New Results on Hard Diffraction from HERA and the Tevatron

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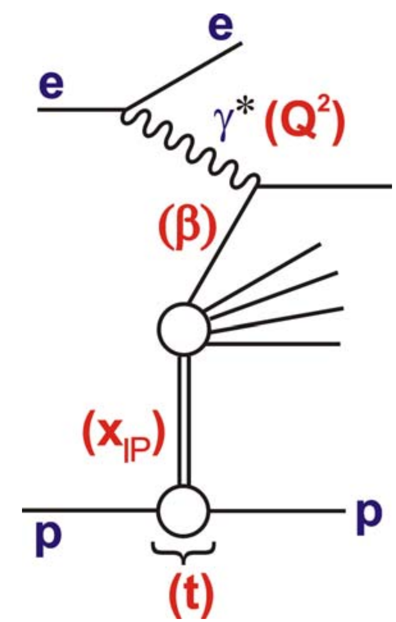
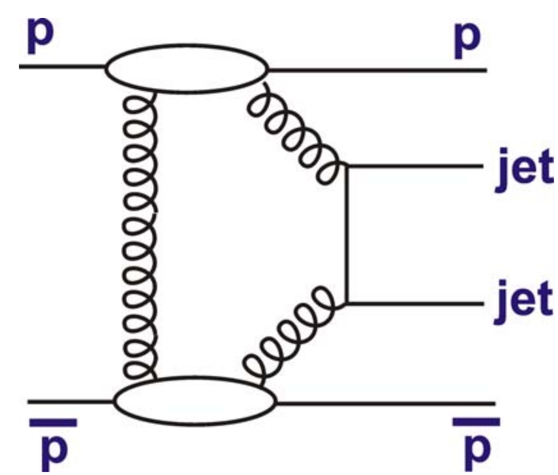
HCP '07, Elba, 24 May 2007



- Extracting Diffractive Parton Densities
- Testing Diffractive Factorisation
- Searching for central exclusive diffractive production



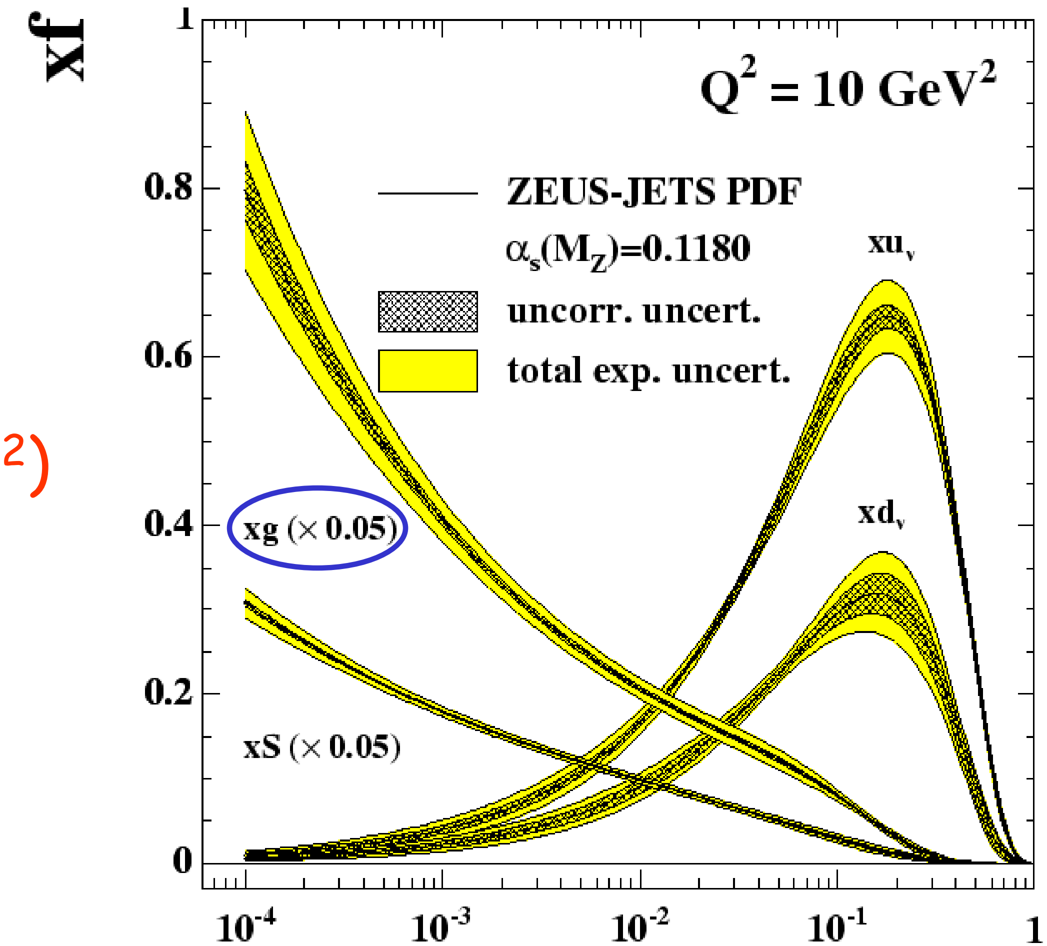
(Apologies for many topics omitted in these personally selected highlights)

Low x Physics and Diffraction

- Low x studies at HERA revealed strong rise of quark density (F_2) and gluon density ($d F_2 / d \ln Q^2$) with decreasing x.

- Gluon terrifyingly big?

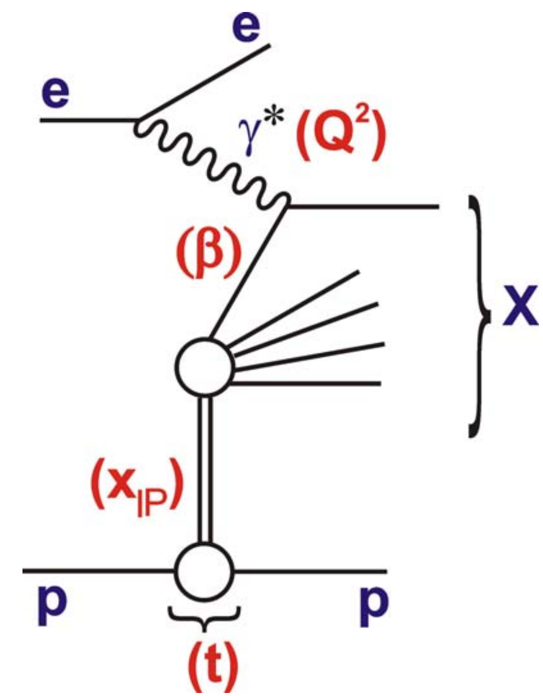
- High density, low coupling limit of QCD



- … large diffractive cross sections observed with leading Q^2 dependence ($ep \rightarrow eXp$ is a constant fraction ~10%)

"Inclusive Diffraction" (SD)

e.g. ep → eXp, pp → Xp …
…characterised by multiple particle production in diffractive system X



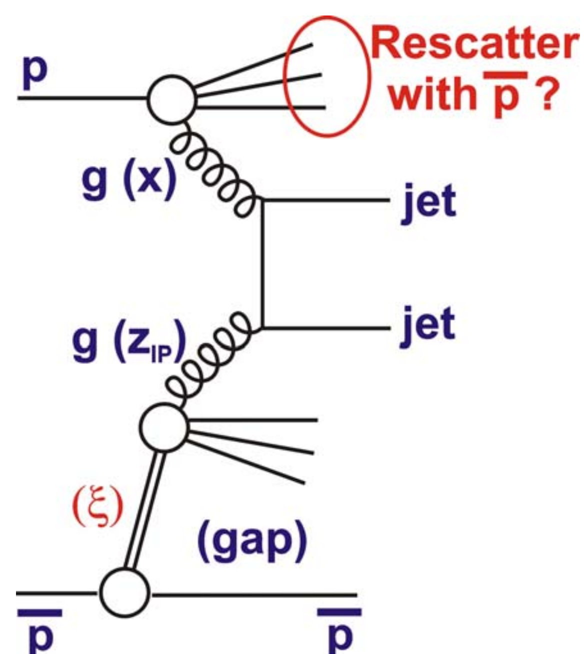
t = squared 4-mom. transfer to proton

x_{IP} (ξ) = fractional proton mom. loss
(mom. frac. IP/p)

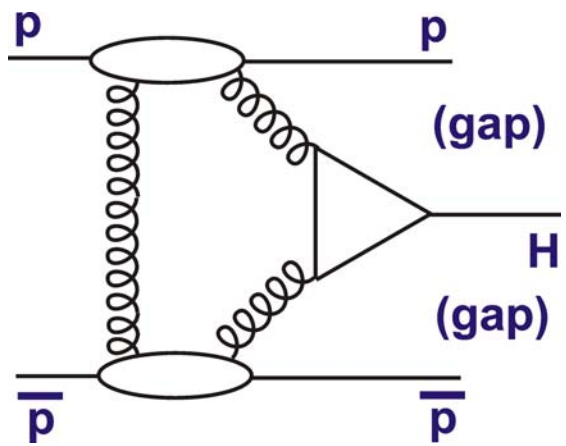
β (z_{IP}) = fraction of total exchanged mom. entering hard scatter
(mom. frac. q / IP or g / IP)

Typically 10% @ HERA, 1% @ Tevatron

… rapidity gap survival factors ~0.1
(soft rescattering / underlying event)



“Central Exclusive Production”



e.g. pp → ppH
both protons remain intact

Higgs or other 0^+ state could
be produced exclusively at LHC with
very good m_H constraint from measured proton energy losses.

“KMR” perturbative calculation (Khoze et al., hep-ex/0507040)
- Visible LHC cross section ~3 fb for M_H = 120 GeV
- Includes 3% gap survival probability
- “factor 2.5 uncertainty”

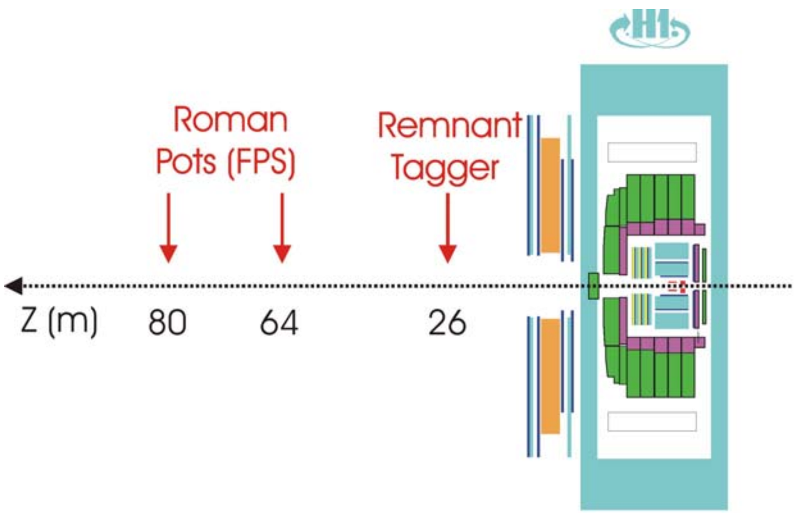
Central Exclusive control channels with much higher cross sections at Tevatron … jets, photons

Linked to inclusive channels via gap survival & backgrounds

Selection Methods

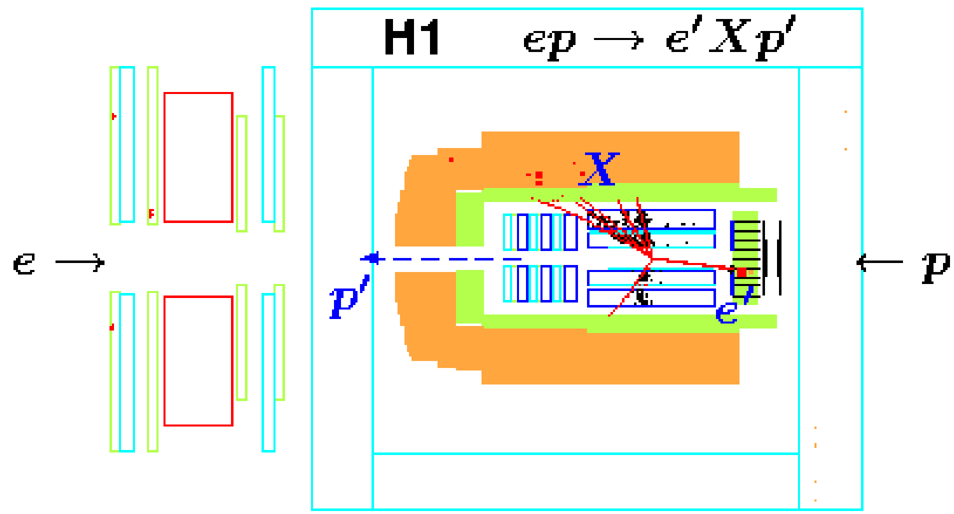
Ideally, measure final state proton directly …

`Roman Pot' inserts to beampipe (e.g. H1 `Forward Proton Spectrometer')



Unambiguous final state proton, but limited statistics

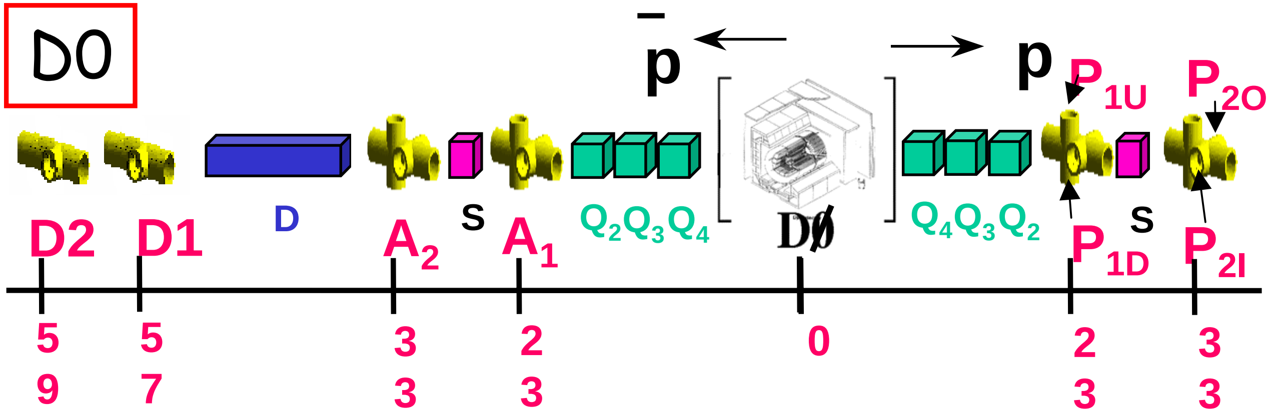
Alternatively identify `Large Rapidity Gap' (empty detectors) adjacent to outgoing (untagged) proton

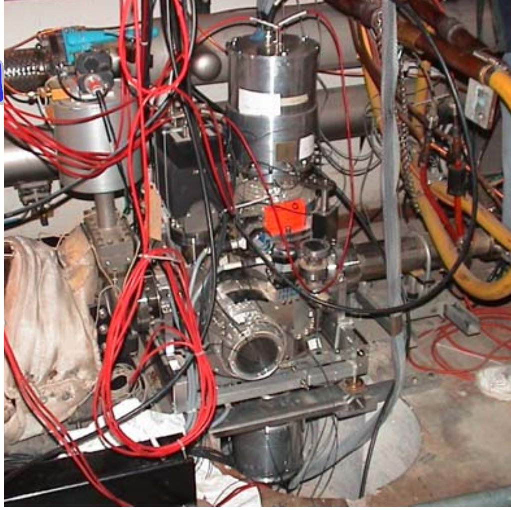


Good statistics, but systematics associated with missing proton

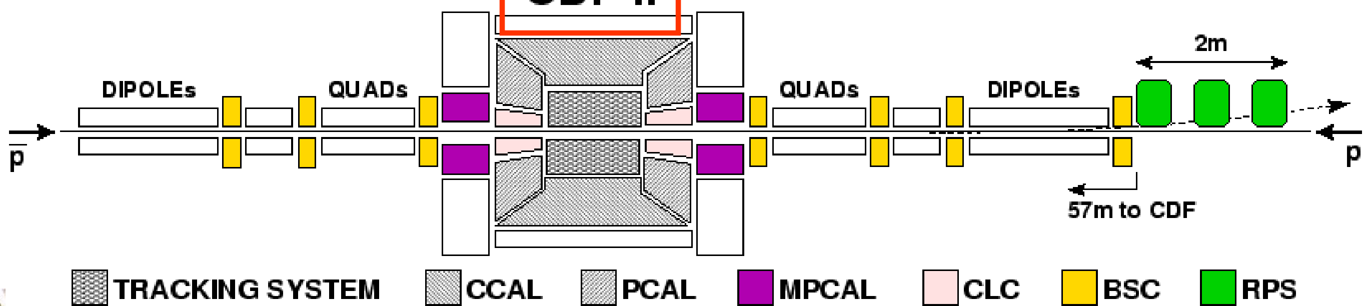
Roman Pots / Fwd Instrumentation

D0

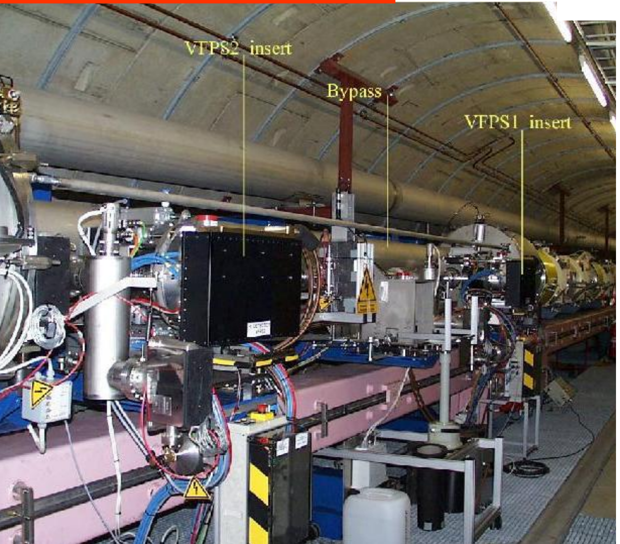


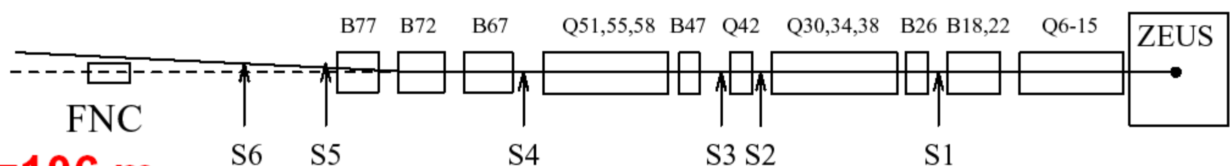


CDF II



H1
VFPS
@ HERA-II

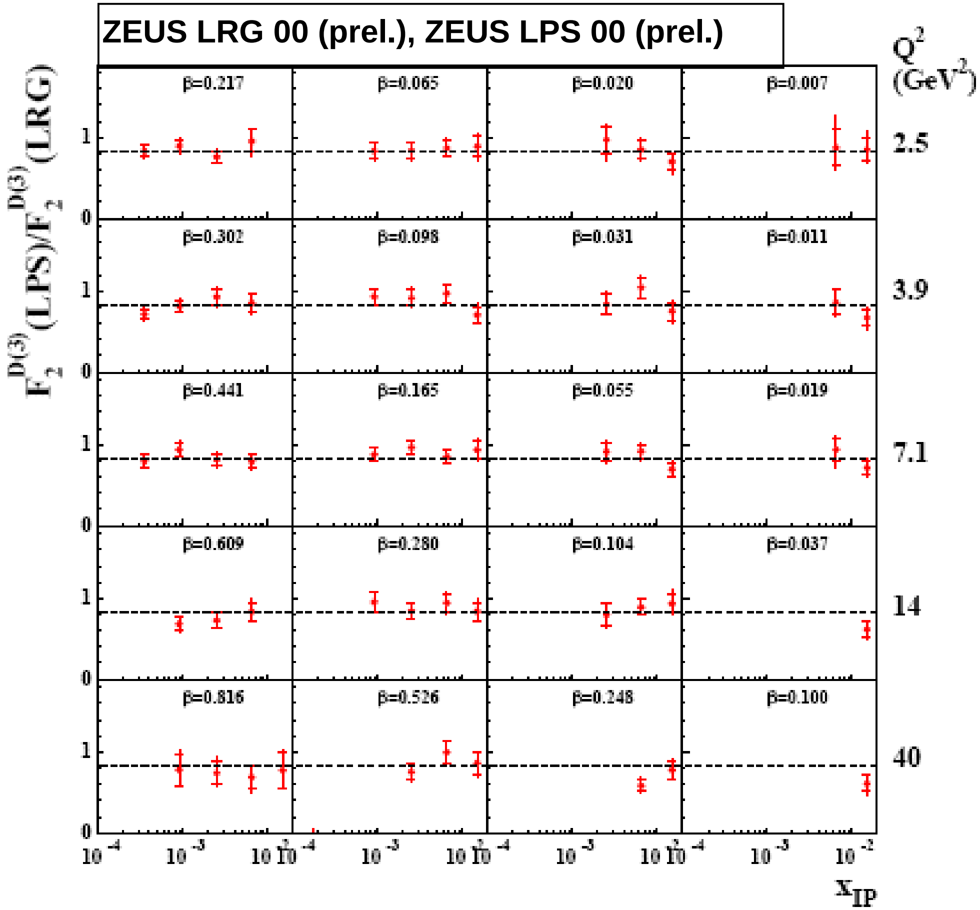


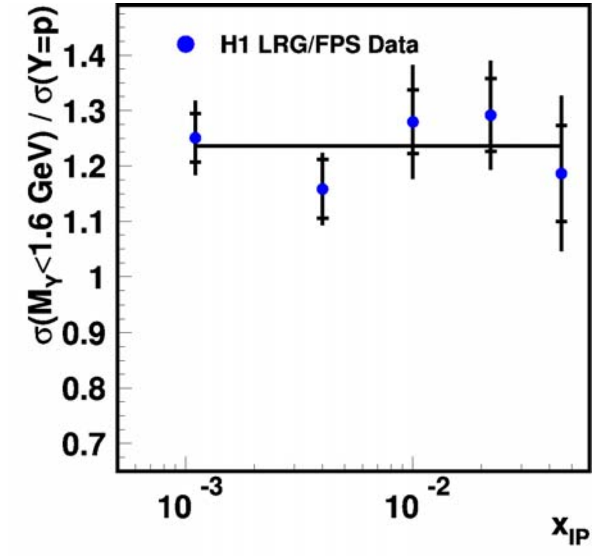


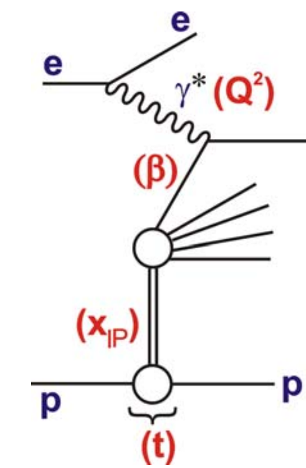
Z=106 m

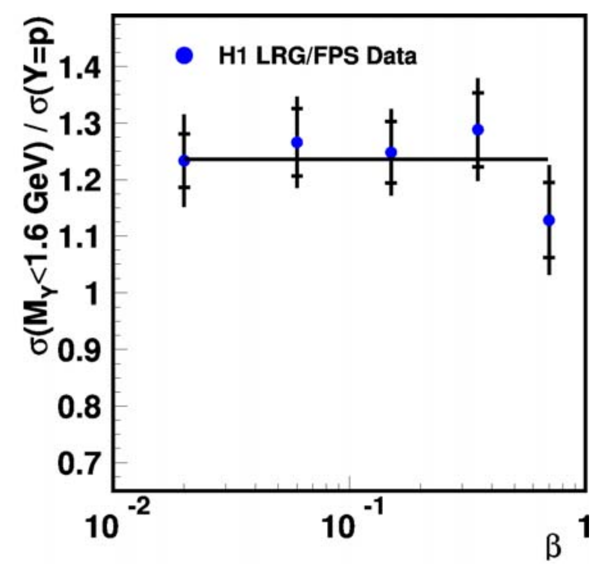
ZEUS

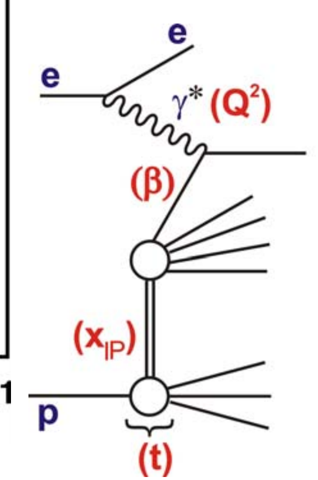
HERA: Comparing Roman Pot with Gap Methods







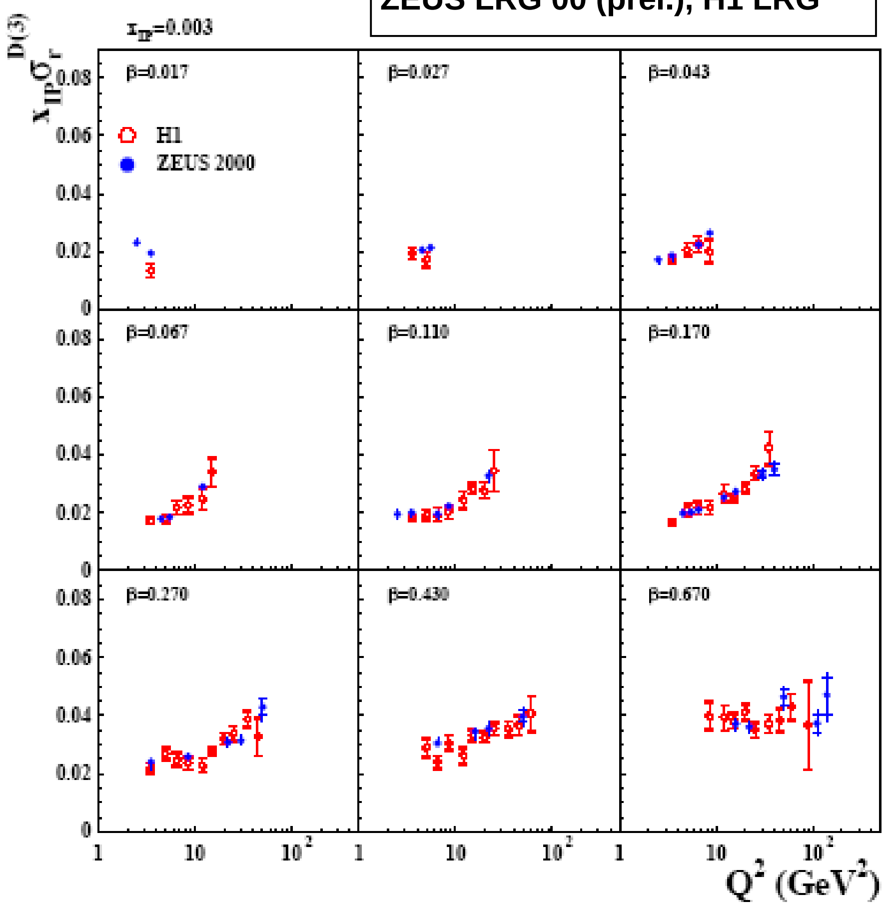


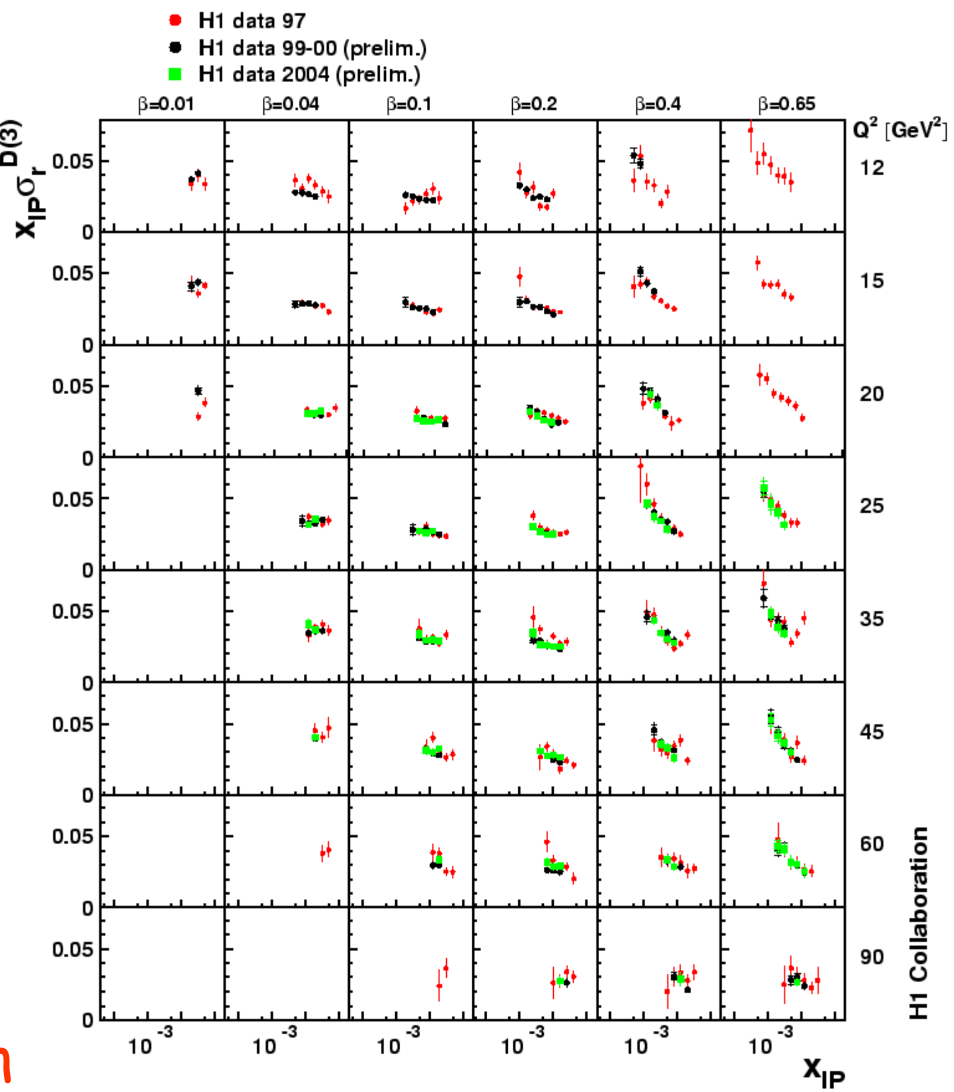


- Good agreement between selection methods with very different systematics!
- ~20% norm. differences (proton diss^n contributions)

Comparing Different Gap Method Samples

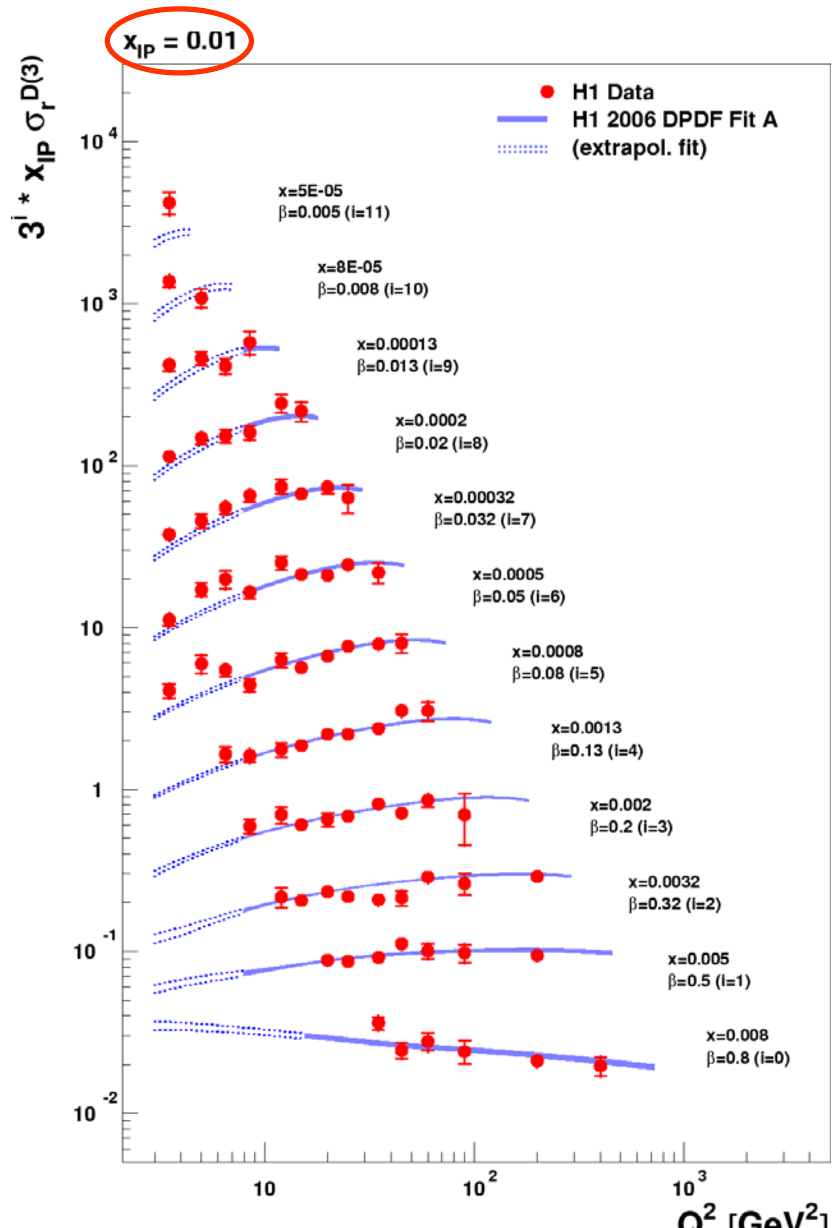
$x_{IP} = 0.003$

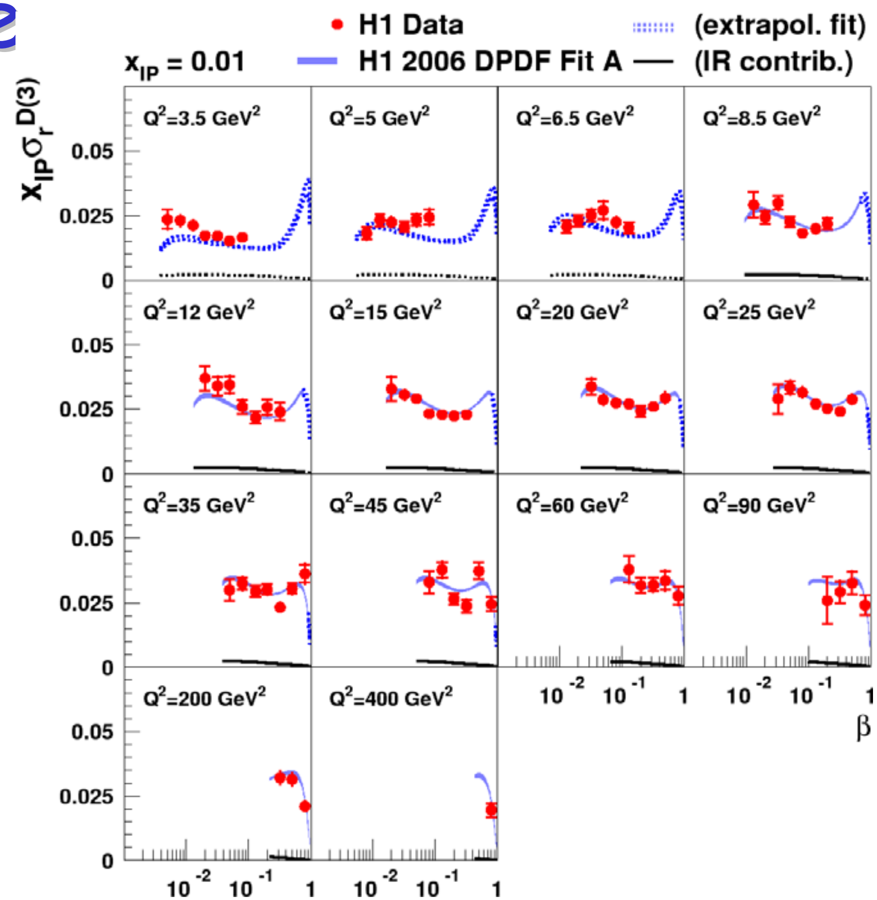




Very good agreement between
H1 and ZEUS and between HERA-I and HERA-II
… good understanding of systematics of gap selection

Subset of H1 Diffractive Structure Func^n Data



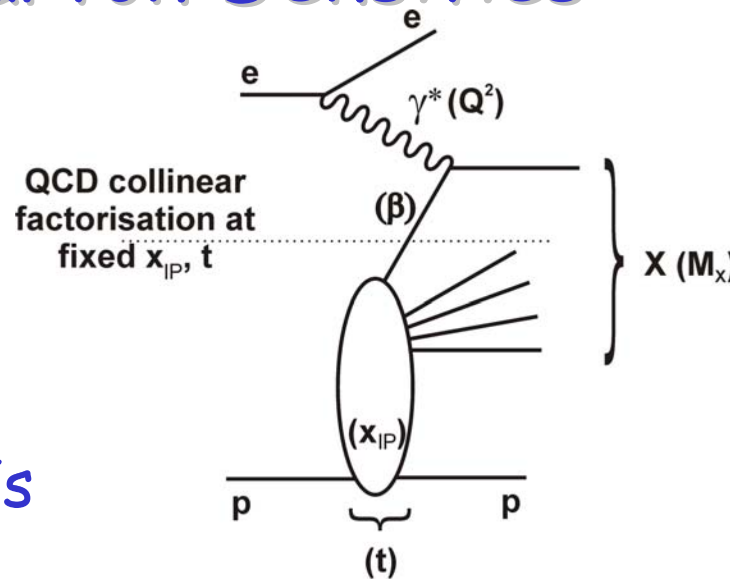


- … similar at 4 more x_{IP} values
- Like an $F_2(\beta, Q^2)$ in each case
- Now reaching $Q^2 = 1600$ GeV^2
- Precision in best regions ~ 5% (stat), 5% (syst), 6% (norm)

Extracting Diffractive Parton Densities

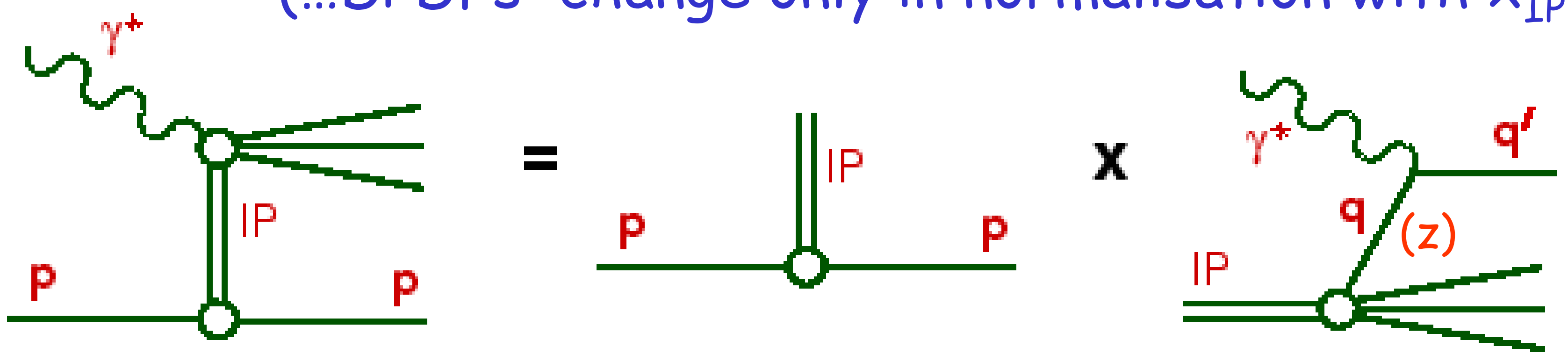
Semi-Inclusive QCD collinear factorisation at fixed x_{IP} and t …

… can define β, x_{IP} and t dependent diffractive parton densities (DPDFs), with Q^2 evolution as for inclusive PDFs



`Proton vertex' factorisation (empirically motivated)

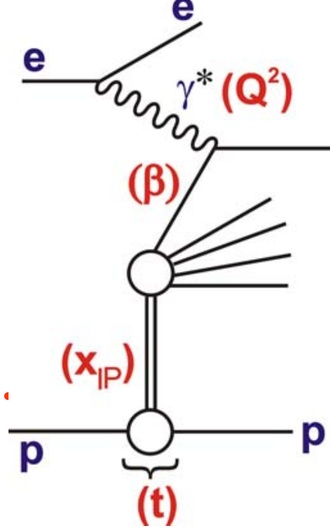
(…DPDFs change only in normalisation with x_{IP}, t)



MEASUREMENT = FLUX (x_{IP}, t) x STRUCTURE (β, Q^2)

(Regge theory) (DGLAP)

Effective Pomeron Trajectory



- Pomeron trajectory from x_{IP} and t dependences.
- Assumed linear: $\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha' t$
- Consistent between H1 & ZEUS, Roman pot & gaps.

H1 Best values:

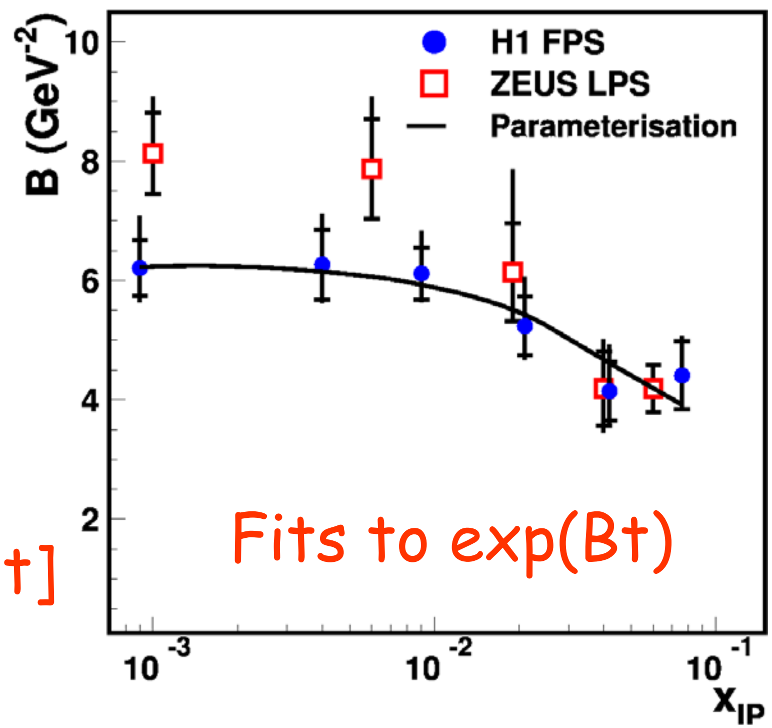
$$\alpha_{IP}(0) = 1.118 \pm 0.008\ (\text{exp.})\ {}^{+0.029}_{-0.010}\ (\text{theory})$$

$$\alpha'_{IP} = 0.06^{+0.19}_{-0.06}\ \text{GeV}^{-2}$$

ZEUS (prel) best values:

$$\alpha_{IP}(0) = 1.117 \pm 0.005\ (\text{stat.})\ {}^{+0.024}_{-0.007}\ (\text{theory})$$

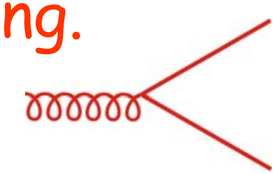
$$\alpha'_{IP} = -0.03 \pm 0.07\ (\text{stat.})\ {}^{+0.04}_{-0.08}\ (\text{sys.})\ \text{GeV}^{-2}$$



- Not a soft IP [$\alpha_{IP}(t) \sim 1.08 + 0.25\ t$]
- ~ independent of β, Q^2 (i.e. proton vertex factorises)

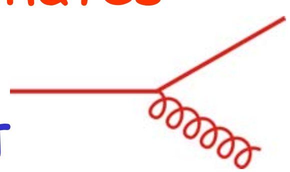
H1 2006 DPDF Fit Results (linear z scale)

- As in inclusive case, σ_r^D gives quark density and its Q^2 dependence gives gluon via g→qqbar splitting.

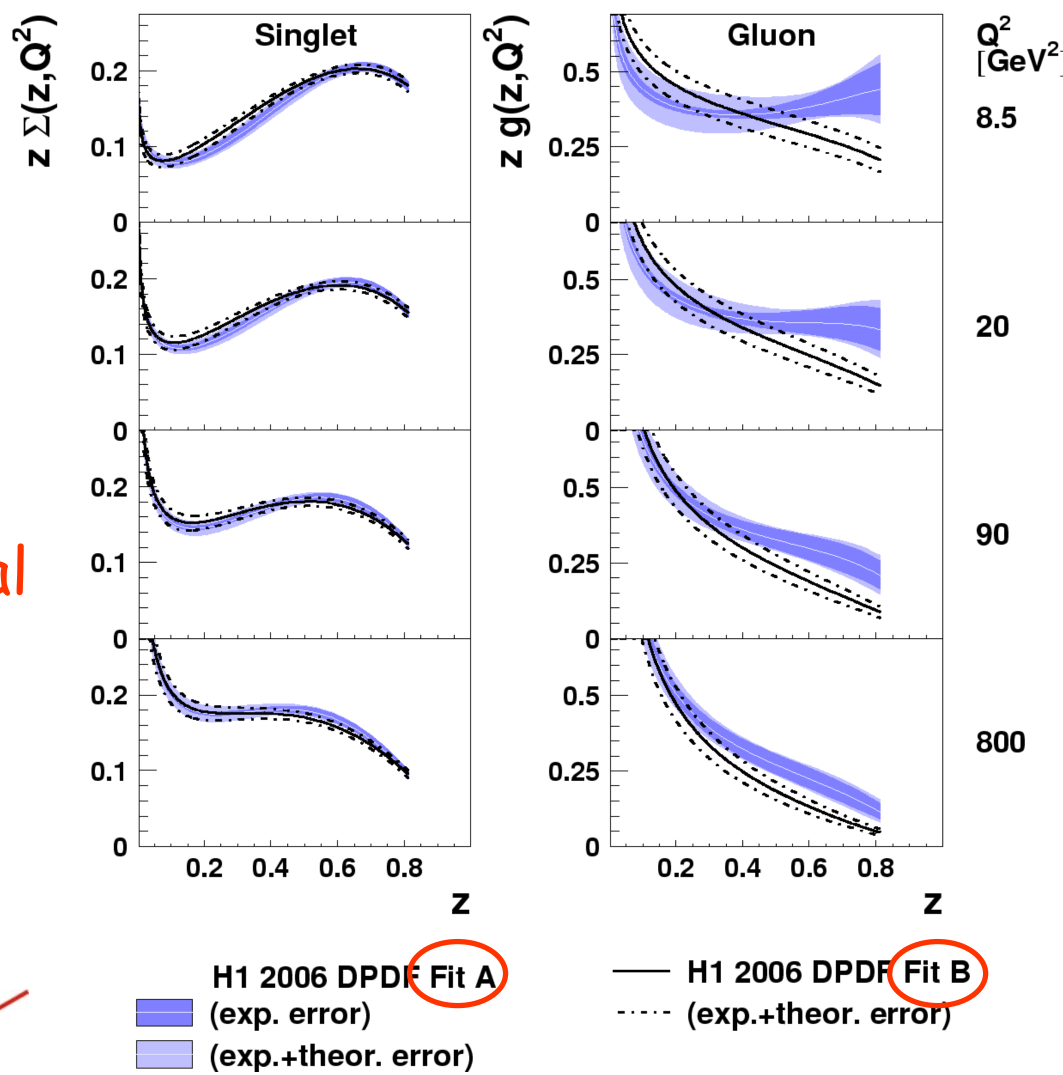


- NLO DGLAP QCD fit … experimental and theoretical uncertainties evaluated.

- Singlet to ~5%, gluon to ~15% at low z, growing at high z (q → qg dominates Q^2 evolution)



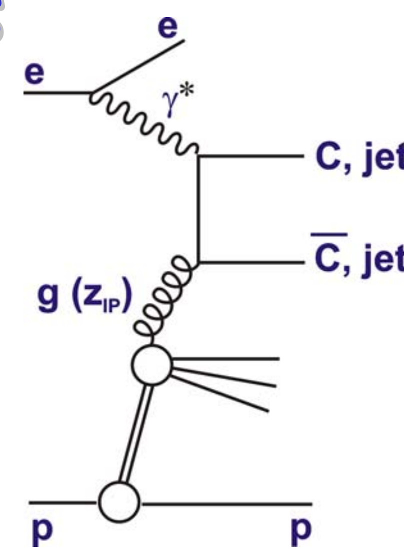
… yet high z is most important region for background to Central Exclusive Production!

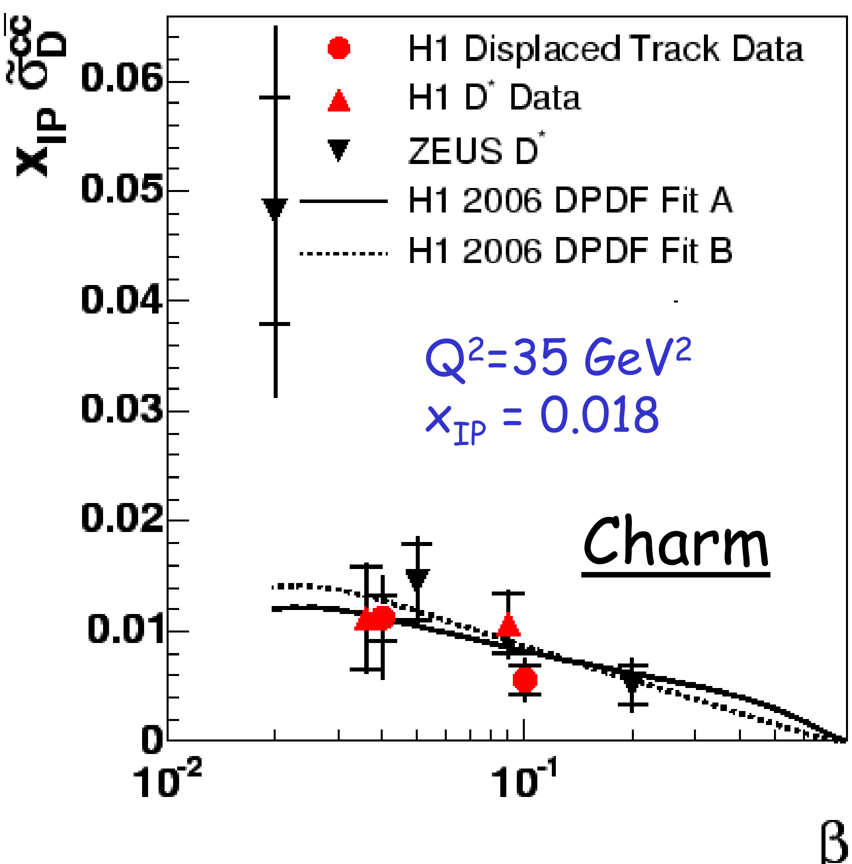


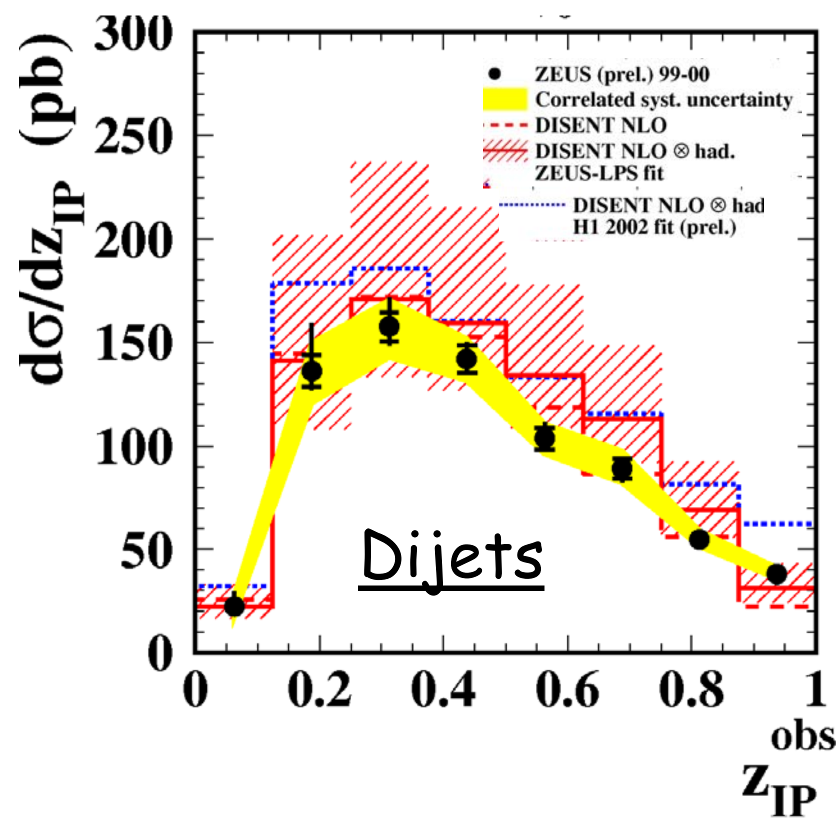
- ~70% gluons z integrated
- See also "ZEUS LPS" fit

Testing Factorisⁿ in DIS Final States

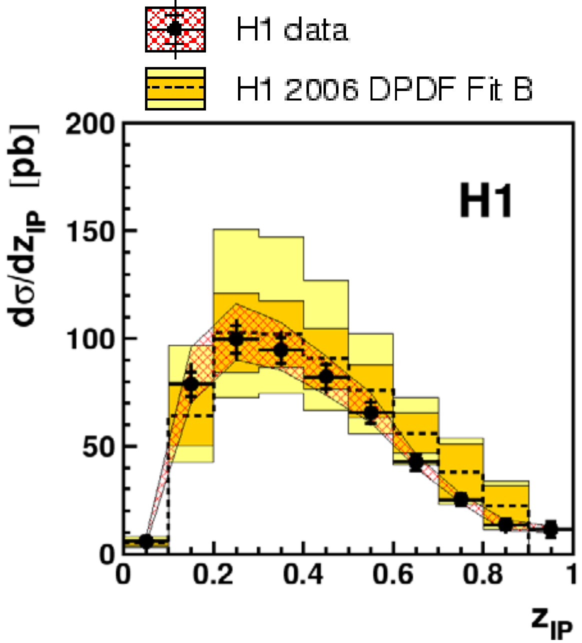
- Gluon DPDF known only indirectly from σ_r^D
- Test using processes driven by to $\gamma^* g \rightarrow q\bar{q}$bar
  - Diffractive charm in DIS (two methods)
  - Diffractive dijets in DIS
- Very good agreement (… for fit B …)



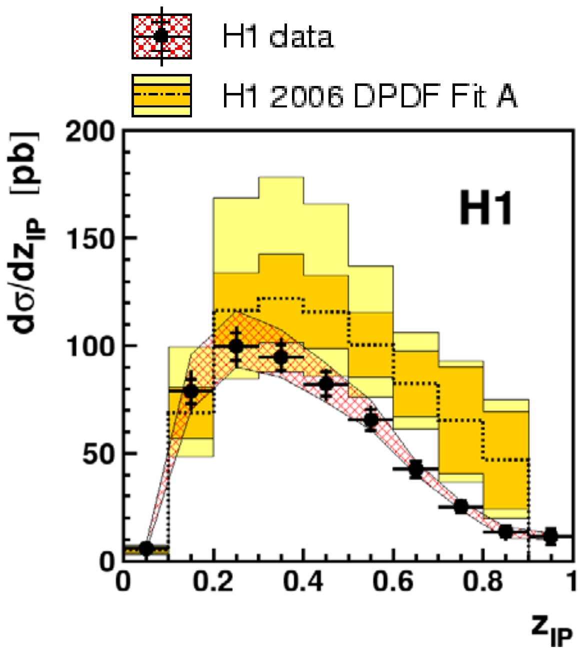


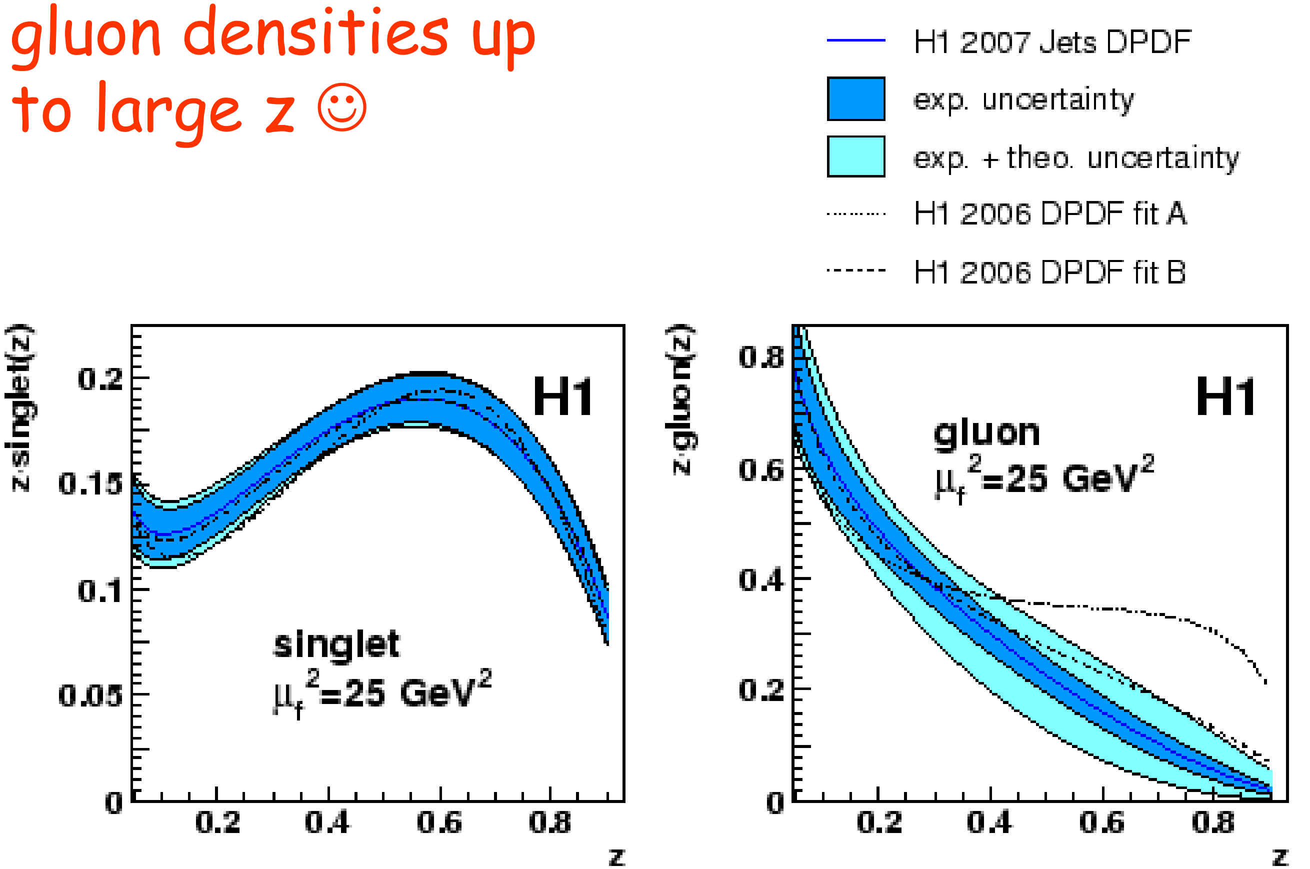


DIS Dijets and the high z Gluon



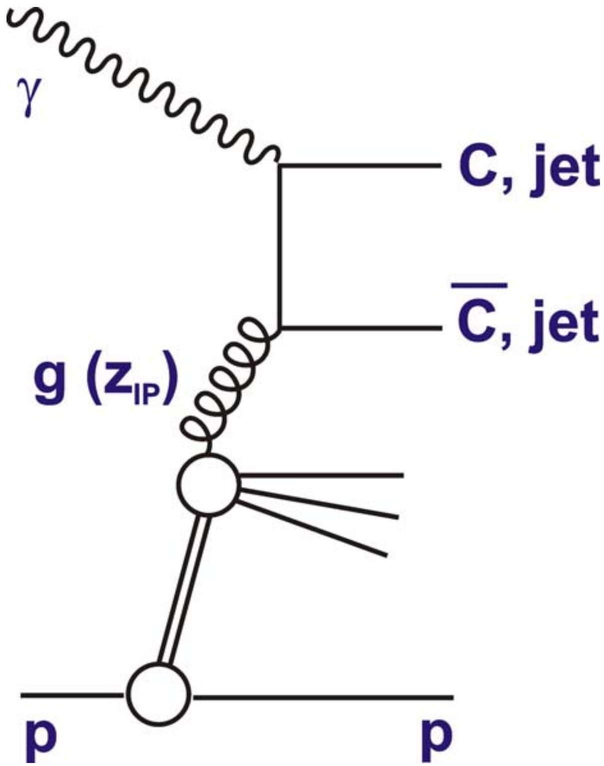
- Dijet data distinguish between `H1 fit A' and `H1 fit B' predictions at high z_{IP}.
- Including jet data in fit yields new `H1 2007 Jets DPDF', with comparable precision on quark and gluon densities up to large z ☺

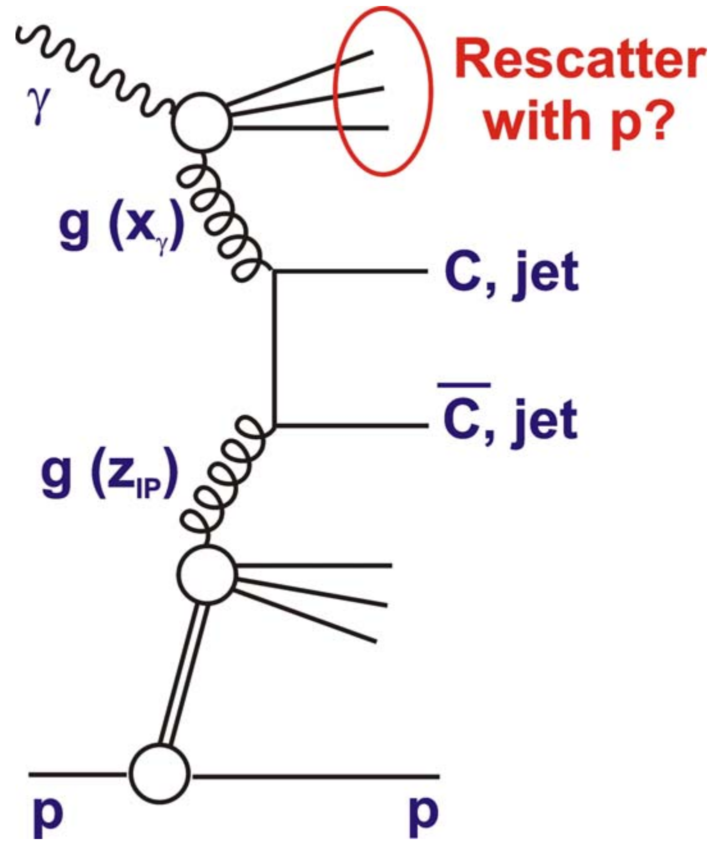




From ep towards pp … Photoproduction, γp

… the $Q^2 \rightarrow 0$ limit of ep scattering – "real" photons

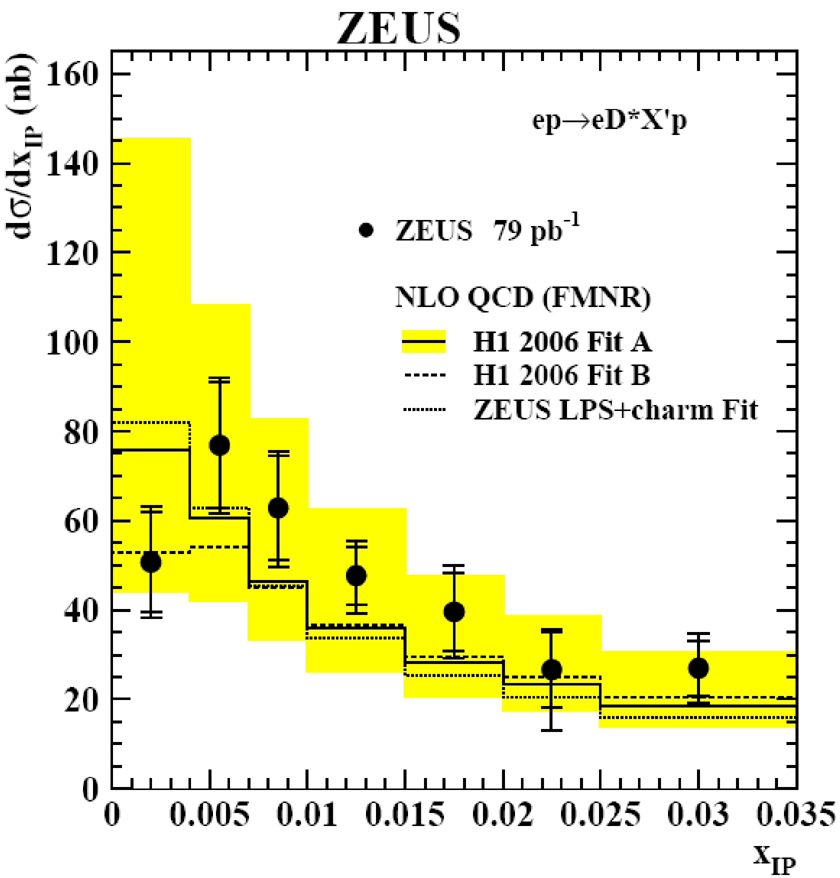


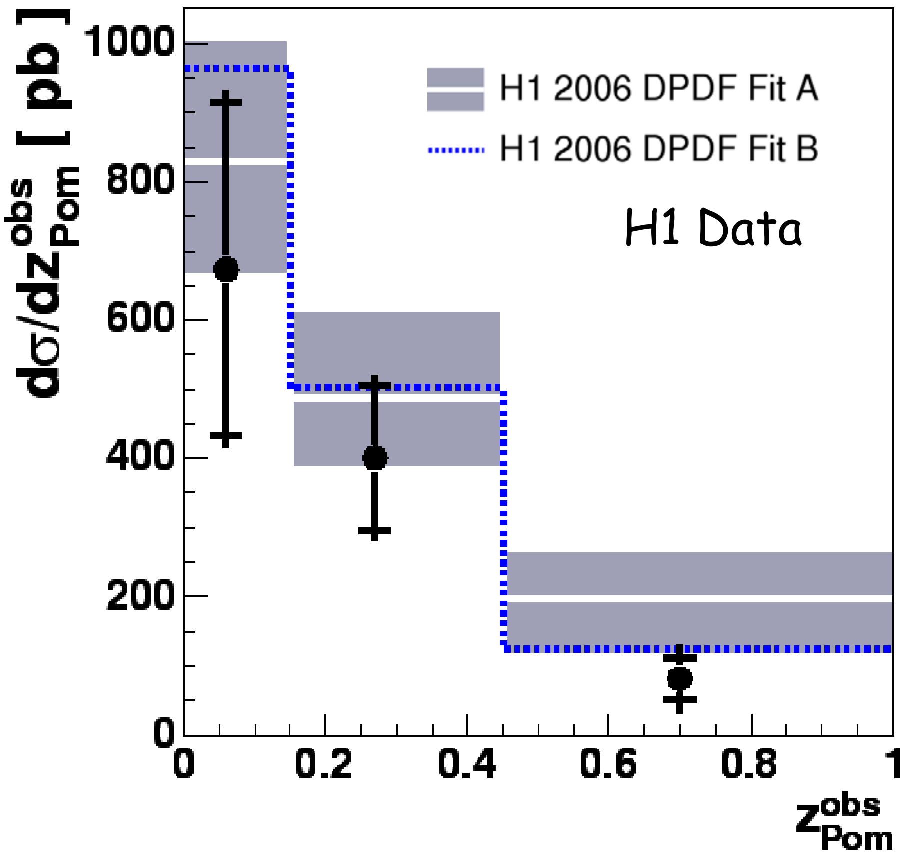


"Direct" photon interactions ($x_\gamma \rightarrow 1$) … expect gap survival probability = unity

"Resolved" photon interactions ($x_\gamma < 1$) … expect gap survival probability < 1

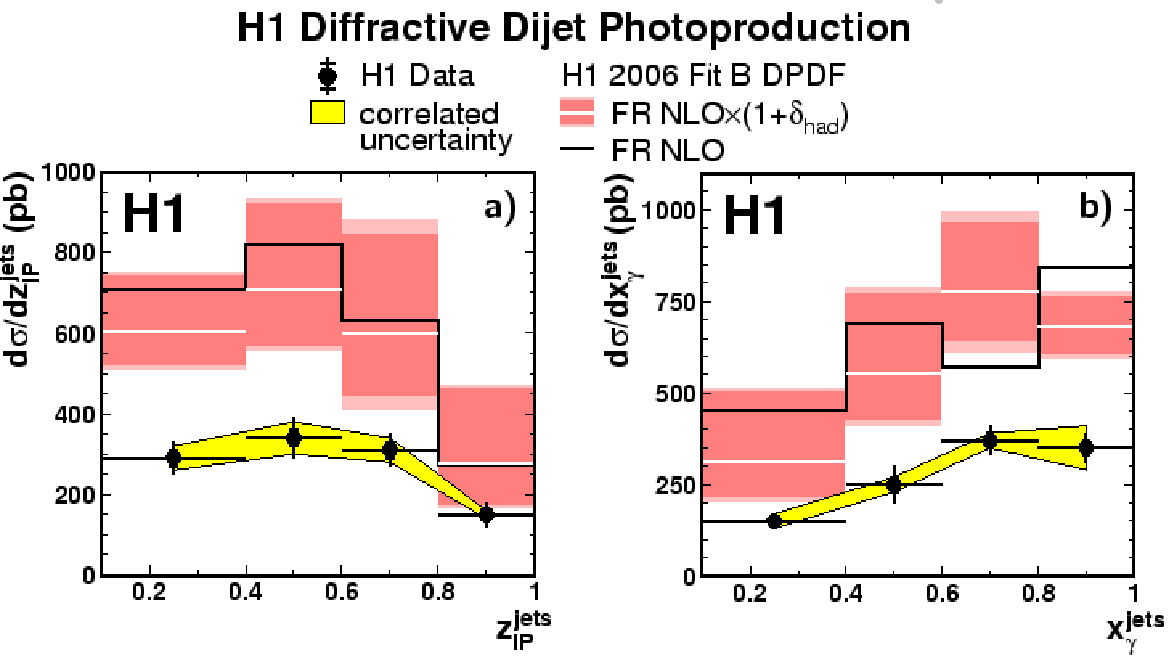
Charm (D*) Photoproduction: Direct Photons

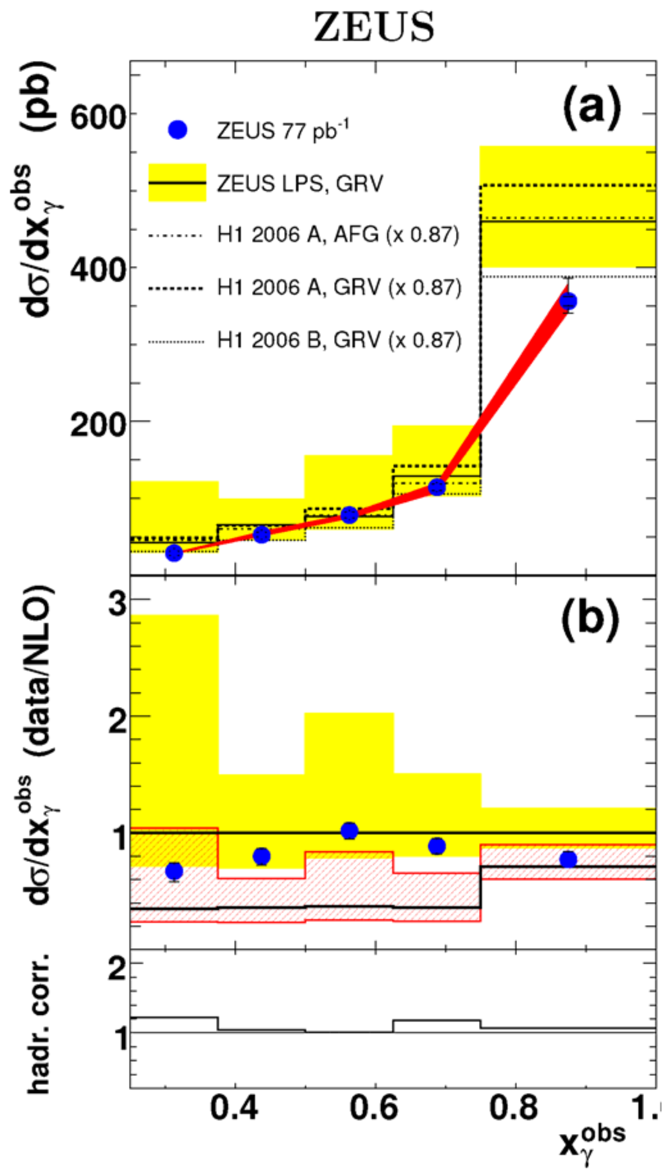




- Charm γp data dominated by direct photon interactions … well described by predictions based on DPDFs
- Large scale uncertainties on theory (as in all final state diffractive studies at HERA) due to low scales accessed.

Jets in Resolved Photoproduction: Gap Survival





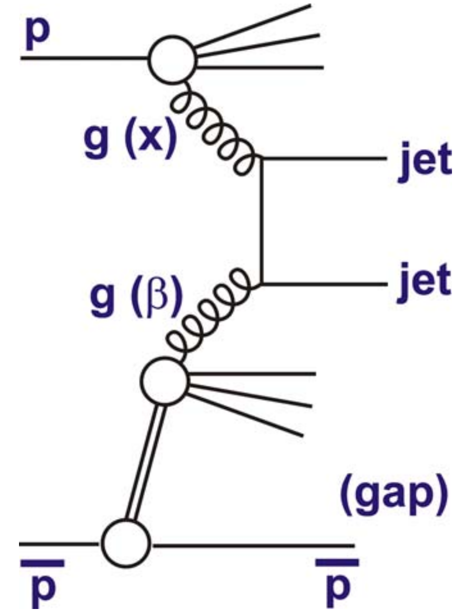
H1: Suppression by factor ~2 observed, but seems to be present in direct as well as resolved processes?!?!

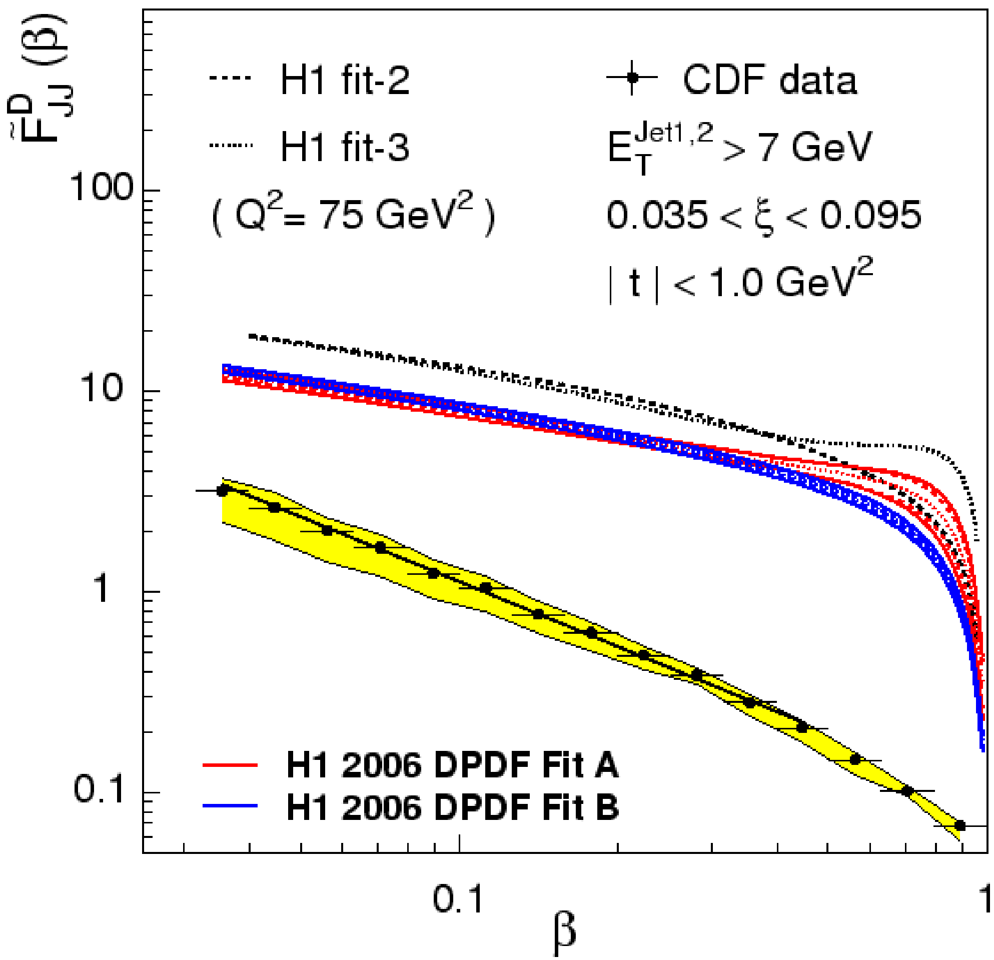
ZEUS: Weak (if any) suppression

Theory (Kaidalov et al): Factor 0.34 expected for resolved only.

... ongoing work to compare and check theory in predictions (e.g. mixing heavy flavour schemes)

Moving to the Tevatron …
x_{IP} integrated effective DPDFs from CDF SD Dijets (Run I)

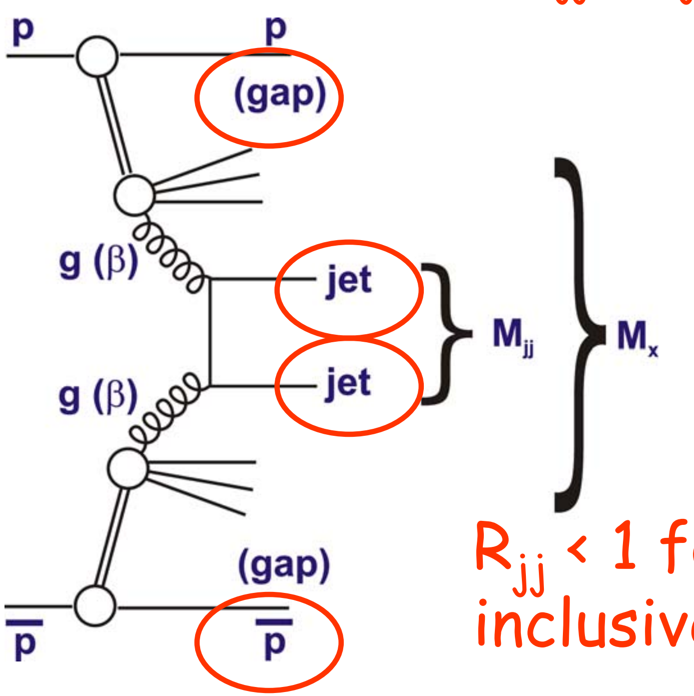




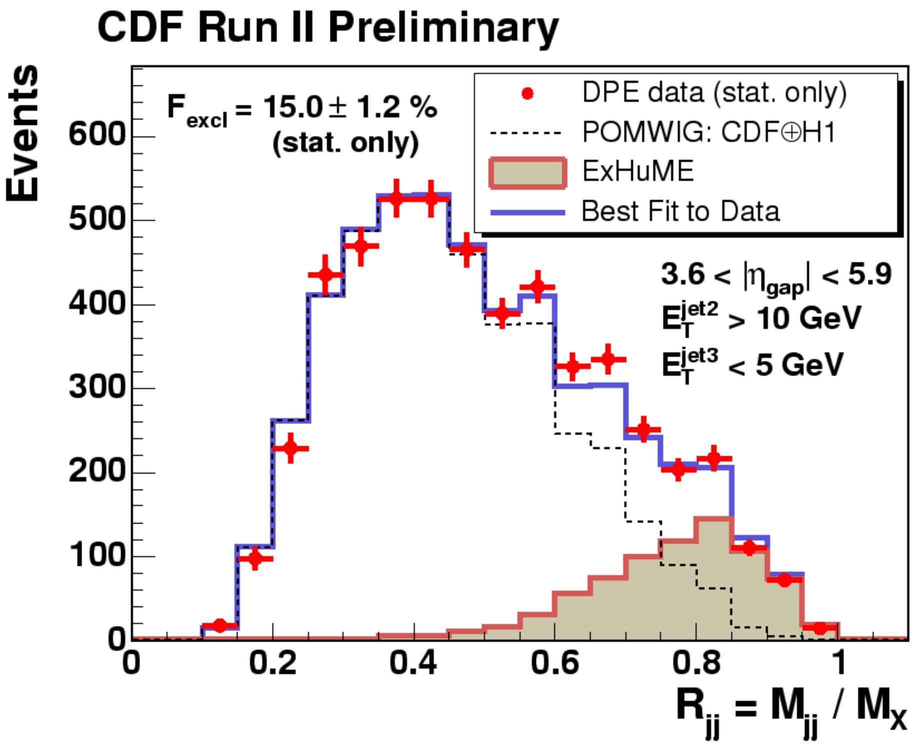
- pbar p → pbar (jjX) is sensitive to DPDFs and can be cleanly predicted using HERA DPDFs
- Factorisation strongly broken by a (β dependent) factor ~10
- See also Run II data …

Exclusive Dijet Production at the Tevatron?

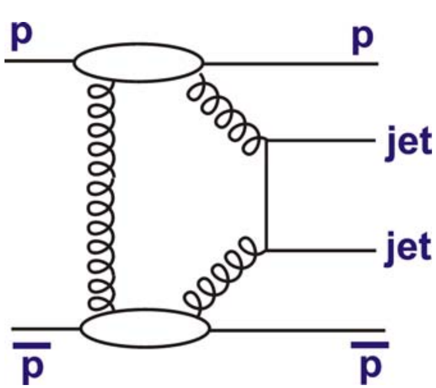
"DPE" dijets, plot $R_{jj}=M_{jj}/M_x$



$R_{jj} < 1$ for inclusive



$R_{jj} \rightarrow 1$ for exclusive (complicated by hadronis^n, higher order QCD …)

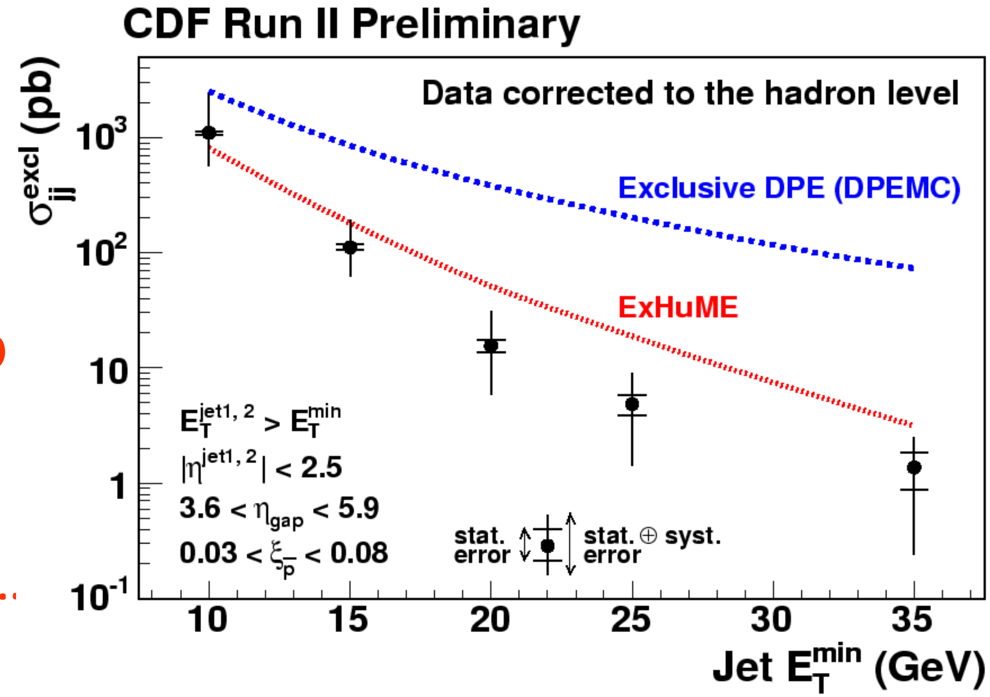


Many comparisons with varying MC modelling and DPDFs … …hard to get rid of signal!

Fit with free normalisation of inclusive, exclusive models to quantify exclusive part …

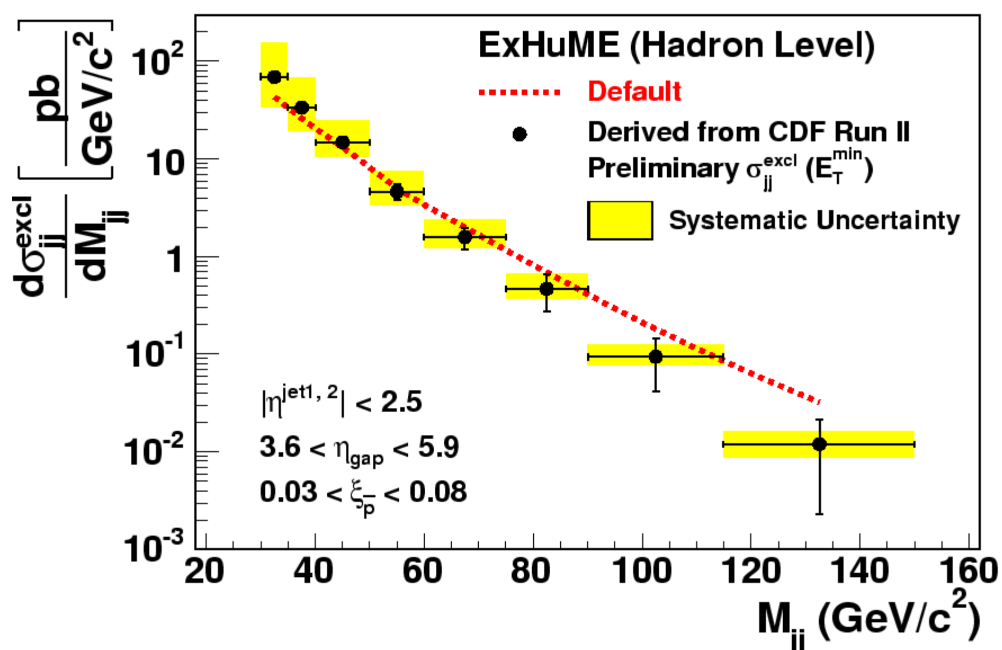
CDF Exclusive Dijet Cross Section

• Cross sections corrected to the hadron level compared with predictions based on central exclusive production ..

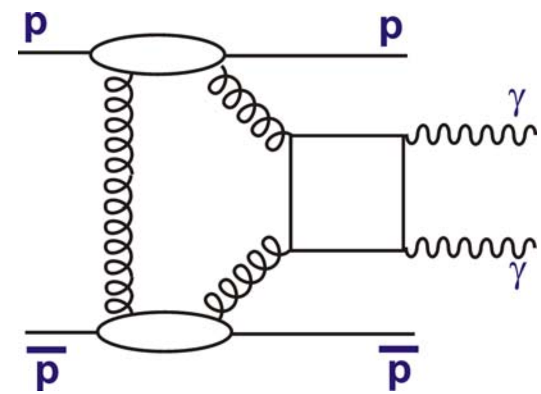


• ExHuME model based on KMR calculation …
- 4.5% gap survival prob
- "Uncertainty factor 2.5"

• Expressed in terms of M_{jj}, signal extends into possible Higgs discovery mass region!

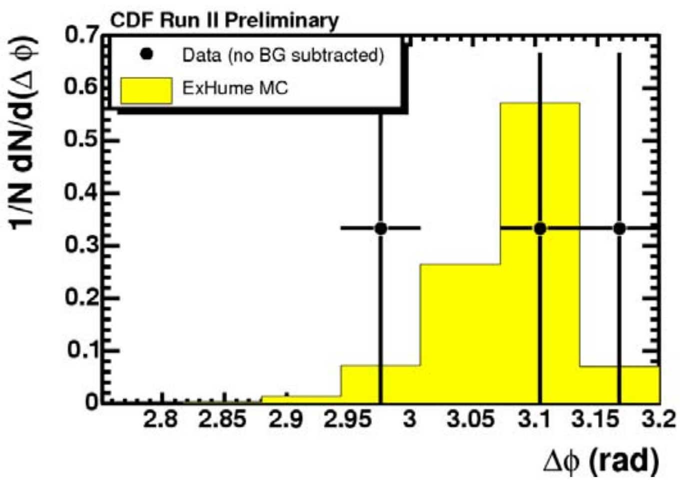


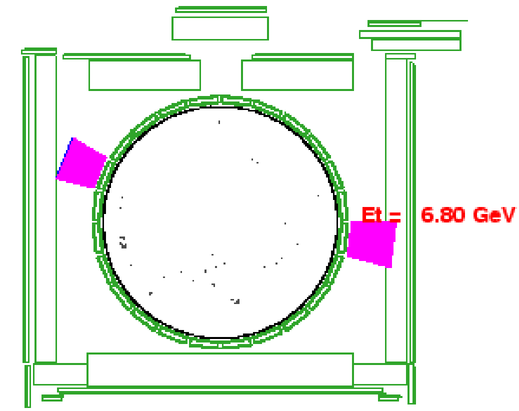
CDF Exclusive Di-photons



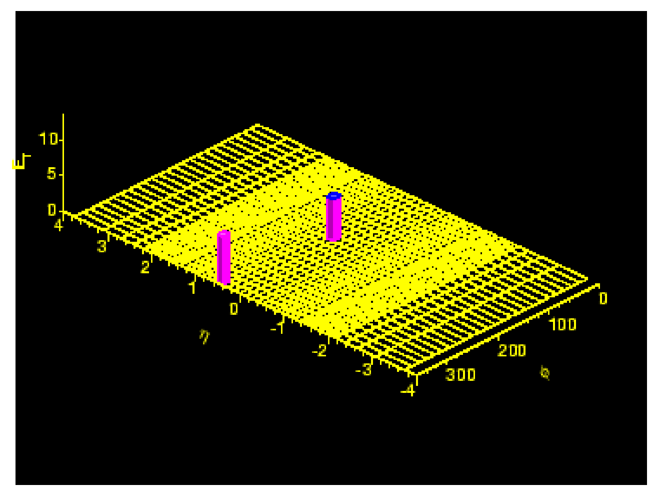
$E_t^{\gamma} > 5$ GeV, $|\eta_\gamma|<1$, detector otherwise consistent with empty (protons not tagged)

3 candidates with background < 0.2





Prediction (KMR) is around 1 event, uncertainty factor 3-5



… hard to explain through other processes (qq or γγ few % of gg)

Summary

- Many measurements of inclusive diffraction at HERA
  - Good agreement between methods, collaborations
  - Much improved precision on diffractive PDFs

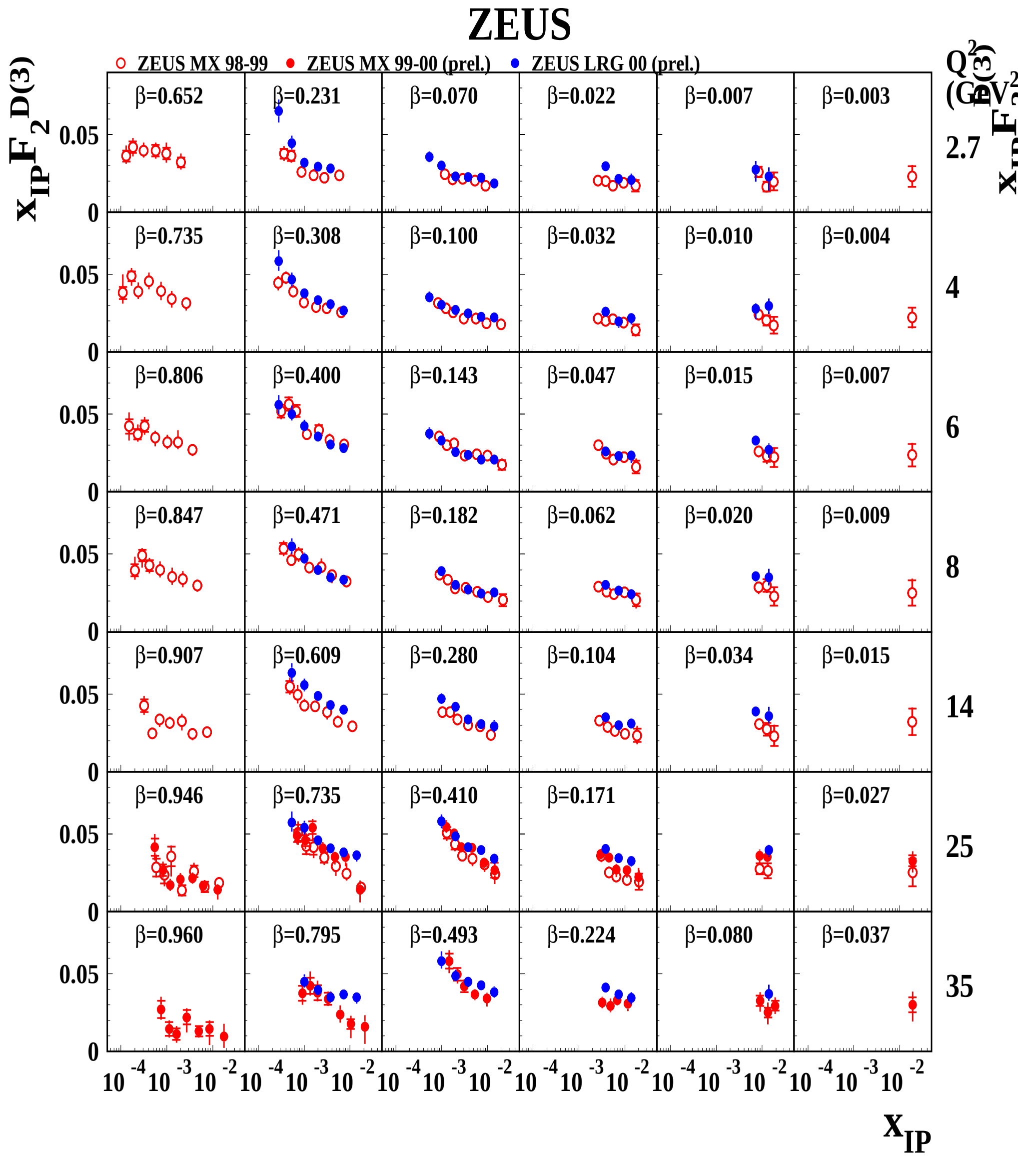
- Many tests of diffractive factorisation using final states
  - Works nicely in DIS (jets now included in fits)
  - Photoproduction needs clarification
  - Clear breakdown in ppbar (gap survivial factors)

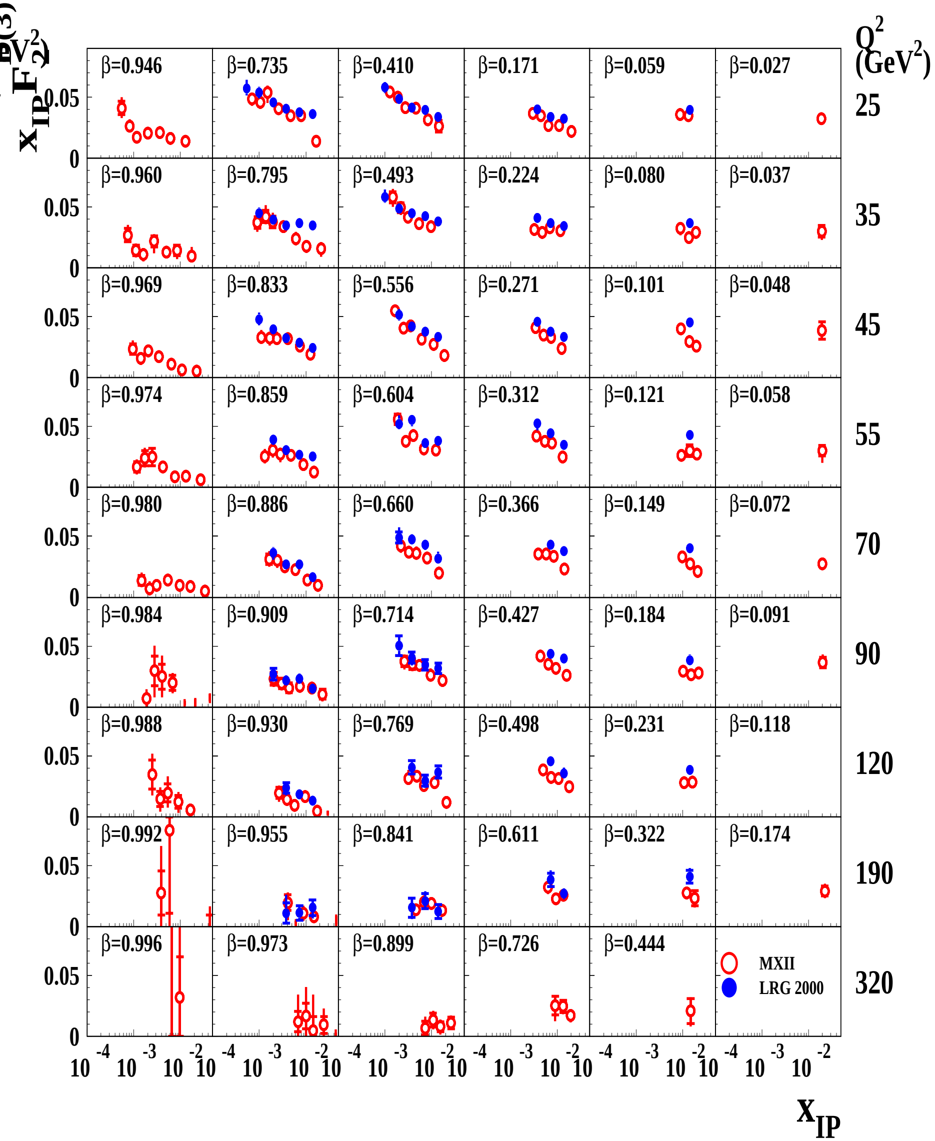
- Increasingly compelling evidence for central exclusive production from CDF at the Tevatron
  - ppbar → ppbar + dijet
  - ppbar → ppbar + $\gamma\gamma$

Could diffraction play a role in Higgs studies at LHC?...

Back up's follow …

ZEUS Mx v LRG

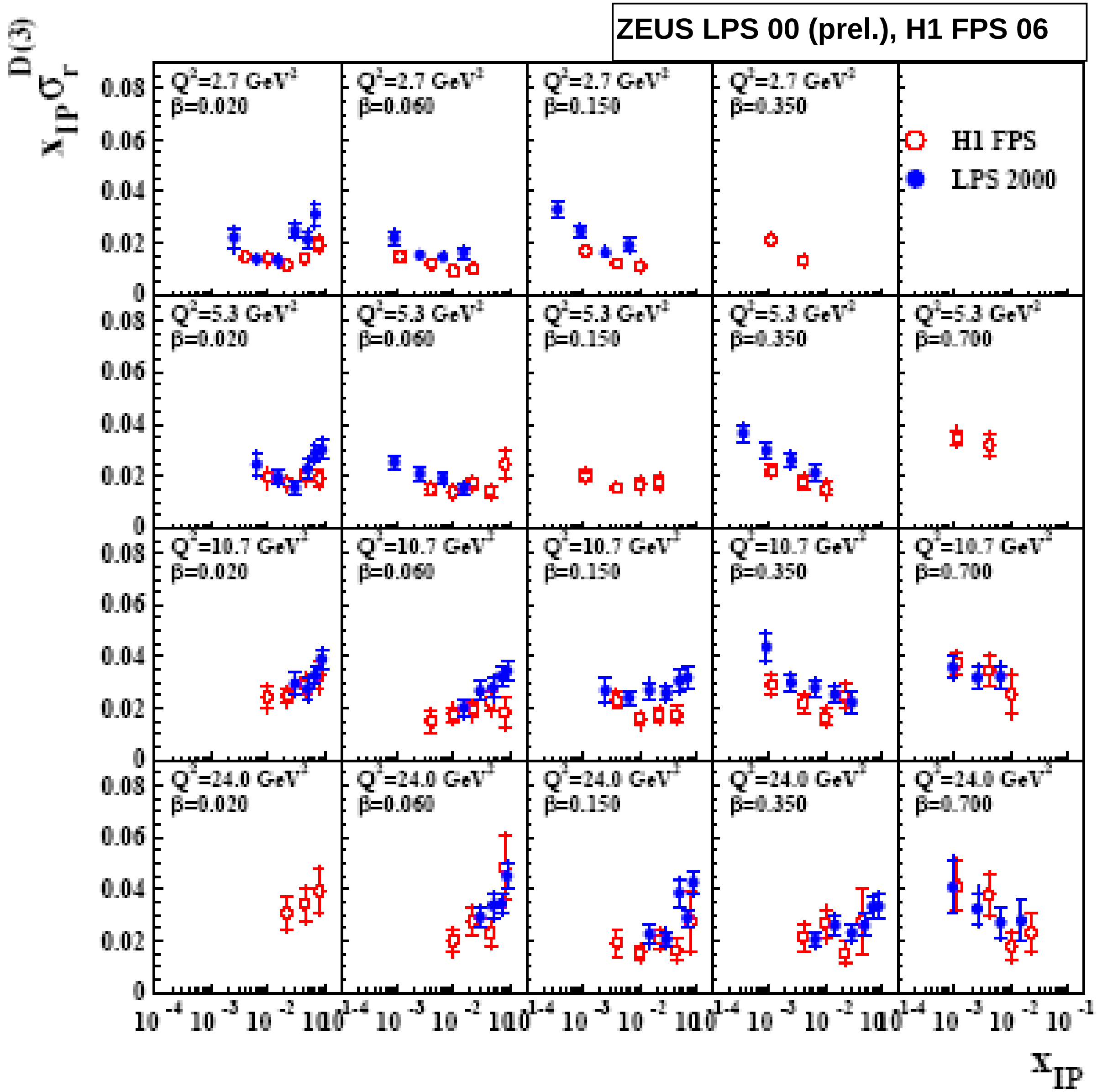




In general reasonable agreement for $x_{IP} < 0.01$

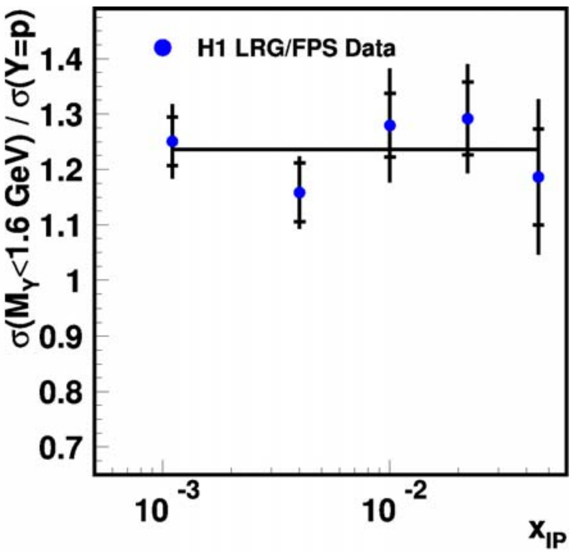
For $x_{IP} > 0.01$ one can expect some differences from Reggeon contributions to the LRG data

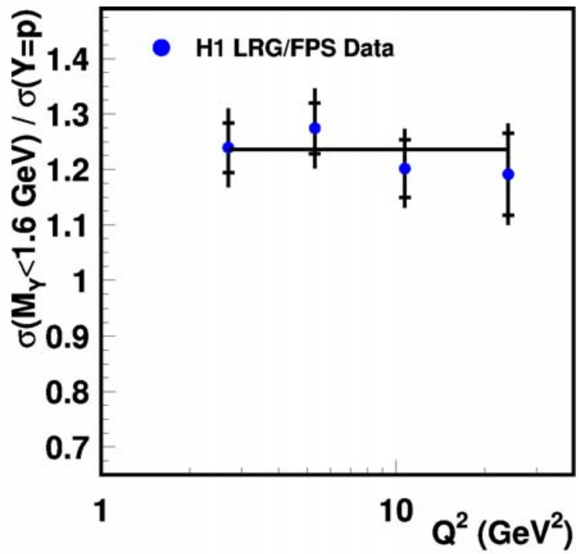
New LPS / FPS Data H1 v ZEUS

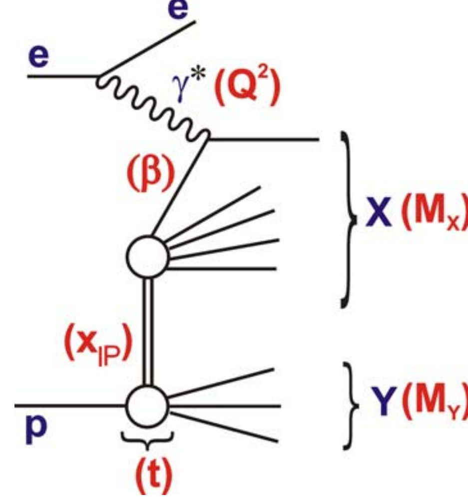


Relative
Norm uncties
15% not shown

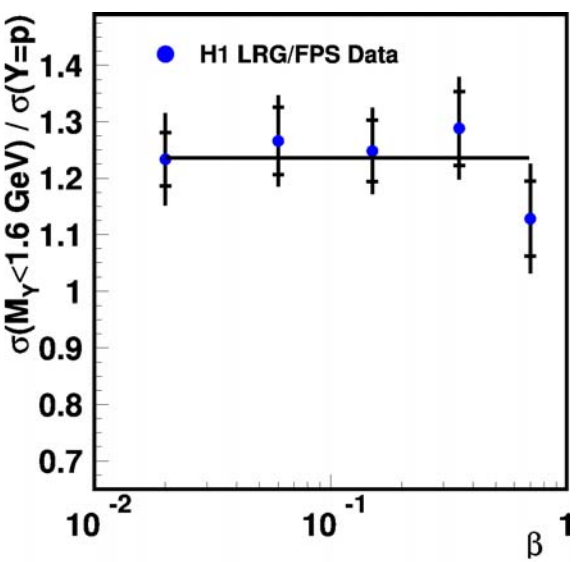
Detailed Comparison LRG v FPS







LRG measurement also done in FPS bins



- Form ratio of measurements as a function of x_{IP}, β or Q^2 after integration over others

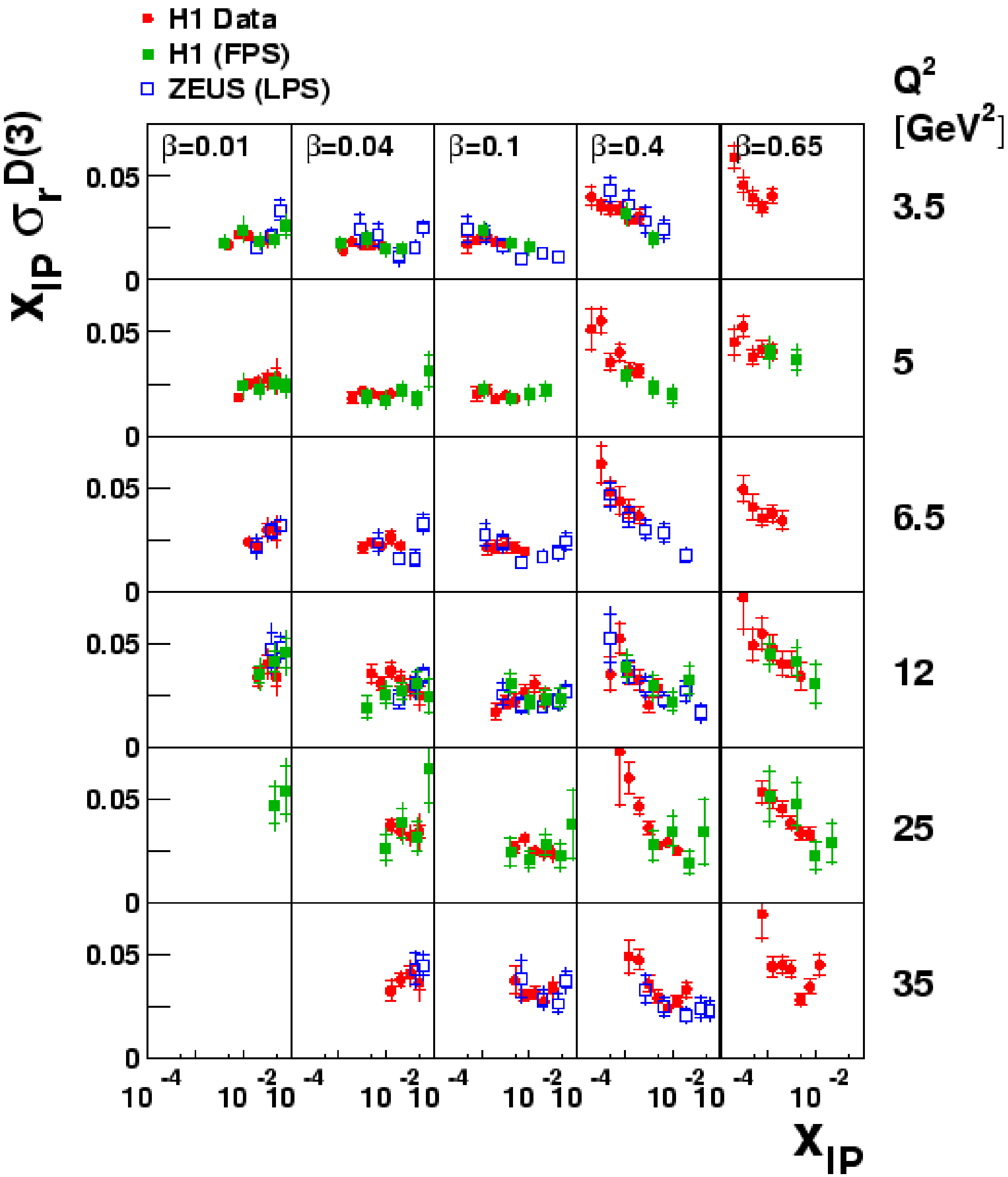
$$\frac{\sigma(M_Y < 1.6\ \text{GeV})}{\sigma(Y = p)} = 1.23 \pm 0.03\ \text{(stat.)} \pm 0.16\ \text{(syst.)}$$

independently of kinematics within errors

- Agreement in detail between methods

- M_Y dependence factorises within (10%) (non-norm^n) errors

H1 LRG v H1 FPS v ZEUS LPS Data



- ZEUS and H1 Roman pot data agree to well within normalisation uncertainties

- Very good agreement between proton-tagging and LRG methods.

- Roman Pot data scaled by global factor of 1.23 to account for proton dissociation (M_Y<1.6 GeV) in LRG data.

QCD Aspects! $\sigma_r^{D(3)}(\beta, Q^2, x_{IP})$ at $x_{IP} = 0.0003$

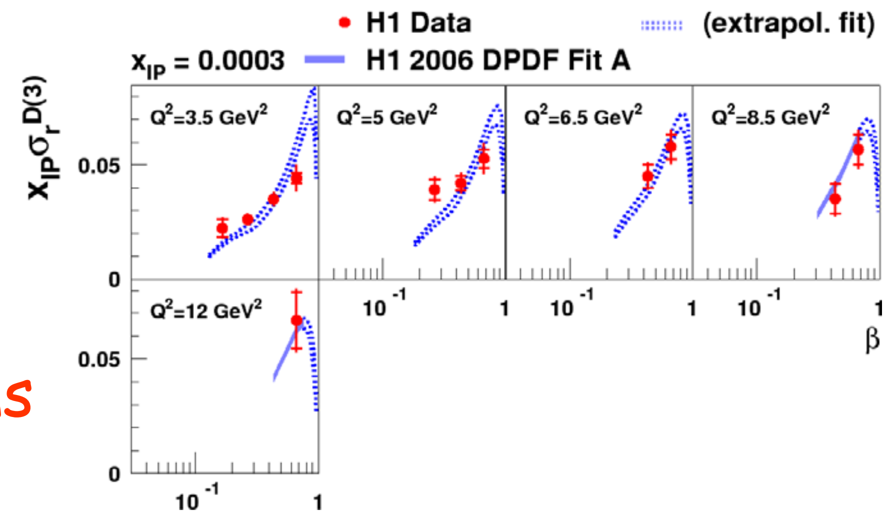
- Study QCD structure with LRG data …Q^2 and β (= x / x_{IP}) dependences at a small number of fixed x_{IP} values.

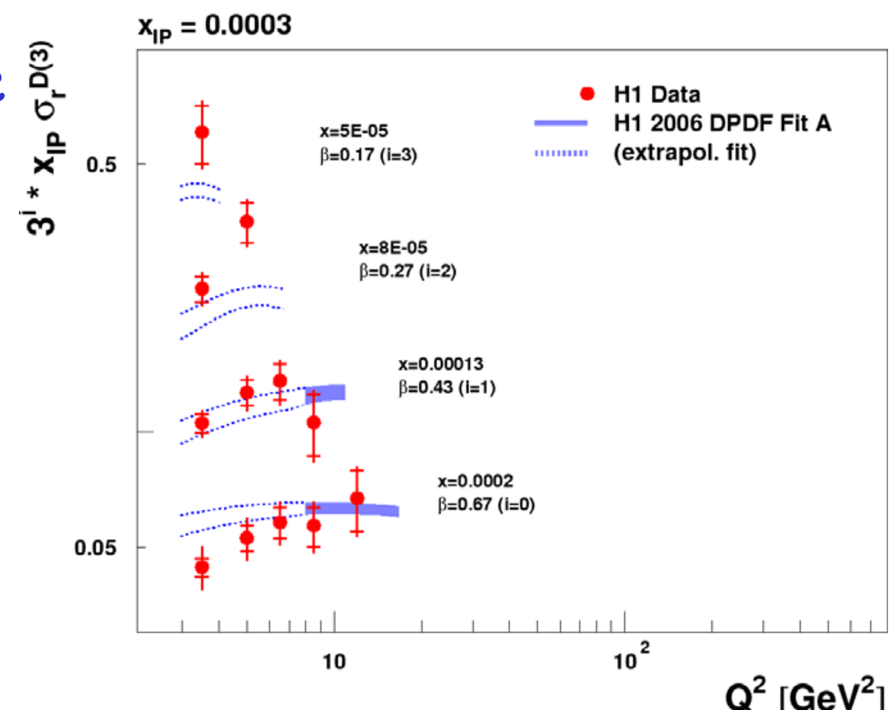
- Good precision – in best regions 5% (stat.), 5% (syst) 6% (norm)

- Directly measures diffractive quark density at fixed x_{IP}

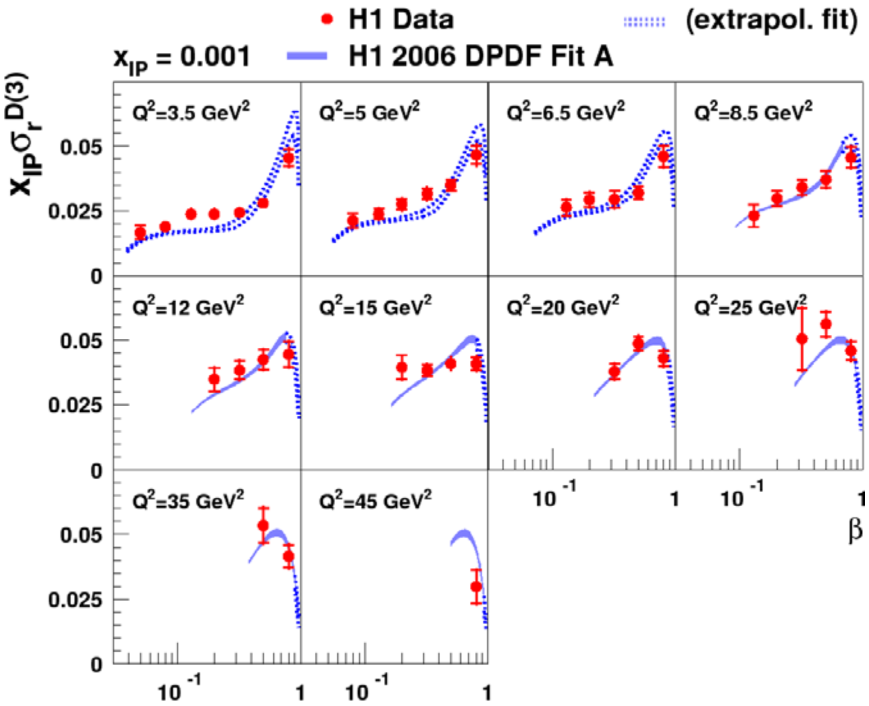
$$\sigma_r^D(\beta, Q^2) \sim F_2^D = \Sigma\, e_q^2\, (q + \bar{q})$$

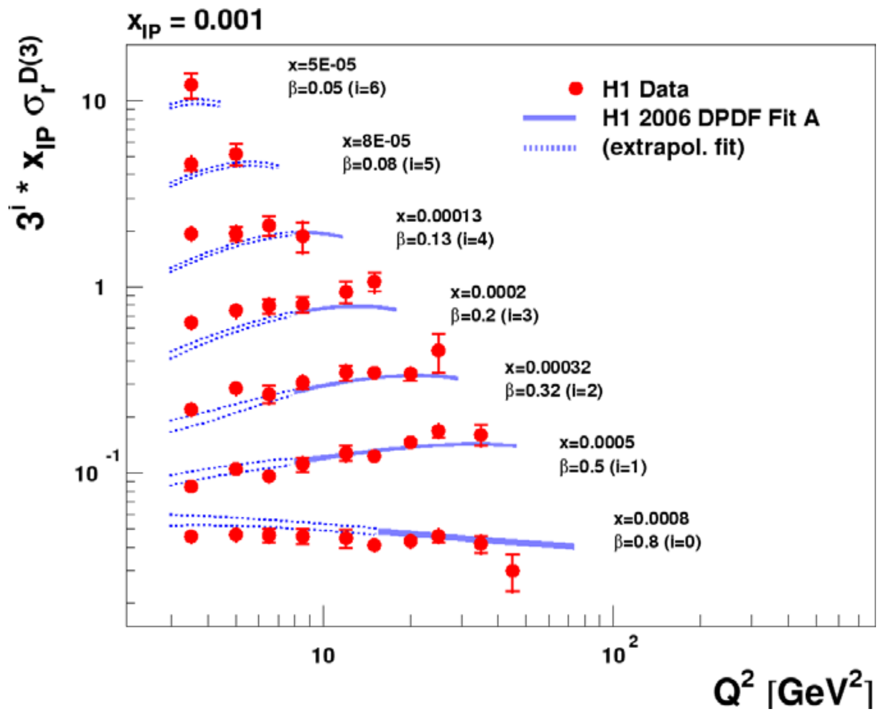
- Data compared with \`H1 2006 DPDF Fit' and error band (assumes proton vertex factorisation - see later)





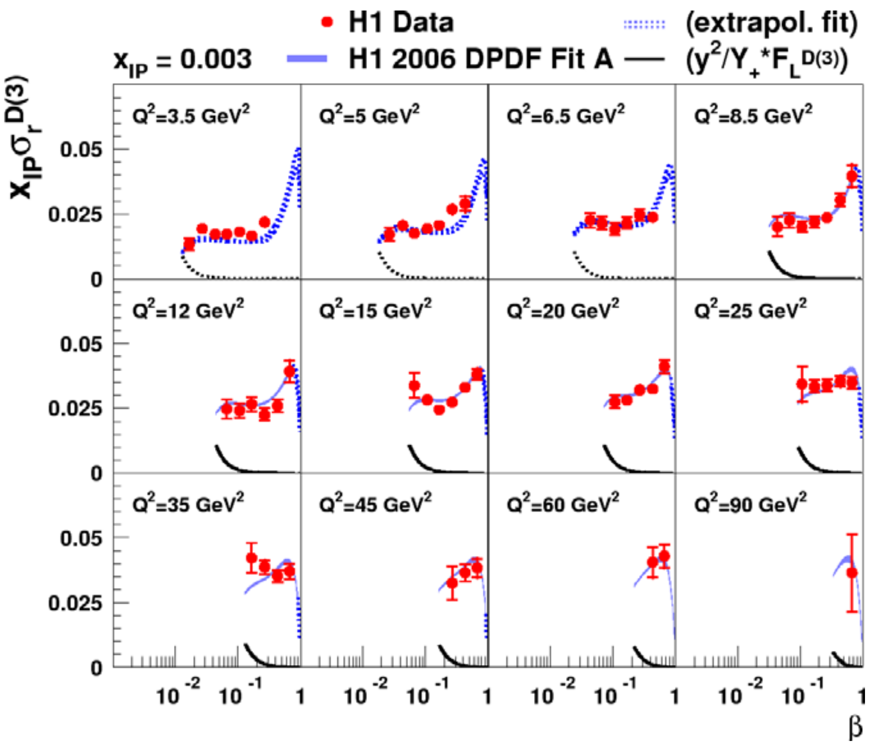
$\sigma_r^{D(3)}(\beta, Q^2, x_{IP})$ at $x_{IP} = 0.001$

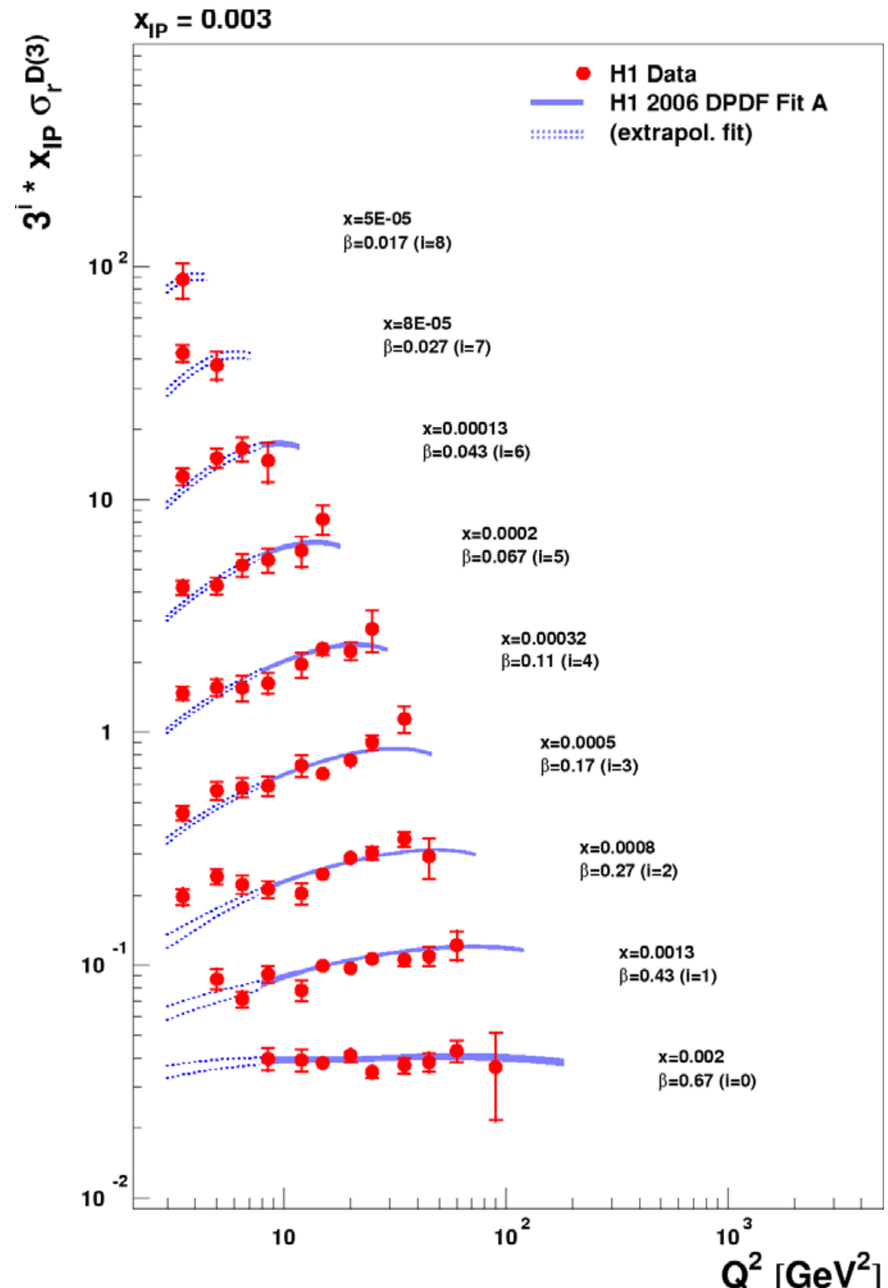




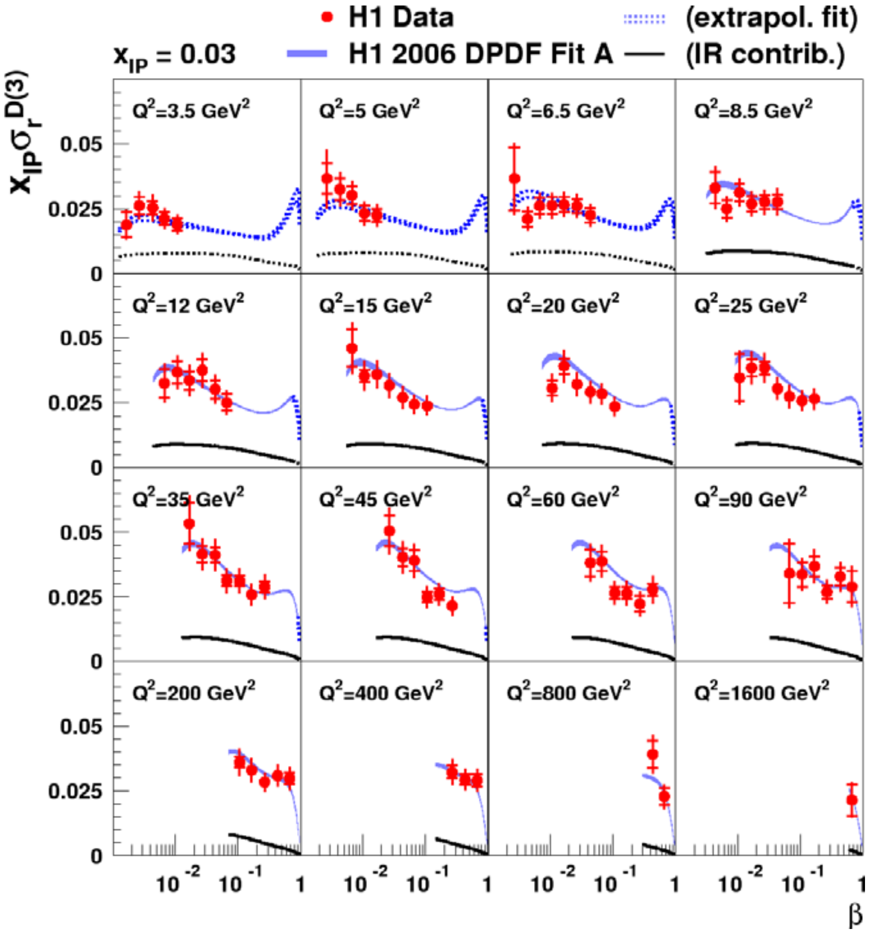
(Like an inclusive F_2 measurement at each value of x_{IP})

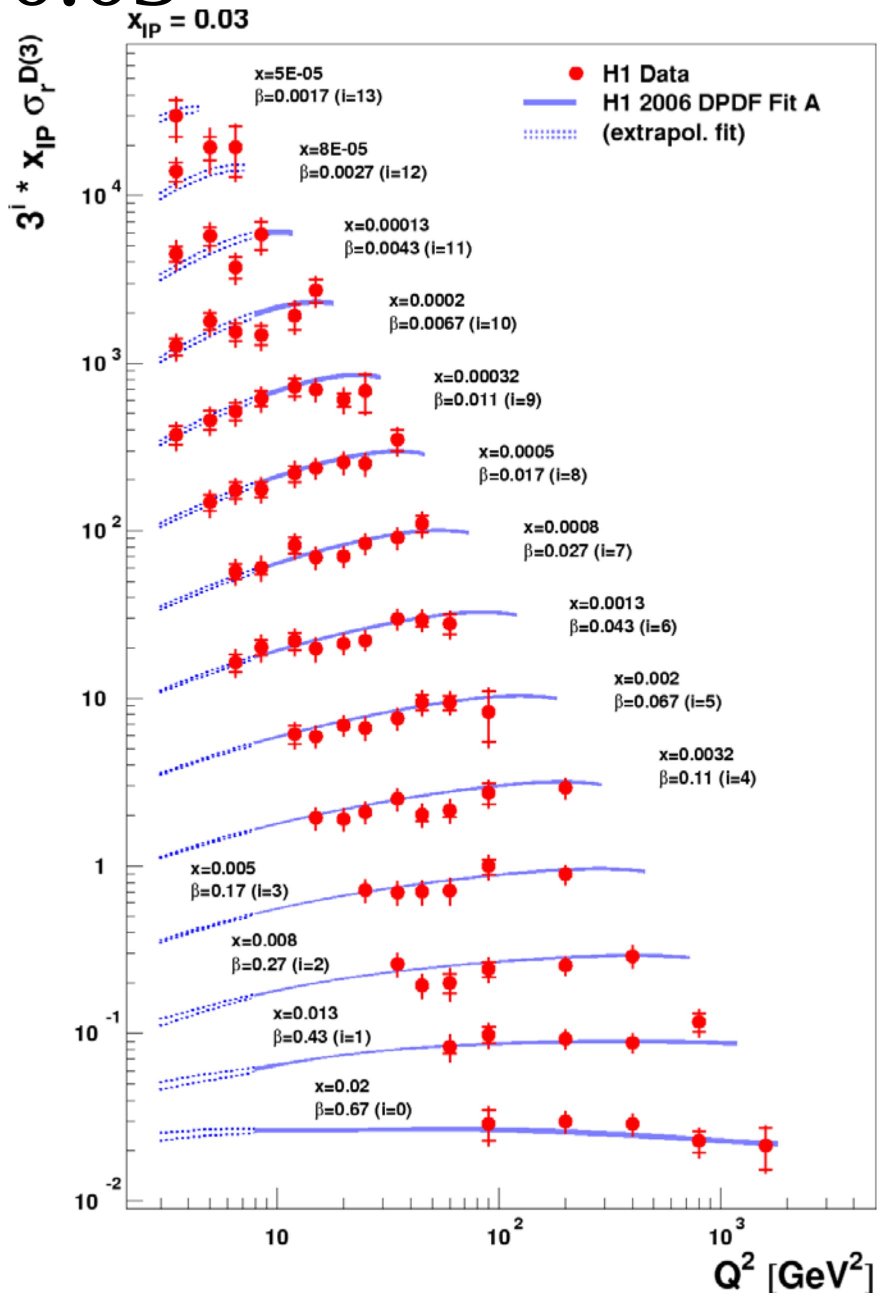
$\sigma_r^{D(3)}(\beta, Q^2, x_{IP})$ at $x_{IP} = 0.003$





$\sigma_r^{D(3)}(\beta, Q^2, x_{IP})$ at $x_{IP} = 0.03$

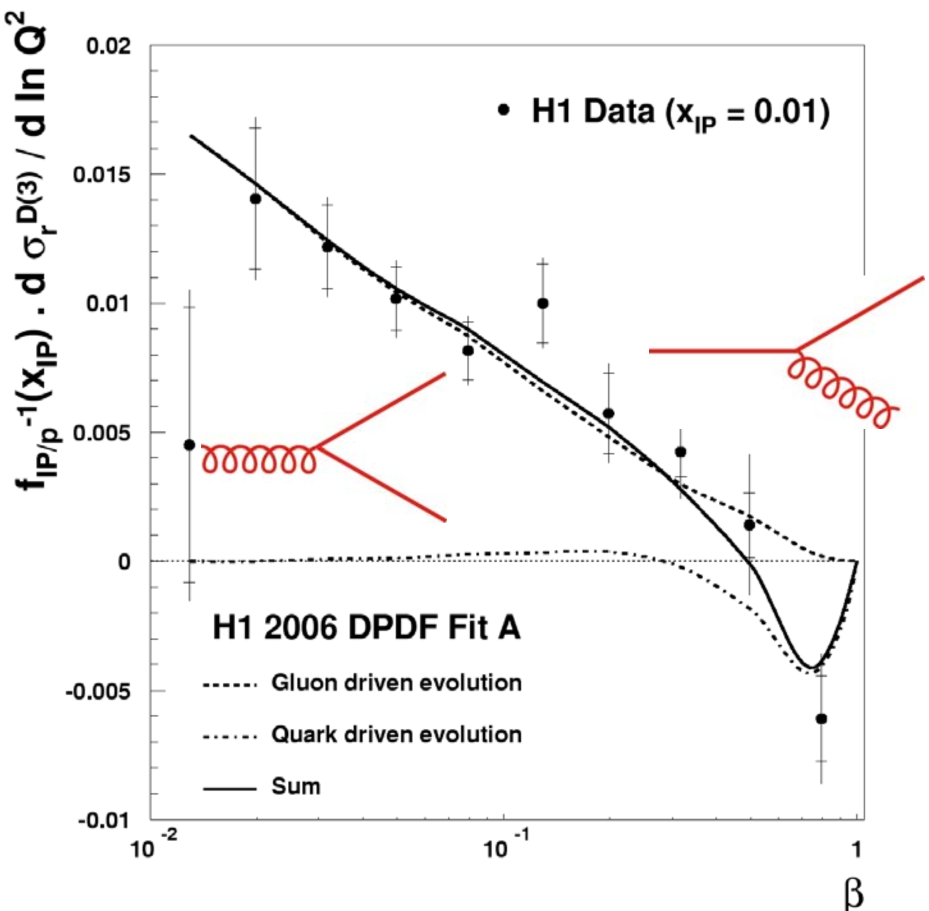


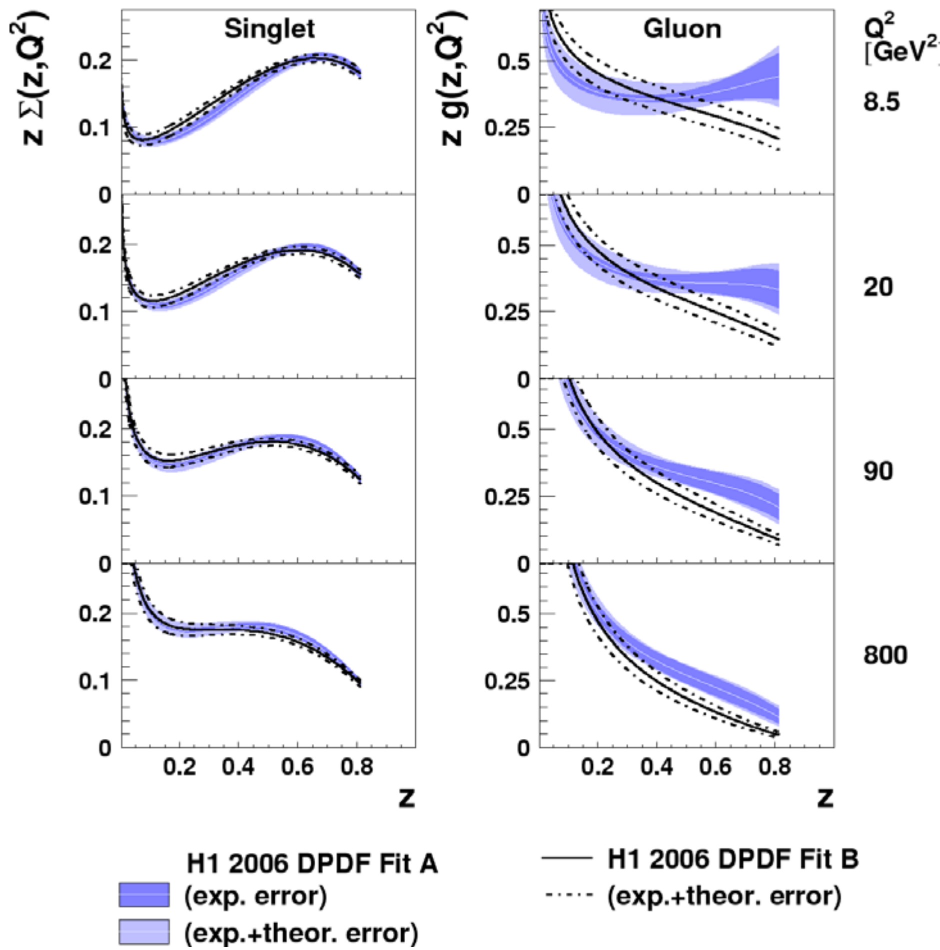


A Closer Look at the High z Region

With only singlet quarks, DGLAP equation for F_2^D …

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

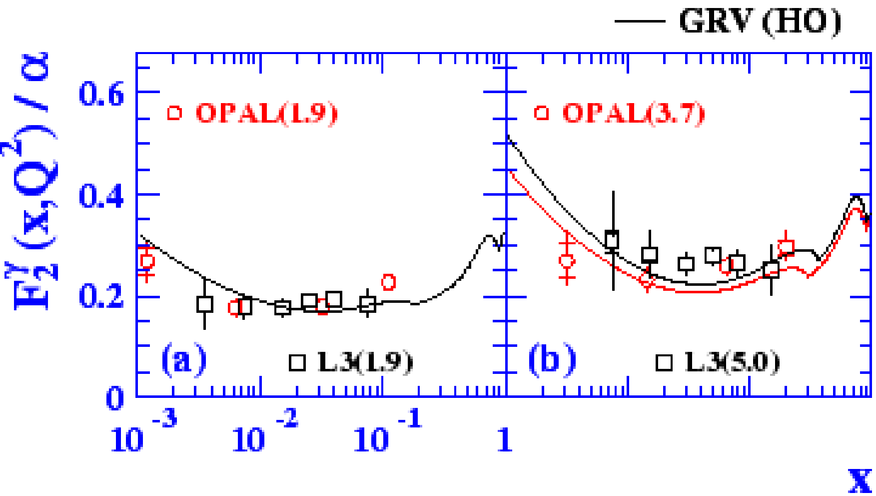


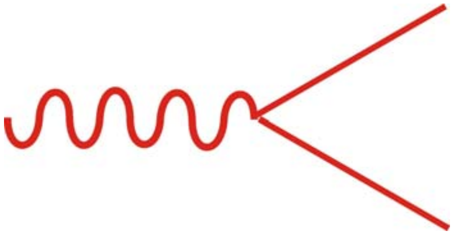


Very different high z gluon but similar χ^2 with modified parameterisation

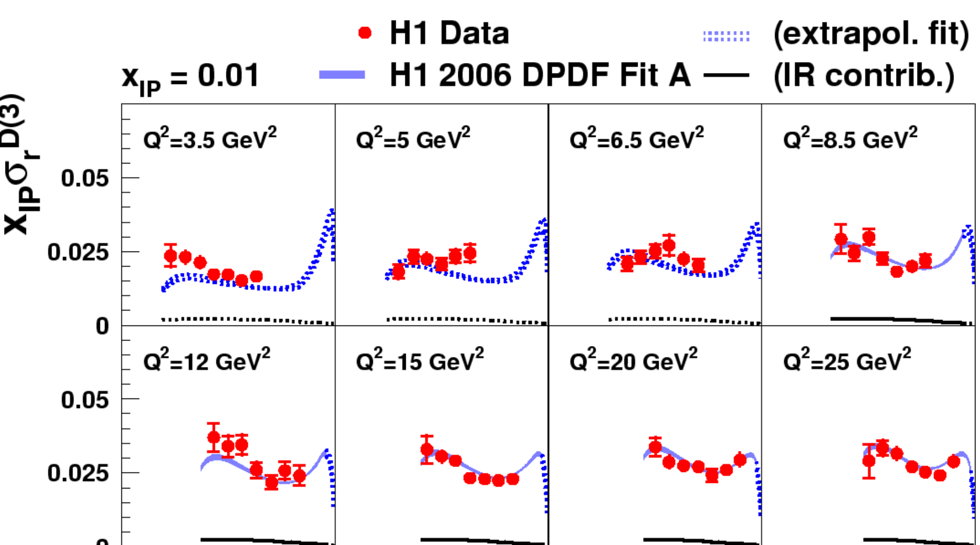
… but what do the DPDFs actually *mean*?

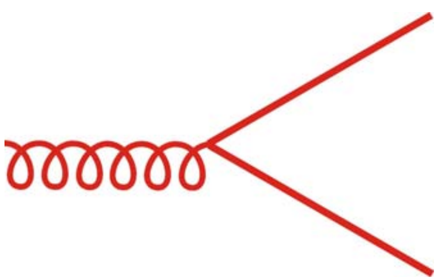
High z behaviour looks a lot like the photon structure function …





Photon \`structure' derived from $\gamma \rightarrow$ qqbar



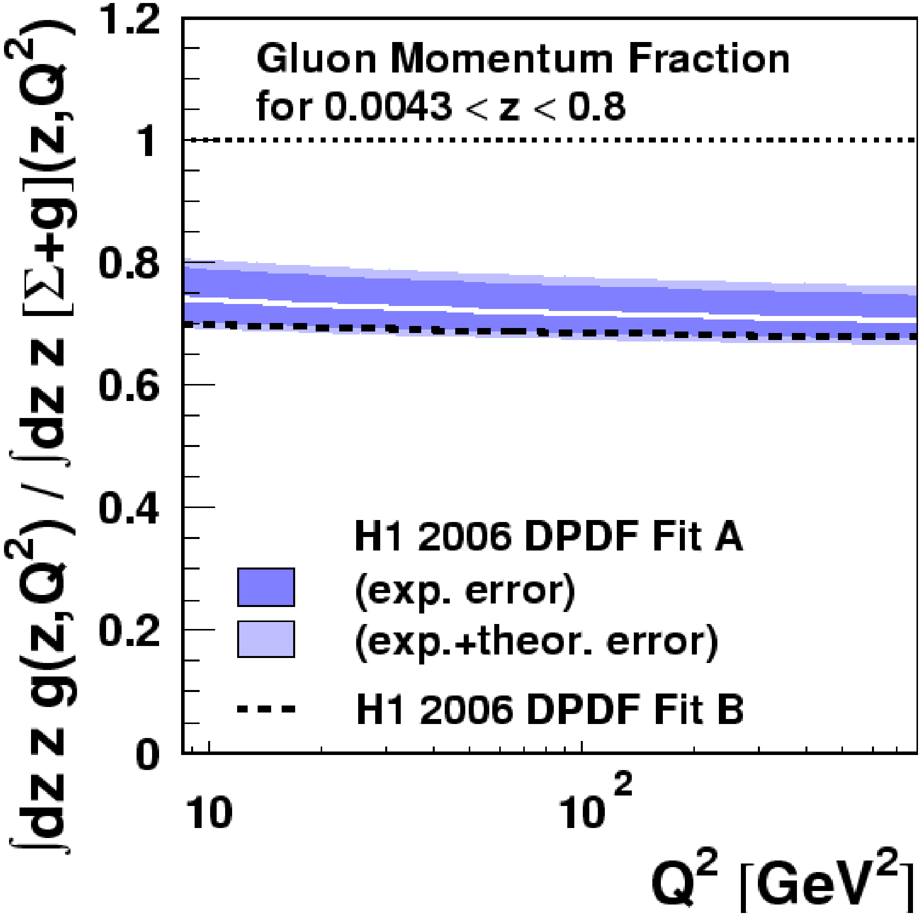


Diffractive DIS derived from $g \rightarrow$ qqbar (and $g \rightarrow$ gg …)
… leading gluon exchange?

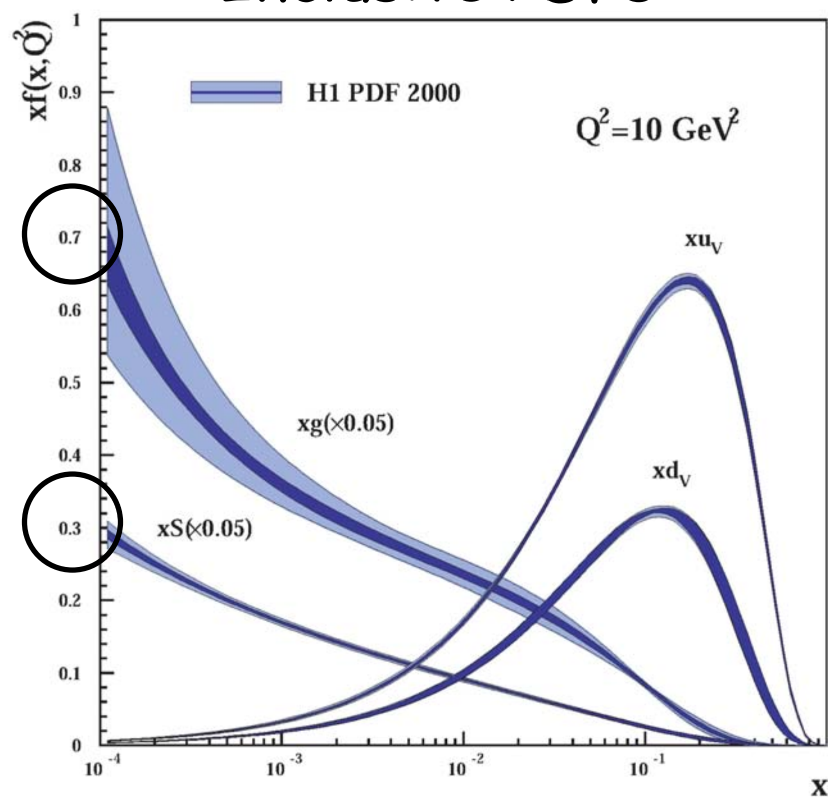
… but what do the DPDFs actually *mean*?

… what about **low z** … ratio of quarks to gluons is about 70:30 for both diffractive PDFs and (low x) inclusive PDFs …

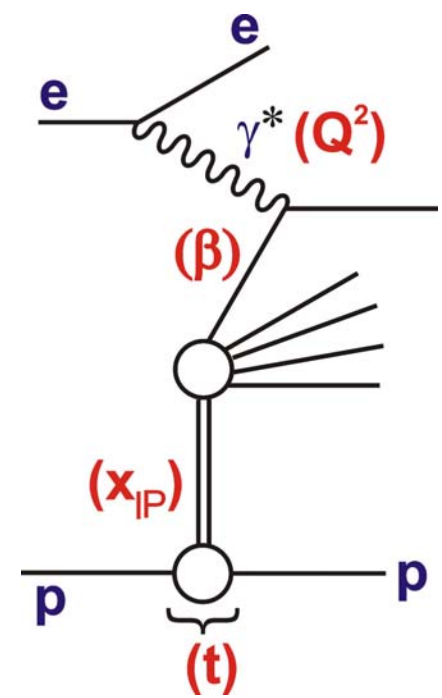
Diffractive PDFs



Inclusive PDFs



Extracting the Quarks and Gluons



- Fit β and Q^2 dependence of LRG data from fixed x_{IP} binning scheme (χ^2 minimisation)

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

- 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.

- Exclude data with $M_X < 2$ GeV or $\beta > 0.8$ (higher twist region) and with $Q^2 < 8.5$ GeV^2 (NLO insufficient?)

Free Parameters of H1 2006 DPDF Fit

5 free parameters for singlet quark $z\Sigma(z,Q_0^2)$, gluon $zg(z,Q_0^2)$ densities, where z is parton momentum fraction (= β for quarks at lowest order, otherwise $>\beta$)

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

$$zg(z,Q_0^2) = A_g (1-z)^{C_g}$$

(gluon insensitive to B_g)

- 1 free parameter $\alpha_{IP}(0)$ describes x_{IP} dependence via flux factor

- 1 free parameter describes normalisation of sub-leading IR, which is otherwise treated as a π^0

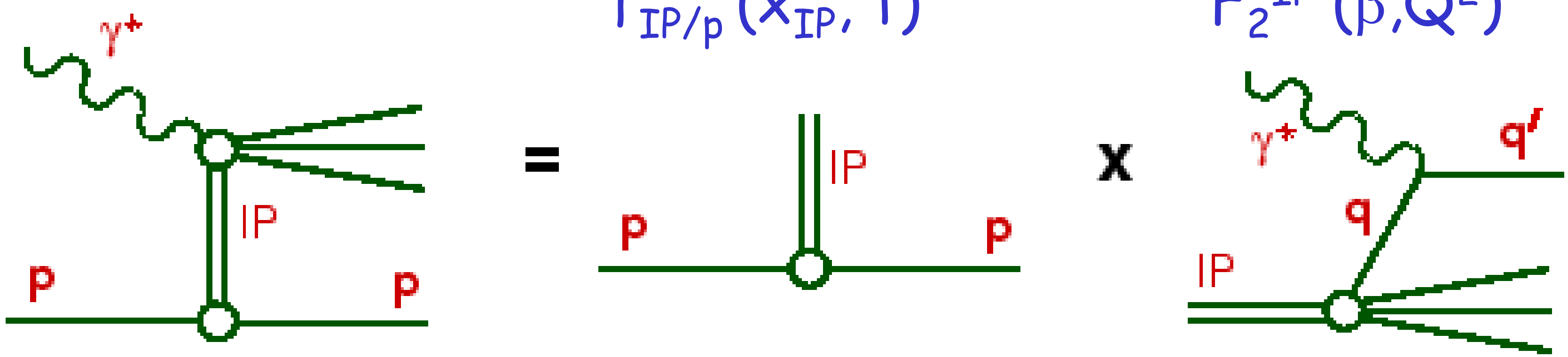
- Results reproducible within errors with many variations in assumptions, parameterisations and other details

Proton Vertex Factorisation and 'Pomeron Flux'

If proton vertex factorisation works, we can factorise out x_{IP}, t (and M_Y) dependence into a `flux factor'

MEASUREMENT = IP FLUX x IP STRUCTURE

$f_{IP/p}(x_{IP}, t)$ $F_2^{IP}(\beta, Q^2)$

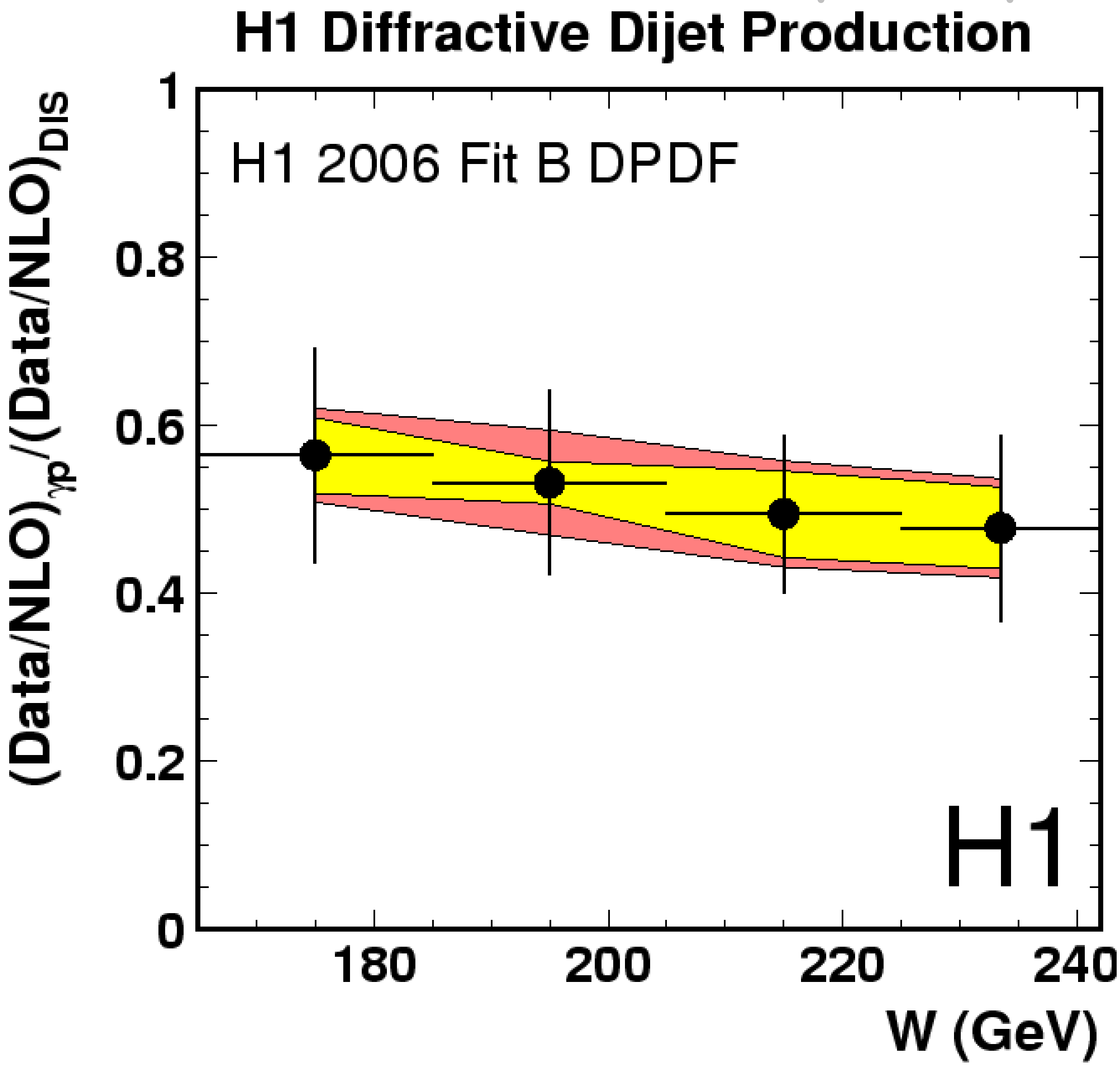


'Flux' parameterisation inspired By Regge theory …

$$f_{IP/p}(x_{IP}, t) = \frac{e^{B_{IP} t}}{x_{IP}^{2\alpha_{IP}(t)-1}}$$

Free parameters - pomeron `trajectory' $\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}\, t$

Double Ratios of DIS : photoproduction



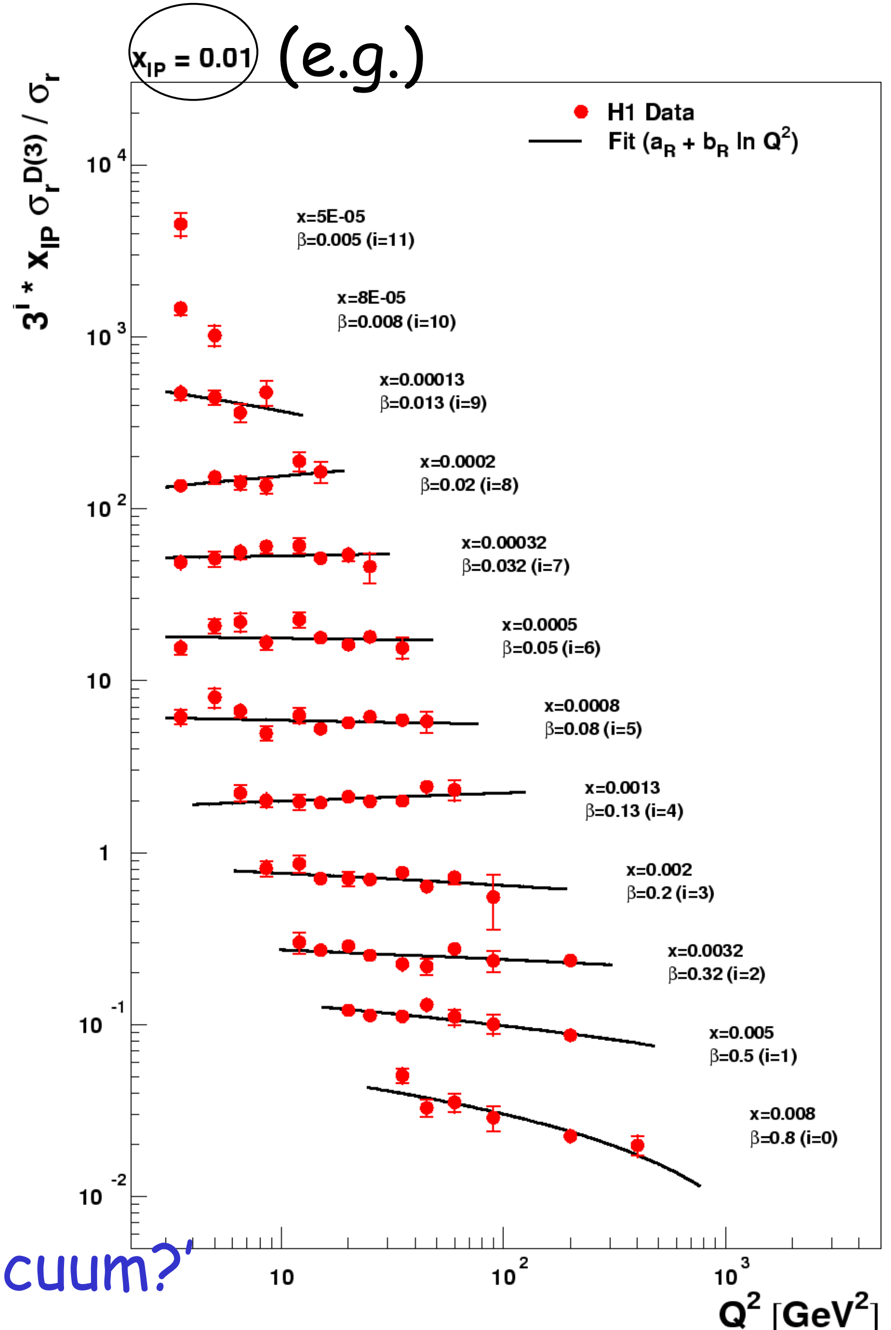
Low x similarity of diffractive & inclusive PDFs

- Similar ratios of quarks to gluons reflected in similar Q^2 evolution of inclusive and diffractive cross sections at low x…

- …Ratio σ_r^D/σ_r ~ independent of Q^2 at fixed x_{IP} and x.

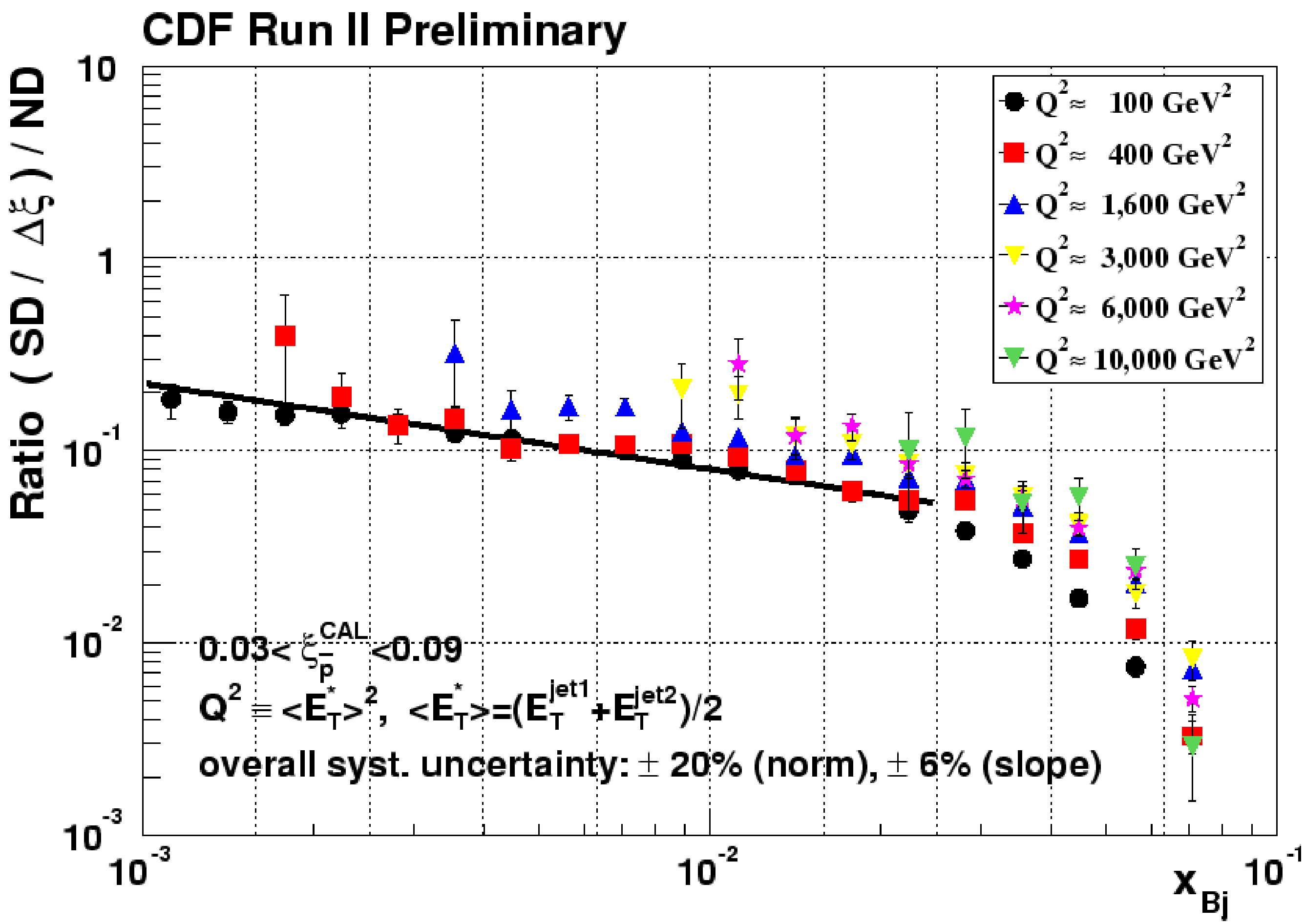
- … away from the influence of valence quarks, PDFs and their evolution is driven only by QCD … same for proton, pomeron, pion, photon …?

(e.g.)

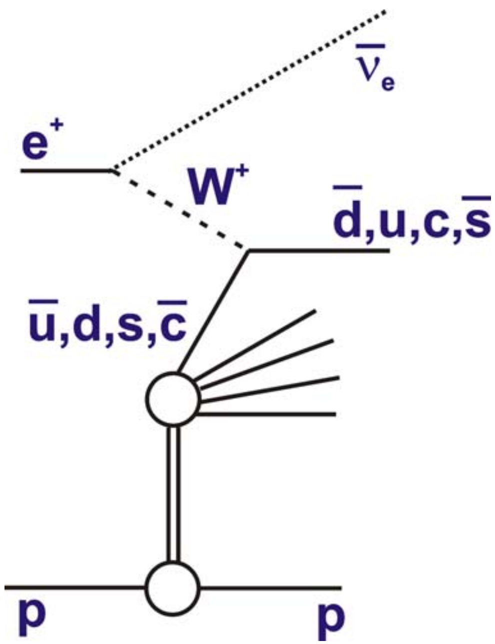


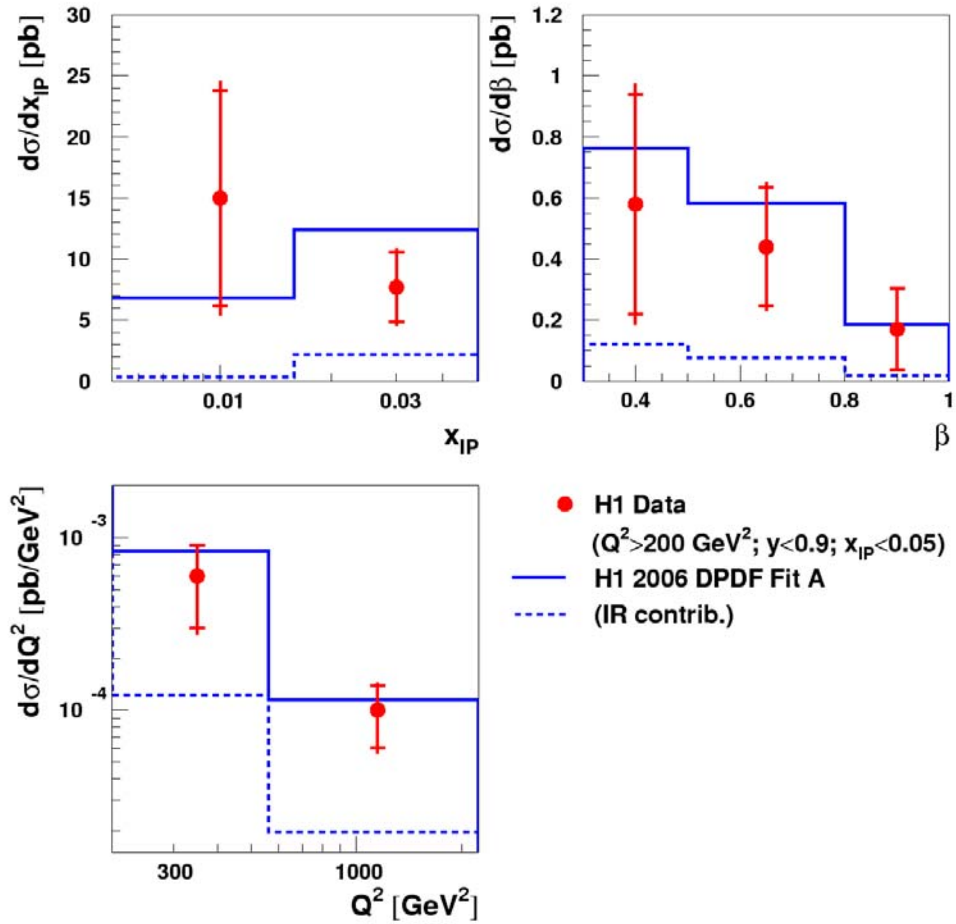
…`universal structure of QCD vacuum?'

Diffractive Structure Fn @ CDF



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