Impact of heavy-quark production measurements on PDFs in the CT18 global QCD analysis

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The CT18 analysis

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Editors' Suggestion

New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC

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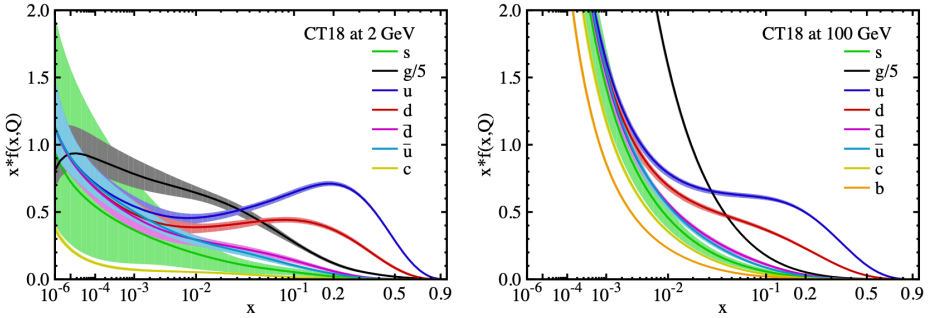


TABLE I. Datasets included in the CT18(Z) NNLO global analyses. Here we directly compare the quality of fit found for CT18 NNLO vs CT18Z NNLO on the basis of χ^2_E, $\chi^2_E/N_{pt,E}$, and S_E, in which $N_{pt,E}$, χ^2_E are the number of points and value of χ^2 for experiment E at the global minimum. S_E is the effective Gaussian parameter [38,42,56] quantifying agreement with each experiment. The ATLAS 7 TeV 35 pb^{-1} W/Z dataset, marked by ‡‡, is replaced by the updated one (4.6 fb^{-1}) in the CT18A and CT18Z fits. The CDHSW data, labeled by †, are not included in the CT18Z fit. The numbers in parentheses are for the CT18Z NNLO fit.

Exp. ID#	Experimental dataset		$N_{pt,E}$	χ^2_E	$\chi^2_E/N_{pt,E}$	S_E
160	HERAI + II 1 fb^{-1}, H1 and ZEUS NC and CC $e^{\pm}p$ reduced cross sec. comb.	[30]	1120	1408 (1378)	1.3 (1.2)	5.7 (5.1)
101	BCDMS F_2^p	[57]	337	374 (384)	1.1 (1.1)	1.4 (1.8)
102	BCDMS F_2^d	[58]	250	280 (287)	1.1 (1.1)	1.3 (1.6)
104	NMC F_2^d/F_2^p	[59]	123	126 (116)	1.0 (0.9)	0.2 (−0.4)
108†	CDHSW F_2^p	[60]	85	85.6 (86.8)	1.0 (1.0)	0.1 (0.2)
109†	CDHSW $x_B F_3^p$	[60]	96	86.5 (85.6)	0.9 (0.9)	−0.7 (−0.7)
110	CCFR F_2^p	[61]	69	78.8 (76.0)	1.1 (1.1)	0.9 (0.6)
111	CCFR $x_B F_3^p$	[62]	86	33.8 (31.4)	0.4 (0.4)	−5.2 (−5.6)
124	NuTeV $\nu\mu\mu$ SIDIS	[63]	38	18.5 (30.3)	0.5 (0.8)	−2.7 (−0.9)
125	NuTeV $\bar{\nu}\mu\mu$ SIDIS	[63]	33	38.5 (56.7)	1.2 (1.7)	0.7 (2.5)
126	CCFR $\nu\mu\mu$ SIDIS	[64]	40	29.9 (35.0)	0.7 (0.9)	−1.1 (−0.5)
127	CCFR $\bar{\nu}\mu\mu$ SIDIS	[64]	38	19.8 (18.7)	0.5 (0.5)	−2.5 (−2.7)
145	H1 σ_r^b	[65]	10	6.8 (7.0)	0.7 (0.7)	−0.6 (−0.6)
147	Combined HERA charm production	[66]	47	58.3 (56.4)	1.2 (1.2)	1.1 (1.0)
169	H1 F_L	[33]	9	17.0 (15.4)	1.9 (1.7)	1.7 (1.4)
201	E605 Drell-Yan process	[67]	119	103.4 (102.4)	0.9 (0.9)	−1.0 (−1.1)
203	E866 Drell-Yan process $\sigma_{pd}/(2\sigma_{pp})$	[68]	15	16.1 (17.9)	1.1 (1.2)	0.3 (0.6)
204	E866 Drell-Yan process $Q^3 d^2\sigma_{pp}/(dQdx_F)$	[69]	184	244 (240)	1.3 (1.3)	2.9 (2.7)
225	CDF run-1 lepton A_{ch}, $p_{T\ell} > 25$ GeV	[70]	11	9.0 (9.3)	0.8 (0.8)	−0.3 (−0.2)
227	CDF run-2 electron A_{ch}, $p_{T\ell} > 25$ GeV	[71]	11	13.5 (13.4)	1.2 (1.2)	0.6 (0.6)
234	DØ run-2 muon A_{ch}, $p_{T\ell} > 20$ GeV	[72]	9	9.1 (9.0)	1.0 (1.0)	0.2 (0.1)
260	DØ run-2 Z rapidity	[73]	28	16.9 (18.7)	0.6 (0.7)	−1.7 (−1.3)
261	CDF run-2 Z rapidity	[74]	29	48.7 (61.1)	1.7 (2.1)	2.2 (3.3)
266	CMS 7 TeV 4.7 fb^{-1}, muon A_{ch}, $p_{T\ell} > 35$ GeV	[75]	11	7.9 (12.2)	0.7 (1.1)	−0.6 (0.4)
267	CMS 7 TeV 840 pb^{-1}, electron A_{ch}, $p_{T\ell} > 35$ GeV	[76]	11	4.6 (5.5)	0.4 (0.5)	−1.6 (−1.3)
268‡‡	ATLAS 7 TeV 35 pb^{-1} W/Z cross sec., A_{ch}	[77]	41	44.4 (50.6)	1.1 (1.2)	0.4 (1.1)
281	DØ run-2 9.7 fb^{-1} electron A_{ch}, $p_{T\ell} > 25$ GeV	[78]	13	22.8 (20.5)	1.8 (1.6)	1.7 (1.4)
504	CDF run-2 inclusive jet production	[79]	72	122 (117)	1.7 (1.6)	3.5 (3.2)
514	DØ run-2 inclusive jet production	[80]	110	113.8 (115.2)	1.0 (1.0)	0.3 (0.4)

TABLE II. Like Table I, for newly included LHC measurements. The ATLAS 7 TeV W/Z data (4.6 fb^{-1}), labeled by ‡, are included in the CT18A and CT18Z global fits, but not in CT18 and CT18X.

Exp. ID#	Experimental dataset		$N_{pt,E}$	χ^2_E	$\chi^2_E/N_{pt,E}$	S_E
245	LHCb 7 TeV 1.0 fb^{-1} W/Z forward rapidity cross sec.	[81]	33	53.8 (39.9)	1.6 (1.2)	2.2 (0.9)
246	LHCb 8 TeV 2.0 fb^{-1} $Z \to e^-e^+$ forward rapidity cross sec.	[82]	17	17.7 (18.0)	1.0 (1.1)	0.2 (0.3)
248‡	ATLAS 7 TeV 4.6 fb^{-1}, W/Z combined cross sec.	[39]	34	287.3 (88.7)	8.4 (2.6)	13.7 (4.8)
249	CMS 8 TeV 18.8 fb^{-1} muon charge asymmetry A_{ch}	[83]	11	11.4 (12.1)	1.0 (1.1)	0.2 (0.4)
250	LHCb 8 TeV 2.0 fb^{-1} W/Z cross sec.	[84]	34	73.7 (59.4)	2.1 (1.7)	3.7 (2.6)
253	ATLAS 8 TeV 20.3 fb^{-1}, Z p_T cross sec.	[85]	27	30.2 (28.3)	1.1 (1.0)	0.5 (0.3)
542	CMS 7 TeV 5 fb^{-1}, single incl. jet cross sec., $R = 0.7$ (extended in y)	[86]	158	194.7 (188.6)	1.2 (1.2)	2.0 (1.7)
544	ATLAS 7 TeV 4.5 fb^{-1}, single incl. jet cross sec., $R = 0.6$	[9]	140	202.7 (203.0)	1.4 (1.5)	3.3 (3.4)
545	CMS 8 TeV 19.7 fb^{-1}, single incl. jet cross sec., $R = 0.7$, (extended in y)	[87]	185	210.3 (207.6)	1.1 (1.1)	1.3 (1.2)
573	CMS 8 TeV 19.7 fb^{-1}, $t\bar{t}$ norm. double-diff. top p_T and y cross sec.	[88]	16	18.9 (19.1)	1.2 (1.2)	0.6 (0.6)
580	ATLAS 8 TeV 20.3 fb^{-1}, $t\bar{t}$ p_T^t and $m_{t\bar{t}}$ abs. spectrum	[89]	15	9.4 (10.7)	0.6 (0.7)	−1.1 (−0.8)

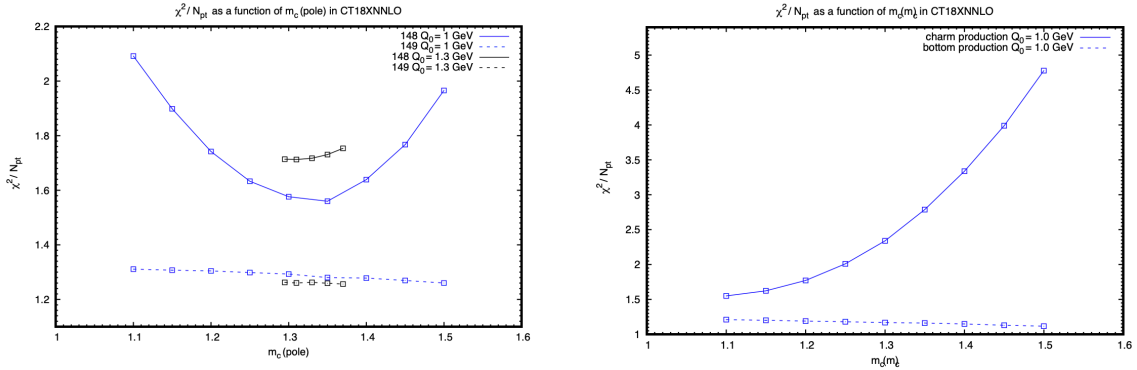
Heavy-flavor production measurements at HERA and LHC currently included in CT18.

2018: New Combination of charm and beauty production at HERA, EPJC (2018), [arXiv:1804.01019].
This analysis extends previous H1 and ZEUS combination of *c* measurements in DIS (EPJC73, (2013) [arXiv:1211.1182]), and includes new *c* and *b* data.

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]

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.

CT18NNLO with new *c* and *b* combination



CT18 global fit discussed in this talk

NNPDF4.0: Fit quality – NNLO

Data set	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
Fixed-target DIS	1881	1.10
HERA	1208	1.21
σ_c	37	2.11
σ_b	26	1.48
Fixed-target Drell-Yan	189	1.00
CDF	28	1.31
D0	37	1.00

Overall good description of the data sets

Two exceptions:

HERA σ_c and ATLAS top pair

Weighted fits analysis:

In case of HERA σ_c:

lack of small-x resummation

See E. Nocera's Talk PDF4LHC March 22nd 2021

MSHT2020 global PDF analysis 2012.04684 [hep-ph]

We remove the combined HERA data on $F_c(x, Q^2)$ [89] and use the final combined data on both $F_c(x, Q^2)$ and $F_b(x, Q^2)$ including full information on the statistical and systematic correlations between them [26]. The fit quality, with $\chi^2/N_{\rm pts} = 1.68$ for 79 points at NNLO, is rather higher than one might expect. However, this appears to be similar to predictions from other groups

See R. Thorne's talk PDF4LHC March 22nd 2021

It seems that all PDF groups are having issues when they include these measurements in their global QCD analyses

- Are these data telling us something?
- Is QCD violated here?
- Is there any BSM model that explains these data?
- ….

Combined charm and bottom HERA SIDIS data

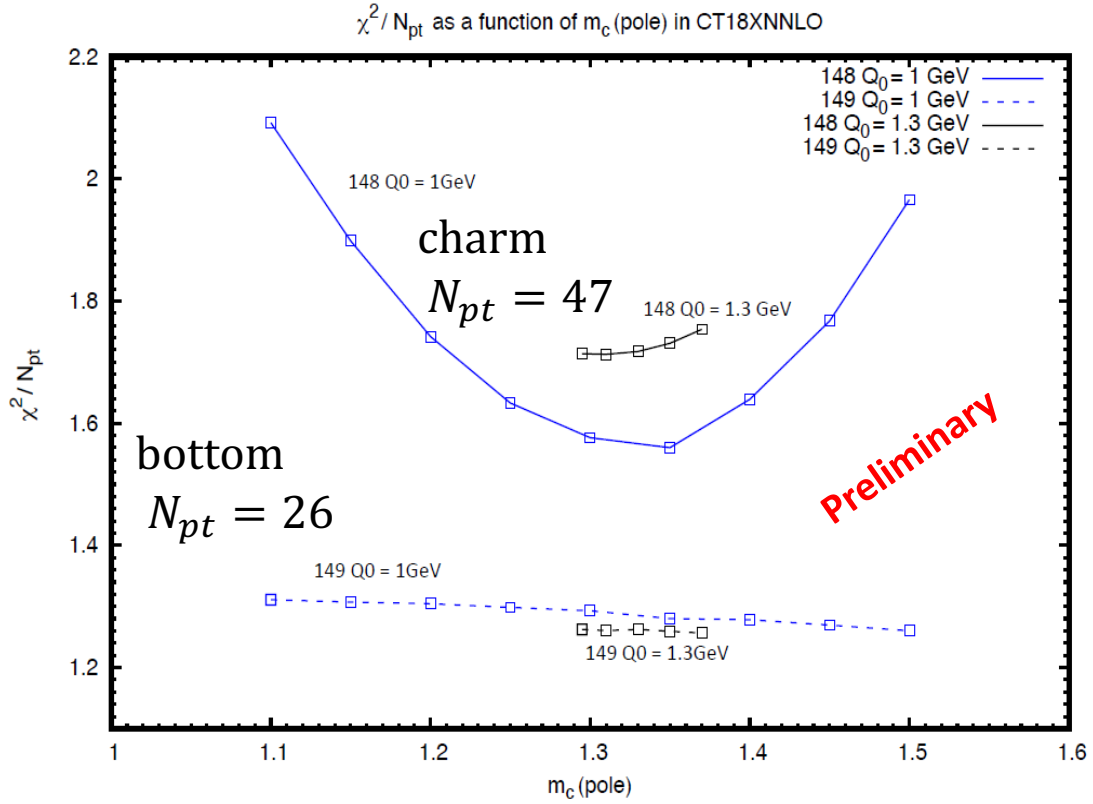
(H1 and ZEUS Coll. 1804.01019) **in the CT18 analysis**

We fit these data using the SACOT-χ heavy-quark scheme at NNLO.

In all tried scenarios, we get χ^2/N_{pt} no less than 1.5, reached when the combined HERA HQ SIDIS data is included with a large statistical weight (100).

These data prefer a harder gluon at intermediate and small x.

Our χ^2 values are similar to those found by MSHT20 and to predictions from other groups reported in Table 4 of the HERA publication.



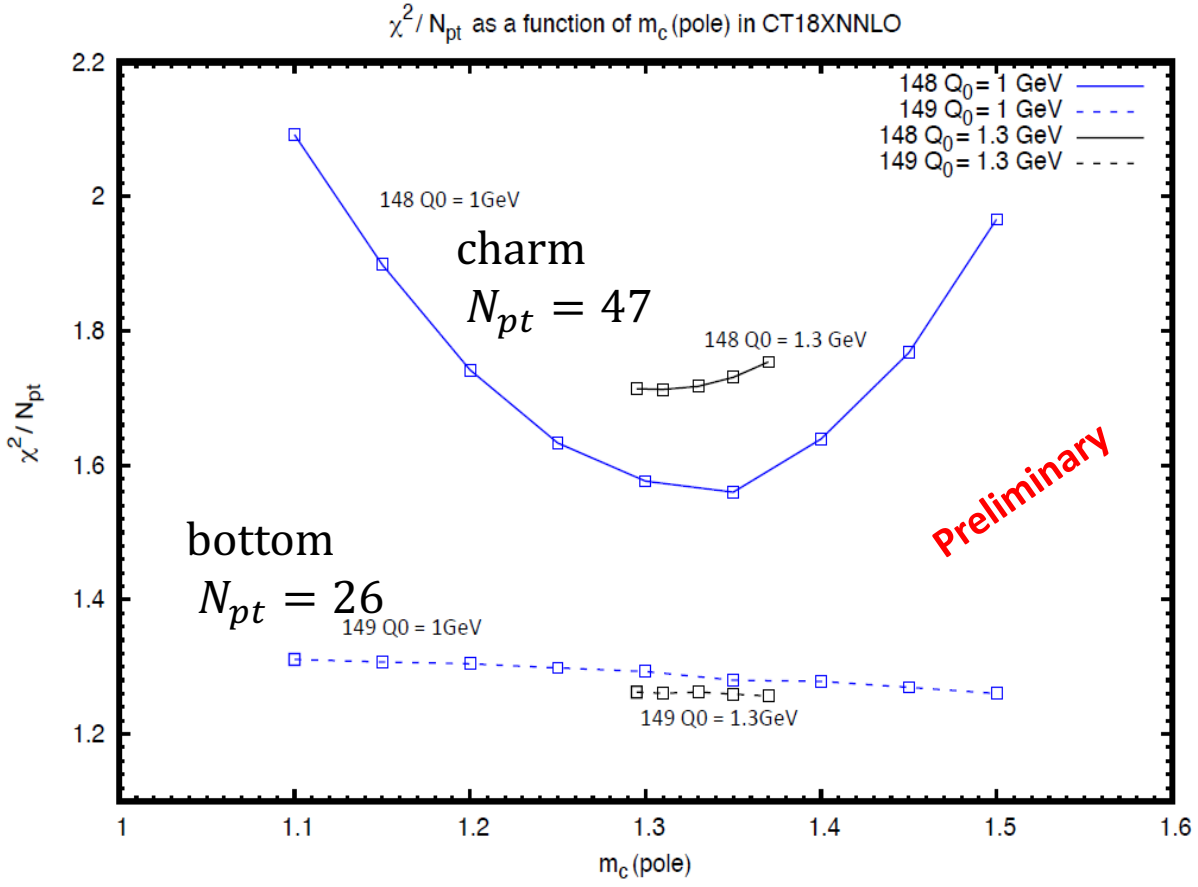
Combined charm and bottom HERA SIDIS data

(H1 and ZEUS Coll. 1804.01019) **in the CT18 analysis**

We explored the following alternative settings in various combinations:

- Fits with increased weights of HERA HQ SIDIS data
- alternative parametrizations of the gluon
- varied MS-bar and pole m_c
- varied initial scale Q_0
- varied parameters of the x-dependent DIS factorization scale
- varied S-ACOT-χ rescaling parameter

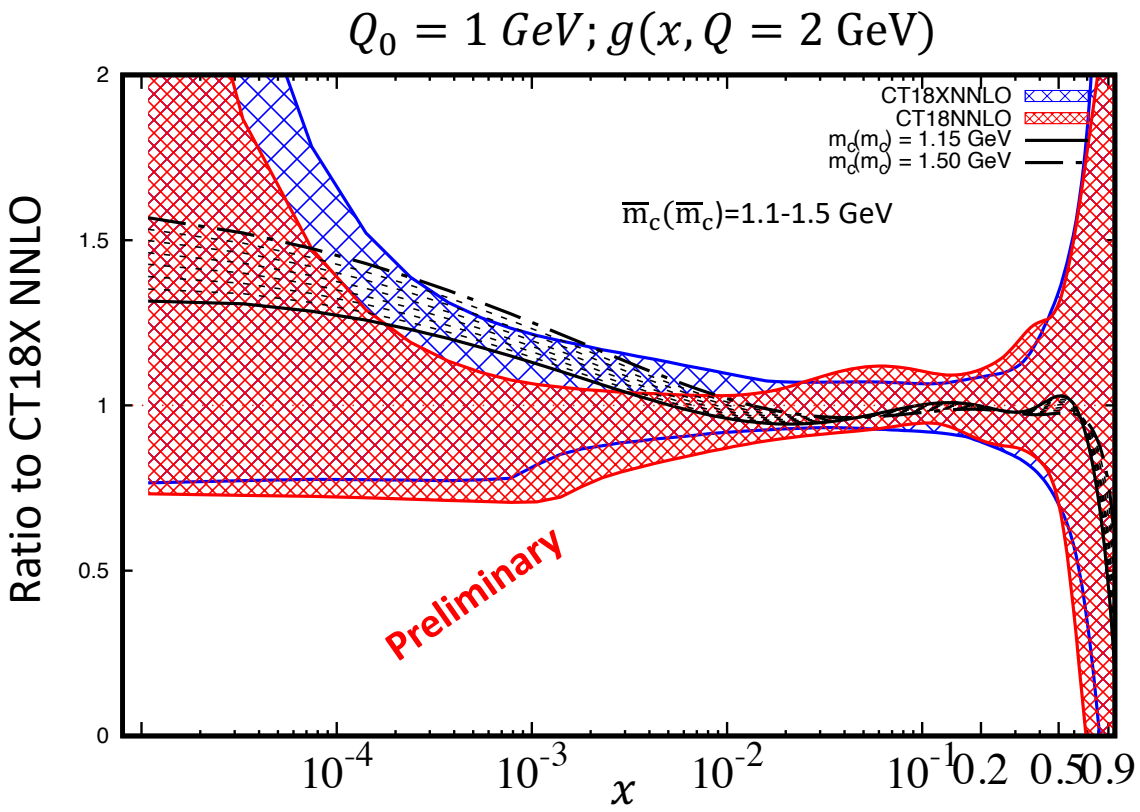
For large weights of the HERA c/b data, the opposing χ^2 pulls arise from:
LHCb 7 and 8 TeV W/Z Xsec, ATLAS 7 and CDF Run-2 incl. jets, CDF Run-2 Z rapidity and D0 Run-2 ele A_{ch} data.

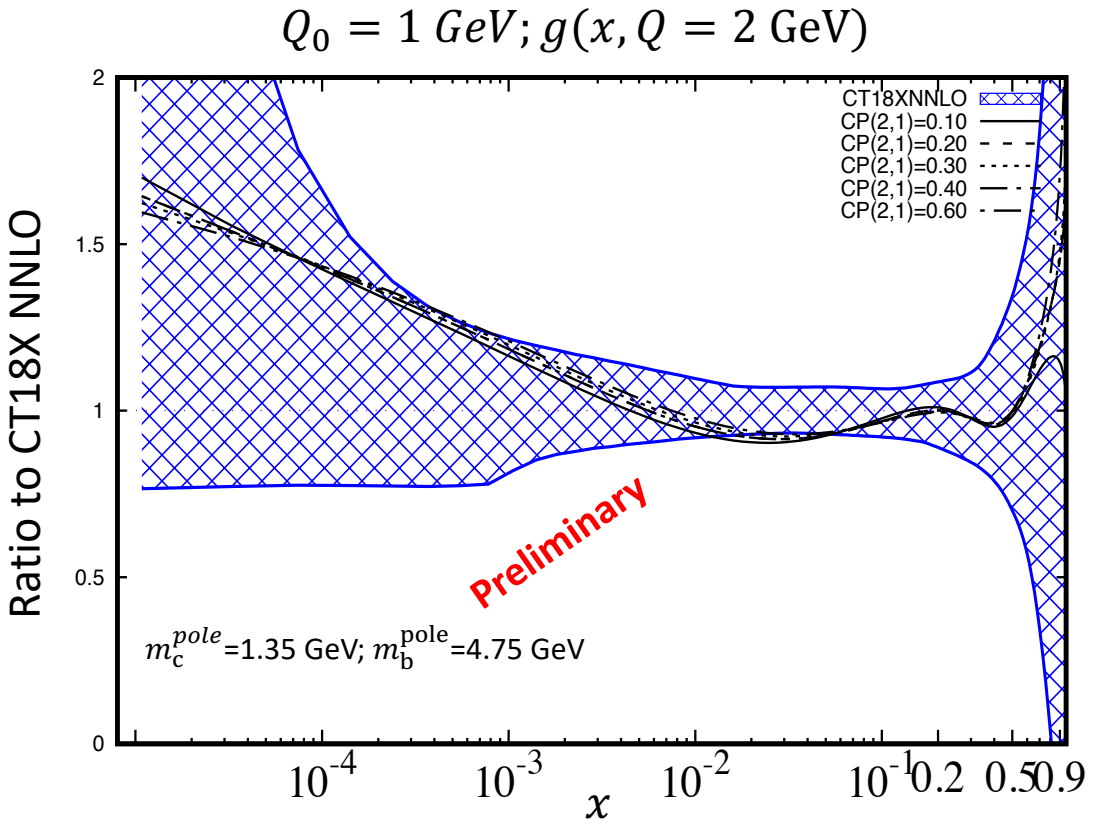


CT18XNNLO + combined HERA c/b DIS data set

Fits with varied $\overline{\mathrm{m}}_{\mathrm{c}}(\overline{\mathrm{m}}_{\mathrm{c}})$

Fits with varied small-x scale





This data set mildly prefers CT18XNNLO to CT18NNLO.

But $\chi^2/\mathrm{N_{pt}}$ is never lower than 1.5 for all explored combinations

$$\mu_{DIS}(x) = A\sqrt{m_Q^2 + B^2/x^C}$$

Vary B=CP(2,1), while keeping A=0.5 and C=0.33 fixed

Conclusions

- These data are important because they also provide indirect constraints on strangeness.
- We tried to vary several parameters in the analysis. But in the best scenario, the $\chi 2$ /Npt is no lower than 1.5.
- All the fits we tried are tricky as parameters are correlated.
- We observe that these data seem to prefer a harder gluon in the intermediate/small x region.
- The $\chi 2$ /Npt which we find is similar to what has been found in MSHT20 and to the predictions from other groups reported in Tab 4 of 1804.01019 EPJC (2018) H1 and Zeus Coll.