Hard Diffraction at HERA - Experimental Perspective

Paul Newman, Birmingham University

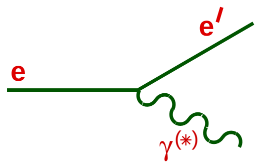
- Introduction to Diffraction at HERA.
- Latest Diffractive Structure Function Data
- QCD structure of $\gamma^{\star} p$ Diffraction
- Energy Dependence of $\gamma^{\star} p$ Diffraction
- Comparisons with Dipole Models
- Hadronic Final State Data
- Relation to hard diffraction in $p\bar{p}$ Scattering
- Prospects for the Future

Closely Related Topics not covered in any depth here:

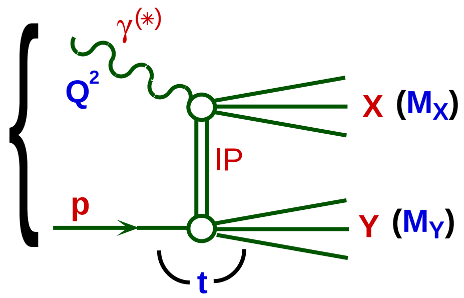
- Diffractive Photoproduction
- Vector Meson Production
- Diffraction at Large $|t|$
- Total $\gamma^{(\star)} p$ cross sections . . .

Diffraction at HERA

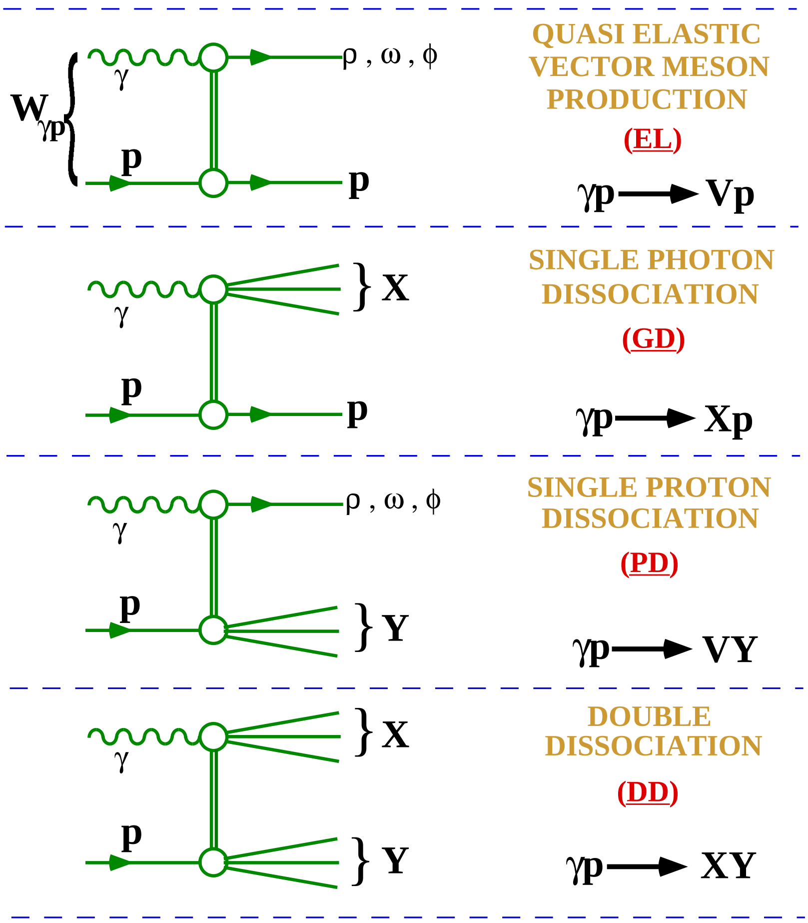
At HERA, diffractive $\gamma^{(\star)}p$ interactions can be studied . . .



×



COLOUR SINGLET EXCHANGE PROCESSES IN γ^*-p INTERACTIONS



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

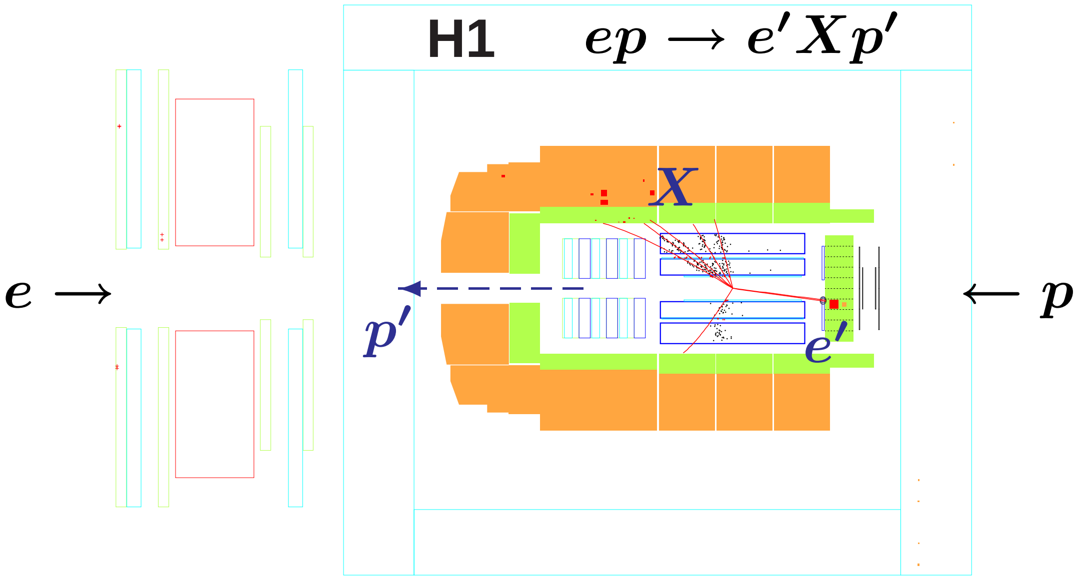
pQCD at $\gamma^* \mathbb{P}$ vertex

γ^* ‘probes’ $\mathbb{P}$?

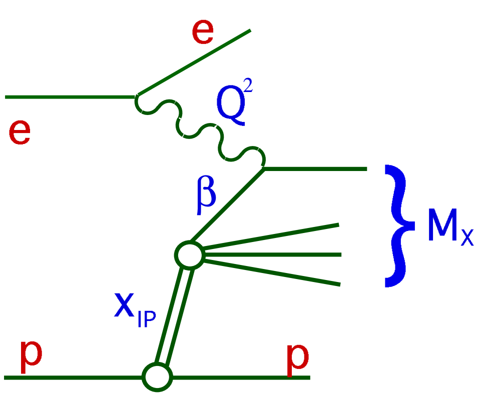
~ 60 H1 / ZEUS publications on diffraction so far!

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

$\gamma^* p \longrightarrow X p$ at HERA



Commonly used kinematic variables . . .



$$x_{I\!P} \equiv \xi = \frac{q.(p-p')}{q.p} = x_{(I\!P/p)}$$

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

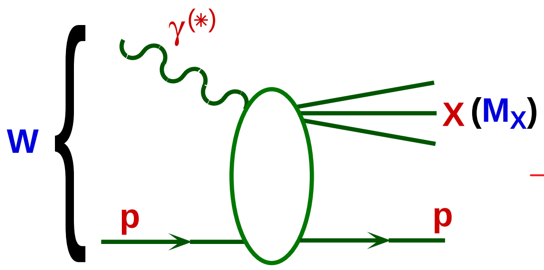
$$(x = x_{I\!P}\beta)$$

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

Experimental Techniques

Two complementary measurement techniques ...

1) Measure Hadrons Comprising X

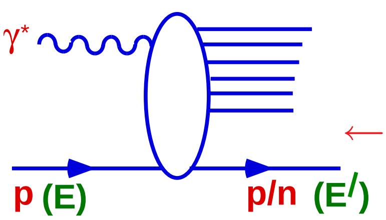


$\longrightarrow$ Largest rapidity gap among final state hadrons.

$\Delta\eta$ 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



$\longleftarrow$ No explicit gap requirement

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

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

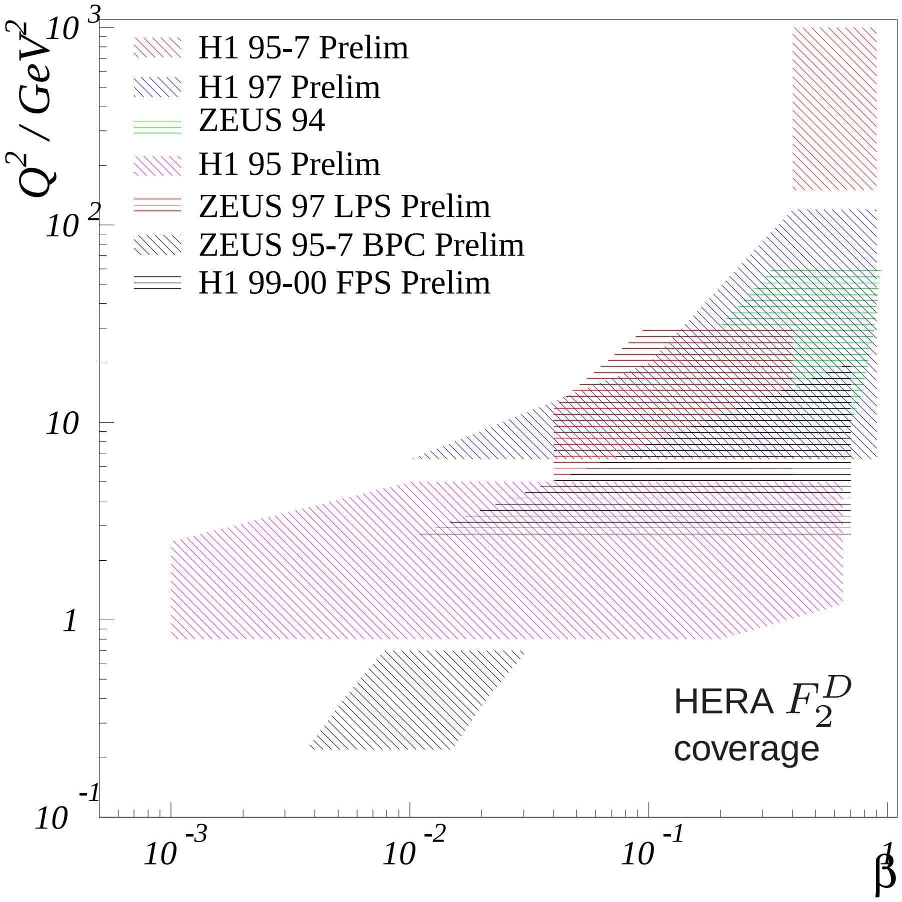
Diffraction of Virtual Photons, $\gamma^\star p \longrightarrow Xp$

Inclusive cross-section $\gamma^* p \rightarrow Xp$ usually presented as a

Diffractive Structure Function . . .

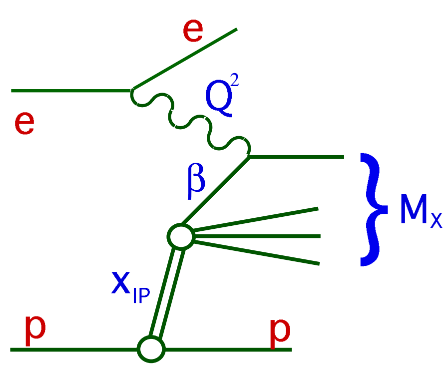
$$F_2^{D[3(4)]}[\beta, Q^2, x_{I\!P}, (t)] = \frac{\beta\ Q^4}{4\pi\alpha^2\ (1-y+y^2/2)}\ \frac{d\sigma_{ep\rightarrow eXY}}{d\beta\ dQ^2\ dx_{I\!P}\ (dt)}$$

(Assumes $F_L^{D[3/(4)]} = 0$)



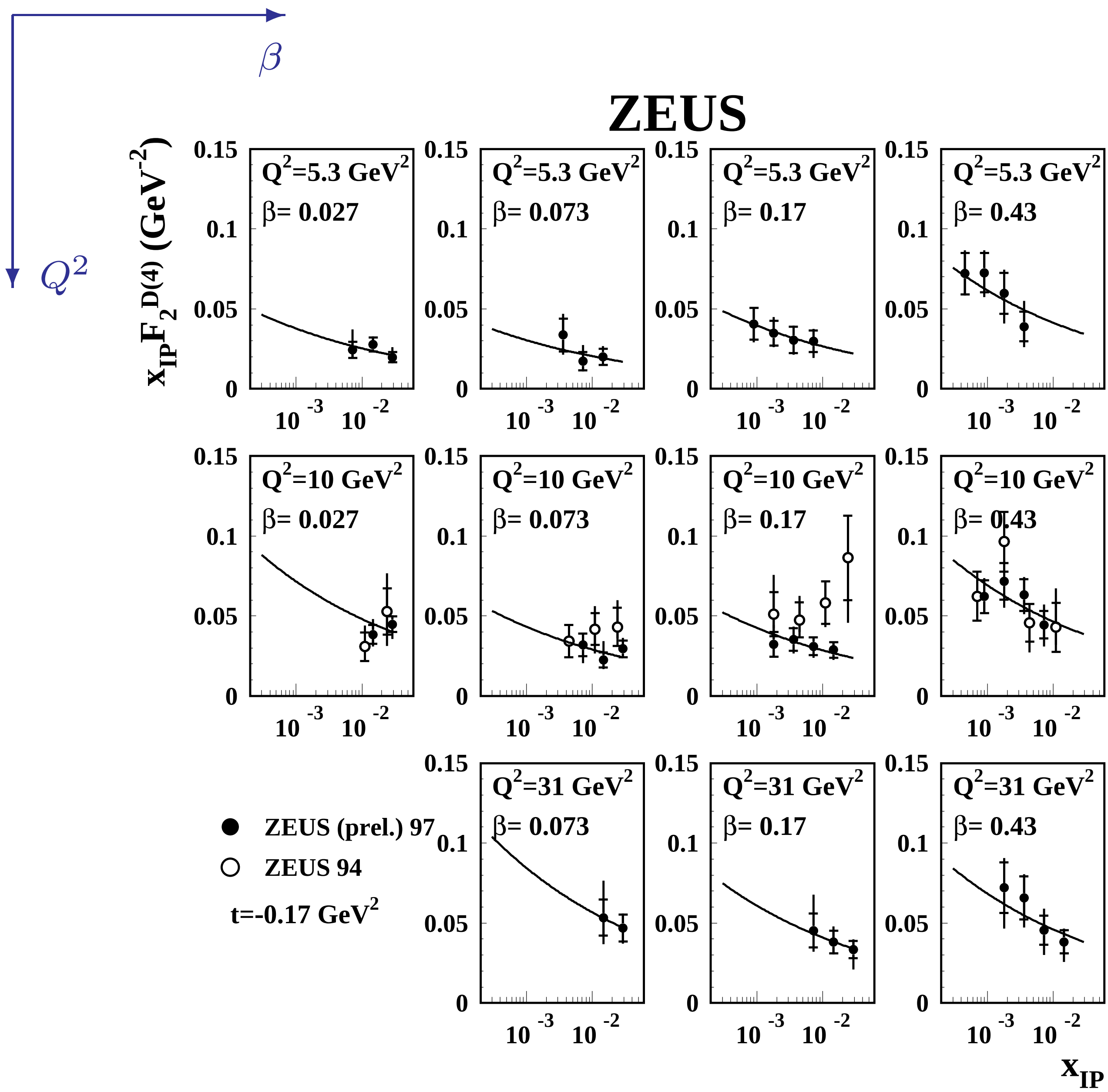
Increasingly precise data spanning wide range in β, Q^2 with $x_{I\!P} < 0.05$

Several new measurements released during 2001



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

Leading proton data allow 4-fold differential cross sections
$\rightarrow F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t)$

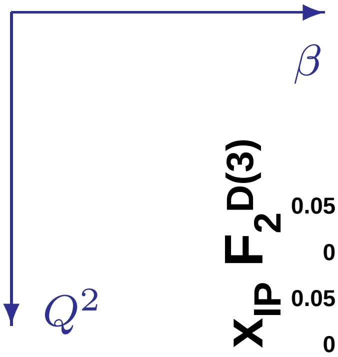


New ZEUS ’97 LPS data give factor 6 increase in statistics

For non-proton tagged data, t poorly reconstructed.

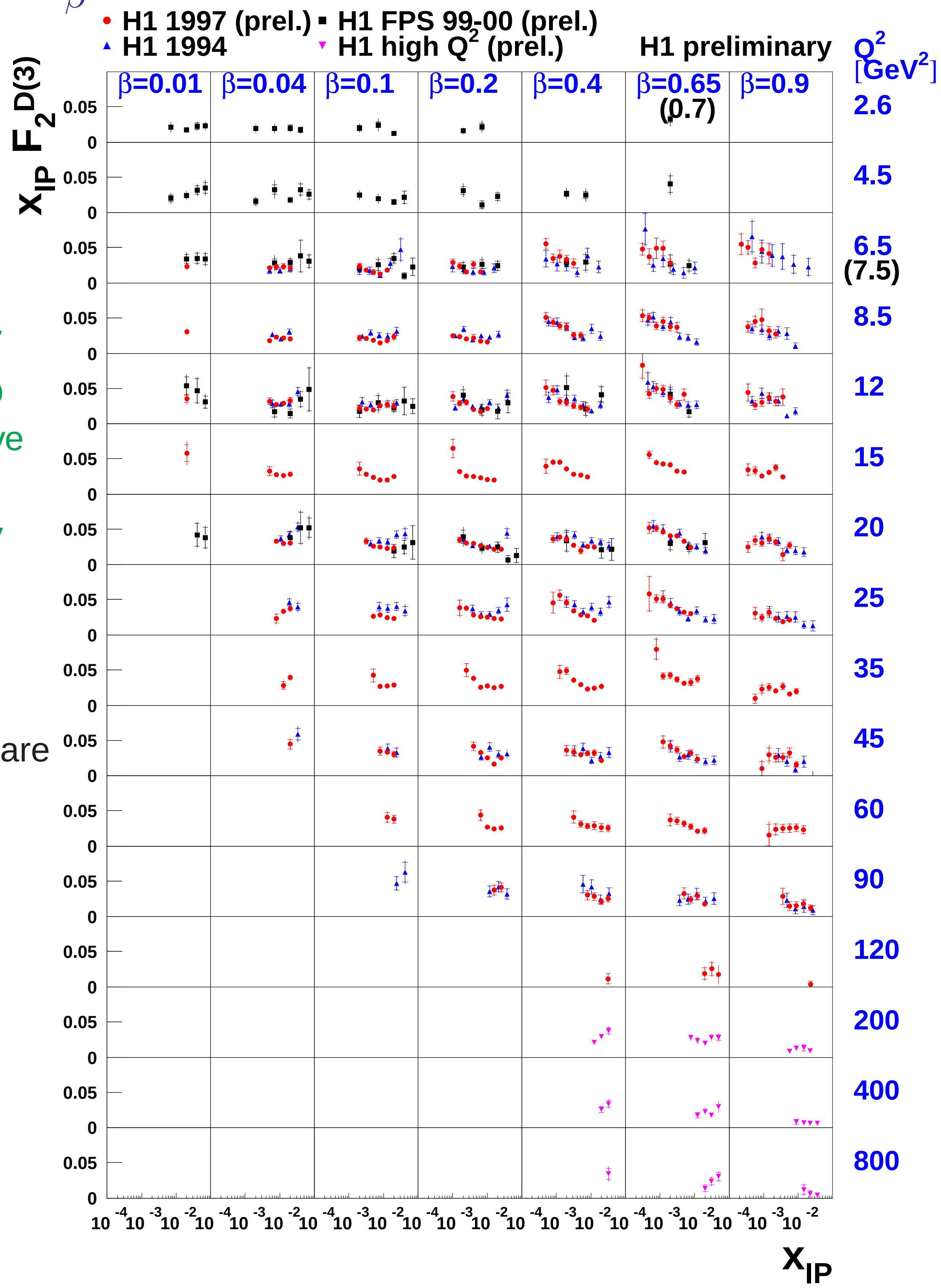
$\rightarrow$ measure $F_2^{D(3)}(\beta, Q^2, x_{I\!P}) = \int \mathrm{d}t \, F_2^{D(4)}$

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

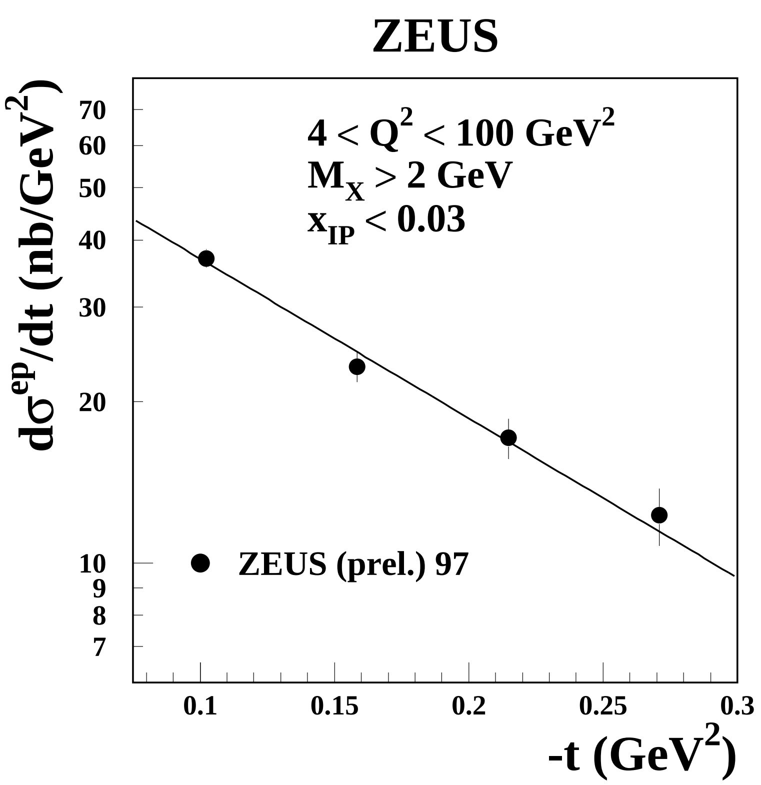


New H1 '97 rapidity gap data improve high Q^2 statistics by factor ~ 5

FPS 99-00 are first low $x_{I\!P}$ data from H1 FPS



t Dependence from Tagged Proton Data



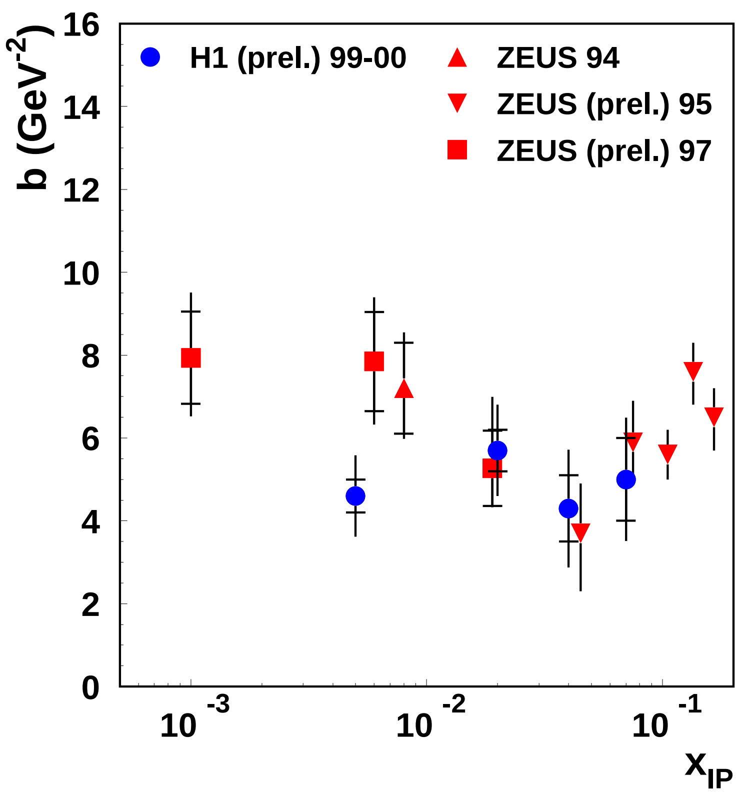
Fit full ZEUS dataset to ...

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

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

Highly peripheral p scattering

Slope larger than for e.g. elastic J/ψ $\longrightarrow$ larger spatial extent at γ^* fluctuation?



Data so far inconclusive on shrinkage.

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

No significant dependence on β, Q^2, M_X

Factorisation Properties of F_2^D

QCD Hard Scattering Factorisation for Diffractive DIS:-

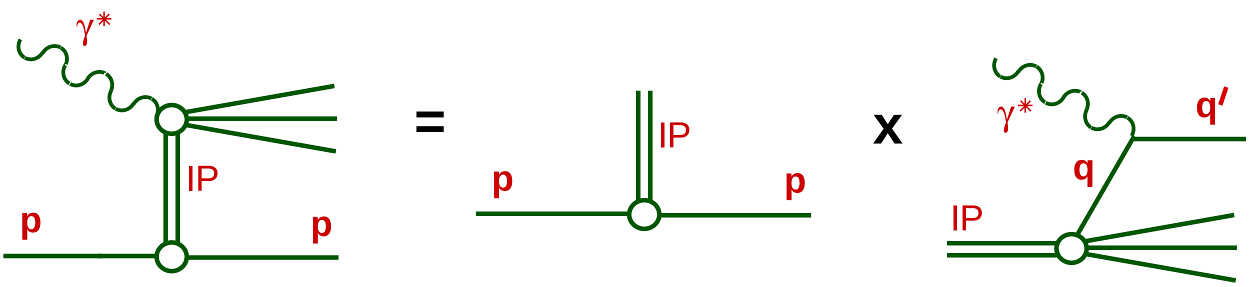
(Trentadue, Veneziano, Berera, Soper, Collins . . .)
Diffractive parton densities $f(x_{I\!P}, t, x, Q^2)$ express proton parton probability distributions with intact final state proton at particular $x_{I\!P}, t \ldots$

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

At fixed $x_{I\!P}, t$, $f(x_{I\!P}, t, x, Q^2)$ evolve with x, Q^2 according to DGLAP equations.

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

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

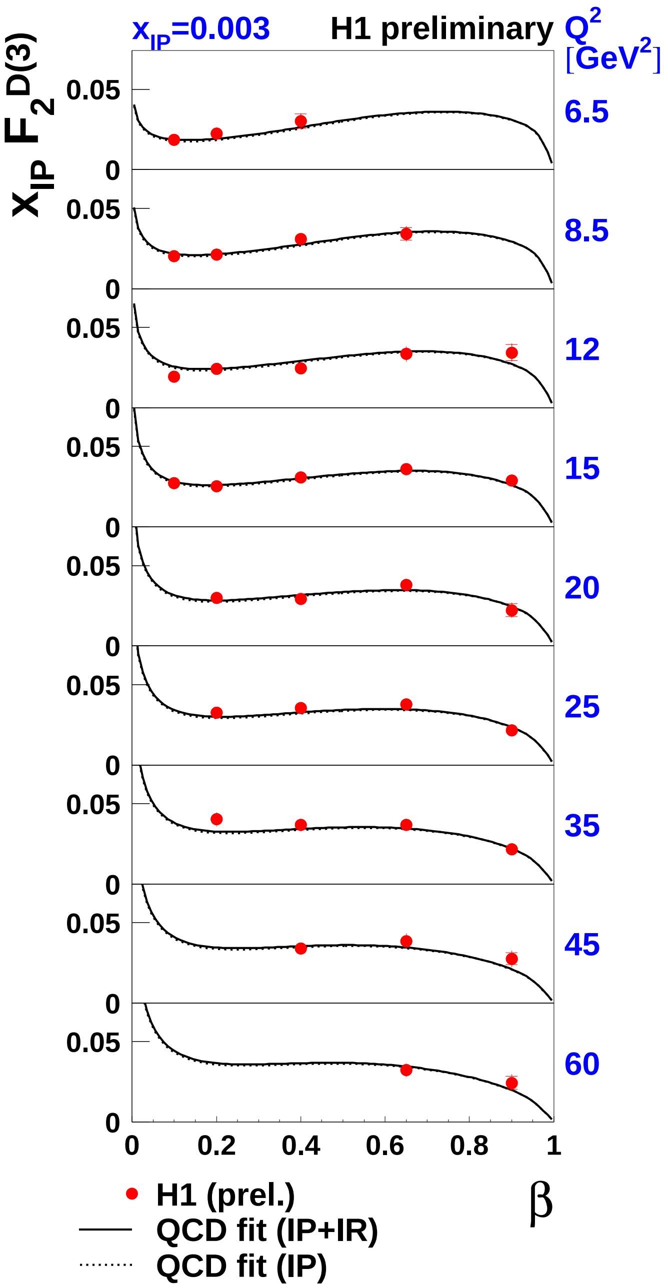


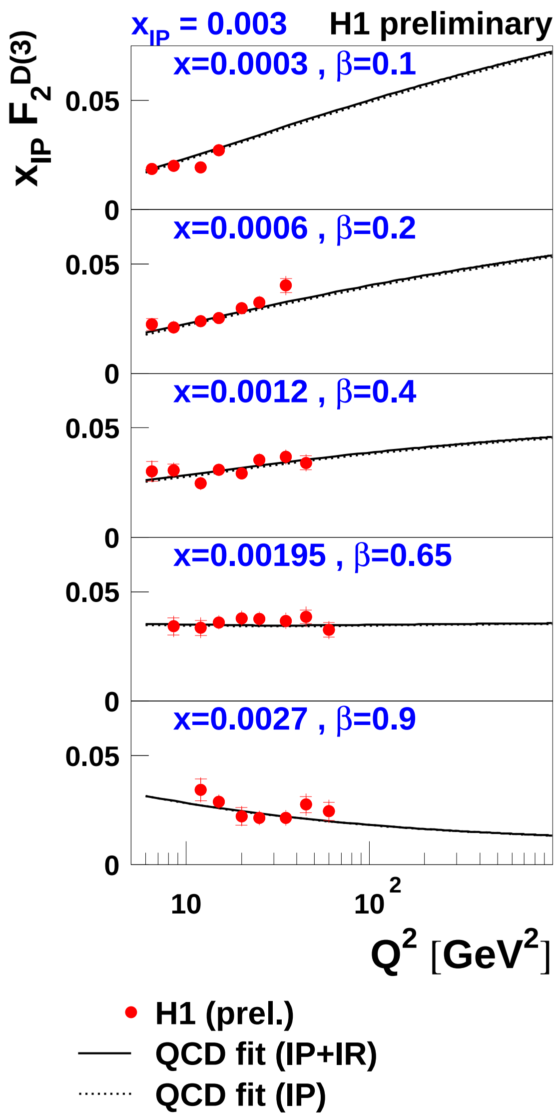
$$\sigma(\gamma^* p \to Xp) \sim f_{\mathbb{P}/\mathrm{p}}(x_{I\!P}, t) \otimes F_2^{\mathbb{P}}(\beta, Q^2)$$

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

β, Q^2 dependence of $F_2^{D(3)}$

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





β dependence relatively flat.

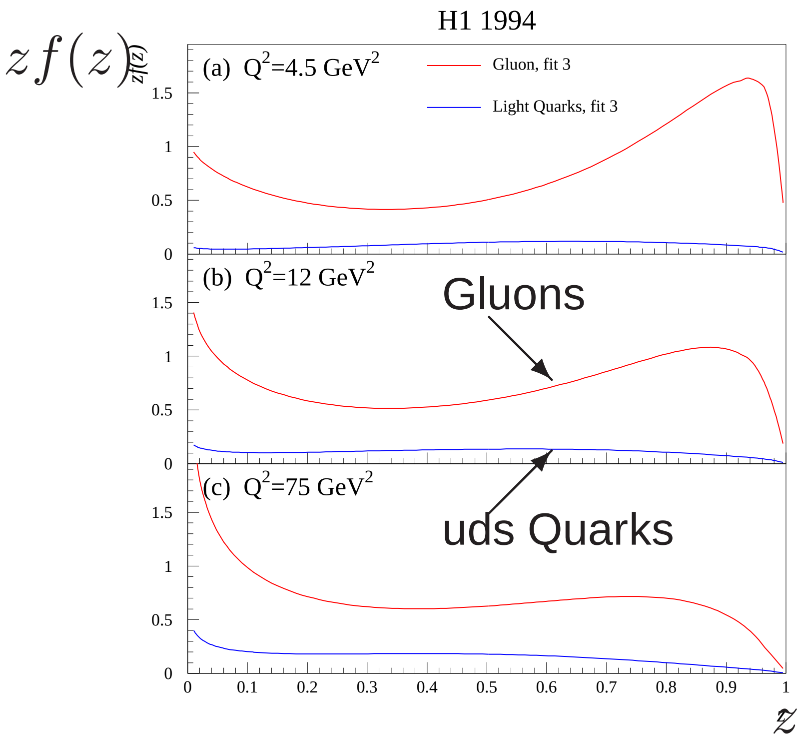
Rising scaling violations with $\ln Q^2$ up to large β

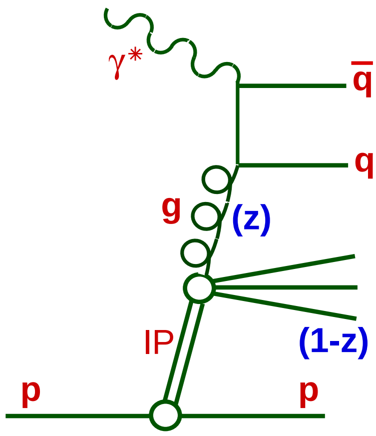
Require large gluon contribution in diffractive pdf's, extending to large fractional momenta.

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?
- .....

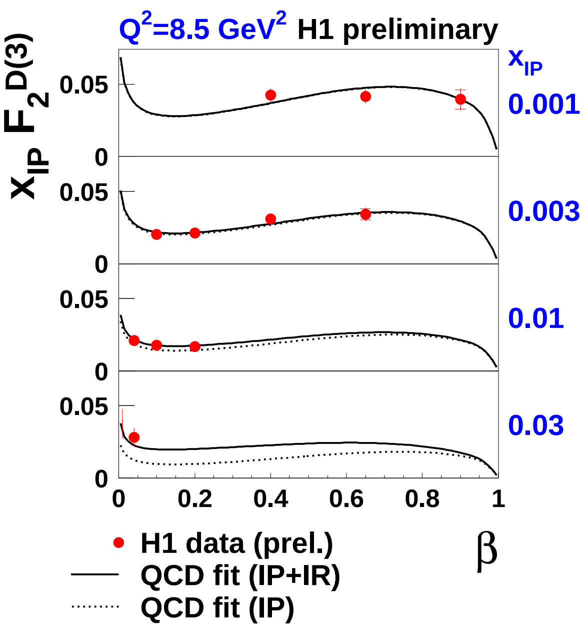
Parton densities implemented in MC models for comparison with final state data. eg . . .

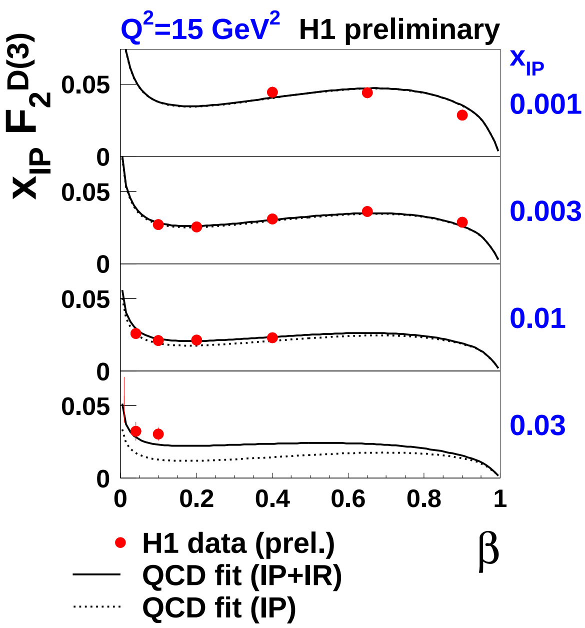
'H1 Fit 3' - 'peaked' gluon (as above)

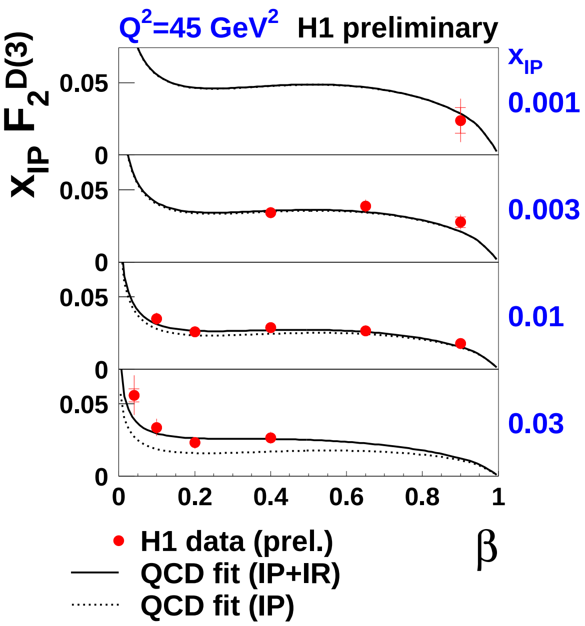
'H1 Fit 2' - 'flat' gluon

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

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

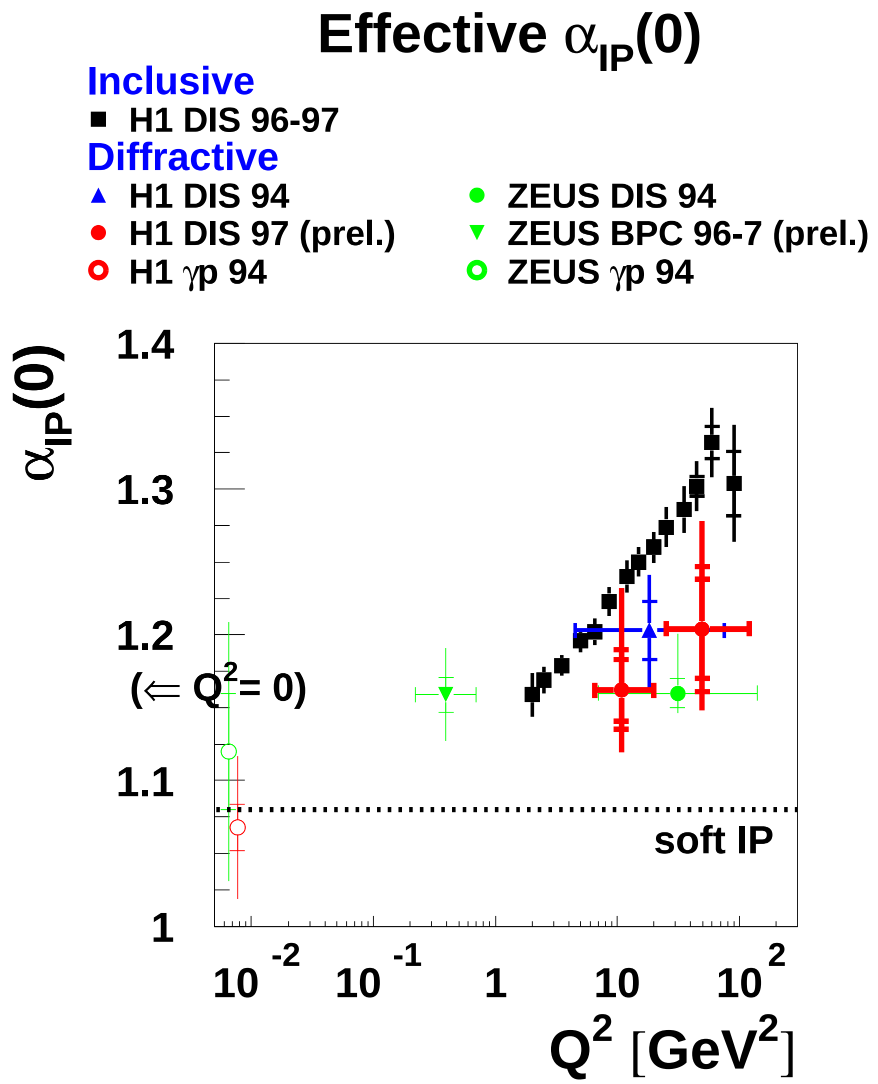
No evidence for breakdown of Regge factorisation hypothesis.

How Universal is the Pomeron?

Compare effective $\alpha_{I\!P}(0)$ from F_2^D and $F_2 \ldots$

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

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



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

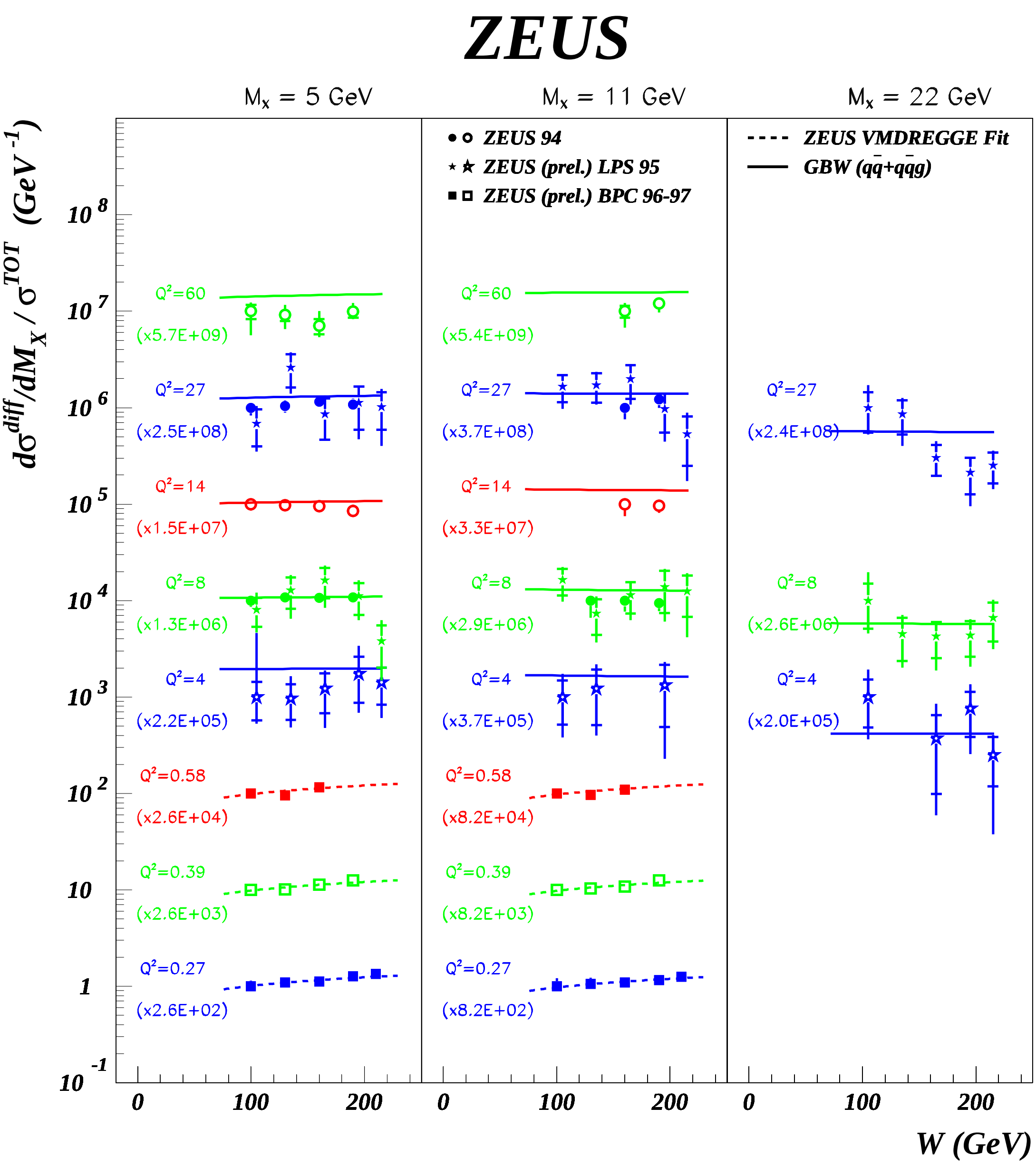
Growth of effective $\alpha_{I\!P}(0)$ slower for diffractive than for inclusive cross section?

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 $\dfrac{\int dt \;\; d\sigma^{\mathrm{diff}}_{\gamma^* p \to XY}/dM_X \;\; dt}{\sigma^{\mathrm{tot}}_{\gamma^* p \to X}} \propto W^{\rho}$

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

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

Interpretation unclear

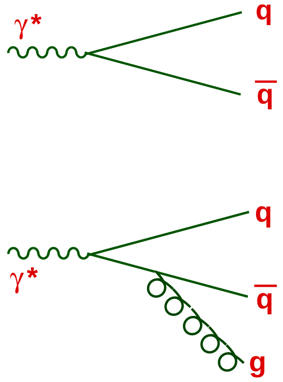
$\longrightarrow$ interplay of hard / soft? (larger dipole sizes in diffraction)

$\longrightarrow$ gluon saturation?

Colour Dipole Models

$\gamma^* \longrightarrow q\bar{q}, q\bar{q}g$ well in advance of target ...

Partonic fluctuations scatter elastically from proton.



$\times$ Cross section for colour dipole to scatter elasttically from proton

Simple relationships between $\sigma_{\rm tot}$, $\sigma_{\rm el}$ and $\sigma_{\rm dif}$

Describe diffraction beyond leading twist (high β?)

Joint description of F_2 and F_2^D ...

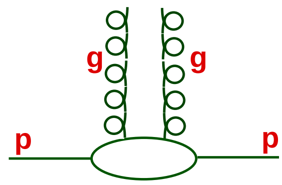
Different approaches to the dipole cross section ...

- Non-perturbative interaction with proton colour field

e.g. 'semi-classical' model
(Buchmüller, Gehrmann, Hebecker)

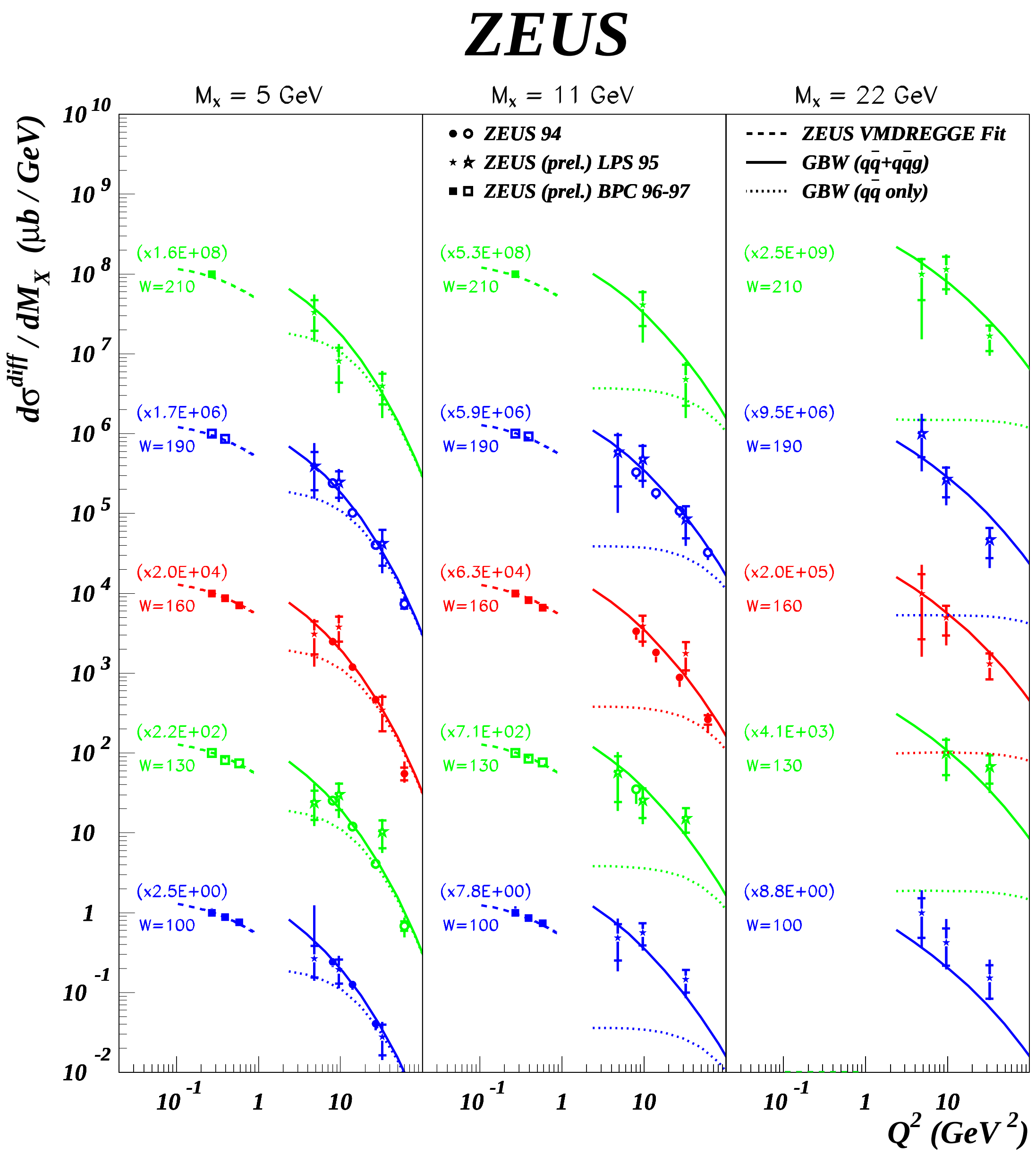
- Partonic - two gluon exchange

e.g. 'saturation' model
(Golec-Biernat, Wüsthoff)



‘Saturation’ Colour Dipole Model

Comparison with ZEUS data . . .

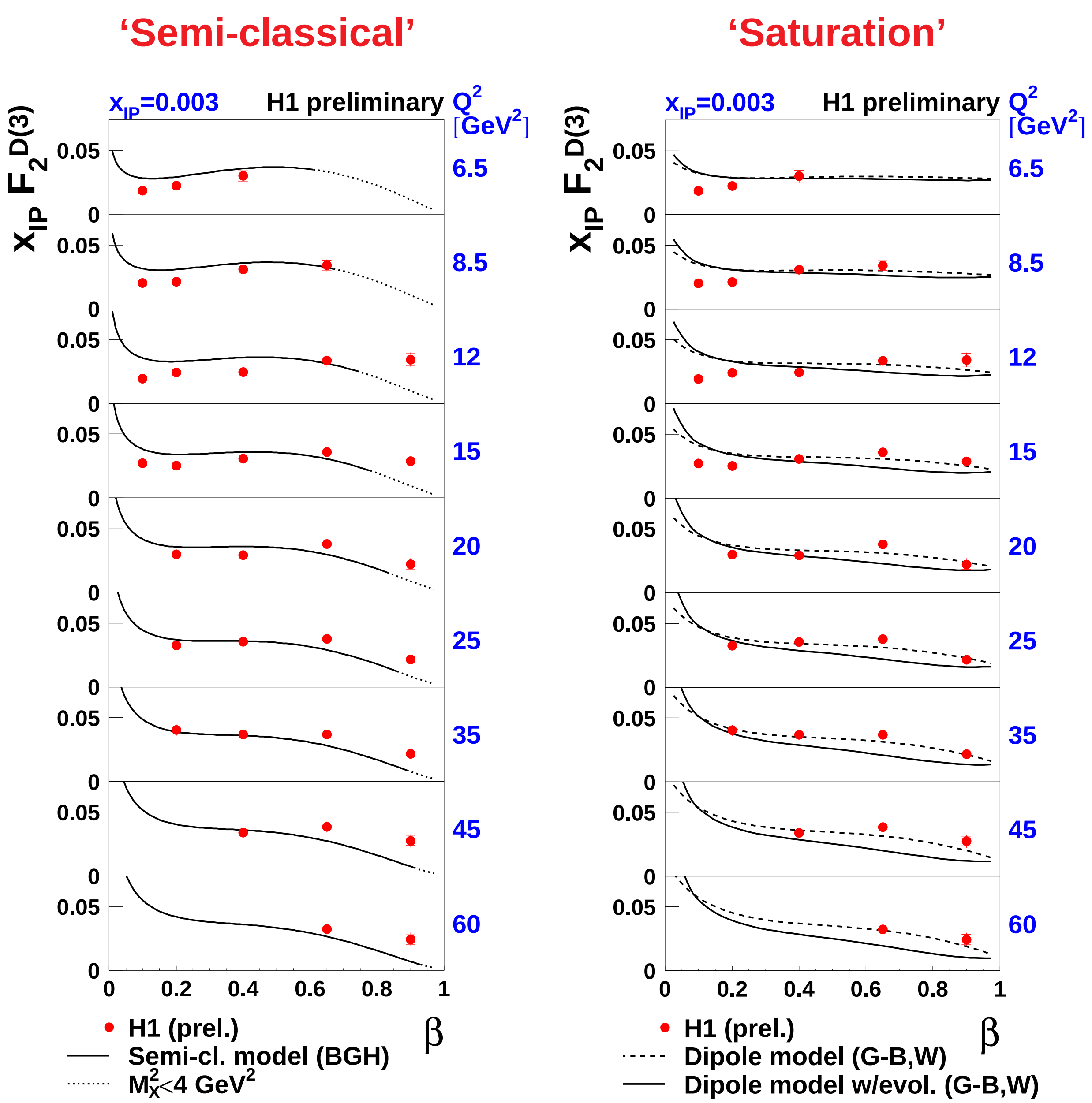


Good description for $Q^2 \geq 4\ \mathrm{GeV}^2$

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

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

Colour Dipole Models



General features reproduced. Exceed data at low β, low Q^2.

Impressive given that models basically constrained by F_2 data!

'Saturation' model - higher twist at high β $\rightarrow$ better description

Inclusion of QCD evolution in 'saturation' model does not help.

Description improves with extra $4/9$ colour factor for $q\bar{q}g$

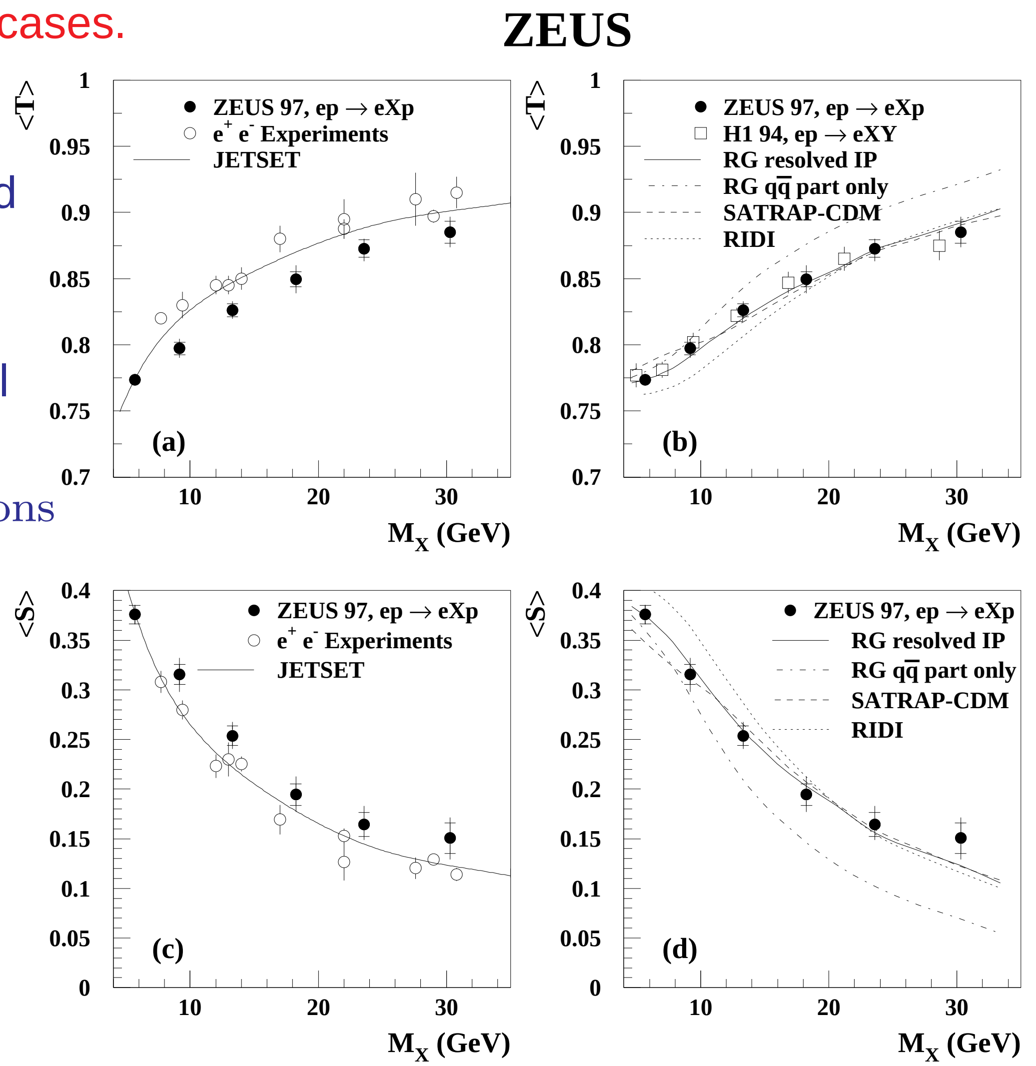
Diffractive Final State Data - Event Shapes

F_2^D only directly measures diffractive quark distribution

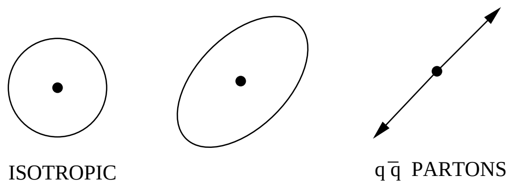
Many hadronic final state observables constrain the gluon distribution / event topology

Very good agreement with diffractive parton densities from F_2^D in almost all cases.

e.g. Thrust and Sphericity indicate less collimated final state than $e^+e^- \to$ hadrons at similar energy.



$1/2 < T < 1$



$1 > S > 0$

Described by models with final states containing > 2 parton leading final state

- $q\bar{q}g$ in dipole models

- BGF in resolved $I\!P$ models

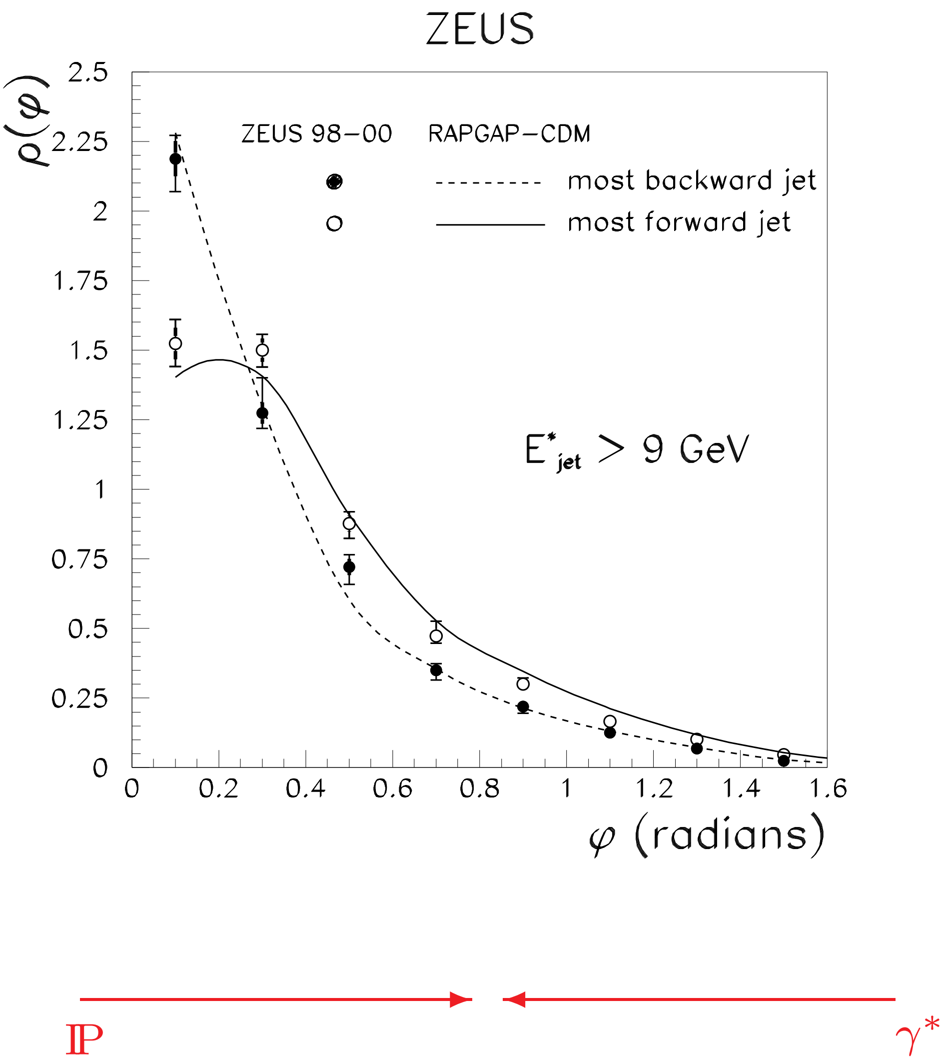
Diffractive Final State Data - Jet shapes

Differential jet shapes of most forward ($\mathbb{P}$ direction) and backward (γ^* direction) jets in 3-jet analysis.

Jet in $\mathbb{P}$ direction broader than jet in γ^* direction.

Jets have similar energies.

Suggests gluon in $\mathbb{P}$ direction. Quarks in γ^* direction.



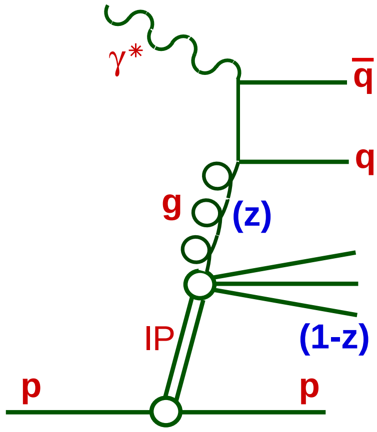
Diffractive Final State Data - Dijets

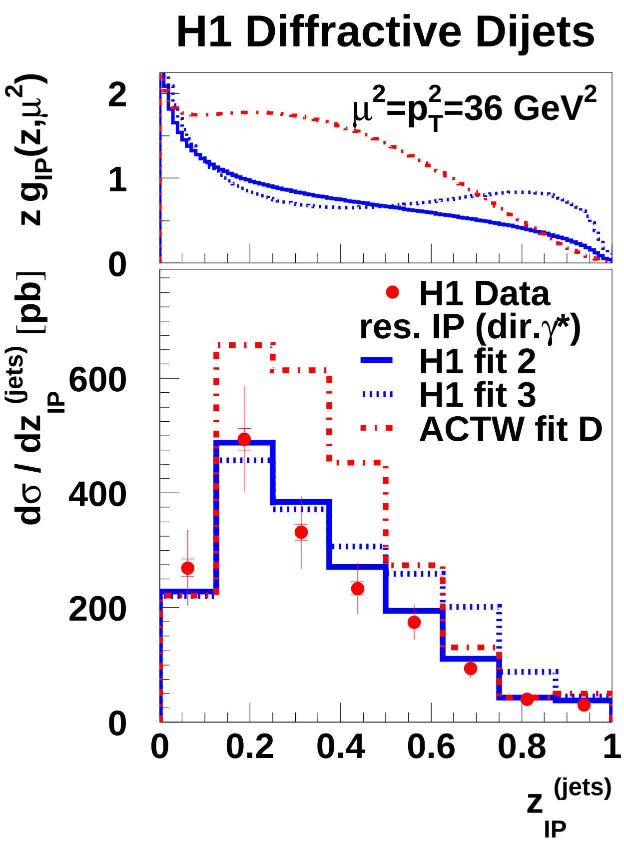
Best tests of gluon come in dijet and open charm studies.

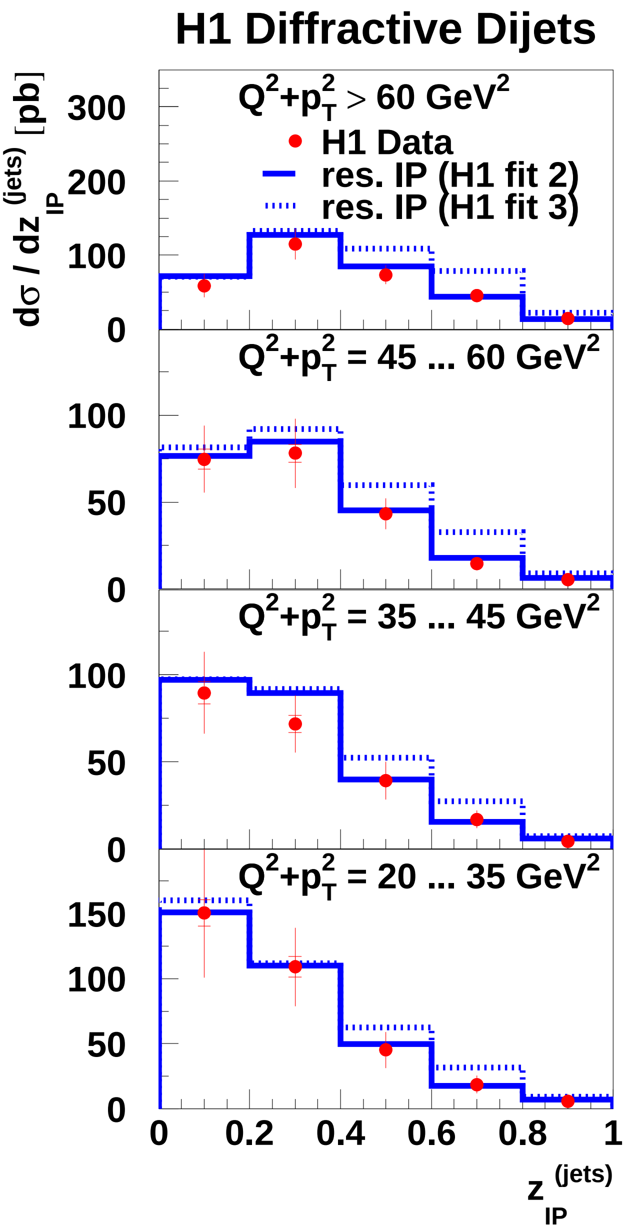
Gluon initiated processes

(boson-gluon fusion).

Rates $\sim$ proportional to gluon density!







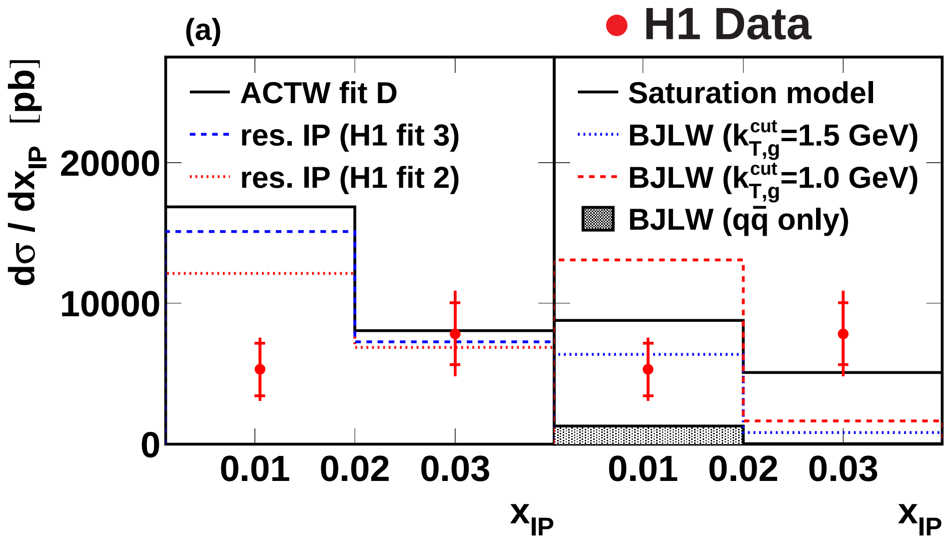
Can distinguish between different fits to F_2^D

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

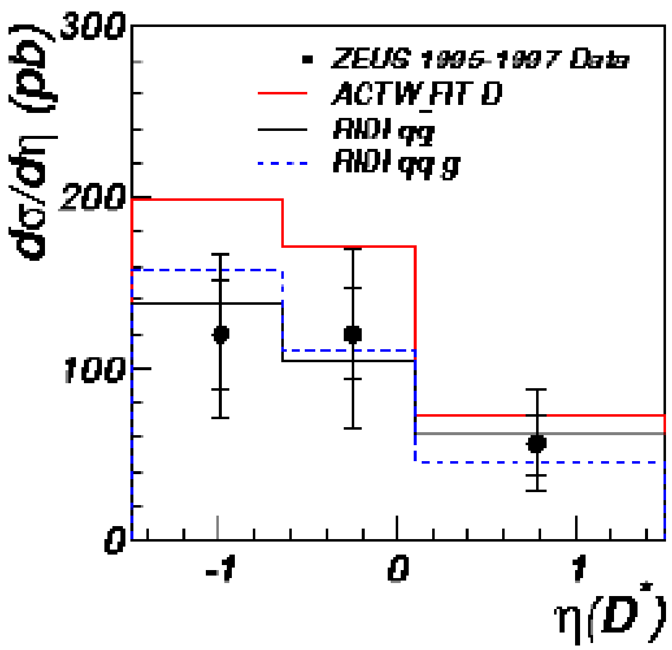
Also supports Regge factorisation (fits double differential $z_{\mathbb{P}}, x_{\mathbb{P}}$ cross secs with $\alpha_{\mathbb{P}}(0) \sim 1.2$)

Diffractive Final State Data - Open Charm

Even low statistics D^* cross sections can discriminate between models.



H1 DIS: $2-3\sigma$ discrepancy from resolved $\mathbb{P}$ model at low $x_{\mathbb{P}}/M_X$.



ZEUS γp: Predicted normalisation exceeds data by $\sim 2\sigma$

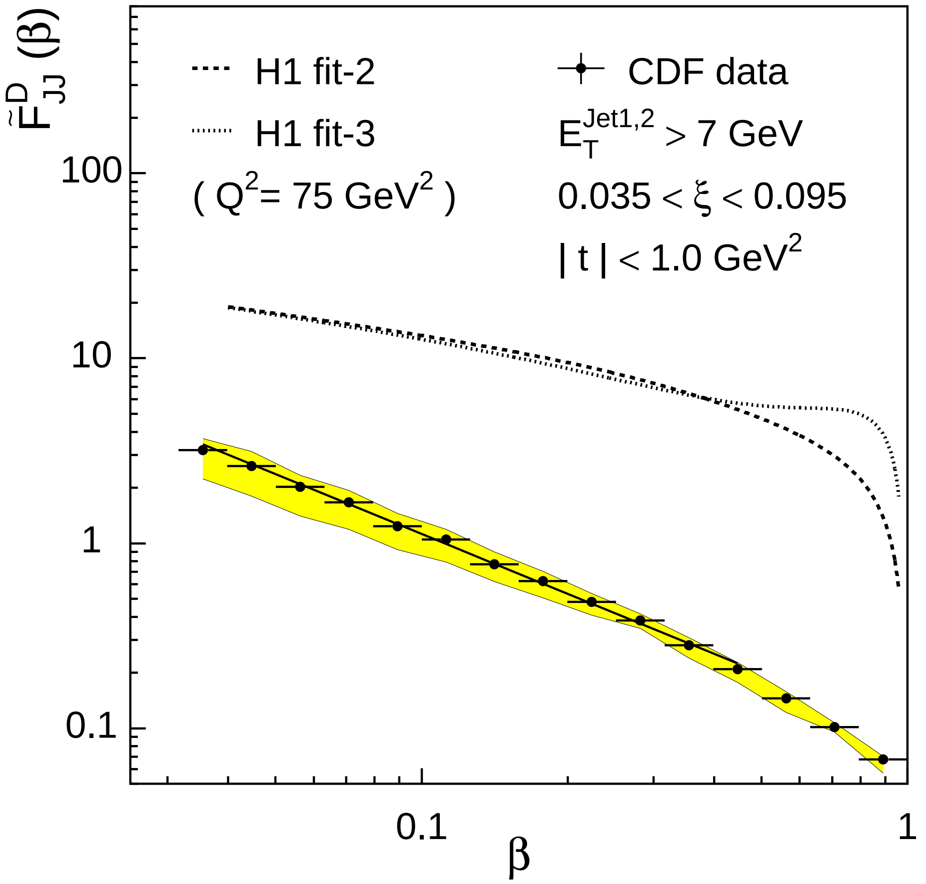
ZEUS DIS: Shapes and normalisation well described by resolved $\mathbb{P}$ models.

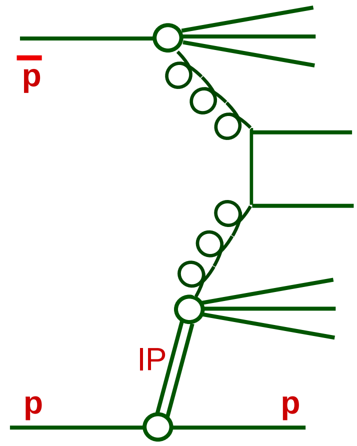
Situation not yet clear

- Statistical Fluctuations?
- First cracks in Resolved $\mathbb{P}$ model?

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?

Expected!

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?)

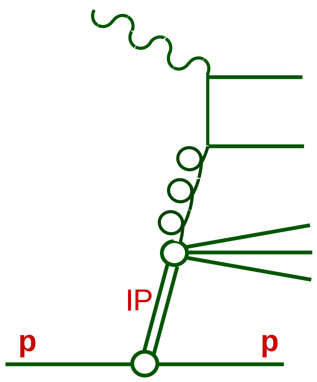
Phenomenological models can explain at least some data

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 . . .

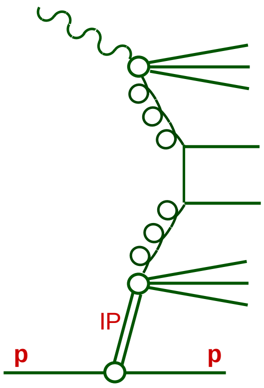
$x_\gamma^{\rm jets}$ = fraction of γ momentum entering the hard scatter.



DIRECT

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

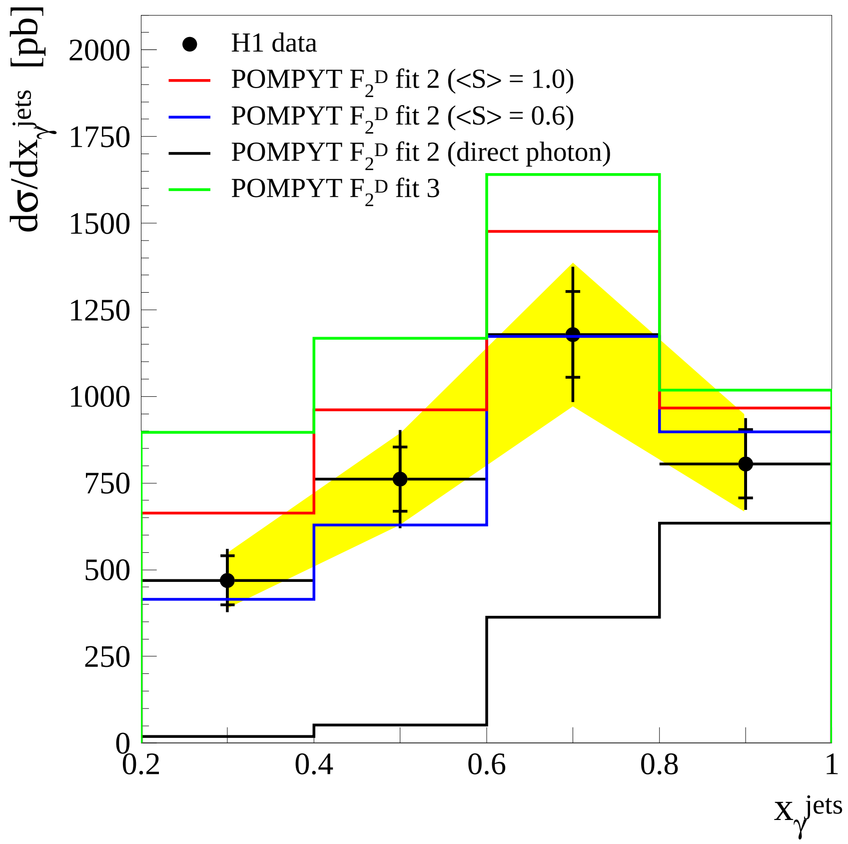
All gaps survive?



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

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!

Much more data needed to distinguish anomaly / fluct^n

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 $\longrightarrow$

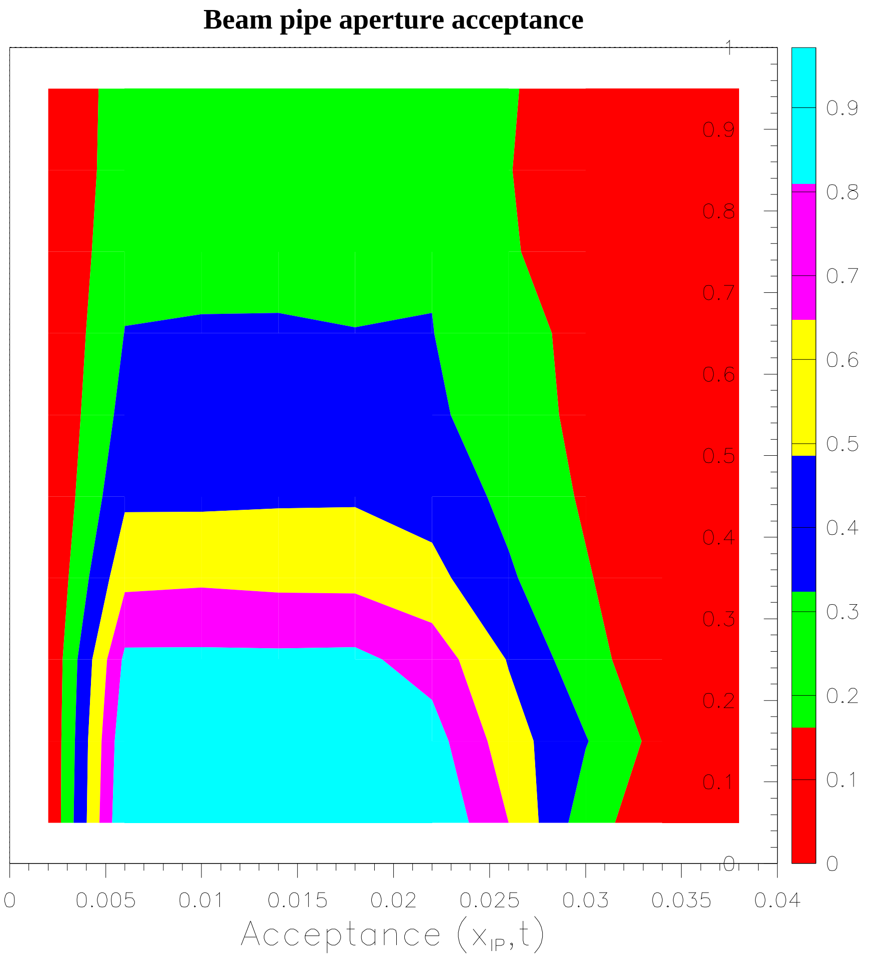
- Efficient triggering for ‘rare’ processes
- Removes rapidity gap selection systematics
- t dependences can be extracted

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

HERA-II Diffractive Shopping List

1) Lots of Precision Measurements!

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

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

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

Final state measurements. e.g. Diffractive open charm.

2) Measurements of t Dependence

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

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

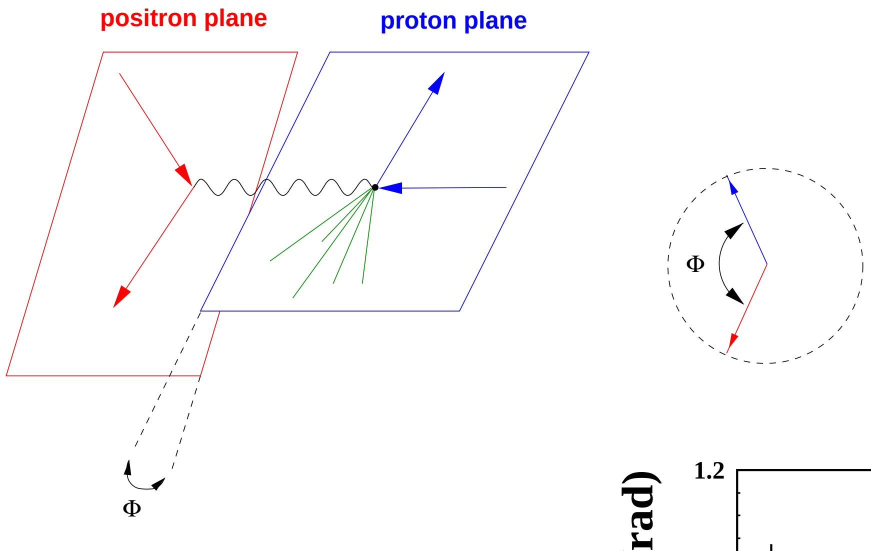
3) Measurements of Longitudinal Photon Contributions

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 $\cos\phi_{ep}$.

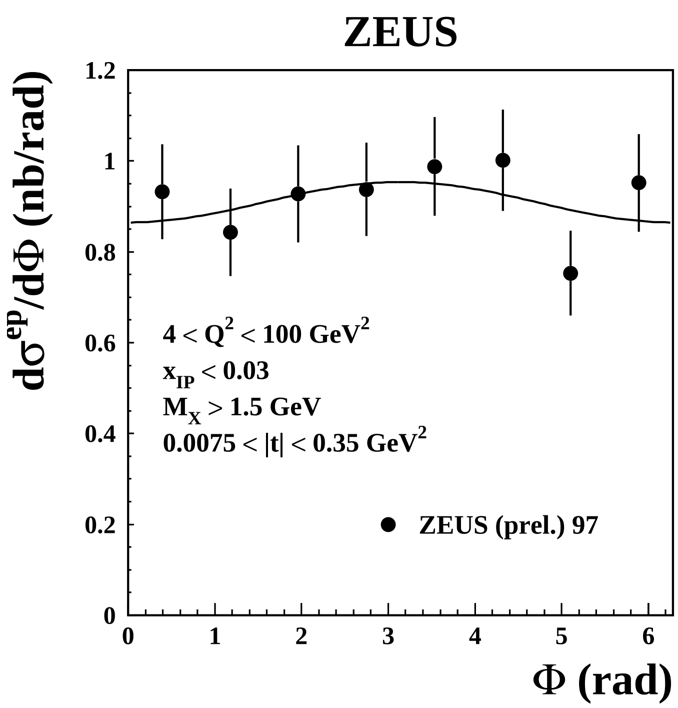


First measurement from ZEUS LPS . . .

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

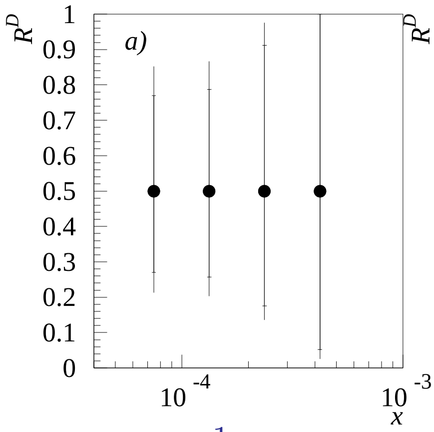
$$A_{LT} = -0.049 \pm 0.058\,(\mathrm{stat})\ {}^{+0.056}_{-0.009}\,(\mathrm{syst})$$

Lots more stats needed!

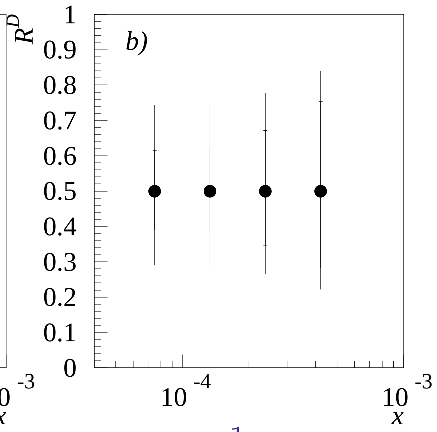


HERA-II Diffractive Shopping List

F_L^D continued: Vary beam energies?



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



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

Vary s to get $\sigma(\beta, Q^2, x_{I\!P})$
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 . . .

- Role of rapidity gap survival probabilities?
- Precise relationship between F_2^D and F_2
- Final states where all partons have high p_T

  e.g. High p_T exclusive $q\bar{q}$ production (high $z_{I\!P}$ dijets)

  Fully pQCD calculable? (Bartels et al.)
- High $|t|$ processes, DVCS, Υ
- . . .

Conclusion

- Hard diffraction is a Complex Subject!
- Hard ep diffraction tackles many fundamental questions in strong interactions
- This talk only scratched the surface (e.g. no VM discussion)

- 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!
