Diffractive Deep-Inelastic Scattering

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Contents:

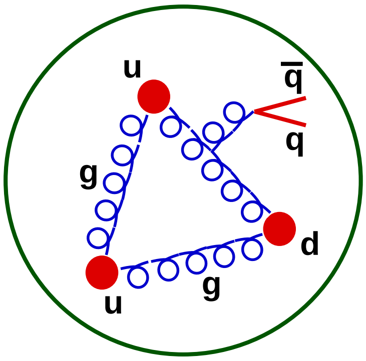
- Strong Interactions and Diffraction.
- The Diffractive Structure Function $F_2^{D(3)}$.
- Regge models of $F_2^{D(3)}$.
- QCD models of $F_2^{D(3)}$.
- Diffractive Final States.
- Leading Baryon Measurements.

Related topics not covered here:

- Diffractive photoproduction.
- Vector meson production.
- Total $\gamma^{(\star)}p$ Cross Sections.

Strong Interactions in the Standard Model

Modern Picture of Hadrons
and Their Interactions:



- Parton Model (e.g. proton = uud)
- SU(3) Gauge Theory, QCD

1) "Hard" Interactions ($< 1\%$ of hadronic cross sections)

- α_s small: "Asymptotic Freedom".
- Well understood within perturbative QCD.

2) "Soft" Interactions ($> 99\%$ of hadronic cross sections)

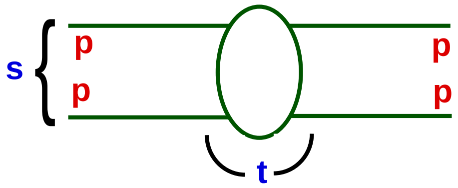
- α_s large: "Infrared Slavery".
- Poorly understood within QCD.
- Many years of "Regge" Phenomenology.

Understanding Soft Hadronic Interactions in terms of QCD is a major challenge to the Standard Model.

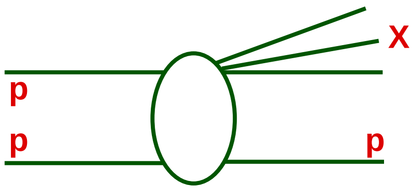
In 'diffractive' Deep-Inelastic Scattering, the interface between 'soft' and 'hard' strong interactions is studied.

Diffractive Processes and the Pomeron

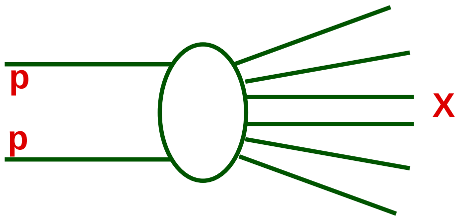
Soft diffraction: elastic, total and dissociation cross sections.



$\sigma^{\mathrm{el}}(pp \to pp)$



$\sigma^{\mathrm{diss}}(pp \to pX)$



$\sigma^{\mathrm{tot}}(pp \to X)$

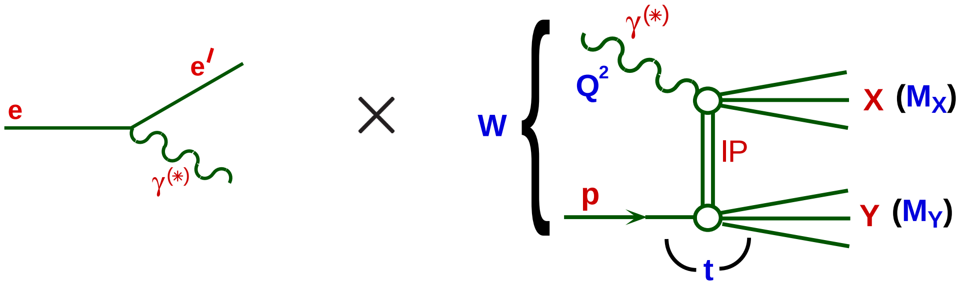
(via the optical theorem)

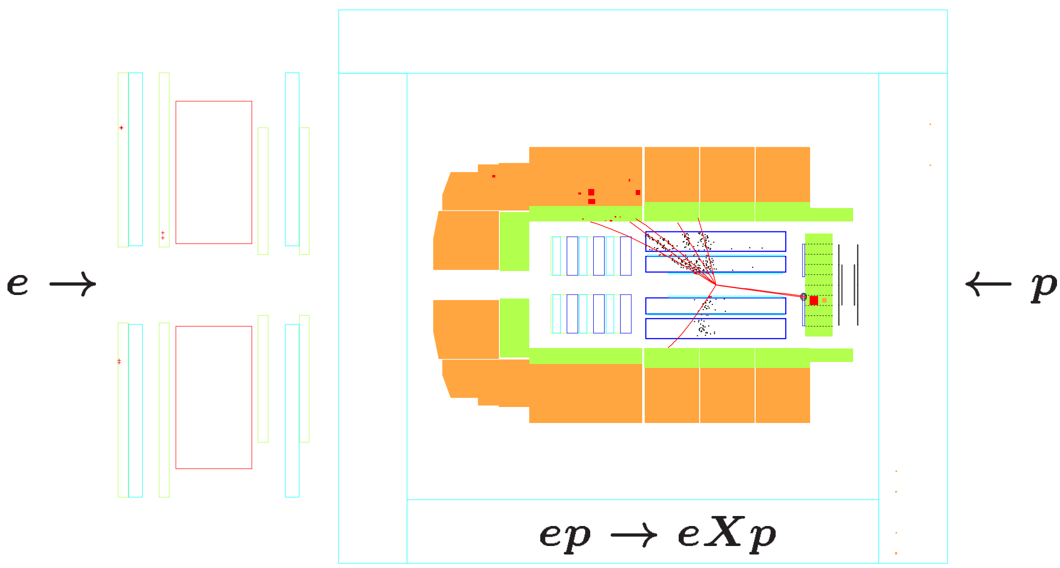
It is useful to think in terms of the exchange of an object with net vacuum quantum numbers - the "pomeron" ($\mathbb{P}$).

- $\alpha_{\mathbb{P}}(t) \simeq 1.081 + 0.26t$
- 'FACTORISES!' Describes the energy dependence of all such hadron-hadron cross sections where $s \gg t$.
- BUT The partonic structure of the interaction remains an enigma!

The Advantages of HERA for Diffraction

At the HERA ep collider, diffractive $\gamma^{(\star)}p$ interactions can be studied.



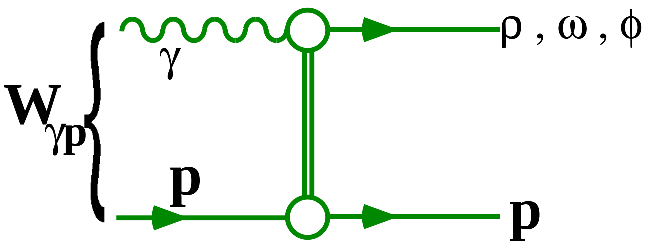


All five kinematic variables can be measured:

- $Q^2 \sim 0$, $|t| \sim 0$. $\rightarrow$ soft physics, soft pomeron.
- Large Q^2. $\rightarrow \gamma^\star$ probes $I\!P$ structure. $\star\star\star$
- Large $|t|$. $\rightarrow$ search for perturbative (BFKL?) $I\!P$.

. . . the non-perturbative $\leftrightarrow$ perturbative transition.

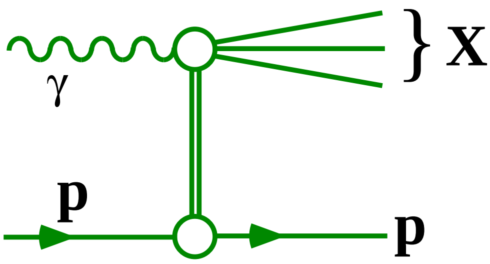
COLOUR SINGLET EXCHANGE PROCESSES IN γ^{*}-p INTERACTIONS



QUASI ELASTIC VECTOR MESON PRODUCTION

(EL)

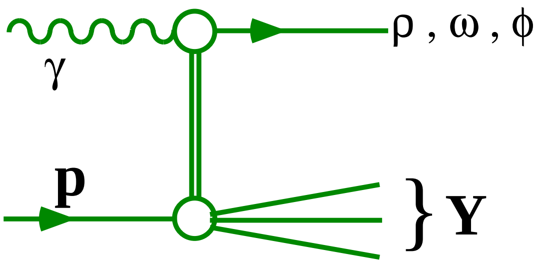
$$\gamma p \longrightarrow Vp$$



SINGLE PHOTON DISSOCIATION

(GD) ⋆⋆⋆

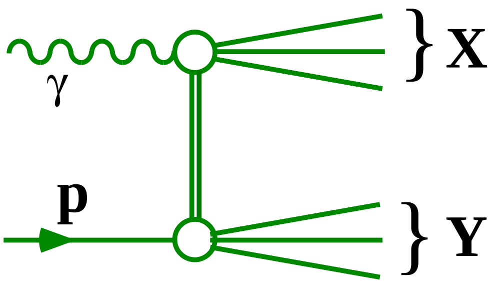
$$\gamma p \longrightarrow Xp$$



SINGLE PROTON DISSOCIATION

(PD)

$$\gamma p \longrightarrow VY$$

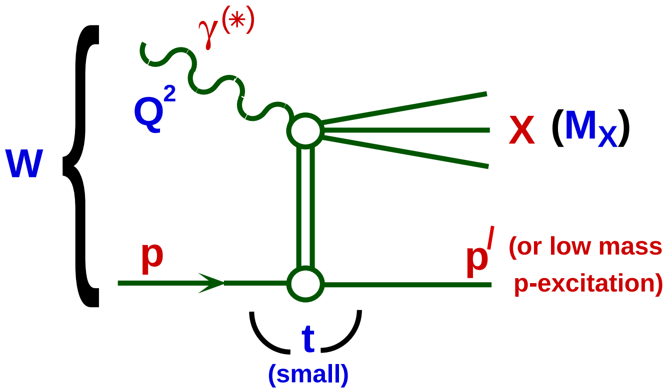


DOUBLE DISSOCIATION

(DD)

$$\gamma p \longrightarrow XY$$

Kinematics of the Process $\gamma^\star p \rightarrow Xp$



- $Q^2 = -q^2$ (Photon virtuality)
- $W^2 = (q+p)^2$ ($\gamma^\star p$ centre of mass energy)
- $M_X^2 = X^2$ (Invariant mass of X)
- $t = (p-p')^2$ (4-momentum transfer squared)

Long distance physics at p - vertex:

$$x_{I\!P} = \frac{q.(p-p')}{q.p} \simeq \frac{Q^2+M_X^2}{Q^2+W^2} = x_{I\!P/\mathrm{p}}$$

$\rightarrow$ Fraction of p momentum transferred to $I\!P$.

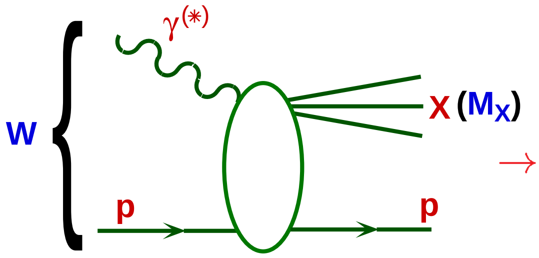
Short distance physics at $\gamma^\star$ - vertex:

$$\beta = \frac{Q^2}{q.(p-p')} \simeq \frac{Q^2}{Q^2+M_X^2} = x_{q/I\!P}$$

$\rightarrow$ Frac. of $I\!P$ momentum carried by quark coupling to $\gamma^\star$.

Experimental Techniques

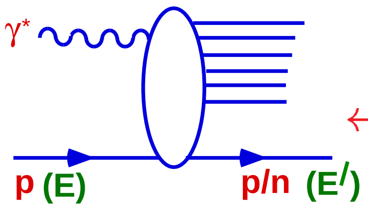
1. Rapidity Gap Selections (H1, ZEUS).



→ Largest rapidity gap among final state hadrons.

$\Delta\eta$ large when $M_X \ll W$

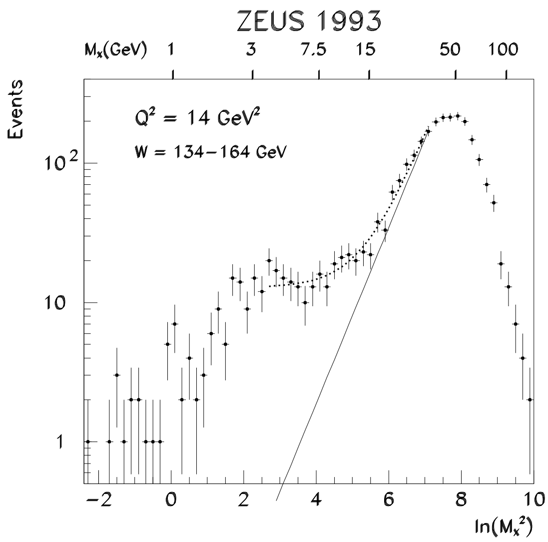
2. Direct Tagging of Leading Baryons (H1, ZEUS).



← May or may not be a large rapidity gap.

$x_{I\!P} = E'/E$ if exclusive p / n at proton vertex.

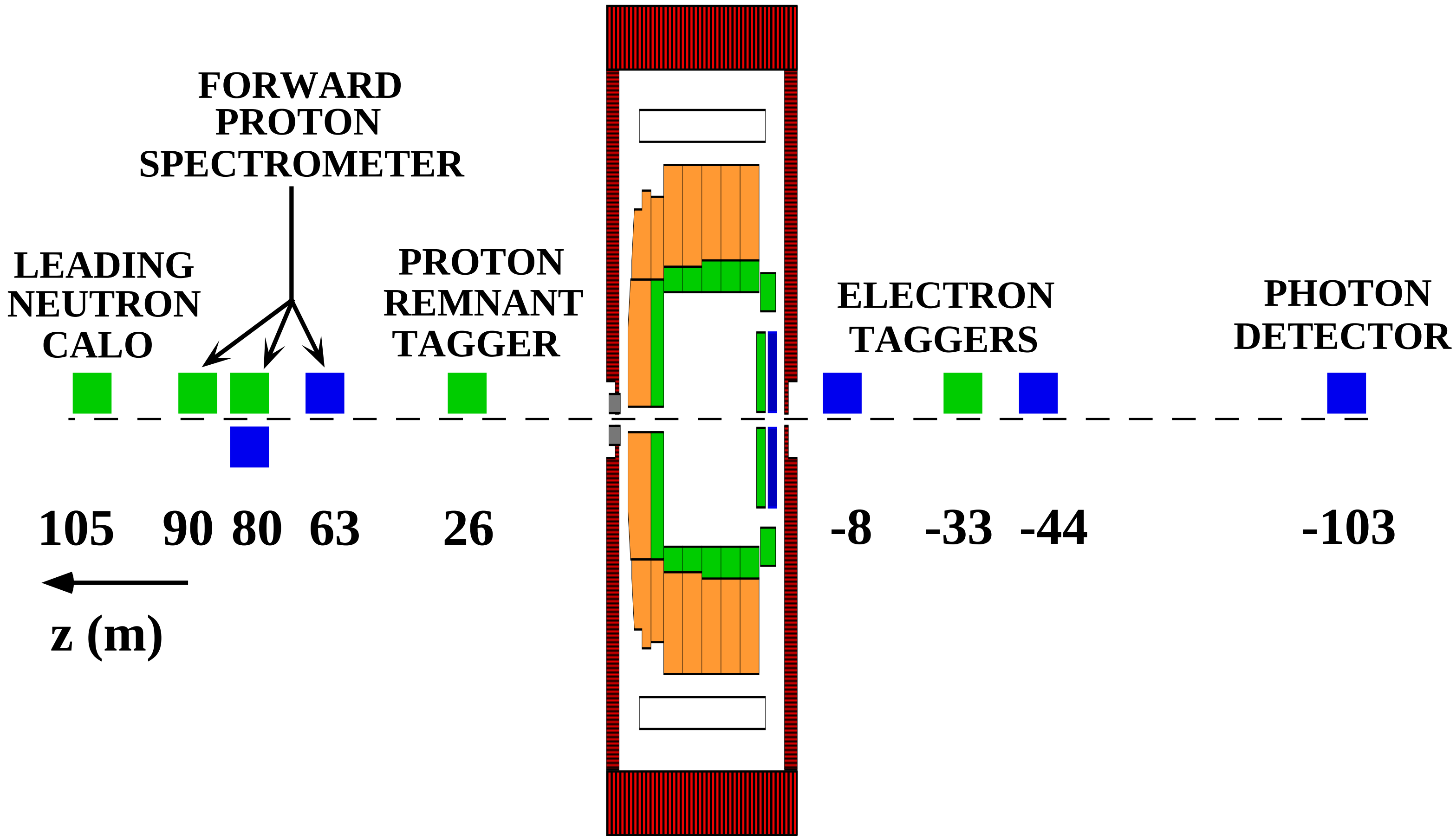
3. Decompose Visible M_X Distribution (ZEUS).



Exponential suppression in M_X distribution for "standard" DIS.

Diffractive contribution identified as excess at small M_X above fit to $Ae^{b \ln M_X}$

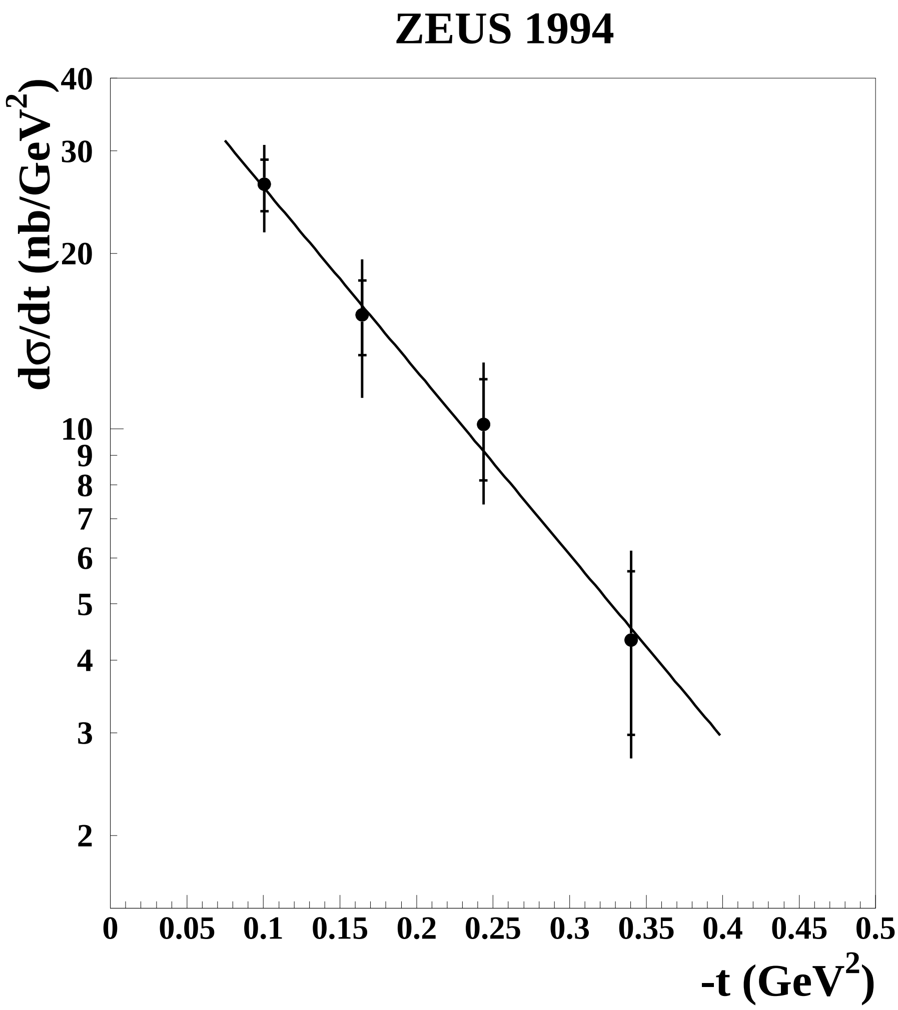
BEAM-LINE INSTRUMENTATION



Measurement of the t Dependence

$5 < Q^2 < 20$ GeV^2 $\quad 0.015 < \beta < 0.5$

$x_{I\!P} < 0.03$



From Direct Proton tagging

Fit to $\frac{d\sigma}{dt} \propto e^{bt}$

$b = 7.2 \ \pm 1.1(\text{stat.}) \ ^{+0.7}_{-0.9}(\text{syst.}) \ \text{GeV}^{-2}$

$\rightarrow$ Highly peripheral scattering.

$\rightarrow$ Slope parameter b is consistent with that expected from soft hadron-hadron diffraction.

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

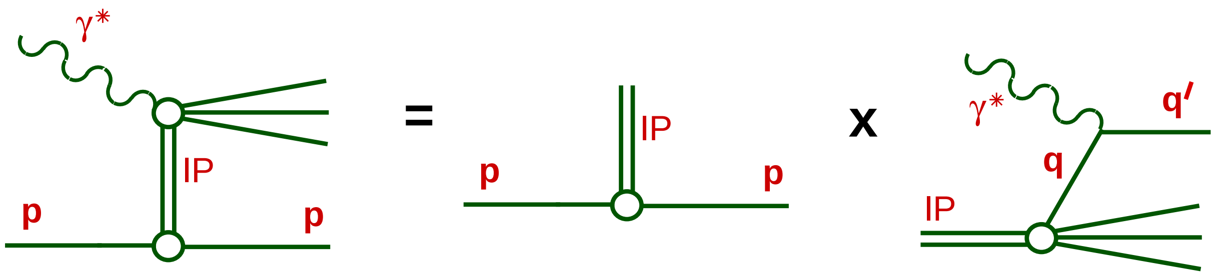
In rapidity gap based analyses, t is not measured.

Semi-inclusive cross section measurements are presented in terms of a ‘diffractive’ structure function $F_2^{D(3)}(\beta, Q^2, x_{I\!P})$, defined as

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

In the H1 case, $|t| < 1\ \mathrm{GeV}^2$ and $M_Y < 1.6$ GeV.

If the $p\mathbb{P}$p vertex factorises (as expected from hadron-hadron physics) then ...



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

...such that $x_{I\!P}$ dependence is universal at all β and Q^2.

The $x_{I\!P}$ Dependence of $F_2^{D(3)}$

Regge theory tells us how to parameterise the short distance physics at the photon vertex:

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

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

$x_{I\!P}$ dependence is found to vary with β ...

...in a Regge model, the measured data require a minimum of two exchanges:

Good fits obtained throughout kinematic range using:

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

$\alpha_{I\!P}(0)$, $\alpha_{I\!R}(0)$, $F_2^{I\!P}(\beta, Q^2)$, $F_2^{I\!R}(\beta, Q^2)$ free fit parameters.

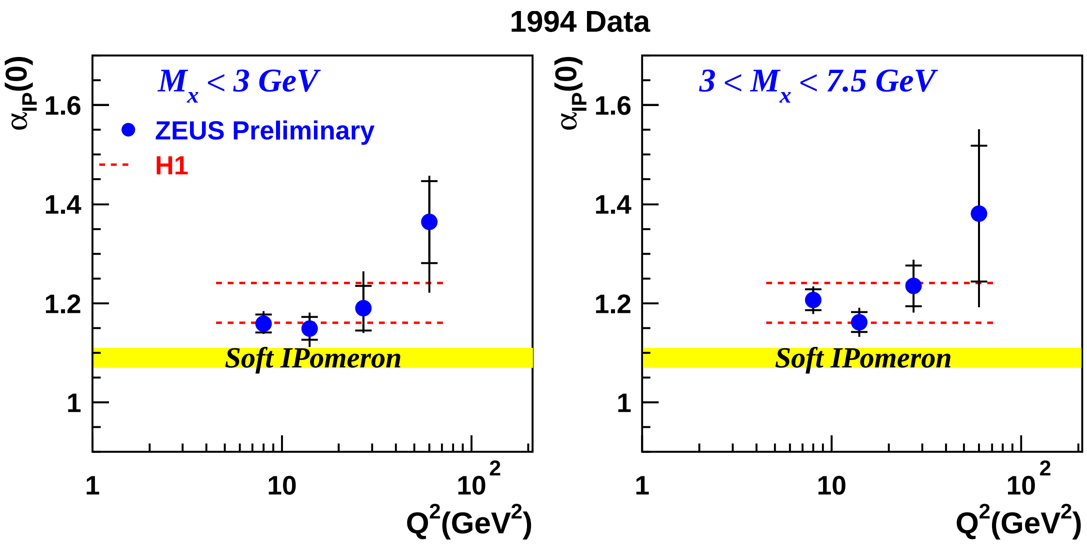
The pomeron intercept and Q^2

From H1 Phenomenological fits:

$\alpha_{I\!P}(0) = 1.203 \pm 0.020$ (stat.) ± 0.013 (syst.) $^{+0.030}_{-0.035}$(model)

Larger than in soft hadron-hadron physics ($\alpha_{I\!P}(0) \sim 1.1$).

Comparison of H1 and ZEUS results:



. . . No significant variation with Q^2 to present precision within measured kinematic range.

Intercept of the sub-leading exchange in the H1 fits:

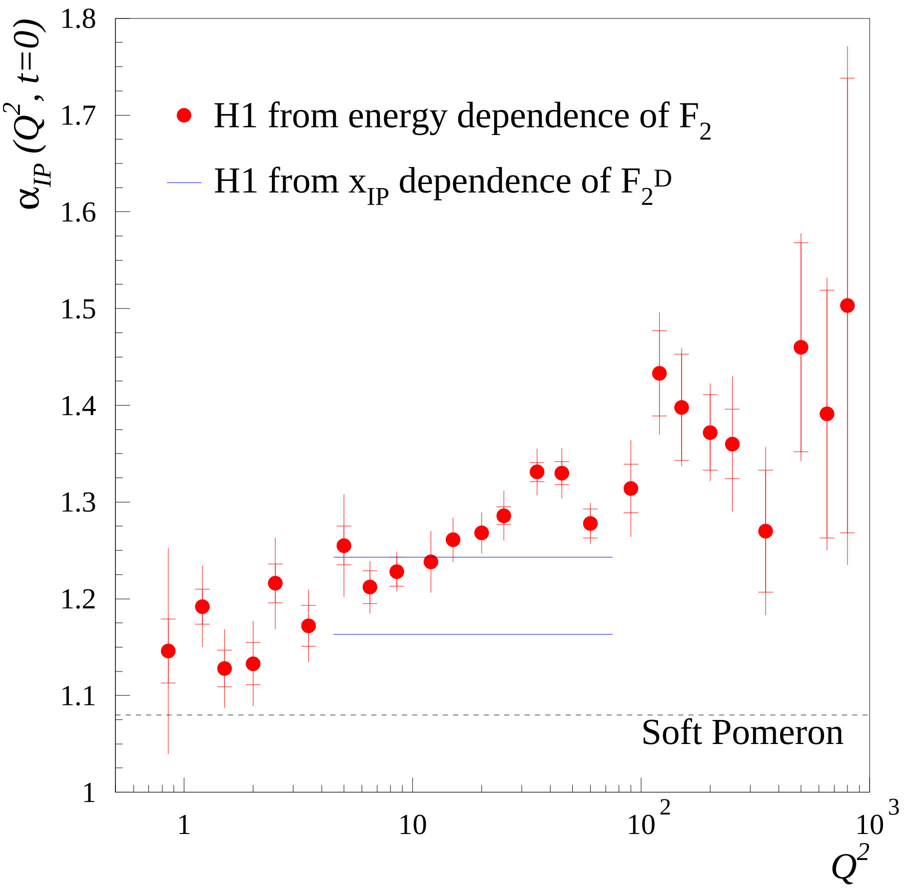
$\alpha_{I\!R}(0) = 0.50 \pm 0.11$ (stat.) ± 0.11 (syst.) $^{+0.09}_{-0.10}$(model)

Consistent with f, ω, ρ or a exchange.

Comparison of $\alpha_{I\!P}(0)$ from F_2 and $F_2^{D(3)}$

$F_2(x,Q^2)$ represents the total $\gamma^{\star}p$ Cross Section

Regge phenomenology $\rightarrow F_2(x,Q^2) \sim x^{1-\alpha_{I\!P}(Q^2,t=0)}$



Is a similar behaviour of the effective pomeron intercept observed in total and dissociation cross sections emerging?

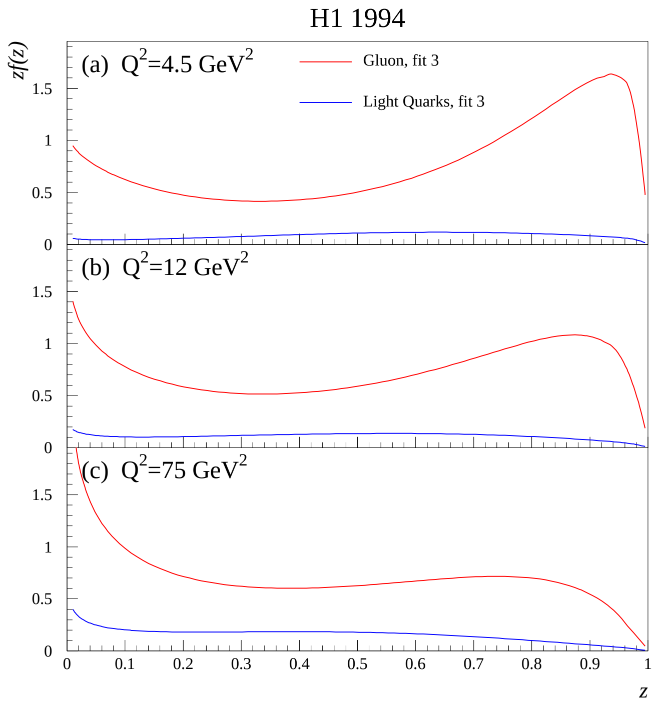
Universal dependence of $\alpha_{I\!P}(0)$ on scale?

Driven by p-gluon distribution? / Screening? / Hard $I\!P$?

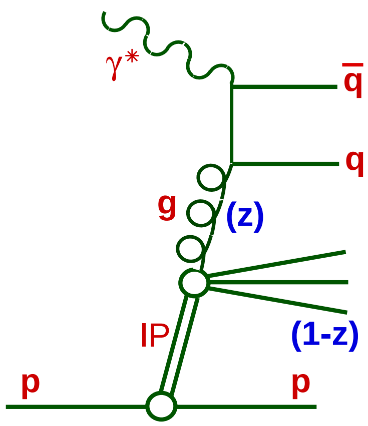
DGLAP Fits to $F_2^{D(3)}$

The β and Q^2 dependence of $F_2^{D(3)}$ can be considered in terms of the QCD evolution of structure functions for the pomeron and sub-leading exchange.
Extend the Regge fits to $x_{I\!P}$ dependence with a QCD motivated model of the β/Q^2 dependence.

- Paramterise $I\!P$ q_s and g distributions with Chebychev polynomials at starting scale $Q_0^2 = 3$ GeV^2.
- Assume a π structure function for $I\!R$.
- Evolve to $Q^2 > Q_0^2$ using NLO DGLAP equations.



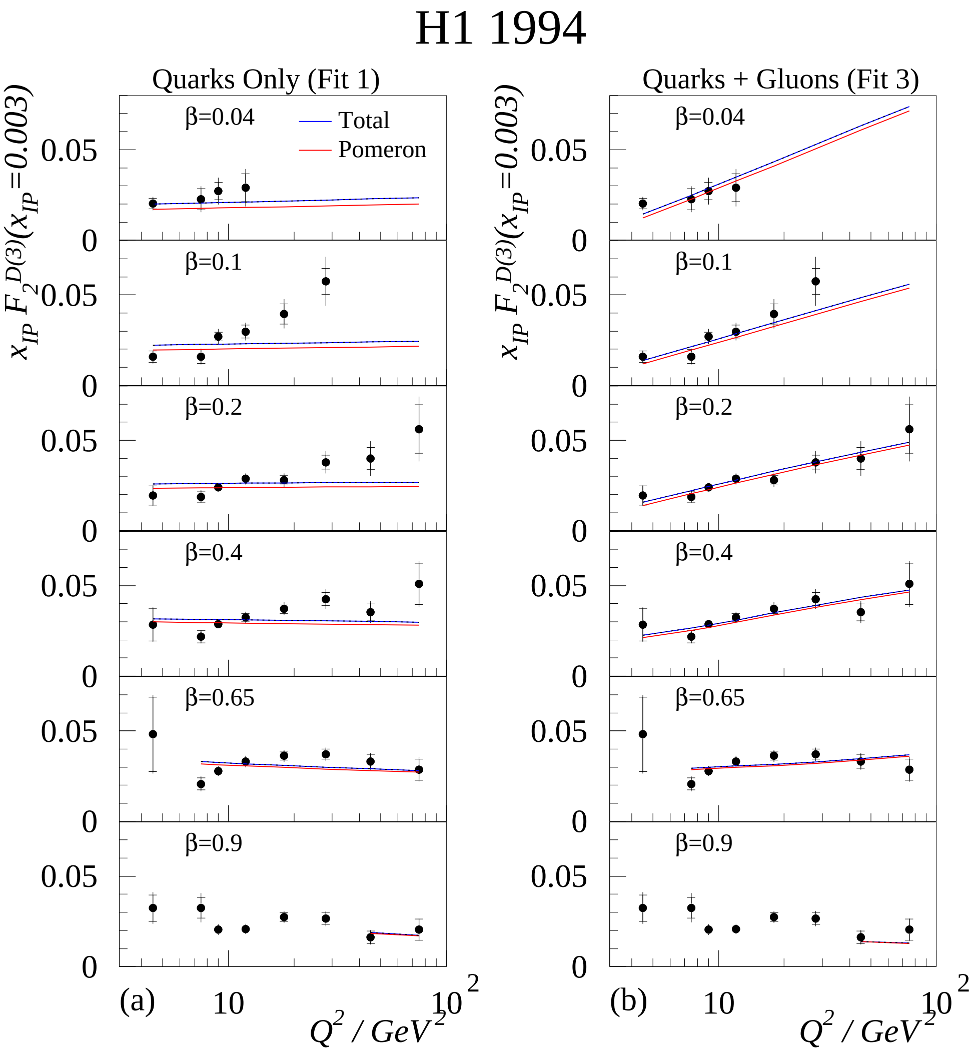
Acceptable fits only when $I\!P$ is dominated by "hard" gluons.



$\sim 90\%$ gluon at $Q^2 = 4.5$ GeV^2, $\sim 80\%$ at $Q^2 = 75$ GeV^2.

Q^2 dependence of $F_2^{D(3)}$

Best fits with (a) Quarks only and (b) Quarks and Gluons at the starting scale.



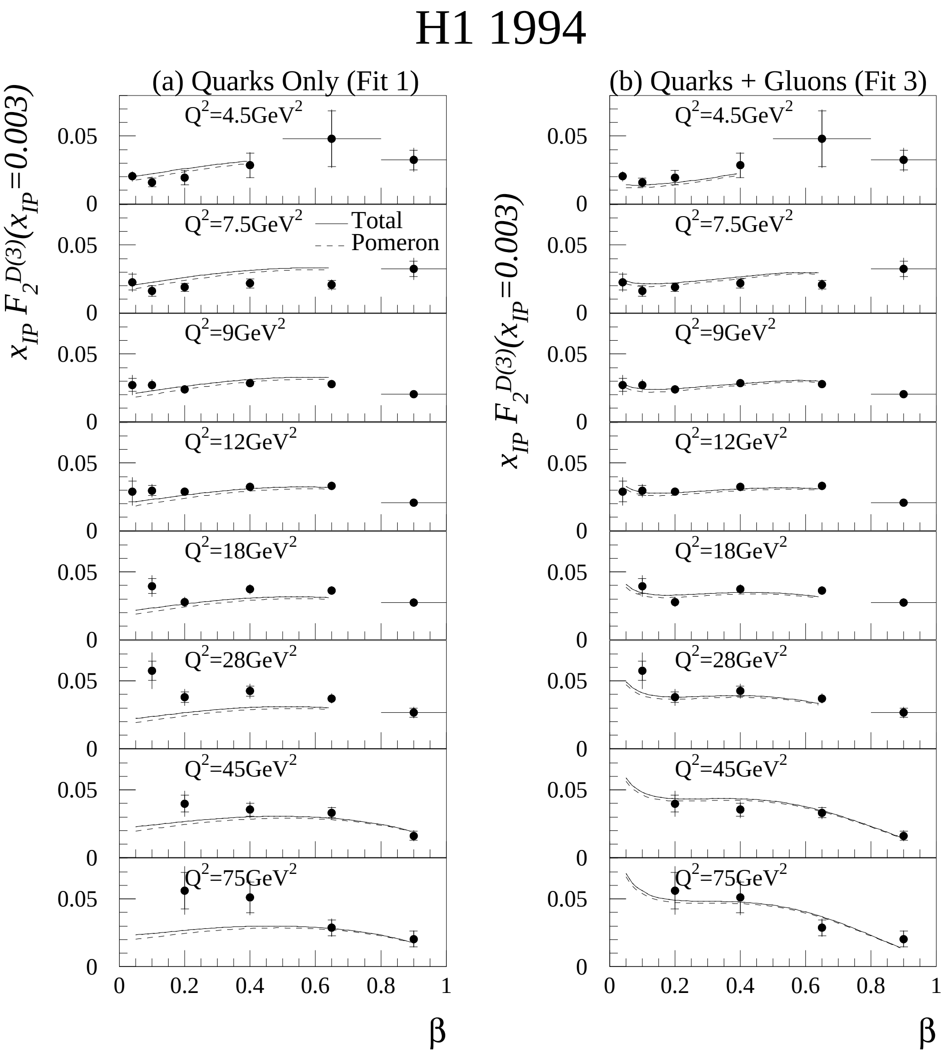
Rising scaling violations persist to $\beta > 0.4$ (contrasts with hadron structure functions).

Quarks only at the starting scale cannot describe the data.

A large gluon density is required.

β dependence of $F_2^{D(3)}$

Best fits with (a) Quarks only and (b) Quarks and Gluons at the starting scale.



Large contributions at high β (contrasts with hadron structure functions).

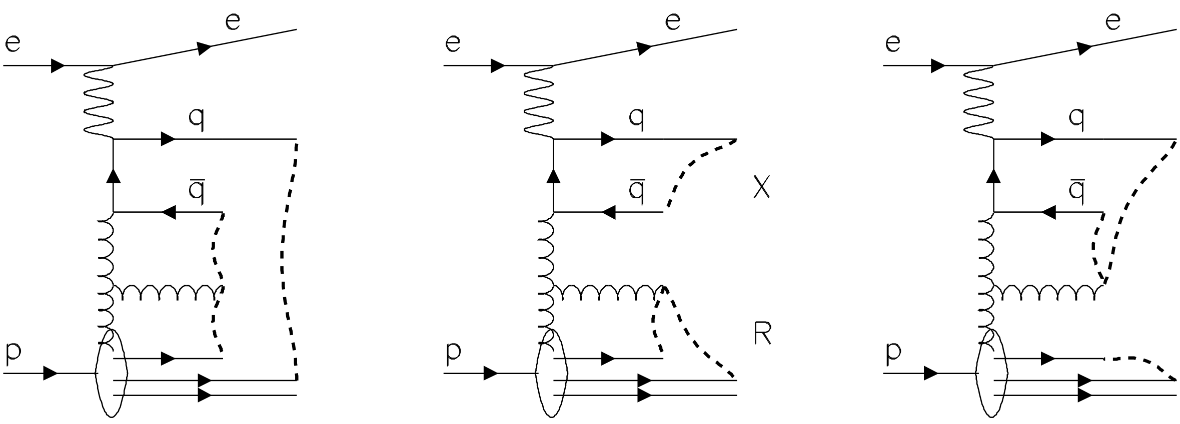
The gluon distribution must have large contributions at high fractional momenta.

Alternative Models of Diffractive DIS

Soft Colour Rearrangement ($\mathbb{P}$-free!)

Start from proton parton distributions with standard matrix elements / parton showers (dominantly BGF at low x).

Additional non-perturbative interactions affect final state colour connections but not parton momenta.

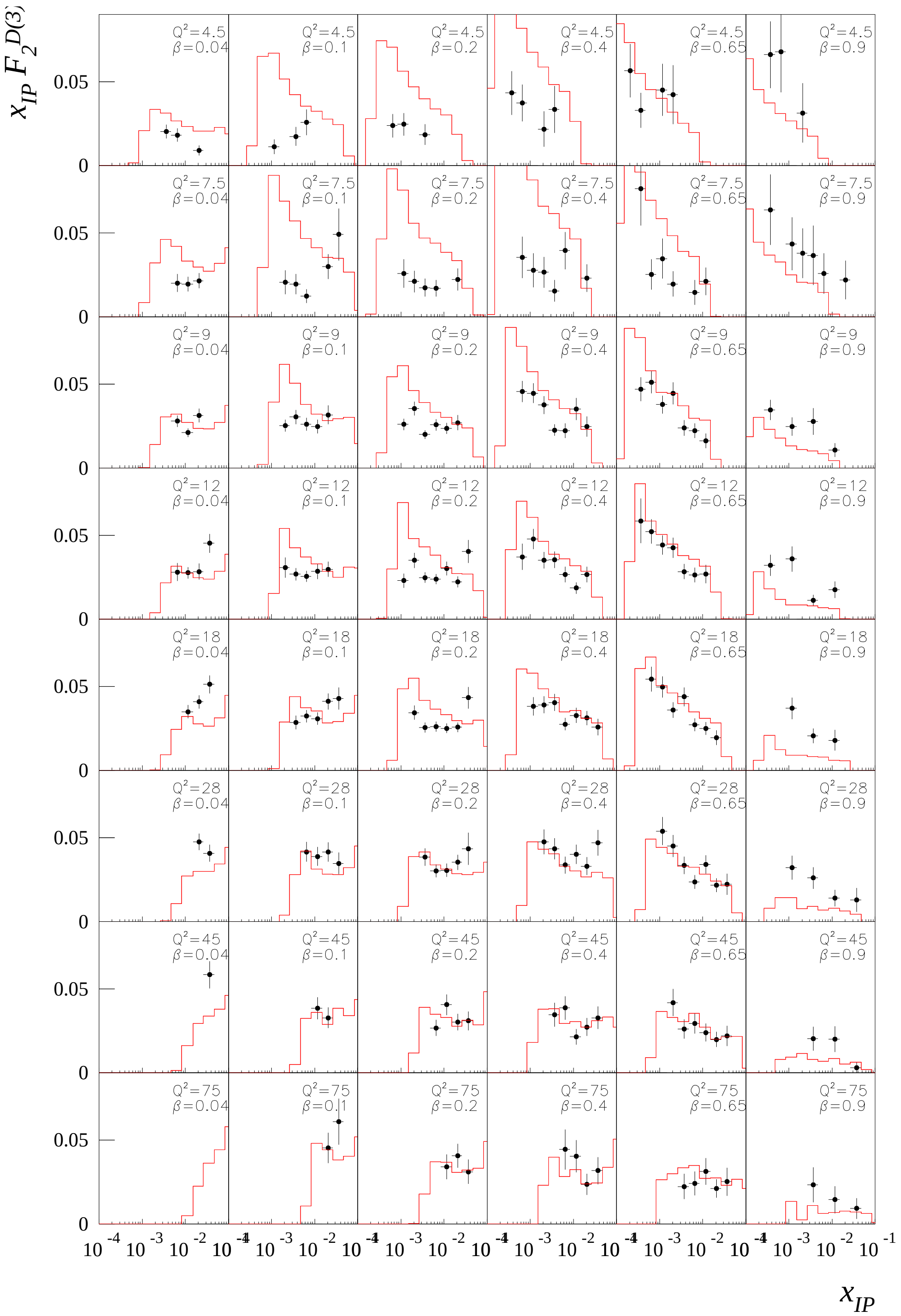


(a) (b) (c)

Implemented in the Monte Carlo model LEPTO 6.5

Free parameter: Probability of Soft Colour Interactions
...to be fixed by data.

Comparison of $F_2^{D(3)}(\beta, Q^2, x_{I\!P})$ and LEPTO 6.5



• **H1 1994 Data**

— **LEPTO**
[Pr(SCI) = 0.5]

$\sim$ reasonable shape in $x_{I\!P}$.

Does not describe Q^2 dependence.

Fails at high β (= low M_X non-perturbative region).

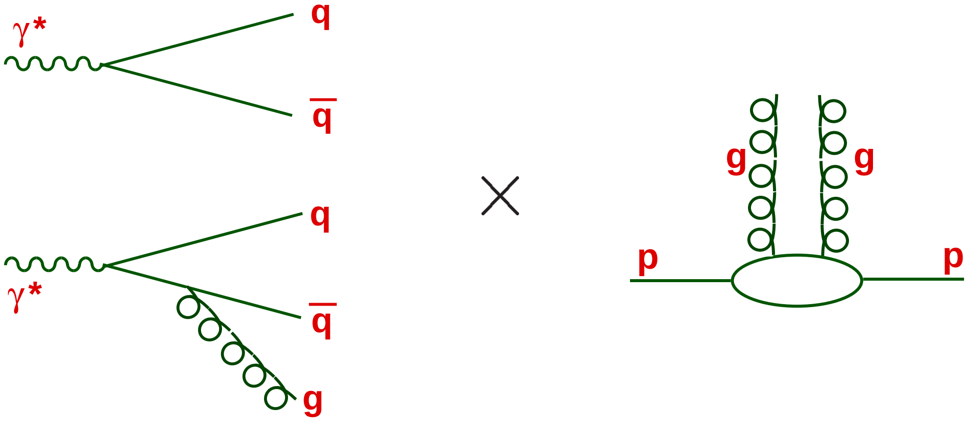
Alternative Models of Diffractive DIS

∼ Two-gluon Exchange models

Many years of development / many variations ...

(Low, Nussinov, Mueller, Donnachie, Landshoff, Nikolaev, Zakharov, Diehl, Bartels, Wüsthoff, Bialas, Peschanski ...)

$q\bar{q}$ / $q\bar{q}g$ production via the exchange of 2 gluons / BFKL ladder from the proton.



e.g. Recent model (Bartels, Wüsthoff) with 3 significant contributions in convenient form to fit to F_2^D data.

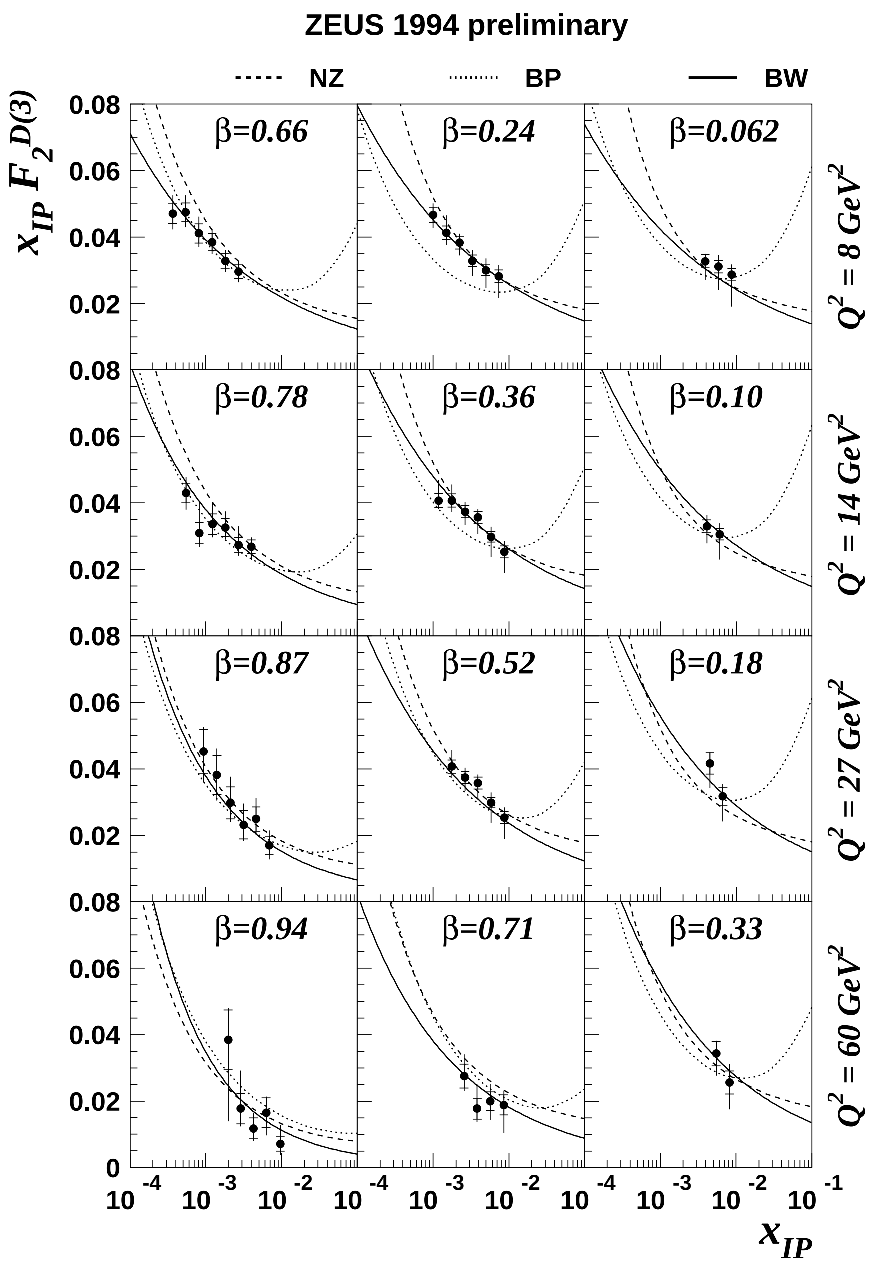
$$F_{q\bar{q}}^{\mathrm{T}} \propto \left(\frac{x_0}{x_{I\!P}}\right)^{n2(Q^2)} \beta(1-\beta)$$

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

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

2-gluon / BFKL Exchange Models

Nikolaev & Zakharov, Bialas & Peschanski and Bartels & Wüsthoff models:



Phton fluctuation / 2-gluon exchange models can be made to describe $F_2^{D(3)}$, even at large β.

β dependence in the Bartels - Wüsthoff model.

Typical decomposition of the data in β and Q^2 in a two-gluon exchange model.

Mixture of $q\bar{q}$ and $q\bar{q}g$ final states.

Higher twist contribution important at large β.

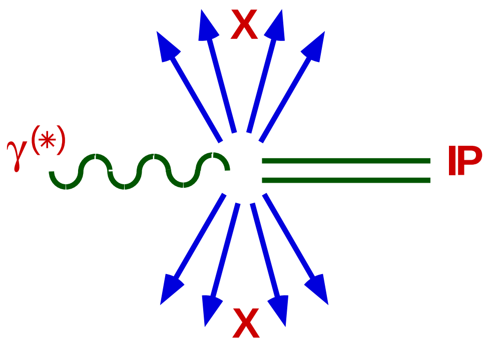
These models make clear predictions for the partonic composition ($q\bar{q}$, $q\bar{q}g$) of the final state X

The final state X at low $x_{I\!P}$

Many hadronic final state observables are sensitive to the QCD Structure of Diffraction

- Thrust (H1, ZEUS), Sphericity (ZEUS)
- Energy flow (H1)
- Particle spectra (H1, ZEUS)
- Paricle multiplicities, correlations (H1)
- Jet rates (ZEUS, H1)
- Charm production rates (ZEUS, H1)

Studies are made in the rest frame of X ($\equiv \gamma^\star I\!P$ centre of mass).
p_T etc. measured relative to the photon (collision) axis in this frame.



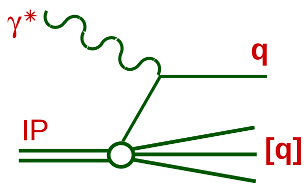
Predictions for the final state *X*

Evolving parton distributions for the pomeron are implemented in the RAPGAP Monte Carlo model.

- RG F_2^D (fit 3): Best QCD fit to F_2^D with a 'hard gluon' dominated structure.
- RG F_2^D (fit 1): Poor QCD fit to F_2^D with quarks only at the starting scale for DGLAP evolution.

$\mathcal{O}(\alpha)$

QPM



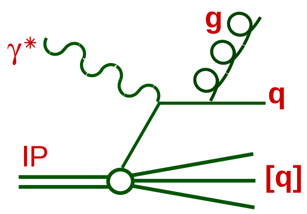
Hard processes

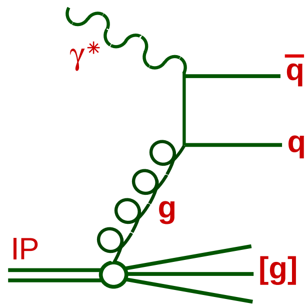
up to $\mathcal{O}(\alpha_s)$

$\mathcal{O}(\alpha\ \alpha_s)$

QCD-C

BGF





↑

Quarkonic IP

Dominant $q\bar{q}$

Low p_T / aligned

Few jets

$\sim 3_c\bar{3}_c$

↑

Gluonic IP

Dominant $q\bar{q}g$

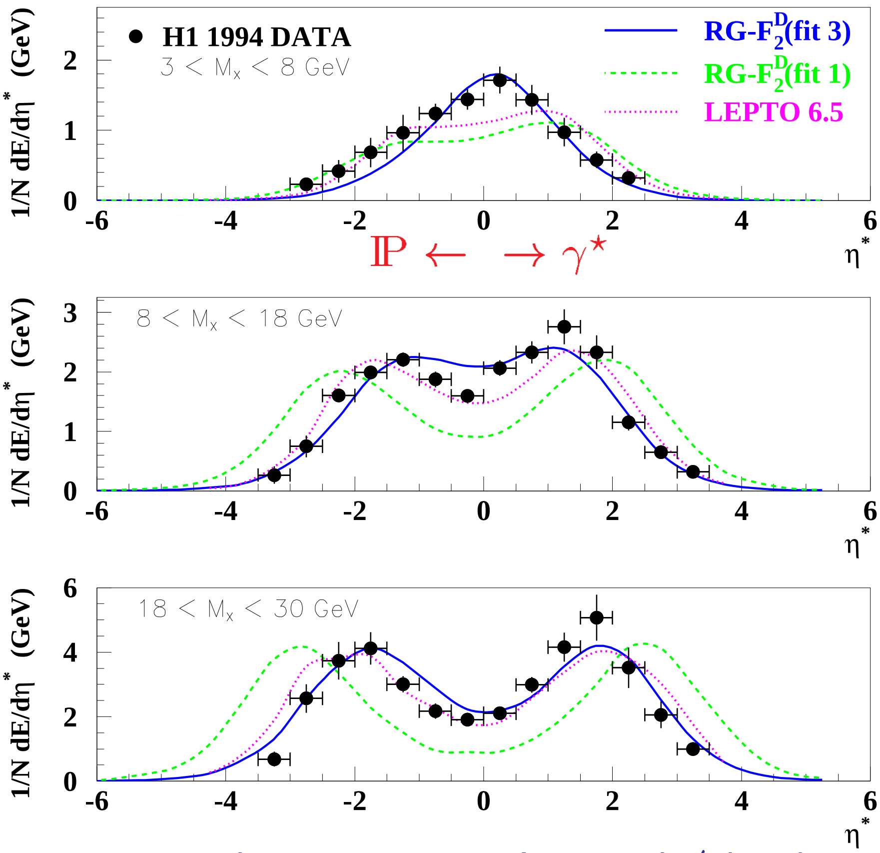
High p_T / non-aligned

Many jets

$\sim 8_c 8_c$

Energy Flow in the Rest frame of X

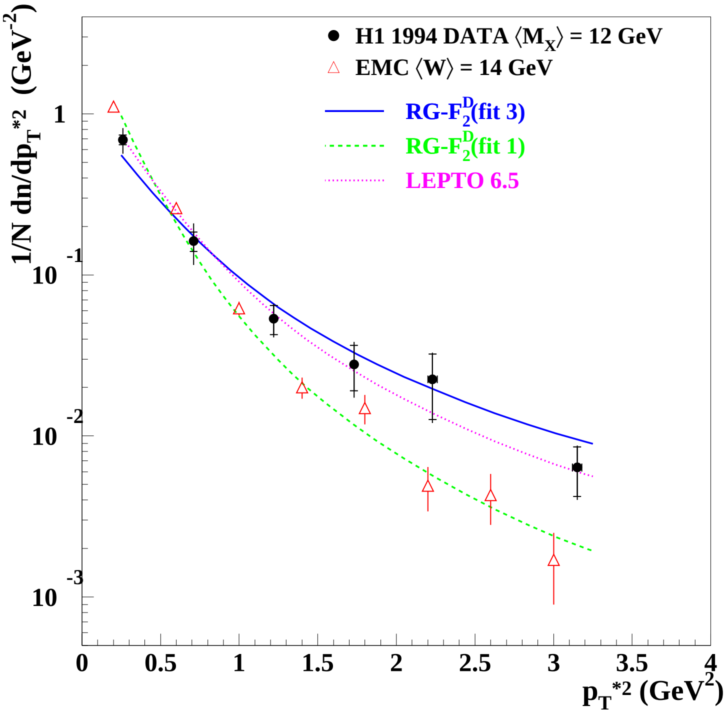
Pseudorapidity $\eta^\star$ relative to $\gamma^\star$ direction in X rest frame.



- Approximately symmetric forward / backward hemispheres.
- 2-jet structure with sizeable central rapidity plateau emerges with increasing M_X.
- Models in which BGF is the dominant process (RAPGAP-g and LEPTO) describe data.
- RAPGAP-q does not describe the data.
- …Gluons are needed to model diffractive final states.

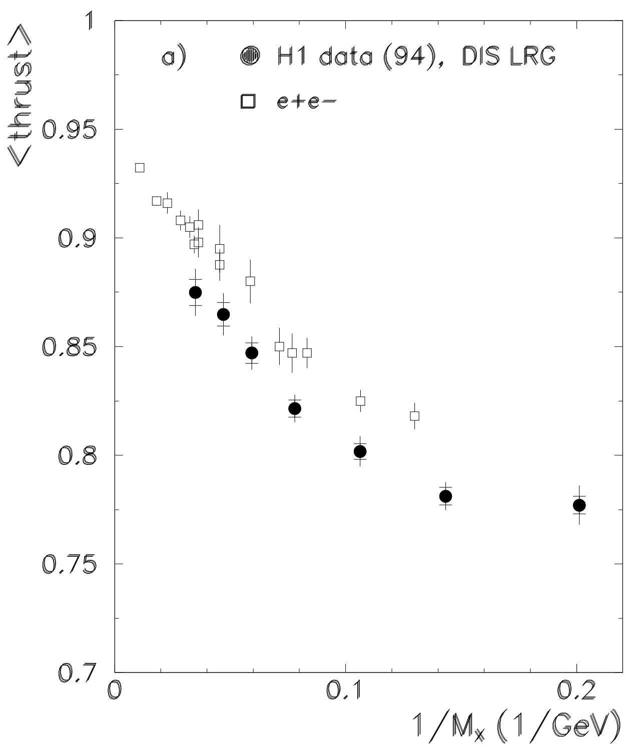
Charged Particle $p_T^\star$ Distribution

$p_T^\star$ measured relative to $\gamma^\star$ axis in rest frame of X

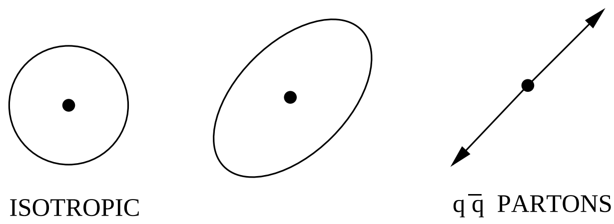


Gluons required to generate hard $p_T^\star$ distribution.

Thrust - measure of ‘2-jettiness’



$$1/2 < T < 1$$

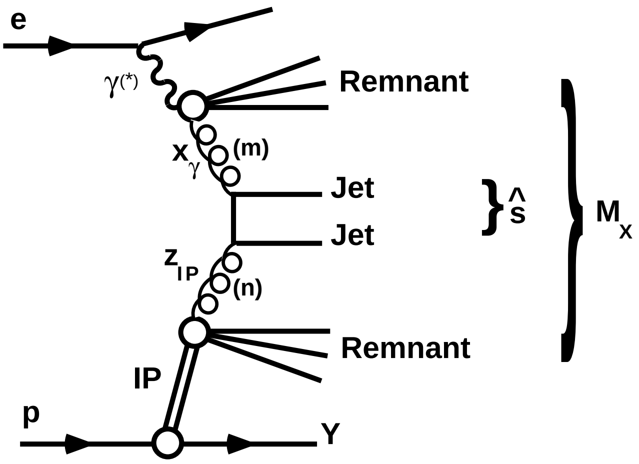


Gluons required to generate lower thrust than $q\bar{q}$.

Hadronisation effects decrease thrust at low M_X .

Dijet Production Rates

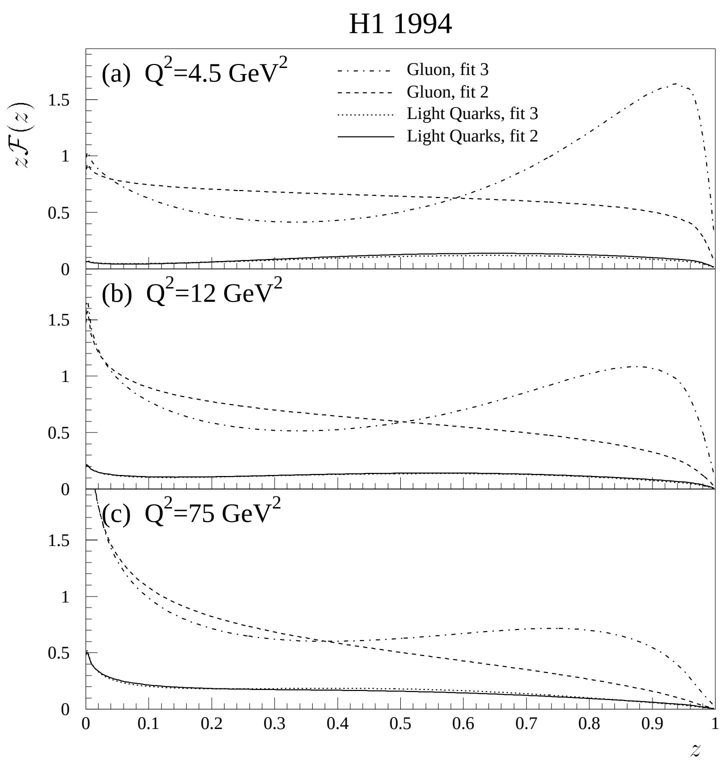
Search for dijet structures as components of the system X
Cone algorithm requiring $p_T^{\rm jet} > 5$ GeV relative to $\gamma^{(\star)}$ axis in rest frame of X.



Can measure fractions of $\gamma^{(\star)}$ and $\mathbb{P}$ momentum transferred to the dijet system.

$$x_\gamma^{\rm jets} = (P.m) \,/\, (P.q)$$

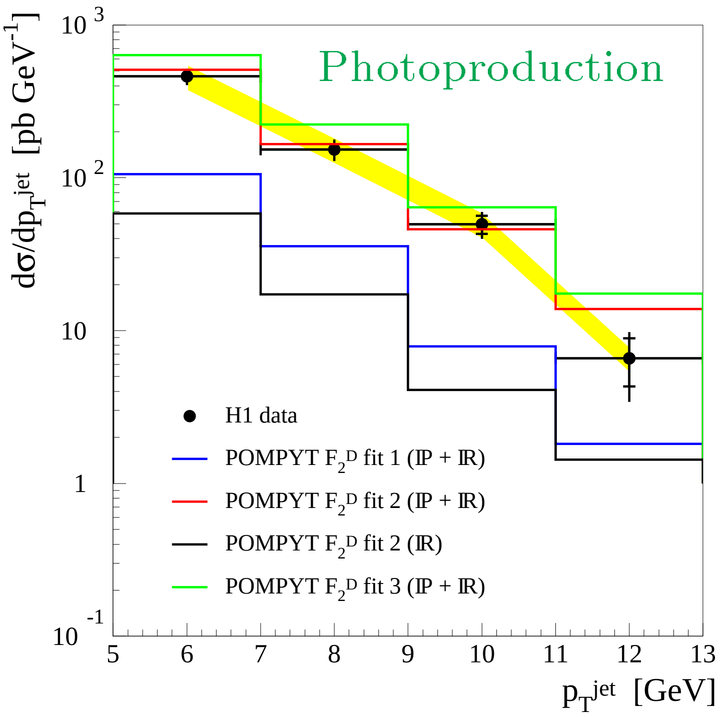
$$z_{\mathbb{P}}^{\rm jets} = (q.n) \,/\, (q.[P - Y])$$



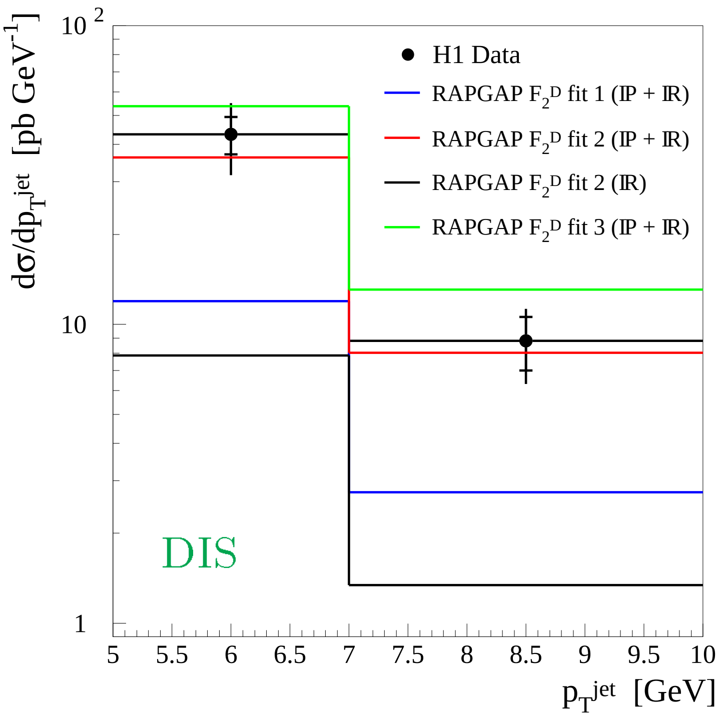
The results are compared with 3 sets of $\mathbb{P}$ and $\mathbb{R}$ parton distributions, evolving with $p_T^{\hat{}}$ as a scale.

Dijet p_T^{jet} Distributions

p_T^{jet} relative to $\gamma^\star$ axis in rest frame of X



Sub-leading exchange contribution $\sim$ 15%

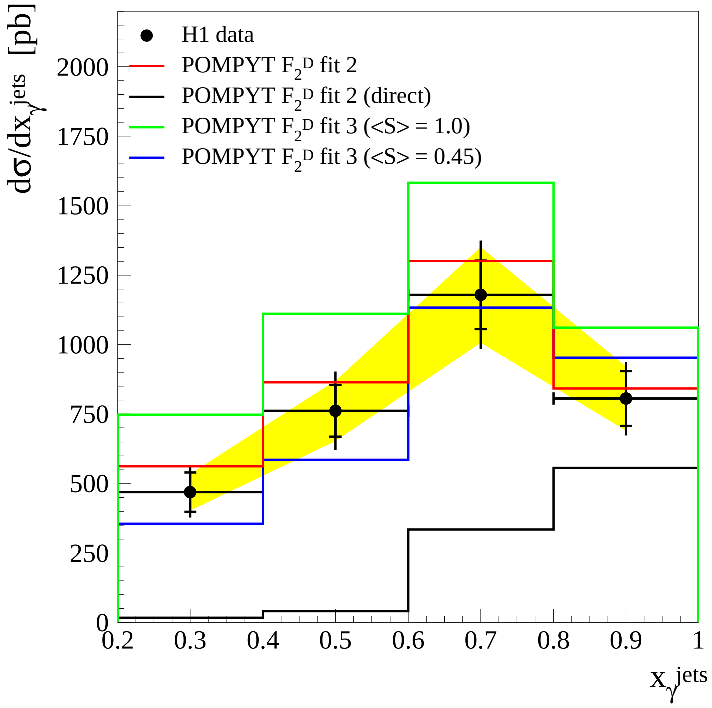


Data described by gluon dominated ℙ

Quark dominated ℙ low by a factor $\sim$ 5

Photoproduction x_γ^{jets} Distributions

Fraction of photon momentum entering the hard scattering.



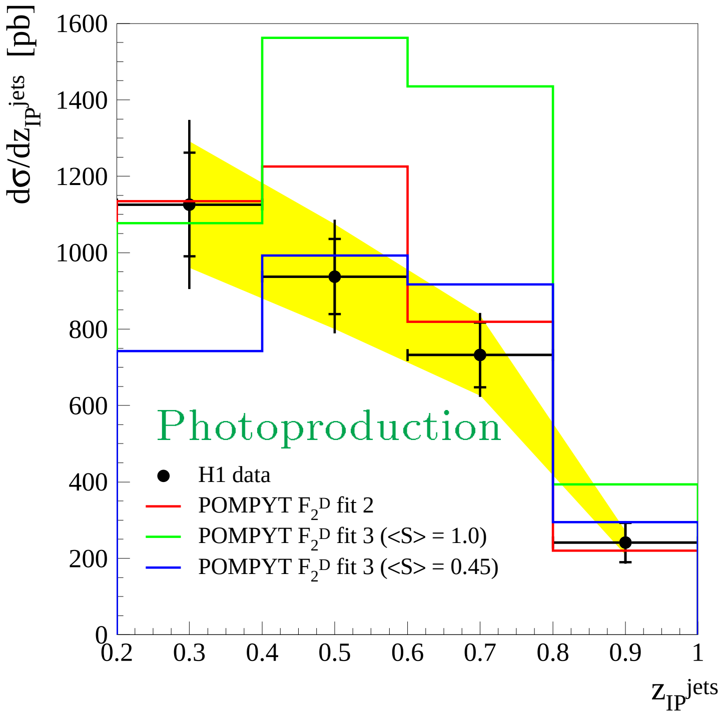
Photoproduction

Both direct $x_\gamma = 1$ and resolved $x_\gamma < 1$ contributions observed.

Possible presence of rapidity gap destruction effects in resolved photoproduction due to spectator interactions: peaked gluon model can describe data with a weight $\langle S \rangle \sim 0.5$ applied to resolved photon events.

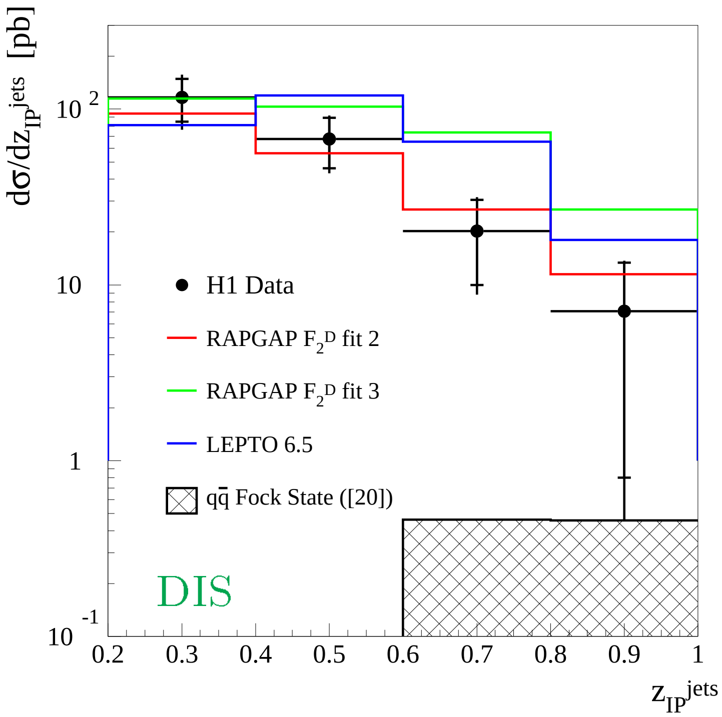
$z_{I\!P}^{\text{jets}}$ Distributions

Fraction of pomeron momentum entering the hard scattering.



Contributions throughout the $z_{I\!P}^{\text{jets}}$ range in both photoproduction and DIS

Can be described by the models with a gluon dominated $I\!P$



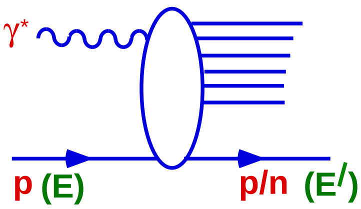
LEPTO - Pr(SCI) $= 0.5$ is close to DIS data.

$q\bar{q}$ final state alone cannot describe data.

$q\bar{q}g$ states also required.

Leading (and not so leading) Baryons

ZEUS and H1 can detect and measure forward protons and neutrons with a wide range of energies.



z (H1) $= x_L$ (ZEUS) $= E'/E$

($z = 1 - x_{I\!P}$ if exclusive p / n at proton vertex.)

Several interesting issues in the large $x_{I\!P}$ region:

- In Regge language, probe the sub-leading exchanges, especially $I = 1$ π-exchange.
- As $x_{I\!P}$ increases, Regge theory must break down somewhere!
- General questions of understanding baryon fragmentation.

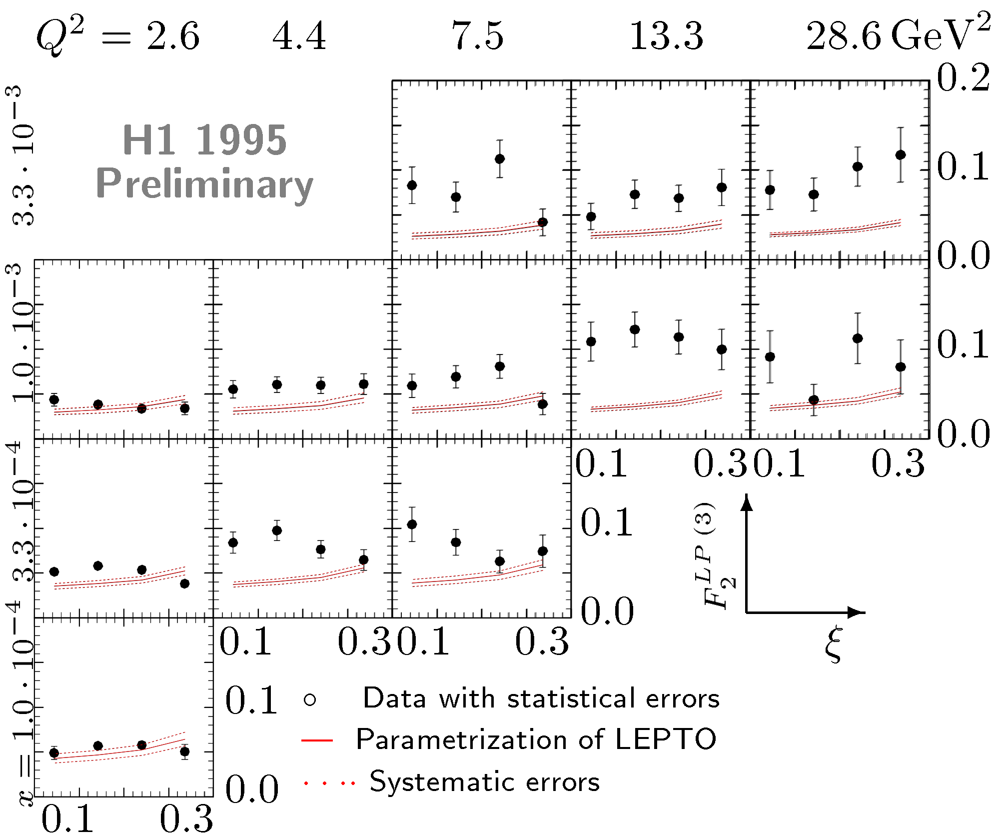
Comparisons are made with . . .

- Factorisable Regge models based on π exchange (RAPGAP, POMPYT)
- Soft Colour Interactions (LEPTO)

Leading Proton Structure Function

Defined in the same way as $F_2^{D(3)}$, but for $p_T^p < 200$ MeV

Measured for $0.7 < z < 0.9$ (little $\mathbb{P}$ exchange).

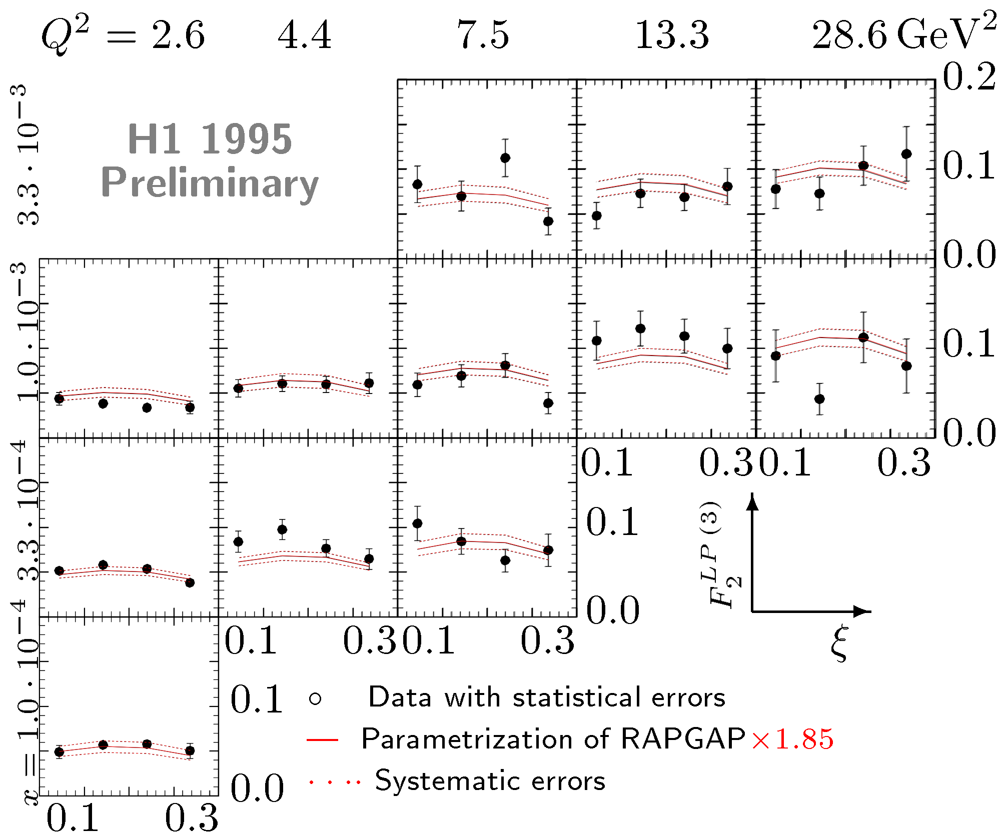


- z dependence $\sim$ flat.
- x and Q^2 depencence similar to inclusive structure function.

LEPTO reproduces leading proton z shape reasonably well. Q^2 scaling violations are not described.

Leading Proton Structure Function

...compared to RAPGAP implementation of Reggeised π^0 exchange with $e\pi$ DIS.



RAPGAP-π describes the shape in all variables reasonably well.

Normalisation in principle well constrained by the model, but measured cross section is larger by a factor ~ 1.85.

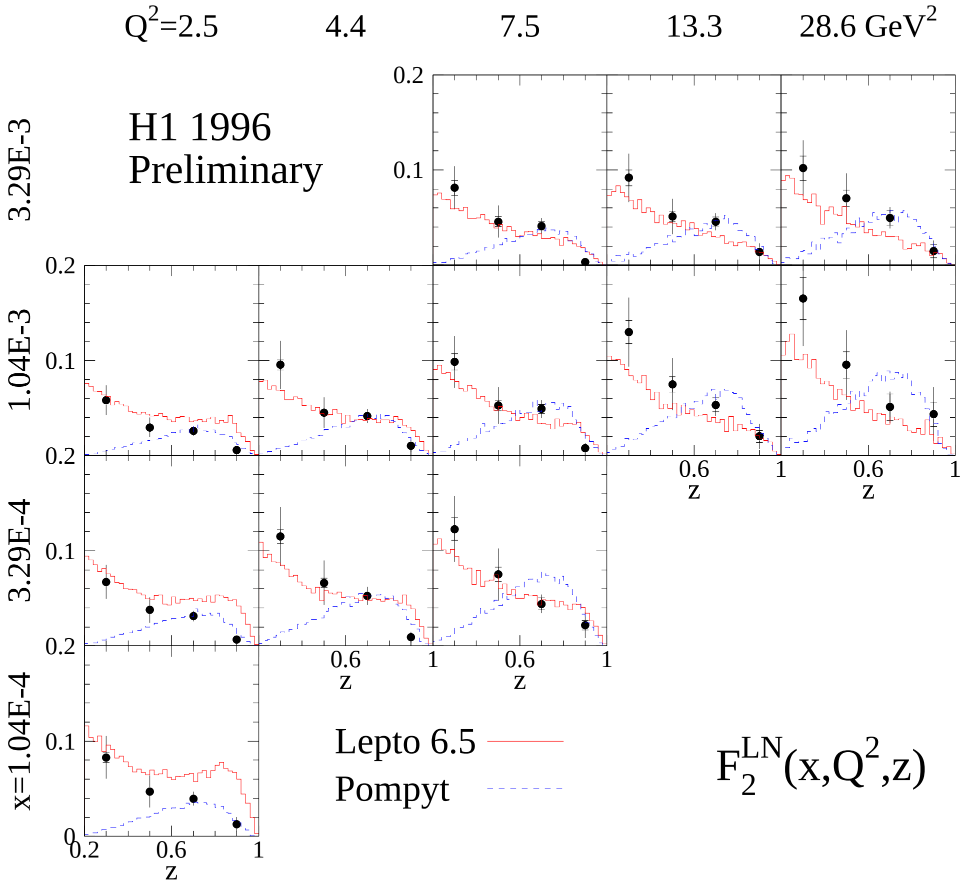
...in a Regge model, more comlicated mixture of exchanges in this region?

Leading Neutron Structure Function

$F_2^{\mathrm{LN}(3)}$ defined for $p_T^n < 200$ MeV

Measured for $0.2 < z < 1$

Compared with POMPYT implementation of π^+ exchange and with LEPTO.



POMPYT-π gives good description for $z \gtrsim 0.7$ with no need for any scaling factors (Isospin-1 exchange only for neutrons).

For $z \lesssim 0.7$, Regge model inappropriate - not exclusive n production.

LEPTO gives a reasonable description at all z.

A combined Regge model of $F_2^{LP(3)}$ and $F_2^{LN(3)}$

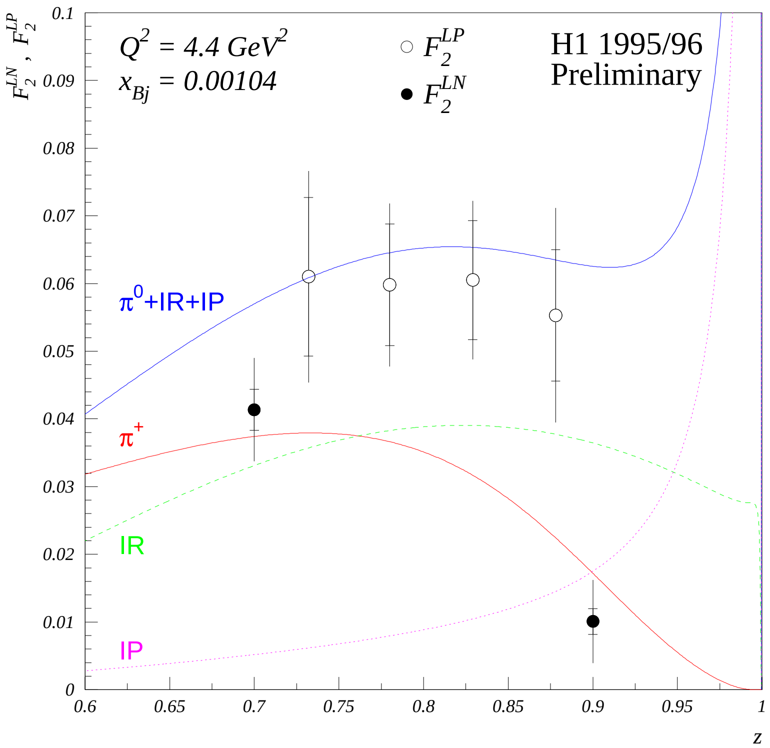
Assume: $\mathbb{P}$ $\alpha(0) \sim 1.2,\ I = 0$ - p

$\mathbb{R}\ (f,\ \omega)$ $\alpha(0) \sim 0.5,\ I = 0$ - p

π $\alpha(0) \sim 0.0,\ I = 1$ - $p,\ n$

Assume: Low-x Structure function universality (GRV-π for all contributions.

Flux normalisations fixed by hadron-hadron data.



...it is possible to build a Regge based model to describe medium - large z proton and neutron production.

Possibilities of extracting π structure function at low x using leading neutrons ...

Summary

- Colour-singlet exchange processes constitute a significant fraction of the DIS cross section.
- Diffractive ($\mathbb{P}$ exchange) interactions are dominant at low $x_{\mathbb{P}}$.
- $\alpha_{\mathbb{P}}(0)$ larger than in soft hadronic interactions.
- QCD analysis of $F_2^{D(3)}$ indicates that the $\mathbb{P}$ is dominated by 'hard' gluons ($\sim 80 - 90\%$ for $4.5 < Q^2 < 75$ GeV^2).
- All hadronic final state measurements are consistent with this picture.
- A complicated mixture of meson exchanges is present at larger $x_{\mathbb{P}}$, with the π dominant in the neutron channel.