Latest tests of hard QCD at HERA

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

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

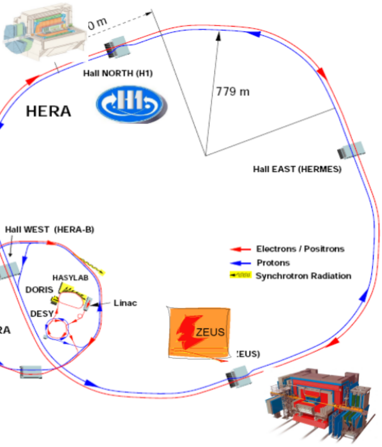
Experimental set-up

HERA Collider

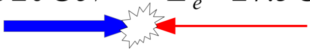
- ep collisions
- $\sqrt{s} = 300 \ldots 318$ GeV and lower energy runs

H1 and ZEUS:

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



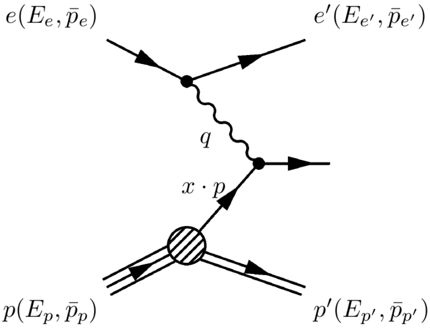
$$E_p = 920\,GeV \qquad E_e = 27.5\,GeV$$



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

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)

Overview

New results from HERA covered in this talk:

- H1 and ZEUS Collaborations,
  "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`

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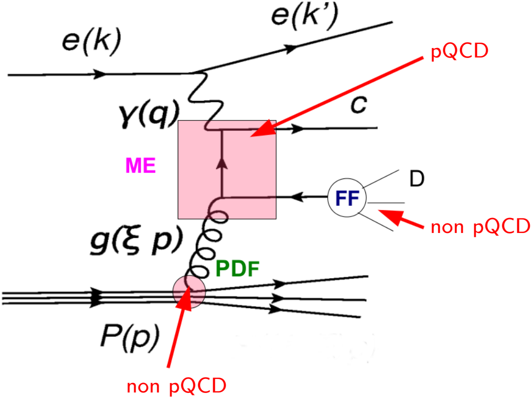
Heavy flavour (HF) production in DIS

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

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



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

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, ...)

detailed discussion in [EPJ C73 (2013) 2311]

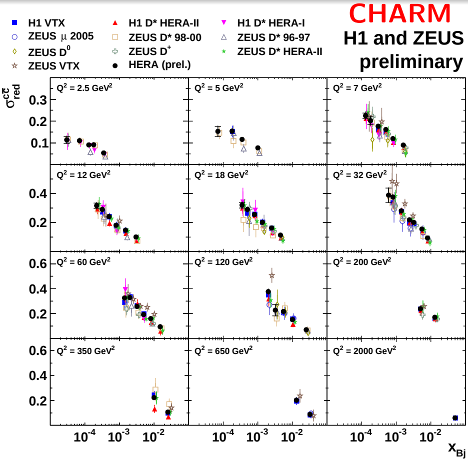
Input data

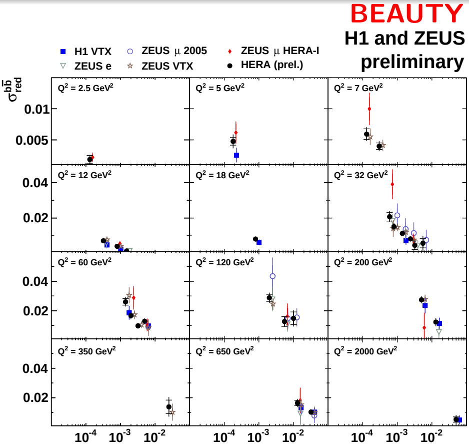
Data set	Tagging	Q^2 range [GeV^2]	N_c	$\mathscr{L}$ [pb^{-1}]	$\sqrt{s}$ [GeV]	N_b
1 H1 VTX [8]	VTX	5 – 2000	29	245	318	12
2 H1 D^{*+} HERA-I [9]	D^{*+}	2 – 100	17	47	318	
3 H1 D^{*+} HERA-II (medium Q^2) [10]	D^{*+}	5 – 100	25	348	318	
4 H1 D^{*+} HERA-II (high Q^2) [11]	D^{*+}	100 – 1000	6	351	318	
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 reduced cross sections: $\sigma_{\mathrm{red}}^{Q\bar{Q}} = \frac{\mathrm{d}^2\sigma^{Q\bar{Q}}}{\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}Q^2} \cdot \frac{x_{\mathrm{Bj}}Q^4}{2\pi\alpha^2\,(1+(1-y)^2)}$
- Combined data provided in kinematic range:
  $2.5 \le Q^2 \le 2000$ GeV^2, $3 \times 10^{-5} \le x_{\mathrm{Bj}} \le 5 \times 10^{-2}$
- 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

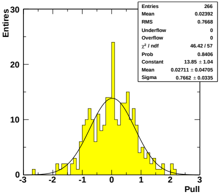




$$\chi^2/\mathrm{dof} = 149/187$$

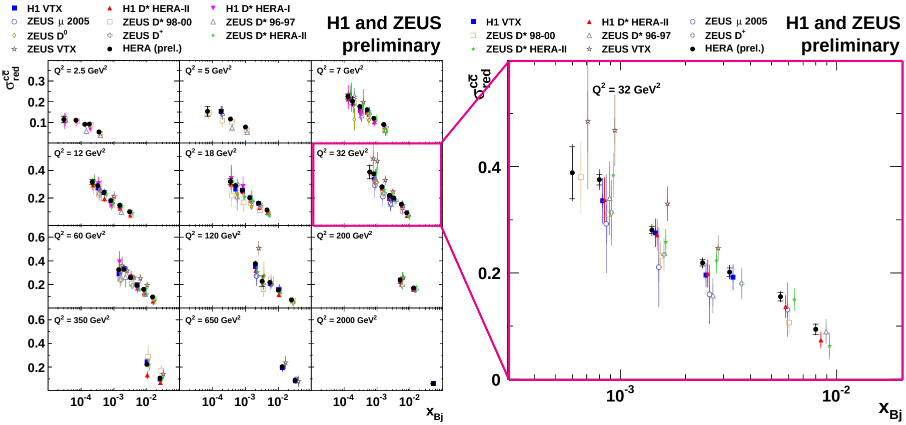
→ **input data are consistent**

→ **significantly reduced uncertainties as compared to the individual measurements**



BACKUP. Combined data

CHARM



Significantly improved precision compared to input measurements

Theoretical predictions compared to combined data

Predictions calculated with OPENQCDRAD interfaced in xFitter

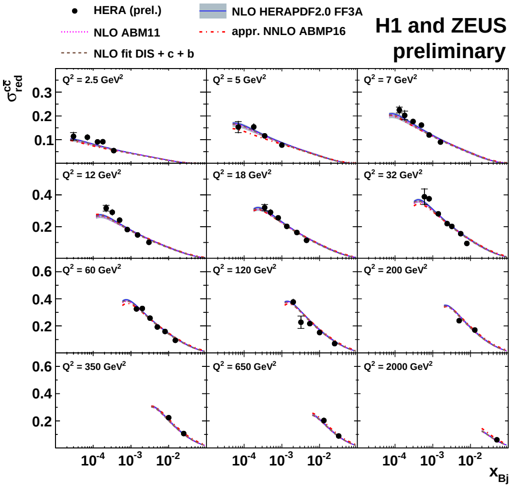
www-zeuthen.desy.de/∼alekhin/OPENQCDRAD

`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

CHARM (beauty in BACKUP)



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

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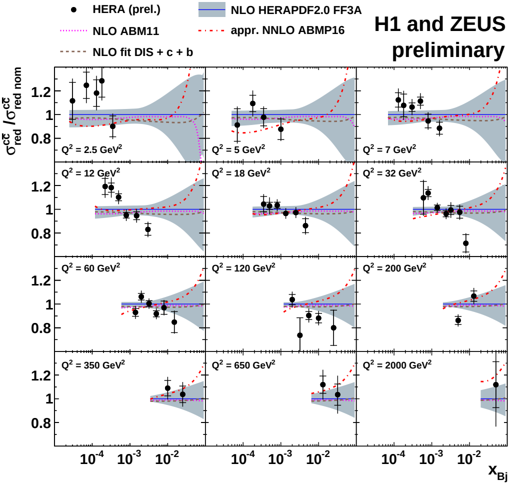


Overall reasonable description, some x slope at low and medium Q^2

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

QCD analysis of combined charm and beauty data

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

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

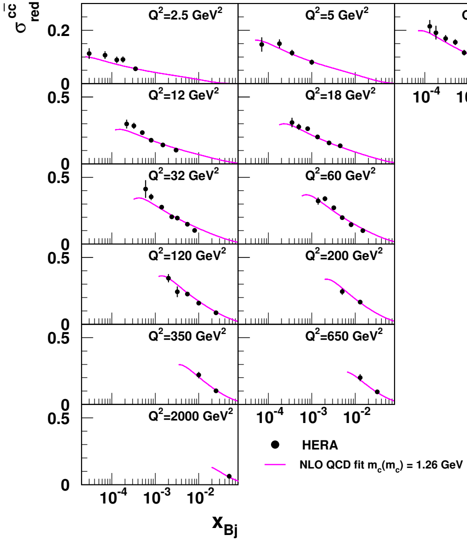
$$\boldsymbol{m_b(m_b) = 4049^{+104}_{-109}(\text{fit})^{+90}_{-32}(\text{mod})^{+1}_{-31}(\text{par})\ \text{MeV}}$$

⇒ 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

Running of m_c from HERA DIS data

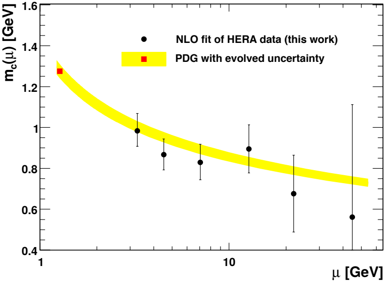
Gizsko et al., arXiv:1705.08863 (work partially done within scope of PROSA, ZEUS and H1 collaborations)



- 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

$$\Downarrow$$

check of QCD running mass concept



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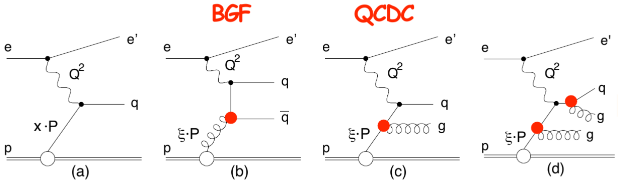
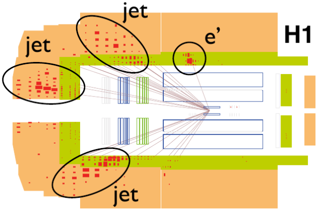
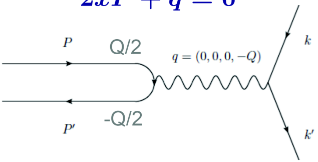
H1 multijet production in NC DIS



elweak coupling $\propto \alpha_S$ $\propto \alpha_S$ $\propto \alpha_S^2$



$$2xP + q = 0$$



- Breit frame: separates QCD processes from EW
- QCD jets at LO are produced via Boson-Gluon Fusion (BGF) and QCD Compton (QCDC):
  → *probe* $g \cdot \alpha_S$ *at LO*

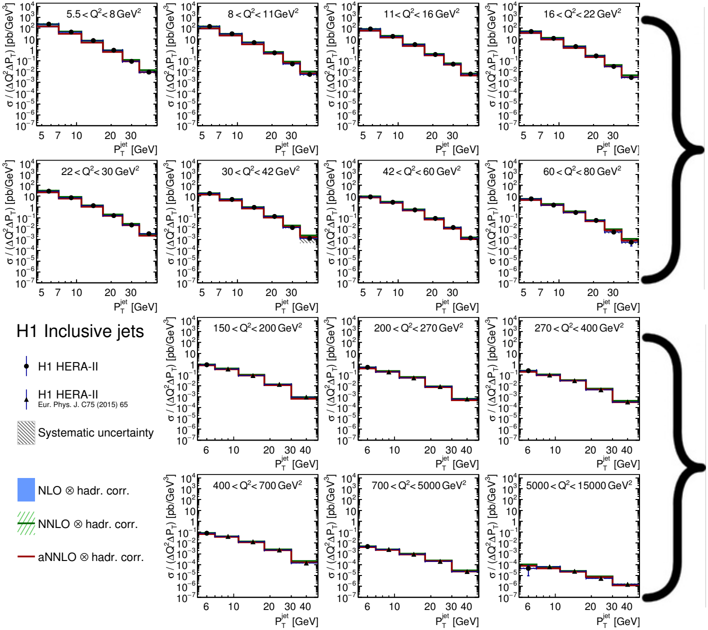
- Jets are reconstructed using k_T algorithm
- Phase space:

DIS:	$5.5 < Q^2 < 80$ GeV^2 $0.2 < y < 0.6$
inclusive jets	$4.5 < p_T^{\text{jet}} < 50$ GeV $-1.0 < \eta^{\text{lab}} < 2.5$
dijets	$5.0 < \langle p_T^{\text{jet}} \rangle_2 < 50$ GeV
trijets	$5.5 < \langle p_T^{\text{jet}} \rangle_3 < 40$ 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

$5.5 < Q^2 < 80$ GeV^2
$0.2 < y < 0.6$

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

[EPJ C77 (2017) 215]

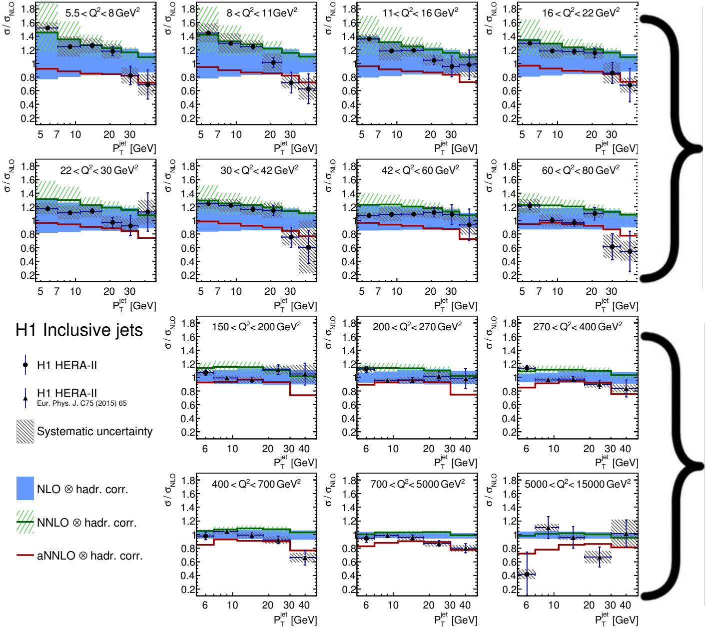
- *High precision data over the whole kinematic range!*
- *Good description by QCD predictions*

$150 < Q^2 < 15000$ GeV^2
$0.2 < y < 0.7$

$5 < p_T^{\text{jet}} < 50$ GeV
$-1.0 < \eta^{\text{lab}} < 2.5$

[EPJ C75 (2015) 65]

H1 inclusive jets: comparison to theoretical predictions



Ratio to NLO

$5.5 < Q^2 < 80$ GeV^2
$0.2 < y < 0.6$
$4.5 < p_T^{\text{jet}} < 50$ 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*

$150 < Q^2 < 15000$ GeV^2
$0.2 < y < 0.7$
$5 < p_T^{\text{jet}} < 50$ GeV
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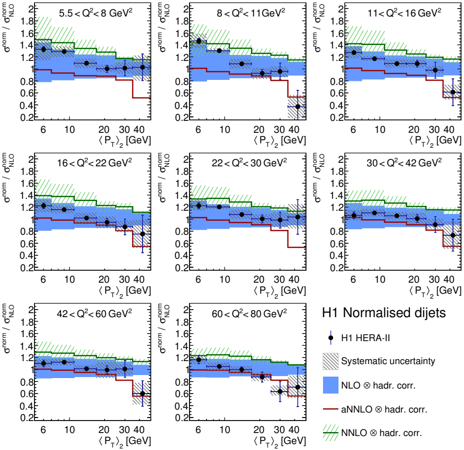
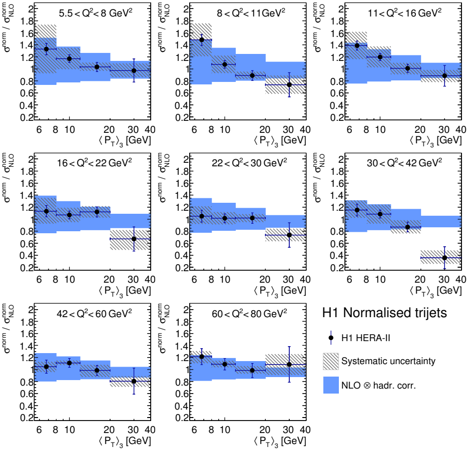
[EPJ C75 (2015) 65]

H1 multijets normalised to NC DIS

Dijets / NC DIS / NLO



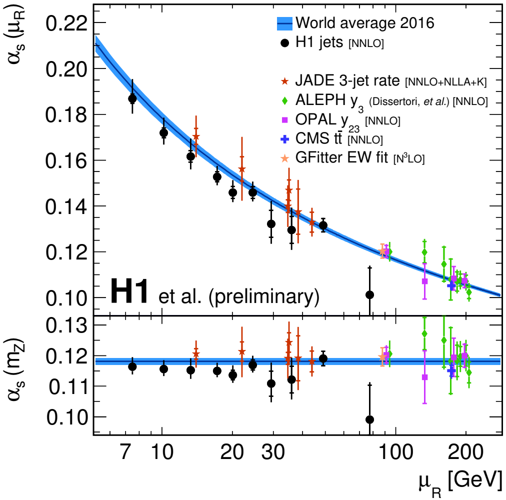
Trijets / NC DIS / NLO

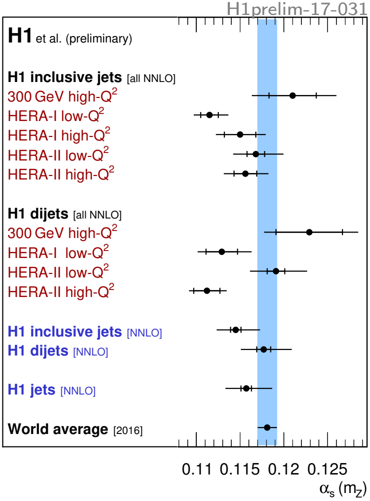


- Experimental systematic unc. partially cancel in ratio Jets / NC DIS
- Improved description of dijets shape by **NNLO calculations**

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: $\chi^2/n_{\mathrm{dof}} = 1.03$, $n_{\mathrm{dof}} = 203$

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

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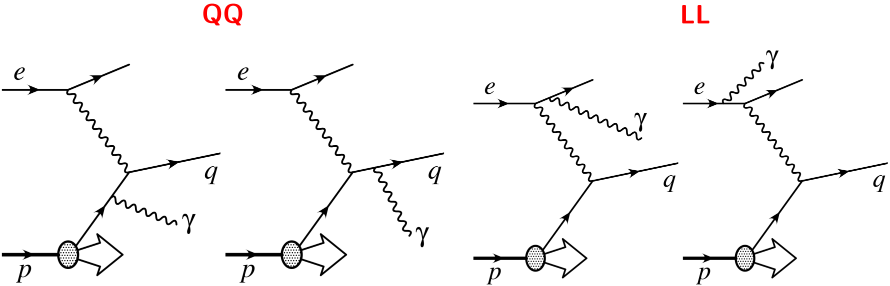
ZEUS isolated photons in DIS

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



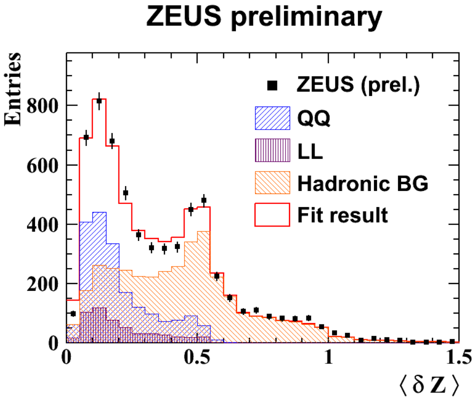
Isolated (prompt) photons can be radiated from:

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

Phase space:

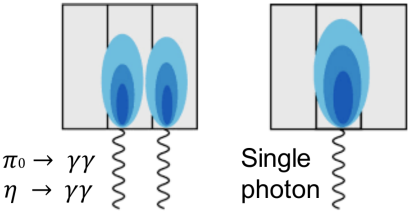
DIS	$10 < Q^2 < 350$ GeV^2
γ	$4 < E_T^\gamma < 15$ GeV $-0.7 < \eta^\gamma < 0.9$
jet	$2.5 < E_T^{\rm jet} < 35$ GeV $-1.5 < \eta^{\rm jet} < 1.8$

ZEUS isolated photons in DIS: signal/background separation



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

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

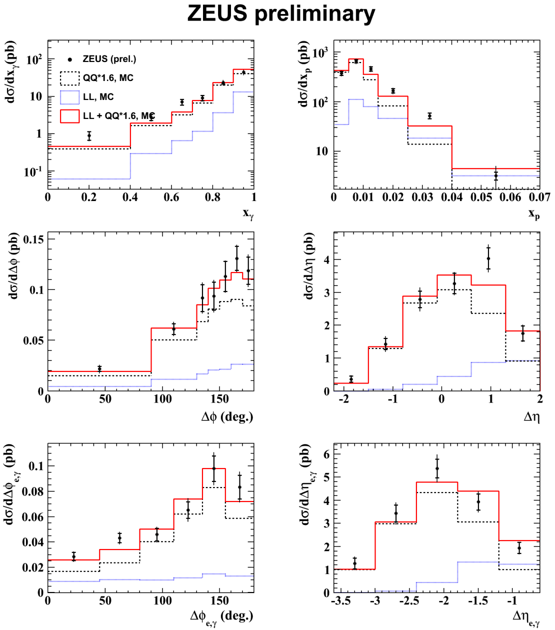


$\pi_0 \rightarrow \gamma\gamma$
$\eta \rightarrow \gamma\gamma$

Single photon

⇒ 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



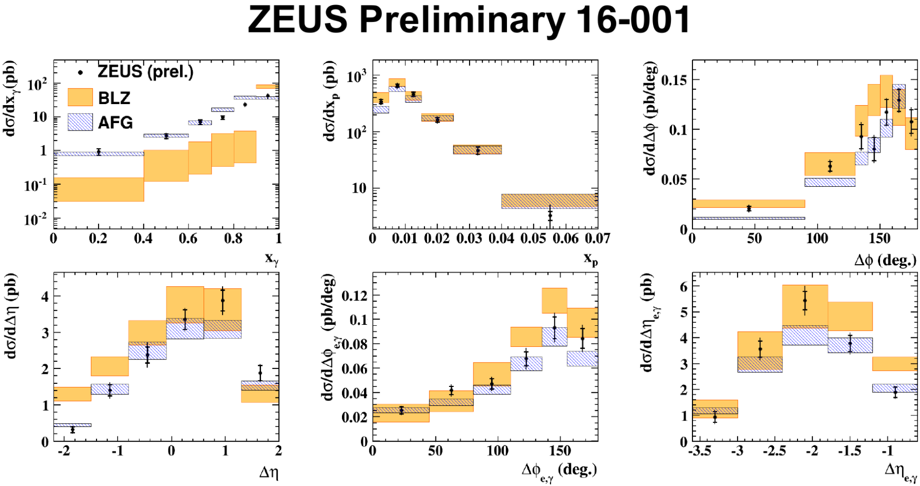
Djangoh (LL) + Pythia (QQ):

- QQ contrbution 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 isolated photons in DIS: comparison to QCD predict.



- 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

Summary

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
- successfull 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
- worser agreement with k_T-factorisation predictions

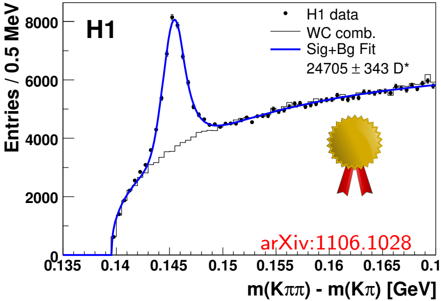
[ZEUS-prel-16-001]

H1 and ZEUS continue producing valuable QCD results after $\mathbf{10}$ *years of HERA shutdown!*

BACKUP

BACKUP. Measurement of charm production at HERA

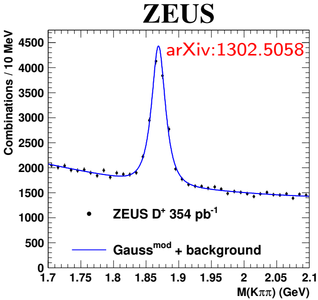
"Golden" decay channel $D^* \to D^0(K\pi)\pi_s$

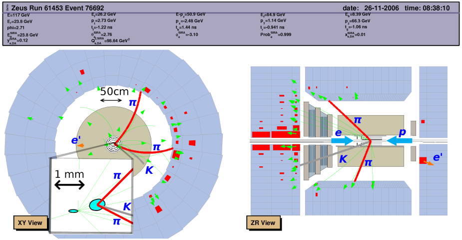


Dedicated H1ZEUS combination:

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

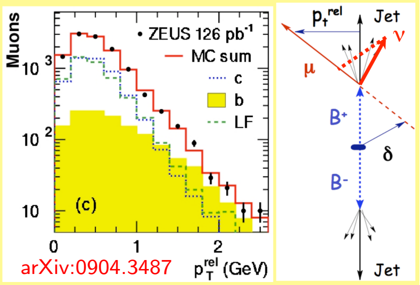
Weakly decaying charm hadrons





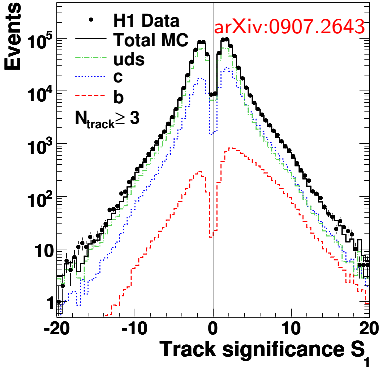
BACKUP. Measurement of c and b production at HERA

Semi-leptonic (SL) HQ decays



arXiv:0904.3487

Inclusive lifetime tagging



arXiv:0907.2643

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** $\sigma_{\mathrm{red}}^{c\bar{c}}$, $\sigma_{\mathrm{red}}^{b\bar{b}}$
  $\sigma_{\mathrm{red}}^{Q\bar{Q}} = \frac{\mathrm{d}^2\sigma^{Q\bar{Q}}}{\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}Q^2} \cdot \frac{x_{\mathrm{Bj}}Q^4}{2\pi\alpha^2\,(1+(1-y)^2)}$ (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
- ⇒ **significant improvement in precision** via cross calibration of different measurement techniques and c/b

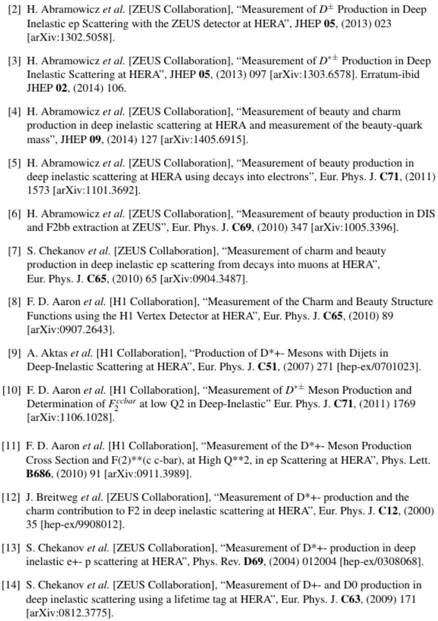
Combined using HERAverager program

[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]

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

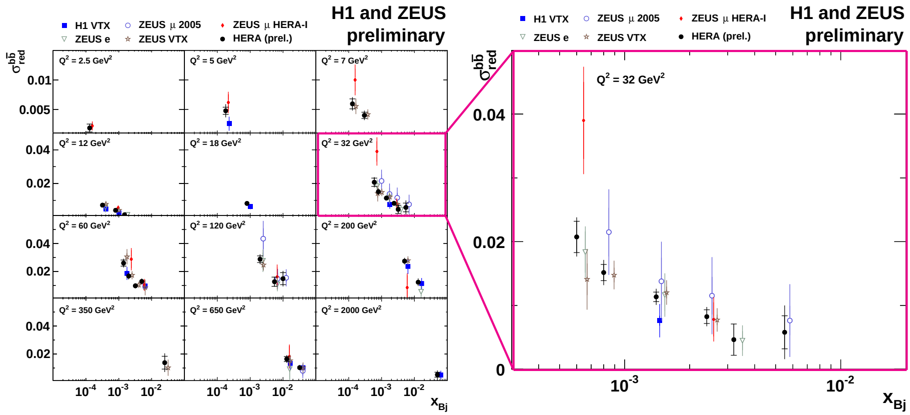
  consistent with extracted from data: $m_c = 1.43 \pm 0.04$ GeV, $m_b = 4.35 \pm 0.11$ GeV

  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. Combined data

BEAUTY



Significantly improved precision compared to input measurements

BACKUP. Data combination

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

Minimised in iterative procedure

BACKUP. Theoretical predictions compared to data

Predictions calculated with OPENQCDRAD interfaced in xFitter

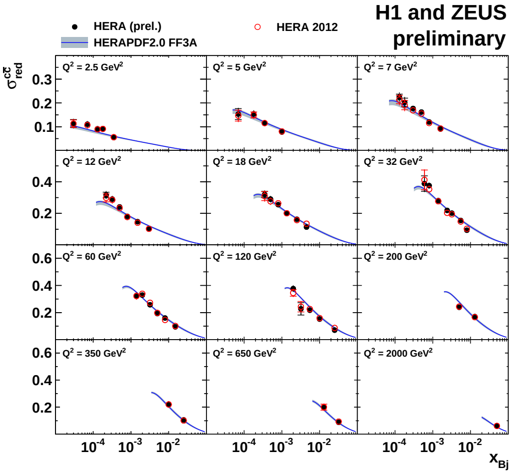
www-zeuthen.desy.de/∼alekhin/OPENQCDRAD

`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

CHARM



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

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

BACKUP. Theoretical predictions compared to data

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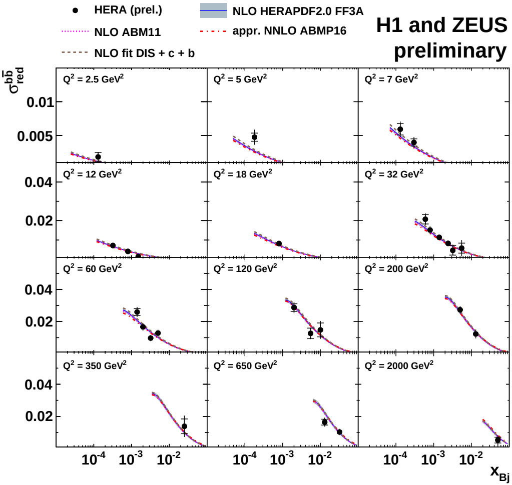
FFN scheme, $n_f = 3$: reliable in this kinematic range

BEAUTY



Overall good description within data uncertainties

BACKUP. Theoretical predictions compared to data

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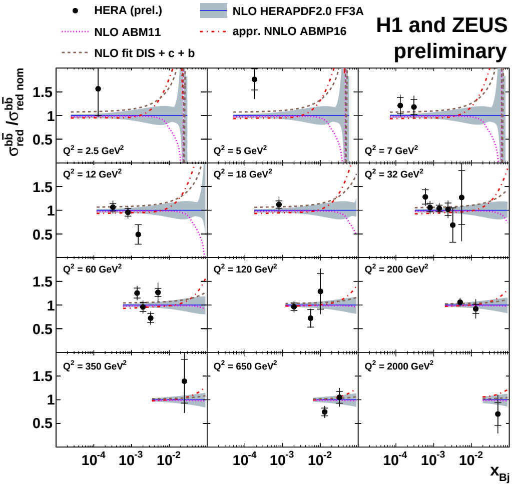
- $m_c(m_c) = 1.27 \pm 0.03$ GeV, $m_b(m_b) = 4.18 \pm 0.03$ GeV [PDG2016], or fitted

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

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]	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

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, $Q^2_{\text{min}} > 3.5$ 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, $f_s = 0.4$:

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

Additional constrains:

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

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

BACKUP. Discussion of HQ mass extraction

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

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

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 (→ 13p):

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

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

13p: $E_{u_v} = 0$

⇒ inclusive HERA data alone cannot constrain HQ masses

⇒ interplay of PDFs and HQ masses needs carefull treatment

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

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