Diffraction at HERA and its Relation to the LHC

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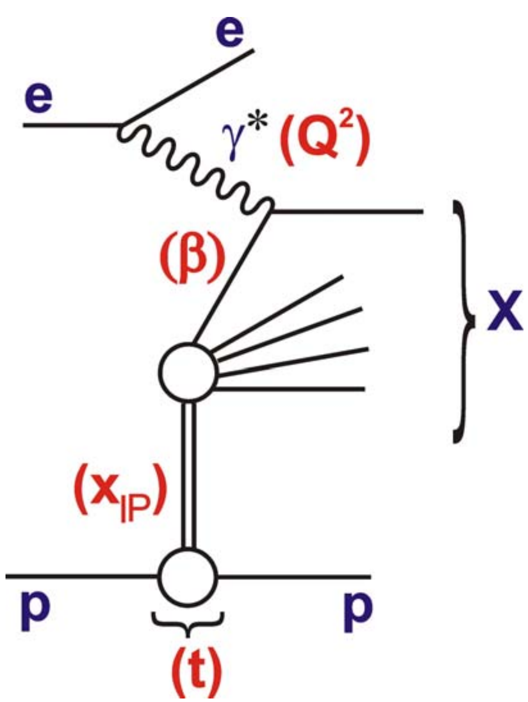
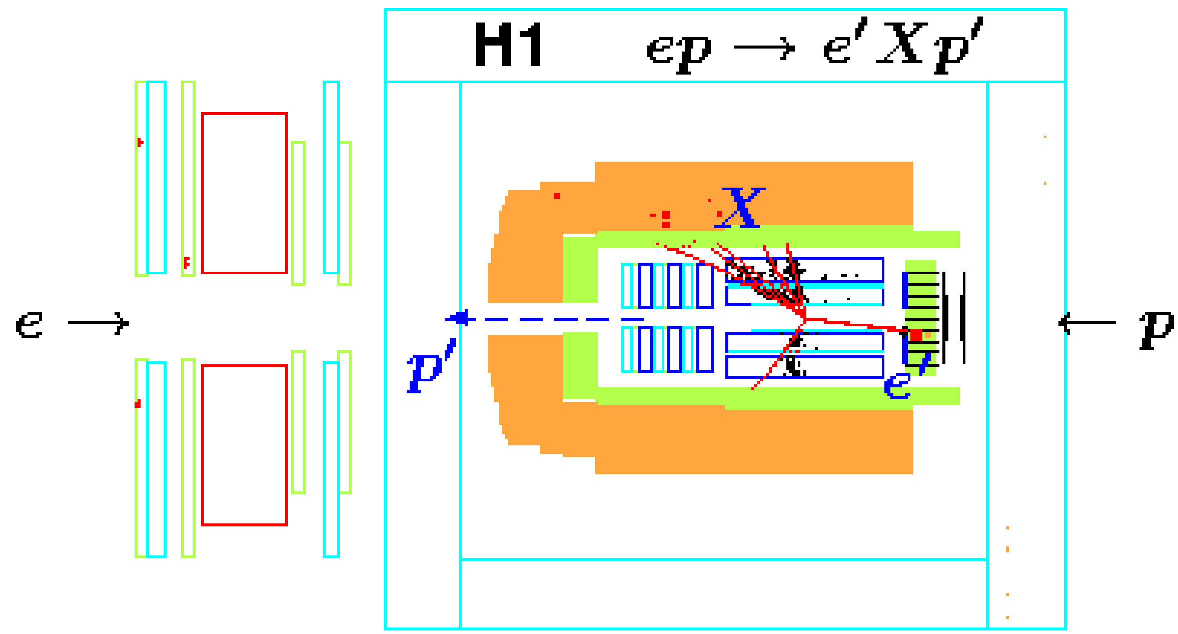
ATLAS and H1 Collaborations

LHC Physics Day on Diffraction
7 May 2009





HERA & Diffraction

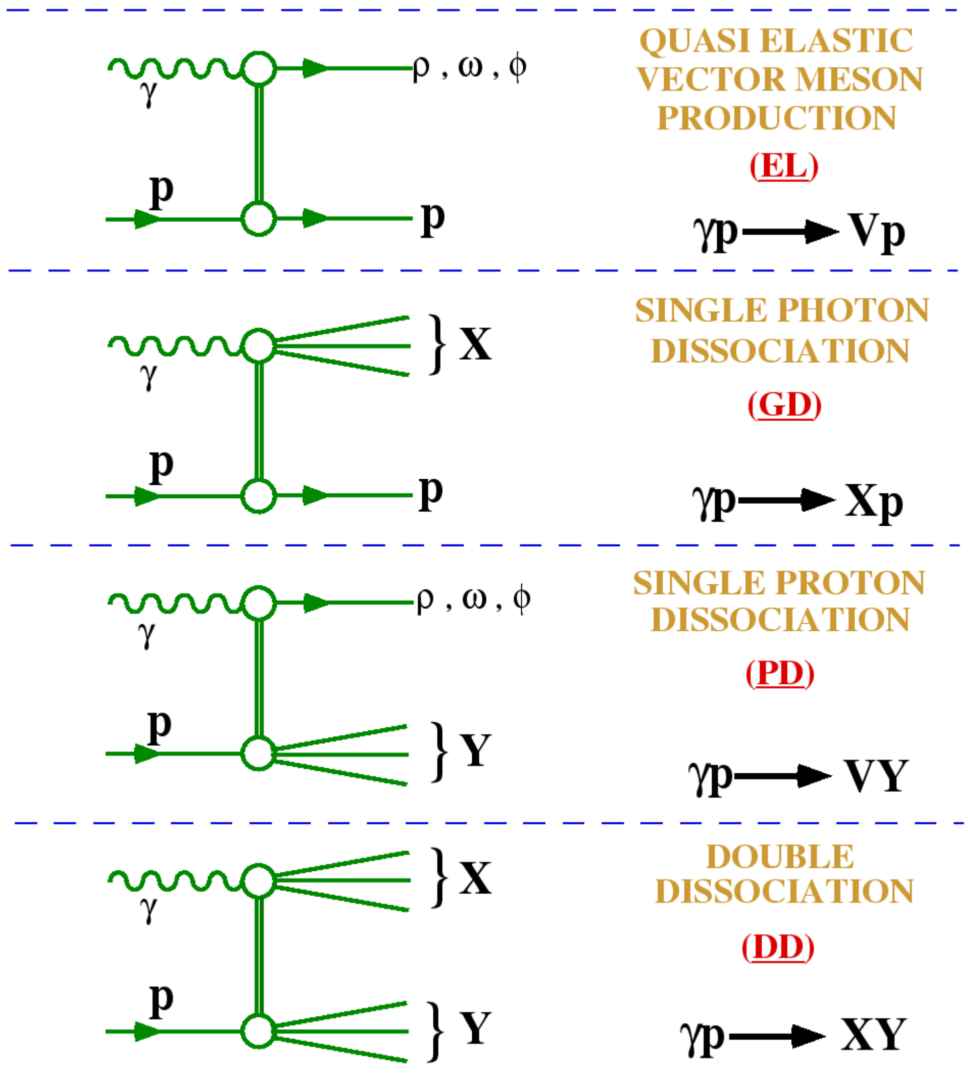
ep / $\gamma^{(*)}$p collisions
at sqrt(s) ~ 300 GeV
1992-2007

~ 0.5 fb^{-1} per expt.

e.g. H1 publications on diffraction (similar numbers in ZEUS):

- Diffractive cross sections (SD,DD): 11 papers
- Diffractive final states: 14 papers
- Quasi-elastic cross sections: 20 papers
- Total cross sections / decomposition: 2 papers

Colour singlet exchange processes at HERA



LHC analogue is pp→pp

LHC analogue is pp→Xp

LHC analogue is pp→pX

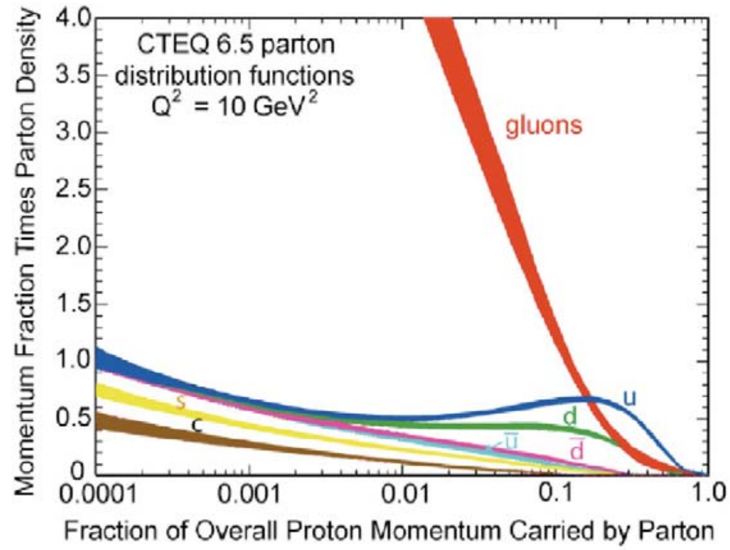
LHC analogue is pp→XY

Favourable kinematics to study X system (photon dissociation)

Low x Physics & Diffraction

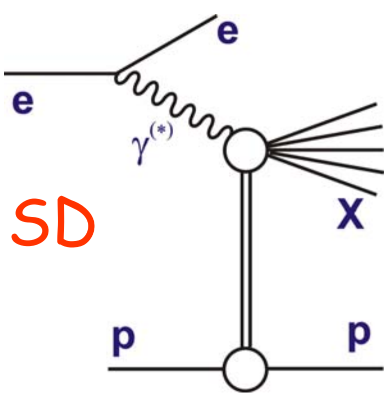
• Low x physics, as revealed by HERA, is the physics of very large gluon densities…

• Associated with a large diffractive contribution

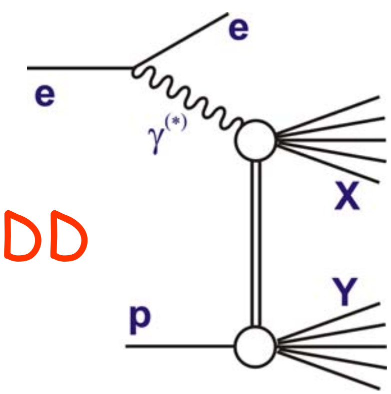


… but how to specify the difference between diffractive and non-diffractive processes?…

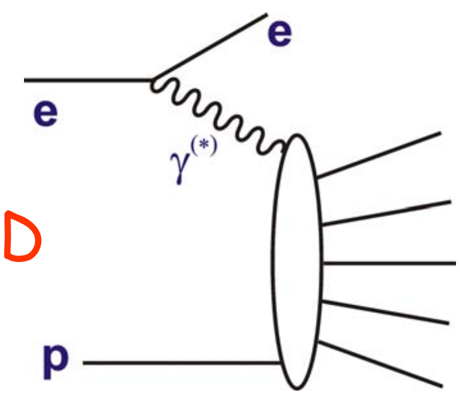
SD



DD



ND



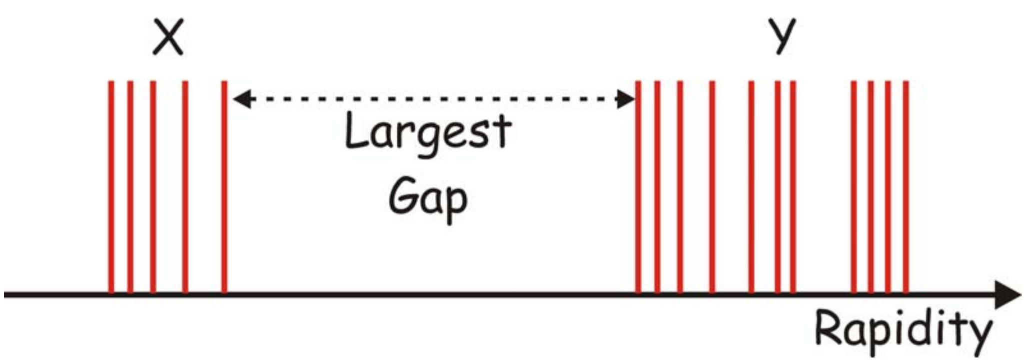
… nature gives smooth transitions between these processes

Definition of Diffraction

Definitions in terms of hadron-level observables …

• For SD ($\gamma p \rightarrow Xp$), can be done in terms of a leading proton

• More general definition to accommodate DD ($\gamma p \rightarrow XY$)
…can be applied to any diff or non-diff final state …
- Order all final state particles in rapidity
- Define two systems, X and Y, separated by the largest rapidity gap between neighbouring particles.



Many tests at HERA show leading proton & gap defs equivalent

• Alternative method (inclusive k_T algorithm decomposition) used for analysis of rapidity gaps between jets

HERA-LHC Workshop 2004-2008

<u>**Workshops on the implications of HERA for the LHC**</u>
(including many contributions on diffraction …)
Procedings available from
http://www.desy.de/~heralhc
807 pages! (March 2009)

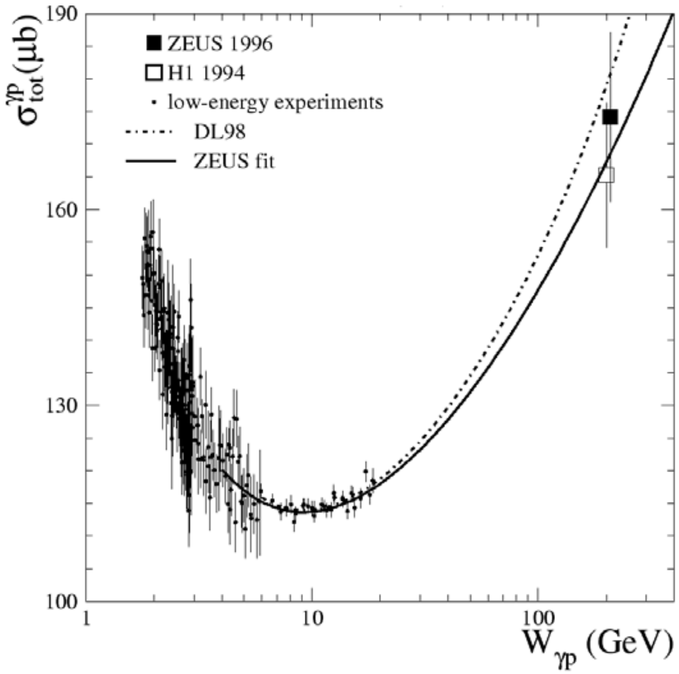
Impressum

Proceedings of the workshop
HERA and the LHC
2nd workshop on the implications of HERA for LHC physics
2006 - 2008, Hamburg - Geneva

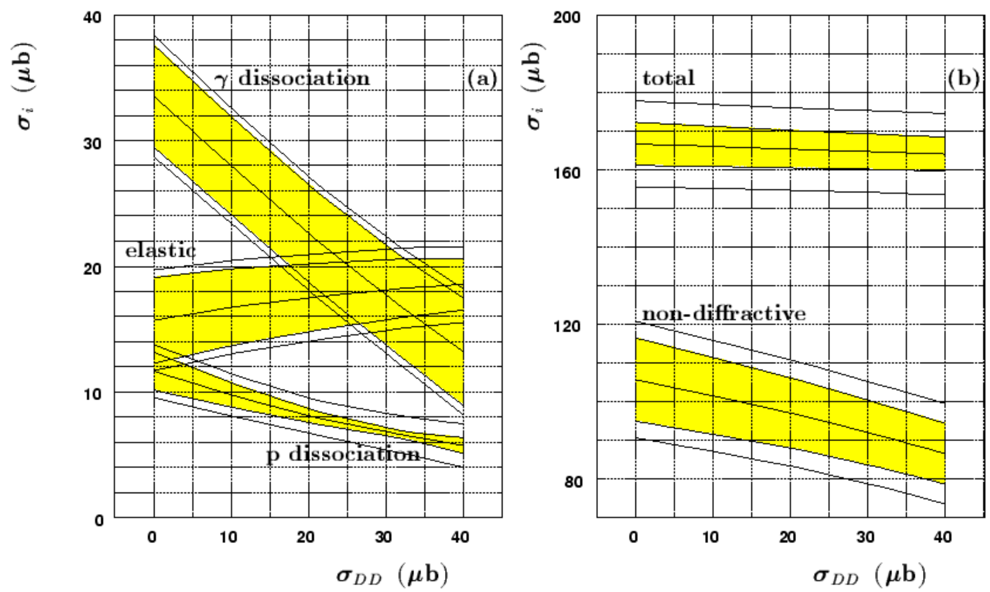
Conference homepage
http://www.desy.de/~heralhc

Online proceedings at
http://www.desy.de/~heralhc/proceedings-2008/proceedings.html

Diffraction as a Dominant Uncertainty in Minimum Bias Analyses



e.g. uncertainties on total cross section measurements dominated by modelling of diffractive contributions not observed in central detectors

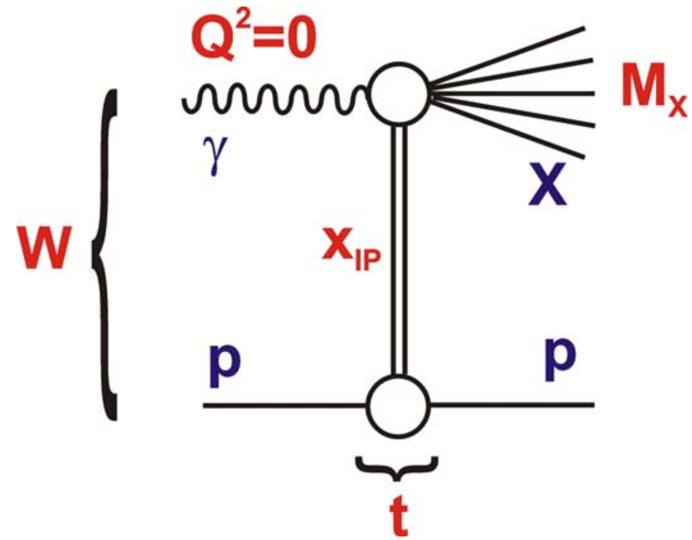


- SD and DD cross sections strongly anti-correlated in this H1 analysis

- Impossible to uniquely define SD, DD …

… operational definitions e.g. $M_X^2/s < 0.05$ … ND is what's left

Single Diffractive Kinematics

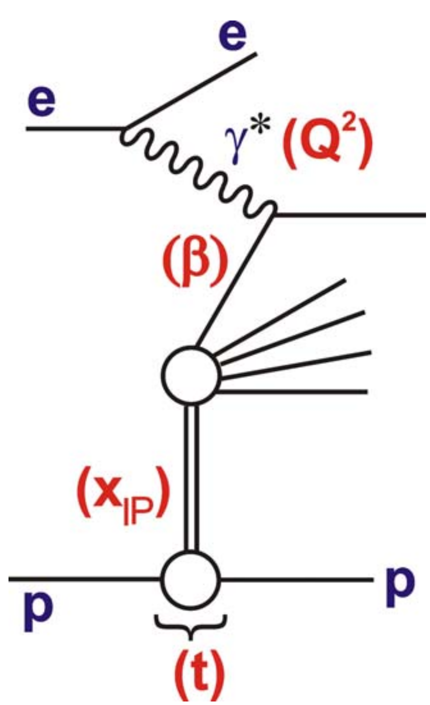


For photon virtuality $Q^2 \rightarrow 0$:

W = γp centre of mass energy

t = squared 4-momentum transfer at proton vertex

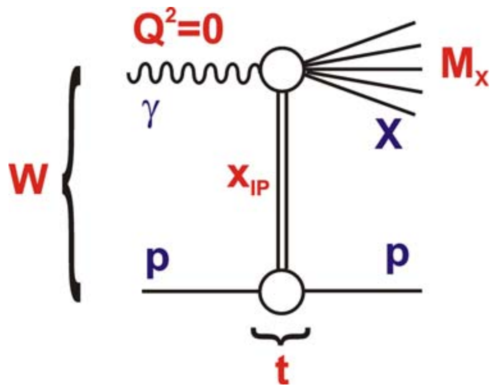
$x_{IP} = \xi = M_X^2/W^2$
= fractional momentum loss of proton (momentum fraction IP/p)

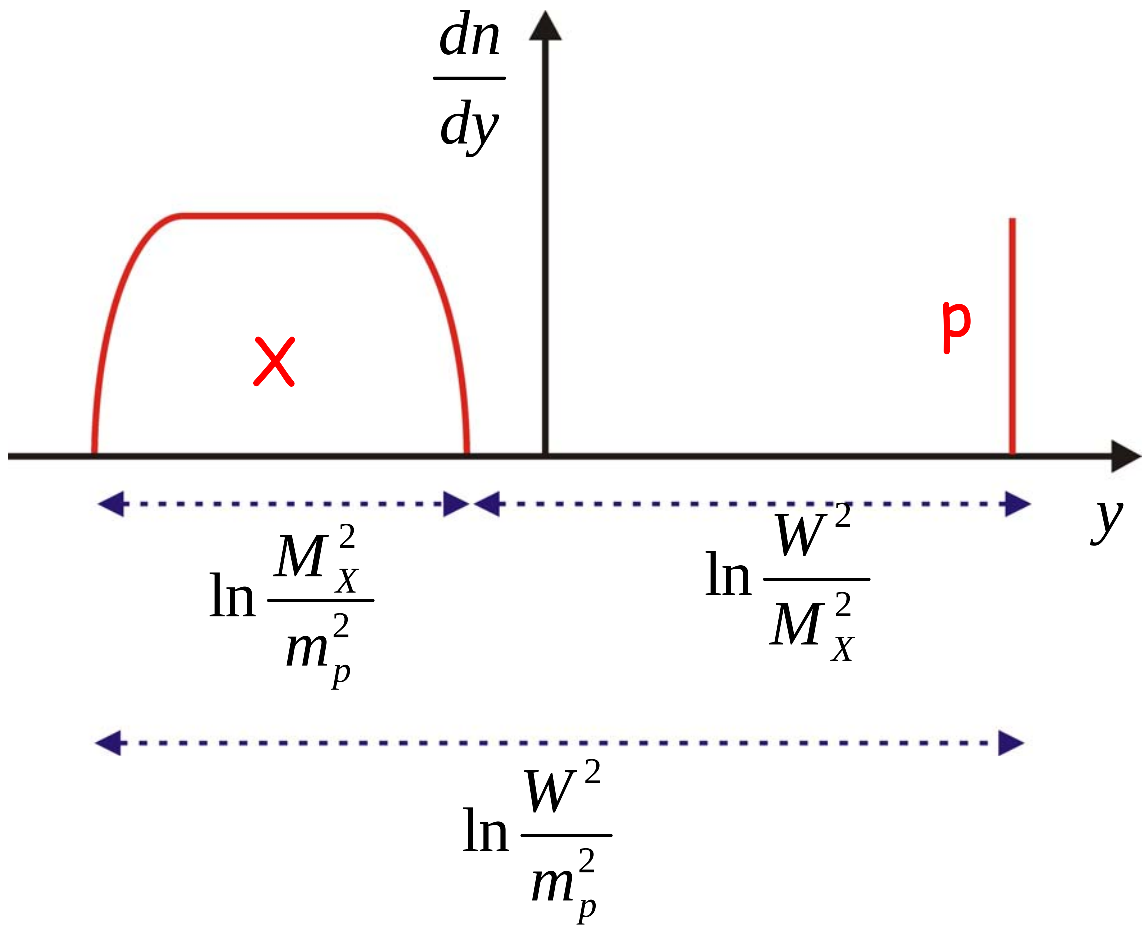


For large Q^2 (partonic structure resolved)

$\beta = x / x_{IP}$
(momentum fraction, struck q / IP)

Basic Single Diffractive Event Topology





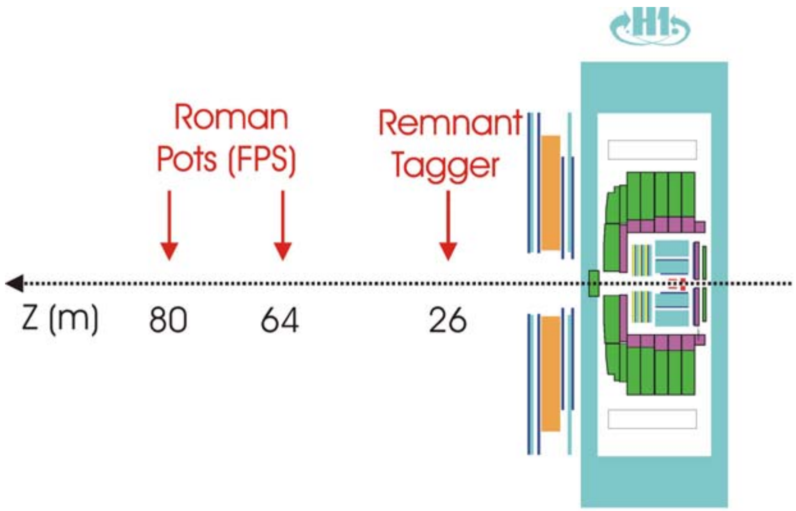
γp system of invariant mass W fragments to produce particles over rapidity range ~ $\ln(W^2/m_p^2)$

Similarly, diffractive system of mass M_X fragments over rapidity range ~ $\ln(M_X^2/m_p^2)$ leaving rapidity gap of size ~$\ln(W^2/M_X^2)$ ~ $-\ln x_{IP}$

Particle production within X shows similar patterns to ND

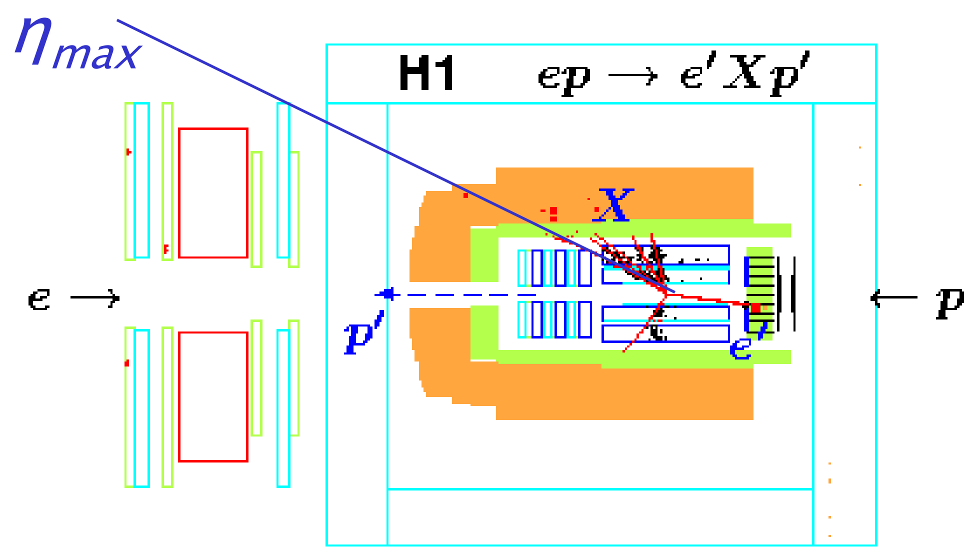
Signatures and Selection Methods

Scattered proton in ZEUS LPS or H1 Leading Proton Spectrometers **(LPS)**



Limited by statistics and p-tagging systematics

`Large Rapidity Gap' **(LRG)** adjacent to outgoing (untagged) proton



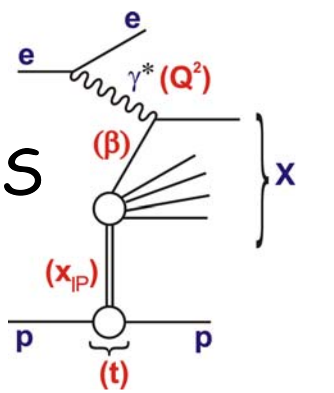
Limited by p-diss systematics

The 2 methods have very different systematics

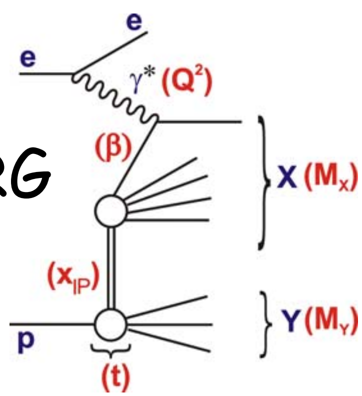
Also `Mx method' via decomposition of diffractive mass distn

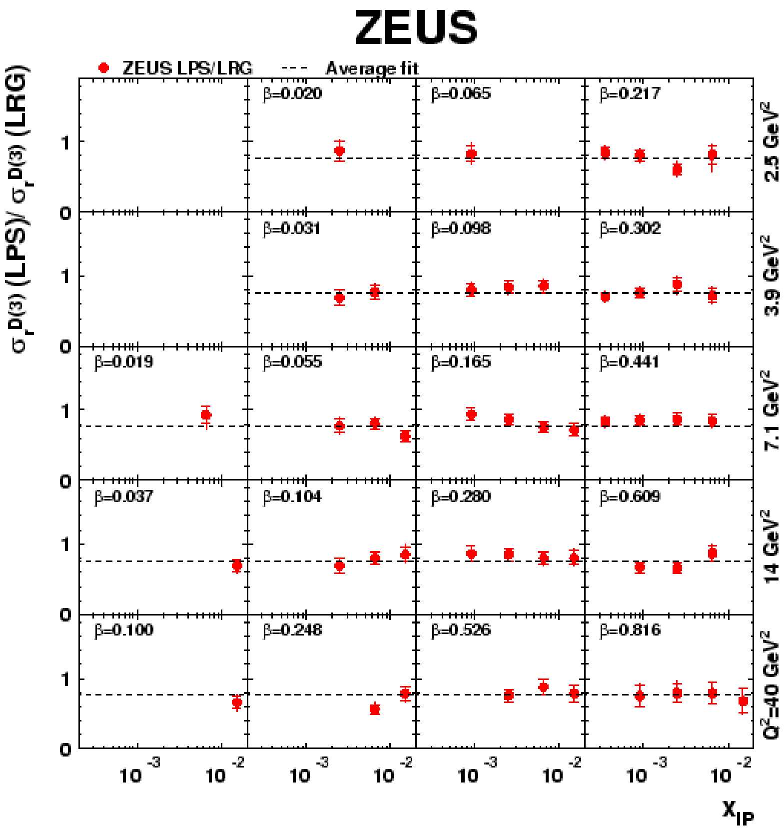
Comparisons between Methods

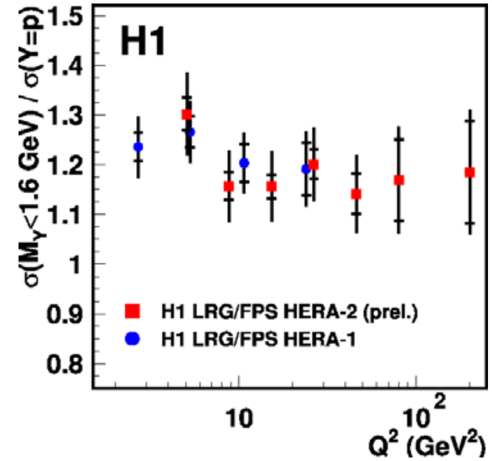
LPS

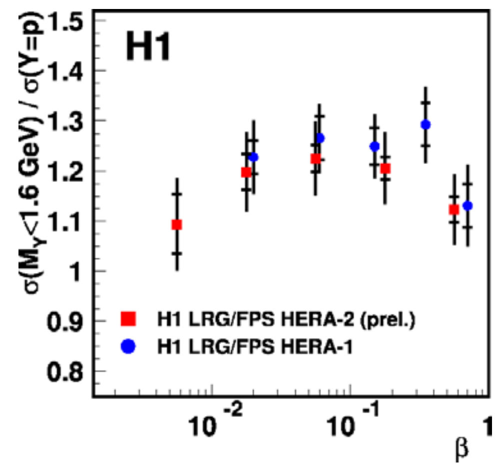


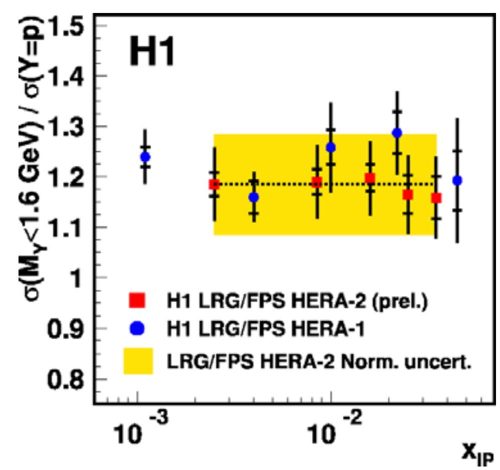
LRG









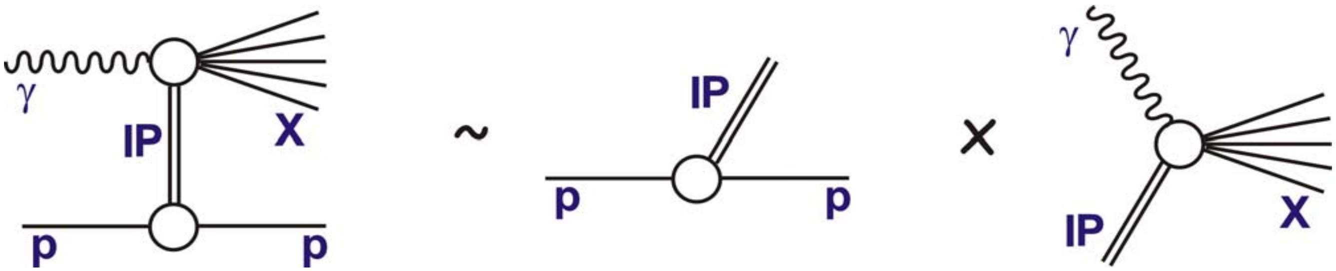


- LRG selections contain typically 20% p diss
- No significant dependence on any variable
- Similar compatibility with Mx method

… **well controlled, precise measurements**

Single Diffractive Photon Dissociation

Basic `proton vertex' factorisation hypothesis
… withstood many HERA tests

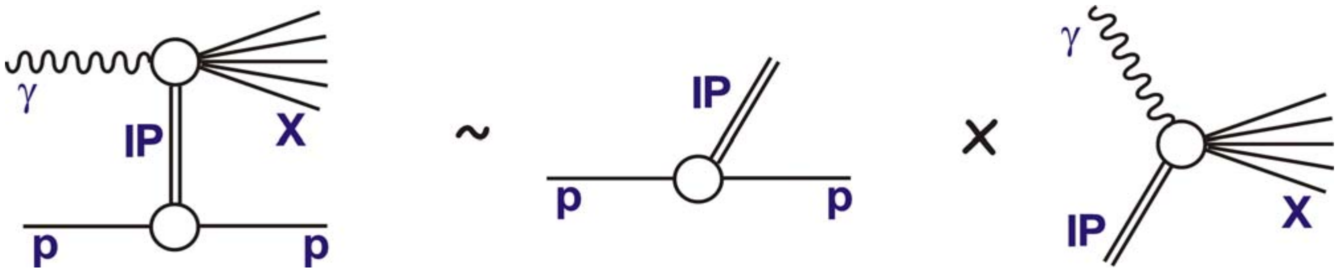


$$f_{IP/p}(x_{IP}, t) \qquad \sigma_{tot}(IP + \gamma \rightarrow X)$$

- Many different analysis extracted pomeron flux $f_{IP/p}$ from (quasi)-elastic and single diffractive cross sections … directly related to same vertex in pp scattering

- Total cross section σ_{tot} (IP + $\gamma \rightarrow$ X) described by:
  - Triple Regge phenomenology for soft processes
  - Diffractive parton densities (DPDFs) for hard processes

Pomeron Flux Factor from Single Diffraction



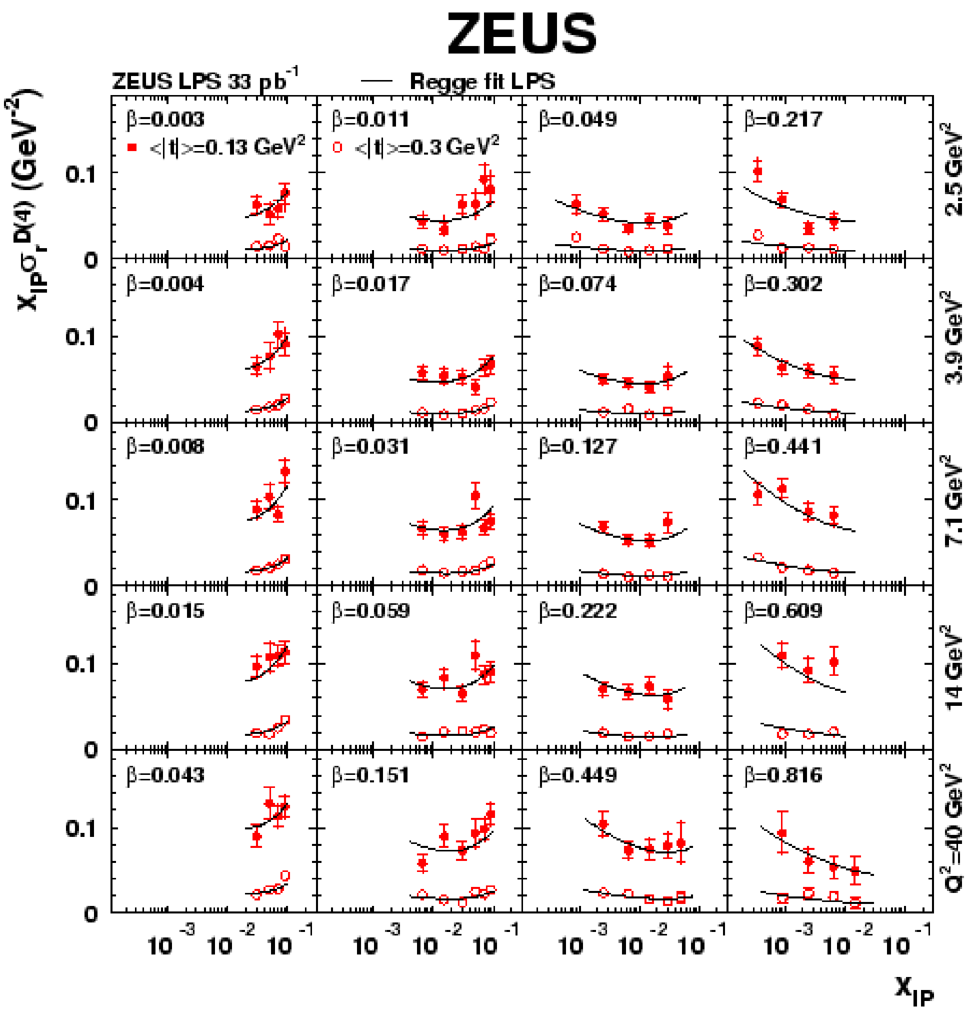
$$f_{IP/p}(x_{IP}, t) \qquad \sigma_{tot}(IP + \gamma \rightarrow X)$$

All x_{IP} and t dependence contained in flux factor.
Standard parameterisation based on Regge theory …

$$f_{IP/p}(x_{IP}, t) = \frac{e^{B_{IP} t}}{x_{IP}^{2\alpha_{IP}(t)-1}} \qquad \alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}\, t$$

Multiple extractions in photoproduction and DIS
Good agreement between experiments …

$\alpha_{IP}(0)$ from Energy Dependences



- Consistent results from many different extractions in DIS and photoproduction

e.g. from Diffractive DIS:

ZEUS

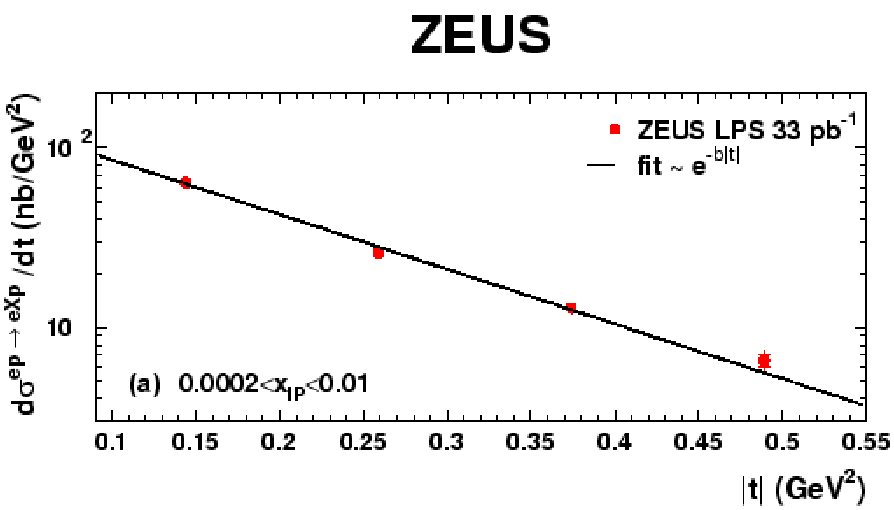
$$\alpha_{IP}(0) = 1.11 \pm 0.03(\text{exp.}) \pm 0.02(\text{model})$$

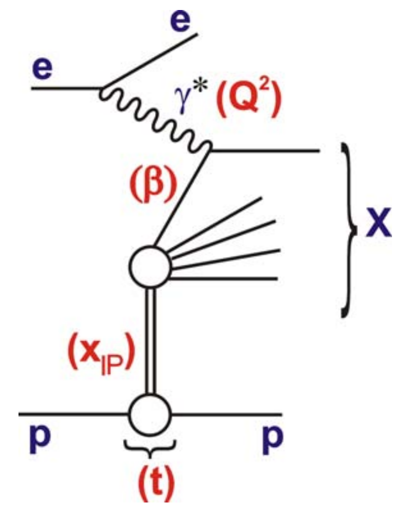
H1

$$\alpha_{IP}(0) = 1.12 \pm 0.01(\text{exp.}) \pm 0.02(\text{model})$$

Consistent with soft IP … e.g. DL fits to σ_{tot} … $\alpha_{IP}(0) \sim 1.08$
Sub-leading exchanges visible at high x_{IP}, low β

t Dependence from LPS / FPS





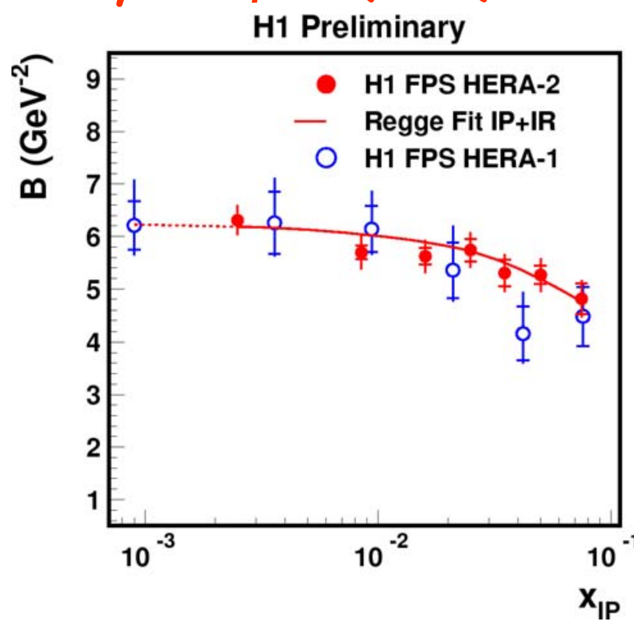
Fitting e^{bt} yields b = 6-7 GeV^{-2}, independently of β, Q^2 (fac'n)

Very little x_{IP} dependence in pomeron dominated low x_{IP} region

ZEUS LPS: $\alpha'_{IP} = -0.01 \pm 0.08 (\text{exp.})$

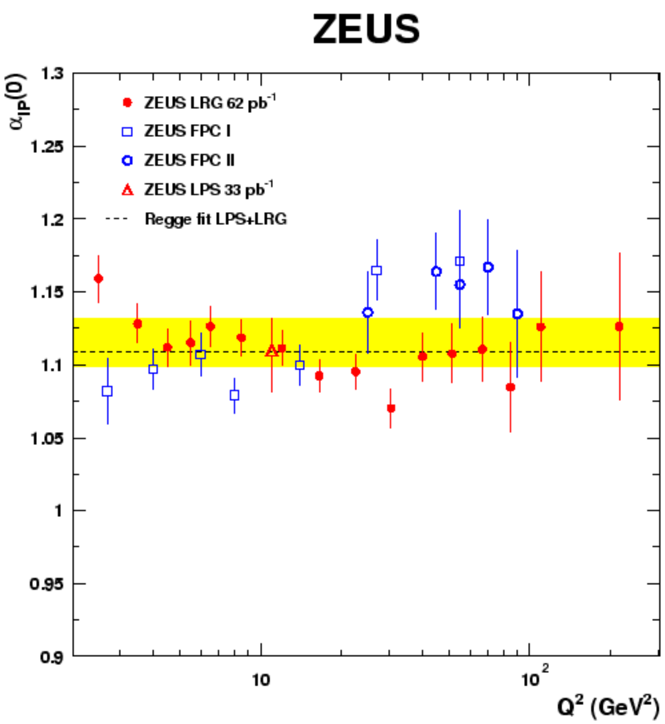
H1 FPS: $\alpha'_{IP} = 0.04 \pm 0.02 \text{ (exp.)} \pm 0.03 \text{ (mod.)}$

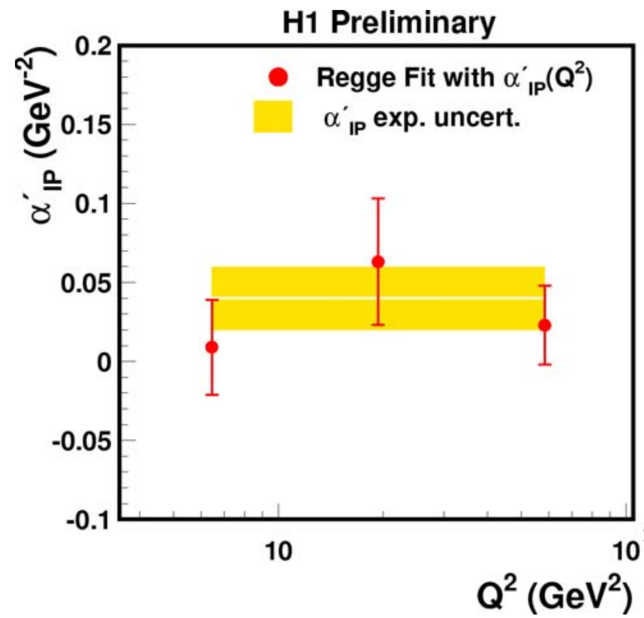
$B_{IP} = 5.7 \pm 0.3 \text{ (exp.)} \pm 0.6 \text{ (mod.)}$

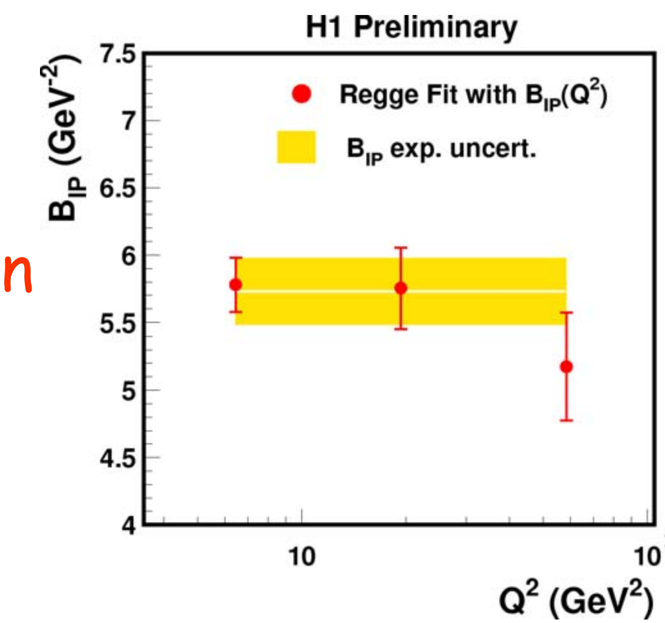


… α_{IP}' different from soft IP → different Multiple interactions / absorption?

Proton Vertex Factorisation Tests







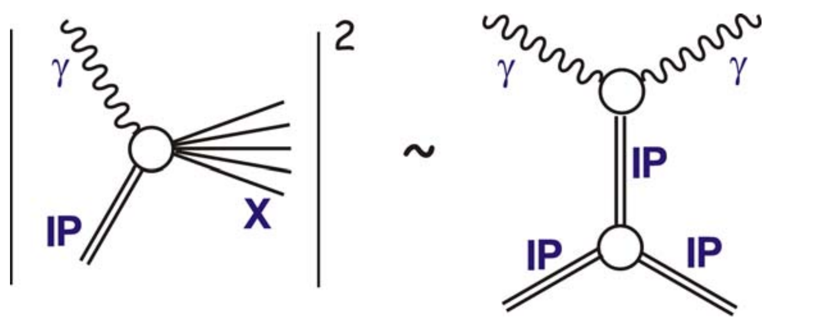
- Pomeron trajectory parameters independent of Q^2 to good approximation (DDIS basically probes a soft pomeron)

- PHOJET and PYTHIA don't yet use flux factor information from HERA

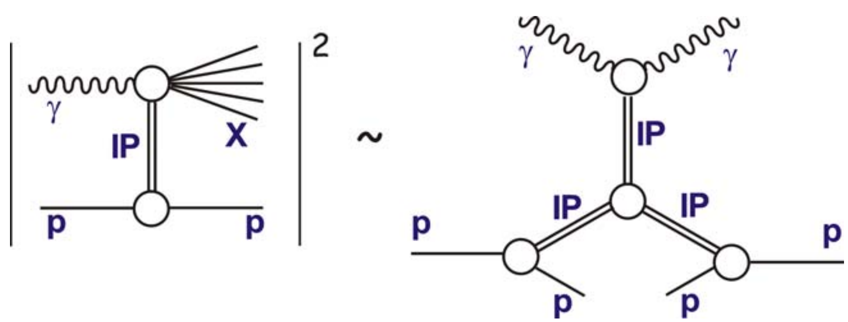
Soft Diffraction in Photoproduction

• When $Q^2 \rightarrow 0$, photon develops its own structure and interacts very much like a vector meson (ρ, ω, ϕ …)
… hadron-hadron scattering ~ soft pp diffraction at the LHC

• Total γIP x-section derived from triple Regge phenomenology
[Similar treatment for DD]



• In addition to pomeron trajectory, triple pomeron amplitude depends on pIP, γIP and 3IP couplings.

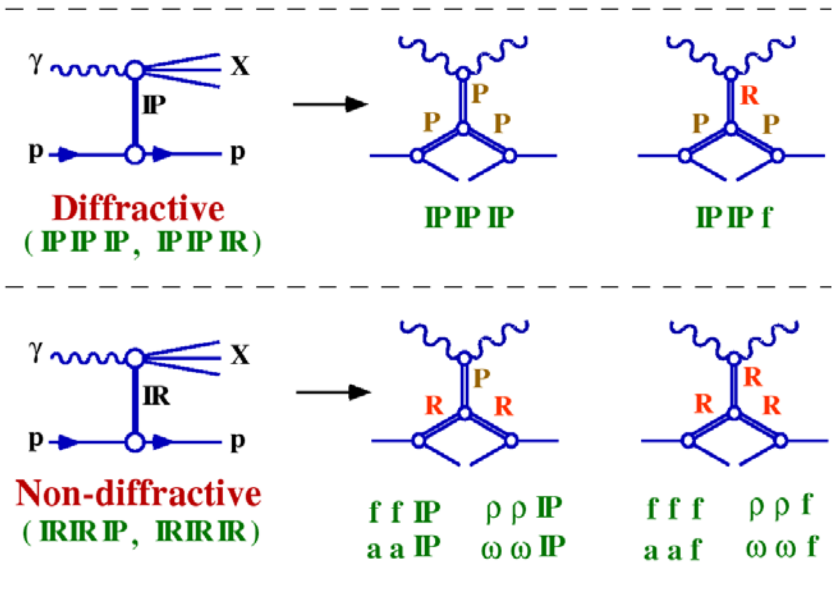


• pIP and gIP couplings from σ_{tot}
3IP coupling only from SD / DD

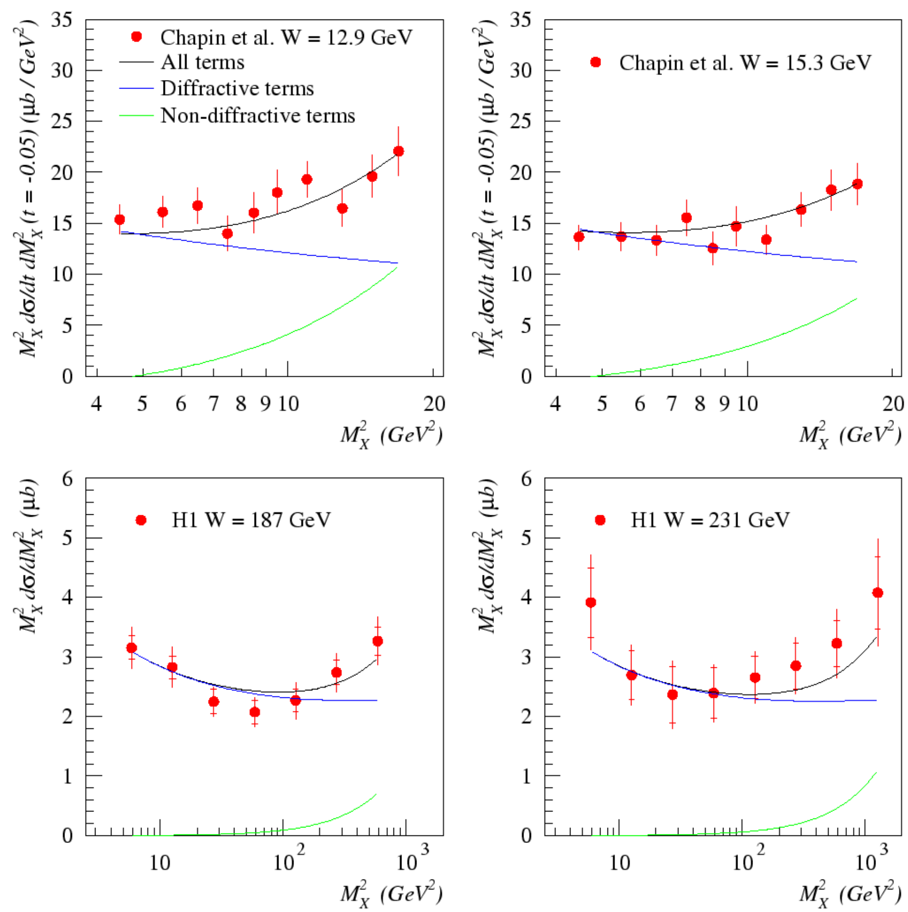
$$\frac{d\sigma}{dt dM_X^2} = \frac{1}{16\pi}\, g_{3IP}(t)\, \beta_{pIP}(t)^2\, \beta_{\gamma IP}(0)\, s^{2\alpha(t)-2}\, M_X^{2[\alpha(0)-2\alpha(t)]} \xrightarrow[t\to 0]{} s^{0.16} \left(\frac{1}{M_X^2}\right)^{1.08} e^{B(\xi)t}$$

Soft γp Single Diffractive Cross Section

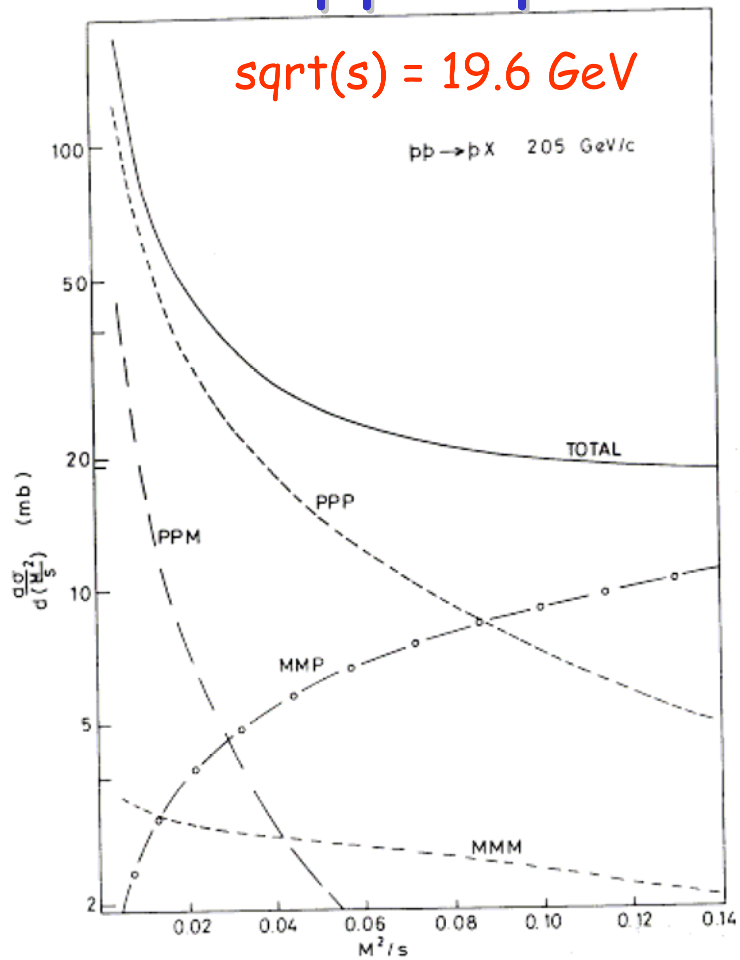
Complication: Triple Regge diagrams can have non-pomeron as well as pomeron contributions



• Example fit to H1 and fixed target $\gamma p \rightarrow Xp$ data shows non-diffractive contributions present at small s and large x_{IP}.

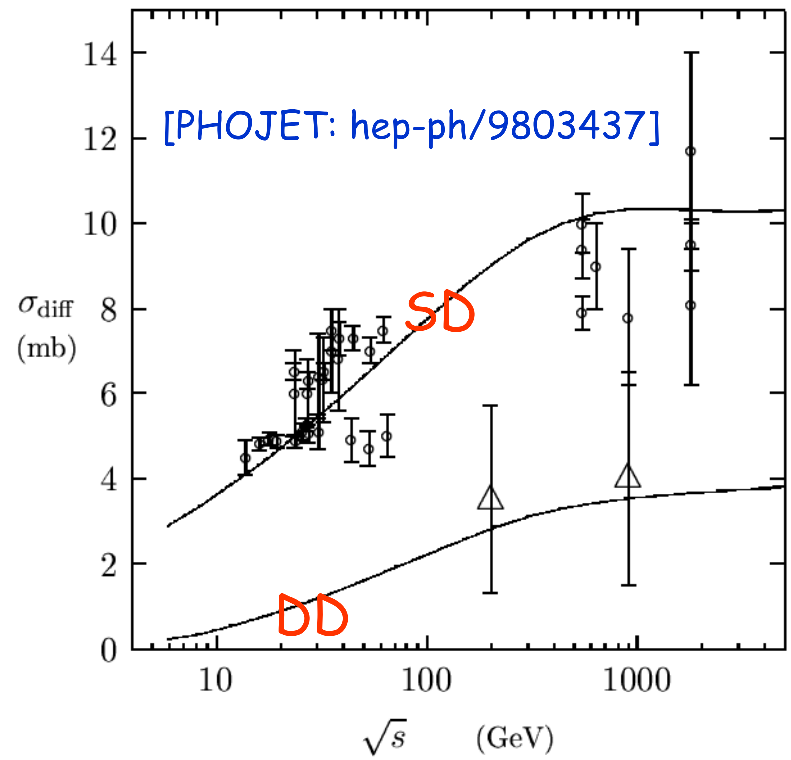


Sub-Leading Terms and pp→ pX



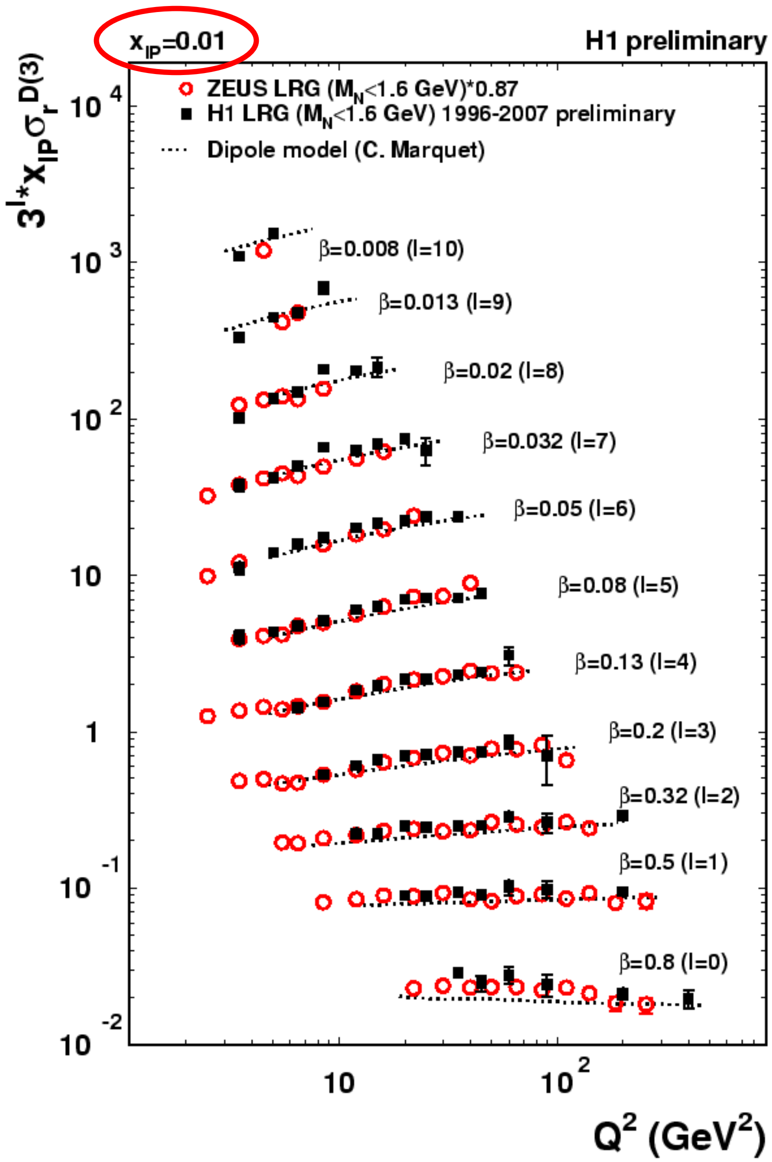
Ancient (ISR) triple Regge phenomenology of pp → pX

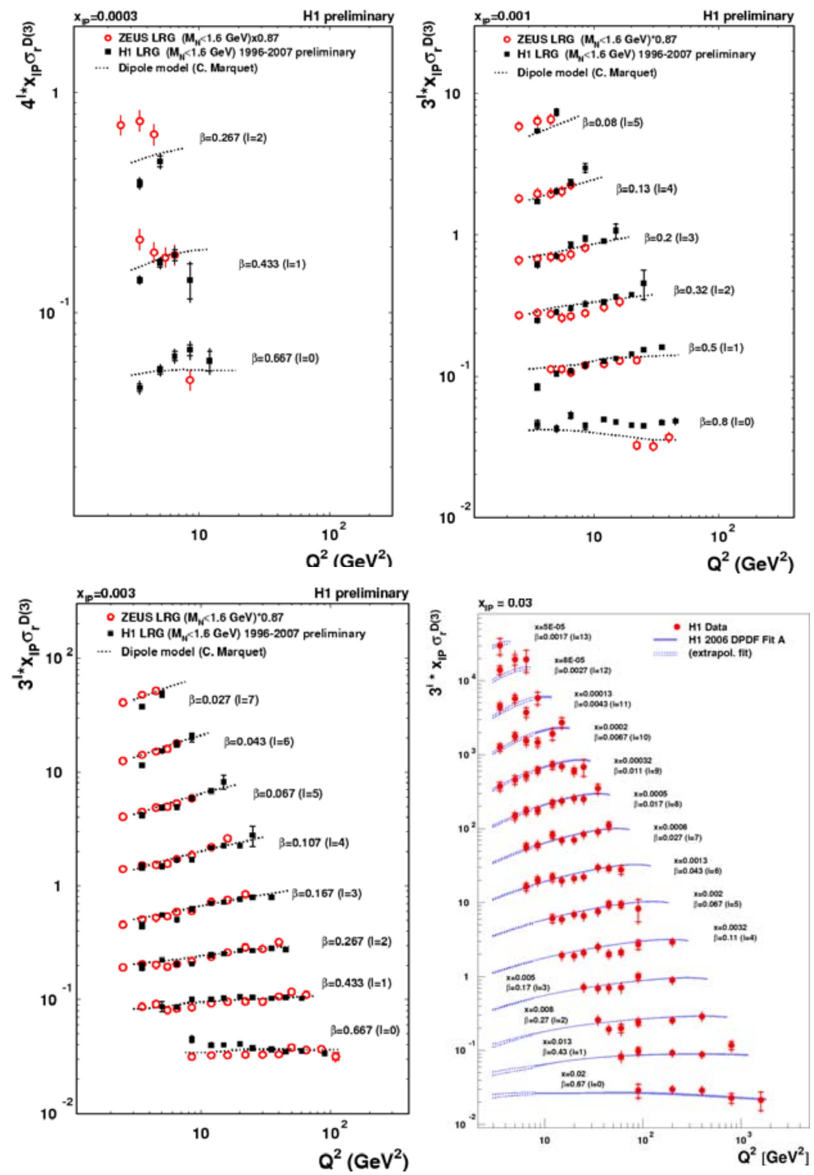
Roberts & Roy: NP B77 (1974) 240
Field & Fox: NP B80 (1974) 367

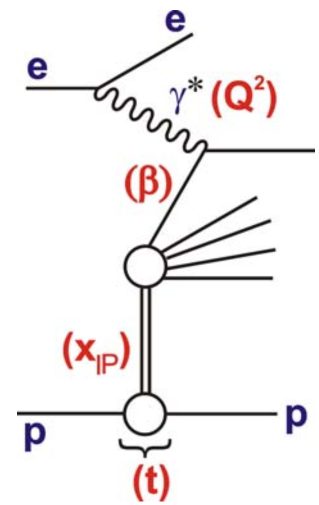


- Sub-leading terms suppressed like 1/sqrt(s) or stronger … negligible at LHC,
- Perhaps influence assumed 3IP coupling in MC models?

ZEUS v H1 Diffractive DIS Data

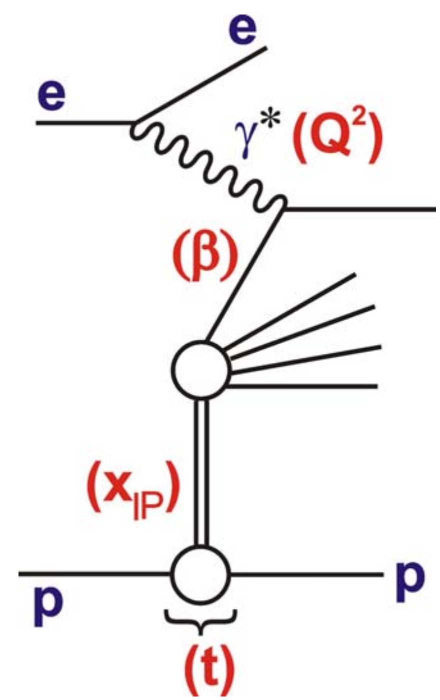






Few % precision over wide kinematic range … still improving …
[~13% normalisation difference between H1 and ZEUS]

Extracting Diffractive Quarks and Gluons



- Fit β and Q^2 dependence of DIS SD data at fixed x_{IP}, similar to inclusive PDF fits

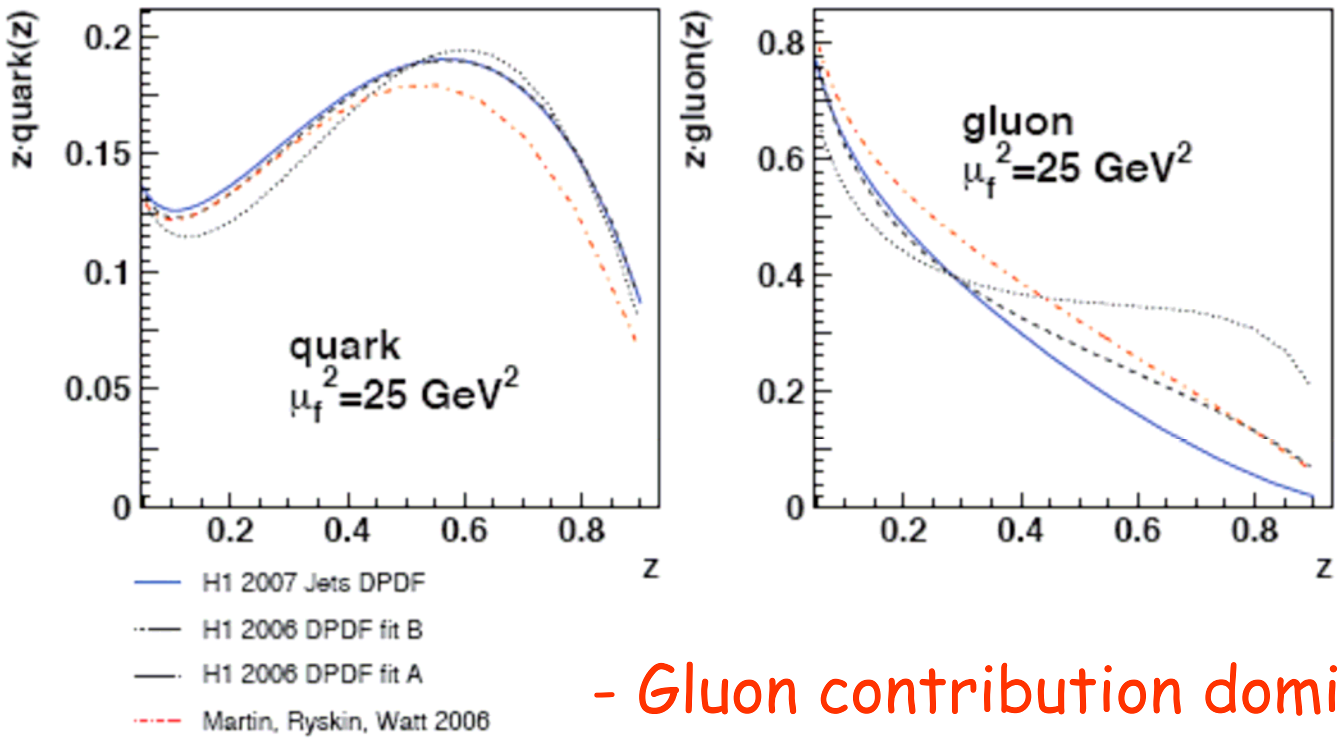
- Use proton vertex factorisation with $\alpha_{IP}(t)$ from FPS and LRG data to relate data from different x_{IP} values with complementary β, Q^2 coverage.

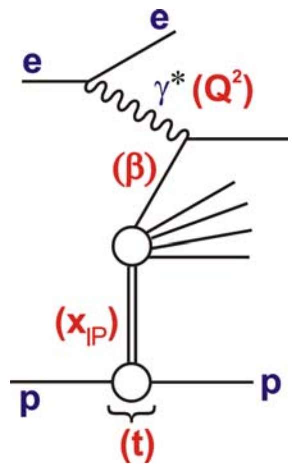
- Parameterise DPDFs at starting scale Q_0^2 for QCD evolution …
… evolve to higher Q^2 using NLO DGLAP equations and fit β and Q^2 dependence for DPDFs

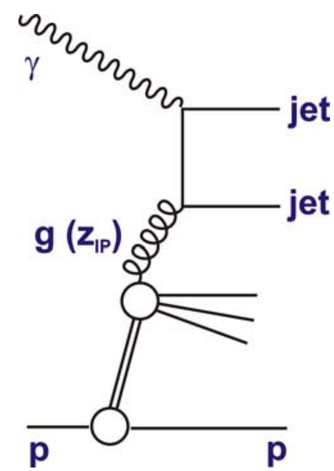
- Include sub-leading exchange (important at large x_{IP})

- Experimental & modelling uncertainties propagated to DPDFs

Comparison of Fits to H1 Data







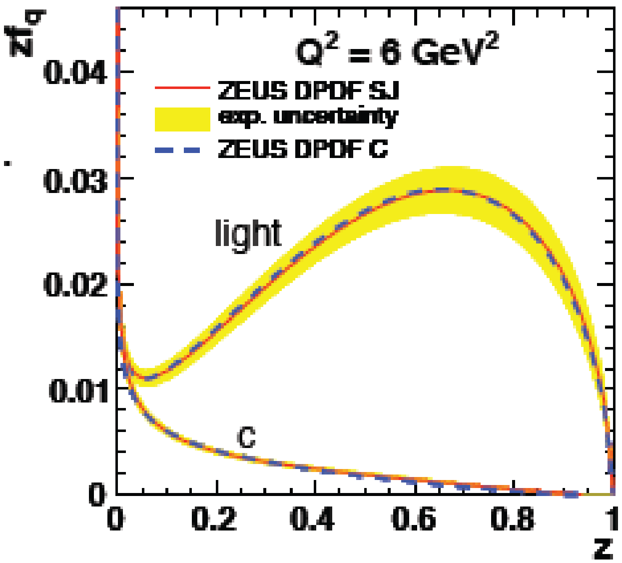
- Gluon contribution dominates

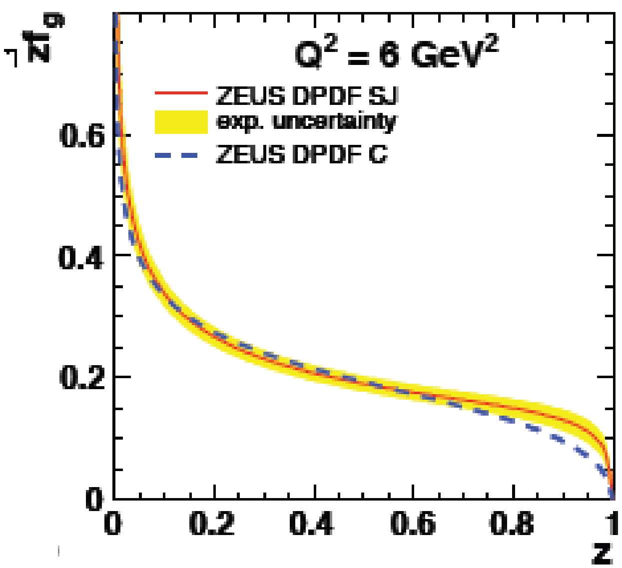
- Quark contribution constrained to ~ 5%

- Gluons constrained to ~15% at low z (=β), growing fast as z→1

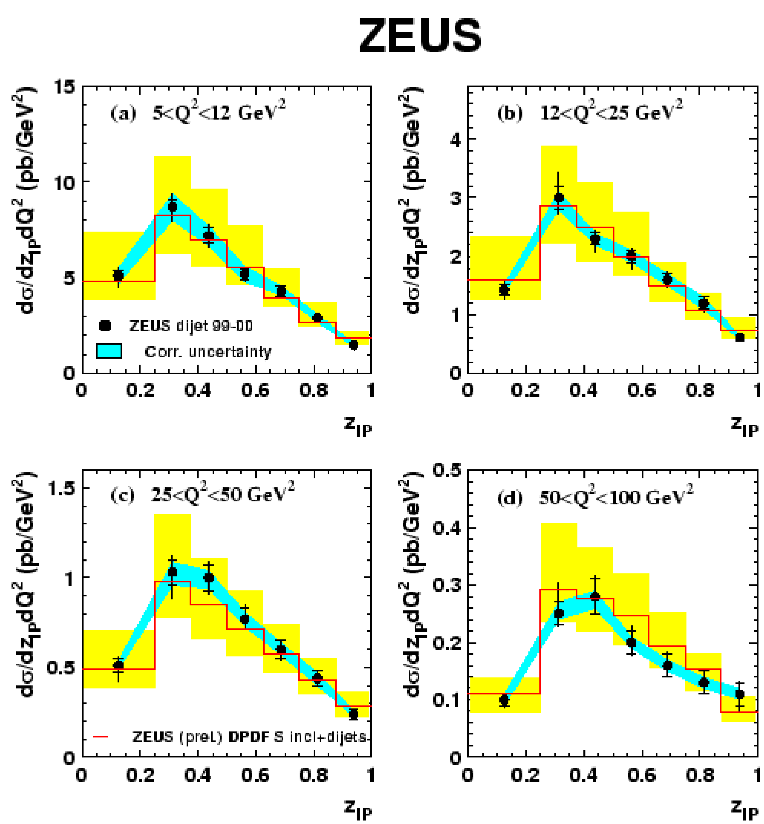
- Better constraints on high z gluon by including diffractive jet data.

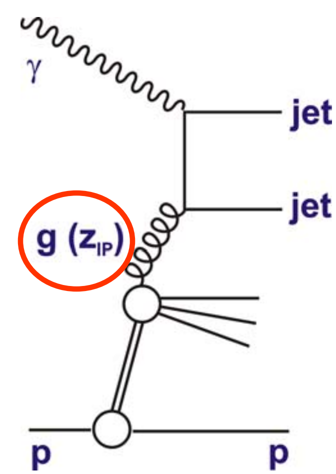
ZEUS DPDFs from Inclusive and Jet Data





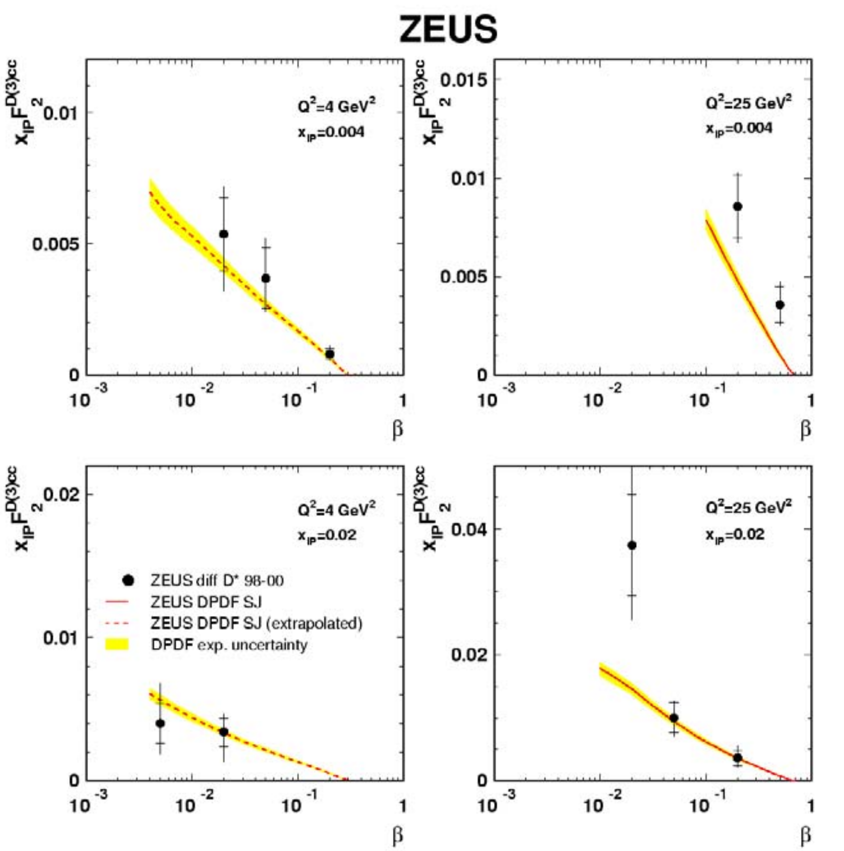
- Recent ZEUS fits to better stats, more sophisticated heavy flavour treatment … consistent with H1 up to normalisation factor in data
- Successful descriptions of diffractive Final state data in DIS …

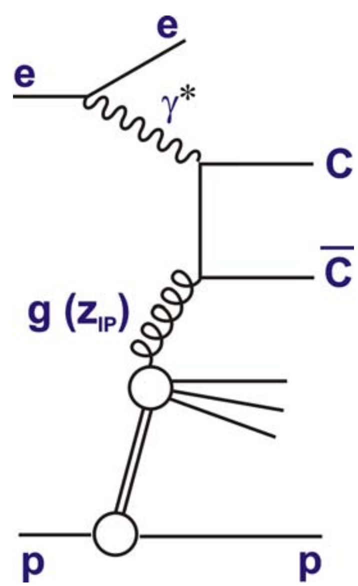


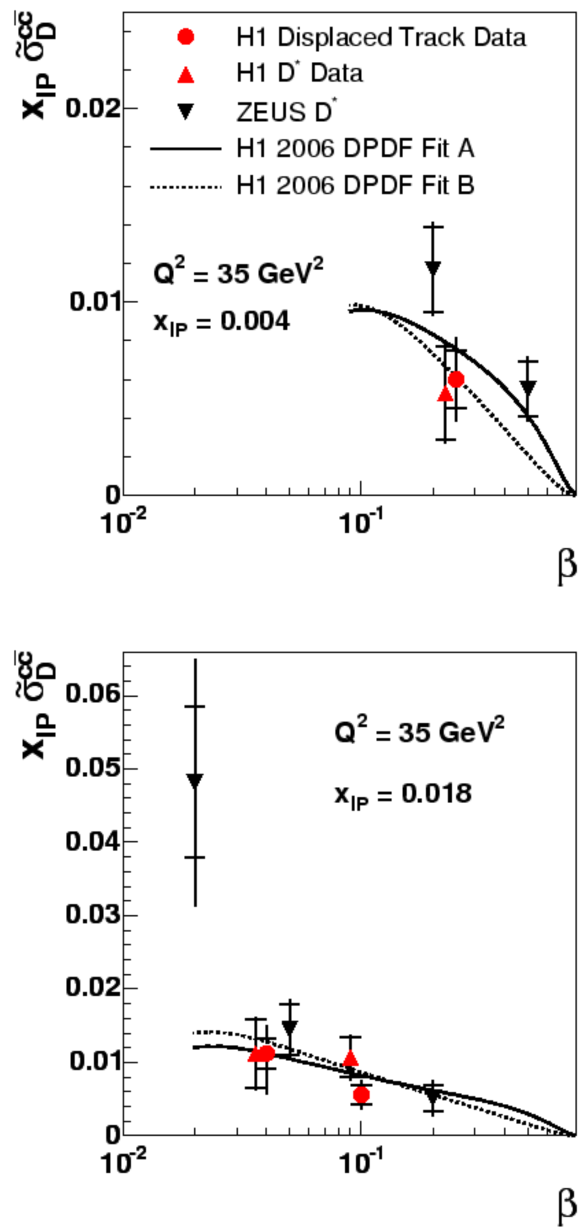


Describing other diffractive DIS processes

As well as inclusive x-sections and jets, DPDFs describe diffractive charged current, charm, particle flow & spectra …

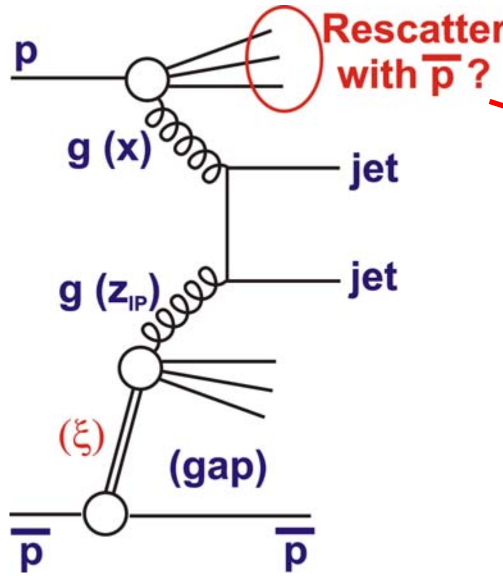


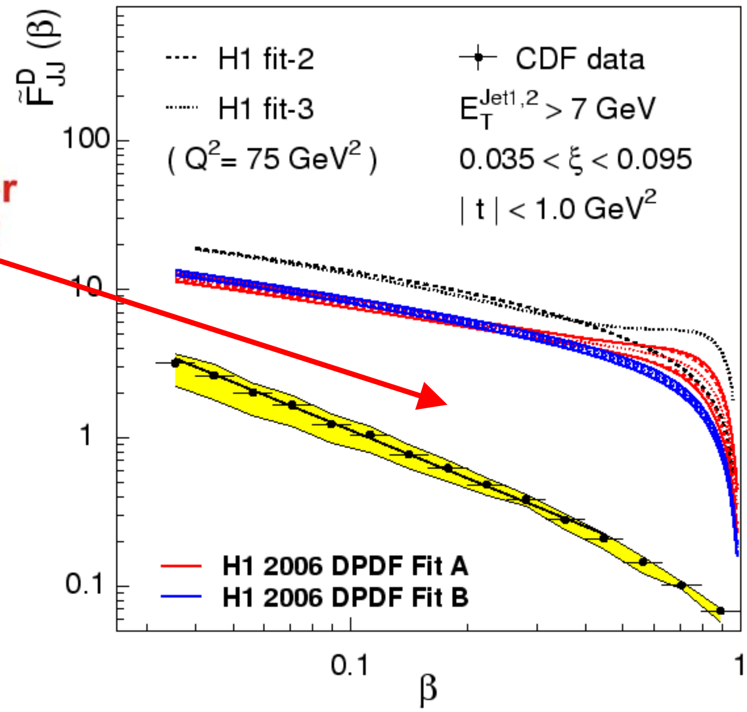




Predicting Tevatron Data

Tevatron effective DPDFs from dijets show strong factor^n breaking compared with HERA DPDFs … `gap survival' factor $S^2 \sim 0.1$





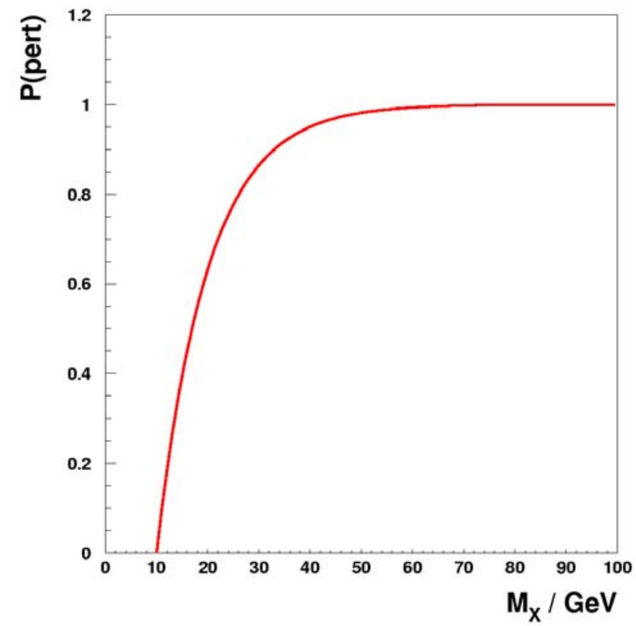
… usually explained by multiple interactions / absorption

- Rapidity gap survival probabilities / multiple interactions relevant not only to (short-distance) gaps between jets
- Also relevant to partonic processes in pp→pX at low t (large impact parameter)

Monte Carlo Implementations

PHOJET

- Fairly standard IP flux
- Two components (soft / hard)
- Divided at pt = 3 GeV
- (Old) CKMT model of DPDFs



PYTHIA8

- Choice of (old) IP fluxes
- Two component (soft / hard)
- Divided according to smooth turn-on
- Hard component dominates for typical LHC M_X values
- Choice of modern DPDFs for hard part

RAPGAP / POMWIG

- Hard component only
- Consistent use of flux and DPDFs from fits to HERA data

None contain models of MI induced Rapidity Gap Destruction

Summary

- Wealth of HERA diffractive data (more to come)

- Well tested cross section definition

- Agreement in detail between leading proton and rapidity gap selection methods

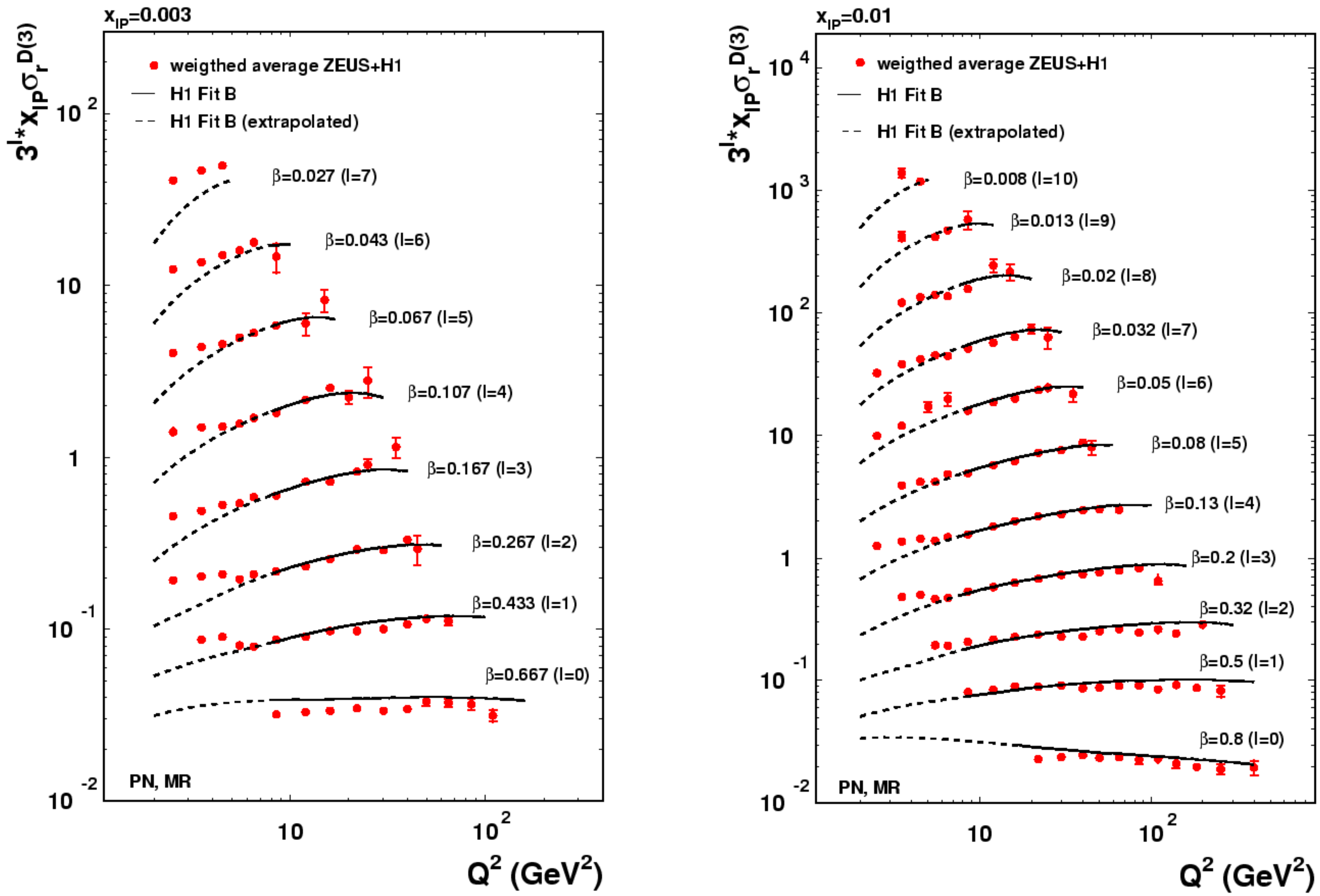
- Proton vertex factorisation with $\alpha_{IP}(t) \sim 1.11\ (+\ \delta t)$ & $b_{IP} \sim 6\ GeV^{-2}$ is good model for the 'soft' physics

- Well tested DPDFs give model for hard diffraction

- Rapidity Gap Survival issues remain to be clarified

Back-ups

First Combined LRG Data (Newman, Ruspa)



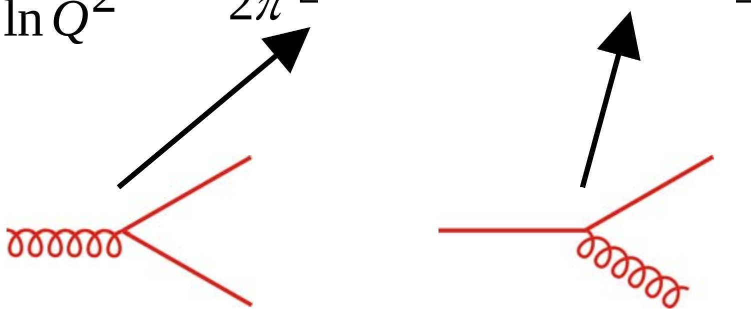
No big conflicts with existing DPDFs (quarks @ low, high β?)

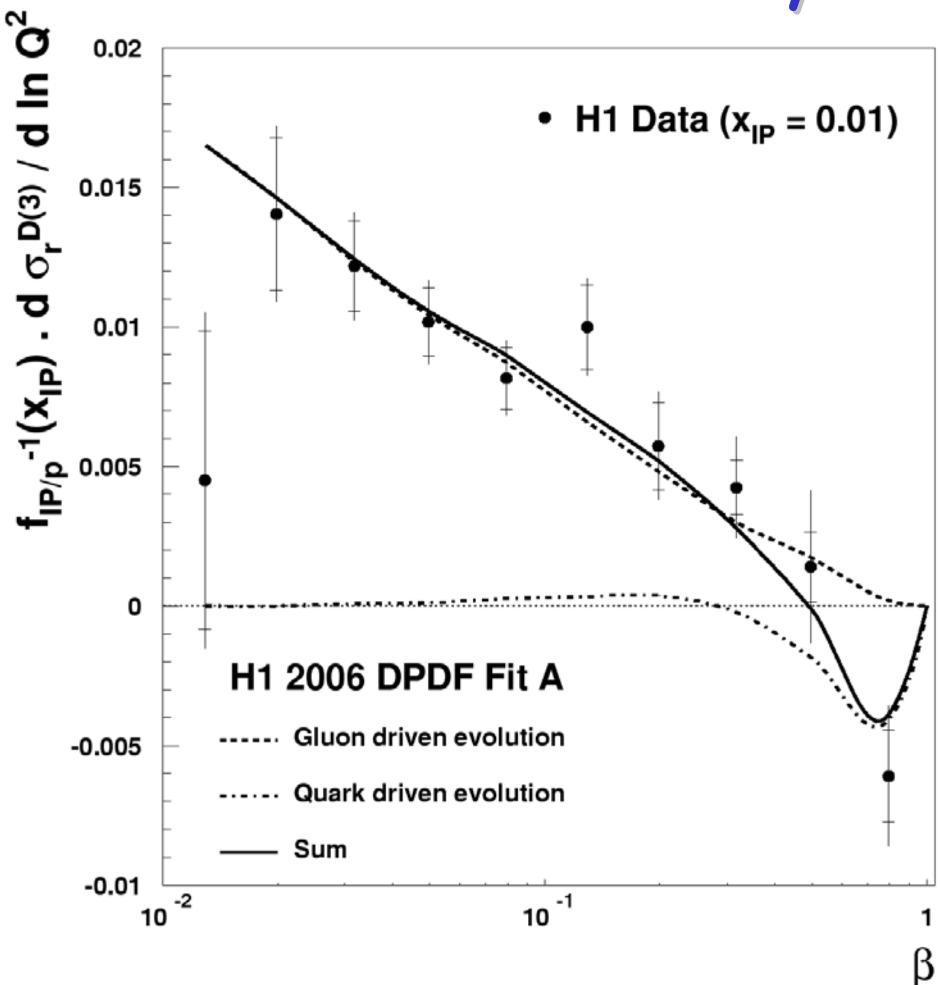
Q^2 Dependence and the Gluon Density

$\sigma_r^{D(3)}$ measures diffractive quark density.

Its dependence on Q^2 is sensitive to diffractive gluon density.

$$\frac{d\sigma_r^D}{d\ln Q^2} \sim \frac{\alpha_s}{2\pi}\left[P_{qg}\otimes g \;+\; P_{qq}\otimes q\right]$$

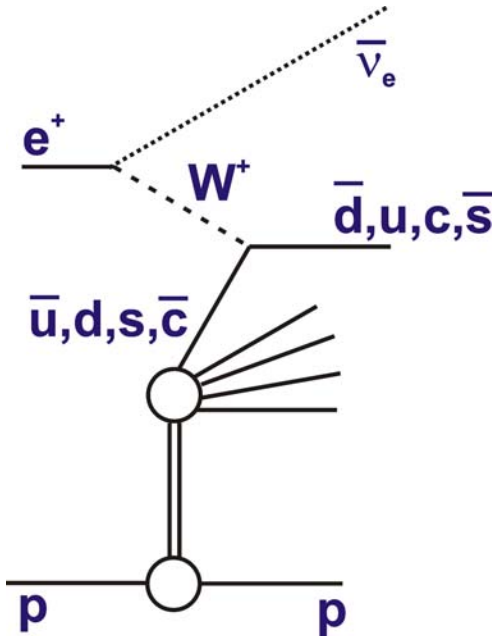


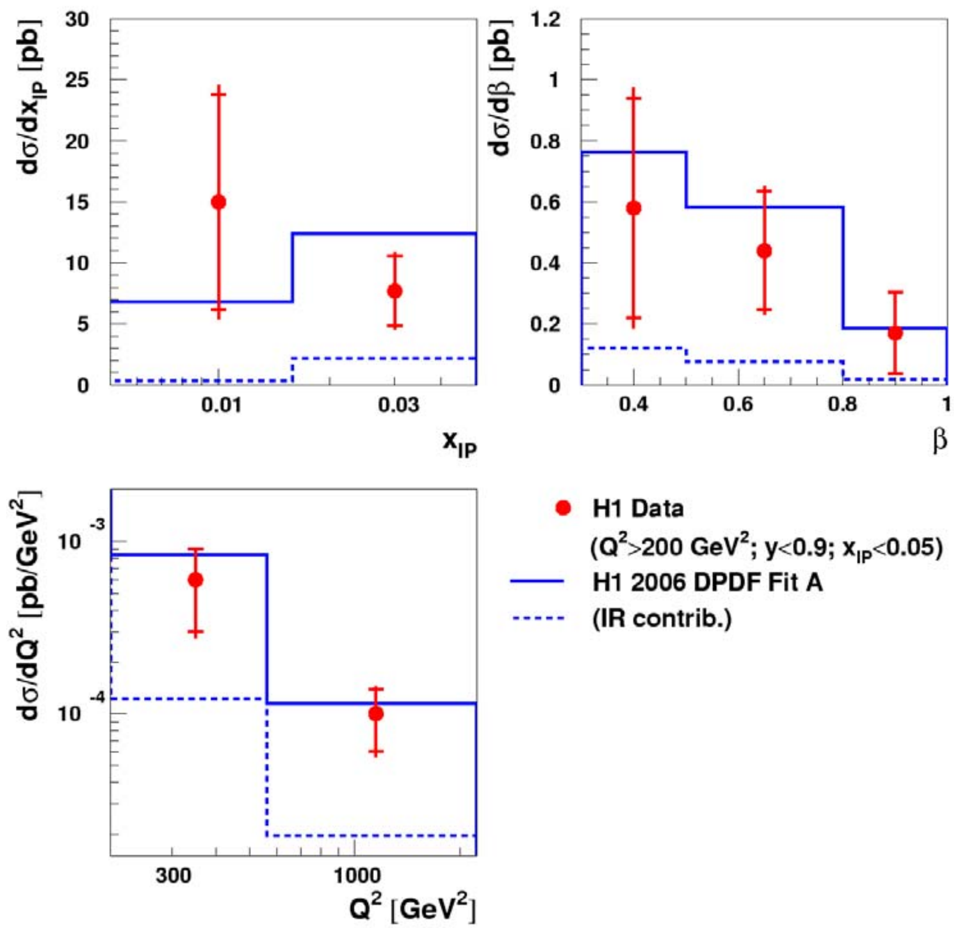


Extract $d\sigma_r^D/d\ln Q^2$ by fitting data at fixed x, x_{IP}

- Low β evolution driven by $g \rightarrow q\bar{q}$ … strong sensitivity to gluon
- High β, relative error on derivative grows, $q \rightarrow qg$ contribution to evolution becomes dominant … sensitivity to gluon is lost!

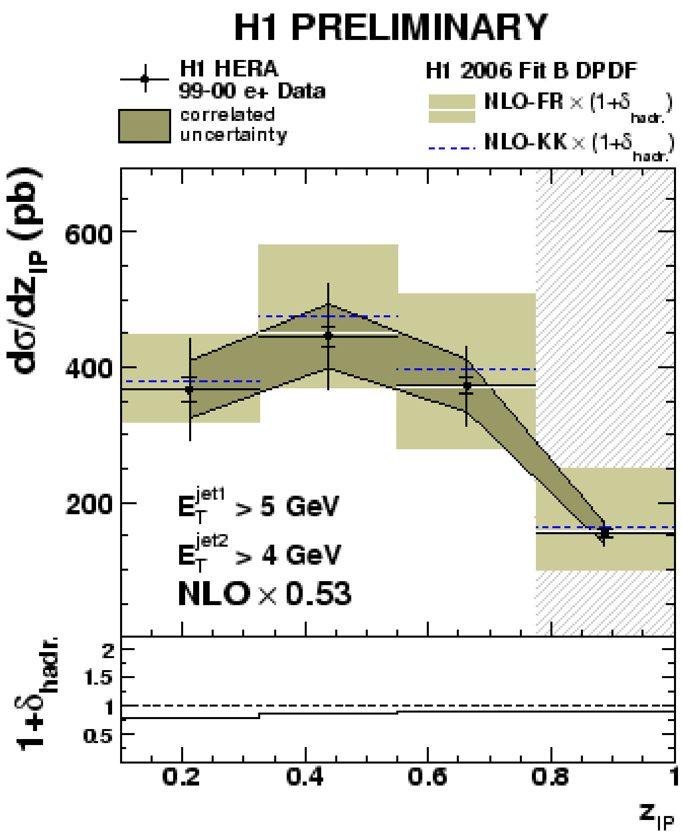
Diffractive Charged Current Cross Section

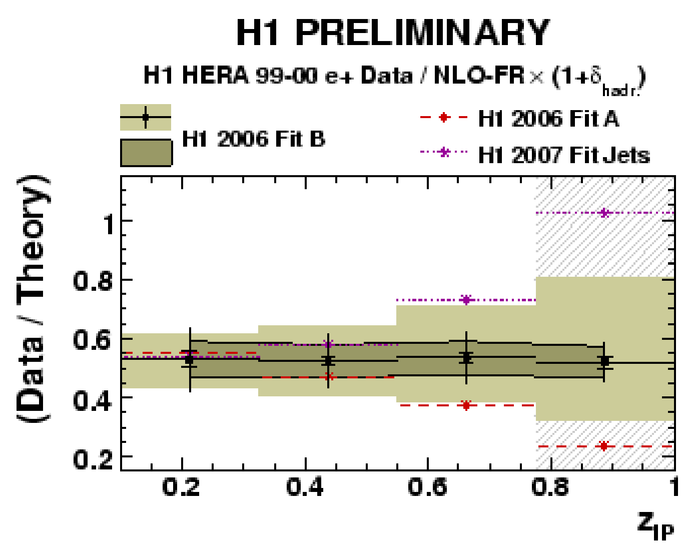




Very similar method of measurement to Neutral Current case.

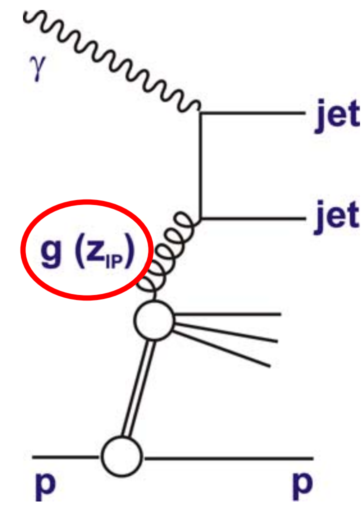
Good agreement with fit prediction (assumes $u = d = s = \bar{u} = \bar{d} = \bar{s}$ and c from BGF) though statistical precision limited so far





X-Section Differential in z_{IP}

$$z_{IP} = \frac{\sum_{jets}(E+p_z)}{2E_p\, x_{IP}}$$



Global suppression ~0.5 needed for NLO calculations … confirms previous result

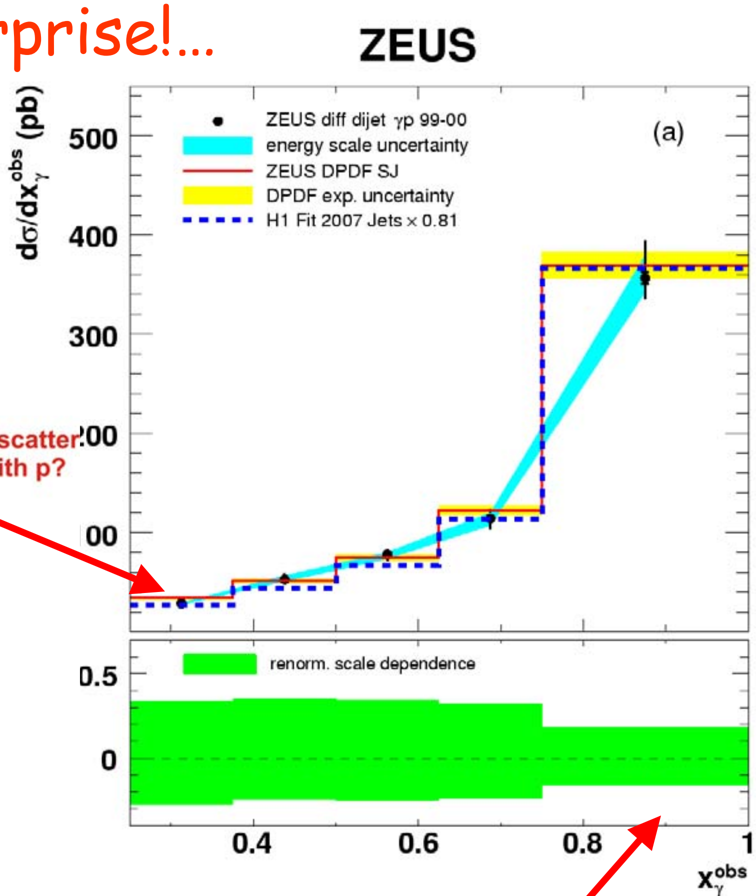
Best shape description from Fit B

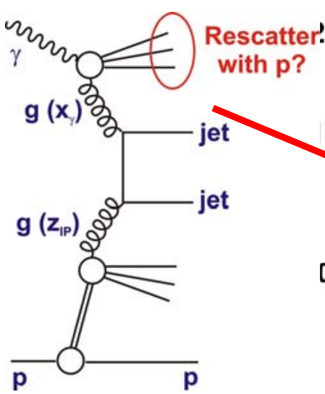
DPDF uncertainties small at low z_{IP}, but explode at high z_{IP} !

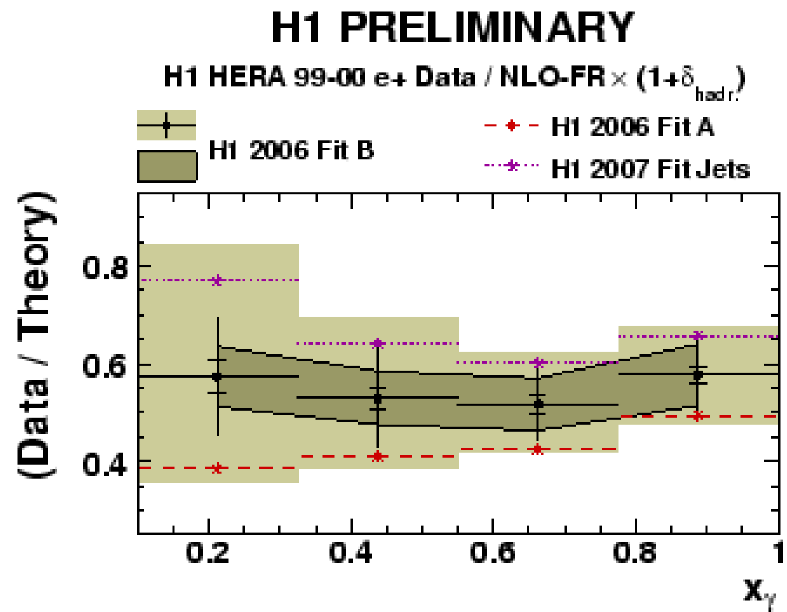
Highest z_{IP} bin is even beyond the range of DPDF fits, so predictions should be taken very cautiously

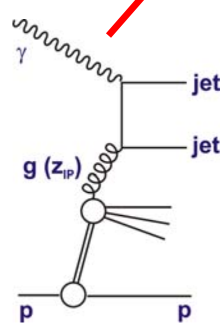
X-Sec Differential in x_γ

… a surprise!…









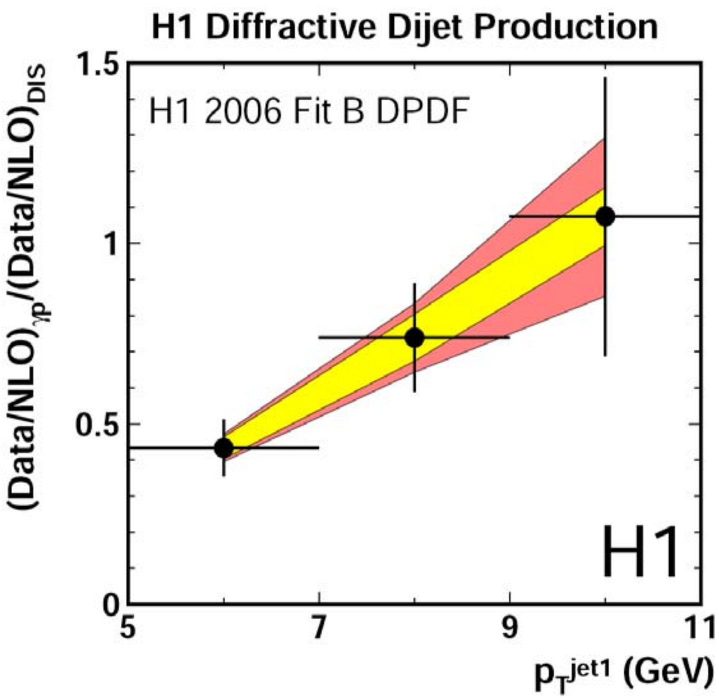
$$x_\gamma = \frac{\sum_{jets}(E - p_z)}{\sum_{HFS}(E - p_z)}$$

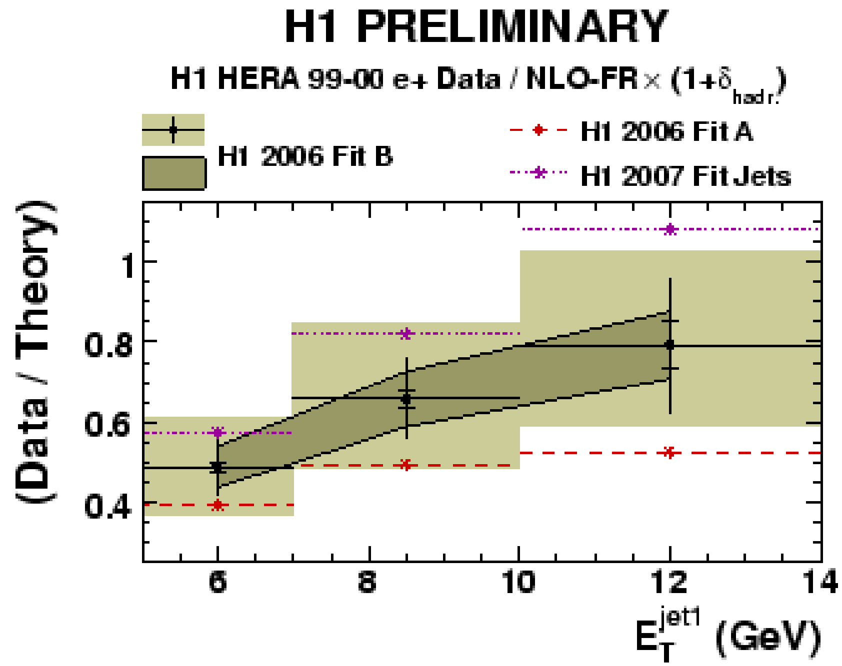
- Good shape description → no significant difference between high / low x_γ !

- H1: $E_t^{jet1} > 5$ GeV
… suppression by factor ~2

- ZEUS: $E_t^{jet1} > 7.5$ GeV
… little or no suppression

Cross Section Differential in E_T





- Suggestions of harder Et dependence in data than NLO theory … thus of E_t dependent gap survival probability

- Could rescattering effects for photon depend on Et, not x_γ?

- Non-trivial kinematic correlations … final conclusion pending!