Inclusive Diffraction at HERA

RINGBERG WORKSHOP: New Trends in HERA Physics 2011,
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on behalf of the H1 and ZEUS Collaborations

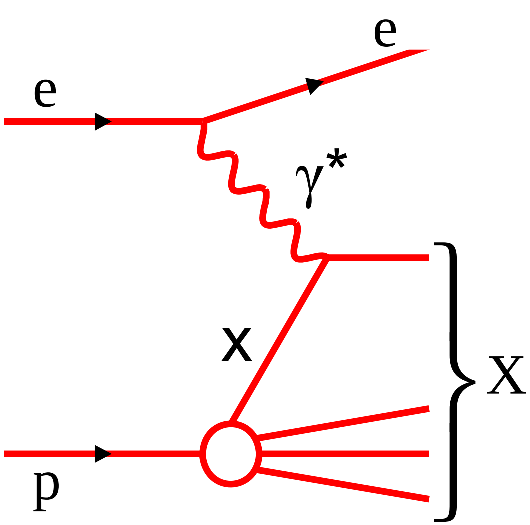
- Selection of Diffraction at HERA
- H1 and ZEUS leading proton data
- LRG cross sections and DPDF fits
- F_L^D measurement
- Factorisation tests

Diffractive DIS at HERA

HERA: ~10% of low-x DIS events are diffractive with no color flow between hadron systems Y(p) and X

➔Probe structure of color singlet exchange with virtual photon

Standard DIS



$F_2 \rightarrow$ probe structure of proton

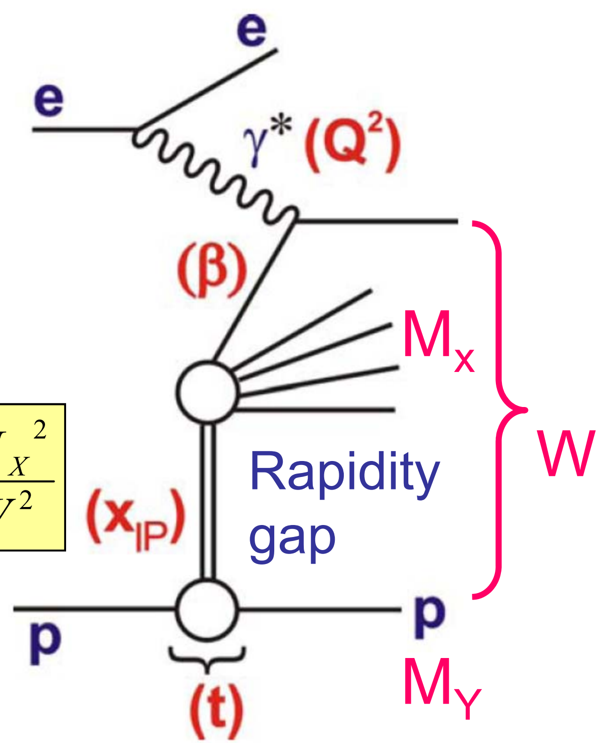
Diffractive DIS

Momentum fraction of color singlet carried by struck quark

$$\beta = \frac{x}{x_{IP}} \approx \frac{Q^2}{Q^2 + M_X^{\ 2}}$$

$$x_{\mathrm{IP}} = \frac{q \cdot (p - p')}{q \cdot p} \approx \frac{Q^2 + M_X^{\ 2}}{Q^2 + W^2}$$

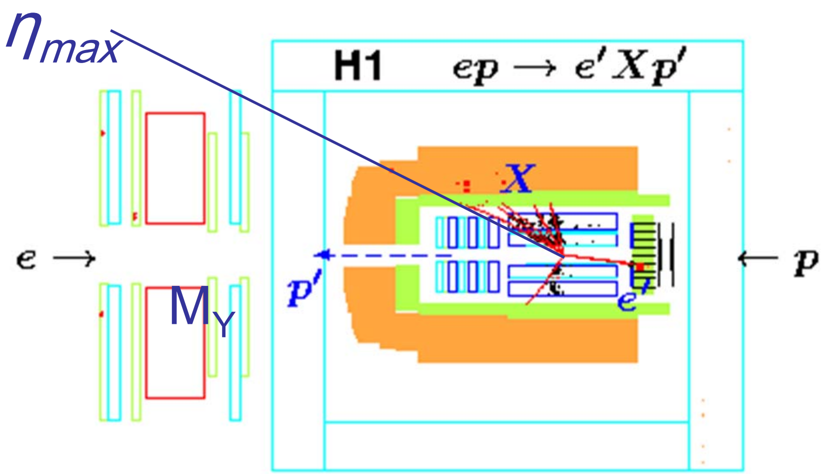
Momentum fraction of proton carried by color singlet exchange



Squared 4-momentum transfer

Selection of diffraction at HERA

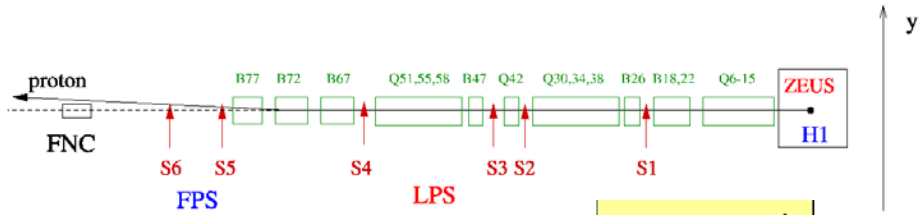
Large rapidity gap (LRG) between leading proton *p* and *X*



- ❑ high statistics, data integrated over $|t|<1GeV^2$
- ❑ p-dissociation contribution
- ❑ limited by systematic uncertainties related to missing proton

➔ LRG and FPS methods have different systematic uncertainties

Proton Spectrometers (PS)



H1 FPS + ZEUS LPS + H1 VFPS

$$x_{IP} = 1 - \frac{E'_p}{E_p}$$

- ❑ free of p-dissociation background
- ❑ x_{IP} and t-measurements
- ❑ access to high x_{IP} range (IP+IR)
- ❑ low geometrical acceptance

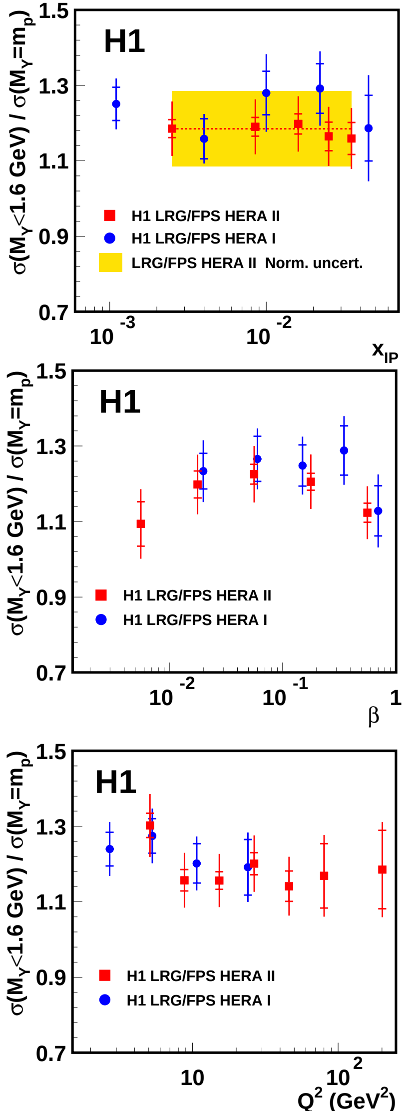
HERA-2:

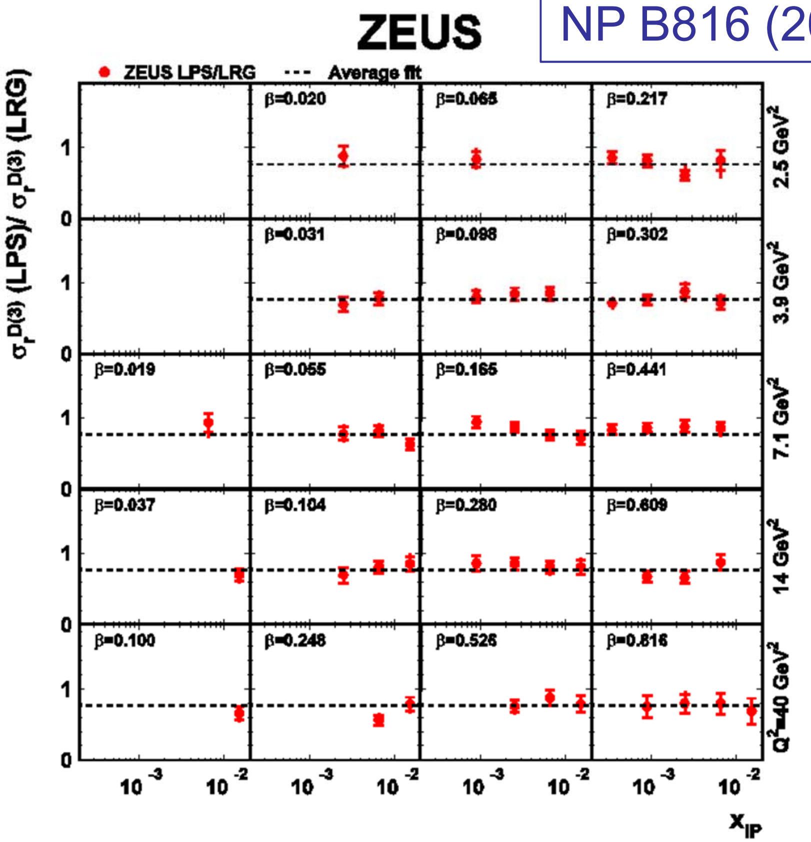
- ➢ H1 FPS detector upgrade

➔ 20 times higher statistics than collected at HERA-1

- ➢ H1 VFPS has high acceptance

Comparisons between Methods





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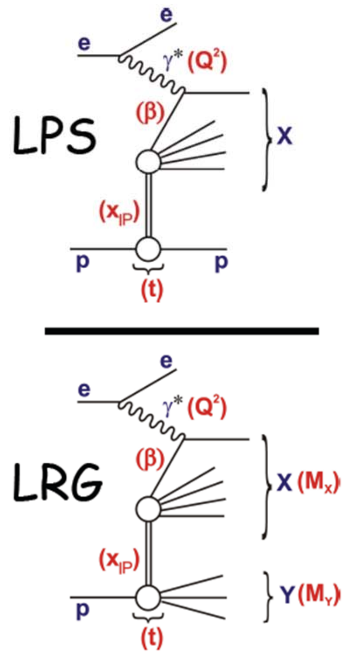

H1: $\sigma(M_Y<1.6\ \mathrm{GeV}) / \sigma(M_Y=M_p) = 1.20 \pm 0.11(\mathrm{exp.})$

- ➔ LRG data contain ~20% of p-diss contribution
- ➔ no significant dependence on Q^2, β, x_{IP}

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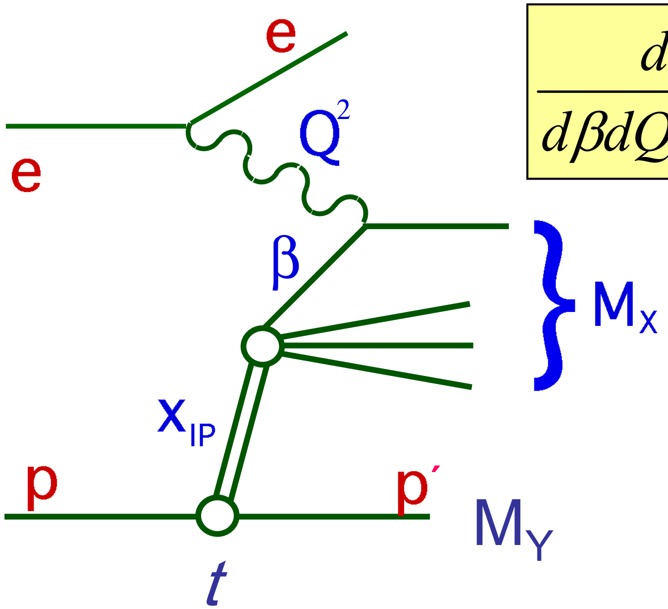
Diffractive Reduced Cross Section



$$\frac{d^4\sigma}{d\beta dQ^2 dx_{IP} dt} = \frac{4\pi\alpha^2}{\beta Q^4}(1 - y + \frac{y^2}{2})\sigma_r^{D(4)}(\beta, Q^2, x_{IP}, t)$$

Relation to F_2^D and F_L^D:

$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{2(1 - y + y^2/2)} F_L^{D(4)}$$

$$\boldsymbol{\sigma_r^D \approx F_2^D} \text{ at low and medium y}$$

$$\boldsymbol{\sigma_r^{D(3)} = \int \sigma_r^{D(4)} dt}$$

→ integrate over $|t|<1$ GeV² to compare PS results with LRG and diffractive PDF predictions

- F_2 directly related to quark density in proton
- $dF_2/d\ln Q^2$ (scaling violations) sensitive to gluon density

- F_L only non-zero in higher order QCD – independent access to gluon density

Factorisation in Diffractive DIS

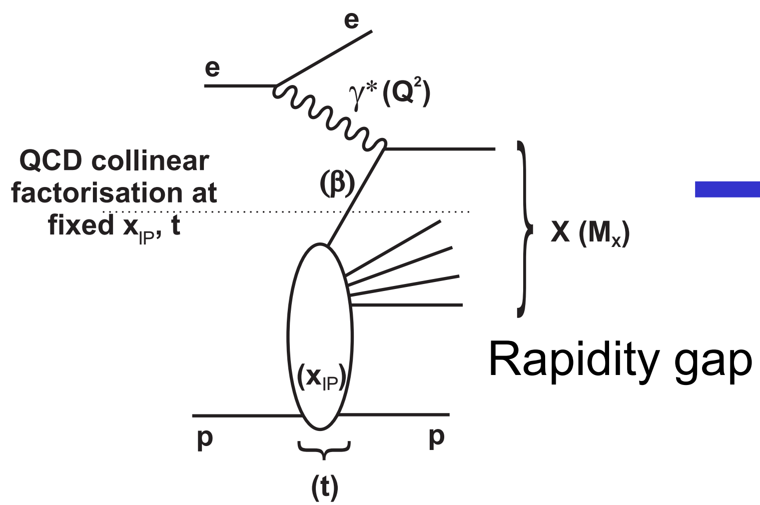
QCD hard scattering collinear factorisation:

$$\sigma^D(\gamma^* p \rightarrow Xp) = \sum_{parton\_i} f_i^D(x,Q^2,x_{IP},t)\cdot\sigma^{\gamma^* i}(x,Q^2)$$

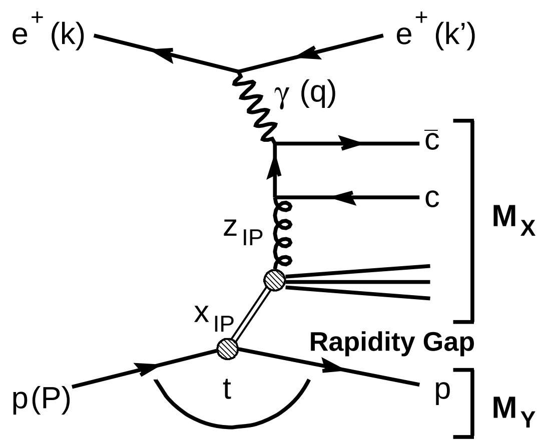
$\sigma^{\gamma^* i}$ - universal hard scattering cross section (same as in inclusive DIS)

f_i^D - Diffractive Parton Distribution Function ➔ obey DGLAP,
universal for diffractive *ep* DIS (inclusive, Dijets, Charm)

❑ Extract DPDFs from QCD fit to inclusive diffractive DIS



❑ Test DPDFs in diffractive Final States (Boson Gluon Fusion)



Factorisation in Diffractive DIS

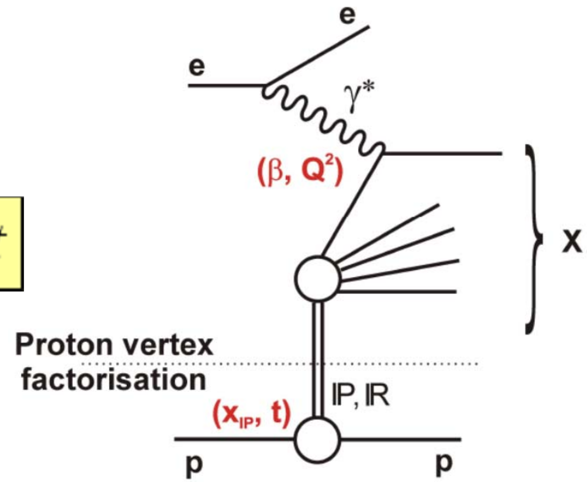
Assumption of proton vertex factorisation for leading $I\!P$ and sub-leading $I\!R$ exchanges ➔ hard scattering is independent of x_{IP} and t

$$F_2^{D(4)}(\beta, Q^2, x_{IP}, t) = f_{IP}(x_{IP}, t) \cdot F_2^{IP}(\beta, Q^2) + n_{IR} \cdot f_{IR}(x_{IP}, t) \cdot F_2^{IR}(\beta, Q^2)$$

- x_{IP} and t dependences are described by Regge motivated $I\!P$ and $I\!R$ fluxes:

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

$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha_{IP}' t$$



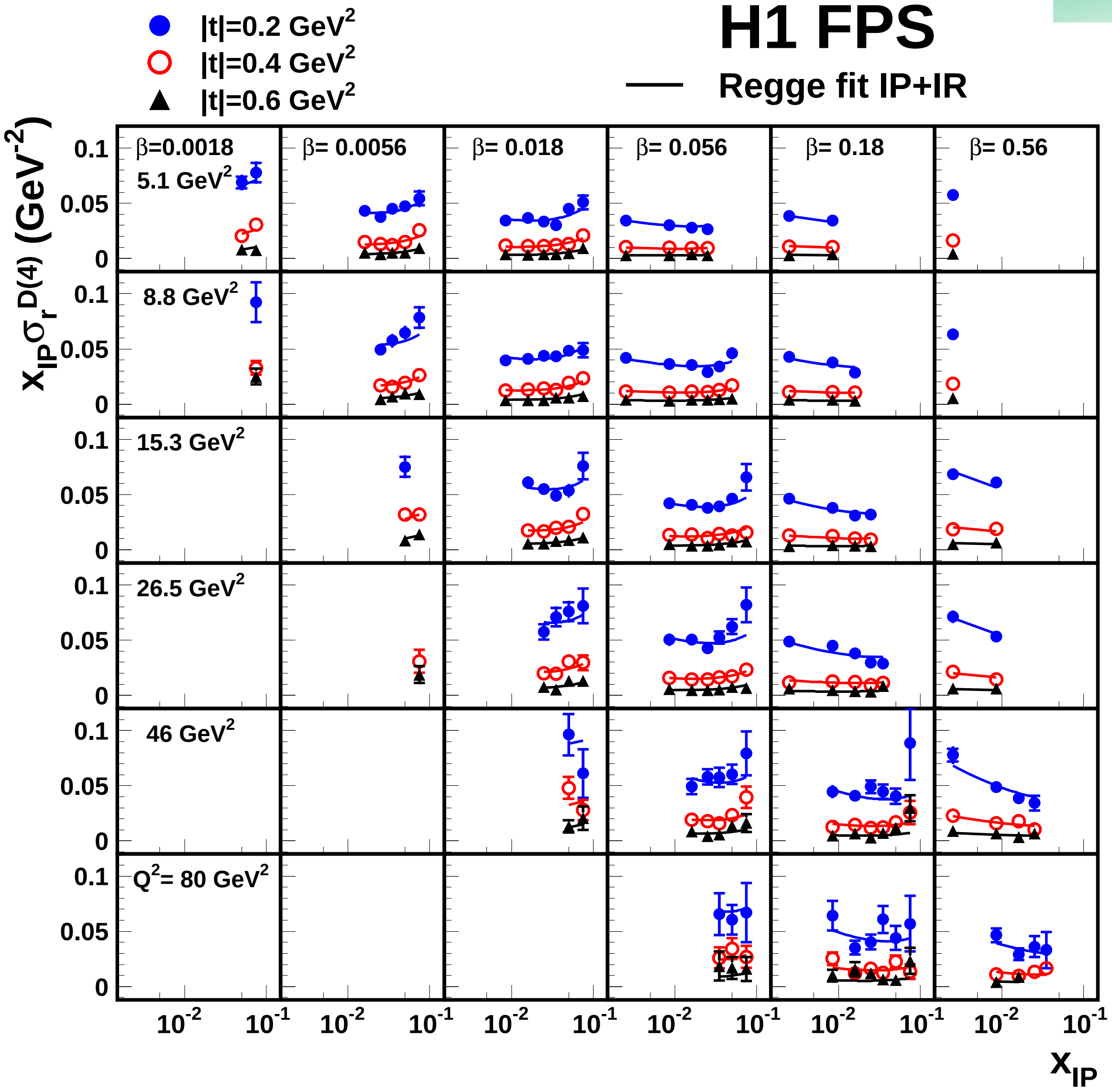
- Dominance of $I\!P$ trajectory with $\alpha_{IP}>1$ at $x_{IP}<0.01$ and contribution of sub-leading $I\!R$ trajectory with $\alpha_{IR}<1$ at higher x_{IP}

$$\frac{d\sigma}{dt} \sim \exp B|t|$$

- Shrinkage of exp t-slope with $\ln(1/x_{IP})$ ➔

$$B = B_{IP} + 2\alpha'_{IP} \ln(1/x_{IP})$$

➔ Perform 'Regge' fits to diffractive data to extract parameters of $I\!P$ flux



$x_{IP}\sigma_r^{D(4)}(\beta,Q^2,x_{IP},t)$

Q^2
5
9
15
26
46
80
GeV^2

New H1 FPS HERA-2 $\sigma_r^{D(4)}$ data:

- $5 < Q^2 < 80$ GeV^2
- luminosity 156 pb^{-1}
- 20 times higher statistics than in HERA-1 data
- norm. uncertainty ~4.3% → smaller than in HERA-1

x_{IP}-dependence in (Q^2,β,t) bins

➔ IP and IR contributions

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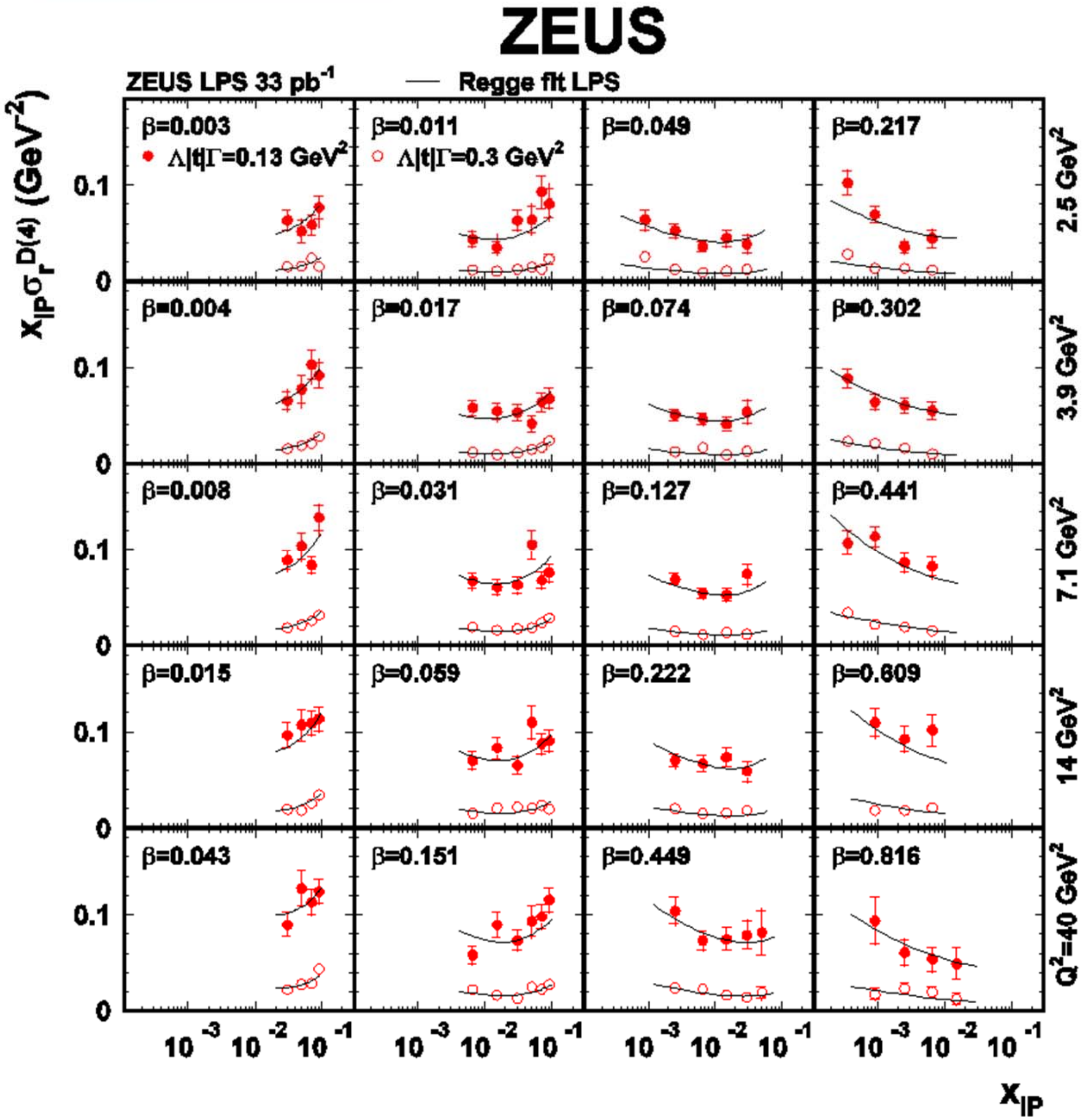
ZEUS LPS: $x_{IP}\sigma_r^{D(4)}$



ZEUS LPS $|t|=0.13$ GeV^2

ZEUS LPS $|t|=0.3$ GeV^2

– Regge fit IP+IR

- luminosity 32.6 pb^{-1}
- norm. uncertainty of ZEUS LPS $\sigma_r^{D(4)}$ data is 7%

x_{IP}-dependence in (β,Q^2,t) bins

➔ IP and IR contributions

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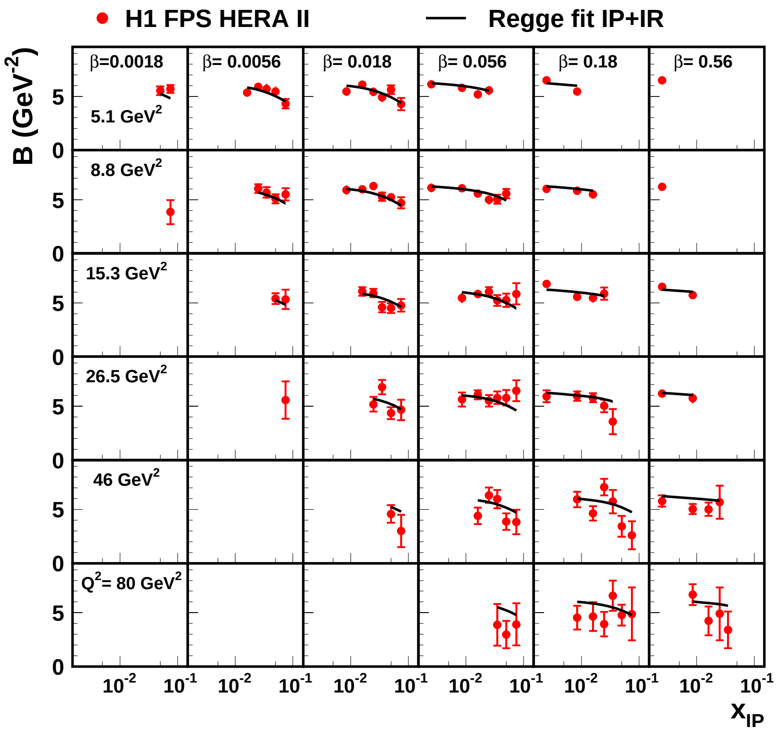
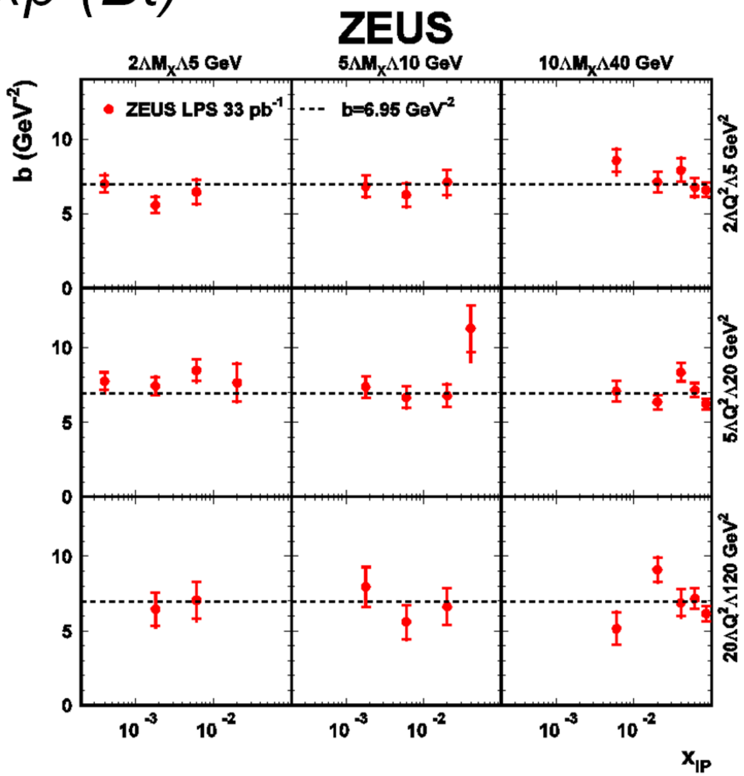
t-slope as a function of Q^2, β, M_x, x_{IP}

$$d\sigma/dt \sim exp\ (Bt)$$



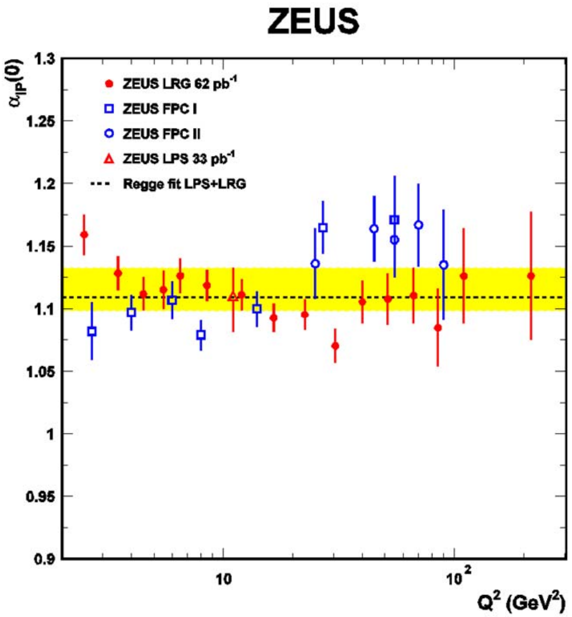


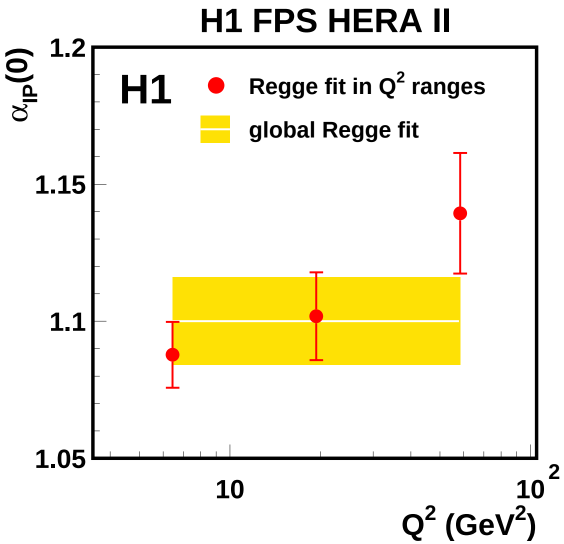
H1 FPS: IR contribution at large x_{IP}

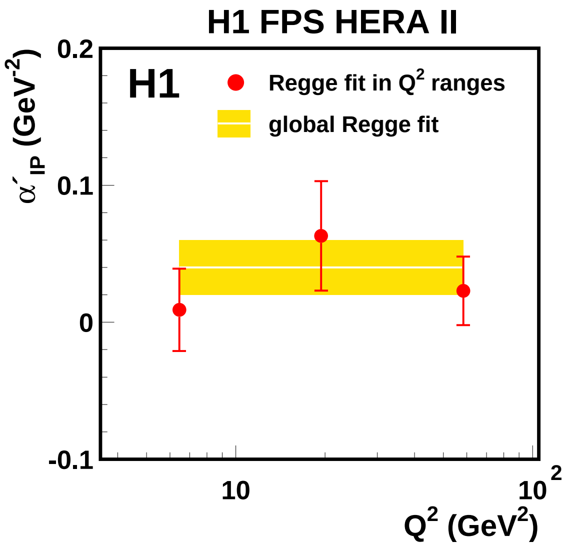
ZEUS LPS: no strong effect from IR contribution

H1 and ZEUS: *t*-slope does not change with β, M_x or Q^2 at fixed x_{IP}
➔ data consistent with proton vertex factorisation

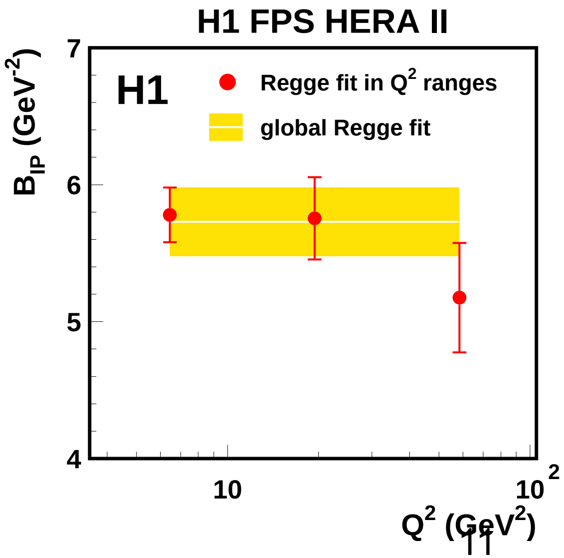
Proton Vertex Factorisation







- ➔ $\alpha_{IP}(0) \simeq 1.10$ in agreement with α_{IP}(soft)~1.08
- ➔ $\alpha'_{IP} \simeq 0 \rightarrow$ no "shrinkage" < α'_{IP}(soft)~0.25 GeV^{-2}
- ➔ B_{IP} consistent with hard process

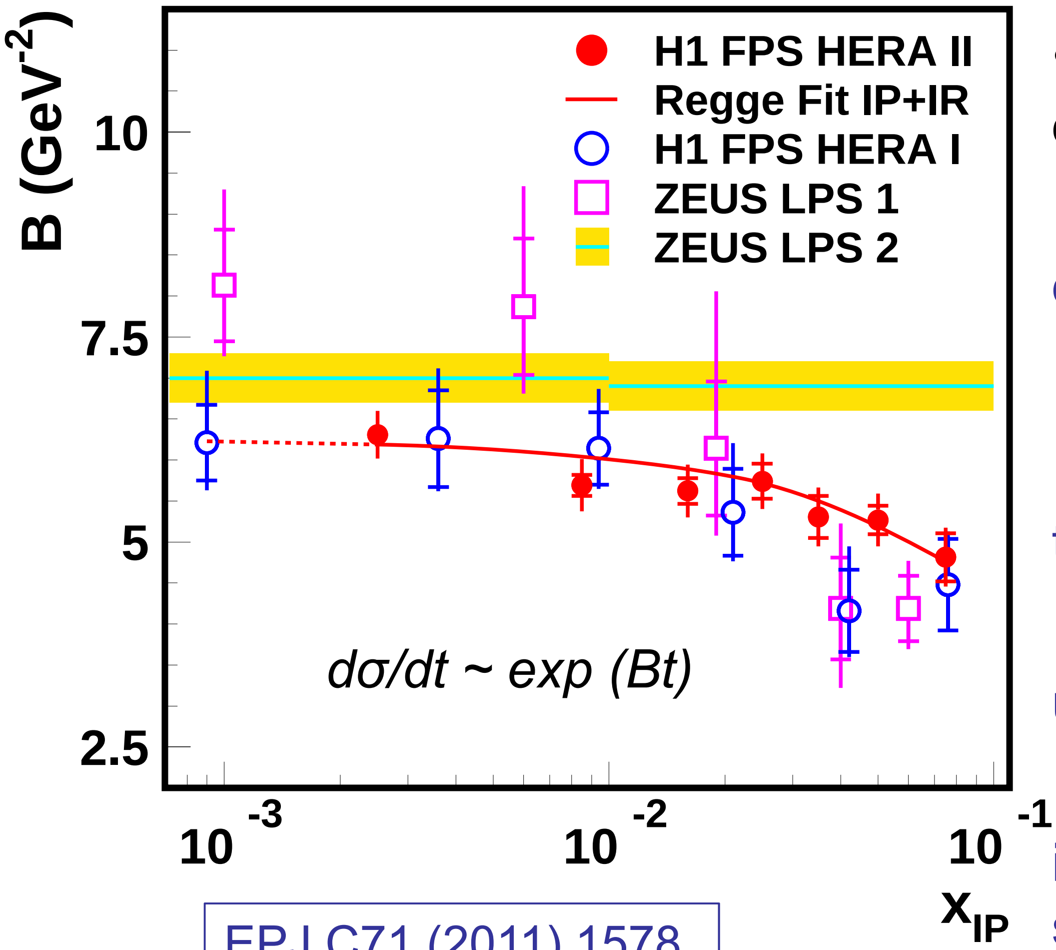


- ➔ no strong dependence of $\alpha_{IP}(0)$, α'_{IP}, B_{IP} on Q^2

- ➔ H1 and ZEUS results are consistent with proton vertex factorisation within uncertainties

t-slope as a function of x_{IP}

H1 Regge fit result: $B(x_{IP}) = f_{IP}(x_{IP}) \cdot B_{IP}(x_{IP}) + f_{IR}(x_{IP}) \cdot B_{IR}(x_{IP})$



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- x_{IP}-dependence of t-slope, data averaged over Q^2 and β

➔H1 FPS HERA-1 and HERA-2 data are consistent, B~5-6 GeV^{-2}

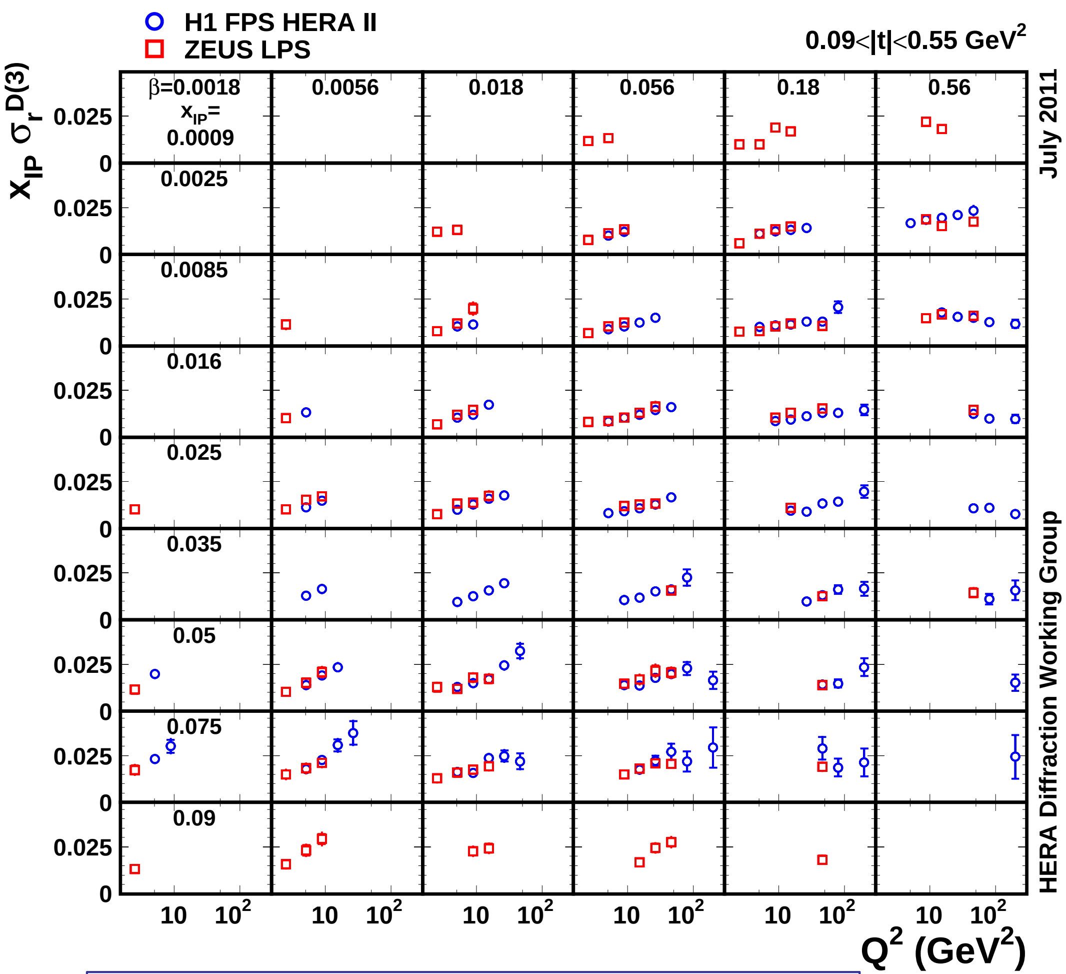
➔IR contribution at high x_{IP}

➔ZEUS LPS2 measures higher t-slope: B ~ 7 GeV^{-2}

➔ are H1 / ZEUS uncertainties underestimated ?

➔ H1 VFPS will provide an independent measurement of t-slope in x_{IP} range 0.009-0.026

$\sigma_r^{D(3)}$: H1 FPS vs ZEUS LPS



H1 prel-11-111, ZEUS prel-11-011

Proton Spectrometer data in $0.09<|t|<0.55 GeV^2$

Q^2-dependence in (β, x_{IP}) bins

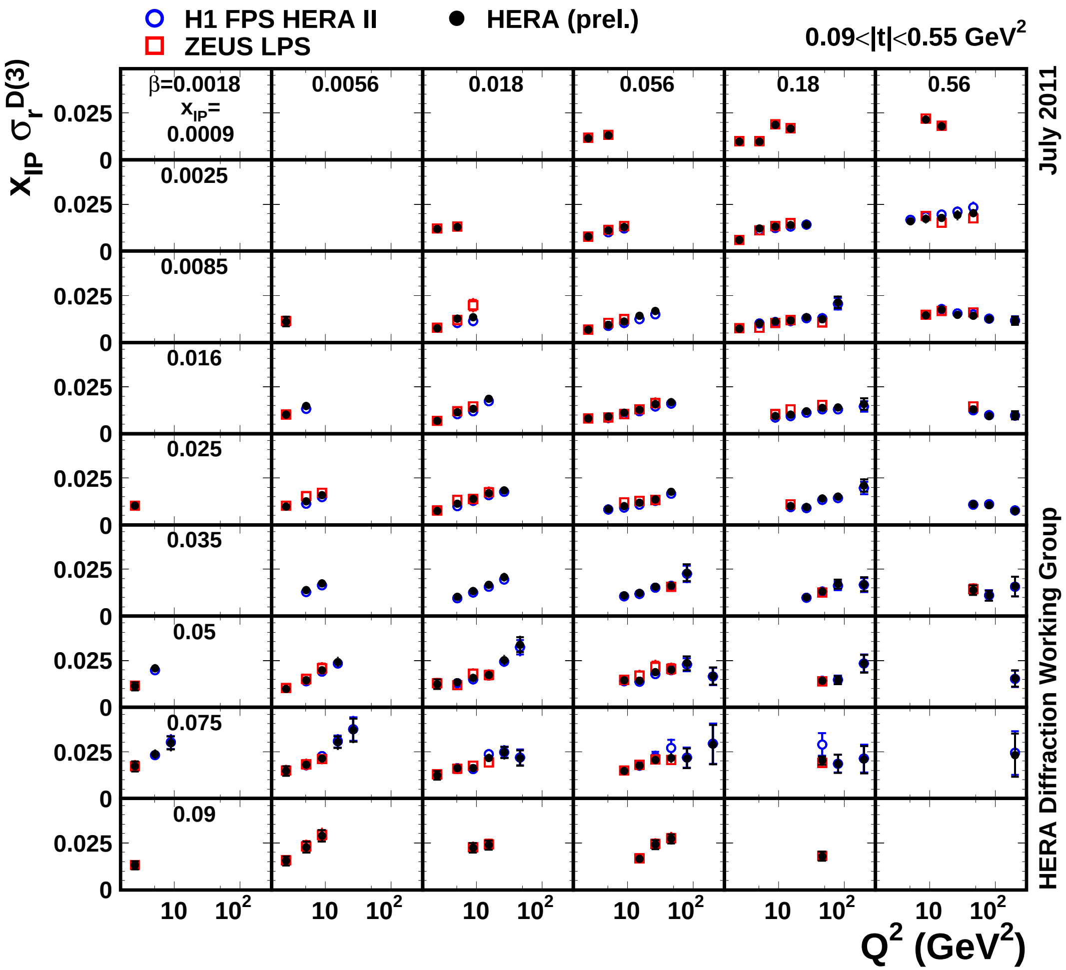
- H1 FPS norm. uncertainty 4.5%, ZEUS LPS norm. uncertainty 7%

H1 / ZEUS: = 0.91 +/- 0.01(stat.) +/- 0.03(syst.) +/- 0.08(norm.)

➔ Reasonable agreement of H1 FPS HERA-2 and ZEUS LPS data in shape & normalisation

➔ Combine H1 and ZEUS cross sections to extend phase space and reduce uncertainties

$\sigma_r^{D(3)}$: H1 FPS vs ZEUS LPS



First combination of H1 and ZEUS diffractive data

➔Combined results from proton spectrometers

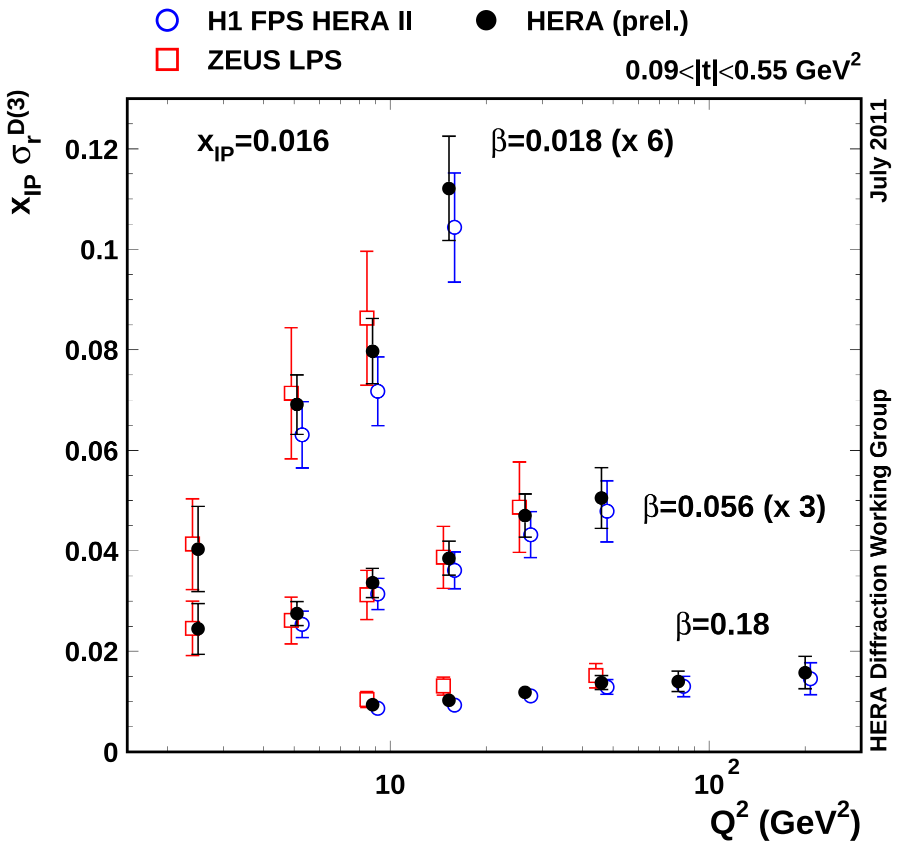
➔Consistency between data sets

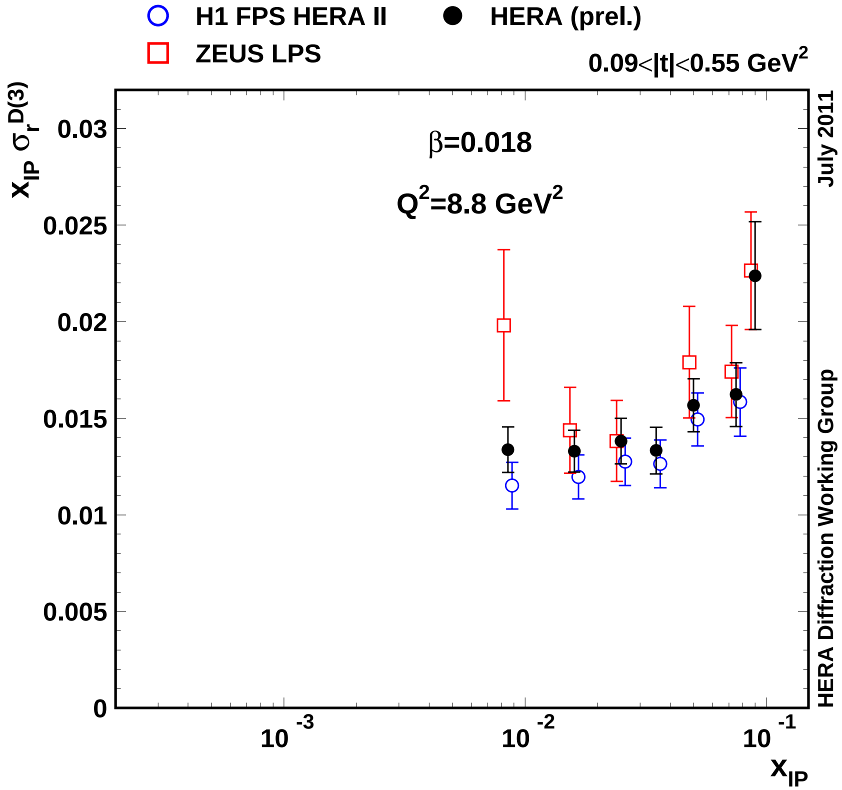
➔Combination method uses iterative χ^2 minimization and include full error correlations [A.Glazov]

➔ Two experiments calibrate each other resulting in reduction of systematic uncertainties

$\sigma_r^{D(3)}$: H1 FPS vs ZEUS LPS

- A detailed look to the combined data





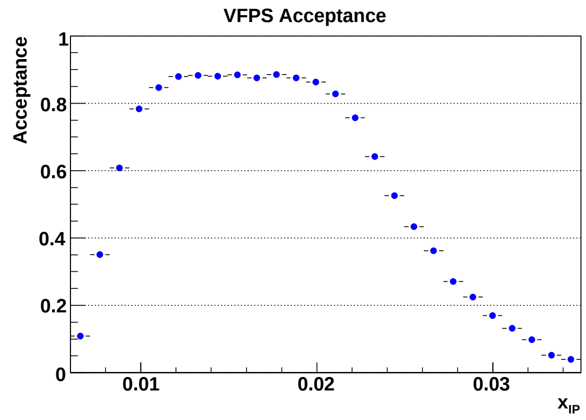
➔ combined data have ~20% smaller uncertainties with respect to H1 data

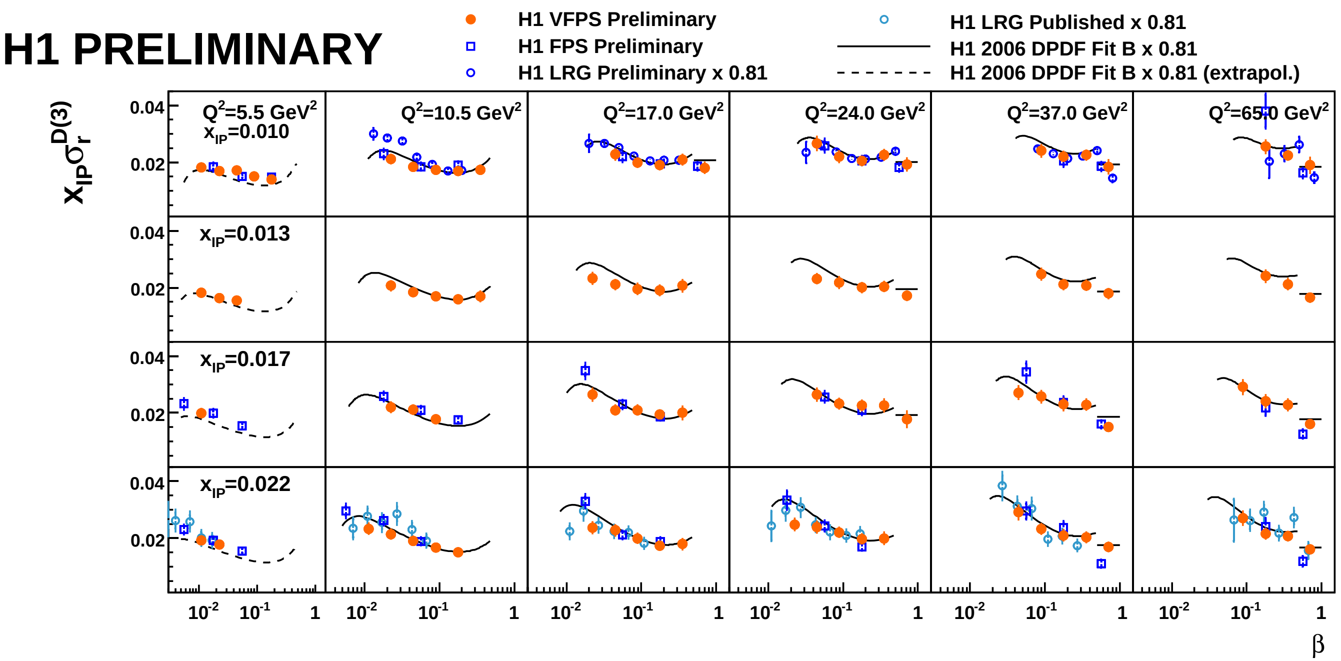
$\sigma_r^{D(3)}$: VFPS vs FPS vs LRG

H1 VFPS has high acceptance in range $0.009<x_{IP}<0.026$, $|t|<0.5$ GeV^2

➔ allows a high precision measurement over this x_{IP} range

➔ VFPS t-slope and $\sigma_r^{D(4)}$ measurements are on the way

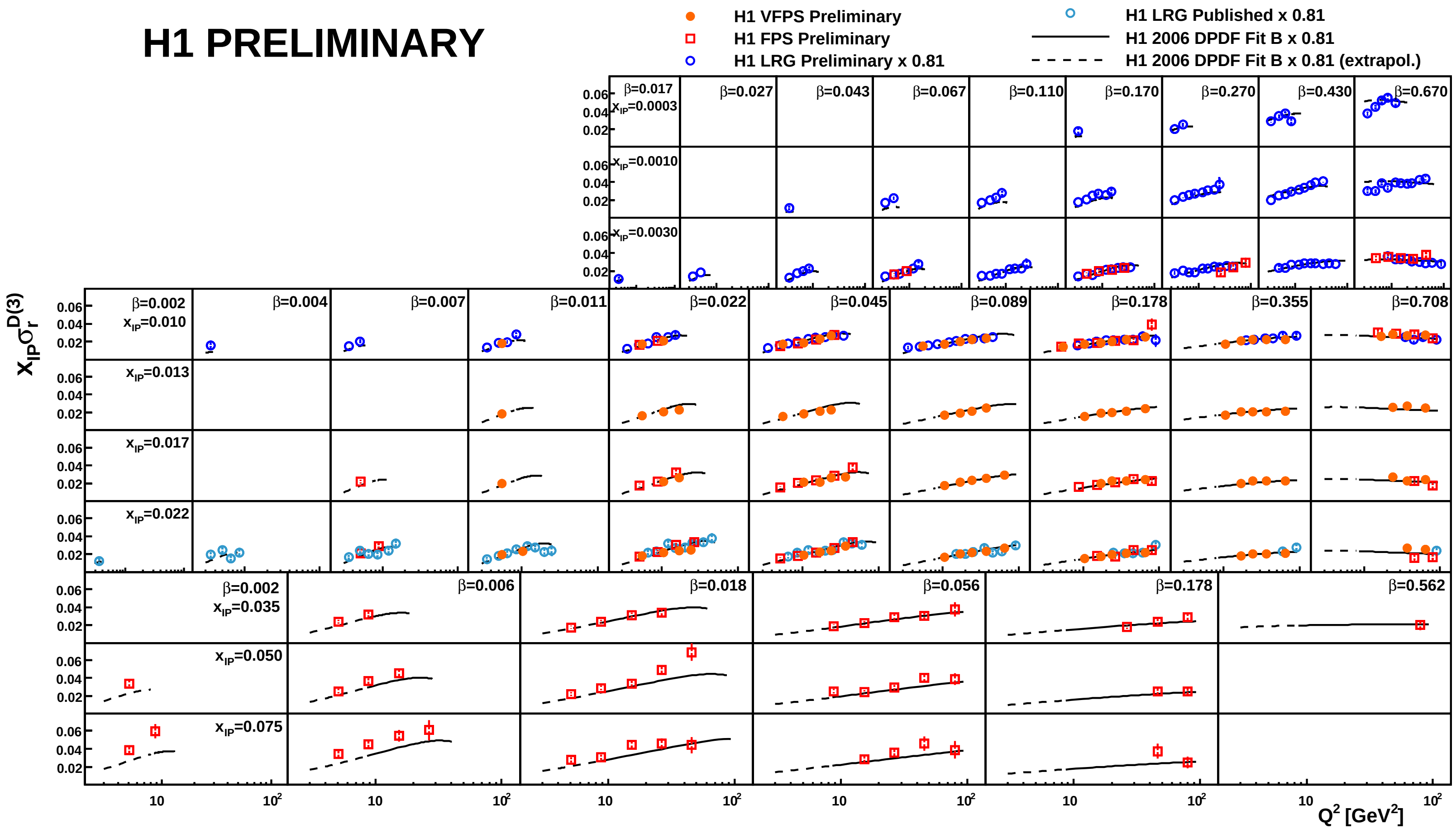




$\sigma_r^{D(3)}$ for $|t|<1$ GeV^2

H1 prel-10-014

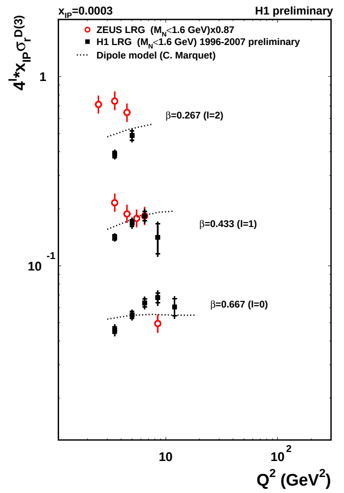
$\sigma_r^{D(3)}$: VFPS vs FPS vs LRG

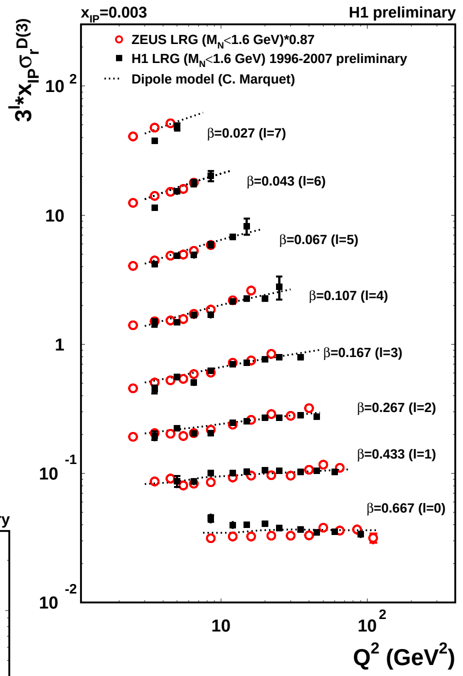


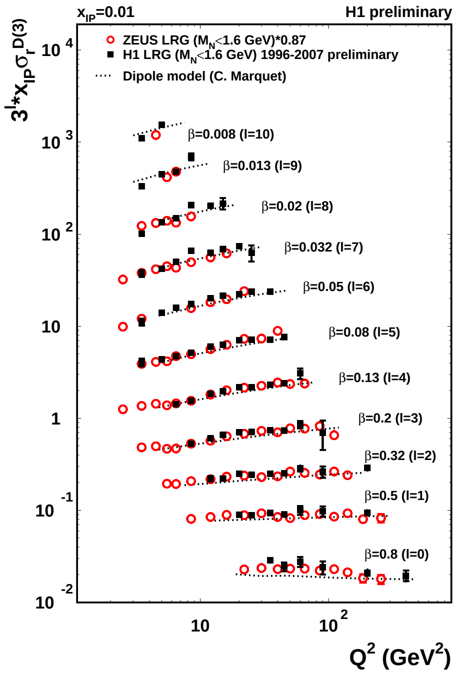
➔ compilation of VFPS, FPS and LRG data vs H1 DPDF Fit B

$$\frac{\text{VFPS}}{\text{FPS}} = 0.96 \pm 0.02(\text{stat.}) \pm 0.11(\text{syst.}) \pm 0.08(\text{norm.})$$

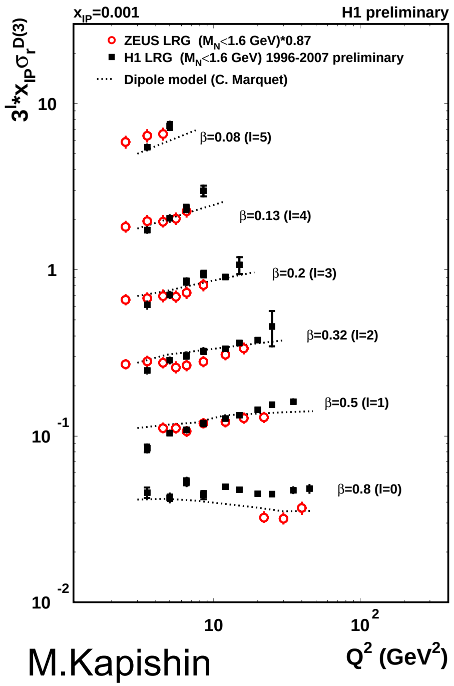
LRG $\sigma_r^{D(3)}$: H1 vs ZEUS







H1 prel-10-011



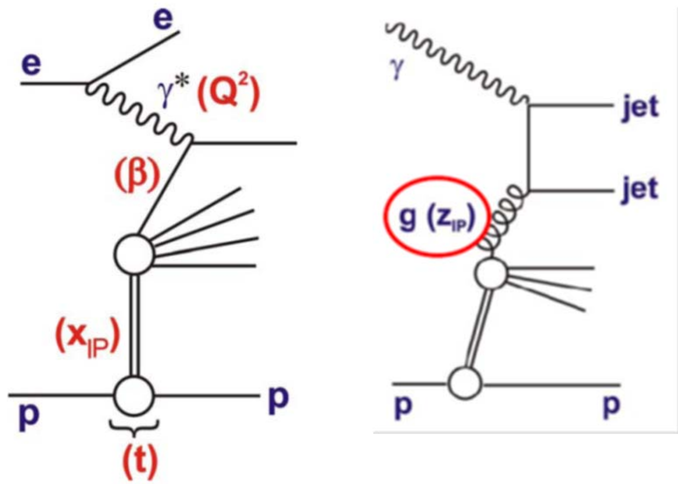
➔ combined 370 pb^{-1} of H1 LRG (HERA-1 and HERA-2) and 62 pb^{-1} of ZEUS LRG (HERA-1)

➔data are in general agreement, normalization difference of 13% is within quoted uncertainties

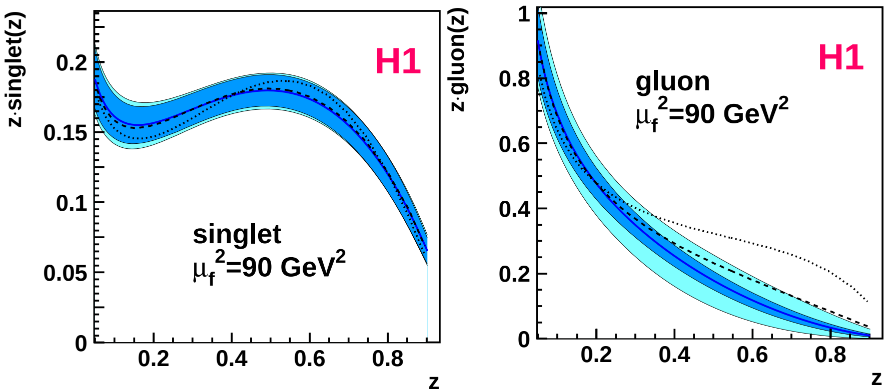
➔detailed quantitative comparison shows differences at low and high β

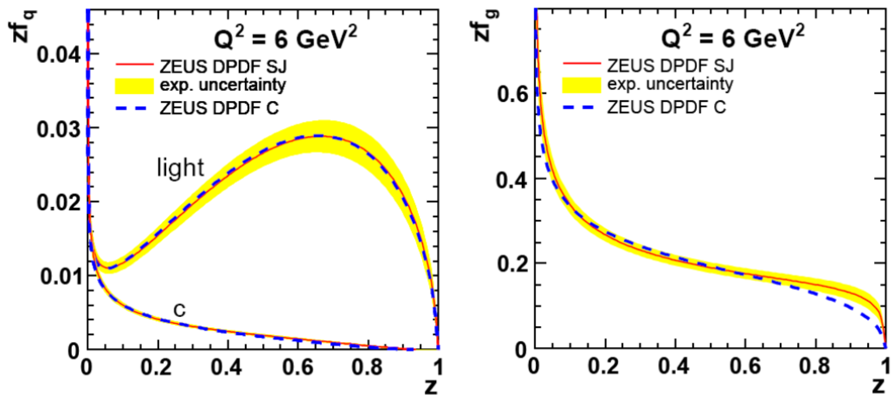
Diffractive PDFs: H1 vs ZEUS

- Fit β and Q^2 dependences at fixed x_{IP}
- Parameterize quark singlet and gluon PDFs at starting scale Q_0 and evolve with Q^2 using NLO DGLAP
- Proton vertex factorisation assumption to fit data from different x_{IP} with complementary β,Q^2 coverage



- Inclusive diffractive DIS cross sections constrain quark singlet and gluon (via scaling violations); Dijet DIS cross sections constrain high z gluon





JHEP: 0710:042 (2007)

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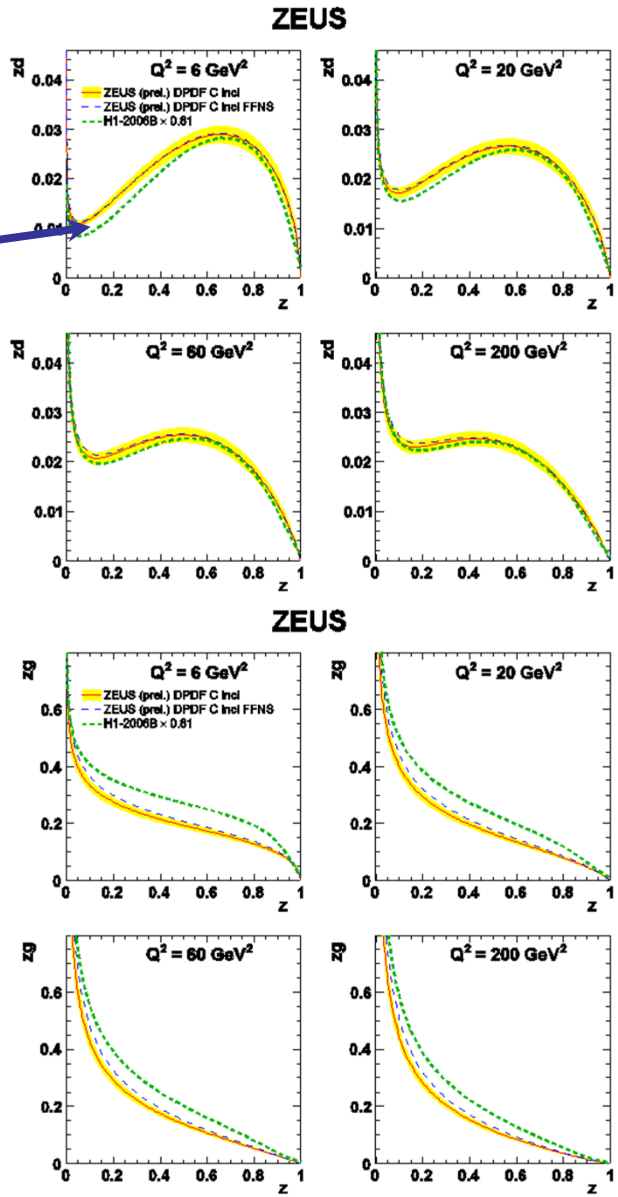
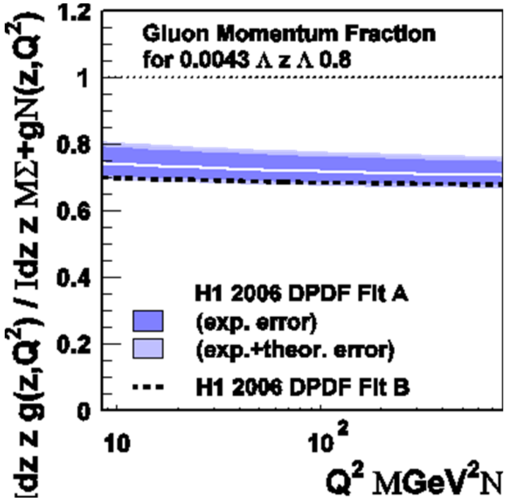
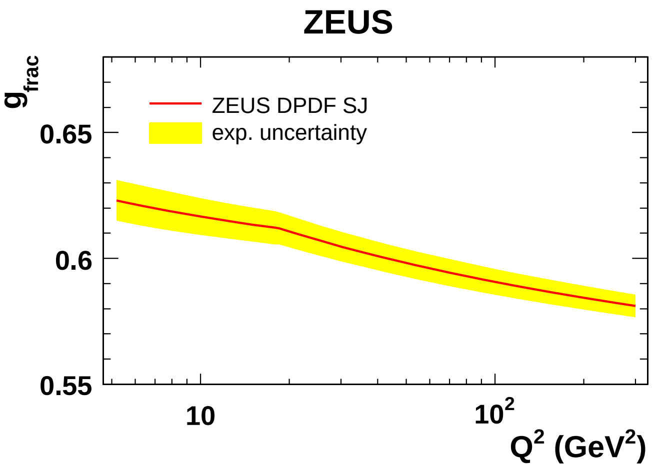
Diffractive PDFs: H1 vs ZEUS

• Recent ZEUS DPDF fits to inclusive LRG & LPS & diffractive Dijet DIS consistent with previous H1 DPDF fits up to normalization factor in data







• Overall ratio of gluon to quark density is 70:30 (H1) or 60:40 (ZEUS) ➔ similar to inclusive PDFs at low x

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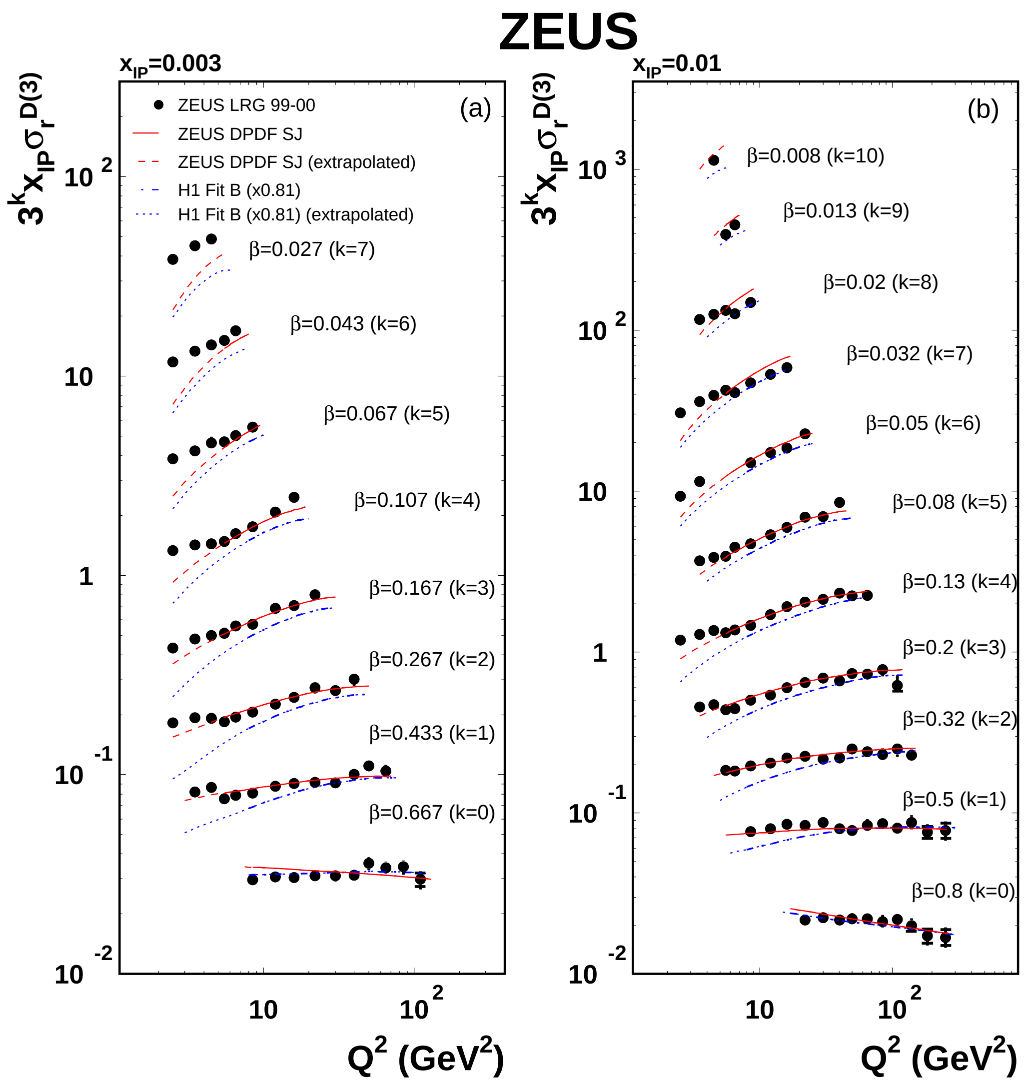
Diffractive PDFs: H1 vs ZEUS



➔H1 DPDF Fit B and ZEUS DPDF Fit SJ predict somewhat different behavior at low Q^2

➔ fits reflect difference in normalization of H1 and ZEUS LRG data

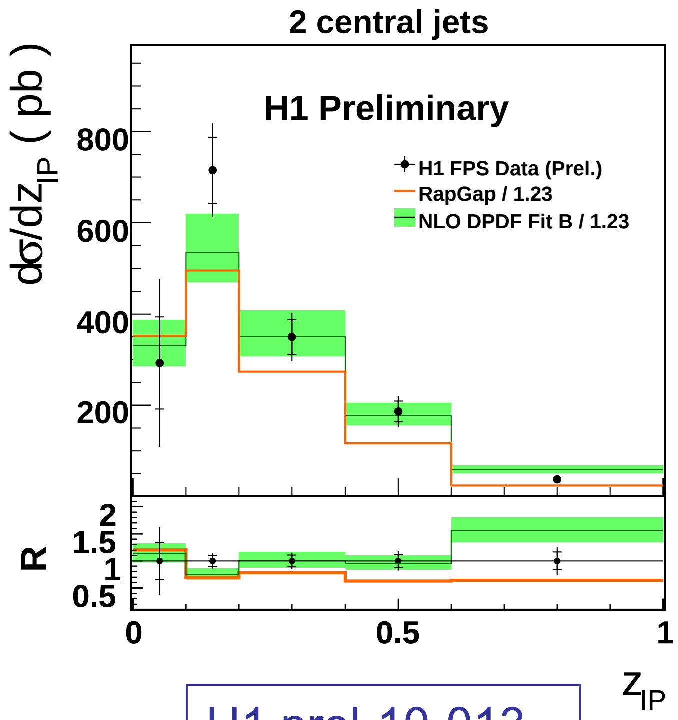
➔ need to understand differences in H1 and ZEUS LRG data sets to combine them and perform a QCD fit

➔ most of H1 LRG data (1999-2000 HERA-1 and HERA-2) are still preliminary

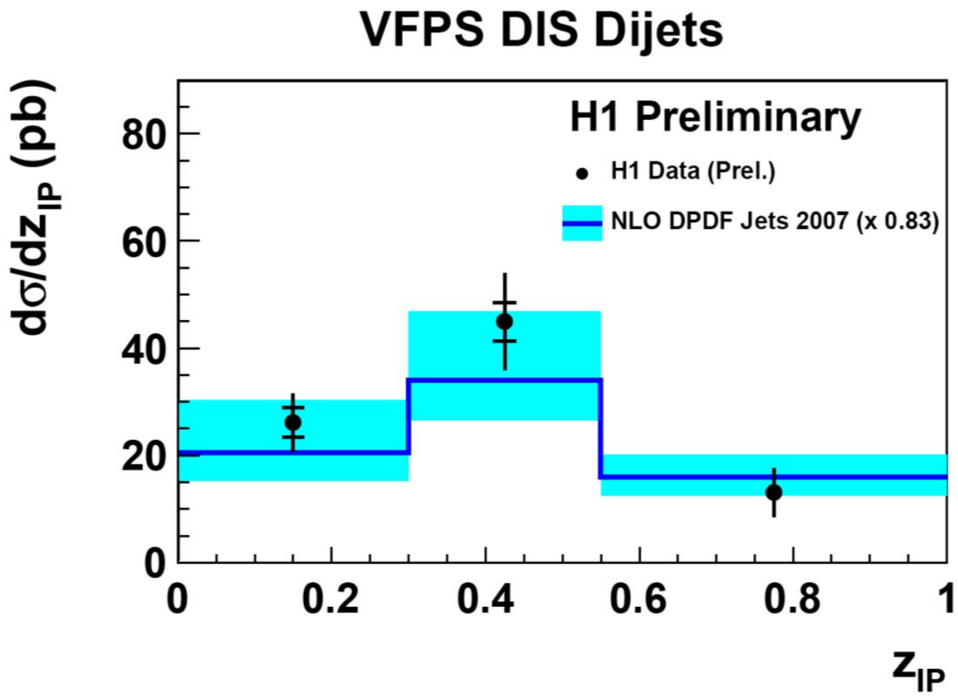
Central Jets in DDIS with tagged proton

FPS: x_{IP}<0.1, p^*_{T1}>5GeV, p^*_{T1}>4GeV, -1<η_{lab}<2.5

VFPS: 0.009<x_{IP}<0.024, p^*_{T1}>5.5GeV, p^*_{T1}>4GeV, -3<η^*<0



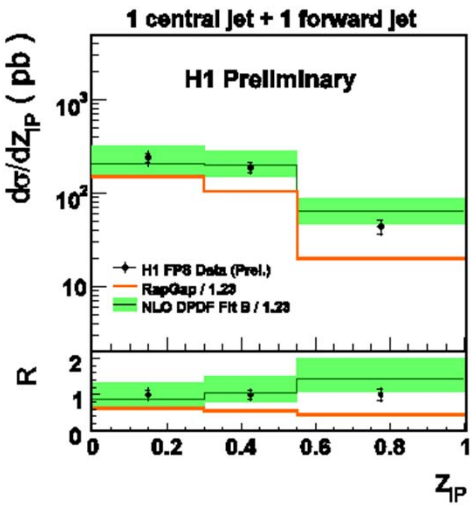
H1 prel-10-013



H1 prel-11-013

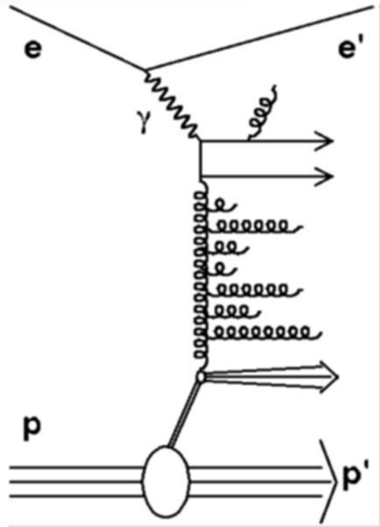
➔NLO predictions based on DPDFs H1 Jets an H1 Fit B describe central dijet production in DIS with tagged leading proton

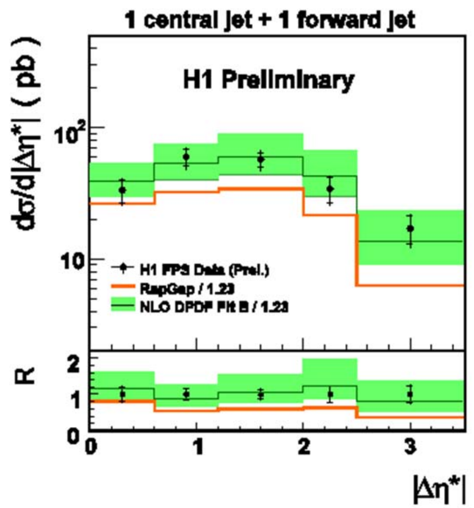
Forward Jets in DDIS with tagged proton



New H1 analysis of Dijet production in DIS with leading proton tagged in FPS:

Forward jet: $p^*_T > 4.5$GeV, $1 < \eta_{fwd} < 2.8$
Central jet: : $p^*_T > 3.5$GeV, $-1 < \eta_{cen} < \eta_{fwd}$



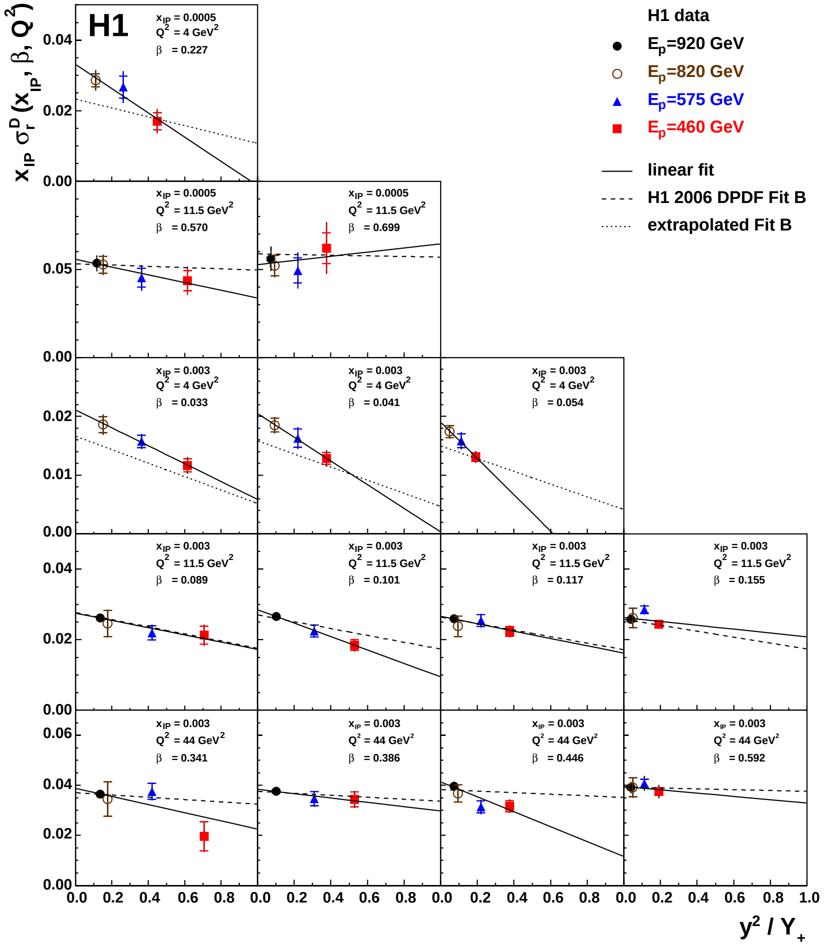


➔extended x_{IP} and η range compared to LRG dijet DIS data

➔dijet selection with DGLAP p_t ordering broken

➔no evidence for configurations beyond DGLAP & DPDF predictions

Linear fits to extract F_L^D



$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{2(1-y+y^2/2)} F_L^{D(4)}$$

➔ measure σ_r^D at fixed Q^2, x_{IP}, β, but different y using LRG data at different proton beam energies

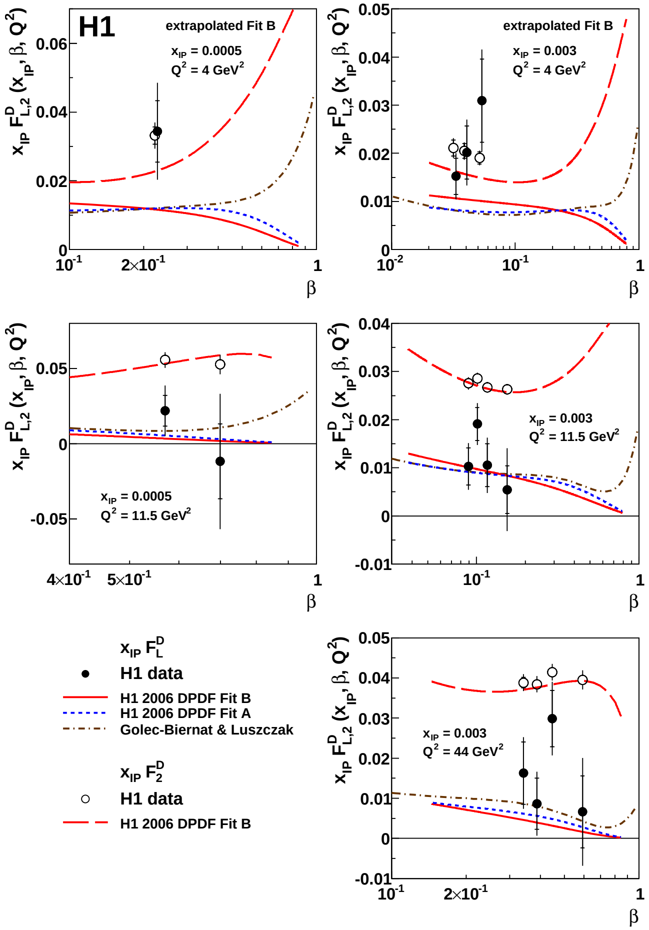
➔perform linear fits to extract F_L^D

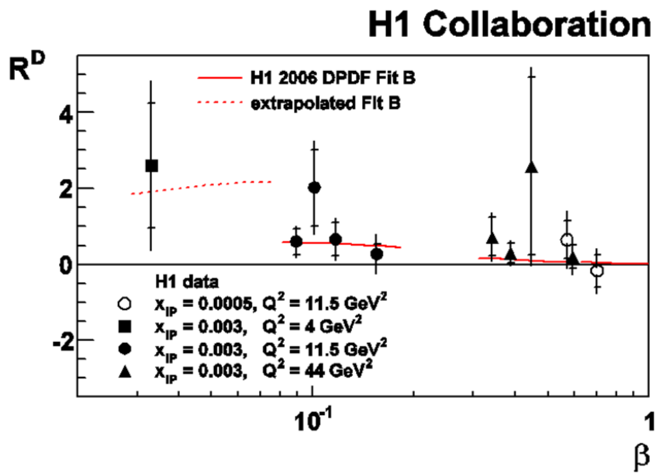
➔ analysis published for full range $Q^2 > 2.5$ GeV^2

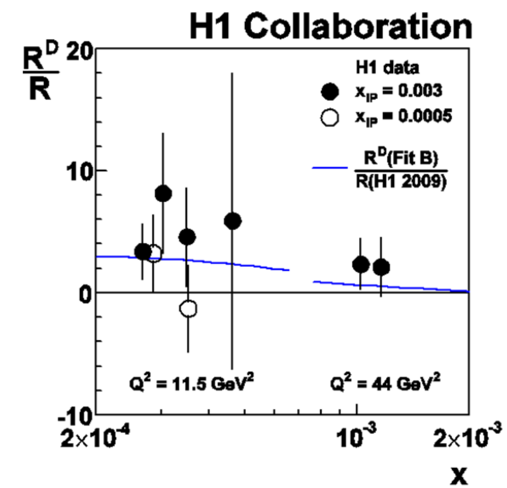
arXiv:1107.3420

F_2^D and F_L^D structure functions

$R = \sigma_L / \sigma_T \rightarrow F_L^D / (F_2^D - F_L^D)$







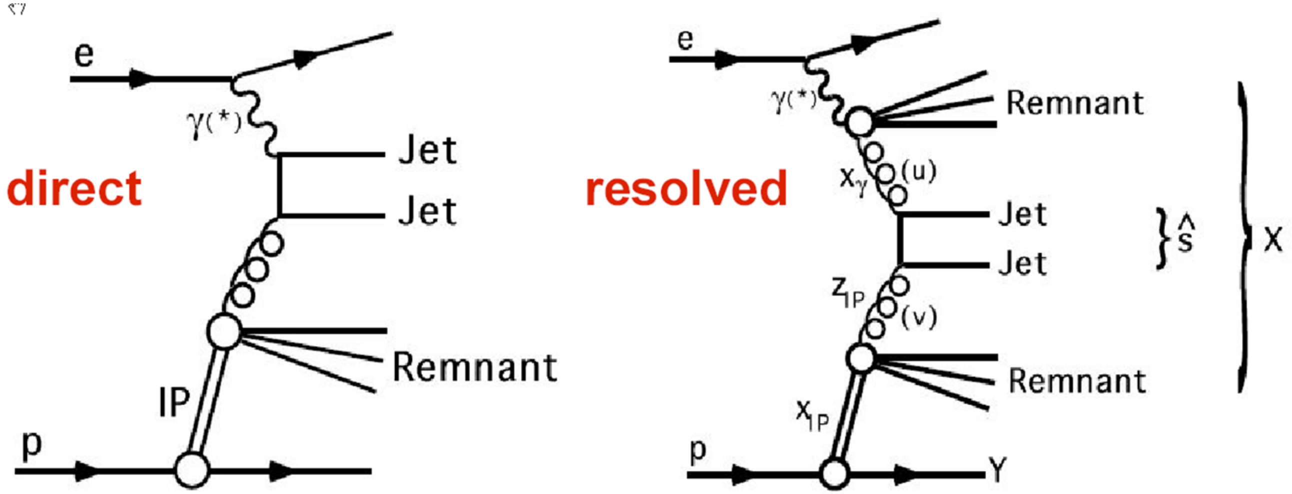
- F_2^D and F_L^D extracted in bins of Q^2, x_{IP} and β

➔ F_2^D and F_L^D data agree with H1 DPDF Fits

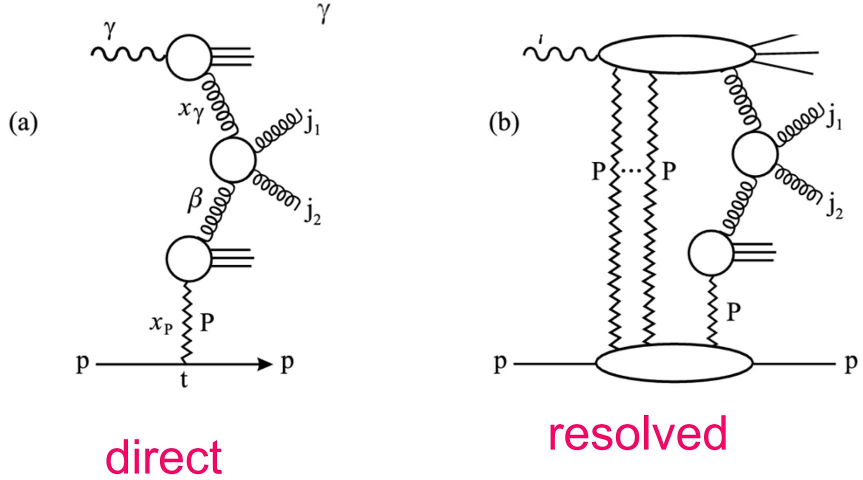
- Ratio of R^D to R(incl DIS) ➔ longitudinal component is larger in diffraction

Test of Factorisation: Dijet Photo-production

small point-like photon　　　large hadron-like photon



$x_\gamma = 1$　　　$x_\gamma < 1$



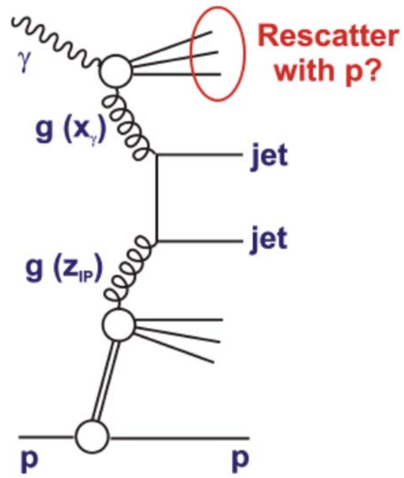
- Q²~0, hard scale → E_t^{jet} process sensitive to gluon density
- Factorisation in Dijet PhP expected to be valid in direct photo-production but broken in resolved photo-production (secondary re-scattering, multi-pomeron exchanges)

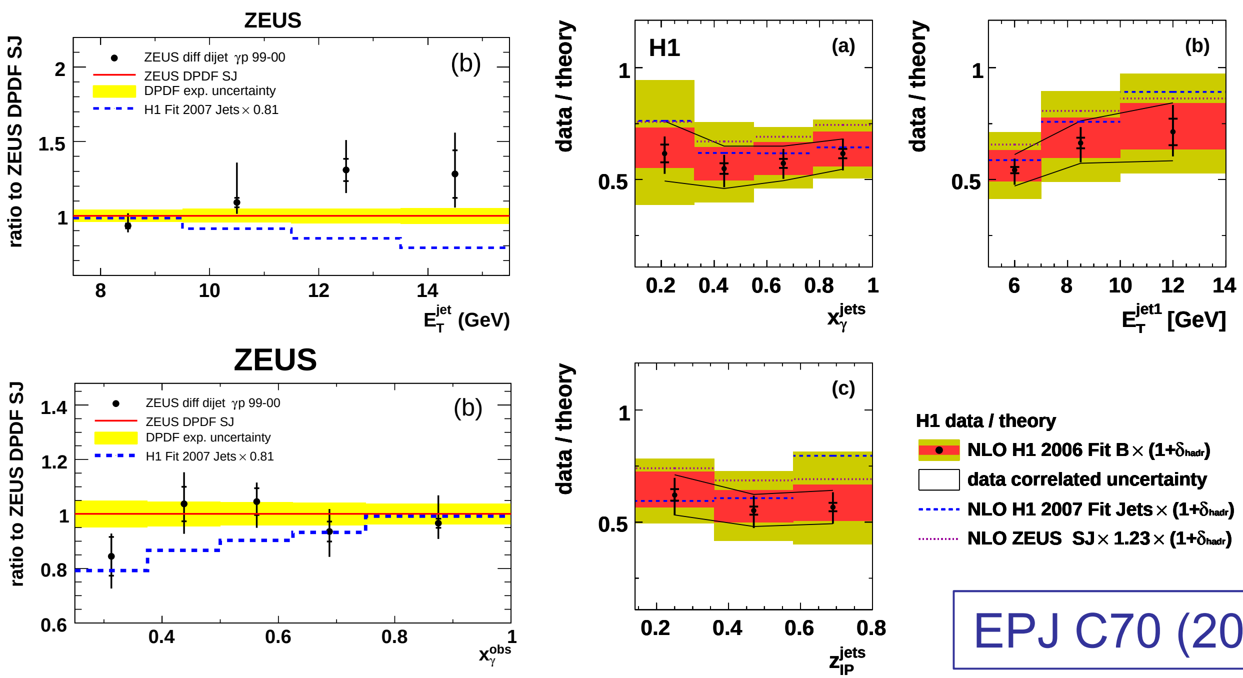
Diffractive Dijet Photo-production

Gap survival probability:

- ZEUS (E_T>7.5 GeV) : no evidence for gap distraction
- H1 (E_T>5 GeV): survival probability < 1 at 2σ,
  ➔ QCD factorisation breaking

$$\sigma(\text{H1 data}) / \sigma(\text{NLO}) = 0.58 \pm 0.12\ (\text{exp.}) \pm 0.14\ (\text{scale}) \pm 0.09\ (\text{DPDF})$$





- gap survival has little dependence on x_γ
- hint of dependence on jet E_T

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Summary

• HERA continue to provide unique diffractive DIS data sensitive to structure of color singlet exchange.

- Agreement in detail between different analysis methods
- Proton vertex factorisation is a good model for diffractive DIS at HERA
- First combination of H1 and ZEUS diffractive data with tagged proton give consistent results
- High statistics H1 and ZEUS LRG data are in general agreement but require detailed combination
- Diffractive PDFs are constrained in QCD fits and tested
- F_L^D structure function is measured by H1
- H1 and ZEUS results for gap survival in diffractive dijet photo-production are not conclusive

Backup slides

Regge fit

- Assume proton vertex factorisation for IP and IR

$$F_2^{D(4)}(\beta,Q^2,x_{IP},t) = f_{IP}(x_{IP},t)\cdot F_2^{IP}(\beta,Q^2) + n_{IR}\cdot f_{IR}(x_{IP},t)\cdot F_2^{IR}(\beta,Q^2)$$

- Parameterization of x_{IP} and t dependences for IP and IR:

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

$$\frac{d\sigma}{dt} \sim \exp B|t|$$

$$\alpha_{IP}(t)=\alpha_{IP}(0)+\alpha_{IP}'t$$

$$B=B_{IP}+2\alpha'_{IP}\ln(1/x_{IP})$$

- Fixed parameters for IR (as in H1 DPDF Fits): $\alpha_{IR}(0)=0.5$, $\alpha'_{IR}=0.3$ GeV^{-2}, $B_{IR}=1.6$ GeV^{-2}, $F_2^{IR}(\beta,Q^2)$ – π structure function, F_L^D contribution corrected using H1 2006 DPDF fit B

- Free parameters: $\alpha_{IP}(0)$, α'_{IP}, B_{IP}, n_{IR} and IP normalization $F_2^{IP}(\beta,Q^2)$ in every (β,Q^2) bin

Results of Regge fits

New H1 FPS HERA-2 result:

$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha_{IP}'t$

$B = B_{IP} + 2\alpha'_{IP}\ln(1/x_{IP})$

$\alpha_{IP}(0) = 1.10 \quad 0.02\ (exp.) \quad 0.03\ (model)$

$\alpha'_{IP} = 0.04 \quad 0.02\ (exp.) \quad {}^{0.08}_{0.60}\ (model)\ GeV^{-2}$

$B_{IP} = 5.73 \quad 0.25\ (exp.) \quad {}^{0.80}_{0.90}\ (model)\ GeV^{-2}$

- ➔ $\alpha_{IP}(0) \simeq \alpha_{IP}$ (soft)~1.08
- ➔ $\alpha'_{IP} \simeq 0 \rightarrow$ no "shrinkage" (α'_{IP}(soft)~0.25 GeV^{-2})
- ➔ B_{IP} consistent with hard process

Compare with published HERA results:

H1 FPS HERA-1 parameterization:

$\alpha_{IP}(0) = 1.114 \pm 0.022(\text{exp.}) \pm^{0.040}_{0.020}(\text{model})$

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

$B_{IP} = 5.5^{-2,0}_{+0.7}\ \text{GeV}^{-2}$

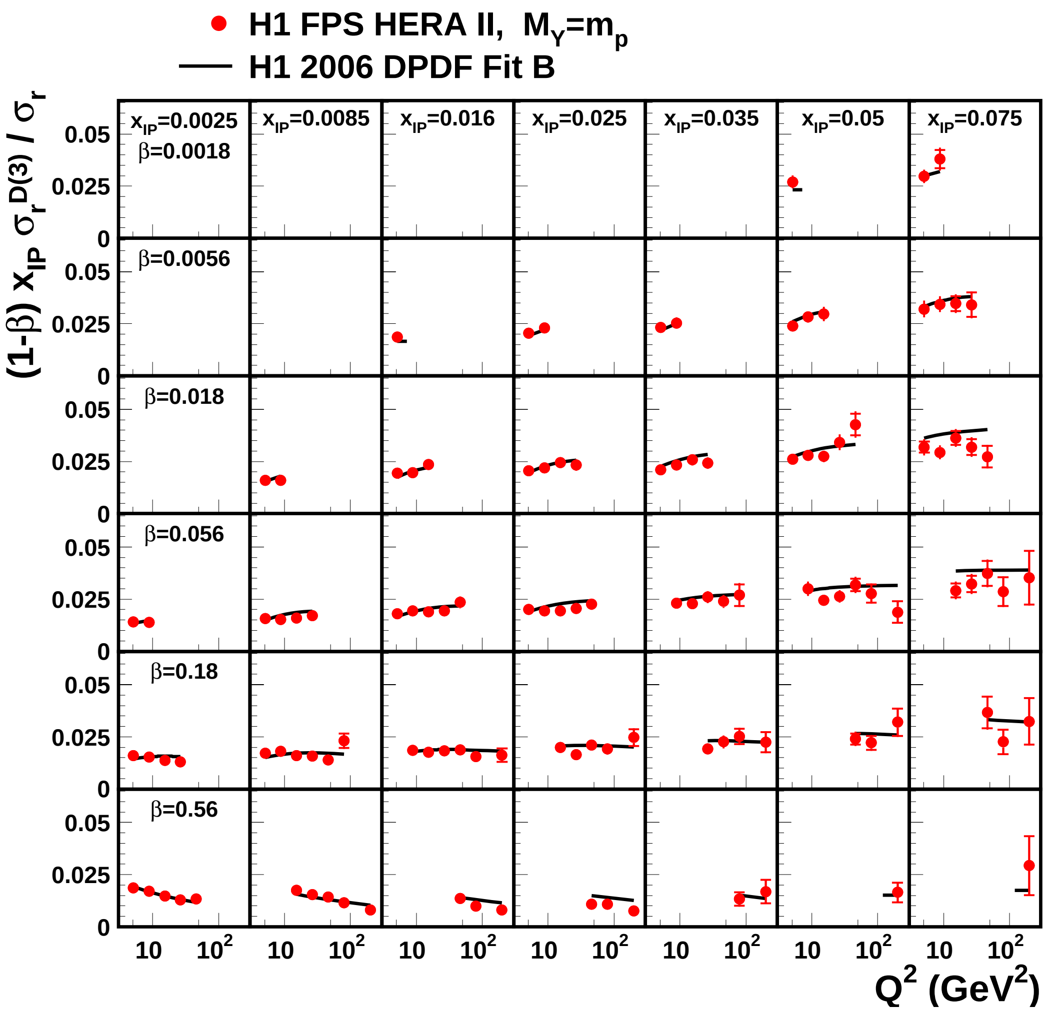
ZEUS LPS Regge fit:

$\alpha_{IP}(0) = 1.11 \pm 0.02(\text{stat.}) \pm^{0.01}_{0.02}(\text{syst.}) \pm 0.02(\text{model})$

$\alpha'_{IP} = -0.01 \pm 0.06(\text{stat.}) \pm^{0.04}_{0.08}(\text{syst.}) \pm 0.04(\text{model})\ \text{GeV}^{-2}$

$B_{IP} = 7.1 \pm 0.7(\text{stat.}) \pm^{1.4}_{0.7}(\text{syst.})\ \text{GeV}^{-2}$

Ratio $\sigma_r^{D(3)} / \sigma_r^{incl}$: Q^2 dependence



Q^2-dependence in (x_{IP},β) bins
M_x>2 GeV, |t|<1GeV^2

➔ Ratio is flat or weakly rises with Q^2 except at highest β

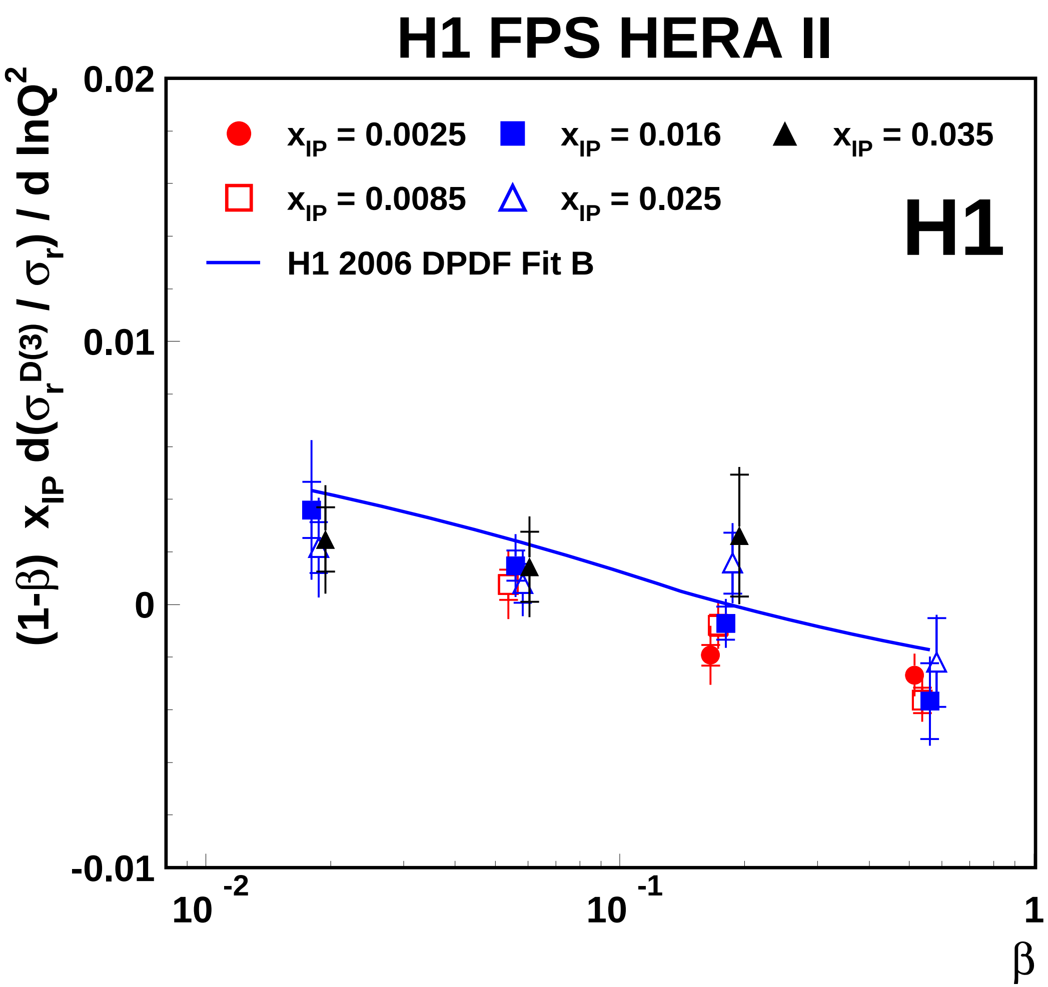
➔ similar shape of diffractive and inclusive quark PDF in proton at low $x=x_{IP}\beta$

➔ extract lnQ^2 derivative sensitive to gluon PDF

Ratio $\sigma_r^{D(3)} / \sigma_r^{incl}$: $\ln Q^2$ derivative

- Slope *D:* $(1-\beta) x_{IP} \sigma_r^D / \sigma_r^{incl} = A + D \ln Q^2$

→ $\ln Q^2$-dependence in selected (x_{IP}, β) bins



- $\ln Q^2$ slope is consistent with zero within 3σ of exp. uncertainties

➔ (gluon/quark)^{diff} ~ (gluon/quark)^{incl} in proton at low $x = x_{IP}\beta$

- weak decrease of $\ln Q^2$ slope with β reproduced by DPDF / PDF predictions