Vector meson production and DVCS at HERA

Robert Ciesielski
(Warsaw University)

on behalf of

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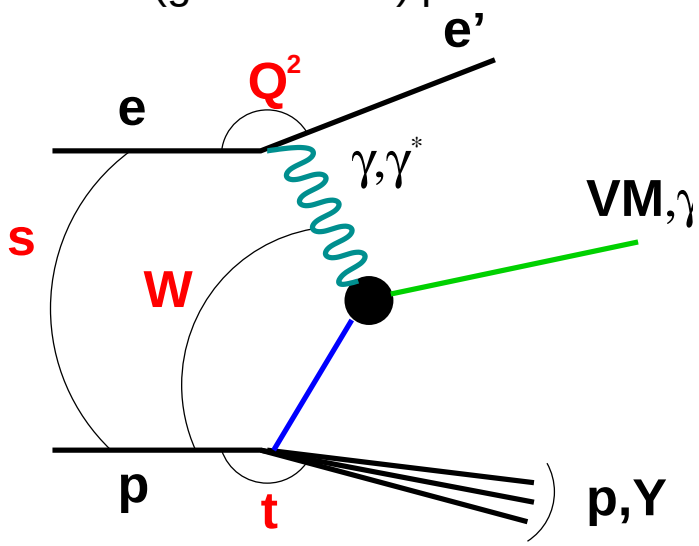
Motivation

- Understand the VM & DVCS dynamics in QCD
- Test QCD in the transition region (soft $\rightarrow$ hard)
- Measure the non-perturbative quantities (generalised) pdfs



Q^2 - γ^* virtuality $\quad 0 < Q^2 < 100\ GeV^2$

W - CM energy of $\gamma^* p$ system ($x = Q^2/W^2$) $\quad 20 < W < 290\ GeV$

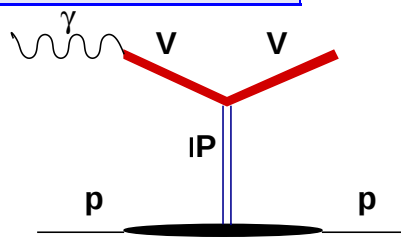
t - 4-mom. transfer squered at p vertex $\quad 0 < |t| < 20\ GeV^2$

VM - vector meson $\quad \rho, \omega, \phi, J/\psi, \psi(2S), \Upsilon$

$\gamma^{(*)} p \rightarrow Vp$ - elastic, $\gamma^{(*)} p \rightarrow VY$ - proton dissociative (dominates at high $|t|$)

VM Production Mechanisms

VDM+Regge Approach (soft)



Soft Pomeron exchange:

$\alpha_P(t) = \alpha_0 + \alpha' t$, ($\alpha_0$=1.08, α'=0.25)

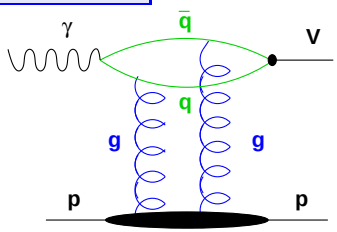
$$d\sigma/dt \propto e^{b_0 t}(W/W_0)^{4(\alpha_{I\!P}(t)-1)}$$

Expected:

- slow rise: $\sigma(W) \simeq W^{\delta}$, $\delta \simeq 0.22$
- shrinkage: $b(W) = b_0 + 4\alpha' ln(W/W_0)t$
- SCHC: ($\gamma^*_L \to V_L$, $\gamma^*_T \to V_T$)
- $\sigma_L \propto 1/Q^2$, $\sigma_T \propto 1/Q^4$

Is it present at large values of Q^2, M^2, t?

pQCD Approach (hard)



two-gluon exchange (LO)

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

$$\sigma_L \propto \alpha_S(Q^2)[xG(x,Q^2)]^2/Q^6$$

Expected:

- fast rise: $\sigma(W) \simeq W^{\delta}$, $\delta \simeq 0.8$
- little shrinkage:, $\alpha' \simeq 0$
- $b_{2g} \simeq 4 - 5GeV^{-2}$, (at high $|t|$: $d\sigma/dt \simeq |t|^{-n}$)
- SCHC violation
- $\sigma_L \propto 1/Q^6$, with $\alpha_S(Q^2)$,$G(Q^2)$ suppresion

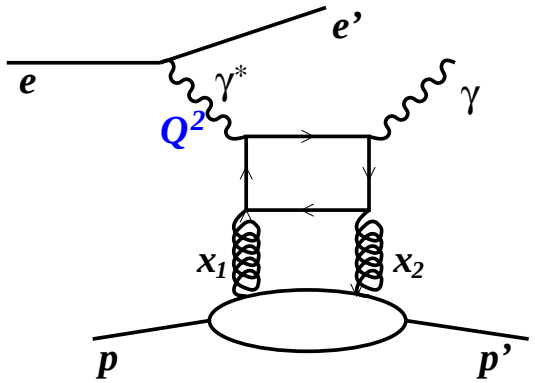
[gluon density rises at low x]

Hard scale: $f(Q^2, M^2, t)$?

Deeply Virtual Compton Scattering (DVCS)

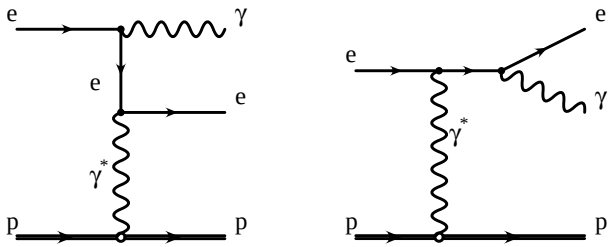
DVCS - diffractive scattering of the virtual photon off a proton ($\gamma^* p \to \gamma p$).

QCD



Main background: Bethe-Heitler process:

QED



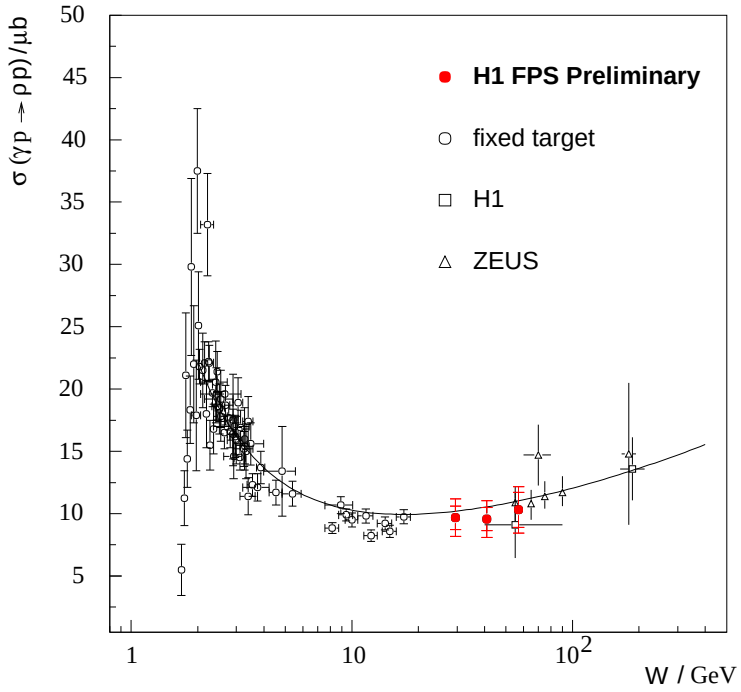
In QCD: Production mechanism similiar to VM, except:

- Final state particle is point-like photon:
  - avoid theoretical complications and uncertainties with VM wave function.
    $\to$ easier access to SPD (Skewed Parton Distributions, $x_1 \neq x_2$)
- cannot distinguish from Bethe-Heitler process ($ep \to ep\gamma$) on an event by event basis:
  - sensitive to $Re\mathcal{A}_{QCD}$ via QCD-QED interference.

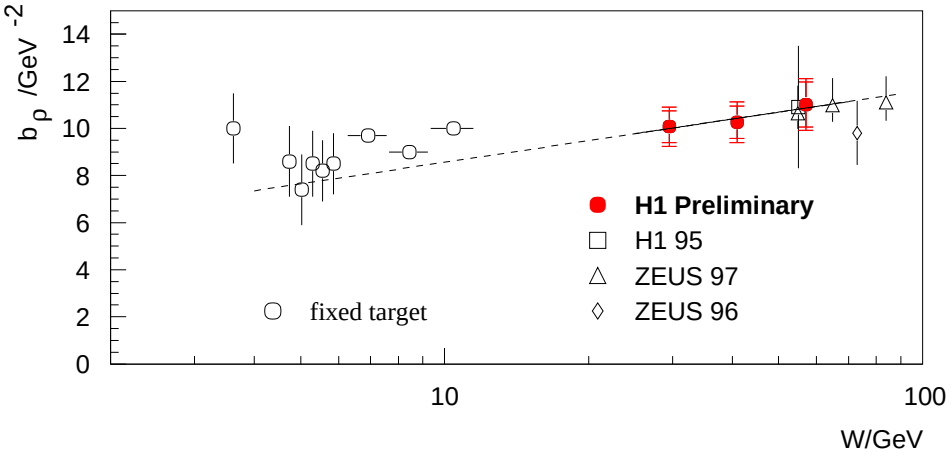
First measurement of $\gamma^* p \to \gamma p$ at HERA ($2 < Q^2 < 100 GeV^2$, $30 < W < 140 GeV^2$, $|t| < 1 GeV^2$)

ρ photoproduction (no hard scale)

Proton fully reconstructed with Forward Proton Spectrometer (H1).



$\sigma_{\gamma p \to \rho p} \propto W^{0.22}$



Shrinkage:

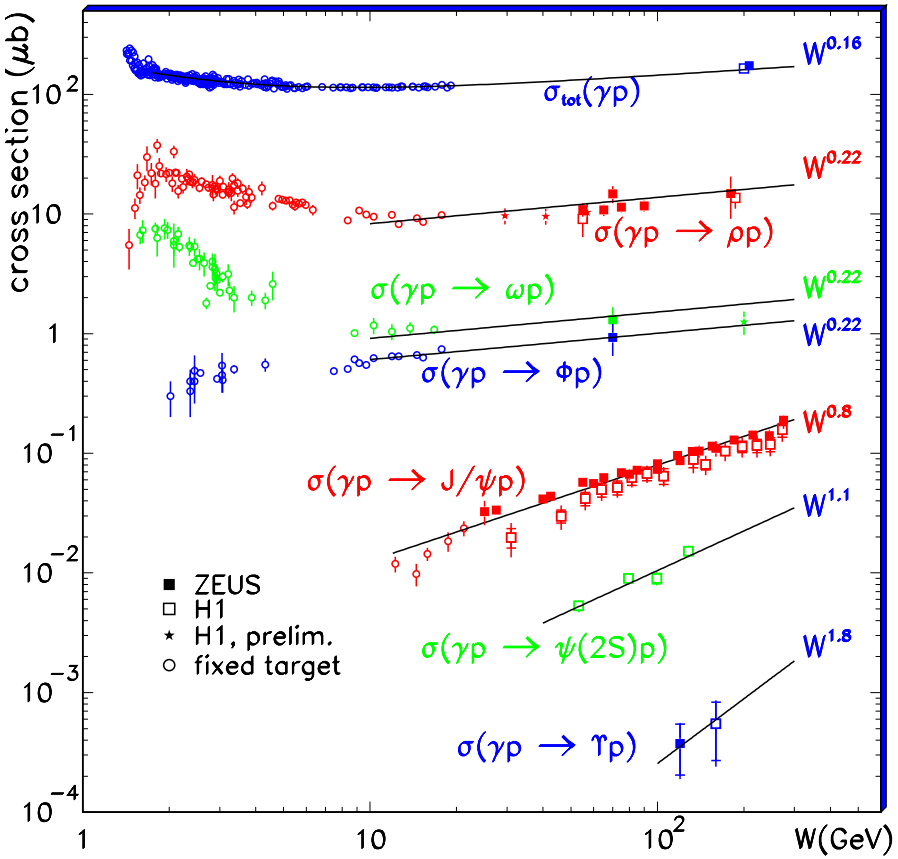
$b(W) = b_0 + 4\alpha' ln(W)$

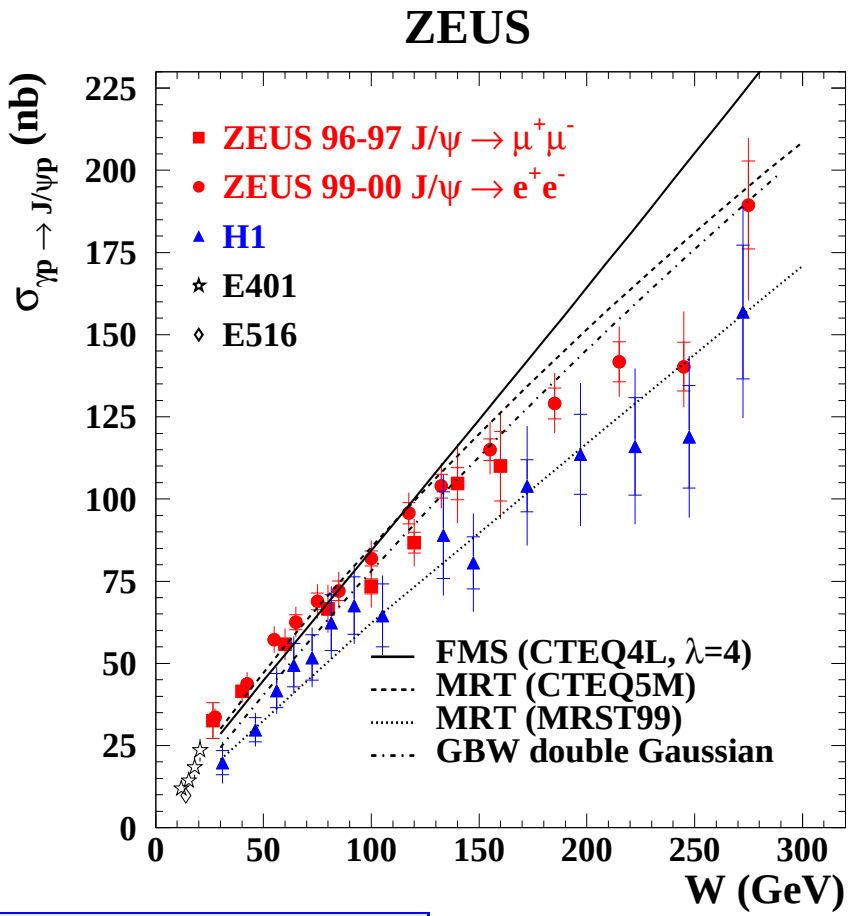
with $\alpha' = 0.25 GeV^{-2}$

$d\sigma/dt \propto e^{bt}$, $b = 10.31 \pm 0.77 \pm 0.52 GeV^{-2}$

Consistent with Regge phenomenology $\rightarrow$ ρ photoproduction is 'soft'.

VM in photoproduction (scale: M^2_{VM})





Steeper W dependence for heavy VMs.

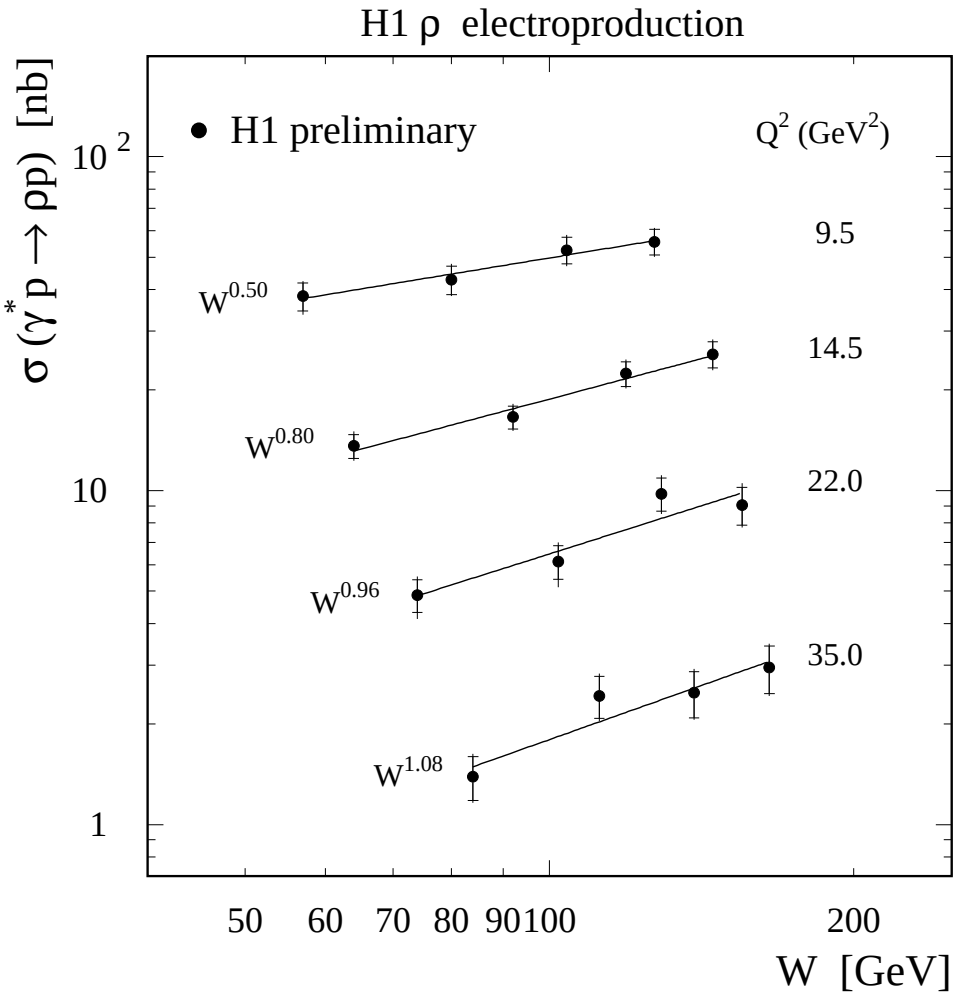
Change of regime (soft $\to$ hard).

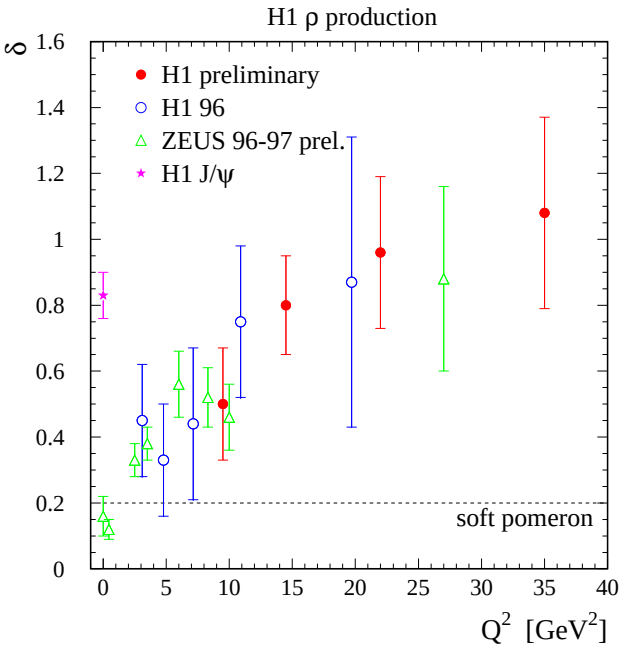
J/ψ photoproduction:

pQCD describes a steep rise of cross section with $M_{J/\psi}$ as a hard scale.

Sensitivity to gluons.

ρ electroproduction (scale: Q^2)



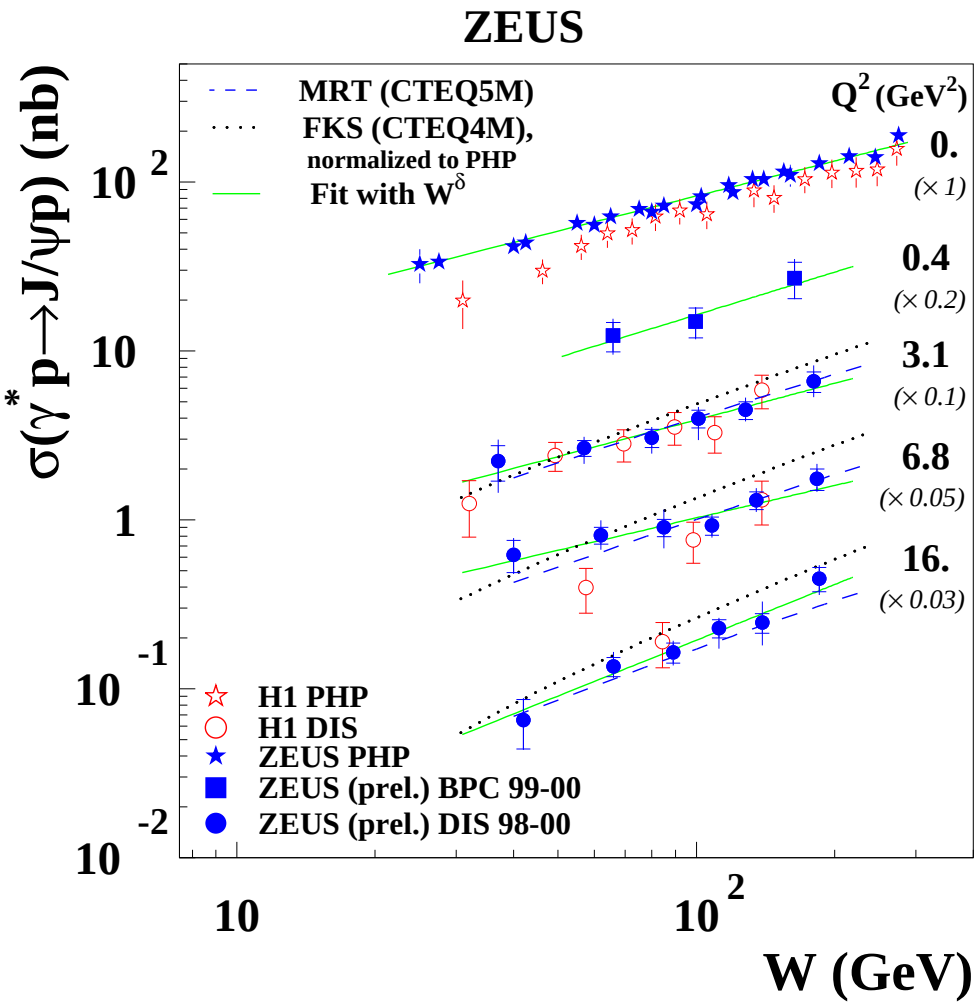


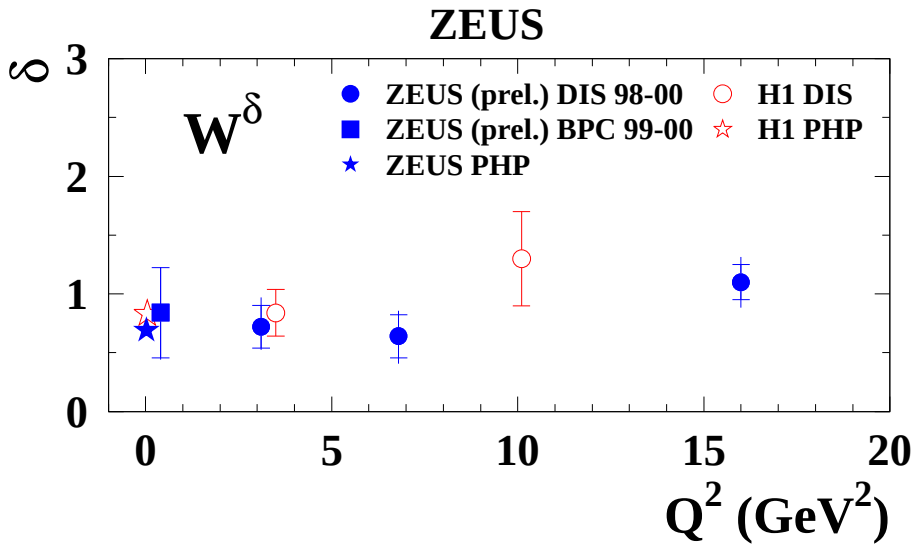
δ rises with Q^2

Transition: 'soft' $\rightarrow$ 'hard' scattering

$\sigma_{\gamma^* p \rightarrow \rho p} \propto W^{\delta}$ at different Q^2 values

J/ψ electroproduction, (scales: Q^2 and $M^2_{J/\psi}$)





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

$\delta \simeq 0.8$,

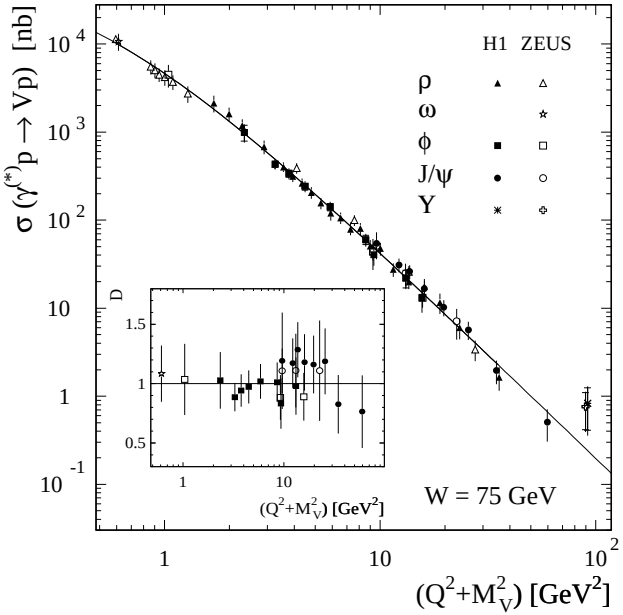
consistant with little or no Q^2 dependence

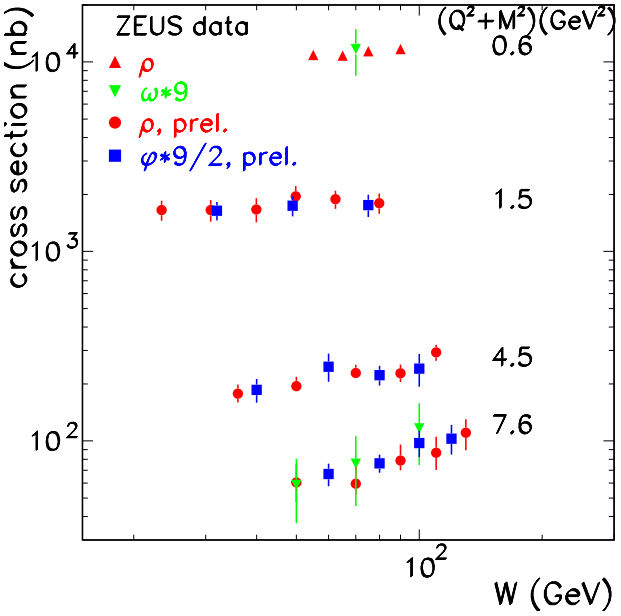
'hard' regime

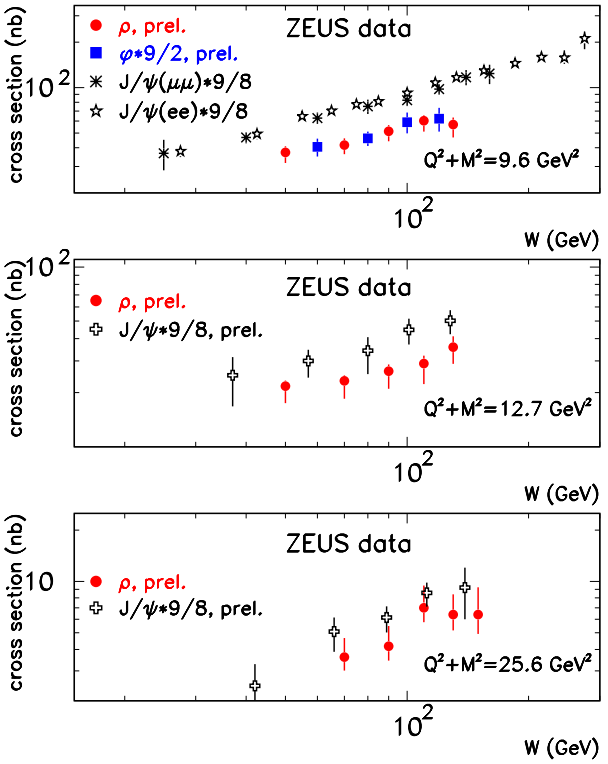
scale: $Q^2 + M^2$

if flavour independence $\Rightarrow \sigma_\rho : \sigma_\omega : \sigma_\phi : \sigma_{J/\psi} : \sigma\Upsilon = 9 : 1 : 2 : 8 : 2$

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







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

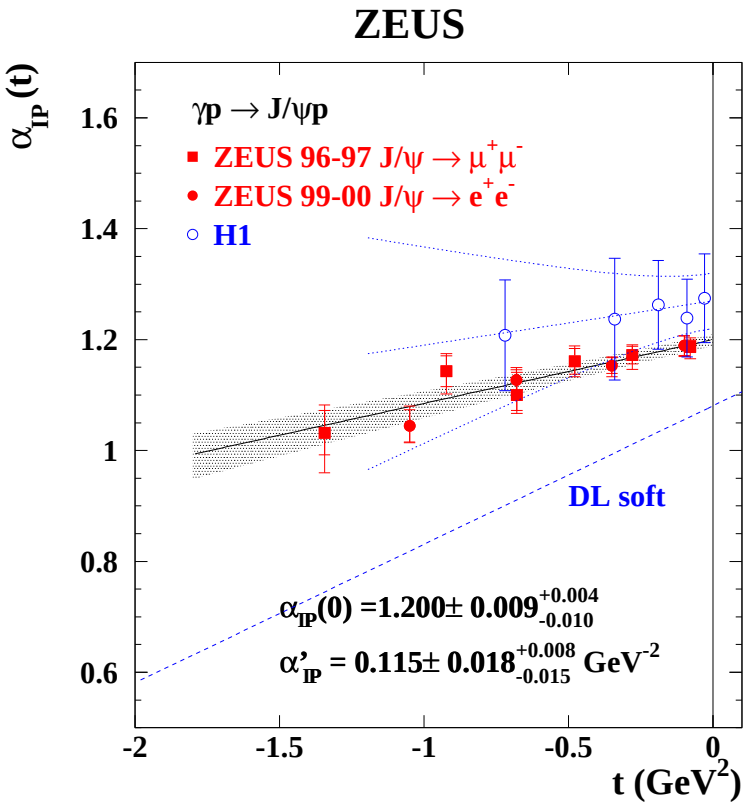
SU(4) – not (VM wave function effects?)

Scaling works for light quarks (u,d,s), but not for heavy (c,b).

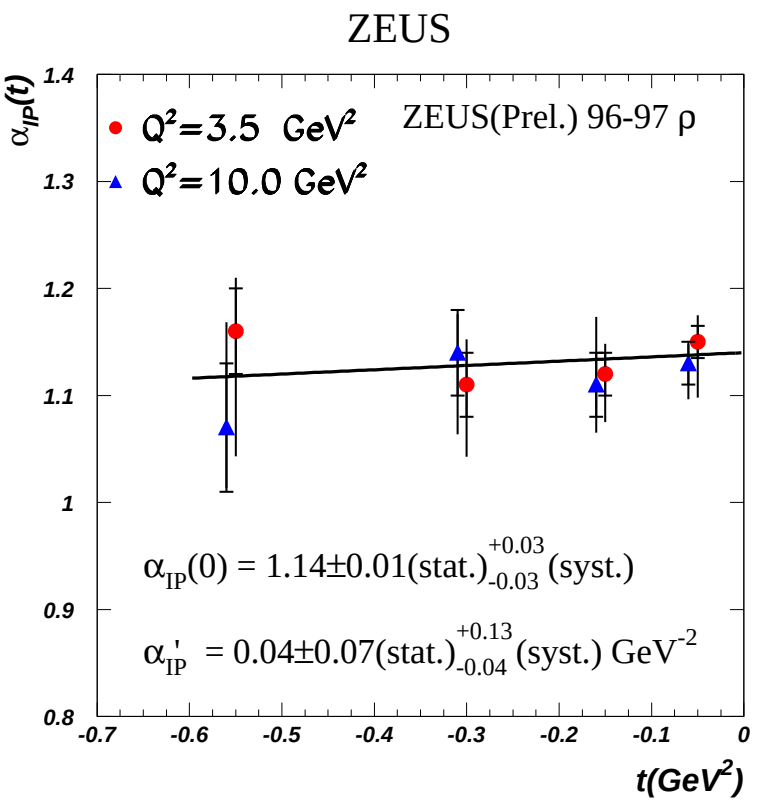
Regge trajectory ($\alpha_{I\!P}(t) = \alpha_0 + \alpha' t$).

Soft Pomeron exchange: α_0=1.08, α'=0.25 (ρ photoproduction)

J/ψ photoproduction (scale: M^2):



ρ electroproduction (scale: Q^2):

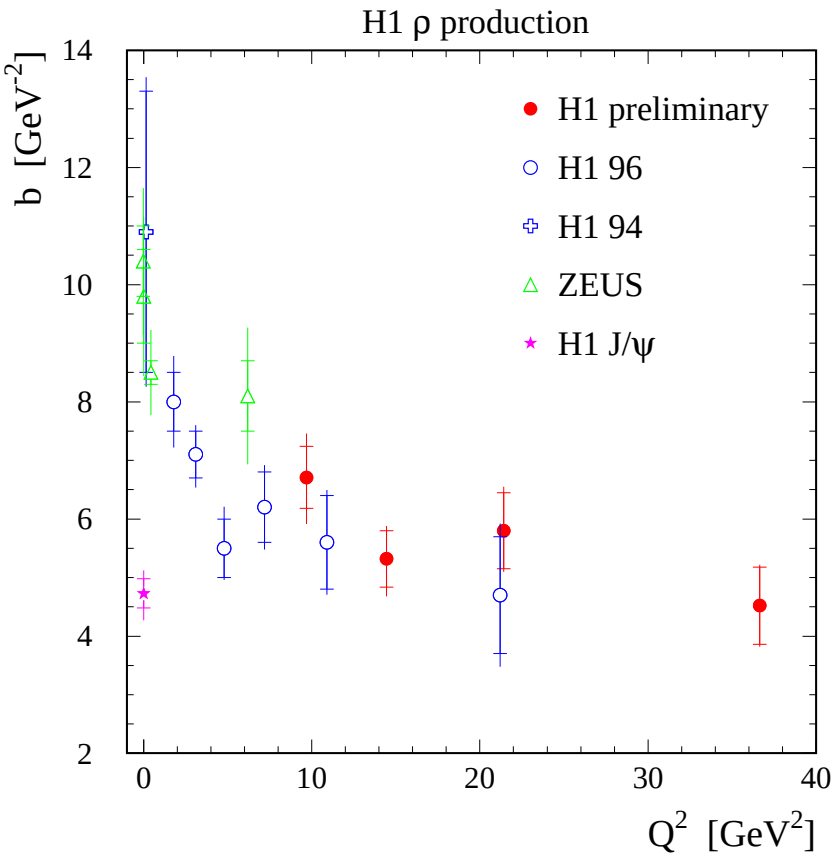


Little shrinkage: $\alpha'_{J/\psi}, \alpha'_\rho < 0.25 GeV^{-2}$

Trajectory depends on VM mass and γ^* virtuality - no universal pomeron.

t dependence

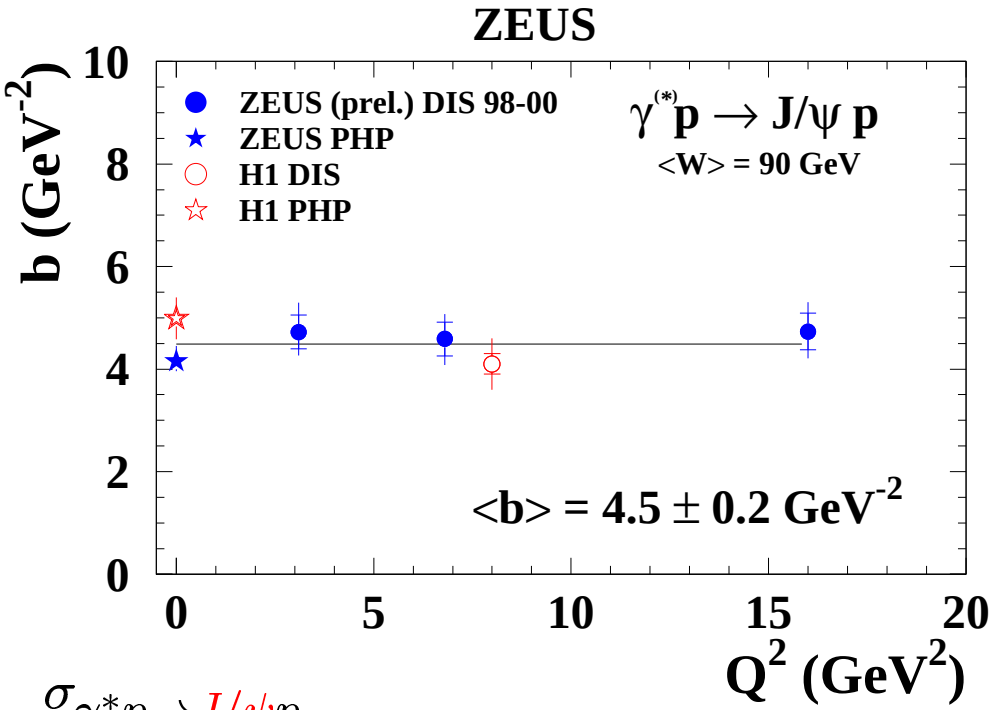
$d\sigma/dt \propto e^{bt}, |t| < 1GeV^2$



$\sigma_{\gamma^* p \to \rho p}$

b decreaces with Q^2

$b \propto r_p^2 + r_{VM}^2$



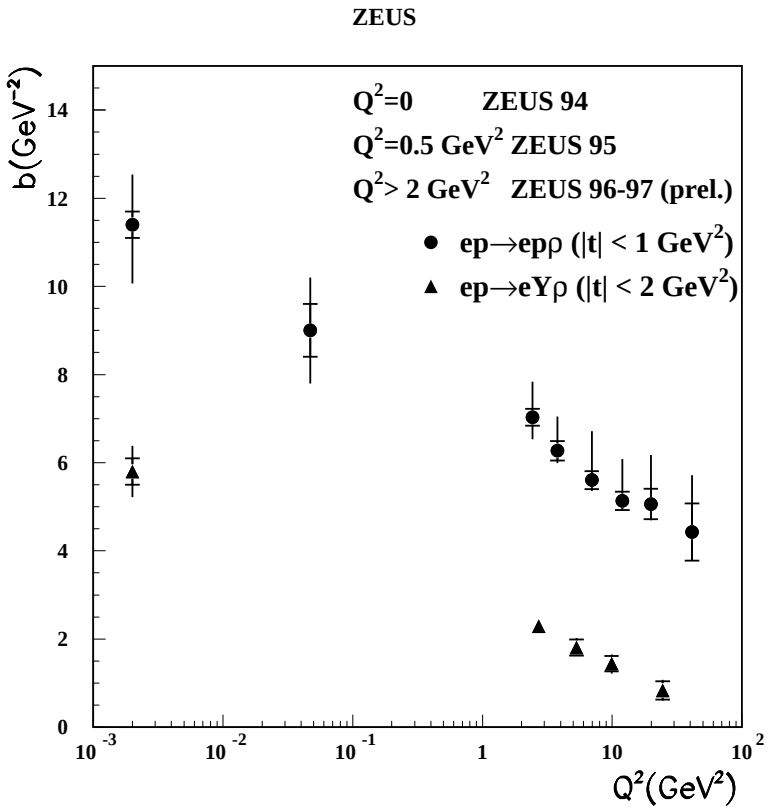
$\sigma_{\gamma^* p \to J/\psi p}$

b constant with Q^2

(asymptotic value of proton size, $b \simeq \frac{R_p^2}{4}$?)

ρ electroproduction

elastic & pdiss. ($|t| < 2GeV^2$)

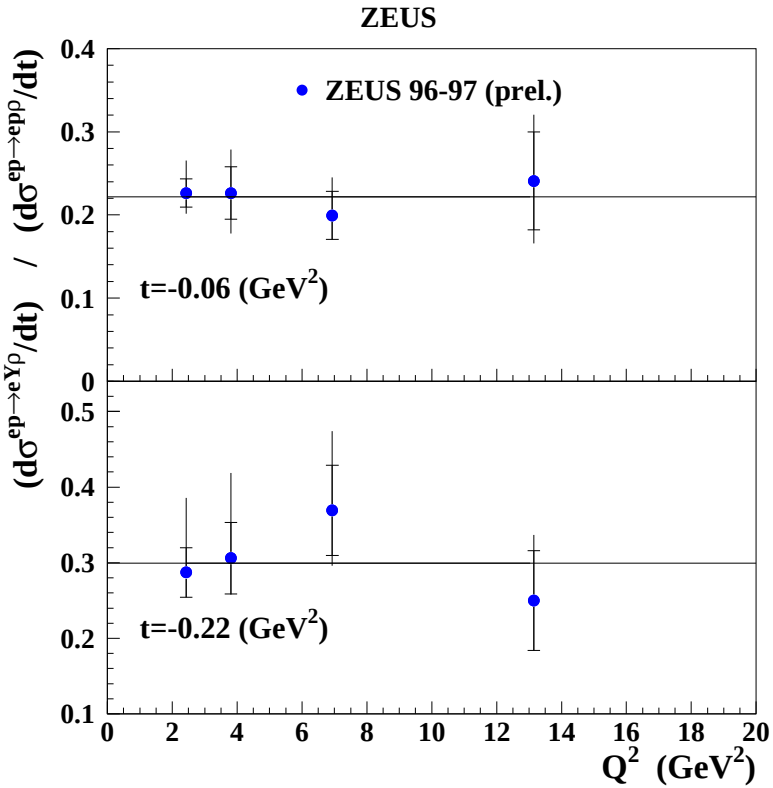


b decreases with Q^2

for both elastic and pdiss. processes.

($b_{pdiss.}$ is small at high Q^2)

pdiss./elastic ratio



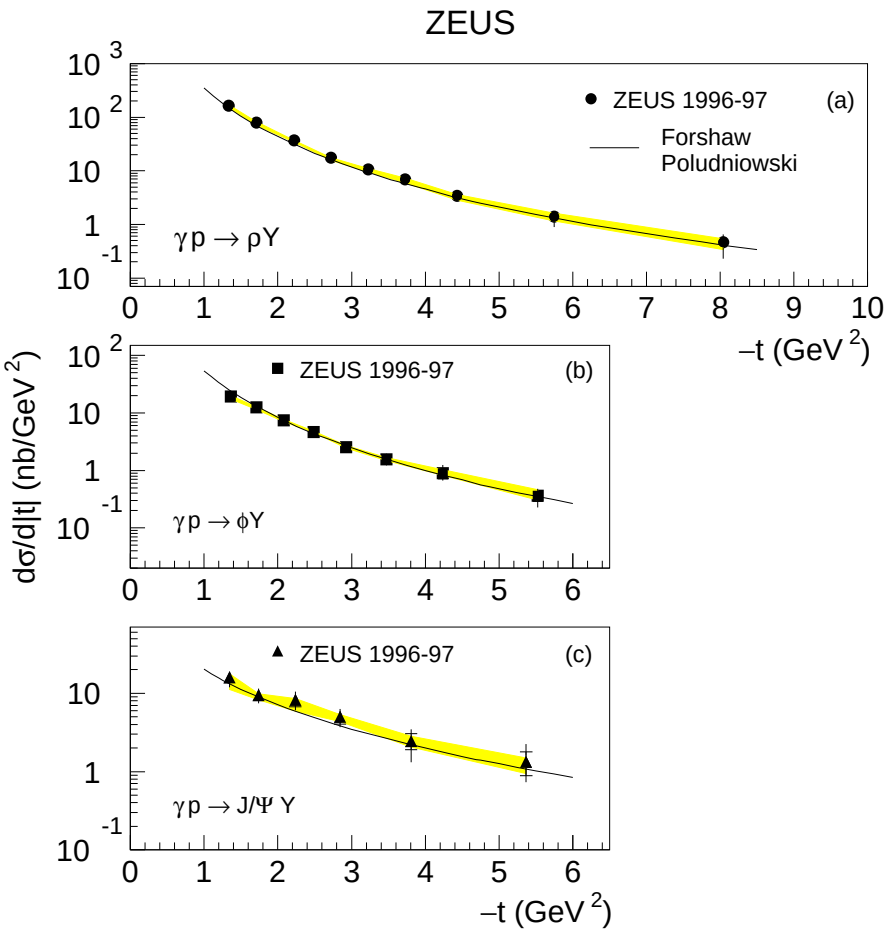
As a function of Q^2, in two bins of t:

consistant with no dependence on Q^2

$\rightarrow$ test of vertex factorisation.

high $|t|$ photoproduction

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



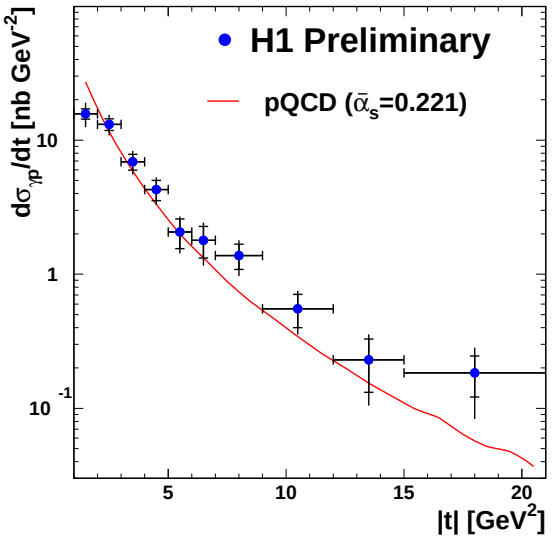
At high $|t|$ - power law behaviour:

$d\sigma/dt \propto |t|^{-n}$ (not exponential)

$\rho: \quad n = 3.21 \pm 0.04 \pm 0.15$

$\phi: \quad n = 2.7 \pm 0.1 \pm 0.2$

$J/\psi: n = 1.7 \pm 0.2 \pm 0.3$

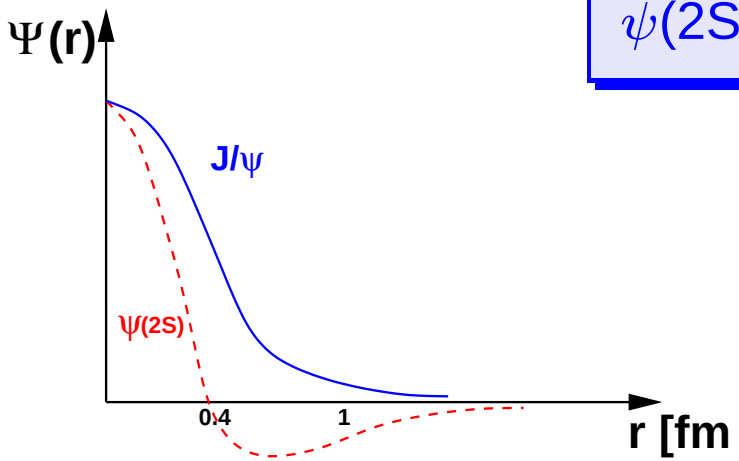


In agreement with LO BFKL (Forshaw, Poludniowski)

t provides a hard scale

(normalization uncertainties: α_S)

ψ(2S) photoproduction



$\Psi(r)$: $r^2_{\psi(2S)} > r^2_{J/\psi}$, node for $\psi(2S)$

t dependence,$(d\sigma/dt \propto e^{bt})$

$b_{\psi(2S)} = 4.31 \pm 0.6 \pm 0.5\ GeV^2$

$b_{J/\psi} = 4.99 \pm 0.3 \pm 0.4\ GeV^2$

Optical interpretation: $(b \propto r_p^2 + r_{VM}^2)$:

$b_{\psi(2S)} > b_{J/\psi}$ $(-)$

QCD: b sensitive to the node in the wave function:

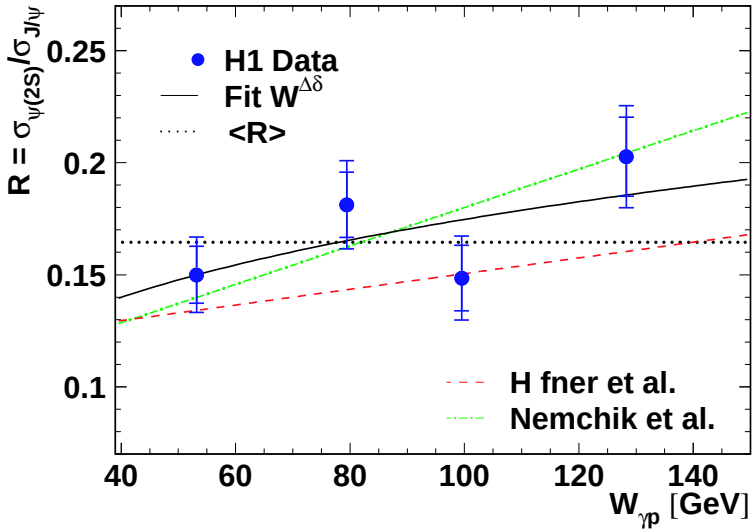
$b_{\psi(2S)} \leq b_{J/\psi}$ $(+)$

W dependence

QCD:

$\rightarrow$ suppression: $R = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}}$=0.17

$\rightarrow \sigma(W) \propto W^{\delta}$: $\delta_{\psi(2S)} \geq \delta_{J/\psi}$



Data consistant with QCD calculations $\rightarrow$ Sensitivity to the wave function of charmonium.

Decay angular distributions

Angular distribution $\rightarrow$ spin density matrix elements $r^{ij}_{kl} \rightarrow$ helicity amplitudes $T_{\lambda_\gamma,\lambda_\rho}$

15 independent combinations of SDME.

observed in soft regime:

S-channel helicity conservation hypothesis:

(SCHC + natural parity exchange)

VM retains γ^* helicity.

only $\gamma_L \rightarrow \rho_L$ ($T_{00} \neq 0$),

$\gamma_T \rightarrow \rho_T$ ($T_{11} \neq 0$)

transitions allowed.

($T_{01} = T_{10} = T_{1-1} = 0$)

expected in a hard regime (pQCD):

quantitative SCHC violation:

Hierarchy at high Q^2:

$\rightarrow |T_{00}| > |T_{11}| > |T_{01}| > |T_{10}| > |T_{1-1}|$

$\rightarrow \sigma_L$ dominates ($R = \sigma_L/\sigma_T$ increaces with Q^2)

$|t|$ dependence:

$\rightarrow T_{11}, T_{00}$: const. with t (no helicity flip)

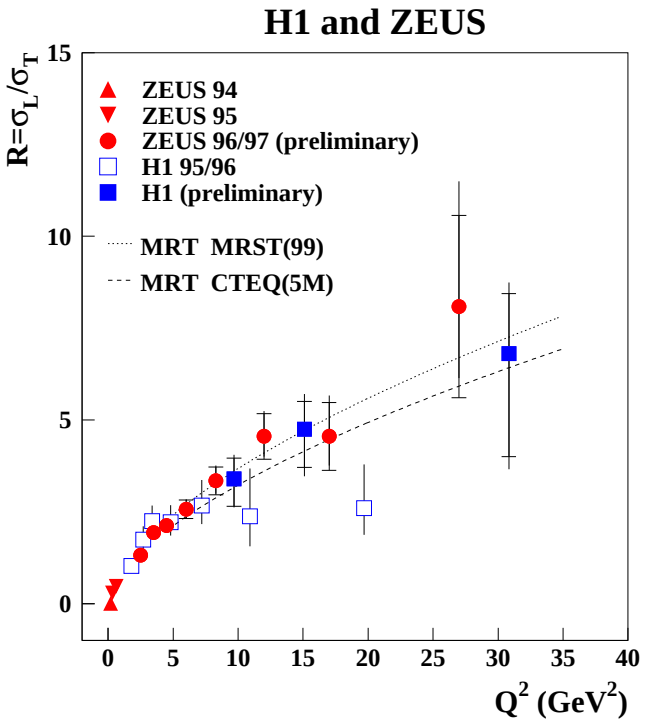
$\rightarrow T_{01}, T_{10} \propto T_{00}\sqrt{t}$ (single flip)

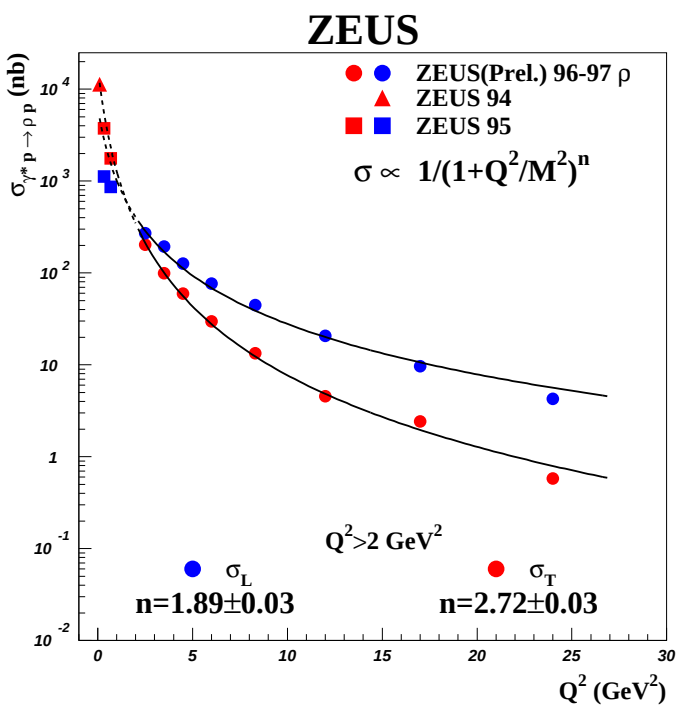
$\rightarrow T_{1-1} \propto T_{00}t$ (double flip)

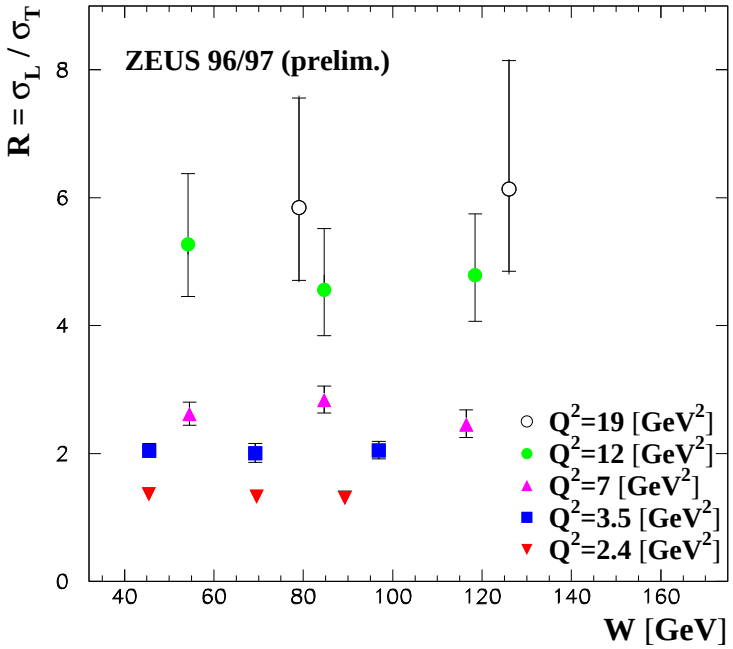
ρ electroproduction

$$r_{00}^{04} = \sigma_L/\sigma_{TOT} \propto |T_{00}|^2 + |T_{01}|^2$$

$$(|T_{00}| \gg |T_{01}|) \Rightarrow R = \frac{\sigma_L}{\sigma_T} \simeq \frac{r_{00}^{04}}{\epsilon(1-r_{00}^{04})}$$



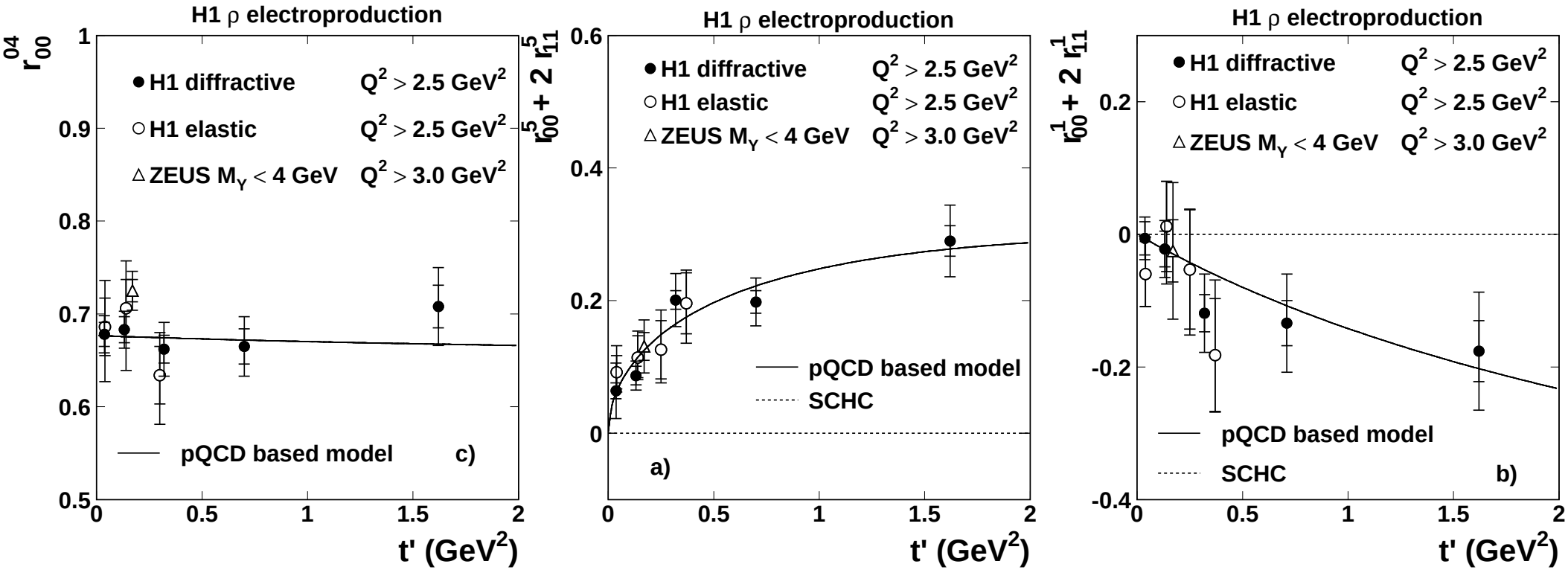




$R = \sigma_L/\sigma_T$ increases with Q^2. ($|T_{00}| > |T_{11}|$)

σ_T has the same W dependence as σ_L.

high $|t|$ ρ electroproduction ($\gamma^* p \to \rho Y$)

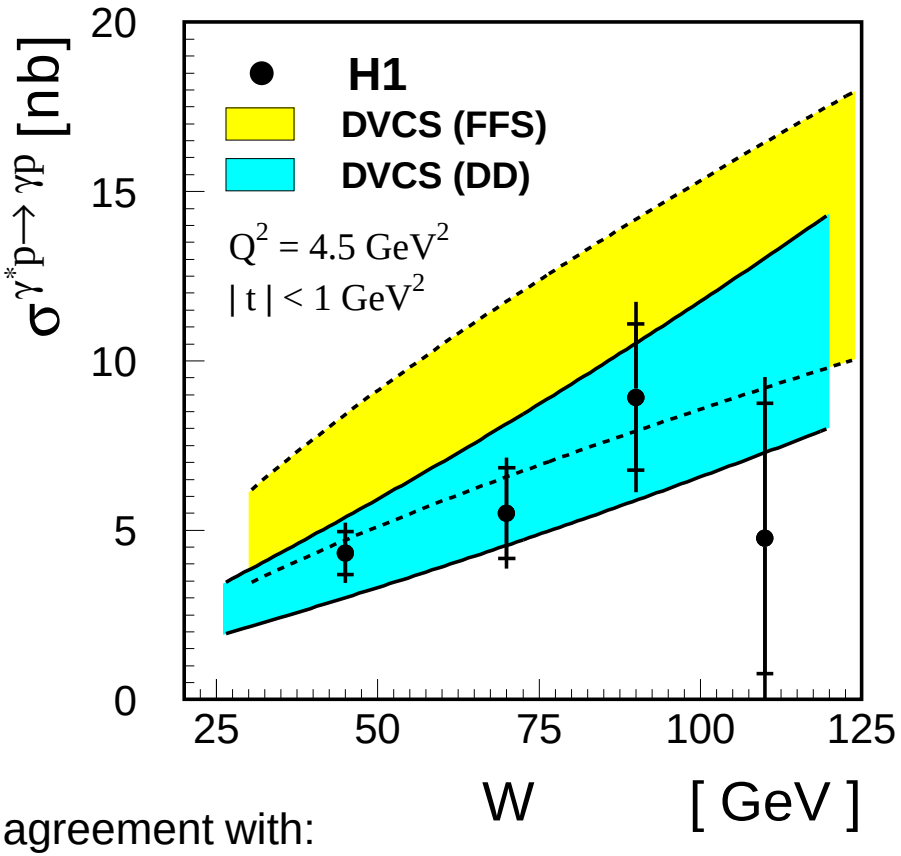


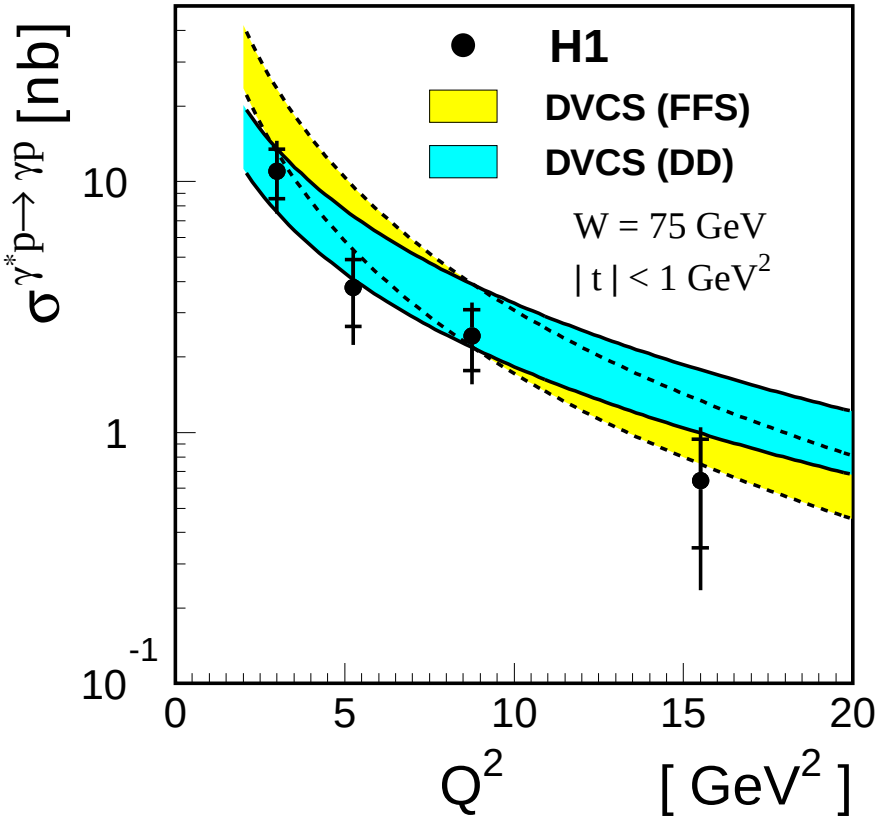
r_{00}^{04} – independent of t (as expected)

$r_{00}^{5} + 2r_{11}^{5} \propto T_{00}T_{01}^{\dagger} + 2T_{11}T_{10}^{\dagger} - 2T_{10}T_{1-1}^{\dagger} \propto \sqrt{t} \Rightarrow$ dominated by single flip

$r_{00}^{1} + 2r_{11}^{1} \propto -|T_{01}|^2 + 2T_{11}T_{1-1}^{\dagger} + 2T_{1-1}T_{11}^{\dagger} \propto -t \Rightarrow$ single flip and double flip contributes,
but negative sign $\Rightarrow |T_{01}| > |T_{1-1}|$

DVCS - H1





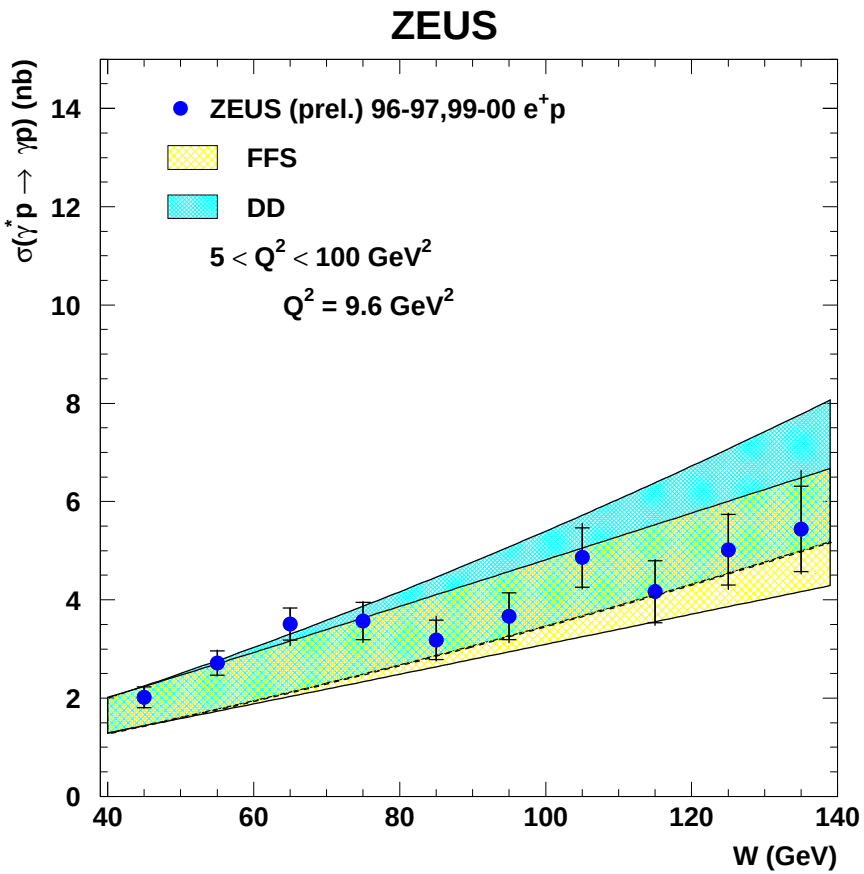
In agreement with:

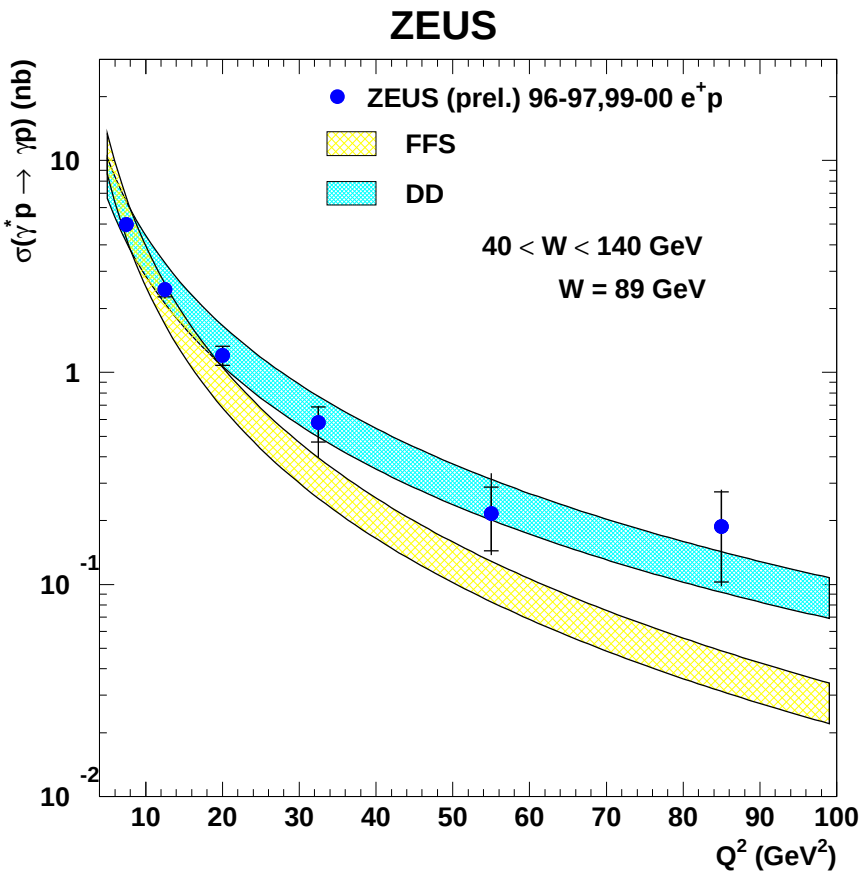
→ Frankfurt, Freund, Strikman (FFS) – QCD based model

→ Donnachie, Dosch (DD) – semiclassical dipole model

Normalisation uncertainty → $5 < b < 9 GeV^{-2}$.

DVCS - ZEUS





In agreement with FSS and DD prediction.

fit with W^{δ}, $\delta = 0.78 \pm 0.10$

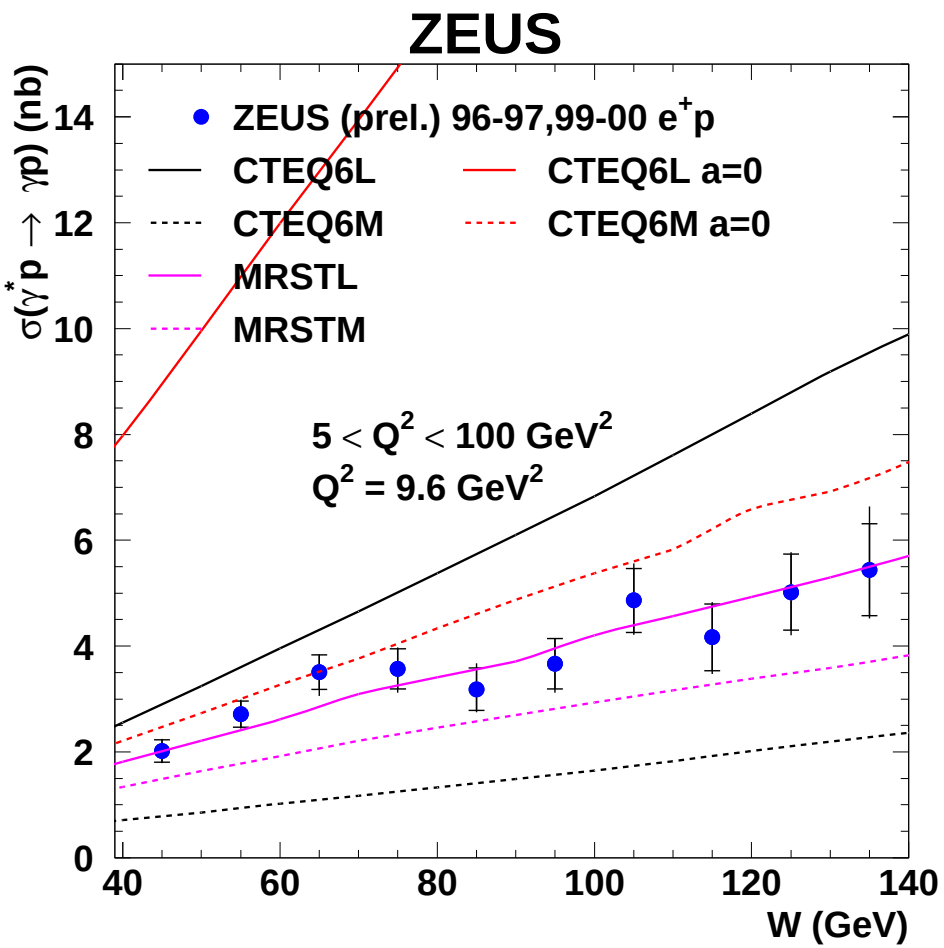
Normalisation uncertainty $\rightarrow$ $4.5 < b < 7 GeV^{-2}$.

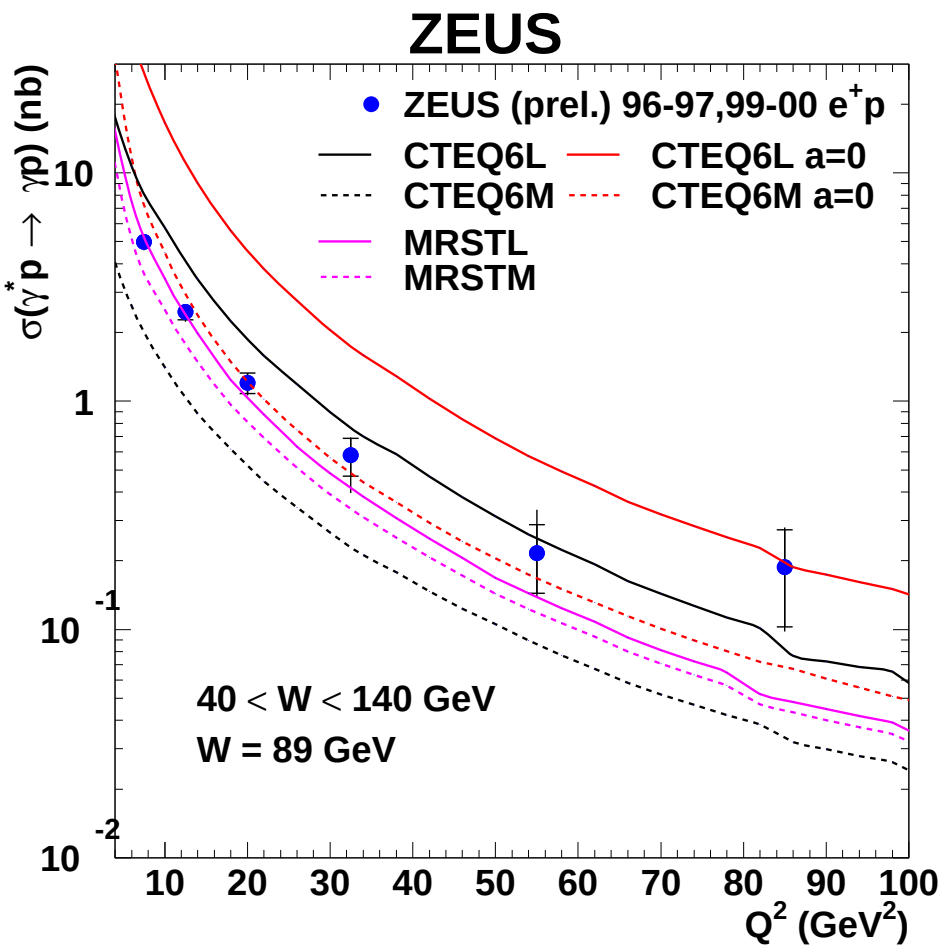
DD favored over FFS.

fit with $(Q^2)^{-n}$, $n = 1.47 \pm 0.07$

Similiar W and t dependence as J/ψ meson. DVCS seems to be a hard process.

DVCS - ZEUS





Data has potential to constrain SPD's.

Freund and McDermott: calculations using PDF's (LO - solid, NLO - dashed).

Summary and Outlook

- **Progress at HERA**
  - high precision data
  - spanning transition (soft $\rightarrow$ hard) in a wide kinematic range
  - Q^2, M^2, t serve as a hard scale
  - SU(3) restored using $Q^2 + M^2$ as a scale, SU(4) not
  - at high values of scales, pQCD successfully describes VMs and DVCS
- **In the future - HERA II**
  - expend Q^2 range, study Υ
  - constrain generalized PDF's