Proton Structure Results from the HERA Collider

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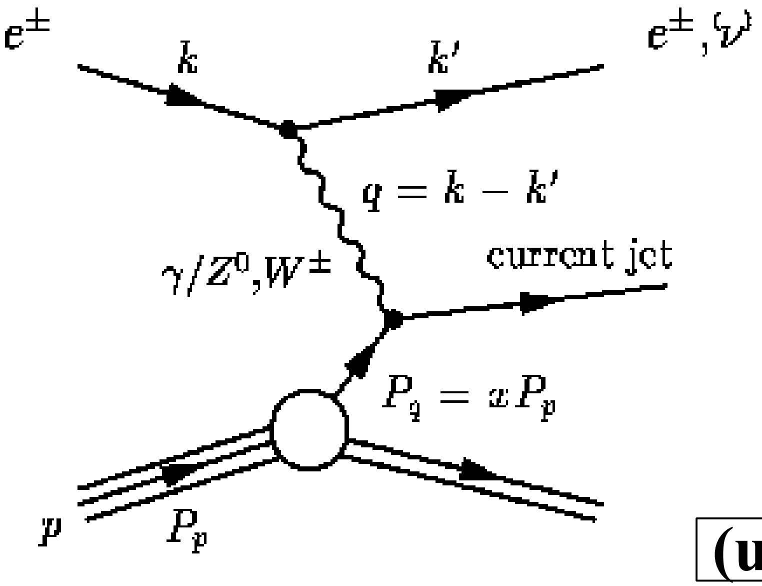
9th International Conference on Structure of Baryons

1. Proton Structure Functions and pQCD analyses
2. DIS cross-section at low x and low Q2
3. DIS diffraction and elastic VM production
4. Conclusions

Structure function and parton distributions:

Deep inelastic scattering



$Q^2 = -q^2$ Virtuality ("size" of probe)

x Mom. fraction of the struck parton.

Factorization: $\sigma_{DIS} \sim f_p(x) \otimes \hat{\sigma}$

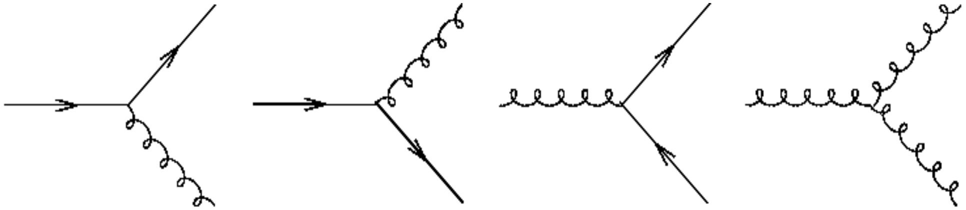
(univeral) parton densities

PQCD cross-sec.

DGLAP evolution equations:

$$\frac{\partial f_p}{\partial \ln Q^2} \sim f_p \otimes P$$

P's are splitting functions:



Str. fcn. and parton dist.:

Neutral Current (γ, Z exchange) interaction

$$\frac{d\sigma^2_{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+ F_2 - y^2 F_L \mp Y_- xF_3)$$

New HERA (H1 and ZEUS) measurements have ca. 3% precision.

$y = Q^2/xs$, the inelasticity parameter, $Y_\pm = (1 \pm (1-y)^2)$

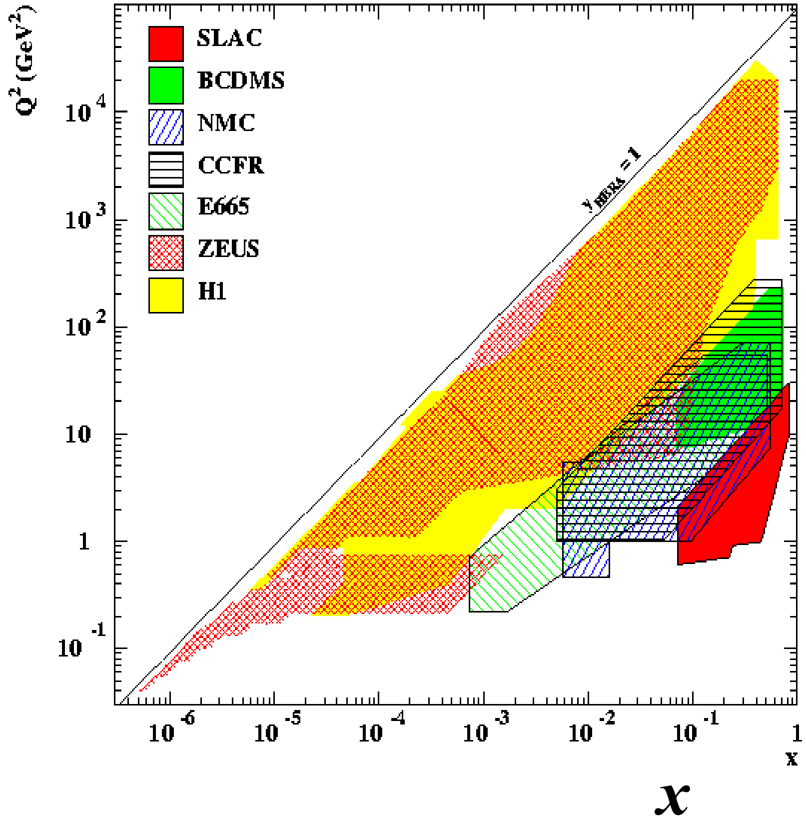
F_2, F_L, and xF_3 are structure functions of the proton.

- F_L: longitudinal component, damped by y^2.
- xF_3: Small at $Q^2 \ll M_Z^2$,

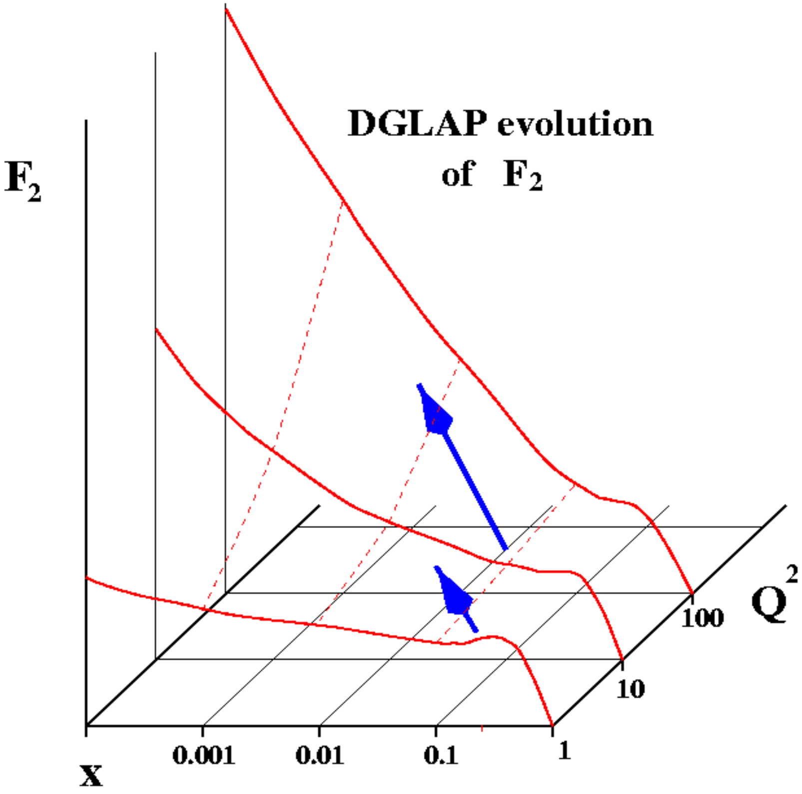
And (LO (or in DIS scheme..))

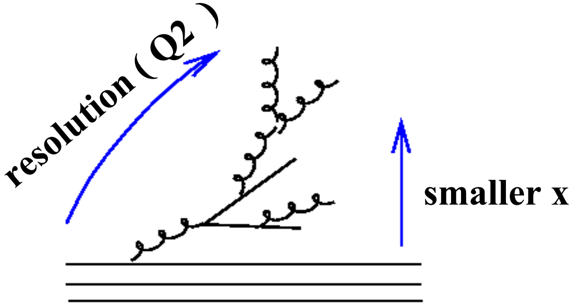
$$F_2(x, Q^2) = x \sum_q e_q^2 (q(x, Q^2) + \bar{q}(x, Q^2))$$

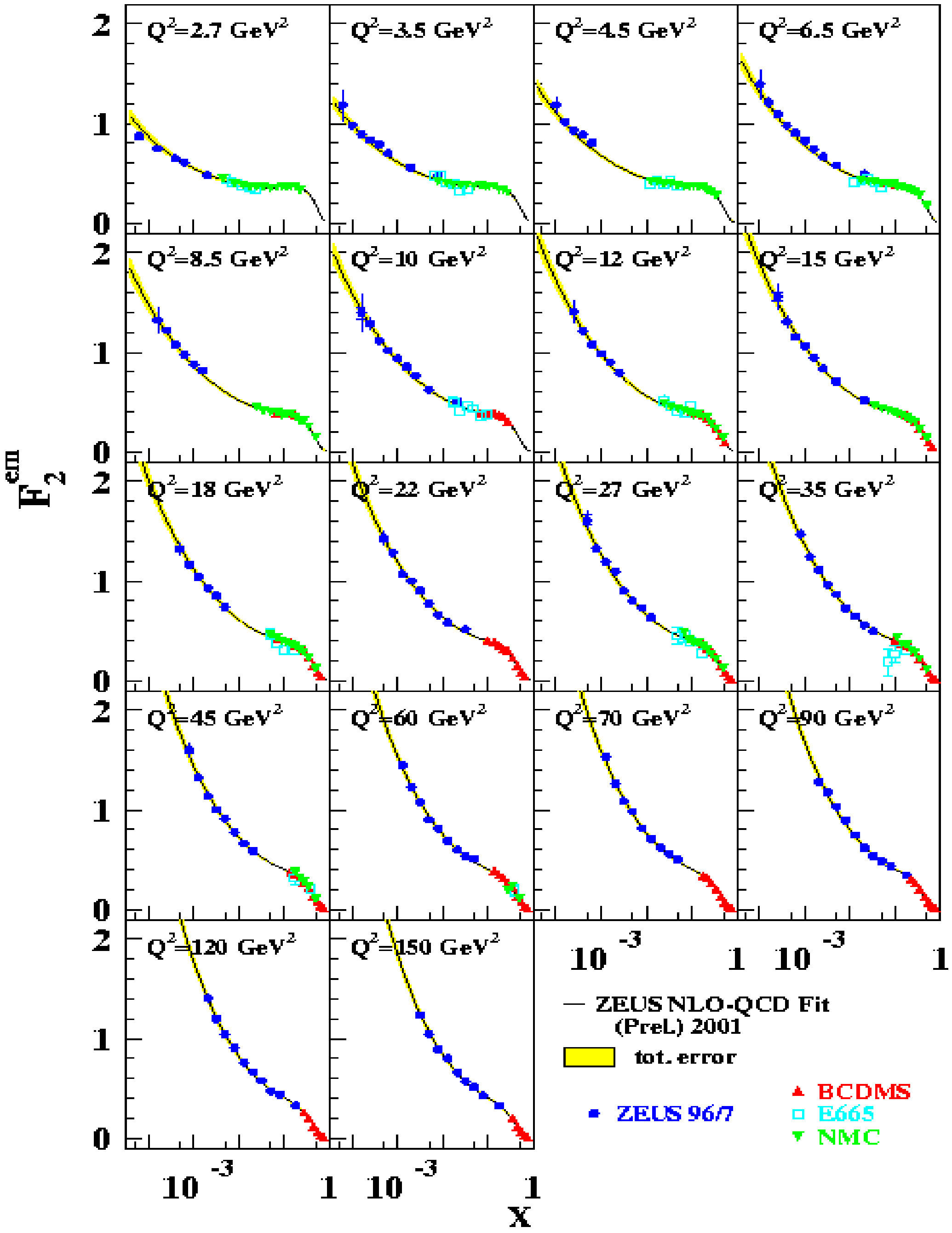
where q, $\bar{q}$ are quark, antiquark densities in the proton.



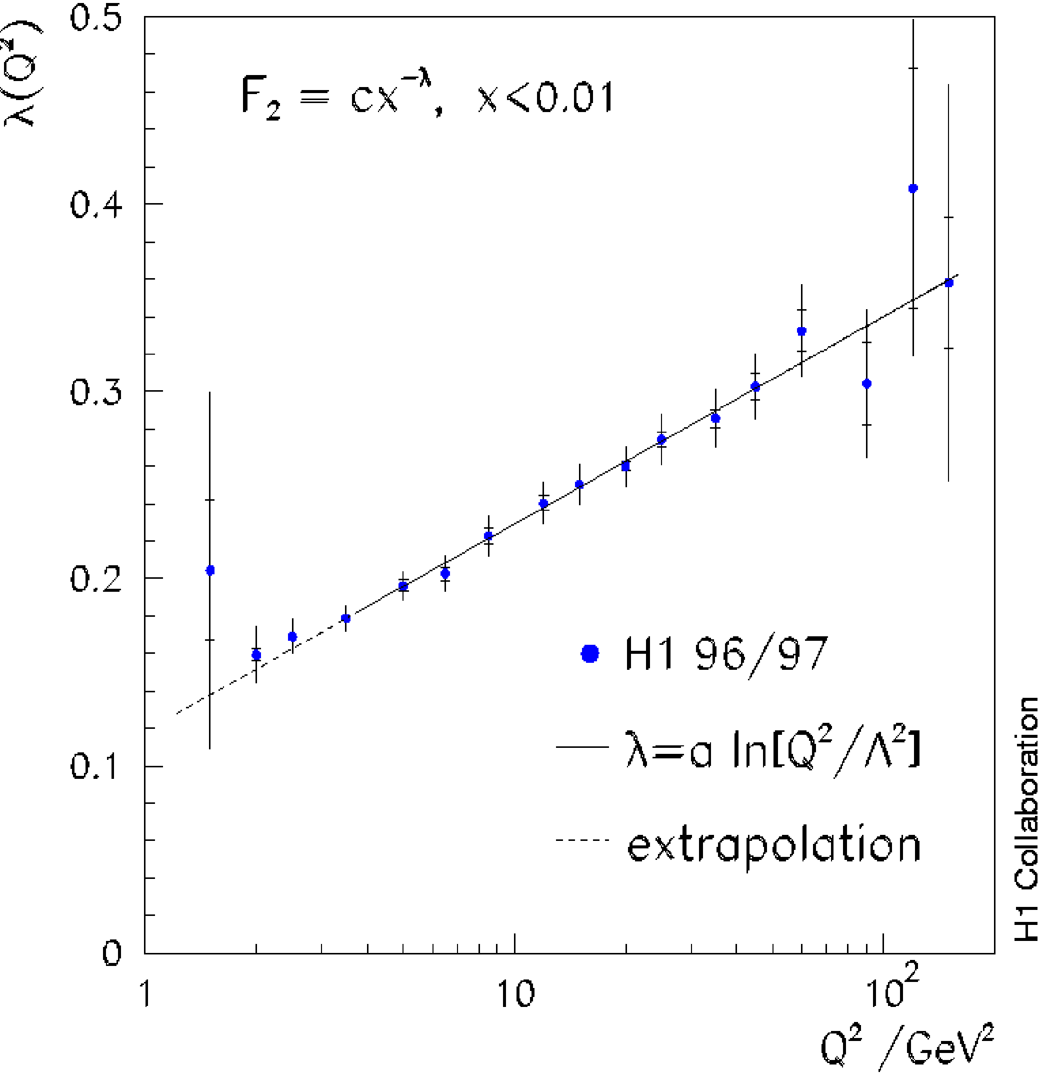
Str. fcn. and parton dist.:







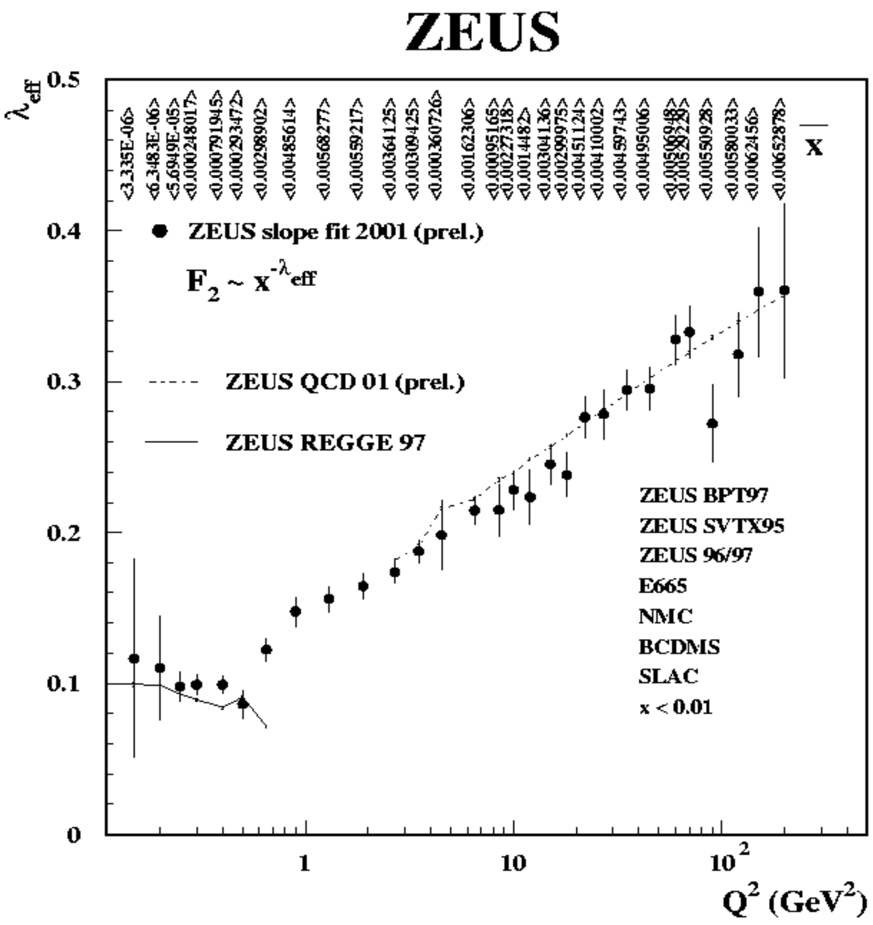
Incr.
Q^2



$F_2 \propto x^{-\lambda}$:

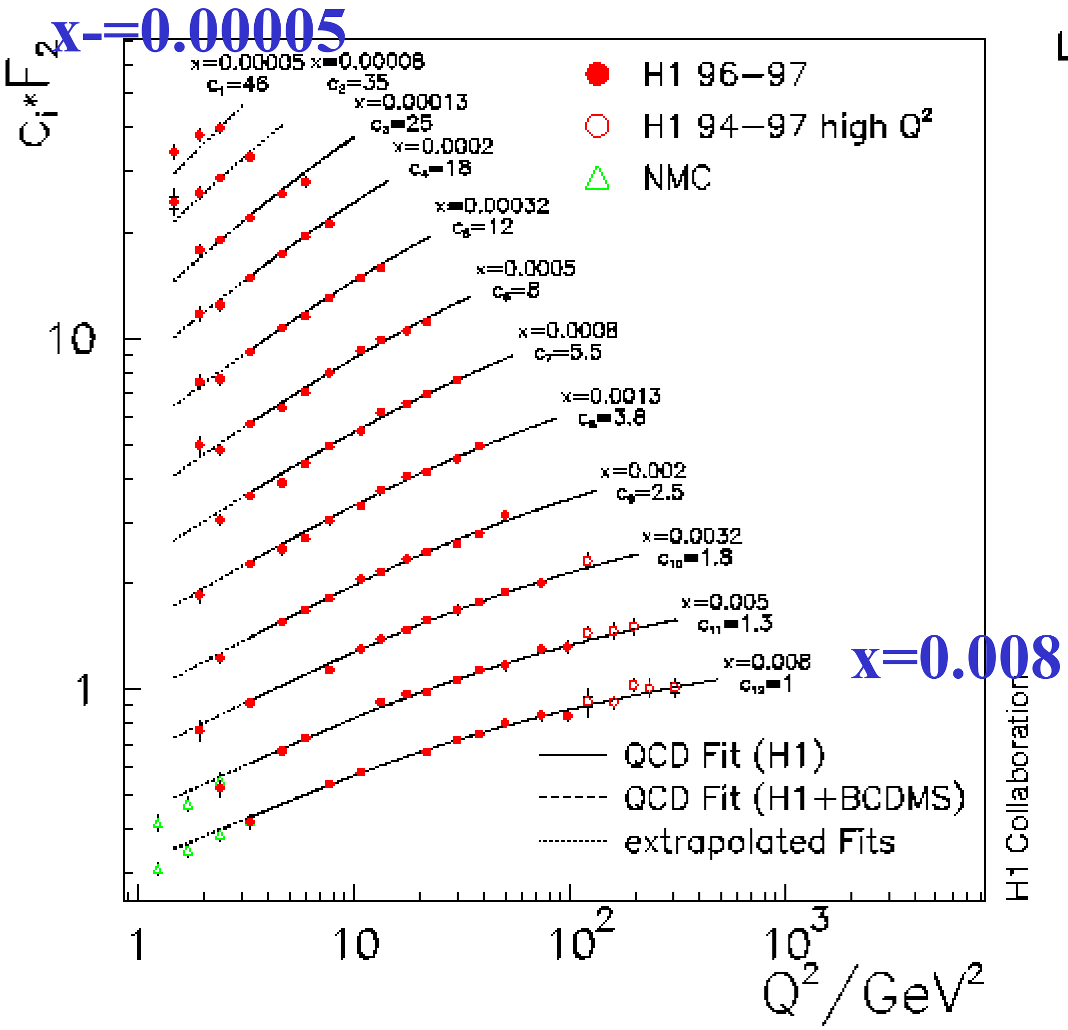
$\lambda \approx 0.2$

($Q^2 \approx 10$ GeV^2)



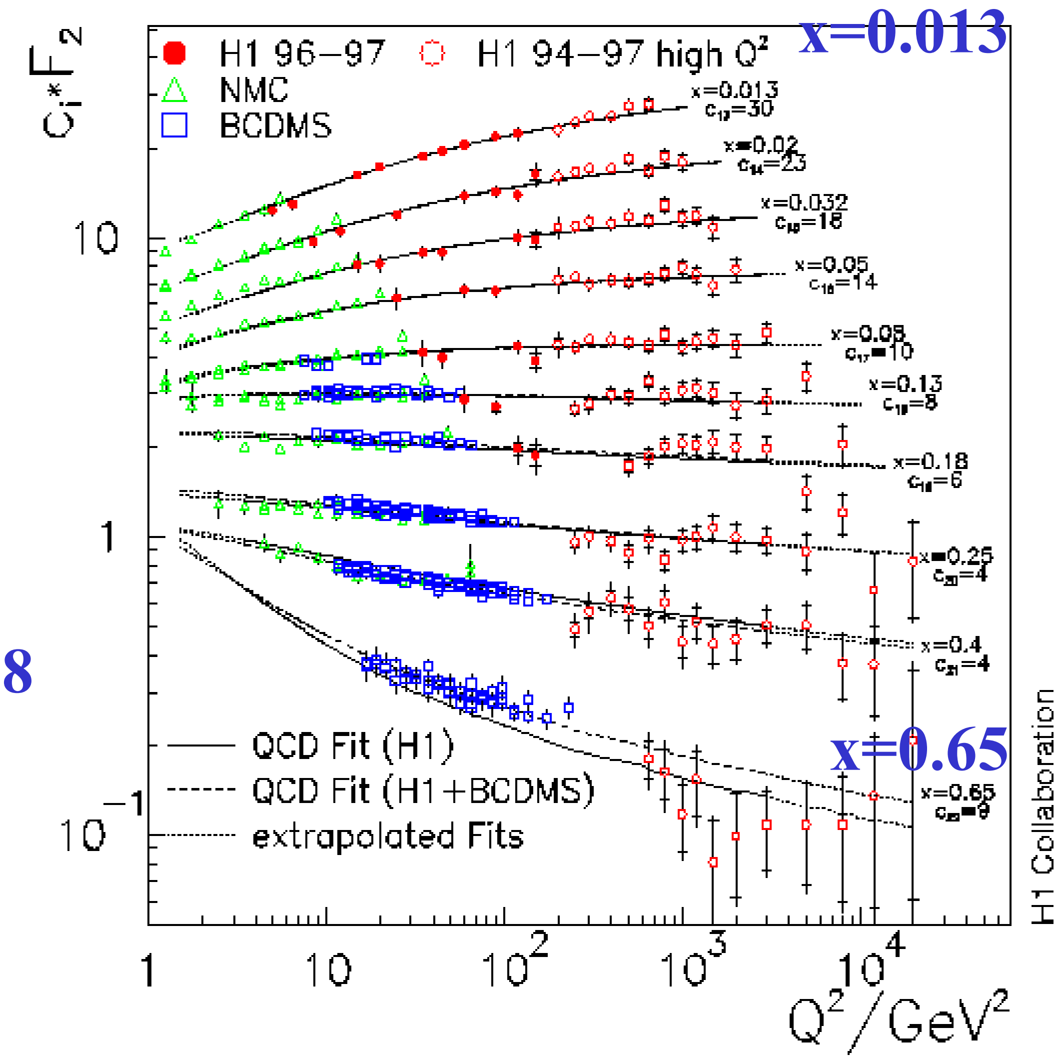
Tends to flatten out at lower Q2 →

Str. fcn. and parton dist.:



x-=0.00005

x=0.008



x=0.013

x=0.65

To LO: $\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s x g$

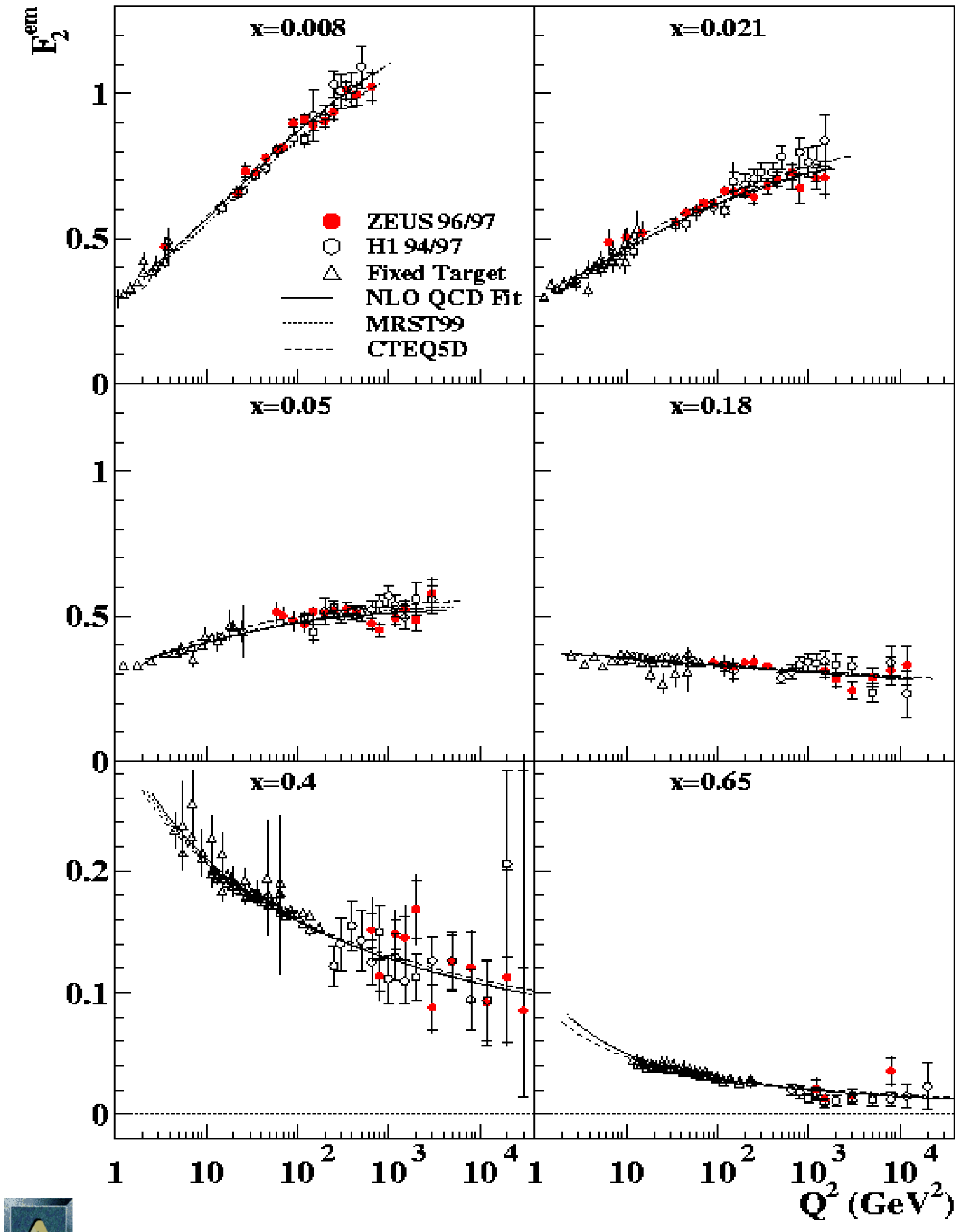
NLO DGLAP fit with q/g paramerized

$$xq(x) = ax^b(1-x)^c[1 + d\sqrt{x} + ex]$$

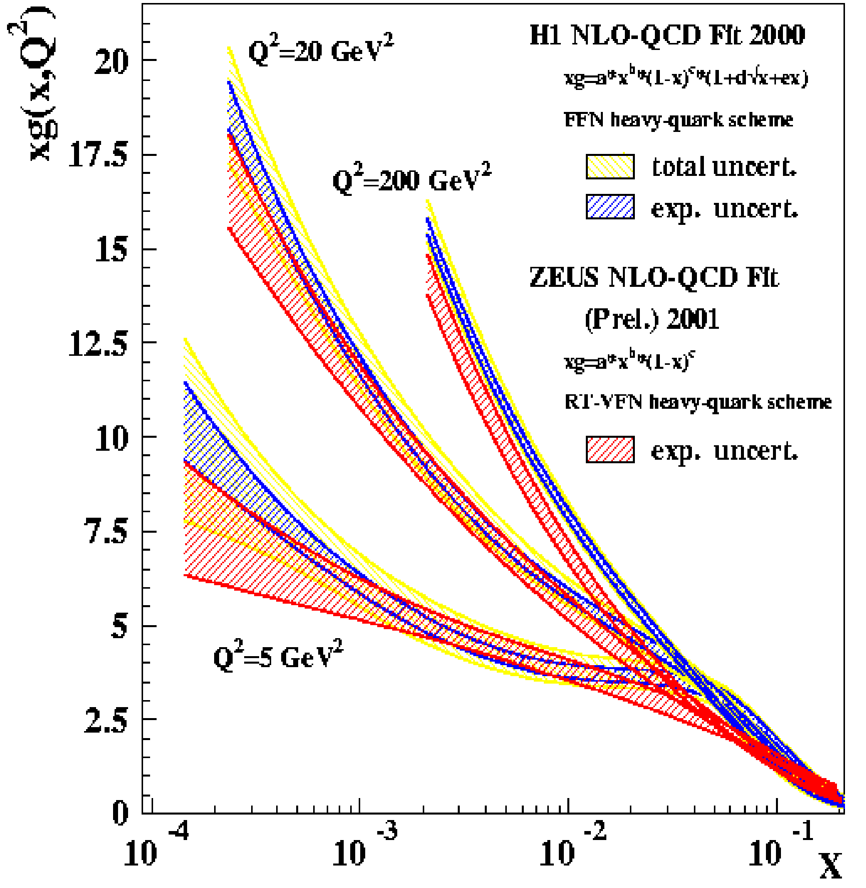
Str. fcn. and parton dist.:

GLUONS

Good agreement H1 and ZEUS



H1+ZEUS



H1

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0017(exp)^{+0.0009}_{-0.0005}\,(model)$$
$$\pm 0.005(\text{theory})$$

ZEUS (prel.)

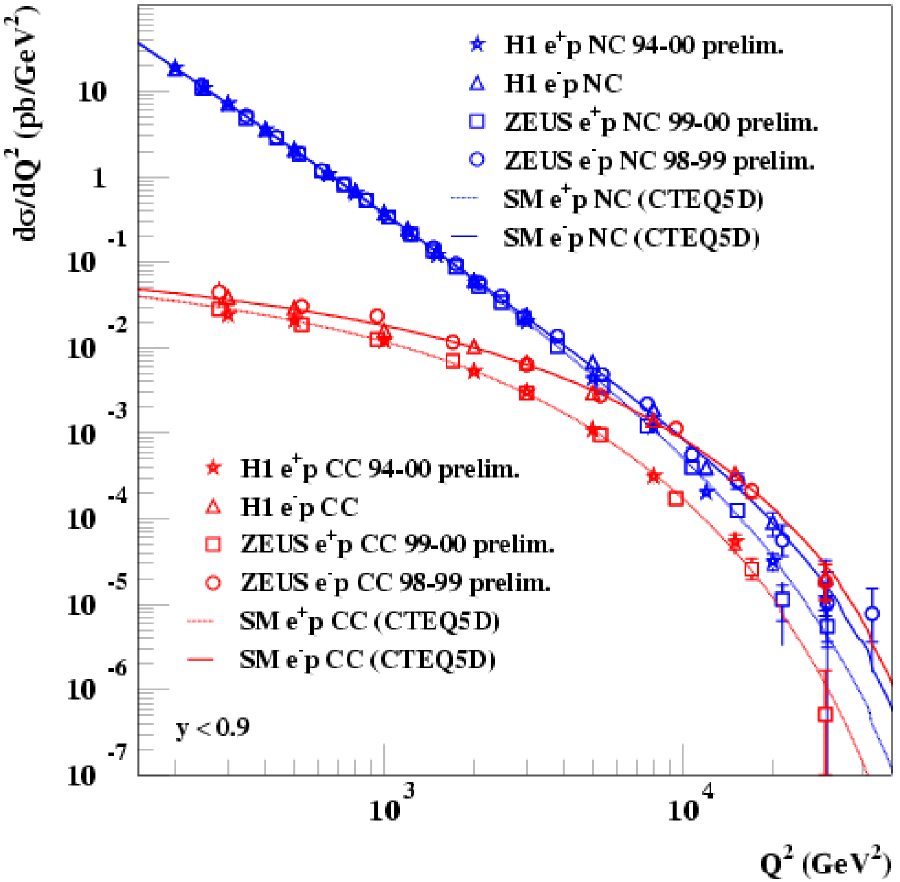
$$\alpha_s(M_Z^2) = 0.117 \pm 0.001(stat + uncorr) \pm 0.005(corr)$$

theory error to be evaluated

Str. fcn. and parton dist.:

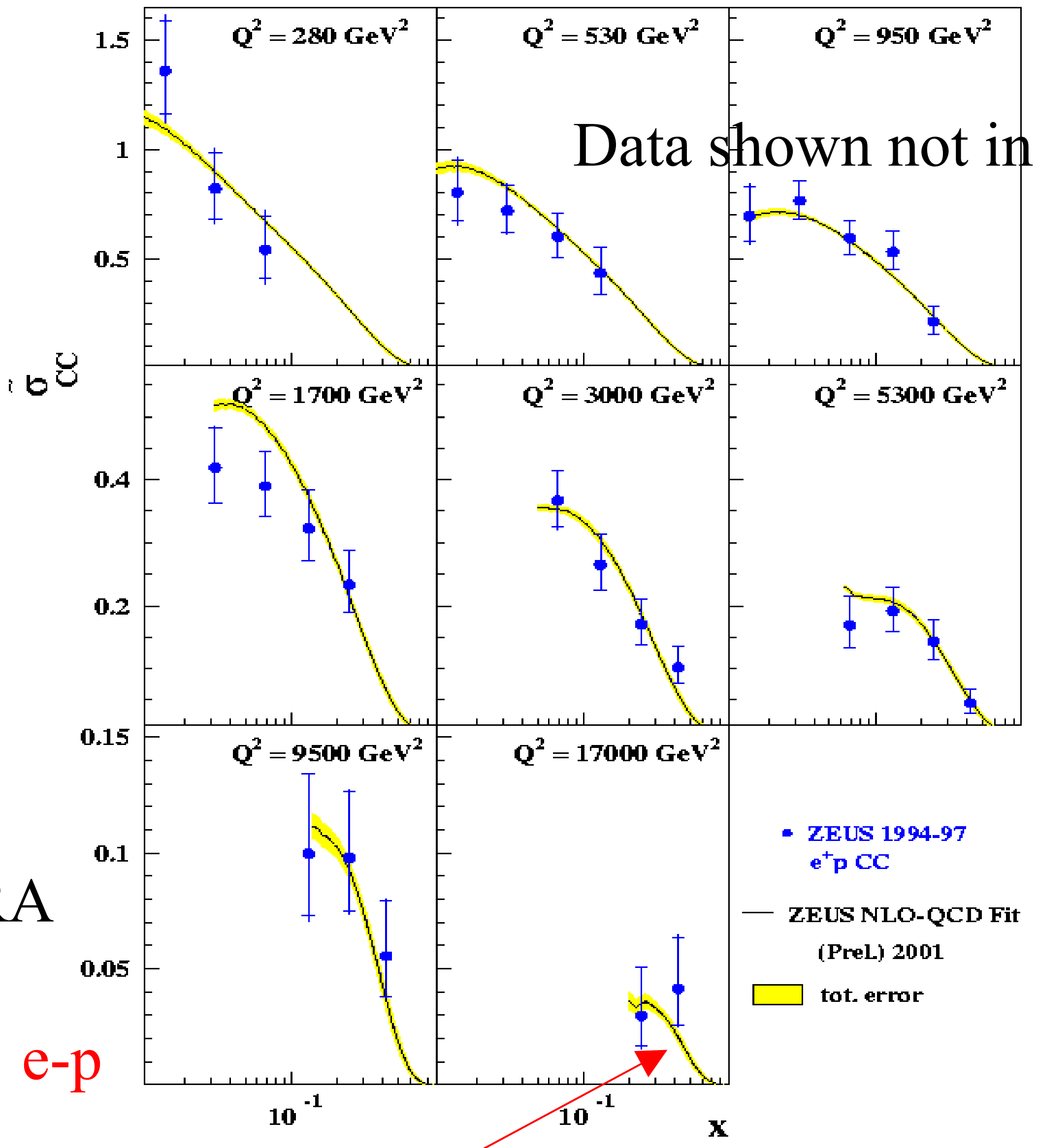
Charged Current cross-section

$$\sigma_{cc}(e^+p) \sim G_F^2\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2[(1-y)^2(d+s)+(\bar{u}+\bar{c})]$$



Measurements of NC and CC at HERA

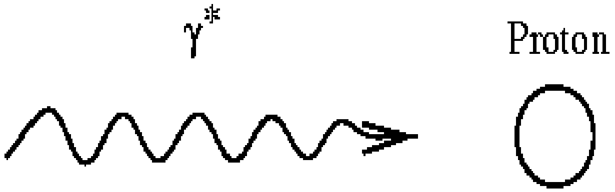
Data shown not in fit



Results ca. 100 pb^{-1} e+p **and** 15 pb^{-1} e-p

HERA upgrade will bring
x10 data by 2005-6.

Precision of DGLAP fit
from Fixed Target exp.results



Note: Small-x ⇒ low Q^2 (Well below 1 GeV^2 at lowest x)

DIS IN THE HADRONIC PICTURE

$W^2 \approx Q^2/x$: the $\gamma^* p$ cms energy squared ("s")

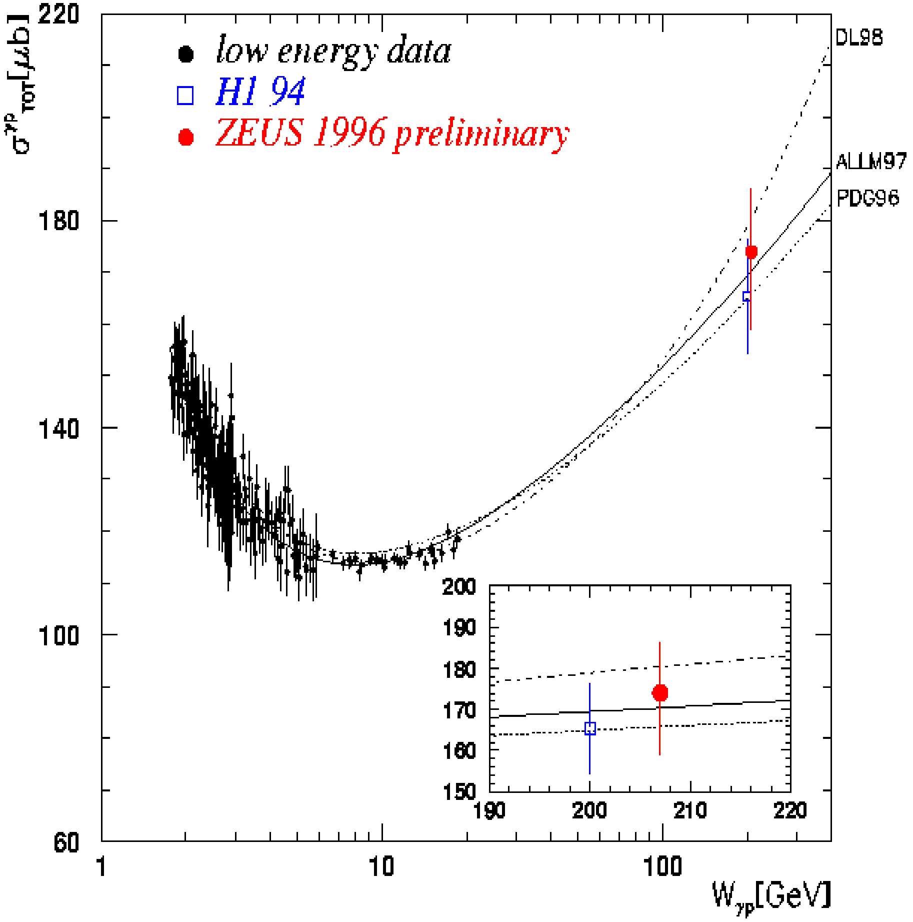
For fixed Q^2: $x^{-\lambda} \to W^{2\lambda}$ ($F_2 \sim W^{0.4}$, $Q^2 \sim 10$ GeV^2)

And at small-x:

$$\sigma_{tot}^{\gamma^* p}(W^2, Q^2) \approx \frac{4\pi^2\alpha}{Q^2} F_2(x \approx Q^2/W^2, Q^2)$$

- F_2 vanishes like Q^2 at low Q^2 (conservation of EM current):
- $\sigma_{tot}^{\gamma p}(W^2)$ described by Regge [$\sim W^{2(\alpha_{\mathbb{P}}-1)}$]

($\alpha_{\mathbb{P}} \approx 1.08$, the "soft Pomeron") i.e. $W^{0.16}$



F_2 at $Q^2 < 1$ GeV
$10^{-3} > x > 10^{-6}$

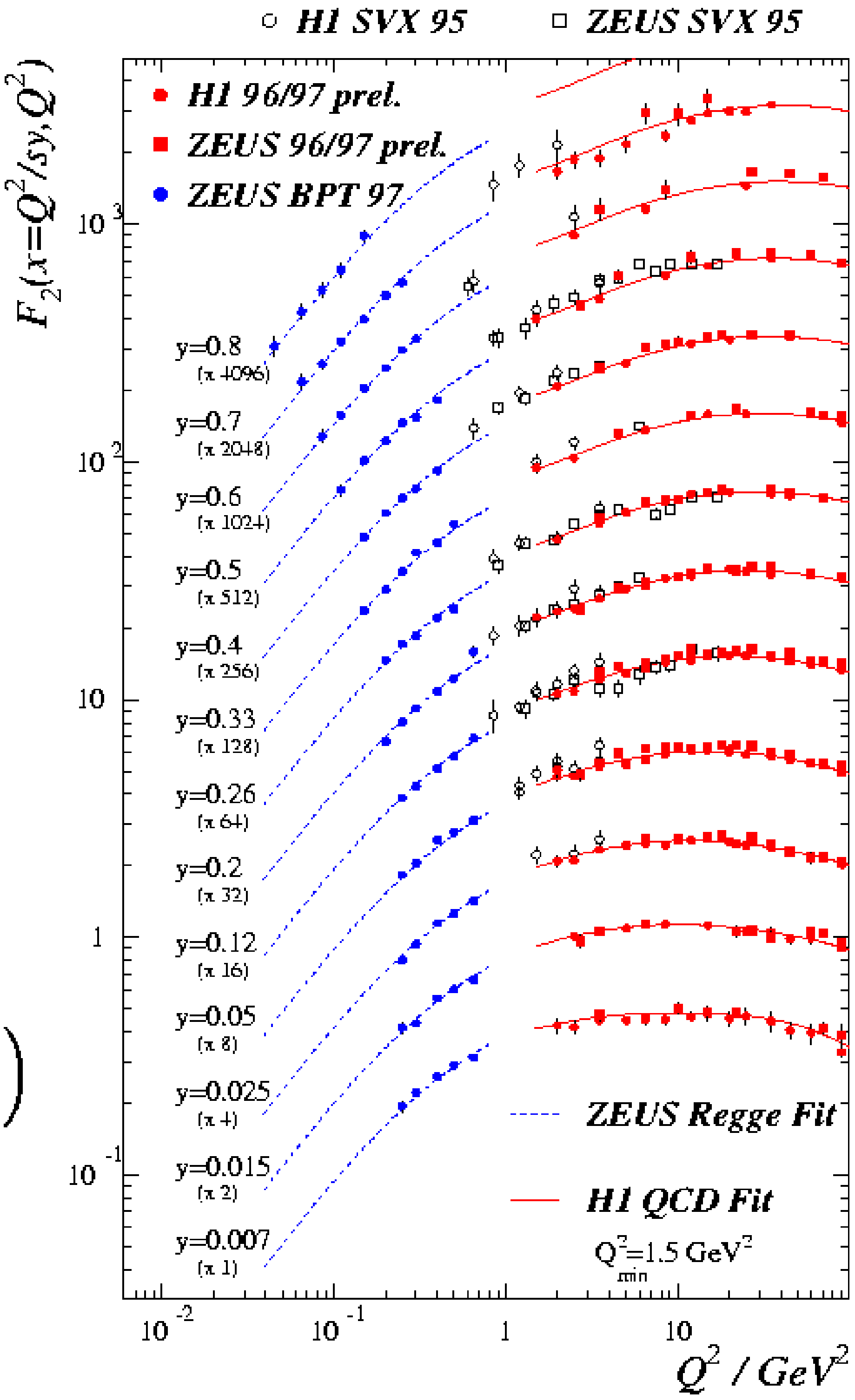
Recall $y = W^2/s$

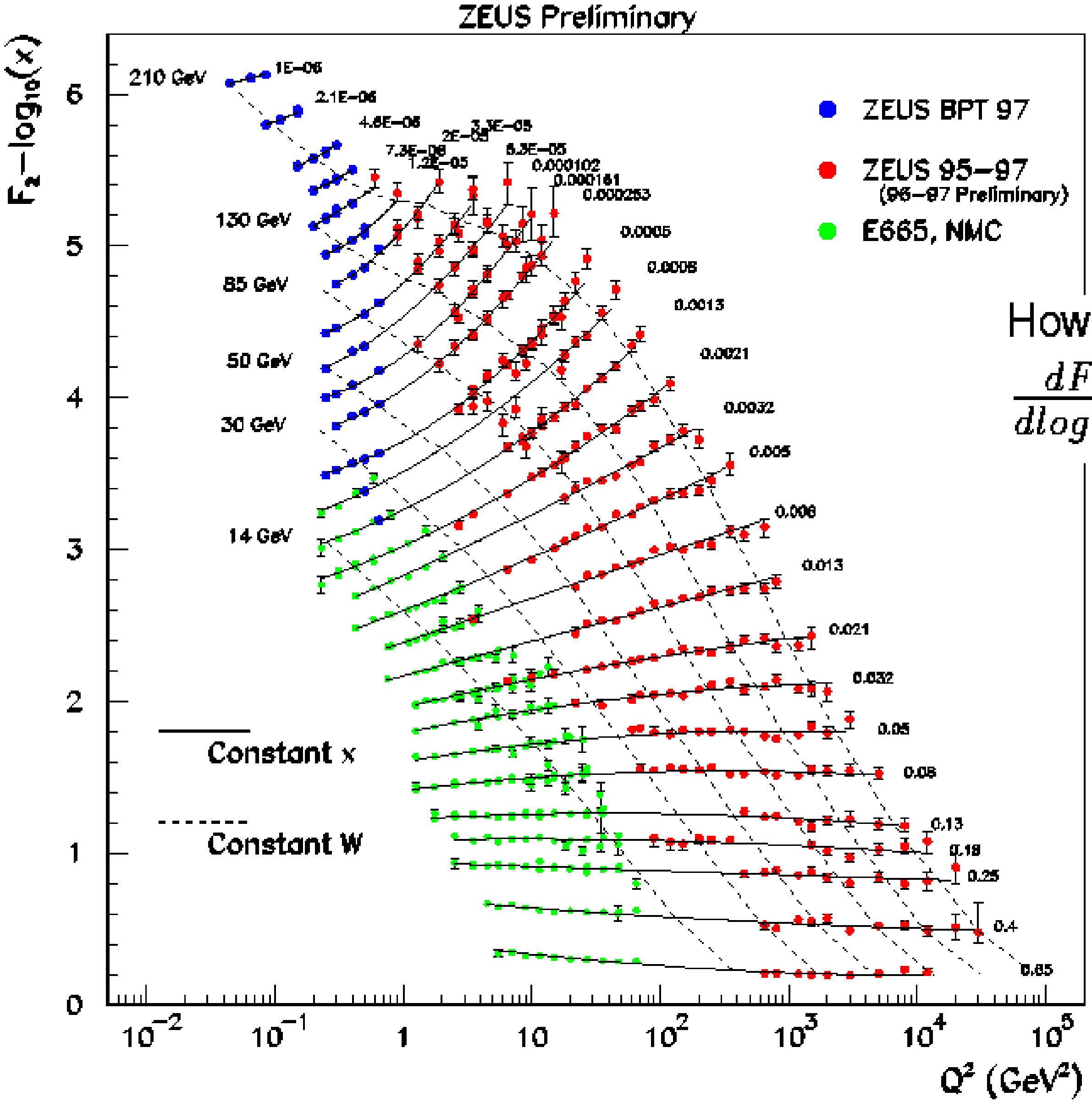
F_2 vanishes like Q^2
at fixed W.

Regge fit:

$$F_2(x,Q^2) = \left(\frac{Q^2}{4\pi^2\alpha}\right)\cdot\left(\frac{M_0^2}{M_0^2+Q^2}\right)\cdot$$
$$\left(A_{\mathbb{R}}\cdot\left(W^2\right)^{\alpha_{\mathbb{R}}-1} + A_{\mathbb{P}}\cdot\left(W^2\right)^{\alpha_{\mathbb{P}}-1}\right)$$

$\alpha_{\mathbb{P}} \approx 1.1$ and $M_0 \approx 0.7$ GeV.





How to make the transition more visible:

$$\frac{dF_2}{dlogQ^2}\Big|_x = B + 2C(logQ^2) \text{ at fixed } W$$

What is happening at low x and medium Q^2?

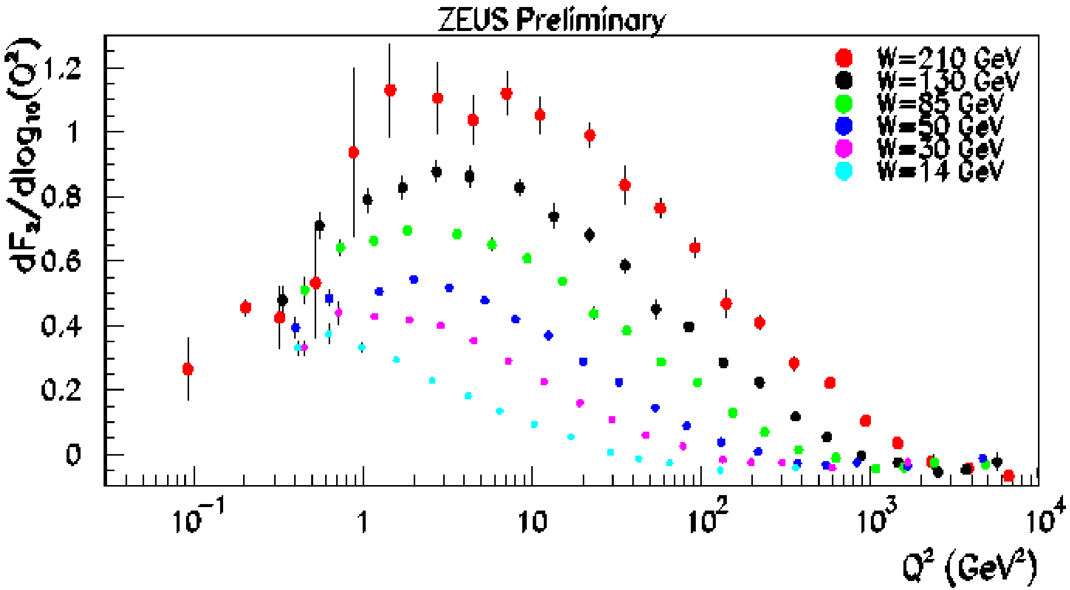
note: offset constant is $\log x$ i.e. no distortion

Lines are fits $A(x) + B(x)logQ^2 + C(x)(logQ^2)^2$

In the low Q^2 region: $F_2 \sim Q^2\sigma_0$, i.e. vanishing like Q^2. Therefore:

$$dF_2/dlog(Q^2) \sim Q^2\sigma_0$$

$\Rightarrow$ x is not an important variable. Q^2 is the important variable in the left hand side of the plots.

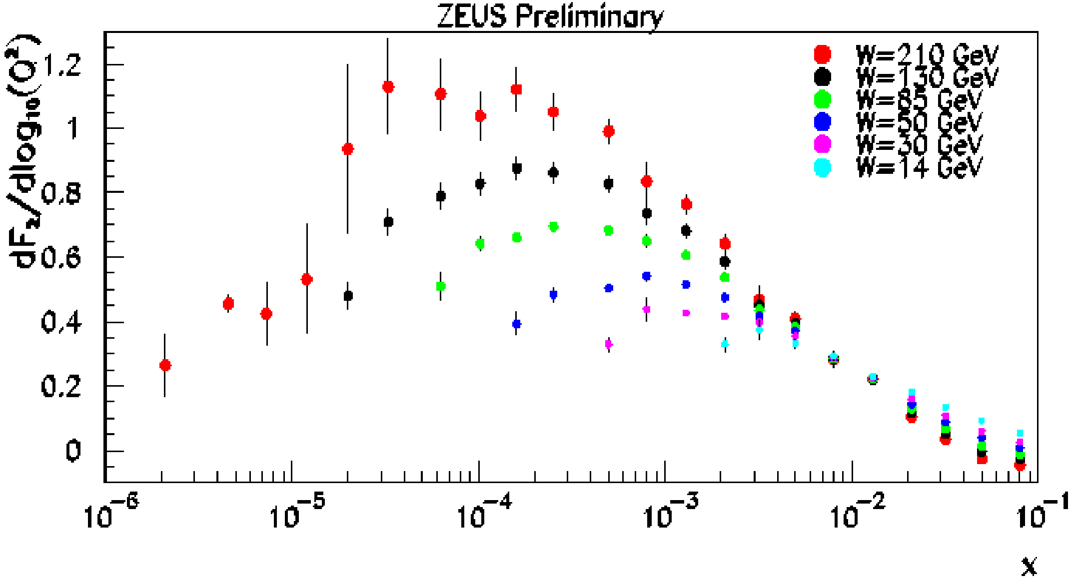


Naively, in the region where GLAP applicable (Q^2 large):

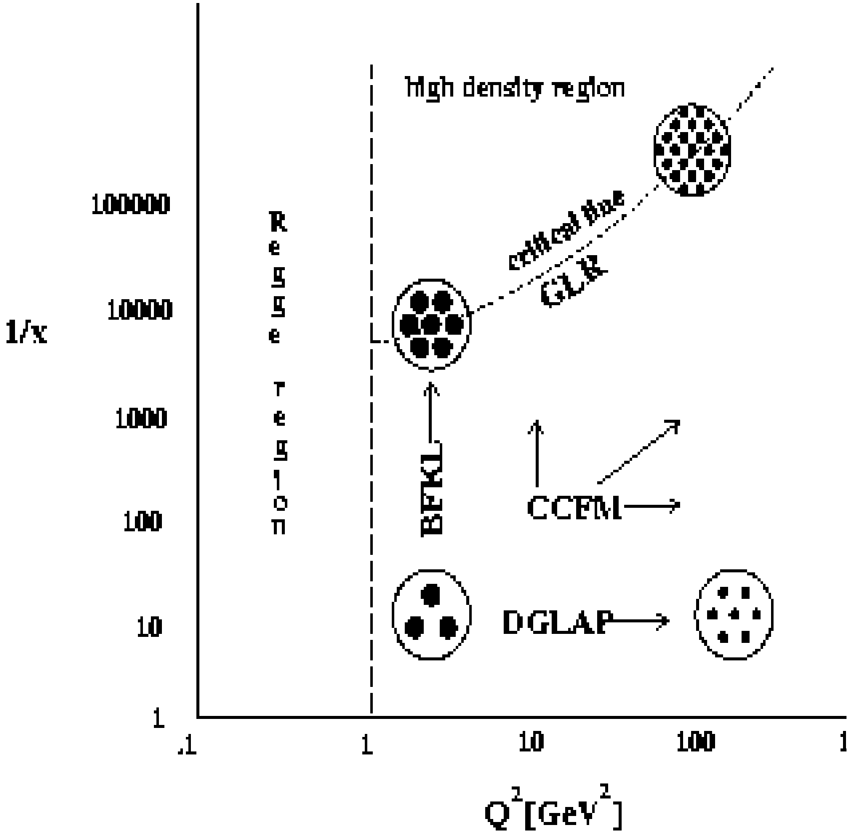
$$dF_2/dlog(Q^2) \sim xg \sim x^{-\lambda}$$

IF λ is a slow function of x and Q^2.

$\Rightarrow$ Q^2 is not an important scale. x is the important variable in the right hand side of the plots.



Beyond DGLAP: pert. QCD considerations

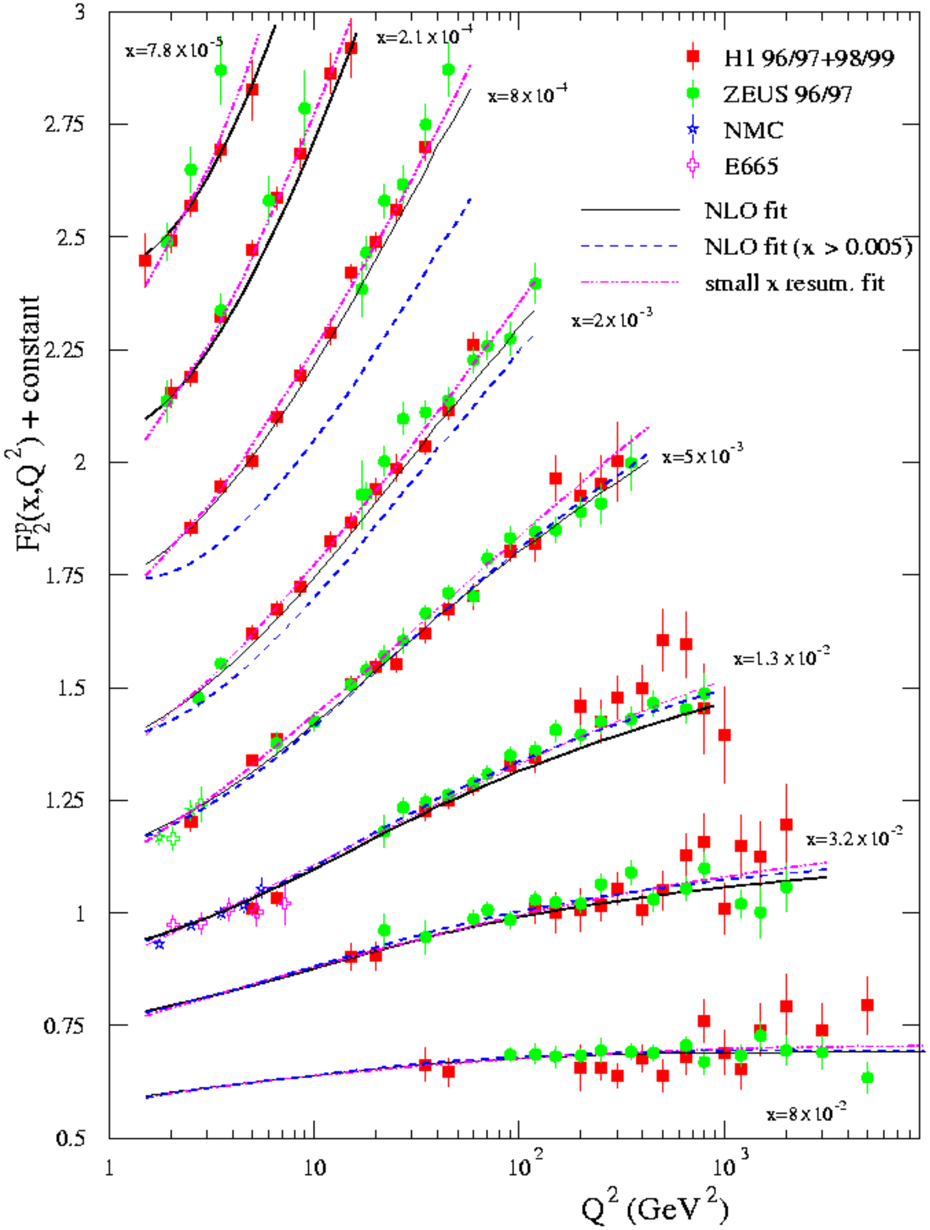


- GLAP fits ($\ln Q^2$ resummation of QCD) can describe data well above $Q^2 > 1$ GeV^2
- Regge fits can describe data well $Q^2 < 1$ GeV^2

- What about $\ln 1/x$ (BFKL,CCFM), higher twist, terms etc.?
- What about shadowing or saturation (GLR): i.e. effects from high density of partons at low-x?

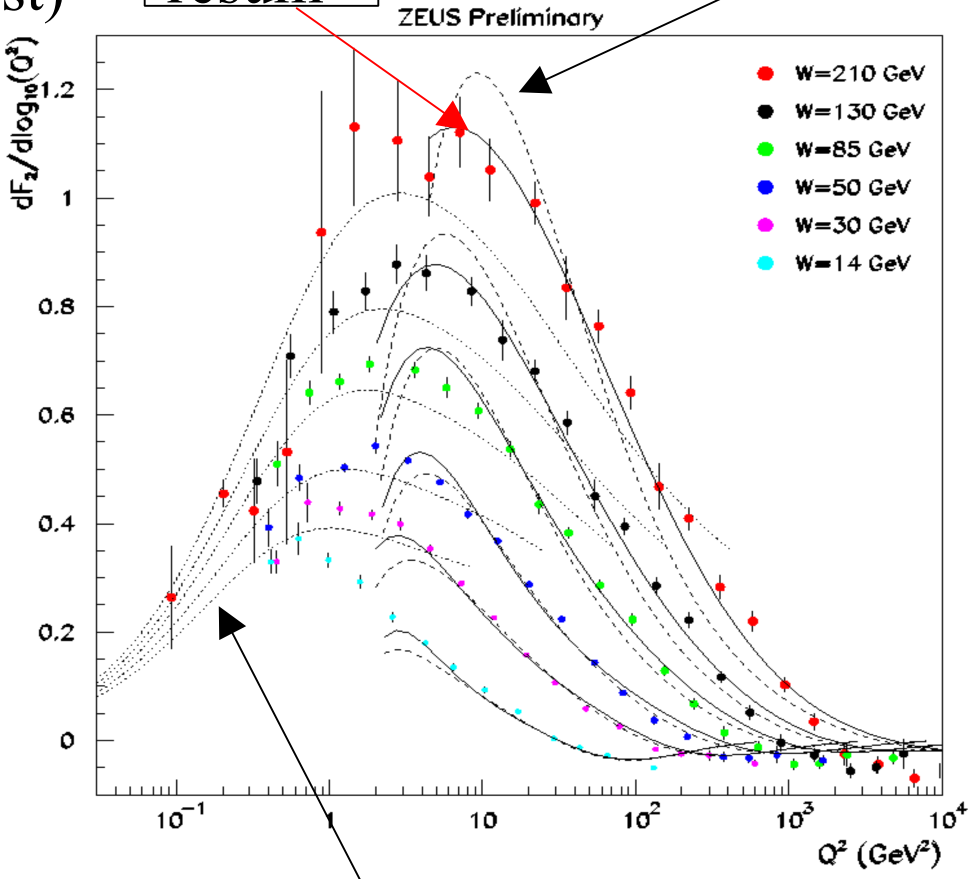
Small x resummation (not full BFKL):

Martin, Roberts, Sterling, Thorne(mrst)



small-x resum

DGLAP

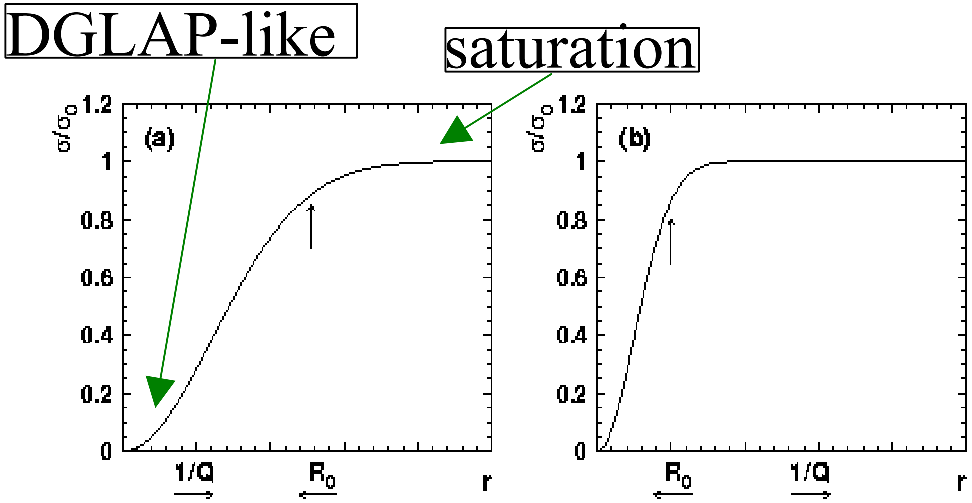


Dipole model

DIPOLE models: a class of phenomenological models

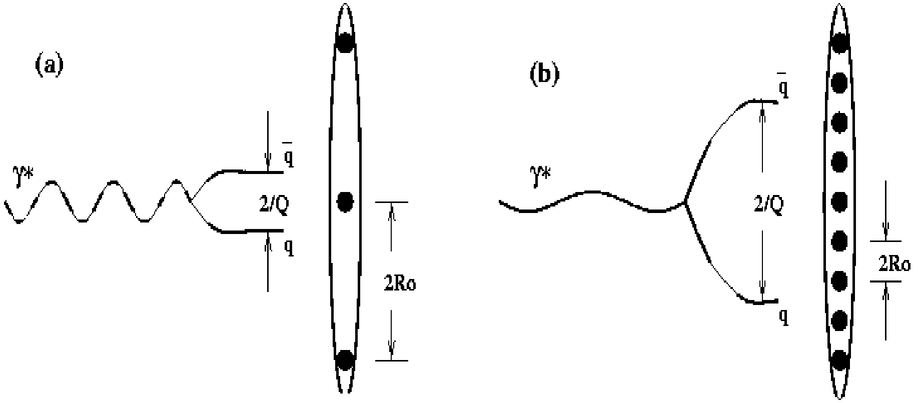
example: Golec-Biernat
&Wuesthoff

- Proton dissociates to a $q\bar{q}$ pair (dipole) upstream of the protons


DGLAP-like

saturation

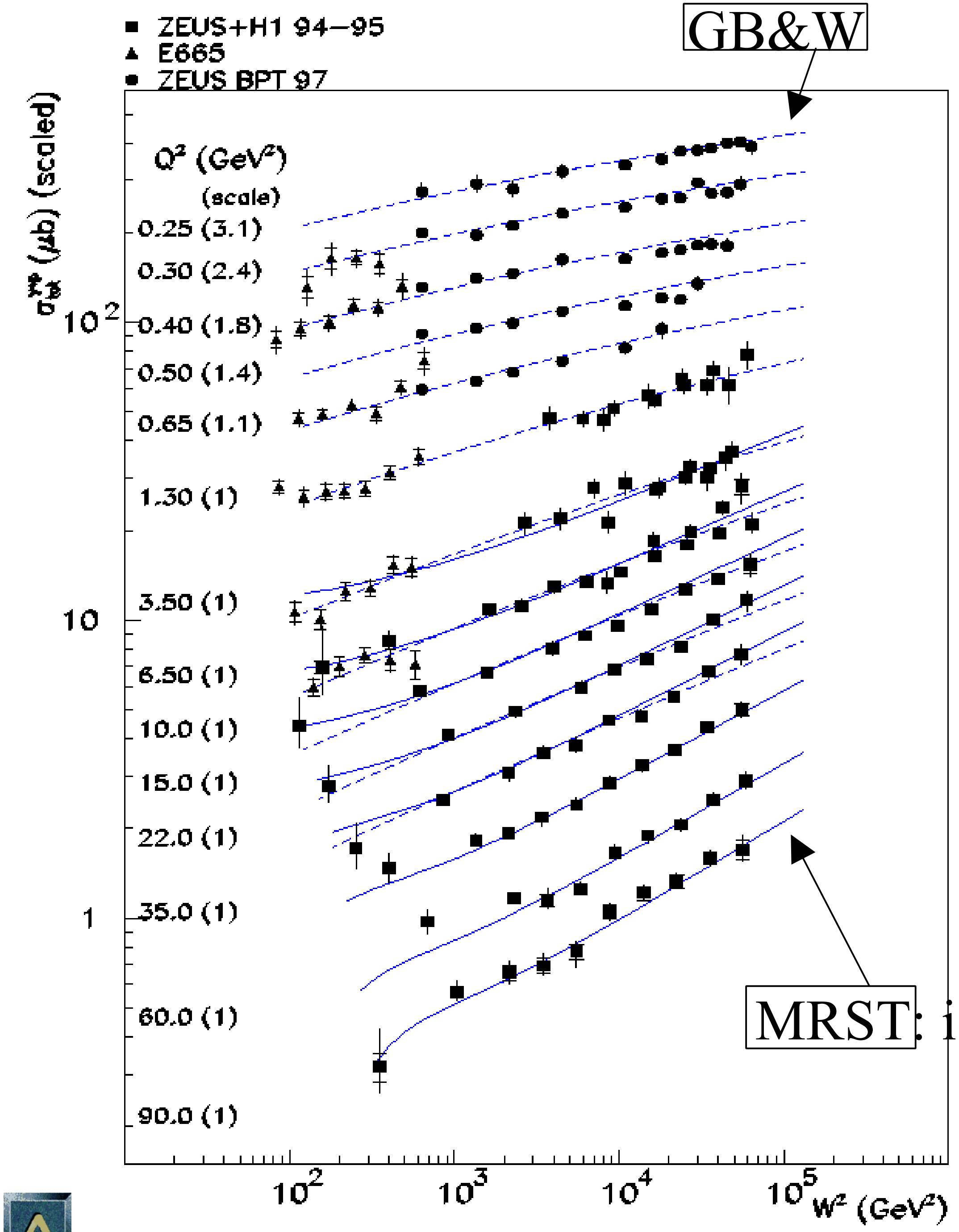
- $\hat{\sigma}_{dipole}$ increases as r^2 at small r. ⇒ Color transparency.
- $\hat{\sigma}_{dipole}$ becomes constant (saturates) at large r.
- At what r the cross section saturates depends on the density of the partons, i.e. x. $\rightarrow \hat{\sigma}_{dipole}(x,r)$
  [$R_0 \sim 1/gluon \sim x^{\lambda}$]



DIPOLE formulation of DIS

$$\sigma = \int d^2r \int dz |\Psi(z,r)|^2 \hat{\sigma}_{dipole}(x,r)$$

GB&W Description of $\sigma_{tot}^{\gamma^* p}$



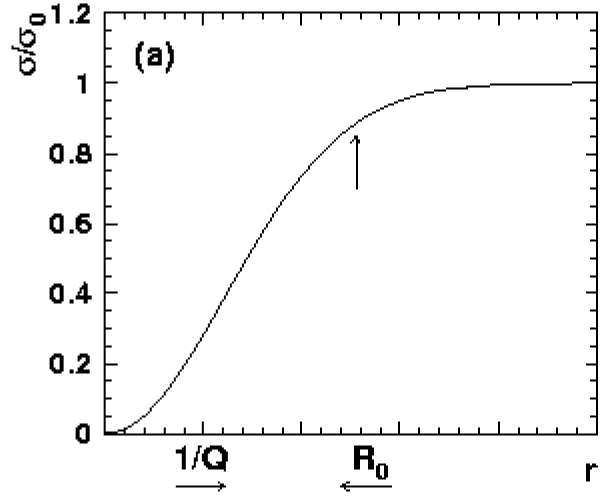
GB&W

MRST: ie DGLAP

Recall: $W^2 \approx Q^2/x$

$$\sigma_{tot}^{\gamma^* p}(W^2,Q^2) \approx \frac{4\pi^2\alpha}{Q^2} F_2(x \approx Q^2/W^2, Q^2)$$

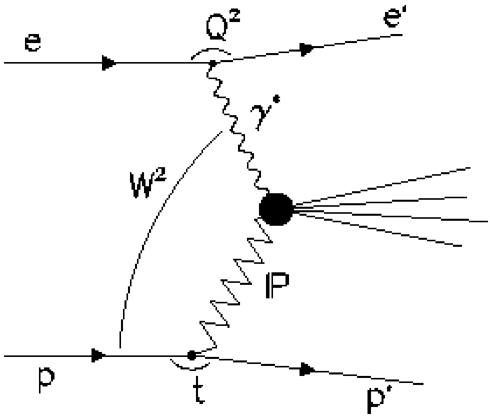
At low x(high W) medium Q2, dipole cross-section away from DGLAP-like region is being probed.



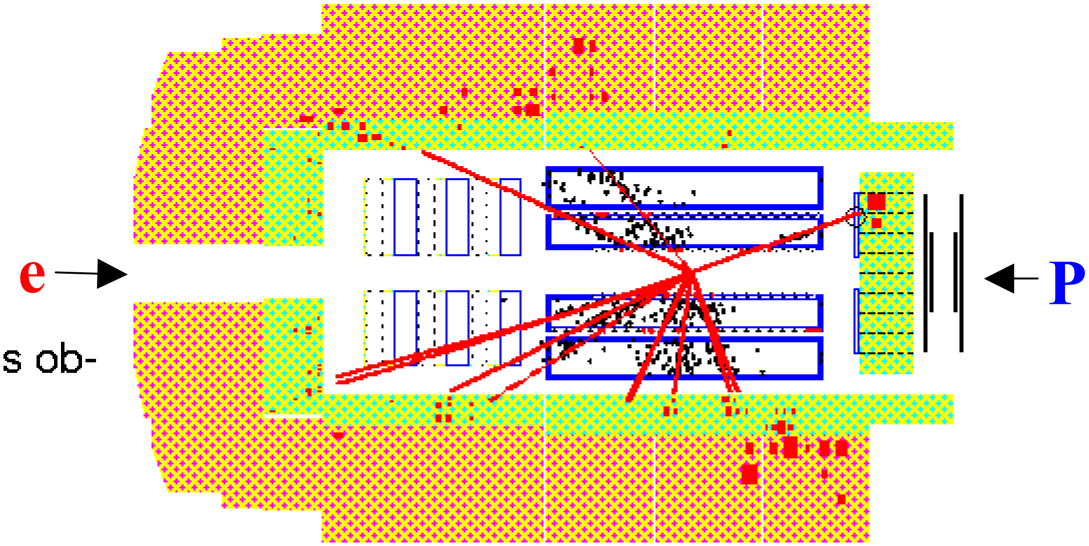
On the other hand, pure DGLAP fits also describe the data.

DIS diffraction at HERA:

At HERA diffractive dissociation of virtual photons is observed ($\approx$ 10%): can we understand this in terms of pQCD?



Exchange of a colorless object. (Pomeron)



Define 3 more variables:

$x_{\mathbb{P}}$: momentum fraction taken by the pomeron.

β: momentum fraction of the struck parton in the pomeron.

t: momentum transfer at the proton vertex.

- Beyond the simple GLAP picture : Need to interact with 2 gluons, at least!
- What is the relationship of diffraction with F_2 at small-x?

The diffractive cross section is written as:

$$\frac{d^3\sigma^D}{d\beta dQ^2 dx_{I\!P}} = \frac{4\pi\alpha^2}{\beta Q^2}\left(1-y+\frac{y^2}{2}\right)F_2^{D(3)}(\beta, Q^2, x_{I\!P})$$

(integrated over t)

Hard factorization has been proven (Collins 1997):

$$F_2^D \sim f^D \otimes \hat{\sigma}$$

Where f^D is the diffractive parton densities.

If Regge factorization is assumed:

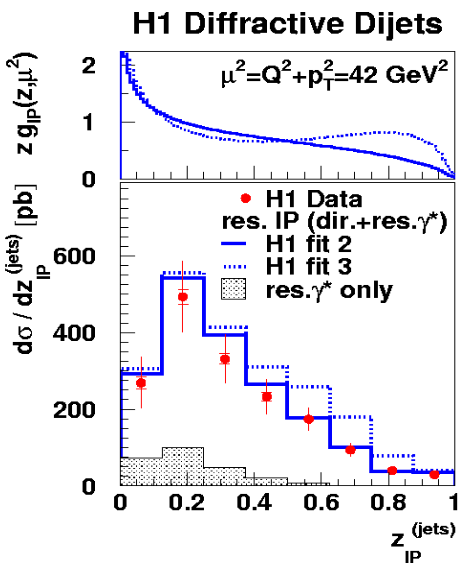
$$F_2^D(x_{I\!P}, t, Q^2, \beta) = f(x_{I\!P}, t)\cdot F_2^{I\!P}(\beta, Q^2)$$

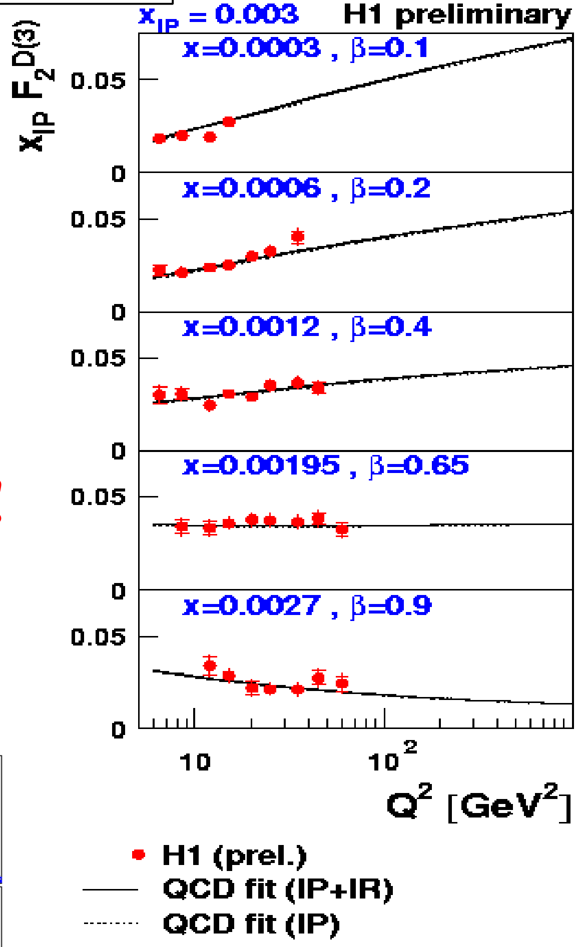
⇒ Can do a GLAP analysis of $F_2^{I\!P}$, the universal (for DIS) Pomeron structure function. (More from Max..)

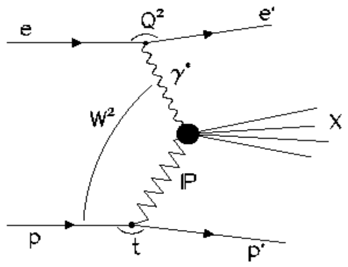
$f(x_{I\!P}, t) \approx 1/x_{I\!P}$, the Pomeron flux factor.

The flux factor must be telling us about gluon correlation in the proton!

Predictive power!





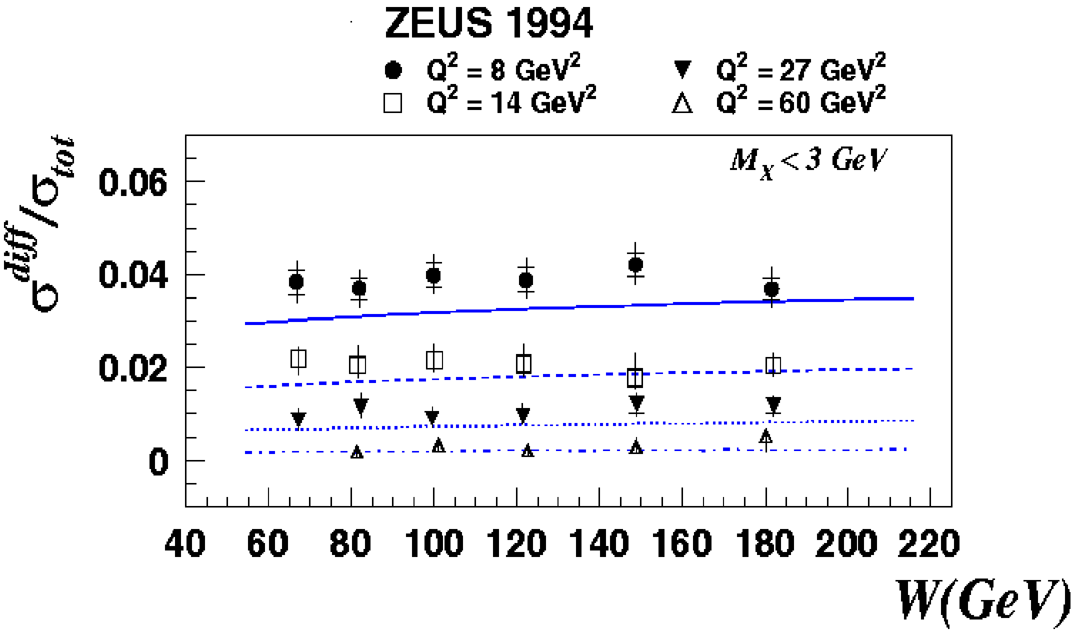


R. Yoshida, ANL, Mar. 4, 2002

However....

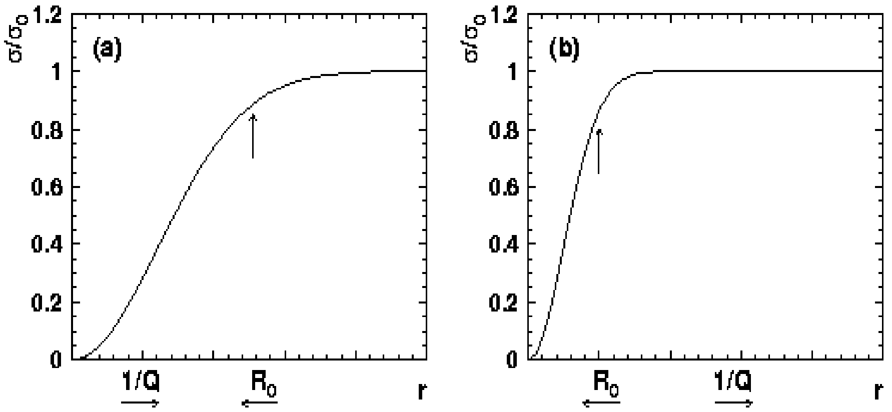
$\Rightarrow$ The origin of the Pomeron flux unexplained.

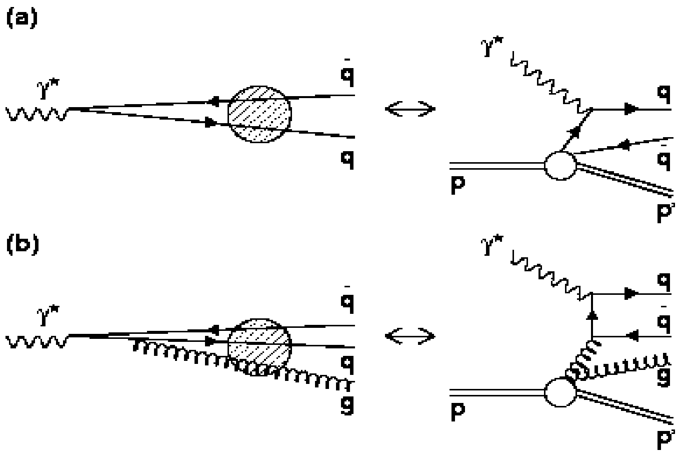
$\Rightarrow$ What is the relationship of σ_{diff} to σ_{tot}?



- Diffraction has the same W^2 (or x) dependence as the total cross section! ($\sigma_{diff} \sim W^{0.4}$, $Q^2 \sim 10$ GeV^2)
- Contradicts naive optical theorem expectation $\Rightarrow \sigma^{tot}_{\gamma^* p} \sim W^a$ then $\sigma^{diff} \sim W^{2a}$
- Contradicts expectation–if $\sigma^{tot}_{\gamma^* p} \sim$ Gluon, then $\sigma^{diff} \sim$ Gluon^2 ??
- $\Rightarrow$ Also contradicts expectation of Regge: $\alpha_{\mathbb{P}} = 1.08$ (i.e. $\sim W^{0.16}$)

The lines in the figure are from the saturation model of Golec-Biernat and Wüsthoff

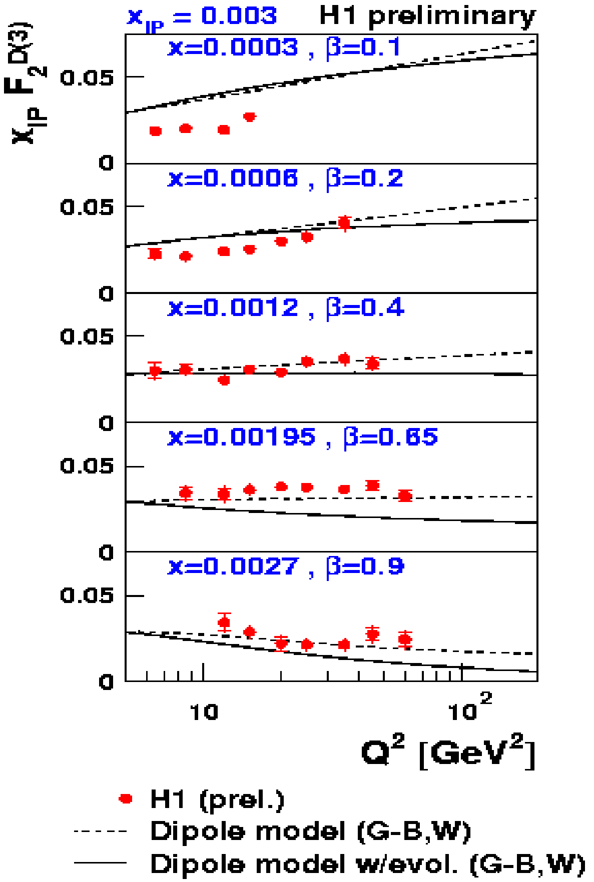




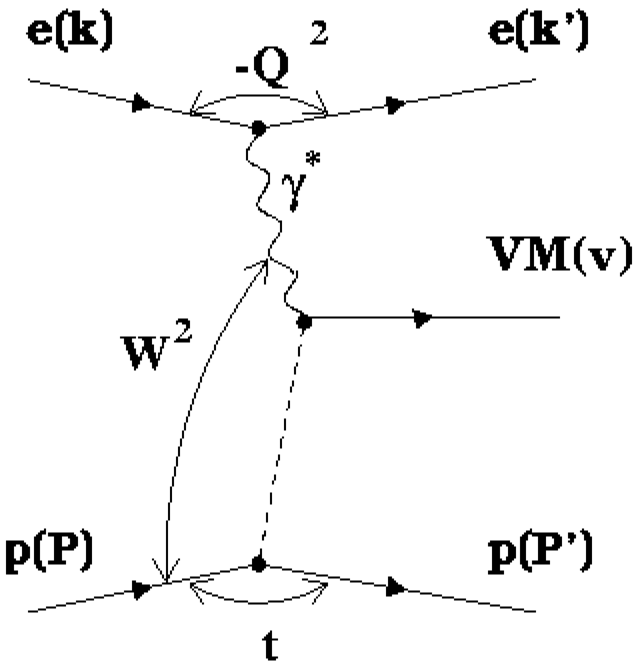
$$\sigma_{diff} \sim \int d^2r \int dz |\Psi_\gamma|^2 \hat{\sigma}_{dipole}{}^2$$

The dipole model qualitatively desribe the data: i.e. give the right behavior for the "pomeron structure"

→ **Simple physical picture : effective correlation of partons due to interplay of photon size and parton separation.**



Elastic Vector Meson Production at HERA:



- Very similar process to the inclusive diffraction
- What is the W dependence?

  Recall:

  $\sigma^{tot}_{\gamma p} \sim W^{2(\alpha_{\mathbb{P}}-1)} \approx W^{2(0.08)} = W^{0.16}$

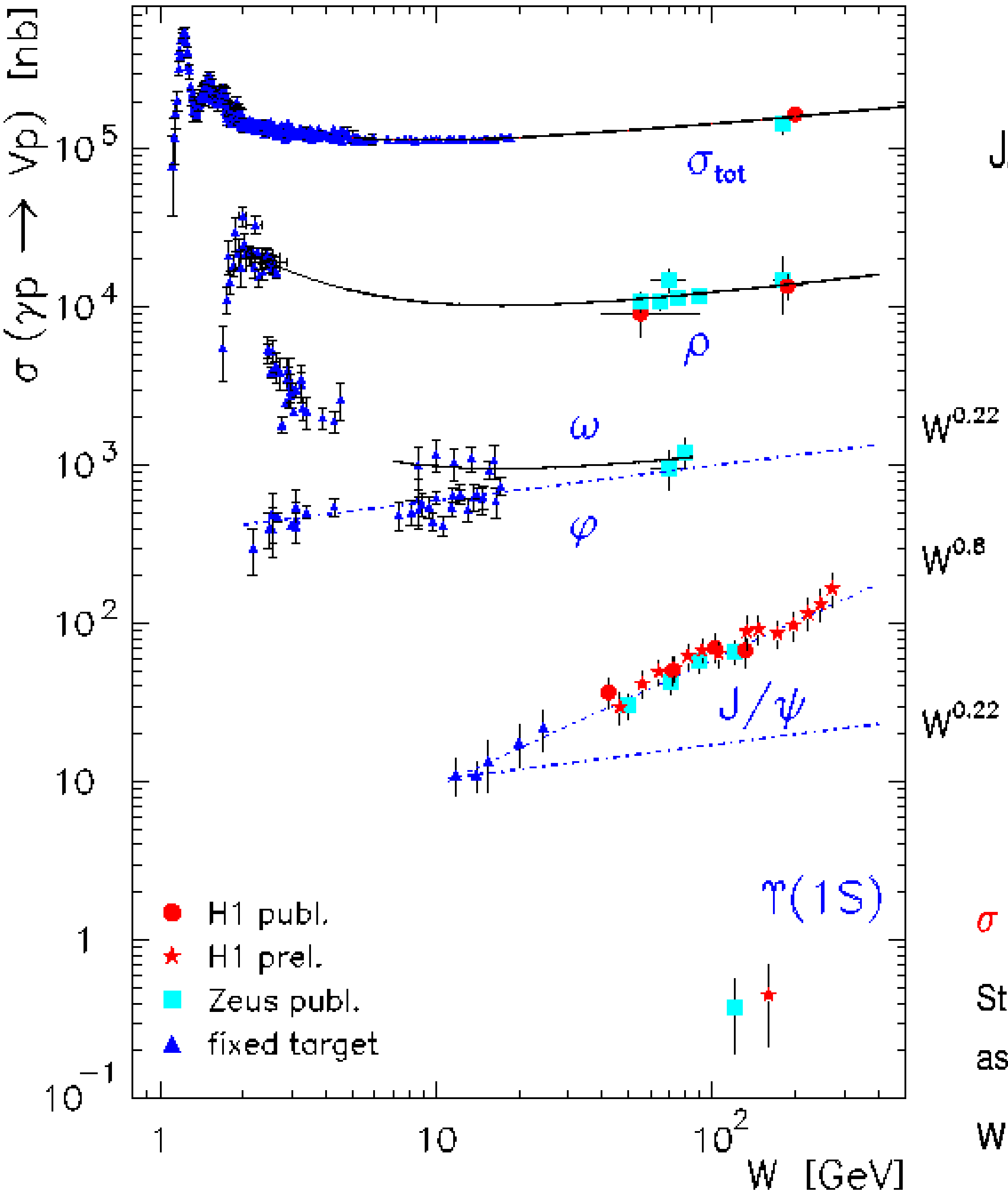
  F_2^p (or $\sigma_{\gamma^* p}$) (at $Q^2 \approx 10$ GeV^2) $\sim x^{-0.2}$

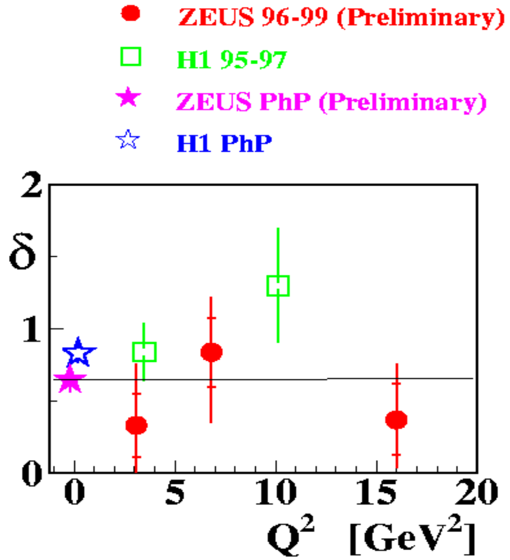
  $\Rightarrow W^{2(0.2)} = W^{0.4}$

  $\sigma^{diff}/\sigma_{\gamma^* p}$ constant.

- What about Vector Meson production ⇒

J/ψ rises like $W^{0.8}$! (i.e. twice F_2 at 10 GeV^2)

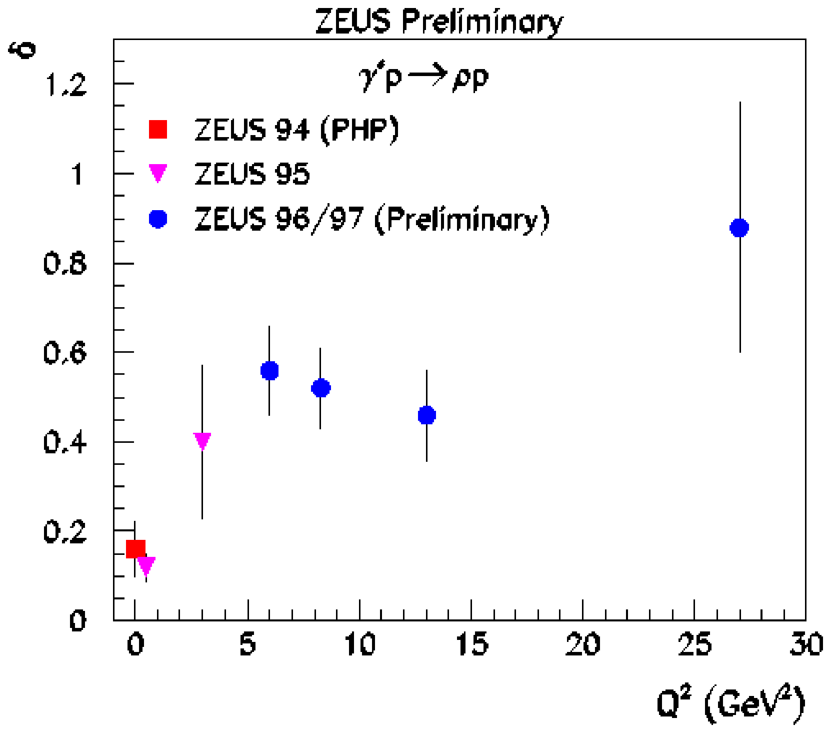




$\sigma \propto W^{\delta}$

Still large errors: slope (δ) consistent with being constant as function of Q^2.

What about the Q^2 dependence of ρ's? ⇒

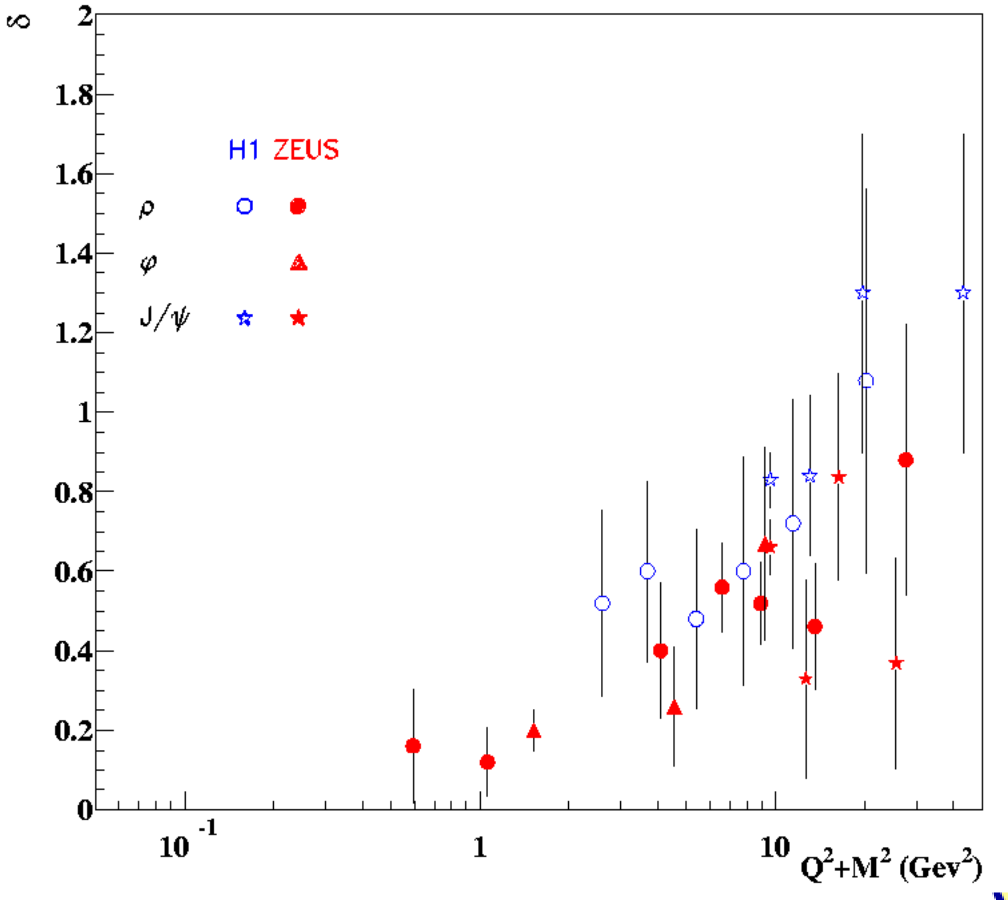


ρ mesons: increasing slope with Q2.

All vector mesons:

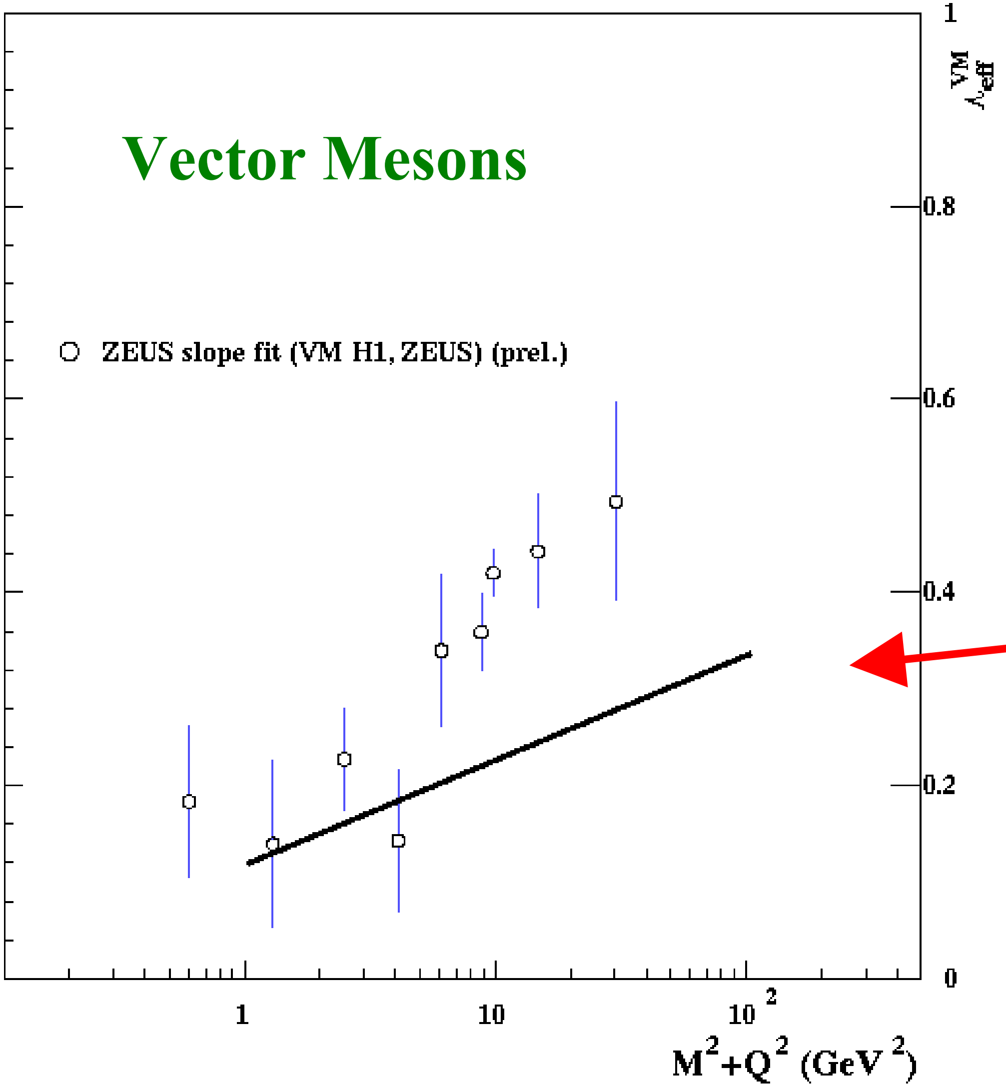
The rise, δ, scales with $Q^2 + M^2_{VM}$!

Elastic VM Production at HERA

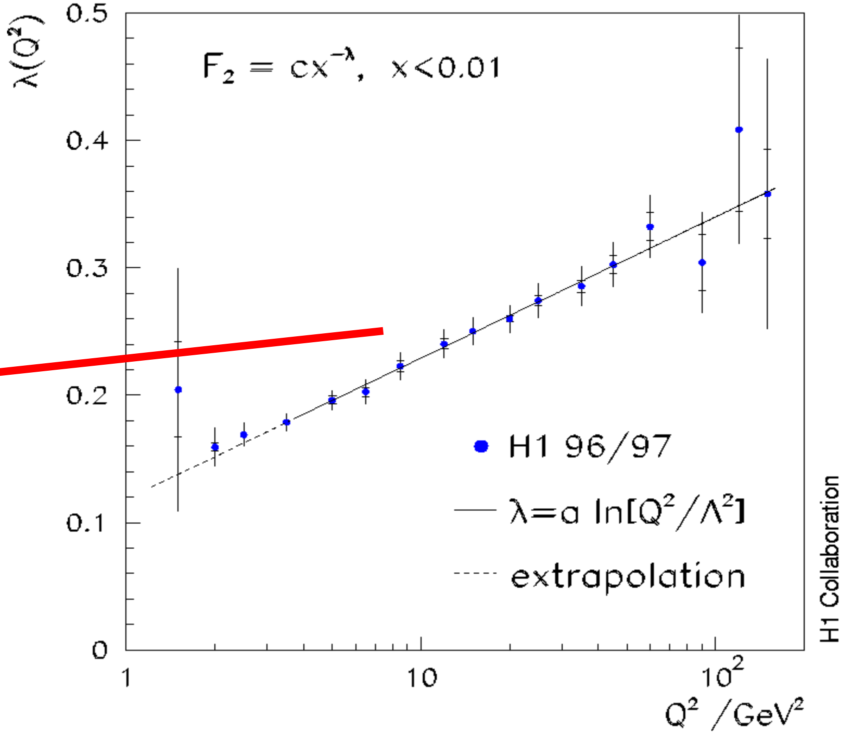


Now compare to F2 (i.e. inclusive DIS)

$$x^{-\lambda} \rightarrow W^{2\lambda}$$

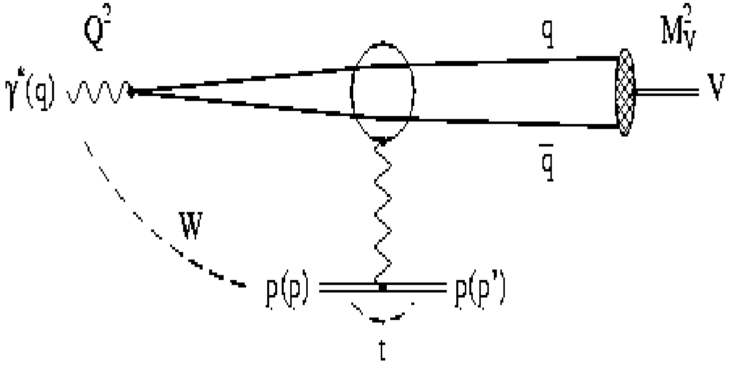


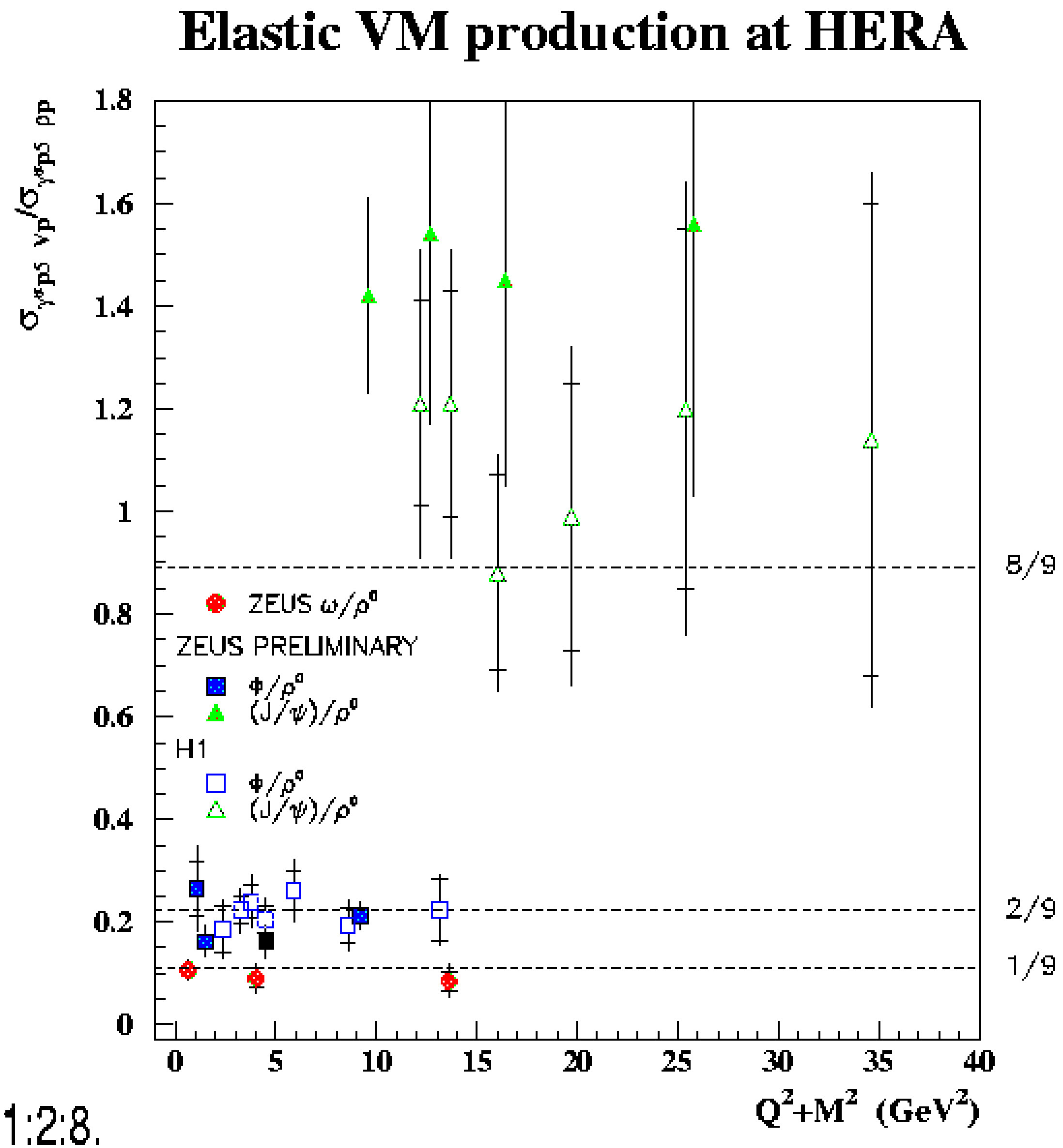
Recall F2 behavior



Naively: $\sigma_{VM} \sim f_V^2 \cdot \hat{\sigma}$?

i.e. coupling times the (dipole?) cross section $\hat{\sigma}$?

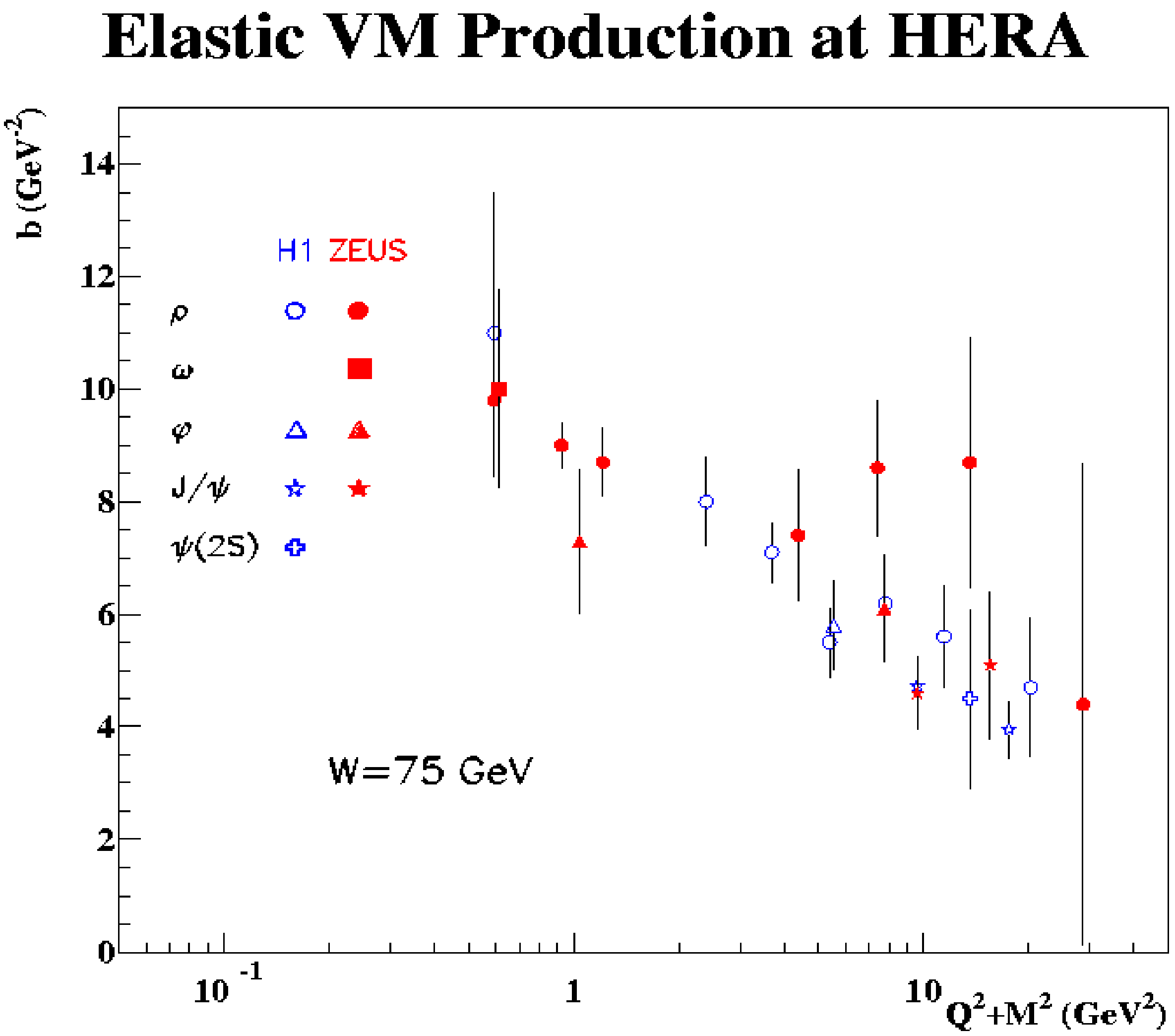




f_V^2 from charges of the quarks: ρ:ω:ϕ:J/ψ → 9:1:2:8.

… and $\hat{\sigma}$ that depends on the dipole radius?

Look at the t slope: $\frac{d\sigma_{VM}}{d|t|} \propto e^{-b|t|}$



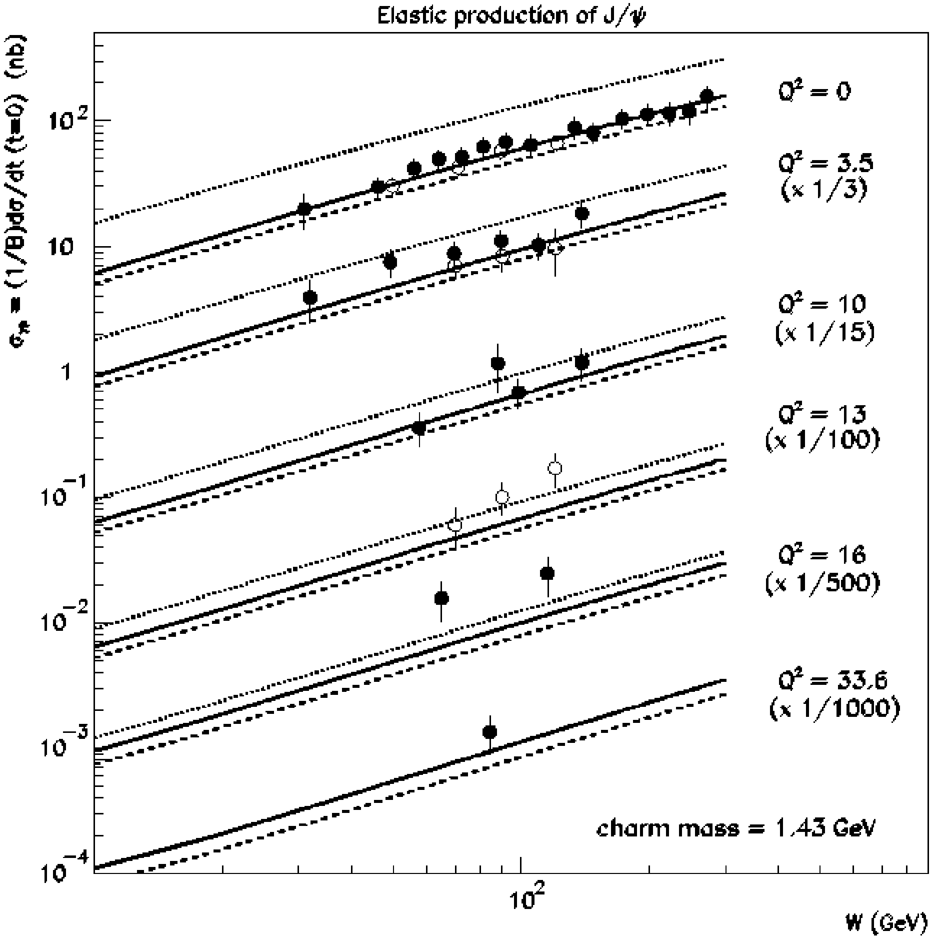
Consistent with $Q^2 + M^2_{VM}$ giving the “size” of the interaction.

Dipole formulation of the VM cross section ⇒

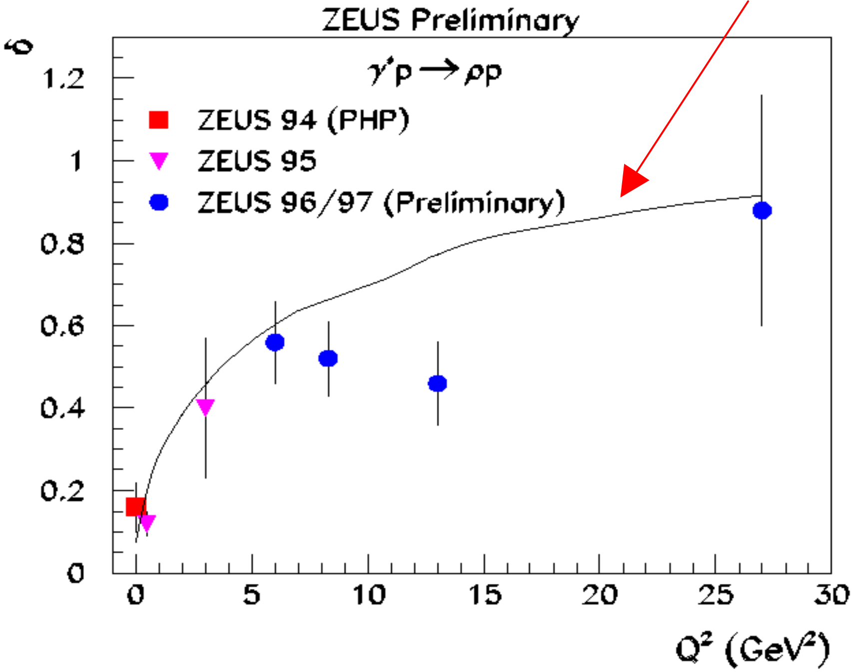
Amplitude: $A = \int dz \int d^2 r \Psi_{VM} \hat{\sigma}_{dipole} \Psi_{\gamma}$

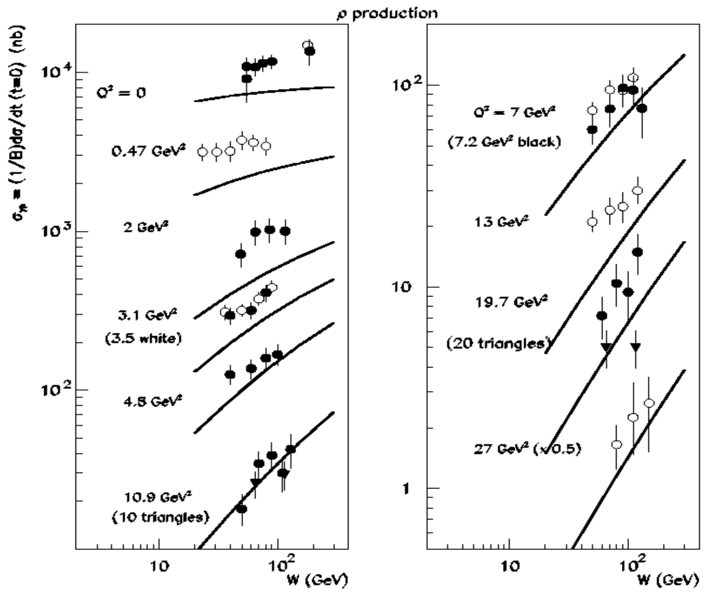
Ψ_{VM}: The vector meson wave function.

Ψ_{γ}: The photon wave function.



GB&W dipole





From paper by Caldwell and Soares

Conclusions and outlook:

Only a part of HERA results on proton structure was presented here.

The measurements of proton structure function F2 at of 3% accuracy over 6 orders magnitude.

-leads to precise determinations of QCD parameters: parton distributions, strong coupling constant.

Looking more closely at small x:

Connection has to exist between small-x and diffraction.

And...

-A simple dipole model can qualitatively demonstrate the connection between DIS, diffraction, and VM production.

-May point the way to bridge the gap, in understanding, between DGLAP, and, low-x and low-Q2 regions.

HERA detectors, will begin to take data again after the luminosity upgrade of the accelerator:
-Will concentrated on high-Q2, high-x, physics.

Meanwhile..a large amount of HERA data on low-x and diffraction is available.