Universität Münster

Impact of Open-Heavy-Flavor Production on nCTEQ Nuclear PDFs

33rd International Workshop on Deep Inelastic Scattering and Related Subjects

Jan Wissmann (jan.wissmann@uni-muenster.de)

In collaboration with my nCTEQ colleagues

nCTEQ
nuclear parton distribution functions

5th of May, 2026

Outline

Part 1: Overview

Part 2: nCTEQ26OHF Setup

Part 3: Fit Results & PDFs

Part 4: Data Set Description

Overview

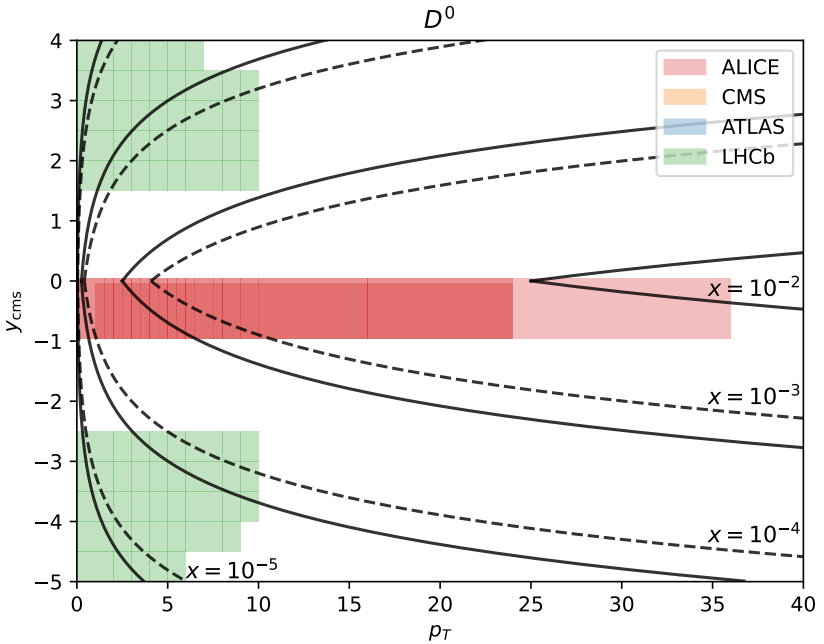
Introduction

- For nCTEQ26 main fit: See previous talk by Tomáš Ježo

→ In this talk: alternative nCTEQ26OHF fit

- Importance of heavy-quark production: data goes to small momentum-fraction $x \approx \frac{p_T}{\sqrt{s}} e^{-y} \sim 10^{-4}$ to 10^{-5}
  → e.g. constrain gluon PDF in low-x region

- Mass effects non-negligible for $p_T \sim m_Q$



[Duwentäster et al. (2022)]

- Predictions for this process in nPDF analyses:
  - nNNPDF3.0: POWHEG+Pythia [Nason (2004)] [Alioli et al. (2010)] [Sjöstrand et al. (2015)]
  - nCTEQ26: Crystal-Ball Function [Kom et al. (2011)] [Lansberg and Shao (2016)] [Kusina et al. (2018)]
  - nCTEQ26OHF: SACOT [Kniehl et al. (2005a)] [Kniehl et al. (2005b)] [Kniehl et al. (2015)]
  - EPPS21: SACOT-m_T [Helenius and Paukkunen (2018)] [Helenius and Paukkunen (2023)]

Flavor Number Schemes

FFNS

Fixed-flavor-number scheme

- one heavy flavor (c quark)
  - heavier flavors: decoupled
  - rest: light flavors (u, d, s quark)
- active flavors n_f fixed
- valid in threshold region ($p_T \sim m_Q$)
  - in asymptotic region: large log $\ln\left(\frac{m_Q^2}{p_T^2}\right)$

ZM-VFNS

Zero-mass variable-flavor-number scheme

- only light flavors / partons (u, d, s, c quark)
  - heavier: decoupled
- active flavors variable: $n_f \to n_f(\mu)$
- valid in asymptotic region ($p_T \gg m_Q$)
  - in threshold region: mass effects $\mathcal{O}(1)$

GM-VFNS

General-mass variable-flavor-number scheme

- one heavy flavor (c quark)
  - heavier flavors: decoupled
  - rest: light flavors (u, d, s quark)
- active flavors variable: $n_f \to n_f(\mu)$
- valid over whole kinematic range
  - include mass effects
  - resum large logs

nCTEQ26: Crystal Ball Function

- Effective matrix element ("Crystal Ball function") [Kom et al. (2011)] [Lansberg and Shao (2016)] [Kusina et al. (2018)] for open heavy-flavor and quarkonium production

$$\sigma_{A+B\to C+X} = \int \mathrm{d}x_1\,\mathrm{d}x_2 f_{1,g}(x_1,\mu)\, f_{2,g}(x_2,\mu)\frac{1}{2\hat{s}}\overline{|\mathcal{A}_{g+g\to C+X}|^2}\,\mathrm{dPS}$$

$$\overline{|\mathcal{A}_{g+g\to C+X}|^2} = \frac{\lambda^2\kappa\hat{s}}{M_C^2}e^{a|y|}\begin{cases} e^{-\kappa\frac{p_T^2}{M_C^2}} & \text{if } p_T \le \langle p_T\rangle \\ e^{-\kappa\frac{p_T^2}{M_C^2}}\left(1+\frac{\kappa}{n}\frac{p_T^2-\langle p_T\rangle^2}{M_C^2}\right)^{-n} & \text{if } p_T > \langle p_T\rangle \end{cases}$$

- $|\mathcal{A}_{g+g\to C+X}|^2$ is fitted to proton data with the fit parameters λ, κ, $\langle p_T\rangle$, n, a and then used in pPb
- only gluon channel is considered

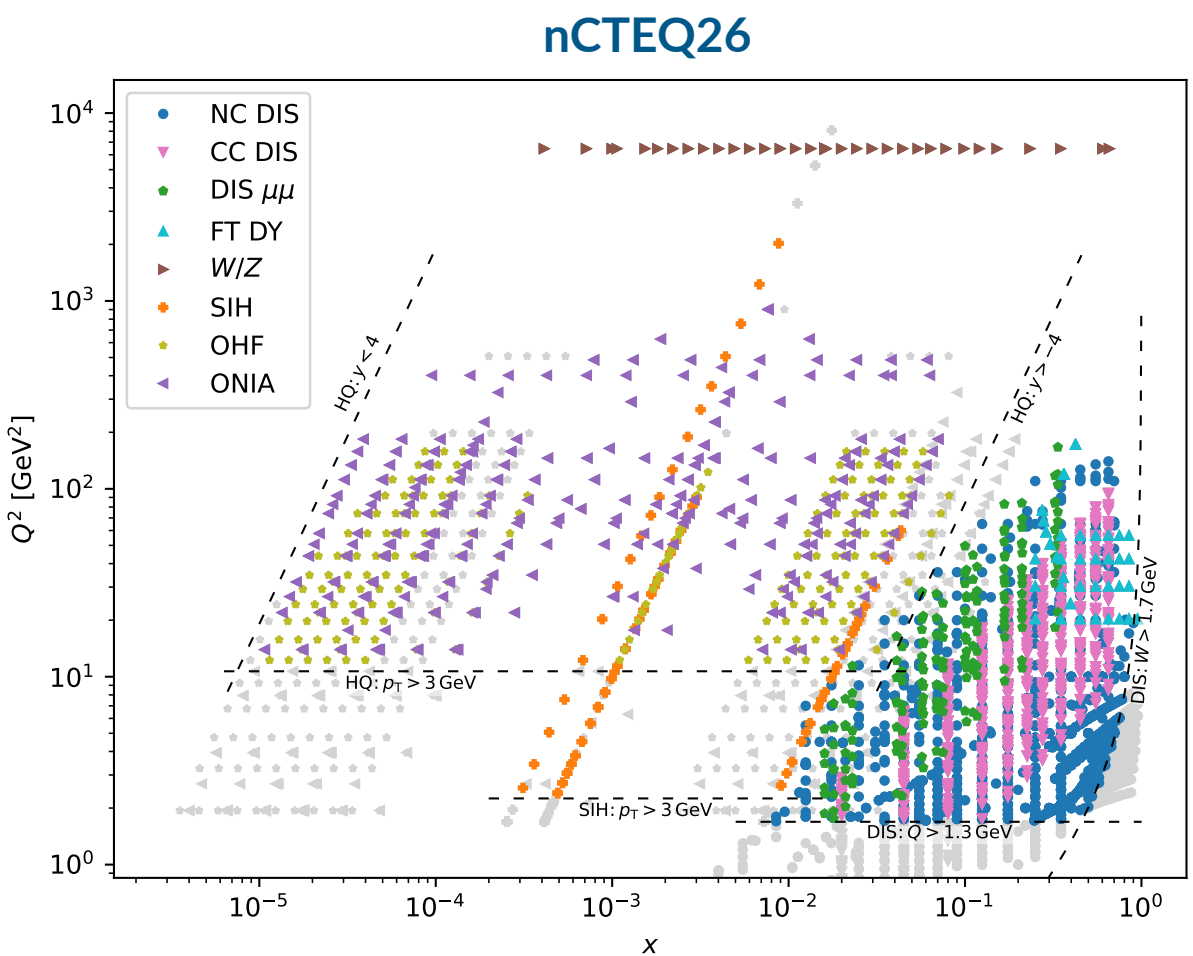
→ Problem: only pA data that has baseline pp data can be fitted

CB parameters (D^0)

nCTEQ15HQ	λ	0.334 57
	κ	1.825 96
	$\langle p_T\rangle$	2.400 97
	n	2.000 76
	a	−0.032 95
nCTEQ26	λ	0.682 23
	κ	1.652 35
	$\langle p_T\rangle$	−0.407 83
	n	1.701 45
	a	−0.014 89

nCTEQ26OHF Setup

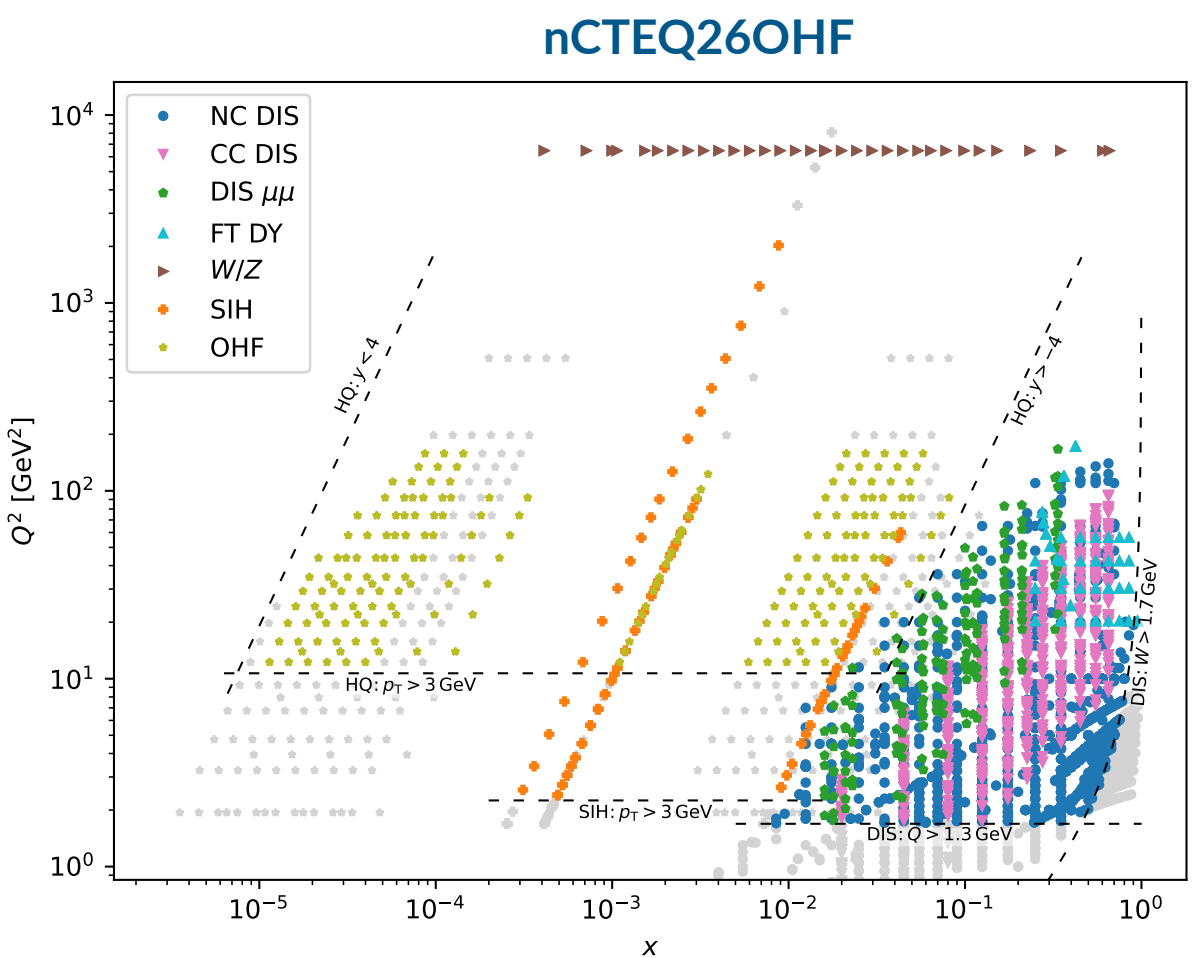
nCTEQ26: Data Overview



	nCTEQ26	nCTEQ26OHF
NC DIS	1277	1277
CC DIS	1068	1068
DIS $\mu\mu$	174	174
FT DY	92	92
W/Z	180	180
SIH	112	112
OHF	209	209
ONIA	486	–
Total	3598	3112

→ In nCTEQ26: Crystal-ball function for open-heavy-flavor and quarkonium data

nCTEQ26OHF: Data Overview



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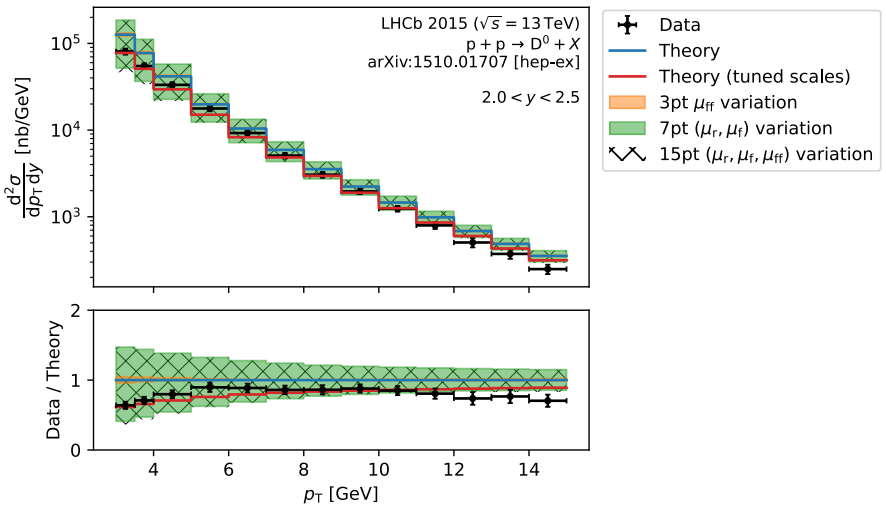
→ In nCTEQ26OHF: SACOT calculation for open-heavy-flavor data

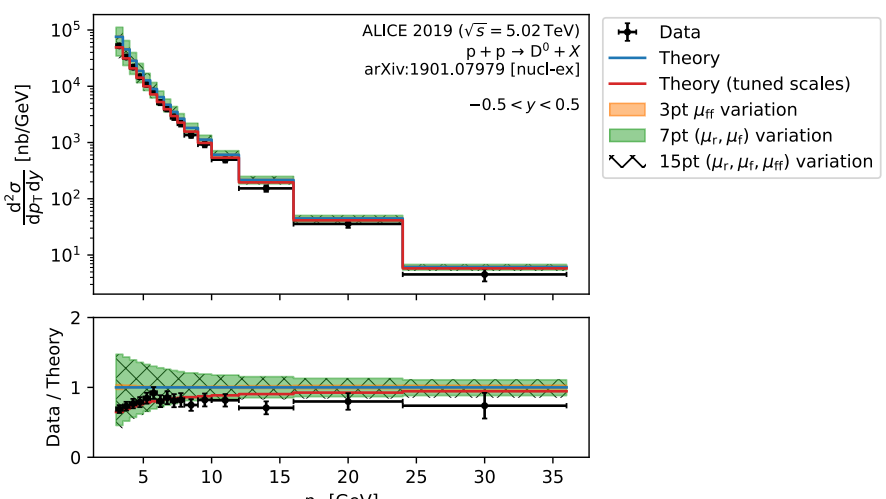
nCTEQ26OHF: GM-VFNS

- GM-VFNS calculation [Kniehl et al. (2005a)] [Kniehl et al. (2005b)] for open-heavy-flavor production
- PineAPPL [Carrazza et al. (2020)] grids that leave open two PDFs and fix the KKKS06 [Kneesch et al. (2008)] fragmentation function
- Tune the scale coefficients to proton-proton data:

$$(\mu_r, \mu_f, \mu_f') = (1, 0.6, 2.5)\sqrt{p_T^2 + 4m_c^2}$$

→ then use this scale choice in the nCTEQ26OHF fit

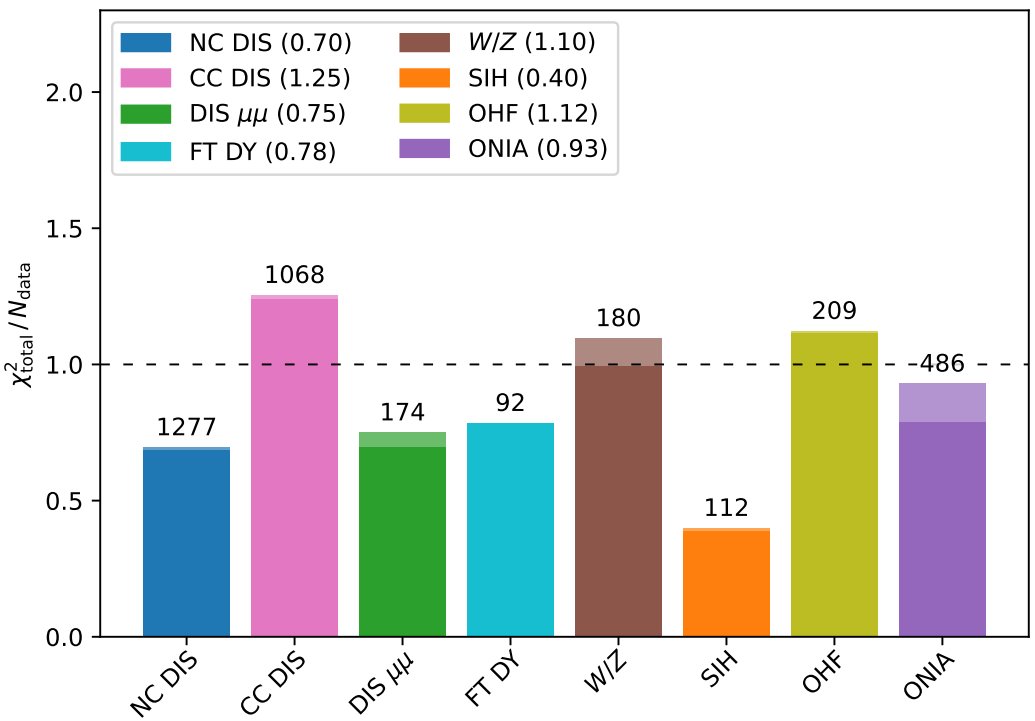




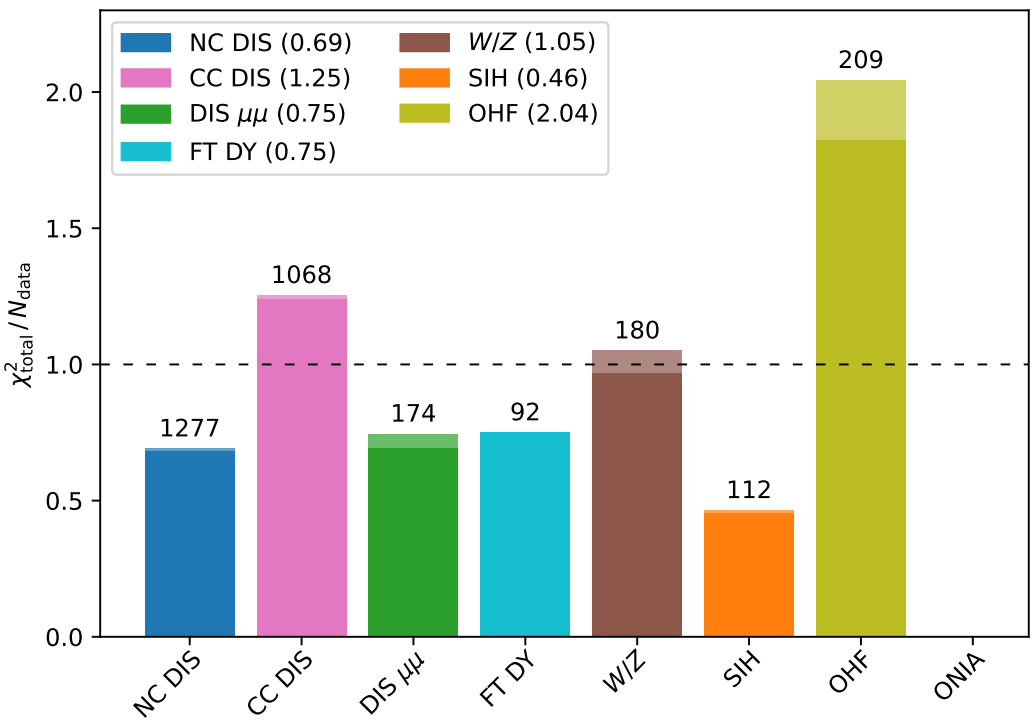
Fit Results & PDFs

χ^2 per process

nCTEQ26

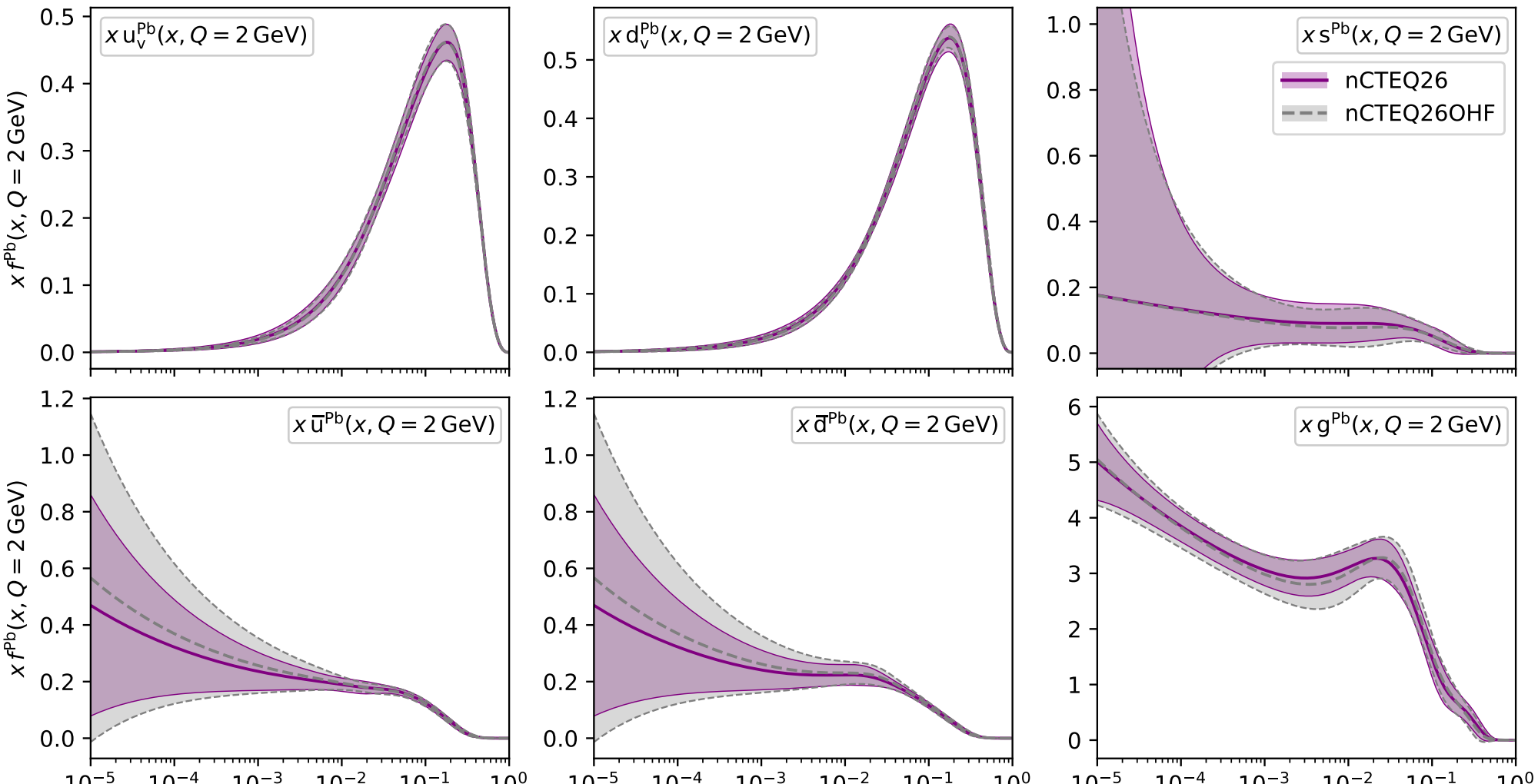


nCTEQ26OHF

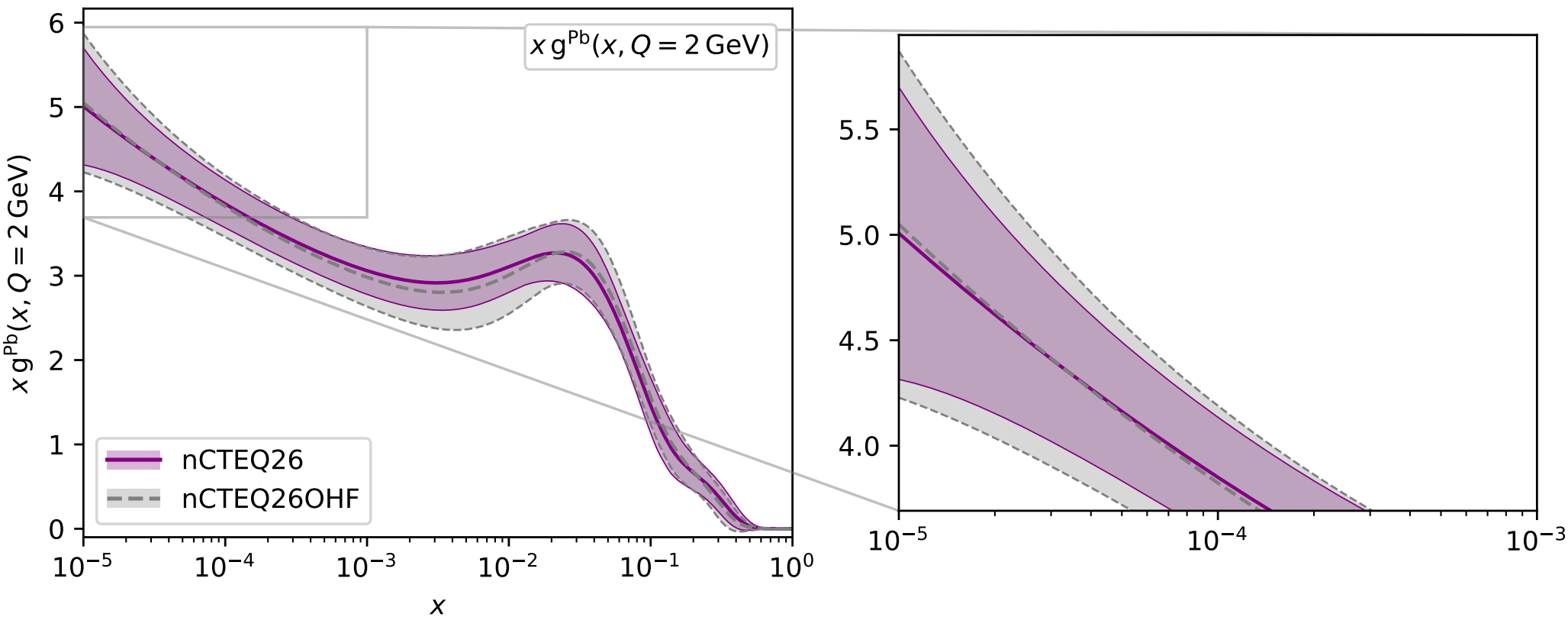


→ Higher χ^2 in OHF (see part 4 of the talk)

PDFs

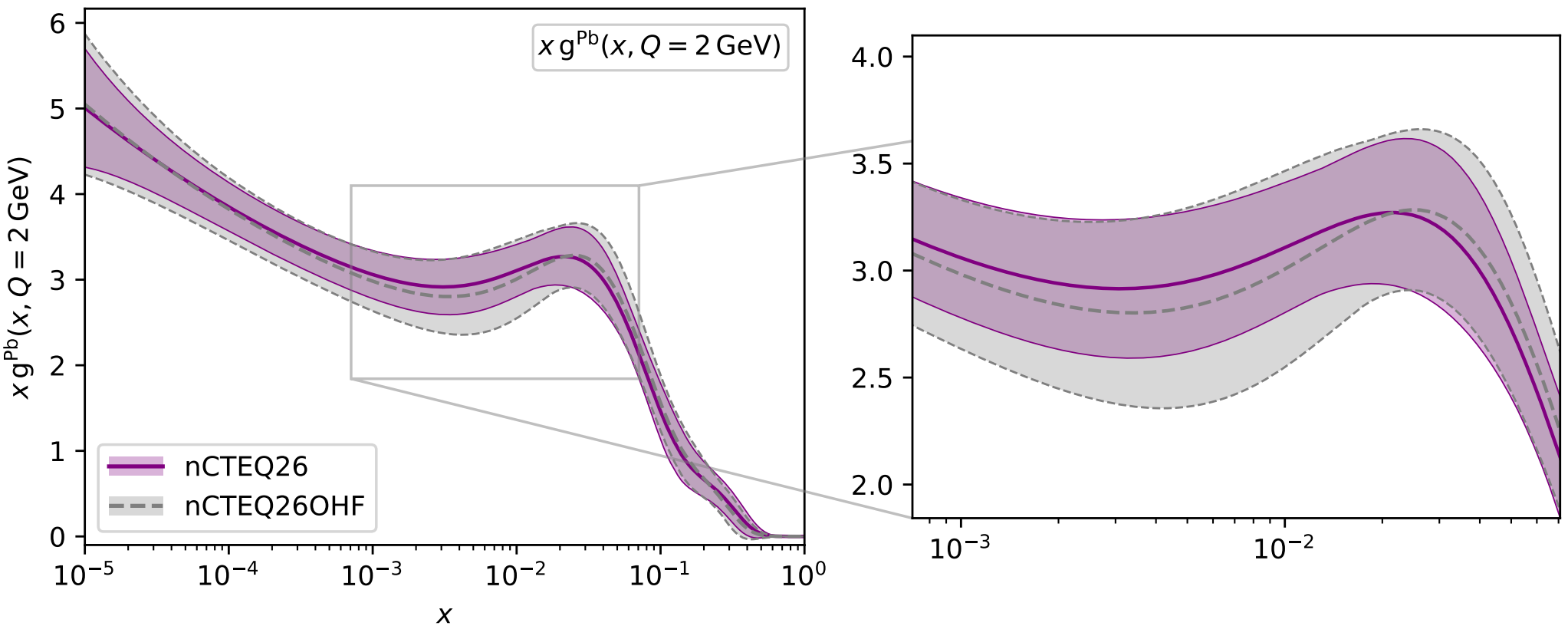

$x\,u_v^{Pb}(x, Q = 2\,\mathrm{GeV})$
$x\,d_v^{Pb}(x, Q = 2\,\mathrm{GeV})$
$x\,s^{Pb}(x, Q = 2\,\mathrm{GeV})$
nCTEQ26
nCTEQ26OHF
$x\,\bar{u}^{Pb}(x, Q = 2\,\mathrm{GeV})$
$x\,\bar{d}^{Pb}(x, Q = 2\,\mathrm{GeV})$
$x\,g^{Pb}(x, Q = 2\,\mathrm{GeV})$
$x\,f^{Pb}(x, Q = 2\,\mathrm{GeV})$

Gluon PDF



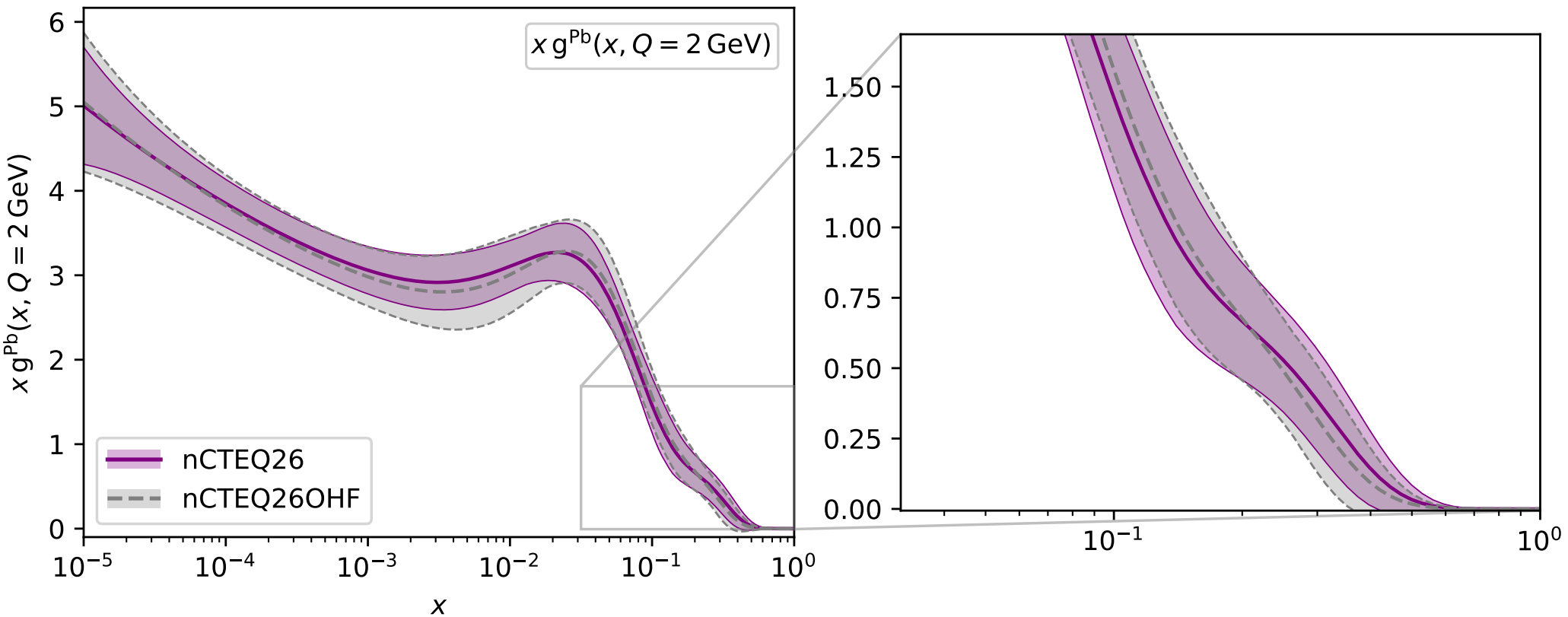
→ Low & mid x: Larger uncertainties in nCTEQ26OHF

Gluon PDF



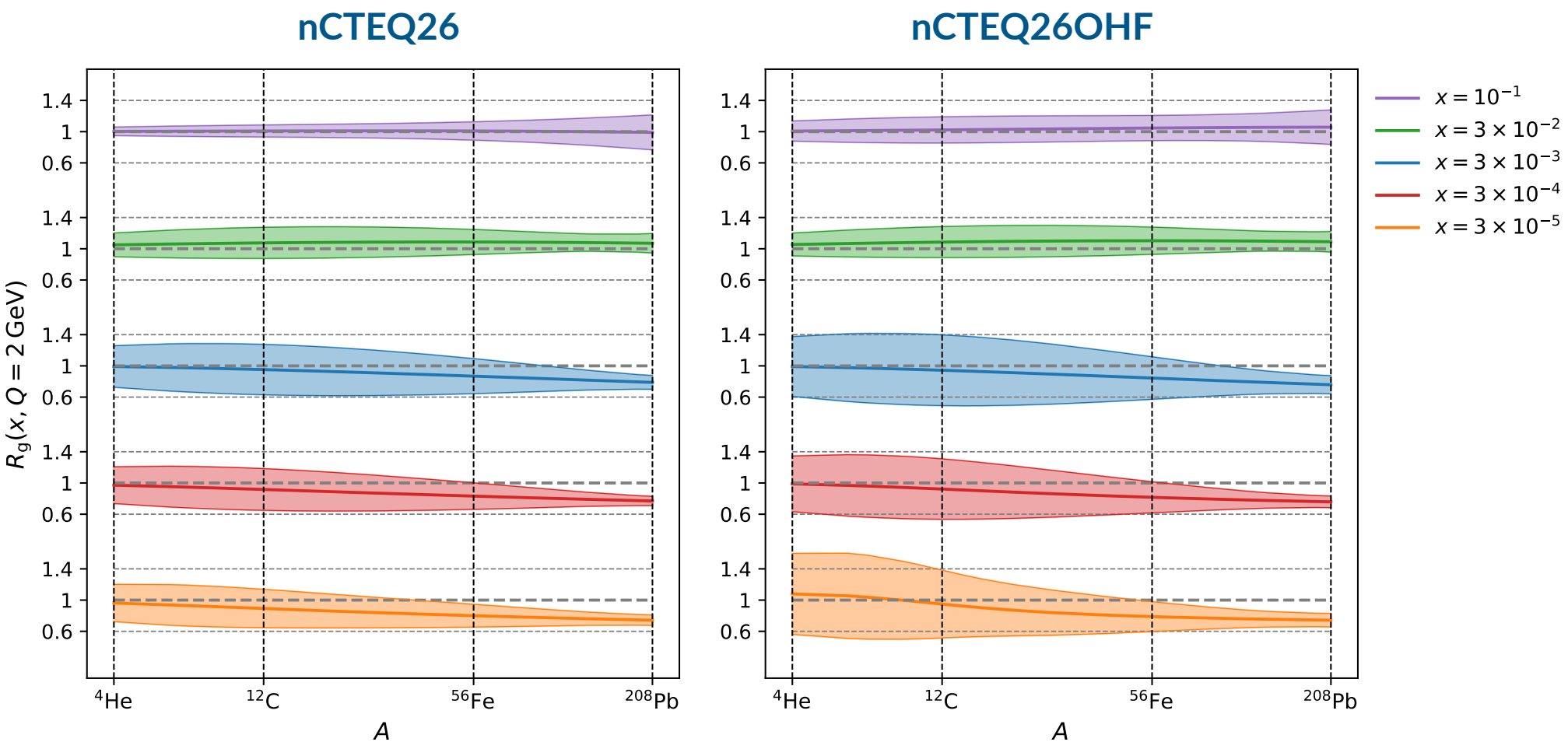
→ Low & mid x: Larger uncertainties in nCTEQ26OHF

Gluon PDF



→ High x: Uncertainties comparable to nCTEQ26

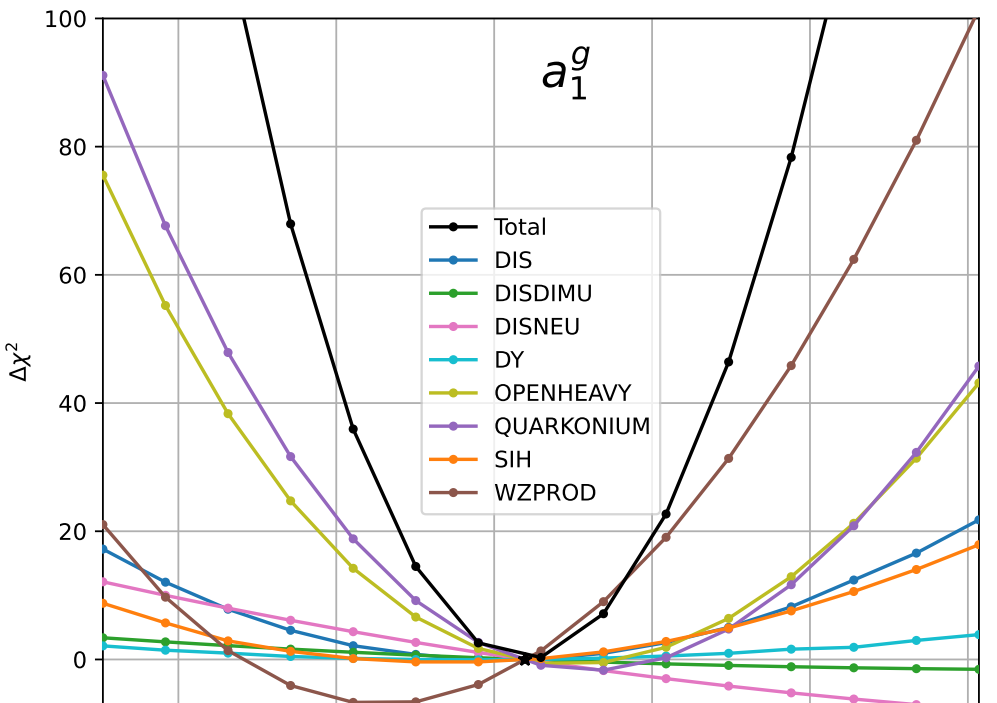
A Dependence



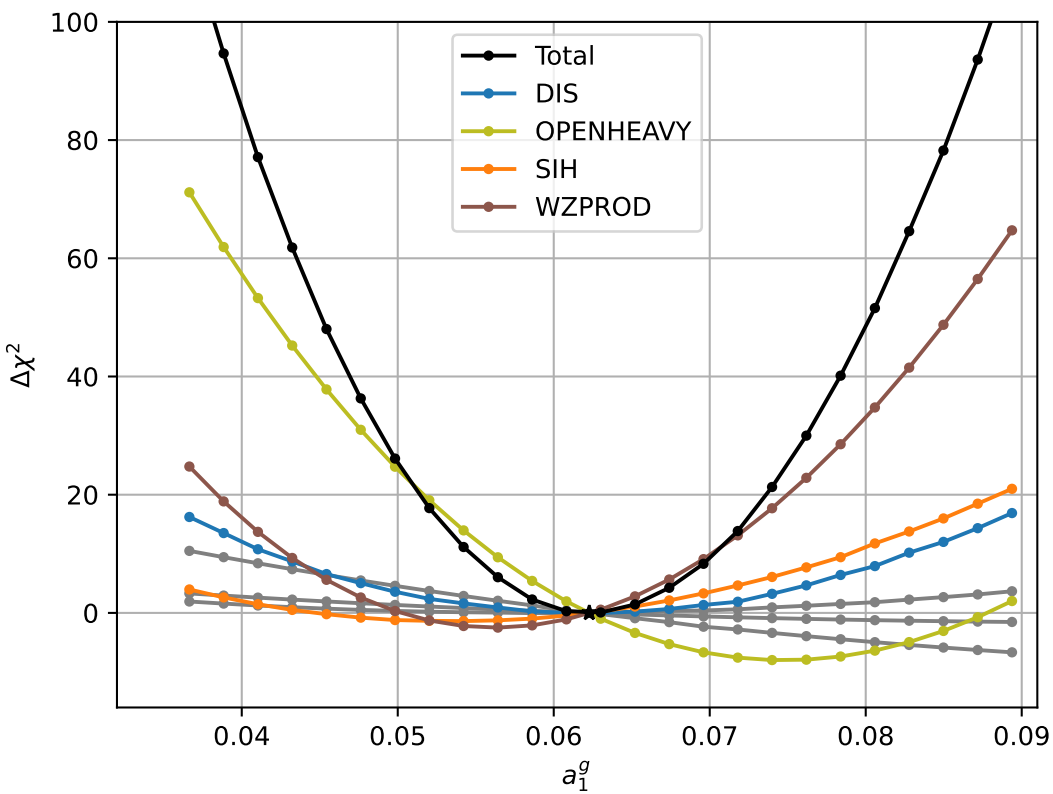
→ Consistently larger gluon uncertainties in nCTEQ26OHF

Constraints on the gluon uncertainty

nCTEQ26



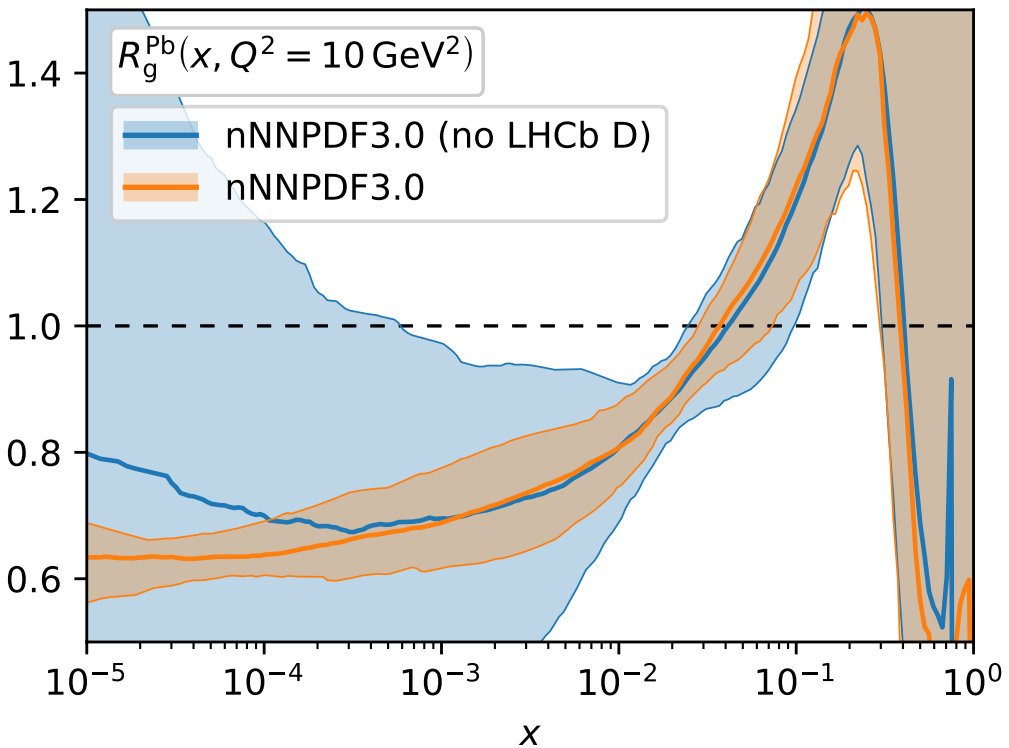
nCTEQ26OHF



→ In both fits: OHF and W/Z pull in opposite directions

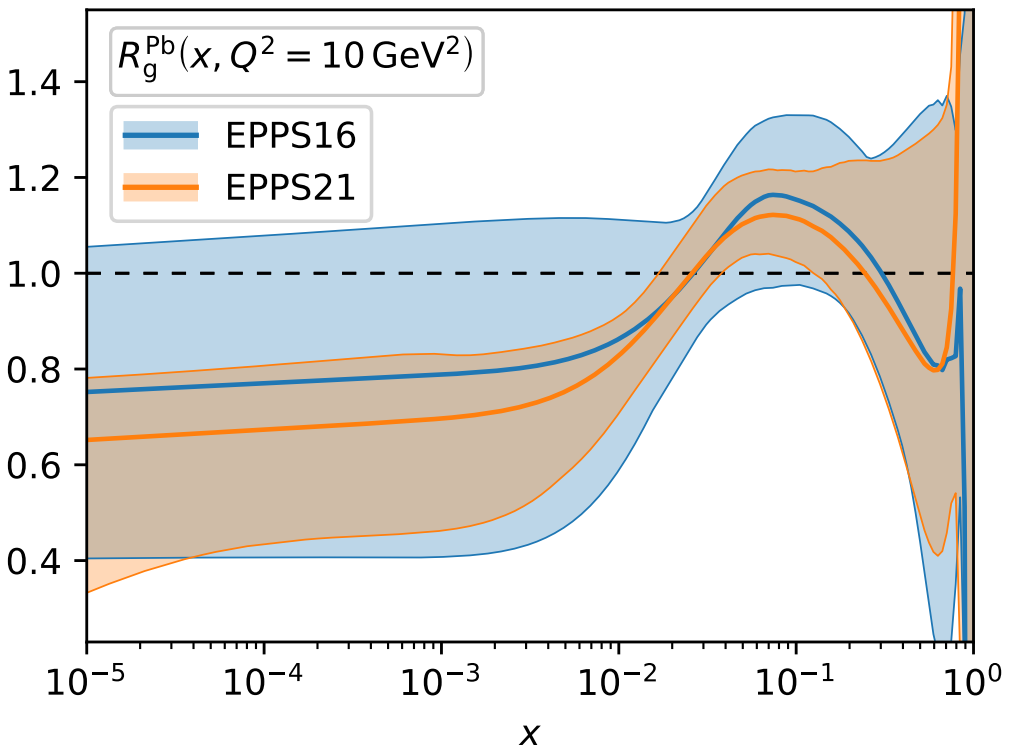
D^0 data in nNNPDF3.0 and EPPS21

nNNPDF3.0 [Abdul Khalek et al. (2022)]



- Data: LHCb 2017 D^0

EPPS21 [Eskola et al. (2022)]

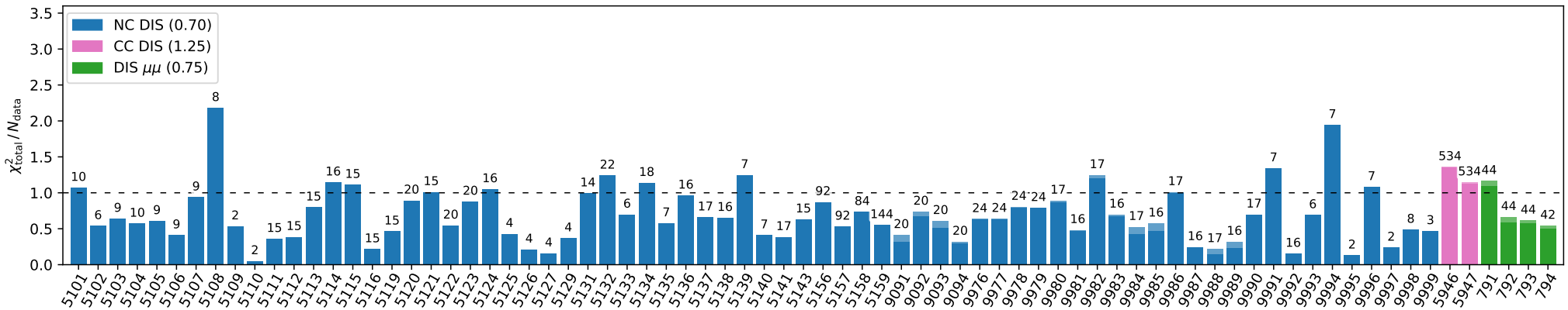


- Data: LHCb 2017 D^0
  (also: CMS dijet, CMS&ATLAS W/Z)

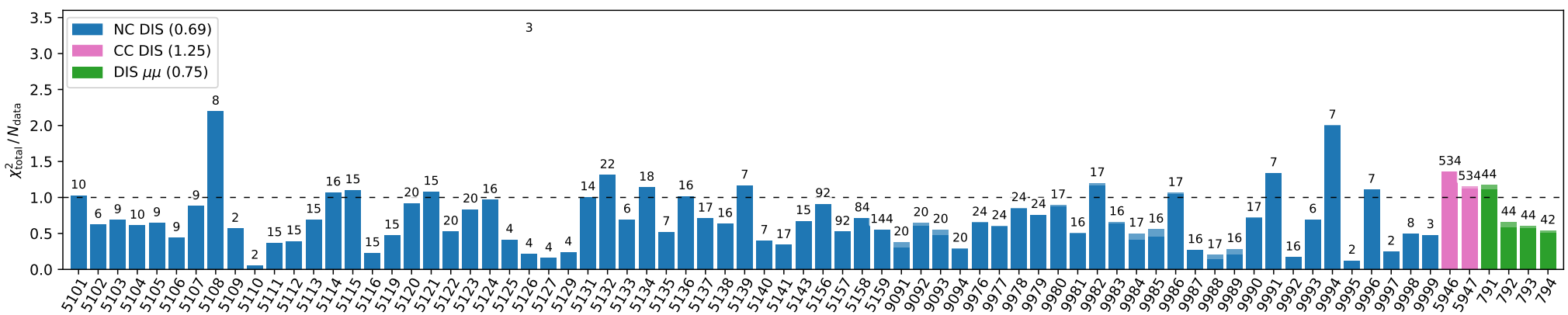
Data set description

χ^2 per data set I

nCTEQ26

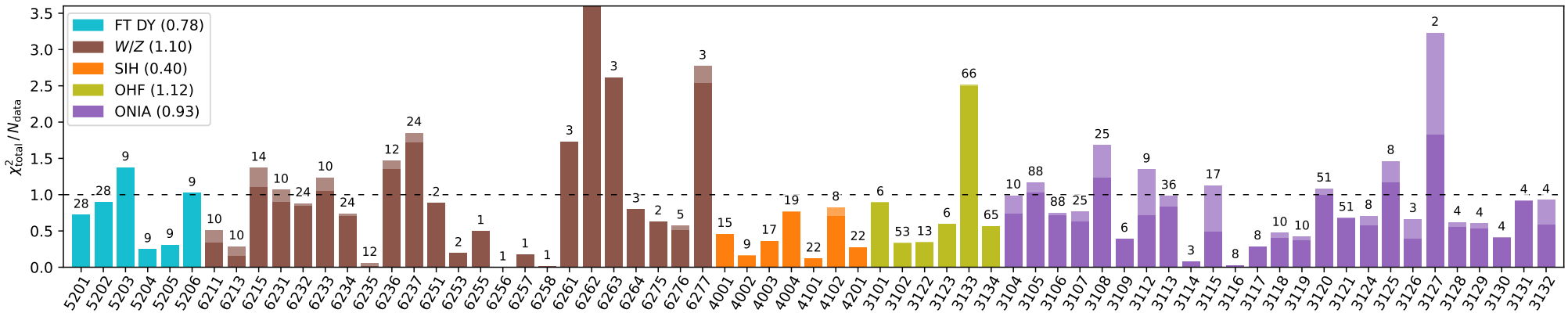


nCTEQ26OHF

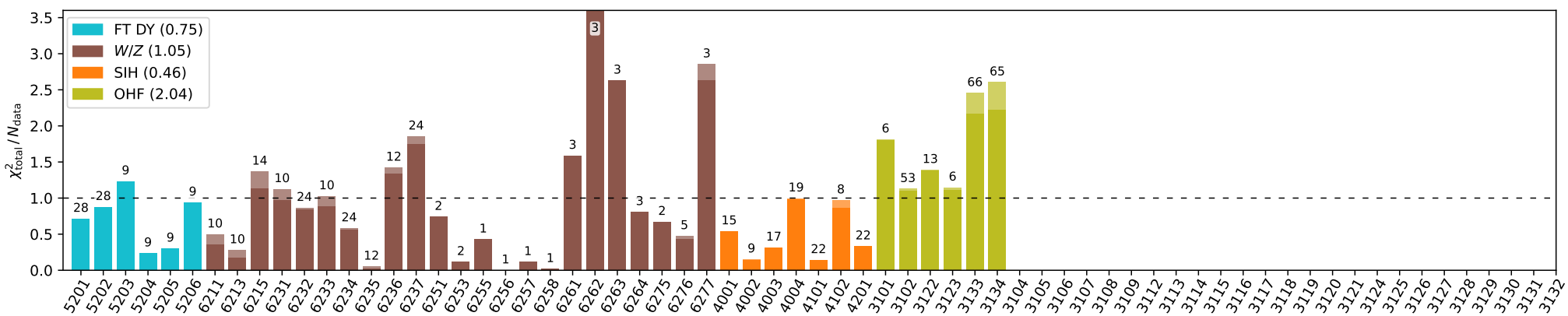


χ^2 per data set II

nCTEQ26

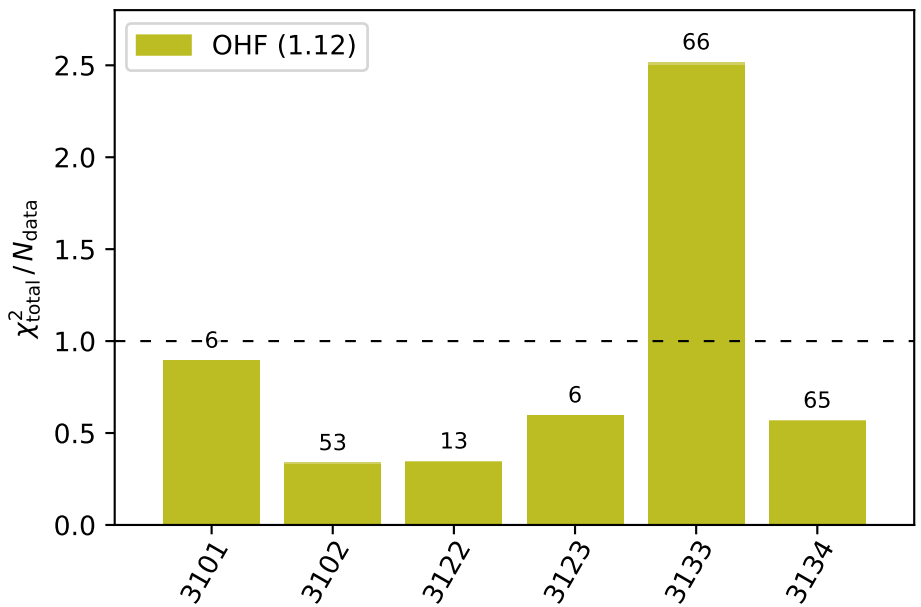


nCTEQ26OHF

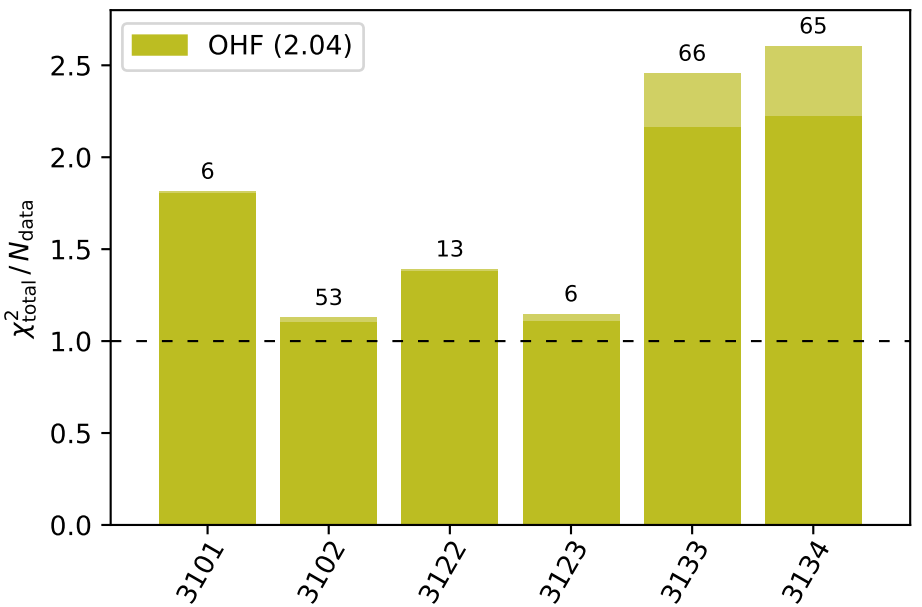


χ^2 per data set: nCTEQ26 & nCTEQ26OHF

nCTEQ26



nCTEQ26OHF

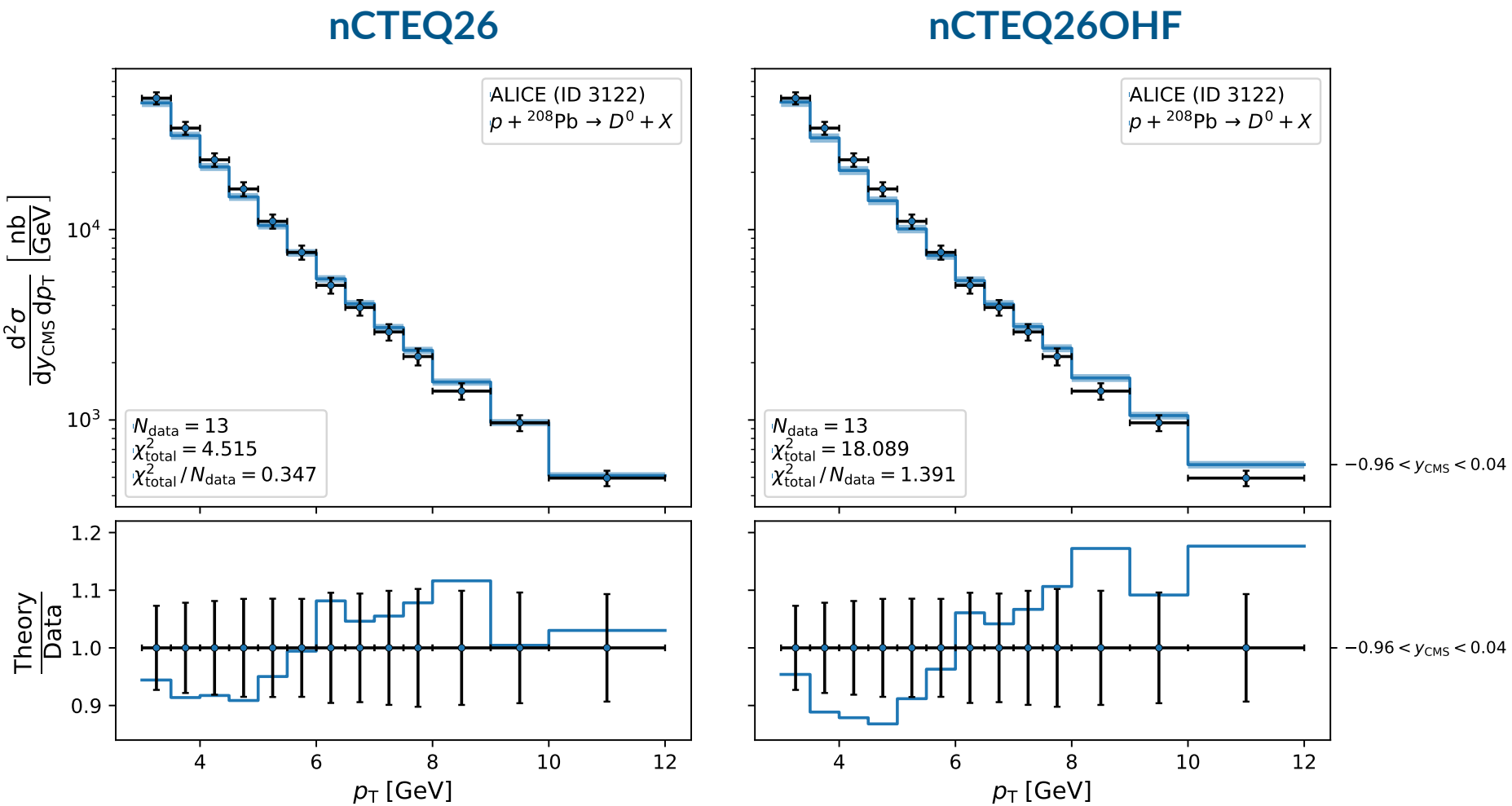


→ 3133: High χ^2 in both fits

→ Larger nCTEQ26OHF χ^2 mainly caused by 3134 (LHCb Run II D^0) & by not including Crystal Ball parameters uncertainties

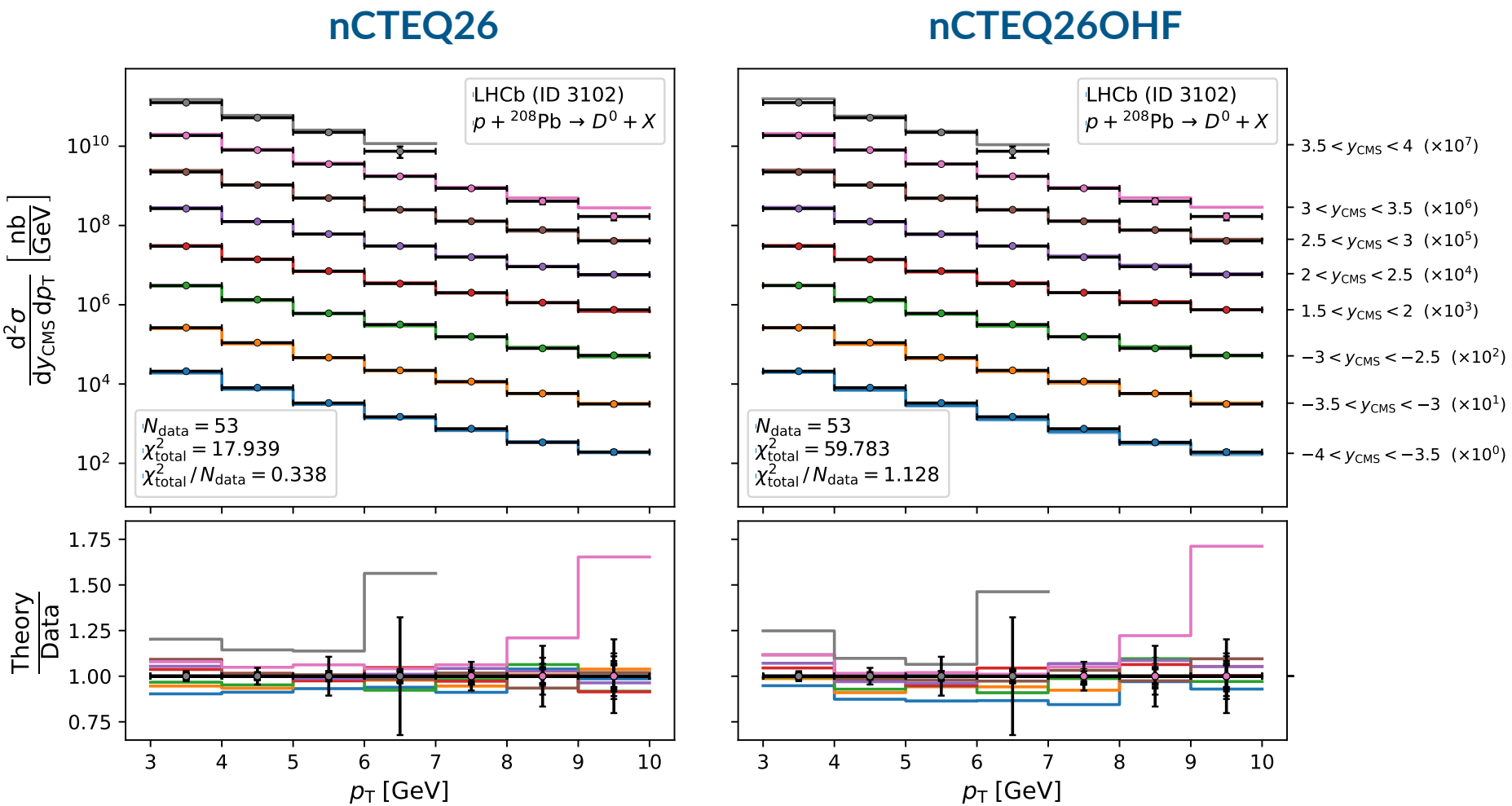
3101: ALICE 2015 ($\sqrt{s} = 5.02$ TeV)
3102: LHCb 2017 ($\sqrt{s} = 5.02$ TeV)
3122: ALICE 2019 ($\sqrt{s} = 5.02$ TeV)
3123: ALICE 2016 ($\sqrt{s} = 5.02$ TeV)
3133: LHCb 2023 ($y > 0$, $\sqrt{s} = 8.16$ TeV)
3134: LHCb 2023 ($y < 0$, $\sqrt{s} = 8.16$ TeV)

Data vs. theory: ALICE 2019 ($\sqrt{s} = 5.02\,\text{TeV}$)



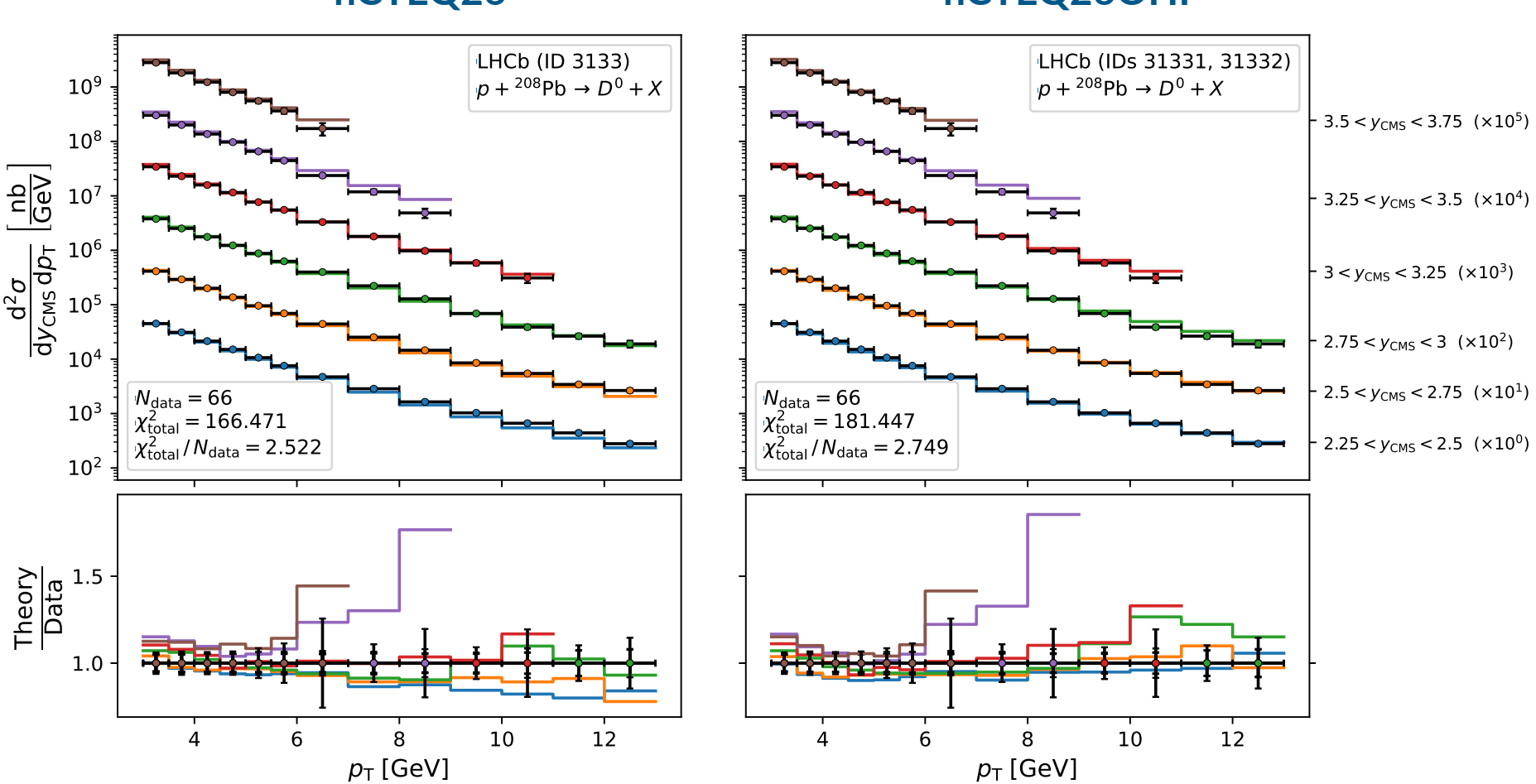
[ALICE Collaboration (2019)]

Data vs. theory: LHCb 2017 ($\sqrt{s} = 5.02\,\text{TeV}$)



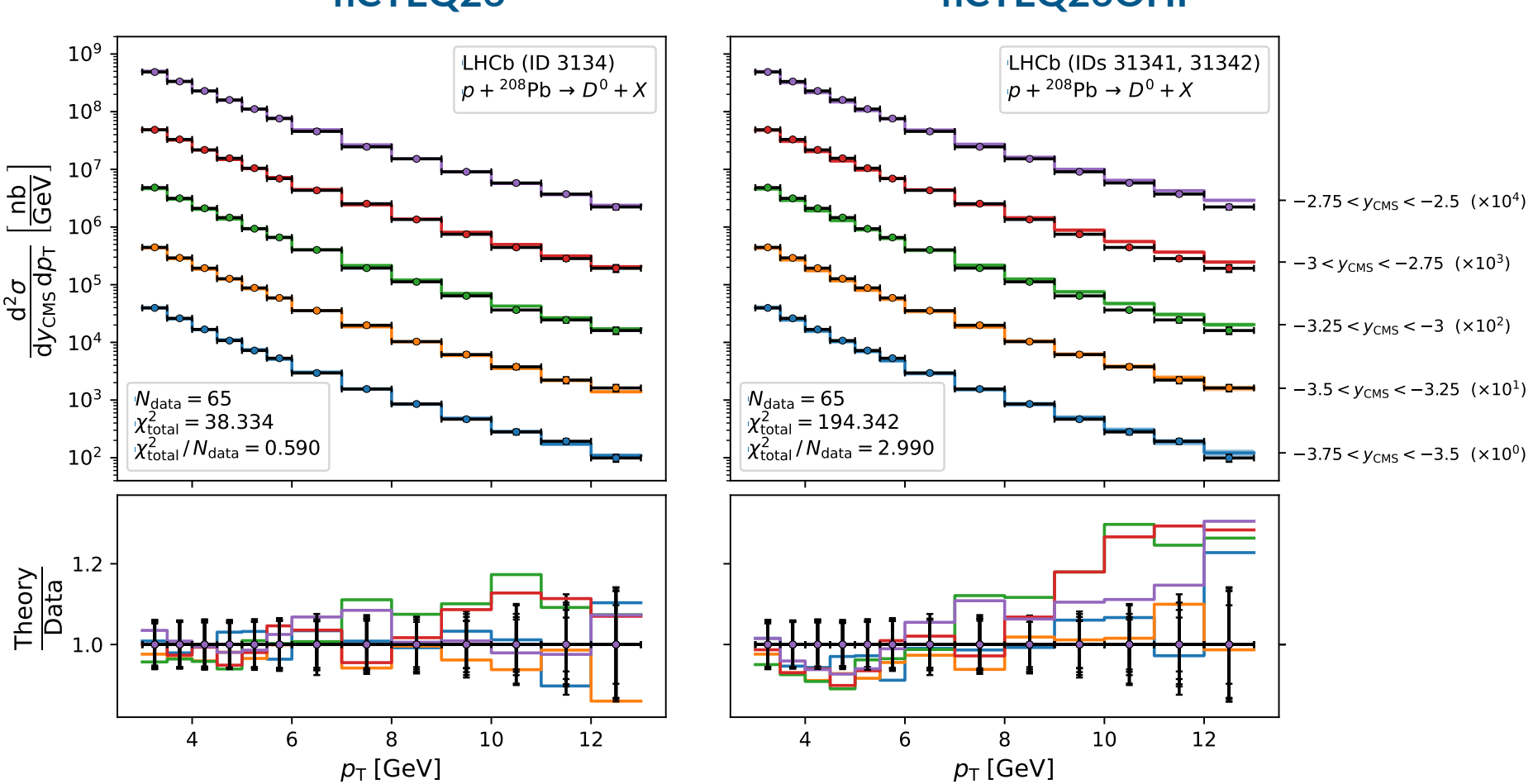
[LHCb Collaboration (2017)]

Data vs. theory: LHCb 2023 ($y > 0$, $\sqrt{s} = 8.16$ TeV)



[LHCb collaboration (2023)]

Data vs. theory: LHCb 2023 ($y < 0$, $\sqrt{s} = 8.16$ TeV)



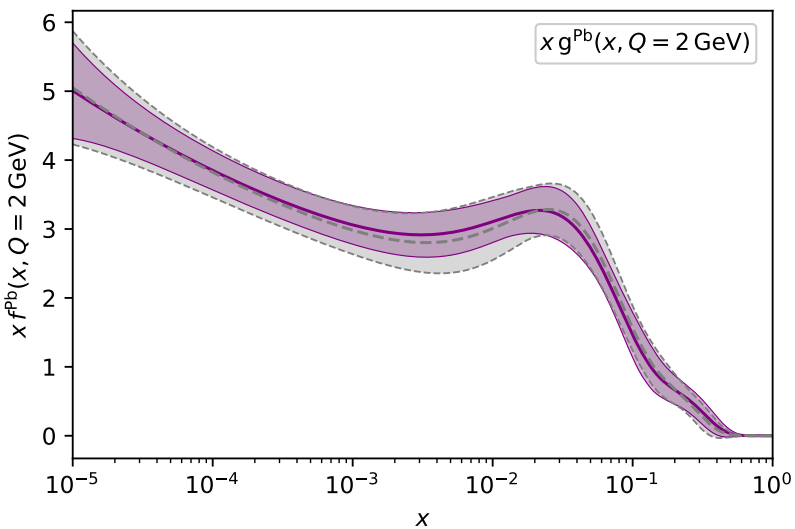
[LHCb collaboration (2023)]

Conclusion

→ Larger gluon uncertainties

→ OHF data still has a lot of constraint
→ similar to EPPS and nNNPDF

→ Larger χ^2 in nCTEQ26OHF: CB theory uncertainties & LHCb D^0 Run II generally difficult to describe?



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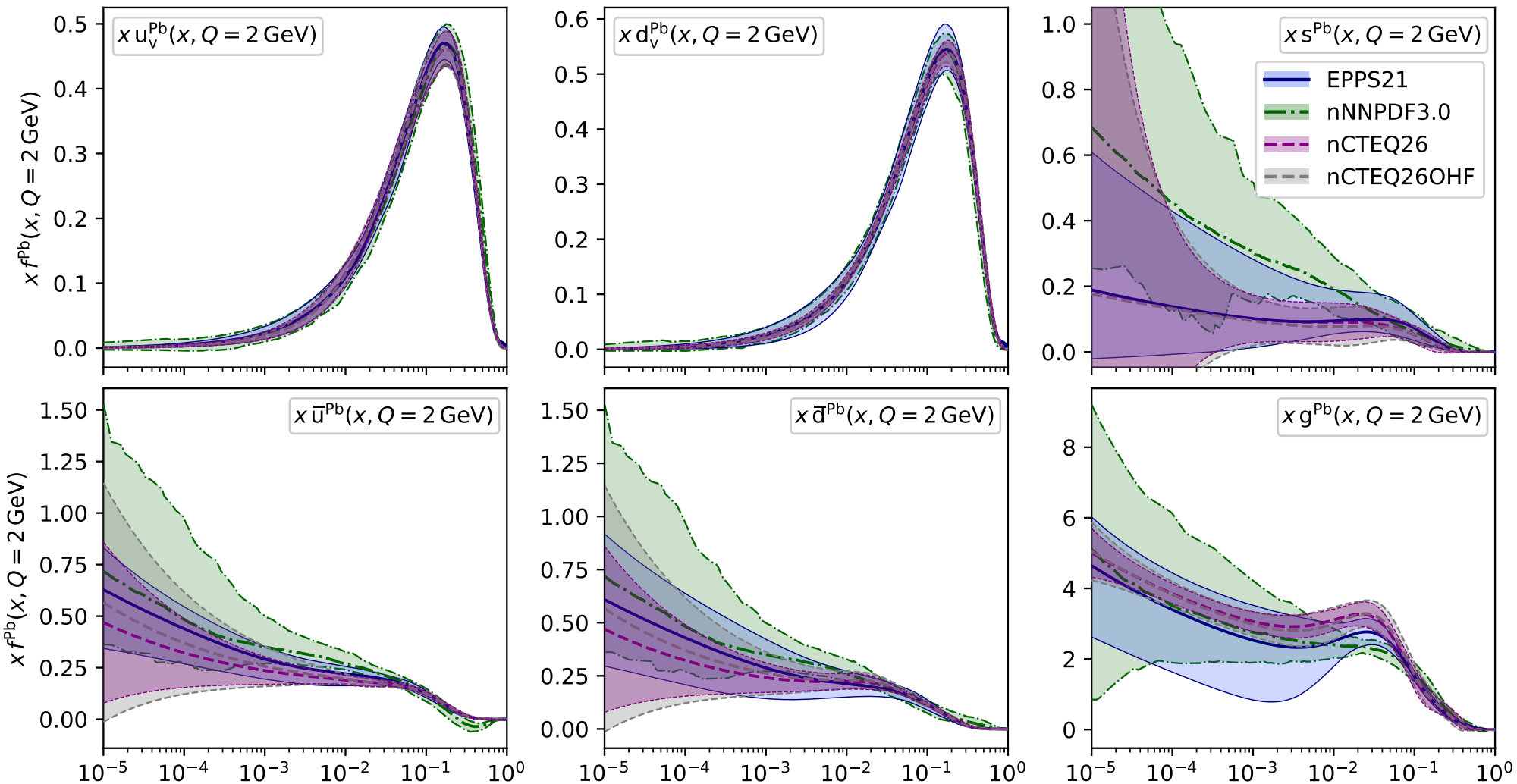
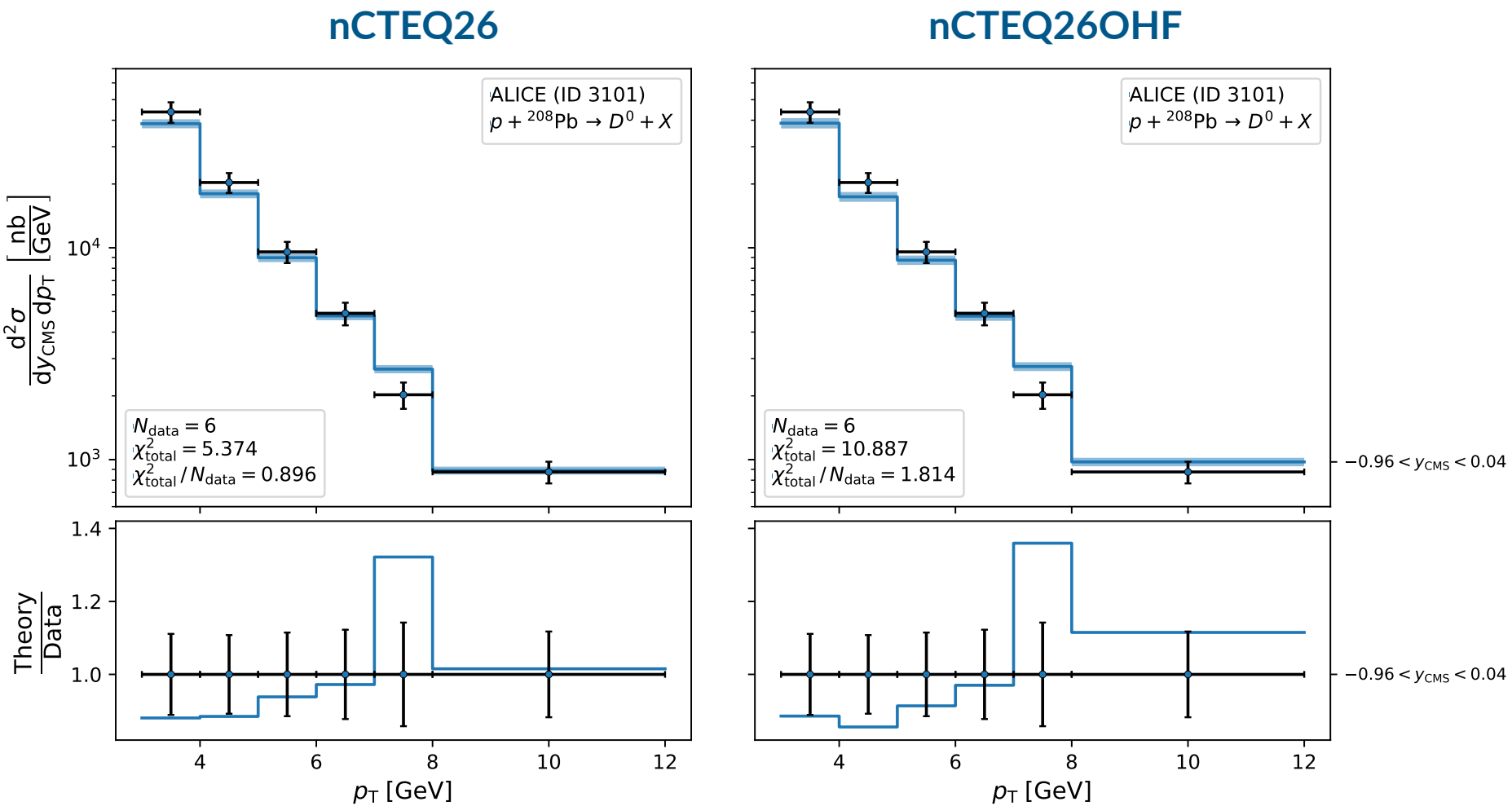
Backup

PDF Comparison

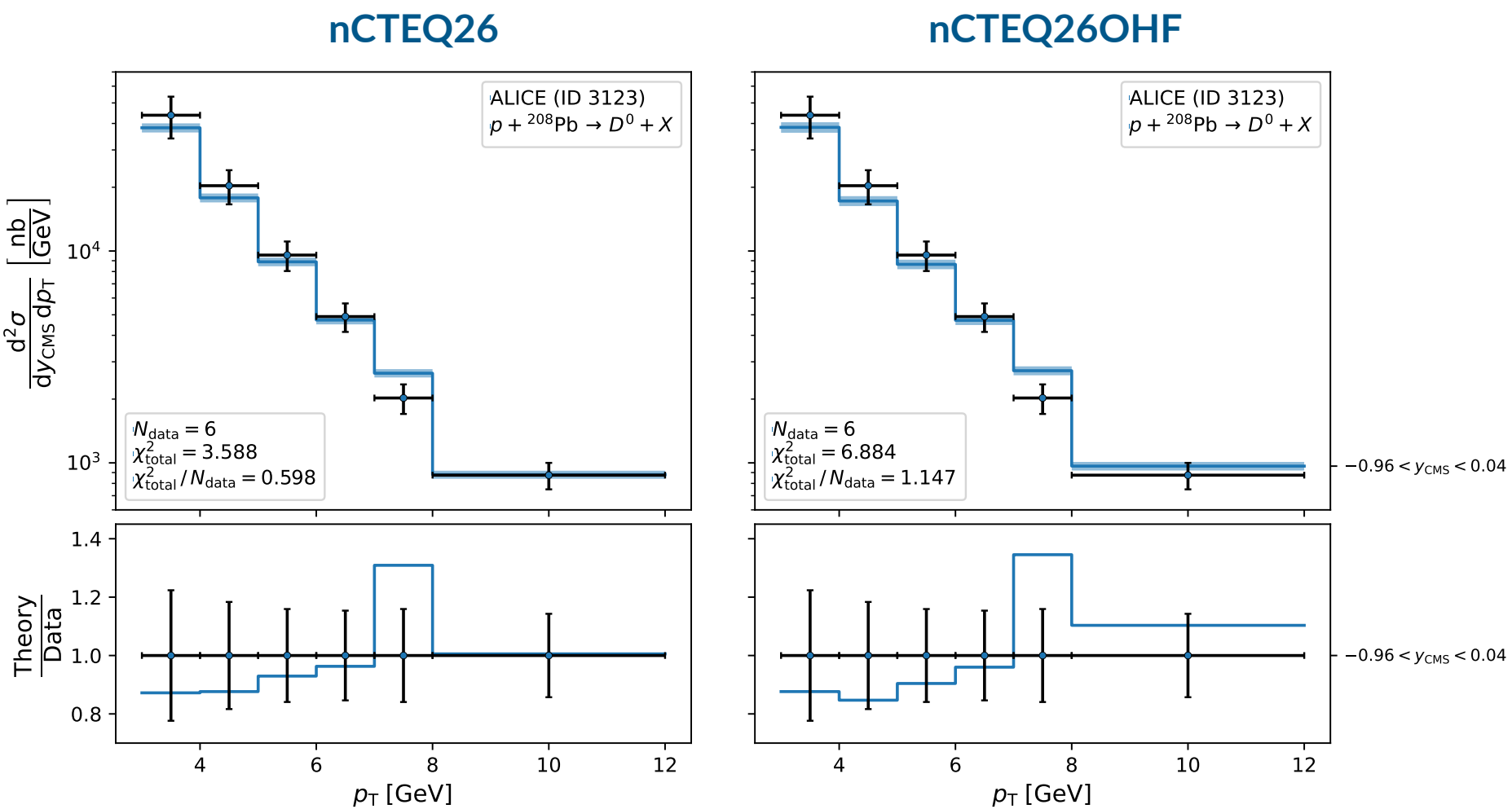


Data vs. theory: ALICE 2015 ($\sqrt{s} = 5.02\,\text{TeV}$)



[ALICE Collaboration (2015)]

Data vs. theory: ALICE 2016 ($\sqrt{s} = 5.02\,\text{TeV}$)



[ALICE Collaboration (2016)]