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Particle Physics and Cosmology
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Jet and Diffraction results from HERA

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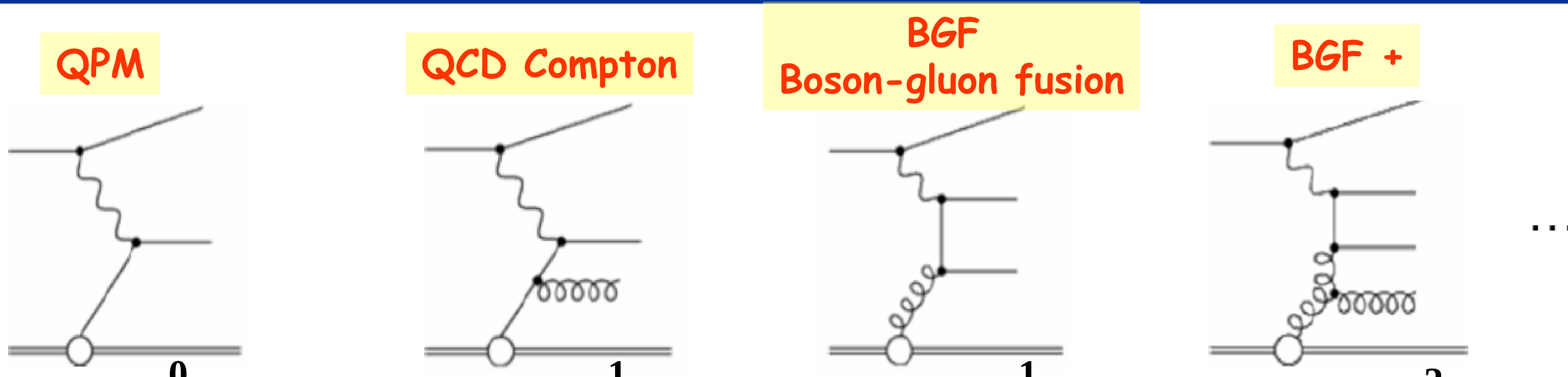
On behalf of the H1 and ZEUS Collaborations

Outline:

- Jet cross sections in DIS and γp and $\alpha_s(M_Z)$
- Measurements of Diffractive DIS
- Tests of diffractive PDFs with jets
- Diffractive heavy vector meson production
- Very Forward Photon production

Physics with Jets at HERA



$\propto \alpha_s^0$ $\propto \alpha_s^1$ $\propto \alpha_s^1$ $\propto \alpha_s^2$

- Measurements of jets provide a powerful ground for precision QCD test

  Cross section depends on: QCD matrix elements, strong coupling α_s, PDF of the proton (and the photon in case of photoproduction)

- Jets are directly sensitive to α_s and gluons already in LO: $\sigma \sim \alpha_s \cdot g(x)$

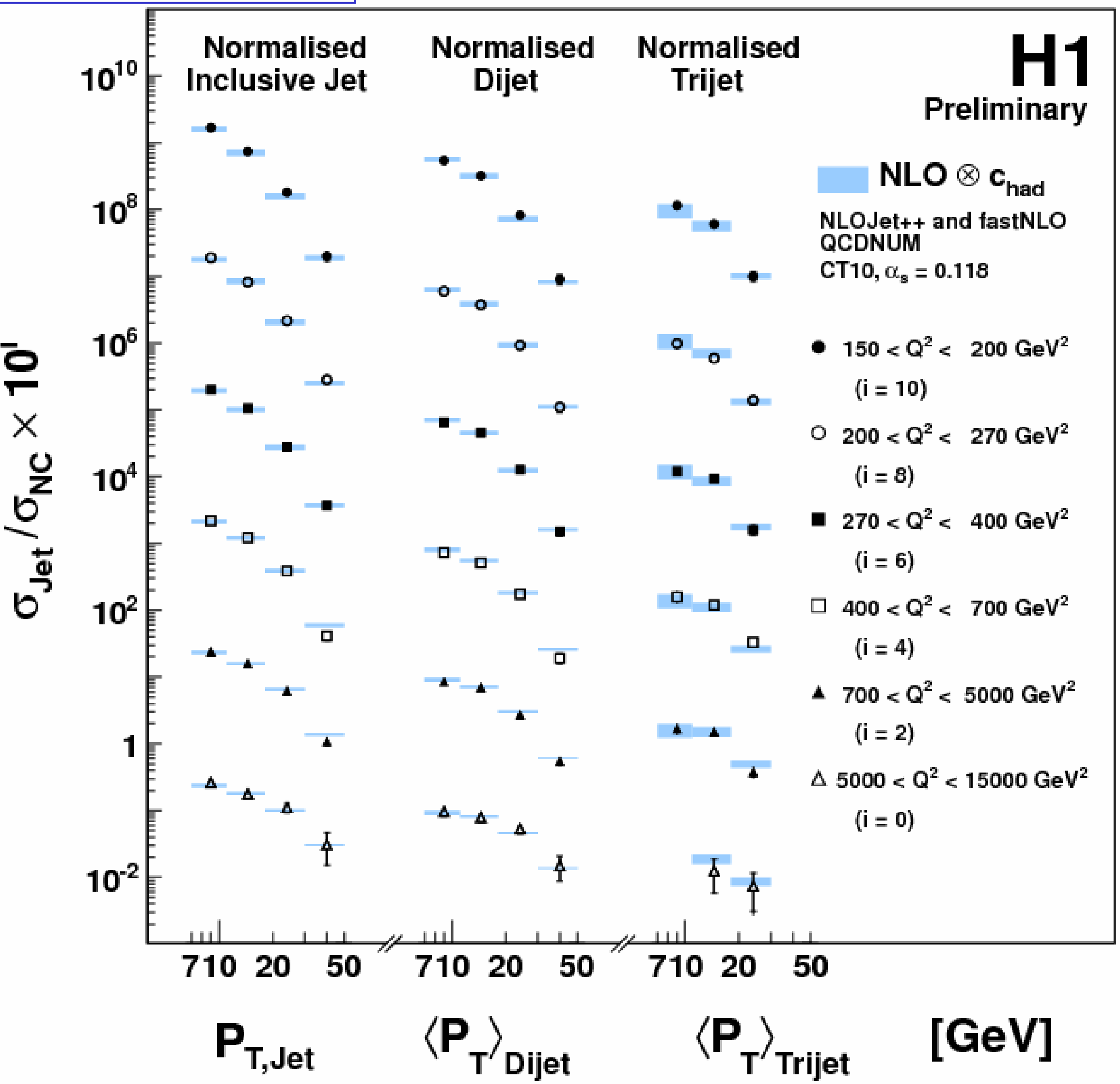
→ extract strong coupling α_s with high precision

→ combined inclusive DIS and jet analyses help to improve constraining gluon density

Wealth of new jet data from HERA available to provide further constrains on gluon PDF at medium and high x and determine the strong coupling α_s

Normalised Jet Cross Sections in DIS at high Q^2

H1 prel-12-031



Inclusive jet, 2-jet, 3-jet production

longitudinally invariant k_T jet algorithm in the Breit frame → collinear and infrared safe

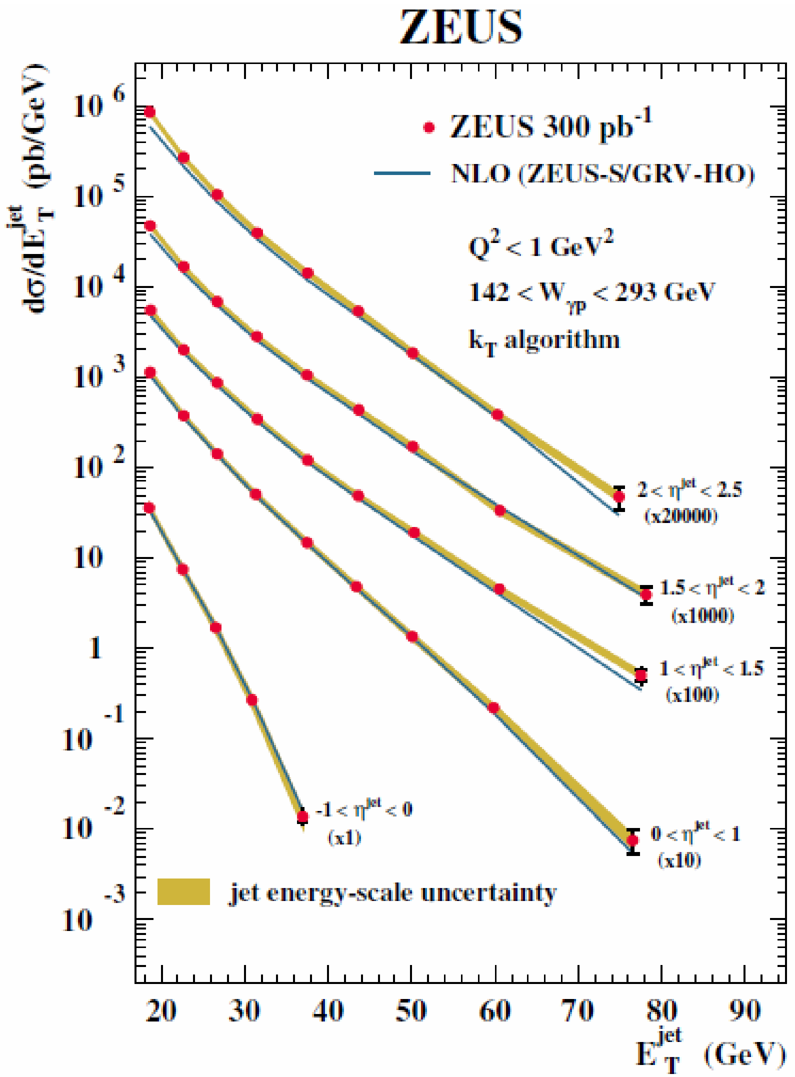
- high precision- 1% jet energy scale uncertainty
- data are well described by NLO calculation with $\mu_r^2 = (Q^2+P_T^2)/2$

Combined NLO fit to normalised inclusive, dijet and trijet cross sections

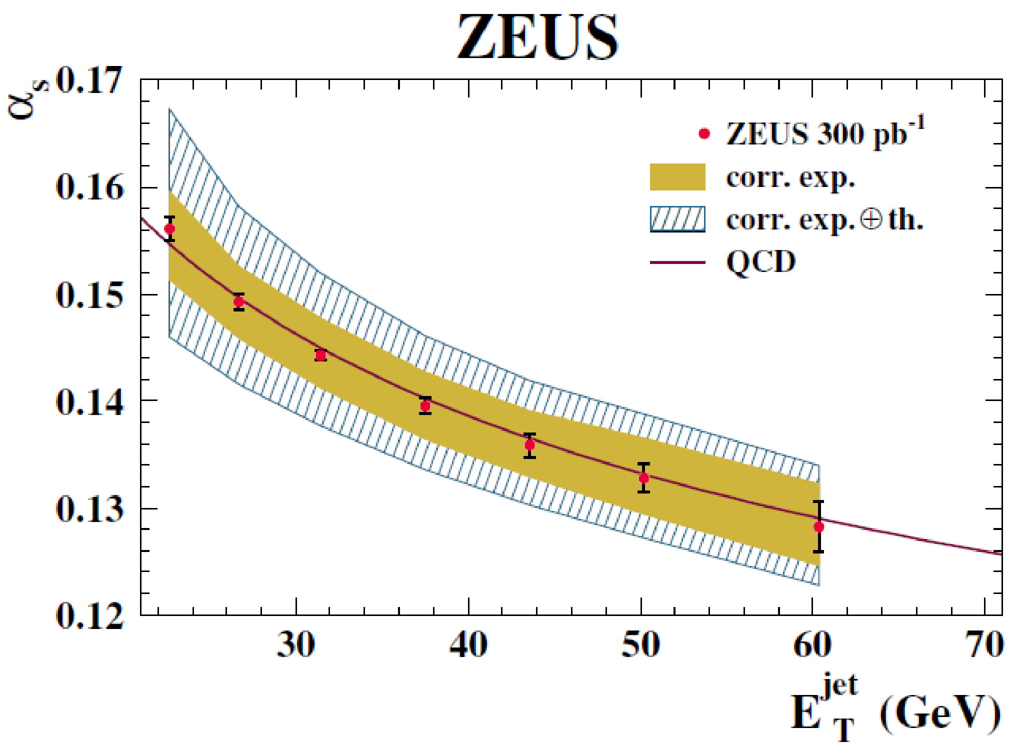
$\alpha_S(M_Z)$=0.1163 ± 0.0011 (exp) ± 0.0014 (PDF) ± 0.0008 (had) ± 0.0039 (theory)

α_s from inclusive jets in photoproduction (Q^2<1 GeV^2)

DESY-12-045

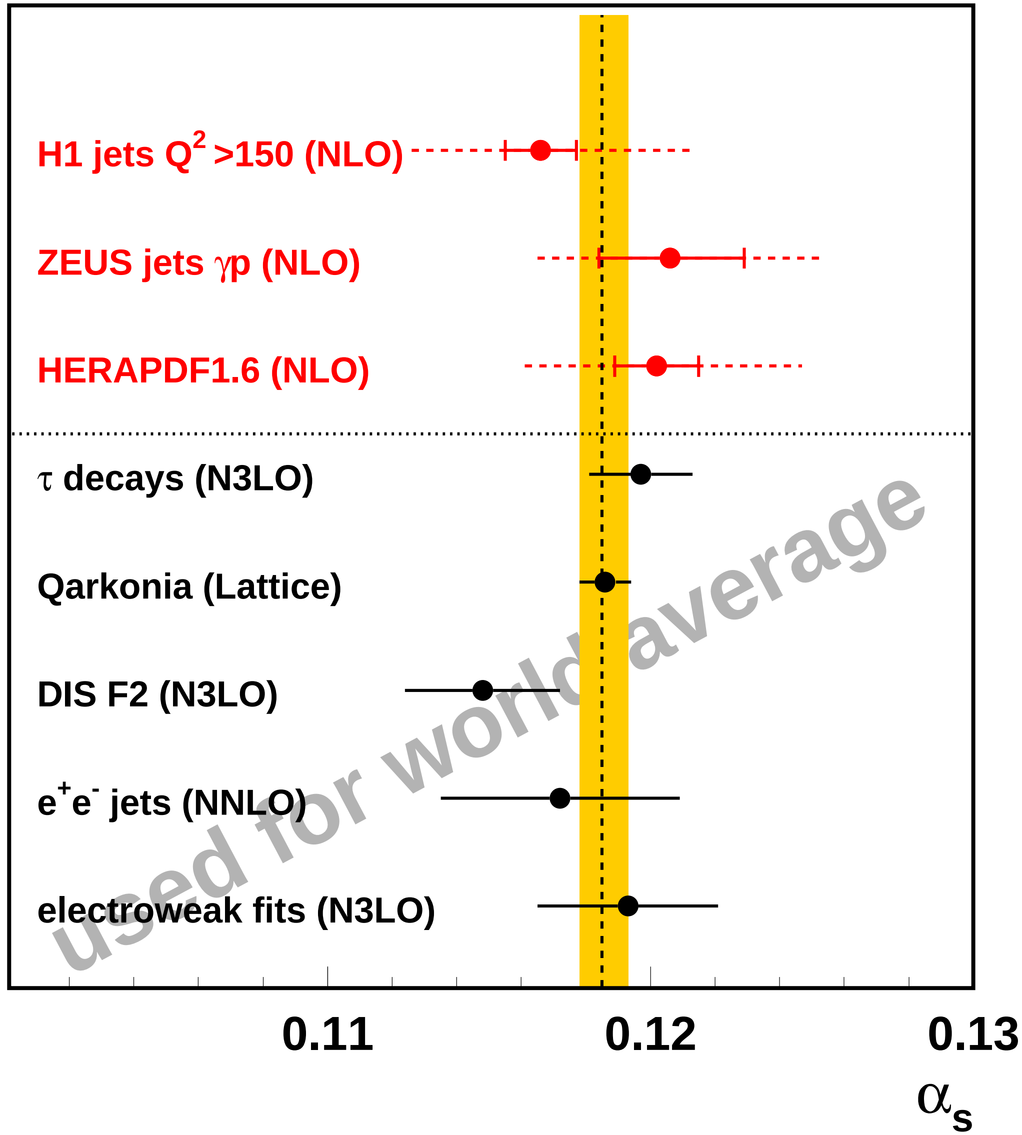


- 1% jet energy scale uncertainty
- large E_T^{jet} accessible
- running of α_s measured in a single experiment



$$\alpha_S(M_Z) = 0.1206 \,^{+0.0023}_{-0.0022}\,(\text{exp.}) \,^{+0.0042}_{-0.0033}\,(\text{theory})$$

Summary on α_s from HERA jet data

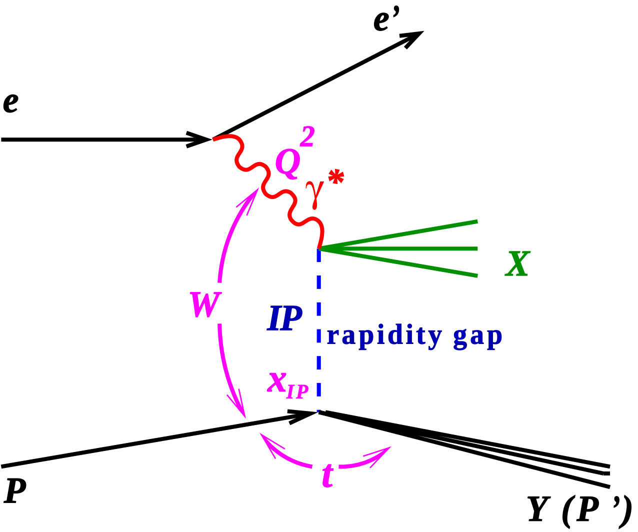


α_s from HERA with small experimental uncertainties.

Large theory uncertainties due to the lack of higher order theory calculations

Diffraction in ep collisions

One of first HERA surprises: ~10% of DIS events have no activity in proton direction → *diffractive interactions*



$Q^2 = -q^2$	photon virtuality
$x = \frac{Q^2}{2q\cdot p}$	Bjorken scaling variable
$W^2 = (p+q)^2$	$\gamma^* p$ CM energy squared
$t = (p - p_Y)^2$	4-momentum transfer squared
$x_{I\!P} = \frac{q\cdot(p-Y)}{q\cdot p}$	fraction of p momentum transferred to $I\!P$ ($x_{I\!P} \simeq 1 - E_Y/E_p$)
$\beta = \frac{Q^2}{2q\cdot(p-Y)}$	fraction of $I\!P$ momentum carried by struck quark ($x_{I\!P}\beta = x$)
M_X	Inv. mass of system X

- t-channel exchange of vacuum quantum numbers
- proton survives the collision intact or dissociates to low mass state, $M_Y \sim O(m_p)$
- large rapidity gap
- small t (four-momentum transfer), small x_{IP} (fraction of proton momentum); $M_X \ll W$

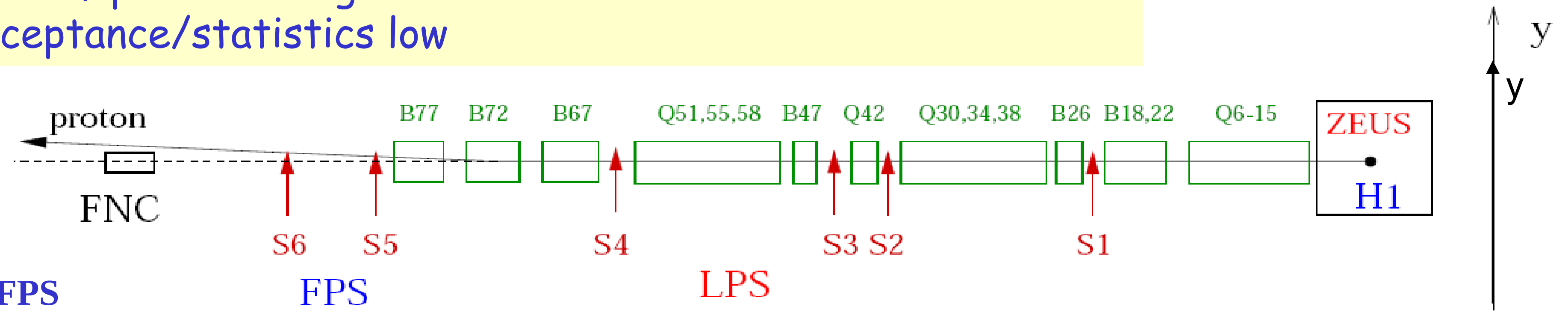
In diffractive DIS, $\gamma^* p \rightarrow XY$, virtual photon resolves structure of colour singlet exchange
- huge progress in understanding diffraction in terms of partons
- essential for the predictions of diffractive cross sections (e.g. diffractive Higgs at LHC)
- related to non-linear evolution (low x saturation), underlying event (gap survival), confinement

Selection of diffractive events at HERA

➢'Leading proton' measuremens

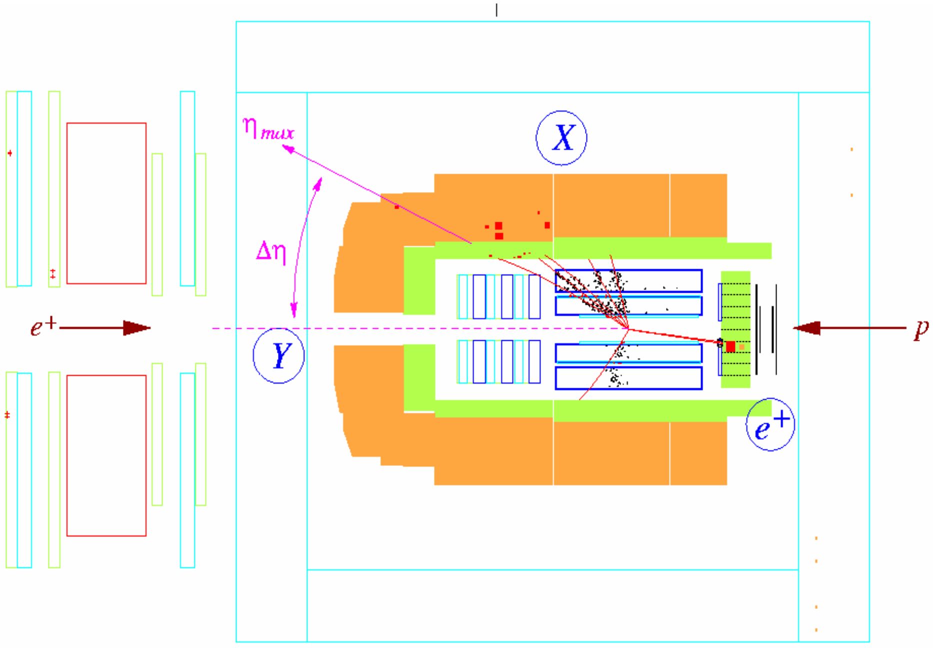
scattered proton detected in 'Roman Pots' (LPS,FPS,VFPS)

- t and x_{IP} measurement
- free of p-diss. background
- acceptance/statistics low



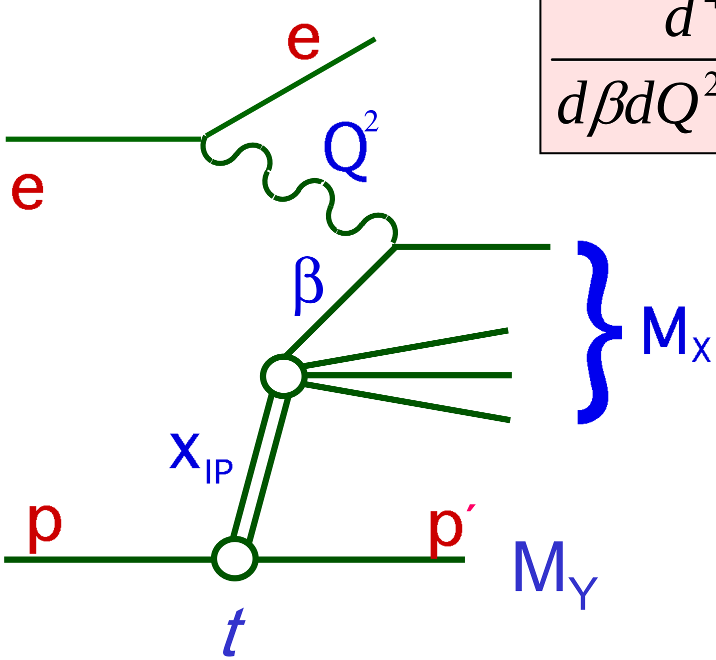
➢'Large Rapidity Gap' method (LRG)

- t is not measured, integrated over $|t|<1$ GeV^2
- contains some p-diss. background
- limited by syst.uncertainties related to missing proton



The methods have different systematic uncertainties

Diffractive reduced *ep* cross section



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

β– momentum fraction of color singlet carried by struck quark

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

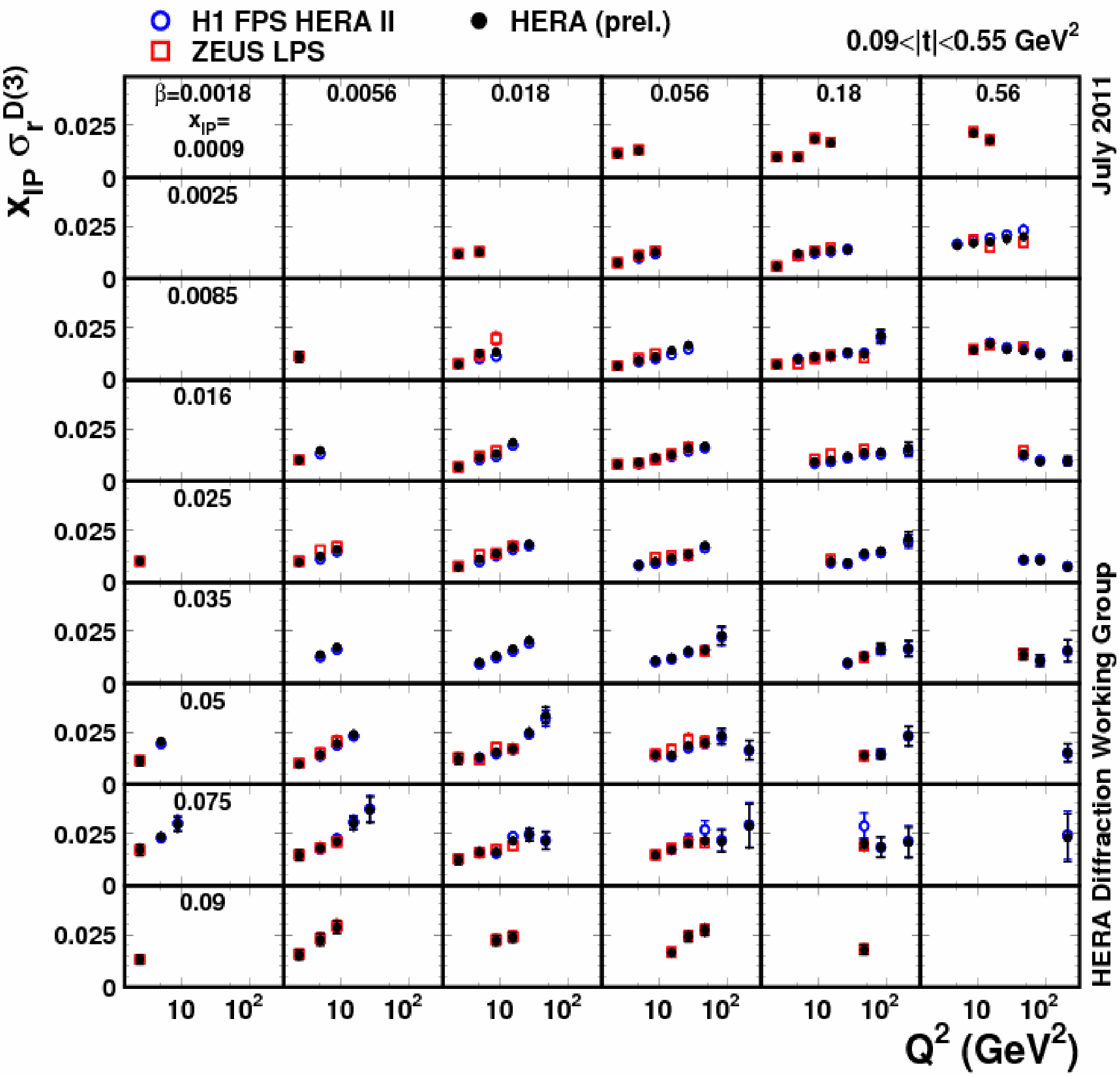
$$\sigma_r^{D(3)} = \int \sigma_r^{D(4)} dt$$

→ integrated over $|t|<1$ GeV^2

Diffractive DIS: reduced cross sections

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

Proton Spectrometer data in 0.09<|t|<0.55 GeV²



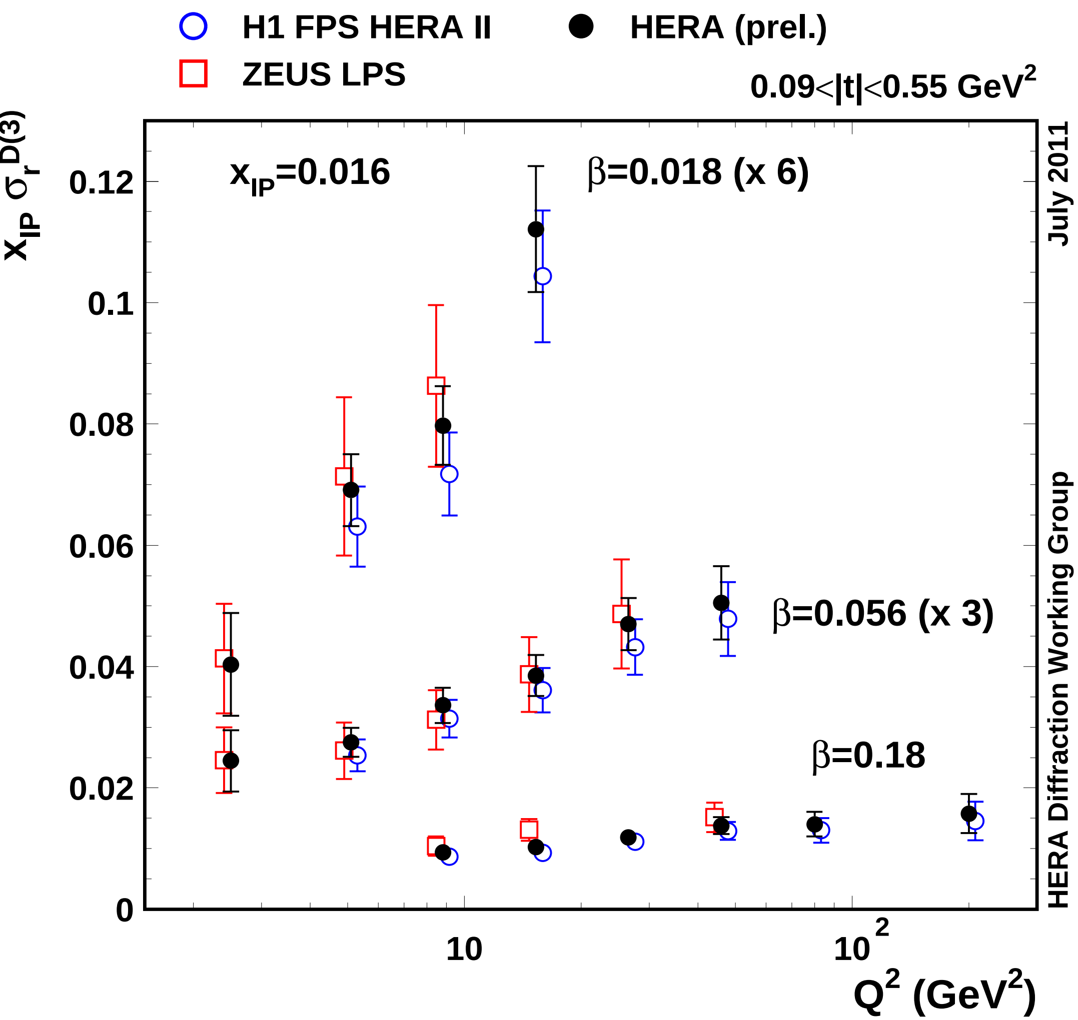
rise with Q² →positive scaling violation up to high β

→Reasonable agreement of H1 FPS and ZEUS LPS data in shape and normalisation

(H1 FPS norm. uncertainty ±4.5%, ZEUS LPS norm. uncertainty ±7%)

→ Combine H1 and ZEUS cross sections to extend phase space and reduce uncertainties: **first combination of H1 and ZEUS diffractive data !**

Combination of H1 FPS/ZEUS LPS data



A detailed look to the combined data

➔Consistency between data sets

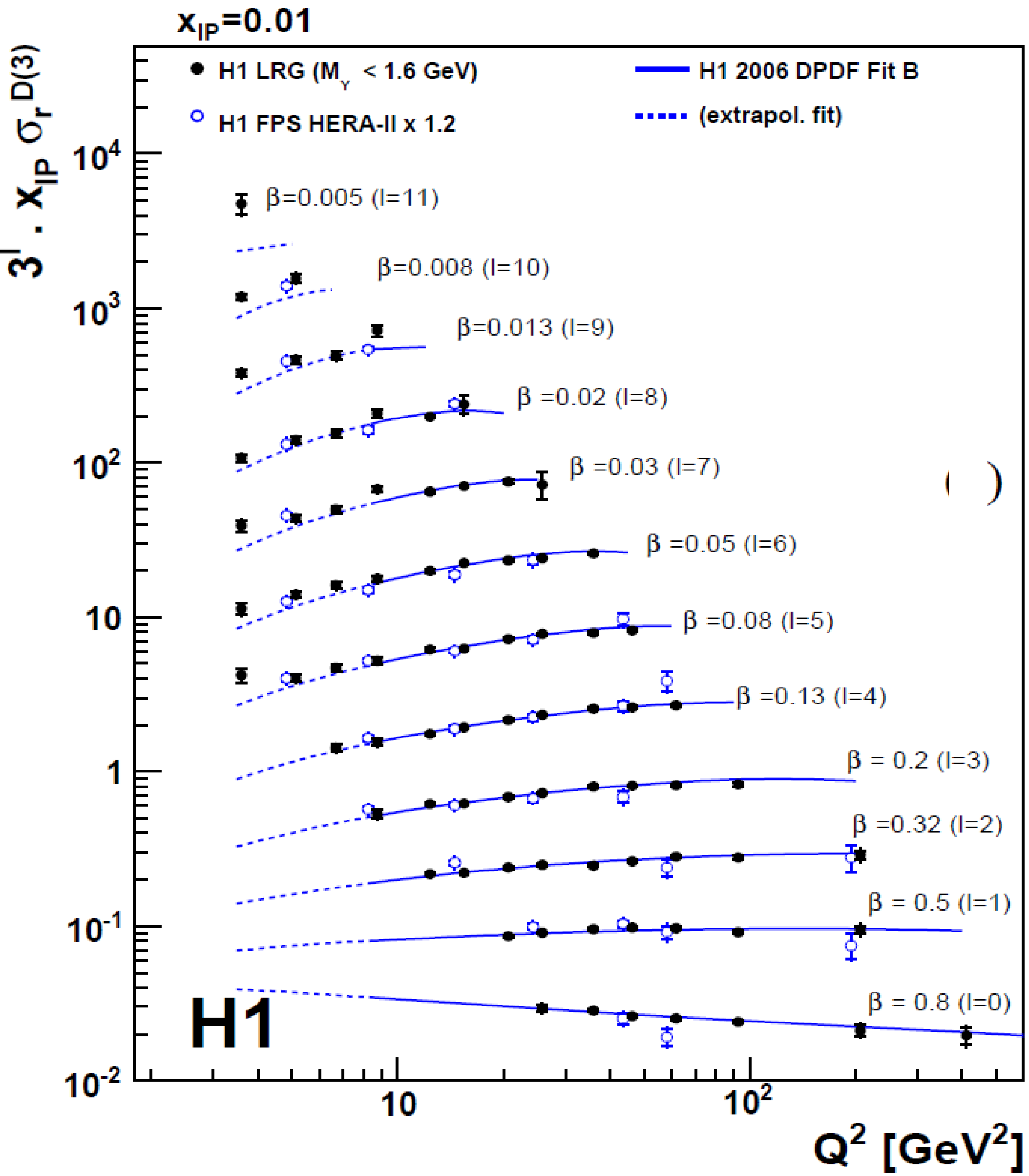
➔Combination method uses iterative χ^2 minimization and include full error correlations

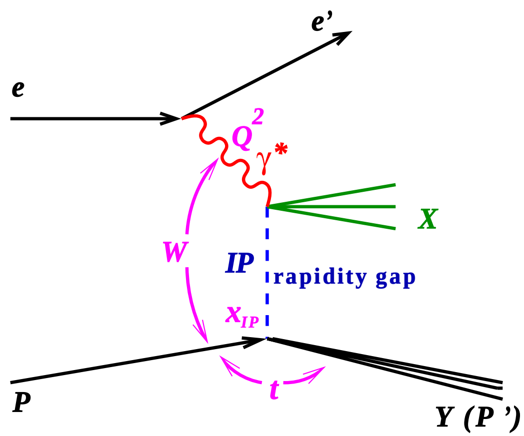
➔ Profit from different detectors: Two experiments 'calibrate' each other resulting in reduction of systematic uncertainties

Combined data have ~25% smaller uncertainties then the most precise data alone

Diffractive DIS measurement with Large Rapidity Gap

DESY-12-041





New data sets combined with previously published data → 35× more data at medium Q^2

- F_2^D-positive scaling violation (rise with Q^2) up to high β → different from F_2
- β-dependence relatively flat

→ large gluon component in diffraction

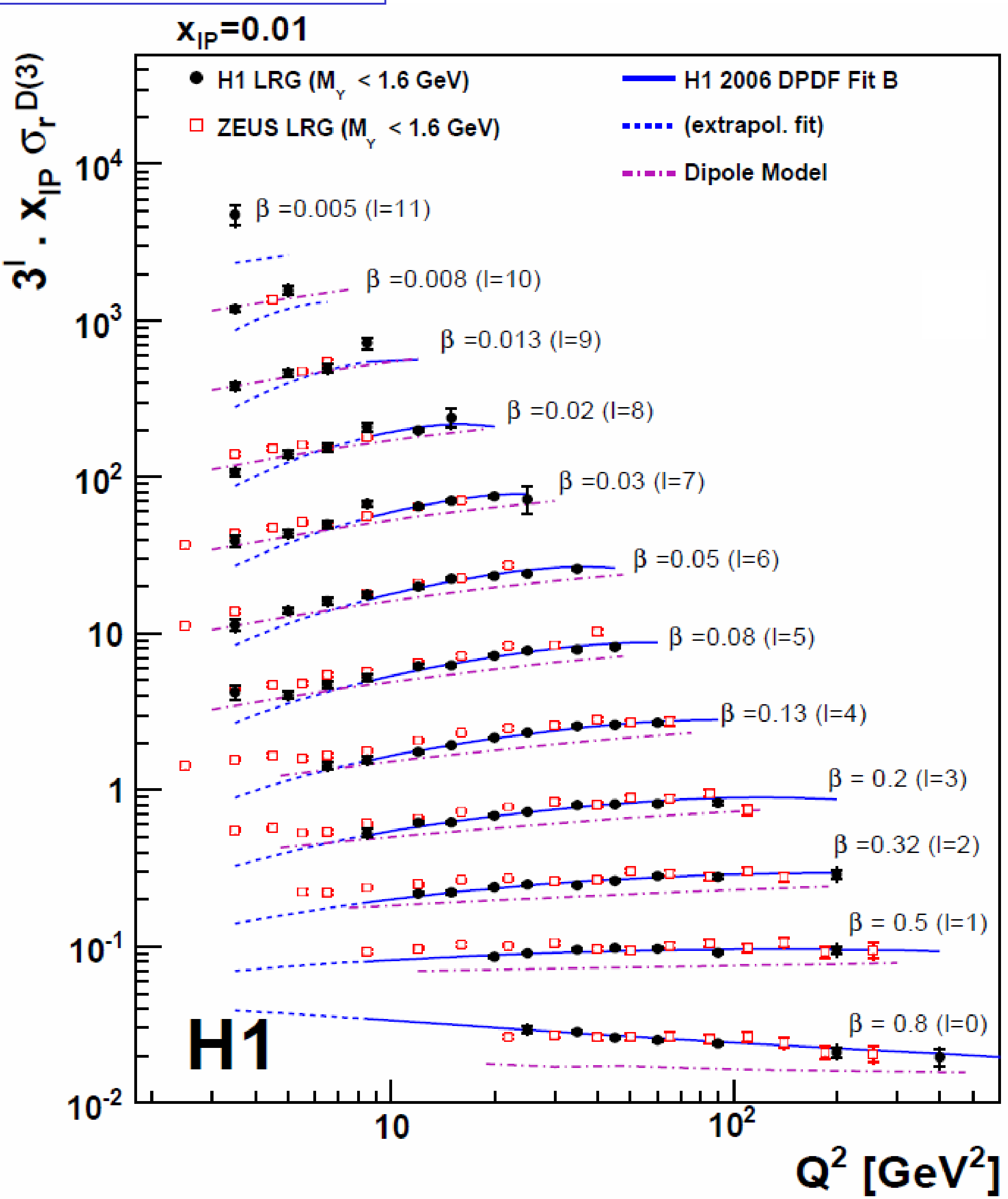
Contribution from proton diffractive dissociation

LRG/FPS=1.203 ± 0.019(exp) ± 0.087(norm)

- LRG and FPS data agree well
- NLO QCD (DPDF) works well for Q^2>10 GeV^2

Diffractive DIS measurement with Large Rapidity Gap

DESY-12-041



Comparison recent H1 and ZEUS measurements (ZEUS data corrected to same Q^2 and M_Y<1.6 GeV)

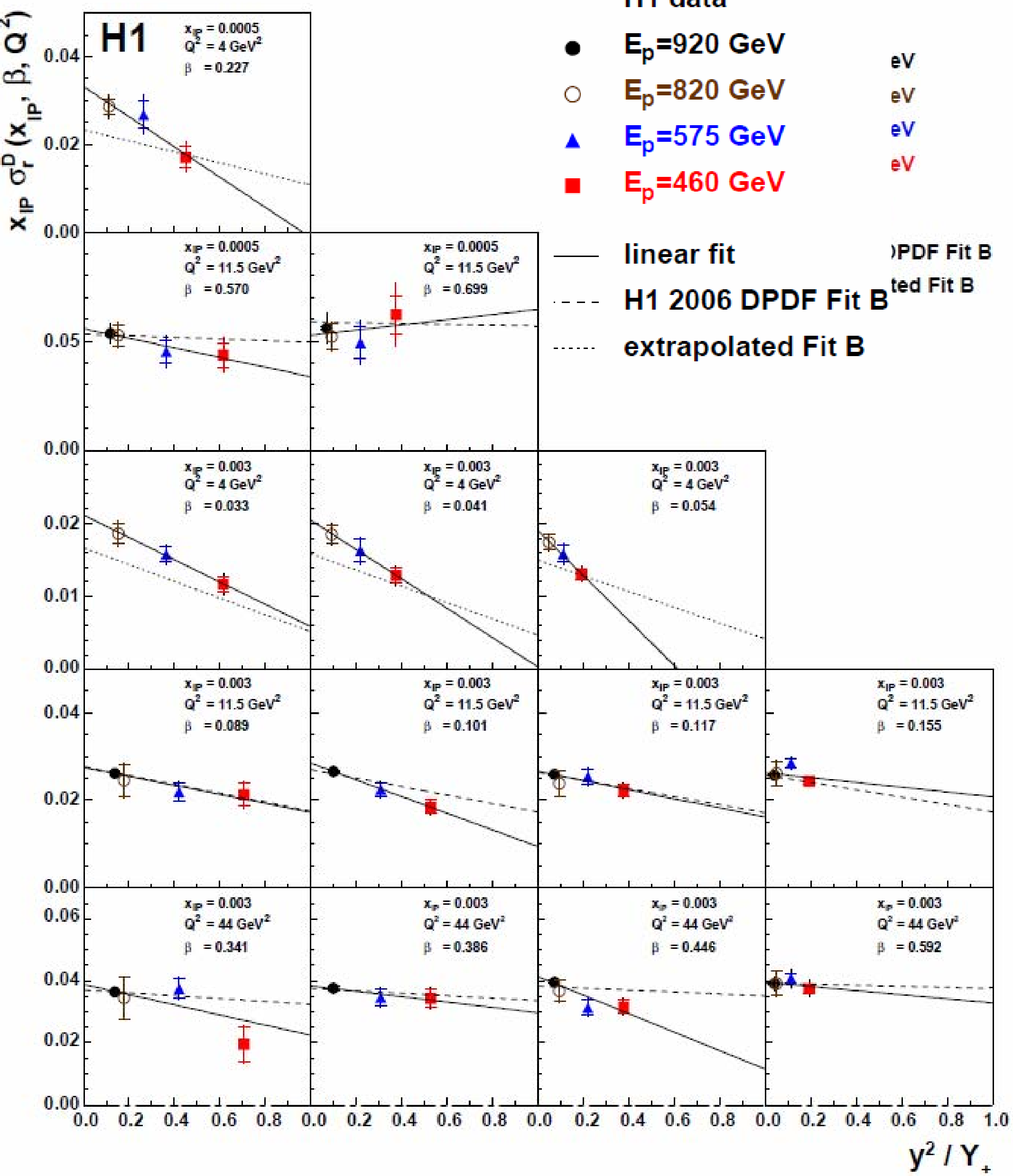
ZEUS data ~10% higher than H1; shape agreement

NLO QCD + DPDF:
- works well for Q^2>10 GeV^2
- underestimate data at low Q^2

Dipole model with saturation:
- close to data at low Q^2
- too low at high Q^2 and β

F_L^D in Diffraction

DESY-11-084

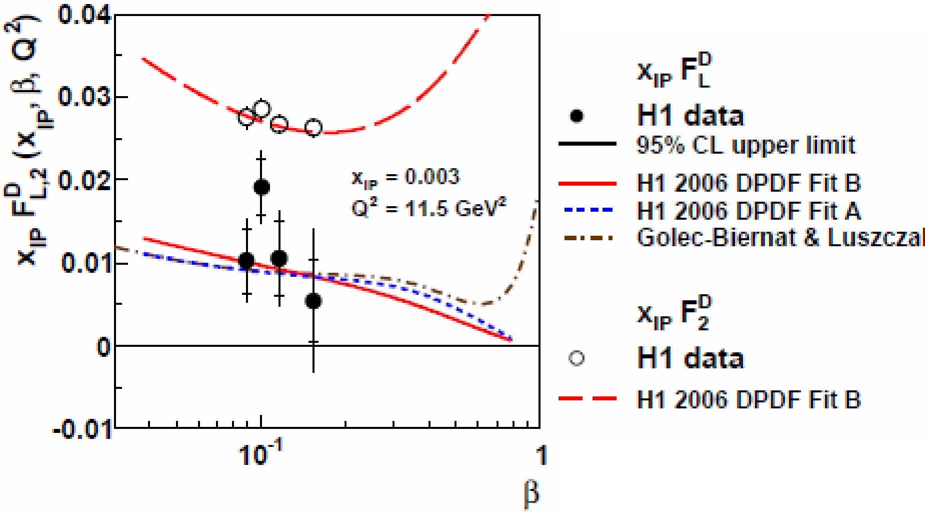


$$\sigma_r^D \propto F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D$$

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

Access to F_L^D if measure σ_r^D at same x, Q^2 and different ep CM energy, i.e. different $E_{p\text{-beam}}$ (remember: $Q^2=xys$)

Direct measurement of F_2^D and F_L^D

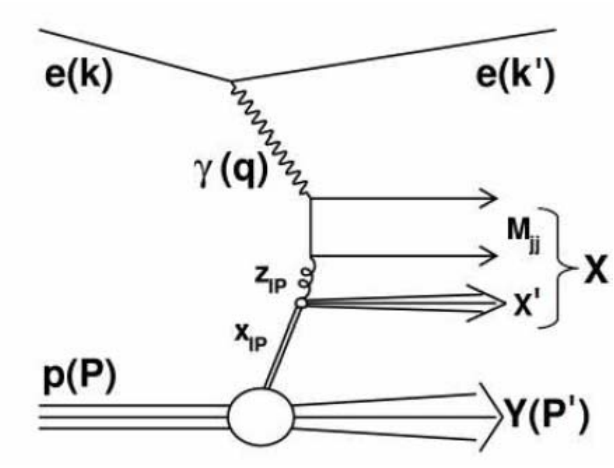


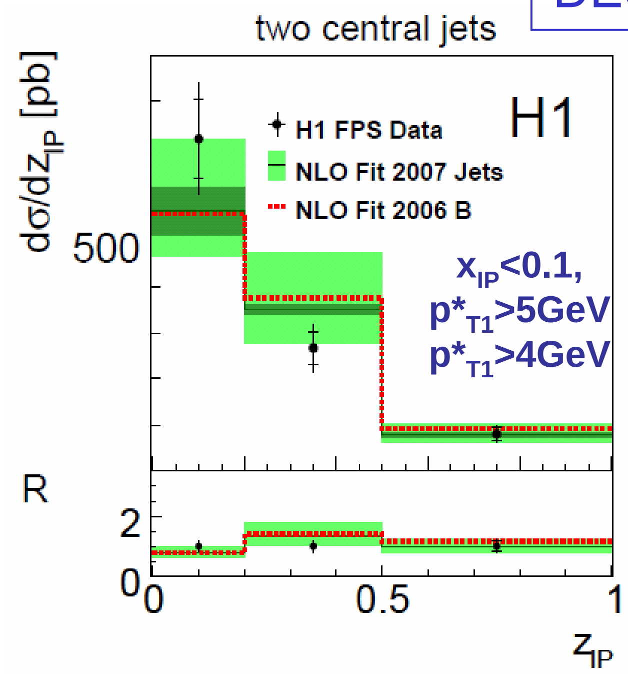
$F_L^D > 0$! → agree with predictions

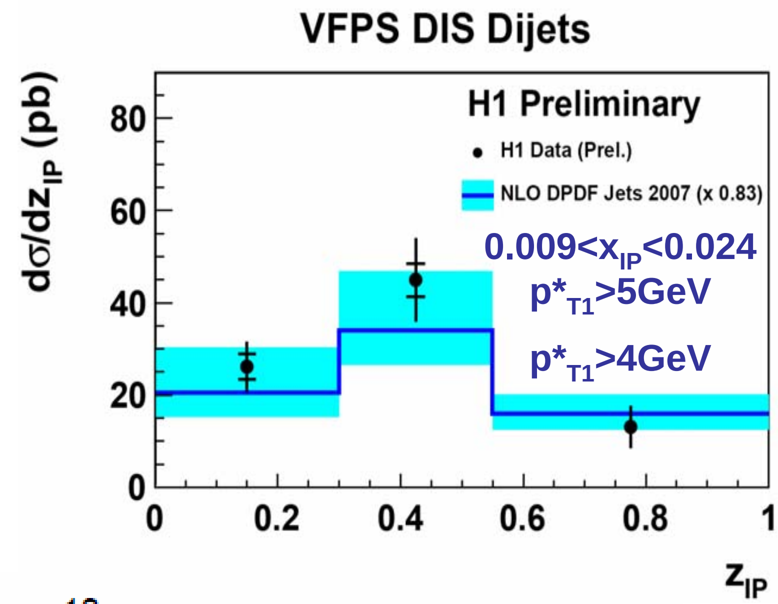
Diffractive central di-jet production (with FPS)

DESY-11-166

H1-prel-11-013

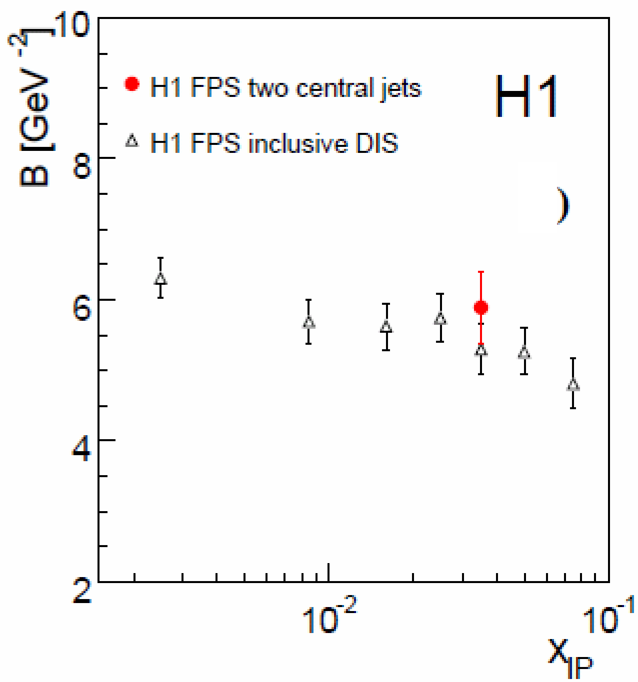






Use diffractive PDFs from the QCD fit to the inclusive diffractive DIS data to make predictions for other diffractive processes

NLO QCD predictions using DPDFs from inclusive diffractive DIS describe jet data well



t-slope consistent with inclusive diffraction
→ proton vertex factorisation holds

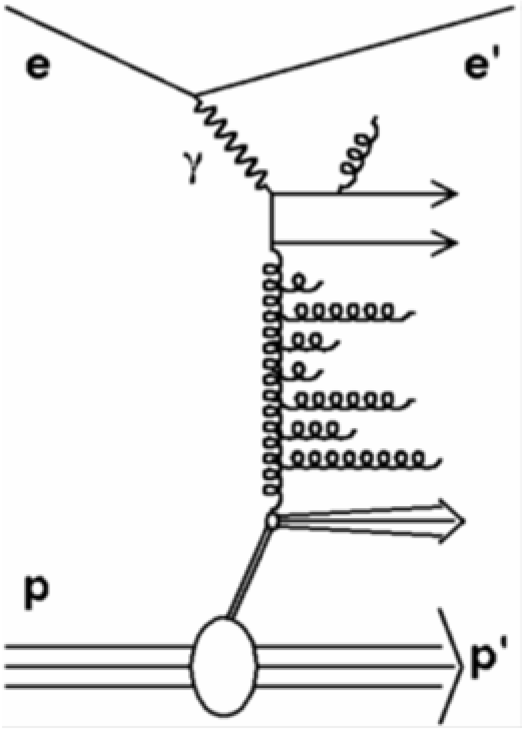
Diffractive forward jet production (with FPS)

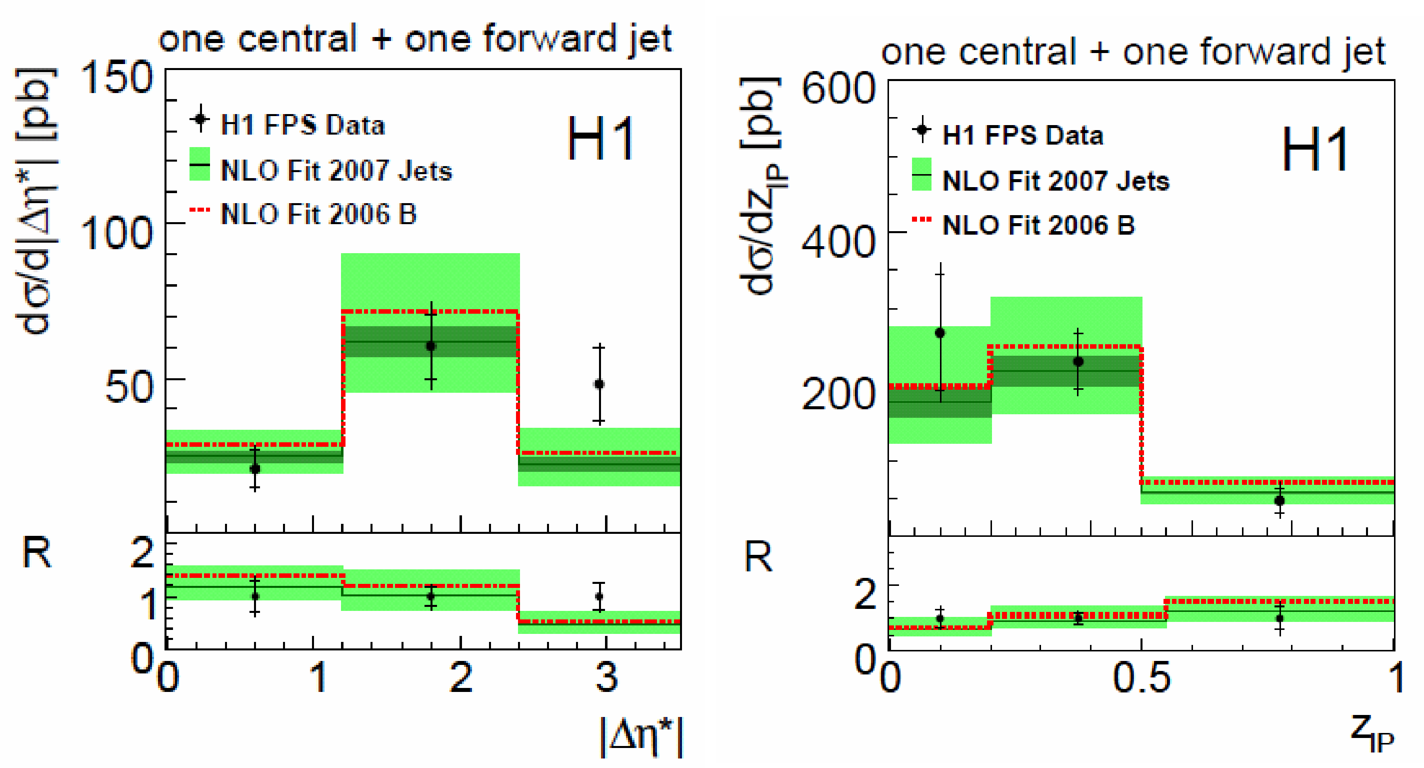
DESY-11-166

1 central+ 1 forward jet:

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

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

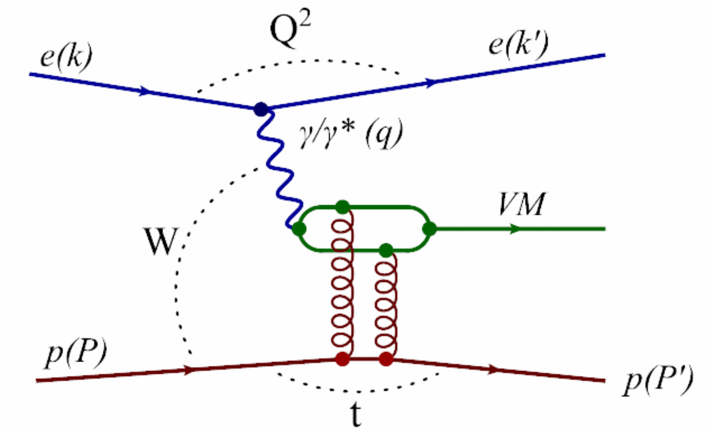




➔dijet selection with DGLAP p_T ordering broken

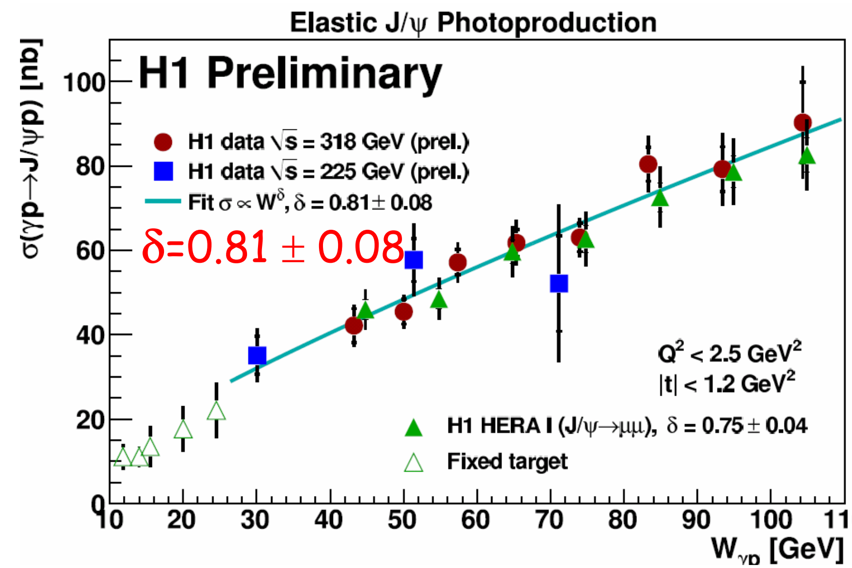
➔no evidence for configurations beyond DGLAP & DPDF predictions

Diffractive Vector meson production: J/ψ



Photoproduction ➔ $Q^2 \sim 0$
Heavy VM mass provides pQCD hard scale

H1-prel-11-011

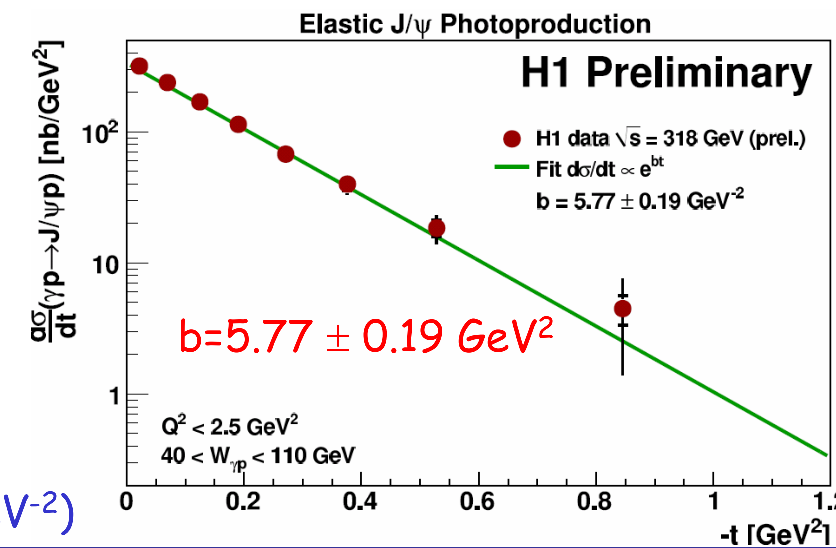


- energy dependence $\sigma \propto W^{\delta}$

expect δ to increase from 'soft'(~0.2) to 'hard'(~0.8) regime

Fast increase of cross section with energy due to gluon density in proton going to low x

$$\sigma \sim \left| x g(x, Q^2) \right|^2$$



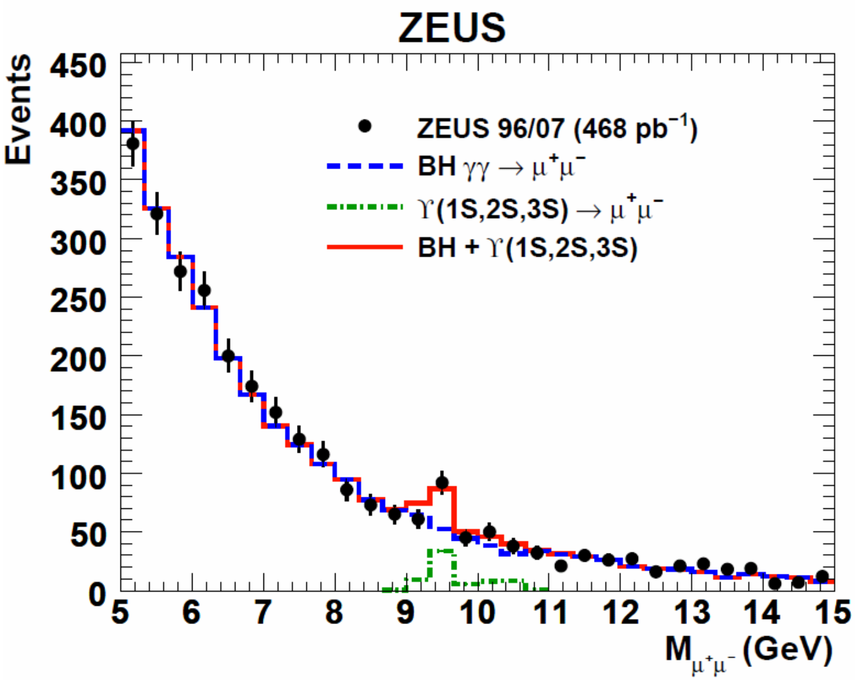
- t - dependence $\frac{d\sigma}{dt} \propto e^{-b|t|}$

b is a measure of transverse size of interaction region

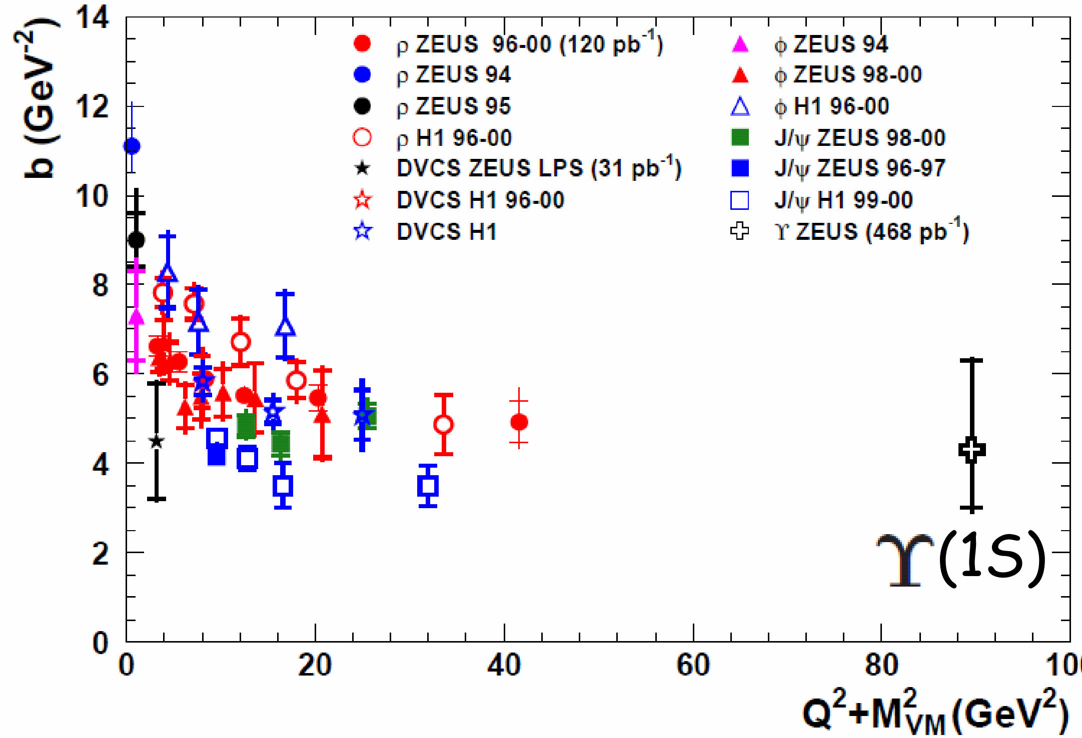
b = $b_V + b_P$; $b_V = 1/(Q^2+M_V^2)$; $b_P = 5\ GeV^{-2}$

expect **b** to decrease from 'soft' (~10 GeV^{-2}) to 'hard' (~5 GeV^{-2})

Diffractive Υ(1S) photoproduction



DESY-11-186



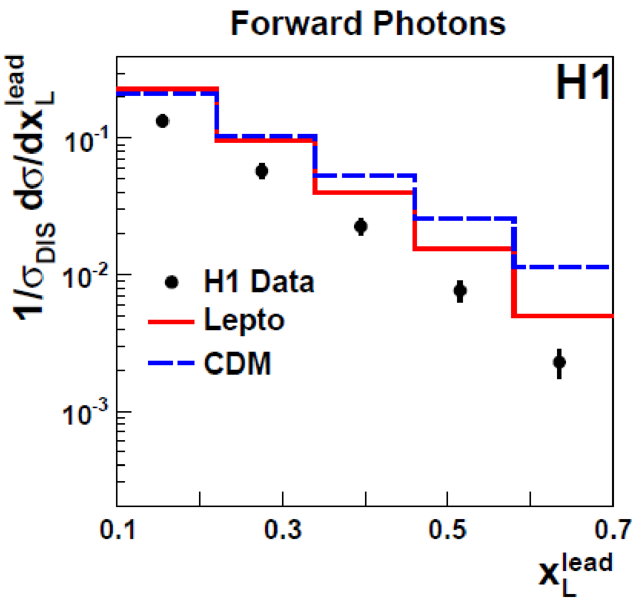
$$b = 4.3\,^{+2.0}_{-1.3}\,(stat.)\,^{+0.5}_{-0.6}\,(syst.)\,GeV^{-2}$$

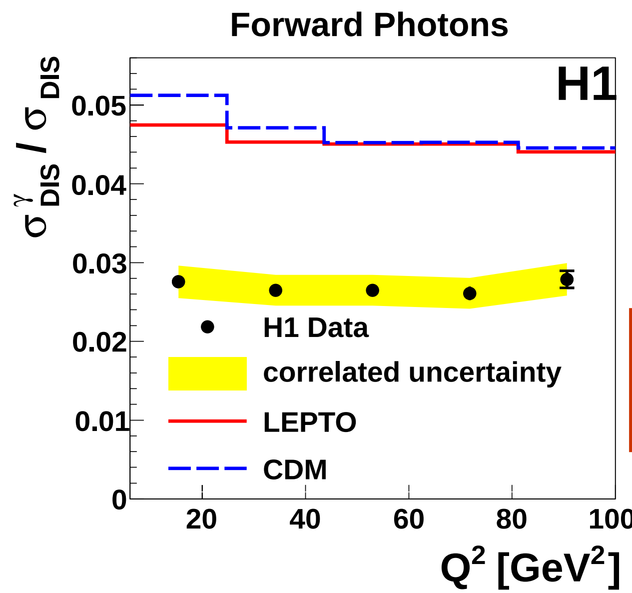
First determination of b slope for Υ (1S)

Production of very forward photons

Forward photons produced at η>7.9 (in lab frame) detected in forward neutron calorimeter at z=106m from IP. Main source of forward photons $\pi^0 \rightarrow \gamma\gamma$

DESY-11-093

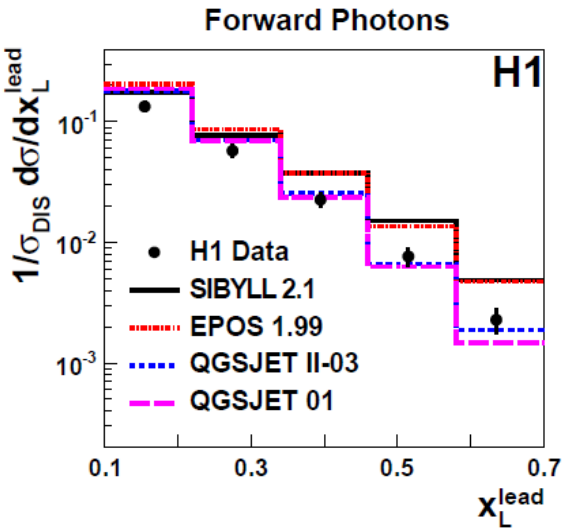


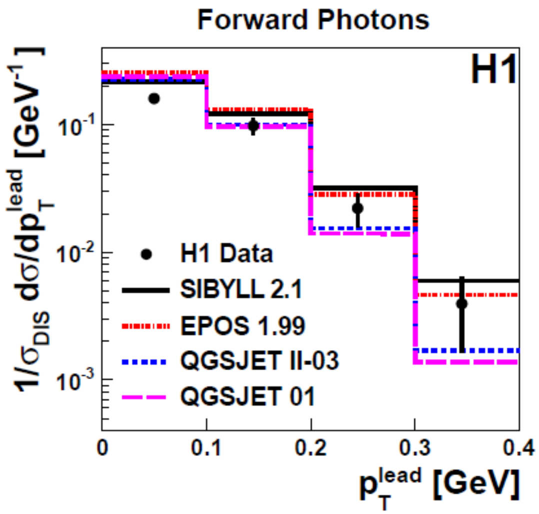


At large η MC predictions much above data ➔ fragmentation to π^0s in p-remnant not well modeled

Photon yield independent of Q^2, x ➔ limiting fragmentation

forward particles are important for the tuning of hadronic interaction models of cosmic rays





Large difference between the predictions.
None of the models describes the data well.

Conclusions

Many new results from HERA on hadronic final states and diffraction

- Jet measurements in DIS and photoproduction provide stringent tests of QCD and proton PDFs

- Inclusion of jet data to NLO QCD fits improves precision on the determination of PDF and $\alpha_s(M_Z)$. Large theory uncertainties due to missing higher order QCD calculations

- Agreement between H1 and ZEUS measurement and between the different methods used to extract diffraction. First combination of H1 and ZEUS diffractive data presented

- Diffractive DIS measurements at HERA are sensitive to the structure of color singlet exchange. Diffractive PDFs constrained from HERA are essential ingredients for the prediction of diffractive cross sections at the LHC.

- In diffractive DIS, the validity of QCD factorisation confirmed by jet measurements

- Very forward particle measurements provide important information for an understanding of proton fragmentation

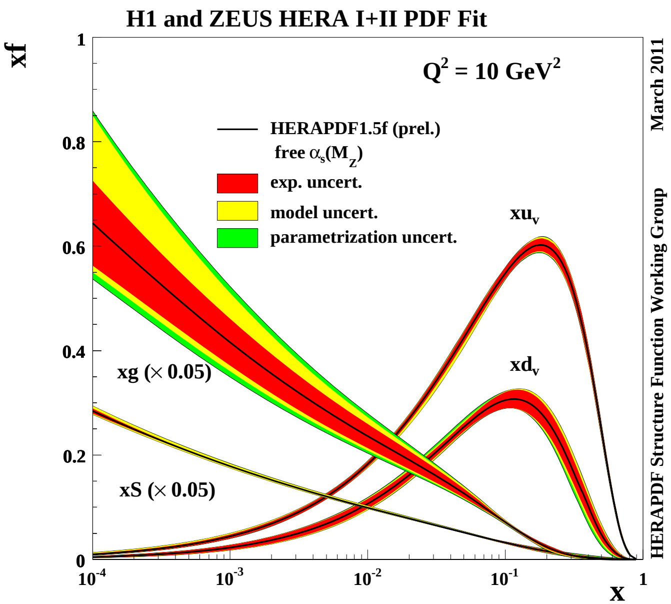
HERA has a reach program that should be completed

backup

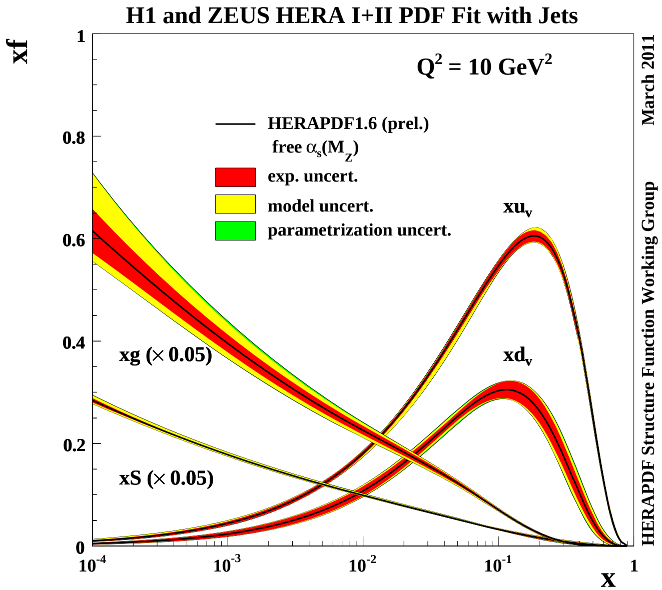
Combined α_s and PDF fit

H1 prel-11-034
ZEUS-prel-11-001

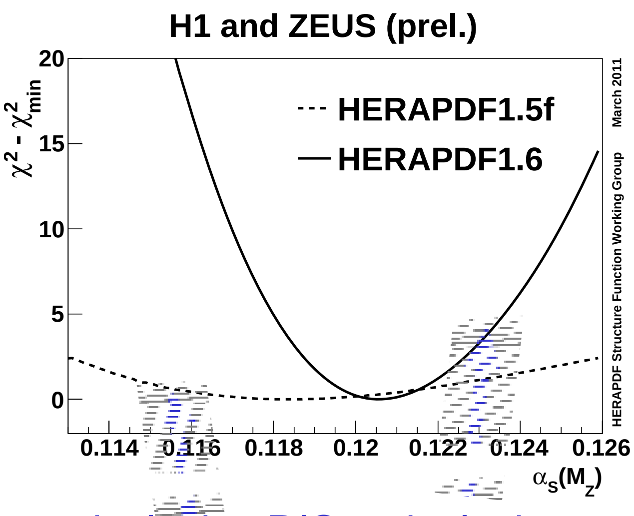
- PDF fit of inclusive DIS data- free α_s leads to large uncertainty on gluon density
- significant reduction of low x gluon uncertainties by including jet DIS data ➔ adding jet data reduces correlation of α_s and gluon PDF



free α_s, no jets
HERAPDF 1.5f



free α_s, with jets
HERAPDF 1.6

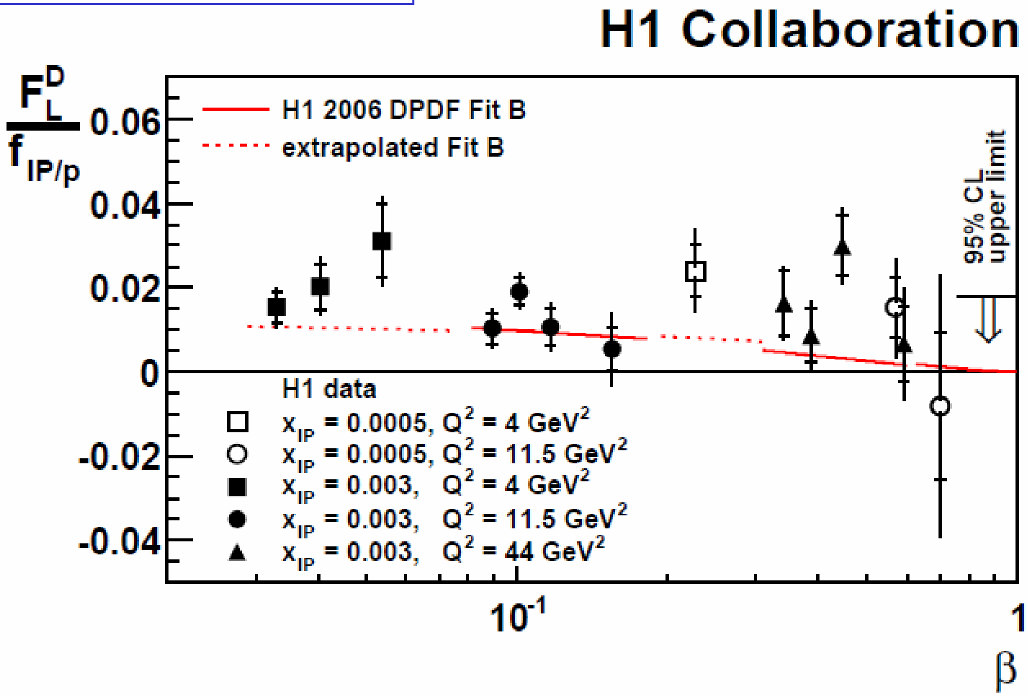


inclusive DIS data only

inclusive DIS + jet data

$$\alpha_s(M_Z)=0.1202 \pm 0.0013\,(\text{exp}) \pm 0.0007(\text{model}) \pm 0.0012\,(\text{hadr})\,^{+0.0045}_{-0.0036}(\text{theory})$$

DESY-11-084

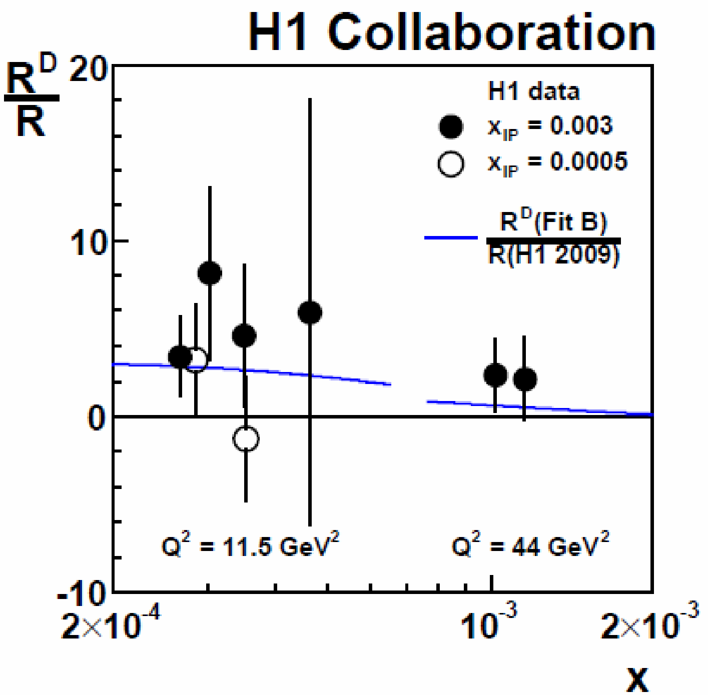


First measurement of F_L^D

Compare contributions from F_L and F_L^D

$$R^D = F_2^D \Big/ \left(F_2^D - F_L^D\right)$$

$R^D/R = 2.8 \pm 1.1$

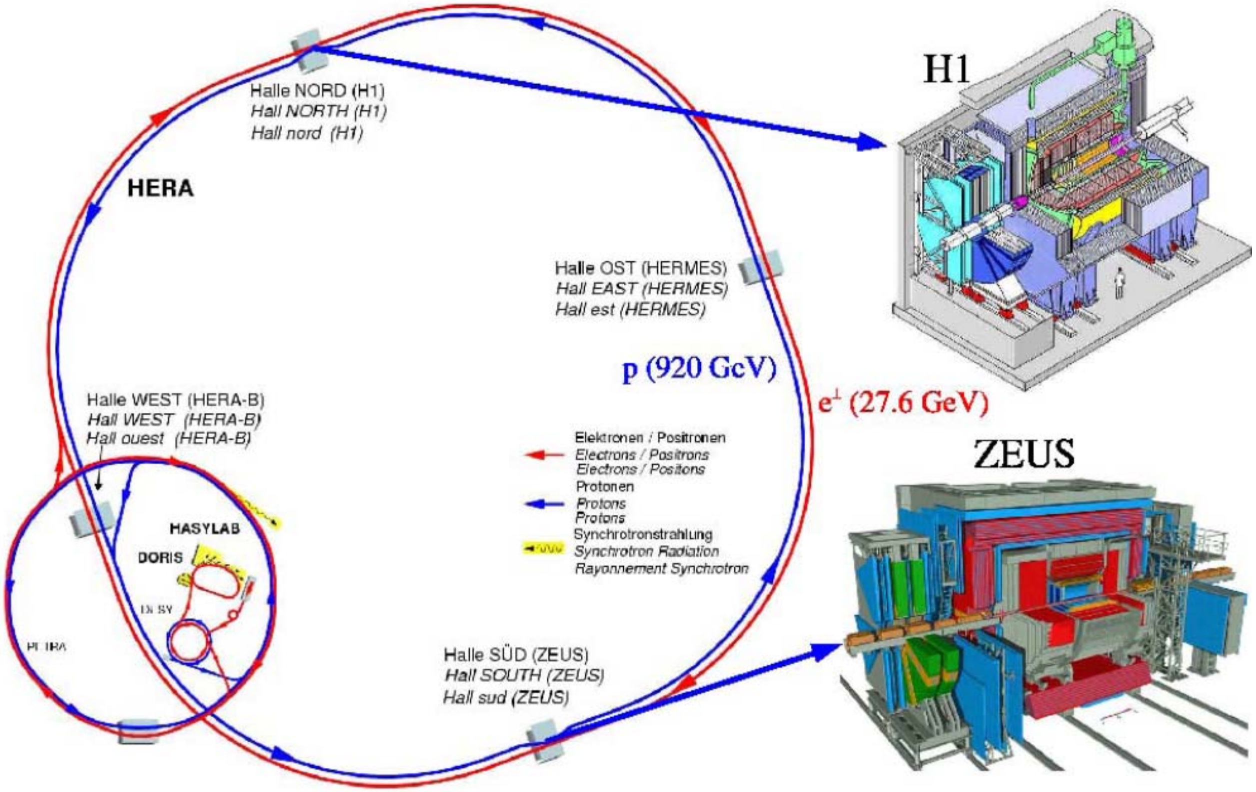


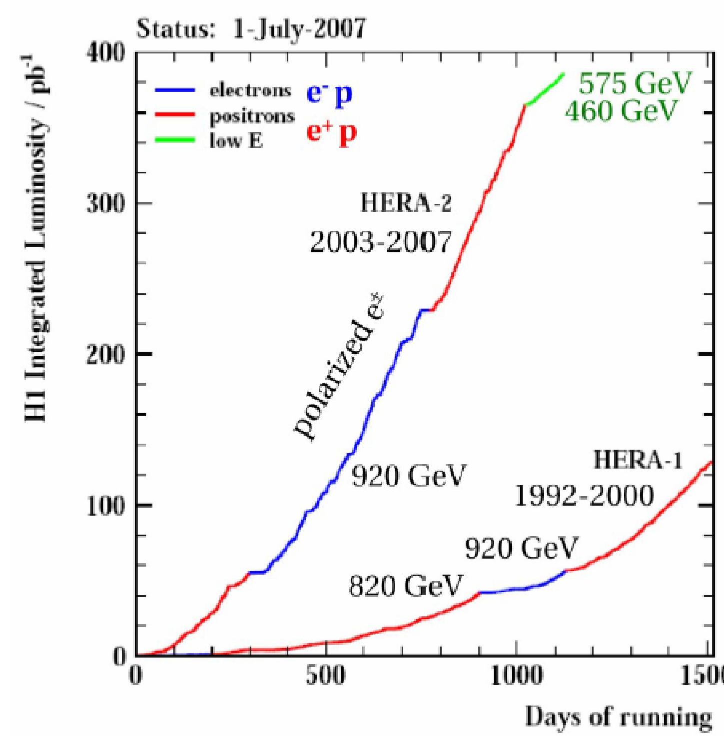
Longitudinal Photons more important in diffraction than in inclusive DIS

The world's only electron/positron-proton collider at DESY, Hamburg

E_e = 27.6 GeV E_p = 920 GeV (also 820, 460 and 575 GeV)

(total centre-of-mass energy of collision up to $\sqrt{s} \approx 320$ GeV)





Two collider experiments: <u>H1 and ZEUS</u>

HERA- the QCD machine

H1+ZEUS: extensive and precision studies of different aspects of QCD, Heavy Flavour production, Physics Beyond the Standard Model, Diffraction,…

HERA-1: 1992 – 2000

HERA-2: 2003 - 2007

total lumi: 0.5 fb^{-1} per experiment