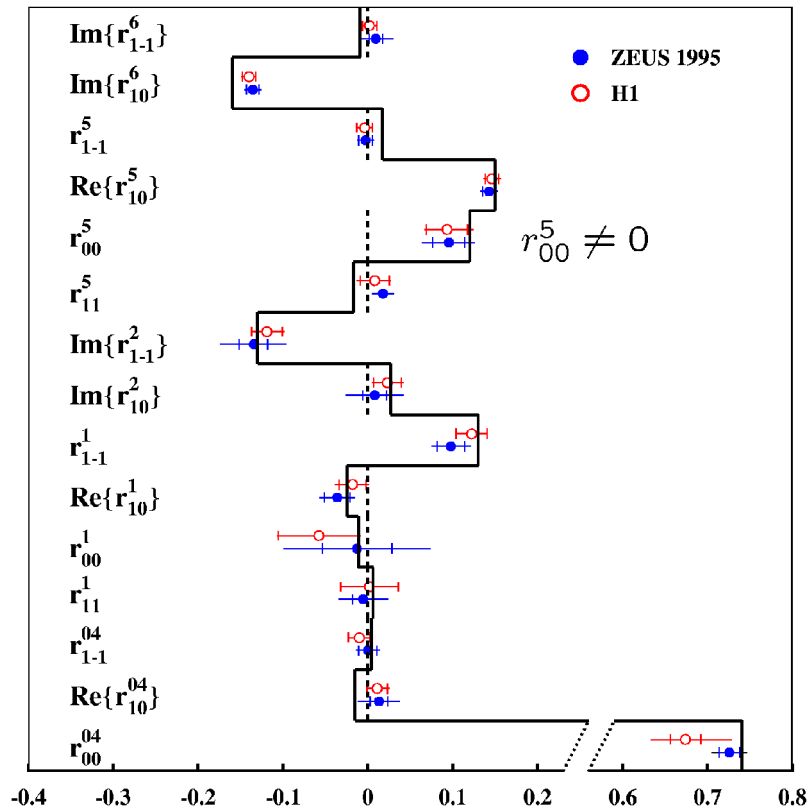


R increase with Q^2 as predicted by pQCD but does not depend on W ...

Helicity studies

Elastic ρ^0 electroproduction: $1 < Q^2 < 60 \text{ GeV}^2$

ρ^0 : ZEUS/EPJ C12 (2000) 393
 H1/PL B483 (2000) 360
 ϕ : H1/EPJ C13 (2000) 371



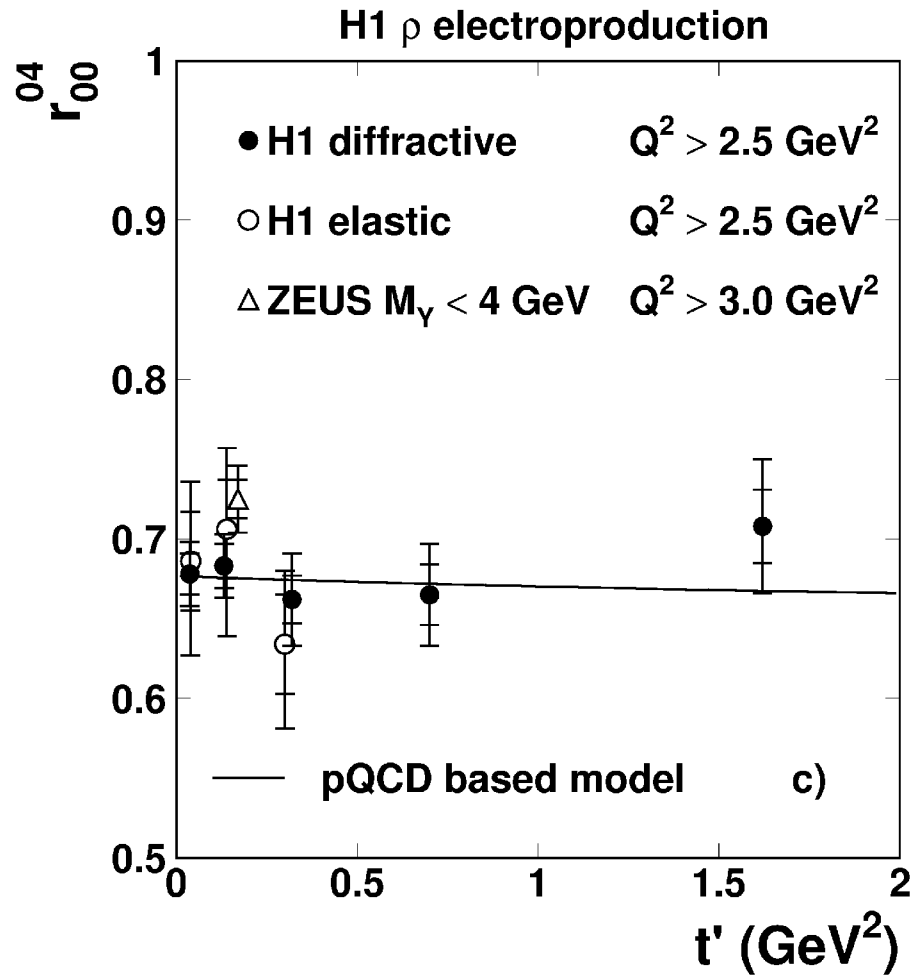
$$r_{00}^5 \sim T_{00} T_{01}^* + T_{01} T_{00}^* \neq 0$$

$\Rightarrow \gamma_T \rightarrow \rho_L$ transition observed

SCHC breaking predicted by
 pQCD model (Ivanov, Kirschner):
 qq interaction with proton
 \Rightarrow helicity flip

Helicity studies

Elastic and p-diss. ρ^0 electroproduction: t dependence of SDME

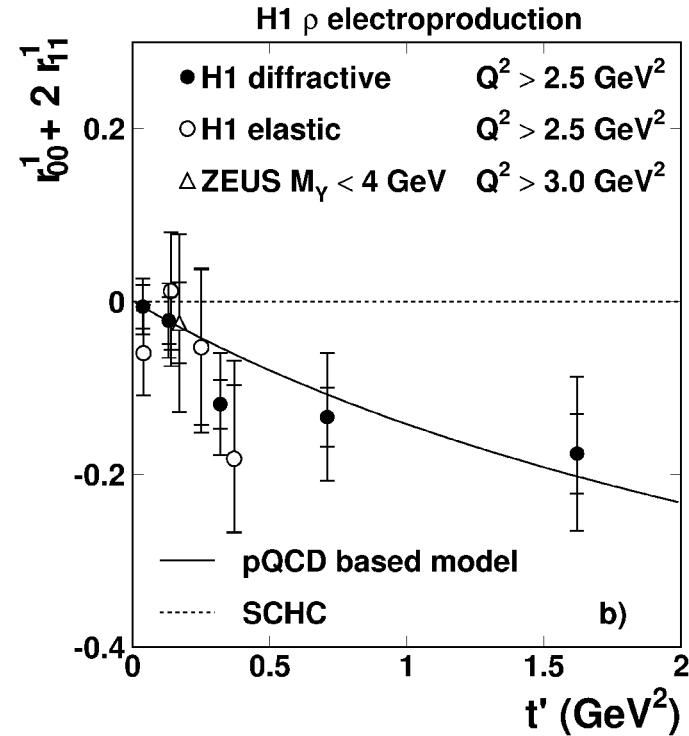
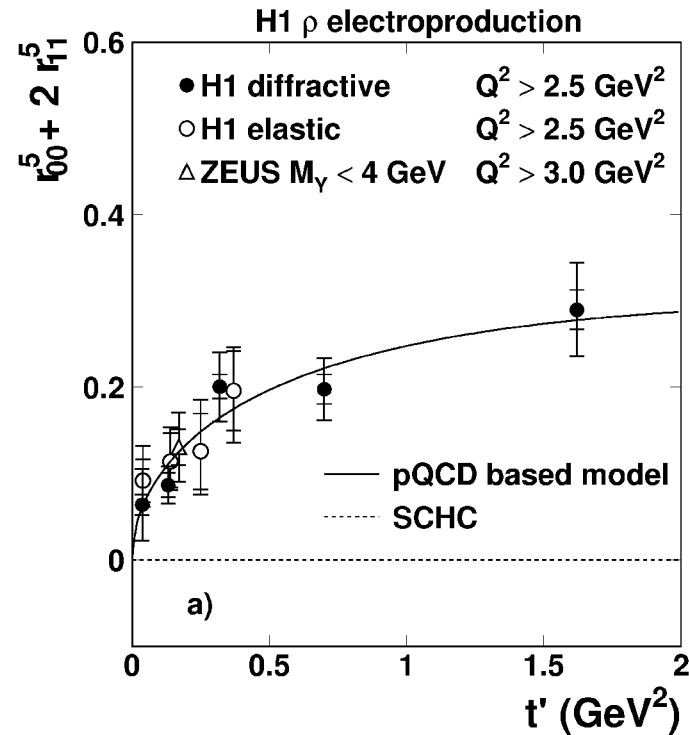


$$R = \sigma_L / \sigma_T = \frac{r_{00}^{04}}{\varepsilon (1 - r_{00}^{04})}$$

No r_{00}^{04} (and R) dependence on t

Helicity studies

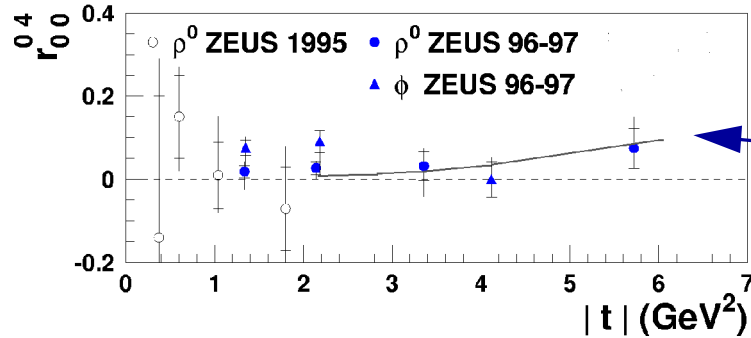
Elastic and p-diss. ρ^0 electroproduction: t dependence of SDME



These SDME are dominated by **single** and **double** flip helicity amplitudes and exhibit **SCHC** violation at larger $|t|$, in accord with **pQCD** expectation.

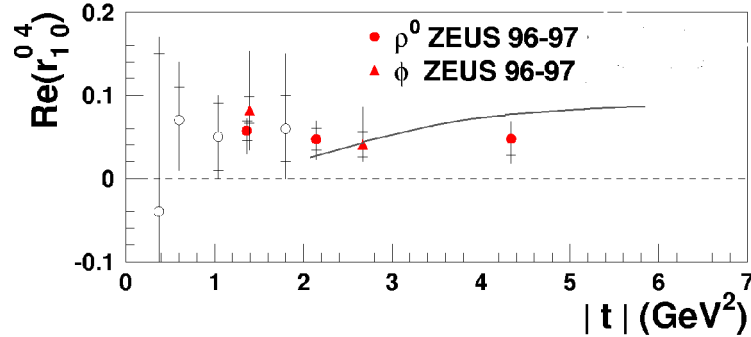
Helicity studies

Proton-dissociative ρ^0 and ϕ photoproduction:

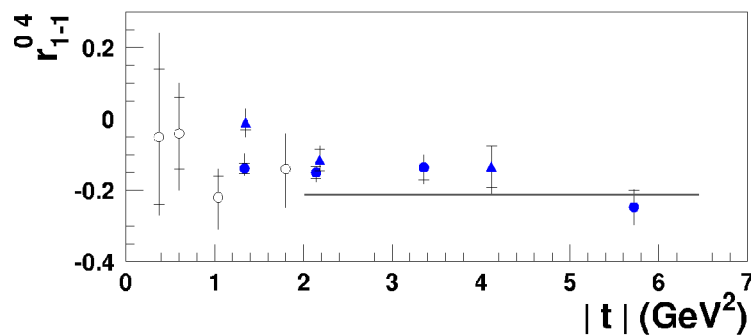


~ single flip

Model Enberg, Motyka & Poludniowski:
VM wave functions a la Ivanov *et al.*,
BFKL exchange with higher conformal
spins \Rightarrow OK!



~ single/double flip



~ double flip

SCHC violated at large $|t|$!

Summary and Outlook

- Continued analysis of HERA I data
 - ⇒ new results of higher precision, in large kinematic region
- Production of vector mesons: non-perturbative - perturbative QCD playground
- At large M_{VM}^2 , Q^2 or $|t|$ the VM production shows expected features of a short distance (hard) process:
 - steep rise of the cross section with energy,
 - harder $|t|$ distribution,
 - SCHC breaking
- Universality in VM production - still an open question

Summary and Outlook

- $|t|$ is confirmed as a hard scale, however not equivalent to Q^2
- In the presence of a hard scale **perturbative QCD** describes many aspects of the data - there is room for **improvement** however
- Outlook:
Still ongoing **HERA I** data analysis,
HERA II - 1 fb^{-1} luminosity expected and upgraded detectors
 \Rightarrow extension of the kinematic range to higher Q^2 and $|t|$