# Vector Mesons and DVCS at HERA

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on behalf of the 

and 

Collaborations

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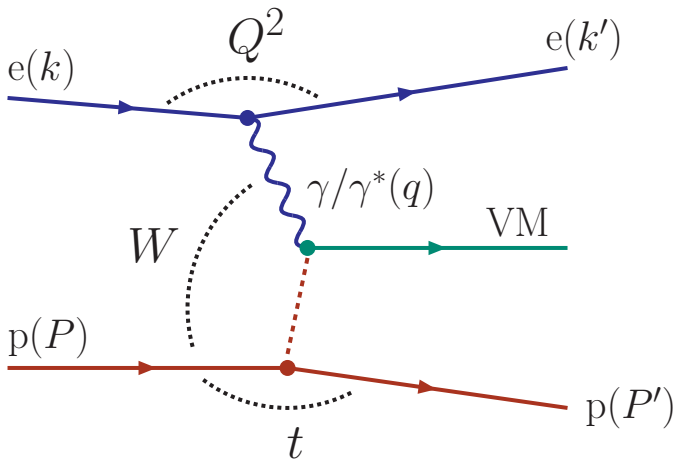
# Exclusive diffraction




experimentally: very clean process in wide kinematic range

| | | |
|---|---|---|
| VM | Vector Meson or $\gamma$ | $\rho, \omega, \phi, J/\psi, \psi', \Upsilon$ |
| $Q^2$ | photon virtuality | $Q^2 = -q^2 = -(k - k')^2$ |
| W | c.m. energy of $\gamma p$ 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:

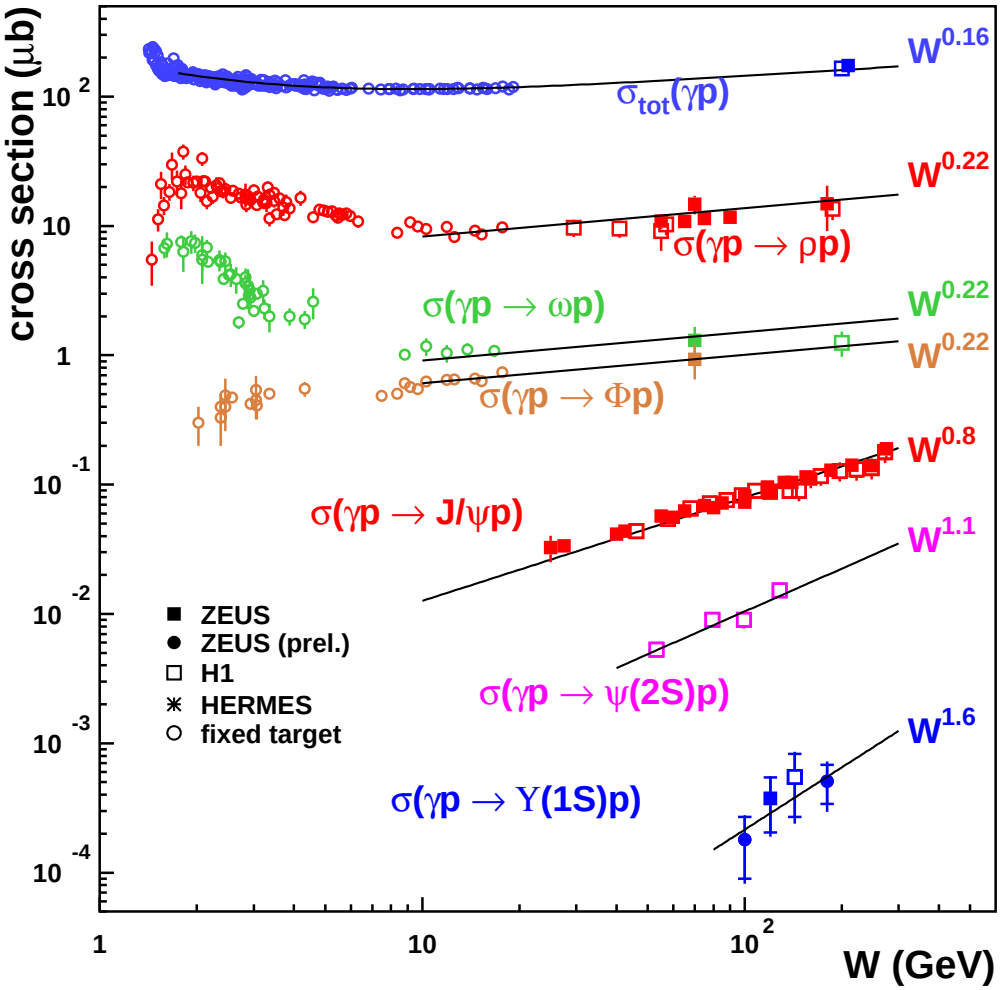
- steep rise of $\sigma(W)$, $\sigma \sim \frac{\alpha_S(Q^2)}{Q^6}[xg(x,Q^2)]^2$, $x \approx Q^2/W^2$
- universal $t$ dependence: $\sim \exp^{-b_{2g}|t|}$, $b_{2g} \sim 4-5\,\mathrm{GeV}^{-2}$ and $\alpha'_{\mathrm{IP}} \approx 0$
- possible SCHC violation

Deeply Virtual Compton Scattering (DVCS):

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

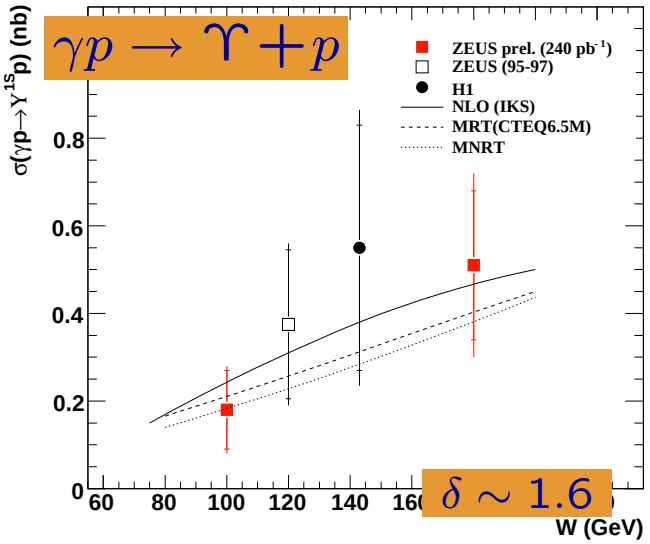
# Vector mesons in photoproduction ($Q^2 \sim 0$)

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



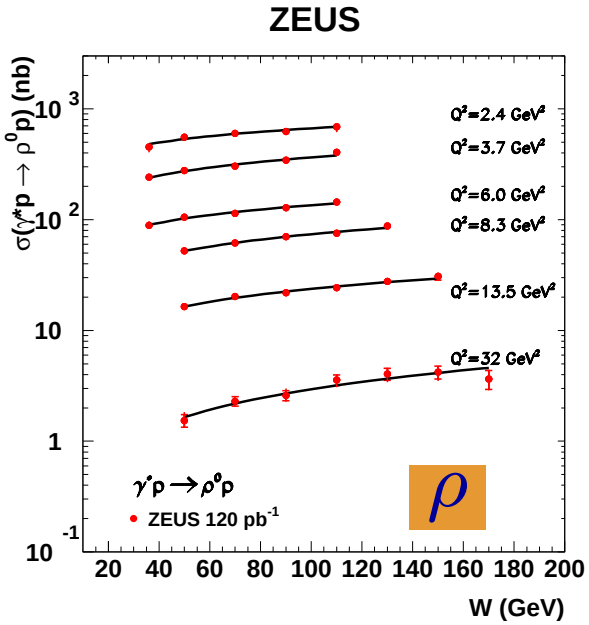

$\sigma(W) \propto W^{\delta}$

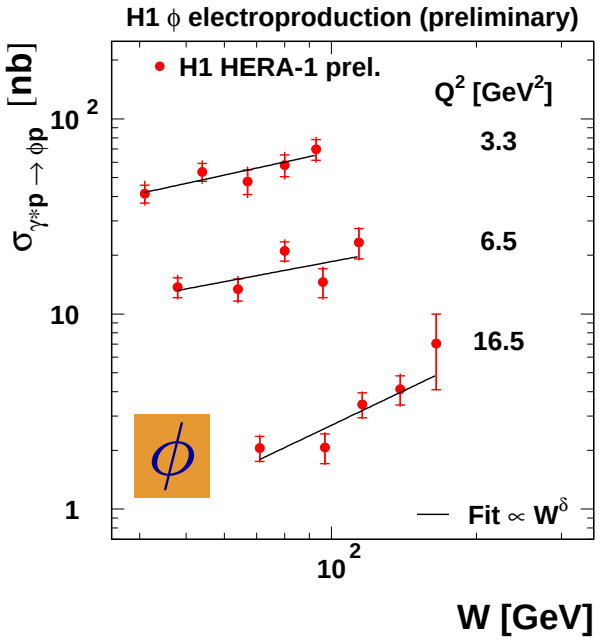
prediction for soft physics: $\delta \sim 0.2$




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

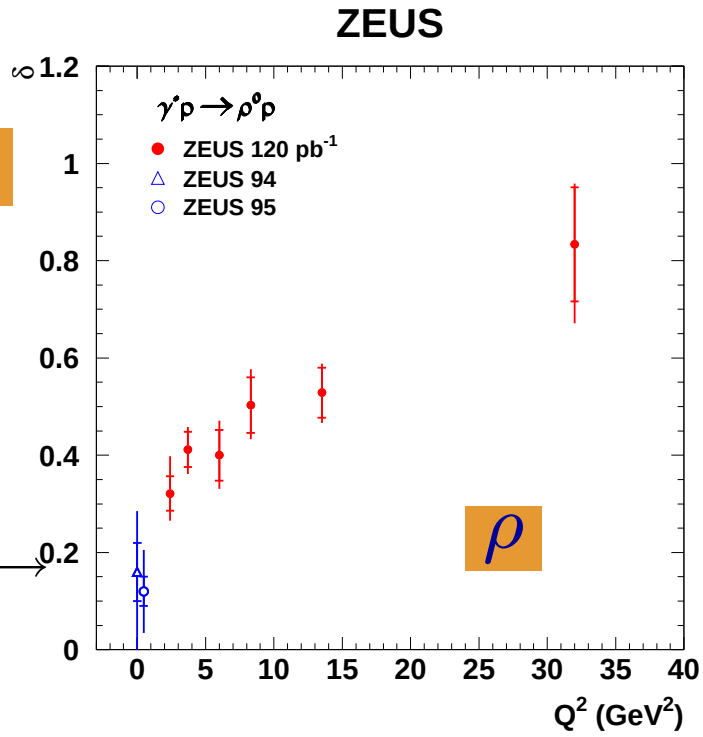
# Exclusive electroproduction of $\rho$ and $\phi$ mesons




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

soft physics prediction $\longrightarrow$

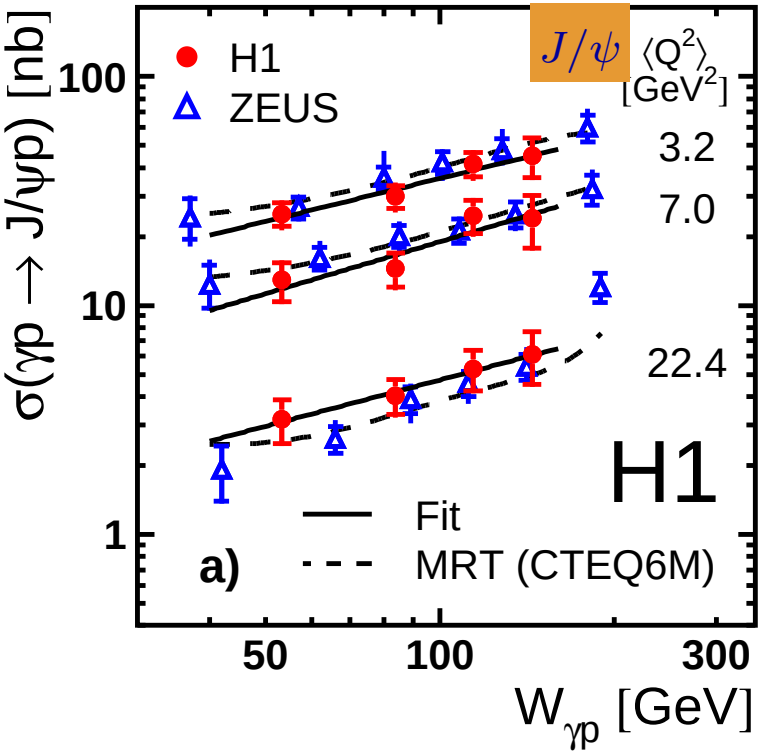


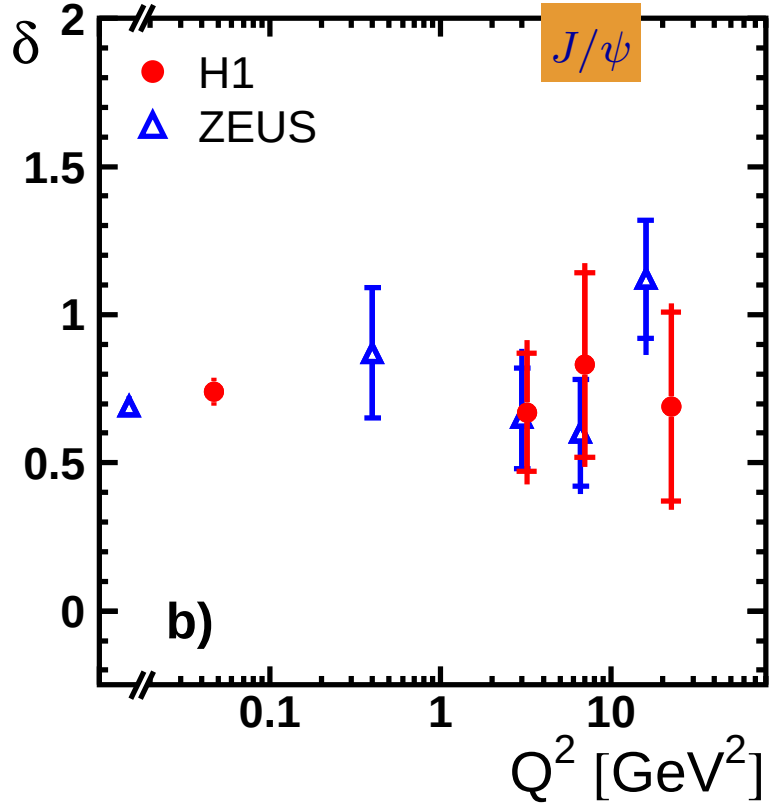

- energy dependence steeper with $Q^2$:

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

- $Q^2$ is the hard scale for $\rho$ and $\phi$

# Exclusive electroproduction of $J/\psi$ meson



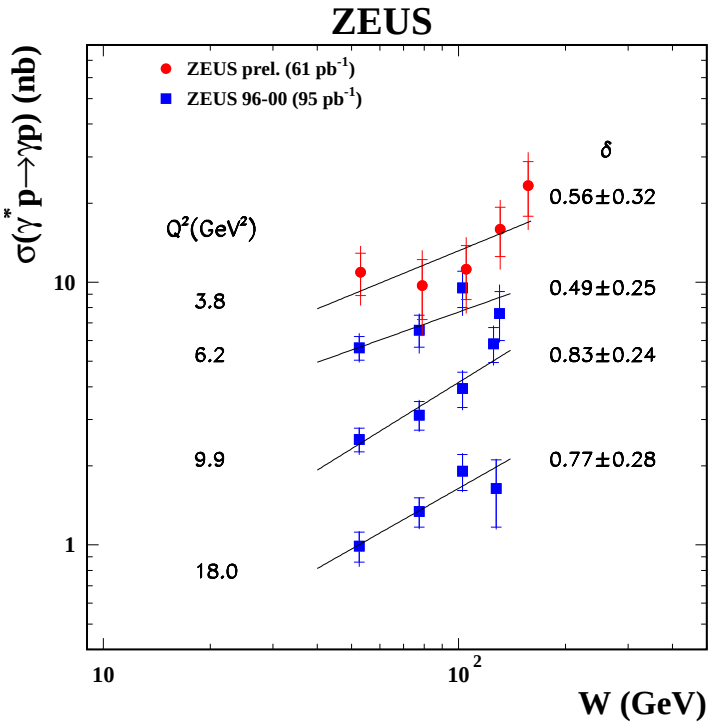



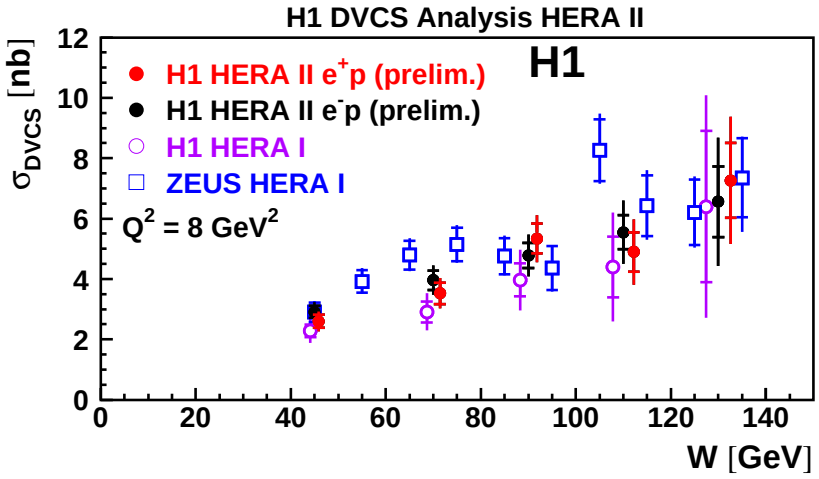

- already for $Q^2 = 0$ strong energy dependence
- no significant change with $Q^2$

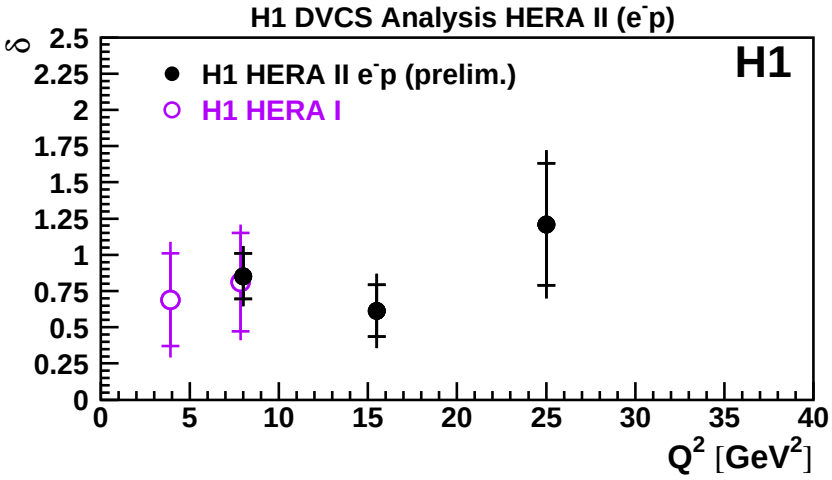
**for $J/\psi$ the mass is dominant scale**

# DVCS: energy dependence

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

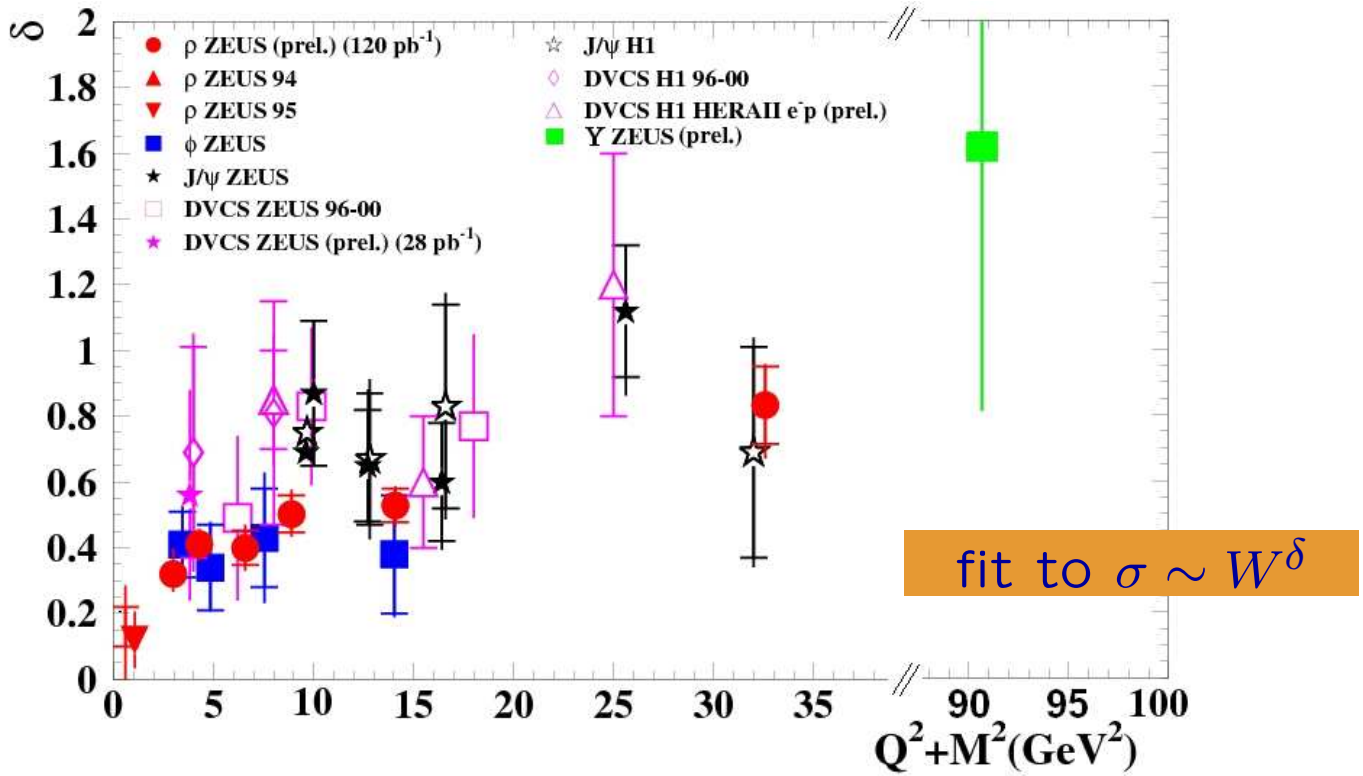



- steep rise with energy
- no significant $Q^2$ dependence

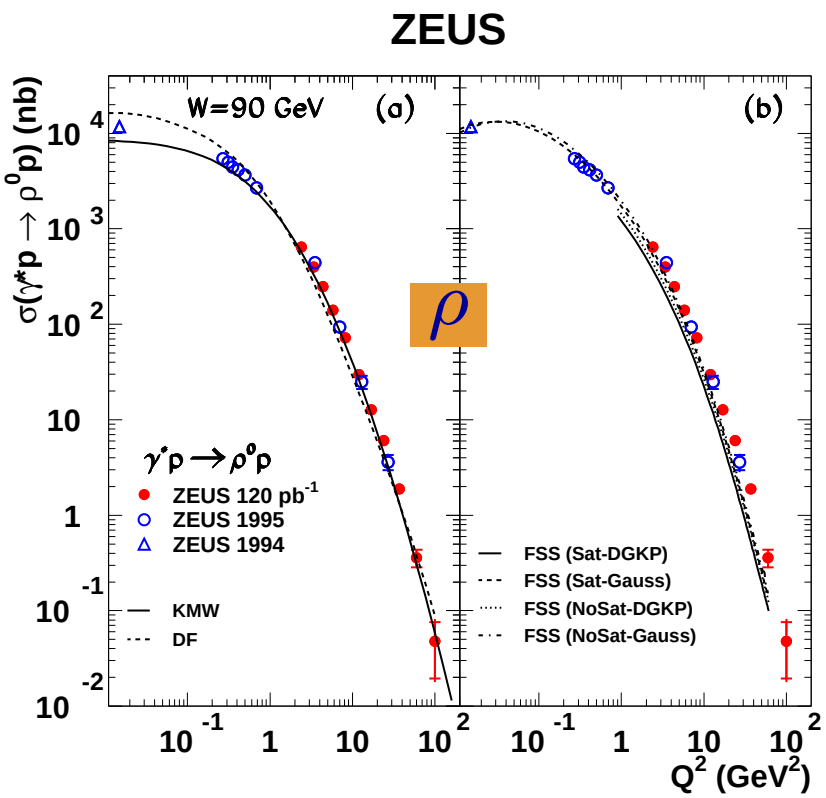
# VM production and DVCS – energy dependence

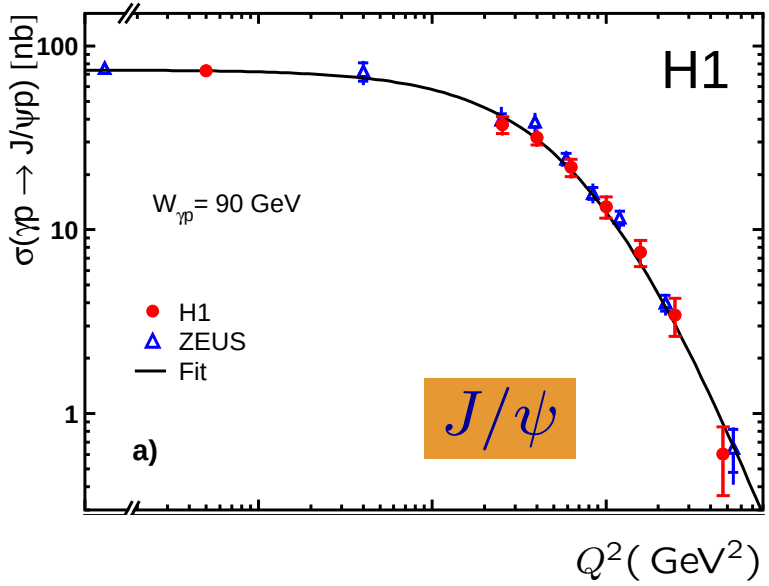



- similar behavior for DVCS and all VMs
- "universal" dependence of $\delta$ on $Q^2 + M_{VM}^2$ $\rightarrow$ transition scale
- $\rho, \phi$ in between from soft to hard regime
- for DVCS steep slope always observed
- $J/\psi$ hard already in photoproduction

# $Q^2$ dependence

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



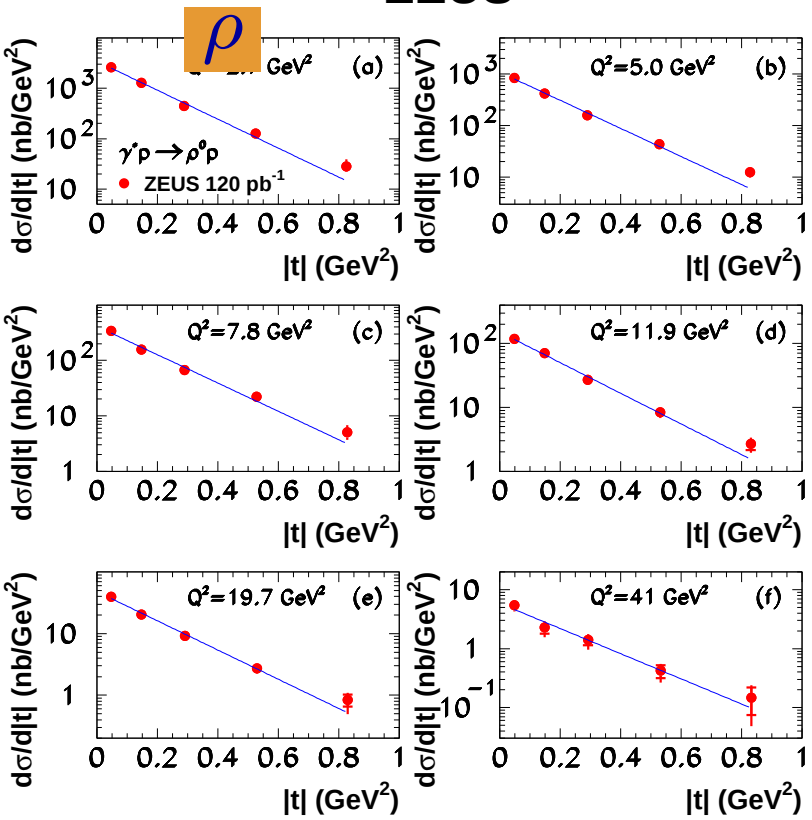

$n$ increasing with $Q^2$ appears to be favored:

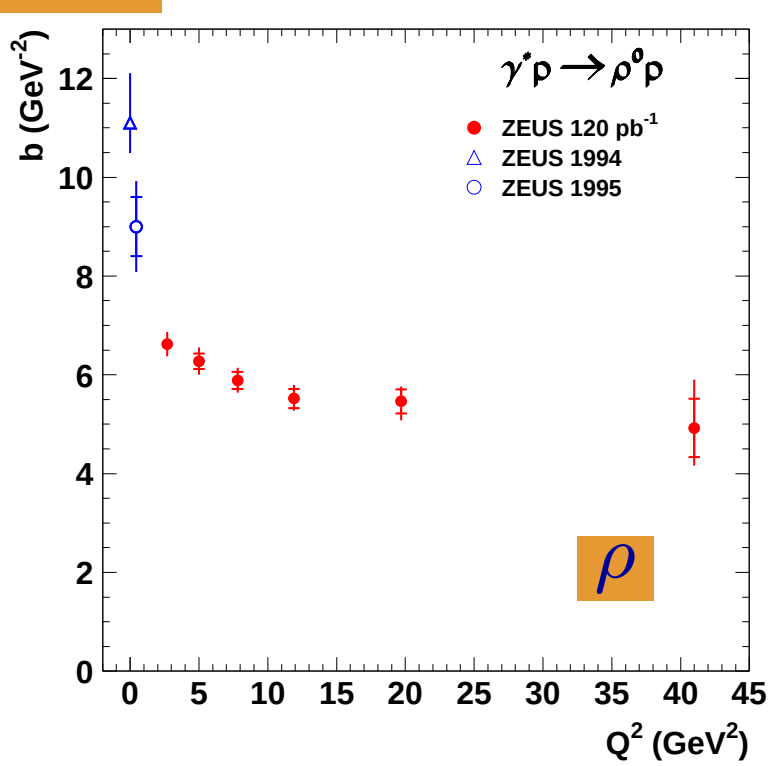
| | | |
|---|---|---|
| $\rho$ | $n = 2.44 \pm 0.09$ | $Q^2 > 10\,\text{GeV}^2$ |
| $\phi$ | $n = 2.087 \pm 0.055 \pm 0.050$ | $2 < Q^2 < 9\,\text{GeV}^2$ |
| | $n = 2.75 \pm 0.13 \pm 0.07$ | $Q^2 > 9\,\text{GeV}^2$ |
| $J/\psi$ | $n = 2.486 \pm 0.080 \pm 0.068$ | all $Q^2$ |
| $\gamma$ | $n = 1.54 \pm 0.09 \pm 0.04$ | $Q^2 > 3\,\text{GeV}^2$ |

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

# $t$ dependence

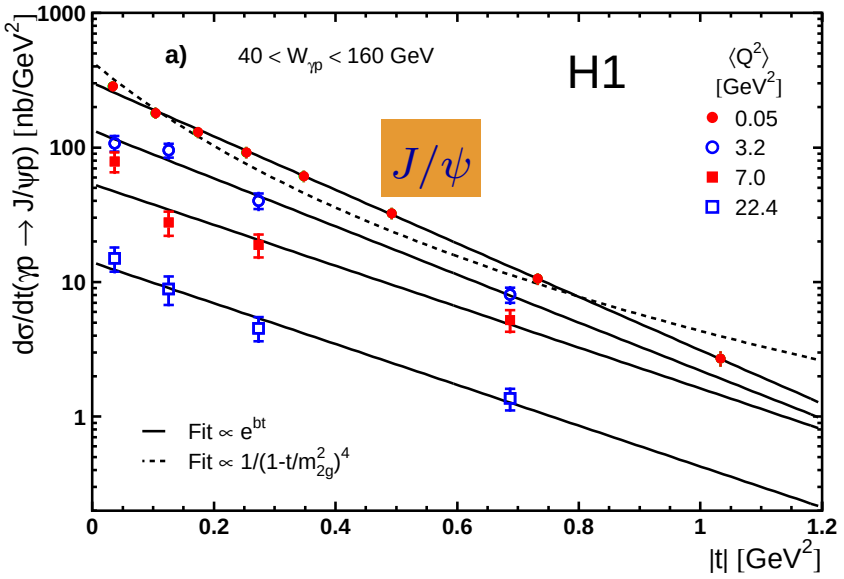
$d\sigma/dt \propto e^{-b|t|}$

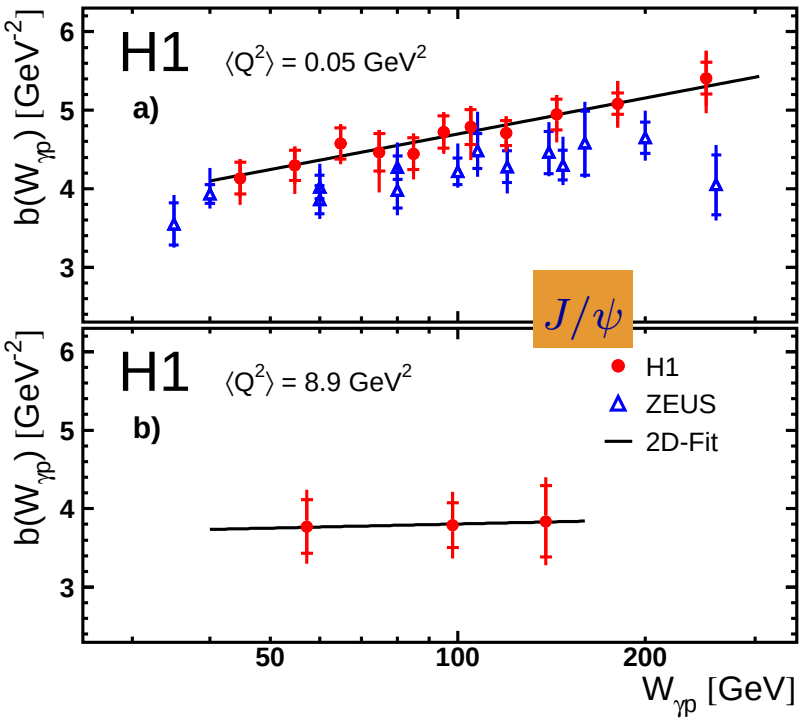


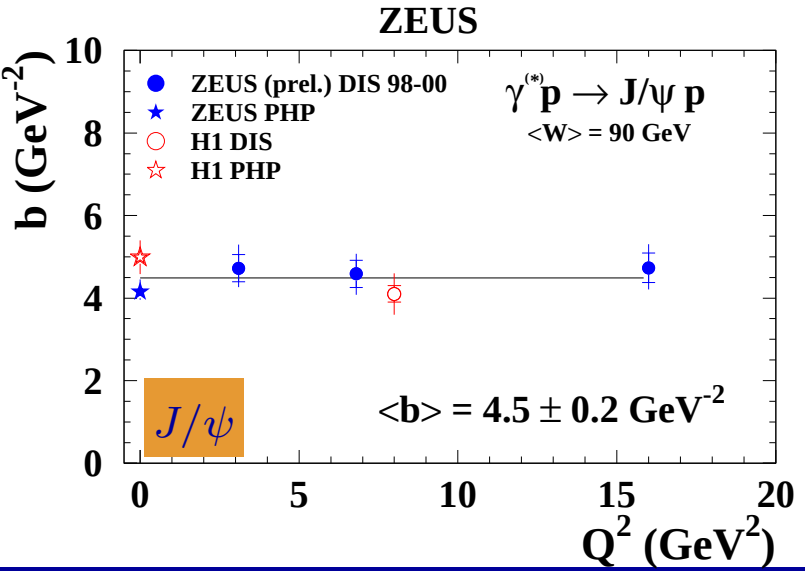

- slope $b \sim r^2_{\perp q\bar{q}} + r^2_{proton}$ characterize the size of interaction
- $b$ decreases with increasing $Q^2$ (from $\sim 10$ to $4-5$)

# $t$ dependence



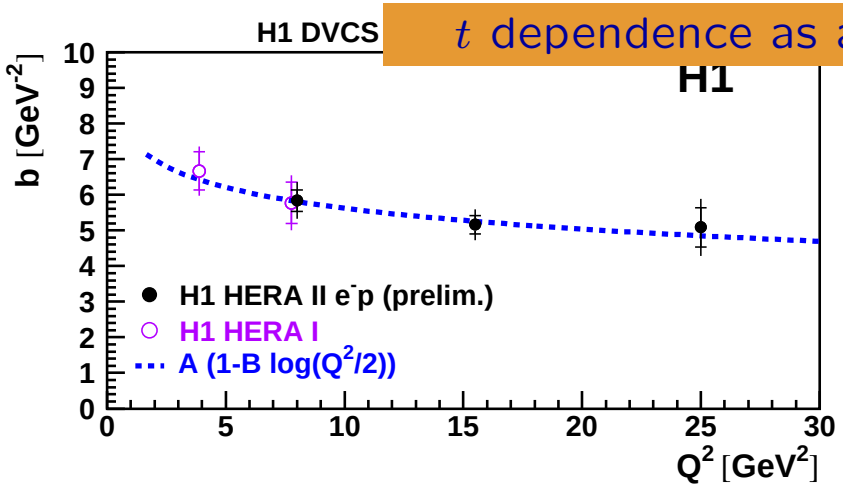



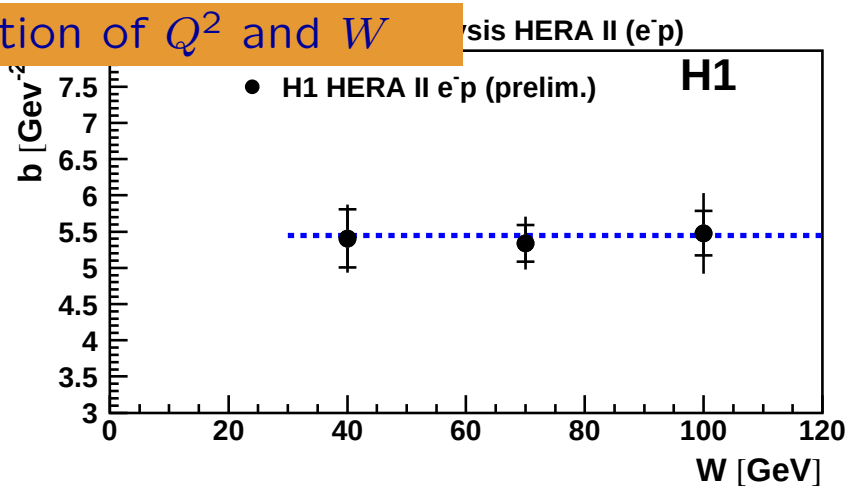

- $Q^2 \approx 0$: $b$ increases with $W$ (shrinkage)
- $Q^2 >> 0$ no energy dependence of $b$
- $b = 4.5 \pm 0.2\,\mathrm{GeV}^{-2}$ (ZEUS)



# DVCS: $t$ dependence

$t$ dependence as a function of $Q^2$ and $W$



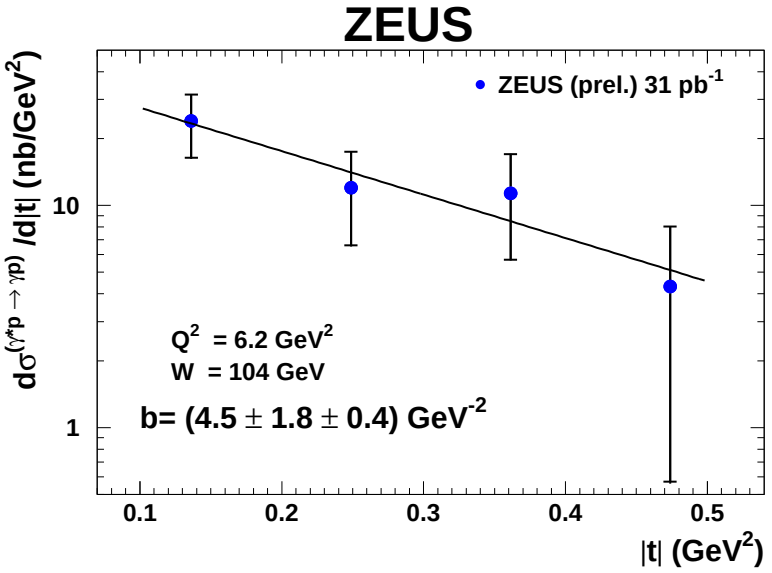




$Q^2$: $b(Q^2) = A[(1 - B \cdot \log(Q^2/2)]$

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

no $W$ dependence of $b$

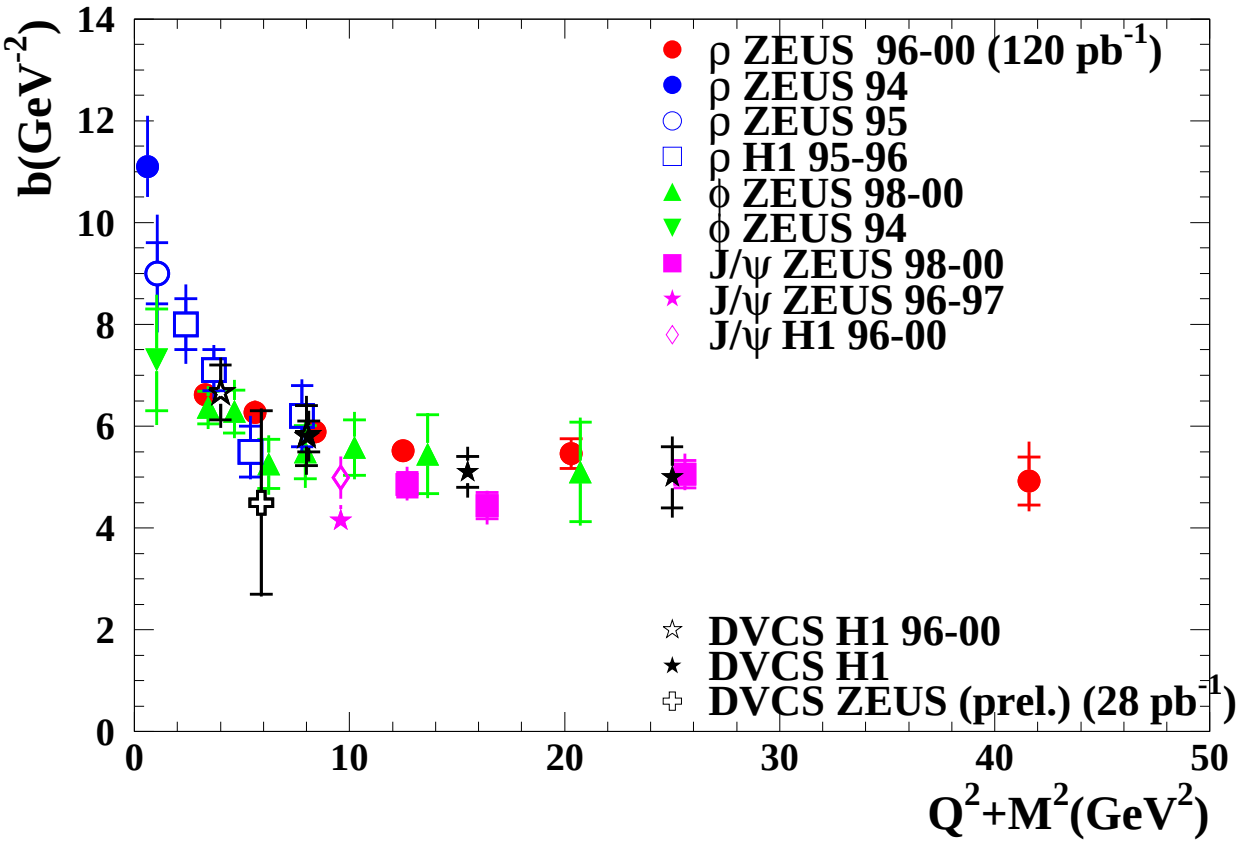
$b = 5.45 \pm 0.19 \pm 0.34\,\text{GeV}^{-2}$




direct $t$ measurement - using Leading Proton Spectrometer

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

# $t$ dependence



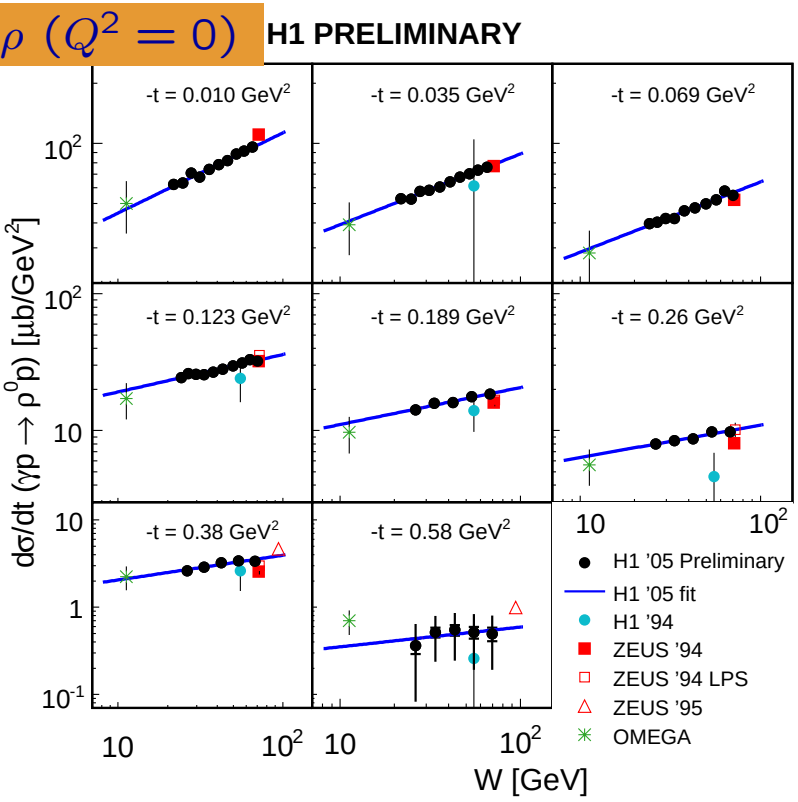

$\frac{d\sigma}{dt} \propto \exp^{-b|t|}$

- $b \sim r^2_{\perp q\bar{q}} + r^2_{proton}$ 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**

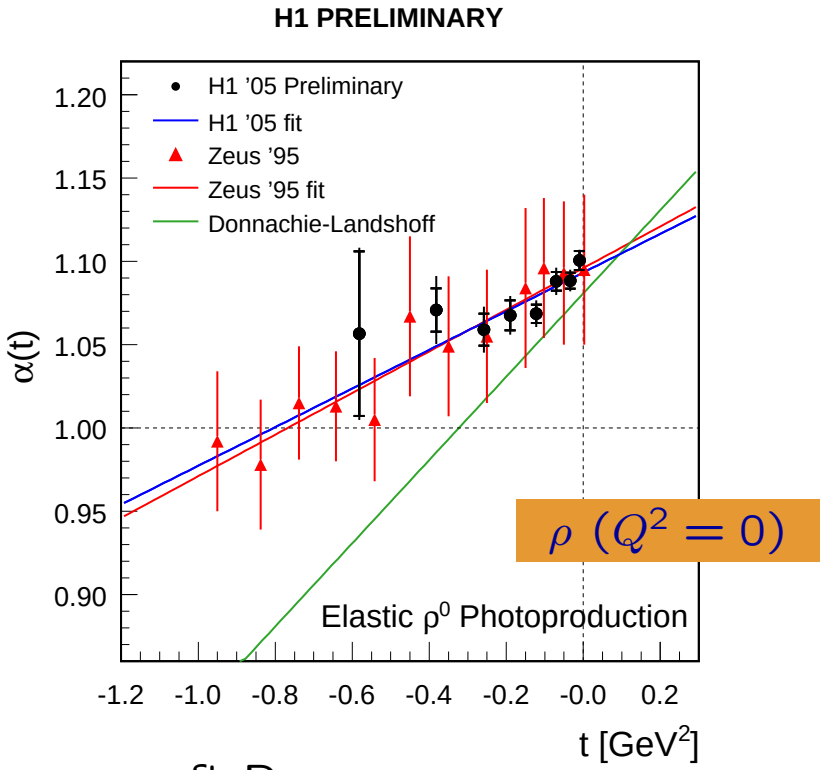
# Effective Pomeron trajectory

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




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

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




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

ZEUS:

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

H1:

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

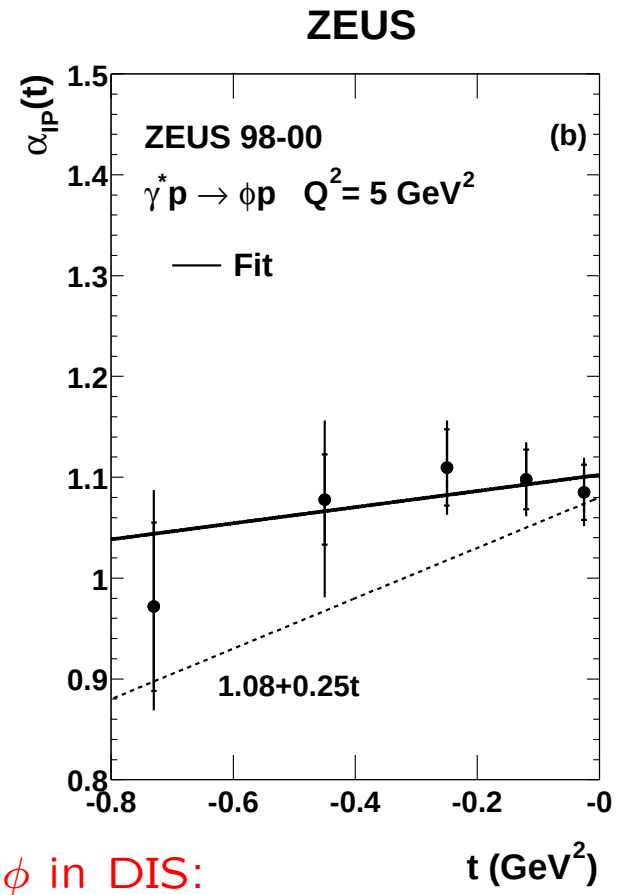
soft Pomeron:

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

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

# Effective Pomeron trajectory

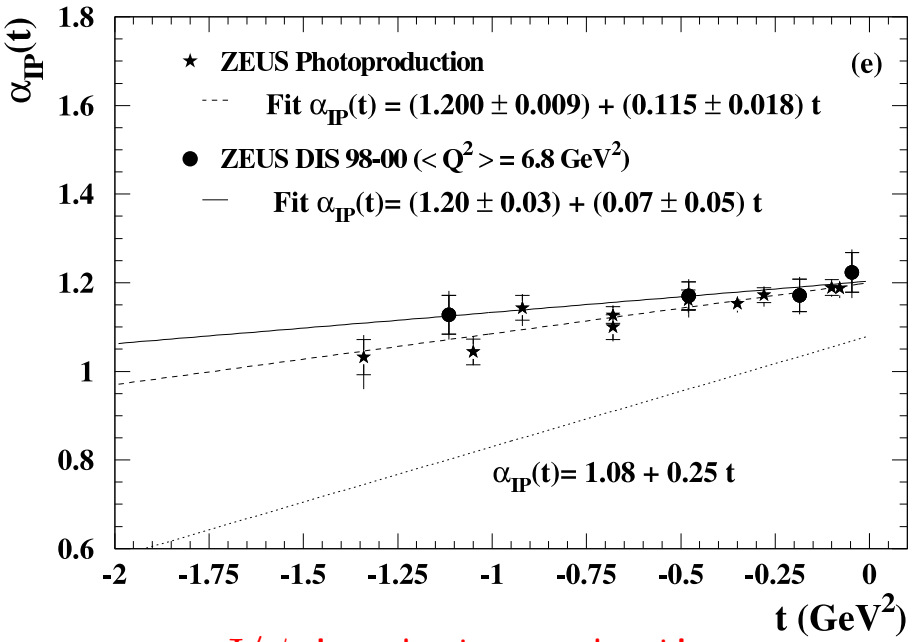
effective pomeron trajectory extracted from $\frac{d\sigma}{dt}$ at fixed $Q^2$




$\phi$ in DIS:

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

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




$J/\psi$ in photoproduction:

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

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

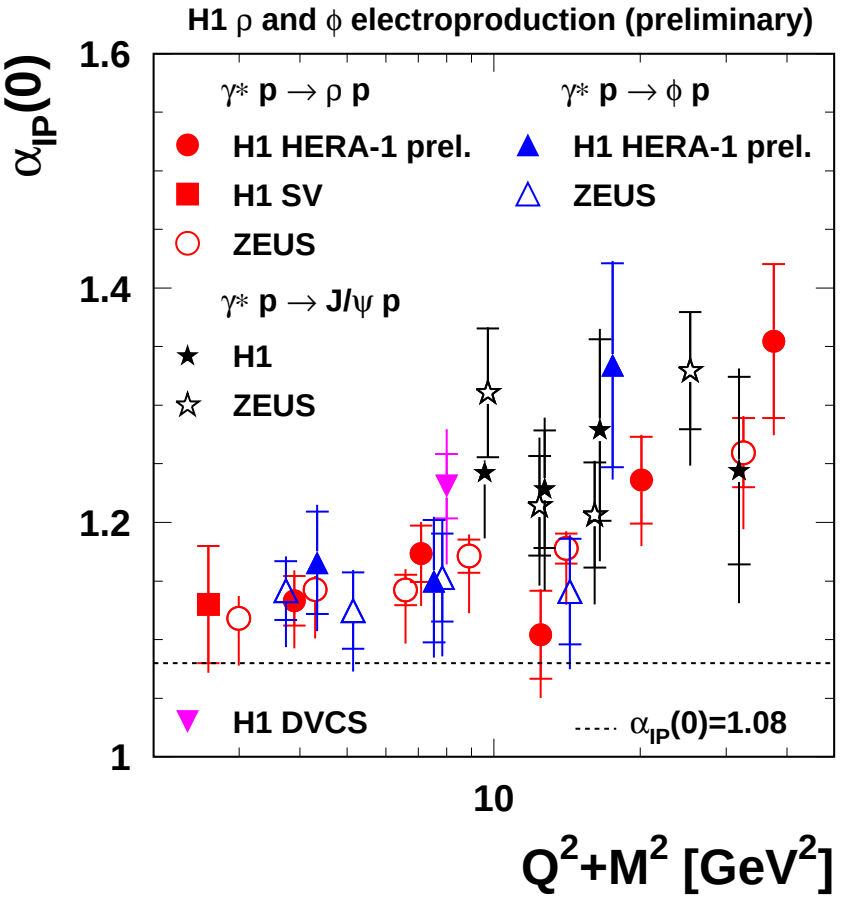
$J/\psi$ in DIS:

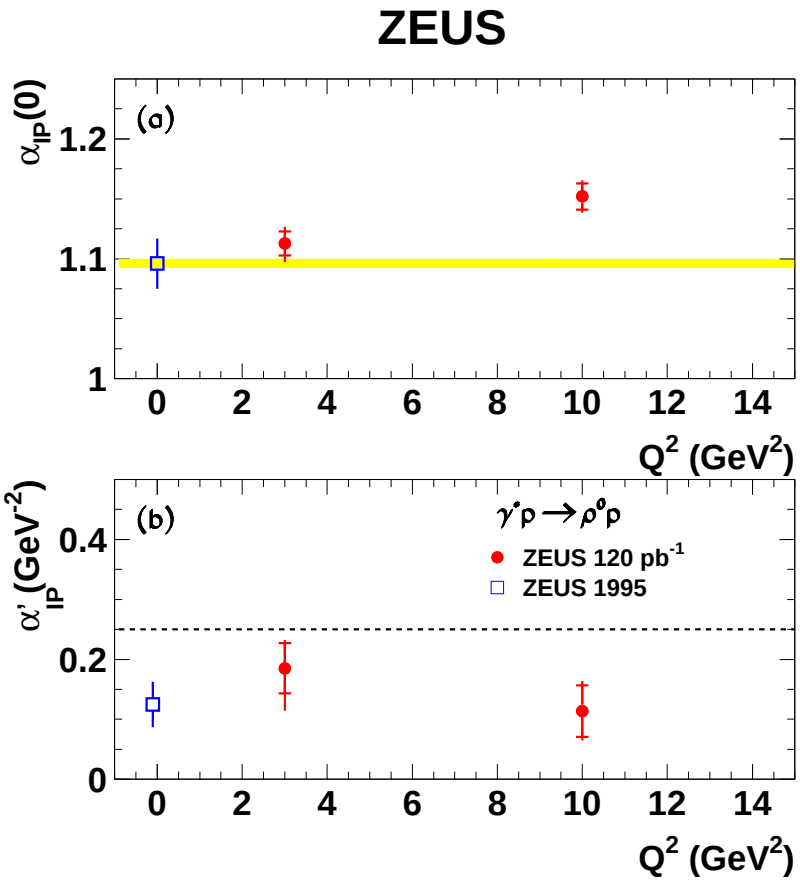
$\alpha_{IP}(0) = 1.20 \pm 0.003$

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

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

# Effective pomeron trajectory



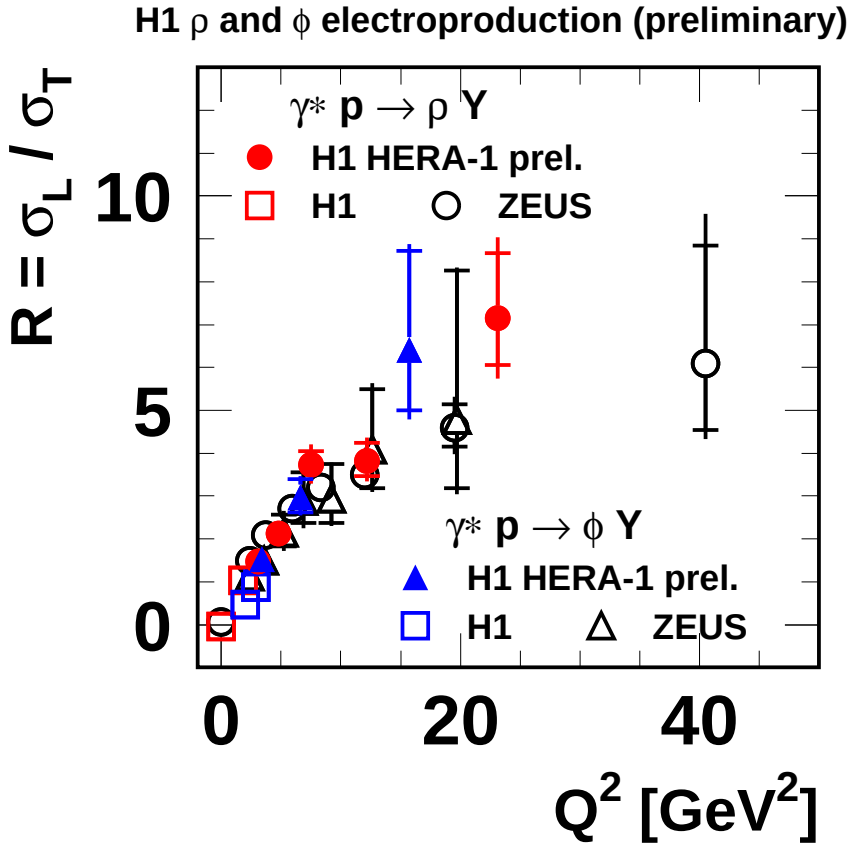

- the intercept $\alpha_{IP}(0)$ rises with increasing $(Q^2 + M^2)$
- no universal pQCD pomeron

# Polarized cross sections

- angular distributions allow to extract $\sigma_L/\sigma_T$

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

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

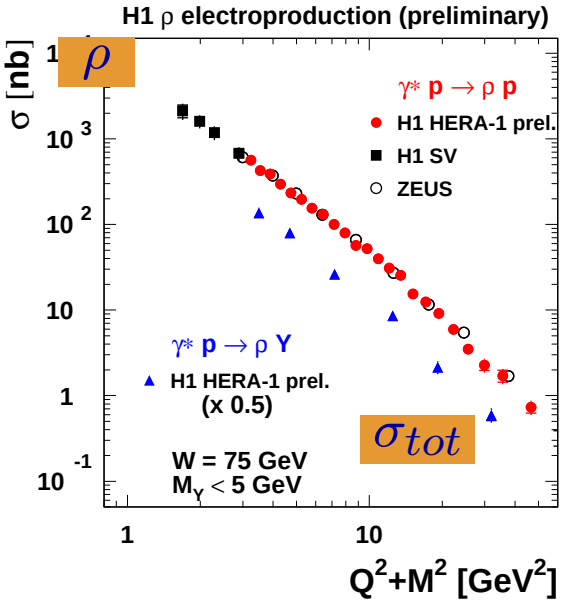



longitudinally polarized $\gamma_L^*$:
- small spatial configuration (large $k_T$)
- $\sigma_L$: steep rise with $W$
- dominates at high $Q^2$

transversely polarized $\gamma_T^*$:
- large spatial configuration (small $k_T$)
- $\sigma_T$: slow rise with $W$

**according to expectations of pQCD - $\sigma_L$ dominates at large $Q^2$**

# Polarized cross sections




- cross section decrease with increasing $Q^2$

  - similar effect observed for proton-dissociation

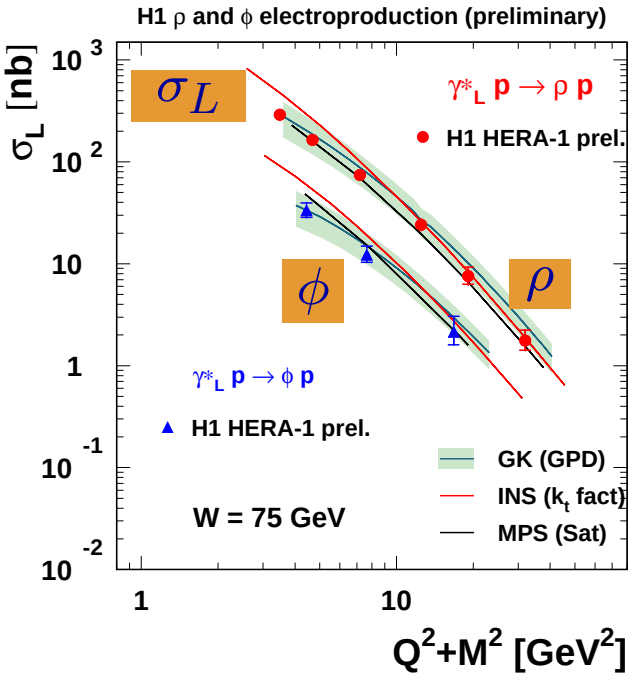
- $\sigma_{tot} \propto (Q^2 + M^2)^{-n}$

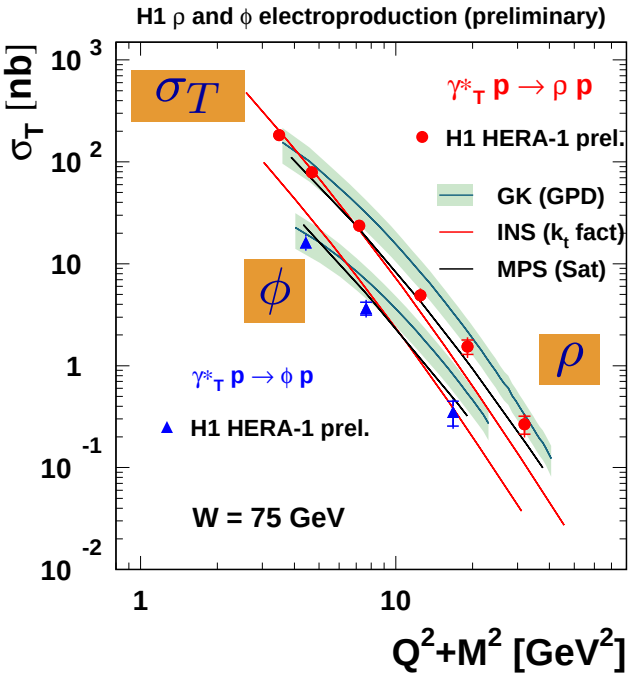
  $n(Q^2) = 2.15 + 0.007 \cdot Q^2$

- $Q^2$ dependence different for $\sigma_L$ and $\sigma_T$

  - the same effect for $\rho$ and $\phi$

$\sigma_L$ better described by models than $\sigma_T$



# DVCS: QCD interpretation

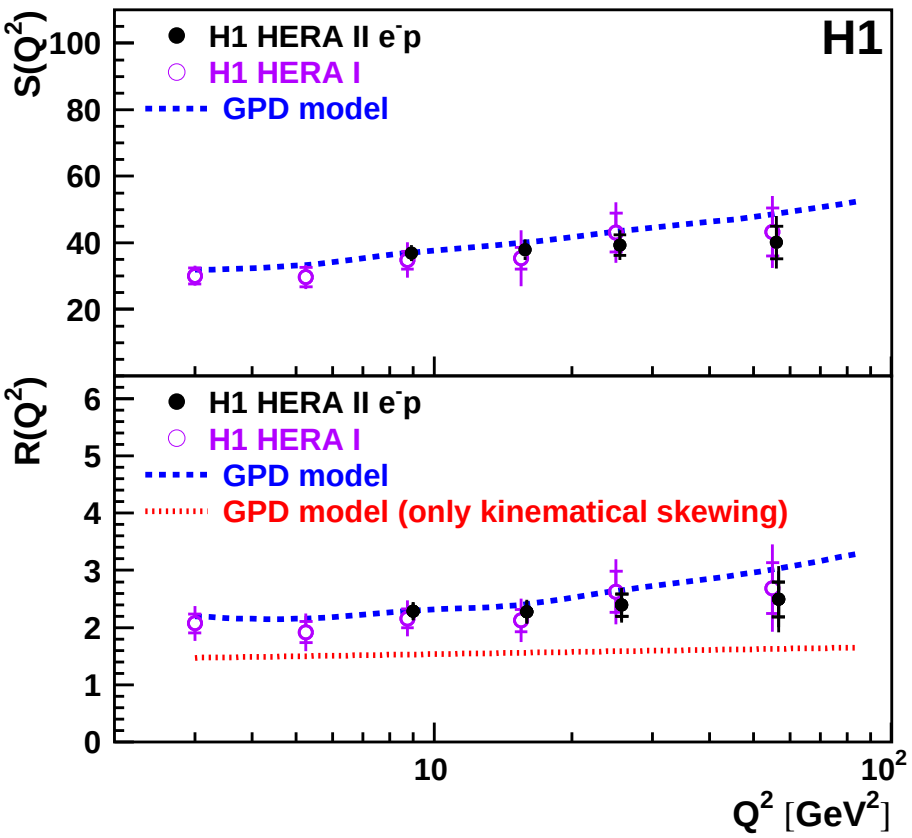
$$S = \sqrt{\frac{\sigma_{DVCS} Q^4 b(Q^2)}{(1+\rho^2)}}$$

- 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