Tevatron and HERA Forward Physics Results and Implications for the LHC

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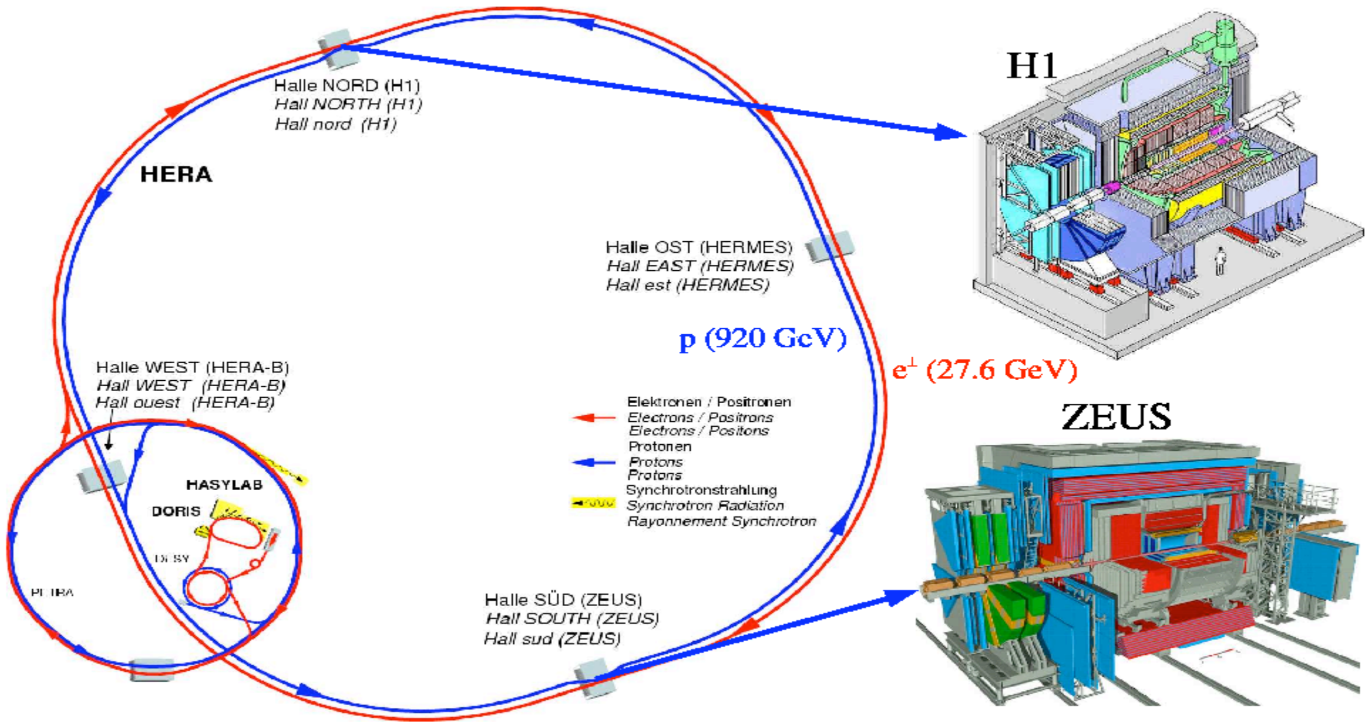
HCP, Evian

Overview

- Inclusive Diffraction
- QCD Fits and Diffractive PDFs
- Diffractive Dijets and Factorisation
- Exclusive Central Production
- Beyond DGLAP
- Vector Mesons, Double Parton Scattering and DVCS
- Summary

The HERA Harvest



- The unique HERA machine collided 27.5 GeV electrons/positrons with protons of 460, 575, 820 and 920 GeV providing 0.5 fb^{-1} to H1 and Zeus
- Precision tests of QCD and a PDF machine in exactly the right range of parton fractional momentum for LHC experiments
- The final precision analyses of HERA data are underway ***now***

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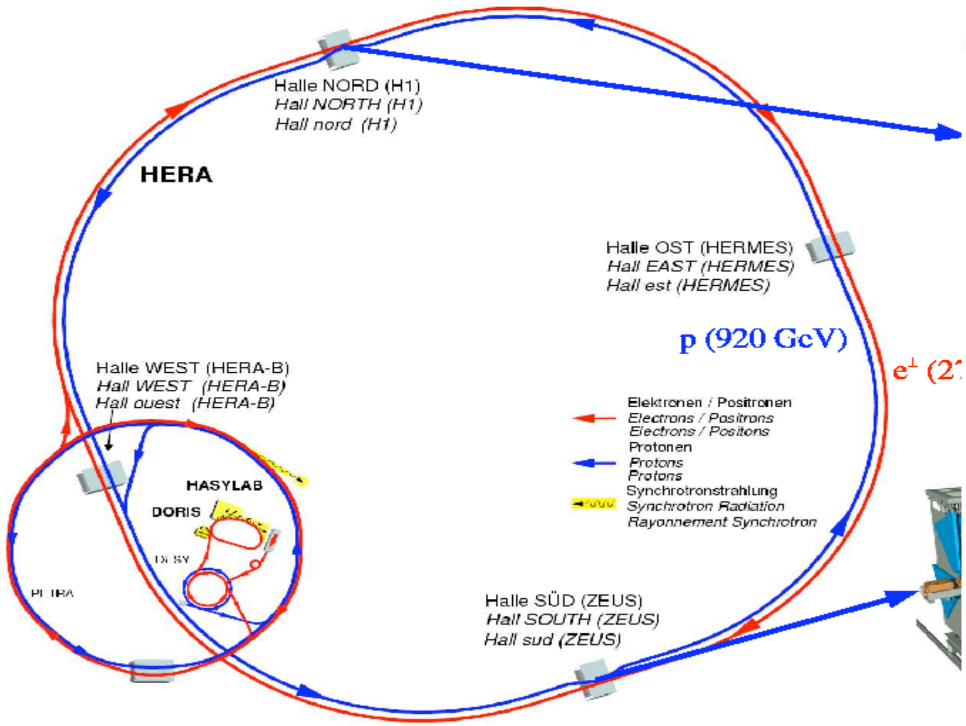

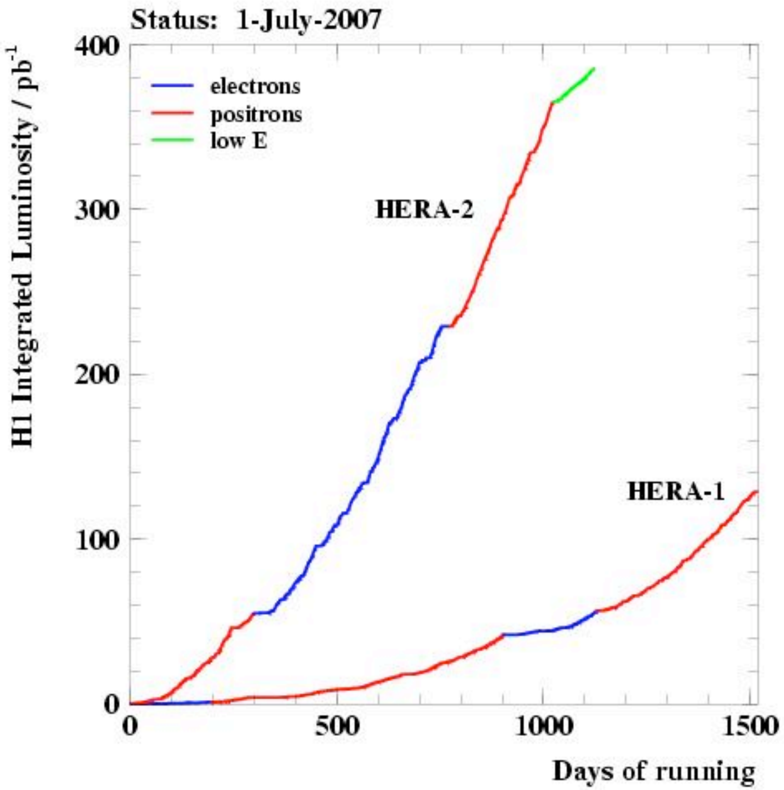

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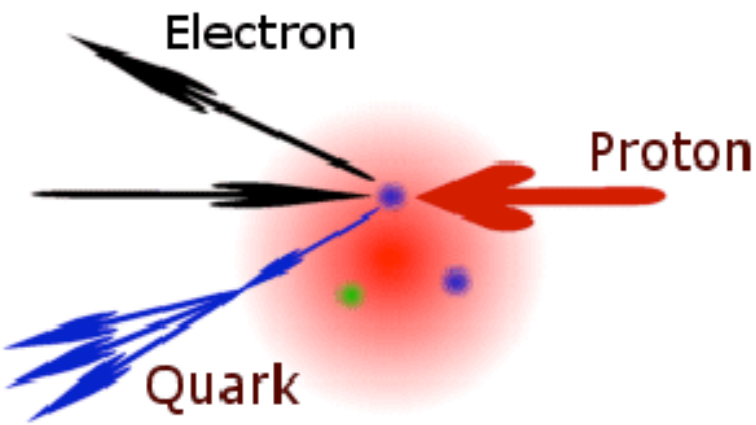
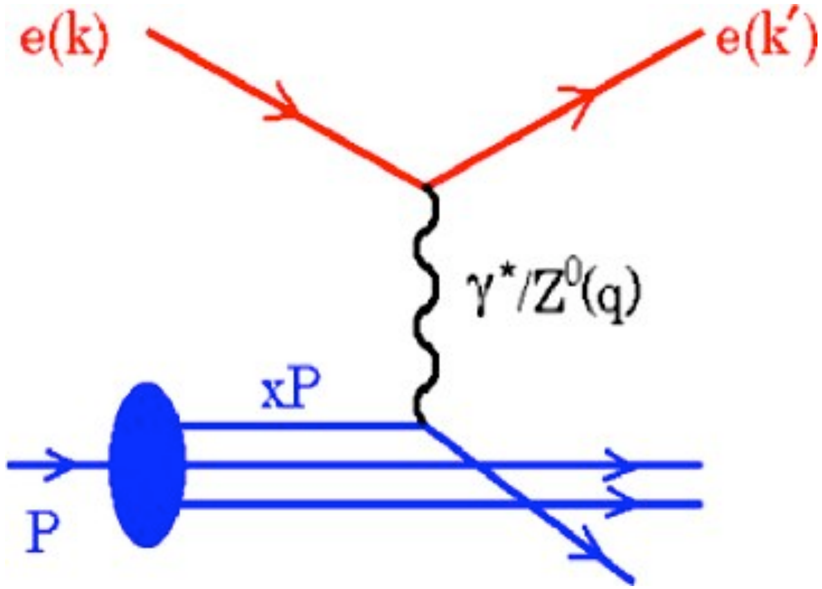
Deep-Inelastic Scattering at HERA



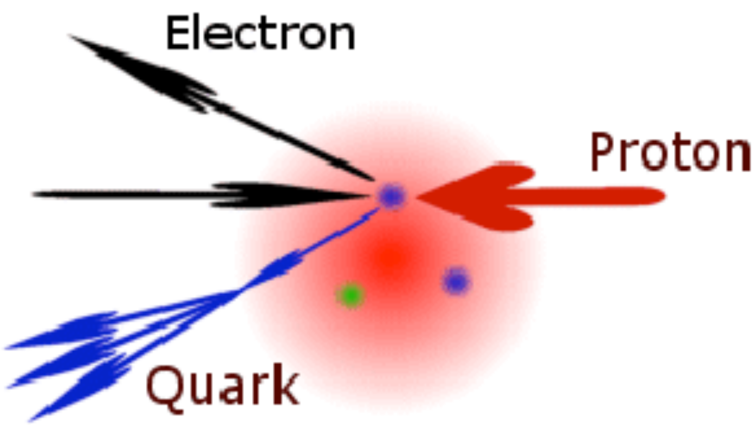


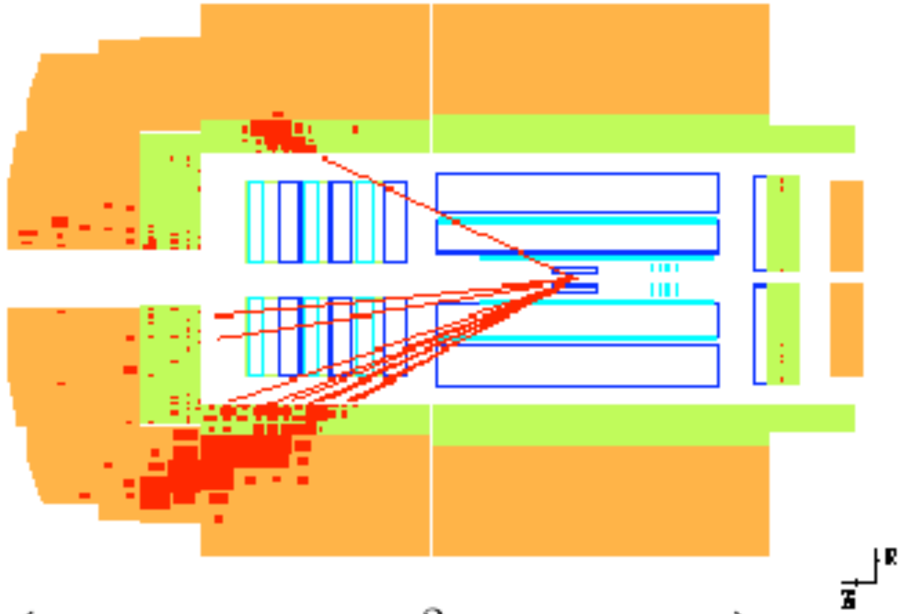
$Q^2 = -q^2 = -(k-k')^2$ *Virtuality / resolving power of the photon*

$x = \frac{Q^2}{2p \cdot q}$ *Momentum fraction of the struck quark*

$y = \frac{p \cdot q}{p \cdot k}$ *Inelasticity of the event*

Deep-Inelastic Scattering at HERA





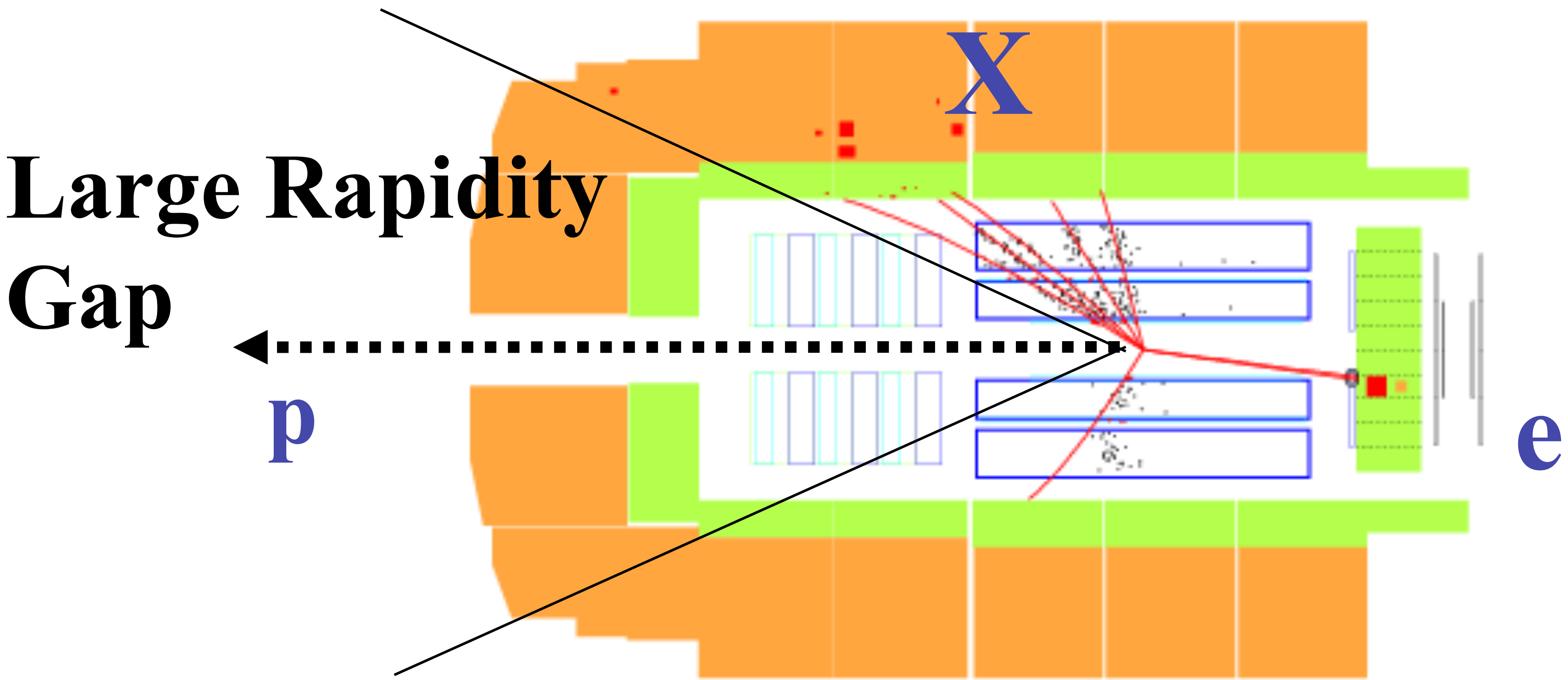
Measure:

$$\frac{d^2\sigma_{NC}^{ep}}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \right)$$

Extract:

- F_2 directly related to (PDFs) quark content: $F_2 \sim x\Sigma e^2(q+q)$
- $dF_2/d\ln Q^2$ (scaling violations) sensitive to gluon content
- F_L only non-zero in higher order QCD – independent access to gluon density and QCD dynamics

Diffractive DIS: $ep \rightarrow eXp$



Unexpectedly (in 1990) we saw that in 10% of DIS events, there is a large gap where there are NO particles produced between the struck quark and the proton

Diffractive DIS was born - electron-Pomeron scattering

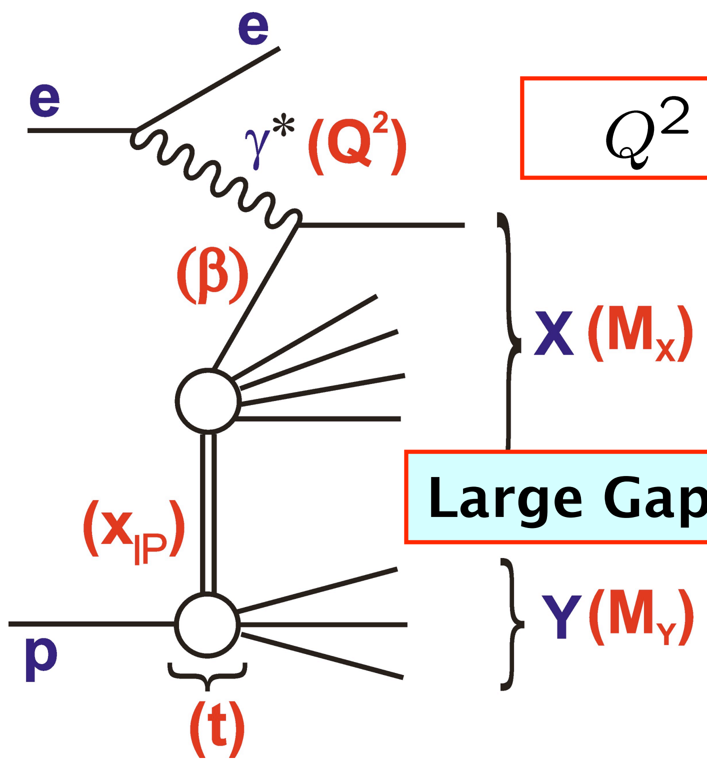
Be prepared for the unexpected!

Diffractive DIS Kinematics and Observables

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

$$\beta = \frac{Q^2}{Q^2+M_X^2}$$

$$x_{I\!P} = \frac{Q^2+M_X^2}{Q^2+W^2}$$



$$Q^2 = sxy$$

Large Gap in Rapidity

$$Y_+ = 1 + (1-y)^2$$

Cross section: $\frac{d^4\sigma^{ep\to eXp}}{dx\,dQ^2\,dx_{I\!P}\,dt} = \frac{4\pi\alpha^2}{xQ^4} Y_+ \,\sigma_r^{D(4)}(x, Q^2, x_{I\!P}, t)$

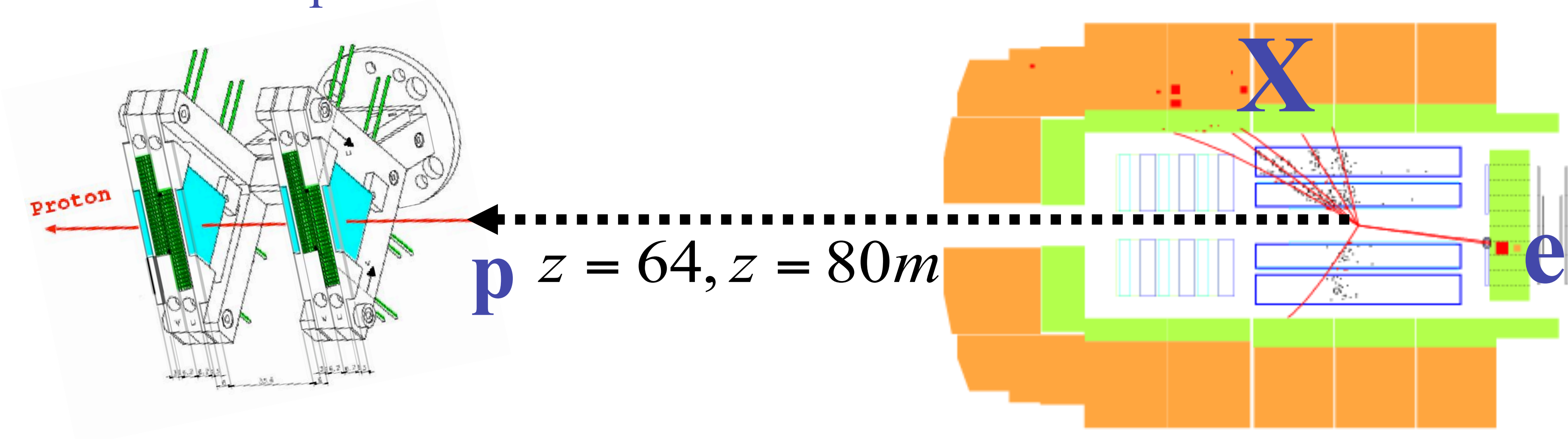
$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{Y_+}F_L^{D(4)}$$

$$\sigma_r^{D(3)} = \int_{-1}^{t_{min}} \sigma_r^{D(4)}\,dt$$

Experimentally selecting $ep \rightarrow eXp$

I Forward/Leading Proton Spectrometer

Central H1 Detector



Measure Leading Proton (FPS/LPS)

No proton dissociation (pdiss)

Measure the *t* dependence

Low detector acceptance

Experimentally selecting $ep \to eXp$

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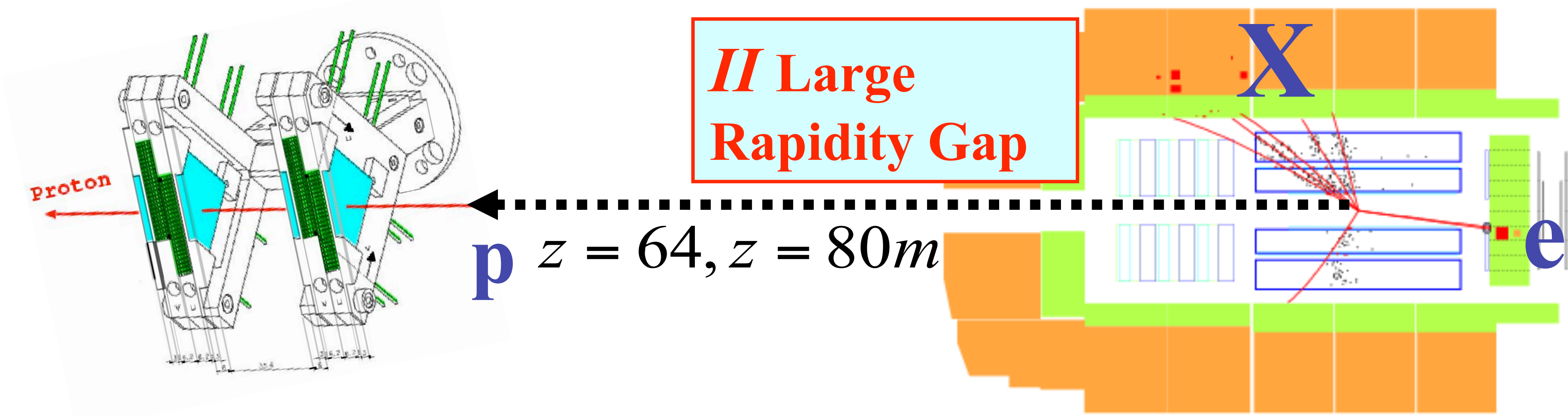


Measure Leading Proton (FPS/LPS)

No proton dissociation (pdiss)

Measure the t dependence

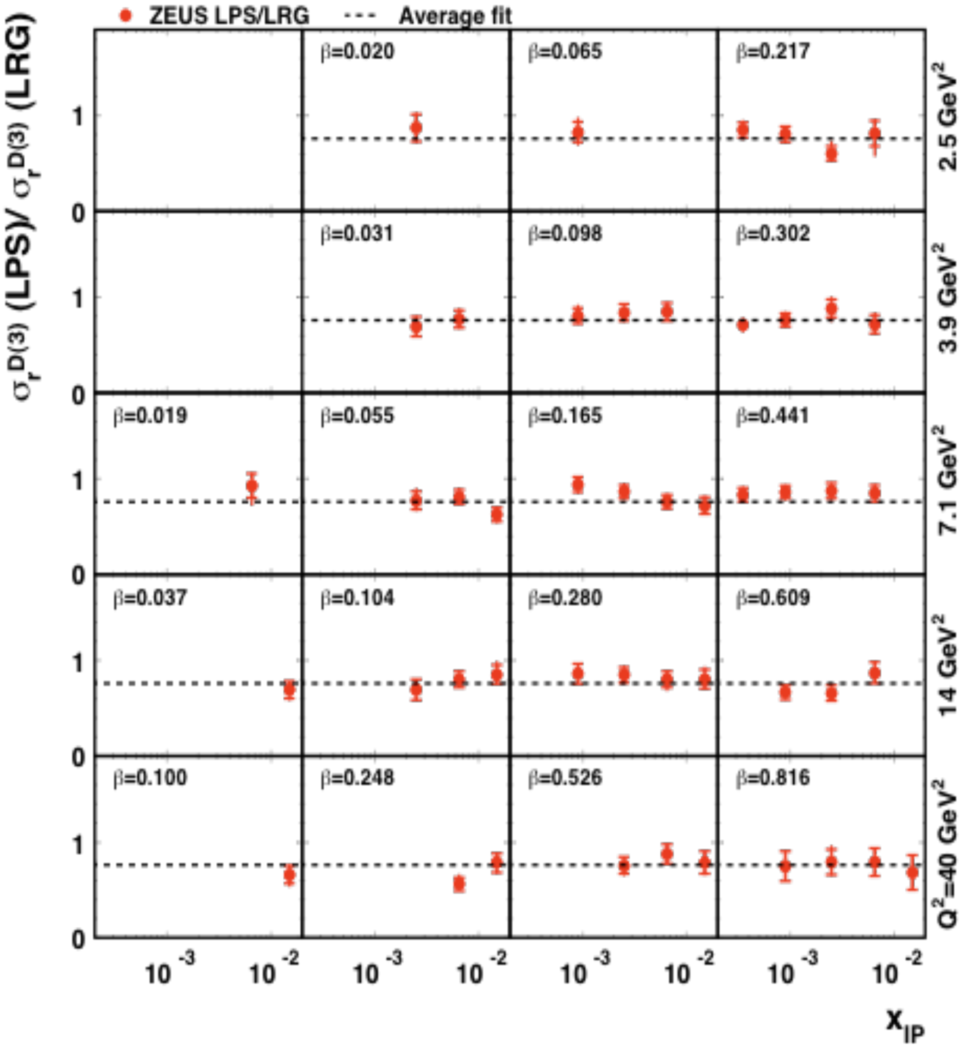
Low detector acceptance

Require Large Rapidity Gap (LRG) spanning at least $3.3 < \eta < \sim 7.5$

Kinematics measured from X system, integrate $|t| < 1.0$ GeV^2, $M_Y < 1.6$ GeV

High detector acceptance → precision

Ratio of Leading Proton / Large Rapidity Gap



The LRG data contains a sizeable proton dissociation background (esimated to be 24% at ZEUS,H1)

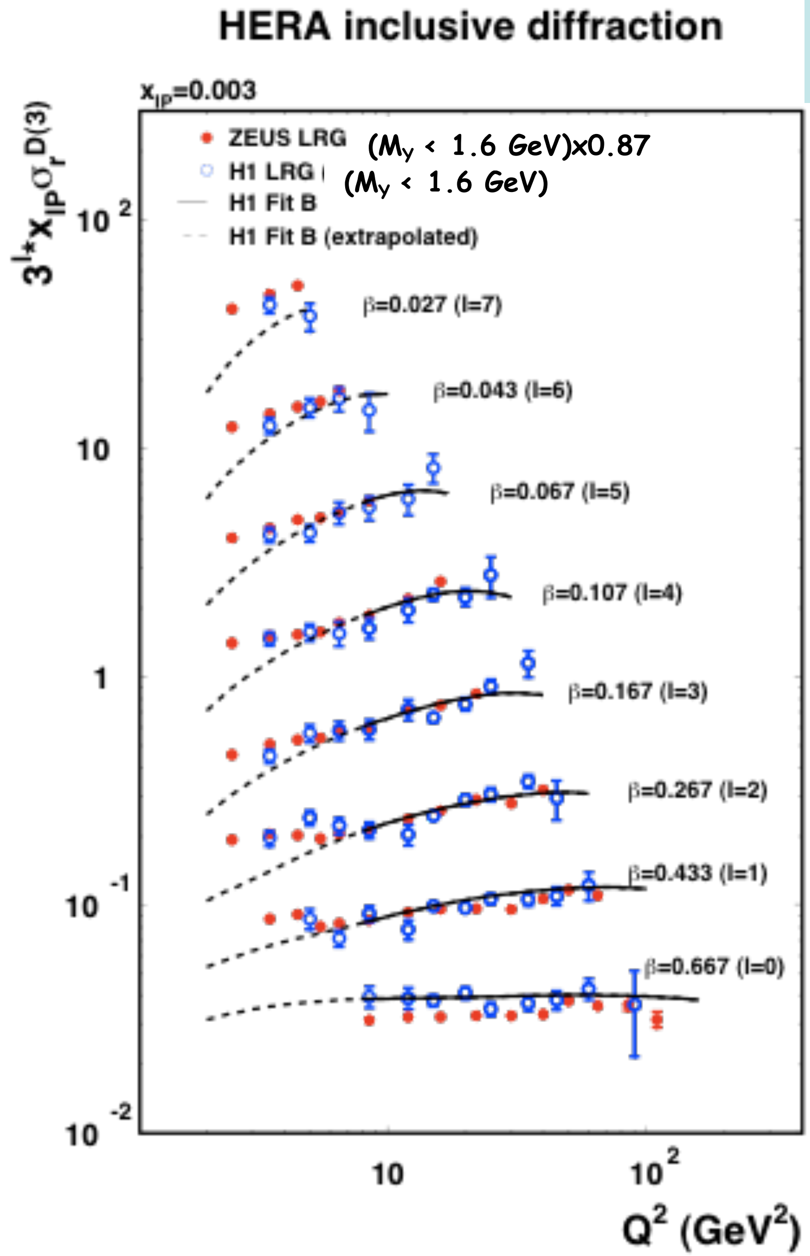
The ratio of leading proton /LRG cross sections is *independent* of Q^2, x_{IP}, β

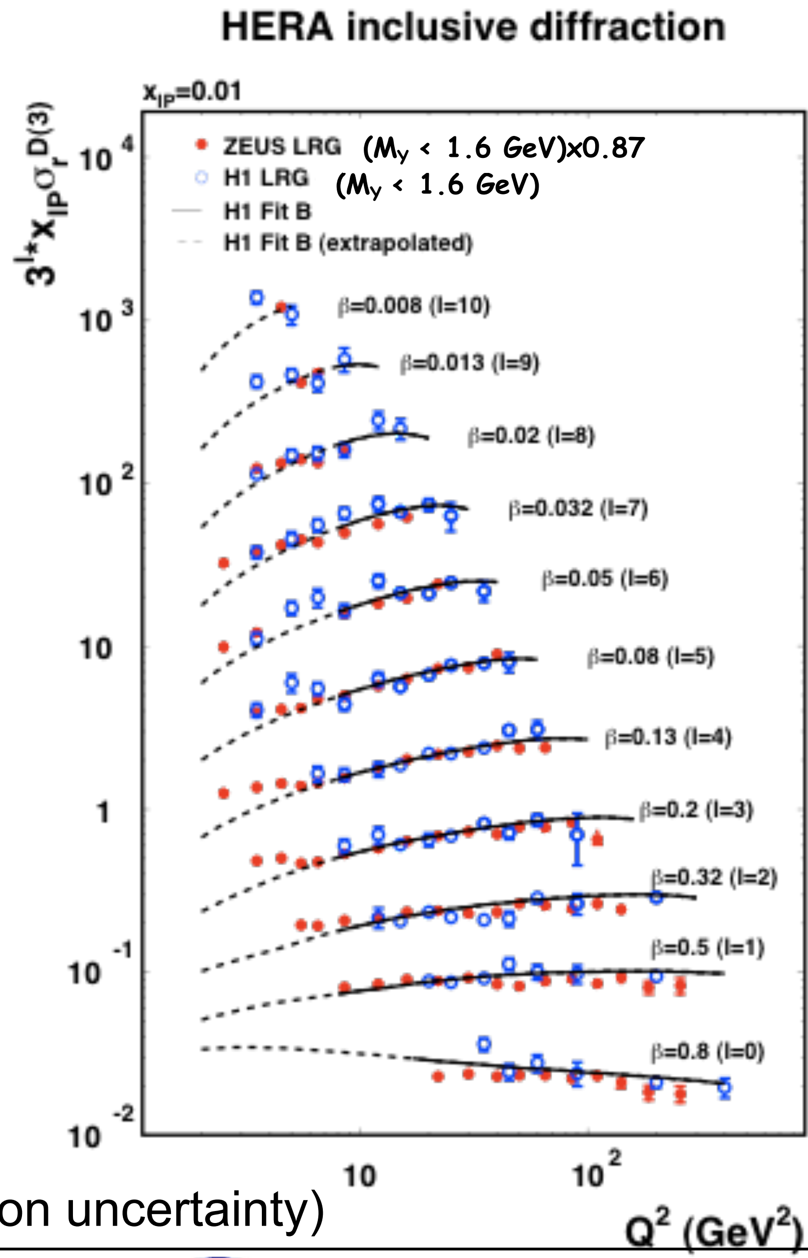
LRG equivalent to Leading Proton up to a normalisation correction to account for pdiss

ZEUS LPS / ZEUS LRG = 0.76 +-0.01(stat) +0.03-0.02(sys) +0.08-0.05 (norm)

→ pdiss background in LRG data: [24 +-1(stat) +2-3(sys) +5-8(norm)]%

HERA Large Rapidity Gap Data

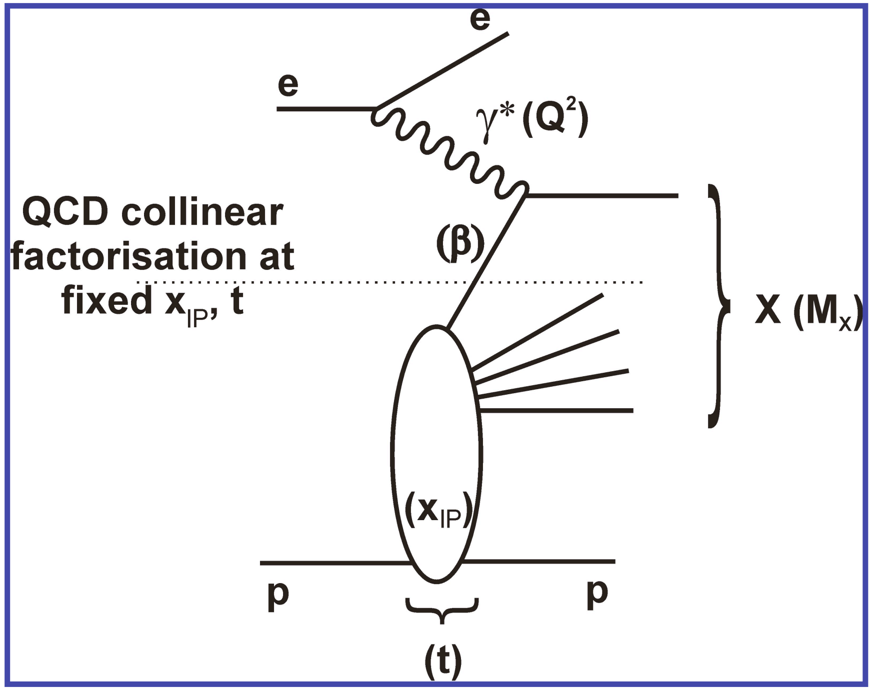




Good agreement between H1 and ZEUS

(ZEUS scaled by 0.87, covered by normalisation uncertainty)

Factorisation in Diffractive DIS

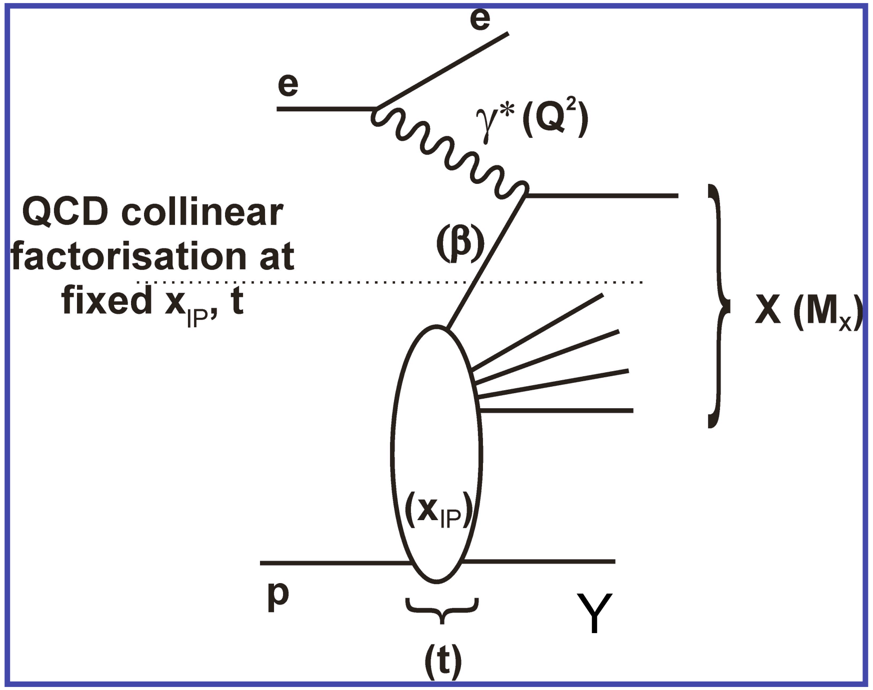


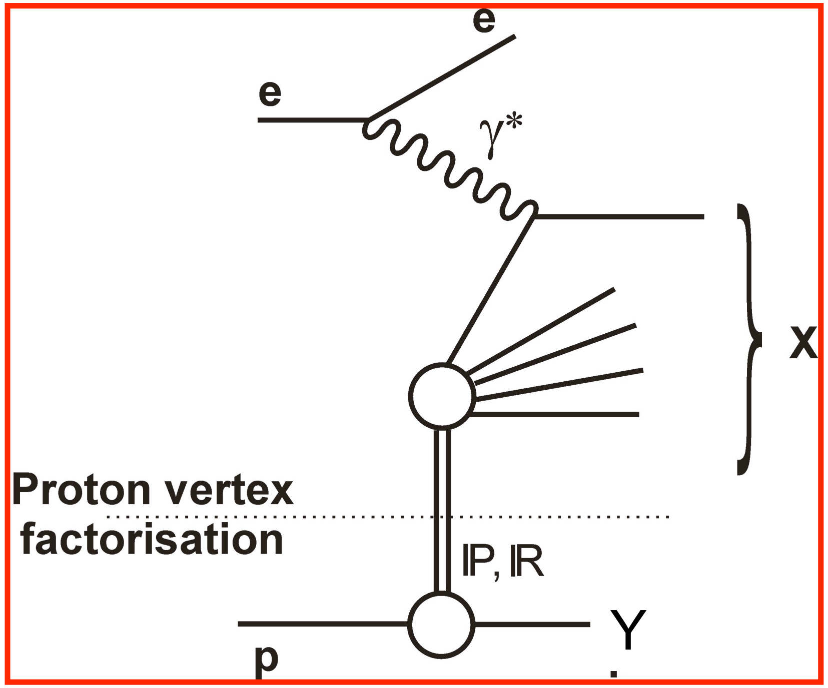
QCD hard scattering collinear factorisation (Collins) at fixed x_{IP} and t

$$d\sigma_{parton\,i}(ep \to eXY) = f_i^D(x, Q^2, x_{I\!P}, t) \otimes d\sigma^{ei}(x, Q^2)$$

Applied after integration over measured M_Y and t ranges

Factorisation in Diffractive DIS





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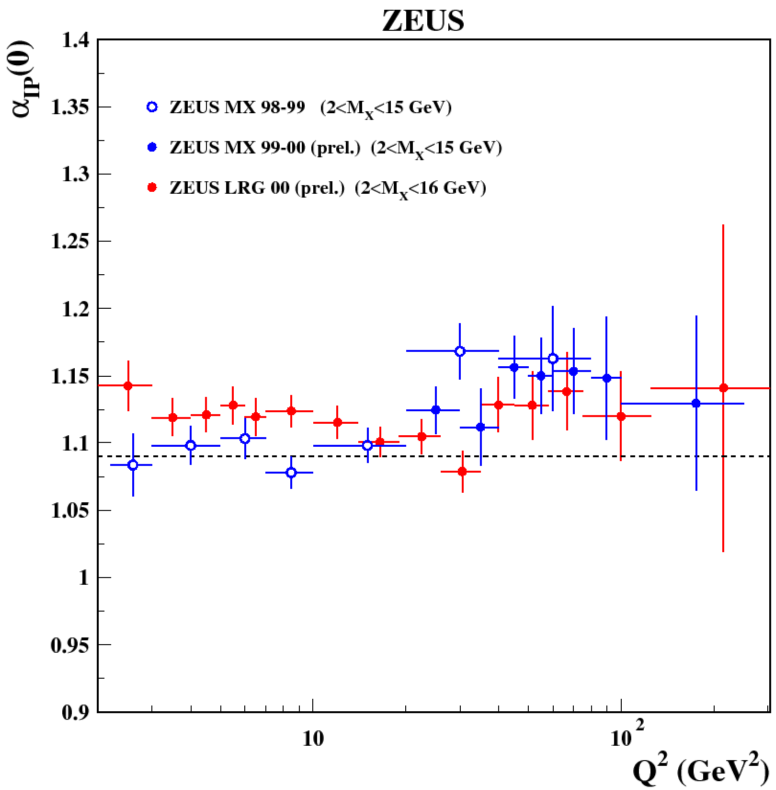
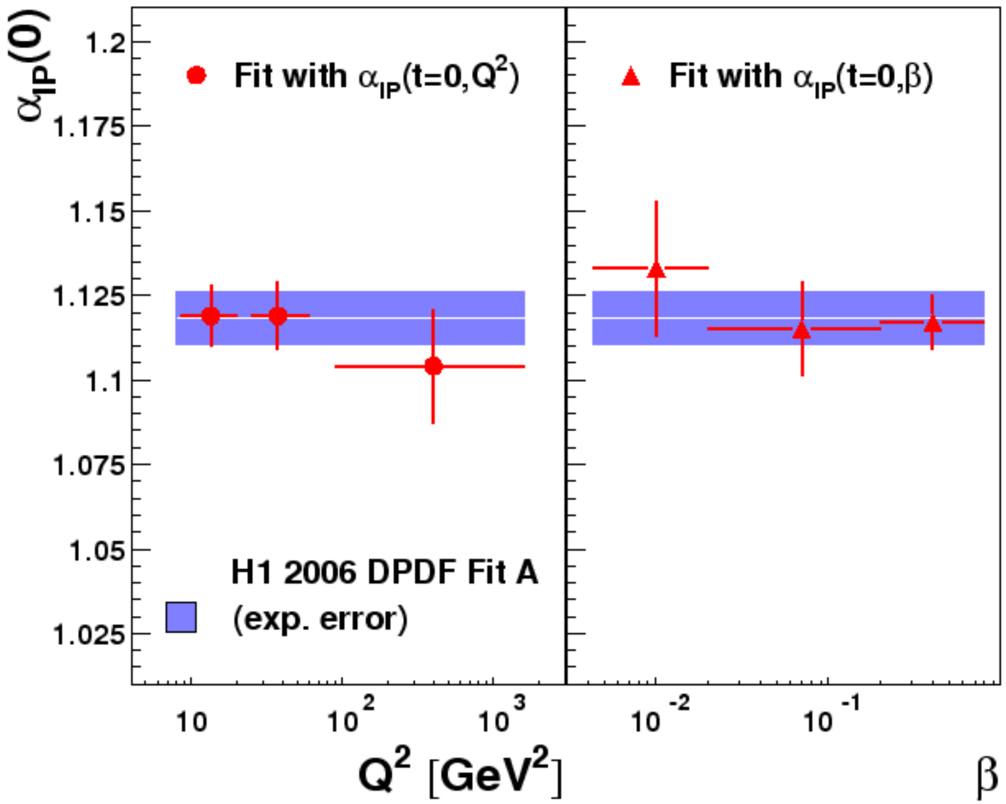
`Proton vertex' factorisation of β and Q^2 from x_{IP}, t, and M_Y dependences

$$f_i^D(x, Q^2, x_{I\!P}, t) = f_{I\!P/p}(x_{I\!P}, t) \cdot f_i^{I\!P}(\beta = \frac{x}{x_{I\!P}}, Q^2)$$

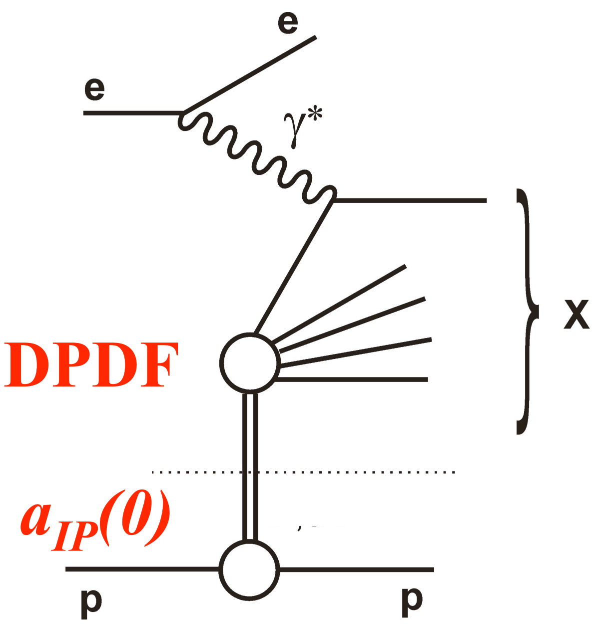
Proton Vertex Factorisation Tests





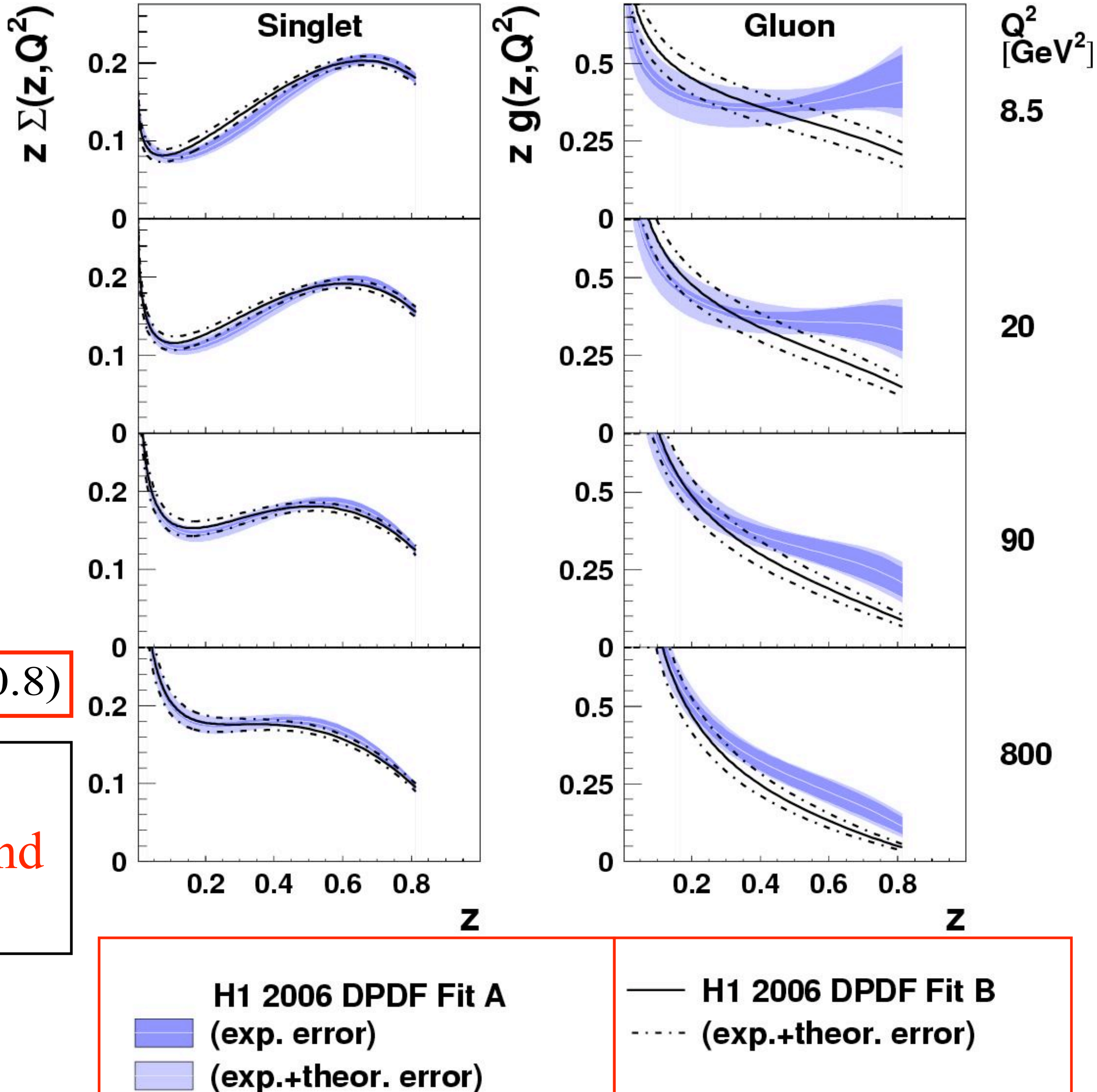
- Measure the x_{IP} dependence of the data as a function of β and Q^2
- The proton vertex factorisation approximation holds within the experimental precision
- This allows an NLO QCD analysis of the β and Q^2 dependences

NLO QCD Fits



$Q^2 \geq 8.5\ \text{GeV}^2$ (and $M_X > 2$ GeV, $\beta \leq 0.8$)

- Fit $\alpha_{IP}(0)$ (x_{IP} dependence).
- Fit 5(4) parameters of DPDFs (β and Q^2 dependences) using NLO QCD



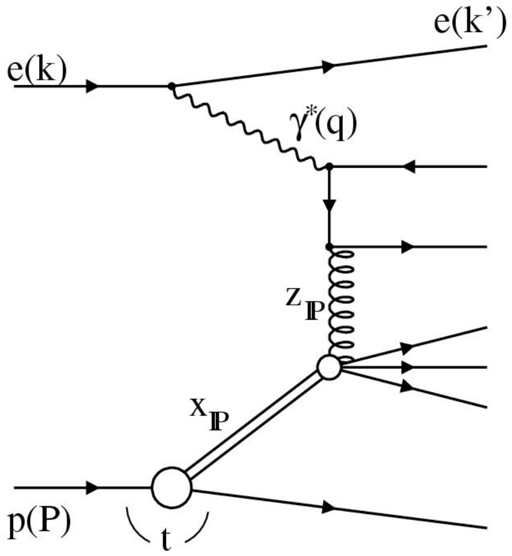
Singlet: $z\Sigma(z,Q_0^2) = A_q z^{B_q}(1-z)^{C_q}$

Gluon: 2 solutions, Fit A and Fit B:

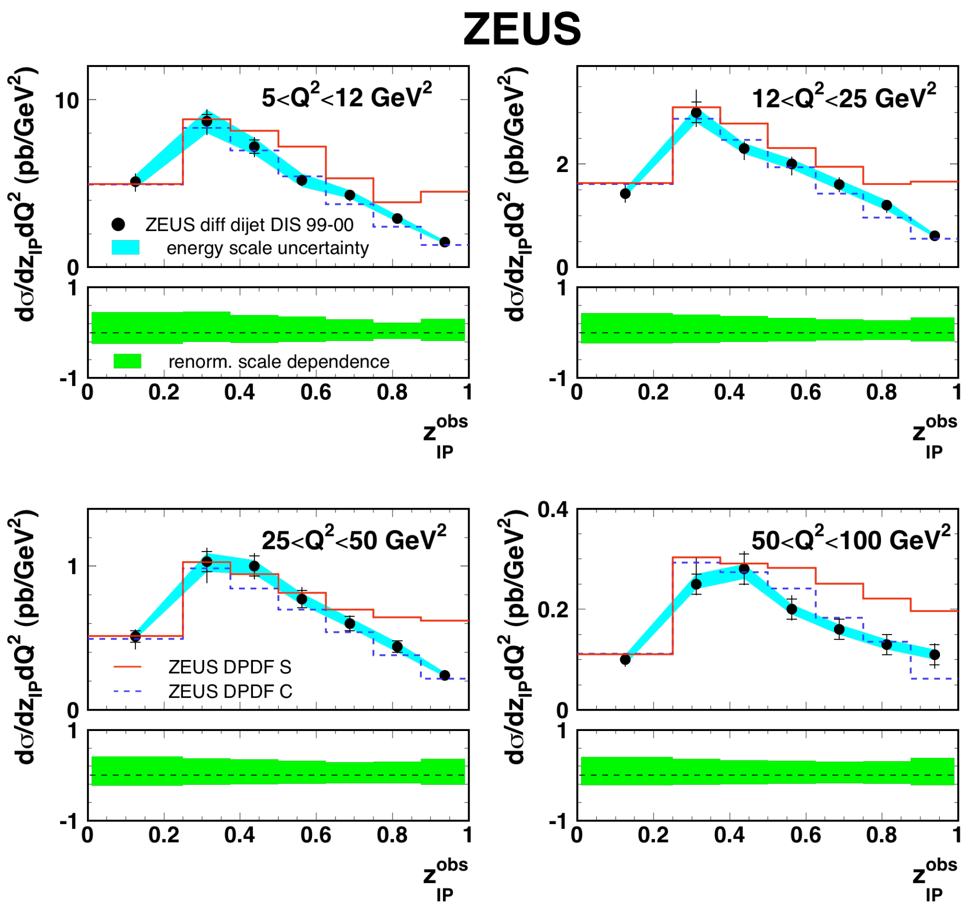
Fit A: $z_g(z,Q_0^2) = A_g(1-z)^{C_g}$

Fit B: $z_g(z,Q_0^2) = A_g$

Comparison with diffractive dijet data in DIS



$$z_{IP} = \frac{M_{12}^2 + Q^2}{M_X^2 + Q^2}$$



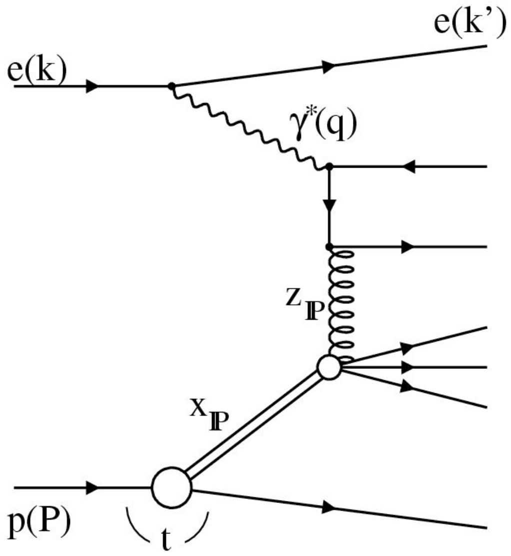
ZEUS collaboration use similar procedure with improved heavy flavour treatment

Compare fits to diffractive dijet data (sensitive to the gluon)

- Dijet data agree with DPDF C (constant gluon at starting scale)

Factorisation holds in diffractive DIS at HERA

Comparison with diffractive dijet data in DIS



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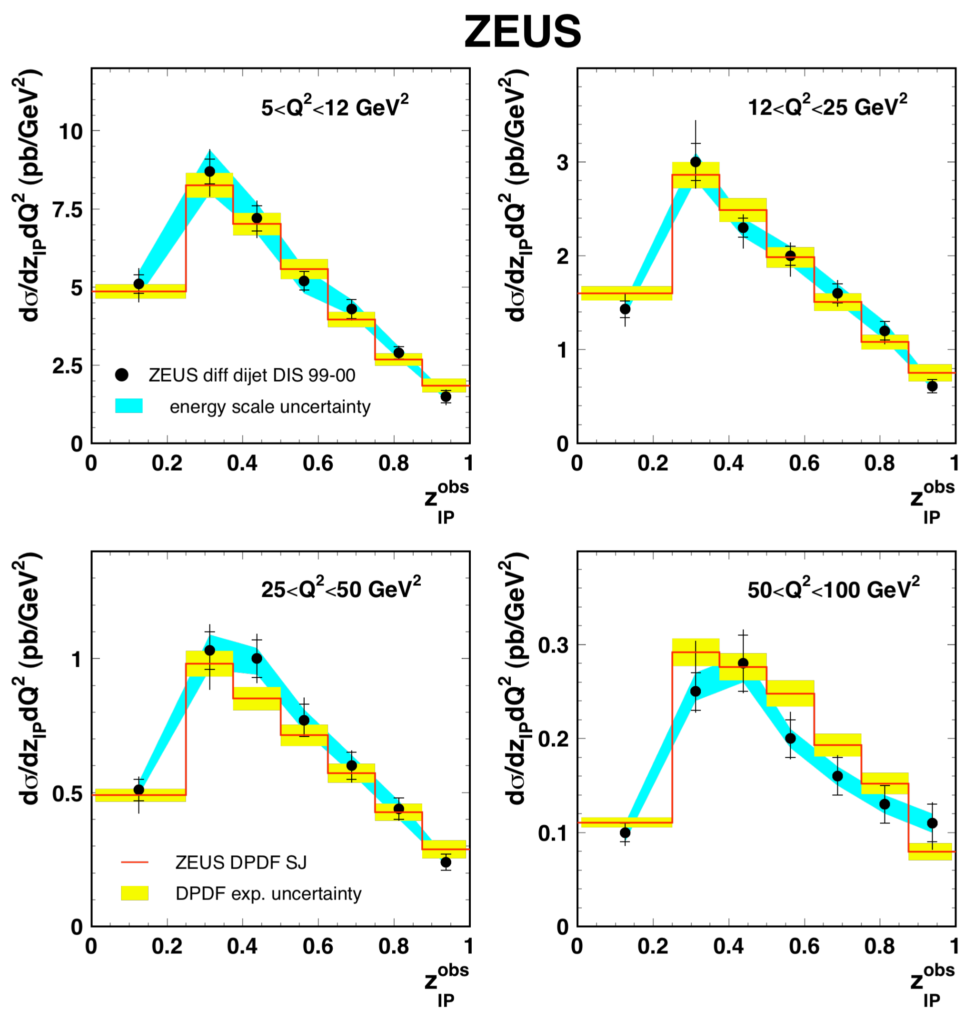
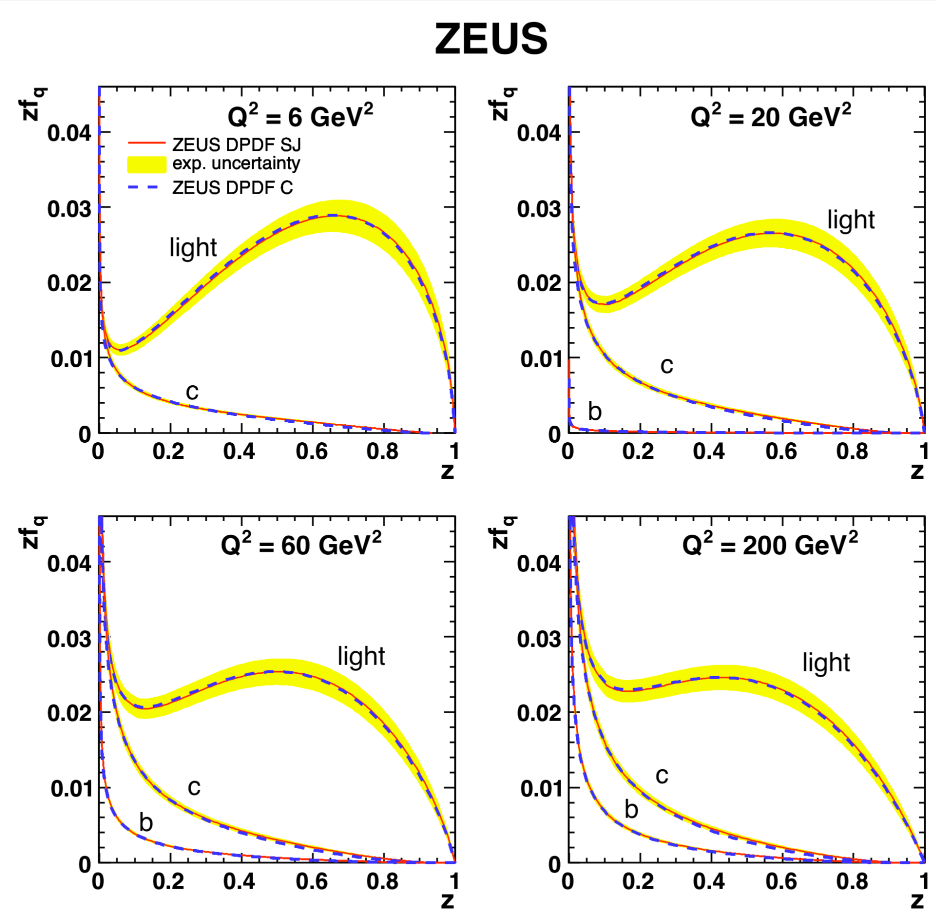


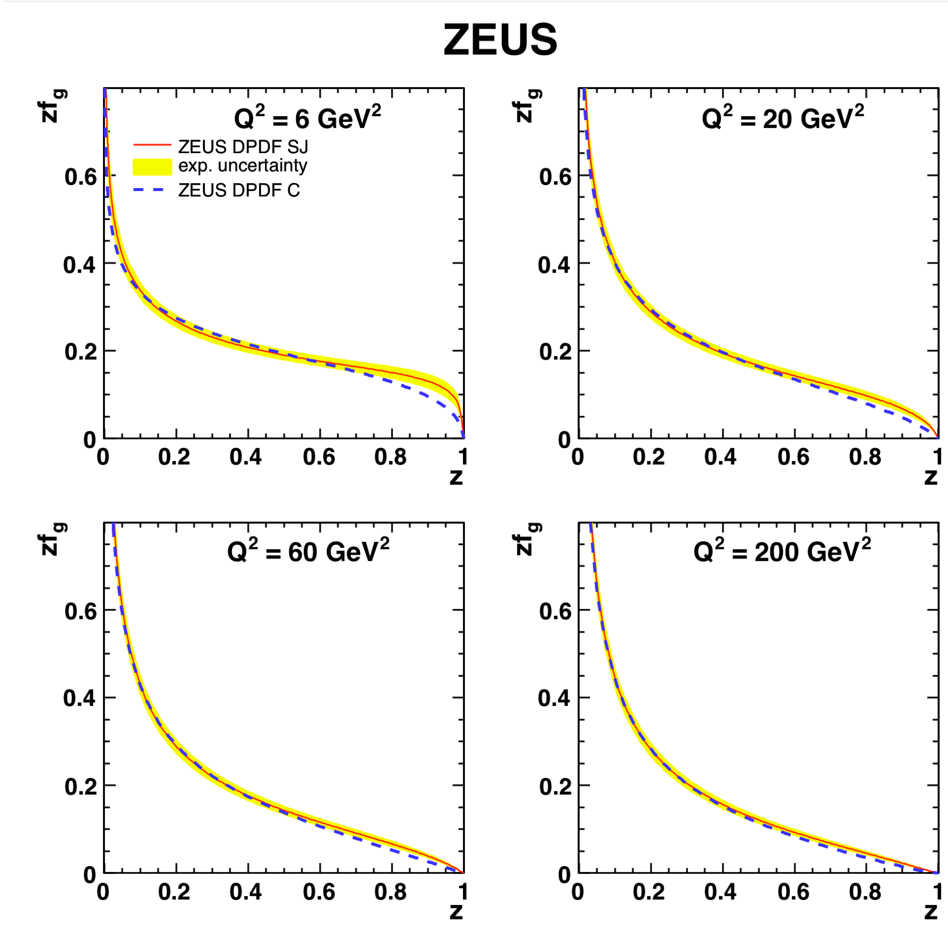
Inclusive data lose sensitivity to the gluon above z_{IP}~0.4

Use the diffractive dijet data as an extra constraint in the fit

Very good simultaneous fit of both inclusive and dijet data achieved

New DPDFs from ZEUS

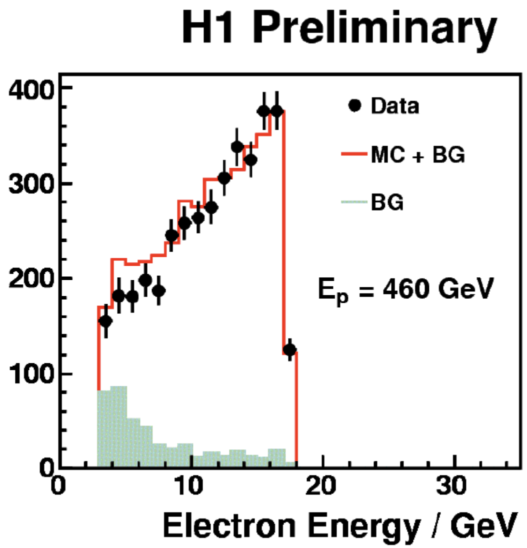




The singlet and gluon are constrained with similar precision across the whole kinematic range – The ZEUS results will be published very soon!!!

$$\sigma_r^D = F_2^D - \frac{y^2}{Y_+} F_L^D$$

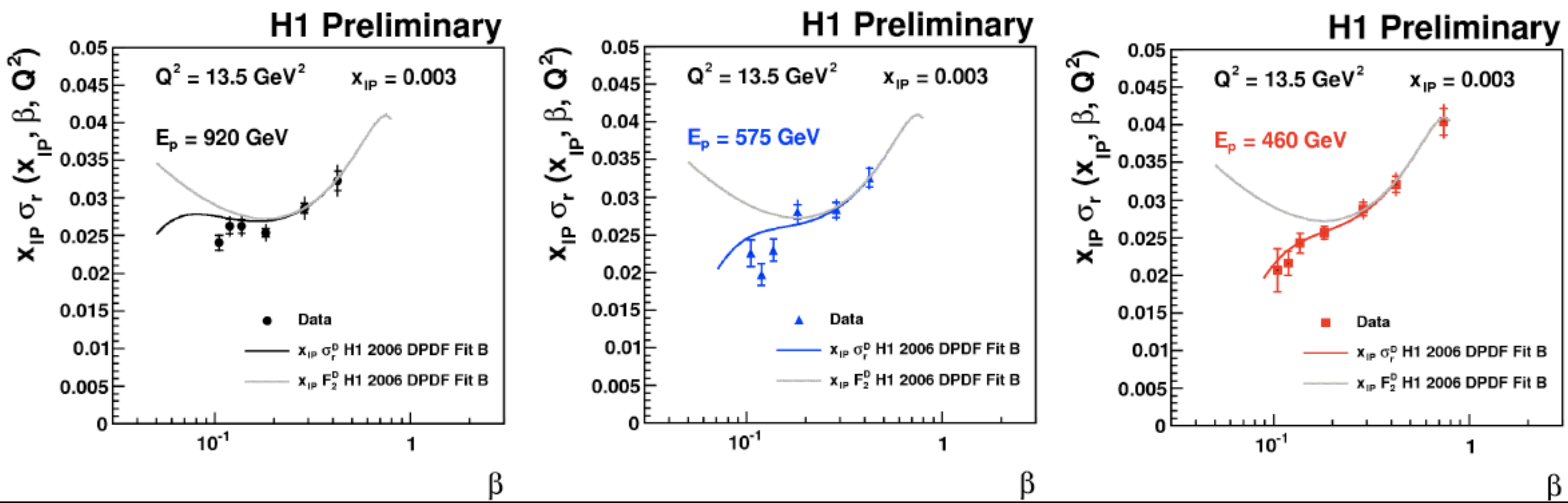
F_L^D



Very challenging measurement, requiring very good understanding of the detector down to low energies

Photoproduction background estimated from the data

Reduced cross section measurements at three proton beam energies, E_p=920, 575 and 460 GeV normalised to E_p=920 at low y (1 and 3%, smaller than the normalisation uncertainties and ~ the statistical precision)



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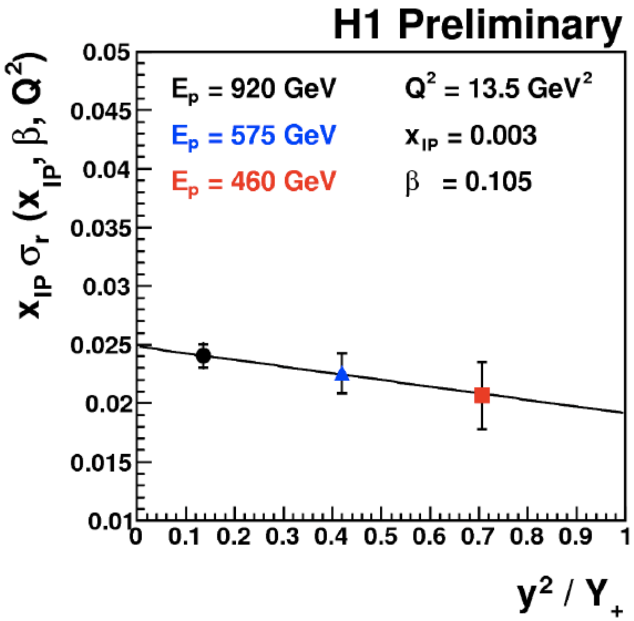
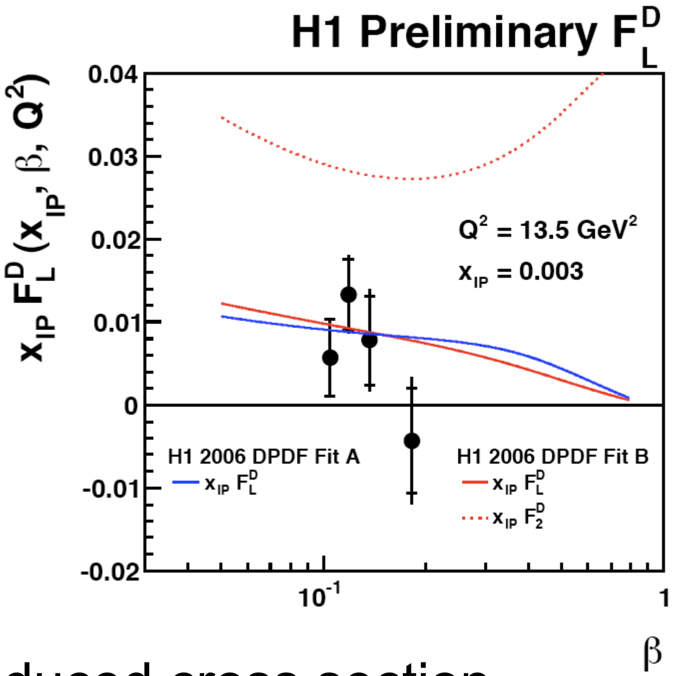
F_L^D





Rosenbluth plot (left) shows the three reduced cross section measurements from three beam energies at fixed Q^2 and β

The measurements of FLD agree well with the predictions of NLO QCD fits (H1 Fit A and B shown here)

Demonstrates the validity of NLO QCD applied to diffractive DIS

Diffraction at hadron colliders

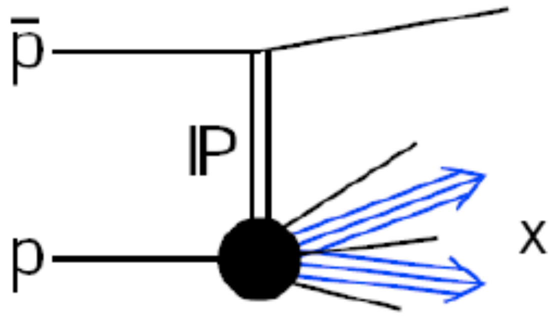
Single diffractive dissociation (SDD)

$p\, p \rightarrow [p' + IP] + p \rightarrow p'\, X$

$\xi = 1 - p'_L/p_L$ fractional longitudinal momentum loss of proton

$t = (p - p')^2$ four-momentum transfer squared at proton vertex

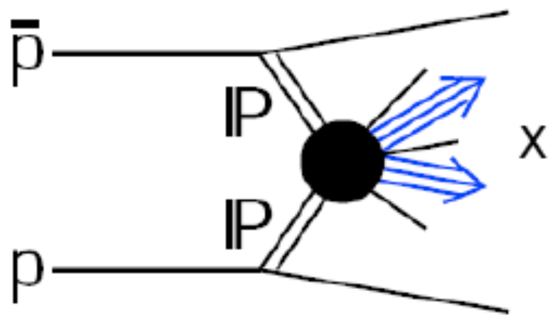
$M_X = X^2$ invariant mass of X



Double Pomeron exchange (DPE)

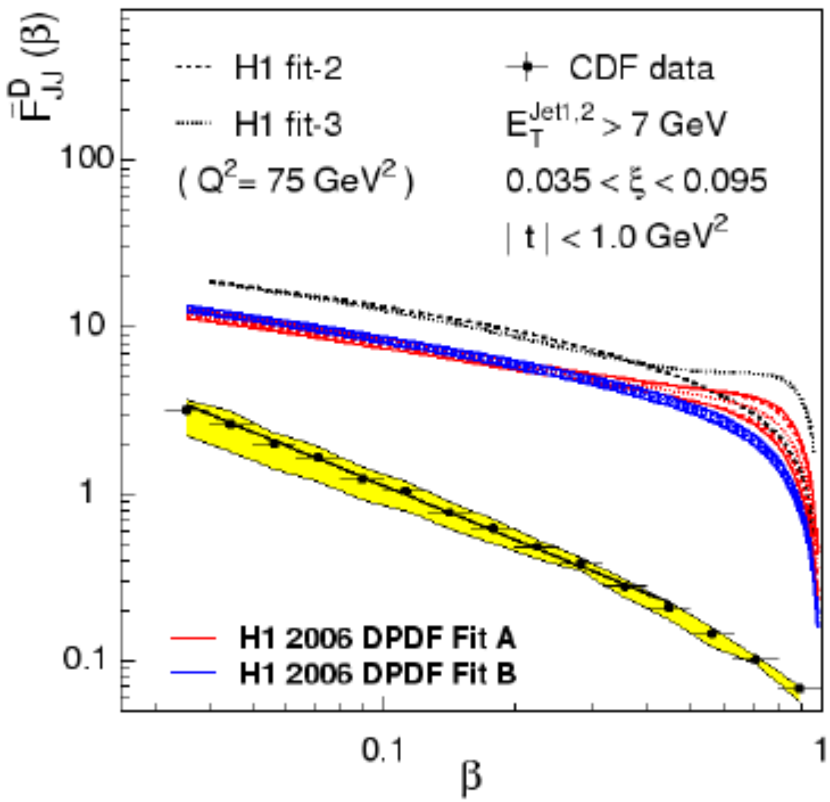
$p_1\, p_2 \rightarrow [p'_1 + IP] + [p'_2 + IP] \rightarrow p'_1\, X\, p'_2$

$\xi_1, \xi_2, t_1, t_2, M_X$



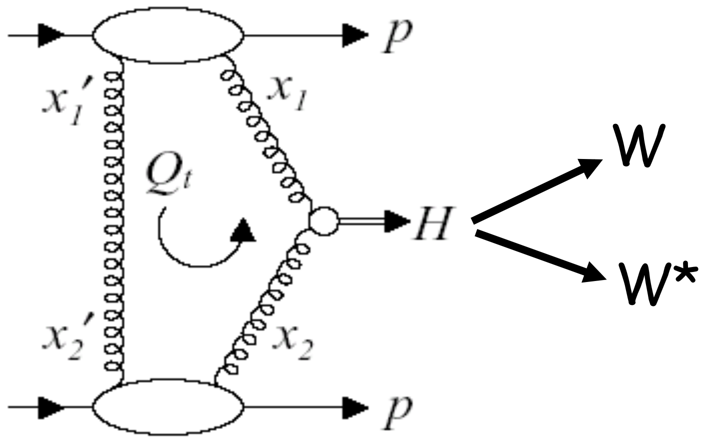
IP = colourless combination of gluons and quarks with vacuum quantum numbers

Exporting DPDFs to Hadron-Hadron machines



When trying to use DPDFs extracted at HERA to predict diffractive dijets at CDF we find…

…a large suppression factor



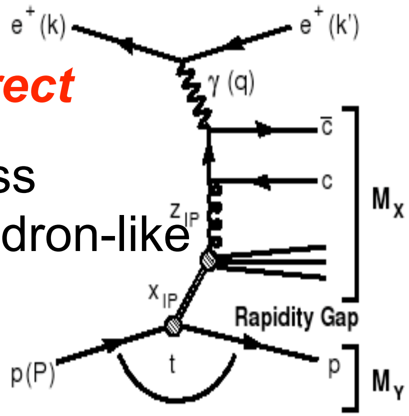
Effect can be qualitatively understood in terms of a survival probability ***S***, soft interactions induced by coloured spectators destroy the rapidity gap

If we want to understand diffraction at the LHC then we need to understand the mechanism behind this in detail

Factorisation tests at HERA

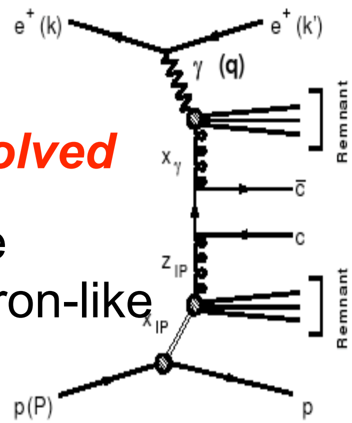
Direct

Less hadron-like



Resolved

More hadron-like



Use photoproduction at HERA to mimic a hadron-hadron collider

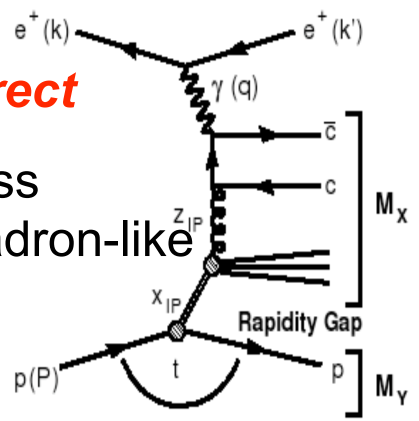
The x_γ variable (photon momentum fraction entering the hard scatter) determines how hadron-like an event is

Expect *Resolved* events (low x_γ) to be more suppressed than *Direct* events (high x_γ)

Factorisation tests at HERA

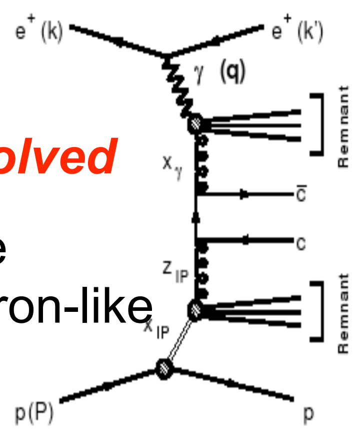
Direct

Less hadron-like



Resolved

More hadron-like



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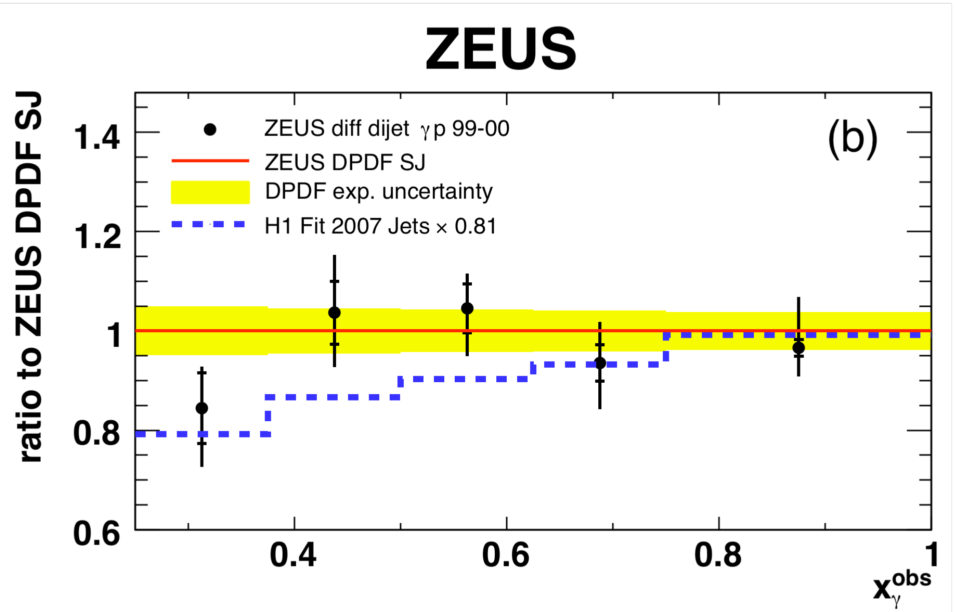


Study diffractive dijets in photoproduction and look at the ratio of data / theory

No indication of an x_γ dependence

Dominating uncertainty from renormalisation scale not shown

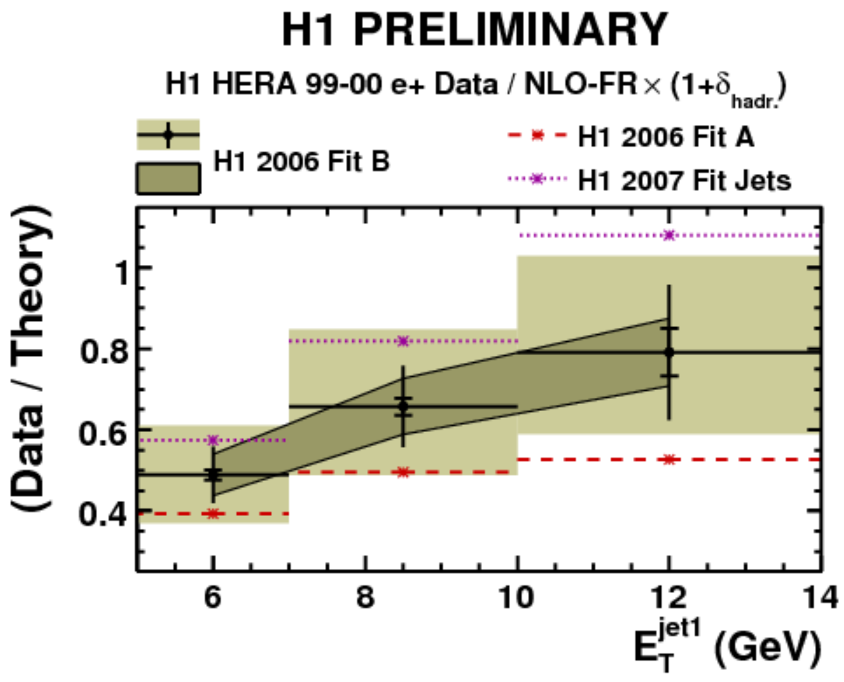
E_T dependence of the suppression

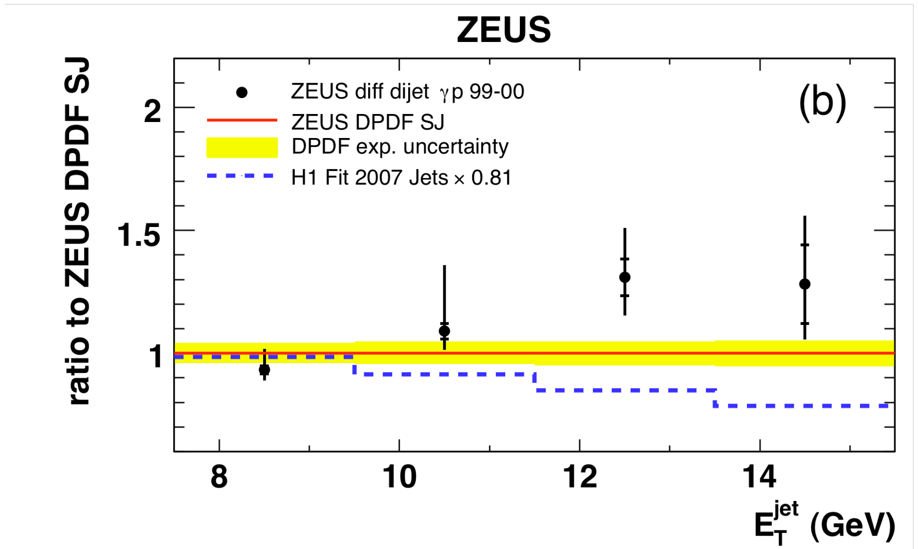
The H1 and ZEUS dijets in photoproduction analyses have different analysis cuts on jet E_T with ZEUS being at higher E_T than H1

Look at the Data/Theory ratio as a function of the E_T of the leading jet

H1 sees a suggestion of an *E_T dependence* of the suppression

ZEUS does not see an E_T dependence in a smaller range of E_T





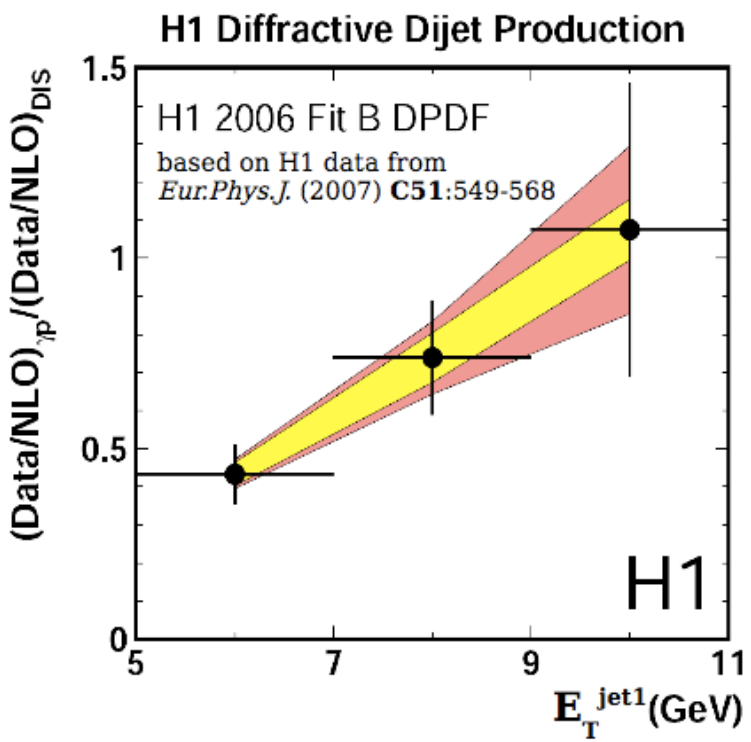
Dominating uncertainty from renormalisation scale not shown in ZEUS plot

Summary on Suppression Studies at HERA

The ratio of data / theory depends on many things including the DPDF set used (H1, ZEUS, with/without DIS dijets, etc.)

It would be interesting to see the Tevatron plot (slide 23) as a function of E_T

Most robust measurement so far comes from the double ratio of data/theory for photoproduction/DIS where some systematics e.g. DPDFs cancel



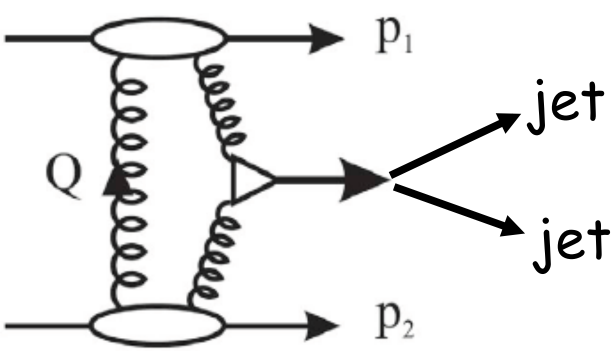
The double ratio does suggest an E_T dependence of ***S***

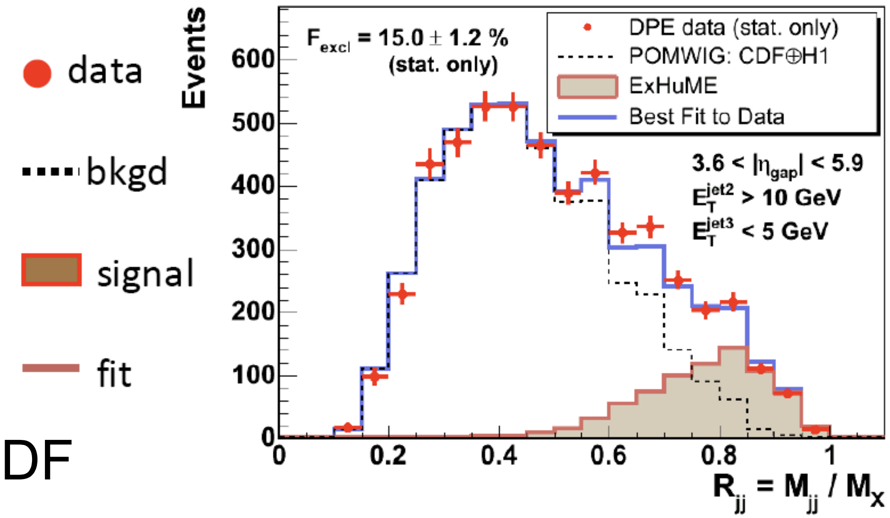
There is no evidence for an x_γ dependence of ***S***

Not understood!

Aside: Looking at the ratio of diffractive to inclusive dijet cross-sections suffers from uncertainties arising from MI effects

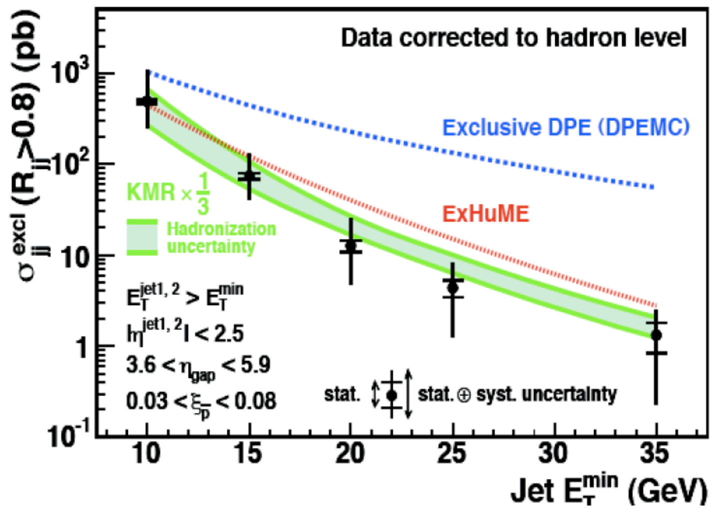
Central Exclusive Production at CDF





Exclusive dijet production observed at CDF

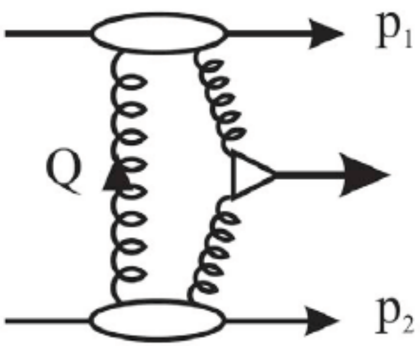
Perturbatively calculable component in excess of the inclusive diffractive background predicted from HERA DPDFs * ***S***



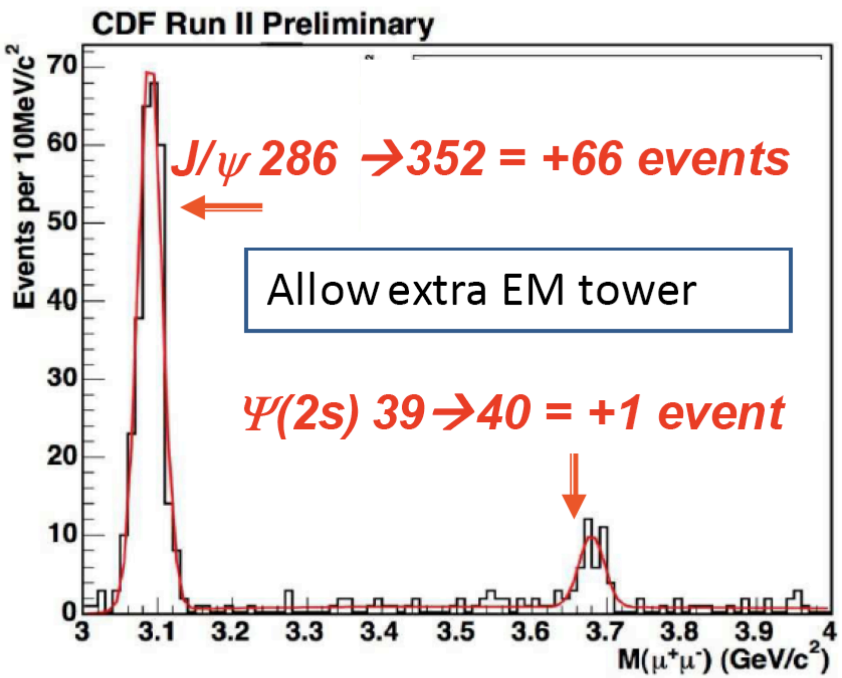
Data in good agreement with theoretical predictions (KMR) and DPE MC

Bolsters confidence in predictions for Central Exclusive Higgs production

Central Exclusive Production at CDF



$$\chi_c \rightarrow J/\psi + \gamma$$



Very rare decay observed at CDF

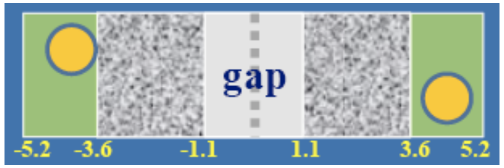
Rate in good agreement with theoretical predictions

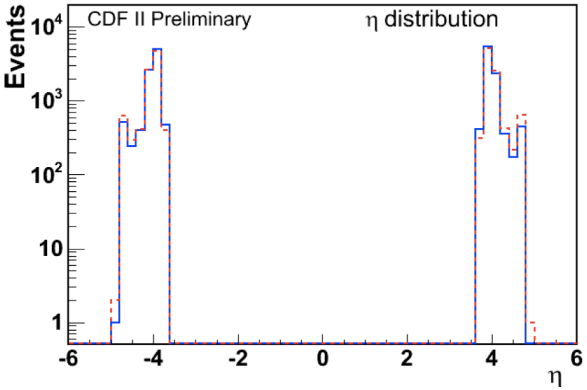
Supports calculations of suppression for hadron colliders

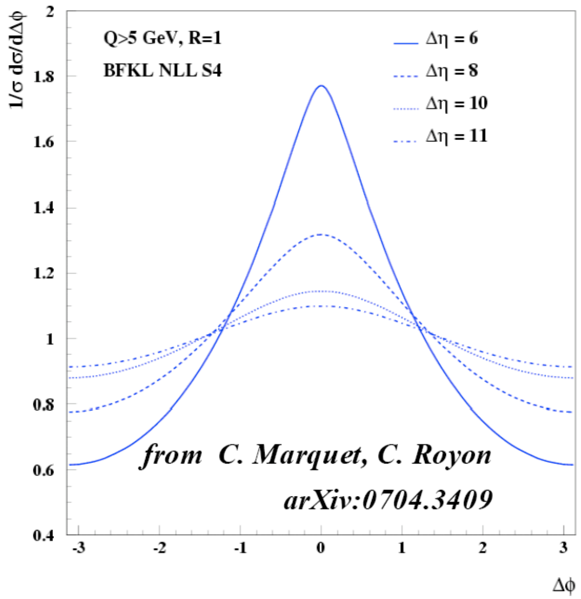
Bolsters confidence in predictions for Central Exclusive Higgs production

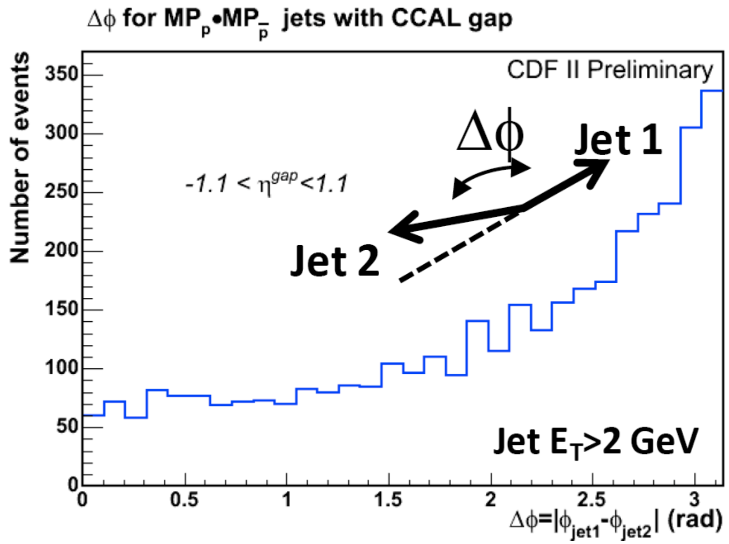
Message from the Tevatron is that the suppression factor calculation works!

Forward Jets with Rapidity Gaps at CDF









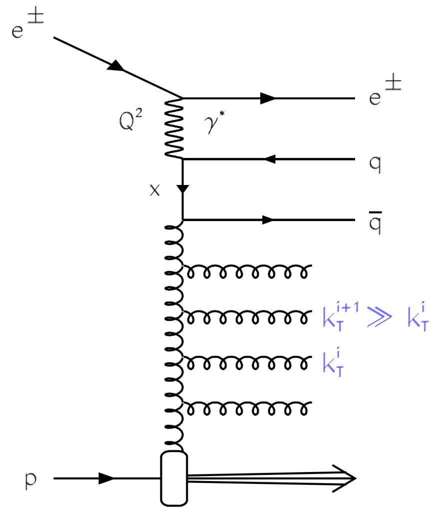
Large Rapidity Gap configuration means BFKL radiation is enhanced

Expect to see large azimuthal decorrelations of the jets

First attempt to look at this at CDF looks promising, although on edge of acceptance with their forward detectors

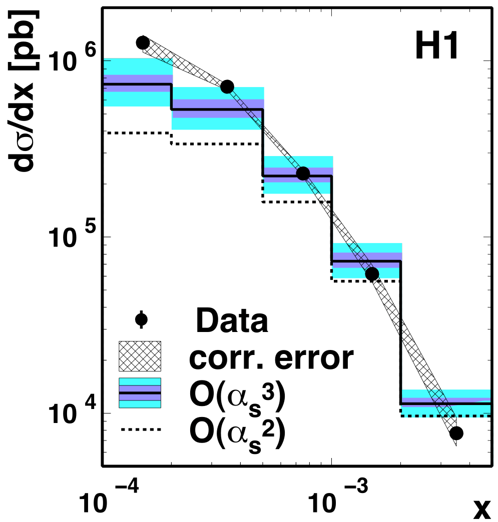
LHC experiments well equipped with forward detectors ➔ more sensitive

3 and 4 Jet Events at Low x at HERA

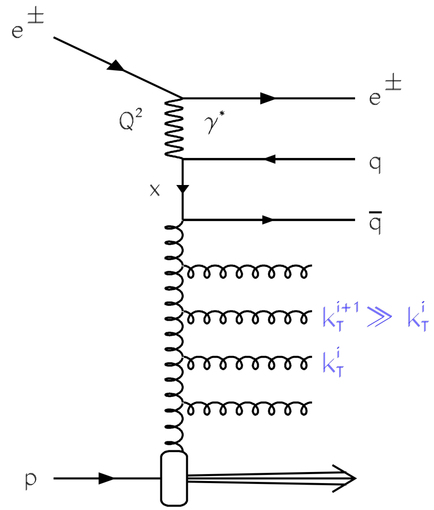


3 (or more) jet events an ideal testing ground to see if DGLAP approximation (k_T ordering of jets) is valid for all available phase space

Compare to NLO $O(\alpha_S^3)$ calculation using NLOJET++



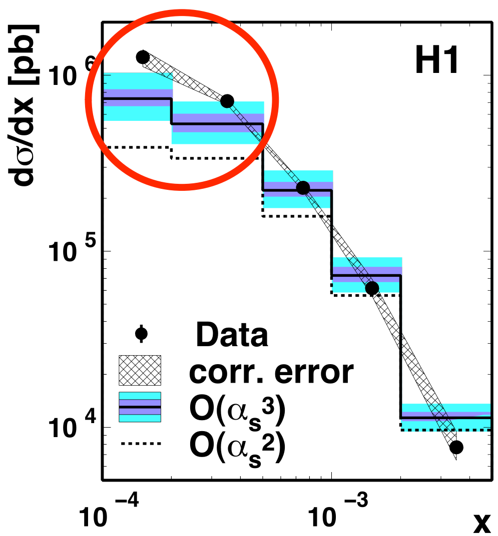
3 and 4 Jet Events at Low *x* at HERA



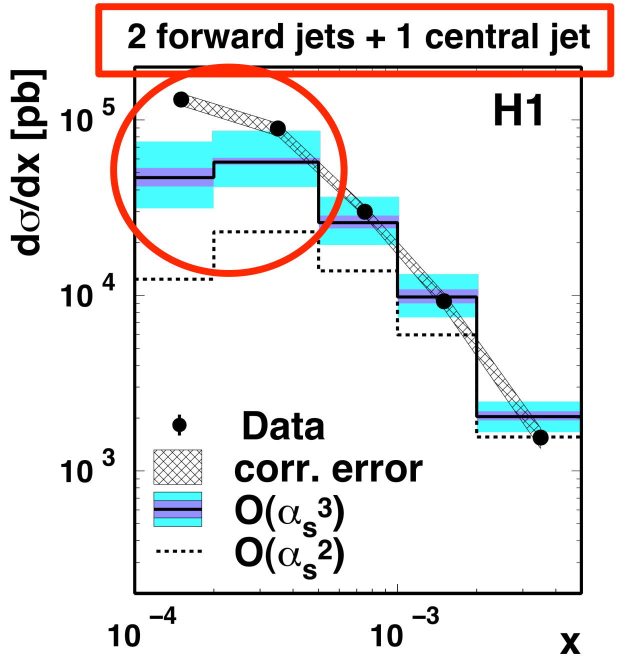
3 (or more) jet events an ideal testing ground to see if DGLAP approximation (k_T ordering of jets) is valid for all available phase space

When asking that 2 of the 3 jets are forward, the discrepancy between data and theory increases

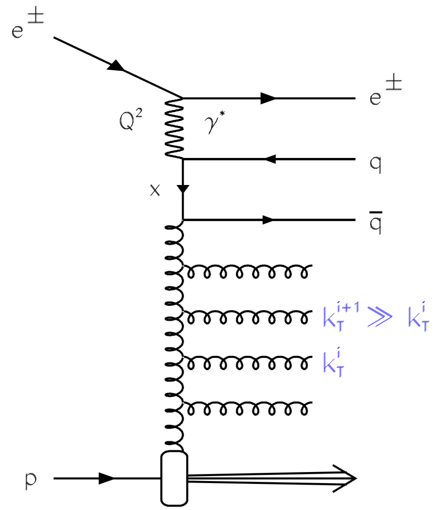
Compare to NLO $O(\alpha_S^3)$ calculation using NLOJET++



NLO fails at low x



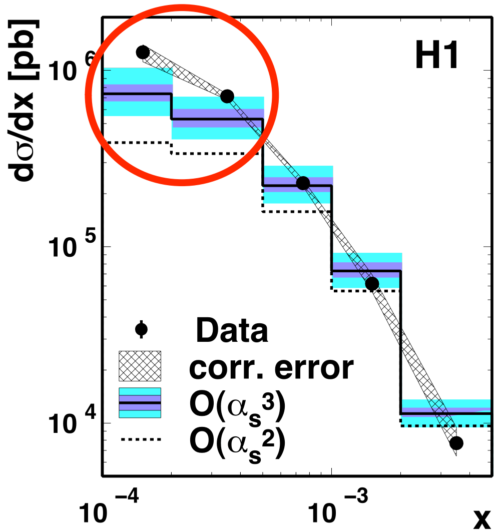
3 and 4 Jet Events at Low *x* at HERA



3 (or more) jet events an ideal testing ground to see if DGLAP approximation (k_T ordering of jets) is valid for all available phase space

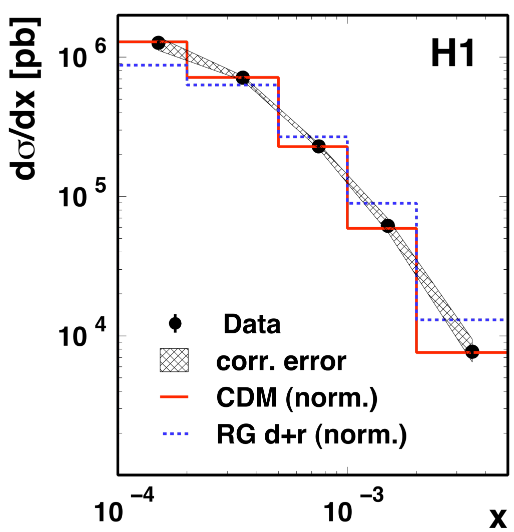
Also test the Colour Dipole Model (CDM) which has no k_T ordering

Compare to NLO $O(\alpha_S^3)$ calculation using NLOJET++



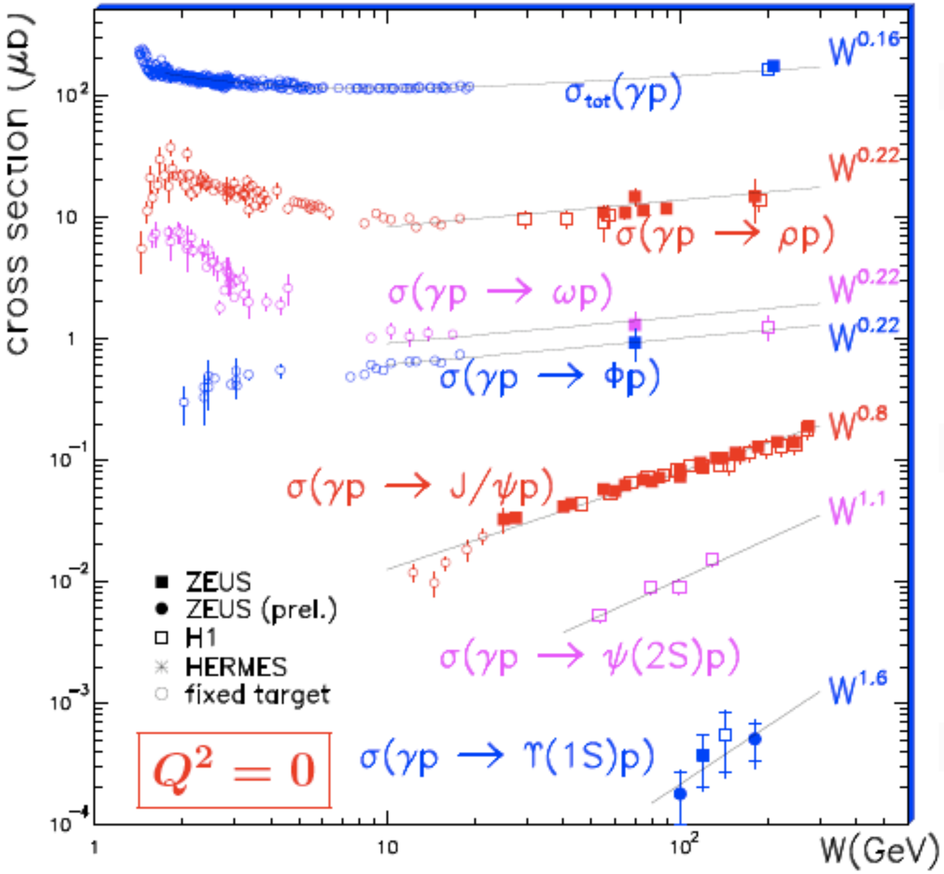
NLO fails at low x

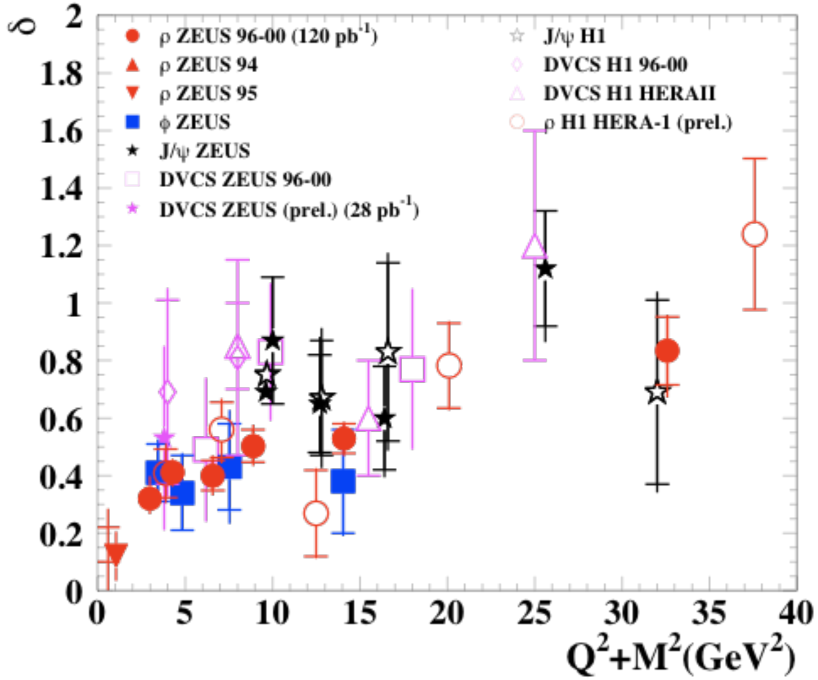
Compare to MC with (RG) and without k_T ordering (CDM)



CDM works at all x

Exclusive Diffraction at HERA: *ep* → *ep VM*



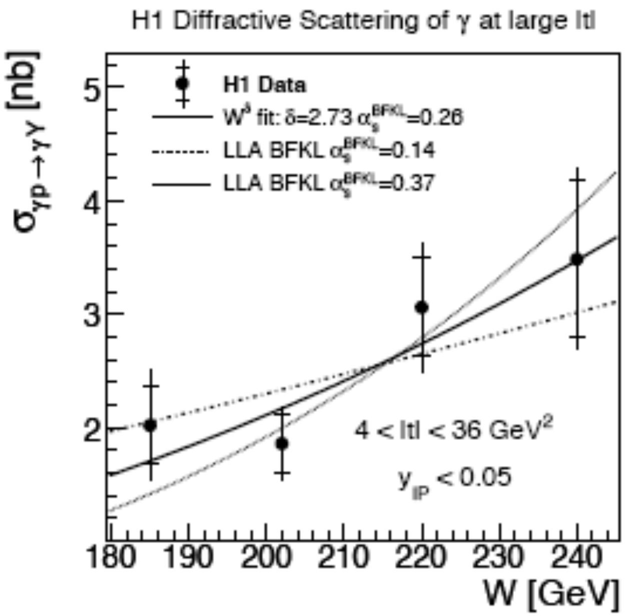


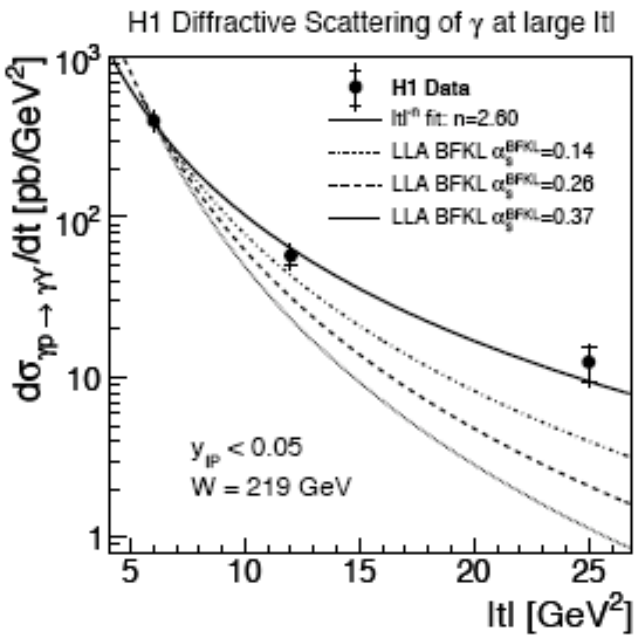
As the VM mass increases, the process gets harder

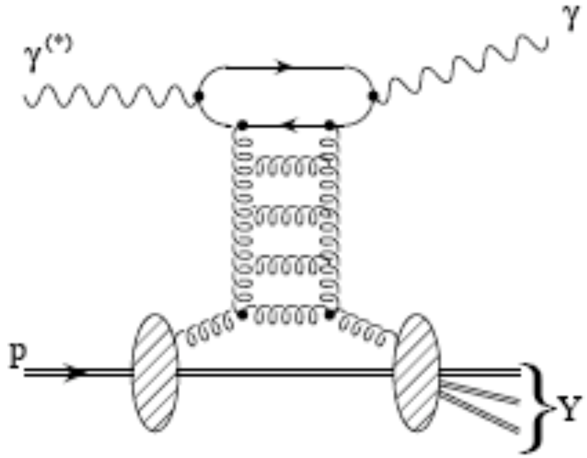
As Q^2 increases, the process gets harder

Many more features, all compatible with predictions of QCD, but no single model can describe them all (sorry, no time to do this justice!)

Diffractive high p_T photons







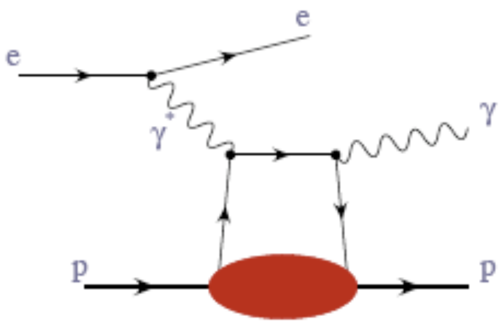
Large t provides a scale for perturbative (BFKL) calculations

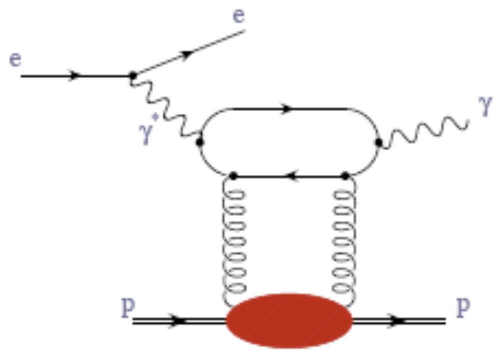
Very hard W dependence

$$W^{\delta} \text{ fit} \rightarrow \delta = 2.73 \pm 1.02^{+0.56}_{-0.78}$$

BFKL prediction describes the data to some extent

Deeply Virtual Compton Scattering





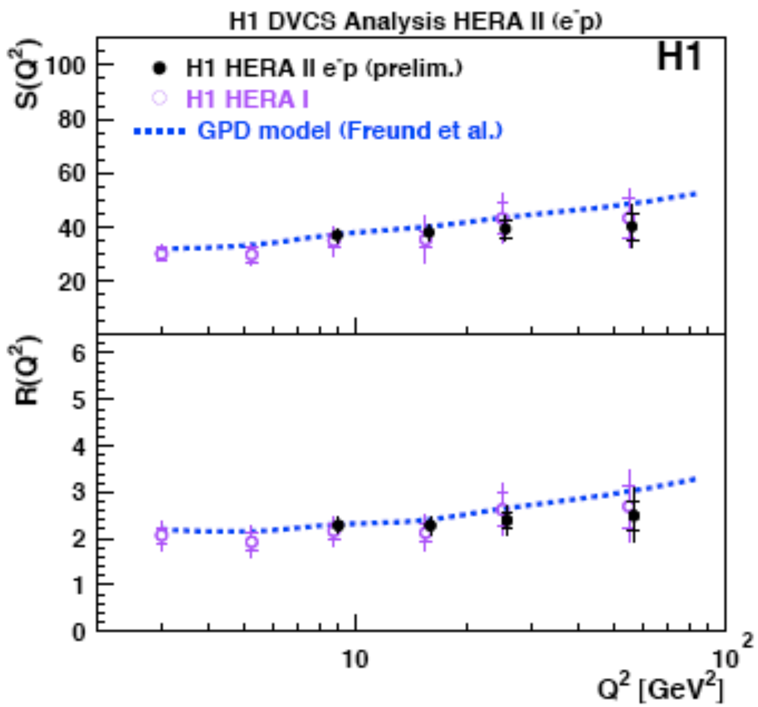
Extract a parton with momentum p_1 and reinsert it with p_2

A fully calculable process sensitive to the transverse correlations of partons - GPDs

Q^2 evolution of GPD: $S = \sqrt{\frac{\sigma_{DVCS}\, Q^4\, b(Q^2)}{(1+\rho^2)}}$

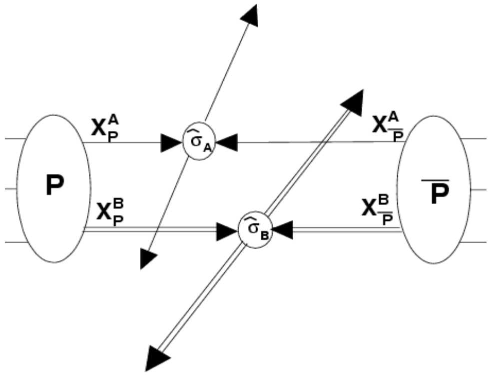
Ratio of GPD to PDF:

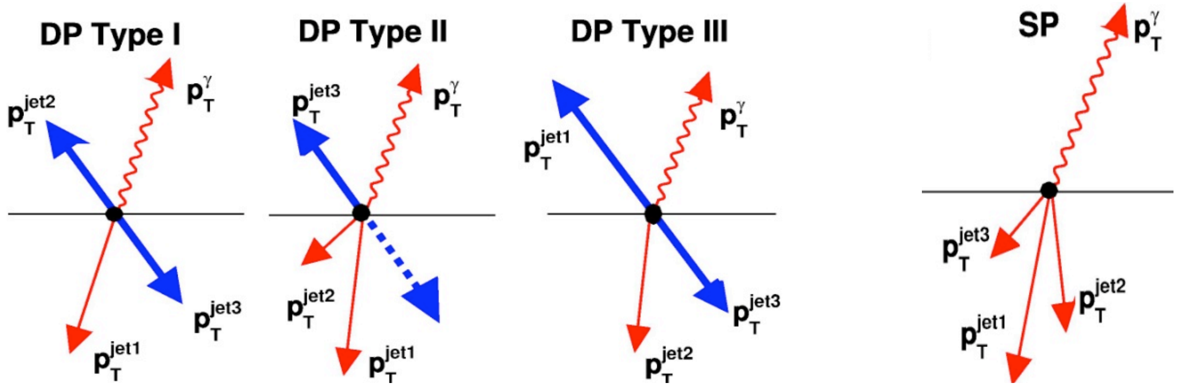
$$R = \frac{\mathcal{I}m\, A(\gamma^* p \rightarrow \gamma p)}{\mathcal{I}m\, A(\gamma^* p \rightarrow \gamma^* p)}$$



The data are well reproduced by the GPD model prediction

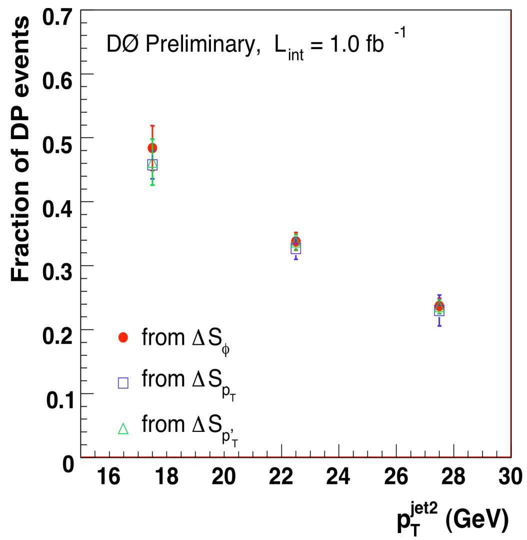
Double-Parton Scattering: γ + 3-jet

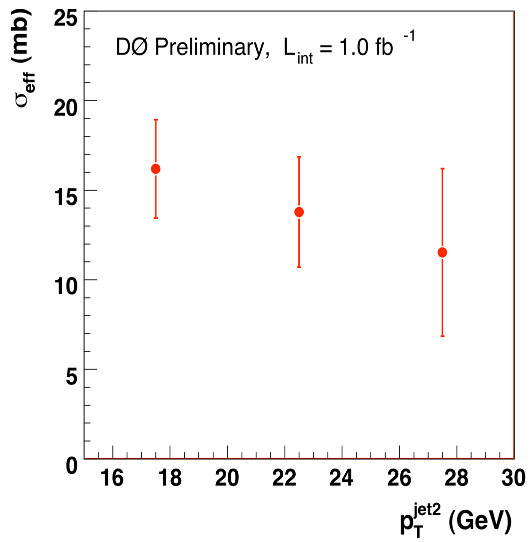




$$\sigma_{DP} = \sigma_{\gamma j}\ \sigma_{jj}/\sigma_{eff}$$

- ≥2 partons interact / hadron collision
- Provides info on spatial distribution of partons in proton
- May impact PDFs
- Background to many rare processes
- DP fraction drops from 0.47 ± 0.04 in $15 < p_{T2} < 20$ GeV to 0.23 ± 0.03 in $25 < p_{T2} < 30$ GeV
- Effective cross section ~constant: averages to σ_{eff} = 15.1±1.9 mb
- In agreement with CDF Run I measurement





Summary

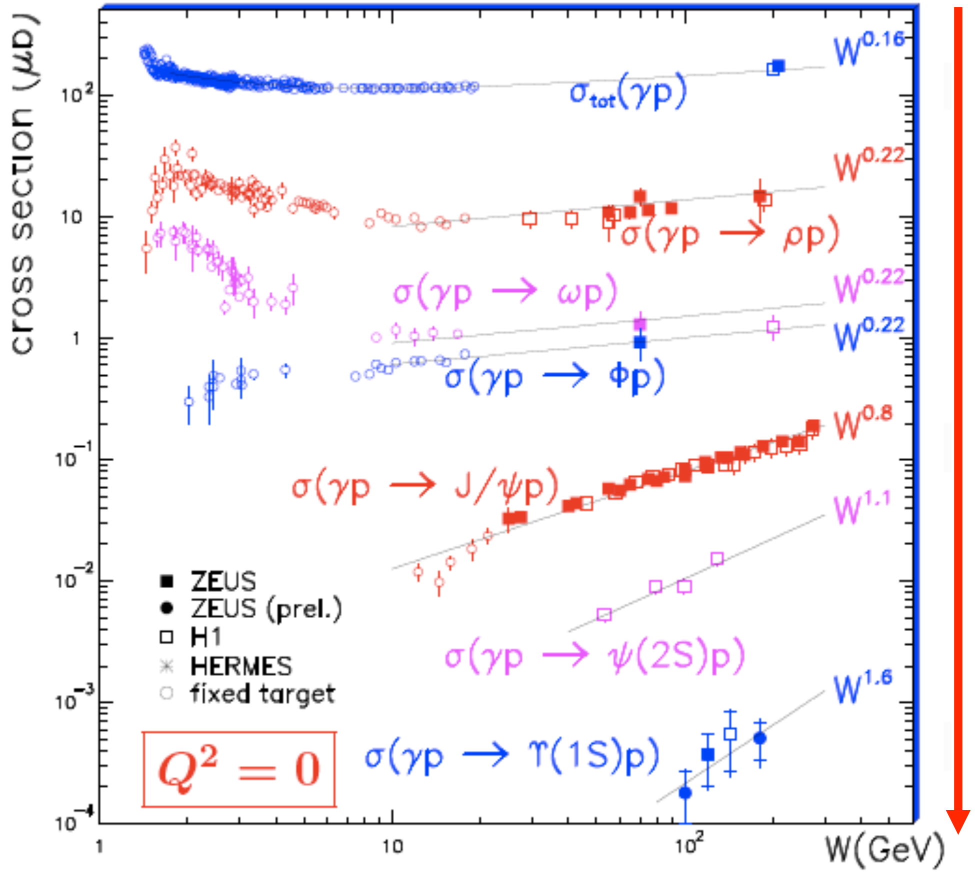
- A wealth of data from H1, ZEUS CDF and D0 and no time to do it all justice

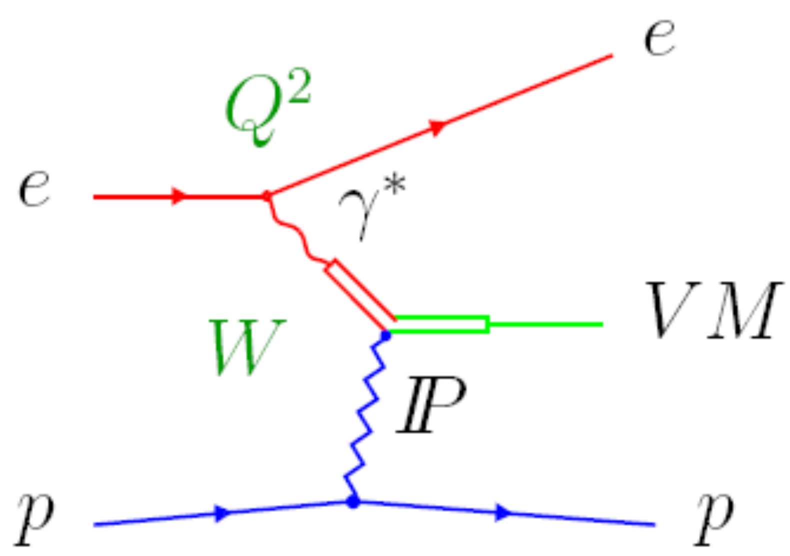
- HERA data shows is that diffractive DIS is understood in terms of DPDFs extracted from NLO QCD fits to β, Q^2 dependences of inclusive data
  - Diffractive dijet data in DIS agree well with predictions of fits to inclusive data
  - Combined fit to inclusive and dijet data constrains both the quark and gluon PDFs to similar good precision
- Diffractive dijet data in photoproduction is not as well understood. Comparing to predictions from NLO QCD, the data is consistent with
  - No x_γ dependence, but a possible E_T dependence
- Tevatron CEP measurements bolster confidence in calculations of ***S***

- Searches for effects beyond the DGLAP approximation show that other models (CDM, BFKL-based) are more successful in some regions
  - LHC will typically be at low x where these effects are expected to be significant
- Vector Meson production consistent with predictions of QCD, but no model capable of explaining all of the features
- DVCS measurements shed light on the parton correlations within the proton
  - Double parton scattering cross section is large - important to understand at LHC

BACK-UP SLIDES FOLLOW

Exclusive Diffraction: *ep → ep VM*





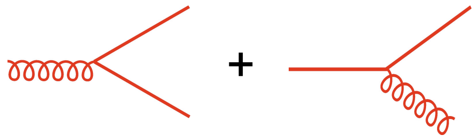
$\sigma \sim W^{\delta}$

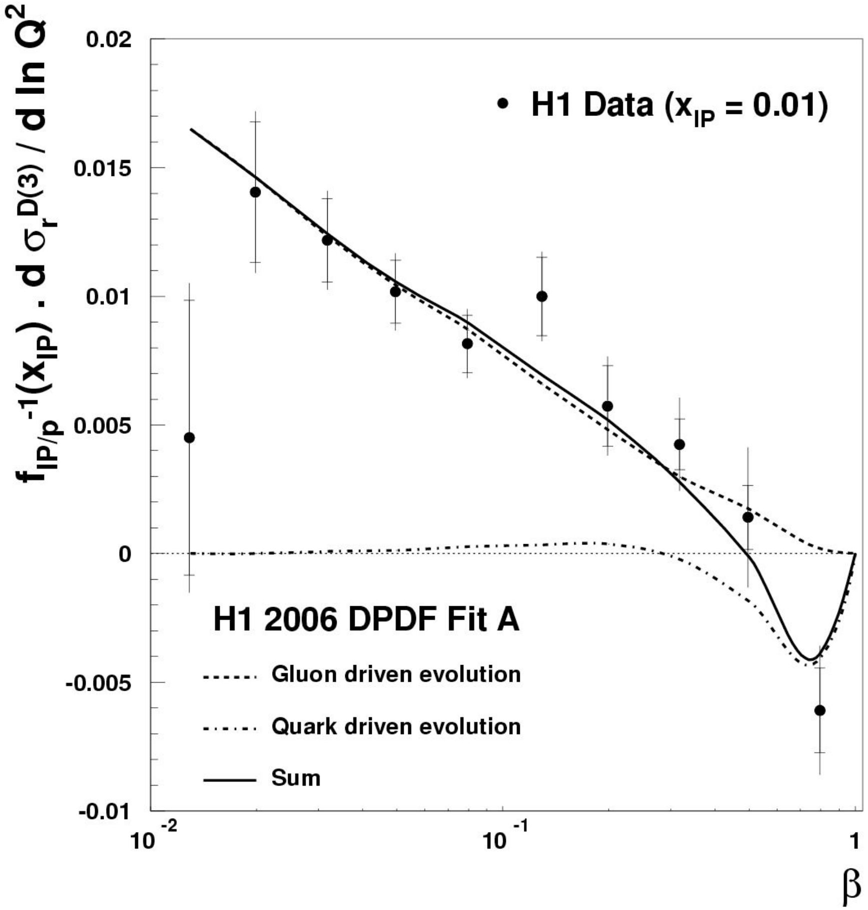
As the VM mass increases, the process gets harder

A Closer Look at the High z Region

We have only singlet quarks, so DGLAP evolution equation for F_2^D ….

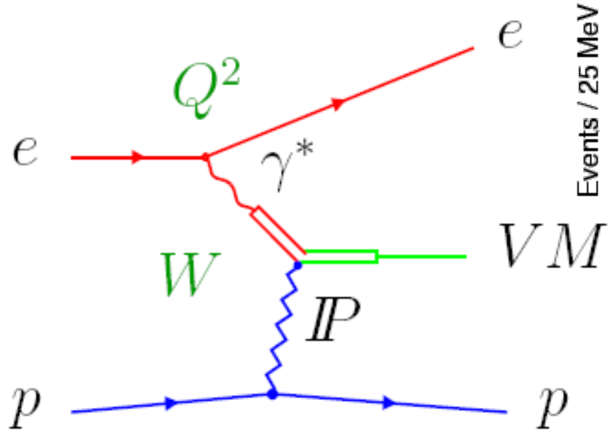
$$\frac{dF_2^D}{d\ln Q^2} \sim \frac{\alpha_s}{2\pi}\left[P_{qg}\otimes g \;+\; P_{qq}\otimes\Sigma\right]$$



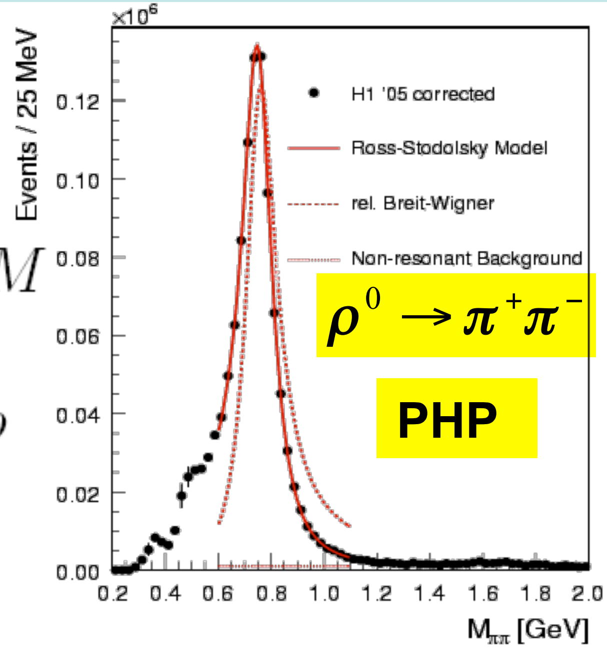


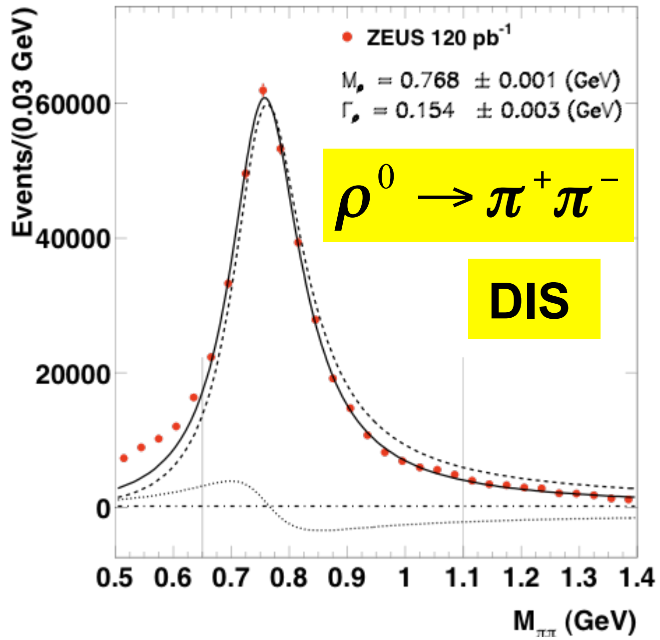
At high β, relative error on derivative grows, $q \rightarrow qg$ contribution to evolution becomes important … sensitivity to gluon is lost

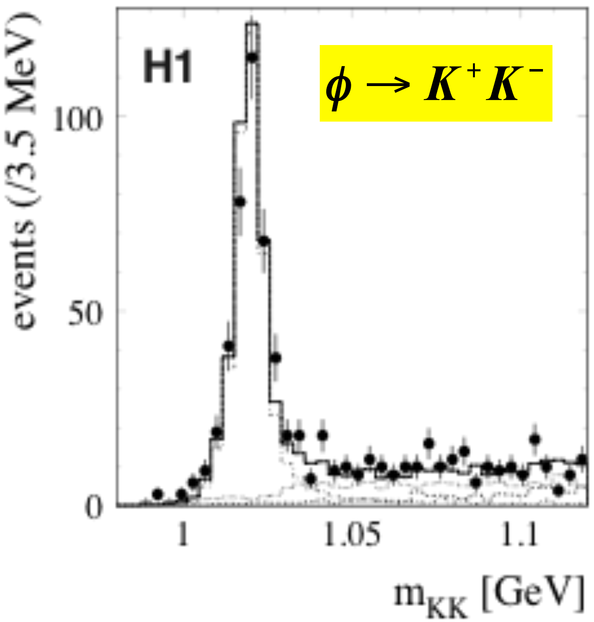
Exclusive Diffraction: *ep → ep VM*

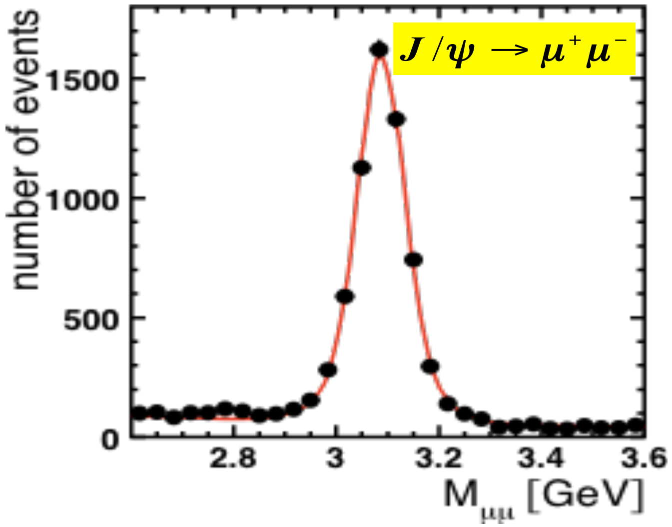


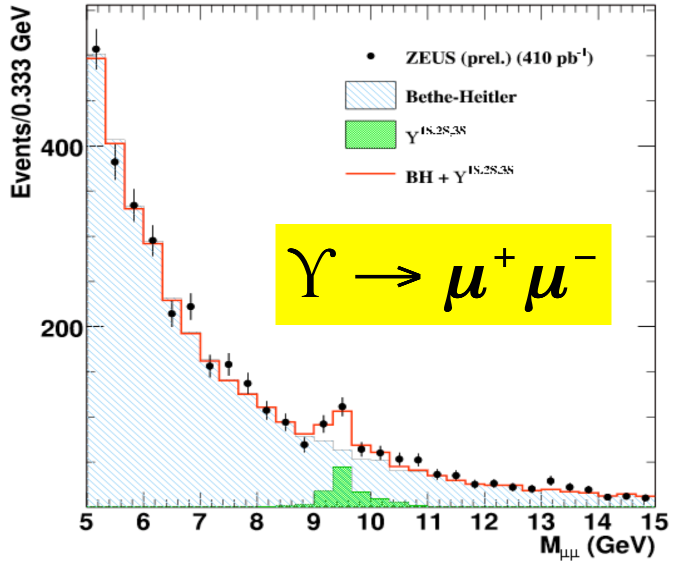
$\sigma \sim W^\delta$





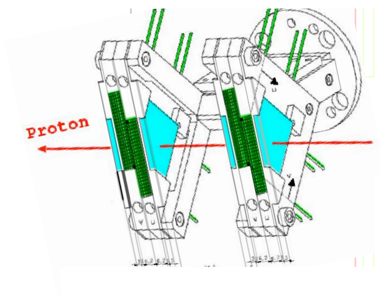




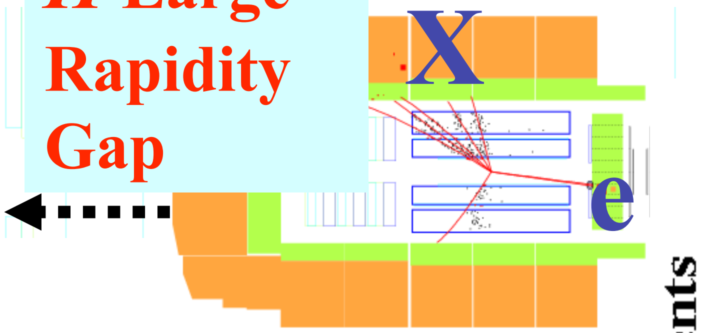


Experimentally selecting $ep \rightarrow eXp$

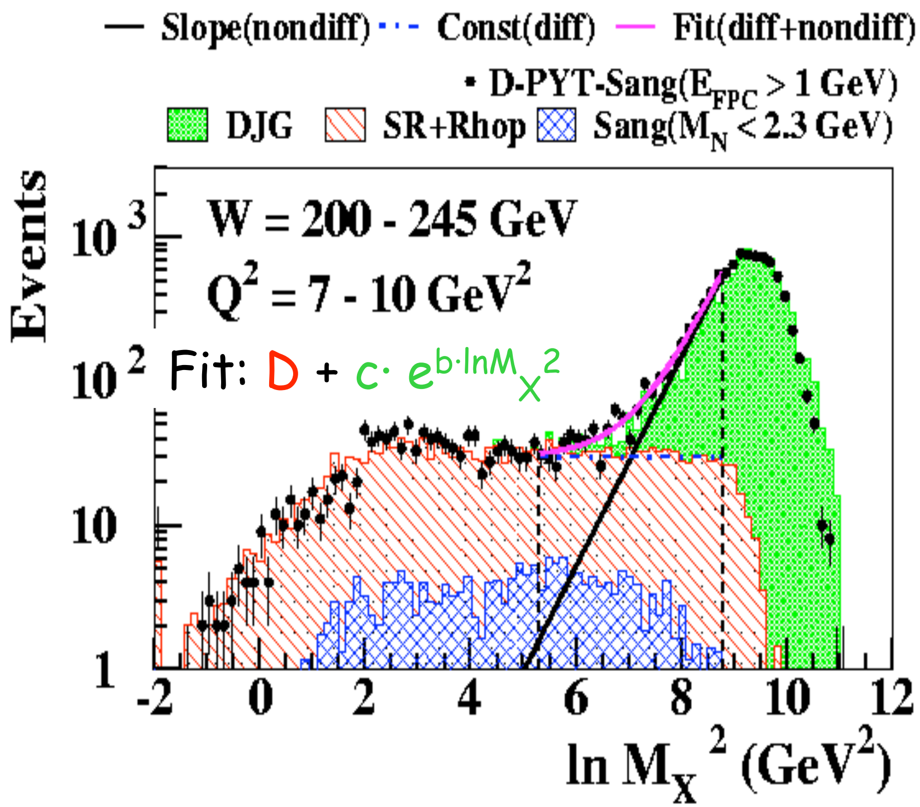
I LPS/FPS



II Large Rapidity Gap



III M_x method



Measure Leading Proton (FPS/LPS)

No proton dissociation

Measure the t dependence

Low detector acceptance

Require Large Rapidity Gap (LRG) spanning at least $3.3 < \eta < \sim 7.5$

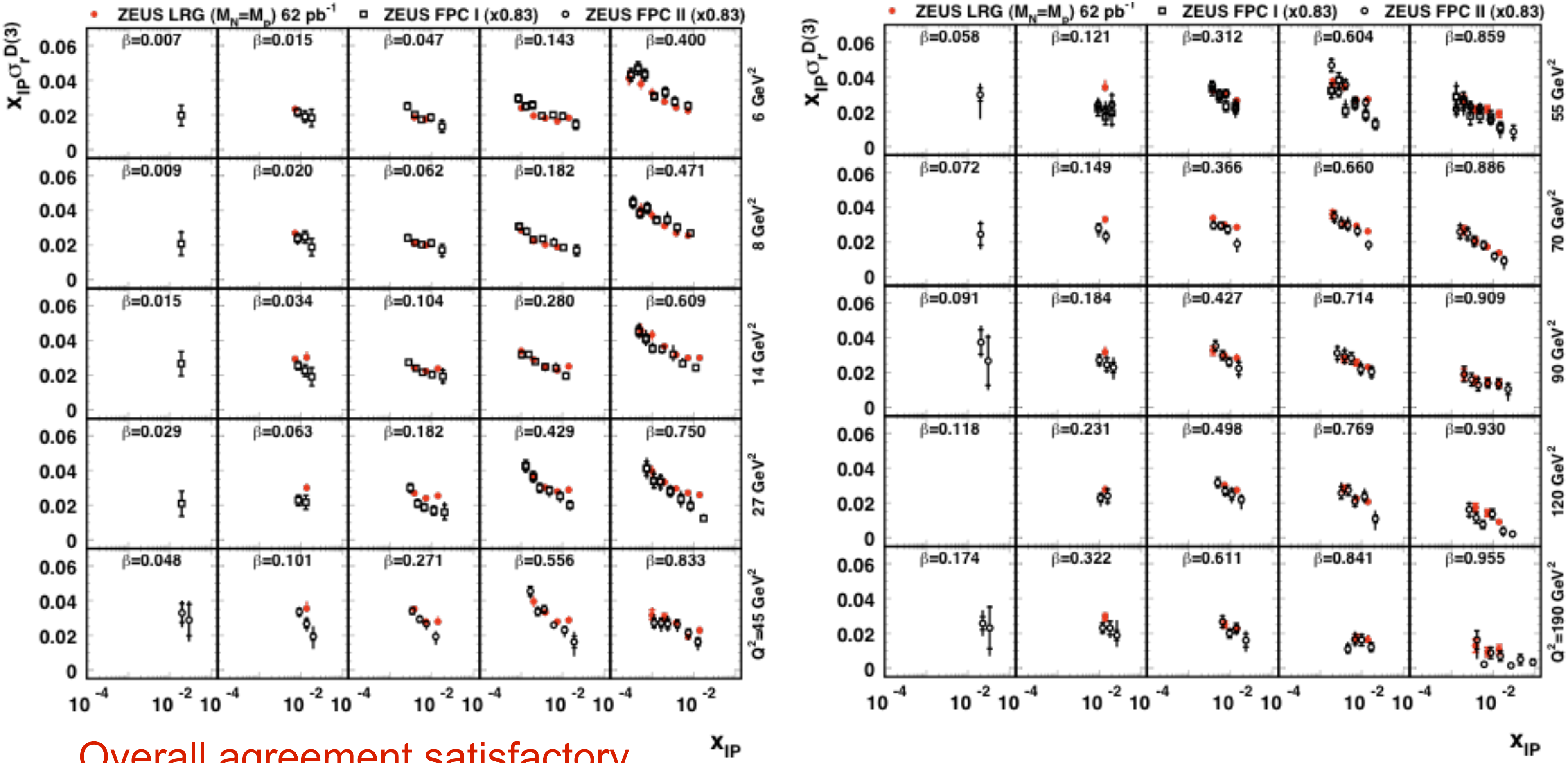
Kinematics measured from X system, integrate $|t| < 1.0$ GeV^2, $M_Y < 1.6$ GeV

High detector acceptance → precision

How do the three experimental techniques compare?

ZEUS LRG vs ZEUS M_x

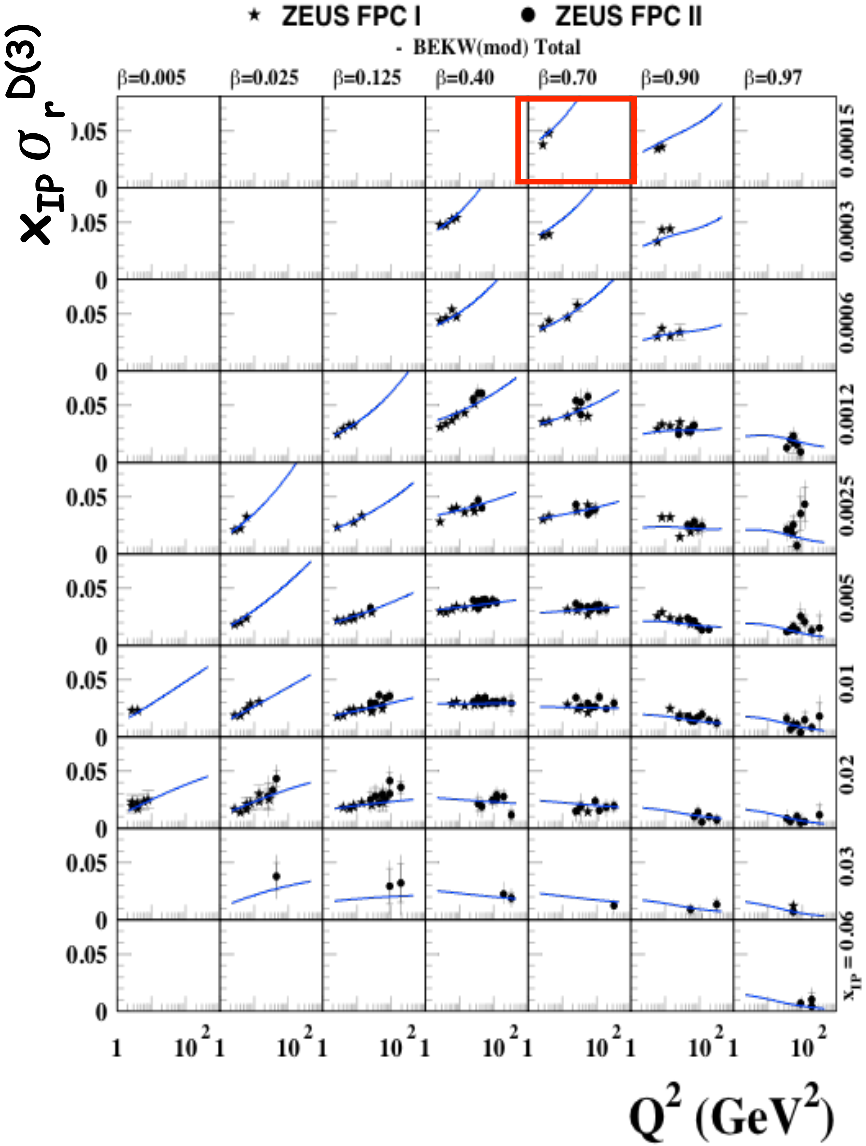
M_x data (M_N < 2.3 GeV) normalised to LRG (M_N=m_p): factor 0.83 ± 0.04
(determined via a global fit) estimates residual p-diss. background in M_x sample

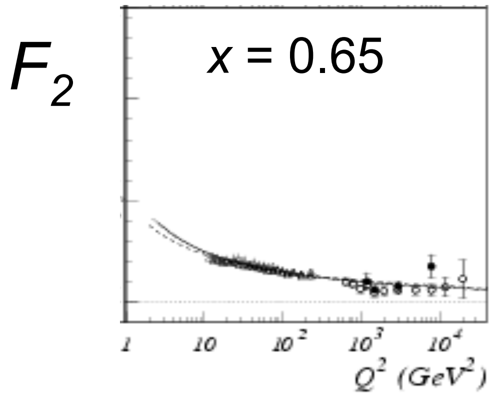


Overall agreement satisfactory

Different x_{IP} dependence ascribed to IR suppressed in M_x data

Q^2 dependence of $\sigma_r^{D(3)}$ ZEUS M_x data



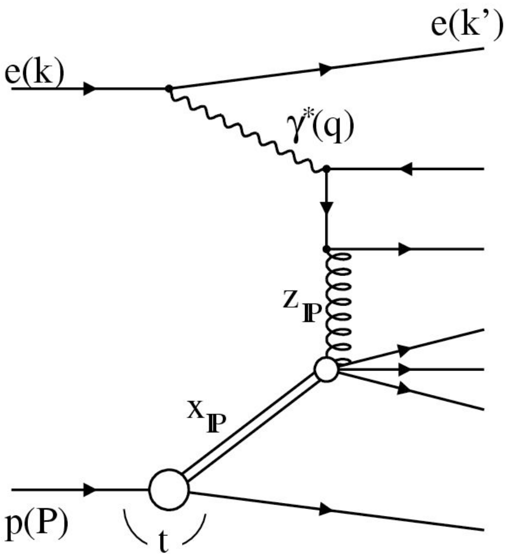


Large positive scaling violations up to high-β values implies that the diffractive exchange is gluon-dominated

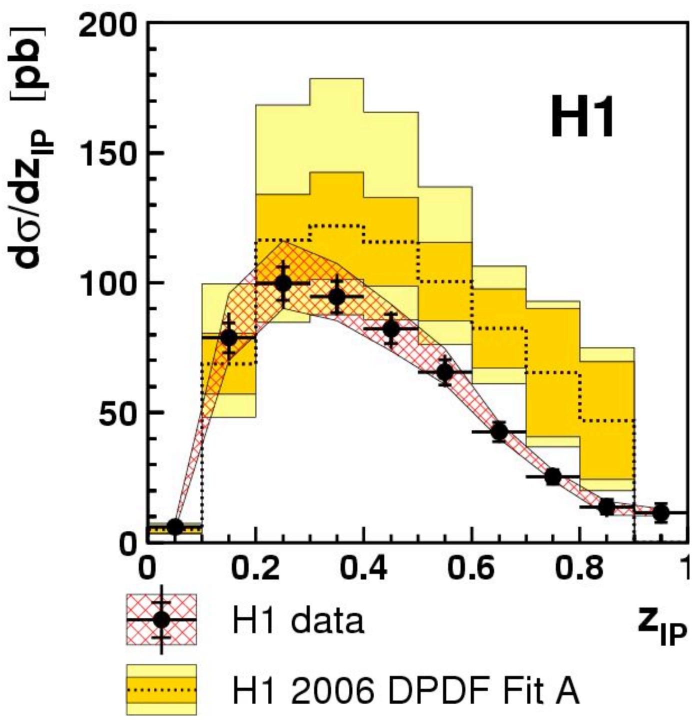
At fixed β the reduced cross section depends on x_{IP} - these data seem to contradict Regge factorisation

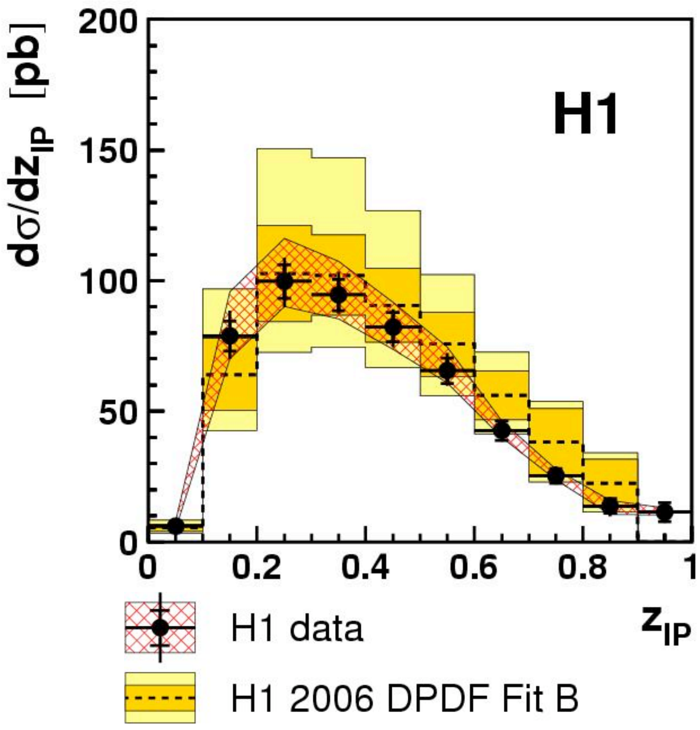
Regge factorisation is only a useful approximation but fits made thus far are insensitive to this mild breaking

Factorisation holds in DIS



$$z_{IP} = \frac{M_{12}^2 + Q^2}{M_X^2 + Q^2}$$





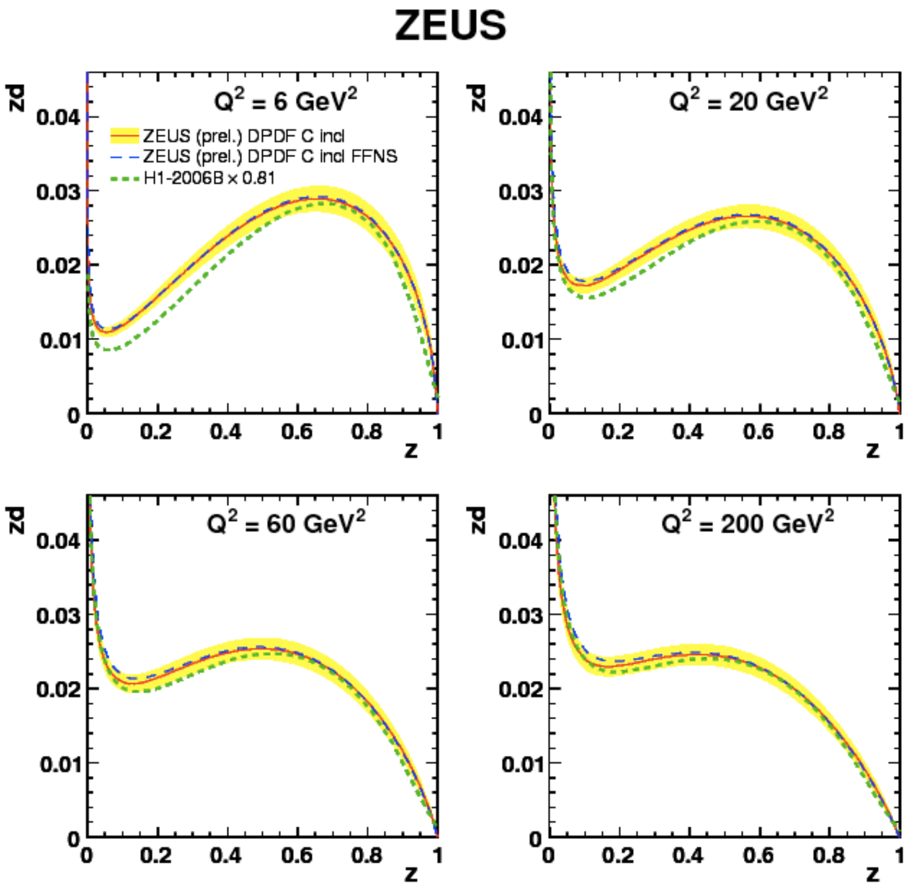
At low z_{IP} (< 0.4) Fit A and Fit B are similar

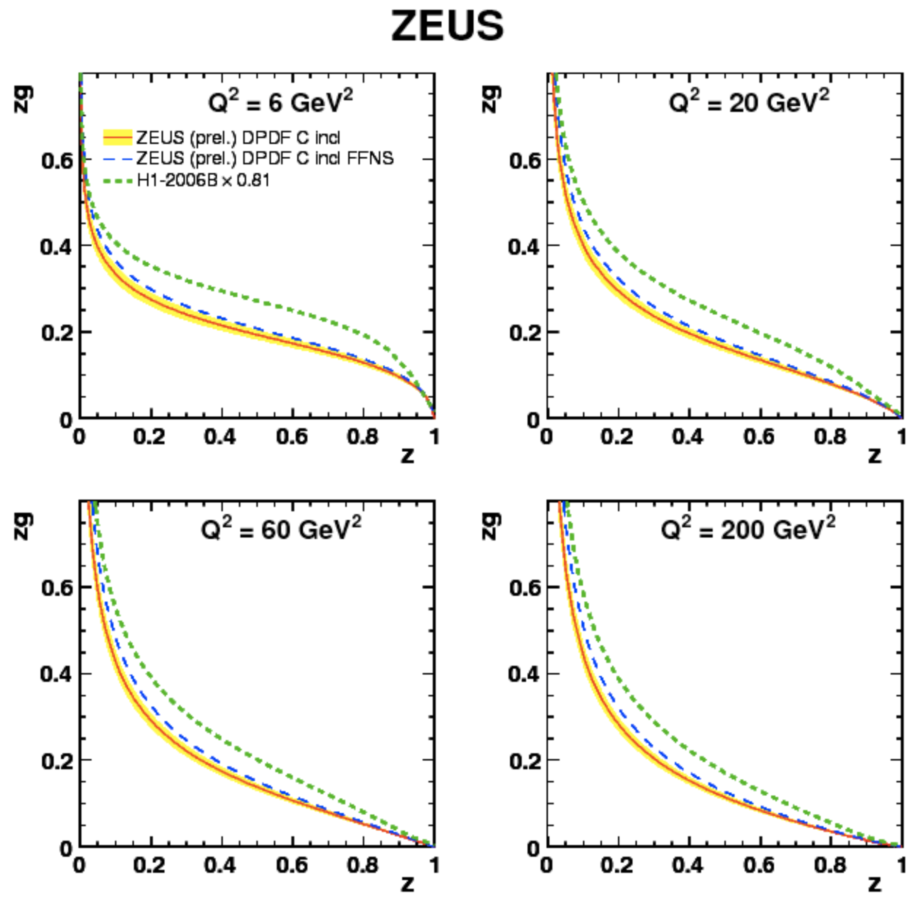
The data are in good agreement with the predictions, consistent with factorisation

At high z_{IP} the data clearly prefer Fit B

Include the diffractive dijet in a combined fit with the inclusive H1 LRG data

DPDFs from H1 and ZEUS





The ZEUS data are the Preliminary version, this comparison will be updated with the published data very soon