Vector Mesons and DVCS at HERA

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on behalf of the 

and 

Collaborations

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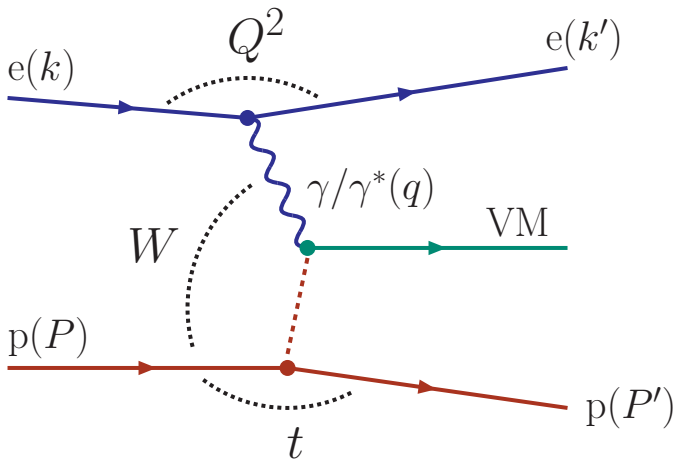
Exclusive diffraction



experimentally: very clean process in wide kinematic range

VM	Vector Meson or γ	$\rho, \omega, \phi, J/\psi, \psi', \Upsilon$
Q^2	photon virtuality	$Q^2 = -q^2 = -(k - k')^2$
W	c.m. energy of γp system	$W = (q + p)^2$
t	(4-mom. transfer)^2 at p-vertex	$t = (P - P')^2$

$\longrightarrow$ **VM at HERA: transition between soft and hard regime**

$\longrightarrow$ **simultaneous control of different scales:** Q^2, $|t|$, M_{VM}^2

Diffractive vector meson production in pQCD

VM = $q\bar{q}$ dipole, exchange of $\geq$ 2 gluons (color singlet – QCD Pomeron)

large Q^2, M_{VM}^2 or $|t| \Rightarrow$ small $q\bar{q}$ and interaction size

hard interaction $\Rightarrow$ perturbative QCD applicable, factorization holds

'Exclusive' VM production:

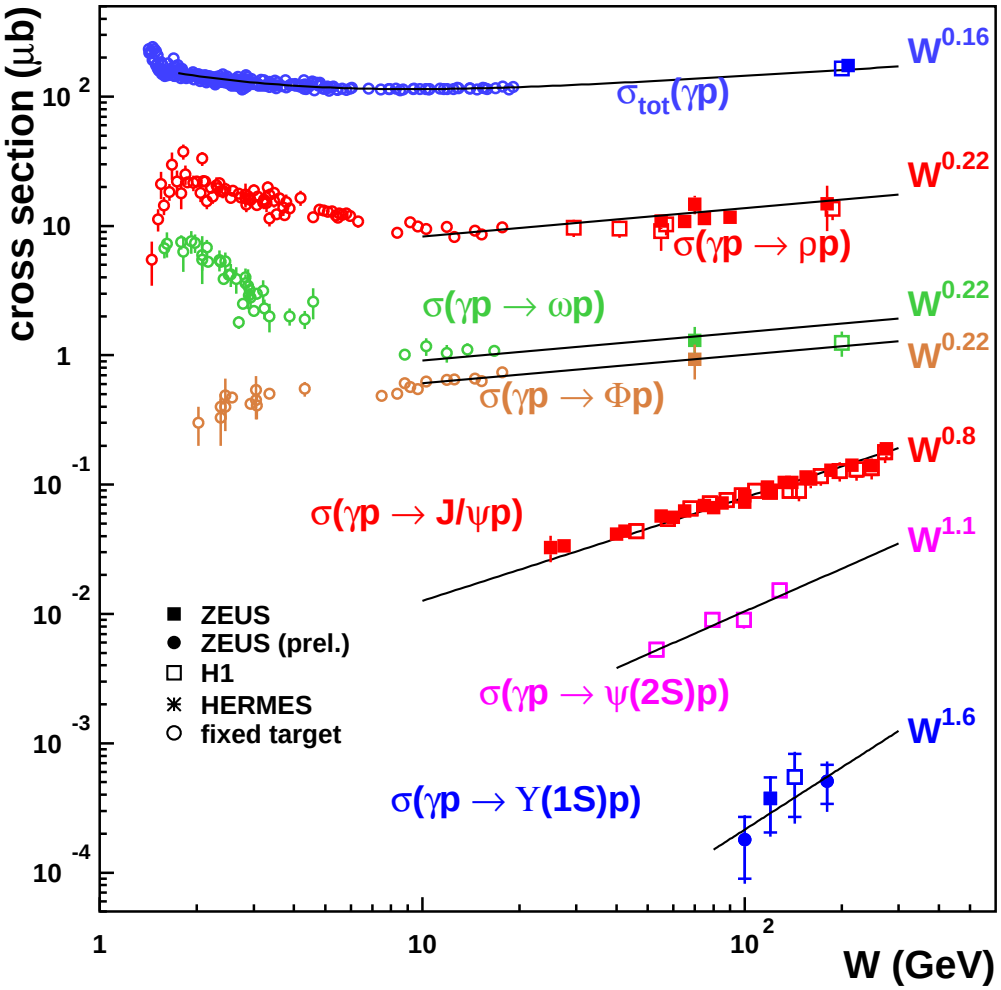
- steep rise of $\sigma(W)$, $\sigma \sim \frac{\alpha_S(Q^2)}{Q^6}[xg(x,Q^2)]^2$, $x \approx Q^2/W^2$
- universal t dependence: $\sim \exp^{-b_{2g}|t|}$, $b_{2g} \sim 4-5\,\mathrm{GeV}^{-2}$ and $\alpha'_{\mathrm{IP}} \approx 0$
- possible SCHC violation

Deeply Virtual Compton Scattering (DVCS):

- similar to VM production, but in the final state γ
- fully calculable in QCD
- no VM wave-function involved
- access to Generalized Parton Distributions (GPDs)

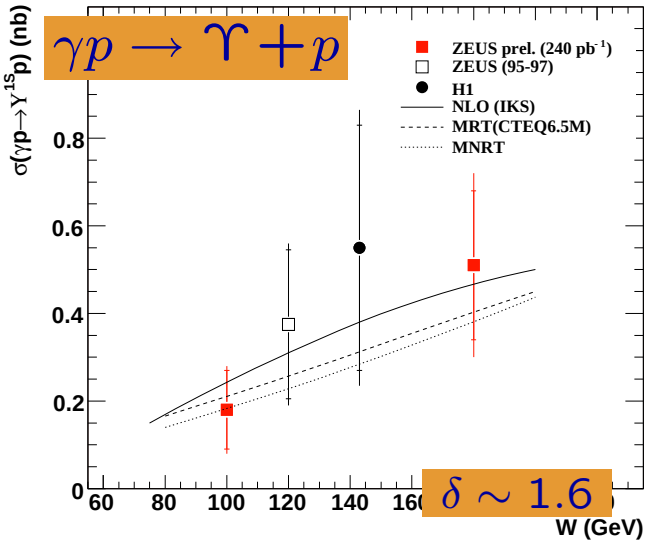
Vector mesons in photoproduction ($Q^2 \sim 0$)

$\gamma p \to V + p$ $(V = \rho, \phi, \omega, J/\psi, \Upsilon)$



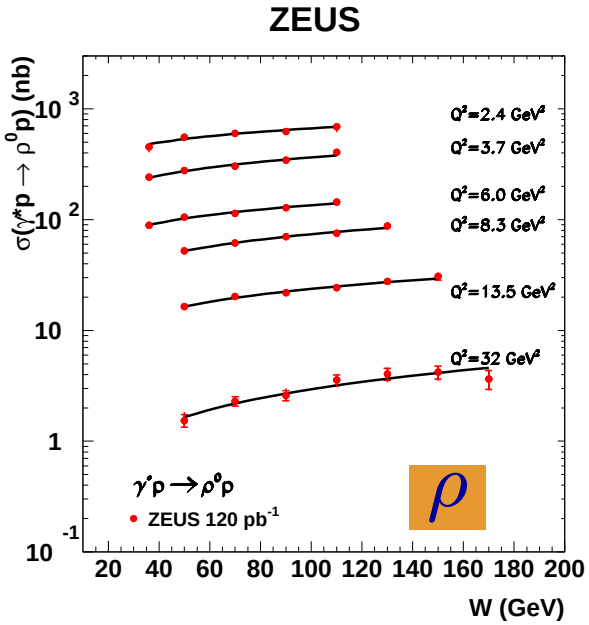
$\sigma(W) \propto W^{\delta}$

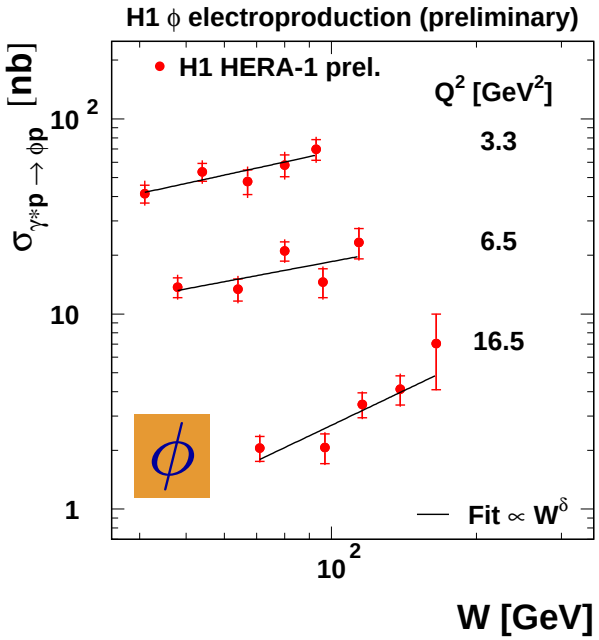
prediction for soft physics: $\delta \sim 0.2$



- the larger M_{VM} the harder process (steeper W dependence)
- **vector meson mass sets hard scale**

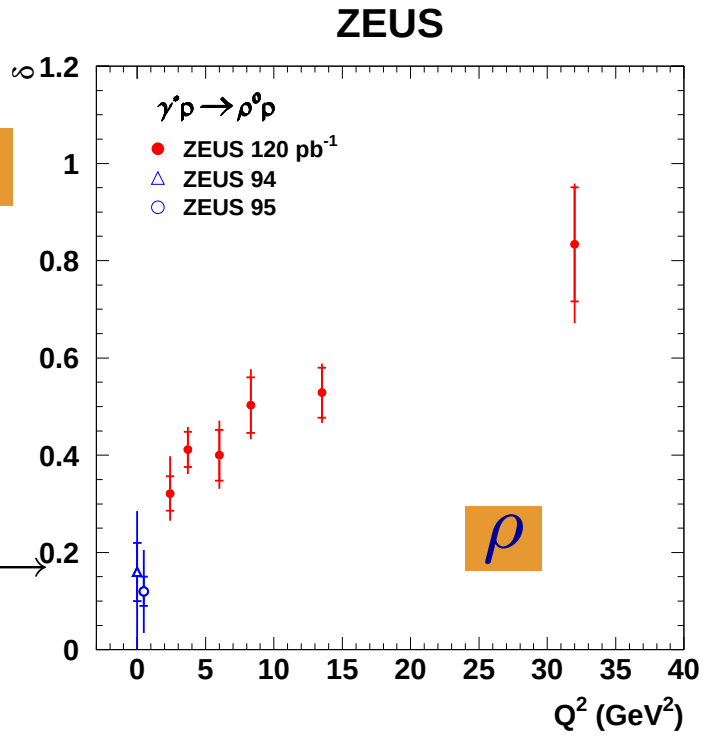
Exclusive electroproduction of ρ and ϕ mesons





$\sigma(W) \propto W^{\delta}$

soft physics prediction $\longrightarrow$

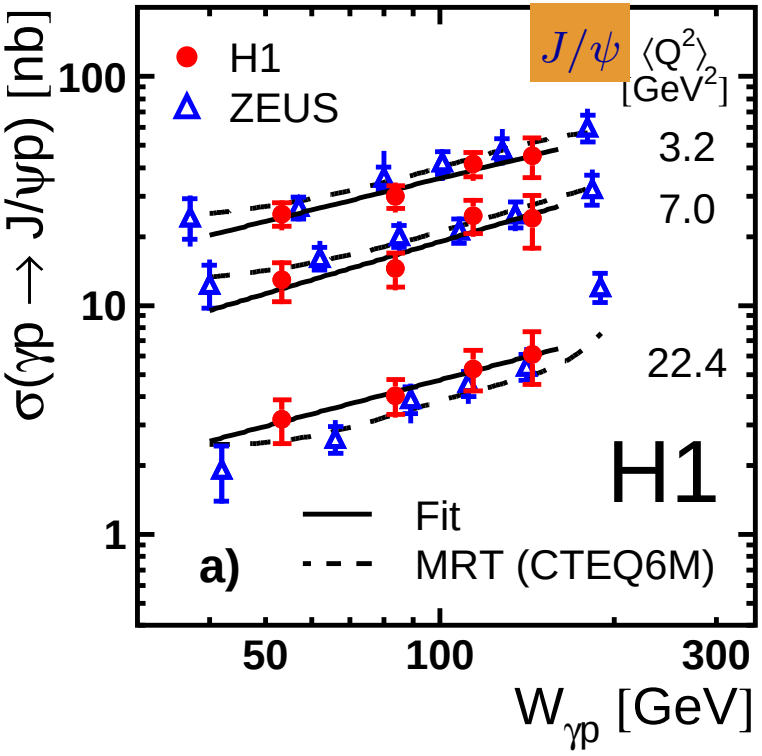


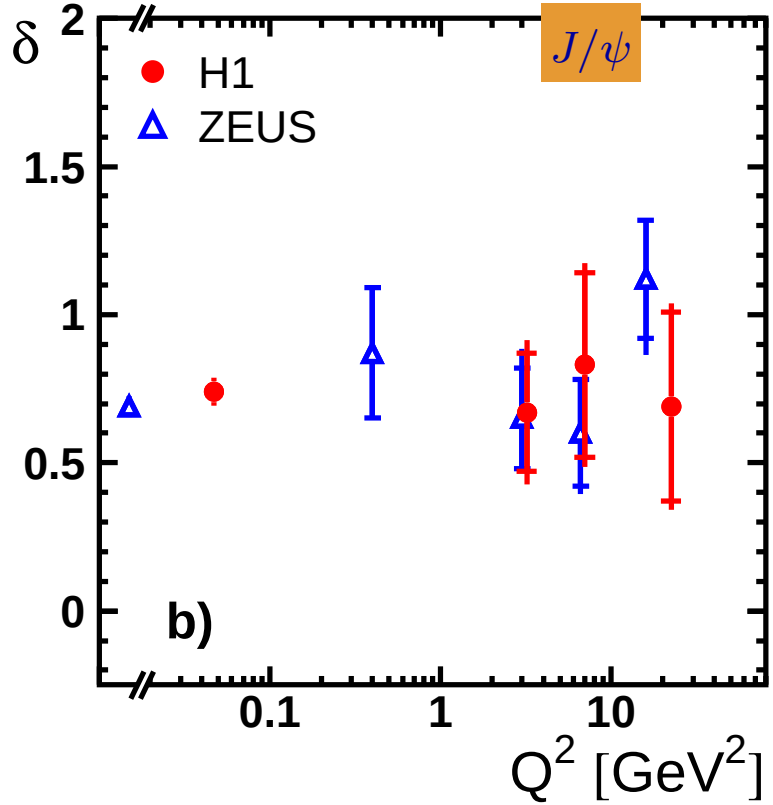
- energy dependence steeper with Q^2:

  $\longrightarrow \sigma(W) \propto W^{\delta(Q^2)}$

- Q^2 is the hard scale for ρ and ϕ

Exclusive electroproduction of J/ψ meson



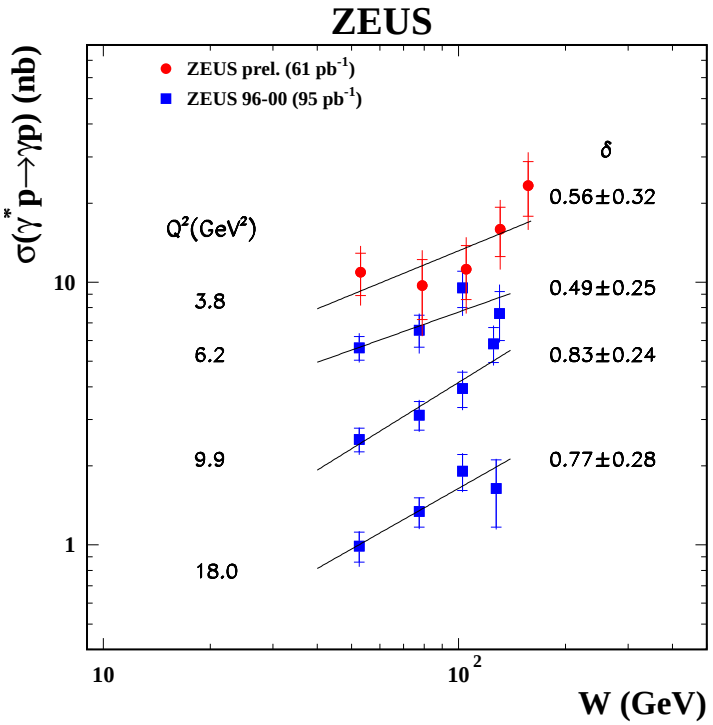


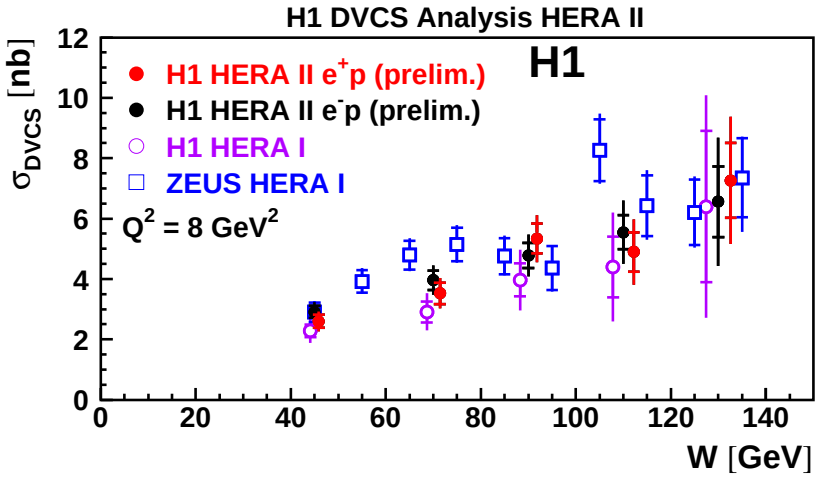
- already for $Q^2 = 0$ strong energy dependence
- no significant change with Q^2

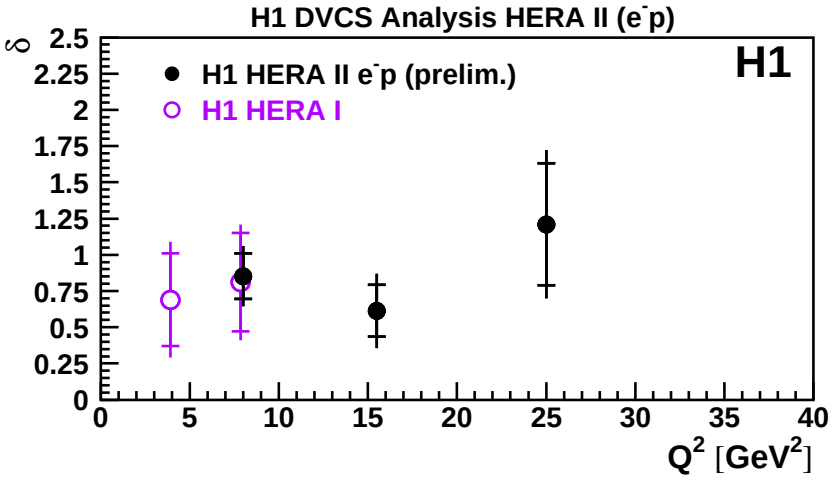
for J/ψ the mass is dominant scale

DVCS: energy dependence

$$\gamma^* p \to \gamma + p$$

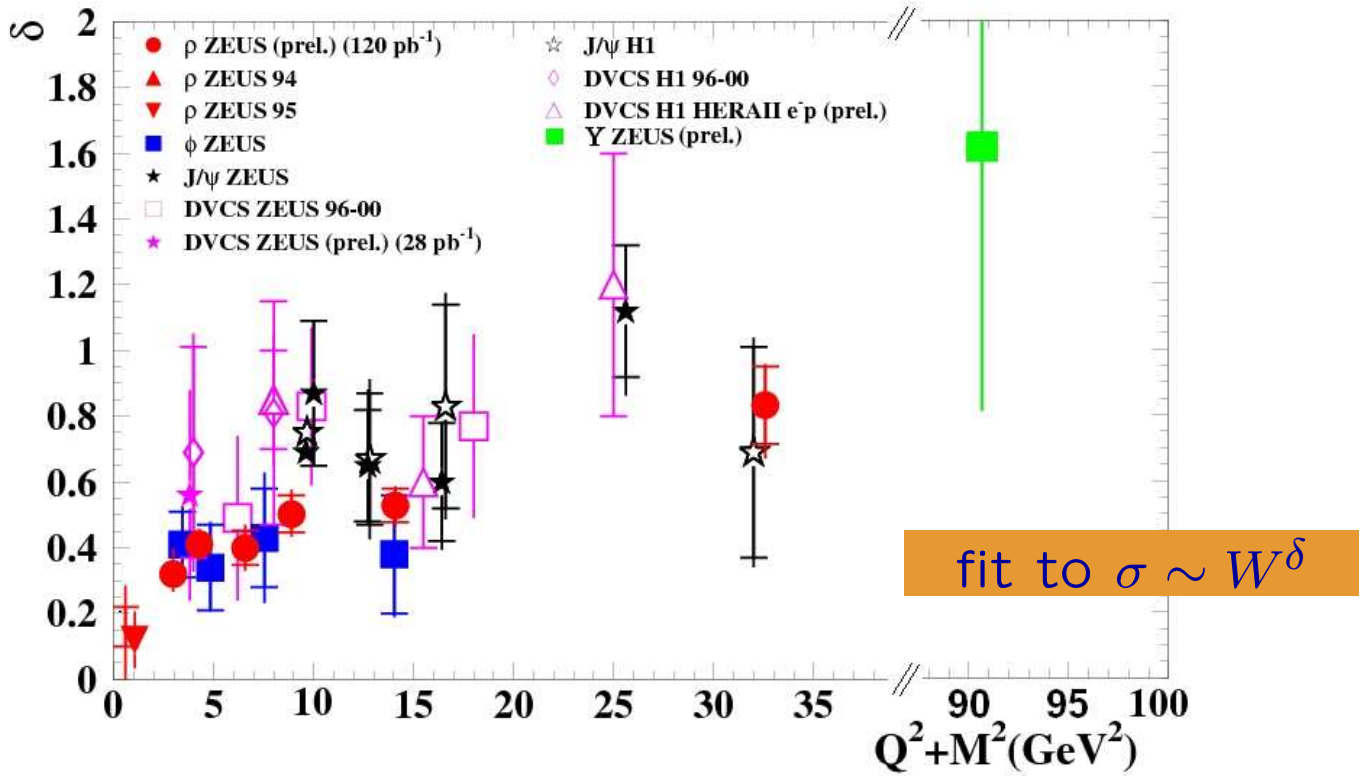






- steep rise with energy
- no significant Q^2 dependence

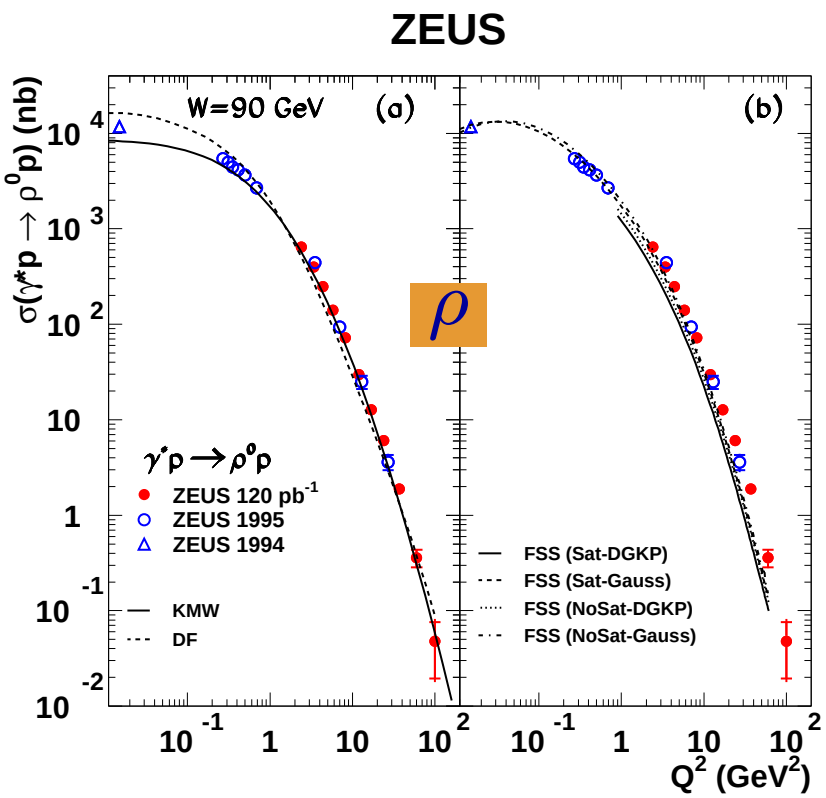
VM production and DVCS – energy dependence

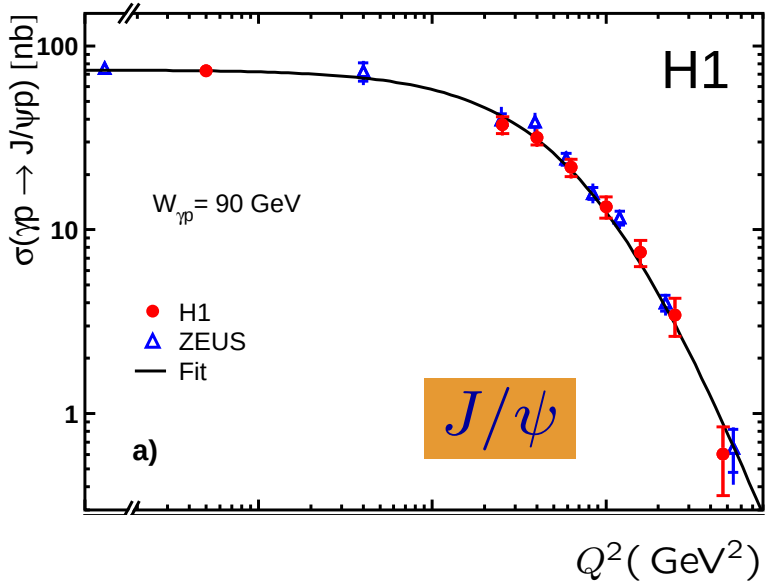


- similar behavior for DVCS and all VMs
- "universal" dependence of δ on $Q^2 + M_{VM}^2$ $\rightarrow$ transition scale
- ρ, ϕ in between from soft to hard regime
- for DVCS steep slope always observed
- J/ψ hard already in photoproduction

Q^2 dependence

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





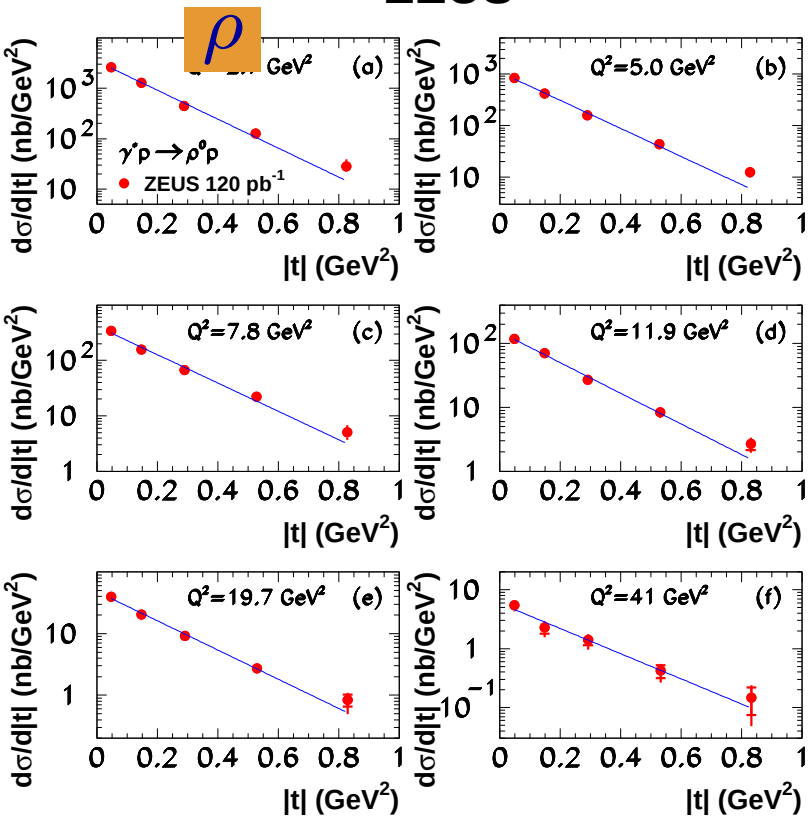
n increasing with Q^2 appears to be favored:

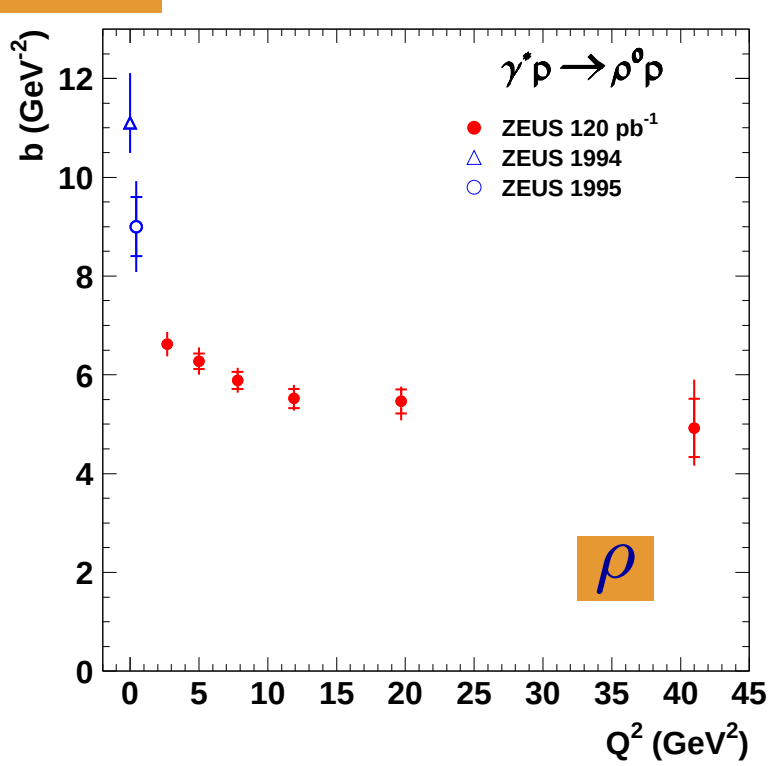
ρ	$n = 2.44 \pm 0.09$	$Q^2 > 10\,\text{GeV}^2$
ϕ	$n = 2.087 \pm 0.055 \pm 0.050$	$2 < Q^2 < 9\,\text{GeV}^2$
	$n = 2.75 \pm 0.13 \pm 0.07$	$Q^2 > 9\,\text{GeV}^2$
J/ψ	$n = 2.486 \pm 0.080 \pm 0.068$	all Q^2
γ	$n = 1.54 \pm 0.09 \pm 0.04$	$Q^2 > 3\,\text{GeV}^2$

none of the models reproduces the data over the full kinematic range

t dependence

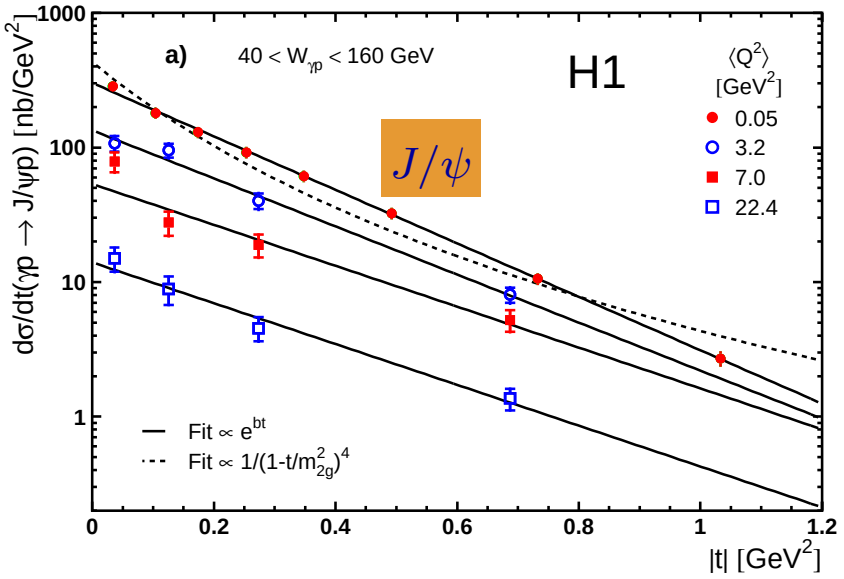
$d\sigma/dt \propto e^{-b|t|}$

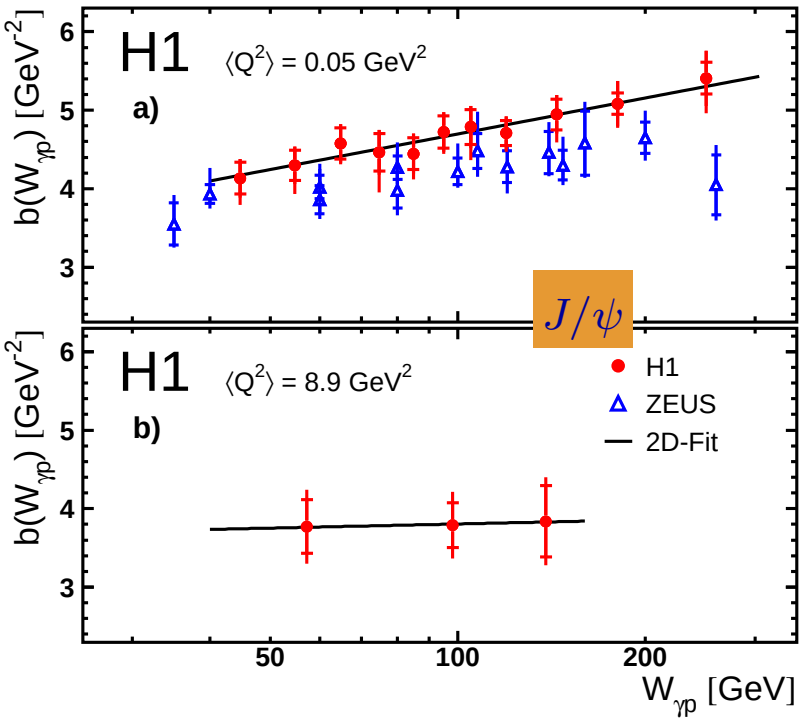




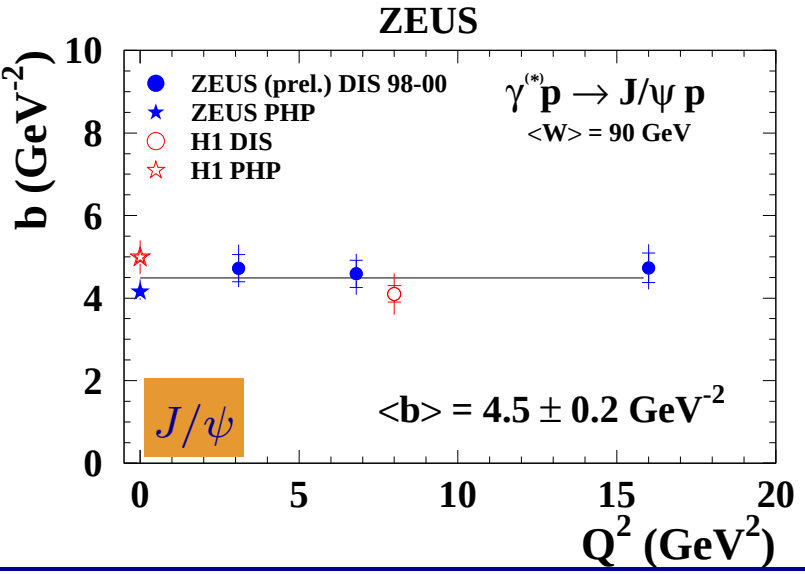
- slope $b \sim r^2_{\perp q\bar{q}} + r^2_{proton}$ characterize the size of interaction
- b decreases with increasing Q^2 (from ~ 10 to $4-5$)

t dependence



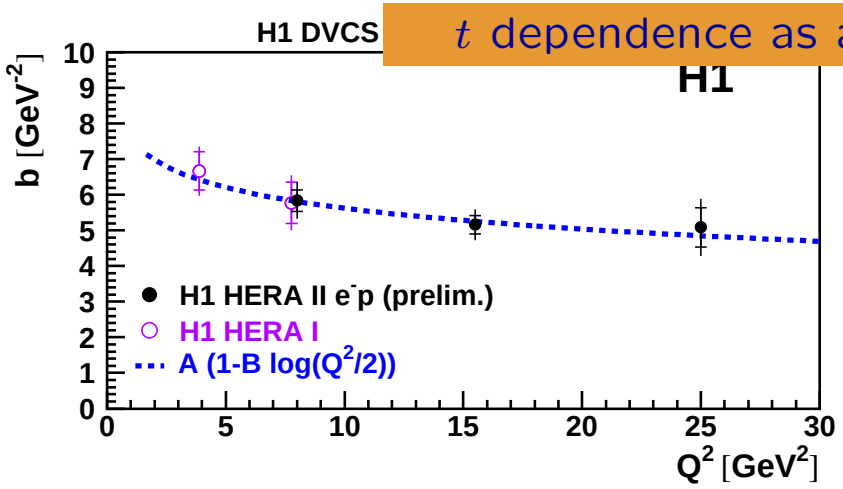


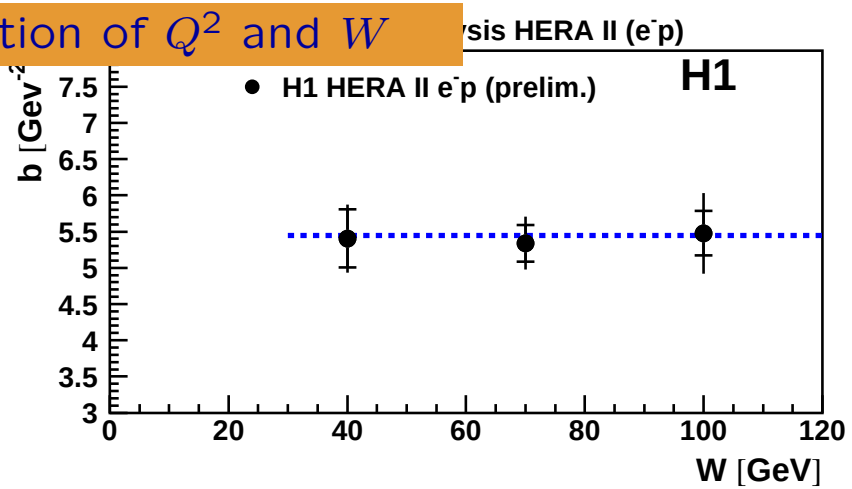
- $Q^2 \approx 0$: b increases with W (shrinkage)
- $Q^2 >> 0$ no energy dependence of b
- $b = 4.5 \pm 0.2\,\mathrm{GeV}^{-2}$ (ZEUS)



DVCS: t dependence

t dependence as a function of Q^2 and W



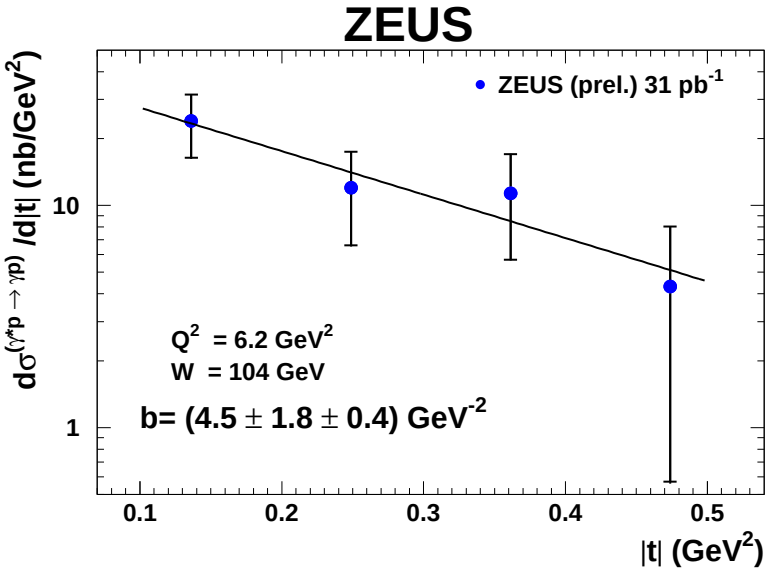


Q^2: $b(Q^2) = A[(1 - B \cdot \log(Q^2/2)]$

$A = 6.98 \pm 0.54\,\text{GeV}^{-2}$, $B = 0.12 \pm 0.03$

no W dependence of b

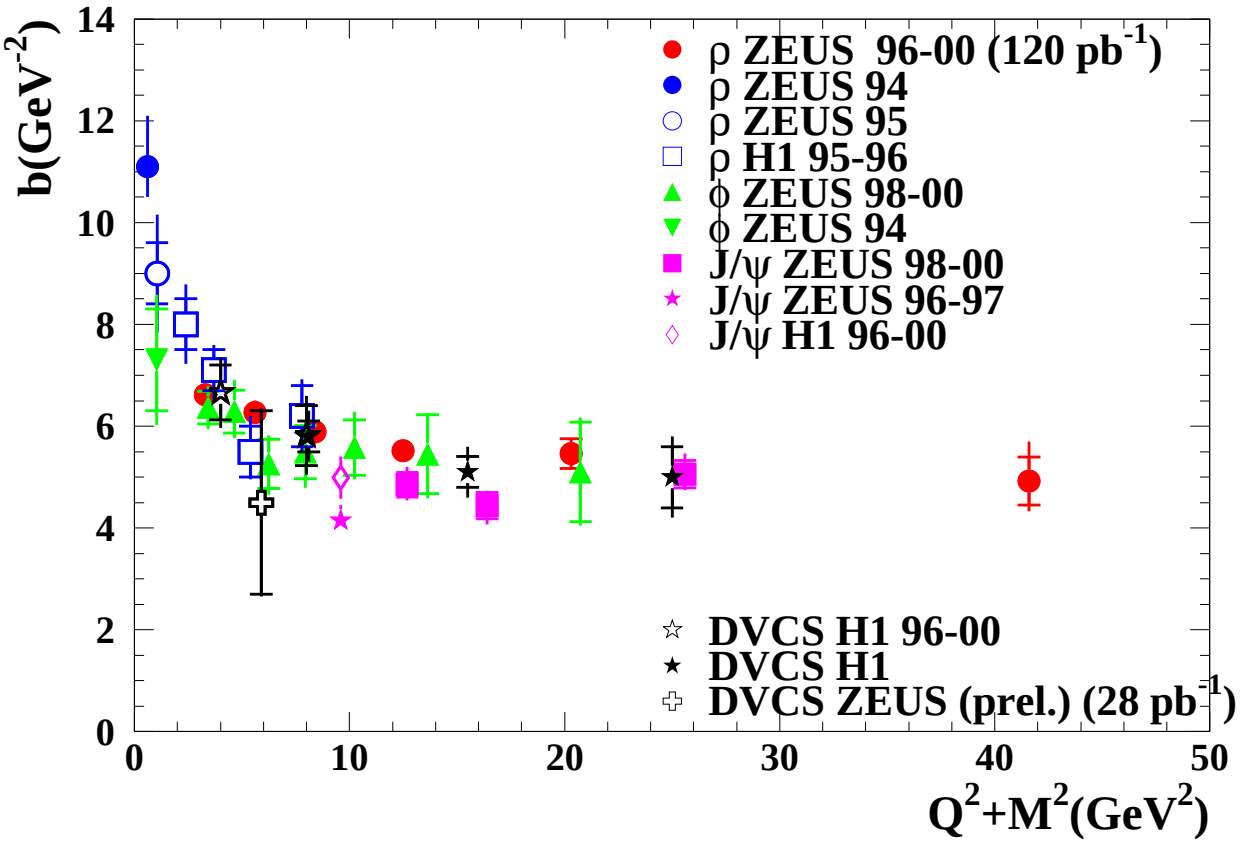
$b = 5.45 \pm 0.19 \pm 0.34\,\text{GeV}^{-2}$



direct t measurement - using Leading Proton Spectrometer

$b = 4.5 \pm 1.8 \pm 0.4\,\text{GeV}^{-2}$

t dependence



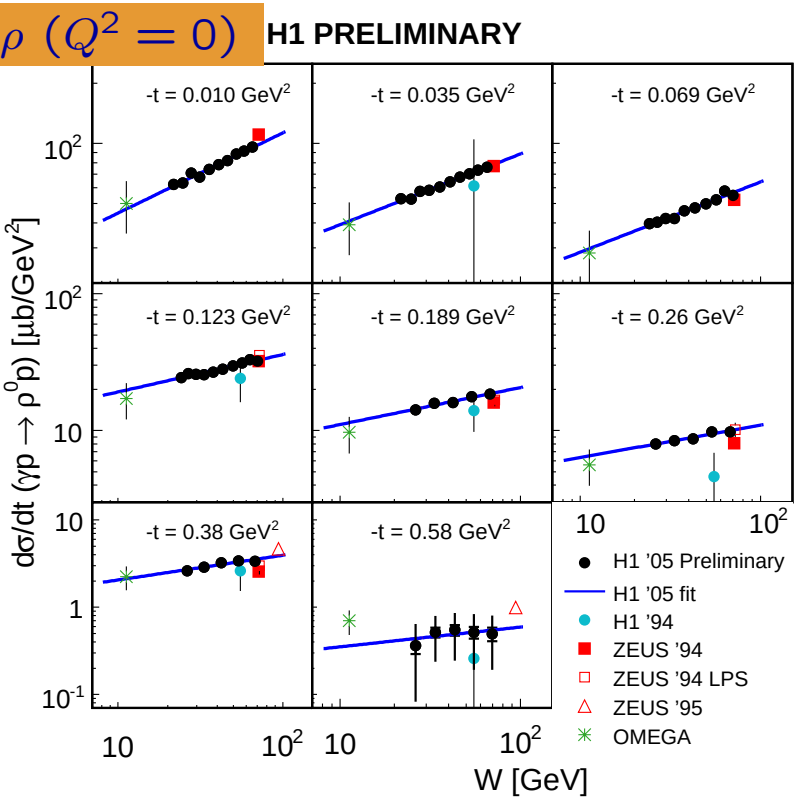
$\frac{d\sigma}{dt} \propto \exp^{-b|t|}$

- $b \sim r^2_{\perp q\bar{q}} + r^2_{proton}$ is the size of interaction
- size of the gluons: $\langle r^2 \rangle = 2 \cdot b \cdot (\hbar c)^2$
  - $r_g \sim 0.6$ fm smaller than charge radius of the proton, $r_p = 0.8$ fm

  $\rightarrow$ **gluons are confined in smaller space than quarks**

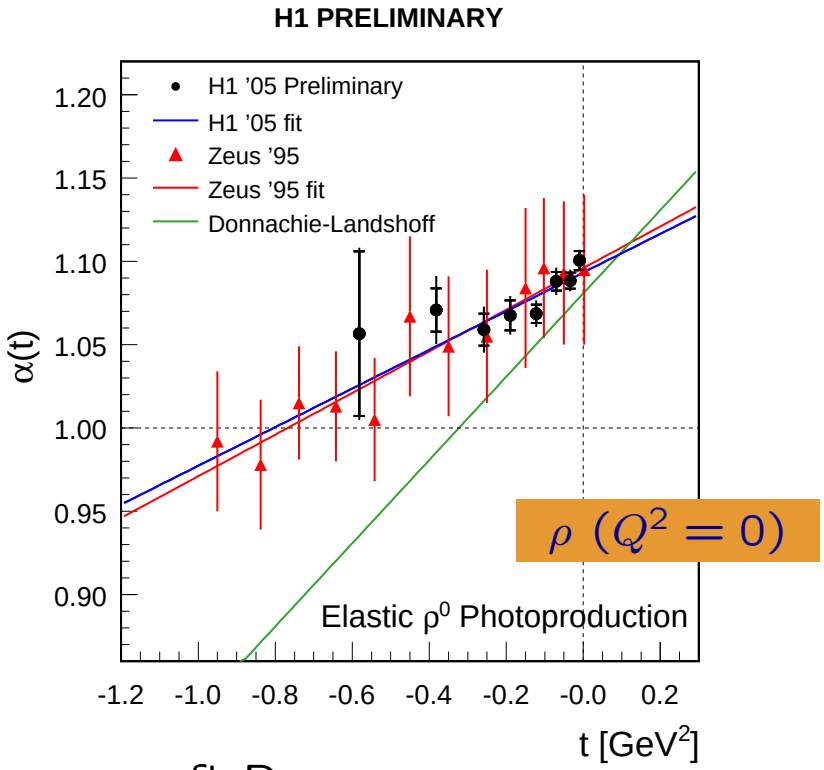
Effective Pomeron trajectory

$\rho\ (Q^2 = 0)$



$$\frac{d\sigma}{dt} \propto e^{-bt} \cdot \left(\frac{W}{W_0}\right)^{4(\alpha_{IP}(t)-1)}$$

$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP} \cdot t$$



$\rho\ (Q^2 = 0)$

ZEUS:

$$\alpha_{IP}(0) = 1.096 \pm 0.021$$
$$\alpha'_{IP} = 0.125 \pm 0.038\ \text{GeV}^{-2}$$

H1:

$$\alpha_{IP}(0) = 1.093 \pm 0.003^{+0.008}_{0.007}$$
$$\alpha'_{IP} = 0.116 \pm 0.027^{+0.036}_{0.046}\ \text{GeV}^{-2}$$

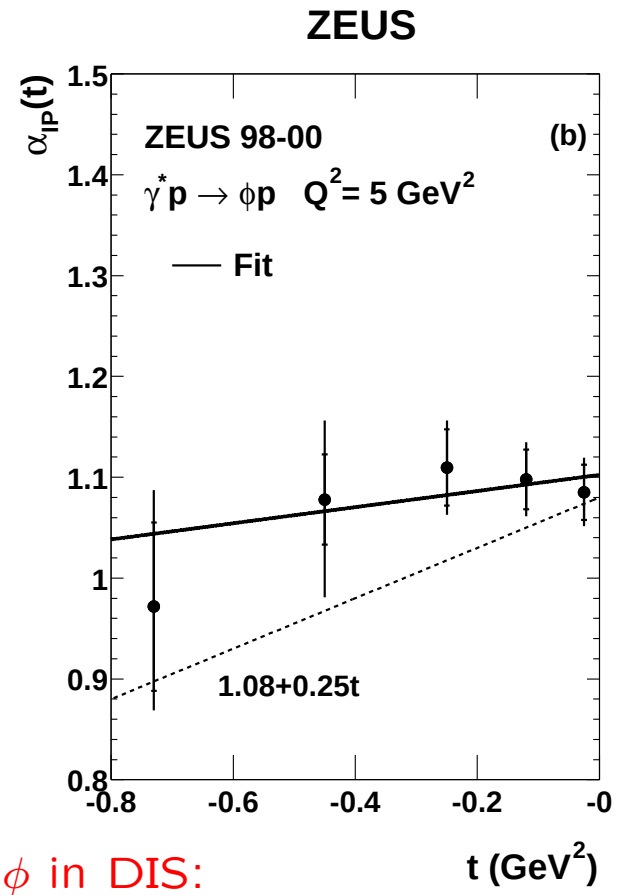
soft Pomeron:

$$\alpha_{IP}(t) = 1.08 + 0.25t$$

$\alpha_{IP}(0)$ **consistent with soft predictions, but** α'_{IP} **much smaller**

Effective Pomeron trajectory

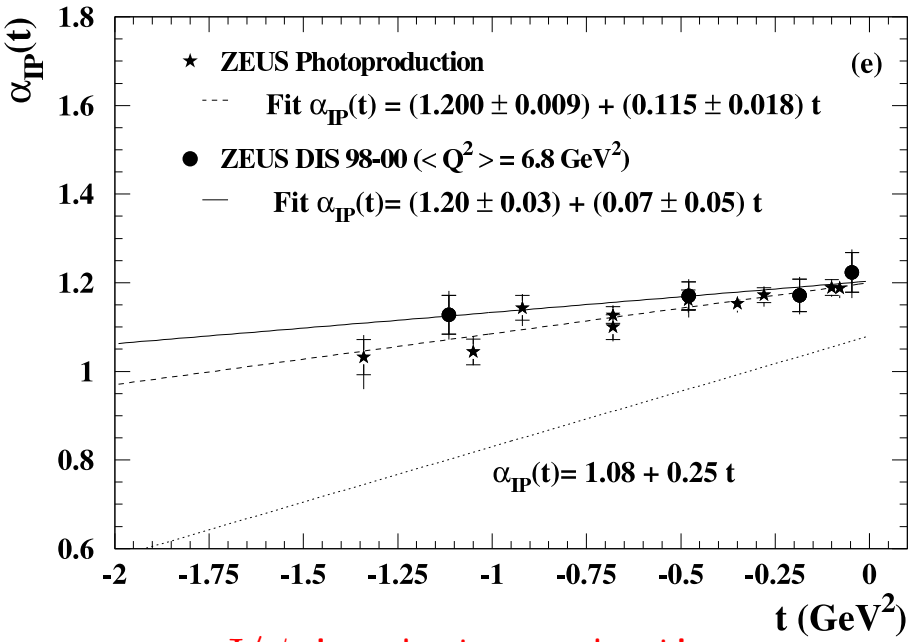
effective pomeron trajectory extracted from $\frac{d\sigma}{dt}$ at fixed Q^2



ϕ in DIS:

$\alpha_{IP}(0) = 1.10 \pm 0.2 \pm 0.2$

$\alpha'_{IP} = 0.08 \pm 0.09 \pm 0.08\,\text{GeV}^{-2}$



J/ψ in photoproduction:

$\alpha_{IP}(0) = 1.20 \pm 0.009$

$\alpha'_{IP} = 0.115 \pm 0.018\,\text{GeV}^{-2}$

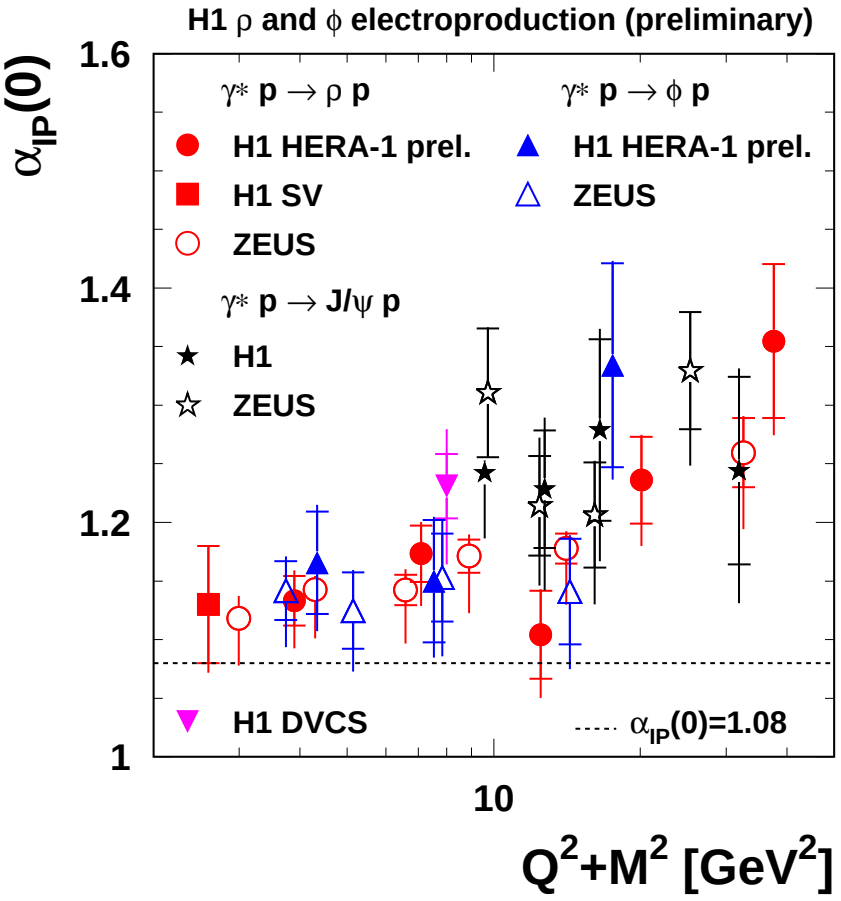
J/ψ in DIS:

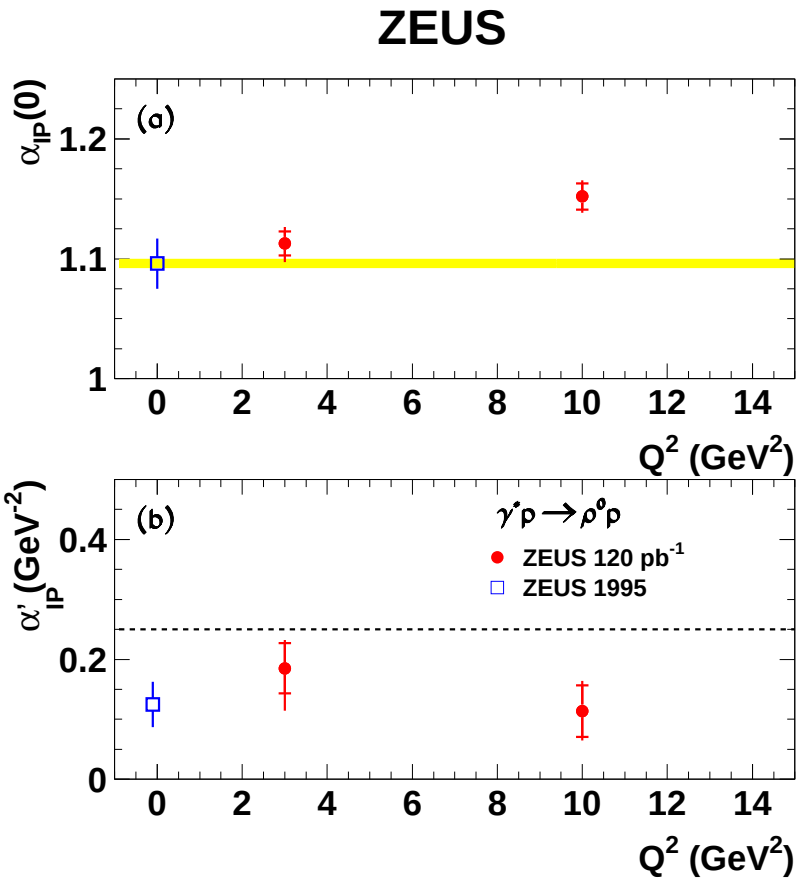
$\alpha_{IP}(0) = 1.20 \pm 0.003$

$\alpha'_{IP} = 0.07 \pm 0.05\,\text{GeV}^{-2}$

all results in well agreement but away from 'soft' Pomeron

Effective pomeron trajectory





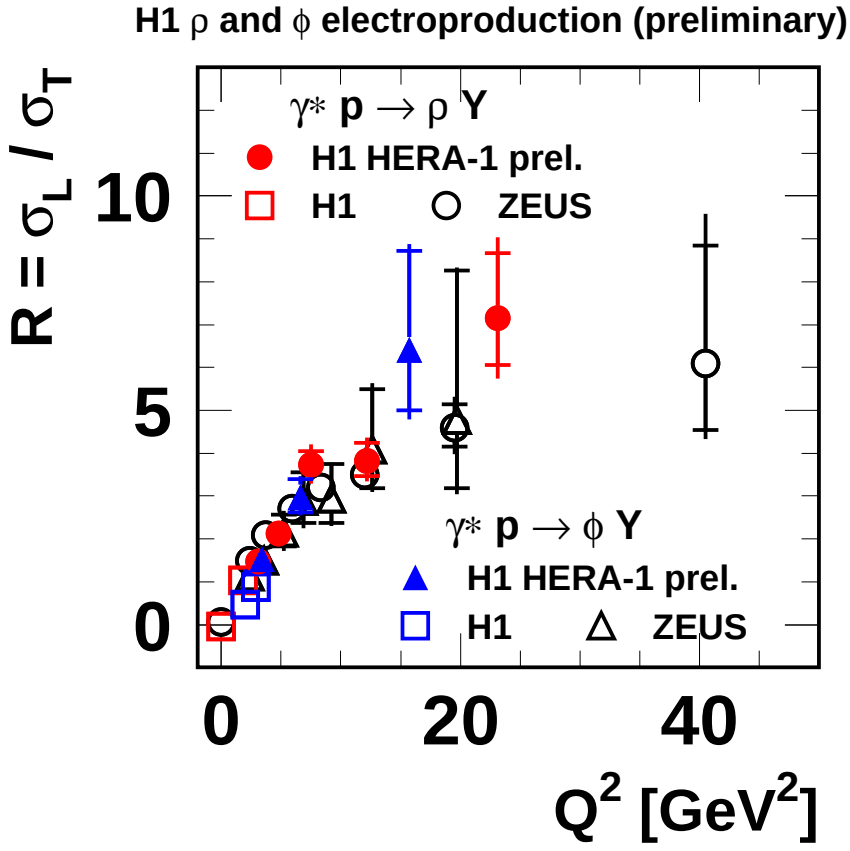
- the intercept $\alpha_{IP}(0)$ rises with increasing $(Q^2 + M^2)$
- no universal pQCD pomeron

Polarized cross sections

- angular distributions allow to extract σ_L/σ_T

$$\sigma = \sigma_T + \epsilon\sigma_L$$

$$R = \frac{\sigma_L}{\sigma_T} = \frac{1}{\epsilon} \cdot \frac{r_{00}^{04}}{1 - r_{00}^{04}}, \; \epsilon \approx 0.99$$

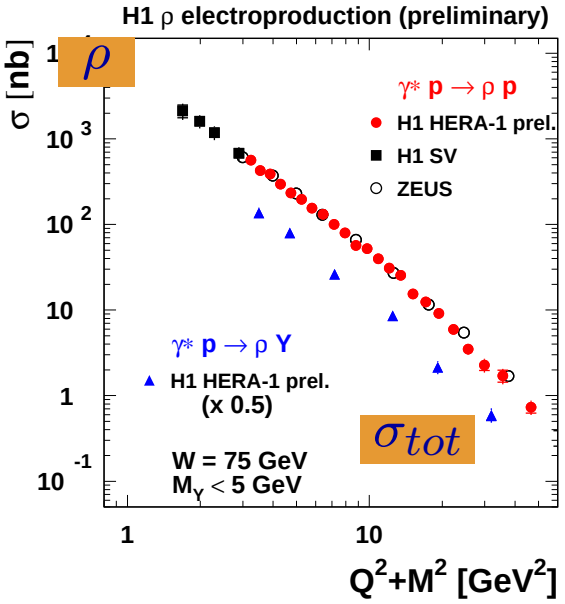


longitudinally polarized γ_L^*:
- small spatial configuration (large k_T)
- σ_L: steep rise with W
- dominates at high Q^2

transversely polarized γ_T^*:
- large spatial configuration (small k_T)
- σ_T: slow rise with W

according to expectations of pQCD - σ_L dominates at large Q^2

Polarized cross sections



- cross section decrease with increasing Q^2

  - similar effect observed for proton-dissociation

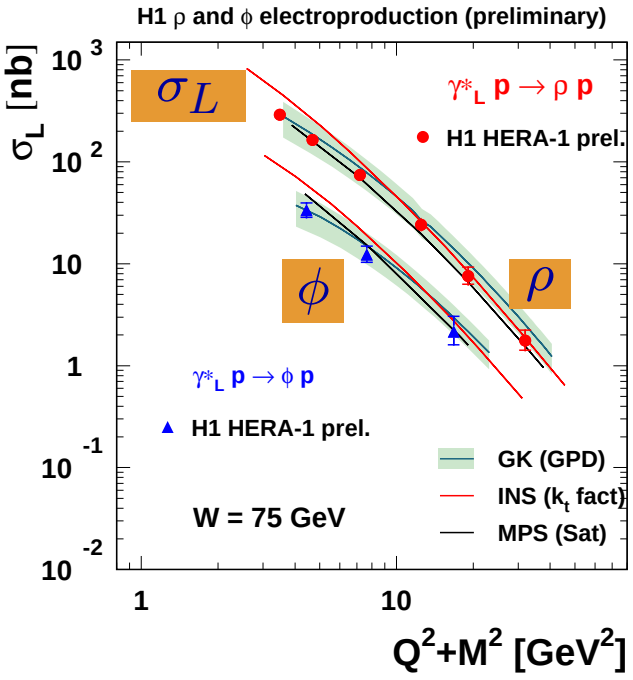
- $\sigma_{tot} \propto (Q^2 + M^2)^{-n}$

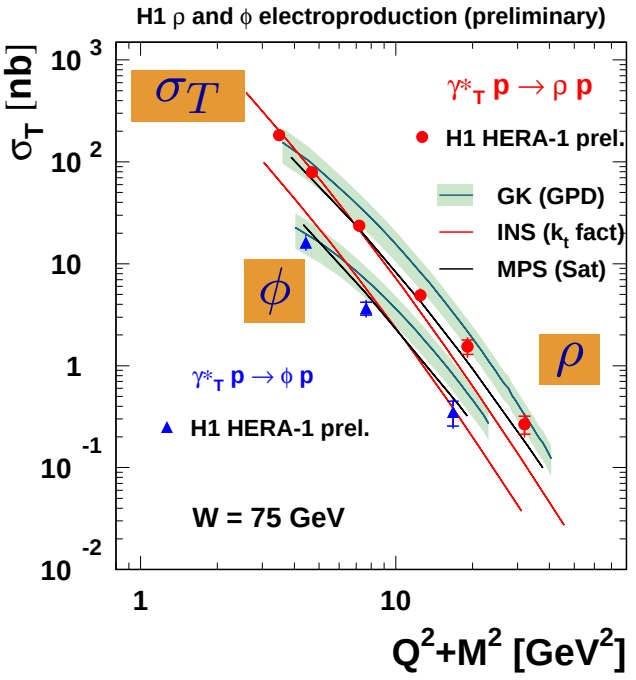
  $n(Q^2) = 2.15 + 0.007 \cdot Q^2$

- Q^2 dependence different for σ_L and σ_T

  - the same effect for ρ and ϕ

σ_L better described by models than σ_T





DVCS: QCD interpretation

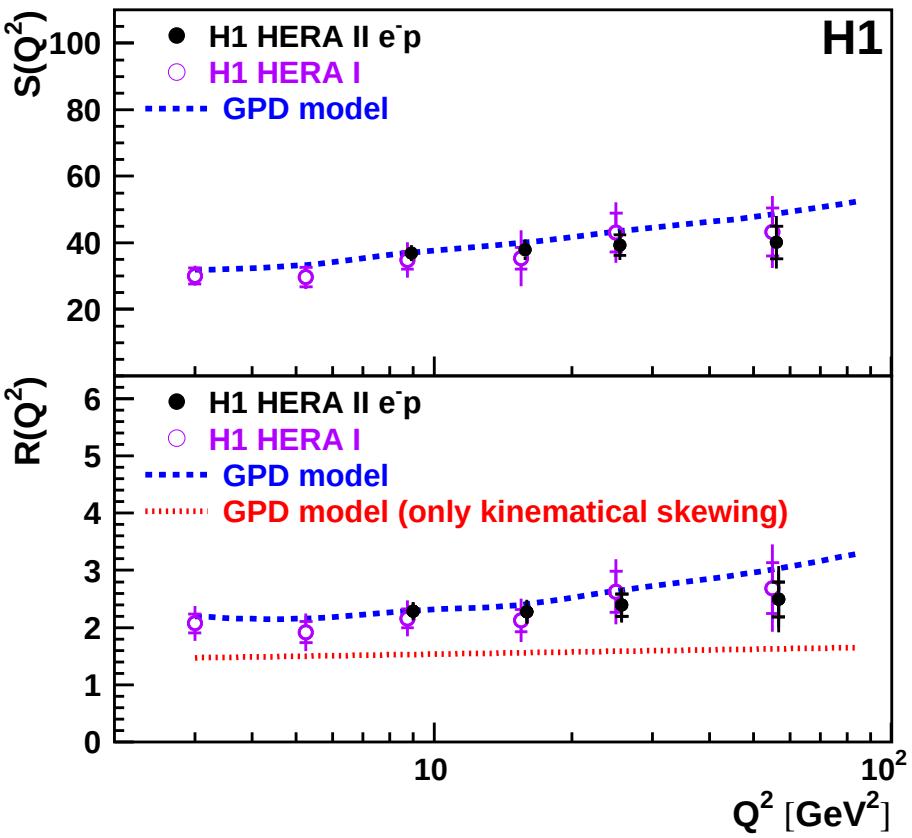
$$S = \sqrt{\frac{\sigma_{DVCS} Q^4 b(Q^2)}{(1+\rho^2)}}$$

- gives Q^2 evolution of GPD

(correct Q^2 dependence of the propagator term and b)

- S evolves with Q^2

$$R = \frac{\Im m A(\gamma^* p \to \gamma p)}{\Im m A(\gamma^* p \to \gamma^* p)} = \frac{4\sqrt{\pi \sigma_{DVCS} b(Q^2)}}{\sigma_T(\gamma^* p \to X)\sqrt{1+\rho^2}}$$



- Skewing effects: $R = 1$ - no skewing, for DVCS $R \sim 2$

- **NLO QCD model (GPD based) describes Q^2 dependence of S and R**
- **set constrains on gluon and sea GPDs**

Summary

- New measurements of VMs in photoproduction and DIS and DVCS process at HERA
- light VMs show transition from soft to hard regime as Q^2 rises
- VM production shows at large M_{VM}^2, Q^2 or $|t|$ features of hard process:
  - steep rise of the cross section with energy
  - harder $|t|$ distribution
- QCD Pomeron is rather not universal
- W and t dependence of DVCS indicate hard process

Outlook:

- HERA II $\Rightarrow$ more statistics in larger kinematic range
- HERA data are still an inspiration for development of the theory