# Progress in the NNPDF global analysis

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# NNPDF From the past ....

**2015** Parton Distributions with threshold (soft gluon) resummation

**2014** NNPDF3.0 global analysis & Closure Test validation

**2013** NNPDF2.3QED and the photon PDF

**2012** NNPDF2.3 global analysis

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*Marco Bonvini's talk*

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04/2016

NNPDF3 fits with intrinsic charm

Summer 2016

NNPDF3.1 global analysis

NNPDF3.1QED fits

sometime in 2016 ....

Updated determinations of alphas and $m_c(m_c)$ from global PDF fit

PDF fits with small-x (BFKL) resummation

# NNPDF ... to the future!

*This talk and Luca Rottoli's talk*

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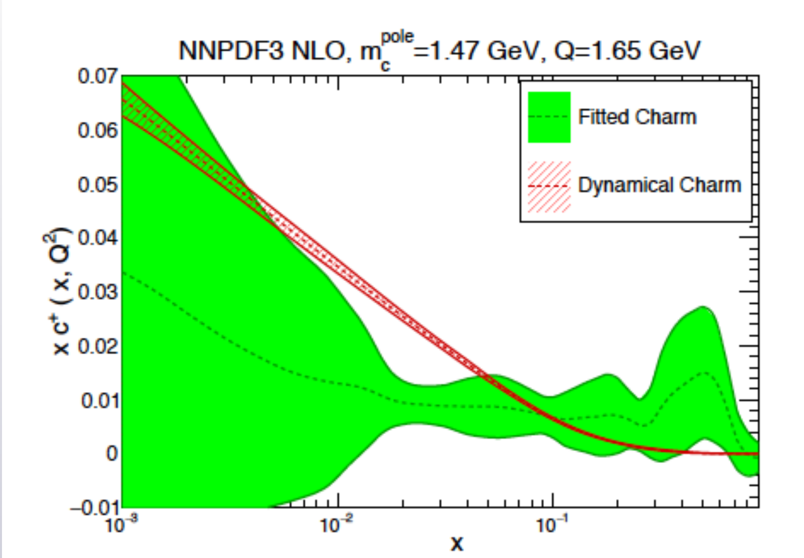
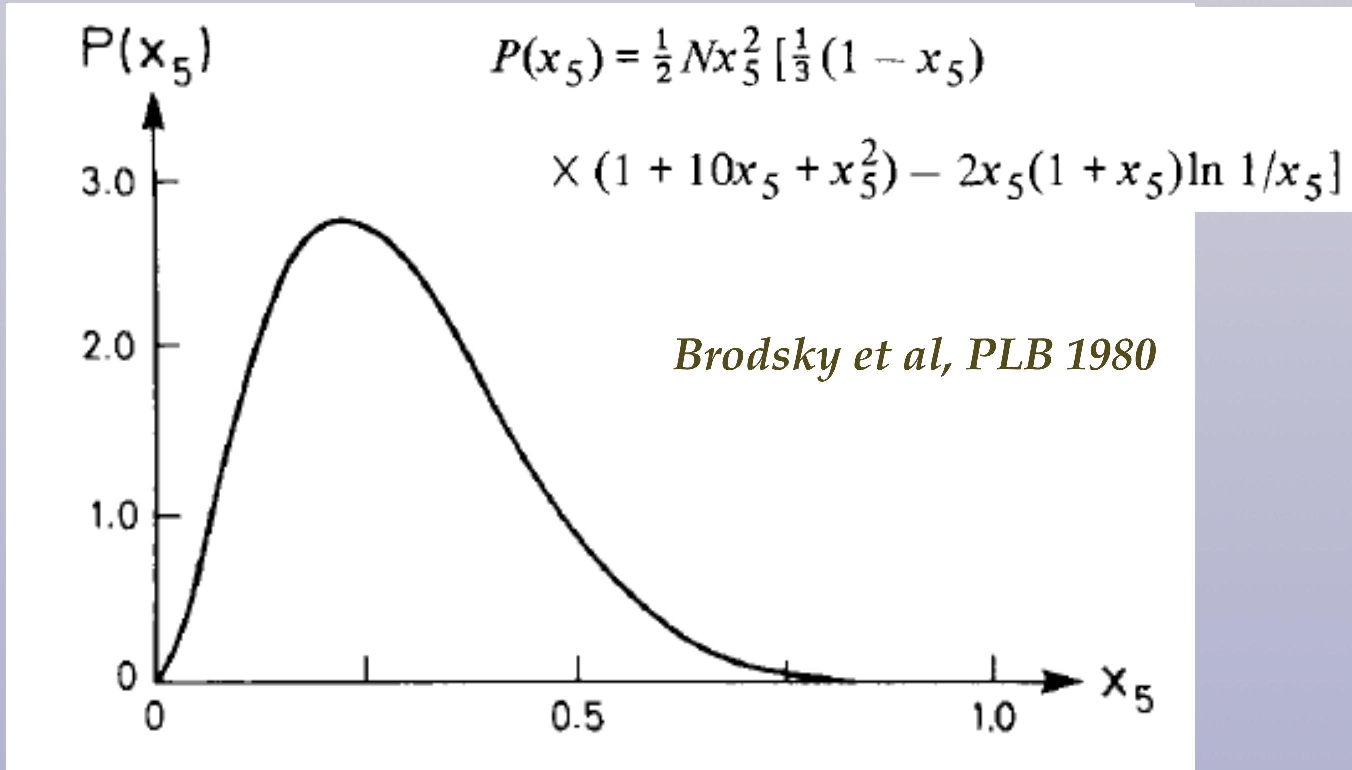



# Model-Independent Determination of the Charm Content of the Proton

*The NNPDF Collaboration*: *R. D. Ball, V. Bertone, M. Bonvini, S. Carrazza, S. Forte, A. Guffanti, N. P. Hartland, JR and Luca Rottoli, arXiv:1604.aaaaa*

# Why fitted charm?

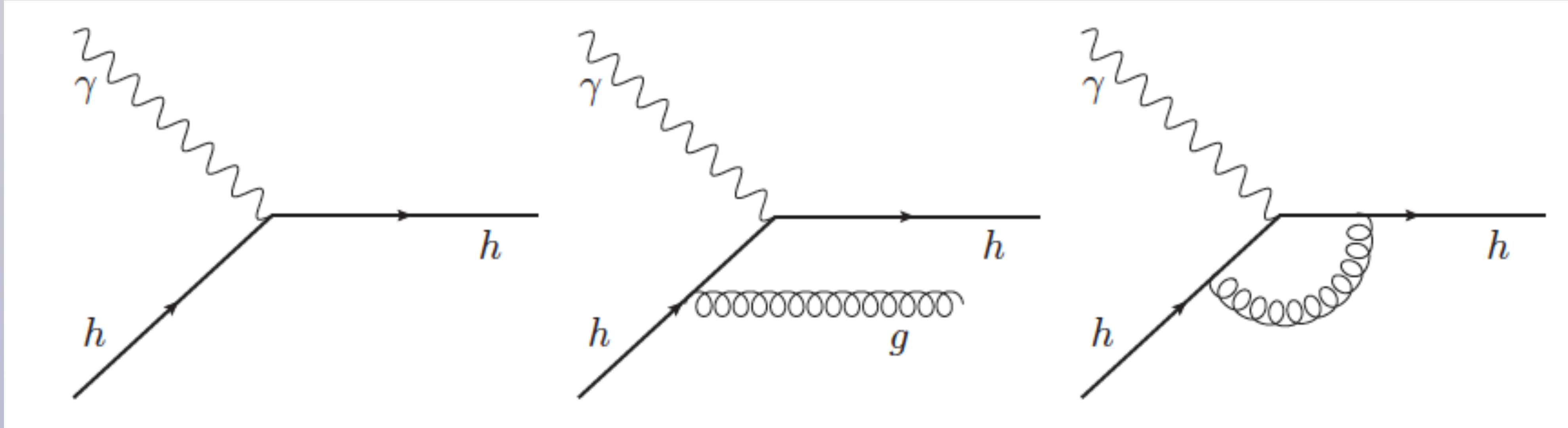
- The motivation **to fit a charm PDF** in a global analysis is **two-fold:**
  - ☑ Stabilise the dependence of **LHC calculations** with respect to **value of the charm mass**
  - ☑ Quantify the **non-perturbative charm component in the proton** and compare with models




**A 30-years old conundrum of QCD!**

# FONLL with fitted charm

- In a global PDF analysis with fitted charm, not enough to add **a new fitted PDF at the input scale**
- **FFN** and **GM-VFN** scheme calculations need to be modified to account for genuinely **new contributions: massive charm-initiated processes**



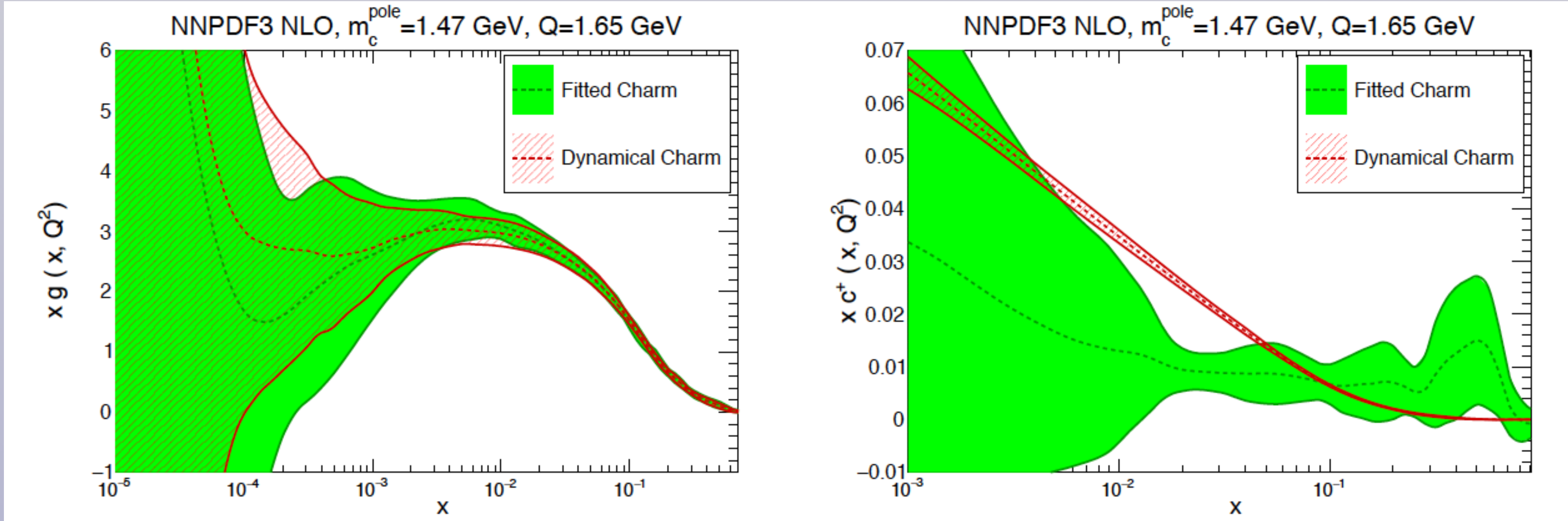

- Coefficient functions for NC and CC **charm-initiated contributions in the massive scheme** up to NLO have been computed (NNLO not available yet)
- FONLL structure functions can be modified to account for **massive charm-initiated contributions**
- Use of **generalized GM-VFN scheme** crucial for any **reliable fit with charm PDFs**

*R. D. Ball, V. Bertone, M. Bonvini, S. Forte, P. Groth-Merrild A. Guffanti, JR and Luca Rottoli, arXiv:1510.00009*
*R. D. Ball, M. Bonvini and L. Rottoli, arXiv:1510.02491*

***more details in Luca Rottoli's talk***

# NNPDF3 fits with intrinsic charm

- **Fit settings** based on the upcoming **NNPDF3.1 global analysis**
- PDF parametrization as in NNPDF3.0, now adding **$c^+(x,Q_0)$** as additional Artificial Neural Network: **same number of free parameters** as all other light quark PDFs
- **Fitted dataset:** same as in NNPDF3.0, with the **HERA legacy combination** and the **EMC charm data**




At low scales, **gluon PDF stable**, but **fitted charm** different from **perturbative charm**

At large-x, a **BHPS-like bump is found**, although PDF uncertainties are still large

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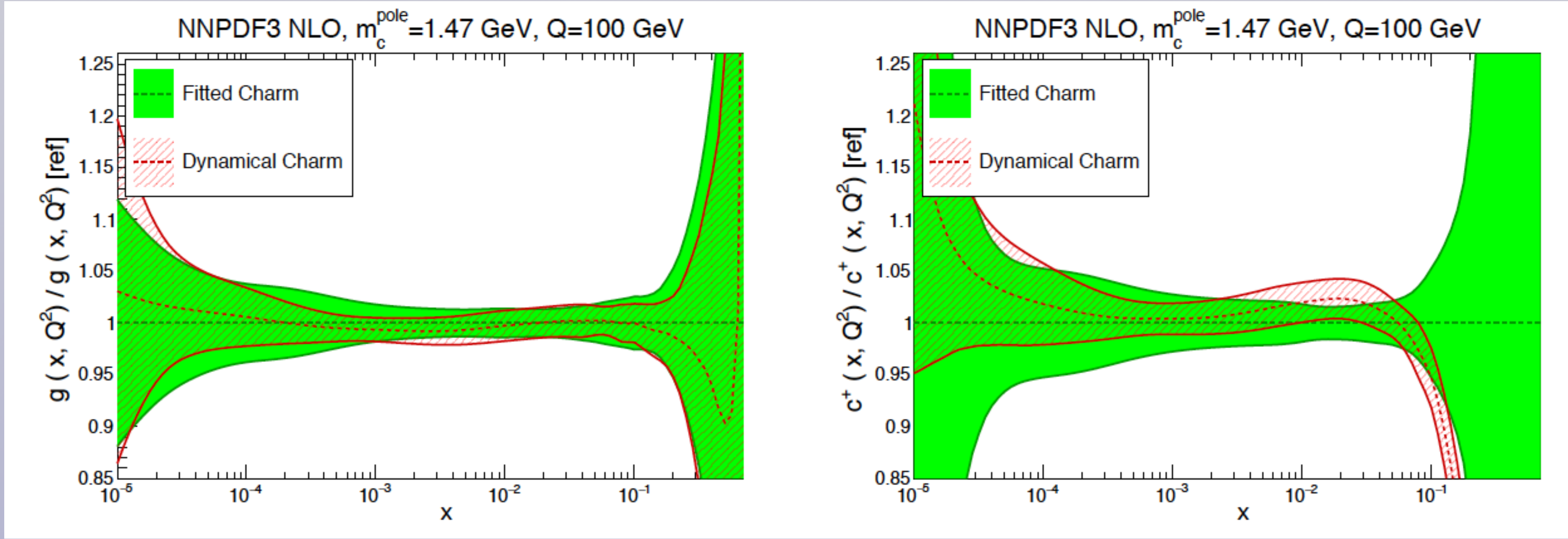



At high scales, **gluon PDF also stable**, with moderate increase in PDF uncertainty

Fitted and dynamical charm PDFs **agree within uncertainties** for the whole range of x

# Fit quality

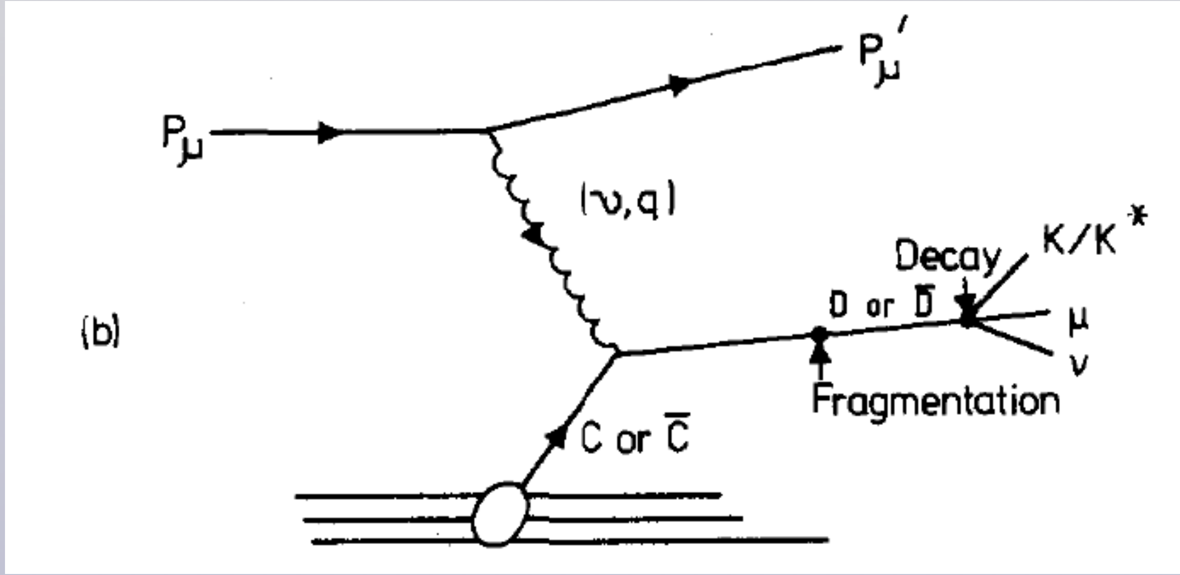
| NNPDF3 NLO $m_c = 1.47$ GeV (pole mass) | | | |
|---|---|---|---|
| Experiment | $N_{\rm dat}$ | $\chi^2/N_{\rm dat}$ fitted charm | $\chi^2/N_{\rm dat}$ dynamical charm |
| NMC | 325 | 1.36 | 1.34 |
| SLAC | 67 | 1.21 | 1.32 |
| BCDMS | 581 | 1.28 | 1.29 |
| CHORUS | 832 | 1.07 | 1.11 |
| NuTeV | 76 | 0.62 | 0.62 |
| EMC | 16 | 1.09 | - (32) |
| HERA inclusive | 1145 | 1.17 | 1.19 |
| HERA $F_2^c$ | 47 | 1.14 | 1.09 |
| DY E605 | 104 | 0.82 | 0.84 |
| DY E866 | 85 | 1.04 | 1.13 |
| CDF | 105 | 1.07 | 1.07 |
| D0 | 28 | 0.64 | 0.61 |
| ATLAS | 193 | 1.44 | 1.41 |
| CMS | 253 | 1.10 | 1.08 |
| LHCb | 19 | 0.87 | 0.83 |
| $\sigma(t\bar{t})$ | 6 | 0.96 | 0.99 |
| Total | 3866 | 1.159 | 1.176 |

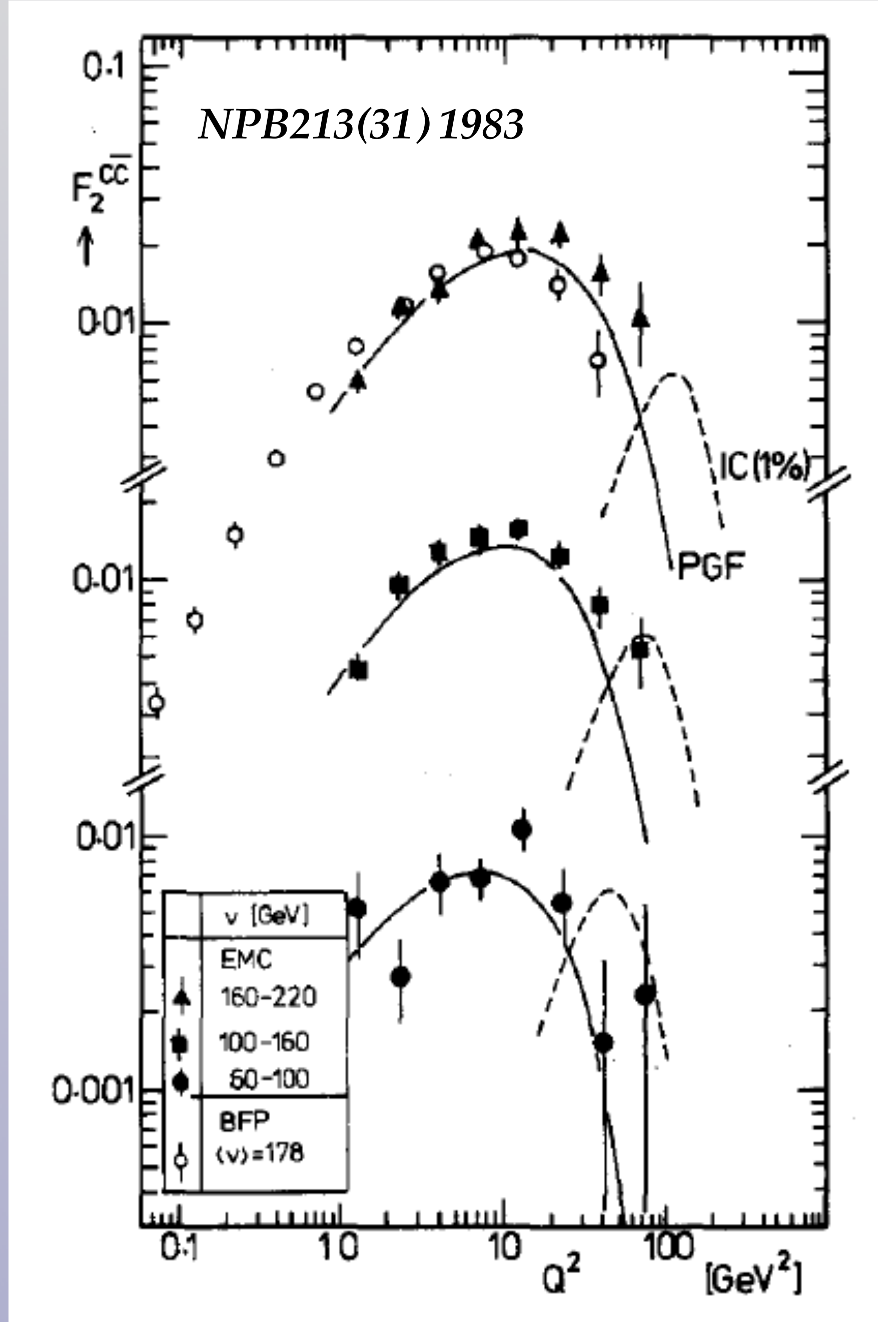
- Fitted charm improves the data/theory agreement

- The most marked **improvements** in the fitted charm case are the **HERA inclusive data** and the **CHORUS neutrino structure functions**

- For the **LHC datasets** the **fit quality is unchanged** when charm is fitted

# The EMC charm data

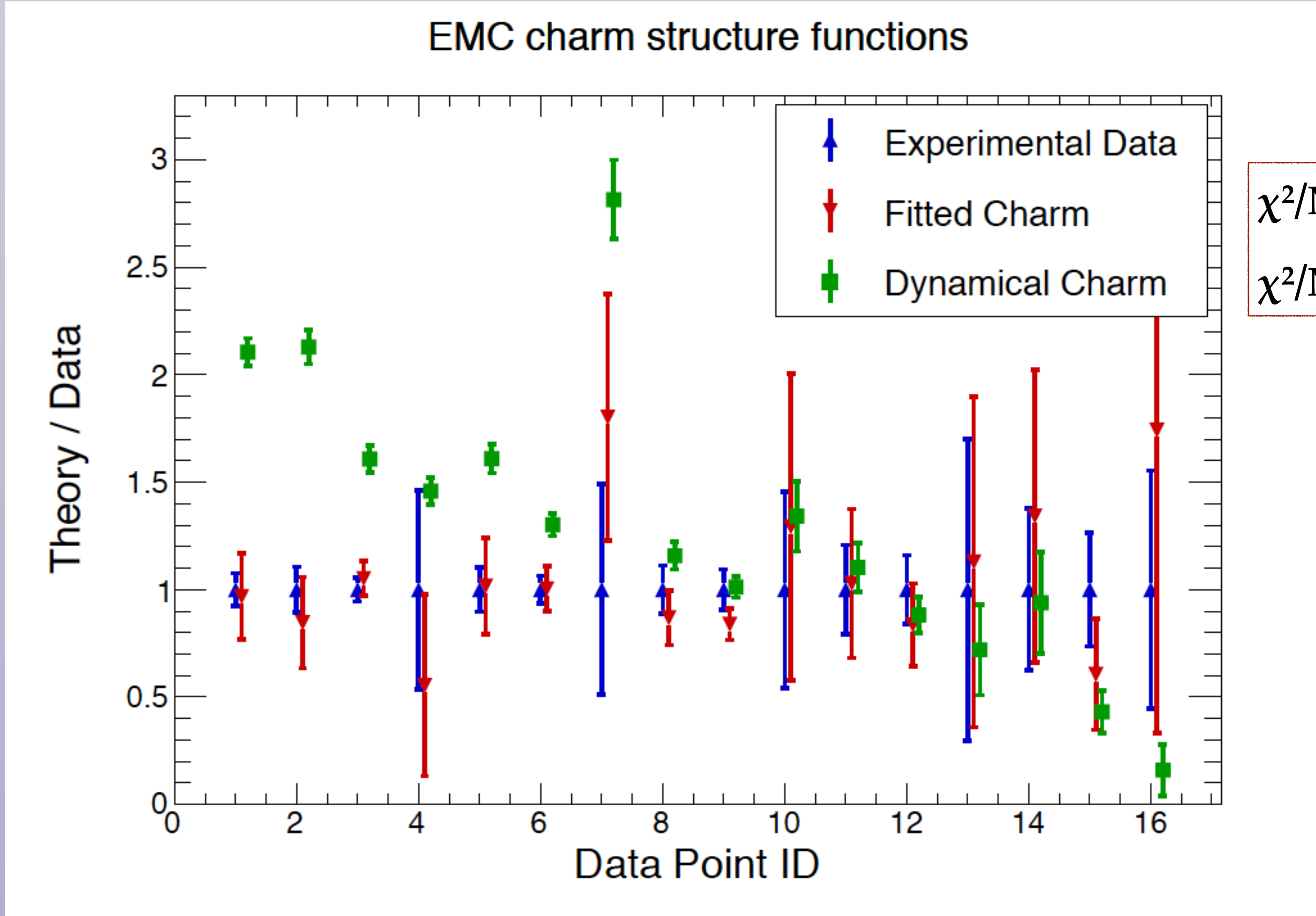



- Since more than 30 years, the EMC charm structure function data advocated as **evidence for intrinsic charm**
- However, previous global PDF fits with fitted charm **unable to achieve satisfactory description** of this experiment
- **arXiv:1408.1708** (Jimenez-Delgado et al) finds $\chi^2/N_{dat}$**=4.4** in their FFN IC analysis

# The EMC charm data

- **Satisfactory description of the EMC charm data** when charm is fitted
- EMC charm data essential to **reduce the PDF uncertainties** in the NNPDF fitted charm
- Improvements as compared to previous studies likely related to the **more flexible charm PDF parametrization adopted here**, not restricted to specific models

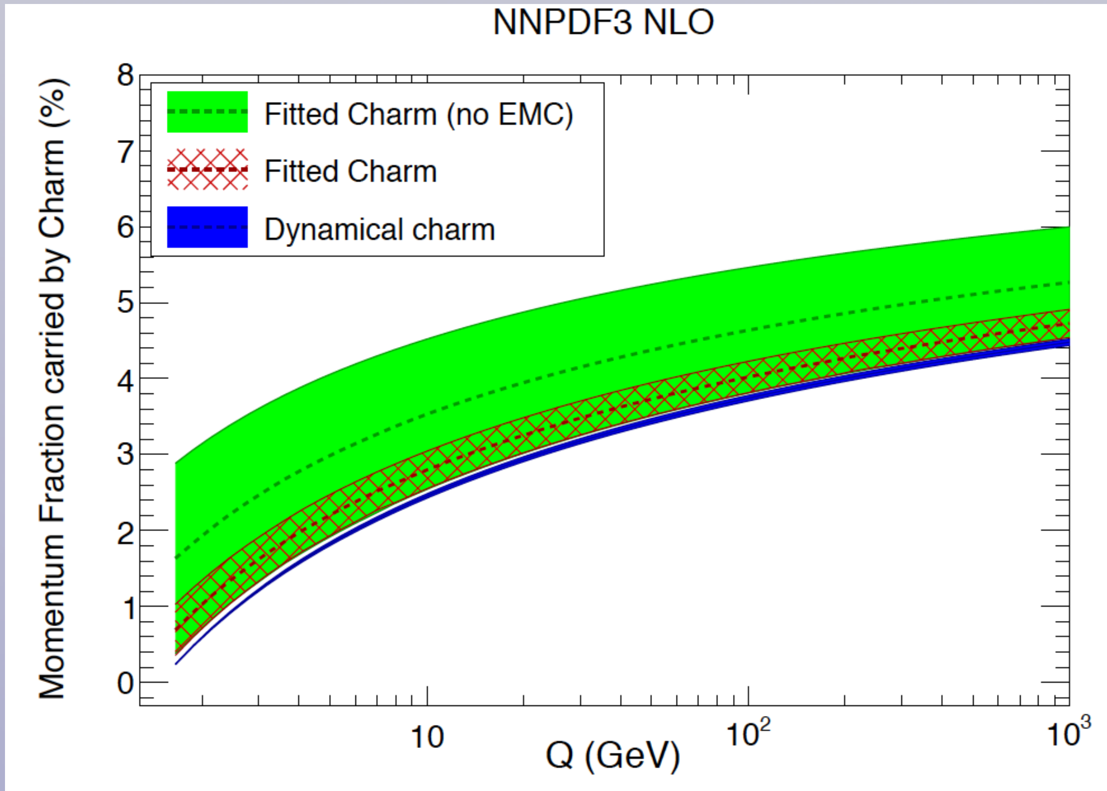



$\chi^2/N_{dat}$=1.08

$\chi^2/N_{dat}$= 31.8

# Charm contribution to proton momentum

| PDF set | $Q$ | $C(Q)$ |
|---|---|---|
| NNPDF3 dynamical charm | 1.65 GeV | $(0.239 \pm 0.003)\%$ |
| NNPDF3 fitted charm | | $(0.7 \pm 0.3)\%$ |
| NNPDF3 fitted charm (no EMC) | | $(1.6 \pm 1.2)\%$ |
| CT14 BHPS1 | 1.3 GeV (1.65 GeV) | 0.7% (1.3%) |
| CT14 BHPS2 | | 2.0% (2.6%) |
| CT14 SEA1 | | 0.6% (1.31%) |
| CT14 SEA2 | | 1.6% (2.2%) |



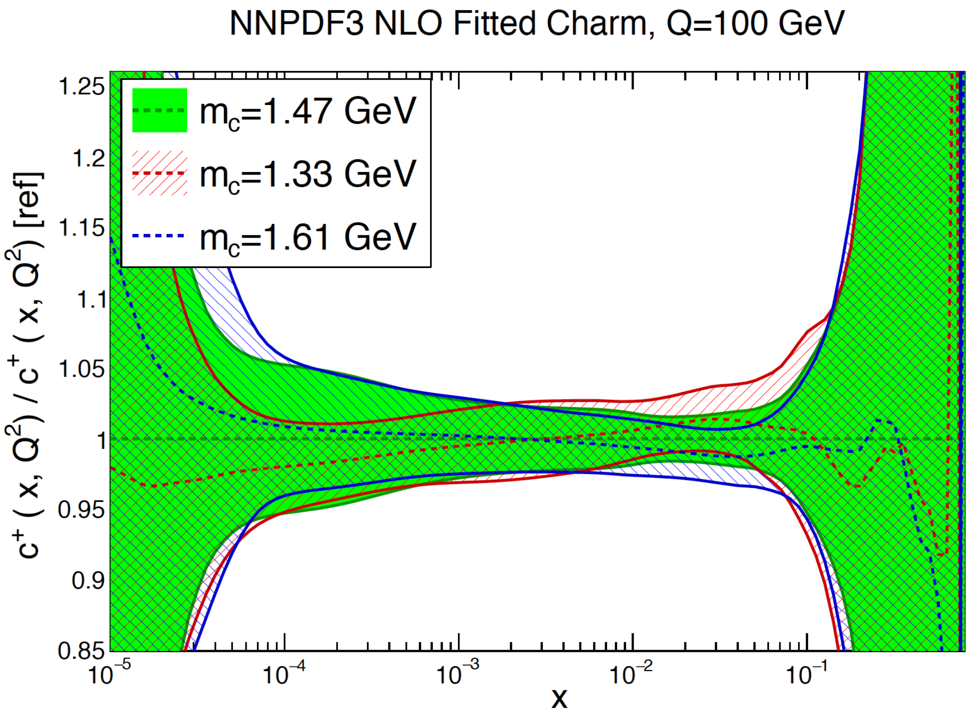

- At Q=1.65 GeV, charm can carry up to **1% of the proton's momentum** at the 68% CL (but consistent also with zero within PDF uncertainties)

- **Overall consistency** between perturbative and fitted charm for all Q

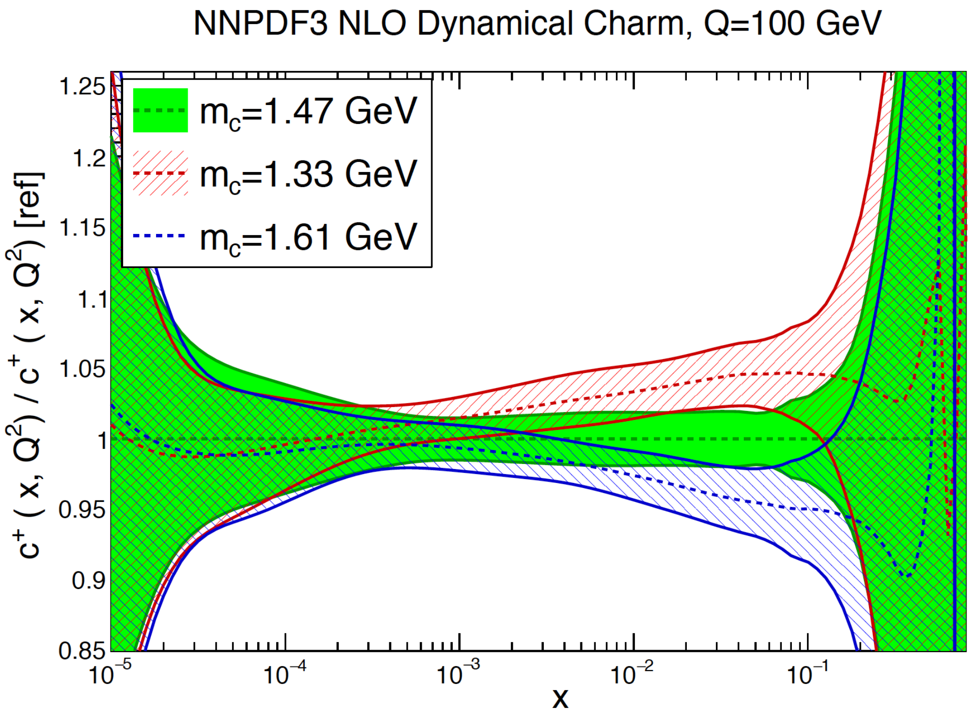
- The **large momentum fractions** carried by the **CT14IC** BHPS2 and SEA2 models are strongly disfavoured

# Stability with charm mass variations

## Fitted Charm




## Dynamical charm

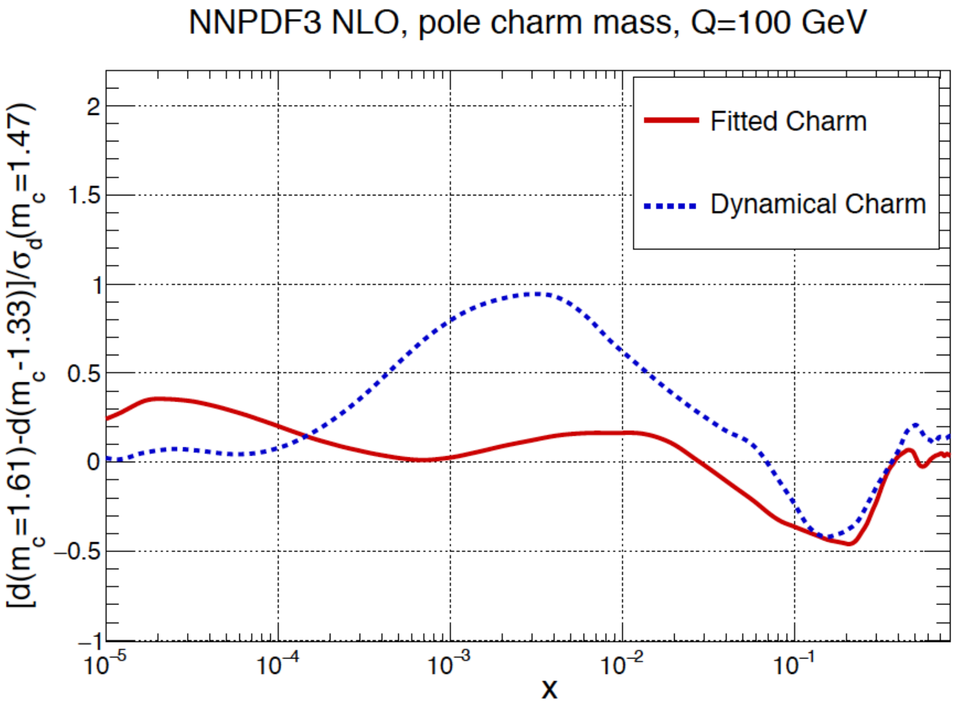



- Study fit stability by **varying the charm mass by +- 5 sigma** with respect to the PDG value, using the **one-loop pole -> running mass conversion**
- If charm is fitted: all PDFs, in particular **charm and gluon,** vary by **less than 1%** in the region relevant for precision phenomenology at the LHC
- PDF sensitivity to $m_c$ larger is **charm is generated dynamically**

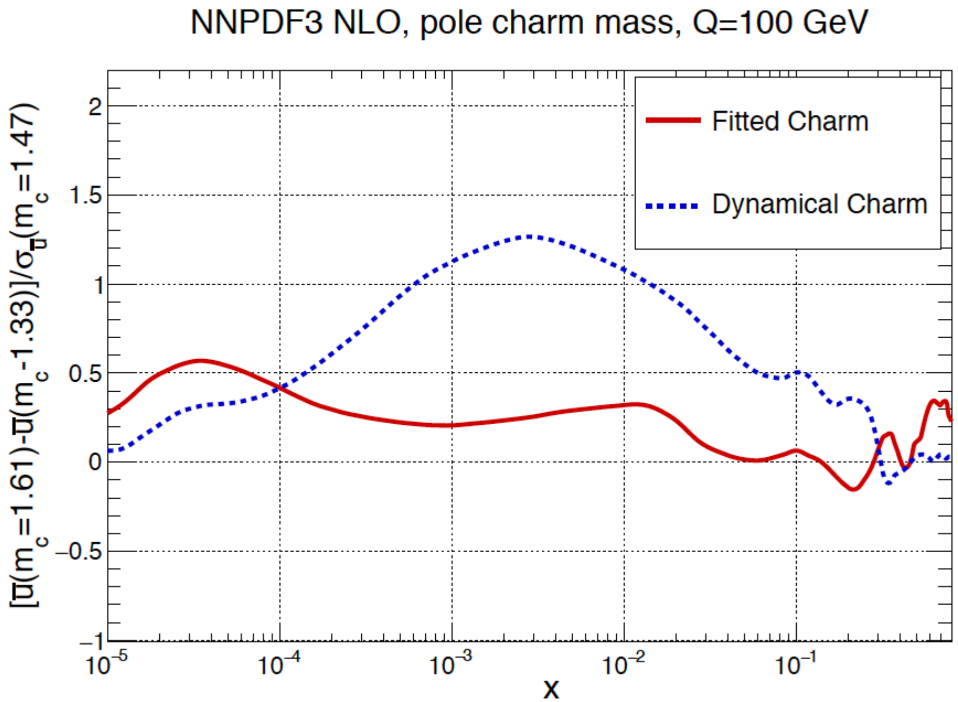
# Stability with charm mass variations

$$P_q(x, Q^2) \equiv \frac{[q(x, Q^2, m_c = 1.61 \text{ GeV}) - q(x, Q^2, m_c = 1.33 \text{ GeV})]}{\sigma_q(x, Q^2, m_c = 1.47 \text{ GeV})} ,$$

## Down quark

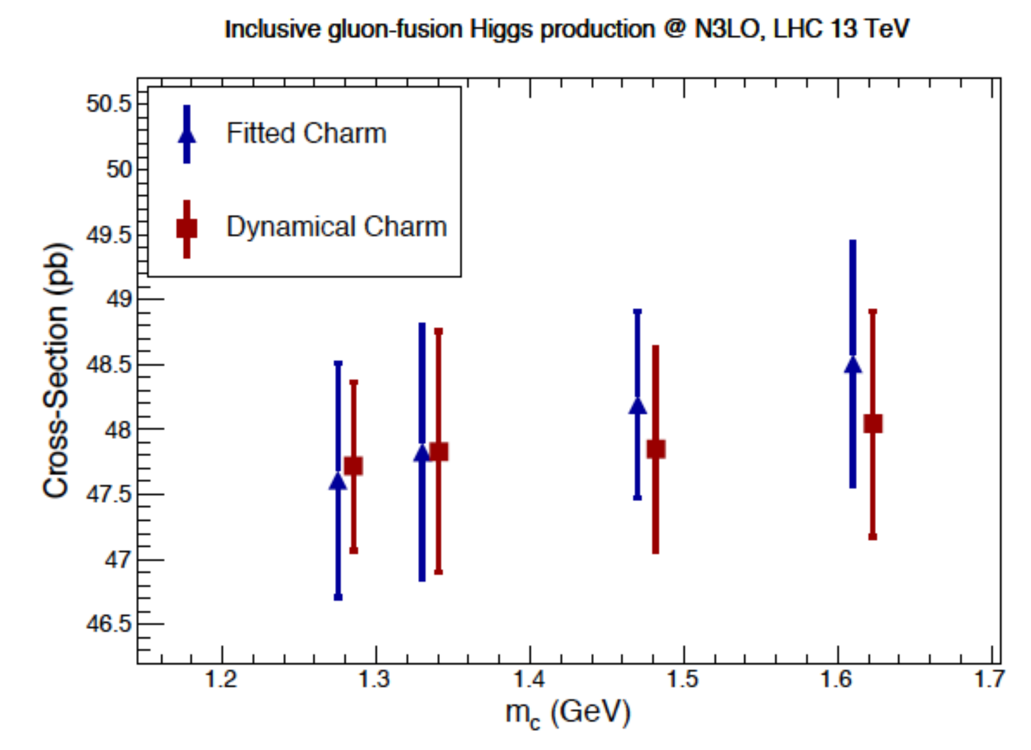


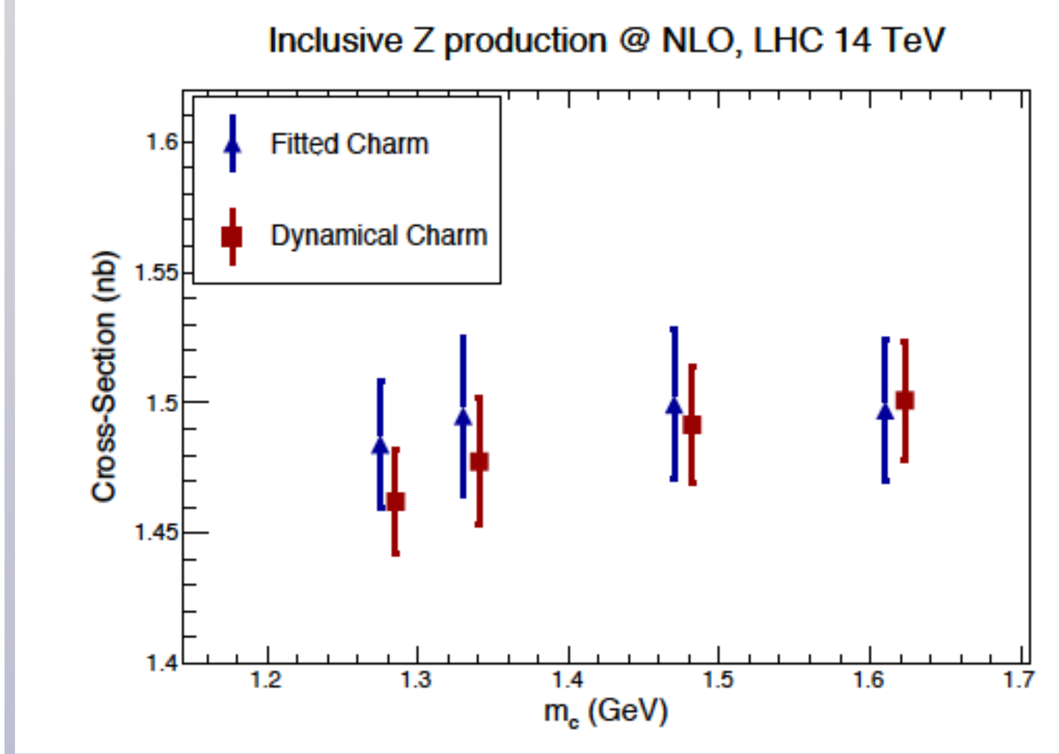

## Anti-Up quark




The improved stability also benefits **flavours not directly linked to the charm mass**, such as the down quark or the anti-up quark

# Stability with charm mass variations



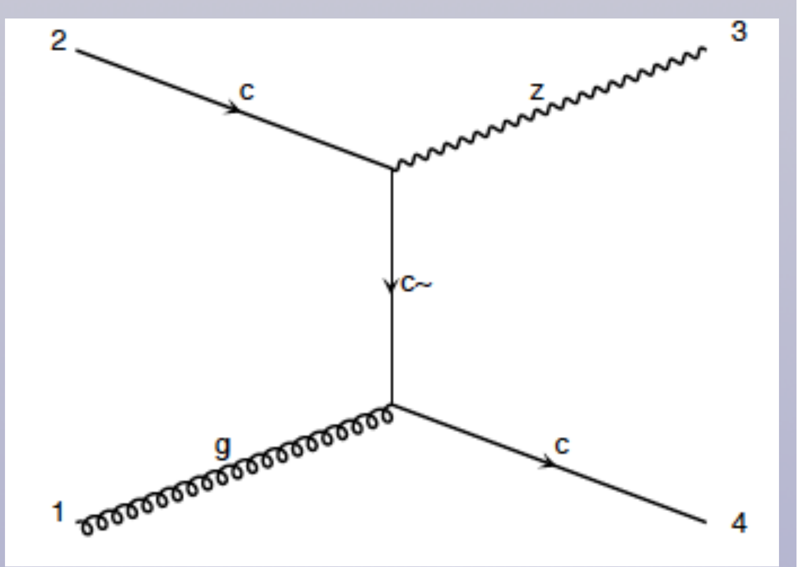

- Similar improved stability wrt the charm mass at the level of **LHC cross-sections**
- **N3LO Higgs cross-section** in gluon-fusion varies by less than **0.5%,** small compared to the PDF uncertainty, even for a **large variation in $m_c$**
- **Electroweak cross-sections** (W, Z) in particular benefit of the enhanced stability: implications for precision measurements such as the **W mass**
- Similar stability observed in the fits with **running heavy quark masses**

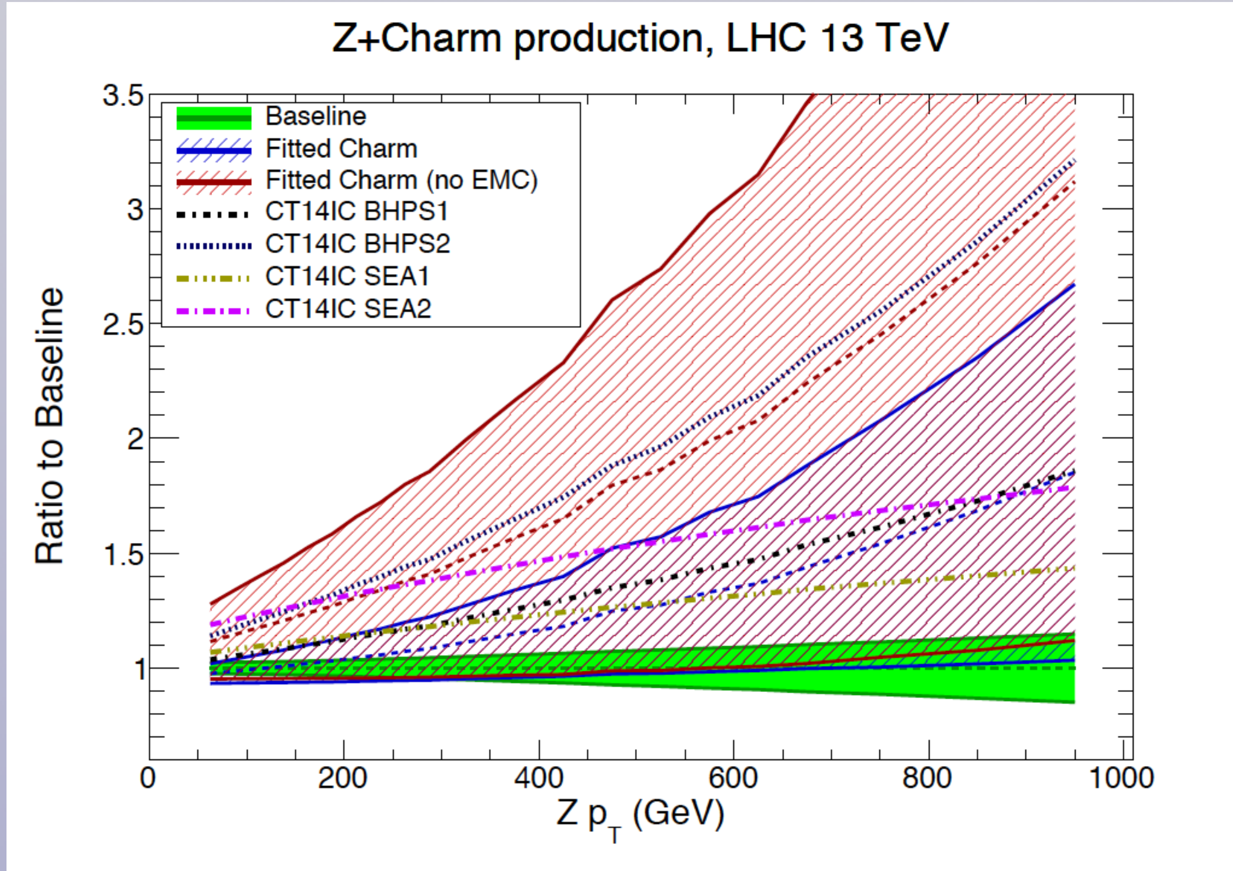
# Phenomenological implications @ LHC

- The differences between **fitted charm** and **perturbative charm** can be explored using a variety of LHC observables such as **D meson production and Z+charm** production

- The **more forward and larger $p_T$ the measurement**, the more sensitive to the large-x charm PDF, and thus to the differences between fitted and dynamical charm

## Z+charm



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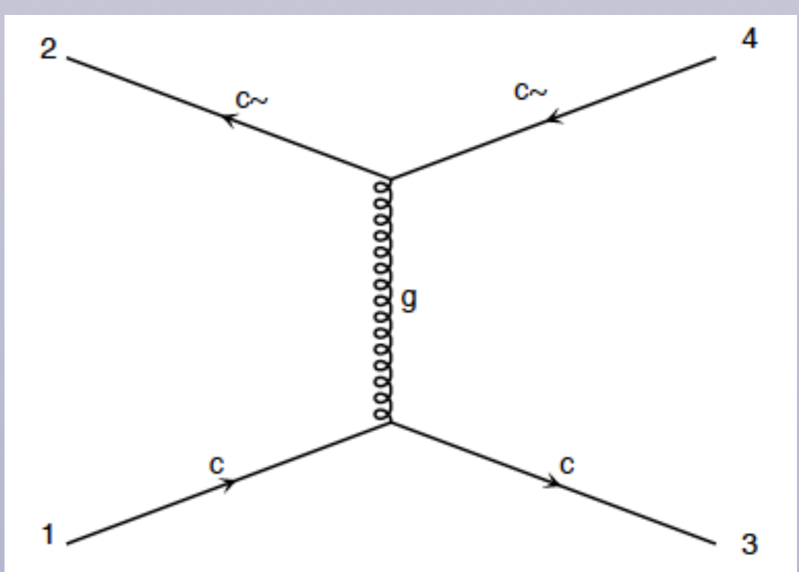
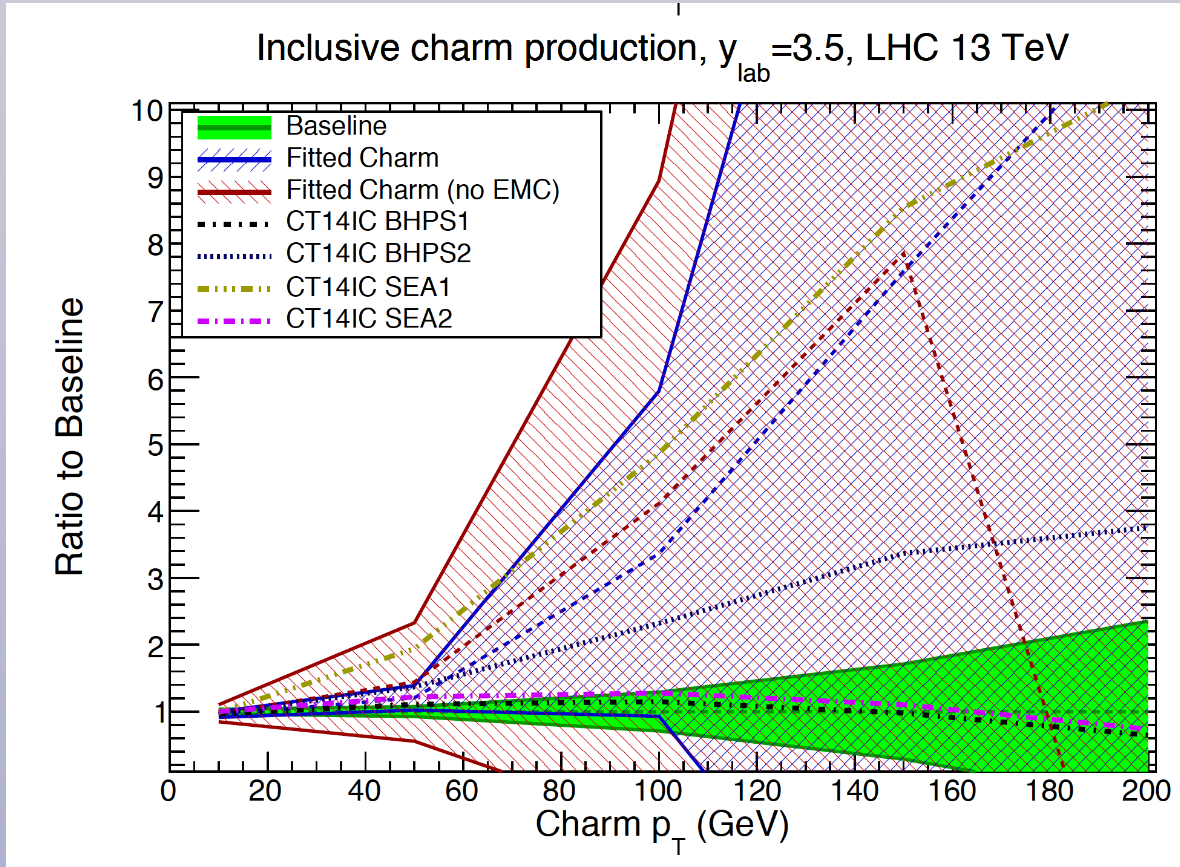
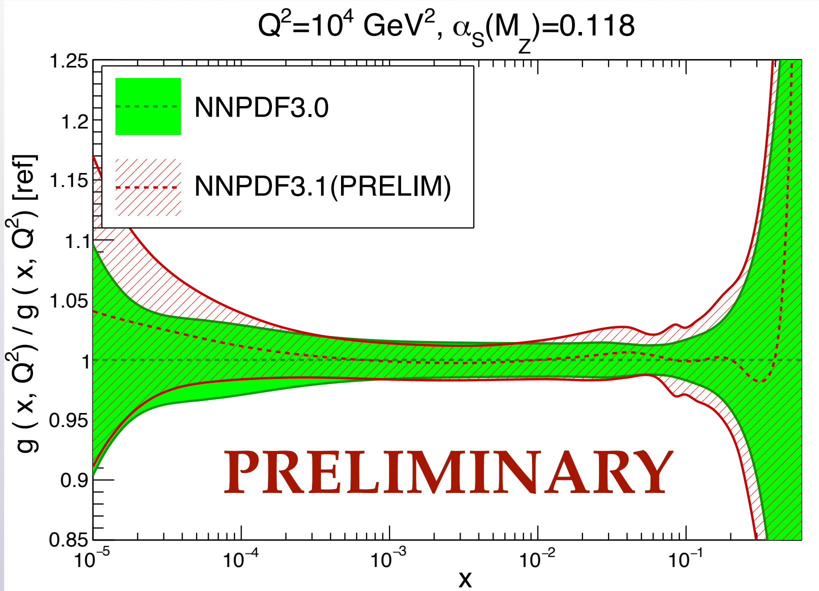
## Charm pair production






# Towards a new global analysis: NNPDF3.1

*The NNPDF Collaboration, in preparation*

# Towards NNPDF3.1

**NNPDF3.1 is the next update of the NNPDF global analyses**

- Several **new additional datasets included**: the **legacy HERA data**, the final Tevatron $W$ asymmetries, ATLAS 2011 inclusive jets, new W,Z data from ATLAS, CMS and LHCb, differential top quark pair rapidity distributions, the Z $p_T$ from ATLAS and CMS, ……

- All theory calculations now based on the public **x-space code APFEL**

- **Pole and running heavy quark mass fits,** for a wide range of **charm and bottom masses**

- **Charm PDF** treated on equal footing as the light quark flavors

- **Extended positivity constraints,** more robust estimate of large-$x$ PDF errors

- Improved determination of preprocessing ranges from the **effective behaviour of PDFs at small and large-$x$**

$$\alpha_{f_i}(x,Q^2) \equiv \frac{\partial \ln[x f_i(x,Q^2)]}{\partial \ln x}\,, \qquad \beta_{f_i}(x,Q^2) \equiv \frac{\partial \ln[x f_i(x,Q^2)]}{\partial \ln(1-x)}\,,$$

*see also arXiv:1604.00024 and Emanuele Nocera's talk*

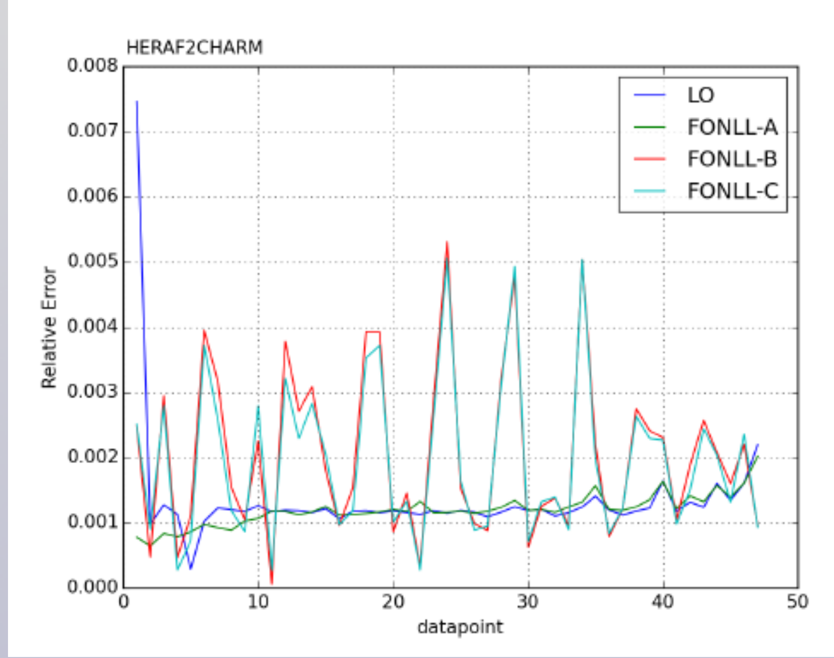
# New datasets in NNPDF3.1

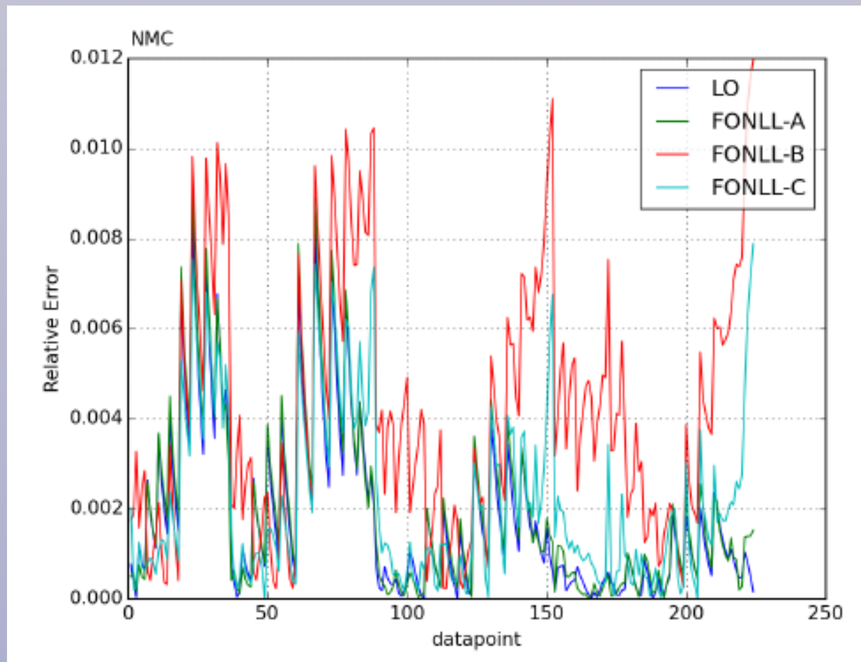
| Measurement | Data taking | Motivation |
|---|---|---|
| LHCb W,Z rapidity dists 7,8 TeV | 2011+2012 | small-x and large-$x$ quarks |
| D0 legacy W asymmetries | Run II | quark flavor separation |
| ATLAS inclusive jets 7 TeV | 2011 | large-$x$ gluon |
| ATLAS low-mass Drell-Yan 7 TeV | 2010+2011 | small-$x$ quarks |
| ATLAS Z pT 7,8 TeV | 2011+2012 | medium-$x$ gluon and quarks |
| ATLAS and CMS tt differential 8 TeV | 2012 | large-$x$ gluon |
| CMS Z pT,y 2D xsecs 8 TeV | 2012 | medium-$x$ gluon and quarks |
| CMS Drell-Yan low+high mass 8 TeV | 2012 | small-$x$ and large-$x$ quarks |
| CMS W asymmetry 8 TeV | 2012 | quark flavor separation |
| CMS 8 TeV and 2.76 TeV jets | 2012 | medium and large-$x$ gluon |

Cut-off date for new data to be included in NNPDF3.1: end of April

# APFEL and APFELcomb

- Up to NNPDF3.0, PDF evolution and DIS structure functions were based on a (private) N-space code, **FKgenerator**
- From NNPDF3.1 we will adopt the public code **APFEL** for all theory calculations
- **Extensive benchmarking** between the two codes performed, as well ad with other codes like **HOPPET and OpenQCDrad**
- For hadronic observables, **APPLgrid** and **FastNLO** grids are pre-convoluted with PDF evolution kernels to optimise fit performance using a new tool, **APFELcomb** (to be publicly released)



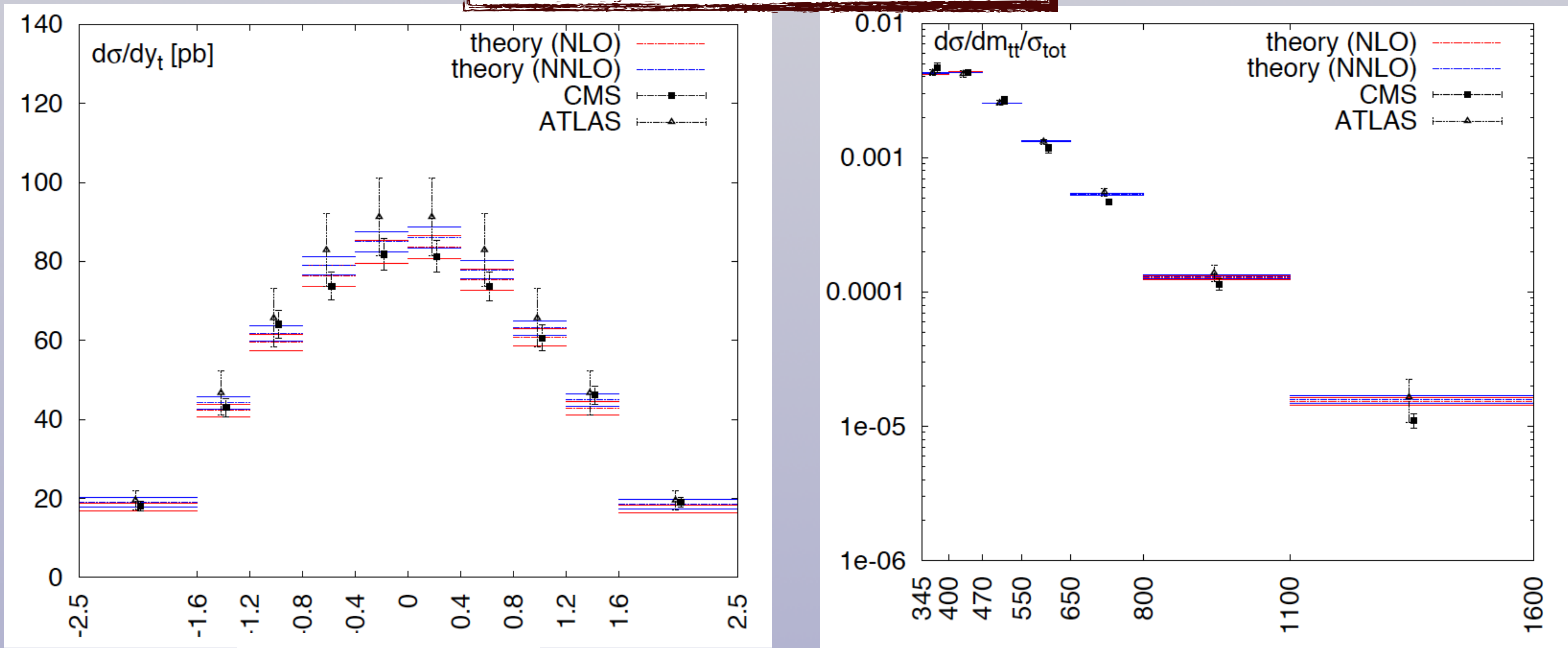

| Observable | APPLGRID | **APFELcomb** |
|---|---|---|
| $W^+$ production | 1.03 ms | 0.41 ms (2.5x) |
| Inclusive jet production | 2.45 ms | 20.1 $\mu$s (120x) |

*more on APFEL in Valerio Bertone's talk*

# Fits with differential top quark pair data

- The recent availability of **exact NNLO results** (*Czakon, Heines, Mitov, arxiv:1511.00549*) makes possible the inclusion of **top quark differential distributions** into the NNLO global analysis
- Exploit the most recent **8 TeV data from ATLAS and CMS** to constrain the **large-$x$ gluon PDF**
- These datasets will be **integral part of NNPDF3.1:** complementary constraints to jet production

**Theory calculations with NNPDF3.0**




**top quark rapidity** **top quark pair invariant mass**

*M. Czakon, N. P. Hartland, A. Mitov, E. R. Nocera, JR, in preparation*

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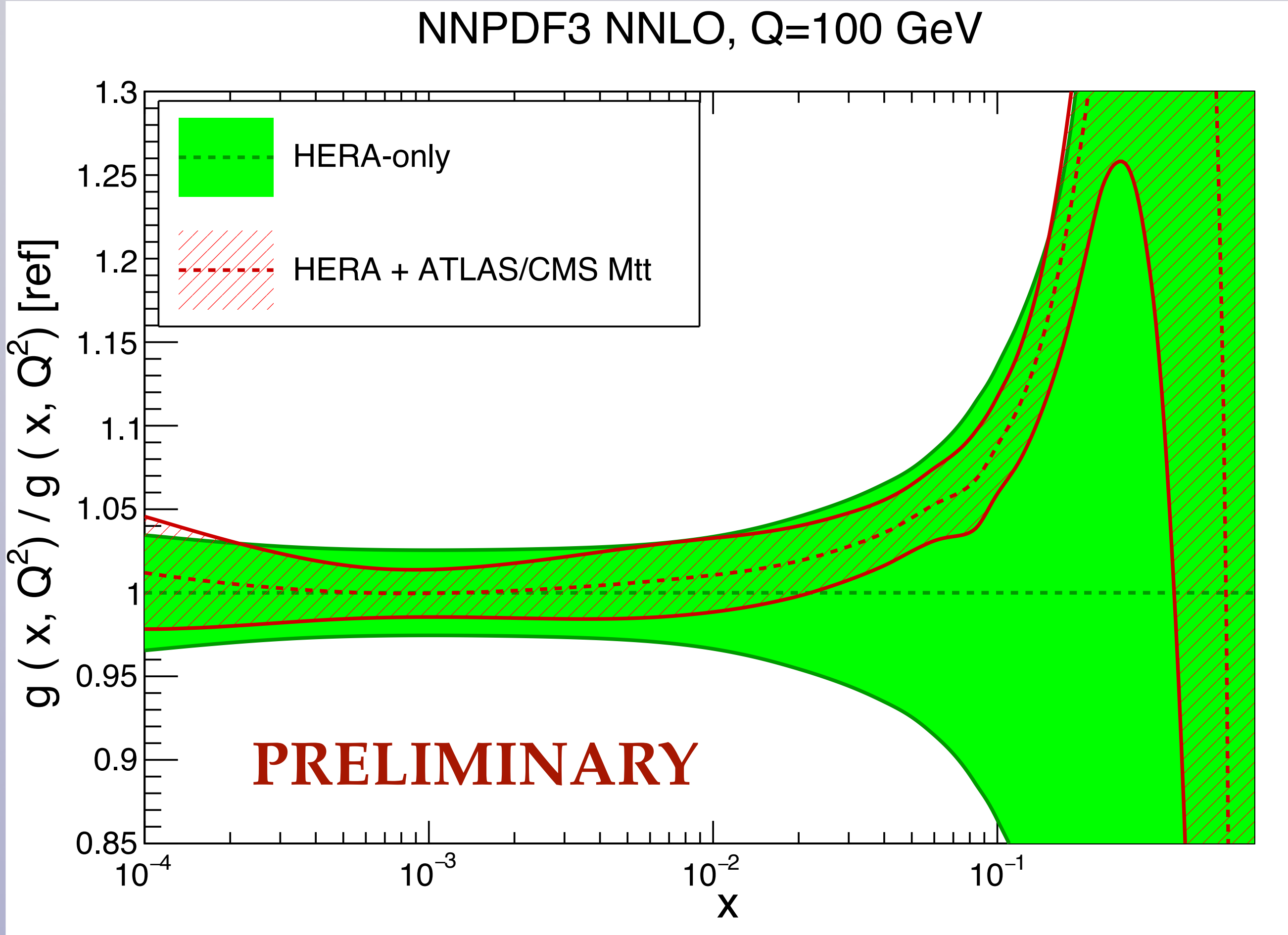
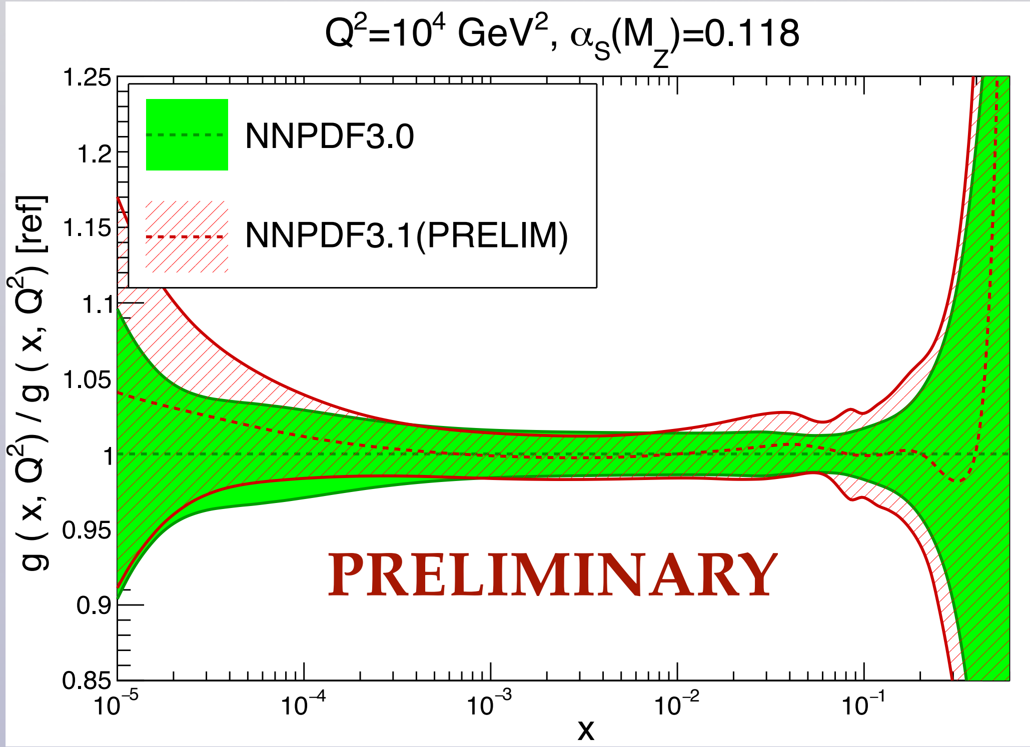
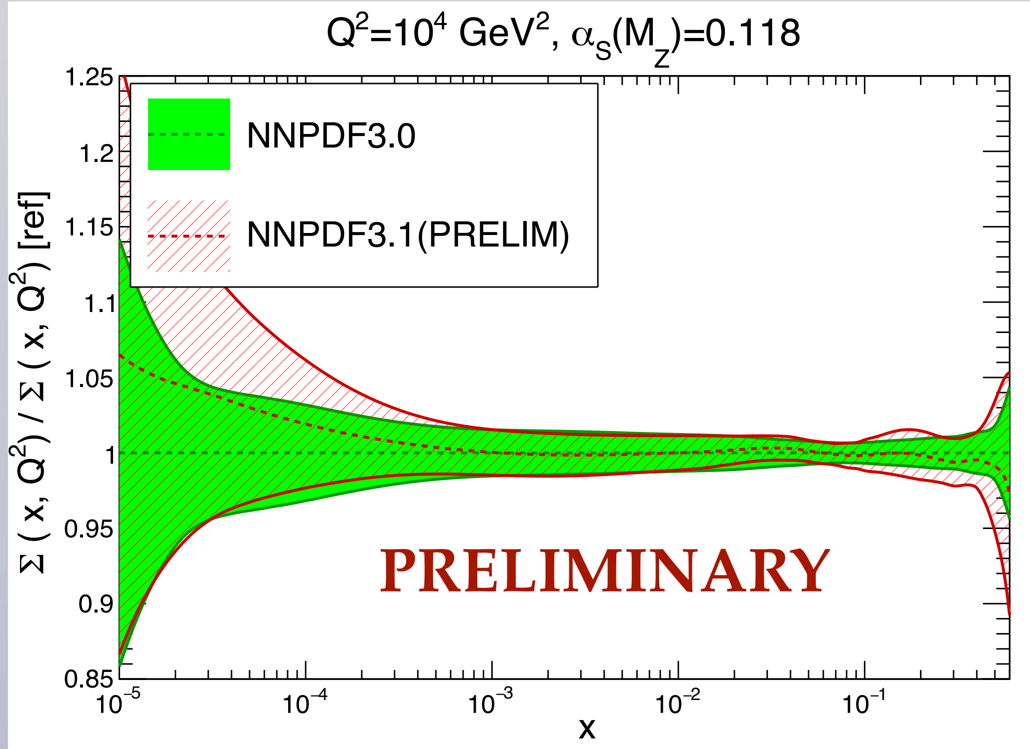



*M. Czakon, N. P. Hartland, A. Mitov, E. R. Nocera, JR, in preparation*

# PDFs: preliminary results



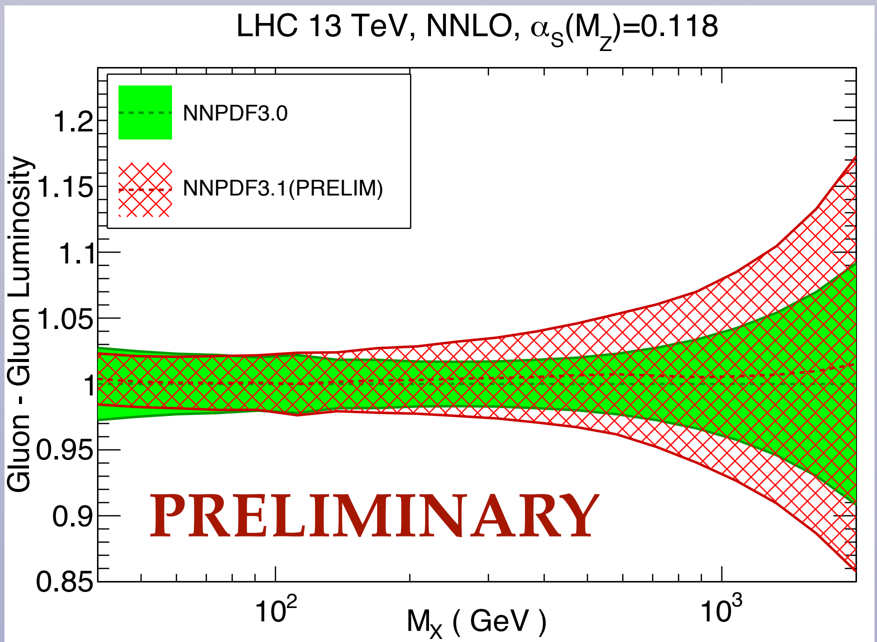



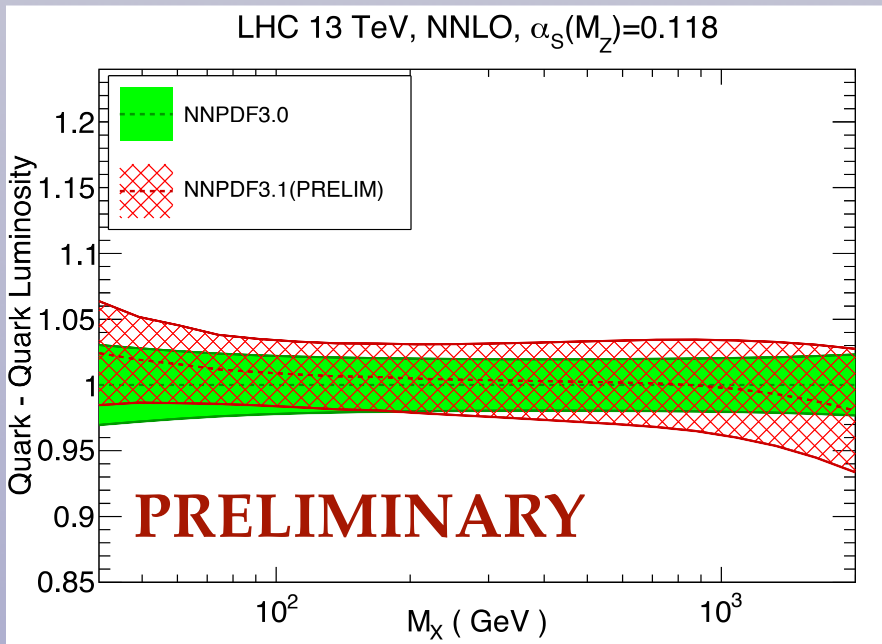

- Still early for any quantitative comparisons …….
- Preliminary results indicate **qualitatively good stability** with respect to NNPDF3.0 in the LHC precision physics region
- PDF uncertainties somewhat larger in **extrapolation regions** from methodological improvements

# LHC phenomenology

| PDF set | ggH N3LO | W+ NLO |
|---|---|---|
| NNPDF3.0 NNLO | 46.6 +- 1.1 pb | 6.56 +- 0.15 nb |
| NNPDF3.1(PRELIM) NNLO | 46.7 +- 1.0 pb | 6.65 +- 0.16 nb |

- **Higgs cross-sections in gluon-fusion** computed at N3LO using ggHiggs
- The **ggH cross-section is very stable** between NNPDF3.0 and NNPDF3.1prelim
- **W cross-sections** computed at NLO using MCFM
- Moderate upwards shift, **well within PDF uncertainties**
- **Similar stability** observed for other cross-sections (also in PDF luminosities)



# Summary and outlook

**First determination of fitted charm in the NNPDF global analysis framework**

- **LHAPDF6 grids** to be made available from the **NNPDF HepForge website,** for a range of charm mass (pole and running) values
- Both PDF sets with fitted charm and the corresponding baselines with dynamical charm
- Follow-up: pheno studies of LHC measurements to constrain non-perturbative charm

**Towards a new global analysis: NNPDF3.1**

- **Several new datasets included**, from the HERA and Tevatron legacy data to precision LHC electroweak production measurements at top quark production differential distributions
- Provided for a **wide range of (pole and running) heavy quark masses**
- Preliminary results indicate **good stability with respect to NNPDF3.0**

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**Towards a new global analysis: NNPDF3.1…**

**Thanks for your attention**

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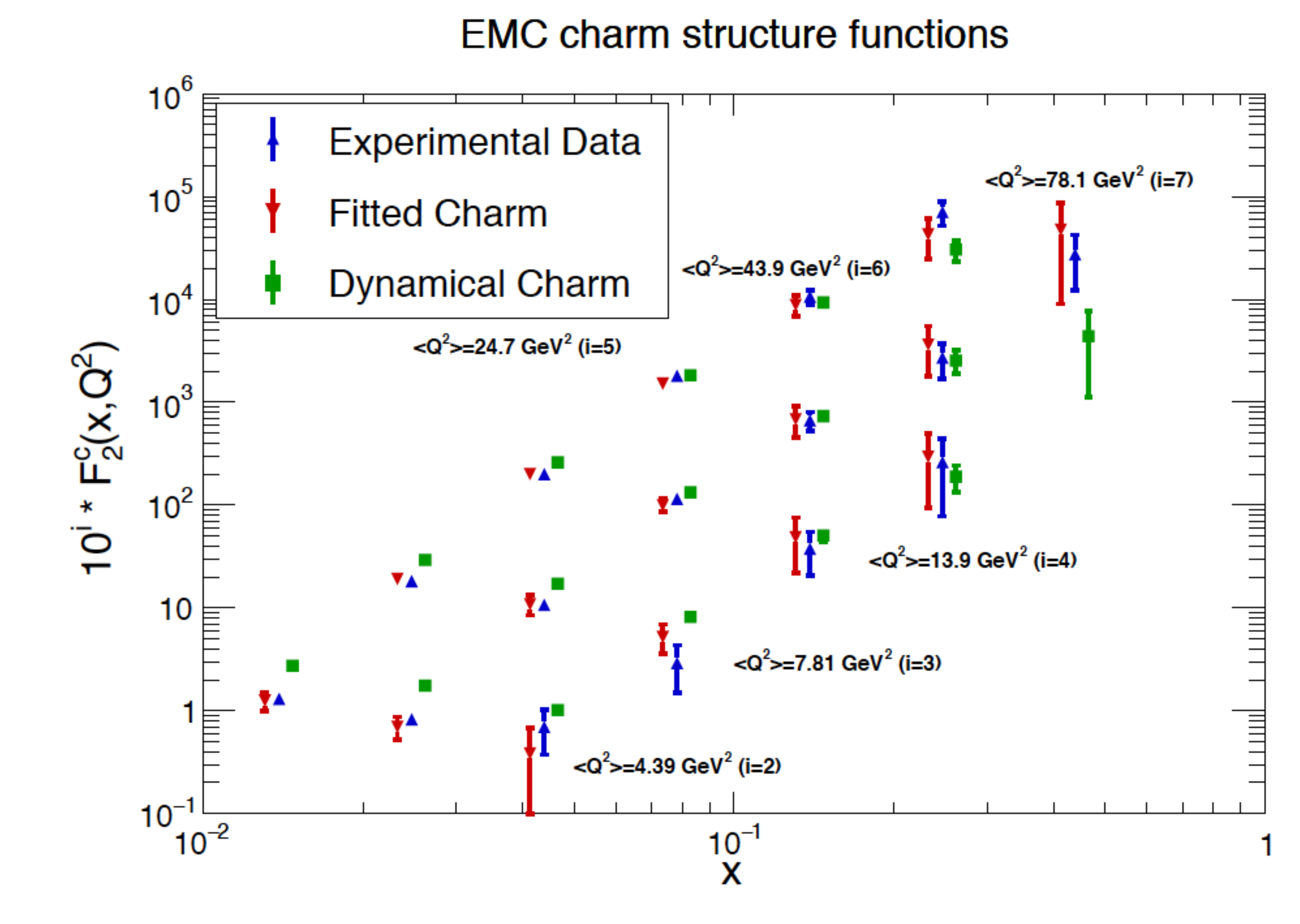
# Additional Material

# The EMC charm data



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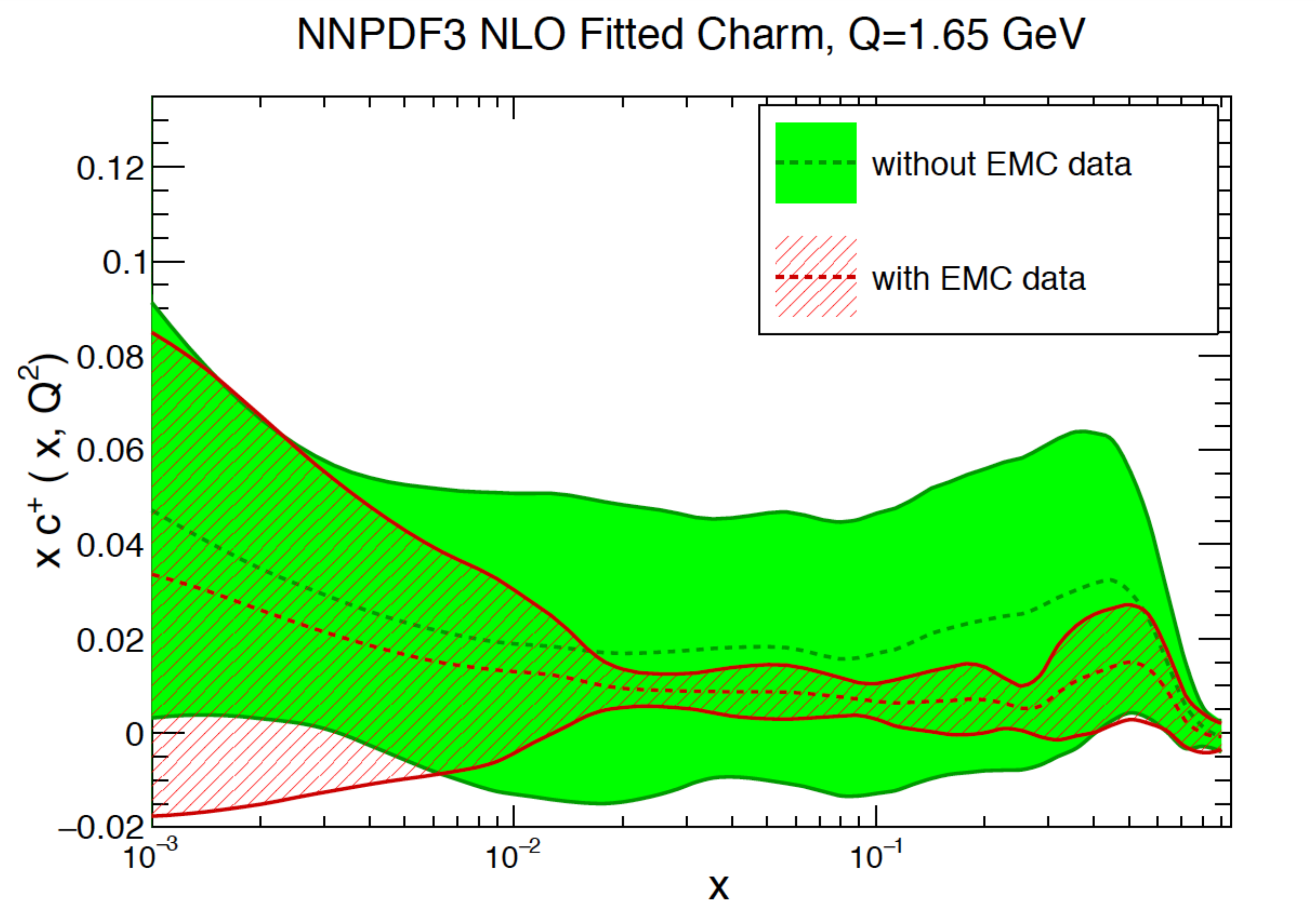
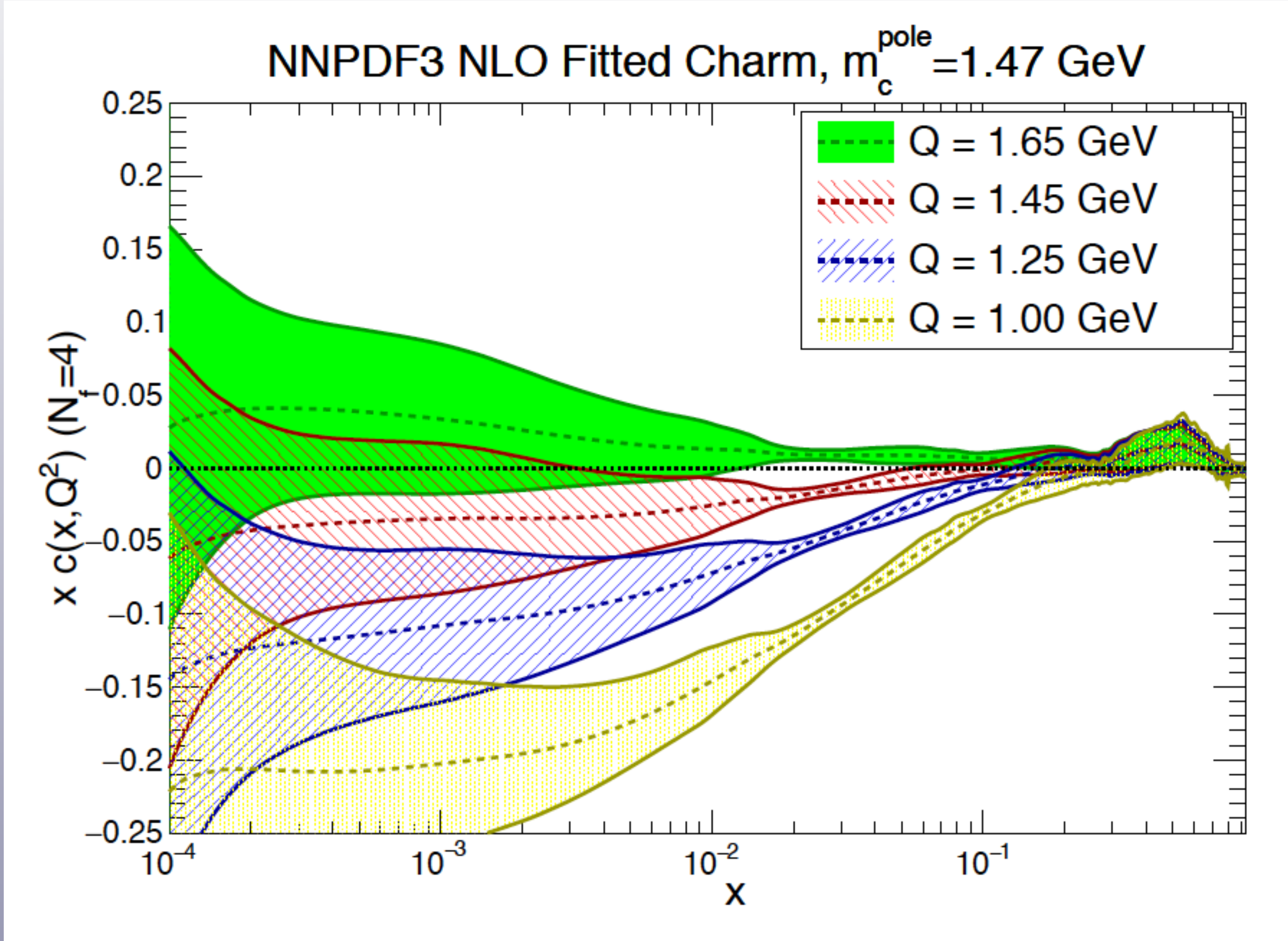


# Disentangling non-perturbative charm



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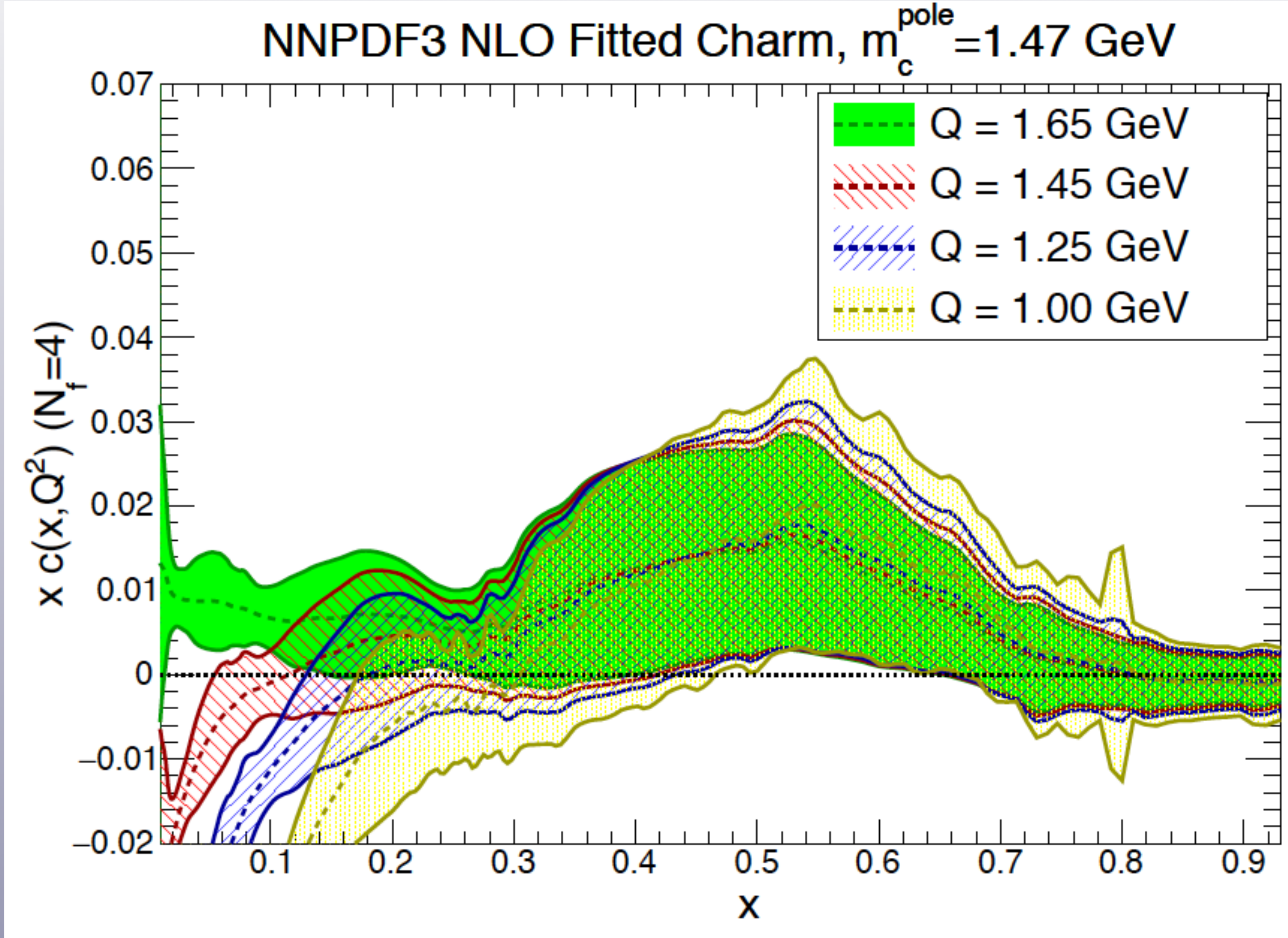

# Comparison with CT14IC