Combination and QCD analysis of charm and beauty production cross sections in DIS at HERA

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for the H1 and ZEUS collaborations

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- Introduction: heavy flavours in DIS
- Combination of charm and beauty data
- Comparison with QCD predictions
- QCD fit and determination of $m_c(m_c)$ and $m_b(m_b)$
- Discussion

final results freshly released: arXiv:1804.01019
The HERA ep collider and experiments

HERA I: \( \sim 130 \text{ pb}^{-1} \) (physics)
HERA II: \( \sim 380 \text{ pb}^{-1} \) (physics)
combined: \( \sim 2 \times 0.5 \text{ fb}^{-1} \)

up to 30% of cross section

\[ e^+ \rightarrow y \gamma Q^2 y x_{Bj} \sqrt{\alpha_s} g(x) \rightarrow \bar{c} c \]

HERA: \( p \) (920 GeV) \( \rightarrow e \) (27.6 GeV)
Deep Inelastic ep Scattering at HERA

HERA:

\( (\ell) \) Electron

\( q \)

\( \gamma, Z \)

Proton (P)

Electron \((\ell')\)

kinematic variables:

\( Q^2 = -q^2 \)

photon (or \(Z\)) virtuality, squared momentum transfer

\( X_{Bj} = \frac{Q^2}{2Pq} \)

Bjorken scaling variable, for \(Q^2 \gg (2m_q)^2\):
momentum fraction of p constituent
(equivalent in LO QPM only)

\( \gamma = \frac{qP}{\ell P} \)

inelasticity, \(\gamma\) momentum fraction (of e)

\( q = \ell - \ell' \)

\( Q^2 \lesssim 1 \text{ GeV}^2; \) photoproduction

\( Q^2 \gtrsim 1 \text{ GeV}^2; \) DIS
Heavy flavour contributions to $\sigma_r$

Measuring cross section

$$\frac{d^2\sigma}{dx\,dQ^2} \approx \frac{2\pi\alpha^2}{Q^4x_{Bj}} \left[1 + (1 - y)^2\right] \sigma_r(x_{Bj}, Q^2)$$

Questions:

1. Why is $Q^2$, $x_{Bj} = Q^2/2pq$ considered in the context of detecting anything?
2. Why are $b\bar{b}$ or $c\bar{c}$ proposed as flavour tagging for $\sigma_r$?
3. What is the significance of $\sigma_r^{bb}$, $\sigma_r^{c\bar{c}}$ in the context of QCD?
Combination of 13 charm+beauty data sets

3 additional charm datasets w.r.t. EPJ C73 (2013) 2311

beauty combined for the first time

account for all systematic correlations between data points, data sets, and between charm and beauty

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Good data consistency: \( \chi^2 = 149/187 \) dof
Charm combination

209 -> 52 data points

3 HERA II data sets added
Beauty combination

57 -> 27 data points

combined for the first time
Fixed Flavour Number Scheme (FFNS)

Example: charm

- No charm in proton
- Full kinematical treatment of charm mass (multi-scale problem: $Q^2, p_T, m_c \rightarrow \text{logs of ratios}$)
- No resummation of logs
- No extra matching parameters

\[ \mu^2 = Q^2 + 4m_c^2 \]
Comparison to FFNS QCD predictions

data reasonably described
best: HERAPDF2.0 FF
and ABKM09NLO

~3σ tension with $x_B$ slope
appr. NNLO does not improve
Comparison to VFNS QCD predictions

Data description reasonable but not better than FF overall. NLO better than appr. NNLO.

Beauty in backup: larger uncertainties -> all consistent

18. 04. 18
NLL resummation of log $1/x$ terms improves $x_{Bj}$ slope but deteriorates normalisation overall, NNPDF3.1sx (fitted charm, arXiv:1710.05935) either with or w/o log $1/x$ resummation not better than HERAPDF (FONLL-C + NLLx see backup)
\( \chi^2 \) and p-values for various QCD predictions

<table>
<thead>
<tr>
<th>Dataset</th>
<th>PDF (scheme)</th>
<th>( \chi^2 ) [p-value]</th>
</tr>
</thead>
<tbody>
<tr>
<td>charm [38]</td>
<td>HERAPDF20_NLO_FF3A (FFNS)</td>
<td>59 [0.23]</td>
</tr>
<tr>
<td></td>
<td>ABKM09 (FFNS)</td>
<td>59 [0.23]</td>
</tr>
<tr>
<td></td>
<td>ABMP16_3_nlo (FFNS)</td>
<td>61 [0.18]</td>
</tr>
<tr>
<td></td>
<td>ABMP16_3_nnlo (FFNS)</td>
<td>70 [0.05]</td>
</tr>
<tr>
<td></td>
<td>HERAPDF20_NLO_EIG (RTOPT)</td>
<td>71 [0.04]</td>
</tr>
<tr>
<td>(N_{\text{data}} = 52)</td>
<td>HERAPDF20_NNLO_EIG (RTOPT)</td>
<td>66 [0.09]</td>
</tr>
<tr>
<td></td>
<td>NNPDF31sx NNLO (FONLL-C)</td>
<td>106 [1.5 \times 10^{-6}]</td>
</tr>
<tr>
<td></td>
<td>NNPDF31sx NNLO+NLLX (FONLL-C)</td>
<td>71 [0.013]</td>
</tr>
<tr>
<td>(N_{\text{data}} = 47)</td>
<td>HERAPDF20_NLO_FF3A (FFNS)</td>
<td>86 [0.002]</td>
</tr>
<tr>
<td></td>
<td>ABKM09 (FFNS)</td>
<td>82 [0.005]</td>
</tr>
<tr>
<td></td>
<td>ABMP16_3_nlo (FFNS)</td>
<td>90 [0.0008]</td>
</tr>
<tr>
<td></td>
<td>ABMP16_3_nnlo (FFNS)</td>
<td>109 [6 \times 10^{-6}]</td>
</tr>
<tr>
<td></td>
<td>HERAPDF20_NLO_EIG (RTOPT)</td>
<td>99 [9 \times 10^{-5}]</td>
</tr>
<tr>
<td>(N_{\text{data}} = 52)</td>
<td>HERAPDF20_NNLO_EIG (RTOPT)</td>
<td>102 [4 \times 10^{-5}]</td>
</tr>
<tr>
<td></td>
<td>NNPDF31sx NNLO (FONLL-C)</td>
<td>140 [1.5 \times 10^{-11}]</td>
</tr>
<tr>
<td></td>
<td>NNPDF31sx NNLO+NLLX (FONLL-C)</td>
<td>114 [5 \times 10^{-7}]</td>
</tr>
<tr>
<td>(N_{\text{data}} = 47)</td>
<td>HERAPDF20_NLO_FF3A (FFNS)</td>
<td>33 [0.20]</td>
</tr>
<tr>
<td></td>
<td>ABMP16_3_nlo (FFNS)</td>
<td>37 [0.10]</td>
</tr>
<tr>
<td></td>
<td>ABMP16_3_nnlo (FFNS)</td>
<td>41 [0.04]</td>
</tr>
<tr>
<td></td>
<td>HERAPDF20_NLO_EIG (RTOPT)</td>
<td>33 [0.20]</td>
</tr>
<tr>
<td>(N_{\text{data}} = 27)</td>
<td>HERAPDF20_NNLO_EIG (RTOPT)</td>
<td>45 [0.016]</td>
</tr>
</tbody>
</table>

Table 4: The \( \chi^2 \), p-values and number of data points of the charm and beauty data with respect to the NLO and approximate NNLO calculations using various PDFs as described in the text. The measurements at \( Q^2 = 2.5 \text{ GeV}^2 \) are excluded in the calculations of the \( \chi^2 \) values for the NNPDF3.1sx predictions, by which the number of data points is reduced to 47, as detailed in the caption of figure 12.
Simultaneous NLO QCD fit of

- combined inclusive DIS data (arXiv:1506.06042), $Q^2_{\text{min}}=3.5 \text{ GeV}^2$
- new combined charm and beauty DIS data (this work)

Simultaneously fit PDF's (a la HERAPDF FF) in FFNS at NLO and charm quark and beauty quark “running” masses in MSbar scheme

- using xFitter [www.xfitter.org], 14 parameters ($\pm 1$)
- NLO DGLAP [QCDNUM] and matrix elements [OPENQCDRAD], $n_f = 3$
- $\mu_F = \mu_R = \sqrt{Q^2 + 4m_Q^2}$, varied by factor 2 (for heavy flavour part only)
- free $m_c(m_c), m_b(m_b)$
- $\alpha_s(M_Z)^{n_f=3} = 0.106$, equivalent to $\alpha_s(M_Z)^{n_f=5} = 0.118 \pm 0.002$
- fit uncertainty using $\Delta \chi^2 = 1$

--> HERAPDF-HQMASS
QCD fit: charm subset

fully consistent with HERAPDF2.0 FF3A

uncertainty breakdown in backup

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

PDG: \[ 1.27 \pm 0.03 \text{ GeV} \] (lattice QCD + time-like processes)

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**Comparison with other $m_c(m_c)$ determinations**

**this work:**

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

latest ABMP16 result: $m_c(m_c) = 1.252^{+0.018}_{-0.032}$ GeV


previous results summarized in

V. Bertone et al., arXiv:1605.01946, JHEP 1608 (2016) 050 :

<table>
<thead>
<tr>
<th>scheme</th>
<th>$m_c(m_c)$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FONLL (this work)</td>
<td>$1.335 \pm 0.043(\text{exp})^{+0.019}<em>{-0.009}(\text{param})^{+0.017}</em>{-0.008}(\text{mod})^{+0.033}_{-0.008}(\text{th})$</td>
</tr>
<tr>
<td>FFN (this work)</td>
<td>$1.318 \pm 0.054(\text{exp})^{+0.011}<em>{-0.010}(\text{param})^{+0.019}</em>{-0.009}(\text{mod})^{+0.036}_{-0.006}(\text{th})$</td>
</tr>
<tr>
<td>FFN (HERA) [9]</td>
<td>$1.26 \pm 0.05(\text{exp}) \pm 0.03(\text{mod}) \pm 0.02(\alpha_s)$</td>
</tr>
<tr>
<td>FFN (Alekhin et al.) [24]</td>
<td>$1.24 \pm 0.03(\text{exp})^{+0.03}<em>{-0.02}(\text{scale})^{+0.06}</em>{-0.07}(\text{th})$ (approx. NNLO)</td>
</tr>
<tr>
<td>FFN (Alekhin et al. NLO)</td>
<td>$1.15 \pm 0.04(\text{exp})^{+0.04}_{-0.00}(\text{scale})$ (NLO)</td>
</tr>
<tr>
<td>S-ACOT-$\chi$ (CT10 str. 1) [29]</td>
<td>$1.12^{+0.05}_{-0.11}$ (strategy 1)</td>
</tr>
<tr>
<td>S-ACOT-$\chi$ (CT10 str. 2)</td>
<td>$1.18^{+0.05}_{-0.11}$ (strategy 2)</td>
</tr>
<tr>
<td>S-ACOT-$\chi$ (CT10 str. 3)</td>
<td>$1.19^{+0.06}_{-0.15}$ (strategy 3)</td>
</tr>
<tr>
<td>S-ACOT-$\chi$ (CT10 str. 4)</td>
<td>$1.24^{+0.06}_{-0.15}$ (strategy 4)</td>
</tr>
<tr>
<td>World average [53]</td>
<td>$1.275 \pm 0.025$</td>
</tr>
</tbody>
</table>

18.04.18 A. Geiser, DIS2018
QCD fit: beauty subset

fully consistent with HERAPDF FF3A

new: \[ m_b(m_b) = 4.05^{+0.10}_{-0.11} \text{ GeV exp/fit} +0.09 -0.03 \text{ mod/scale} +0.00 -0.03 \text{ par} \]

ZEUS: \[ m_b(m_b) = 4.07^{+0.14}_{-0.14} \text{ GeV exp/fit} +0.08 -0.08 \text{ mod/scale} +0.05 -0.00 \text{ par} \]

PDG: \[ 4.18 \pm 0.03 \text{ GeV (lattice QCD + time-like processes)} \]
PDFs consistent with those of inclusive data only (and c, b masses fixed to PDG)

-> inclusive data (and c,b mass values) dominate in fixing PDF
QCD fit: inclusive data, parametrisation uncert.

Reminder, full fit: $\Delta \chi^2=1$

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

Using inclusive HERA data only (14p):

- $m_c(m_c) = 1798^{+144}_{-134}$ (exp/fit) MeV
- $m_b(m_b) = 8450^{+2280}_{-1810}$ (fit) MeV

no full uncertainty evaluation, but large sensitivity to PDF parametrisation ($\rightarrow$ 13p):

- $m_c(m_c) = 1798 \rightarrow 1450$ MeV,
- $m_b(m_b) = 8450 \rightarrow 3995$ MeV

$\rightarrow$ inclusive HERA data alone cannot constrain HQ masses reliably

$\rightarrow$ interplay of PDFs and HQ masses needs careful treatment
QCD fit: charm x slope

plot data/fit vs. \langle x \rangle of incoming partons (rather than x_{Bj}) for each data point

LO: \quad \langle x \rangle = x_{Bj} \cdot \left(1 + \frac{\hat{s}}{Q^2}\right)

\langle x \rangle calculated at NLO using HVQDIS

\rightarrow \text{common } \langle x \rangle \text{ trend for all } Q^2
QCD fit with $x_{Bj} > 0.01$ for inclusive data

can improve low $x$ charm slope
(no longer constrained by inclusive)

but fails to describe low $x$ inclusive data

$\rightarrow$ not a solution (but hint)
Conclusions

Final HERA charm and beauty data in DIS have been combined including all correlations. Charm precision improved by ~20%, beauty combined for the first time.

Data are reasonably described by FFNS (best) and VFNS predictions (NLO better than approx. NNLO), but show ~3σ tension in x slope w.r.t inclusive.

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

$$m_c(m_c) = 1290^{+46}_{-41}(\text{exp/fit})^{+62}_{-14}(\text{mod})^{+3}_{-31}(\text{par}) \text{ MeV}$$

$$m_b(m_b) = 4049^{+104}_{-109}(\text{exp/fit})^{+90}_{-32}(\text{mod})^{+1}_{-31}(\text{par}) \text{ MeV}$$

In agreement with world average and previous measurements (not affected by x slope tension within uncertainties).

More detailed studies of x slope tension -> can not be solved by varying the gluon density, or adding higher orders, or resumming log 1/x terms, within the respective pQCD frameworks

-> further investigations useful.
Backup
Comparison to previous charm combination
Comparison to FFNS predictions

beauty:
Comparison to FFNS and VFNS predictions

Beauty:

[Graphs showing comparisons between different models and experimental data for H1 and ZEUS]
### QCD fit: systematic uncertainties

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

Table 5: List of uncertainties for the charm- and beauty-quark mass determination. The PDF parameterisation uncertainties not shown have no effect on $m_c(m_c)$ and $m_b(m_b)$. 

18. 04. 18  
A. Geiser, DIS2018
QCD fit: charm

fully consistent
with
HERAPDF2.0FF3A
QCD fit: beauty

fully consistent with HERAPDF2.0FF3A
QCD fit: beauty x slope

plot data/fit vs. \langle x \rangle of incoming partons (rather than \( x_{Bj} \)) for each data point

LO: \[ x = x_{Bj} \cdot \left( 1 + \frac{s}{Q^2} \right) \]

\langle x \rangle calculated at NLO using HVQDIS

\rightarrow beauty consistent with charm but does not add information
χ² as function of min. x_{Bj} cut
QCD fit with $x_{Bj} > 0.01$ for inclusive data

charm and beauty mass floating

gluon at $x < 0.01$ inconsistent with inclusive fit
FONLL-C fit of inclusive data

arXiv:1802.00064 (XFitter team):
FONLL-C inclusive fit with and without NLLx resummation

personal remark:
FONLL-C inclusive fit with NLLx qualitatively consistent with FF charm
+ $x > 0.01$ inclusive fit (compare previous slide)
→ combine both worlds by applying NLLx to light flavours only in FF scheme?

Figure 3: The up valence PDF $xu_u$, the gluon PDF $xg$ and the total singlet PDF $x\Sigma$ for the final fits with (NNLO+NLLx) and without (NNLO) $\ln(1/x)$ resummation.
Comparison of HERAPDF with FONLL-C + NLLx

for inclusive data only

from
arXiv:1802.00064:

inclusion of NLLx resummation with FONLL-C achieves similar performance as HERAPDF2.0 FF3B