Inclusive and Semi-Inclusive Cross-Sections at low x at HERA

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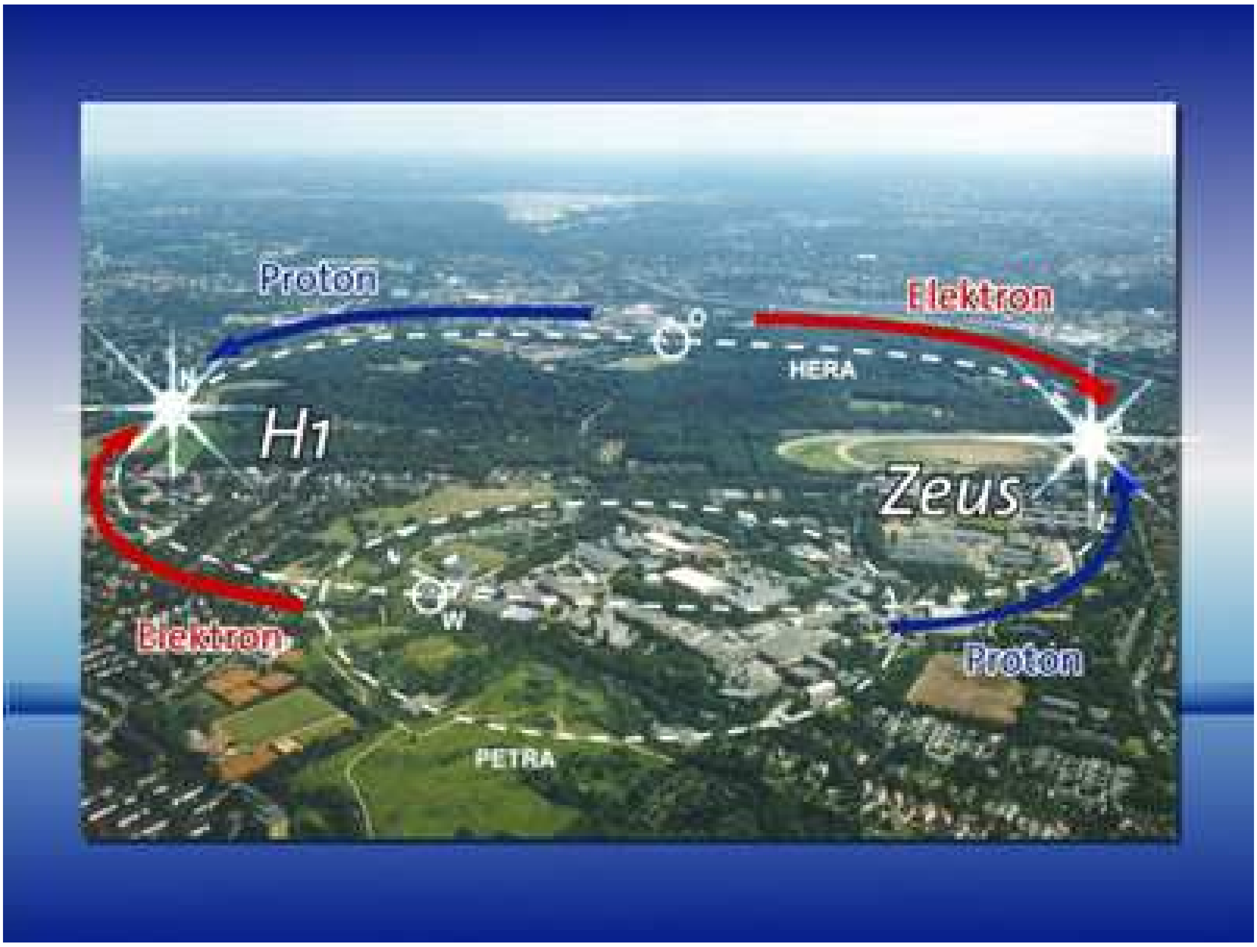
- Introduction to HERA.
- Deep Inelastic Scattering at Low x
- Diffractive DIS
- QCD Description / Diffractive Parton Densities
- Energy Dependence / effective $\alpha_{\mathbb{P}}(0)$
- Relation to hard diffraction in $p\bar{p}$ Scattering
- Dipole Models
- Future Prospects

The HERA ep Collider



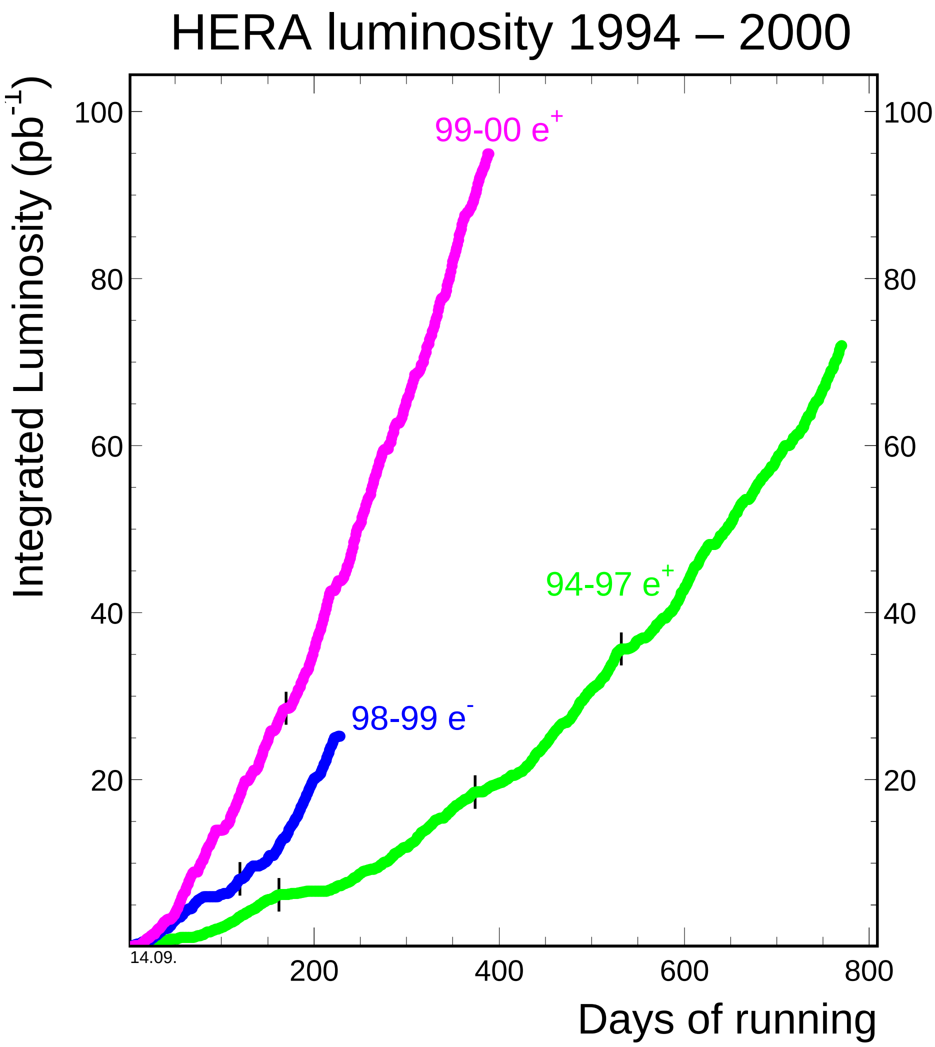
$$e^{\pm} \Longrightarrow \quad \Longleftarrow p$$

$\mathbf{27.6}$ **GeV** $820 - 920$ **GeV**

$$\sqrt{s_{ep}} \approx \mathbf{300 - 319}\ \textbf{GeV}$$

2 Collider Experiments: H1 and ZEUS

HERA Luminosity and Status



Steady improvement in machine performance.

Design performance exceeded in 2000!

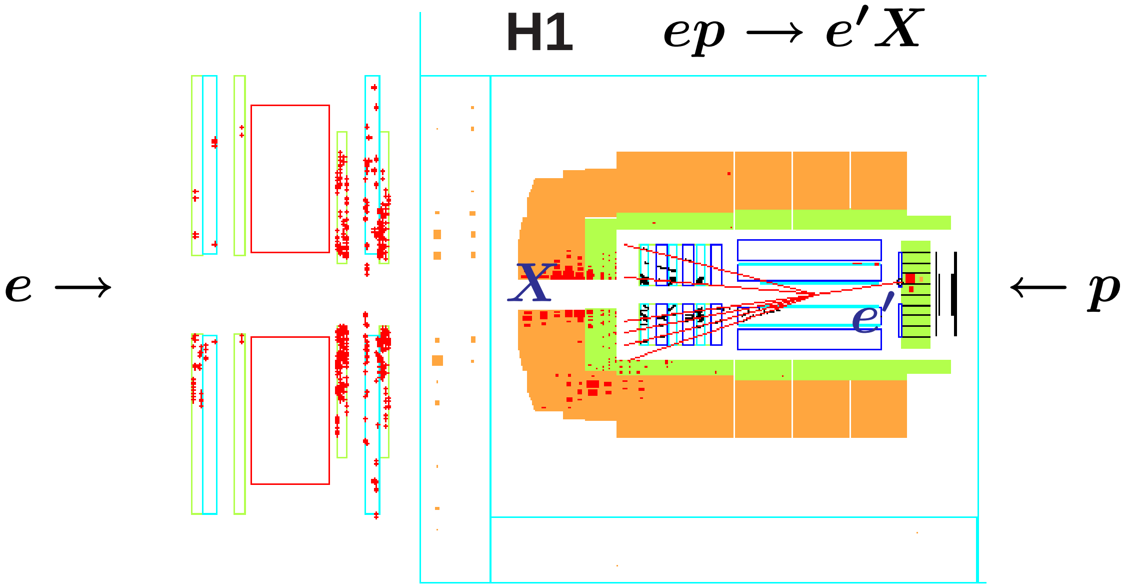
H1 / ZEUS full datasets $> 120\,\mathrm{pb}^{-1}$ for analysis

Luminosity upgrade mid 2000 - end 2001

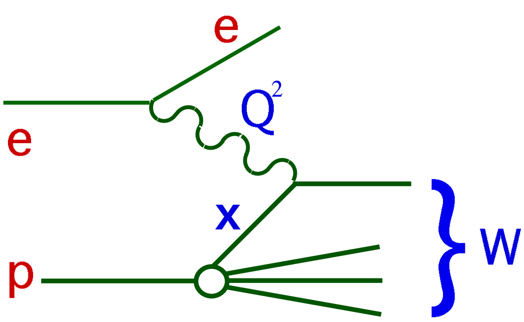
Factor 5 increase in luminosity expected $\rightarrow 240\,\mathrm{pb}^{-1}/\mathrm{yr}$

Recommissioning in progress

Deep Inelastic Scattering at HERA



Kinematic variables . . .



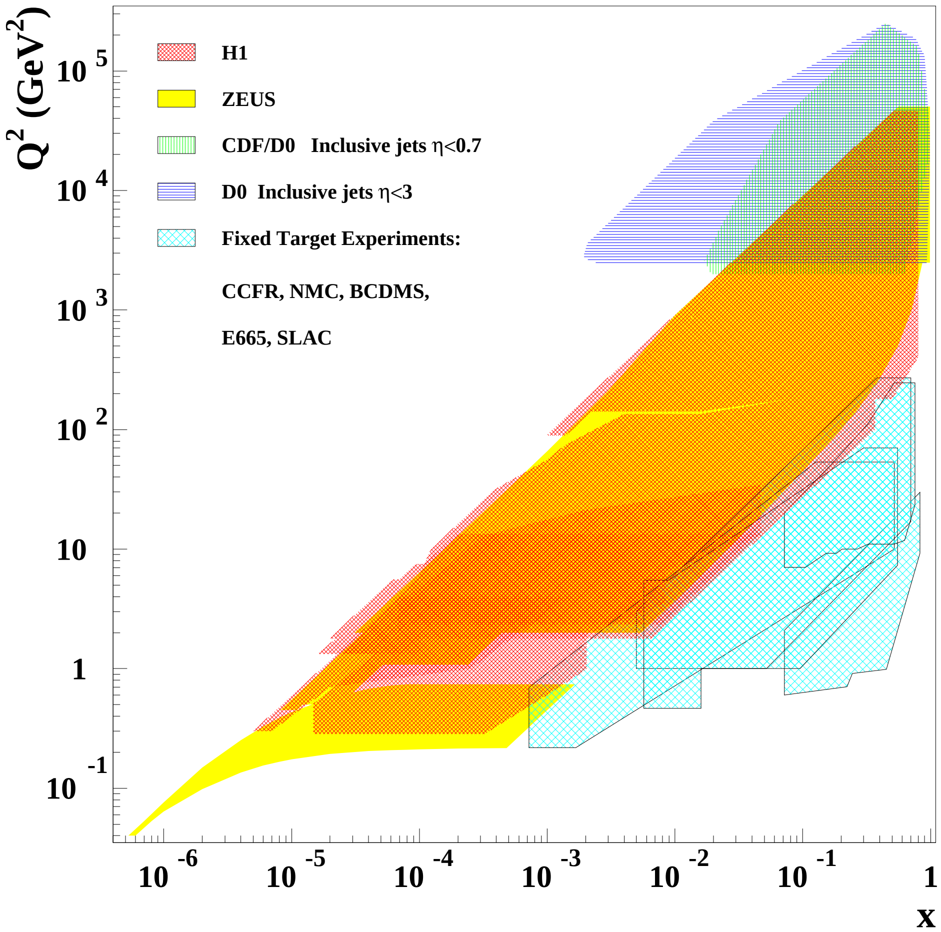
Q^2, photon virtuality

$x = x_{(q/p)}$

$W^2 \sim Q^2/x$, $\gamma^* p$ CMS energy

Ideal facility to study strong interactions at high energy

Kinematic Range



$\rightarrow x < 10^{-5}$ $\rightarrow Q^2 > 10000\ \mathrm{GeV}^2$ $W \rightarrow 300\ \mathrm{GeV}$

Overlap with fixed target experiements at high x, low Q^2

Overlap with Tevatron at high x, high Q^2

Structure Functions

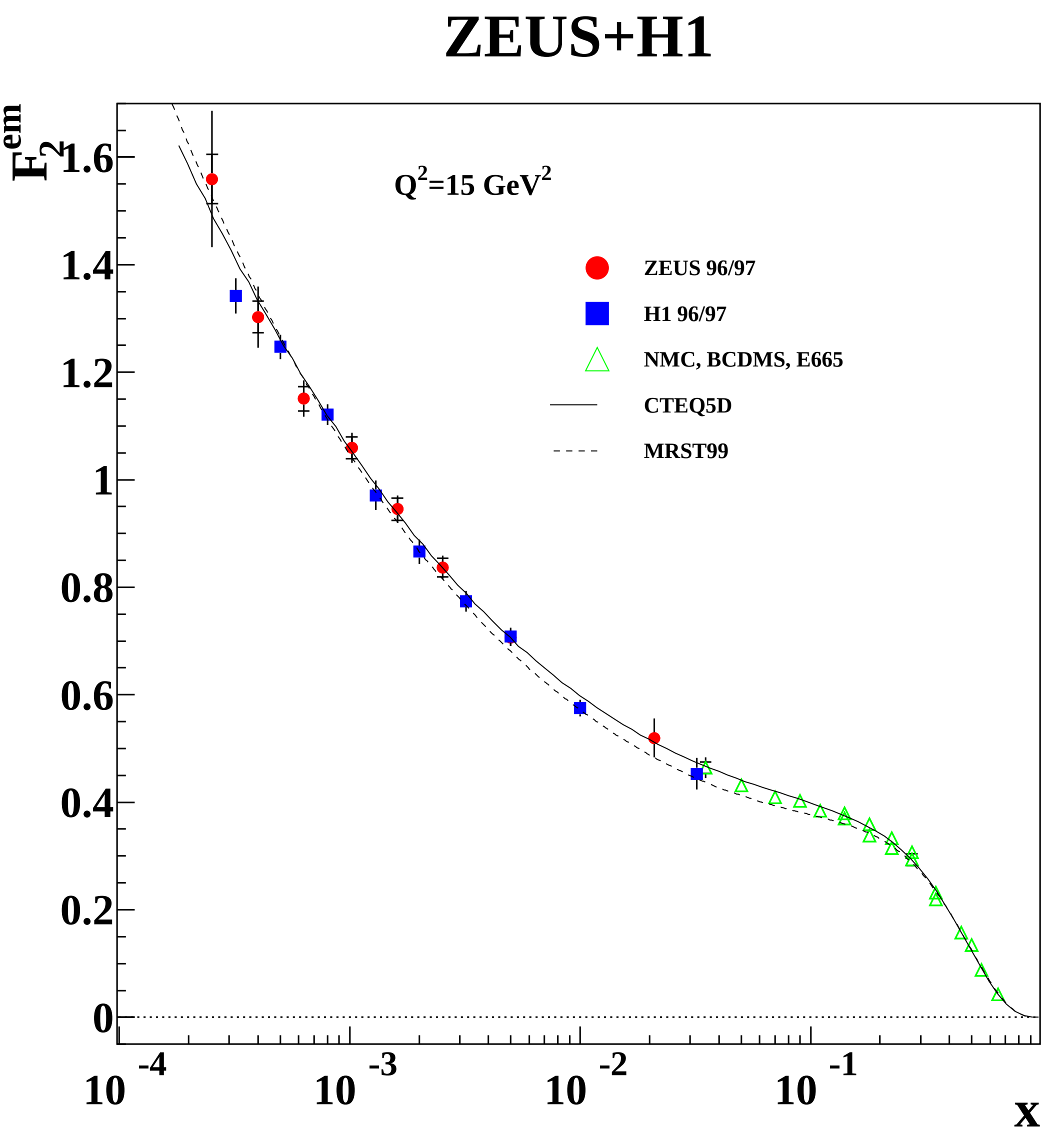
Unpolarised DIS cross sections discussed in terms of Structure Functions F_2, F_L, xF_3

$$\frac{d^2\sigma^\pm}{dx\ dQ^2} \simeq \frac{2\pi\alpha^2}{xQ^4}(Y_+F_2 \mp Y_-xF_3 - y^2F_L)$$

$$[\ Y_\pm = 1 \pm (1-y)^2 \quad ; \quad y = Q^2/s_{ep}x\ ]$$

$F_2 \sim q + \bar{q}$ (dominant in most of HERA phase space.)

[$xF_3 \sim q - \bar{q} \sim$ valence. $F_L \sim$ gluon]



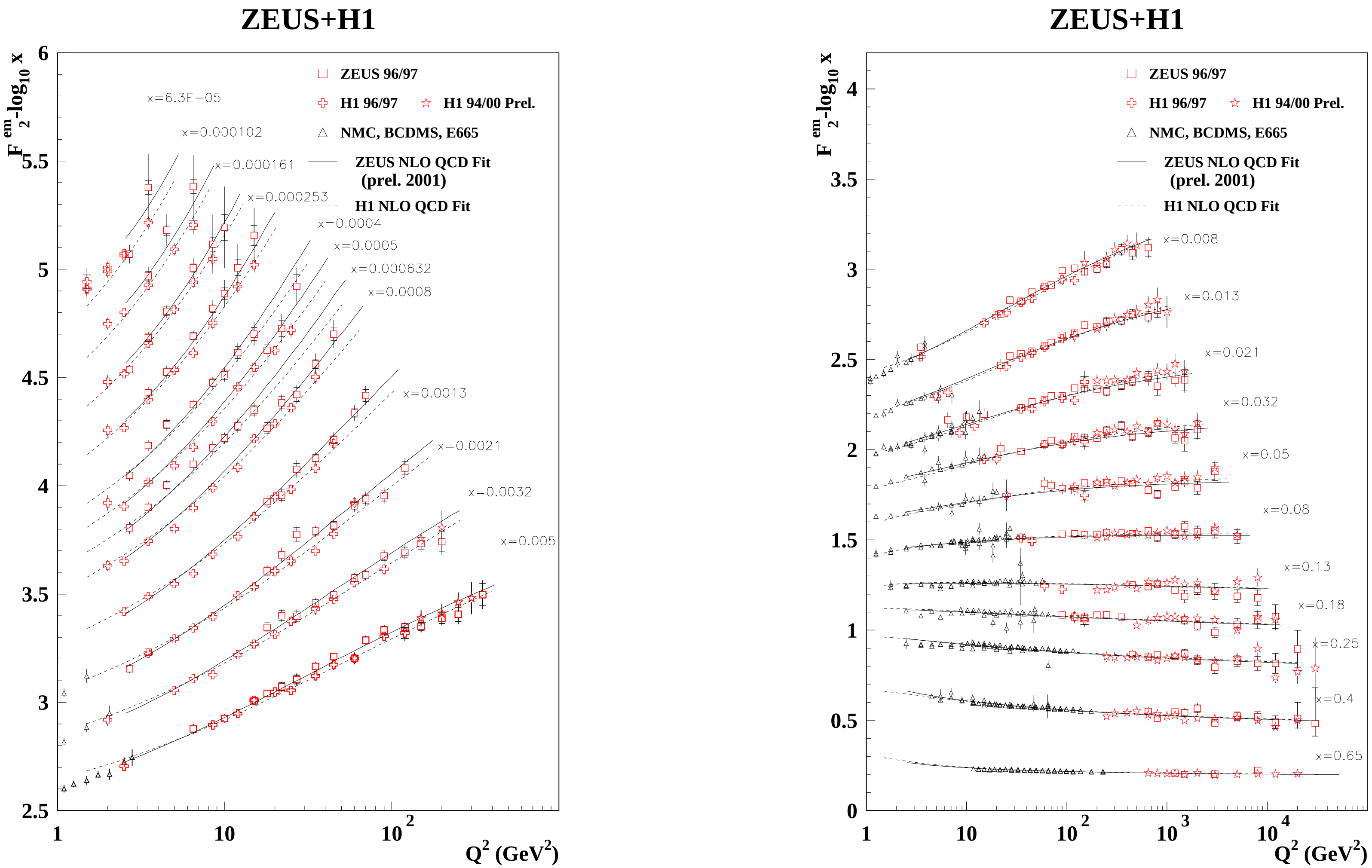
High Precision F_2

1% (stat) $\oplus$ 3% (syst)

Good agreement between ZEUS, H1 and fixed target experiments.

Strong rise $\longrightarrow$ low x

Scaling Violations of F_2



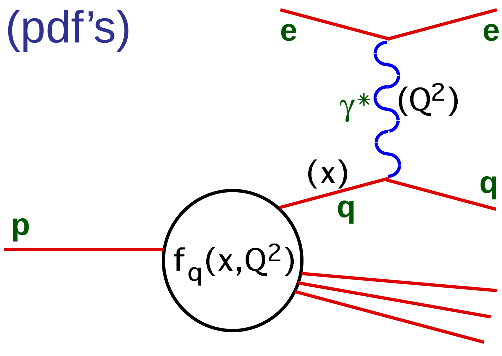
Scaling violations due to gluon radiation.

DIS and Perturbative QCD

QCD Hard Scattering Factorisation:

$\longrightarrow$ Non-perturbative aspects / divergencies

factorise into universal Parton Densities (pdf's)



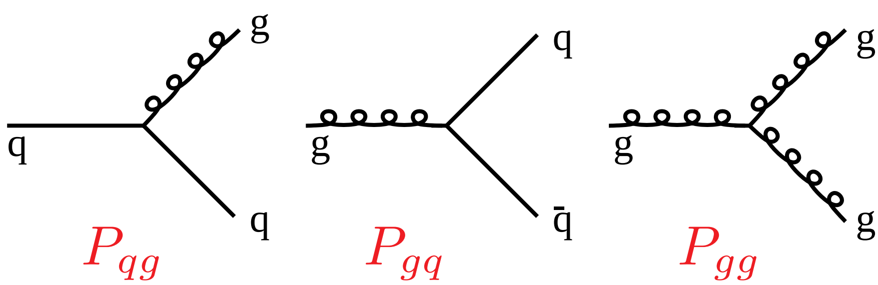
$$\sigma_{\rm DIS} \sim f_q(x,Q^2) \otimes \hat{\sigma}_{\rm pQCD}$$

pdf's inherrently non perturbative

x dependence not known a priori

DGLAP equations predict Q^2 evolution via splitting functions

$$\frac{\partial f_q}{\partial \ln Q^2} \sim f_q \otimes P$$



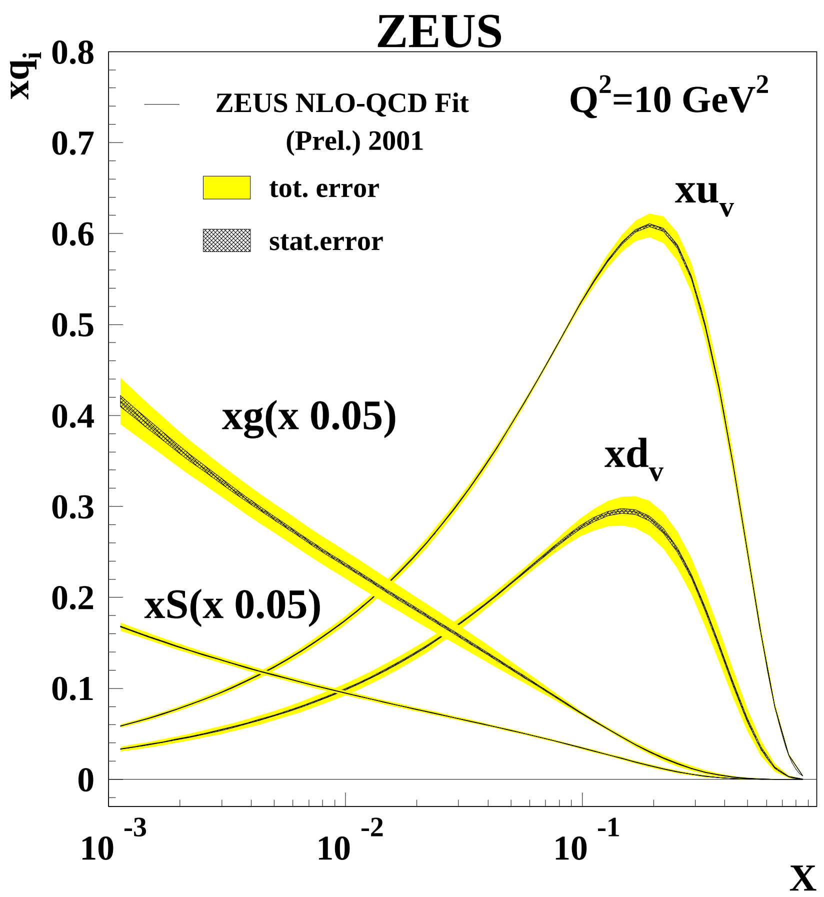
$$F_2 \sim x[q(x) + \bar{q}(x)] \qquad\qquad \frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s x g(x)$$

$\longrightarrow$ DGLAP fits to F_2 data yield pdf's and α_s

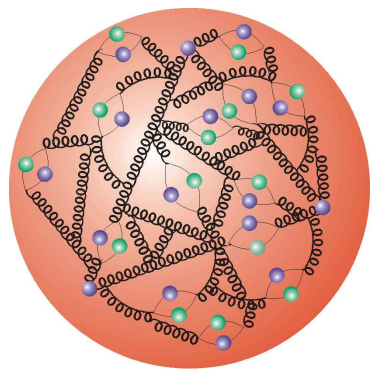
Example Parton Densities

DGLAP fits at NLO by many authors

pdf's determined with full treatment of errors and correlations!



Gluon heavily dominant at low x



QCD at very high parton densities!

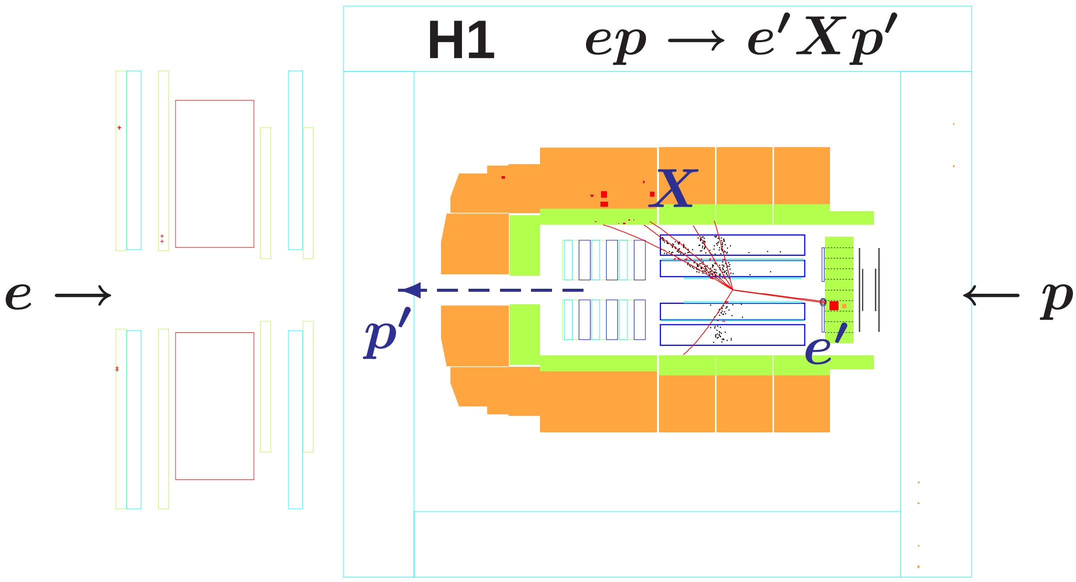
High precision α_s. e.g. H1 NLO:

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0017\,(\mathrm{exp})\,{}^{+0.0009}_{-0.0005}\,(\mathrm{model})$$

Theoretical error (higher orders) ~ 0.005 dominates.

Diffractive DIS

Early result from HERA: $\sim 10\%$ of low x DIS events are of the type $ep \to eXp$



Can be viewed as a diffractive $\gamma^{(\star)}p$ interactions ...

Poses many interesting questions ...

- How is diffractive DIS related to inclusive DIS?

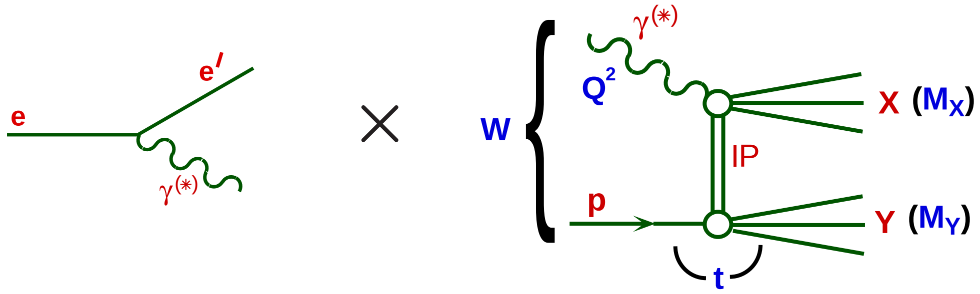
  $\to$ Partonic description?

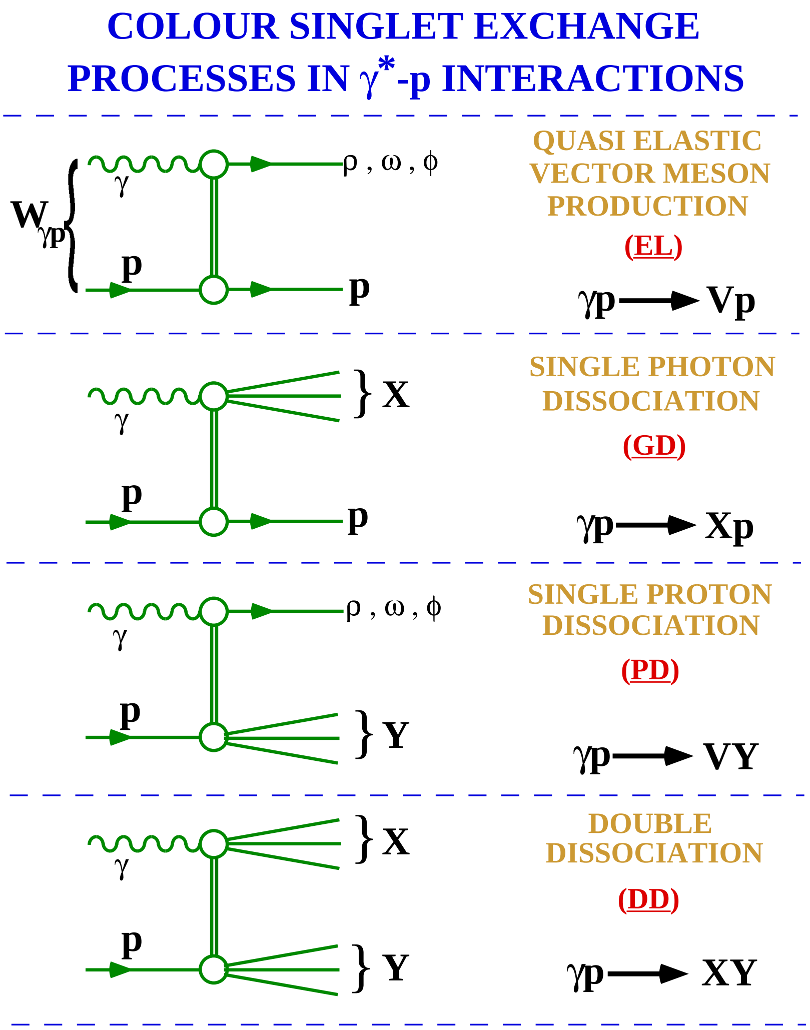
- How is diffr. DIS related to diffr. hadron-hadron scattering?

  $\to$ Effective Pomeron trajectory evaluation

Diffraction at HERA

More generally, diffractive process is $\gamma^{(*)}p \rightarrow XY \ldots$





All four processes can be measured with varying Q^2, W, t, M_X, M_Y

- $Q^2 \sim 0\ ,\ t \sim 0$

Similar to soft hadronic diffraction.

- Large $|t|$

pQCD calculation of $\mathbb{P}$?

- Large Q^2

pQCD at $\gamma^* \mathbb{P}$ vertex

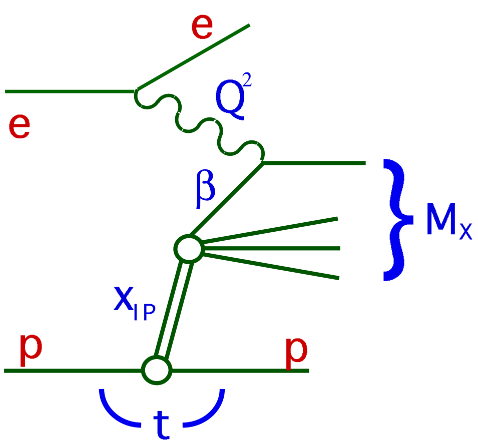
γ^* 'probes' $\mathbb{P}$?

~ 60 H1 / ZEUS publications on diffraction so far!

This talk mostly concerned with $\gamma^\star p \rightarrow Xp$, large Q^2, small $|t|$

$ep \longrightarrow eXp$ at HERA

Commonly used kinematic variables . . .



$$x_{I\!P} \equiv \xi = \frac{Q^2+M_X^2}{Q^2+W^2} = x_{(\mathrm{I\!P}/\mathrm{p})}$$

$$\beta = \frac{Q^2}{Q^2+M_X^2} = x_{(q/\mathrm{I\!P})}$$

$$(x = x_{I\!P}\,\beta)$$

$$t = (p-p')^2$$

Often presented as a Diffractive Structure Function . . .

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

(Assumes $F_L^{D(4)} = 0$)

. . . or integrated over t

$$F_2^{D(3)}[\beta, Q^2, x_{I\!P}] = \frac{\beta\; Q^4}{4\pi\alpha^2\;(1-y+y^2/2)} \quad \frac{\mathrm{d}\sigma_{ep\to eXp}}{\mathrm{d}\beta\;\mathrm{d}Q^2\;\mathrm{d}x_{I\!P}}$$

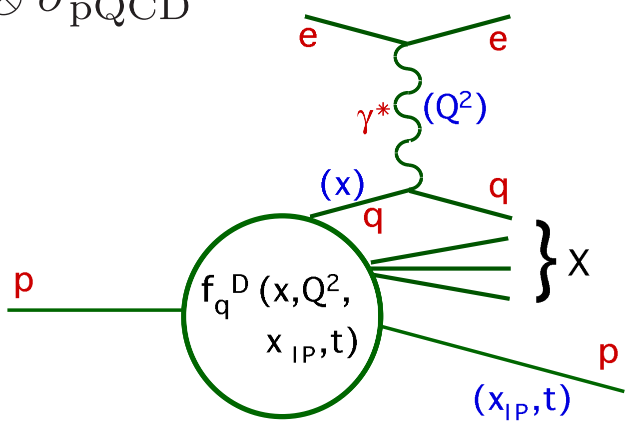
Factorisation Properties of F_2^D

QCD Hard Scattering Factorisation for Semi-Inclusive DIS:-

(Trentadue, Veneziano, Berera, Soper, Collins . . .)

Diffractive parton densities $f_q^D(x_{I\!P}, t, x, Q^2)$ express *conditional* proton parton probability distributions with constraint of final state proton at particular $x_{I\!P}, t \ldots$

$$\sigma_{\rm DIS}^{\rm Dif} \sim f_q^D(x_{I\!P}, t, x, Q^2) \otimes \hat{\sigma}_{\rm pQCD}$$



At fixed $x_{I\!P}, t$, $f_q^D(x_{I\!P}, t, x, Q^2)$ evolve with x, Q^2 according to same DGLAP equations as inclusive $f_q(x, Q^2)$

Framework exists to include higher order operators (Blümlein, Robaschik)

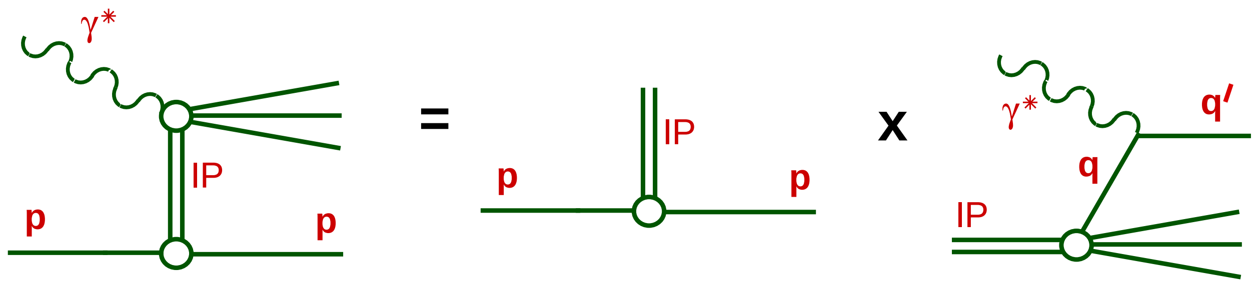
Diffractive pdf's universal within diffractive DIS.

QCD factorisation not proved for hadron-hadron diffraction . . . non-factorisable contributions identified.

Factorisation Properties of F_2^D

'Regge' Factorisation ("resolved $\mathbb{P}$ model"):-

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



$$\sigma_{\mathrm{DIS}}^{\mathrm{Dif}} \sim f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \otimes F_2^{\mathbb{P}}(\beta, Q^2)$$

$$\sim f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \otimes f_q^D(\beta, Q^2) \otimes \hat{\sigma}_{pQCD}$$

$\mathbb{P}$ flux factors $f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t)$ from Regge theory . . .

$f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) = \frac{e^{Bt}}{x_{\mathbb{P}}^{2\alpha(t)-1}}$ where . . . $\alpha(t) = \alpha(0) + \alpha' t$

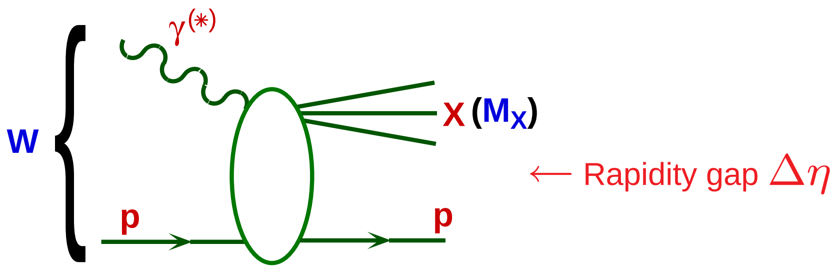
Diffractive DIS probes the $\mathbb{P}$ of hadron-hadron scattering?

NB - No firm basis in QCD!

Experimental Techniques

Two complementary measurement techniques ...

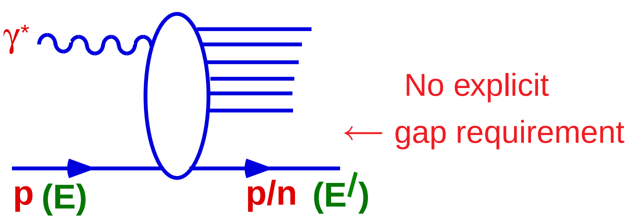
1) Measure Hadrons Comprising X



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

- Ample statistics!
- Large systematics from unseen proton - elastic or dissoc'?
- t measurements not generally possible.
- Becoming harder to trigger

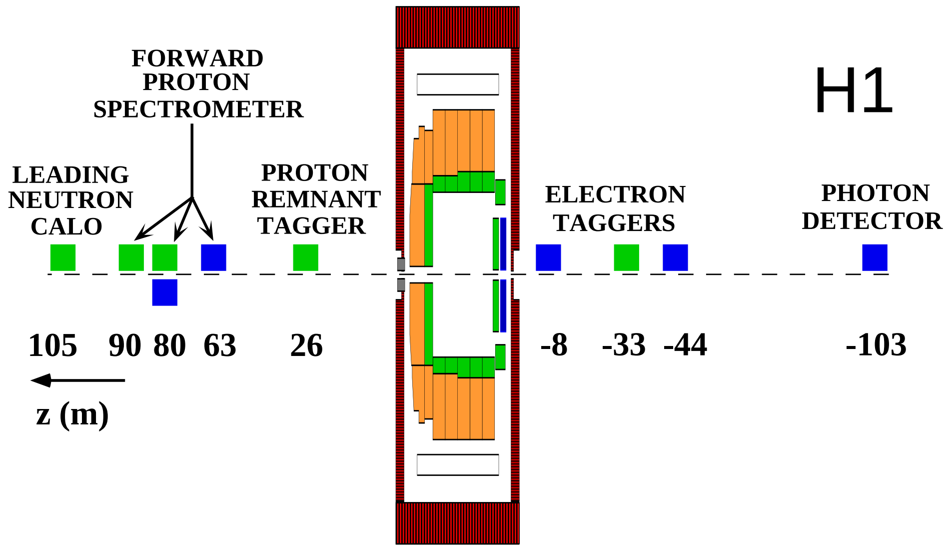
2) Tag and measure Leading Proton in Dedicated Detectors

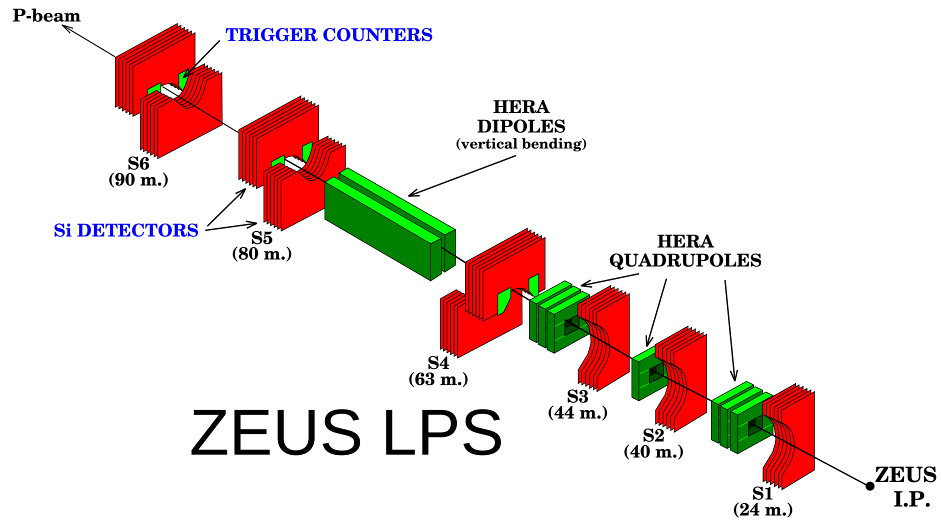


$x_{I\!P} = E'/E$ if exclusive p at proton vertex.

- t measurements possible.
- Systematics can be reduced.
- Detector acceptance can be poor. $\longrightarrow$ limited stats so far.

BEAM-LINE INSTRUMENTATION





Both experiments have forward proton and neutron detectors

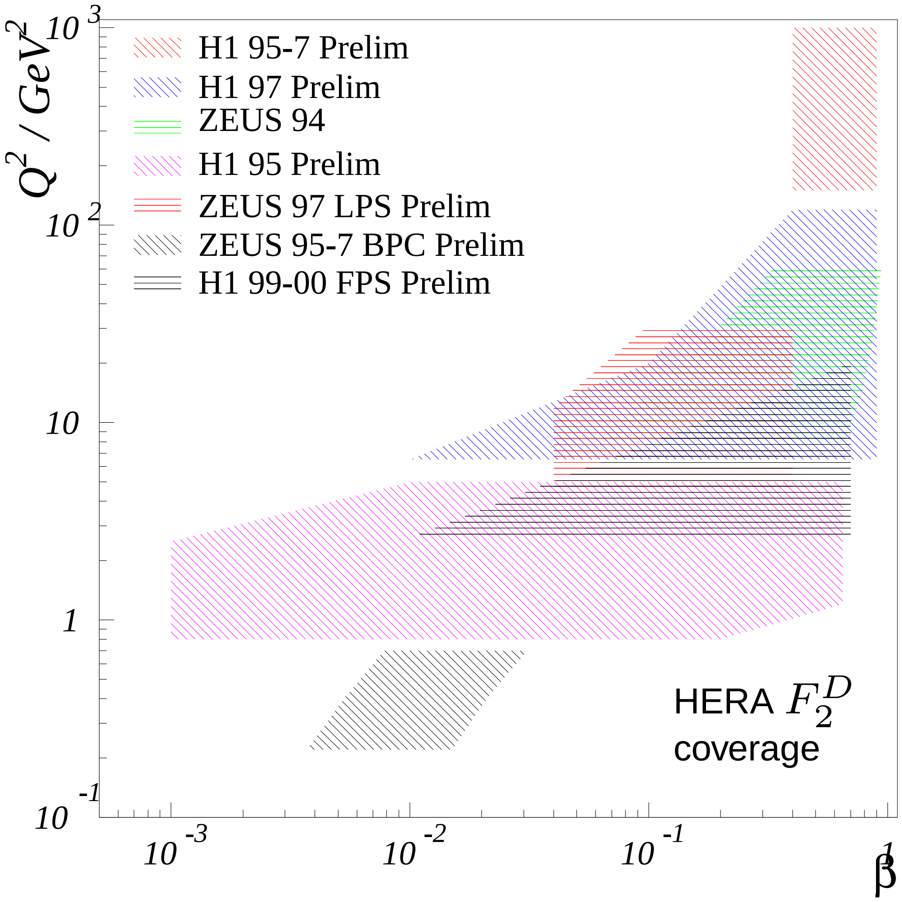
For protons:

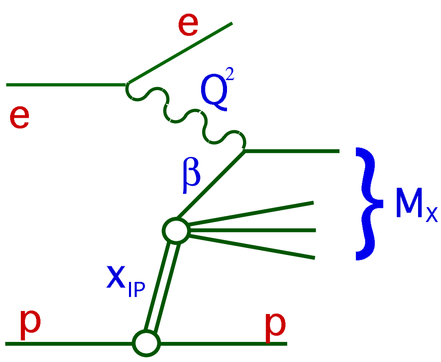
ZEUS: 6 silicon strip stations 24-90 m downstream

H1: 4 scintillating fibre hodoscope stations 63-90 m downstream

H1 upgrade: High acceptance VFPS planned around 200 m downstream

Diffractive DIS Kinematic Plane





Increasingly precise data spanning wide range in β, Q^2 with $x_{I\!P} < 0.05$

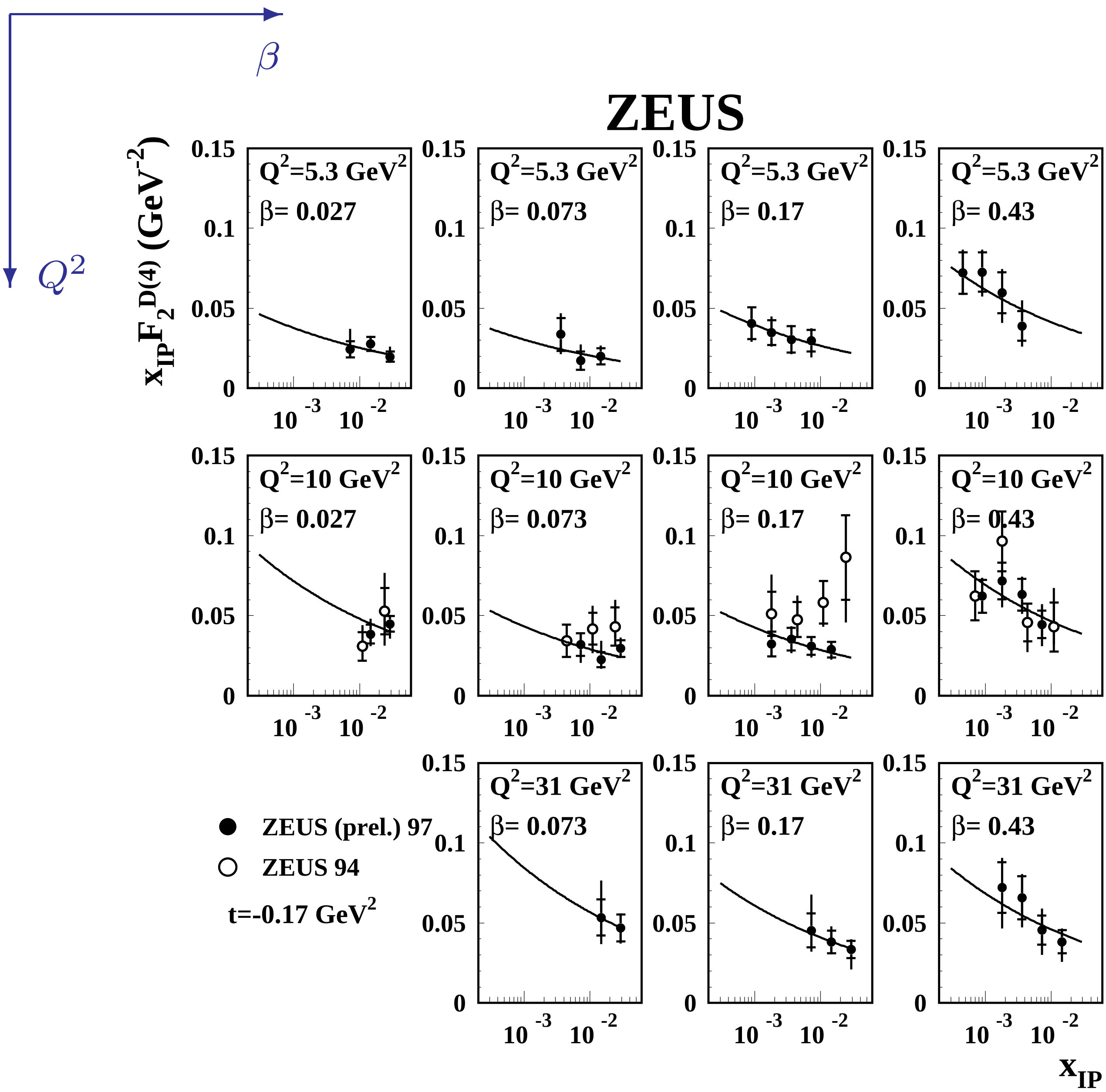
Several new H1 / ZEUS preliminary measurements released during 2001

... New generation of F_2^D measurements

ZEUS LPS $F_2^{D(4)}$ Data

Leading proton data allow 4-fold differential cross sections

$\rightarrow F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t)$



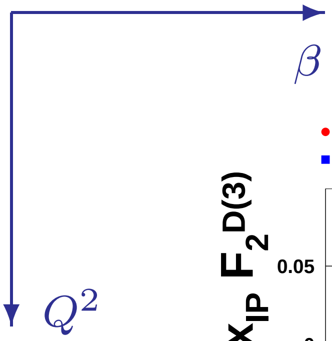
New ZEUS '97 LPS data give factor 6 increase in statistics

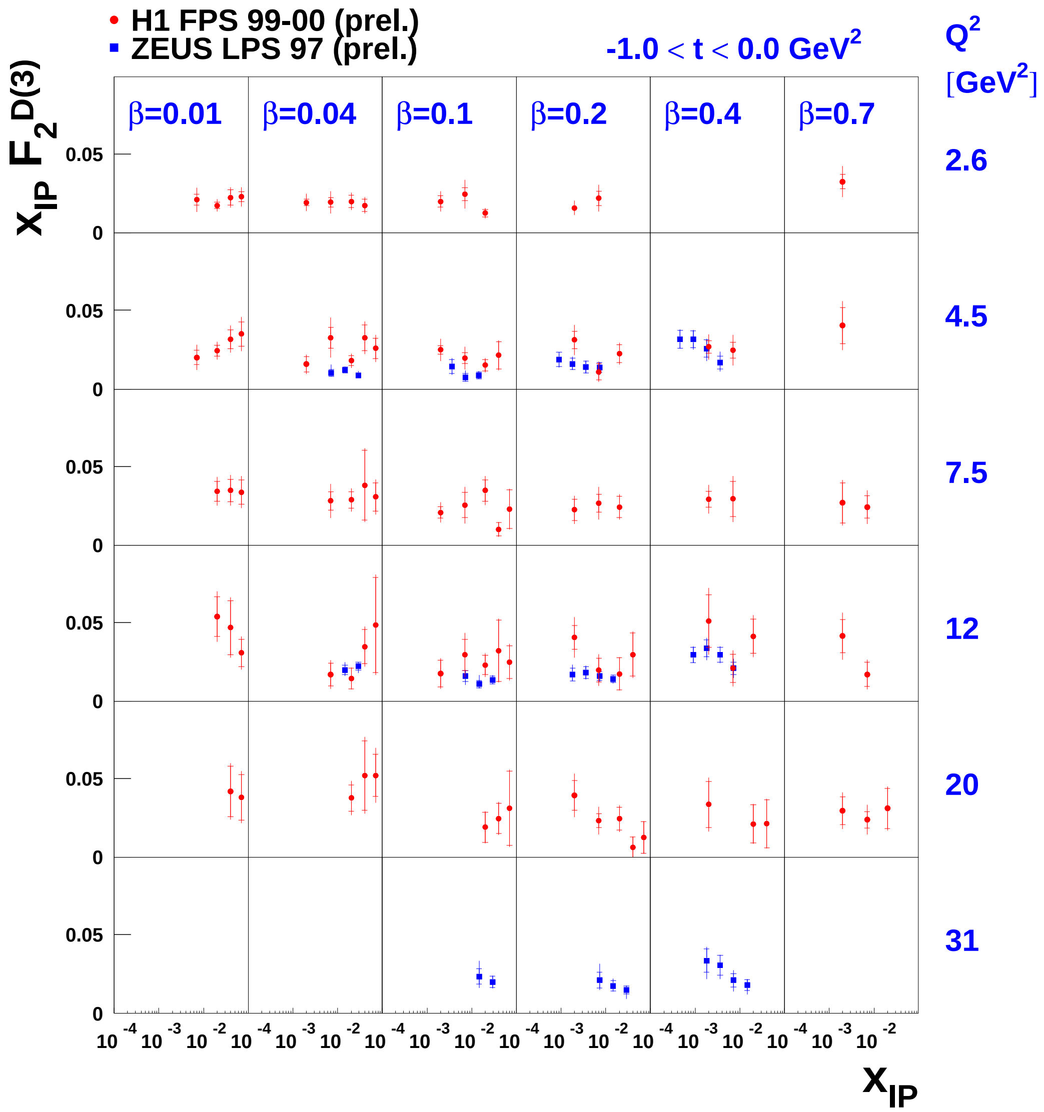
Common $x_{I\!P}$ dependence in all (β, Q^2) bins (Regge fac^{n})

LPS only $\rightarrow \alpha_{I\!P}(0) = 1.13 \pm 0.03\,(\mathrm{stat})\,^{+0.03}_{-0.01}\,(\mathrm{syst})$

Leading Proton $F_2^{D(3)}$ Data

Comparison of H1 FPS and ZEUS LPS data after t integration

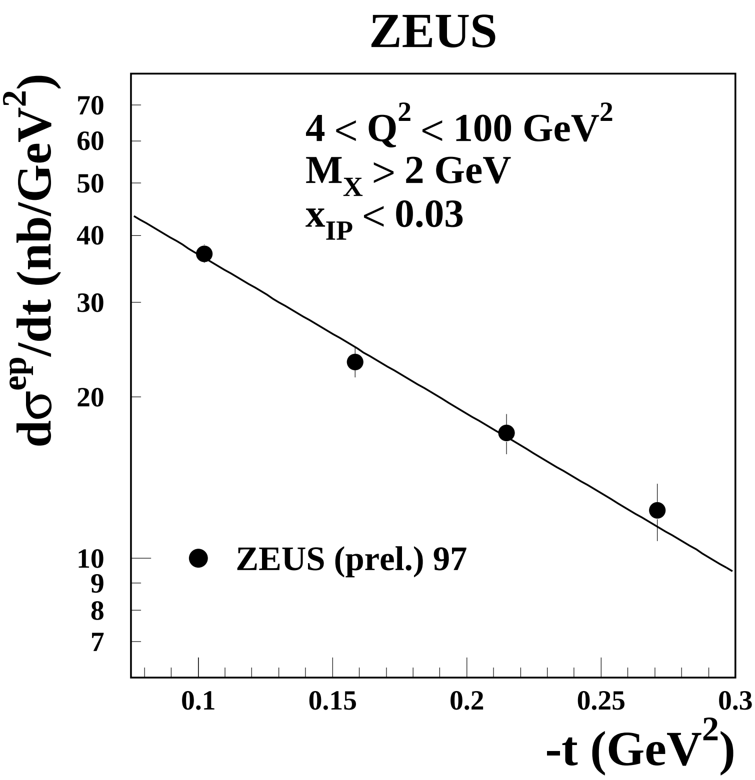




Good agreement between H1 and ZEUS

Main limitation remains statsitical

t Dependence from Tagged Proton Data



Fit full ZEUS dataset to ...

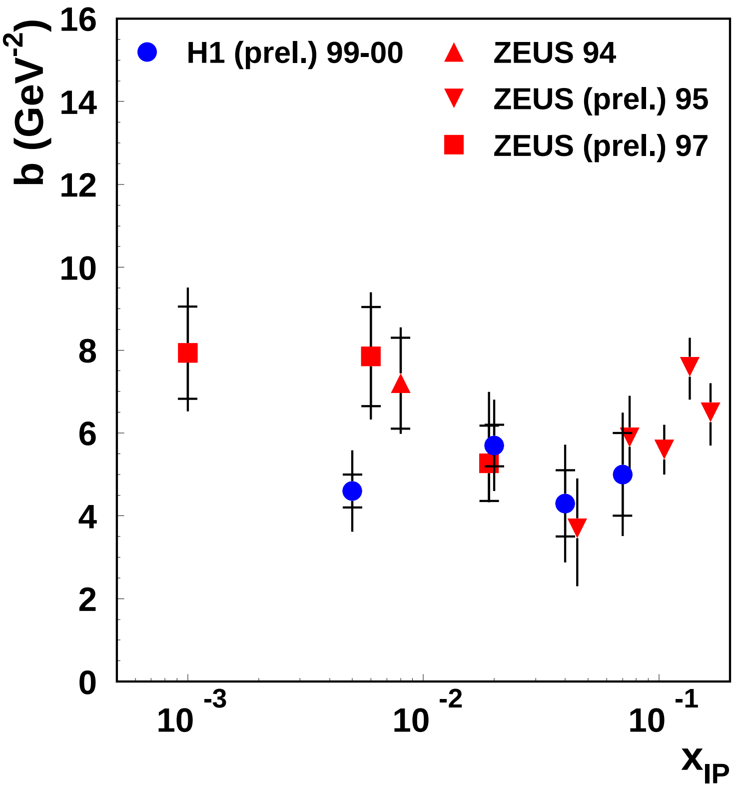
$$\frac{d\sigma}{dt} \propto e^{(b\ t)}$$

$$b = 6.8 \pm 0.6\,(\text{stat.})\ {}^{+1.2}_{-0.7}\,(\text{syst.})\ \text{GeV}^{-2}$$

Highly peripheral p scattering

Slope larger than for e.g. $\gamma p \longrightarrow J/\psi p$

$\longrightarrow$ larger spatial extent at γ^* vertex

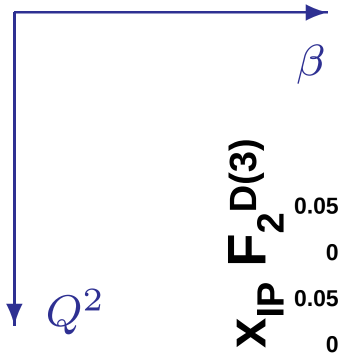


No significant dependence on β, Q^2, M_X

Data so far inconclusive on shrinkage.

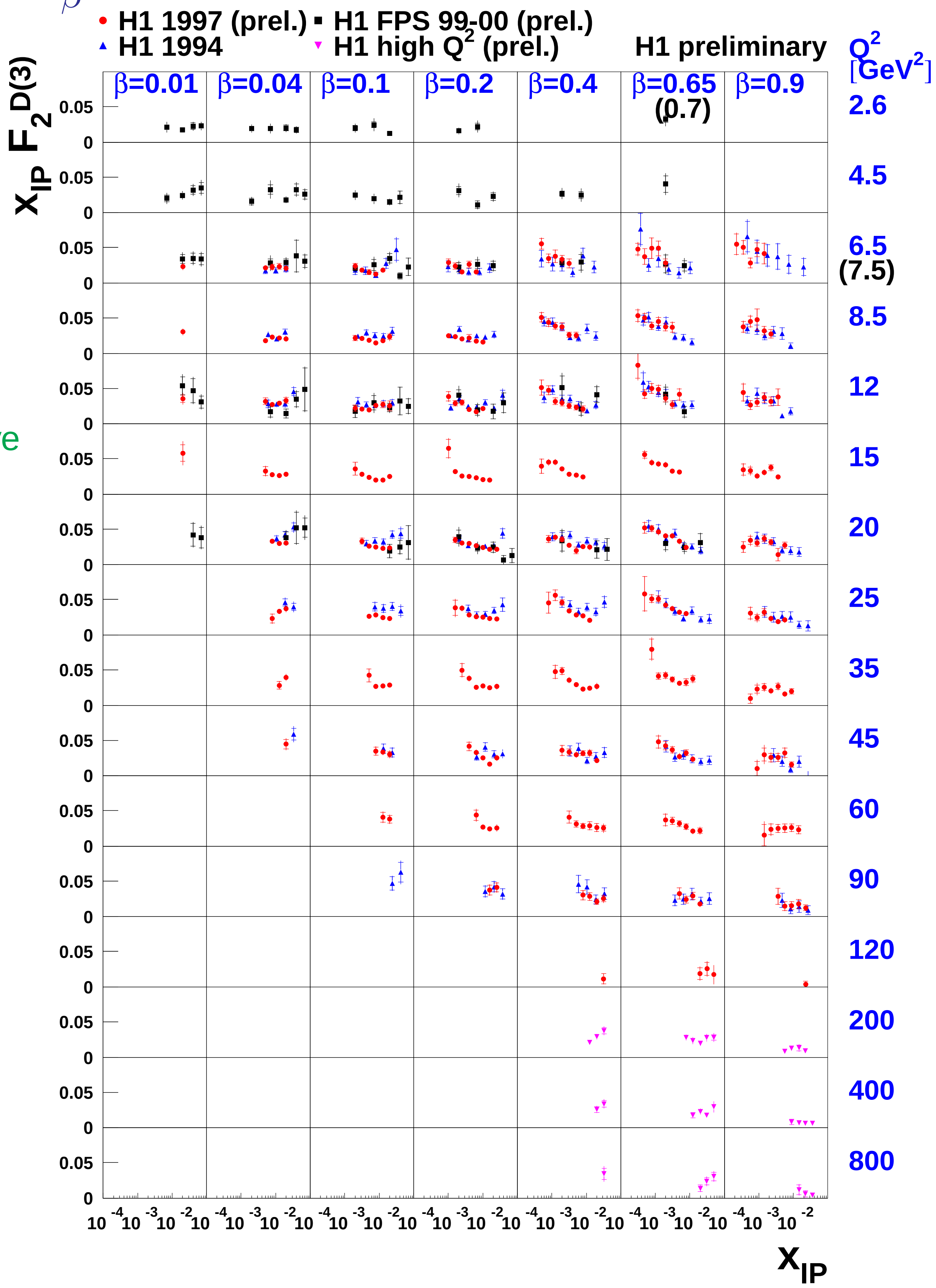
$$(\ b = b_0 + 2\,\alpha' \ln \frac{1}{x_{I\!P}})$$

Compilation of H1 $F_2^{D(3)}$ Data



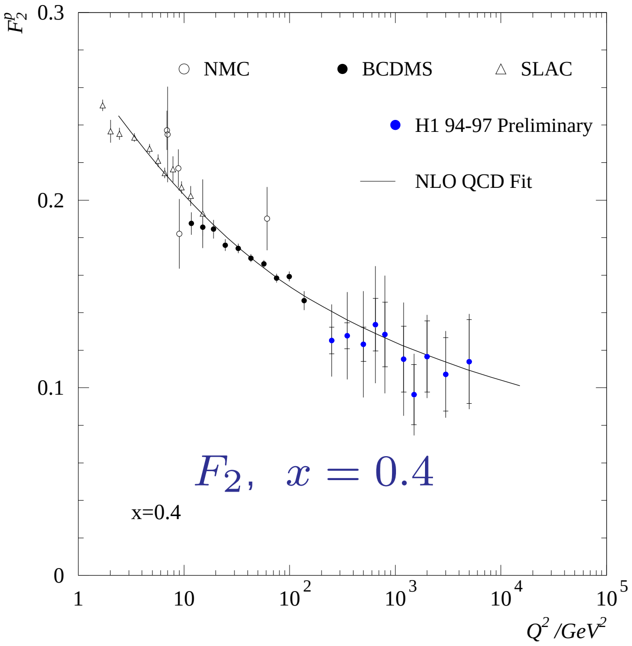
New H1 '97 rapidity gap data improve high Q^2 statistics by factor ~ 5

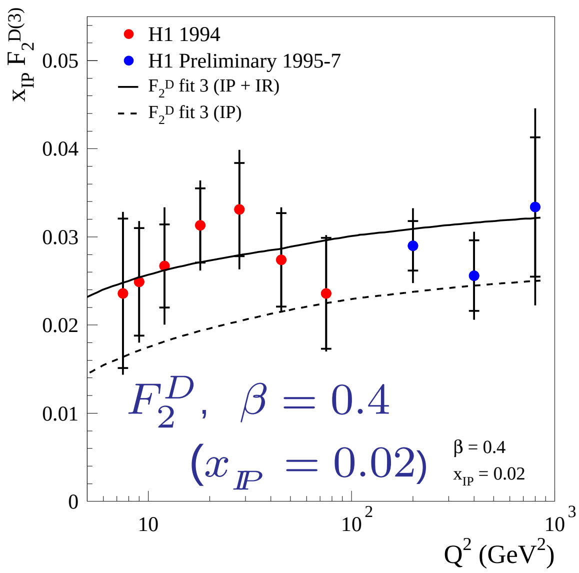
Agreement between rapidity gap and leading proton data



β, Q^2 dependence of $F_2^{D(3)}$

Scaling violations of F_2^D at momentum fraction β very different from F_2 at $x = \beta$





Implies large gluon density at high momentum fraction in diff$^{\rm n}$.

(β, Q^2) dependences of $F_2^{D(3)}$ at fixed $x_{I\!P}$ sensitive to diffractive parton densities integrated over t.

e.g. Fits to new H1 data at 4 FIXED $x_{I\!P}$ values . . .

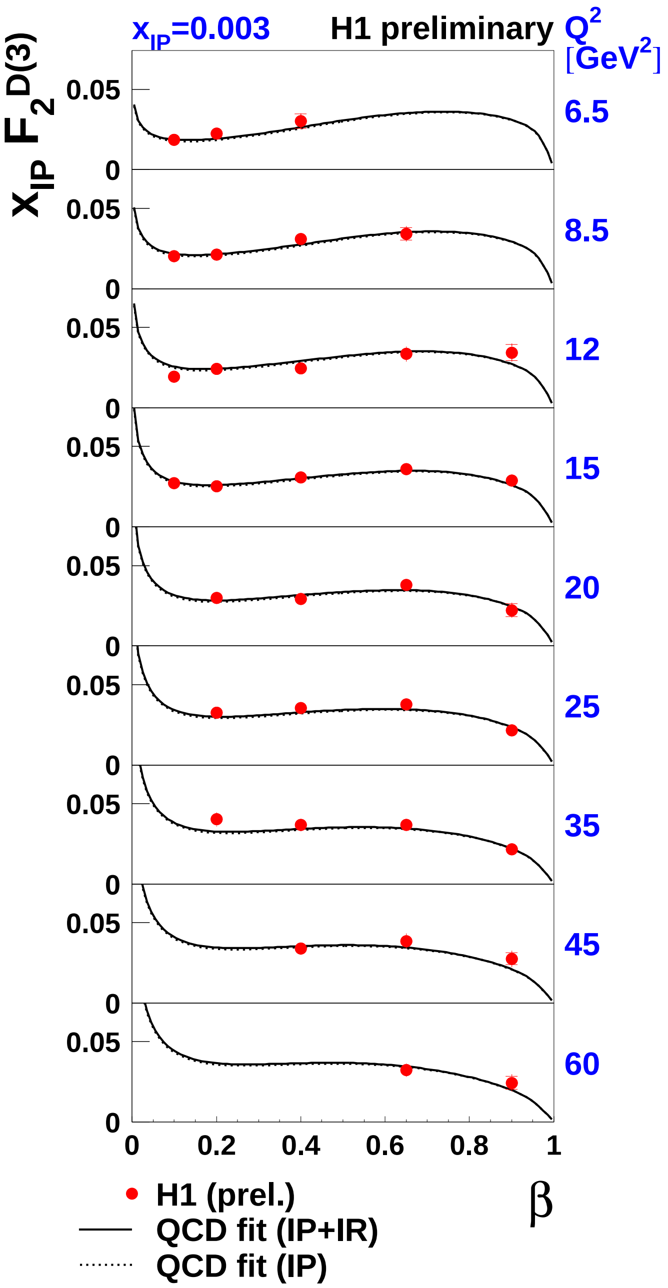
Parameterise (u, d, s) singlet, gluon densities at $Q_0^2 = 2\ \mathrm{GeV}^2$.

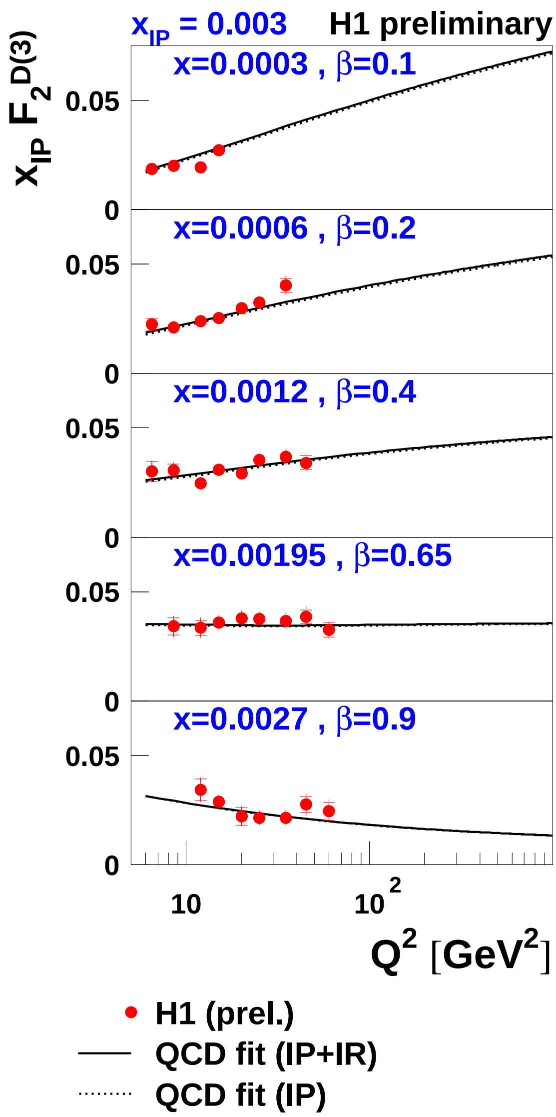
Fit β, Q^2 dependence using DGLAP equations.

Regge motivated parameterisation of $x_{I\!P}$ dependence.

β, Q^2 dependence of $F_2^{D(3)}$

Example results at $x_{I\!P} = 0.003$



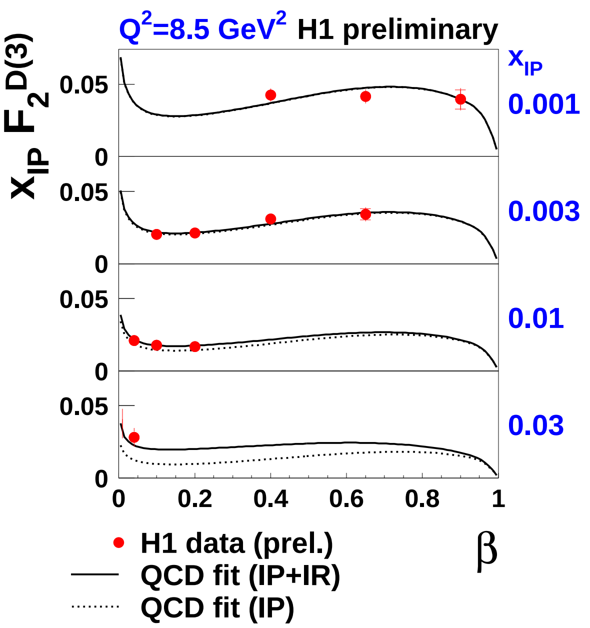


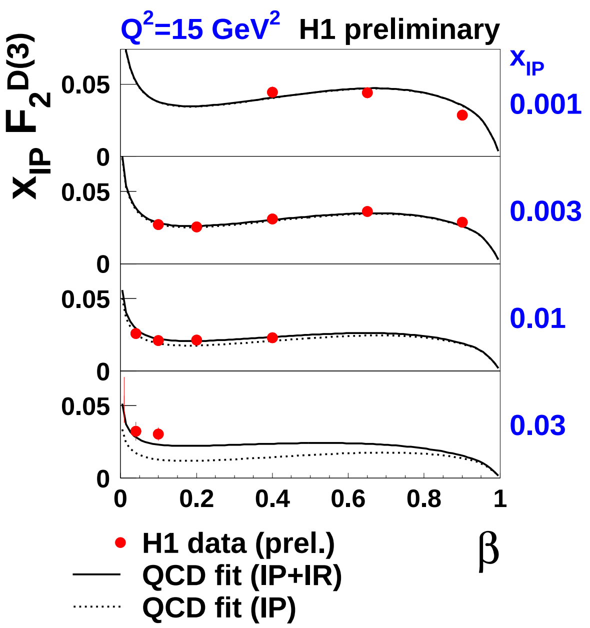
β dependence relatively flat.

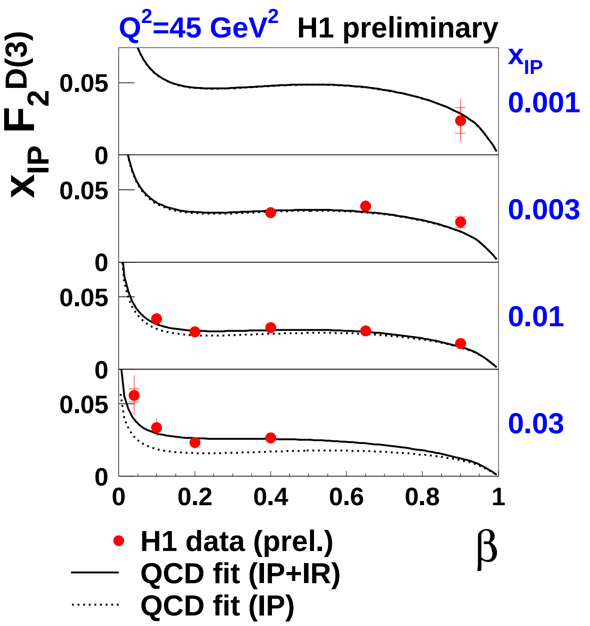
Rising scaling violations with $\ln Q^2$ up to large β

Require large gluon contribution in diffractive pdf's, extending to large fractional momenta.

Variation of diffractive pdf's with $x_{I\!P}$?







Variations with $x_{I\!P}$ well described by Regge flux factors.

Small sub-leading exchange ($I\!R$) contribution required at high $x_{I\!P}$, low β (c.f. D&L $\sigma_{\rm tot}$)

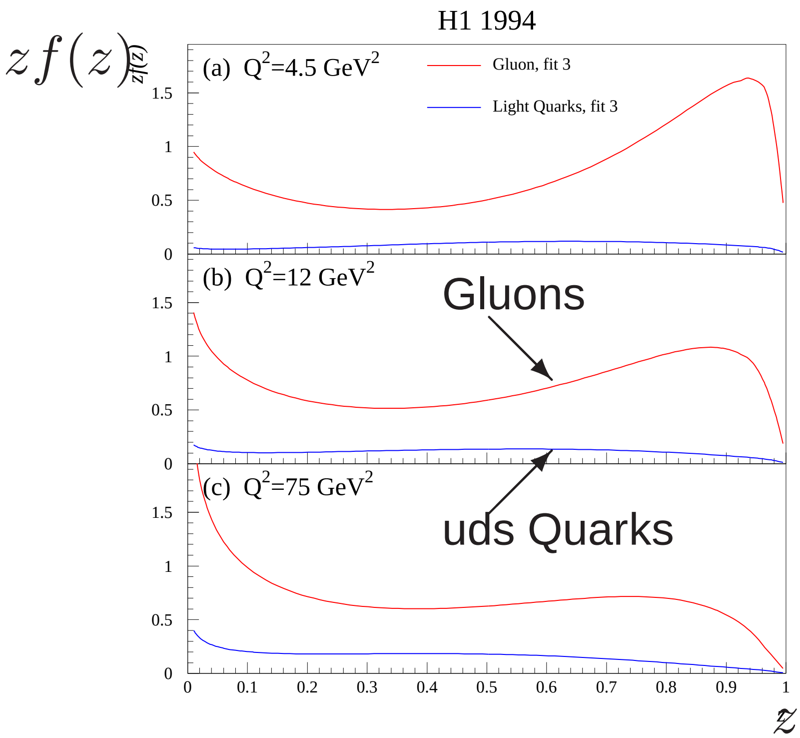
Regge factorisation hypothesis holds within measured range

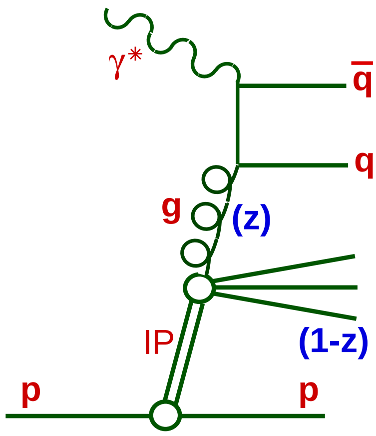
Diffractive pdfs change only in normalisation with $x_{I\!P}$?

Diffractive Parton Densities

Various sets of diffractive parton densities extracted from DGLAP fits to (β, Q^2) dependence of $F_2^{D(3)}$

Usually assume Regge factorisation for $x_{I\!P}$ dependence.





DGLAP analysis yields huge gluon distribution extending to high z

Complications:

- Poorly constrained high z region $\longrightarrow \sigma_L$?
- Higher twist contributions present?
- .....

Parton densities implemented in MC models for comparison with final state data. eg . . .

'H1 Fit 3' - 'peaked' gluon (as above)

'H1 Fit 2' - 'flat' gluon

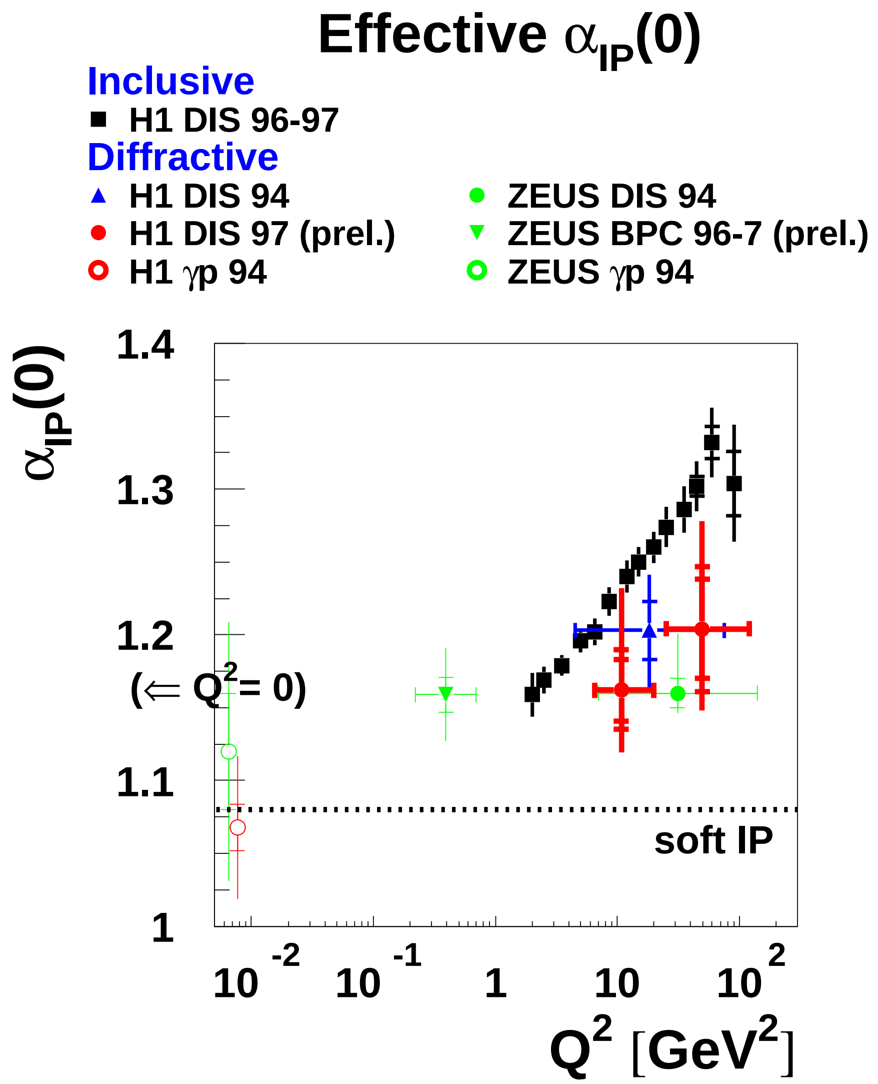
'ACTW' - combined fits to H1 and ZEUS 94 data

How Universal is the Pomeron?

Compare effective $\alpha_{\mathbb{P}}(0)$ from F_2^D and F_2 ...

Total x-section $\gamma^* p \to X$ $\quad F_2 \sim A(Q^2)\ x^{1-\alpha_{\mathbb{P}}(0)}$

Diss^n x-section $\gamma^* p \to Xp$ $\quad x_{\mathbb{P}} F_2^D \sim B(\beta, Q^2)\ x_{\mathbb{P}}^{2-2\langle\alpha_{\mathbb{P}}(t)\rangle}$



$\alpha_{\mathbb{P}}(0)$ grows with Q^2 $\rightarrow$ larger than soft $\mathbb{P}$ at large Q^2

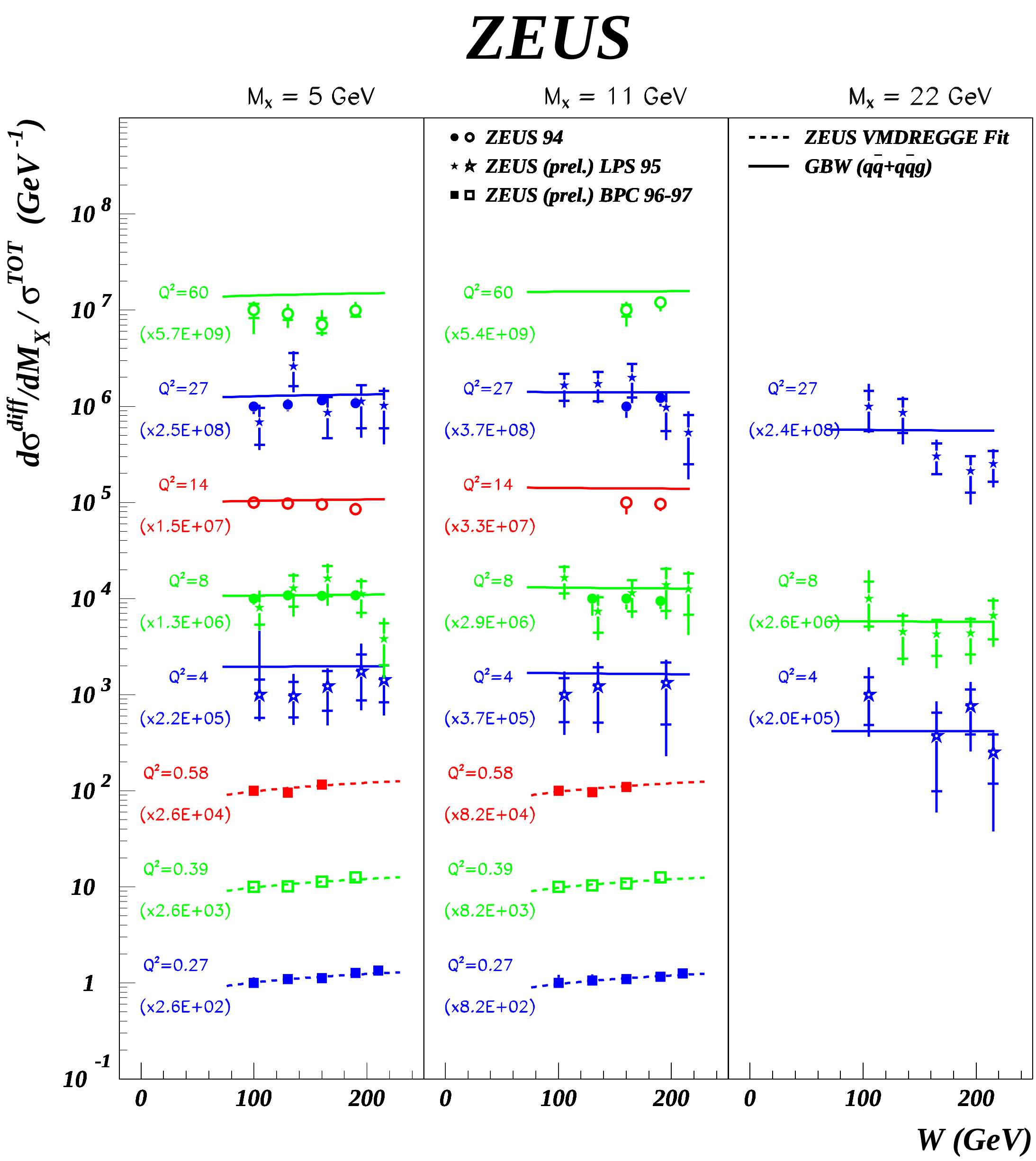
Growth of effective $\alpha_{\mathbb{P}}(0)$ slower for diffractive than for inclusive cross section?

Energy dependences of diffractive and inclusive cross sections become similar at large Q^2

The pomeron as a single pole cannot describe all HERA F_2^D and F_2 data (also c.f. VM).

Energy Dependence of F_2 and F_2^D

ZEUS data on diffractive / inclusive ratio over wide Q^2 range.



Fits to $$\frac{\int \mathrm{d}t \;\; \mathrm{d}\sigma^{\mathrm{diff}}_{\gamma^* p\to XY}/\mathrm{d}M_X \;\, \mathrm{d}t}{\sigma^{\mathrm{tot}}_{\gamma^* p\to X}} \propto W^\rho$$

$\rho = 0.24 \pm 0.07\,(\mathrm{stat})$ $\quad$ ($0.27 \leq Q^2 \leq 0.58\,\mathrm{GeV}^2$ - Regge-like)

$\rho = 0.00 \pm 0.03\,(\mathrm{stat})$ $\quad$ ($Q^2 \geq 4\,\mathrm{GeV}^2$ - Not Regge-like)

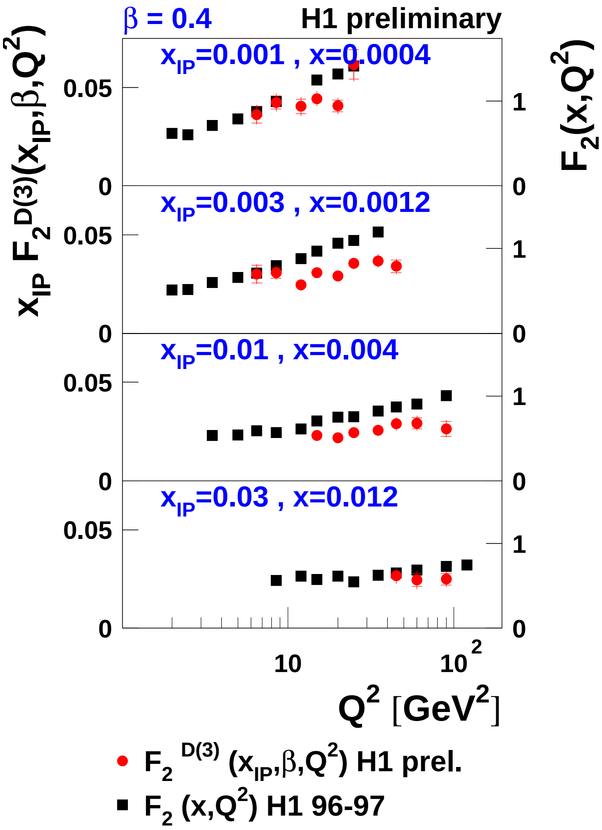
Interpretation unclear

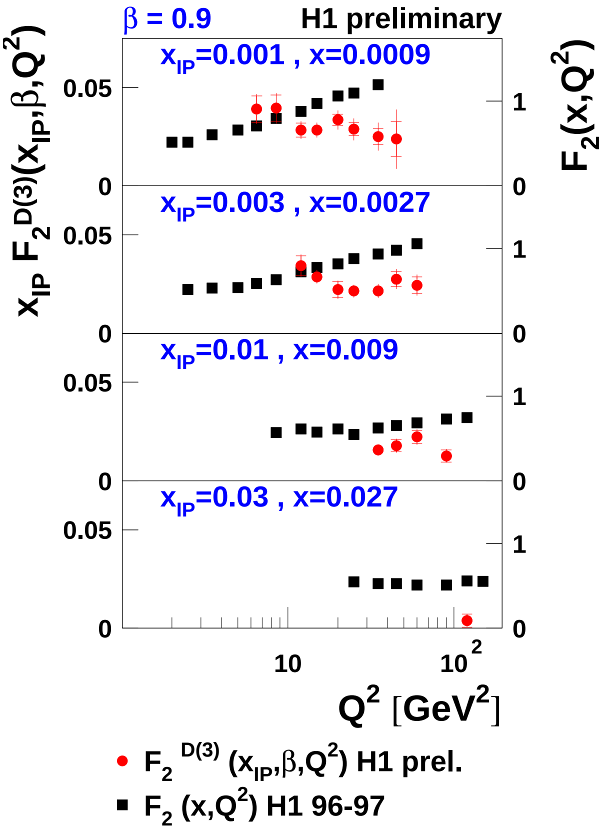
$\longrightarrow$ interplay of hard / soft? (larger dipole sizes in diffraction)

$\longrightarrow$ gluon saturation?

Scaling Violations of F_2 and F_2^D

Compare scaling violations of F_2^D at $x = (x_{I\!P} \cdot \beta)$ with F_2 at x





When compared at the same $\underline{x}$ . . .

F_2^D shows similar Q^2 dependence to F_2 at low β.

At $\beta = 0.9$, F_2^D falls with Q^2 whereas F_2 continues to rise.

Dynamics change at high β

e.g. Q^2 suppressed higher twist contributions (e.g. elastic VM production) present at high β

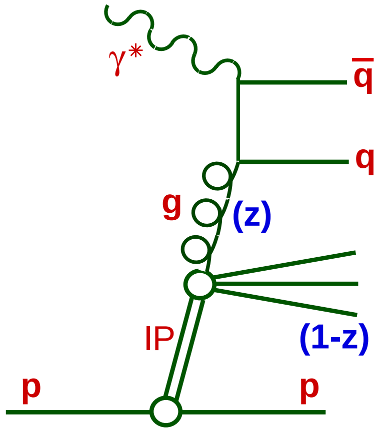
Diffractive Final State Data - Dijets

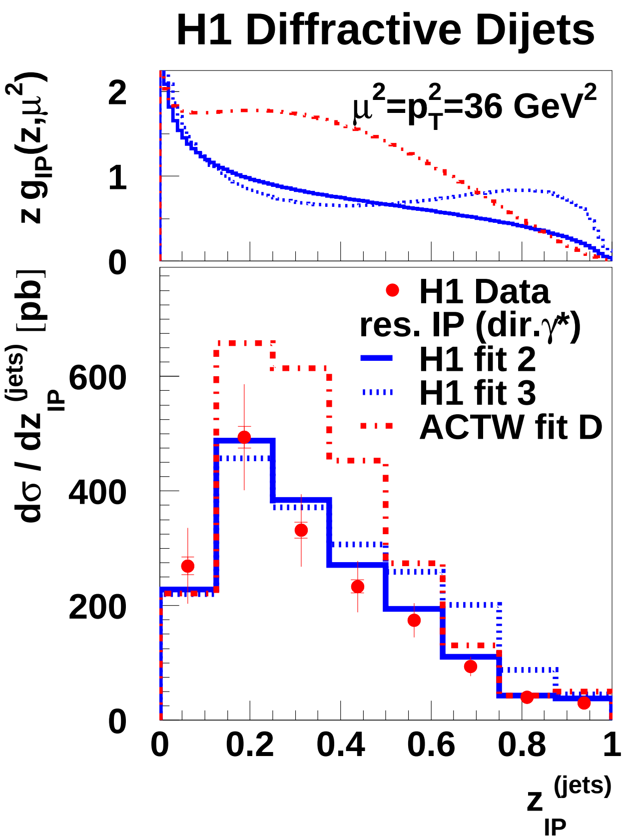
Best tests of gluon come in dijet and open charm studies.

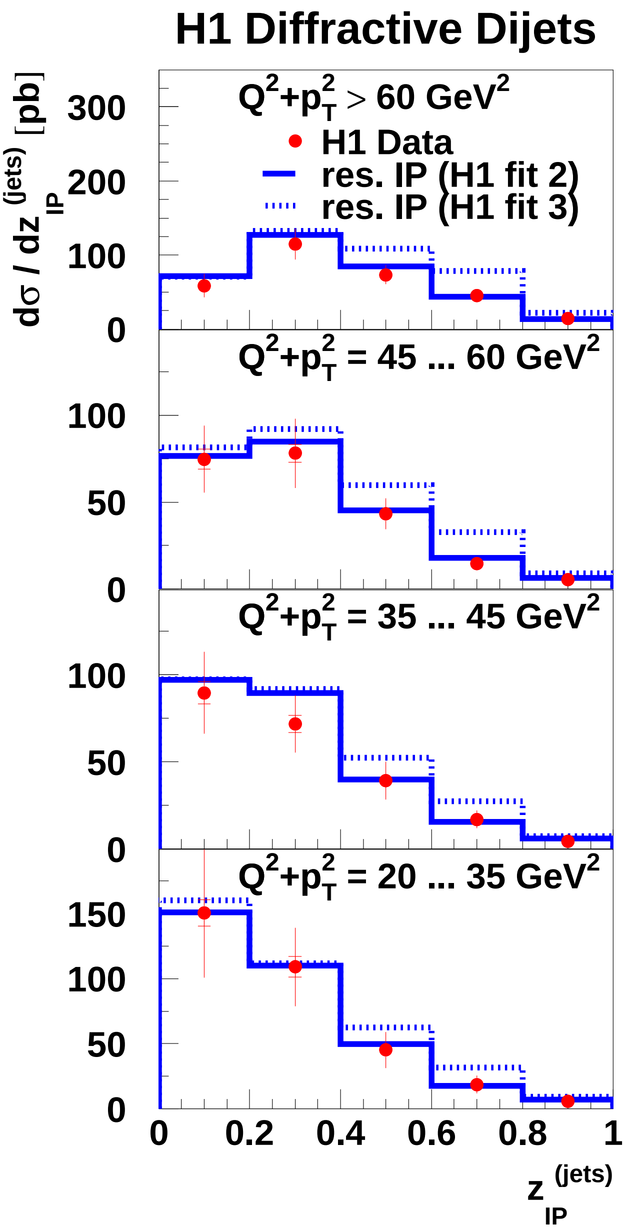
Gluon initiated processes

(boson-gluon fusion).

Rates $\sim$ proportional to gluon density!







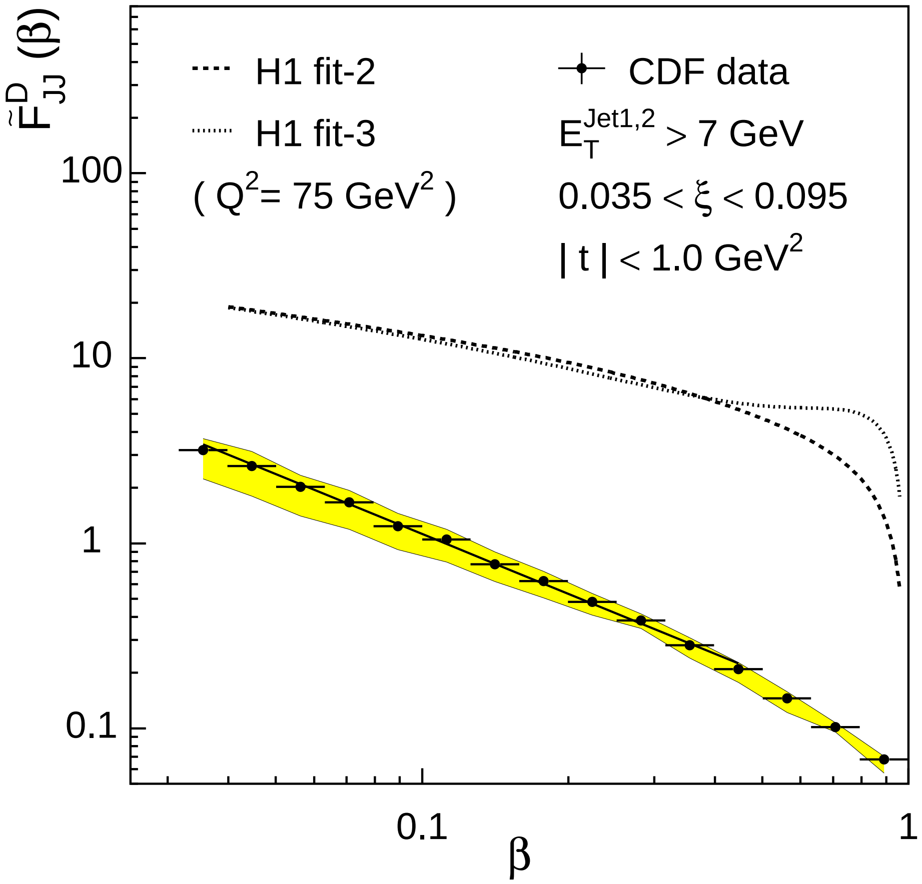
Can distinguish between different fits to F_2^D

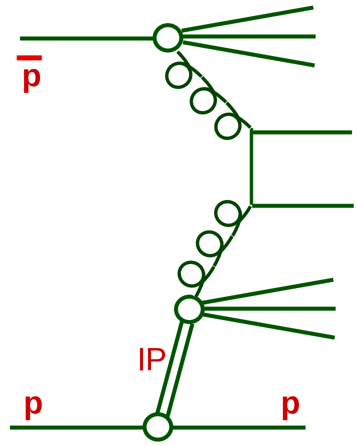
H1 fit 2 (‘flat’ gluon) works spectacularly (too!) well.

Also supports Regge factorisation (fits double differential $z_{\mathbb{P}}, x_{\mathbb{P}}$ cross secs with $\alpha_{\mathbb{P}}(0) \sim 1.2$)

How Universal are Diffractive Partons?

Model Tevatron diffractive dijets using $\mathbb{P}$ partons from F_2^D.





Prediction inconsistent in both shape and normalisation. Catastrophe?

Discrepancies in all channels at the Tevatron (W, b, J/ψ, double pomeron exchange) . . .

Discrepancies are process and kinematics dependent

Associated with hadronic remnant reinteractions (absorptive corrections?)

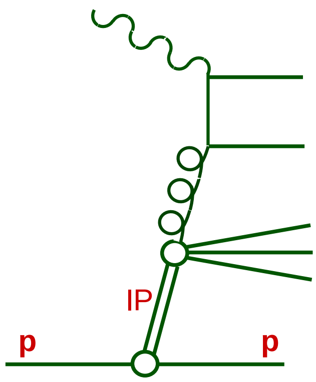
Phenomenological models can explain at least some data

Deeper understanding of 'gap survival' needed to explain connection between diffractive DIS and hadronic diffraction

Possible control experiment? - γp Dijets

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

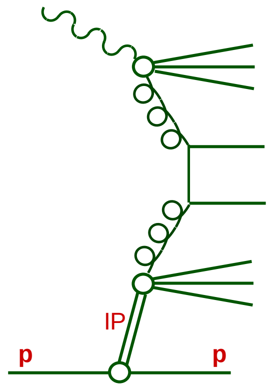
$x_\gamma^{\rm jets}$ = fraction of γ momentum entering the hard scatter.



DIRECT

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

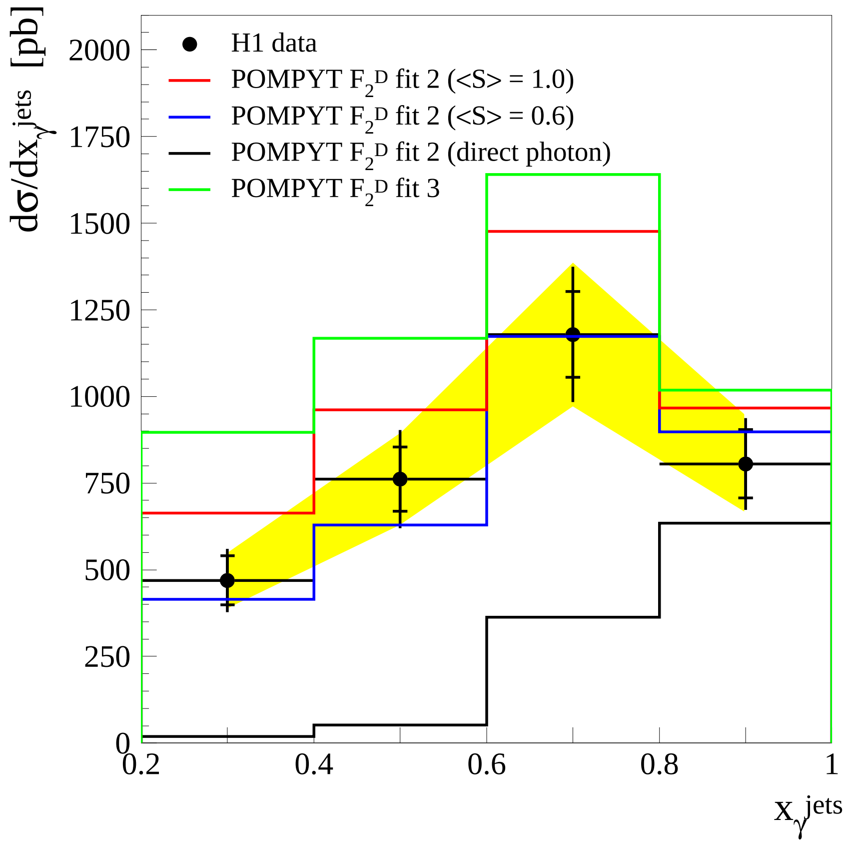
All gaps survive?



RESOLVED

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

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.

No evidence (yet) for large factorisation breaking in resolved γp

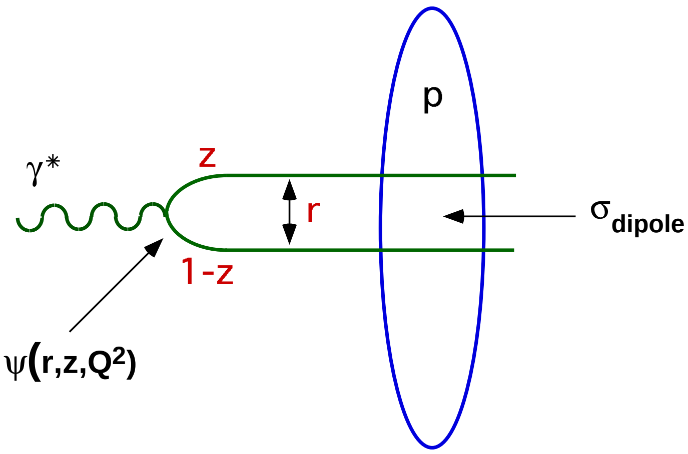
Colour Dipole Models

Alternative approach to low $\boldsymbol{x}$: Proton rest frame

γ^* lifetime $\sim m_p/x$, $\rightarrow\sim 1000\ \mathrm{fm}$ at HERA

$\gamma^* \rightarrow q\bar{q}$ well in advance of target

Treat DIS as interaction between proton and $q\bar{q}$ dipole (or higher multiplicity)



Diffractive processes when dipoles scatter elastically.

$\psi_{T,L}(r, z, Q^2)$: Light cone $\gamma^* \rightarrow q\bar{q}$ wavefunctions

$\sigma_{\mathrm{dipole}}(x, r)$: Dipole cross section on proton - model dependent, but universal.

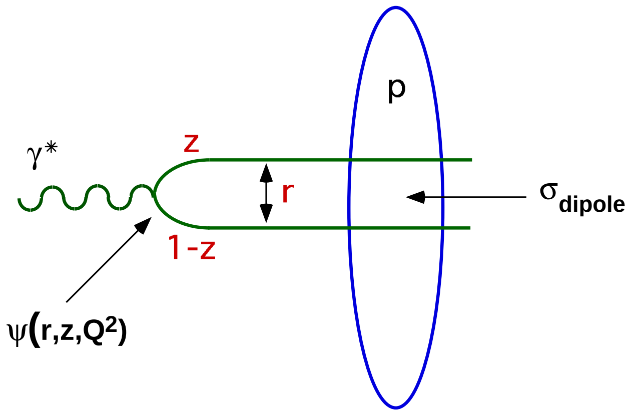
Simple relationships between σ_{tot}, σ_{el} and σ_{dif}

e.g. Golec-Biernat & Wüsthoff Model

Simple parameterisation of dipole cross section . . .

- $\sim r^2$ as $r \to 0$ (pQCD)
- $\to$ const. as $r \to \infty$
- Saturation radius

  $R_0(x) \sim x^{\lambda/2}$



Partonic model for diffraction:

$F_2^D \sim$ 2 gluon exchange, $F_2 \sim$ 1 gluon

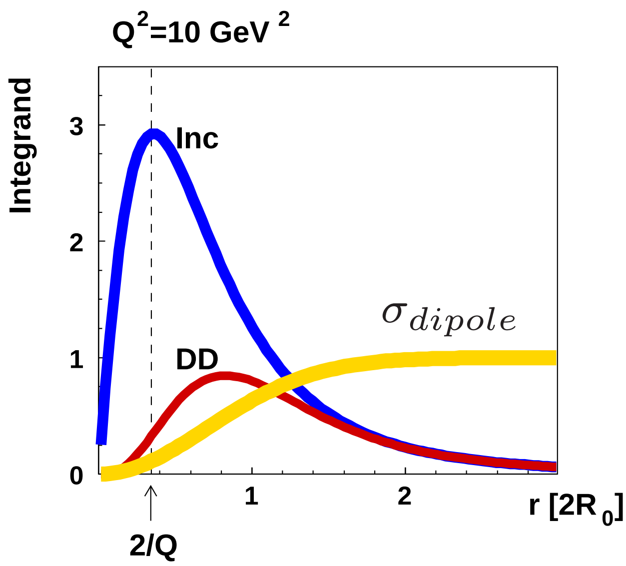
F_2: $\sigma_{T,L}(x,Q^2) = \int \mathrm{d}^2r\,\mathrm{d}z \;\left|\psi_{T,L}(r,z,Q^2)\right|^2 \;\sigma_{\mathrm{dipole}}(x,r)$

F_2^D: $\sigma_{T,L}(x,Q^2) = \int \mathrm{d}^2r\,\mathrm{d}z \;\left|\psi_{T,L}(r,z,Q^2)\right|^2 \;\sigma^2_{\mathrm{dipole}}(x,r)$

Extra factor of σ_{dipole} in diffractive case gives increased weight to large dipole sizes.

Large $r \to$ small k_{T}

Bigger 'soft' contribution in diffractive case



Explanation for different effective $\alpha_{\mathbb{P}}(0)$ for F_2 and F_2^D

Golec-Biernat & Wüsthoff Model and F_2^D

3 parameter fit $\rightarrow \sigma_{dipole}$ from F_2 (fair description).

Reasonable consensus on terms needed for F_2^D

Bartels, Ellis. Kowalski, Wüsthoff

Intermediate β: $\gamma_T^* \rightarrow q\bar{q}$

High β: $\gamma_L^* \rightarrow q\bar{q}$ (Q^2 suppressed higher twist)

Low β: $\gamma_T^* \rightarrow q\bar{q}g$

Serious attempt to calculate F_2^D including all 3 components

Free parameters in σ (dipole)

fixed by fits to $F_2(x, Q^2)$

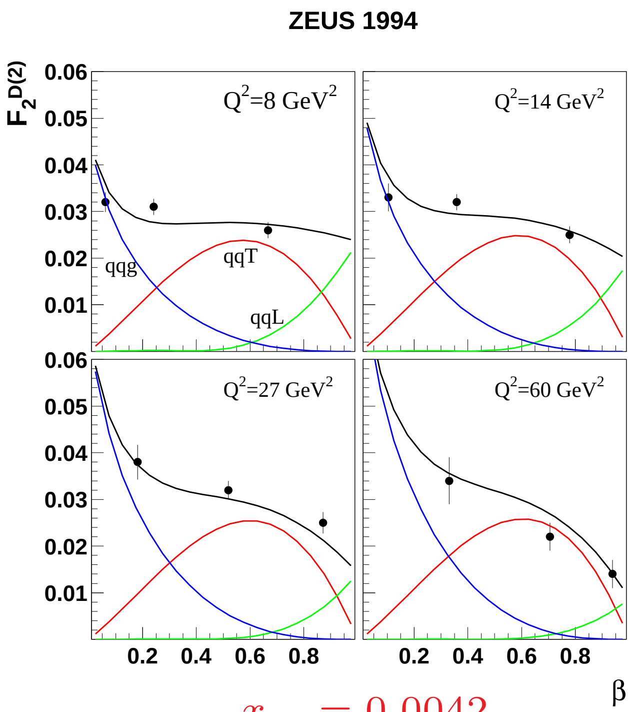
Diffractive cross section at $t = 0$

then predicted.

1 extra parameter (t slope)

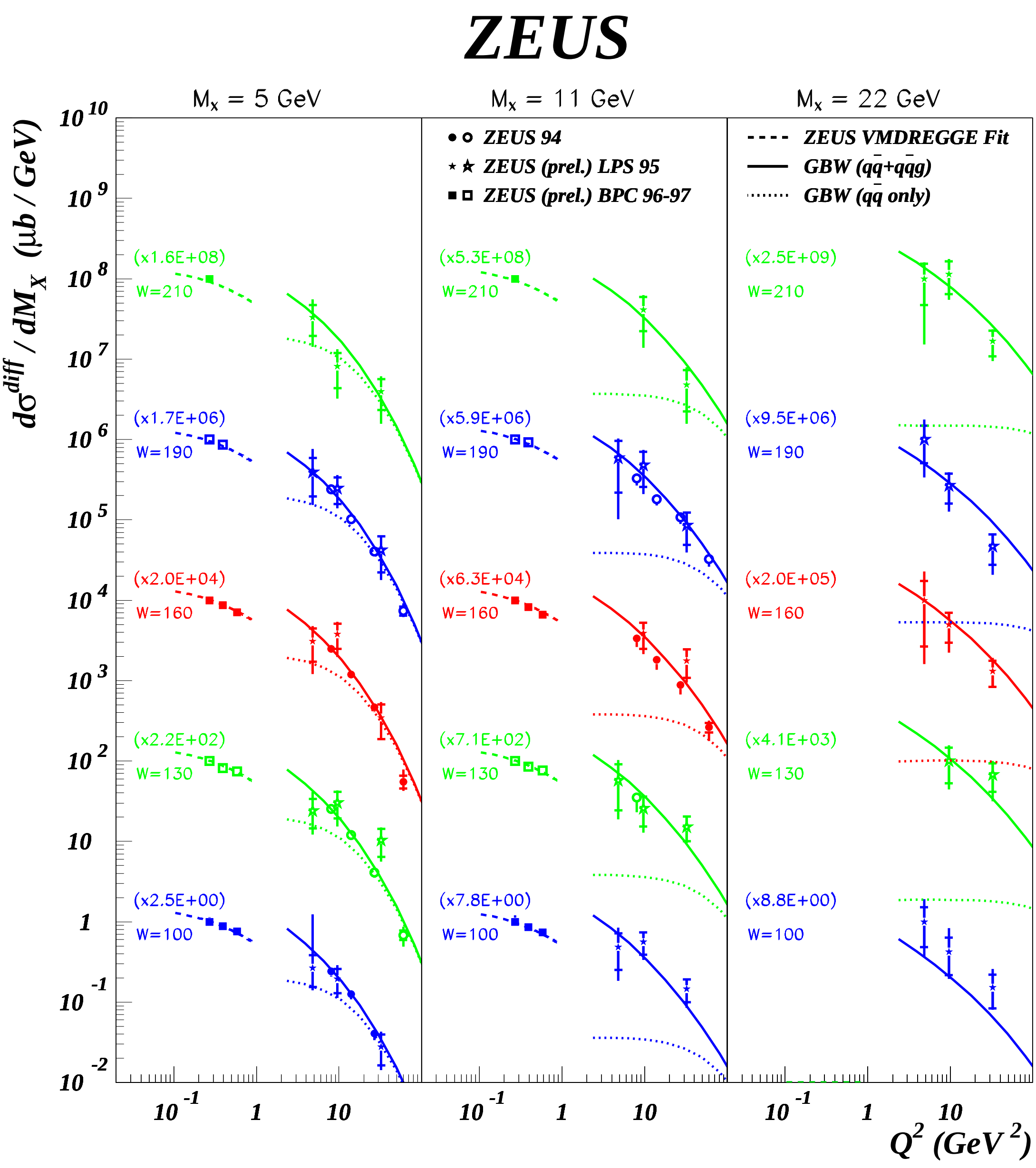
Impressive agreement with

F_2^D data.



$x_{I\!P} = 0.0042$

Comparison with ZEUS Data



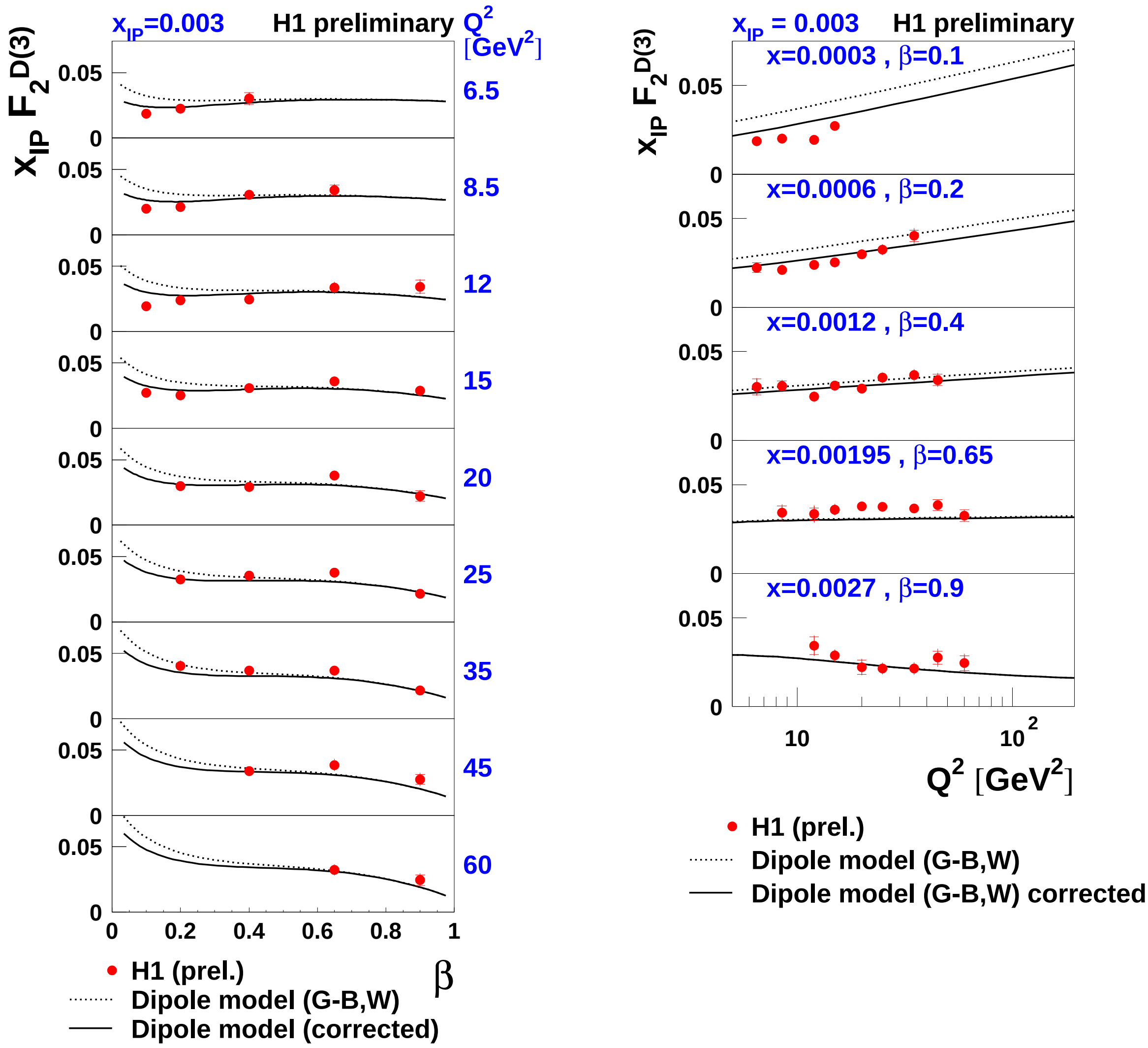
Good description for $Q^2 \geq 4\ \mathrm{GeV}^2$

$q\bar{q}g$ photon fluctuation dominant for large M_X $\equiv$ small β

Model not yet able to describe $Q^2 \leq 1\ \mathrm{GeV}^2$

Comparison with H1 Data

Recent development - modified $q\bar{q}g$ treatment (colour factors added in line with other dipole models)



Good description, except at lowest $\beta\ \equiv$ highest M_X

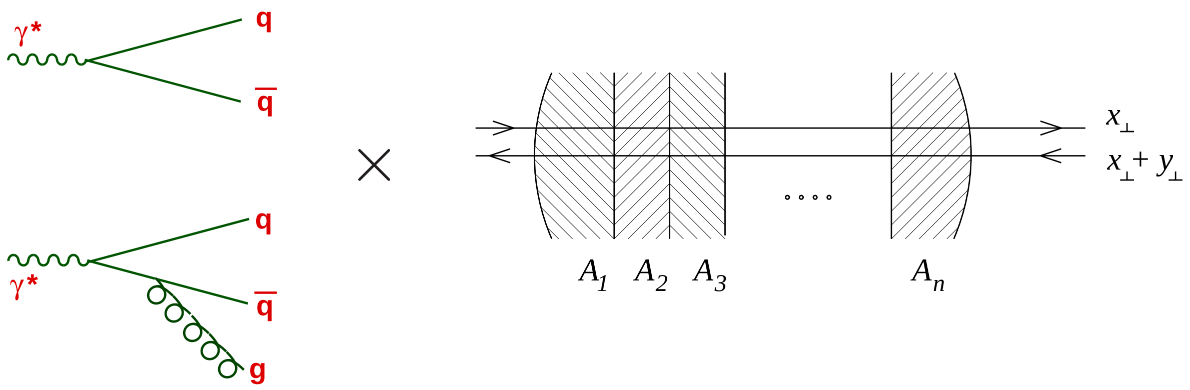
Contains higher twist contributions at high β . . .

Can generate falling Q^2 dependence at $\beta = 0.9$

Non-perturbative model for σ_{dipole}

Dipole cross section treated non-perturbatively . . .

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.

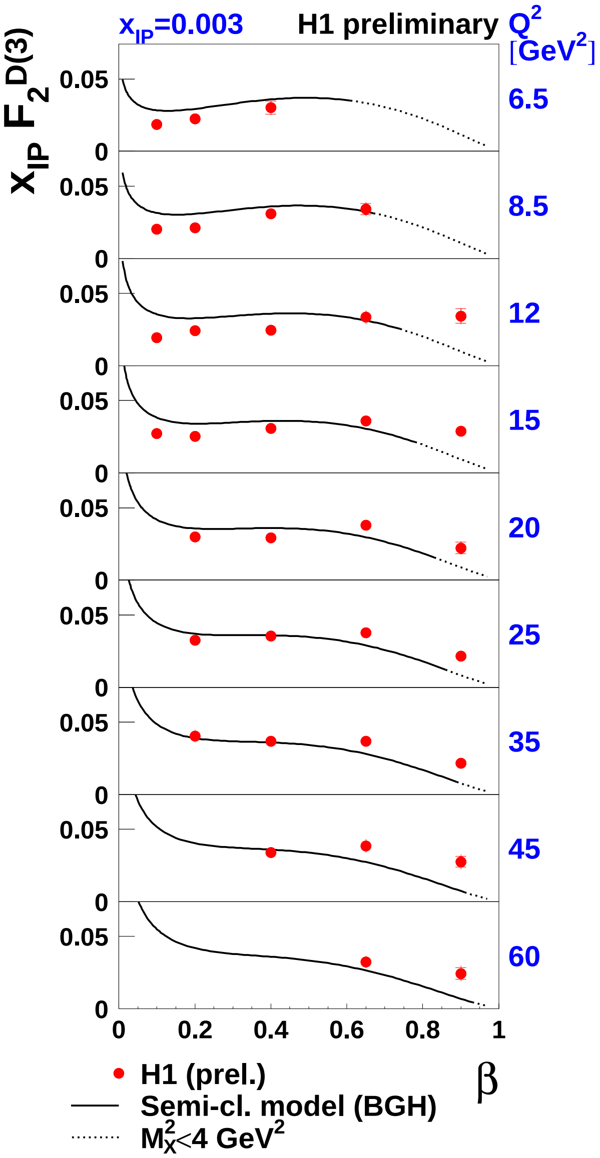
Simulataneous description of F_2 and F_2^D reduced to a 4 parameter fit.

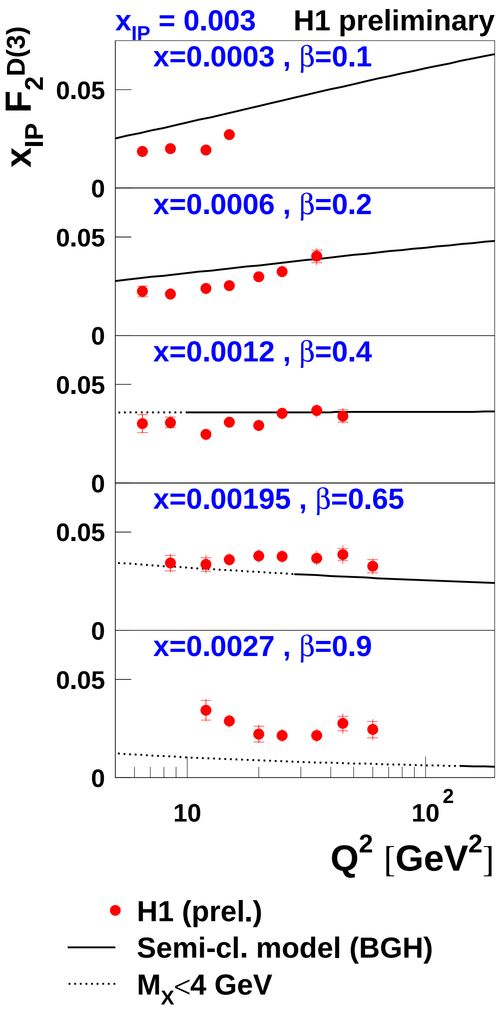
Able to predict flat F_2^D/F_2

Non-perturbative Dipole Model

Based on four parameter fit to previous F_2 and F_2^D data.

No higher twist treatment. - Restricted to $M_x > 4\,\mathrm{GeV}$





General features of data well reproduced.

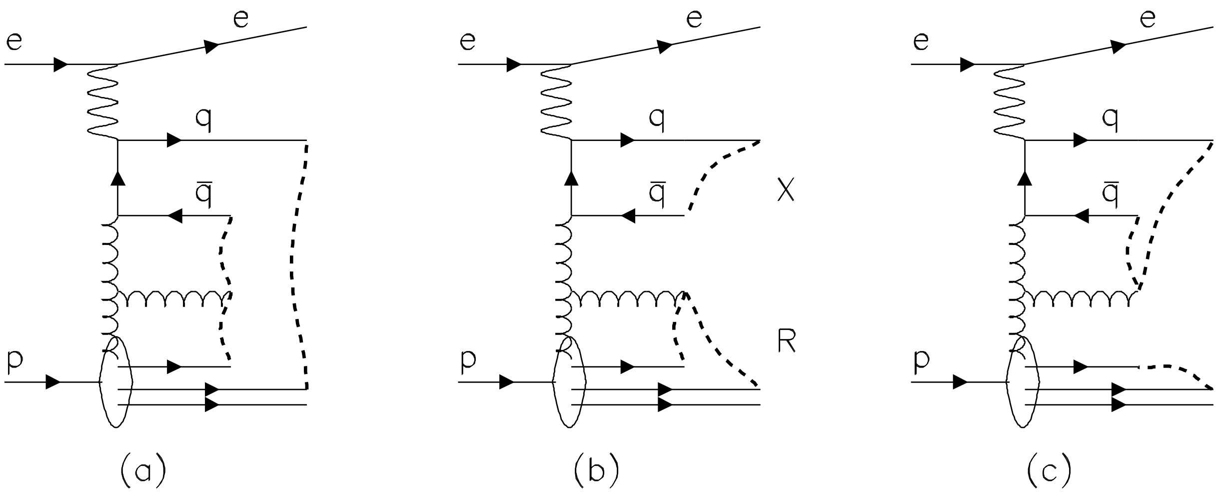
Predictions exceed data at low β, low Q^2.

Soft Colour and F_2^D

Completely non-perturbative model of rapidity gap formation. - Soft Colour Rearrangements

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

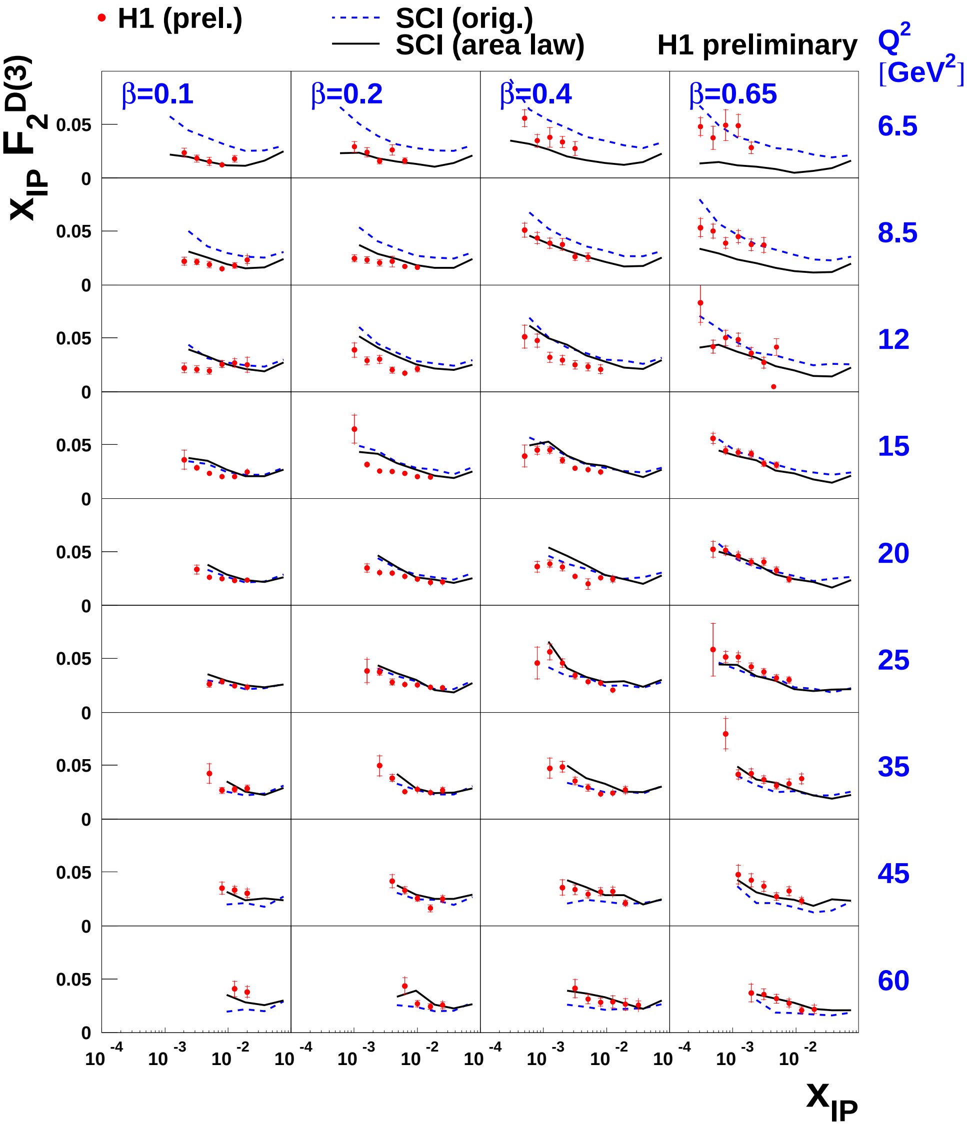
Additional non-perturbative interactions affect final state colour connections but not parton momenta.



Only one free parameter! - Probability of Soft Colour Interactions . . . to be fixed by data.

Recent refinement - Generalised Area Law model. - Rearrangement Probability $\propto$ difference in generalised areas of string configurations before and after rearrangement.

Comparison with H1 Data



Normalisation fixed by previous F_2^D data

Good description considering simplicity of model

GAL refinement improves description at low β

What Does The Future Hold?

Hard diffraction is a major success story of HERA-I

10-fold increase in statistics available at HERA-II!

Current Limitations on our Understanding . . .

1) Statistics

$F_2^{D(3)}$ systematically limited for low Q^2 after HERA-I

$F_2^{D(4)}$, t dependence, many final states statistically limited . . .

e.g. Diffractive open charm - only few 10s of D^* events!

2) Experimental Systematics

Rapgap selection dominates $F_2^{D(3)}$ systematics due to:

- Poorly constrained Forward detector efficiencies
- Poorly known p-diss^n cross section, t, M_Y distributions

3) Model Comparisons

Unknown t dependence can make model comparisons hard.

e.g. Dipole / 2 gluon exchange calculations yield $\left[\frac{\mathrm{d}\sigma}{\mathrm{d}t}\right]_{t=0}$

Normalisation of predictions $\sim 1/B$

Many other uncertainties in hadron level predictions (eg jets)

Very Forward Proton Spectrometer

High acceptance direct tagging of leading protons $\longrightarrow$

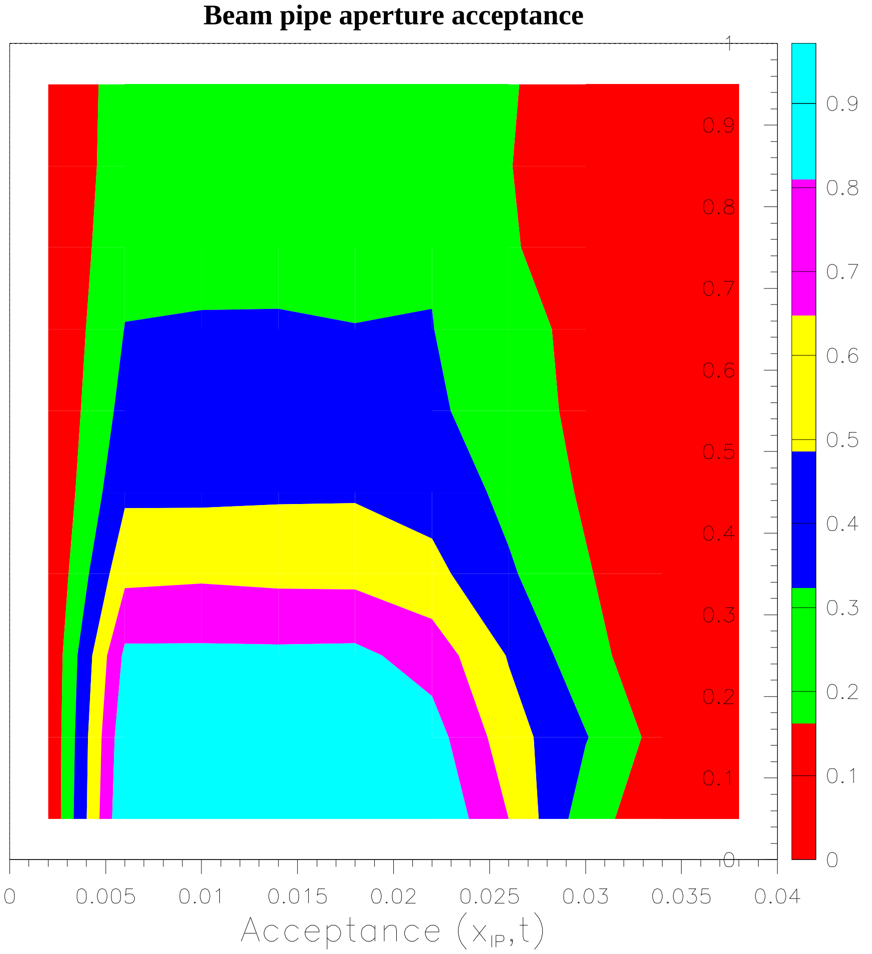
- Efficient triggering for 'rare' processes
- Removes rapidity gap selection systematics
- t dependences can be extracted

New tool for HERA-II

H1 VFPS

Roman pots at
$z \sim 200$ m
from 2002-3

Close to 100%
acceptance for
$x_{I\!P} \lesssim 0.02$
$|t| \lesssim 0.25$ GeV^2



Complements existing LPS / FPS . . .

Smaller ($x_{I\!P}$, t) coverage, but higher tagging efficiency

See talk of Pierre van Mechelen

HERA-II Diffractive Shopping List

1) Lots of Precision Measurements!

Precise (β, Q^2) dependence of F_2^D at fixed $(x_{\mathbb{P}}, t)$ (e.g. VFPS)

- Do diffractive parton densities vary in shape with t?
- Precision tests of hard scattering fac$^{\rm n}$ (e.g. with dijets)

$x_{\mathbb{P}}$ dependences. - Where does Regge fac$^{\rm n}$ break down?

2) Measurements of t Dependence

- Required to fully test validity of QCD models.
- *Variation* of t slope with other variables $(x_{\mathbb{P}}, W \ldots)$ contains important dynamical information (α', shrinkage)
- Can we measure $B(\beta, Q^2, x_{\mathbb{P}})$?

Existing LPS / FPS should give smallest systematics but limited statistics.

VFPS will give 3-4 bins for $0 < |t| < 0.8 \ \mathrm{GeV}^2$.

HERA-II Diffractive Shopping List

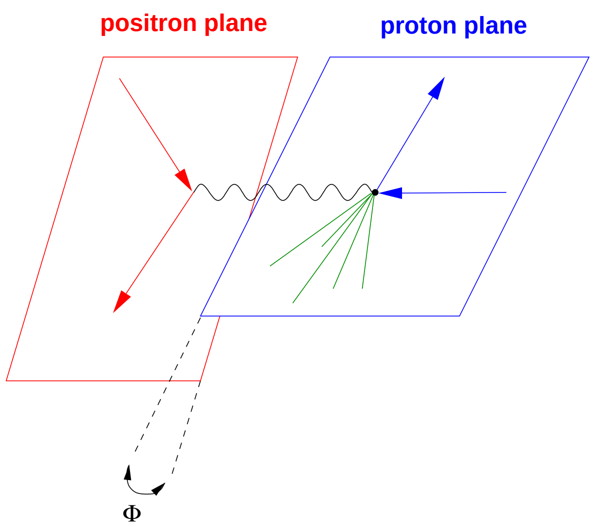
3) Measurements of Longitudinal Photon Contributions

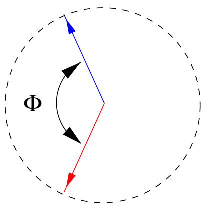
pQCD calculable Higher Twist σ_L dominant at high β? (cf VM)

Leading Twist F_L^D tests hard scattering fac$^{\mathrm{n}}$ (gluon at NLO)

Azimuthal Correlations?

Interference between transverse and longitudinal photon induced processes leads to modulation in $\cos\phi_{ep}$.



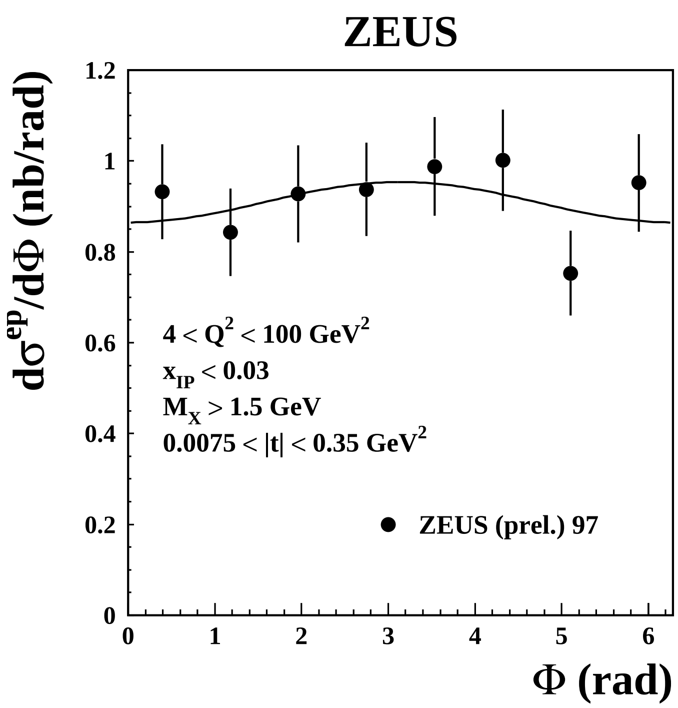


First measurement from ZEUS LPS . . .

$$\frac{d\sigma}{d\cos\phi} \propto 1 + A_{LT}\cos\phi$$

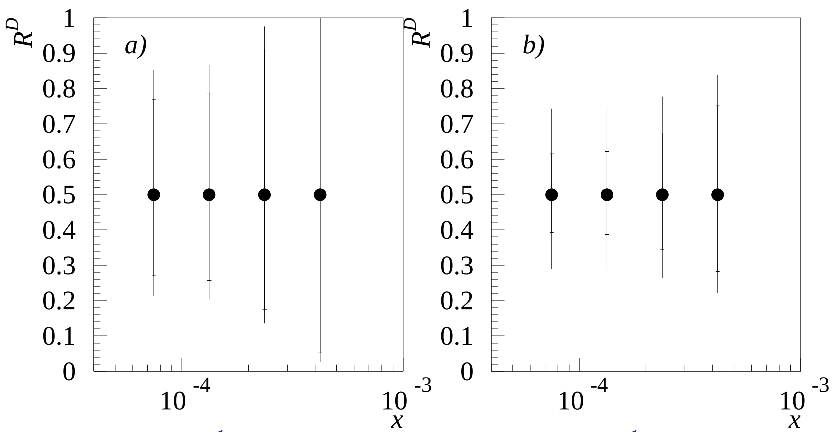
$$A_{LT} = -0.049 \pm 0.058\,(\mathrm{stat})\,{}^{+0.056}_{-0.009}\,(\mathrm{syst})$$

Lots more stats needed!



HERA-II Diffractive Shopping List

F_L^D continued: Vary beam energies?



$10\,\mathrm{pb}^{-1}$ @ 500 GeV
$50\,\mathrm{pb}^{-1}$ @ 820 GeV

$50\,\mathrm{pb}^{-1}$ @ 500 GeV
$250\,\mathrm{pb}^{-1}$ @ 820 GeV

Vary s to get $\sigma(\beta, Q^2, x_{IP})$ at different y

$50\,\mathrm{pb}^{-1}$ at $E_p = 500\,\mathrm{GeV}$

$\sim 40\%$ measurement of $R^D = F_L^D/(F_2^D - F_L^D)$

Comparable stat and syst errors

4) Many more unanswered questions . . .

- Precise relationship between F_2^D and F_2
- Role of rapidity gap survival probabilities?
- . . .
- . . .

Conclusion

- Hard diffraction is a Complex Subject!
- Hard ep diffraction tackles many fundamental questions in strong interactions
- This talk only scratched the surface. See also . . .

  Hadronic Final States (Ada Solano)

  Vector Meson Production (Arik Kreisel)

  High $|t|$ diffraction (Angela Wyatt)

- Should be lots more data to come . . .
  - HERA-I still under analysis ($> 100\,\mathrm{pb}^{-1}$ per experiment)
  - HERA-II ($\sim 1\,\mathrm{fb}^{-1}$ per experiment by 2006)
- New detectors - H1 VFPS . . .
- Scope for much higher Precision!

- Many open questions remain.
- Lots of experimental / phenomenological challenges!
