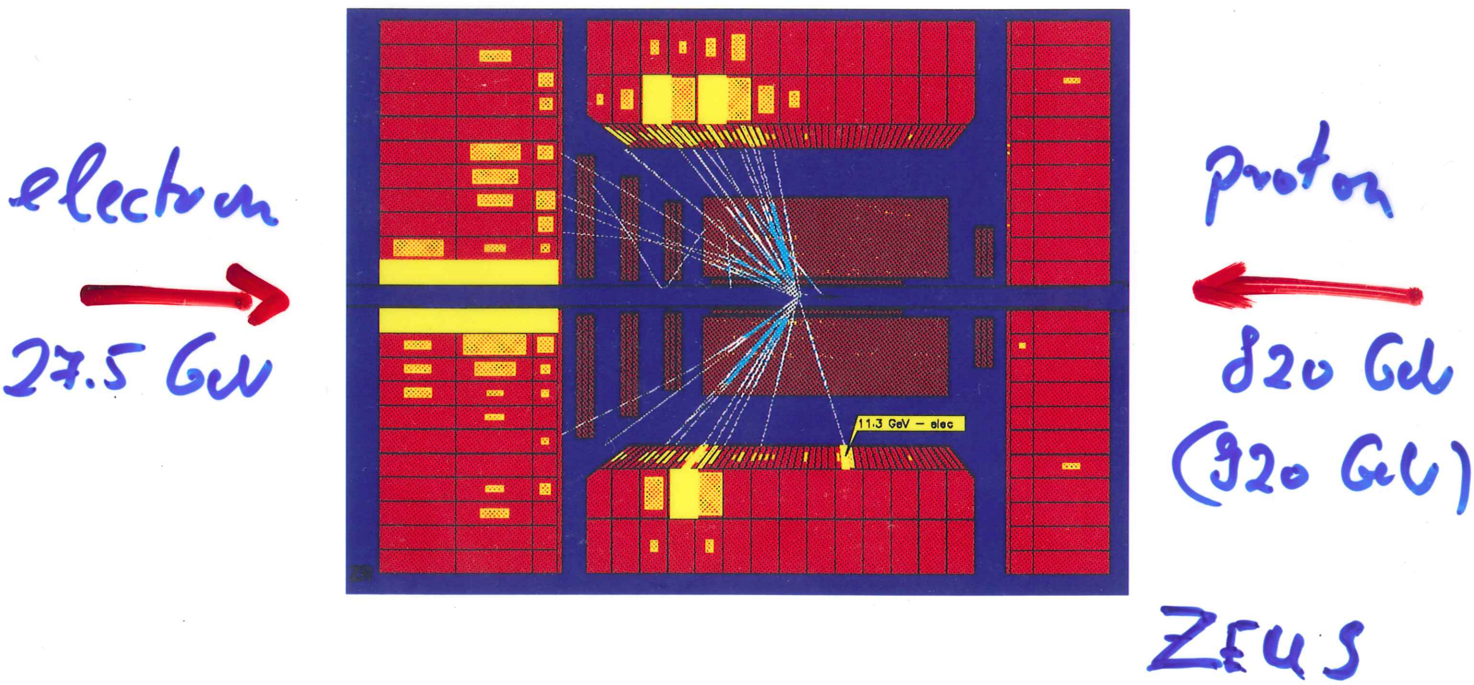
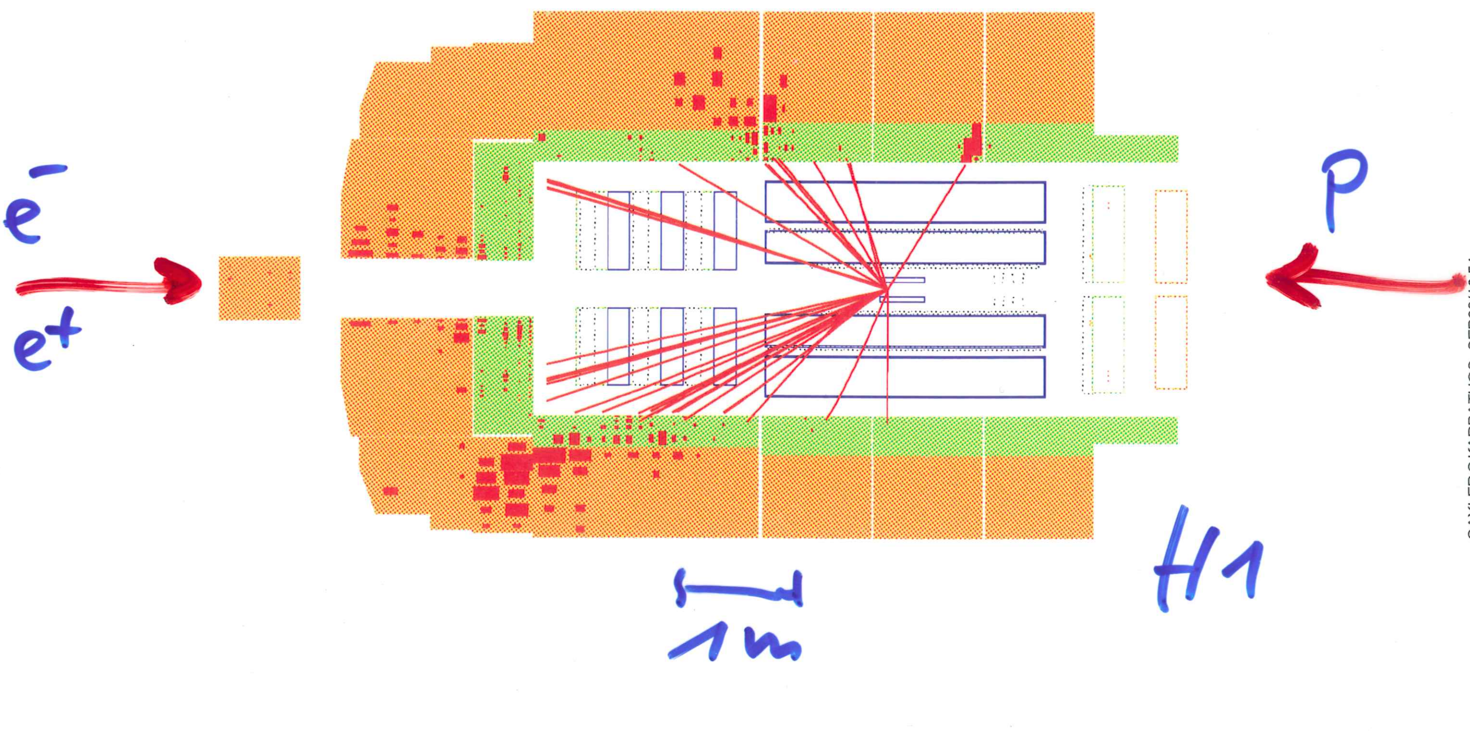
Antananarivo , October, 2001

Experimental Results on non-perturbative Physics at HERA

Jörg Gayler, DESY
for H1 and ZEUS





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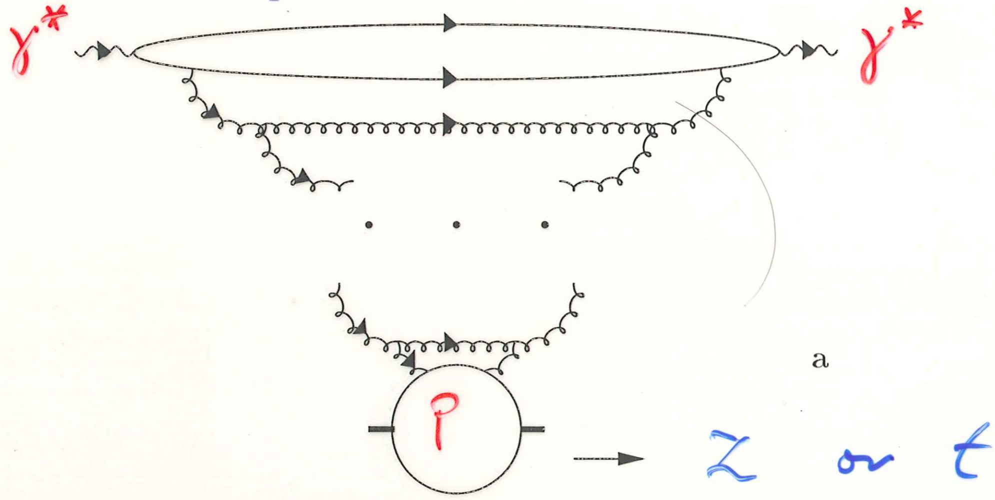
Introduction

$\gamma^* p$ total cross section in p restframe :



$q\bar{q}$ colour dipole formed at large distance

$$z \text{ or } t \sim 1/m_p x$$

well outside p

transverse size of Q^2 fluctuation

$$< r^2 > \sim \ 4/Q^2$$

hard, early gluon radiation :

pQCD explains rise of $\sigma_{tot}^{\gamma^* p}$ with energy

however :

photoproduction ($Q^2 \to 0$)

and diffractive processes

(formation of particles similar to initial state)

are related to large distances and/or to confinement,

i.e. to the later soft emissions

HERA explores transition from short distance phenomena to the confinement problem

[a] see discussion J. Bartels, H. Kowalski, hep-ph/0010345

this talk

- rise of F_2 at low x
- inclusive diffractive scattering
- Vector Meson production
- DVCS Deep Virtual Compton Scattering

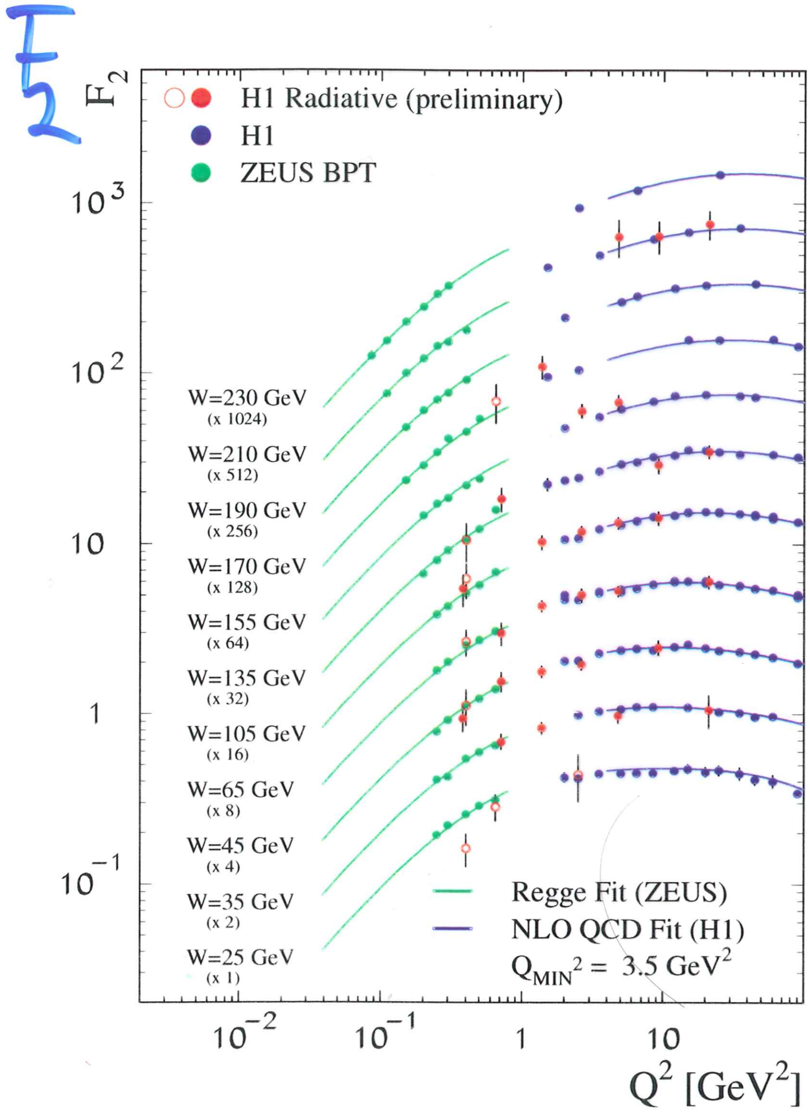
results available on many more non perturbative phenomena :

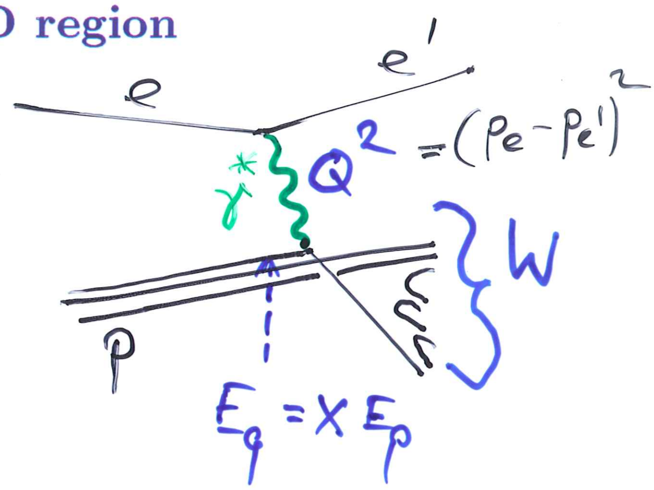
- $ep \to enX(\pi$ exchange$)$
- Instanton search
- Odderon search ($\to$ J. Stiewe)
- fragmentation
- photon structure

  ...

Inclusive $ep \to eX$, $\gamma^* p \to X$

Regge phenomenology **pQCD region**





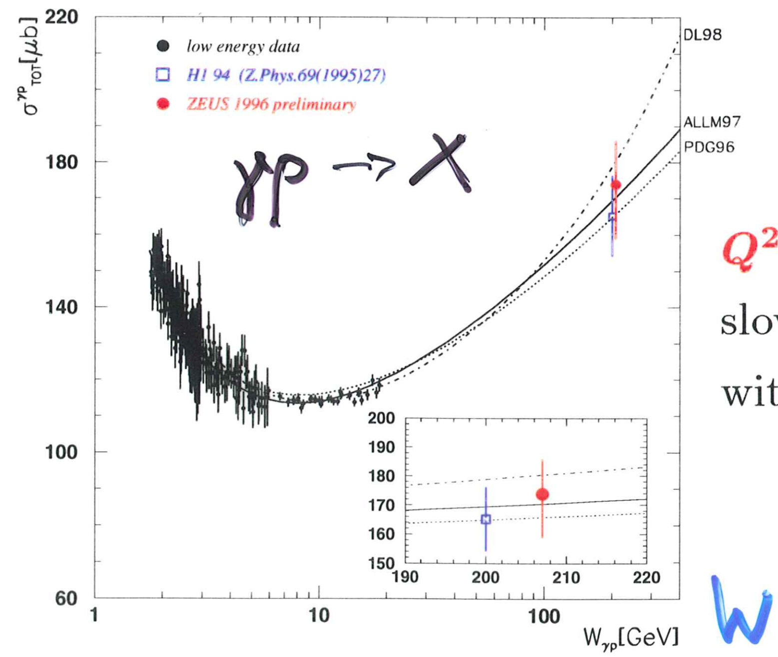
$$W^2 = Q^2(1/x - 1)$$

$Q^2 \to 0 : F_2 \to 0$

$(\sigma_{tot}^{\gamma^* p} = 4\pi\alpha^2/Q^2 \; F_2$,

finite for $Q^2 \to 0)$

Regge models
like in
soft hadronic
interactions

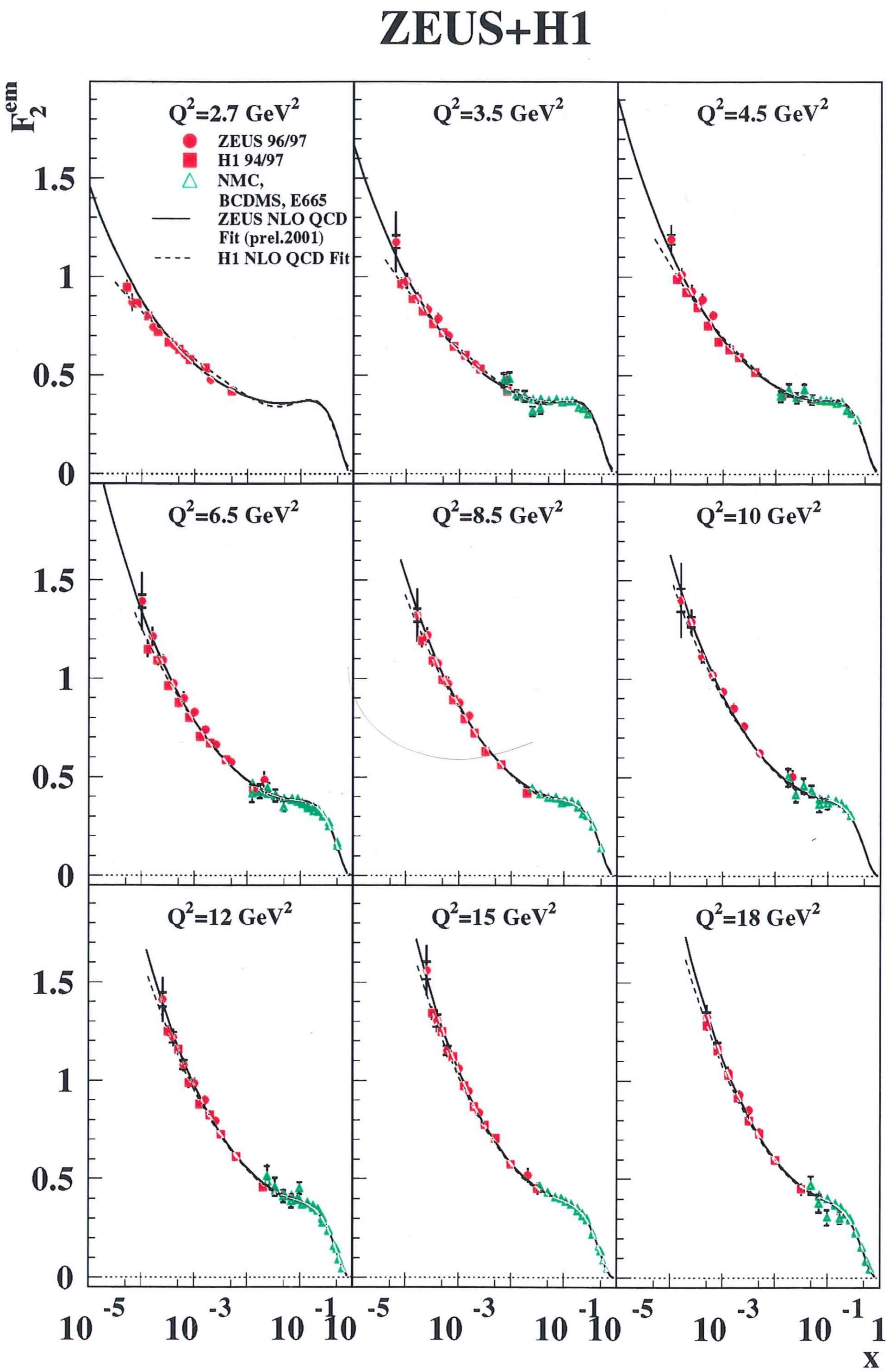


$Q^2 = 0$

slow increase of σ

with $W = \sqrt{s}$

Energy dependence $Q^2 \gtrapprox 3\ \mathrm{GeV}^2$, DIS



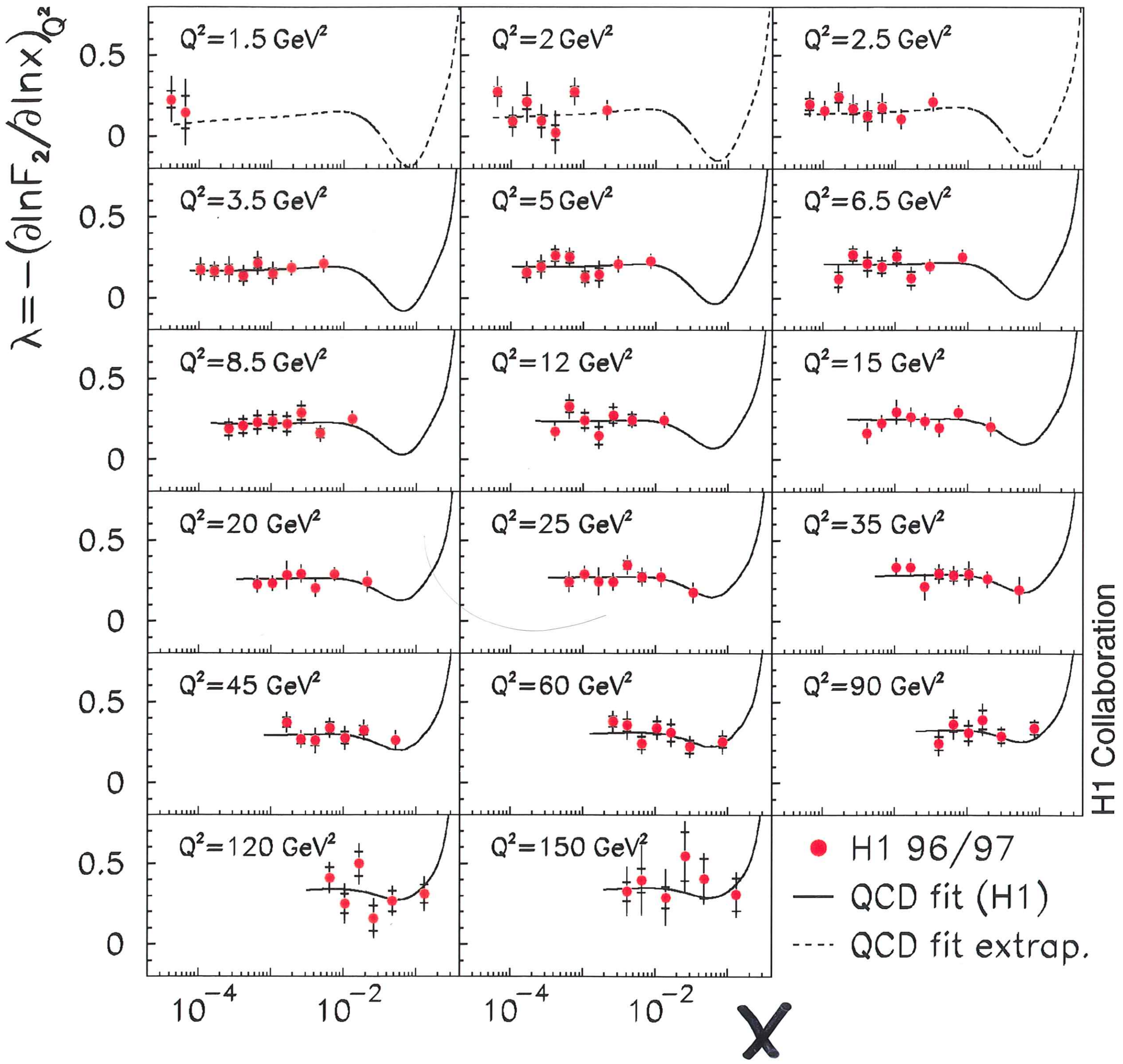
$$W^2 = Q^2\left(\frac{1}{x} - 1\right)$$

x

DIS: rapid increase with energy

signs of saturation ?

consider $\lambda = d \ln F_2 / d \ln x|_{Q^2}$ as function of x



fixed Q^2, $x < 0.01$: $\lambda \approx$ const

$\rightarrow F_2 \sim x^{-\lambda(Q^2)}$

no taming of rise visible yet for $Q^2 \geq 1.5$ GeV^2 (~pQCD region)

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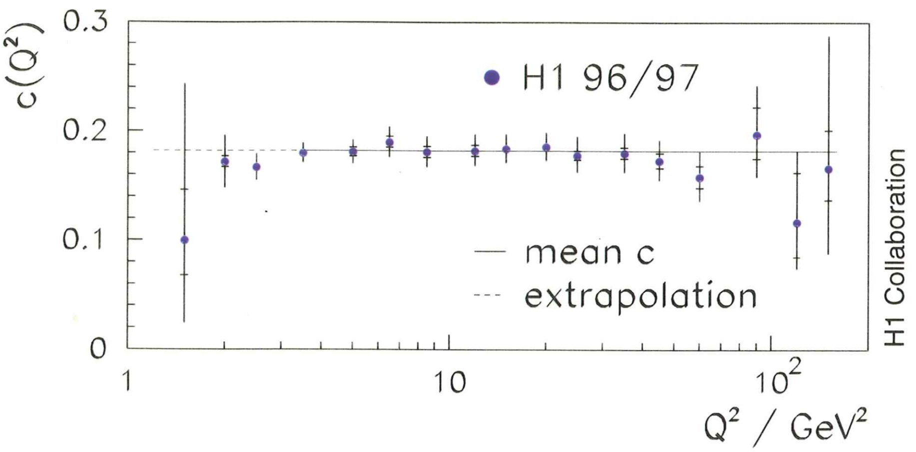
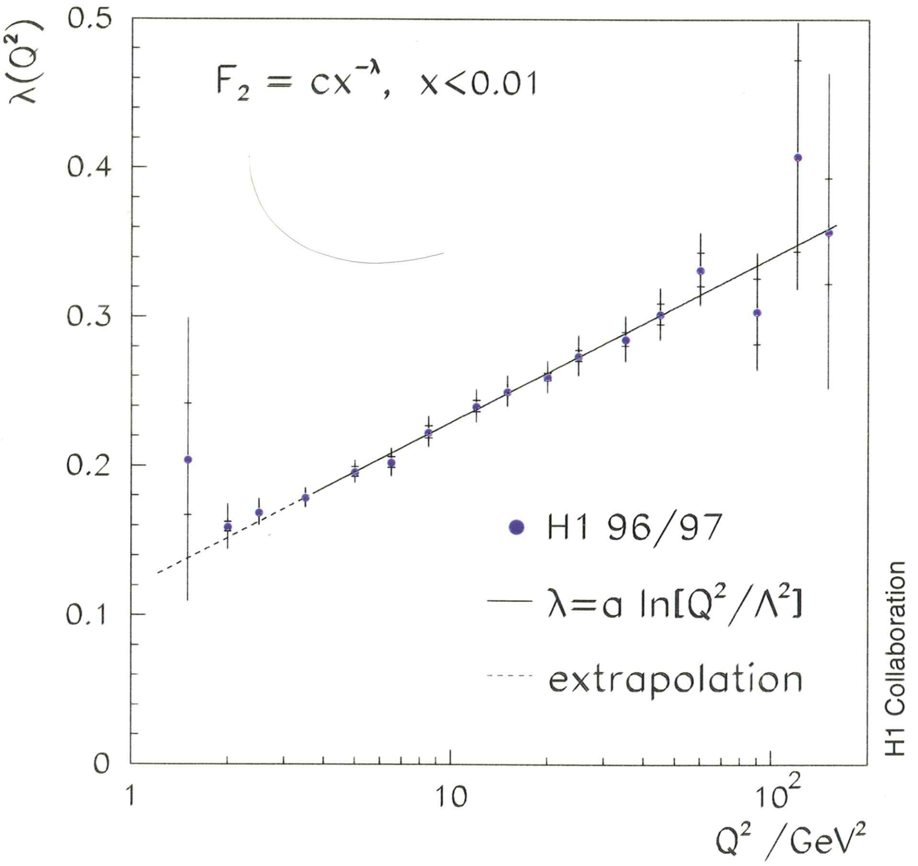
Very simple parametrization, $x < 0.01$

$$F_2 = c \cdot x^{-\lambda(Q^2)} \;, \quad \lambda(Q^2) = a \cdot \ln[Q^2/\Lambda^2]$$





$$a = 0.0481 \pm .0013 \pm .0037 \qquad \Lambda = 292 \pm 20 \pm 51 MeV$$

Transition to small Q^2

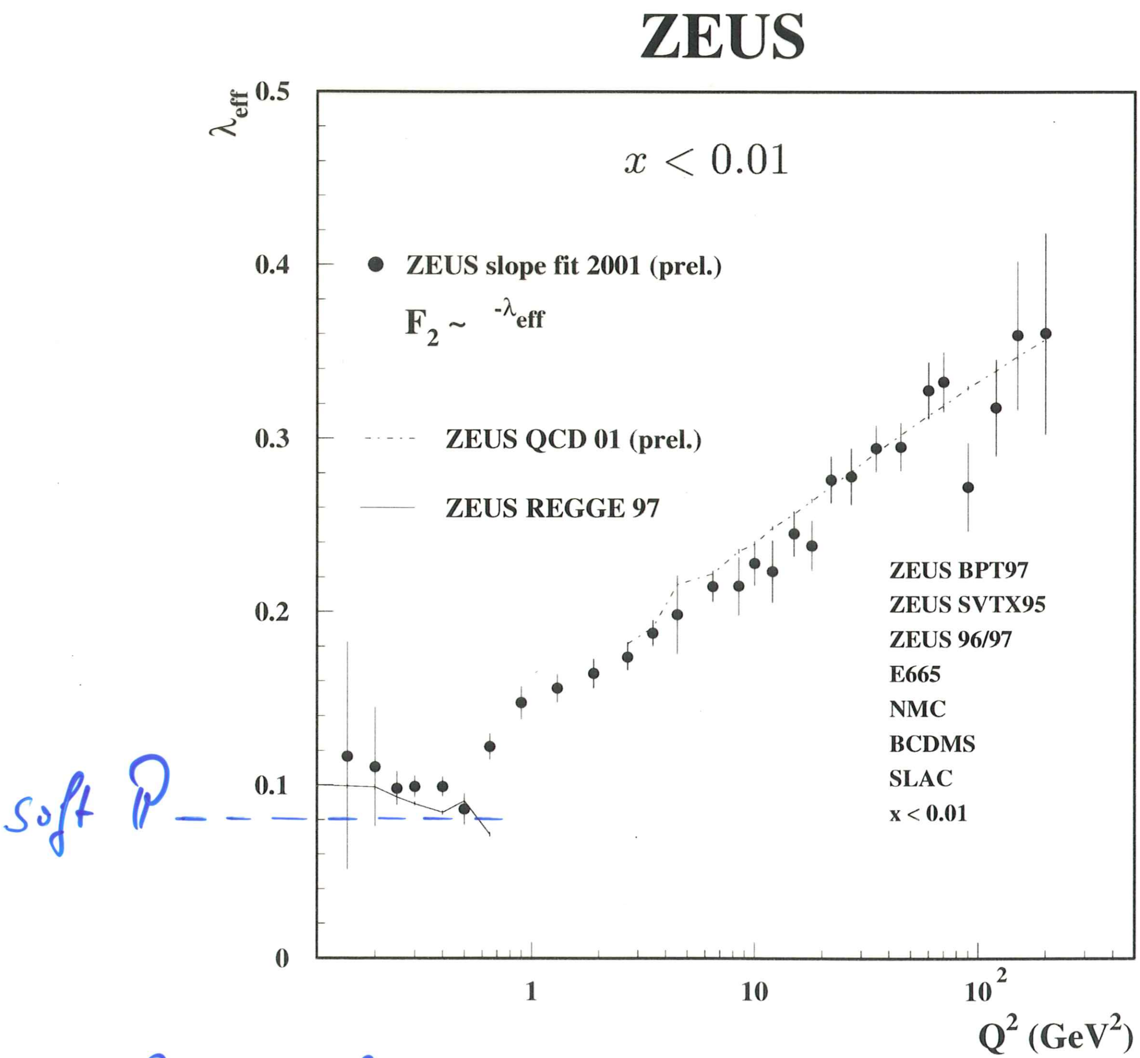
$\sigma_{tot}^{\gamma^* p} = 4\pi\alpha^2/Q^2 \; F_2 \; \sim x^{-\lambda}/Q^2$
$s = W^2 \sim Q^2/x$

Hadronic interactions at high energy:

Regge theory: $\sigma_{tot} \sim s^{\alpha_{I\!P}(0)-1}$

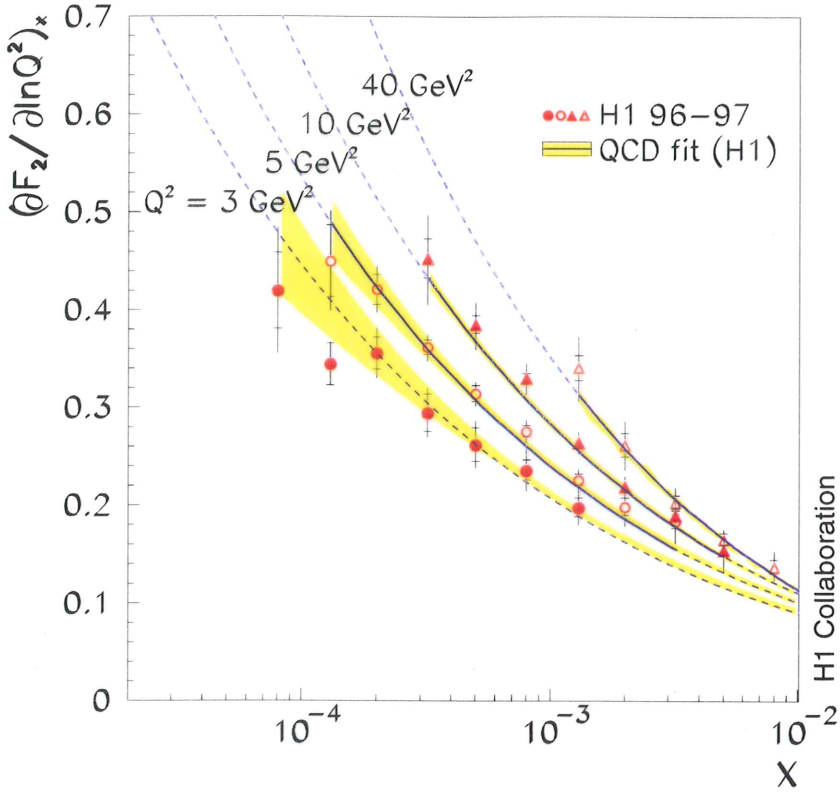
$\alpha_{I\!P}(0) - 1 \approx 0.08$ (Donnachie, Landshoff)

$\rightarrow$ expect **$F_2 \sim x^{-(\alpha_{I\!P}(0)-1)} \approx x^{-0.08}$, $\lambda \approx 0.08$**



$Q^2 \lesssim 1\,\text{GeV}^2$: rise similar hadronic interactions
in pQCD region: $\lambda \sim \ln Q^2$

what shows $dF_2/d\ln Q^2$?



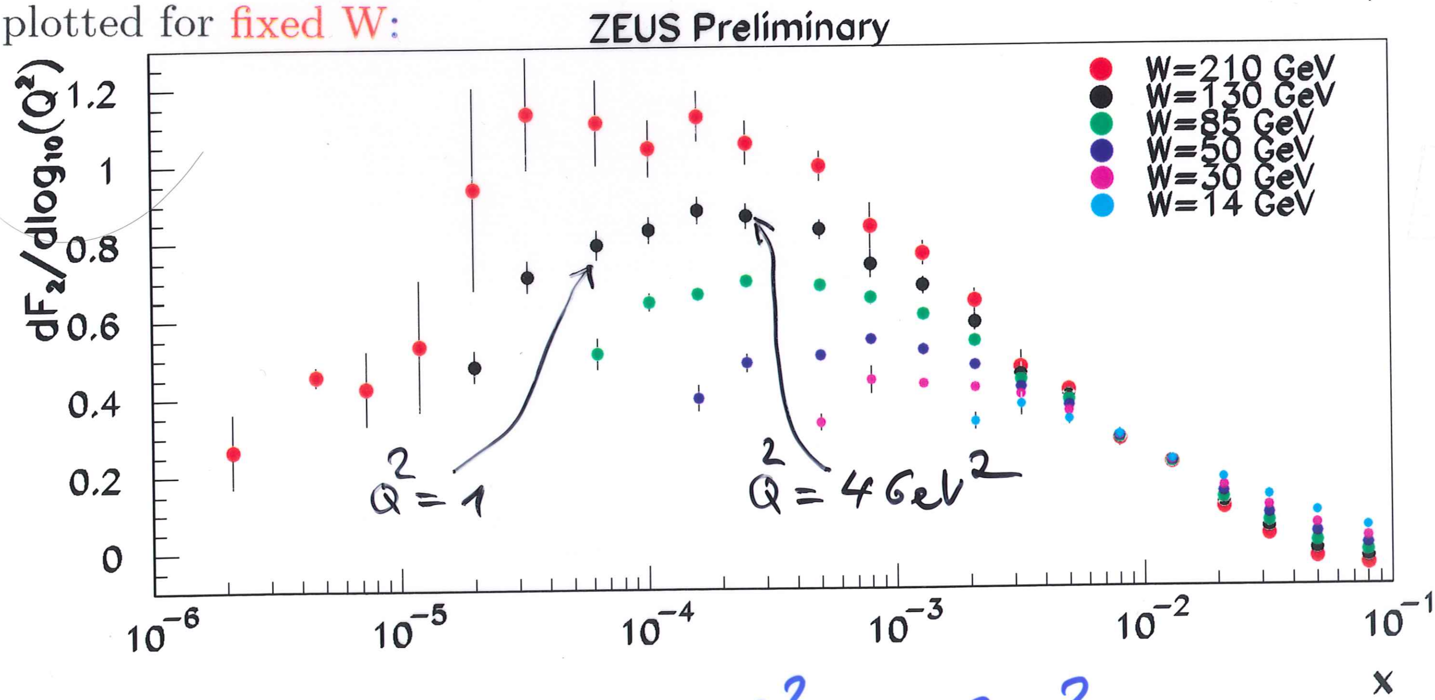
above parametrization

$F_2 \sim x^{-\lambda}$ gives

$dF_2/d\ln Q^2 \sim F_2(-\ln x)$

rise consistent with pQCD (NLO fits)

plotted for fixed W:



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flattening even at $Q^2 > 1$ GeV^2

but note decrease of Q^2

we see damping of rise as $Q^2 \to 0$

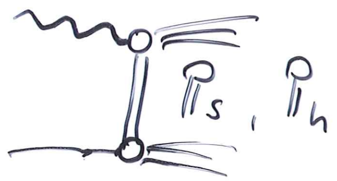
no taming of rise at fixed Q^2

Models and Transition $Q^2 \to 0$

Different models are used to deduce the structure of the interaction by comparison with the data

$2I\!P$ models (Donnachie, Landshoff)

$F_2 = f_0(Q^2)x^{-\epsilon_0} + f_1(Q^2)x^{-\epsilon_1}$



$\epsilon_0 \approx 0.44$	$\epsilon_0 \approx 0.08$
hard $I\!P$	soft $I\!P$

fluxes f_0 and f_1 by fit to F_2 data

$\to F_2^{charm}$ described by hard $I\!P$ only

$2I\!P$ + dipoles (Donnachie, Dosch)

proton as q di-q system

small (large) dipoles couple to hard (soft) $I\!P$

parameter from F_2 and pp interactions

$\to (F_2), F_L, \sigma_{\gamma p}^{tot}, F_2^{charm}, \gamma p \to J/\psi p, \gamma^* p \to \gamma p$ (DVCS) $\cdots$

Vector Dominance + colour dipoles (Schildknecht)

$\to \sigma_{\gamma p}^{tot}, F_2$

colour dipole models

$\gamma^* \to q\bar{q}, q\bar{q}g \quad \times \quad$ dipole-p cross section

e.g. 'semi-classical model' (Buchmüller, Gehrmann, Hebecker)

non-perturbative interaction with proton colour field

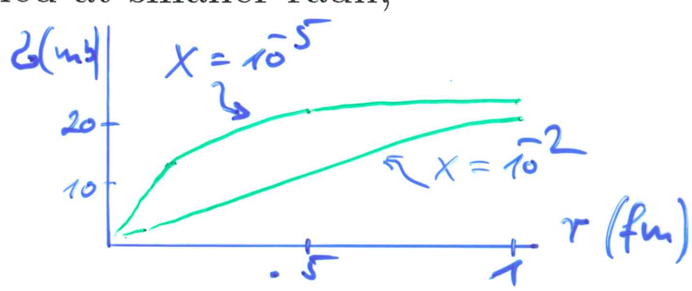
e.g. 'saturation model' (Golec-Biernat, Wüsthoff)

saturation at large radii, i.e. small Q^2, p_t^2

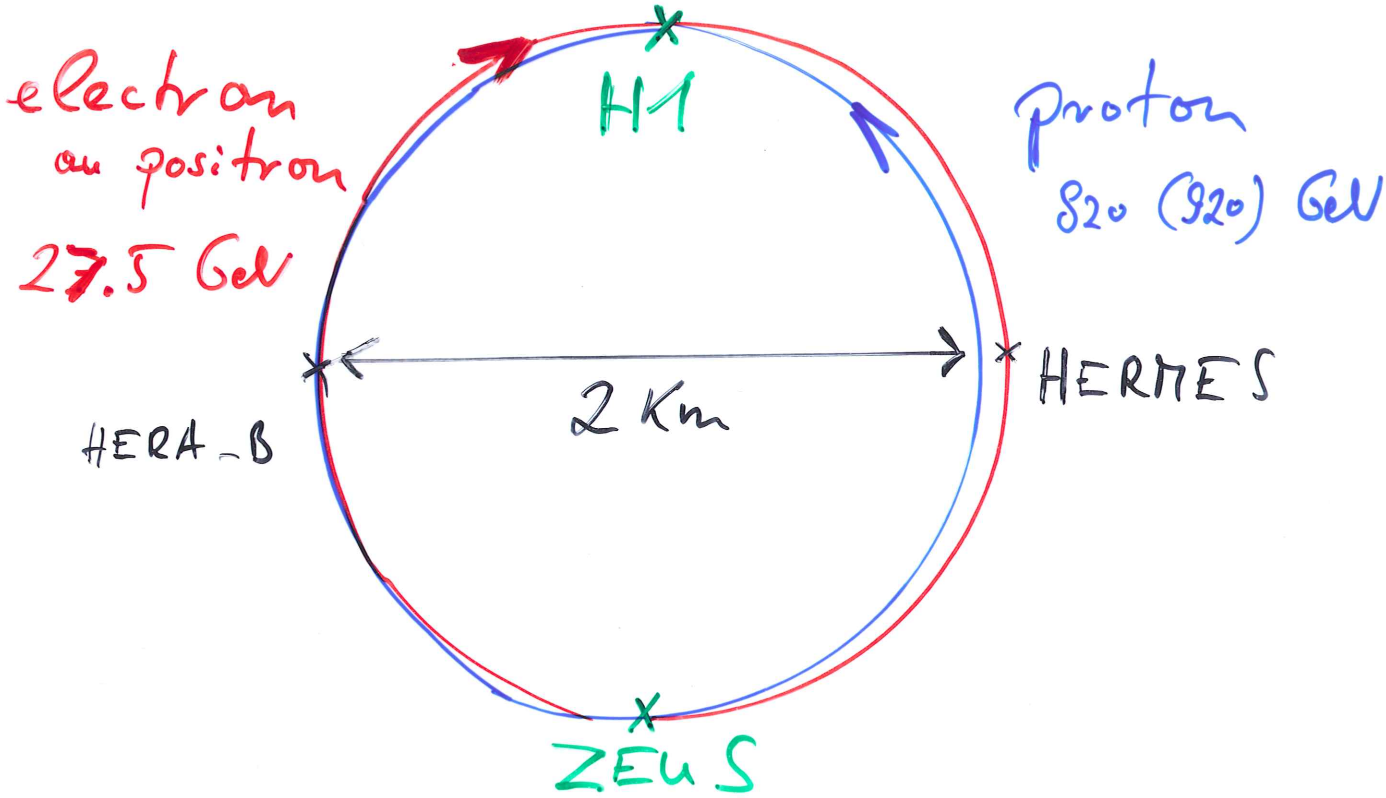
at smaller x_{Bj}, saturation is reached at smaller radii,

i.e. already at larger Q^2, p_t^2.

$\to F_2$, inclusive diffraction

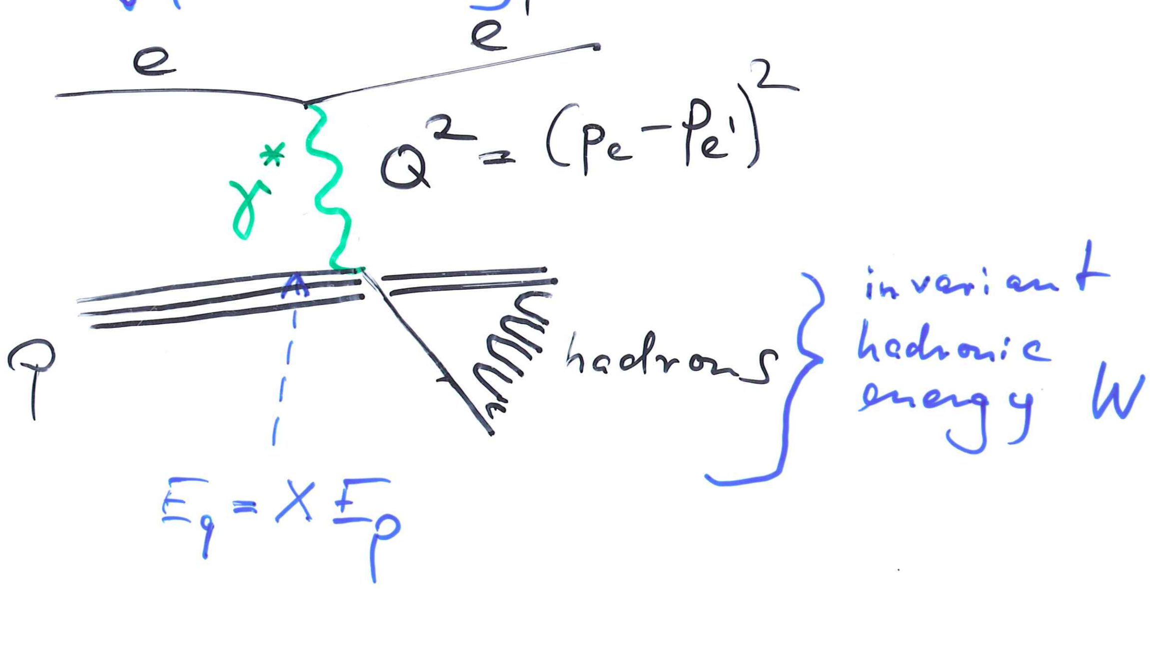


HERA, Hamburg, Allemagne



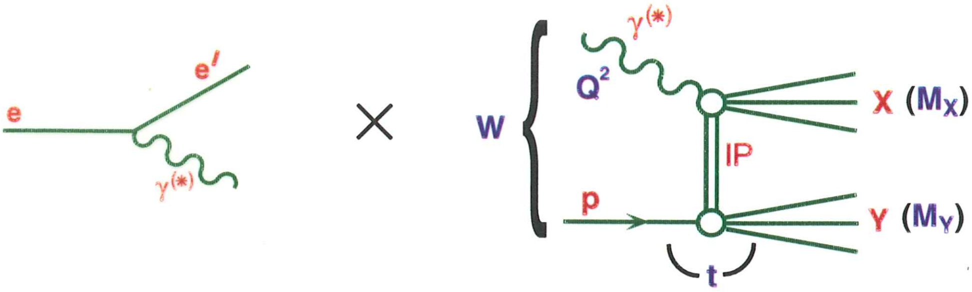
DESY Laboratory

virtual $\gamma^* p$ scattering:

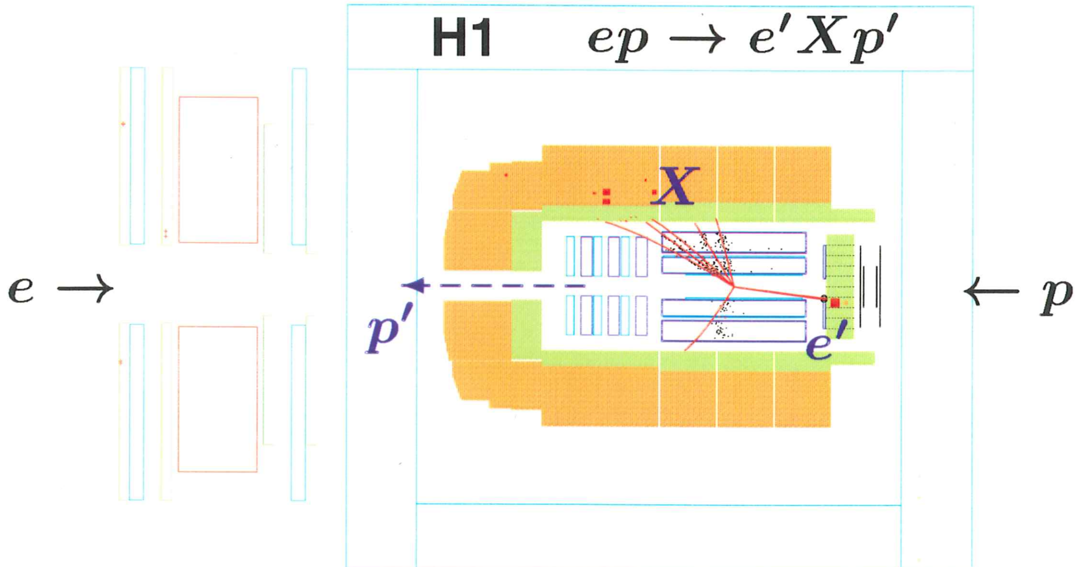


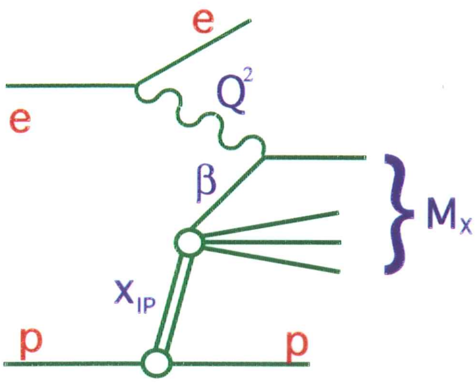
Diffraction at HERA

diffractive $\gamma^{(\star)}p$ interactions



discuss here large Q^2, low $|t|$, $Y = p$





$$x_{I\!P} = \frac{q.(p-p')}{q.p} = x_{(I\!P/\mathrm{p})}$$

$$\beta = \frac{Q^2}{q.(p-p')} = x_{(\mathrm{q}/I\!P)}$$

$$(x = x_{I\!P}\,\beta)$$

Diffraction of Virtual Photons, $\gamma^{\star}p \rightarrow Xp$

Two complementary measurement techniques :

1. Require large rapidity gap separating p from X

   reconstruct kinematics from X

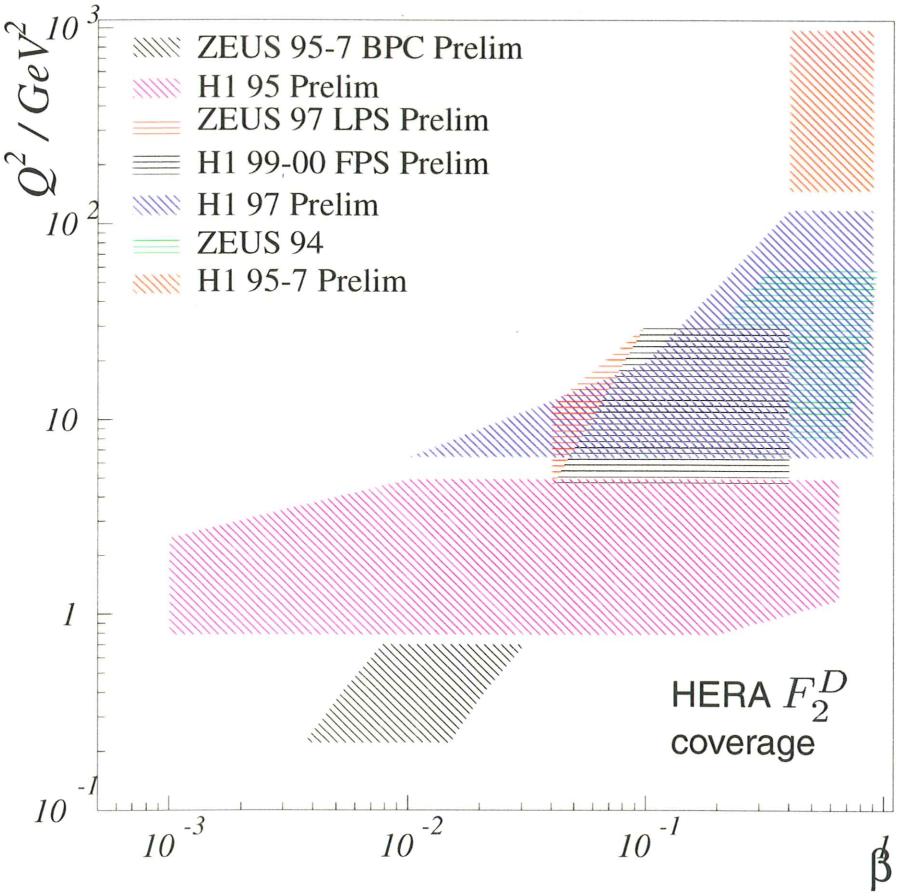
2. Direct measurement of Leading Protons

   results support the gap selection method

Data presented as a Diffractive Structure Function

$$F_2^{D(3)}(\beta, Q^2, x_{I\!P}) = \frac{\beta\, Q^4}{4\pi\alpha^2\ (1-y+y^2/2)}\ \frac{d\sigma_{ep\rightarrow eXY}}{d\beta\ dQ^2\ dx_{I\!P}}$$

(Assumes $F_L^{D(3)} = 0$)



New H1 data

$6.5 \leq Q^2 \leq 120\ \mathrm{GeV}^2$,

$0.04 \leq \beta \leq 0.9$

$x_{I\!P} < 0.05$

Selected by demanding large rapidity gap

Integrated over

$M_Y < 1.6\ \mathrm{GeV}$,

$|t| < 1\ \mathrm{GeV}^2$

Factorisation Properties of $F_2^{D(3)}$

QCD Hard Scattering Factorisation for Diffractive DIS:-

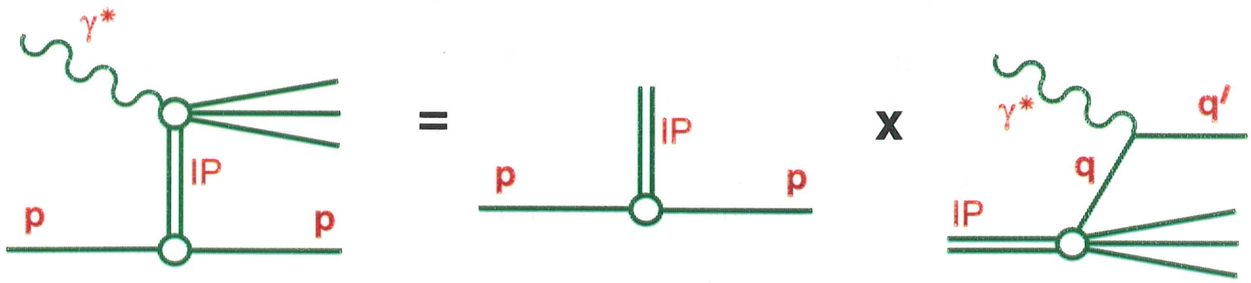
(Trentadue, Veneziano, Berera, Soper, Collins ...)
Diffractive parton densities $f(x_{I\!P}, t, x, Q^2)$ express proton parton probability distributions with intact final state proton at particular $x_{I\!P}, t$ ...

$$\sigma(\gamma^* p \to Xp) \sim \sum_i f_{i/p}(x_{I\!P}, t, x, Q^2) \otimes \hat{\sigma}_{\gamma^* i}(x, Q^2)$$

At fixed $x_{I\!P}, t$, $f(x_{I\!P}, t, x, Q^2)$ evolve with x, Q^2 according to DGLAP equations.

'Regge' Factorisation:-

Soft hadron phenomenology suggests a universal *pomeron* ($I\!P$) exchange can be introduced, with flux dependent only on $x_{I\!P}, t$ (Donnachie, Landshoff, Ingelman, Schlein ...)



$$\sigma(\gamma^* p \to Xp) \sim f_{I\!P/p}(x_{I\!P}, t) \otimes F_2^{I\!P}(\beta, Q^2)$$

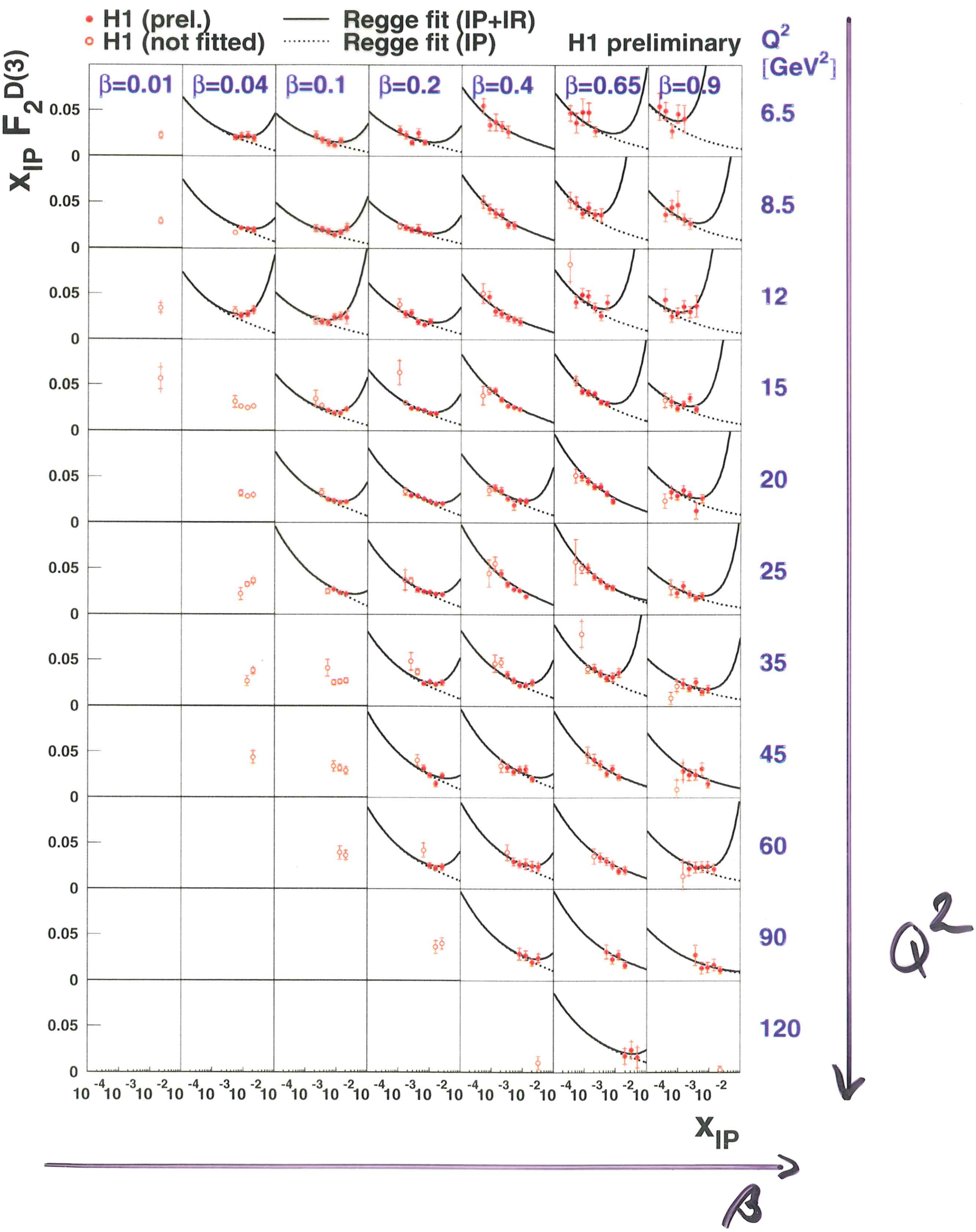
$$\sim f_{I\!P/p}(x_{I\!P}, t) \otimes \sum_i f_{i/I\!P}(\beta, Q^2) \otimes \hat{\sigma}_{\gamma^* i}(\beta, Q^2)$$

‘Regge’ Fits to H1 1997 F_2^D Data

Test ‘Regge’ fac’n by fitting $x_{I\!P}$ dependence at fixed β, Q^2.

Data well described by exchange of two universal trajectories $I\!P$ and $I\!R$ ($\chi^2/\mathrm{ndf} = 0.95$).

No evidence for variation of $\alpha_{I\!P}(0)$ with β, Q^2.



Variation of Energy Dependence with Q^2

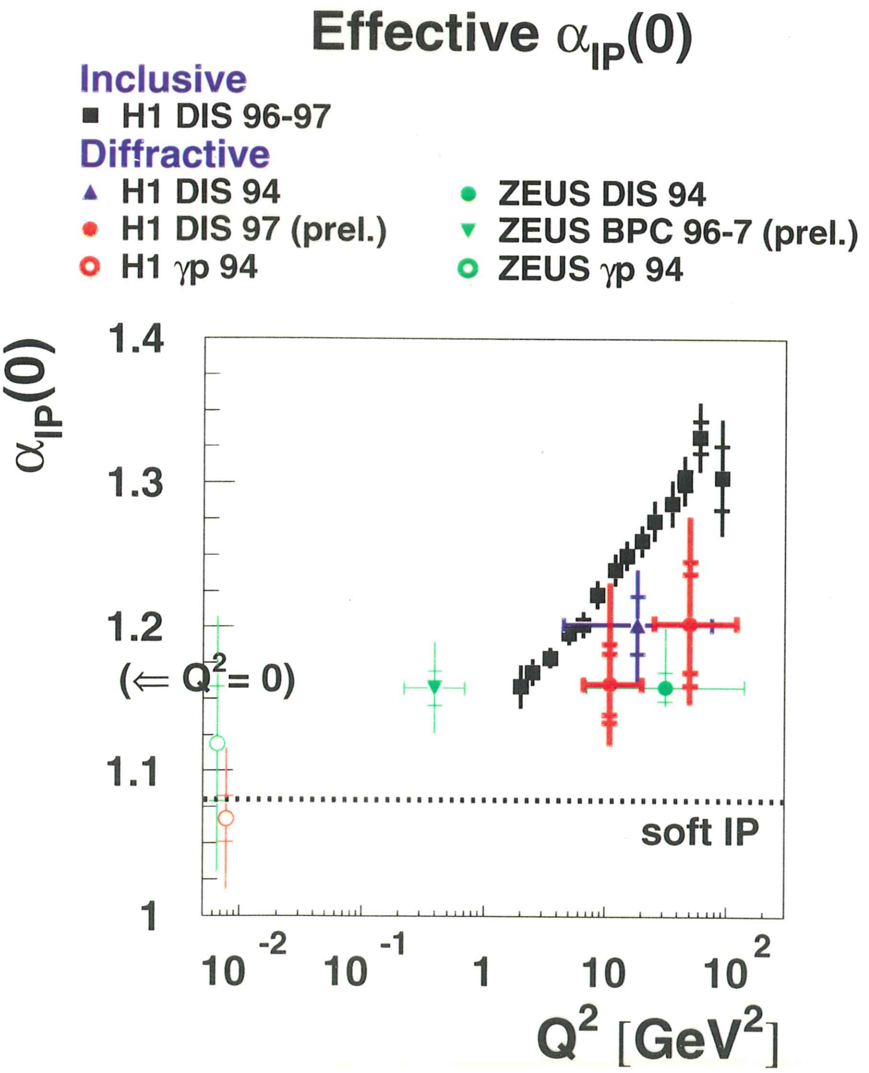
$\alpha_{I\!P}(0) = 1.173 \pm 0.018\,(\text{stat.}) \pm 0.017\,(\text{syst.})\ ^{+0.063}_{-0.035}\,(\text{model})$

Compatible results if data divided into two Q^2 ranges

Compare effective $\alpha_{I\!P}(0)$ from F_2^D and F_2

$x_{I\!P}\, F_2^D \sim A(\beta, Q^2)\ x^{2-2\langle\alpha_{I\!P}(t)\rangle}$ $\qquad$ $F_2 \sim C(Q^2)\ x^{1-\alpha_{I\!P}(0)}$

$C(Q^2)\, x^{-\lambda}$



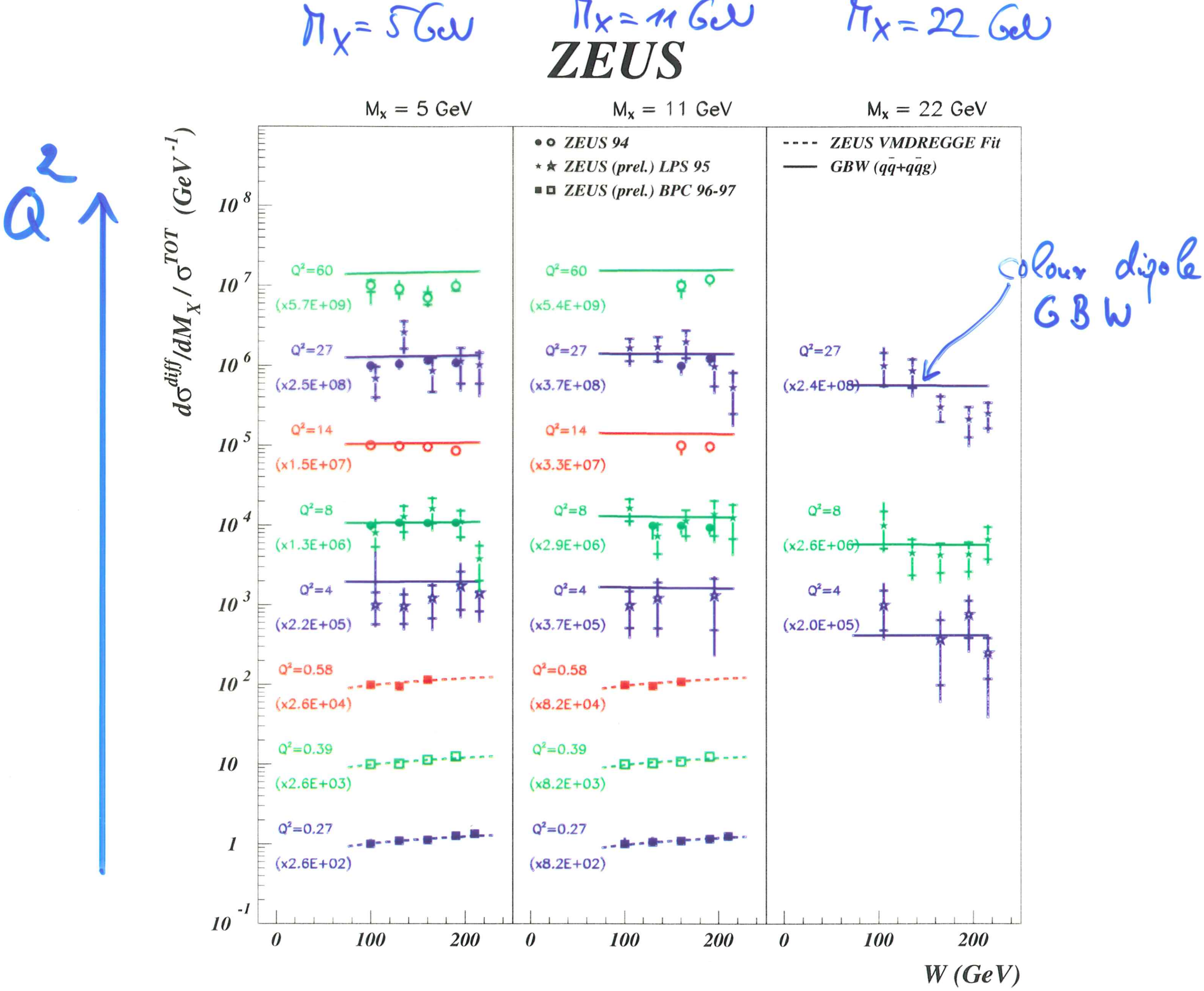
$\alpha_{I\!P}(0)$ grows with Q^2, gets larger than soft $I\!P$

Effective $\alpha_{I\!P}(0)$ seems to grow slower than in inclusive ep

Energy dependences of diffractive and inclusive cross sections become similar at large Q^2 !

Energy Dependence of Diffractive to Inclusive Ratio

ZEUS data on diffractive / inclusive ratio over wide Q^2 range.



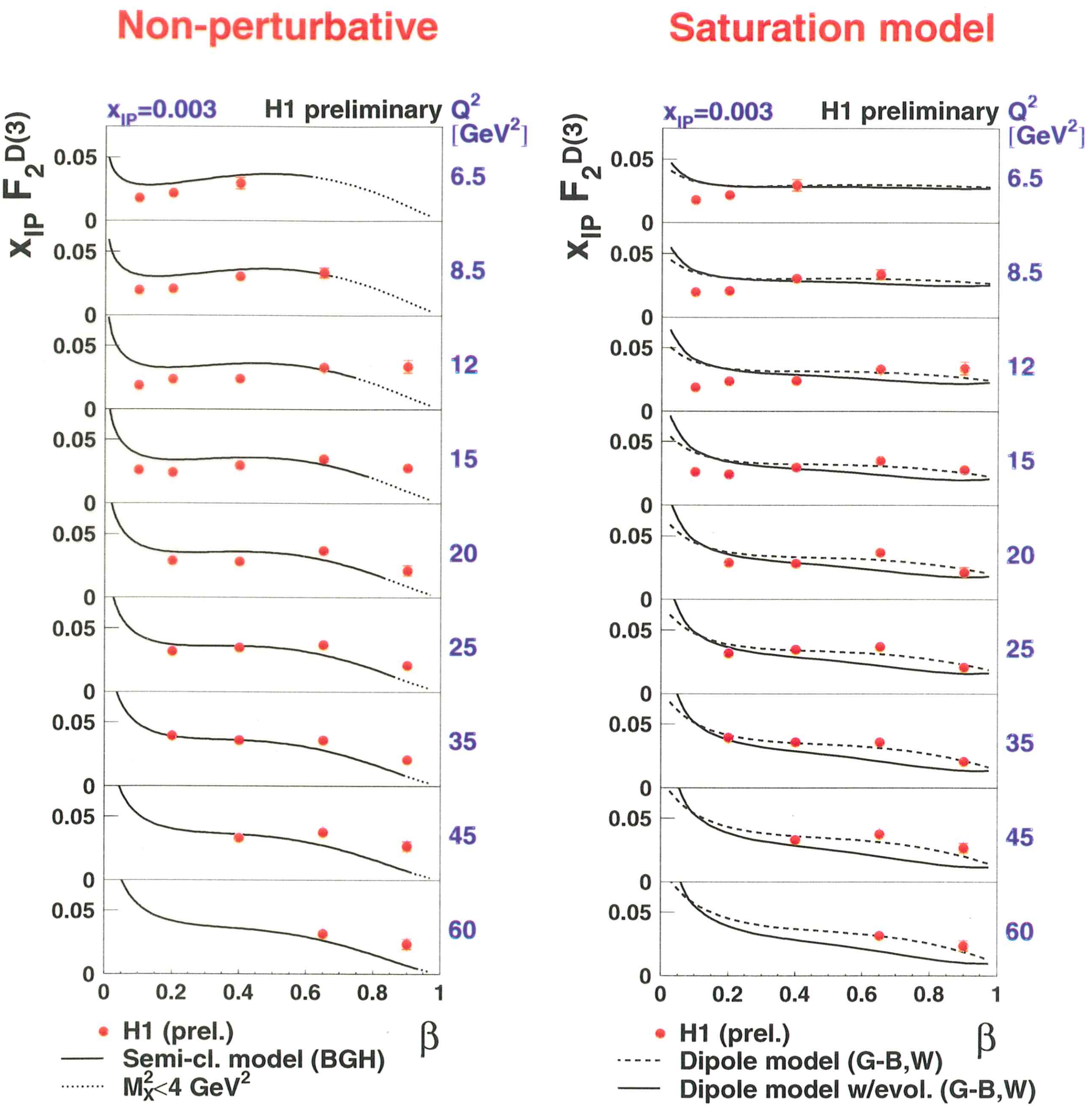
Fits to $\frac{\int dt \;\; d\sigma^{\mathrm{diff}}_{\gamma^* p \to XY} / dM_X \;\; dt}{\sigma^{\mathrm{tot}}_{\gamma^* p \to X}} \propto W^{\rho}$

$\rho = 0.24 \pm 0.07\,(\mathrm{stat}) \quad (0.27 \leq Q^2 \leq 0.58\ \mathrm{GeV}^2)$

$\rho = 0.00 \pm 0.03\,(\mathrm{stat}) \quad (Q^2 \geq 4\ \mathrm{GeV}^2)$

expect $\rho > 0$, for a common $\alpha_{I\!P}(0)$

Colour Dipole Models



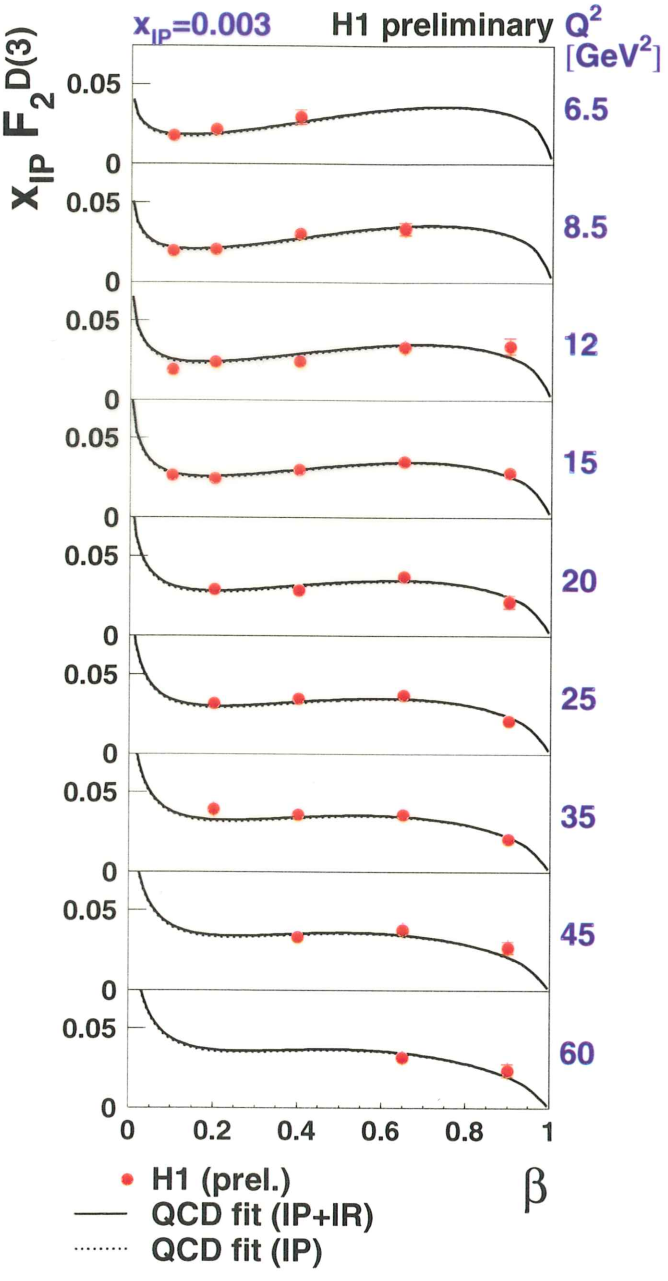
both models (constrained by F_2 data) describe general features,

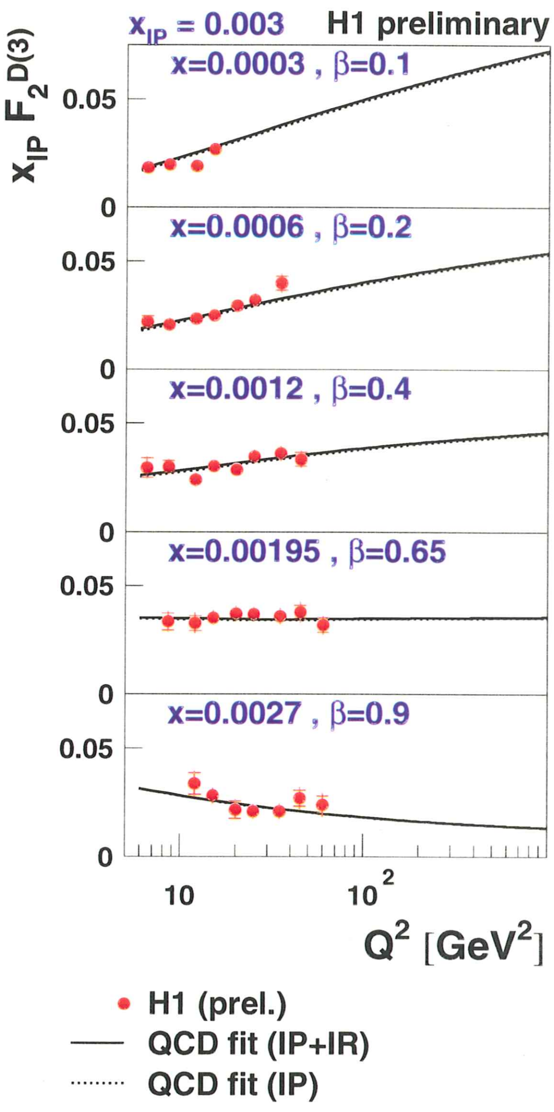
both high at low Q^2 , low β.

Saturation models describe data better at high β (higher twist), but Q^2 evolution does not help.

β, Q^2 dependence of $F_2^{D(3)}$

Example results at $x_{I\!P} = 0.003$



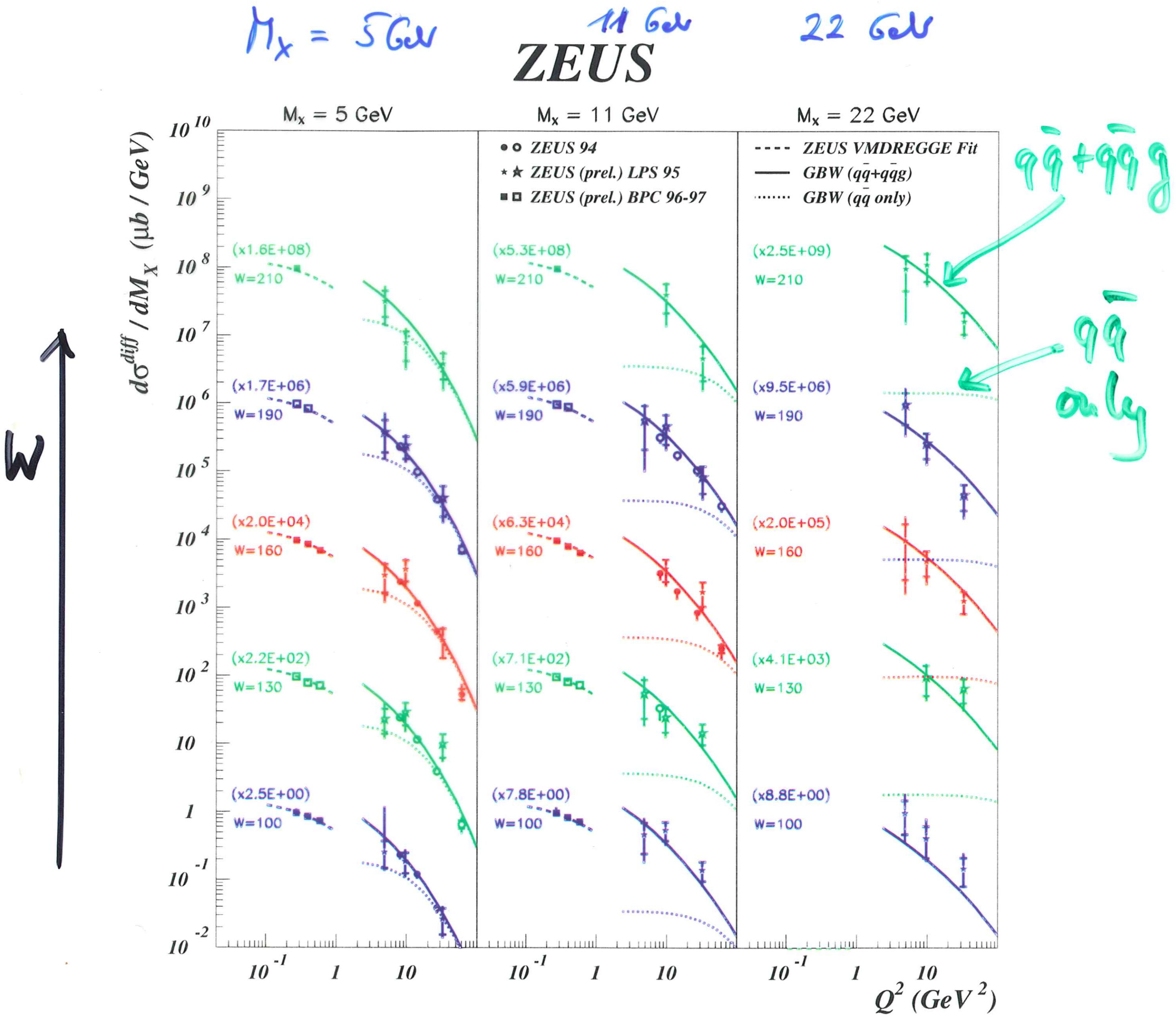


β dependence relatively flat.

Rising scaling violations with $\ln Q^2$ up to large β.

Large gluon component required by DGLAP QCD fit (for pdf's of $I\!P$) extending to large fractional momenta β .

Colour Dipole Model (saturation GBW)

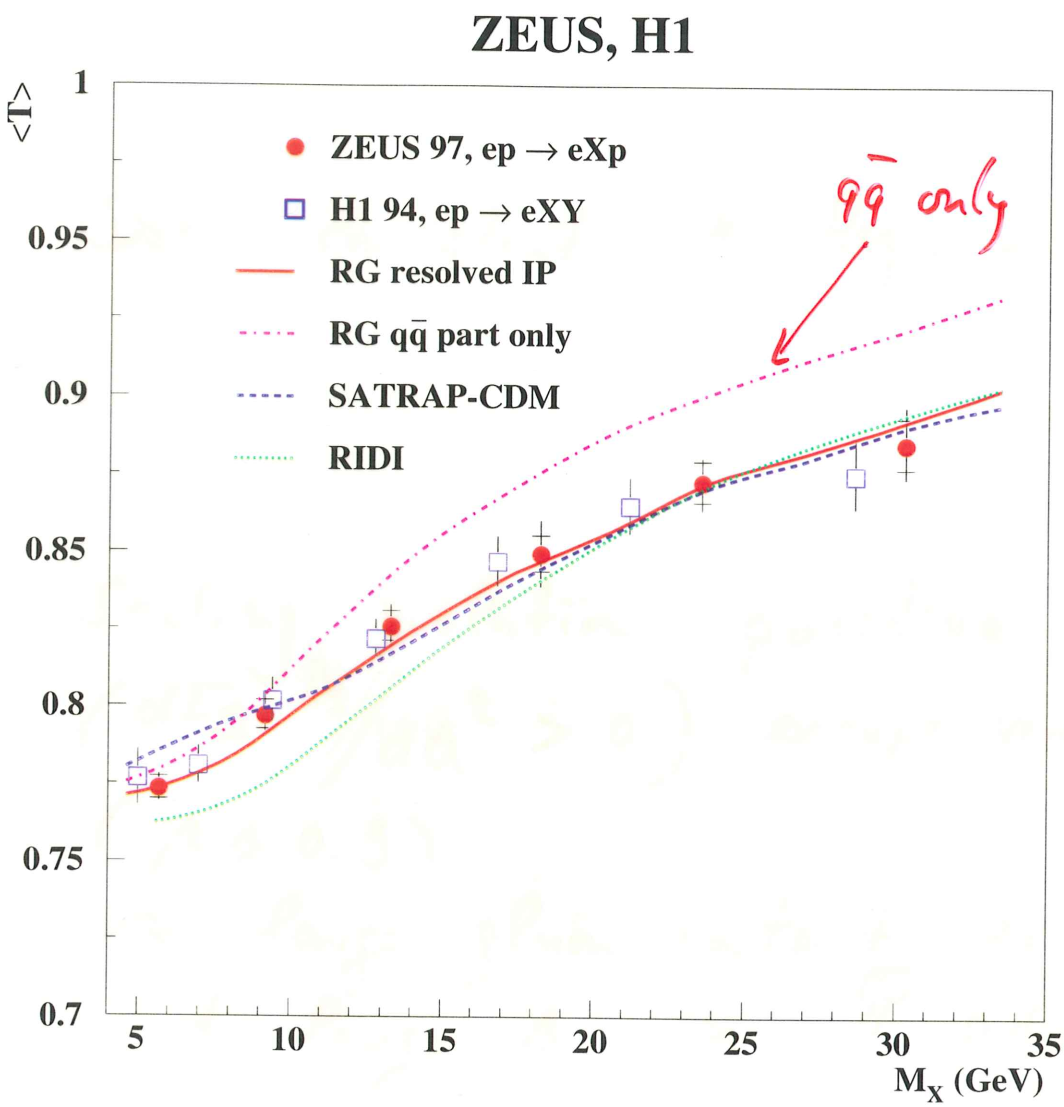


Good description for $Q^2 \geq 4\,\mathrm{GeV}^2$

Model not yet describing $Q^2 \leq 1\,\mathrm{GeV}^2$

$q\bar{q}g$ photon fluctuation dominant at large M_X (i.e. small β)

Final State in inclusive diffraction, example of thrust



Events more collimated with increasing M_x

Monte Carlo models based on

resolved $I\!P$ (RAPGAP, H. Jung)

or photon dissociation models

(2 gluon exchange, RIDI, Ryskin)

(SATRAP, H. Kowalski, H. Jung, incorporating colour dipole model, Golec-Biernat, Wüsthoff)

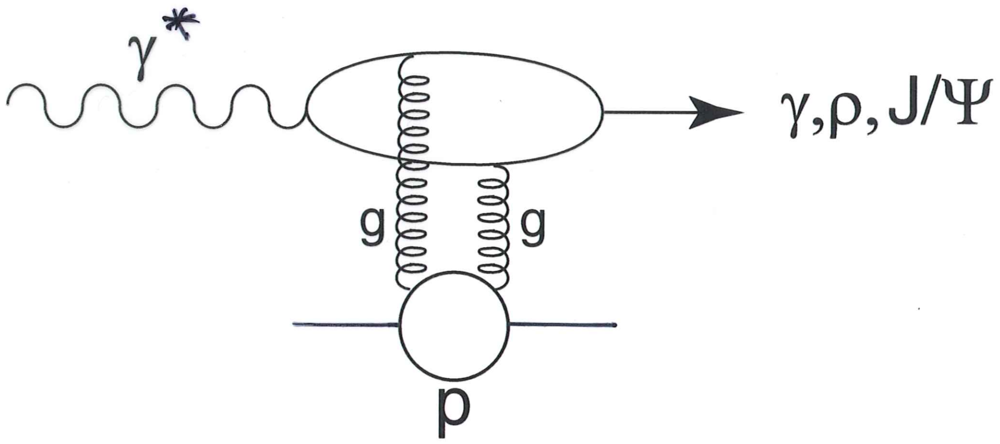
describe main features of final state.

Summary Inclusive Diffraction

- Copious new F_2^{D3} data, improving precision
- Data consistent with Regge factorization
- Effective $\alpha_{I\!P}$ larger than soft $I\!P$ at large Q^2
- Scaling violation positive ($dF_2^{D3}/dQ^2 > 0$) except very large β ($\beta \gtrsim 0.5$)
  $\rightsquigarrow$ large gluon content extending to large β in $I\!P$ pdfs
- $\gamma^* p$ cms energy dependence of diffractive and total cross section similar at large Q^2
- dipole models give reasonable description of data (not all details yet)

Elastic production of Vector particles

in simple picture of 2 gluon exchange :



Final state is similar to initial state

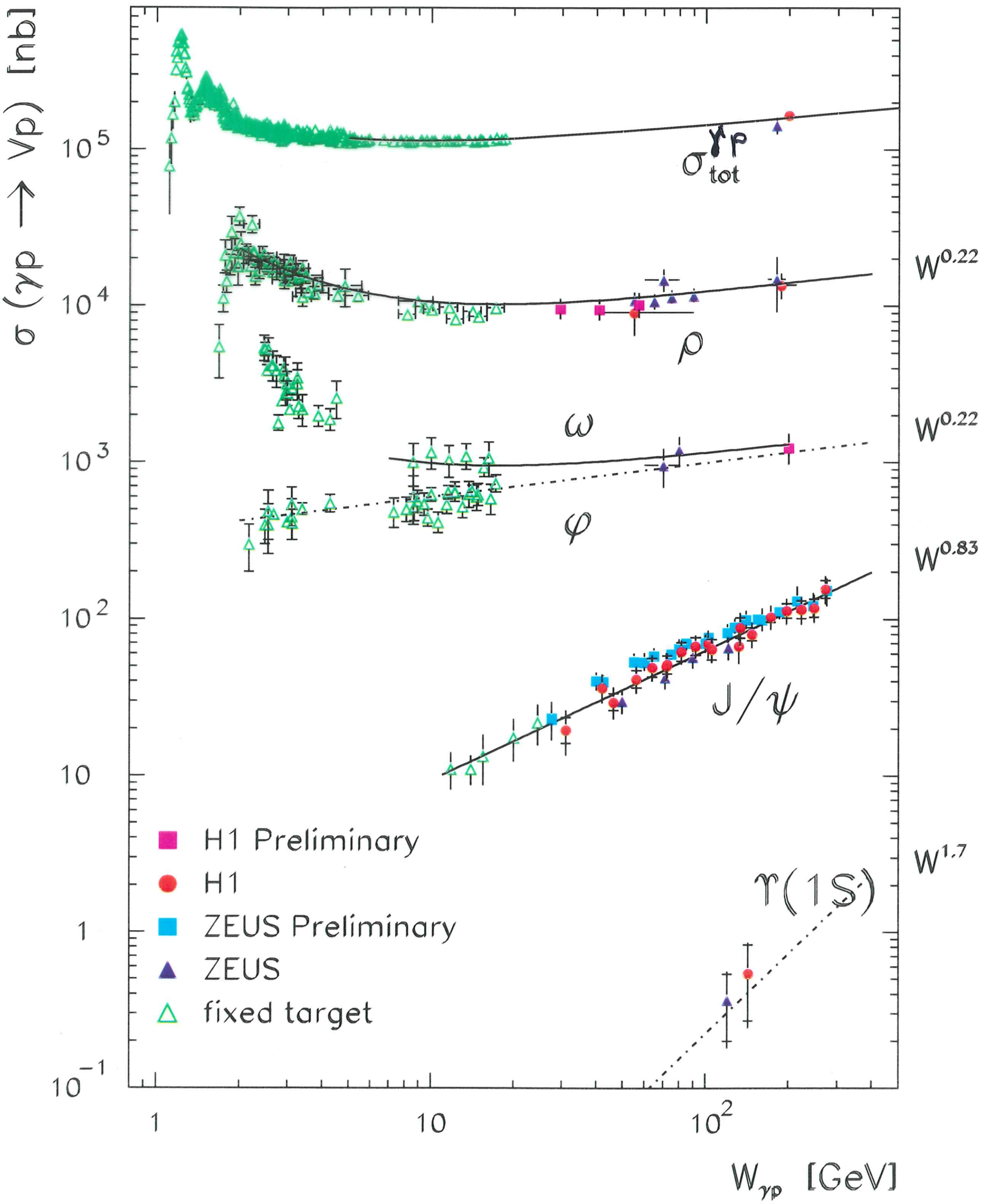
→ (optical theorem)

reaction in close relation to $\sigma^{tot}_{\gamma^* p}$ (i.e. to F_2)

possible to change transverse interaction radius

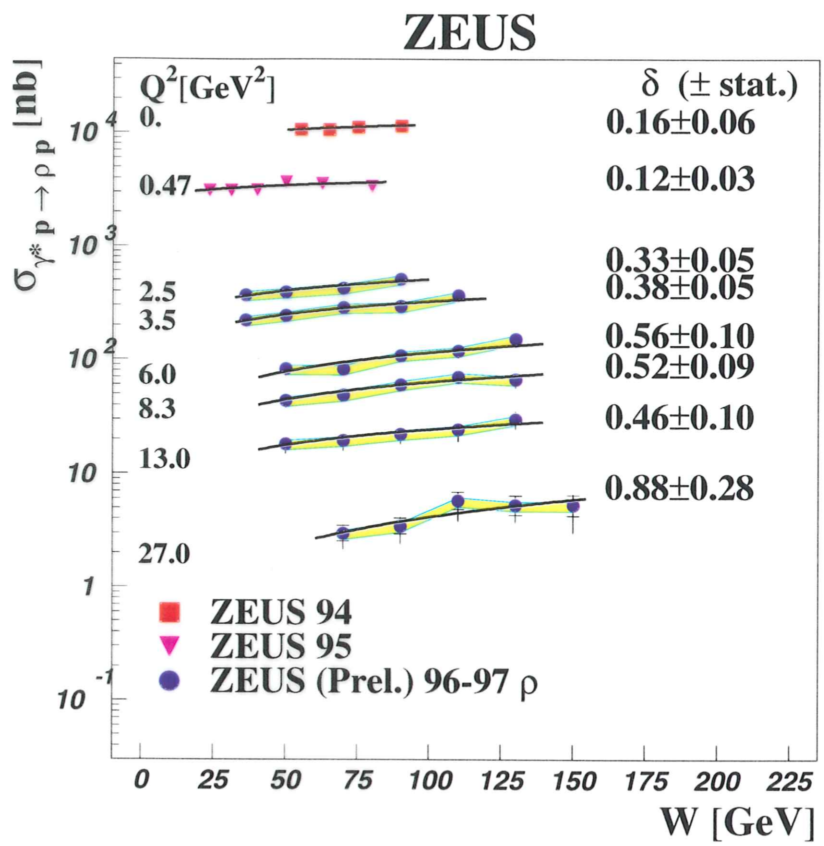
by change of Q^2 and particle mass

Vector Mesons, $Q^2 = 0$

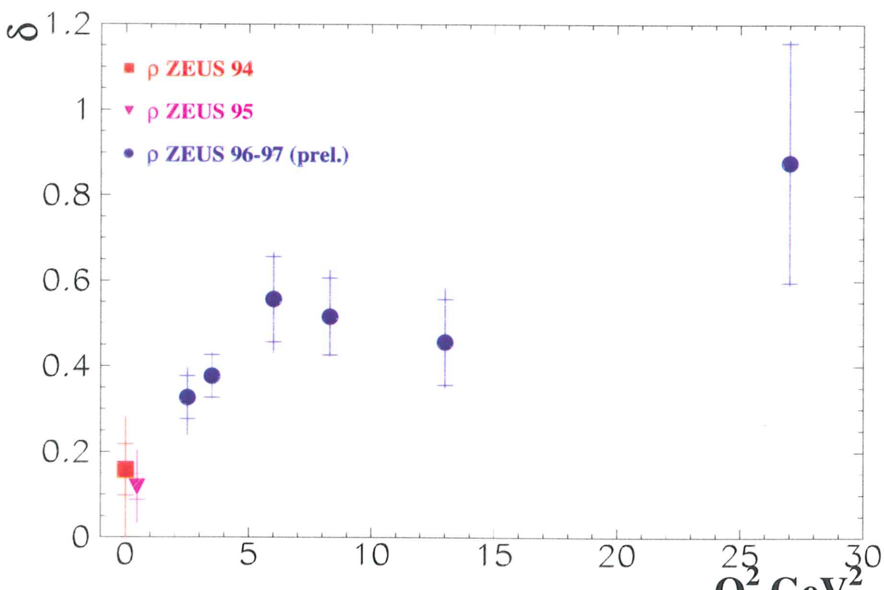


steeper rise with W for large VM masses

Energy dependence of ρ production for different Q^2



$\sigma \sim W^\delta$

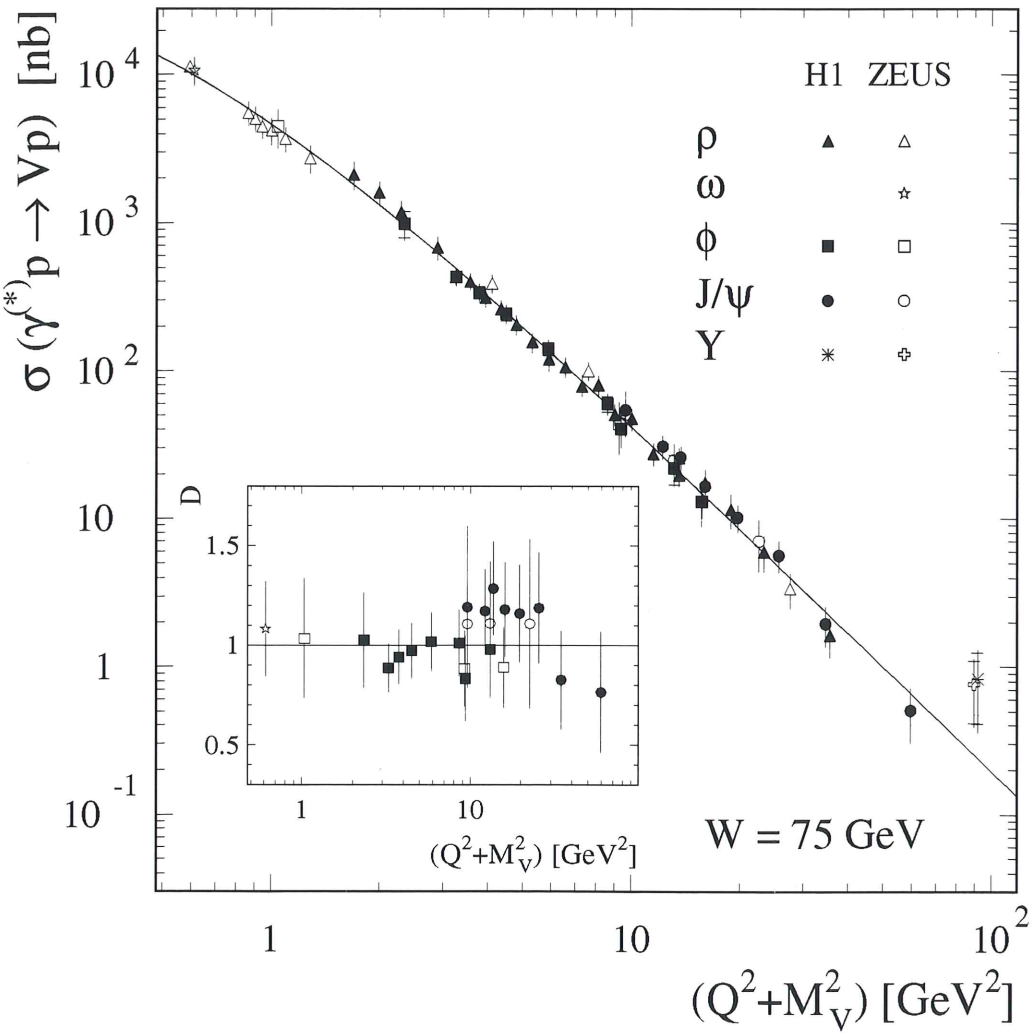


steeper W rise with increasing Q^2

Dependence on $Q^2 + M_V^2$

Cross sections scaled by SU(4) factors:

$\rho^0 : \omega : \Phi : J/\Psi = 9 : 1 : 2 : 8$

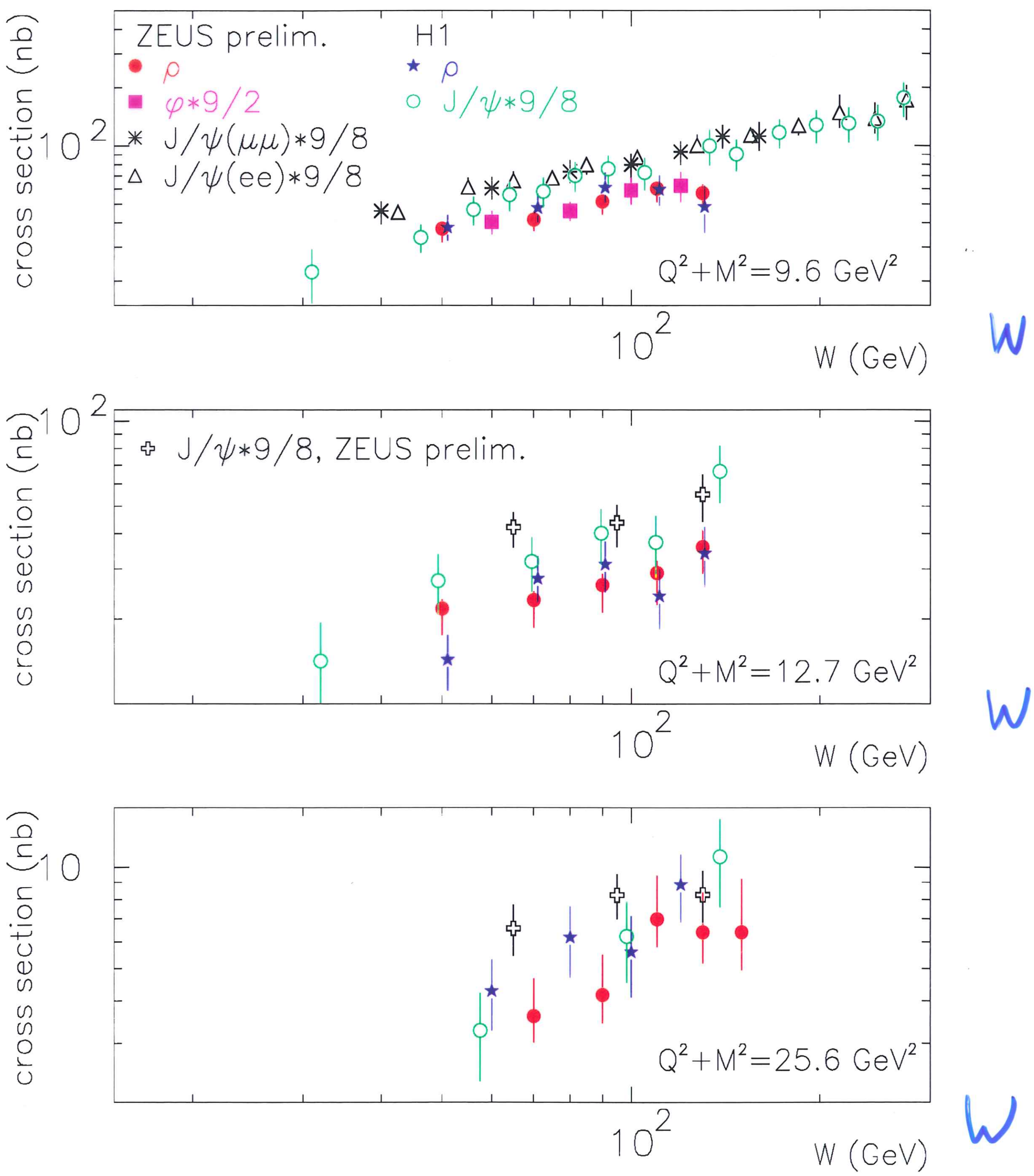


relevant mass ~ $Q^2 + M_V^2$

beautiful plot

but δ_ℓ and δ_t enter

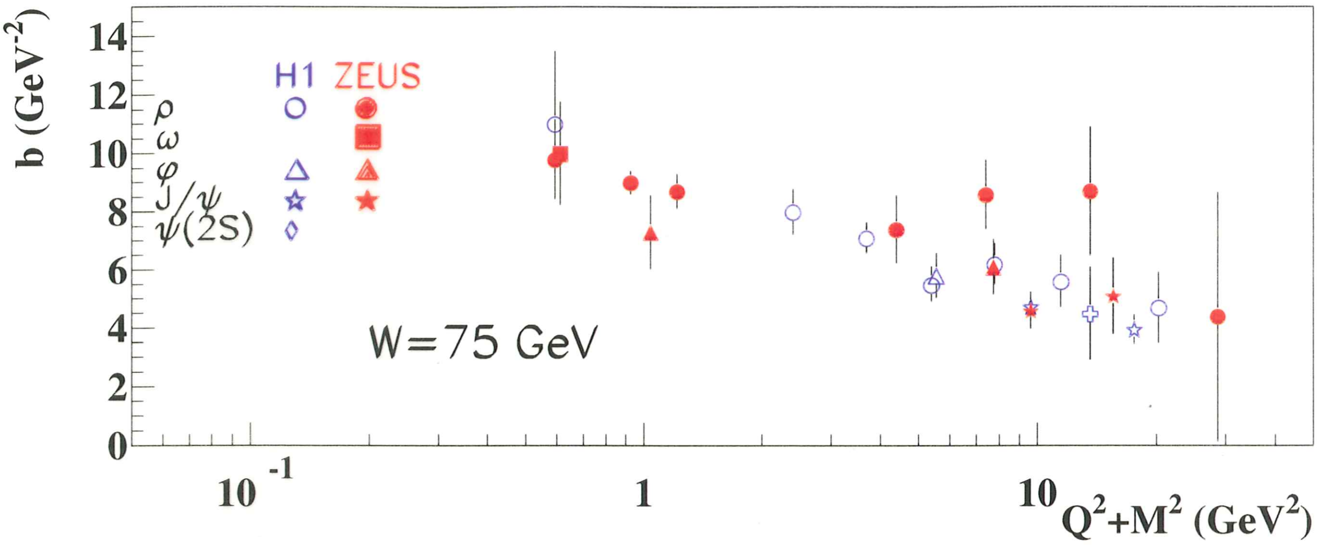
More data on scaling with $Q^2 + M_V^2$



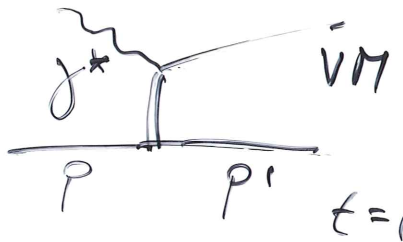
closer look reveals differences

J/ψ cross section above SU(4) scaling

b slopes of vector mesons



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



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

$b \sim R^2$ transverse size of interaction region

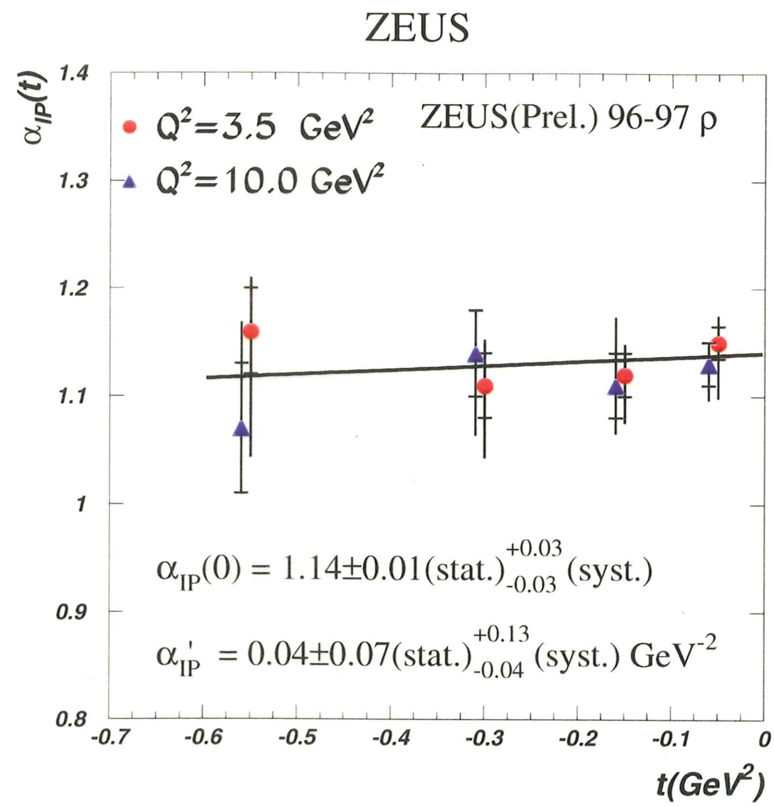
$R \downarrow$ if $Q^2 + M^2 \uparrow$

Is effective size increasing with energy also at large Q^2, M_V^2 ?

(as seen in soft hadronic interactions)

Trajectories

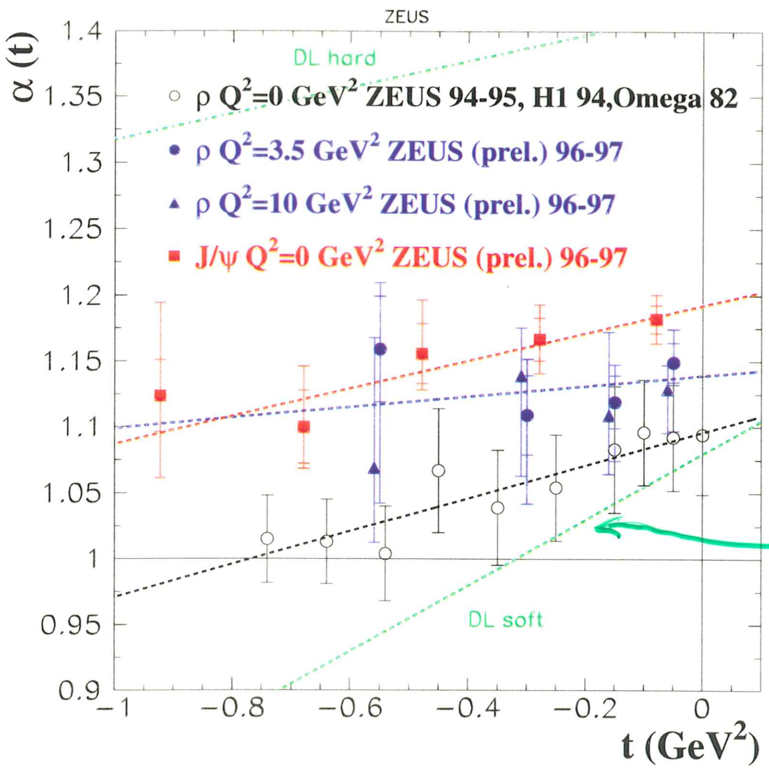
study W dependence for different t



for comparison
soft hadronic interactions
(DL):

$\alpha_{I\!P} \approx 1.08$

$\alpha'_{I\!P} \approx 0.25\ \text{GeV}^{-2}$

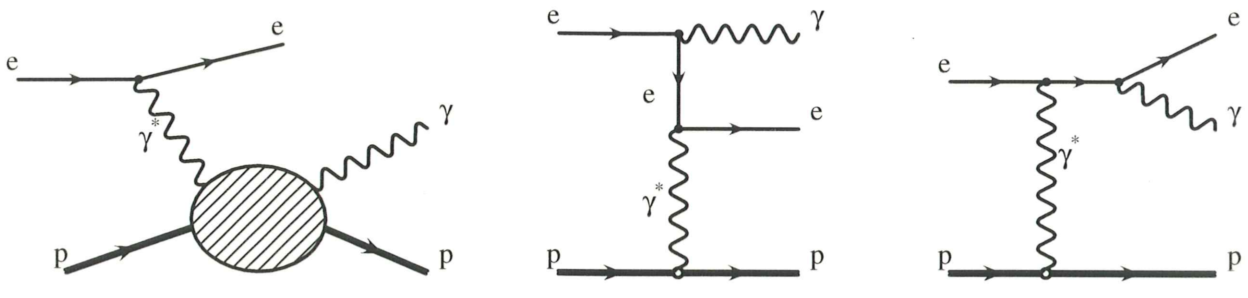


DL soft P

data: $\rho^0 (Q^2 > 0)$, J/ψ :
interaction radius may increase with E
but less than expected from soft hadr. processes

DVCS, Deep Virtual Compton Scattering

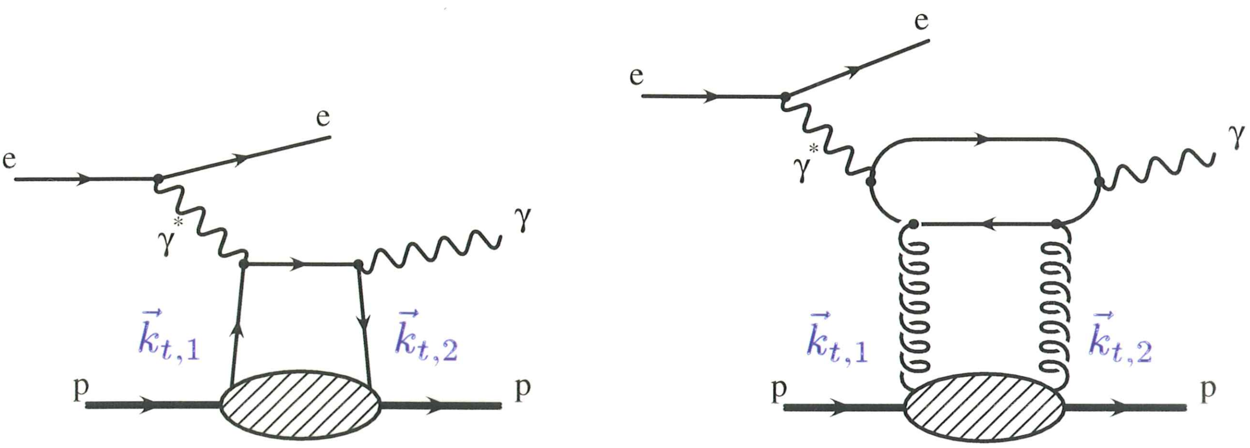
DVCS　　　　　　Bethe Heitler



a)　　　b)　　　c)

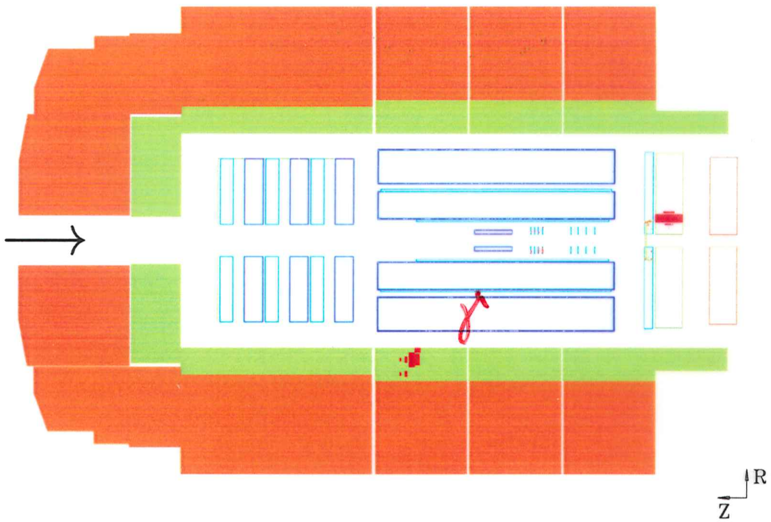
interest :

- light scattering off quarks, clean diffractive process
- proton vertex similar as in VM production, but no complication by quark wave functions of VM state
- experimental access to SPDs (Skewed or generalized Parton Distributions) of proton



a)　　　b)

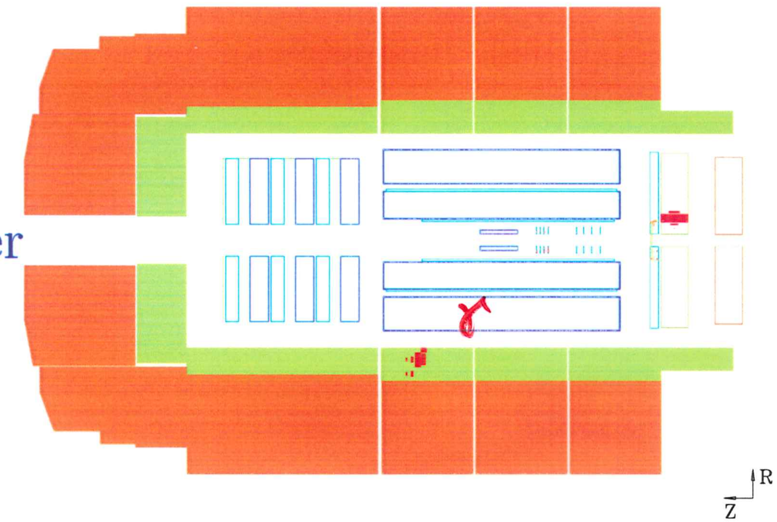
Analysis strategy

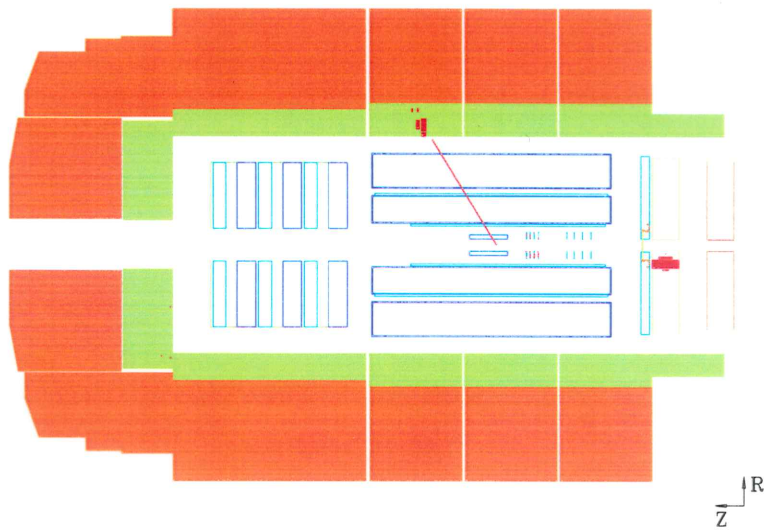
- DVCS $e^+ \longrightarrow$  $\longleftarrow p$

γ–sample

e^+–sample

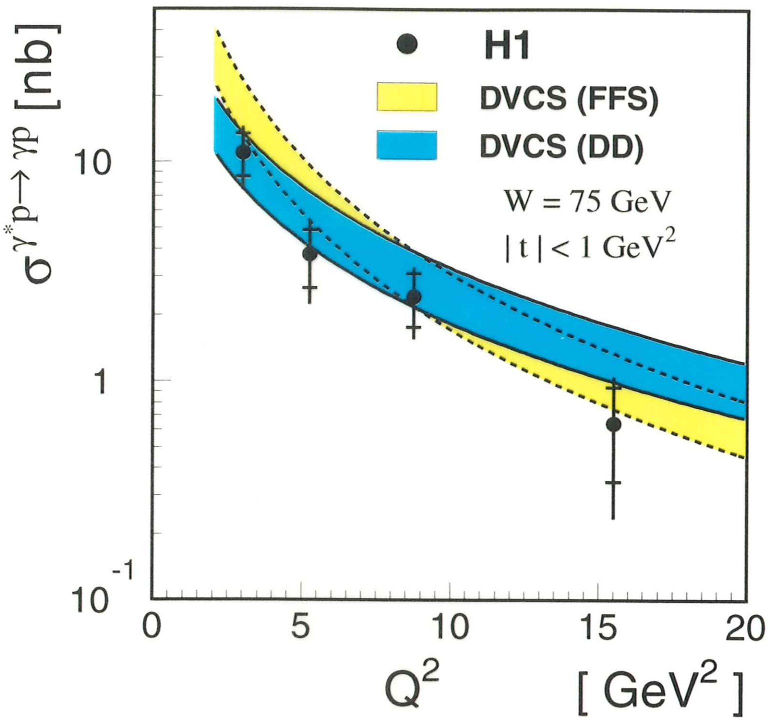
- Bethe-Heitler





DVCS results (H1)

$\gamma^* p \to \gamma p$ cross sections (Bethe-Heitler process subtracted)



FFS

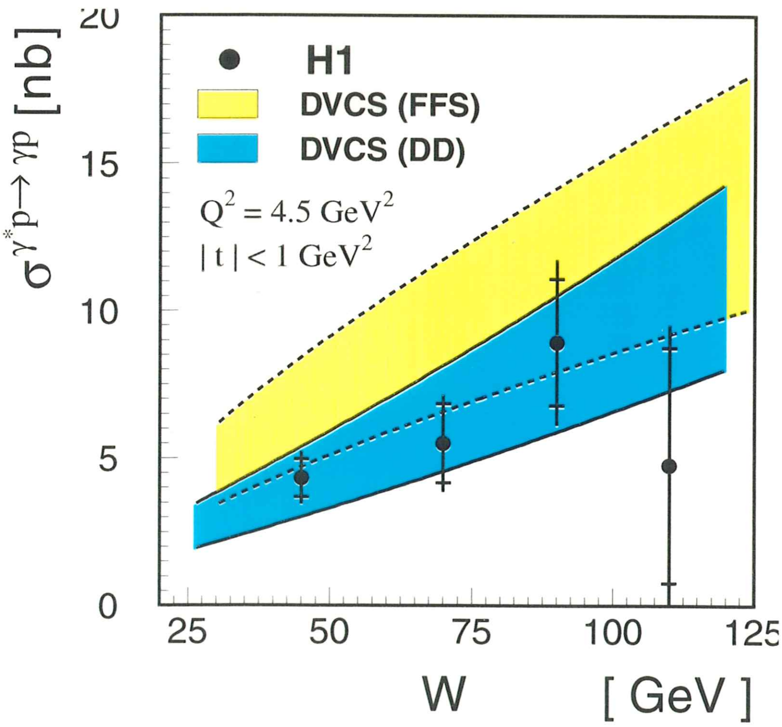
(Frankfurt, Freund and Strikman):

QCD model with non-perturbative elements

DD

(Donnachie and Dosch):

$I\!P$ and $I\!R$ exchange and dipole model



bands correspond to assumed t slope variation $5 < b < 9$ GeV^{-2} in models

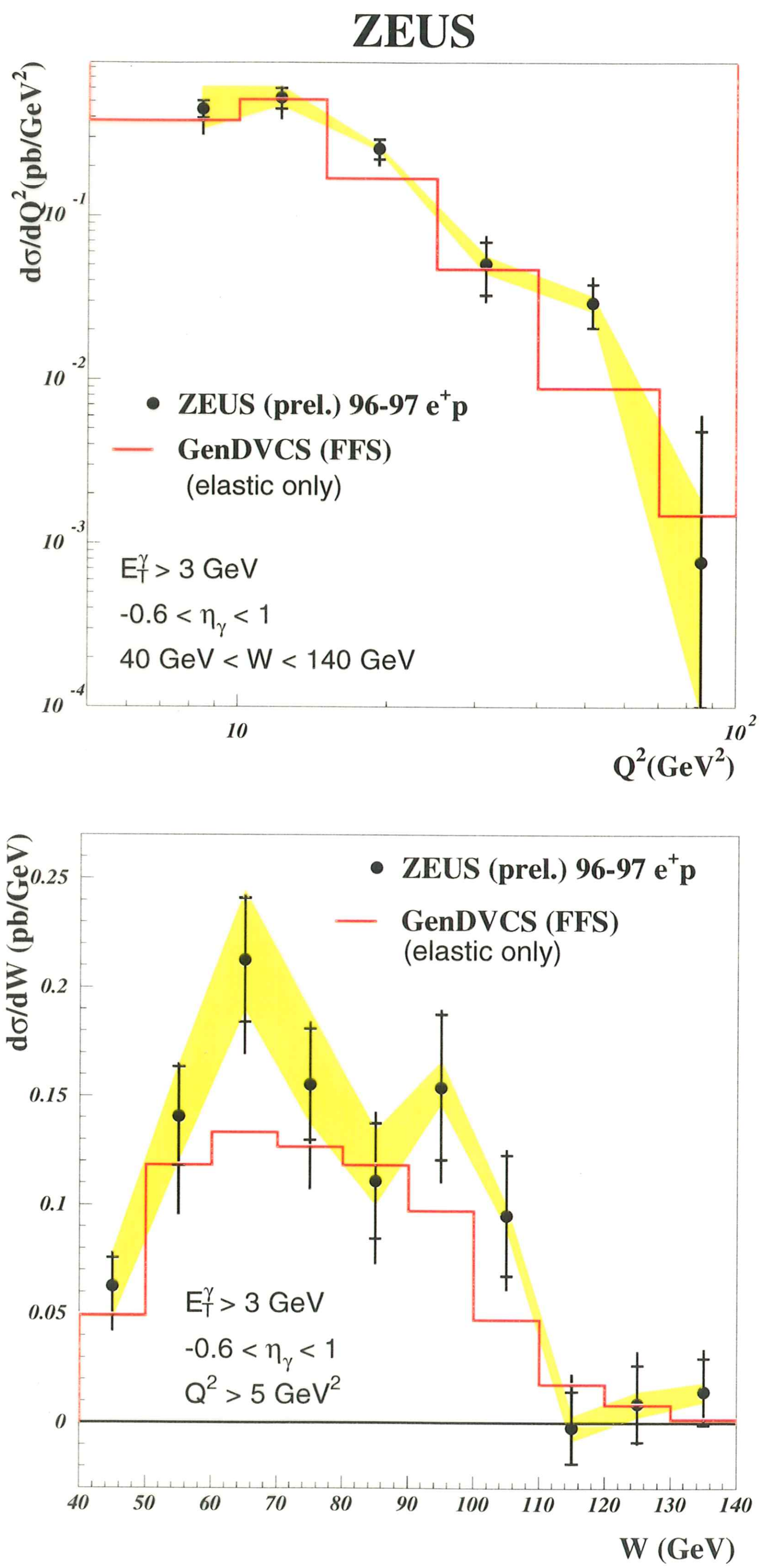
Data described by FFS and DD within errors

NLO comparisons forthcoming (Freund, McDermott)

DVCS results (ZEUS)

Comparison with Monte Carlo based on **FFS**.

Data include proton dissociation estimated to ≈ 20%



data consistent with FFS

Interference of DVCS with Bethe-Heitler
(HERMES)

Interference DVCS $*$ BH $\sim$ $e_L \cdot P_L \cdot \sin(\Phi) \cdot \mathrm{Im}\widetilde{\mathrm{M}}^{1,1}$

e_L lepton charge

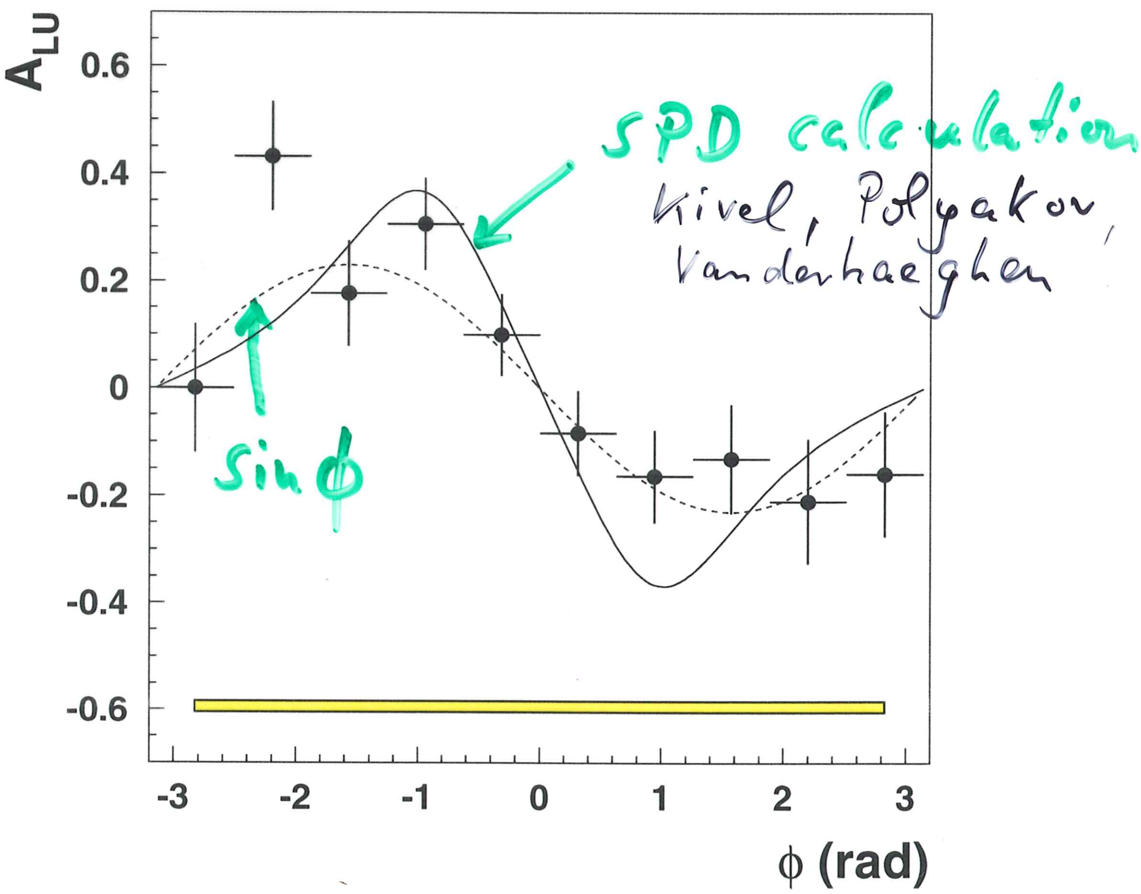
P_L long. lepton beam polarization

Φ azimuth beteeen lepton plane and plane of γ^* and γ

$\widetilde{M}^{1,1}$ combination of DVCS helicity amplitudes

Measure beam spin asymmetry A_{LU} vs. Φ :

$Q^2 > 1\ \mathrm{GeV}^2$, $W^2 > 4\ \mathrm{GeV}^2$



DVCS clearly established
X-section and interference

Data consistent with QCD models

promise constraints on SPD

Conclusions

- HERA provides information on transition short → long distance phenomena
- transition to small Q^2 of $\sigma_{\gamma^* p}$ (F_2) can be described as saturation effect, transition to small x ($Q^2 \gtrsim 2\ \mathrm{GeV}^2$) <u>not</u> at present energies
- colour singlet exchange in diffractive reactions can be described by $\mathbb{P}$ pdfs (resolved $\mathbb{P}$). Data require large gluon component

Conclusion (cont.)

- Vector meson production:
  - energy dependence steep when small transverse objects (J/ψ, ρ^0 at high Q^2)
  - Indication that have little shrinkage, i.e. effective size of interaction not significantly growing with energy
- DVCS
  - interesting new process
  - cross section measured
  - interference with Bethe-Heitler observed
  - new information on proton structure (GPDs)