Combination and QCD analysis of charm and beauty production cross sections in DIS at HERA

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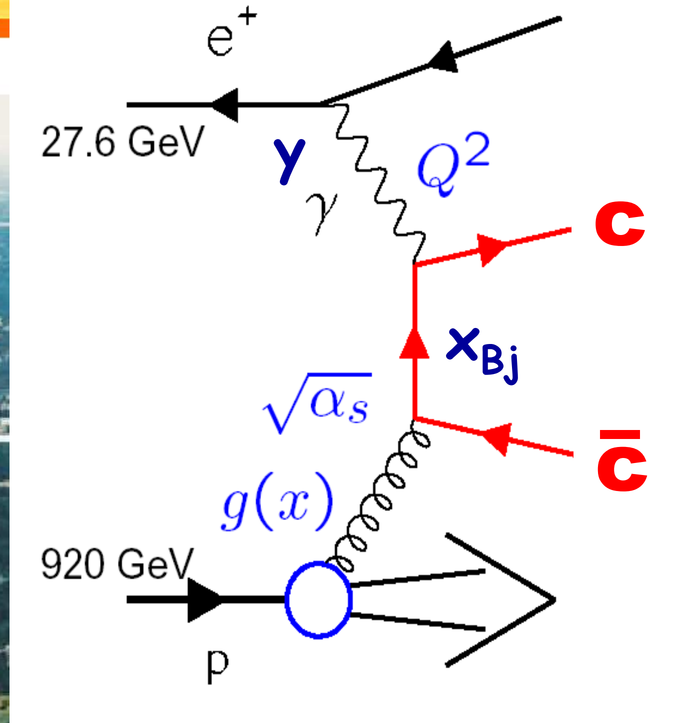
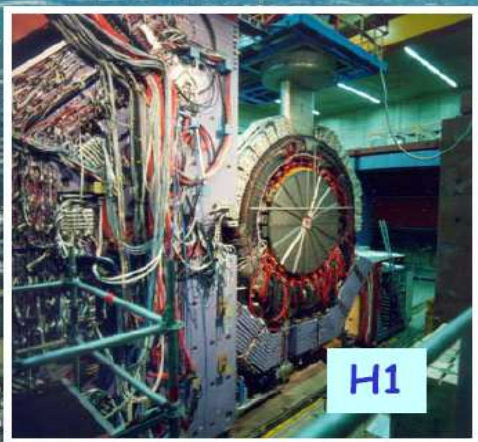
- Introduction: heavy flavours in DIS
- Combination of charm and beauty data
- Comparison with QCD predictions
- QCD fit and determination of $m_c(m_c)$ and $m_b(m_b)$
- Discussion

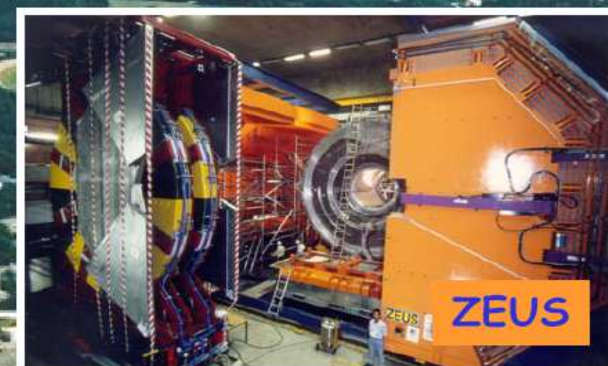
final results freshly released: arXiv:1804.01019

The HERA ep collider and experiments



up to 30% of cross section





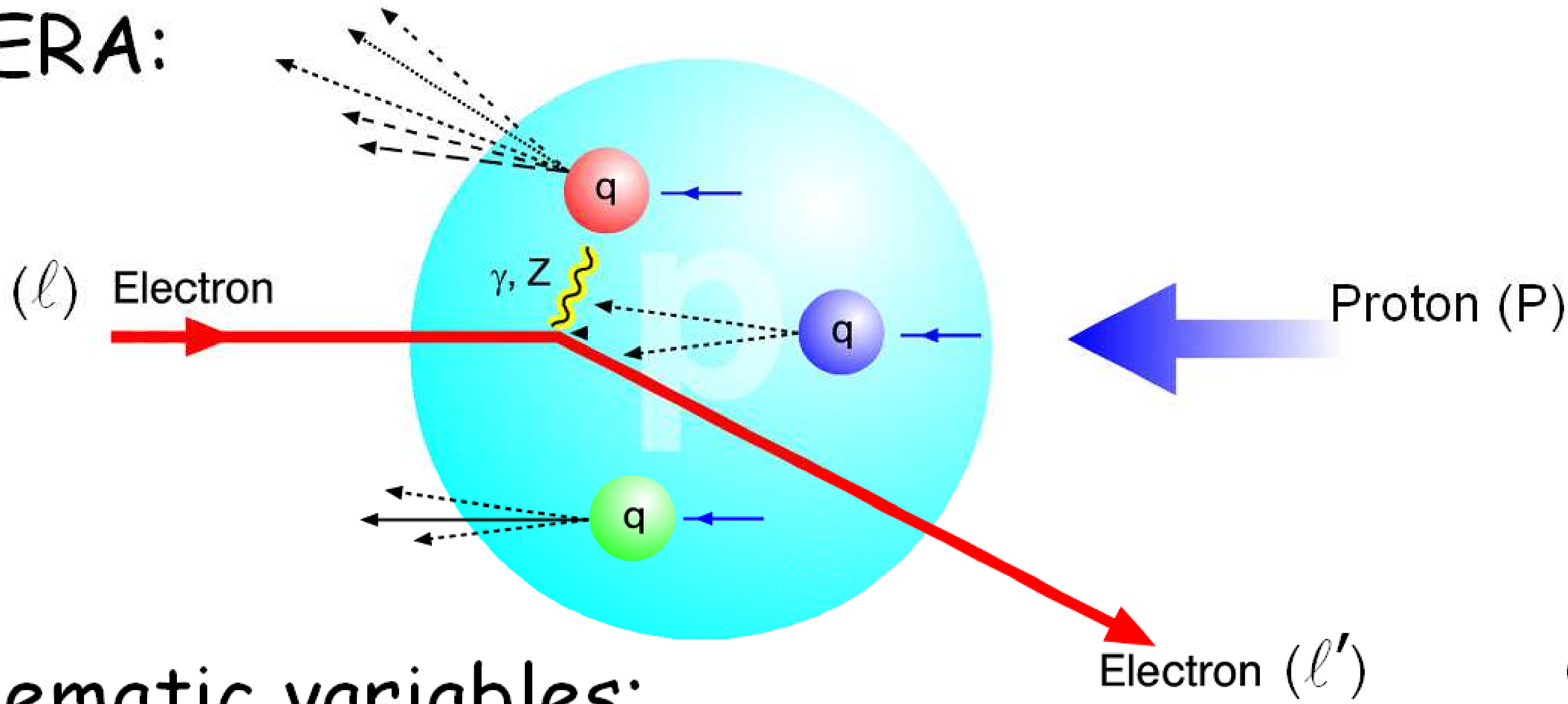
HERA I: ~ 130 pb^{-1} (physics)

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

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

Deep Inelastic ep Scattering at HERA

HERA:



$q = \ell - \ell'$

kinematic variables:

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

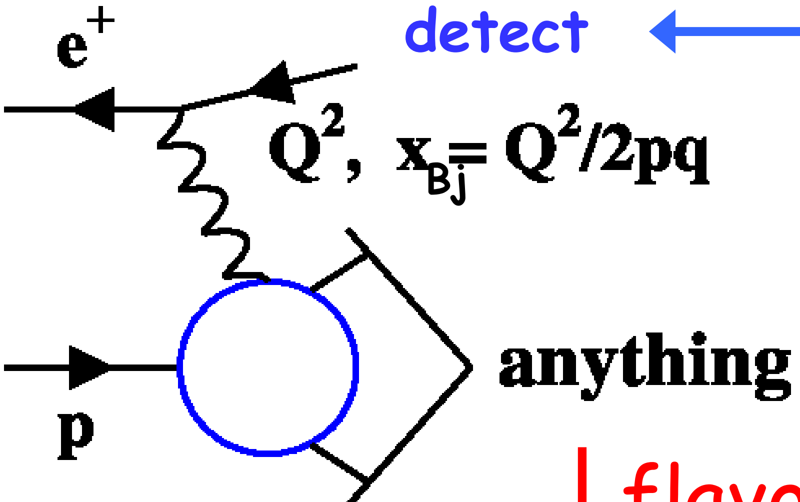
$x_{Bj} = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction x of p constituent
(equivalent in LO QPM only)

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

$Q^2 \lesssim 1$ GeV^2:
photoproduction

$Q^2 \gtrsim 1$ GeV^2:
DIS

Heavy flavour contributions to σ_r

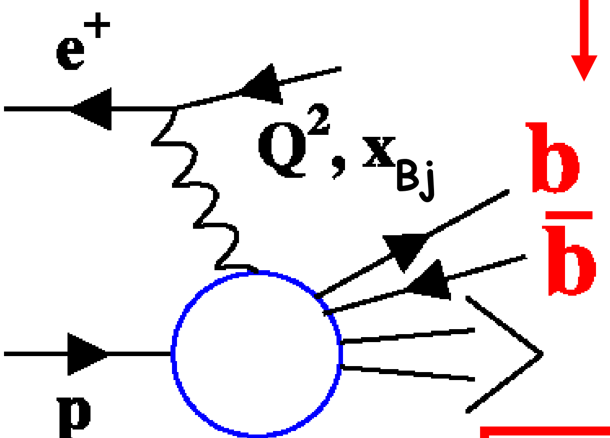


detect ⟷

Measure cross section

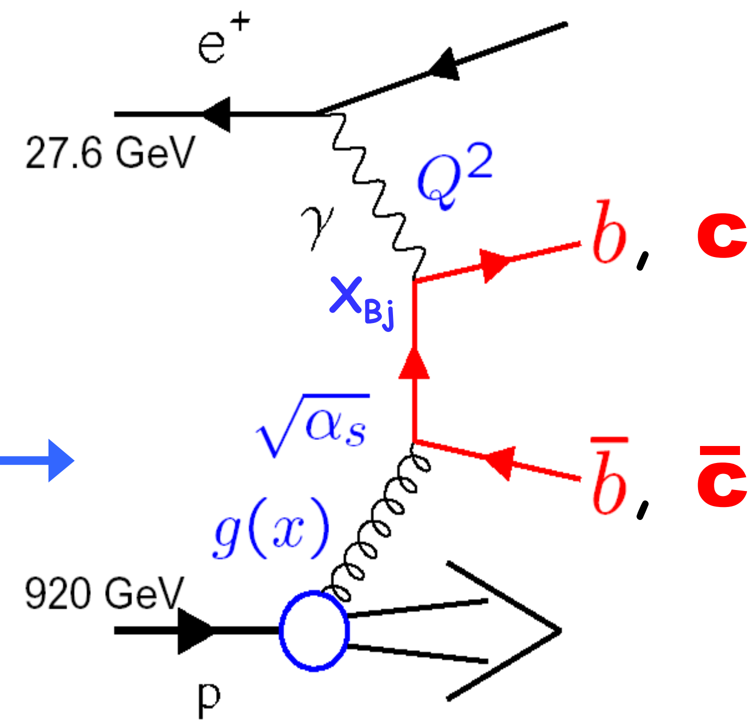
$$\frac{d^2\sigma}{dx_{Bj}\,dQ^2} \cong \frac{2\pi\alpha^2}{Q^4 x_{Bj}}\left[1+(1-y)^2\right]\sigma_r(x_{Bj},Q^2)$$

flavour tagging ↓



-> $\sigma_r^{b\bar{b}}$, $\sigma_r^{c\bar{c}}$

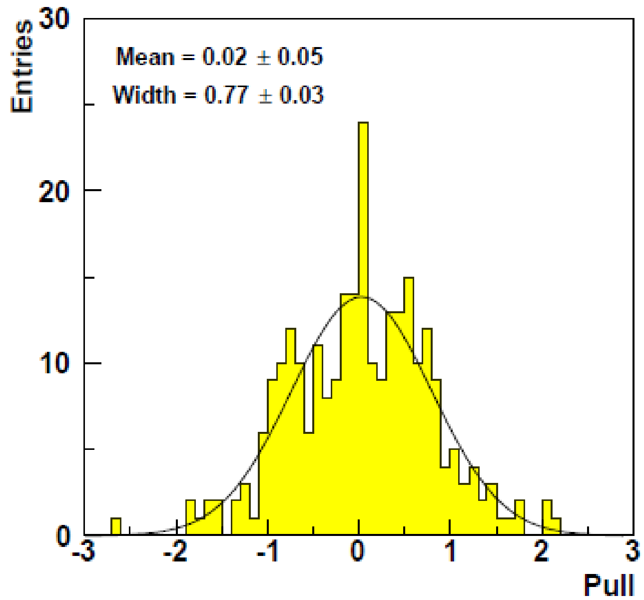
QCD ⟷



Combination of 13 charm+beauty data sets

arXiv:1804.01019

	Dataset	Tagging	Q^2 range [GeV^2]	$\mathscr{L}$ [pb^{-1}]	$\sqrt{s}$ [GeV]	N_c	N_b
1	H1 VTX [14]	VTX	5 – 2000	245	318	29	12
2	H1 $D^{*\pm}$ HERA-I [10]	D^{*+}	2 – 100	47	318	17	
3	H1 $D^{*\pm}$ HERA-II (medium Q^2) [20]	D^{*+}	5 – 100	348	318	25	
4	H1 $D^{*\pm}$ HERA-II (high Q^2) [15]	D^{*+}	100 – 1000	351	318	6	
5	ZEUS D^{*+} 96-97 [4]	D^{*+}	1 – 200	37	300	21	
6	ZEUS D^{*+} 98-00 [6]	D^{*+}	1.5 – 1000	82	318	31	
7	ZEUS D^0 2005 [12]	D^0	5 – 1000	134	318	9	
8	ZEUS μ 2005 [13]	μ	20 – 10000	126	318	8	8
9	ZEUS D^+ HERA-II [21]	D^+	5 – 1000	354	318	14	
10	ZEUS D^{*+} HERA-II [22]	D^{*+}	5 – 1000	363	318	31	
11	ZEUS VTX HERA-II [23]	VTX	5 – 1000	354	318	18	17
12	ZEUS e HERA-II [19]	e	10 – 1000	363	318		9
13	ZEUS μ +jet HERA-I [16]	μ	2 – 3000	114	318		11



good data consistency:
χ^2= 149/187 dof

3 additional charm datasets w.r.t. EPJ C73 (2013) 2311

beauty combined for the **first time**

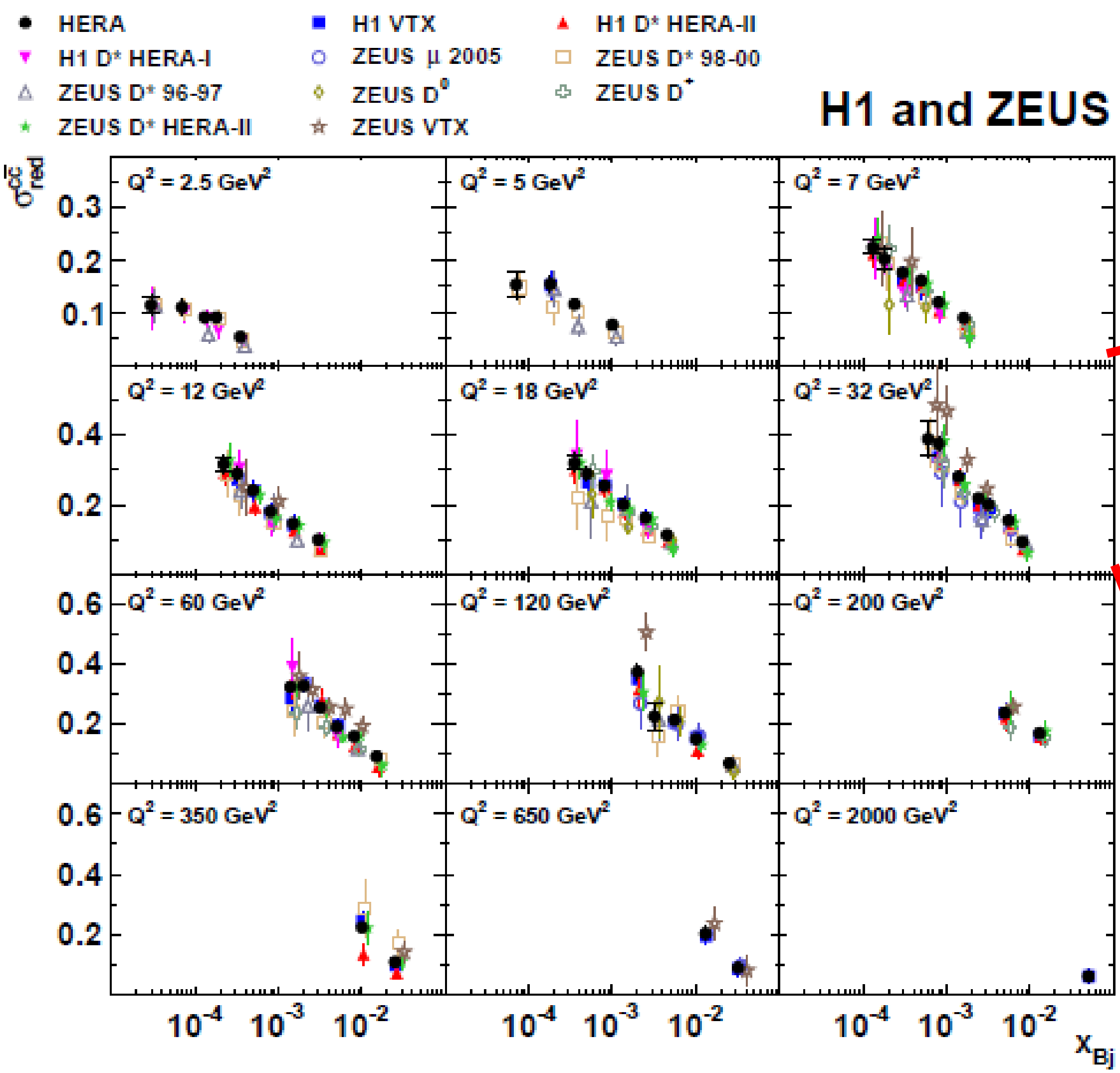
account for **all systematic correlations between data points, data sets, and between charm and beauty**

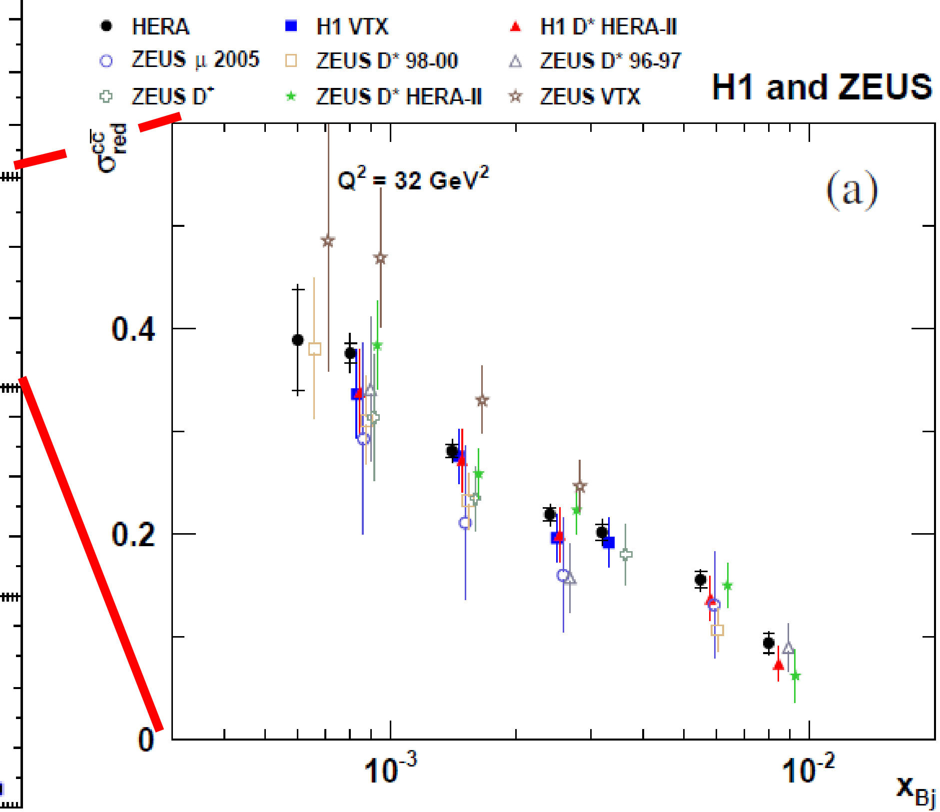
Charm combination

arXiv:1804.01019

209 -> 52 data points

3 HERA II data sets added



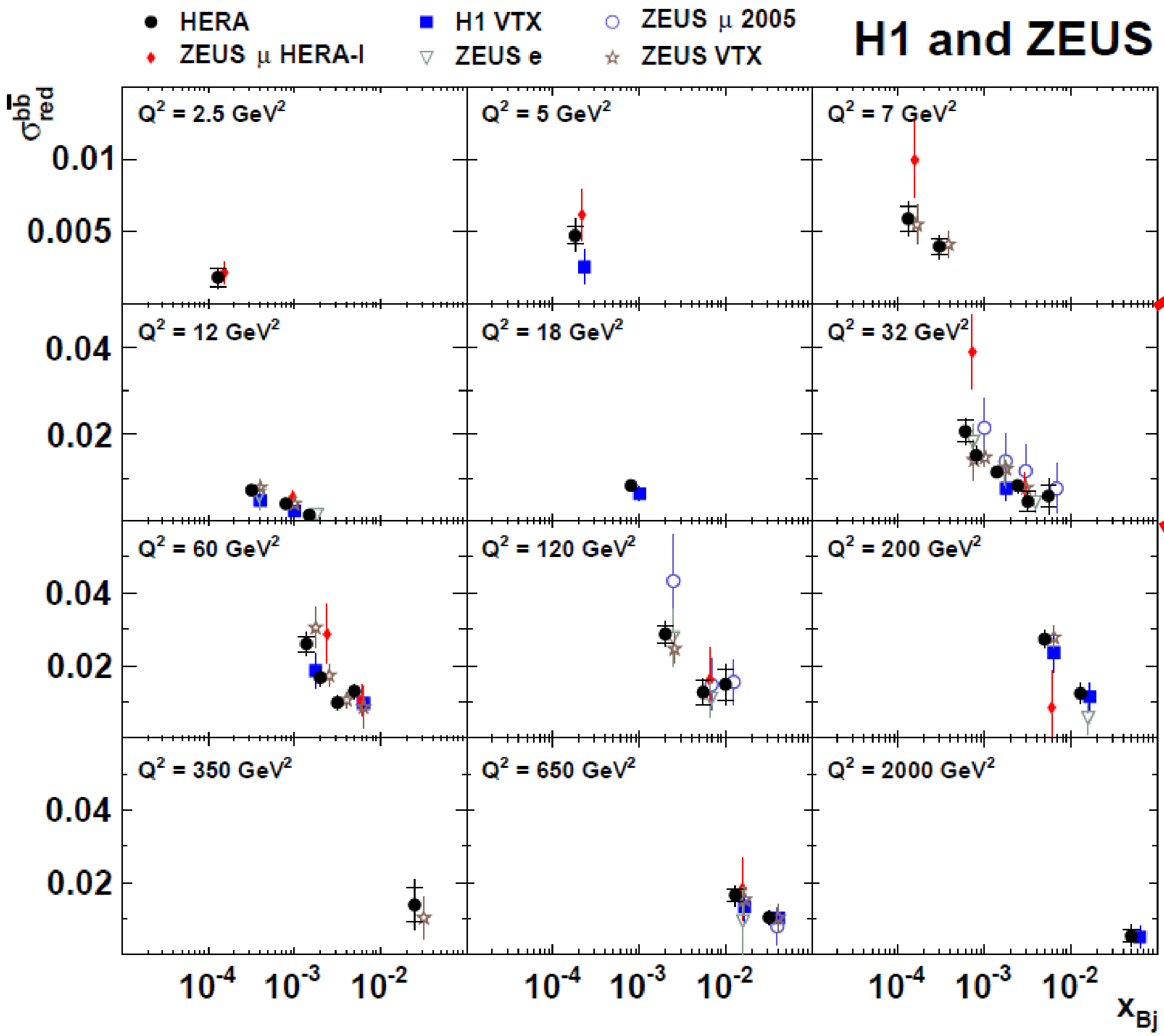


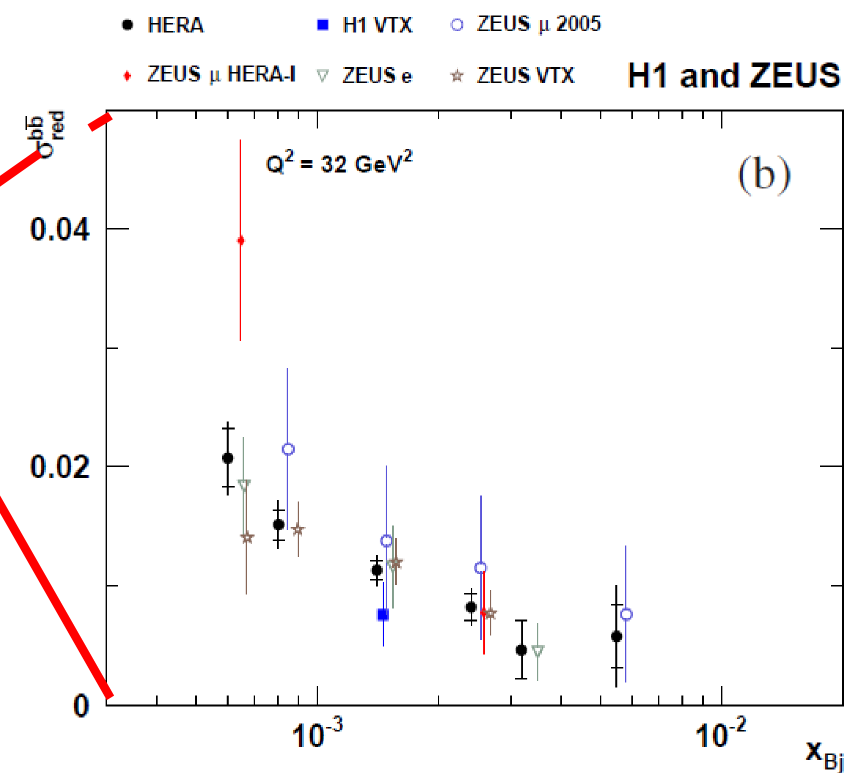
Beauty combination

arXiv:1804.01019

57 -> 27 data points

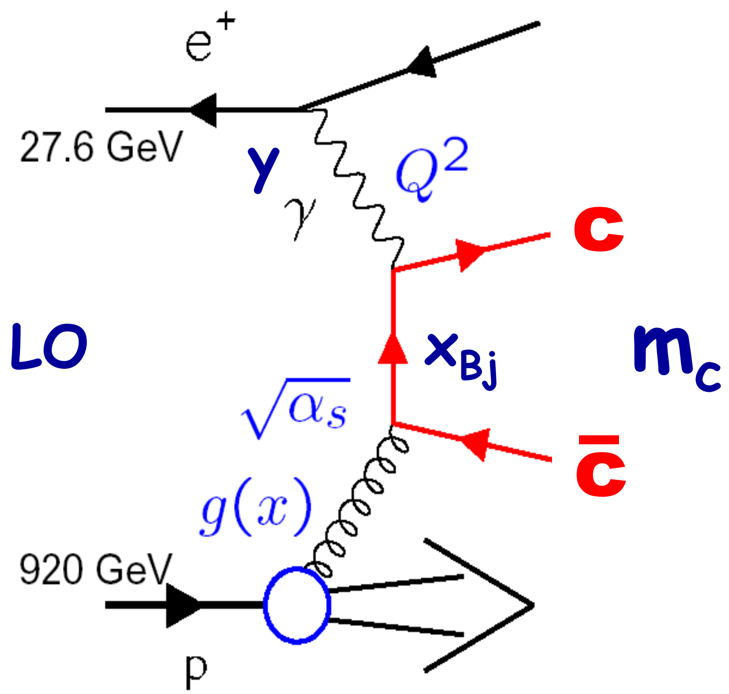
combined for the first time





Fixed Flavour Number Scheme (FFNS)

example: charm



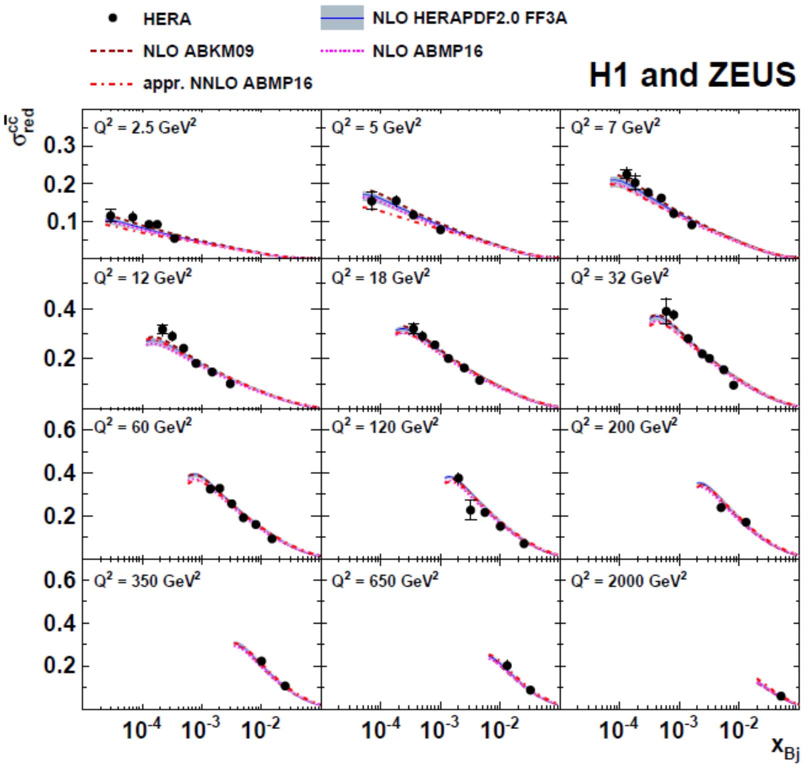
+ NLO (+partial NNLO) corrections,

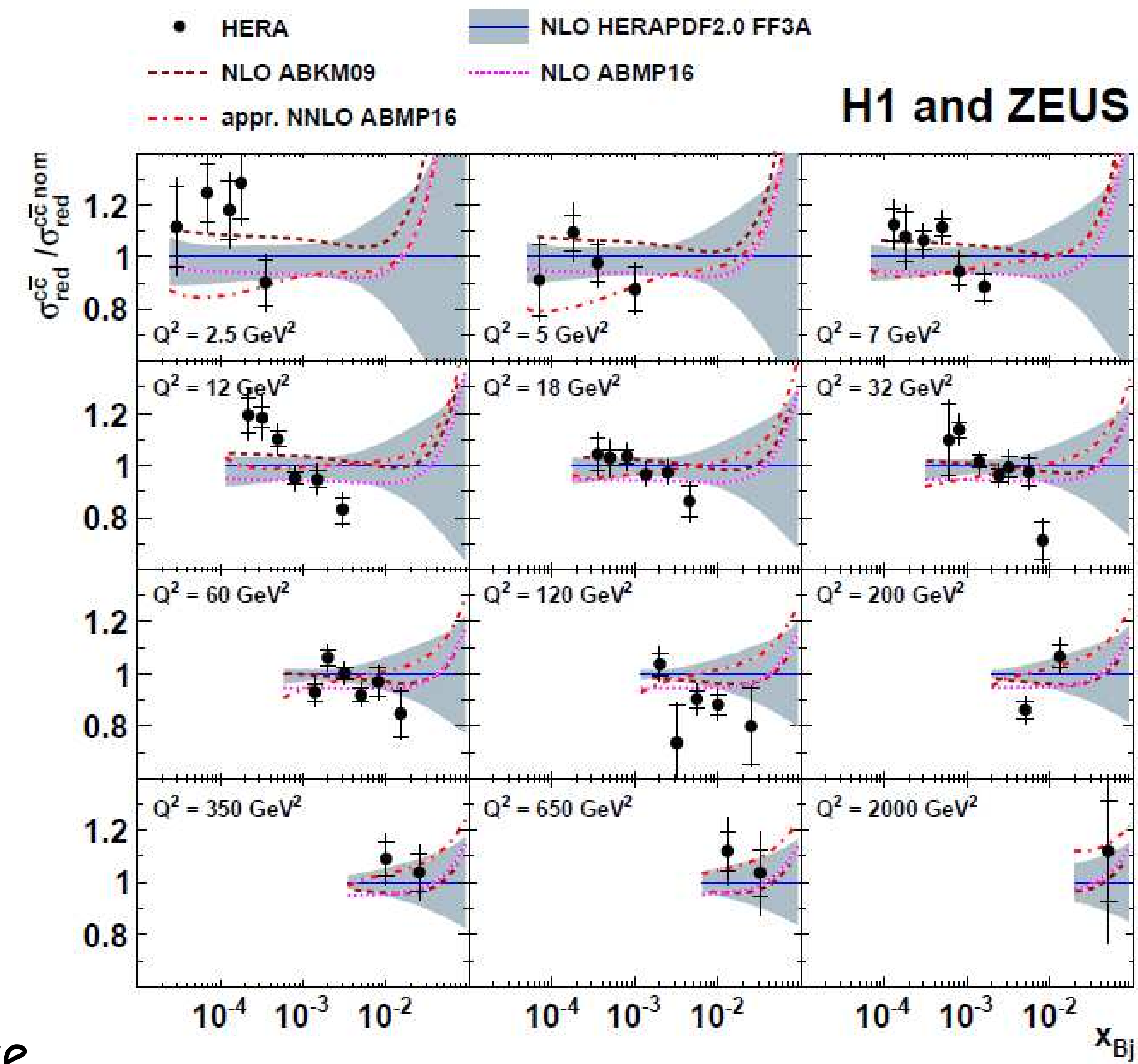
"natural" scale:
$\mu^2 = Q^2 + 4m_c^2$

- 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 ☺

Comparison to FFNS QCD predictions

arXiv:1804.01019





data reasonably described

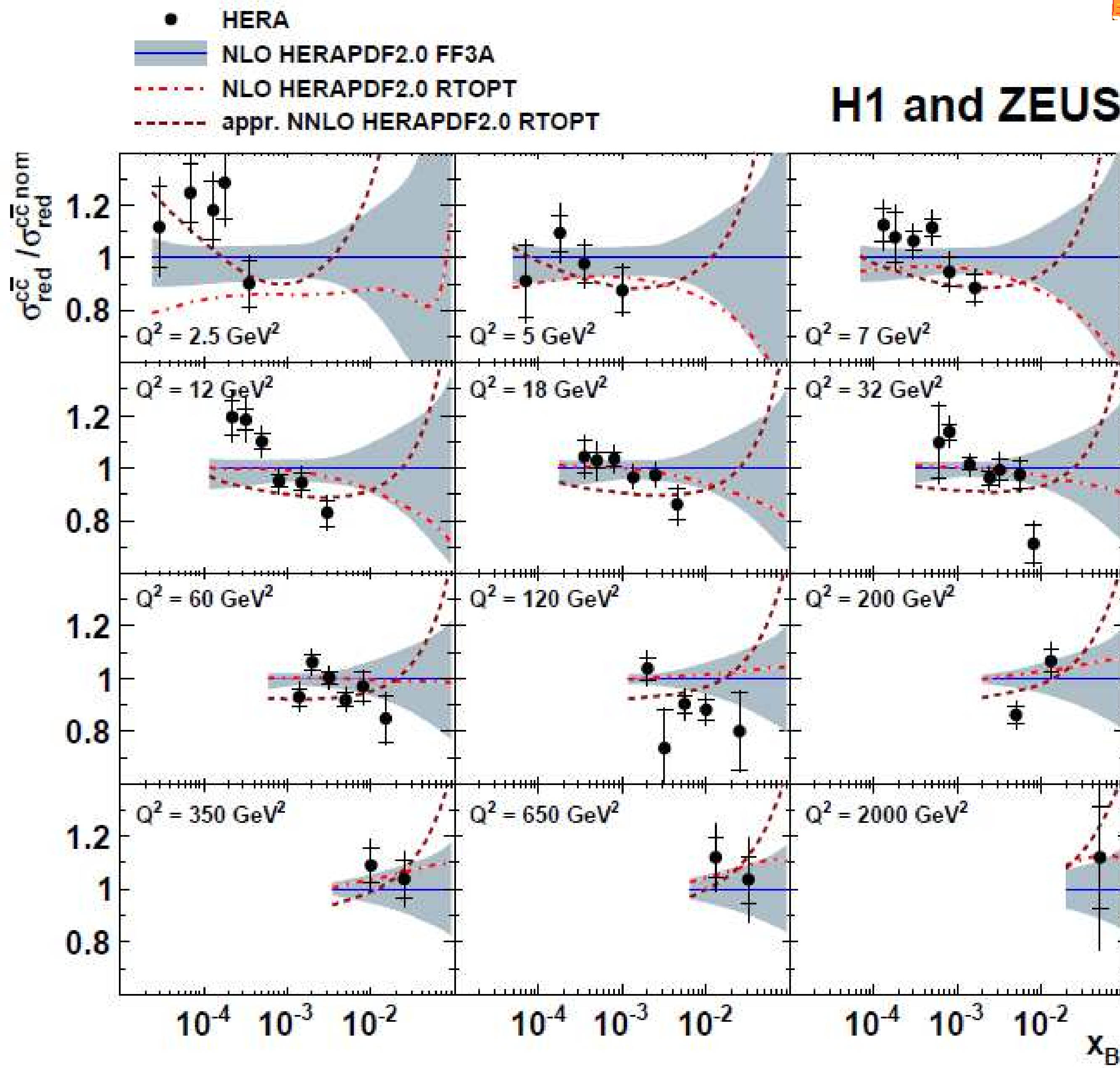
best: HERAPDF2.0 FF
and ABKM09NLO

~3σ tension with x_{Bj} slope

appr. NNLO does not improve

Comparison to VFNS QCD predictions

arXiv:1804.01019



data description reasonable but not better than FF

overall, **NLO better than appr. NNLO**

beauty in backup: larger uncertainties

-> all consistent

Predictions w/o and with log 1/x resummation

arXiv:1804.01019

NLL resummation of log 1/x terms improves x_{Bj} slope but deteriorates normalisation

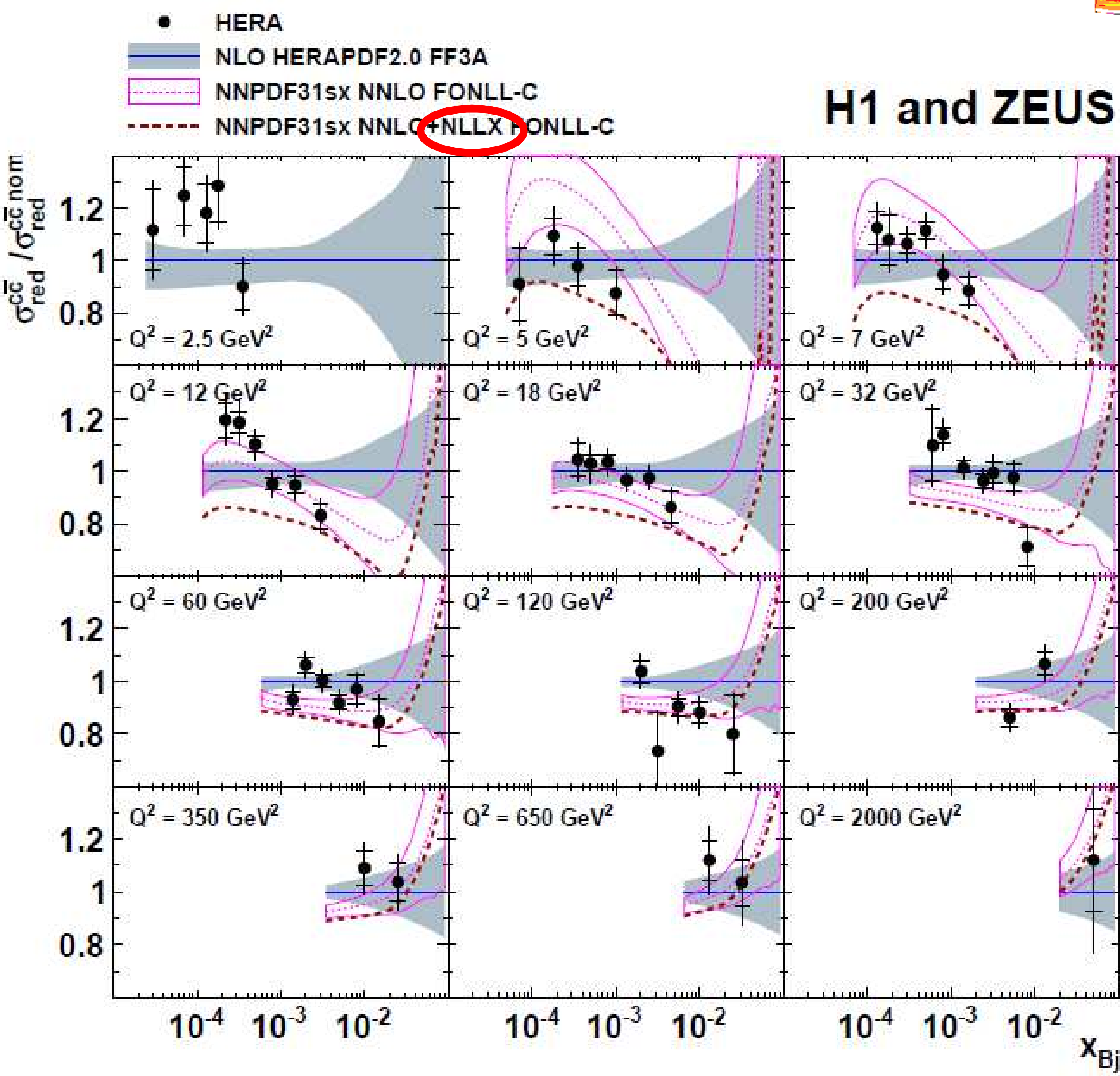
overall, NNPDF3.1sx

(fitted charm, arXiv:1710.05935)

either with or w/o log 1/x resummation

not better than HERAPDF

(FONLL-C + NLLx see backup)



χ^2 and p-values for various QCD predictions

arXiv:1804.01019

central predictions

Dataset	PDF (scheme)	χ^2 [p-value]
charm [38]	HERAPDF20_NLO_FF3A (FFNS)	59 [0.23]
	ABKM09 (FFNS)	59 [0.23]
	ABMP16_3_nlo (FFNS)	61 [0.18]
	ABMP16_3_nnlo (FFNS)	70 [0.05]
	HERAPDF20_NLO_EIG (RTOPT)	71 [0.04]
(N_{data} = 52)	HERAPDF20_NNLO_EIG (RTOPT)	66 [0.09]
	NNPDF31sx NNLO (FONLL-C)	106 [$1.5 \cdot 10^{-6}$]
(N_{data} = 47)	NNPDF31sx NNLO+NLLX (FONLL-C)	71 [0.013]
charm, this analysis	HERAPDF20_NLO_FF3A (FFNS)	86 [0.002]
	ABKM09 (FFNS)	82 [0.005]
	ABMP16_3_nlo (FFNS)	90 [0.0008]
	ABMP16_3_nnlo (FFNS)	109 [$6 \cdot 10^{-6}$]
	HERAPDF20_NLO_EIG (RTOPT)	99 [$9 \cdot 10^{-5}$]
(N_{data} = 52)	HERAPDF20_NNLO_EIG (RTOPT)	102 [$4 \cdot 10^{-5}$]
	NNPDF31sx NNLO (FONLL-C)	140 [$1.5 \cdot 10^{-11}$]
(N_{data} = 47)	NNPDF31sx NNLO+NLLX (FONLL-C)	114 [$5 \cdot 10^{-7}$]
beauty, this analysis	HERAPDF20_NLO_FF3A (FFNS)	33[0.20]
	ABMP16_3_nlo (FFNS)	37 [0.10]
	ABMP16_3_nnlo (FFNS)	41 [0.04]
	HERAPDF20_NLO_EIG (RTOPT)	33 [0.20]
(N_{data} = 27)	HERAPDF20_NNLO_EIG (RTOPT)	45 [0.016]

previous combined charm

new combined charm

beauty

Table 4: The χ^2, p-values and number of data points of the charm and beauty data with respect to the NLO and approximate NNLO calculations using various PDFs as described in the text. The measurements at $Q^2 = 2.5$ GeV^2 are excluded in the calculations of the χ^2 values for the NNPDF3.1sx predictions, by which the number of data points is reduced to 47, as detailed in the caption of figure 12.

QCD fit

arXiv:1804.01019

Simultaneous NLO QCD fit of

- combined **inclusive DIS** data (arXiv:1506.06042), Q^2_{min}=3.5 GeV^2
- new combined **charm and beauty DIS** data (this work)

Simultaneously fit **PDF's** (a la **HERAPDF** FF) in FFNS at NLO and **charm quark and beauty quark "running" masses** in MSbar scheme

- using xFitter [www.xfitter.org], 14 parameters (±1)
- NLO DGLAP [QCDNUM] and matrix elements [OPENQCDRAD], nf = 3
- $\mu_F = \mu_R = \sqrt{Q^2 + 4m_Q^2}$, varied by factor 2 (for heavy flavour part only)
- **free $m_c(m_c)$, $m_b(m_b)$**
- $\alpha_s(M_Z)^{nf=3} = 0.106$, equivalent to $\alpha_s(M_Z)^{nf=5} = 0.118 \pm 0.002$
- fit uncertainty using $\Delta\chi^2 = 1$

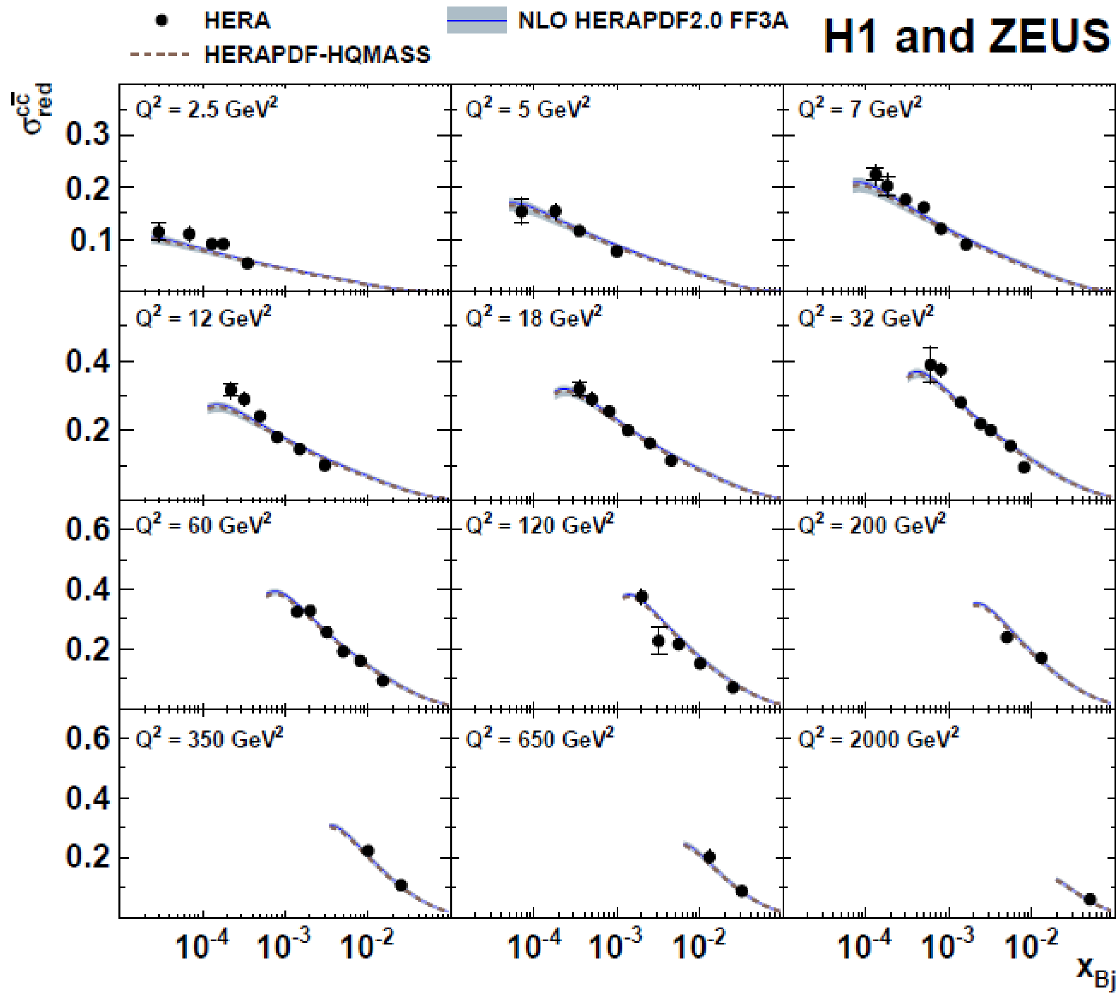
-> HERAPDF-HQMASS

QCD fit: charm subset

arXiv:1804.01019

fully consistent
with HERAPDF2.0 FF3A

uncertainty breakdown
in backup



$m_c(m_c) = 1.29 \,^{+0.05}_{-0.04}\,\text{exp/fit}\;^{+0.06}_{-0.01}\,\text{mod/scale}\;^{+0.00}_{-0.03}\,\text{par}$ GeV

PDG: 1.27 ±0.03 GeV (lattice QCD + time-like processes)

Comparison with other $m_c(m_c)$ determinations

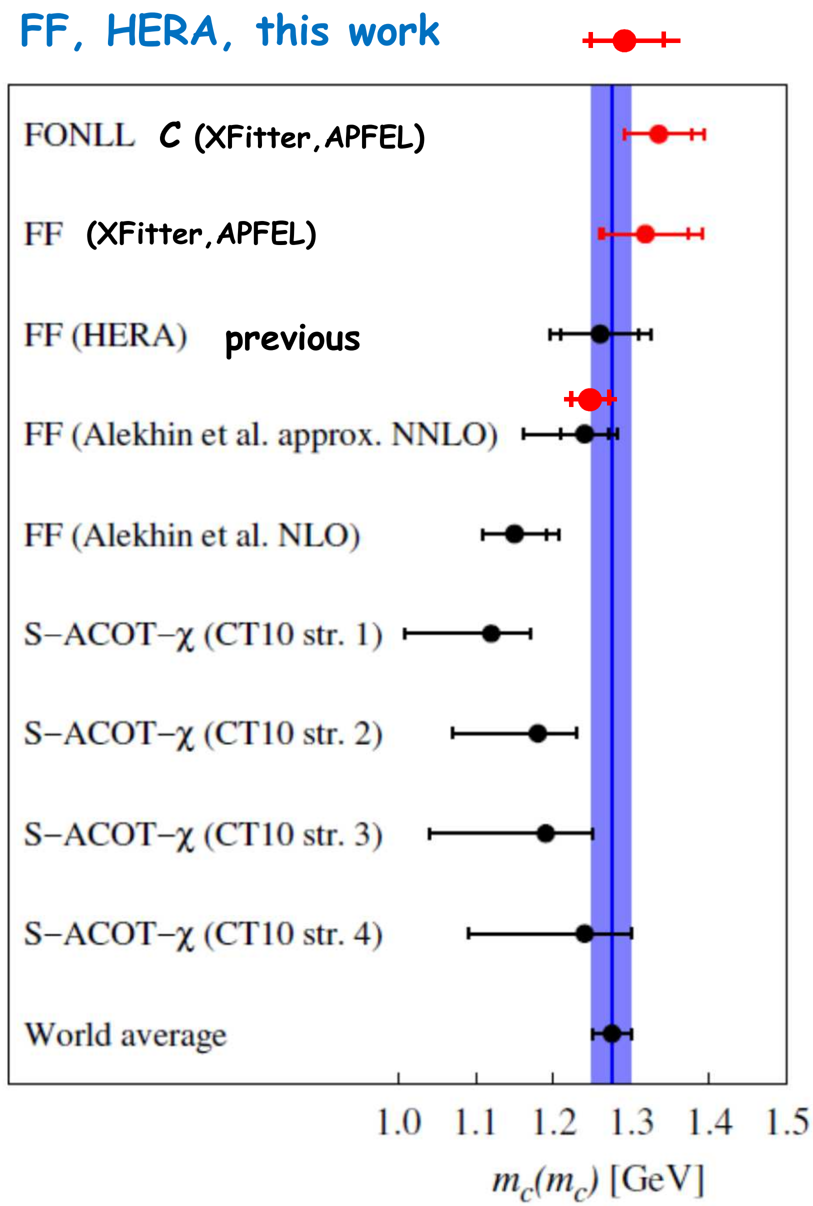
this work:

$m_c(m_c) = 1.29\ ^{+0.05}_{-0.04}\ \text{exp/fit}\ ^{+0.06}_{-0.01}\ \text{mod/scale}\ ^{+0.00}_{-0.03}\ \text{par}$ GeV

latest ABMP16 result: $m_c(m_c) = 1.252 \pm 0.018 \pm 0.032$ GeV
S. Alekhin et al., arXiv:1701.05383,
Phys. Rev. D96 (2017) 014011

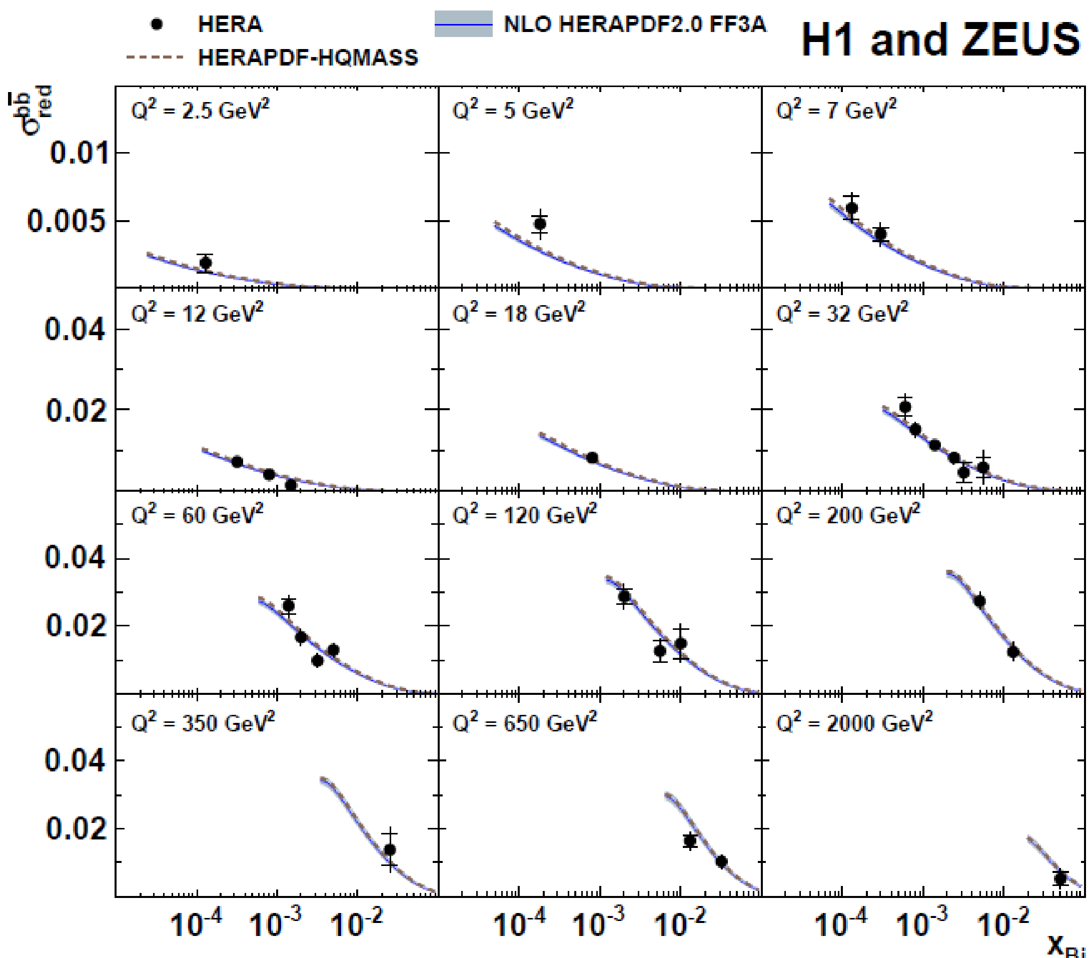
previous results summarized in
V. Bertone et al., arXiv:1605.01946,
JHEP 1608 (2016) 050 :

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



QCD fit: beauty subset

arXiv:1804.01019



fully consistent with
HERAPDF FF3A

new: $m_b(m_b) = 4.05\ ^{+0.10}_{-0.11}\ \text{exp/fit}\ ^{+0.09}_{-0.03}\ \text{mod/scale}\ ^{+0.00}_{-0.03}\ \text{par}$ GeV

ZEUS: $m_b(m_b) = 4.07 \pm 0.14_{\text{exp/fit}}\ ^{+0.08}_{-0.08}\ \text{mod/scale}\ ^{+0.05}_{-0.00}\ \text{par}$ GeV

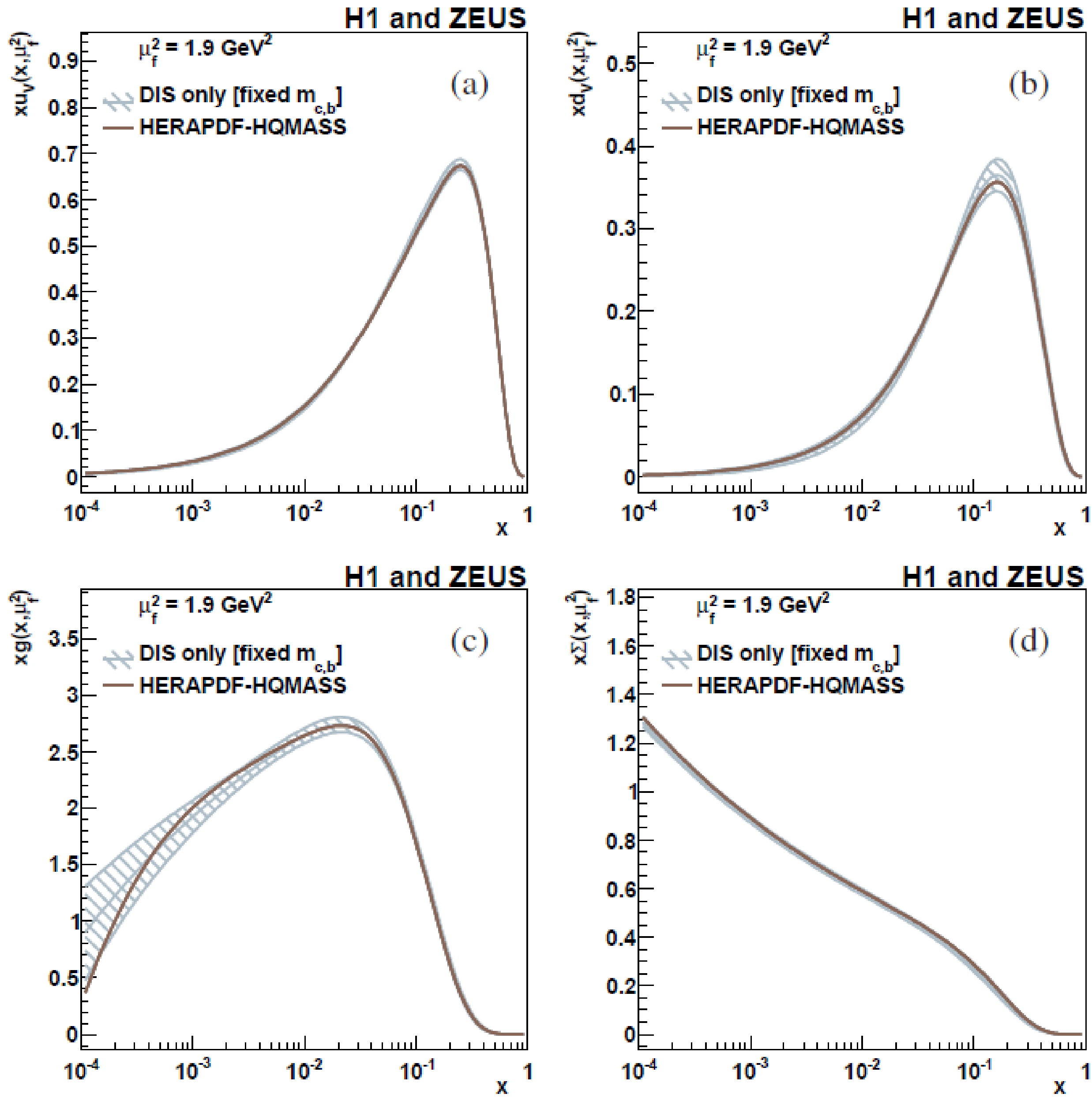
PDG: 4.18 ± 0.03 GeV (lattice QCD + time-like processes)

QCD fit: inclusive data subset

arXiv:1804.01019

PDFs consistent with those of inclusive data only
(and c, b masses fixed to PDG)

-> **inclusive data**
(and c,b mass values)
dominate in fixing PDF



QCD fit: inclusive data, parametrisation uncert.

Reminder, **full fit**: $\Delta\chi^2=1$ scale dom 14p->15p,13p

- **$m_c(m_c)$ = 1290 $^{+46}_{-41}$(exp/fit) $^{+62}_{-14}$(mod) $^{+3}_{-31}$(par) MeV**
- **$m_b(m_b)$ = 4049$^{+104}_{-109}$(exp/fit)$^{+90}_{-32}$(mod) $^{+1}_{-31}$(par) MeV**

dominant effect:

Using **inclusive HERA data only** (14p):

- $m_c(m_c)$ = 1798$^{+144}_{-134}$ (exp/fit) MeV
- $m_b(m_b)$ = 8450$^{+2280}_{-1810}$(fit) MeV

no full uncertainty evaluation, but large sensitivity to **PDF parametrisation** (-> 13p):

- $m_c(m_c)$ = 1798 -> 1450 MeV,
- $m_b(m_b)$ = 8450 -> 3995 MeV

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

13p: $E_{u_v} = 0$

-> inclusive HERA data alone cannot constrain HQ masses reliably

-> interplay of PDFs and HQ masses needs careful treatment

QCD fit: charm x slope

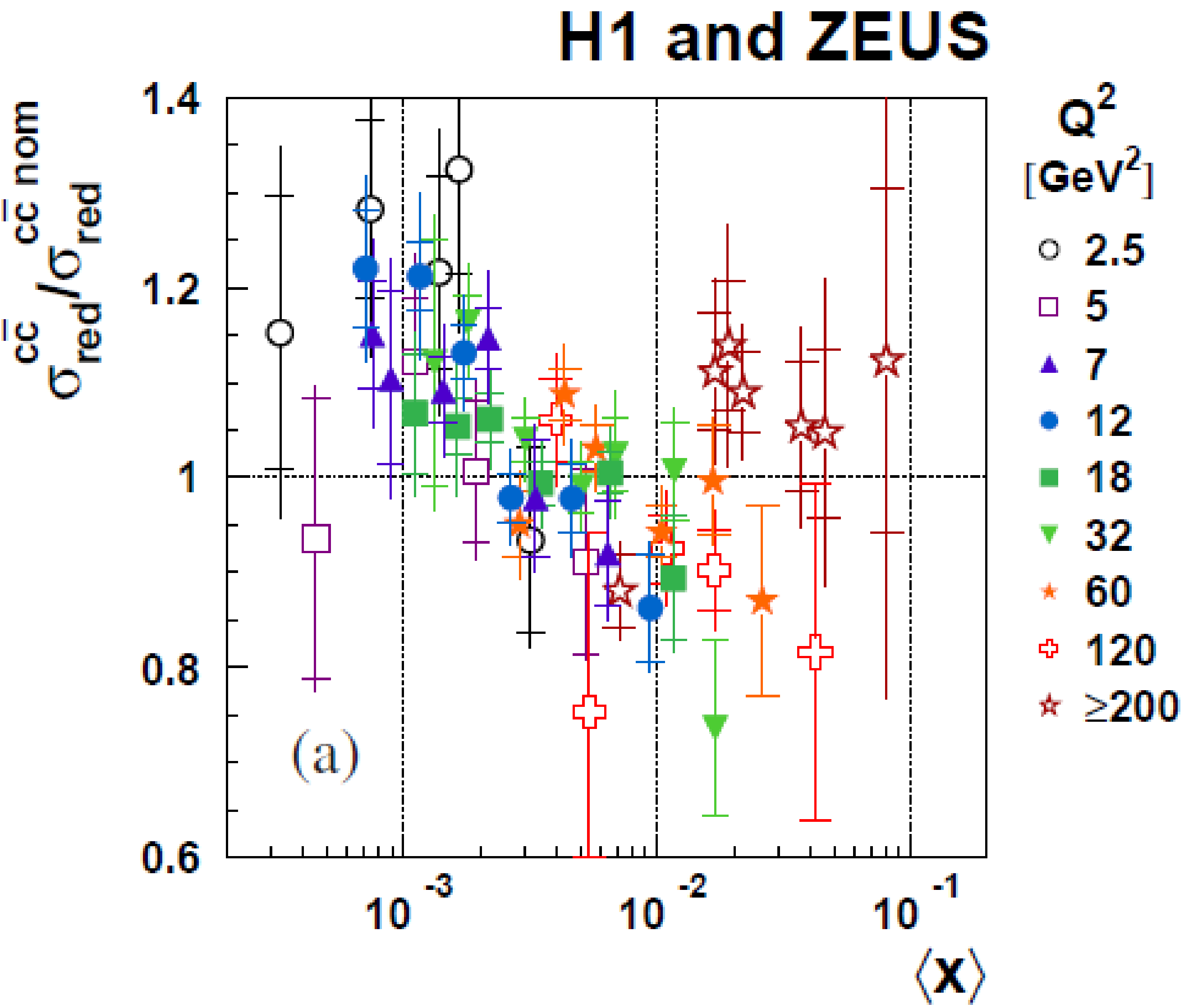
arXiv:1804.01019

plot **data/fit**
vs. <x> of
incoming partons
(rather than x_{Bj})
for each data point

LO: $x = x_{\mathrm{Bj}} \cdot \left(1 + \frac{\hat{s}}{Q^2}\right)$

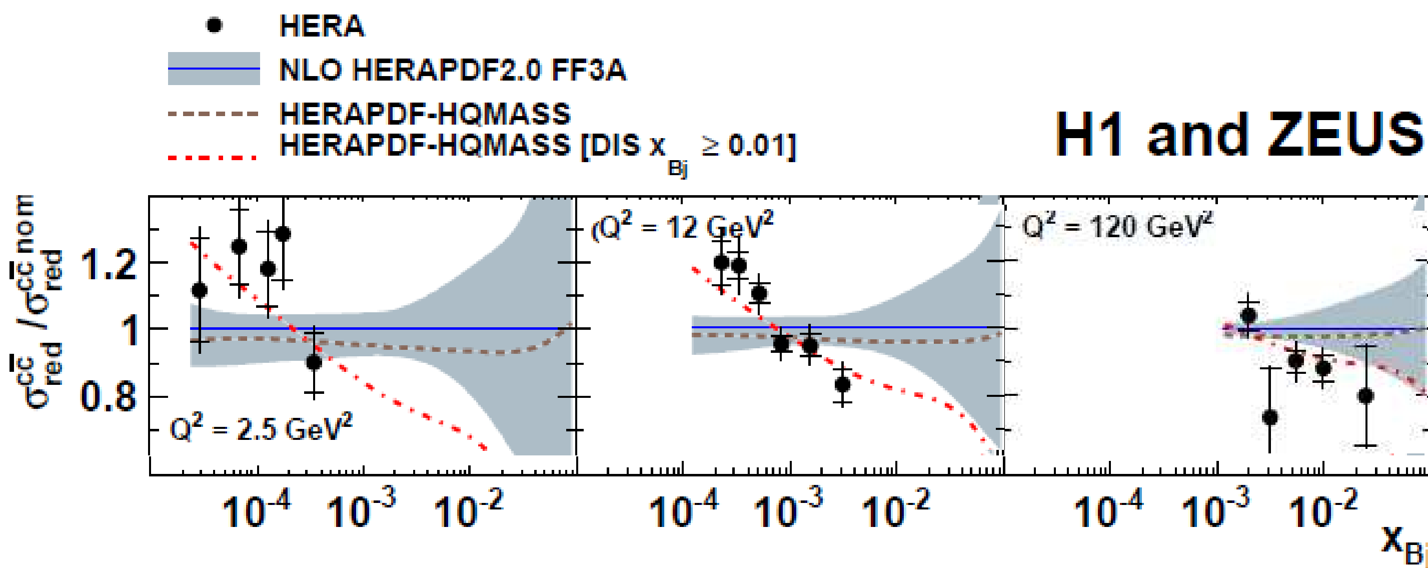
<x> calculated at **NLO**
using HVQDIS

-> common <x> trend
for all Q^2

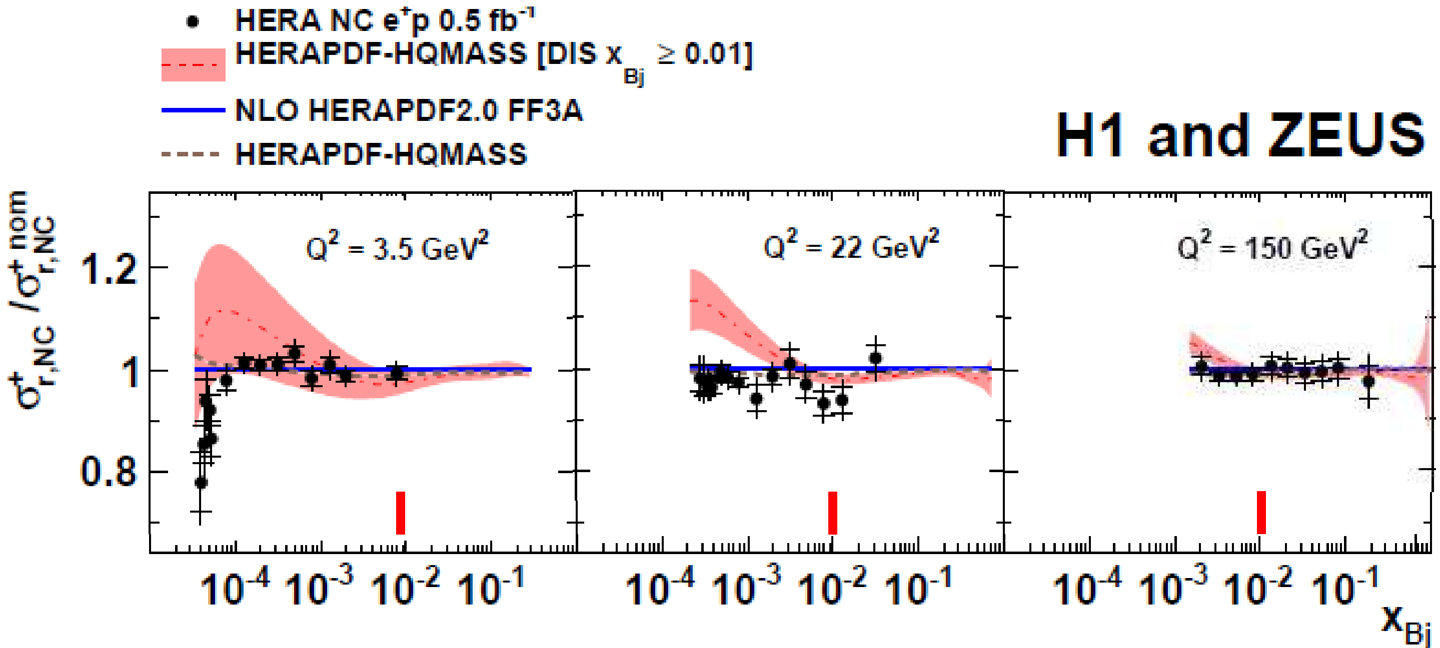


QCD fit with $x_{Bj} > 0.01$ for inclusive data

can **improve**
low x charm slope
(no longer constrained by inclusive)



but **fails to describe low x inclusive data**



-> not a solution
(but hint)

Conclusions

- **Final HERA charm and beauty data in DIS have been combined including all correlations**
  charm precision improved by ~20%, beauty combined for the first time

- **Data are reasonably described by FFNS** (best) **and VFNS predictions** (NLO better than approx. NNLO), **but show ~3σ tension in x slope** w.r.t inclusive

- **QCD fit of inclusive, charm and beauty data** (simultaneous fit of PDFs, m_c and m_b in FFNS at NLO) **yields**

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

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

  in agreement with world average and previous measurements

  (not affected by x slope tension within uncertainties)

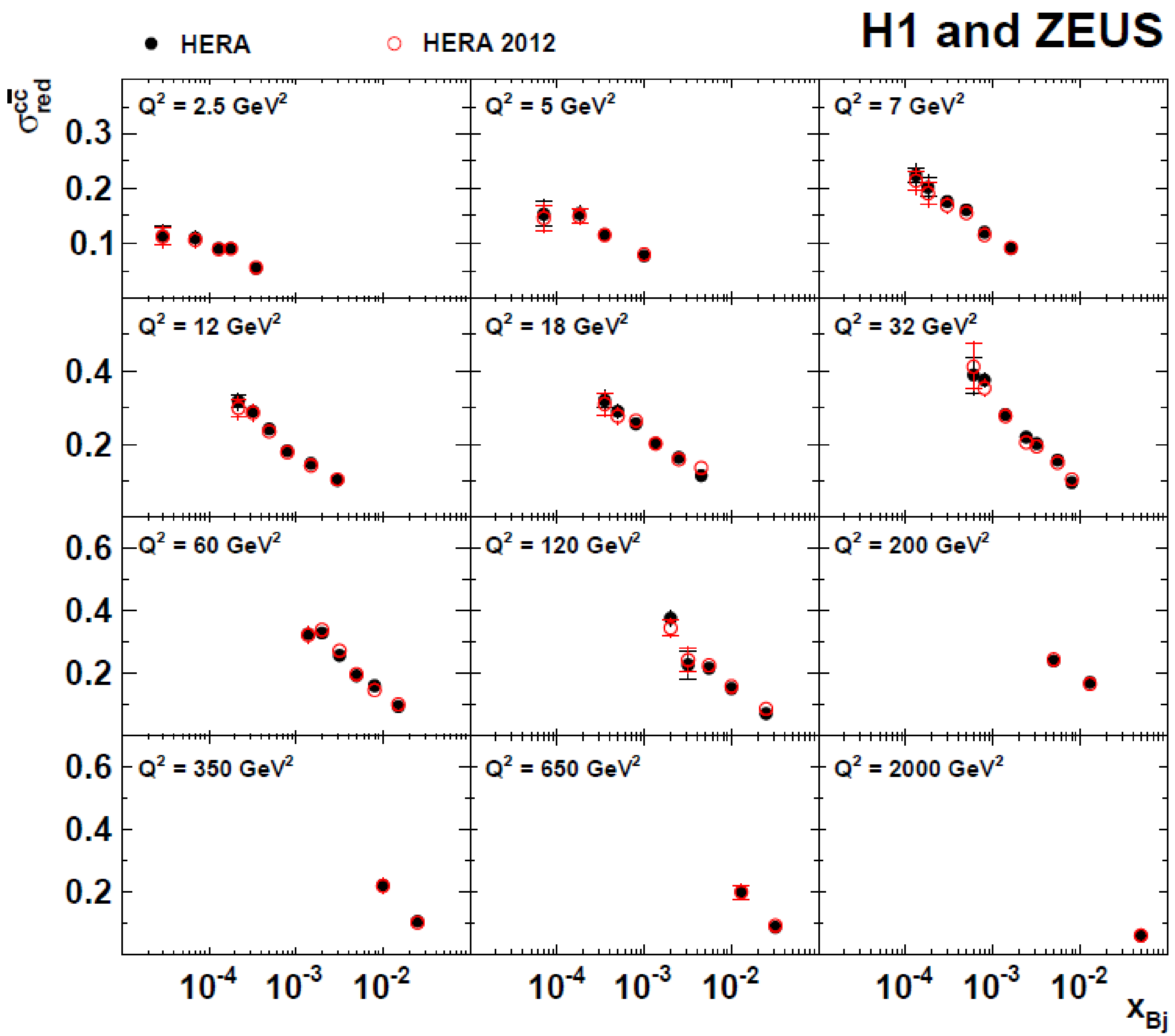
- More detailed studies of x slope tension -> **can not be solved by varying the gluon density, or adding higher orders, or resumming log 1/x terms,** within the respective pQCD frameworks

  -> further investigations useful

Backup

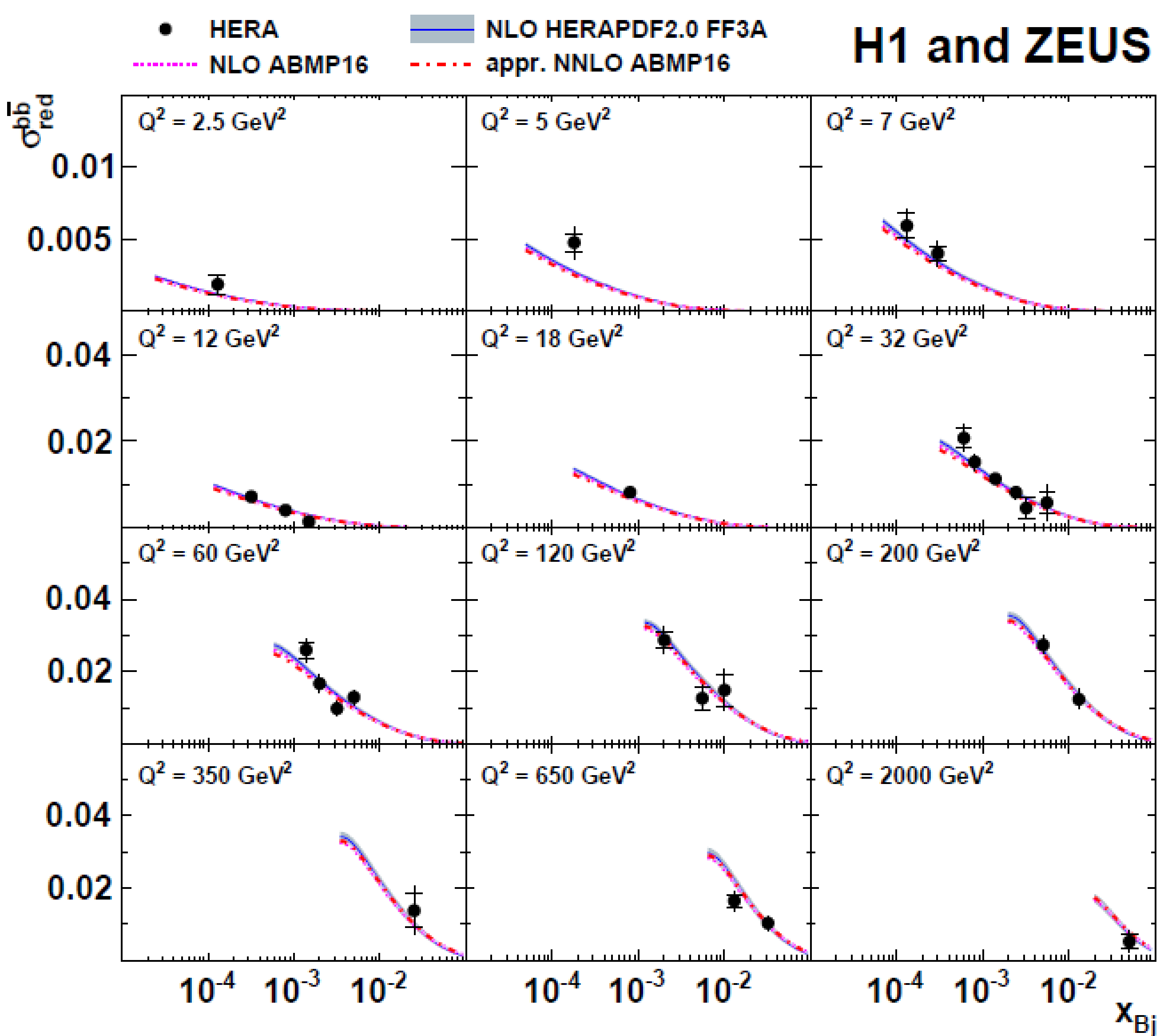
Comparison to previous charm combination

arXiv:1804.01019



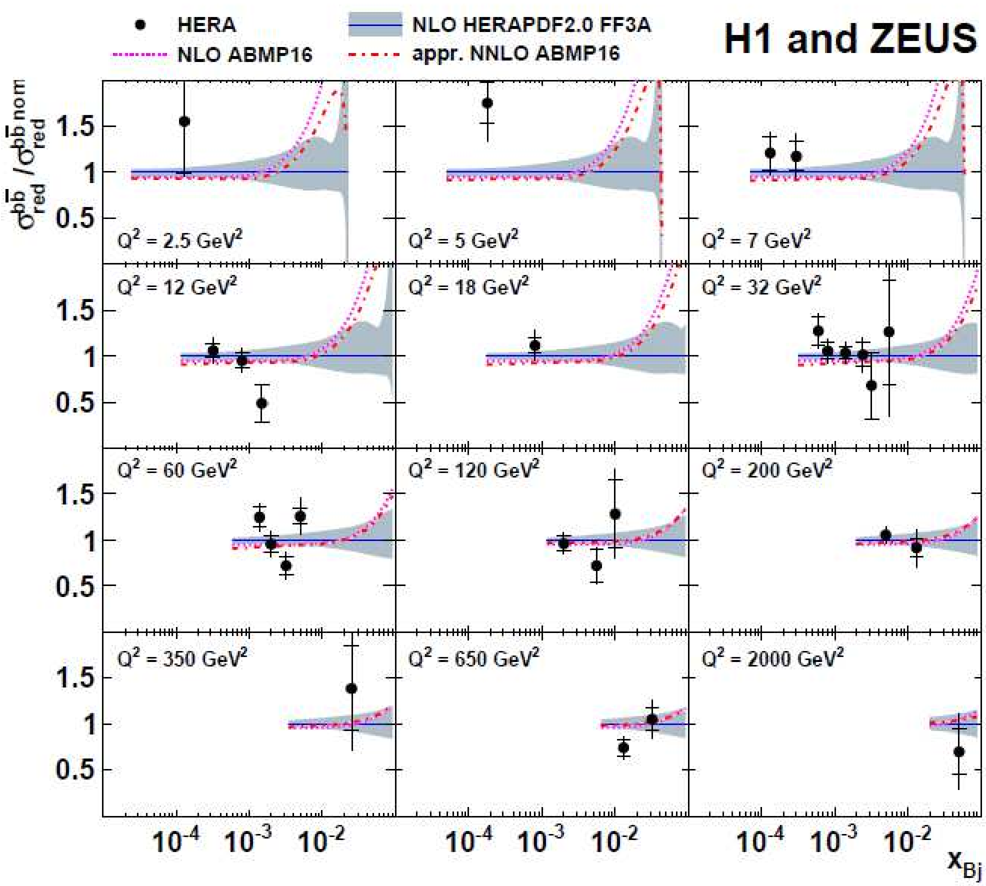
Comparison to FFNS predictions

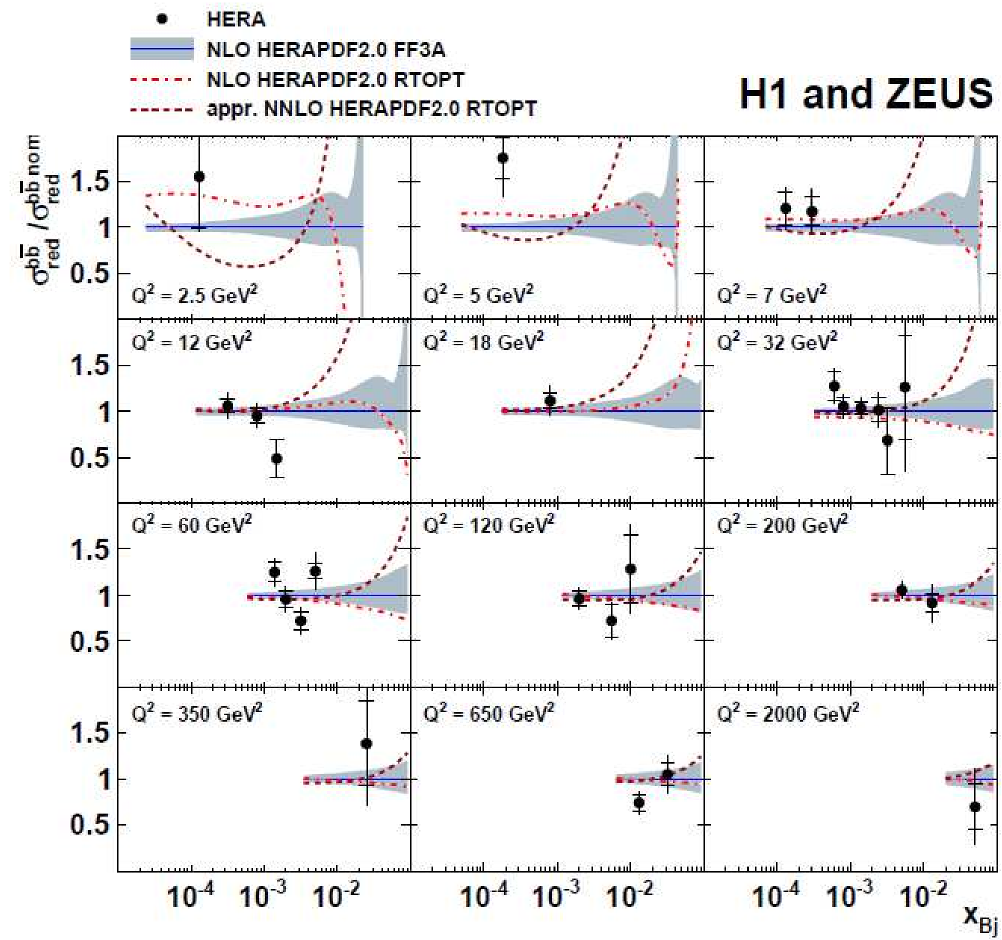
beauty:



Comparison to FFNS and VFNS predictions

Beauty:





QCD fit: systematic uncertainties

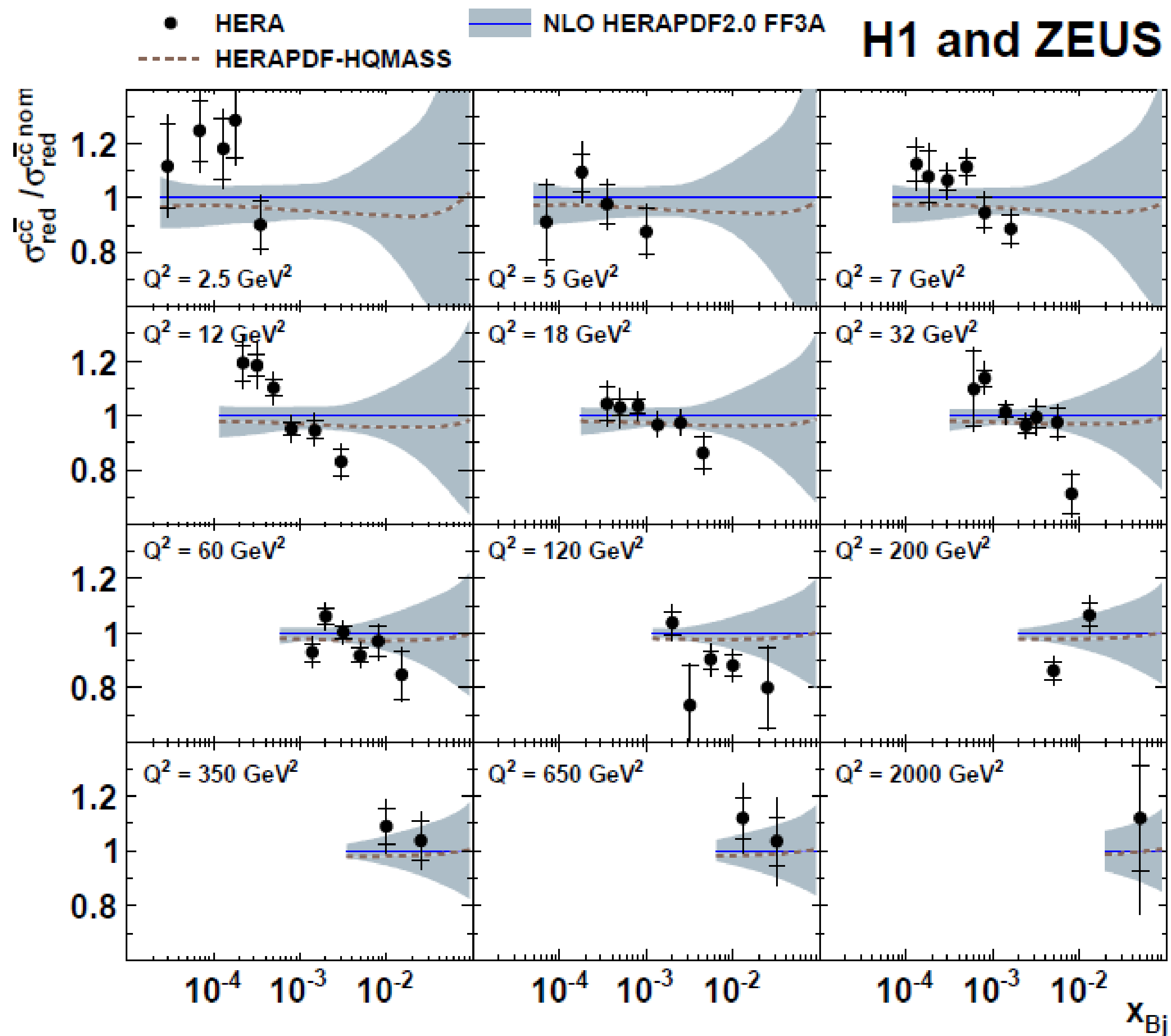
arXiv:1804.01019

Parameter	Variation	$m_c(m_c)$ uncertainty [GeV]	$m_b(m_b)$ uncertainty [GeV]
Experimental / Fit uncertainty			
Total	$\Delta\chi^2 = 1$	$^{+0.046}_{-0.041}$	$^{+0.104}_{-0.109}$
Model uncertainty			
f_s	$0.4^{+0.1}_{-0.1}$	$^{-0.003}_{+0.004}$	$^{-0.001}_{+0.001}$
$Q^2_{\rm min}$	$3.5^{+1.5}_{-1.0}$ GeV^2	$^{-0.001}_{+0.007}$	$^{-0.005}_{+0.007}$
$\mu_{r,f}$	$\mu_{r,f}\,^{\times 2.0}_{\times 0.5}$	$^{+0.030}_{+0.060}$	$^{-0.032}_{+0.090}$
$\alpha_s^{n_f=3}(M_Z)$	$0.1060^{+0.0015}_{-0.0015}$	$^{-0.014}_{+0.011}$	$^{+0.002}_{-0.005}$
Total		$^{+0.062}_{-0.014}$	$^{+0.090}_{-0.032}$
PDF parameterisation uncertainty			
$\mu^2_{f,0}$	1.9 ± 0.3 GeV^2	$^{+0.003}_{-0.001}$	$^{-0.001}_{+0.001}$
E_{u_v}	set to 0	-0.031	-0.031
Total		$^{+0.003}_{-0.031}$	$^{+0.001}_{-0.031}$

Table 5: List of uncertainties for the charm- and beauty-quark mass determination. The PDF parameterisation uncertainties not shown have no effect on $m_c(m_c)$ and $m_b(m_b)$.

QCD fit: charm

arXiv:1804.01019

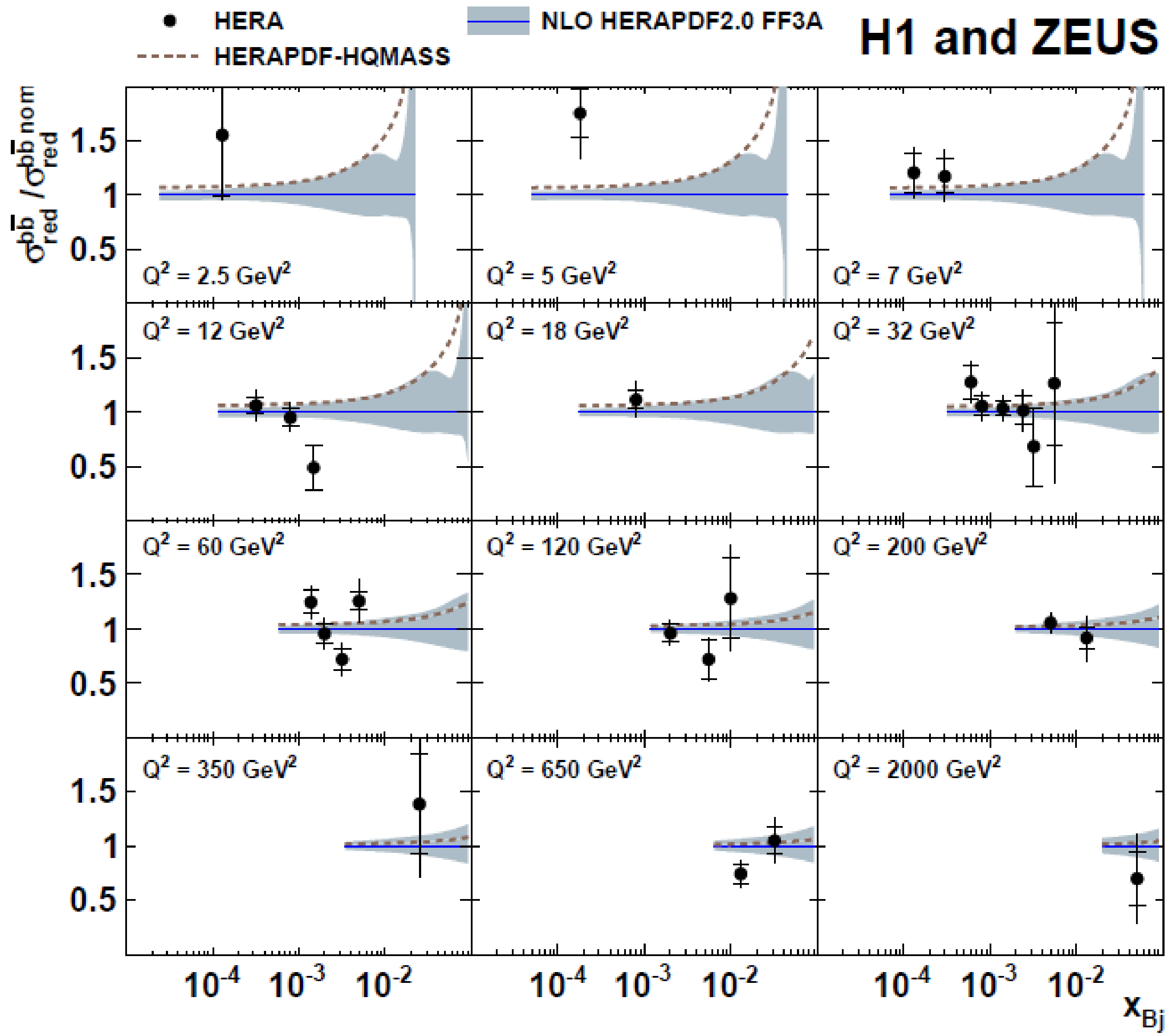


fully consistent with HERAPDF2.0FF3A

QCD fit: beauty

arXiv:1804.01019

fully consistent with HERAPDF2.0FF3A



QCD fit: beauty x slope

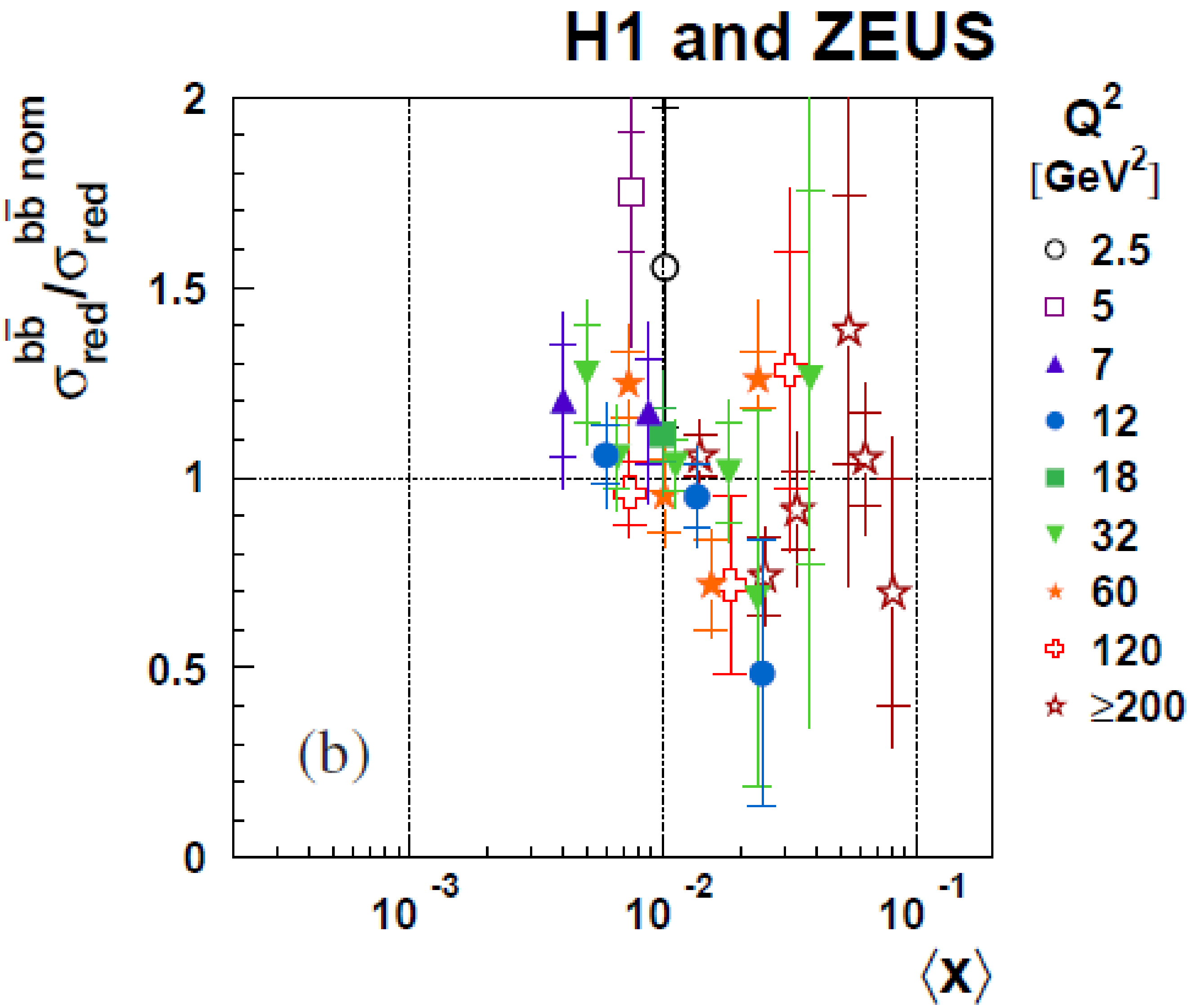
arXiv:1804.01019

plot data/fit
vs. <x> of
incoming partons
(rather than x_{Bj})
for each data point

LO: $x = x_{\mathrm{Bj}} \cdot \left(1 + \frac{\hat{s}}{Q^2}\right)$

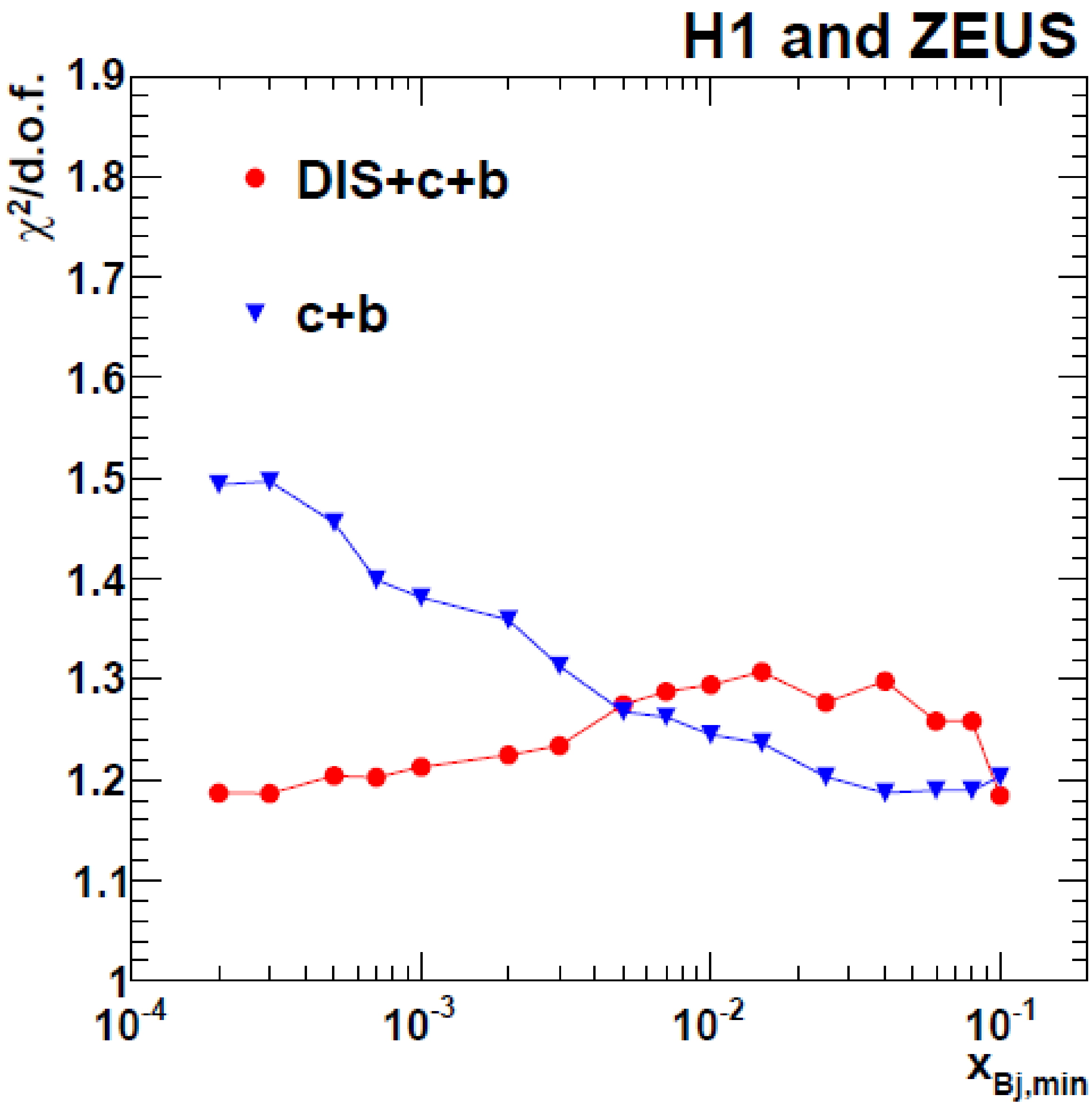
<x> calculated at NLO
using HVQDIS

-> **beauty consistent with charm but does not add information**



χ^2 as function of min. x_{Bj} cut

arXiv:1804.01019

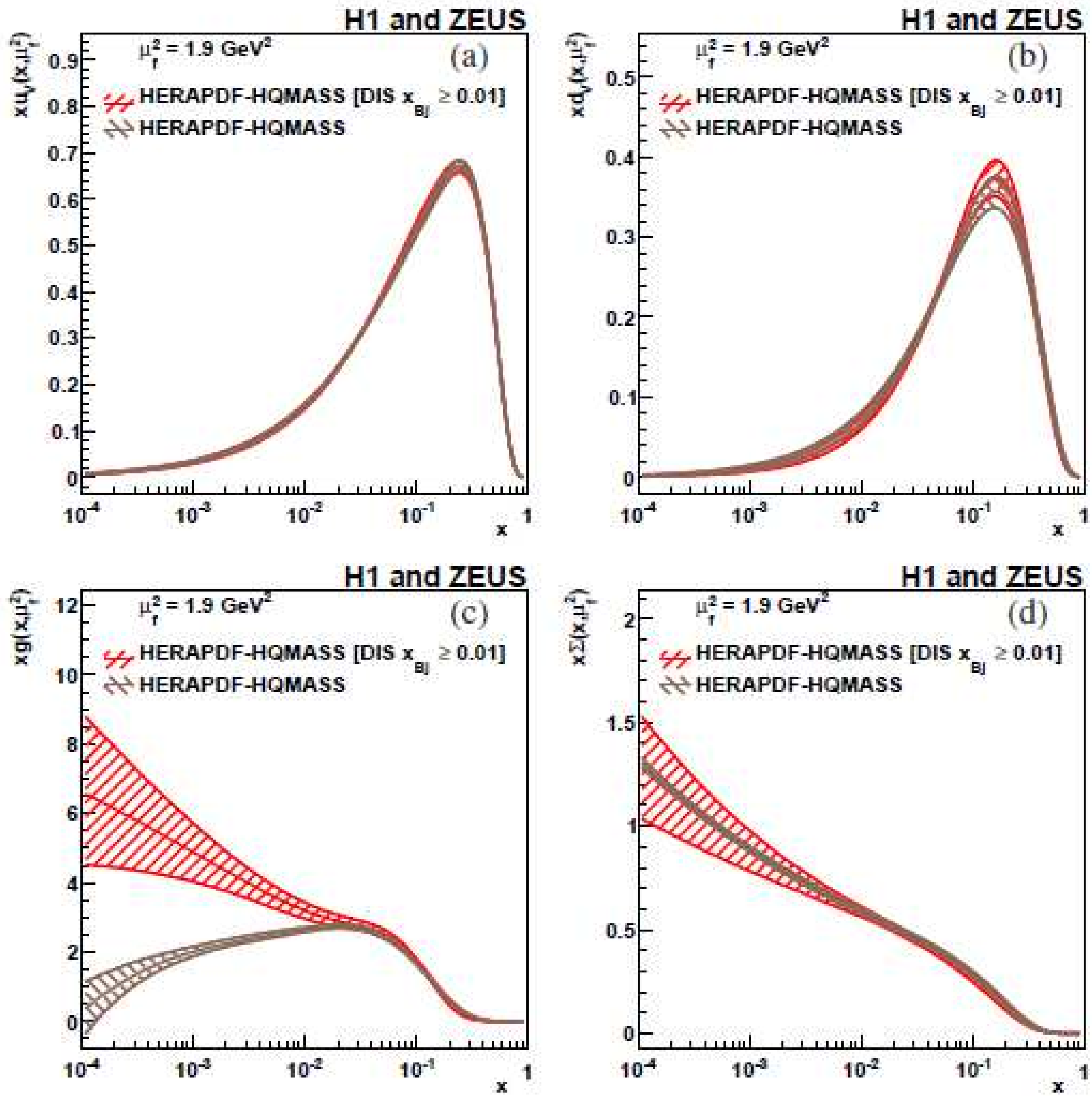


QCD fit with $x_{Bj} > 0.01$ for inclusive data

arXiv:1804.01019

charm and
beauty mass
floating

gluon at $x < 0.01$
inconsistent
with
inclusive fit



FONLL-C fit of inclusive data

arXiv:1802.00064 (XFitter team):

FONLL-C inclusive fit with and without NLLx resummation

personal remark:

FONLL-C inclusive fit with NLLx qualitatively consistent with FF charm

+ x > 0.01 inclusive fit (compare previous slide)

-> combine both worlds by applying NLLx to light flavours only in FF scheme?

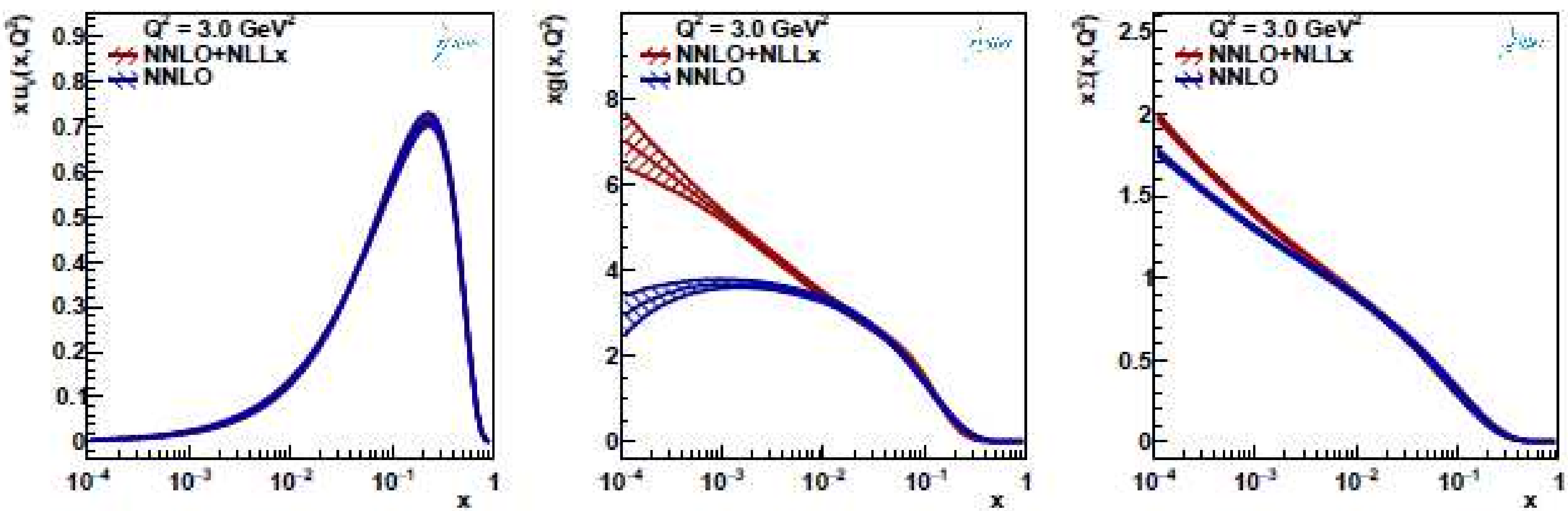


Figure 3 The up valence PDF xu_v, the gluon PDF xg and the total singlet PDF $x\Sigma$ for the final fits with (NNLO+NLLx) and without (NNLO) $\ln(1/x)$ resummation.

Comparison of HERAPDF with FONLL-C + NLLx

for inclusive data only

from arXiv:1802.00064 :

	Step-1	Step-2	Step-3	Step-4
	HERAPDF2.0 NNLO	FONLL-C	Move Q_0^2 and charm threshold	include NLLx resummation
HERA χ^2/d.o.f	1363/1131	1387/1131	1389/1131	1316/1131

Table 1 The χ^2 per degree of freedom (d.o.f.) for the PDF fits under different conditions, starting from the settings for the HERAPDF2.0 NNLO.

from arXiv:1506.06042:

HERAPDF	Q^2_{min}[GeV^2]	χ^2	d.o.f.	χ^2/d.o.f
2.0 NLO	3.5	1357	1131	1.200
2.0HiQ2 NLO	10.0	1156	1002	1.154
2.0 NNLO	3.5	1363	1131	1.205
2.0HiQ2 NNLO	10.0	1146	1002	1.144
2.0 AG NLO	3.5	1359	1132	1.201
2.0HiQ2 AG NLO	10.0	1161	1003	1.158
2.0 AG NNLO	3.5	1385	1132	1.223
2.0HiQ2 AG NNLO	10.0	1175	1003	1.171
2.0 NLO FF3A	3.5	1351	1131	1.195
2.0 NLO FF3B	3.5	1315	1131	1.163
2.0Jets $\alpha_s(M_Z^2)$ fixed	3.5	1568	1340	1.170
2.0Jets $\alpha_s(M_Z^2)$ free	3.5	1568	1339	1.171

Table 4: The values of χ^2 per degree of freedom for HERAPDF2.0 and its variants.

inclusion of NLLx resummation with FONLL-C achieves similar performance as HERAPDF2.0 FF3B