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

Oleksandr Zenaiev (DESY)
on behalf of H1 and ZEUS collaborations

[Eur.Phys.J. C78 (2018) 473]

ICHEP
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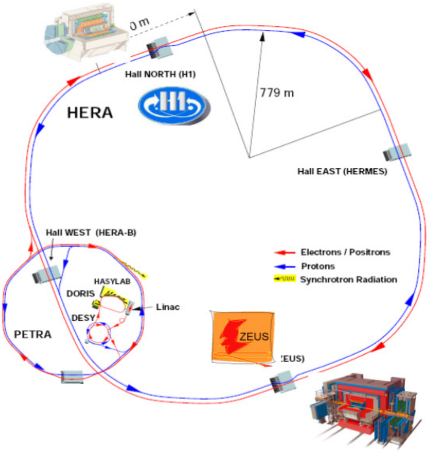
Experimental set-up

HERA Collider

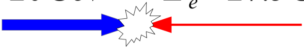
- *ep* collisions
- $\sqrt{s} = 300 \ldots 318$ GeV and lower energy runs

H1 and ZEUS:

- 4π multipurpose detectors
- $\mathcal{L} \sim 500$ pb^{-1} per each experiment



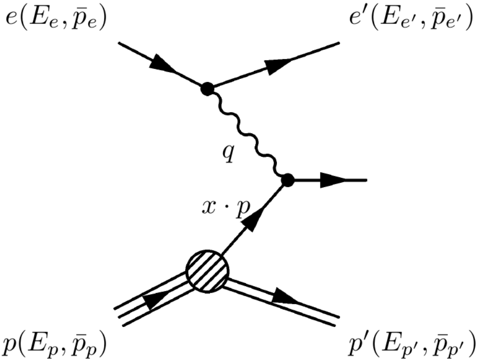
$E_p = 920\,GeV$ $E_e = 27.5\,GeV$



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

Kinematics

$$Q^2 = -q^2 = -(e - e')^2$$
$$x_{Bj} = \frac{Q^2}{2q \cdot p} \quad (= x \text{ in QPM})$$
$$y = \frac{q \cdot p}{q \cdot e}$$
$$s = (e + p)^2$$
$$Q^2 = s x_{Bj} y$$



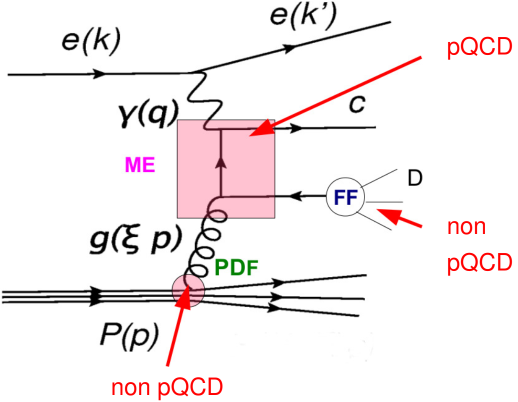
- Any two of the variables (Q^2, x_{Bj}, y) define kinematics
- $Q^2 > 1\ GeV^2$ — deep inelastic scattering (DIS)
- $Q^2 < 1\ GeV^2$ — photoproduction processes (PHP)

Heavy flavour (HF) production in DIS

Test of pQCD (multiple hard scales: Q^2, $p_T(Q)$, m_Q)

Charm and beauty in DIS are predominantly produced via Boson-Gluon Fusion (BGF)

$$\sigma = \text{PDF} \otimes \text{ME} \otimes \text{FF}$$



Production is directly sensitive to g PDF in the proton and HQ masses

PDF: parton distribution functions
ME: (hard) matrix element
FF: fragmentation function & fraction

pQCD approximation of heavy flavour production

Fixed Flavour Number Scheme (FFNS)

- c,b-quarks are massive $\Rightarrow$ not a part of the proton, produced perturbatively in hard scattering
- valid for $Q^2 \sim m^2_{c,b}$

Zero Mass Variable Flavour Number Scheme (ZMVFNS)

- c,b-quarks are massless $\Rightarrow$ a part of the proton
- valid for $Q^2 >> m^2_{c,b}$

General Mass Variable Flavour Number Scheme (GMVFNS)

- equivalent to FFNS at low Q^2
- equivalent to ZMVFNS at high Q^2
- not unique (RT, ACOT, FONLL, ...)

detailed discussion in [EPJ C73 (2013) 2311]

Input data

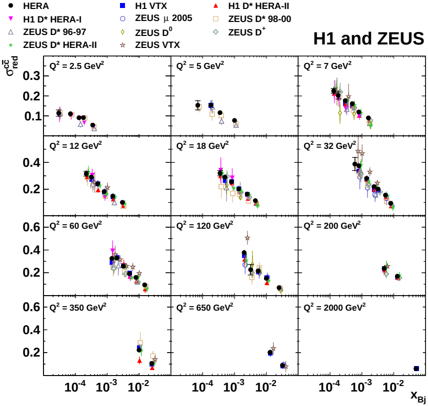
Data set	Tagging	Q^2 range [GeV^2]	N_c	$\mathcal{L}$ [pb^{-1}]	$\sqrt{s}$ [GeV]	N_b
1 H1 VTX [8]	VTX	5 – 2000	29	245	318	12
2 H1 D^{*+} HERA-I [9]	D^{*+}	2 – 100	17	47	318	
3 H1 D^{*+} HERA-II (medium Q^2) [10]	D^{*+}	5 – 100	25	348	318	
4 H1 D^{*+} HERA-II (high Q^2) [11]	D^{*+}	100 – 1000	6	351	318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

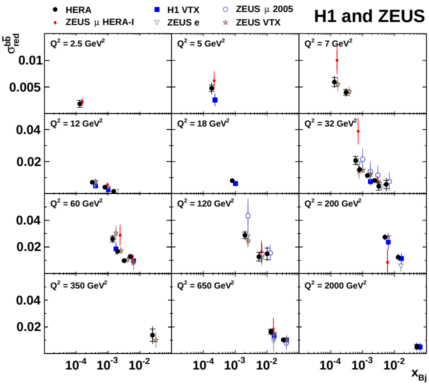
(corresponding references can be found in backup)

- Combined reduced cross sections: $\sigma_{\rm red}^{Q\bar{Q}} = \frac{d^2\sigma^{Q\bar{Q}}}{dx_{\rm Bj}dQ^2} \cdot \frac{x_{\rm Bj}Q^4}{2\pi\alpha^2\,(1+(1-y)^2)}$
- $2.5 \leq Q^2 \leq 2000$ GeV^2, $3 \times 10^{-5} \leq x_{\rm Bj} \leq 5 \times 10^{-2}$
- Input 209 *c*, 52 *b* data points $\Rightarrow$ combined 52 *c*, 27 *b* points
- **Extends previous HERA charm combination with 3 new *c* data sets and 5 new *b*: first combination of HERA *b* data**

Combined data

CHARM [best $\delta \sim 5\%$] BEAUTY [best $\delta \sim 15\%$]

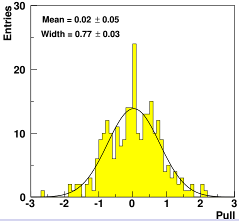




$\chi^2/\mathrm{dof} = 149/187$

→ input data are consistent

→ significantly reduced uncertainties as compared to the individual measurements



Theoretical predictions (FFNS) compared to combined data

Predictions obtained with OPENQCDRAD interfaced in xFitter

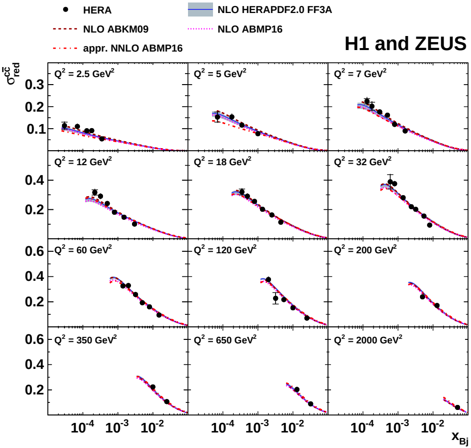
www-zeuthen.desy.de/∼alekhin/OPENQCDRAD

`www.xfitter.org`

- input PDFs: HERAPDF2.0FF3A, ABM11, ABKM09, ABMP16
- $\mu_f = \mu_r = \sqrt{Q^2 + 4m_Q^2}$, varied by factor 2 (dominant unc.)
- $m_c(m_c) = 1.27 \pm 0.03$ GeV, $m_b(m_b) = 4.18 \pm 0.03$ GeV [PDG2016]

FFNS, $n_f = 3$: reliable in this kinematic range

FFNS, CHARM (beauty in BACKUP)



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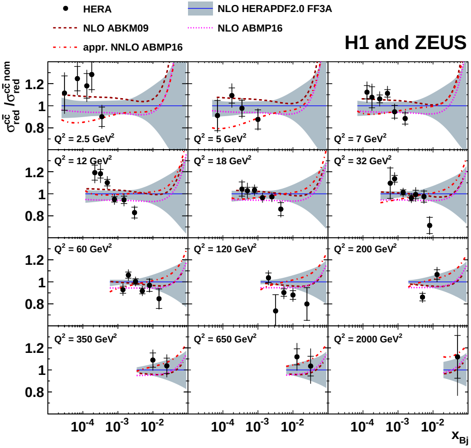


→ **overall fair description, somewhat different *x* slope**

→ **description not improved at approx. NNLO or VFNS** *(backup)*

Similar to HERAPDF2.0 FF:

- performed using xFitter [www.xfitter.org]
- inclusive HERA data + **new combined *c*&*b* data**
- NLO DGLAP [QCDNUM] and matrix elements [OPENQCDRAD], $n_f = 3$
- $\mu_f = \mu_r = \sqrt{Q^2 + 4m_Q^2}$ varied by factor 2 (model unc.)
- **free $m_c(m_c)$, $m_b(m_b)$**
- $\alpha_s(M_Z)^{n_f=3} = 0.106$ ($\rightarrow \alpha_s(M_Z)^{n_f=5} = 0.118$)
- HERAPDF parametrisation, 14p
- fit uncertainty using $\Delta\chi^2 = 1$, model and parametrisation uncertainties

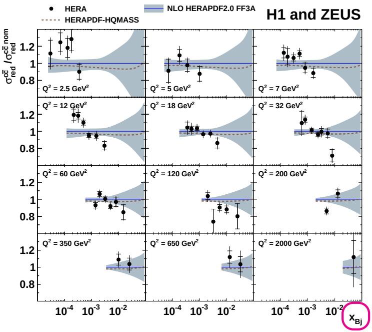
$$m_c(m_c) = 1290^{+46}_{-41}(\text{fit})^{+62}_{-14}(\text{mod})^{+3}_{-31}(\text{par})\ \text{MeV}$$

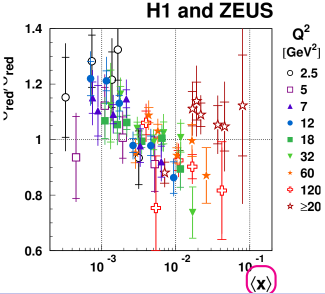
$$m_b(m_b) = 4049^{+104}_{-109}(\text{fit})^{+90}_{-32}(\text{mod})^{+1}_{-31}(\text{par})\ \text{MeV}$$

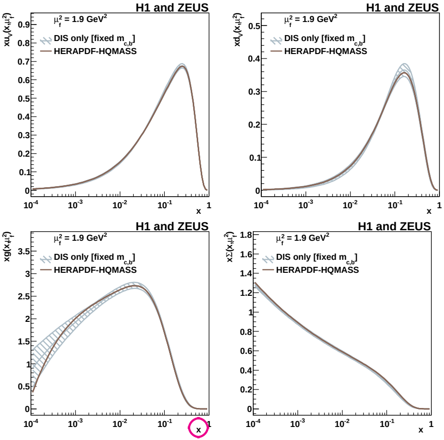
⇒ determined precise HQ masses consistent with world average

PDG2016: $m_c(m_c) = 1270 \pm 30$ MeV, $m_b(m_b) = 4180^{+40}_{-30}$ MeV

QCD analysis of combined charm and beauty data: PDFs

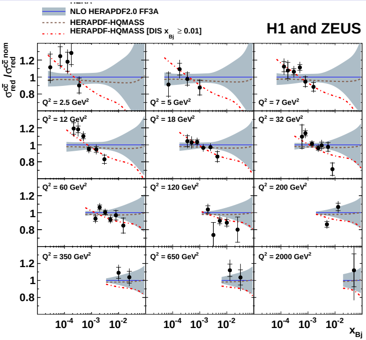


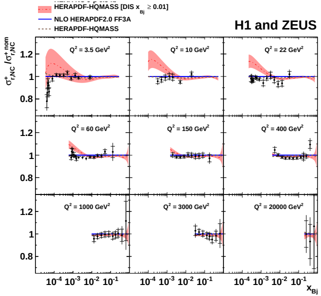


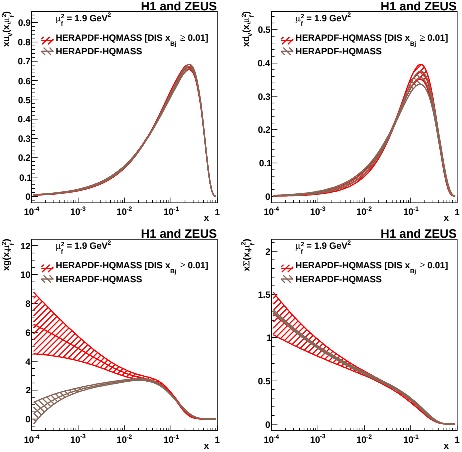


- $x \neq x_{\mathrm{Bj}}$ for BGF!
- small impact of HF data on PDFs
- difference in x slope persists after fit

QCD analysis of combined charm and beauty data: PDFs







- cut $x_{\mathrm{Bj}} > 0.01$ on inclusive data
- observed change for low x gluon:

$\rightarrow$ better description of HF data

$\rightarrow$ but worser description of (not fitted) inclus. data

New combined HERA charm and beauty data:

- improvement in precision w.r.t previous HERA results for charm
- first combined HERA results for beauty
- enable precise determination of charm and beauty masses
- reveal tension in describing simultaneously HF and inclusive HERA data

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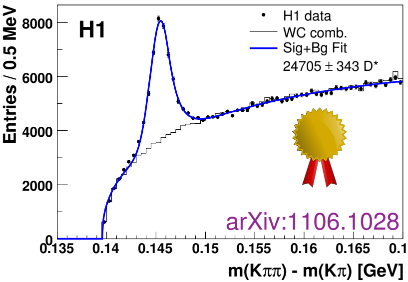
[Eur.Phys.J. C78 (2018) 473]

HERA experiments continue producing valuable results
$>$ **10** *years after HERA was shut down!*

BACKUP

"Golden" decay channel $D^{*} \to D^{0}(K\pi)\pi_{s}$

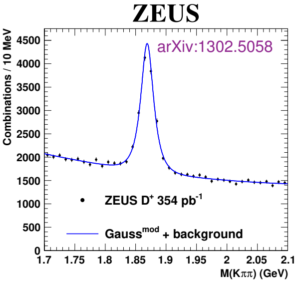


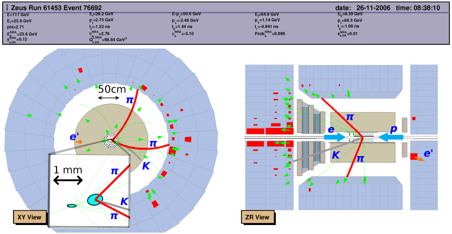
Dedicated H1ZEUS combination:

"Combination of differential $D^{*\pm}$ cross-section measurements in deep-inelastic ep scattering at HERA"

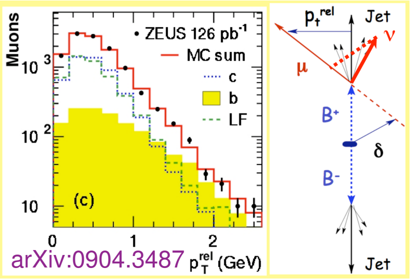
[JHEP09 (2015) 149]

Weakly decaying charm hadrons

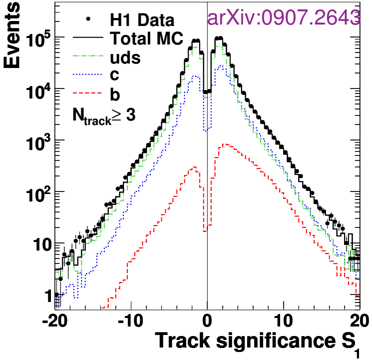




Semi-leptonic (SL) HQ decays



Inclusive lifetime tagging



Recent reviews of HF production at HERA:

- O. Behnke, A. Geiser, M. Lisovyi, “Charm, Beauty and Top at HERA”, Prog. Part. Nucl. Phys. 84 (2015) 1
- O.Z., “Charm Production and QCD Analysis at HERA and LHC ”, Eur. Phys. J. C77 (2017) 151

BACKUP. Combination procedure

- fiducial cross sections extrapolated to full phase space using consistent NLO predictions [HVQDIS], account for relevant unc.
- combined at the level of **reduced cross sections** $\sigma_{\rm red}^{c\bar{c}}$, $\sigma_{\rm red}^{b\bar{b}}$
  $\sigma_{\rm red}^{Q\bar{Q}} = \frac{{\rm d}^2\sigma^{Q\bar{Q}}}{{\rm d}x_{\rm Bj}{\rm d}Q^2} \cdot \frac{x_{\rm Bj}Q^4}{2\pi\alpha^2\,(1+(1-y)^2)}$ (full phase space)
  ($Q\bar{Q}$ stands either for $c\bar{c}$ or $b\bar{b}$)
- combination accounts for correlation of systematic uncertainties, as well as correlation of c and b from same measurements
- $\Rightarrow$ **significant improvement in precision** via cross calibration of different measurement techniques and c/b

Combined using HERAverager program

[https://wiki-zeuthen.desy.de/HERAverager]

well established combination method used in:

- previous HERA charm combination [EPJ C73 (2013) 2311]
- HERAPDF2.0 [EPJ C75 (2015) 580]
- ATLAS papers [1603.09222, 1512.02192, 1606.01736, 1612.03016]

[2] H. Abramowicz *et al.* [ZEUS Collaboration], "Measurement of $D^{\pm}$ Production in Deep Inelastic ep Scattering with the ZEUS detector at HERA", JHEP **05**, (2013) 023 [arXiv:1302.5058].

[3] H. Abramowicz *et al.* [ZEUS Collaboration], "Measurement of $D^{*\pm}$ Production in Deep Inelastic Scattering at HERA", JHEP **05**, (2013) 097 [arXiv:1303.6578]. Erratum-ibid JHEP **02**, (2014) 106.

[4] H. Abramowicz *et al.* [ZEUS Collaboration], "Measurement of beauty and charm production in deep inelastic scattering at HERA and measurement of the beauty-quark mass", JHEP **09**, (2014) 127 [arXiv:1405.6915].

[5] H. Abramowicz *et al.* [ZEUS Collaboration], "Measurement of beauty production in deep inelastic scattering at HERA using decays into electrons", Eur. Phys. J. **C71**, (2011) 1573 [arXiv:1101.3692].

[6] H. Abramowicz *et al.* [ZEUS Collaboration], "Measurement of beauty production in DIS and F2bb extraction at ZEUS", Eur. Phys. J. **C69**, (2010) 347 [arXiv:1005.3396].

[7] S. Chekanov *et al.* [ZEUS Collaboration], "Measurement of charm and beauty production in deep inelastic ep scattering from decays into muons at HERA", Eur. Phys. J. **C65**, (2010) 65 [arXiv:0904.3487].

[8] F. D. Aaron *et al.* [H1 Collaboration], "Measurement of the Charm and Beauty Structure Functions using the H1 Vertex Detector at HERA", Eur. Phys. J. **C65**, (2010) 89 [arXiv:0907.2643].

[9] A. Aktas *et al.* [H1 Collaboration], "Production of D*+- Mesons with Dijets in Deep-Inelastic Scattering at HERA", Eur. Phys. J. **C51**, (2007) 271 [hep-ex/0701023].

[10] F. D. Aaron *et al.* [H1 Collaboration], "Measurement of $D^{*\pm}$ Meson Production and Determination of F_2^{ccbar} at low Q2 in Deep-Inelastic" Eur. Phys. J. **C71**, (2011) 1769 [arXiv:1106.1028].

[11] F. D. Aaron *et al.* [H1 Collaboration], "Measurement of the D*+- Meson Production Cross Section and F(2)**(c c-bar), at High Q**2, in ep Scattering at HERA", Phys. Lett. **B686**, (2010) 91 [arXiv:0911.3989].

[12] J. Breitweg *et al.* [ZEUS Collaboration], "Measurement of D*+- production and the charm contribution to F2 in deep inelastic scattering at HERA", Eur. Phys. J. **C12**, (2000) 35 [hep-ex/9908012].

[13] S. Chekanov *et al.* [ZEUS Collaboration], "Measurement of D*+- production in deep inelastic e+- p scattering at HERA", Phys. Rev. **D69**, (2004) 012004 [hep-ex/0308068].

[14] S. Chekanov *et al.* [ZEUS Collaboration], "Measurement of D+- and D0 production in deep inelastic scattering using a lifetime tag at HERA", Eur. Phys. J. **C63**, (2009) 171 [arXiv:0812.3775].

→ Take measured visible x-section $\sigma_{\rm vis}$ and extrapolate to full phase space $\sigma_{\rm red}$ using consistent NLO setup: $\sigma_{\rm red} = \sigma_{\rm vis} \frac{\sigma_{\rm red}^{\rm NLO}}{\sigma_{\rm vis}^{\rm NLO}}$ [HVQDIS]

→ Combine $\sigma_{\rm red}$ accounting for bin-to-bin correlations [HERAverager]

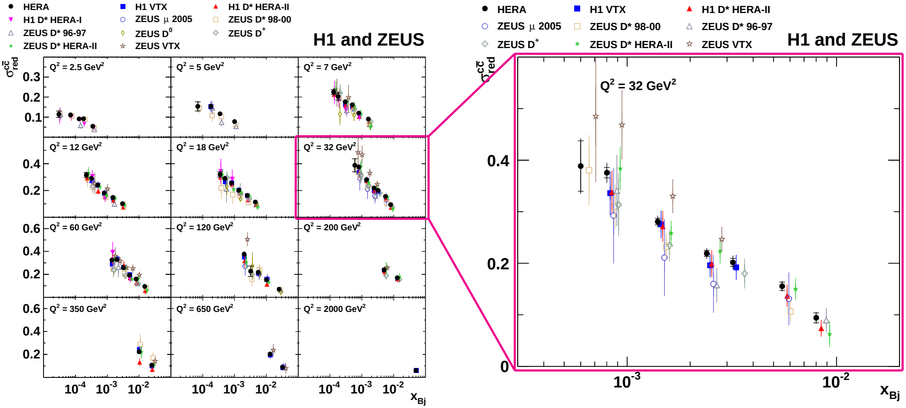
NLO setup for extrapolation as in [DESY-12-172]

- pole masses $m_c = 1.5 \pm 0.15$ GeV, $m_b = 4.5 \pm 0.25$ GeV
  consistent with extracted from data: $m_c = 1.43 \pm 0.04$ GeV, $m_b = 4.35 \pm 0.11$ GeV
  and consistent with PDG: $m_c = 1.67 \pm 0.07$ GeV, $m_b = 4.78 \pm 0.06$ GeV
- $\mu_R = \mu_F = \sqrt{Q^2 + 4m_Q^2}$, varied simultaneously by factor 2
- $\alpha_s^{n_f=3}(M_Z) = 0.105 \pm 0.002$ [$\alpha_s^{n_f=5}(M_Z) = 0.116 \pm 0.002$]
- HERAPDF1.0 FFNS, $n_f = 3$, assign 2% uncor. unc.
  (checked vs HERAPDF2.0: see backup)
- *c* fragmentation: Kartvelishvili frag. function parametrised as step function with k_T kink (H1, ZEUS meas. [DESY-08-080, DESY-08-209])
- *b* fragmentation: Peterson $\epsilon_b = 0.0035 \pm 0.0020$ [NP B565 (2000) 245]
- charm fragmentation fractions [EPJ C76 (2016) 397]
- branching ratios PDG2016
- hadronisation uncertainties for data with jets in the final state

$$\chi^2(\mathbf{m}, \mathbf{b}) = \sum_{e=1}^{N_e} \sum_{i=1}^{N_m} \frac{\left(m_i - \sum_{j=1}^{N_s} \Gamma_i^{e,j} b^{e,j} - \mu_i^e\right)^2}{\sigma_i^{e\,2}} + \sum_{j=1}^{N_s} b^{e,j\,2}$$

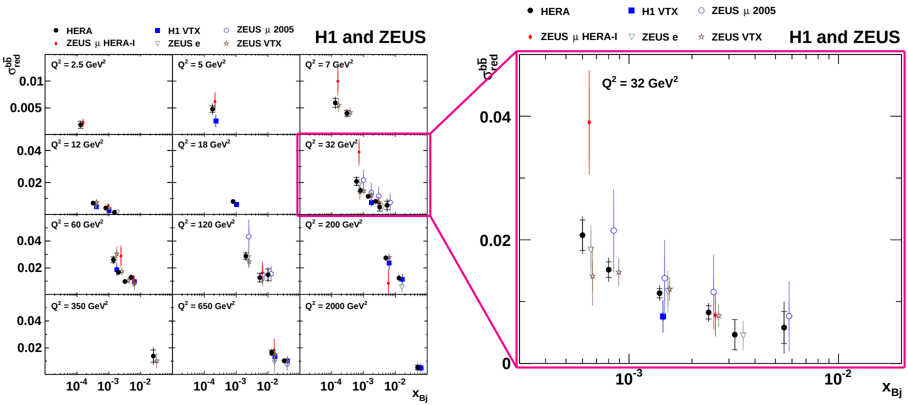
Minimised in iterative procedure

CHARM



→ **Significantly improved precision compared to input measurements**

BEAUTY



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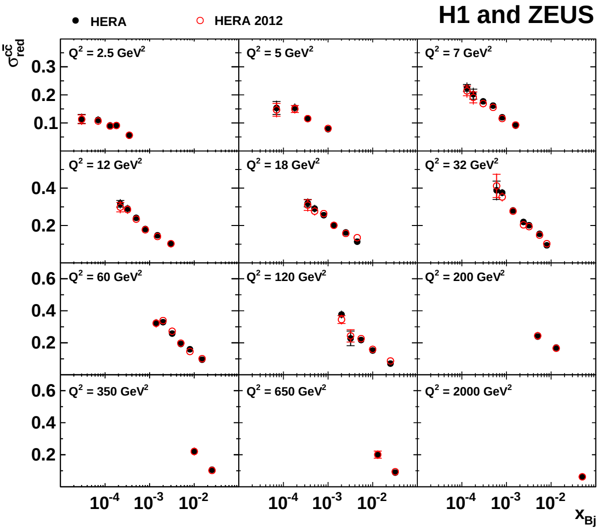
BACKUP. New charm data compared to previous HERA results



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`www.xfitter.org`

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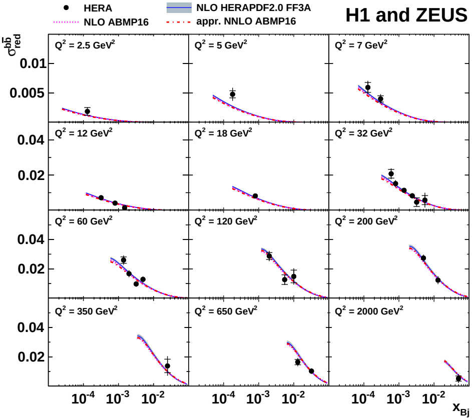
FFNS, $n_f = 3$: reliable in this kinematic range

FFNS, BEAUTY



→ overall fair description, somewhat different *x* slope
→ description not improved at approximate NNLO

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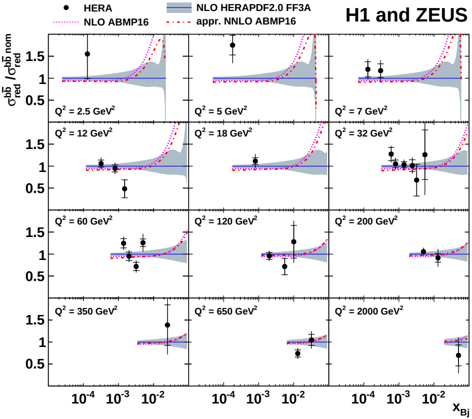

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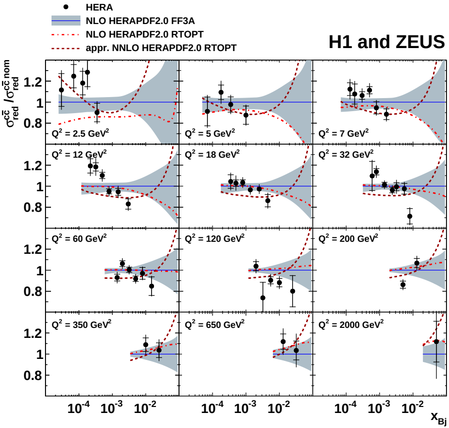
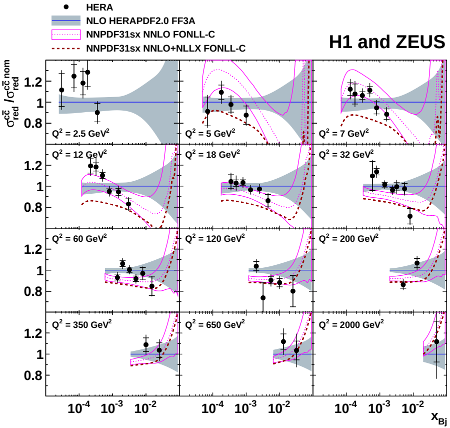
RTOPT [default HERAPDF2.0]



NNPDF3.1 w/ and w/o small-x resummation [1710.05935]



→ considered VFNS predictions do not give better data description

→ NNPDF3.1: better x_{Bj} slope, but worse normalisation and Q^2

BACKUP. QCD analysis settings

Similar to HERAPDF2.0 FF, using running HQ mass definition:

- xFitter-1.2.0
- Input data:
  - HERA $e^{\pm}p$ inclusive data, $Q^2_{\rm min} > 3.5$ GeV^2 [1506.06042]
  - new HERA c and b combined
- FFNS $n_f = 3$ ('FF ABM RUNM'), ($\alpha_s(F_L) = \alpha_s(F_2)$)
- $\alpha_s^{n_f=3}(M_Z) = 0.106$
- free $m_c(m_c)$, $m_b(m_b)$, or PDG $m_c(m_c) = 1.27$ GeV, $m_c(m_c) = 4.18$ GeV
- DGLAP NLO [QCDNUM]
- PDF parametrisation: 14p HERAPDF at $\mu^2_{f0} = 1.9$ GeV^2, $f_s = 0.4$:

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

Additional constrains:

$A_{\bar{U}} = A_{\bar{D}}(1-f_s)$, $B_{\bar{U}} = B_{\bar{D}}$, $C'_g = 25$

$$\int_0^1 [\textstyle\sum_i (q_i(x) + \bar{q}_i(x)) + g(x)] x dx = 1$$
$$\int_0^1 [u(x) - \bar{u}(x)] dx = 2,$$
$$\int_0^1 [d(x) - \bar{d}(x)] dx = 1$$

- fit ($\Delta\chi^2 = 1$), model (scales, α_s, f_s, $Q^2_{\rm min}$) and par. (μ_{f0}, $E_{u_v} = 0$) unc.

BACKUP. Discussion of HQ mass extraction

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

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

Results have sizable model and parametrisation uncertainty:

- *model uncertainties dominated by scale variations*
- *parametrisation uncertainties dominated by reduced 13p form: closely related to inclusive HERA data in the fit*

Using inclusive HERA data only:

$m_c(m_c) = 1798^{+144}_{-134}(\text{fit})$ MeV

$m_b(m_b) = 8450^{+2280}_{-1810}(\text{fit})$ MeV

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

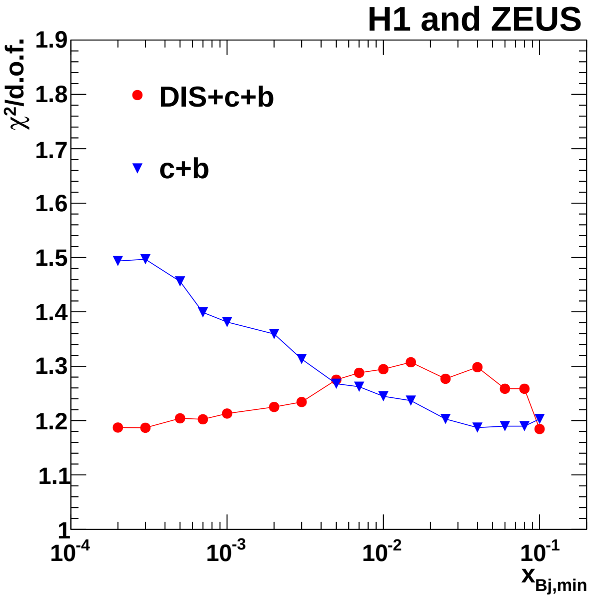
$m_c(m_c) = 1798 \rightarrow 1450$ MeV,
$m_b(m_b) = 8450 \rightarrow 3995$ MeV

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

13p: $E_{u_v} = 0$

$\Rightarrow$ inclusive HERA data alone cannot constrain HQ masses reliably
$\Rightarrow$ interplay of PDFs and HQ masses needs carefull treatment

Increasing impact of HF data on gluon: $x_{\mathrm{Bj,min}}$ χ^2 scan



BACKUP. $m_c(m_c)$ extraction in FFNS and VFNS

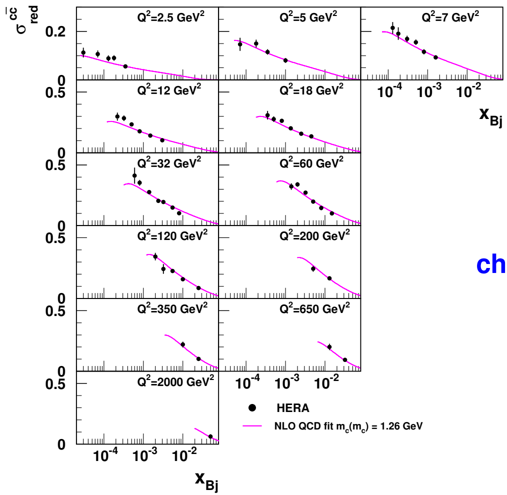
JHEP 1608 (2016) 050

variation	FONLL-C	FFN
central	1.335 ± 0.043	1.318 ± 0.054
$Q_0^2 = 1.5$	1.354 [+0.019]	1.329 [+0.011]
D_{uv} non-zero	1.340 [+0.005]	1.308 [−0.010]
$f_s = 0.3$	1.338 [+0.003]	1.320 [+0.002]
$f_s = 0.5$	1.332 [−0.003]	1.315 [−0.003]
$m_b(m_b) = 3.93$ GeV	1.330 [−0.005]	1.312 [−0.006]
$m_b(m_b) = 4.43$ GeV	1.343 [+0.008]	1.324 [+0.006]
$\alpha_s(M_Z) = 0.1165$	1.342 [+0.007]	1.332 [+0.014]
$\alpha_s(M_Z) = 0.1195$	1.329 [−0.006]	1.300 [−0.018]
$\mu_F^2 = \mu_R^2 = 2 \cdot Q^2$	1.347 [+0.012]	1.314 [−0.004]
$\mu_F^2 = \mu_R^2 = Q^2/2$	1.361 [+0.026]	1.363 [+0.045]
FONLL Damping power = 1	1.352 [+0.017]	–
FONLL Damping power = 4	1.327 [−0.008]	–

A determination of $m_c(m_c)$ from HERA data using a matched heavy-flavor scheme

- consistent results obtained in FFNS and FONLL, with somewhat different decomposition of uncertainties
- $\Rightarrow$ VFNS can be used for $\overline{\text{MS}}$ mass extraction, if all uncertainties from extra parameters are considered

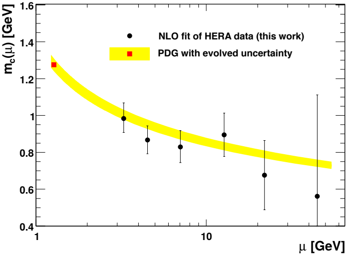
Gizsko et al., PLB775 (2017) 233 (work partially done within scope of PROSA, ZEUS and H1 coll.)



- Determined using earlier published HERA charm data [EPJ C73 (2013) 2311]
- $\overline{\rm MS}$ charm mass $m_c(m_c)$ extracted in regions of Q^2 and translated to appropriate scale μ

$\Downarrow$

check of QCD running mass concept



New combined HERA charm and beauty data

Eur.Phys.J. C78 (2018) 473

- improvement in precision w.r.t previous HERA results for charm
- first combined HERA results for beauty
- enable precise determination of charm and beauty masses
- reveal tension in describing both HF and inclusive HERA data

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

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