Latest tests of hard QCD at HERA

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on behalf of the H1 and ZEUS collaborations

18th Lomonosov Conference, MSU, 23-30 August 2017

Experimental set-up

HERA Collider

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

H1 and ZEUS:

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

$$\begin{array}{c} E_p = 920 \text{ GeV} \quad E_e = 27.5 \text{ GeV} \\ \text{—————} \rightarrow \text{ } \leftarrow \text{—————} \\ \sqrt{s} = 318 \text{ GeV} \end{array}$$

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

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

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

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

$$Q^2 = sxy$$

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

$Q^2 > 1 \text{ GeV}^2$ — deep inelastic scattering (DIS)

$Q^2 < 1 \text{ GeV}^2$ — photoproduction processes (PHP)

New results from HERA covered in this talk:

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“Combination and QCD analysis of beauty and charm production cross section measurements in deep inelastic ep scattering at HERA”
[preliminary] H1prelim-17-071, ZEUS-prel-17-01
https://www.desy.de/h1zeus/combined_results/index.php?do=heavy_flavours
- H1 Collaboration,
“Measurement of Jet Production Cross Sections in Deep-inelastic ep Scattering at HERA”
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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

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

↓

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

PDF: parton distribution functions

ME: (hard) matrix element

FF: fragmentation function & fraction

Fixed Flavour Number Scheme (FFNS)

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

Zero Mass Variable Flavour Number Scheme (ZMVFNS)

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

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, ...)

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: $\sigma_{\text{red}}^{Q\bar{Q}} = \frac{d^2\sigma^{Q\bar{Q}}}{dx_{\text{Bj}}dQ^2} \cdot \frac{x_{\text{Bj}}Q^4}{2\pi\alpha^2(1+(1-y)^2)}$
- Combined data provided in kinematic range:
 $2.5 \leq Q^2 \leq 2000 \text{ GeV}^2$, $3 \times 10^{-5} \leq x_{\text{Bj}} \leq 5 \times 10^{-2}$
- 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**

CHARM H1 and ZEUS preliminary

BEAUTY H1 and ZEUS preliminary

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

→ input data are consistent

→ significantly reduced uncertainties as compared to the individual measurements

CHARM

Significantly improved precision compared to input measurements

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

CHARM (beauty in BACKUP)

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

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

CHARM (beautv in BACKUP)

Overall reasonable description, some x slope at low and medium Q^2
 Small sensitivity to PDFs, appr. NNLO do not improve description

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

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

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

$\Rightarrow$ **determined precise HQ masses consistent with world average**

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

Running of m_c from HERA DIS data

Gizsko et al., arXiv:1705.08863 (work partially done within scope of PROSA, ZEUS and H1 collaborations)

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

check of QCD running mass concept

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[preliminary] ZEUS-prel-16-001

H1 multijet production in NC DIS

$$2xP + q = 0$$

- Breit frame: separates QCD processes from EW

- QCD jets at LO are produced via **Boson-Gluon Fusion (BGF)** and **QCD Compton (QCDC)**:
 $\rightarrow$ probe $g \cdot \alpha_S$ at LO

- Jets are reconstructed using k_T algorithm

- Phase space:

DIS: $5.5 < Q^2 < 80 \text{ GeV}^2$
 $0.2 < y < 0.6$

inclusive jets $4.5 < p_T^{\text{jet}} < 50 \text{ GeV}$
 $-1.0 < \eta^{\text{lab}} < 2.5$

dijets $5.0 < \langle p_T^{\text{jet}} \rangle_2 < 50 \text{ GeV}$

trijets $5.5 < \langle p_T^{\text{jet}} \rangle_3 < 40 \text{ GeV}$

+ extension of high- Q^2 meas. [EPJ C75 (2015) 65]

- Simultaneous unfolding of (multi)jet and NC DIS events, respecting all statistical correlations

H1 inclusive jets: comparison to theoretical predictions

Cross sections

$$5.5 < Q^2 < 80 \text{ GeV}^2$$

$$0.2 < y < 0.6$$

$$4.5 < p_T^{\text{jet}} < 50 \text{ GeV}$$

$$-1.0 < \eta^{\text{lab}} < 2.5$$

[EPJ C77 (2017) 215]

- High precision data over the whole kinematic range!

- Good description by QCD predictions

$$150 < Q^2 < 15000 \text{ GeV}^2$$

$$0.2 < y < 0.7$$

$$5 < p_T^{\text{jet}} < 50 \text{ GeV}$$

$$-1.0 < \eta^{\text{lab}} < 2.5$$

[EPJ C75 (2015) 65]

H1 inclusive jets: comparison to theoretical predictions

Ratio to NLO

$$5.5 < Q^2 < 80 \text{ GeV}^2$$

$$0.2 < y < 0.6$$

$$4.5 < p_T^{\text{jet}} < 50 \text{ GeV}$$

$$-1.0 < \eta^{\text{lab}} < 2.5$$

[EPJ C77 (2017) 215]

NNLO calculations

[PRL 117 (2016) 042001]:

- *improved shape*
- *reduced scale unc. at high scales*

$$150 < Q^2 < 15000 \text{ GeV}^2$$

$$0.2 < y < 0.7$$

$$5 < p_T^{\text{jet}} < 50 \text{ GeV}$$

$$-1.0 < \eta^{\text{lab}} < 2.5$$

[EPJ C75 (2015) 65]

H1 multijets normalised to NC DIS

Dijets / NC DIS / NLO

Trijets / NC DIS / NLO

- Experimental systematic unc. partially cancel in ratio **Jets / NC DIS**
- Improved description of dijets shape by **NNLO** calculations

H1 multijets: extraction and running of α_s at NNLO

H1 Collaboration and V. Bertone, J. Currie, T. Gehrmann, C. Gwenlan, A. Huss, J. Niehues, M. Sutton

Fit to inclusive and dijet data: $\chi^2/n_{\text{dof}} = 1.03$, $n_{\text{dof}} = 203$

$$\alpha_s(m_Z) = 0.1157(6)_{\text{exp}}(3)_{\text{had}}(6)_{\text{PDF}}(12)_{\text{PDF}\alpha_s}(2)_{\text{PDFset}} \left(\begin{smallmatrix} +27 \\ -21 \end{smallmatrix} \right)_{\text{scale}}$$

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[preliminary] ZEUS-prel-16-001

ZEUS isolated photons in DIS

ZEUS-prel-16-001, complements ZEUS publication PLB 715 (2012) 88: new variables

QQ

LL

Isolated (prompt) photons can be radiated from:

- **quarks (QQ):** part of hard process, provide insights into QCD
- **leptons (LL)**

Phase space:

DIS $10 < Q^2 < 350 \text{ GeV}^2$

γ $4 < E_T^\gamma < 15 \text{ GeV}$
 $-0.7 < \eta^\gamma < 0.9$

jet $2.5 < E_T^{\text{jet}} < 35 \text{ GeV}$
 $-1.5 < \eta^{\text{jet}} < 1.8$

ZEUS preliminary

$$\langle \delta Z \rangle = \frac{\sum_i E_i |Z_i - Z_{\text{cluster}}|}{(w_{\text{cell}} \sum_i E_i)}$$

δZ is energy-weighted mean width of the electromagnetic shower (cluster) in calorimeter relative to its centroid

$\Rightarrow$ calorimeter granularity was used to separate prompt γ (QQ and LL) from hadronic background (e.g. $\pi^0 \rightarrow \gamma\gamma$)

ZEUS isolated photons in DIS: comparison to MC models

ZEUS preliminary

Djangoh (LL) + Pythia (QQ):

- QQ contribution scaled by 1.6
- LL contribution taken as predicted

→ good description for all variables

- $x_\gamma = \frac{E^\gamma - p_z^\gamma + E^{\text{jet}} - p_z^{\text{jet}}}{2E_e y_{JB}}$
- $x_p = \frac{E^\gamma + p_z^\gamma + E^{\text{jet}} + p_z^{\text{jet}}}{2E_p}$
- $\Delta\phi = \phi^{\text{jet}} - \phi^\gamma$
- $\Delta\eta = \eta^{\text{jet}} - \eta^\gamma$
- $\Delta\phi_{e,\gamma} = \phi^e - \phi^\gamma$
- $\Delta\eta_{e,\gamma} = \eta^e - \eta^\gamma$

ZEUS Preliminary 16-001

- NLO collinear factorisation by Aurenche, Fontannaz and Guillet (AFG) [1704.08074]
→ describe all variables well
- k_T -factorisation by Baranov, Lipatov and Zotov (BLZ) [PRD81 (2010) 094034]
→ fair agreement, except x_γ

New preliminary combined HERA HQ data:

- improvement in precision w.r.t previous HERA results on charm
- first combined HERA results on beauty
- enables precise determination of charm and beauty masses

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

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

Measurement of multijet production by H1:

- high precision data over wide Q^2 , p_T kinematic range
- successful test of recently appeared NNLO calculations: improved p_T shape at NNLO, smaller scale uncertainties
- enables precise determination and check of running of α_S

[EPJ C77 (2017) 215, EPJ C75 (2015) 65, H1prelim-17-031]

Measurement of isolated photons by ZEUS:

- good agreement with NLO collinear factorisation predictions
- worse agreement with k_T -factorisation predictions

[ZEUS-prel-16-001]

H1 and ZEUS continue producing valuable QCD results after 10 years of HERA shutdown!

BACKUP

BACKUP. Measurement of charm production at HERA

“Golden” decay channel
 $D^* \rightarrow D^0(K\pi)\pi_s$

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

ZEUS Run 61453 Event 76692				date: 26-11-2006 time: 09:38:10	
$E_{\text{beam}} = 27.6 \text{ GeV}$	$E_{\text{beam}} = 27.6 \text{ GeV}$	$E_{\text{beam}} = 27.6 \text{ GeV}$	$E_{\text{beam}} = 27.6 \text{ GeV}$	$E_{\text{beam}} = 27.6 \text{ GeV}$	$E_{\text{beam}} = 27.6 \text{ GeV}$
$\sqrt{s} = 31.1 \text{ GeV}$	$\sqrt{s} = 31.1 \text{ GeV}$	$\sqrt{s} = 31.1 \text{ GeV}$	$\sqrt{s} = 31.1 \text{ GeV}$	$\sqrt{s} = 31.1 \text{ GeV}$	$\sqrt{s} = 31.1 \text{ GeV}$
$\theta_{\text{had}} = 2.1$	$\theta_{\text{had}} = 2.1$	$\theta_{\text{had}} = 2.1$	$\theta_{\text{had}} = 2.1$	$\theta_{\text{had}} = 2.1$	$\theta_{\text{had}} = 2.1$
$\theta_{\text{lep}} = 23.8 \text{ GeV}$	$\theta_{\text{lep}} = 23.8 \text{ GeV}$	$\theta_{\text{lep}} = 23.8 \text{ GeV}$	$\theta_{\text{lep}} = 23.8 \text{ GeV}$	$\theta_{\text{lep}} = 23.8 \text{ GeV}$	$\theta_{\text{lep}} = 23.8 \text{ GeV}$
$\theta_{\text{had}} = 1.2$	$\theta_{\text{had}} = 1.2$	$\theta_{\text{had}} = 1.2$	$\theta_{\text{had}} = 1.2$	$\theta_{\text{had}} = 1.2$	$\theta_{\text{had}} = 1.2$
$\theta_{\text{lep}} = 23.8 \text{ GeV}$	$\theta_{\text{lep}} = 23.8 \text{ GeV}$	$\theta_{\text{lep}} = 23.8 \text{ GeV}$	$\theta_{\text{lep}} = 23.8 \text{ GeV}$	$\theta_{\text{lep}} = 23.8 \text{ GeV}$	$\theta_{\text{lep}} = 23.8 \text{ GeV}$
$\theta_{\text{had}} = 1.2$	$\theta_{\text{had}} = 1.2$	$\theta_{\text{had}} = 1.2$	$\theta_{\text{had}} = 1.2$	$\theta_{\text{had}} = 1.2$	$\theta_{\text{had}} = 1.2$

BACKUP. Measurement of c and b production at HERA

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** $\sigma_{\text{red}}^{c\bar{c}}$, $\sigma_{\text{red}}^{b\bar{b}}$
$$\sigma_{\text{red}}^{Q\bar{Q}} = \frac{d^2\sigma^{Q\bar{Q}}}{dx_{\text{Bj}}dQ^2} \cdot \frac{x_{\text{Bj}}Q^4}{2\pi\alpha^2(1+(1-y)^2)} \text{ (full phase space)}$$

($Q\bar{Q}$ 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].
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- [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^{*+} Meson Production and Determination of F_2^{charm} 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 $F(2)^{(c \text{ c-bar})}$, 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 D^0 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 σ_{vis} and extrapolate to full phase space σ_{red} using consistent NLO setup: $\sigma_{\text{red}} = \sigma_{\text{vis}} \frac{\sigma_{\text{red}}^{\text{NLO}}}{\sigma_{\text{vis}}^{\text{NLO}}}$ [HVQDIS]
- Combine σ_{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

BEAUTY

Significantly improved precision compared to input measurements

$$\chi^2(\mathbf{m}, \mathbf{b}) = \sum_{e=1}^{N_e} \sum_{i=1}^{N_m} \frac{\left(m_i - \sum_{j=1}^{N_s} \Gamma_i^{e,j} b^{e,j} - \mu_i^e\right)^2}{\sigma_i^{e2}} + \sum_{j=1}^{N_s} b^{e,j2}$$

Minimised in iterative procedure

Predictions calculated with OPENQCDRAD interfaced in xFitter

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www.xfitter.org

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- $m_c(m_c) = 1.27 \pm 0.03$ GeV, $m_b(m_b) = 4.18 \pm 0.03$ GeV [PDG2016], or fitted

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

CHARM

H1 and ZEUS preliminary

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

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

BEAUTY

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

BACKUP. Theoretical predictions compared to data

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

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

- xFitter-1.2.0
- Input data:
 - HERA $e^\pm p$ inclusive data, $Q_{\min}^2 > 3.5 \text{ GeV}^2$ [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 $m_c(m_c) = 1.27 \text{ GeV}$, $m_c(m_c) = 4.18 \text{ GeV}$
- DGLAP NLO [QCDNUM]
- PDF parametrisation: 14p HERAPDF at $\mu_{f0}^2 = 1.9 \text{ GeV}^2$, $f_s = 0.4$:

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

Additional constrains:

$$\begin{aligned}A_{\bar{U}} &= A_{\bar{D}}(1 - f_s), \quad B_{\bar{U}} = B_{\bar{D}}, \quad C'_g = 25 \\ \int_0^1 [\sum_i (q_i(x) + \bar{q}_i(x)) + g(x)] dx &= 1 \\ \int_0^1 [u(x) - \bar{u}(x)] dx &= 2, \\ \int_0^1 [d(x) - \bar{d}(x)] dx &= 1\end{aligned}$$

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

BACKUP. Discussion of HQ mass extraction

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

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

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:

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

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

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

$$m_c(m_c) = 1798 \rightarrow 1450 \text{ MeV},$$

$$m_b(m_b) = 8450 \rightarrow 3995 \text{ MeV}$$

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

$$13p: E_{u_v} = 0$$

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

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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	$1.340 [+0.005]$	$1.308 [-0.010]$
$f_s = 0.3$	$1.338 [+0.003]$	$1.320 [+0.002]$
$f_s = 0.5$	$1.332 [-0.003]$	$1.315 [-0.003]$
$m_b(m_b) = 3.93 \text{ GeV}$	$1.330 [-0.005]$	$1.312 [-0.006]$
$m_b(m_b) = 4.43 \text{ GeV}$	$1.343 [+0.008]$	$1.324 [+0.006]$
$\alpha_s(M_Z) = 0.1165$	$1.342 [+0.007]$	$1.332 [+0.014]$
$\alpha_s(M_Z) = 0.1195$	$1.329 [-0.006]$	$1.300 [-0.018]$
$\mu_F^2 = \mu_R^2 = 2 \cdot Q^2$	$1.347 [+0.012]$	$1.314 [-0.004]$
$\mu_F^2 = \mu_R^2 = Q^2/2$	$1.361 [+0.026]$	$1.363 [+0.045]$
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