HERA Small-x and/or Diffraction

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For the ZEUS and H1 Collaborations

RADCOR, Carmel, 14 Sept., 2000

- **Proton Structure Function F_2 at Small-x**

"OR"...

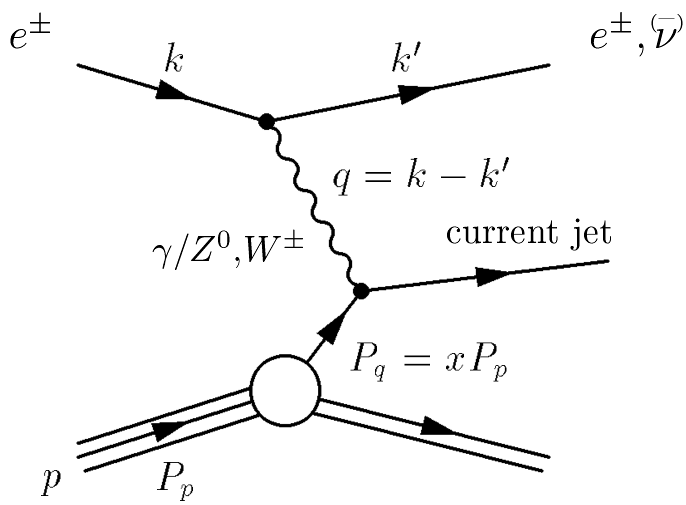
- **Diffraction at HERA**
  - **Diffraction in DIS**
  - **Diffractive Vector Meson Production**

"AND"...

- **F_2 at Small-x Revisited**
- **Conclusion**

I. F_2 at Small-x

A short review of DIS...



$Q^2 = -q^2$: virtuality (“size” of the probe)

x: mom. frac. of the struck parton (inf. mom. frame)

Factorization, i.e.:

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

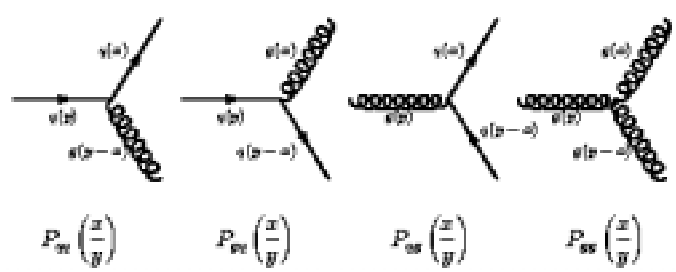
$f_p(x)$: (universal) parton densities of the proton.

$\hat{\sigma}$: partonic cross section.

GLAP evolution equation:

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

Where P are the splitting fnc:



Experimentally, we measure (At $Q^2 \ll M_Z^2$, and ignoring F_l):

$$\frac{d\sigma^2}{dxdQ^2} \approx \frac{2\pi\alpha^2}{xQ^4}(1 + (1-y)^2)F_2(x, Q^2)$$

$y = Q^2/xs$, the inelasticity parameter

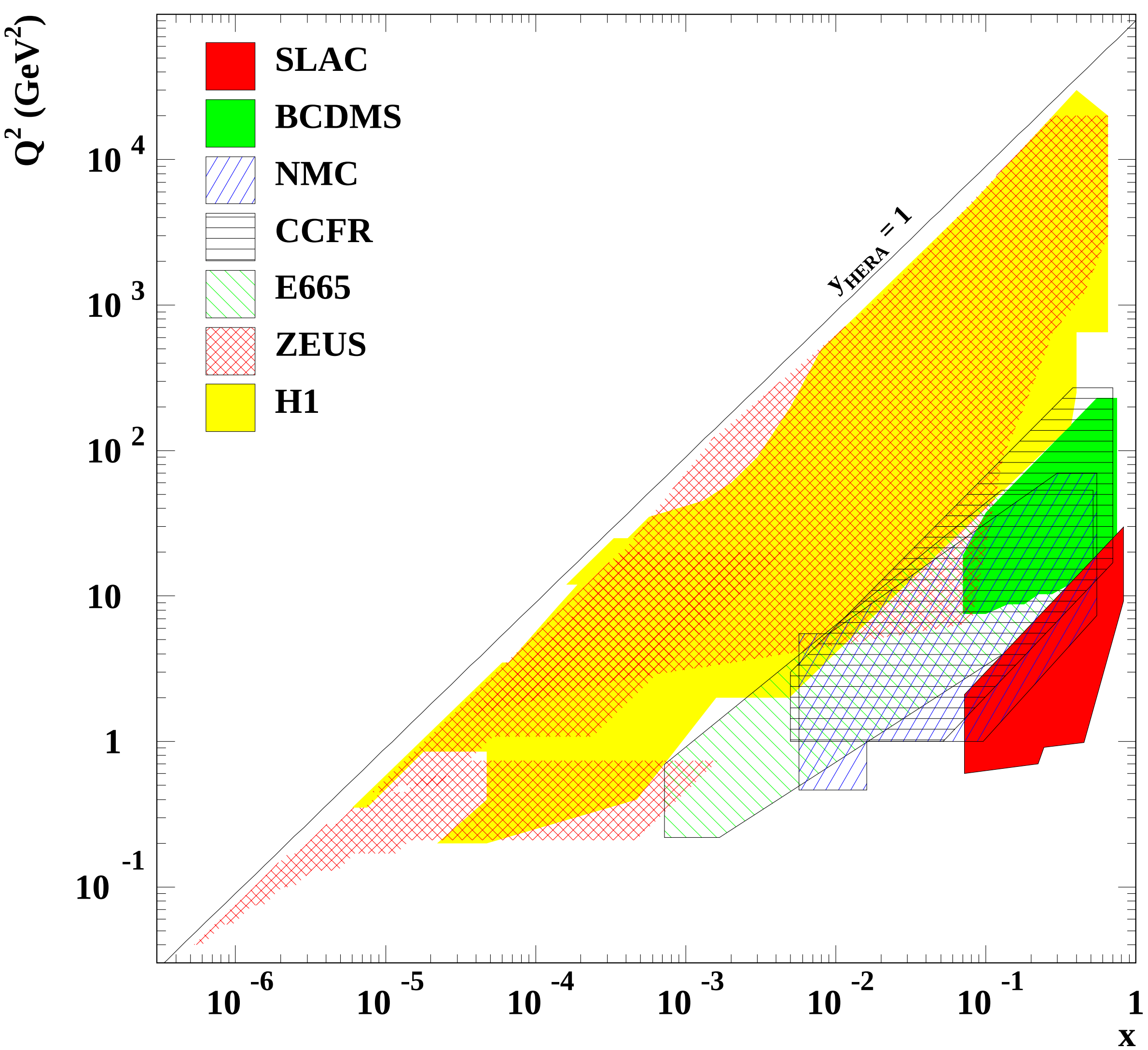
And (LO (or in DIS scheme..))

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

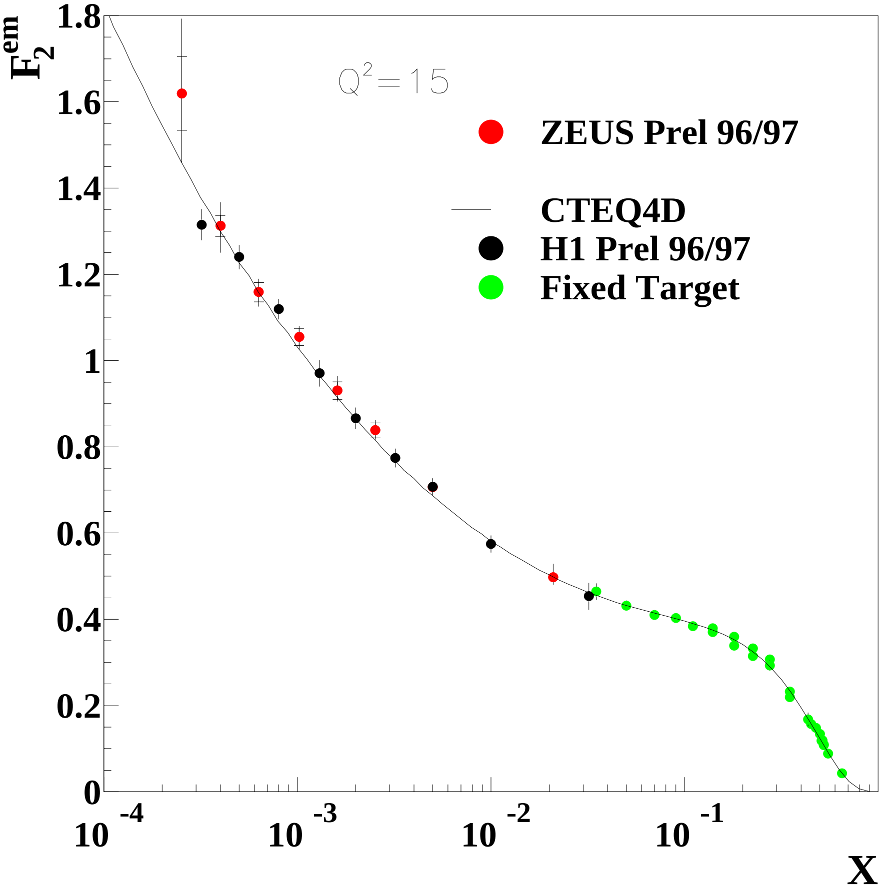
where q, $\bar{q}$ are quark, antiquark PDF's.

HERA ep collider: $\sqrt{s} \approx 300$ GeV $\Rightarrow$

Q^2 and x can be varied over 6 orders of magnitude.



F_2 rises at small-x..

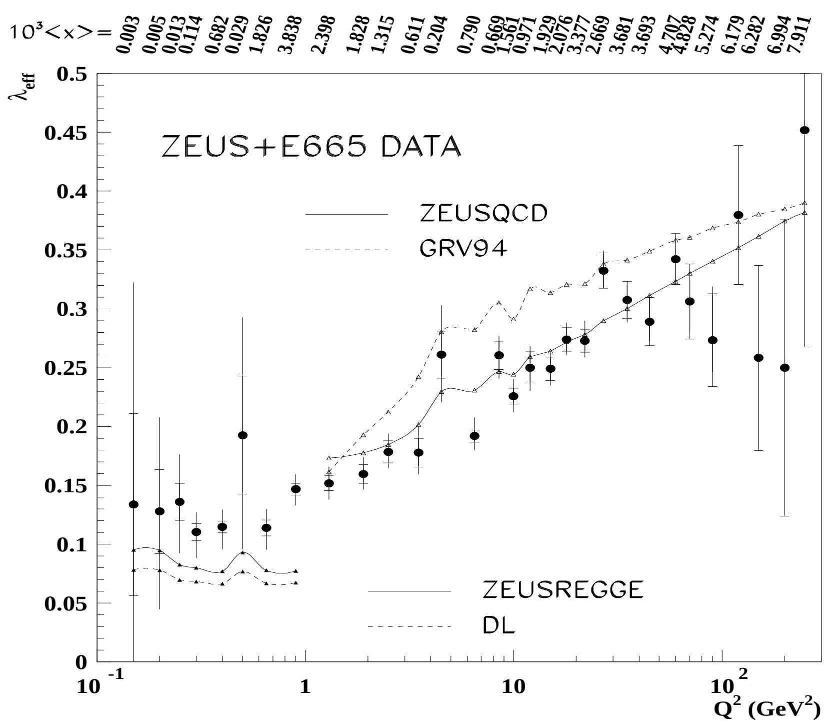


$\Rightarrow$ parton densities are rising at small-x Naively: valence quark $\rightarrow$ gluons $\rightarrow$ sea quarks $\rightarrow$ more gluons etc. etc.

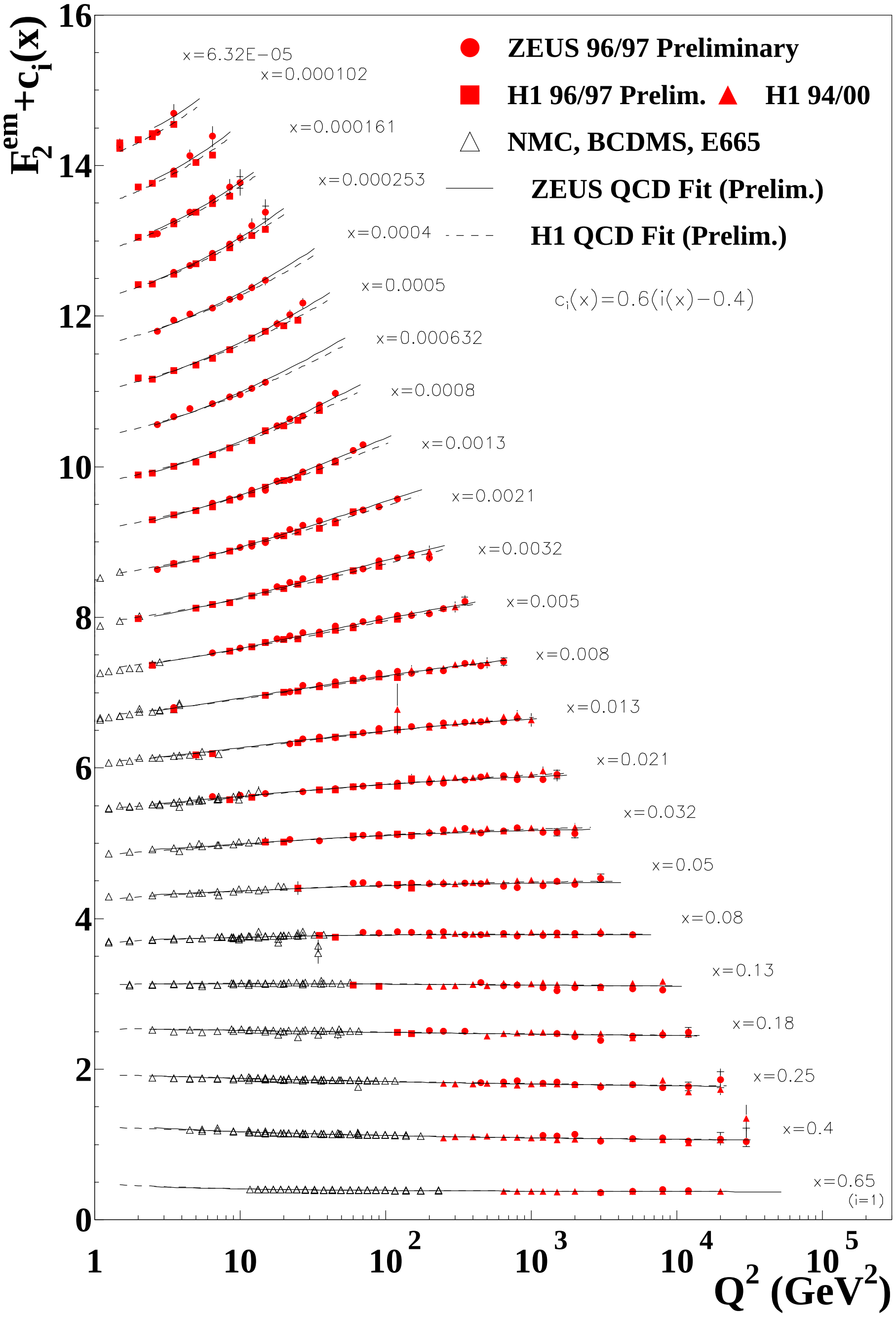
$F_2 \propto x^{-\lambda}$:

$\lambda \approx 0.2$

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



Proton Structure Function F_2



The GLAP fits describe the data well $Q^2 > 1$ GeV

Additive constant c_i added for display purpose

An Example of a NLO GLAP fit to F_2: ZEUS 95 fit

- Use ZEUS 94, 95, NMC and BCDMS data. $Q^2 > 1$ GeV^2 and $W^2 > 10$ GeV^2.

- Fit for gluon (xg) sea quark (xS) and singlet ($x\Delta_{ud}$) distribution in the form:
$Ax^{\delta}(1-x)^{\eta}\times$(Polynomial in $\sqrt{x}$)
using the GLAP evolution.

- Input u and d valence distribution taken from MRS(R2).

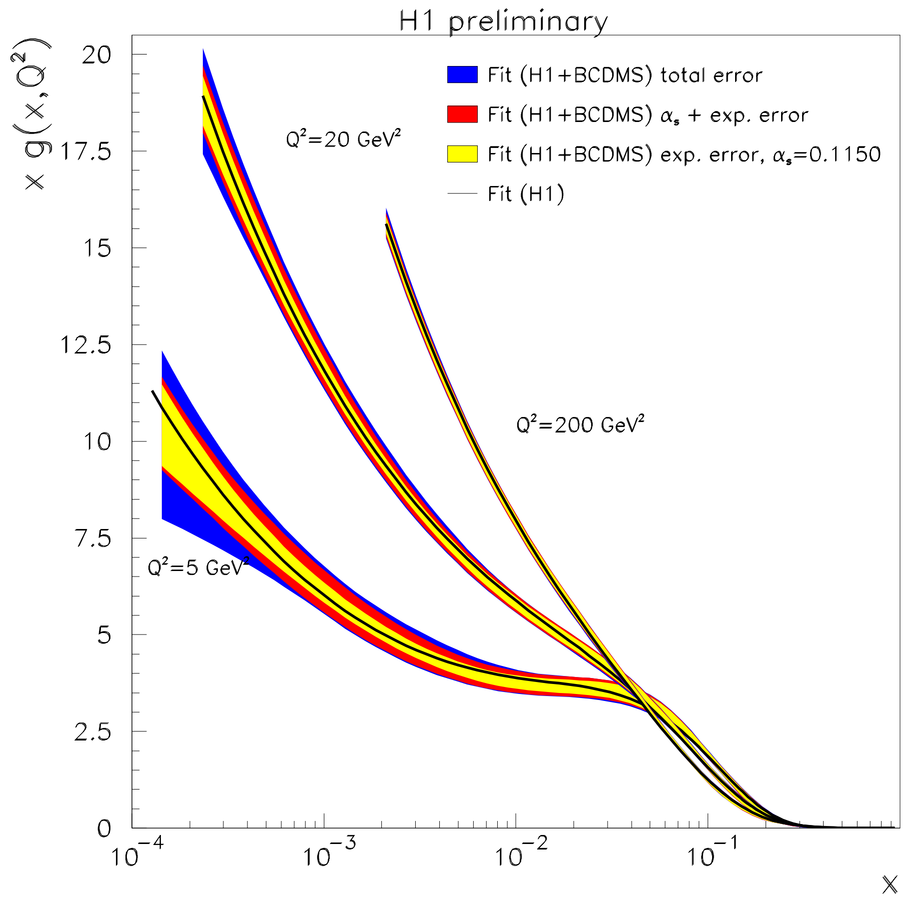
- Applying momentum sum rule: 11 parameters.

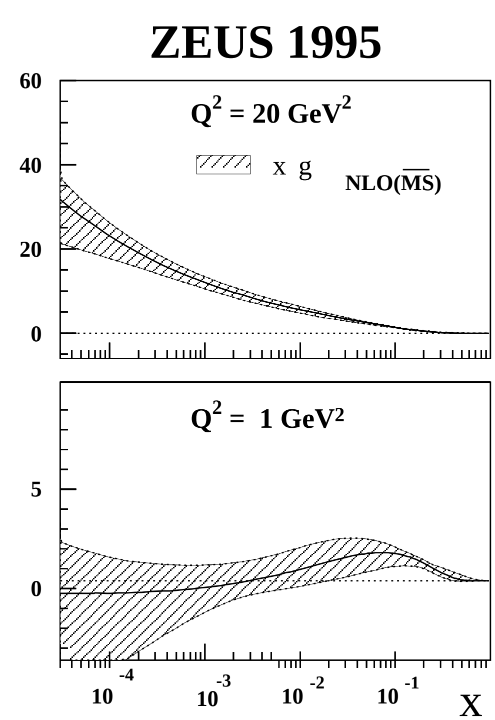
- Primary uncertainties: experimental errors and α_s,m_c, and the strange quark content ΔK_s.

- Additional uncertainties include, changing Q_0 and gluon density parametrized with a Chebycheff polynomial.

In LO: $\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s x g(x, Q^2)$

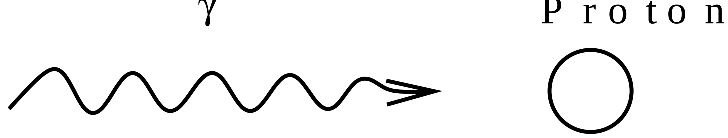
Gluons from a NLO GLAP fit to the F_2 measurements





Gluons rise at low-x as expected.

At the lowest Q^2 becomes compatible with 0 at low-x (F_2 itself is rising somewhat..)



Note: Small-$x \Rightarrow$ 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")

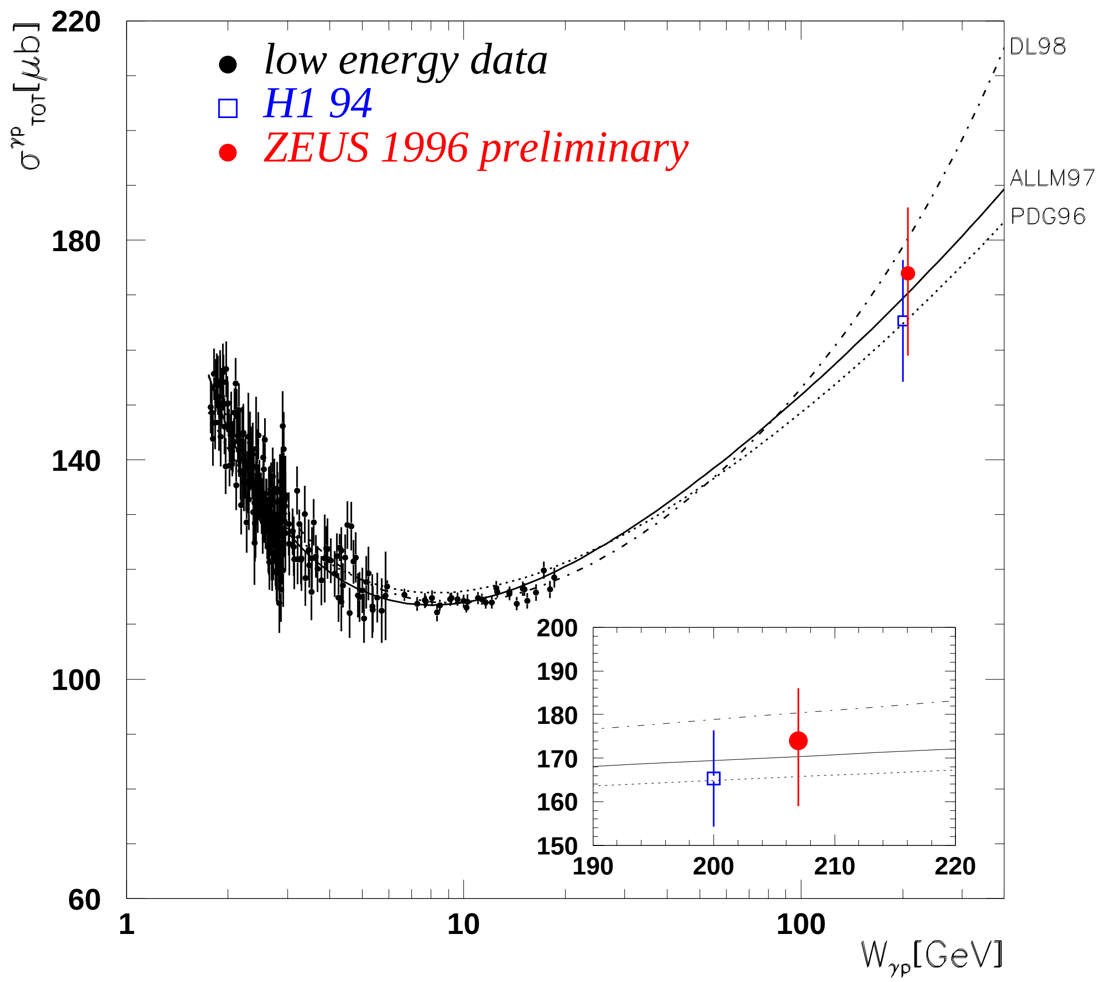
For fixed Q^2: $x^{-\lambda} \rightarrow W^{2\lambda}$

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")

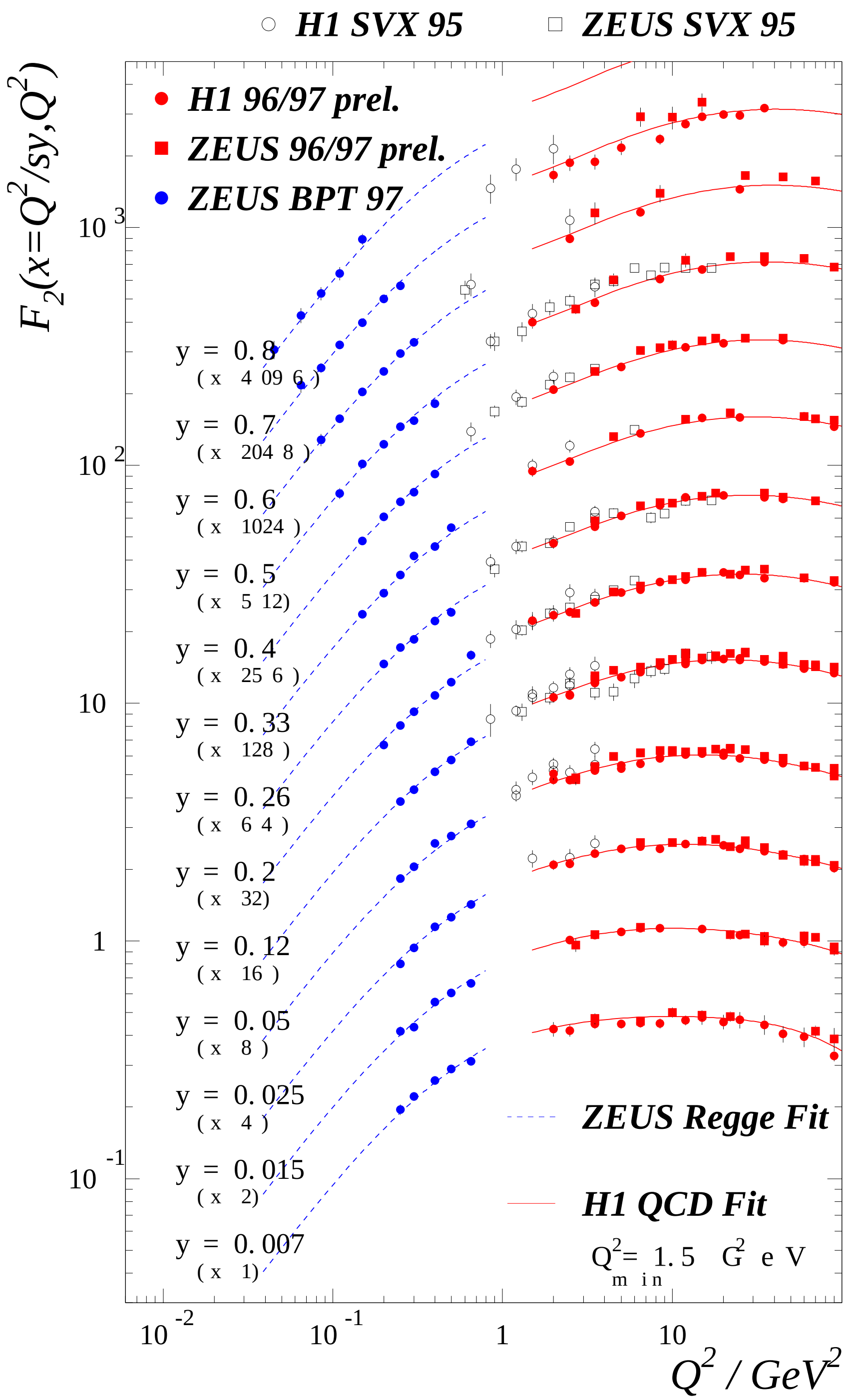


F_2 at $Q^2 < 1$ GeV

$10^{-3} > x > 10^{-6}$

Recall $y = W^2/s$

F_2 vanishes like Q^2 at fixed W.



Regge fit:

$$F_2(x,Q^2) = \left(\frac{Q^2}{4\pi^2\alpha}\right) \cdot \left(\frac{M_0^2}{M_0^2+Q^2}\right) \cdot$$

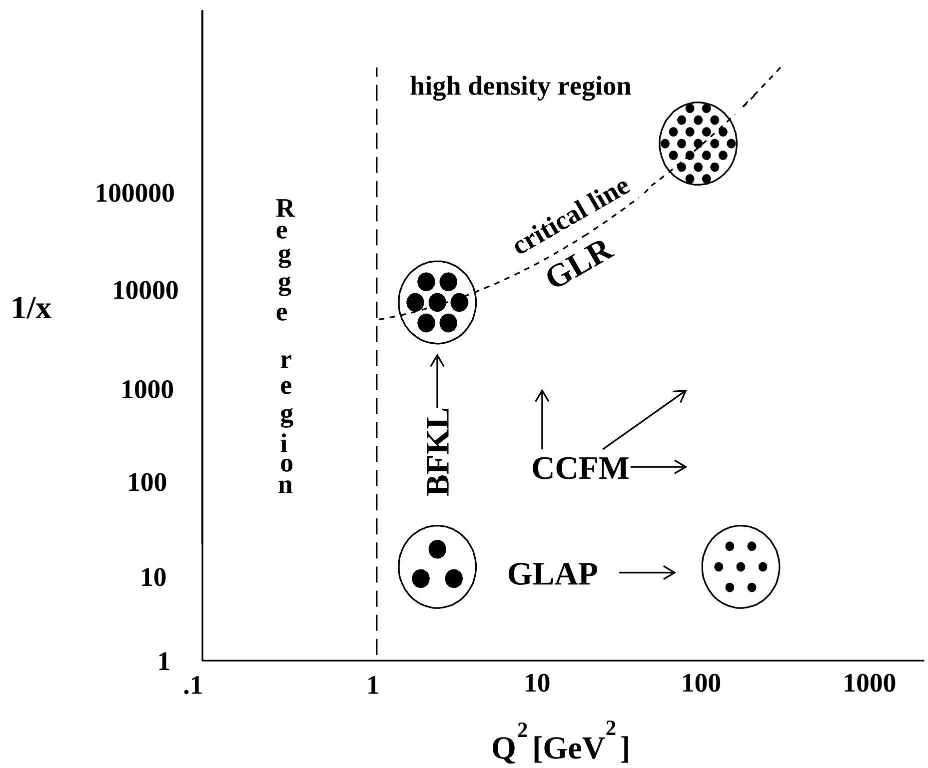
$$\left(A_{\mathbb{R}} \cdot (W^2)^{\alpha_{\mathbb{R}}-1} + A_{\mathbb{P}} \cdot (W^2)^{\alpha_{\mathbb{P}}-1}\right)$$

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

Summarizing thus far..

- 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

BUT...



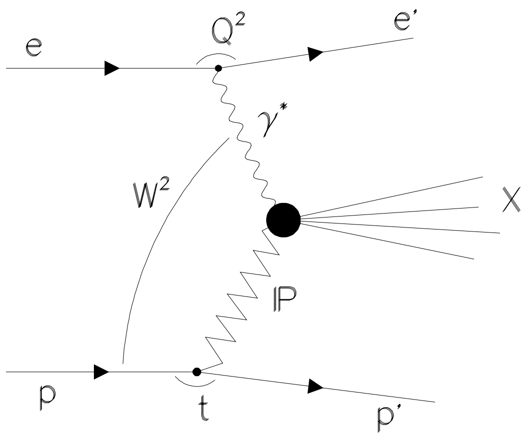
- What about $\ln 1/x$ (BFKL,CCFM), higher twist, terms etc.?
- What about shadowing or saturation (GLR): i.e. effects from high density of partons at low-x?

Let's look at DIS diffraction $\Rightarrow$

II. Diffraction in DIS

INCLUSIVE DIFFRACTION

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:

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

(integrated over t)

Hard factorization has been proven (Collins 1997):

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

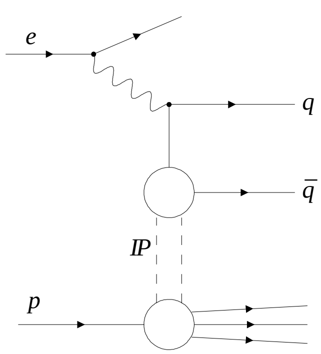
Where f^D is the diffractive parton densities.

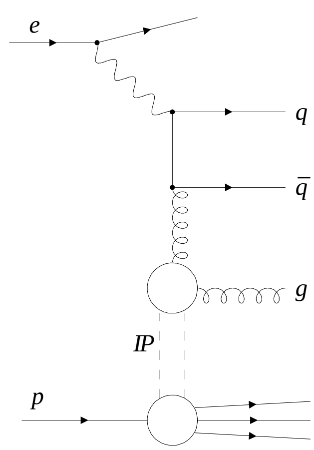
If Regge factorization is assumed:

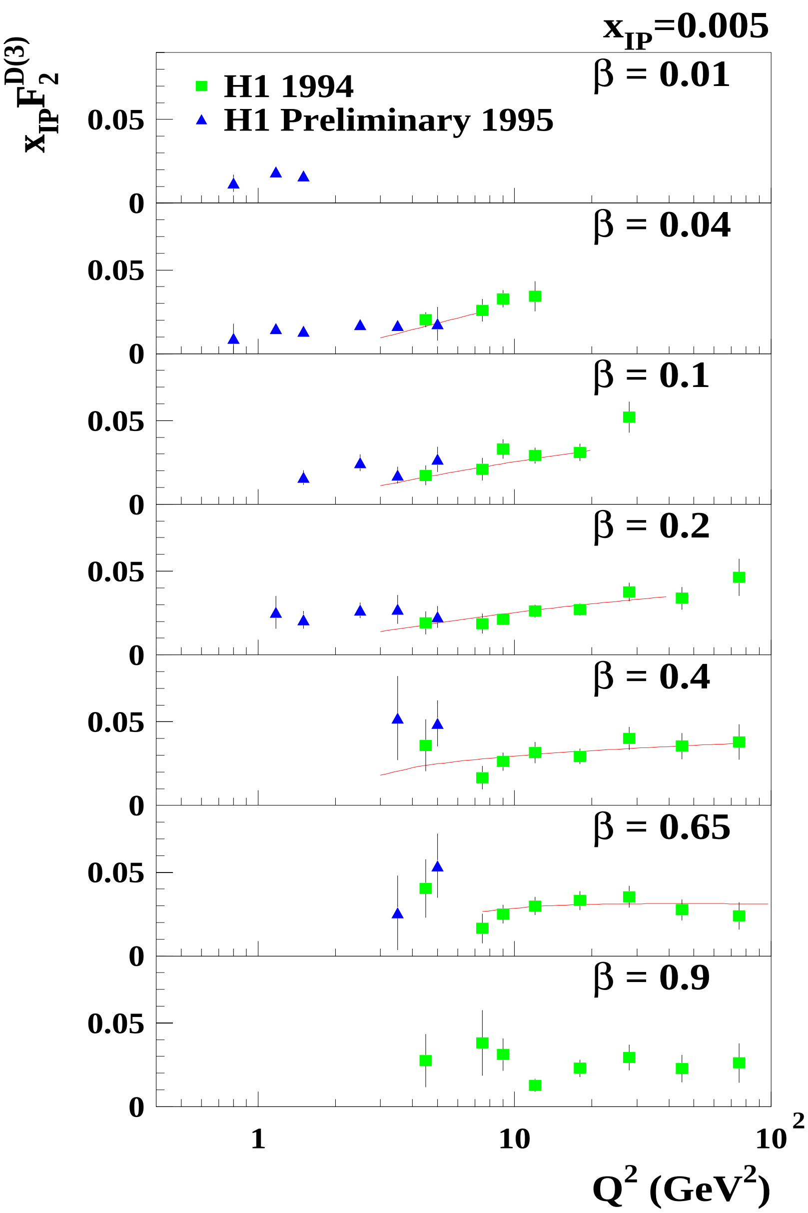
$$F_2^D(x_{\mathbb{P}}, t, Q^2, \beta) = f(x_{\mathbb{P}}, t) \cdot F_2^{\mathbb{P}}(\beta, Q^2)$$

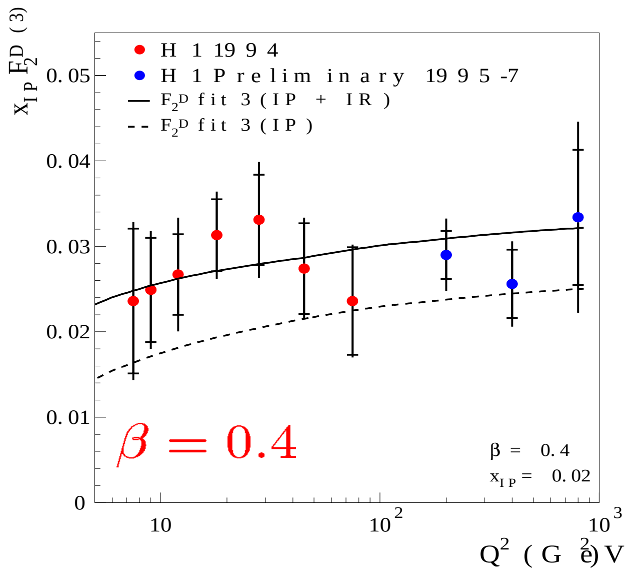
$\Rightarrow$ Can do a GLAP analysis of $F_2^{\mathbb{P}}$, the Pomeron structure function.

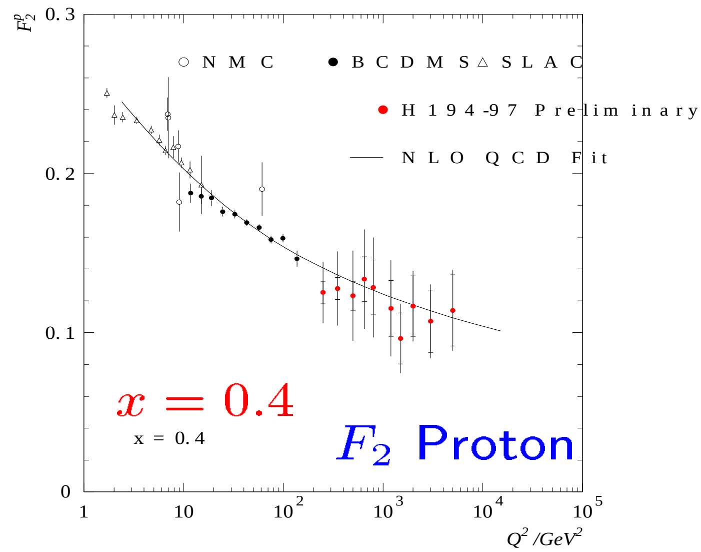
$f(x_{\mathbb{P}}, t) \approx 1/x_{\mathbb{P}}$, the Pomeron flux factor.







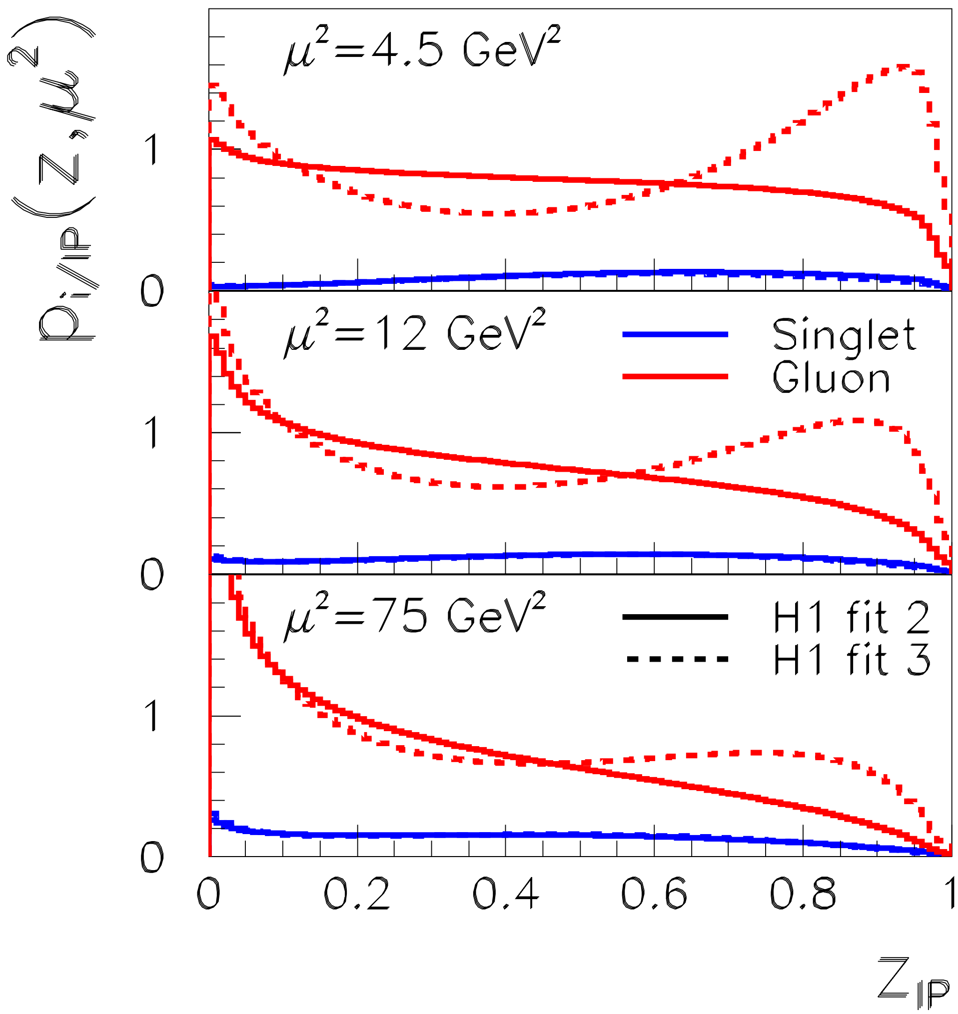




$x_{\mathbb{P}} F_2^D \sim F_2^{\mathbb{P}}$

- The evolution of the Pomeron is relatively flat in Q^2
- Implies gluon dominated structure $\Rightarrow$

Gluon dominated Pomeron..



P_i: momentum density of the parton i.

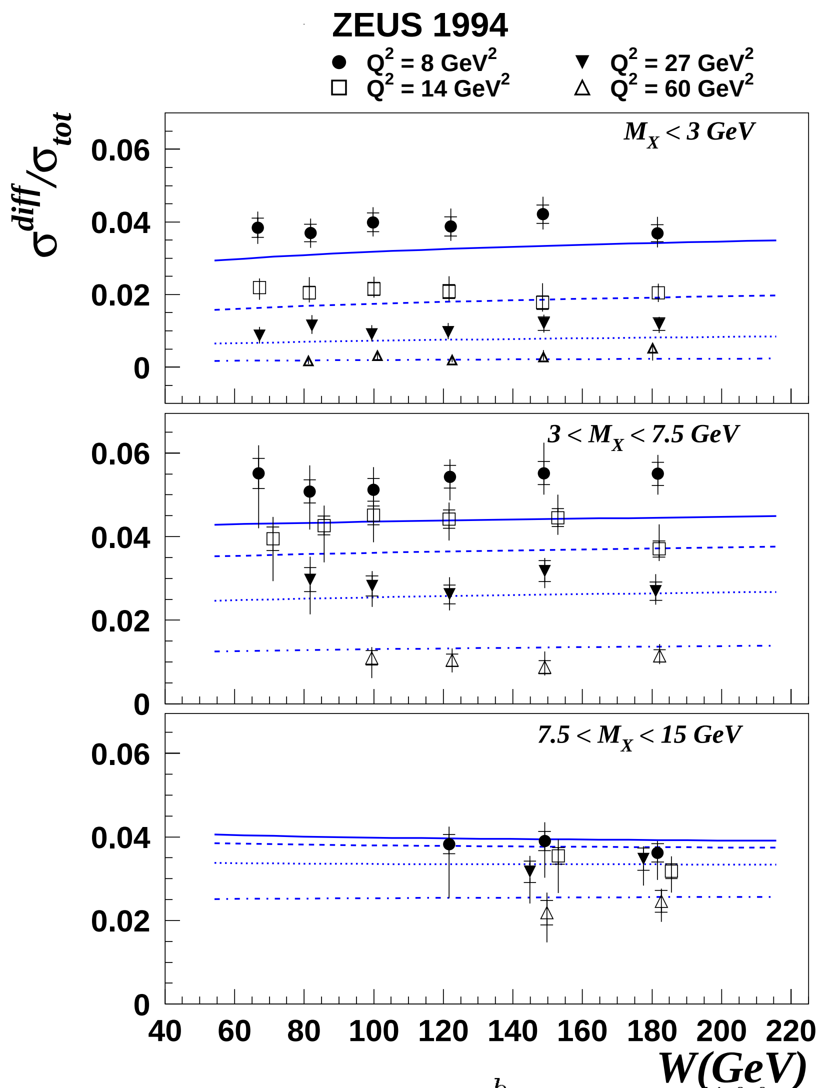
$Z_{\mathbb{P}} \approx \beta$

$\mu^2 = Q^2$

BUT...

What is the relationship with F_2^{proton}?

Try looking at it from a different point of view.. $\Rightarrow$

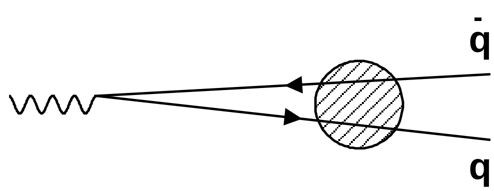


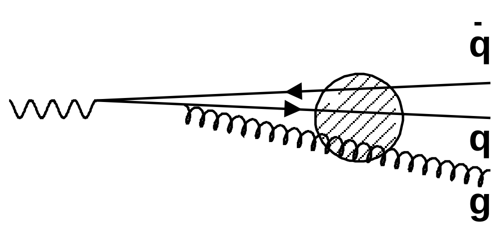
$$\frac{\sigma^{diff}}{\sigma^{tot}} \equiv \frac{\int_{M_a}^{M^b} dM_x \frac{d\sigma^{diff}}{dM_x}}{\sigma^{tot}_{\gamma^* p}}$$

- Diffraction has the same W^2 (or x) dependence as the total cross section!
- Contradicts optical theorem $\Rightarrow \sigma^{tot}_{\gamma^* p} \sim W^a$ then $\sigma^{diff} \sim W^{2a}$
- Contradicts expectation–if $\sigma^{tot}_{\gamma^* p} \sim$ Gluon, then $\sigma^{diff} \sim$ Gluon^2 ??

IMPACT PARAMETER SPACE (OR DIPOLE) PICTURE

- Proton dissociates to a $q\bar{q}$ pair (dipole) upstream of the protons
- The interaction is written in terms of the dipole cross section $\hat{\sigma}_{dipole}(x, r)$
  r: the radius of the dipole
  x: parton density in the proton
- Q^2 also enters via the photon wave function ($\Psi \Rightarrow$ determines the radius r)





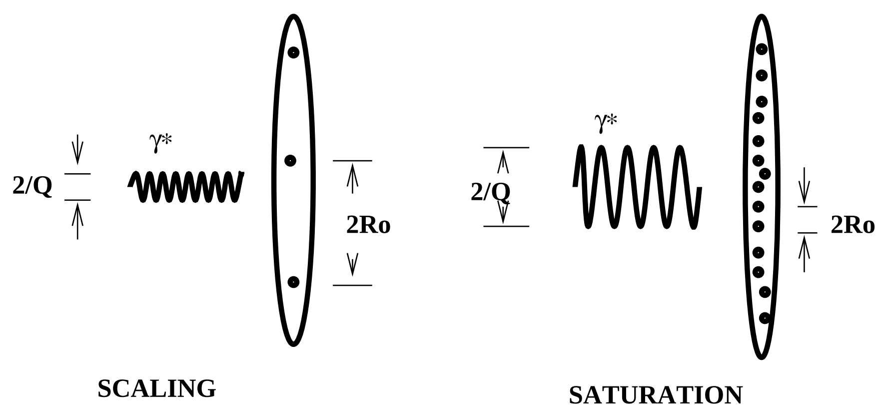
$$\sigma^{diff} \sim \int d^2r \int dz |\Psi(z, r)|^2 \hat{\sigma}^2_{dipole}(x, r)$$

z: momentum sharing of the dipole.

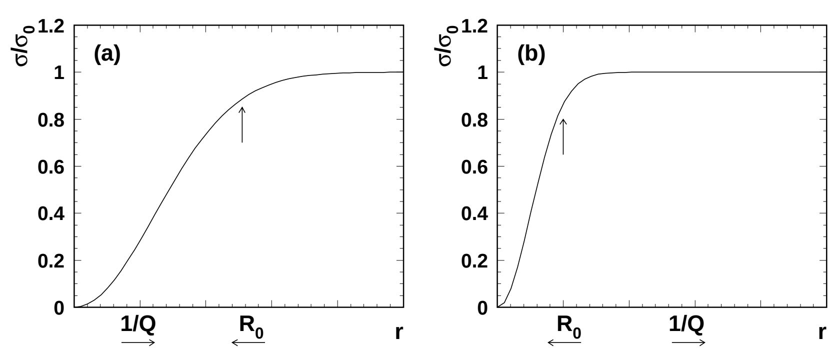
DIPOLES continued.. Long history: many models, calculations from many authors see B. Foster (hep-ex/0008069) for references..

The following discussion is from model by Golec-Biernat and Wuesthoff (GB&W).

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

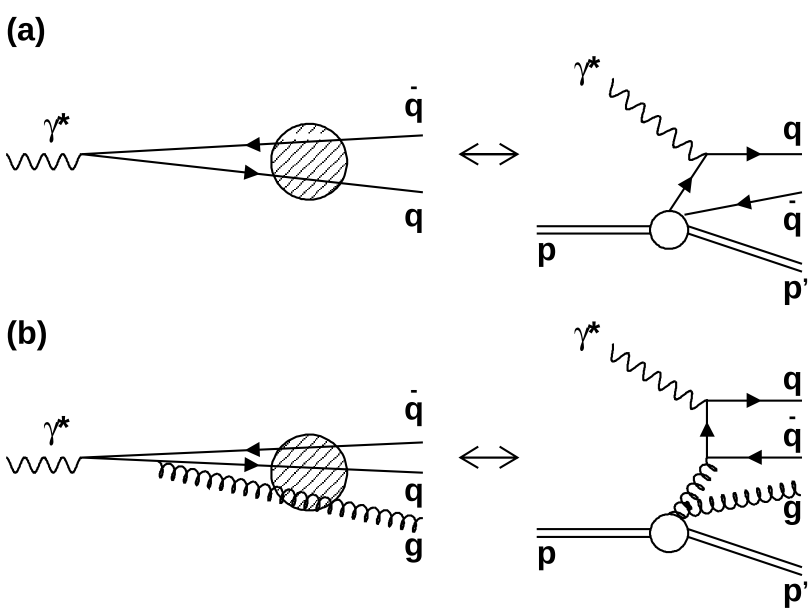


Dipole cross section:



DIPOLES continued..

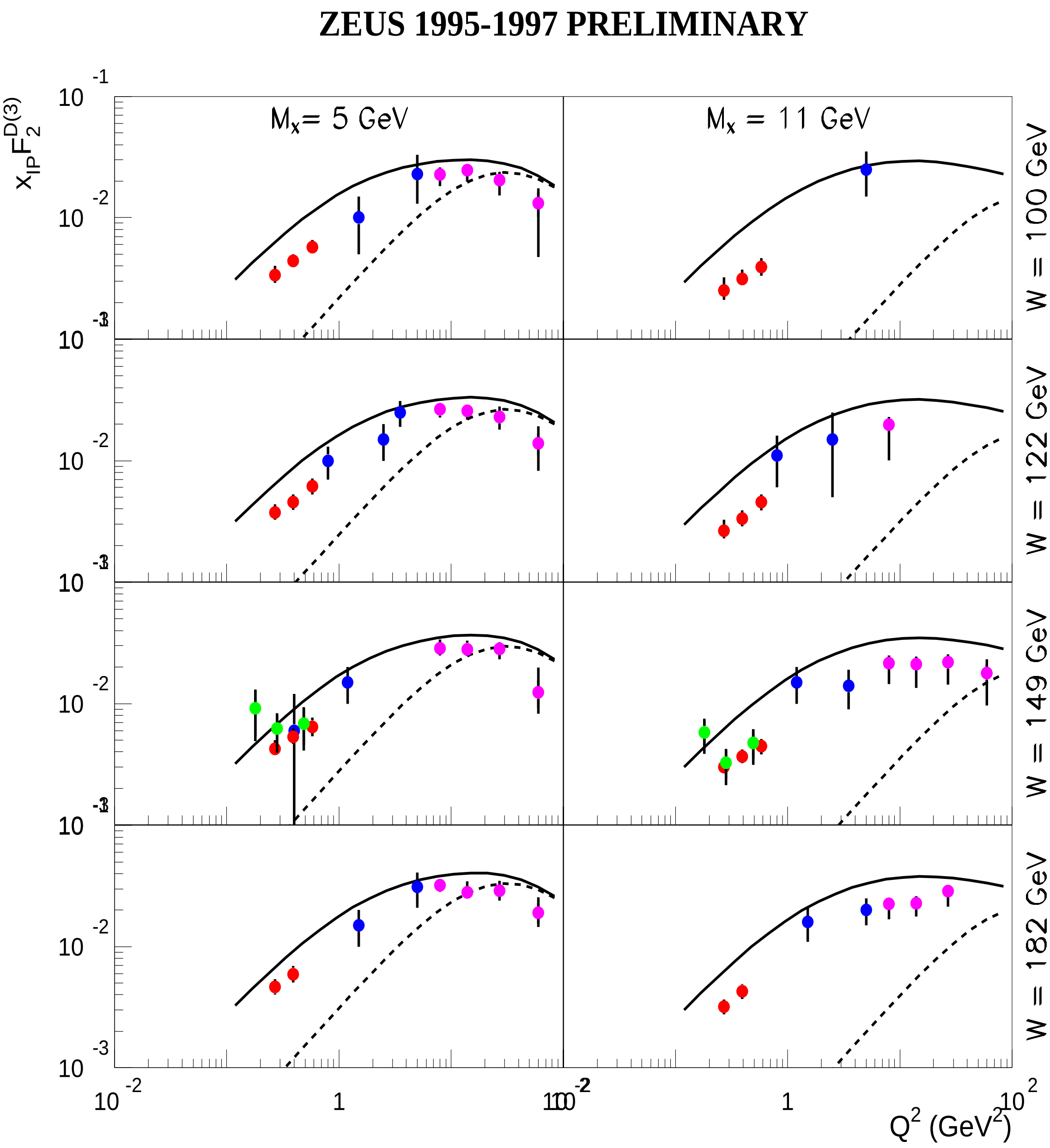
- The W (or x) dependence of σ^{diff} is moderated by saturation. $\rightarrow$ lines in the ratio plot.
- $\hat{\sigma}_{dipole}$ should be applicable to F_2^{proton}, VM production, as we will see.
- Boost to inf. mom. frame:



Gives good description of Pomeron structure function

Recent measurement of diffraction at low-Q^2 $\Rightarrow$

Measurement of $x_{I\!P} F_2^{D(3)}$ vs Q^2



ZEUS BPC 96-97 PRELIMINARY (Method I)

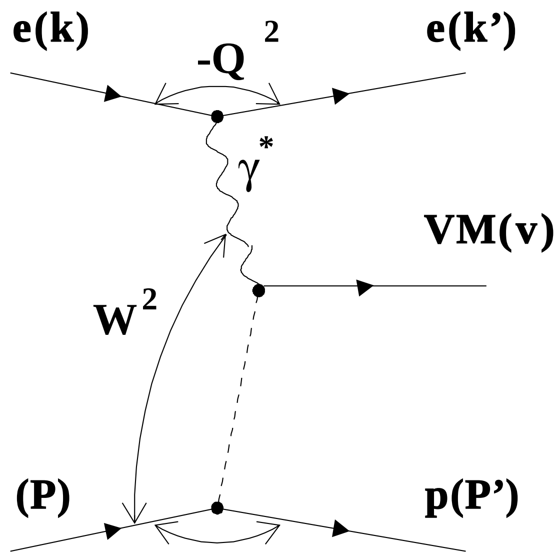
ZEUS LPS 95 PRELIMINARY (Method II)

H1 shifted vertex 95 PRELIMINARY

ZEUS DIS 94

Curves by K. Golec-Biernat (private comunication)

DIFFRACTIVE VECTOR MESON PRODUCTION



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

  Recall:

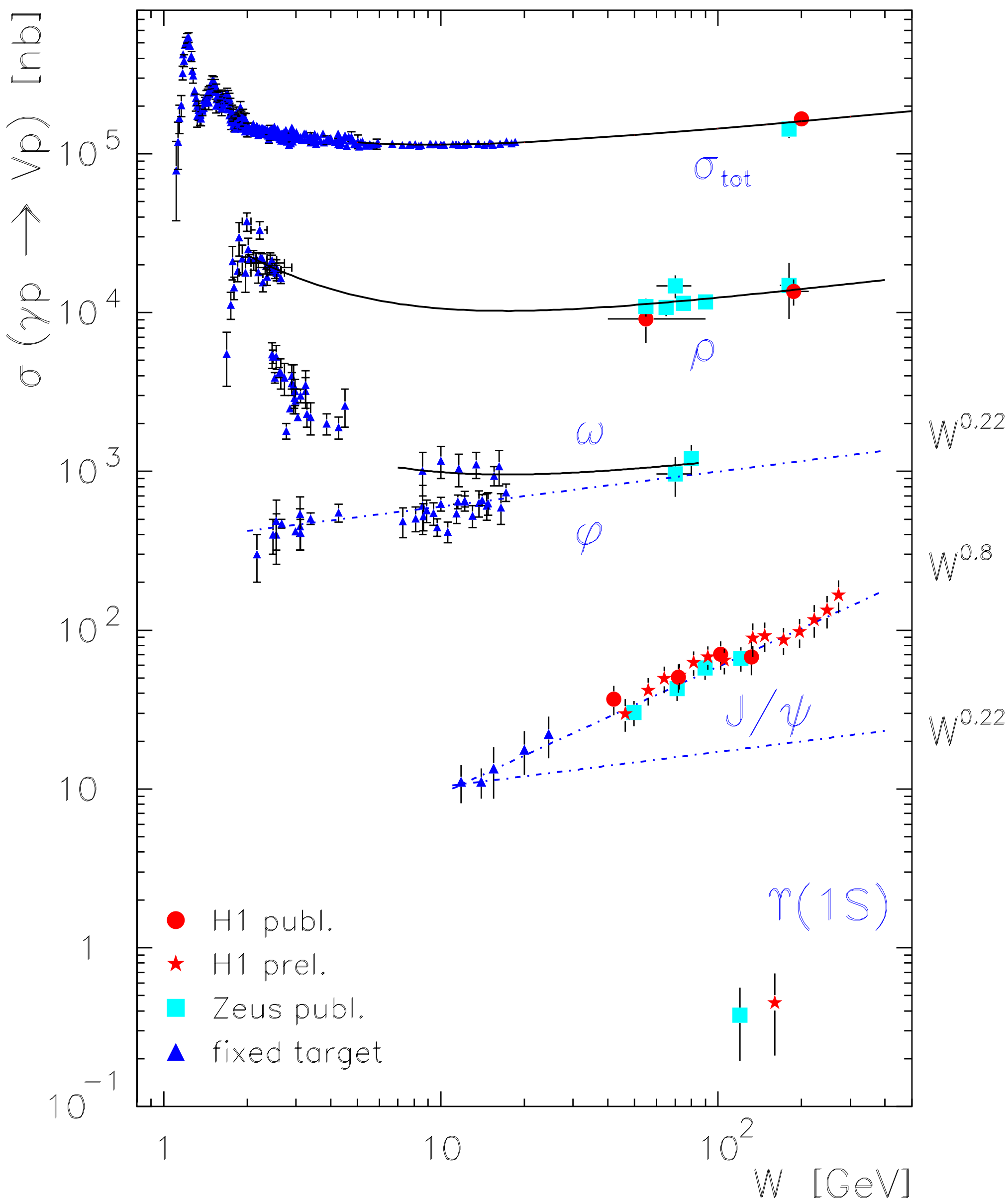
  $\sigma^{tot}_{\gamma p} \sim W^{2(\alpha_{\mathbb{P}}-1)} \approx W^{2(0.08)} = W^{0.16}$

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

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

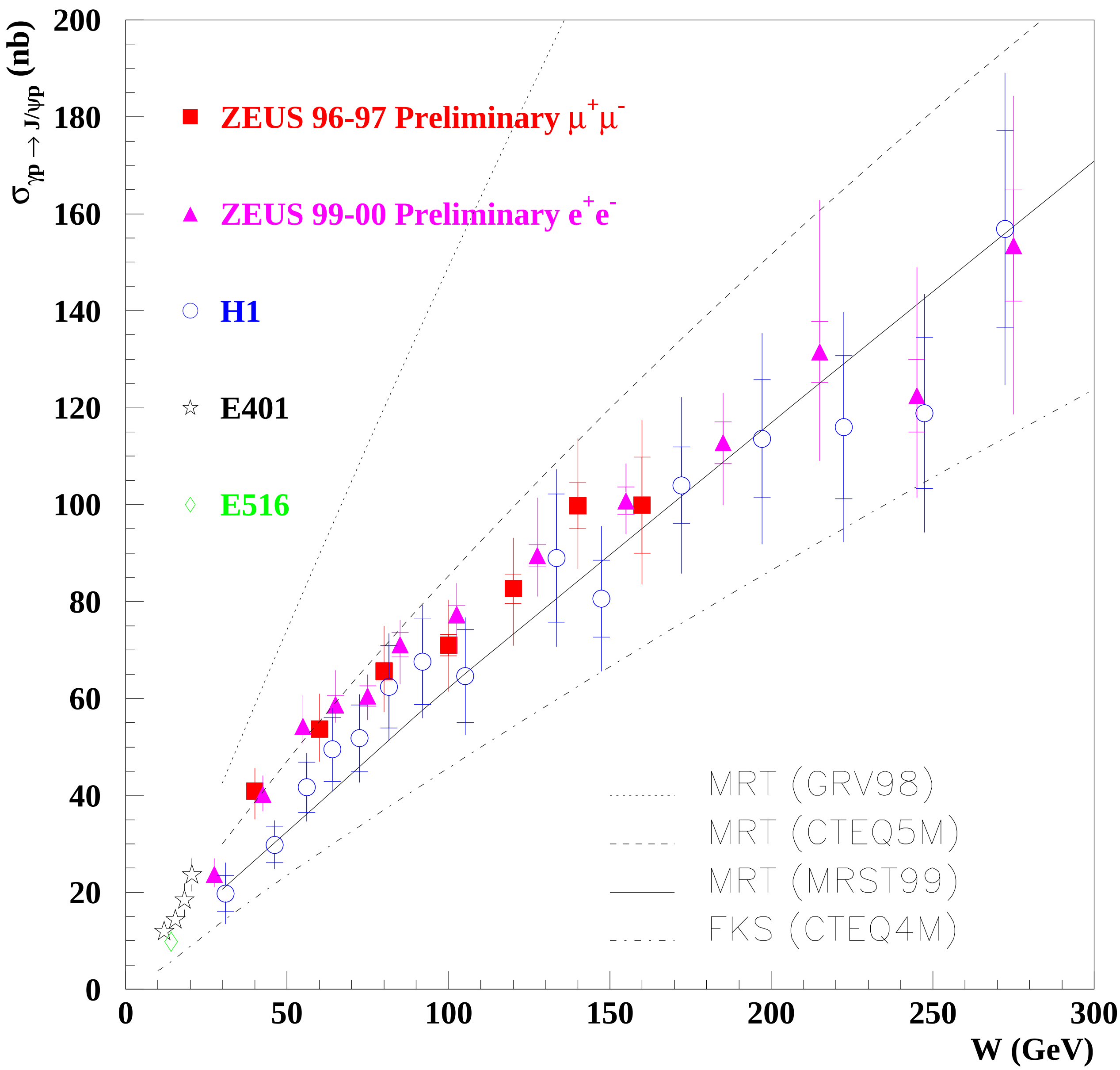
  $\sigma^{diff}/\sigma_{\gamma^* p}$ constant.
- What about Vector Meson production $\Rightarrow$

PHOTPRODUCTION OF VECTOR MESONS



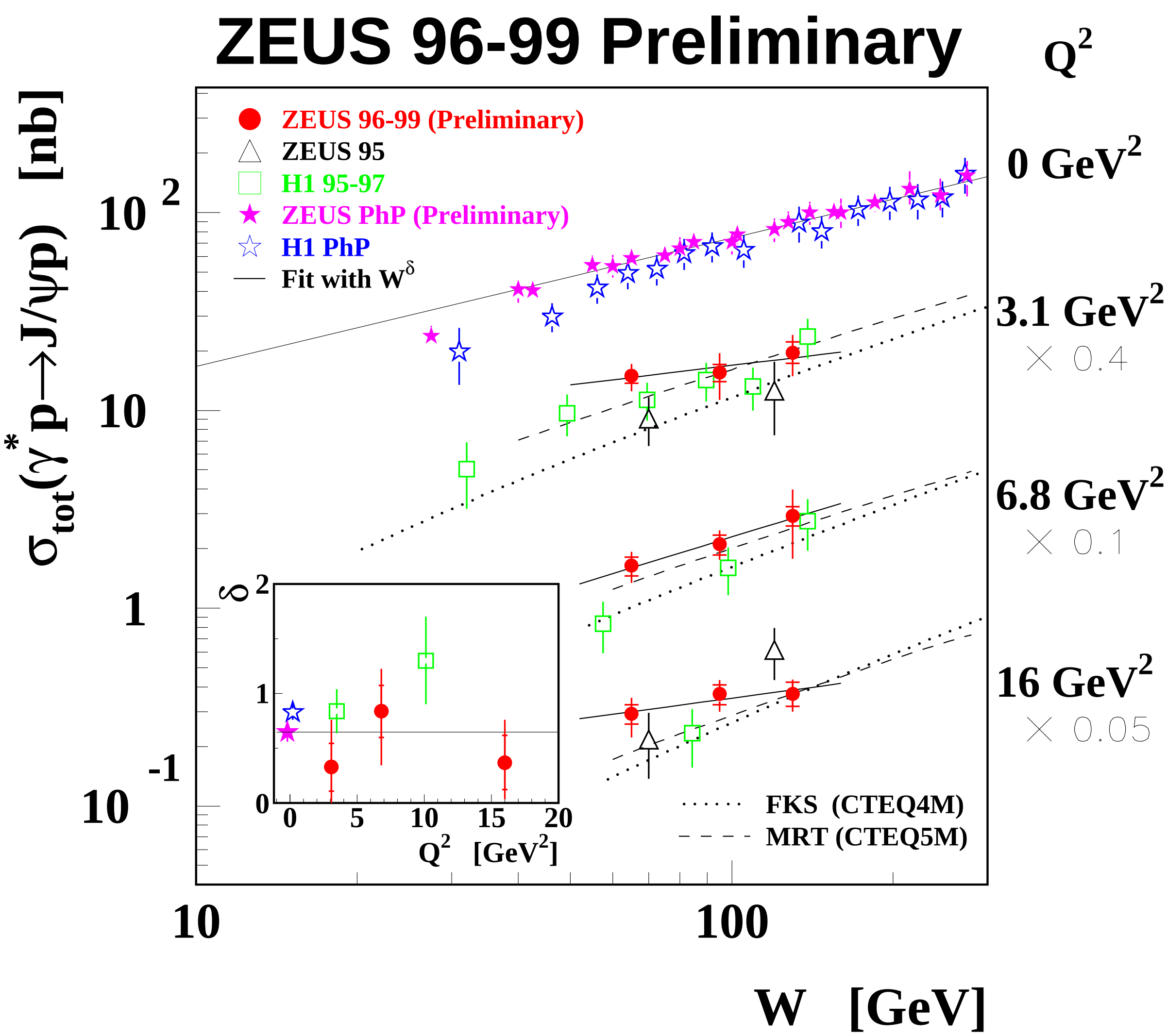
J/ψ rises like $W^{0.8}$! (i.e. twice F_2 at 10 GeV^2)

Compilation of latest HERA measurements (J/ψ $Q^2 = 0$)



Model calculations with $\sigma \sim \text{Gluon}^2$ works reasonably well.

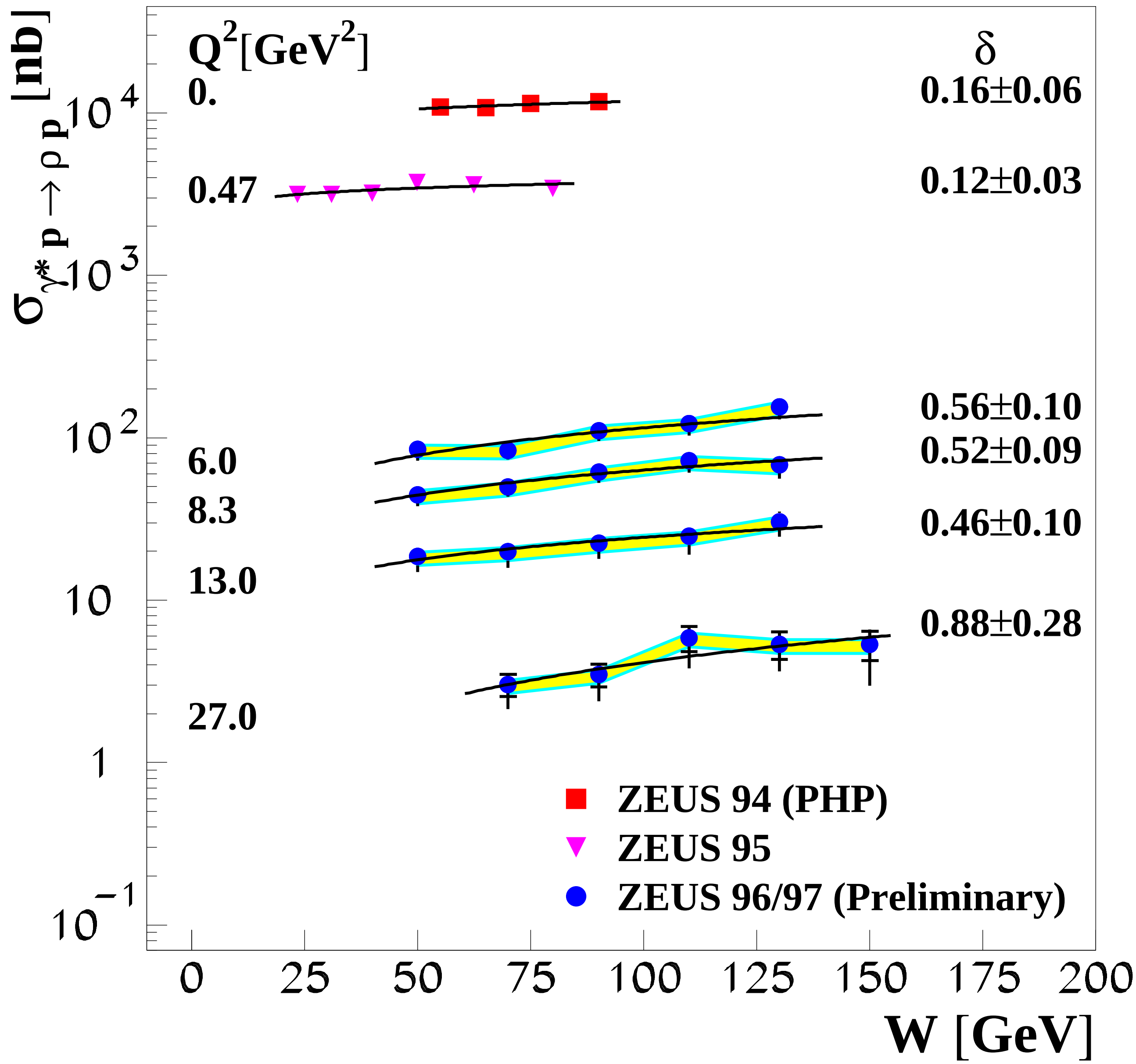
What about the Q^2 dependence $\Rightarrow$



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

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

What about the Q^2 dependence of ρ's? $\Rightarrow$

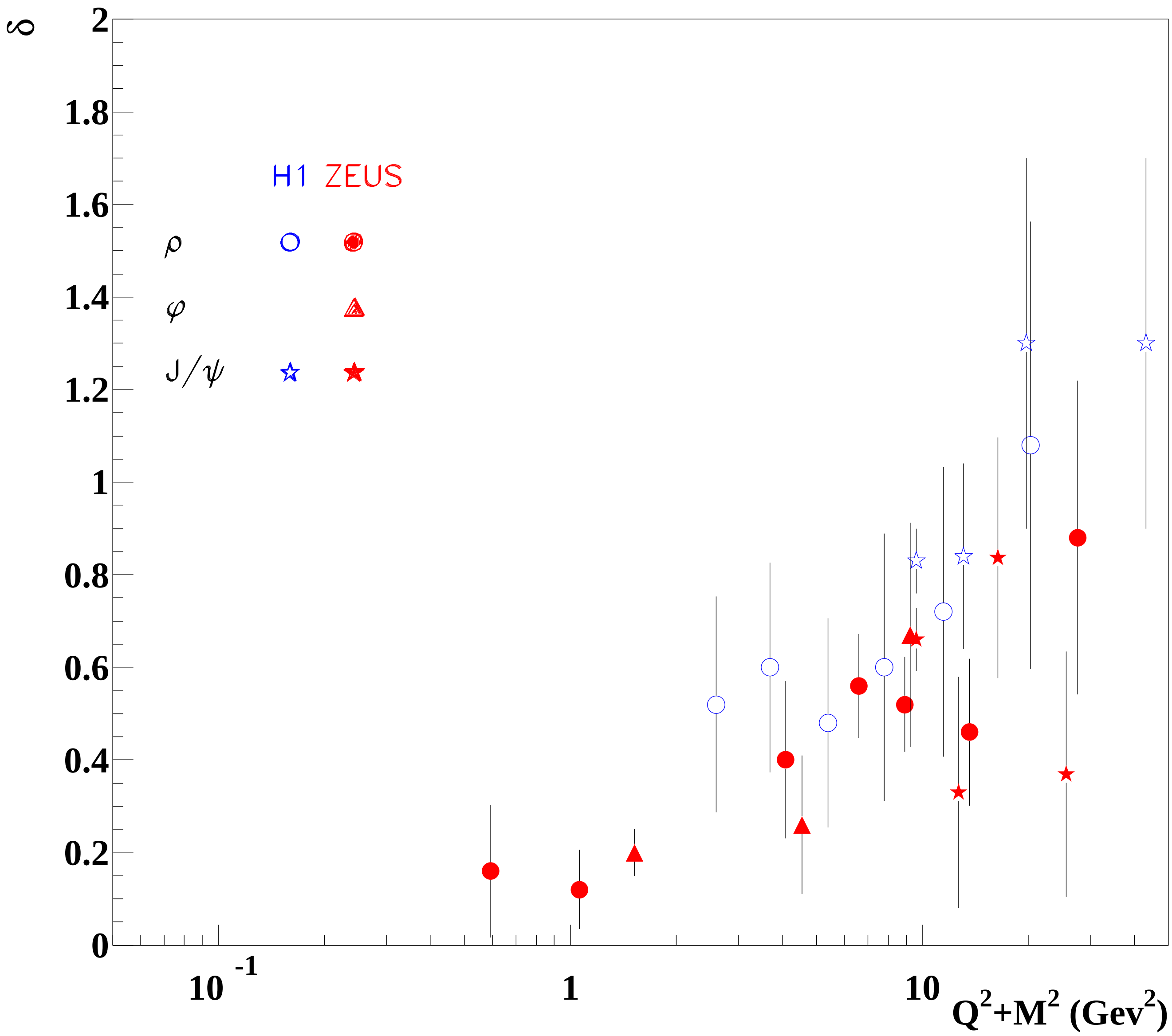


$\sigma \propto W^{\delta}$

δ increases with Q^2

At Q^2 of 27 GeV^2, $\sigma \sim W^{0.88}$!

Elastic VM Production at HERA

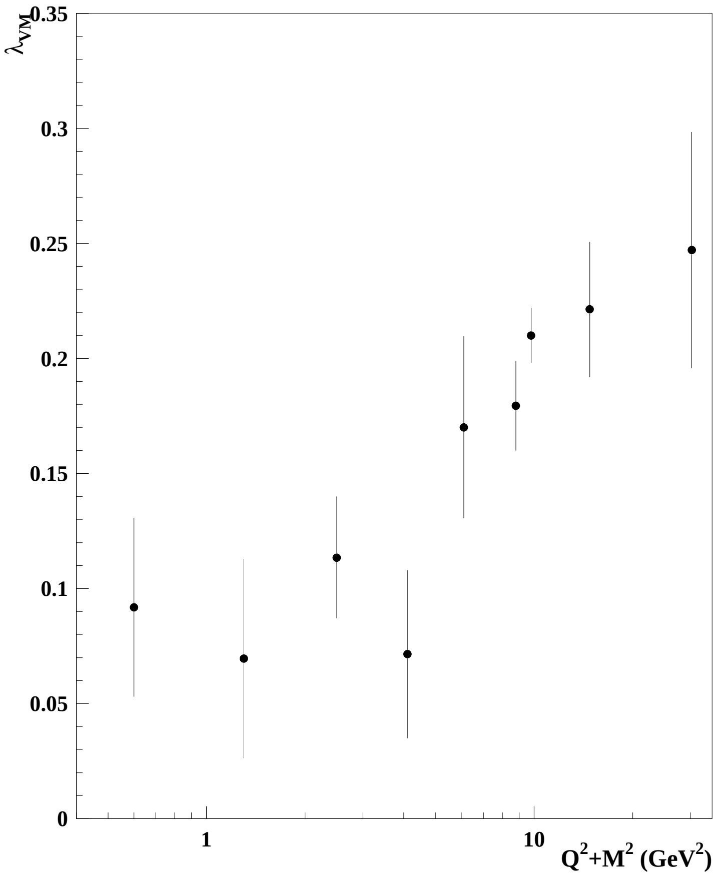


The rise, δ, scales with $Q^2 + M_{VM}^2$!

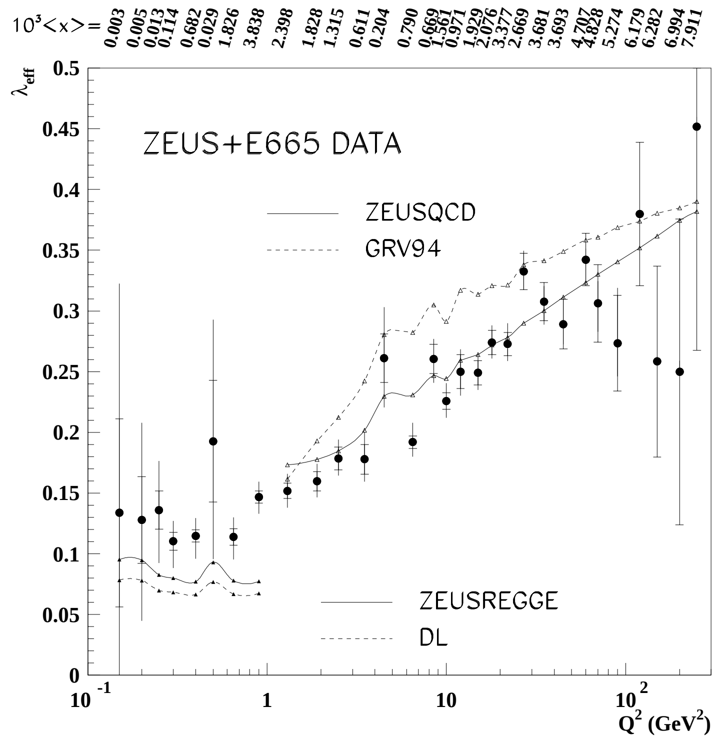
Defining λ_{VM} where $\sigma \sim x^{-2\lambda_{VM}}$)

Recall: $F_2^p \sim x^{-\lambda}$ so there's a factor 2

Elastic VM Production at HERA



Inclusive DIS



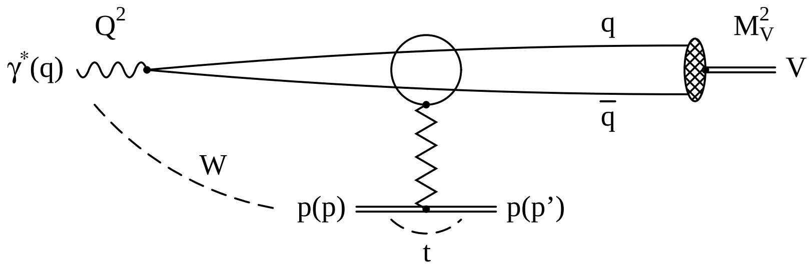
$$\lambda_{VM} \text{ (at } Q^2 + M^2_{VM}) \approx \lambda_{F_2} \text{ (at } Q^2)$$

$\Rightarrow$ VM rises approximately twice as fast as F_2.

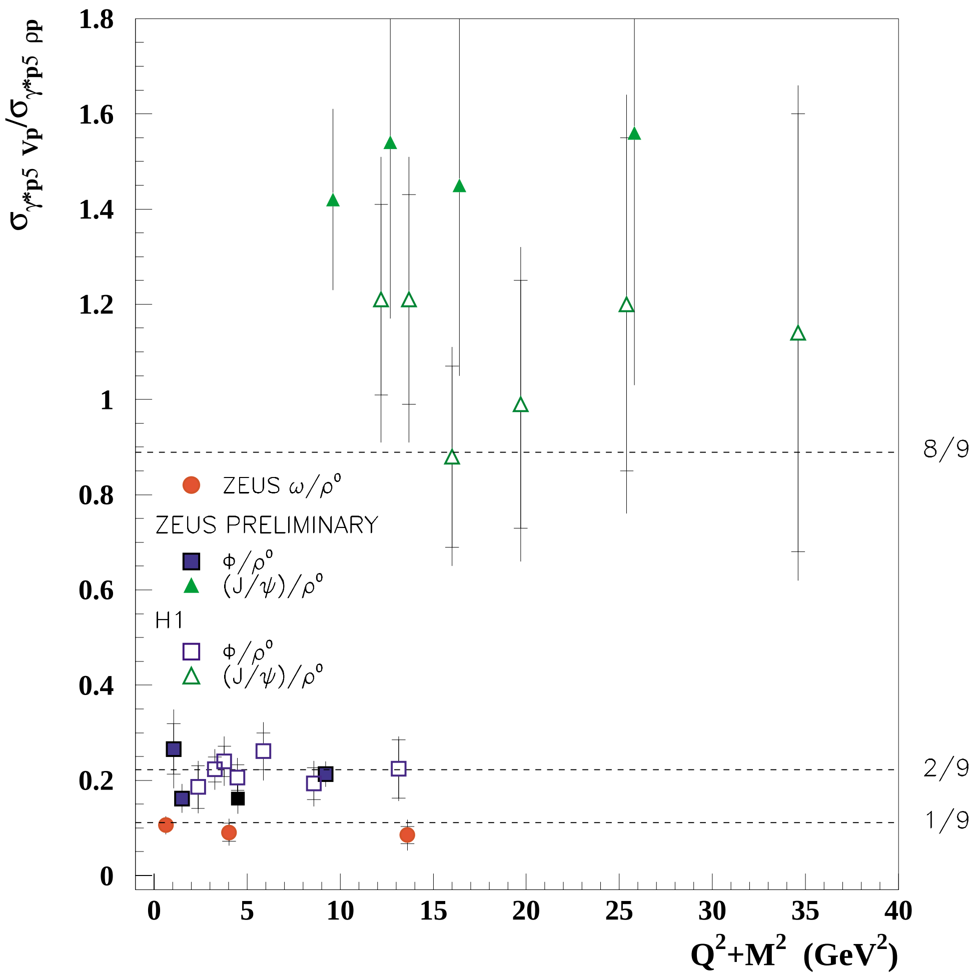
Look at the ratios of different species of VM $\Rightarrow$

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

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



Elastic VM production at HERA

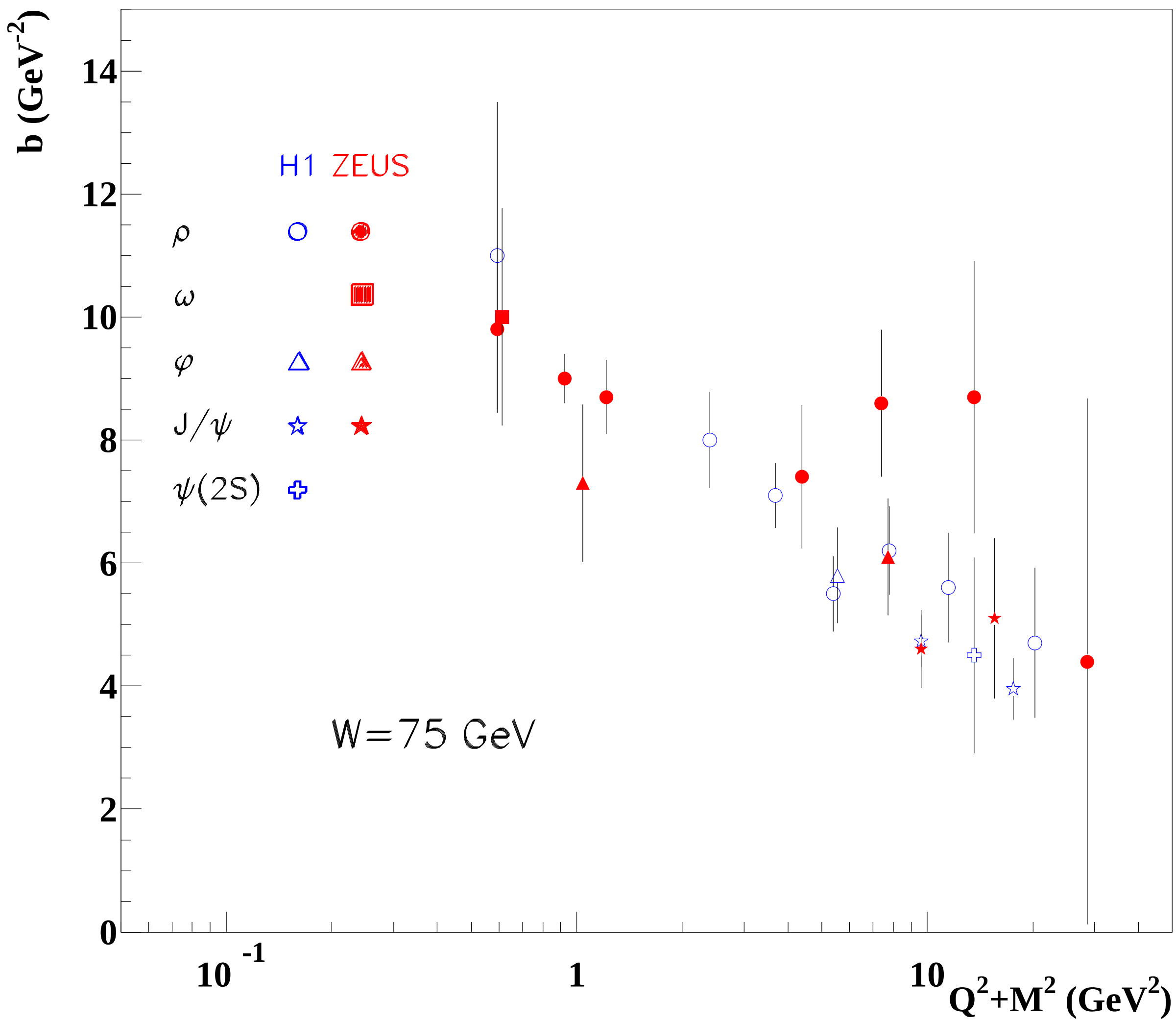


f_V^2 from charges of the quarks: ρ:ω:ϕ:J/ψ $\rightarrow$ 9:1:2:8.

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

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

Elastic VM Production at HERA



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

Dipole formulation of the VM cross section $\Rightarrow$

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

Ψ_{VM}: The vector meson wave function.

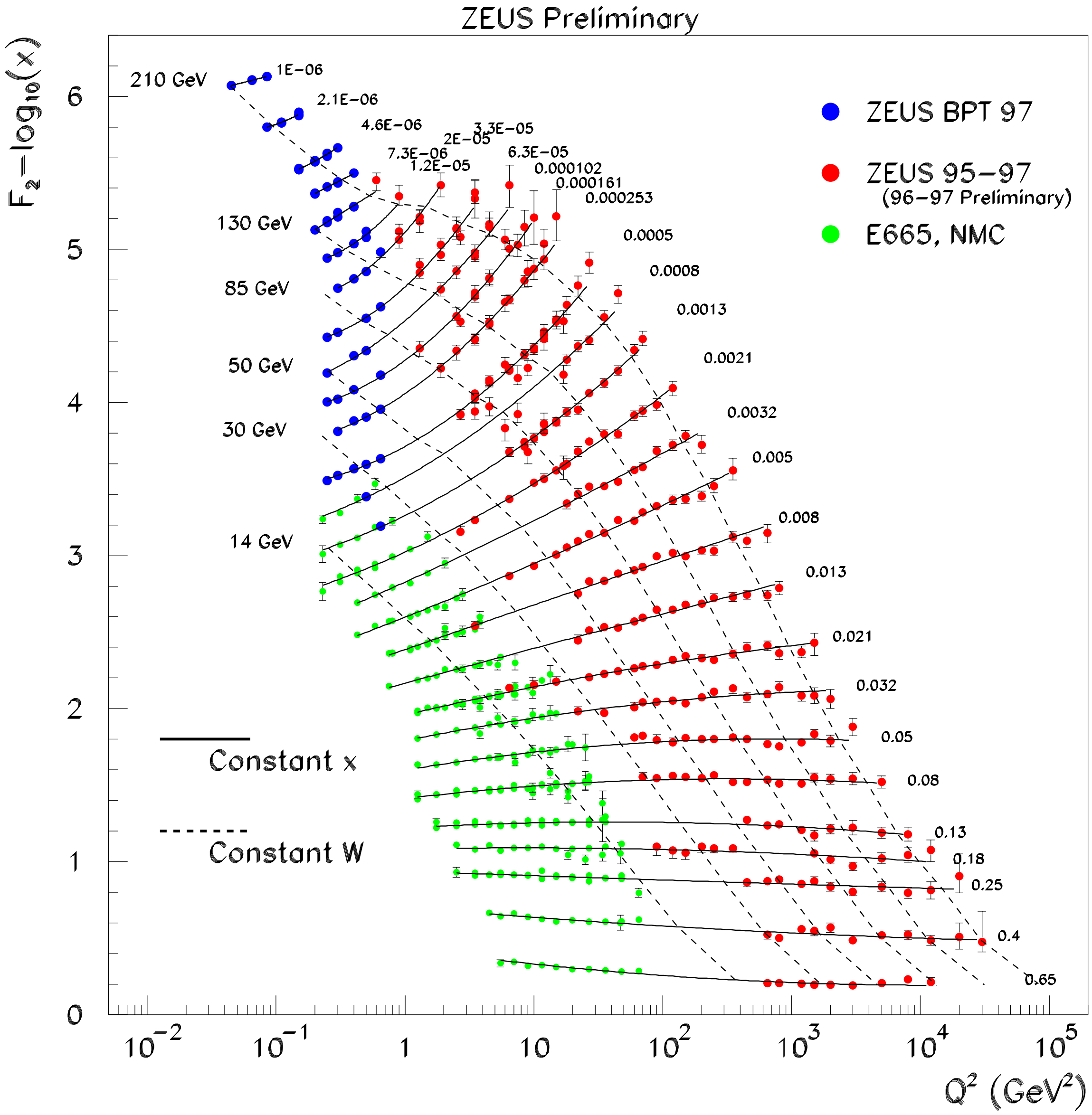
Ψ_γ: The photon wave function.

Using GB&W $\hat{\sigma}_{dipole}$–same as that for inclusive diffraction: can qualitatively describe ρ and J/ψ production.

(private communication: Mara S. Soares)

III. F_2 at Small-x Revisited

Do we really understand all of this?



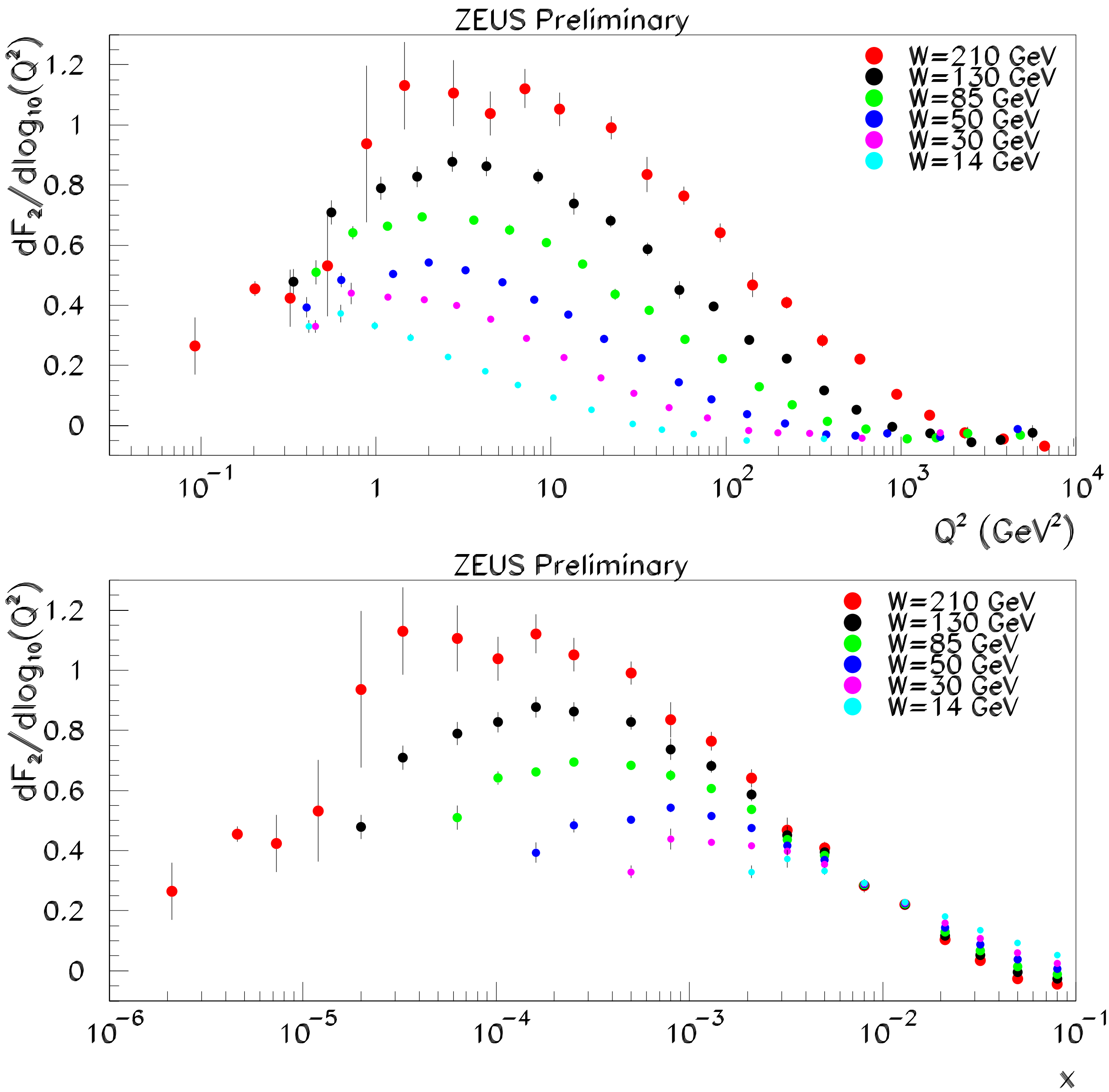
What is happening at low x and medium Q^2?

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

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

How to make the transition more visible:

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



What does this shape mean? ⇒

(Remember $W^2 = Q^2/x$ at low-x)

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 (bottom plot) is the important variable in the right hand side of the plots.

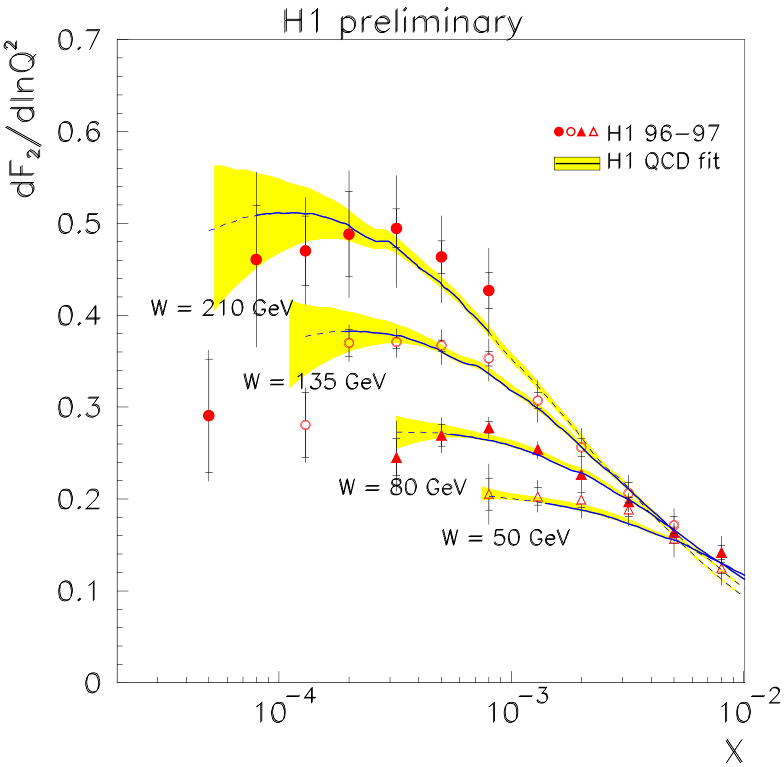
In the low Q^2 region: $F_2 \sim Q^2\sigma_0$, i.e. vanishing like Q^2. Therefore:

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

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

Transition at Q^2 as high as 5 GeV^2?!

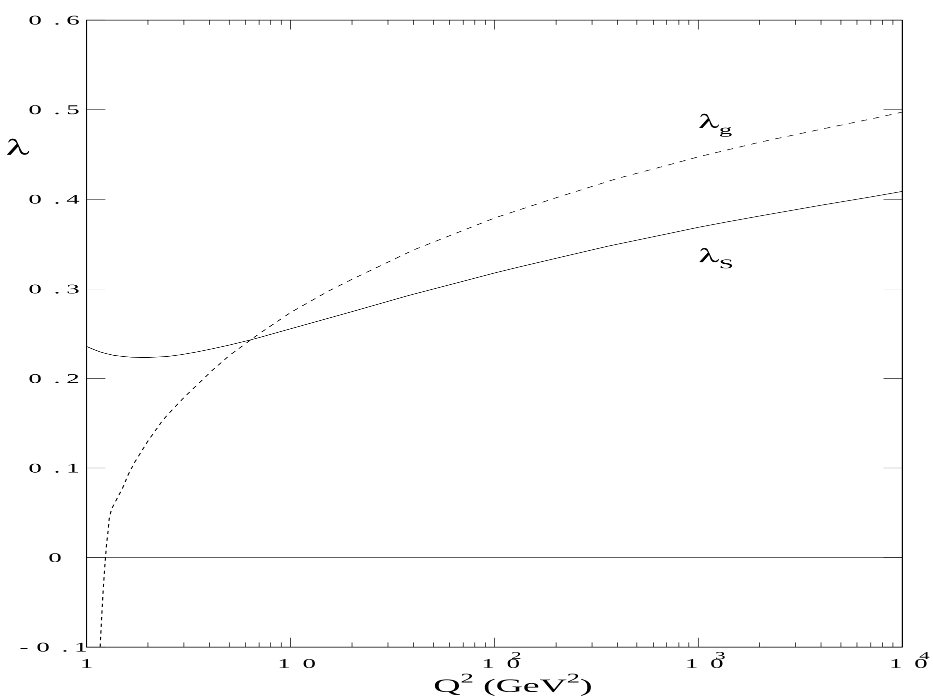
But GLAP fit does well down to 1 GeV^2 $\Rightarrow$



H1 NLO GLAP fit. How do the GLAP go around the corner?

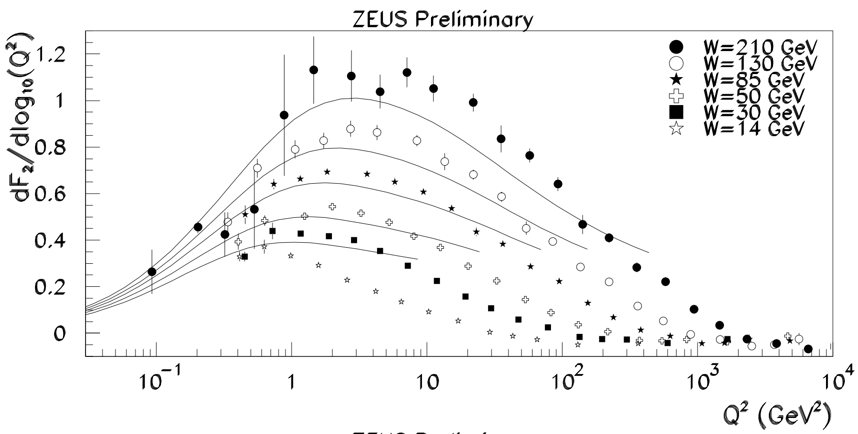
λ falls rapidly below Q^2 of 10 GeV^2

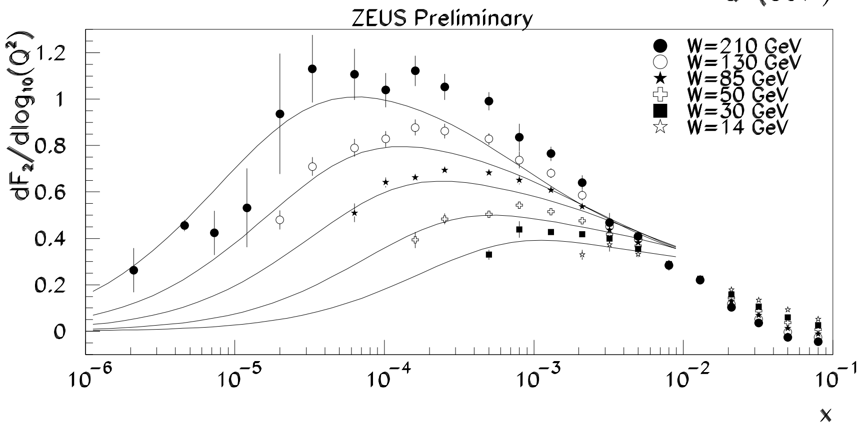
MRST fit parameters



DIPOLE formulation of DIS

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





Using the same GB&W $\hat{\sigma}_{dipole}$ as for diffraction and VM. Has the correct qualitative behavior.

$x^{-\lambda}$ to Q^2 dependence arises from the dipole saturation mechanism. (i.e. cross section goes flat $\Rightarrow F_2$ falls like Q^2).

Recall

$$\sigma_{tot}^{\gamma^* p} = \frac{4\pi^2\alpha}{Q^2} F_2$$

COMMENTS

- GB&W model is a simple 3 parameter “guess” of the dipole cross-section. However...

  1. A GLAP like piece $\to$ part which $\sim r^2$ and
  2. A saturation region where is it flat and
  3. In between region which is parametrized and..

  Qualitatively describes small-x AND diffraction

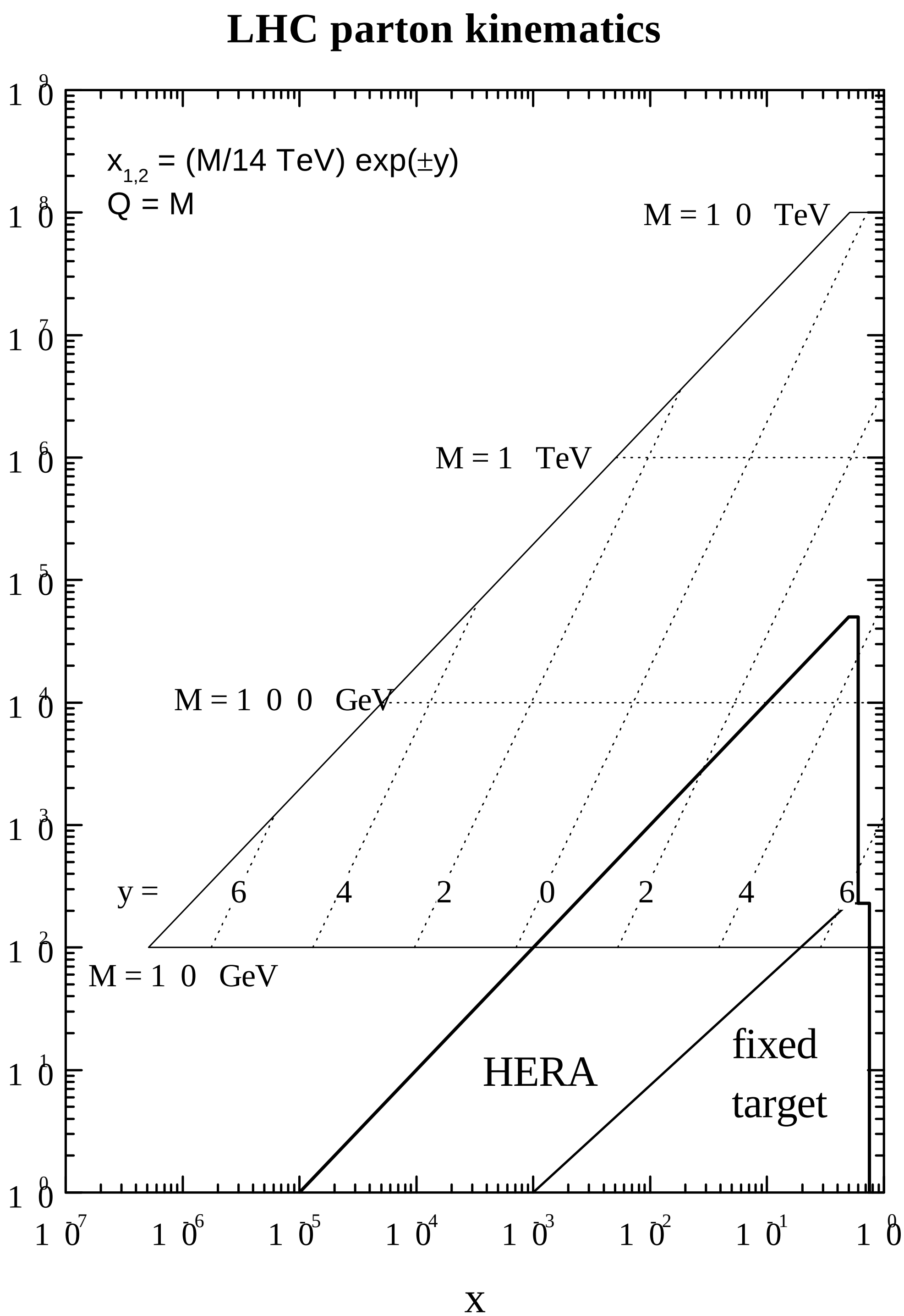
  According to this model, we are probing regions 3 and 2 at relatively high Q^2 (> 1 GeV^2). $\Rightarrow$ hope to describe this perturbatively.

  Much work is going on in this direction: $1/x$ resummation, CCFM (MC program CASCADE), higher-twist terms, HDQCD (high density QCD), which I did not review.

- How can GLAP fits be successful if all of this is right?
  Fits have many parameters and...
  Evolution length (Q^2 range) required by the data at Small-x is not large (yet).

If GLAP is no longer applicable at low x:

Implications for LHC cross sections could be big..



IV Conclusion

- A wealth of HERA data exists on small-x and diffraction. (Much more than has been covered here).

- F_2 at small-x can be described to Q^2 of 1 GeV^2 by GLAP fits.. however..

- A connection has to exist between diffraction and small-x (here demostrated using GB&W model.. but basically it is the optical theorem).

- The simple dipole model of GB&W can qualitatively describe the main behaviours of F_2 at small x, DIS diffraction, and diffractive vector meson production.

- Need to understand small x AND (not or) diffraction together. Hope is that we can do this perturbatively.