Combined measurement of charm and beauty production in DIS and extraction of m_c and m_b

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for the H1 and ZEUS collaborations (+extensions)

Low-x 2017
Bari, Italy
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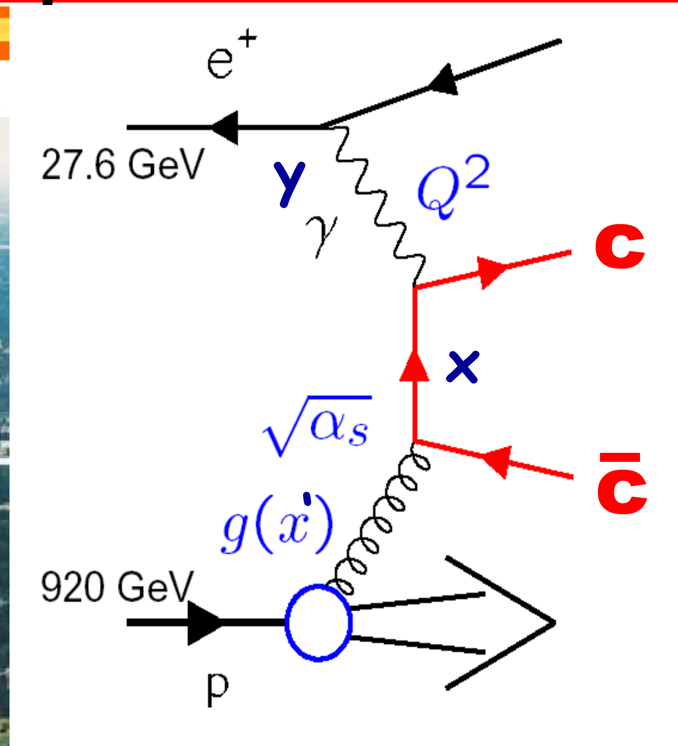
- **Introduction**
- **HERA charm and beauty data combination**
- **Charm and beauty mass fits**
- **Running of masses and Yukawa couplings**
- **Conclusions**

H1prelim-17-071, ZEUS-prel-17-001

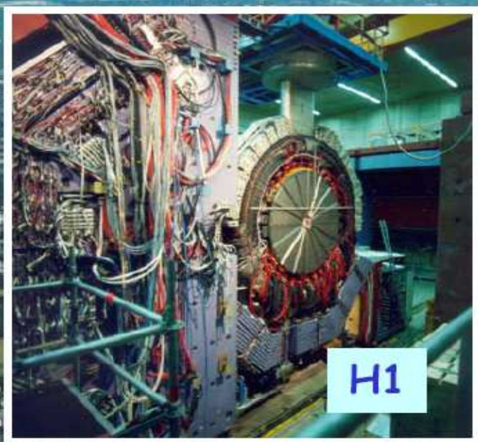
compare also talk O. Zenaiev DIS17

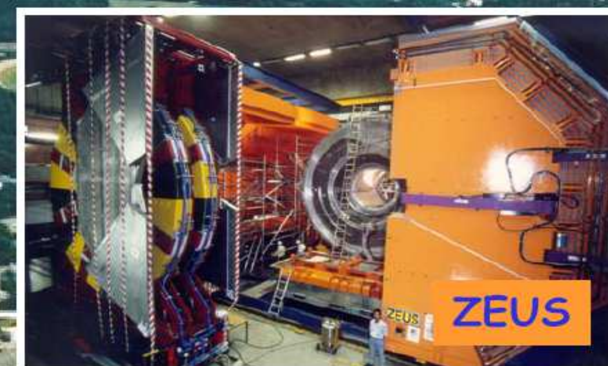
arXiv:1705.08863, PoS CHARM2016 (2017) 012

The HERA ep collider and experiments



up to 30% of cross section



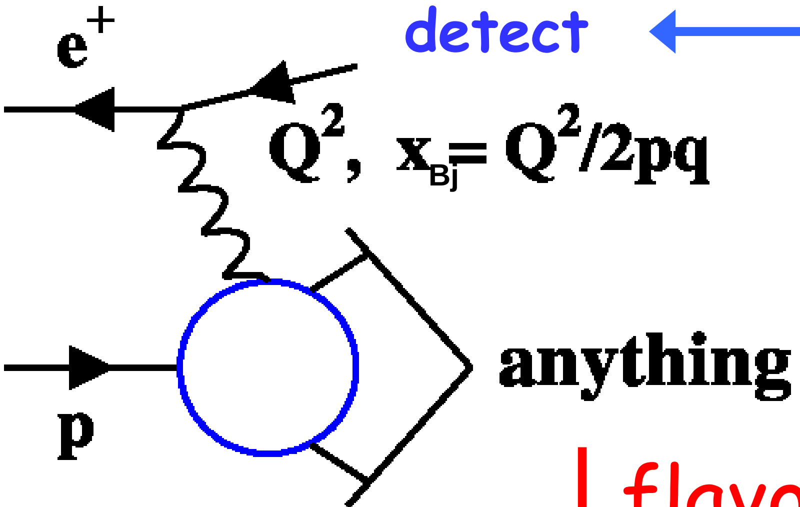


HERA I: ~ 130 pb^{-1} (physics)

HERA II: ~ 380 pb^{-1}(physics)

combined: ~ 2 x 0.5 fb^{-1}

Heavy flavour contributions to DIS

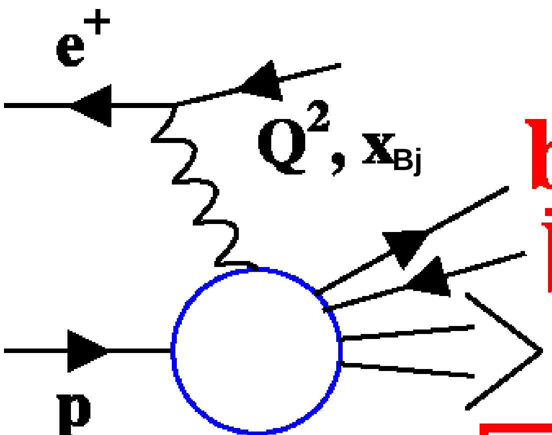


detect ↔

Measure cross section

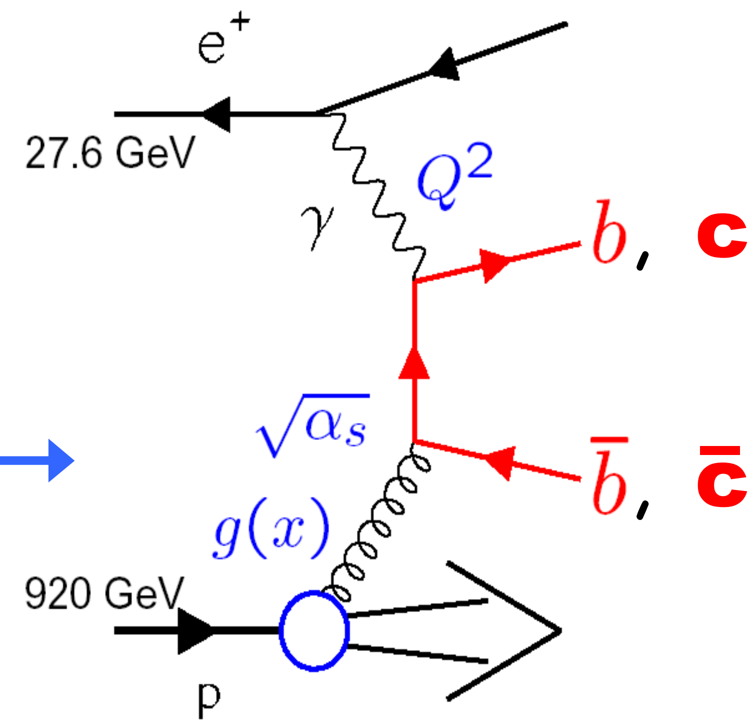
$$\frac{d^2\sigma}{dx_{Bj}dQ^2} \simeq \frac{2\pi\alpha^2}{Q^4 x_{Bj}} \cdot \left[1+(1-y)^2\right] \; \sigma_{red}$$

flavour tagging (e.g. D*)



b $\bar{b}$ or c $\bar{c}$

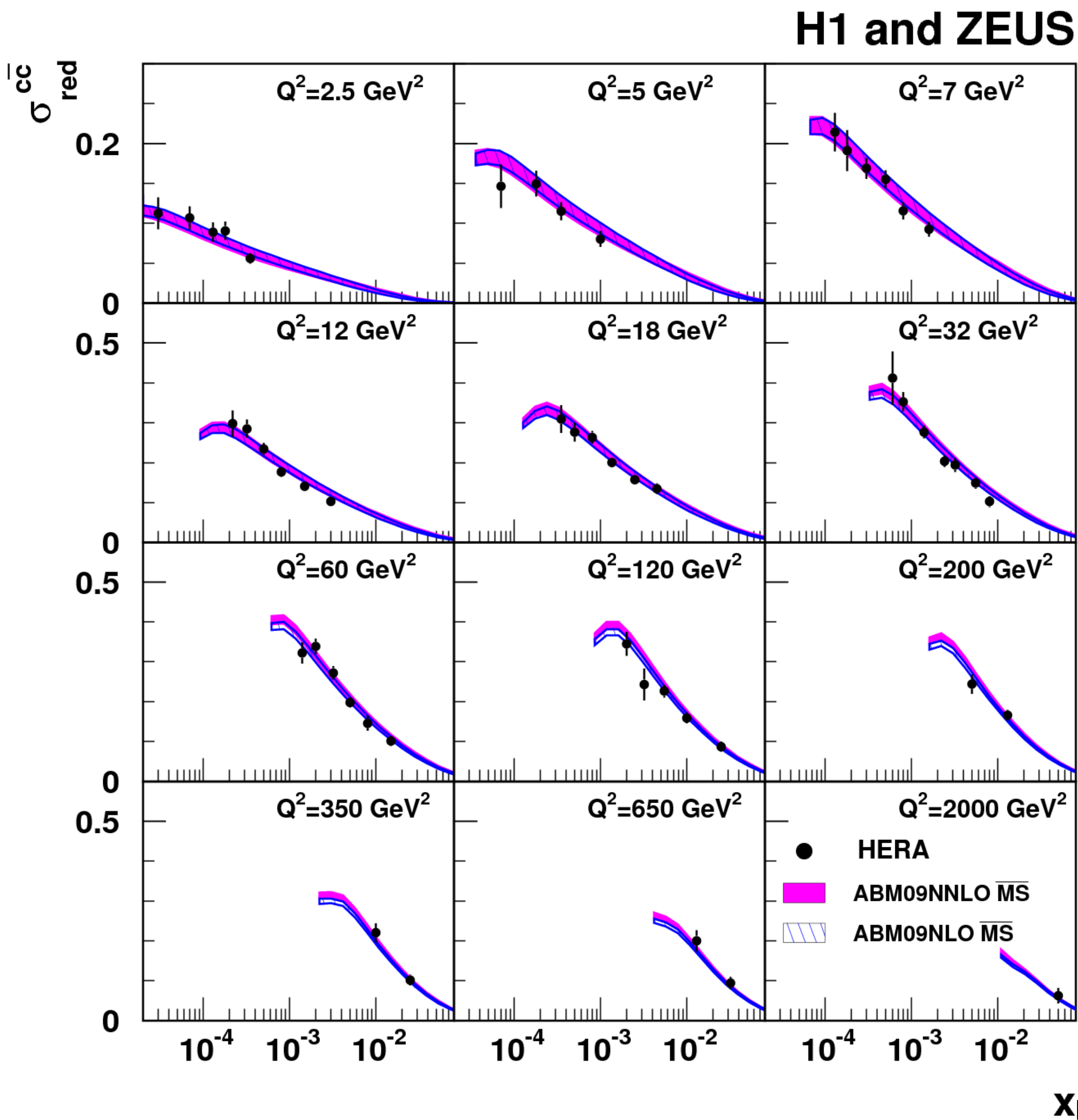
QCD ↔



-> $P_T(D^*)$, etc.

Combination of inclusive charm data

Reminder:



EPJ C73 (2013) 2311

9 data sets,
5 tagging methods

very good description of combined data by fixed flavour predictions in full kinematic range, small theory uncertainties

measure charm mass

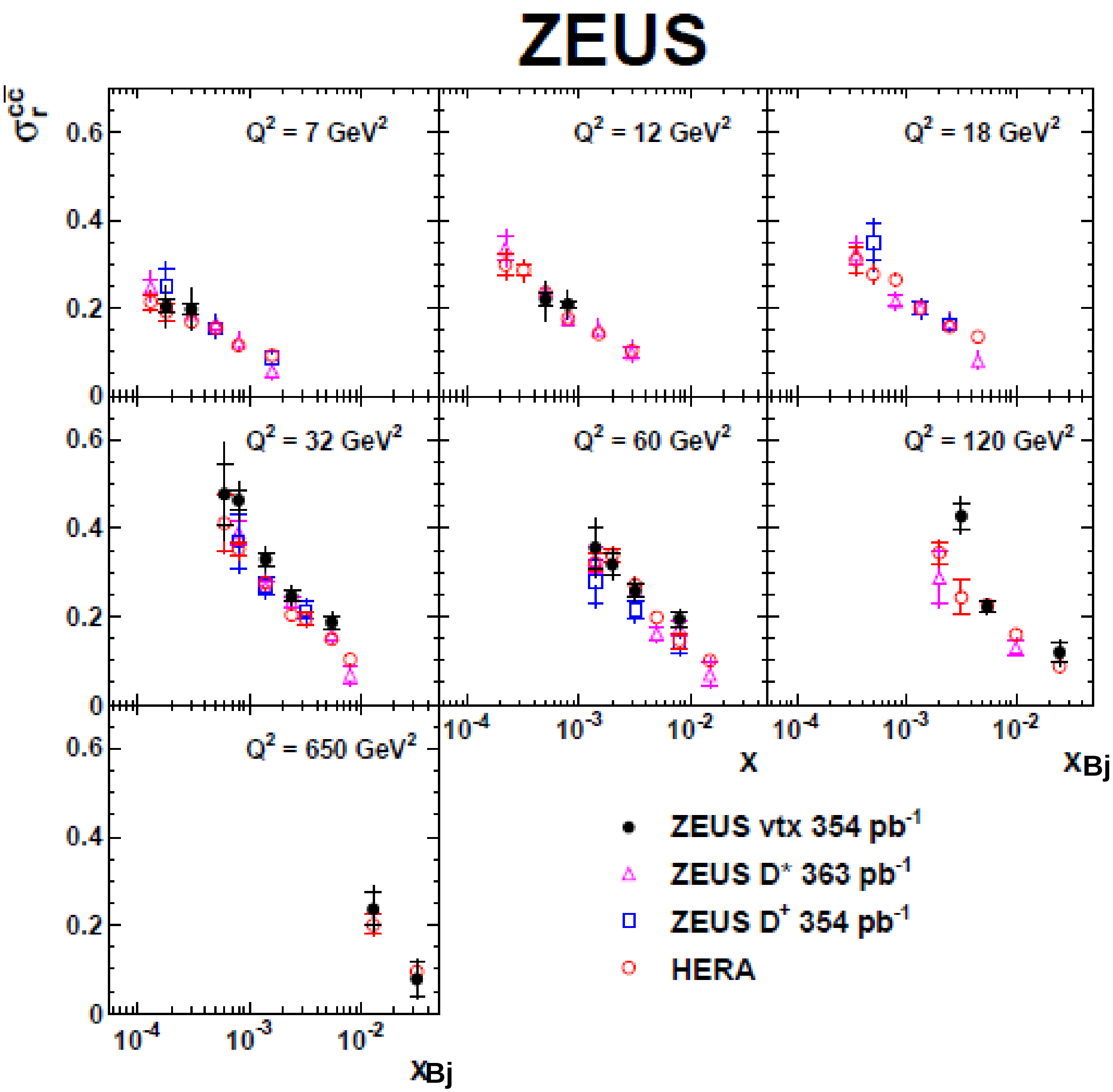
$m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{\alpha s}$ GeV

PDG: 1.27 ±0.03 GeV
(lattice, …)

Further charm results in DIS: D*, D^+, vtx

JHEP 05 (2013) 023
JHEP 05 (2013) 097
JHEP 1409 (2014) 127

Reminder:



→ completes HERA measurements

→ consistent findings

→ will further improve combination, PDF and m_c fits

→ recombine H1 and ZEUS

and add beauty, including c-b-correlations

Data sets to be combined

H1prelim-17-071, ZEUS-prel-17-001

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^+ removed)**	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

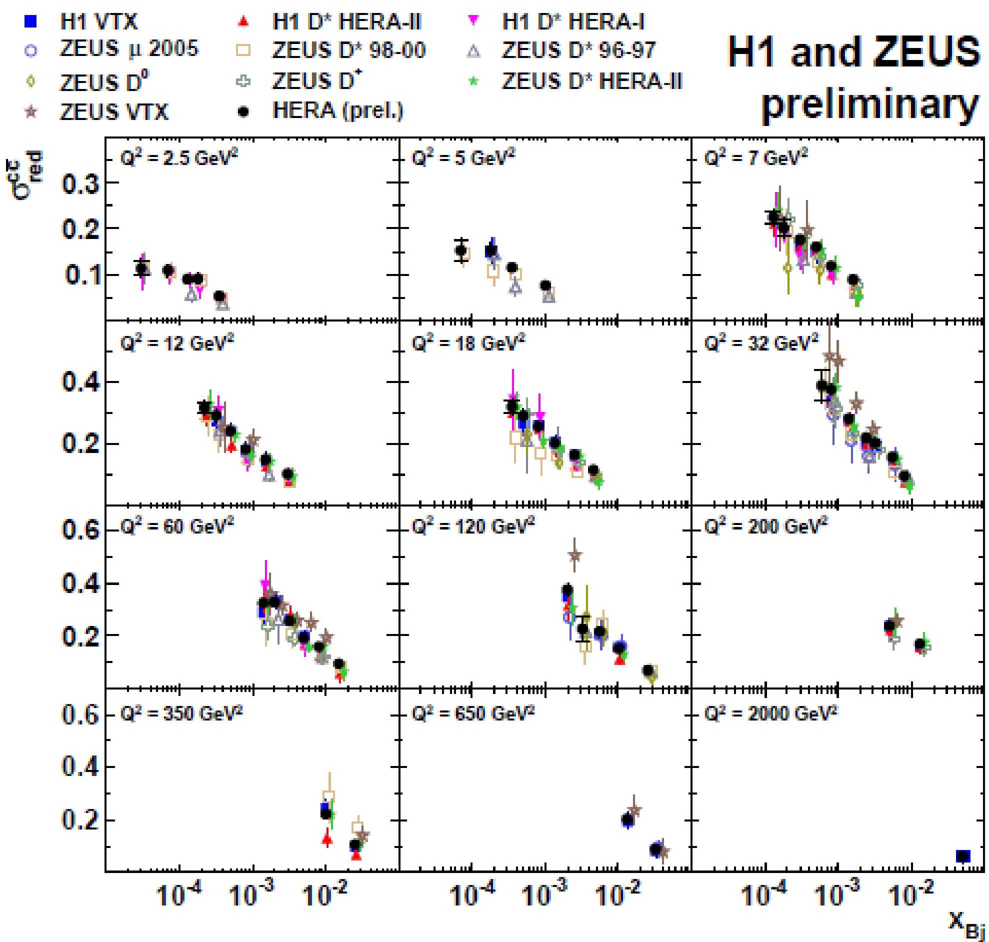
new points added

- 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 ⇒ combined 52 c, 27 b points

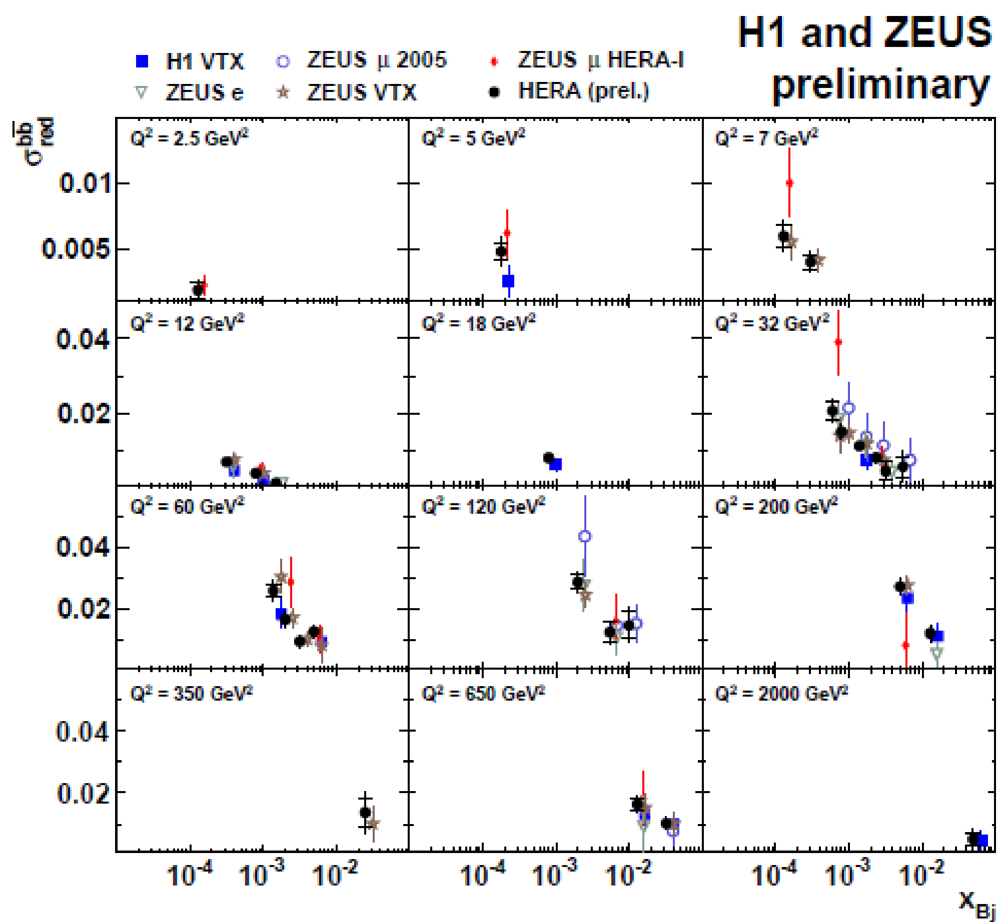
Combined data

H1prelim-17-071, ZEUS-prel-17-001

CHARM



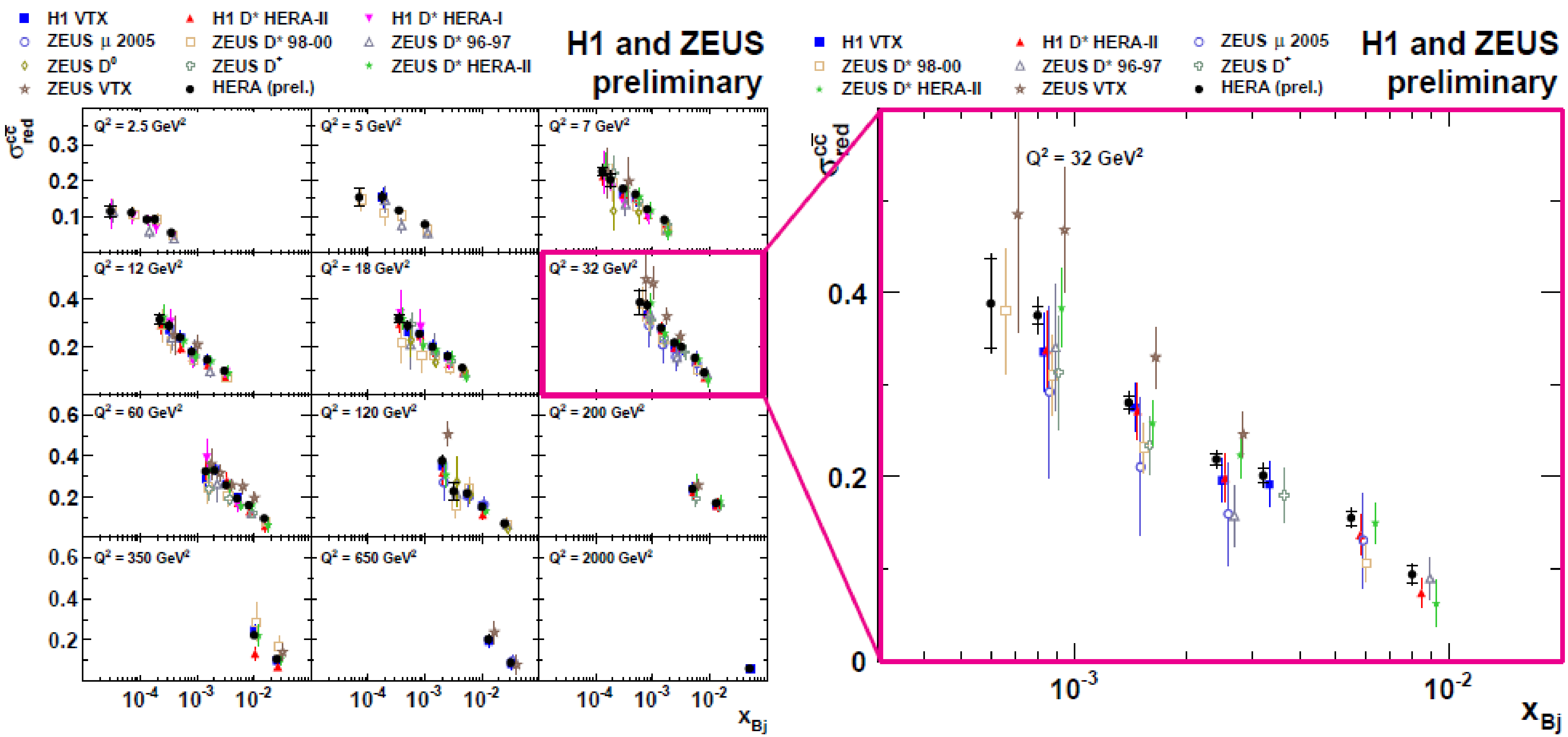
BEAUTY



χ^2/dof = 149/187, including correlations: input data are consistent

Charm

H1prelim-17-071, ZEUS-prel-17-001

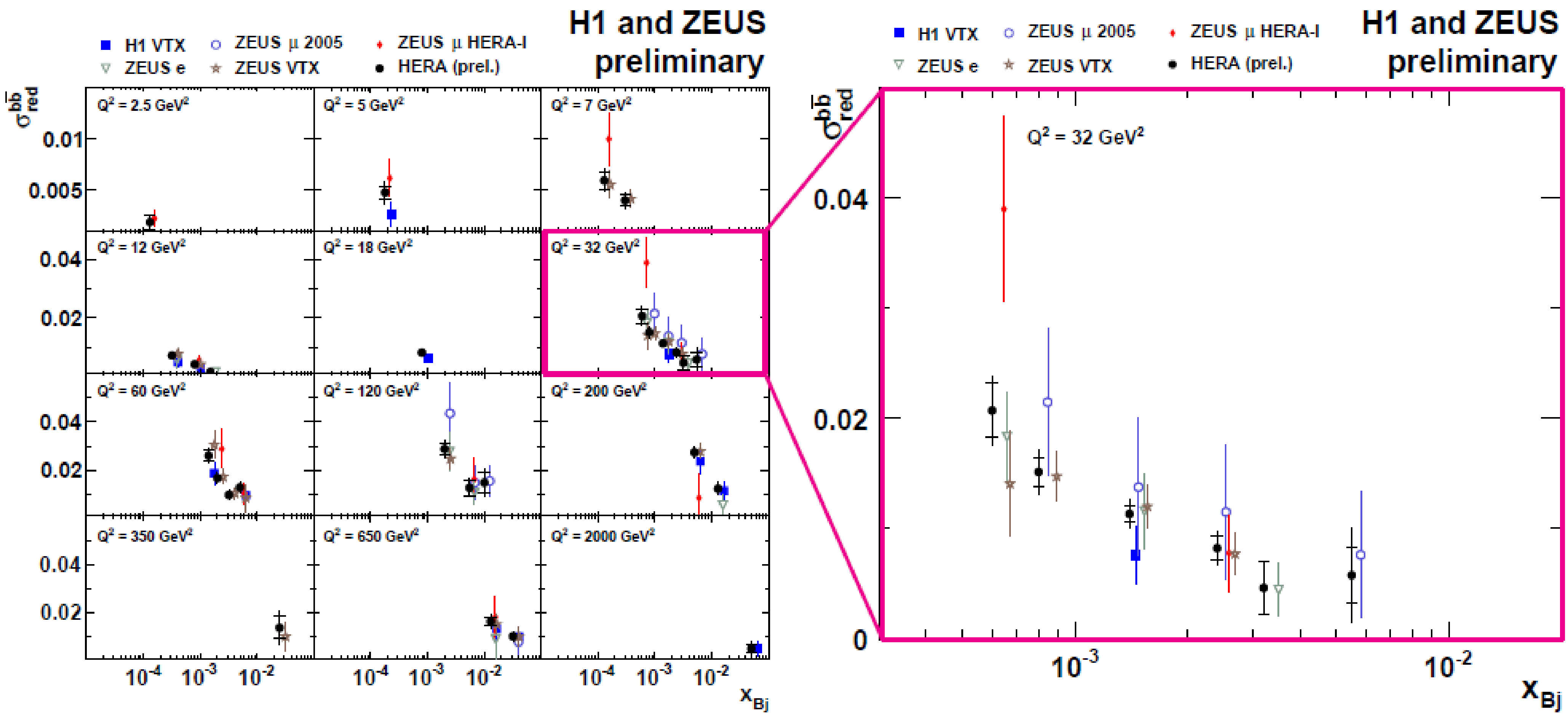


significantly improved precision compared to individual measurements

noticeably (up to ~20%) improved precision compared to previous charm combination, final HERA combination

Beauty

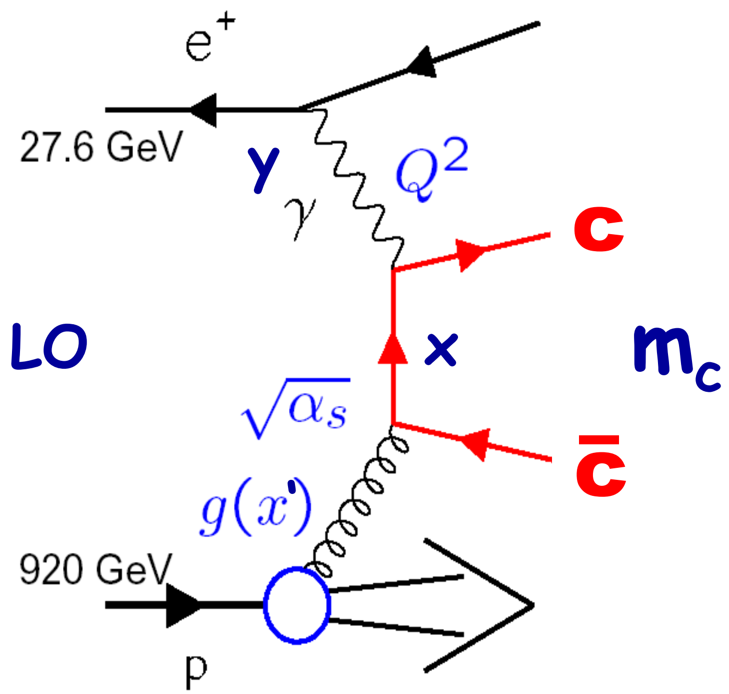
H1prelim-17-071, ZEUS-prel-17-001



significantly improved precision compared to individual measurements

first (and final) HERA beauty DIS combination

Fixed Flavour Number Scheme (FFNS)



+ NLO (+partial NNLO) corrections,

"natural" scale:
$\mu^2 = Q^2 + 4m_c^2$

- no charm in proton
- full kinematical treatment of charm mass ☺
  (multi-scale problem: Q^2, p_T, m_c -> logs of ratios)
- no resummation of logs ☹
- no extra matching parameters ☺

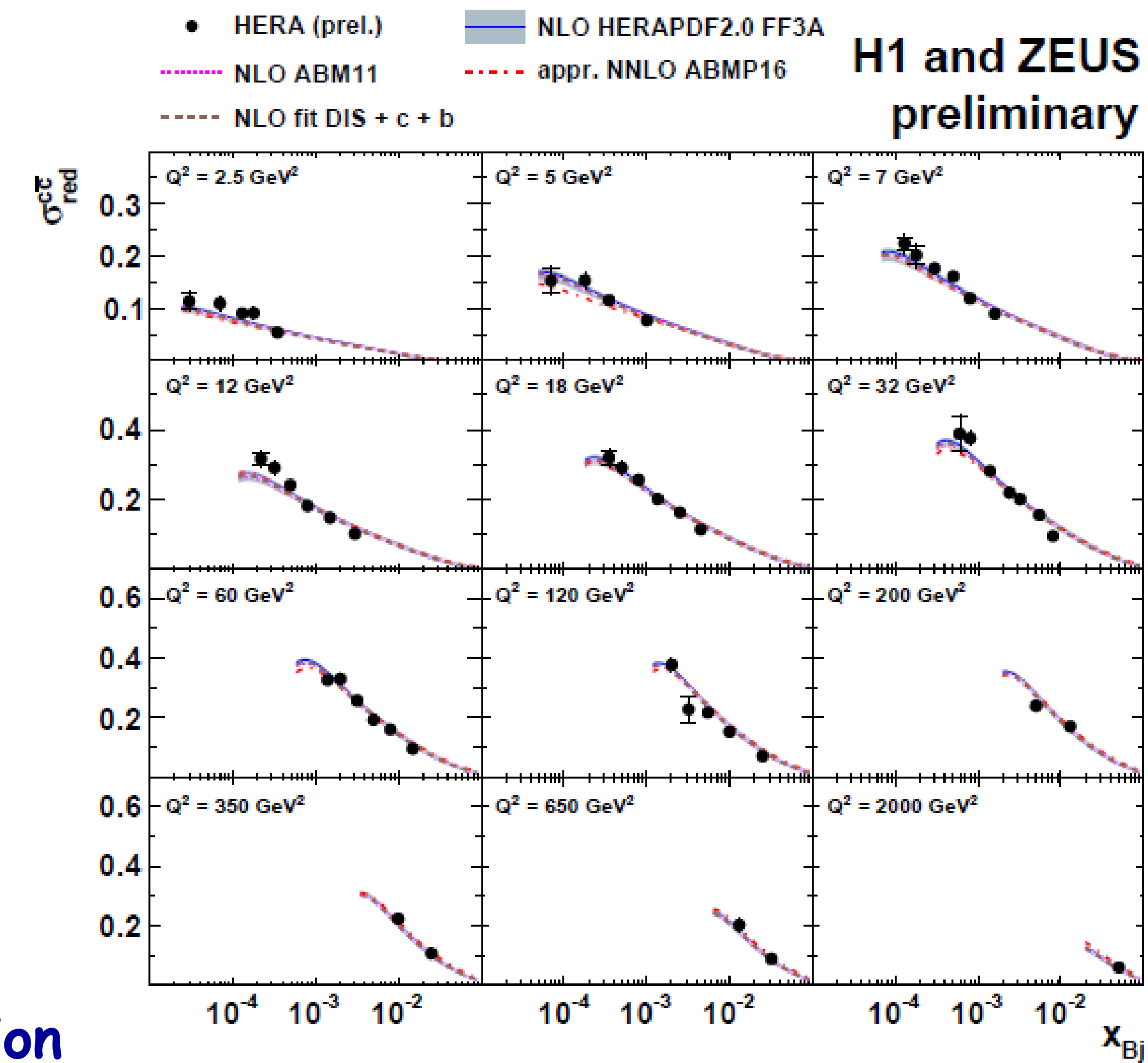
Theoretical predictions vs. charm

H1prelim-17-071, ZEUS-prel-17-001

Theoretical predictions calculated using xFitter

[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



overall reasonable description

x_{Bj} slope shallower in theory than in data at low and medium Q^2

Comparison to previous combination: charm

H1prelim-17-071, ZEUS-prel-17-001

Theoretical predictions calculated using xFitter

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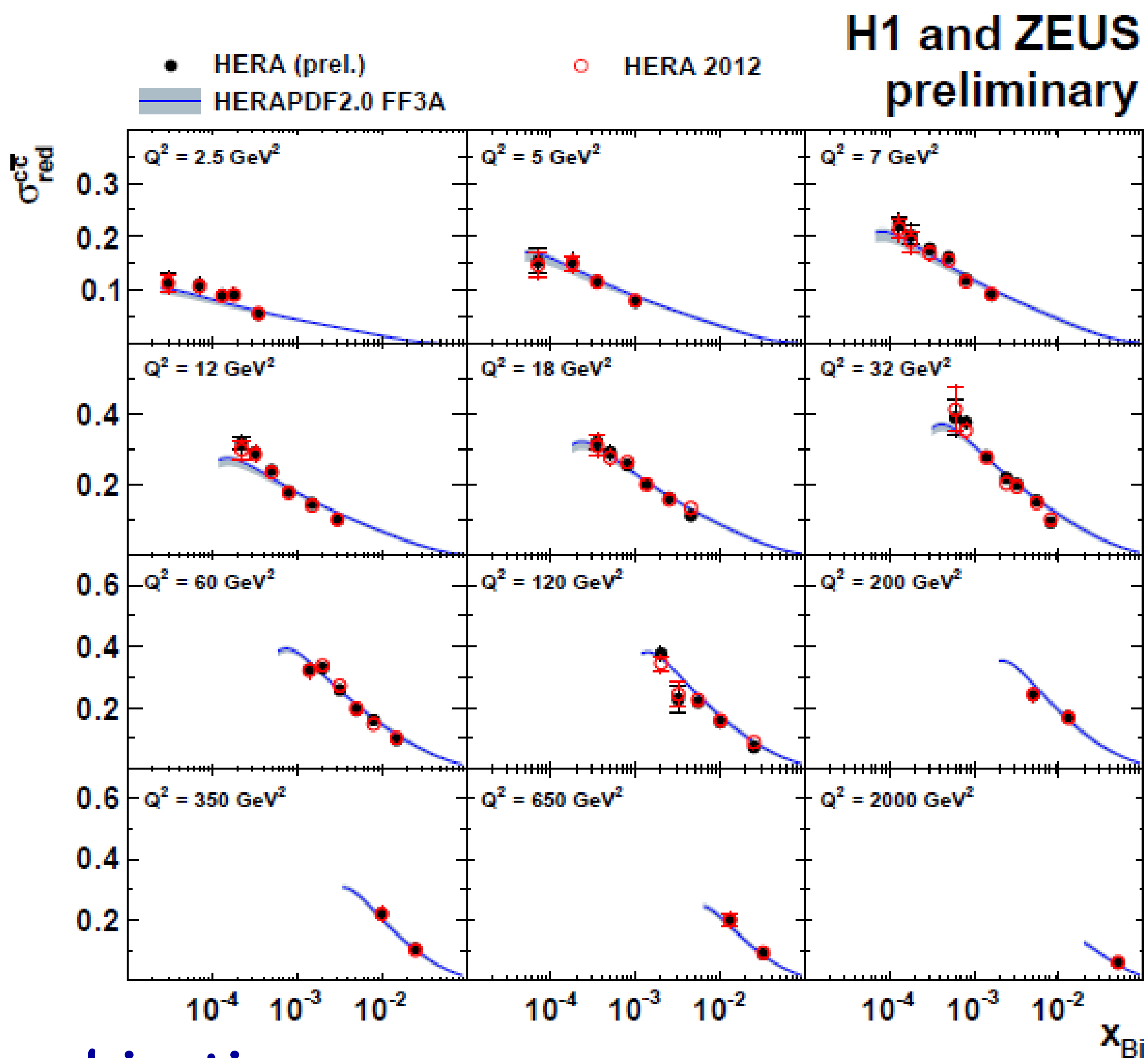


same effect as in previous combination, reduced uncertainty -> effect more visible

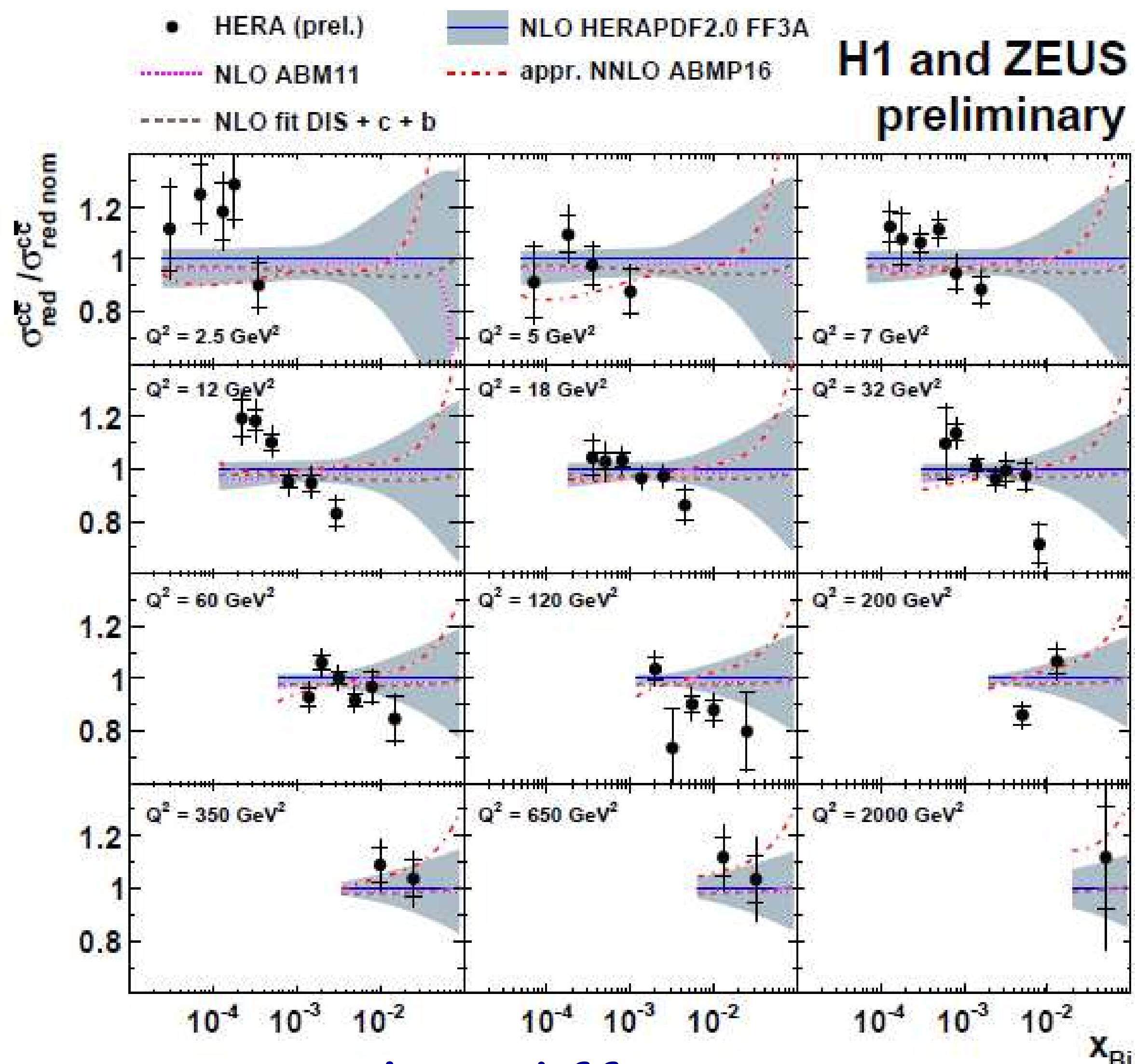
Ratio data/predictions, charm

H1prelim-17-071, ZEUS-prel-17-001

Theoretical predictions calculated using xFitter

[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



overall reasonable description, some x_{Bj} slope differences (as before)
approximate NNLO does not improve description

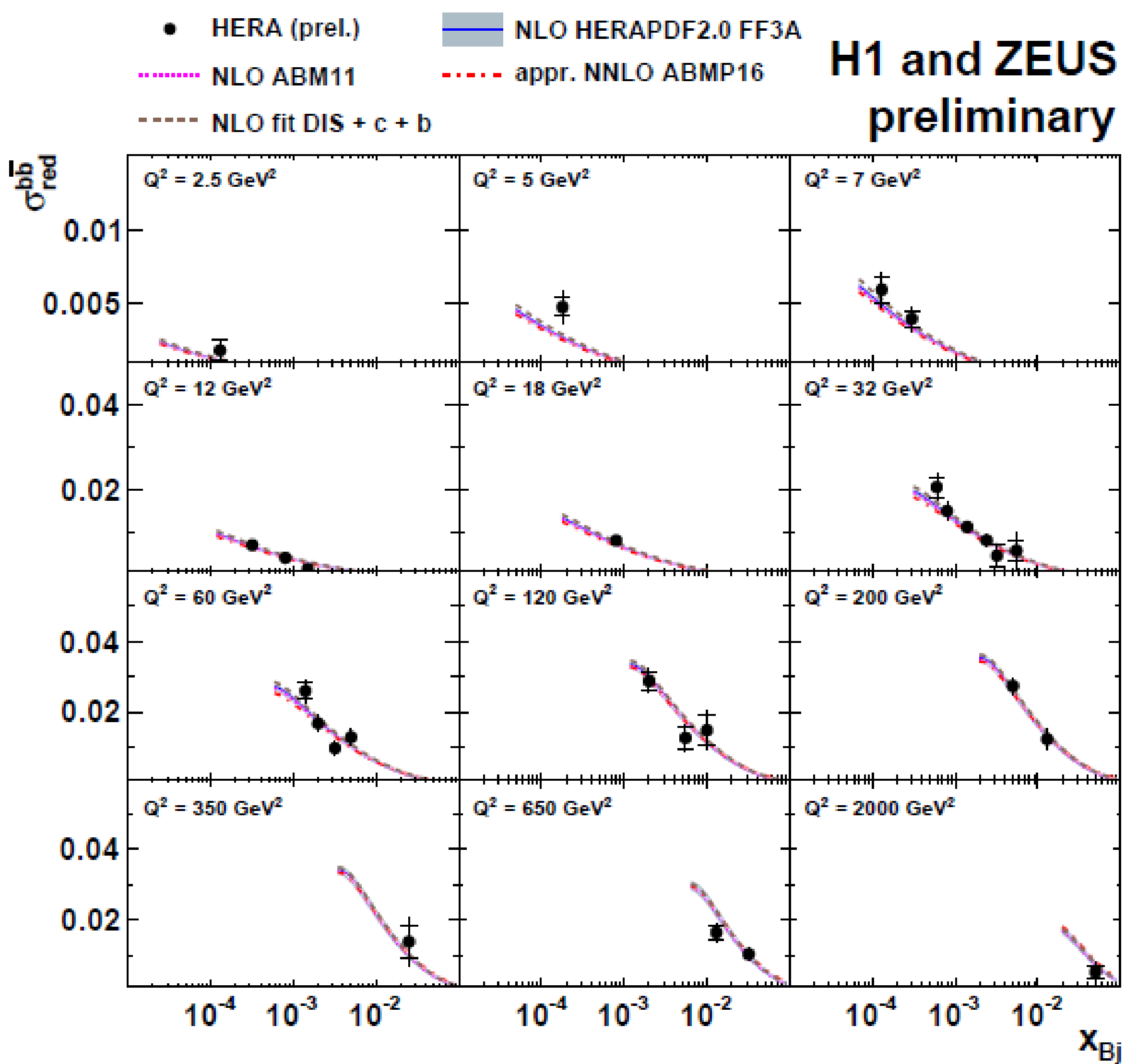
Theoretical predictions vs. beauty

H1prelim-17-071, ZEUS-prel-17-001

Theoretical predictions calculated using xFitter

[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



overall good description
(larger data uncertainties, smaller x_{Bj} range)

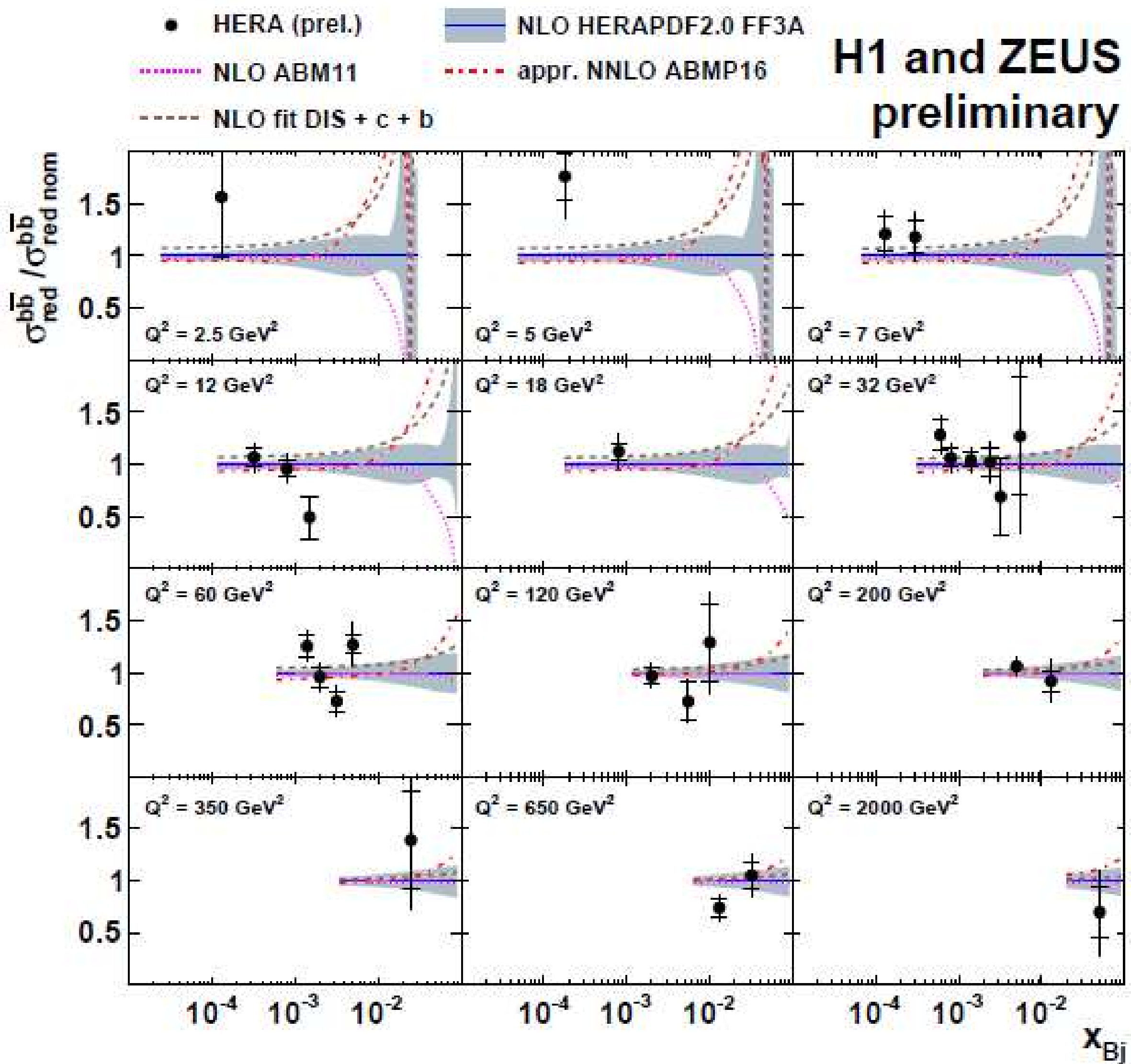
Ratio data/predictions, beauty

H1prelim-17-071, ZEUS-prel-17-001

Theoretical predictions calculated using xFitter

[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



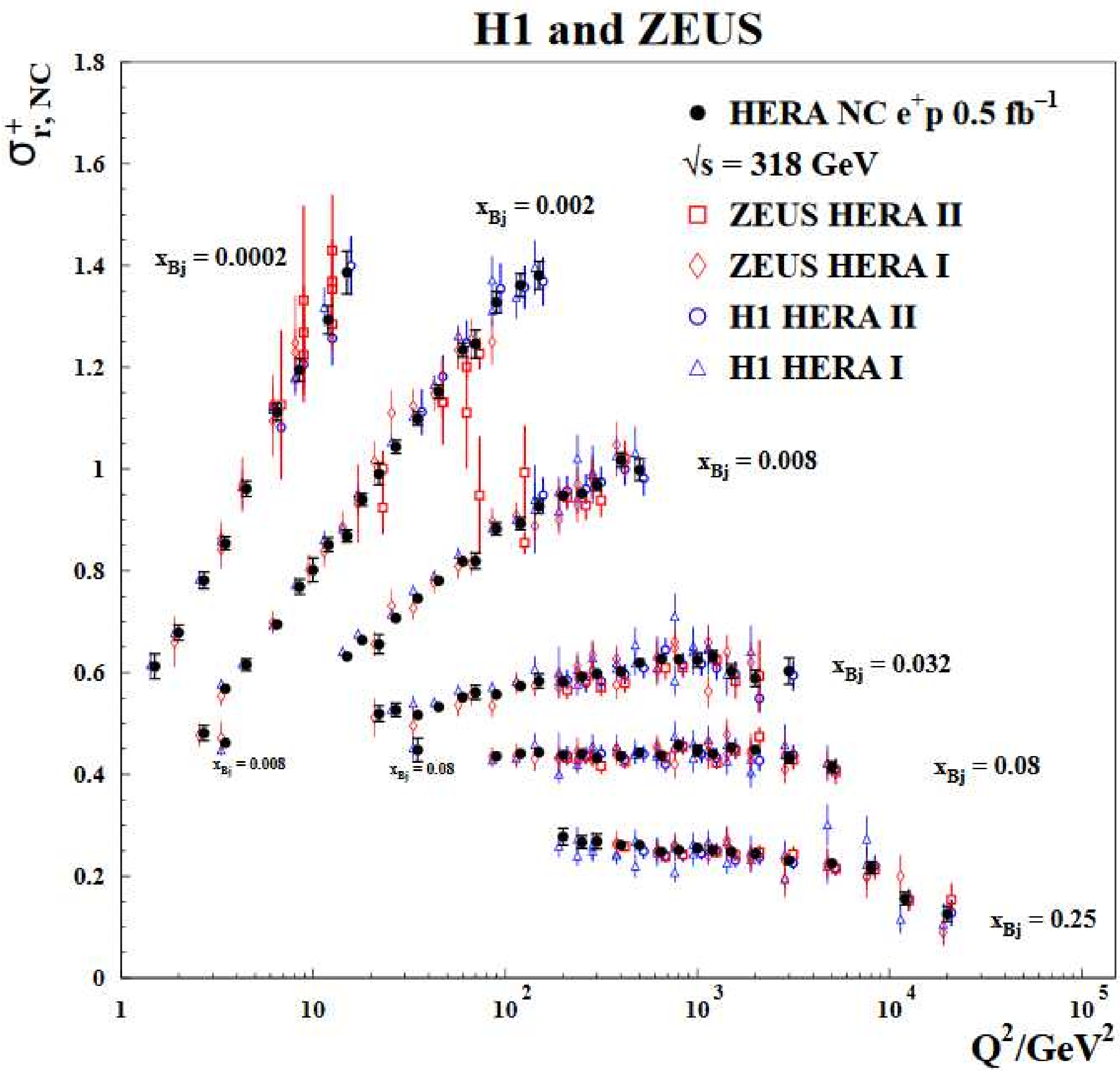
overall good description

approx. NNLO corrections + PDF effects are small in measured range

Combined inclusive HERA II DIS data

EPJC 75 (2015) 580

example:



use for overall QCD analysis

QCD analysis of combined charm, beauty and inclusive DIS 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

Check: fit inclusive DIS data only

H1prelim-17-071, ZEUS-prel-17-001

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

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

somewhat unphysical ...

No full uncertainty evaluation, but large sensitivity to PDF parametrisation observed:

$m_c(m_c) = 1798 \rightarrow 1450\ \text{MeV},\ m_b(m_b) = 8450 \rightarrow 3995\ \text{MeV}$
in 13p reduced parametrisation

recover ~ physical values!
(PDG: 1270 and 4180 MeV)

-> inclusive data alone can not reliably constrain HQ masses

-> can yield bias (see also arXiv:1605.01946, JHEP 1608 (2016) 050),
interplay between PDFs and HQ masses needs careful treatment

-> use difference between 13p and 14p parametrisations as additional systematic uncertainty

Fit inclusive, charm and beauty data

H1prelim-17-071, ZEUS-prel-17-001

measure charm and beauty quark masses in MSbar scheme

improved data precision — now includes scale variations — 13p vs. 14p

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

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

compare previous: EPJ C73 (2013) 2311

$m_c(m_c)$ = 1.26 $\pm 0.05_{exp}$ $\pm 0.03_{mod}$ $\pm 0.02_{\alpha s}$ GeV

$m_b(m_b)$ = 4.07 $\pm 0.14_{fit}$ $^{+0.01}_{-0.07\ mod}$ $^{+0.05}_{-0.00\ par}$ $^{+0.08}_{-0.05\ th}$ GeV

JHEP 1409 (2014) 127

ZEUS vtx only — includes scale

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

significant improvement w.r.t. and consistent with previous H1/ZEUS mass determinations

Comparison with previous $m_c(m_c)$ results

from DIS data

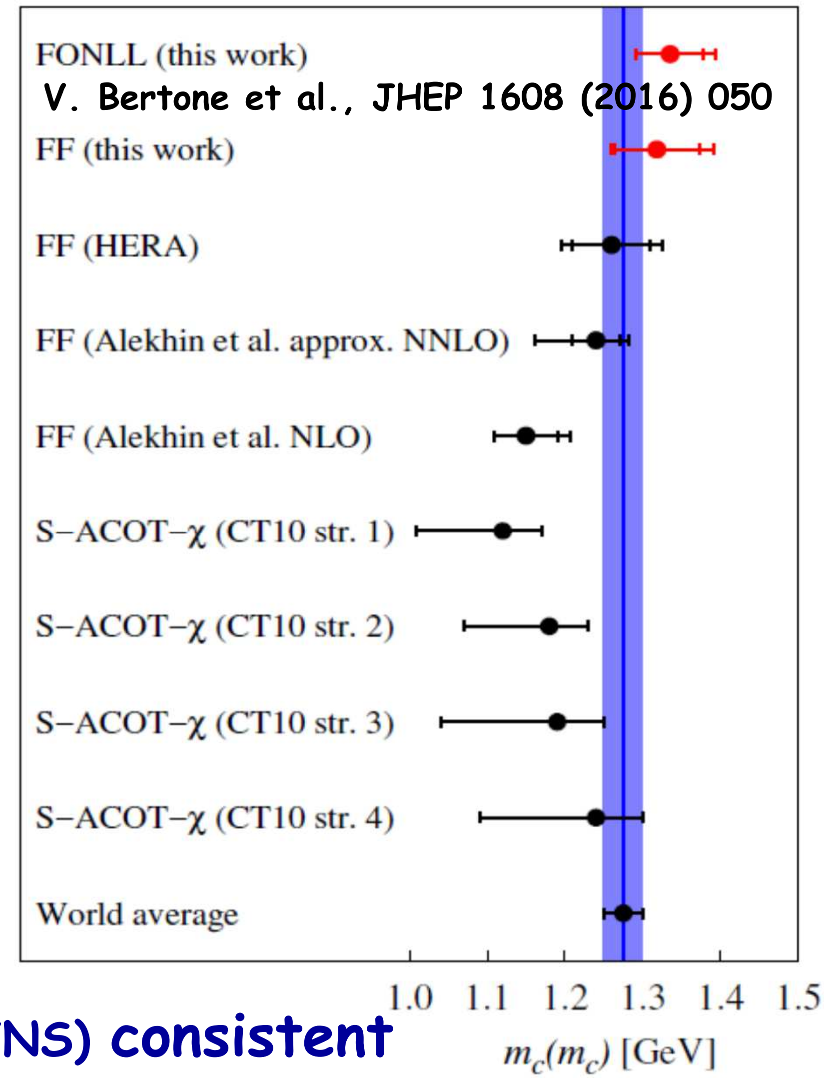
$$m_c(m_c) = 1290^{+46}_{-41}(\text{fit})^{+62}_{-14}(\text{mod})^{+7}_{-31}(\text{par})\ \text{MeV}$$

H1/ZEUS preliminary

scheme	$m_c(m_c)$ [GeV]
FONLL (this work)	$1.335 \pm 0.043(\text{exp})^{+0.019}_{-0.000}(\text{param})^{+0.011}_{-0.008}(\text{mod})^{+0.033}_{-0.008}(\text{th})$
FFN (this work)	$1.318 \pm 0.054(\text{exp})^{+0.011}_{-0.010}(\text{param})^{+0.015}_{-0.019}(\text{mod})^{+0.045}_{-0.004}(\text{th})$
FFN (HERA) [9]	$1.26 \pm 0.05(\text{exp}) \pm 0.03(\text{mod}) \pm 0.02(\text{param}) \pm 0.02(\alpha_s)$
FFN (Alekhin *et al.*) [24]	$1.24 \pm 0.03(\text{exp})^{+0.03}_{-0.02}(\text{scale})^{+0.00}_{-0.07}(\text{th})$ (approx. NNLO)
	$1.15 \pm 0.04(\text{exp})^{+0.04}_{-0.00}(\text{scale})$ (NLO)
S-ACOT-χ (CT10) [29]	$1.12^{+0.05}_{-0.11}$ (strategy 1)
	$1.18^{+0.05}_{-0.11}$ (strategy 2)
	$1.19^{+0.06}_{-0.15}$ (strategy 3)
	$1.24^{+0.06}_{-0.15}$ (strategy 4)
World average [53]	1.275 ± 0.025

ABMP, arXiv:1701.05838
HERA, DY, ttbar and nu fixed target
approx. NNLO
$m_c(m_c)$ = 1.252 $\pm 0.018_{fit}$ GeV (not full uncertainty)

FF (new c/b + HERA II)



all results (NLO, approx. NNLO, FFNS, VFNS) consistent

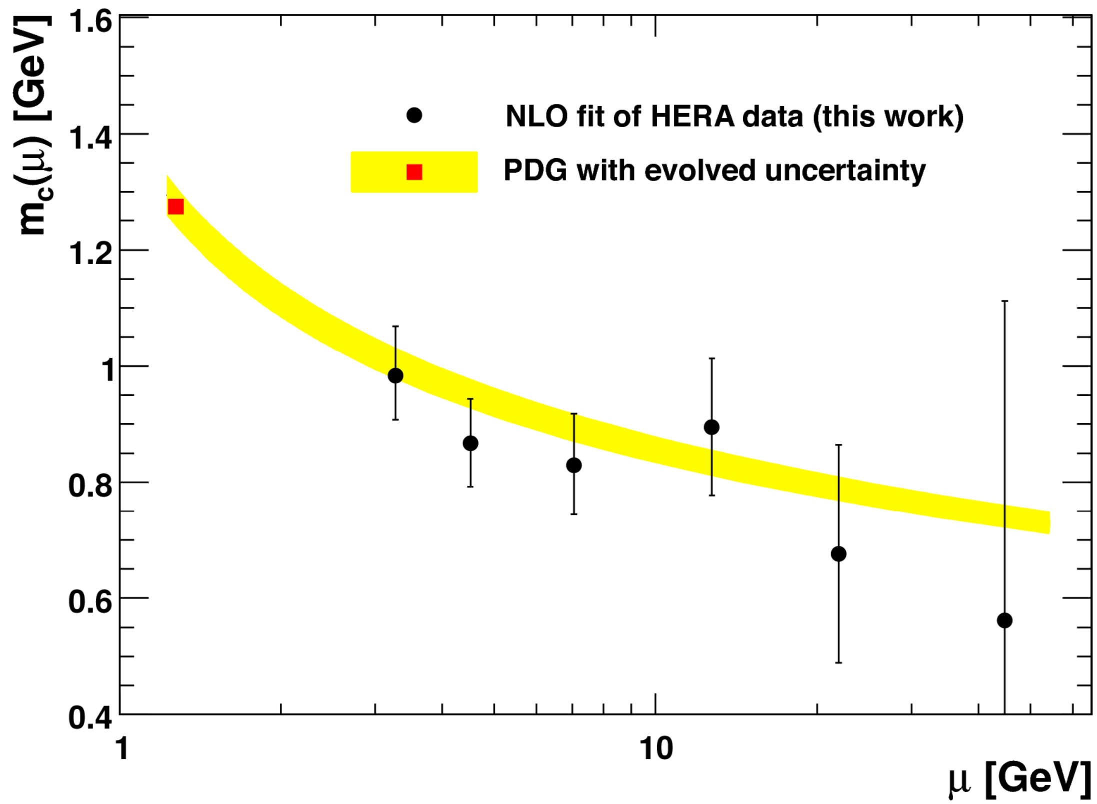
Charm quark mass running

A. Gizhko et al., arXiv:1705.08863

- subdivide (previous) HERA DIS charm data into 6 kinematic intervals, determine running of charm-quark mass in MSbar scheme for the first time (conceptually similar to running of α_s from jets)

- interplay/treatment of correlations between mass and PDF fits nontrivial, details see arXiv:1705.08863

- charm-quark mass running consistent with QCD



see also A.G. DIS17

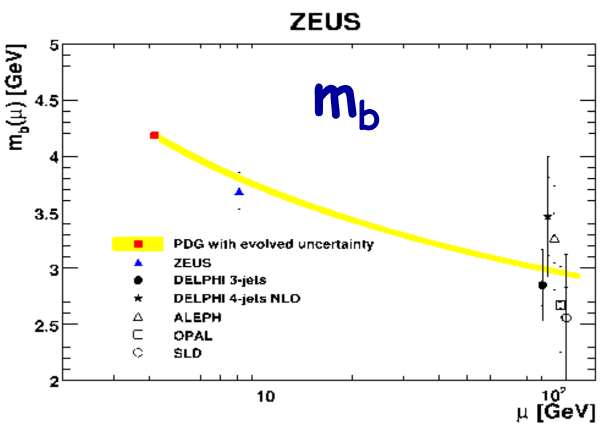
Running of α_s and quark Yukawa couplings

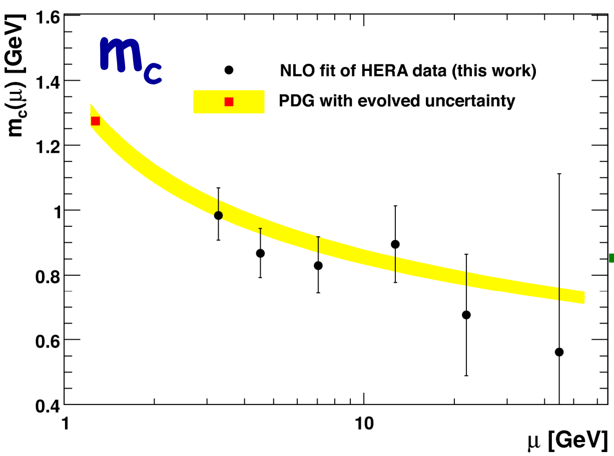
PoS CHARM2016 (2017) 012

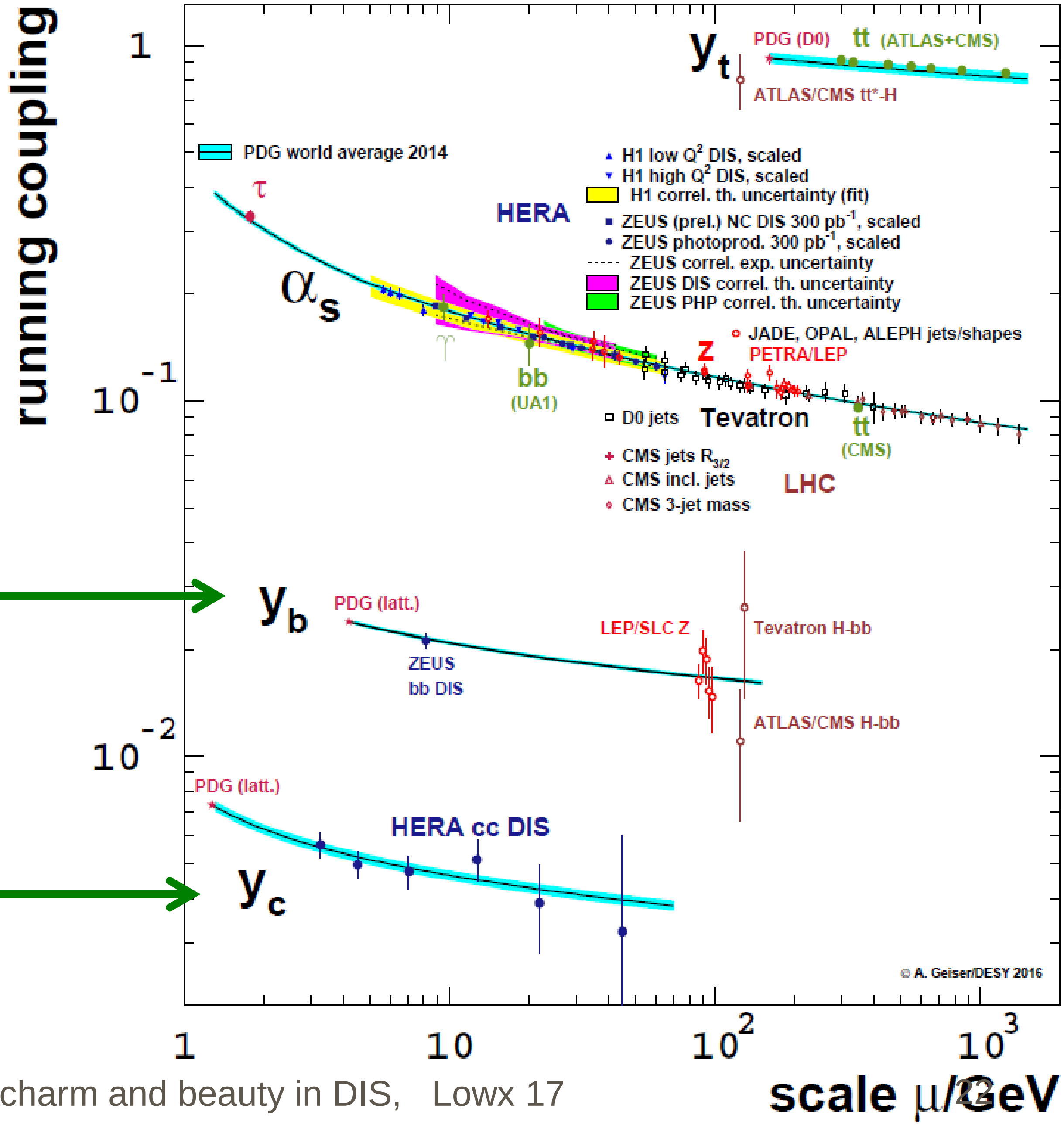
relate m_t, m_b, m_c to associated Higgs Yukawa couplings

LO EW (+NLO QCD) formula:

$$y_Q = \sqrt{2}m_Q/v$$







Summary and conclusions

- final HERA DIS charm and beauty data have been combined
  -> very good consistency, full correlations, reduced uncertainties, replaces previous charm combination

- well-described by NLO QCD in FFNS
  -> measure charm and beauty quark masses in MSbar scheme

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

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

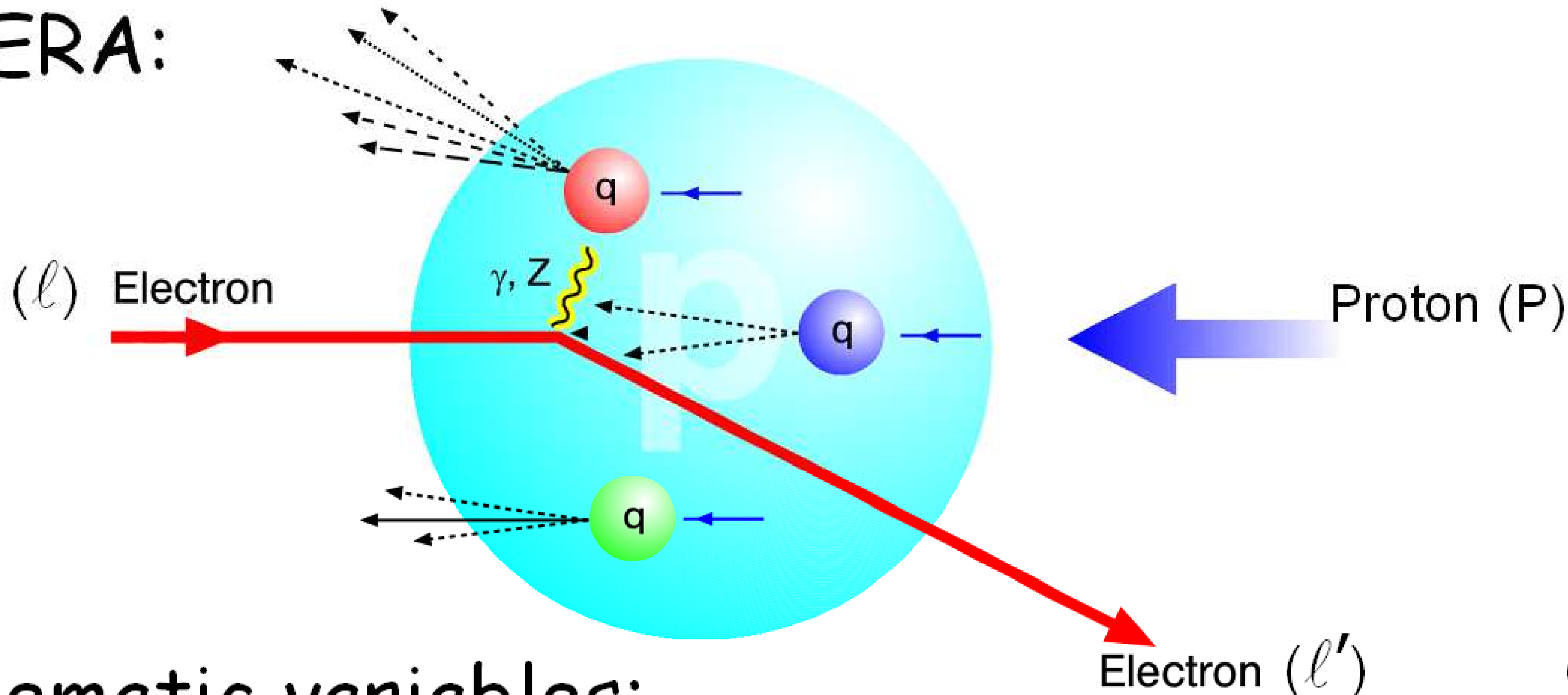
- split (previous) combined charm data into subsets spanning different scales
  -> first determination of charm quark mass running, consistent with QCD

- convert to Higgs Yukawa couplings
  -> representation of running Yukawa couplings with running of strong coupling

Backup

Deep Inelastic ep Scattering at HERA

HERA:



$q = \ell - \ell'$

kinematic variables:

$Q^2 = -q^2$ photon (or Z) virtuality, squared momentum transfer

$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

$y = \frac{qP}{\ell P}$ inelasticity,
γ momentum fraction (of e)

$Q^2 \lesssim 1\ \mathrm{GeV}^2$: photoproduction

$Q^2 \gtrsim 1\ \mathrm{GeV}^2$: DIS

Why are heavy flavours important?

- charm contribution to inclusive DIS data ~10-30%!
- **kinematic effect of mass, fragmentation effects**
- **competing scales for perturbative expansion**

  e.g. m, Q^2, p_T -> terms $\log Q^2/m^2$

  $\log p_T^2/m^2$ etc.

⇒ "**massless**" treatment allows resummation beyond NLO,
but fails near "mass threshold" -> avoid !

=> "**massive**" treatment gets kinematics right,
but does not allow resummation (fixed flavour number schemes)
or induces ambiguities in QCD corrections near flavour threshold
(variable flavour number schemes, available for semi-inclusive only)

check theory against HERA data

χ^2 for different predictions

H1prelim-17-071, ZEUS-prel-17-001

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

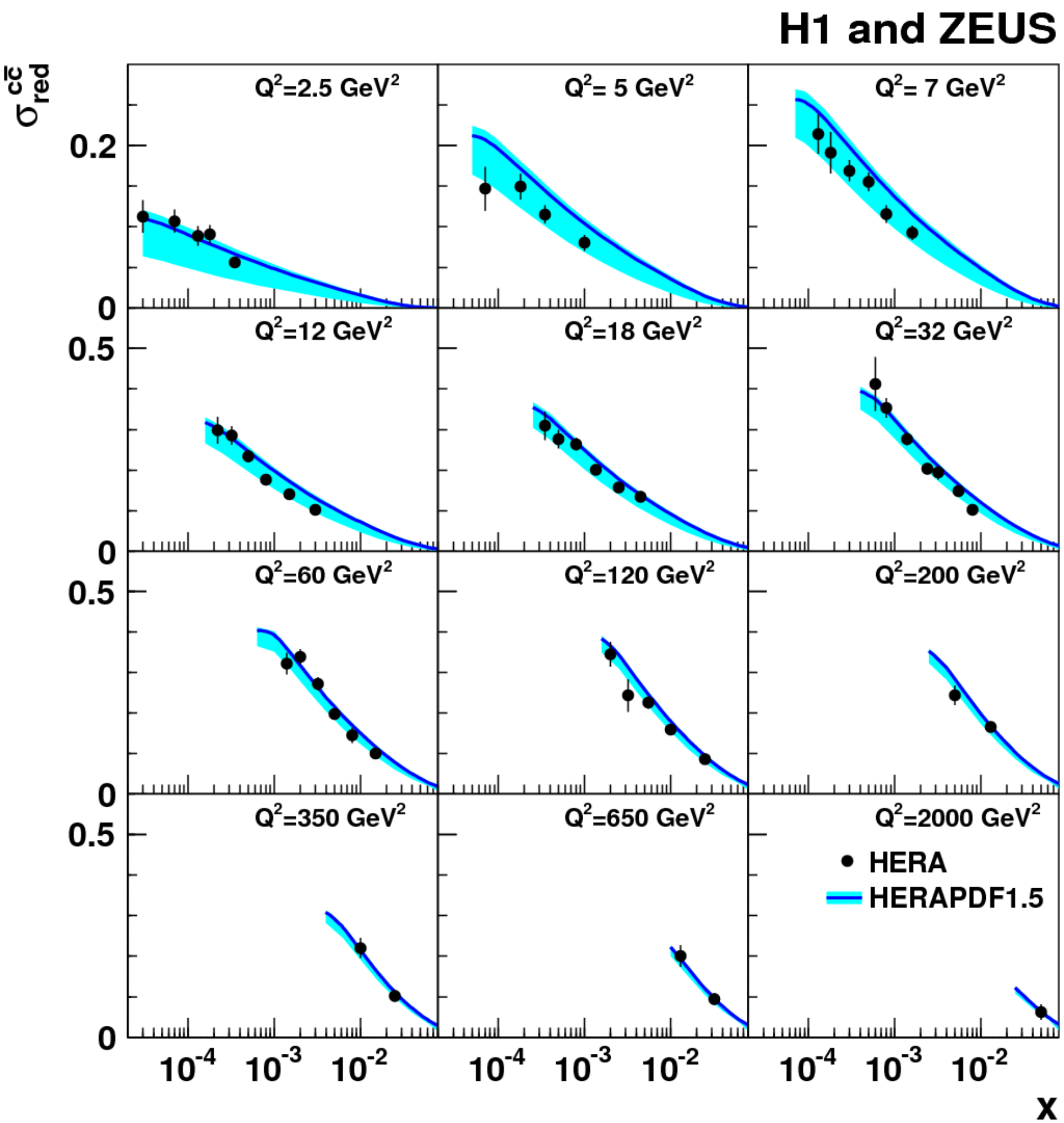
(most precise individual public data sets for c and b from HERA to date)

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

Previous combination compared to VFNS

EPJ C73 (2013) 2311



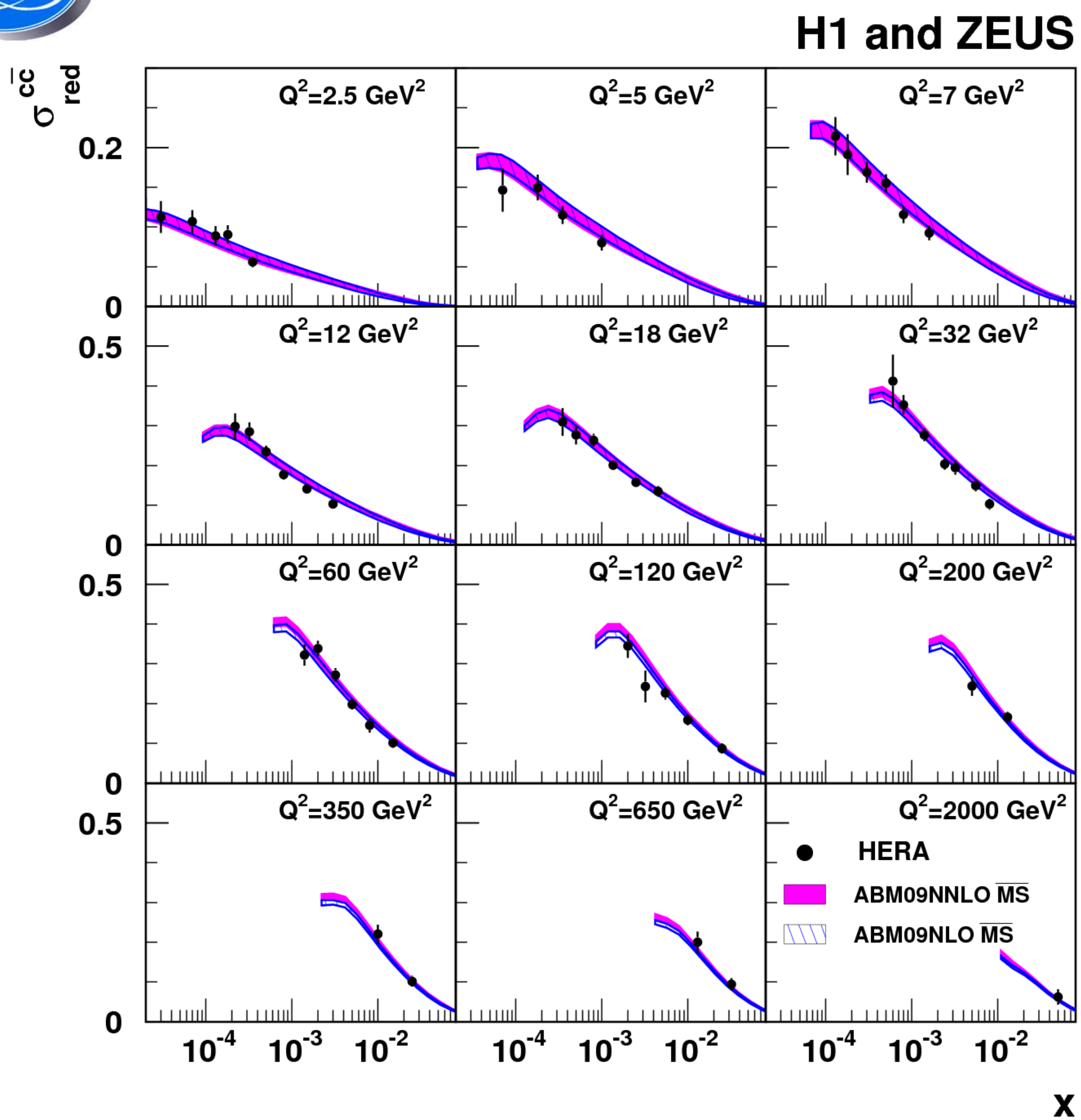
well described using HERAPDF1.5 (VFNS)
(fitted from inclusive DIS only)

strong charm mass dependence
(blue band: 1.35->1.6 GeV)

constrains PDFs,
-> talk O. Zenaiev

Previous combination compared to ABM FFNS

EPJ C73 (2013) 2311



very good description of data in full kinematic range

unambigous treatment of m_c in all terms of calculation

here: $\overline{MS}$ running mass

(similar predictions for pole mass)

Combination procedure

H1prelim-17-071, ZEUS-prel-17-001

- 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

QCD analysis settings

H1prelim-17-071, ZEUS-prel-17-001

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:

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

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

Running of α_s and quark masses m_Q

- **α_s running depends on number of coulours N_C and number of quark flavours n_f**

$$\alpha_s(\mu) = \frac{\alpha_s(\mu_0)}{1 + \alpha_s \times (11N_C - 2n_f)/12\pi \ \ln(\mu^2/\mu_0^2)}$$

- **quark mass running depends on α_s , e.g.**

$m_Q(\text{pole}) = m_Q(m_Q)\ (1 + 4/3\ \alpha_s/\pi)$

$= m_Q(\mu)\ (1 + \alpha_s/\pi\ (4/3 + \ln(\mu^2/m_Q^2))$

leading order QCD formulae

or

$$m_Q(\mu) = m_Q(m_Q) \times \left(\frac{\alpha_s(\mu)}{\alpha_s(m_Q)}\right)^{c_0}$$

$$c_0 = 4/(11 - 2n_f/3) \underset{n_f = 3}{=} 4/9$$

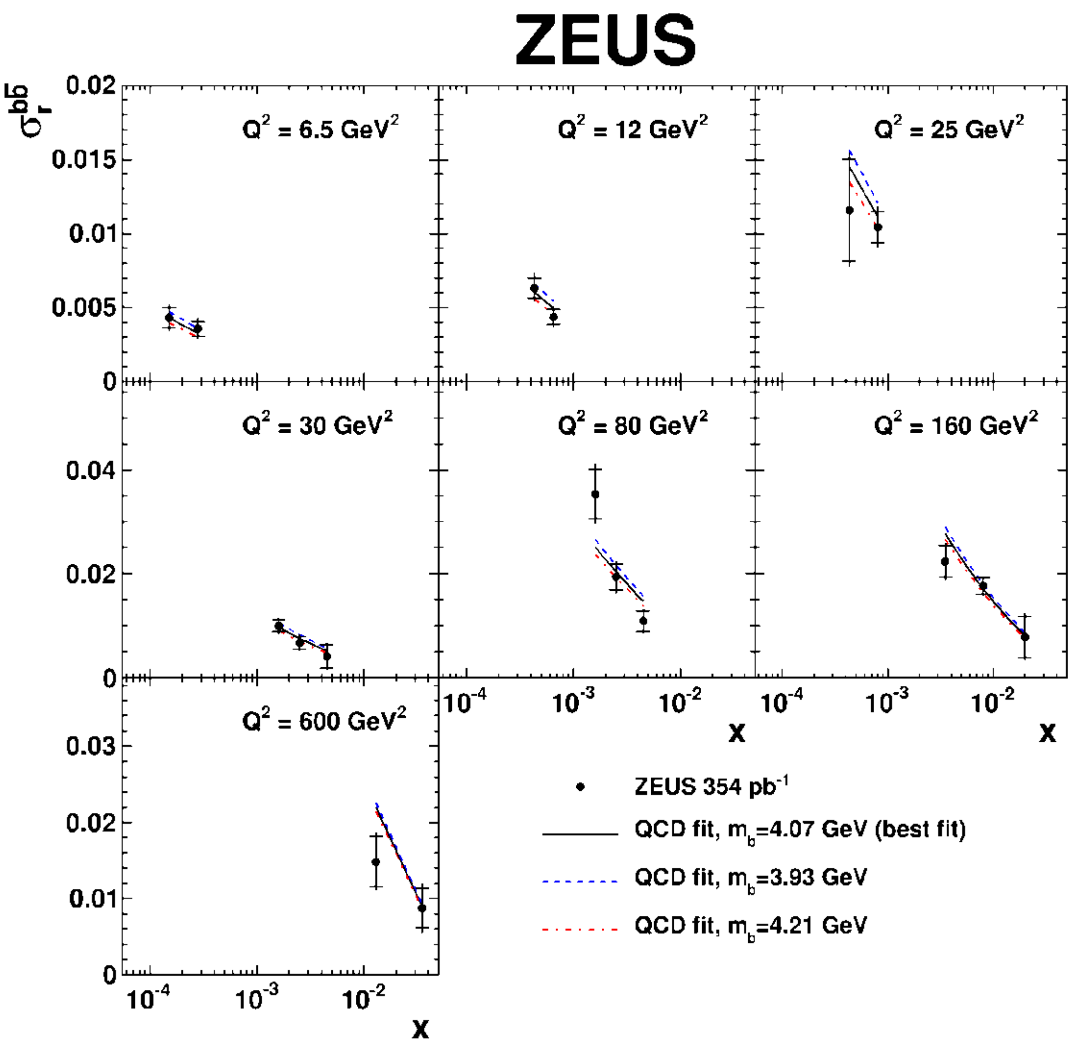
N_c

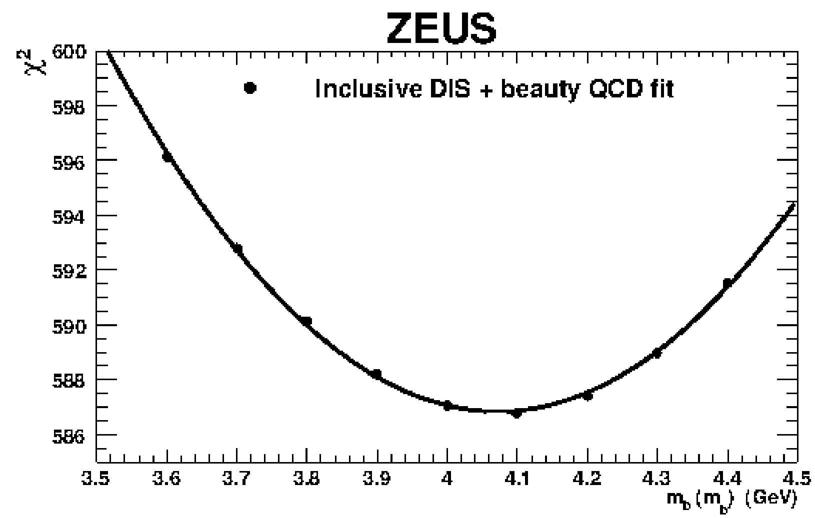
- part of gluon field around quark not 'visible' any more when 'looking' at smaller distances/larger energy scales

-> ***effective quark mass decreases***

m_b from reduced beauty cross section

DESY-14-083





uncertainty evaluation
similar to charm running case

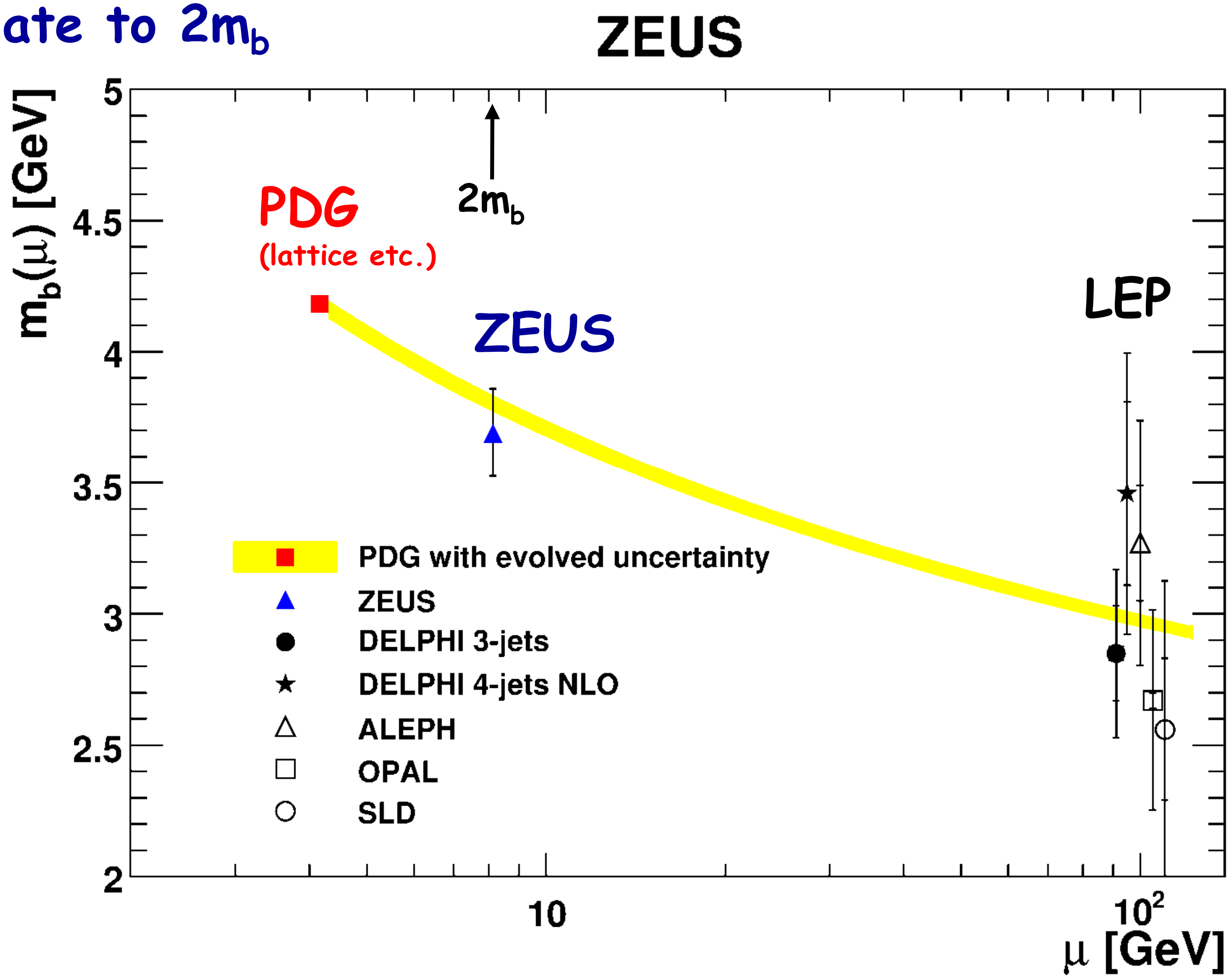
$m_b(m_b) = 4.07 \pm 0.14_{fit}\ {}^{+0.01}_{-0.07}\,{}_{mod}\ {}^{+0.05}_{-0.00}\,{}_{par}\ {}^{+0.08}_{-0.05}\,{}_{th}$ GeV

PDG: 4.18 ± 0.03 GeV (lattice QCD + time-like processes)

The running beauty quark mass

ZEUS, JHEP 1409 (2014) 7; review, arXiv:1506.07519
LEP, Eur. Phys. J. C55 (2008) 525 Prog. Part. Nucl. Phys. 84 (2015) 1

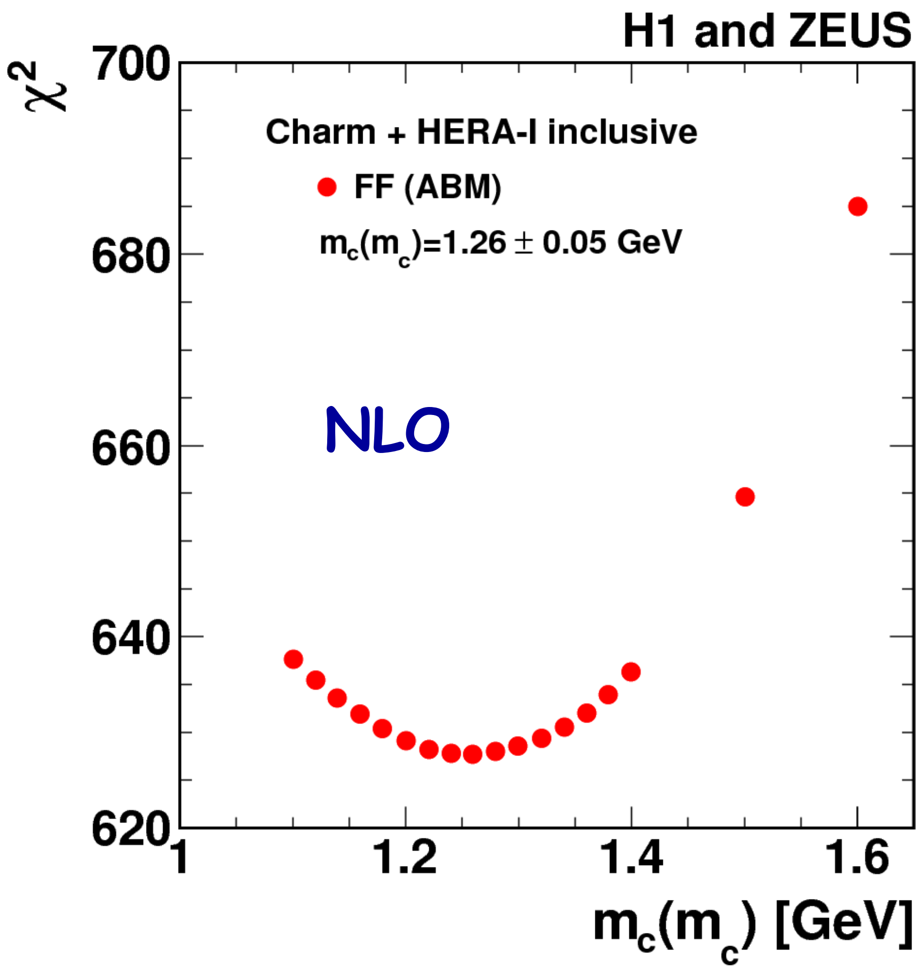
translate to $2m_b$



MSbar scheme

measurement of $\overline{MS}$ charm mass

EPJ C73 (2013) 2311



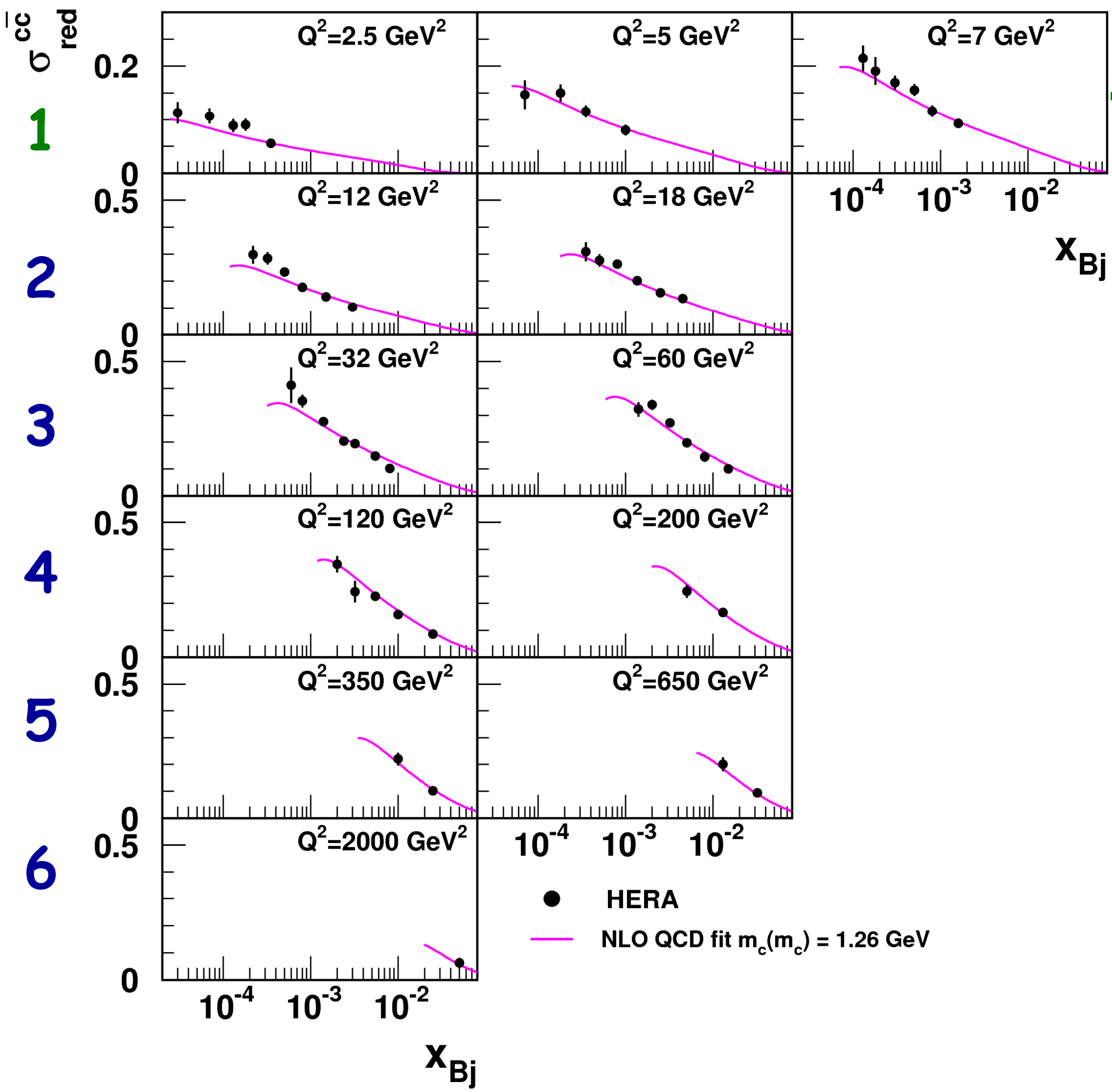
simultaneous fit of combined charm data and inclusive HERA I DIS data

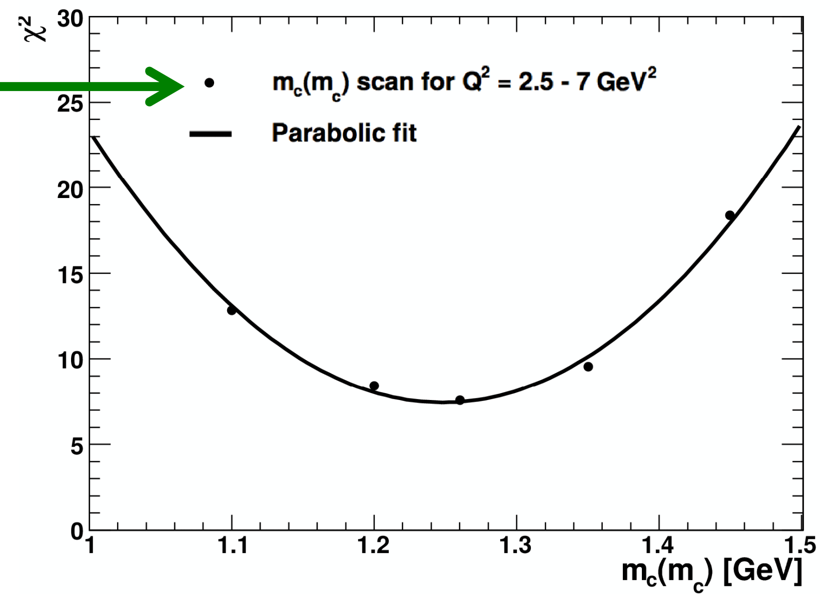
$m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{\alpha s}$ GeV

PDG: 1.275 ±0.025 GeV (lattice QCD + time-like processes)

Measurement of m_c running

A. Gizhko et al., DESY-17-048





Step 1:
extract $m_c(m_c)$ separately for 6 different kinematic ranges in $\mu^2 = Q^2+4m_c^2$

(take log average for central scale)

m_c fit and uncertainties

A. Gizhko et al., DESY-17-048

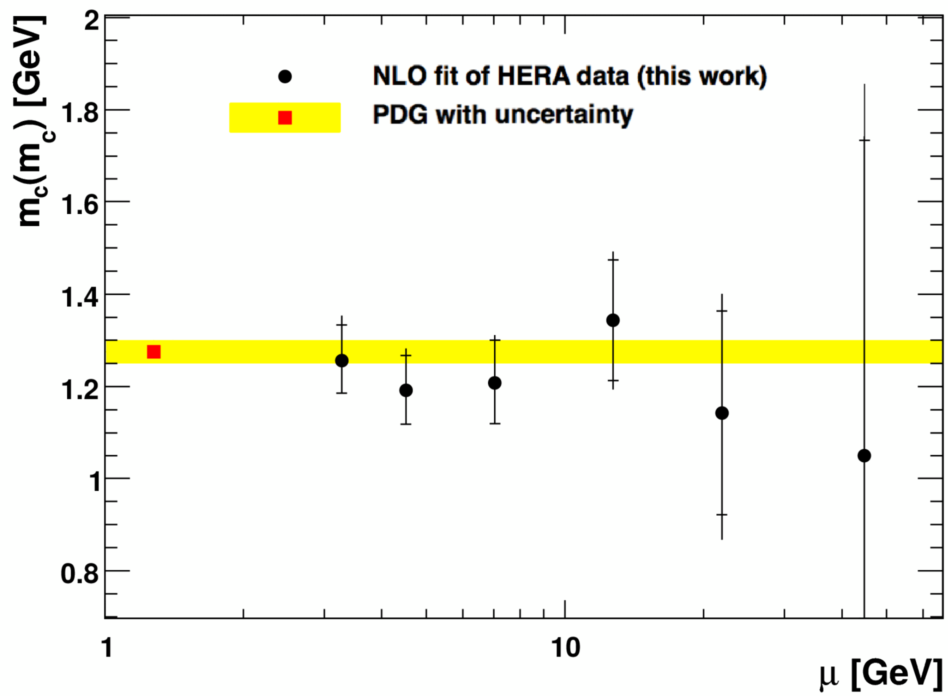
use appropriate PDF set for each mass (from inclusive DIS data only), fit charm data

Fit uncertainty
- Was estimated by taking $\triangle\chi^2 = 1$ (dominant uncertainty)

Parametrisation
- Adding extra parameter in the PDF parametrisation

Model uncertainty
- Variation of the strangeness supression factor
- Lower cut on Q^2 for inclusive data
- The evolution starting scale
- The b-quark mass

Theory
- Variation of α_s
- Variation of the factorisation and renormalization scales of heavy quarks by factor 2 -> outer error bar



sensitivity to $m_c(m_c)$ decreases with increasing scale $\mu^2 = Q^2+4m_c^2$

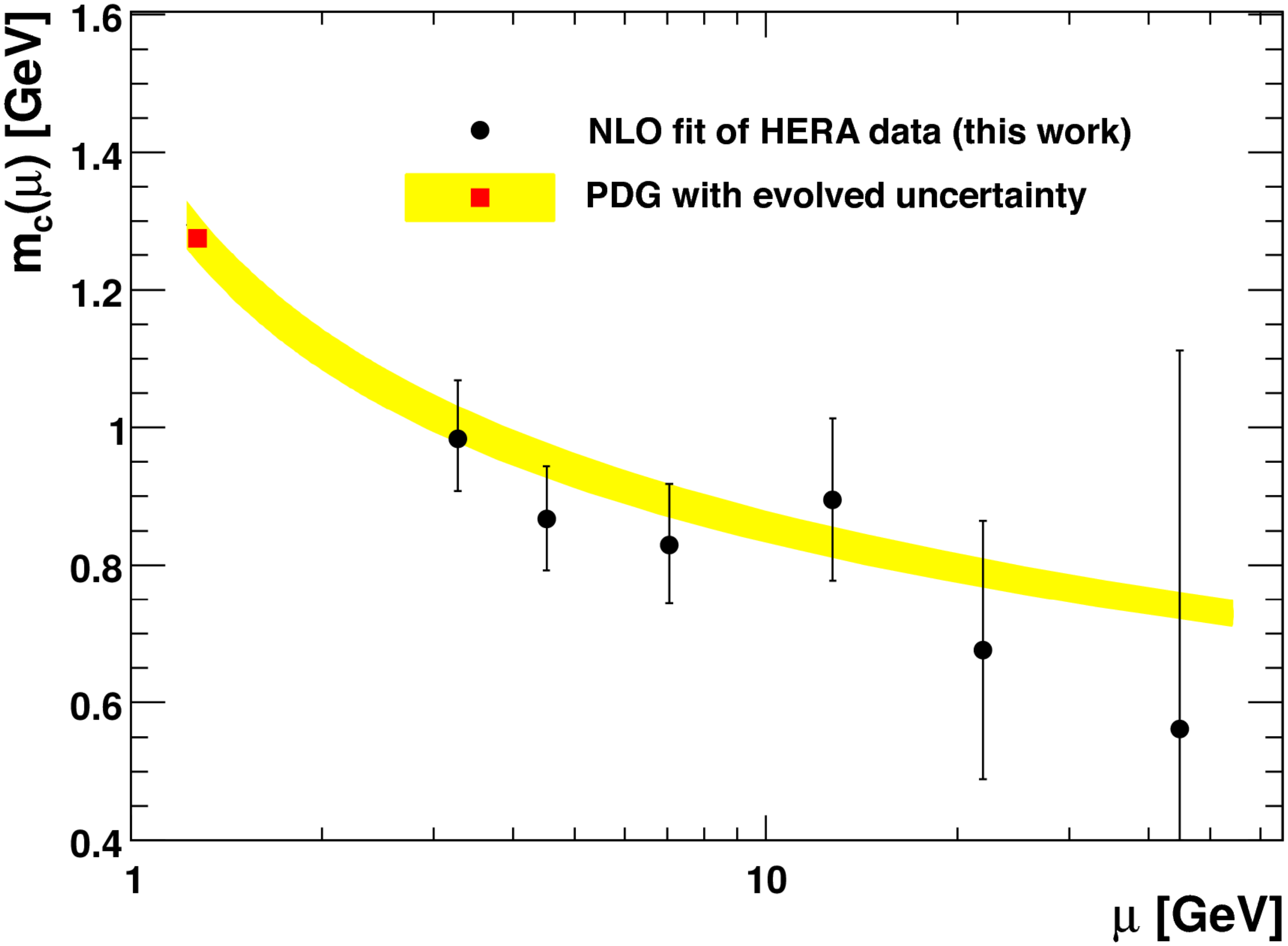
'in reality', have measured $m_c(\mu)$ at each scale

The running charm quark mass

A. Gizhko et al., DESY-17-048

Step 2: translate back to $m_c(\mu)$, which was actually measured, using LO formula consistent with NLO $\overline{MS}$ QCD fit

(OpenQCDrad, Alekhin et al.)

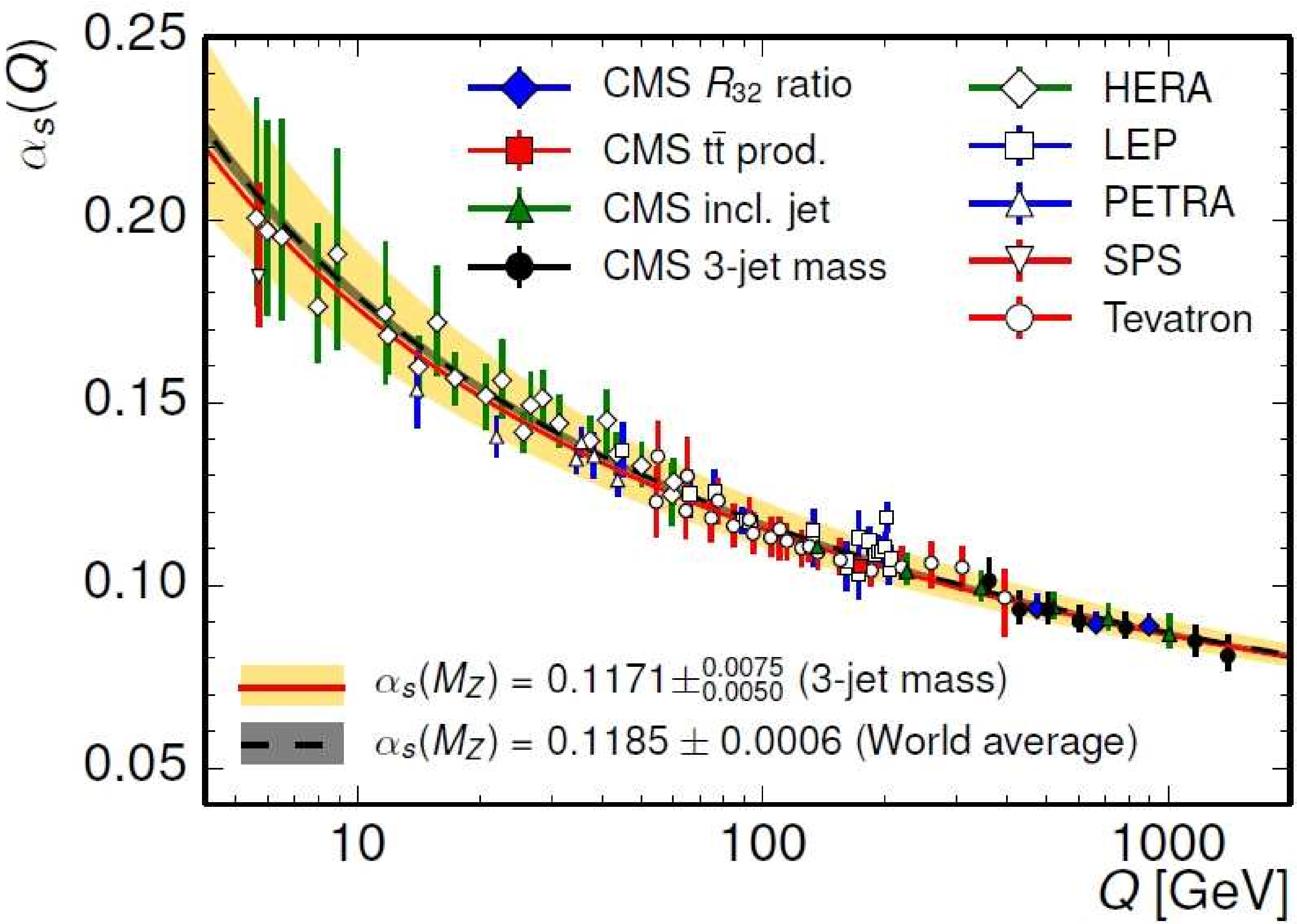


running mass concept in QCD is self-consistent !

Running of strong coupling „constant“ α_s

reminder EPJC 75 (2015) 186

e.g. from jet production at e+e-, ep, and pp at DESY, Fermilab and CERN



updates see talks
K. Rabbertz
and D. Britzger

Yes, it runs!