Inclusive Diffraction at HERA

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on behalf of the
H1 and ZEUS Collaborations

Diffraction 2012

International Workshop on Diffraction in High-Energy Physics
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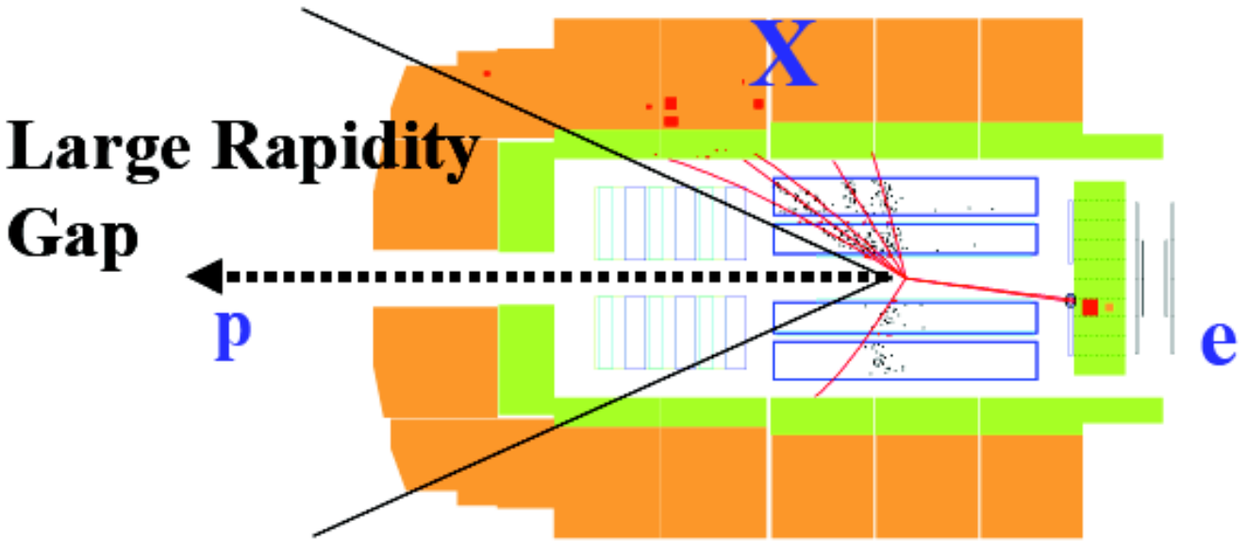
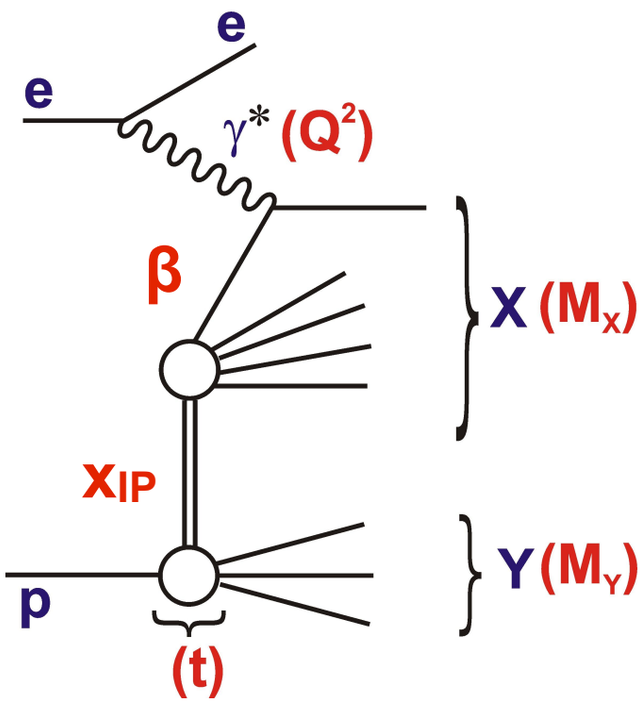
Diffractive DIS





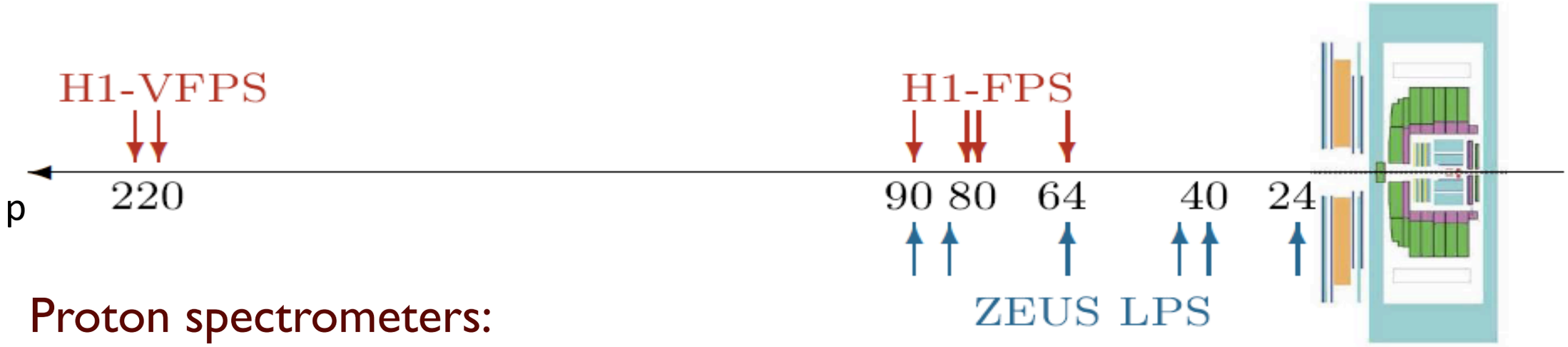
- Differential cross section:

$$\frac{\mathrm{d}^4\sigma^{ep\to eXp}}{\mathrm{d}\beta\mathrm{d}Q^2\mathrm{d}x_{I\!P}\mathrm{d}t} = \frac{4\pi\alpha^2}{\beta Q^4}\cdot\left(1-y+\frac{y^2}{2}\right)\cdot\sigma_r^{D(4)}(\beta,Q^2,x_{I\!P},t)$$

- Diffractive reduced cross-section (related to structure functions):

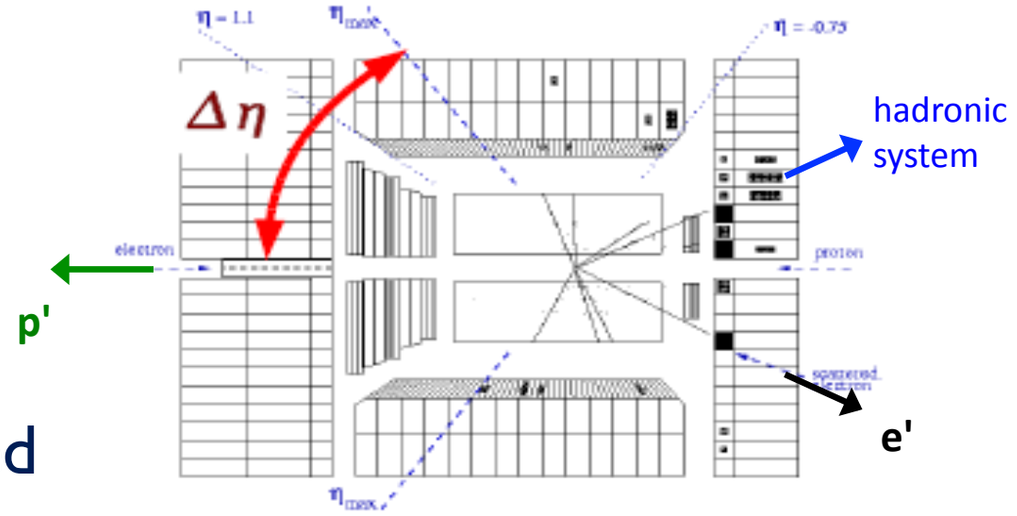
$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{1+(1-y)^2}\,F_L^{D(4)}$$

Selection of diffractive events



- Proton spectrometers:
  - Measures t
  - Less statistics
  - Proton tagging systematics

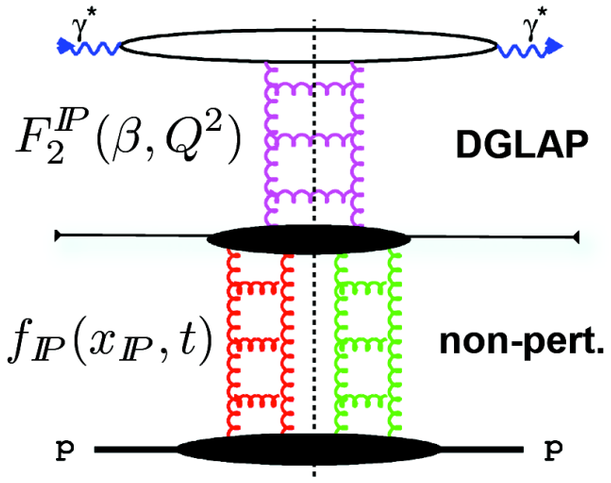
- Large Rapidity Gap:
  - Integrates over $|t| < 1\ \mathrm{GeV}^2$
  - More statistics
  - Proton dissociation needs to be controlled



- Different kinematical coverage

Theoretical views on diffraction

- Infinite momentum frame: partons

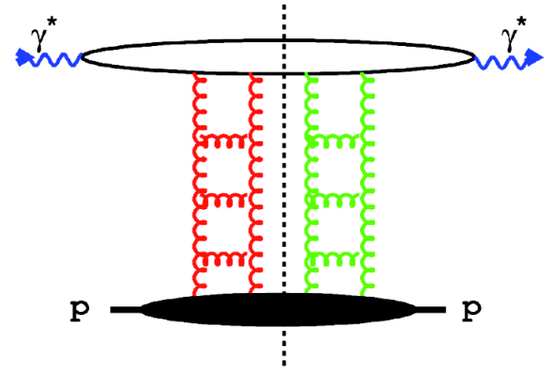


- Factorization is assumed.

$$F_2^D = f_{I\!P}(x_{I\!P}, t)\, F_2^{I\!P}(\beta, Q^2)$$
$$f_{I\!P} = \frac{e^{bt}}{x_{I\!P}^{2\alpha_{I\!P}-1}}$$

- Diffractive parton densities can be derived.

- Proton rest frame: dipoles



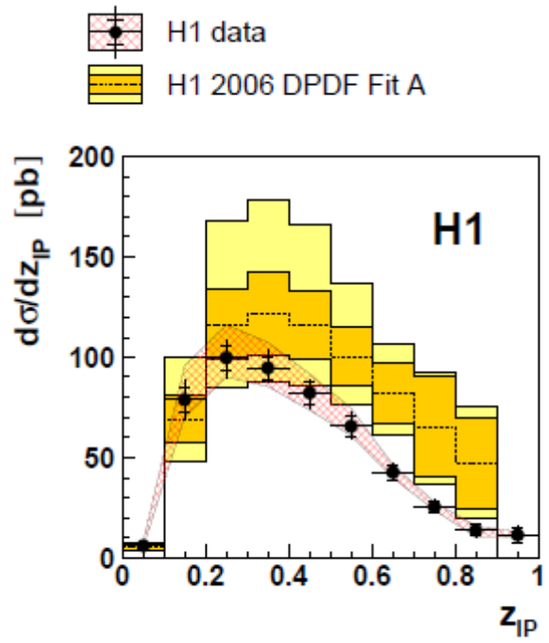
- Long-living quark pair interacts with the gluons from the proton.

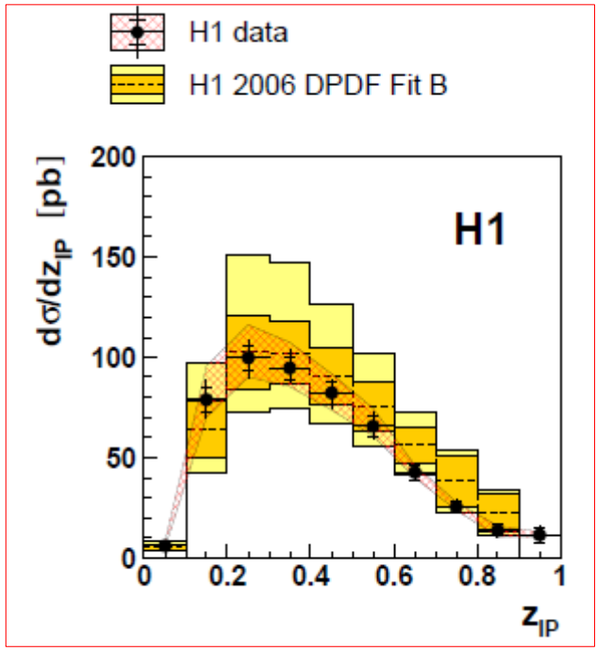
$$d\sigma_{diff}^{\gamma^* p}/dt \propto \int dz dr^2 \Psi^* \sigma_{qq}^2(x, r^2, t) \Psi$$

- Direct relation to inclusive DIS.
- Incorporates saturation dynamics.
- No extra parameters for diffraction are needed.

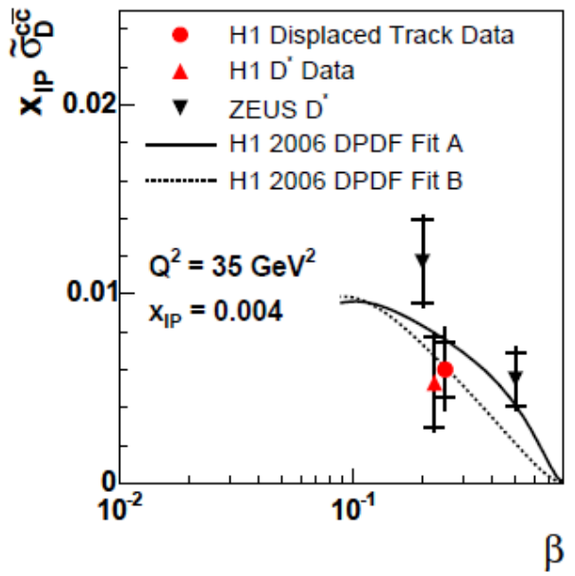
Tests of QCD factorization

- Diffractive dijets in DIS
  - Compatible with the parton densities from H1 2006 DPDF Fits.
  - QCD factorization holds.





- Diffractive charm production
  - Low statistics.

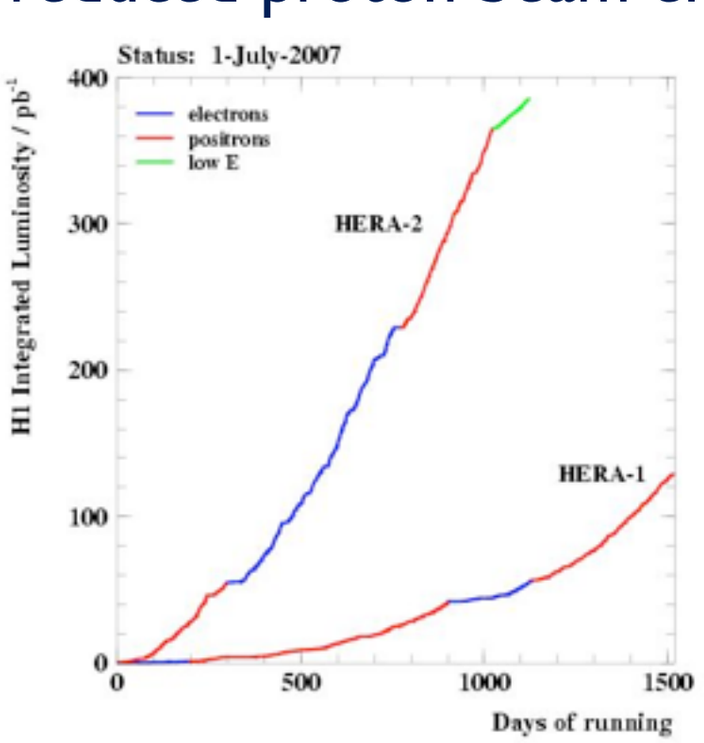


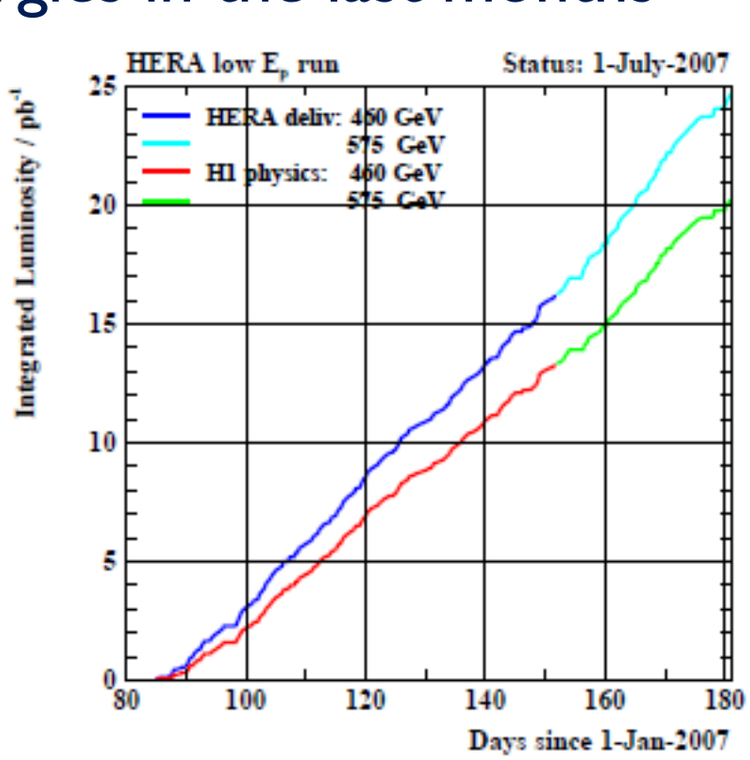
- FLD measurement
  - Probes low x_{IP} and β region inaccessible by dijets and D*.

$$F_L^D \sim x\, g(x)$$

HERA runs

- HERA operated in 1993 - 2007, colliding electrons or positrons at 27.5 GeV with protons.
- Nominal proton beam energy:
  - E_p = 820, 920 GeV (HERA-I phase)
  - E_p = 920 GeV (HERA-II phase)
- HERA was operating at reduced proton beam energies in the last months of data taking.
  - E_p = 460 GeV
  - E_p = 575 GeV





- The low energy data serve for the purposes of the FL and FLD measurements.

Precision LRG cross sections by H1

- H1 data from HERA-I and HERA-II are combined.
  [Eur. Phys. J. C72 (2012) 2074]

- Kinematical coverage:

  $3.5 < Q^2 < 1600$ GeV^2
  $0.0017 < \beta < 0.8$
  $0.0003 < x_{IP} < 0.03$

Data Set	Q^2 range (GeV^2)	Proton Energy E_p (GeV)	Luminosity (pb^{-1})
New data samples			
1999 MB	$3 < Q^2 < 25$	920	3.5
1999-2000	$10 < Q^2 < 105$	920	34.3
2004-2007	$10 < Q^2 < 105$	920	336.6
Previously published data samples			
1997 MB	$3 < Q^2 < 13.5$	820	2.0
1997	$13.5 < Q^2 < 105$	820	10.6
1999-2000	$133 < Q^2 < 1600$	920	61.6

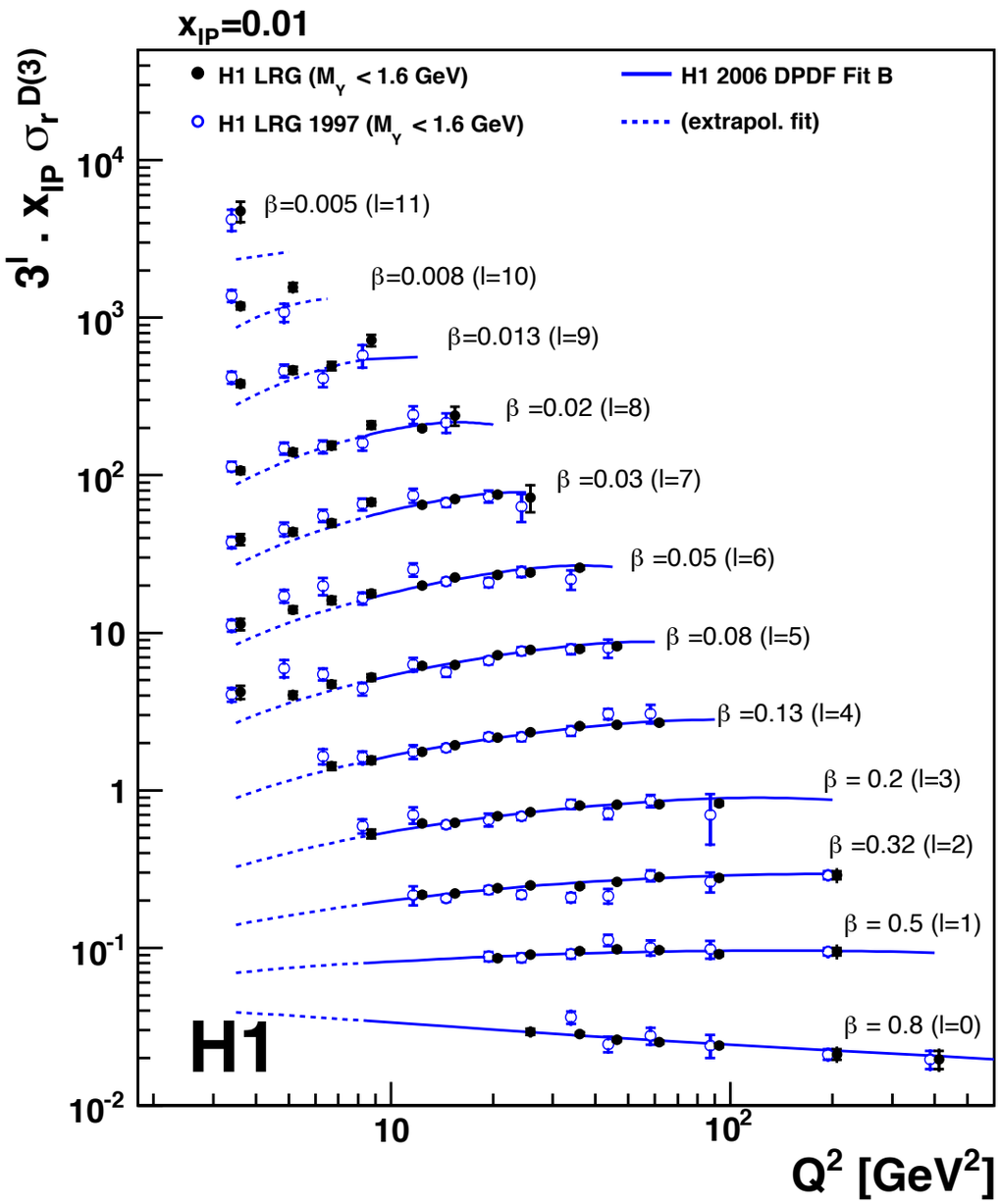
- Iterative χ^2 minimization is used for the combination.

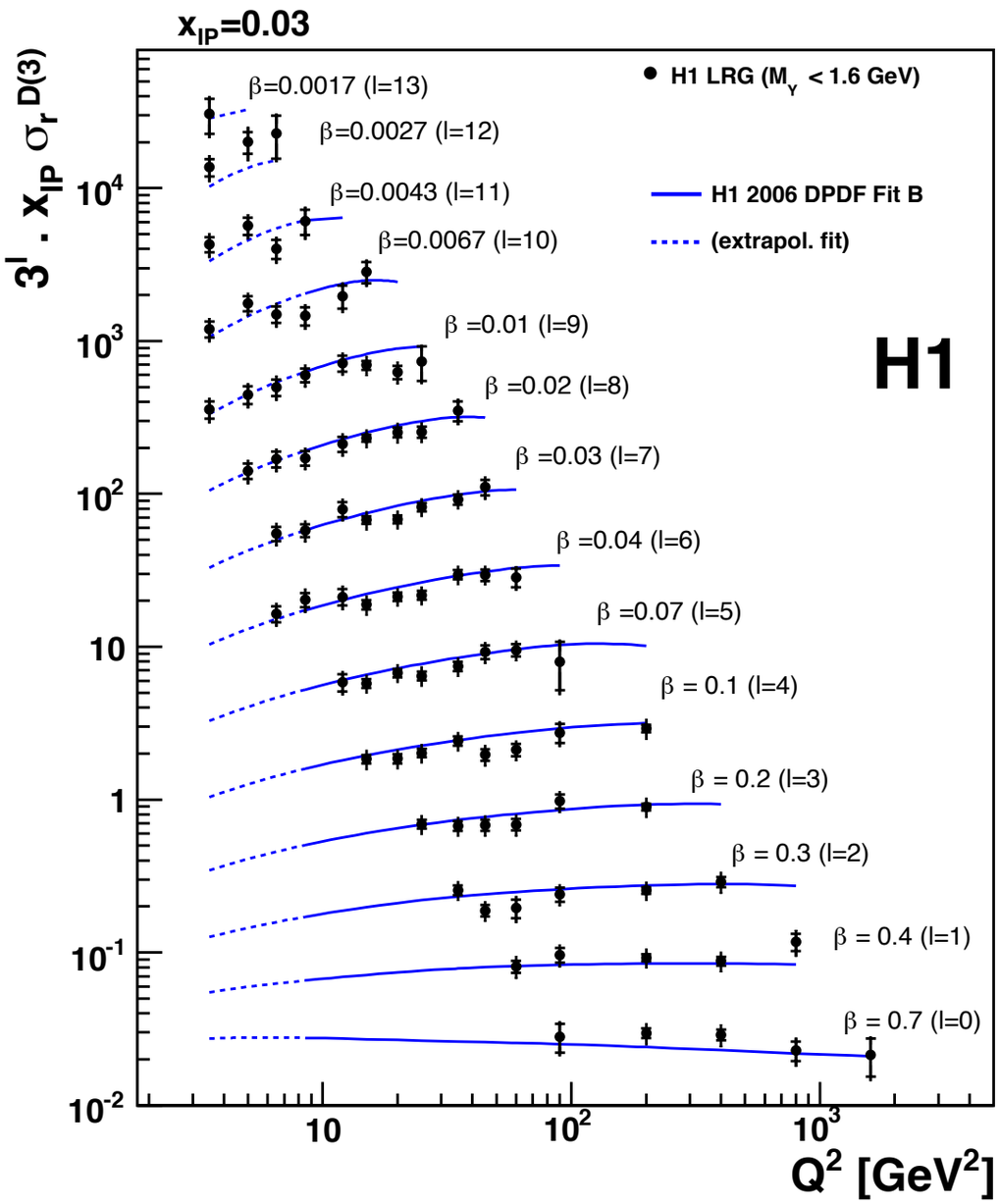
  $\chi^2/\text{ndf} = 371/320$

➡ The total uncertainty of the combined results is 4% to 7%.
(typically factor of 1.5 − 2 improvement in precision with respect to the previously published results)

Precision LRG cross sections by H1

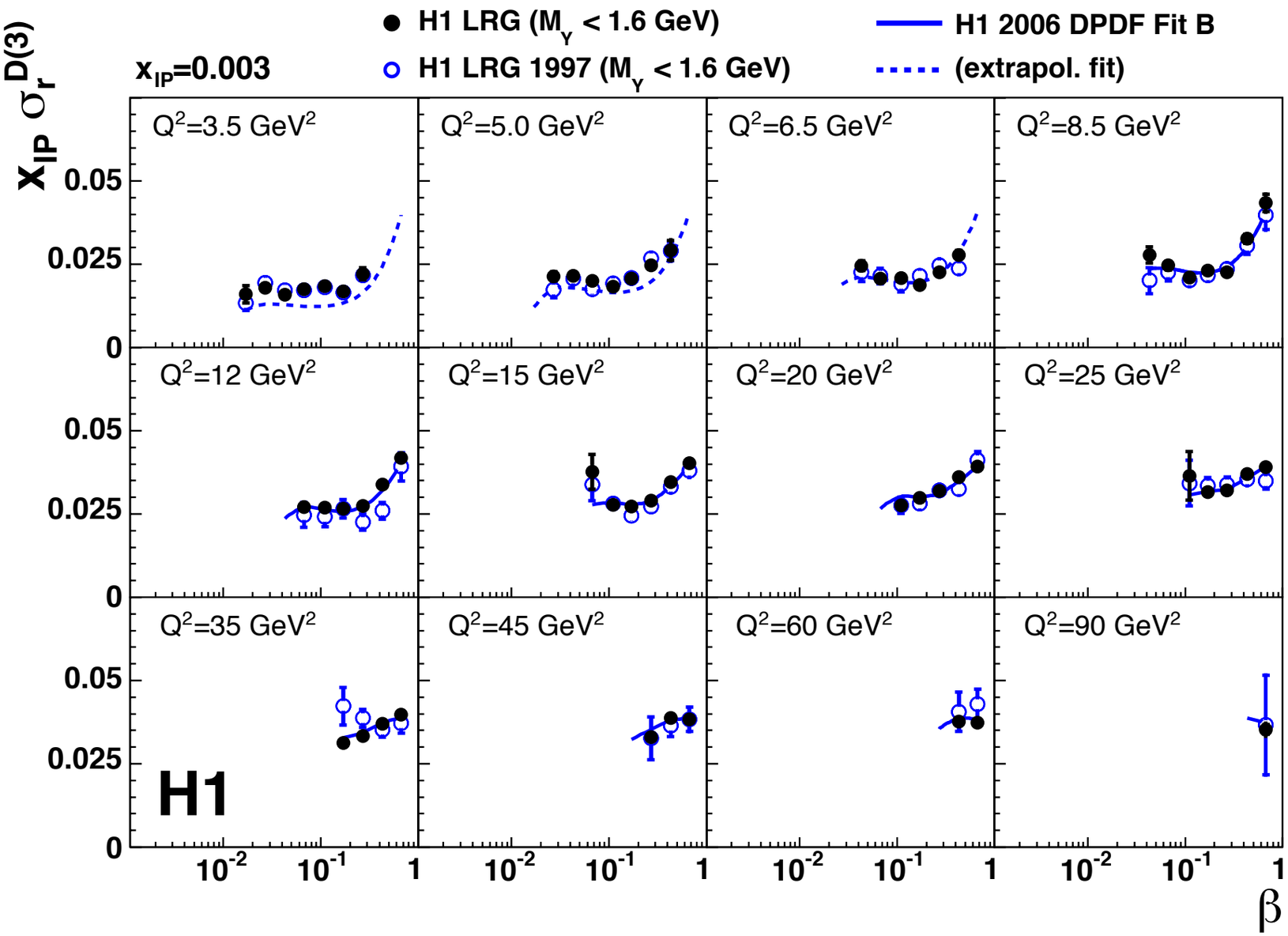
- Data are combined in four x_{IP} bins: 0.0003, 0.001, 0.003, 0.01
- At x_{IP} = 0.03, only the HERA I measurements exist.





H1 LRG measurements

- Example of β dependence compared to H1 DPDF Fit B.
- H1 2006 DPDF Fits are known to underestimate data at $Q^2 < 8.5$ GeV^2.
  [Eur. Phys. J. C48 (2006) 715-748]

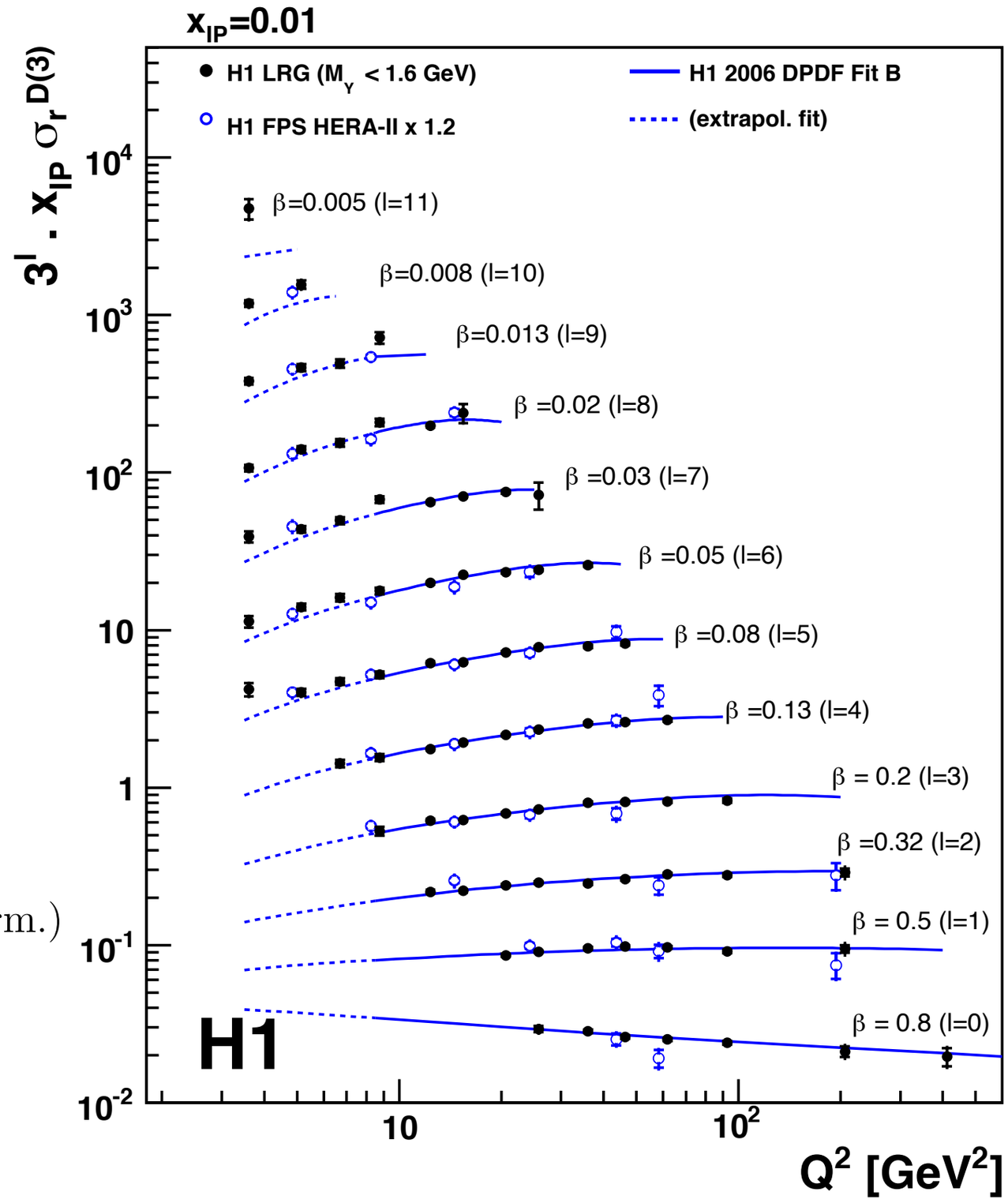


LRG and proton spectrometer results

- LRG selection also accepts diffractive events where the proton dissociates into a final state Y which is not detected due to the detector acceptance around the beam pipe.
- LRG measurements are corrected to $M_Y < 1.6$ GeV using Monte Carlo.
- Ratio of the LRG and the proton spectrometer results quantifies the contribution of the proton dissociation in LRG.

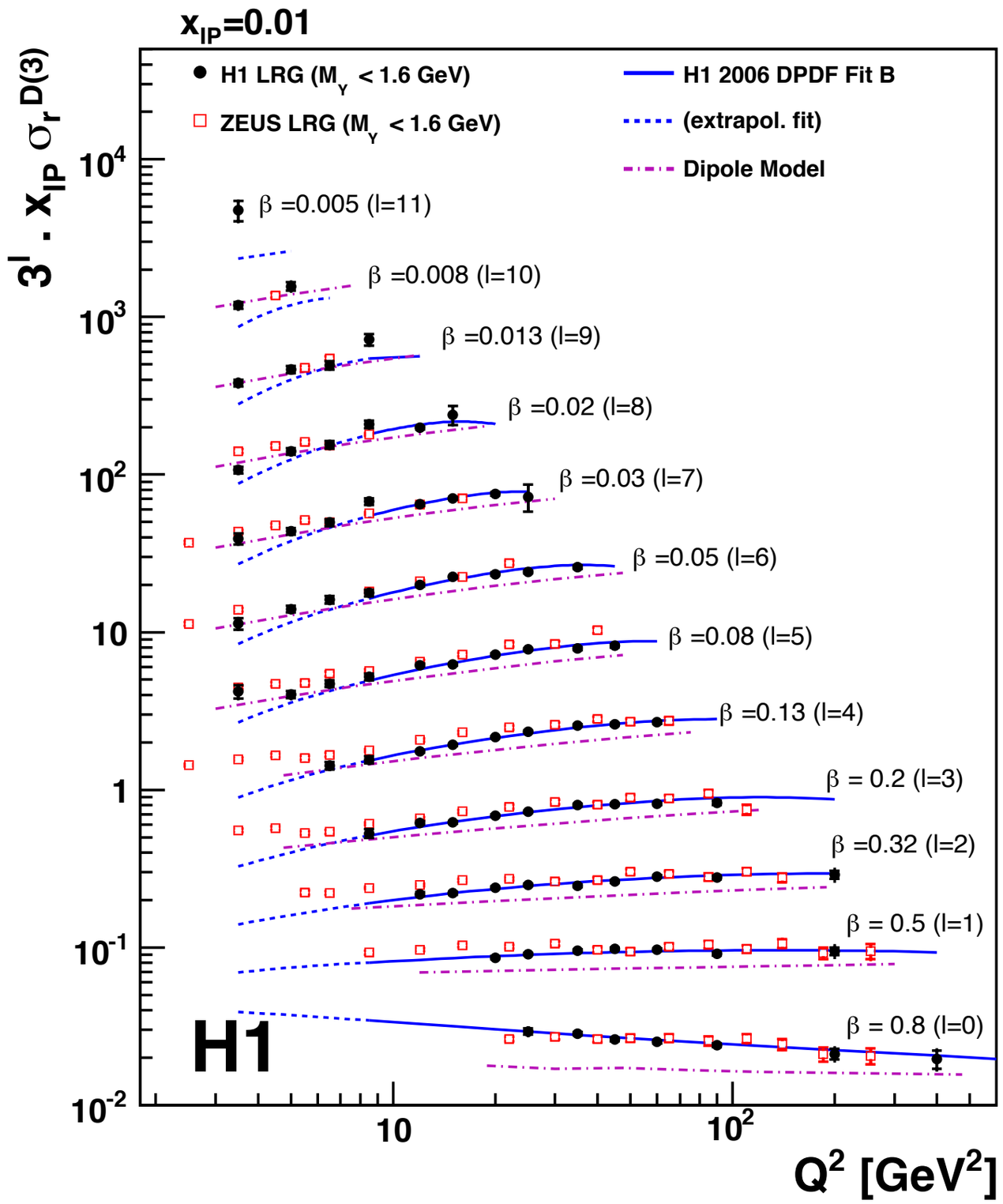
$$\frac{\sigma\left(M_Y < 1.6\,\mathrm{GeV}\right)}{\sigma\left(Y = p\right)} = 1.203 \pm 0.019(\mathrm{exp.}) \pm 0.087(\mathrm{norm.})$$

➡ No Q^2 or β dependence observed.



H1 and ZEUS LRG measurements

- Good agreement between H1 and ZEUS in general.
- ~10% normalization difference (within the uncertainties).
- H1 DPDF Fit B, obtained from a QCD fit to the H1 LRG HERA-1 data, works well at high Q^2.
- Dipole model gives better description at low Q^2 but fails at high Q^2.



Pomeron trajectory

- Regge fit to LRG cross section:

$$F_2^{D(3)}(Q^2,\beta,x_{I\!P}) = f_{I\!P/p}(x_{I\!P})\ F_2^{I\!P}(Q^2,\beta) + n_{I\!R}\ f_{I\!R/p}(x_{I\!P})\ F_2^{I\!R}(Q^2,\beta)$$

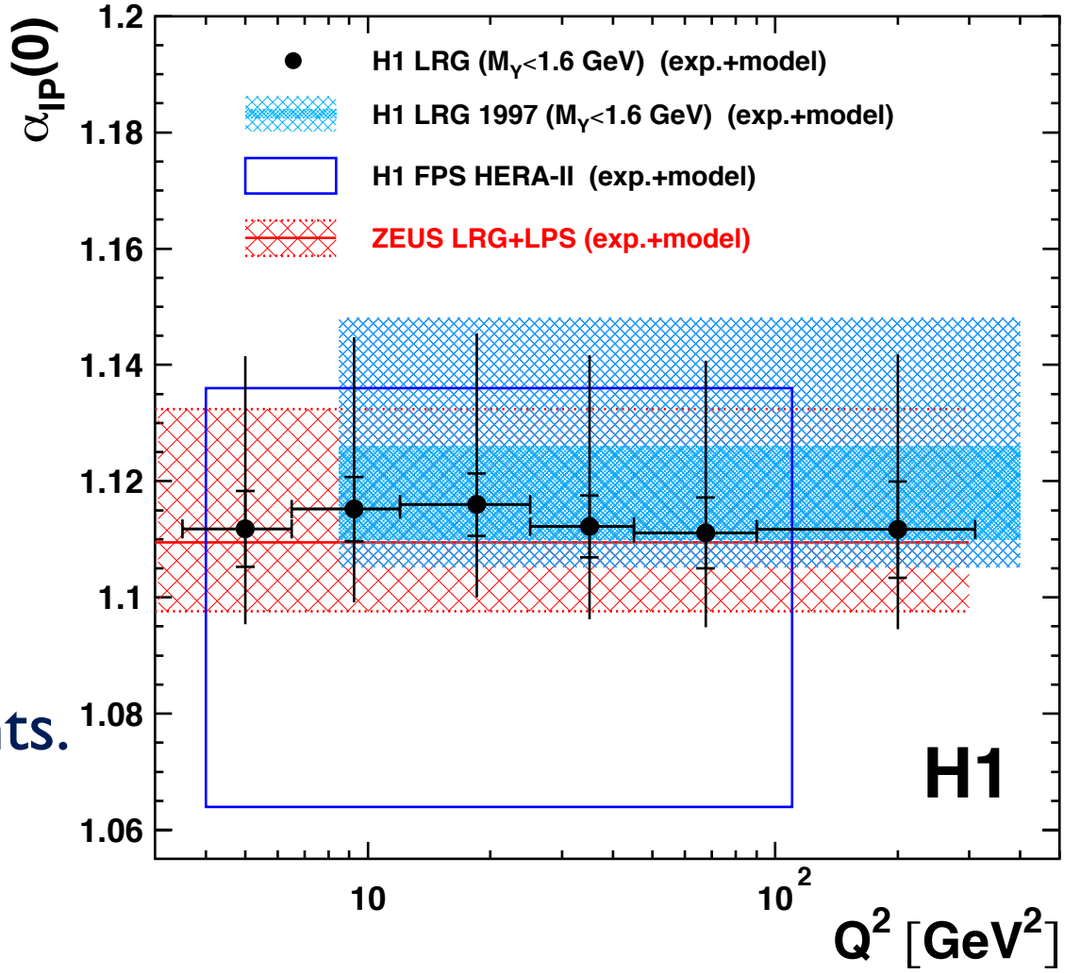
$$f_{I\!P/p,I\!R/p}(x_{I\!P}) = \int_{t_{cut}}^{t_{min}} \frac{e^{B_{I\!P,I\!R}t}}{x_{I\!P}^{2\alpha_{I\!P,I\!R}(t)-1}}\mathrm{d}t$$

$$\alpha_{I\!P,I\!R}(t) = \alpha_{I\!P,I\!R}(0) + \alpha'_{I\!P,I\!R}t$$

➡ Mean value of the pomeron intercept:

$$\alpha_{I\!P}(0) = 1.113\ \pm 0.002\ (\mathrm{exp.})\ ^{+0.029}_{-0.015}\ (\mathrm{model})$$

- Independent of Q^2 (within the statistical uncertainties).
- Good agreement of all HERA measurements.
- Supports the proton vertex factorization.

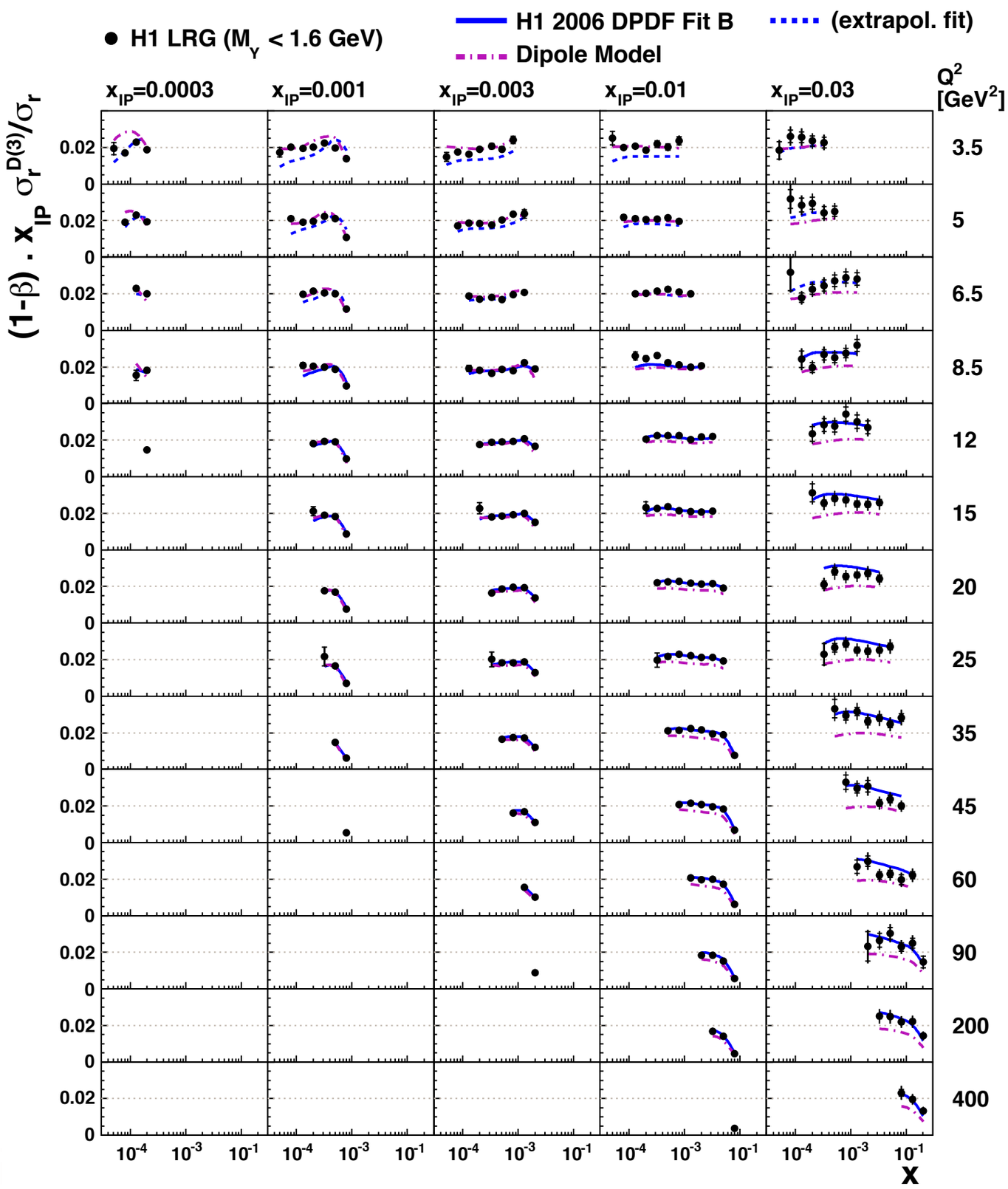


Ratio to inclusive DIS

- Assuming proton vertex factorization, the ratio is expected to be independent of Q2.

$$\frac{\sigma_r^{D(3)}(x_{I\!P}, x, Q^2)}{\sigma_r(x, Q^2)} \cdot (1-\beta)\, x_{I\!P}$$

- The ratio is flat in x, apart at highest β.
- This trend is reproduced by both DPDF and dipole model predictions.
- Ratio of quarks and gluons is similar in diffractive and inclusive DIS.

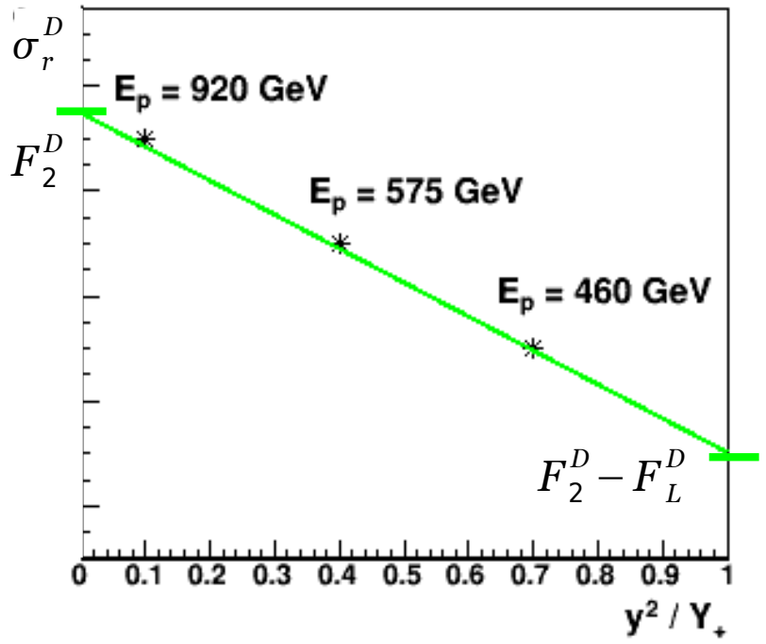


FLD measurement

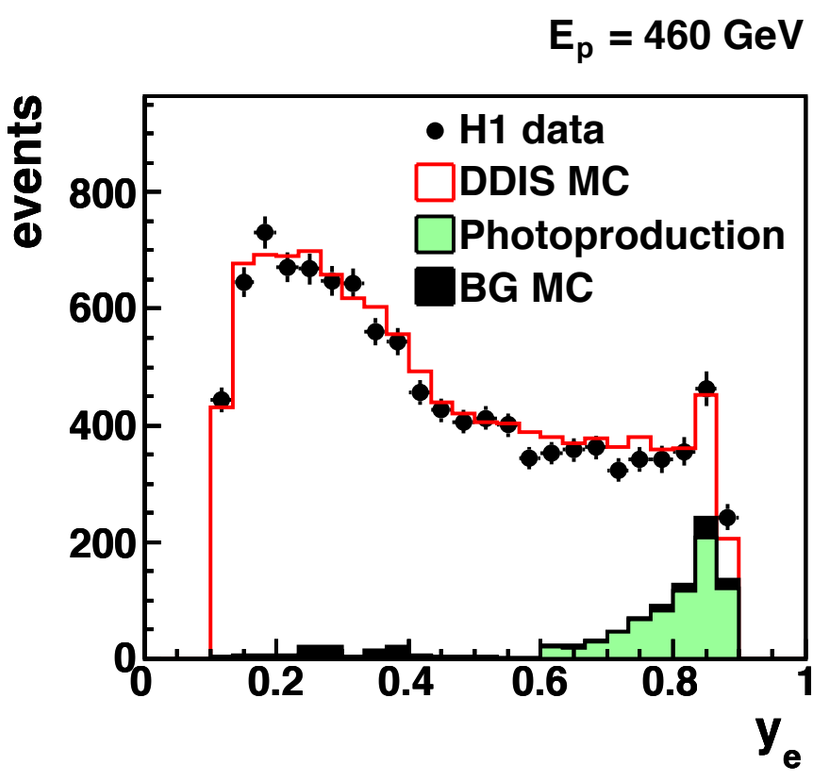
- FLD is sensitive to gluons and provides an independent test of QCD factorization.
- The FLD and F2D structure functions can be separated only by combining measurements at different y (for fixed x_{IP}, β, Q^2).

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

$$Q^2 = x_{IP}\, \beta\, y\, s$$



- Data at different centre-of-mass energy are needed.
- Highest sensitivity to FLD is at high y (low β).
- Challenging measurement due to high level of photoproduction background.



FLD extraction

- The following data sets are used:

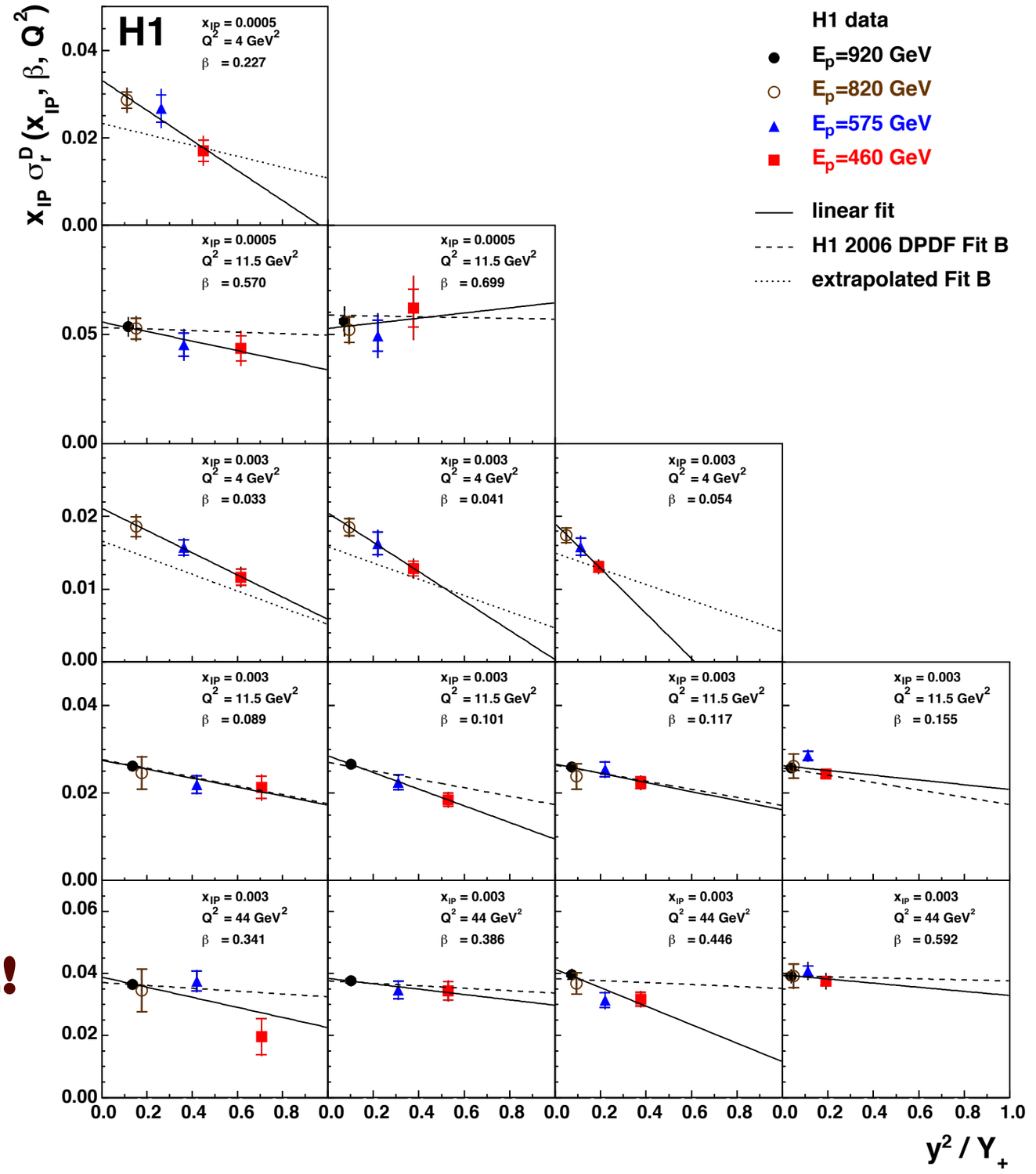
  E_p = 820 GeV 13 pb^{-1}
  E_p = 920 GeV 127 pb^{-1}
  E_p = 460 GeV 9 pb^{-1}
  E_p = 575 GeV 5 pb^{-1}

➡ Diffractive reduced cross-sections are measured in bins of x_{IP}, β, Q^2:

  x_{IP} = 0.0005, 0.003
  Q^2 = 4, 11.5, 44 GeV^2

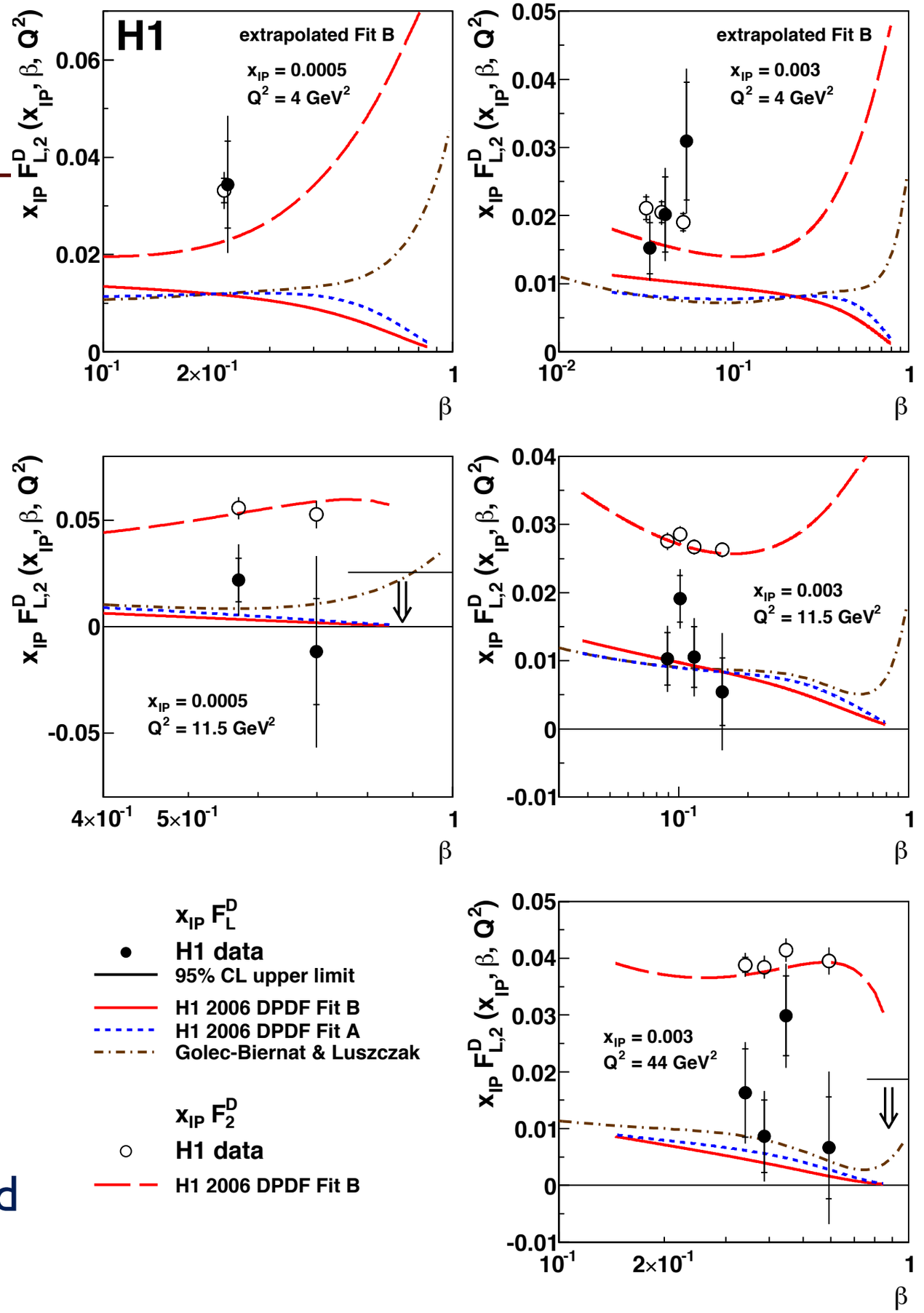
- Data cross-sections are sensitive to FLD at high y (low β).

➡ **First direct FLD measurement!**
[Eur.Phys.J. C72 (2012) 1836]

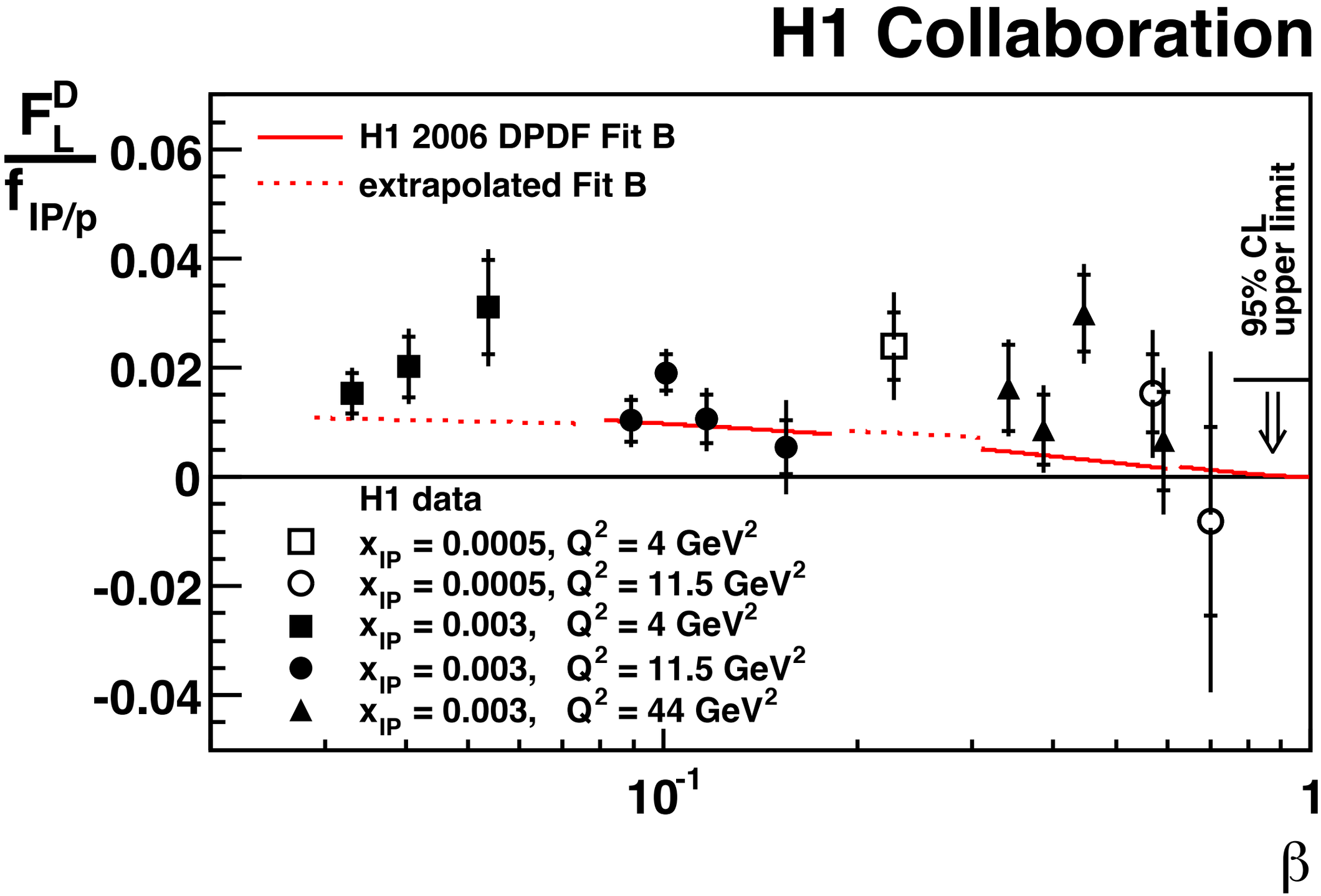


FLD and F2D

- FLD and F2D is measured in bins of x_{IP}, β, Q^2 at:
  - $x_{IP} = 0.0005,\ 0.003$
  - $Q^2 = 4,\ 11.5,\ 44\ \text{GeV}^2$
  - $0.033 < \beta < 0.7$
- For $Q^2 \geq 11.5\ \text{GeV}^2$, the measurements are consistent with H1 DPDF Fits but also models considering higher twist longitudinal contributions to diffraction.
- There are significant non-zero FLD measurements in each x_{IP}, Q^2 bin.
- **Five FLD points are greater than 0 by more than 3σ.**
- Upper limits on FLD and F2D at the 95% confidence level are derived at the highest β bins (at $\beta = 0.76$).

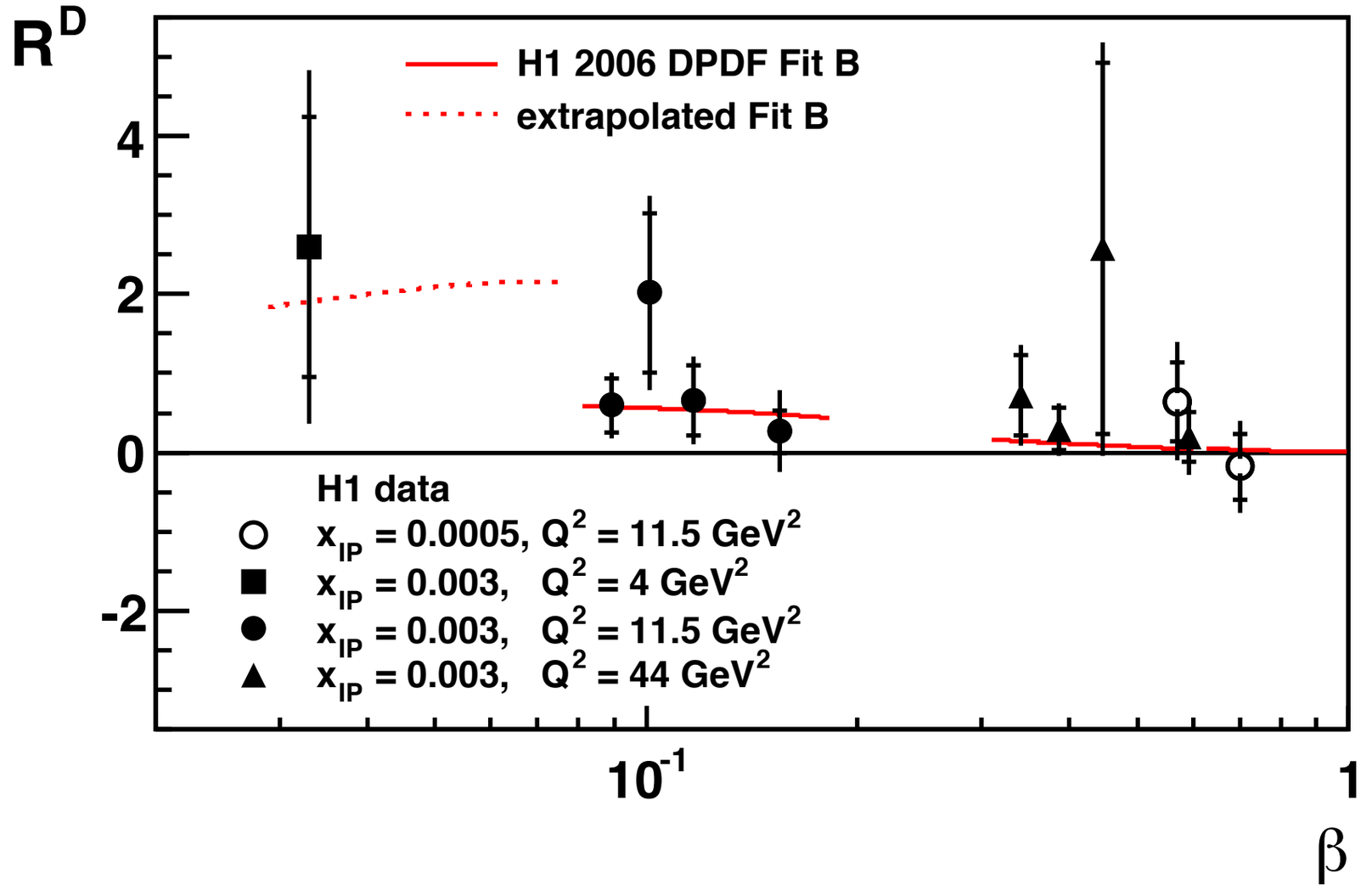


FLD results


H1 Collaboration
$F_L^D / f_{IP/p}$
H1 2006 DPDF Fit B
extrapolated Fit B
95% CL upper limit
0.06
0.04
0.02
0
-0.02
-0.04
H1 data
x_{IP} = 0.0005, Q^2 = 4 GeV^2
x_{IP} = 0.0005, Q^2 = 11.5 GeV^2
x_{IP} = 0.003, Q^2 = 4 GeV^2
x_{IP} = 0.003, Q^2 = 11.5 GeV^2
x_{IP} = 0.003, Q^2 = 44 GeV^2
10^{-1}
1
β

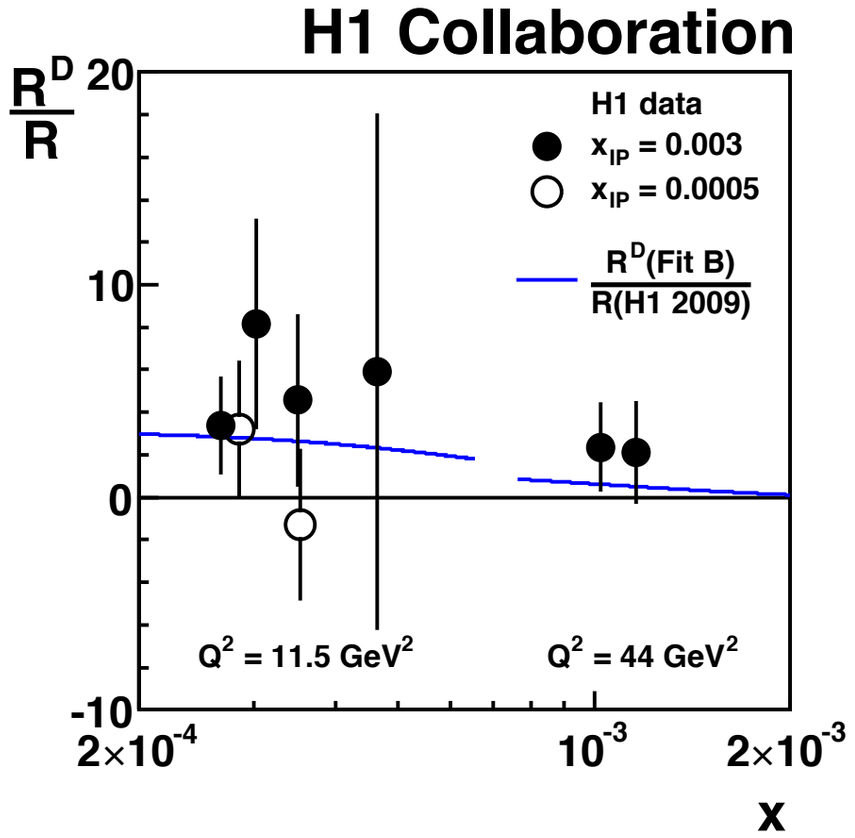
Photoabsorption ratio for diffraction

$$R^D = F_L^D/(F_2^D - F_L^D)$$



- Data are compatible with H1 2006 DPDF Fit B.
- Data at Q^2 = 11.5 GeV^2 indicate that the longitudinally and transversely polarized photon cross-sections are of the same order of magnitude (RD ~ 1 and F2D ~ 2·FLD).

Ratio R^D/R



- Ratio R^D/R quantifies relative importance of longitudinally and transversely polarized photons in inclusive and diffractive scattering.
- Data are reproduced by H1 2006 DPDF Fit B and H1 PDF 2009.
- $R^D/R = 2.8 \pm 1.1$
- Longitudinally polarized photon contribution plays larger role in diffraction than in the inclusive case.

Summary

- H1 precision LRG measurement using the full dataset is available.
- Overall good agreement between H1 and ZEUS results.
- 20% difference is observed between the LRG and proton spectrometer results due to the proton dissociation.

- H1 has performed the first direct measurement of FLD.
- The results are compatible with the DPDF fits and models considering higher twist longitudinal contributions to diffraction.
- Longitudinally polarized cross section plays larger role in diffraction than in the inclusive case.

- HERA measurements support the proton vertex and QCD factorization.

backup

Diffractive Reduced Cross-Sections

- Diffractive reduced cross-sections are measured in bins of x_{IP}, β, Q^2:

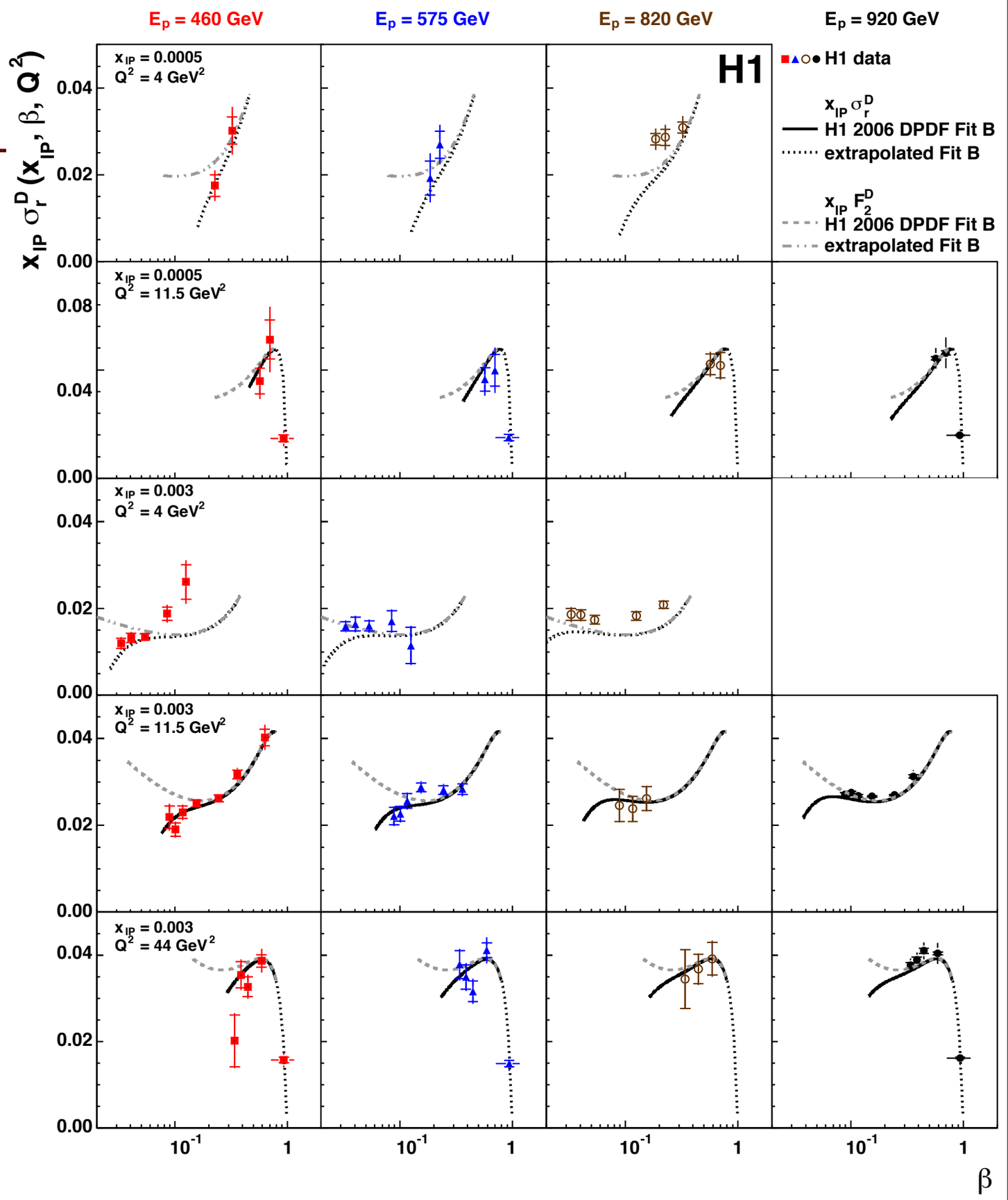
  x_{IP} = 0.0005, 0.003
  Q^2 = 4, 11.5, 44 GeV^2

- Only the average cross-section is given in the highest β bin.

- H1 2006 DPDF Fits are known to underestimate data at $Q^2 < 8.5$ GeV^2. (DESY-06-048)

- Data cross-sections are sensitive to FLD at high y (low β).

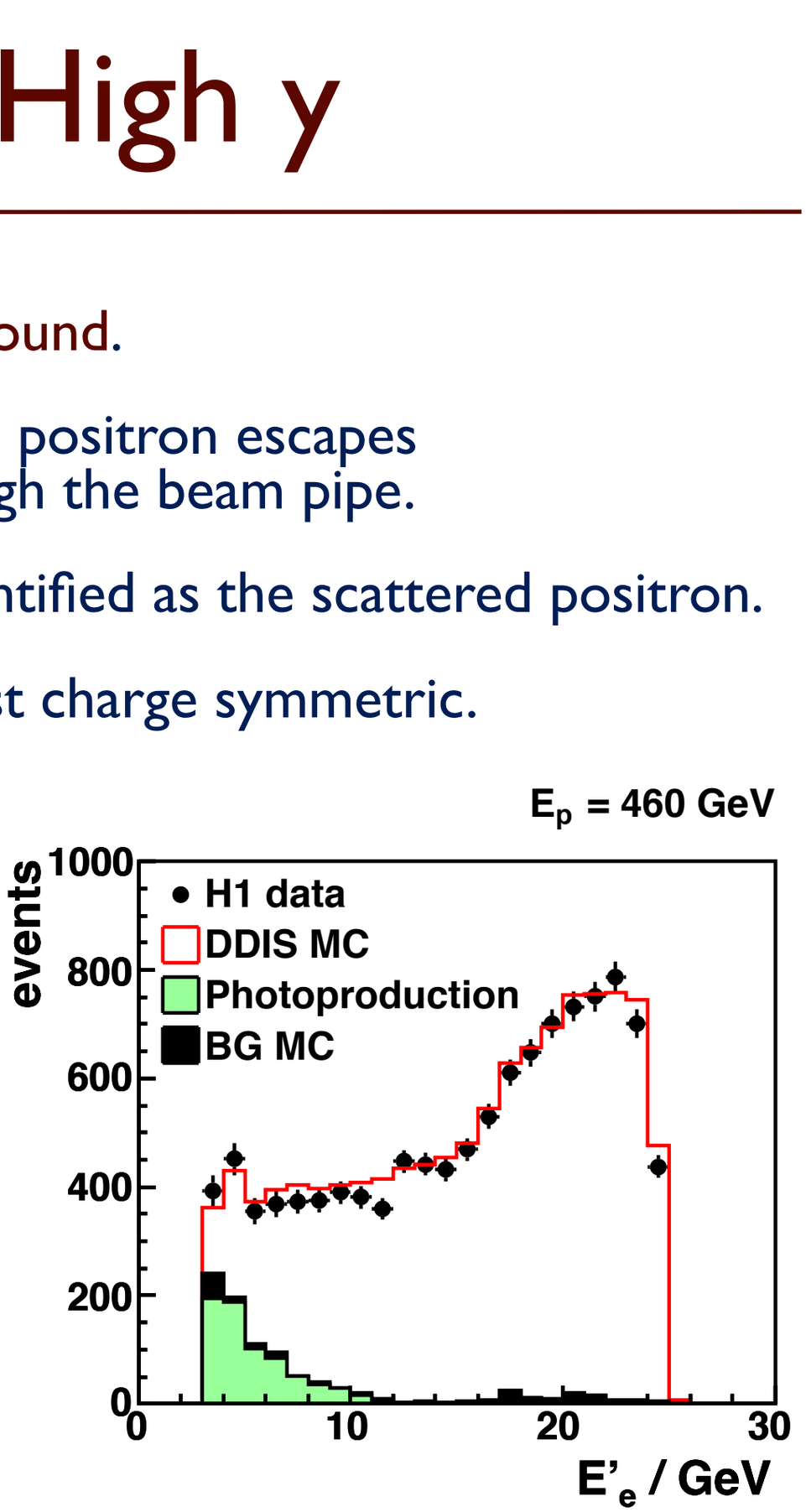
- Data support the hypothesis that $\sigma_r^D \to 0$ as $\beta \to 1$.



Background at High y

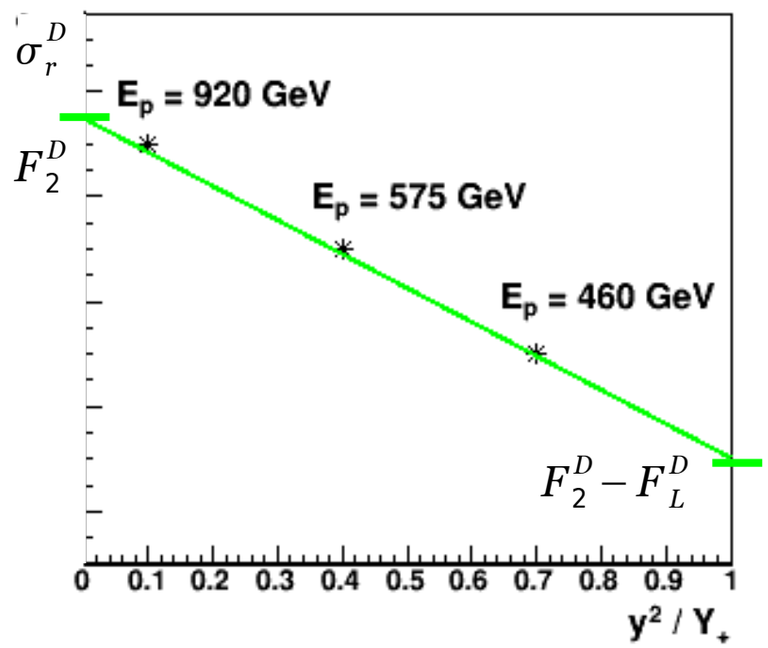
- Data at high y contain photoproduction background.
  - In photoproduction processes, the scattered positron escapes from the central detector undetected through the beam pipe.
  - Hadronic final state particles can be mis-identified as the scattered positron.
  - Background from hadronic particles is almost charge symmetric.

- Photoproduction background is subtracted in a data-driven way using the reconstructed charge of the scattered positron candidate.
  - N^+ = signal events + background from π^+
  - N^- = background from π^-
  - $N_{signal} = N^+ - N^-$



Normalization of Data Sets

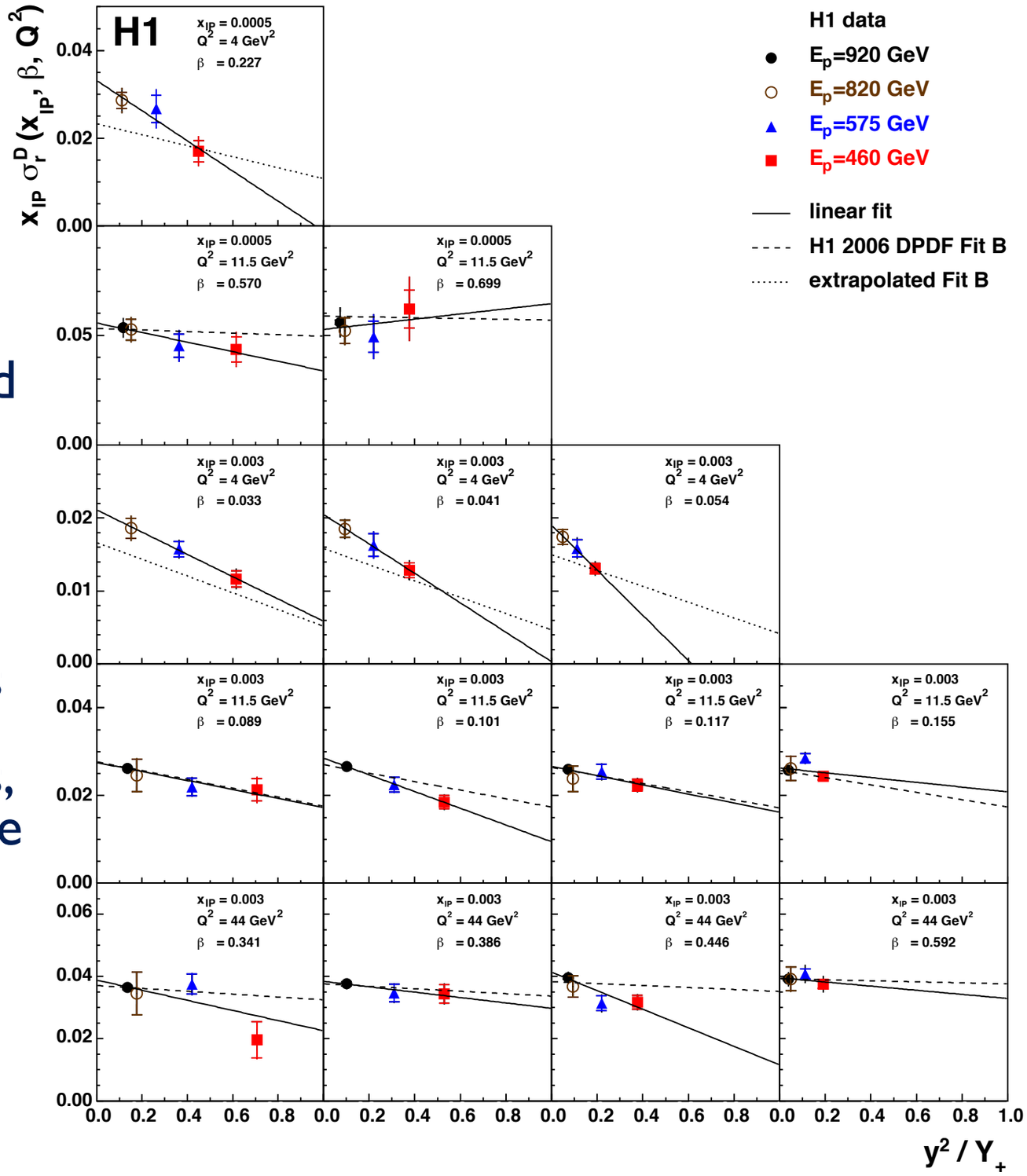
- Luminosity is measured with 3% (4%) precision for E_p = 920 (460, 575) GeV data.
- Due to the acceptance of the forward detectors near the beam-pipe, the Large Rapidity Gap selection accepts events with dissociated protons up to $M_Y \sim 1.6$ GeV.
- The data cross-section measurements are corrected to $M_Y < 1.6$ GeV, $|t| < 1$ GeV^2 using simulation.
- Systematic uncertainty on this correction is 7% and it is strongly correlated between the data sets.



- For optimal extraction of FLD, the cross-section measurements at low y (where the sensitivity to FLD is minimal) are normalized to H1 2006 Fit B.
- Normalization factors of 0.97, 0.99, 0.97 are needed for E_p = 460, 575, 920 GeV.
- The E_p = 820 GeV data set is already consistently normalized as it was used to determine H1 2006 DPDF Fit B.

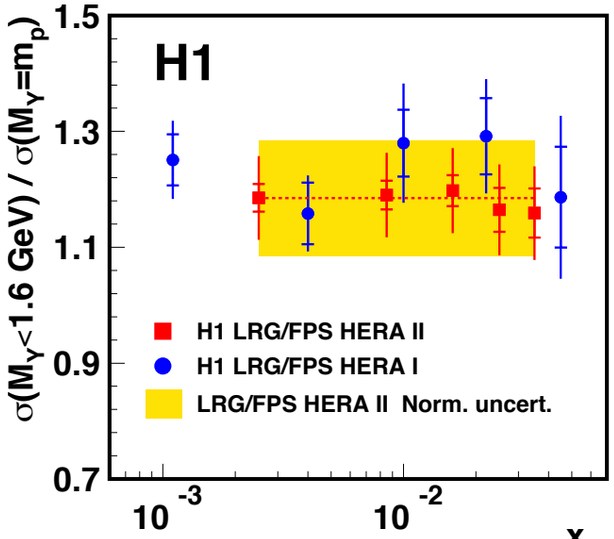
Extraction of FLD and F2D

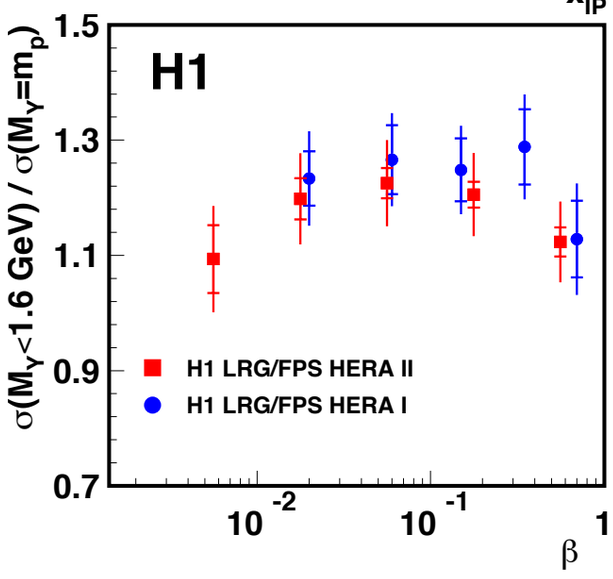
- FLD and F2D are extracted as parameters of a linear fit in the Rosenbluth plots.
- Errors on FLD and F2D are evaluated in the fits to the cross-section measurements with:
  - statistical errors only
  - statistical and uncorrelated errors
  - statistical and uncorrelated errors, where the cross-section points are shifted up and down for each correlated systematic uncertainty (offset method)

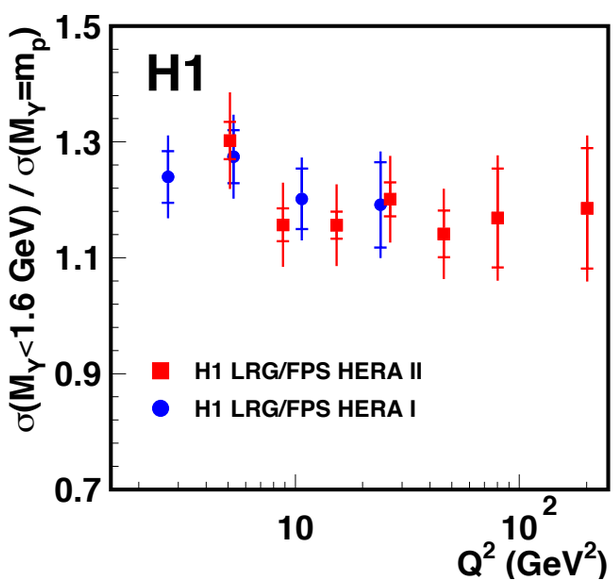


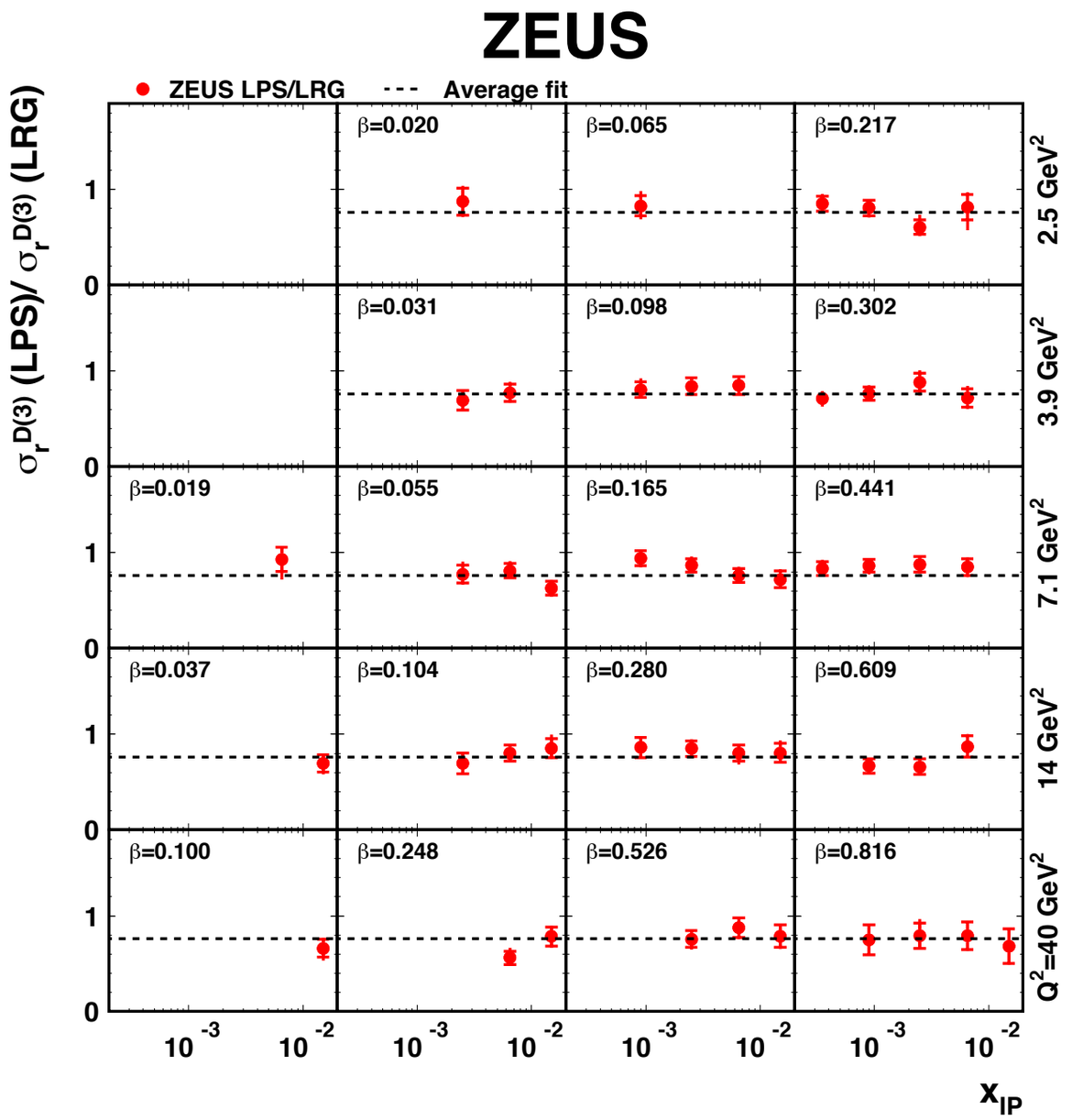
LRG and proton spectrometer results

- Ratio of the LRG and the proton spectrometer results quantifies the contribution of the proton dissociation in LRG.
- Both H1 and ZEUS measure constant ratio.





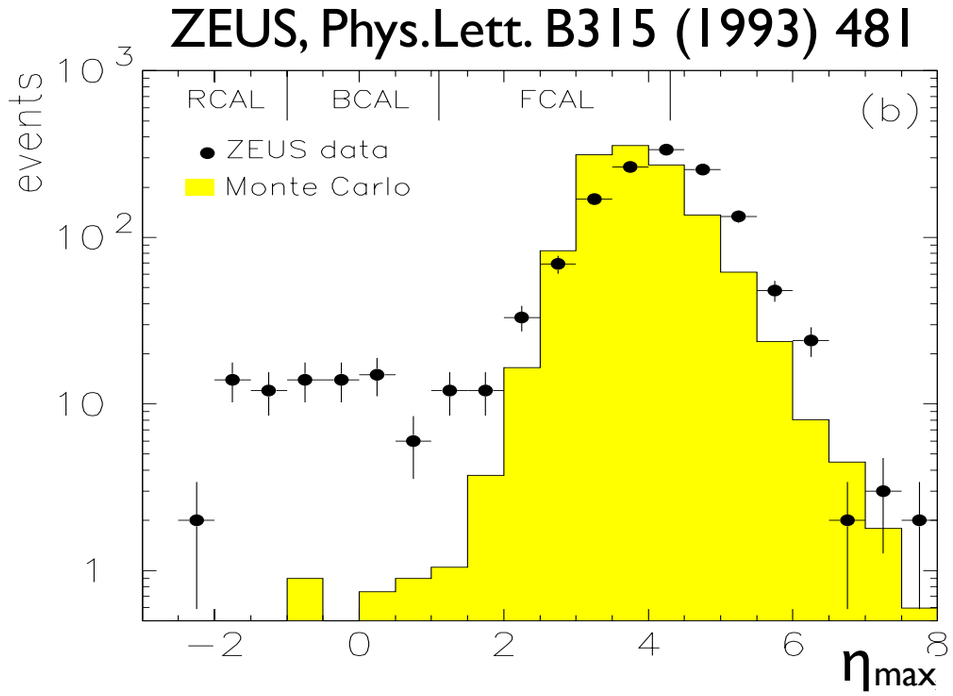




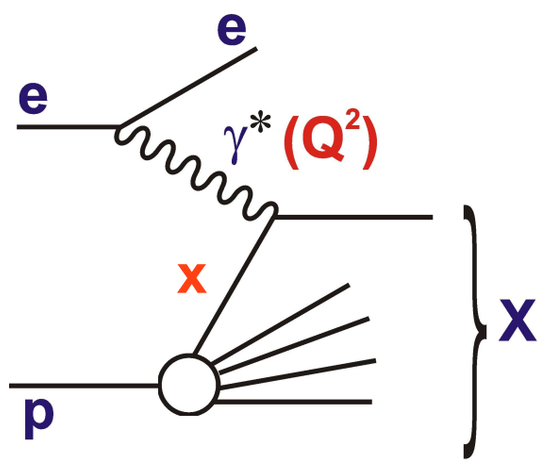
Diffraction at HERA

- It was a surprise at HERA to see that ~10% of inclusive DIS events have a large gap in rapidity in the forward direction.

➡ diffractive events



- Standard DIS: **ep → e'X**



- Diffractive DIS: **ep → e'Xp'**