Diffractive Scattering at HERA

Paul Newman

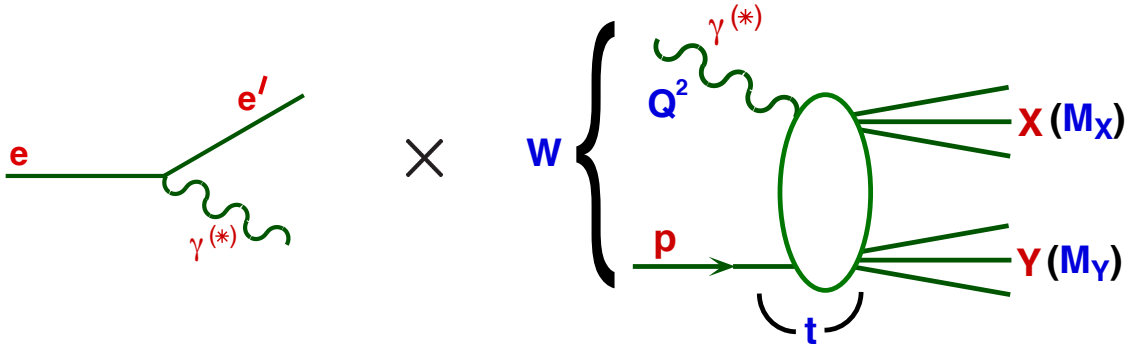
University of Birmingham

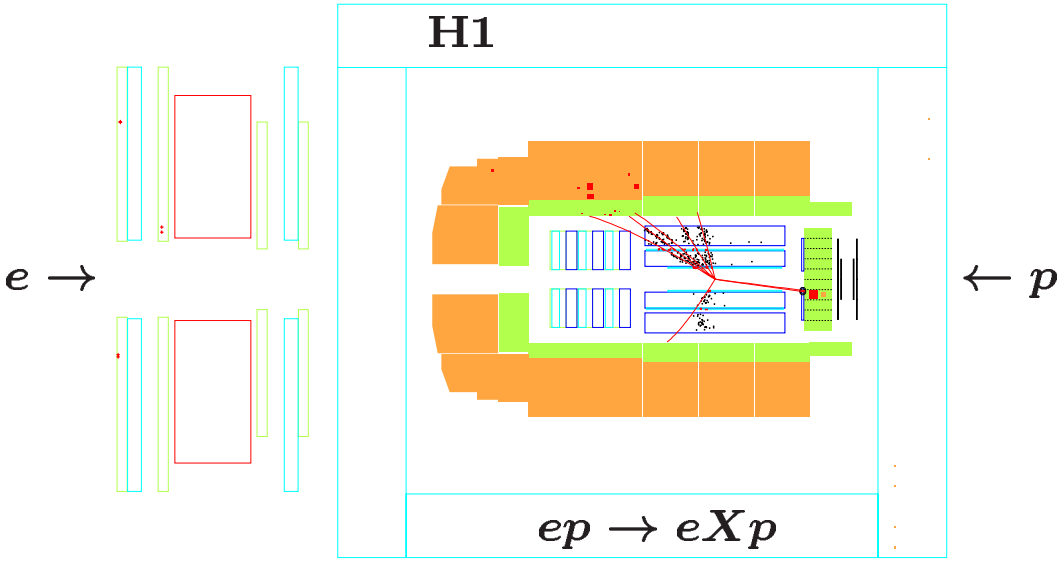
Representing the H1 and ZEUS Collaborations.

- Why Study Diffractive *ep* Interactions?
- Experimental Techniques.
- Inclusive Diffractive DIS.
- Other Colour Singlet Exchanges.
- The Hadronic Final State in Diffractive DIS.

Why Study Diffraction at HERA?

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

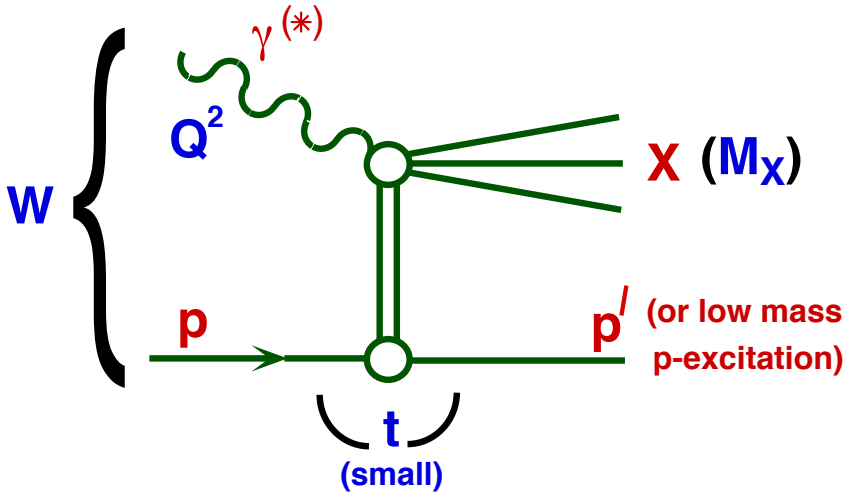




Measurements of all five kinematic variables can be made:

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

Kinematics of $\gamma^\star p \to Xp$ at low $x_{I\!P}$



Long distance physics at p - vertex:

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

$\to$ Fraction of p momentum transferred to longitudinal momentum of exchange

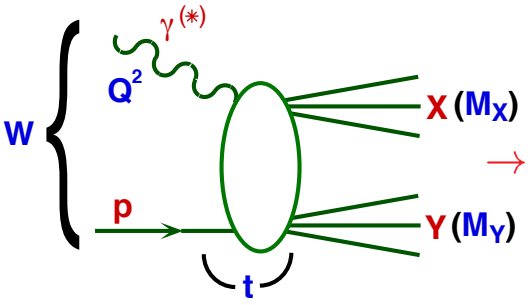
Short distance physics at $\gamma^\star$ - vertex:

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

$\to$ Fraction of exchange momentum carried by quark coupling to $\gamma^\star$.

Experimental Techniques

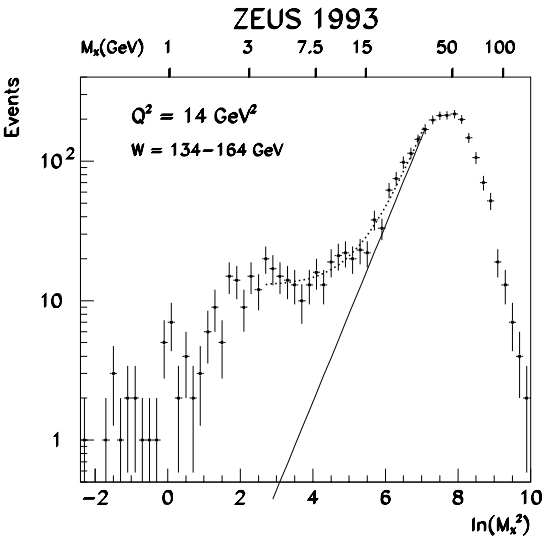
1. Rapidity Gap Selections (H1, ZEUS).



Largest rapidity gap among final state hadrons.

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

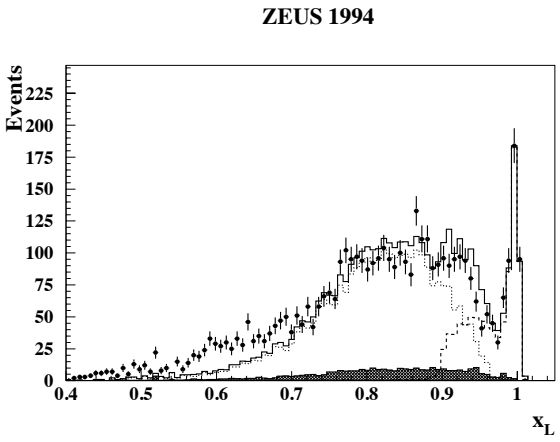
2. Decompose Reconstructed M_X Distribution (ZEUS).

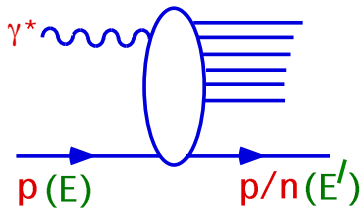


Exponential suppression in M_X distribution for "standard" DIS.

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

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





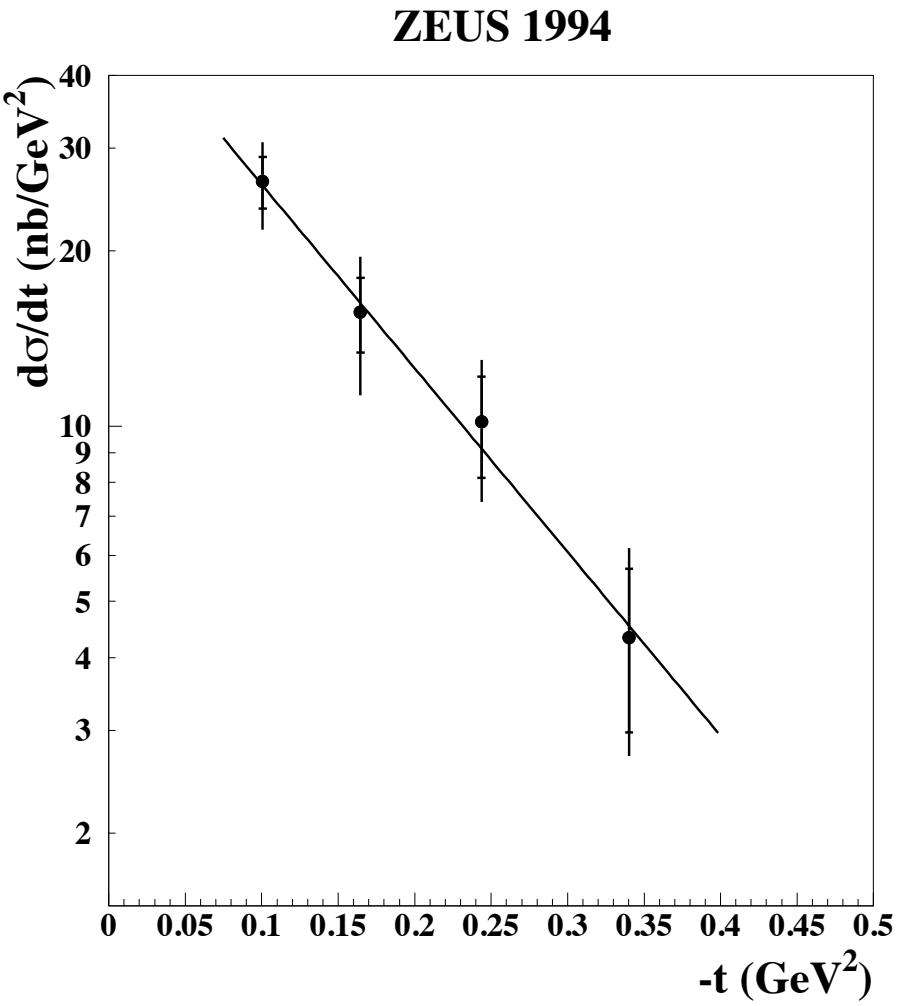
$x_L = E'/E$

$= 1 - x_{I\!P}$ if exclusive p / n

Measurement of the t Dependence

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

$x_L (\sim 1 - x_{I\!P}) > 0.97$



From Direct Proton tagging

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

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

$\rightarrow$ Highly peripheral scattering, characteristic of diffraction.

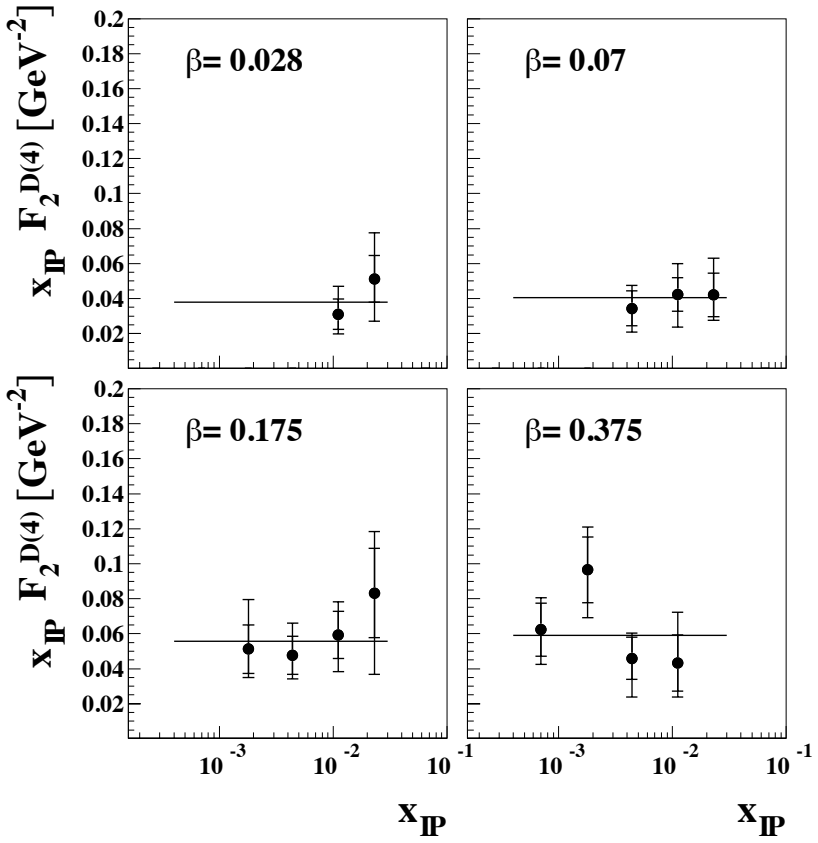
The "Diffractive" Structure Function $F_2^{D(4)}$

Define a structure function $F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t)$:

$$\frac{\mathrm{d}\sigma^{ep\to eXp}}{\mathrm{d}\beta\,\mathrm{d}Q^2\,\mathrm{d}x_{I\!P}\,\mathrm{d}t} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2[1+R^{D(4)}]}\right) F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t)$$

All analyses assume $R^{D(4)} = 0$

ZEUS 1994



From Direct Proton tagging

$\langle Q^2 \rangle = 8$ GeV^2

$\langle t \rangle = -0.17$ GeV^2

Fit to $F_2^D(4)(\beta, Q^2, x_{I\!P}, t) = A(\beta)\,(1/x_{I\!P})^a$ ...

$a = 1.00 \pm 0.09$ (stat.) $^{+0.11}_{-0.05}$ (syst.)

as expected for diffractive exchange with $\alpha_{I\!P} \sim 1$

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

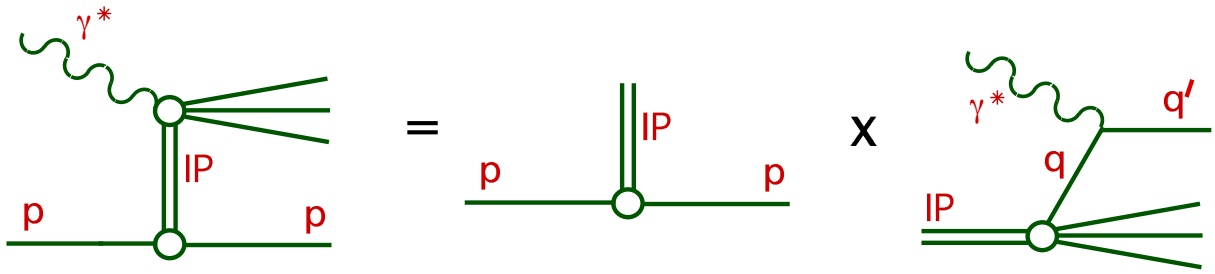
The final state proton or its excitation is not measured in Rapidity gap based analyses.

H1 measure $F_2^{D(3)}(\beta, Q^2, x_{I\!P})$, where:

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

with $-1 < t < t_{min}(x_{I\!P})$ and $M_Y < 1.6$ GeV.

Regge theory gives us a means of factorising the long distance physics at the proton vertex from the short distance physics at the photon vertex:

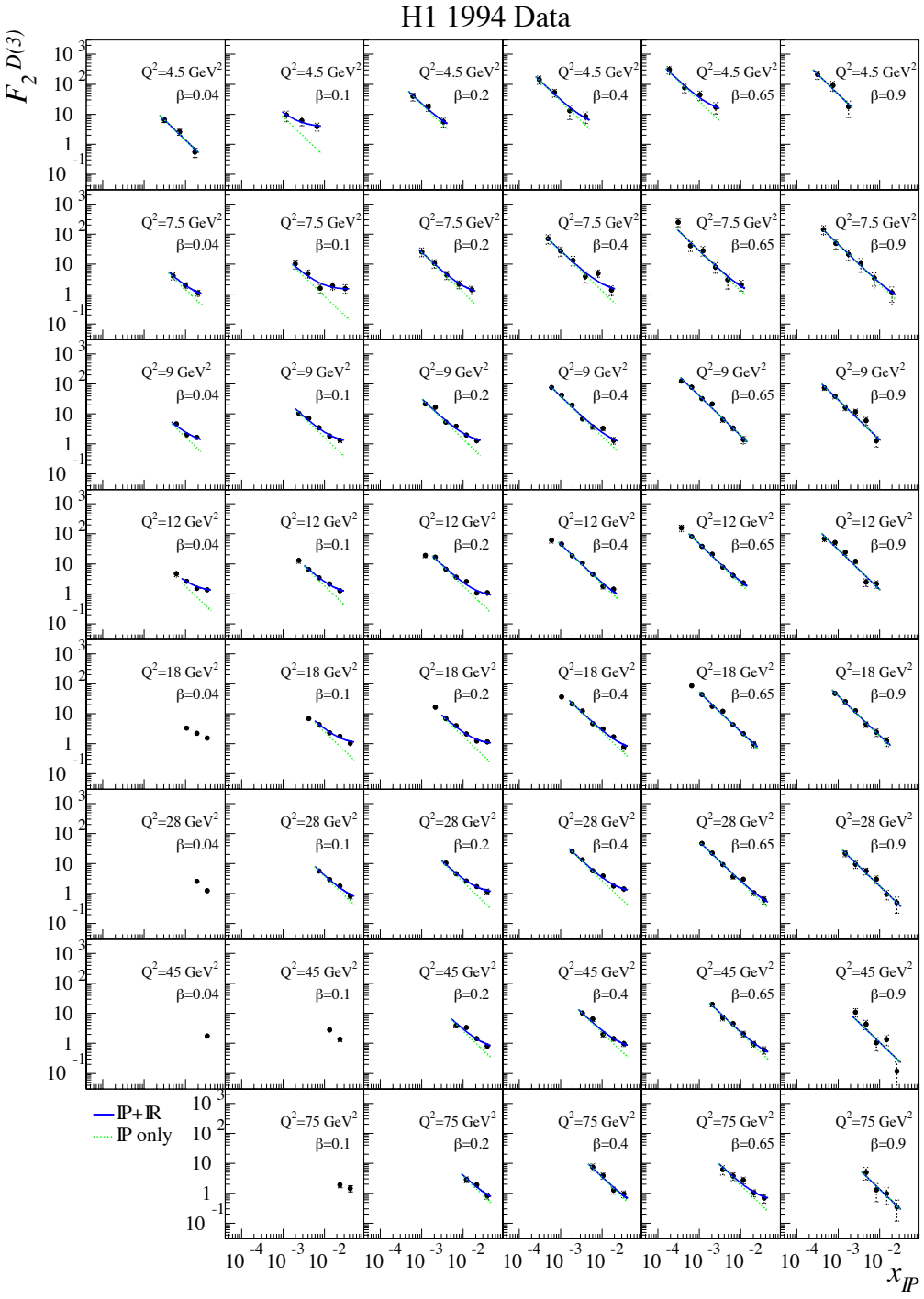


$$F_2^{D(3)}(\beta, Q^2, x_{I\!P}) \quad \propto \quad f_{I\!P/\mathrm{p}}(x_{I\!P}) \quad \times \quad F_2^{I\!P}(\beta, Q^2)$$

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

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

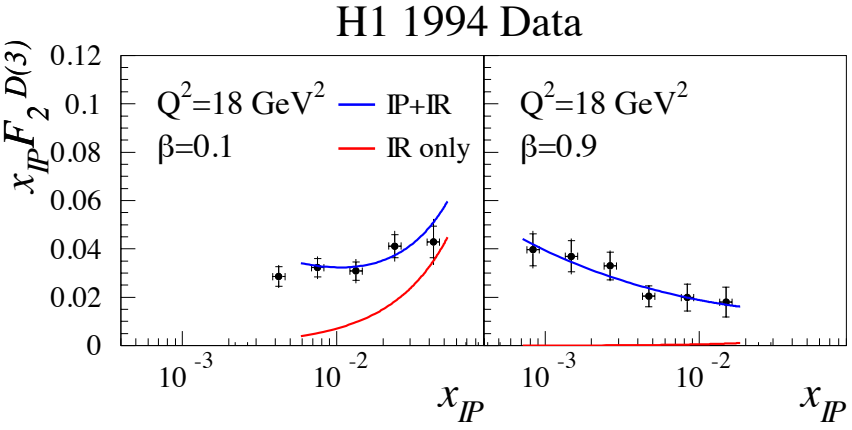
$F_2^{D(3)}$ with Phenomenological Regge Fit.



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

Phenomenological fits to H1 Data

$x_{I\!P}$ dependence is found to vary with β and Q^2 ...



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

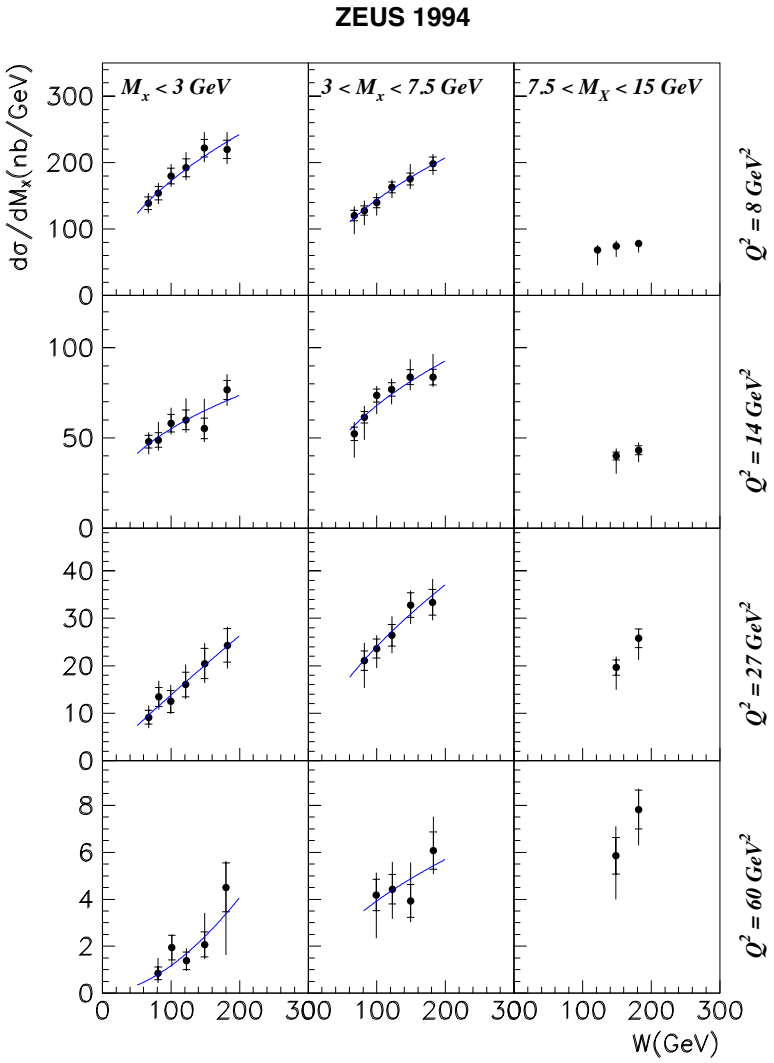
Good fits obtained throughout kinematic range using:

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

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

M_X Subtraction Method

After subtracting exponentially rising M_X distribution, ZEUS measure $\mathrm{d}\sigma_D^{ep\to eXY}/\mathrm{d}M_X$ $(M_Y < 4$ GeV)



Fit to Regge motivated form,

$$\frac{\mathrm{d}\sigma_D^{ep\to eXY}}{\mathrm{d}M_X}(M_X, W, Q^2) \propto \left(W^2\right)^{2\,\overline{\alpha_{I\!P}}-2}$$

where $\overline{\alpha_{I\!P}}$ is t averaged value of trajectory.

The pomeron intercept and Q^2

From H1 Phenomenological fits:

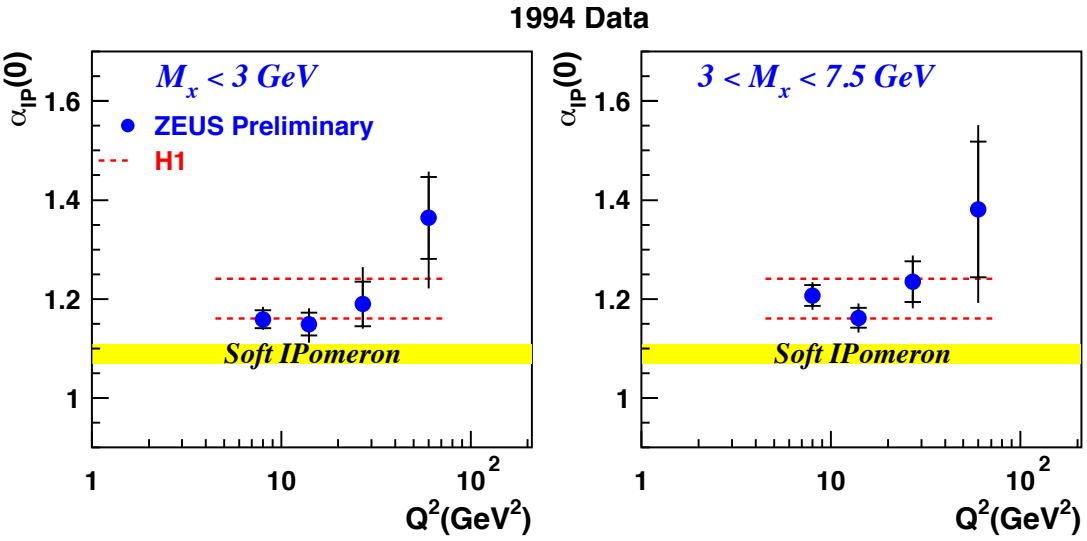
$\alpha_{I\!P}(0) = 1.203 \pm 0.020\ (\text{stat.}) \pm 0.013\ (\text{syst.})\ ^{+0.030}_{-0.035}(\text{model})$

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

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

Consistent with f, ω, ρ or a exchange.

Comparison of H1 and ZEUS results:



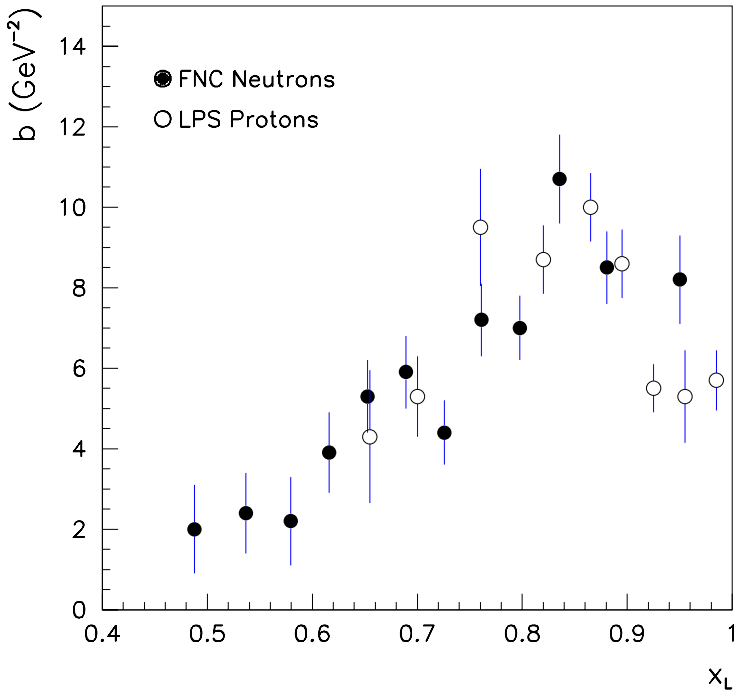
ZEUS data corrected by 0.03 from $\overline{\alpha_{I\!P}}$ to $\alpha_{I\!P}(0)$

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

Extending the $x_{I\!P}$ Range

Direct p-tagging detectors sensitive for $x_{\rm L} \gtrsim 0.6$.
Leading neutron calorimeters allow separation of isospin exchanging trajectories.
...Study the sub-leading exchanges.

ZEUS fits of $\mathrm{d}\sigma/\mathrm{d}t \propto e^{bt}$ in $x_{\rm L}$ bins.



$\leftarrow \pi$

$\leftarrow I\!P$

Strong dependence of t slope on $x_{\rm L}$.

Generated by a complicated mixture of $I\!P$, $I\!R$, π exchange with shrinkage effects and proton dissociation?

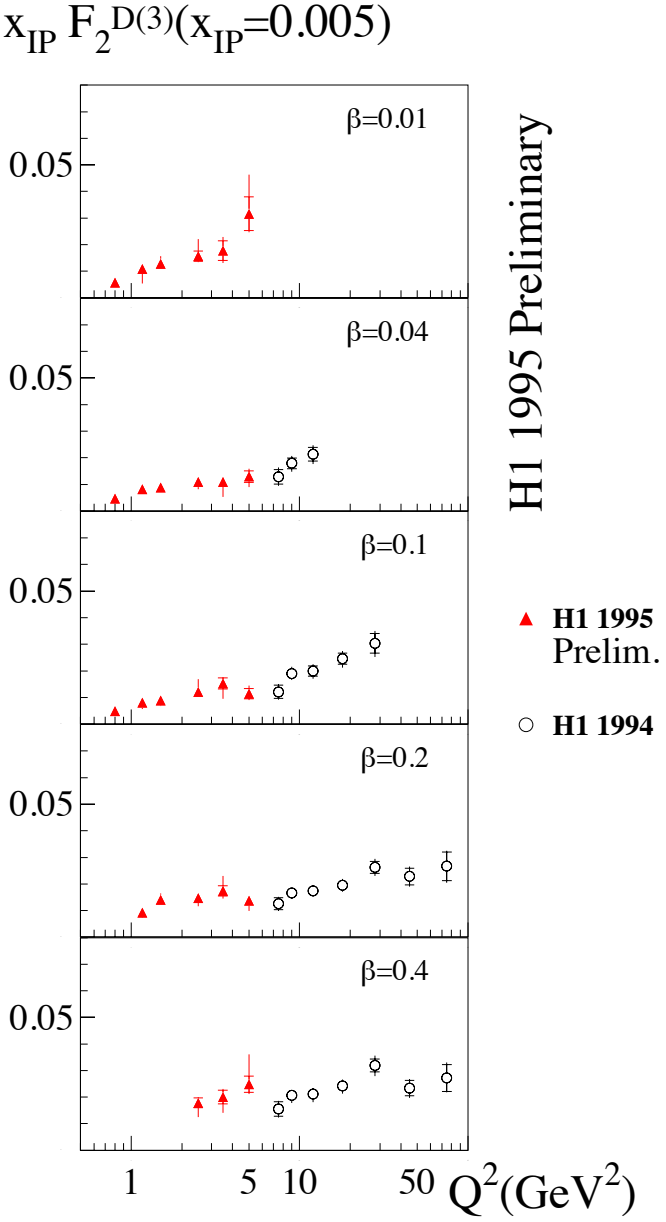
p, n similar for $x_{\rm L} \lesssim 0.9$.

For $0.75 \lesssim x_{\rm L} \lesssim 0.9$ consistent with expectation for π.

Similar conclusions in other studies. $\rightarrow$ work ongoing.

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

$F_2^D(3)$ $(\beta, Q^2, x_{I\!P} = 0.005)$ is closely related to $F_2^{I\!P}(\beta, Q^2)$



Measurement extended to $Q^2 = 0.8$ GeV^2

Rising scaling violations persist to $\beta \geq 0.4$

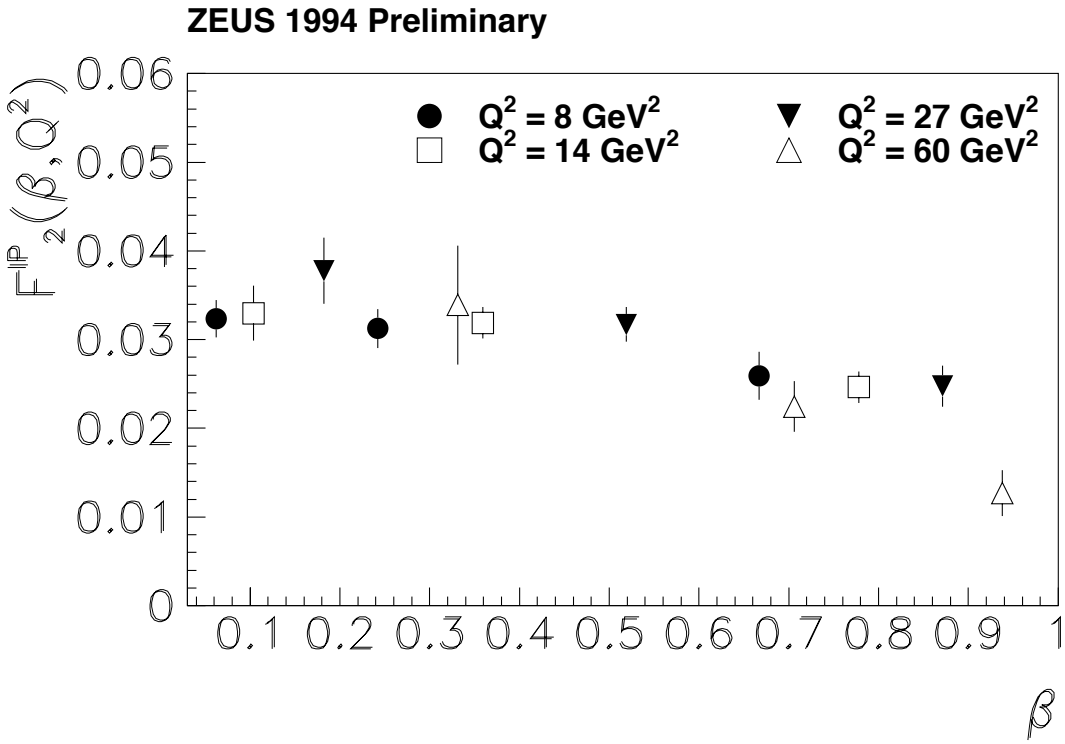
...Highly suggestive that gluons play a major role.

β dependence of $F_2^{D(3)}$

β dependence of

$$F_2^{D(2)}(\beta, Q^2) \propto F_2^{D(3)}(\beta, Q^2, x_{I\!P} = 0.0042)$$

extracted from ZEUS mass subtraction analysis.



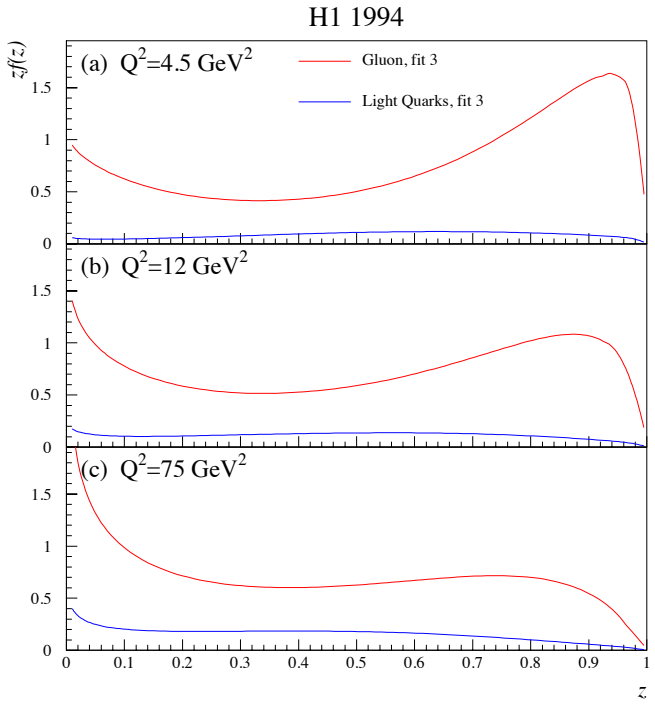
$I\!P$ structure function approximately flat in β throughout measured range.

Contrasts sharply with hadron structure functions.

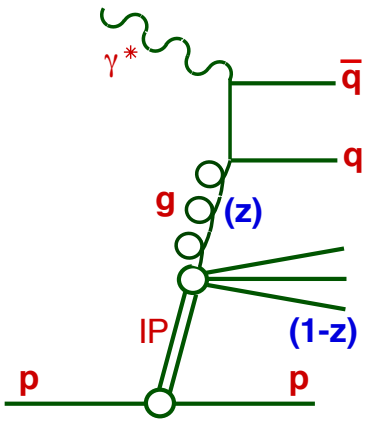
DGLAP Fits to $F_2^{D(3)}$

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.

Complications: DGLAP applicability? $F_{\rm L}^D$? higher twist?

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

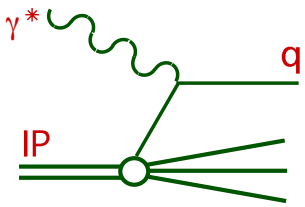
Many hadronic final state observables are sensitive to the QCD Structure of Diffraction

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

All consistent with a dominant $\gamma^* g \to q\bar{q}$ + low p_T process

$\mathcal{O}(\alpha)$

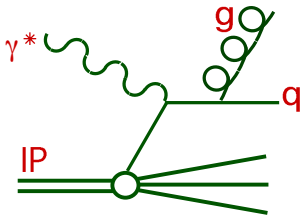
QPM

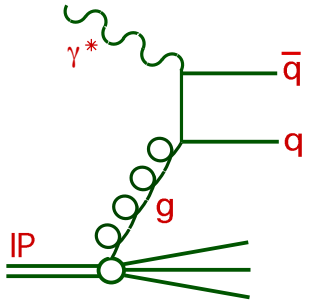


$\mathcal{O}(\alpha\ \alpha_s)$

QCD-C

BGF





↑

Quark induced

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

Low p_T

Aligned

↑

Gluon induced

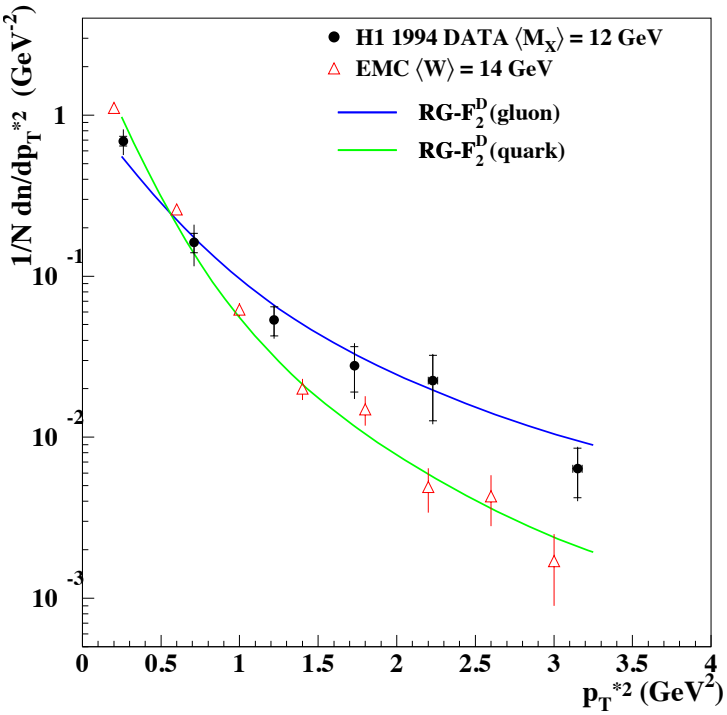
$\sim 8_c 8_c$

High p_T

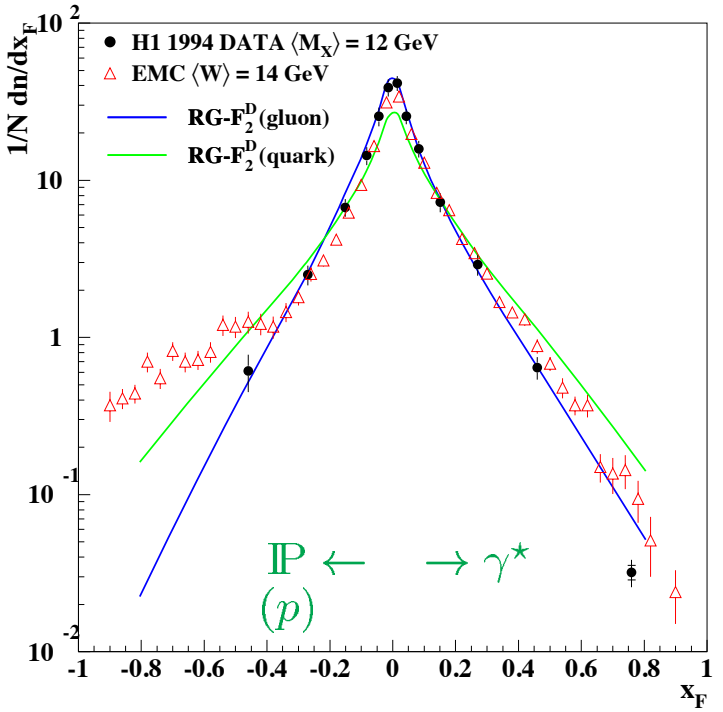
Non-aligned

Charged Particle Spectra

$p_T^\star$, $x_{\rm F}$ measured relative to $\gamma^\star$ axis in rest frame of X



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



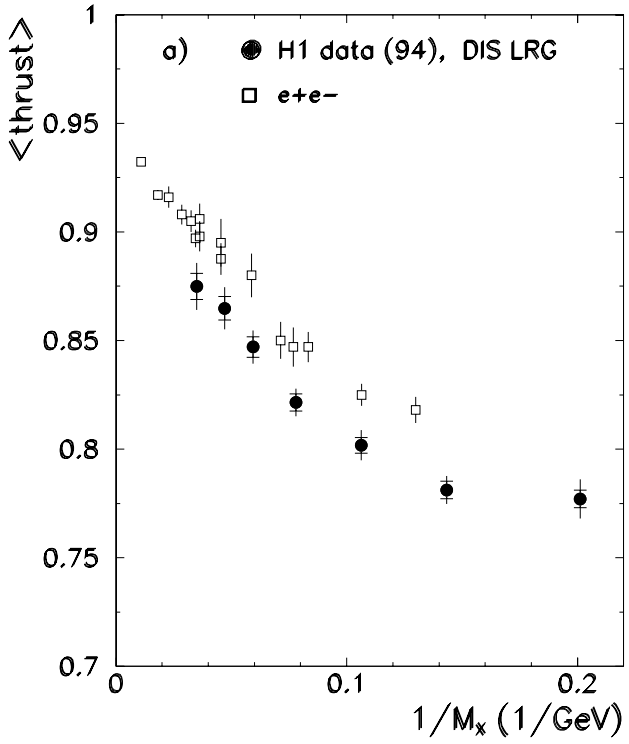
$x_{\rm F} = 2p_{\rm L}^\star / M_X$

Symmetry between forward and backward hemispheres.

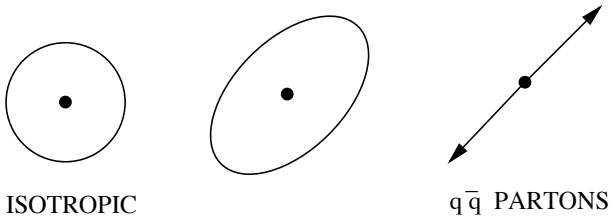
No extended 'pomeron remnant'.

Jet Structure

Thrust - measure of '2-jettiness'

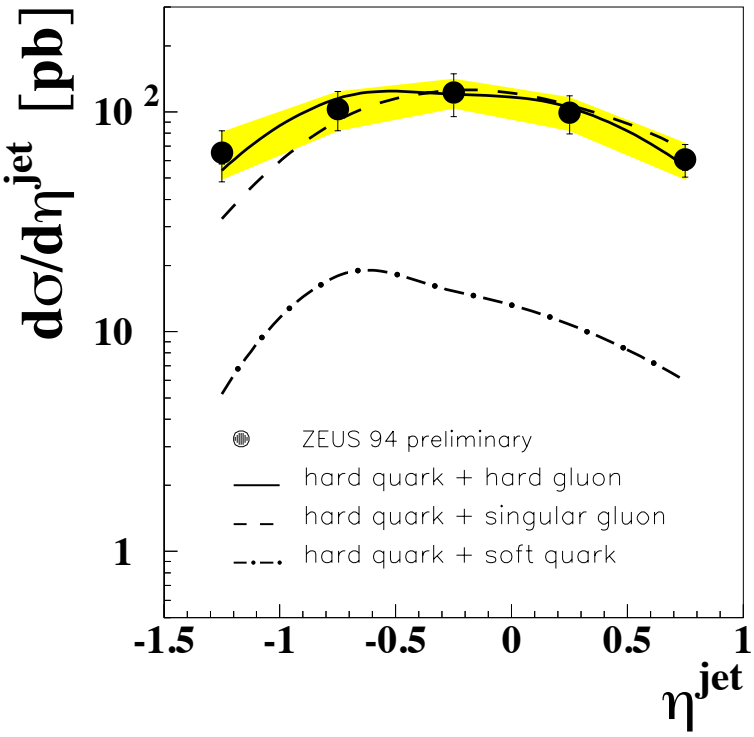


$$1/2 < T < 1$$



Gluons required to generate lower thrust than $q\bar{q}$.
Hadronisation effects decrease thrust at low M_X.

Dijet Photoproduction



Combined fit to $F_2^{D(3)}$ and γp jet rate

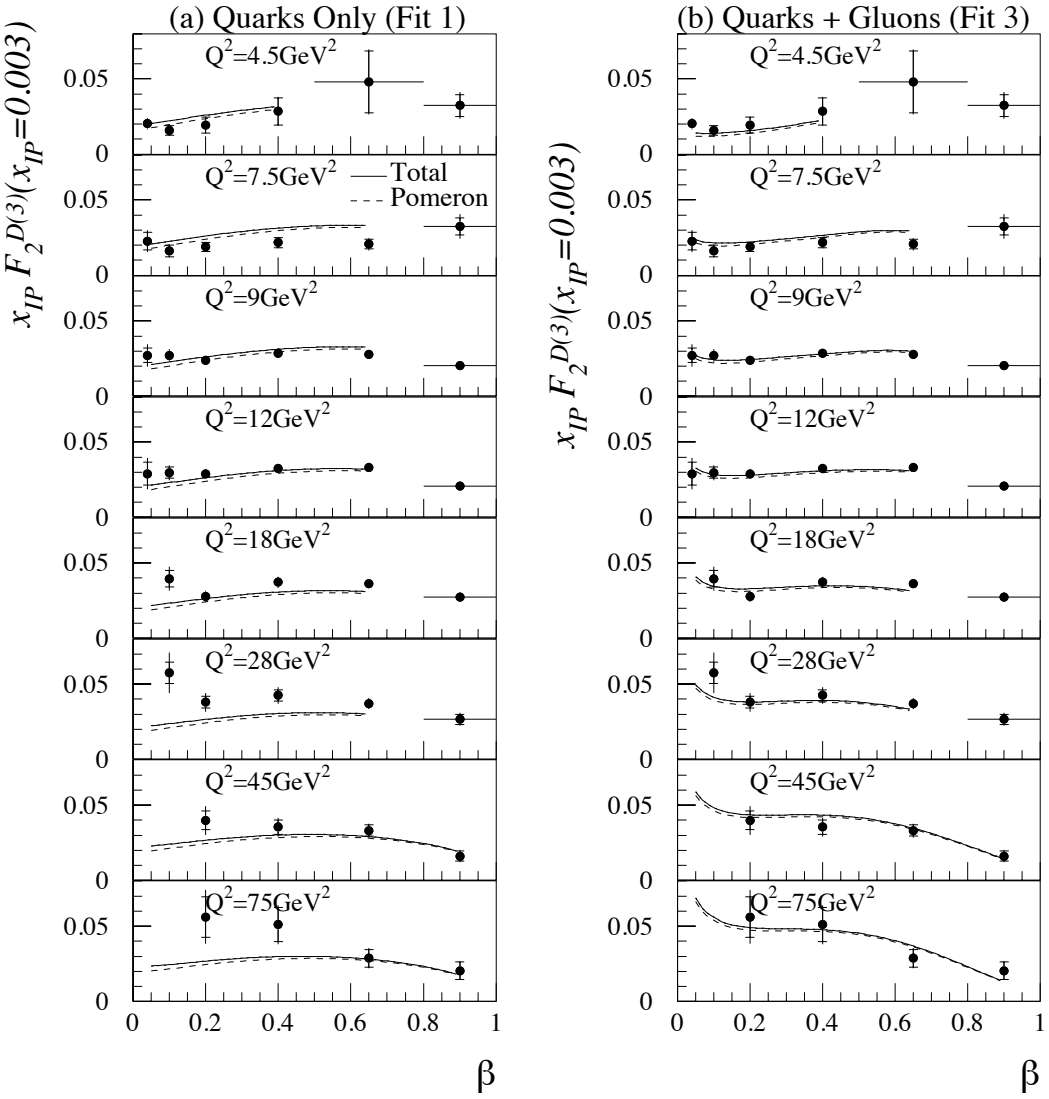
$\mathbb{P}$ pdf's at scale Q for F_2^D, scale E_t for jets.

Simultaneous description when $\mathbb{P}$ is $\sim 90\%$ hard gluons

Diffractive factorisation approximately obeyed.

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.
- The diffractive exchange is dominated by 'hard' gluons ($\sim 80-90\%$ for $4.5 < Q^2 < 75$ GeV^2).
- Hadronic final state analyses all indicate a dominant $\gamma^\star g \to q\bar{q}$ + low p_T process.
- A complicated mixture of meson exchanges is present at larger $x_{\mathbb{P}}$.

β dependence of $F_2^{D(3)}$

H1 1994