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

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on behalf of the H1 and ZEUS collaborations

H1prelim-17-071

ZEUS-prel-17-01

DIS 2017, Birmingham, 3-7 April 2017

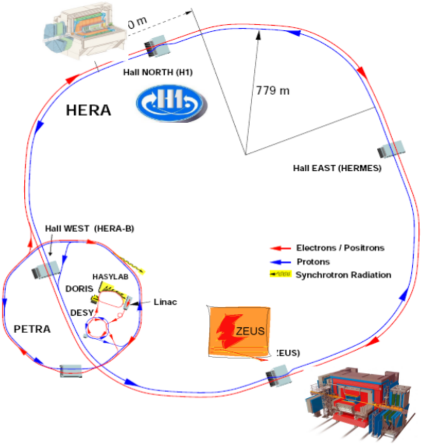
Experimental set-up

HERA Collider

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

H1 and ZEUS:

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



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

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

Kinematics

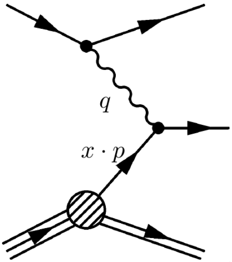
$$Q^2 = -q^2 = -(e - e')^2$$

$$x = \frac{Q^2}{2q \cdot p}$$

$$y = \frac{q \cdot p}{q \cdot e}$$

$$s = (e + p)^2$$

$$Q^2 = sxy$$



Any two of the variables (Q^2, x, y) define kinematics

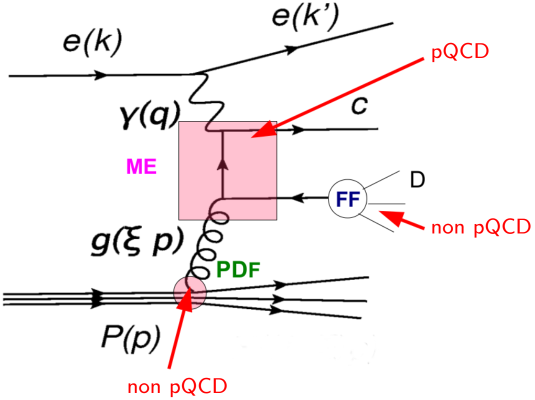
$Q^2 > 1\ GeV^2$ — deep inelastic scattering (DIS)
$Q^2 < 1\ GeV^2$ — photoproduction processes (PHP)

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) process

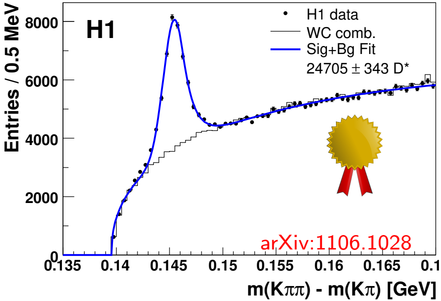
$$\boldsymbol{\sigma} = \mathbf{PDF} \otimes \mathbf{ME} \otimes \mathbf{FF}$$



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

Overview of experimental techniques used to measure charm and beauty production at HERA

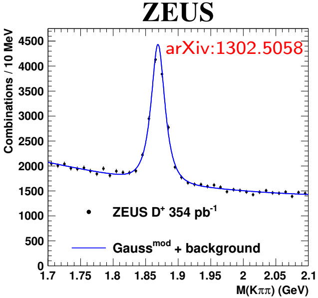
"Golden" decay channel $D^* \to D^0(K\pi)\pi_s$

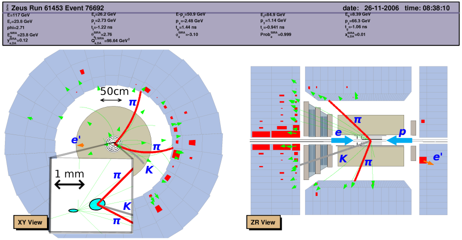


Dedicated H1ZEUS combination:

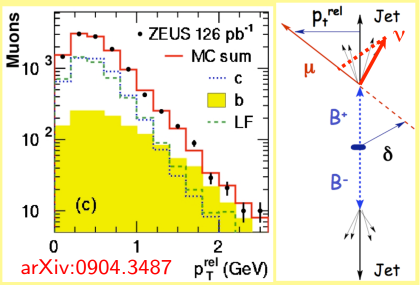
"Combination of differential $D^{*\pm}$ cross-section measurements in deep-inelastic ep scattering at HERA" [JHEP09 (2015) 149]

Weakly decaying charm hadrons

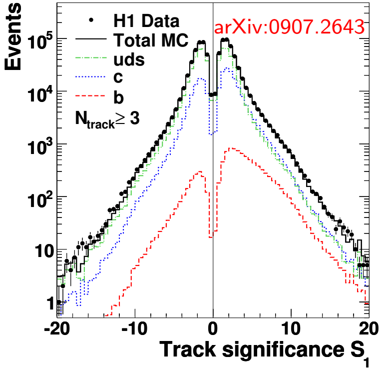




Semi-leptonic (SL) HQ decays



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

Combination of charm and beauty HERA data

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]

Input data

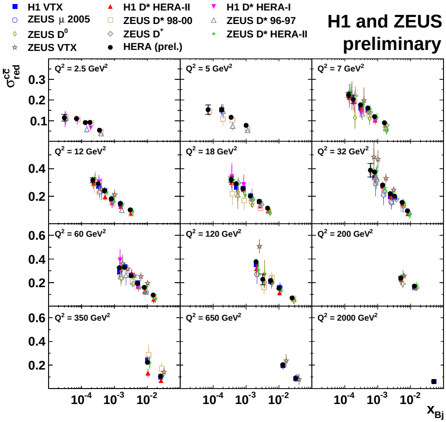
	Data set	Tagging	Q^2 range [GeV^2]	N_c	$\mathscr{L}$ [pb^{-1}]	$\sqrt{s}$ [GeV]	N_b
1	H1 VTX [8]	VTX	5 – 2000	29	245	318	12
2	H1 D^{*+} HERA-I [9]	D^{*+}	2 – 100	17	47	318	
3	H1 D^{*+} HERA-II (medium Q^2) [10]	D^{*+}	5 – 100	25	348	318	
4	H1 D^{*+} HERA-II (high Q^2) [11]	D^{*+}	100 – 1000	6	351	318	
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)

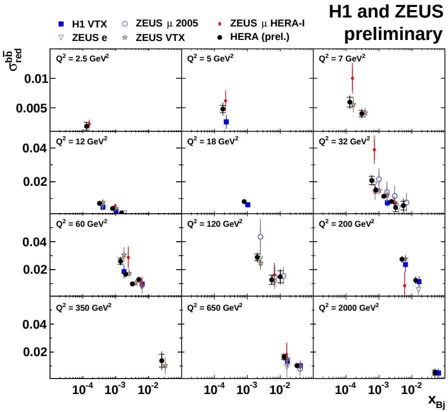
- Combined data provided in kinematic range: $2.5 \leq Q^2 \leq 2000$ GeV^2, $3 \times 10^{-5} \leq x_{\rm Bj} \leq 5 \times 10^{-2}$
- Input 209 c, 52 b data points $\Rightarrow$ combined 52 c, 27 b points
- **Extends previous HERA charm combination with 3 new c data sets and 5 new b: first combination of HERA b data**

Combined data

CHARM



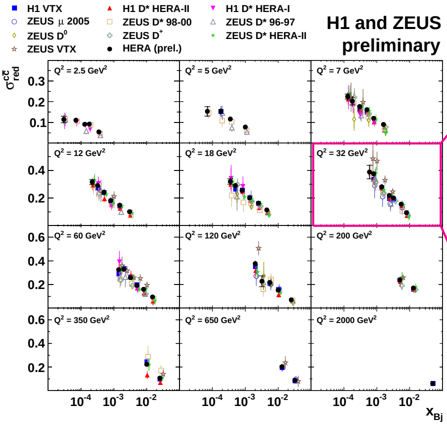
BEAUTY

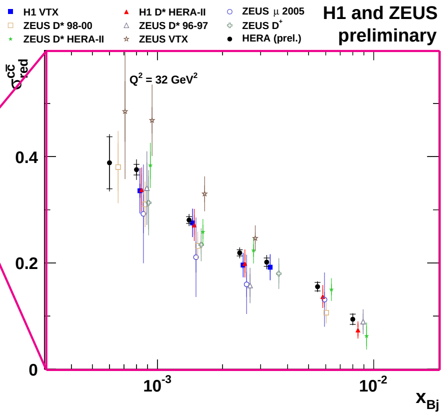


$\chi^2/\mathrm{dof} = 149/187$: **input data are consistent**

Combined data

CHARM

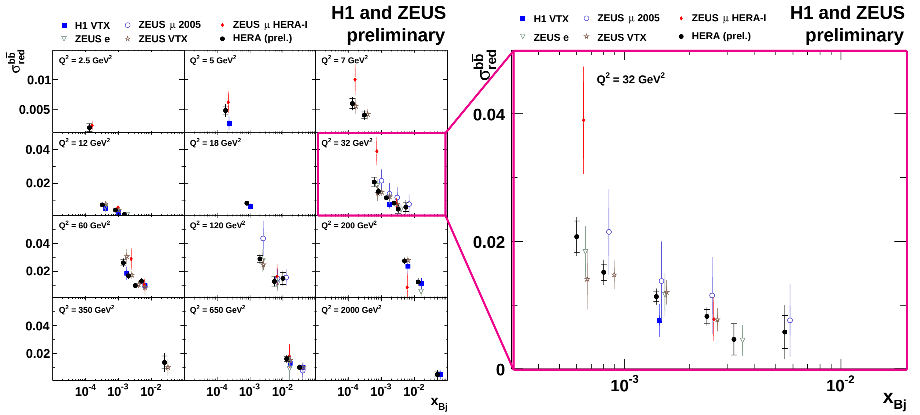




Significantly improved precision compared to input measurements

Combined data

BEAUTY



Significantly improved precision compared to input measurements

Theoretical predictions compared to combined data

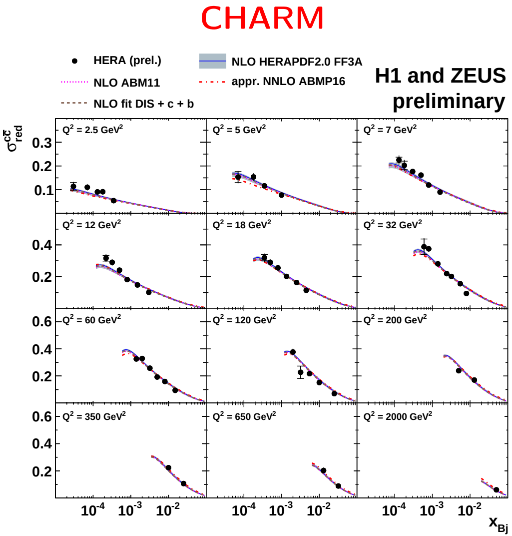
Predictions calculated with OPENQCDRAD interfaced in xFitter

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

`www.xfitter.org`

- input PDFs: HERAPDF2.0FF3A, ABM11, ABMP16, or fitted
- NLO or approx. NNLO as implemented in OPENQCDRAD
- $\mu_f = \mu_r = \sqrt{Q^2 + 4m_Q^2}$, 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], or fitted

FFN scheme, $n_f = 3$: reliable in this kinematic range



Overall reasonable description, some x slope at low and medium Q^2

Theoretical predictions compared to combined data

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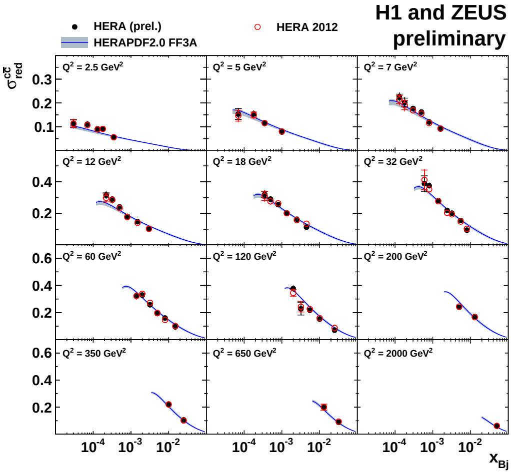
FFN scheme, $n_f = 3$: reliable in this kinematic range

CHARM



Overall reasonable description, some x slope at low and medium Q^2

Same in previous H1ZEUS charm combination, but within larger unc.

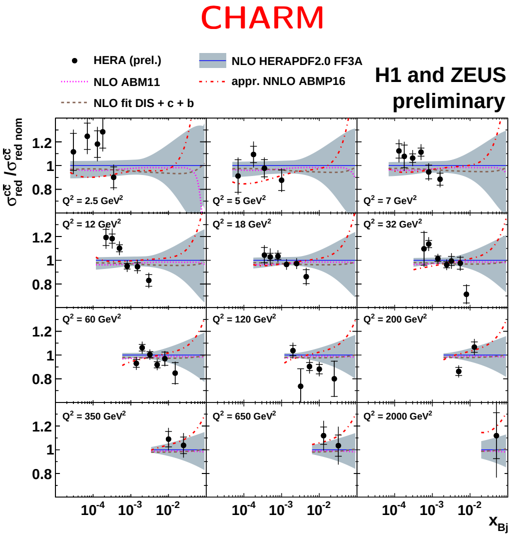
Predictions calculated with OPENQCDRAD interfaced in xFitter

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

`www.xfitter.org`

- input PDFs: HERAPDF2.0FF3A, ABM11, ABMP16, or fitted
- NLO or approx. NNLO as implemented in OPENQCDRAD
- $\mu_f = \mu_r = \sqrt{Q^2 + 4m_Q^2}$, 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], or fitted

FFN scheme, $n_f = 3$: reliable in this kinematic range



Overall reasonable description, some x slope at low and medium Q^2

Small sensitivity to PDFs, appr. NNLO do not improve description

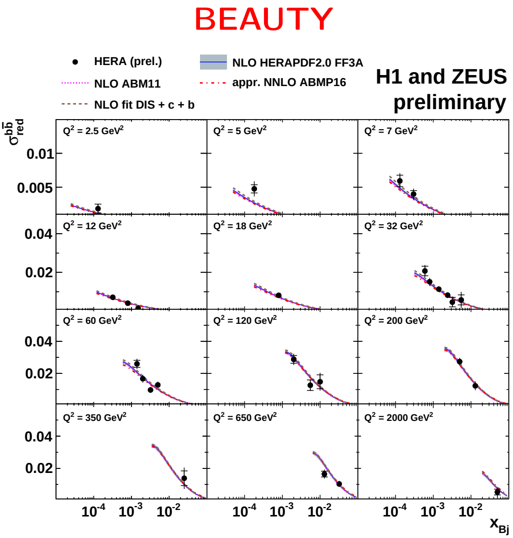
Predictions calculated with OPENQCDRAD interfaced in xFitter

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

`www.xfitter.org`

- input PDFs: HERAPDF2.0FF3A, ABM11, ABMP16, or fitted
- NLO or approx. NNLO as implemented in OPENQCDRAD
- $\mu_f = \mu_r = \sqrt{Q^2 + 4m_Q^2}$, 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], or fitted

FFN scheme, $n_f = 3$: reliable in this kinematic range



Overall good description within data uncertainties

Predictions calculated with OPENQCDRAD interfaced in xFitter

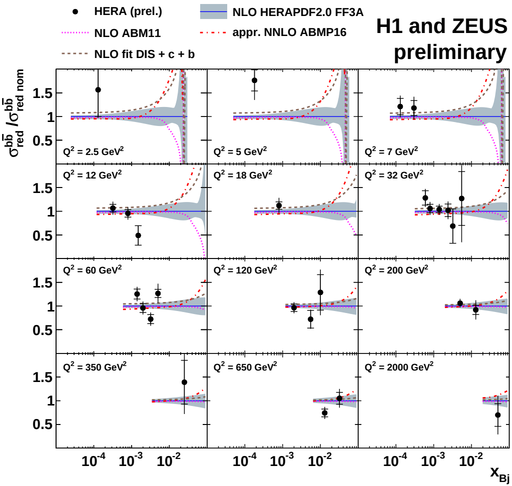
www-zeuthen.desy.de/∼alekhin/OPENQCDRAD

www.xfitter.org

- input PDFs: HERAPDF2.0FF3A, ABM11, ABMP16, or fitted
- NLO or approx. NNLO as implemented in OPENQCDRAD
- $\mu_f = \mu_r = \sqrt{Q^2 + 4m_Q^2}$, 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], or fitted

FFN scheme, $n_f = 3$: reliable in this kinematic range

BEAUTY



Overall good description within data uncertainties

Small sensitivity to PDFs and higher order corrections

Theoretical predictions compared to combined data

Dataset	PDF	χ^2	χ^2 with PDF unc.
HERA 2012 c [1]	HERAPDF20_NLO_FF3A_EIG	59	59
	abm11_3n_nlo	62	62
(dof = 52)	ABMP16_3_nnlo	64	63
New combined c	HERAPDF20_NLO_FF3A_EIG	86	85
	abm11_3n_nlo	92	91
(dof = 52)	ABMP16_3_nnlo	101	99
ZEUS VTX b [4]	HERAPDF20_NLO_FF3A_EIG	14	14
	abm11_3n_nlo	13	13
(dof = 17)	ABMP16_3_nnlo	14	14
New combined b	HERAPDF20_NLO_FF3A_EIG	33	33
	abm11_3n_nlo	34	34
(dof = 27)	ABMP16_3_nnlo	39	39

[1] previous HERA charm combination EPJ C73 (2013) 2311

[4] ZEUS b lifetime tagging measurement JHEP09 (2014) 127

(most precise individual public data sets for c and b from HERA to date)

Quantitatively confirms observed findings:

- larger tension for new charm data owing to reduced uncertainties
- appr. NNLO does not improve data description compared to NLO
- overall small sensitivity to input PDFs

QCD analysis and determination of charm and beauty masses

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

$$m_c(m_c) = 1290^{+46}_{-41}(\text{fit})^{+62}_{-14}(\text{mod})^{+7}_{-31}(\text{par})\ \text{MeV}$$

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

$\Rightarrow$ **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

Discussion of HQ mass extraction

$$\boldsymbol{m_c(m_c) = 1290^{+46}_{-41}(\text{fit})^{+62}_{-14}(\text{mod})^{+7}_{-31}(\text{par})\ \text{MeV}}$$

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

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: $E_{u_v} = 0$

⇒ inclusive HERA data alone cannot constrain HQ masses

⇒ interplay of PDFs and HQ masses needs carefull treatment

Summary

New preliminary combined HERA HQ data:

- $11\ c + 5\ b$ input data sets $\Rightarrow c + b$ sets with full cross correlations
- input data are **consistent**
- **improvement in precision** w.r.t previous HERA results on **charm**
- **first** combined HERA results on **beauty**

Comparison to theory and QCD analysis:

- overall reasonable description, some tension in x slope for charm
- **precise extraction** of $m_c(m_c)$, $m_b(m_b)$

H1prelim-17-071, ZEUS-prel-17-01

`https://www.desy.de/h1zeus/combined_results/index.php?do=heavy_flavours`

BACKUP

BACKUP. Input data

[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].

BACKUP. Combination procedure

- 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

BACKUP. Data combination

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

Minimised in iterative procedure

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, $Q^2_{\min} > 3.5$ 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, $Q^2_{\min}$) and par. $(\mu_{f0}, E_{u_v} = 0)$ unc.

BACKUP. pQCD approximation of heavy flavour production

Fixed Flavour Number Scheme (FFNS)

- c,b-quarks are massive ⇒ 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 ⇒ 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, ...)

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

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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 $\overline{\mathrm{MS}}$ mass extraction, if all uncertainties from extra parameters are considered