Low x Physics at HERA

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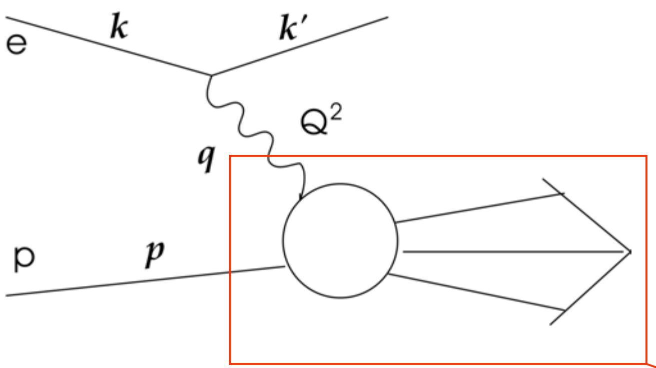
for
H1 and ZEUS

Outline

x? - is deep inelastic scattering Bjorken x

- Formalism and phase space
- F_2 at low x
- Contexts and Pictures
- More details on F_2 at low x
- F_2 at very low Q^2 & transition to photoproduction
- Universality at low x?
- Diffractive Processes
- Proton rest frame & dipole models
- Summary

Inelastic Scattering Formalism



For $Q^2 << M_Z^2$

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

$Y_+ = 1 + (1-y)^2; \quad y^2 F_L^{eN}$ is small

$$F_2 = \sum_i e_i^2 (q_i + \overline{q}_i); \quad \text{pQCD}, \quad \frac{\partial q}{\partial \ln Q^2} \sim q \otimes P$$

Kinematics

$$Q^2 = -(k-k')^2 \qquad x = \frac{Q^2}{2p.q} \qquad y = \frac{p.q}{p.k}$$

$$s = (k+p)^2$$

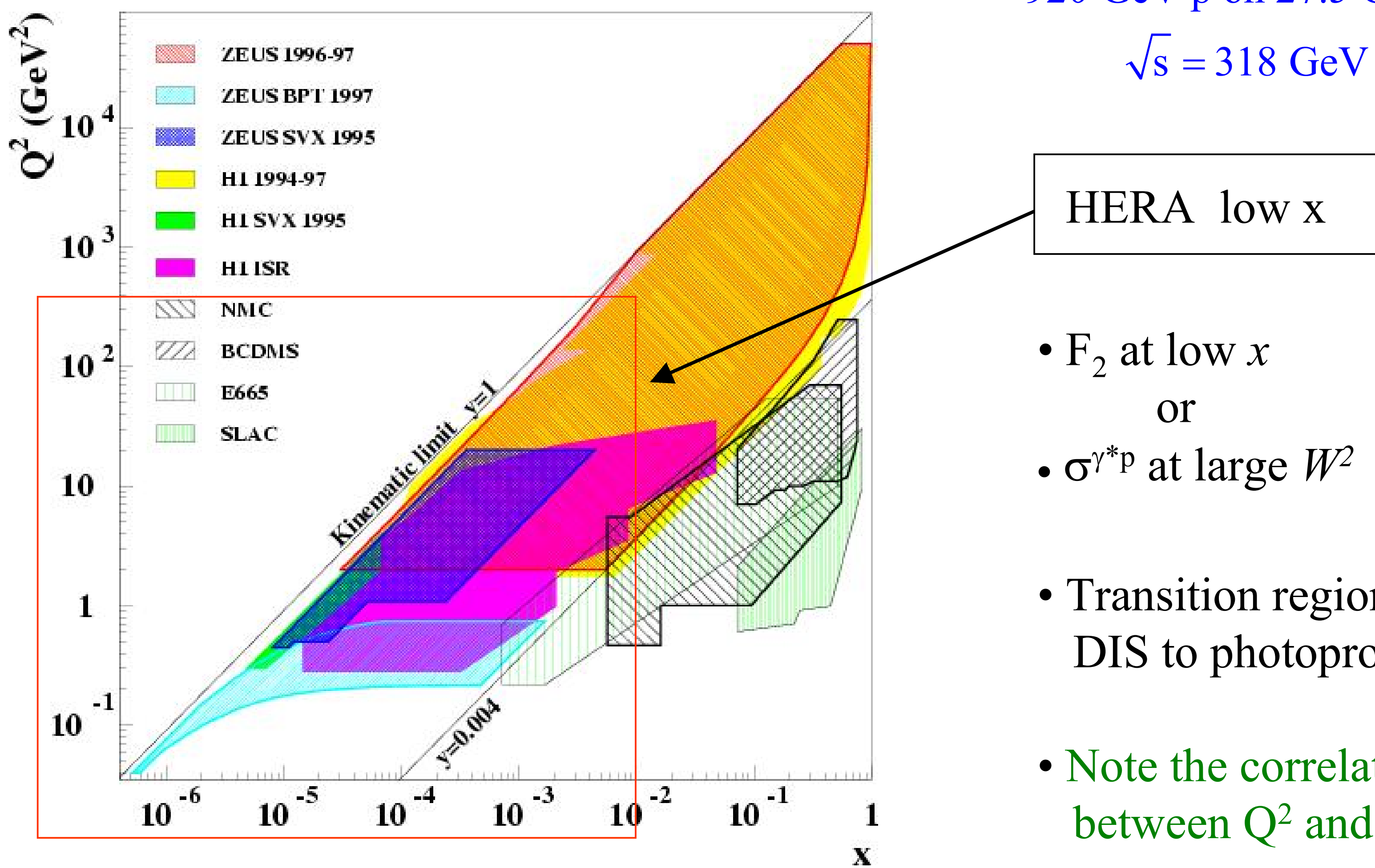
$$Q^2 = sxy \qquad W^2 = (q+p)^2 = \frac{Q^2}{x}(1-x)$$

inelasticity, $y = (E - E')/E$ in a fixed target frame

At small x

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

HERA & DIS kinematic regions



920 GeV p on 27.5 GeV $e^{\pm}$

$\sqrt{s} = 318$ GeV

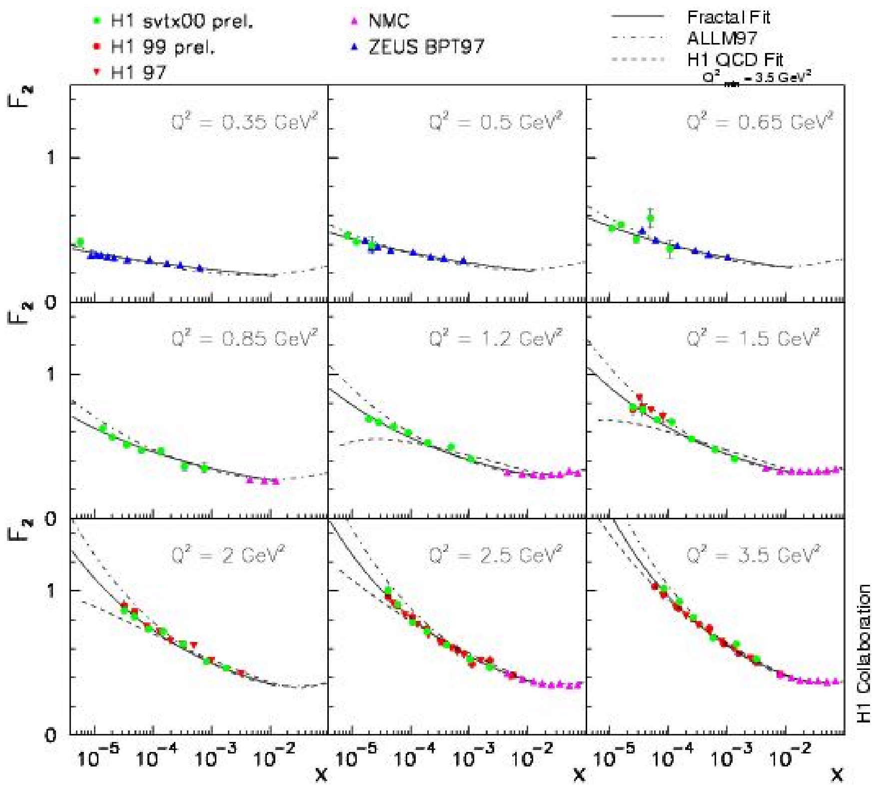
- F_2 at low x
  or
- $\sigma^{\gamma^* p}$ at large W^2

- Transition region
  DIS to photoproduction

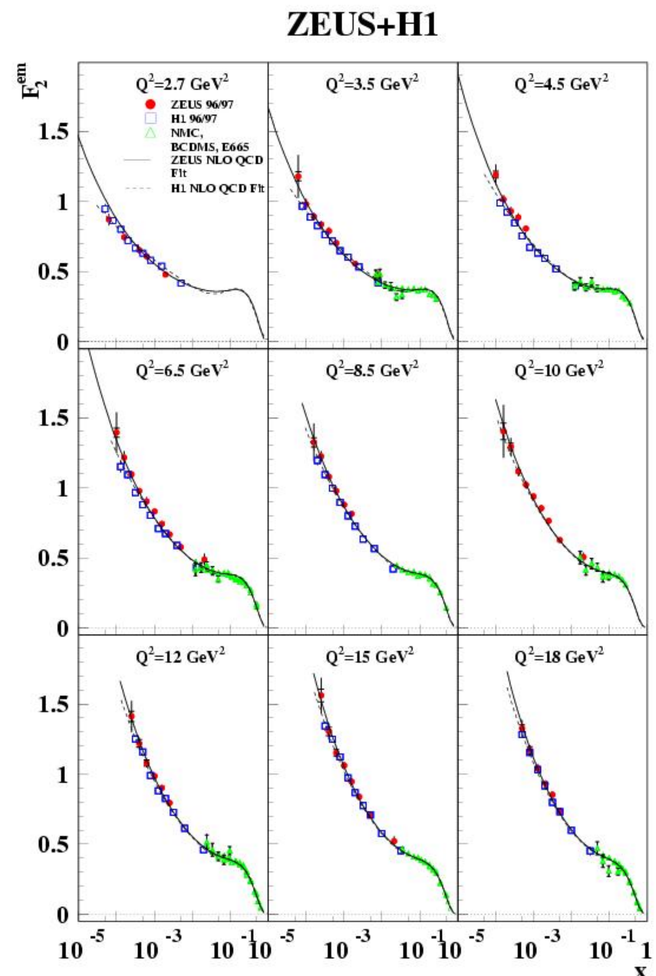
- Note the correlation
  between Q^2 and x

The rise of F_2 at low x

very low Q^2



medium Q^2



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

σ(γ*p) rises more rapidly with W^2 as Q^2 increases

Contexts

low x $\leftrightarrow$ large W^2

low x

- pQCD
- DGLAP NLO sufficient?
- ln(1/x) summmations
- BFKL
  - –perturbative Pomeron
- gluon dominance
- universality?
- vary ‘size’ of γ^*
- saturation

Hadron-hadron

- optical theorem

  $\sigma_{tot} \sim \mathrm{Im}\langle\gamma^* p|A|\gamma^* p\rangle / w^2$
- forward elastic amplitude
- Regge theory

  $\sigma_{tot} \sim \mathrm{const.}(w^2)^{\alpha(0)-1}$

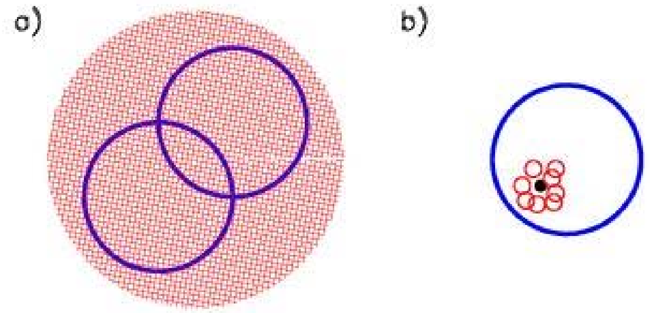
  Pomeron $\alpha(0)-1 = 0.08$
- quasi-elastic scattering
- diffraction
- unitarity limit

→ Colour Dipole models ←

Interaction pictures

hadron-hadron γ*p interaction

Transverse views of particle interactions



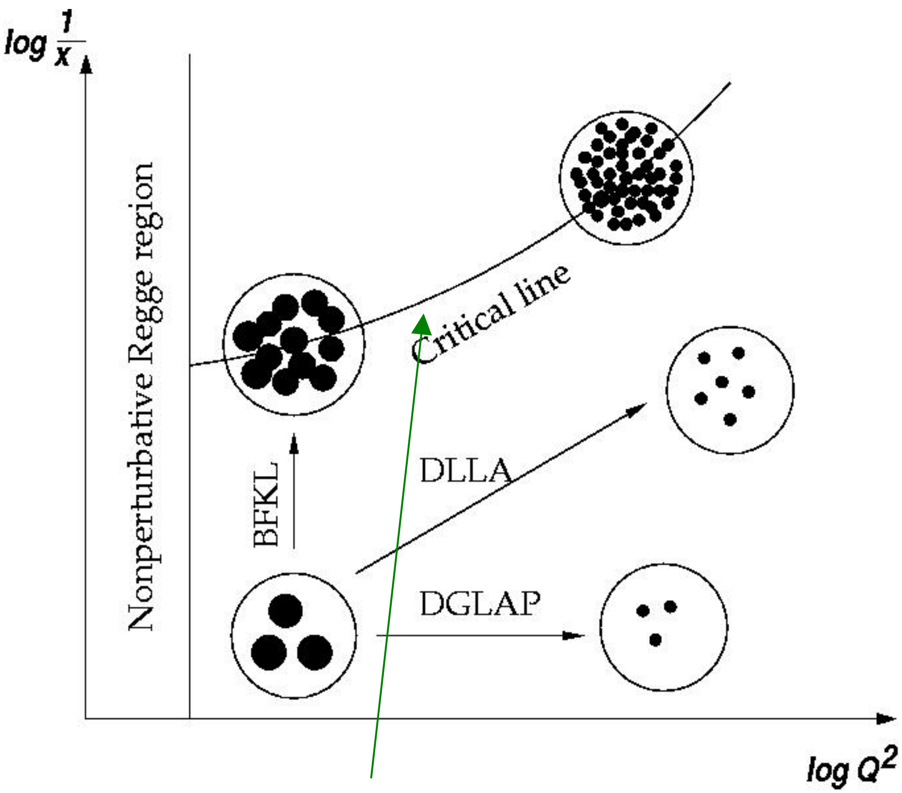
Bartels & Kowalski

a) Diffuse gluon 'radiation cloud' drives the interaction and size of interaction region, which is larger than the hadrons, grows slowly with energy

b) γ* with small transverse dimensions, d, interacting with a proton – also with a radiation cloud but more intense because of limited size – calculable using pQCD

At HERA the size of the photon can be varied from that of hadron (photoproduction) to much smaller, since d ~ 1/Q

High gluon density and saturation



Gluon dynamics dominates
but how rapidly does F_2 increase?

- DGLAP dominated by gluon splitting function $P_{gg} \sim 1/x$

- DLLA

$$\exp\sqrt{(12\alpha_S/\pi)\ln 1/x \ln Q^2/Q_0^2}$$

- BFKL

  $\sim x^{-\lambda}$ with λ as large as 0.5

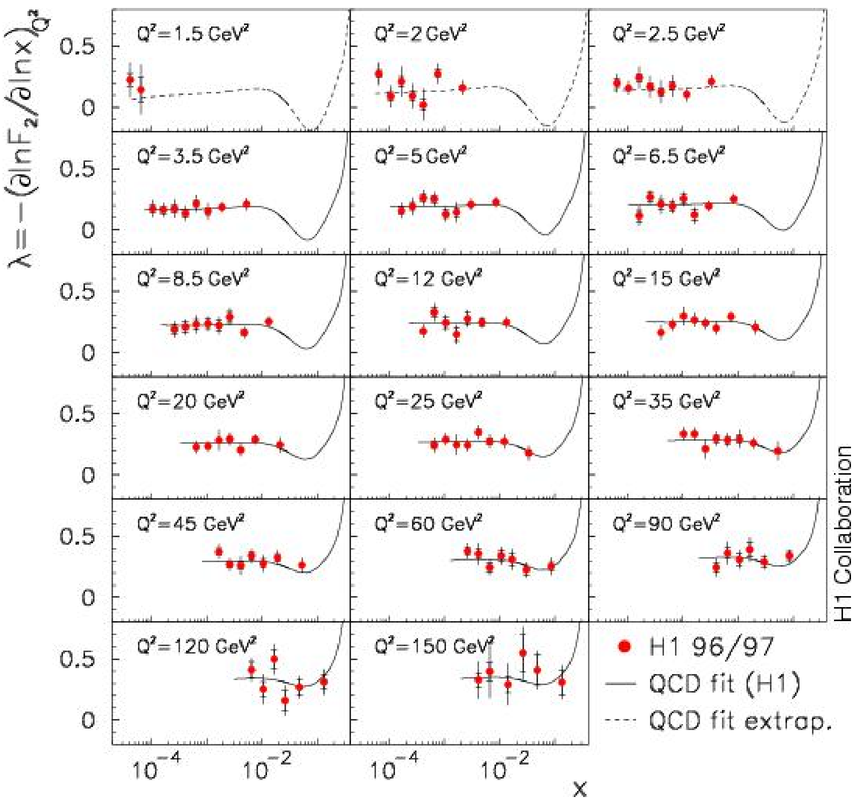
- Critical line indicates region above which saturation will occur – gluons overlap – nonlinear evolution

- Other summations:
  - CCFM (angular ordering)
  - those from Thorne; Altarelli et al

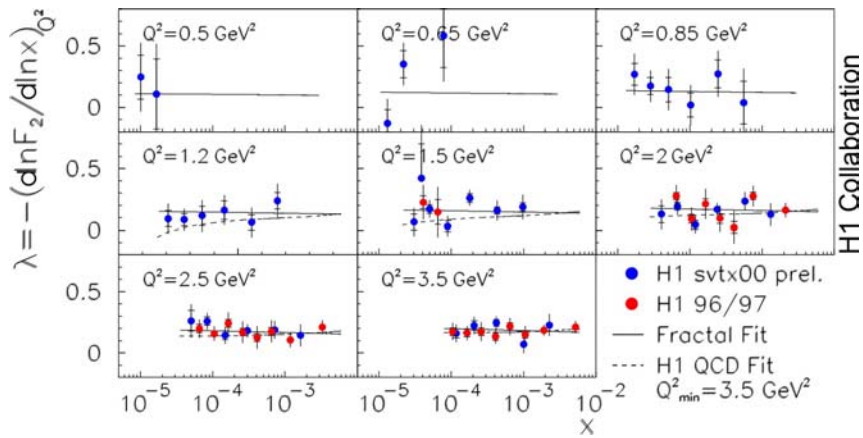
- on the edge or just outside the reach of HERA?

Model independent study of F_2 at low x

H1 nominal vertex



H1 shifted vertex - preliminary

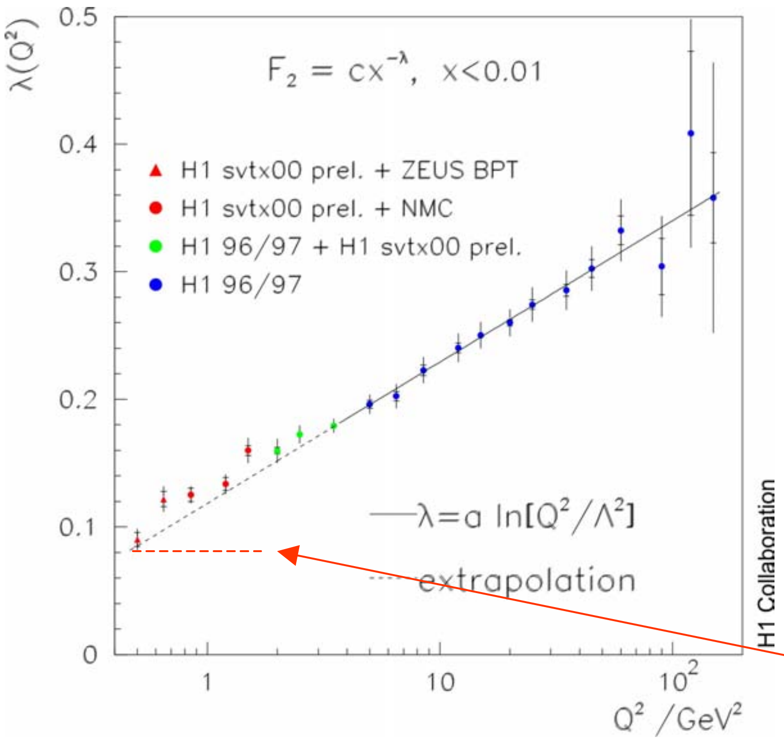


$F_2(x,Q^2) \sim x^{-\lambda(Q^2)}$ or

$$\lambda(Q^2) = -\frac{\partial \ln F_2}{\partial \ln x}\Big|_{Q^2}$$

- characterise the rise of F_2 – taking full account of errors
- for Q^2 fixed and $x < 0.01$, λ roughly constant

$\lambda(Q^2)$ vs Q^2



$F_2(x,Q^2) \approx c(Q^2)x^{-\lambda(Q^2)}$

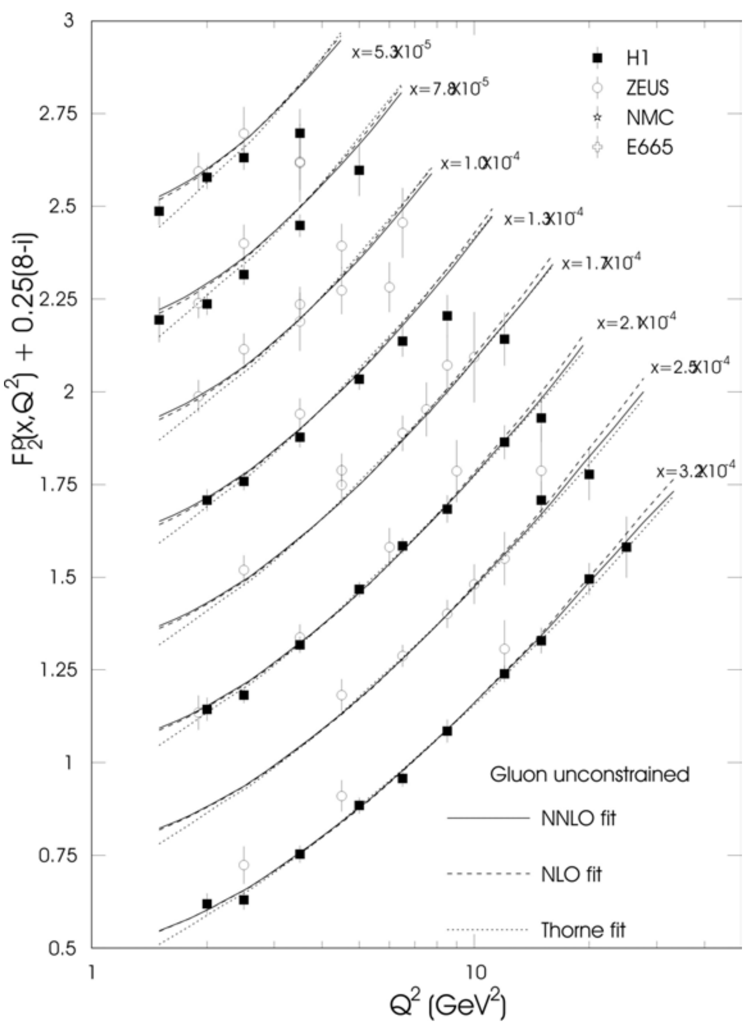
with $c(Q^2) \approx 0.18$ indep. of Q^2

- no sign of rise slowing at large Q^2 and small x as might be expected from saturation
- at very small Q^2 the value of λ is consistent with that expected from hadron-hadron scattering: $\lambda \sim 0.08$

Fit $\lambda(Q^2) = a\ln(Q^2/\Lambda^2)$ gives

$\Lambda = 292 \pm 20(\text{stat}) \pm 51(\text{sys})$

Beyond standard NLO evolution?



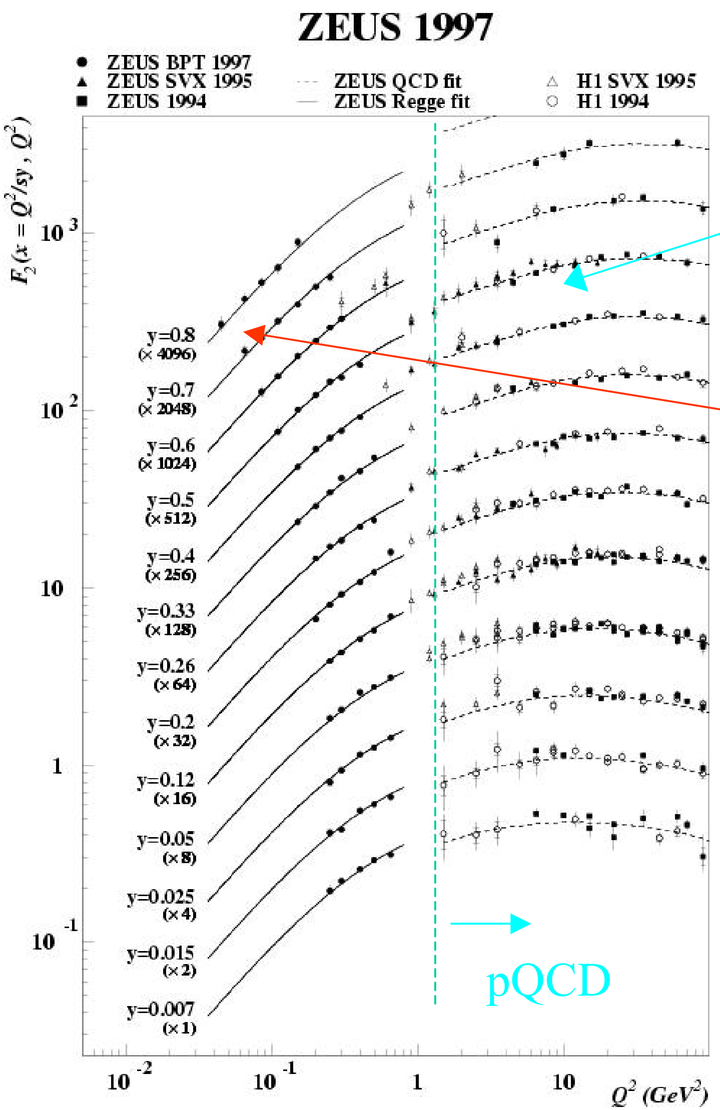
From the MRST team

F_2 at low x fit using DGLAP NLO, NNLO and some resummation of $\ln(1/x)$ terms (Thorne fit)

All give acceptable fits - parton densities are different but need other observables (eg F_L) to distinguish.

Standard NLO DGLAP fits describe data at low x down to $Q^2 \sim 1.5$ GeV^2
- more in Milstead's talk

F_2 as Q^2 tends to zero



- NLO pQCD describes F_2 down to $Q^2 \sim 1.5$ GeV^2
- At very small Q^2, EM current conservation requires

$$F_2(x,Q^2) \rightarrow Q^2 \times const. \text{ as } Q^2 \rightarrow 0$$

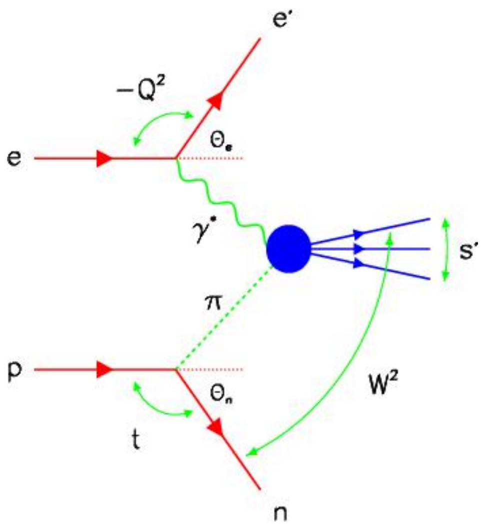
- Data shows a smooth transition in Q^2
- Many models describe the transition region

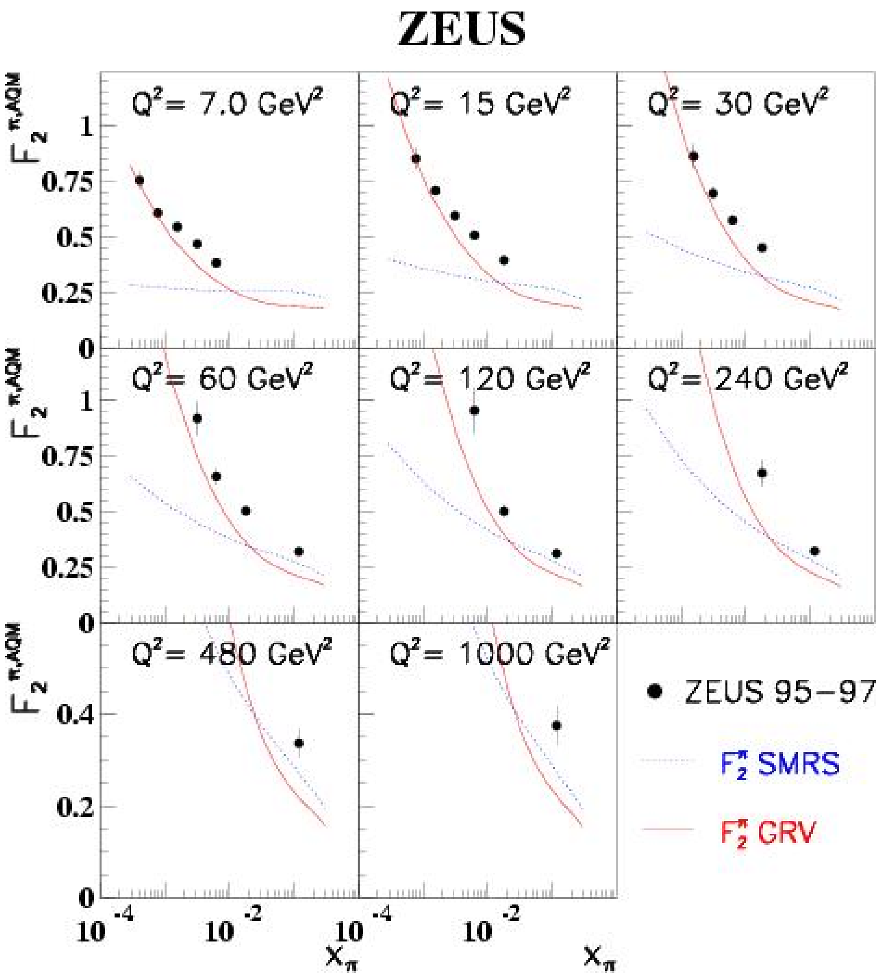
- Regge based approaches
- Generalised Vector Dominance
- Colour dipoles (more later)
- Self-similarity

Universality at low x

- At small x the dynamics of Q^2 evolution is dominated by gluon splitting
- Far from the valence region in x, the identity of the parent particle becomes unimportant
- Recently both H1 and ZEUS have published measurements of deep inelastic scattering with an identified forward neutron in the final state
- Is there evidence of similar rapid growth at small x in other structure functions?
- At small p-n momentum transfers (‘t’), single pion exchange dominates and the pion structure function can be isolated

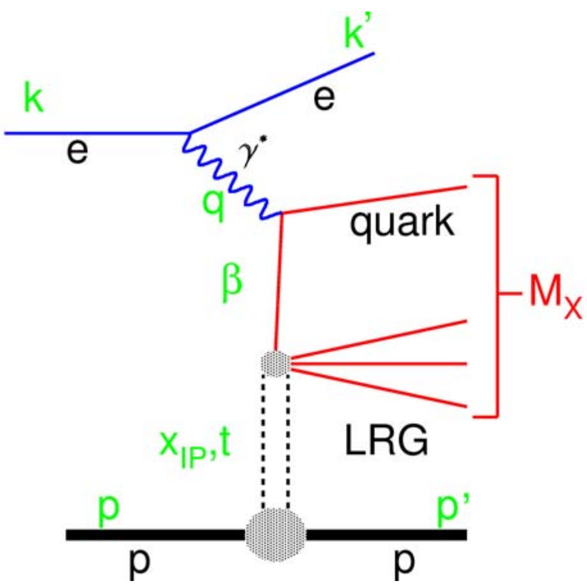
F^{π} at low x





Although there is uncertainty in the normalisation, there is no doubt that F^{π} is rising steeply at low x

Diffraction at HERA



Identify diffractive events either using leading proton spectrometer or LRG in main detector

$\gamma^* p \rightarrow Xp$

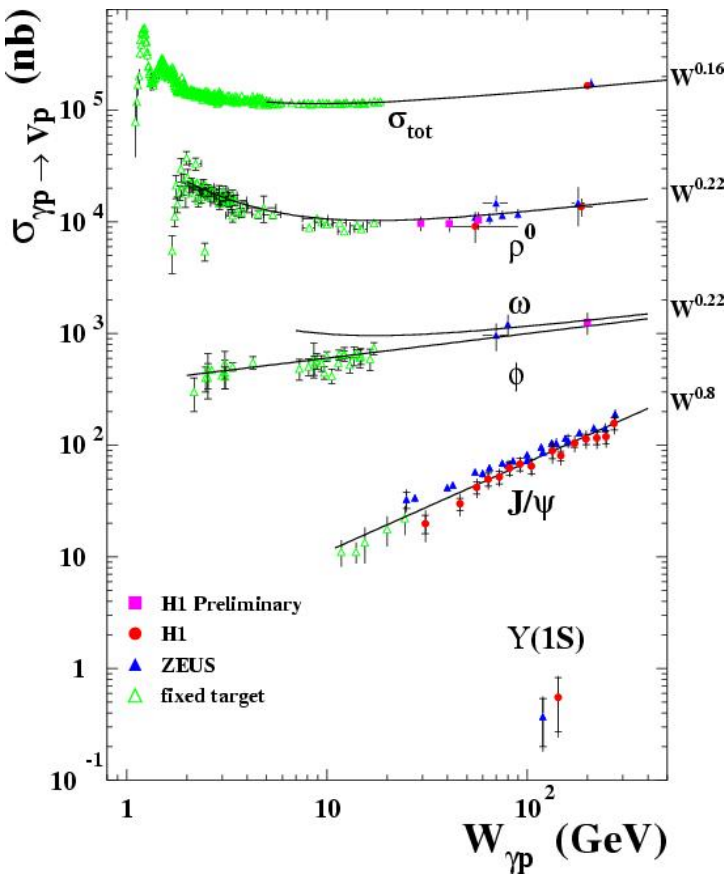
- involves vacuum q. no. exchange
- X is a vector meson or a hadronic system separated from the proton by a large rapidity gap (LRG)

- At HERA
  - vector mesons vs Q^2
  - inclusive diffraction vs M_X & Q^2
  - hard diffraction and jets

  W^2 dependence of all of these

Concentrate on the W^2 dependence of diffractive cross-sections

Vector meson photoproduction



σ(γp → Vp) vs W for real photoproduction of vector mesons compared with $\sigma_{tot}(\gamma p)$

lines indicate a power law fit

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

to data with W > 10 GeV

for ρ, ω, ϕ $\delta \sim 0.22$

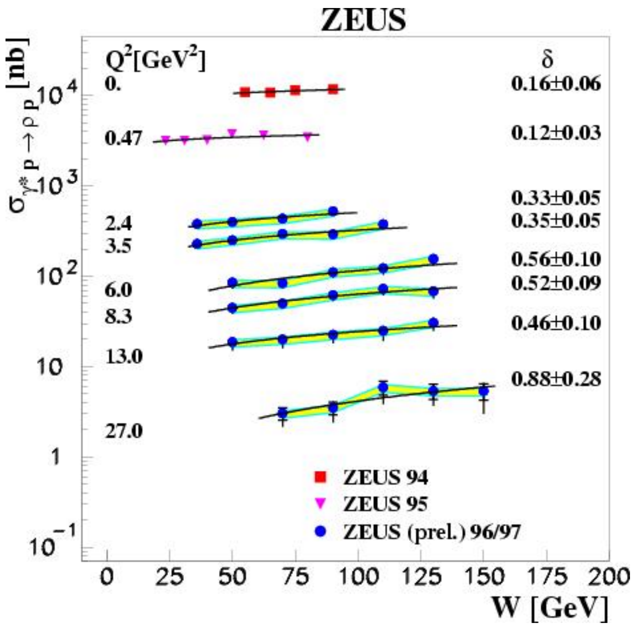
comparable to $\delta \sim 0.16$ for $\sigma_{tot}(\gamma p)$

for J/ψ $\delta \sim 0.8$

Faster rise if hard scale is set by large M_V

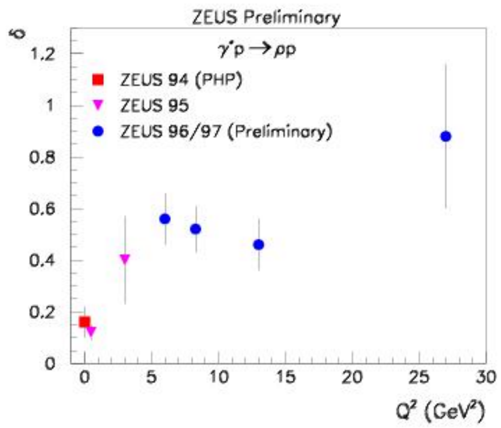
ρ^0 production vs Q^2

$\sigma(\gamma^* p \rightarrow \rho^0 p)$ measured as a function of W and Q^2



At fixed Q^2 fit

$\sigma \sim W^{\delta}$ as before



δ increases from 0.16 to 0.88

as Q^2 increases from 0 to 27 GeV^2

NB use $\lambda \sim \delta/4$ to compare rates of rise in diffraction ($|A|^2$) and $\sigma_{tot}(\gamma^* p)$ (ImA)

faster rise as γ^* provides the hard scale

Inclusive diffraction/total vs W

Regge theory:

$$\frac{d\sigma^{D}_{\gamma^* p}/dM_X}{\sigma^{tot}_{\gamma^* p}} \propto \frac{(W^2)^{2\bar{\alpha}_{IP}-2}}{(W^2)^{\alpha_{IP}(0)-1}} = W^{0.19}$$

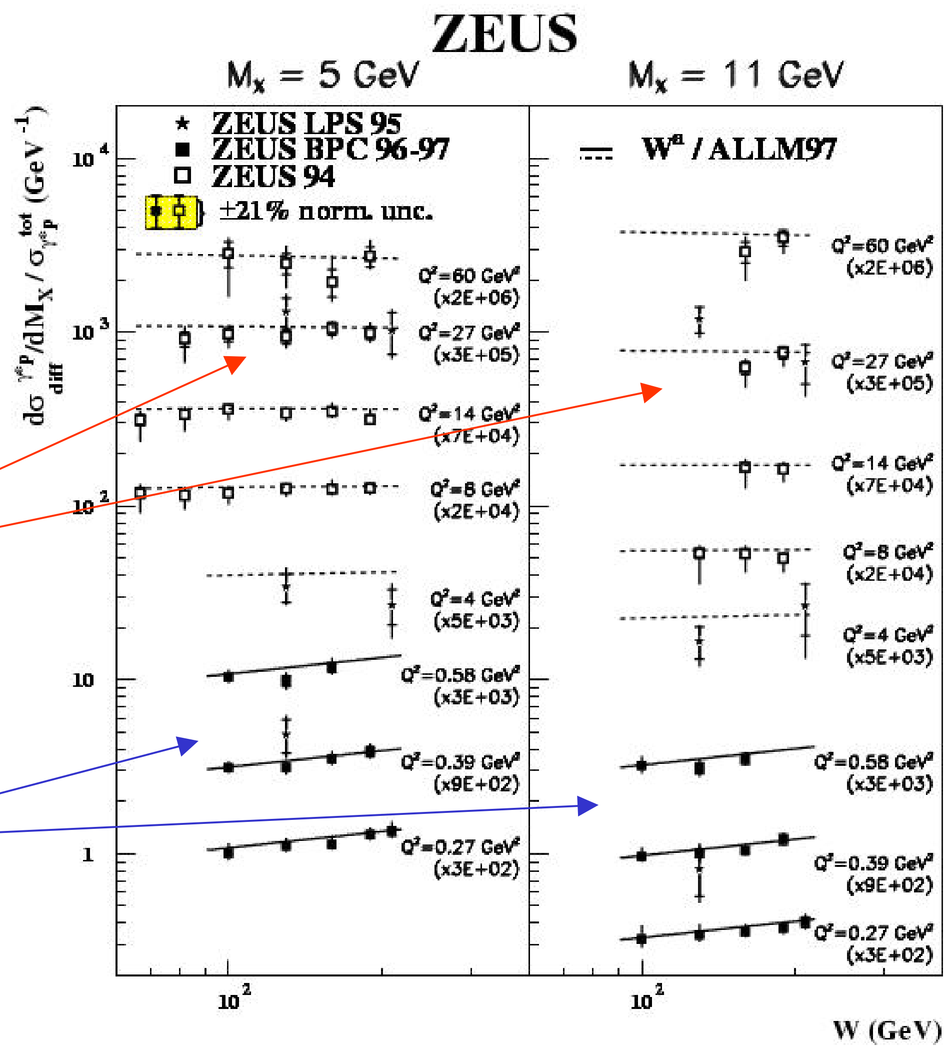
fit $$\frac{\int dt\, d\sigma^{D}_{\gamma^* p\to Xp}/dM_X dt}{\sigma^{tot}_{\gamma^* p\to X}} \propto W^{\rho}$$

high Q^2: $\rho = 0.00 \pm 0.03(stat.)$

Ratio does not follow soft Regge prediction

low Q^2: $\rho = 0.24 \pm 0.07(stat.)$

Compatible with Regge prediction (soft physics)



Putting it all together

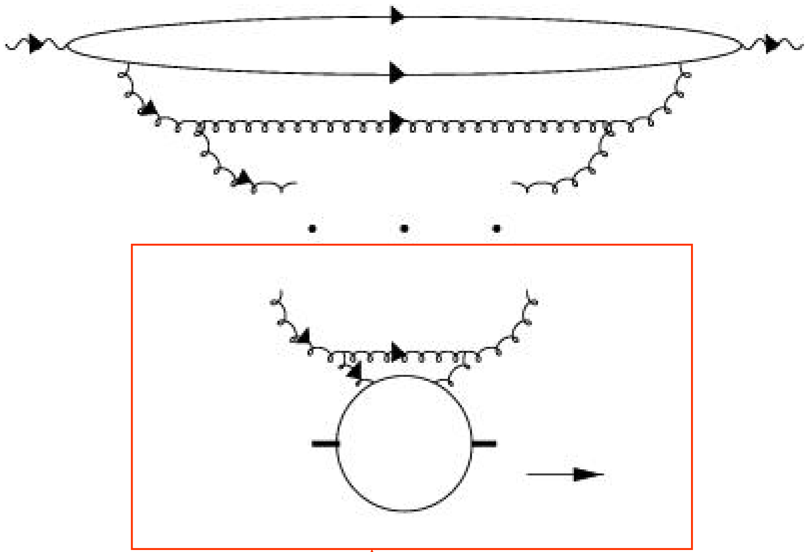
Results so far:

- low x rise of $F_2 \longrightarrow \sigma_{tot}(\gamma^*p)$ increases faster with W^2 than expected from hadron-hadron scattering
- similar features seen in other quasi-elastic processes where there is a hard scale
- dominance of gluon dynamics & some evidence for universality at low x
- smooth transition from DIS to photoproduction at $Q^2 = 0$ many models to describe this

- the hard scale is associated with small transverse size of the probe (γ^*) or final state particle (vector meson)

- is there a framework in which all this can be put together?

Proton rest frame view



proton rest frame view of the $\gamma^* p$ interaction

$\gamma^* \rightarrow q\bar{q}$ followed by multiple gluon radiation

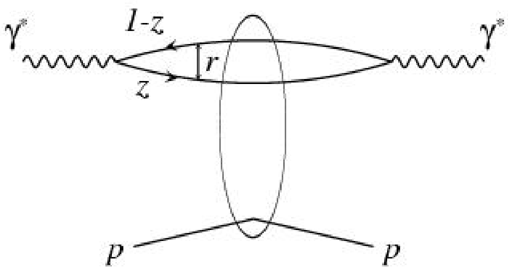
The $q\bar{q}$ dipole forms a long time $t \sim 1/(m_p x)$ before interacting with the proton

As the cascade grows the energy and k_T of the gluons decreases – their transverse size grows – no longer calculable perturbatively

colour dipole models

Nikolaev & Zakharov; Golec-Biernat & Wuesthoff; Mueller; Gotsman, Levin & Maor; Buchmuller & Hebecker..; Forshaw, Shaw, McDermott...

Colour Dipole Models with saturation



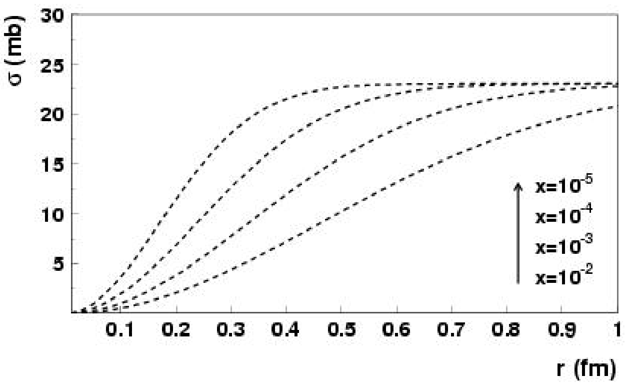
r transverse separation, conjugate to k_T
z longitudinal photon momentum fraction

known wave function

$$\sigma_{\gamma^* P} = \int d^2r\, dz\, \Psi^*_{\gamma^*}(r,z,Q^2)\, \sigma_{qq}(x,r)\, \Psi_{\gamma^*}(r,z,Q^2)$$

model unknown dipole cross-section σ_{qq} (e.g. Golec-Biernat & Wuesthoff)

$$\sigma_{qq}(x,r) = \sigma_0 \left\{ 1 - \exp(-r^2/4R_0^2(x)) \right\}; \quad R_0(x) = (x/x_0)^{\lambda/2}$$

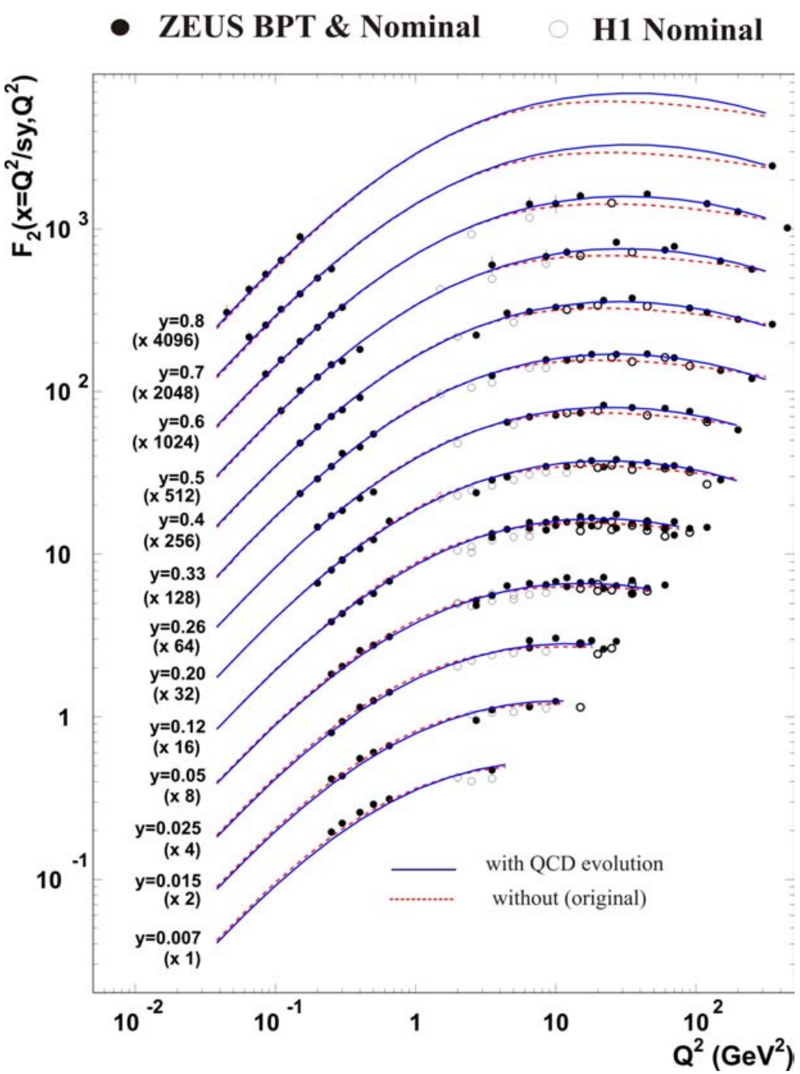


$r << R_0 \qquad \sigma_{qq} \propto r^2 x^{-\lambda}$

$r >> R_0 \qquad \sigma_{qq} \propto \sigma_0$

unitarity bound built in & approach controlled by $R_0(x)$

Colour Dipole Model fitted to inclusive data



$$\sigma_{qq}(x,r) = \sigma_0 \left\{ 1 - \exp(-r^2 / 4R_0^2(x) \right\}$$

$$R_0(x) = (x/x_0)^{\lambda/2}$$

Three parameters: λ, x_0, σ_0 to be fitted.

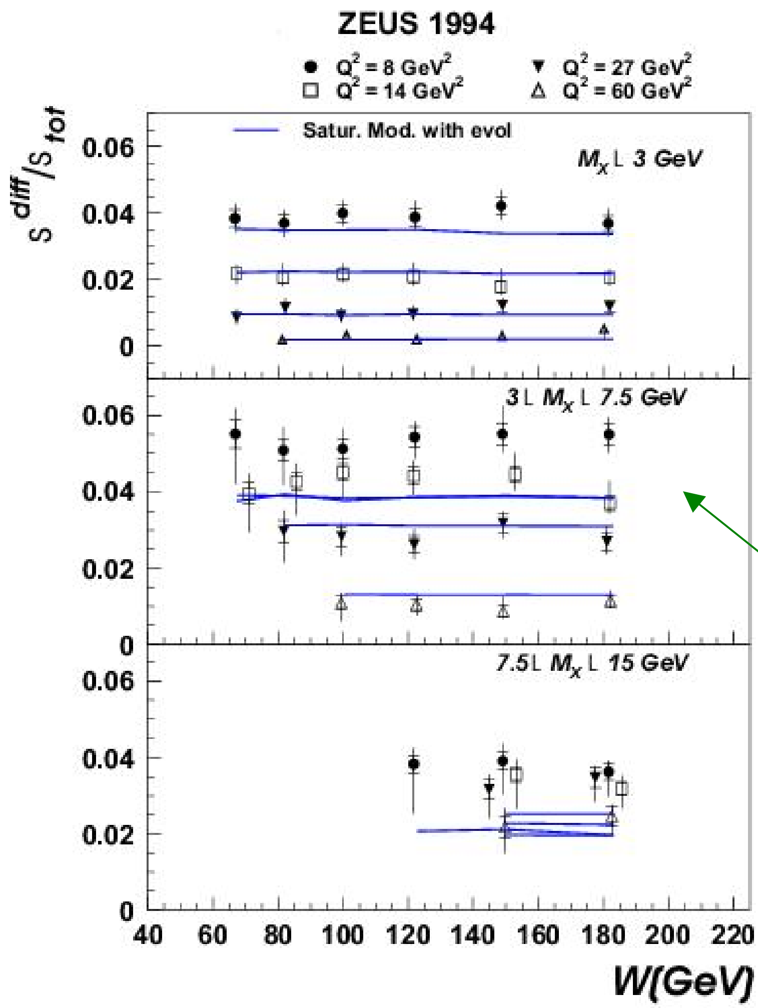
Extension (G-B, Bartels &Kowlaski - DIS02) include QCD evolution by requiring

$$\sigma_{qq}(r,x) = \frac{\pi^2}{3} r^2 \alpha_S xg(x, C/r^2), \text{ at small } r$$

xg evolves - 5 parameter fit - improves description of high Q^2 data

- Cannot use this agreement as verifying saturation at HERA, as many other models give similar agreement, including non-saturating dipole models.

Hard diffraction in the colour dipole model



- Dipole models provide a natural framework for hard diffraction – with the same σ_{qq} and parameters as determined from inclusive data

$$\frac{d\sigma^{\mathrm{Diffr}}_{\gamma^* \mathrm{P}}}{dt}\Big|_{t=0} \propto \left|\Psi_{\gamma^*}(Q^2, r)\right|^2 \otimes \sigma^2_{\mathrm{qq}}(x, r)$$

- While not perfect, the dipole model does give a constant ratio for $\sigma^{\mathrm{Diffr}}/\sigma^{\mathrm{All}}$ in DIS – a key feature of the data that the soft Regge theory does not reproduce

- Also describes behaviour of δ for

$$\sigma(\gamma^* p \to \rho^0 p) = const \times W^{\delta(Q^2)}$$

Summary

• HERA has provided high precision data on F_2 at low *x* and hard diffractive scattering

• Rise of F_2 at low *x* mirrored in other processes when appropriate hard scale is present

• Aspects of universality in the low *x* dynamics hinted at

• Colour dipole models are promising – but saturation not proven at HERA

• HERA has opened up new avenues in strong interaction physics

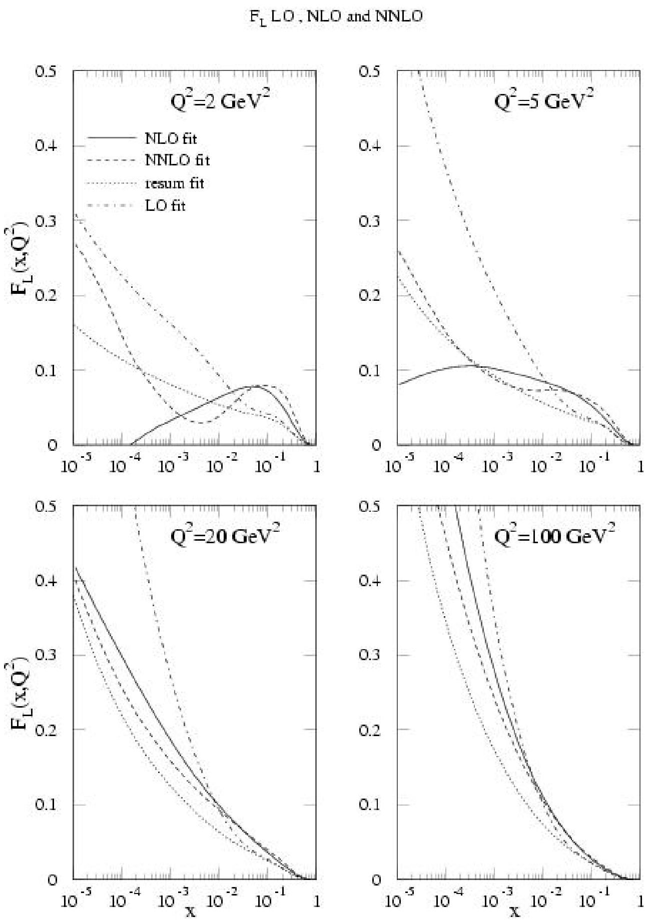
- high density perturbative gluon dynamics

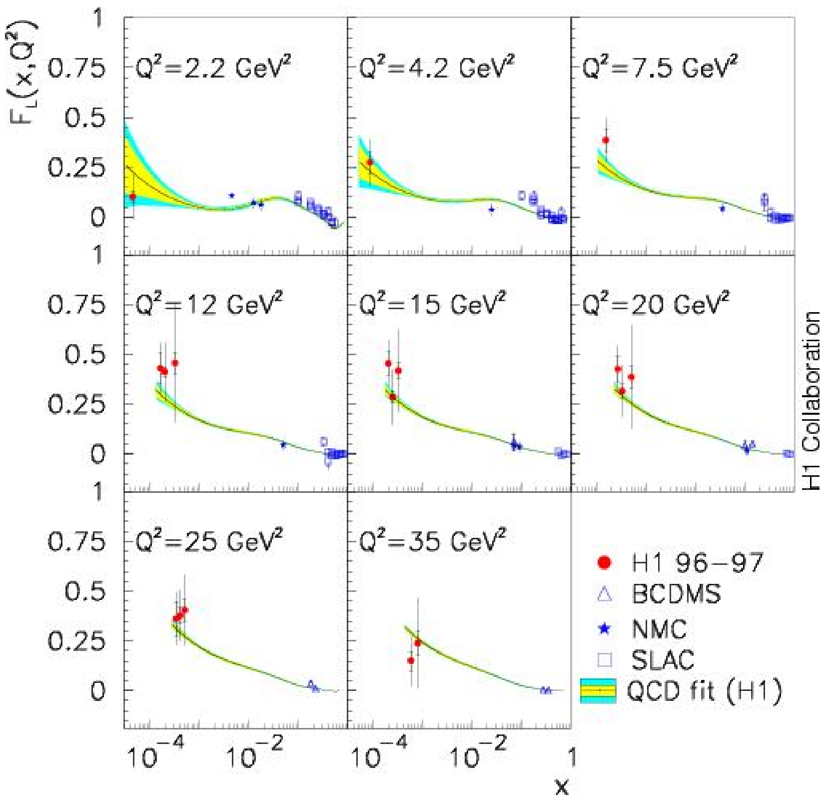
- deepened the relationship between diffractive scattering and the physics driving rising total cross-sections

• Essential input for physics at the Tevatron, RHIC & the LHC

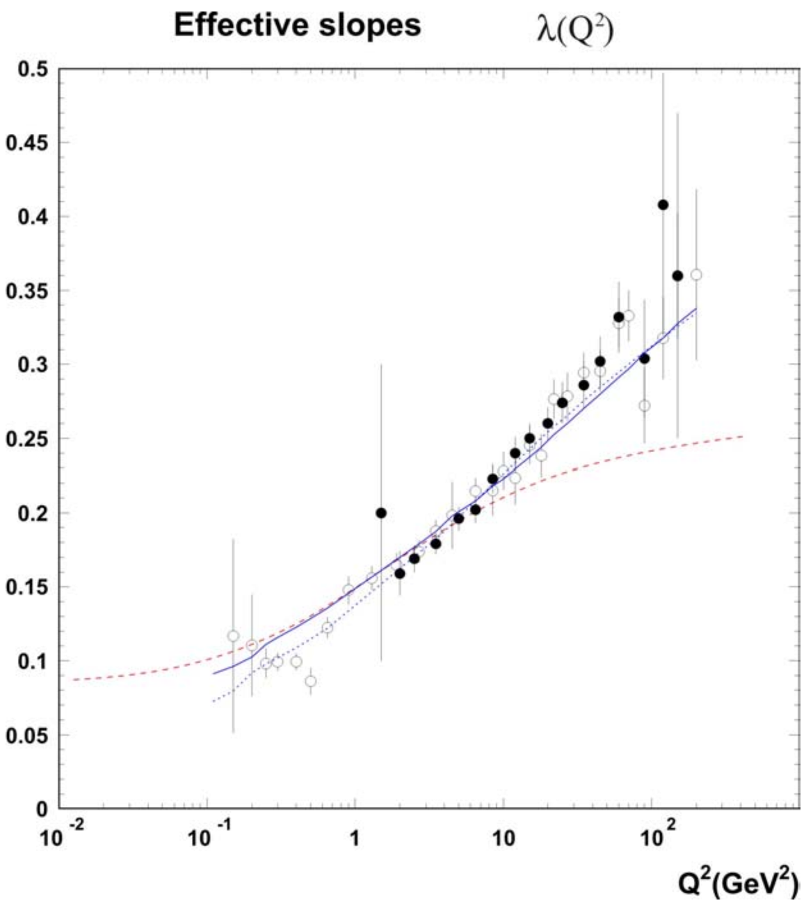
Thanks to many colleagues on H1, ZEUS and in the 'HERA low x club', for real and virtual help in preparing this talk.

F_L – models and data





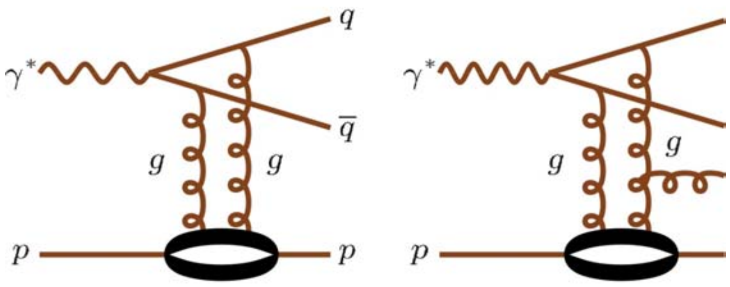
Dipole model description of λ(Q^2)



ZEUS & H1 data

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

Clearly need the inclusion of QCD evolution to get a reasonable description of λ above medium Q^2 values



Dipole models for Vector Mesons

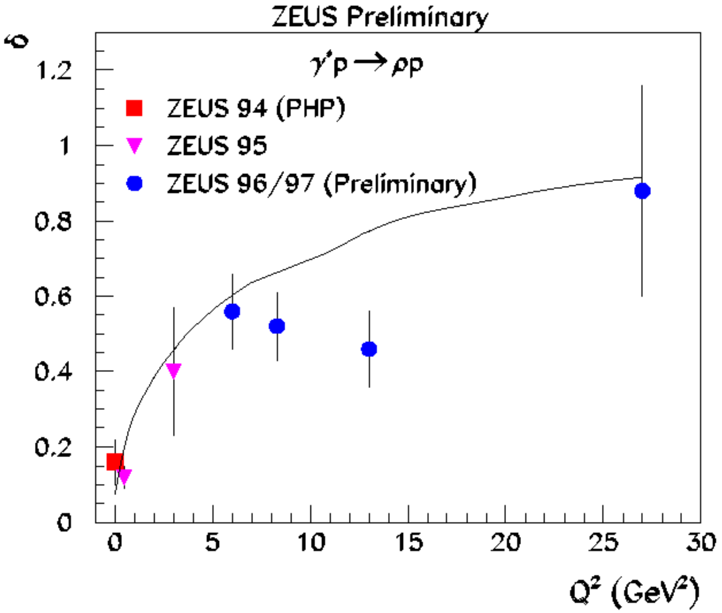
This is being studied by a number of groups – the results are encouraging.

References:

Munier hep-ph/0206117

Caldwell & Soares hep-ph/0101085

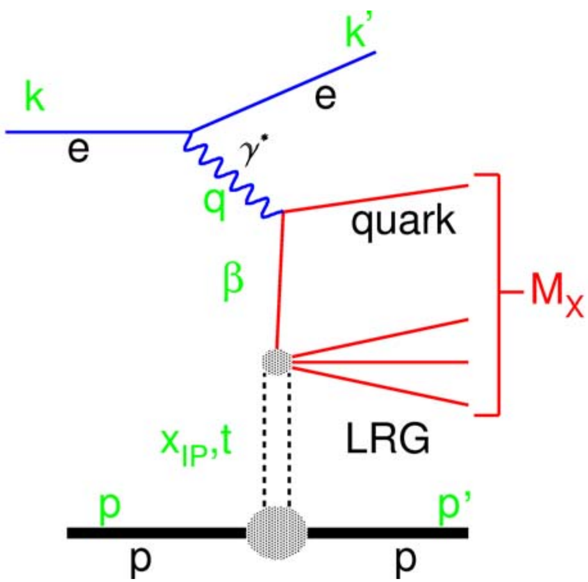
Forshaw, Kerley & Shaw Phys Rev D60 074012 (1999)



Plot shows the calculation from Caldwell & Soares of $\delta(Q^2)$, where

$$\sigma(\gamma^* p \rightarrow \rho^0 p) = const \times W^{\delta(Q^2)}$$

Variables in diffractive DIS



DIS

$$Q^2 = -q^2$$
$$x = Q^2/2p\cdot q$$
$$W^2 = (q+p)^2$$
$$M_X{}^2 = (q+P-P')^2$$

Diffractive

$$t = (p-p')^2 \approx -\frac{p_t^2}{x_L}$$

$$x_L = \frac{p'_z}{p_z} \approx 1 - x_{IP}$$

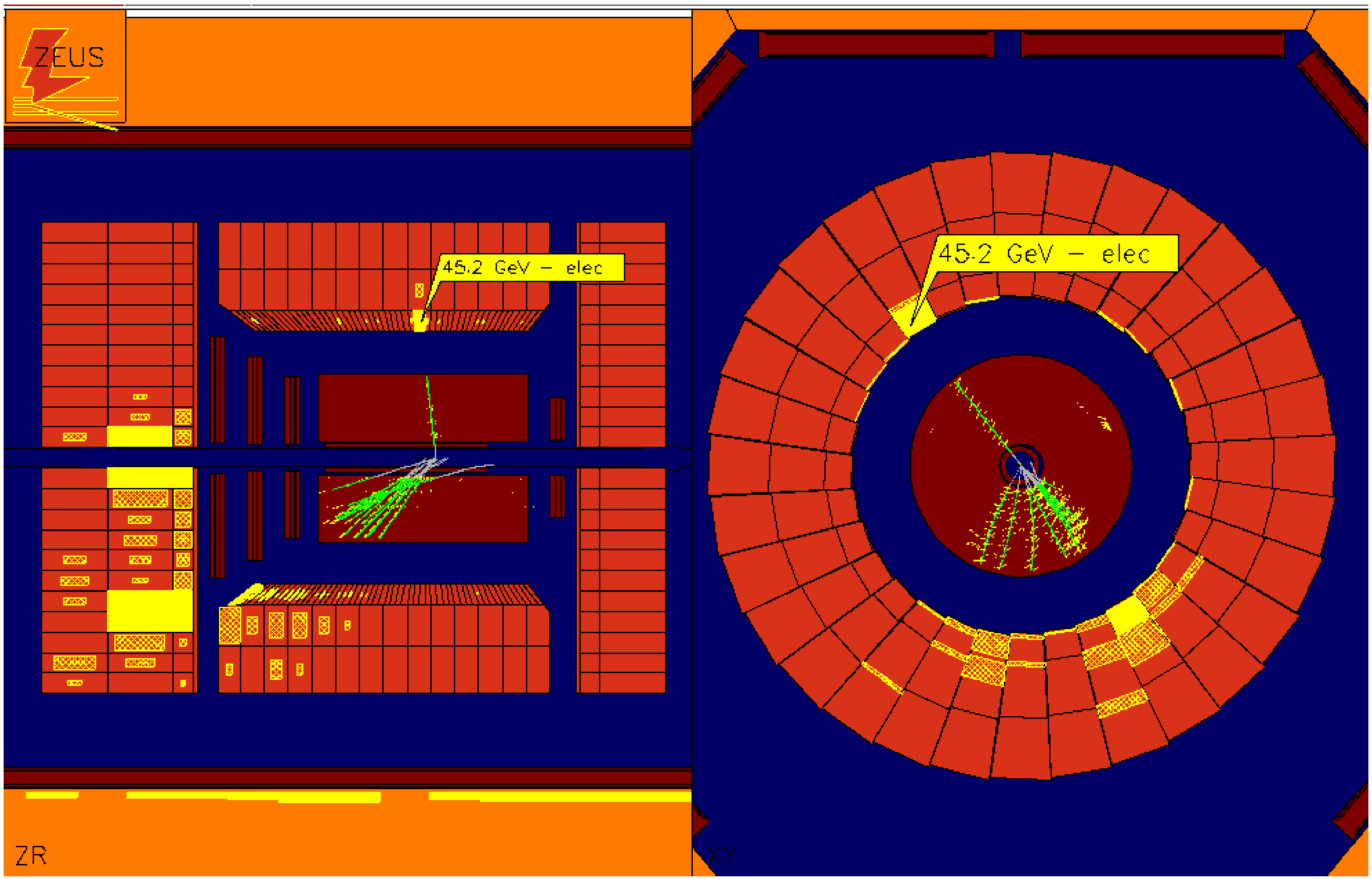
$$x_{IP} = \frac{q\cdot(p-p')}{q\cdot p} \approx \frac{Q^2+M_X^2}{Q^2+W^2}$$

$$\beta = \frac{Q^2}{2q\cdot(p-p')} \approx \frac{Q^2}{Q^2+M_X^2}$$

Identify diffractive events either using leading proton spectrometer or LRG in main detector.

If the forward proton is not detected then there will be up to 20% background from proton dissociation.

Standard NC event in ZEUS



Diffractive DIS event in ZEUS