Diffractive Deep-Inelastic Scattering

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Contents:

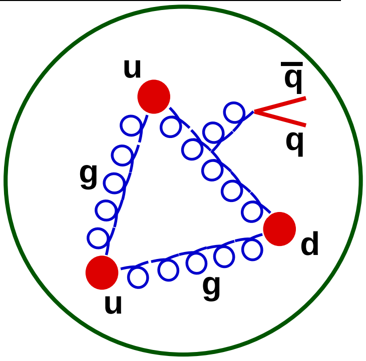
- Strong Interactions and Diffraction.
- The Diffractive Structure Function $F_2^{D(3)}$.
- Regge models of $F_2^{D(3)}$.
- QCD models of $F_2^{D(3)}$.
- Exclusive Vector Meson Cross Sections.
- Diffractive Final States.

Related topics not covered here:

- Diffractive photoproduction.
- Diffraction at Large $|t|$ & BFKL.
- 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)

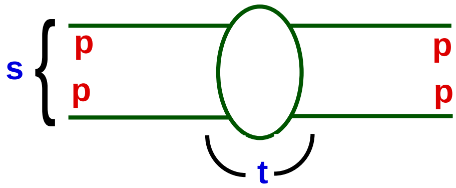
- α_s large: "Infrared Slavery".
- Poorly understood within QCD.
- Many years of "Regge" Phenomenology.

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

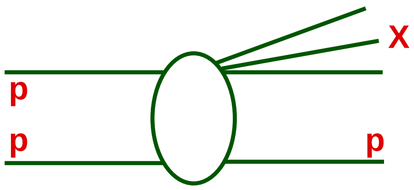
In 'diffractive' Deep-Inelastic Scattering, the interface between 'soft' and 'hard' strong interactions is studied.

Diffractive Processes and the Pomeron

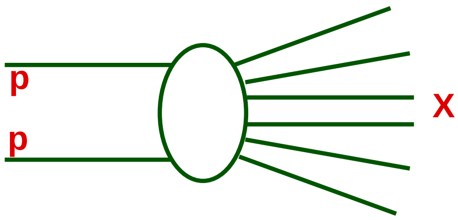
Soft diffraction: elastic, total and dissociation cross sections.



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



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



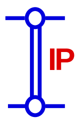
$\sigma^{\rm tot}(pp \to X)$

(via the optical theorem)

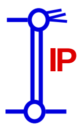
It is useful to think in terms of the exchange of an object with net vacuum quantum numbers - the “pomeron” ($\mathbb{P}$).

- $\alpha_{\mathbb{P}}(t) \simeq 1.081 + 0.26t$ [$\mathbb{P}$ ‘trajectory’].
- ‘FACTORISES!’ Describes the energy dependence of all such hadron-hadron cross sections where $s \gg t$.
- BUT The partonic structure of the interaction is unspecified! . . . This structure can be investigated at HERA.

Regge Predictions

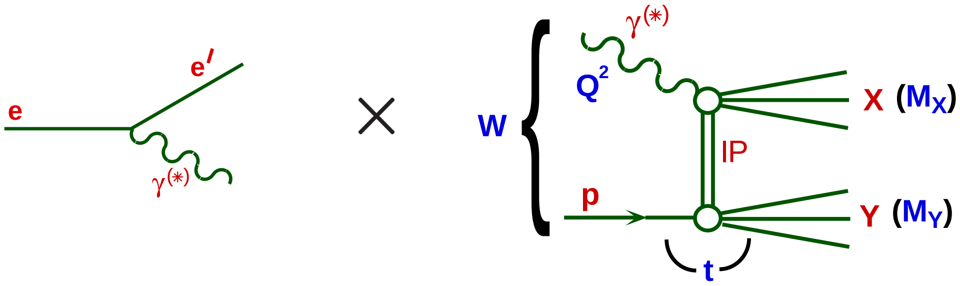


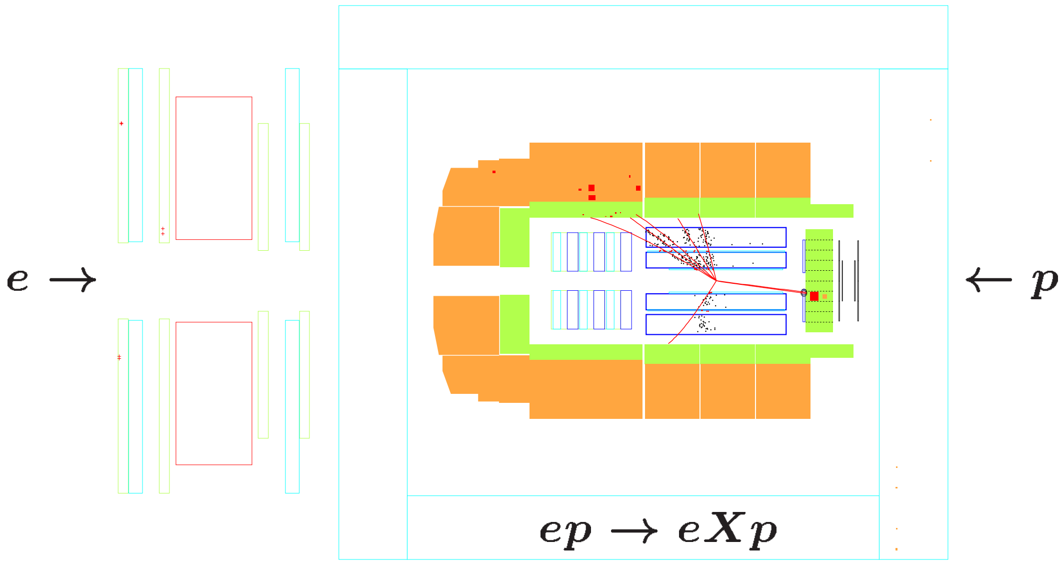
$$\mathrm{d}\sigma^{\mathrm{el}}/\mathrm{d}t \propto s^{2\alpha_{\mathbb{P}}(t)-2}$$



Diffraction at HERA

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



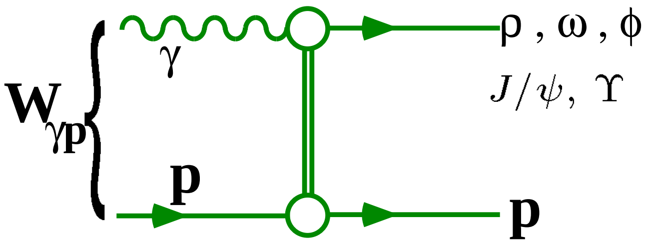


All five kinematic variables can be measured:

- $Q^2 \sim 0$, $|t| \sim 0$. → similar to soft h-h diffraction.
- Large Q^2. → γ^* probes IP structure.
- Large $|t|$. → search for perturbative (BFKL?) IP.

. . . the non-perturbative ↔ perturbative transition.

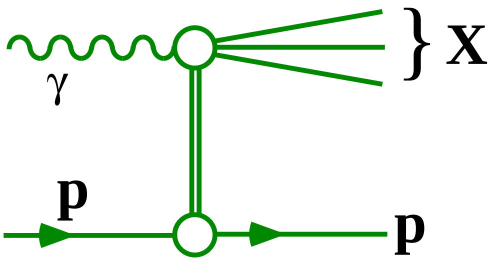
COLOUR SINGLET EXCHANGE PROCESSES IN γ^*-p INTERACTIONS



QUASI ELASTIC VECTOR MESON PRODUCTION

(EL)

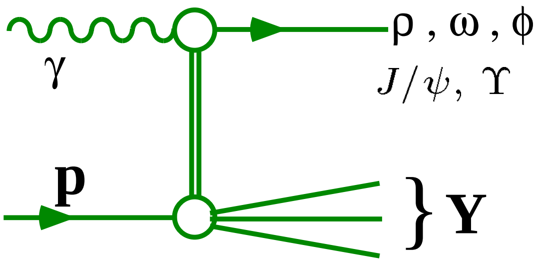
$\gamma p \longrightarrow Vp$



SINGLE PHOTON DISSOCIATION

(GD)

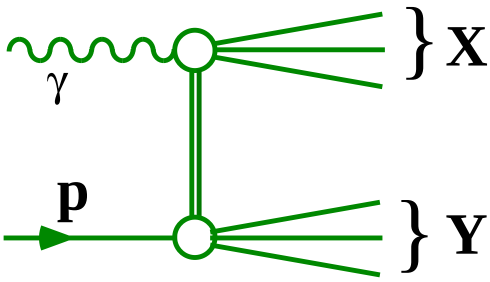
$\gamma p \longrightarrow Xp$



SINGLE PROTON DISSOCIATION

(PD)

$\gamma p \longrightarrow VY$



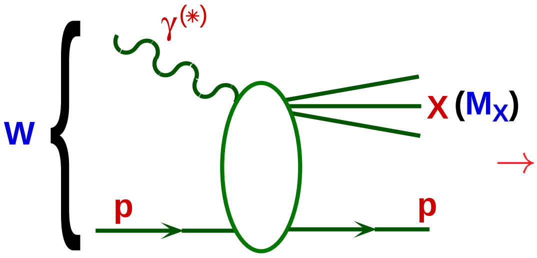
DOUBLE DISSOCIATION

(DD)

$\gamma p \longrightarrow XY$

Experimental Techniques

1. Rapidity Gap Selections (H1, ZEUS).

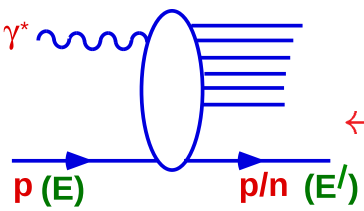


Largest rapidity
$\rightarrow$ gap among
final state hadrons.

$\Delta\eta$ large when

$M_X \ll W$

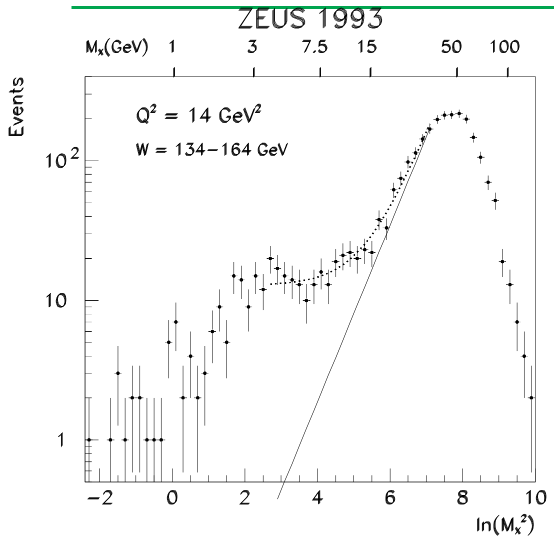
2. Direct Tagging of Leading Baryons (H1, ZEUS).



May or may not
$\leftarrow$ be a large
rapidity gap.

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

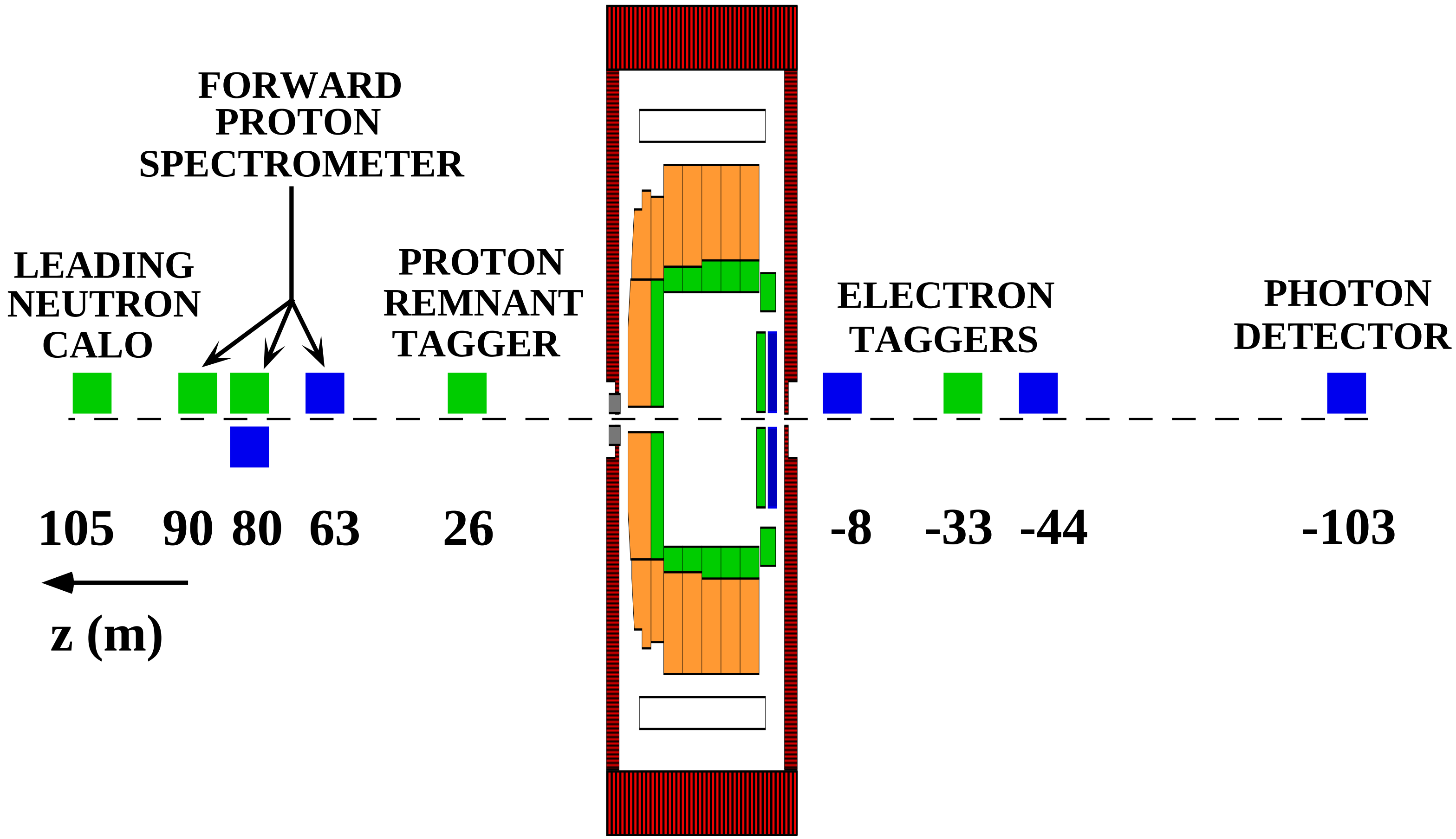
3. Decompose Visible M_X Distribution (ZEUS).



Exponential suppression in M_X distribution for "standard" DIS.

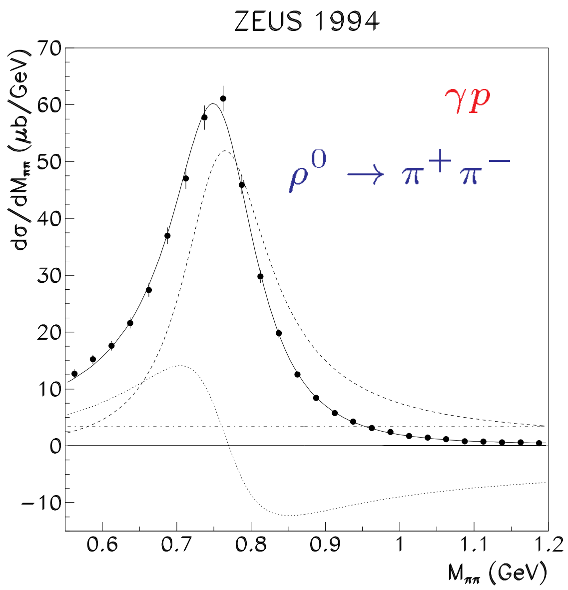
Diffractive contribution identified as excess at small M_X above fit to $Ae^{b \ln M_X}$

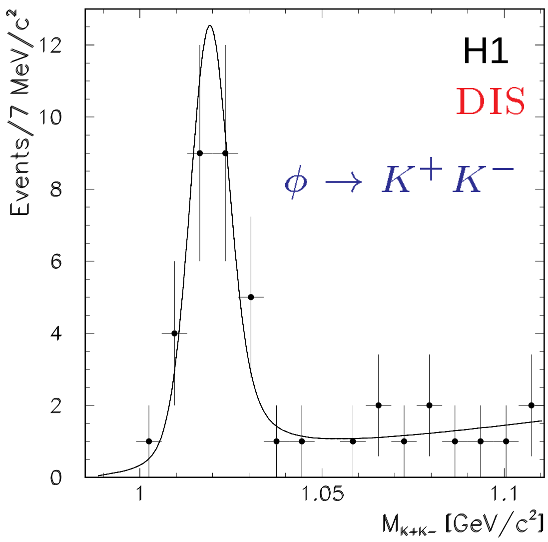
BEAM-LINE INSTRUMENTATION

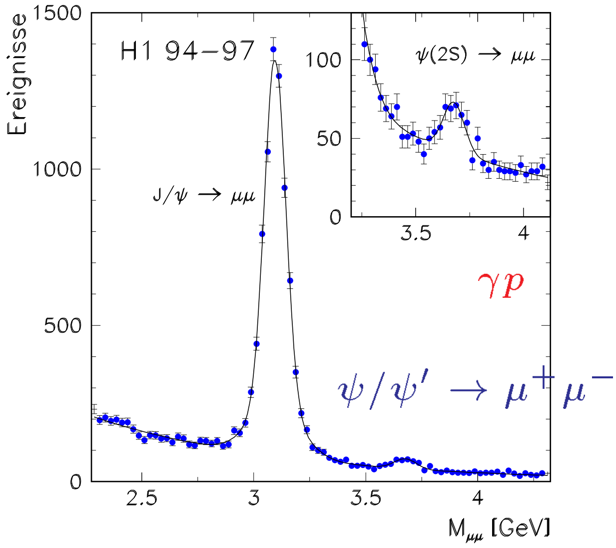


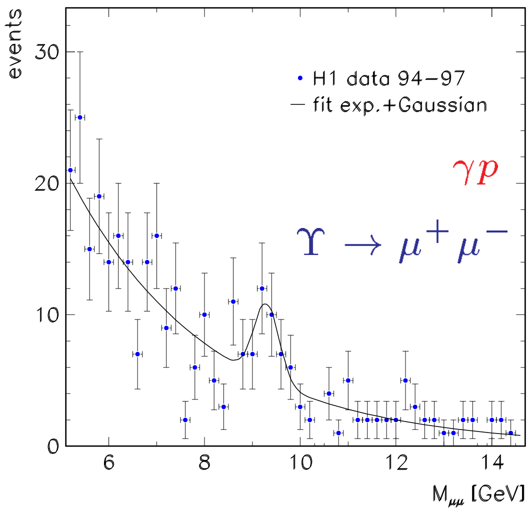
Vector Meson Signals

Vector Meson Production Studied over a wide range in kinematic variables Q^2, t, W, m_V.
Results on ρ, ω, ϕ, J/ψ, Υ, ρ', ψ'.

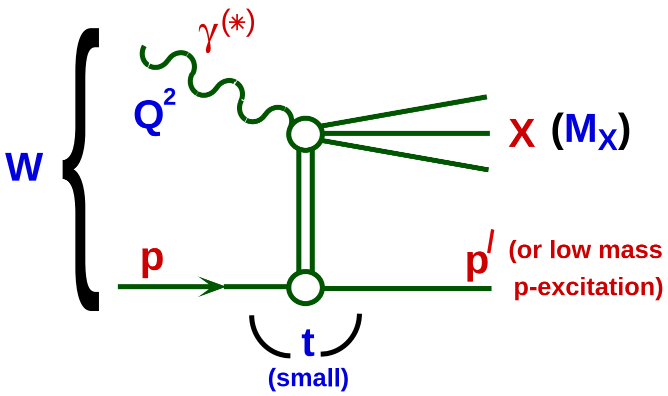








Inclusive Diffractive DIS, $\gamma^\star p \rightarrow Xp$



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

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 $I\!P$.

($I\!P$ exchange dominates at low $x_{I\!P}$)

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

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

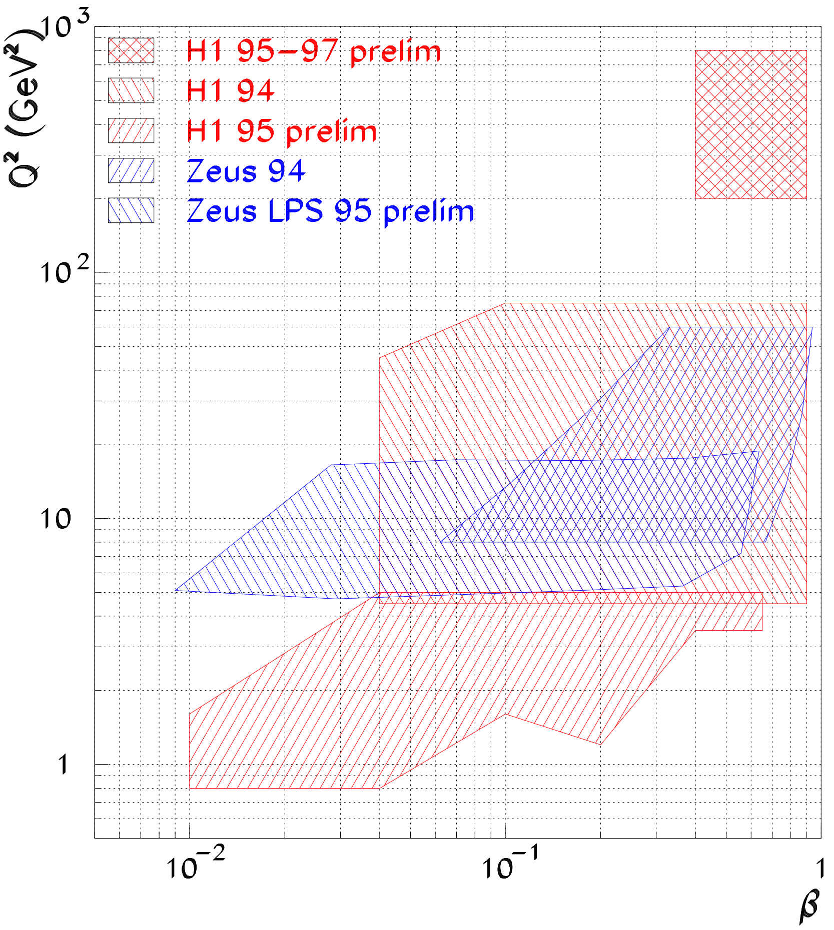
$\rightarrow$ Frac. of $I\!P$ momentum carried by quark coupling to $\gamma^\star$.

($x_{\mathrm{Bj}} = \beta \cdot x_{I\!P}$)

The “Diffractive” Structure Function $F_2^{D(4)}$

Diffractive cross section measurements are usually presented as a ‘diffractive’ structure function $F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t)$, defined as

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

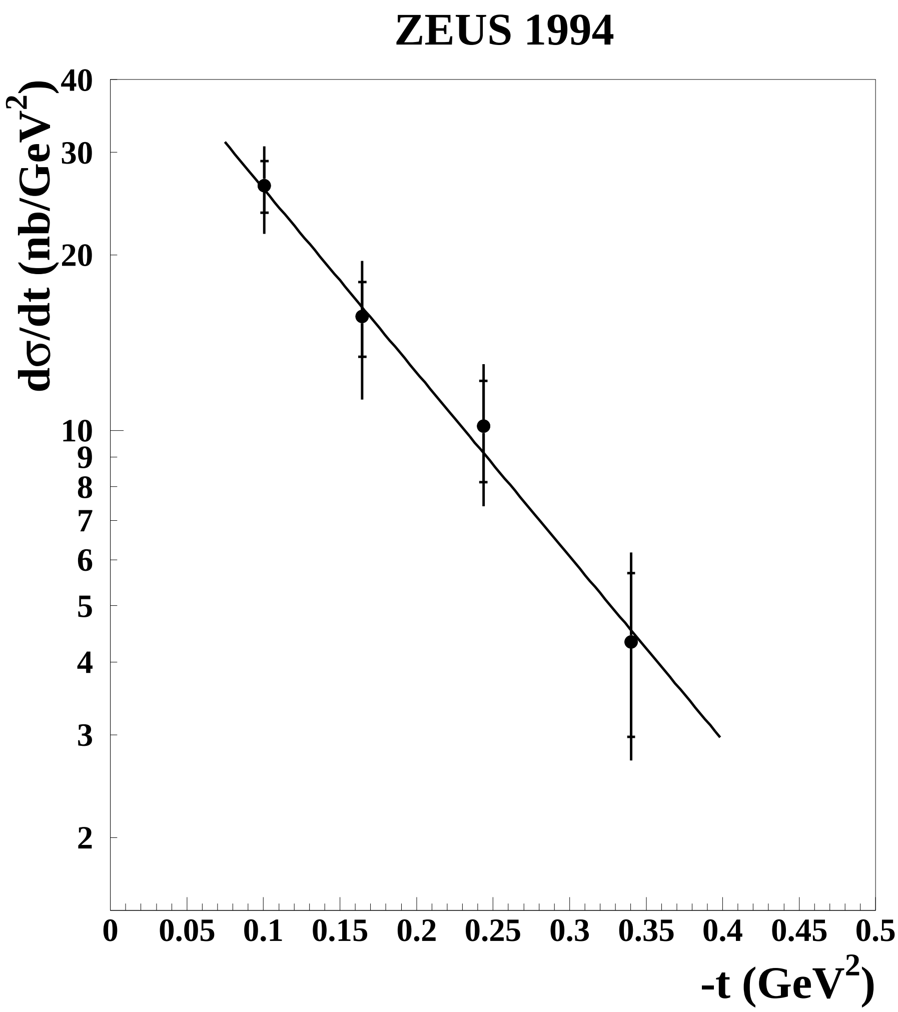


Copious F_2^D data spanning
$10^{-4} < x_{I\!P} < 0.05$
$10^{-2} < \beta < 0.9$
$0.8 < Q^2 < 800$

Measurement of the t Dependence

$5 < Q^2 < 20\ \mathrm{GeV}^2 \qquad 0.015 < \beta < 0.5$

$x_{I\!P} < 0.03$



From Direct Proton tagging

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

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

→ Highly peripheral scattering.

→ Slope parameter b is consistent with that expected from soft hadron-hadron diffraction.

Factorisation in Diffractive DIS

QCD Hard Scattering Fac'n for Diffractive DIS:-

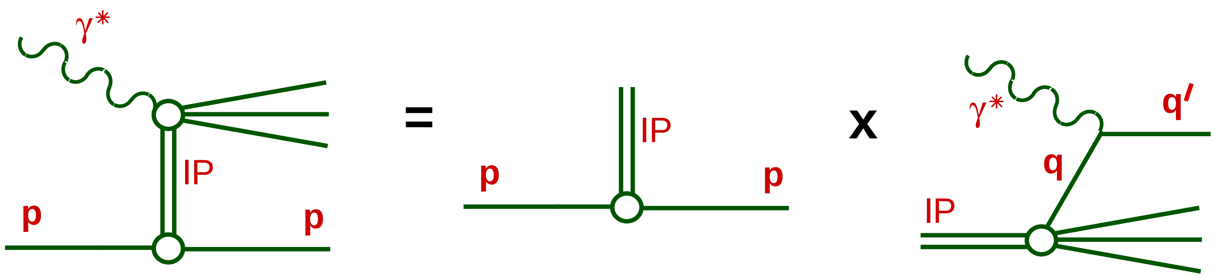
(Trentadue, Veneziano, Berera, Soper, Collins):
Diffractive parton distributions $f(x_{I\!P}, t, x, \mu^2)$ can be defined, expressing proton parton probability distributions with intact final state proton at particular $x_{I\!P}, t$ ...

$$\sigma(\gamma^* p \to Xp) \sim \sum_i f_{i/p}(x_{I\!P}, t, x, Q^2) \otimes \hat{\sigma}_{\gamma^* i}(x, Q^2)$$

At fixed $x_{I\!P}$, t, diffractive partons evolve in x, Q^2 according to DGLAP equations.

Regge Factorisation:-

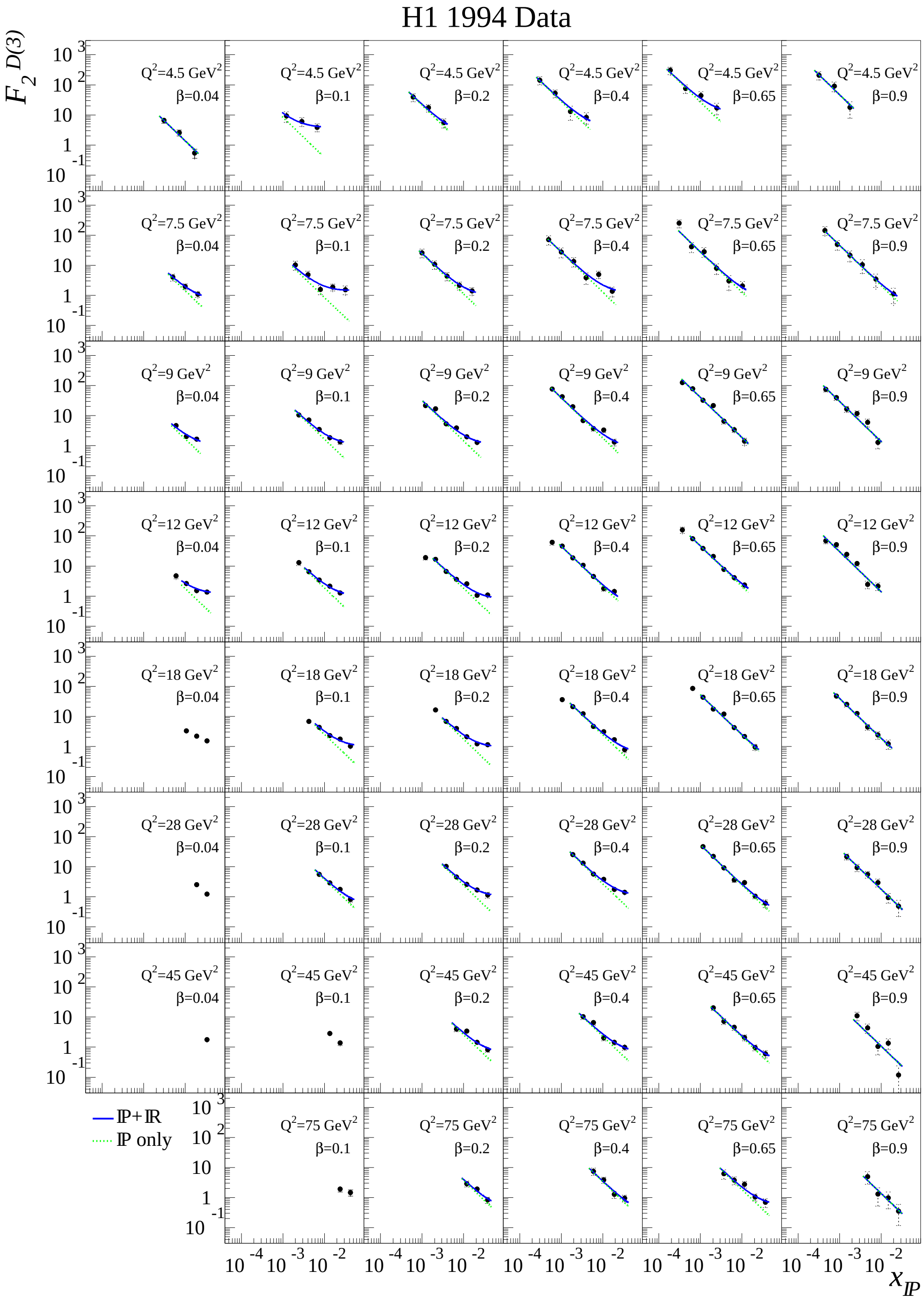
Soft hadron phenomenology suggests a universal *pomeron* ($\mathbb{P}$) exchange can be introduced, with flux dependent only on $x_{I\!P}$, t (Donnachie, Landshoff, Ingelman, Schlein):-



$$\sigma(\gamma^* p \to Xp) \sim f_{\mathbb{P}/\mathrm{p}}(x_{I\!P}, t) \otimes F_2^{\mathbb{P}}(\beta, Q^2)$$

$$\sim f_{\mathbb{P}/\mathrm{p}}(x_{I\!P}, t) \otimes \sum_i f_{i/\mathbb{P}}(\beta, Q^2) \otimes \hat{\sigma}_{\gamma^* i}(\beta, Q^2)$$

$F_2^{D(3)}$ with Phenomenological Regge Fit.



Rapidity gap selection:

t not measured.

$$F_2^{D(3)}(\beta, Q^2, x_{I\!P}) = \int_{-1GeV^2}^{t_{\min}} dt\ F_2^{D(4)}$$

Characteristic diffractive dependence on energy.

$\sim 1/x_{I\!P}$

Deviations from simple Regge model at large $x_{I\!P}$, small β.

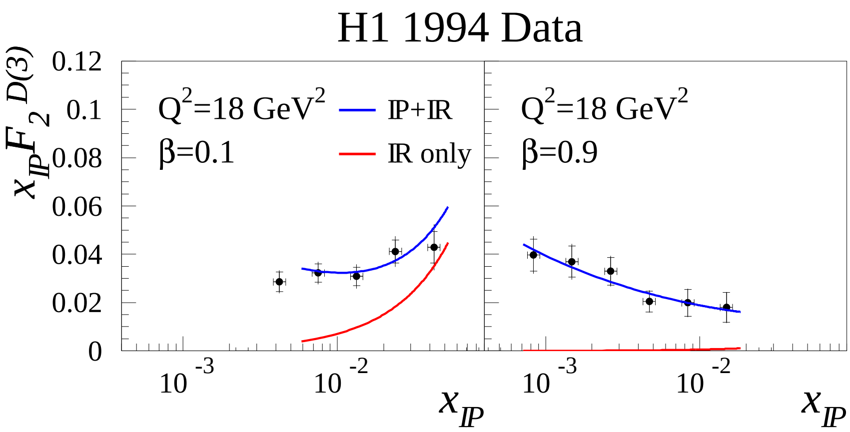
The $x_{I\!P}$ Dependence of $F_2^{D(3)}$

Regge theory gives us a means of parameterising the long distance physics at the proton vertex:

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

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

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



$$\frac{\chi^2}{\mathrm{n.d.f.}} = \frac{258}{168}\ (\mathrm{I\!P}\ \mathrm{only})$$

$$\frac{\chi^2}{\mathrm{n.d.f.}} = \frac{121}{121}\ (\mathrm{I\!P} + \mathrm{I\!R})$$

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

Good fits obtained throughout kinematic range using:

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

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

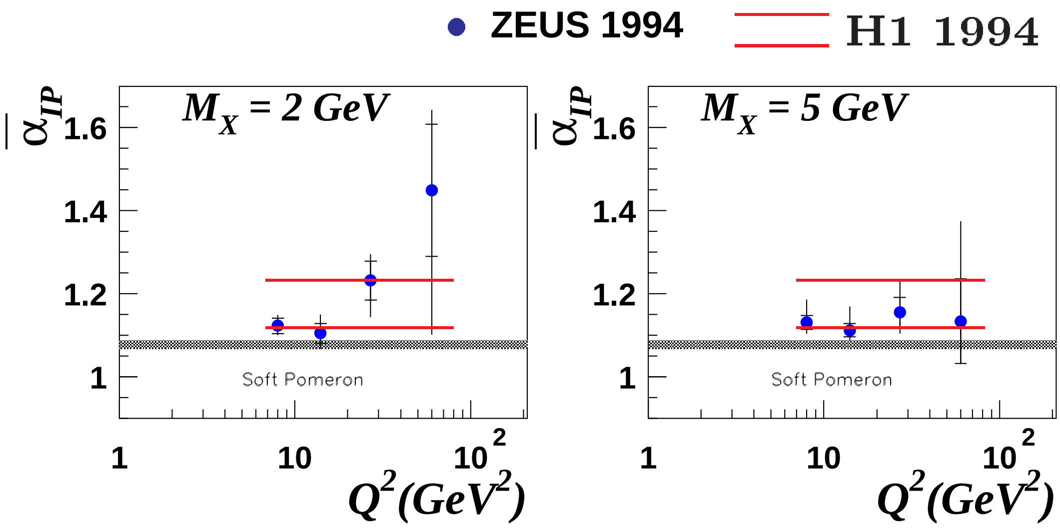
The pomeron intercept and Q^2

From H1 Phenomenological fits:

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

Larger than in soft hadron-hadron physics ($\alpha_{I\!P}(0) \sim 1.1$).
Similar to exclusive J/ψ production.

Comparison of H1 and ZEUS results:



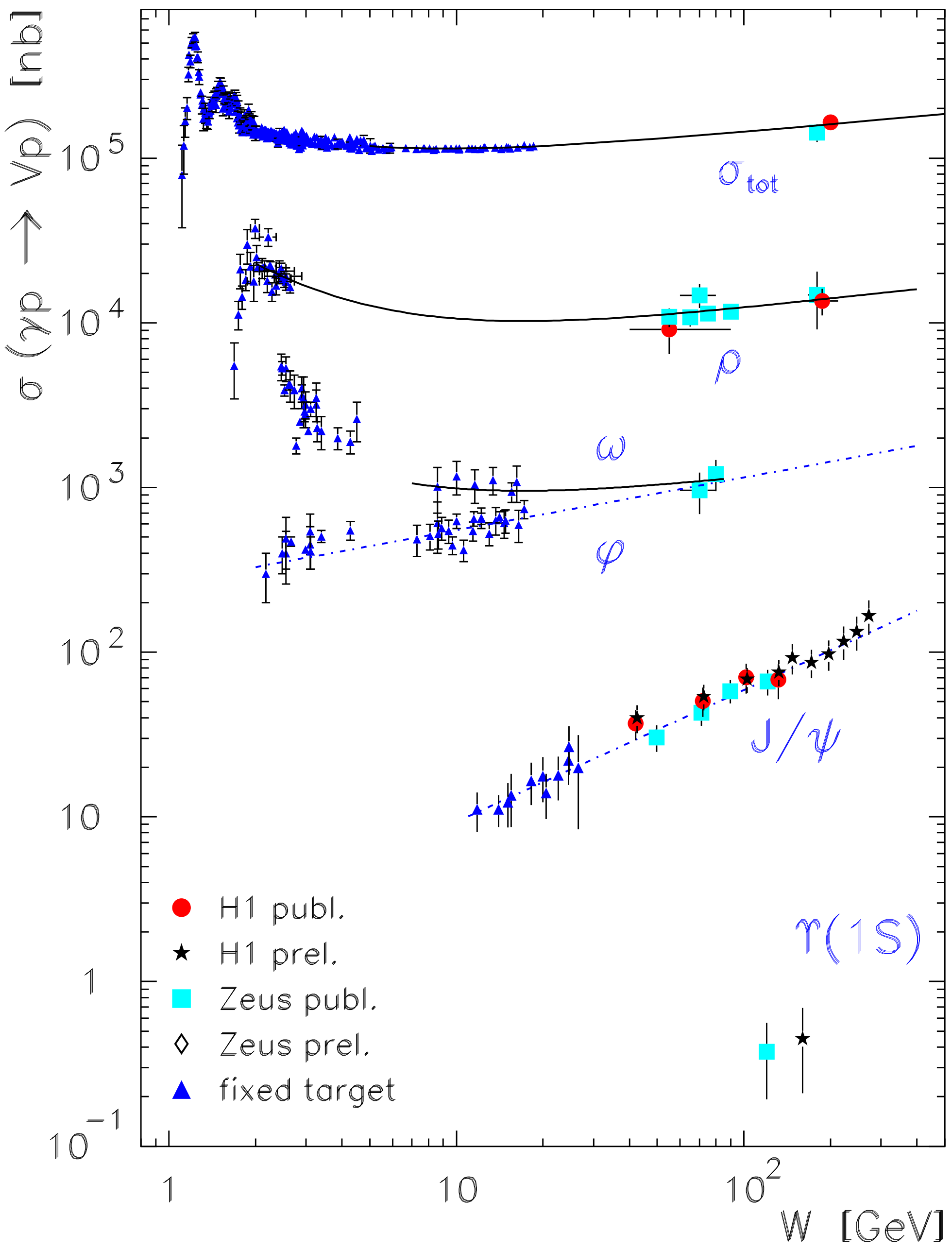
...No significant variation with Q^2 within measured kinematic range to present precision.

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

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

Consistent with f, ω, ρ or a exchange.

Energy Dependence of Vector Meson Photoproduction



$\sigma^{\gamma p}_{tot} \sim W^{2\alpha_{I\!P}(0)-2}$

$W^{0.16}$

$W^{0.23}$

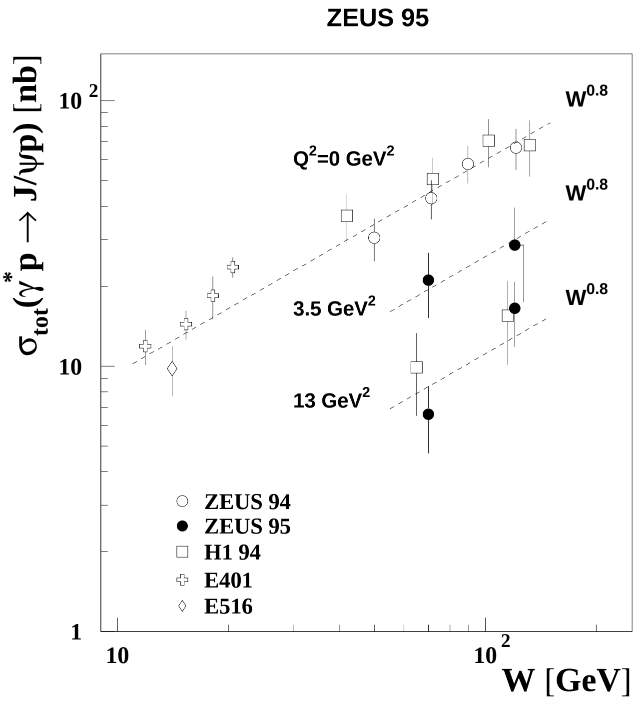
$W^{0.32}$

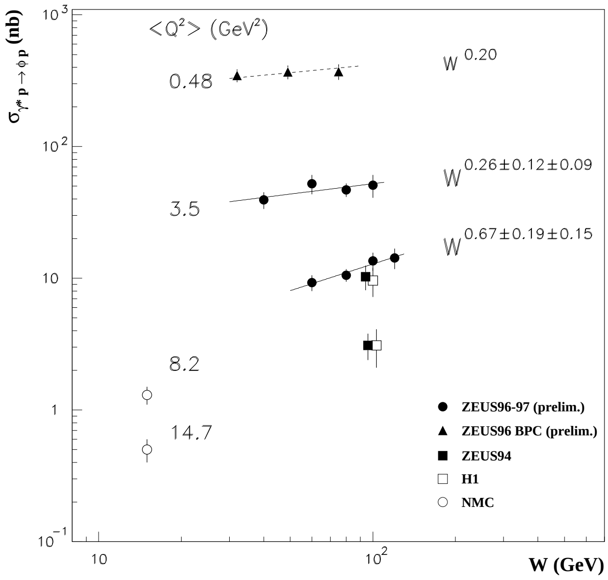
$W^{0.8}$

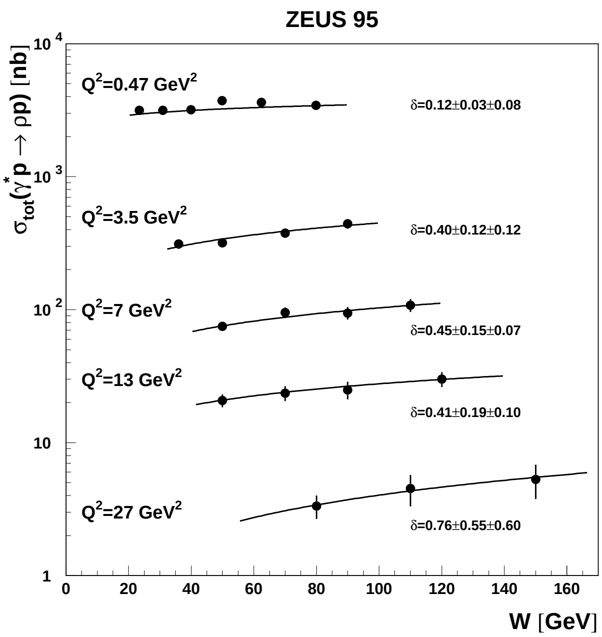
$\sigma^{\gamma p \to Vp} \sim W^{4\alpha_{I\!P}(\langle t \rangle)-4}$

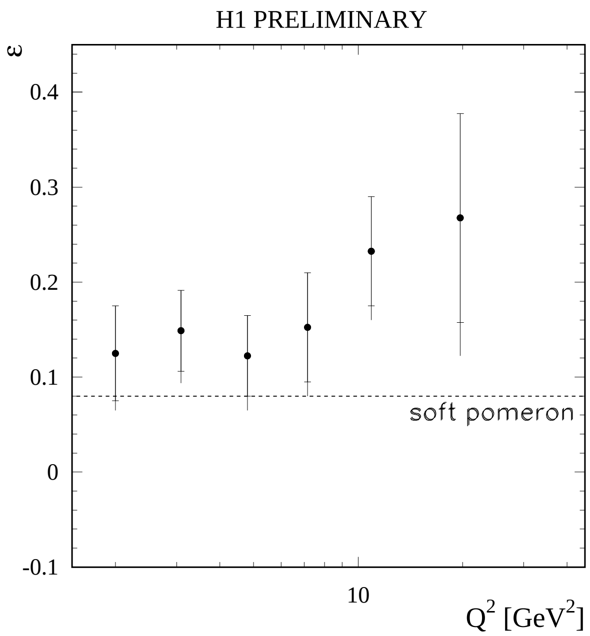
Effective $\alpha_{I\!P}(0)$ depends on vector meson mass at $Q^2 = 0$.

Energy Dependence of Vector Meson Electroproduction









Effective $\alpha_{I\!P}(0)$ depends on Q^2 and vector meson mass.

J/ψ has strong W dependence at $Q^2 = 0$

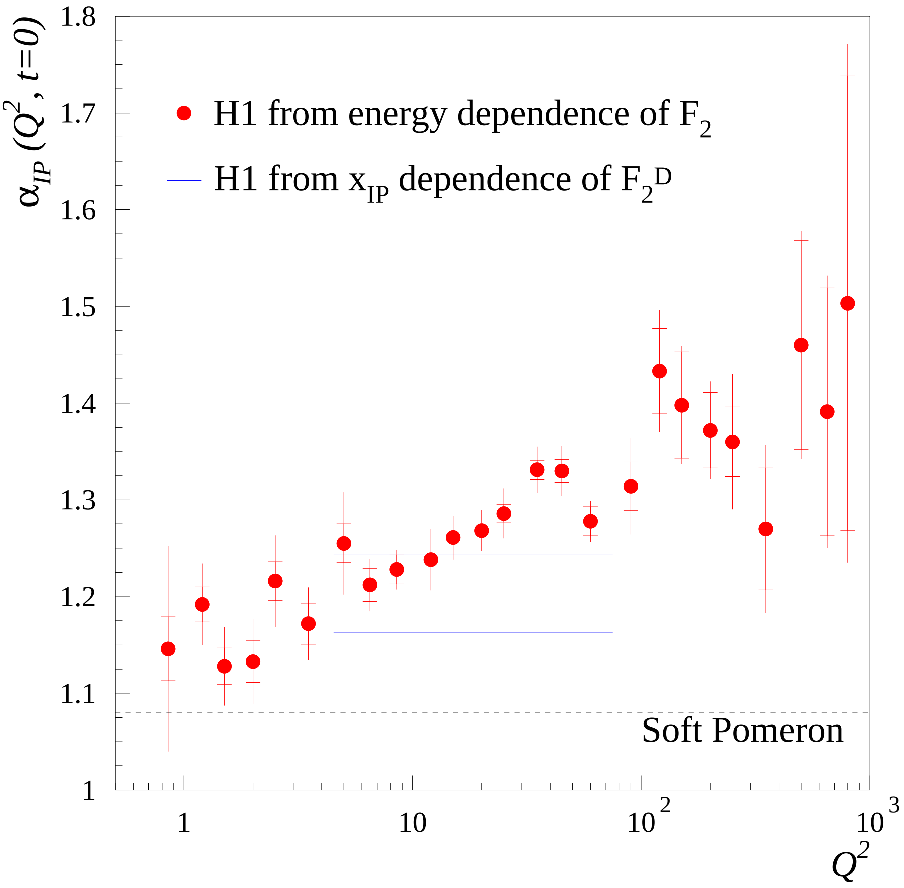
ρ, ϕ dependence on W steepens with Q^2

ϕ steepens faster than ρ?

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

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

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

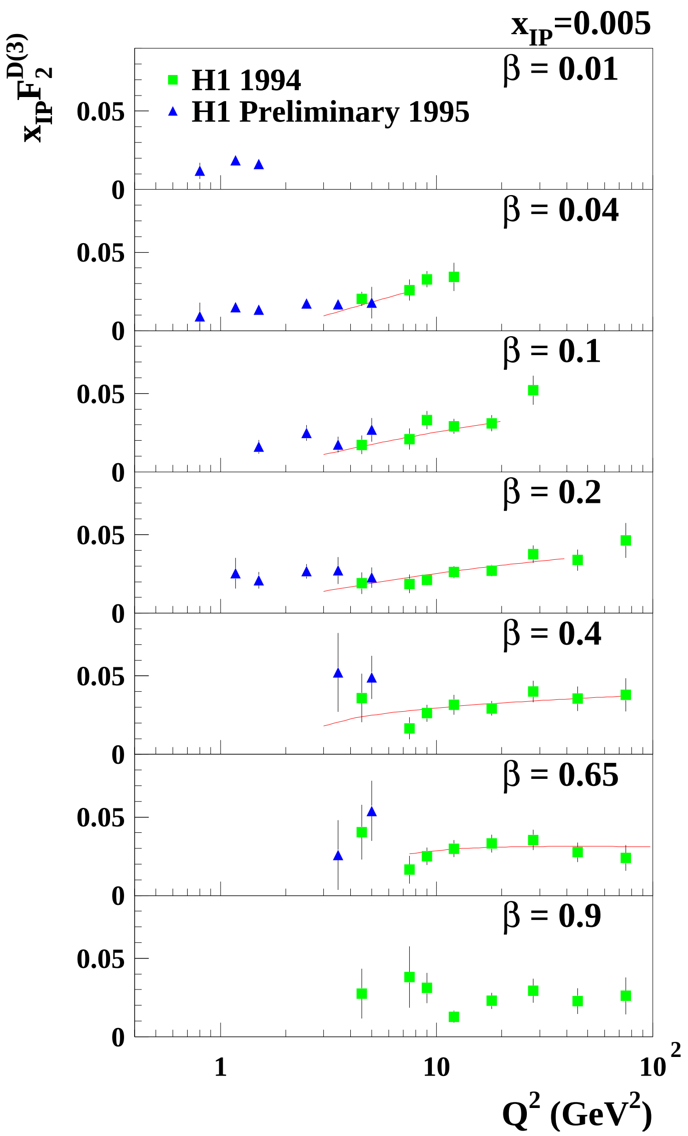


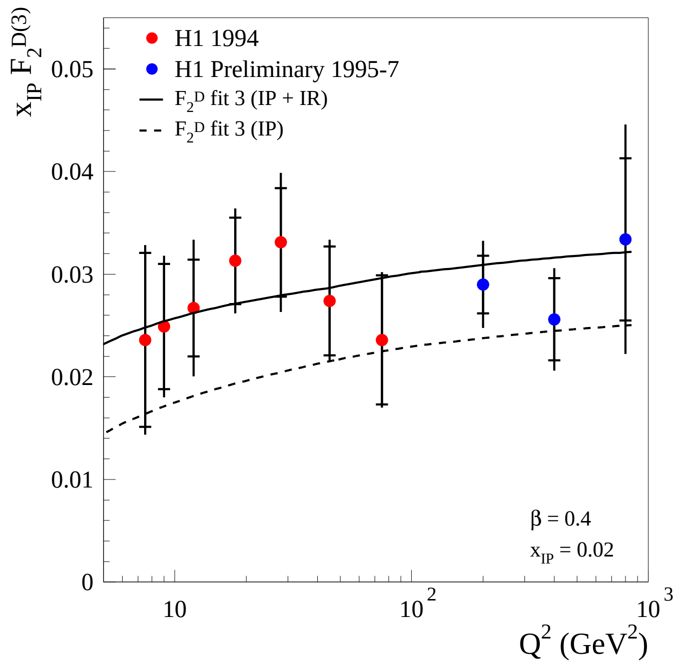
Is the scale dependence of the effective pomeron intercept similar for total, dissociative, elastic cross sections?

c.f. Donnachie & Landshoff soft + hard $I\!P$ model.

Is it all driven by p-gluon distribution?... or its square?...

Scaling Violations of $F_2^{D(3)}$





Including data for

$0.8 < Q^2 < 800$ GeV^2

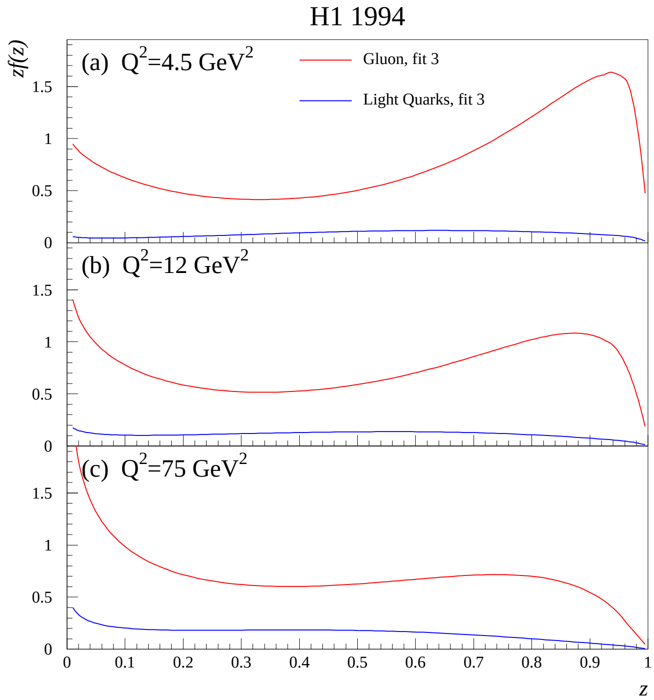
Rising scaling violations over large range of Q^2 up to large β [c.f. $F_2(x,Q^2)$].

Highly suggestive of a gluon dominated mechanism.

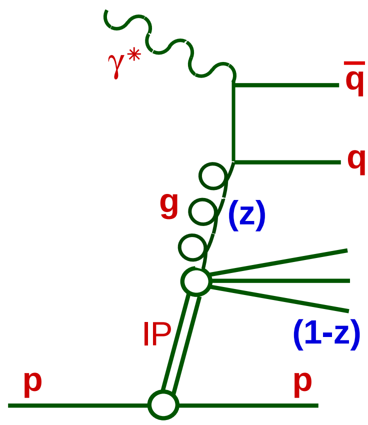
DGLAP Fits to $F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$

Regge factorisation hypothesis approximately valid for F_2^D.
Can we think of the pomeron as a partonic object?

DGLAP fit to β, Q^2 dependence to extract parton densities for the exchange.



Acceptable fits only when $I\!P$ is dominated by "hard" gluons.
$\sim 90\%$ gluon at $Q^2 = 4.5$ GeV^2



Complications:

- $x_{I\!P}$ dependence stronger than soft hadronic physics.
- Sub-leading exchanges also present (interference?)
- Very poorly constrained high x region.
- Higher twist contributions likely to be present.

Predictions for the final state X

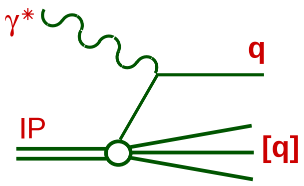
If QCD & Regge factorisation valid, IP partons extracted from F_2^D can be applied to all diffractive hard scattering.

In terms of DGLAP evolving IP model, distinguish between quark and gluon dominated pomeron.

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

$\mathcal{O}(\alpha)$

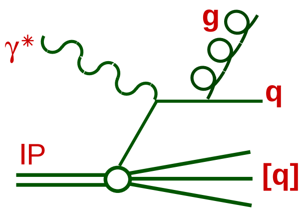
QPM

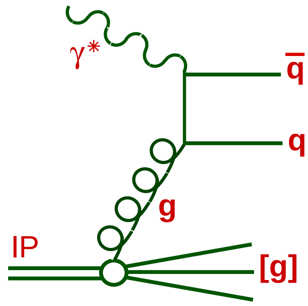


$\mathcal{O}(\alpha\ \alpha_s)$

QCD-C

BGF

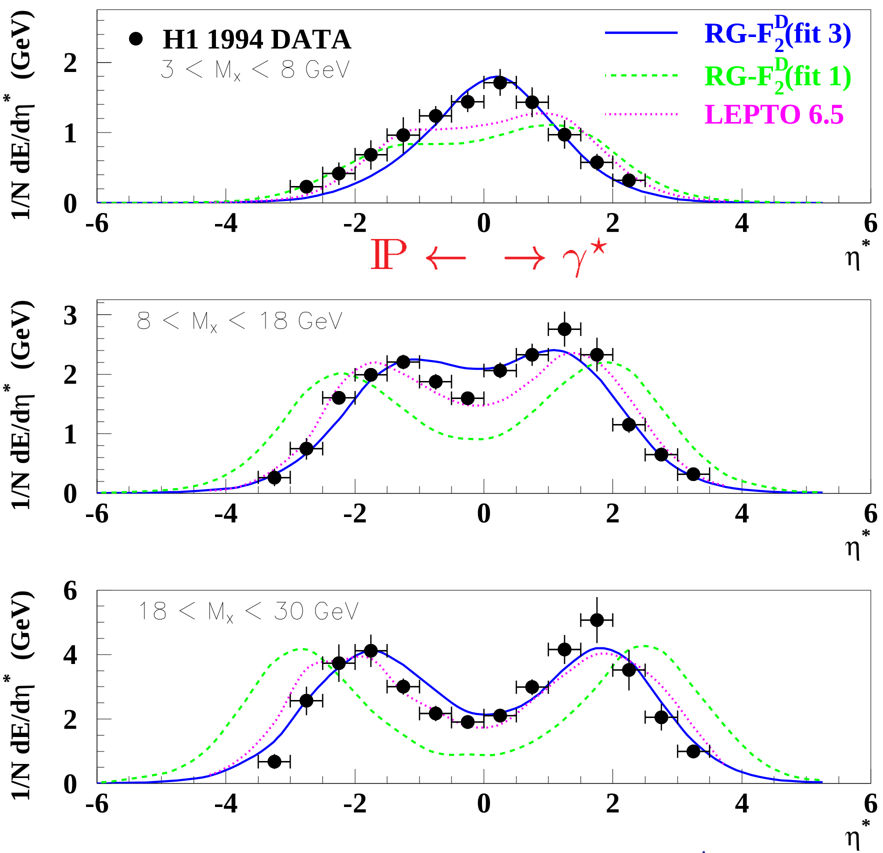




↑ Quarkonic IP	↑ Gluonic IP
Dominant $q\bar{q}$	Dominant $q\bar{q}g$
Low p_T / aligned	High p_T / non-aligned
Few jets /charm	Many jets / charm
$\sim 3_c\bar{3}_c$	$\sim 8_c 8_c$

Energy Flow in the Rest frame of X

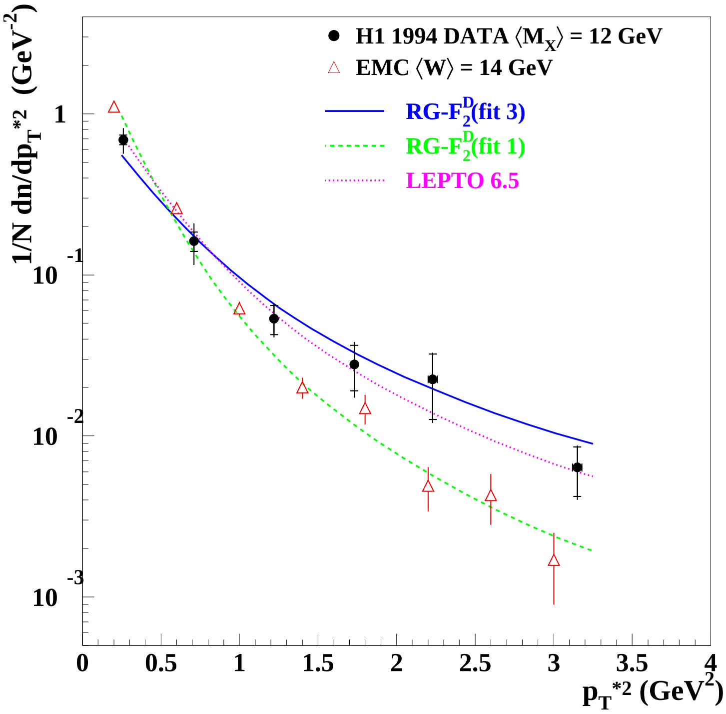
Pseudorapidity $\eta^\star$ relative to $\gamma^\star$ direction in X rest frame.



- 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

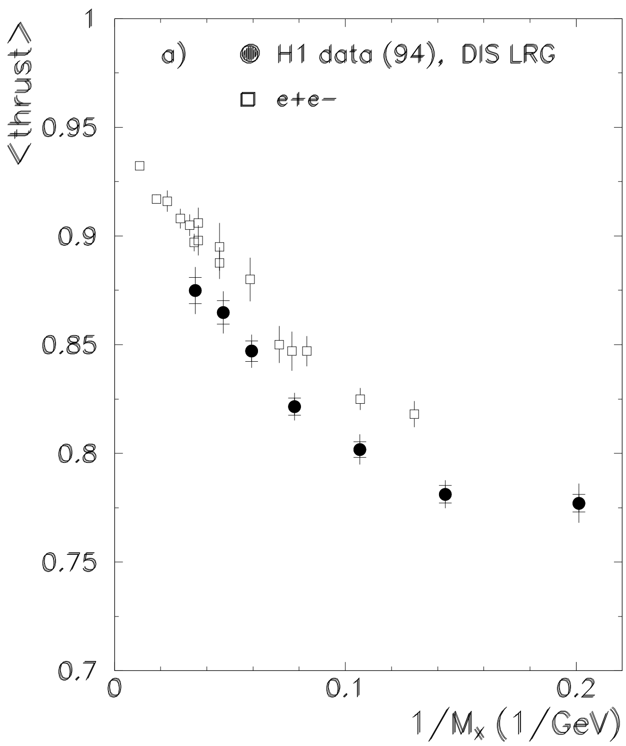
$p_T^\star$ measured relative to $\gamma^\star$ axis in rest frame of X



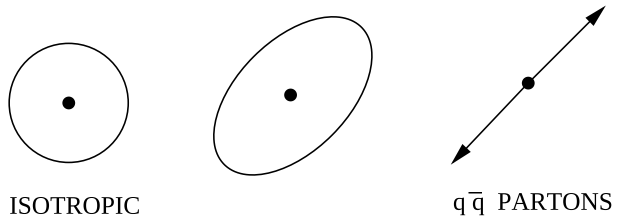
Gluons required to generate hard $p_T^\star$ distribution.

BGF / $q\bar{q}g$ contributions.

Thrust - measure of ‘2-jettiness’



$$1/2 \;<\; T \;<\; 1$$



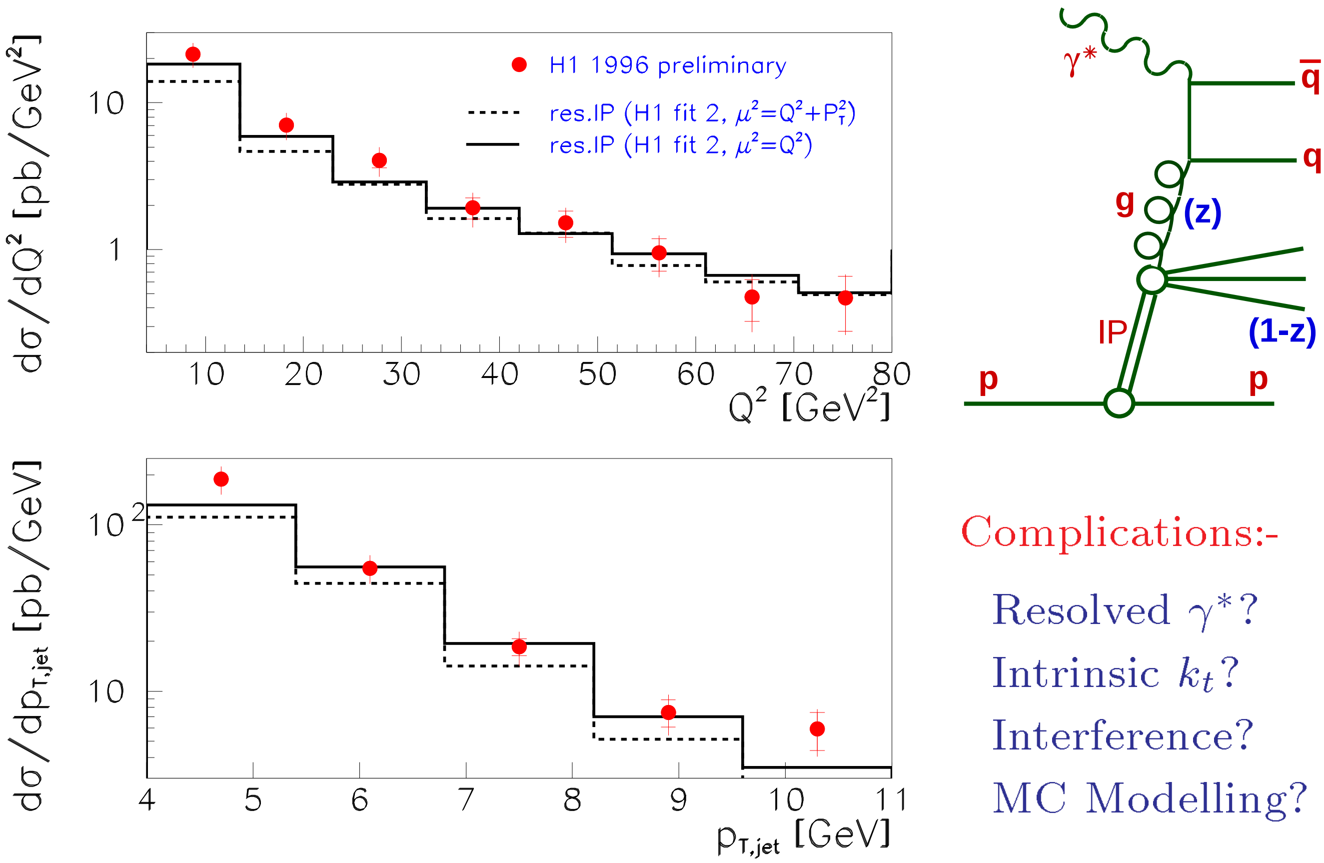
Gluons required to generate lower thrust than $q\bar{q}$.

Hadronisation effects decrease thrust at low M_X .

Diffractive Final State Data - Dijets

Many hadronic final state observables at HERA well described by models based on pomeron partons (event shapes, E-flow, charged particle spectra, multiplicity . . .).

Most stringent tests come in dijet and open charm rates and distributions. - Direct sensitivity to gluon!



Complications:-

Resolved γ^*?

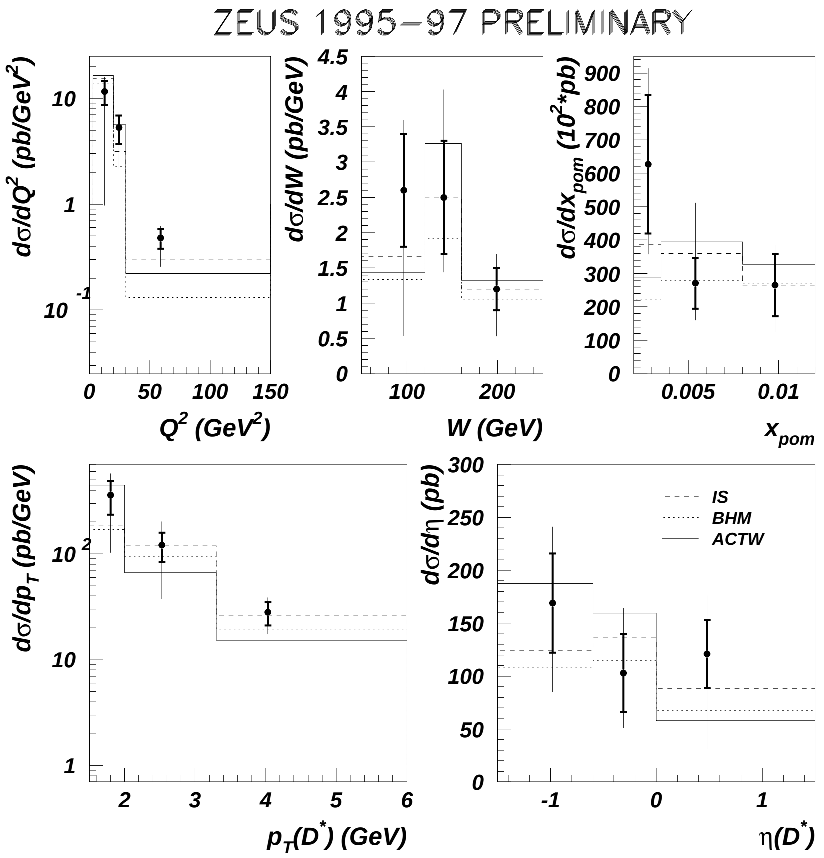
Intrinsic k_t?

Interference?

MC Modelling?

Diffractive Final State Data - Open Charm

H1 / ZEUS conclusions differ on diffractive charm . . .

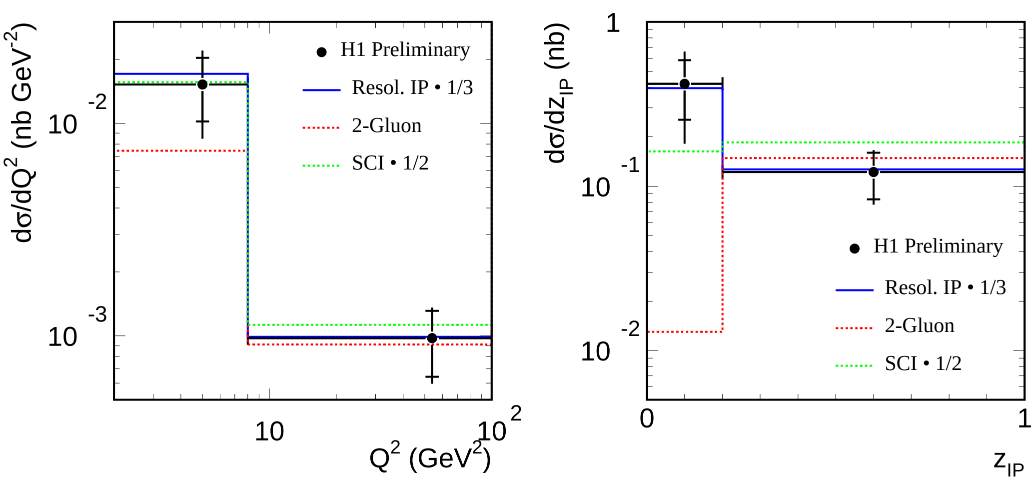


ZEUS $D^* \to K\pi\pi$ & $D^* \to K4\pi$

Rates and distributions well modelled by IP partons (ACTW)

H1 $D^* \to K\pi\pi$

Shapes well described, but normalisation difference of factor ~ 3!



Different kinematic regions? Poor statistics?

How Universal are Diffractive Partons?

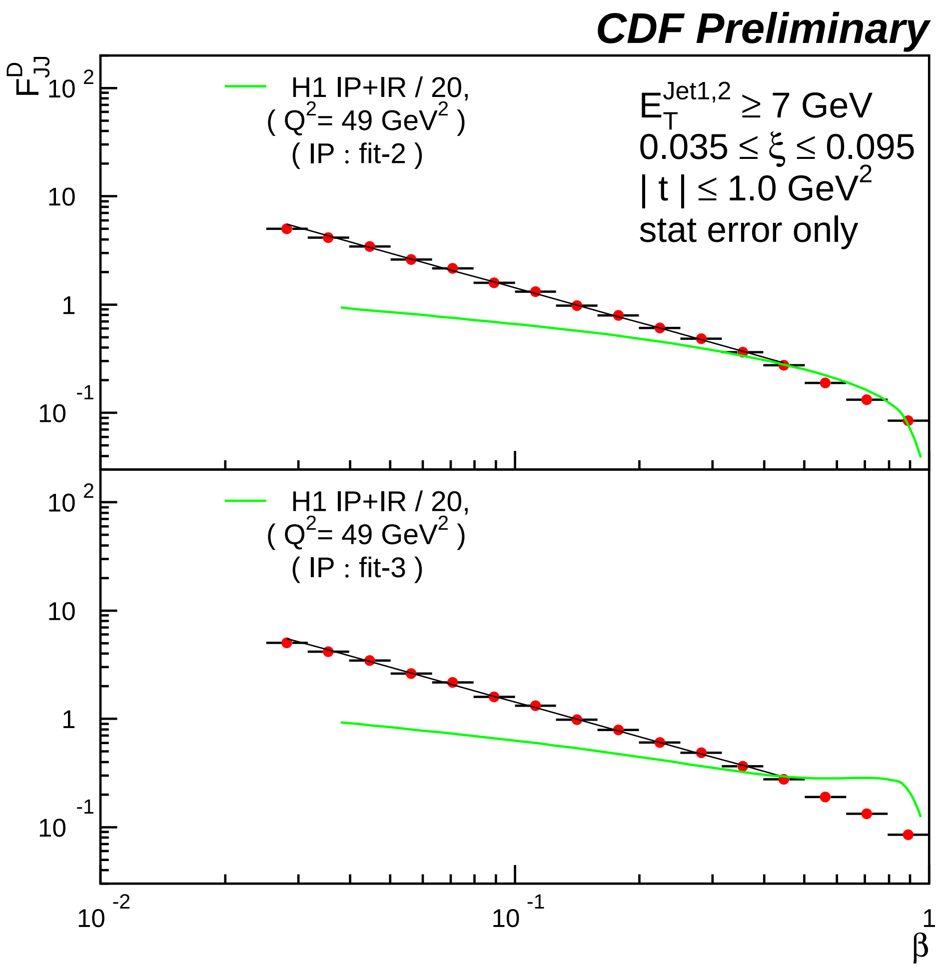
Model $\bar{p}p$ (Tevatron) diffraction using $\mathbb{P}$ partons from F_2^D.

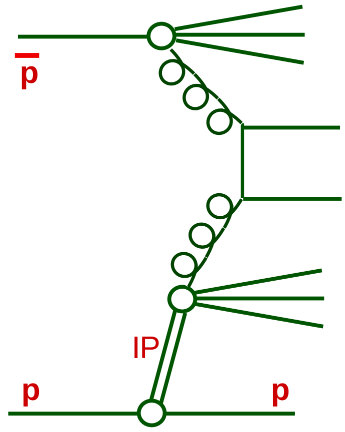
CDF measure diffractive / inclusive dijet ratio and extract

$$F_{\rm JJ}^D = \frac{N^{\rm diff}}{N^{\rm incl}}(x_{\bar{p}}) \quad \left\{x_{\bar{p}} g(x_{\bar{p}}) + \frac{4}{9}[q(x_{\bar{p}}) + \bar{q}(x_{\bar{p}})]\right\}_{\bar{p}}$$

Assuming factorisation

$$F_{\rm JJ}^D \propto \left\{\beta g(\beta) + \frac{4}{9} x[q(\beta) + \bar{q}(\beta)]\right\}_{\mathbb{P}} \;\otimes\; f_{\mathbb{P}/\rm p}(\xi)$$





Prediction using $\mathbb{P}$ partons from F_2^D inconsistent in both shape and normalisation.

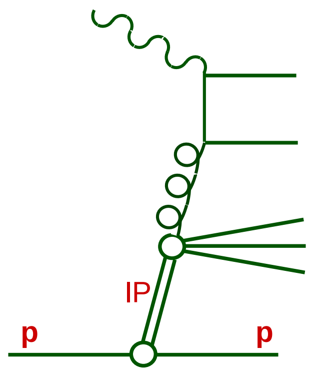
Similar factorisation breaking observed for diffractive W, b production in $\bar{p}p$. - Associated with hadronic remnants?

Possible control experiment? - γp Dijets

Do remnant reinteractions destroy rapidity gaps?

Hard diffractive photoproduction provides photon interactions with and without remnants ...

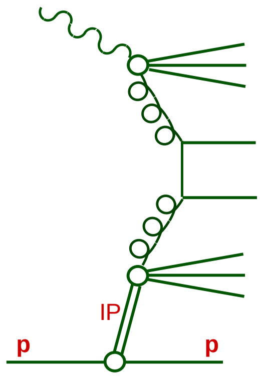
x_γ^{jets} = fraction of γ momentum entering the hard scatter.



DIRECT

$x_\gamma^{\text{jets}} \sim 1$

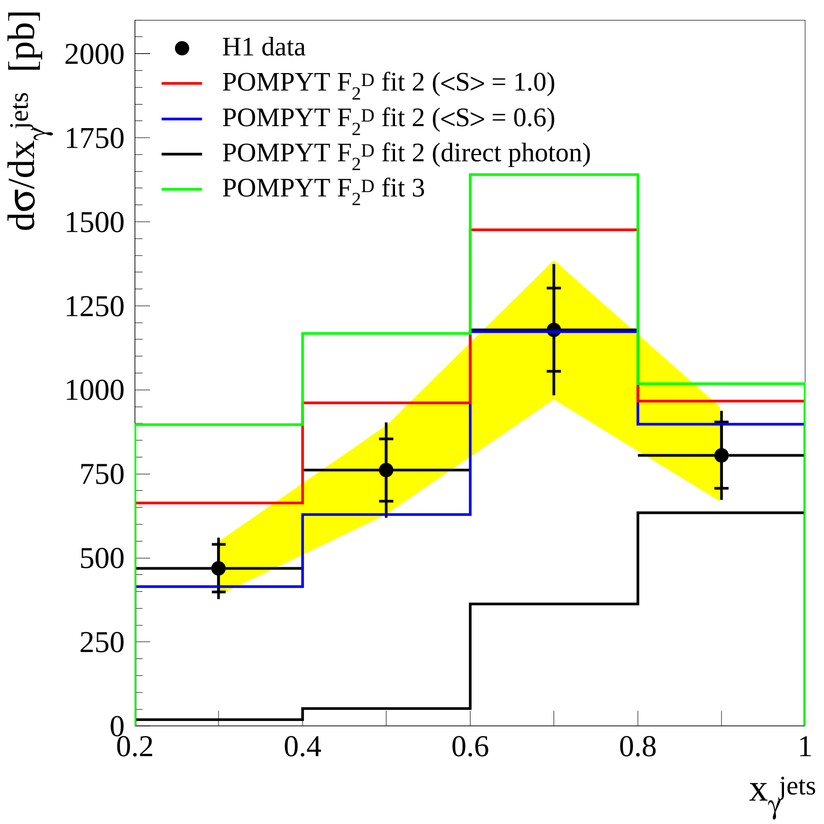
All gaps survive?



RESOLVED

$x_\gamma^{\text{jets}} < 1$

Some gaps destroyed?



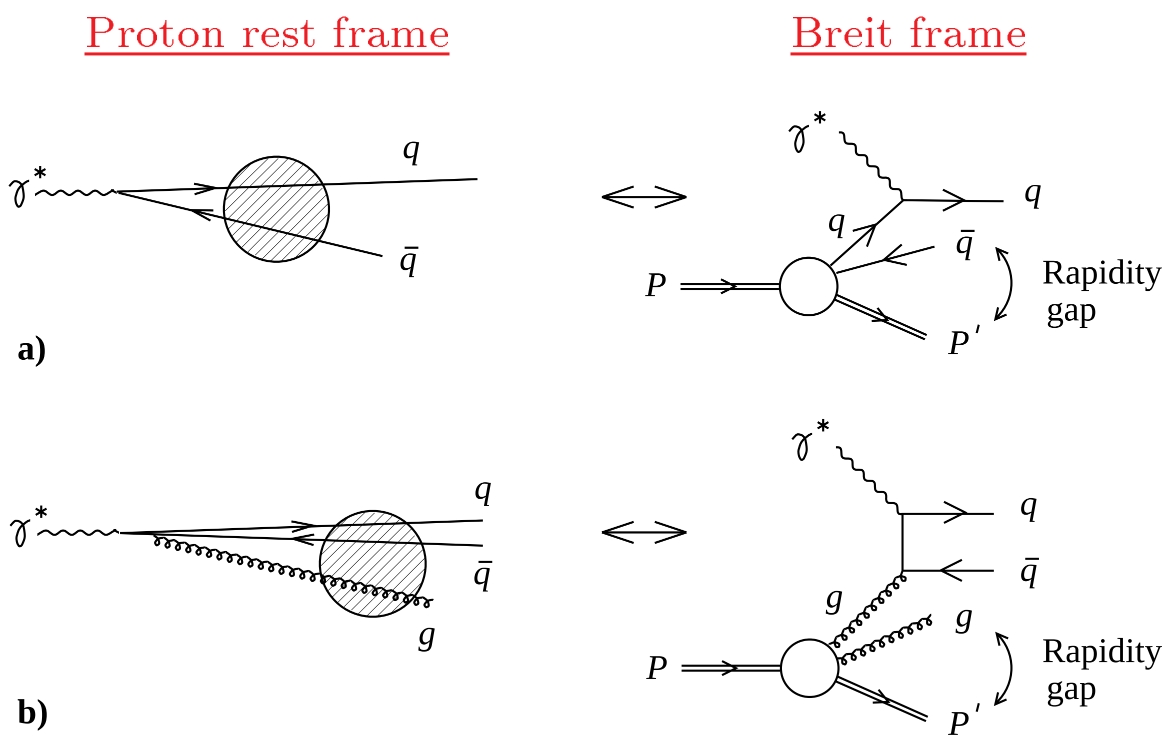
Description based on diffractive partons improved by suppressing resolved interactions by 'gap survival probability' of 0.6

Improved data and MC modelling needed for firm conclusions.

A Detour into the Proton Rest Frame

$\gamma^* \to q\bar{q}$, $q\bar{q}g$ well in advance of target . . .
Partonic fluctuations scatter 'elastically' from proton.

Correspondance between frames (Buchmüller, Hebecker, McDermott . . .)



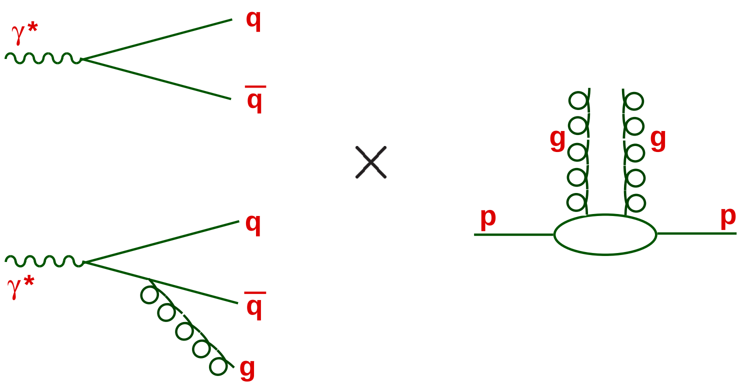
Knowledge of the light cone wavefunctions of $q\bar{q}$ $3-\bar{3}$ and $(q\bar{q})g$ $8-8$ dipole is sufficient to predict β dependence.

$$q\bar{q} \sim \beta(1-\beta) \qquad\qquad (q\bar{q})g \sim (1-\beta)^3$$

A model for the diffractive scattering from the proton is still required to describe $x_{I\!P}$ dependence.

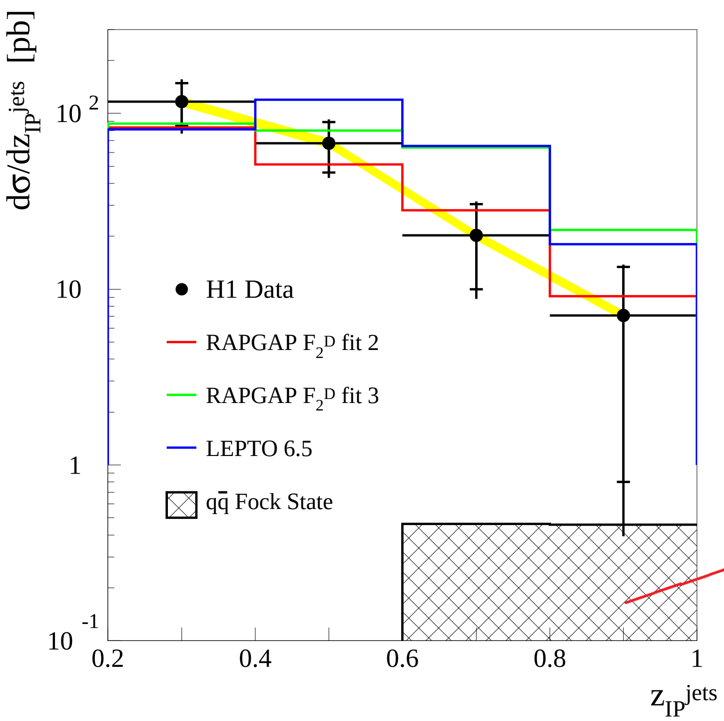
Two-gluon Models

Simplest model for diffractive interaction is a pair of gluons with opposite colour charge.

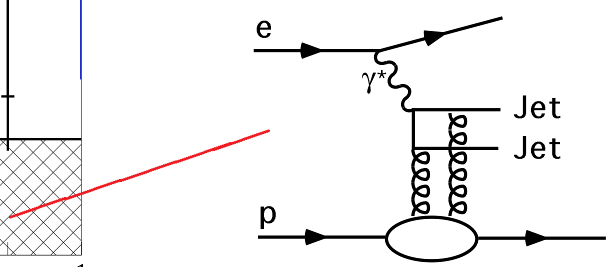


Many years of development by many authors

Calculation (Bartels et al) for dijet electroproduction shows that $q\bar{q}$ contribution alone is insufficient.



$z_{\mathbb{P}}^{\mathrm{jets}}$ = fraction of exchanged ($\mathbb{P}$) momentum transferred to dijets.



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

A two-gluon model for F_2^D

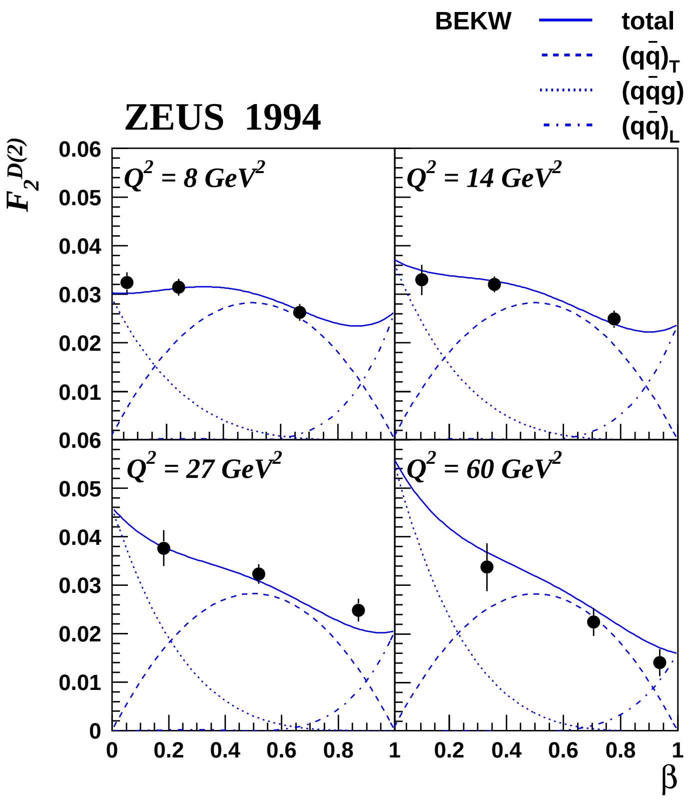
Recent simple 3 component parameterisation (BEKW)

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

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

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

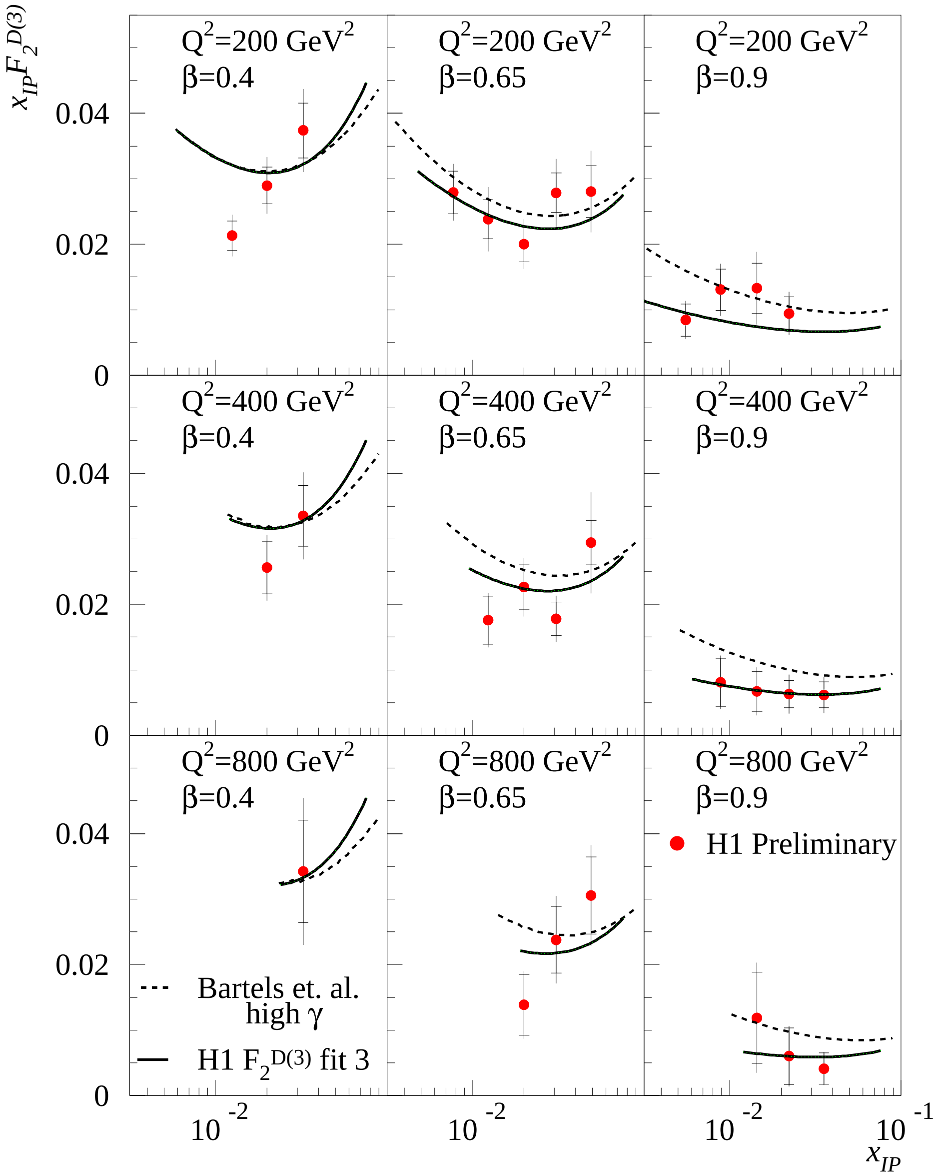
(HT)



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

Higher twist contribution important at large β.

New $F_2^{D(3)}$ Data at large Q^2

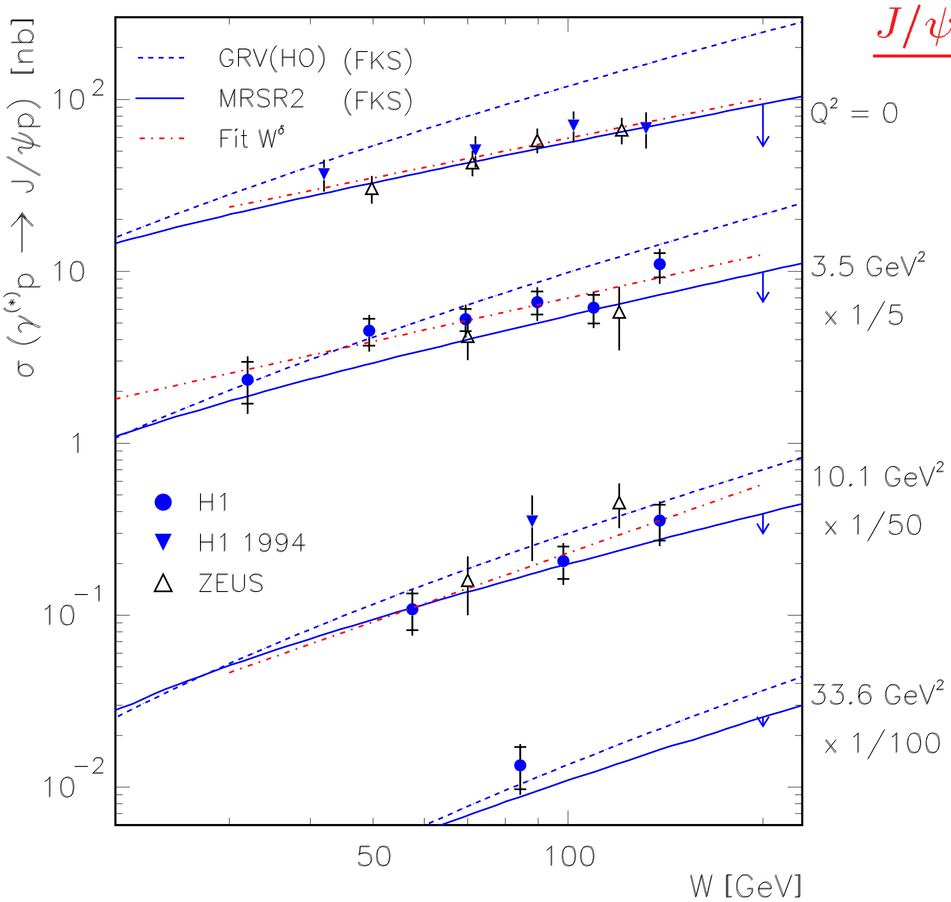


Extrapolations of both DGLAP and 2-gluon exchange models can describe the data up to $Q^2 = 800\ \mathrm{GeV}^2$.

Two-gluon models of VM Production

Two gluon exchange models have been applied successfully to exclusive channels ($\gamma^* p \to V p$) ....

J/ψ, ($\sigma_{\rm L} + \sigma_{\rm T}$)



Compared to model of Frankfurt et al.,

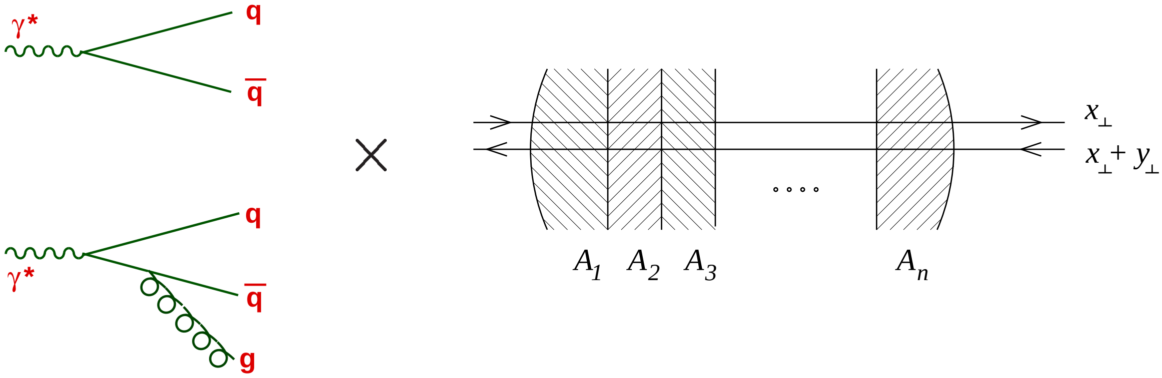
$$\frac{d\sigma}{dt}\bigg|_{t=0} \sim \left|xg(x,\mu^2)\right|^2 \quad \text{with} \quad \mu^2 = (Q^2 + m_\psi^2)/4$$

and different gluon distributions.

Similar approaches have been applied to ρ at high Q^2.
Remarkably successful in shape and normalisation.

Non-perturbative model for Diffr. Interaction

Dipoles scatter through superposition of proton colour fields according to a semi-classical model. (Buchmüller, Hebecker, Gehrmann, McDemott)



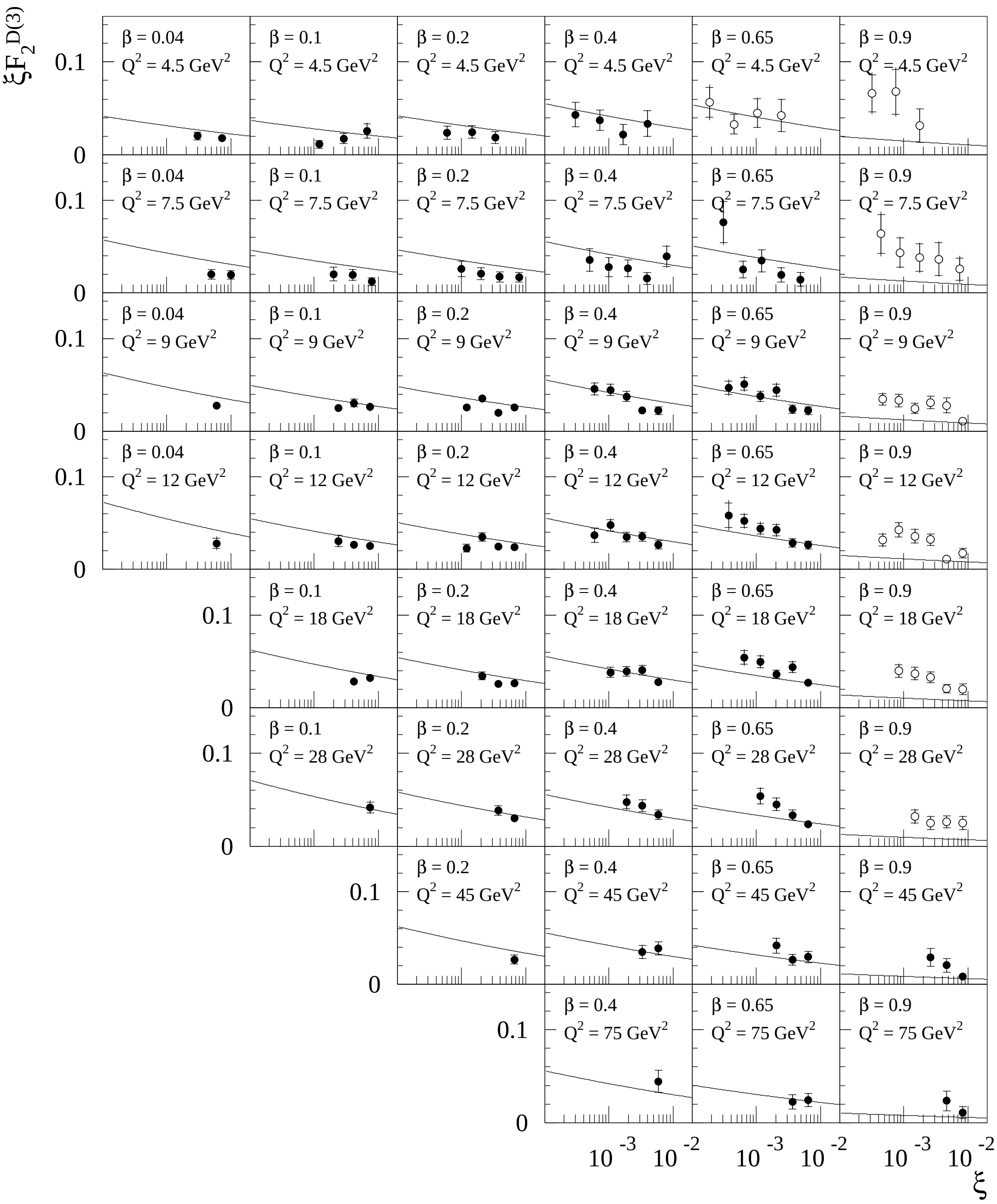
All final states contribute to F_2

Final states with net colour singlet $q\bar{q}$ / $q\bar{q}g$ contribute to F_2^D.

Cross sections can be expressed as convolutions of diffractive / inclusive quark / gluon distributions with hard scattering cross sections. (Hebecker)

Using DGLAP to evolve these partons, the simulataneous description of F_2 and F_2^D is reduced to a 4 parameter fit.

H1 $F_2^{D(3)}$ in Semi-Classical Model



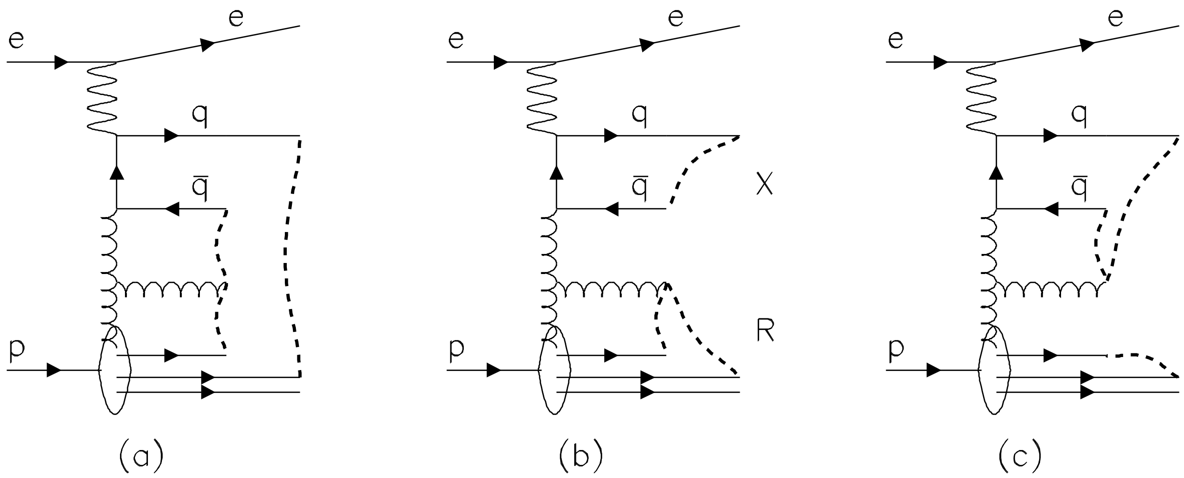
Good description of F_2 also obtained.

Remarkable with so few parameters!

Soft Colour Rearrangement Model

Start from standard matrix elements / parton showers description of $F_2(x, Q^2)$ (dominantly BGF at low x).

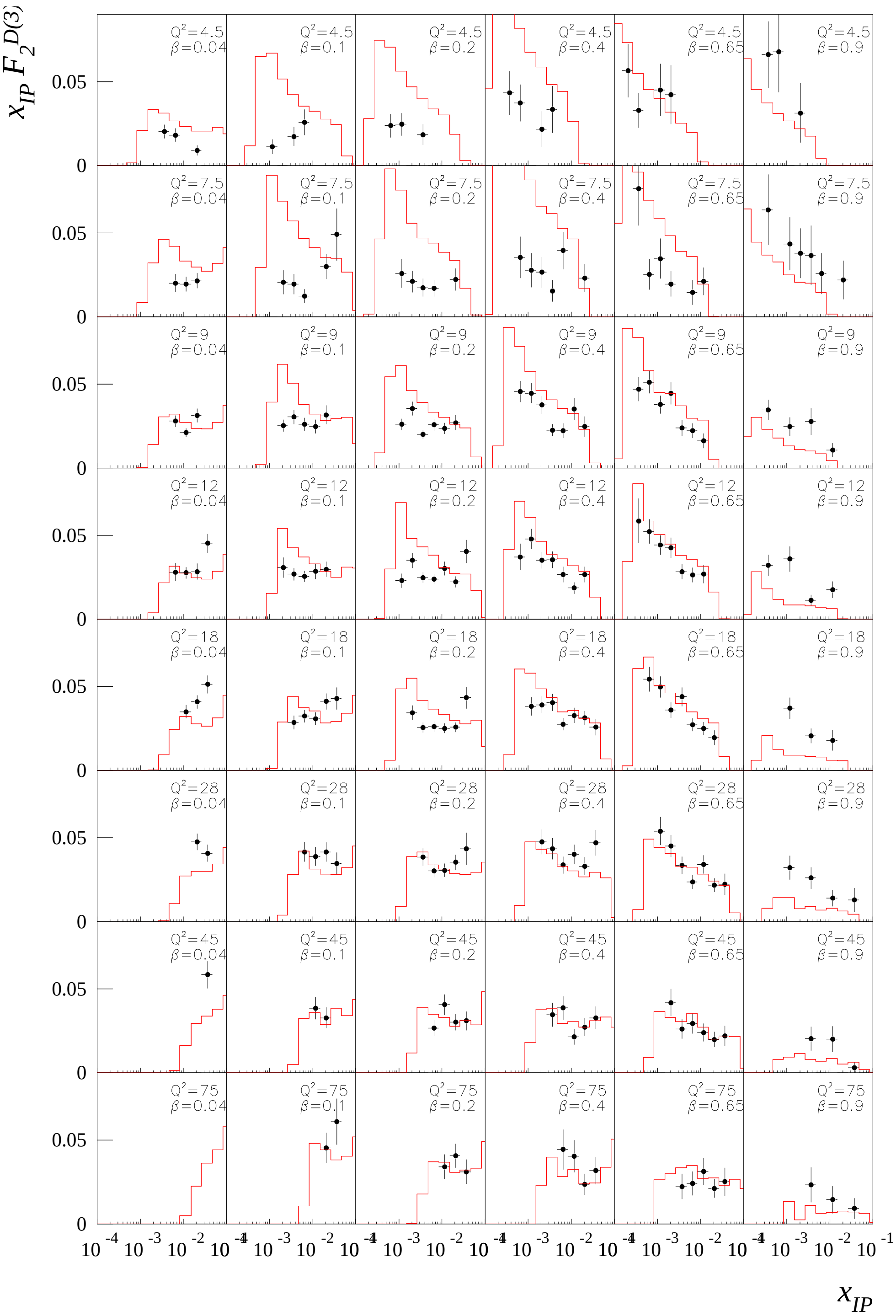
Additional non-perturbative interactions affect final state colour connections but not parton momenta.



Implemented in the Monte Carlo model LEPTO

Only one 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).

Summary

- Colour-singlet exchange processes constitute a significant fraction of the DIS cross section.
- Data span the transition between ‘soft’ and ‘hard’ diffraction.
- Intercept of the effective $I\!P$ depends on hard scales for elastic, total and dissociative data.
- Additional meson exchanges present at larger $x_{I\!P}$ in the dissociative channel
- $F_2^{D(3)}$ and final state studues indicate that the $I\!P$ is dominated by ‘hard’ gluons.
- Diffractive factorisation works well for HERA data, fails for Tevatron data.
- Where the pomeron is ‘hard’, 2-gluon exchange models of vector meson production are successful.
- Clear evidence for $q\bar{q}g$ as well as $q\bar{q}$ final states in DIS diffractive dissociation.
- Models based on non-perturbative colour interactions are broadly successful.