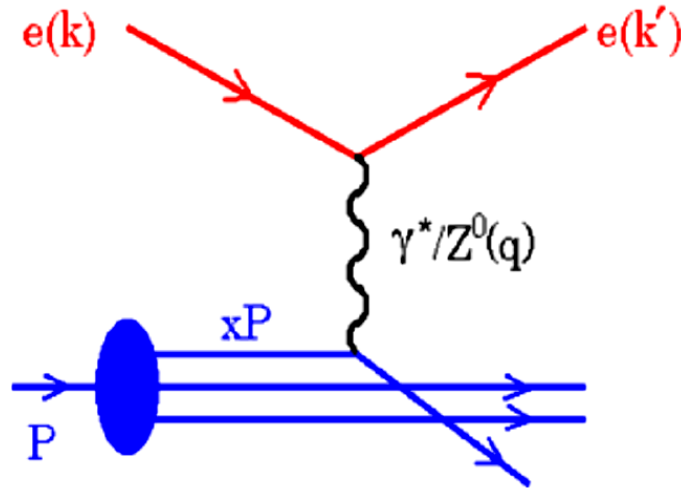# Precision Measurements of the Proton Structure by H1 and ZEUS

S. Glazov, DESY,
for H1 and ZEUS collaborations
DIS 2011

Proton structure probe

Neutral current Deep Inelastic Scattering (DIS) cross section:

$$\frac{d^2\sigma^\pm}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x}\sigma_r^\pm =$$

$$= \frac{2\pi\alpha^2 Y_+}{Q^4 x}\left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3\right]$$

where factors $Y_\pm = 1 \pm (1-y)^2$ and y^2 define polarisation of the exchanged boson and $y = Q^2/(S\,x)$.

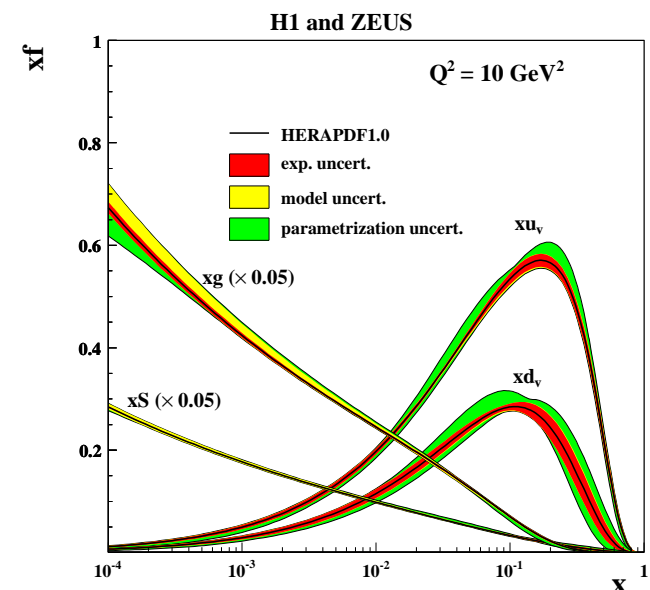Kinematics is determined by boson virtuality Q^2 and Bjorken x.

At leading order:

$$F_2 = x\sum e_q^2(q(x) + \bar{q}(x))$$

$$xF_3 = x\sum 2e_q a_q(q(x) - \bar{q}(x))$$

$$\sigma_{CC}^+ \sim x(\bar{u} + \bar{c}) + x(1-y)^2(d+s)$$
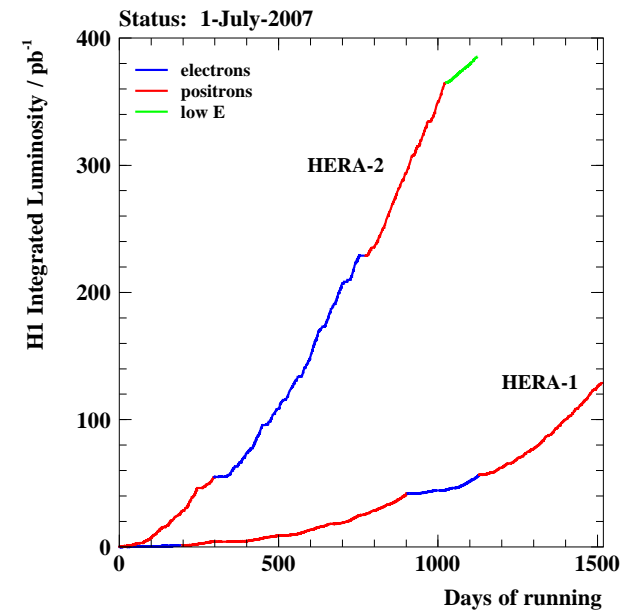
$$\sigma_{CC}^- \sim x(u+c) + x(1-y)^2(\bar{d}+\bar{s})$$

$xg(x)$ — from F_2 scaling violation, jets and F_L

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HERA, H1 and ZEUS.

$$E_e \times E_p = 27.5 \times 920 \, \text{GeV}^2$$

$$\sqrt{s} = 318 \, \text{GeV}$$

$$L = 5 \cdot 10^{31} \, \text{cm}^{-2} \text{s}^{-1}$$

e beam polarisation.

Integrated luminosity: about 500 pb^{-1} per experiment.

Overview of H1 and ZEUS Results

- High Q^2, high x.
  - Combined Measurement of Neutral and Charged Current Cross Sections at HERA, H1prelim-10-141 ZEUS-prel-10-017
  - PDF fits including HERA-II high Q^2 data, H1prelim-10-142 ZEUS-prel-10-018
  - High Q^2 NC and CC e^+p measurement using HERA-II data. ZEUS-prel-11-003.
  - Measurement of neutral current (e^+p) cross sections at high x using HERA-II data, ZEUS-prel-11-004

- Low Q^2, low x.
  - Measurement of the Inclusive $e^\pm p$ Scattering Cross Section at High Inelasticity y and of the Structure Function F_L. H1 Collaboration, Eur.Phys.J.C71 (2011) 1579, 12/10

- Fits using exclusive final states
  - QCD Analysis of Combined H1 and ZEUS F_2^{cc} Data, H1prelim-10-143 ZEUS-prel-10-019
  - Jets at high Q^2, H1prelim-11-0xx
  - Jet cross sections used in PDF Fit, H1prelim-11-034, ZEUS-11-001
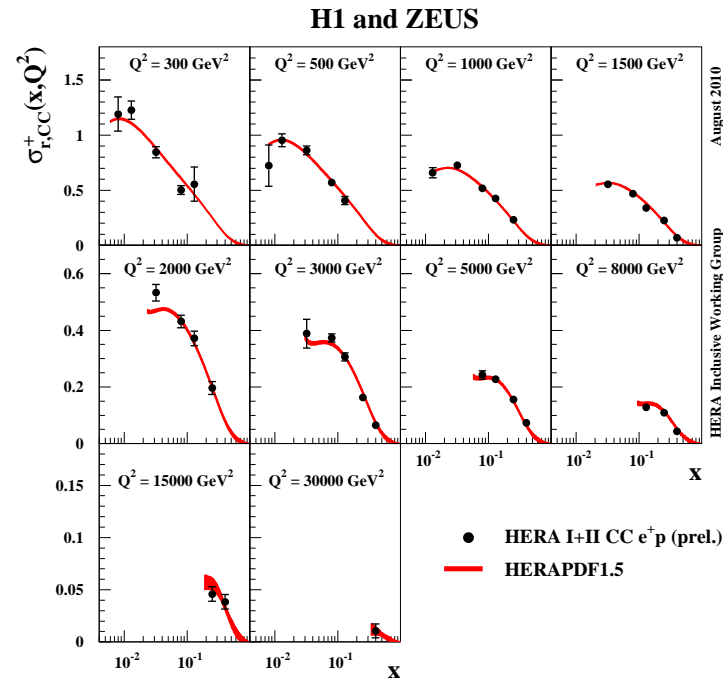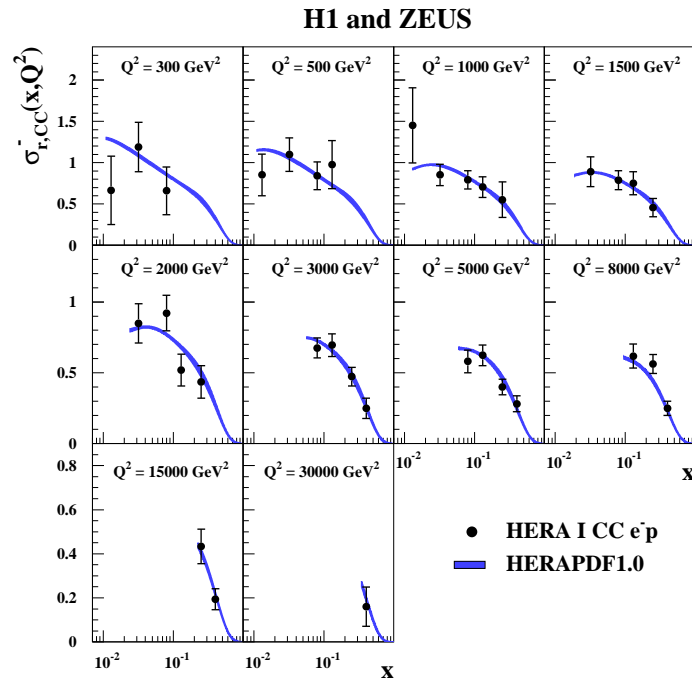
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High Q^2, high x

(H1prelim-10-141,ZEUS-prel-10-017),
(H1prelim-10-142,ZEUS-prel-10-018), ZEUS-prel-10-018,
ZEUS-prel-11-004

(Also talks of J. Sztuk-Dambietz, A. Caldwell, S. Trevor, I. Singh)

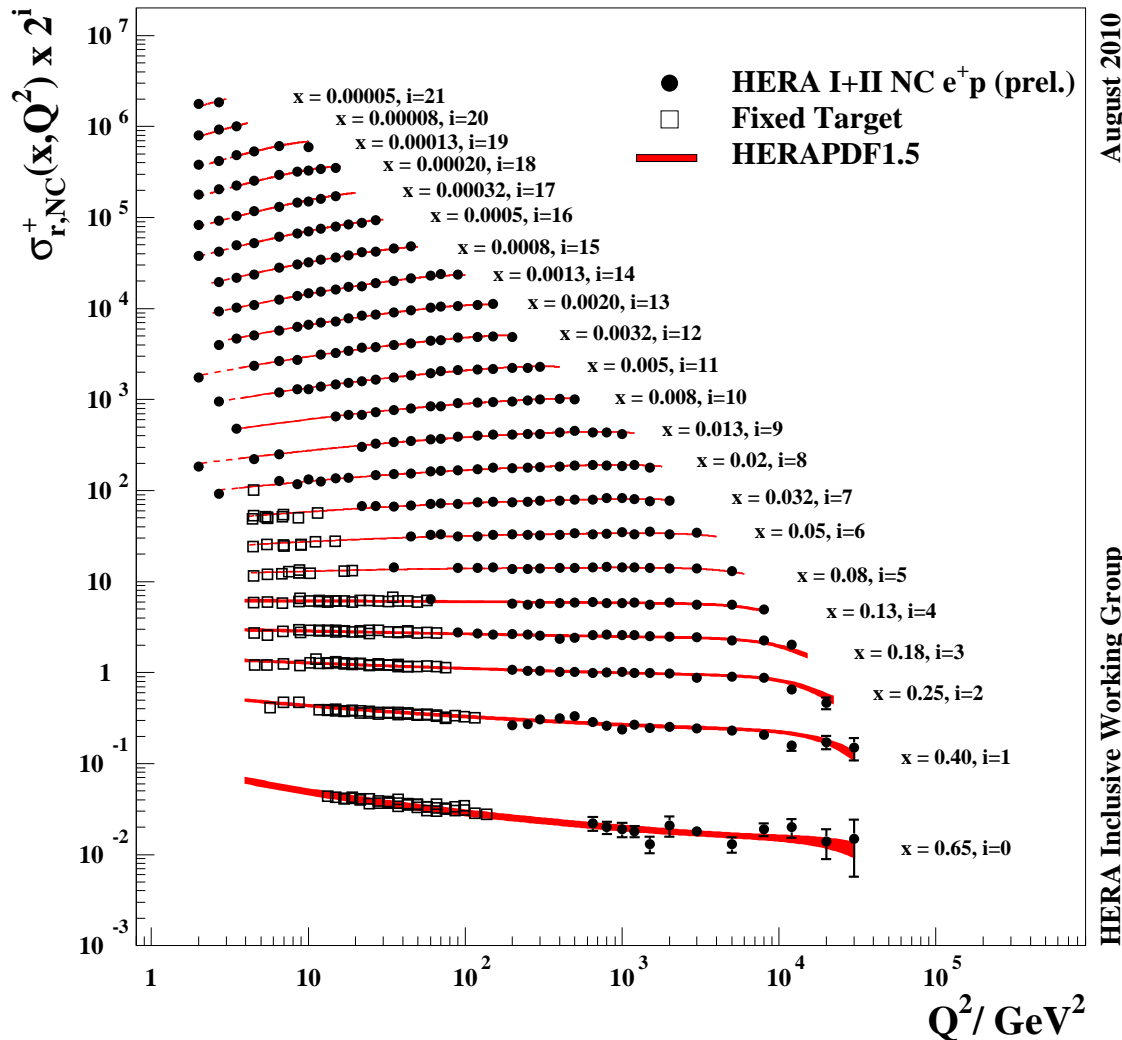# Combined H1 and ZEUS HERA-I-HERA-II measurements

- Combination of HERA-I and HERA-II data collected by H1 and ZEUS, for CC and NC processes (missing only NC e^+p from ZEUS, which comes next!).

- 674 combined data points with 134 sources of systematic uncertainty.

- Significantly more precise $e^{\pm}p$ CC and e^-p NC data compared to HERA-I combination.
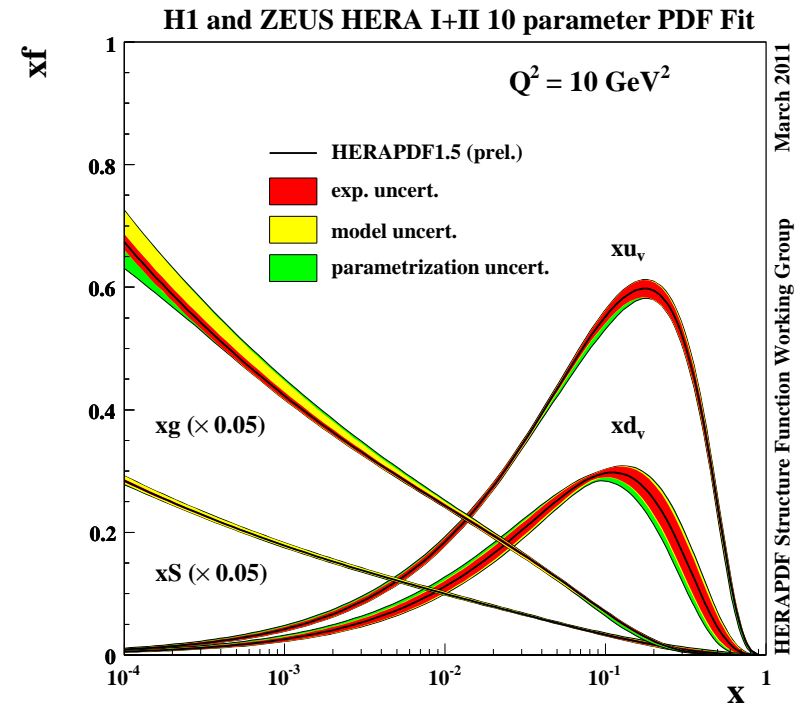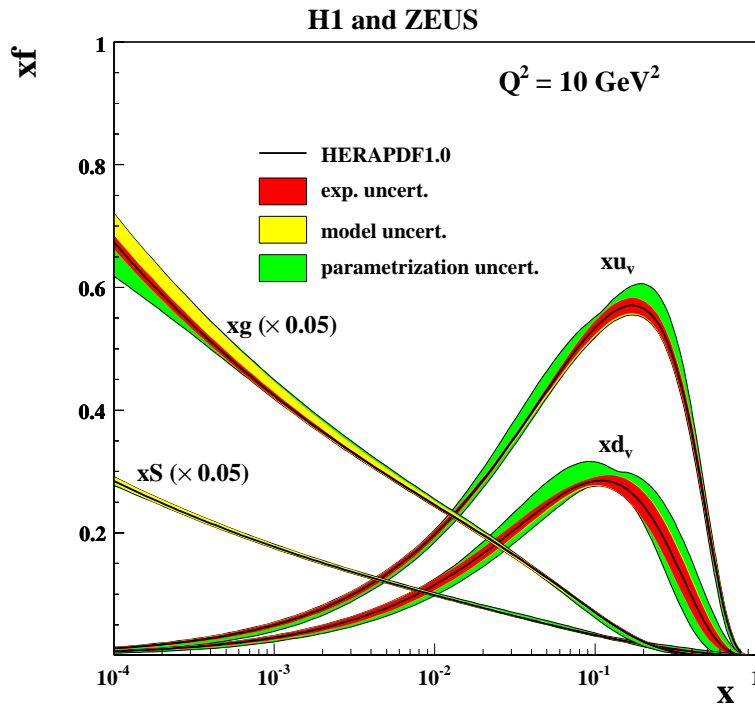
6

HERAPDF1.5 Fit

H1 and ZEUS

- NLO HERAPDF1.5 (prel.) fit
- Good agreement between DGLAP prediction and the data.
- Extrapolation to low Q^2 is consistent with fixed target data.

https://www.desy.de/h1zeus/combined_results/index.php?do=proton_structure
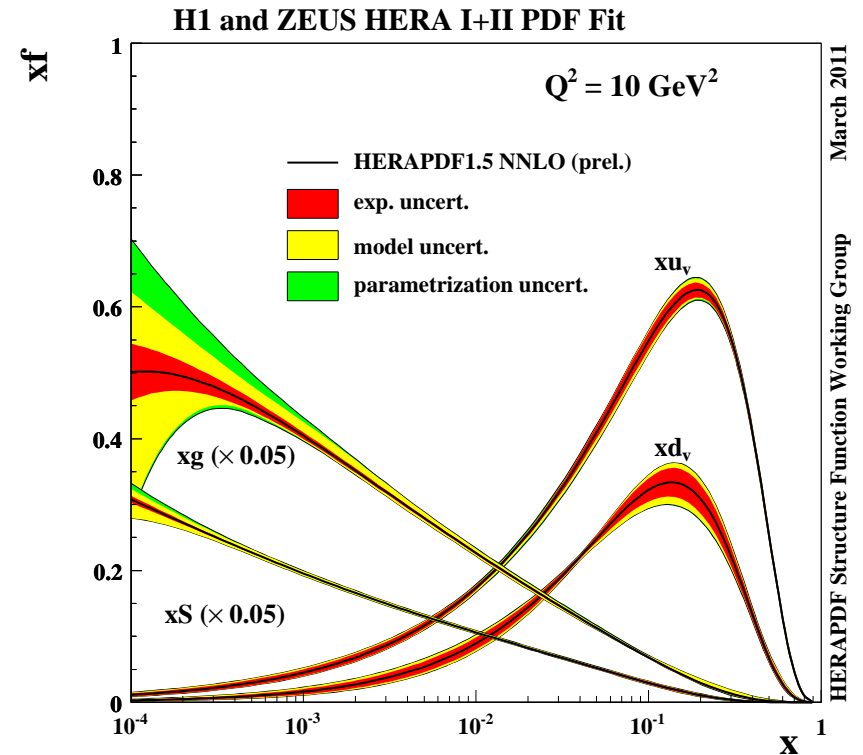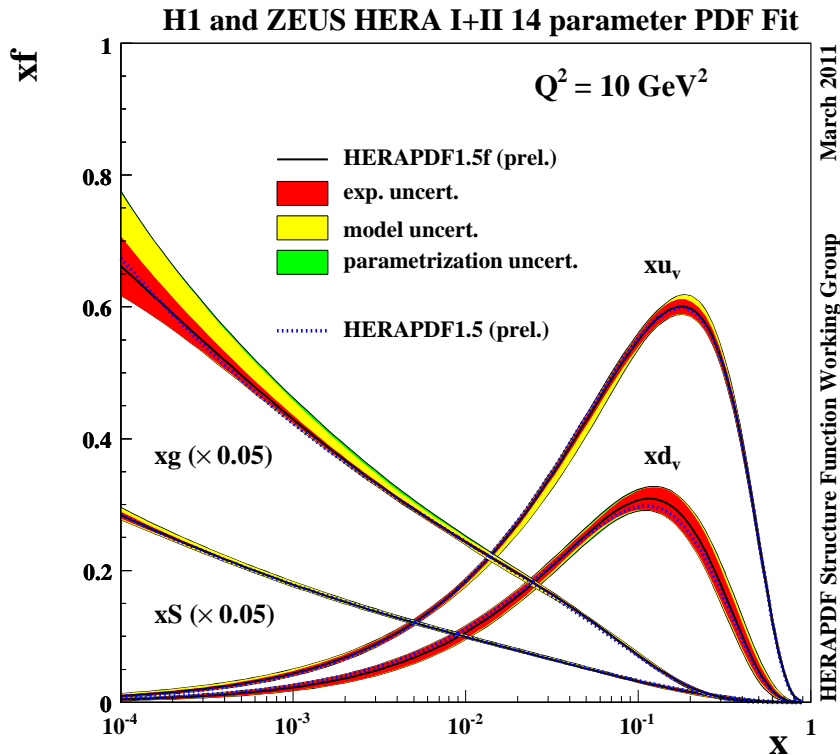
7

HERAPDF1.0 and HERAPDF1.5 fits

- Fits parameterise $x\bar{U}$, $x\bar{D}$, xu_v, xd_v and g using
  $xf(x) = Ax^B(1-x)^C(1 + Dx + Ex^2)$ form.

- Experimental, model and parameterisation uncertainties are estimated.

- HERAPDF1.5 fit provides determination of the valence quark densities at high x with reduced uncertainties compared to HERAPDF1.0.

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HERAPDF1.5 NNLO fit

H1 and ZEUS HERA I+II 14 parameter PDF Fit

$Q^2 = 10$ GeV^2

March 2011

HERAPDF Structure Function Working Group

- HERAPDF1.5f (prel.)
- exp. uncert.
- model uncert.
- parametrization uncert.
- HERAPDF1.5 (prel.)

xu_v

$xg (\times 0.05)$

xd_v

$xS (\times 0.05)$

H1 and ZEUS HERA I+II PDF Fit

$Q^2 = 10$ GeV^2

March 2011

HERAPDF Structure Function Working Group

- HERAPDF1.5 NNLO (prel.)
- exp. uncert.
- model uncert.
- parametrization uncert.

xu_v
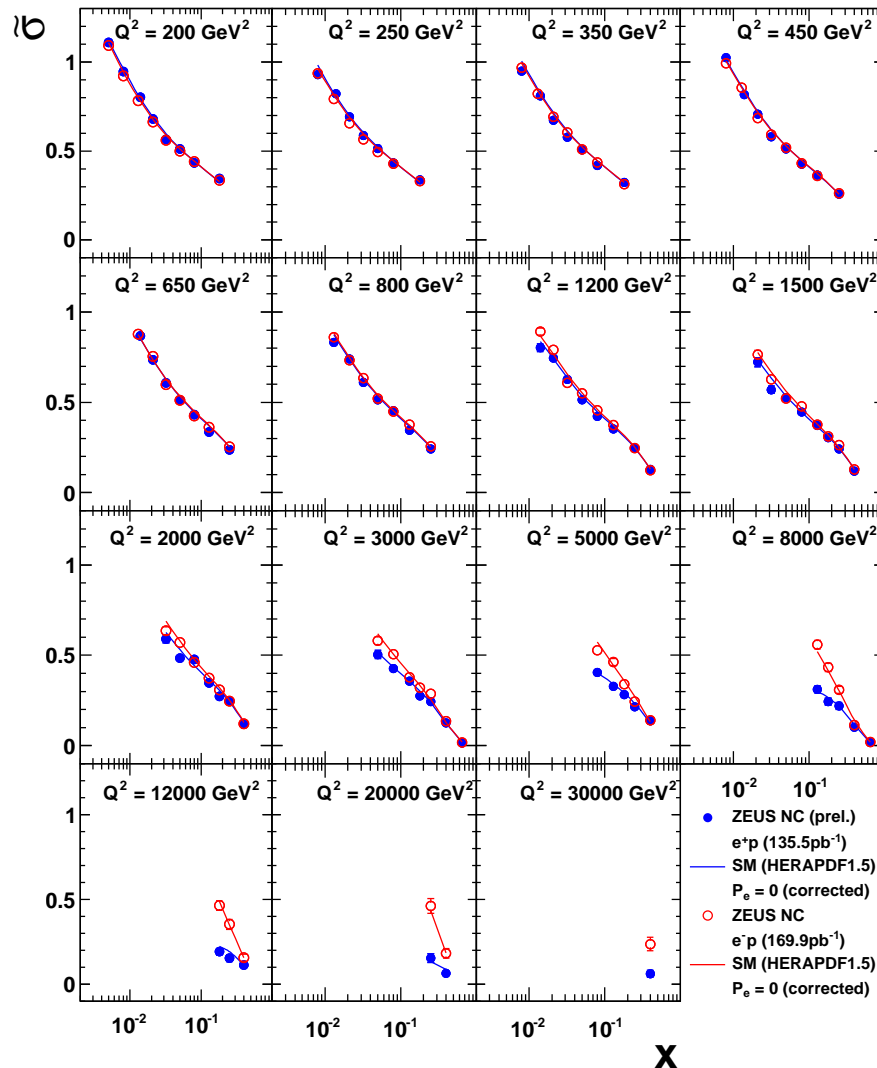
$xg (\times 0.05)$

xd_v

$xS (\times 0.05)$

- NNLO QCD fit using fixed $\alpha_S(M_Z) = 0.1176$.

- Flexible gluon: $xg(x) = Ax^B(1-x)^C - A'x^{B'}(1-x)^{25}$.

- $\chi^2/N_{\text{d.f.}}$ is comparable between NLO and NNLO fits: $744.3/660$ vs $735.1/660$.

- HERAPDF1.5NNLO has harder gluon at high x compared to HERAPDF1.0NNLO fit.
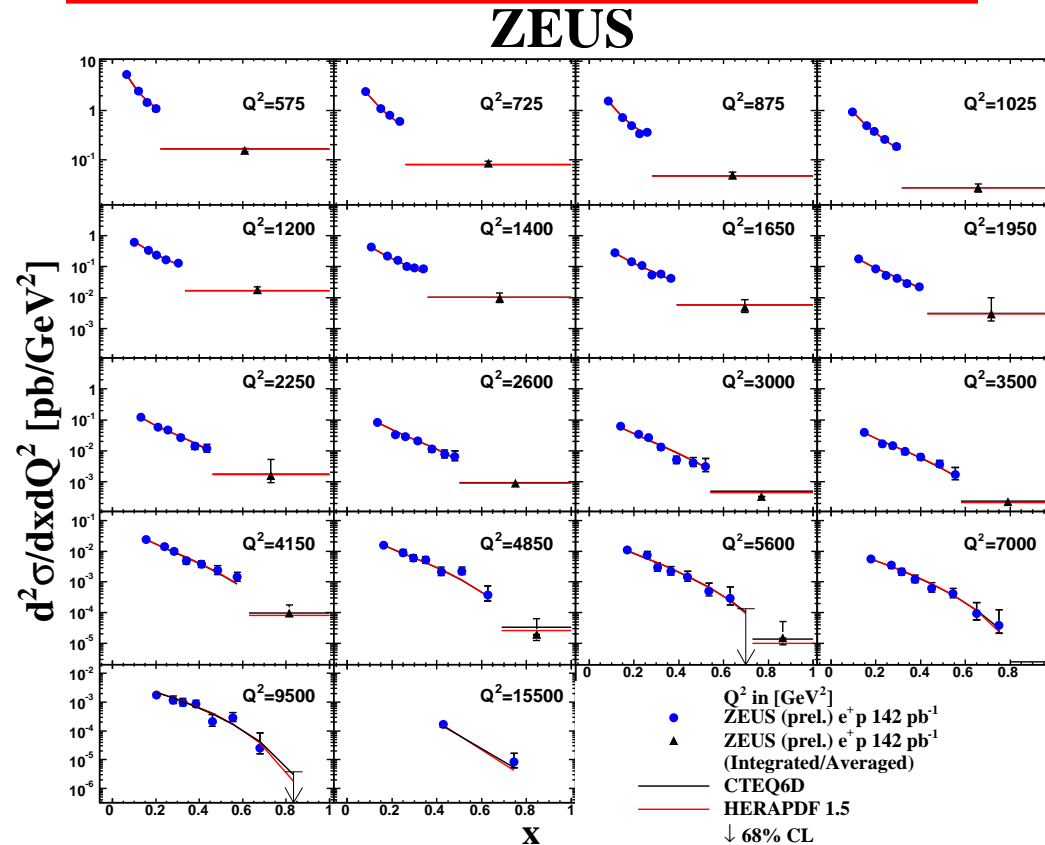
9

ZEUS NC e^+p data

ZEUS

- ZEUS new preliminary NC e^+p measurement based on complete HERA-II sample. $\rightarrow$ last inclusive sample for HERA-II.

- Data are compared to HERA-II e^-p sample and predictions based on HERAPDF1.5 fit.

- Difference between e^-p and e^+p cross sections can be used to measure xF_3 and constrain valence quarks.

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ZEUS

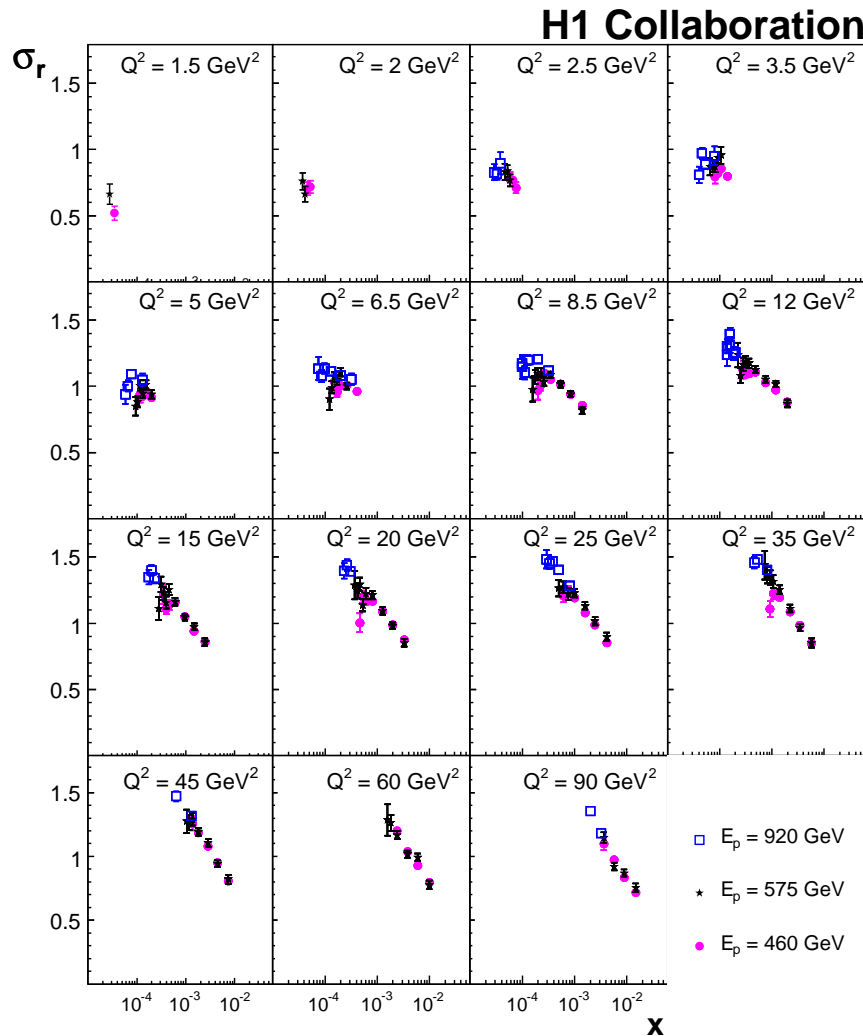- Not so many accurate constraints on PDFs at largest x.

- Resolution of kinematic reconstruction at HERA degrades for low $y < 0.01$

$\rightarrow$ Integrated $x_{min} < x \leq 1$ measurement. ZEUS-prel-11-004.

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Low x, Low Q^2, High y

H1 Collab., Eur.Phys.J.C71 (2011) 1579, 12/10
(Also talk of A. Petrukhin)
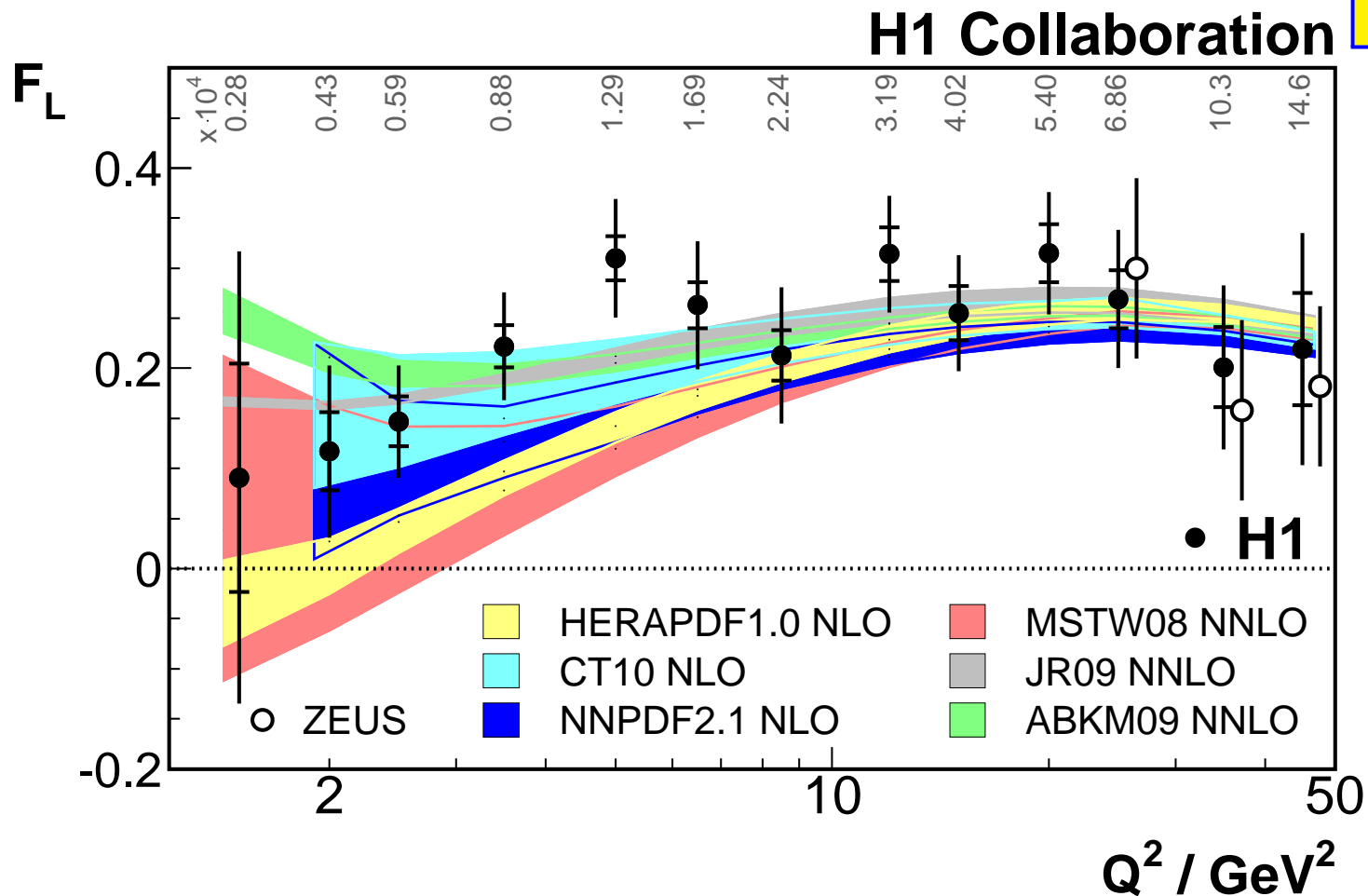
Measurement of Cross Section at High y

H1 Collaboration

- Analysis of HERA-II data sample with dedicated extension to low $E'_e \rightarrow$ high inelasticity y.
- Reduction of the errors at high y for $E_p = 920$ by factor of ~ 2 compared to HERA-I sample.
- Reduced proton energy run for $E_p = 460$ GeV and $E_p = 575$ GeV.
- Extension of the kinematic reach to $Q^2 \geq 1.5$ GeV^2.

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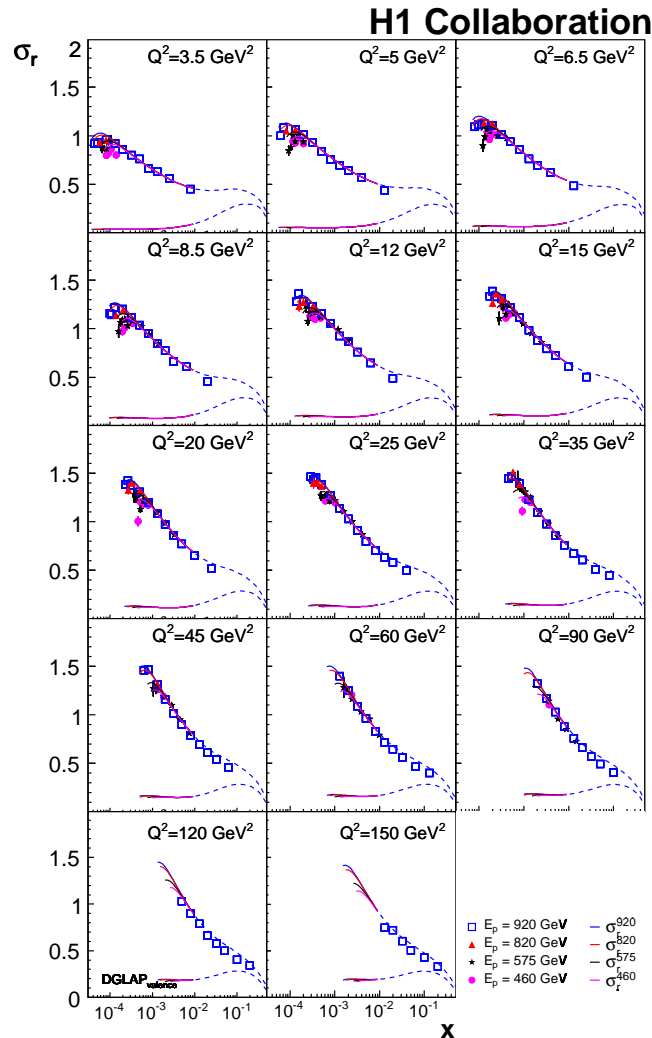
Measurement of the Structure Function F_L

H1 Collaboration

Measurement of the structure function F_L extended to $Q^2 \geq 1.5 \text{ GeV}^2$ and compared to predictions from PDF groups. Good agreement, within the uncertainties.

Low x phenomenology: DGLAP vs Dipole

Compare DGLAP and DIPOLE models in the region of phase space valid for both: $x < 0.01$ and $Q^2 \geq 3.5\,\text{GeV}^2$.

- Three DIPOLE models: GBW, IIM and B-SAT and two different DGLAP models for heavy flavors and inclusion of higher orders for F_L: RT and ACOT.

- Valence quark contribution sizable even for $x < 0.01$. Use DGLAP estimate to correct for it.

- Best $\chi^2/N_{\text{d.f.}}$ is for ACOT (248/249), followed by IIM (259/252) and B-SAT (262/252).

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Inclusive ++ Results

H1prelim-11-0xx, (H1prelim-11-034, ZEUS-11-001),
(H1prelim-10-143,ZEUS-prel-10-019)

(Also talks of R. Kogler, K. Nowak, R. Plačakytė)

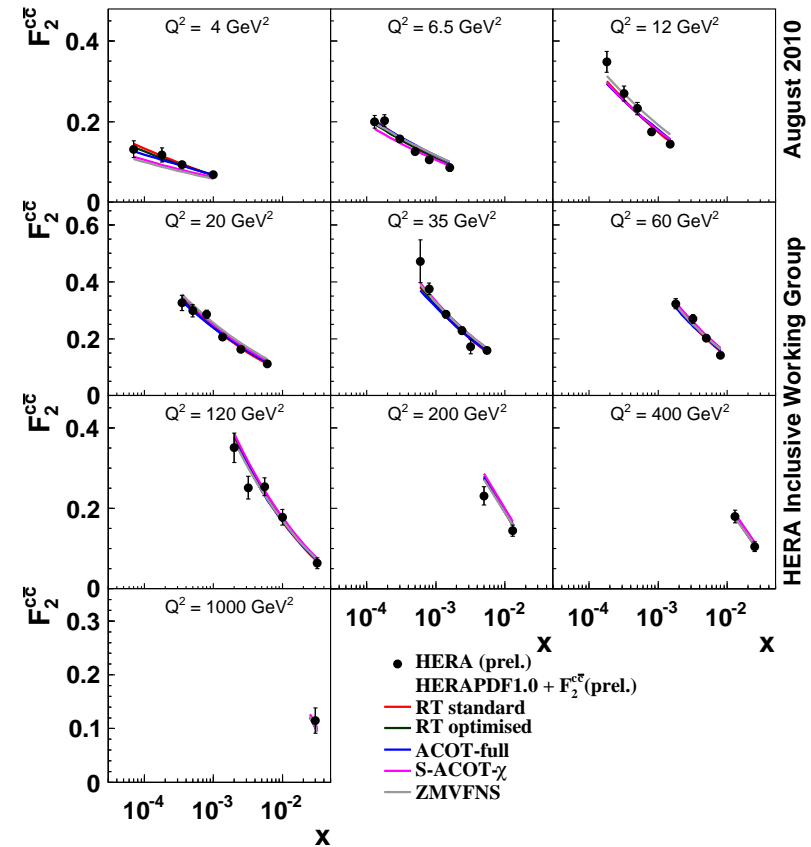# Decomposing u and c densities at low x

talk of R. Plačakytė

Inclusive structure function F_2 is sensitive to

$$F_2 \sim 4\left(U + \bar{U}\right) + \left(D + \bar{D}\right),$$

where $U = u + c$ and $D = d + s + b$. At low x and $Q^2 \gg m_C^2$, contribution of charm to F_2 reaches 30%.
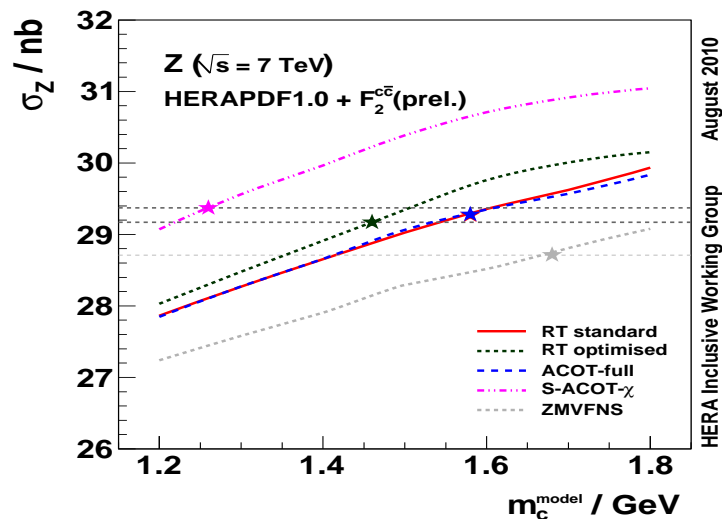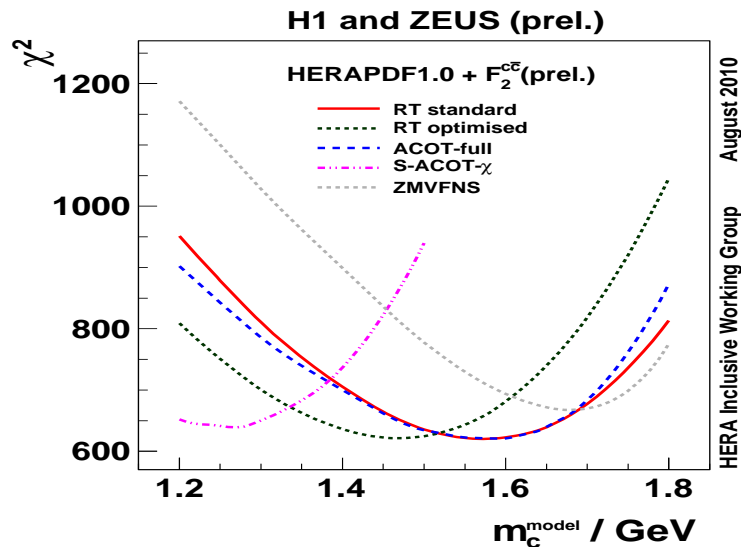
Determination of charm contribution is a mixed theoretical/experimental problem: it can be calculated given the gluon density, however description of the charm threshold is complicated leading to a number of matching schemes (RT, ACOT, FONLL...).

Combined HERA F_2^{cc} data reaches $5 - 10\%$ precision per point, can be used to study different HF models.

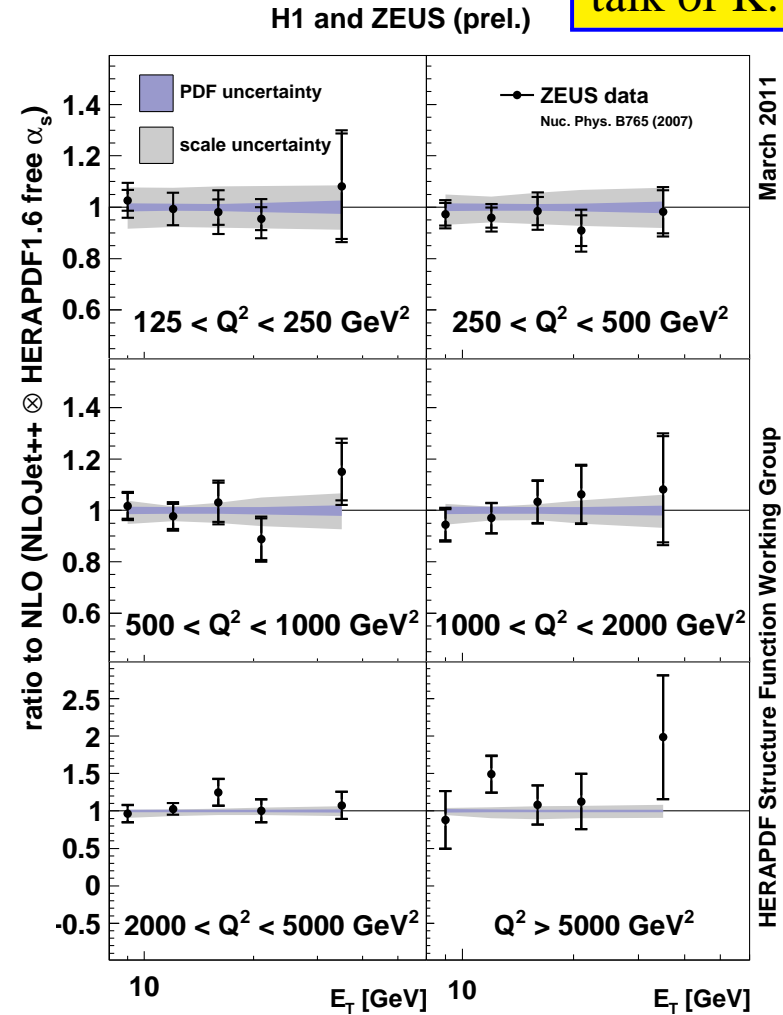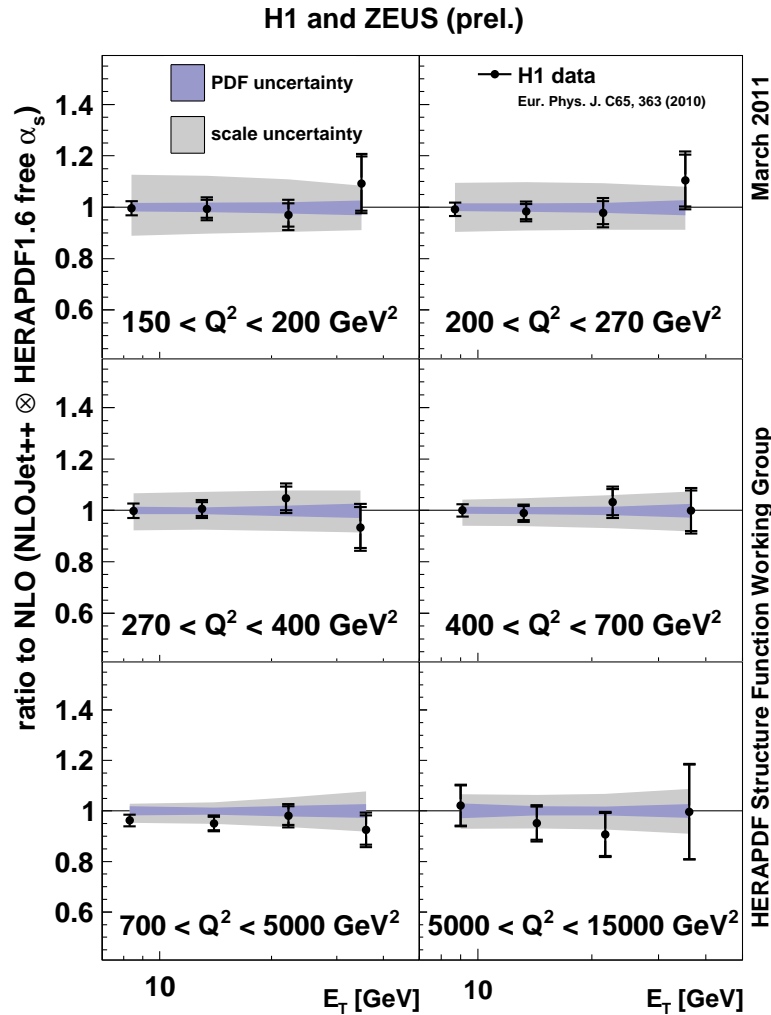# Scan of m_c^{model} and Predictions for LHC

All models use a parameter m_c^{model} which is related to the charm pole mass. Use it as a free parameter to tune the models to the charm data.

Fits to combined HERA-I inclusive and F_2^{cc} data using different models for HF treatment.

Large $\sim$ 7% spread of the total $pp \rightarrow Z$ cross section predictions for m_c^{model} scan between $1.2 - 1.8$ GeV and also for a fixed m_c^{model} when considering different models. However, the spread is reduced to $< 1.0\%$ (excluding ZMVFNS) when predictions are evaluated at the $m_c^{model}(opt)$ values.

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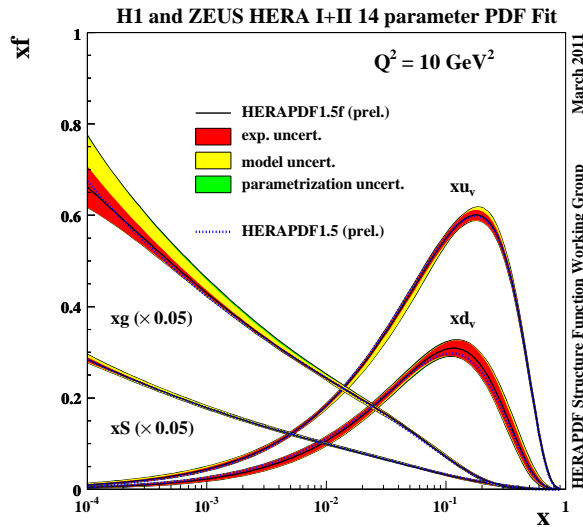# Combined DIS+Jets Fit

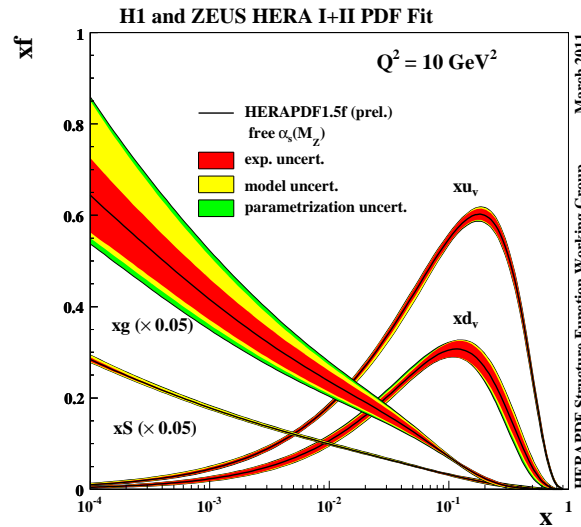**H1 and ZEUS (prel.)**

H1 and ZEUS (prel.)

- Fit combined inclusive HERA I+II data and add to this fit published inclusive jet samples from H1 and ZEUS.

- Good description of the jet cross sections: HERAPDF1.6 set.

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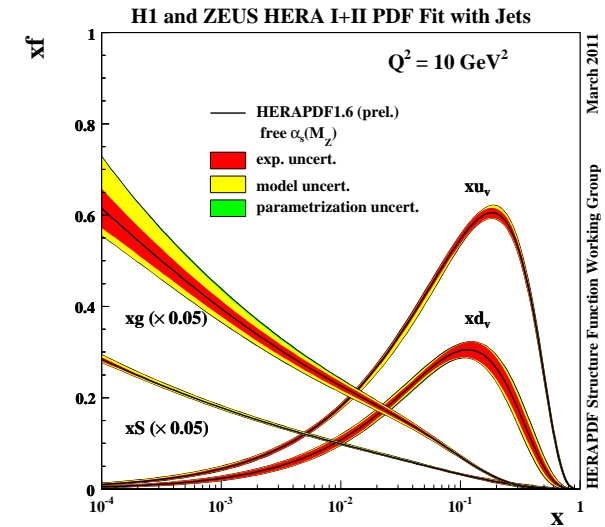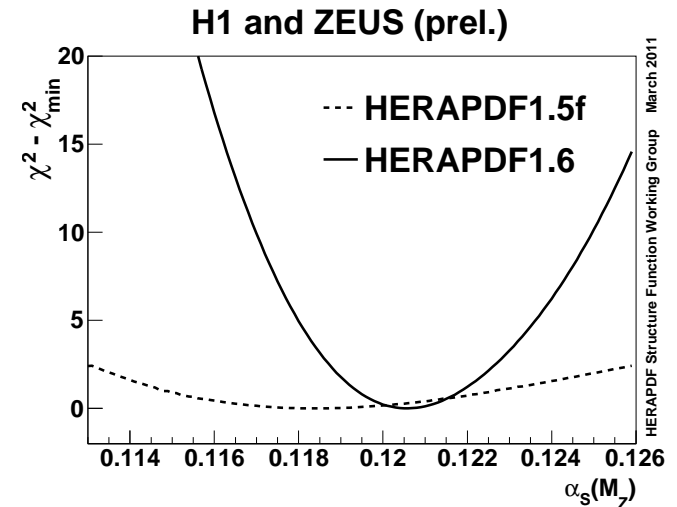# Combined Jet+DIS inclusive fit and $\alpha_S(m_Z)$

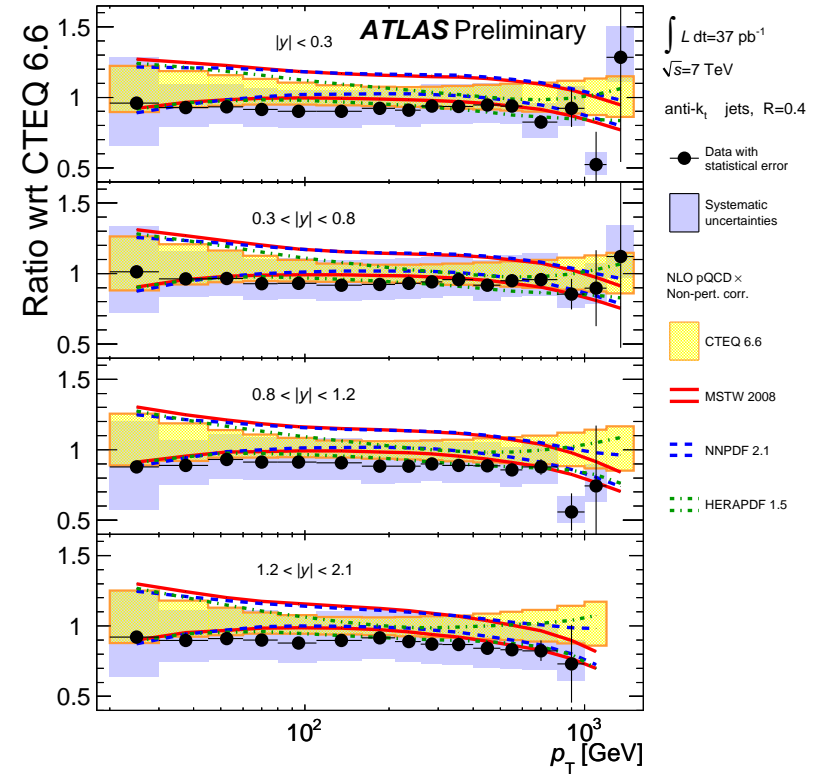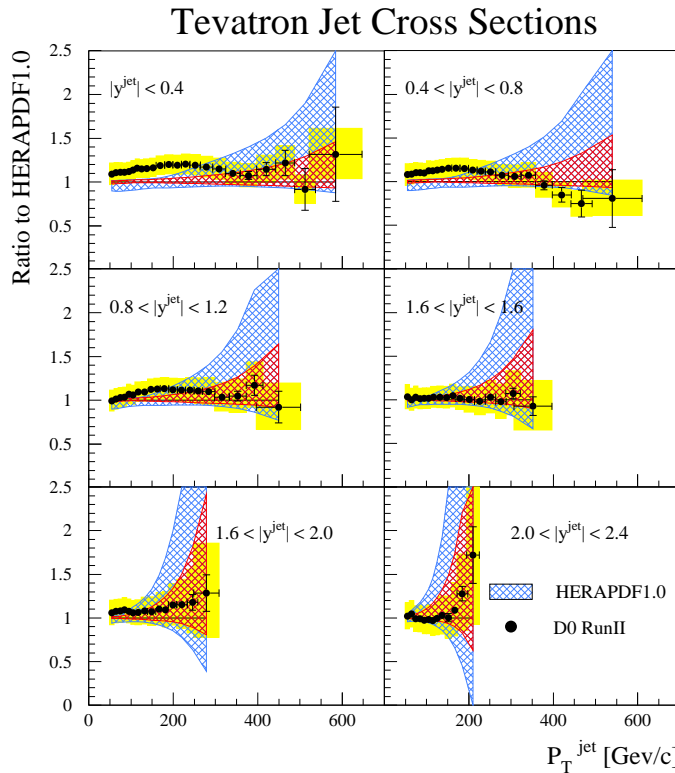Fix α_S, no jets　　　　　Free α_S, no jets　　　　　Free α_S, + jets

- Freeing α_S in fits increases $xg(x)$ uncertainty at low x due to large $xg(x)$-α_S correlation.
- Inclusion jets allows to reduce this correlation and improve uncertainty.
- $\alpha_S(M_Z)$ = 0.1202 ± $0.0013(\text{exp})$ ± $0.0007(\text{mod})$ ± $0.0012(\text{had})^{+0.0045}_{-0.0036}(\text{th})$.
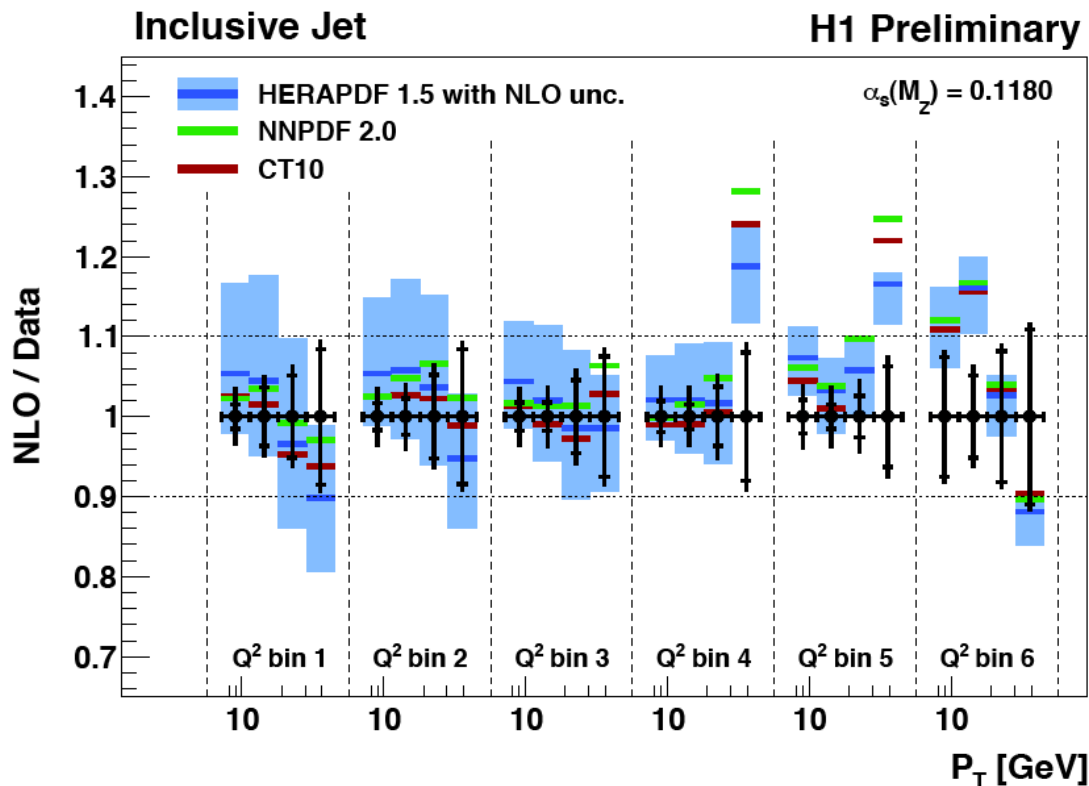

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HERA PDF Compared to $p\bar{p}$ and pp Jets

Tevatron Jet Cross Sections

- HERAPDF sets do not include jet data, yet gives satisfactory description of these data.

- For Tevatron (D0), HERAPDF is somewhat below predictions, for ATLAS, HERAPDF provides the best description of the data.

H1 Measurement of Inclusive and Multi-jets

- New measurement of inclusive and multi-jet cross section for $150 < Q^2 < 15000 \text{ GeV}^2$.

- Compared to predictions from recent PDF sets: CT10, NNPDF2.1, HERAPDF1.5

→ Some preference for HERAPDF1.5, mostly due to high x high Q^2 bins were CT10, NNPDF2.1 are high due to Tevatron jet data.
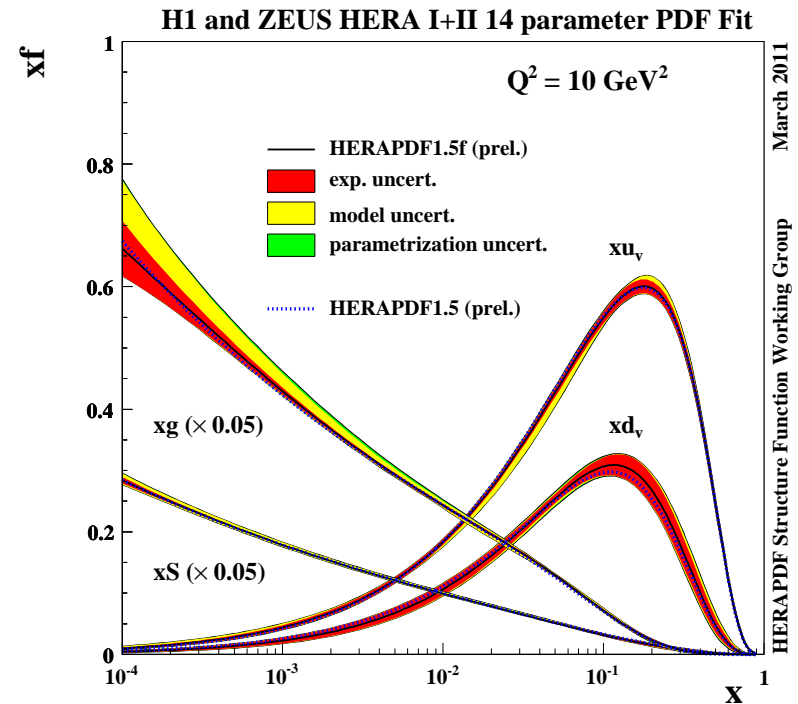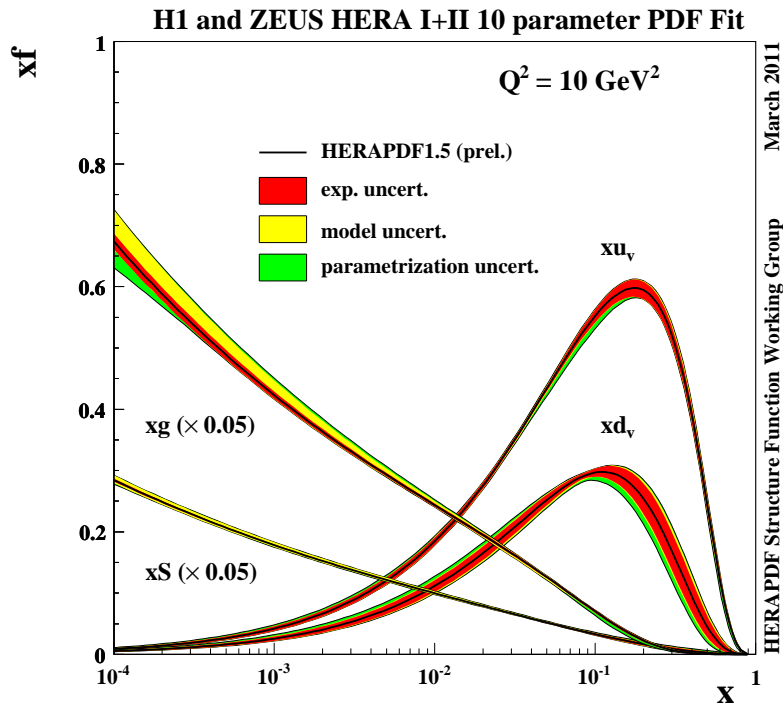
Summary

- Many new results from HERA during last year

- New HERA-II data improve precision at high x, in particular for u_v.

- Combination of the H1 and ZEUS data brings ultimate precision for PDFs. PDF analysis is performed at NLO and NNLO.

- New H1 results provide F_L measurement down to $Q^2 = 1.5$ GeV^2, new input for low x phenomenological analyses.

- Combined charm data fix heavy flavour models parameter variation, reduce PDF uncertainties for the LHC predictions.

- Fit to inclusive + DIS-jet data provides determination of $\alpha_S(M_Z)$ with consistent treatment of PDF uncertainties.

$\rightarrow$ HERA continues to provide data essential for physics at the LHC. The data is the main ingredient for all modern PDF fits. HERAPDF fits provide alternative PDF sets with well understood experimental and theory uncertainties.
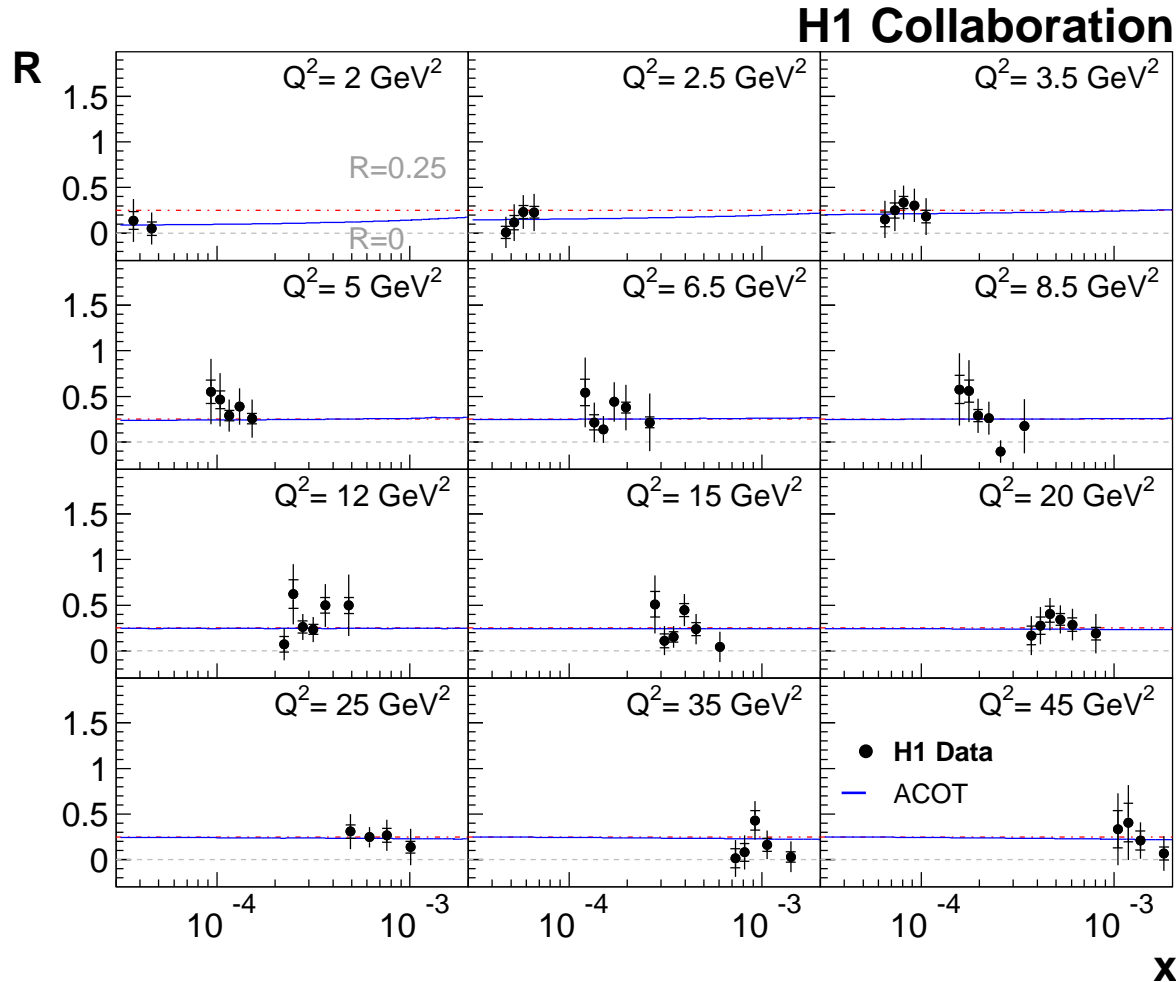
EXTRAS

HERAPDF1.5 and HERAPDF1.5f fits

- Fits parameterise $x\bar{U}$, $x\bar{D}$, xu_v, xd_v and g using $xf(x) = Ax^B(1-x)^C(1 + Dx + Ex^2)$ form.

- Recently fits were extended from 10 to 14 parameters, by relaxing assumptions that $B_{u_v} = B_{d_v}$, using extra term for u_v and flexible parameterisation for the gluon: $xg(x) = Ax^B(1-x)^C - A'x^{B'}(1-x)^{25}$.

$\rightarrow$ similar overall errors, more flexible shapes (important for NNLO).

Measurement of the ratio R

H1 Collaboration

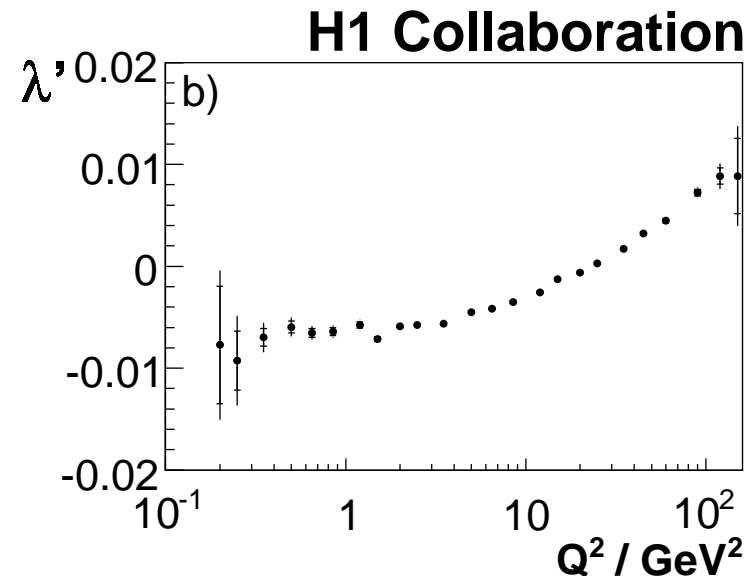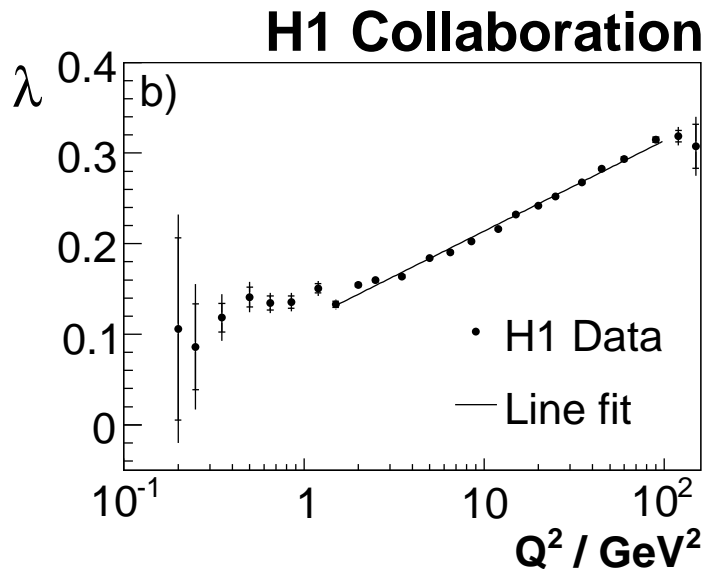- Measurements of the structure function F_L and F_2 can be presented as a measurement of the ratio

$$R = \frac{F_L}{F_2 - F_L}.$$

For $Q^2 \geq 3.5 \text{ GeV}^2$, data are consistent with constant $R = 0.26 \pm 0.05$

Low x phenomenology: λ fit

- Using $R = 0.26$, calculate $F_2 = \sigma_r \left/ \left(1 - \frac{R}{1+R} \frac{y}{1+(1-y)^2}\right)\right.$

- Fit F_2 in each Q^2 bin assuming (modified) power-law behaviour:

$$F_2 = Cx^{-\lambda+\lambda' \ln x}$$

Offset-method fit assuming $\lambda' = 0$

$\chi^2/dof = 538/350$

Offset-method fit assuming $\lambda = 0.25$

$\chi^2/dof = 464/350$

Rise of F_2 is tamed compared to pure power-law for $Q^2 \leq 10$ GeV^2.