Charm and beauty at HERA

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for the HERA collaborations
H1 and ZEUS

Outline

- The HERA collider
- Charm and beauty production in deep-inelastic scattering
- Data combination
- The new combined HERA charm and beauty data
- Comparisons to NLO QCD
- Extraction of the charm and beauty quark masses

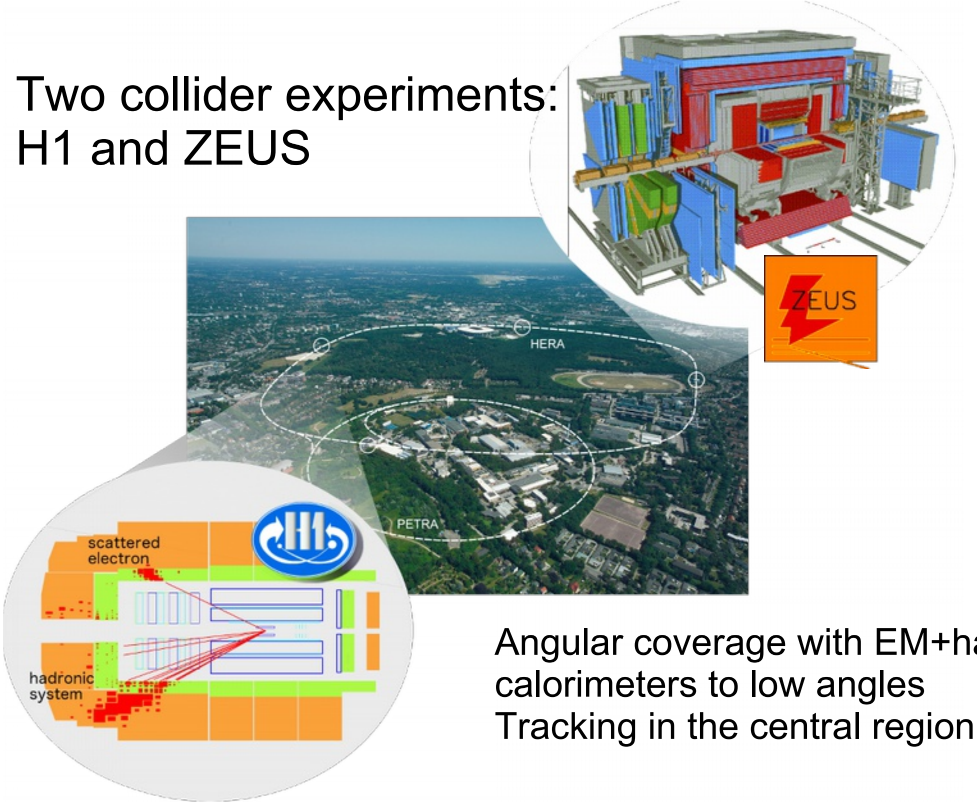
Eur.Phys.J. C78 (2018) 473

The HERA collider

- World's only ep collider 1992-2007
- 920 x 27.6 GeV ($\sqrt{s}$=320 GeV)
- Two collider experiments, H1 and ZEUS
- Integrated Luminosity:

  ~2×0.5 fb^{-1}
- $e^{+}p$ and $e^{-}p$ data

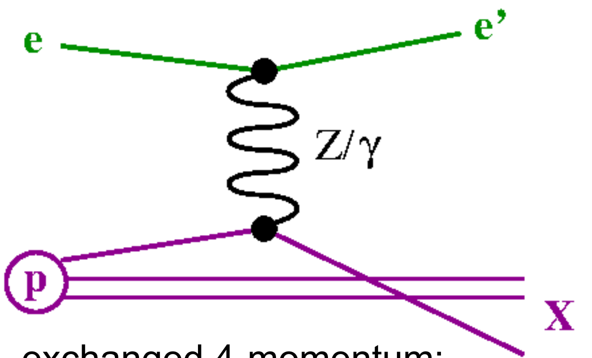
Two collider experiments:
H1 and ZEUS



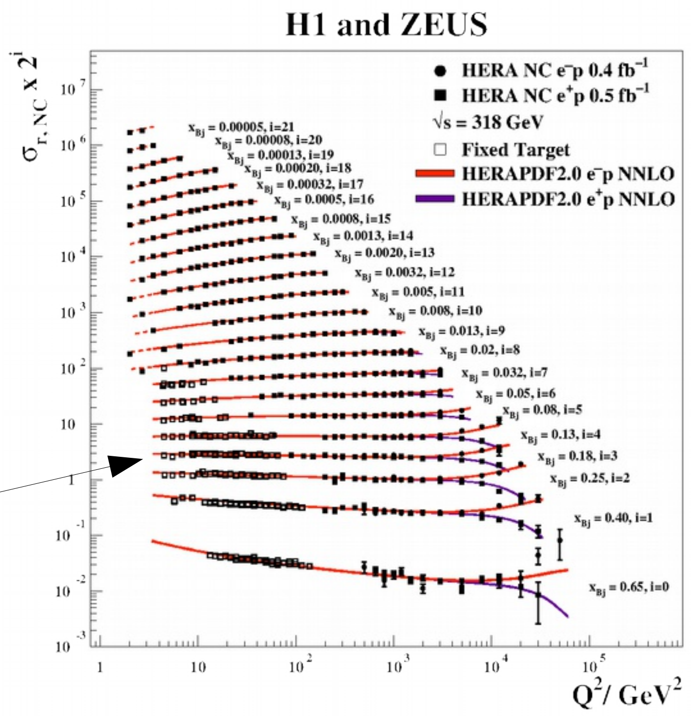
Angular coverage with EM+had calorimeters to low angles
Tracking in the central region

Deep-inelastic scattering at HERA

- Inclusive processes
  - Neutral current (NC)
  - Charged current (CC)
- Momentum transfer $Q^2=-q^2$
- Inelasticity $y=(pq)/(pe)$
- Bjorken-x: $x=Q^2 / sy$
- Inclusive cross section measurements from HERA: essential to determine proton PDFs
- What does HERA tell us about charm and beauty in the proton?



exchanged 4-momentum:
$$q=e-e'=X-p$$



$$\sigma_{\text{red}} \sim \sum_i Q_i^2 (xq + x\bar{q})$$ at leading order

Charm and beauty production at HERA

- New data combination presented today: HERA cross sections with extra condition of a charm or beauty hadron in the final state
  - Charm contributes up to ~30% at high scales Q²
  - Beauty contributes up to ~1% at high scales Q²
- Experimental methods
  - High pt lepton
  - Reconstructed D,D* mesons
  - Impact parameter, secondary vertex

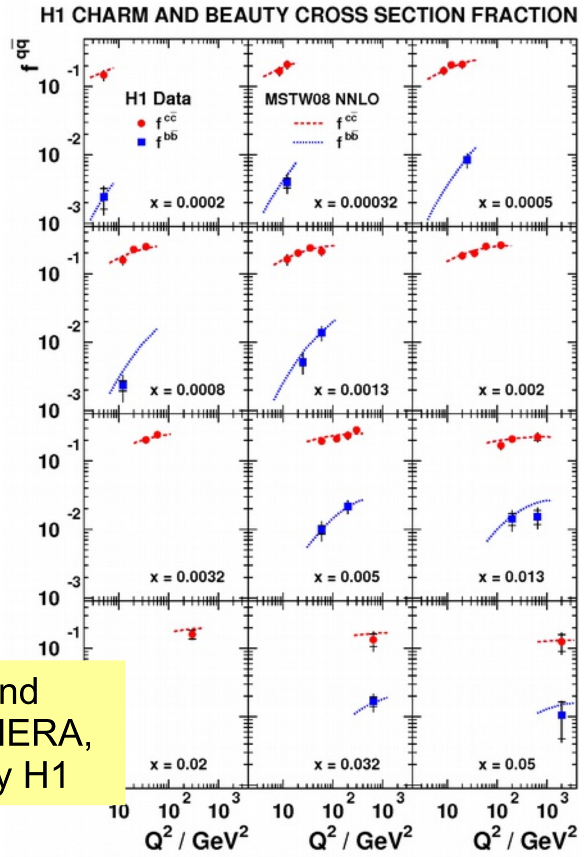


Illustration: Charm and beauty fractions at HERA, measured in 2009 by H1

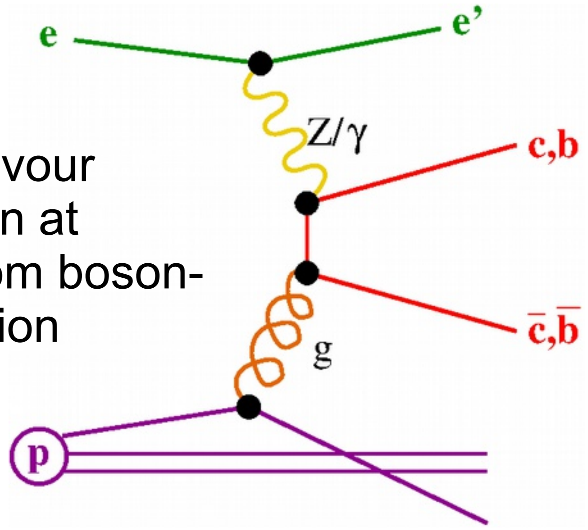
Predictions for charm and beauty in DIS

Measured quantity: reduced cross section with charm or beauty in the final state, at fixed Q^2,x (extrapolated to full phase-space)

Reduced cross section: double-differential cross section divided by kinematic factors.

$$\sigma_{\text{red}}^{Q\bar{Q}} = \frac{d^2\sigma^{Q\bar{Q}}}{dx\,dQ^2}\,\frac{Q^4 x}{2\pi\alpha^2\left(1+(1-y)^2\right)}$$

Heavy flavour production at HERA from boson-gluon fusion



NLO calculations:

- fixed-flavour number scheme (FFNS): proton PDF only contains light flavours u,d,s and the gluon. Heavy quarks are produced in the matrix element [e.g. boson-gluon fusion]
- Variable-flavour number scheme (VFNS): massless c,b quarks are part of the PDF. Heavy quarks are produced both in the matrix element and in the proton PDF at sufficiently high scales (matching between massive and massless coefficient functions is required for DIS predictions)

HERA combination of charm and beauty

- Two experiments H1 and ZEUS
- First combination of HERA charm data published in 2012

  Eur.Phys.J.C73 (2013) 2311

- This talk: new combination of charm and beauty data

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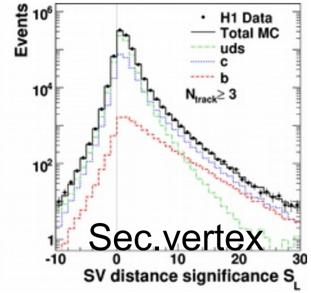
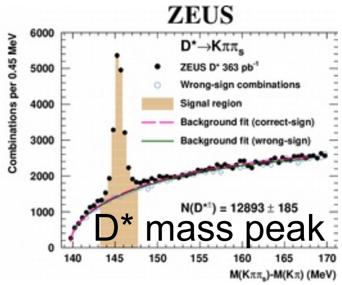
- 13 input datasets, using various experimental methods
- Consistent extrapolation to full phase space prior to combining





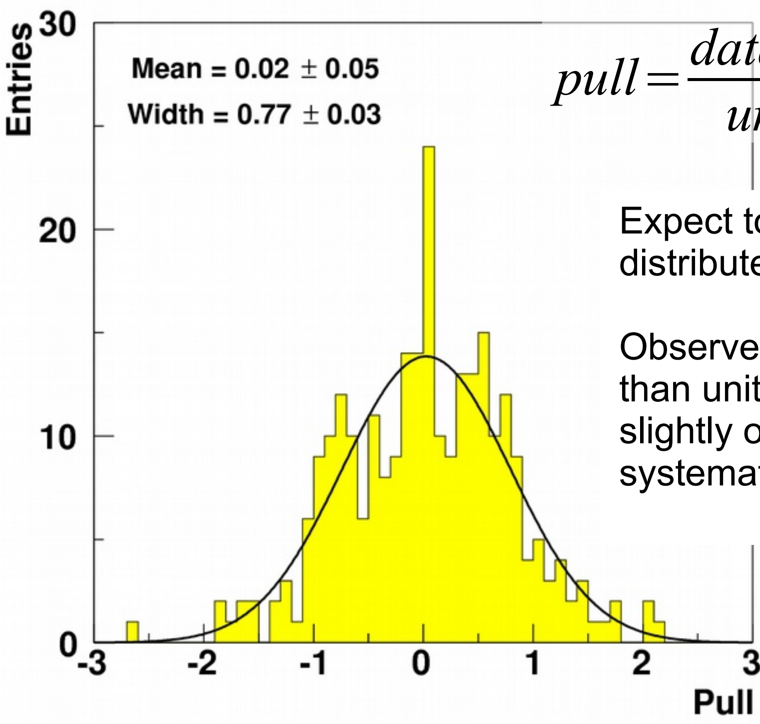
	Dataset	Tagging	Q^2 range [GeV^2]	$\mathcal{L}$ [pb^{-1}]	$\sqrt{s}$ [GeV]	N_c	N_b
1	H1 VTX [14]	VTX	5 – 2000	245	318	29	12
2	H1 $D^{*\pm}$ HERA-I [10]	D^{*+}	2 – 100	47	318	17	
3	H1 $D^{*\pm}$ HERA-II (medium Q^2) [20]	D^{*+}	5 – 100	348	318	25	
4	H1 $D^{*\pm}$ HERA-II (high Q^2) [15]	D^{*+}	100 – 1000	351	318	6	
5	ZEUS D^{*+} 96-97 [4]	D^{*+}	1 – 200	37	300	21	
6	ZEUS D^{*+} 98-00 [6]	D^{*+}	1.5 – 1000	82	318	31	
7	ZEUS D^0 2005 [12]	D^0	5 – 1000	134	318	9	
8	ZEUS μ 2005 [13]	μ	20 – 10000	126	318	8	8
9	ZEUS D^+ HERA-II [21]	D^+	5 – 1000	354	318	14	
10	ZEUS D^{*+} HERA-II [22]	D^{*+}	5 – 1000	363	318	31	
11	ZEUS VTX HERA-II [23]	VTX	5 – 1000	354	318	18	17
12	ZEUS e HERA-II [19]	e	10 – 1000	363	318		9
13	ZEUS μ +jet HERA-I [16]	μ	2 – 3000	114	318		11

Input data consistency

- Combination is done using a fit
- Number of input data points:

  209 (charm) + 57 (beauty)
- Fit: $\chi^2/n_{DF}=152/187$
- Inputr data are consistent
- Pulls indicate that uncertainties may be somewhat conservative
- Combined cross sections:

  52 charm and 27 beauty measurements

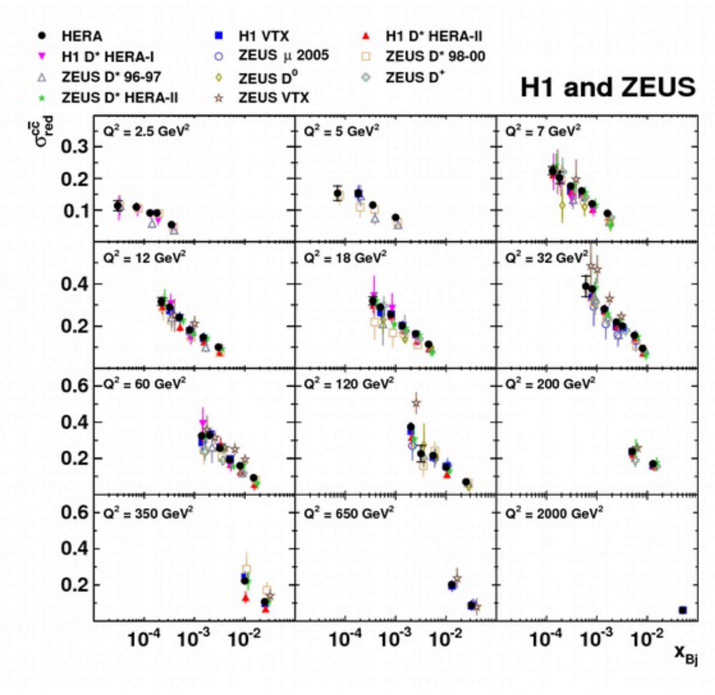


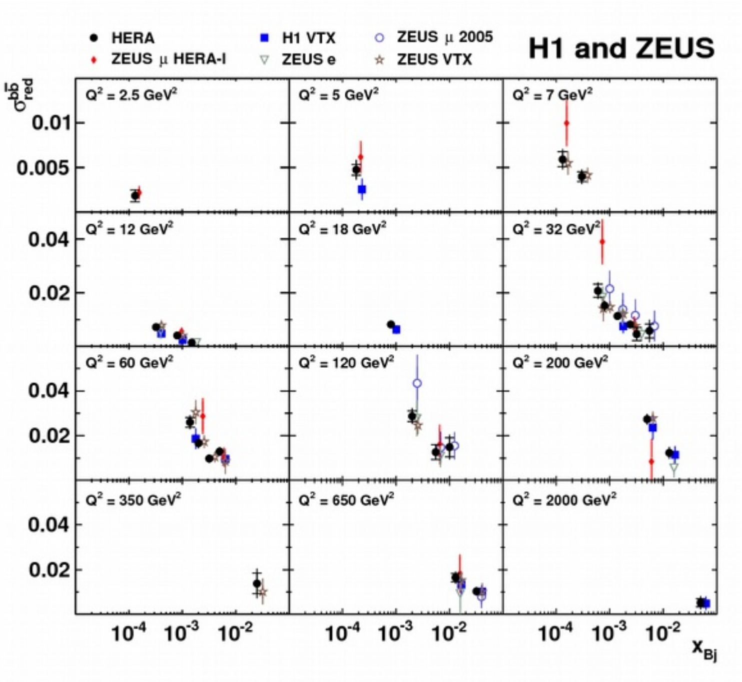
$$pull=\frac{data-average}{uncertainty}$$

Expect to find normal distributed Gaussian.

Observed width is smaller than unity. Possible reason: slightly overestimated systematic uncertainties

Combined cross sections



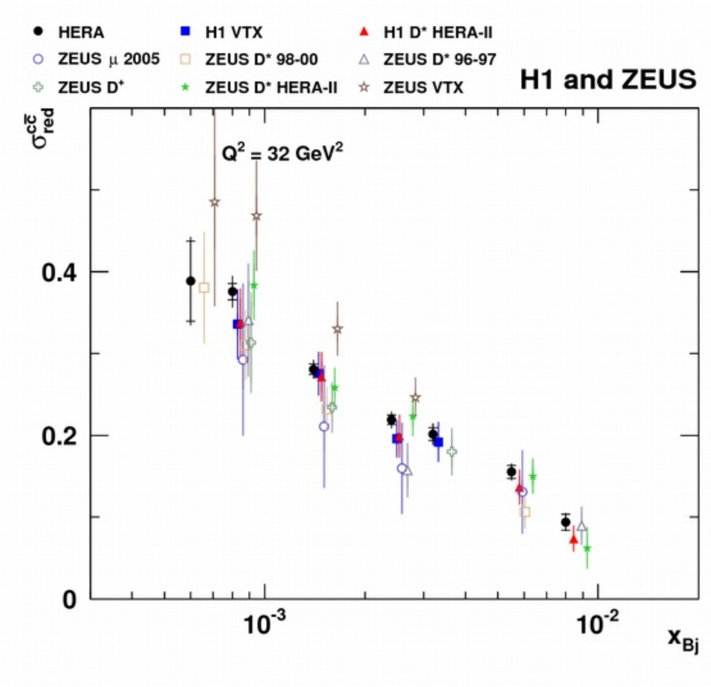


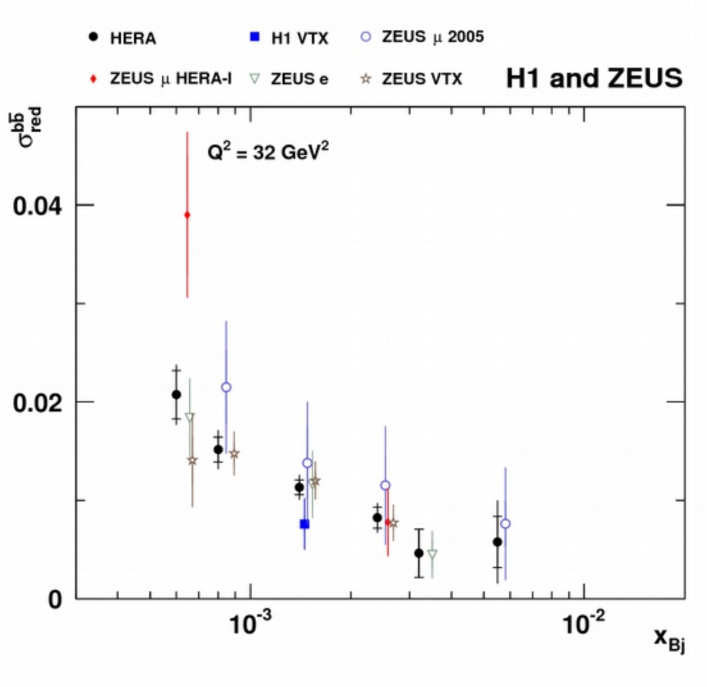
Combined charm and beauty data are measured in 12 bins of Q^2. For fixed Q^2, there are up to six measurements in x.

Precision of the combined data is much improved over the individual data points

Combined data are shown in black, in comparison to input data

Combined cross sections





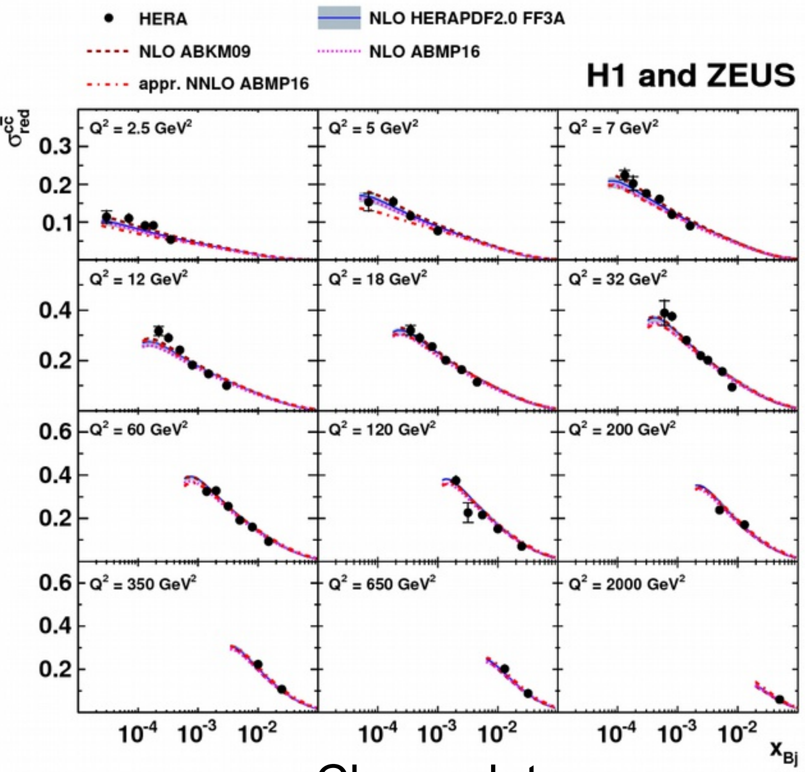
Combined charm and beauty data are measured in 12 bins of Q^2. For fixed Q^2, there are up to six measurements in x.

Precision of the combined data is much improved over the individual data points

Example: Q^2=32 GeV^2

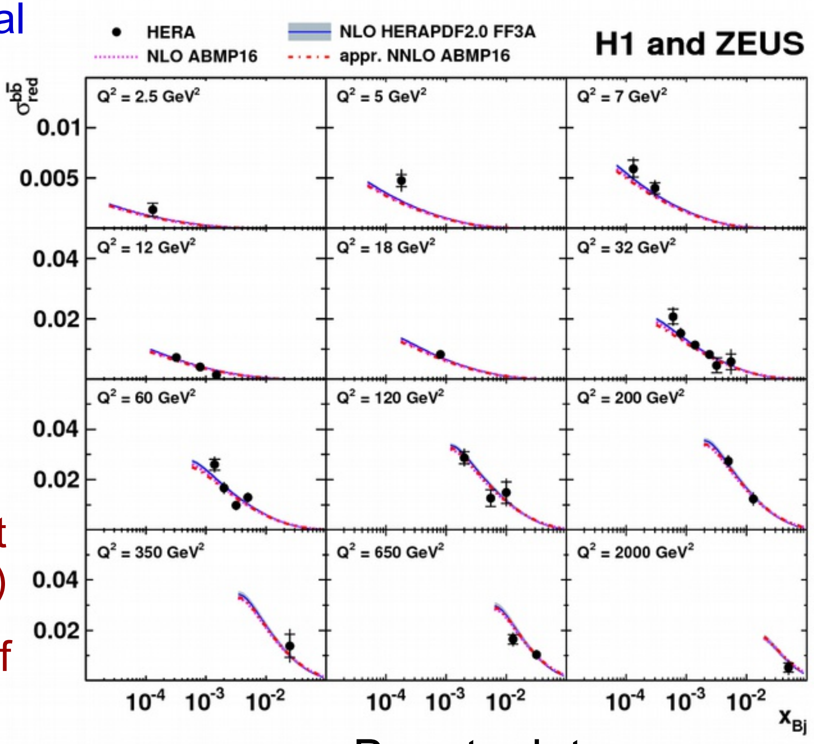
Combined data are shown in black, in comparison to input data

Comparison to NLO QCD (FFNS)



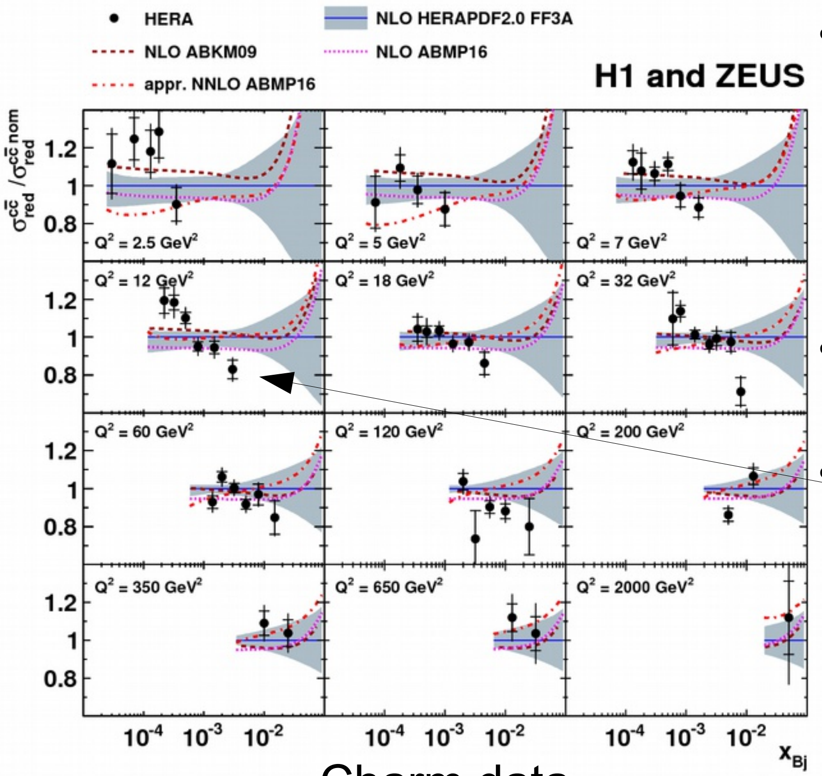
Charm data

- Rise to low x: typical for sea and gluon
- Cross section evolves with Q²
- NLO predictions describe data reasonably well
- Improved precision compared to the 2012 measurement (see backup slides)
- First combination of HERA beauty data



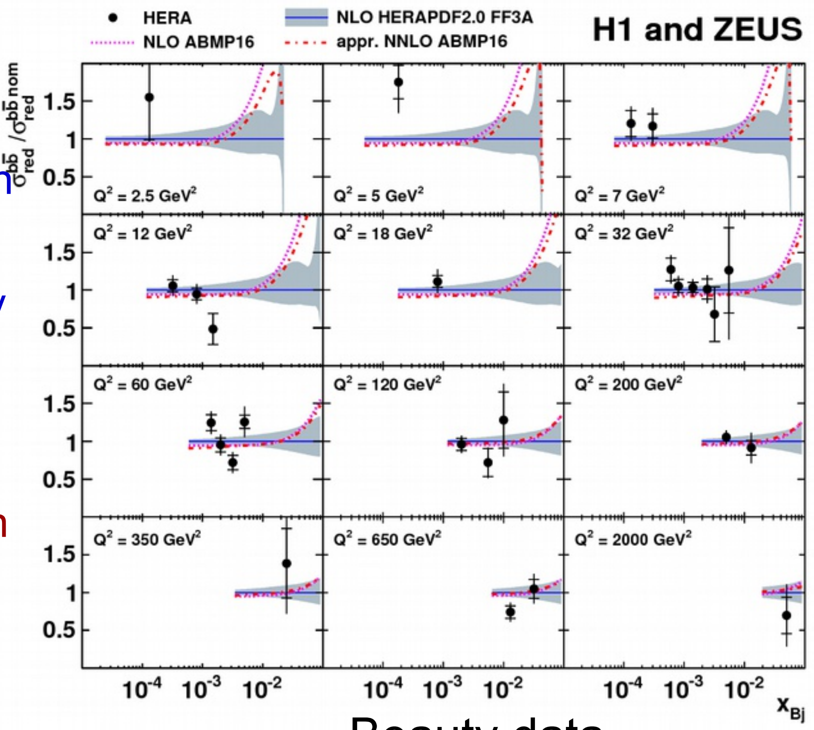
Beauty data

Comparison to NLO QCD (FFNS)



Charm data

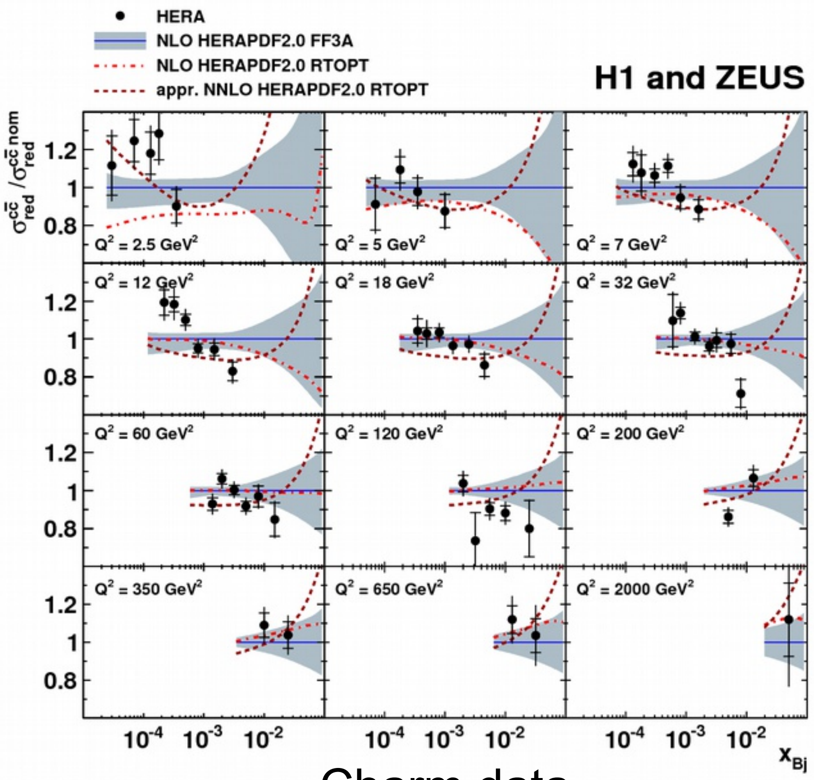
- Overall satisfactory description of the HERA c and b data by NLO QCD, not much dependent on PDF choice
- No improvement by approximate NNLO
- Slope difference between data and theory as a function of x is visible for charm data at Q^2~12 GeV²



Beauty data

Data and predictions are normalized to HERAPDF2.0 FF3A

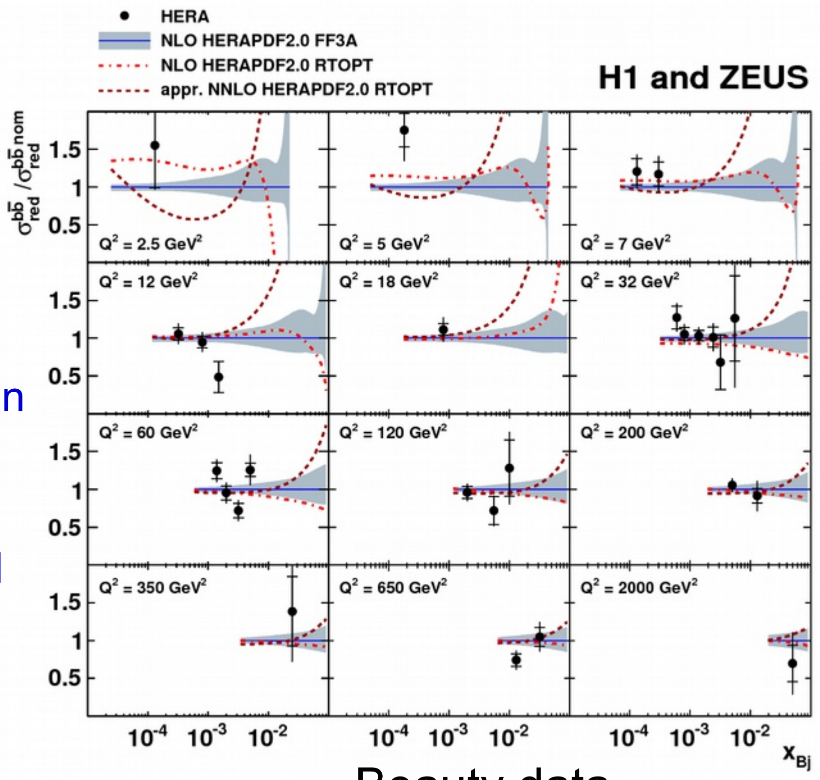
Comparison to VFNS (RTopt)



Charm data

VFNS: dashed
FFNS: solid

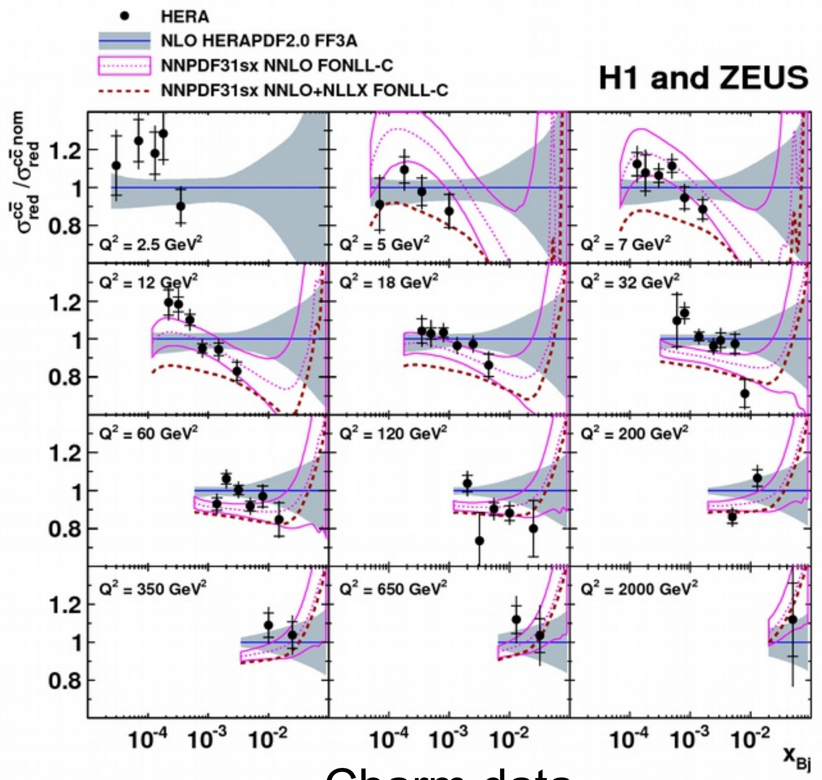
- Differences between variable-flavour and fixed-flavour are most pronounced at small scales and in the high-x region
- Slope difference between data and prediction near Q^2=12 GeV^2 is present for both FFNS and VFNS



Beauty data

Data and predictions are normalized to HERAPDF2.0 FF3A

Charm data and low-x resummation



Charm data

- Compare to calculation in NNLO VFNS (FONLL-C) with and without low-x resummation [magenta curves]
- Also shown: FFNS (NLO)
- At sufficiently large Q^2, slope in x is somewhat better described by NNLO-VFNS, even better if resummation is included
- Problem: calculations are not able to describe the Q^2-dependence well

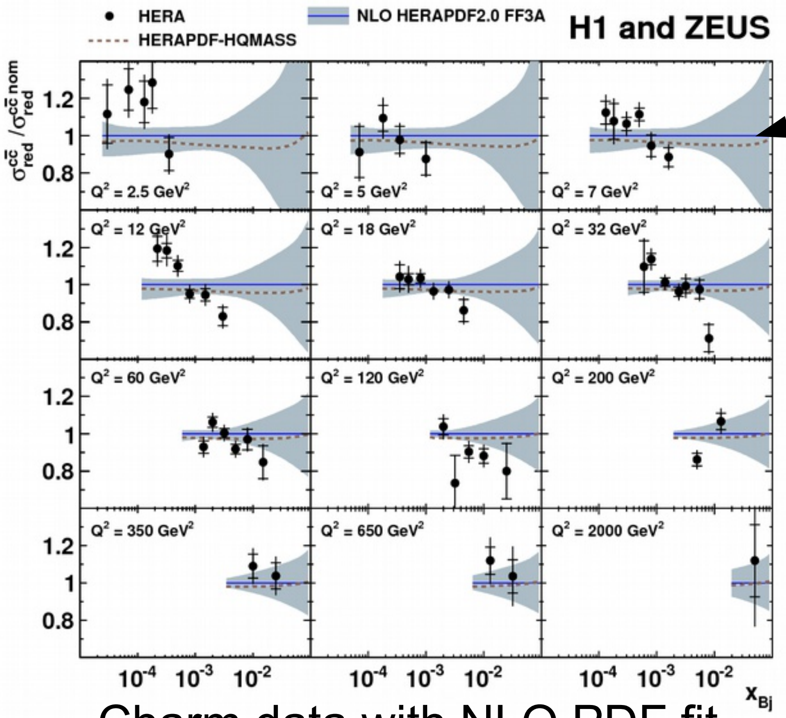
Data and predictions are normalized to HERAPDF2.0 FF3A

Quantitative comparisons data-theory

- χ^2-tests are performed of calculations against the data
- For beauty, the data are not good enough to discriminate
- For charm, all the predictions have poor χ^2: smallest tension of ~3σ for NLO-FFNS
- HERAPDF2.0 NLO (FFNS) is studied further in a dedicated QCD fit
  - Extract heavy quark masses
  - Investigate tensions to data

Dataset	PDF (scheme)	χ^2 [p-value]
charm, this analysis ($N_{data}=52$)	HERAPDF20_NLO_FF3A (FFNS)	86 [0.002]
	ABKM09 (FFNS)	82 [0.005]
	ABMP16_3_nlo (FFNS)	90 [0.0008]
	ABMP16_3_nnlo (FFNS)	109 [$6\cdot10^{-6}$]
	HERAPDF20_NLO_EIG (RTOPT)	99 [$9\cdot10^{-5}$]
	HERAPDF20_NNLO_EIG (RTOPT)	102 [$4\cdot10^{-5}$]
($N_{data}=47$)	NNPDF31sx NNLO (FONLL-C)	140 [$1.5\cdot10^{-11}$]
	NNPDF31sx NNLO+NLLX (FONLL-C)	114 [$5\cdot10^{-7}$]
beauty, this analysis ($N_{data}=27$)	HERAPDF20_NLO_FF3A (FFNS)	33[0.20]
	ABMP16_3_nlo (FFNS)	37 [0.10]
	ABMP16_3_nnlo (FFNS)	41 [0.04]
	HERAPDF20_NLO_EIG (RTOPT)	33 [0.20]
	HERAPDF20_NNLO_EIG (RTOPT)	45 [0.016]

NLO QCD fit and c,b masses



Charm data with NLO PDF fit

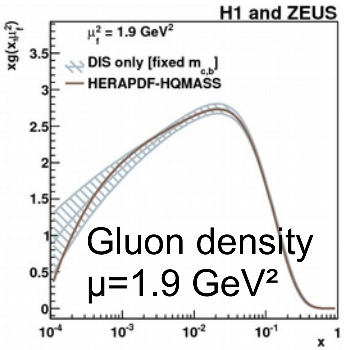
Data and fit are normalized to HERAPDF2.0 FF3A

- Charm and beauty data together with HERA inclusive DIS data are taken as input to a NLO QCD fit (dashed)
- Simultaneously extract PDFs and c,b masses

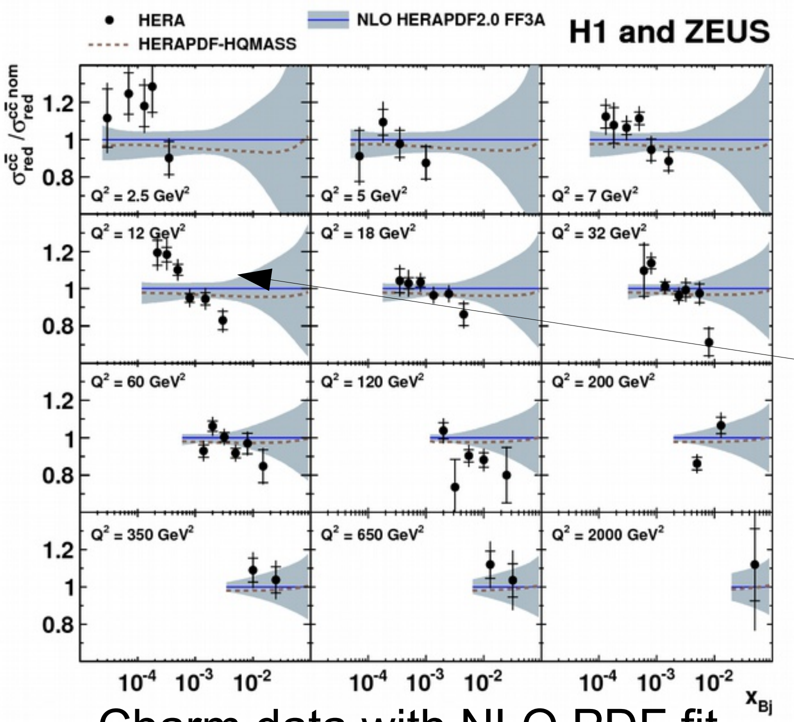
$$m_c(m_c) = 1290^{+46}_{-41}\,(\text{fit})\,^{+62}_{-14}\,(\text{model})\,^{+3}_{-31}\,(\text{param})\ \text{MeV}$$
$$m_b(m_b) = 4049^{+104}_{-109}\,(\text{fit})\,^{+90}_{-32}\,(\text{model})\,^{+1}_{-31}\,(\text{param})\ \text{MeV}$$

- Masses and PDFs are compatible previous HERA analyses and with world data

PDG: $m_c(m_c) = 1270 \pm 30\ \text{MeV}$
and $m_b(m_b) = 4180 \pm 30\ \text{MeV}$



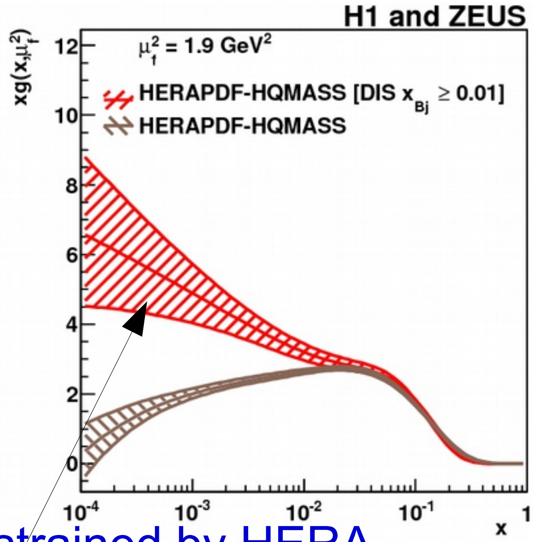
NLO QCD fit and 3σ tension to data



Charm data with NLO PDF fit

Data and fit are normalized to HERAPDF2.0 FF3A

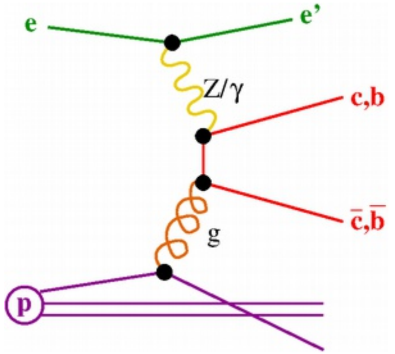
- Charm and beauty data together with HERA inclusive DIS data are taken as input to a NLO QCD fit (dashed)
- Fit is not able to improve or ~3σ tension of theory to data (slope in x)



- Reason: low-x gluon is constrained by HERA inclusive data
- Test: exclude inclusive data at low x and repeat fit → large change in fitted gluon density
- Further material in backup slides

Summary

- New combination of charm and beauty double-differential cross section measurements in deep-inelastic scattering at HERA
- Test of QCD with massive quarks (multiple scale problem)
- Fixed-flavour and variable-flavour number schemes
- None of the calculations is perfect, tension ~3σ
- PDF fit: charm and beauty data constrain quark masses



→ measure quark masses
from HERA data alone

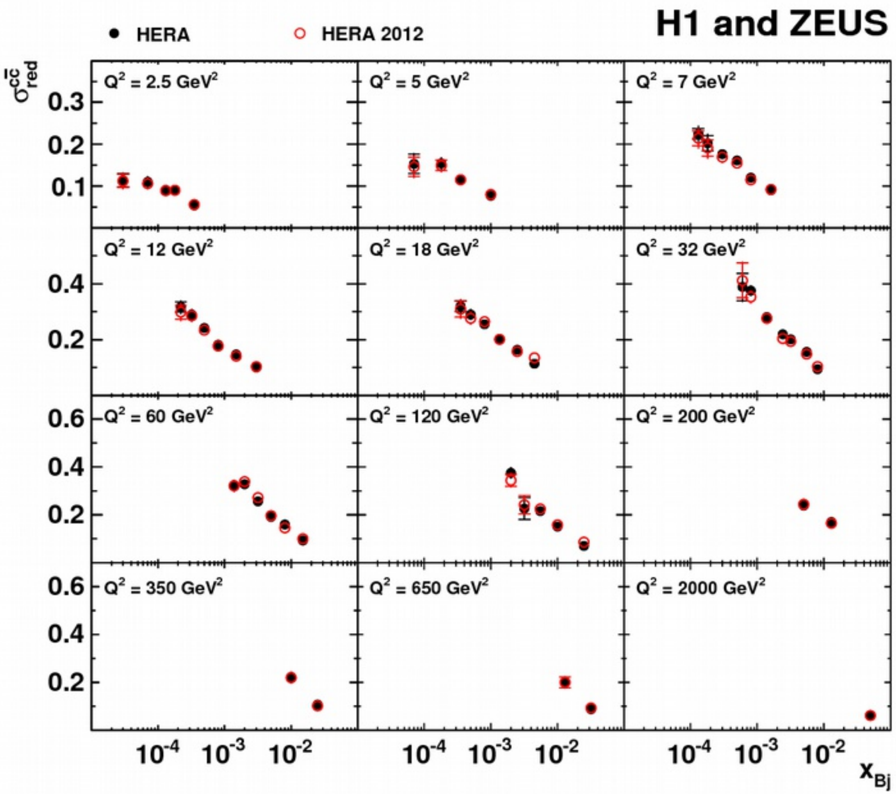
$$m_c(m_c) = 1290^{+46}_{-41}(\text{fit})\,^{+62}_{-14}(\text{model})\,^{+3}_{-31}(\text{param})\ \text{MeV}$$
$$m_b(m_b) = 4049^{+104}_{-109}(\text{fit})\,^{+90}_{-32}(\text{model})\,^{+1}_{-31}(\text{param})\ \text{MeV}$$

Further details in: Eur.Phys.J. C78 (2018) 473

Backup

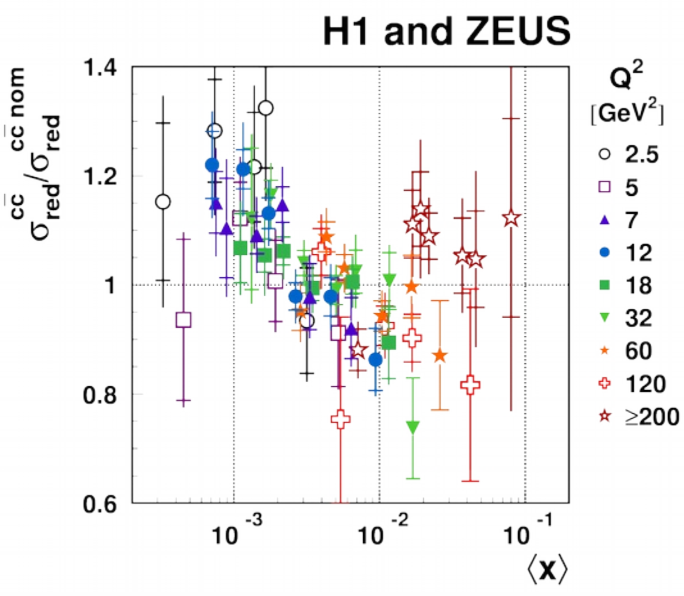
Charm combination: 2017 and 2012

- Compare 2017 combination to 2012 combination of charm data
- Central points are similar
- Improved uncertainties by ~20% at intermediate Q²

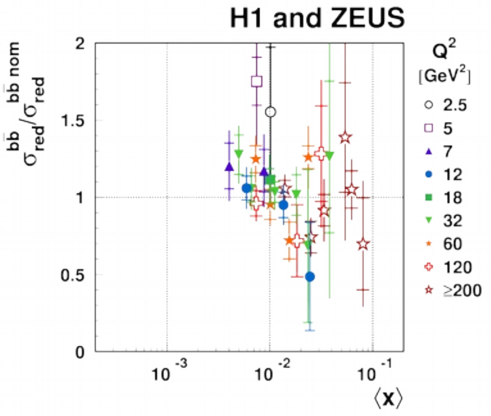


Investigation of tension in x

- For each analysis bin, calculate average partonic x (in NLO calculation)
- Show ratio data to NLO-FF3A as a function of partonic x
- Ratio shows a clear rise at low x, with contributions from several Q² bins



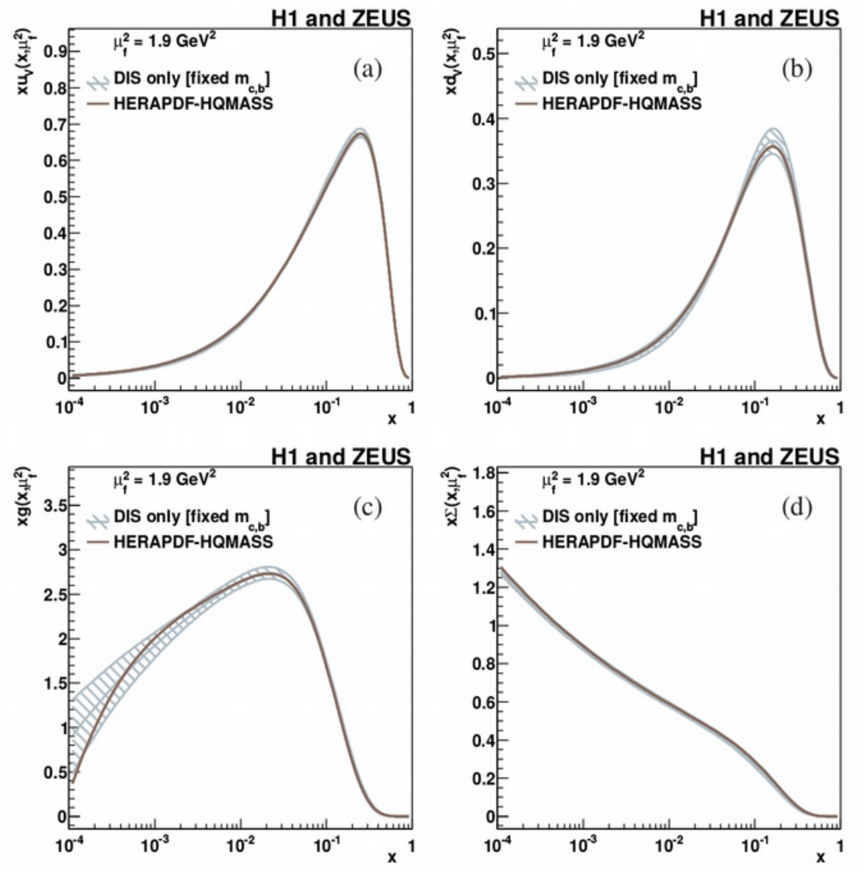
Charm data



Beauty data: probing only small range in <x>, no evidence for slope

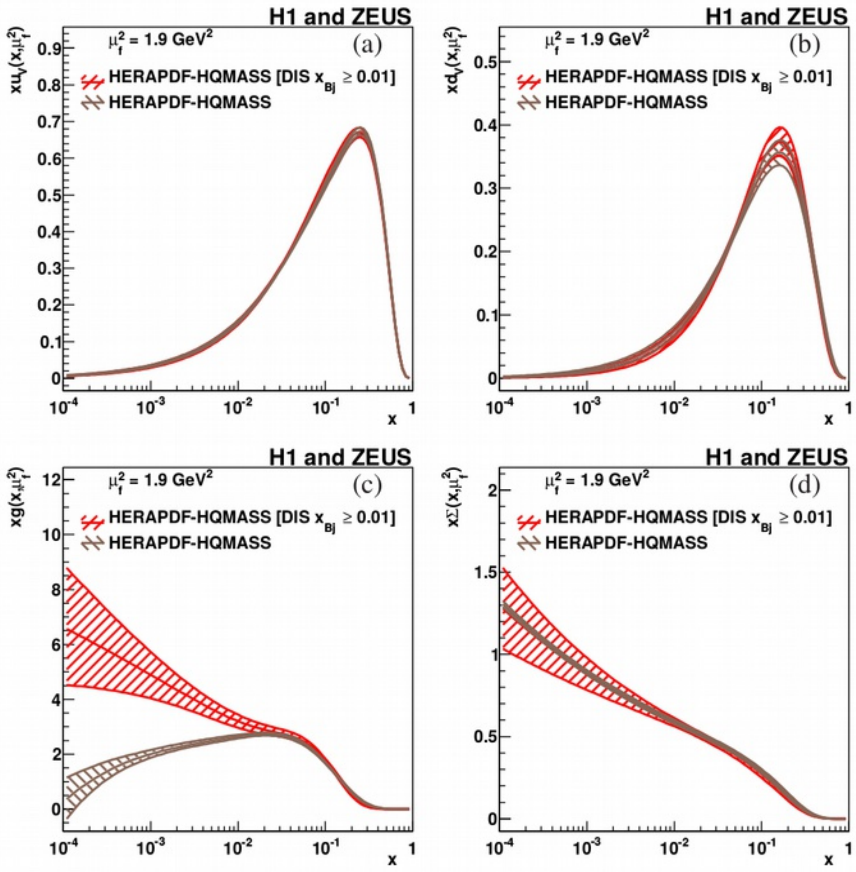
NLO QCD fit: resulting PDFs

- Comparison of PDFs
  - Fit of DIS data alone, with fixed c and b masses
  - Fit of DIS data and c+b data, with free c and b masses
- Both PDFs are similar (largely constrained by inclusive DIS data)
- c+b data constrains c and b quark masses

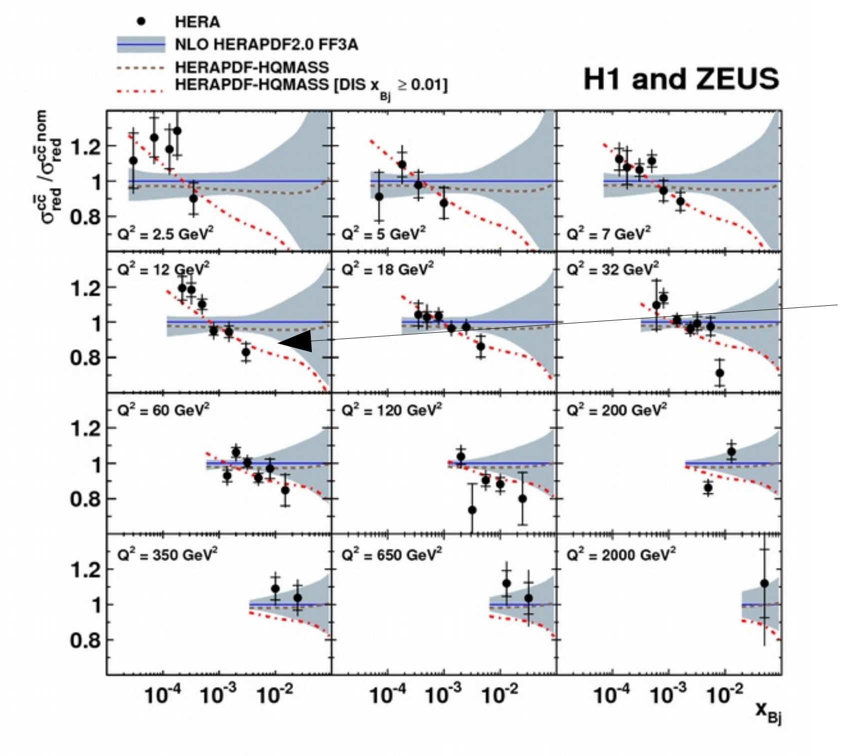


NLO QCD fit: PDFs with x-cut

- Comparison of PDFs from fits of DIS data and c+b data
  - Nominal fit
  - Fit with cut x>0.01 on inclusive data
- Large change in gluon density



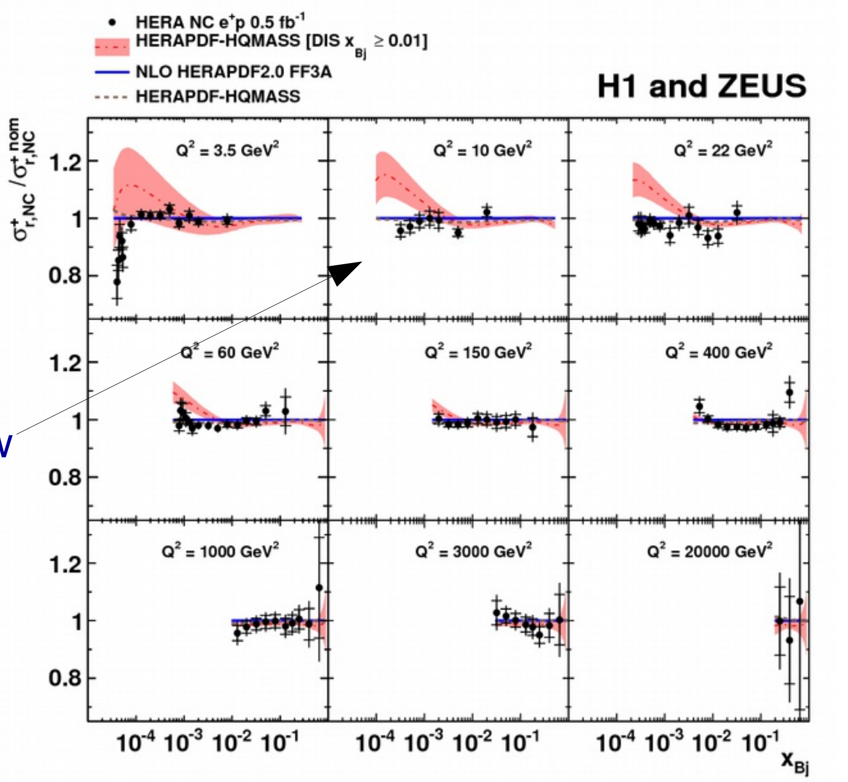
QCD fit with cut in x



Fit with cut x>0.01 on inclusive data:

Charm data are then well described

Inclusive data at low x are then not described at all



QCD fit settings

- Table: theory settings and uncertainties
- A_g, A_{uv}, A_{dv} constrained by sum rules
- Fit parameters: same 14 free parameters as for HERAPDF fits
- Fit quality: chi^2=1435/1208

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v}x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

$$C'_g = 25$$

$$f_s = x\bar{s}/(x\bar{d} + x\bar{s})$$

$$B_{\bar{U}} = B_{\bar{D}} \text{ and } A_{\bar{U}} = A_{\bar{D}}(1-f_s)$$

Parameter	Variation	$m_c(m_c)$ uncertainty [GeV]	$m_b(m_b)$ uncertainty [GeV]
Experimental / Fit uncertainty			
Total	$\Delta\chi^2 = 1$	$^{+0.046}_{-0.041}$	$^{+0.104}_{-0.109}$
Model uncertainty			
f_s	$0.4^{+0.1}_{-0.1}$	$^{-0.003}_{+0.004}$	$^{-0.001}_{+0.001}$
$Q^2_{\min}$	$3.5^{+1.5}_{-1.0}$ GeV^2	$^{-0.001}_{+0.007}$	$^{-0.005}_{+0.007}$
$\mu_{r,f}$	$\mu_{r,f}{}^{\times 2.0}_{\times 0.5}$	$^{+0.030}_{+0.060}$	$^{-0.032}_{+0.090}$
$\alpha_s^{n_f=3}(M_Z)$	$0.1060^{+0.0015}_{-0.0015}$	$^{-0.014}_{+0.011}$	$^{+0.002}_{-0.005}$
Total		$^{+0.062}_{-0.014}$	$^{+0.090}_{-0.032}$
PDF parameterisation uncertainty			
$\mu^2_{f,0}$	1.9 ± 0.3 GeV^2	$^{+0.003}_{-0.001}$	$^{-0.001}_{+0.001}$
E_{u_v}	set to 0	-0.031	-0.031
Total		$^{+0.003}_{-0.031}$	$^{+0.001}_{-0.031}$

Extrapolation to full phase space

- Extrapolation is done using FFNS calculation HVQDIS which also includes fragmentation

$$\sigma_{\mathrm{red}}^{Q\overline{Q}}(x_{\mathrm{Bj}}, Q^2) = \sigma_{\mathrm{vis,bin}} \frac{\sigma_{\mathrm{red}}^{Q\overline{Q},\mathrm{th}}(x_{\mathrm{Bj}}, Q^2)}{\sigma_{\mathrm{vis,bin}}^{\mathrm{th}}}.$$

Fragmentation functions, decay rations etc all set to their “best” known values.
Full details are described in the paper

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- HVQDIS settings

HERAPDF1.0

$$\mu_{\mathrm{r}} = \mu_{\mathrm{f}} = \sqrt{Q^2 + 4m_{\mathrm{Q}}^2}$$

$$\alpha_s^{n_f=3}(M_Z) = 0.105 \pm 0.002$$

$$m_b = 4.50 \pm 0.25 \text{ GeV},$$

$$m_c = 1.50 \pm 0.15 \text{ GeV},$$