VM and real photon production in a Regge-pole model

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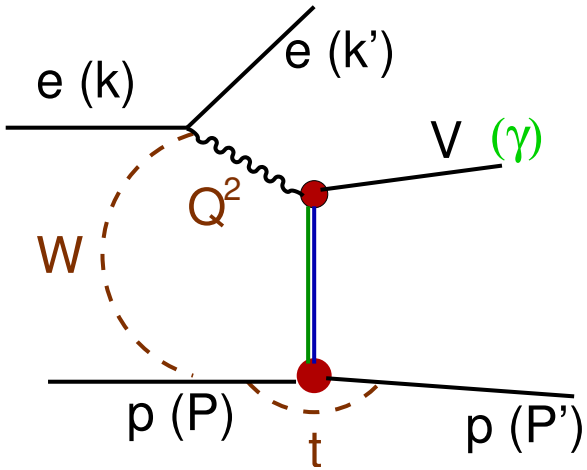
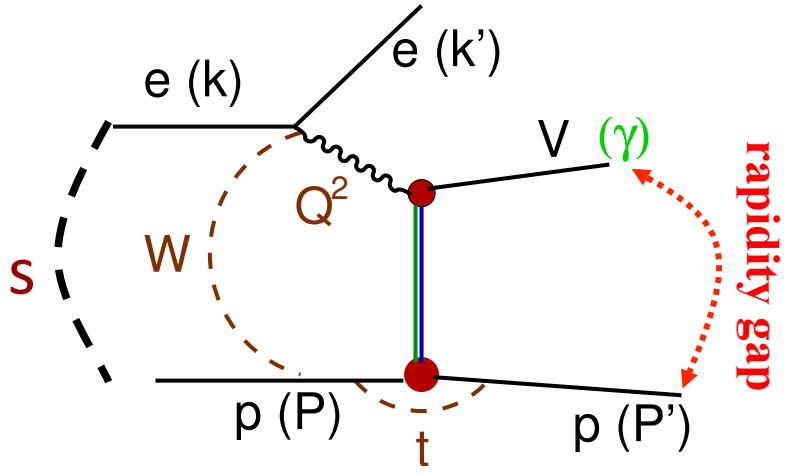


DIS 2011
XIX International Workshop on Deep-Inelastic Scattering and Related Subjects
Newport News, VA (USA), *April 11 – 15, 2011*

Planing of the talk

- Exclusive Diffraction
- Real photon (DVCS) and Vector Meson Production
- Pomeron in hh and ep collisions
- Regge model: DVCS and VMP
- A geometrical approach to the Regge theory
- Summary

Exclusive diffraction



Main kinematic variables

electron-proton centre-of-mass energy:

$$s = (k+p)^2 \approx 4E_e E_p$$

photon virtuality:

$$Q^2 = -q^2 = -(k-k')^2 \approx 4E_e E_e' \sin^2\frac{\theta}{2}$$

photon-proton centre-of-mass energy:

$$W^2 = (q+p)^2, \text{ where}: m_p < W < \sqrt{s}$$

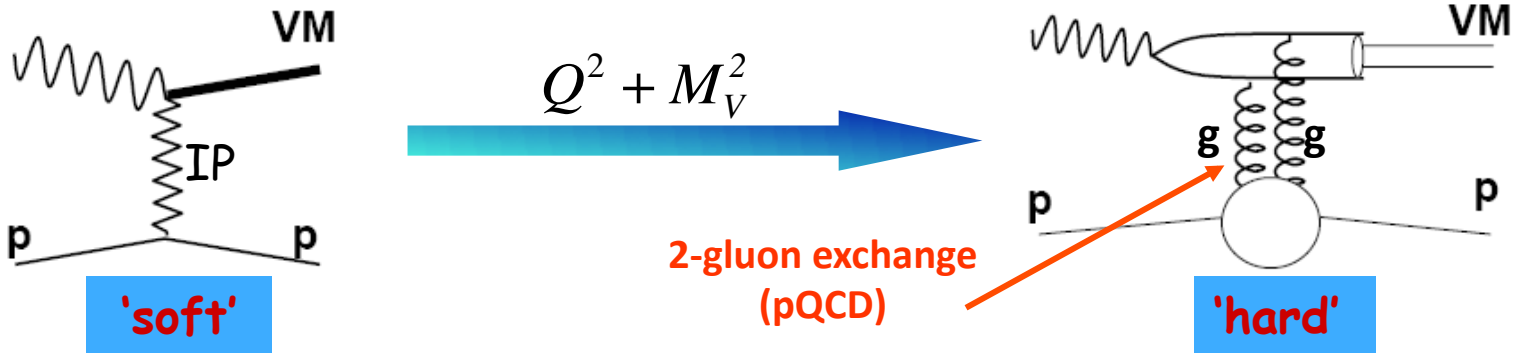
square 4-momentum at the *p* vertex:

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

- **Vector Mesons production in diffraction**
- **Deeply Virtual Compton Scattering**

Diffraction: soft -> hard

Vector Meson production (ρ, ϕ, J/ψ, Υ, γ)



Gluon density in the proton

Cross section proportional to probability of finding 2 gluons in the proton

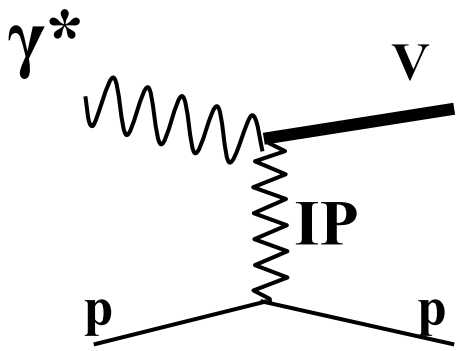
$$\begin{cases} \sigma \propto [x\, g(x,\mu^2)]^2 \\ \mu^2 \propto (Q^2 + M_V^2) \end{cases}$$

$\sigma(W) \propto W^{\delta}$ → δ increases from soft (~0.2, "soft Pomeron") to hard (~0.8, "hard Pomeron")

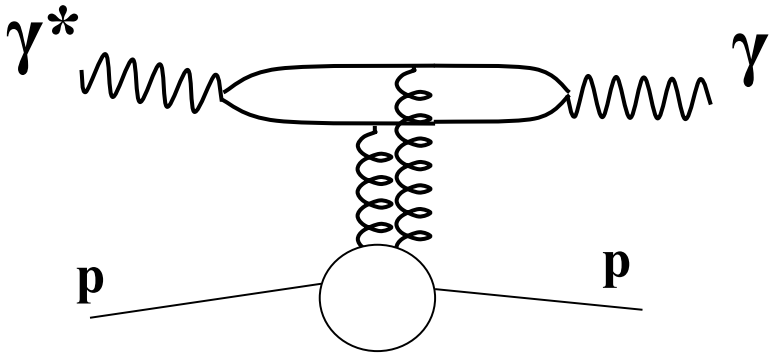
$\frac{d\sigma}{dt} \propto e^{-b|t|}$ → *b* decreases from soft (~10 GeV^{-2}) to hard (~4-5 GeV^{-2})

Deeply Virtual Compton Scattering

VM (ρ, ω, φ, J/ψ, Υ)



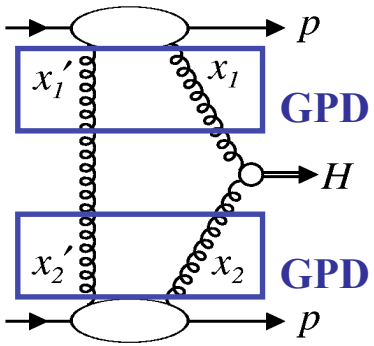
DVCS (γ)



Scale: $Q^2 + M^2$ ⟷ Q^2

DVCS properties:

- Similar to VM production, but γ instead of VM in the final state
- No VM wave-function involved
- Important to determine Generalized Parton Distributions sensible to the correlations in the proton
- GPD_s are an ingredient for estimating diffractive cross sections at LHC



Pomeron Trajectory

Regge-type: $\frac{d\sigma}{dt}(W) = \exp(b_0 t) \cdot W^{2\left[2\alpha_{IP}(t)+2\right]}$

First measured in h-h scattering

Soft Pomeron values
$\alpha(0) \approx 1.09$
$\alpha' \approx 0.25$

Linear Pomeron trajectory

$$\alpha(t) = \alpha(0) + \alpha'(t)t$$

$\alpha(0)$ and α' are foundamental parameters to represent the basic features of strong interactions

$\alpha(0)$: determines the energy dependence of the diff. Cross section

$$\frac{d\sigma}{dt} \propto \exp(b_0 t) \cdot W^{4\alpha(t)-4} = W^{4\alpha(0)-4} \cdot \exp(bt); \qquad b = b_0 + 4\alpha' \ln(W)$$

α': determines the energy dependence of the transverse extention system

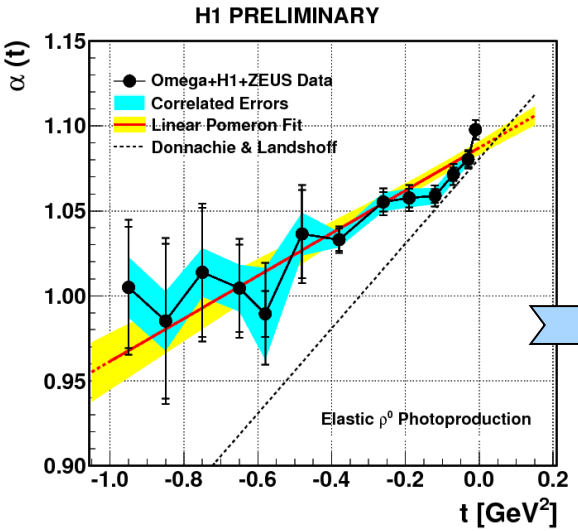
Pomeron trajectory in ep collisions

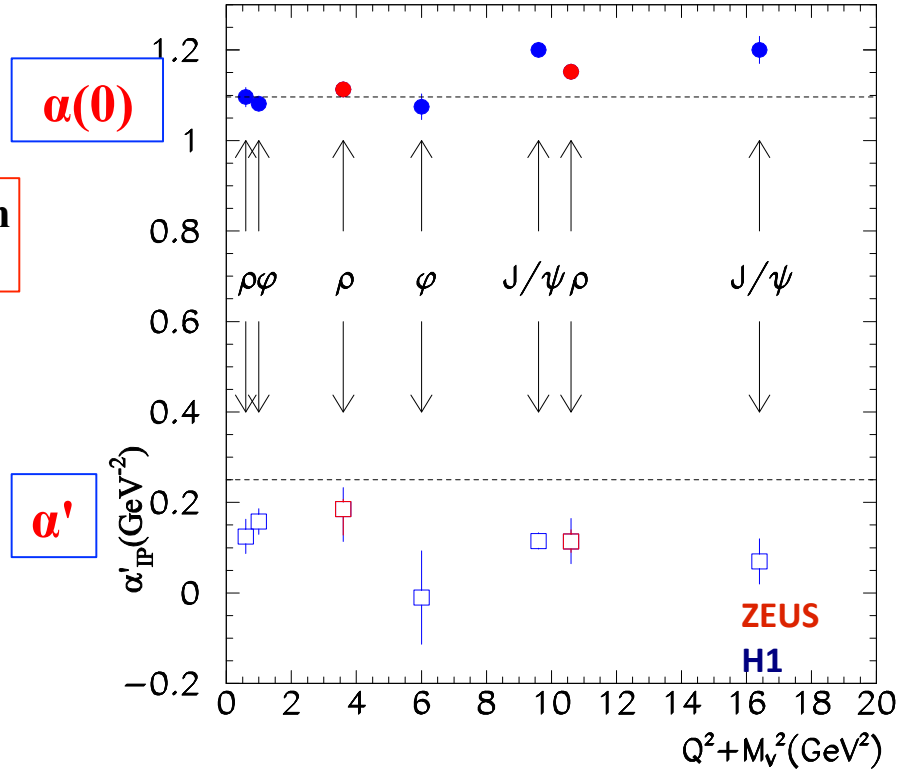
Trajectory varies with the scale

$\alpha_{IP}(t) = 1.09 + 0.25t$ measured in hh scattering

In electron-proton interactions:

- As the scale gets harder the intercept grows up to 1.2
- The Pomeron slope is around ~0.1





ρ (light VM); elastic photoproduction (Q^2=0), **SOFT regime**:

$\alpha(0) = 1.087 \pm 0.003 \pm 0.003 \approx \alpha(0)\ (pp)$

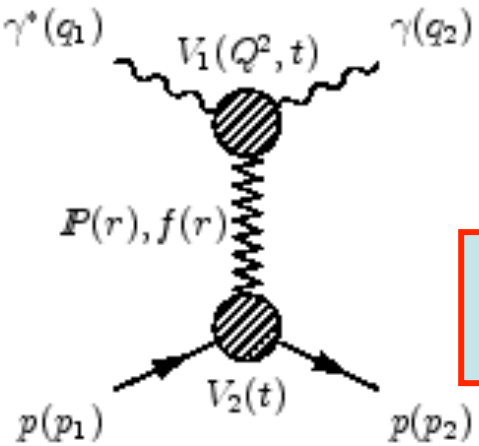
$\alpha' = 0.126 \pm 0.013 \pm 0.012\ GeV^{-2} \approx 0.5\ \alpha'\ (pp)$

✓ **Two different soft Pomeron trajectories?**

✓ **Size of two protons system growing twice faster with energy than a single proton ($\gamma\ p$ system)?**

Regge-type DVCS amplitude

M. Capua, S. F., R. Fiore, L. L. Jenkovszky, and F Paccanoni
Published in: Physics Letters B645 (Feb. 2007) 161-166



$$V_1 = e^{b\beta(z)}$$

$$V_2 = e^{b\alpha(t)}$$

A new variable is introduced: $z = t - Q^2$

Applications for the model can be:

- **Study of various regimes of the scattering amplitude vs *Q2, W, t* (perturbative –> unperturbative QCD)**
- **Study of GPD$_s$**

DVCS amplitude: $$A\left(s,t,Q^2\right)_{\gamma^* p \to \gamma p} = -A_0 V_1\left(t,Q^2\right) V_2(t)\left(-is/s_0\right)^{\alpha(t)}$$

the *t* dependence at the vertex *pIPp* is introduced by: $$\alpha(t) = \alpha(0) - \alpha_1 \ln\left(1 - \alpha_2 t\right)$$

the vertex *γ*IPγ* is introduced by the trajectory: $$\beta(z) = \beta(0) - \beta_1 \ln\left(1 - \beta_2 z\right)$$

indicating with: $L = \ln\left(-is/s_0\right)$ **the DVCS amplitude can be written as:**

$$A\left(s,t,Q^2\right)_{\gamma^* p \to \gamma p} = -A_0 e^{b\alpha(t)} e^{b\beta(z)}\left(-is/s_0\right)^{\alpha(t)} = -A_0 e^{(b+L)\alpha(t)+b\beta(z)}$$

Regge-type Aplitude: extension to VMP

G. Ciappetta, S. F., R. Fiore, L. L. Jenkovszky, and A. Lavorini

$$Q^2 \rightarrow \tilde{Q}^2 = Q^2 + M_V^2$$

Model is general:
it can be easily extended to VMP

$$\frac{d\sigma(s,t,\tilde{Q}^2)}{dt} = \frac{\pi}{s^2}\left|A(s,t,\tilde{Q}^2)\right|^2$$

$$\left|A(s,t,\tilde{Q}^2)_{\gamma^* p \rightarrow V(\gamma)p}\right| = \left|\underline{-A_0 e^{b_1\alpha(t)} e^{b_2\beta(z)}\left(-is/s_0\right)^{\alpha(t)}}\right| = -A_0 e^{(b_1+L)\alpha(t)+b_2\beta(z)}$$

Real and Imaginary part explicitly contained

$$B(s,t,\tilde{Q}^2) = \frac{d}{dt}\ln\left[\frac{d\sigma(s,t,\tilde{Q}^2)}{dt}\right]$$

$$\alpha(t) = \alpha(0) - \alpha_1 \ln(1-\alpha_2 t)$$

$$\beta(z) = \beta(0) - \beta_1 \ln(1-\beta_2 z) \qquad z = t - Q^2$$

$$\sigma(s,t,\tilde{Q}^2) = \int_{t_{\min}}^{t_{\max}} \frac{d\sigma(s,t,\tilde{Q}^2)}{dt} dt \overset{t_{\min}\approx 0}{\approx} \sigma_{el}(s,\tilde{Q}^2) = \left[\frac{1}{B(s,t,\tilde{Q}^2)} \cdot \frac{d\sigma(s,t,\tilde{Q}^2)}{dt}\right]_{t=0}$$

We refined the parameters… the most of them being constrained by plausible assumptions:

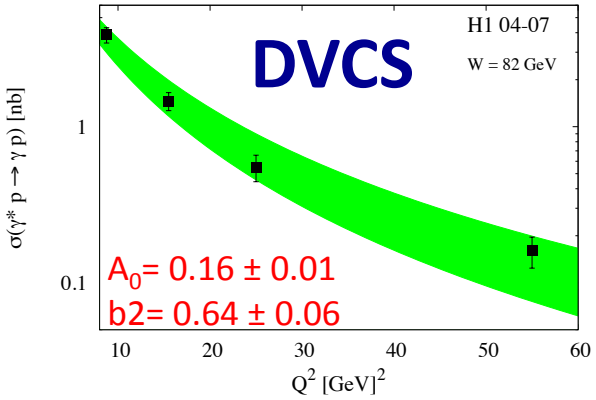
soft D-L Pomeron trajectory parameters:

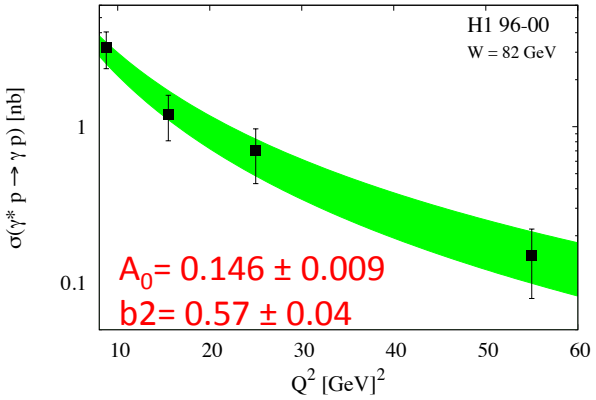
- intercept: $\alpha(0) = \beta(0) = 1.09$
- slope: $\alpha' = \alpha_1\alpha_2 = \beta' = 0.25$

- $b_1 = 2.0$ (known from h-h scattering)
- $s_0 = 1.0$ (approx. the square proton mass)
- $\alpha_1 = \beta_1 = 2.0$ (quark counting rule, range:[1-3])
- $\alpha_2 = \alpha'/\alpha_1 = 0.25/\alpha_1 = \beta_2 = 0.125$

The free parameters remaining are the normalization, A_0 and b_2

Fit to HERA: xsec vs Q^2 - DVCS

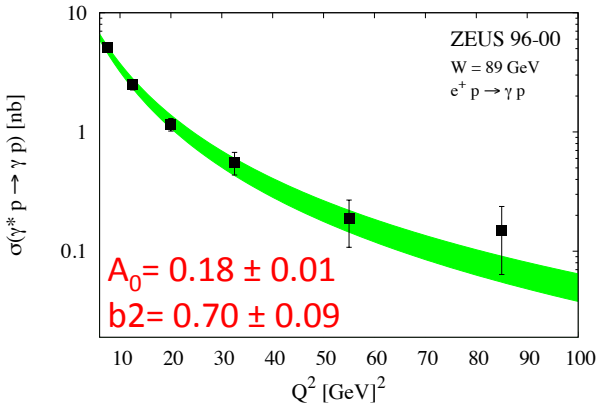


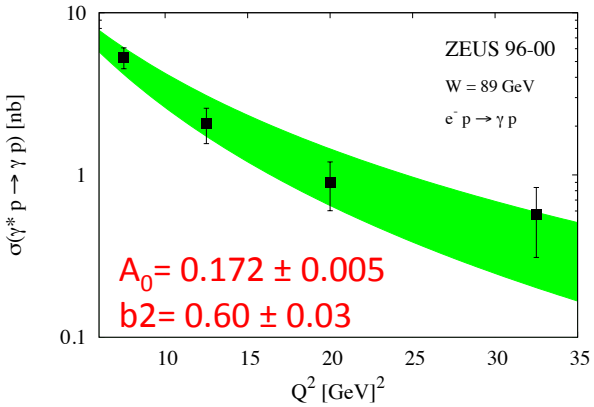


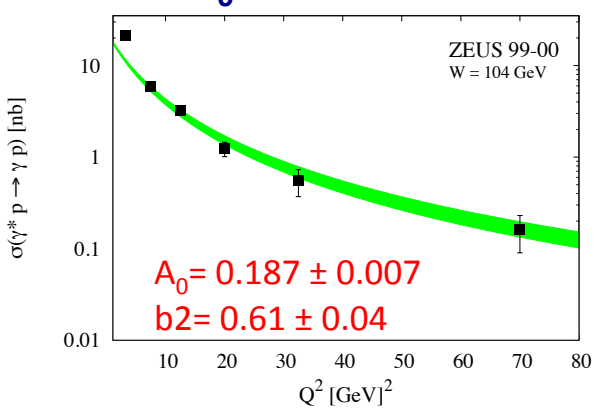
The parameter b_2 was estimated, For each process, via a two-parameters fit on $\sigma(Q^2)$, being the most sensible to it, fixed in the Fits to all the other distributions

DVCS: **$\langle b_2 \rangle$= 0.55 ± 0.02**

A_0 ~ 0.17





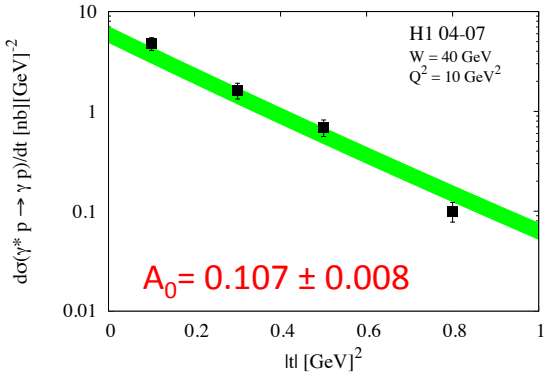


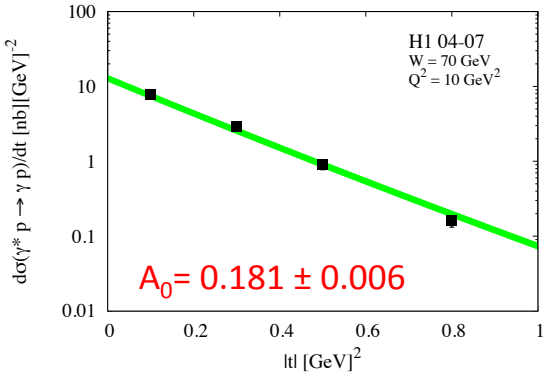
The uncertainty green band is calculated according to the uncertainty on the A_0 and b_2 parameters

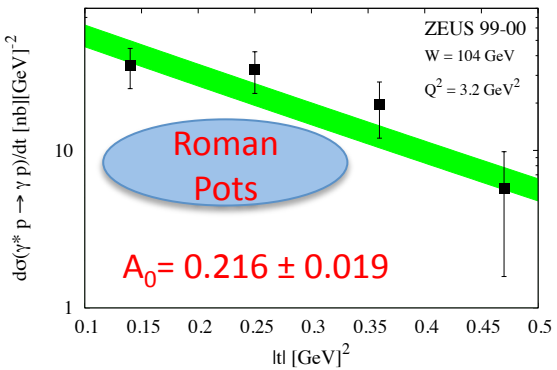
$$\sigma\left(s,t,\tilde{Q}^2\right) \overset{t_{\min}\approx 0}{\approx} \sigma_{el}\left(s,\tilde{Q}^2\right) = \left[\frac{1}{B\left(s,t,\tilde{Q}^2\right)} \cdot \frac{d\sigma\left(s,t,\tilde{Q}^2\right)}{dt}\right]_{t=0}$$

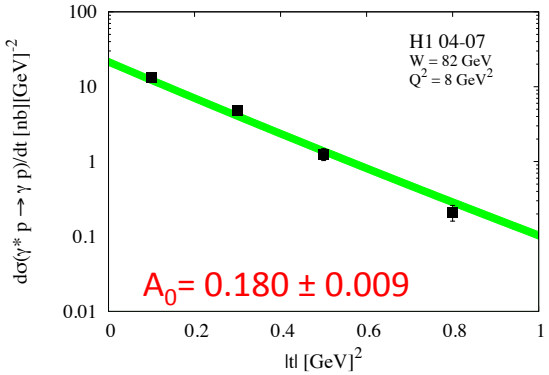
Satisfactory description of $\sigma_{DVCS}(Q^2)$ (Q^2>5 GeV^2)

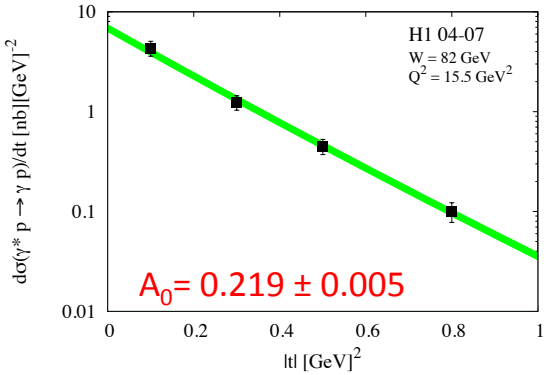
Fit to HERA: dσ/d|t| - DVCS







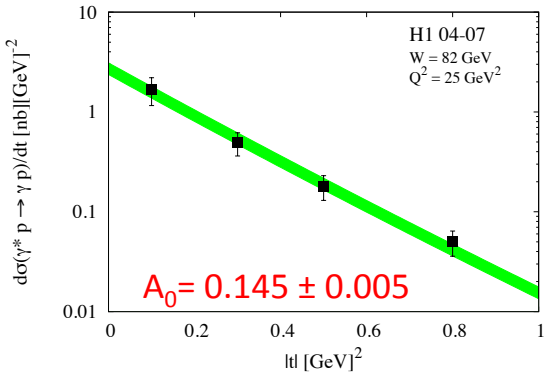


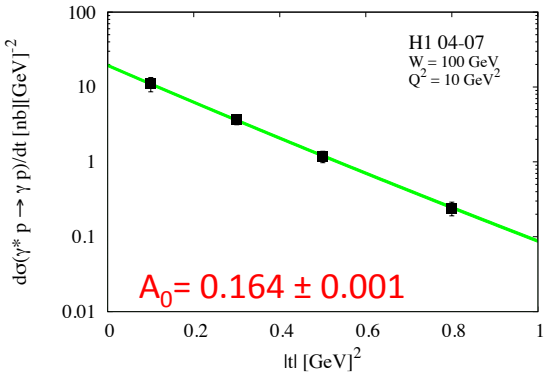


DVCS

b_2= 0.55 fixed

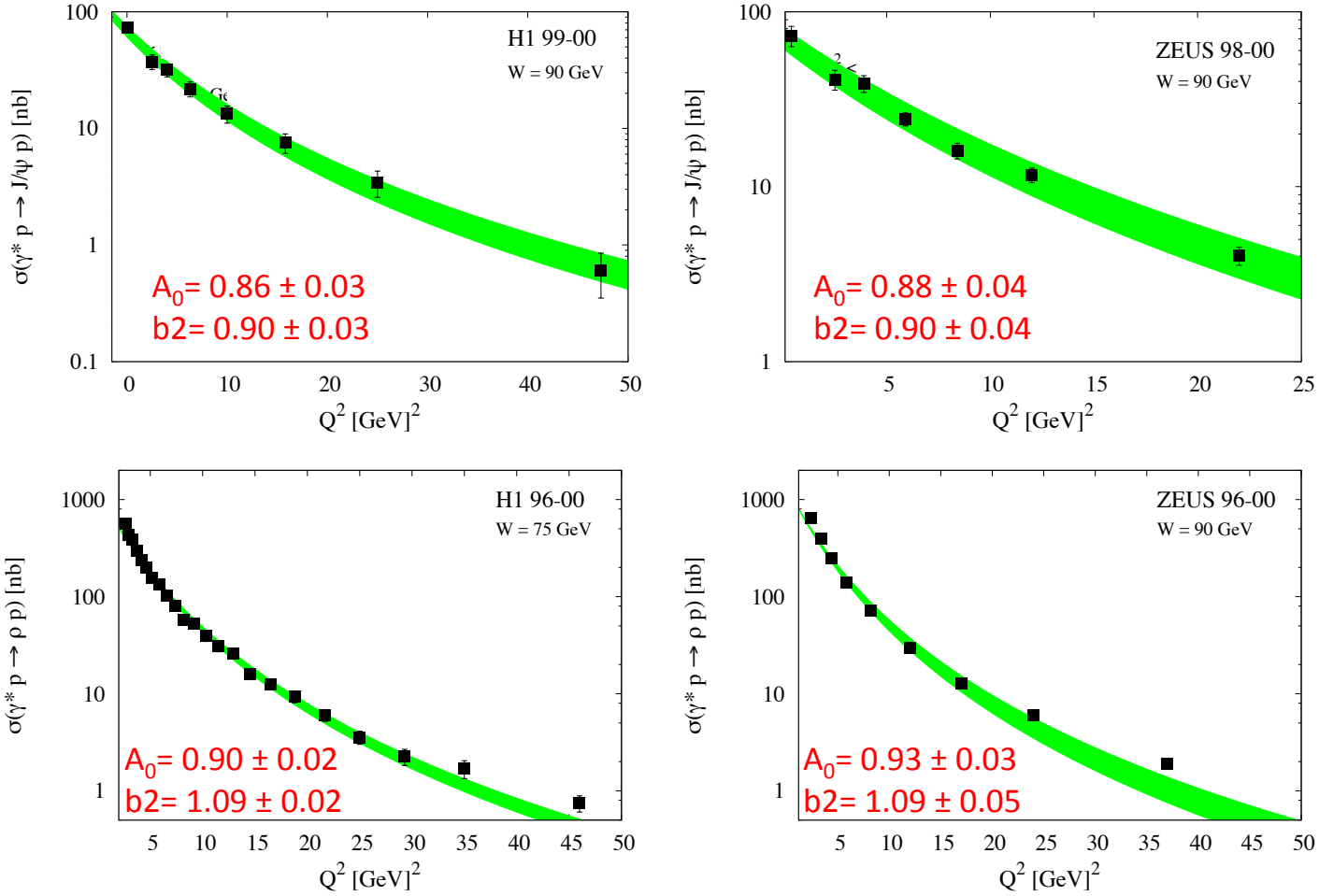
$$\frac{d\sigma\left(s,t,\tilde{Q}^2\right)}{dt} = \frac{\pi}{W^4}\left|-A_0 e^{b_1\alpha(t)} e^{b_2\beta(z)}\left(-is/s_0\right)^{\alpha(t)}\right|^2$$





Good description of $d\sigma_{DVCS}/d|t|$

Fit to HERA: xsec vs Q^2



J/Ψ

$\langle b_2 \rangle = 0.90 \pm 0.03$

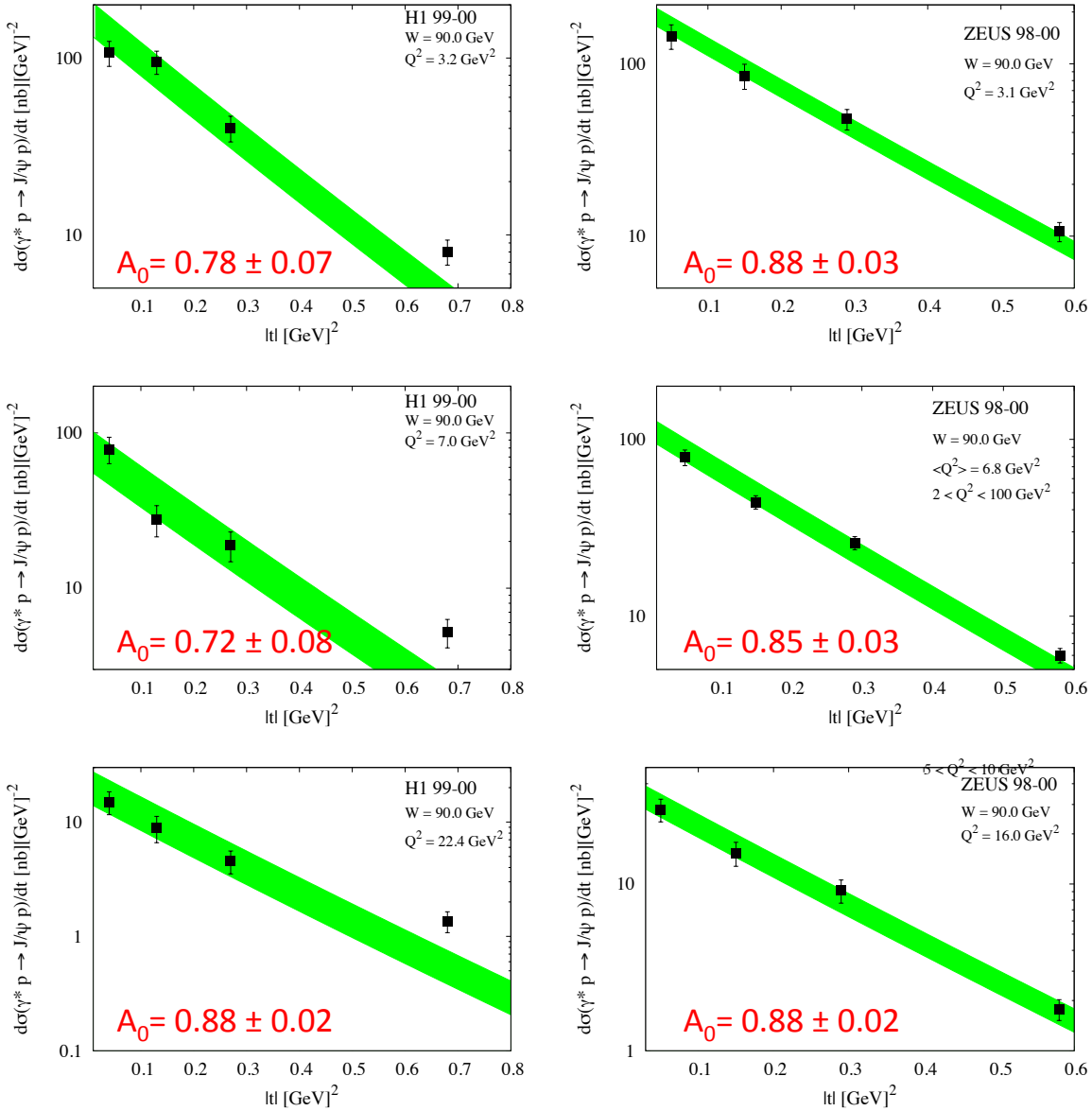
$A_0 \sim 0.9$

ρ^0

$\langle b_2 \rangle = 1.09 \pm 0.02$

- ✓ Good description of heavy mesons, J/Ψ
- ✓ ρ^0 is well reproduced at moderate Q^2
- ✓ For ρ^0, a parameter b_2 varying with Q^2 seems to be favored

Fit to HERA: dσ/d|t| - J/Ψ

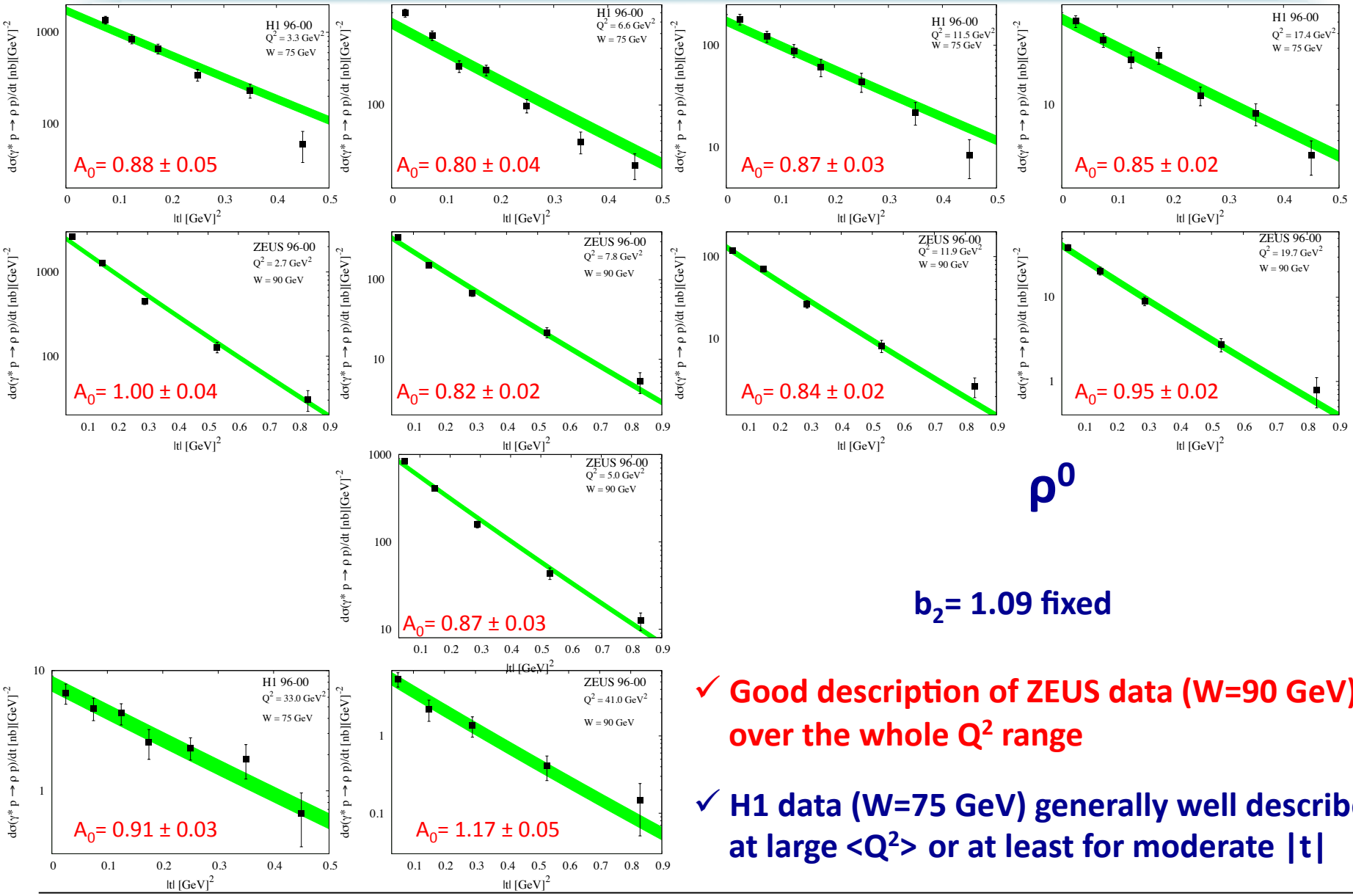


J/Ψ

b_2= 0.90 fixed

- ✓ Good description of $d\sigma_{DVCS}/d|t|$, $|t|<0.6$ GeV²
- ✓ ZEUS data described over the whole range

Fit to HERA: dσ/d|t| - ρ^0

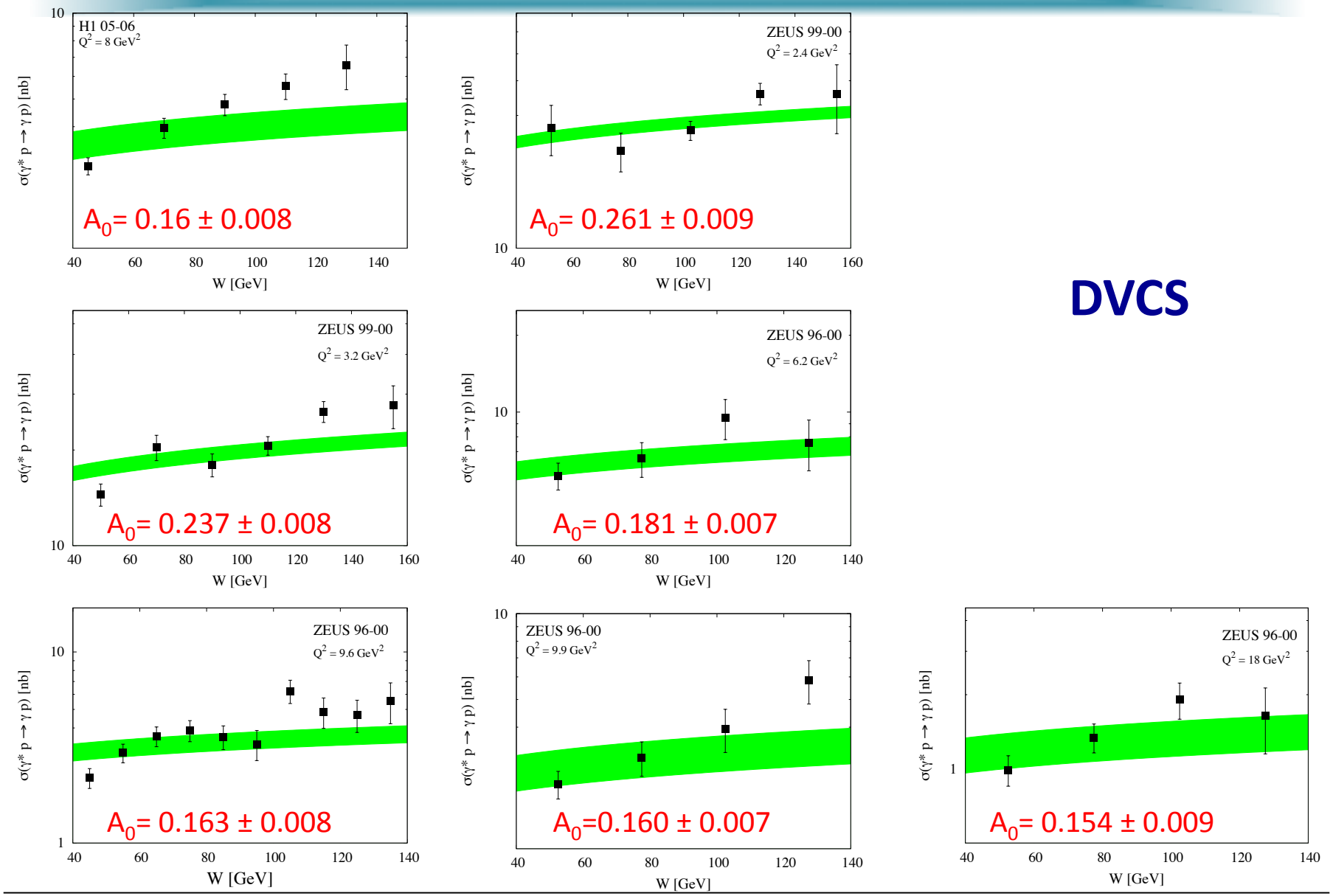


ρ^0

b_2= 1.09 fixed

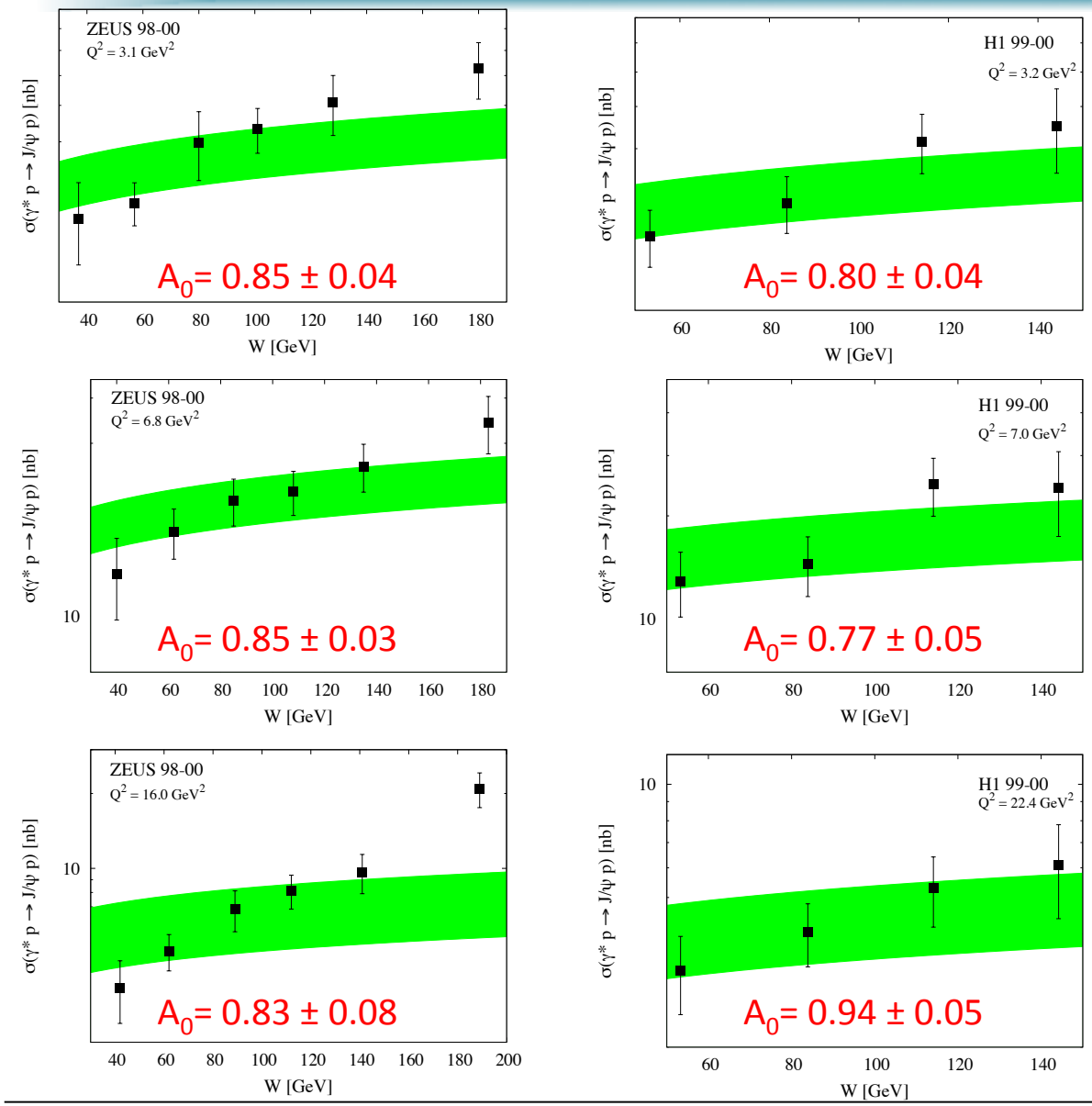
- ✓ **Good description of ZEUS data (W=90 GeV), over the whole Q^2 range**
- ✓ **H1 data (W=75 GeV) generally well described at large <Q^2> or at least for moderate |t|**

Fit to HERA: xsec vs W



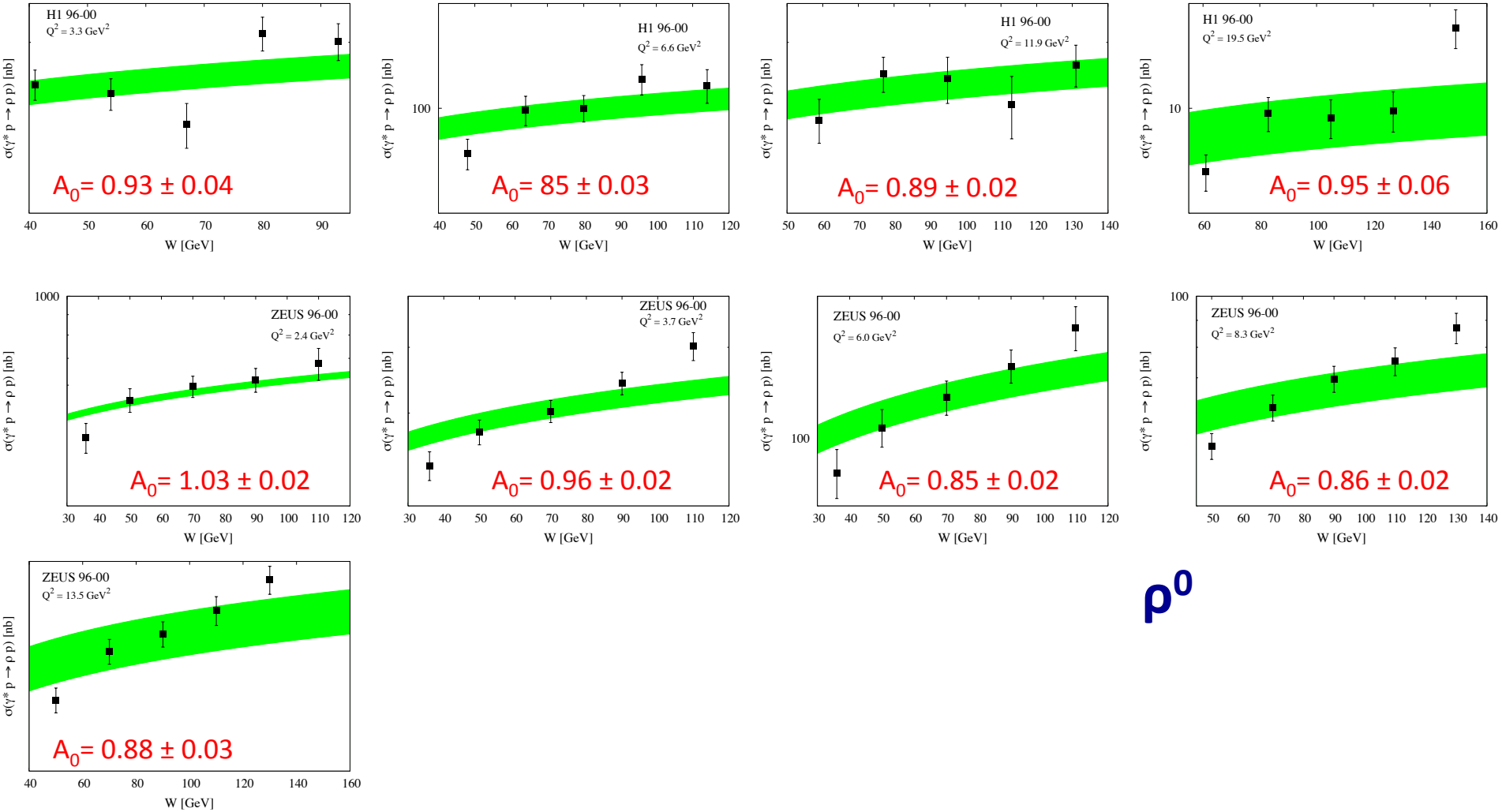
DVCS

Fit to HERA: xsec vs W



J/Ψ

Fit to HERA: xsec vs W – ρ^0



ρ^0

Discussion

Considerations:

- **We presented the most challenging scenario**
  - **One only Pomeron trajectory, as mesured in h-h interactions ("universal Pomeron")**
  - **Only two free parameters, the normalization and b_2**

Parameters of the fit:

DVCS	J/Ψ	ρ^0
$\langle b_2 \rangle = 0.55 \pm 0.02$	$\langle b_2 \rangle = 0.90 \pm 0.03$	$\langle b_2 \rangle = 1.09 \pm 0.02$(varies vs Q^2)
$A_0 \sim 0.17$	$A_0 \sim 0.9$	$A_0 \sim 0.9$

Results:

- ✓ **The model fairly reproduces $d\sigma/dt$ and total xsec vs Q^2**
- ✓ **Describing $\sigma(W)$ in a large Q^2 range is always challanging for Regge-type models, expecially for light particles (soft -> hard transition)**

Different approaches are possible to better describe the data versus the scale Q^2+M^2, we consider:

- ✓ **the two (or multiple) Pomeron components approach**
- ✓ **the "geometrical" approach**

Two Pomeron components approach

Concept of the two Pomeron components first introduced in:
A. Donnachie and P. V. Landshoff, arXiv:0803.0686v1 [hep-ph]

We may consider the Pomeron as an "effective" one containing the contribution from two (i.g. multiple) components, each one with a Q^2-independent trajectory

$$A_{tot} = A_s + h \cdot A_h$$

$$A_i\left(s,t,Q^2\right)_{\gamma^* p \to \gamma p} = -A_0 e^{b\alpha(t)} e^{b\beta(z)} \left(-is/s_0\right)^{\alpha(t)} = -A_0 e^{(b+L)\alpha(t)+b\beta(z)}$$

$$\alpha_i(t) = \alpha(0) - \alpha_1 \ln\left(1 - \alpha_2 t\right)$$

$$\beta_i(z) = \beta(0) - \beta_1 \ln\left(1 - \beta_2 z\right)$$

i = soft; hard

Soft Pomeron:

$$\alpha_{soft}(t) = 1.09 + 0.25t$$

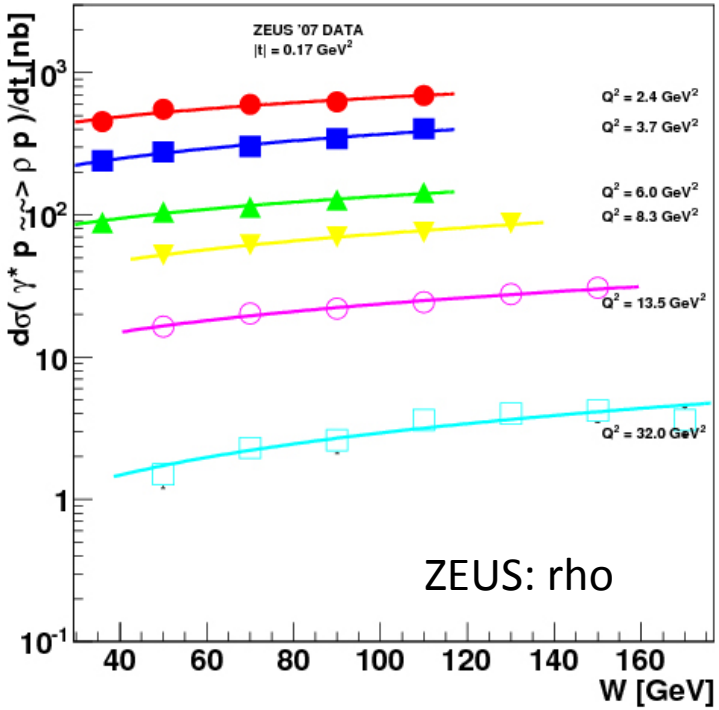
Hard Pomeron:

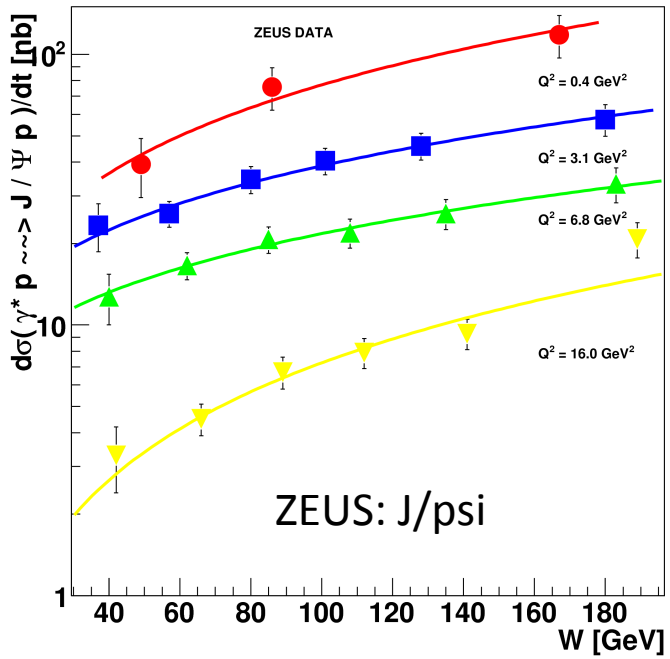
$$\alpha_{hard}(t) = 1.30 + 0.02t$$

Now we have two components of the Pomeron

Two Pomeron components – σ(W)

$$A_{tot} = A_s + h \cdot A_h$$





- **Successful description of the total xsec. in energy**
- **Contributions from other reggeons found to be negligible at HERA energies**

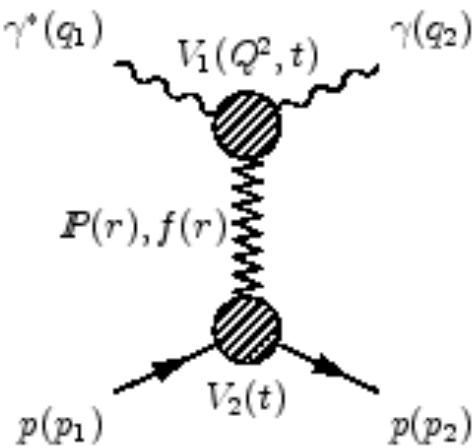
For a complete review of results see:

- L. Jenkovszky, S. Fazio, R. Fiore, A. Lavorini, ISMD09 Proceedings
- Trento workshop on diffraction for LHC 2010: http://diff2010-lhc.physi.uni-heidelberg.de/

"Reggeometry"

$$\frac{d\sigma}{dt} \sim e^{bt} \rightarrow b = R^2 \propto \frac{1}{\tilde{Q}^2}$$

For not too large |t| - the exponential slope is linked to the interaction radius which is a function of the inverse mass virtuality



More precisely: $b=b_1 + b_2 = R_1^2 + R_2^2$
R_1^2 and R_2^2 being the two radii corresponding to the upper and lower vertex of the diagram

In the case of a Regge model:

$$A(s,t,\tilde{Q}^2) = \xi(t)\beta(t,\tilde{Q}^2)(s/s_0)^{\alpha(t)}$$

$\xi(t) = e^{-i\pi\alpha(t)}$ -> signature
$\beta(t,\tilde{Q}^2) = e^{(b_1+b_2)t}$ -> residue

In a first approach – to be fine-tuned

$$\beta(t,\tilde{Q}^2) = \exp\left[4\left(\frac{1}{Q^2+M_V^2} + \frac{1}{2m_p^2}\right)t\right]$$

$b_1 = c/\tilde{Q}^2 \quad b_2 = d/2m_p^2$ m_p is the proton mass

c and *d* being free parameters

The slope can be calculated as: $B(s) = 2(b_1 + b_2 + \alpha' L)$

A complete test of this "geometric" Regge picture vs HERA data is our next task

Summary and outlook

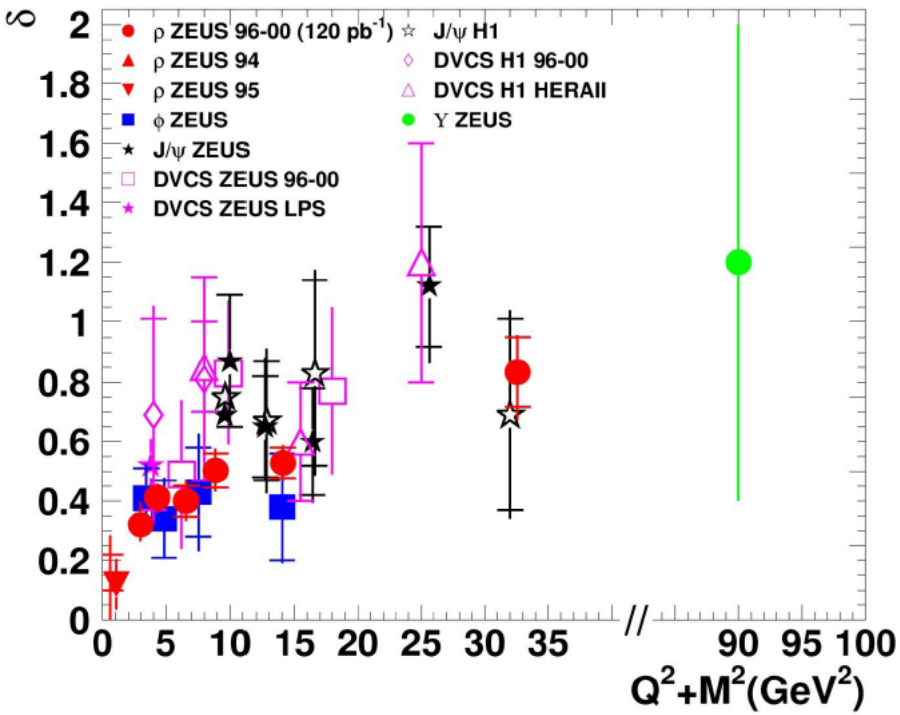
- A Regge-type model using a logarithmic trajectory and very few free parameters describes HERA data on DVCS and VMP
- The challenge of the description of $\sigma(W)$ in a large Q^2 domain can be succeeded considering two Pomeron components: a hard trajectory apart from the soft one
- Much room for further improvements, the geometrical picture
- The real and imaginary parts of the DVCS (and VM) amplitude, essential ingredients for the GPDs, are explicitly contained in the model

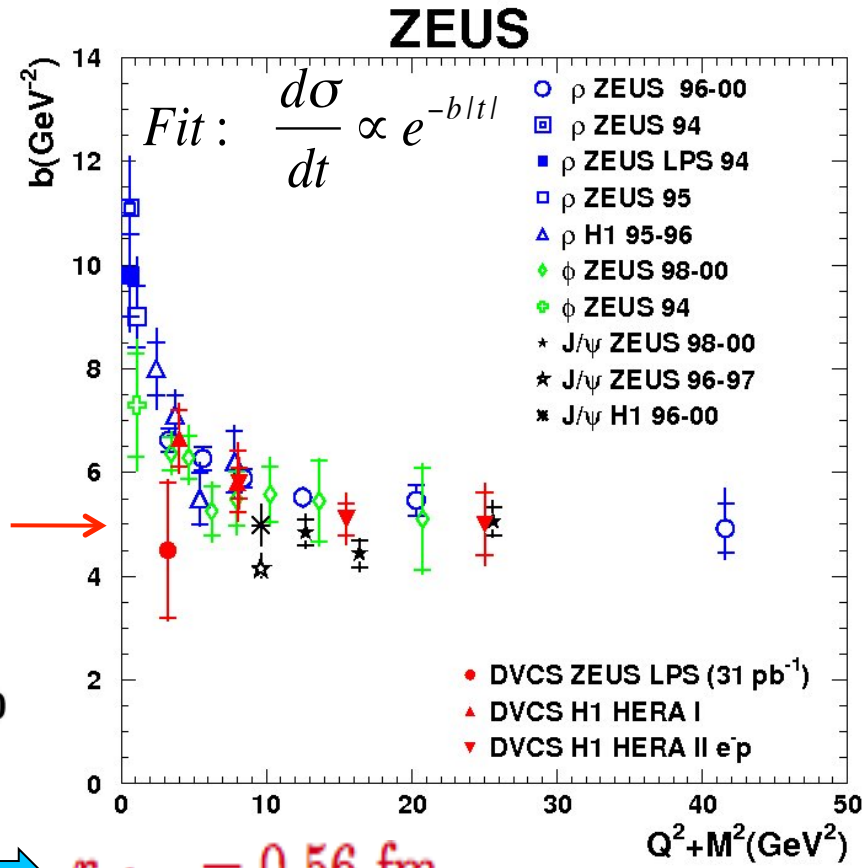
BACK UP

VMP and DVCS @ HERA

Summary of the W,t-dependence for all VMs + DVCS measured at HERA

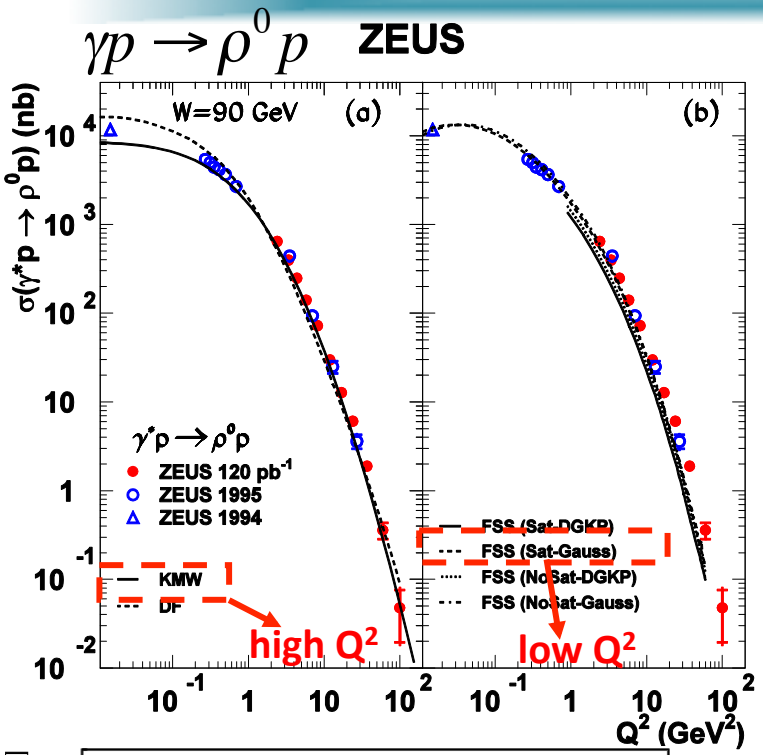
$$Fit:\ \sigma \sim W^{\delta}$$

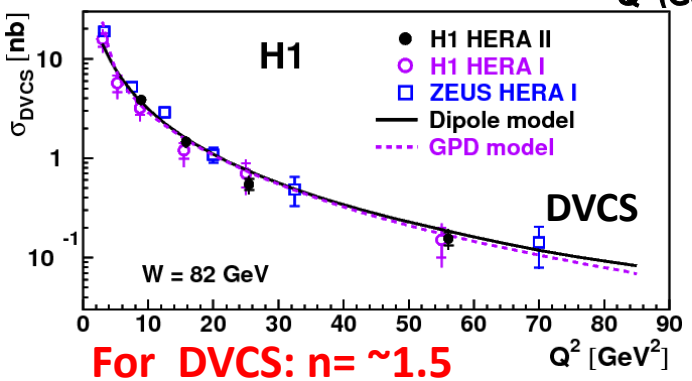




Size of the gluons: $\langle r^2 \rangle = 2 \cdot b \cdot (\hbar c)^2$ ➡ $r_{glue} = 0.56$ fm

Total xsec dependences @ HERA



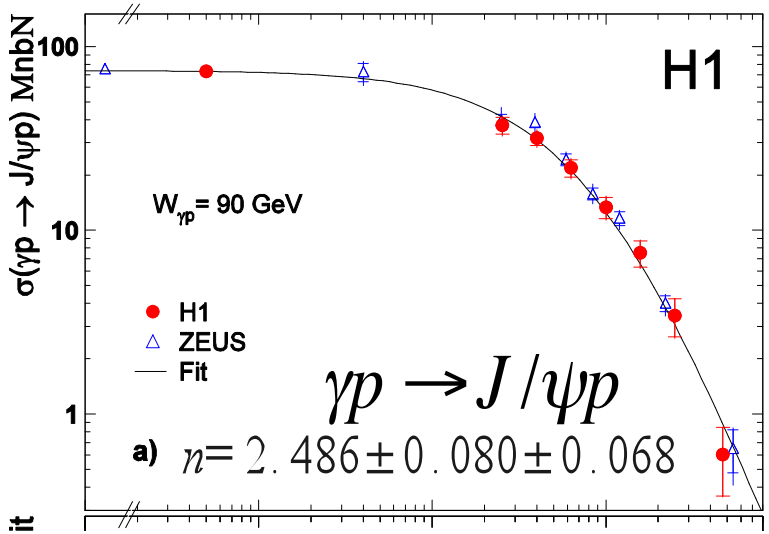


For DVCS: n= ~1.5

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

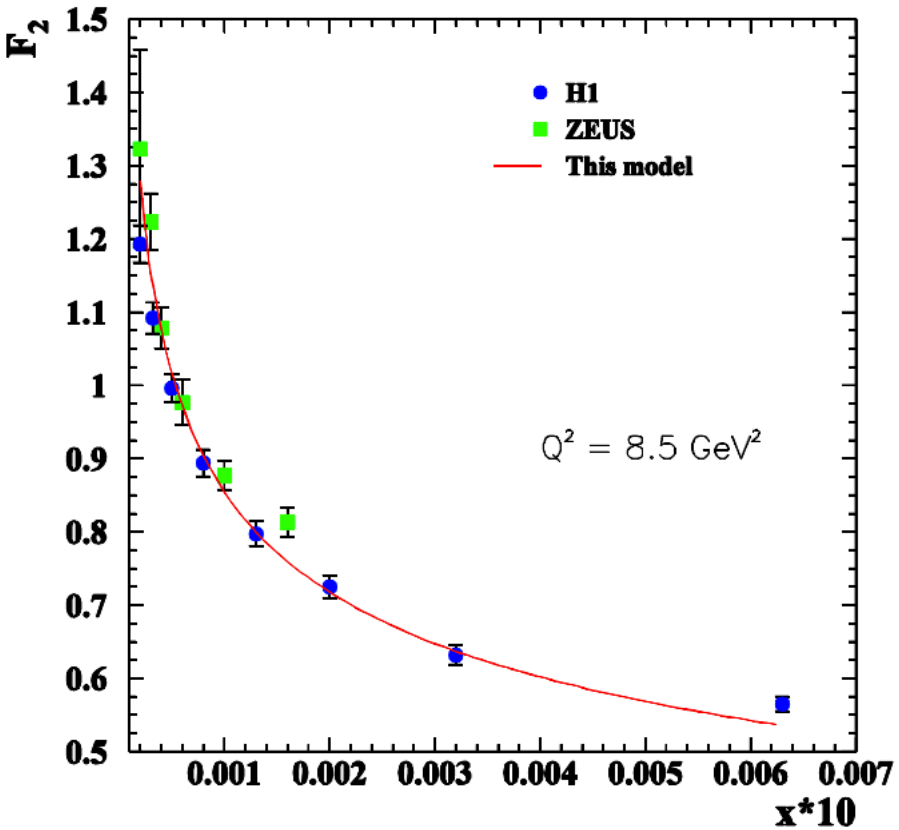
Fit to whole Q^2 range gives bad χ^2/df (~70)

n **increasing with** ***Q^2*** **appears to be favored**



F_2 structure function

Comparison between HERA data and the model prediction for
$F_2(s,Q^2)$ **DIS structure function**



$$F_2\left(s,Q^2\right) \approx \frac{(1-x)Q^2}{\pi\alpha_e}\Im A(s,Q^2)/s$$

Function is plotted with all parameters fixed

Really good agreement!

The model reproduces experimental data at small *x* and moderate Q^2