VM and real photon production in a Regge-pole model

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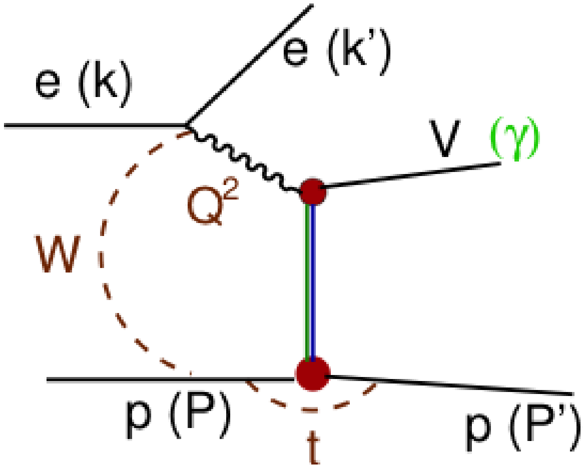


Low-x

Santiago de Compostela, ***June 2 – 7, 2011***

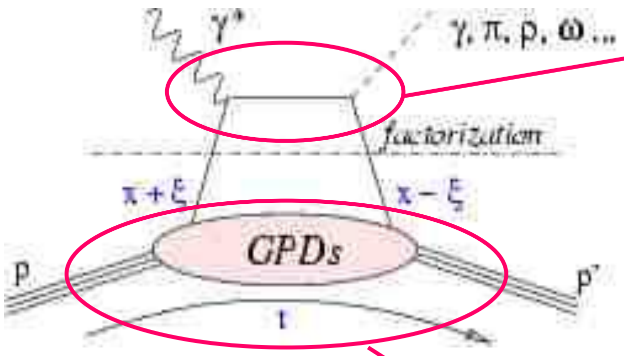
Plan:

- Experimantal situation in DVCS and VMP;

  ep vs hh data; the Pomeron in ep and hh;
- Theory: QCD- and Regge-factorization; from GPD to

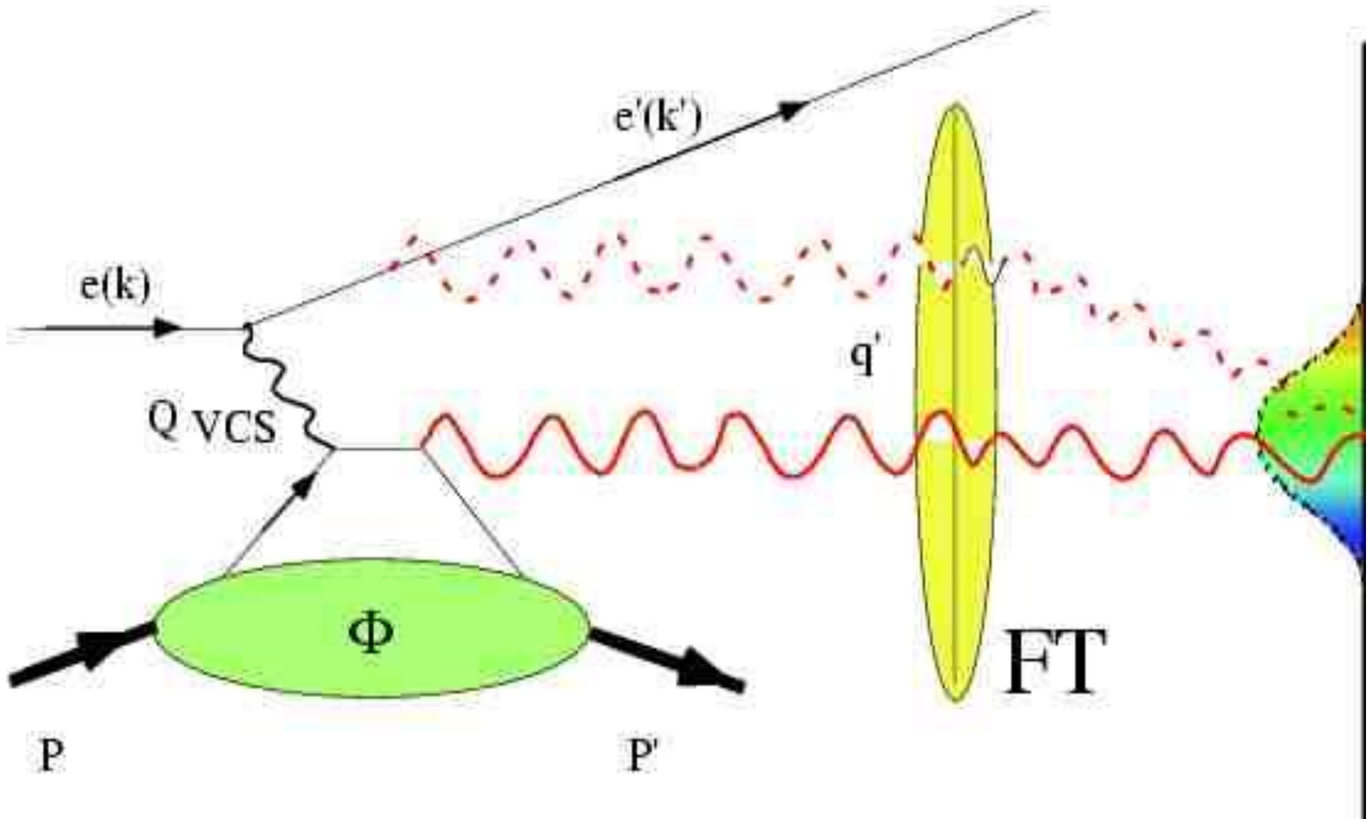
  realistic processes and vv.
- DVCS & VMP; the "radius" of the real photon?
- Regge model: DVCS and VMP
- A geometrical approach to the Regge theory
- Summary

QCD-factorized form of a DVCS scatterigg amplitude



pQCD

non-perturbative region



e'(k')
e(k)
q'
Q VCS
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.

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

The basic object of the theory

$$A(s,t,Q^2)$$

$$A(s,t,Q^2=m^2)$$ (on mass shell)

$$\Im m A(s,t=0,Q^2) \sim F_2$$ 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

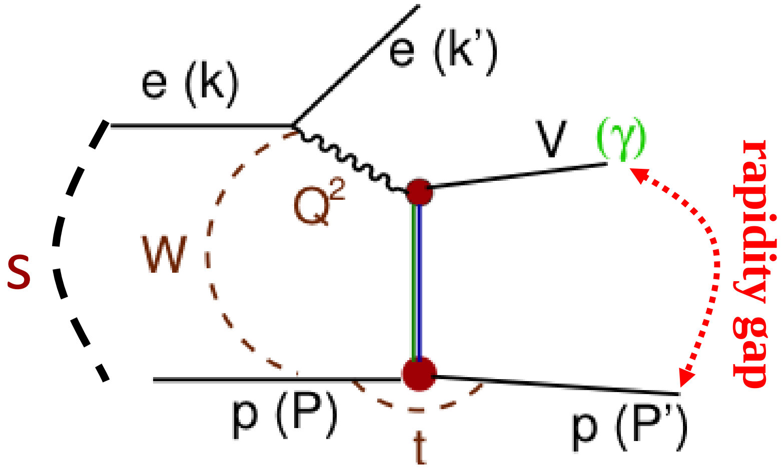
$$\Im m A(\gamma^* p \to \gamma^* p)\Big|_{t=0} \sim F_2(x_B,Q^2) = x_B q(x_B,Q^2)$$

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

?

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

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:

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

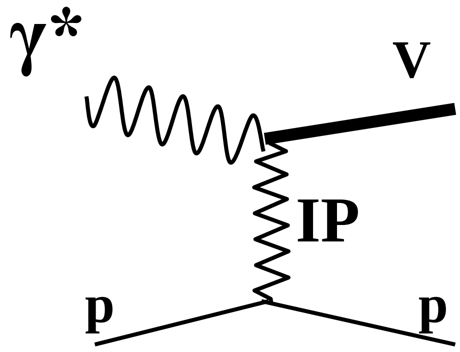
square 4-momentum at the *p* vertex:

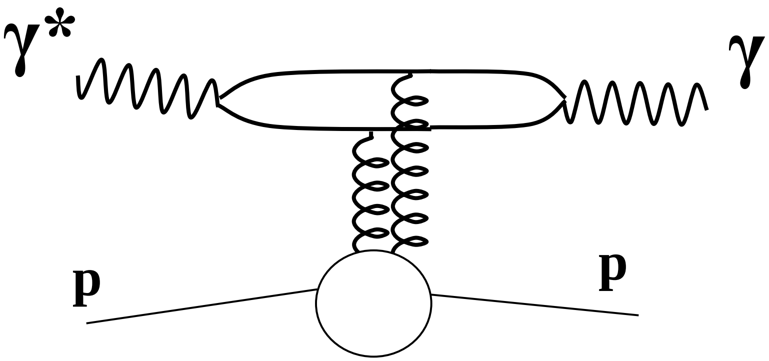
$$t = (p' - p)^2$$

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

Deeply Virtual Compton Scattering

VM (ρ, ω, φ, J/ψ, Y) DVCS (γ)

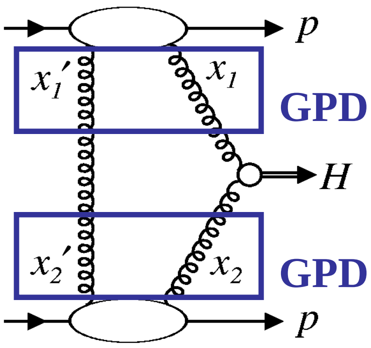




Scale: $Q^2 + M^2$ ⟷ Q^2

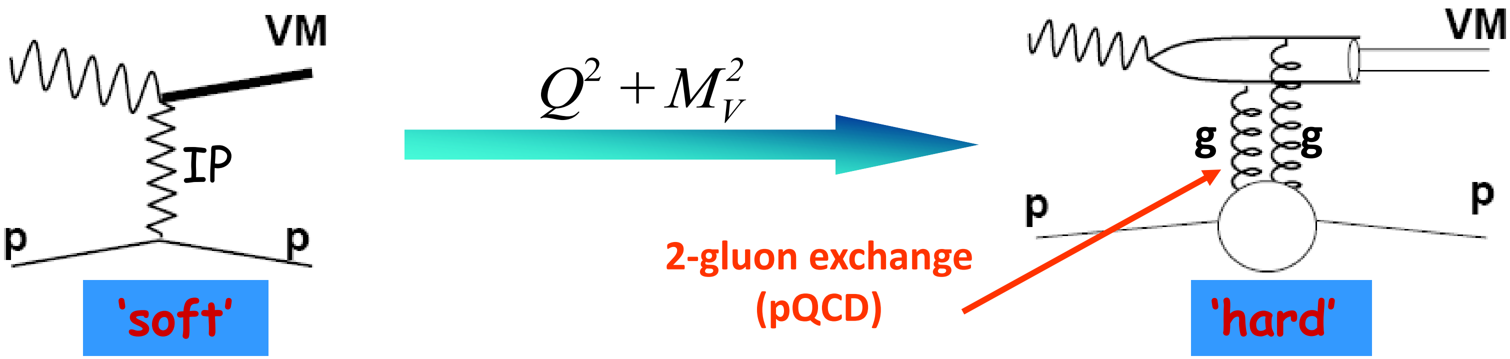
DVCS properties:

- **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

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

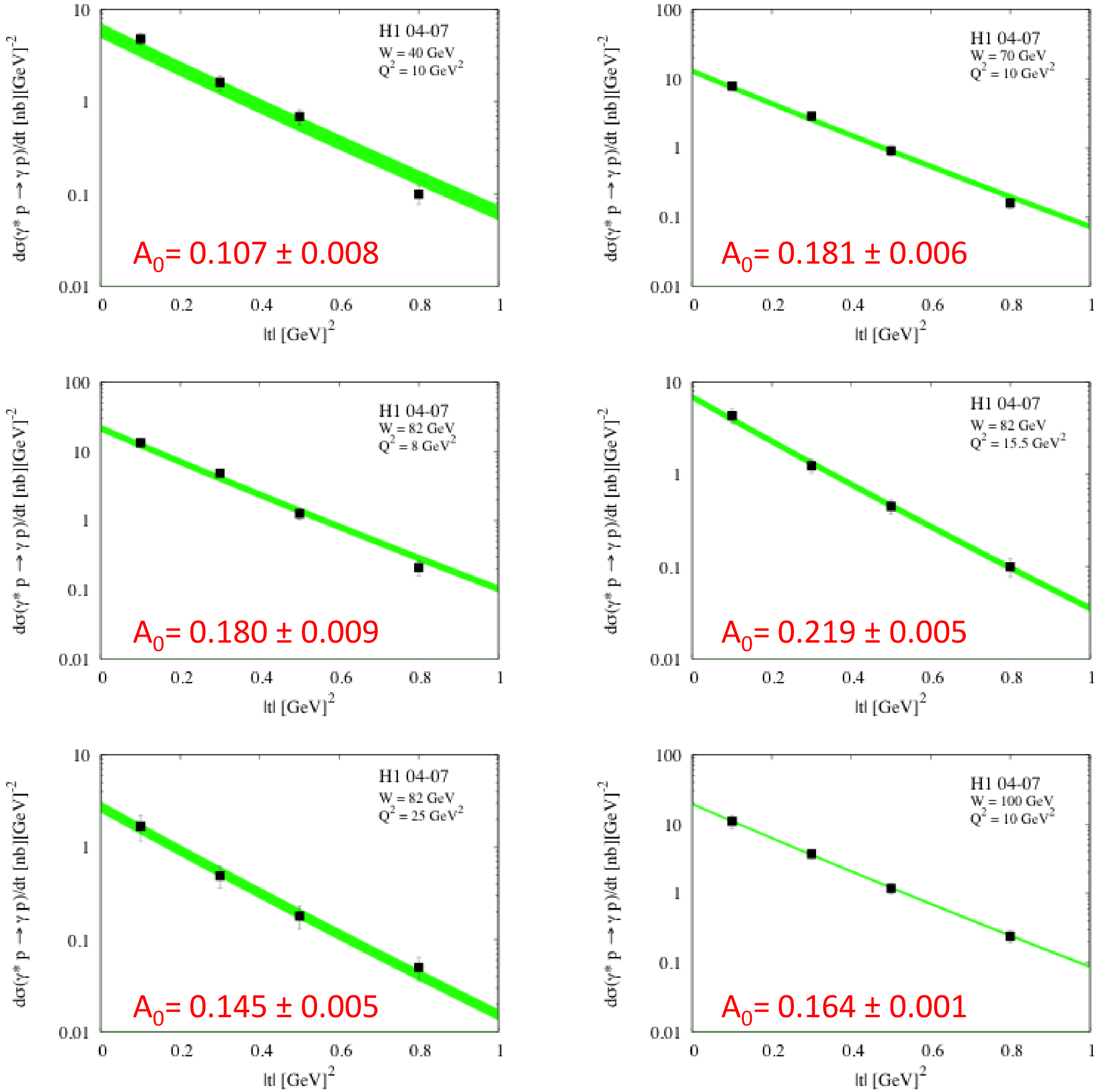
$$\sigma(W) \propto W^{\delta}$$

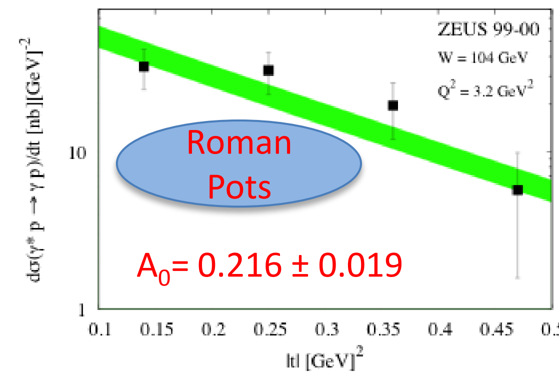
➡ δ increases from soft (~0.2, "soft Pomeron") to hard (~0.8, "hard Pomeron")

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

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

Fit to HERA: dσ/d|t| - DVCS



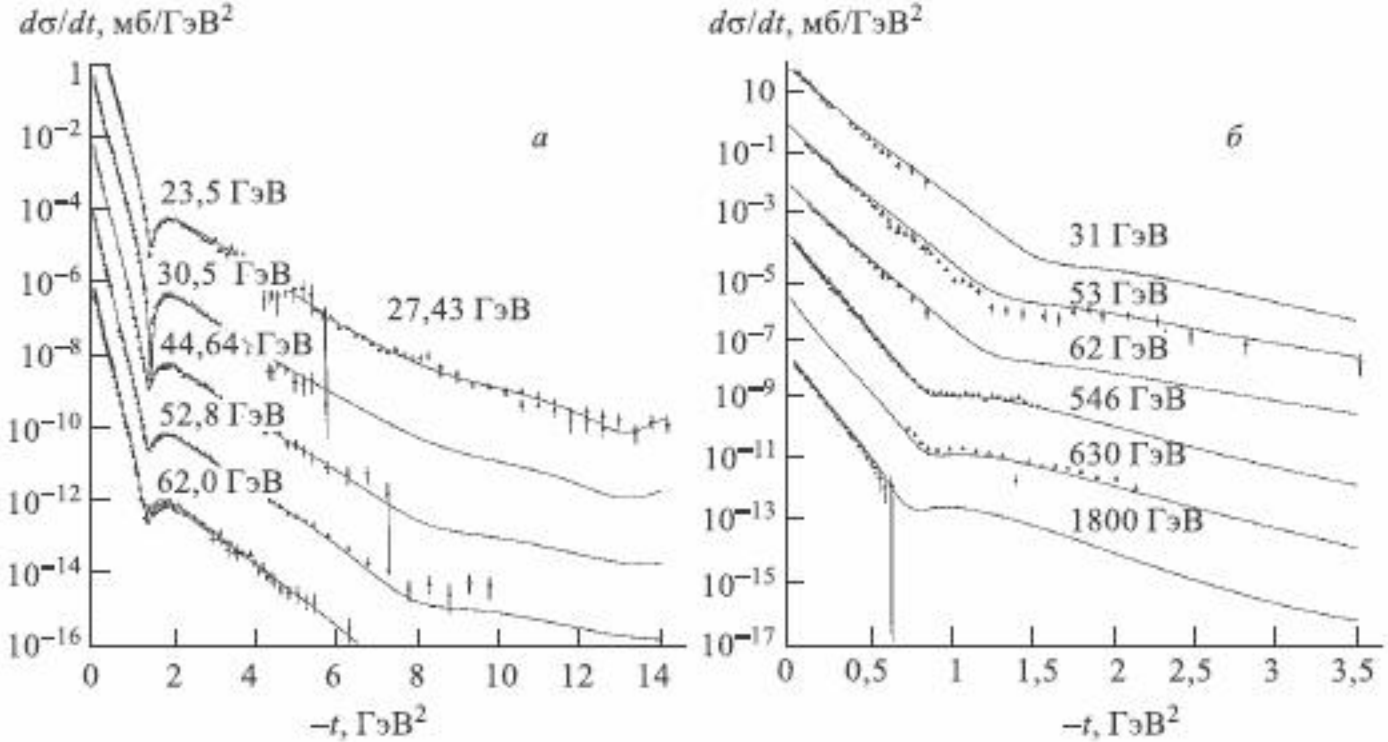


DVCS

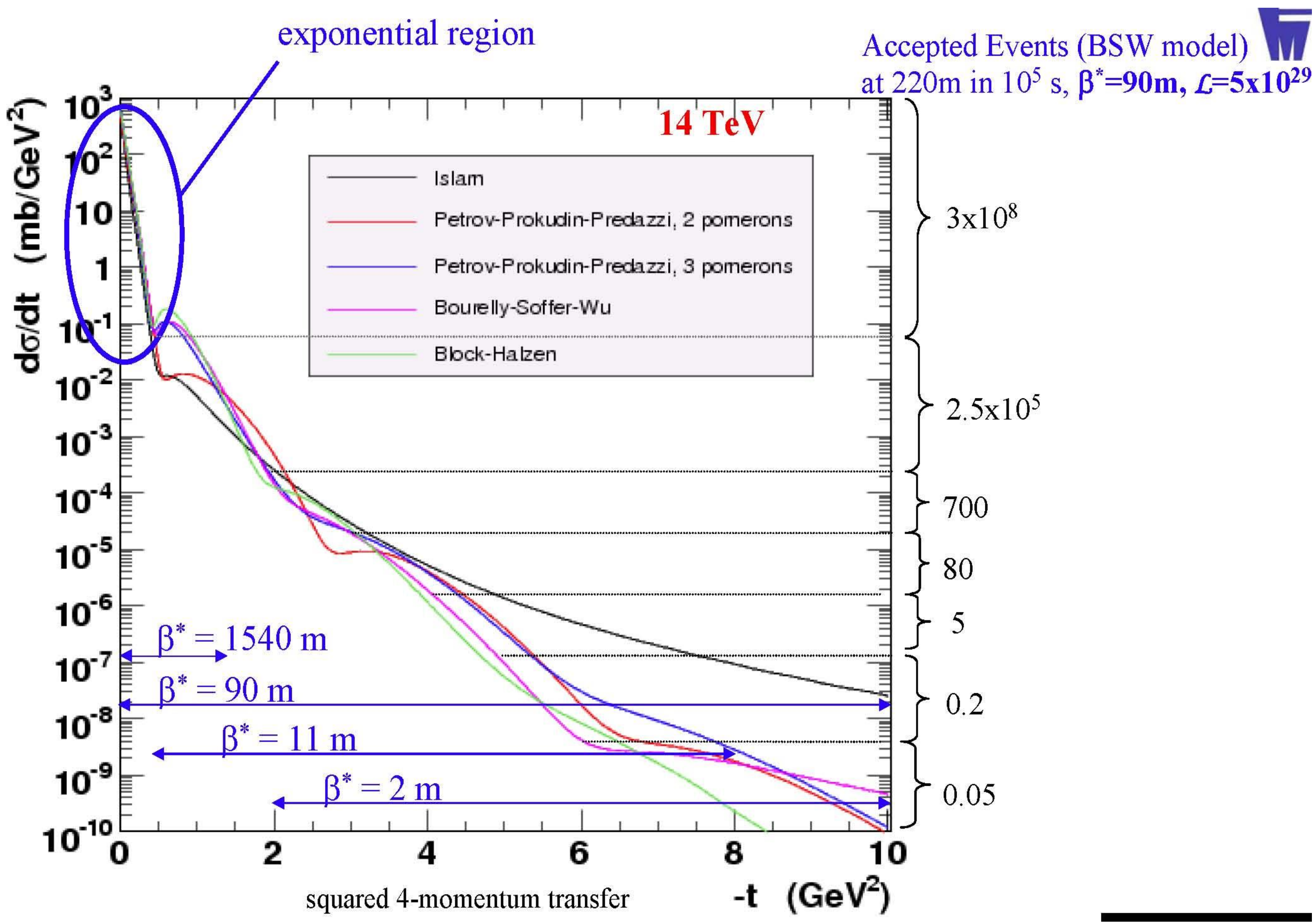
b_2= 0.55 fixed

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

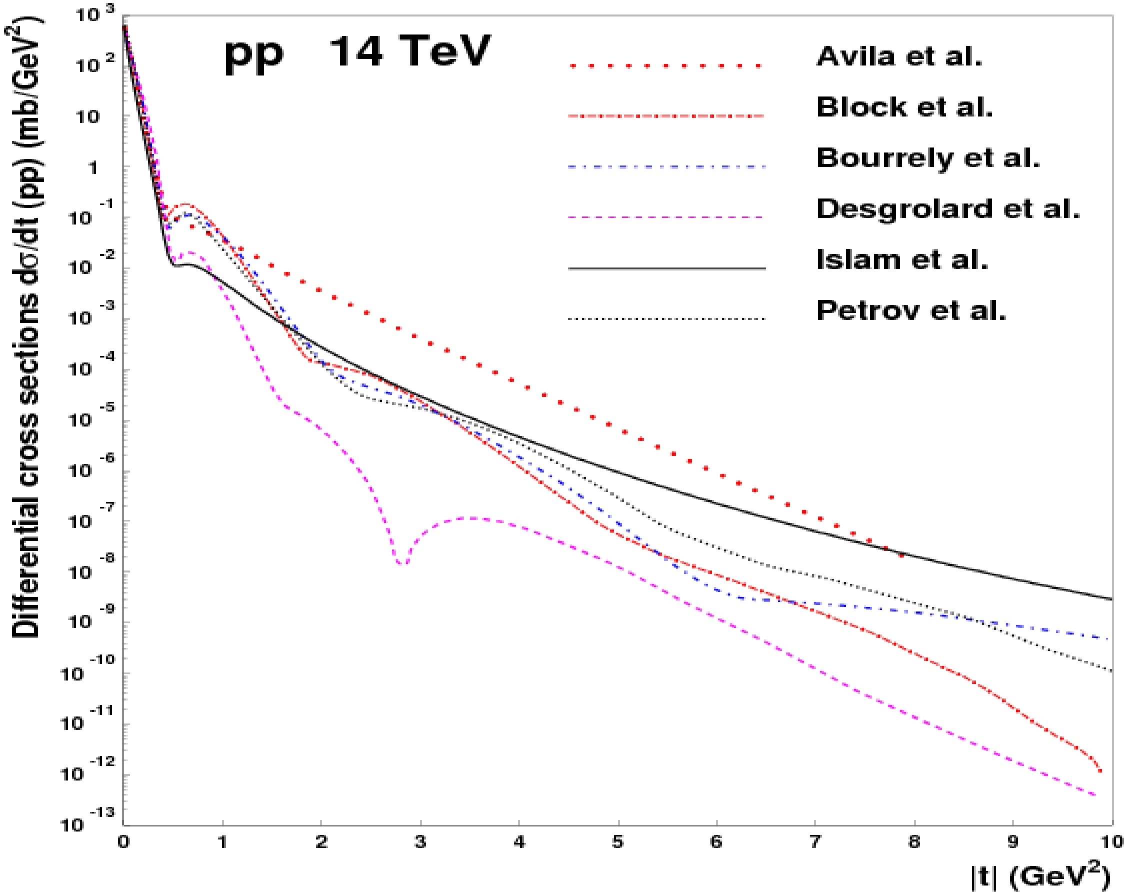
Good description of $d\sigma_{DVCS}/d|t|$



dσ/dt, мб/ГэВ²
a
23,5 ГэВ
30,5 ГэВ
27,43 ГэВ
44,64 ГэВ
52,8 ГэВ
62,0 ГэВ
−t, ГэВ²
dσ/dt, мб/ГэВ²
б
31 ГэВ
53 ГэВ
62 ГэВ
546 ГэВ
630 ГэВ
1800 ГэВ
−t, ГэВ²



exponential region
Accepted Events (BSW model)
at 220m in 10^5 s, β*=90m, L=5x10^29
14 TeV
Islam
Petrov-Prokudin-Predazzi, 2 pomerons
Petrov-Prokudin-Predazzi, 3 pomerons
Bourelly-Soffer-Wu
Block-Halzen
dσ/dt (mb/GeV^2)
3x10^8
2.5x10^5
700
80
5
0.2
0.05
β* = 1540 m
β* = 90 m
β* = 11 m
β* = 2 m
squared 4-momentum transfer
-t (GeV^2)


pp 14 TeV
Avila et al.
Block et al.
Bourrely et al.
Desgrolard et al.
Islam et al.
Petrov et al.
Differential cross sections dσ/dt (pp) (mb/GeV²)
|t| (GeV²)

$$\sigma_t(s) = \frac{4\pi}{s} Im A(s,t=0); \quad \frac{d\sigma}{dt} = \frac{\pi}{s^2}|A(s,t)|^2.$$

$$\sigma_{el} = \int_{t_{min\approx -s/2 \approx \infty}}^{t_{thr.\approx 0}} \frac{d\sigma}{dt}; \quad \sigma_{in} = \sigma_t - \sigma_{el}; \quad B(s,t) = \frac{d}{dt} \ln\left(\frac{d\sigma}{dt}\right);$$

$$A_{pp}^{p\bar{p}}(s,t) = P(s,t) \pm O(s,t) + f(s,t) \pm \omega(s,t) \rightarrow_{LHC} \approx P(s,t) \pm O(s,t),$$

where P, O, f. ω are the Pomeron, odderon and non-leading Reggeon contributions.

C. Merino, C. Pajares, M.M. Ryzhinskiy, Yu.M. Shabelski,
Pomeron and Odderon Contributions at LHC Energies; arXiv:1007.3206;

α(0)\C	+	-
1	P	O
1/2	f	ω

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

Linear Pomeron trajectory

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

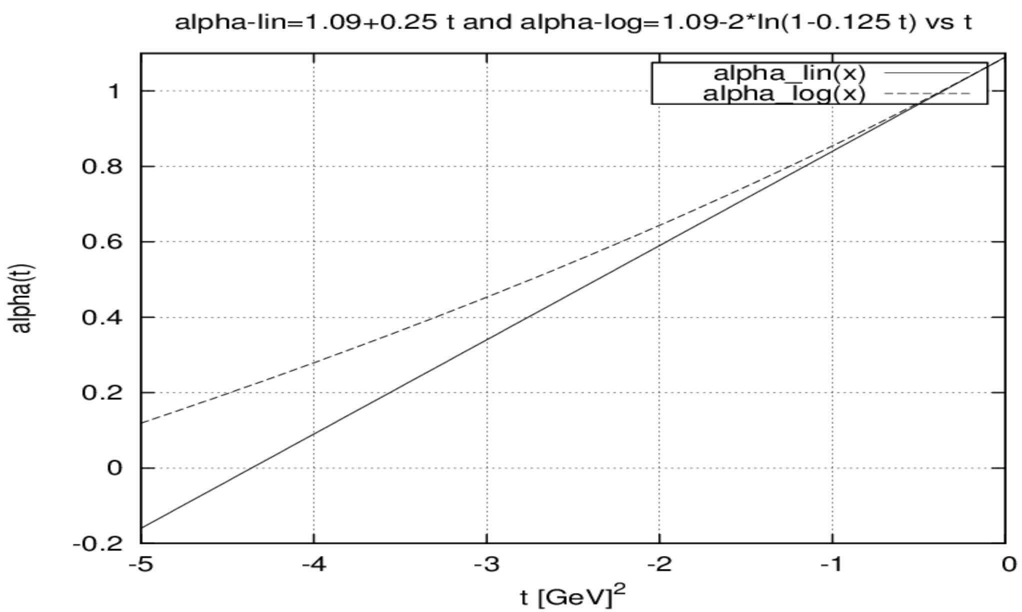
α(0) and α' are foundamental parameters to represent the basic features of strong interactions

Soft Pomeron values
α(0) ≈ 1.09
α' ≈ 0.25

α(0): determines the energy dependence of the diff. Cross section

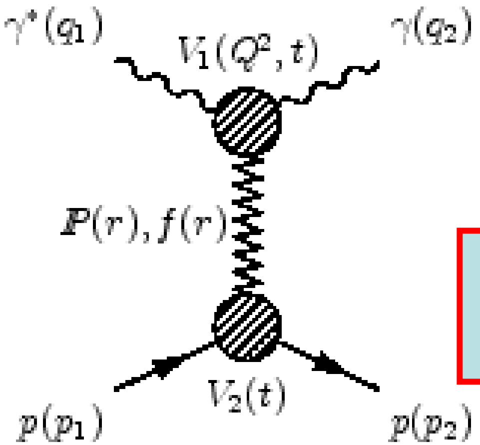
$$\frac{d\sigma}{dt} \propto \exp(b_0 t) \cdot W^{4\alpha(t)-4} = W^{4\alpha(0)-4} \cdot \exp(bt); \qquad b = b_0 + 4\alpha' \ln(W)$$

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


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

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: $$\beta(z) = \beta(0) - \beta_1 \ln(1 - \beta_2 z)$$

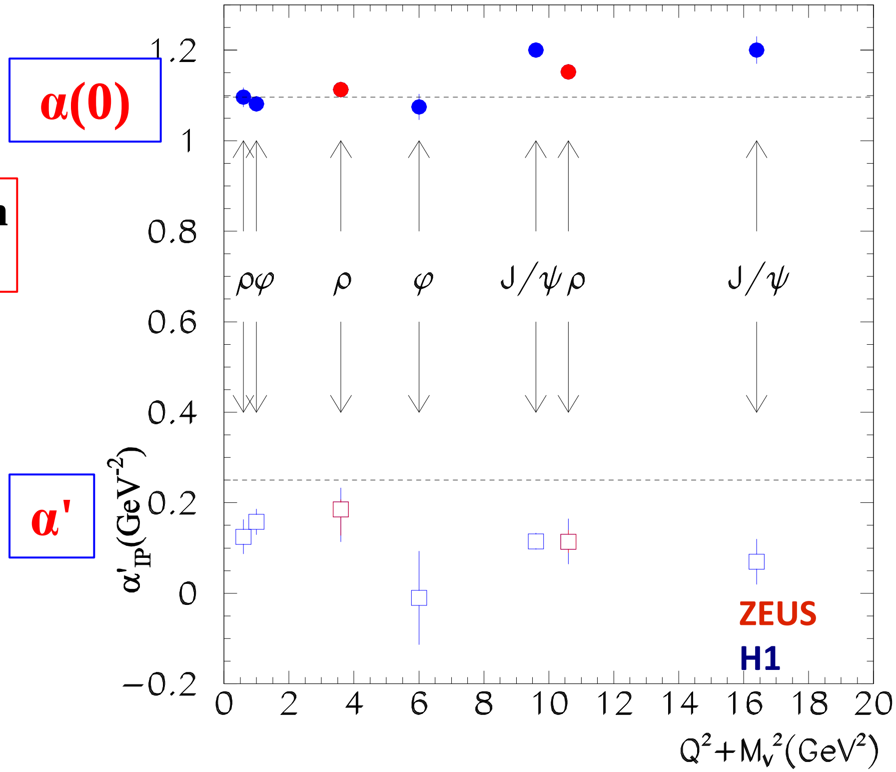
indicating with: $L = \ln(-is/s_0)$ the DVCS amplitude can be written as:

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

Pomeron trajectory in ep collisions

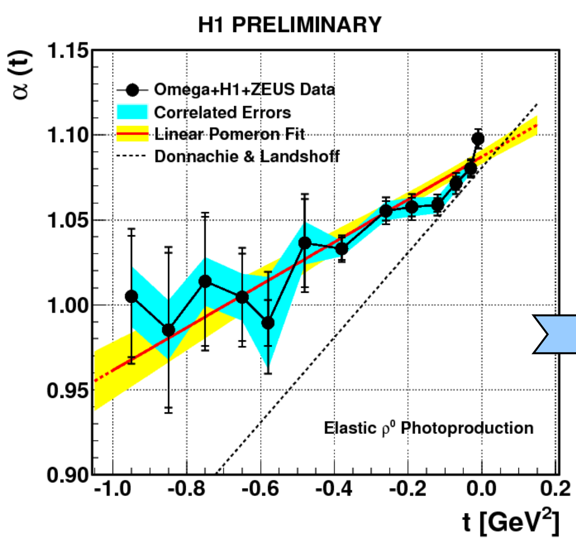
The “effectie” trajectory varies with the scale

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

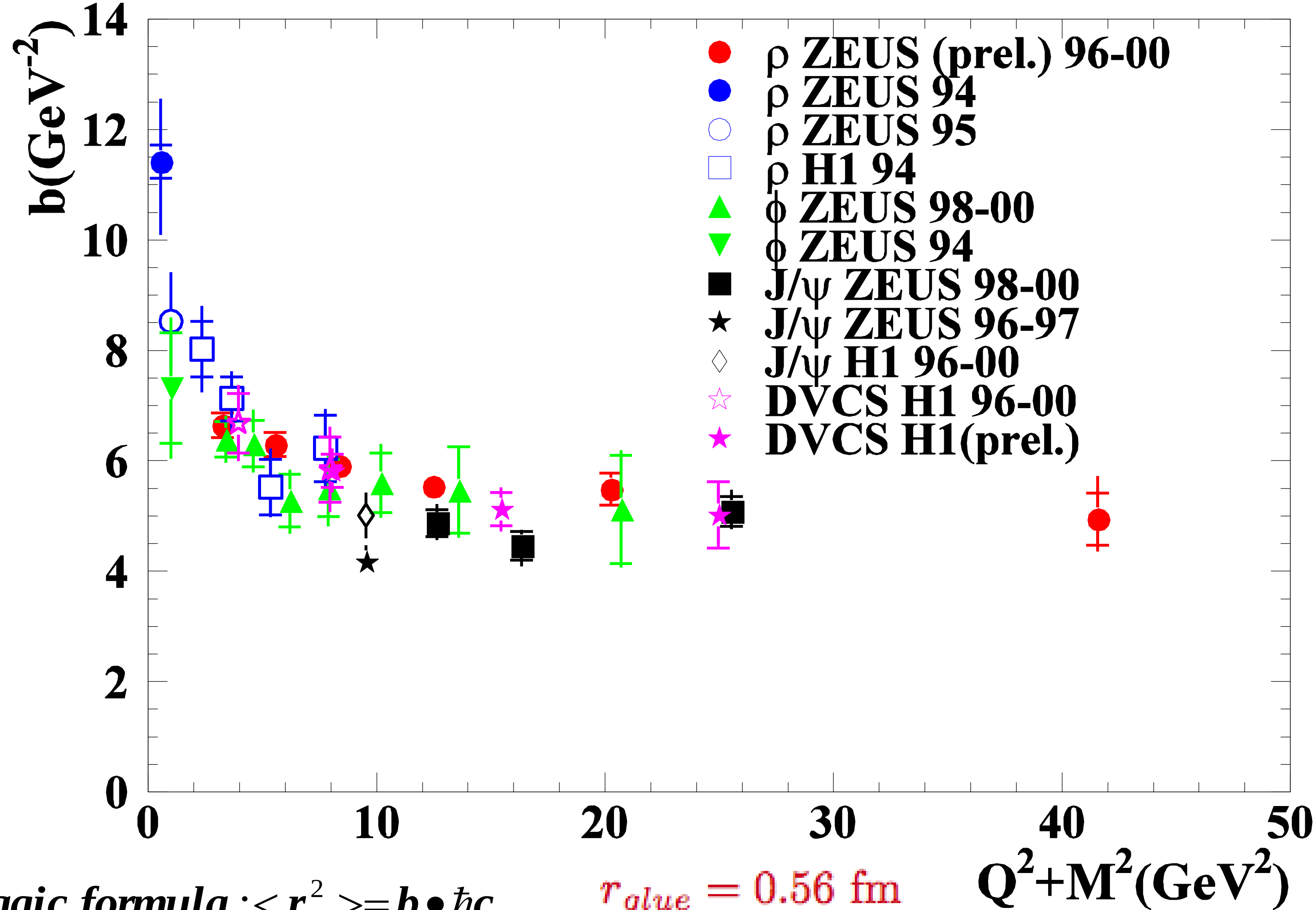
$\alpha(0) = 1.087 \pm 0.003 \pm 0.003 \approx \alpha(0)$ (*pp*)

$\alpha' = 0.126 \pm 0.013 \pm 0.012$ 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(Q²+M²) - VM



Magic formula : $< r^2 >= b \bullet \hbar c$

$r_{glue} = 0.56$ fm

$r_{proton} = 0.8$ 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**

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

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

Real and Imaginary part explicitly contained

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

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

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

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

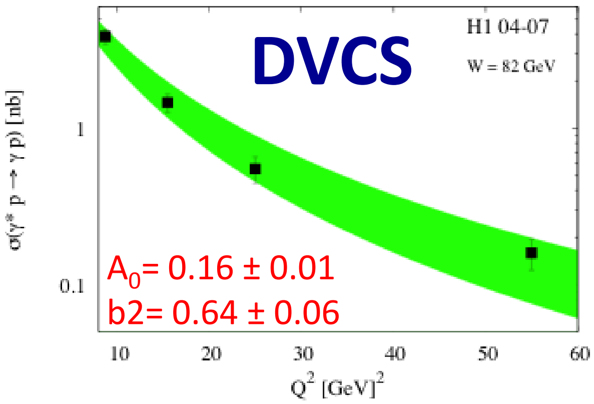
We refined the parameters… the most of them being constrained by plausible assumptions:

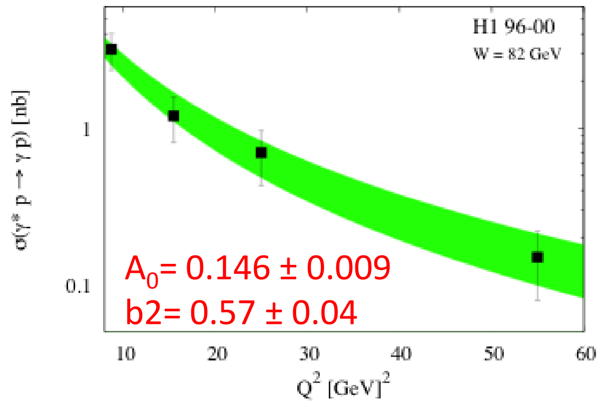
soft D-L Pomeron trajectory parameters:
- intercept: $\alpha(0) = \beta(0) = 1.09$
- slope: $\alpha' = \alpha_1\alpha_2 = \beta' = 0.25$

- $b_1 = 2.0$ (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

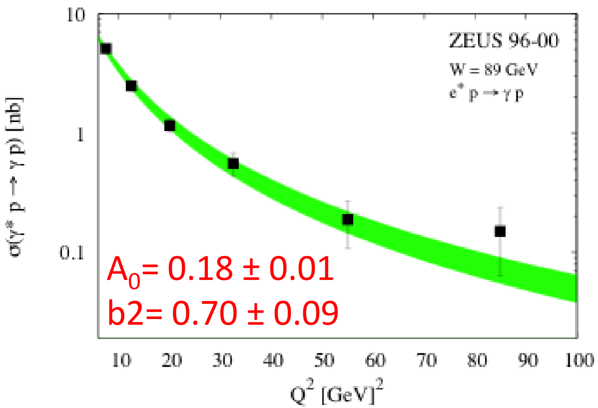


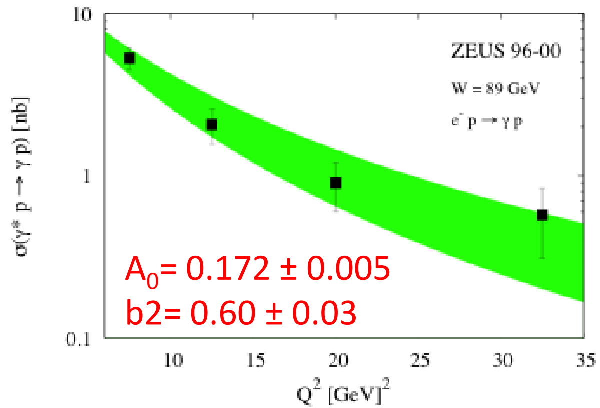


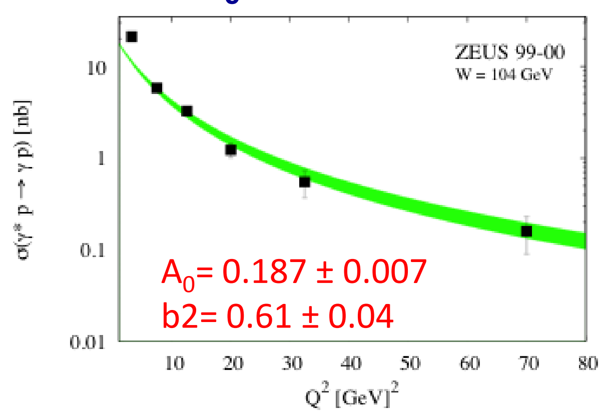
The parameter b_2 was estimated, For each process, via a two-parameters fit on σ(Q^2), being the most sensible to it, fixed in the Fits to all the other distributions

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

A_0 ~ 0.17





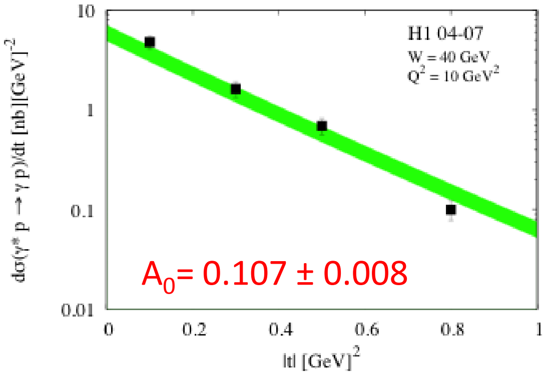


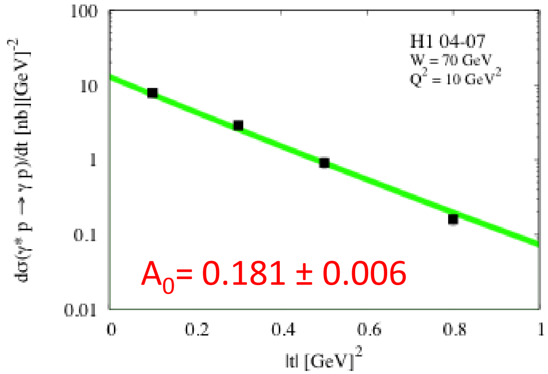
The uncertainty green band is calculated according to the uncertainty on the A_0 and b_2 parameters

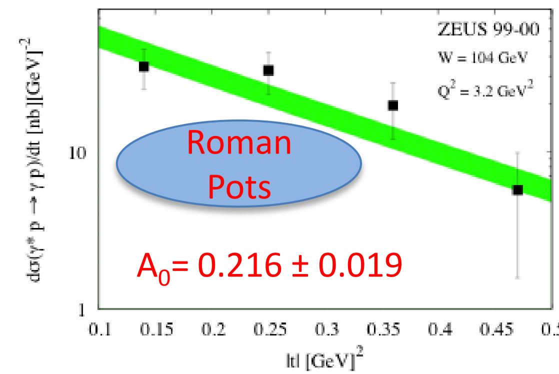
$$\sigma\left(s,t,\tilde{Q}^2\right) \overset{t_{\min}\approx 0}{\approx} \sigma_{el}\left(s,\tilde{Q}^2\right) = \left[\frac{1}{B\left(s,t,\tilde{Q}^2\right)} \cdot \frac{d\sigma\left(s,t,\tilde{Q}^2\right)}{dt}\right]_{t=0}$$

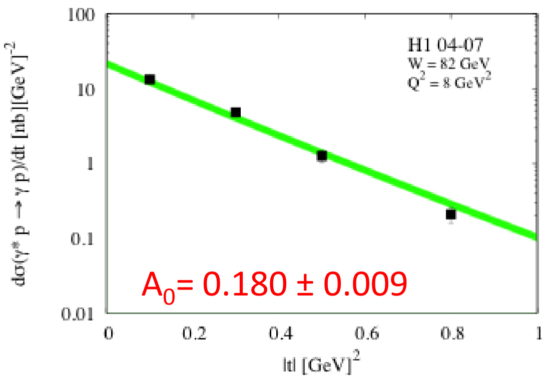
Satisfactory description of $\sigma_{DVCS}(Q^2)$ (Q^2>5 GeV^2)

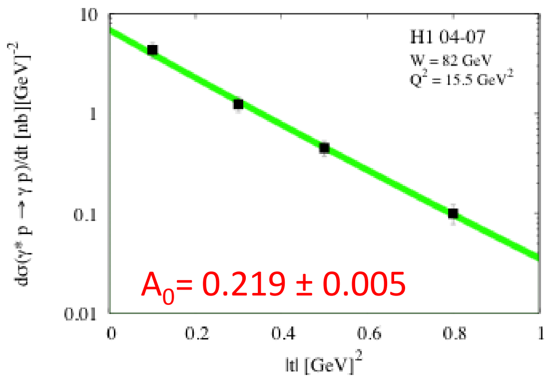
Fit to HERA: dσ/d|t| - DVCS

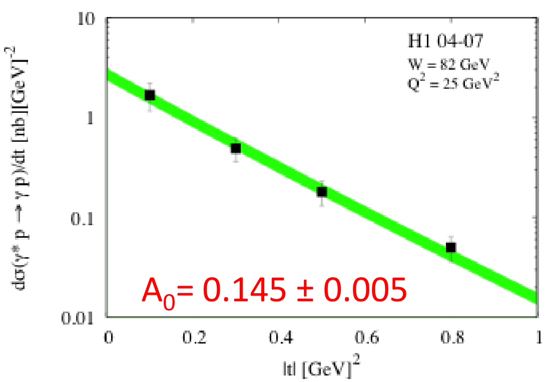


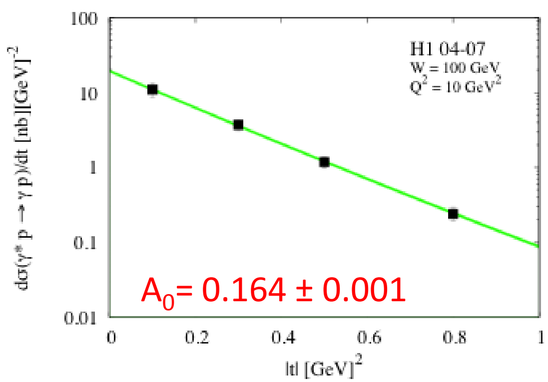












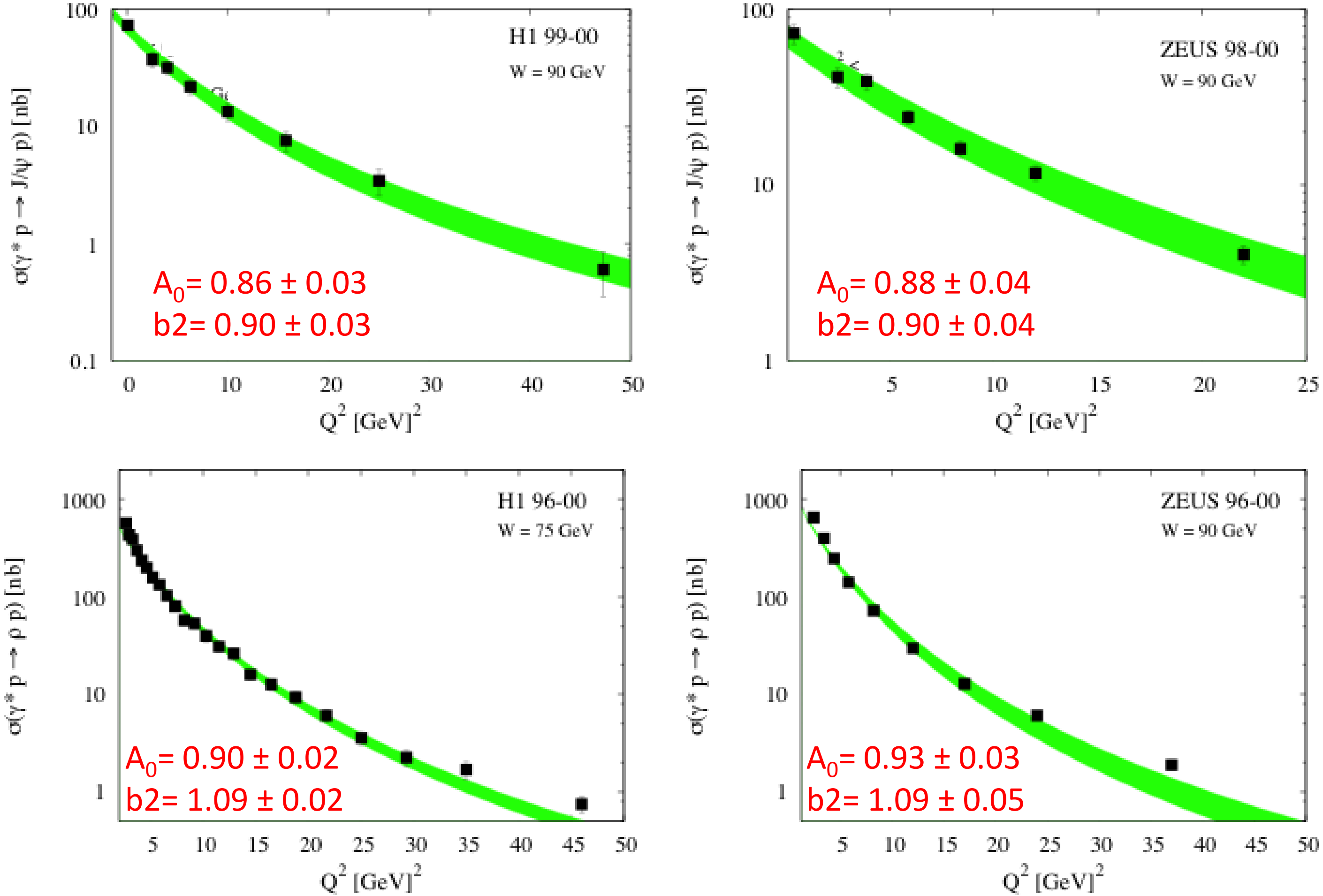
DVCS

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

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

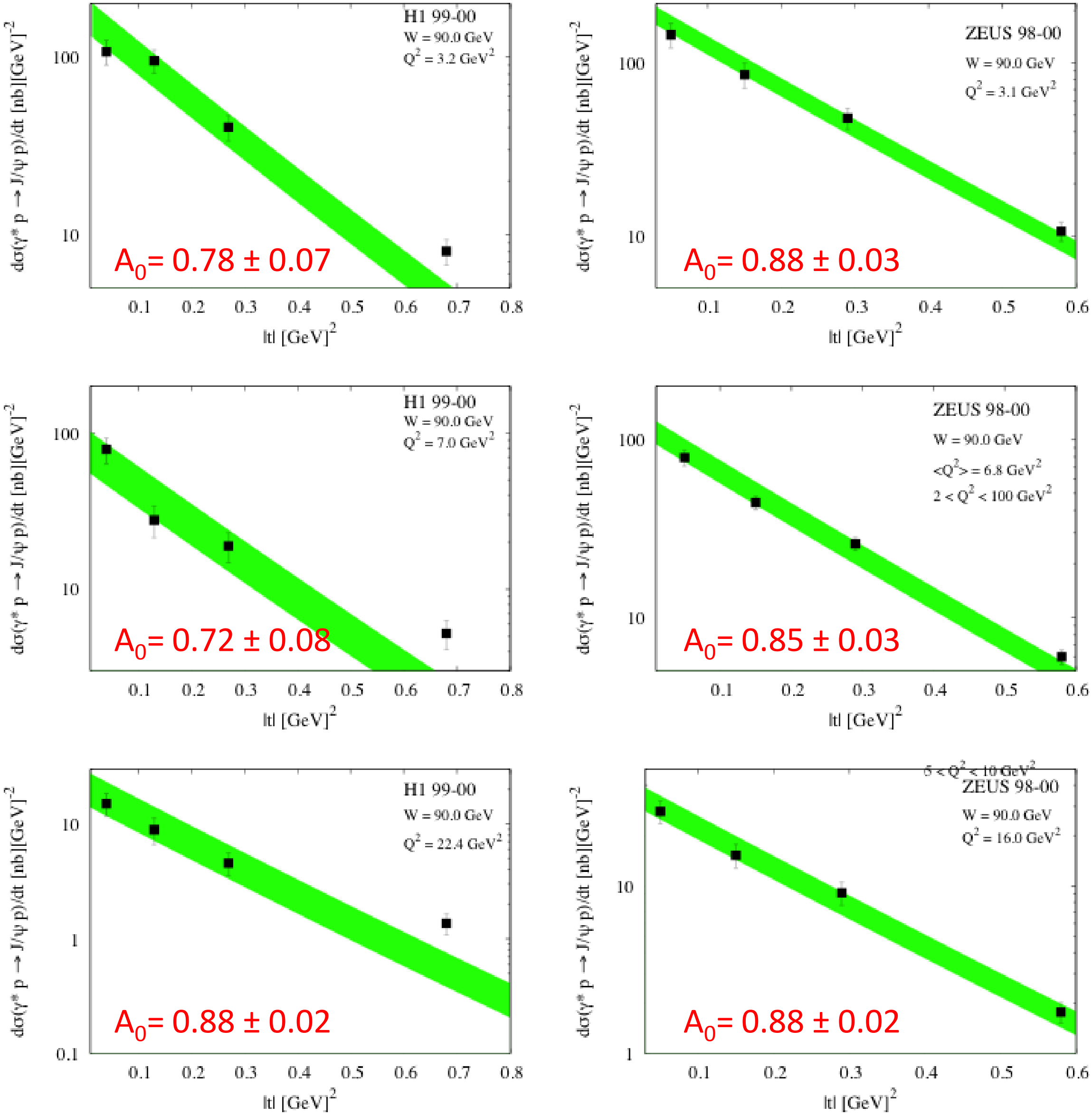
$A_0 \sim 0.9$

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: $d\sigma/d|t|$ - J/Ψ

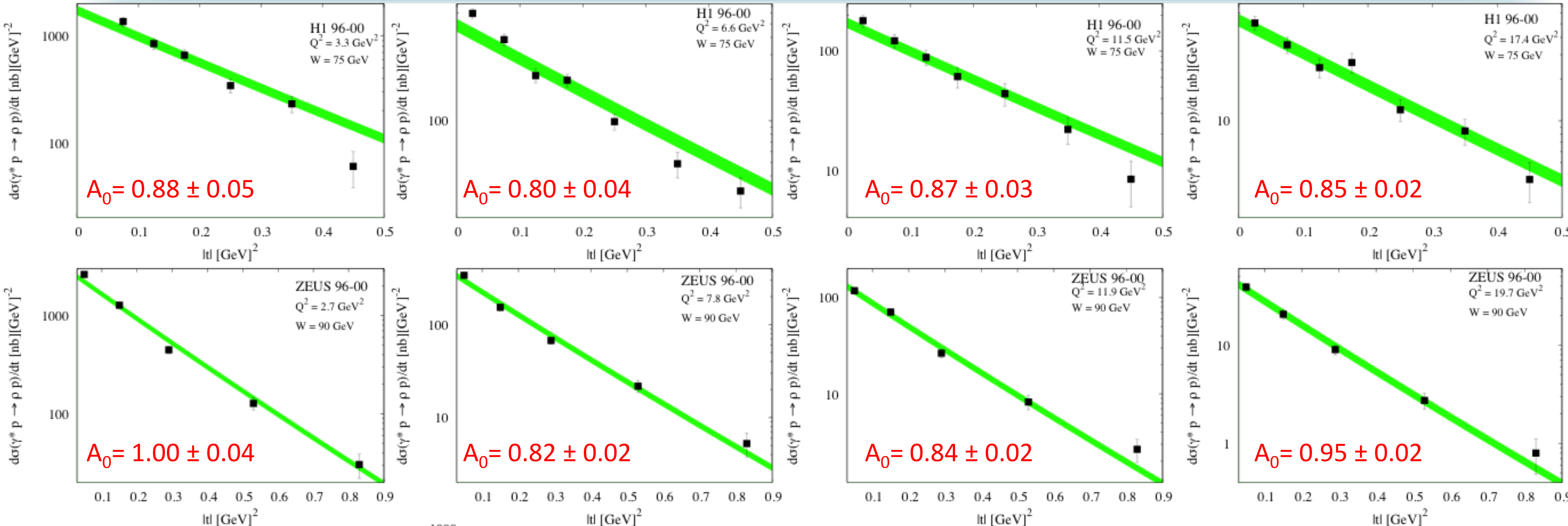


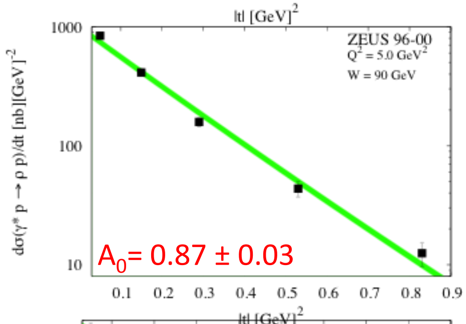
J/Ψ

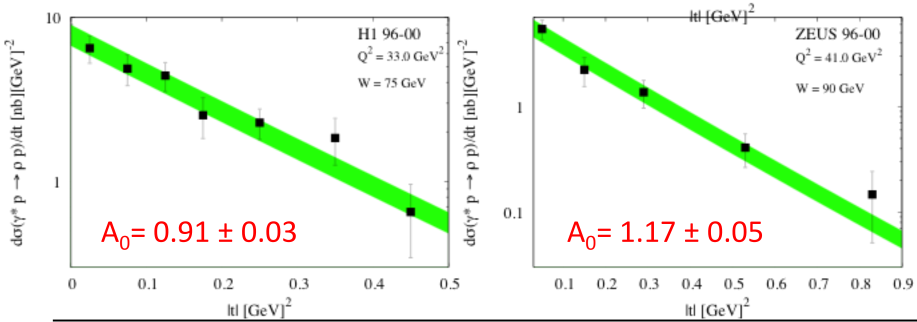
b_2= 0.90 fixed

- ✓ 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





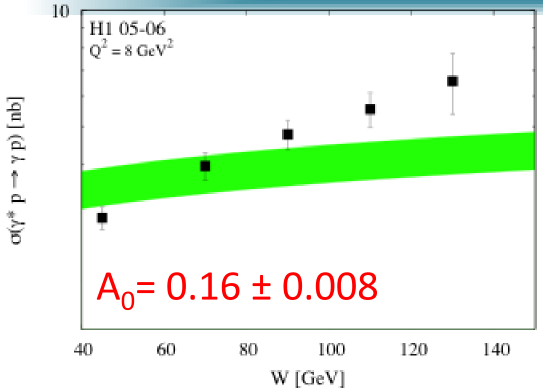


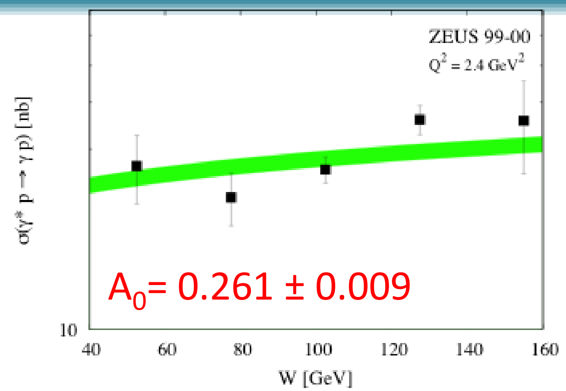
ρ^0

b_2= 1.09 fixed

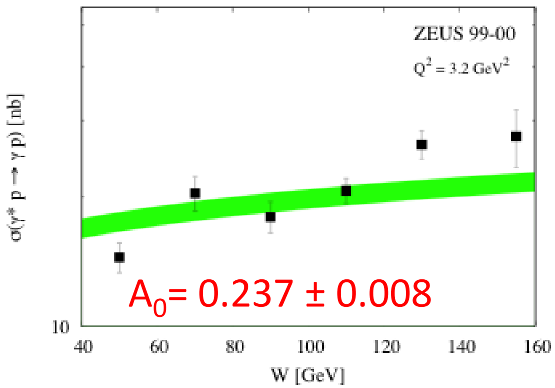
- ✓ Good description of ZEUS data (W=90 GeV), over the whole Q^2 range
- ✓ H1 data (W=75 GeV) generally well described at large <Q^2> or at least for moderate |t|

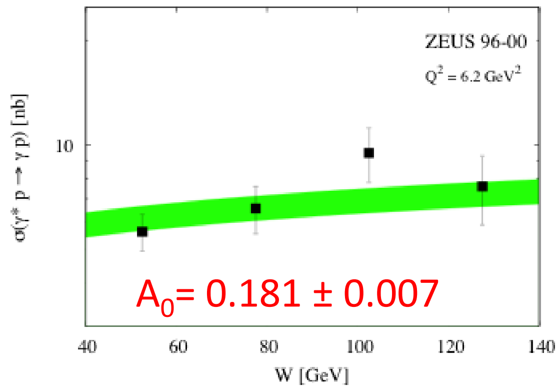
Fit to HERA: xsec vs W

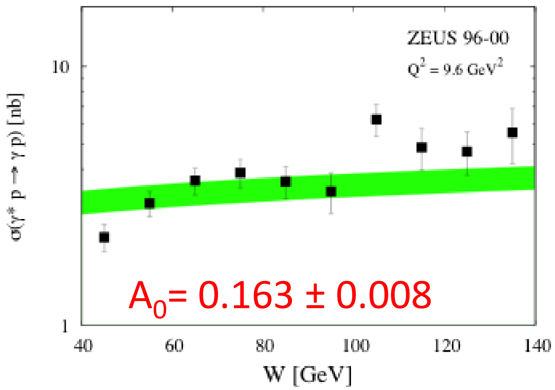


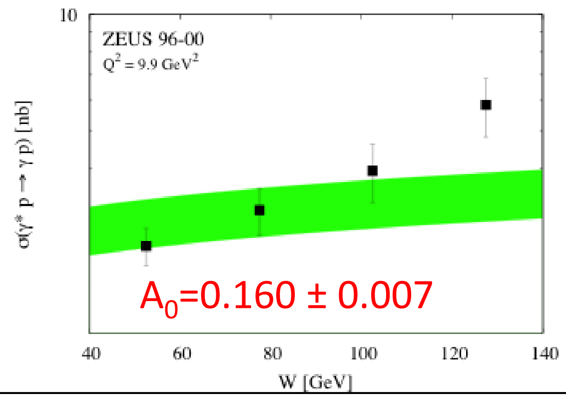


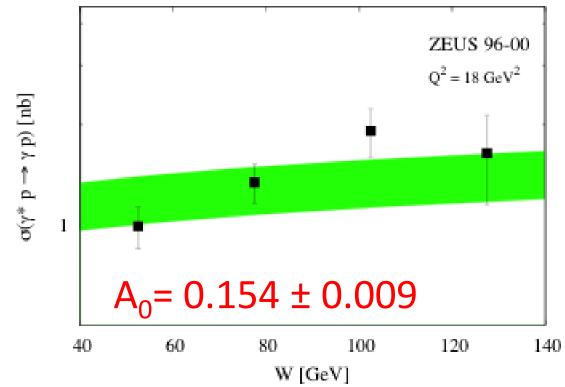
DVCS





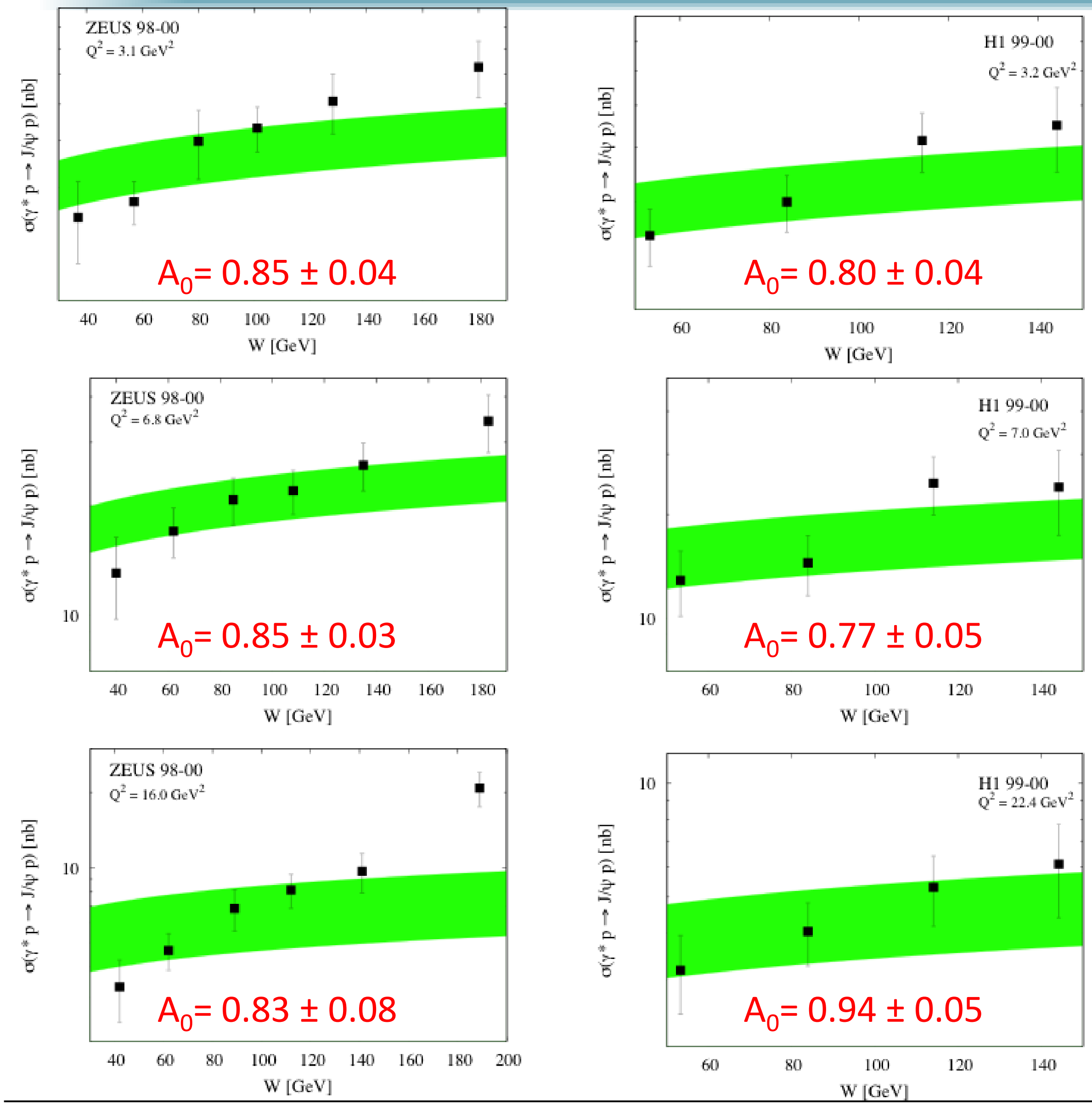




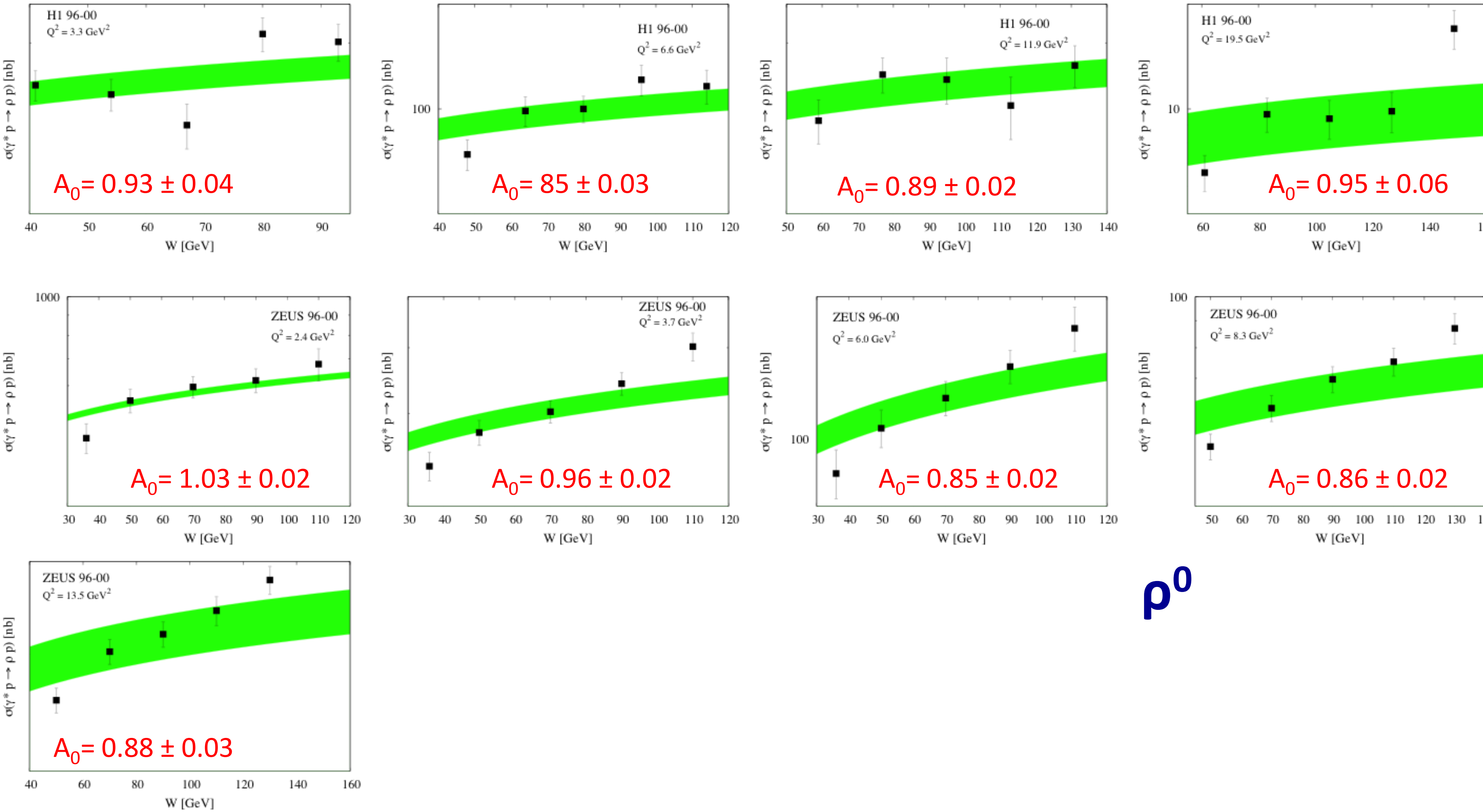


Fit to HERA: xsec vs W

J/Ψ



Fit to HERA: xsec vs W – ρ^0



ρ^0

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

Coll.	Years	W [GeV]	$\|A_0\|$ [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
$\langle b_2\rangle = 0.55 \pm 0.02$	$\langle b_2\rangle = 0.90 \pm 0.03$	$\langle b_2\rangle = 1.09 \pm 0.02$(varies vs Q^2)
$A_0 \sim 0.17$	$A_0 \sim 0.9$	$A_0 \sim 0.9$

Results:

- ✓ **The model fairly 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:

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

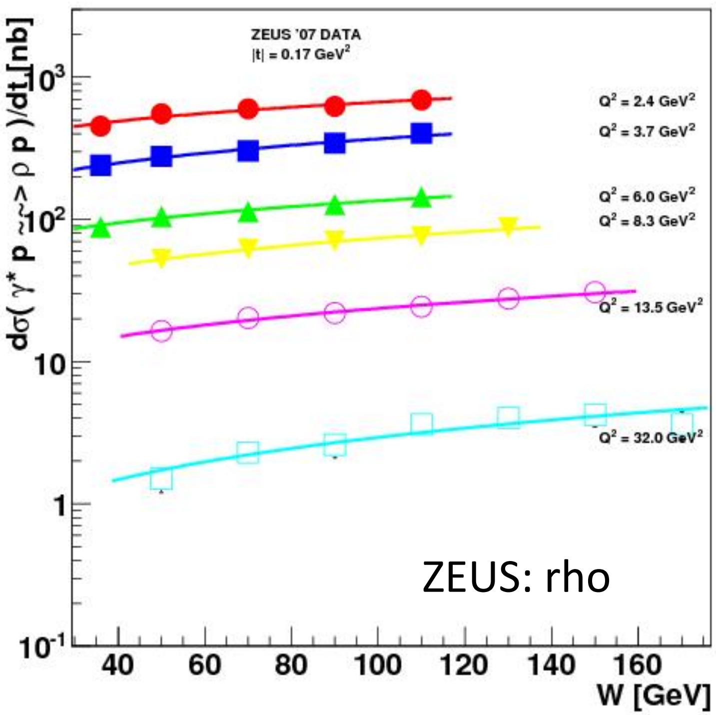
Hard Pomeron:

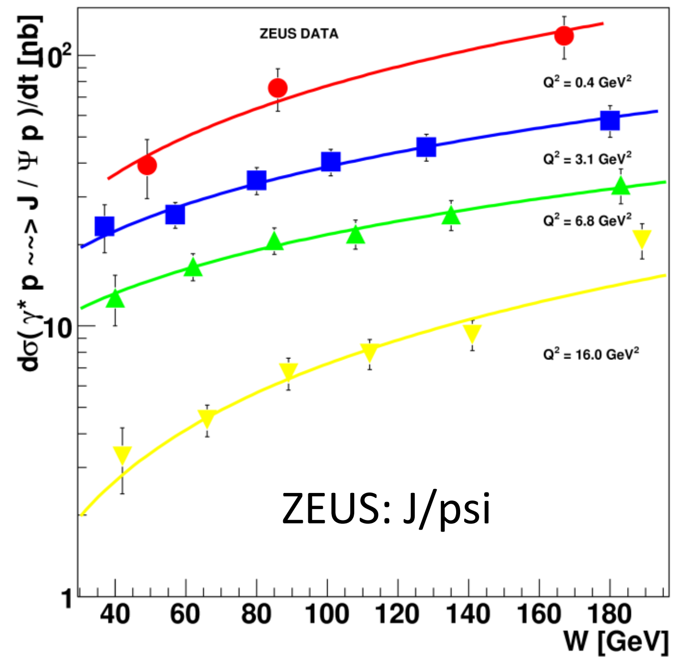
$$\alpha_{hard}(t) = 1.30 + 0.02t$$

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**

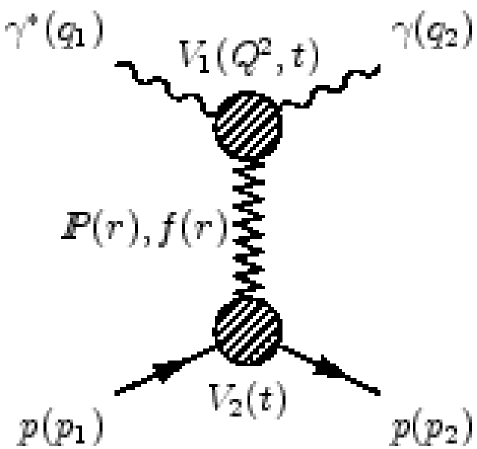
For a complete review of results see:

- 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

In a first approach – to be fine-tuned

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

m_p is the proton mass
c and *d* being free parameters

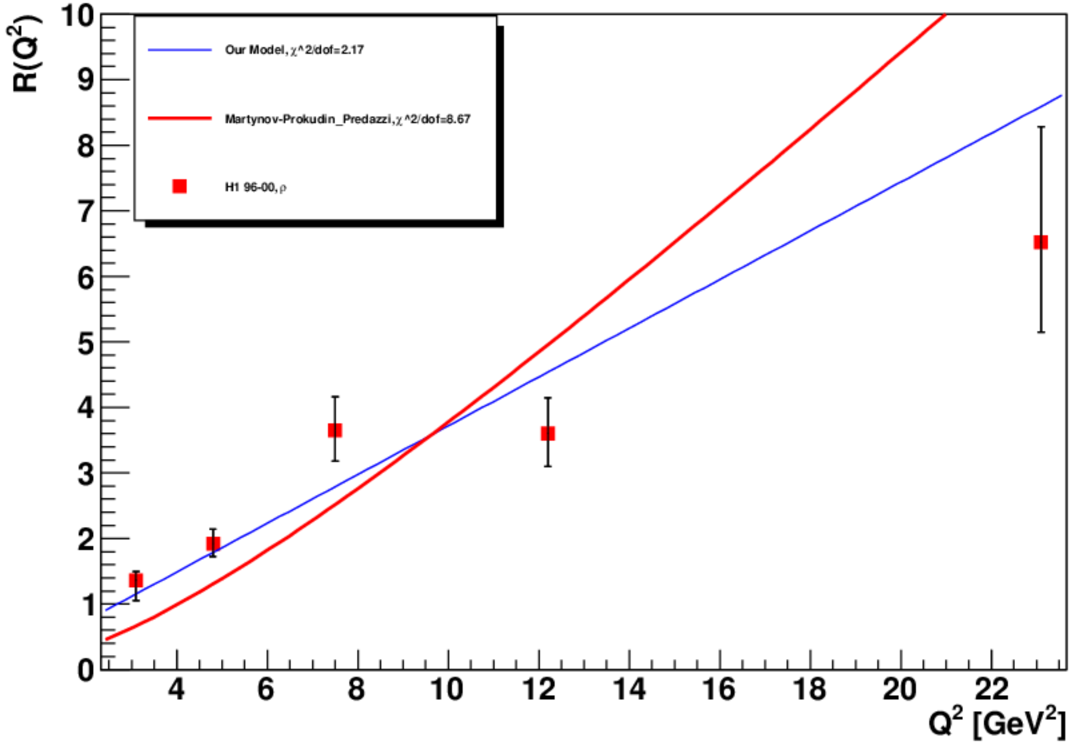
$$\beta(t,\tilde{Q}^2) = \exp\left[4\left(\frac{1}{Q^2+M_V^2}+\frac{1}{2m_p^2}\right)t\right]$$

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

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

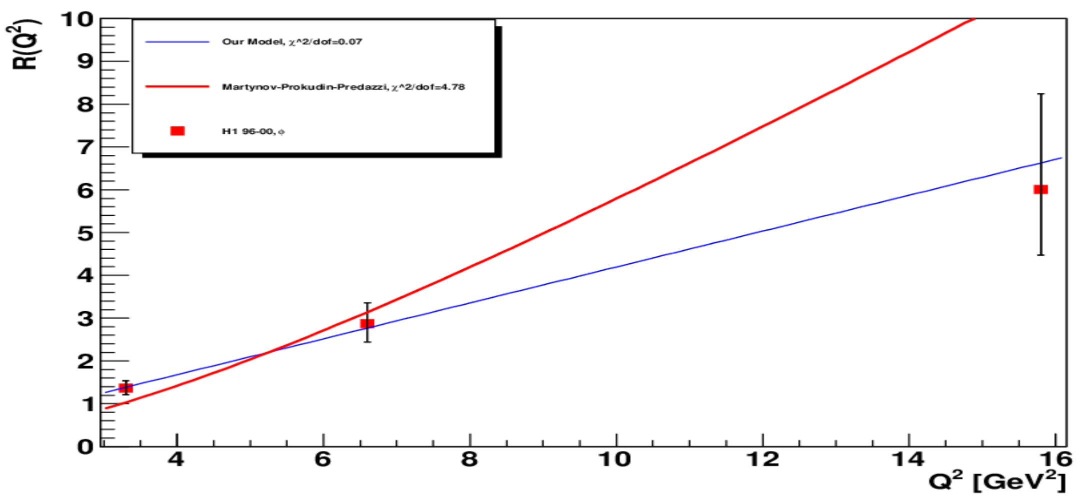
Summary and outlook

- **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 σ(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 (“Reggeometry”)**
- **The real and imaginary parts of the DVCS (and VM) amplitude, essential ingredients for the GPDs, are explicitly contained in the model**


Our Model, χ^2/dof=2.17
Martynov-Prokudin_Predazzi, χ^2/dof=8.67
H1 96-00, ρ
R(Q²)
Q² [GeV²]
0
1
2
3
4
5
6
7
8
9
10
4
6
8
10
12
14
16
18
20
22

R(ɣ→ρ)

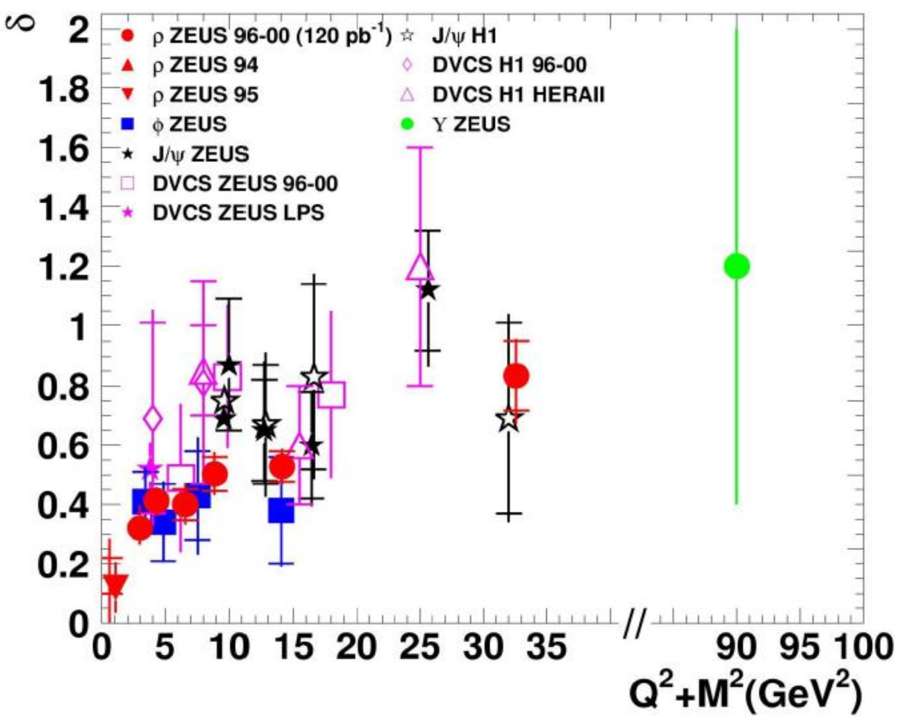
$R(\gamma \to \phi)$

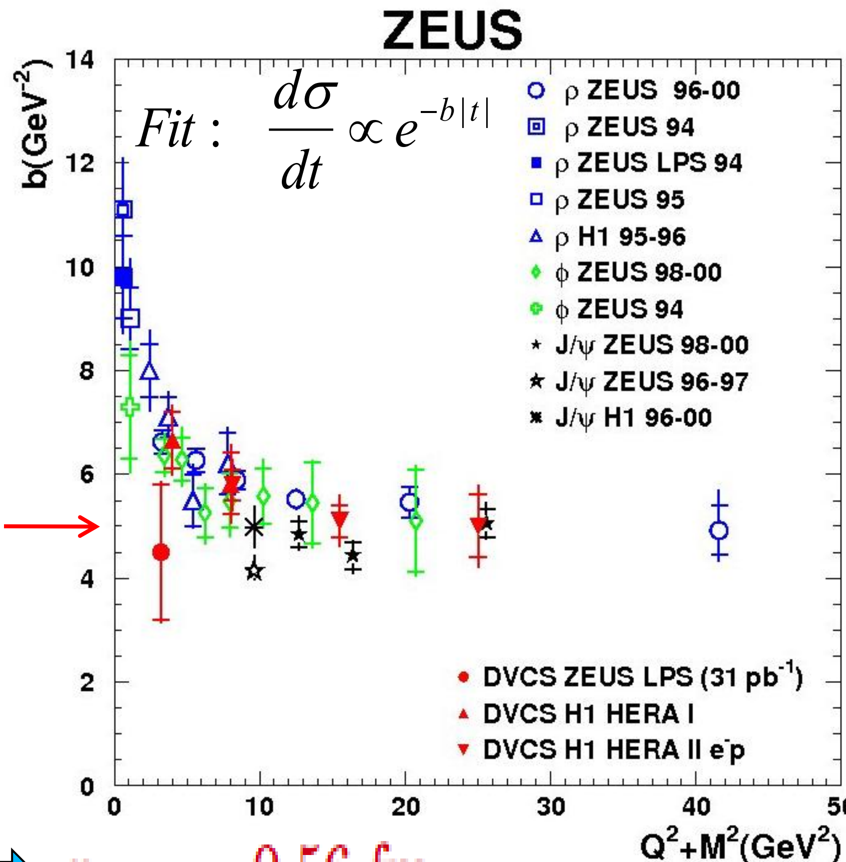


VMP and DVCS @ HERA

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

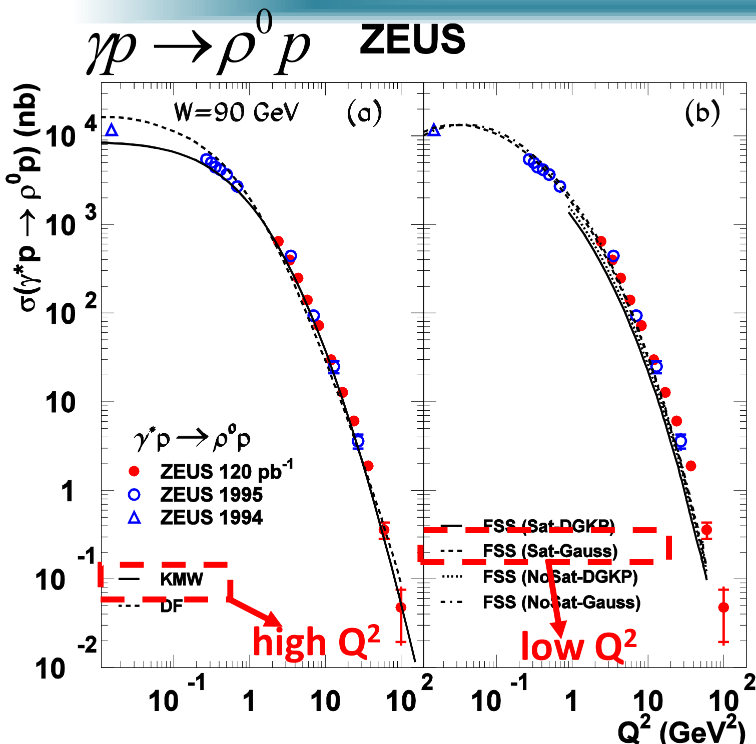
$Fit: \ \sigma \sim W^{\delta}$





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

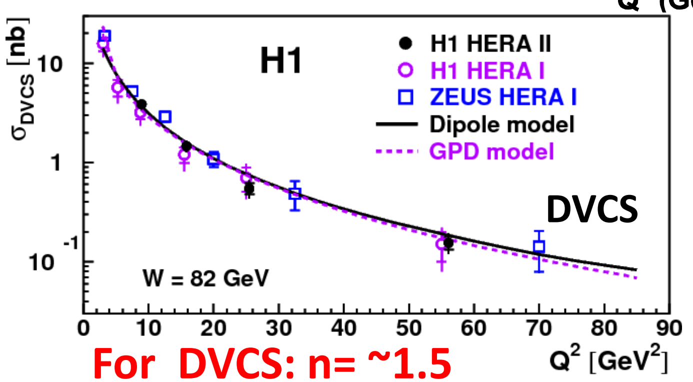
Total xsec dependences @ HERA



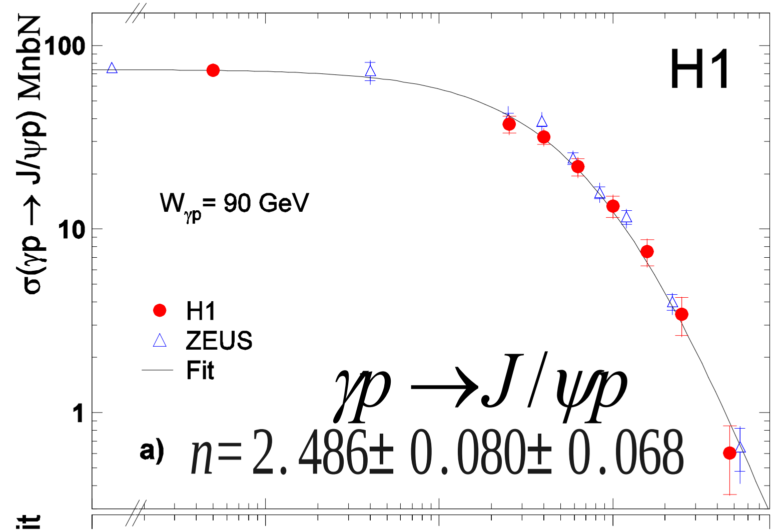
$$\sigma \propto \left(Q^2 + M^2\right)^{-n}$$

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

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

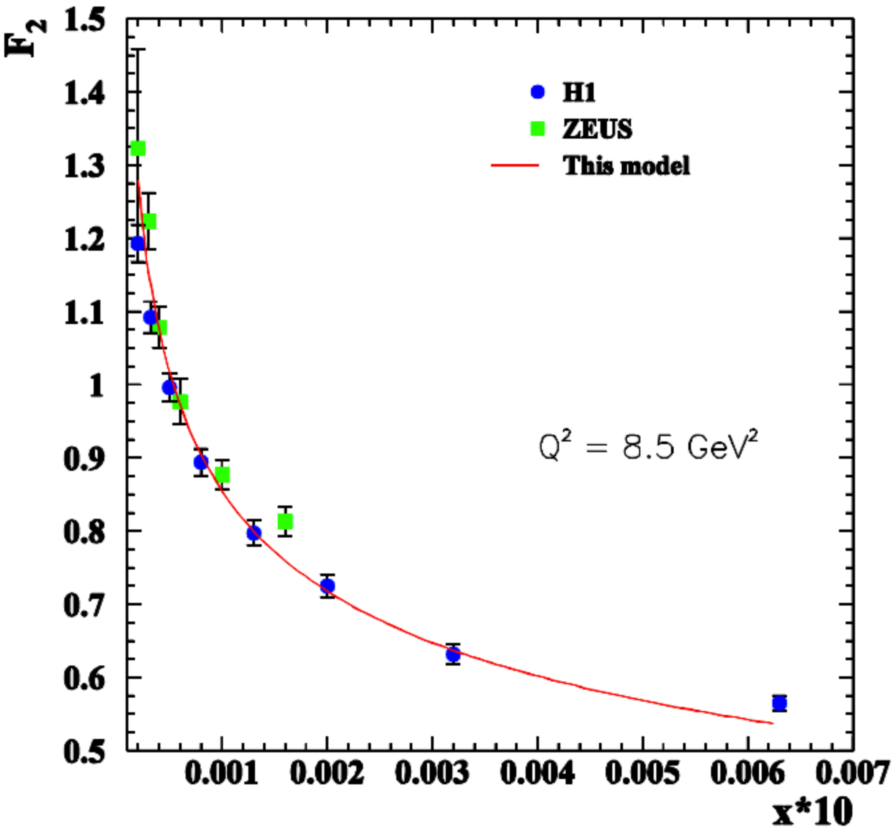


For DVCS: n= ~1.5



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*