Small-x Physics and Diffraction
– An Experimentalist's Overview

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Motivation

- The two discoveries at HERA:

  1. The strong rise of F_2 towards low x
  2. The high cross section for hard diffraction

- Understanding of the high-energy, i.e. small x limit of QCD
- Do we enter a new regime of high parton densities (saturation) at low x and when do we reach the unitarity limit?
- Where and how does the transition from perturbative QCD ($Q^2 \gg \Lambda_{QCD}$) to soft (non-perturbative) hadronic physics at $Q^2 = 0$ take place?
- What is the region of validity of DGLAP and BFKL ?
- How can we understand the phenomenon of diffraction in the context of (p)QCD?
- Is the "Pomeron" universal or if not, why not?

Outline – Small-x

- Introduction: Deep inelastic Scattering at HERA (Reminder)
- Introduction to BFKL evolution
- Inclusive DIS: Problems of DGLAP?
- Measurements of F_L

- The small-x limit and Saturation
- Rise of F_2 at low x
- Transition region at low Q^2

- QCD Dynamics through hadronic final state measurements
- Virtual photon structure
- CCFM evolution
- Forward jet and particle production

Outline – Diffraction

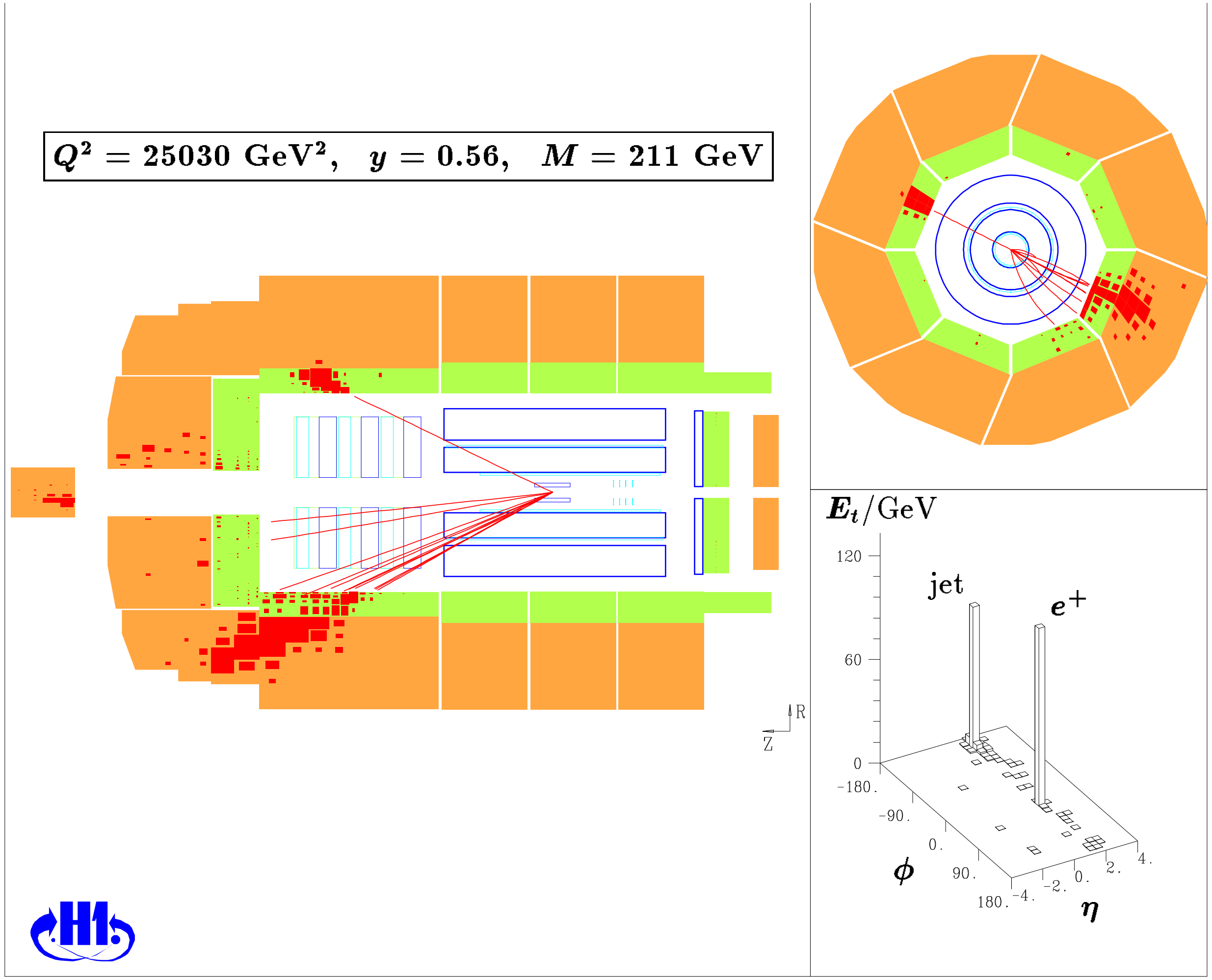
- Observation of hard diffraction at HERA
- Soft hadron-hadron interactions and Regge theory

- Inclusive Diffraction in DIS at HERA
- Diffractive final states at HERA: Jets, Charm
- 2-gluon exchange models
- Light vector meson production

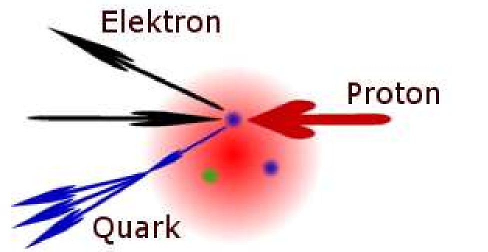
- Diffraction at the Tevatron

Reminder: Deep Inelastic Scattering at HERA

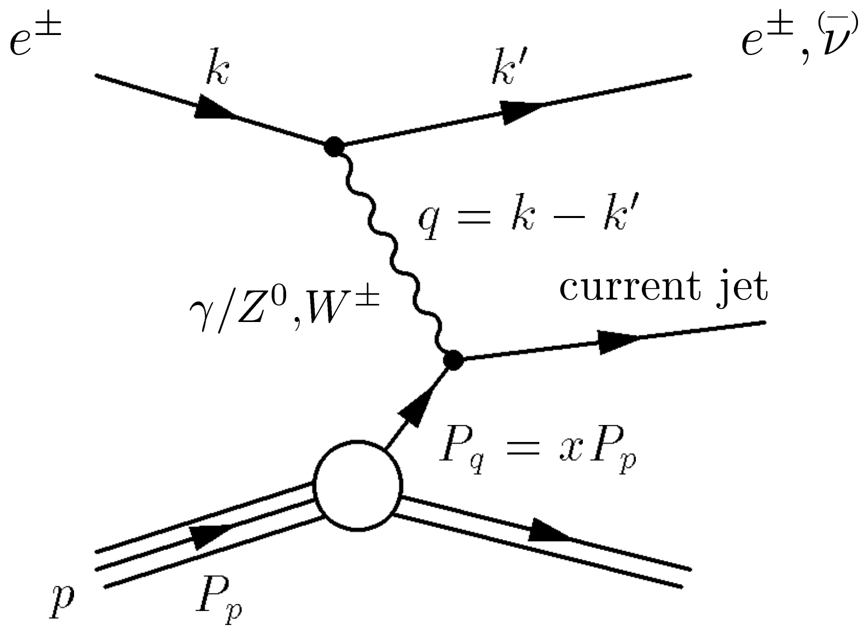
A "typical" DIS event at high Q^2 in the H1 detector:



Protons: $E_p = 920$ GeV
Electrons: $E_e = 27.5$ GeV



Reminder: Deep Inelastic Scattering at HERA



$Q^2 = -q^2 = (k - k')^2$
Photon virtuality

$x = \frac{-q^2}{2P\cdot q}$ $(0 < x < 1)$
Parton momentum fraction "Bjorken-x"

$s = (k + P)^2 = 4E_eE_p \sim (320\ \mathrm{GeV})^2$
ep CMS energy squared

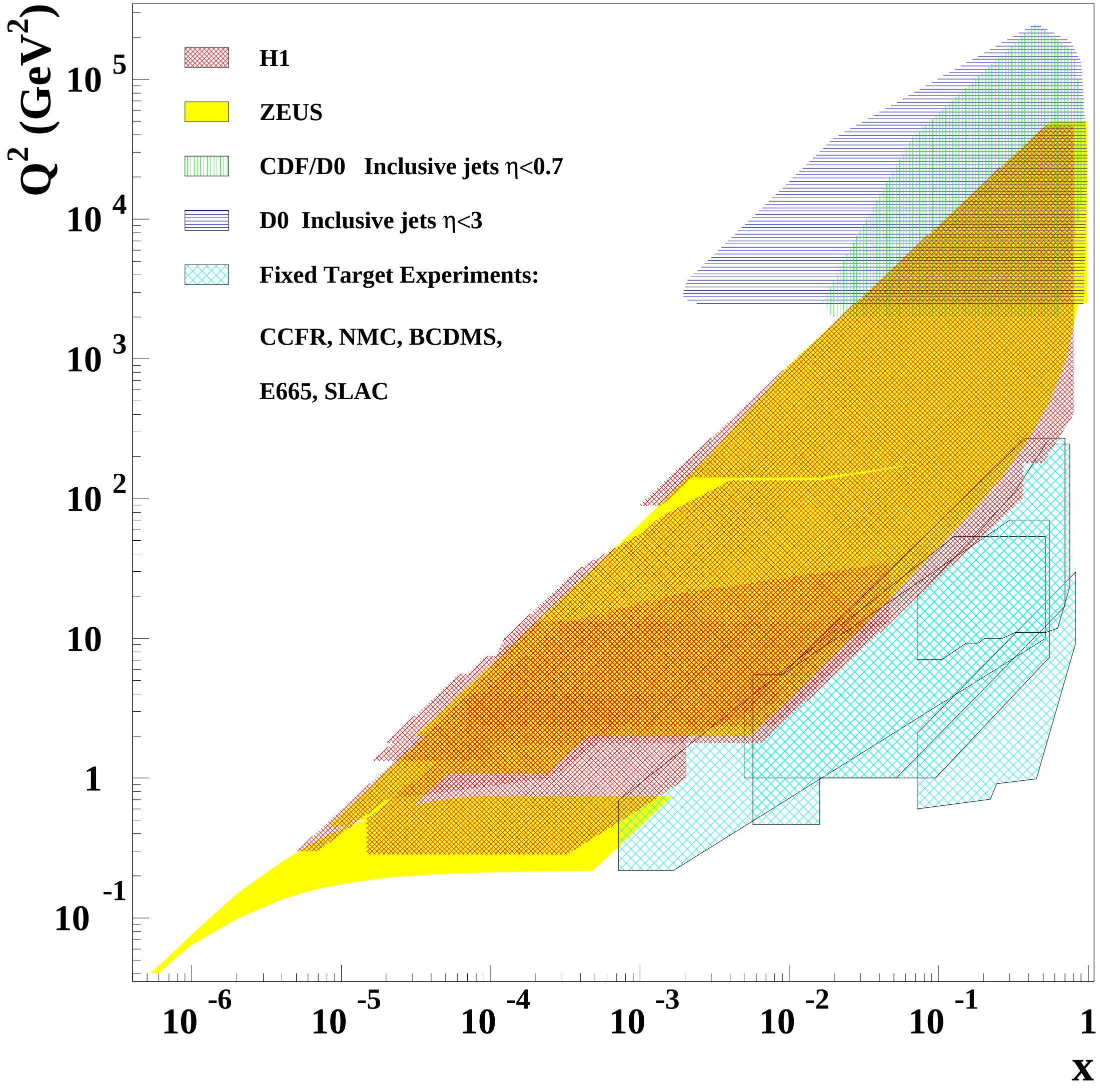
$y = \frac{P\cdot q}{P\cdot k} = Q^2/xs$ $(0 < y < 1)$
inelasticity, approx. $y = 1 - \frac{E'_e}{E_e}$

$W^2 = (q + P)^2 = ys - Q^2$
$\gamma^* p$ CMS energy squared

Cross section and structure functions (neglecting Z^0 exchange):

$$\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left(\left[1 - y + \frac{y^2}{2}\right] F_2 - \frac{y^2}{2} F_L\right)$$

DIS Kinematic plane

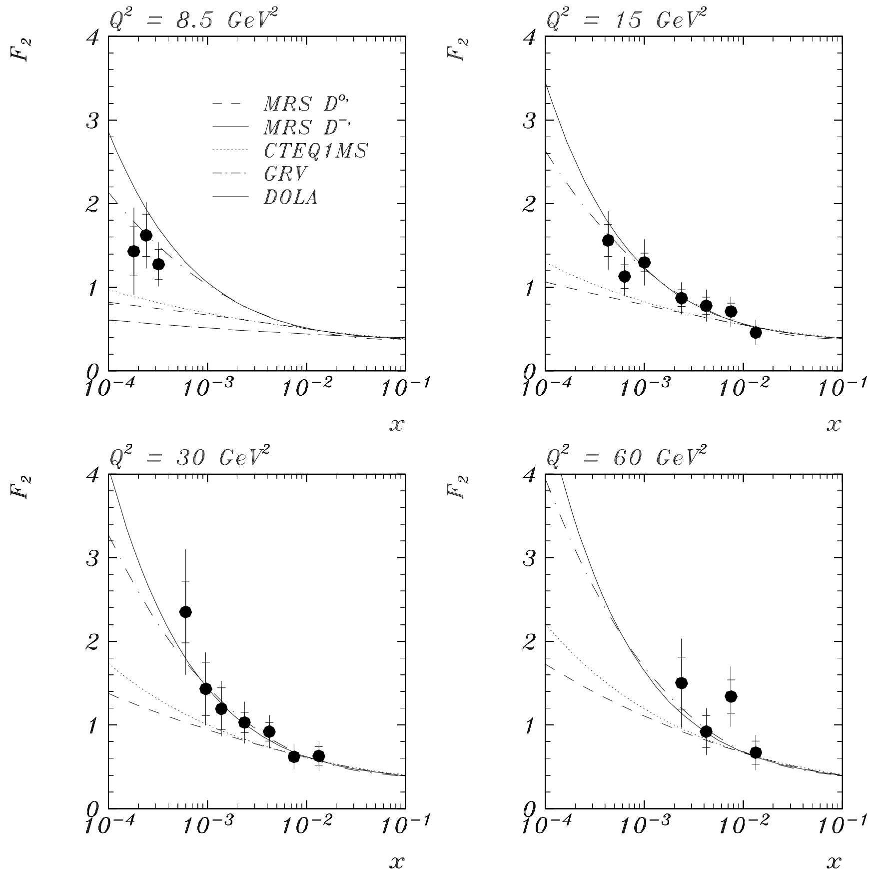


- high Q^2, high x: Tevatron jets
- medium Q^2, high x: Fixed target expts.
- HERA: high CMS energy gives extension of 2-3 orders of magnitude towards lower x at same Q^2

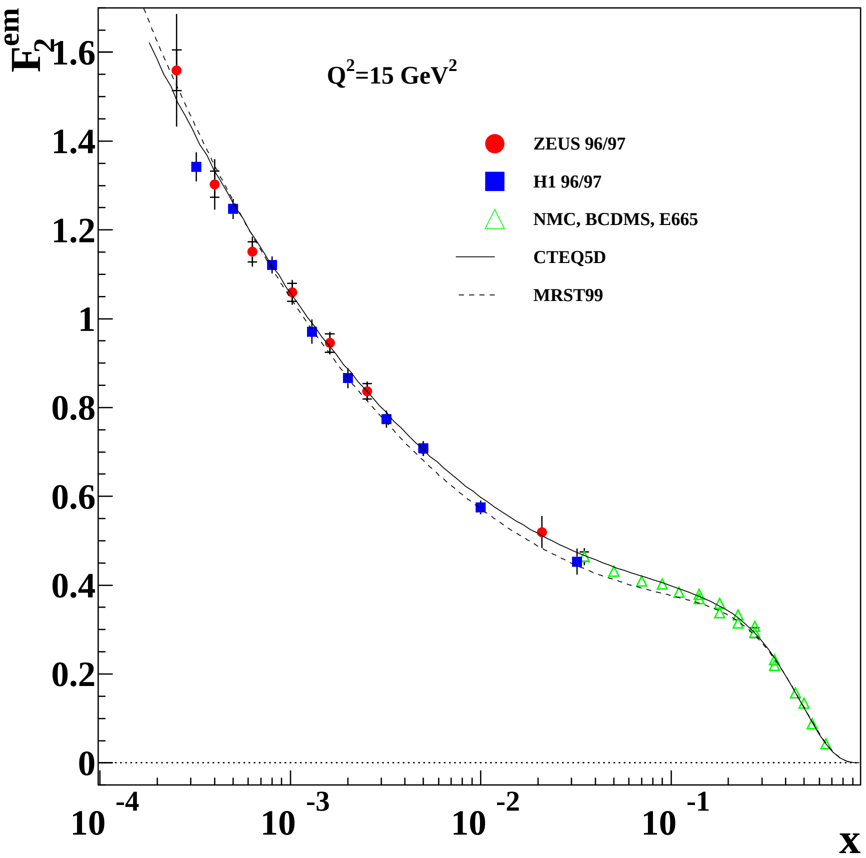
The HERA discovery: Steep rise of F_2 at low x

Before HERA: low-x behaviour of F_2 unknown (see spread of then existing pdf's)

1993: First HERA data



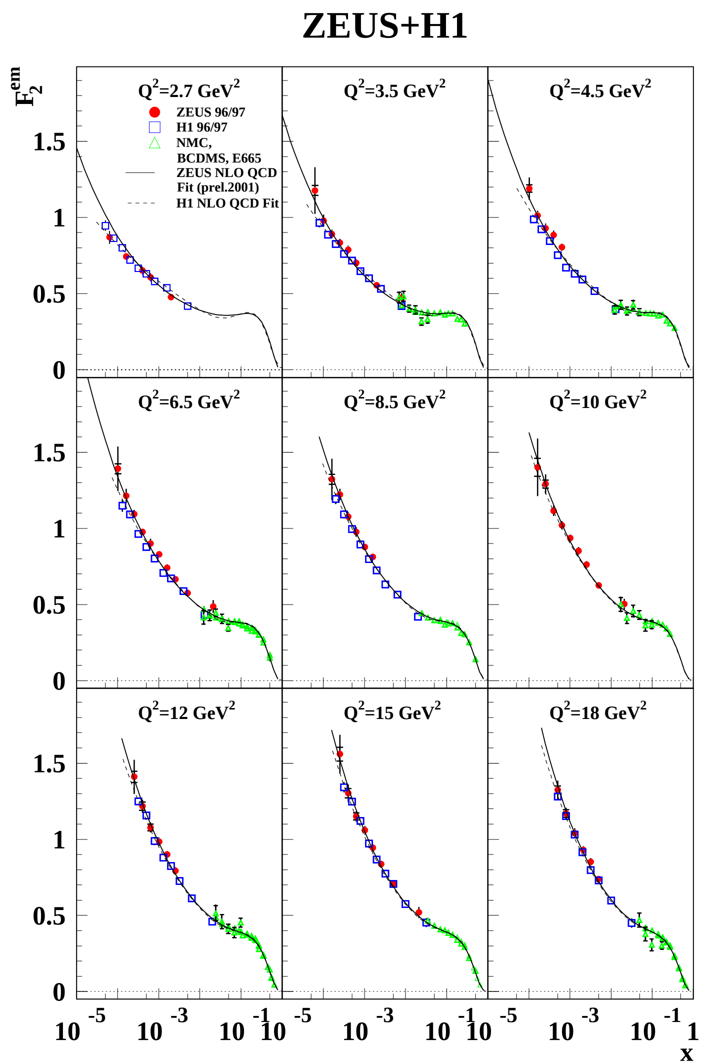
2000: high precision (few percent)!



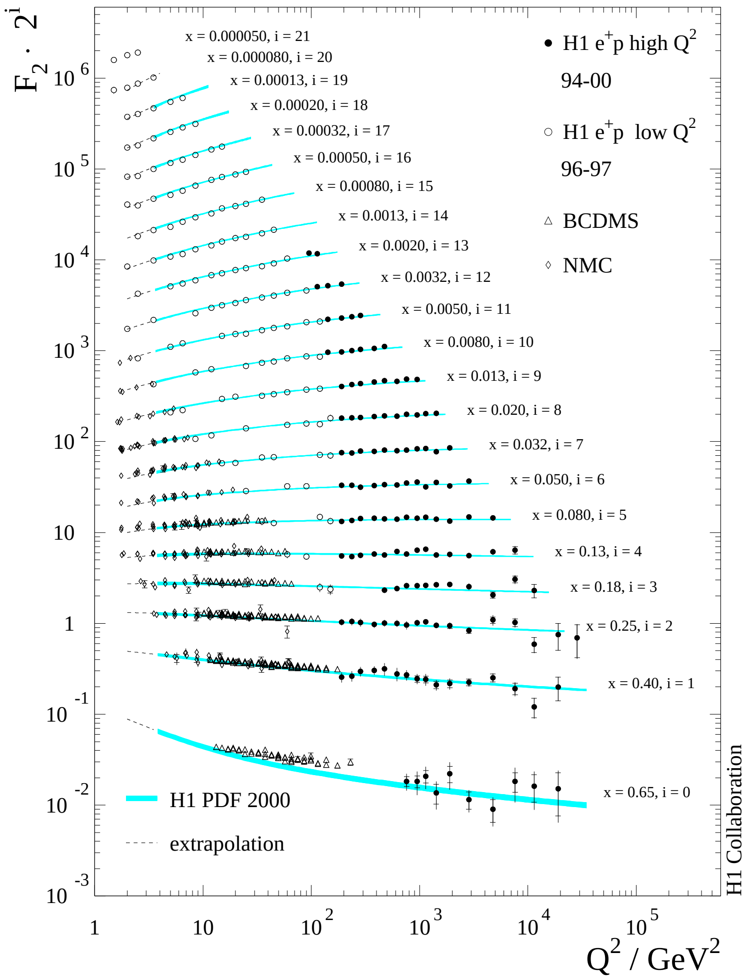
Rise was expected, but turned out to be very steep!

x and Q^2 dependence of $F_2(x, Q^2)$

x dependence:



Q^2 dependence:



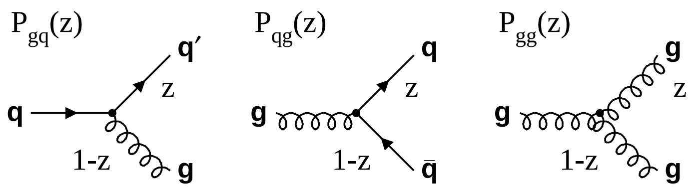
DGLAP evolution

DGLAP evolution equations:

$$\frac{\mathrm{d}q_i(x,Q^2)}{\mathrm{d}\ln Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{\mathrm{d}z}{z}\left[q_i(z,Q^2)P_{qq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{qg}\left(\frac{x}{z}\right)\right]$$

$$\frac{\mathrm{d}g(x,Q^2)}{\mathrm{d}\ln Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{\mathrm{d}z}{z}\left[\sum_i q_i(z,Q^2)P_{gq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{gg}\left(\frac{x}{z}\right)\right]$$

Splitting functions:



$$P_{qq}(z) = P_{gq}(1-z) = \frac{4}{3}\left[\frac{1+z^2}{(1-z)_+}\right] + 2\cdot\delta(1-z)$$

$$P_{qg}(z) = \frac{1}{2}\left(z^2 + (1-z)^2\right)$$

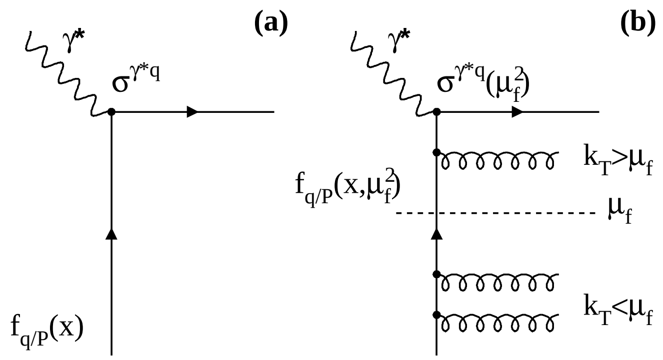
$$P_{gg}(z) = 6\left[\frac{z}{(1-z)_+} + \frac{1-z}{z} + z(1-z)\right] + (11 - \frac{n_f}{3})\cdot\delta(1-z)$$

- Leading powers of $\alpha_s \log Q^2/Q_0^2$ are considered
- No absolute prediction for $p_i(x,Q^2)$!
- Describes only evolution of pdf's with Q^2
- Need input for x-dependence at starting scale Q_0^2
- Determine pdf's from global fit

From DGLAP to BFKL evolution

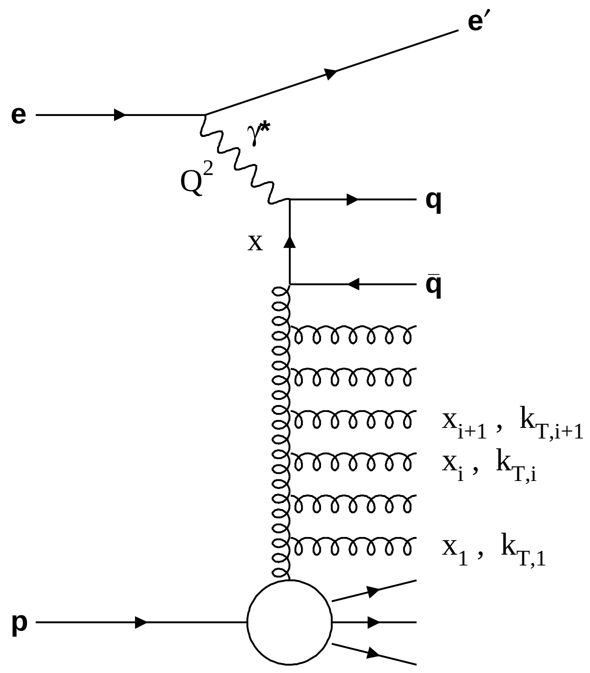
DGLAP:

- collinear singularities factorized in pdf
- evolution in $Q^2 \sim p_T^2$ or k_T^2
- $\sigma \sim \sigma_0 \int \frac{dz}{z} C\left(\frac{x}{z}\right) f(z, Q^2)$
- Strong ordering in k_T along ladder



What happens at low x?

- DGLAP includes only $[\alpha_s^m \log(Q^2/Q_0^2)^n]$ terms
- At very low x, terms $[\alpha_s^m \log(1/x)^n]$ must become important (e.g. at HERA?)
- If $\log(Q^2/Q_0^2) \ll \log(1/x)$,
  need resummation of terms $[\alpha_s^m \log(1/x)^n]$
  to all orders by keeping full Q^2 dependence
- Must relax strong ordering of k_T,
  need integration over full k_T phase space



BFKL evolution

- Integration over full k_T phase space:

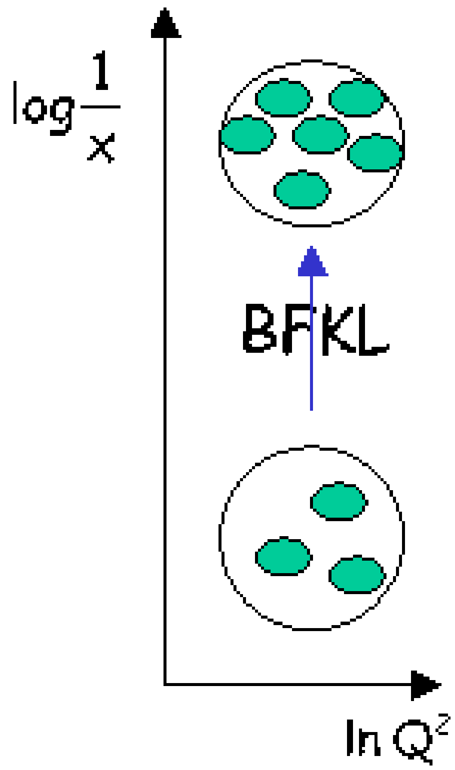
- Unintegrated gluon distribution $f(x, k_T^2)$:
  $xg(x,Q^2) = \int_{\mu^2}^{Q^2} \frac{dk_T^2}{k_T^2} f(x,k_T^2)$

- n-rung contribution f_n given in terms of f_{n-1}, i.e. strong ordering in x

- Recursion relation
  $f_n(x_n, k_T^2) = \int_{x_n}^{1} \frac{dx_{n-1}}{x_{n-1}} \int dk_{T,n-1}^2 \mathcal{K}(k_{T,n}^2, k_{T,n-1}^2) f_{n-1}(x_{n-1}, k_{T,n-1}^2)$
  ($\mathcal{K}(k_{T,n}^2, k_{T,n-1}^2)$ is the "BFKL kernel")

- Leads to differential form:
  $\frac{df(x_n,k_{T,n}^2)}{d\log(1/x)} = \int dk_{T,n}^2 \mathcal{K}(k_{T,n}^2, k_{T,n-1}^2) f(x_{n-1}, k_{T,n-1}^2)$

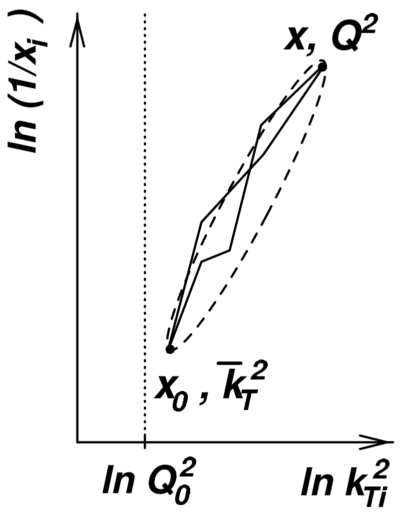
- Solution at LO:
  $f(x,k_T^2) \sim \sqrt{k_T} \frac{\left(\frac{x}{x_0}\right)^{-\lambda}}{\sqrt{2\pi\lambda'' \log(x_0/x)}} \exp\left(\frac{-\log(k_T^2/\bar{k}_T^2)}{2\lambda'' \log(x_0/x)}\right)$
  $\lambda = \frac{3\alpha_s}{\pi} 4\log 2 \approx 0.5$



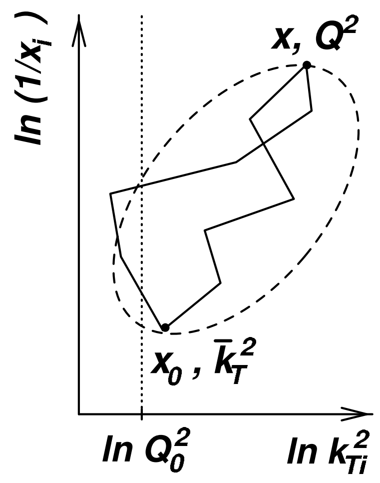
QCD Evolution: DGLAP vs BFKL

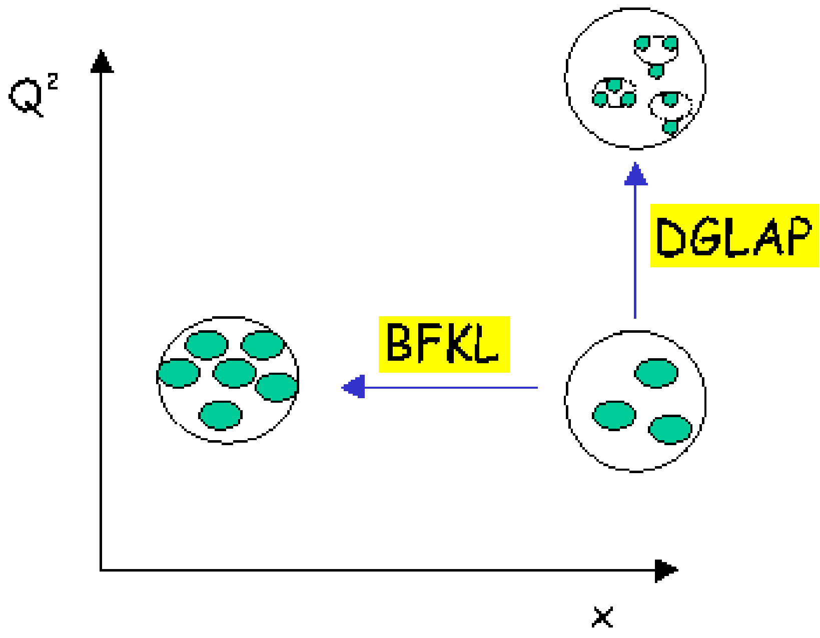
Evolution in the $(k_T^2, 1/x)$ plane:

DGLAP



BFKL





- Strong ordering of transverse momenta

- Diffusion pattern along ladder
- Problem: "Diffusion into infrared"

BFKL: summary

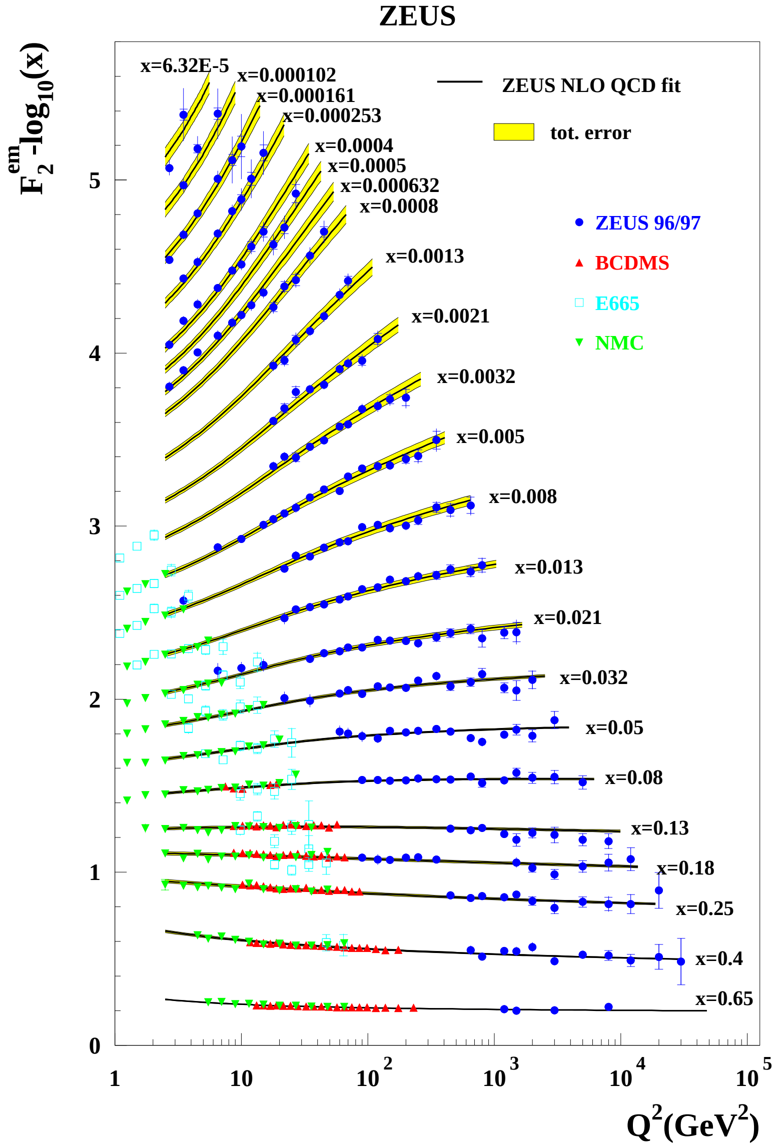
Summary:

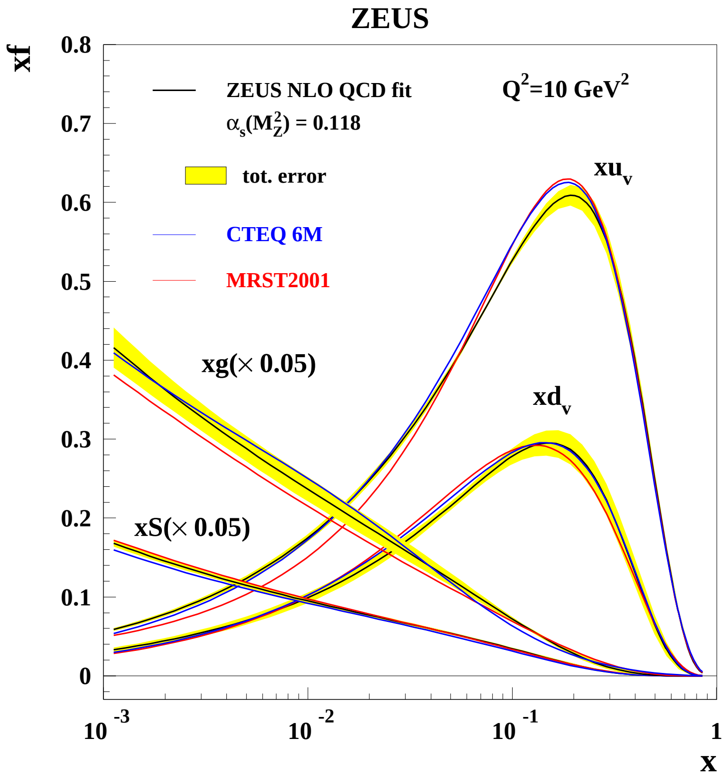
- In limit of small x and moderate Q^2 BFKL is more appropriate
- BFKL resums $\log(1/x)$ terms
- leads to power behaviour $xg(x, Q^2) = x^{-0.5}$ (at LO)
- However: too steep for latest data:
  $\longrightarrow$ need to include running of α_s
  $\longrightarrow$ need to perform NLO calculation:
- NLO BFKL:
  corrections are large and negative
  indication that λ gets smaller

Search for BFKL effects at HERA:

- Present $F_2(x, Q^2)$ data very well described by NLO DGLAP fits
- BFKL effects maybe present in data but "hidden" by flexibility of DGLAP input distributions?
- More promising to search for BFKL in final state ? (see later)

Success of NLO DGLAP

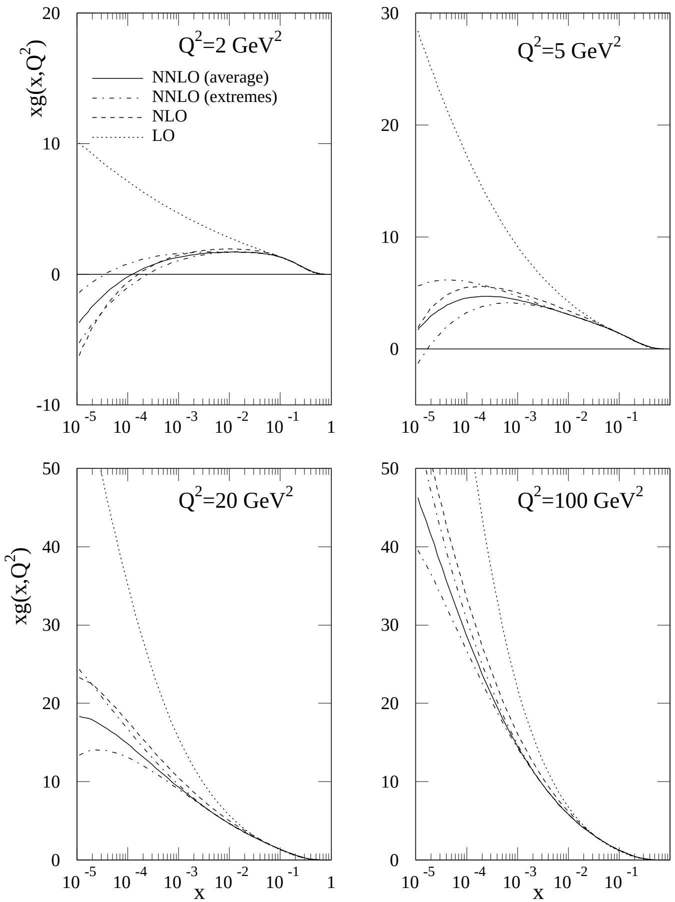


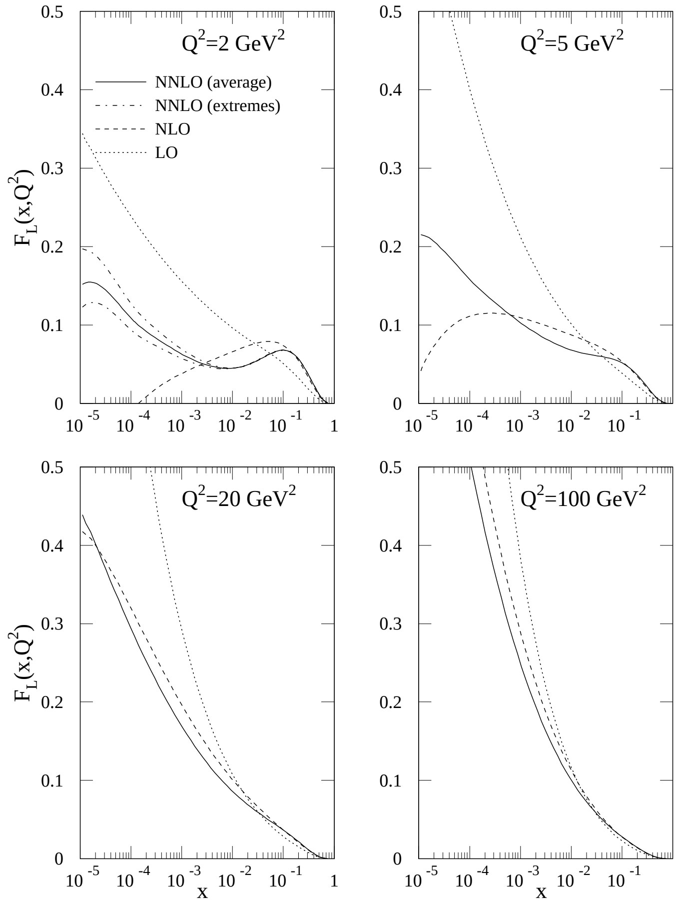


- QCD fit to ZEUS+other data
- Very good description of data for $Q^2 > 2.5$ GeV^2
- Precise determination of pdf's
- BFKL not needed?!

DGLAP problems (?)

Recent MRST global analysis (including approx. NNLO):

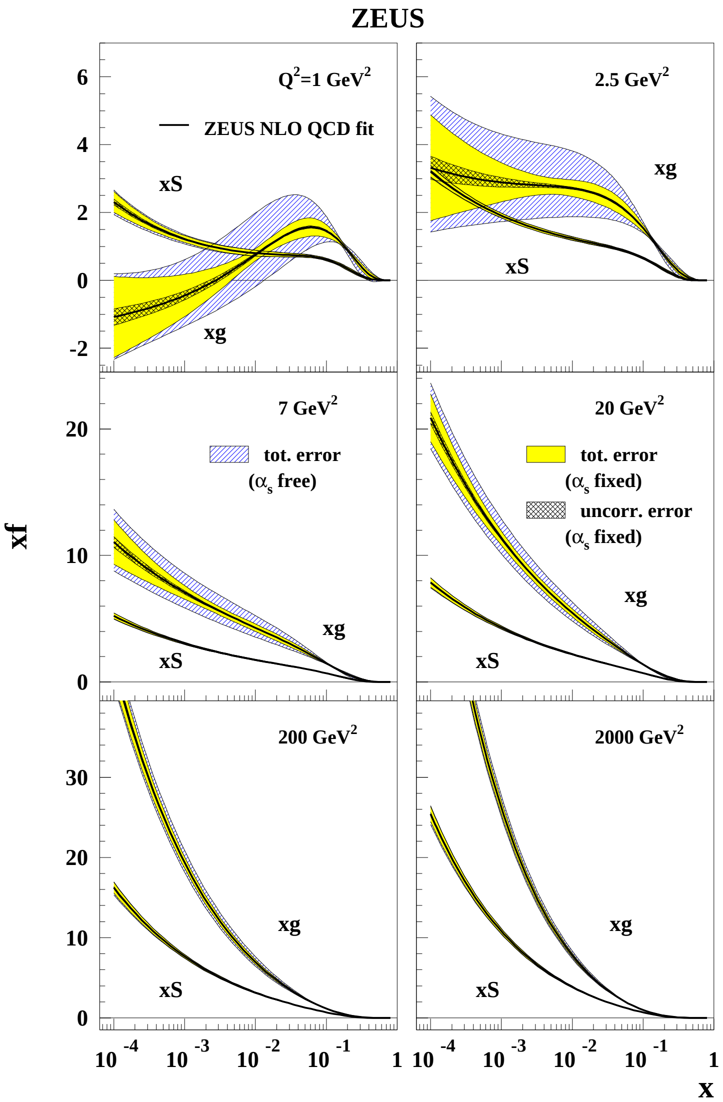




Gluon negative at low x and Q^2
(not an observable)

NLO F_L negative at low x and Q^2
NNLO F_L positive,
huge (oscillating) differences!

DGLAP problems (?)



ZEUS gluon also negative at small Q^2

Remarks:

- $xg(x, Q^2)$ is not an observable, so not immeaditely a problem
- But F_L is an observable and it should not be negative!
- N.B. Sea quarks from $g \rightarrow q\bar{q}$ splitting, but there is no glue at low Q^2 and x, but there is sea!
- Does all this indicate that pure DGLAP is insufficient?
  ... or pert. theory not justified when $Q^2 = 1$
  $\alpha_s(Q^2 = 1\ \mathrm{GeV}^2) \sim 0.5(\mathrm{LO})\ 0.4(\mathrm{NLO})$
- It is very important to measure F_L at low Q^2, also because of its close relation to the gluon

The longitudinal structure function $F_L(x, Q^2)$

Reminder:

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

where $Y_+ = 1 + (1 - y)^2$

F_2 and F_L are related to the total and the longitudinal γ absorption cross sections:

$$F_2(x, Q^2) = \frac{Q^2}{4\pi^2\alpha}\left[\sigma_T(x, Q^2) + \sigma_L(x, Q^2)\right]$$

$$F_L(x, Q^2) = \frac{Q^2}{4\pi^2\alpha}\,\sigma_L(x, Q^2)$$

One often defines the "reduced cross section" $\sigma_r(x, Q^2)$:

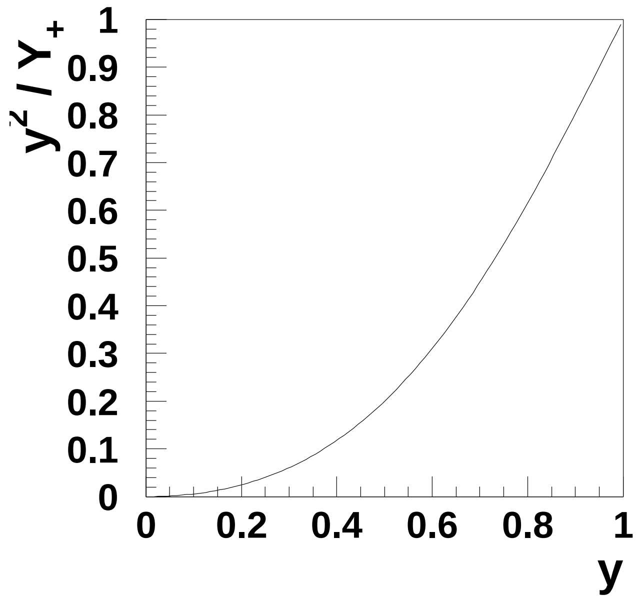
$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \sigma_r(x, Q^2)$$

So that

$$\sigma_r(x, Q^2) = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

The longitudinal structure function $F_L(x, Q^2)$

- Due to positivity of cross sections: $0 \leq F_L \leq F_2$
- In QPM, $F_L = 0$ (quarks have only longit. momentum, "Callan-Cross rel.")
- In QCD, $F_L > 0$ (quarks interact via gluons, struck quark can have transverse momentum)
- Due to its origin, F_L is directly connected with the gluon distribution
- At NLO: $F_L \sim \frac{\alpha_s}{2\pi} \left[C_q^L \otimes F_2 + C_g^L \otimes \sum_i e_i^2 \, zg(z, Q^2) \right]$

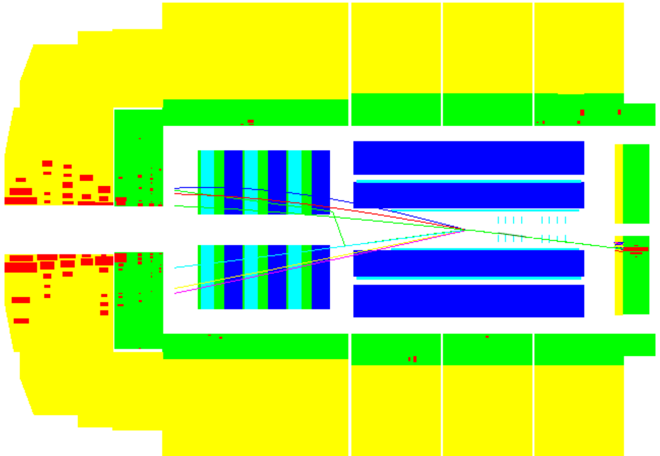


Measurement of $F_L(x, Q^2)$ at HERA:

- At fixed ep CMS energy, only two indep. variables: x, Q^2
  $\longrightarrow$ cannot disentangle $F_2(x, Q^2)$ and $F_2(x, Q^2)$
- Possibilities for direct measurements:
  1. Measure cross sections at two different CMS energies, e.g. lower E_p (HERA-II)
  2. "simulate" lower E_e by analysing ISR events (exp. difficult)
- Alternative: Exploit fact that F_L contributes only at high y

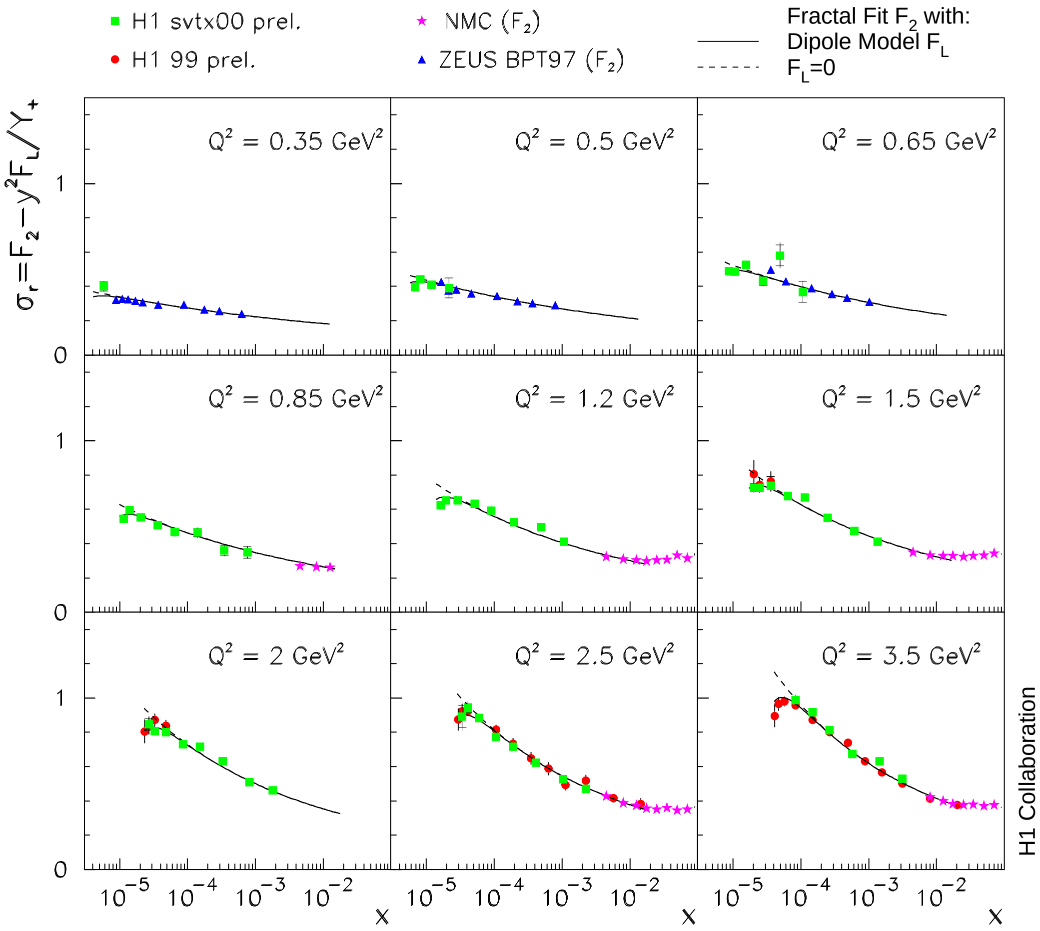
F_L extraction at high y (H1)

H1 event at low Q^2:



- At high y: detect low energy ($E'_e > 3$ GeV) electrons
- BST (Backward Silicon Tracker) used for background rejection
- At low y, hadronic jet goes forward, so no vertex in central tracker (BST vertex)

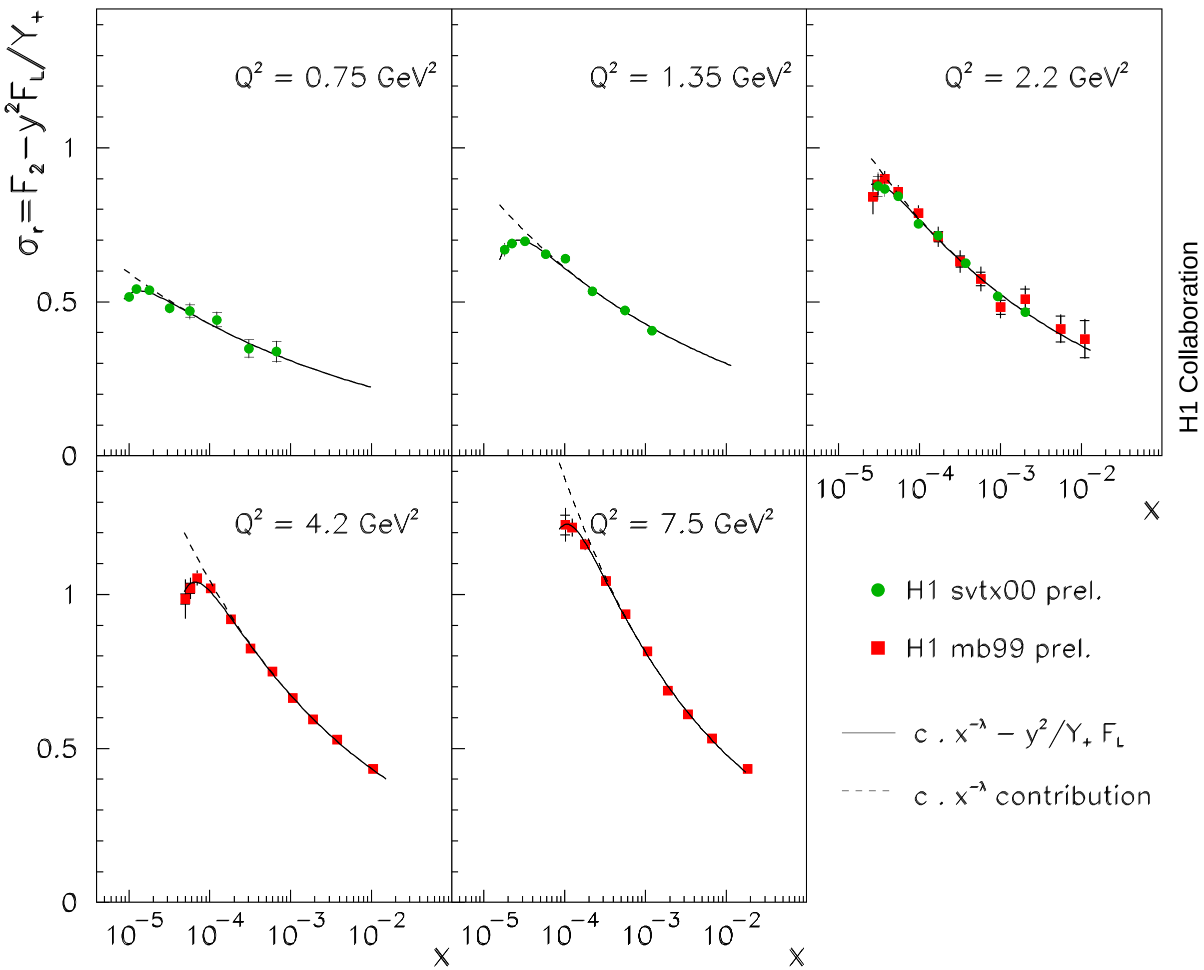
Reduced cross section at low Q^2



F_L manifests as turnover at low x (i.e. high y) ($Q^2 = sxy$)

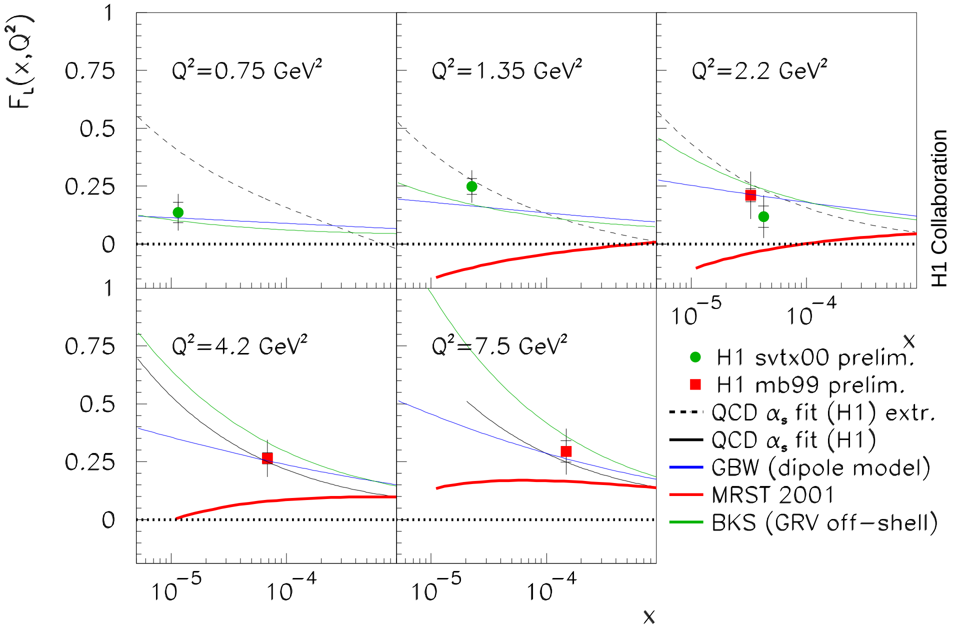
F_L extraction at high y (H1)

- Shape at high y driven by kinematic factor y^2/Y_+
- F_2 at low x well described by $x^{-\lambda}$ (see later)
- Fit to data $\sigma_r(x, Q^2) = cx^{-\lambda} - \frac{y^2}{Y_+} F_L(Q^2)$
- Extract one $F_L(< x >, Q^2)$ value per Q^2x bin

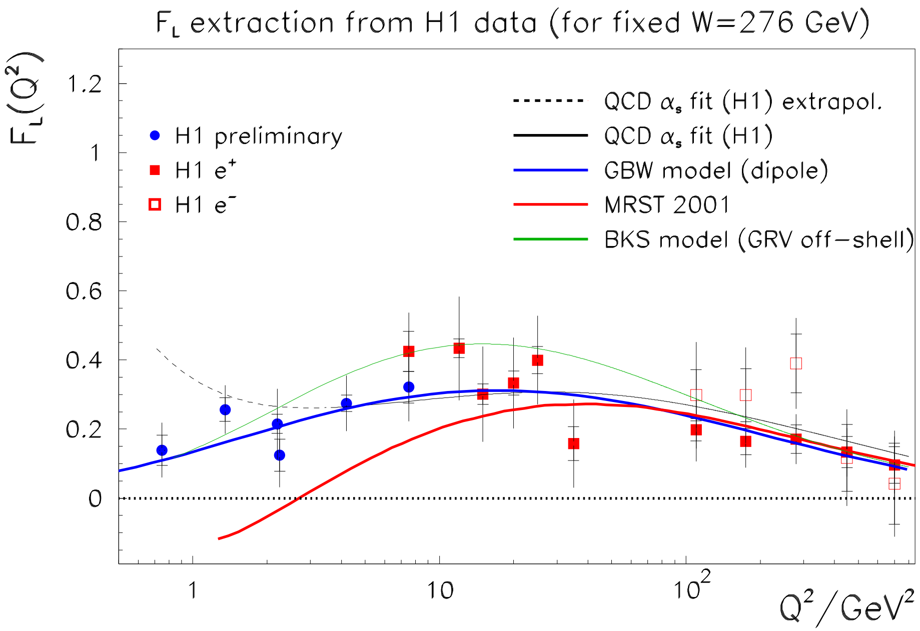


F_L extraction at high y (H1)

F_L vs. x:



F_L vs. Q^2 at fixed W:



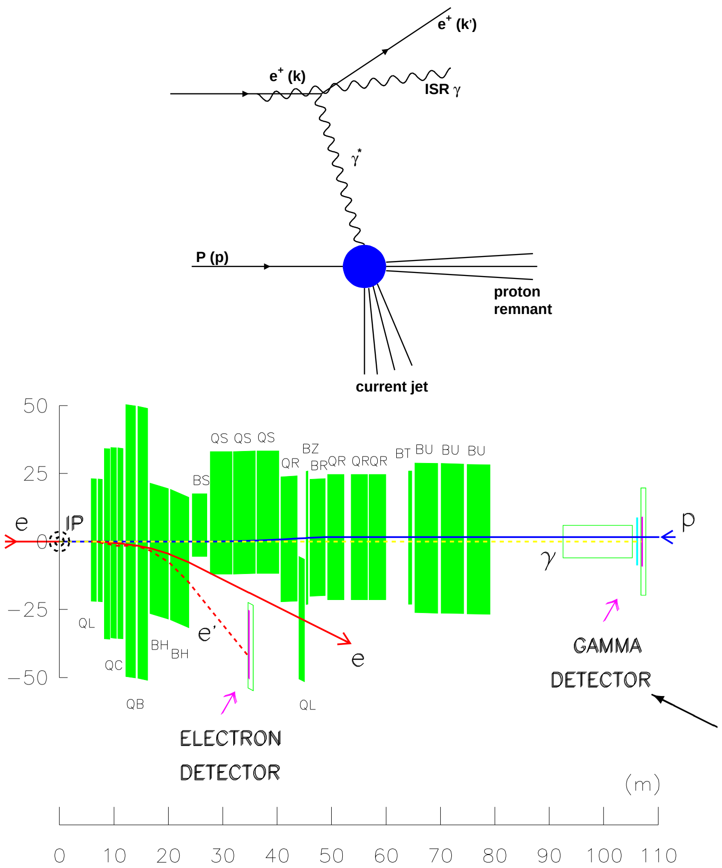
- Consistent with F_L from NLO QCD fit for $Q^2 \geq 1.35\ \mathrm{GeV}^2$
- F_L MRST 2001 too low at small x and Q^2
- Discrimination between models

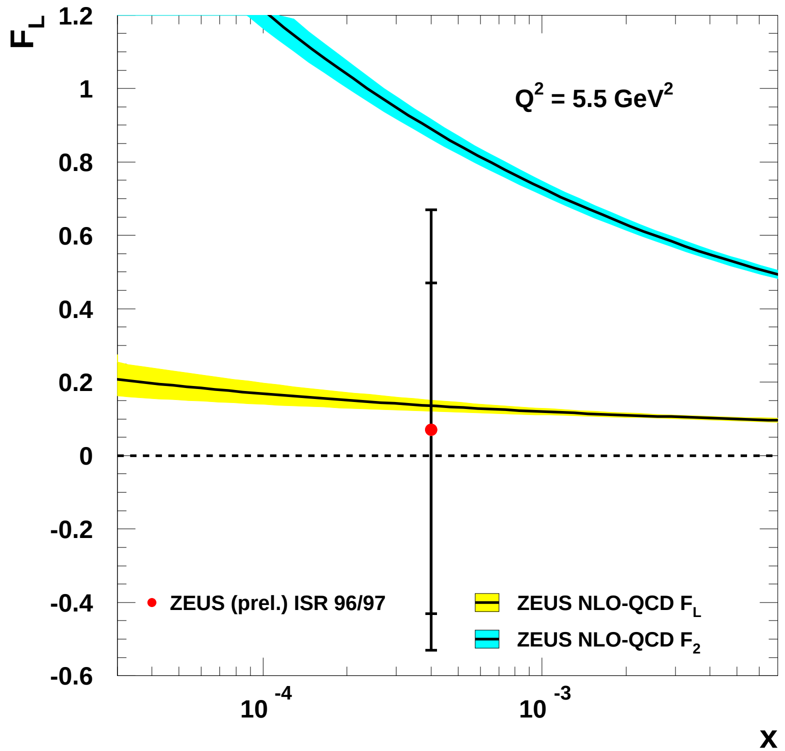
F_L extraction is important consistency check for DGLAP QCD

Direct measurement without reduced E_p?

F_L measurement using ISR events (ZEUS)

Use initial state QED radiation events to "emulate" lower E_e:



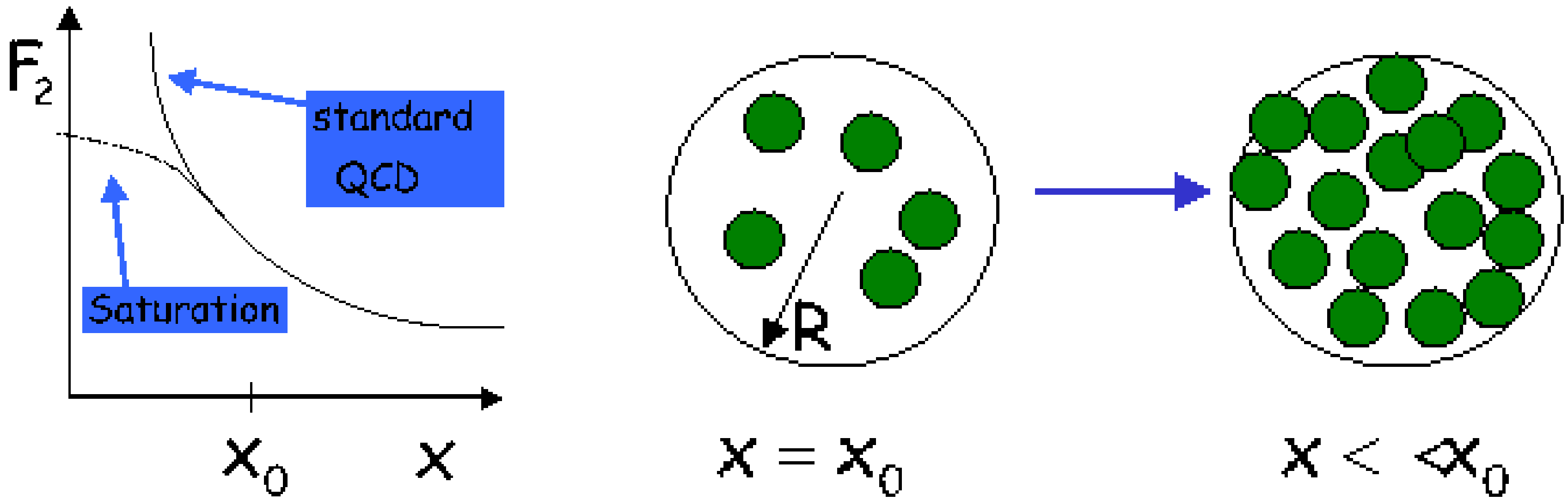


Bremsstrahlung photon detected in small-angle calorimeter

- Experimentally challenging
- Improve with more data

Introduction: The low-x limit of F_2 and Saturation

- Remember: $x \sim \frac{1}{W^2}$, i.e. small x corresponds to the high-energy limit of γp scattering
- Due to unitarity considerations (probability for interaction < 1), the rise towards small x / high energies cannot commence "forever"
- Expect that at some point the number of gluons becomes so big that recombination / screening effects start to play a role



- Possible experimental observation: Taming of the rise of F_2 at very low x
- Question: Do we see hints for saturation at HERA?

Introduction: The low-x limit of F_2 and Saturation

Naive estimate:

$$N_g \sigma_{gg} \approx xg(x, Q^2) \frac{\alpha_s(Q^2)}{Q^2} = \pi R^2$$

where
– N_g: Number of gluons per unit rapidity with transv. size $1/Q$
– σ_{gg}: Transv. area of single gluon (gluon-gluon cross section)
– $R \approx 1 \text{ fm} \approx 5 \text{ GeV}$

$$\kappa = xg(x, Q^2) \frac{\alpha_s(Q^2)}{\pi R^2 Q^2}$$

$\kappa \ll 1$:
Interaction between gluons negligible

$\kappa \gg 1$:
Recombination / shadowing effects important

Numerical estimate shows that at HERA saturation is irrelevant ?!

GLR Equation (Gribov, Levin, Ryskin):

Gluon recombination competes with usual evolution:

$$\frac{df(x, k_T^2)}{d\log(1/x)} = \mathcal{K} \otimes f(x, k_T^2) - \frac{81 \alpha_s^2(k_T^2)}{16 R^2 k_T^2} (x f(\xi, k_T^2))^2$$

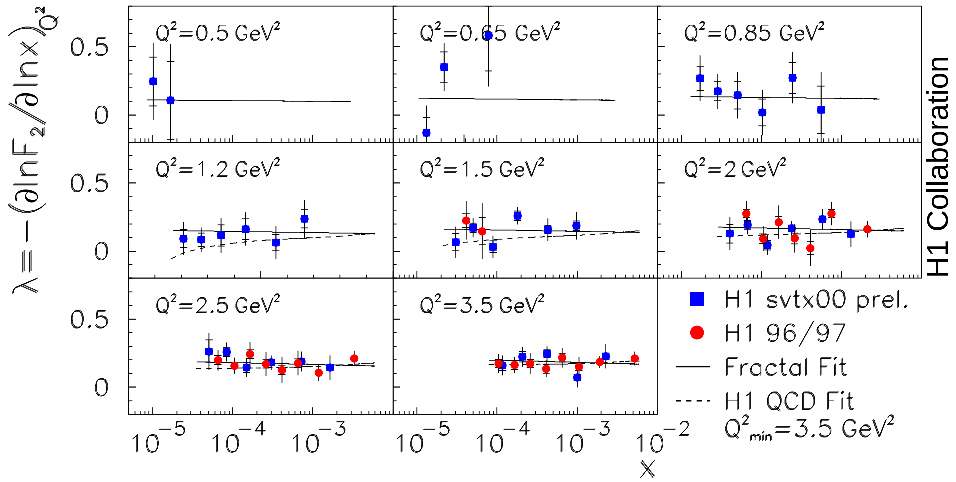
Non-linear evolution: at some point, non-linear term cancels linear term
$\rightarrow$ evolution stops (saturation)

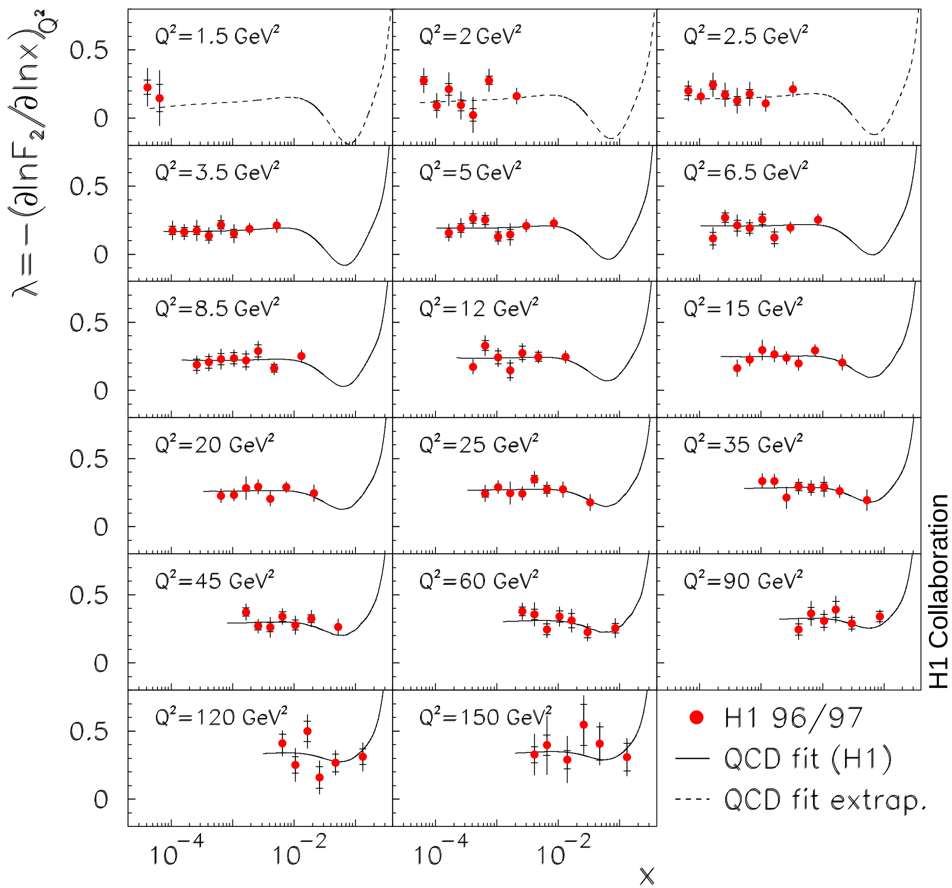
$\rightarrow$ look at Data

The rise of F_2 at low x

HERA high precision data allow to study rise of F_2 locally

$$\lambda = -\left(\frac{d\log F_2}{d\log x}\right)_{Q^2}$$



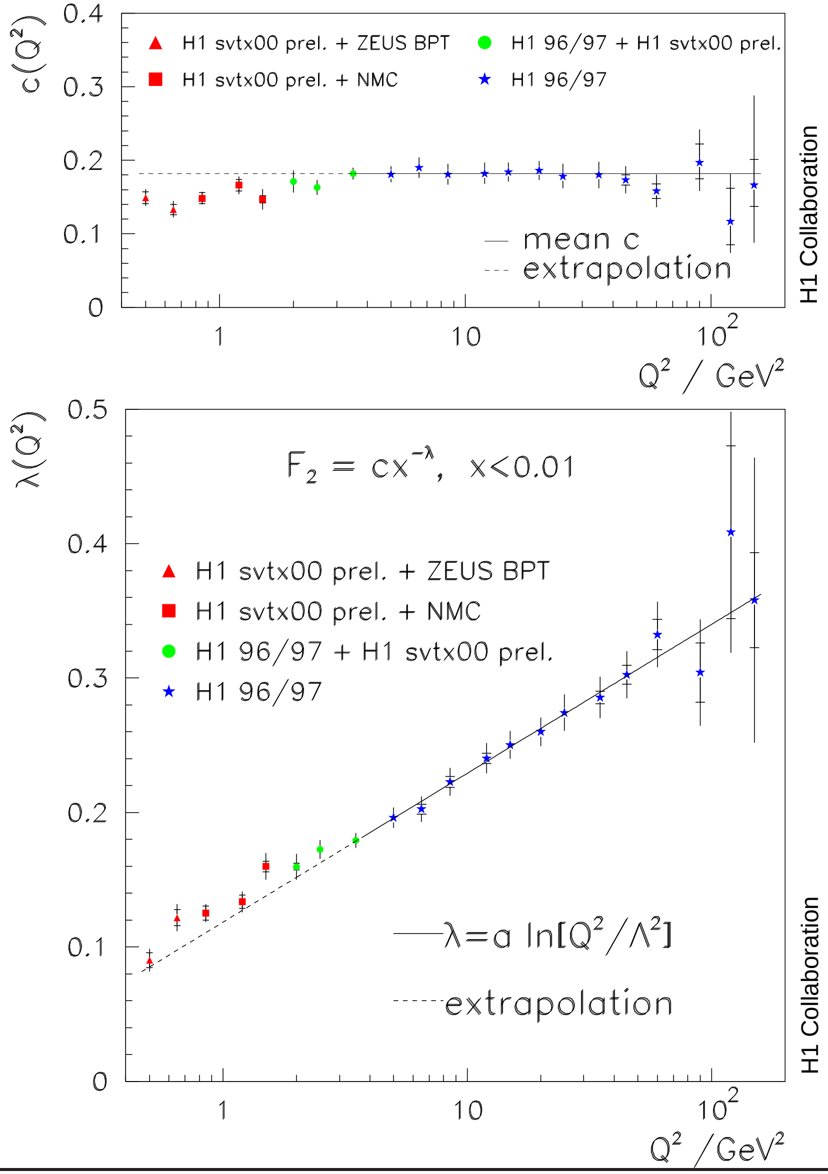


- At low $x < 0.01$ (away from valence region), λ constant at given Q^2, i.e. $F_2(x, Q^2) = c(Q^2)x^{-\lambda}$
- λ increases with Q^2

The rise of F_2 at low x

- Assume now that λ independent of x at fixed Q^2:
  $F_2 = cx^{-\lambda(Q^2)}$
- 1. Make fit at each $Q^2 \geq 3.5\ \mathrm{GeV}^2$
- 2. Fit λ values according to
  $\lambda(Q^2) = a \log(Q^2/\Lambda^2)$
  Result:
  $a = 0.0481 \pm 0.0013 \pm 0.0037$
  $\Lambda = (292 \pm 20 \pm 51) MeV$

No sign of taming of rise at low x seen!

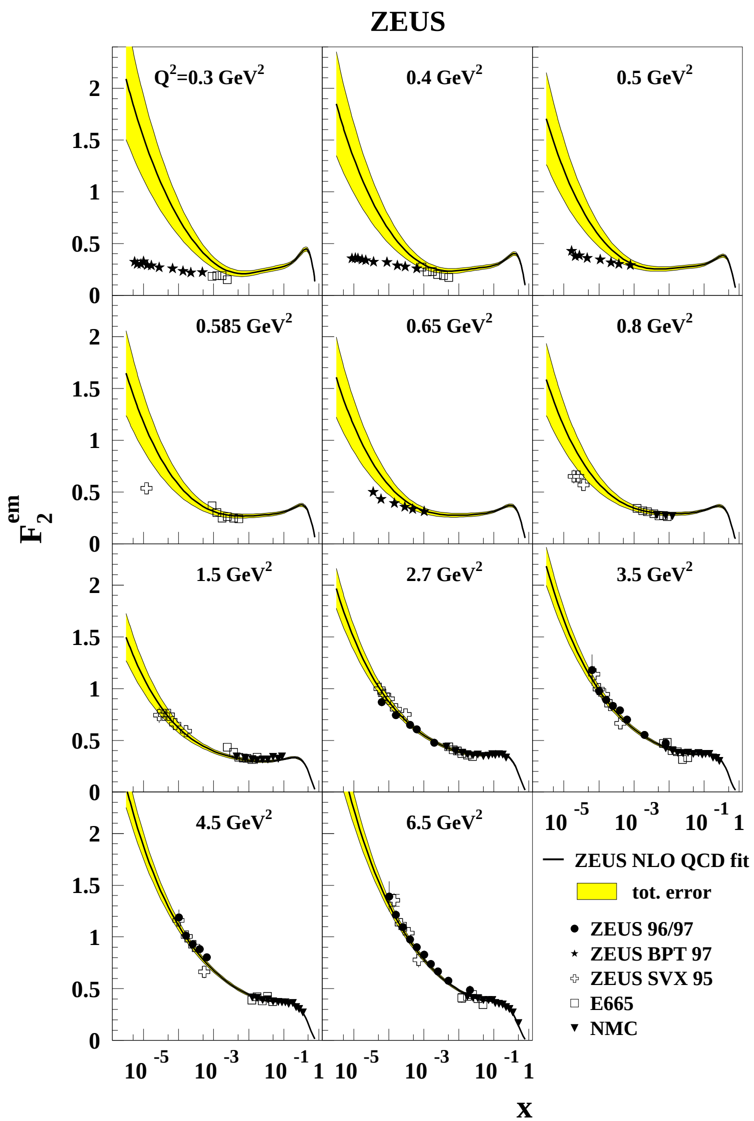


Transition region at low Q^2

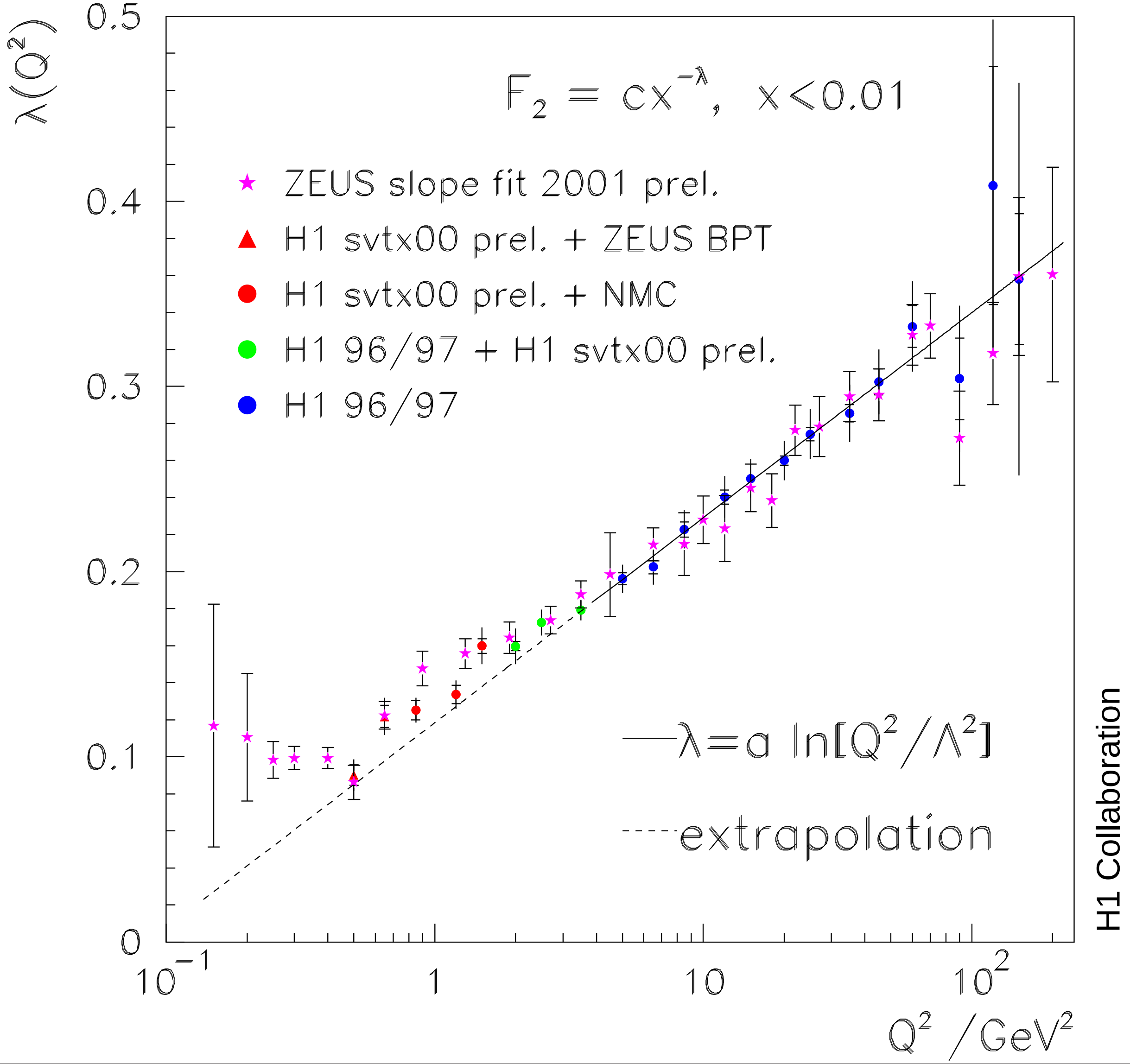
- F_2 "lays down" towards low Q^2
- How far does pQCD work?
- Where and how is the transition to the non-perturbative region?
- How can we understand the soft regime?

- DGLAP works well down to $Q^2 \sim 1\ \mathrm{GeV}^2$, but $\alpha_s(1\ \mathrm{GeV}^2) \sim 0.4$!
- Is $Q^2 \sim 1\ \mathrm{GeV}^2$ large enough?

- What is the picture at low Q^2?



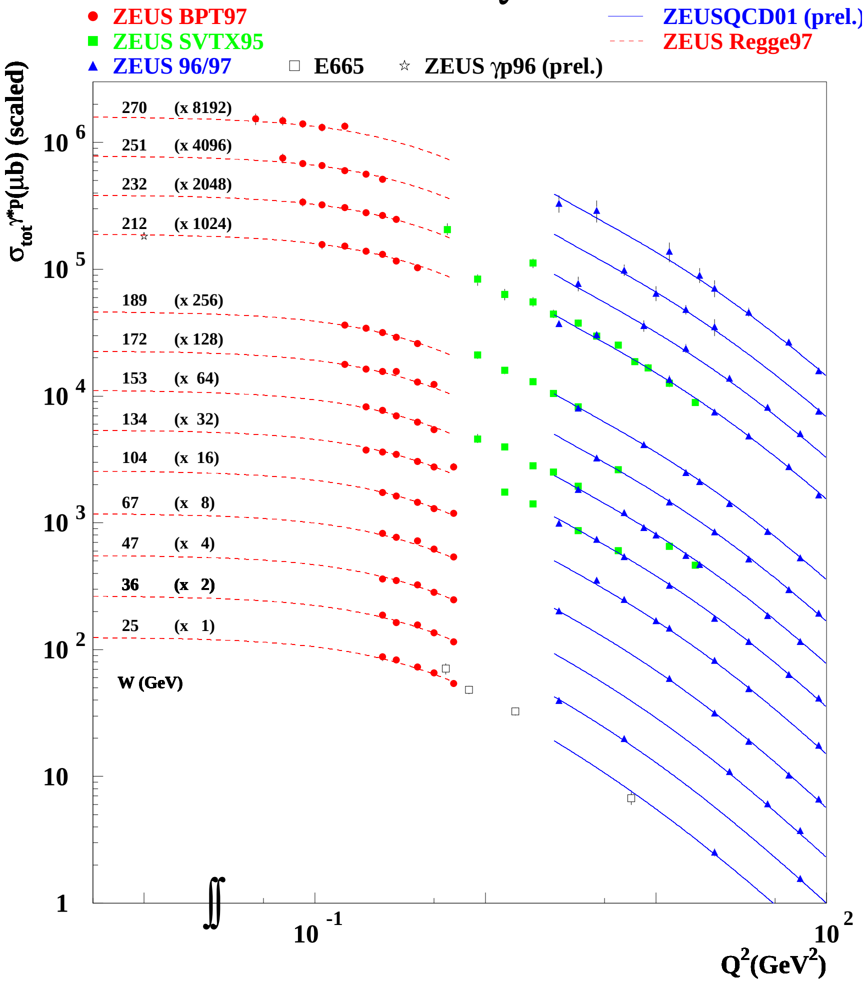
Transition region at low Q^2



- Smooth, logarithmic increase of slope λ with Q^2
- At $Q^2 \sim 1$ GeV^2, values around 0.1 are reached

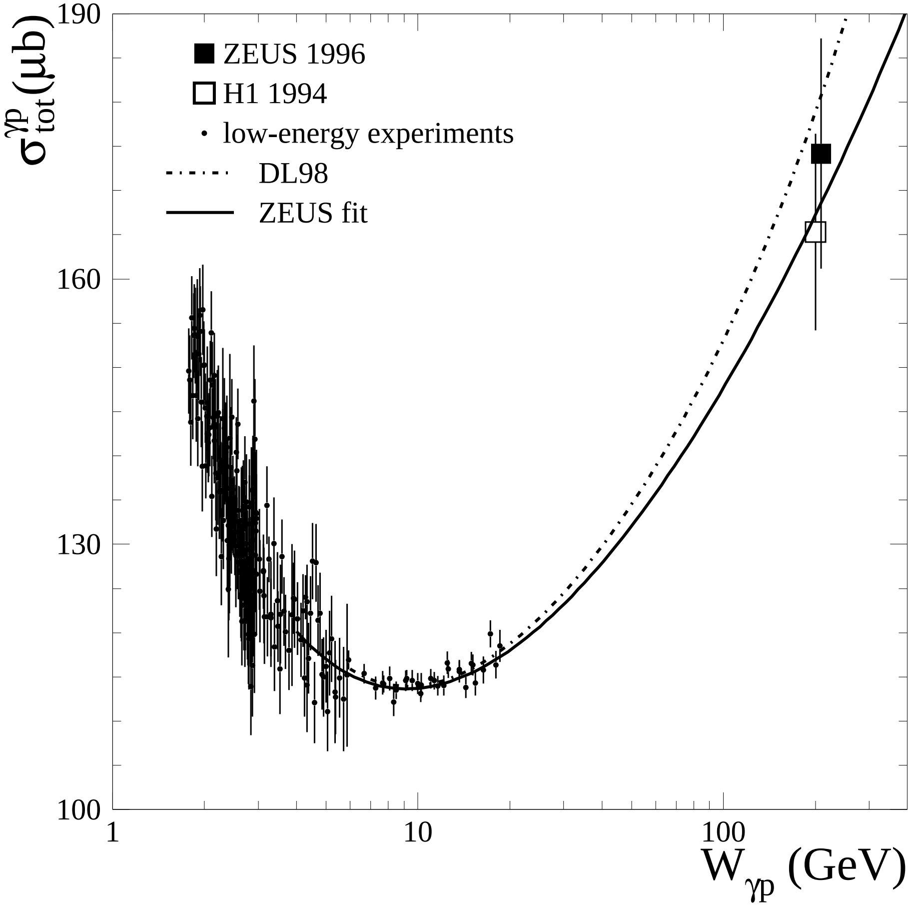
Photon-proton cross section

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



Very low Q^2: $\sigma \sim const.$, $F_2 \sim Q^2$

Total γp cross section vs. energy:



At high energies: $\sigma \sim s^{0.08}$ ("soft Pomeron")

$\longrightarrow$ see second part!

Investigating QCD dynamics through final state processes

- We have seen: inclusive cross section extremely well described by NLO DGLAP, down to lowest x
- But: at low x, we expect contributions $\sim [\alpha_s^m \log(1/x)^n]$ to play a role
- Is DGLAP too flexible (parameterization of input pdf's)?

$\longrightarrow$ More promising to look into final state?!

- Study NLO (i.e. $\mathcal{O}(\alpha_s)$) processes:
  Jet production in DIS
- Interplay of more than one scale Q^2, p_T, (m_q)
- Enhance phase space sensitive to dynamics of QCD cascade (forward jets, forward π^0)

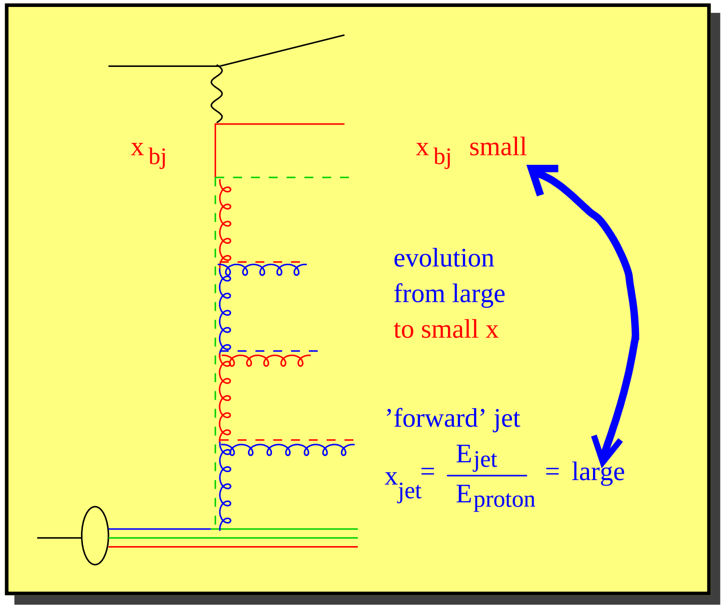
Processes:

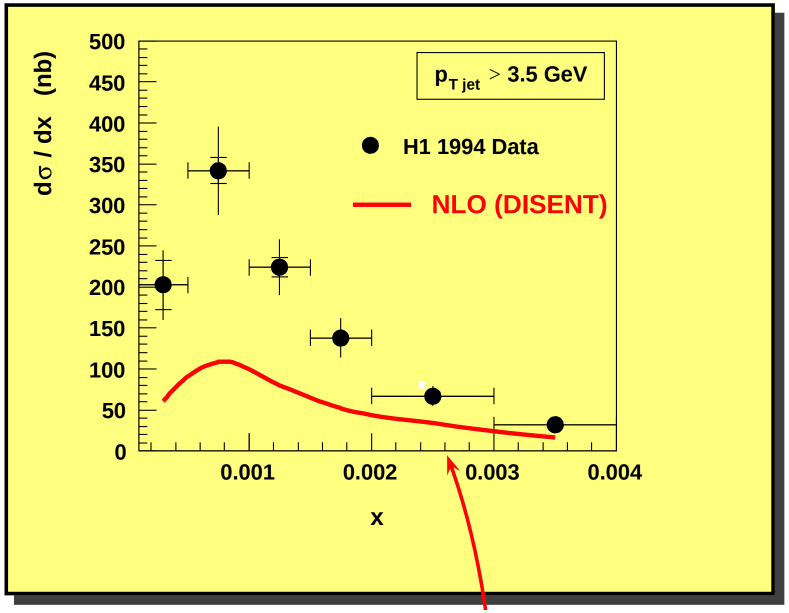
- Dijets
- Forward jets and π^0's

Hadronic final state: DGLAP in trouble

"Forward" jets:

small x_{bj}, $p_{T,jet} \approx Q^2$, large $x_{jet} = E_{jet}/E_p$ (Mueller-Navelet Jets)





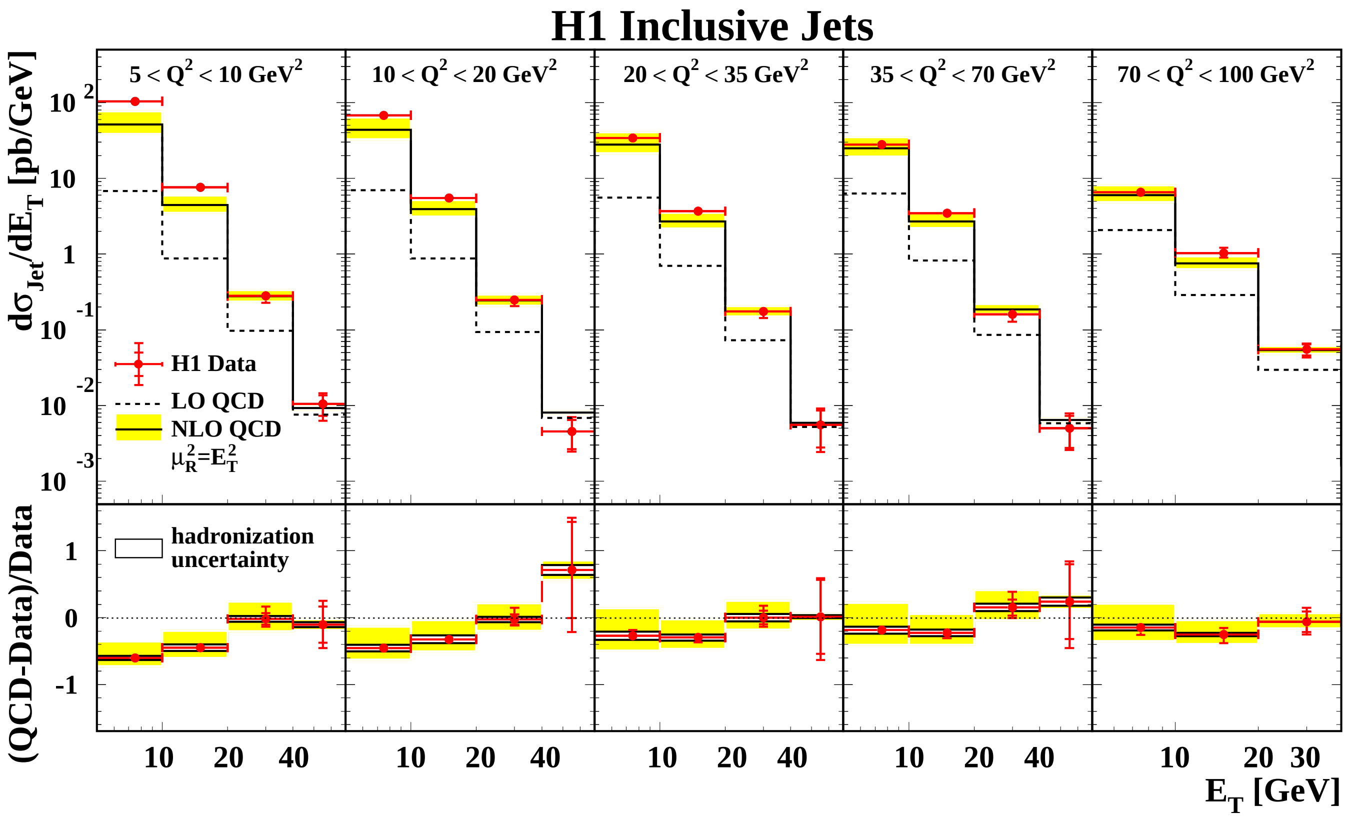
→ Suppress DGLAP (k_T ordered) evolution

NLO DGLAP far below data!

Hadronic final state: DGLAP in trouble

Inclusive jets in forward region:

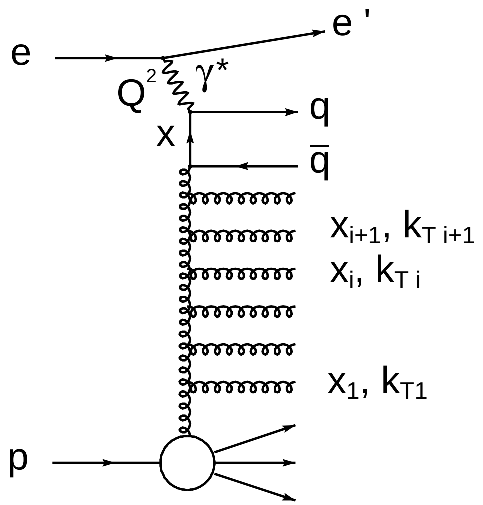
$1.5 < \eta < 2.8, 7^o < \theta_{jet} < 25^o$



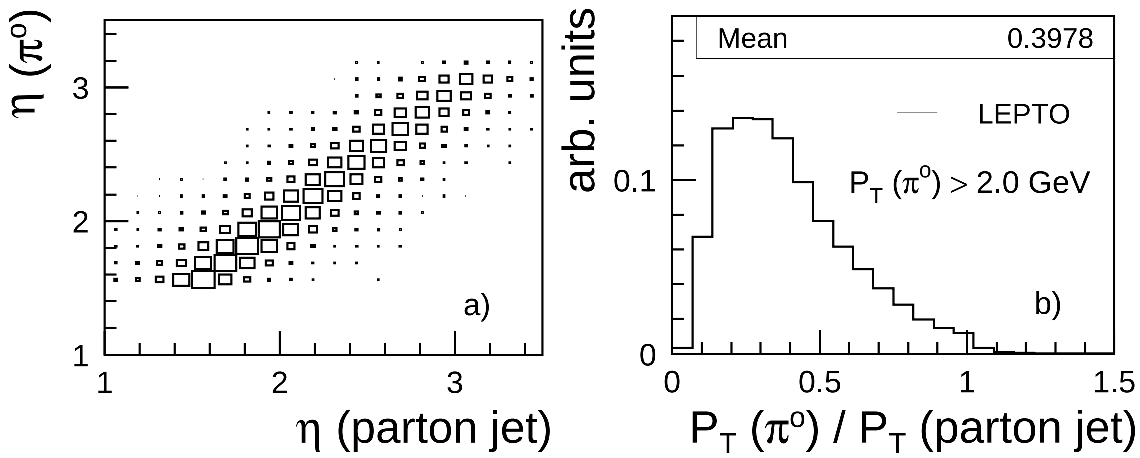
- huge NLO corrections (need NNLO)
- problems at low Q^2 ($Q^2 \ll p_T^2$)

Forward jet or particle production in DIS

high p_T forward jets and particles are sensitive to underlying parton dynamics



$\Rightarrow \pi^0, jet$



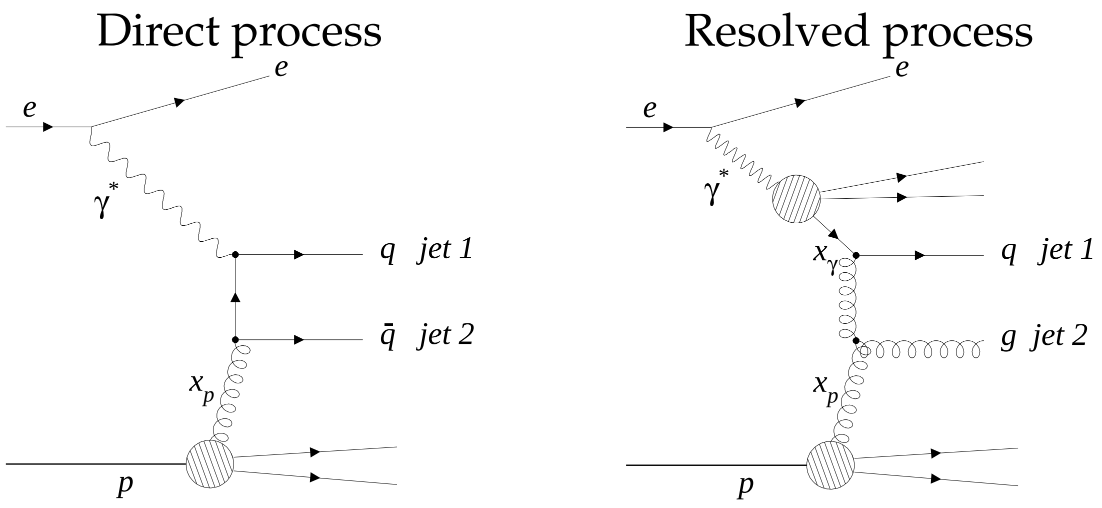
(Dis-) Advantages of jet and π^0 measurements:

Forward jets	**Forward π^0**
+ better parton correlation	- fragmentation effects more significant
+ higher rates	- smaller rate
- ambiguities of jet algorithms	
- exp. difficult in very fwd. region	+ identification posssible in more fwd. region

Concept of resolved virtual photons

Well known that real ($Q^2 = 0$) photon can behave as hadron: $\gamma \to q\bar{q} + \ldots$ and VM components

Idea: For jet production in DIS, p_T of jets can "resolve" structure of virtual photon:



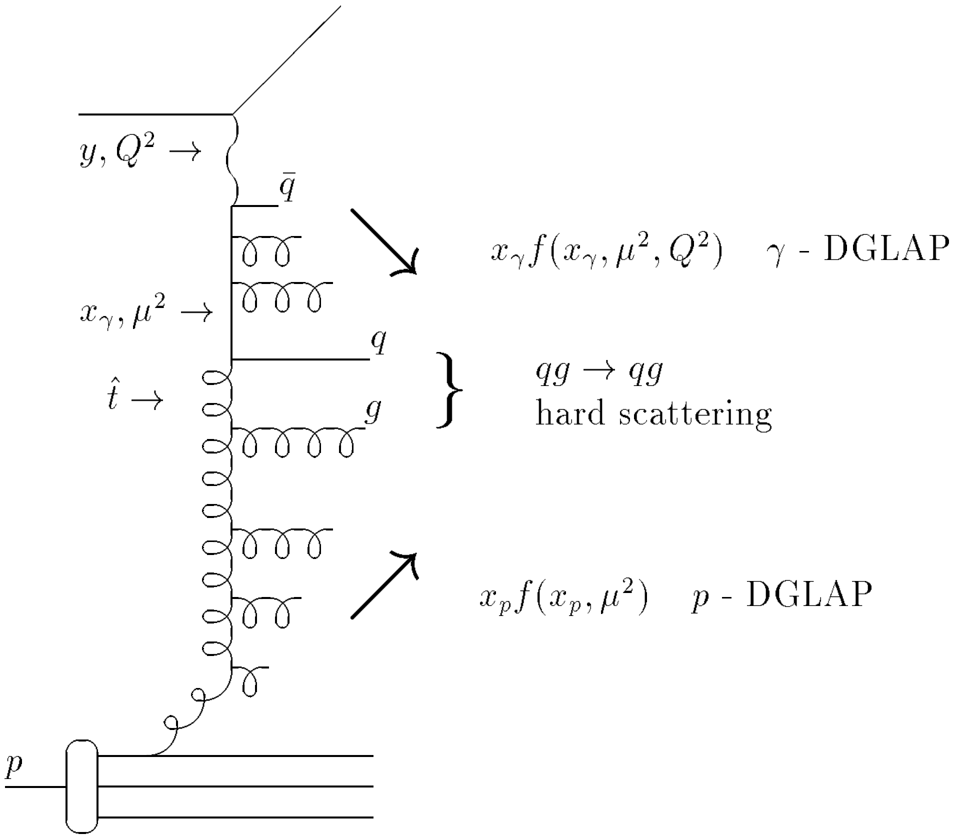
x_γ: momentum fraction of parton from photon

$x_\gamma = 1$: direct
$x_\gamma < 1$: resolved

$$\frac{d^5\sigma^{ep}}{dy\, dx_\gamma\, d\xi\, d\cos\hat{\theta}\, dQ^2} = \frac{1}{32\pi s} \frac{f_{\gamma/e}(y, Q^2)}{y} \sum_{ij} \frac{f_i^{\gamma^*}(x_\gamma, \mu_f^2, Q^2)}{x_\gamma} \frac{f_j^P(\xi, \mu_f^2)}{\xi} \hat{\sigma}(\cos\hat{\theta}) \,,$$

γ^* pdf's $f_i^{\gamma^*}(x_\gamma, \mu_f^2, Q^2)$ correspond to real photon, with damping depending on Q^2,p_T^2
Models: e.g. Schuler and Sjöstrand (SaS) or Drees and Godbole (DG)

Concept of resolved virtual photons

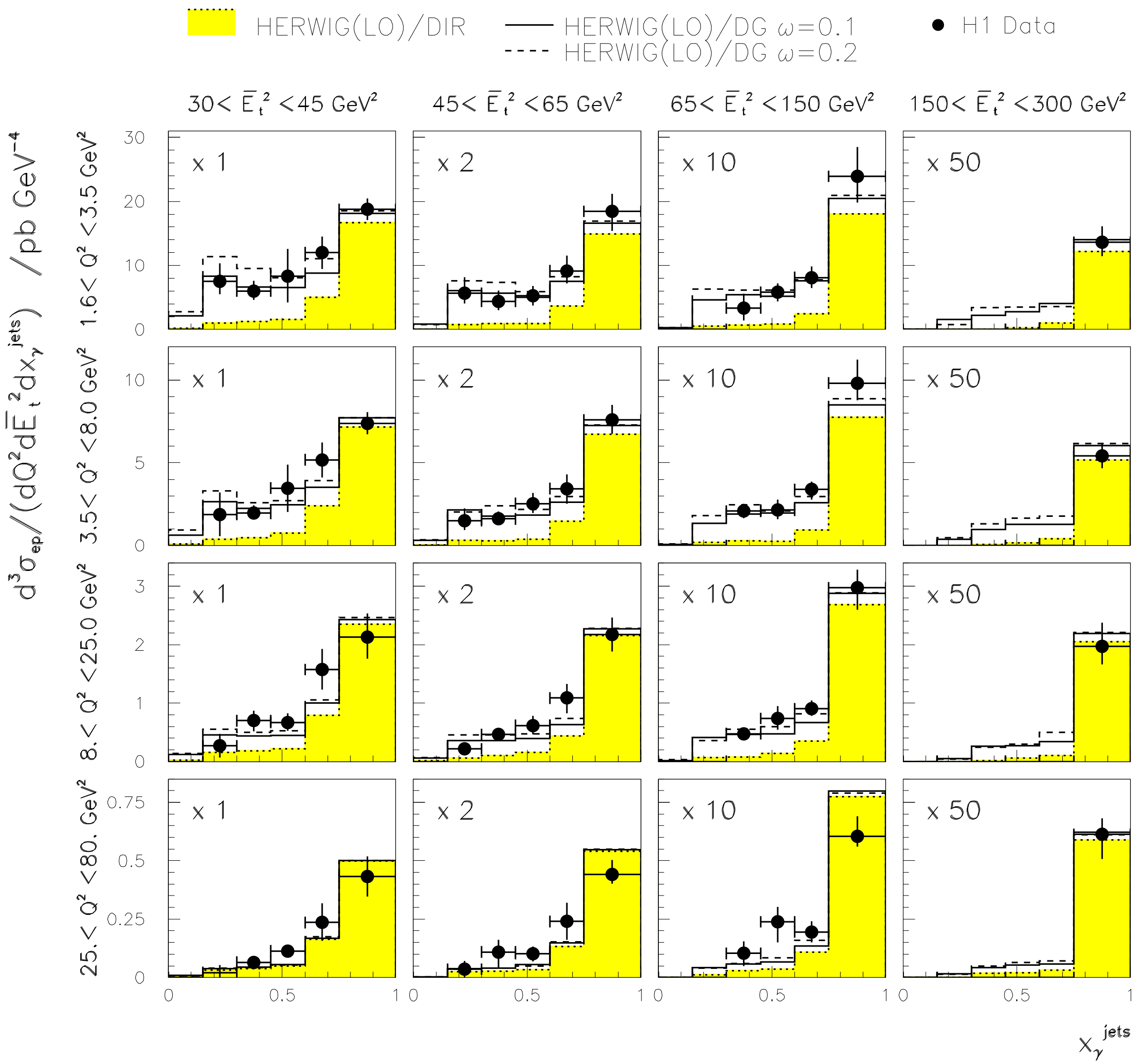


- contribution from non-ordered k_T along the ladder
- DGLAP evolution from photon (top) and proton (bottom); hard scatter in "middle"

→ Phenomenological approach to take non-ordered k_T and/or higher orders into account

Implemented in Monte Carlo event generators (e.g. RAPGAP, HERWIG)

Virtual photon structure in dijet events

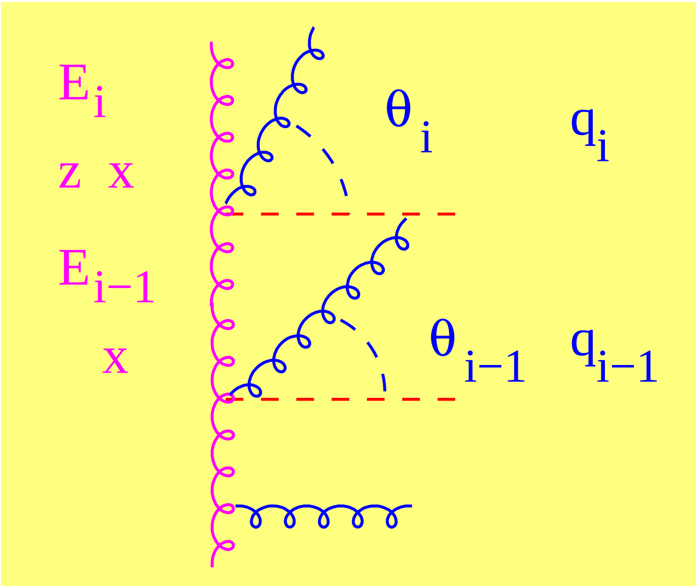


Triple differential dijet cross section $\dfrac{d^3\sigma}{dQ^2 dE_T dx_\gamma}$:

- Significant cross section at low x_γ
- resolved contribution important at low Q^2 ($E_T^2 \gg Q^2$)
- Problems:
  – Choice of scale?
  – Conceptual?

Also supported by energy flow measurements in γ hemisphere

CCFM evolution: The solution?



Catani, Ciafaloni, Fiorani, Marchesini

Angular ordering of emissions:
$\theta_{i-1} < \theta_i$

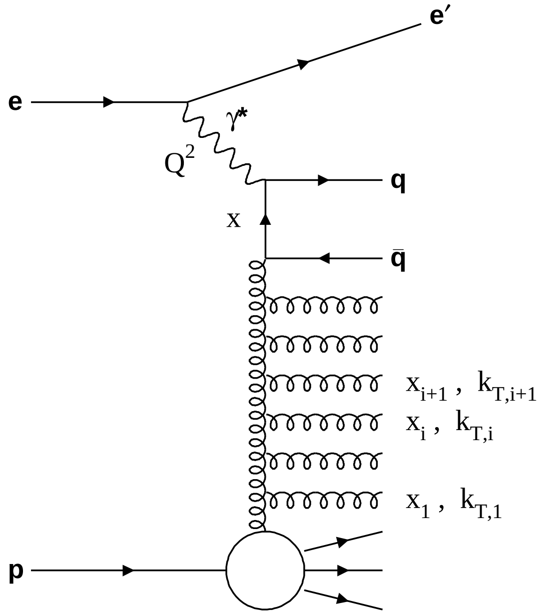
Related quantity: $\xi_i = \frac{p_{T,i}^2}{s x_{i-1}(1-z_i)}$
$\xi_{i-1} < \xi_i$
When using rescaled transverse momentum $q_i = \frac{p_{T,i}}{1-z_i}$:
$z_{i-1} q_{i-1} < q_i$

- Large z: p_T ordering (DGLAP)
- Small $z \rightarrow 0$: no restriction on p_T (BFKL)

- Use of off-shell matrix elements (not k_T integrated, "k_T factorization")
- Un-integrated gluon density $\mathcal{A}(x, k_T^2, \mu^2)$: $\int_0^{\mu^2} dk_T^2 \mathcal{A}(x, k_T^2, \mu^2) = xg(x, \mu^2)$

CCFM evolution equation: $\mu^2 \frac{d}{d\mu^2} \frac{x\mathcal{A}(x,k_T^2,\mu^2)}{\delta_s(\mu^2,Q_0^2)} = \int dz \frac{d\Phi}{2\pi} \frac{\tilde{P}(z,(\mu/z)^2,k_t^2)}{\delta_s(\mu^2,Q_0^2)} x' \mathcal{A}(x', k'^2_T, (\mu/z)^2)$

CCFM evolution



Initial state QCD cascade in angular ordered region

CCFM evolution equation:

$$\mu^2 \frac{d}{d\mu^2} \frac{x\mathcal{A}(x,k_T^2,\mu^2)}{\Delta_s(\mu^2,Q_0^2)} = \int dz \frac{d\Phi}{2\pi} \frac{\tilde{P}(z,(\mu/z)^2,k_t^2)}{\Delta_s(\mu^2,Q_0^2)} x'\mathcal{A}(x', k'^2_T, (\mu/z)^2)$$

with the splitting function:

$$\tilde{P}(z, \mu^2, k_t^2) = \frac{\bar{\alpha}_S(q^2(1-z)^2)}{1-z} + \frac{\bar{\alpha}_S(k_T^2)}{z} \Delta_{ns}(z, \mu^2, k_t^2)$$

where

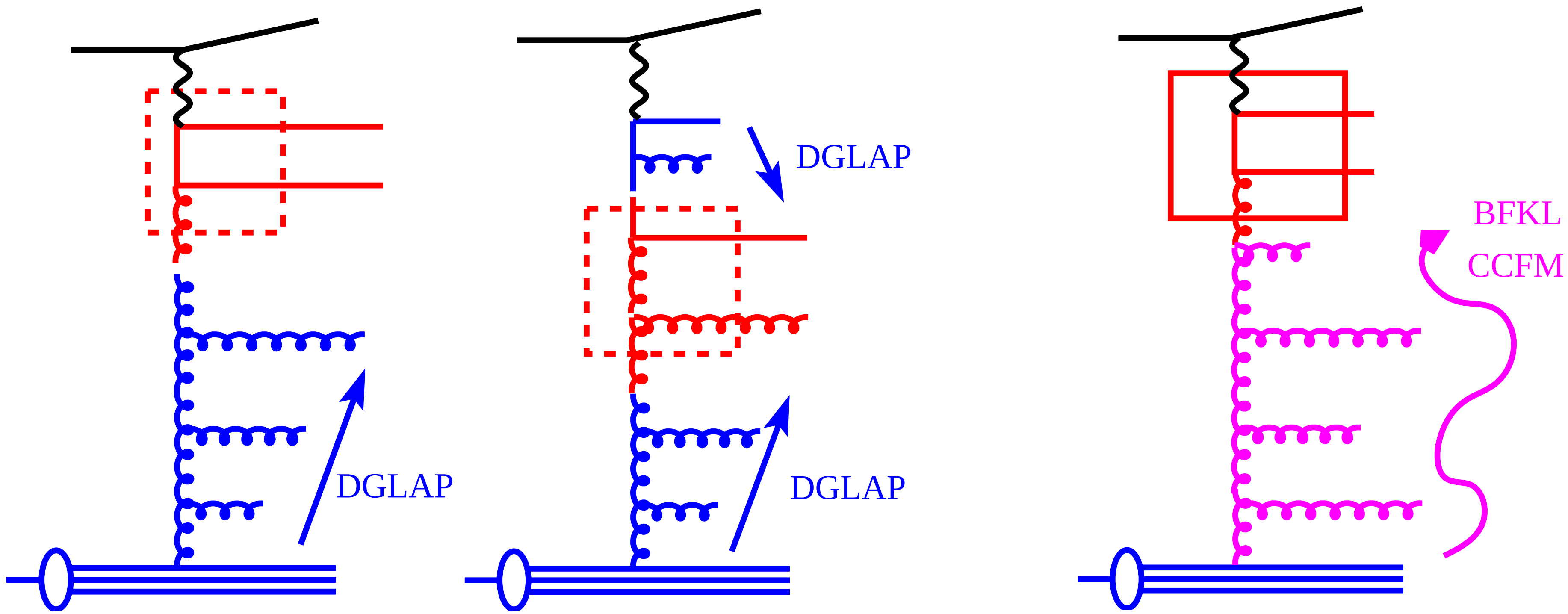
$\Delta_s(\mu^2, Q_0^2)$, $\Delta_{ns}(z, \mu^2, k_T^2)$:
are the "Sudakov" and "non-Sudakov" form factors

Presently formulated only at leading order

Summary of approaches to small-x dynamics

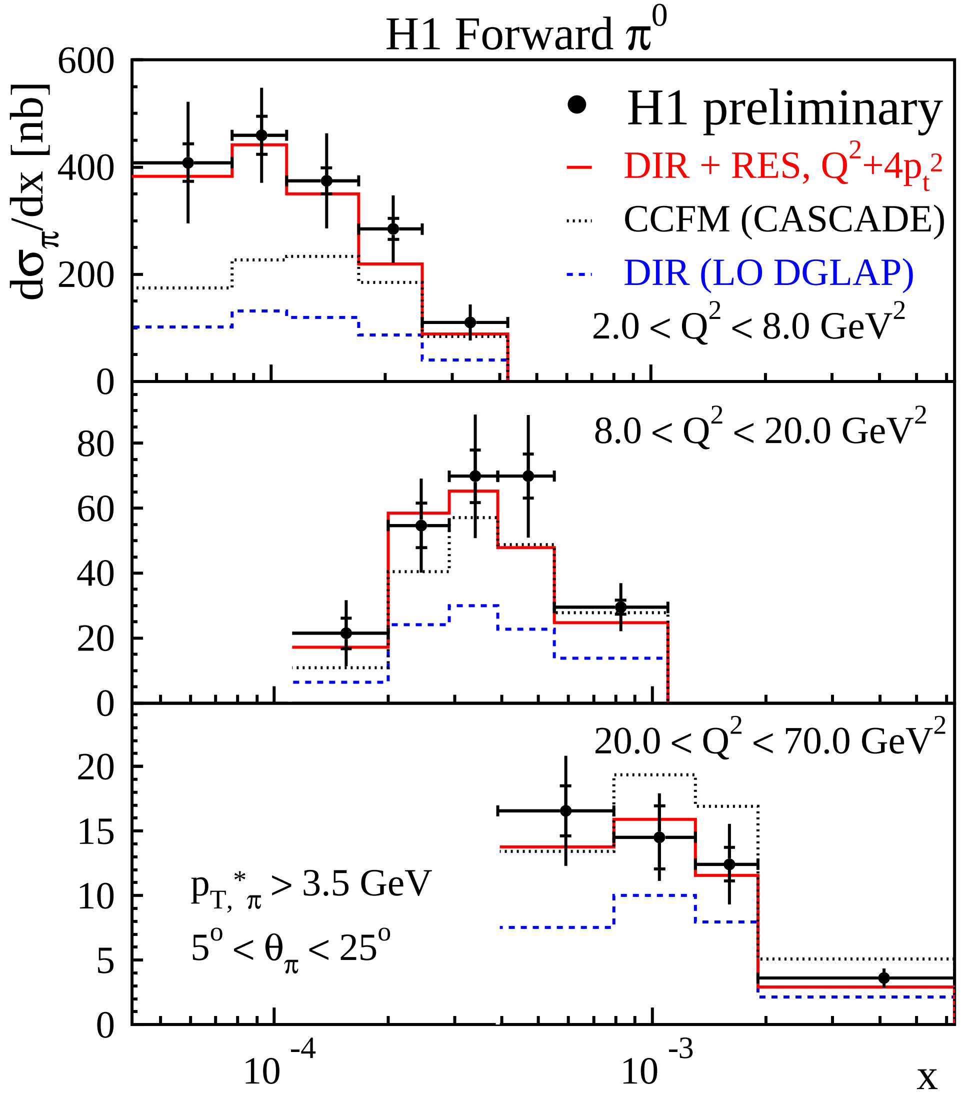
DGLAP | BFKL | CCFM

LO | resolved photon | k_t − factorization



ordered in p_T | ordered in energy | in angle

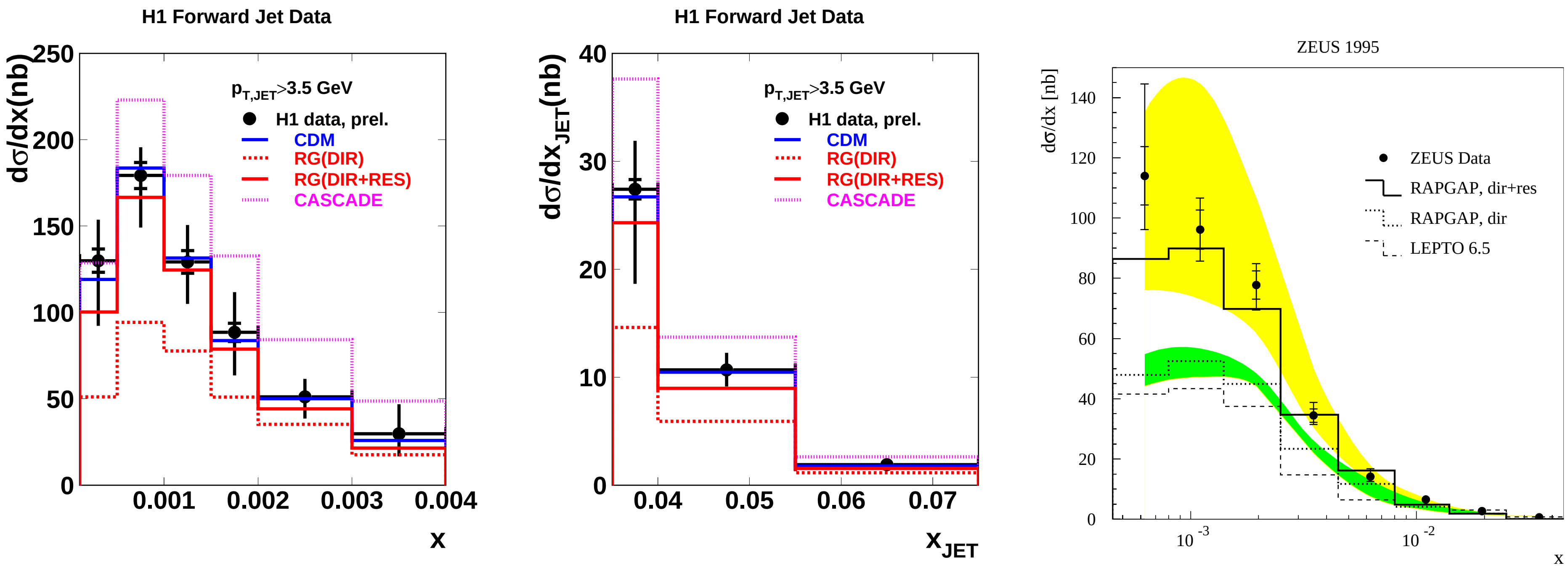
Forward π^0 production



$p^*_{T,\pi} > 3.5$ GeV
$5^o < \theta_\pi < 25^o$

- DGLAP dir.+ res. γ^*: good description
- DGLAP dir. only: too low
- CCFM: OK except lowest Q^2, x

Forward jet production



Large differences between models:

- CDM (random p_T emissions, $\sim$ BFKL): very good
- DGLAP: resolved γ^* needs to be included
- CCFM: too high

... but also still large uncertainties of data as well as models (scale)

Summary: Small-x

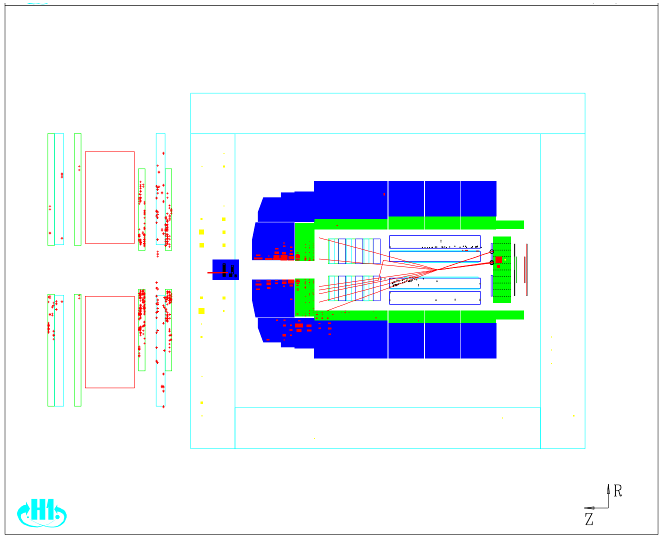
Inclusive DIS:

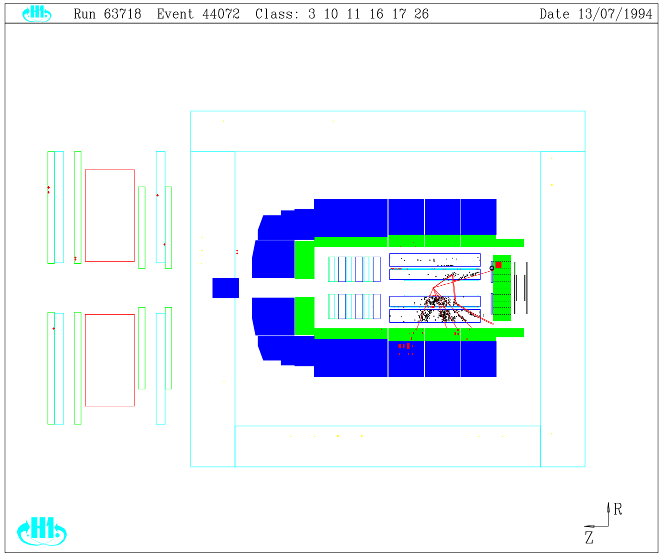
- NLO DGLAP very successful in describing present F_2 data down to $Q^2 \sim 1~\mathrm{GeV}^2$ (too flexible?)
- BFKL not (yet) needed ?!
- No sign of saturation seen at smallest x at HERA
- Smooth transition perturbative – non-perturbative observed at around $Q^2 \sim 1~\mathrm{GeV}^2$ (flattening of $\lambda(Q^2)$)
- Measurements of $F_L(x, Q^2)$ important consistency check of DGLAP QCD

Final states:

- Jet production very sensitive to low-x dynamics (heavy flavour production also, but not covered here)
- In particular, forward jets and π^0's: Strong discriminating power between different approaches
- Concept of resolved γ^* supported by data, although theoretically not very firmly rooted
- CCFM tries to interpolate between DGLAP and BFKL, promising results, but beyond LO?
- NNLO DGLAP very welcome!

Observation of diffractive DIS at HERA





Standard DIS event:

- Parts of proton remnant detected in proton beam direction
- Colour flow between current jet and p remnant:
  Production of excta particles

Diffractive DIS event:

- No proton remnant detected
- Large gap without particle production between current jet and p beam direction
- Interpretation: p stays intact, escapes down beam pipe
- Photon scattered off colourless component ”in” proton (often called ”Pomeron”)

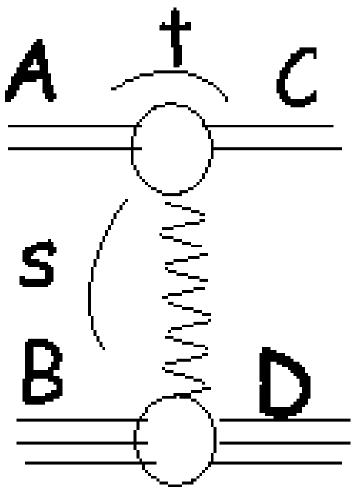
But what is the Pomeron?

Soft hadron-hadron collisions

- Total hadronic cross sections (e.g. $p\bar{p} \to X$) are $\mathcal{O}(\mathrm{mb})$
- in pQCD, can calculate e.g. hard jet production ($p\bar{p} \to$ jet + jet + X), which is $\mathcal{O}(\mathrm{pb})$
  $\to$ In pQCD, can calculate only tiny fraction of cross section!

And what about the rest?

- In the 60's (before the advent of the quark model and QCD), Regge theory was developed to address
  – particle spectrum
  – forces between particles
  – high energy behaviour of cross sections



It starts with the "S-Matrix" prescription:

Consider the $2 \to 2$ process $AB \to CD$:

$S =< \mathrm{out}|\mathrm{in} >$ is the scattering amplitude,
where $S = 1_{\mathrm{M}} + iT$

Two-body scattering $A + B \to C + D$

Mandelstam variables

$s = (p_a + p_b)^2$ total CMS energy

$t = (p_a - p_c)^2$ exchanged (4-monentum transfer)^2

$u = (p_a - p_d)^2$

$s + t + u = m_a^2 + m_b^2 + m_c^2 + m_d^2$

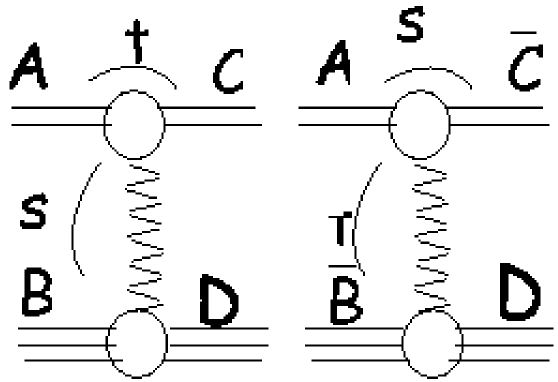
$$a + b \to c + d$$

Regge theory based on 3 Postulates:

- Lorentz invariance:
  $S = S(s, t)$

- Unitarity:
  $SS^\dagger = S^\dagger S = 1_{\mathrm{M}}$
  conservation of probability, leads to optical theorem:
  $\sigma_{tot}(s) \sim \frac{1}{s}\mathrm{Im}\, T(s, t = 0)$

- Analyticity:
  S matrix is analytic function of Lorentz invariants with only those singularities req. by unitarity



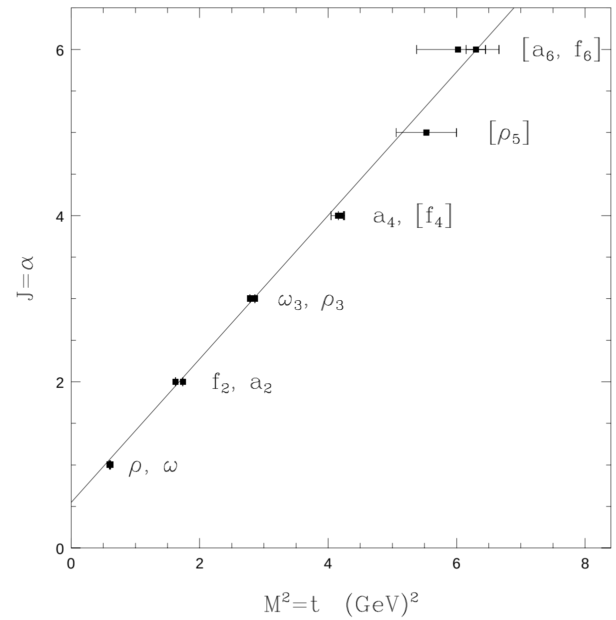
Crossing symmetry :
$T_{AB \to CD}(s, t) = T_{A\bar{C} \to \bar{B}D}(t, s)$
(arises from analyticity)

Regge theory

Consider: $pp \to n\Delta$

- Naive model: Pion exchange (s-wave): amplitude contains propagator of the form
  $T(s,t) \sim \frac{1}{m_\pi^2 - t}$
  a) $t < 0$ ("t-channel")
  b) $t > 0$: a pole appears at $t = m_\pi^2$ in "s-channel"
- More general: allow exchange of all mesons with appropriate quantum numbers:
  $T(s,t) = \sum_{l=0}^{\infty}(2l+1)T_l(t)P_l(\cos\theta_l)$
  where
  $T_l(t)$ partial wave function
  P_l Legendre polynom
- Hypothesis: $T_l(t) \sim \frac{1}{l-\alpha(t)}$ ("Regge pole")
- Asymtotically at large s, small $|t|$:
  $T(s,t) \sim \beta_a(t)\beta_b(t)\left(\frac{s}{s_0}\right)^{\alpha(t)}$
  $\frac{d\sigma}{dt} = \frac{1}{s^2}|T(s,t)|^2 = [\beta_a(t)\beta_b(t)]^2\left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$

Chew, Frautschi (1961):



$\alpha(t)$ generalized angular momentum
Integer at part. masses $I = \alpha(m^2)$

Approx: linear: $\alpha(t) = \alpha_0 + \alpha' t$
Regge trajectory

$\beta_i(t)$: related to form factor

Regge theory

- Via optical theorem, total cross section is:
  $\sigma_{tot}(s) = \frac{1}{s}\text{Im}\, T(s, t = 0) \sim [\beta_a(0)\beta_b(0)]\, s^{\alpha(0)-1}$

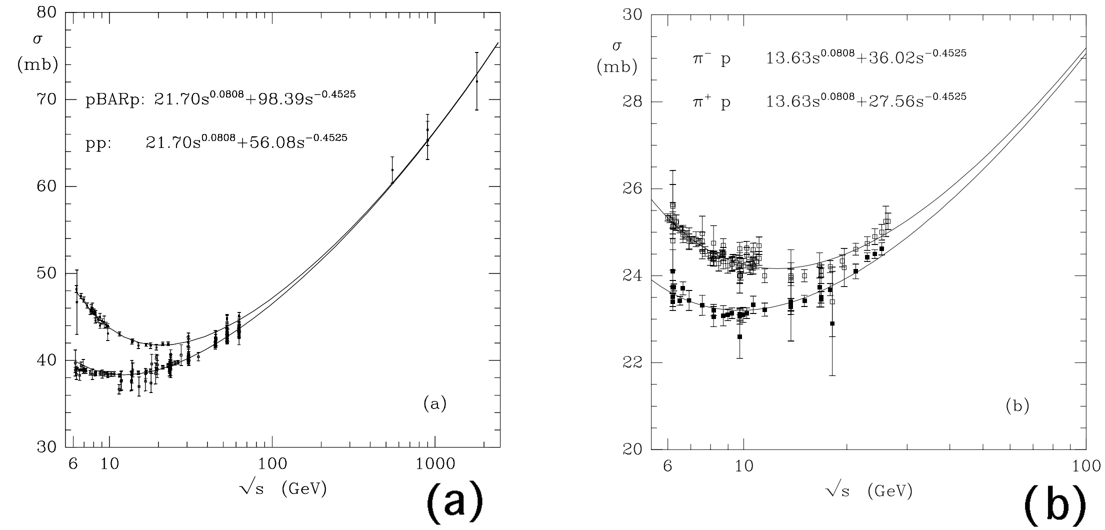
- If $\beta(t) \sim e^{bt}$ is assumed (good at small $|t|$):
  $\frac{d\sigma}{dt} = [\beta_a(t)\beta_b(t)]^2 \left(\frac{s}{s_0}\right)^{2\alpha(t)-2} = \frac{d\sigma}{dt}\Big|_{(t=0)} e^{Bt}$
  where $B = b_{0,a} + b_{0,b} + 2\alpha' \log\left(\frac{s}{s_0}\right)$ ("shrinkage")
  for proton, $b_{0,p} \approx 5\ \text{GeV}^{-2}$ corresponding to p radius $R_p = 1$ fm

pp and πp data:

At low energies:
$\sigma \sim s^{0.55-1}$ (ρ^0 trajectory)

At high energies rising!

But: For all reactions with charge exchange, $\alpha(0) < 1$ (Pomeranchuk theorem, 1959)!



The "Pomeron"

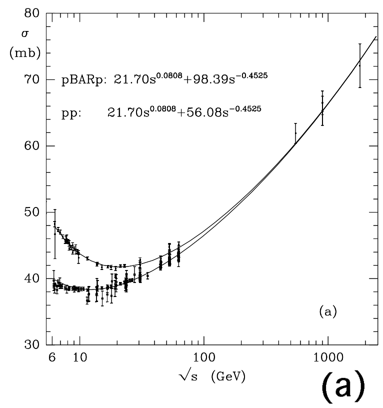
- To parameterize high energy behaviour, introduce new trajectory with $\alpha(0) > 1$: The Pomeron trajectory

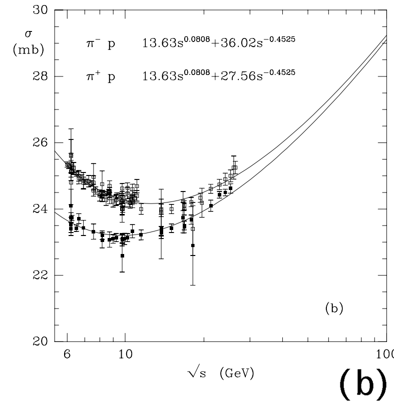
- Pomeron exchange: only vacuum quantum numbers exchanged;

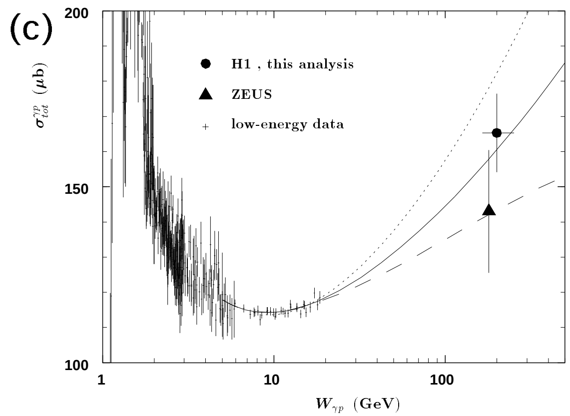
  Pomeron mediates elastic scattering

- Fits to data (e.g. Donnachie, Landshoff):
  $\alpha_{I\!P}(t) = 1.08 + 0.25t$

- Also describes γp scattering:
  $F_2(x, Q^2) \sim f(Q^2)x^{-\lambda}$, i.e.
  W^λ, where $\lambda \sim 0.1$ for $Q^2 \to 0$

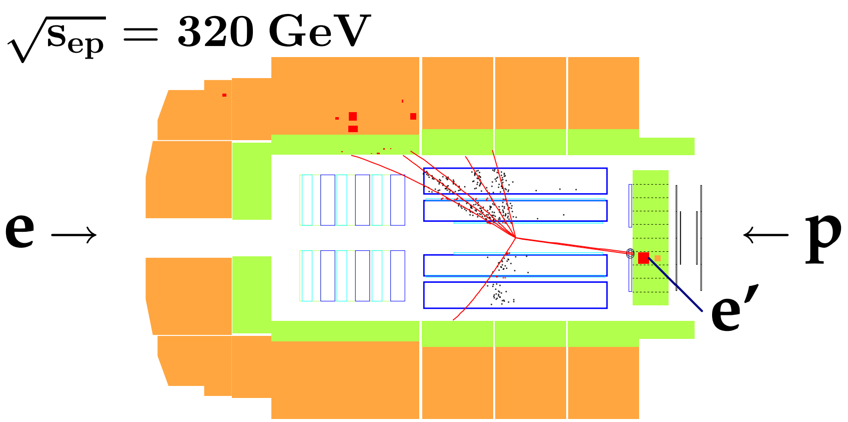






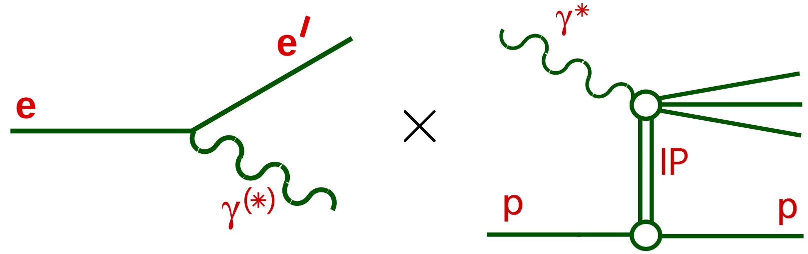
Diffraction at HERA

- HERA: An ideal laboratory to study hard diffraction:
- 10% of low-x DIS events are diffractive



Virtual photon γ^* as a probe

Can be viewed as diffractive $\gamma^* p$ interaction:



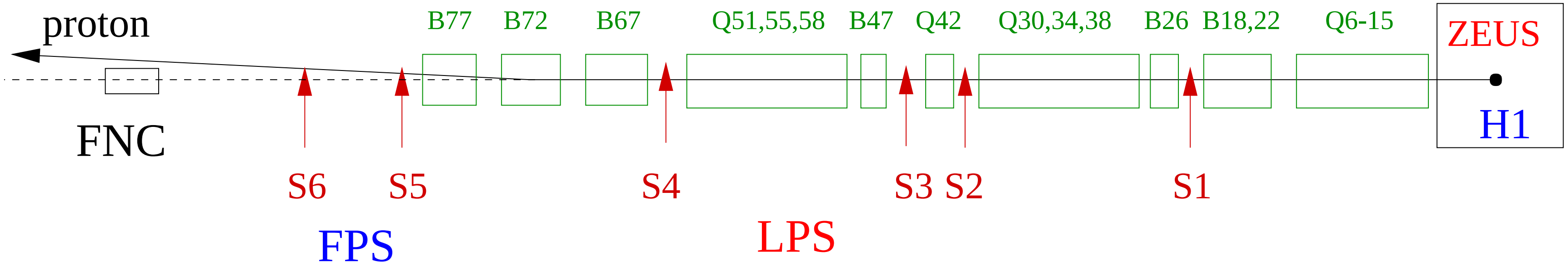
- Inclusive DIS:
  Probe proton structure ($F_2(x, Q^2)$)

- Diffractive DIS:
  Probe structure of
  colour singlet exchange!

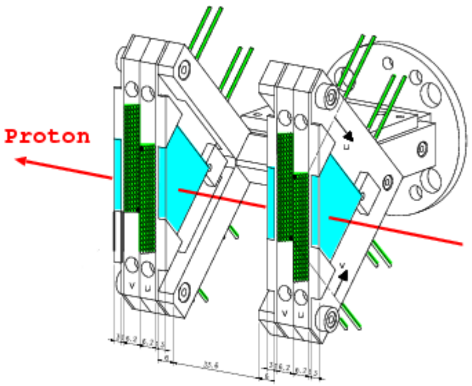
NB 1: "hard" means presence of hard scale (here Q^2)

NB 2: Hard diffraction first observed at $Sp\bar{p}S$ (UA8) in dijet production (p_T as hard scale)

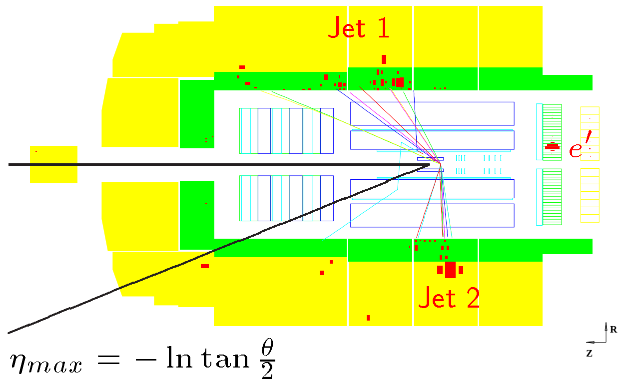
Experimental Techniques



Forward Proton Spectrometers
at $z = 24\ldots90$ m



Rapidity Gap Selection
in central detector



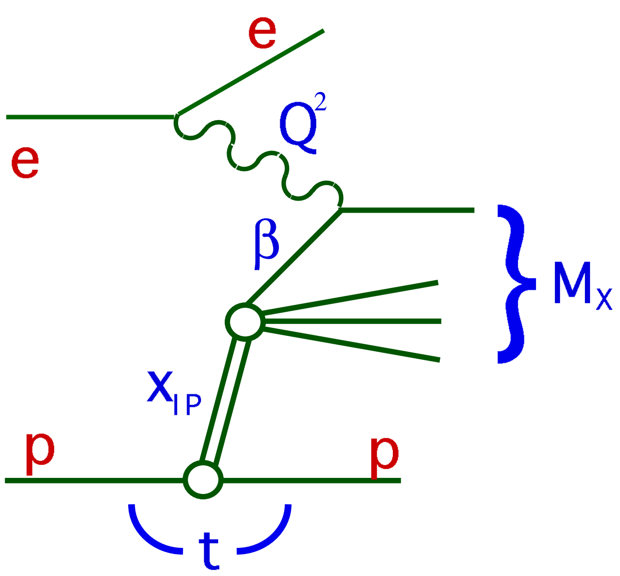
Measure leading proton

- Free of dissociation bkgd.
- Measure p 4-momentum
- low statistics (acceptance)

Require large rapidity gap

- $\Delta\eta$ large when $M_{\mathrm{central}} \ll W_{\gamma p}$
- integrate over outgoing p system
- high statistics

Diffractive Cross section and Structure Functions



$x_{I\!P} = \xi = \frac{Q^2+M_X^2}{Q^2+W^2} = x_{I\!P/p}$
(momentum fraction of colour singlet exchange)

$\beta = \frac{Q^2}{Q^2+M_X^2} = x_{q/I\!P}$
(fraction of exchange momentum of q coupling to γ^*, $x = x_{I\!P}\beta$)

$t = (p-p')^2$
(4-momentum transfer squared)

Diffractive reduced cross section σ_r^D:

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

Structure functions F_2^D and F_L^D:

$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{2(1-y+y^2/2)}F_L^{D(4)}$$

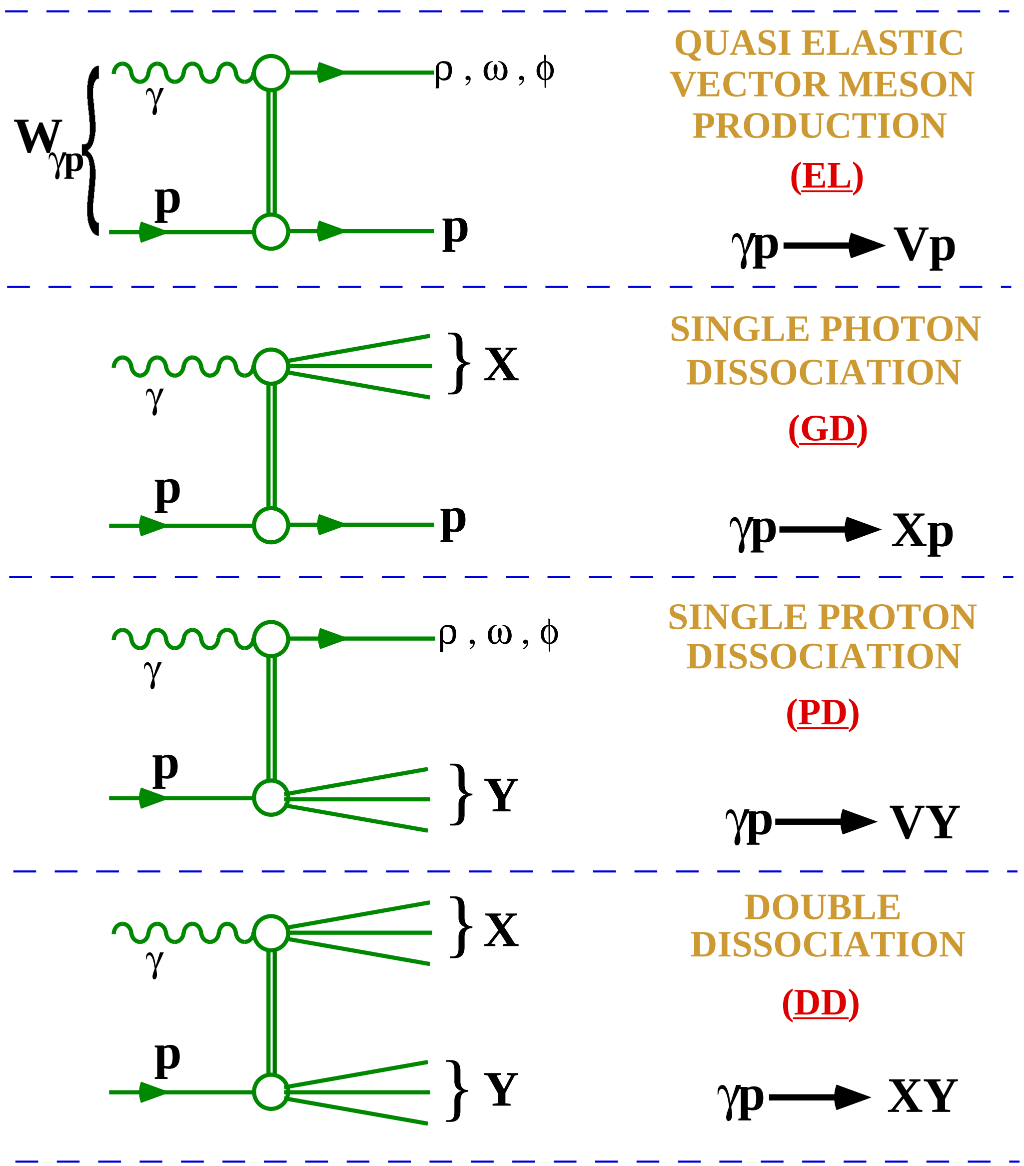
Integrated over t: $F_2^{D(3)} = \int dt\; F_2^{D(4)}$

– Longitudinal F_L^D: affects σ_r^D at high y

– If $F_L^D = 0$: $\sigma_r^D = F_2^D$

[γ inelasticity $y = Q^2/sx$]

Diffractive Processes in γp Interactions



- All 4 processes can be measured with varying Q^2, W, t, M_X, M_Y
- $Q^2 \sim 0$, $|t| \sim 0$: similar to soft hadronic diffraction
- large Q^2: γ^* probes diffractive exchange
- large $|t|$: perturbative QCD applicable to $I\!P$ (BFKL)?

Factorization in Diffraction

Proof of QCD Factorization for diffractive DIS:

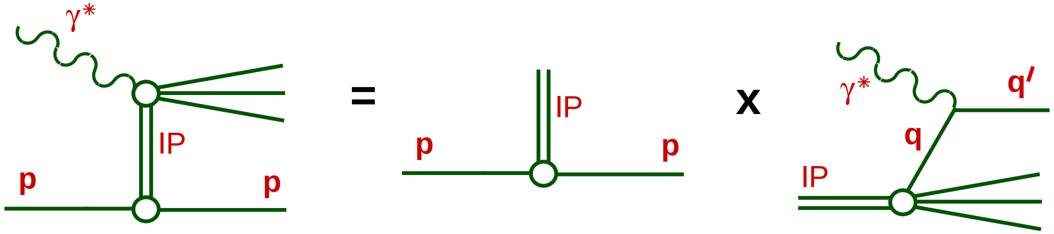
- Diffractive parton distributions (Trentadue, Veneziano, Berera, Soper, Collins, ...):

$$\frac{d^2\sigma(x,Q^2,x_{I\!P},t)^{\gamma^* p\to p' X}}{dx_{I\!P}\ dt} = \sum_i \int_x^{x_{I\!P}} d\xi \hat{\sigma}^{\gamma^* i}(x,Q^2,\xi)\ p_i^D(\xi,Q^2,x_{I\!P},t)$$

- $\hat{\sigma}^{\gamma^* i}$ hard scattering part, as in incl. DIS
- p_i^D diffractive PDF's in proton, conditional probabilities, valid at fixed $x_{I\!P}$, t, obey (NLO) DGLAP

Regge Factorization / 'Resolved Pomeron' model:

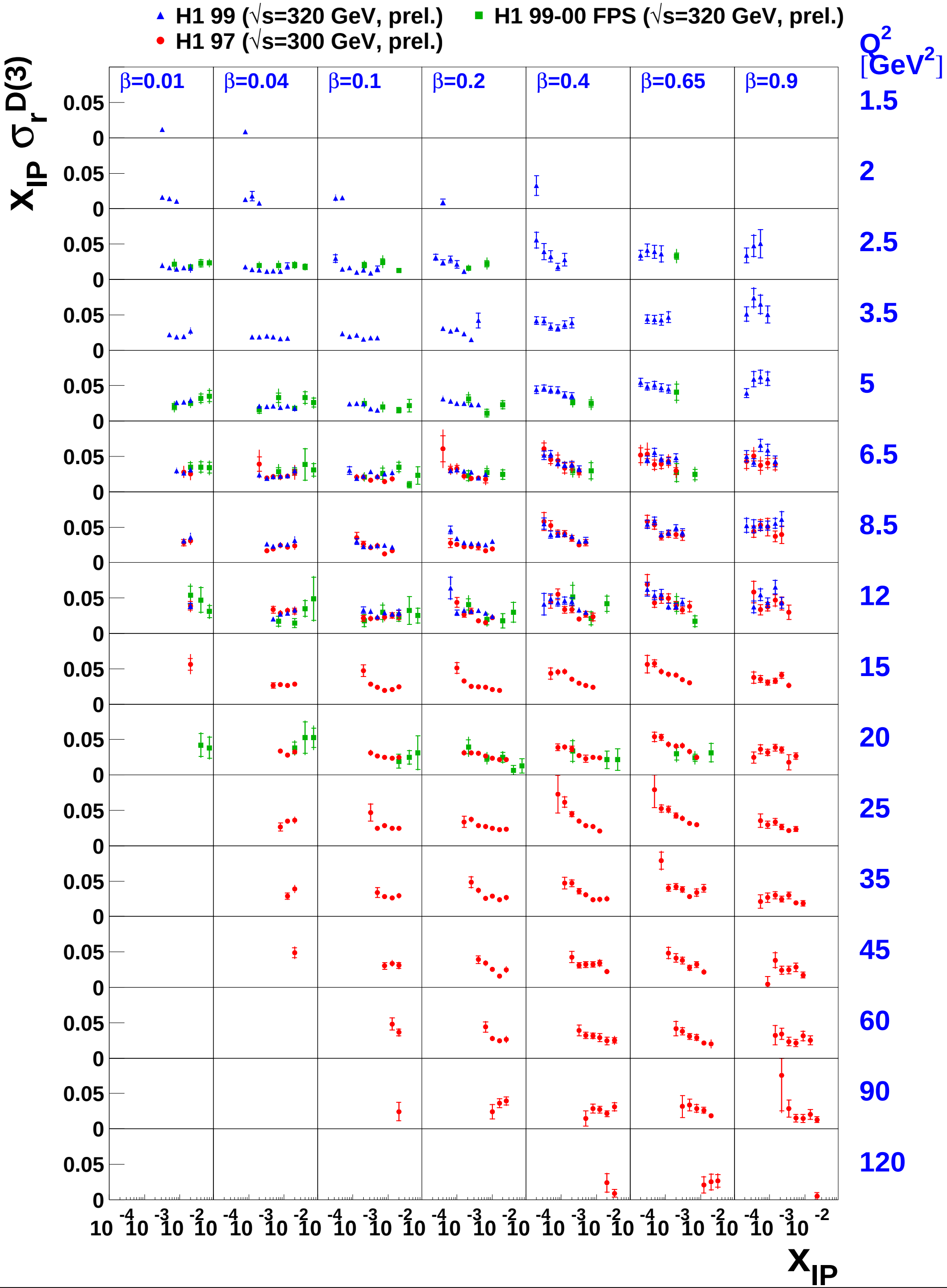
$x_{I\!P}, t$ dependence factorizes out (Donnachie, Landshoff, Ingelman, Schlein, ...):



- additional assumption, no proof !
- consistent with present data if sub-leading $I\!R$ included

$$F_2^D(x_{I\!P},t,\beta,Q^2) = f_{I\!P/p}(x_{I\!P},t)\ F_2^{I\!P}(\beta,Q^2)$$

Shape of diffr. PDF's indep. of $x_{I\!P}$, t, normalization controlled by Regge flux $f_{I\!P/p}$



Recent σ_r^D Measurements

- $1.5 < Q^2 < 12\ \mathrm{GeV}^2$
- $6.5 < Q^2 < 120\ \mathrm{GeV}^2$
  Measurements based on rapidity gap method
- $2.5 < Q^2 < 20\ \mathrm{GeV}^2$
  Measurement using H1 FPS
  (Forward Proton Spectrometer)

– Agreement between methods

High precision measurements of β (or x) and Q^2 dependences

$\Rightarrow$ **DGLAP QCD interpretation**

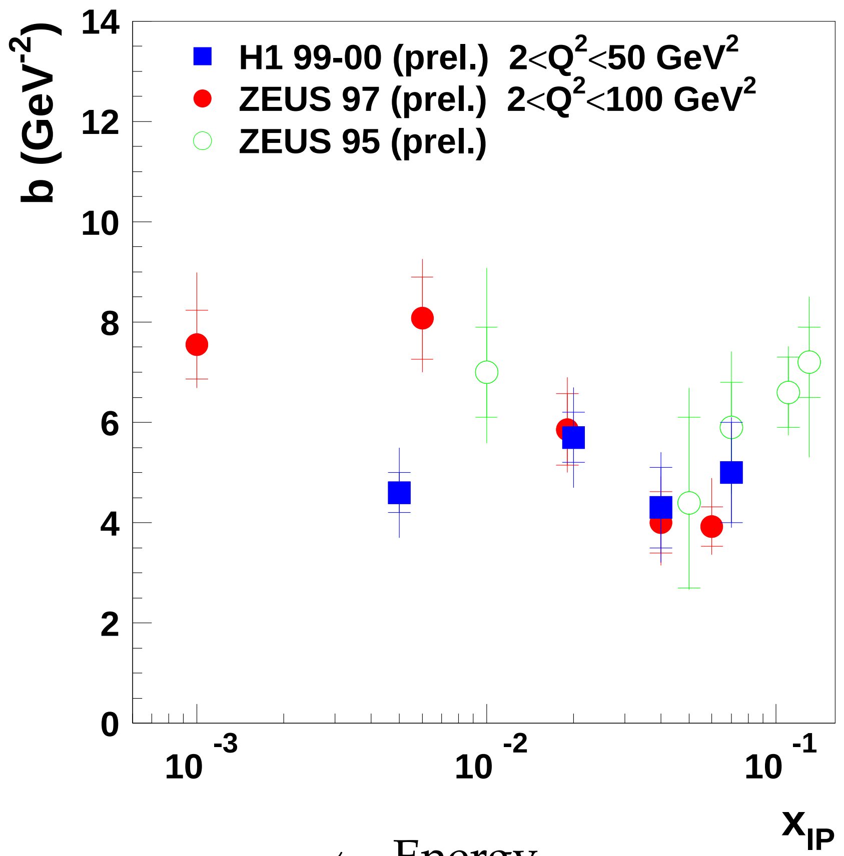
Forward Proton Detectors: t Measurement

$\frac{d\sigma}{d|t|}$ measured for $-0.4 \lesssim t < |t|_{\min}$

Exponential fit to t distribution:

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

b is related to
the interaction radius: $b = R^2/4$



← Energy

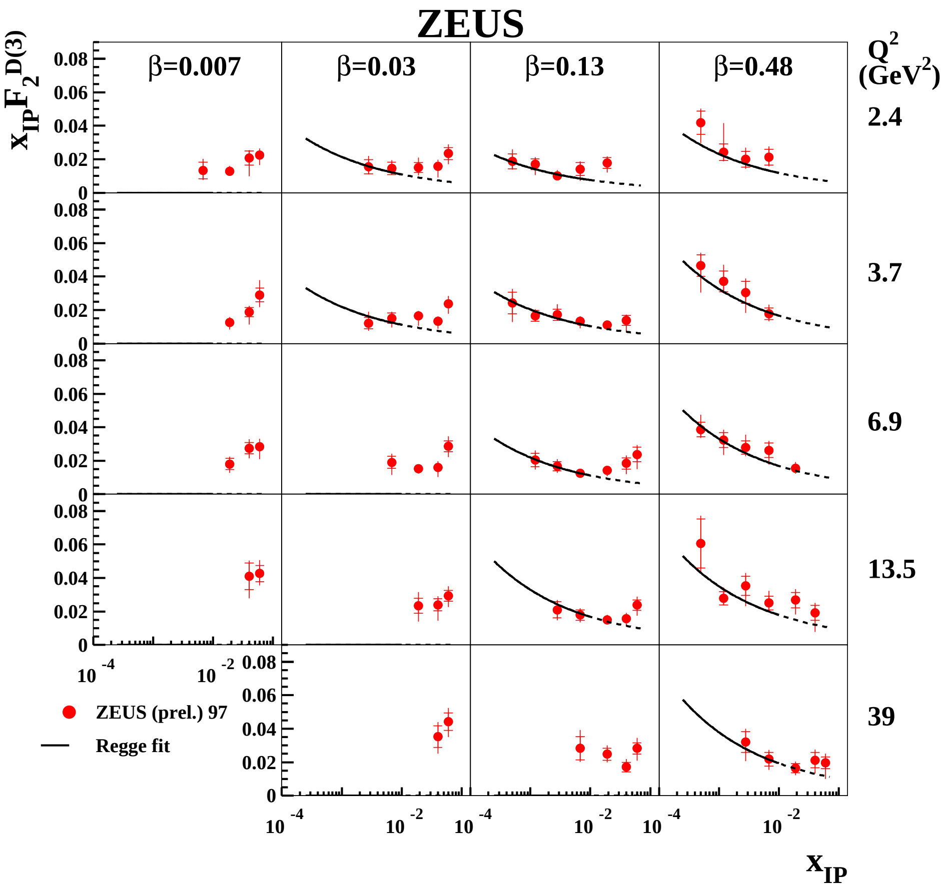
In Regge phenomenology expect ‘shrinkage’:
(proton gets ‘bigger’ with increasing energy)

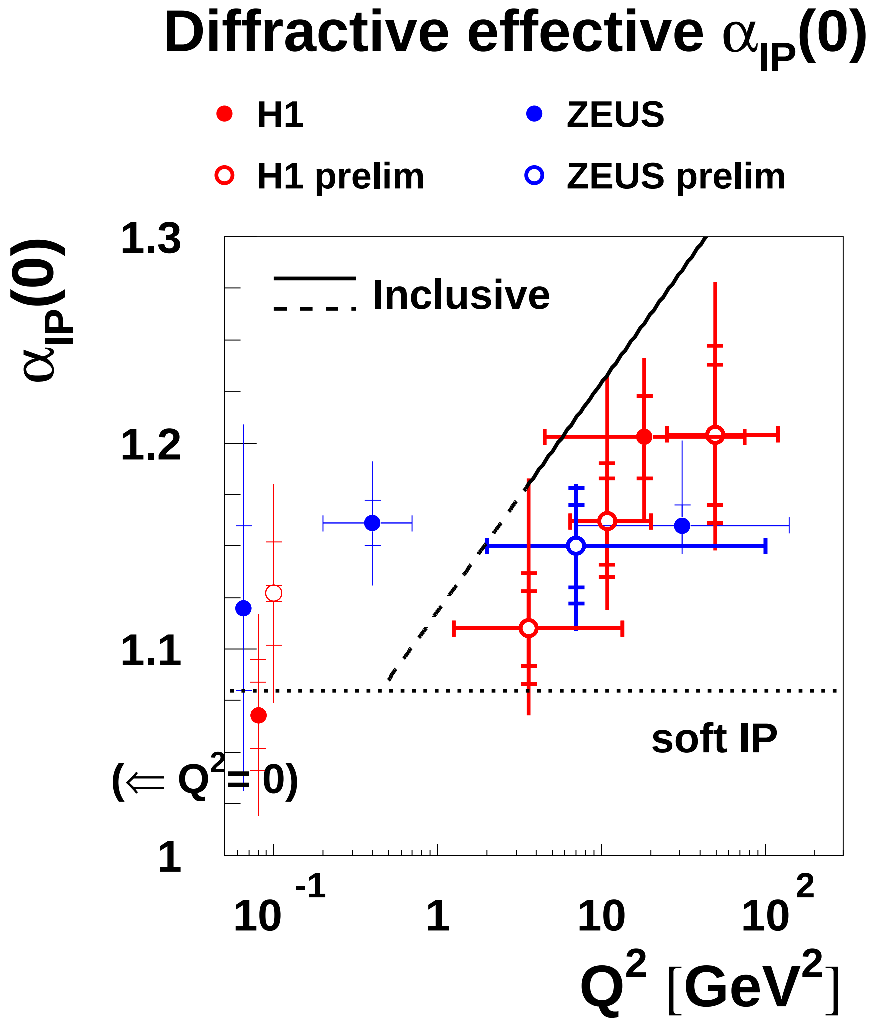
$$b = b_0 + 2\alpha' \log \frac{1}{x_{I\!P}} \qquad x_{I\!P} \sim M_X^2 / W_{\gamma p}^2$$

So far inconclusive ...

Energy dependence and $\alpha_{I\!P}(0)$

Example: ZEUS LPS data





Fit to $x_{I\!P}$ dependence:

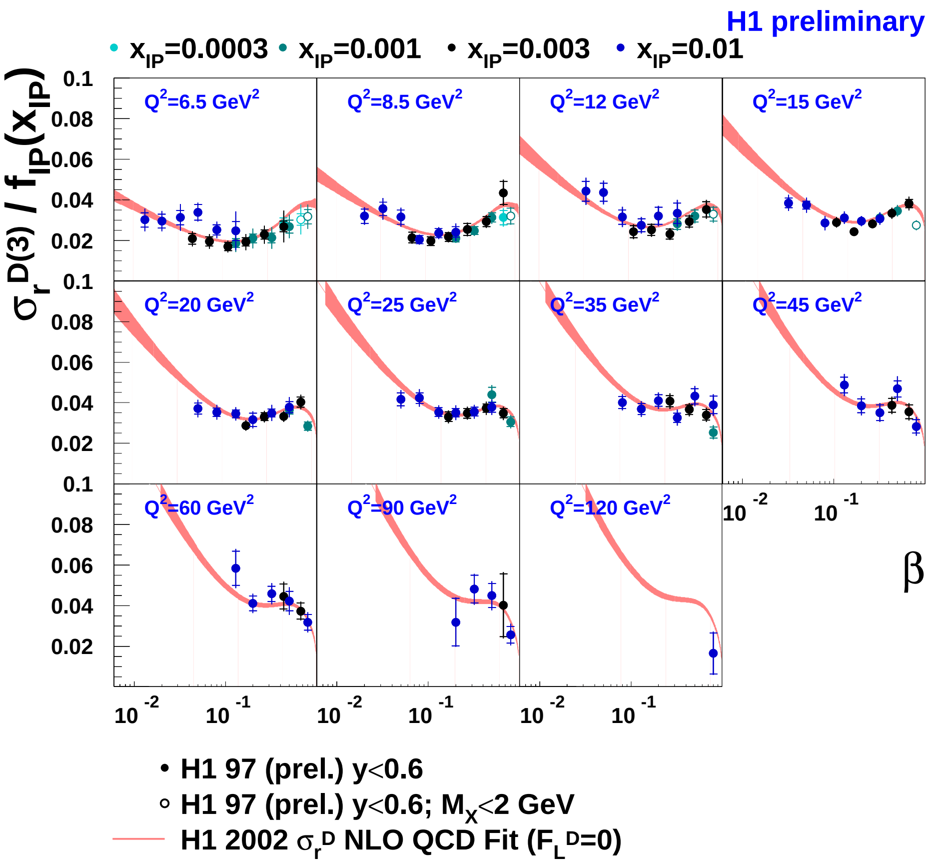
$$F_2^D(x_{I\!P}, \beta, Q^2) = \left(\frac{1}{x_{I\!P}}\right)^{2\overline{\alpha_{I\!P}}-1} \cdot A(\beta, Q^2)$$

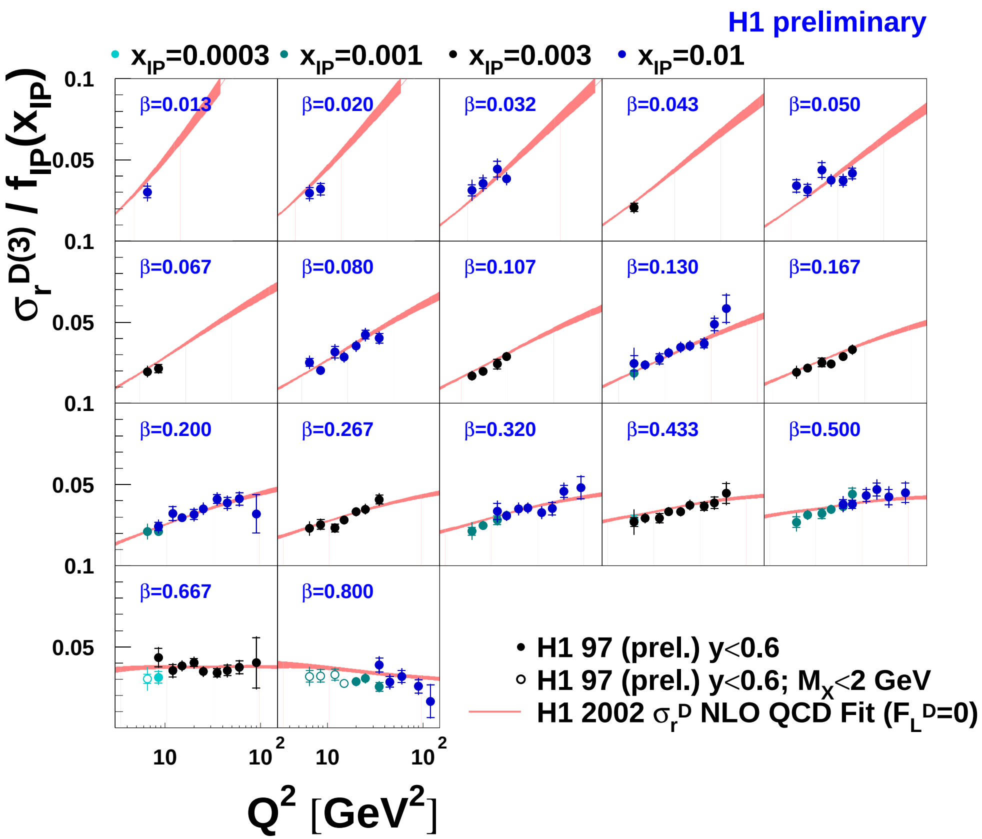
Indications for increase with Q^2 ?

Naive expectation $\alpha_{I\!P}^{\mathrm{diff.}}(0) = 2\ \alpha_{I\!P}^{\mathrm{inc}}(0)$ fails in DIS region?

Precise H1 Measurement of β, Q^2 dependences

Prerequisite for NLO DGLAP QCD fit:





β dep.: $\sim \sum_i e_i^2 (q_i^D + \bar{q}_i^D)$ Q^2 dep.: $\sim \alpha_s \otimes g^D(\beta, Q^2)$

– $x_{I\!P}$ dep. taken out: factorization holds for $x_{I\!P} < 0.01$

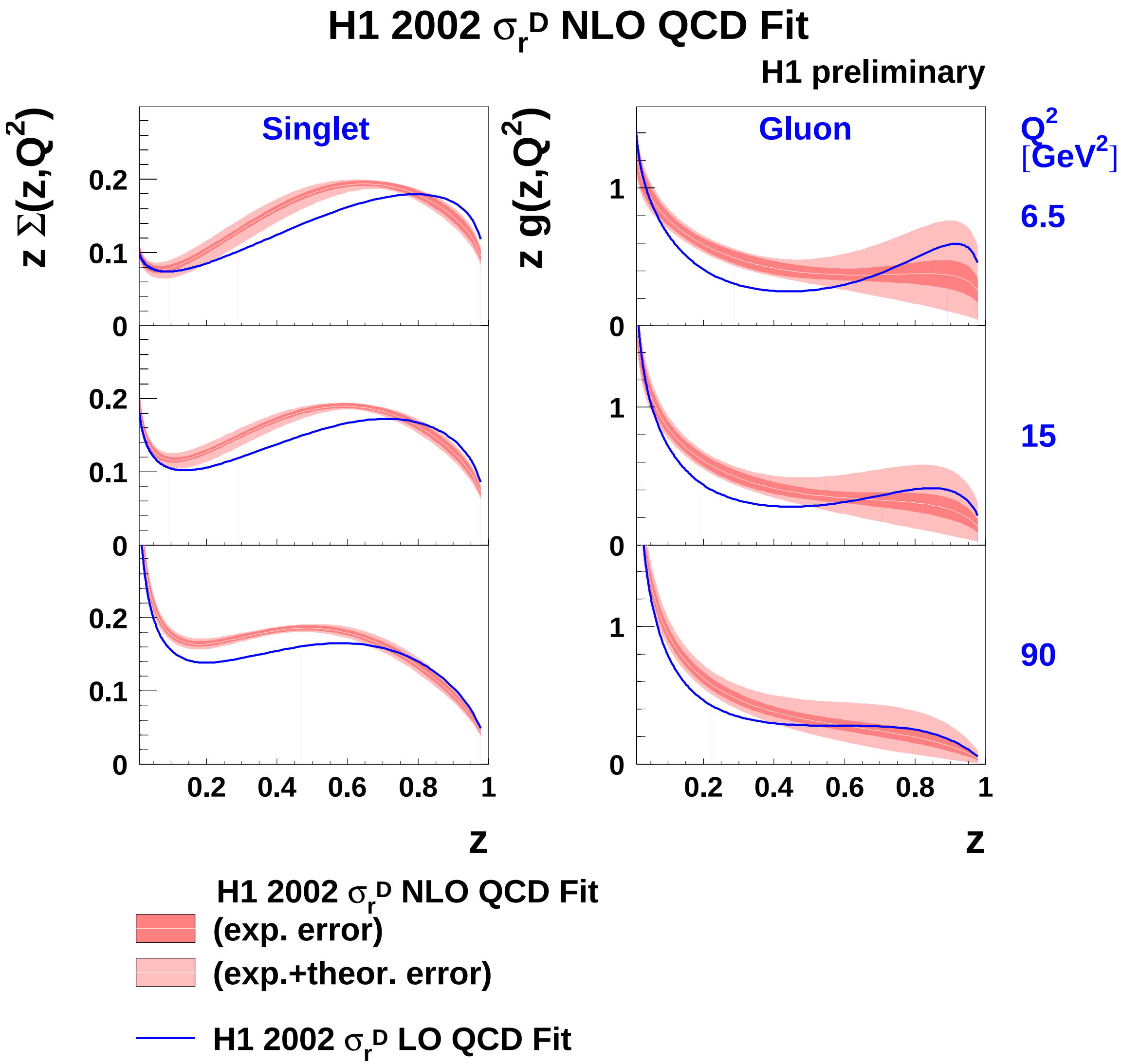
– rising for $\beta \to 1$ at low Q^2

– positive scaling violations expect for largest β (gluon dominance)

NLO DGLAP QCD Fit to σ_r^D

QCD Fit Technique:

- Regge factorization (c.f. data)
- Singlet Σ and gluon g parameterized at $Q_0^2 = 3\ \mathrm{GeV}^2$
- NLO DGLAP evolution
- Fit data for $Q^2 > 6.5\mathrm{GeV}^2, M_X > 2\ \mathrm{GeV}$
- For first time propagate exp. and theor. uncertainties !

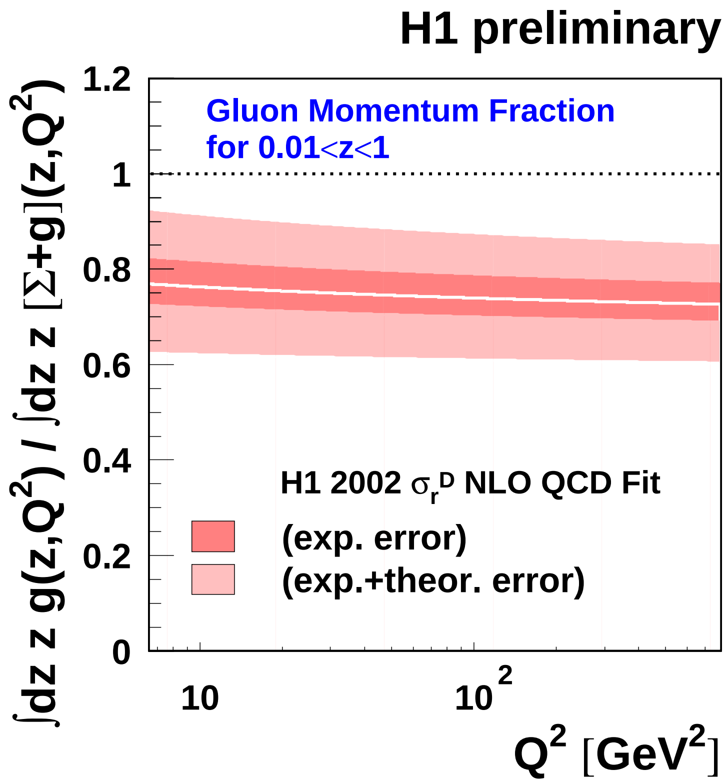


PDF's of diffractive exchange:

- Extending to large fractional momenta z
- Gluon dominated
- Σ well constrained
- substantial uncertainty for gluon at highest z
- Similar to previous fits

NLO QCD Fit: Gluon fraction and F_L^D

Integrate PDF's over measured range:

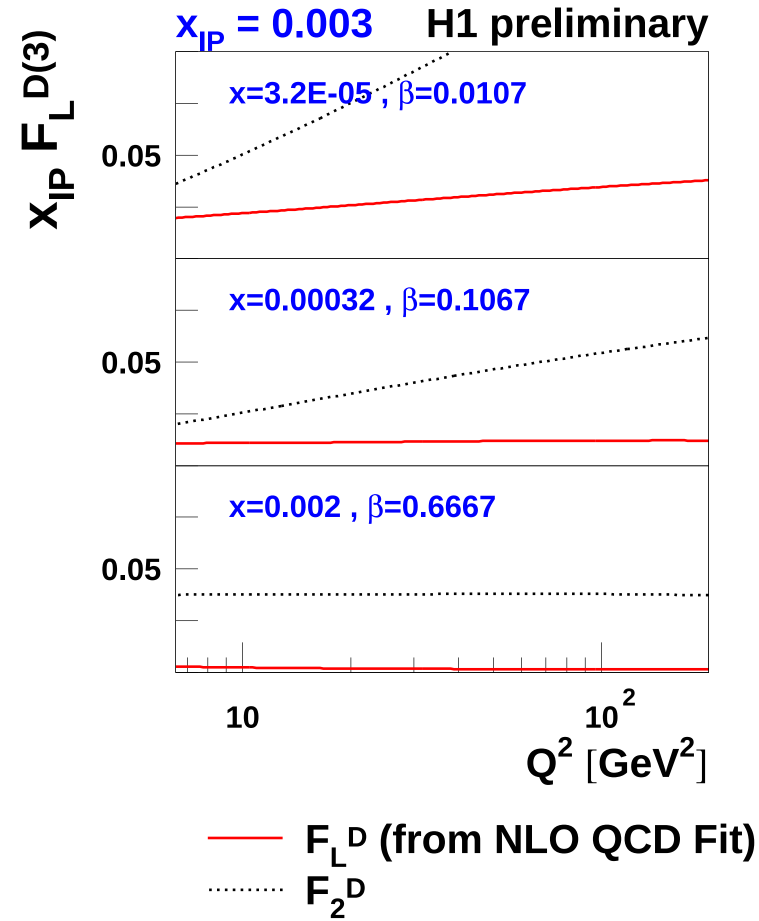


Momentum fraction of diffractive exchange carried by gluons:

$$75 \pm 15\%$$

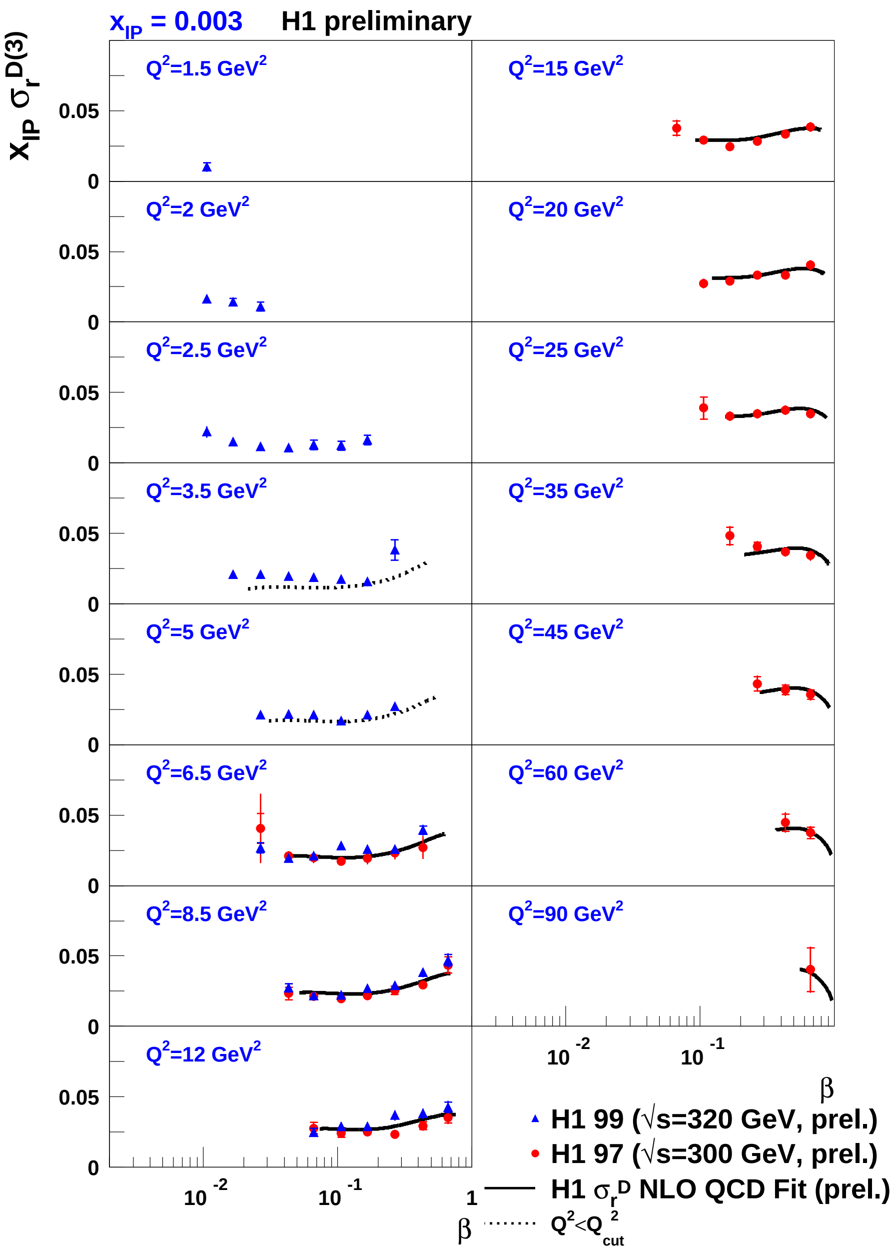
Longitudinal F_L^D:

$$F_L^D \sim \frac{\alpha_s}{2\pi}\left[C_q^L \otimes F_2^D + C_g^L \otimes \sum_i e_i^2\, zg^D(z,Q^2)\right]$$



$\Rightarrow F_L^D$ large at low Q^2, low β

NLO QCD fit: β dependence

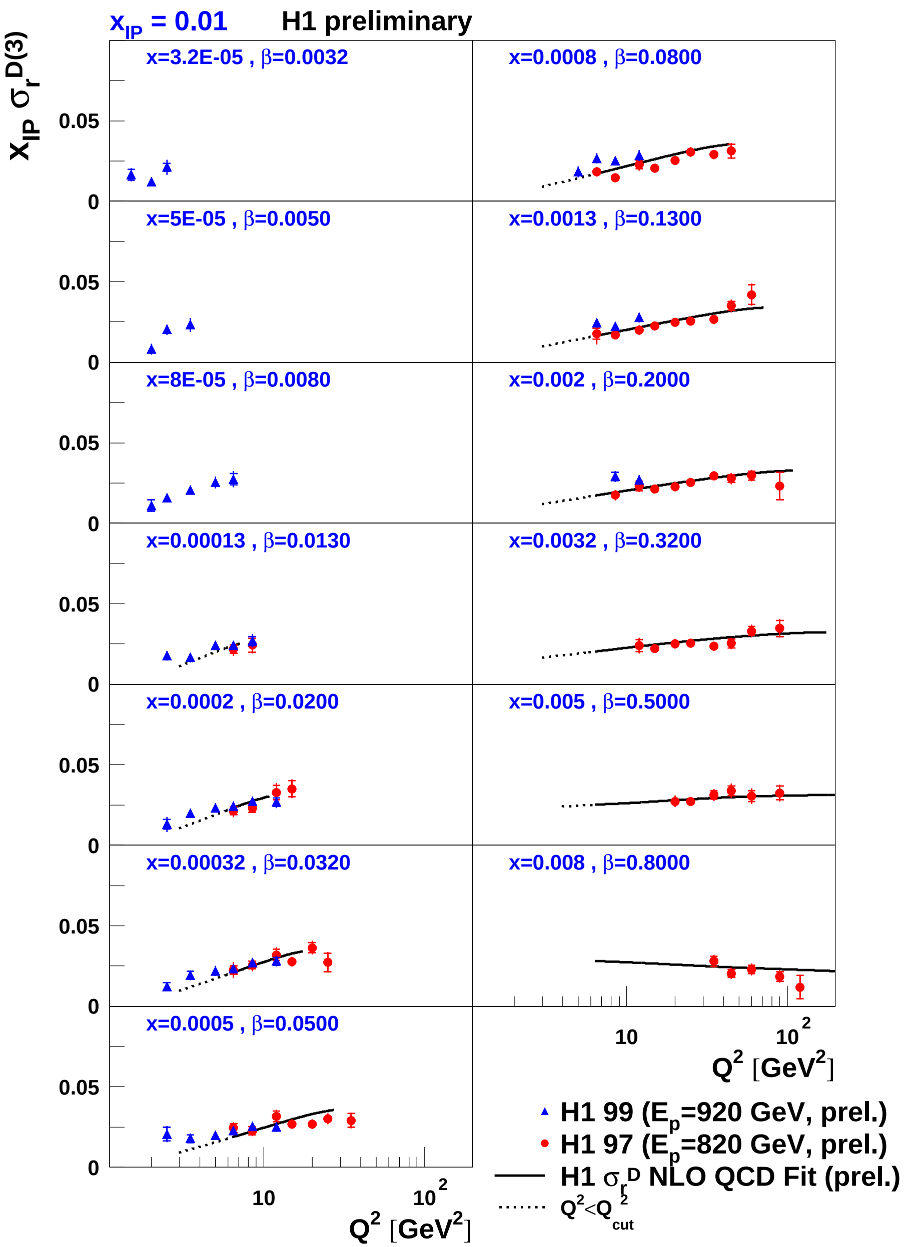


Example data at $x_{I\!P} = 0.003$:

- Rising behaviour for $\beta \to 1$ at low Q^2, reflected by $\Sigma(\beta, Q^2)$
- QCD fit to data for $Q^2 > 6.5\ \mathrm{GeV}^2$
- Extension to lower β, Q^2 with new 99 data! (blue points)
- Indication of breakdown of QCD fit at $Q^2 = 3.5\ \mathrm{GeV}^2$

$\Rightarrow$ new low Q^2 data as additional constraint in future fits!

NLO QCD fit: Q^2 dependence



Example data at $x_{I\!P} = 0.01$:

- Q^2 scaling violations well constrained by data
- Rising except at highest β
- Well reproduced by QCD fit for $Q^2 > 3.5\ \mathrm{GeV}^2$
- New low Q^2 data (blue points) above fit at low Q^2 (not included in fit)

Diffractive final states at HERA

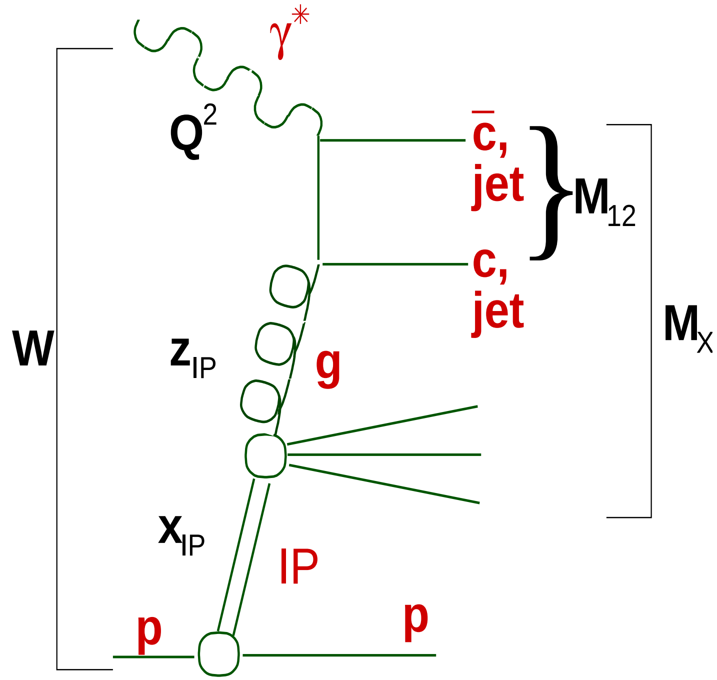
Motivation:

- Processes discussed here:
  – Dijet production in DIS
  – D^* meson production in DIS
  – Dijet production in photoproduction $Q^2 \sim 0$

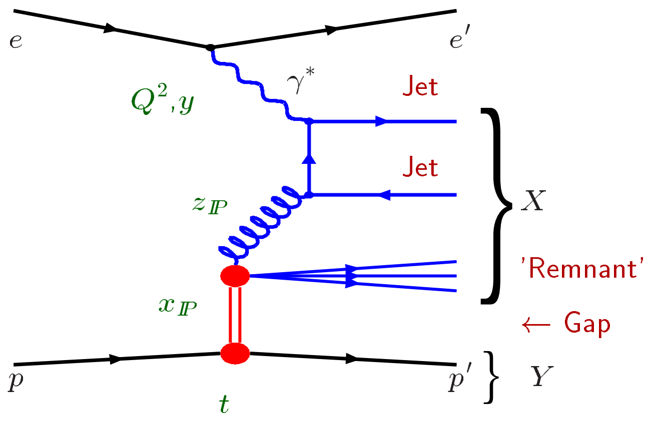
- Test QCD factorization in diffraction:
  Use diffractive parton densities obtained
  from inclusive measurements to predict cross sections
  for final states such as jet or heavy flavour production

- High sensitivity to
  the diffractive gluon distribution (BGF diagram)

- Jet p_T and heavy quark mass m_c provide
  additional hard scale in process



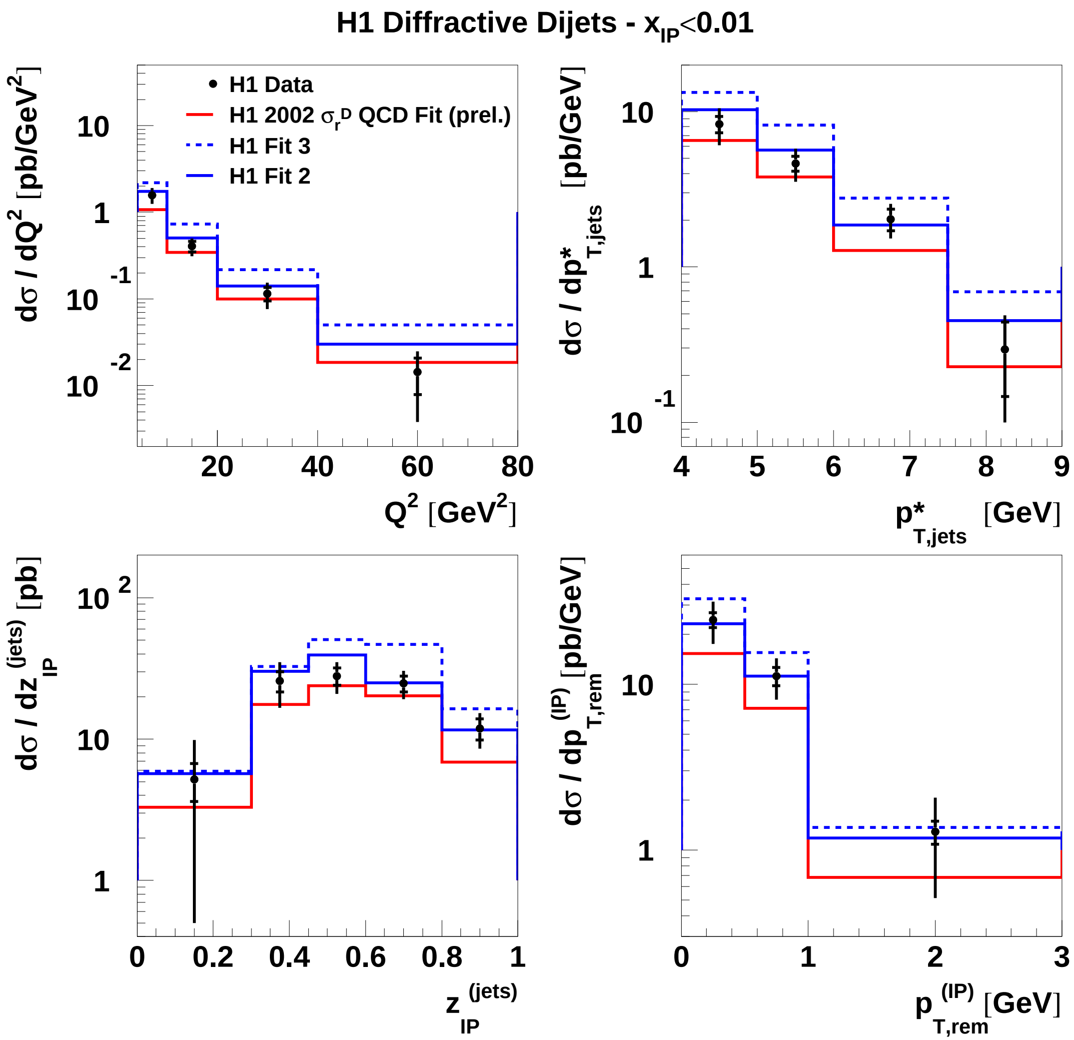
Diffractive Jets in DIS



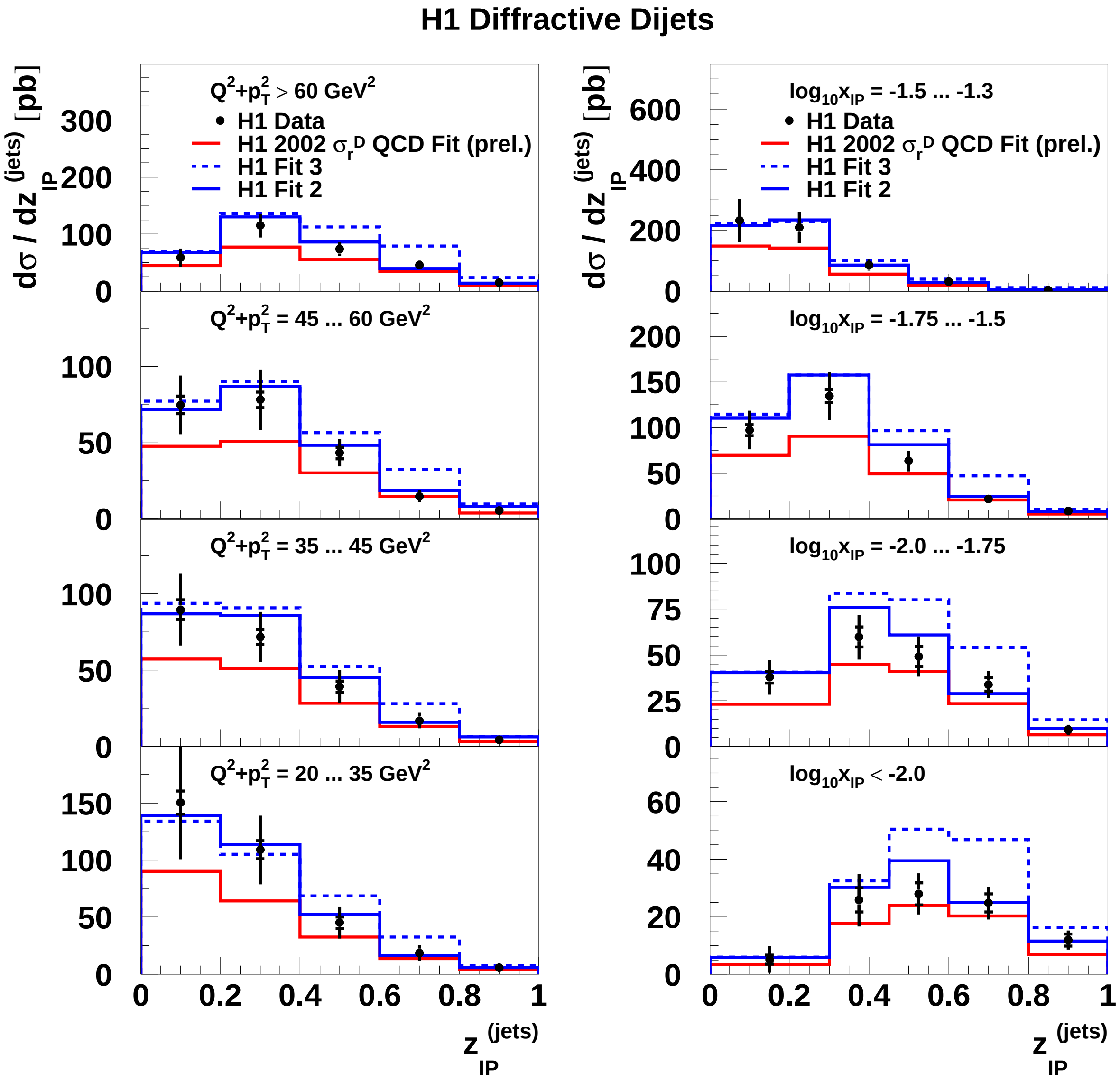
$4 < Q^2 < 80 \text{ GeV}^2$
$p_T^* > 4 \text{ GeV}$
cone jet algorithm

Diffractive pdf's interfaced to
LO Monte Carlo + parton showers

→ Good agreement with pdf's within uncertainties
("fits 2,3": published; "2002 fit" new fit with smaller gluon)



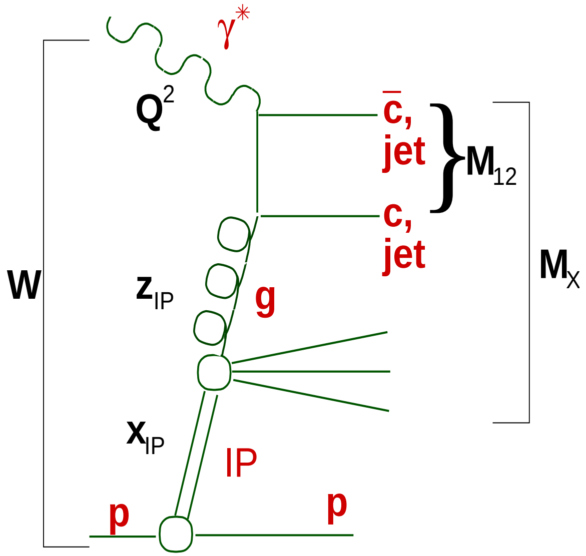
Diffractive Jets in DIS

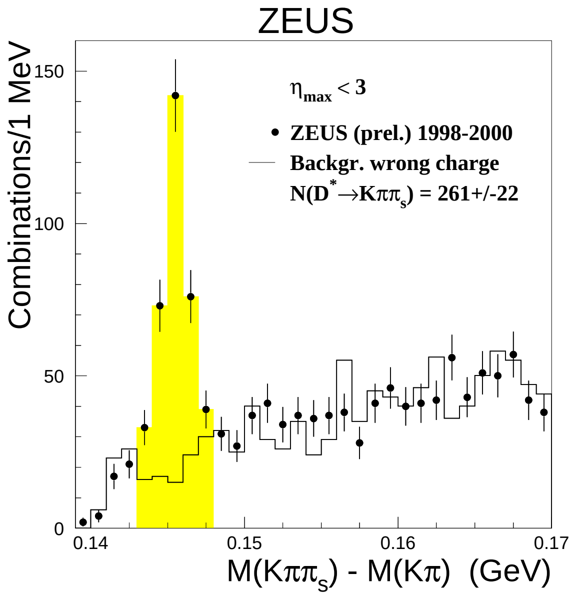


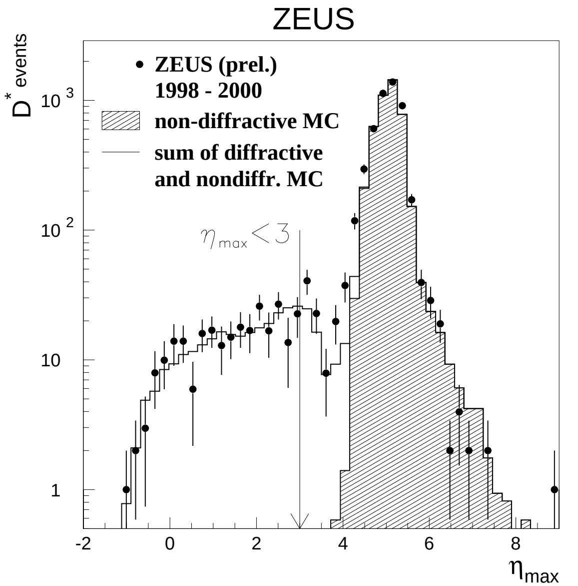
Left: $z_{I\!P}$ in bins of $Q^2 + p_T^2$
Right: $z_{I\!P}$ in bins of $x_{I\!P}$

- Consistent with:
  – evolution of diffractive pdf's with scale
  – factorization in $x_{I\!P}$
- Also double differential cross sections in agreement within uncertainties
- Support for validity of QCD factorization in diffractive DIS

Diffractive D^* in DIS



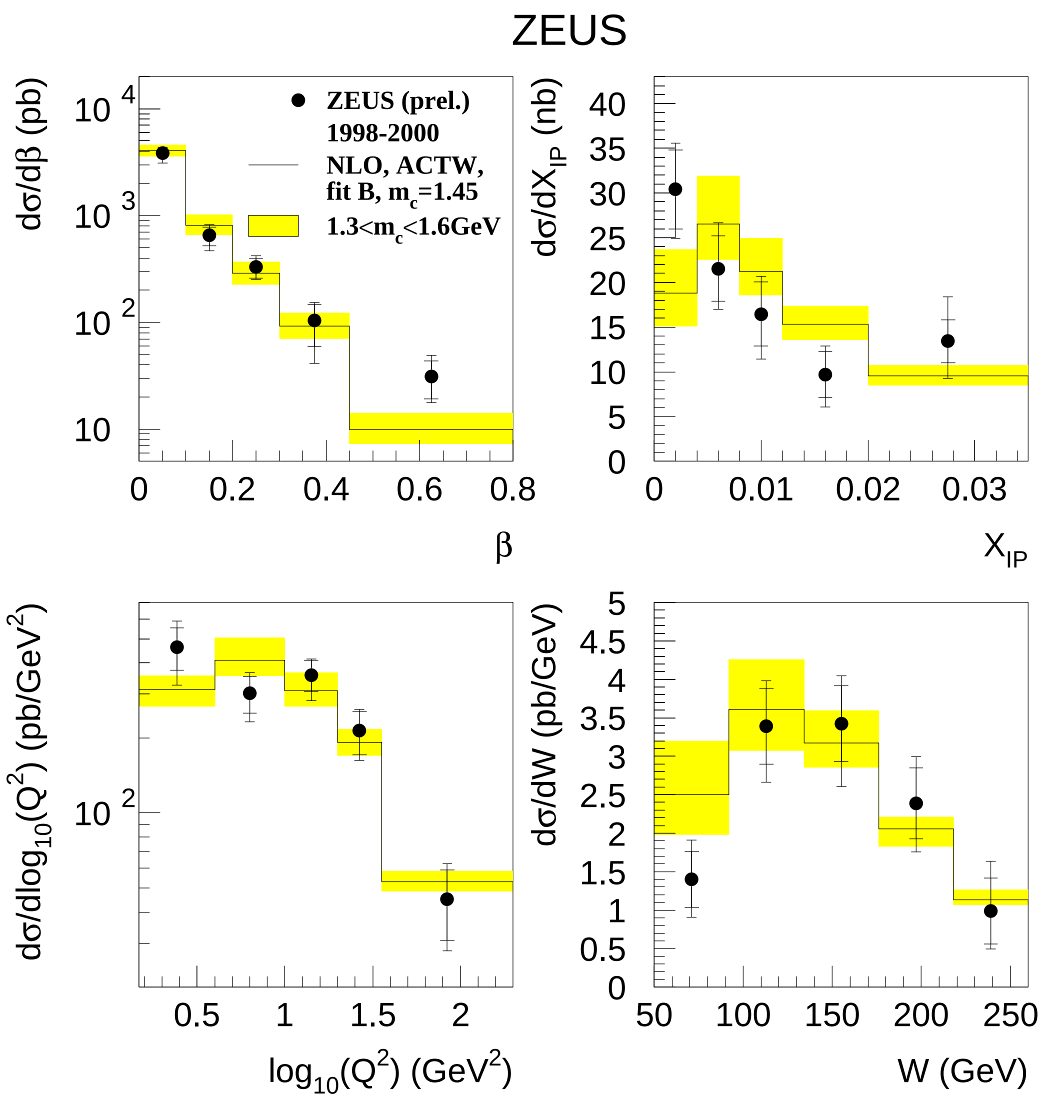




Decay mode:
$D^* \to D^0\pi_s \to K\pi\pi_s$ (BR: 2.5%)

$\eta_{max} = 3.0$
$x_{I\!P} < 0.035$
$1.5 < Q^2 < 200 \text{ GeV}^2$
$p_{T,D^*} > 1.5 \text{ GeV}$
$-1.5 < \eta_{D^*} < 1.5$

Diffractive D^* in DIS



- Theory: gluon dominated pdf's from inclusive fits (ACTW), interfaced to NLO matrix elements
- Differential cross sections well described by calculation!

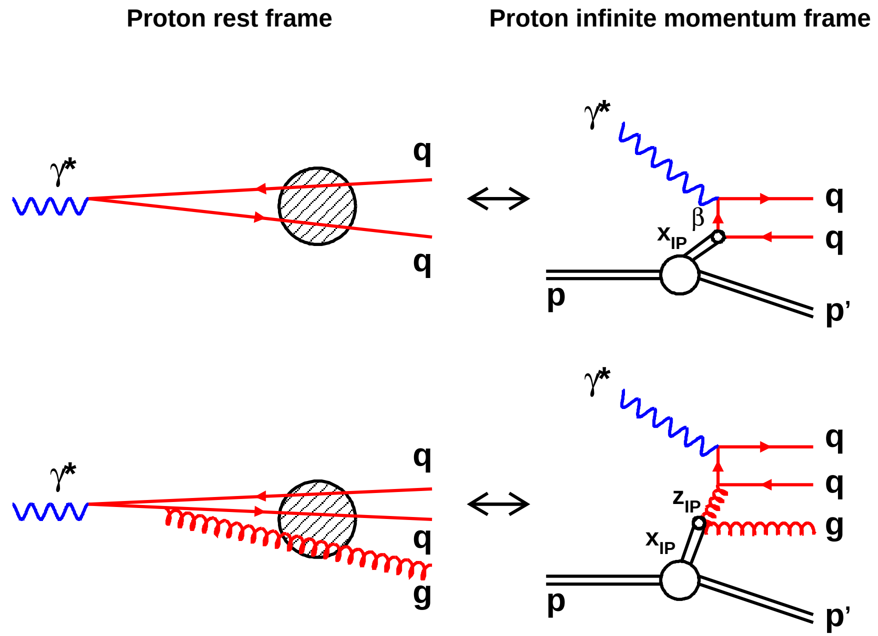
→ Support for QCD factorization in diffractive DIS!

Proton rest frame picture

Can also view the process in frame where proton is at rest:

- Proton fluctuates into $q\bar{q}$, $q\bar{q}g$, ... state well in advance of target proton
- Photon fluctuation scatters elastically off proton
- $q\bar{q}$: diffractive quark scattering (QPM)
- $q\bar{q}g$: diffractive gluon scattering (BGF)

  (beyond LO relation between frames unclear)
- At high M_X and/or p_T, $q\bar{q}g$ or higher multiplicities expected to dominate



Natural relation between inclusive and diffractive cross secions.

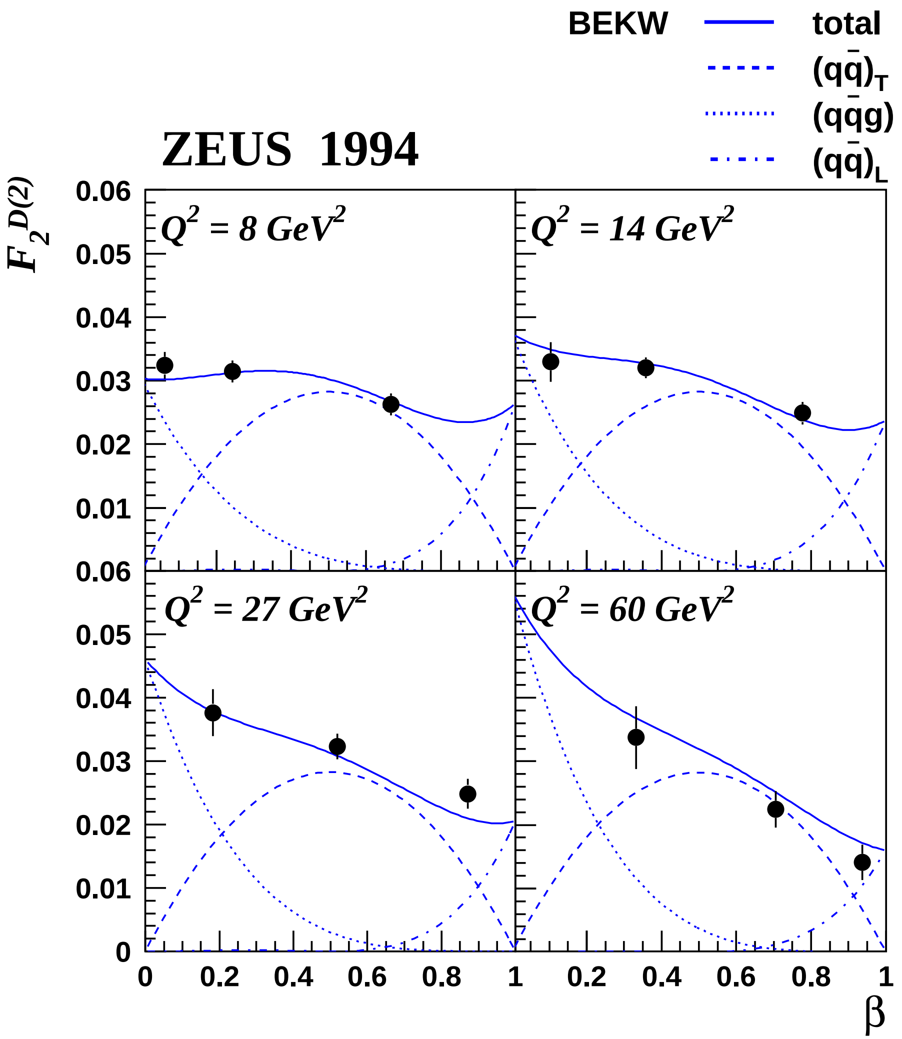
Colour Dipole / 2-gluon exchange models

Bartels, Ellis, Kowalski, Wüsthoff

- Parameterize F_2^D in terms of:
  - $F_{q\bar{q}}^T \sim \beta(1-\beta)$
  - $\frac{Q_0^2}{Q^2} F_{q\bar{q}}^L \sim \beta^3(1-2\beta)^2$
  - $F_{q\bar{q}g}^T \sim (1-\beta)^\gamma$

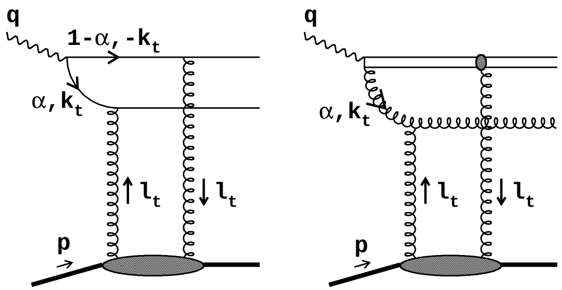
  (from wave function properties)

- Note $\beta = \frac{Q^2}{Q^2+M_X^2}$
- $q\bar{q}g$ important at low β, high M_X
- $q\bar{q}_L$ important at high β, low M_X



Colour Dipole / 2-gluon exchange models

Simplest parton level realization of colour singlet exchange: two gluons with cancelling colour charges



Diffractive cross section:

$$\left.\frac{d\sigma^{\gamma^* p}_{T,L}}{dt}\right|_{t=0} \sim \int d^2\mathbf{r} \int_0^1 d\alpha |\Psi_{T,L}(\alpha,\mathbf{r})|^2 \, \hat{\sigma}^2(r^2, x, \ldots)$$

Dipole cross section may be expressed as:

$$\hat{\sigma}(x,\mathbf{r}) \sim \int \frac{d^2\mathbf{l}_t}{l_t^2} \left[1 - e^{i\mathbf{r}\cdot\mathbf{l}}\right] \alpha_s(l_t^2)\mathcal{F}(x, l_t^2)$$

Where $\mathcal{F}(x, l_t^2)$ is un-integrated gluon density in proton

- Small P_T, large size dipoles: similar to soft hadron hadron scattering
- High P_T, small size dipoles: perturbation theory may be applicable

Golec-Biernat, Wüsthoff model (GBW):

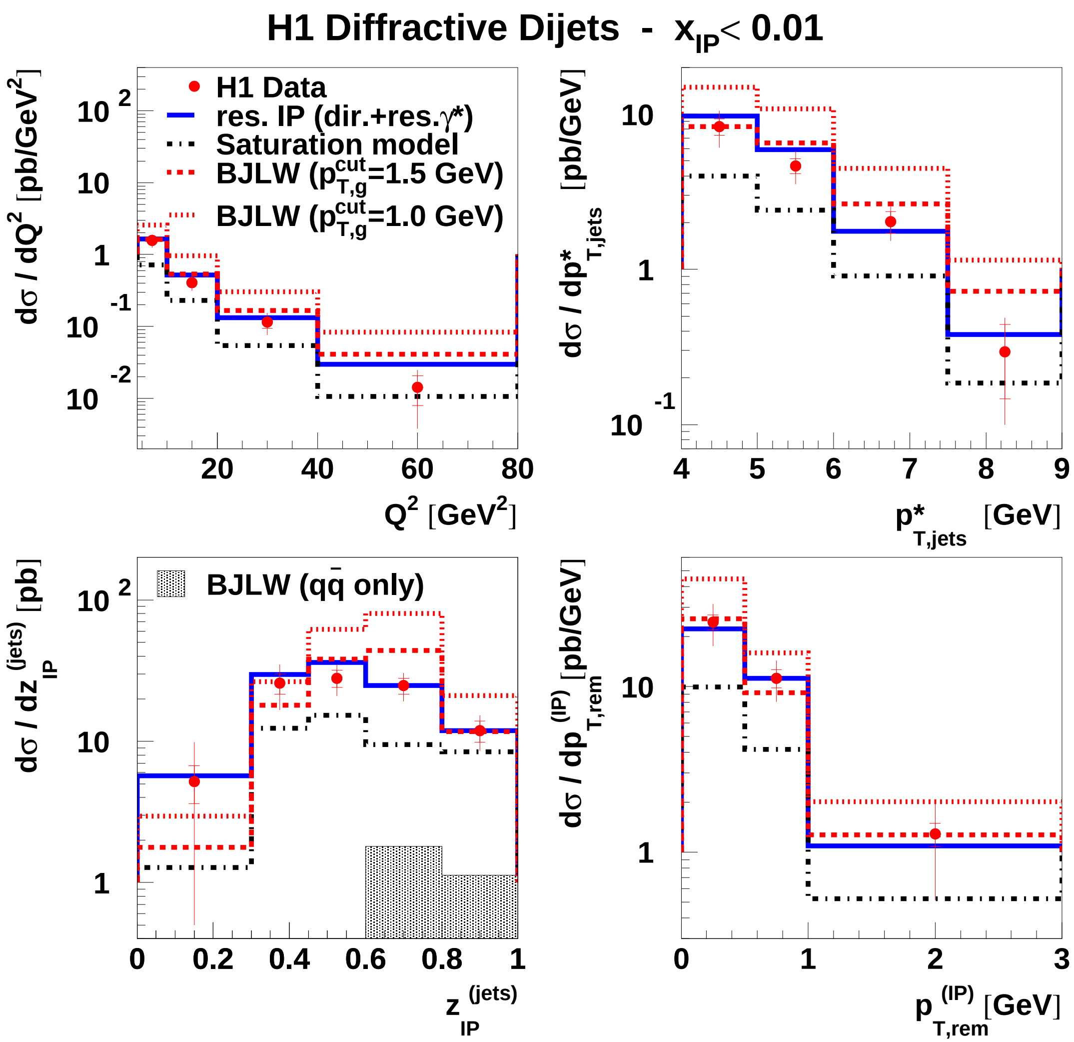
– parameters fixed by fit to $F_2(x, Q^2)$, σ^D then predicted
– Strong p_T ordering assumed

Bartels, Jung, Lotter, Kyrieleis, Wüsthoff (BJLW)

– Perturbative calculation in low-β, low-$x_{I\!P}$ limit
– For $q\bar{q}g$ require high p_T of all 3 partons (only for jets!)
– non-p_T ordered configurations included, need cut-off for $p_{T,g}$

Colour Dipole / 2-gluon exchange models and jet data

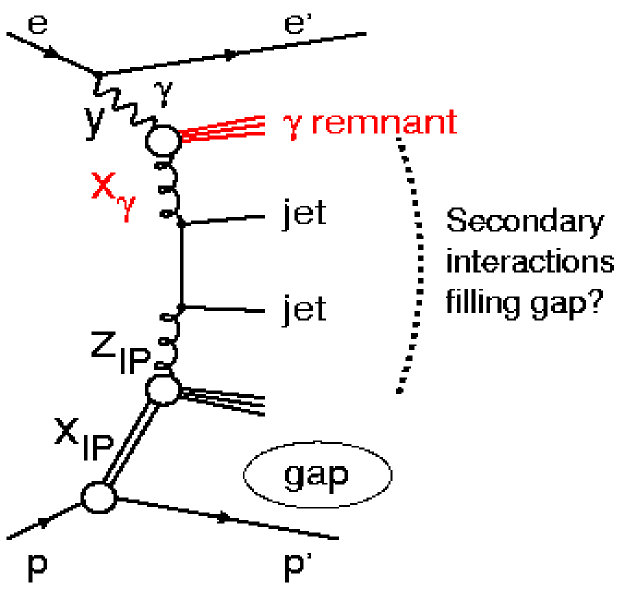
- BJLW able to describe data if $p_{T,g} > 1.5$ GeV
- GBW too low (only k_T ordered configurations)



→ 2-gluon models able to reasonably describe diffractive jet/charm production in DIS

Diffractive Jets in Photoproduction

At $Q^2 \sim 0$, the photon can act as a hadron



$x_\gamma = 1$: direct process
DIS-like

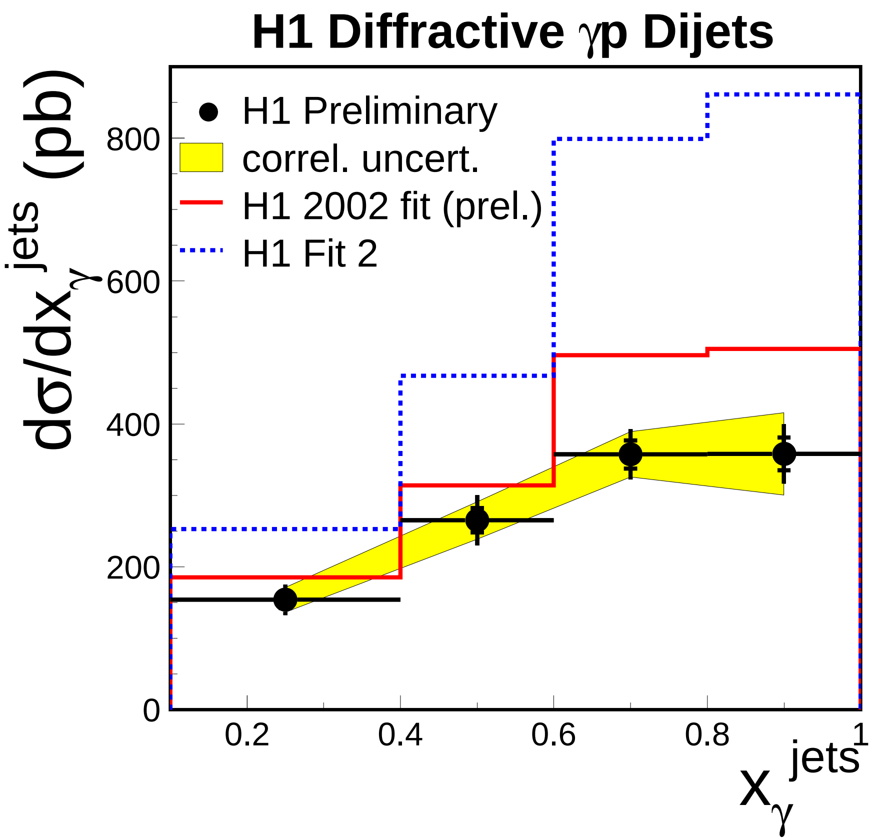
$x_\gamma < 1$: resolved process
hadron-hadron like

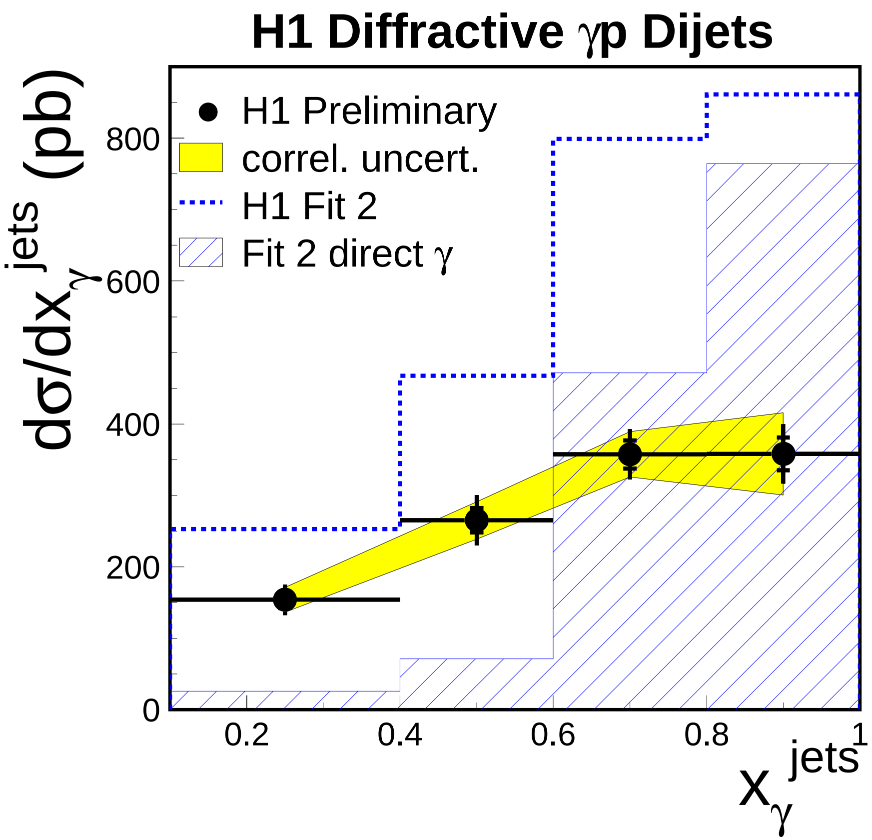
- QCD factorization should NOT work for hadron-hadron diffraction
- Presence of second hadron may lead to additional spectator interactions which break up proton
- Suppression of diffractive events relative to DIS?

Diffractive Jets in Photoproduction

$Q^2 < 0.01\ \mathrm{GeV}^2, 165 < W < 240\ \mathrm{GeV}$

inclusive k_T algorithm, $p_{T,1} > 5\ \mathrm{GeV}, p_{T,2} > 4\ \mathrm{GeV}$

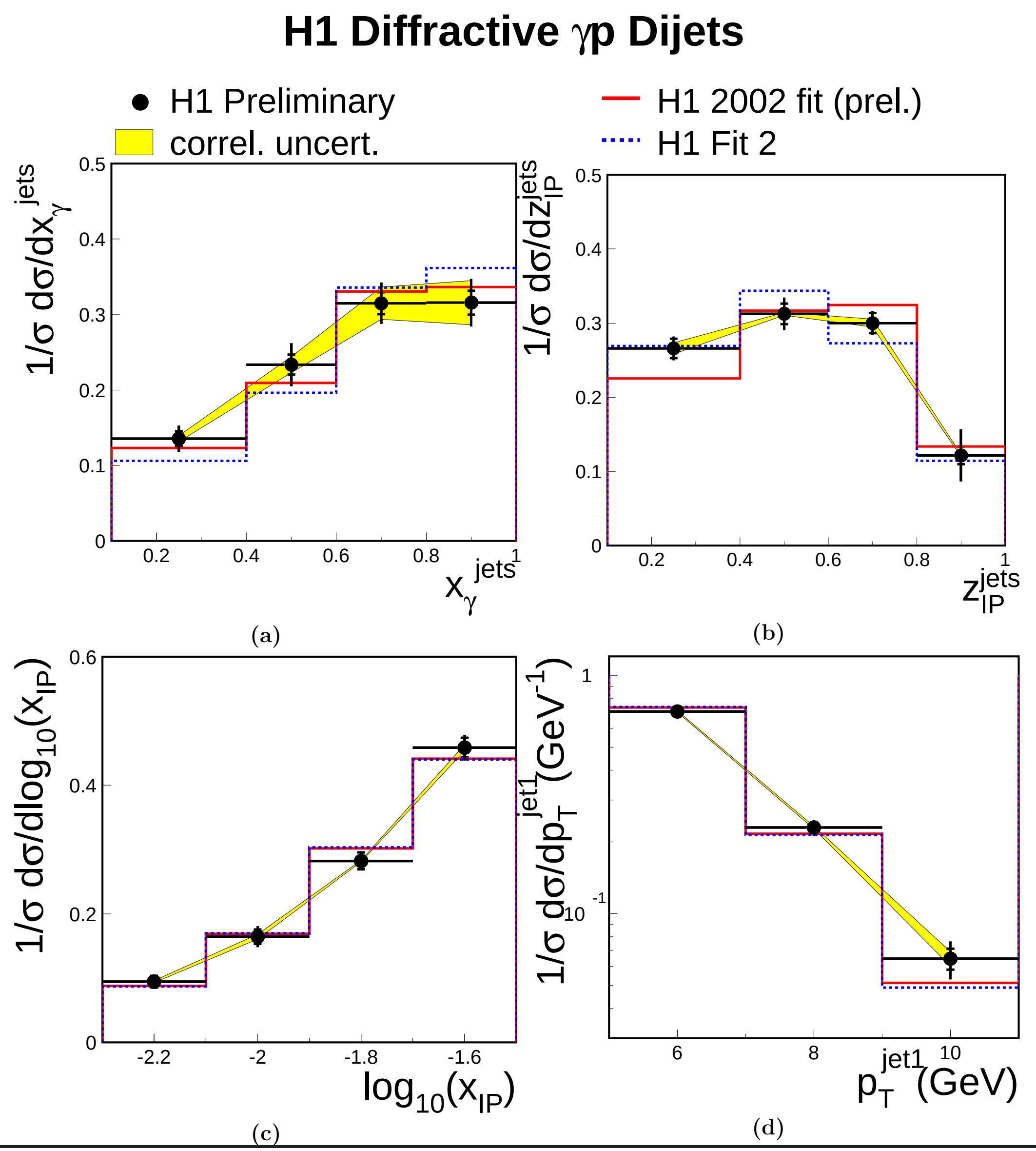




– Old and new fits overestimate data
– "fit 2" (best descr. of DIS jets) fac. 1.8 too high

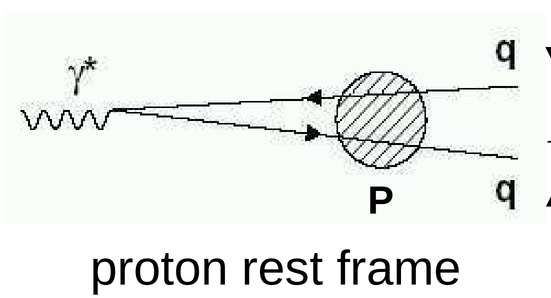
– Suppression of resolved AND direct events!
– BUT: Uncertainties (LO comparison)

Diffractive Jets in Photoproduction



Normalized cross sections:

- Shapes well described!
- Direct and resolved suppressed by same factor
- Possible explanation:
  Suppression depends only on size of photon $R \sim 1/Q$??

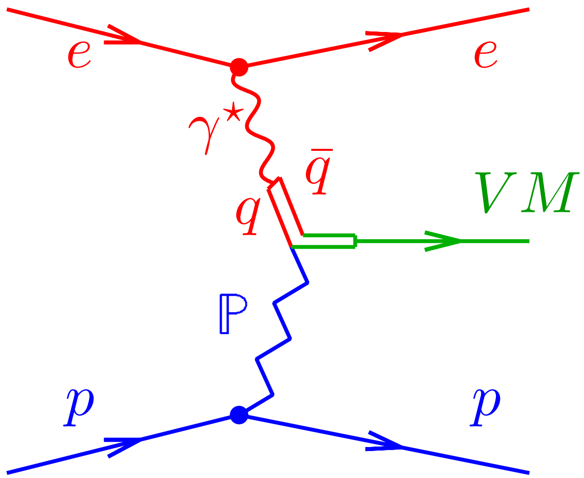


$$R \propto \frac{1}{Q}$$

Diffractive Vector Meson Production

A very clean laboratory to study diffraction at HERA ...

Soft Pomeron model:



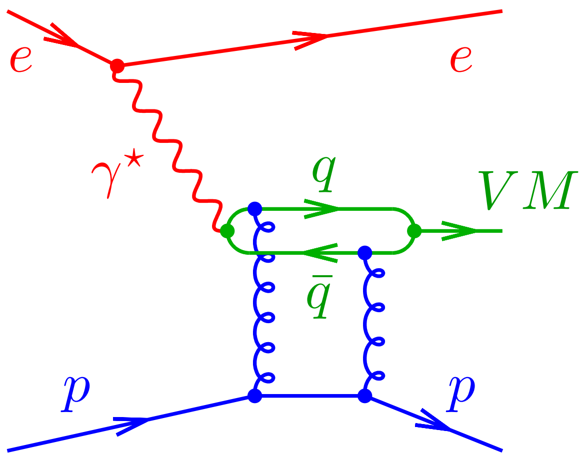
$\alpha_{I\!P}(t) = \alpha(0) + \alpha' t$

$\sigma \sim (W^2)^{2(\alpha(t)-1)} \sim W^{0.22}$

$\frac{d\sigma}{dt} \sim e^{Bt}$
$B = b_0 + 4\alpha' \log(W^2/W_0^2)$

Works for light VM, at $Q^2 \sim 0$, $|t| \sim 0$

Perturbative QCD:



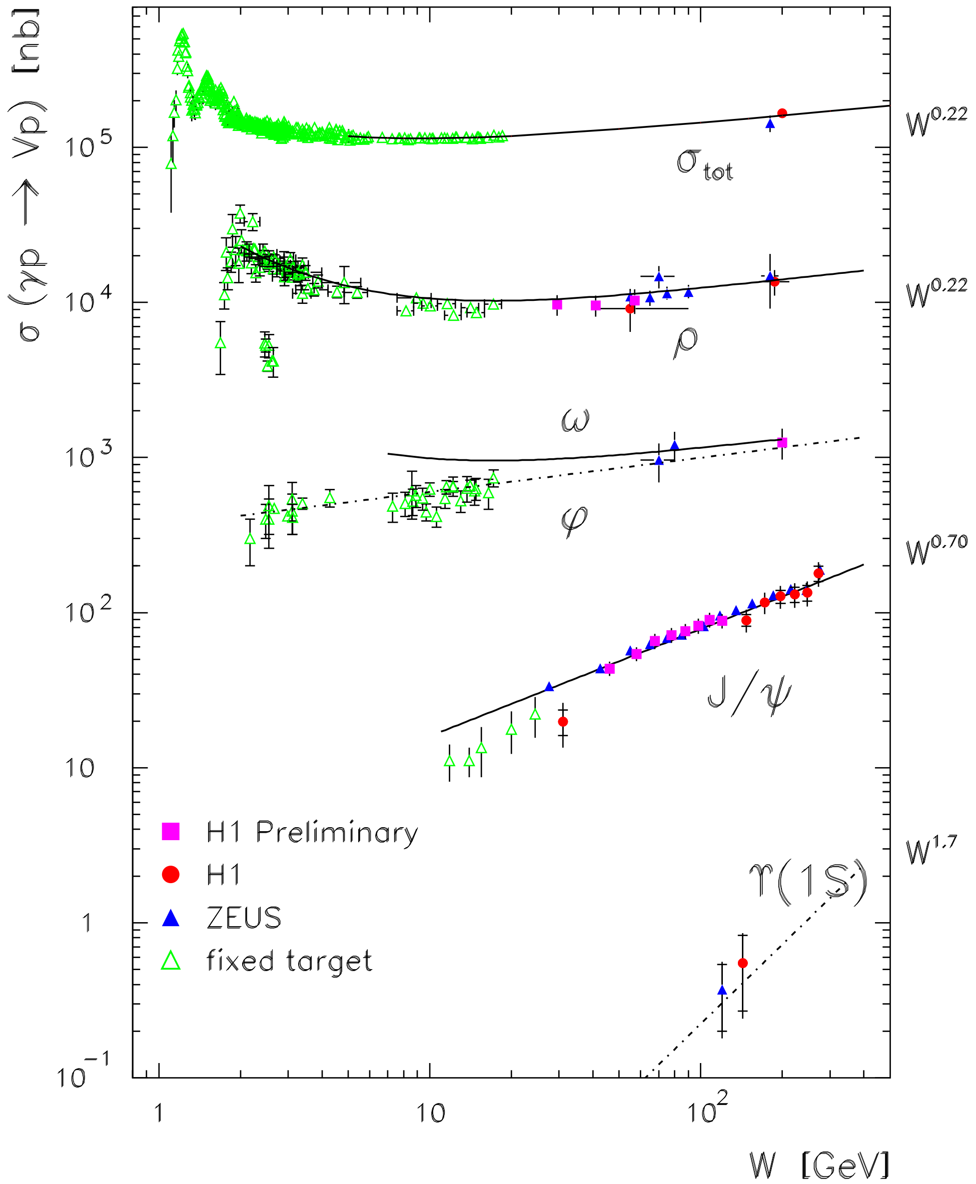
Exchange of 2 or more gluons

$\sigma \sim (xg(x, Q^2))^2$
steeper rise with W (rise of gluon at low x)

no or small shrinkage

Works in presence of hard scales (M_V, Q^2, $|t|$)

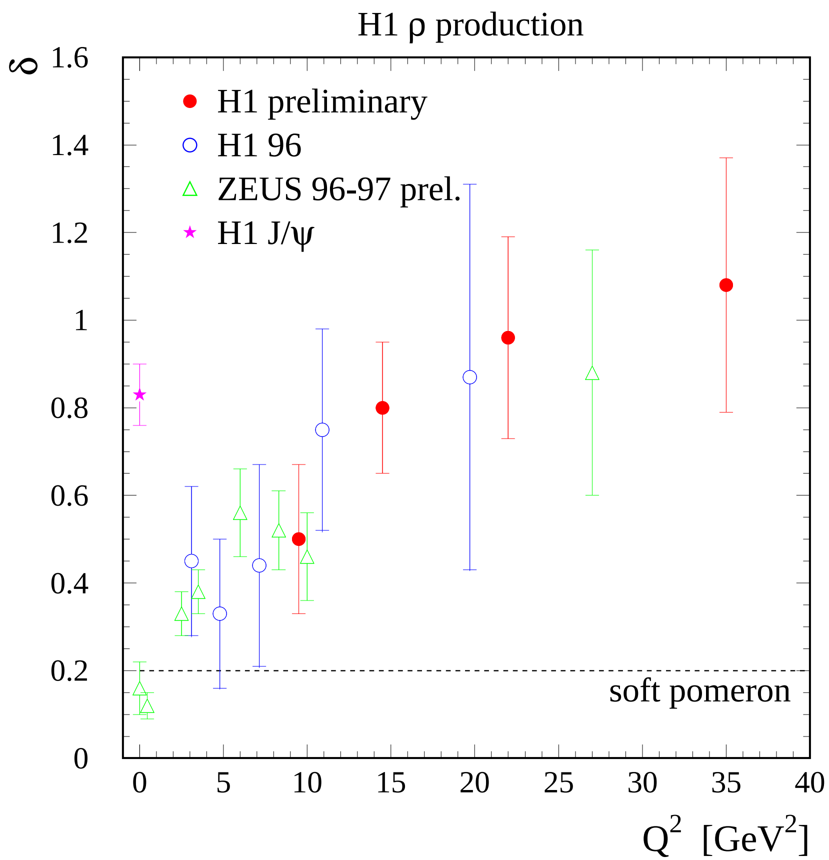
Vector Meson Photoproduction vs W



- ρ^0: Compatible with soft pomeron expectation
- Steeper rise with W for heavy vector mesons
- M_V as hard scale

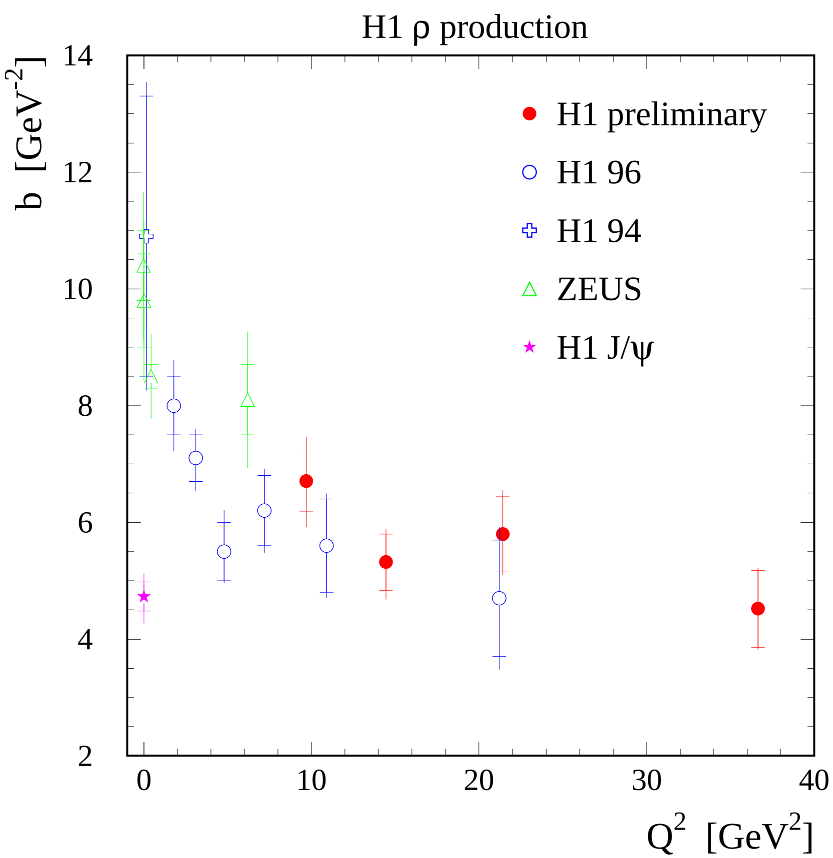
Q^2 dependence of ρ^0 and J/Ψ

W^δ fit in bins of Q^2:



– W slope increases with Q^2
– ρ^0 at high Q^2 similar to J/Ψ at $Q^2 = 0$

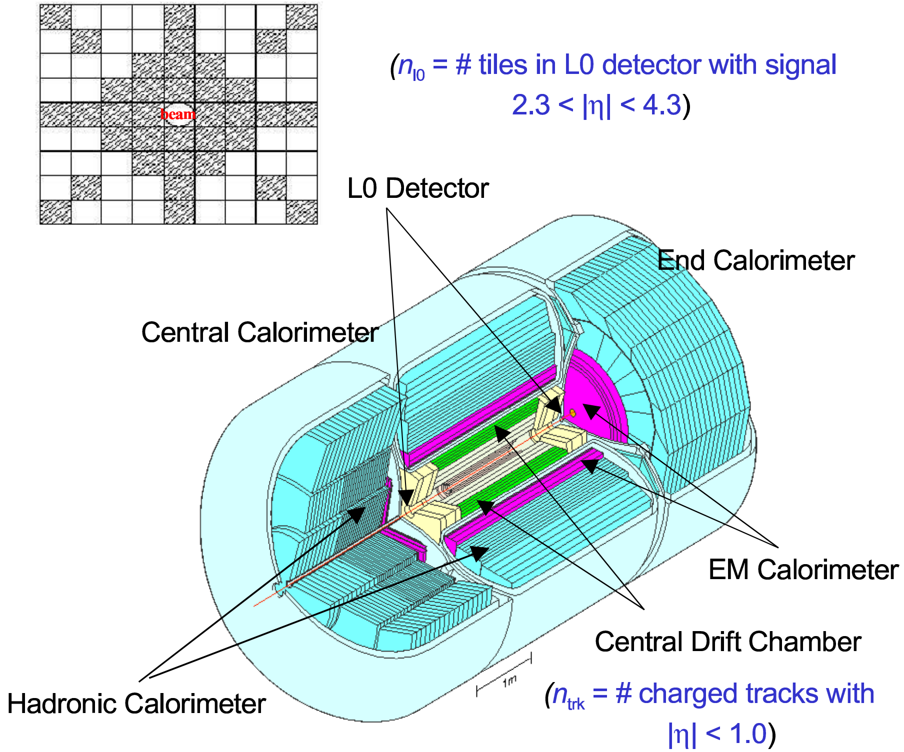
e^{bt} fit in bins of Q^2:



– b related to $R^2_{VM} + R^2_p$ ("interaction size")
– at high Q^2 or M_V: point-like interaction

Diffraction at the Tevatron – Introduction

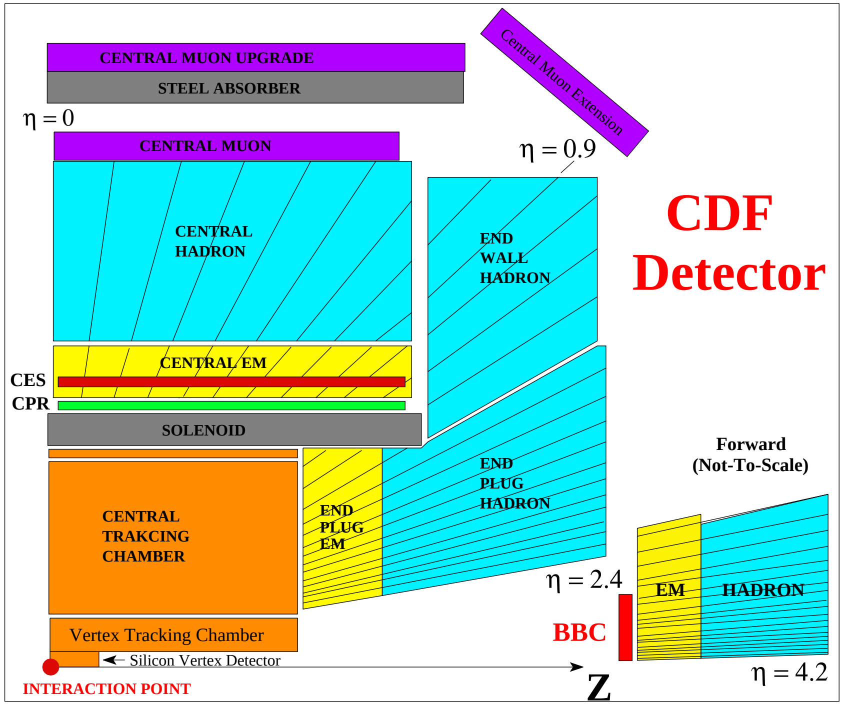
D0 Detector



(n_{cal} = # cal towers with energy above threshold)

Central Gaps		
EM Calorimeter	E_T > 200 MeV	|η| < 1.0
Forward Gaps		
EM Calorimeter	E > 150 MeV	2.0 < |η| < 4.1
Had. Calorimeter	E > 500 MeV	3.2 < |η| < 5.2)

CDF Detector



Rapidity Gap Detectors

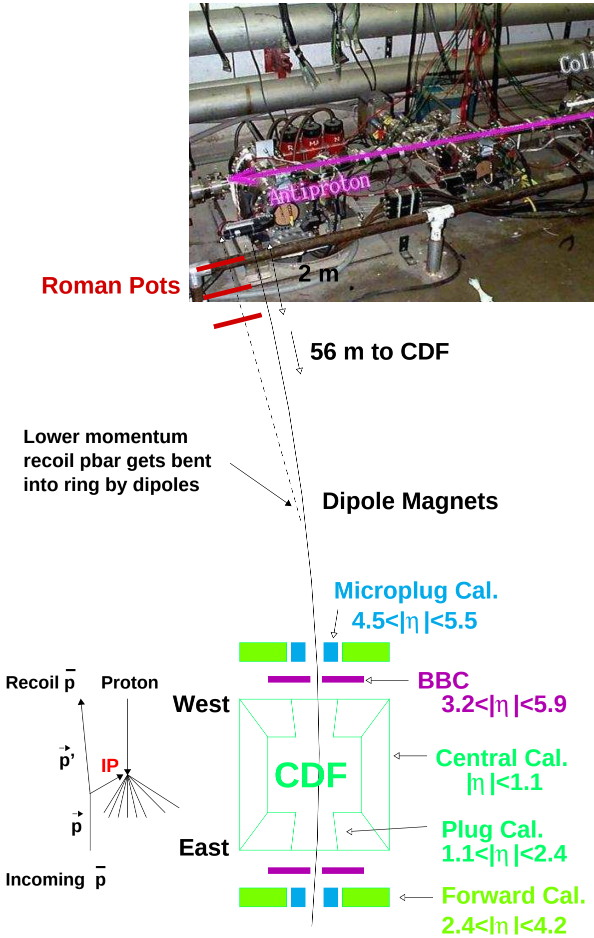
BBC	$3.2 < \|\eta\| < 5.9$	Charged particles
FCAL	$2.4 < \|\eta\| < 4.2$	Charged and neutral

Require no hits in BBC and no tower with energy above 1.5 GeV in the forward region

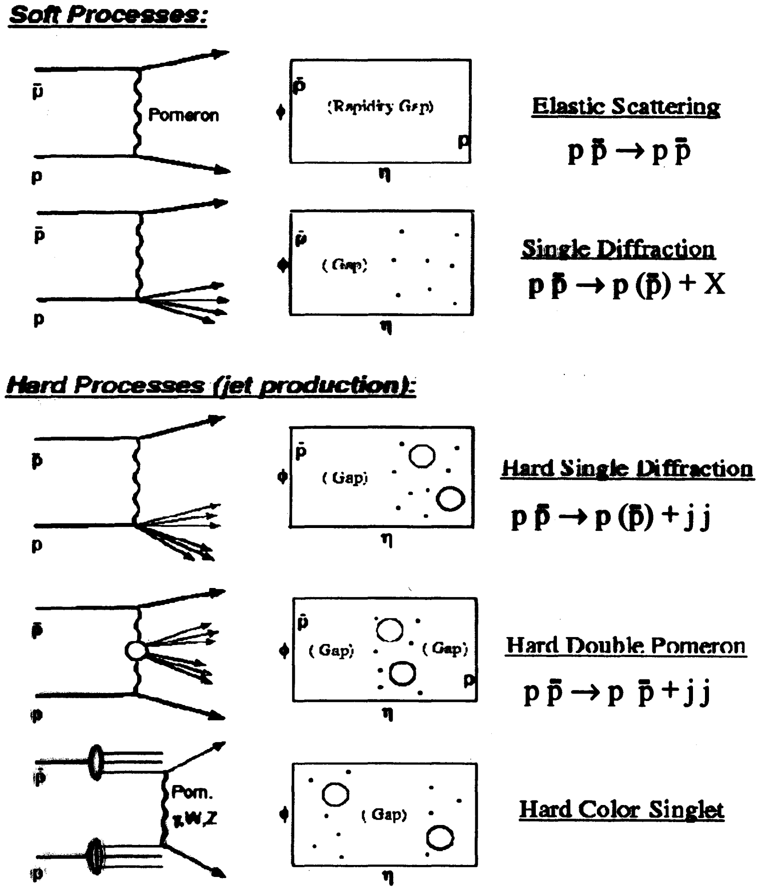
Diffraction at the Tevatron – Introduction

CDF roman pots:

Roman Pot was employed in 1995-96 run



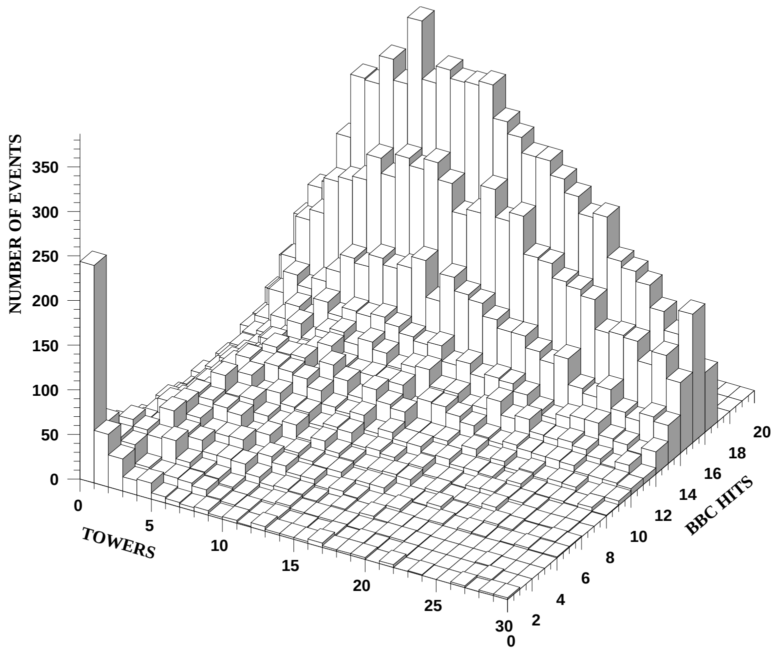
Diffractive Processes in $p\bar{p}$



Can only discuss hard single diffraction here ...

Single Diffraction: jets, W, $b\bar{b}$, J/Ψ (CDF)

– Dijets, $E_T > 20$ GeV, $|\eta| < 1.8$
– Rapidity gap on one side



– Estimate number of events in $(0, 0)$ bin above background by smooth 2D extrapolation
– Acceptance correction with MC

Determine "gap fraction" $R_{jj}[SD/ND]$

Diffractive W, dijet and b at $\sqrt{s} = 1800$ GeV

✔ Diffractive W production $q\bar{q} \to W,\ gq \to Wq$

$$R_W[\frac{SD}{ND}] = [1.15 \pm 0.51(stat) \pm 0.20(syst)]\%$$

$(p_T^e > 20$ GeV/c$, |\eta^e| < 1.1, \not{E}_T > 20$ GeV$, \xi < 0.1)$

✔ Diffractive dijet production $gg \to gg,\ qg \to qg$

$$R_{jj}[\frac{SD}{ND}] = [0.75 \pm 0.05(stat) \pm 0.09(syst)]\%$$

$(E_T^{jet} > 20$ GeV$, 1.8 < |\eta^{jet}| < 3.5, \eta_1\eta_2 > 0, \xi < 0.1)$

✔ Diffractive $b\bar{b}$ production $gg \to b\bar{b},\ q\bar{q} \to b\bar{b}$

$$R_{b\bar{b}}[\frac{SD}{ND}] = [0.62 \pm 0.19(stat) \pm 0.16(syst)]\%$$

$(p_T^e > 9.5$ GeV/c$, |\eta^e| < 1.1, \xi < 0.1)$

✔ Diffractive J/ψ production $gg \to J/\psi(g)$

$$R_{J/\psi}[\frac{SD}{ND}] = [1.45 \pm 0.25(stat \oplus syst)]\%$$

$(p_T^\mu > 2$ GeV/c$, |\eta^\mu| < 1.0, \xi < 0.1)$

$R[\frac{SD}{ND}]$ is or order 1 % for W, dijet, $b\bar{b}$ & J/ψ

(c.f. $5 - 10\%$ at HERA)

Single Diffraction: jets, W, $b\bar{b}$, (CDF)

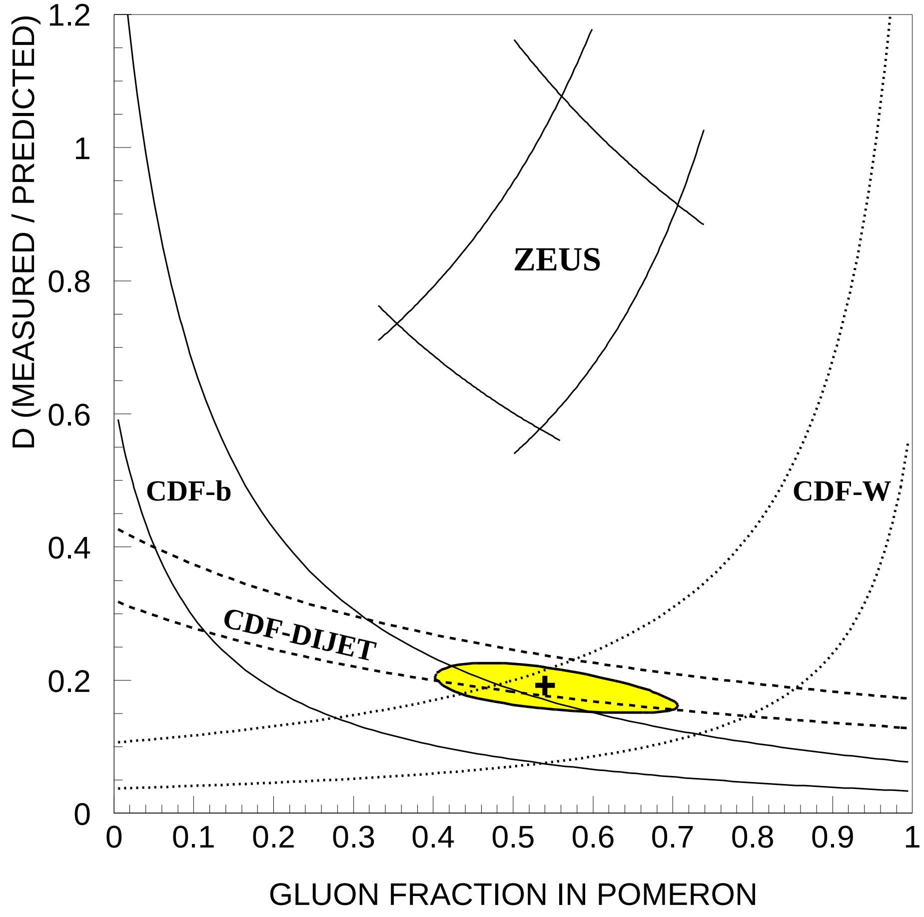
Partonic structure of "Pomeron":

- W: sensitive to quarks ($q\bar{q} \rightarrow W^{\pm}$) only
- jets, $b\bar{b}$ sensitive to quarks and gluons

Gluon fraction in Pomeron:
$f_g = 0.54 \pm 0.15$

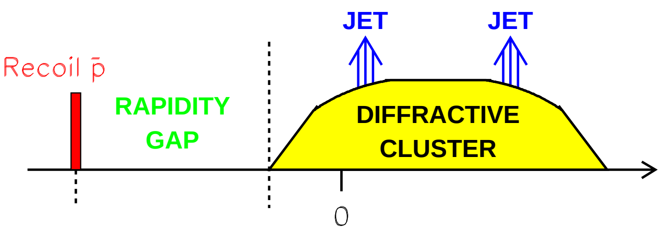
Ratio measured over predicted cross section:
$D[Measured/Predicted] = 0.19 \pm 0.04$

$\rightarrow$ Gluon fraction similar (slightly lower) than from H1/ZEUS results, but normalization too low!



Dijets with leading antiproton (CDF)

- Measure effective structure function for diffractive dijets
  $F_{jj}^{D}(x_{I\!P}, t, \beta, p_T^2)$
  where $F_{jj}^{(D)} = x[g^{(D)} + \frac{4}{9}q^{(D)}]$



- Cross section:
  $$\frac{d^5\sigma^{p\bar{p}\to\bar{p}jjX}}{dx_p dx_{I\!P} dt d\beta dp_T^2} \sim \frac{F_{jj}(x_p,p_T^2)}{x_p} \frac{F_{jj}^D(x_{I\!P},t,\beta,p_T^2)}{\beta} \frac{d\hat{\sigma}}{dp_T^2}$$

Motivation:

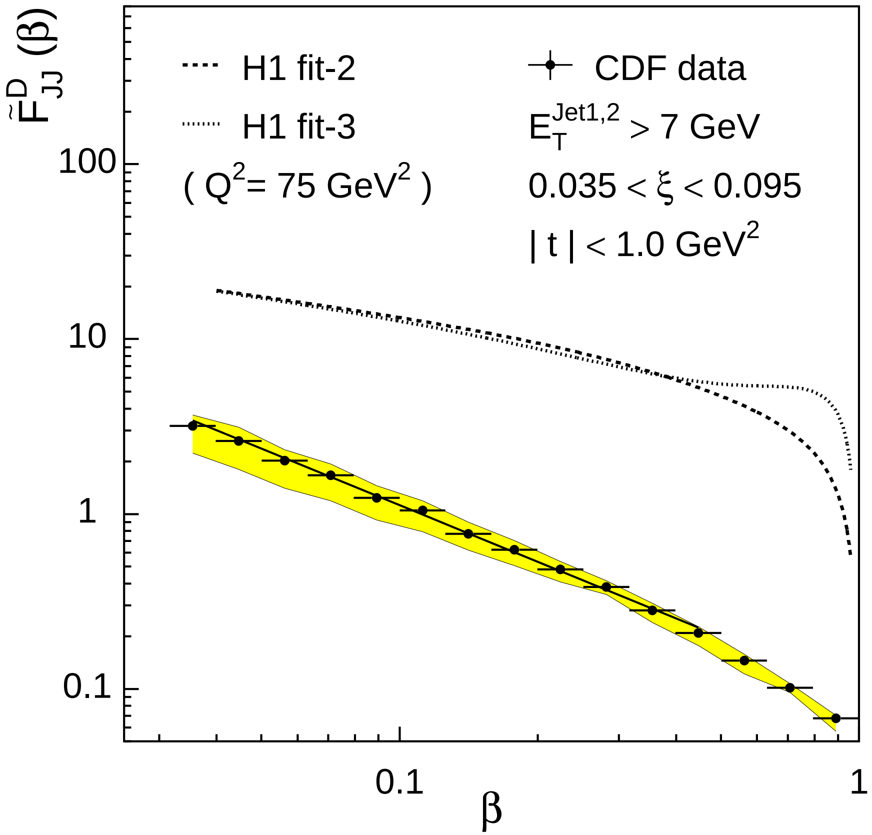
- Tests of factorization by comparison:
  – of different $p\bar{p}$ CMS energies (630 and 1800 GeV)
  – with prediction based on HERA F_2^D QCD fit pdf's

- Test of Regge factorization
  $F_{jj}^{D}(x_pom, t, \beta, p_T^2) = f_{I\!P/p}(x_{I\!P}, t) \cdot F_{jj}^{I\!P}(\beta, p_T^2)$

Principle of measurement: Measure Ratio $R[SD/ND]$, multiply with non-diffr. $F_{jj}^{(th.)}$

Dijets with leading antiproton (CDF)

Measured $F_{jj}^{D}(\beta)$:

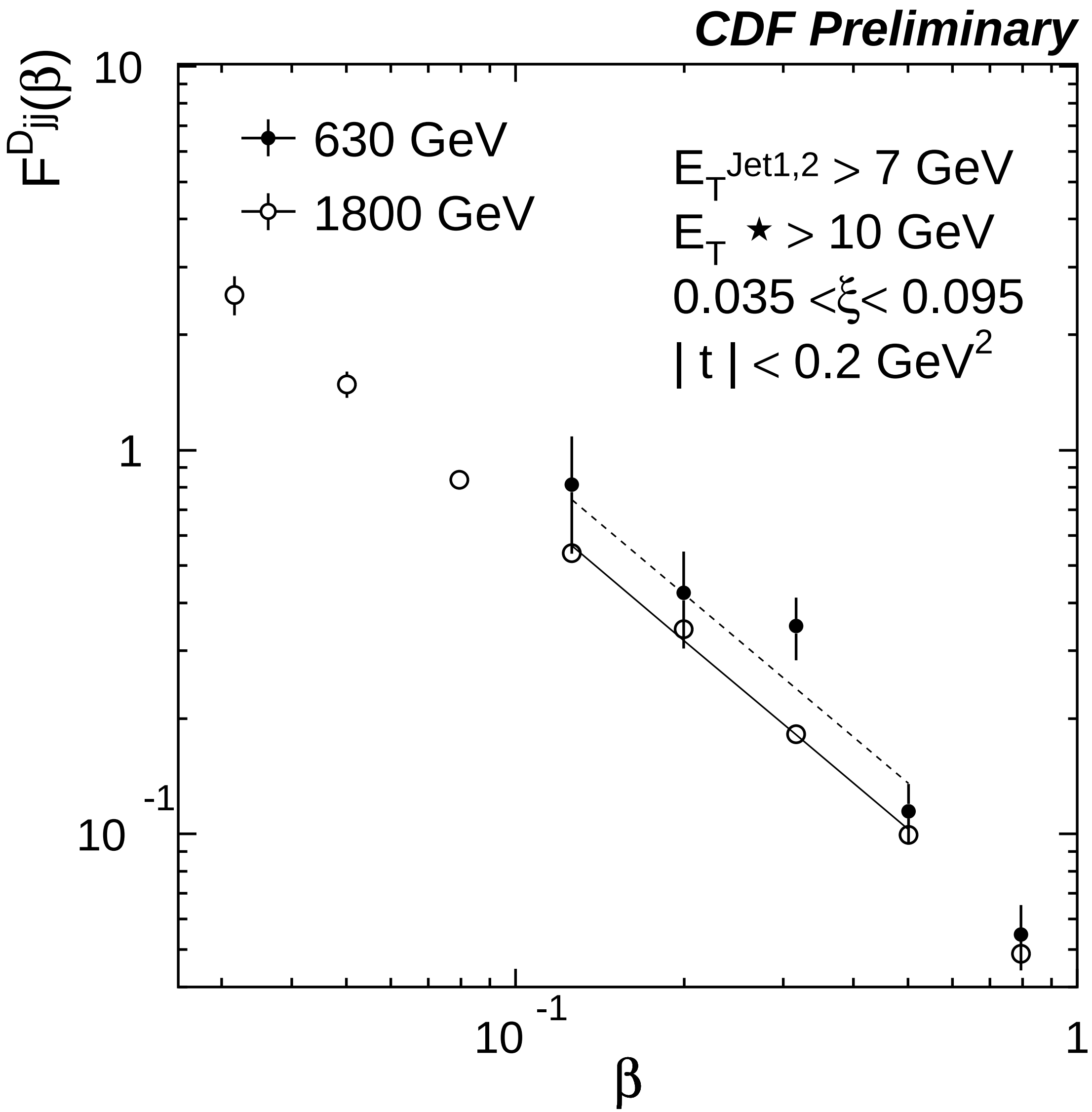


→ one order of magnitude below expectation from HERA!

- Serious breakdown of factorization when comparing HERA vs TEVATRON
- Possible interpretation:
  2nd second hadron in initial state source of spectator interactions

  → suppression of diffractive events ?!
- Challenge for theory
  (as well as expts.)

Diffractive dijets at 630 and 1800 GeV (CDF)



- F_{jj}^{D} larger for 630 than 1800 GeV (”moves towards HERA”)
- $R[630/1800] = 1.3 \pm 0.2^{+0.4}_{-0.3}$ ... but not significantly

Summary: Diffraction

- Hard diffraction studied at HERA and TEVATON

- Based on proof of QCD factorization in diffractive DIS, diffractive pdf's have been extracted
- Diffractive pdf's dominated by gluon
- Application to DIS jets,charm successfull!
- Regge factorization supported by data
- Alternative approach of 2-gluon exchange can describe jet/charm data as well

- Diffractive vector meson production ideal laboratory to study transition soft-hard

- Suppression of rate of diffractive events in photoproduction at HERA and at the TEVATRON w.r.t. HERA, one of the big challenges for theory

- TEVATRON Run 2: New roman pots for D0
- HERA Run 2: New very forward proton spectrometer (VPPS)

Diffraction is a topic which is actively pursued by many people (expts. and thy.), and it remains one of the biggest challenges in our understanding of QCD