Diffraction at HERA: Inclusive Measurements and the Final State

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representing the

H1 and ZEUS

collaborations

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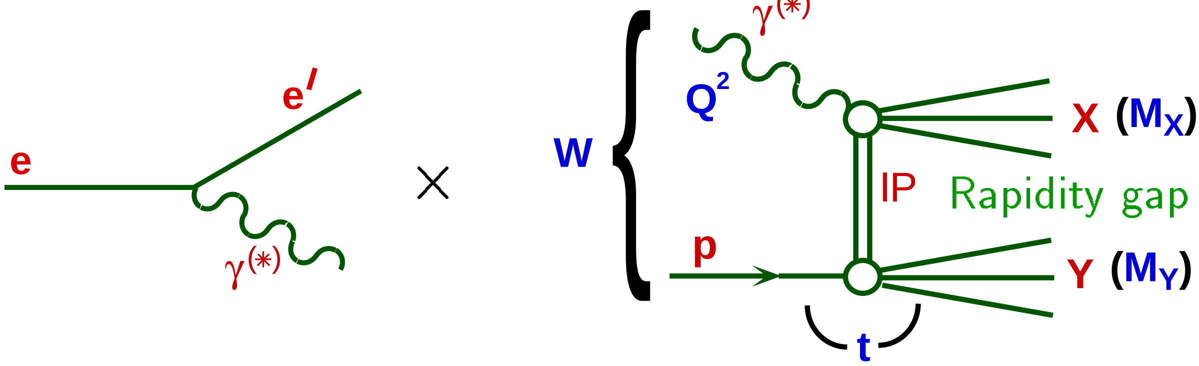
- Introduction: Diffraction at HERA
- Inclusive diffraction (F_2^D) and models
- Hadronic final state
  (Energy flow, Event shapes, Dijets, Charm)
- Leading baryons
- Summary

Diffraction at HERA

At HERA, diffractive $\gamma^{(*)}p$ interactions can be studied:



Variables:

$Q^2 = -q^2$	γ virtuality
$W = (q+p)^2$	γp CM energy
$t = (p-p')^2$	(momentum transfer)^2 at p vertex
M_X, M_Y	Masses of X and Y

Additional Variables:

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

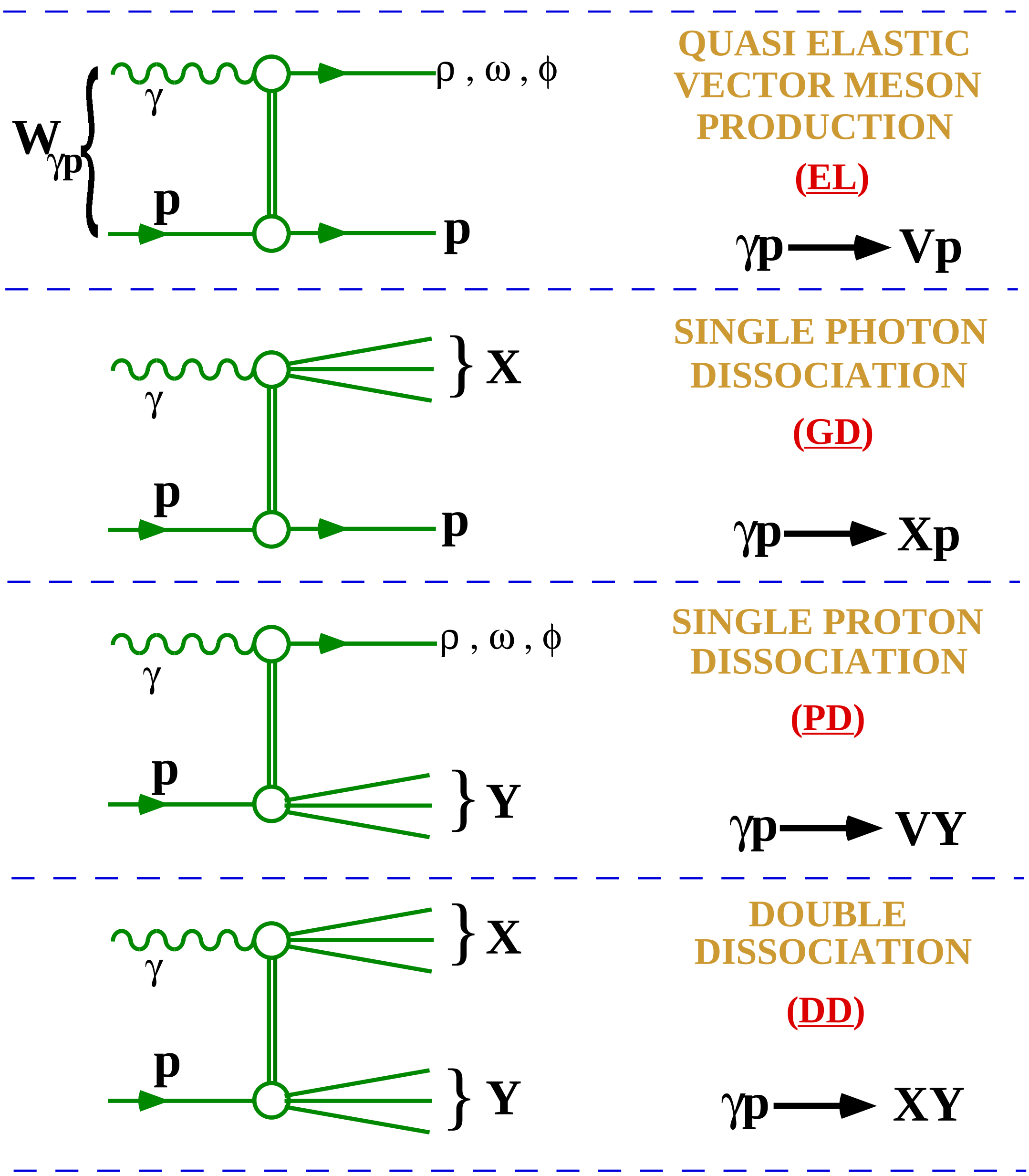
$\rightarrow$ long. momentum fraction transferred from p to exchange

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

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

- $Q^2 \approx 0$, $|t| \approx 0$: similar to soft hadron-hadron interaction
- $Q^2 \gg 0$: γ^* probes IP structure

Colour singlet exchange processes in $\gamma^* p$ interactions



→ Vector meson production (EL+PD) covered by talk of S. Kananov

→ Focus here on inclusive diffraction, diffractive final states and leading baryon production

The Diffractive Structure Function F_2^D

Most general case: Define five-fold differential cross section:

$$\frac{d\sigma(ep\to eXY)}{dx_{I\!P}\ dt\ dM_Y\ d\beta\ dQ^2} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1-y+\frac{y^2}{2(1+R^{D(5)})}\right)\ \times F_2^{D(5)}(x_{I\!P},t,M_Y,\beta,Q^2)$$

$R^{D(5)}$: Ratio $\sigma_L/\sigma_T \to$ neglected!

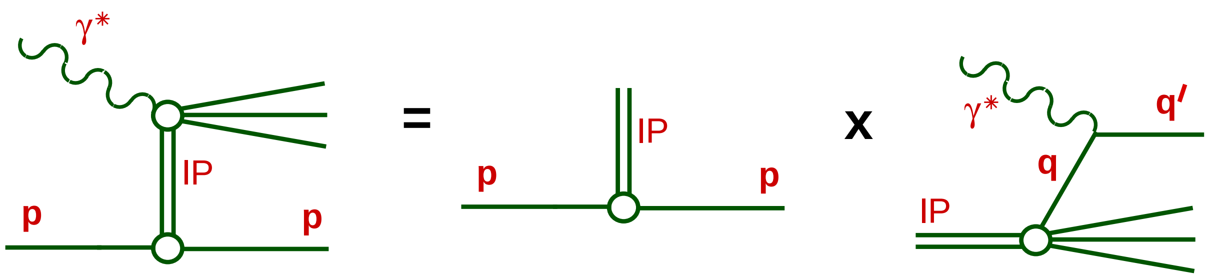
If Y is not measured, integrate over M_Y,t

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

Inclusive diffractive DIS:
$Q^2 \gg 0\ GeV^2$, small M_X, small M_Y:

$x_{I\!P} \ll 1$	(H1: $x_{I\!P} < 0.05$)
small $\vert t\vert$	(H1: $\vert t\vert < 1\ GeV^2$)
small M_Y	(H1: $M_Y < 1.6\ GeV$)

Factorizable Ansatz:



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

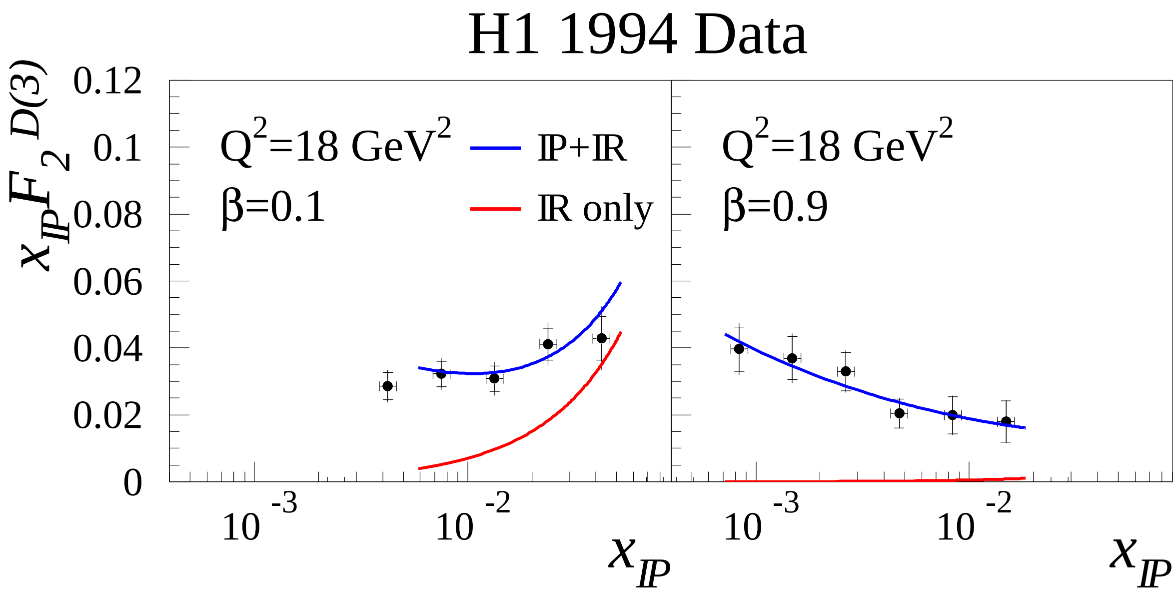
Regge parametrization of $F_2^{D(3)}$

Parametrize long-distance physics at p vertex using Regge phenomenology:

$$f_{I\!P/p}(x_{I\!P}) = \int_{-1\ GeV^2}^{t_{min}(x_{I\!P})} \left(\frac{1}{x_{I\!P}}\right)^{2\alpha_{I\!P}(t)-1} e^{b_{I\!P}t}\, dt$$

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

$F_2^{D(3)}$ (H1 1994): $x_{I\!P}$ dependence varies with β



$\rightarrow$ Additional sub-leading exchange necessary:

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

H1 phenomenological Regge fits with free parameters:
$\alpha_{I\!P}(0),\ \alpha_{I\!R}(0),\ F_2^{I\!P}(\beta, Q^2),\ F_2^{I\!R}(\beta, Q^2)$

The Pomeron intercept $\alpha_{I\!P}(0)$

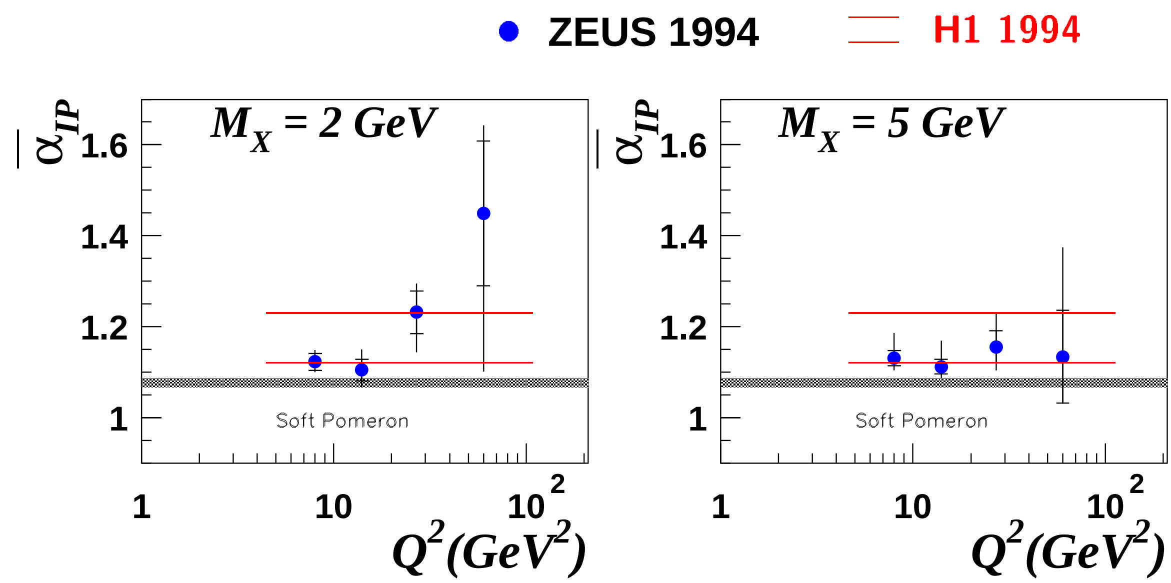
Result from the H1 Regge fit:

- $\alpha_{I\!P}(0) = 1.203 \pm 0.020 \pm 0.013 \pm 0.035$
  higher than in soft hadron-hadron physics ($\alpha_{I\!P}^{soft} = 1.08$)
- $\alpha_{I\!R}(0) = 0.50 \pm 0.11 \pm 0.11 \pm 0.10$
  consistent with $f, \omega, \rho,$ etc. exchange

$\longrightarrow$ Diffractive DIS at HERA dominated by $I\!P$ exchange!

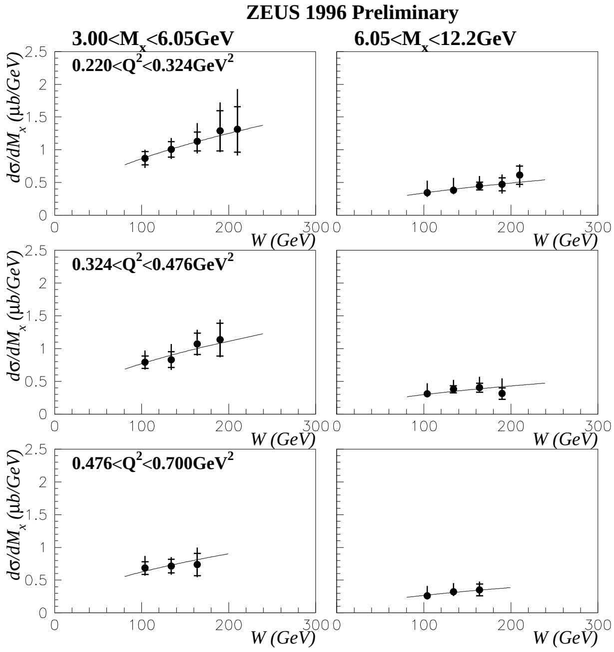
Comparision of H1 and ZEUS:

$\overline{\alpha}_{I\!P}$: averaged over t

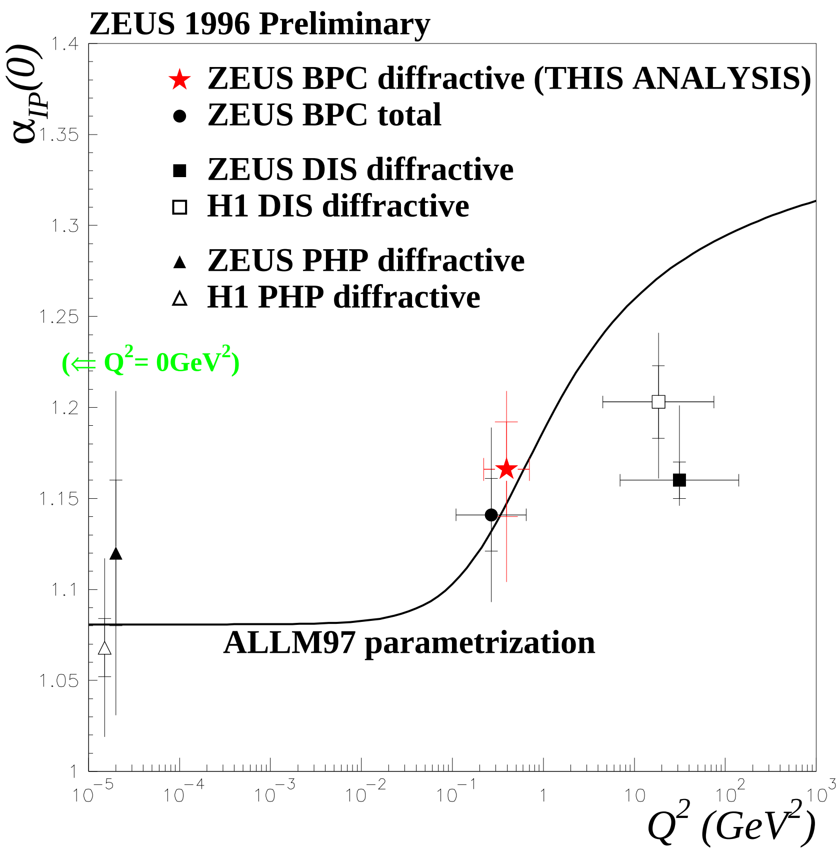


$\longrightarrow$ no significant variation within $Q^2 = 8 \ldots 80\ GeV^2$!
$\longrightarrow$ agreement between ZEUS and H1 on $\alpha_{I\!P}(0)$!

The Pomeron intercept at very low Q^2



- New ZEUS results
- use Beam Pipe Calorimeter (BPC)
- $Q^2 = 0.22 - 0.7\ GeV^2$
- extract $\alpha_{I\!P}(0)$ from fit to $\frac{d\sigma}{dM_X^2} \sim W^{2(2\overline{\alpha}_{I\!P}-2)}$

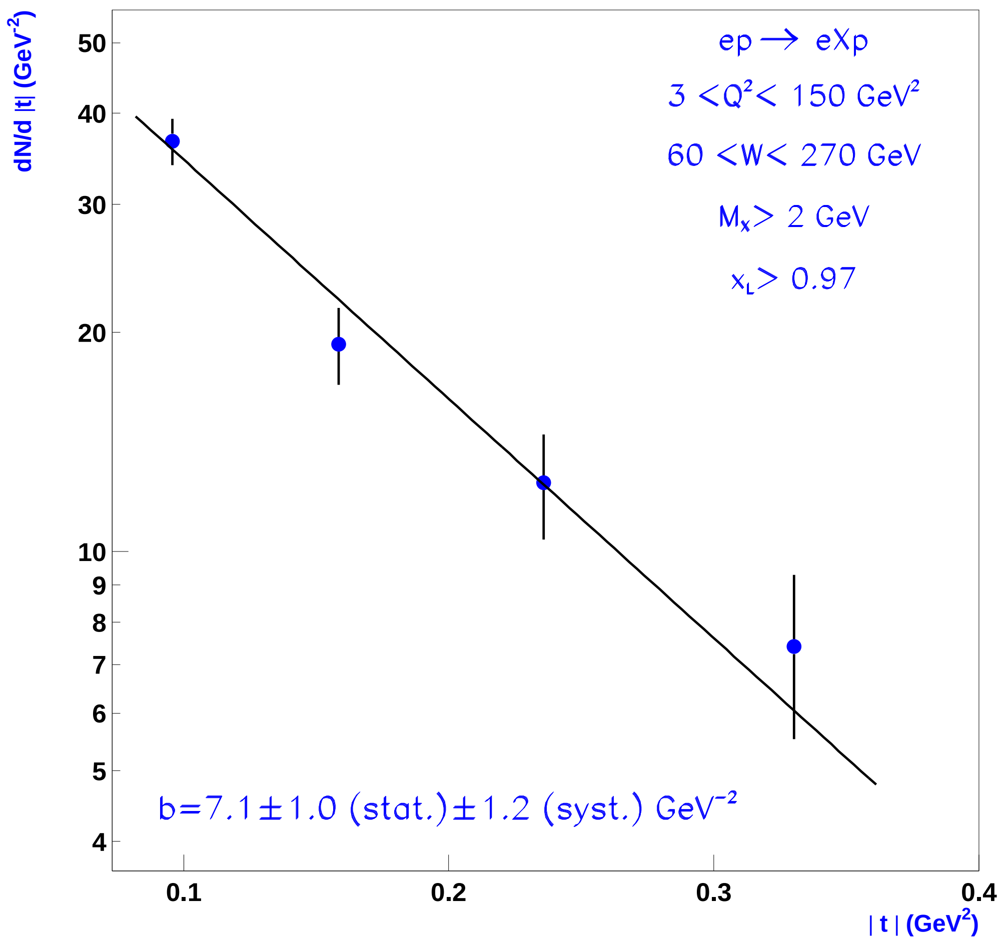


→ access to transition region!

Measurement of the t dependence

- t can only be measured if outgoing proton is tagged directly!
- Fit to $\frac{d\sigma}{dt} \propto e^{bt}$

ZEUS 1995 Preliminary (LPS)

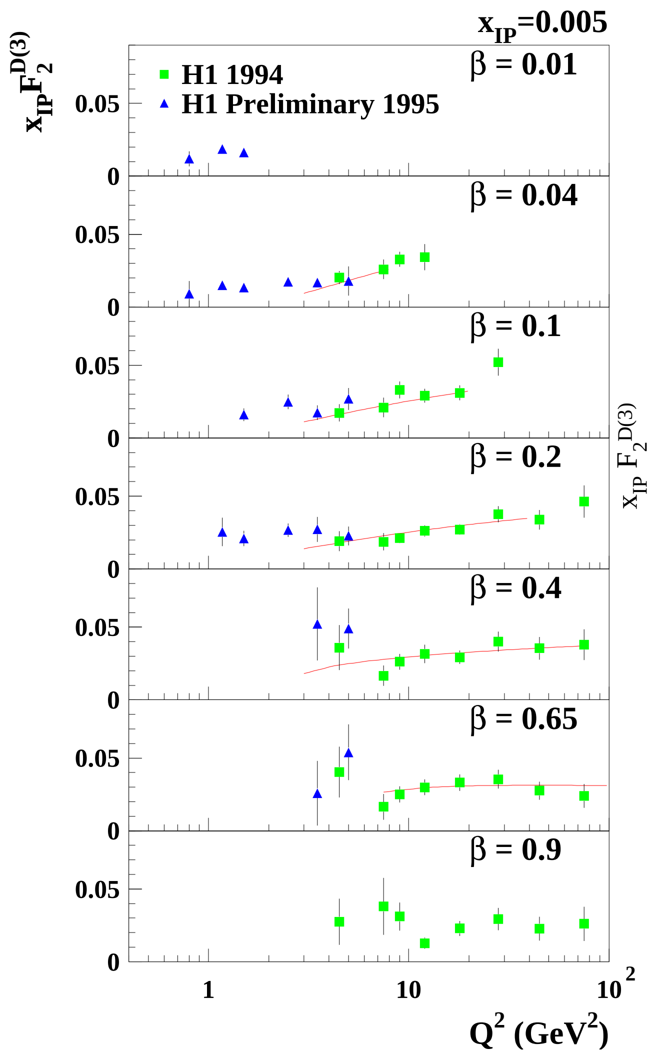


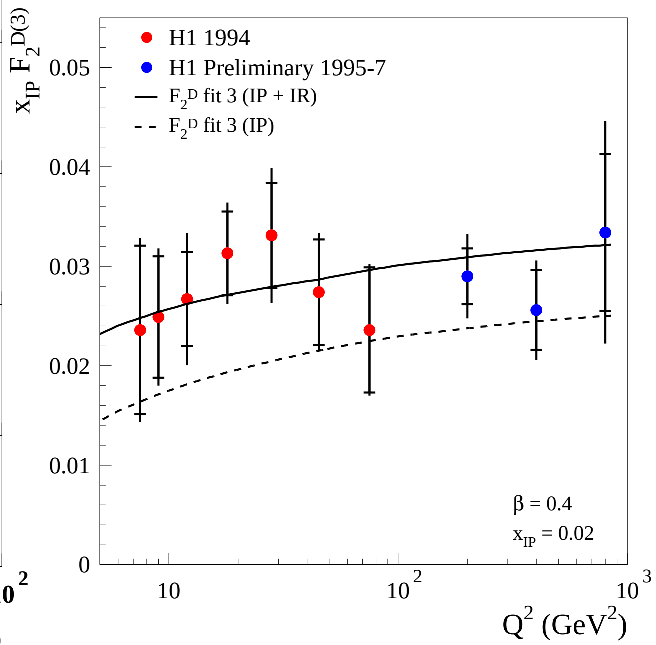
$$b = 7.1 \pm 1.0(stat.) \pm 1.2(syst.)\ GeV^{-2}$$

→ Consistent with soft hadron-hadron interactions!

QCD Analysis of $F_2^{D(3)}$ (H1)

H1 observes scaling violations:





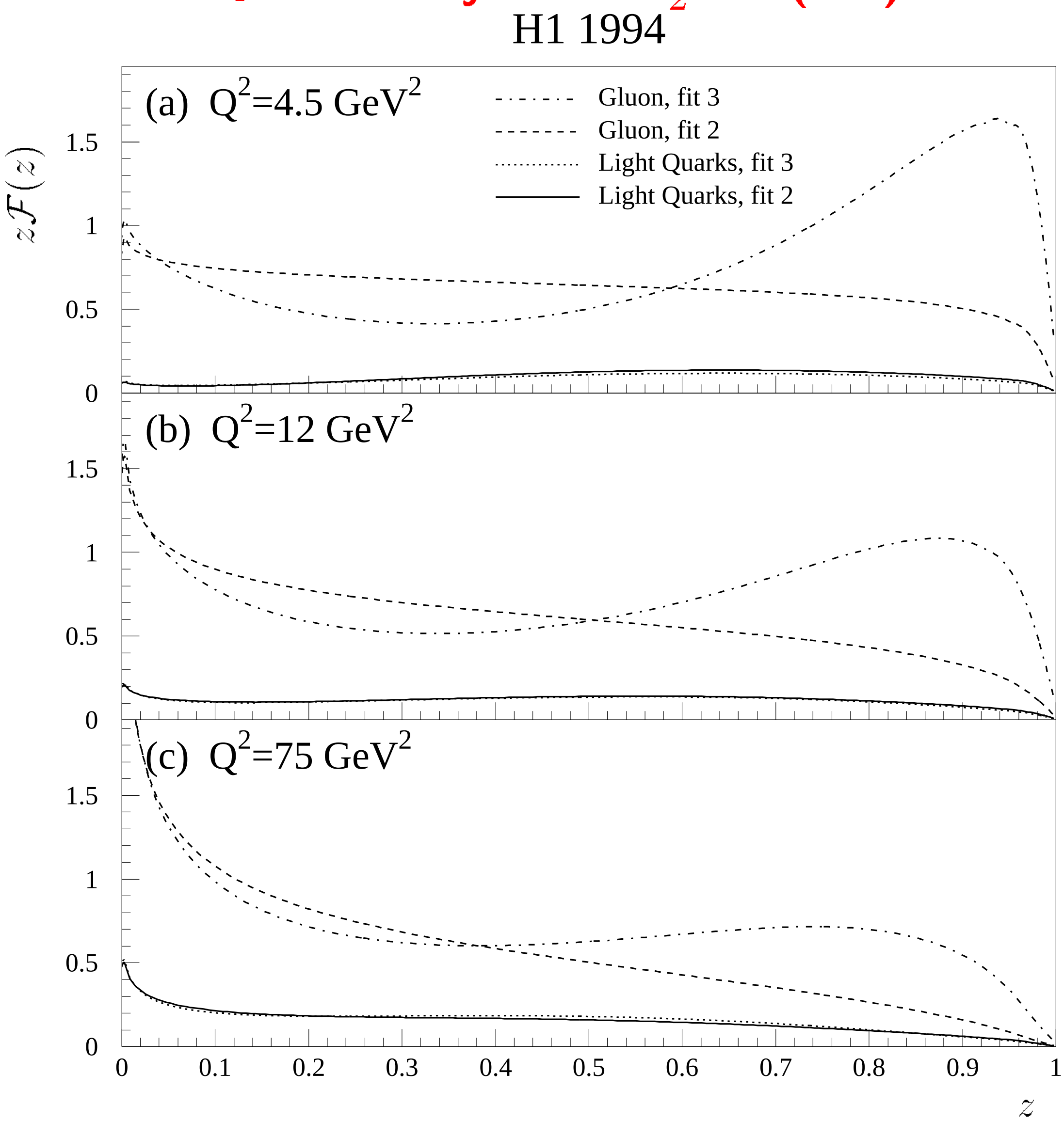
H1 F_2^D low Q^2 (95) H1 F_2^D (94)

H1 F_2^D (94) H1 F_2^D high Q^2 (95-97)

Q^2: 1 10 100 ≀≀ 10 100 1000

- flat or rising behaviour, even at large beta!

QCD Analysis of $F_2^{D(3)}$ (H1)

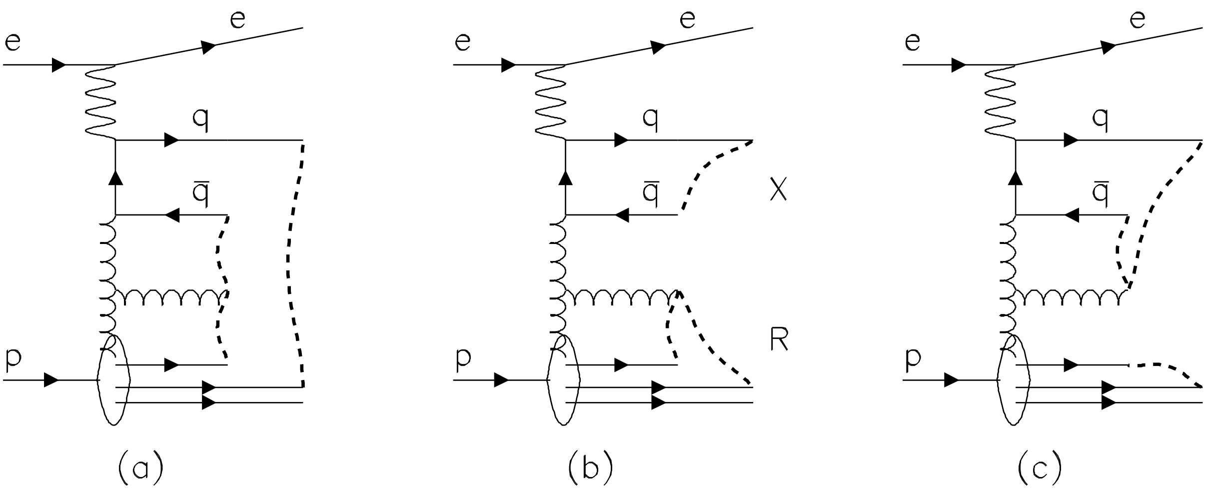


- within resolved IP model (Ingelman, Schlein), obtain PDF's for IP through DGLAP QCD analysis
- can be successfully extended into low and high Q^2 regions!
- fit 2: 'flat gluon' solution
  fit 3: 'peaked gluon' solution

80 – 90% gluons!

SCI Model for Diffractive DIS

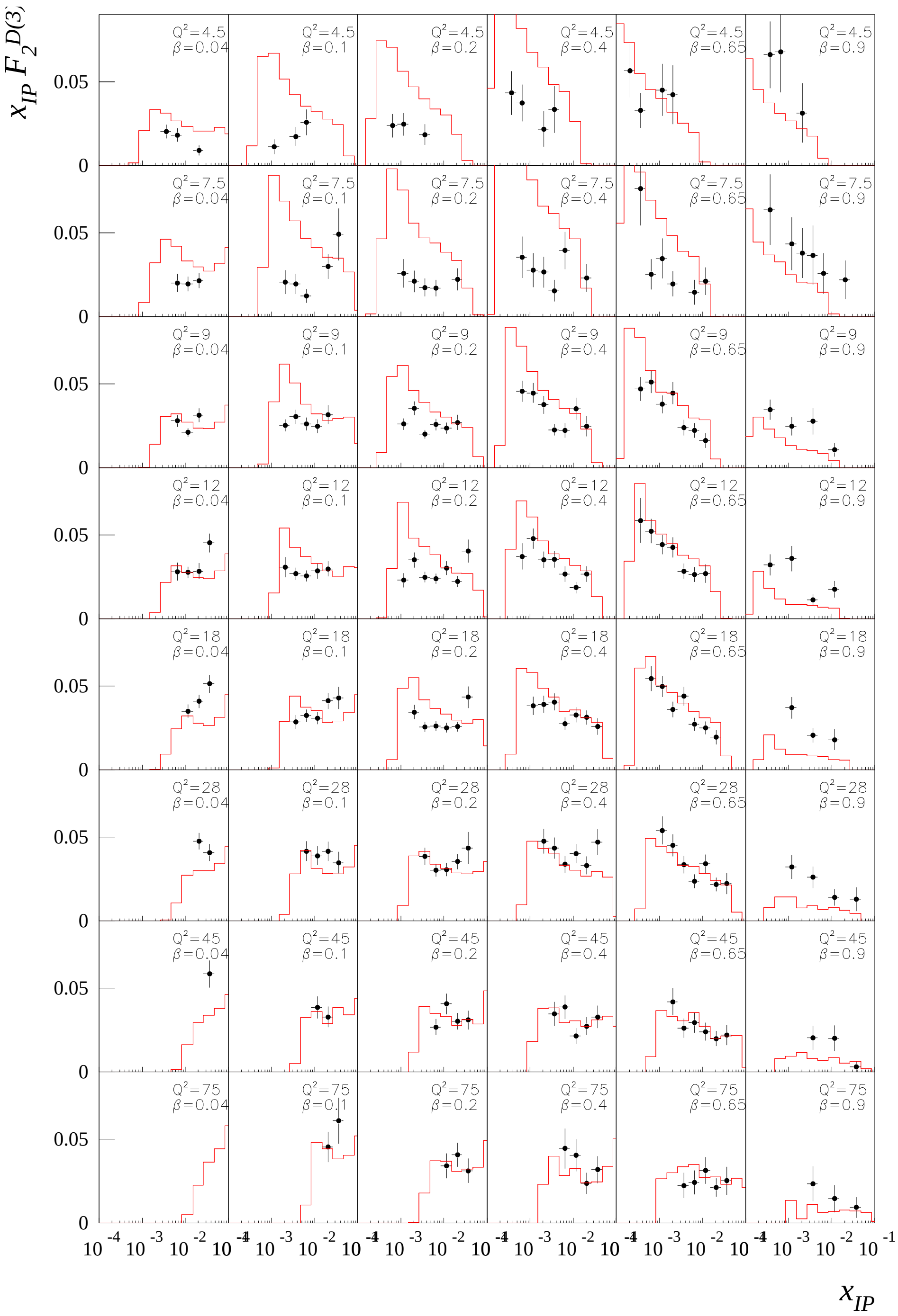
Edin, Ingelman, Rathsman: Soft Colour Interactions



- Start from standard QCD ME+PS description of $F_2(x, Q^2)$
- low x: dominated by Boson-gluon-fusion
- additional non-perturbative interactions affect final-state colour connections but not parton momenta

- free parameter: probability R_{SCI} to be fixed by data
- implemented in LEPTO 6.5

$F_2^{D(3)}$ H1 and LEPTO 6.5



$R_{SCI} = 0.5$

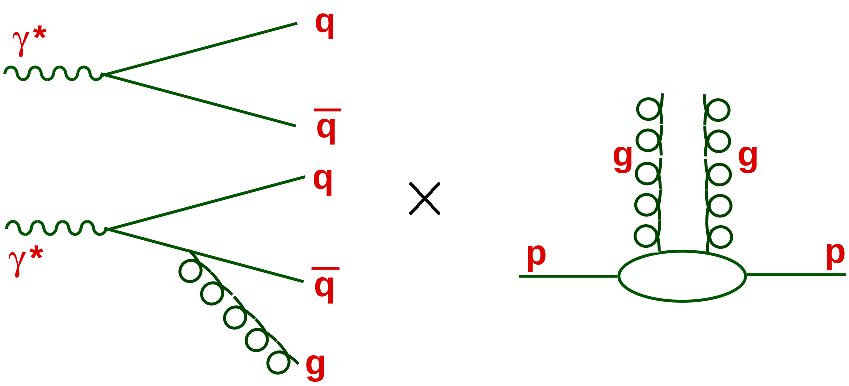
reasonable x_{IP}-shape

does not describe Q^2 dep.

fails at high β

2-gluon exchange models

- Many models available:
  Low, Nussinov, Mueller, Donnachie, Landshoff, Nikolaev, Zakharov, Diehl, Bartels, Wüsthoff, Bialas, Peschanski, ...
- $q\bar{q}$ / $q\bar{q}g$ production via gg-exchange / BFKL ladder



Example: BEKW (Bartels, Ellis, Kowalski, Wüsthoff) model:

- Investigate decomposition into leading / higher twist, longitudinal / transverse γ interactions, $q\bar{q}$ / $q\bar{q}g$ final states
- 3 significant contributions to F_2^D, 9 free parameters:

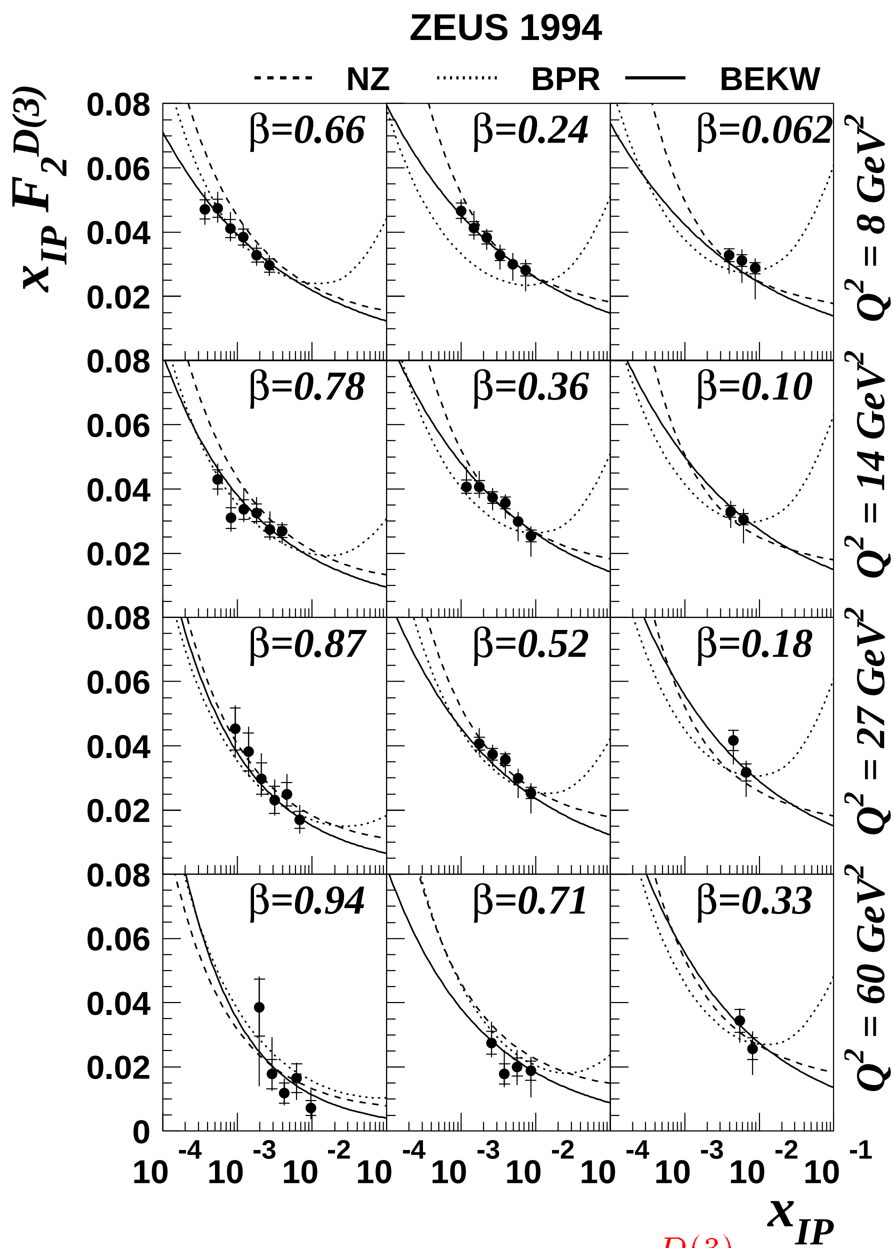
$$F_{q\bar{q}}^{\mathrm{T}} = A \left(\frac{x_0}{x_{I\!P}}\right)^{n2(Q^2)} \beta(1-\beta)$$

$$F_{q\bar{q}g}^{\mathrm{T}} = B \left(\frac{x_0}{x_{I\!P}}\right)^{n2(Q^2)} \alpha_s \ \ln\left(\frac{Q^2}{Q_0^2}+1\right) \ (1-\beta)^{\gamma}$$

$$\Delta F_{q\bar{q}}^{\mathrm{L}} = C \left(\frac{x_0}{x_{I\!P}}\right)^{n4(Q^2)} \frac{Q_0^2}{Q^2} \left[\ln\left(\frac{Q^2}{4Q_0^2\beta}+\frac{7}{4}\right)\right]^2 \beta^3(1-2\beta)^2$$

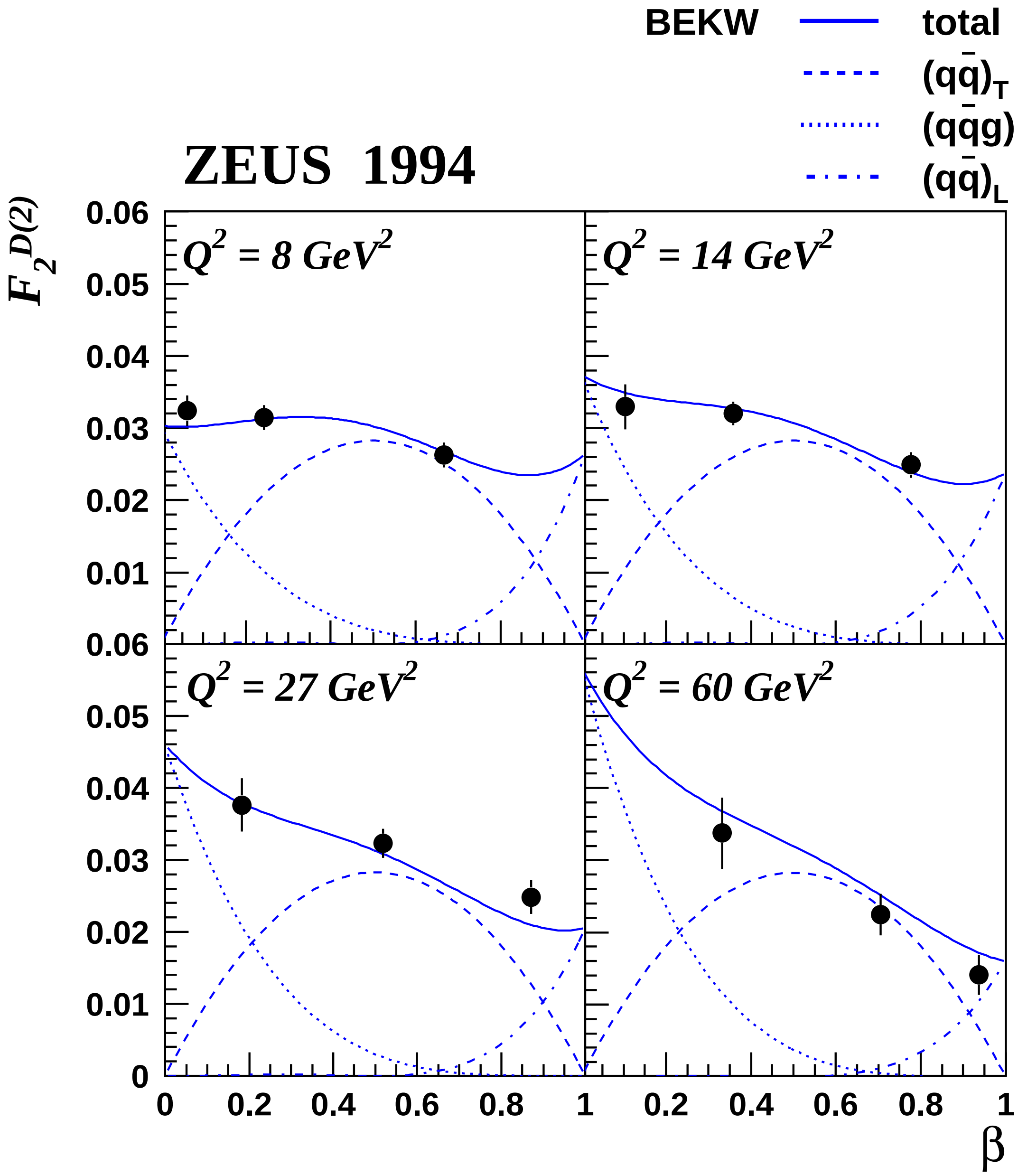
$F_2^{D(3)}$ ZEUS 1994 / 2 gluon models

NZ: Nikolaev, Zakharov
BPR: Bialas, Peschanski (incl. $I\!R$)
BEKW: Bartels, Ellis, Kowalski, Wüsthoff



→ Parameters can be fixed to describe $F_2^{D(3)}$, even at large β

β dependence in BEKW model



- Mixture of $q\overline{q}$ / $q\overline{q}g$ states
- Higher twist contributions important at large β

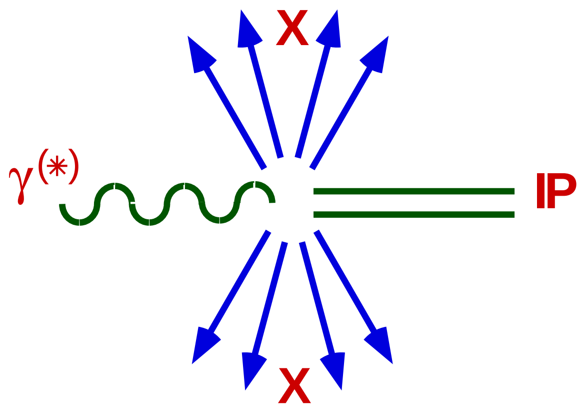
$\longrightarrow$ Clear prediction for partonic composition of final states!

Diffractive Final States

Motivation:

- Hadronic final state observables sensitive to QCD structure of diffraction
- Resolved IP model: distinguish q / g dominated IP
- 2-gluon models: decomposition into $q\bar{q}$, $q\bar{q}g$

Studies made in $\gamma^* I\!P$ - CMS (rest frame of X):



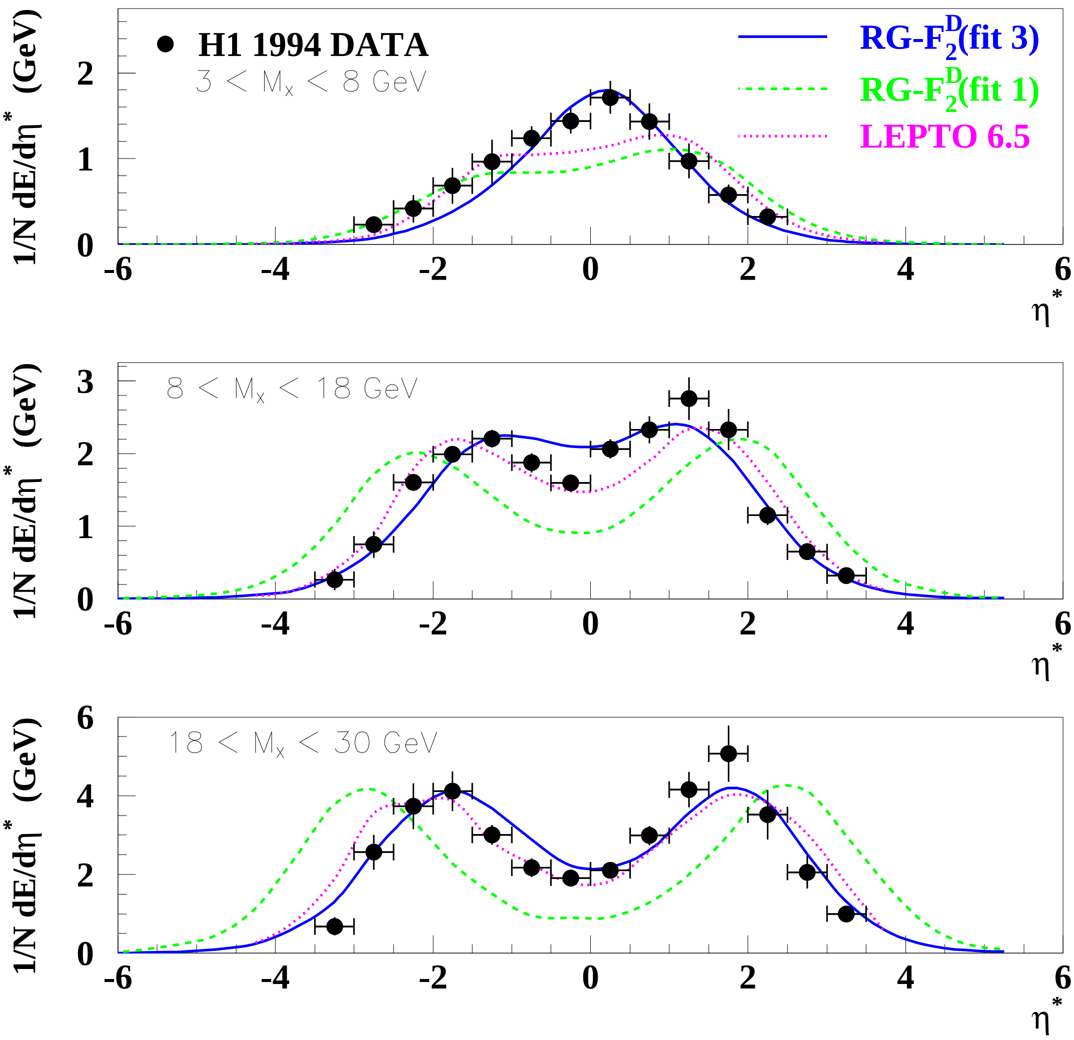
- q induced:
  low p_T, aligned
- g induced:
  high p_T, non-aligned

Topics:

- Energy Flow
- Event Shapes (Thrust, Sphericity)
- (Particle spectra, multiplicites, correlations) not here...
- Dijet production
- Open charm (D^*) production

Energy Flow (H1)

$I\!P \quad \Leftarrow \quad \Rightarrow \quad \gamma^*$



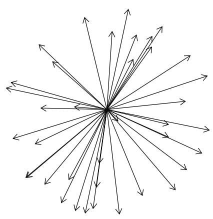
- large M_X: central rapidity pleateau emerges
  $\rightarrow$ gluons are needed to model finals state!
- RAPGAP q-dominated IP fails!
- RAPGAP g-dominated IP and SCI: reasonable description (except SCI at low M_X)

(Measurement in agreement with ZEUS LPS 1997)

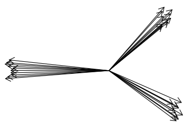
Event Shapes: Thrust and Sphericity

Observables:

- Thrust definition: $T = \max \frac{\sum_i |n \cdot p_i|}{\sum_i |p_i|}$
- Sphericity definition: $S = 3/2(\lambda_2 + \lambda_3)$,
  where the λ_k are eigenvalues of the Sphericity tensor
  $S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |p_i|^2}$.



$T \to \frac{1}{2}$ $S \to 1$



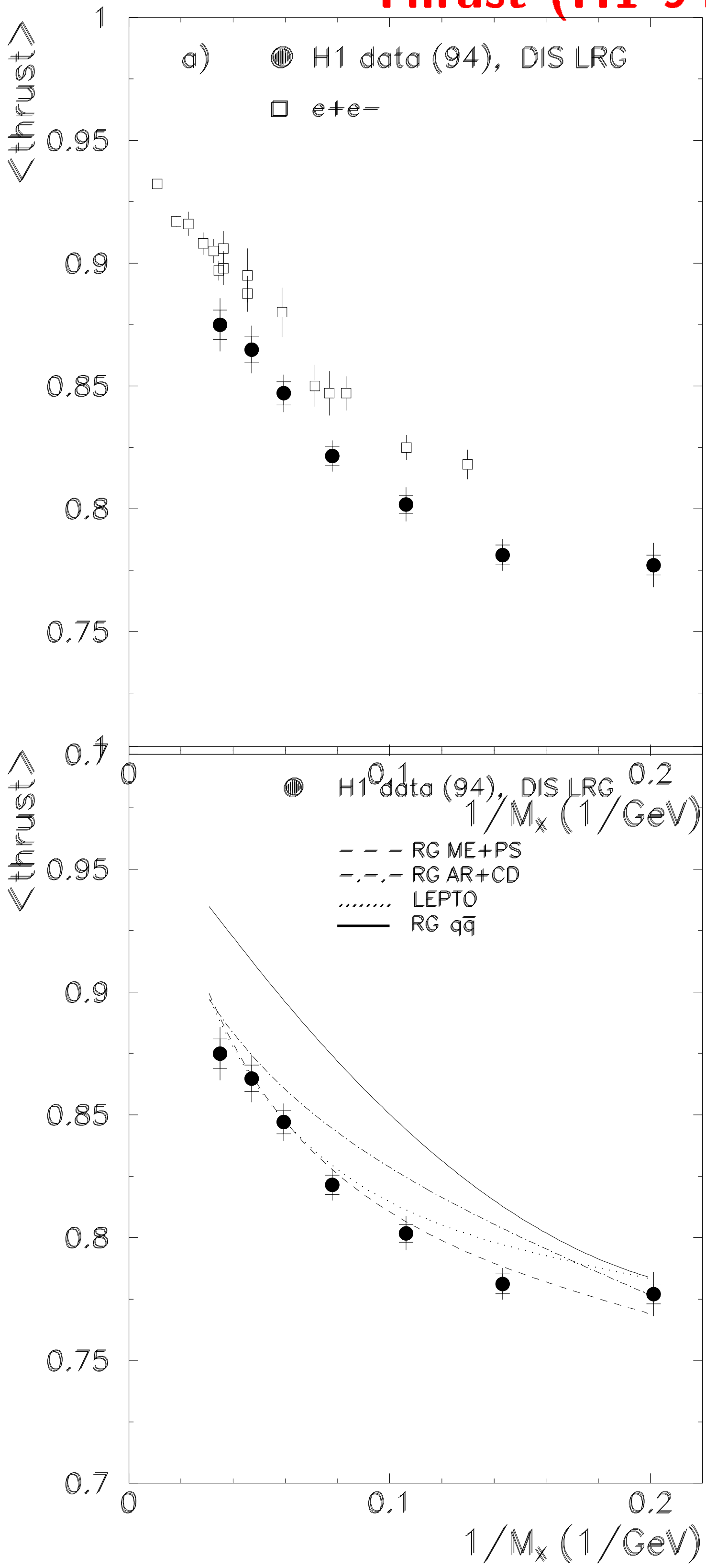
$T \to \frac{3}{4}$ $S \to \frac{1}{2}$

$T \to 1$ $S \to 0$

Measurements:

- H1 1994 Data: $x_{I\!P} < 0.05$,
  $10 < Q^2 < 100\ GeV^2, 4 < M_X < 36\ GeV$
- ZEUS 1997 LPS Data: $0.0003 < x_{I\!P} < 0.03$,
  $4 < Q^2 < 90\ GeV^2, 4 < M_X < 35\ GeV$

Thrust (H1 94)



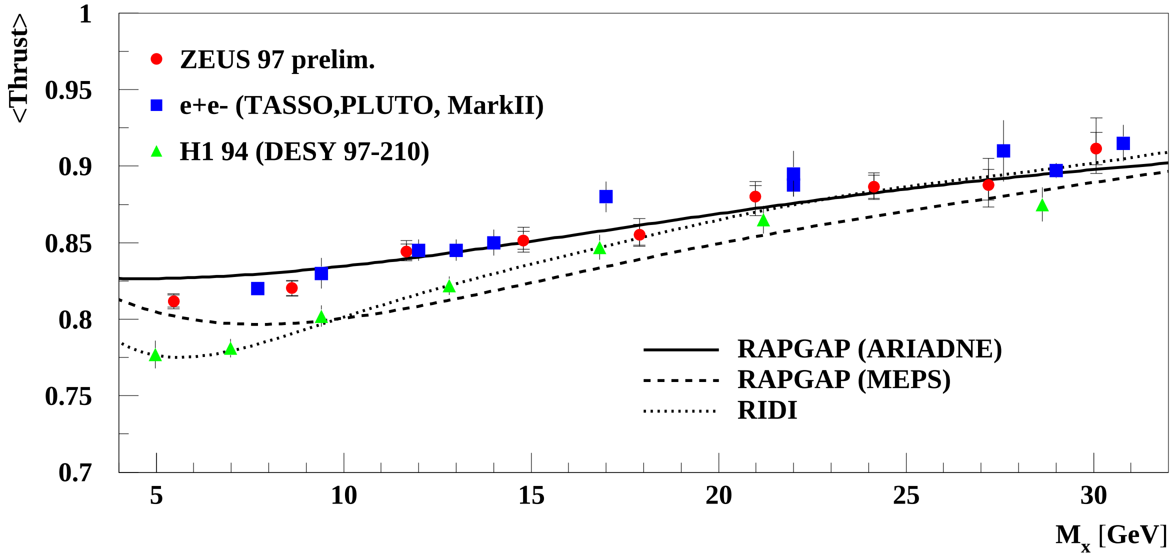
$M_X \to \infty$,
$1/M_X \to 0$:
hadronisation corrections negligible

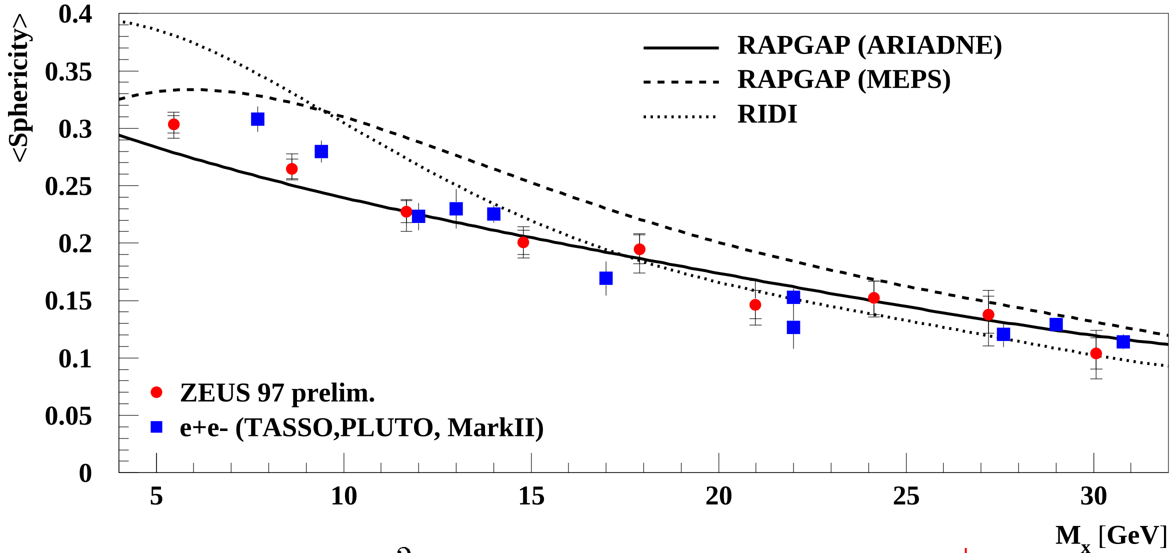
increases with M_X

lower than in e^+e^-:
$\to$ higher parton multiplicities more important, e.g. $q\bar{q}g$

MEPS o.k!
CDM fails!

Thrust/Sphericity (ZEUS 97 LPS)





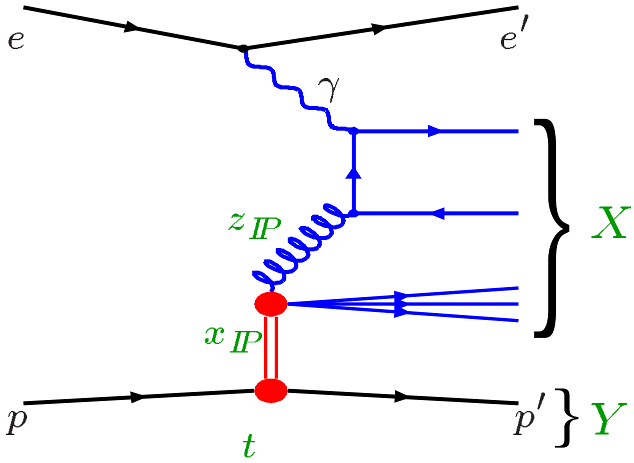
- independent of $Q^2, x_{I\!P}, W$, agreement with e^+e^-
- Rapgap + Hadronisation: MEPS fails! CDM o.k.!

- RIDI (Ryskin $\gamma^* \rightarrow q\overline{q}(g)$): fails at low M_X
  $\rightarrow$ too 2-jet like!

$\rightarrow$ Discrepancy H1-ZEUS!

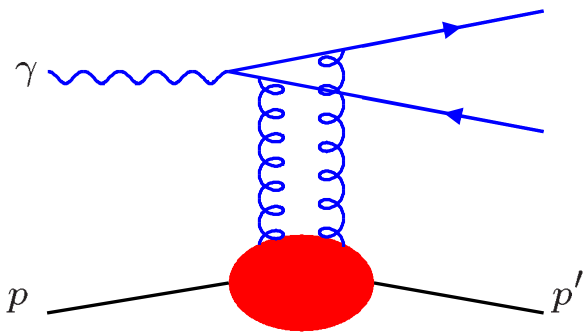
Diffr. Jet and Charm Production: Models

Motivation for Jets, Charm: Large sensitivity to gluons!



Resolved IP Model (Ingelman, Schlein)

$z_{I\!P}$: Momentum fraction from IP entering hard process: $z_{I\!P} \leq 1$

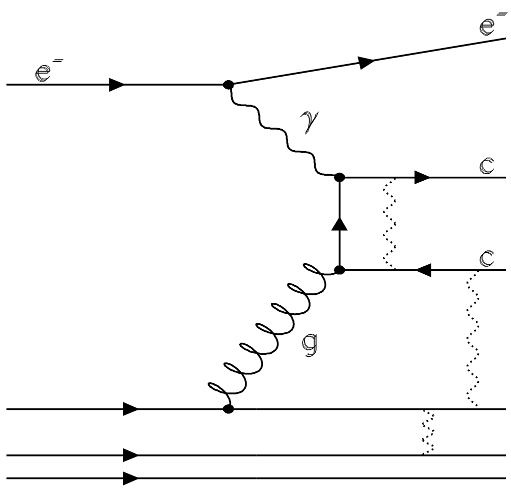


2-gluon $q\overline{q}$ Model (e.g. Bartels et al.)

$M_X = M_{q\overline{q}}$

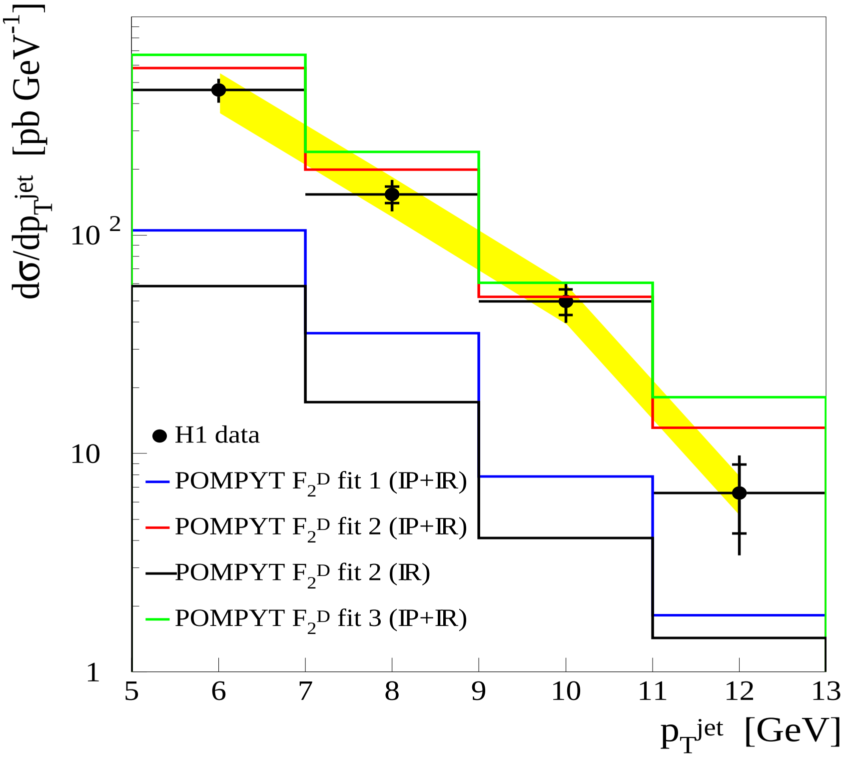
$z_{I\!P} = 1$

(at parton level, not for $q\overline{q}g$)



SCI model

Diffractive Dijets (H1 1994)

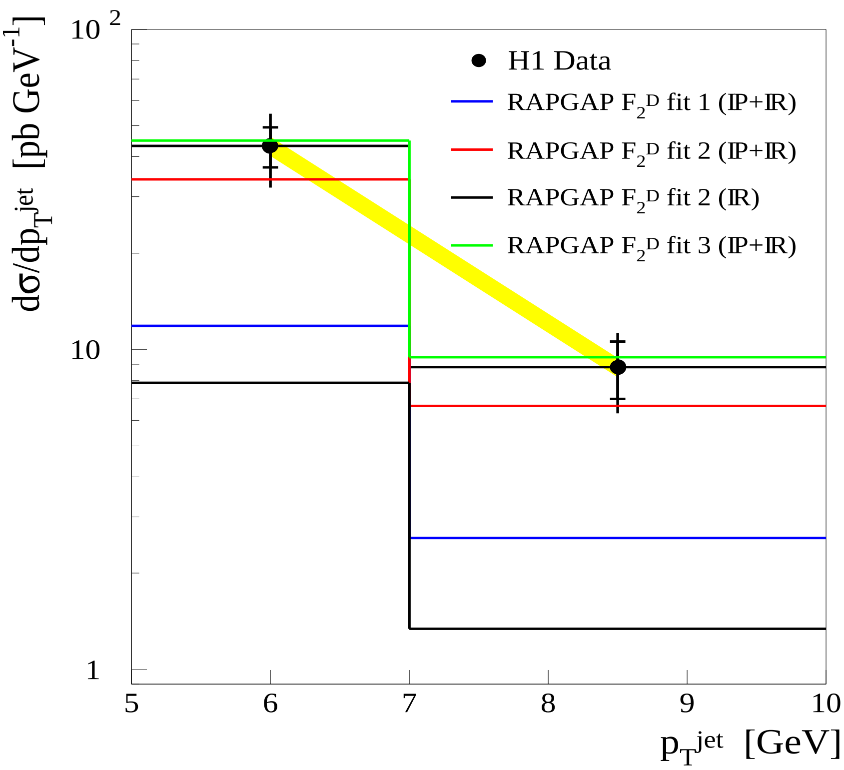


p_T spectra

Photoproduction:
$Q^2 < 0.01\ GeV^2$

DIS:
$7.5 < Q^2 < 80\ GeV^2$

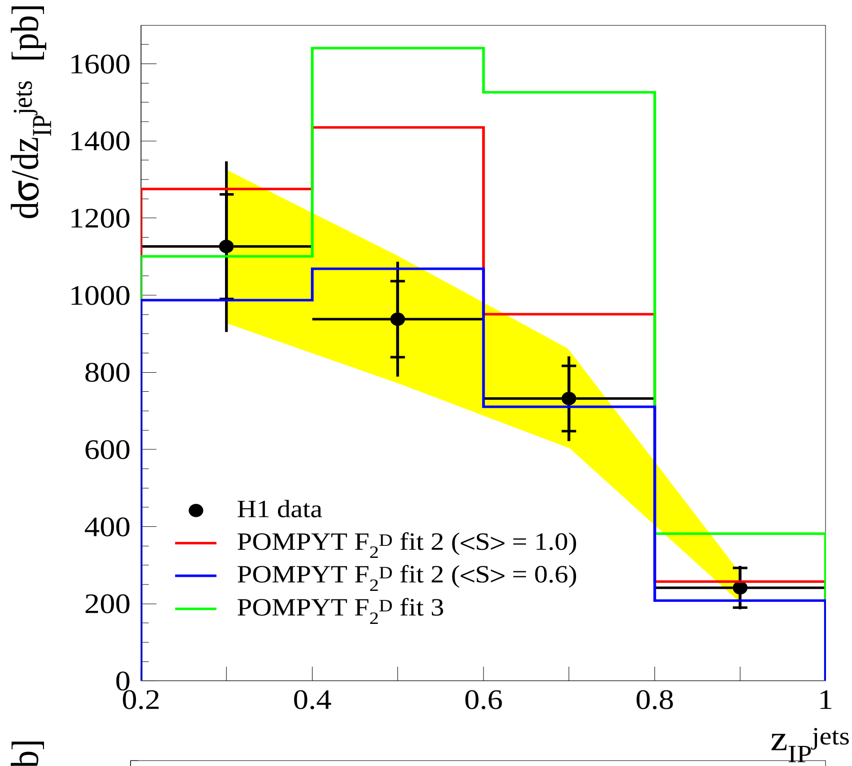
X contains
N=2 jets with
$p_T > 5\ GeV$

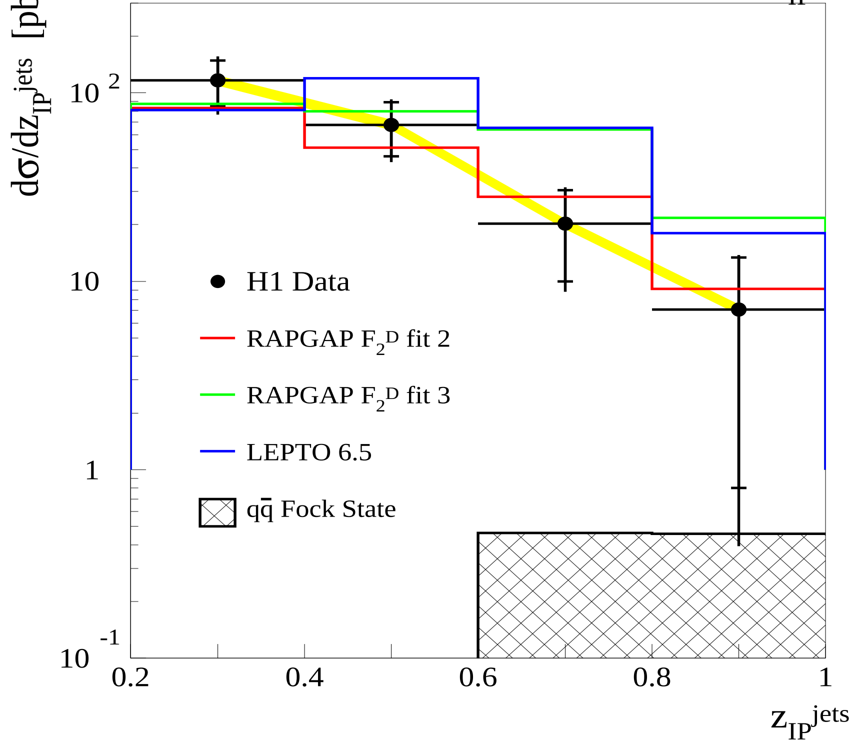


resolved IP ,
q dom. (●):
→ low by
factor 3-6!

resolved IP ,
g dom. (● ●):
→ reasonable
description!

Dependence on fractional momentum from IP





$z_{I\!P}$ spectra

have to introduce $< S >= 0.6$ for res. γp

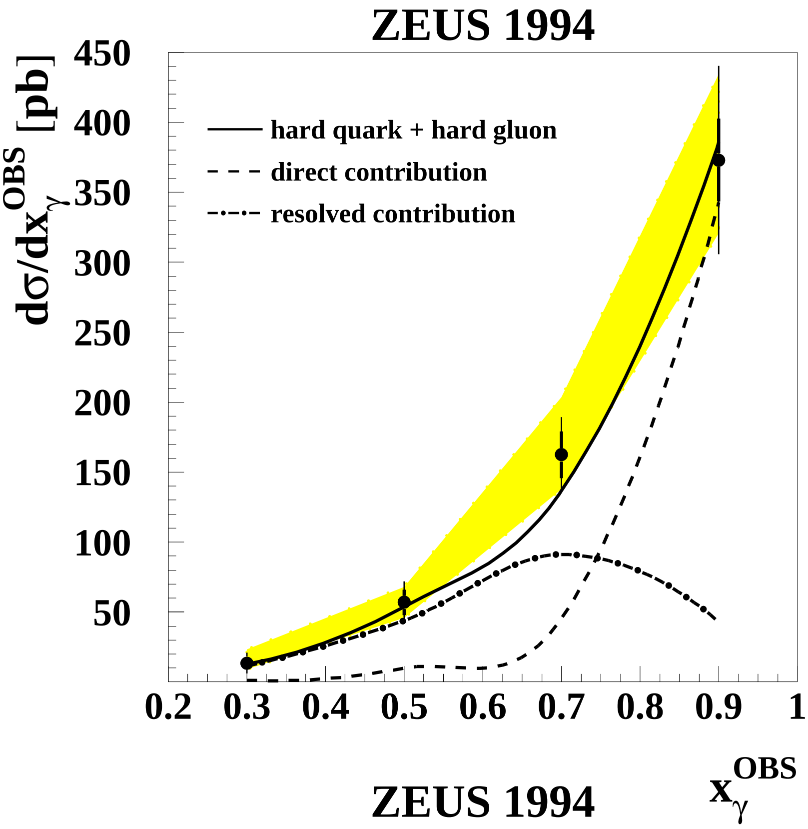
g dom. res. $I\!P$ reasonable! (fit 2 better than fit 3)

Bartels $q\bar{q}$ (DIS): only at large $z_{I\!P}$; → large M_X (low $z_{I\!P}$): $q\bar{q}g$!

SCI model (DIS): similar to res. $I\!P$ fit 3

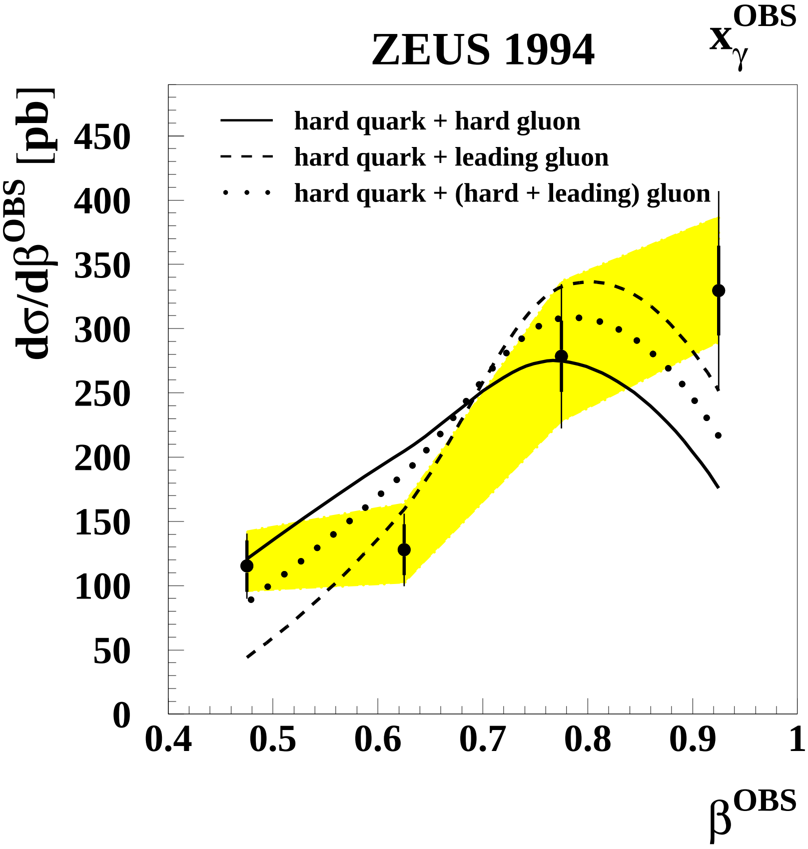
→ Momentum distribution neither soft nor 'super-hard'

Dijets in γp (ZEUS 94)



$p_T > 6\ GeV$

Combined DGLAP QCD fits to Jet cross sections and $F_2^{D(3)}$ within resolved IP model

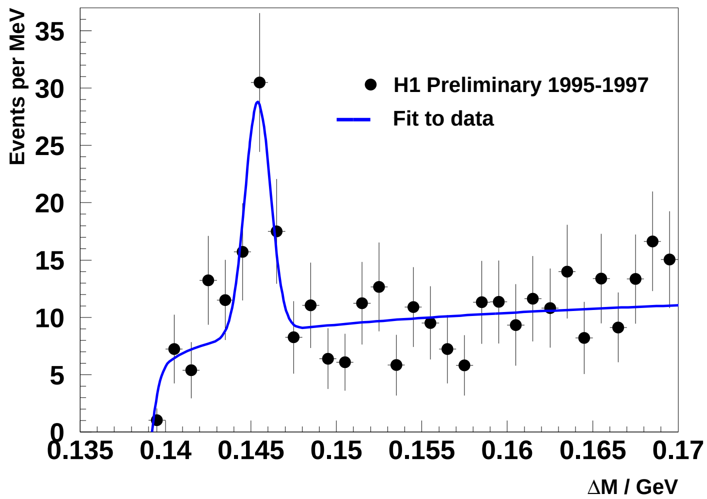


acceptable fits only if $I\!P$ dominated by hard gluons

Gluon fraction in IP : $70 - 80\%$

Charm production: $ep \to e(D^*X)Y$

H1 data (95-97): $D^* \to K\pi\pi$ $L = 21\ pb^{-1}$



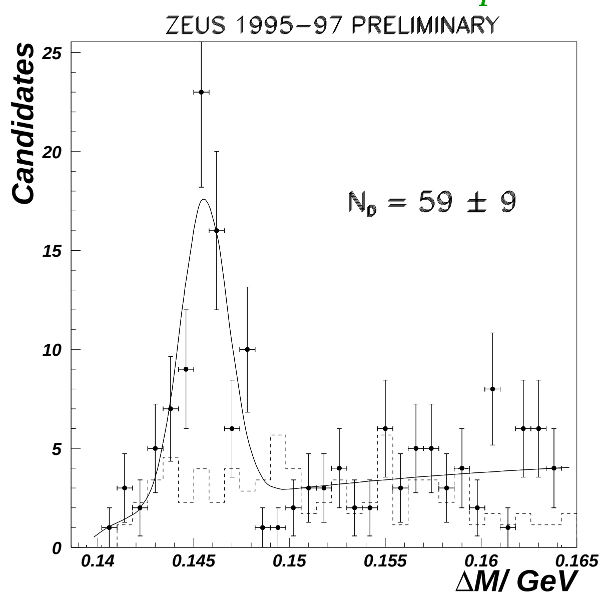
$2 < Q^2 < 100\ GeV^2$
$x_{I\!P} < 0.04$
$p_T(D^*) > 2\ GeV$

$N(D^*) = 38 \pm 10 \pm 4$

$\sigma = (154 \pm 45 \pm 35)\ pb$

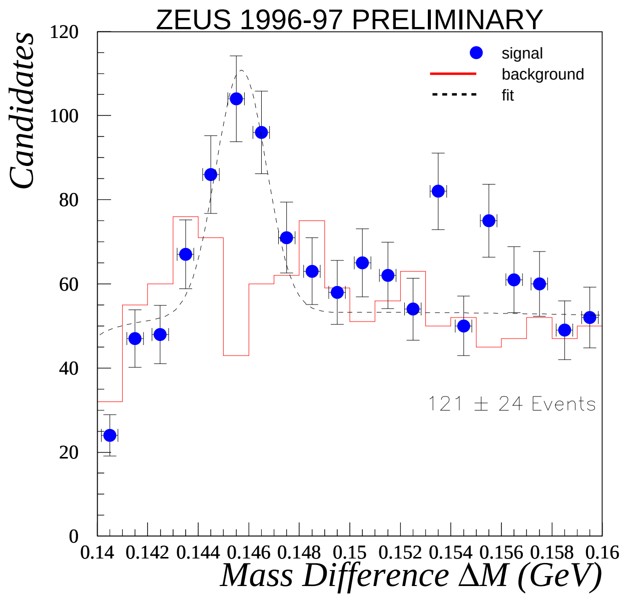
ZEUS data (95-97, 96-97):

$D^* \to K\pi\pi$ $L = 43\ pb^{-1}$



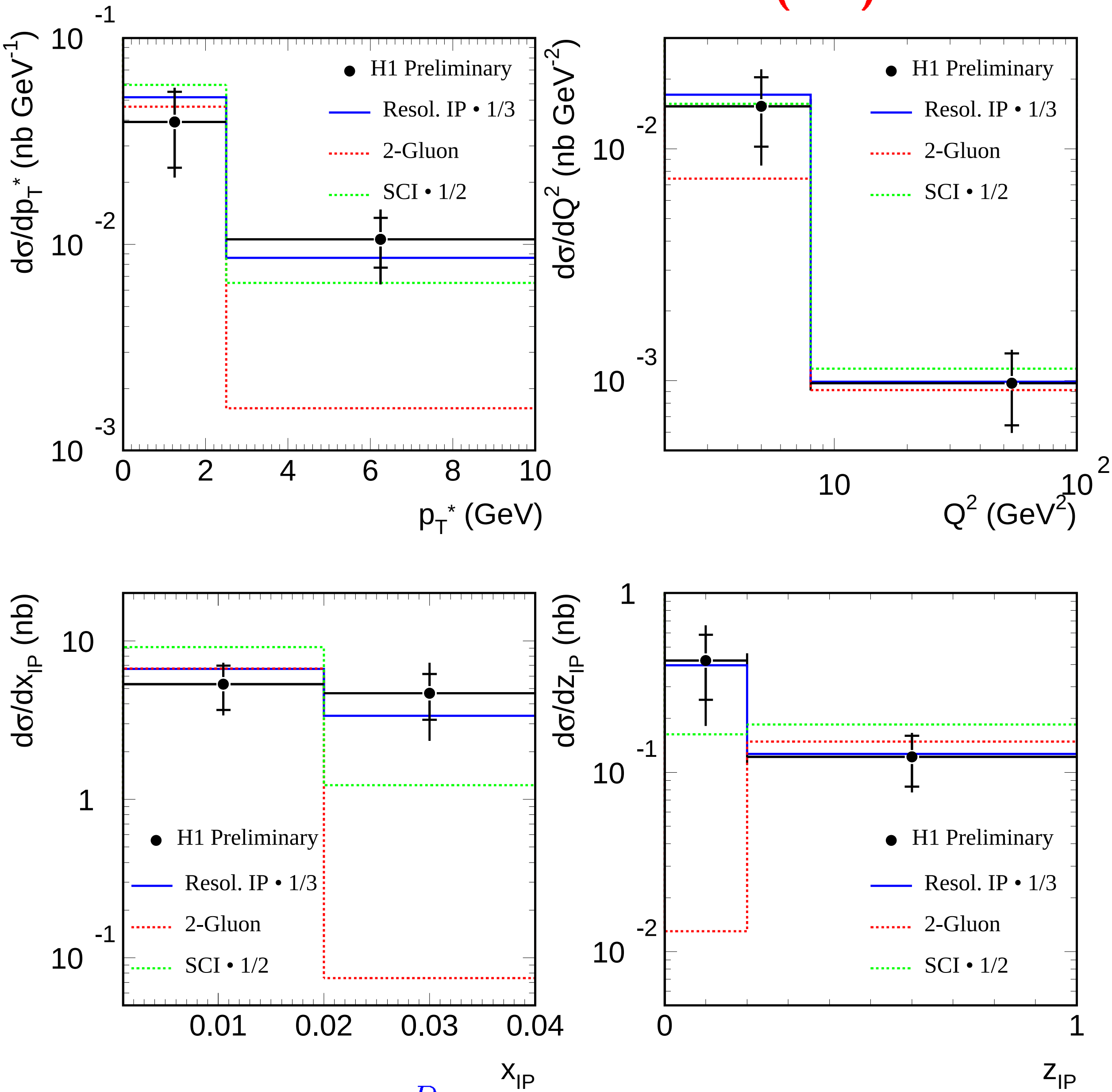
$3 < Q^2 < 150\ GeV^2$
$p_T(D^*) > 1.5\ GeV$
$x_{I\!P} < 0.012$

$D^* \to K4\pi$ $L = 37\ pb^{-1}$



$1 < Q^2 < 480\ GeV^2$
$p_T(D^*) > 2.0\ GeV$
$x_{I\!P} < 0.015$

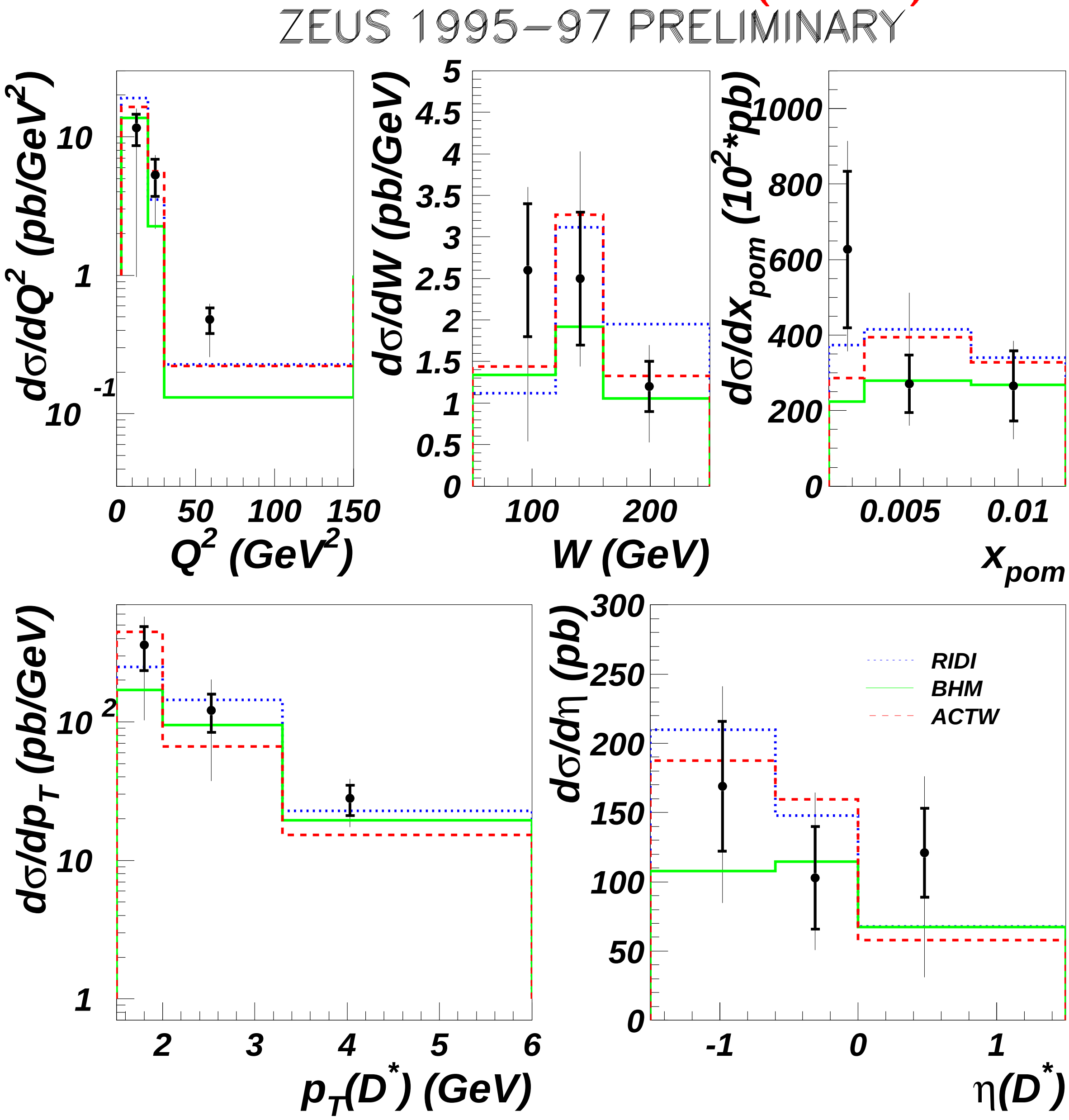
$D^* \to K\pi\pi$ cross sections (H1)



- Resolved $I\!P$, H1 F_2^D fits: Shapes o.k., but but rate too high by a factor of 3!
- 2-gluon model, Bartels $q\overline{q}$: reasonable normalization, but fails at large masses (large $x_{I\!P}$, low $z_{I\!P}$) $\to$ need $q\overline{q}g$!
- SCI model: Shapes o.k., but rate too high by a factor of 2!

$\to$ In contrast to other H1 measurements!!

$D^* \to K\pi\pi$ cross sections (ZEUS)



- ACTW: gluon dominated res. IP model
- RIDI: Ryskin's pQCD model $q\overline{q}$ AND $q\overline{q}g$! (normalized)
- BHM: SCI model

→ reasonable description by all models!

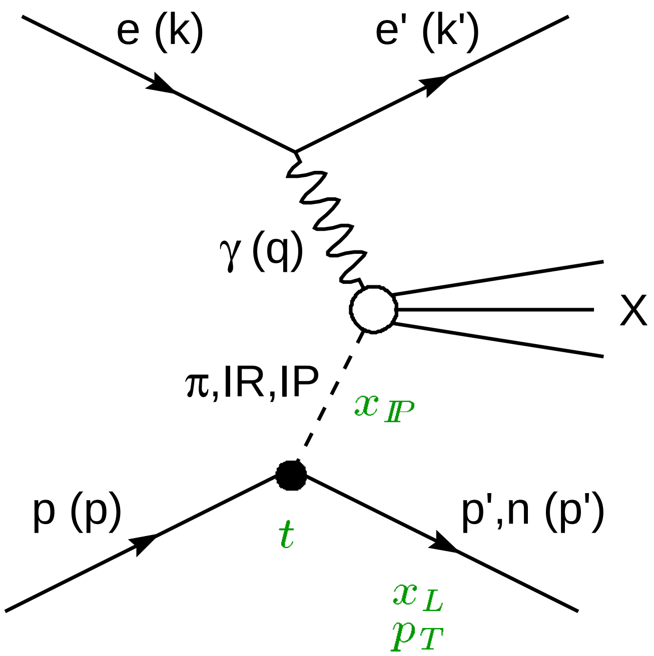
→ Disagreement H1-ZEUS! Need more work...

Leading Baryon Production

Introduction:

- H1 and ZEUS use *forward detectors*:
  Proton spectrometers and Neutron calorimeters
  located $60 \ldots 110\ m$ downstream the IP
- forward $p's$ and $n's$ measured over wide energy range

Kinematics:



p, n long. momentum:
x_L (ZEUS) $= z$ (H1)

$x_L = 1 - x_{I\!P}$
(if exclusive p, n)

$x_L \approx E'/E$

p, n trans. momentum:
p_T

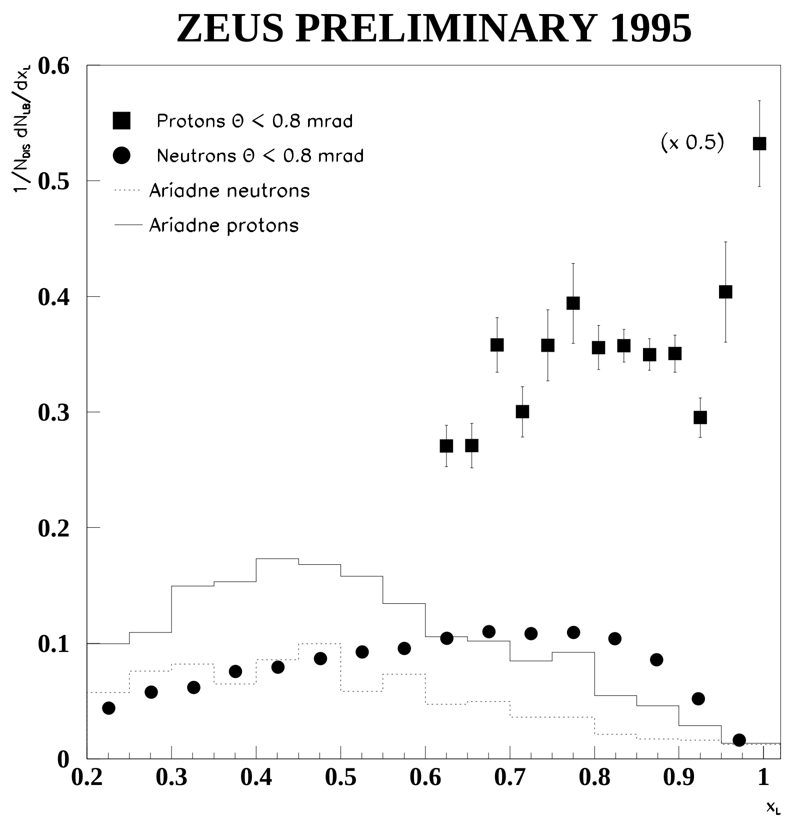
Questions:

- Description of p fragmentation region by 'standard models'
- Applicability of Regge models to soft physics at p vertex at large $x_{I\!P}$
- Probe sub-leading exchanges (e.g. π) at large $x_{I\!P}$

Detector acceptances:

	H1	ZEUS
Leading p	$p_T < 0.2\ GeV$ $0.7 < x_L < 0.9$	$p_T < 0.5\ GeV$ $0.6 < x_L < 1.0$
Leading n	$p_T < 0.2\ GeV$ $0.2 < x_L < 1.0$	$\theta < 0.8\ mrad$ $0.6 < x_L < 1.0$

x_L distribution (ZEUS)



Frac. of DIS events with leading baryon

$$\frac{1}{N_{DIS}} \frac{dN_{LB}}{dx_L}$$

$0.11 < Q^2 < 0.65$
$3 < Q^2 < 254$
(GeV^2)

- diffractive peak at $x_L \approx 1$
- If pure π exch., exp. $N_{LP} = \frac{1}{2} N_{LN}$ But: $N_{LP} \gg N_{LN}$!
- Ariadne Colour Dipole Model (CDM) fails to describe data!

Regge model of baryon production

$$F_2^{LB(3)}(z,\beta,Q^2) = \sum_{i=\pi,I\!P,I\!R} f_{i/p}(z) \cdot F_2^i(\beta,Q^2)$$

- Protons: add contributions from π^0, $I\!P$, $I\!R$
  $I\!R = f_2$ (neglect other secondary reggeons)
- Neutrons: only π^+ exchange contributes
  (shown by the data)

- Flux factors: $f_{i/p}(z)$ from Hadron-Hadron data:
  $f_{\pi/p}(z,t) = C\frac{g^2_{\pi Np}}{16\pi^2}(1-z)^{1-2\alpha'_\pi t}\frac{|t|}{(m_\pi^2-t)^2}\exp\left(2R_\pi^2(t-m_\pi^2)\right)$
  with
  $C = 2/3$ for n's, $C = 1/3$ for p's.
  $f_{I\!P/p}(z,t) = \frac{54.4\ GeV^{-2}}{8\pi^2}(1-z)^{1-2\alpha_{I\!P}(t)}\exp\left(2R_{I\!P}^2 t\right)$
  $f_{I\!R/p}(z,t) = \frac{390\ GeV^{-2}}{8\pi^2}(1-z)^{1-2\alpha_{I\!R}(t)}\exp\left(2R_{I\!R}^2 t\right)$
  with
  $\alpha_{I\!P}(t) = 1.08 + 0.25\ GeV^{-2}t,\ R_{I\!P}^2 = 1.9\ GeV^{-2}$
  $\alpha_{I\!R}(t) = 0.50 + 0.90\ GeV^{-2}t,\ R_{I\!R}^2 = 2.0\ GeV^{-2}$

- Structure functions:
  large $x_{I\!P} \to$ low β: F_2^π, $F_2^{I\!P}$, $F_2^{I\!R}$ not much constrained.

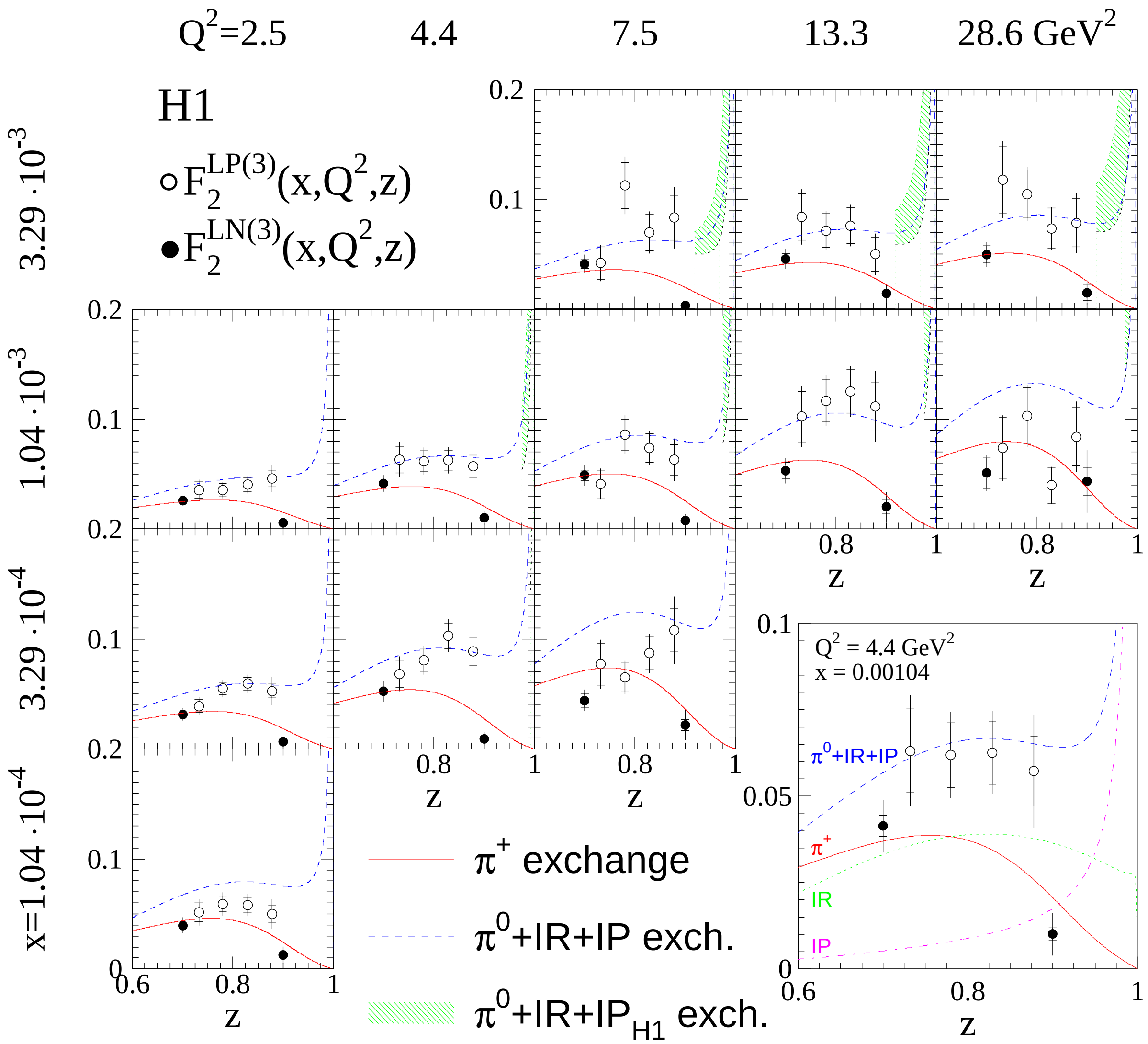
  $F_2^\pi = F_2^\pi(GRV)$
  $F_2^{I\!R} = F_2^\pi$
  $F_2^{I\!P} = (0.026/0.12) \cdot F_2^\pi$ (c.f. Szczurek et al.)

Semi-inclusive structure functions (H1)

$2 < Q^2 < 50\ GeV^2$

$0.00006 < x < 0.006$

$p_T < 0.2\ GeV$



F_2^{LN} rises to lower z, higher $x_{I\!P}$ $\rightarrow$ π-exchange!
F_2^{LP} approx flat $\rightarrow$ sum of $I\!P + I\!R + \ldots$

$$\frac{d\sigma(ep \rightarrow e(p,n)X}{dx\ dQ^2\ dz} = \frac{4\pi\alpha^2}{xQ^4}\left(1 - y + \frac{y^2}{2}\right)\ F_2^{LB(3)}(x, Q^2, z)$$

Constraint on F_2^π (H1)

If

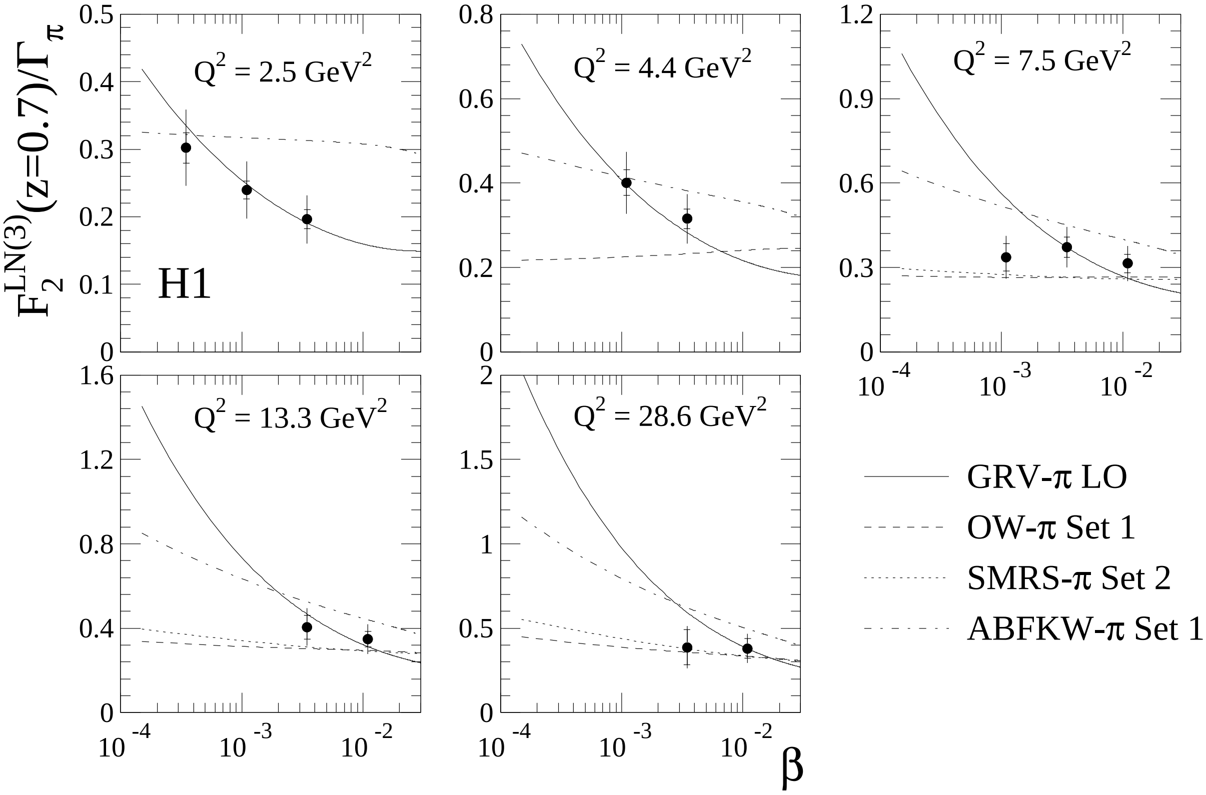
$$F_2^{LN(3)}(z,\beta,Q^2) = f_{\pi/p}(z) \cdot F_2^\pi(\beta,Q^2)$$

and

$$\Gamma_\pi = \int_t f_{\pi/p}(z=0.7,t)\ dt$$

then

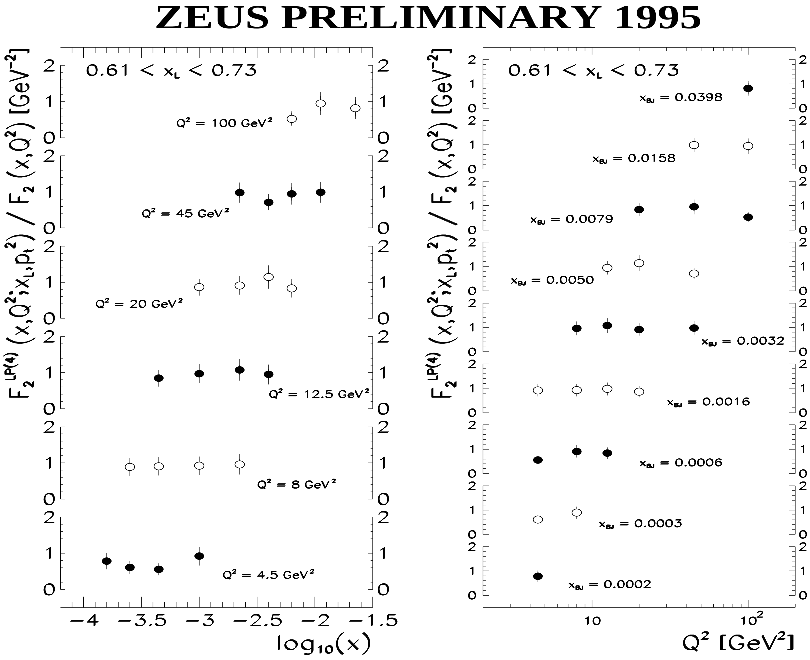
$$\frac{F_2^{LN(3)}(z{=}0.7,\beta,Q^2)}{\Gamma_\pi} = F_2^\pi(\beta,Q^2)$$



→ Consistent with GRV(LO)!

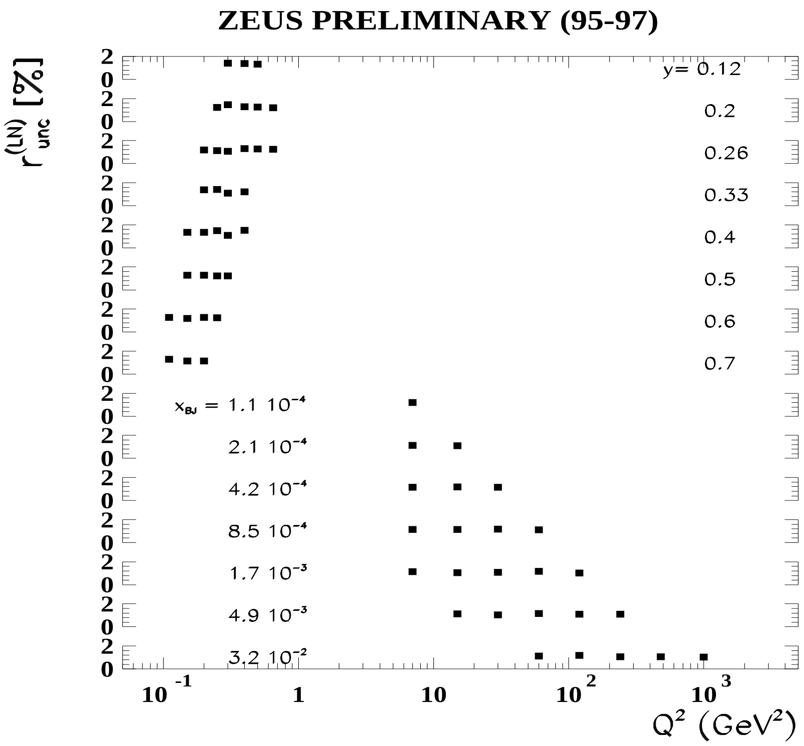
→ First constraint on F_2^π at $x < 0.02$!

Ratios LB / all DIS (ZEUS)



$$\frac{F_2^{LP}}{F_2^{DIS}}$$

flat in x, Q^2
in ranges
$4.5 < Q^2 < 100\ GeV^2$
$0.0002 < x < 0.04$



$$\frac{N_{LN}}{N_{DIS}}$$

flat in Q^2
in ranges
$0.1 < Q^2 < 0,7$ and
$7 < Q^2 < 1000\ GeV^2$

→ same x behaviour, Q^2 scaling as $F_2(x, Q^2)$
→ LB production factorising from hard interaction
(in Regge or Fragmentation picture)

Summary

- At HERA, the QCD dynamics of diffractive scattering can be studied
- - $\alpha_{I\!P}(0)$ in DIS higher than for soft IP ,
  now: transition region (very low Q^2) accessible!
  - t slope compatible with hadron-hadron scattering
- - Resolved IP model (Ingelman, Schlein) with gluon dominated $(80 - 90\%)$ parton densities evolving with DGLAP describes H1 data for inclusive diffr. DIS and several hadronic final state observables (Energy flow, Jets, etc.)
  - New results on diffractive charm production!
  $\rightarrow$ H1 sees discrepancy to other hadr. final states, but also disagrees with ZEUS! More work to be done!
- - Soft Colour Interaction (SCI) model: some problems, esp. at low Q^2
  - Several 2-gluon models on the market, free parameters can be tuned to describe H1 and ZEUS data;
  $\rightarrow$ clear need for $q\overline{q} + q\overline{q}g$ states!
- Leading baryons:
  - Clean sample of diffractive events (w.o. LRG etc.)
  - Neutrons: saturated by pion exchange
  $\rightarrow$ extraction of F_2^{π} at $x < 0.02$!
  -Protons: described by sum of $I\!P + I\!R + \pi$-exchange