Hard Diffraction in ep Scattering at HERA – Probing the Structure of Colour Singlet Exchange

Frank-Peter Schilling / DESY

http://www.desy.de/~fpschill

H1 Collaboration

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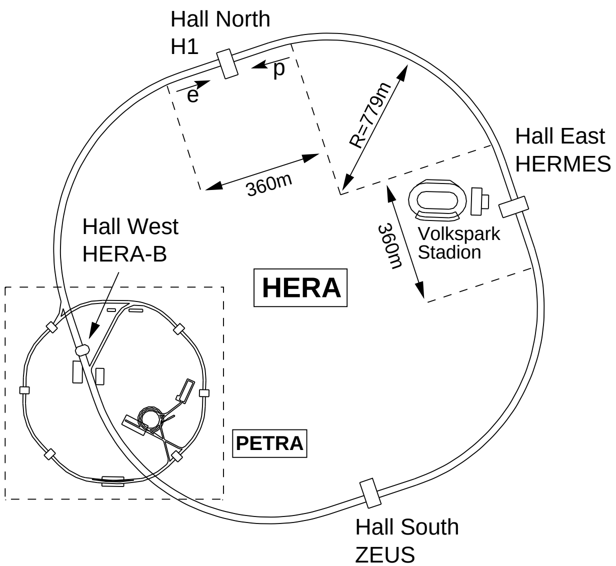
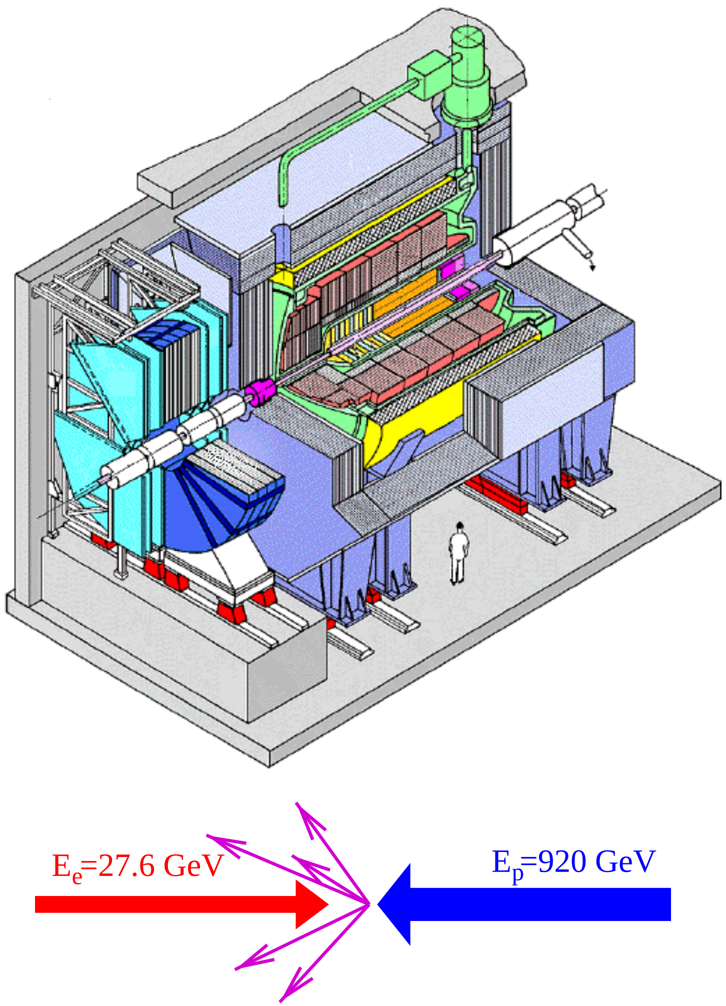
- Introduction to HERA and H1
- Deep inelastic scattering (DIS)
- Diffractive DIS and $F_2^{D(3)}$
- Diffractive jet production
- Summary and conclusions

HERA and the H1 Detector



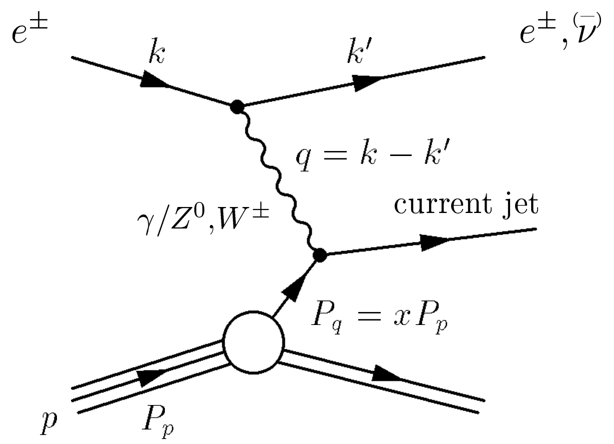


H1, ZEUS: ep collisions at $\sqrt{s} = 320$ GeV

HERA-B: p-beam on fixed target: [CP violation in $B^0\bar{B}^0$]

HERMES: e-beam on polarized target: Spin structure

Deep Inelastic Scattering (DIS) at HERA



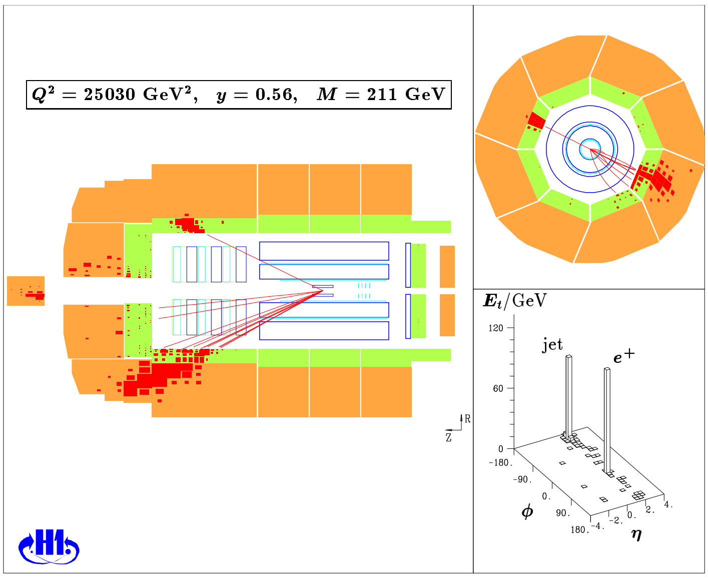
$$Q^2 = -q^2 = (k - k')^2$$

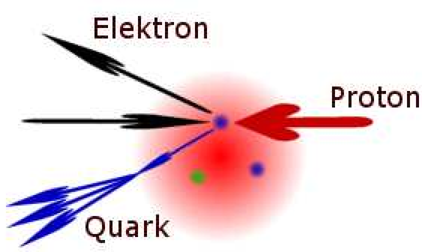
Photon virtuality,
"Resolution power"

$$x = \frac{-q^2}{2P \cdot q} \quad (0 < x < 1)$$

Parton momentum fraction in p ("Bjorken-x")

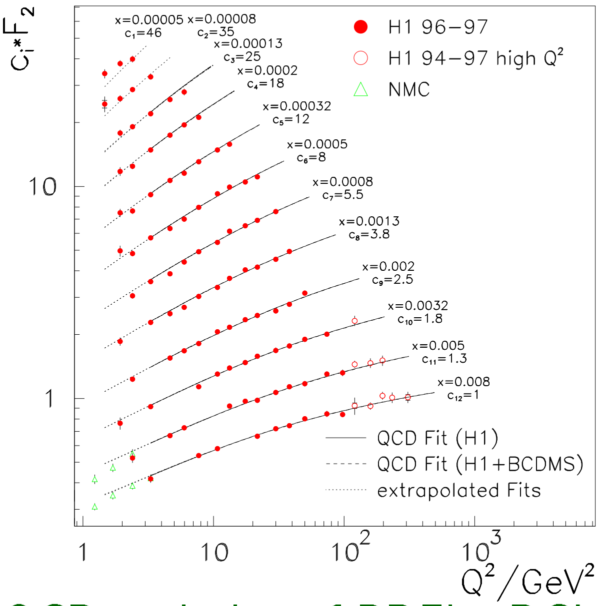
- Highly virtual point-like photon γ^* in DIS at HERA probes proton structure with unprecedented resolution

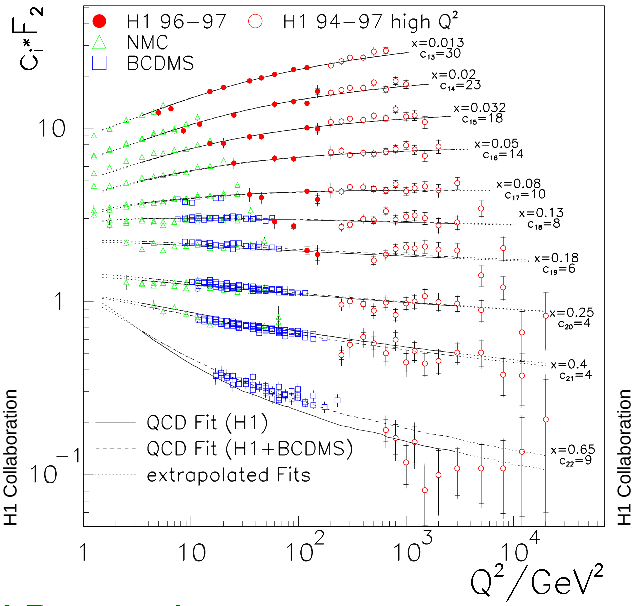




- Scattering off coloured object:
  $\rightarrow$ p breaks up ("proton remnant")

Proton Structure: F_2, $g(x)$ and α_s

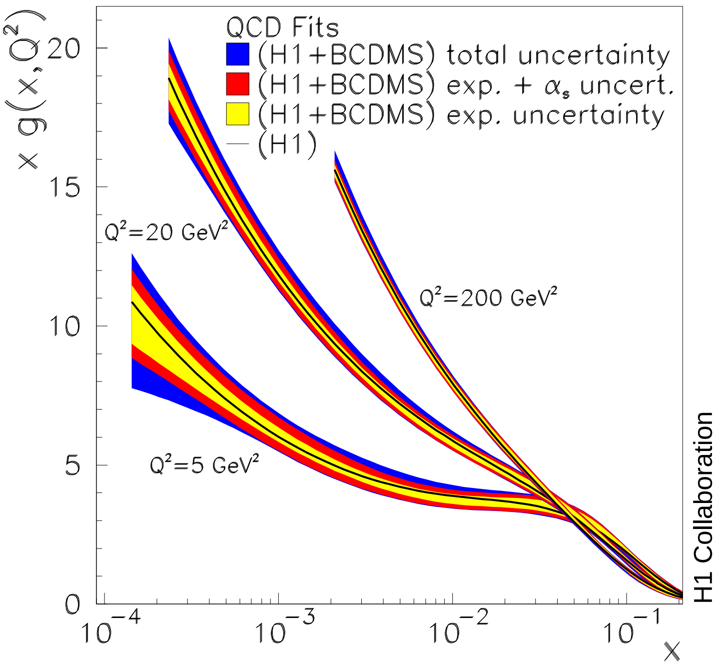


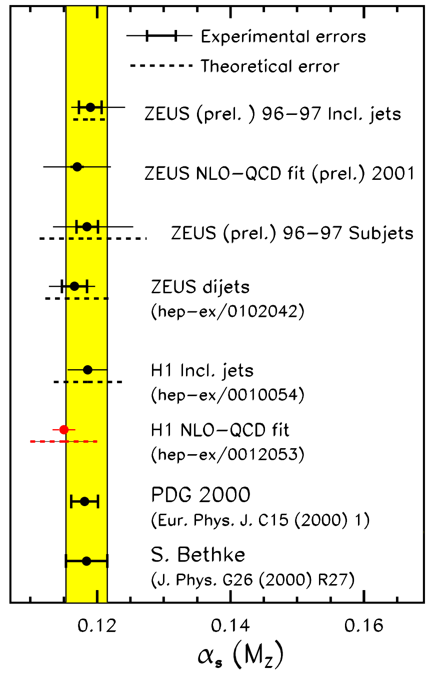


QCD evolution of PDF's: DGLAP equations, e.g.

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

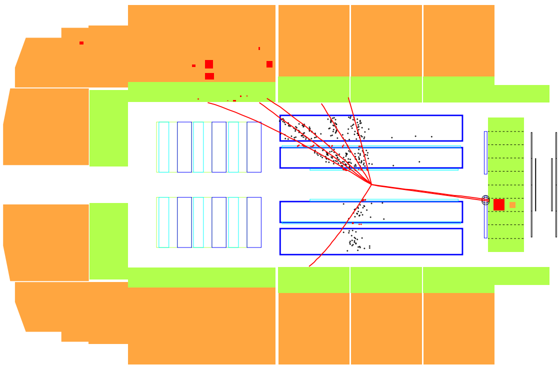
NLO QCD fits to F_2: $g(x)$ and α_s



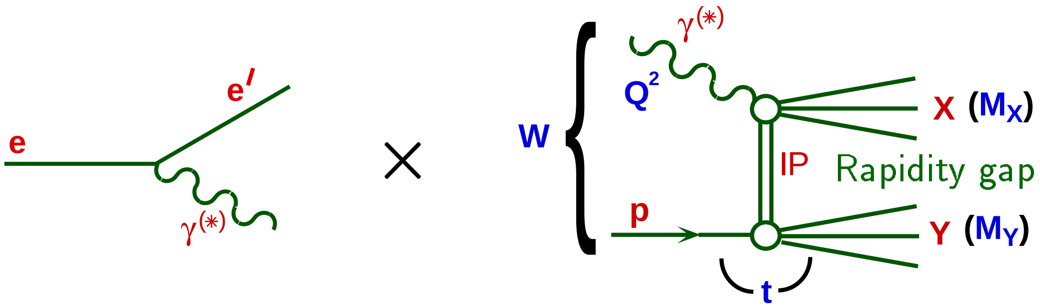


"Large Rapidity Gap" Events in DIS

- 10% of DIS events exhibit large gap without hadronic activity in outgoing p region



- γ^* scatters off colorless state in p ("Pomeron")
- p (or low-mass excitation) escapes through beampipe



$t = (p - p')^2$:	(momentum transfer)^2 at p vertex
M_X, M_Y:	Masses of X and Y

$$x_{I\!P} = \frac{q\cdot(p-Y)}{q\cdot p} = \frac{Q^2+M_X^2-t}{Q^2+W^2-M_p^2}$$

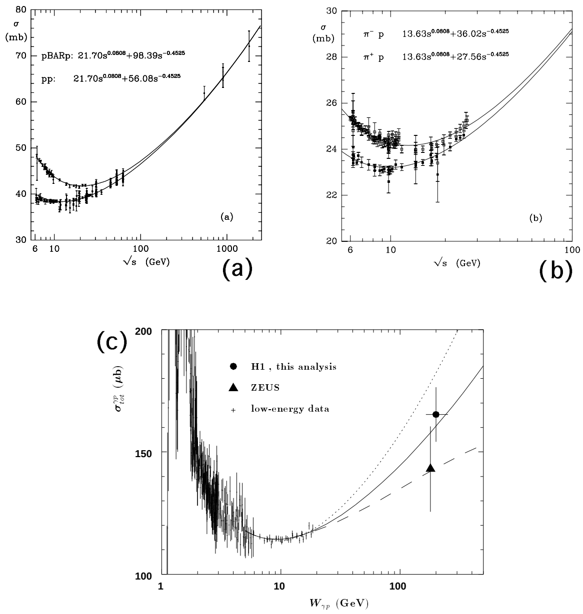
$\longrightarrow$ long. momentum fraction transferred from p to exchange

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

$\longrightarrow$ fraction of exchange momentum carried by q coupling to γ

Reminder: The "Pomeron"

Pre-QCD: Introduced as pseudo-particle to parameterize elastic high energy scattering at small momentum transfers:



Pomeron trajectory:

$$\alpha(t) = \alpha(0) + \alpha' t = 1.08 + 0.25\, t$$

Vacuum quantum numbers
$\rightarrow$ $I\!\!P$ mediates elastic and diffractive scattering

Differential and total cross section:

$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}|T(s,t)|^2 = f(t)\left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$$

$$\sigma_{tot} \sim \frac{1}{s}\mathrm{Im}(T(s,t))|_{(t=0)} = s^{\alpha(0)-1}$$

$\Rightarrow$ Today: Understand colour singlet exchange in terms of QCD (quark and gluon dynamics)!

Diffractive DIS: Probing $I\!P$ Structure

Inclusive DIS: Structure Function $F_2(x, Q^2)$:

$$\frac{\mathrm{d}^2\sigma(incl.)}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{xQ^4}\left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2)$$

Diffractive DIS: Diffractive Structure Function F_2^D:

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

[integrating over t]

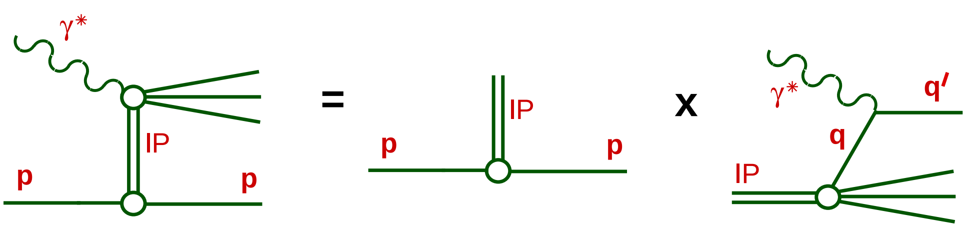
→ point-like virtual γ^* in DIS probes structure of colour singlet exchange!

QCD factorization in diffractive DIS: [proof Collins 1998]

$$F_2^D(x, Q^2, x_{I\!P}, t) \sim C_i \otimes p_i^D \quad (+\text{higher twist})$$

– C_i: coefficient functions, as in incl. DIS
– p_i^D: diffractive PDF's, evolve with DGLAP, universal

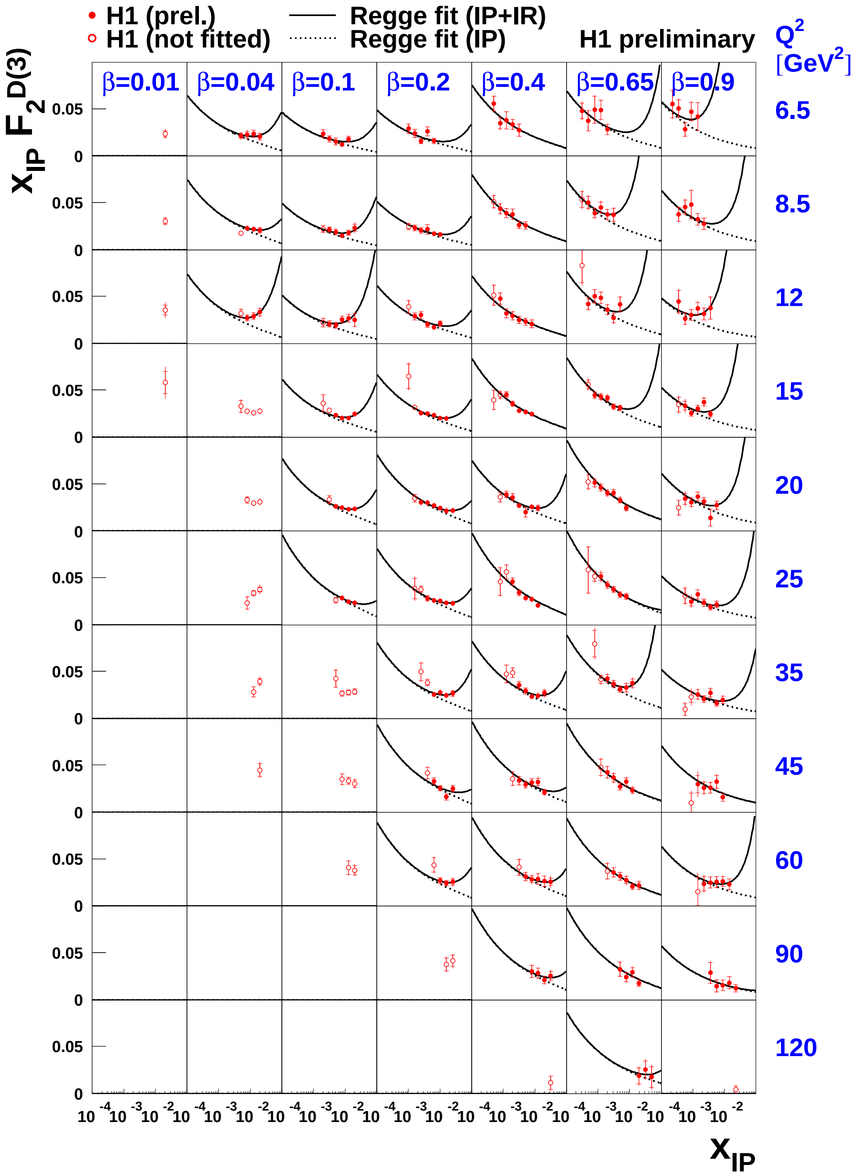
Add. assumption: factorizing $x_{I\!P}$ dependence ['Regge' fact.]



$$F_2^{D(3)}(x_{I\!P}, \beta, Q^2) = f_{I\!P/p}(x_{I\!P}) \times F_2^{I\!P}(\beta, Q^2)$$

The Diffractive Structure Function $F_2^{D(3)}$

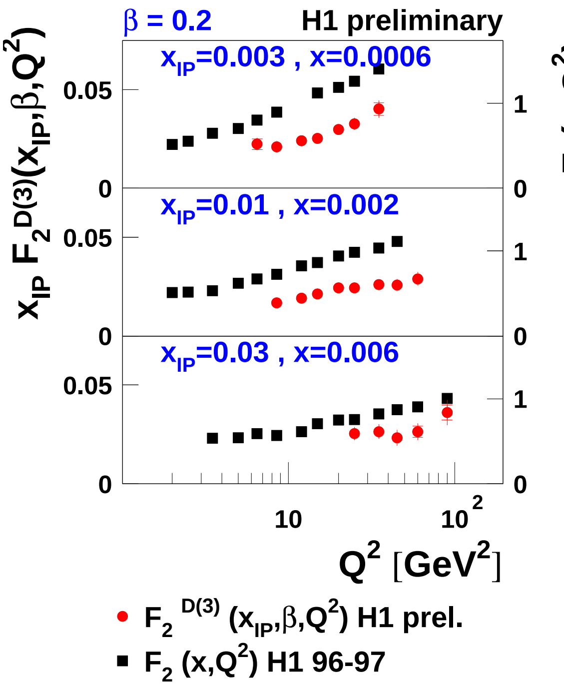
Released for EPS (Budapest) and LP (Rome) 2001 !

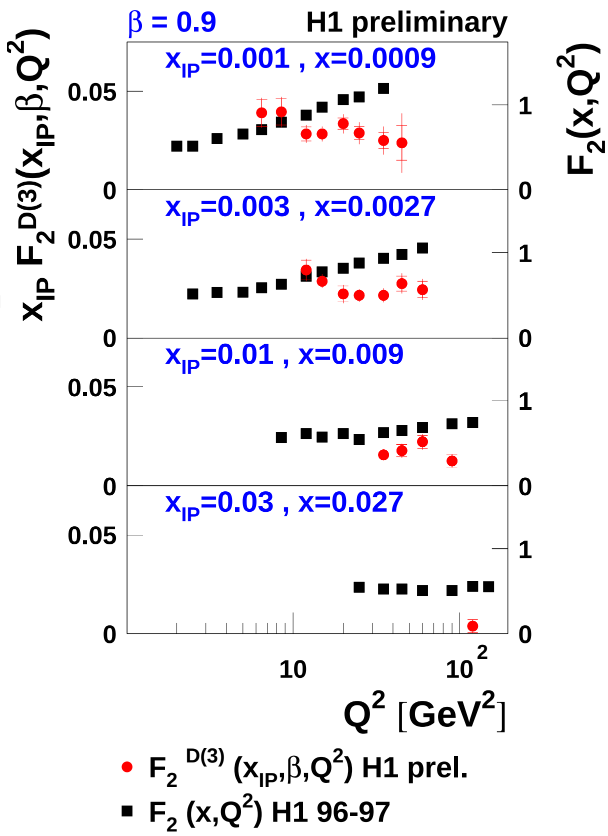


- Well described by factorizing $x_{I\!P}$ dependence (Regge factorization) with $\alpha_{I\!P}(0) = 1.17 > 1.08$
- Sub-leading exchange ($I\!R$) needed at high $x_{I\!P}$

Q^2 Dependence of F_2^D and F_2

Compare Q^2 dependence of F_2 and F_2^D at same fixed x:



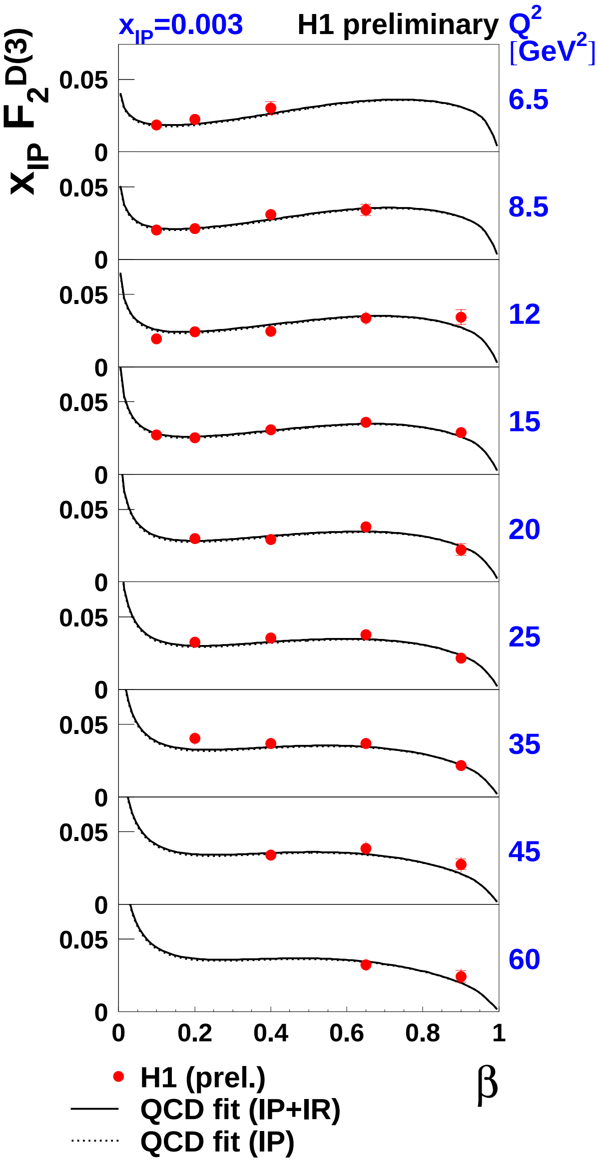


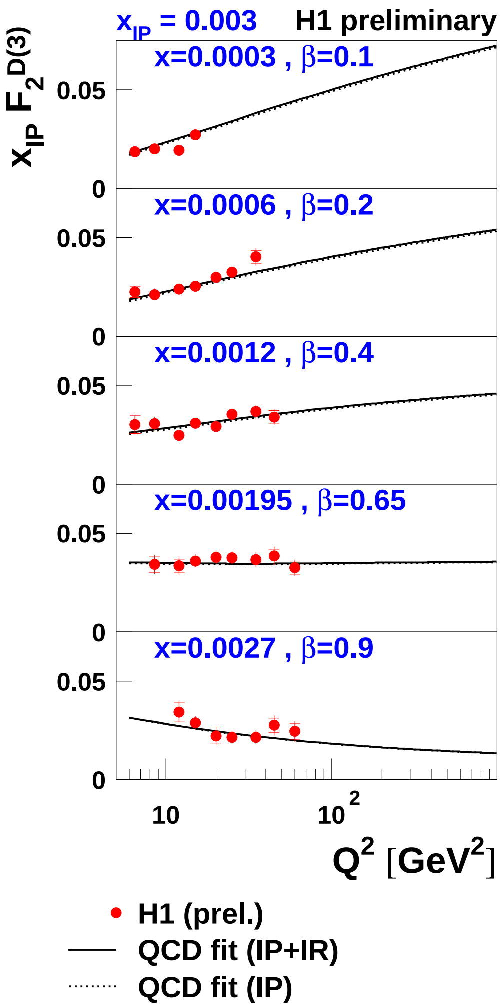
- Small β: F_2^D rises with Q^2 similar to F_2
- Large β: F_2^D falls with Q^2 where F_2 still rises!

→ Different dynamics at work!
→ Sign of Q^2 suppressed higher twist contributions ?!

β and Q^2 Dependence of $F_2^{D(3)}$

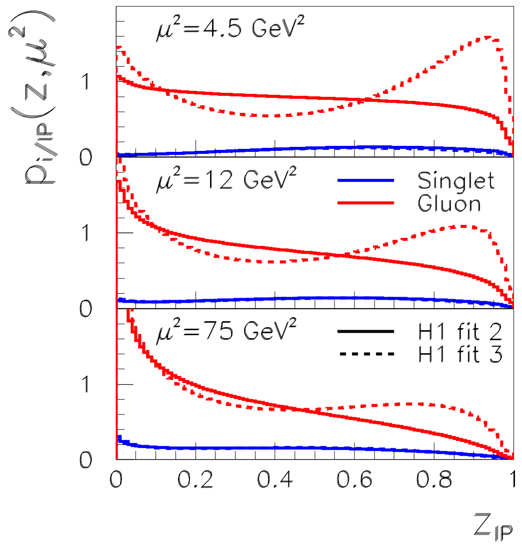
At fixed $x_{\mathbb{P}}$ (example: $x_{\mathbb{P}} = 0.003$):





- Positive scaling violations up to large values of β !
- Strongly suggestive of partonic structure dominated by gluons [splitting $g \rightarrow q\bar{q}$]
- Well described by DGLAP QCD fits with quark singlet + gluon distribution parameterized at $Q_0^2 = 2\ \mathrm{GeV}^2$

Diffractive PDF's from QCD fit



[from fits to previous H1 data]

Gluons

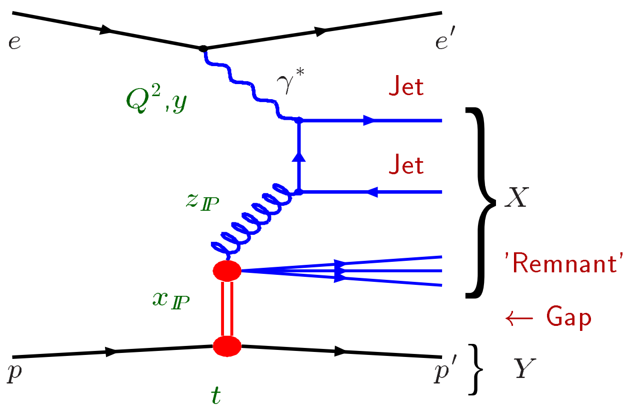
$\gg$

Quarks

Large uncertainty on gluon distribution
(indirect determination from scaling violations)

Diffractive Dijet Production

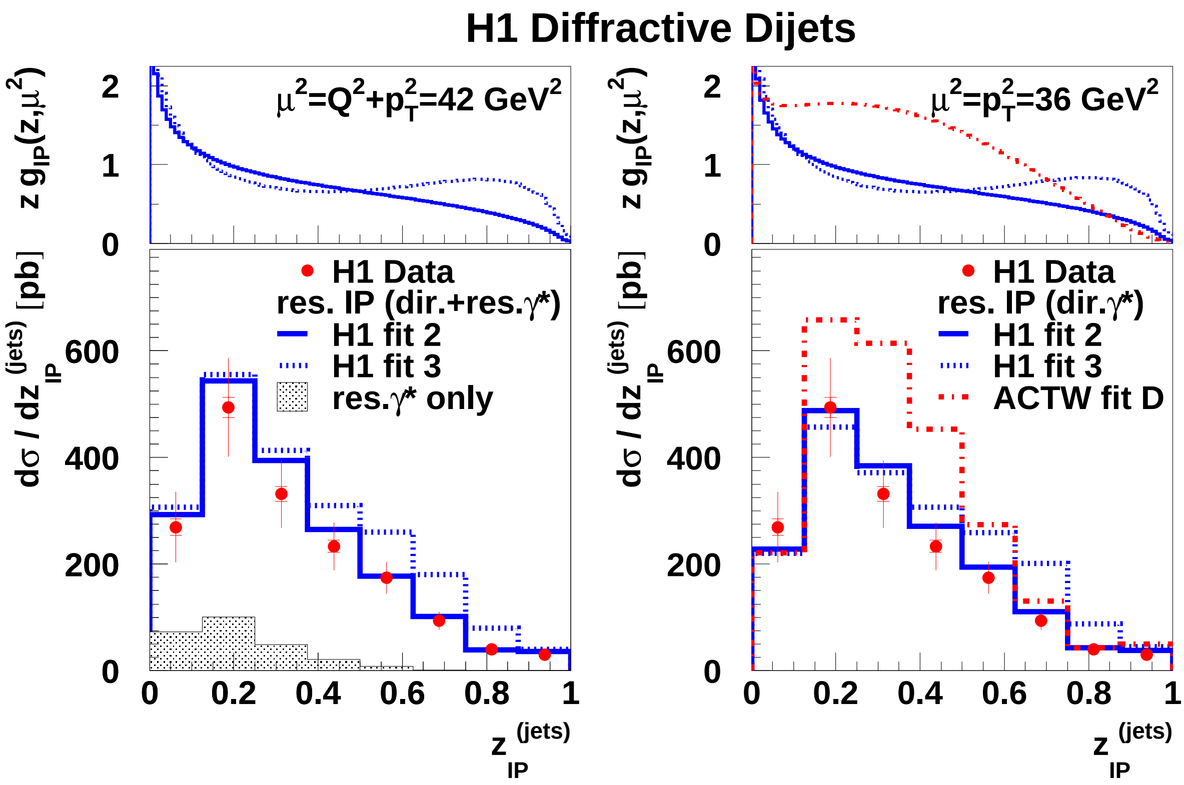
– Direct sensitivity to g^D through $\mathcal{O}(\alpha_s)$ process (BGF)
– Jet P_T provides second hard scale



... QCD factorization predicts that PDF's extracted from F_2^D should describe jet cross sections ...

Diffractive Dijet Cross Sections

Eur. Phys. J. C 20 (2001) 29 [hep-ex/0012051]



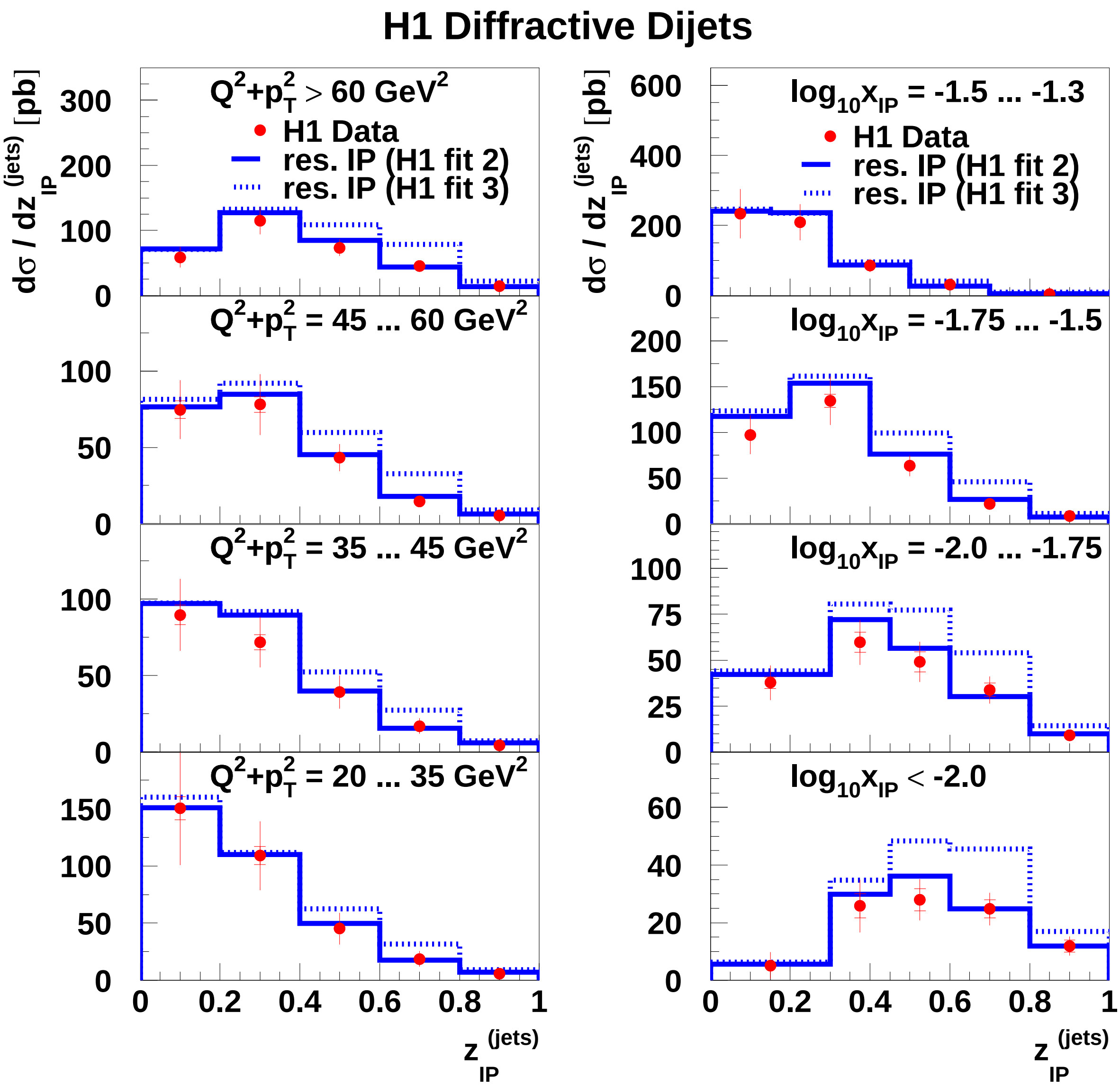
– $z_{I\!P}$: Momentum fraction of exch. entering hard scattering

$$z_{I\!P}^{(jets)} = \frac{Q^2+M_{jj}^2}{Q^2+M_X^2}$$

- Dijet cross sections give tight constraints on shape and normalization of g^D
- Very good description if "H1-Fit 2" parameterization is used

– Consistent with QCD factorization in diffractive DIS
– Strong support for gluon-dominated structure of colour-singlet exchange

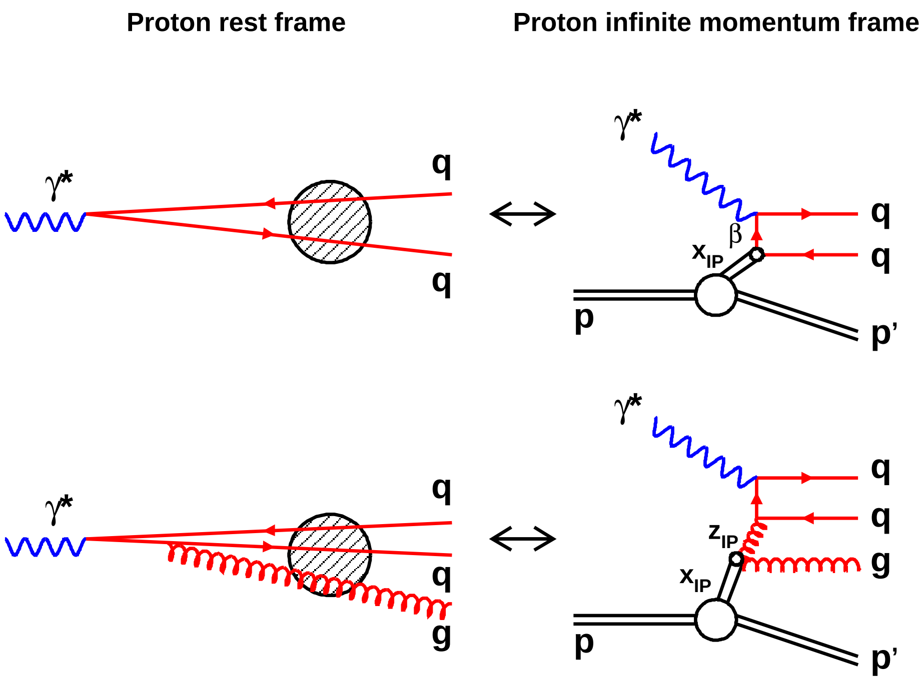
Features of Diffractive PDF's



- Data consistent with DGLAP evolution of PDF's with factorization scale $\mu^2 = Q^2 + p_T^2$
- Also compatible with factorization of $x_{I\!P}$ dependence $[f_{I\!P/P}(x_{I\!P}) \otimes p_i^D(z, \mu^2)]$ [Regge factorization]

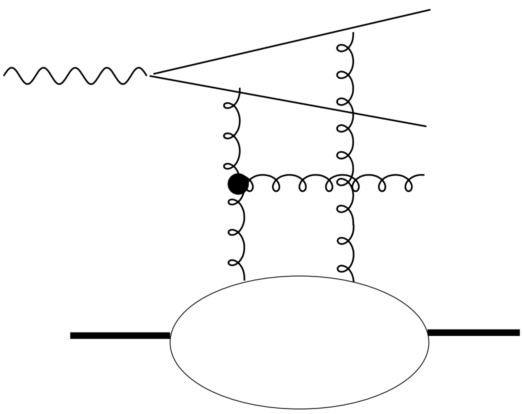
Dipole Models and 2-gluon Exchange

p at rest: $q\bar{q}$,$q\bar{q}g$,... fluct. of γ^* scatter elastically off p:



– $q\bar{q}g$ should dominate at large M_X, small β
– small-size, high-p_T dipole configurations: $\longrightarrow$ pQCD ?!

$$\sigma_{T,L}^{\gamma^* p} \sim |\Psi_{T,L}|^2 \otimes \sigma^2_{Dipole}$$

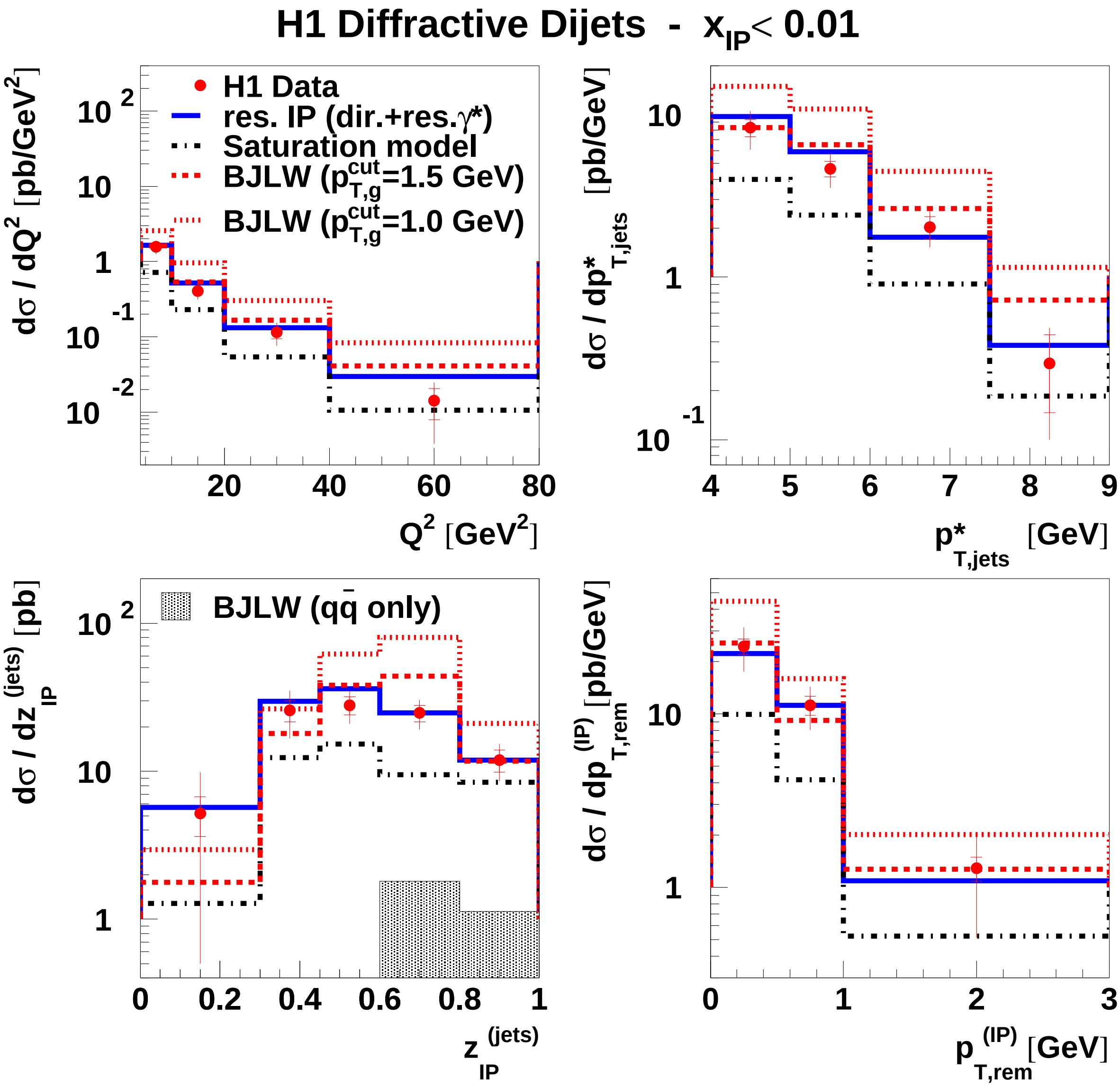


simplest configuration in QCD: 2 gluons

$$\hat{\sigma}^2 \sim |x_{I\!P}\, g(x_{I\!P}, \mu^2)|^2$$

Dipole Models and 2-gluon Exchange

Dijet Cross Sections for $x_{I\!P} < 0.01$:



- $q\bar{q}g$ configurations dominate over $q\bar{q}$
- 2-gluon QCD model (BJLW) can describe dijet cross sections (not suited for inclusive F_2^D)

Conclusions

- Diffraction in DIS at HERA: Virtual photon probes structure of colour singlet exchange (the "Pomeron")
- New measurements of diffractive structure function F_2^D have reached high precision, comparable with inclusive measurements !
- Proof of QCD factorization for diffractive DIS provides firm theoretical basis
- F_2^D and jet production measurements consistently confirm picture of diffr. PDF's heavily dominated by gluons and evolving with DGLAP
- Calculations based on 2-gluon exchange successful for high p_T final states (also for charm production)