Exclusive diffractive production of VM and a real photon at HERA in a Regge-pole model

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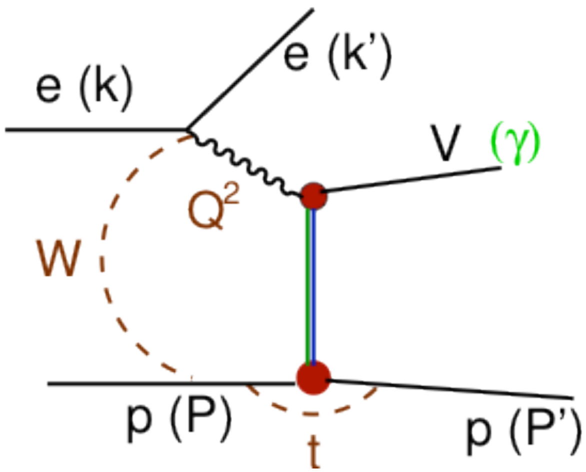


EDS ("Blois" @ Vietnam)
Quy Nhon, ***December 15 – 20, 2011***

Plan:

- Experimantal situation in DVCS and VMP;

  ep vs hh data; the Pomeron in ep and hh;

- Theory: QCD- and Regge-factorization; from GPD to

  realistic processes and vv.

- DVCS & VMP; the “radius” of the real photon?

- Regge model: DVCS and VMP

- A geometrical approach to the Regge theory

- Summary

The basic object of the theory

$$A(s,t,Q^2) \rightarrow A(s,t,Q^2=m^2) \text{ (on mass shell)}$$

$$A(s,t,Q^2) \rightarrow \Im m A(s,t=0,Q^2) \sim F_2 \quad \text{DIS}$$

Reconstruction of the DVCS amplitude from DIS

$$F_2 \sim \Im m A(\gamma^* p \to \gamma^* p)\Big|_{t=0} \to \Im m A(\gamma^* p \to \gamma p)\Big|_{t=0}$$

$$\to A(\gamma^* p \to \gamma p)\Big|_{t=0} \to A(\gamma^* p \to \gamma p)$$

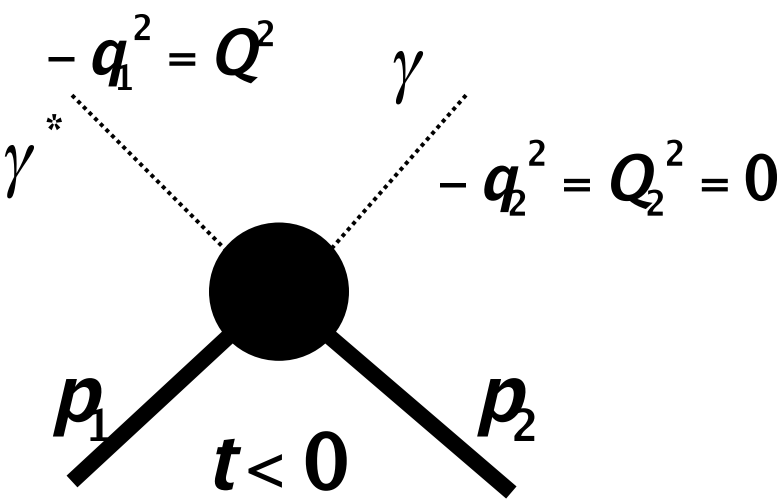
or

$$\Im m A(\gamma^* p \to \gamma^* p)\Big|_{t=0} \sim F_2(x_B,Q^2) = x_B q(x_B,Q^2)$$

$$q(x_B,Q^2) \to q(\xi,\eta,t,x_B,Q^2) \rightarrow$$

$$\rightarrow \xi q(\xi,\eta,t,x_B,Q^2) \overset{?}{=} GPD(\xi,\eta,t,x_B,Q^2)$$

DVCS kinematics



$$P = p_1 + p_2, \quad q = (q_1 + q_2)/2$$

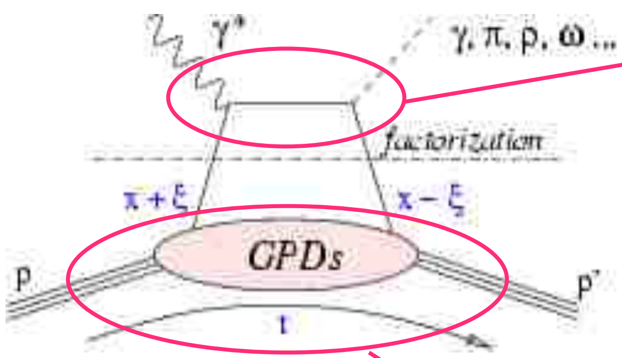
$$\Delta = p_2 - p_1, \quad t = \Delta^2$$

$$x_B = \frac{-q_1^2}{2p_1q_1} = \frac{Q^2}{2p_1q_1}$$

$$\xi = \frac{-q^2}{2Pq} = x_B \frac{1 + \frac{\Delta^2}{2Q^2}}{2 - x_B + x_B \frac{\Delta^2}{Q^2}}$$

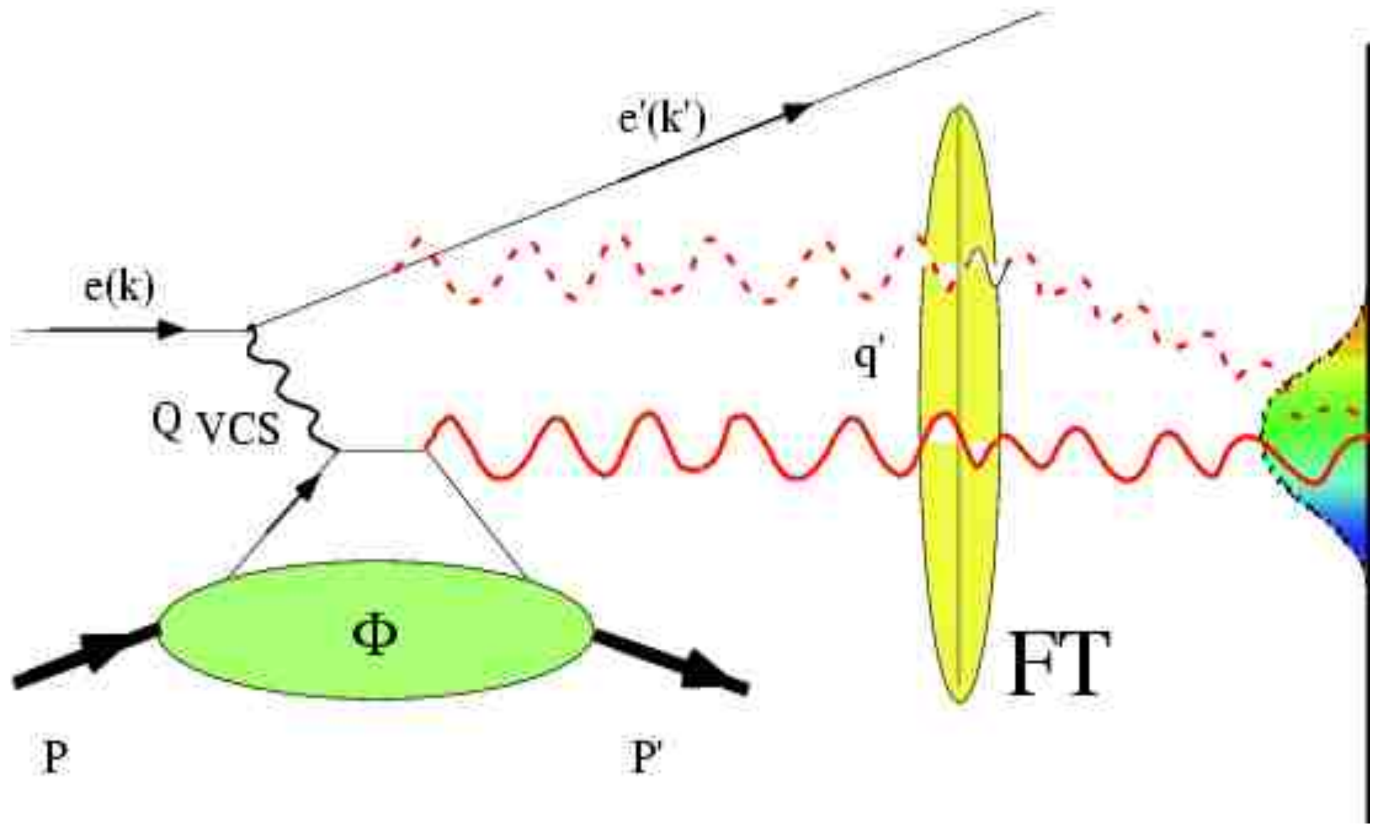
$$\eta = \frac{\Delta q}{Pq} = -\xi \left(1 + \frac{\Delta^2}{2Q^2}\right)^{-1}$$

QCD-factorized form of a DVCS scatterigg amplitude



pQCD

non-perturbative region



e(k)
e'(k')
Q VCS
q'
Φ
FT
P
P'

GPDs cannot be measured directly,
instead they appear as convolution integrals,
difficult to be inverted !

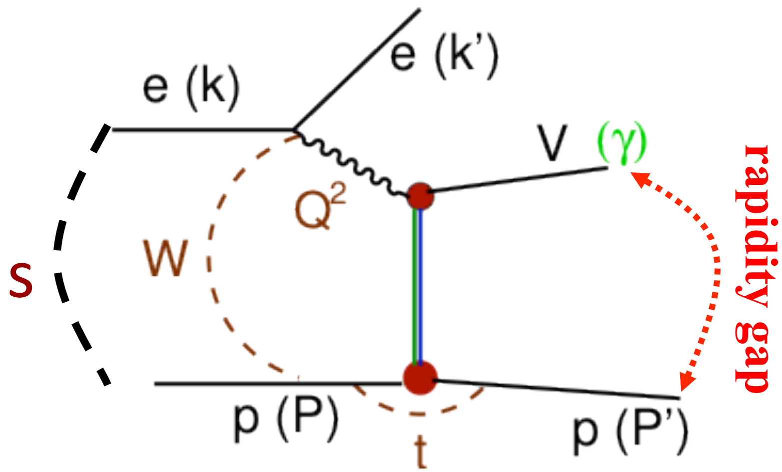
$$A(\xi,\eta,t) \sim \int_{-1}^{1} dx \frac{GPD(x,\eta,t)}{x-\xi+i\varepsilon}$$

"Handbag"

We need clues from phenomenological models - Regge behaviour, t-factorization etc.

$$\sigma_{tot} \sim \Im m A, \qquad \frac{d\sigma}{dt} \sim |A|^2$$

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:

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

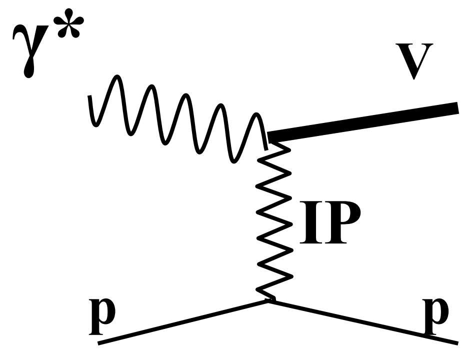
square 4-momentum at the *p* vertex:

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

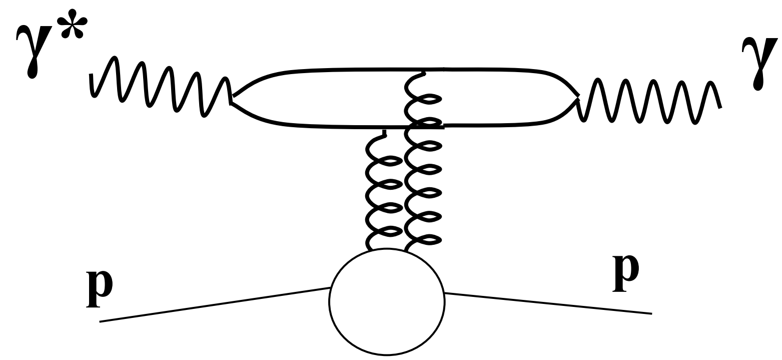
- **Vector Mesons production in diffraction**
- **Deeply Virtual Compton Scattering**

Deeply Virtual Compton Scattering

VM (ρ, ω, φ, J/ψ, Y)



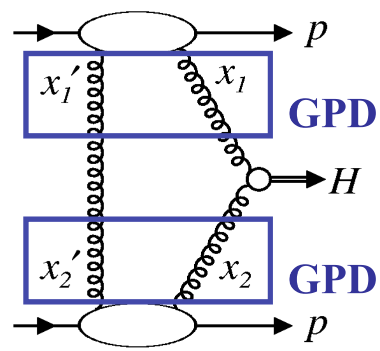
DVCS (γ)



Scale: $Q^2 + M^2$ ⟷ Q^2

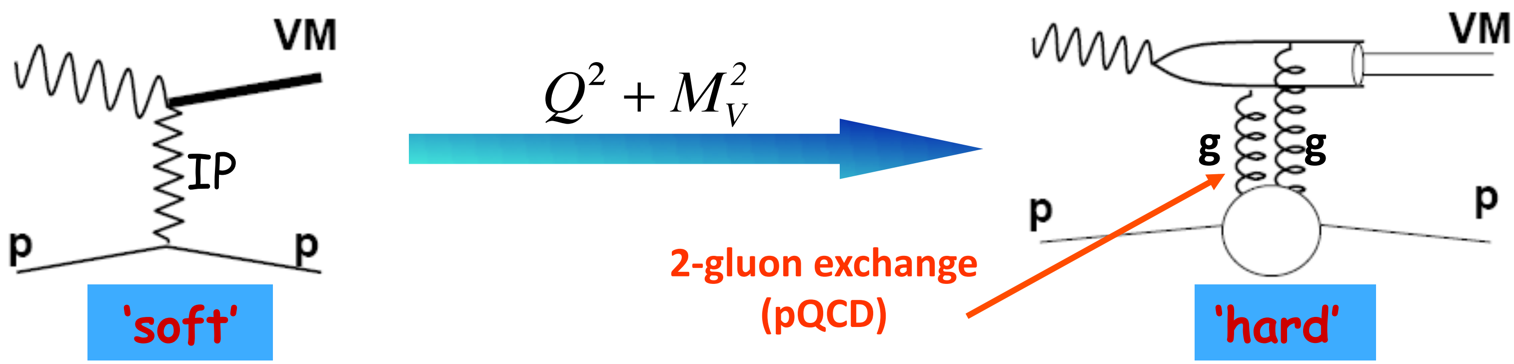
DVCS properties:

- **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 the LHC**



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

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

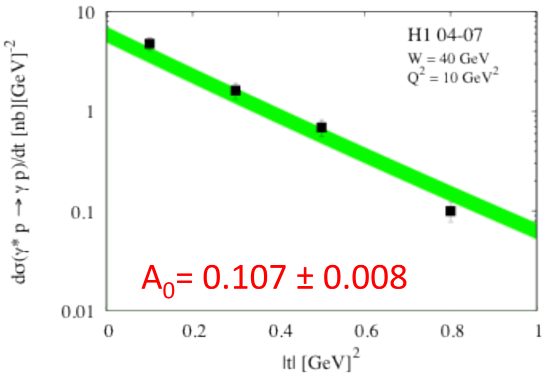
$$\sigma(W) \propto W^{\delta}$$

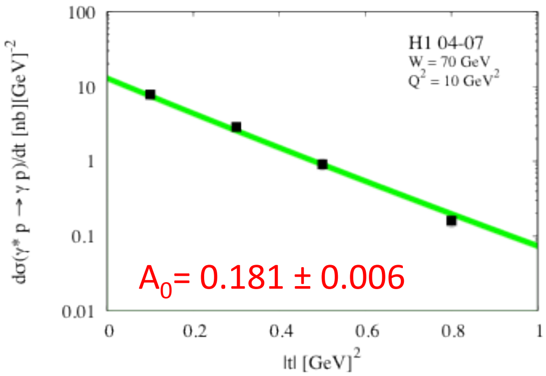
δ increases from soft (~0.2, "soft Pomeron") to hard (~0.8, "hard Pomeron")

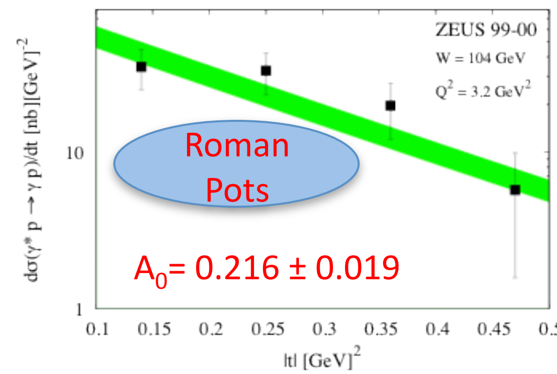
$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

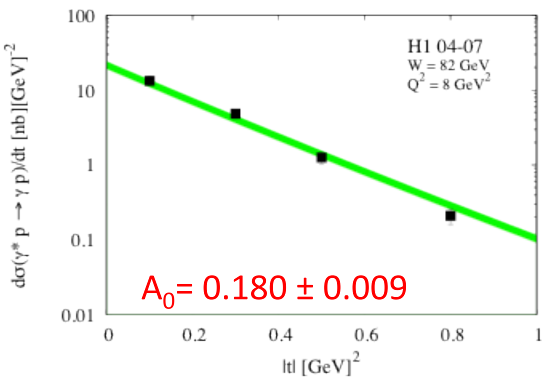
b decreases from soft (~10 GeV^{-2}) to hard (~4-5 GeV^{-2})

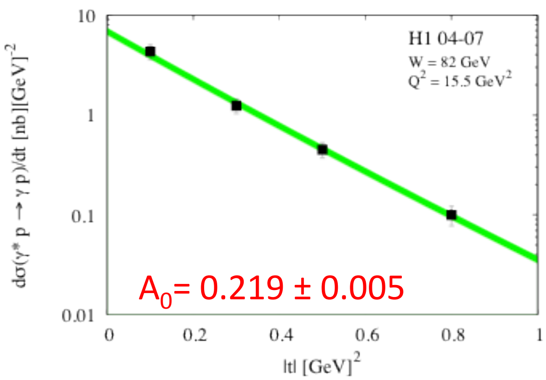
Fit to HERA: dσ/d|t| - DVCS







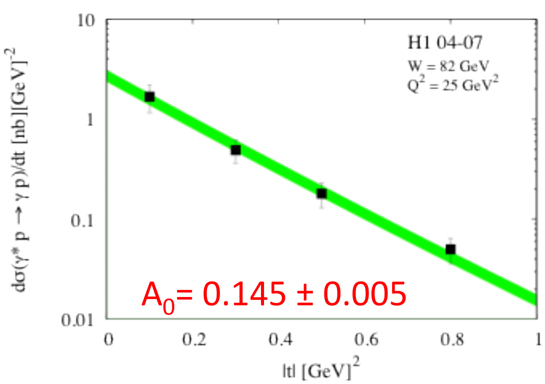


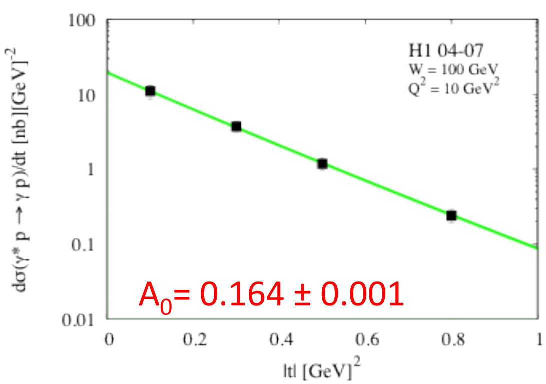


DVCS

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 $d\sigma_{DVCS}/d|t|$

Pomeron Trajectory

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

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

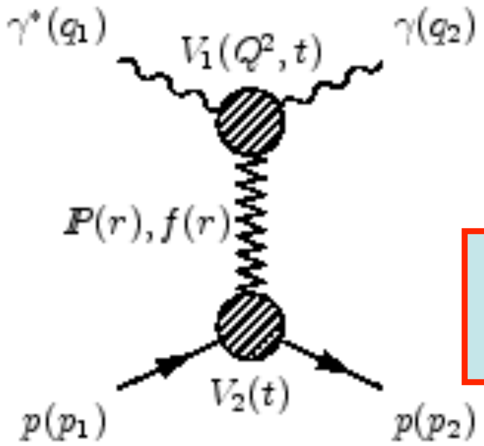
$\alpha(0)$: determines the energy dependence of the diff. Cross section

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

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

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

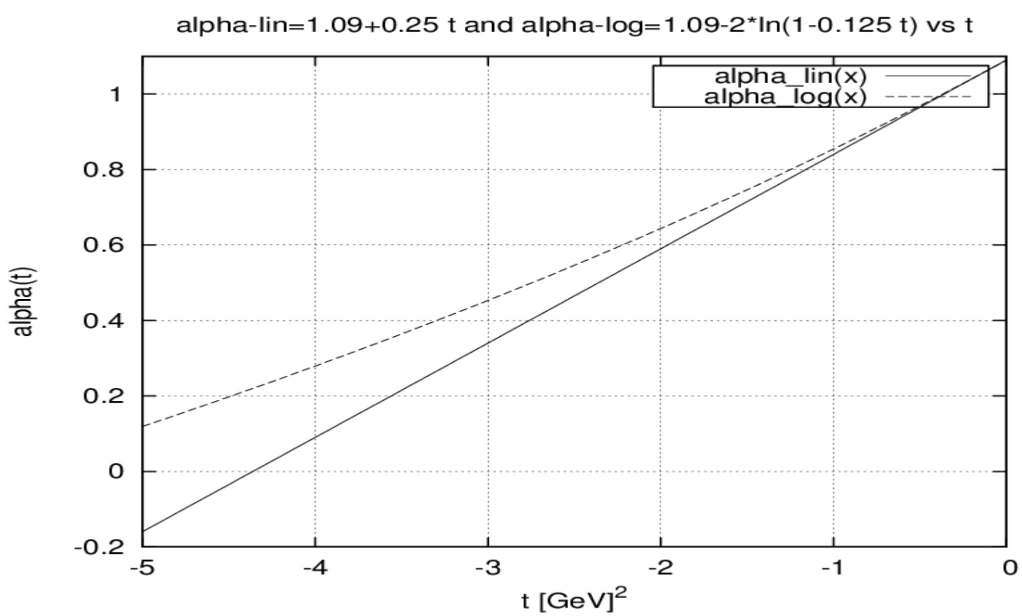
DVCS amplitude: $$A(s,t,Q^2)_{\gamma^* p\to\gamma p} = -A_0 V_1(t,Q^2)V_2(t)(-is/s_0)^{\alpha(t)}$$

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

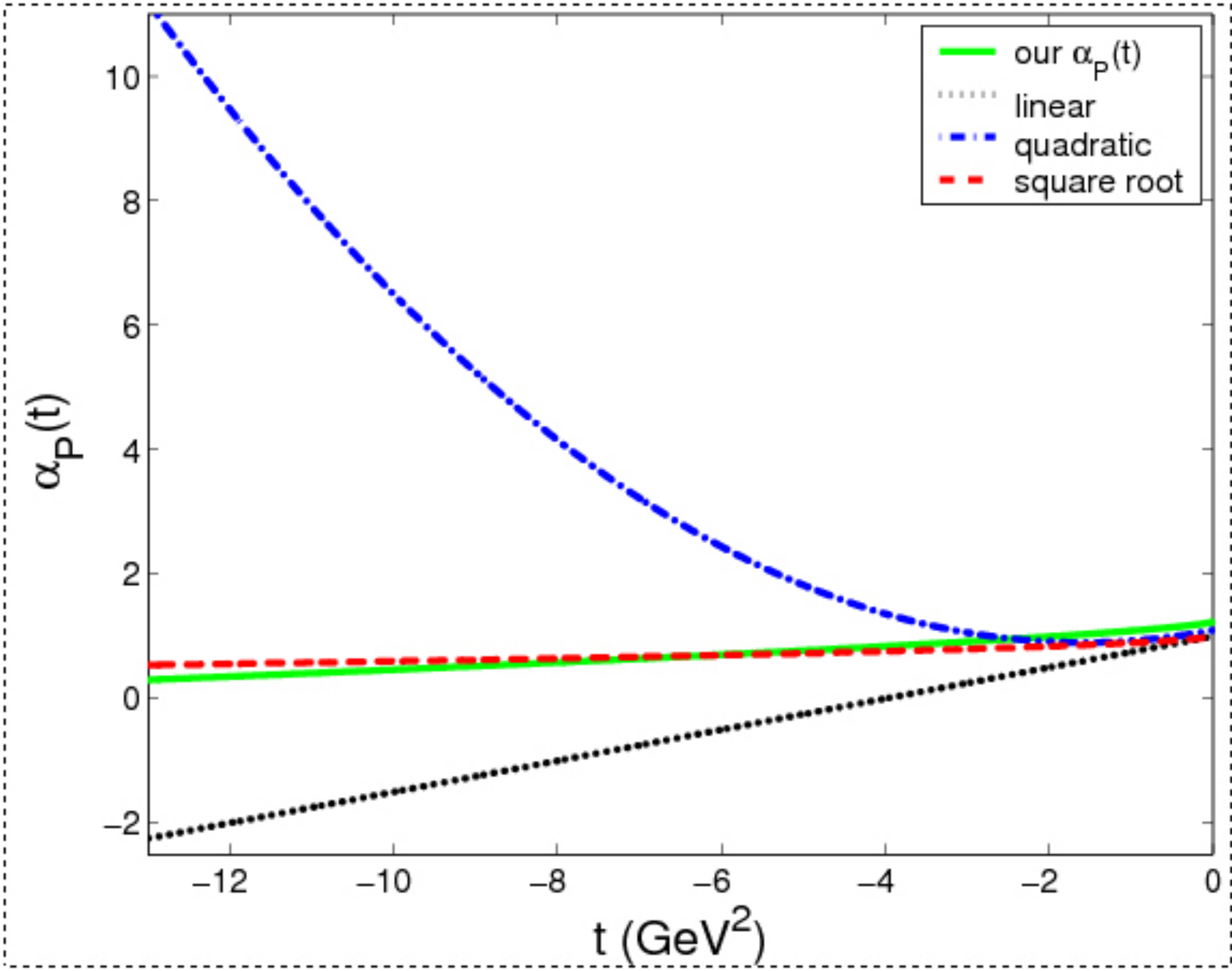
the vertex *γ*IPγ* is introduced by the trajectory: $$\beta(z) = \beta(0) - \beta_1 \ln(1-\beta_2 z)$$

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

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



alpha-lin=1.09+0.25 t and alpha-log=1.09-2*ln(1-0.125 t) vs t
alpha_lin(x)
alpha_log(x)
alpha(t)
1
0.8
0.6
0.4
0.2
0
-0.2
-5
-4
-3
-2
-1
0
t [GeV]2

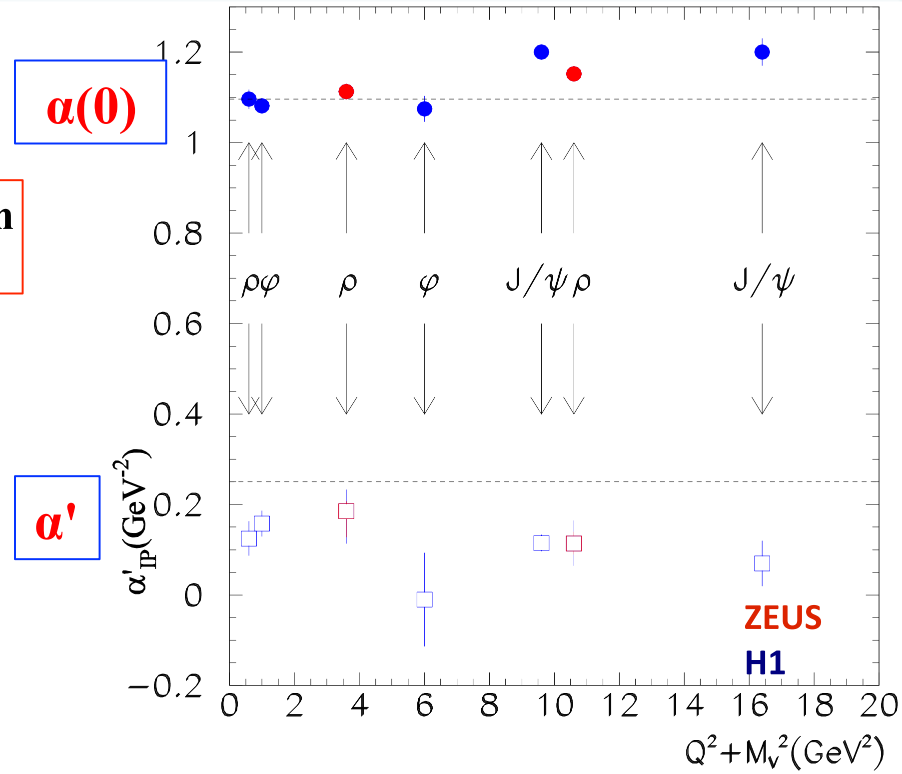


our $\alpha_P(t)$
linear
quadratic
square root
$\alpha_P(t)$
t (GeV^2)
10
8
6
4
2
0
−2
−12
−10
−8
−6
−4
−2
0

Pomeron trajectory in ep collisions

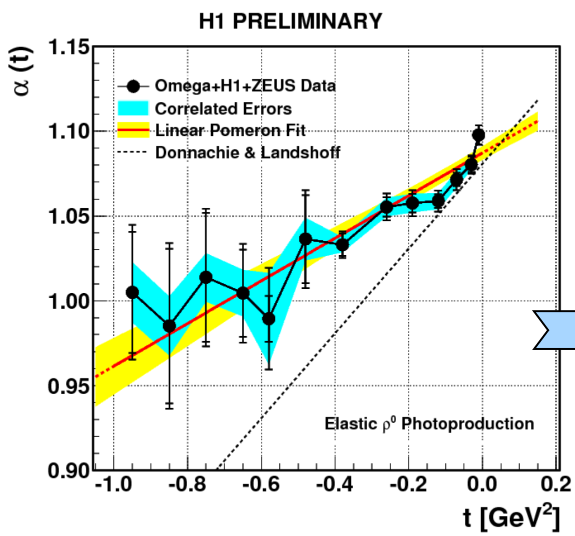
The "effectie" trajectory varies with the scale

$\alpha_{IP}(t) = 1.09 + 0.25t$ 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**:

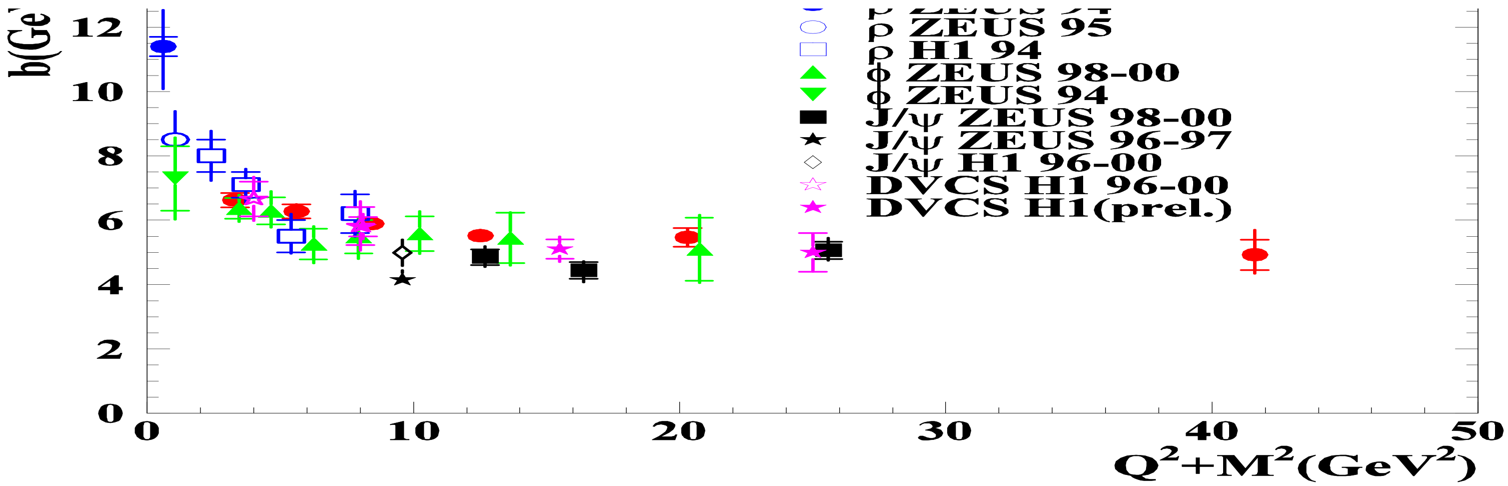
$\alpha(0) = 1.087 \pm 0.003 \pm 0.003 \approx \alpha(0)$ (*pp*)

$\alpha' = 0.126 \pm 0.013 \pm 0.012$ 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 (γ *p* system)?**

b(Q^2+M^2) - VM



$Magic\ formula: \langle r^2 \rangle = b \bullet \hbar c$

$r_{glue} = 0.56 \text{ fm}$

$r_{proton} = 0.8 \text{ fm}$

Regge-type Aplitude: extension to VMP

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

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

The model is general:
it can be easily extended to VMP

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

Real and Imaginary part explicitly contained

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

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

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

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

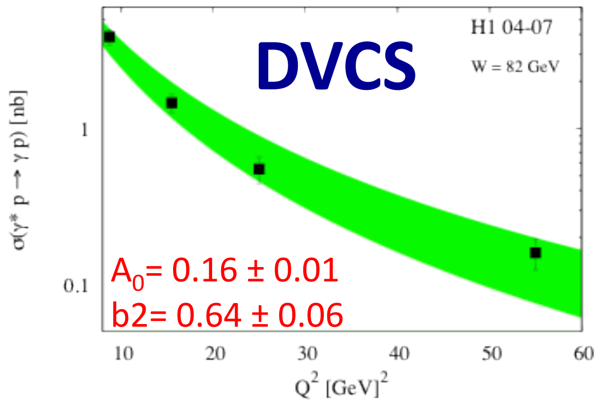
We refined the parameters… the most of them being constrained by plausible assumptions:

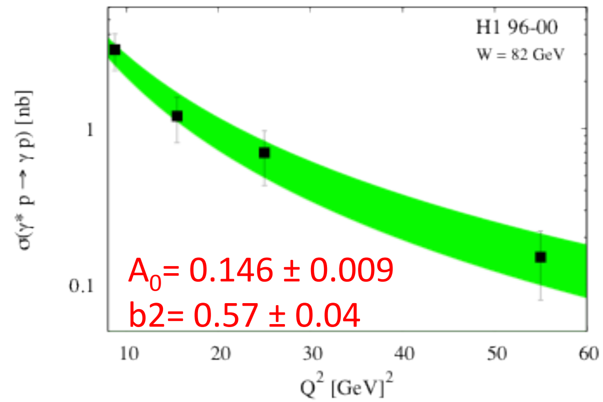
soft D-L Pomeron trajectory parameters:
- intercept: $\alpha(0) = \beta(0) = 1.09$
- slope: $\alpha' = \alpha_1\alpha_2 = \beta' = 0.25$

- $b_1 = 2.0$ (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

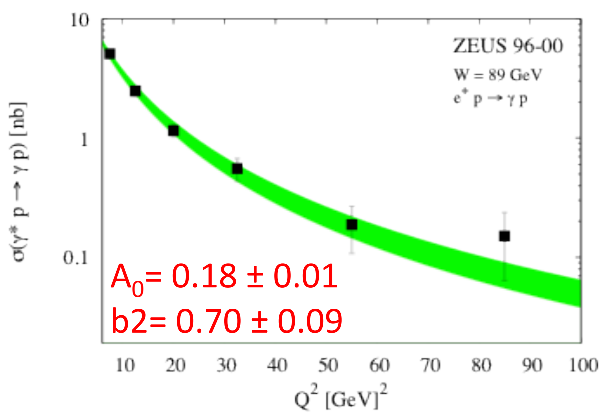


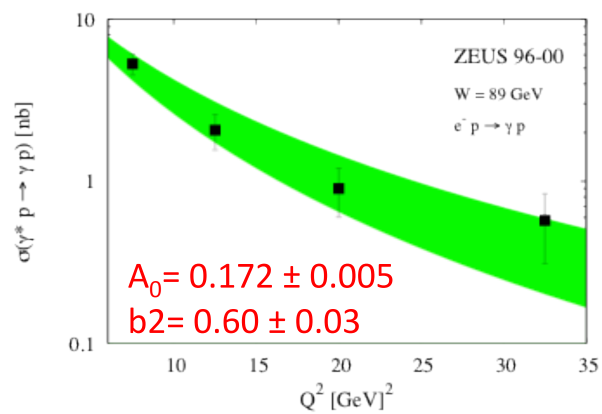


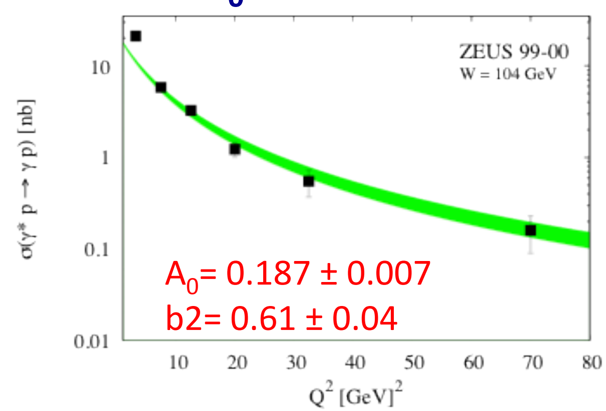
The parameter b_2 was estimated, For each process, via a two-parameters fit on $\sigma(Q^2)$, being the most sensible to it, fixed in the Fits to all the other distributions

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

$A_0 \sim 0.17$





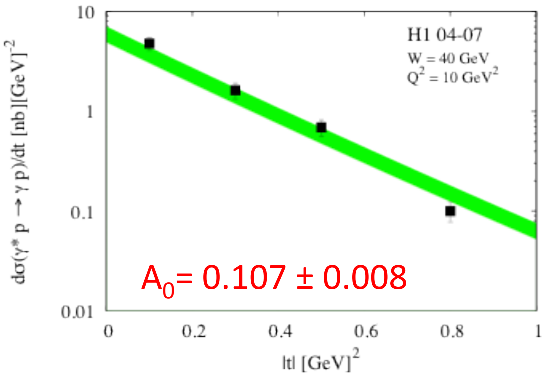


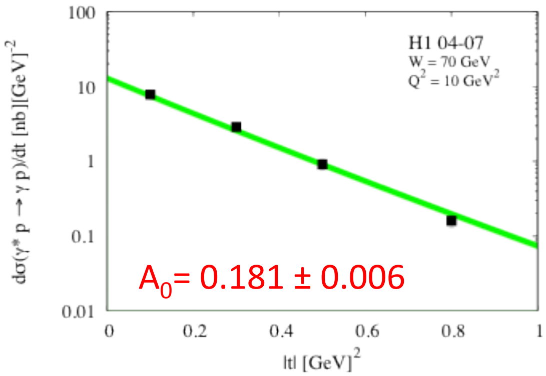
The uncertainty green band is calculated according to the uncertainty on the A_0 and b_2 parameters

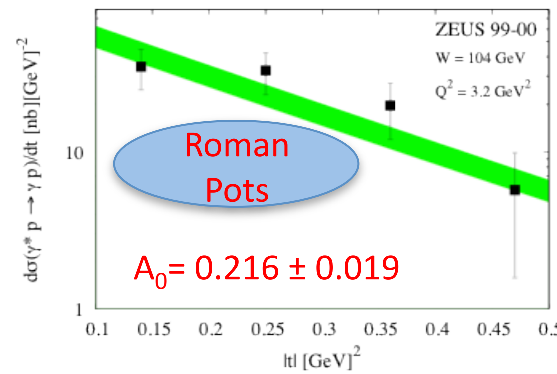
$$\sigma(s,t,\tilde{Q}^2) \overset{t_{min}\approx 0}{\approx} \sigma_{el}(s,\tilde{Q}^2) = \left[\frac{1}{B(s,t,\tilde{Q}^2)} \cdot \frac{d\sigma(s,t,\tilde{Q}^2)}{dt}\right]_{t=0}$$

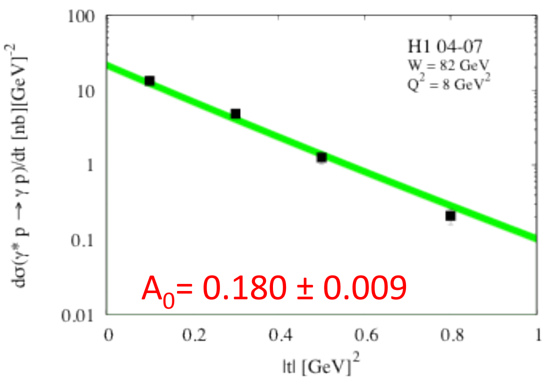
Satisfactory description of $\sigma_{DVCS}(Q^2)$ ($Q^2 > 5\ GeV^2$)

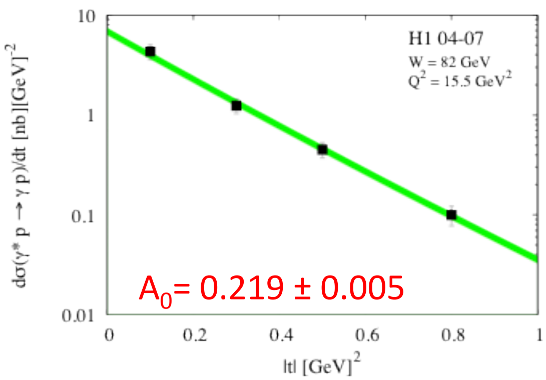
Fit to HERA: dσ/d|t| - DVCS







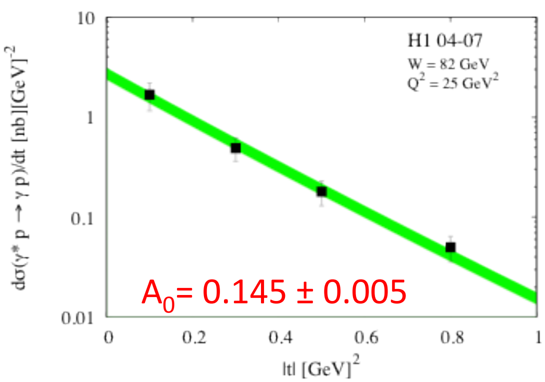


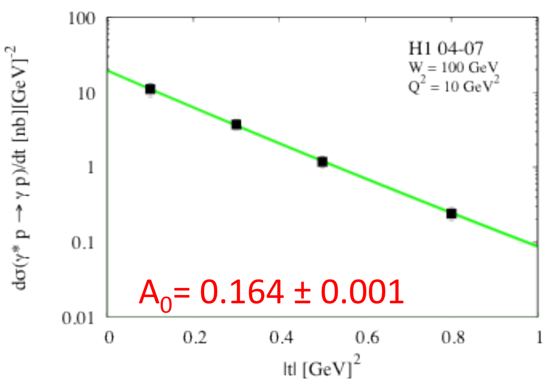


DVCS

b_2= 0.55 fixed

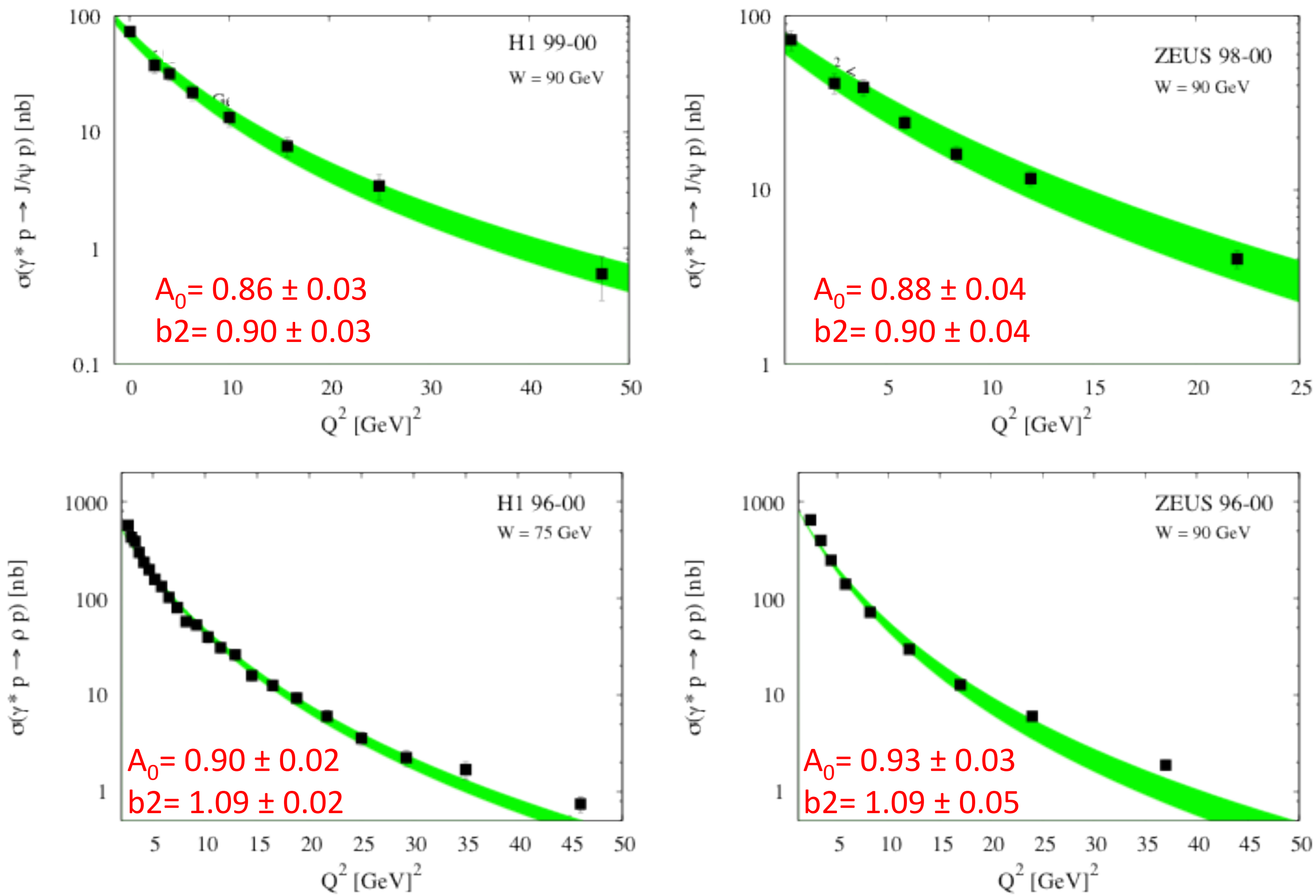
$$\frac{d\sigma(s,t,\tilde{Q}^2)}{dt} = \frac{\pi}{W^4}\left|-A_0 e^{b_1\alpha(t)} e^{b_2\beta(z)} \left(-is/s_0\right)^{\alpha(t)}\right|^2$$





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

Fit to HERA: xsec vs Q^2



J/Ψ

$\langle b_2 \rangle$= 0.90 ± 0.03

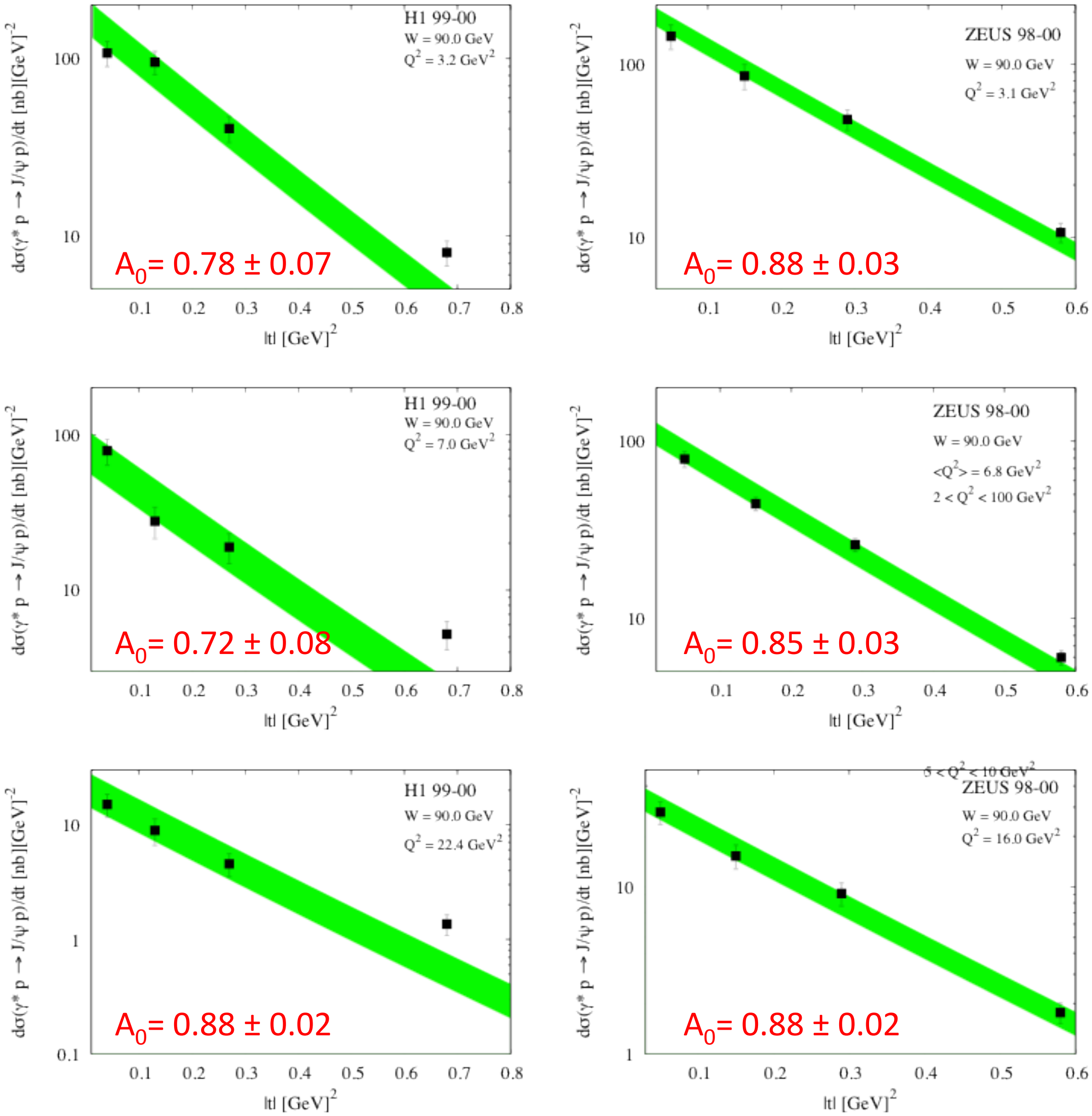
A_0 ~ 0.9

ρ^0

$\langle b_2 \rangle$= 1.09 ± 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: $d\sigma/d|t|$ - J/Ψ

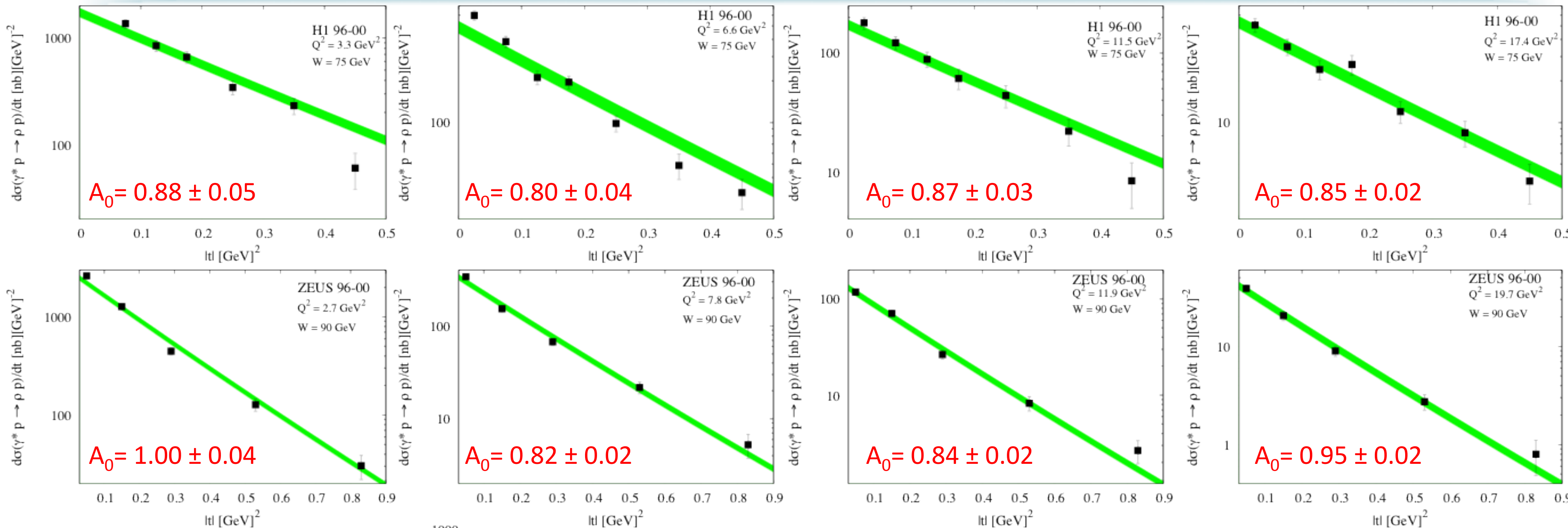


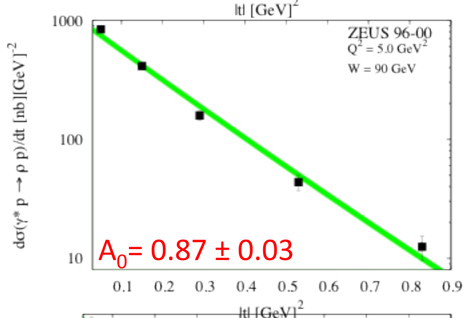
J/Ψ

b_2= 0.90 fixed

- ✓ Good description of $d\sigma_{DVCS}/d|t|$, $|t|<0.6$ GeV^2
- ✓ ZEUS data described over the whole range

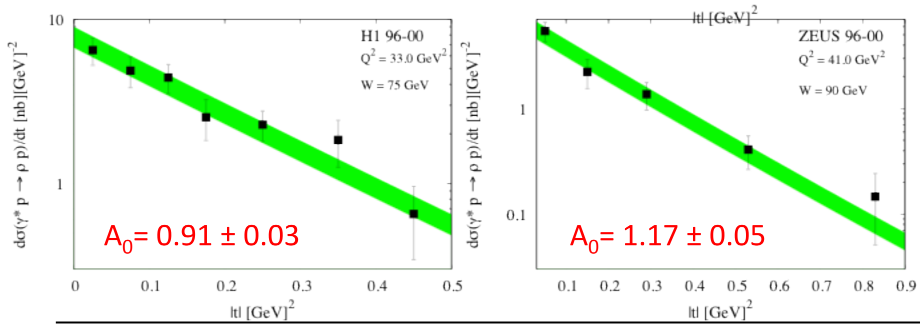
Fit to HERA: dσ/d|t| - ρ^0





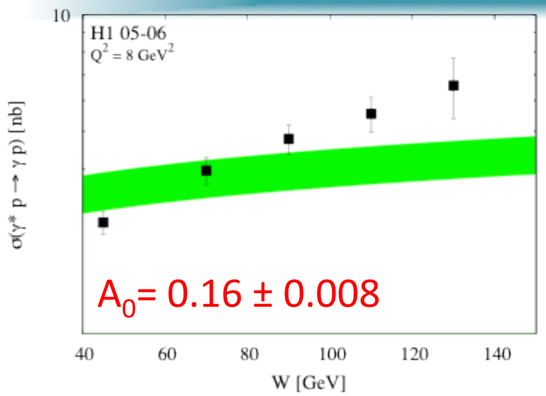
ρ^0

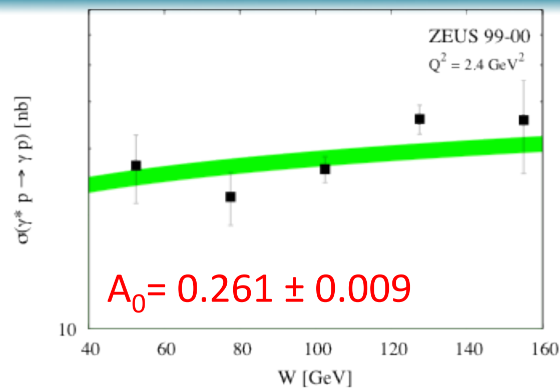
b_2= 1.09 fixed



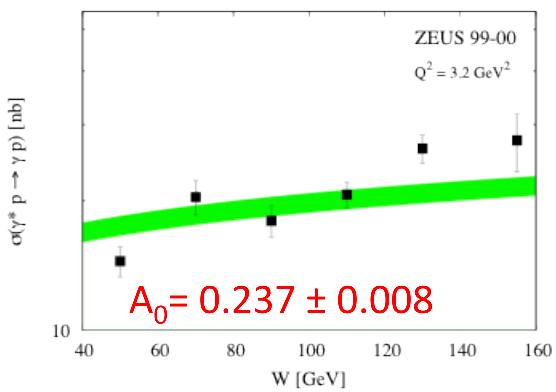
- ✓ **Good description of ZEUS data (W=90 GeV), over the whole Q^2 range**
- ✓ **H1 data (W=75 GeV) generally well described at large <Q^2> or at least for moderate |t|**

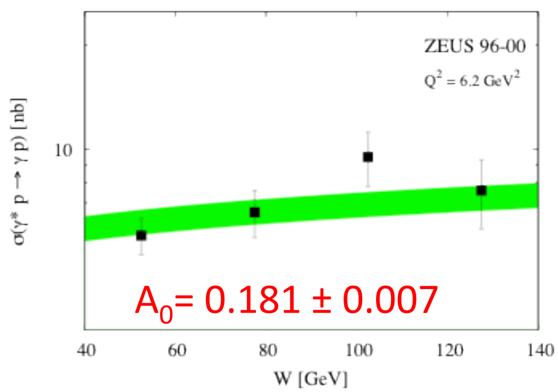
Fit to HERA: xsec vs W

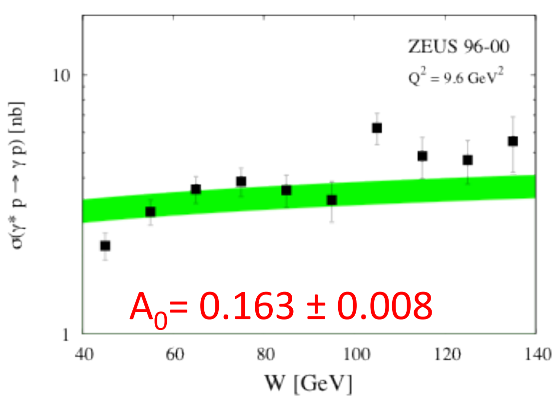


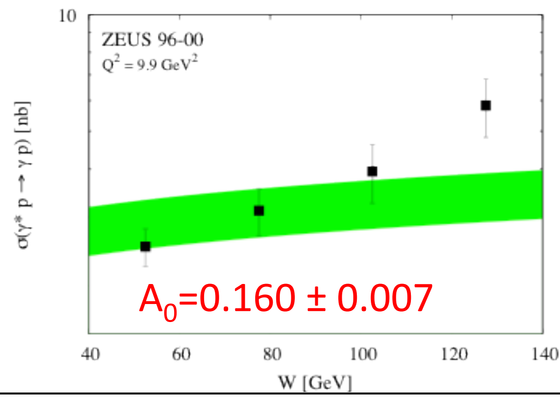


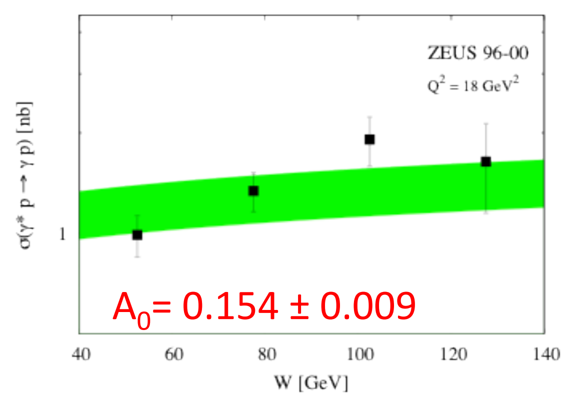
DVCS



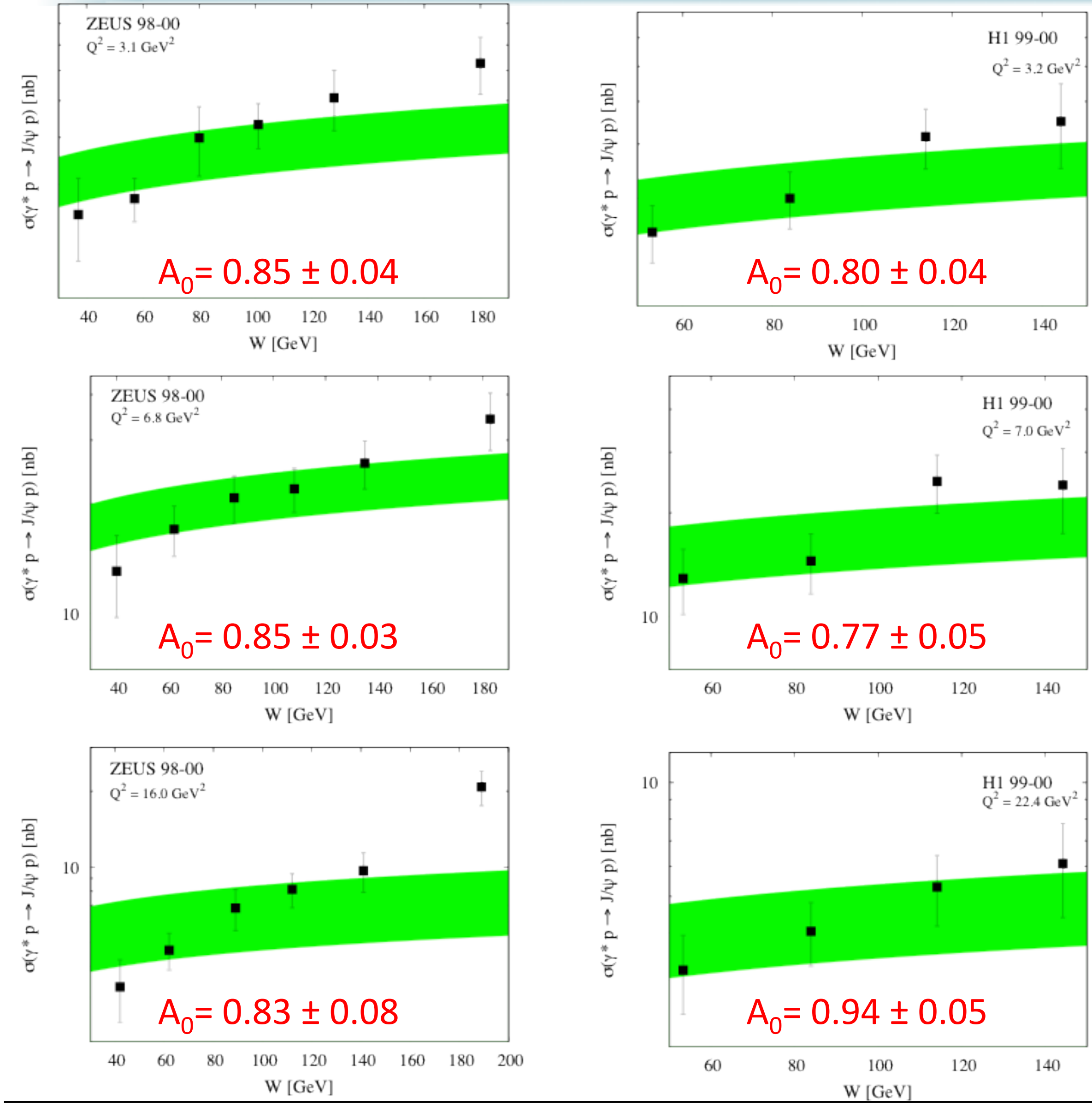








Fit to HERA: xsec vs W

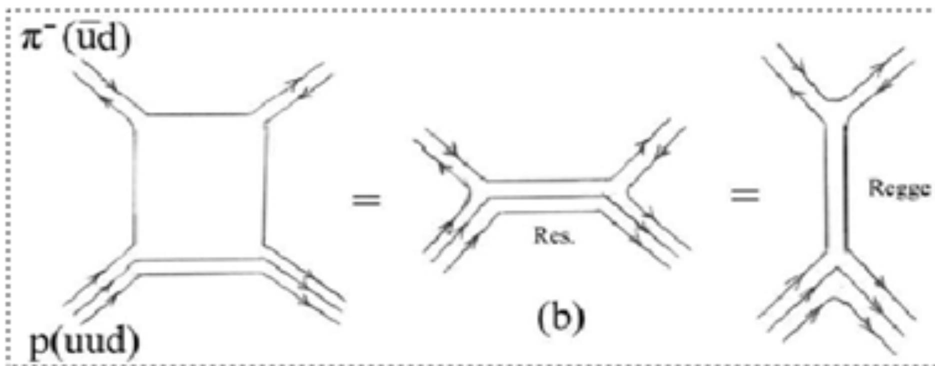


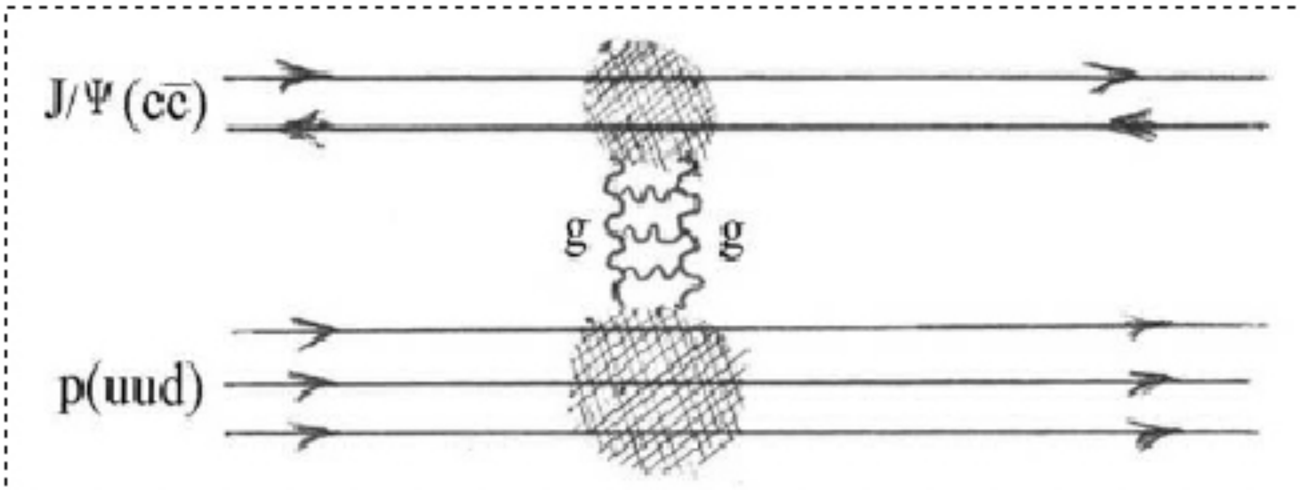
J/Ψ

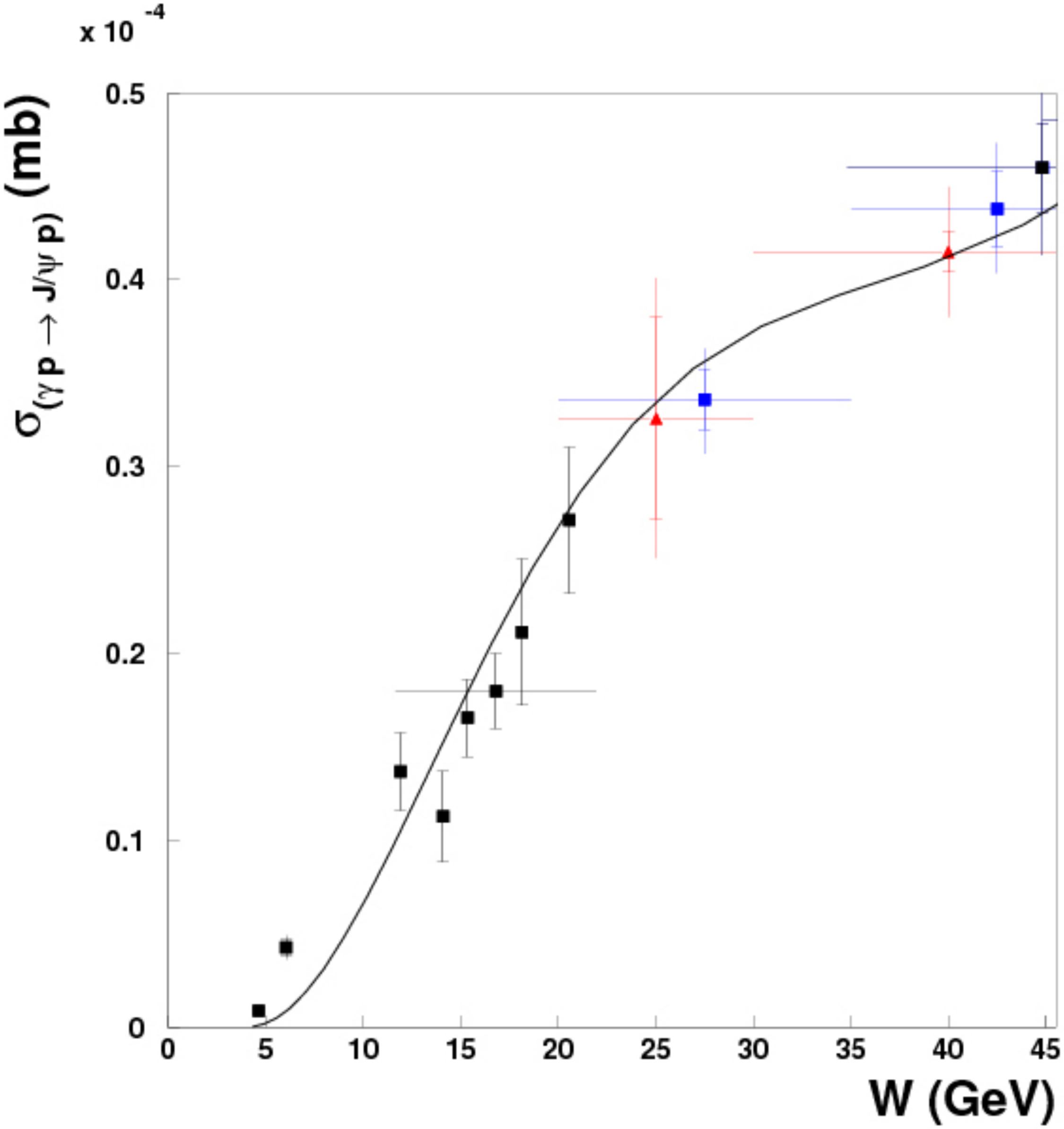
N.B.: J/Psi photoproduction is a "golden plate" reaction to test diffraction. What is low-energy diffraction? =Background!

See:

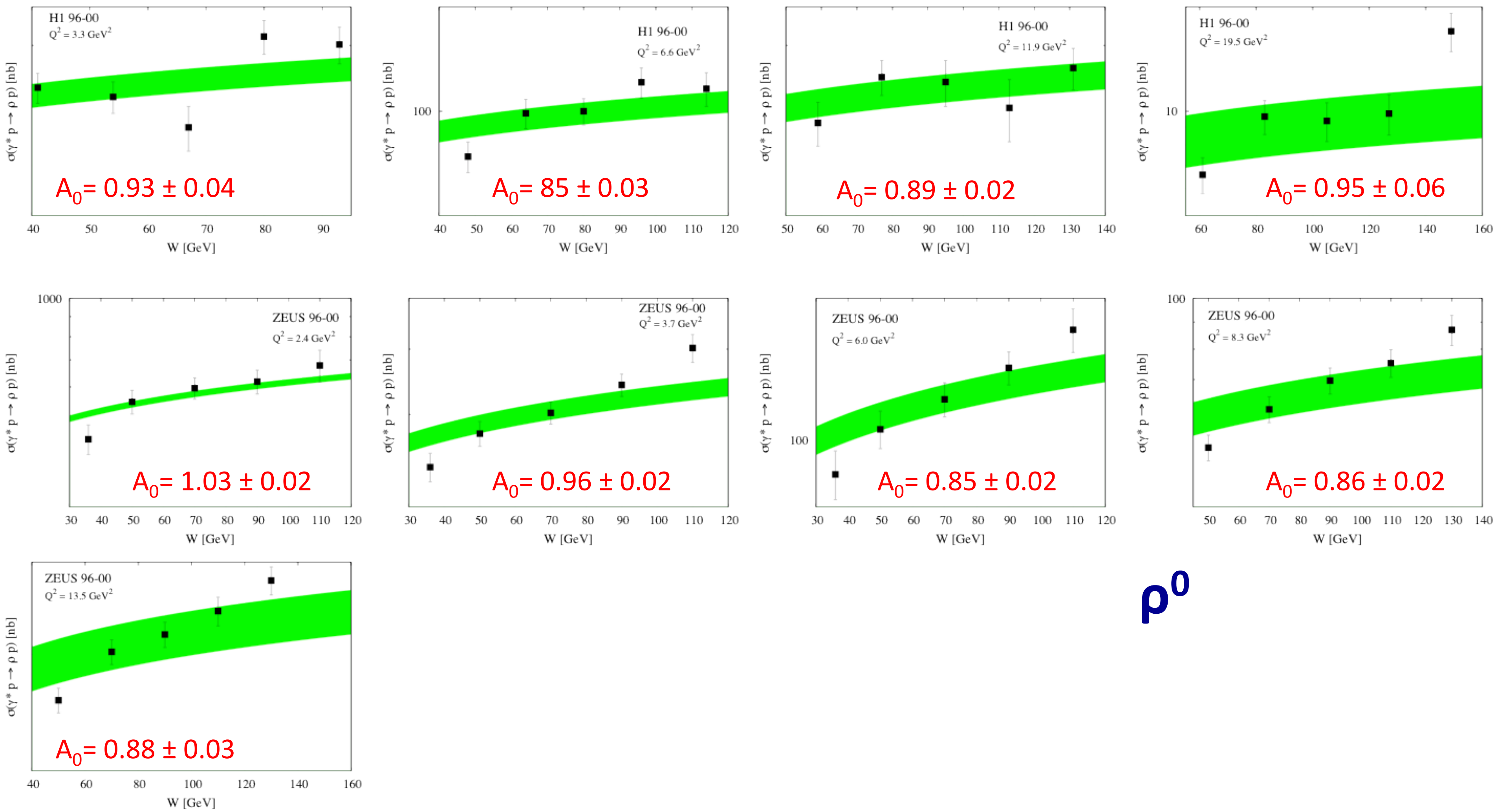
R. Fiore et al. *Exclusive J/Psi electroproduction in a dual model* , Phys.Rev.D80:116001, 2009, arXiv:0911.2094


π^- ($\bar{u}$d)
p(uud)
=
Res.
(b)
=
Regge


J/Ψ (cc̄)
g
g
p(uud)


x 10^-4
σ(γ p → J/ψ p) (mb)
0.5
0.4
0.3
0.2
0.1
0
0 5 10 15 20 25 30 35 40 45
W (GeV)

Fit to HERA: xsec vs W – ρ^0



ρ^0

$\sigma_{(\gamma^* \ p \ -> \ \gamma \ p)}(Q^2)$

Coll.	Years	W [GeV]	$\lvert A_0 \rvert$ [nb]$^{1/2}$	b_2	$\tilde{\chi}^2$
H1	04-07	82	0.164127 ± 0.01187	0.641492 ± 0.05536	1.13815
H1	96-00	82	0.161587 ± 0.01114	0.655892 ± 0.06876	0.684361
ZEUS (e^- p)	96-00	89	0.177467 ± 0.01255	0.703354 ± 0.09093	0.569761
ZEUS (e^+ p)	96-00	89	0.170452 ± 0.004545	0.595772 ± 0.02587	0.36618
ZEUS	99-00	104	0.208865 ± 0.009548	0.769323 ± 0.07719	3.33664

$< b_2 >$
$0.6895877975 \pm 0.0207579082$

Discussion

Considerations:

- **We presented a simple model with**
  - **One a single 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
$<b_2>= 0.55 \pm 0.02$	$<b_2>= 0.90 \pm 0.03$	$<b_2>= 1.09 \pm 0.02$(varies vs Q^2)
$A_0 \sim 0.17$	$A_0 \sim 0.9$	$A_0 \sim 0.9$

Results:

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

High Q^2 shold include QCD evolution and/or unitarit (see: N. Armesto, A. B. Kaidalov, C. A. Salgado, and K. Tywoniuk, “A unitarized model of inclusive and diffractive DIS with Q2-evolution”, arXiv:1001.3021;

- ✓ **the two (or multiple) Pomeron components approach** (Donnachie-Landshoff, hep-ph/0803.0686); N. Armestro et al. arXiv:1001.3021);
- ✓ **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:

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

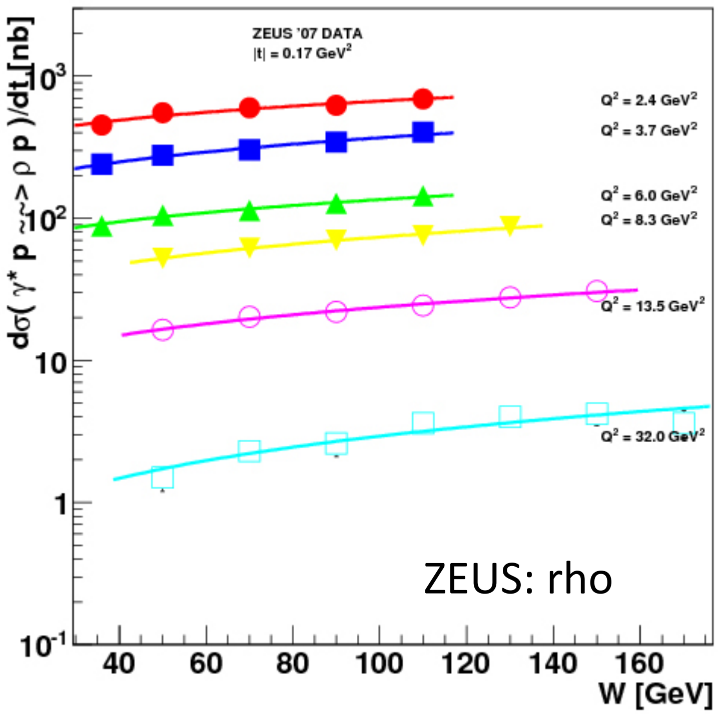
Hard Pomeron:

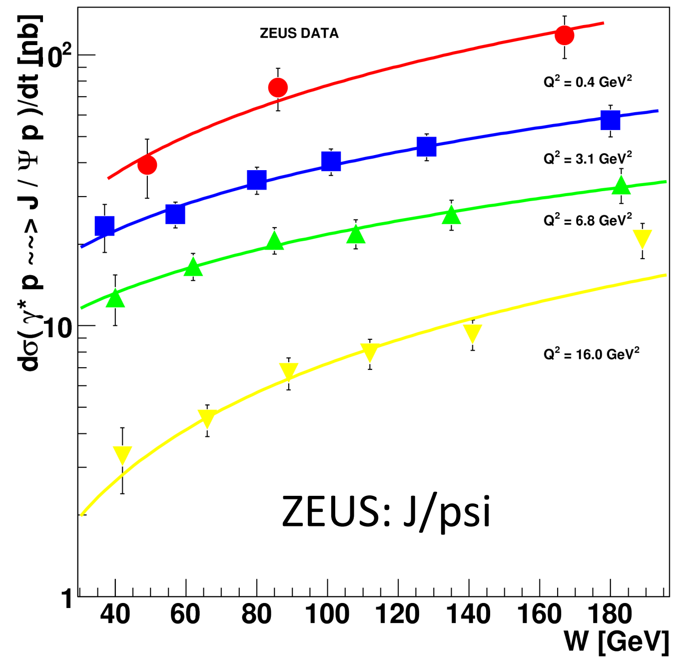
$$\alpha_{hard}(t) = 1.30 + 0.02t$$

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**

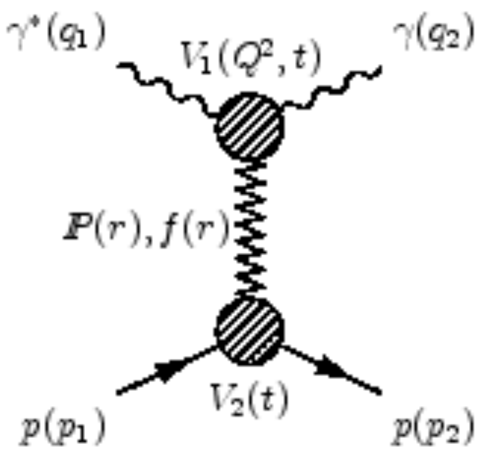
For a complete review of results see:

- 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

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

c and *d* being free parameters

In a first approach – to be fine-tuned

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

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

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

Summary and outlook

1 A Regge-type model using a logarithmic trajectory and a few free parameters describes HERA data on DVCS and VMP

2. The real and imaginary parts of the DVCS (and VM) amplitude, essential ingredients for the GPDs, are explicitly contained in the model;

3. There is only one Pomeron in nature (both at the LHC and HERA), but it may have more components, their weithts changing with the virtuality. The trajectory is non-linear;

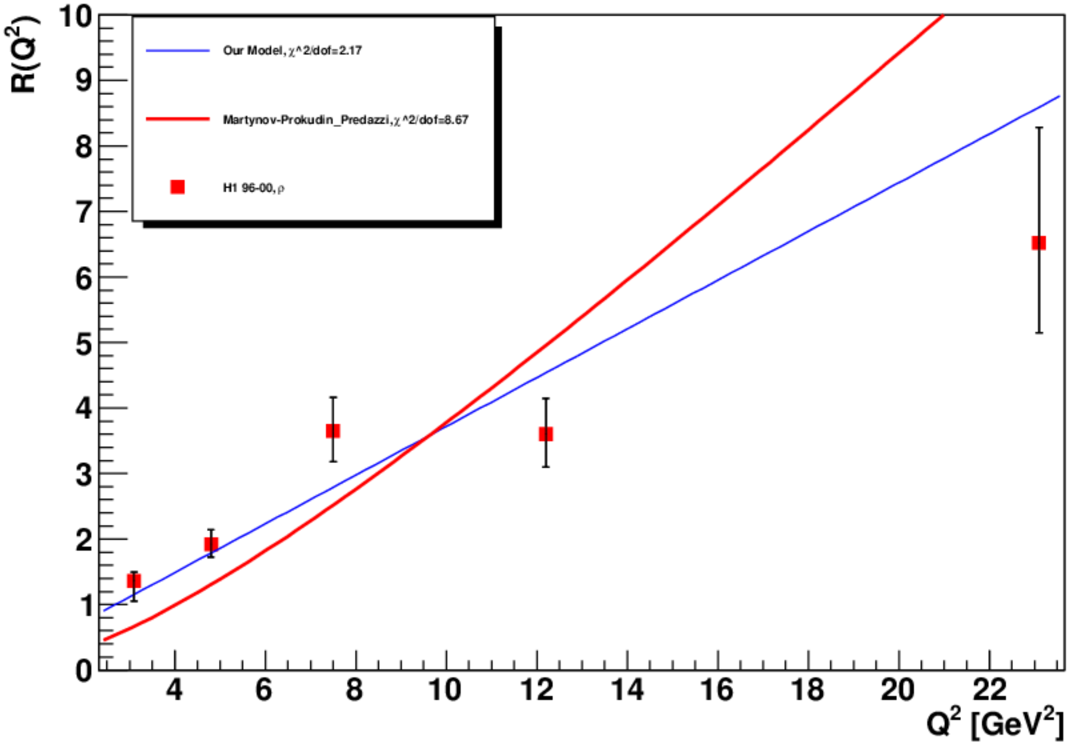
4. Is the dip-bump structure in the differential cross section a universal (pp, ep, DD,…) feature of high-enrgy diffraction?

5. The quality of the hadronic data (e.g. LHC) is superior to those of DVCS or VMD, however ep is more informative concenring the nucleon structure (GPD); dip in J/Psi electroproduction,…?

6. GPD can be an input (to calculate DVCS etc) or output (deconvolution);

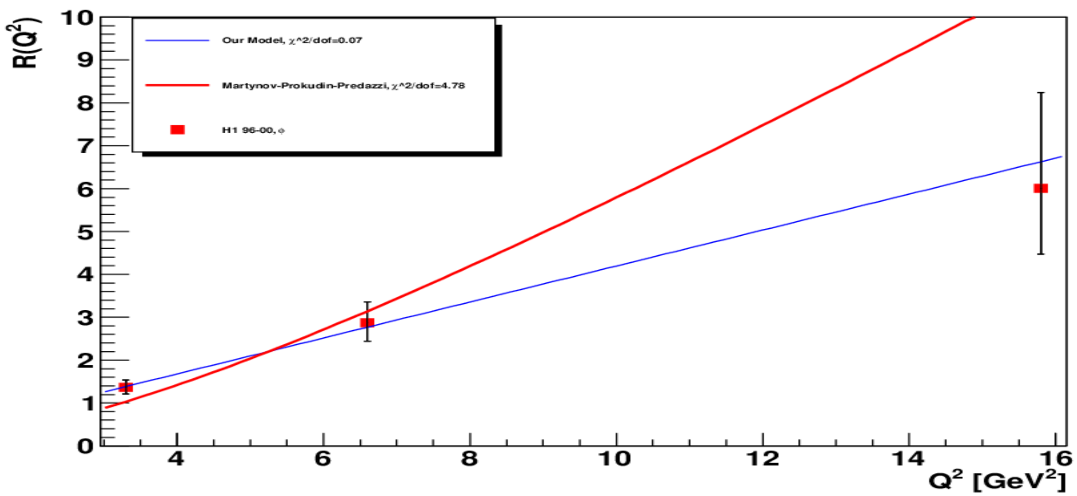
7. Matching(?) Regge behaviour with DGLAP evolution; L. Csernai *et al.:* From Regge Behavior to DGLAP Evolution, Eur.Phys.J. C24 (2002) 205-211, hep-ph/0112265;

8. The spin structure of DVCS and VMP is poorly known, more, both theoretical and experimental studies needed.


R(Q^2)
10
9
8
7
6
5
4
3
2
1
0
4
6
8
10
12
14
16
18
20
22
Q^2 [GeV^2]
Our Model, χ^2/dof=2.17
Martynov-Prokudin_Predazzi, χ^2/dof=8.67
H1 96-00, ρ

R(ϒ→ρ)

R(ϒ→ϕ)

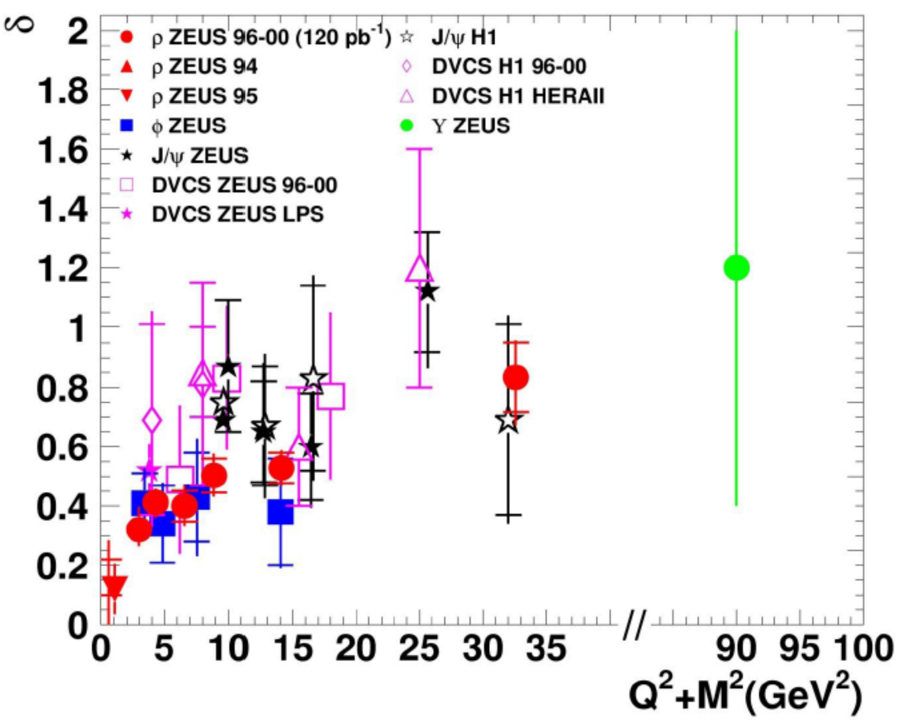


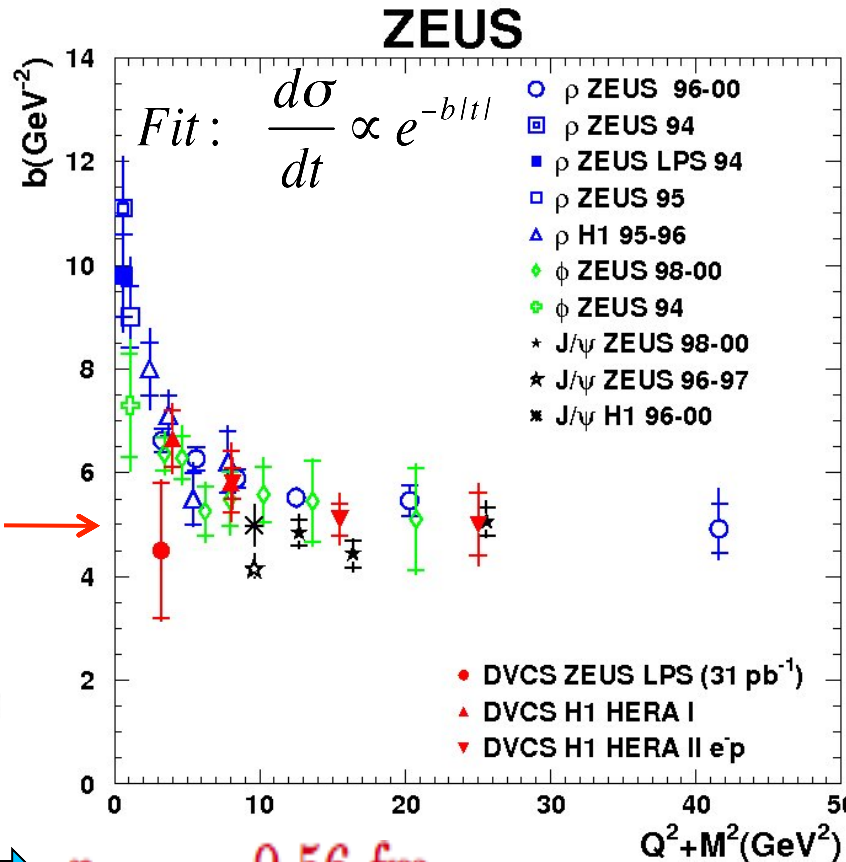
R(Q^2)
10
9
8
7
6
5
4
3
2
1
0
4
6
8
10
12
14
16
Q^2 [GeV^2]
Our Model, χ^2/dof=0.07
Martynov-Prokudin-Predazzi, χ^2/dof=4.78
H1 96-00, ϕ

VMP and DVCS @ HERA

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

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

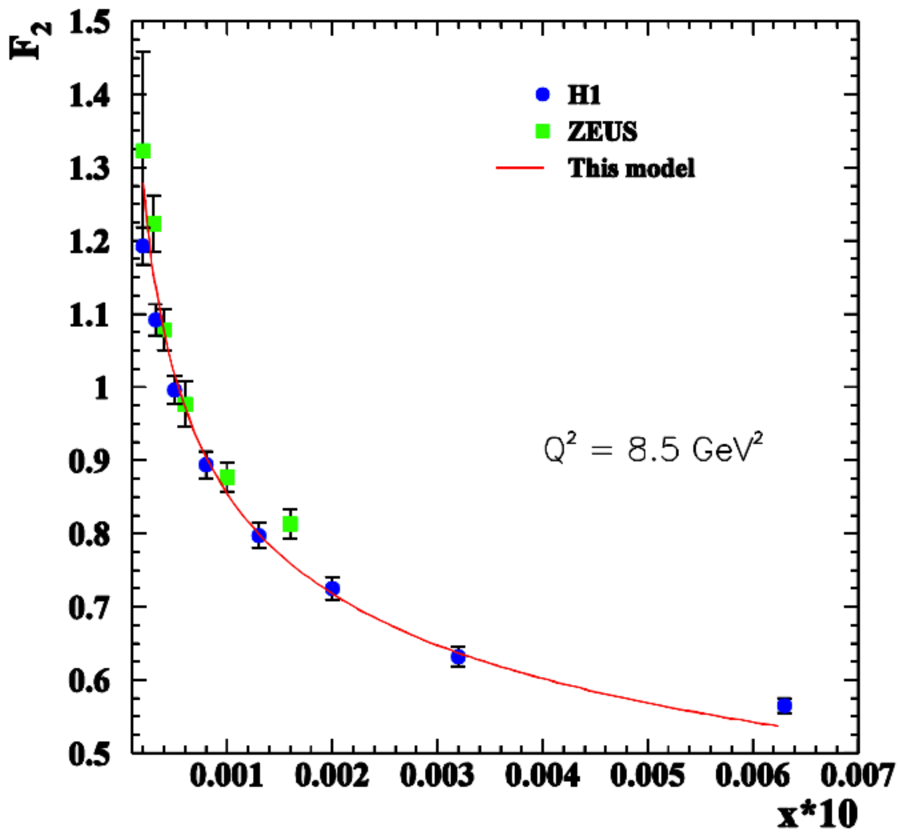




Size of the gluons: $\langle r^2 \rangle = 2 \cdot b \cdot (\hbar c)^2$ ➡ $r_{glue} = 0.56$ fm

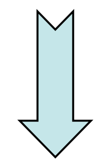
F_2 structure function

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*

Cam on!