Partonic Interpretation of Diffraction at HERA

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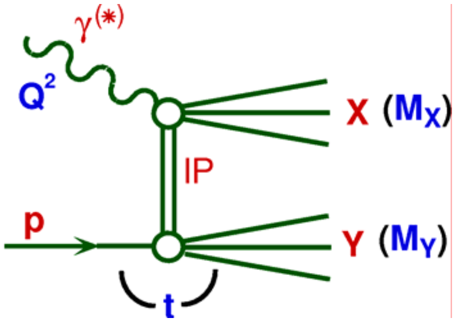
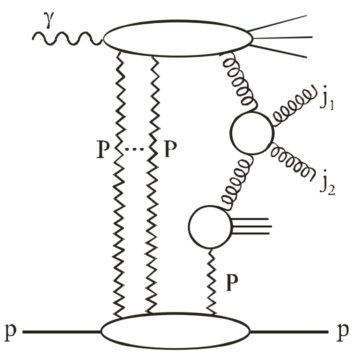
- Introduction
- Experimental Methods
- General Features of Diffraction at HERA
- Partonic Structure from QCD Fits
- Tests of QCD Factorization
- Summary and Conclusions





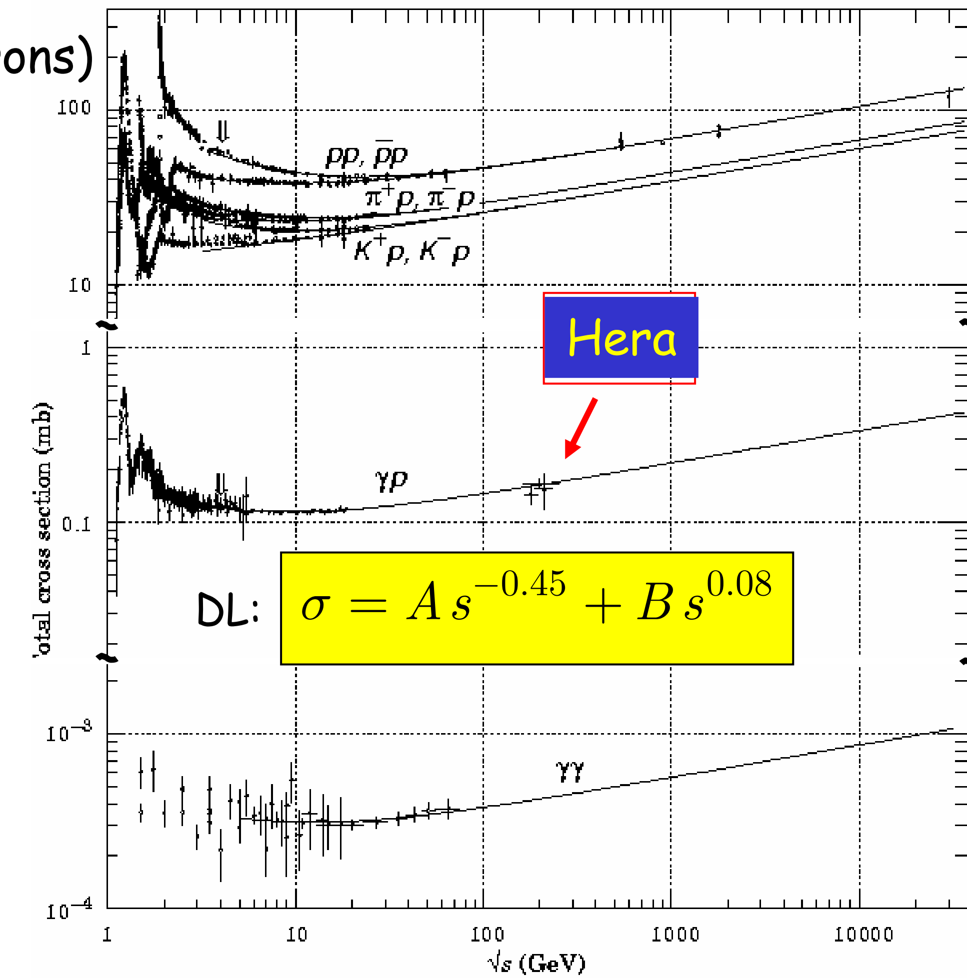
Introduction

- All total cross sections involving strongly interacting particles (hadrons) show approximate constancy, more precisely: universal slow rise, towards high energy

- „constant" cross sections arise from Diffractive Phenomena

- Regge theory: trajectory in the t-channel
  vacuum QNE = „Pomeron"

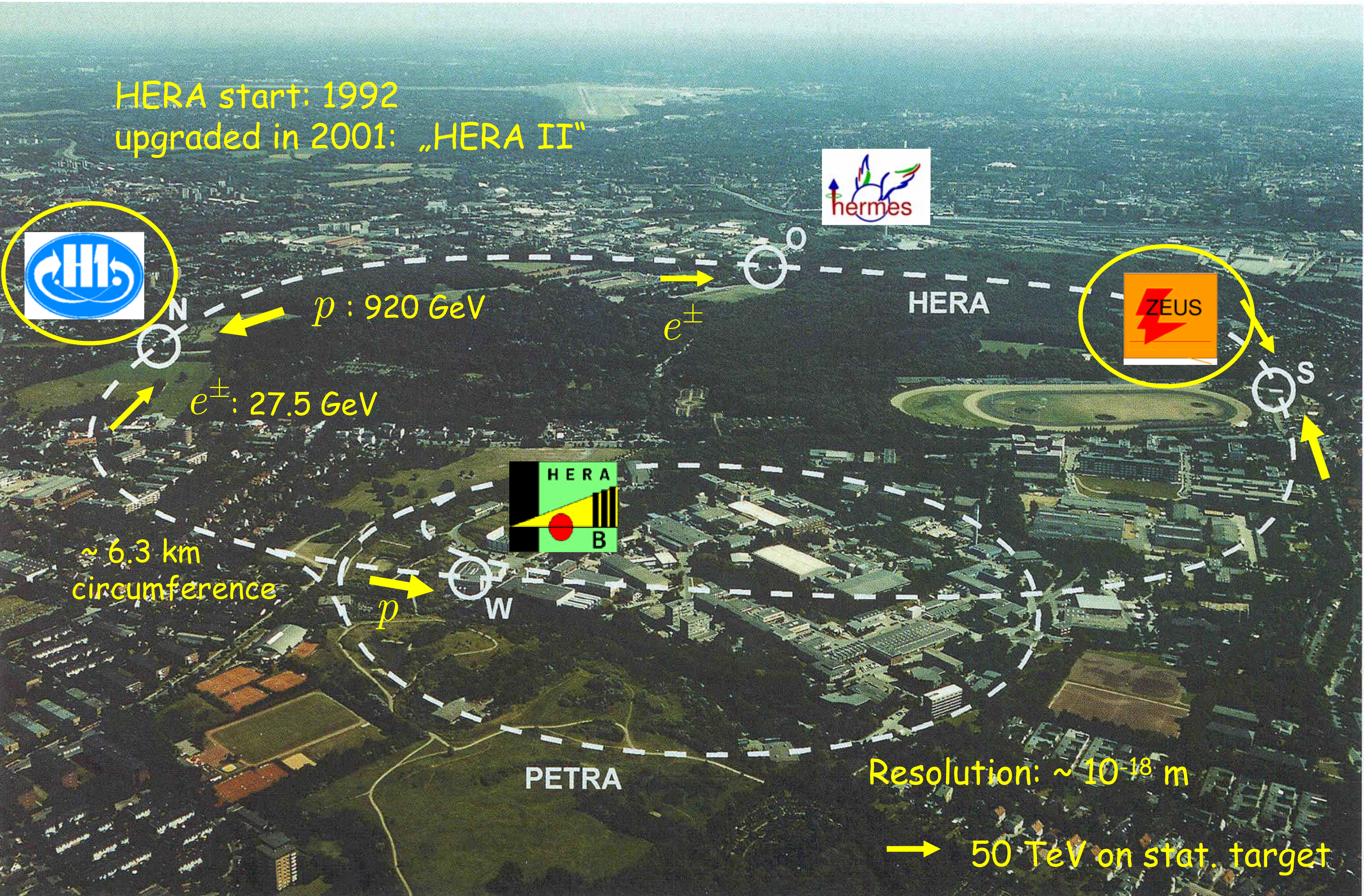
- QCD: colorless exchange
  Gluons, quarks in a color singlet ?



DL: $\sigma = A\,s^{-0.45} + B\,s^{0.08}$

What is diffraction in the partonic language ?

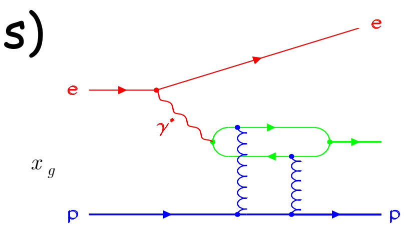
HERA – the world's largest electron microscope
(Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany)



Diffraction in $\gamma^* p$ Interactions

various phenomenological models:

- Regge-motivated (factorizable Pomeron)
- Soft Color Interactions
- Color Dipole Models (2 gluon exchange models, saturation models)



Diffraction very interesting wrt saturation: may be the first place where saturation shows up.

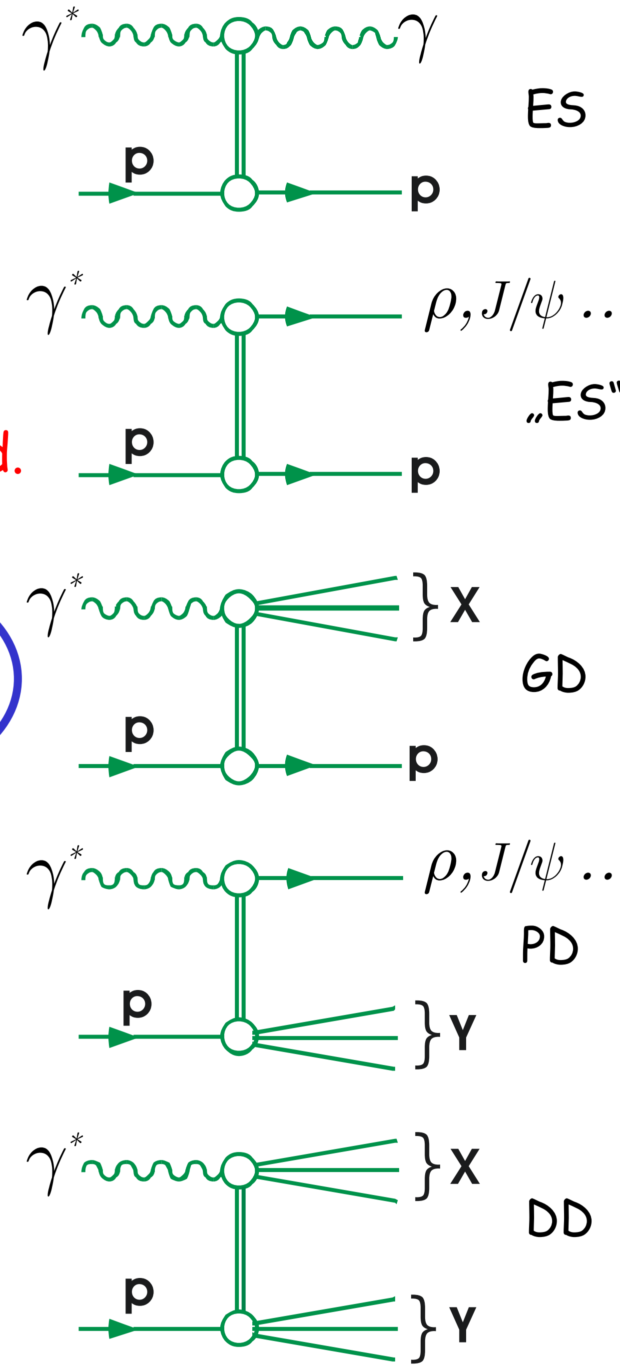
DVCS

quasi-elastic VM prod.

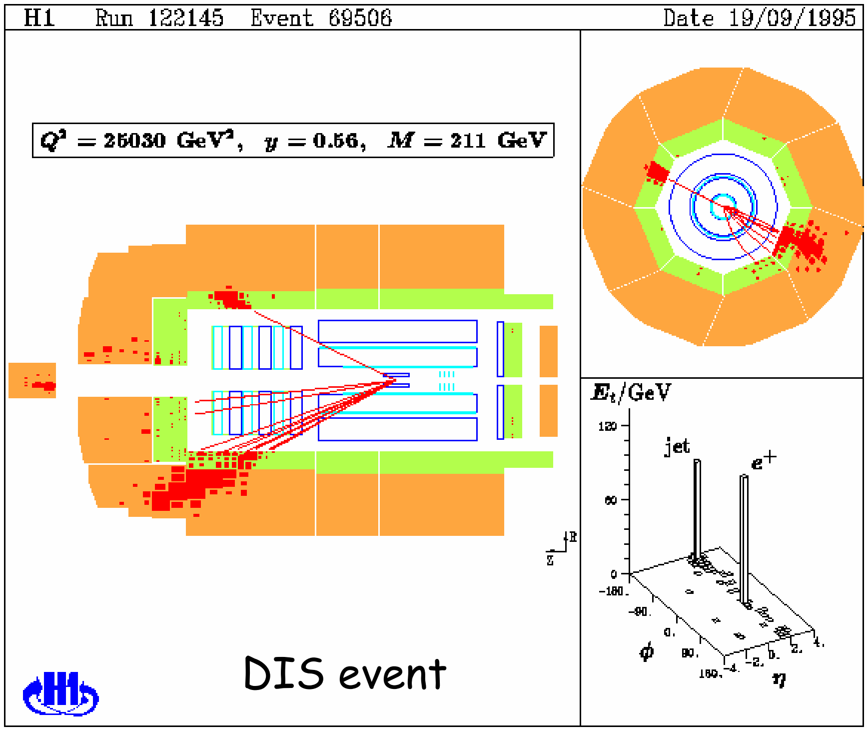
photon dissoc.

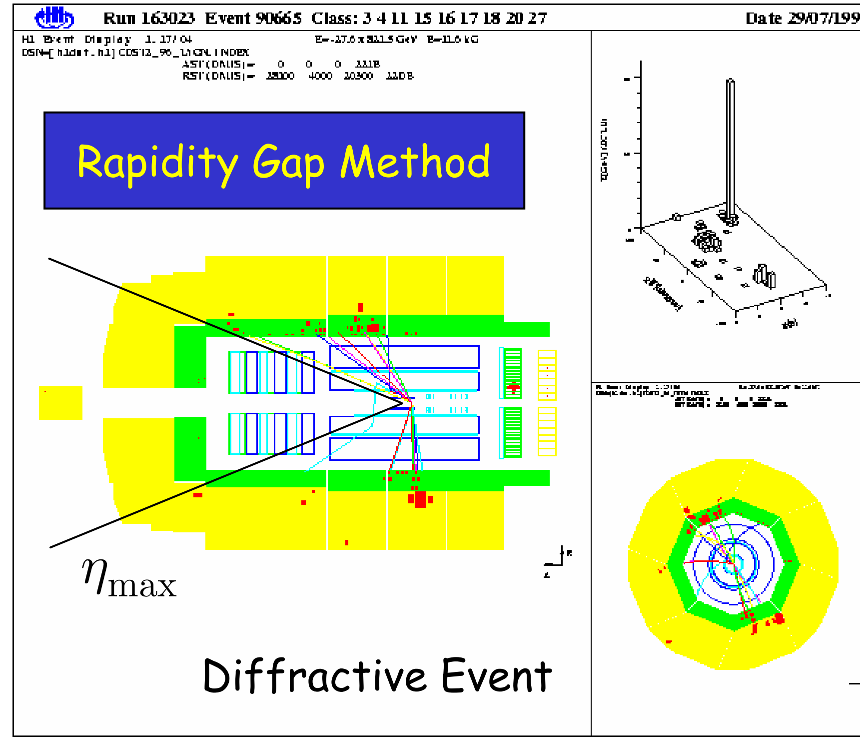
proton dissoc.

$W_{\gamma^* p}$

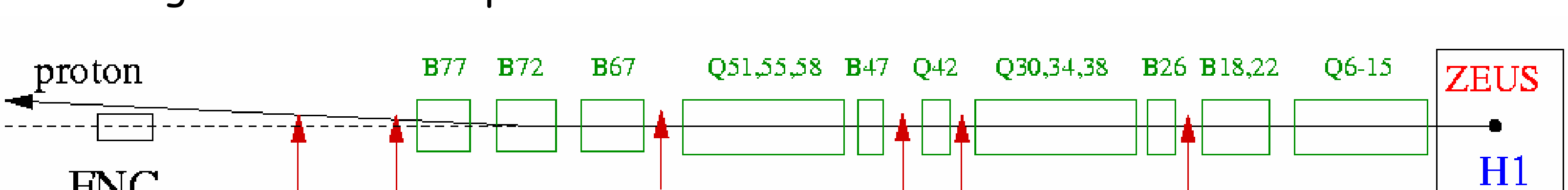


Experimental Techniques





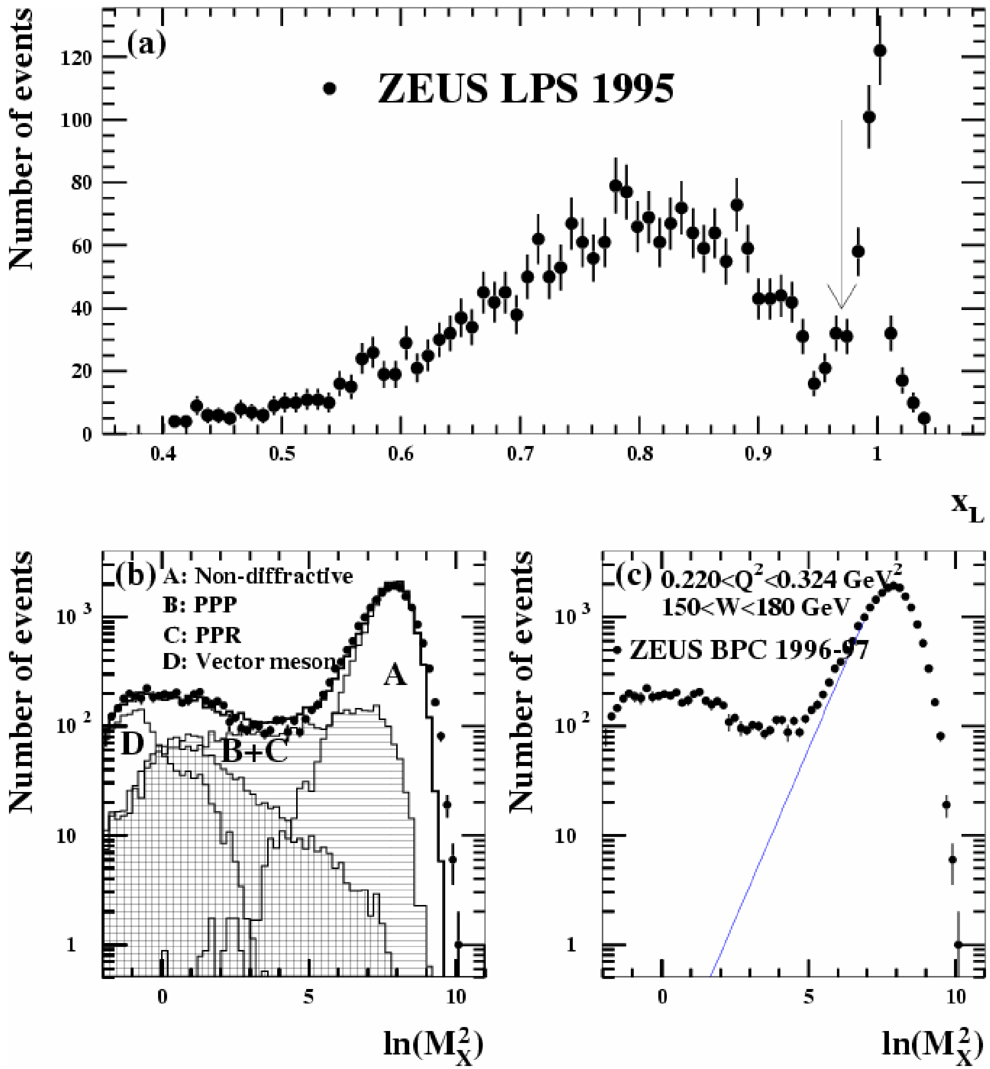
Measuring the scattered proton



Forw. Neutron C.

FPS Forw. Pr. Spect. LPS Leading Proton Spectrometer

Experimental Techniques (cont.)



LPS Method

proton scattered at small angles, measured in LPS, get longitudinal and transverse momentum components

$$x_L = p_L \,/\, p$$

M_X Method

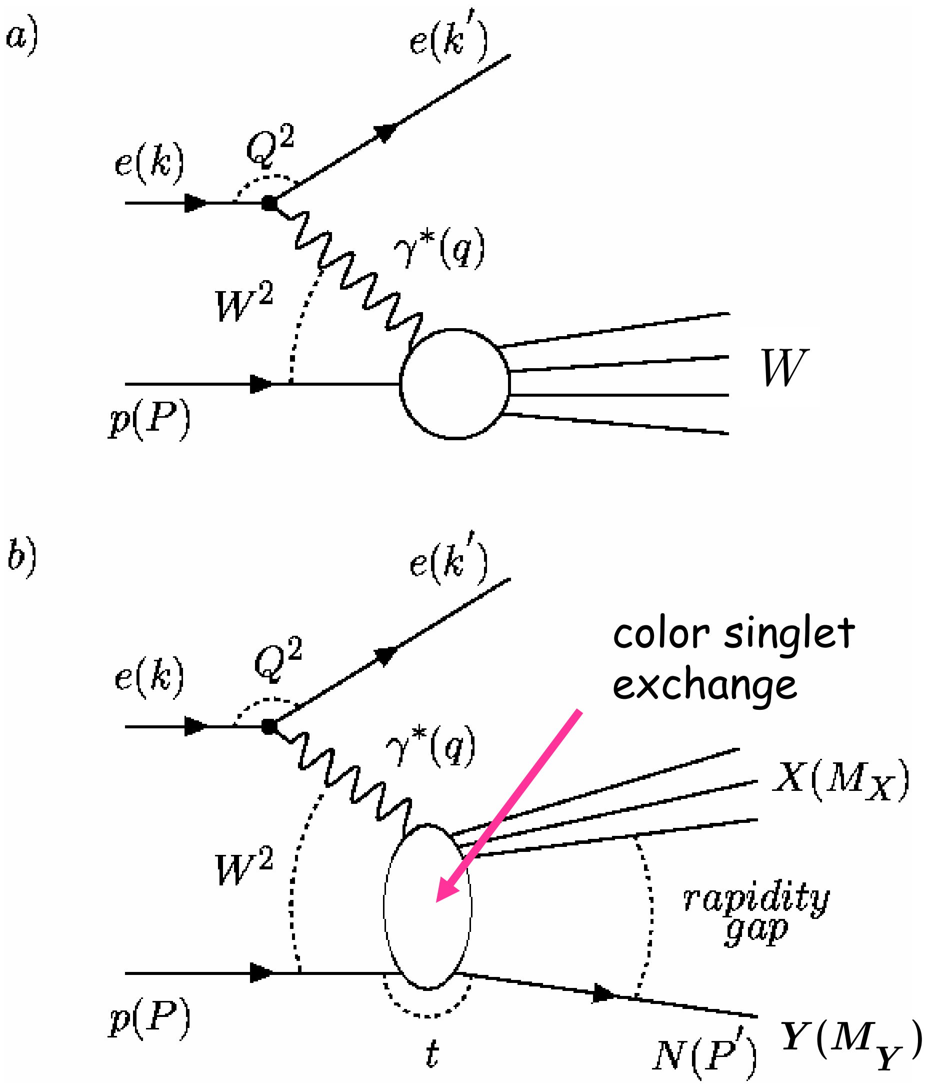
QCD radiation suppressed between struck quark and proton remnant ➡ rapidity gap

M_X distribution flat in $\ln M_X^2$

fit to non-diff mass distribution:

$$\frac{dN}{d\ln M_X^2} = D + Ce^{B\ln M_X^2}$$

Probing the Partonic Nature of Diffractive Exchange



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

(momentum transfer)^2

virtuality of γ^*

→ („size" of the probe)$^{-1}$

$$x = \frac{Q^2}{2\,P \cdot q}$$

fraction of the proton momentum carried by the charged parton

$$y = \frac{P \cdot q}{P \cdot k}$$

fraction of the electron energy carried by the virtual photon („inelasticity")

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

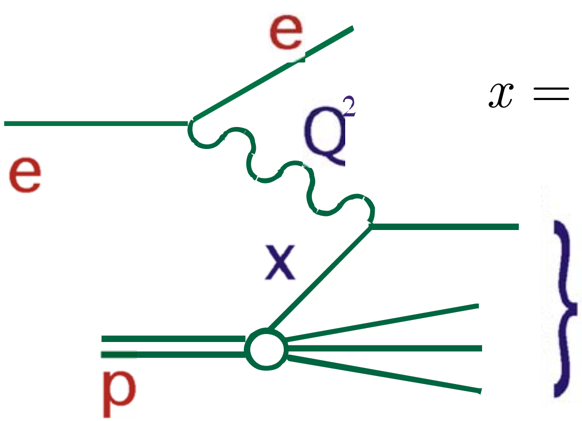
center of mass energy of ep system

$$W^2 = (q + P)^2$$

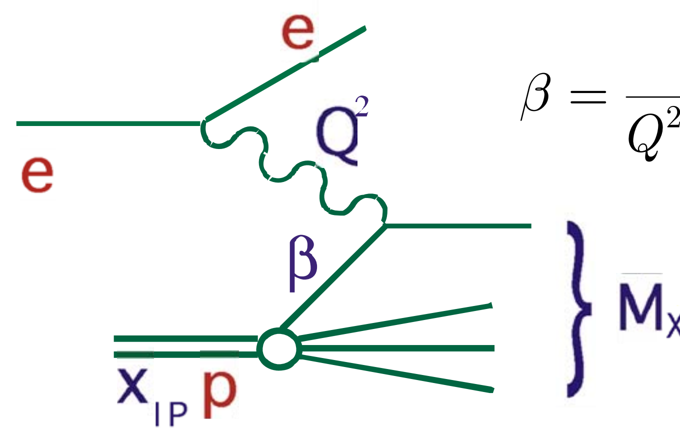
(mass)^2 of $\gamma^* p$ system

$$Q^2 = sxy$$

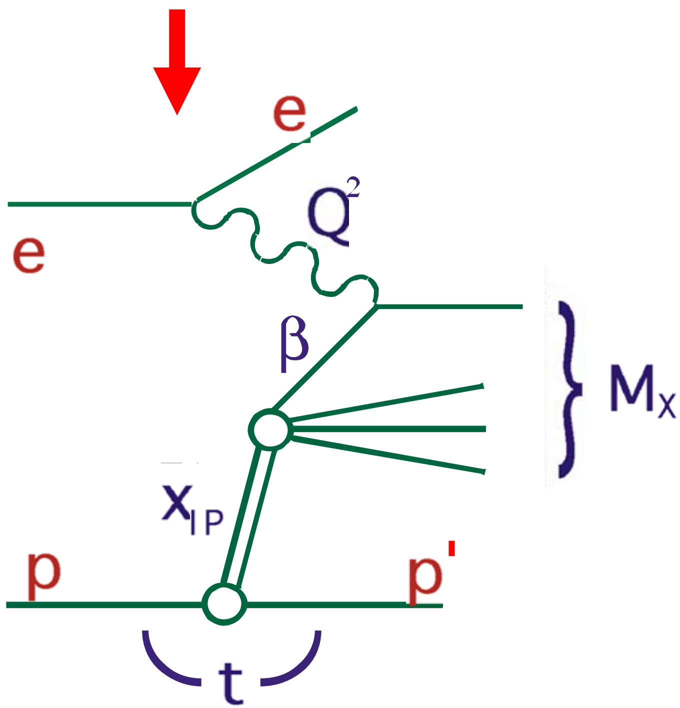
Probing the Partonic Nature of Diffractive Exchange (cont.)



$$x = \frac{Q^2}{Q^2 + W^2}$$



$$\beta = \frac{Q^2}{Q^2 + M_X^2}$$



$$x_{\mathbf{P}} = \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

x (DIS) $\Leftrightarrow$ β (Diff. DIS)

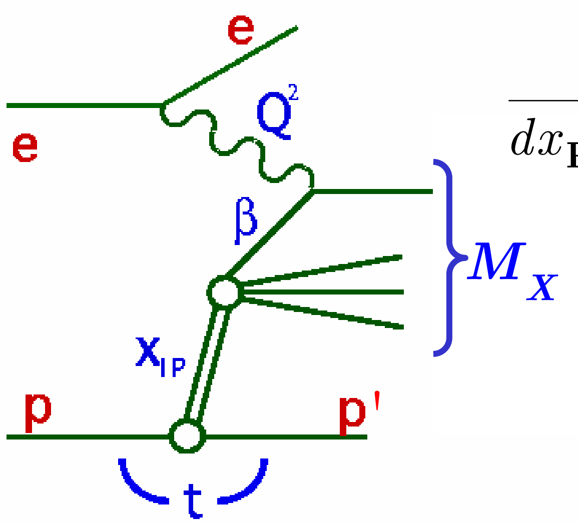
momentum fraction of color singlet exchange relative to the proton

$$\beta = \frac{Q^2}{Q^2 + M_X^2} = x \,/\, x_{\mathbf{P}}$$

momentum fraction of charged constituent of the diffractive exch., participating in the hard scattering

$t = (p - p')^2$ (momentum transfer)^2 at proton vertex

Diffractive Cross Sections and QCD Factorization



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

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

($F_L^{D(4)}$ can be neglected at low y)

(QCD) Factorization for diffractive scattering (Collins et al.):

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

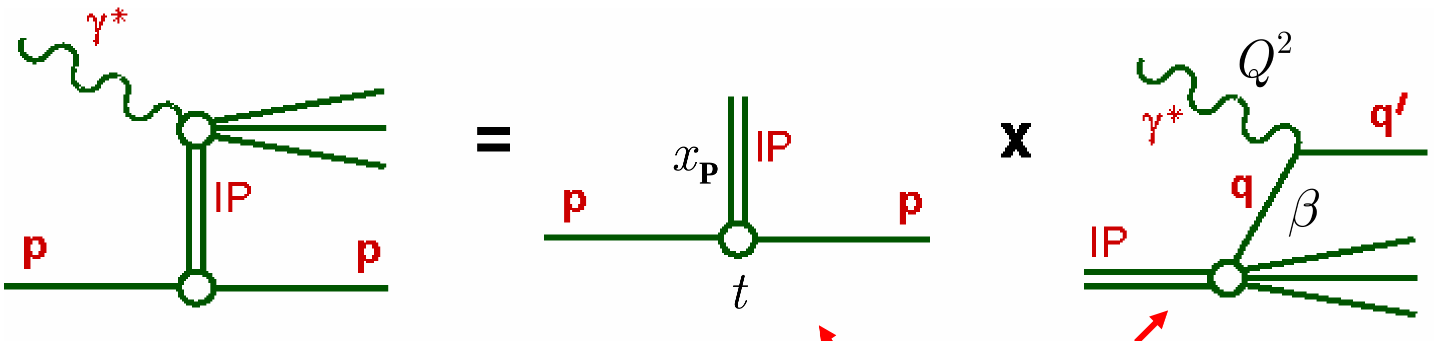
$f_i^D(\xi,Q^2,x_{\mathbf{P}},t)$ diffractive PDF's of flavor i in the proton, for fixed $x_{\mathbf{P}},t$ (evolves in Q^2 according to DGLAP)

$\hat{\sigma}^{\gamma^* i}(\xi,Q^2)$ universal, hard scattering cross section, calculable in pQCD

Regge Factorization

Additional assumption (no proof):

Regge factorization, the „Resolved Pomeron" (Ingelman-Schlein-Model)



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

Pomeron flux factor

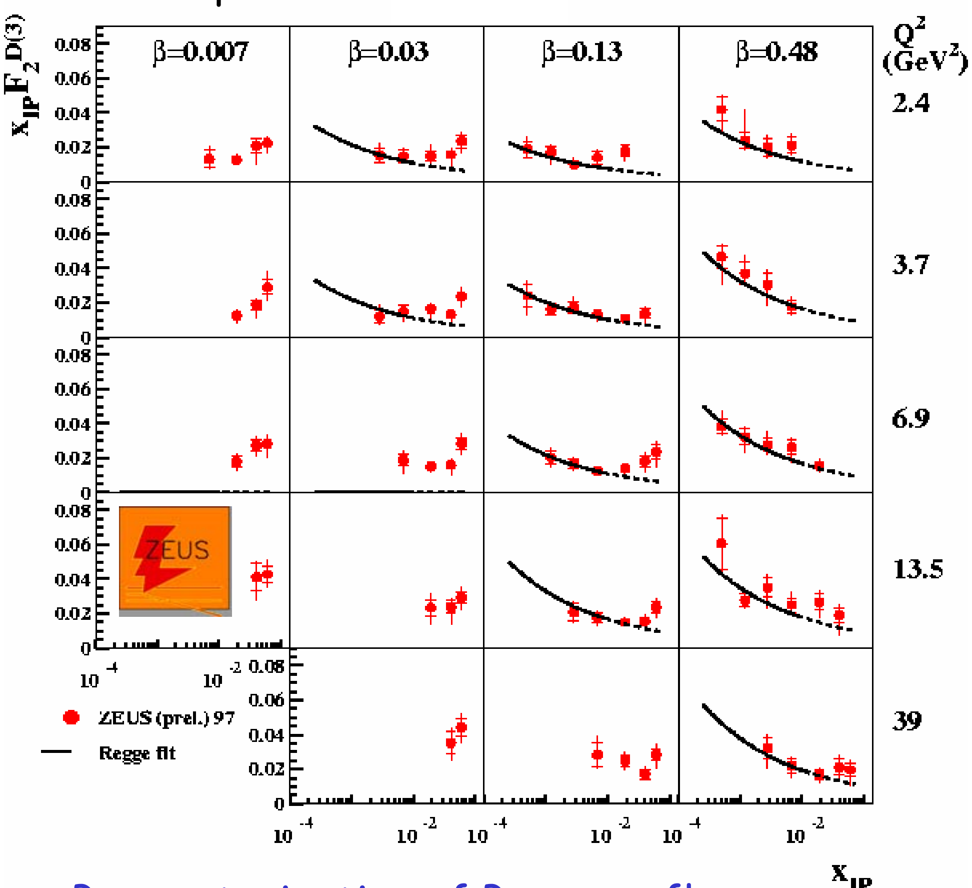
- shape of diffr. PDF's independent of $x_{\mathbf{P}}, t$
- normalization of F_2^D controlled by Pomeron flux

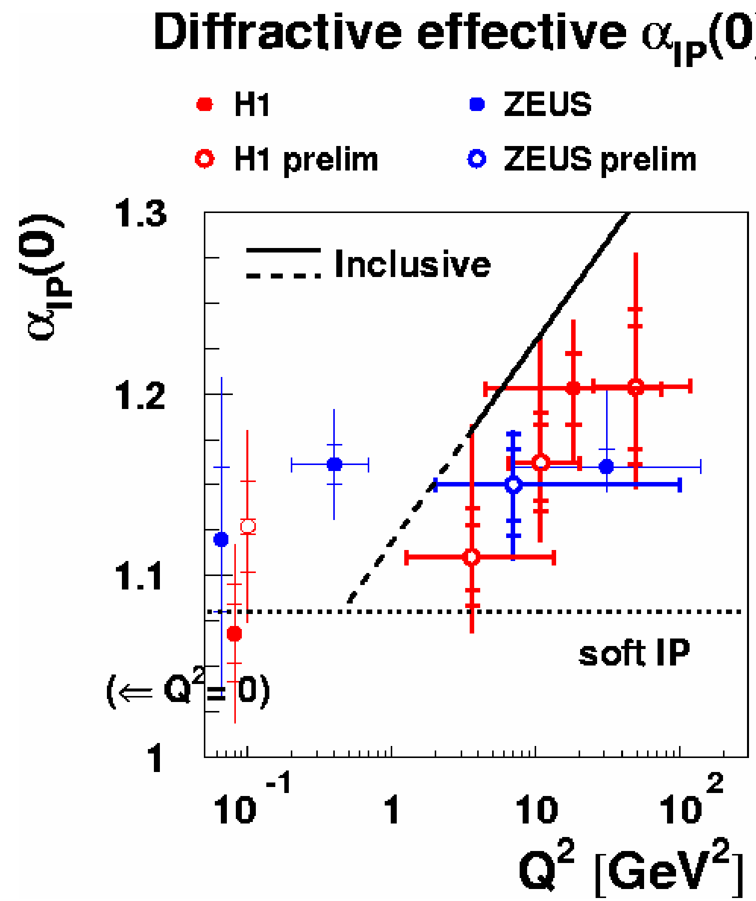
Integration over t (usually unobserved):

$$\sigma_r^{D(3)} = F_2^{D(3)} = \int dt F_2^{D(4)}$$

Experimental Test of Regge Factorization

Example: ZEUS LPS data





Parameterization of Pomeron flux:

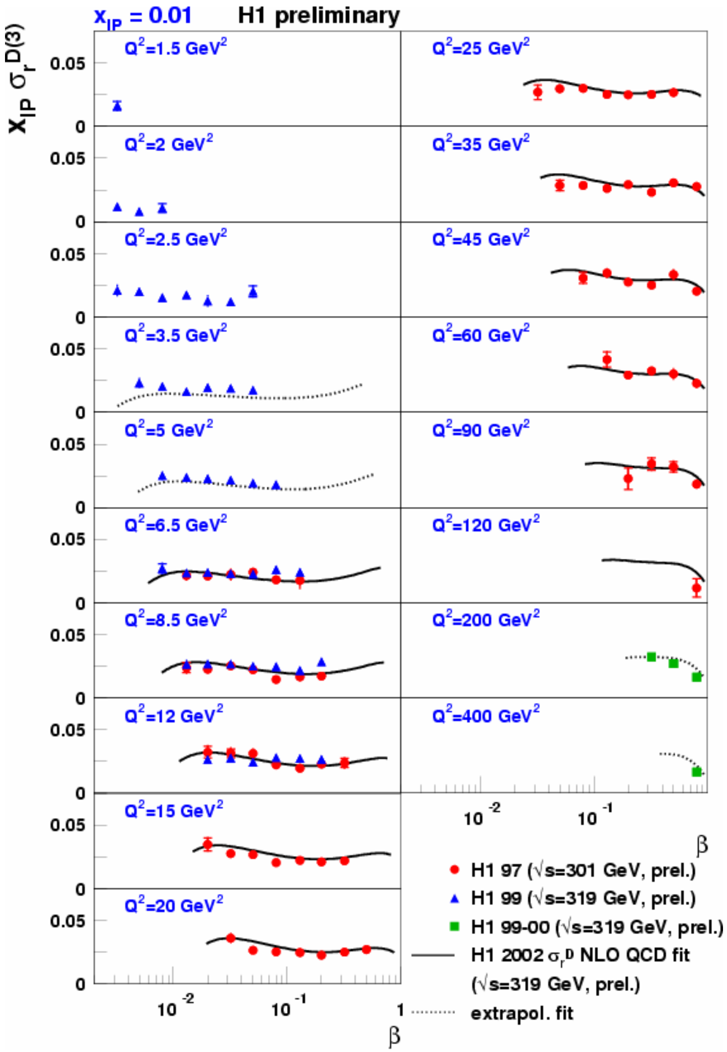
$$f_{\mathbf{P}/p}(x_{\mathbf{P}}, t) = \frac{1}{(x_{\mathbf{P}})^{2\tilde{\alpha}_{\mathbf{P}}(0)-1}} \int dt\, e^{B_{\mathbf{P}} t}$$

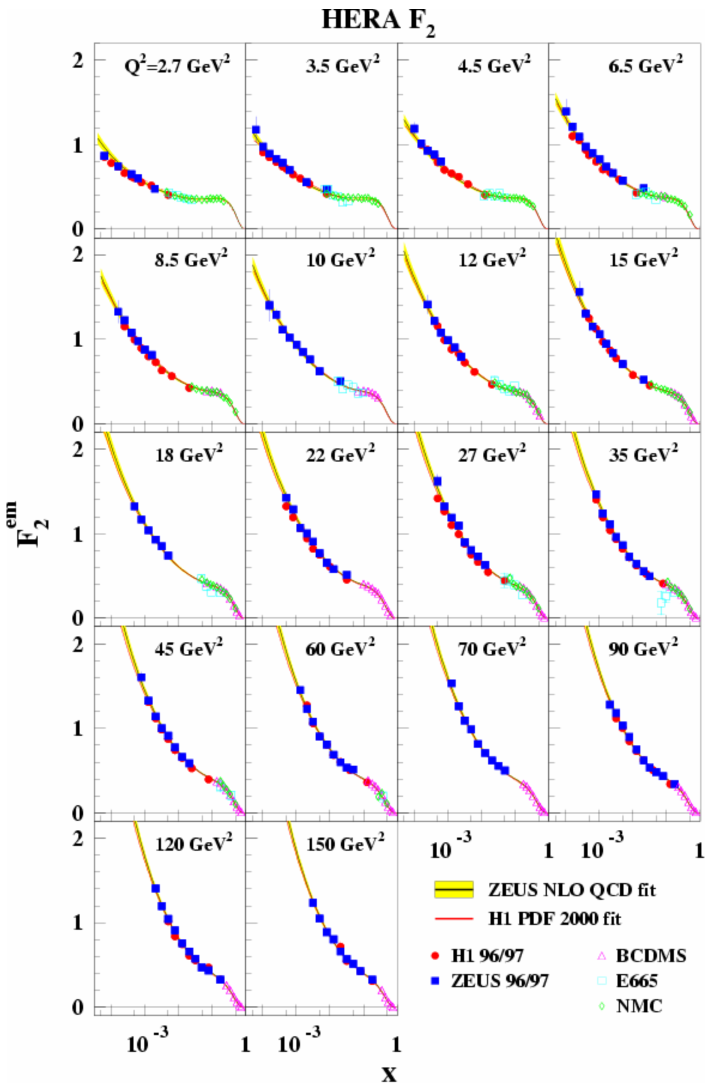
at low $x_{\mathbf{P}}$ $(x_{\mathrm{P}} < 0.01)$
data support Regge factorization

higher $x_{\mathbf{P}}$: sub-leading Reggeons necessary

Diffractive vs Inclusive DIS

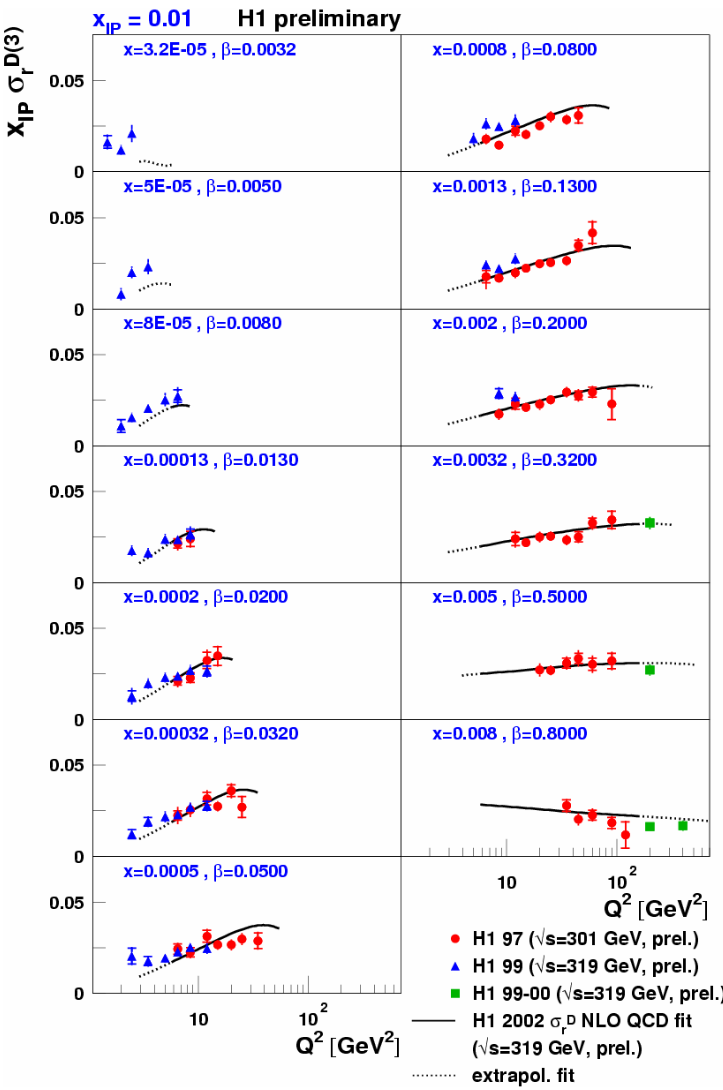
β (Diff. DIS) $\Leftrightarrow$ x (DIS)





weak dependence on β , similar to the photon (few partons ?)

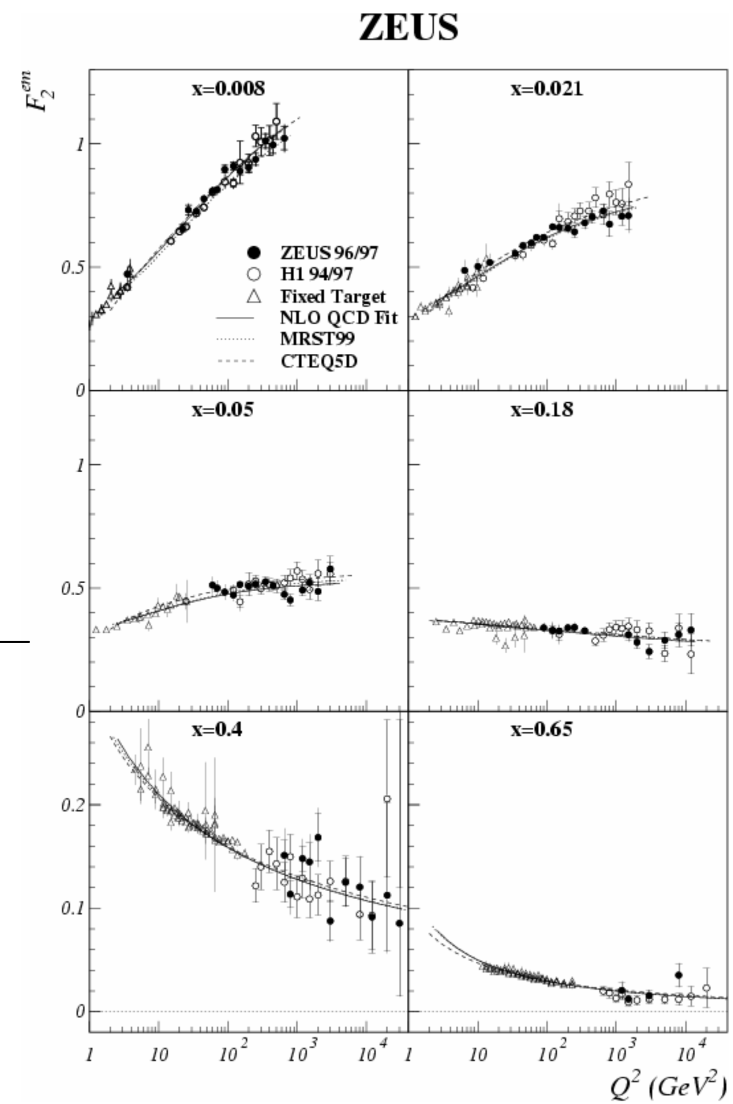
Diffractive vs Inclusive DIS (cont.): Q^2 dependence



diff:
scal.
viol.

$+ \leftrightarrow -$

~ 0.6



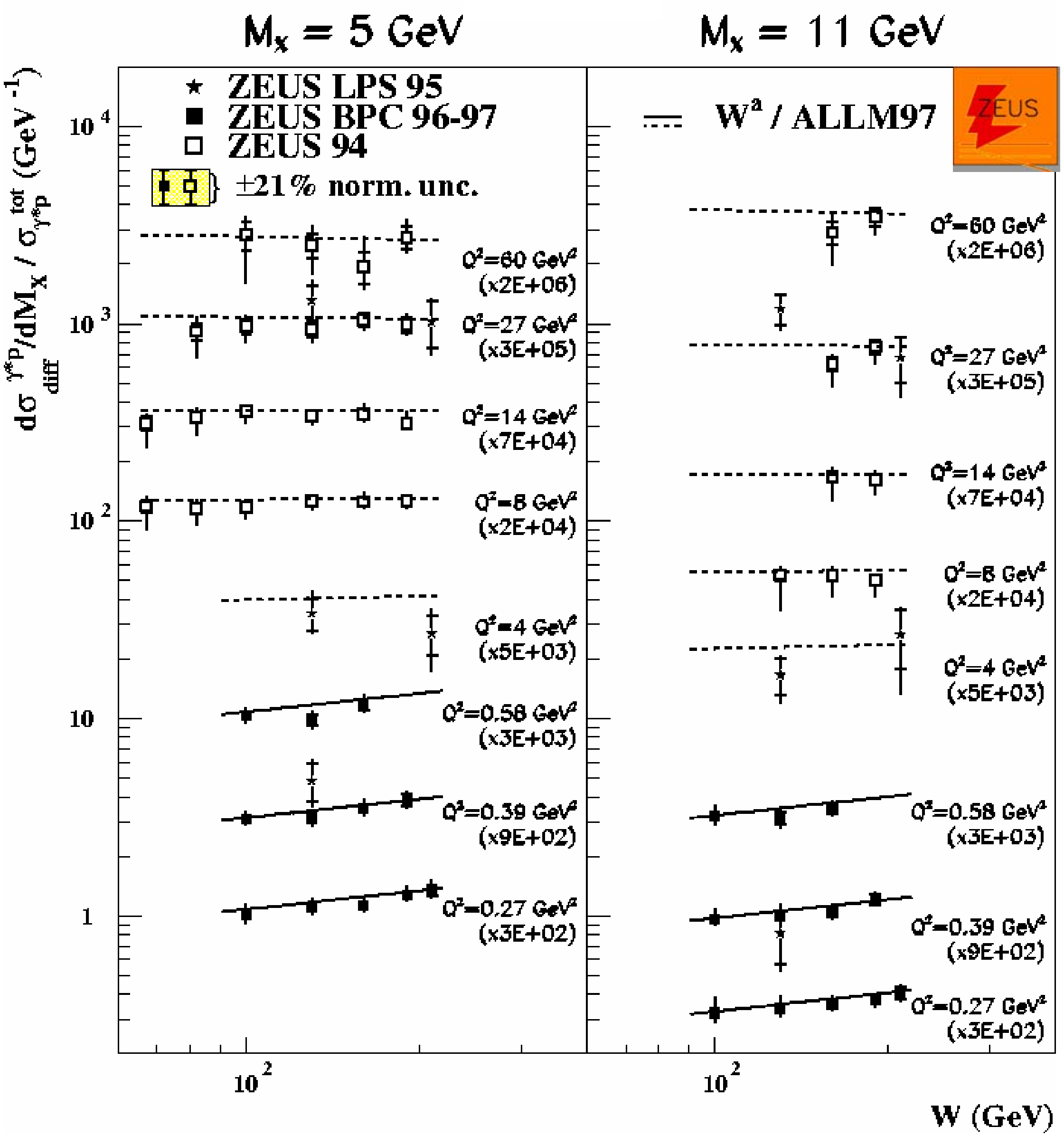
incl:
scal.
viol.

$+ \leftrightarrow -$

~ 0.15

Positive scaling violations up to large β : gluon-dominated („few“ gluons)

Diffractive vs Inclusive DIS (cont.): W dependence



$$R = \frac{\int dt\,(d\sigma_D^{\gamma^* p} \,/\, dM_X)}{\sigma_{tot}^{\gamma^* p}}$$

$$\approx \frac{(W^2)^{2(\tilde{\alpha}_{\mathbf{P}}-1)}}{(W^2)^{(\alpha_{\mathbf{P}}-1)}} \sim W^{\rho}$$

Transition region:

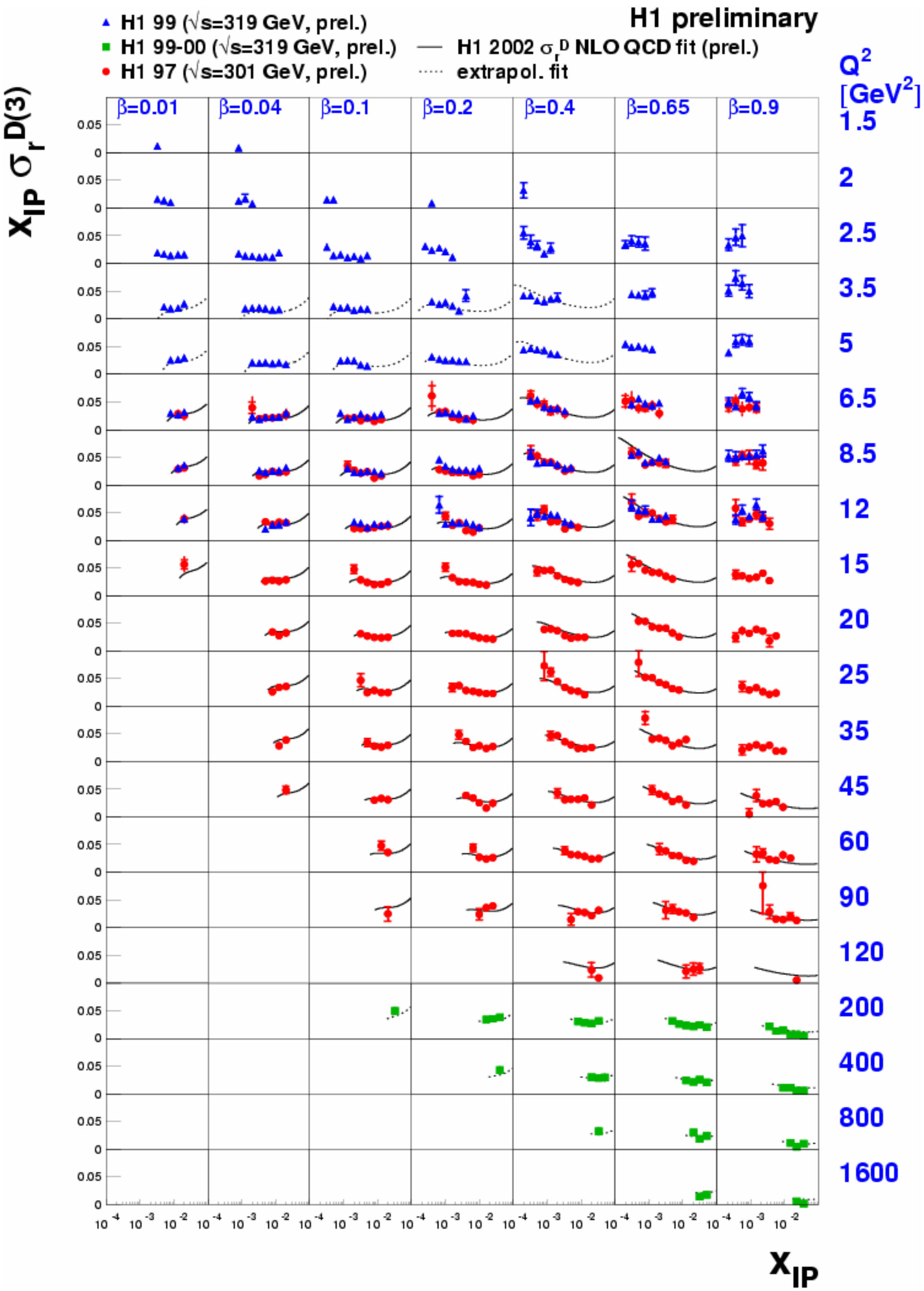
$$\rho = 0.24 \pm 0.07\,(\text{stat.})$$

diffractive steeper than inclusive (Regge-like)

DIS region:

$$\rho = 0.00 \pm 0.03\,(\text{stat.})$$

same energy dependence (QCD-like, e.g. saturation models)



Full HERA I data set

- $1.5 < Q^2 < 12\,\mathrm{GeV}^2$
- $6.5 < Q^2 < 120\,\mathrm{GeV}^2$

  (using rapidity gap method)

Statistics improved by a factor 5 !

- $2.5 < Q^2 < 20\,\mathrm{GeV}^2$

  (based on Forw. Proton Spect.)

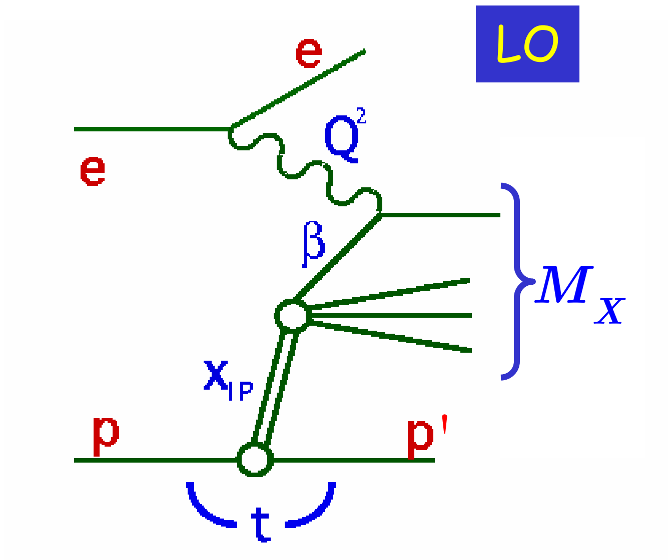
Agreement between both methods
(similar results from ZEUS)

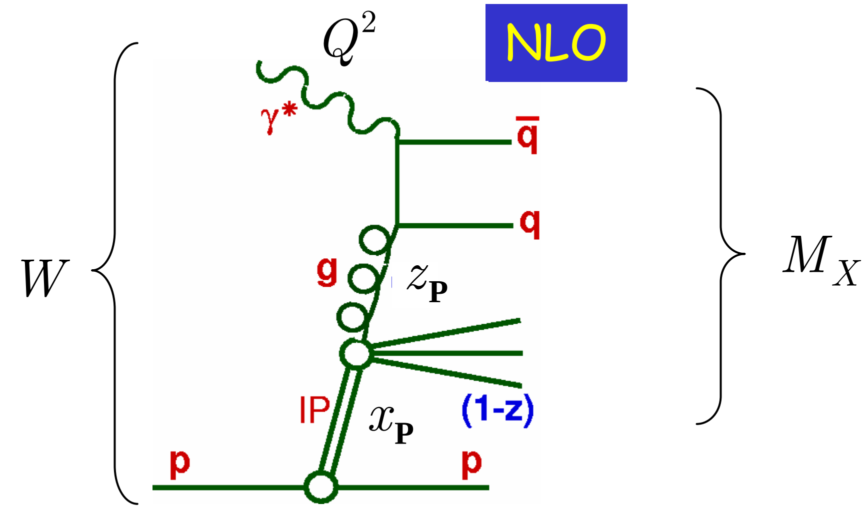
With high precision data now DGLAP analysis possible (similar to DIS):

→ partonic structure of diffraction

(curves from QCD fit, see below)

Partonic Structure of Diffraction: (LO, NLO DGLAP fits)





- ansatz for the partonic structure:

$$\Sigma = \sum_{i=\text{light}} e_i^2 (q(z,Q^2) + \overline{q}(z,Q^2))$$

$$u = d = s = \overline{u} = \overline{d} = \overline{s}$$

$$G = g(z,Q^2) \qquad Q_0^2 = 3 \text{ GeV}^2$$

(squared Chebychev polynomials (3 params) times exponential damping for $z \to 1$)

- charm via boson gluon fusion

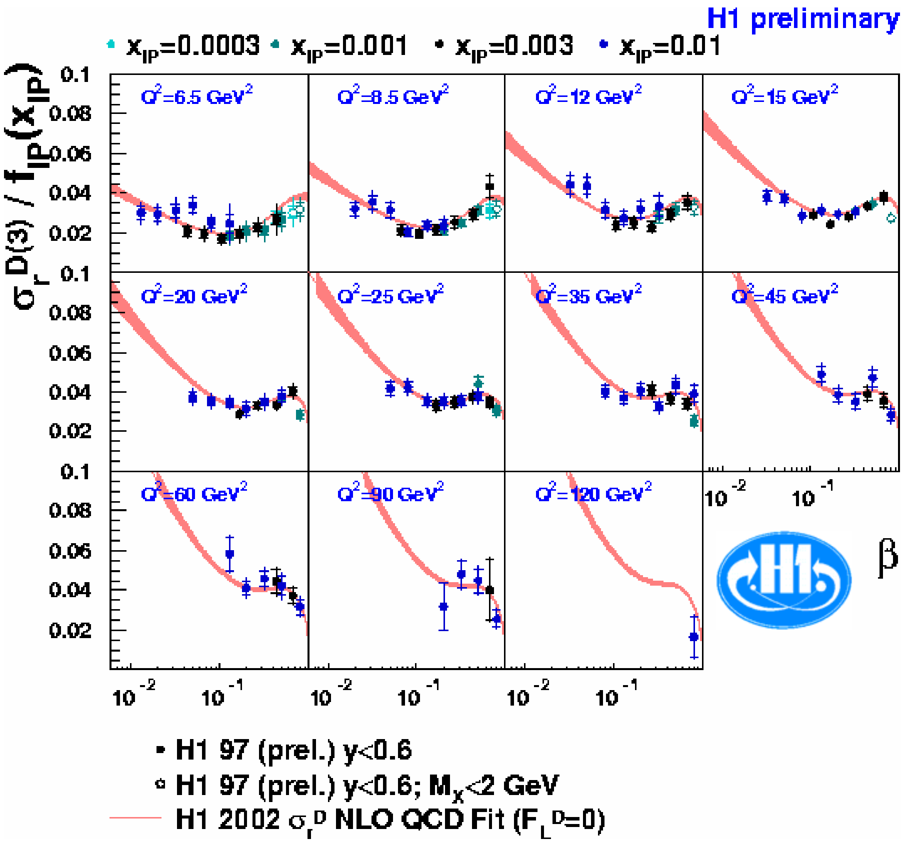
$$\Lambda = 200 \pm 30 \,\text{MeV},$$

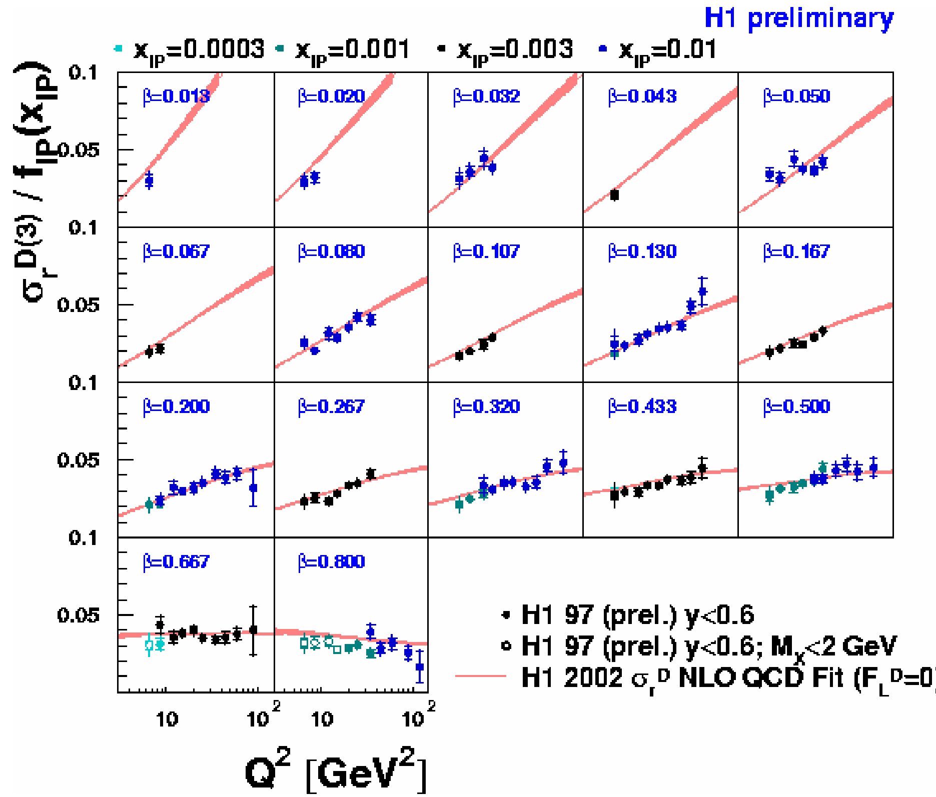
$$m_c = 1.5 \pm 0.1 \,\text{GeV}$$

- F_L^D via QCD relation

- NLO DGLAP fit for singlet and gluon contributions to $\sigma_r^{D(3)}(\beta, Q^2, x_{\mathrm{P}})$

Partonic Structure of Diffraction (cont.)





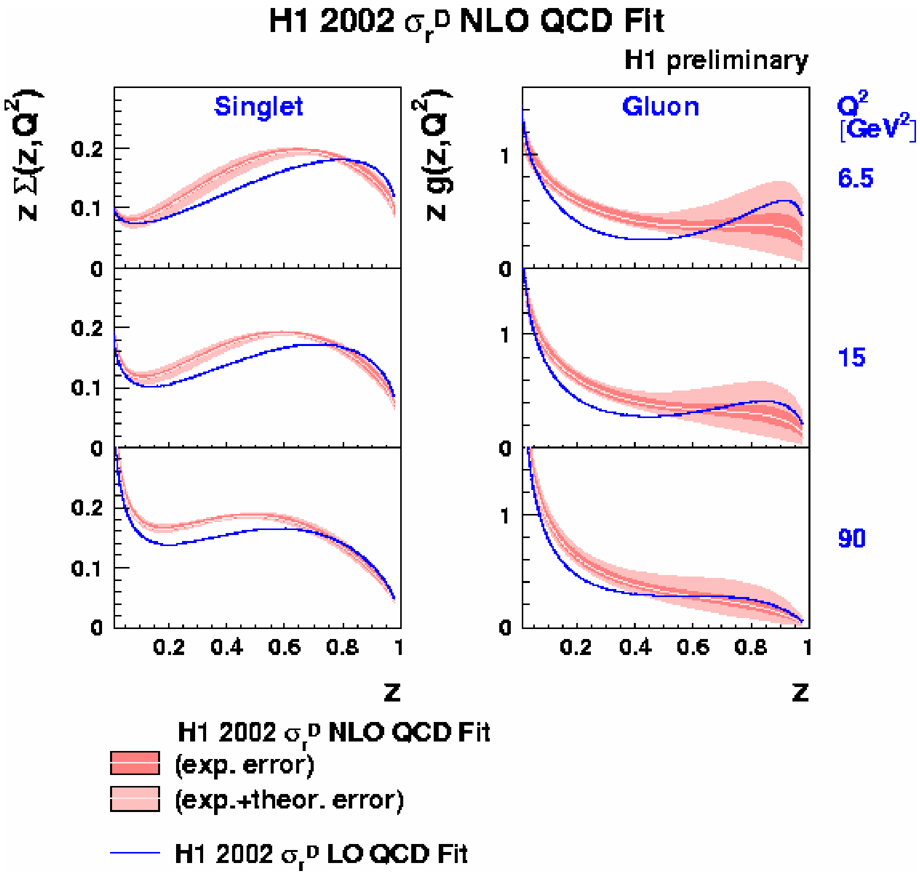
restrict data to $x_{\mathbf{P}} < 0.01$

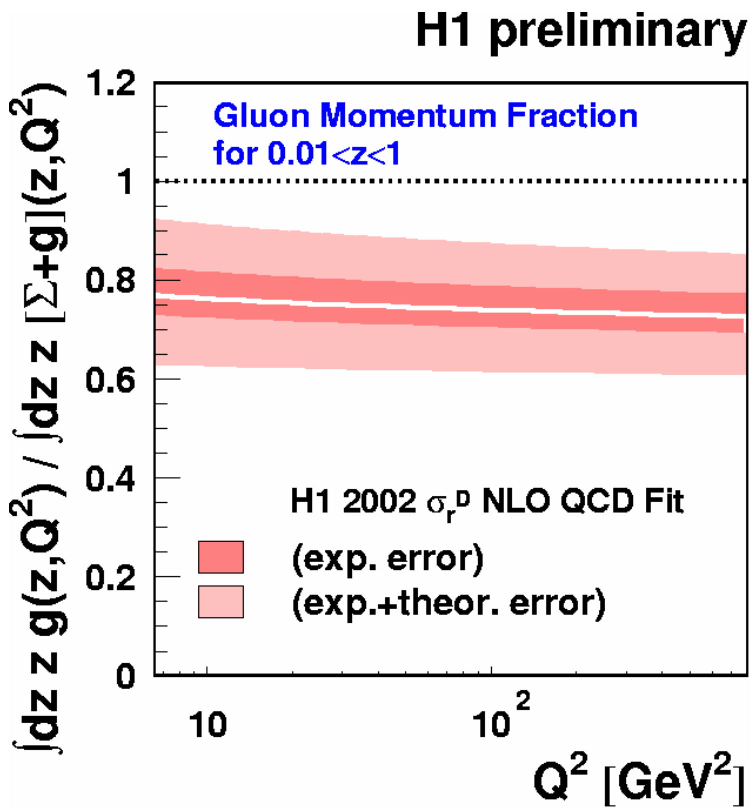
(pomeron factorization holds)

gluon distribition mainly determined from scaling violations

→ positive scaling violations even for large β : ***gluon dominates***

Partonic Structure of Diffraction (cont.)





Gluon momentum fraction:

$$(75 \pm 15)\,\%$$

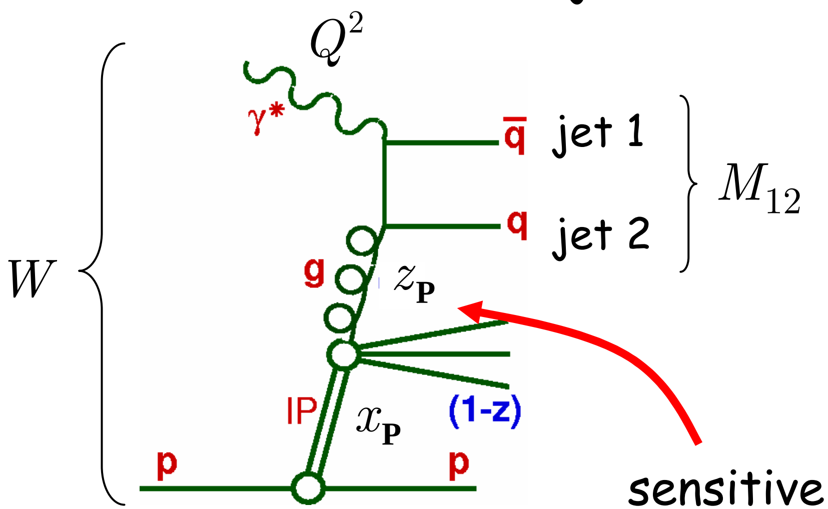
- Full propagation of experimental uncertainties (inner error bands)
- Theoretical uncertainties (outer bands): $\Lambda = 200 \pm 30\,\mathrm{MeV},\ m_c = 1.5 \pm 0.1\,\mathrm{GeV}$

Diffraction is gluon-dominated

Detailed Tests of the Partonic Picture

→ test QCD factorization using diffractive pdf's

di-jets



charm production

$\bar{c}$

$c \to D^*$

M_X

$$\beta = \frac{Q^2}{Q^2 + M_X^2}$$

LO: $z_{\mathbf{P}} = \beta$

higher order:

$$0 < \beta < z_{\mathbf{P}}$$

sensitive to the gluon content

Q^2: photon virtuality

W: $\gamma^* p$ cms emergy

M_X: mass of diffr. System

M_{12}: inv. 2-jet mass

$$x_{\mathbf{P}} = \frac{Q^2 + M_X^2}{Q^2 + W^2}$$ momentum fraction carried by pomeron

$$z_{\mathbf{P}} = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$ momentum fraction carried by the parton inside the pomeron entering the hard subprocess

Dijets in DIS Diffractive Scattering

- measure z_{P} directly from identified jets (CDF cone algo.)

→ new p_T cuts w.r.t. published data (Eur. Phys. J. C20 (2001) 29)

$p_{T,1(2)} > 5(4)\,\mathrm{GeV}$

(NLO unstable if $\mathrm{cut}(p_{T1}) \sim \mathrm{cut}(p_{T2})$)

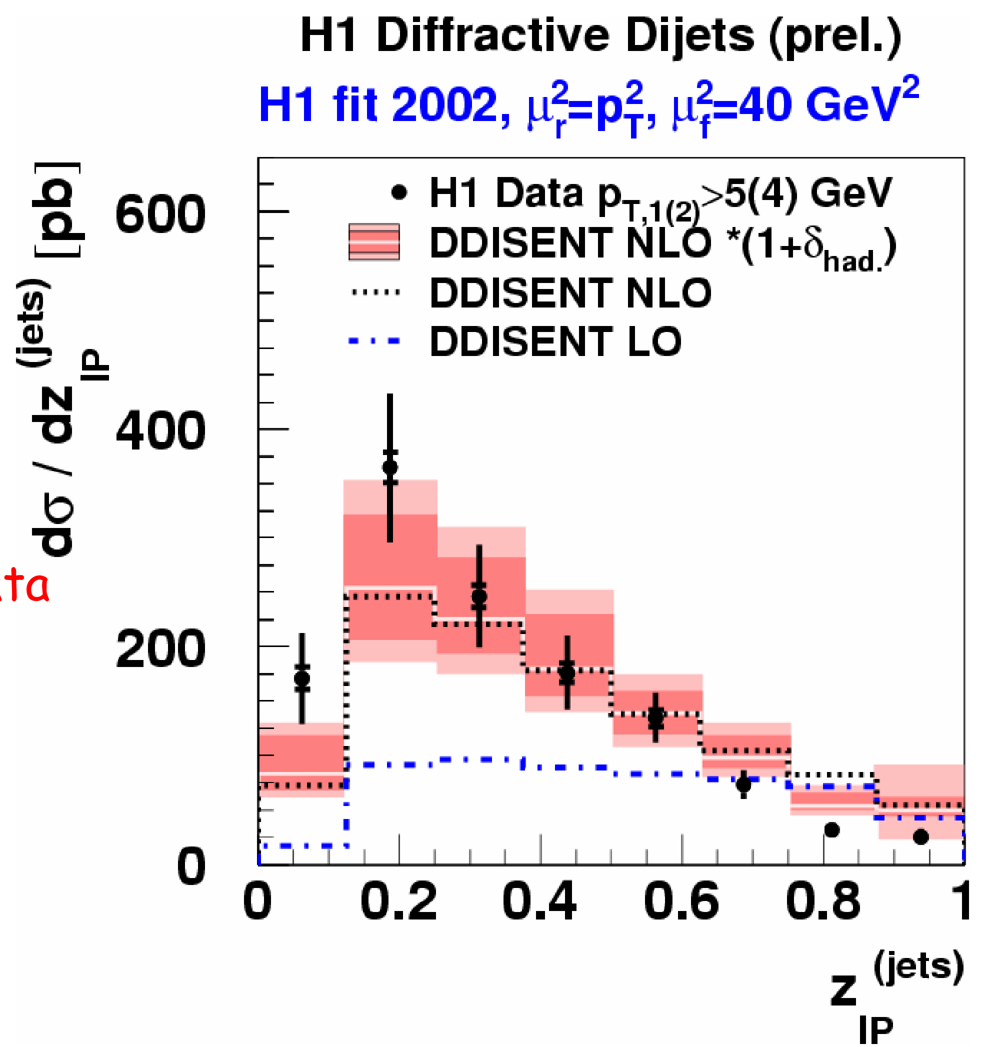
- compare with MC predictions using gluon from H1-QCD fit to inclusive data

→ NLO calculations using DISENT

$\mu_R^2 = p_T^2, \quad \mu_F^2 = 40\,\mathrm{GeV}^2$

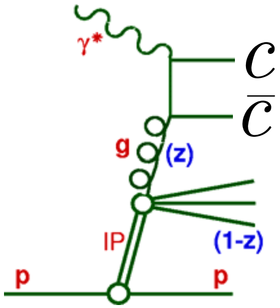
$\Lambda_{\mathrm{QCD}} = 0.2\ \mathrm{GeV}$

correction to hadron level applied



→ NLO calculations agree with data – factorization seems to work

Charm Production in Diffraction



- Charm directly probes the gluonic component of the Pomeron
- very sensitive to different dpdf's

- $1.5 < p_{\perp}(D^*) < 10.0\,\mathrm{GeV}$

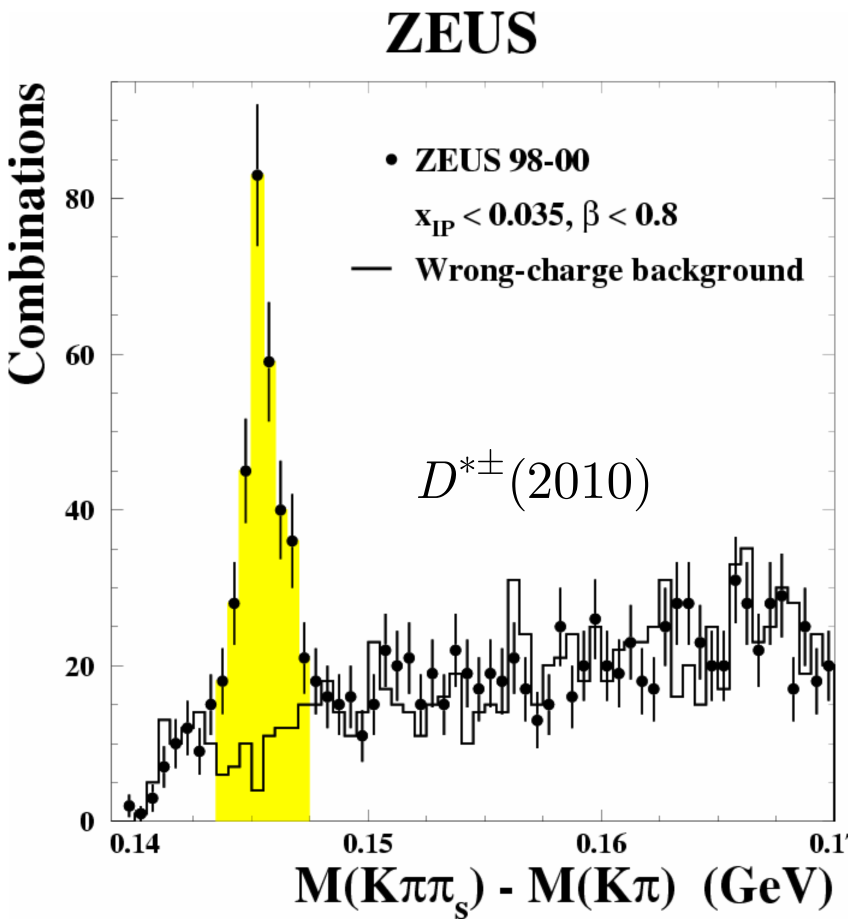
  $-1.5 < \eta(D^*) < 1.5$

  $0.02 < y < 0.7$

  $1.5 < Q^2 < 200\ \mathrm{GeV}^2$

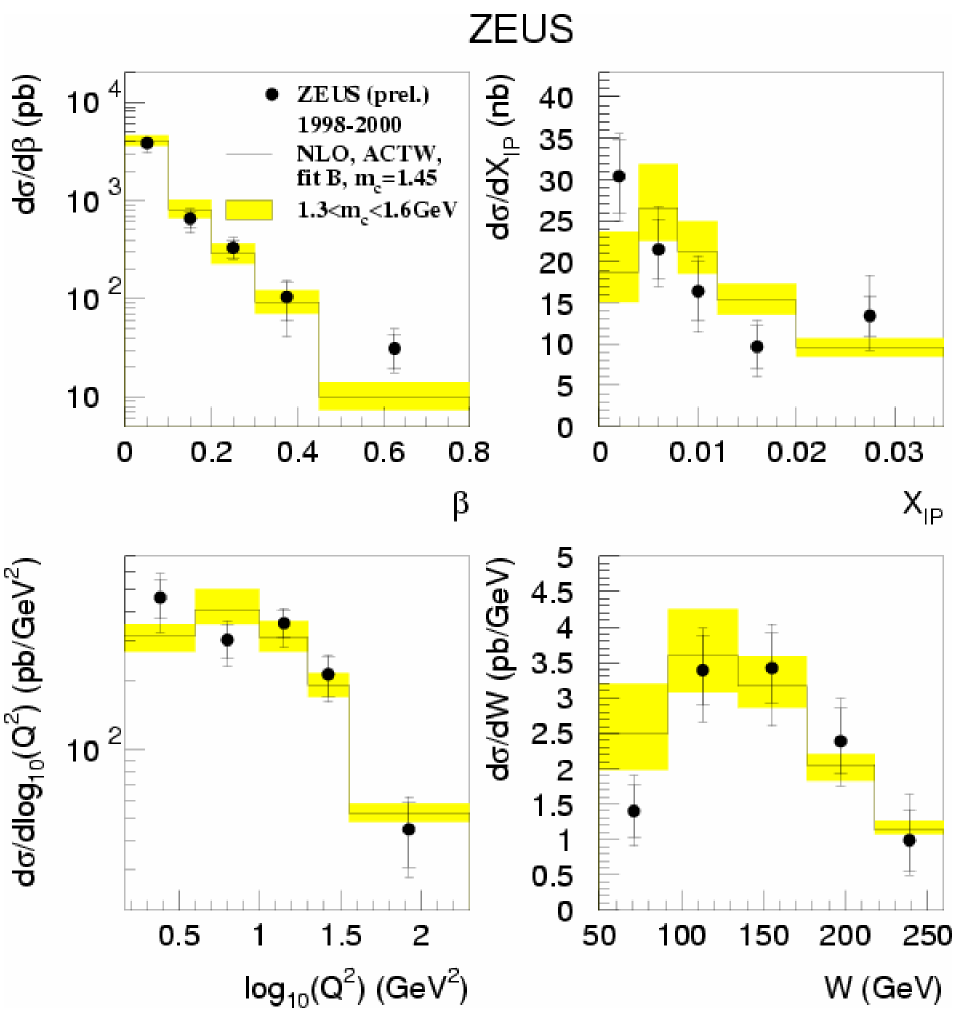
  $\beta < 0.8$

- $x_{\mathbf{P}} < 0.035$ (suppress subleading Reggeon exchange)



data still statistics limited

Charm Production in Diffraction (cont.)



Predictions:

use gluon pdf from a NLO QCD fit (Alvero et al.) to inclusive diffractive data (similar to the H1 fit)

data well described, both by QCD model (HVQDIS, Harris et al.)

in addition (not shown):

$$R_D \equiv \frac{\sigma_{DIF}(c\bar{c})}{\sigma_{DIS}(c\bar{c})} = 6.3 \pm 0.6 \pm 0.7\,\%$$

(Charm not suppressed in diffraction)

Charm rate independent of x_{D^*}, W and Q^2

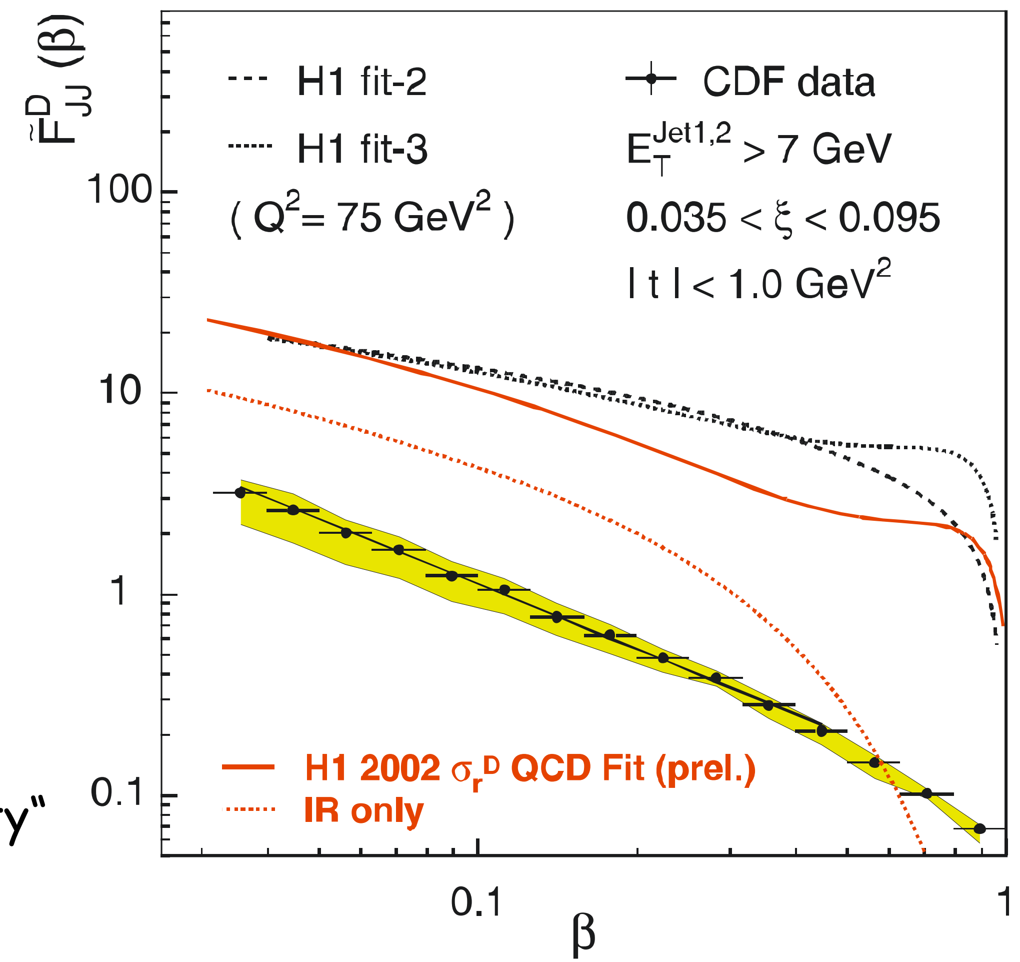
→ also for charm factorization seems to work

Further Tests of QCD Factorization in Diffraction

One step further: use dpdf's to predict di-jets at the Tevatron

Observe serious breakdown of factorization:

Prediction from HERA an order of magnitude too large



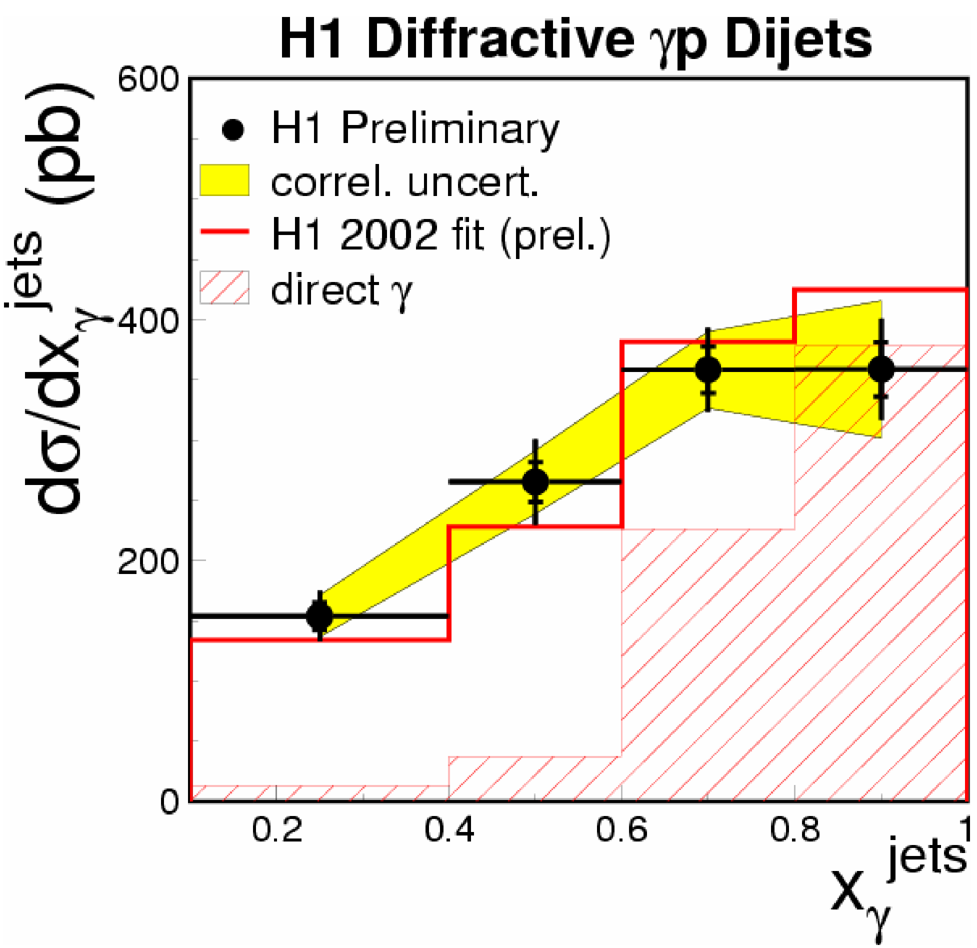
Generally for Tevatron:

Also other diffractive processes only of order 1 %

Possible reason: additional hadron in the initial state, rescattering, reduction of „gap survival probability" (Kaidalov, Khoze et al.)

Further Tests (cont.) : Di-Jets in Diffractive Photoproduction

→ low virtuality photons at HERA are „hadrons"

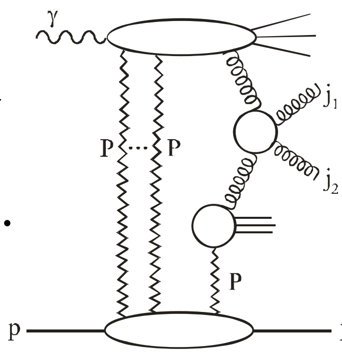


$Q^2 < 0.01\ \mathrm{GeV}^2,\ 0.3 < y < 0.65$

$x_{\mathrm{P}} < 0.03$

$p_{T,1(2)} > 5(4)\ \mathrm{GeV}$

jets: incl. k_T algor.



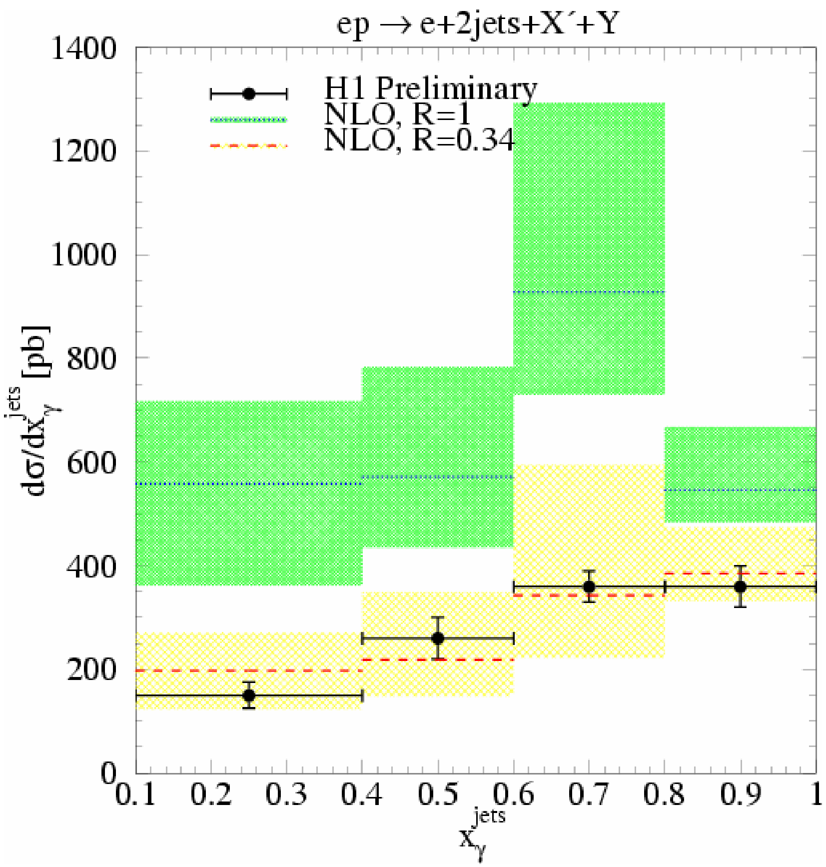
LO MC (Rapgap) with
dpdf from H1 fit
does describe the data !

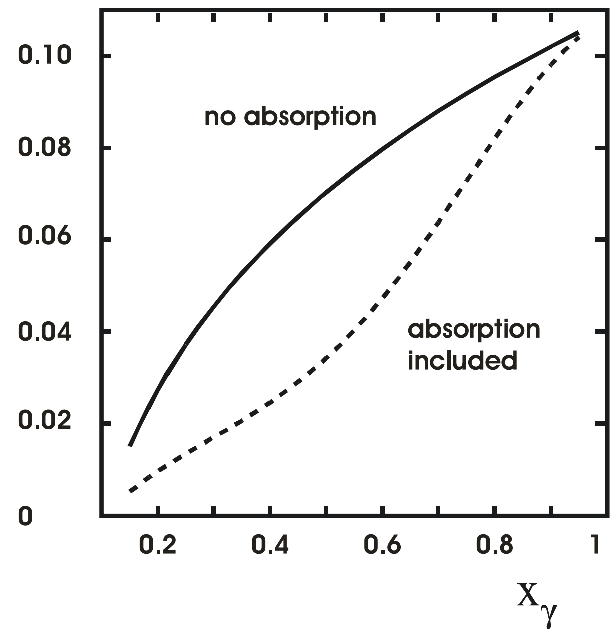
$\mu^2 = p_T^2$

No violation of factorization
in „hadron physics" at HERA ?

Factorization Tests in Diffractive Photoproduction (cont.)

NLO calculation by Klasen & Kramer (2004)
resolved photon contributions:





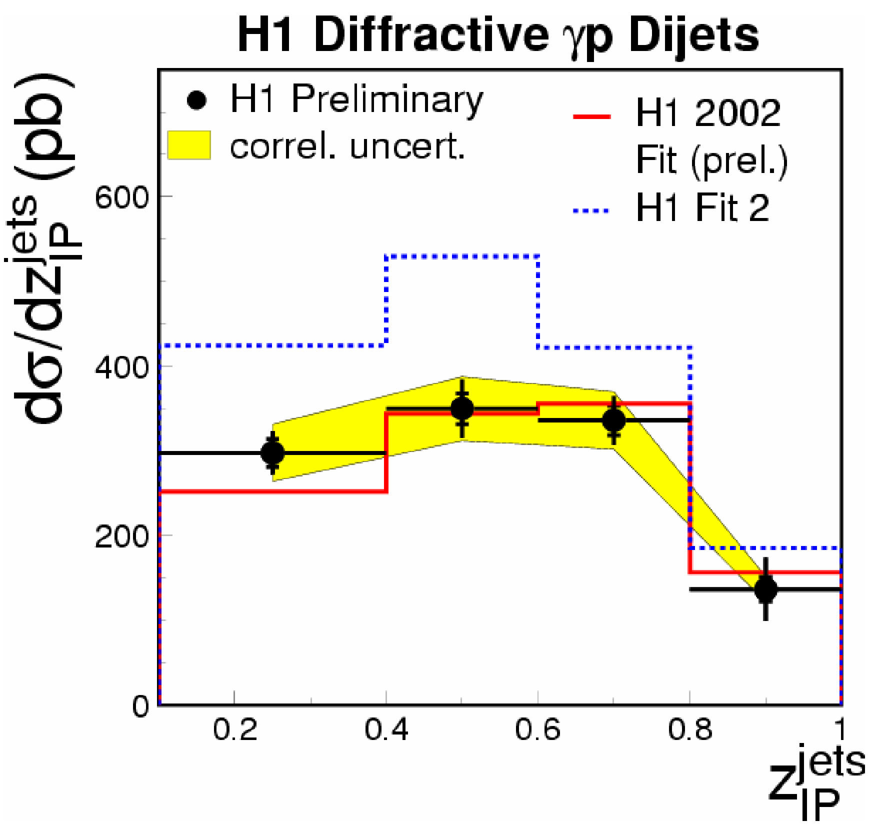
factor ~ 3 reduction seems to match with the data

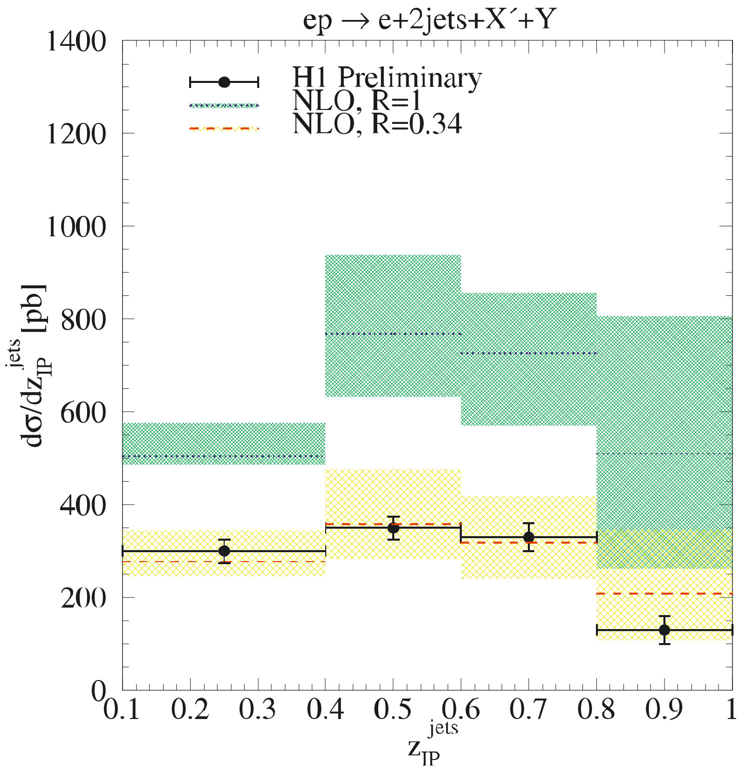
(absorption correction suggested by Kaidalov, Khoze et al., 2003)

Summary and Conclusions

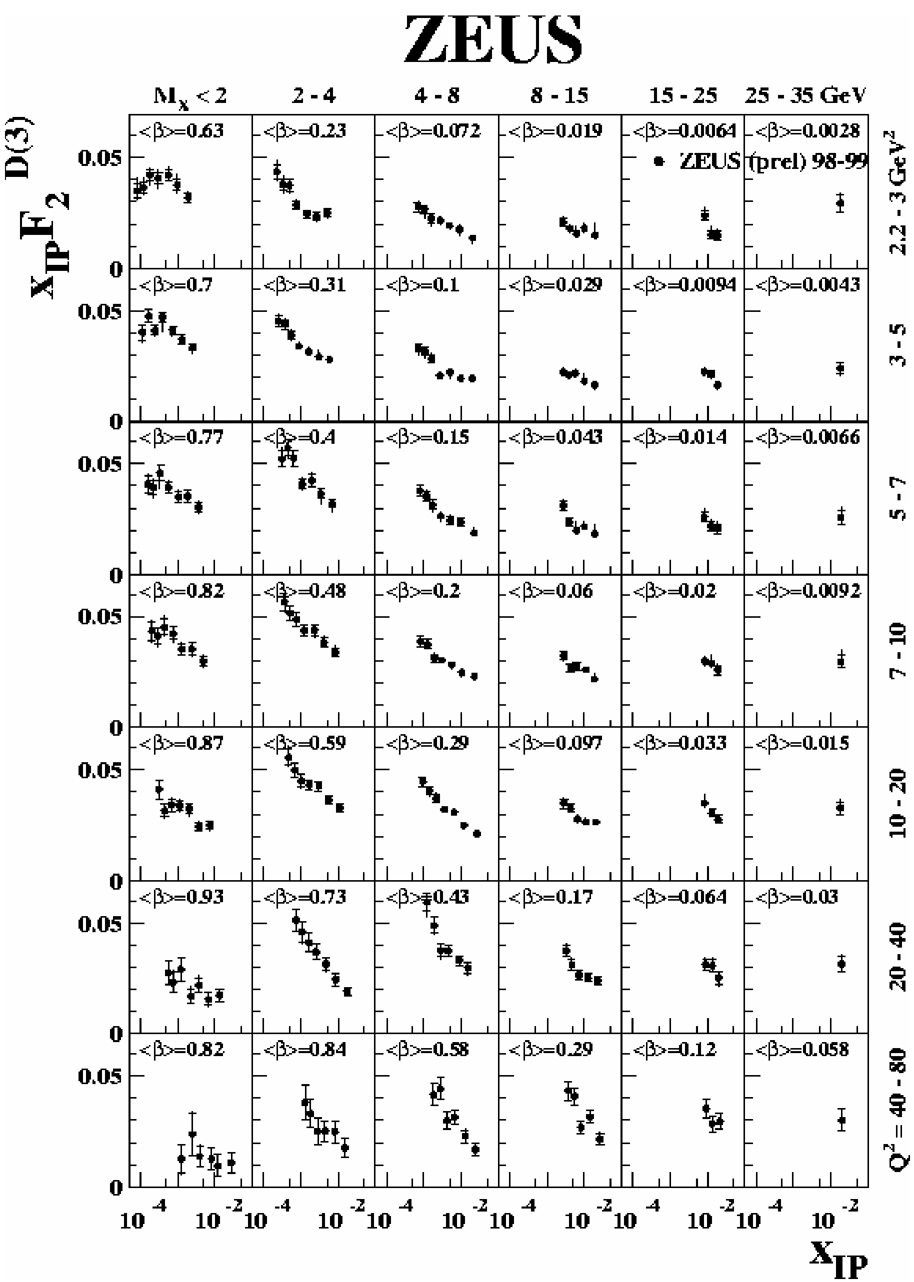
- Diffraction phenomena govern the main part of the cross section in soft hadronic interactions and, surprisingly (?), a substantial part of hard scattering at HERA
- QCD models based on 2-gluon exchange seem to describe the hard-scale diffractive processes, Regge picture fails in diffractive DIS
- Strong experimental evidence for gluonic structure of diffractive exchange NLO QCD fit to diffractive data: gluons dominate (~75%).
- QCD factorization verified at HERA in diffractive DIS (di-jets, charm) Strong breaking of factorization seen with di-jets at the Tevatron,
- LO/NLO predictions for HERA photoproduction of di-jets possibly not yet fully understood
- Diffraction (color singlet exchange) continues to be a major challenge for QCD and, possibly, is a key to understand confinement

BACKup


H1 Diffractive γp Dijets
H1 Preliminary
correl. uncert.
H1 2002
Fit (prel.)
H1 Fit 2
dσ/dz_IP^jets (pb)
0
200
400
600
0.2
0.4
0.6
0.8
1
z_IP^jets


ep → e+2jets+X´+Y
H1 Preliminary
NLO, R=1
NLO, R=0.34
dσ/dz_IP^jets [pb]
0
200
400
600
800
1000
1200
1400
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
z_IP^jets

$F_2^{D(3)}$ measurements by ZEUS



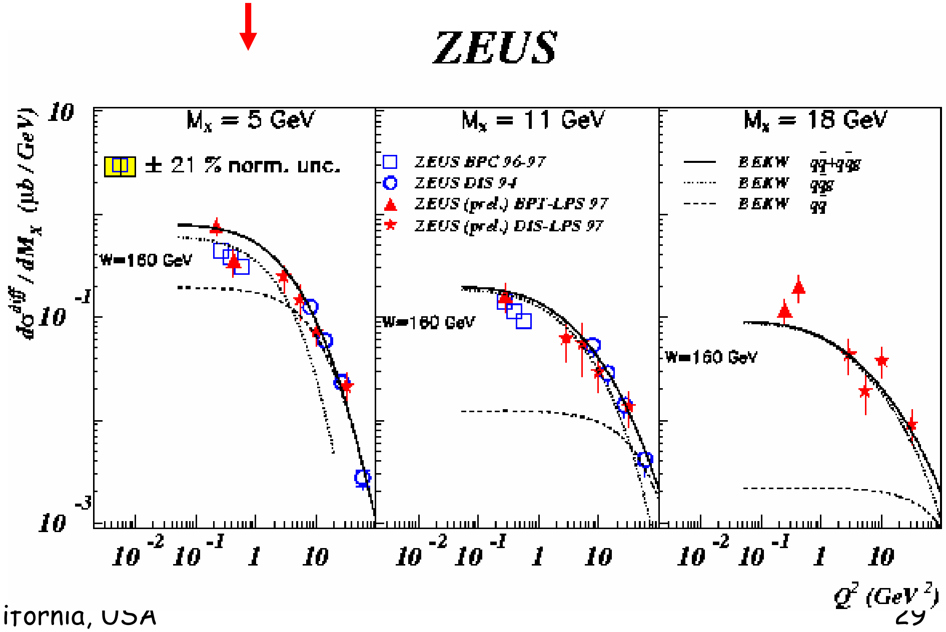
$2.2 < Q^2 < 80\,\mathrm{GeV}^2$

using improved Forward Calorimeter

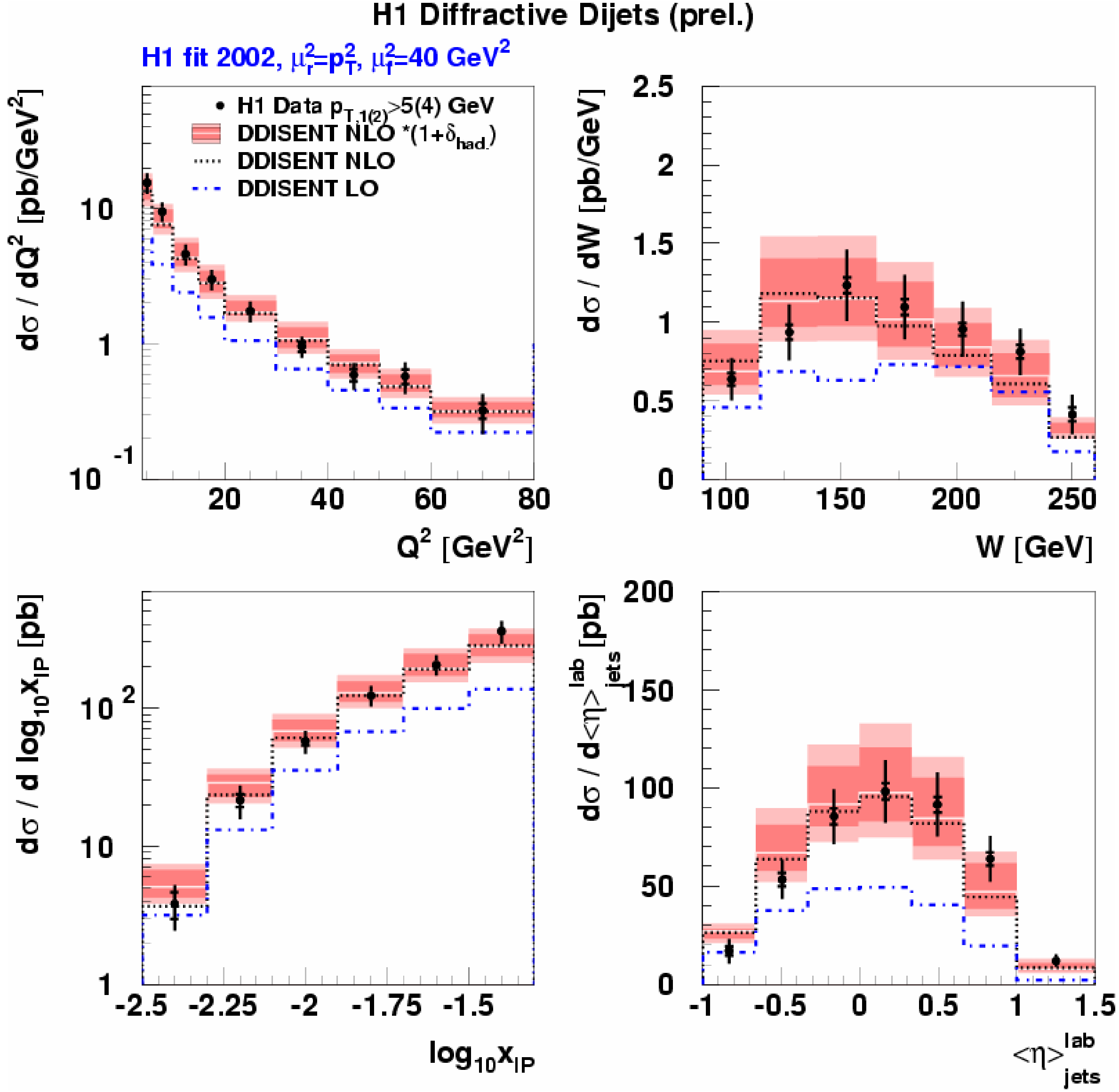
Leading Proton Spectrometer data:

$0.03 < Q^2 < 0.585\,\mathrm{GeV}^2$

(transition region to photoproduction)

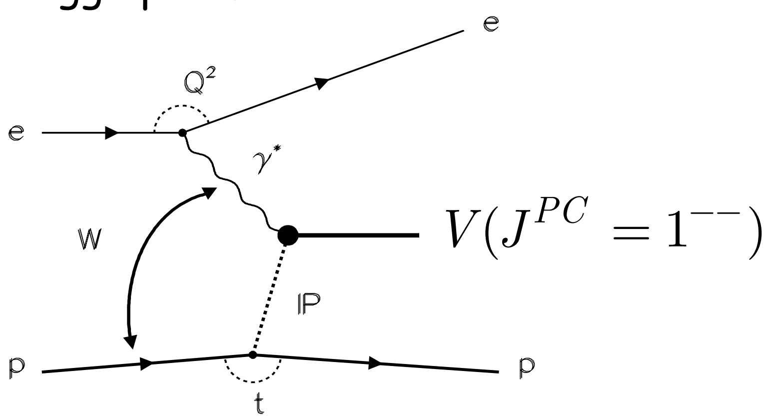


Dijets in DIS Diffractive Scattering (cont.)



Photoproduction of Vector Mesons

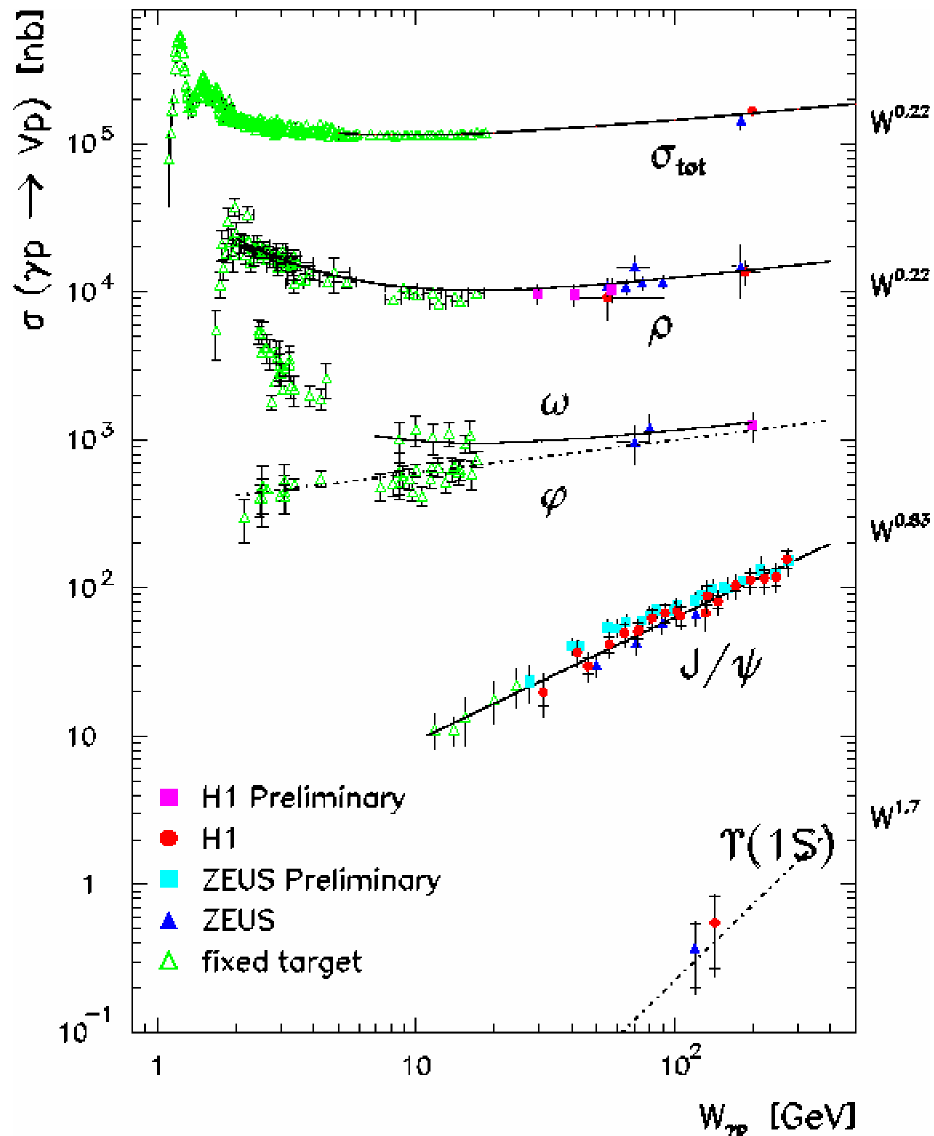
Regge picture



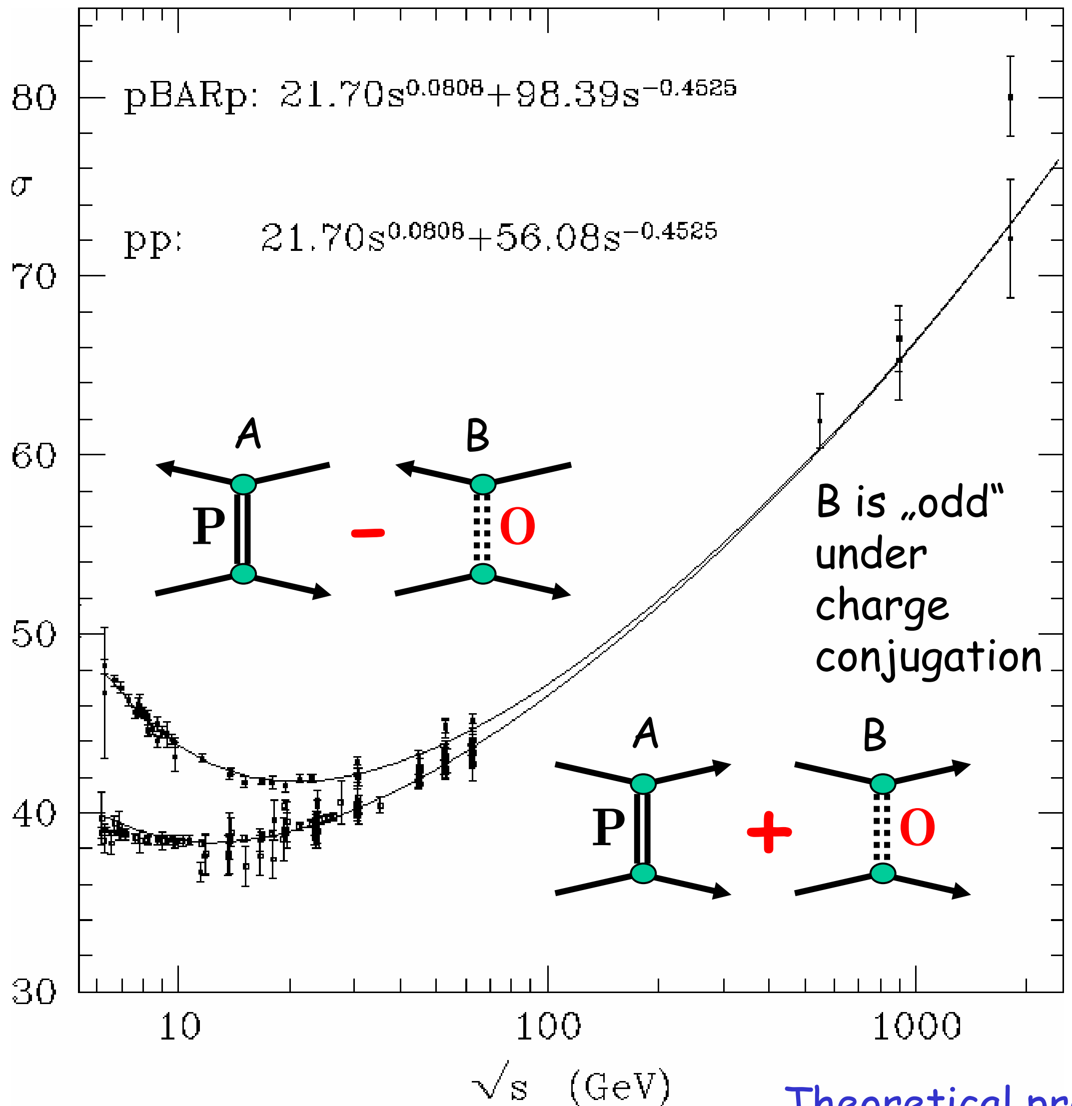
Total cross sections for photoproduction of vector mesons:

- $\rho\,,\,\omega\,,\,\phi$ show Regge behaviour
  $\sigma(\gamma\, p \rightarrow Vp) \propto W^{0.22}$
- J/ψ not described by Regge, strong rise of cross section
  $\sigma(\gamma\, p \rightarrow J/\psi\, p) \propto W^{0.8}$

Break-down of Pomeron Universality



The Odderon



Odderon invented by Lukaszuk and Nicolescu (1973) to account for possible differences in hadron-hadron and antihadron-hadron scattering at high energies

If B non-zero at high energies, i.e. a diffractive amplitude:

$$\Delta\sigma = \sigma(pp) - \sigma(\overline{p}p) \neq 0$$

for $s \rightarrow \infty$

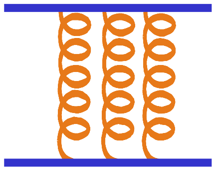
Experimental difficulties (due to presence of the Pomeron):

- Subtraction of 2 large numbers
- No data on pp at high energy !

Theoretical problem: Odderon possibly suppressed in pp reactions

Do we need an Odderon ?

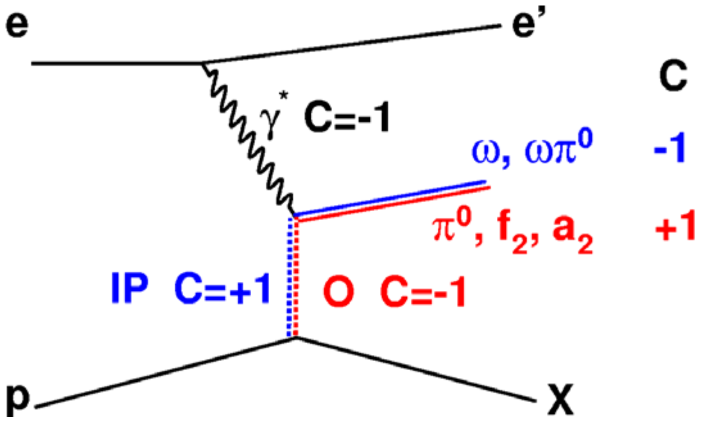
The „Odderon" is a firm prediction from pQCD: 3-gluon state with C = P = -1 (see talk by C. Ewerz)

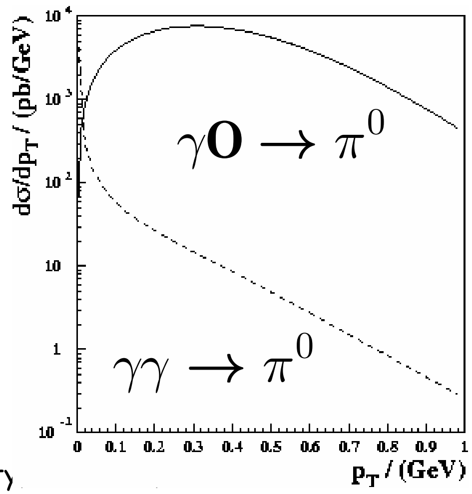


If so, how to find it :

HERA is an ideal place to study the Odderon:

- very high photon-proton center-of-mass energies (up to 300 GeV)
- can select exculsive processes where the Pomeron cannot contribute (thus measure a potential Odderon contribution directly, no subtraction)
- theoretical (non-pQCD) model exist for exclusive processes: E. R. Berger, A. Donnachie, H.G. Dosch, W. Kilian, O. Nachtmann, M. Rueter





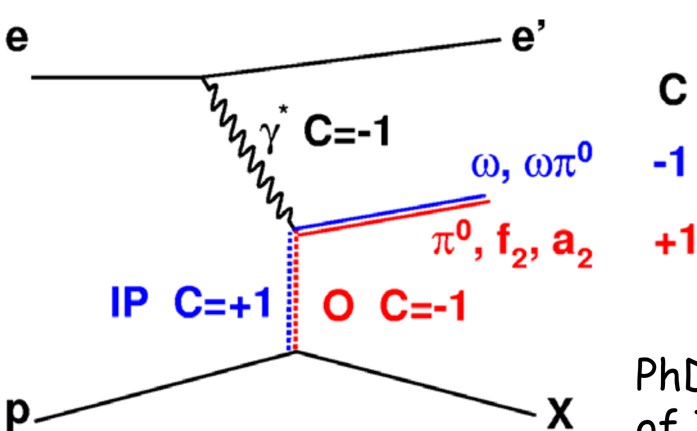
Cross section NOT suppressed if state X is a negative-parity baryon (e.g. N^*)

Cross sections for f_2, a_2 an order of magnitude smaller

Odderon Search in Multi-Photon Final States

Why multi-photon final states ?

- to test the diffractive nature of Odderon need large photon-proton energy (meson is emitted into backward part of detector)
- low mass mesons deposit all their energy in backward region of detector
- no tracking detector in backward area
- photons give full energy → calorimetric measurement (VLQ, SpaCal)



Reactions investigated:

Diploma thesis of T.Golling

$$\gamma p \to N^* \pi^0, \; \pi^0 \to 2\gamma$$

$$\gamma p \to N^* f_2(1270), \; f_2 \to \pi^0 \pi^0 \to 4\gamma$$

$$\to N^* a_2(1320), \; a_2 \to \pi^0 \eta \to 4\gamma$$

$$\to X\omega, \; \omega \to \pi^0 \gamma \to 3\gamma$$

$$\to X\omega\pi^0, \qquad \to 5\gamma$$

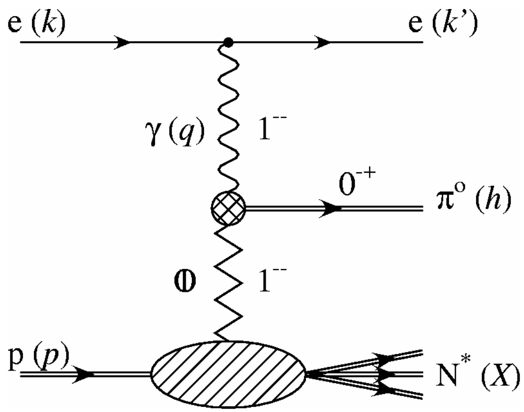
PhD Thesis of T. Berndt

$N^* : P = -1$

$b_1(1235)$?

Exclusive π^0 Photoproduction

$$ep \to e' N^* \pi^0$$



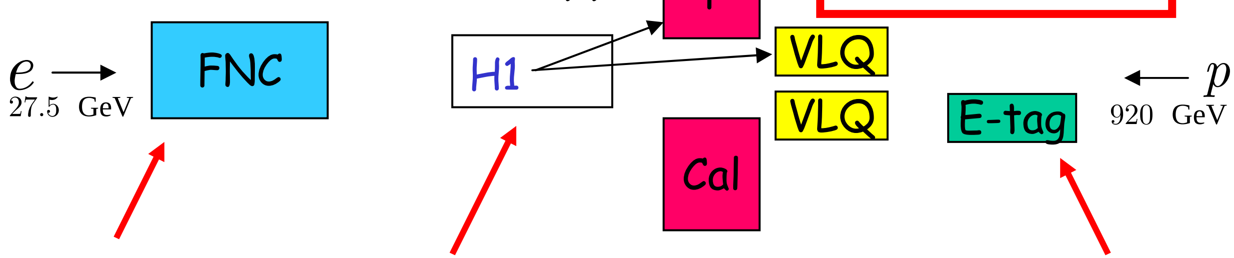
$$N^* \Rightarrow N^*(1520, 3/2^-), N^*(1535, 1/2^-), \ldots$$

$N^* \to n + \pi' s$ (neutron detected in forward calorimeter)

$\pi^0 \to \gamma\gamma$ (photons detected in VLQ and SpaCal)

$Q^2 < 0.01\ \mathrm{GeV}^2$ (photoproduction, energy measured via e-tagger)

$N^* \to n\pi$ $\quad$ $\pi^0 \to \gamma\gamma$ $\quad$ $\gamma p \to \pi^0 N^*$

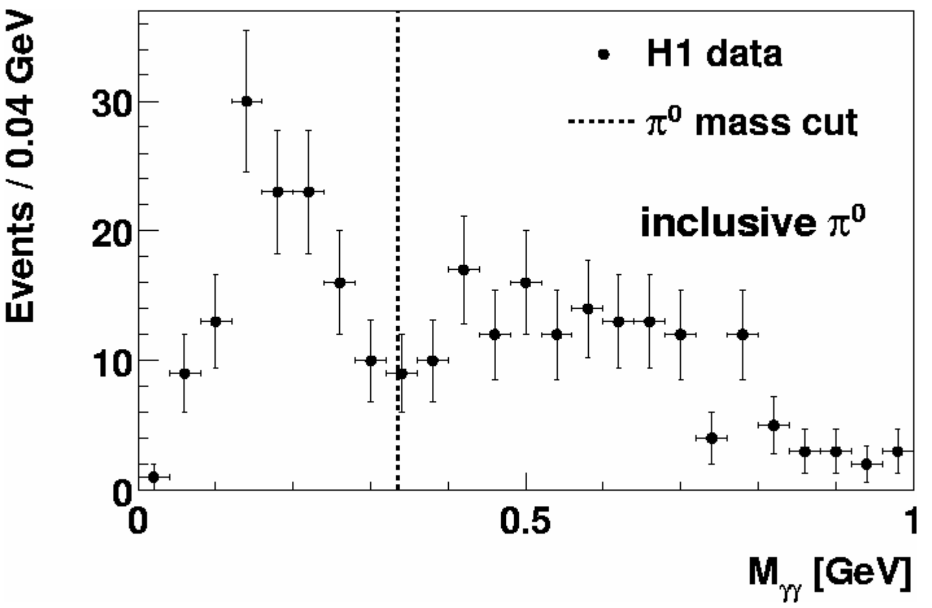


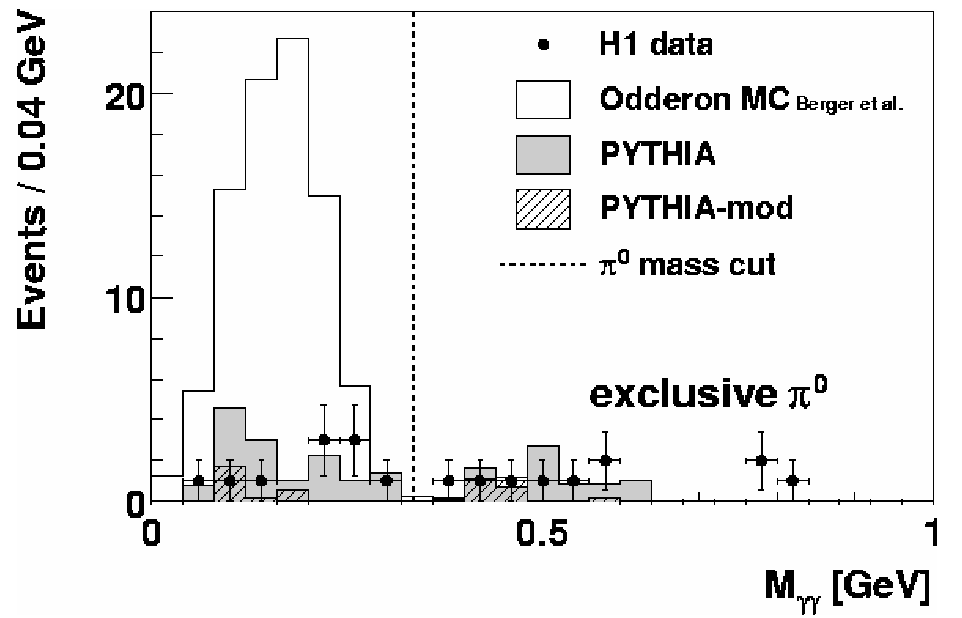
Neutron detector (calorimeter)

No charged particles: nominal interaction point used as origin of photons

Photon energy via measurement of scattered electron

Exclusive π^0 Photoproduction (cont.)

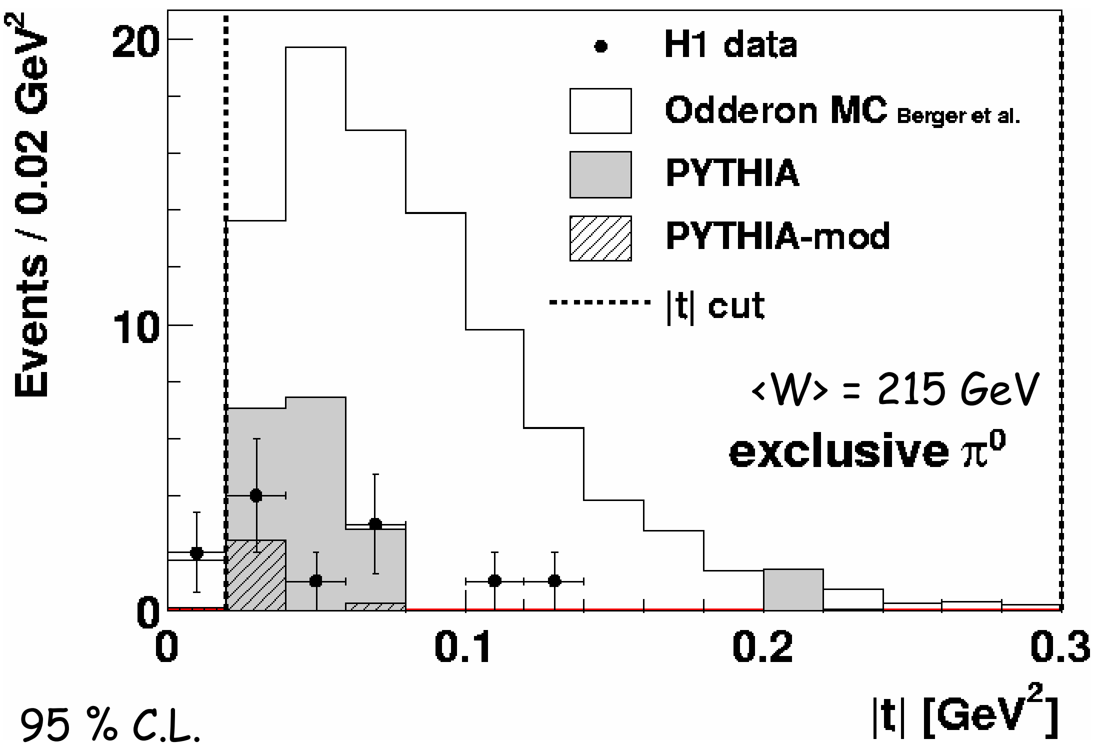




- H1 is able to detect π^0 in VLQ/SpaCal
- Neutrons can be detected with good efficiency (signaling N^* production)
- Acceptance/efficiencies are under control

- After cuts against „inelastic" events some events remain, compatible with expected background
- Expected signal from Berger et al. model is not seen

Limit on Exclusive π^0 Photoproduction



Event distribution as function of the momentum transfer at the proton vertex.

Reason: limited acceptance

(goes to 0 as t approaches 0, small for $|t| > 0.5$)

Cross section limit given in range $0.02 < |t| < 0.3$ GeV^2

95 % C.L.

$$\sigma_{\gamma p \to \pi^0 N^*}(\gamma O - \text{fusion}) < 49 \text{ nb}$$

200 nb expected for diffractive Odderon in same kinematic range ($\alpha_O(0) = 1$)

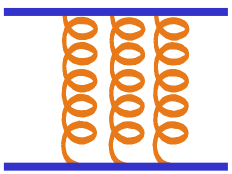
Interpretation of result:

→ Odderon-photon coupling could be smaller than in Berger et. al.

→ Odderon intercept is smaller than 0.7 (no longer „diffractive")

Summary on the Odderon

- A 2-gluon color singlet state („Pomeron") with C=P=+1 seems firmly established in strong interactions to mediate diffractive phenomena, most importantly to produce constant cross sections („BFKL Pomeron")



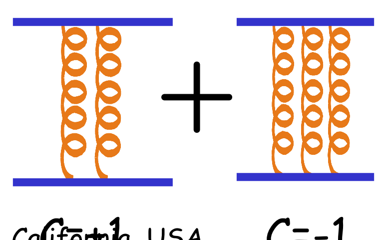
- The C=P=-1 3-gluon color singlet state („Odderon") is a natural extension of this idea.
- Detection of Odderon usually plagued by presence of the dominating „background" from the Pomeron („subtraction of big numbers")
- HERA provides a unique possibility to directly measure the Odderon (exclude Pomeron explicitly by quantum numbers), reliable (factor 2) non-perturbative calculations exist.

→ BUT: **No signal found yet !**

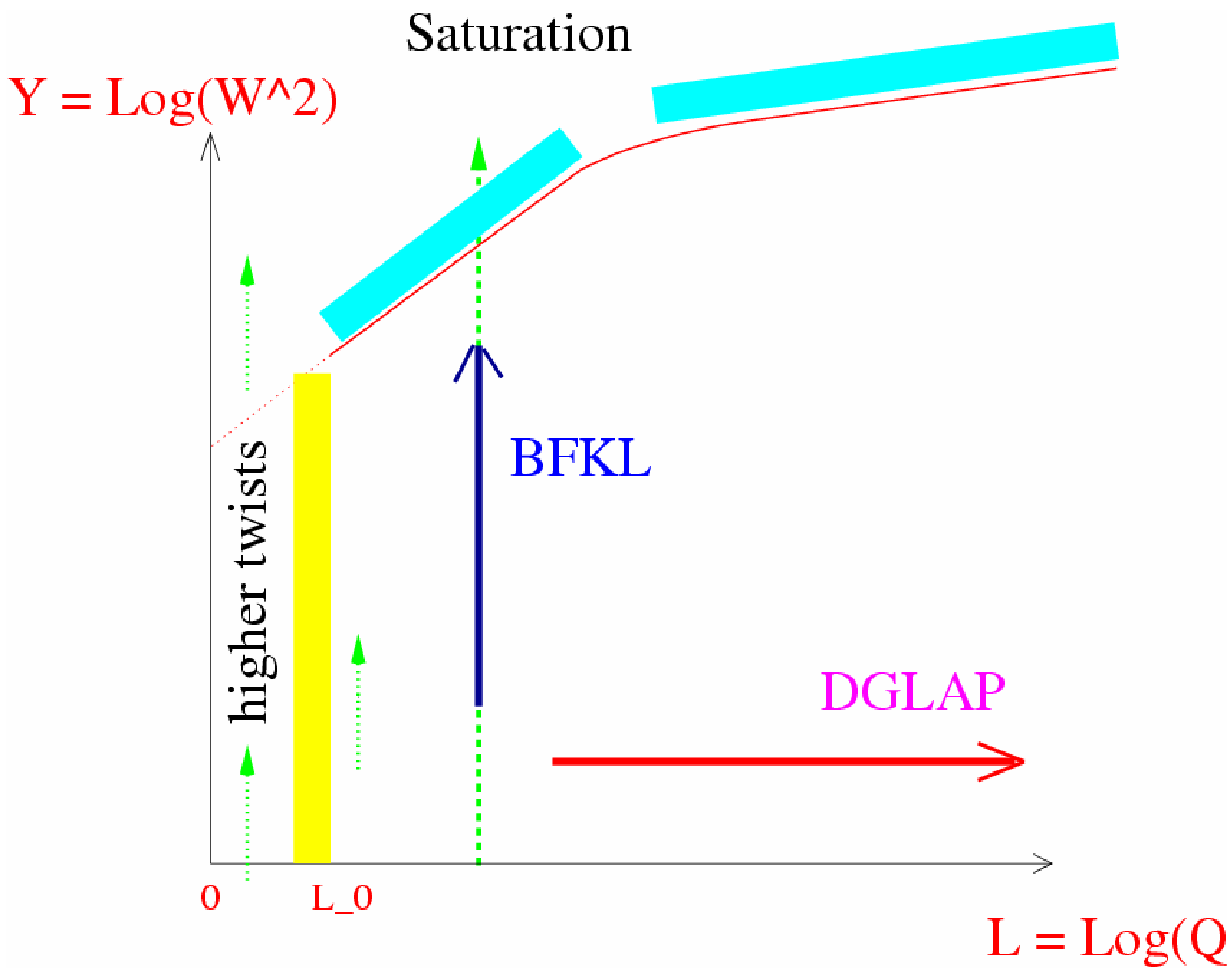
How to continue ?

More Data !!
→ HERA II
(new VFPS)

Recent suggestion (Teryaev et al. ICHEP 2002)



Charge/spin asymmetries in 2-pion photoproduction (at HERA II)
→ interference effects


Saturation
Y = Log(W^2)
higher twists
BFKL
DGLAP
0
L_0
L = Log(Q