Combination and QCD analysis of charm and beauty production cross-section measurements in deep inelastic ep scattering at HERA

Uri Karshon

Weizmann Institute of Science, ISRAEL

on behalf of the
H1 and ZEUS Collaborations

PHOTON 2019

INFN Laboratori Nazionali di Frascati (Rome, Italy)

June 3 - 7, 2019

O U T L I N E

Introduction and motivation

Heavy quark production in DIS

Combination of charm and beauty data

Comparison with QCD predictions

QCD analysis

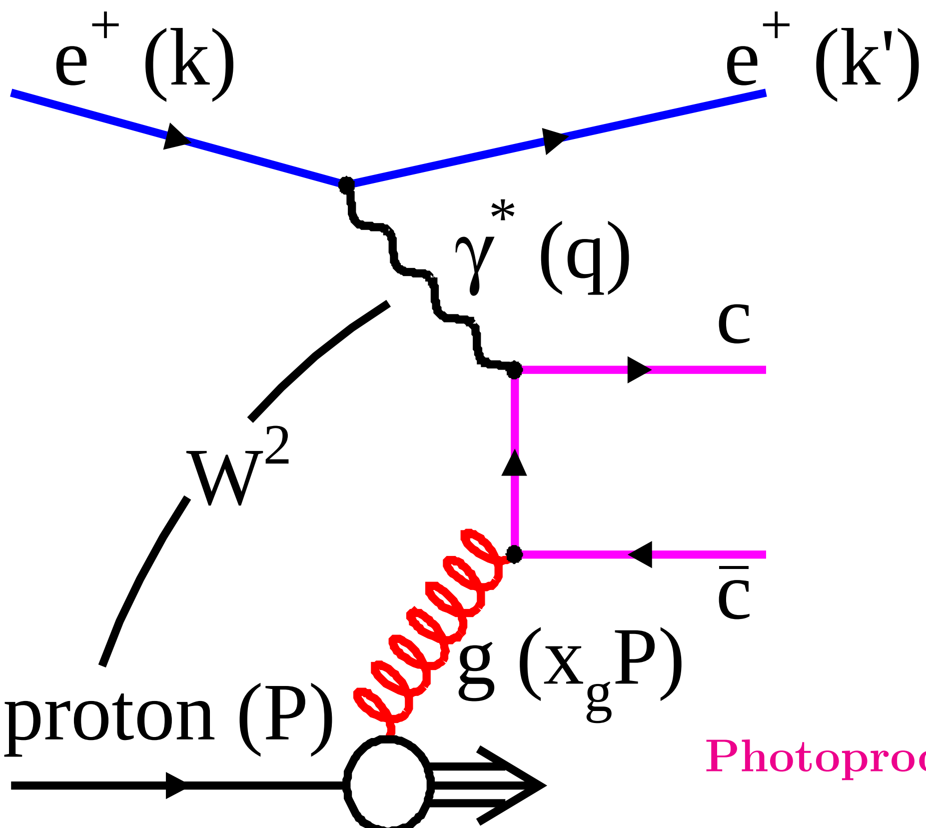
Summary

Introduction and motivation

Measurements of open charm (c) and beauty (b) production in neutral current (NC) deep inelastic electron (or positron)- proton scattering (DIS) at HERA yield crucial input for tests of QCD.

Charm quark c (charge $\frac{2}{3}$): Coupling to γ stronger than d, s, b quarks (charge $-\frac{1}{3}$)

$\Rightarrow$ Large charm production cross section at HERA



$e^{\pm}(k)+p(P) \rightarrow e^{\pm}(k')+X;\ s = (P+k)^2$

Photon virtuality:

$Q^2 = -q^2 = -(k-k')^2$

Bjorken x: $x_{B_j} = \frac{Q^2}{2q\cdot P}$

Inelasticity: $y = \frac{q\cdot P}{k\cdot P}$

$Q^2 = s x_{B_j} y$

$W = \gamma^* p$ CM energy

Photoproduction (PHP): $Q^2 \simeq 0\, GeV^2$ ($e^{\pm}$ undetected)

Deep Inelastic Scattering (DIS): $Q^2 > few\, GeV^2$ ($e^{\pm}$ detected)

Introduction and motivation

In LO QCD the dominant process in Heavy Quark production ($HQ = c$ or b) in DIS is Boson-Gluon fusion (BGF)

At least two heavy quarks (HQ) are present in final state

$\Rightarrow x_g$ of incoming gluon different from x_{B_j} measured at photon vertex

Charm contribution to inclusive DIS cross section is up to 30% at HERA

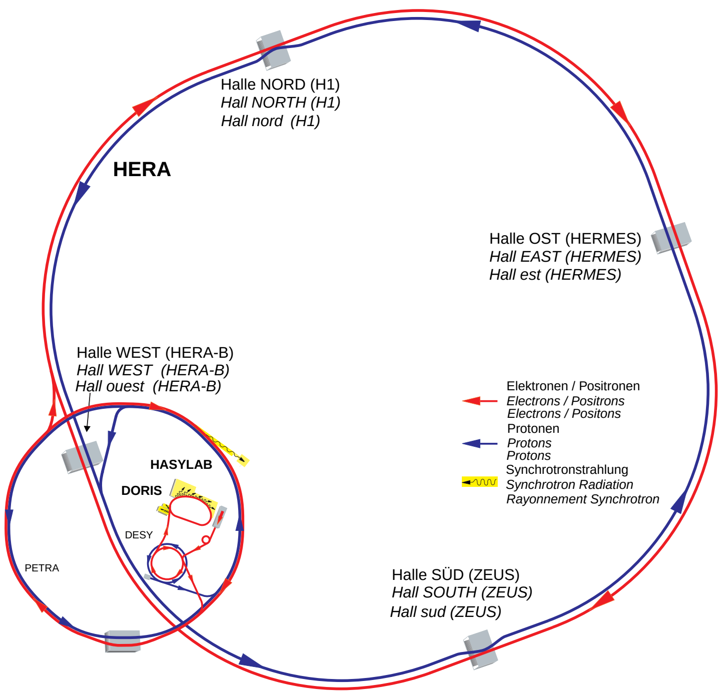
Production is directly sensitive to the gluon density in the proton and to the HQ (c, b) masses

Test QCD by comparing data to next-to-leading order (NLO) predictions + partial NNLO corrections

Multiple hard scales $(Q^2, m_{HQ}, p_T(HQ))$:
Perturbative calculations possible

Non-perturbative part not calculable in QCD

Experimental set-up



HERA was a unique $e^{\pm}p$ collider

$E(e^{\pm}) = 27.6$ GeV ; $E(p) = 820/920$ GeV

$E(p) >> E(e^{\pm})$

$\Rightarrow$ Asymmetric Detector(along beam)

	HERA I	HERA II
	1995-2000	2003-2007
$\mathcal{L}_{int}/exp.$	≈ 130	$\approx 380\, pb^{-1}$

$\approx$ half HERA II data taken with e^+p

$\approx$ half HERA II data taken with e^-p

Tunnel 6.3 km ($< \frac{1}{4}$ Circumference of LHC Tunnel)

2 Collider Rings: Lepton and Proton **2 Lepton Beams: e^- or e^+**

2 Proton Beam Energies: $820, 920\ GeV$ **2 Main Experiments: H1, ZEUS**

2 Run Periods: HERA I, HERA II **2 Event Types: DIS, Photoproduction**

Heavy quark production in DIS

Several QCD NLO schemes for HQ (c or b) production:

1)Massive scheme: $Q^2 \approx m^2_{HQ}$ Fixed flavour number scheme (FFNS)

3 active flavours in proton; HQ not considered as parton in proton

c or b produced perturbatively in hard scattering (see p.2)

Mass effects correctly included

Spoiled by large logs of $Q^2/m^2_{HQ}, p_t/m_{HQ}$ ... $\Rightarrow$ No logs resummation

2)Massless scheme: $Q^2 >> m^2_{HQ}$

Zero-mass variable flavour number scheme (ZM-VFNS)

c or b treated as massless parton

Resummation of large logarithms of Q^2/m^2_{HQ}

$\Rightarrow$ c or b density added as an extra flavour to the light quarks

At intermediate Q^2 the 2 schemes should be merged

3) General-mass variable flavour number scheme (GM-VFNS)

Equivalent to FFNS for $Q^2 \leq m^2_{HQ}$ and to ZM-VFNS for $Q^2 > m^2_{HQ}$

Interpolation in between (various schemes interpolate differently)

Used in parton density function (PDF) fits (useful at LHC)

Combination of charm and beauty data

Heavy quark reduced cross sections, $\sigma_{red}^{Q\bar{Q}}$, were measured in the kinematic range:

$$2.5 < Q^2 < 2000 \text{ GeV}^2;\ 3 \cdot 10^{-5} < x_{B_j} < 5 \cdot 10^{-2}$$

$$\frac{d^2\sigma^{Q\bar{Q}}}{dx_{B_j}dQ^2} = \frac{2\pi\alpha^2}{x_{B_j}Q^4}[(1+(1-y)^2)\sigma_{red}^{Q\bar{Q}}]$$

Combined 13 charm + beauty data sets of D^*, D^+, D^0, μ and liftime tag data from various HERA I and HERA II analyses of H1 and ZEUS

Combination method accounts for correlations of statistical and systematic uncertainties for all datasets

Eur.Phys.J C78 (2018) 473

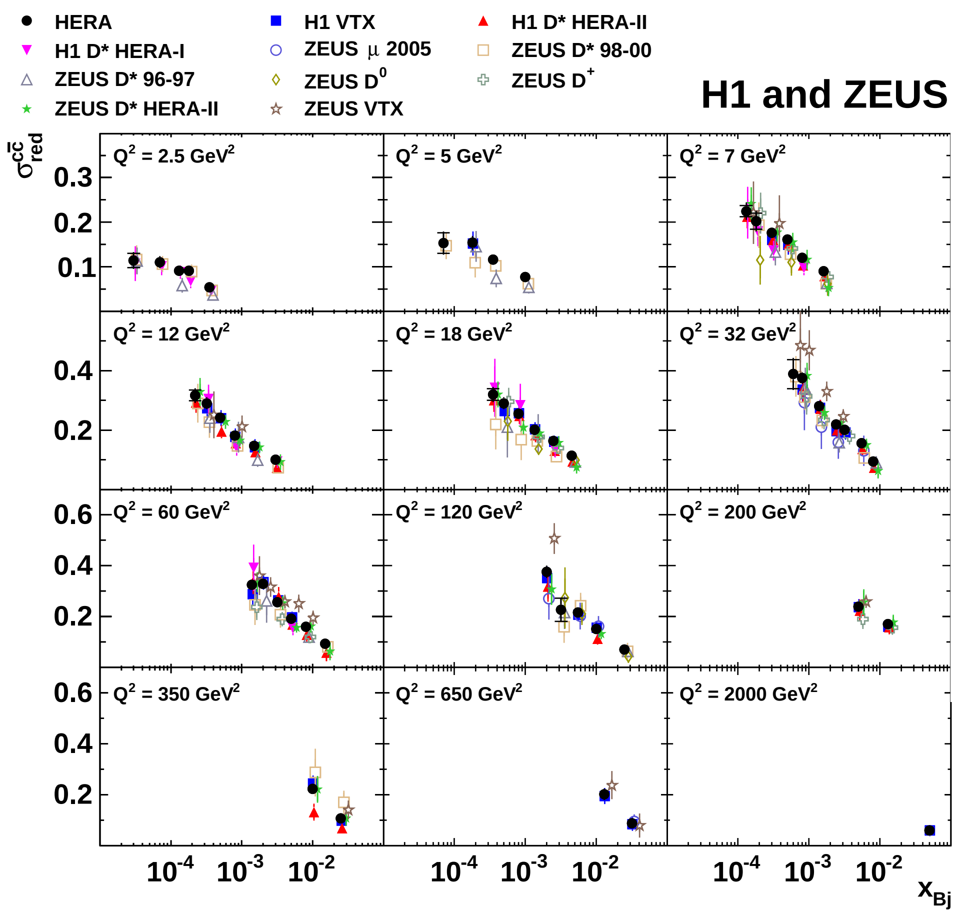
Superseeds previous combination of 9 data sets EPJ C73 (2013) 2311

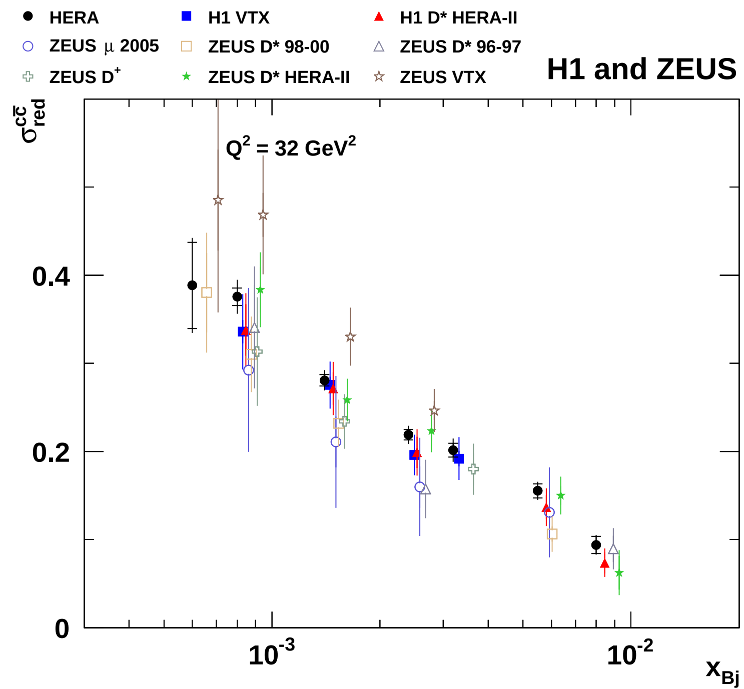
Beauty combined for the first time

Combined data compared to predictions using various PDFs within FFNS and VFNS schemes

Combination of charm data

Reduced cross sections $\sigma_{red}^{c\bar{c}}$ as function of x_{B_j} for fixed Q^2 values





Enlarged plot for $Q^2 = 32$ GeV^2

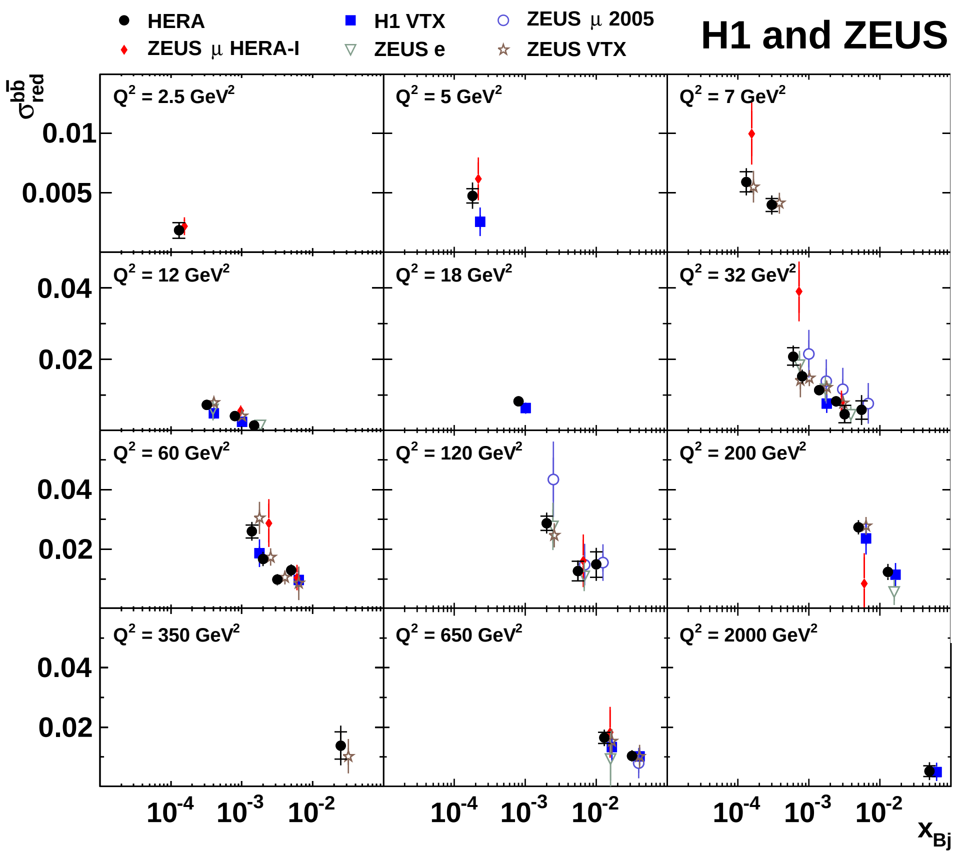
Combined results uncertainty much better than each most precise data set

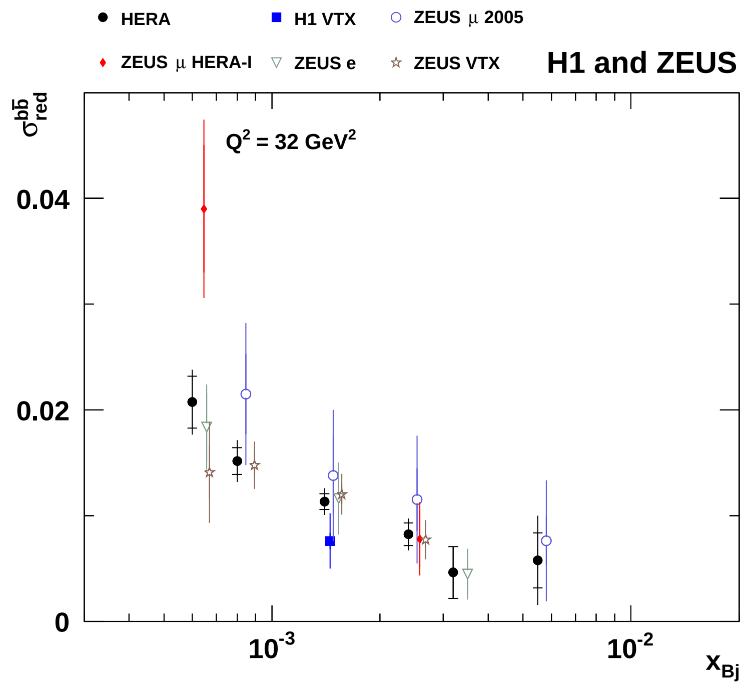
Combined results - filled circles: Inner error bars - uncorreolated uncertainties

Outer error bars - total uncertainties

Combination of beauty data

Reduced cross sections $\sigma^{b\bar{b}}_{red}$ as function of x_{B_j} for fixed Q^2 values





Enlarged plot for $Q^2 = 32$ GeV^2

b-results combined for the first time

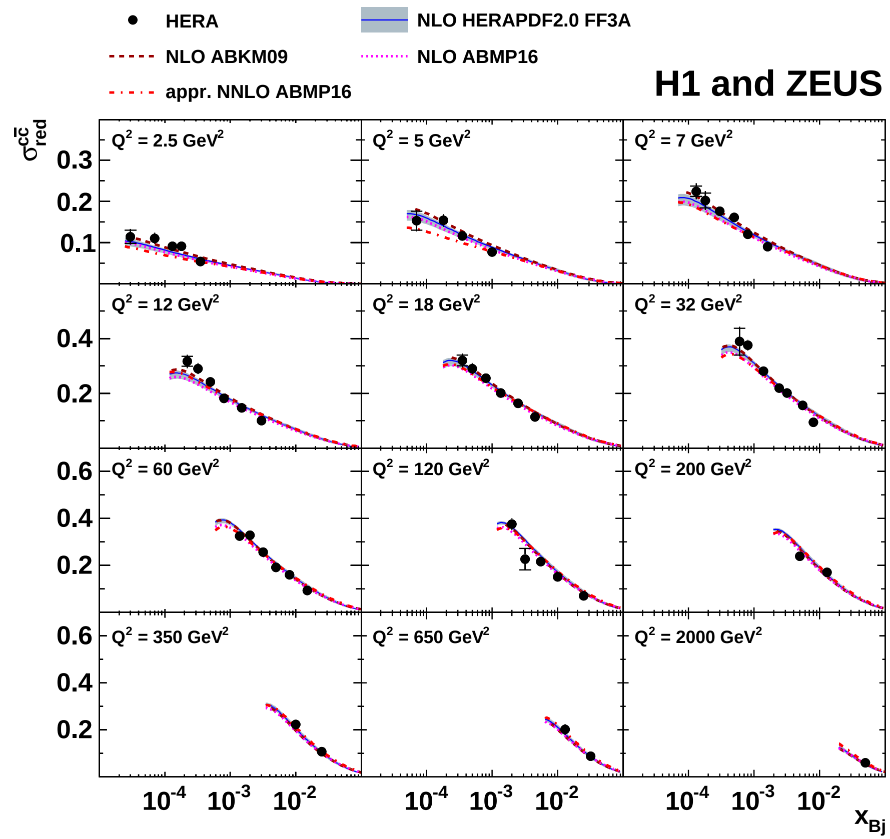
Combined results - filled circles: Inner error bars - uncorreolated uncertainties

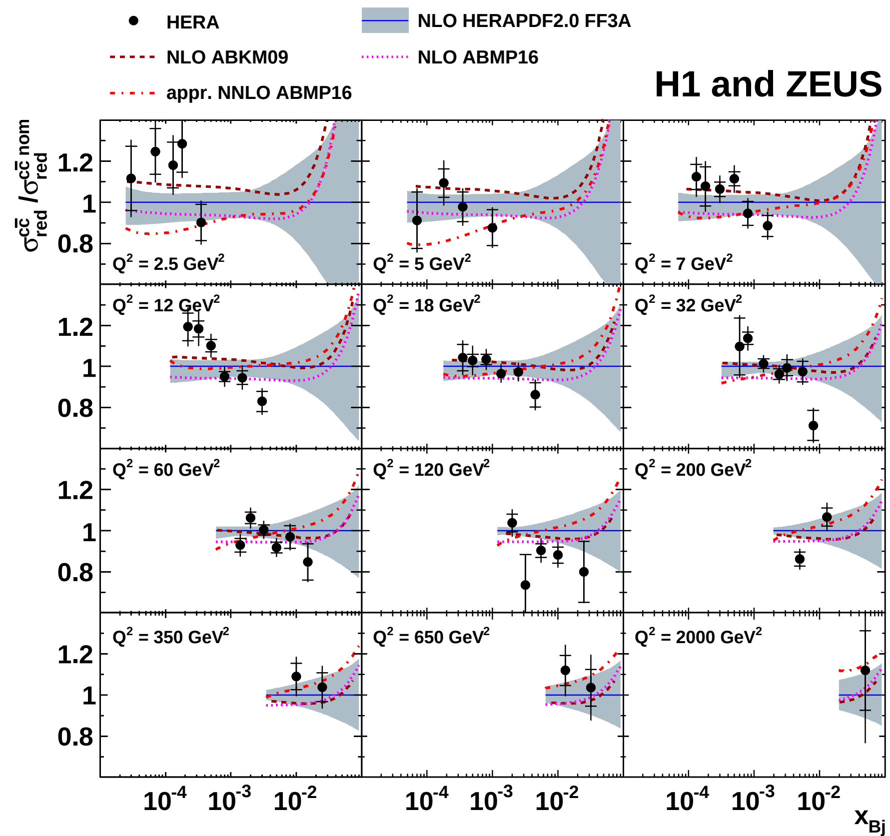
Outer error bars - total uncertainties

Comparison with QCD predictions

Combined charm/beauty data compared with QCD calculations using various schemes and PDF sets at NLO and approximate NNLO

$\sigma_{red}^{Q\bar{Q}}$ comparison to FFNS in the $\overline{MS}$ running mass scheme with m_{HQ} PDG values





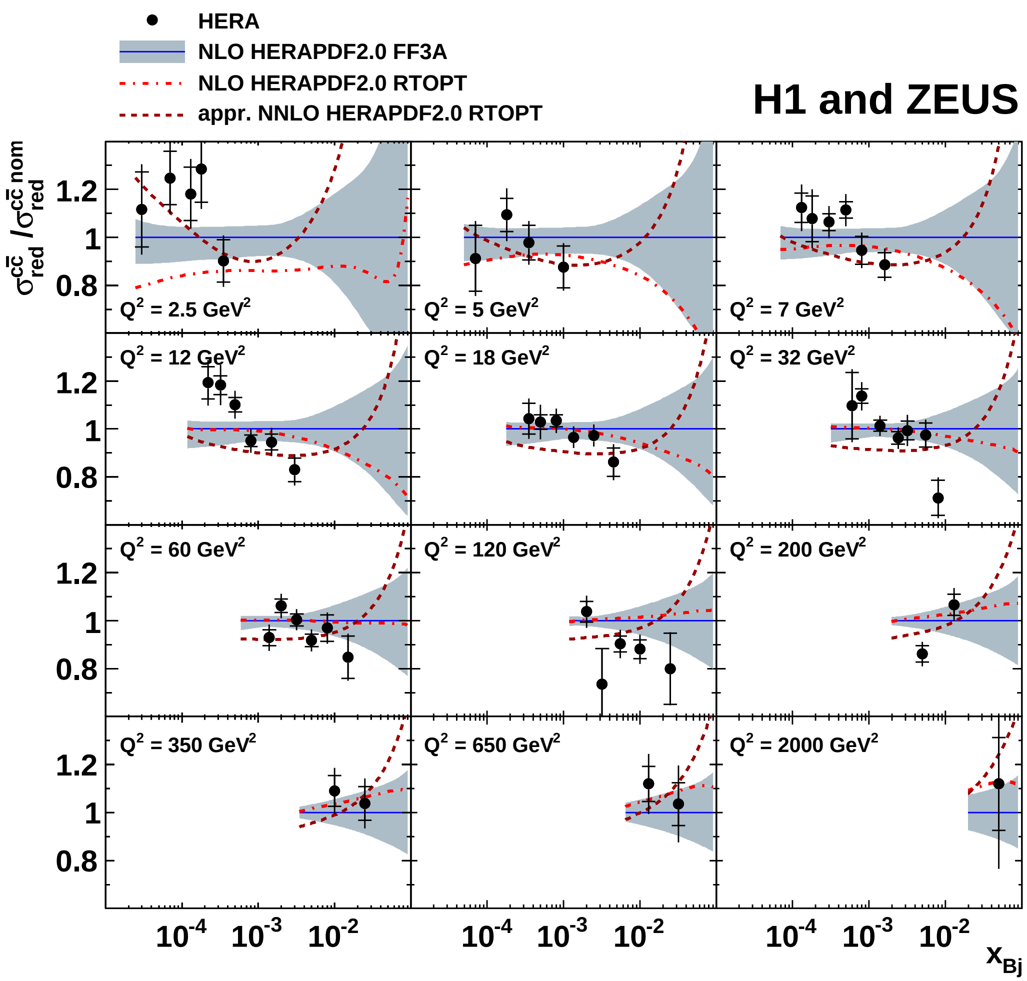
FFNS reasonably describe the charm data; best with HERAPDF and ABKM09

x_{B_j} slope steeper than predicted in ratio of data to nominal FFNS NLO FF3A

Description not improved with approximate NNLO

$\sigma_{red}^{b\bar{b}}$ predictions in good agreement with data within large uncertainties

Comparison to VFNS predictions



NLO VFNS predictions consistent with data and with reference calculation (FFNS NLO FF3A)

VFNS not better than FFNS

Approx. NNLO is ≈ 10 percent smaller than reference cross section in region $12 \leq Q^2 \leq 120$ GeV^2

For $Q^2 \leq 7$ GeV^2 x_{B_j} slope of NNLO is better than reference calculation

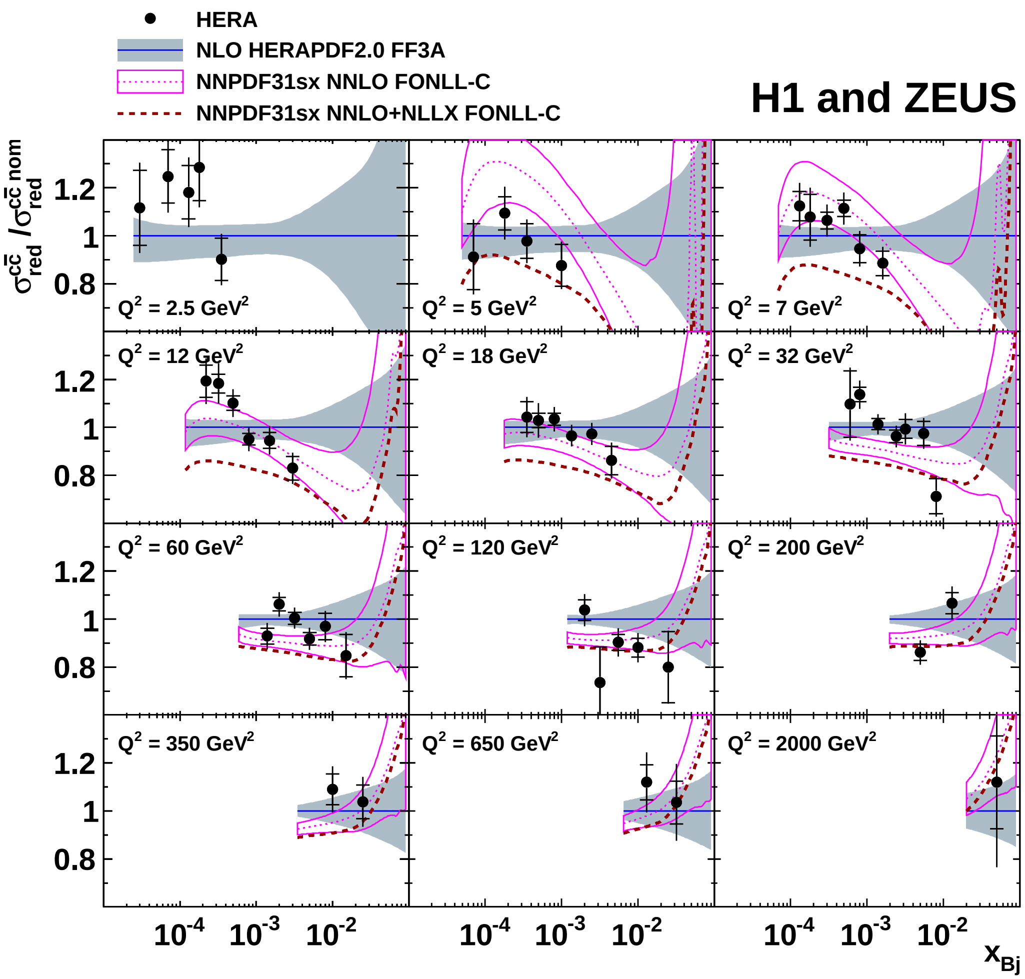
Some tension in x_{B_j} slope as for FFNS predictions

For beauty production, difference between calculations small with respect to experimental uncertainties → all is consistent

Comparison with QCD predictions

Proton PDFs with NLO+NNLO fixed order supplemented by NLLx low-x resummation improve agreement at low-x

Comparison to FONLL-C scheme with (NNLO+NLLsx) and without (NNLO) low-x_{B_j} resummation (Ball et al., arXiv: 1710.05935)



Better description of x_{B_j} slope in both calculations for $Q^2 < 32$ GeV^2

Predictions mostly below data mainly for NNLO+NLLsx

Overall description not improved w.r.t. FFNS reference calculation

From χ^2 analysis, NLO FFNS gives best description of charm data

For beauty, good agreement with theory within larger uncertainties

QCD analysis

Combined c and b together with combined inclusive DIS ($Q^2_{min} = 3.5$ GeV^2) used to perform simultaneous NLO QCD fit to determine running heavy-quark masses $m_c(m_c)$ and $m_b(m_b)$

Fit simultaneously PDF's in FFNS at NLO and c, b quarks running masses in $\overline{MS}$ scheme via NLO DGLAP evolution with number of active flavours $n_f = 3$

For heavy flavour part scales set to $\mu_F = \mu_R = \sqrt{Q^2 + 4m^2_{HQ}}$

$m_c(m_c), m_b(m_b)$ free parameters in fit ; μ_F, μ_R factor./renormal. scales

$\alpha_s(M_Z)$ for $n_f = 3$ set to 0.106, corresponding to 0.118 for $n_f = 5$

Experimental uncertainty determined from fit using $\Delta\chi^2 = 1$

Total uncertainty obtained by adding exp./fit, model uncertainty (mainly from QCD scale variation) and PDF parameterisation uncertainty in quadrature

HERAPDF-HQMASS is the resulting PDF set of the fit

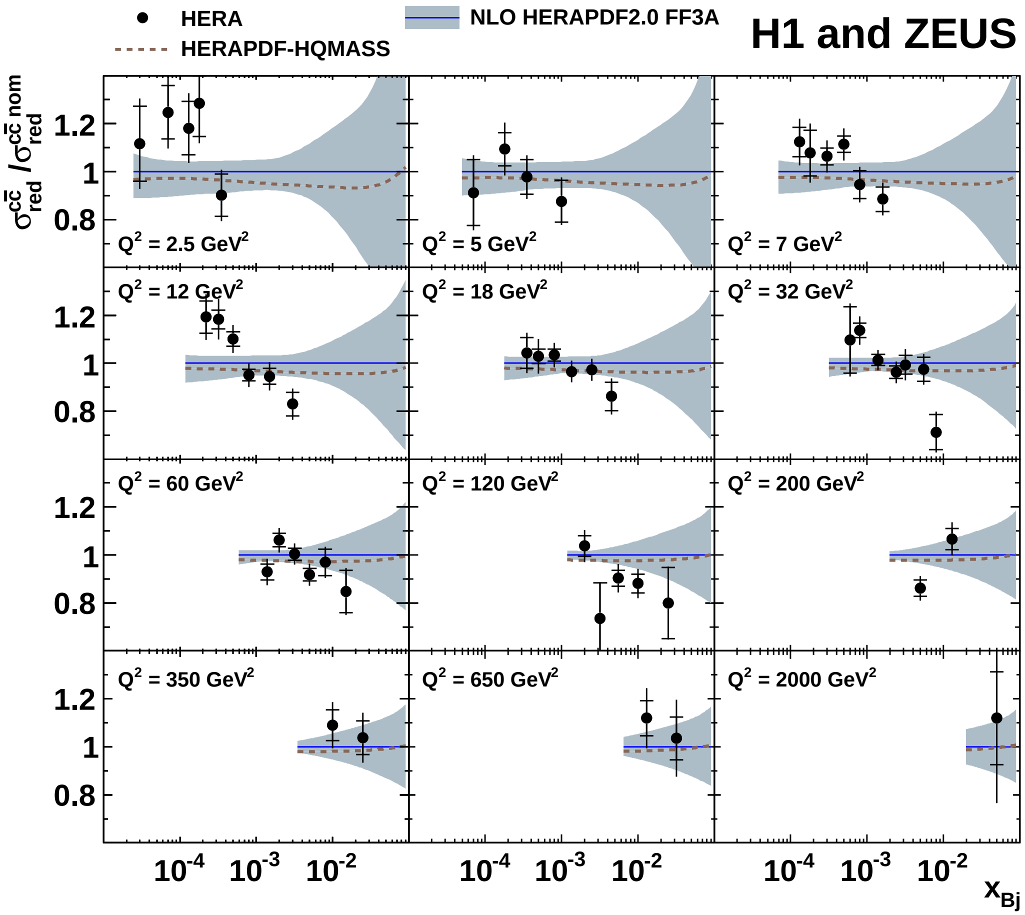
$$m_c(m_c) = 1.29^{+0.05}_{-0.04}(exp./fit)^{+0.06}_{-0.01}(mod.)^{+0.00}_{-0.03}(par.)\ \text{GeV}$$

$$m_b(m_b) = 4.05^{+0.10}_{-0.11}(exp./fit)^{+0.09}_{-0.03}(mod.)^{+0.00}_{-0.03}(par.)\ \text{GeV}$$

Consistent with PDG2016: $m_c(m_c) = 1.27 \pm 0.03$ GeV ; $m_b(m_b) = 4.18^{+0.04}_{-0.03}$ GeV

QCD analysis

Ratios of data and HERAPDF-HQMASS to the nominal FFNS NLO



Charm data described almost identical for both calculations

Steeper x_{B_j} dependence in data vs. theory persists also after fit

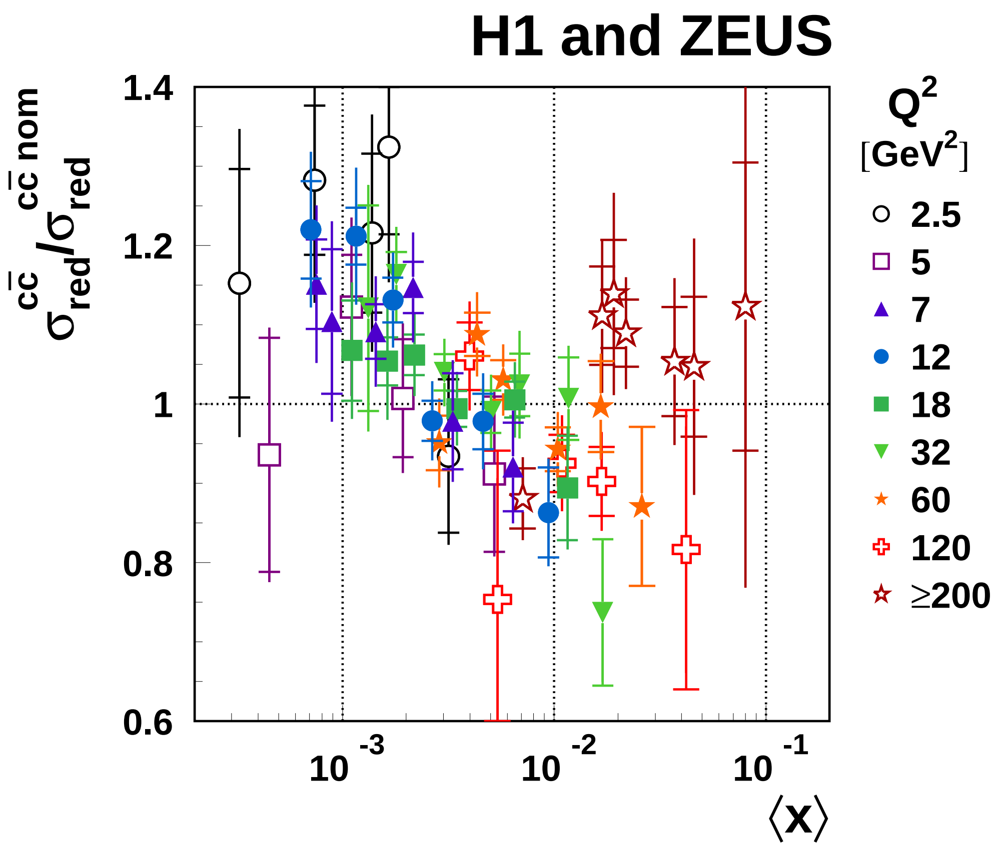
For beauty good agreement between theory and data within large uncertainties

QCD analysis

Ratio of $\sigma_{red}^{c\bar{c}}$ to NLO FFNS nominal predictions based on HERAPDF-HQMASS as function of $< x >$ for different Q^2 values

$< x >$ is the geometric mean of x_g calculated at NLO

In LO $x_g = x_{B_j}.(1 + (\bar{s}/Q^2))$; $\bar{s}$ = invariant mass of heavy quark pair



For charm, clear deviation from reference calculation:

Steeper $< x >$ slope for all Q^2

No conclusion for beauty data due to larger exp. uncertainties

QCD analysis

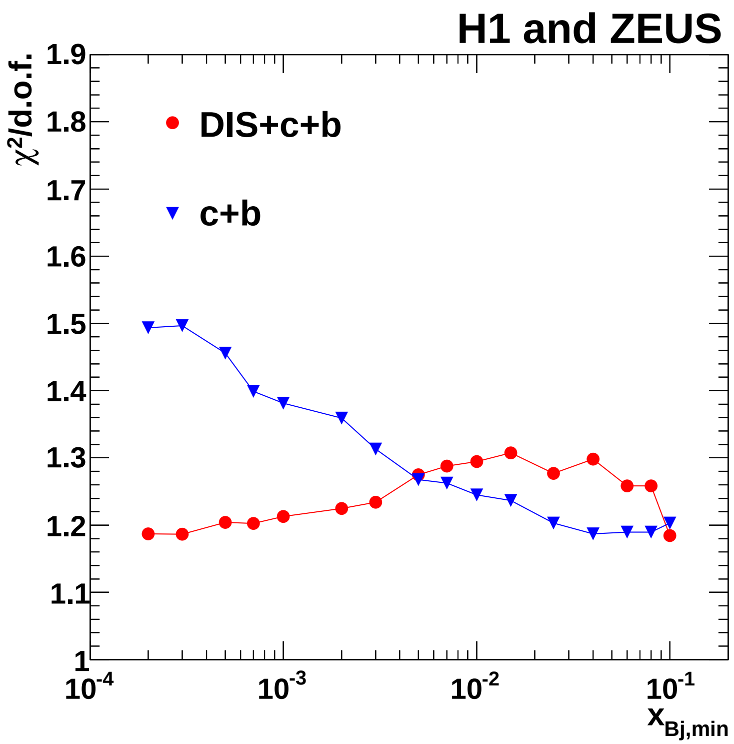
Inclusive DIS cross section constrains gluon density indirectly via scaling violation and directly via higher order corrections

Heavy-flavour production probes gluon directly at leading order

Can enhance impact of charm measurement on gluon determination in QCD fit due to high precision of $\sigma_{red}^{c\bar{c}}$

A cut of $x_{B_j} > x_{B_j,min}$ on inclusive data only in the fit reduces impact of inclusive data in determination of gluon density function

χ^2 per degree of freedom of QCD fit as function of $x_{B_j,min}$



Triangles: heavy-flavour data only

Dots: inclusive data + heavy flavour data

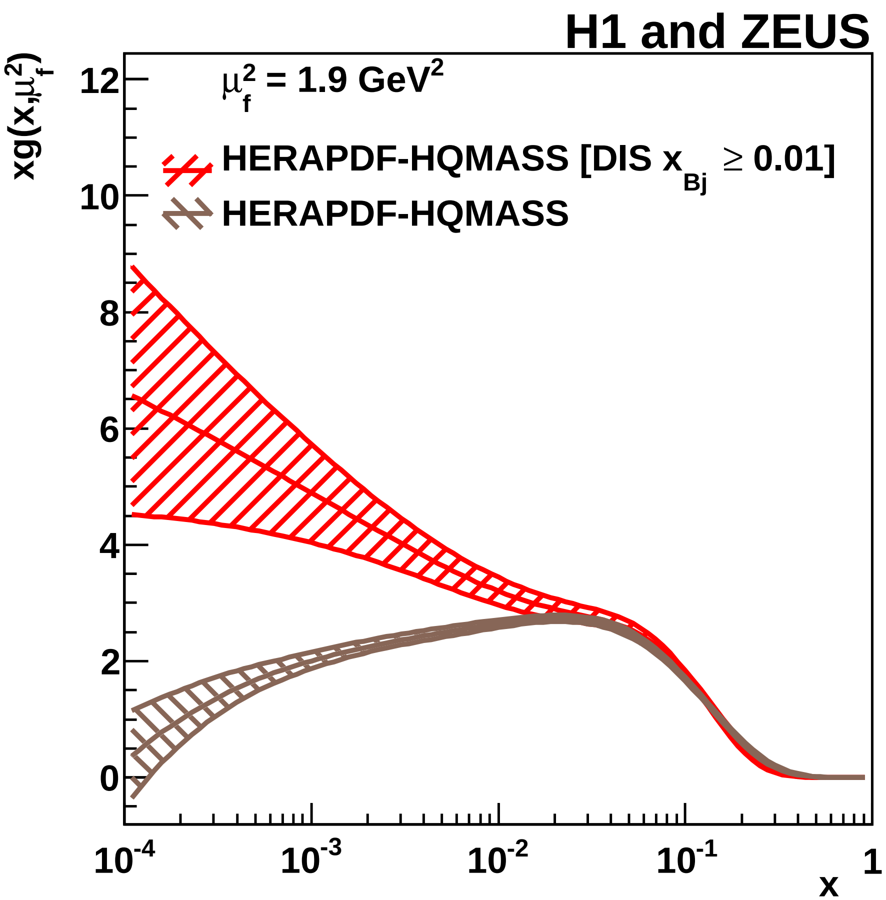
χ^2/d.o.f. for heavy-flavour improves significantly with rising $x_{B_j,min}$

χ^2/d.o.f. for inclusive + heavy-flavour slightly larger than without a x_{B_j} cut

$x_{B_j,min} = 0.01$ chosen for further studies

QCD analysis

Resulting gluon density function, $xg(x, \mu_f^2)$, at starting scale $\mu_f^2 = 1.9$ GeV^2 of HERAPDF-HQMASS obtained from QCD fit to combined inclusive and heavy-flavour data



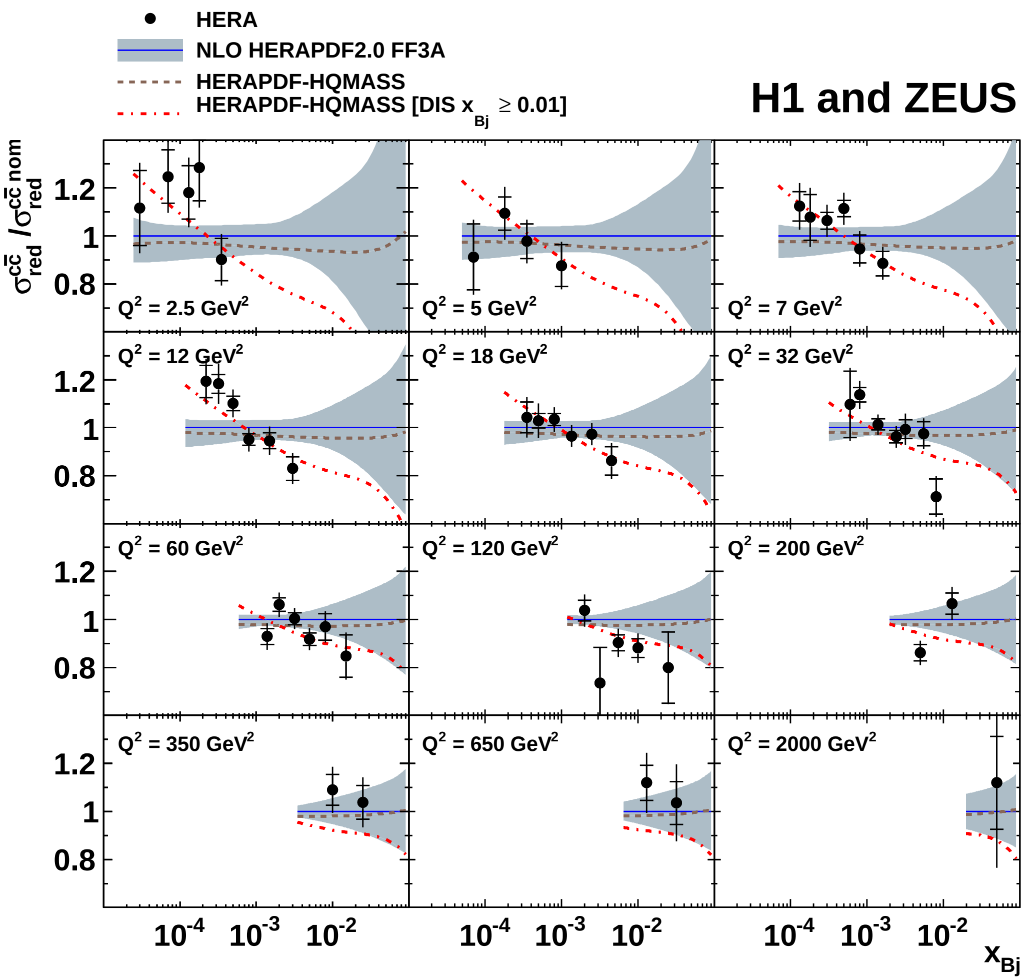
Lower curve: No cut on x_{Bj}

Upper curve: With cut $x_{B_j} > 0.01$ to inclusive data only

Low x gluon density function with $x_{B_j} > 0.01$ cut describes much better the charm data

QCD analysis

Ratio of $\sigma_{red}^{c\bar{c}}$ to NLO FFNS nominal predictions
as function of x_{B_j} for different Q^2 values (full circles)
based on HERAPDF-HQMASS (dashed lines) and on
fit with $x_{B_j} > 0.01$ for inclusive data (dashed dotted lines)



Fit with x_{B_j} cut on inclusive data rise more strongly towards small x_{B_j} and describe data much better than other predictions

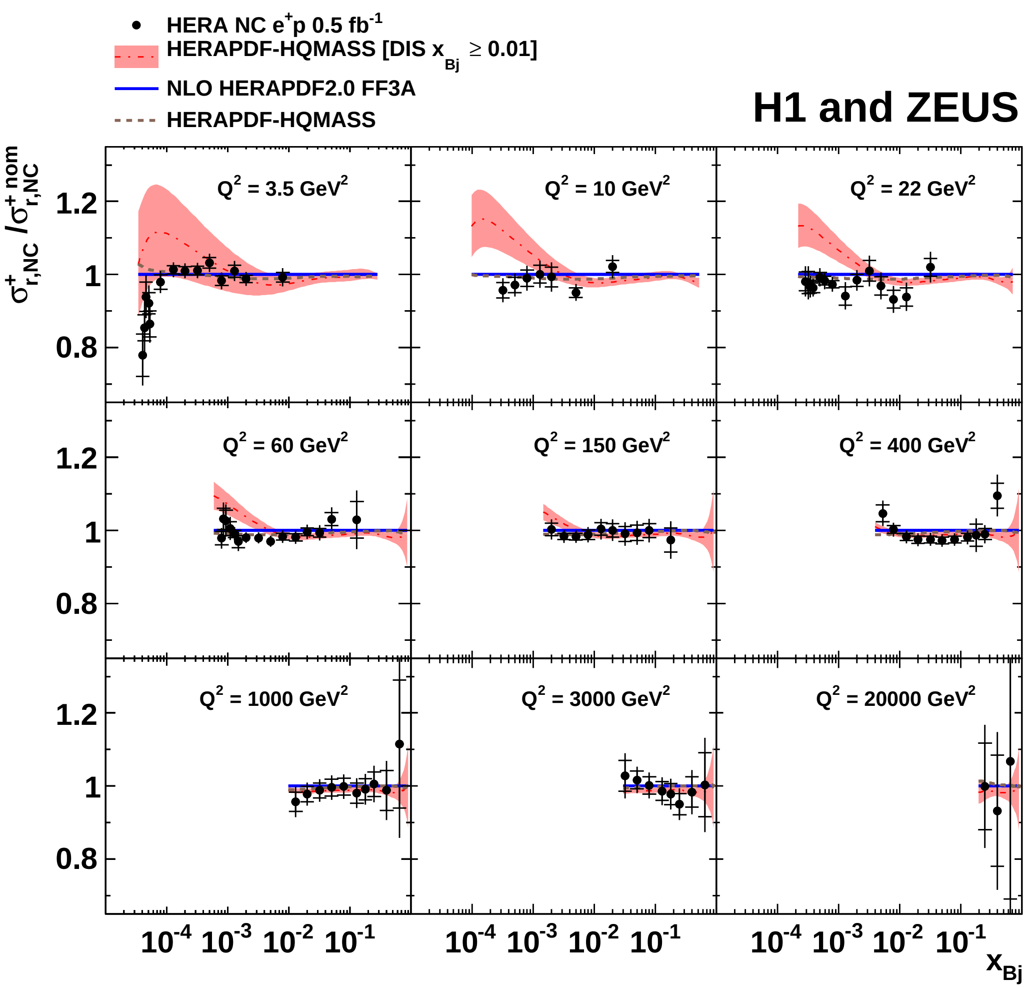
Predictions from fit with x_{B_j} cut follow nicely the charm data

No significant improvement in description of beauty data

Heavy-quark masses obtained from fit with x_{B_j} cut are consistent with those described before

QCD analysis

Ratio of combined inclusive reduced cross section for NC e^+p DIS, $\sigma^+_{r,NC}$, to NLO FFNS reference cross section, $\sigma^{+nom}_{r,NC}$ (full circles) based on HERAPDF-HQMASS (dashed lines) and on fit with $x_{Bj} > 0.01$ for inclusive data (dashed dotted lines)



Predictions based on NLO FFNS and on HERAPDF-HQMASS agree with inclusive measurement

Calculations with $x_{Bj} > 0.01$ cut for inclusive data fail to describe low-x inclusive data

Impossible to resolve difference in describing simultaneously inclusive and charm measurements by changing gluon density

Unlikely to improve at NNLO which gives poorer description than NLO for charm data

Summary

Final combined H1 + ZEUS charm(ing) and beauty(ful) results in DIS with full HERA data, including all correlations
$\Rightarrow$ tighter constraints on QCD

Charm precision improved by $\approx 20\%$;
Beauty combined for the first time

Charm data reasonably described by FFNS (best) and VFNS (NLO better than approx. NNLO);
$\approx 3\sigma$ tension in x-slope w.r.t inclusive data

Beauty data well described by all QCD predictions within larger experimental uncertainties

QCD fit of inclusive, charm and beauty data (simultaneous fit of PDFs, m_c, m_b in FFNS at NLO) yields:

$$m_c(m_c) = 1.29^{+0.05}_{-0.04}(exp./fit)^{+0.06}_{-0.01}(mod.)^{+0.00}_{-0.03}(par.)\ \text{GeV}$$

$$m_b(m_b) = 4.05^{+0.10}_{-0.11}(exp./fit)^{+0.09}_{-0.03}(mod.)^{+0.00}_{-0.03}(par.)\ \text{GeV}$$

in agreement with PDG and previous measurements

Summary

x slope tension cannot be solved by varying gluon density,
adding higher orders or resumming log $1/x$ terms
$\rightarrow$ further investigations needed

DESY news release June 16 2018 on this analysis:
"Final combined H1 + ZEUS results on heavy quark production
Culmination of over 20 years of work
10 years after end of data taking HERA experiments
continue to produce high-level publications
Together with previous HERA results will appear in future text books
Has application to physics studies at the LHC in CERN
HERA data still challenging best theoretical descriptions
of fundamental structure of matter
Collaborations look forward to further theoretical developments
inspired by these unique results"

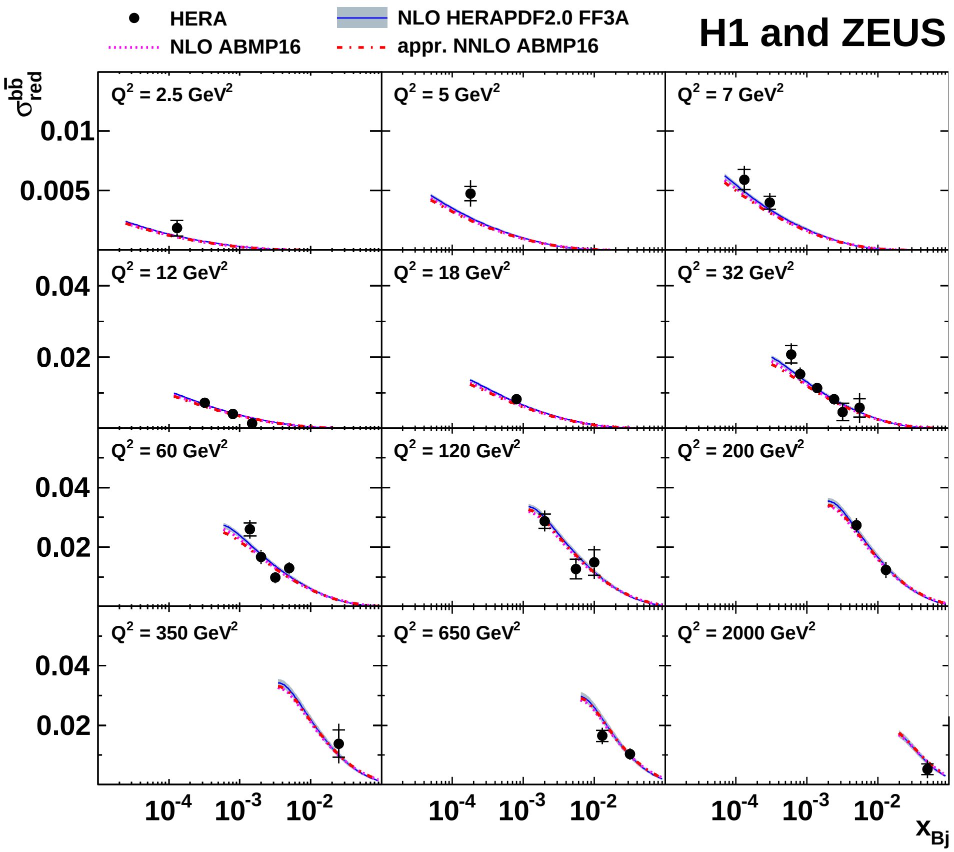
Backup

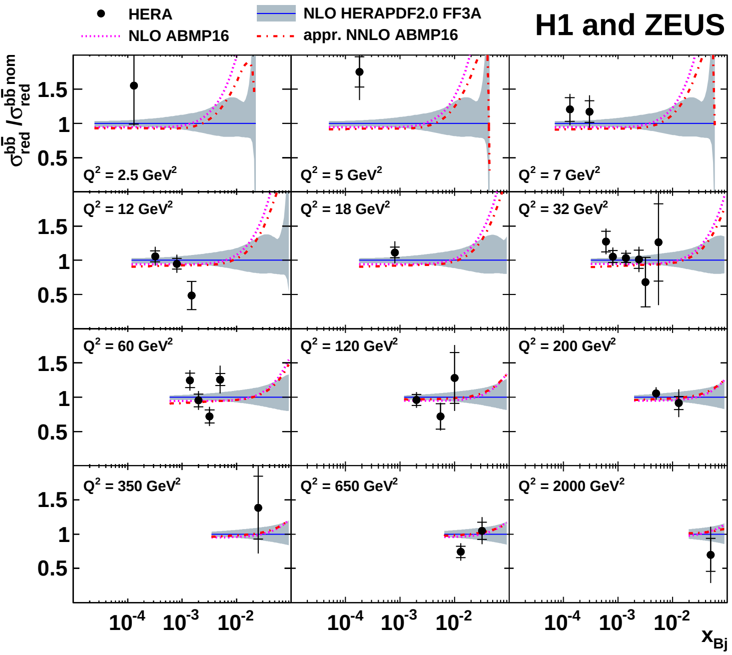
Combination of 13 c+b data sets

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

Reduced b cross section

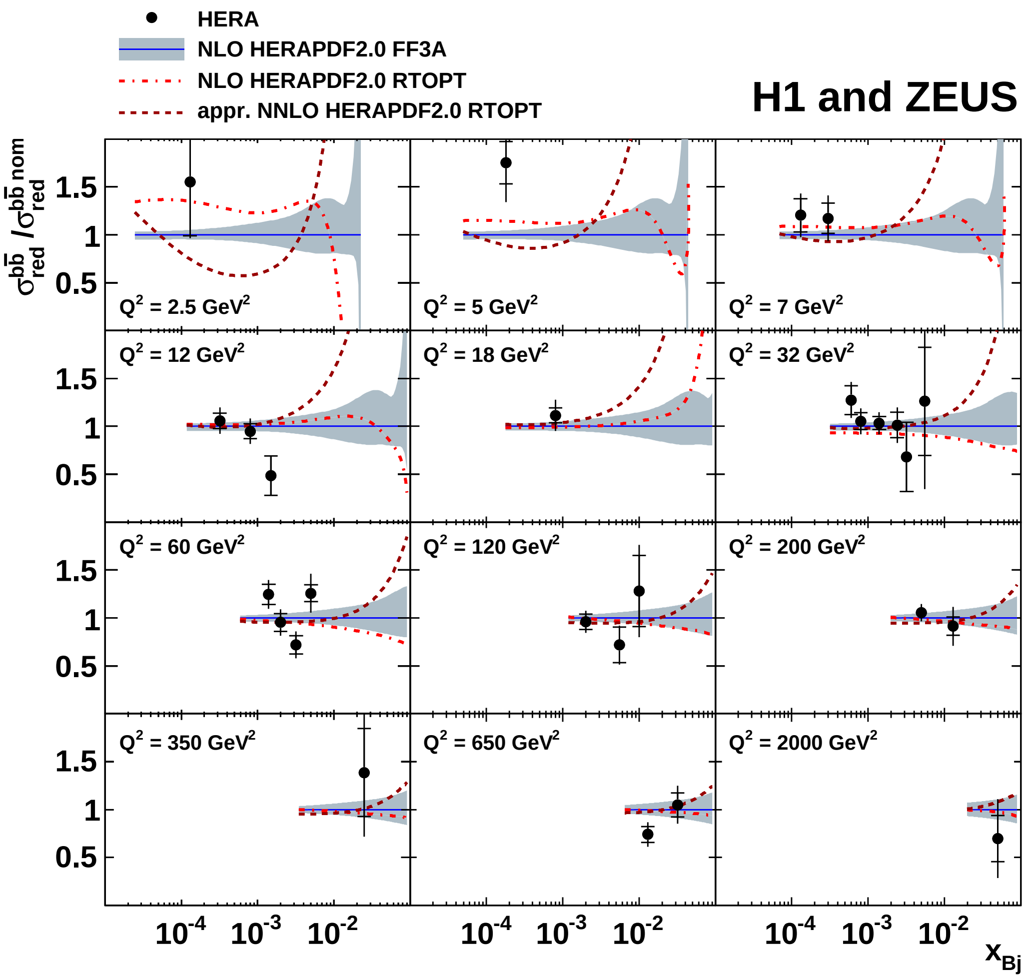
Comparison to FFNS



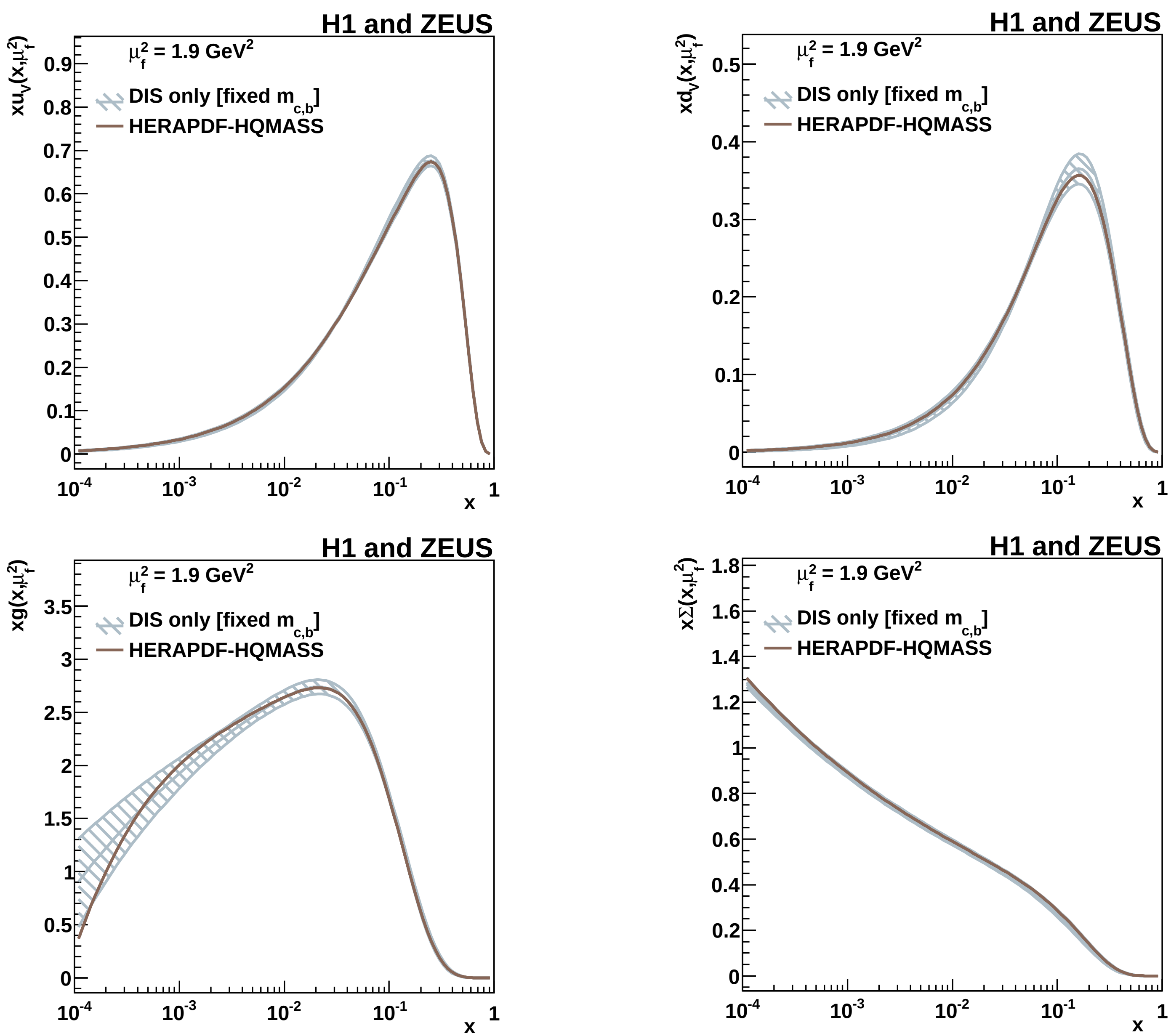


Reduced b cross section

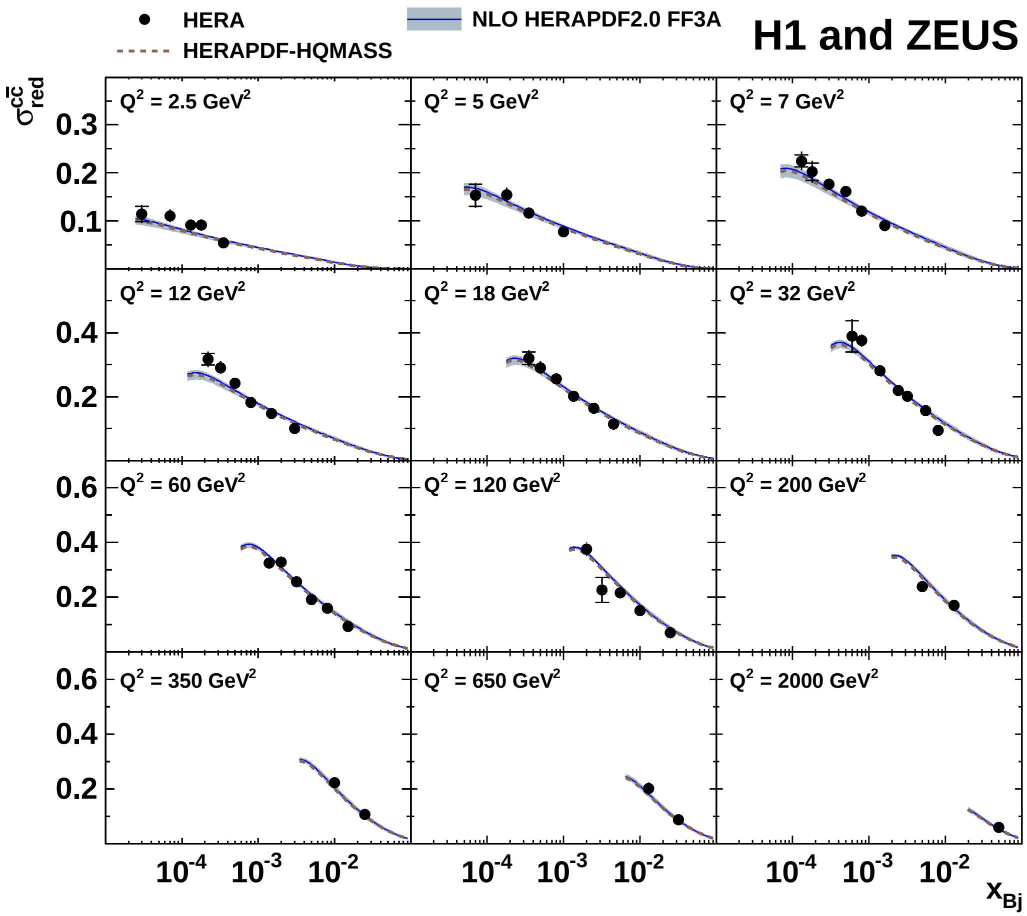
Comparison to VFNS



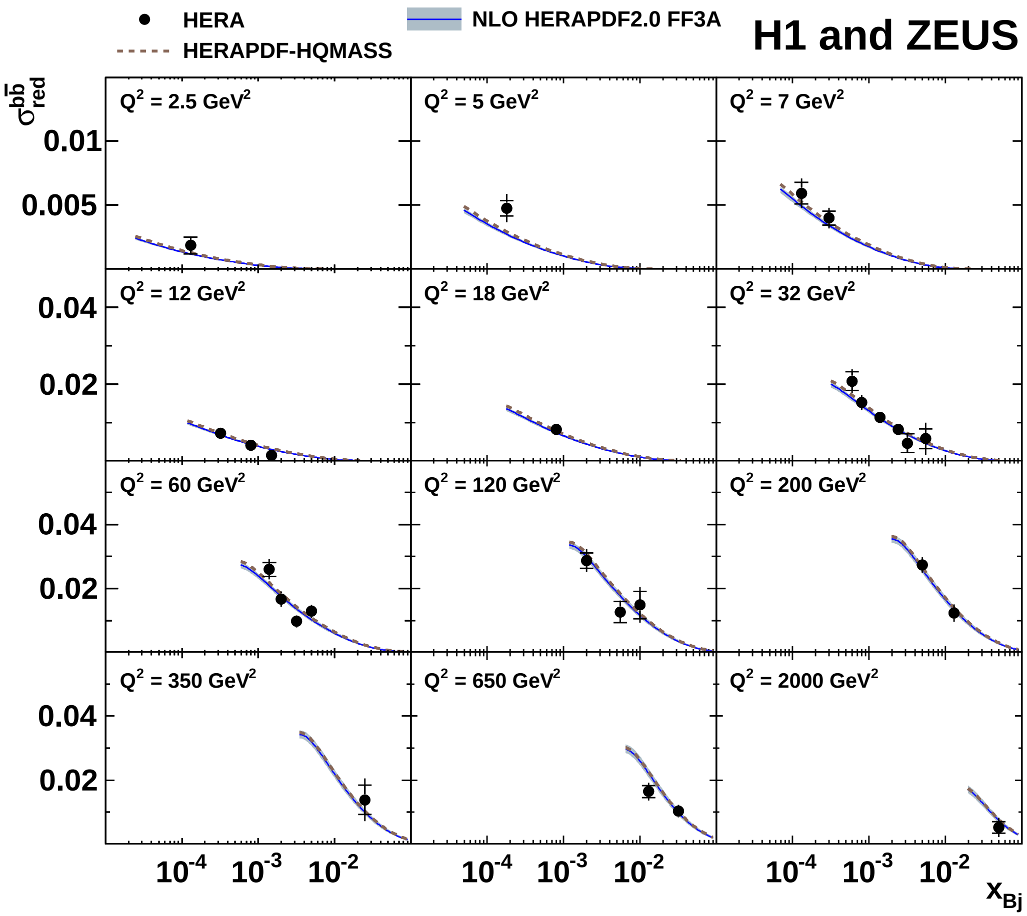
PDFs


H1 and ZEUS
μ_f^2 = 1.9 GeV^2
DIS only [fixed $m_{c,b}$]
HERAPDF-HQMASS
$xu_v(x,\mu_f^2)$
$xd_v(x,\mu_f^2)$
$xg(x,\mu_f^2)$
$x\Sigma(x,\mu_f^2)$
x

QCD fit charm subset



QCD fit beauty subset



QCD fit beauty subset