PDF4BSM
Parton Distributions in the Higgs Boson Era

erc
European Research Council

Science & Technology Facilities Council

NNPDF

Progress in the NNPDF global analysis

Juan Rojo
STFC Rutherford Fellow
Rudolf Peierls Center for Theoretical Physics
University of Oxford

QCD@LHC2016
Zurich, 22/08/2016

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

NNPDF From the past ....

Marco Bonvini's talk

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

NNPDF … to the future!

05/2016

NNPDF3 fits with intrinsic charm

Fall 2016

NNPDF3.1 global analysis

NNPDF3.1QED fits

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

PDF fits with small-x (BFKL) resummation

NNPDF ... to the future!

04/2016

This talk

NNPDF3 fits with intrinsic charm

Fall 2016

This talk

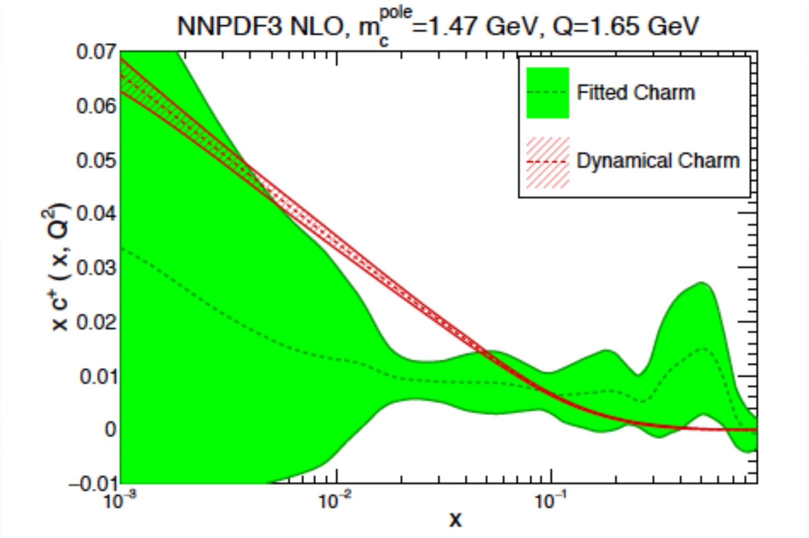
NNPDF3.1 global analysis

NNPDF3.1QED fits

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

Marco Bonvini's talk

PDF fits with small-x (BFKL) resummation

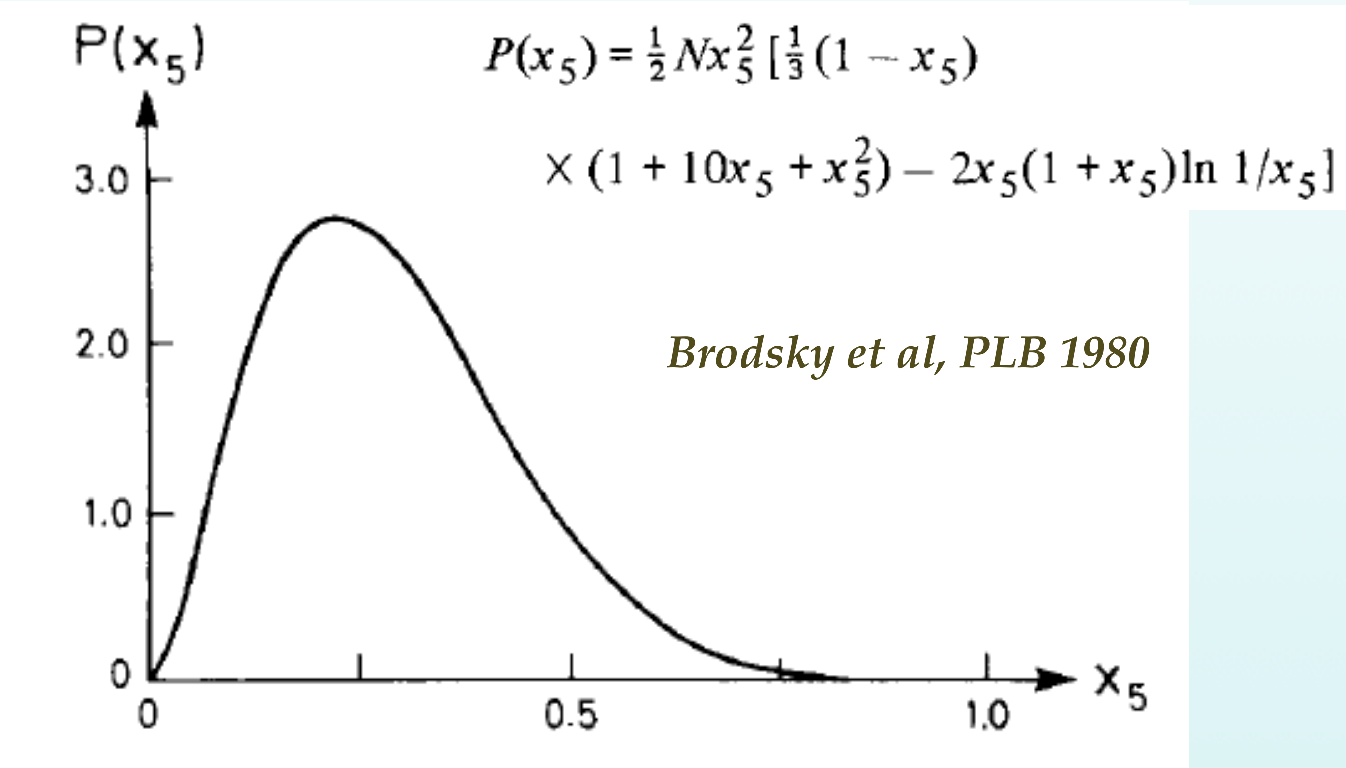


Model-Independent Determination of the Charm Content of the Proton

The NNPDF Collaboration: *R. D. Ball, V. Bertone, M. Bonvini, S. Carrazza, S. Forte, A. Guffanti, N. P. Hartland, JR and Luca Rottoli,* ***arXiv:1605.06515***

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



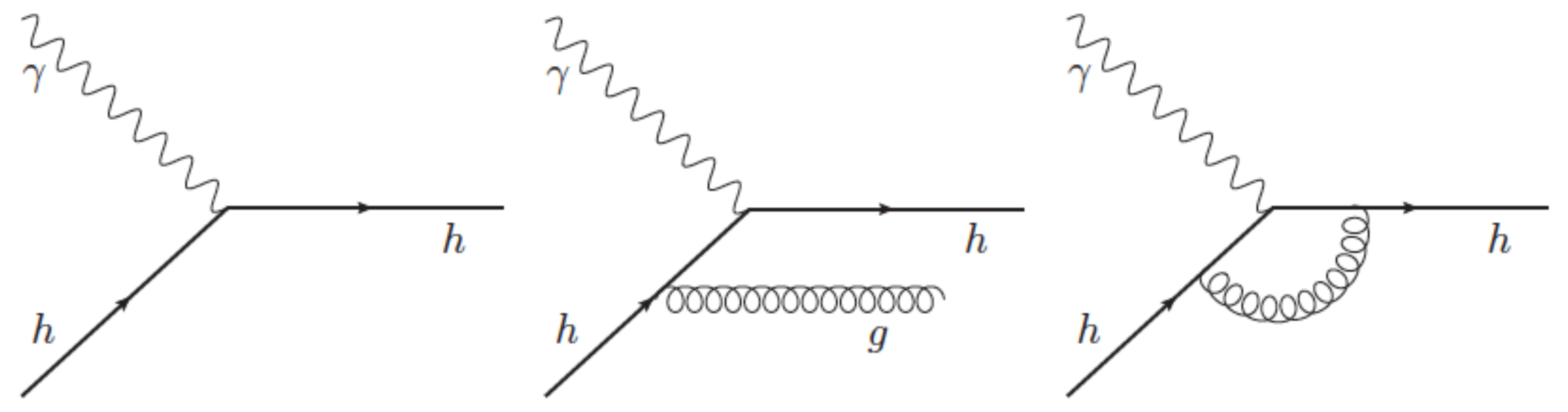
$$P(x_5) = \tfrac{1}{2} N x_5^2 \left[\tfrac{1}{3}(1 - x_5) \times (1 + 10x_5 + x_5^2) - 2x_5(1 + x_5)\ln 1/x_5 \right]$$

Brodsky et al, PLB 1980

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**

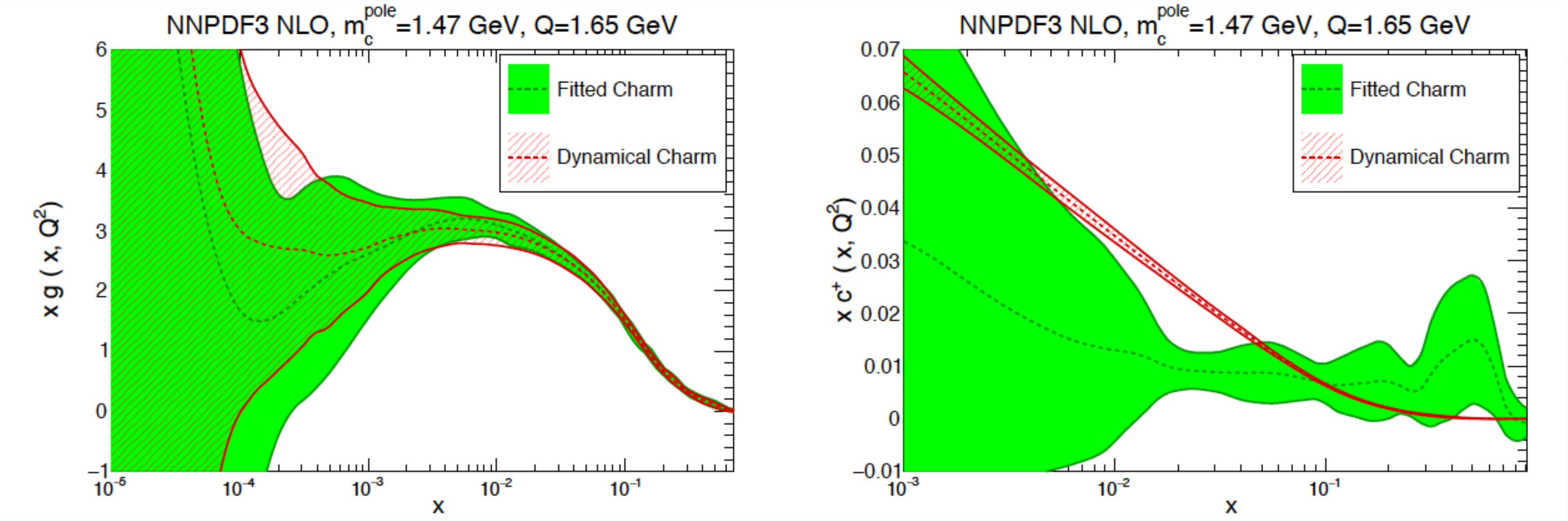


- Coefficient functions for NC and CC **charm-initiated contributions in the massive scheme** up to NLO have been computed (NNLO not available yet)
- FONLL structure functions can be modified to account for **massive charm-initiated contributions**

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

NNPDF3 fits with intrinsic charm

- 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**

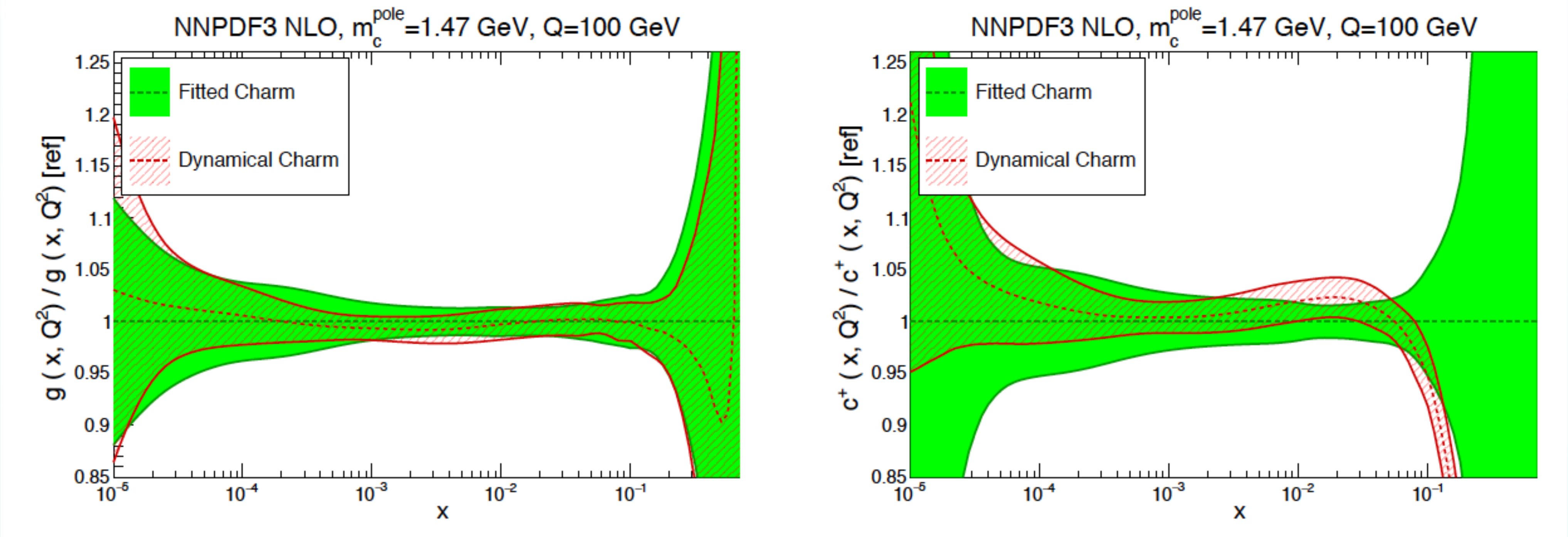


At low scales, **gluon PDF stable**, but **fitted charm** different from **perturbative charm**

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

NNPDF3 fits with intrinsic charm

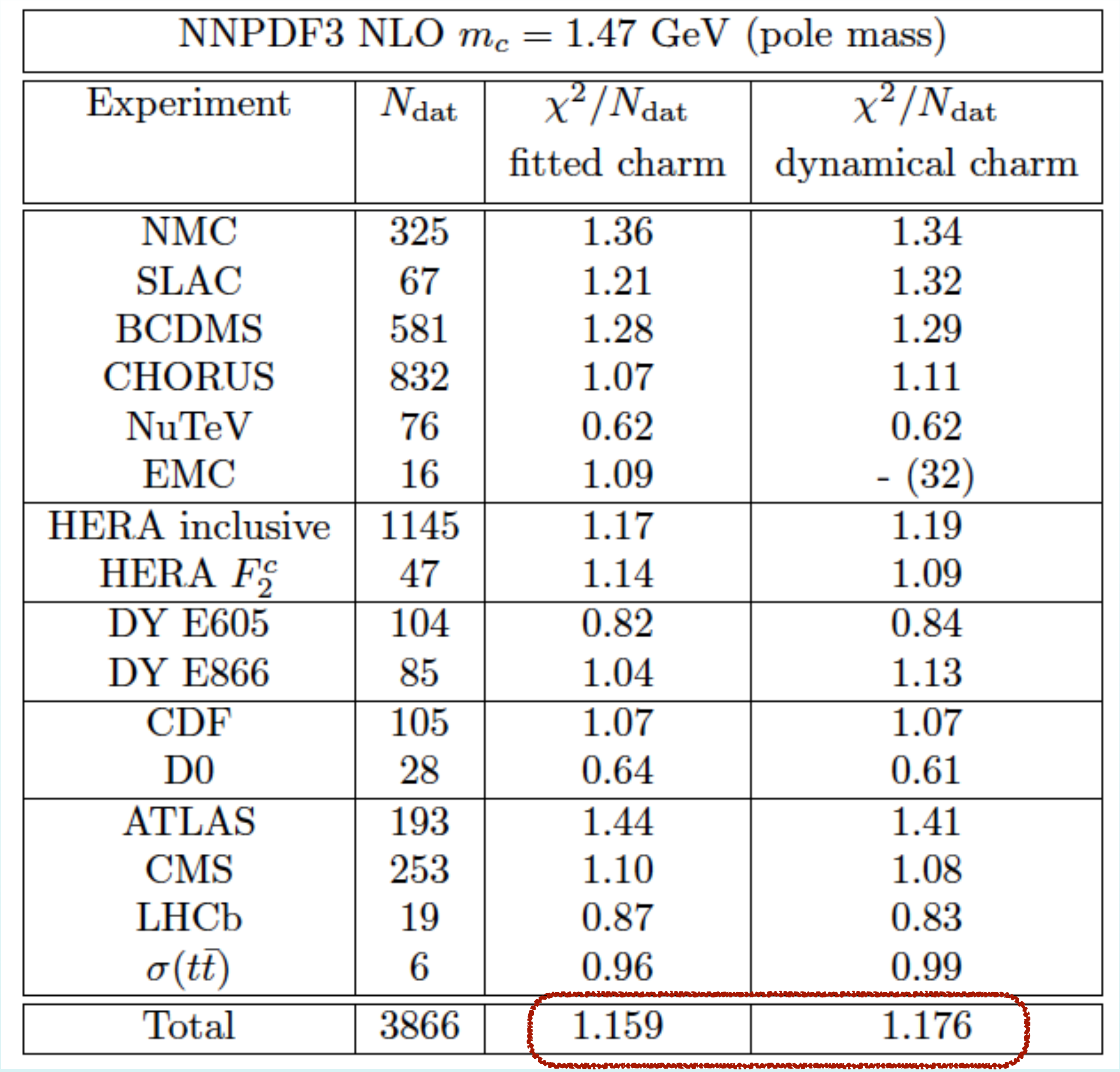
- PDF parametrization as in NNPDF3.0, now adding **$c^+(x,Q_0)$** as additional Artificial Neural Network: **same number of free parameters** as all other light quark PDFs
- **Fitted dataset:** same as in NNPDF3.0, with the **HERA legacy combination** and the **EMC charm data**



At 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_{dat}	χ^2/N_{dat} fitted charm	χ^2/N_{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

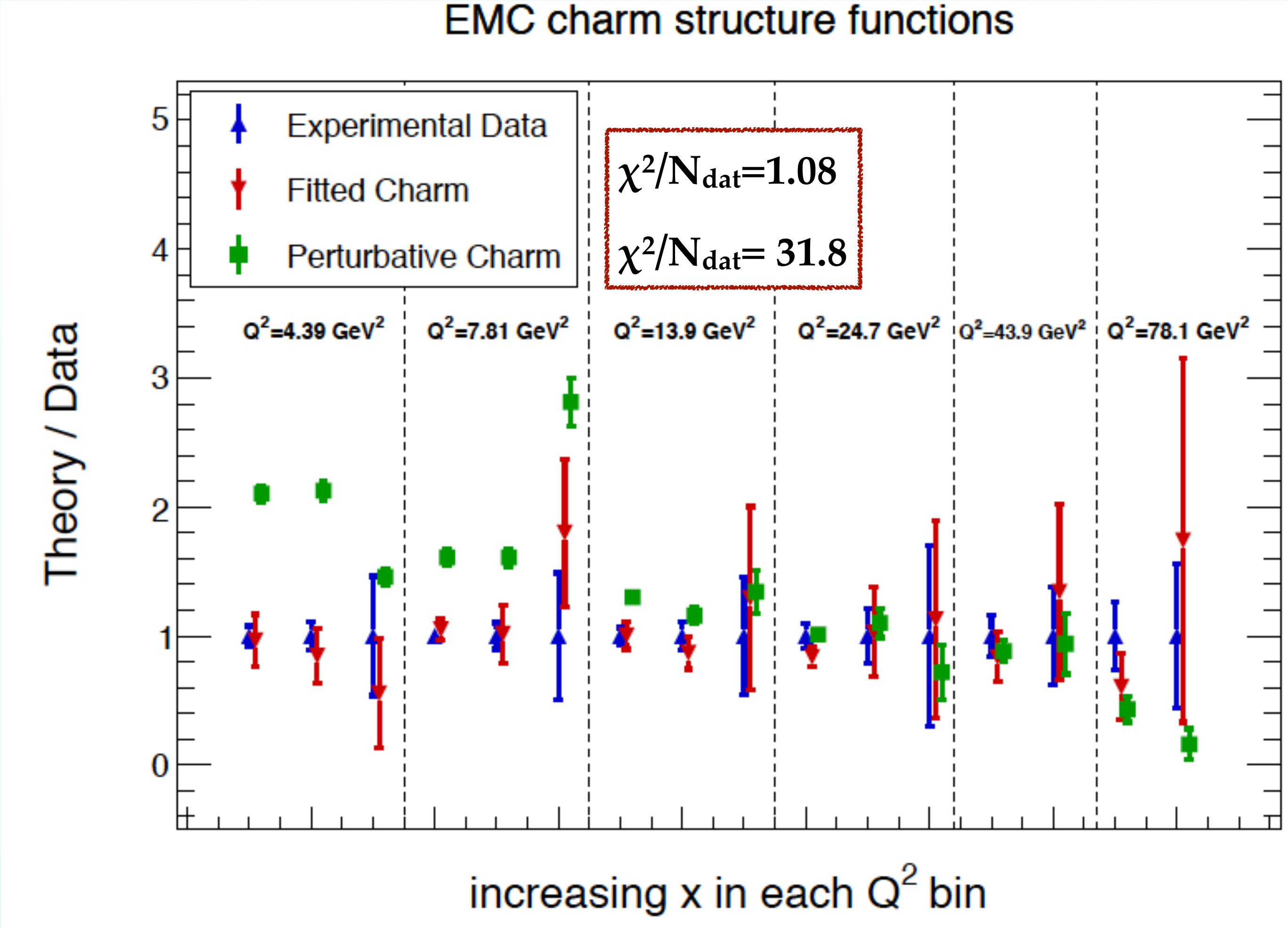
- Fitted charm improves the data/theory agreement

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

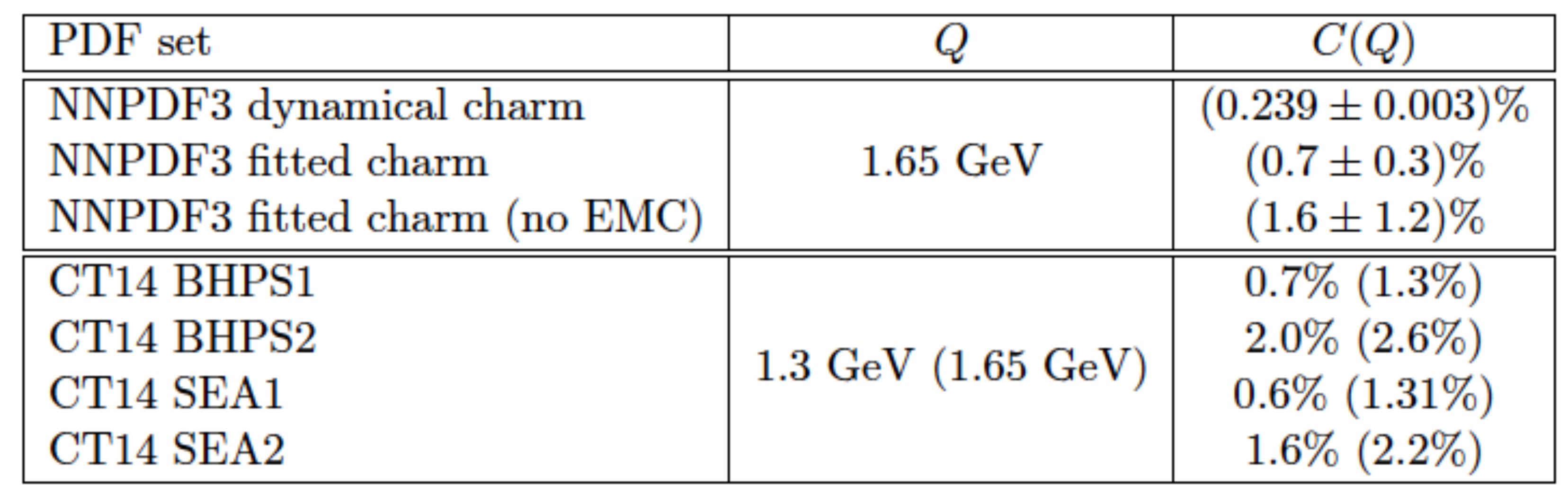
- For the **LHC datasets** the **fit quality is unchanged** when charm is fitted

The EMC charm data

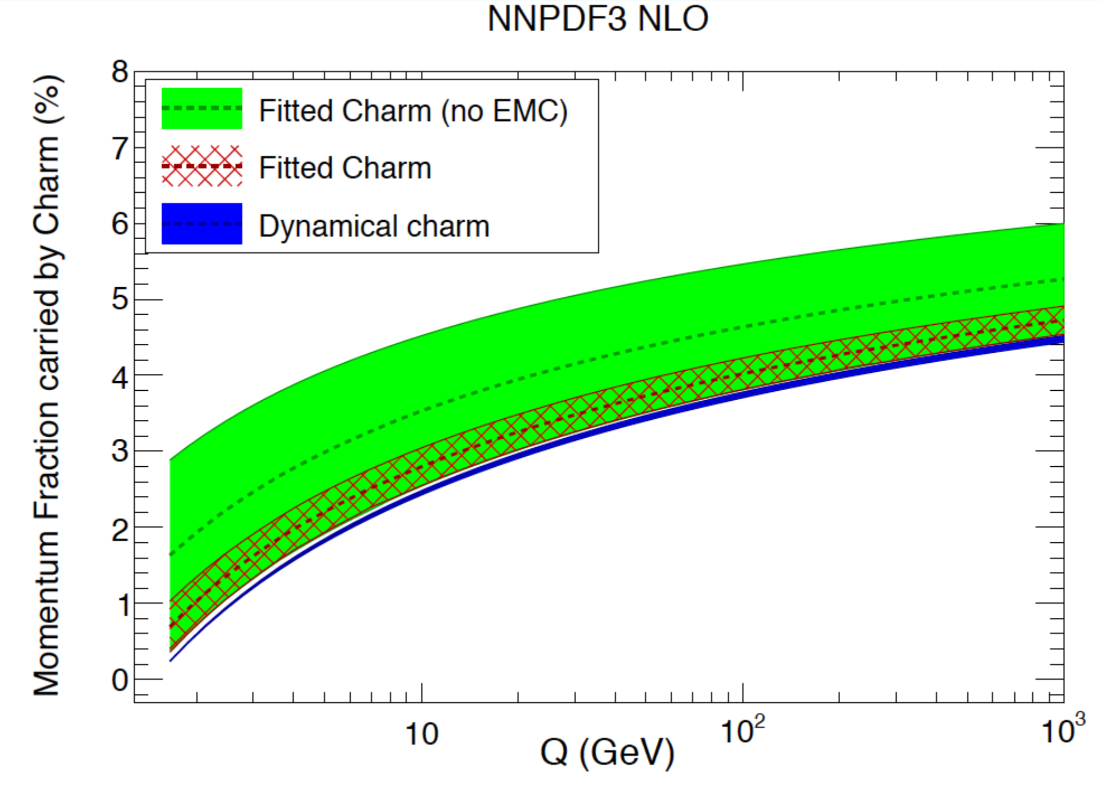
- **Satisfactory description of the EMC charm data** when charm is fitted
- EMC charm data essential to **reduce the PDF uncertainties** in the NNPDF fitted charm
- Improvements as compared to previous studies likely related to the **more flexible charm PDF parametrization adopted here**, not restricted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



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%)



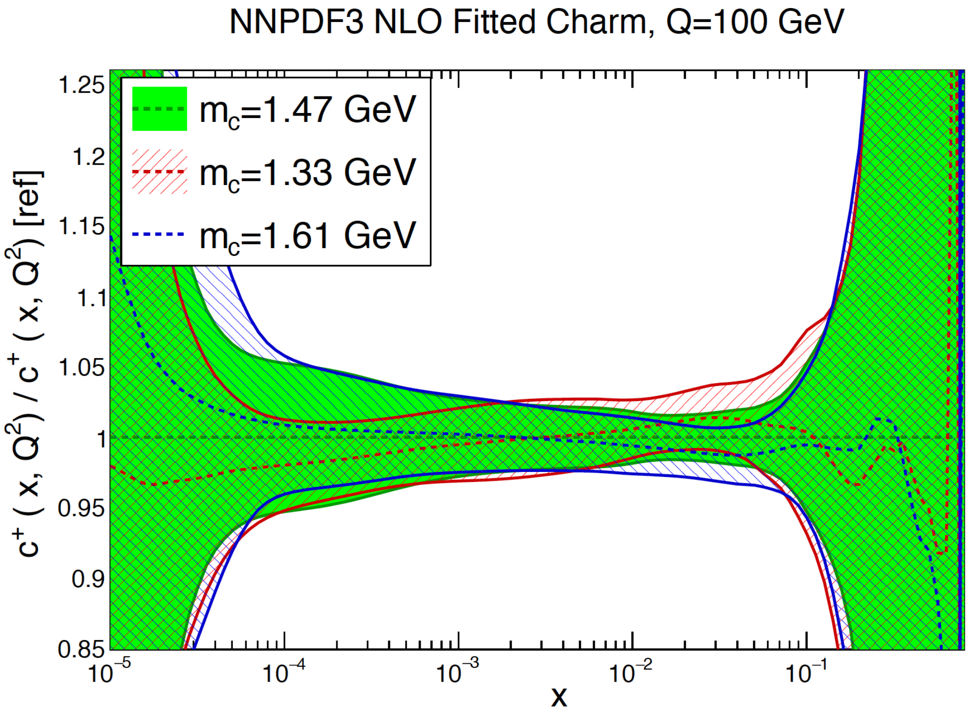
- At Q=1.65 GeV, charm can carry up to **1% of the proton's momentum** at the 68% CL (but consistent also with zero within PDF uncertainties)

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

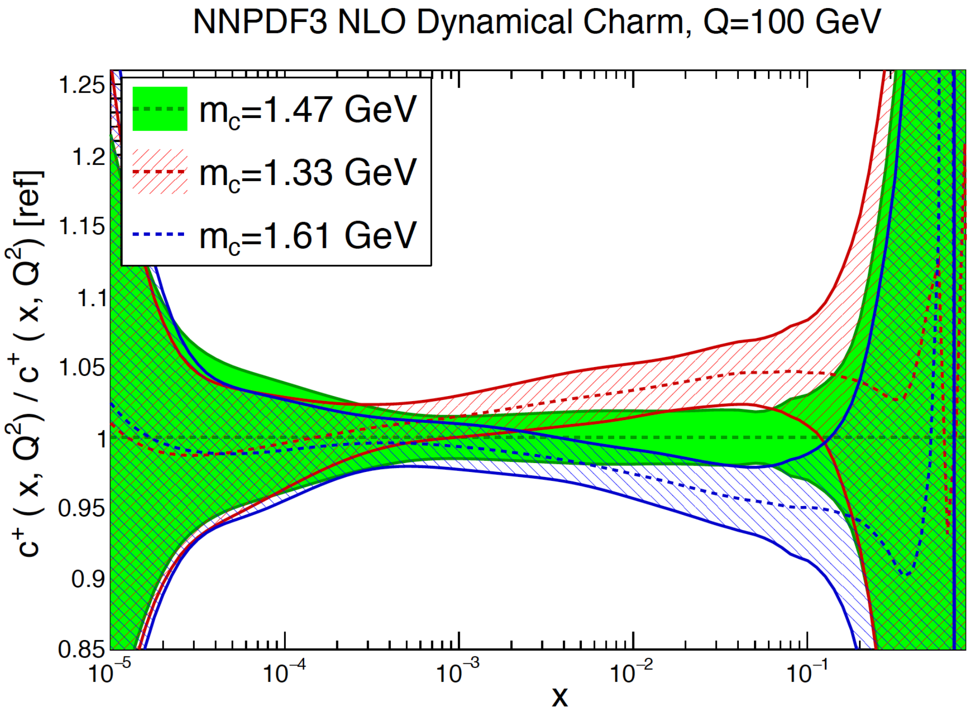
- The **large momentum fractions** carried by the **CT14IC** BHPS2 and SEA2 models are strongly disfavoured

Stability with charm mass variations

Fitted Charm



Dynamical charm

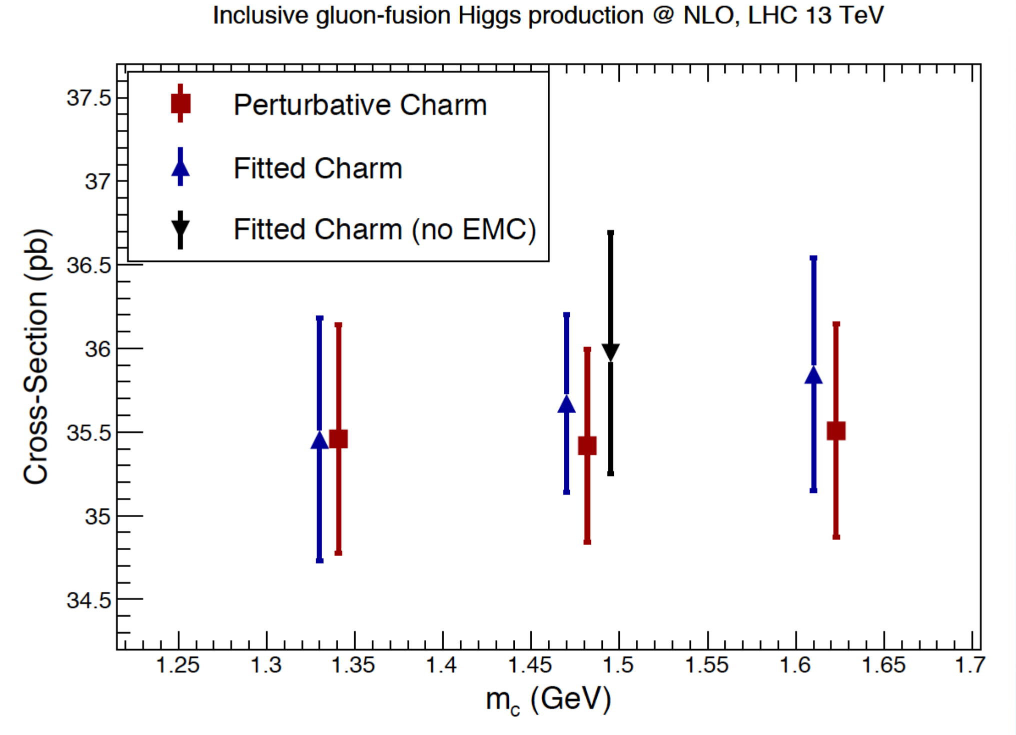


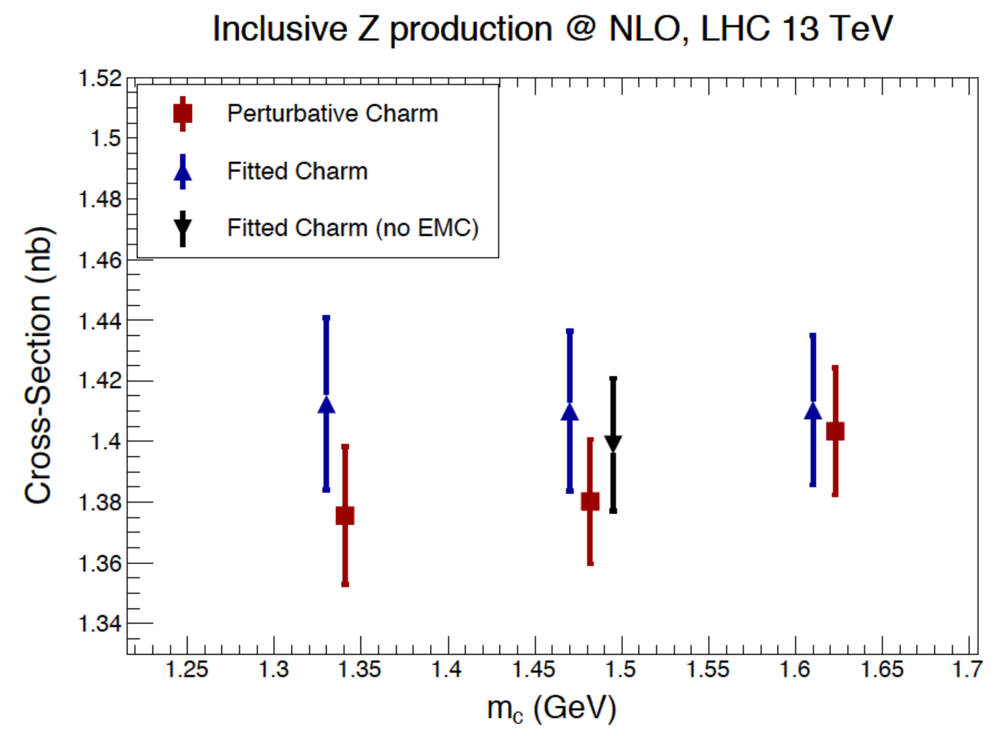
- Study fit stability by **varying the charm mass by +- 5 sigma** with respect to the PDG value, using the **one-loop pole -> running mass conversion**

- 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





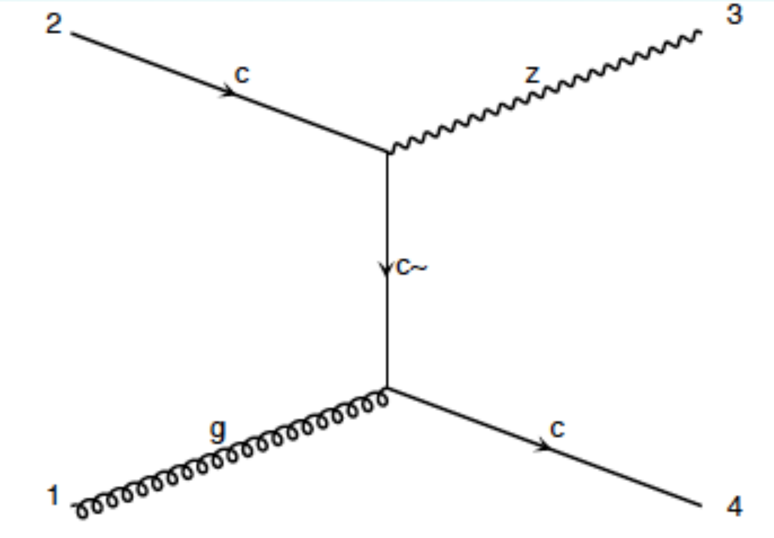
- Similar improved stability with the charm mass at the level of **LHC cross-sections**
- **Higgs cross-section** in gluon-fusion varies by less than **0.5%,** small compared to the PDF uncertainty, even for a **large variation in m_c**
- **Electroweak cross-sections** (W, Z) in particular benefit of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

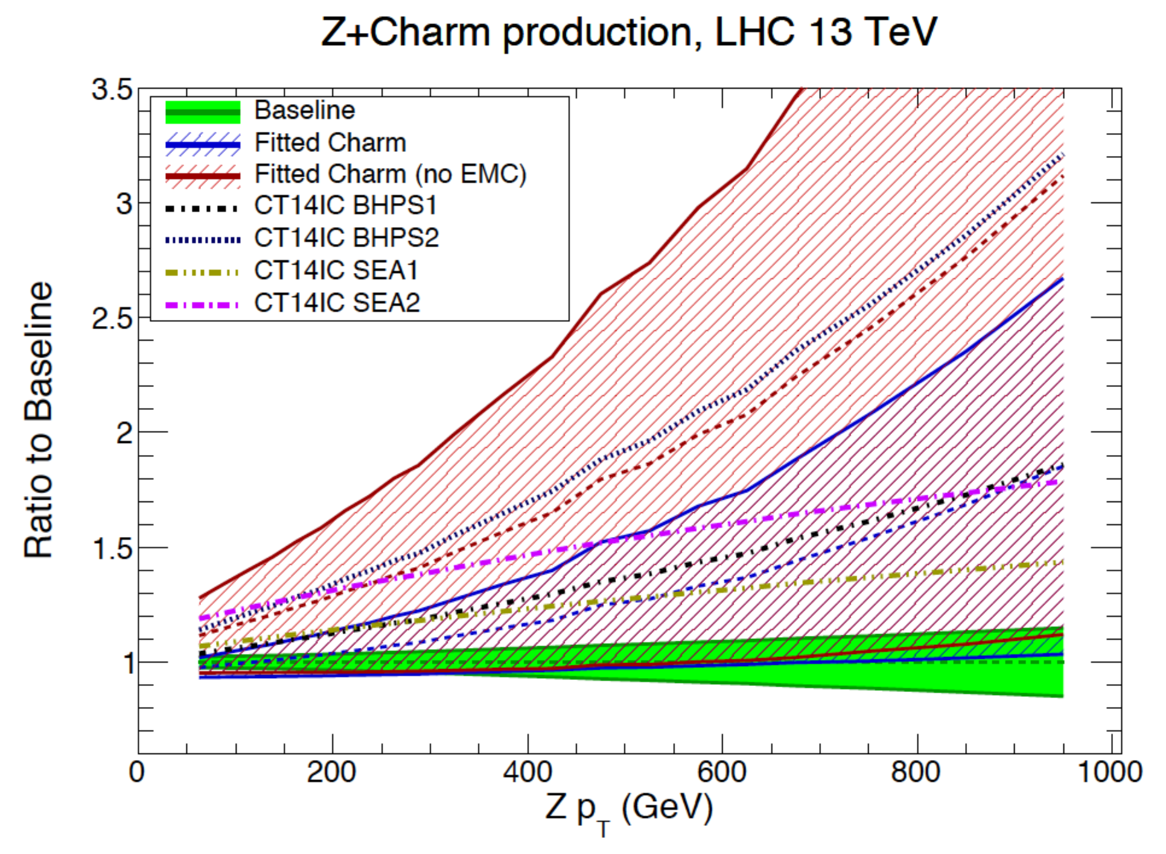
Phenomenological implications @ LHC

- 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





Phenomenological implications @ LHC

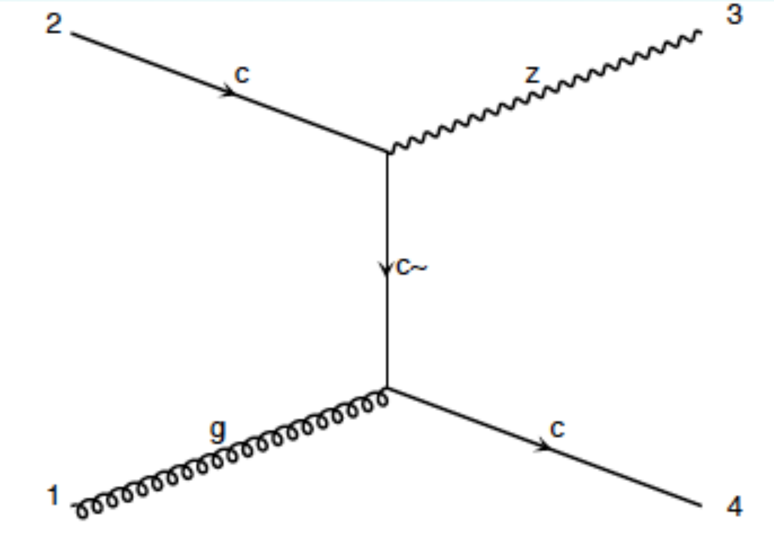
- The differences between **fitted charm** and **perturbative charm** can be explored using a variety of LHC observables such as **D meson production and Z+charm** production

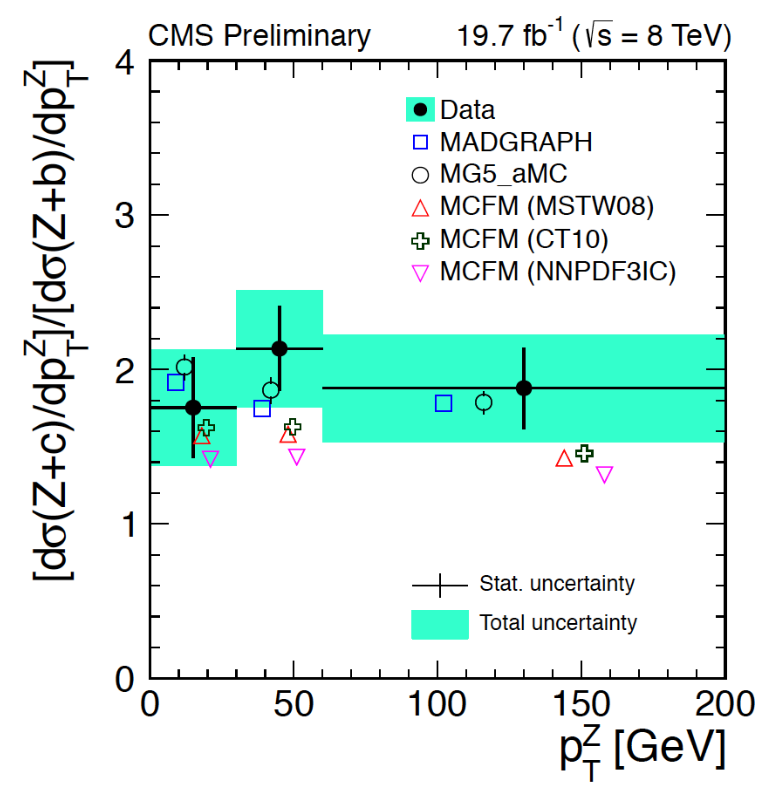
- The **more forward and larger p_T the measurement**, the more sensitive to the large-x charm PDF, and thus to the differences between fitted and dynamical charm

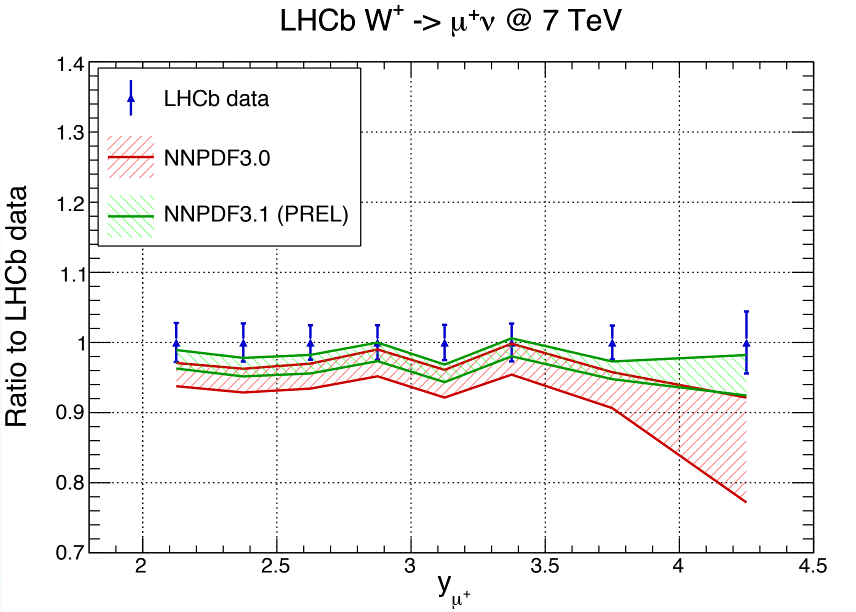
Z+charm

- NNPDF3IC recently c**ompared with CMS data at 8 TeV** in **CMS-PAS-15-009**

- Need **high-stats 13 TeV data** to probe the region where fitted and perturbative charm differ most







Towards a new global analysis: NNPDF3.1

The NNPDF Collaboration, in preparation

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 Ratio	2012	medium and large-x gluon

APFEL and APFELcomb

- Up to NNPDF3.0, PDF evolution and DIS structure functions were based on a (private) N-space code, **FKgenerator**

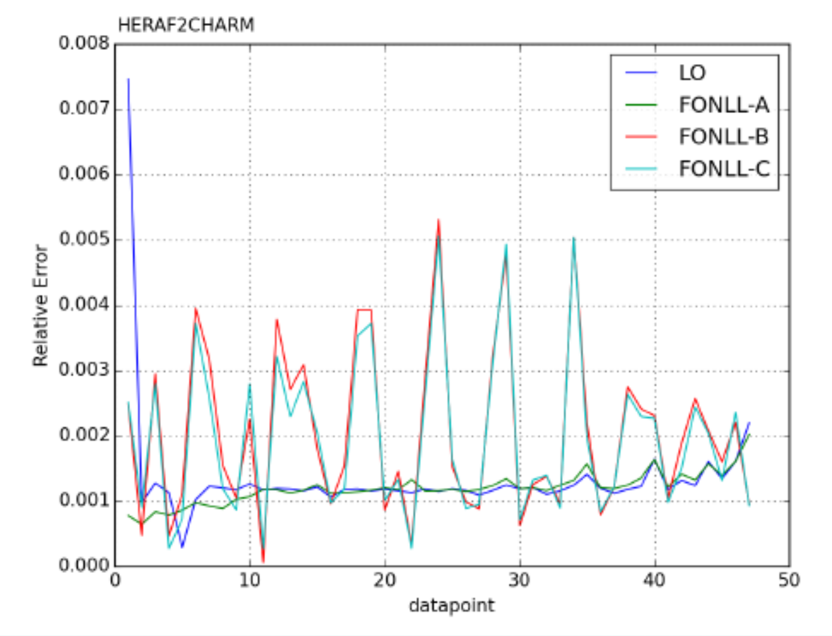
- From NNPDF3.1 we will adopt the public code **APFEL** for all theory calculations

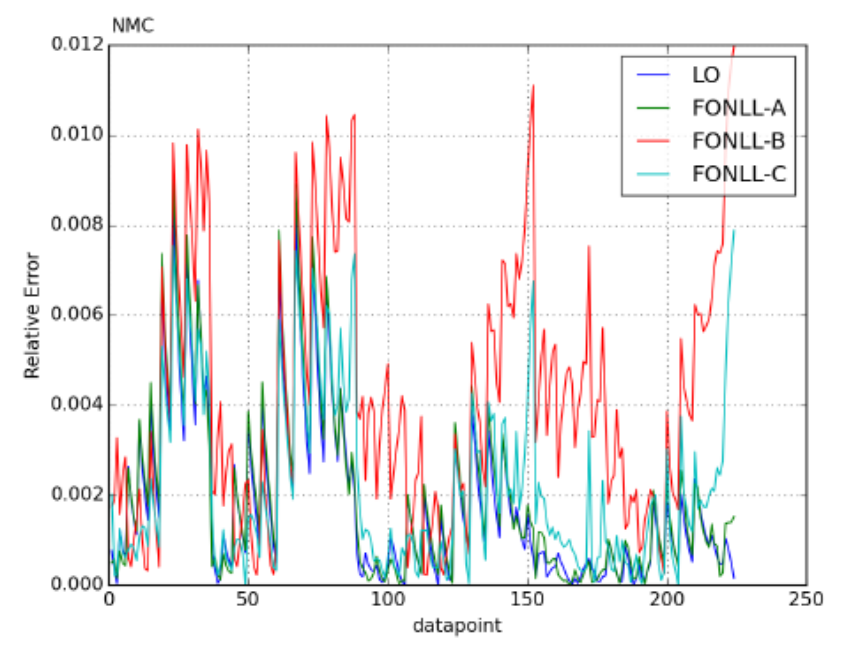
- **Extensive benchmarking** between the two codes performed, as well ad with other codes like **HOPPET and OpenQCDrad**

- 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 μs (120x)

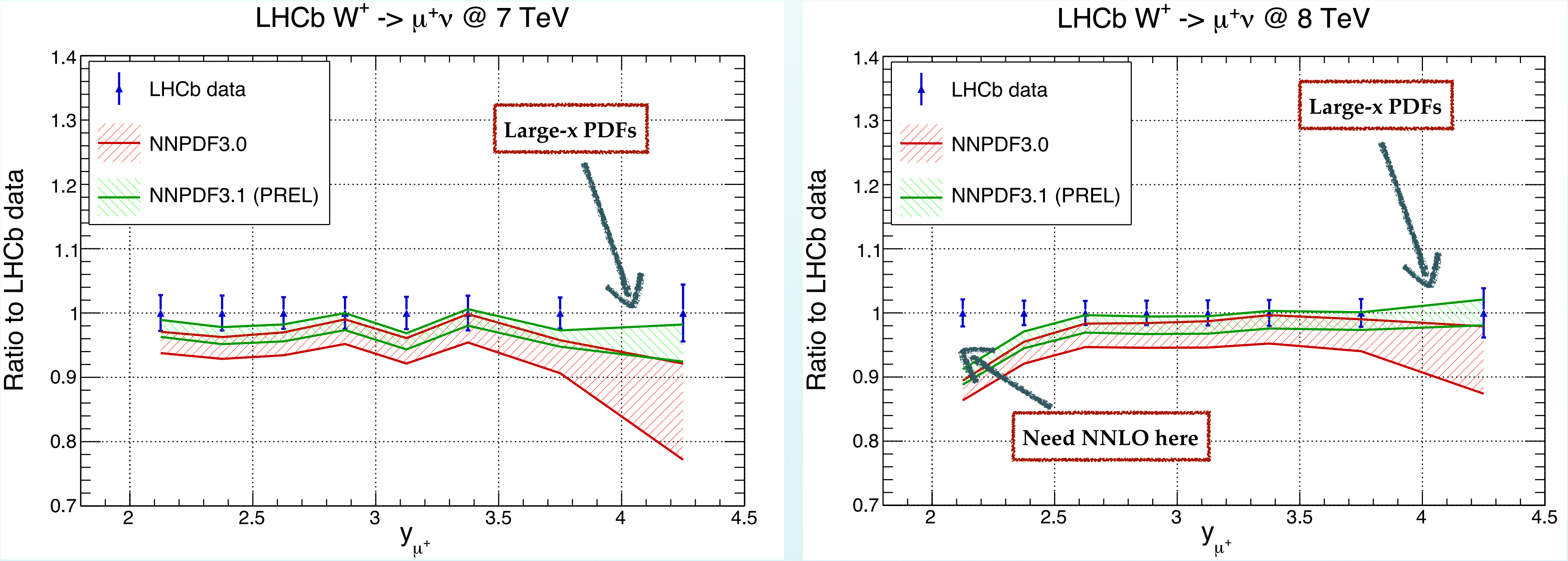
APFEL: Bertone, Carrazza, Rojo, ***arXiv:1310.06515***
APFELcomb: Bertone, Carrazza, Harland, ***arXiv:1605.02070***





LHCb Run I combination (muons)

- LHCb has provided their **combination of all Run I measurements on W -> μ ν and Z -> μ μ**
- Reasonable **description at NLO** for NNPDF3.1, significant **reduction of PDF uncertainties at large-x**
- **NNLO/NLO K-factors** can be large - compute them with **FEWZ** and **MCFM@NNLO**
- LHCb 8 TeV electron data also very recently available



Large-x PDFs

Large-x PDFs

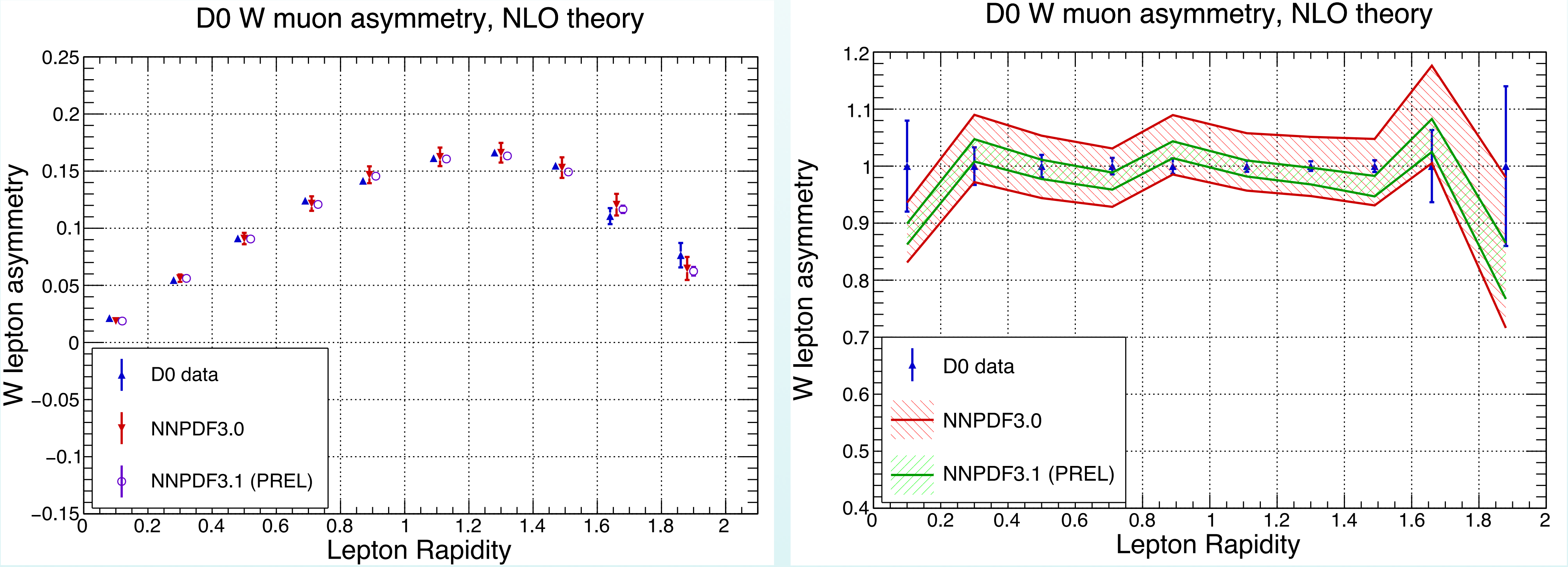
Need NNLO here

χ^2/N_{dat} (W+Z,NLO, 7 TeV) = 1.6

χ^2/N_{dat} (W+Z,NLO, 8 TeV) = 2.5

Tevatron legacy W asymmetries

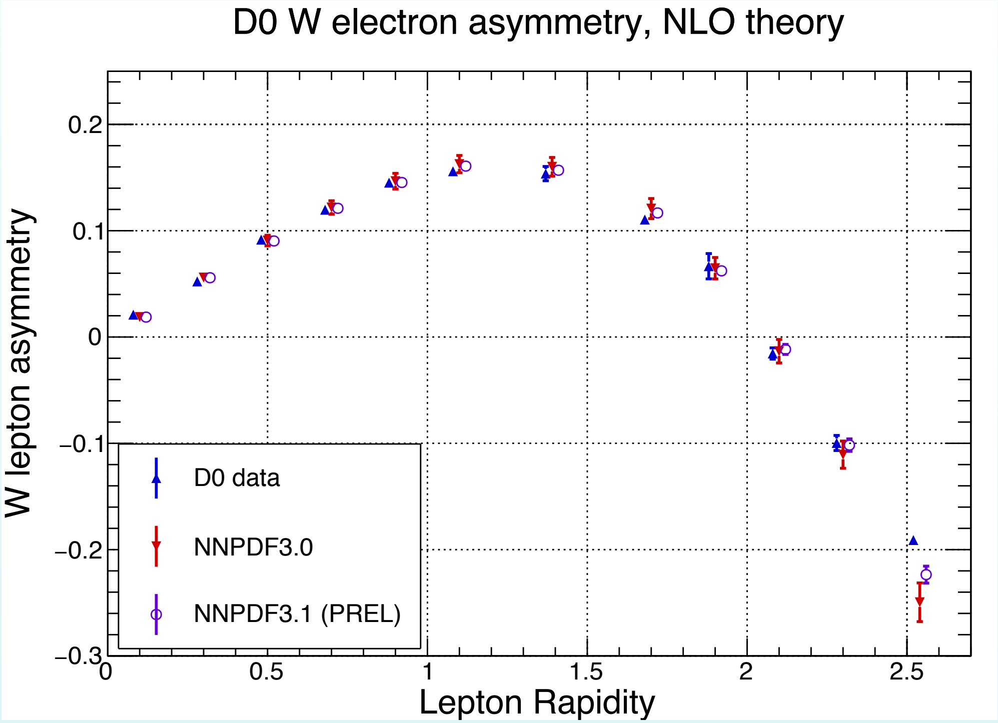
- The **legacy Tevatron measurements on W asymmetries** based on the full dataset now available
- Consider only data at the **lepton level from D0** (exclude reconstructed W data from CDF)
- Good agreement with NNPDF3.1 NLO, substantial reduction of PDF uncertainties: **improved flavor separation**

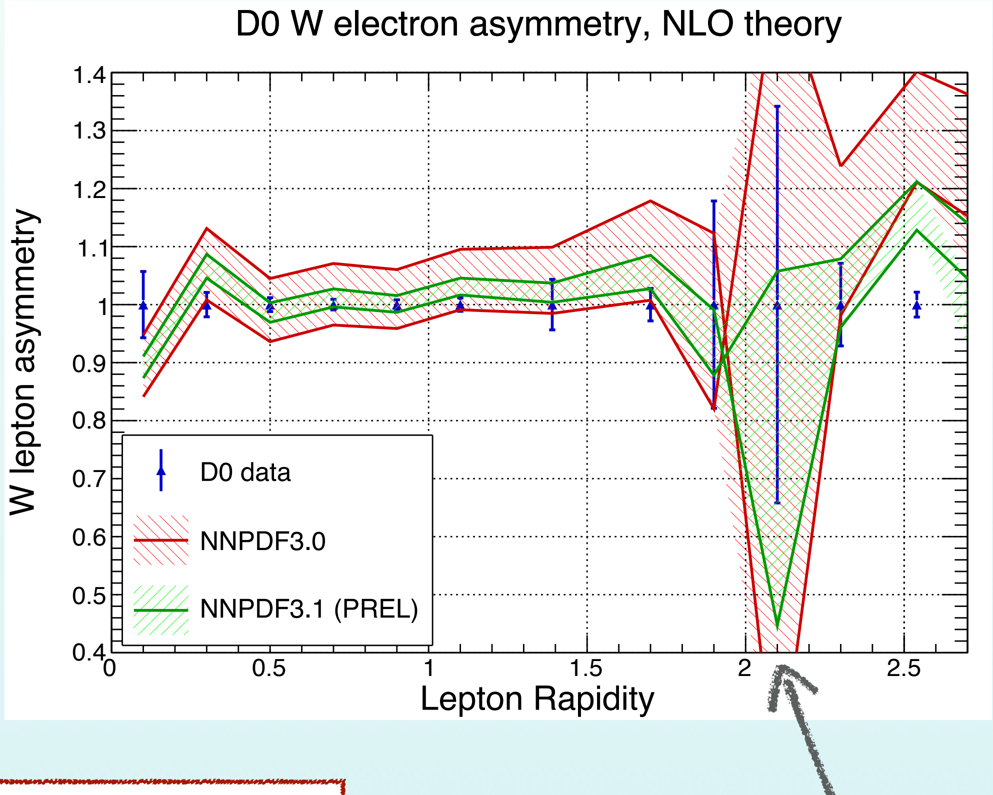


χ^2/N_{dat} (NLO, muon asy) = 1.3

Tevatron legacy W asymmetries

- The **legacy Tevatron measurements on W asymmetries** based on the full dataset now available
- Consider only data at the **lepton level from D0** (exclude reconstructed W data from CDF)
- Good agreement with NNPDF3.1 NLO, substantial reduction of PDF uncertainties: **improved flavor separation**





χ^2/N_{dat} (NLO, electron asy) = 1.4

asymmetry crosses zero

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

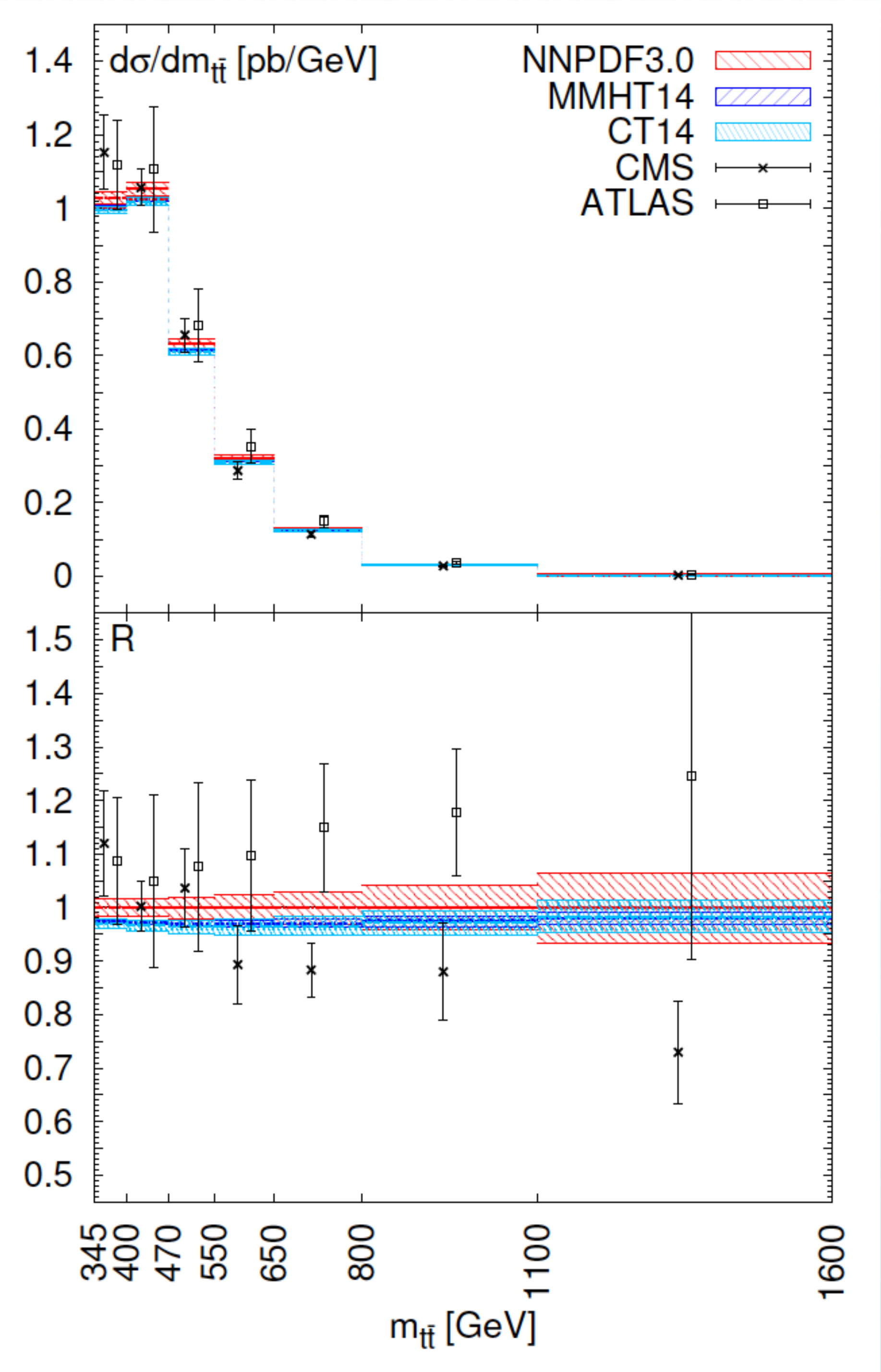
- Exploit the most recent **8 TeV data from ATLAS and CMS** to constrain the **large-*x* gluon PDF**

- These datasets will be **integral part of NNPDF3.1:** complementary constraints to jet production

- Some **tension** between the ATLAS and CMS data observed: under investigation

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

+ Emanuele'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

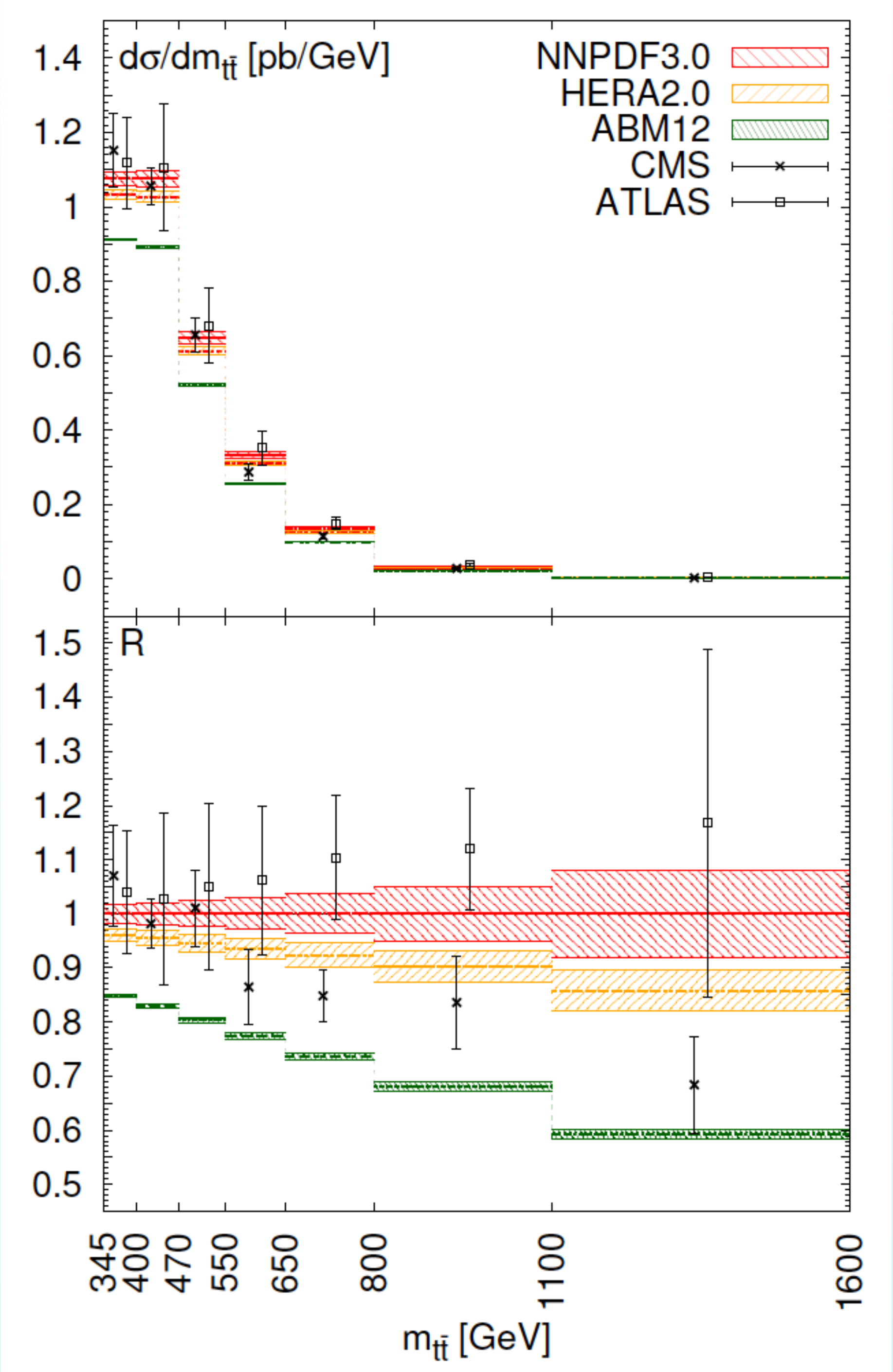
- Exploit the most recent **8 TeV data from ATLAS and CMS** to constrain the **large-*x* gluon PDF**

- These datasets will be **integral part of NNPDF3.1:** complementary constraints to jet production

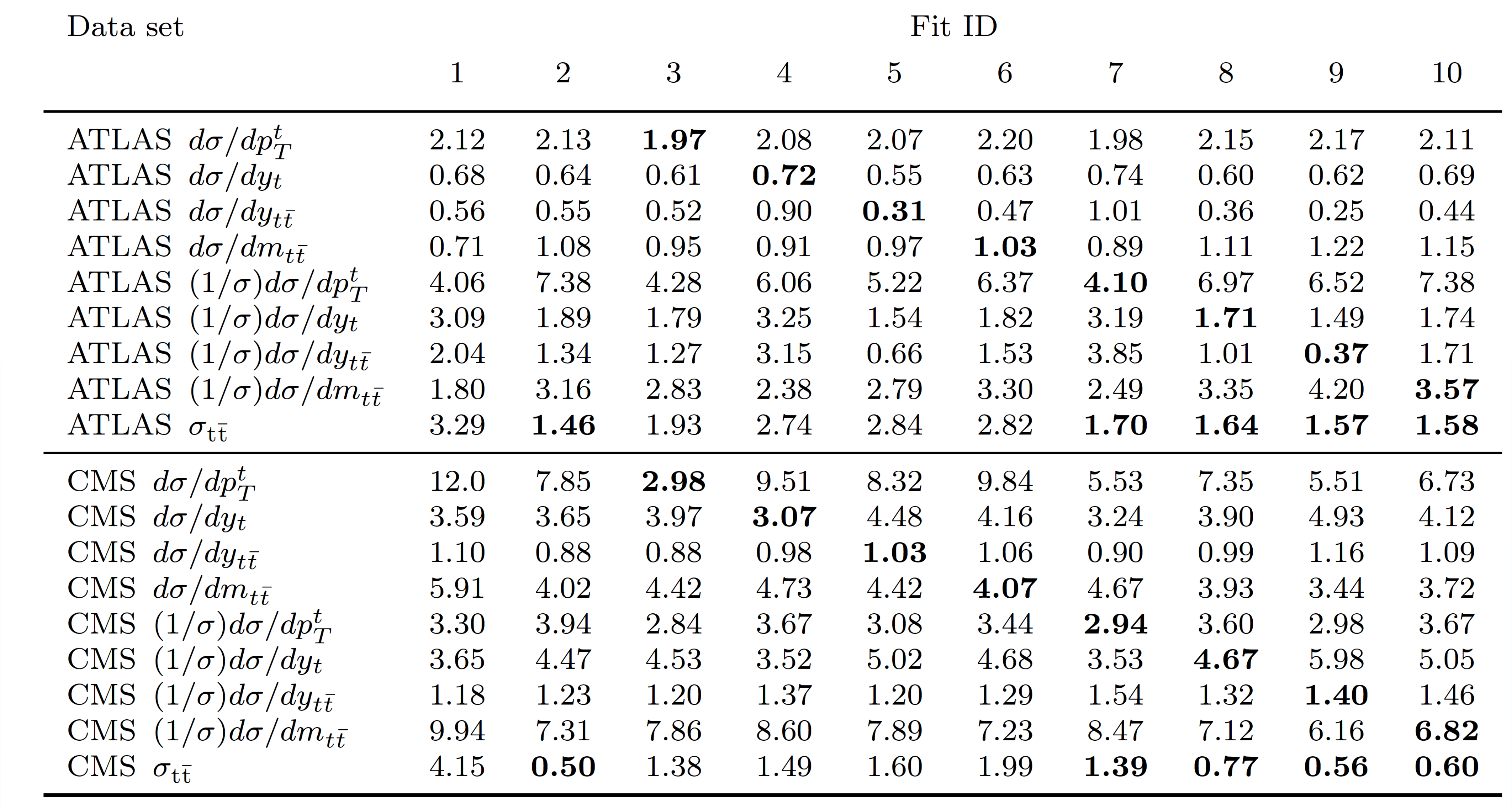
- Some **tension** between the ATLAS and CMS data observed: under investigation

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

+ Emanuele's talk



Fits with differential top quark pair data



Data set	Fit ID 1	2	3	4	5	6	7	8	9	10
ATLAS $d\sigma/dp_T^t$	2.12	2.13	**1.97**	2.08	2.07	2.20	1.98	2.15	2.17	2.11
ATLAS $d\sigma/dy_t$	0.68	0.64	0.61	**0.72**	0.55	0.63	0.74	0.60	0.62	0.69
ATLAS $d\sigma/dy_{t\bar{t}}$	0.56	0.55	0.52	0.90	**0.31**	0.47	1.01	0.36	0.25	0.44
ATLAS $d\sigma/dm_{t\bar{t}}$	0.71	1.08	0.95	0.91	0.97	**1.03**	0.89	1.11	1.22	1.15
ATLAS $(1/\sigma)d\sigma/dp_T^t$	4.06	7.38	4.28	6.06	5.22	6.37	**4.10**	6.97	6.52	7.38
ATLAS $(1/\sigma)d\sigma/dy_t$	3.09	1.89	1.79	3.25	1.54	1.82	3.19	**1.71**	1.49	1.74
ATLAS $(1/\sigma)d\sigma/dy_{t\bar{t}}$	2.04	1.34	1.27	3.15	0.66	1.53	3.85	1.01	**0.37**	1.71
ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$	1.80	3.16	2.83	2.38	2.79	3.30	2.49	3.35	4.20	**3.57**
ATLAS $\sigma_{t\bar{t}}$	3.29	**1.46**	1.93	2.74	2.84	2.82	**1.70**	**1.64**	**1.57**	**1.58**
CMS $d\sigma/dp_T^t$	12.0	7.85	**2.98**	9.51	8.32	9.84	5.53	7.35	5.51	6.73
CMS $d\sigma/dy_t$	3.59	3.65	3.97	**3.07**	4.48	4.16	3.24	3.90	4.93	4.12
CMS $d\sigma/dy_{t\bar{t}}$	1.10	0.88	0.88	0.98	**1.03**	1.06	0.90	0.99	1.16	1.09
CMS $d\sigma/dm_{t\bar{t}}$	5.91	4.02	4.42	4.73	4.42	**4.07**	4.67	3.93	3.44	3.72
CMS $(1/\sigma)d\sigma/dp_T^t$	3.30	3.94	2.84	3.67	3.08	3.44	**2.94**	3.60	2.98	3.67
CMS $(1/\sigma)d\sigma/dy_t$	3.65	4.47	4.53	3.52	5.02	4.68	3.53	**4.67**	5.98	5.05
CMS $(1/\sigma)d\sigma/dy_{t\bar{t}}$	1.18	1.23	1.20	1.37	1.20	1.29	1.54	1.32	**1.40**	1.46
CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$	9.94	7.31	7.86	8.60	7.89	7.23	8.47	7.12	6.16	**6.82**
CMS $\sigma_{t\bar{t}}$	4.15	**0.50**	1.38	1.49	1.60	1.99	**1.39**	**0.77**	**0.56**	**0.60**

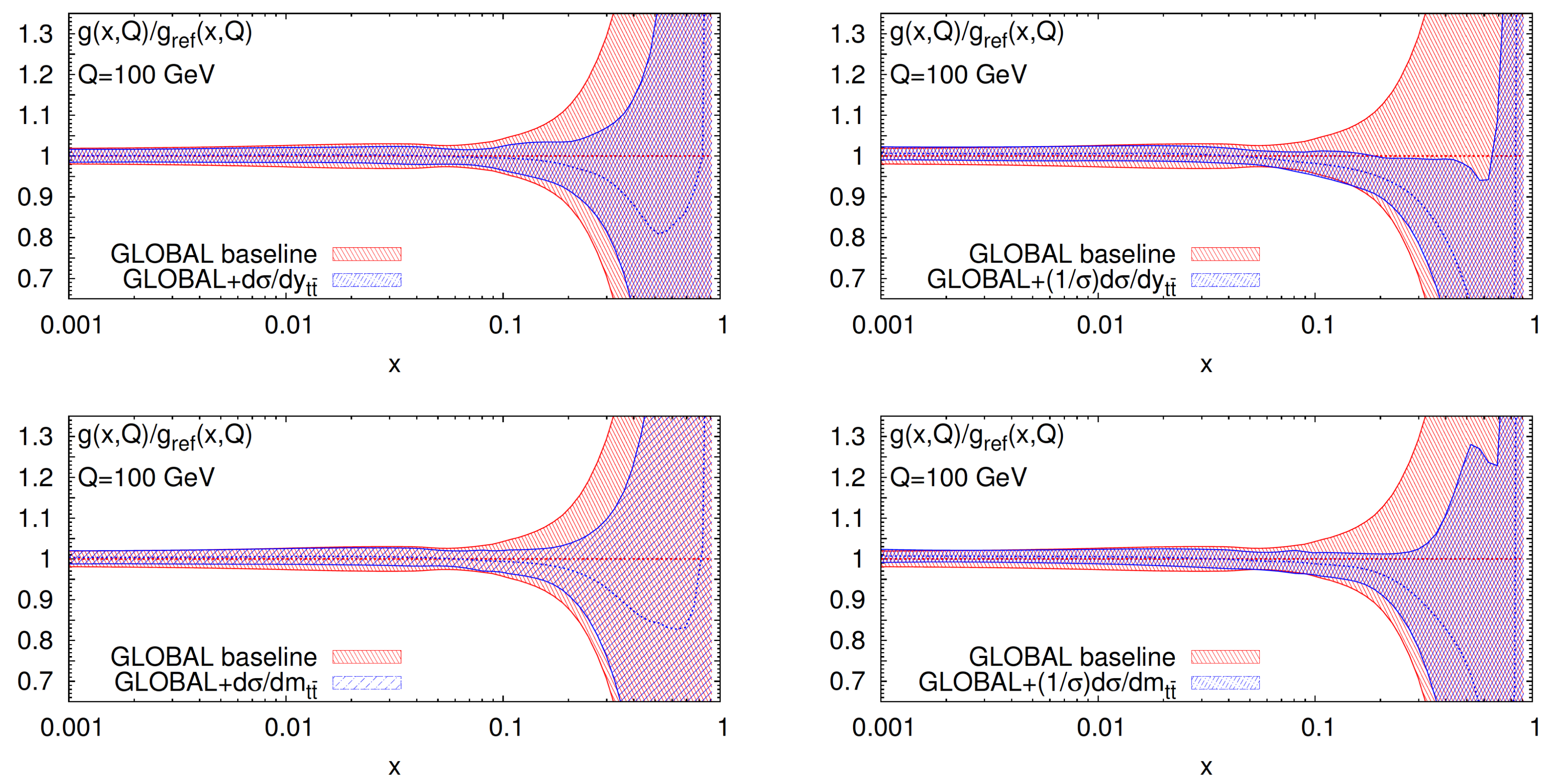
χ^2/N_{dat} for various combinations of top quark differential distribtuions added to the NNPDF3 global analysis

Some difficultly in fitting the CMS distributions at the same time as the ATLAS ones ….

Poor description of the top transverse momentum distributions, both ATLAS and CMS

Fits with differential top quark pair data

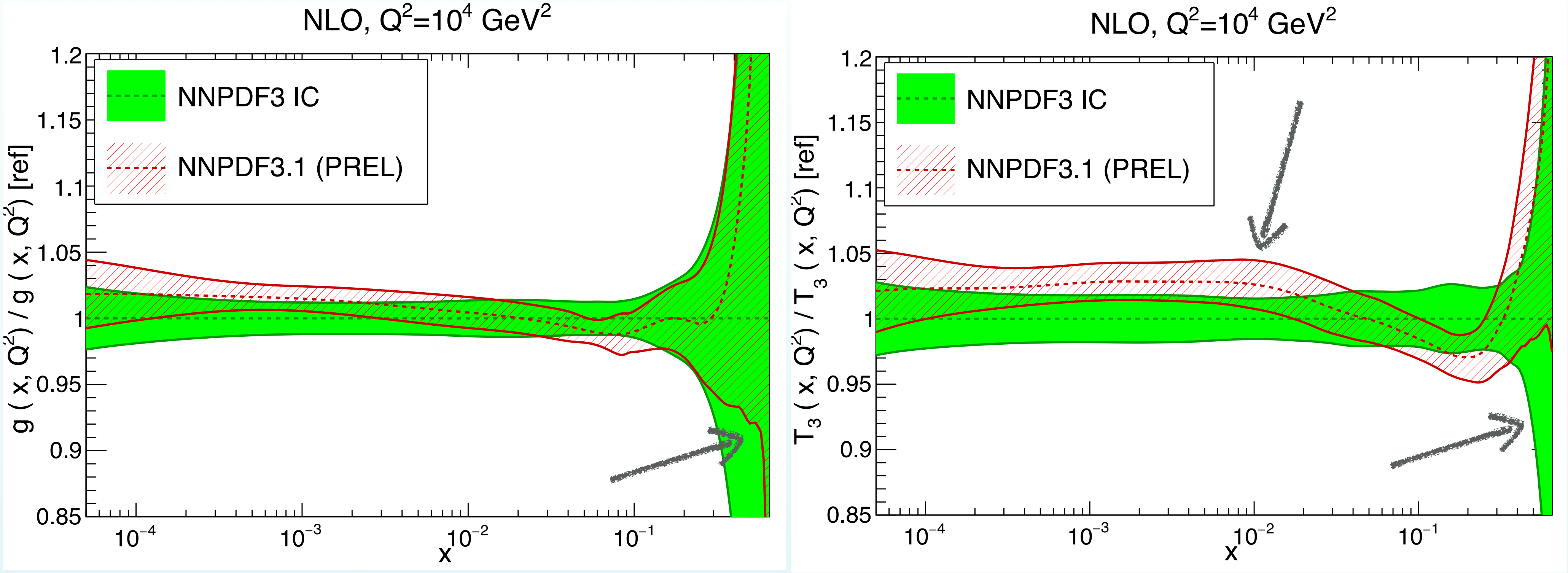
Since **only one distribution per experiment** can be added at the same time in the global fit, need to determine the consistent choice which **maximizes the constrains on the large-x gluon**



Significant constraints on **large-x gluon** from **global fit** without inclusive jet data (not available at NNLO)

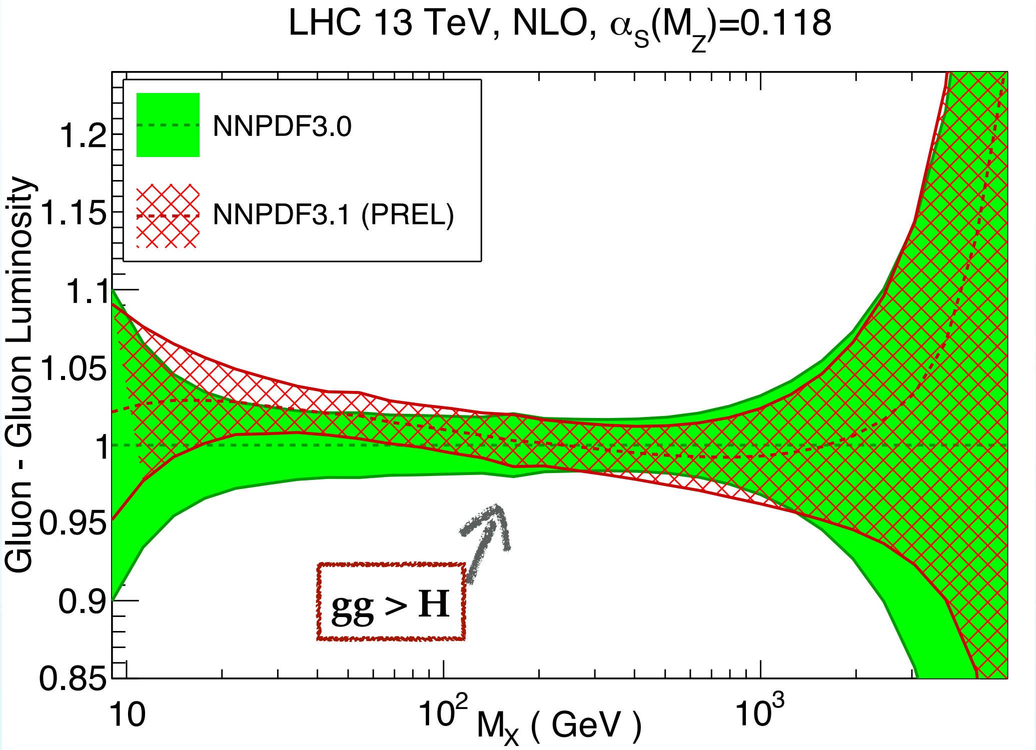
Normalized distributions, supplemented by total inclusive cross-sections, exhibit more constraining power

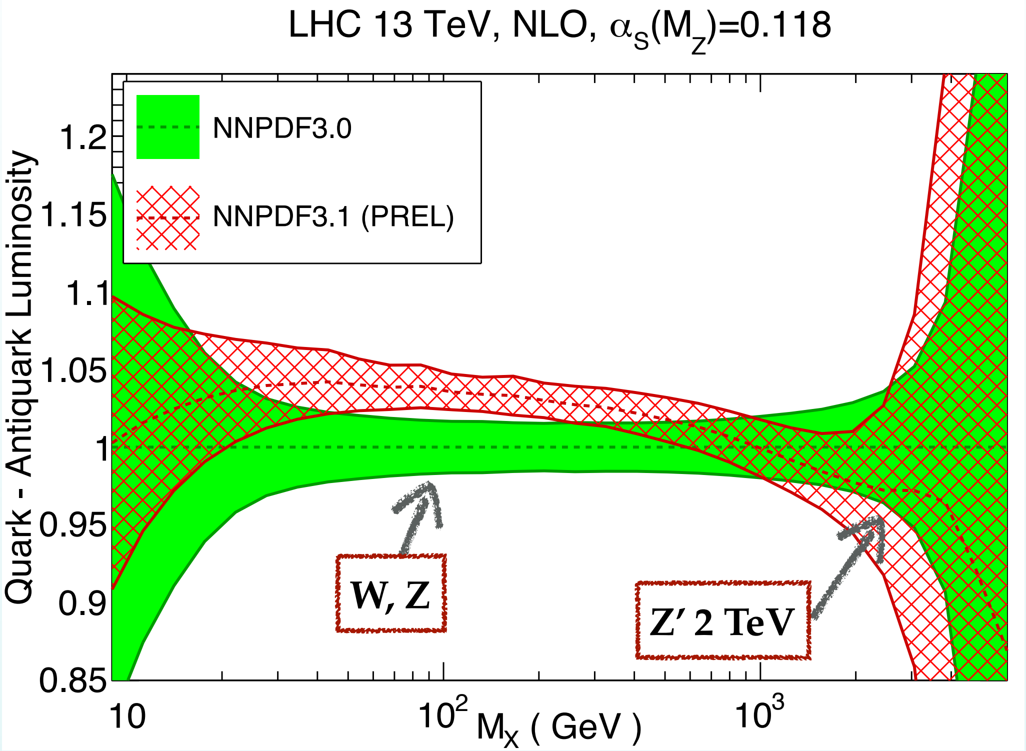
NNPDF3.1 vs NNPDF3.0



- Preliminary results indicate **qualitatively good stability** with respect to NNPDF3.0
- All PDFs exhibit **reduced PDF uncertainties** at large-x region
- Gluon reasonably stable
- **Improved light quark flavor separation** from all the new electroweak data from Tevatron and LHC

NNPDF3.1 vs NNPDF3.0





- Gluon-induced PDF luminosities stable between 3.0 and 3.1, with reduced PDF errors in the latter
- **Quark-antiquark luminosities increase by few percent** in region relevant for precision ***W* and *Z* production** data at the LHC: **improves agreement between NNLO and data**
- Highlights importance of recent collider data for an **improved quark flavor separation**

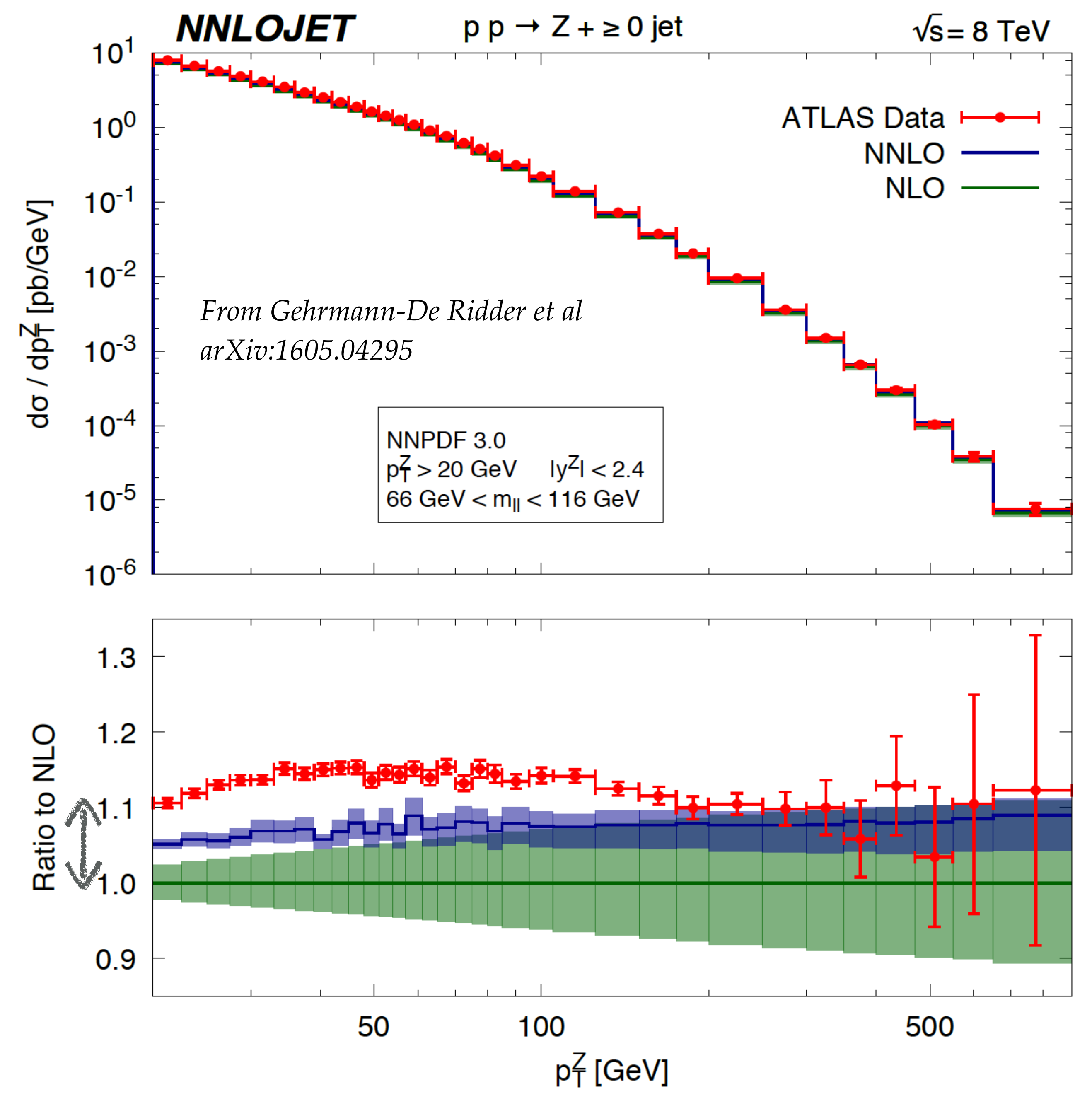
The Z p_T distribution

High-precision, theoretically very clean process

Comparison between **NNLO calculations** and **LHC data** with **NNPDF3.0**

Some **tension for the unnormalized distributions** even at NNLO - it is a **PDF issue?**

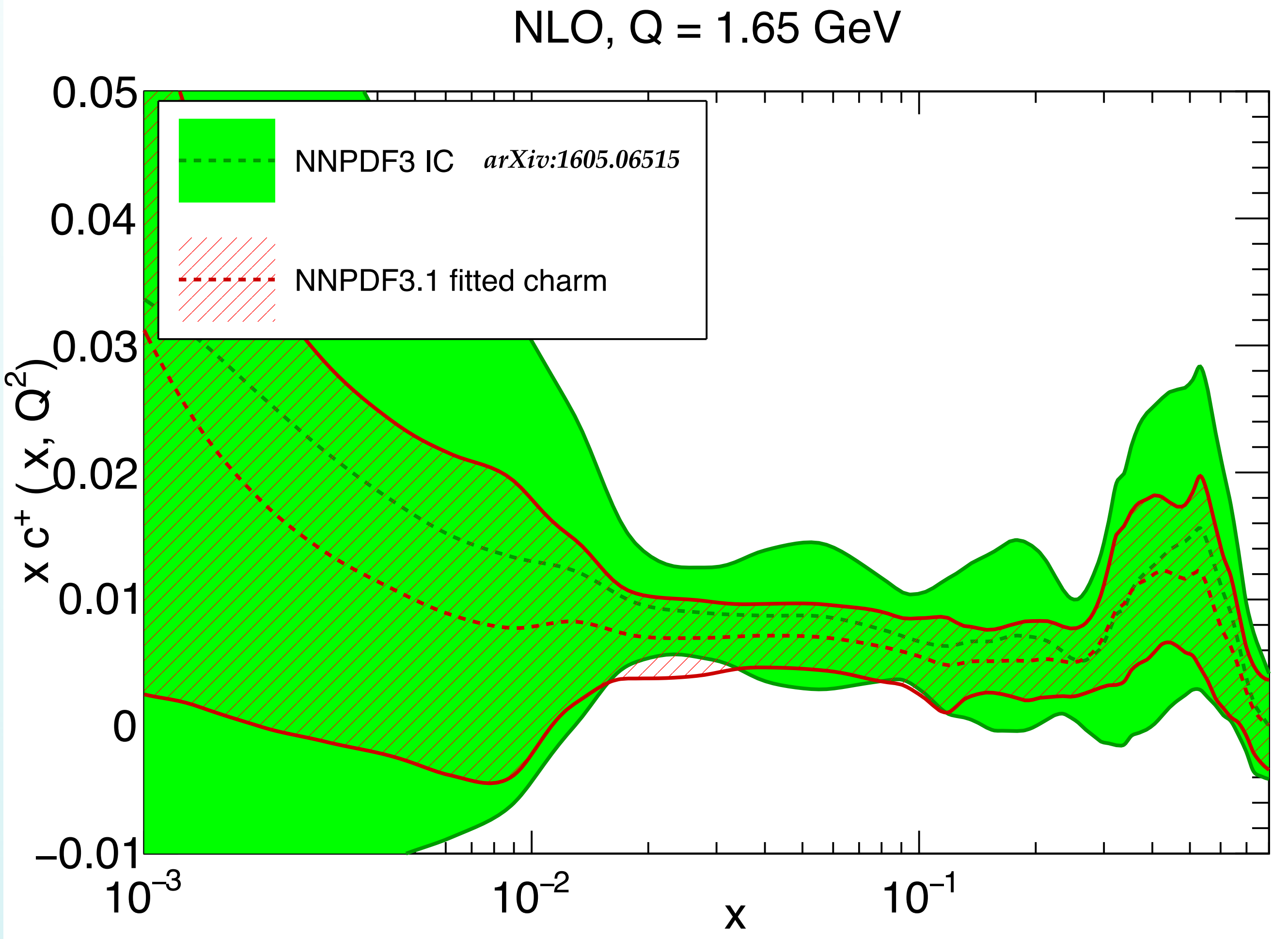
Agreement should improve once **NNPDF3.1 becomes available** thanks to updated flavor separation



From Gehrmann-De Ridder et al arXiv:1605.04295

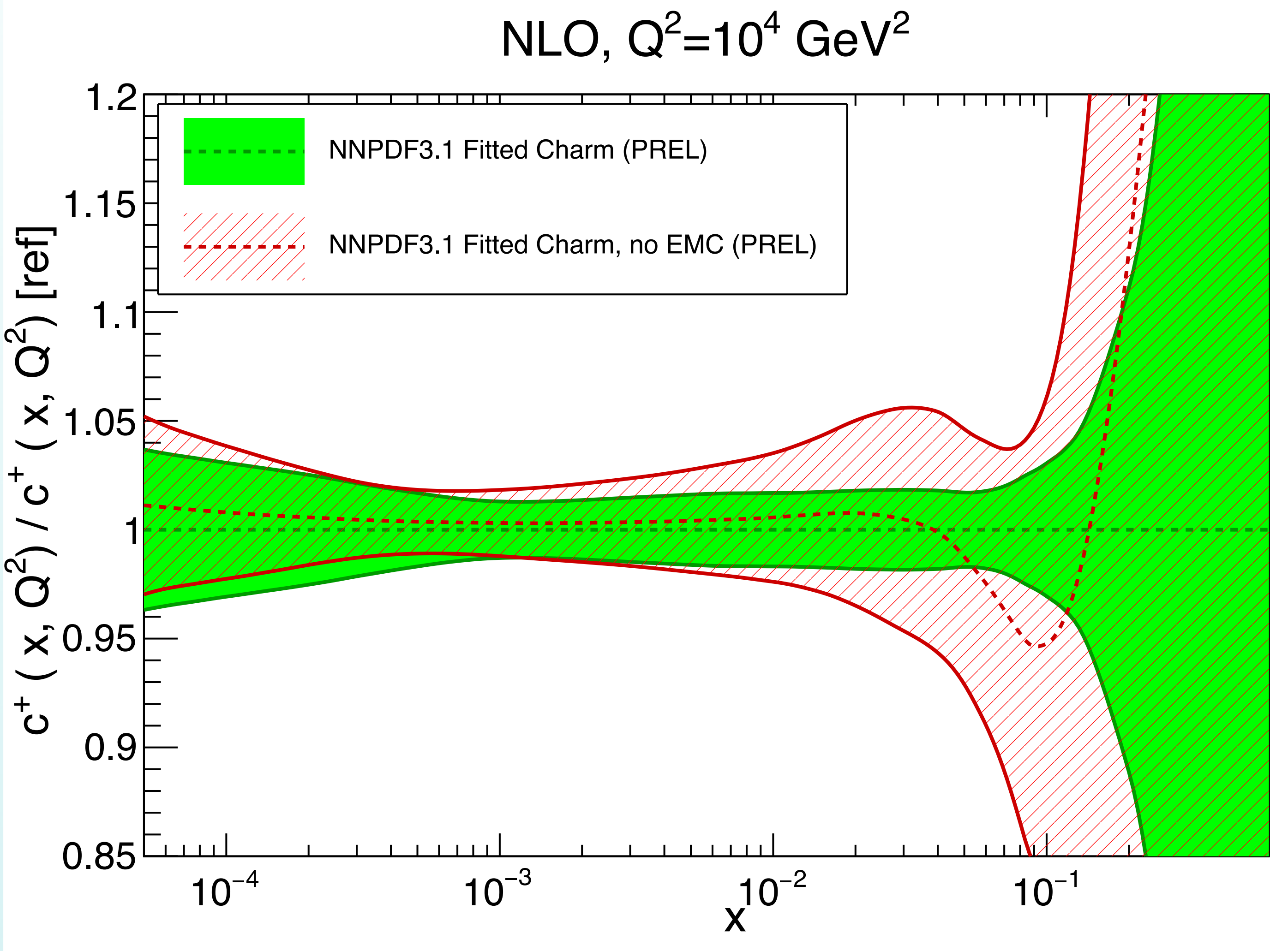
Fitted charm stability

- The additional datasets included in NNPDF3.1, in particular the new Tevatron and LHCb measurements, further **constrain the charm PDF**
- Results are nicely consistent with those of the NNPDF3 IC paper, with **reduced PDF uncertainties**
- **Impact of EMC data** is now rather reduced when added on top of the NNPDF3.1 dataset



Fitted charm stability

- The additional datasets included in NNPDF3.1, in particular the new Tevatron and LHCb measurements, further **constrain the charm PDF**
- Results are nicely consistent with those of the NNPDF3 IC paper, with **reduced PDF uncertainties**
- **Impact of EMC data** is now rather reduced when added on top of the NNPDF3.1 dataset



Summary and outlook

First determination of fitted charm in the NNPDF global analysis framework

- **LHAPDF6 grids** available from the **NNPDF HepForge website,** for a range of charm mass (pole and running) values
- The final answer concerning the **amount of non-perturbative charm allowed** can be determined by **LHC measurements at Run II**
- Improved stability with respect to charm mass variations

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
- Preliminary results indicate in general good **stability with respect to NNPDF3.0,** with main differences being a **reduction of the large-x PDF uncertainties** and an **improved flavor separation**, specially relevant for precision electroweak production data at the LHC
- NNPDF3.1 with fitted charm **confirms and strengthens the conclusions of the NNPDF3 IC study**

Summary and outlook

First determination of fitted charm in the NNPDF global analysis framework

- **LHAPDF6 grids** available from the **NNPDF HepForge website,** for a range of charm mass (pole and running) values
- The final answer concerning the **amount of non-perturbative charm allowed** can be determined by **LHC measurements at Run II**
- Improved stability with respect to charm mass variations

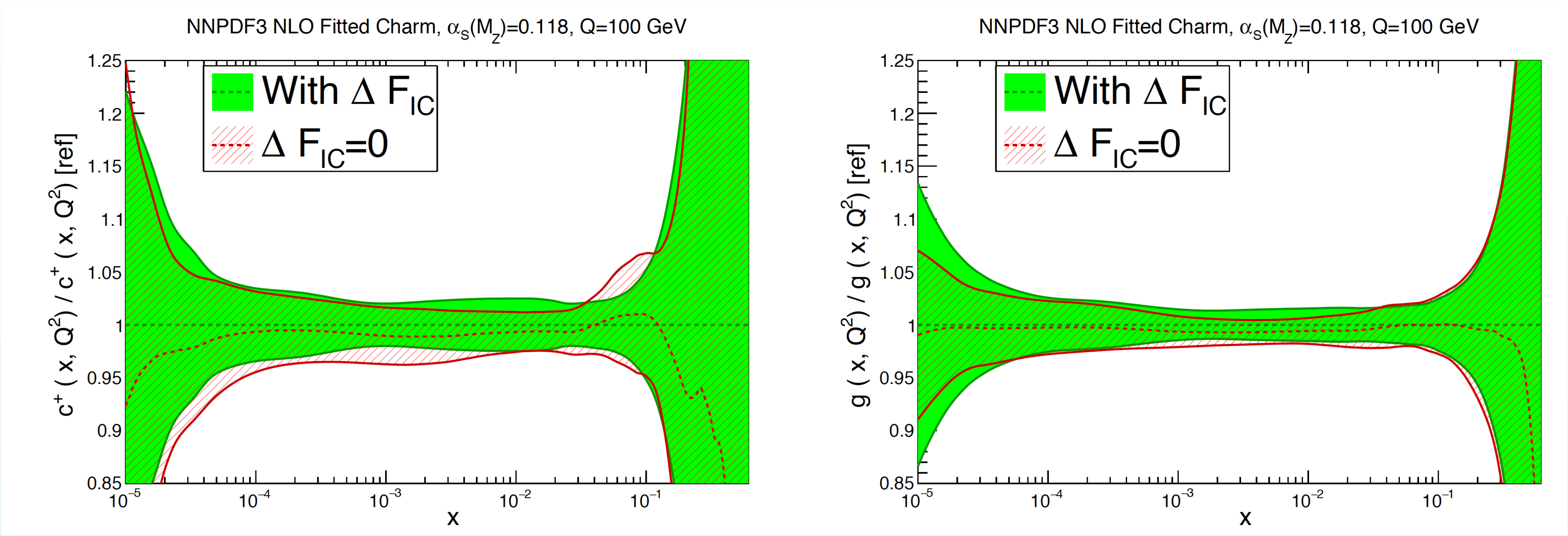
Towards a new global analysis: NNPDF3.1

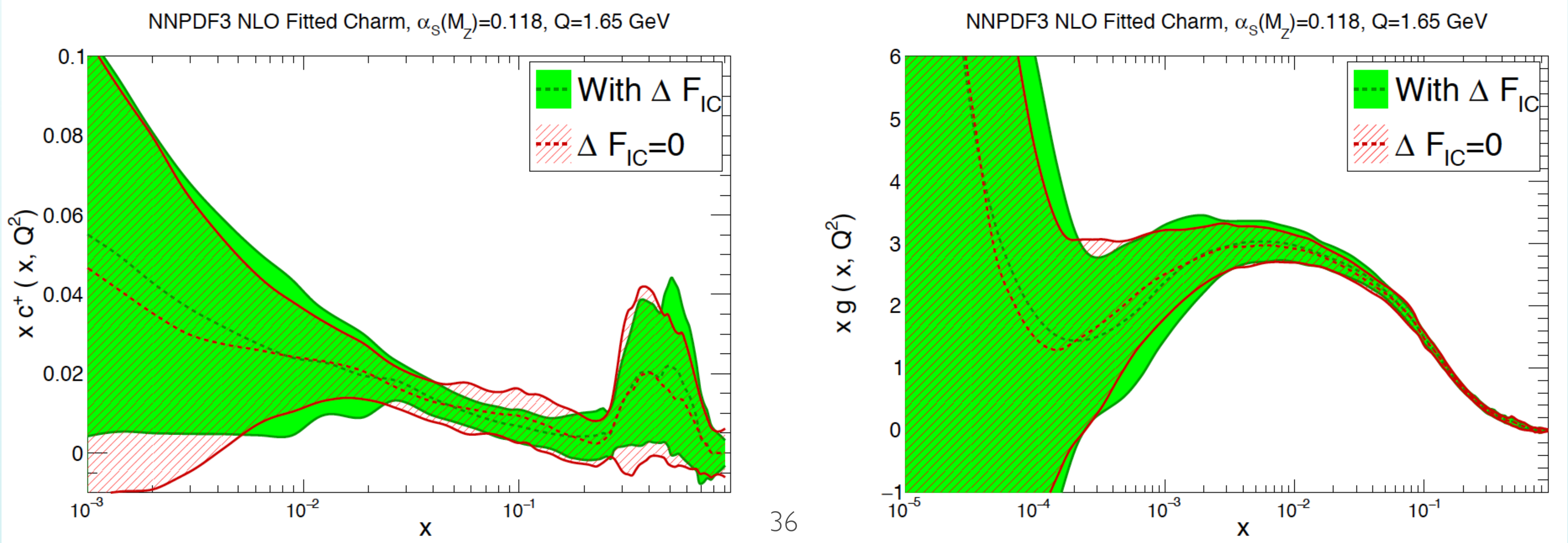
- **Several new datasets i** evatron legacy data to precision LHC electroweak prod uark production differential distributions
- Preliminary res in general good **stability with respect to NNPDF3.0,** with main differences being a **reduction of the large-x PDF uncertainties** and an **improved flavor separation**, specially relevant for precision electroweak production data at the LHC
- NNPDF3.1 with fitted charm **confirms and strengthens the conclusions of the NNPDF3 IC study**

Thanks for your attention

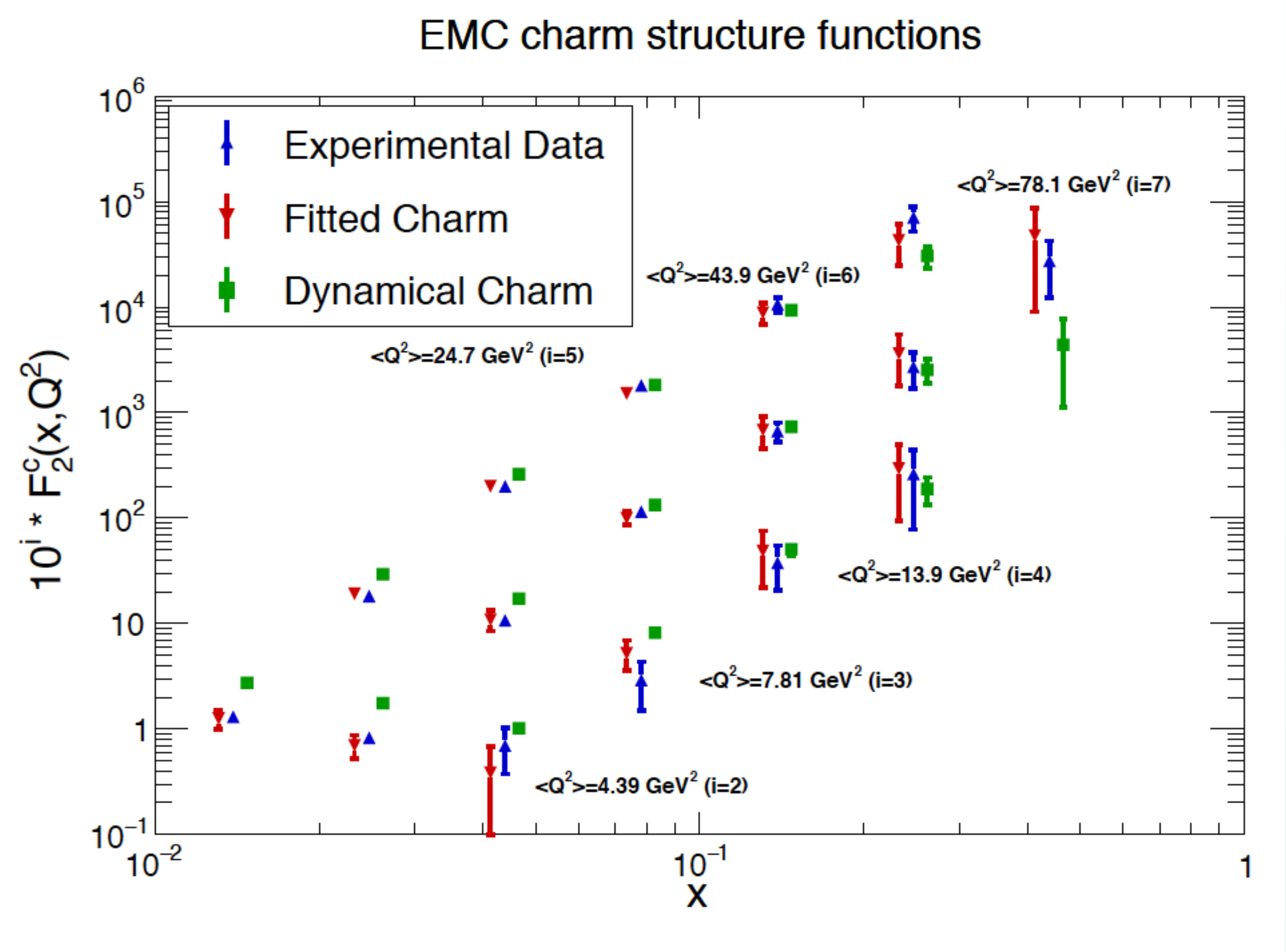
Additional Material

Impact of modified GM-VFN

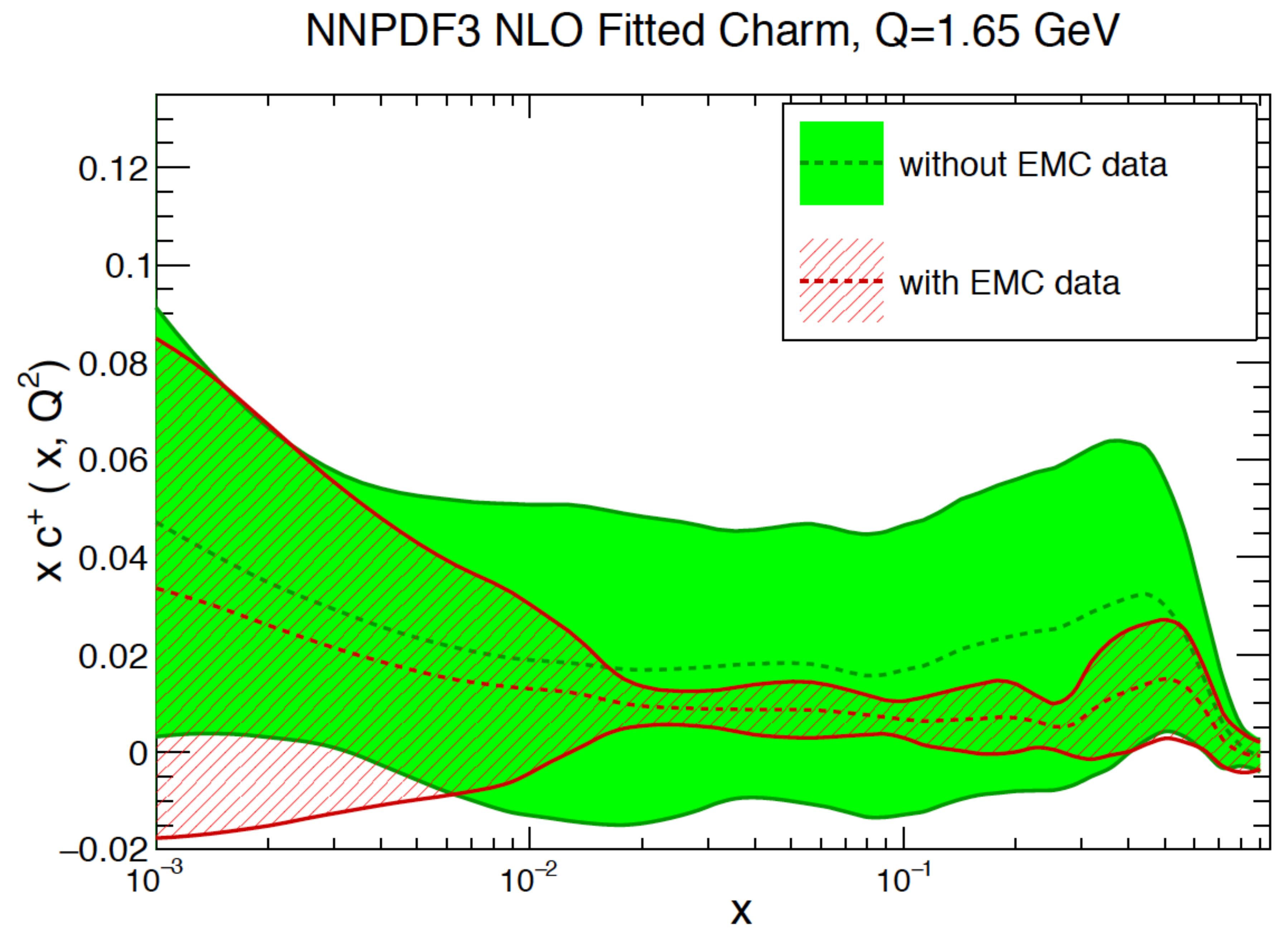




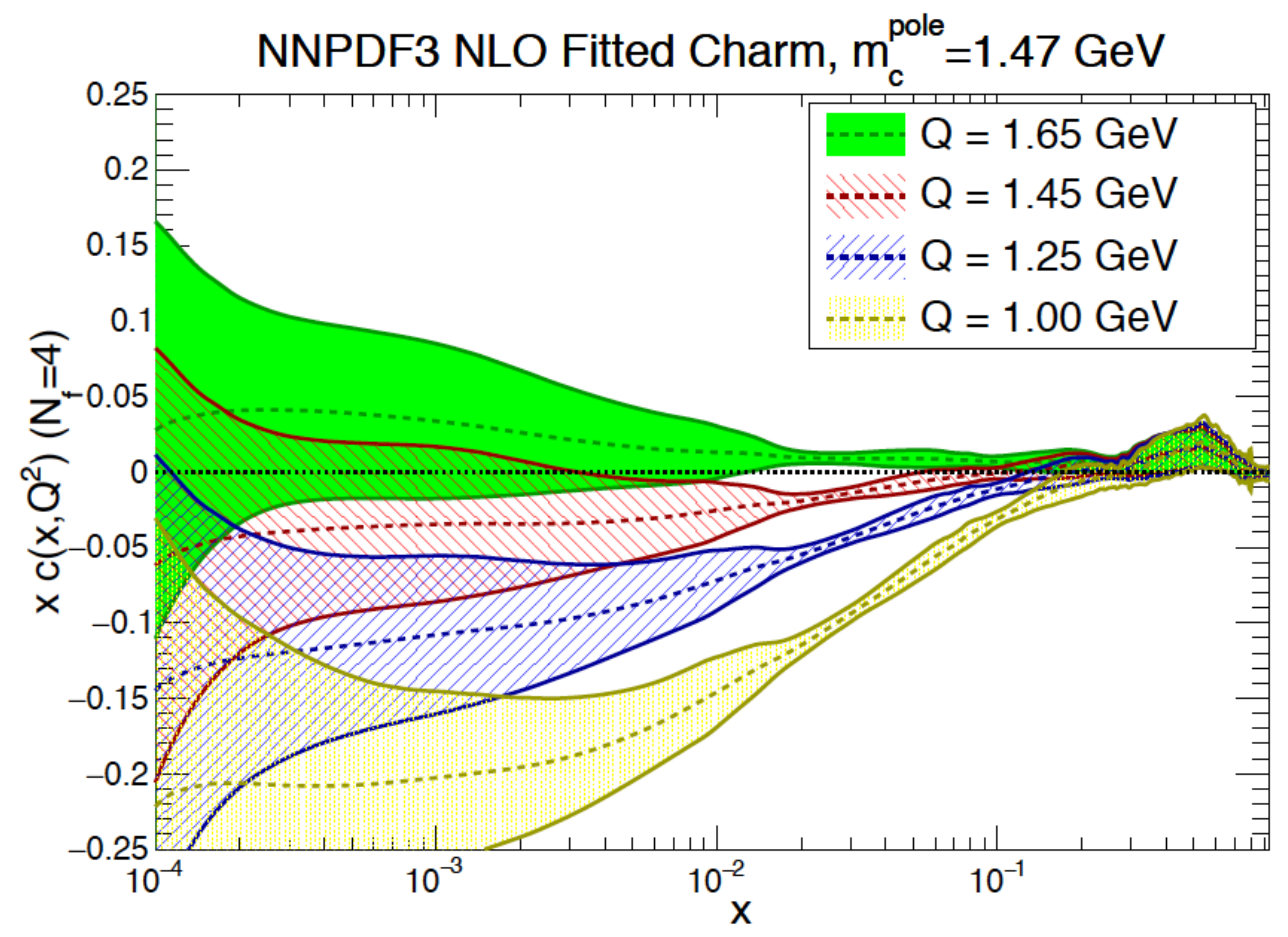
The EMC charm data



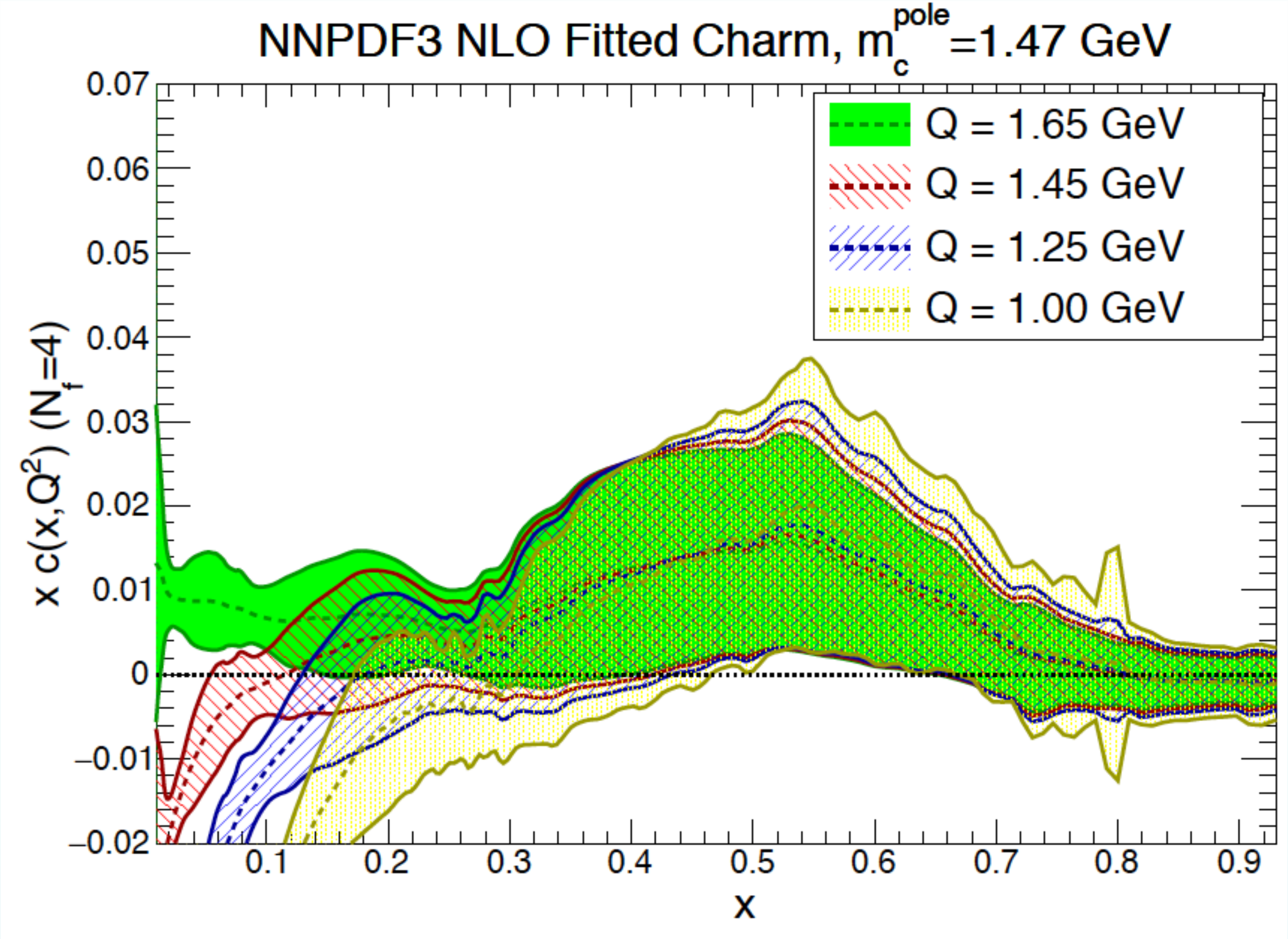
The EMC charm data



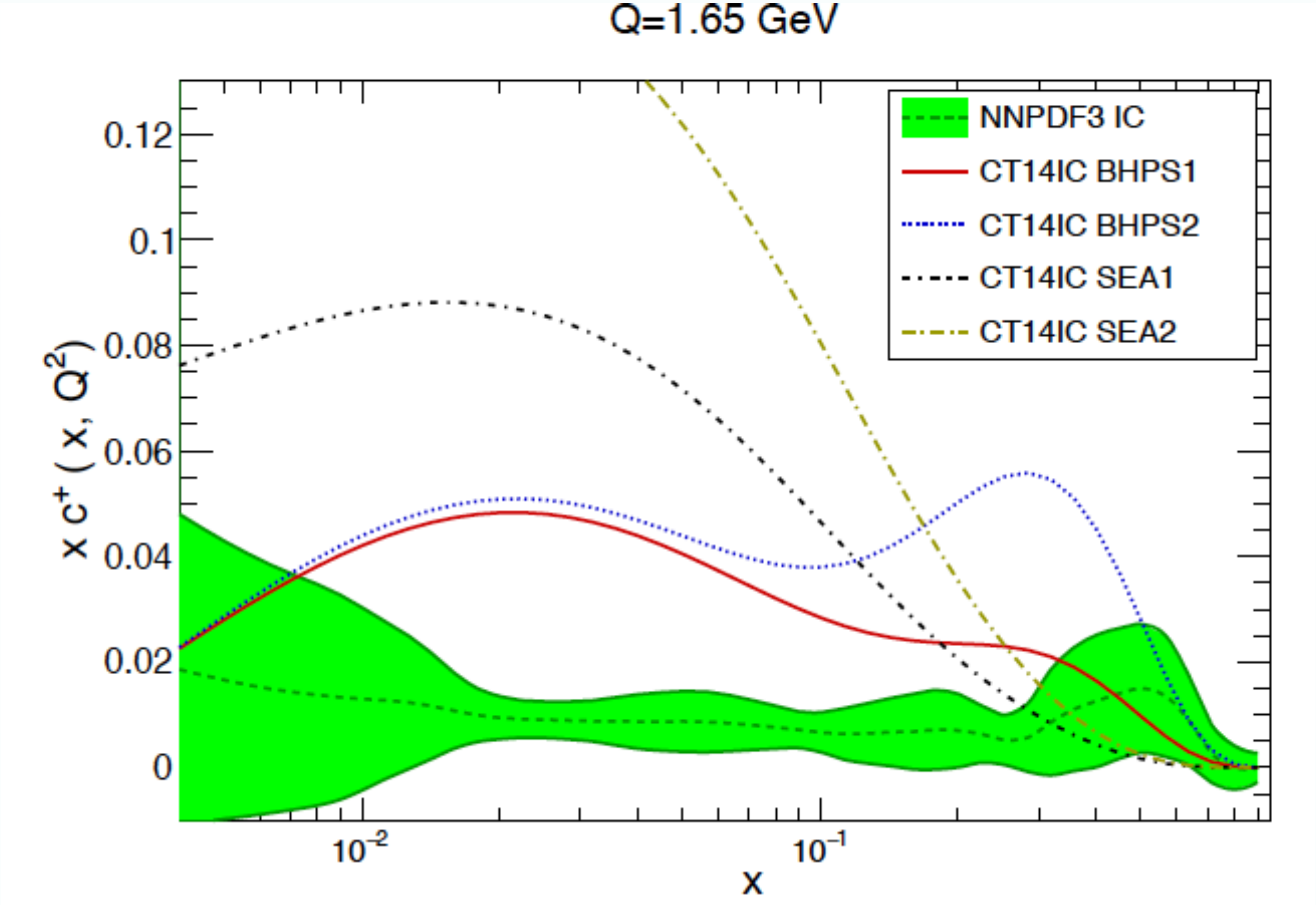
Disentangling non-perturbative charm



Disentangling non-perturbative charm



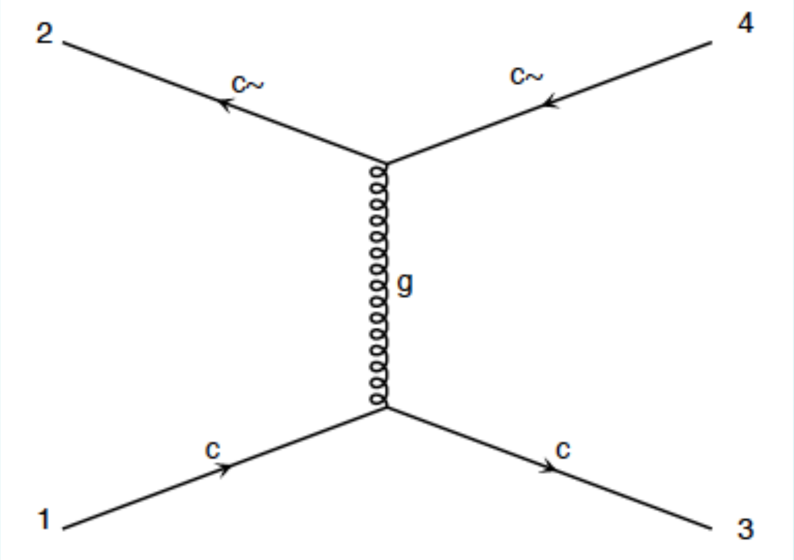
Comparison with CT14IC

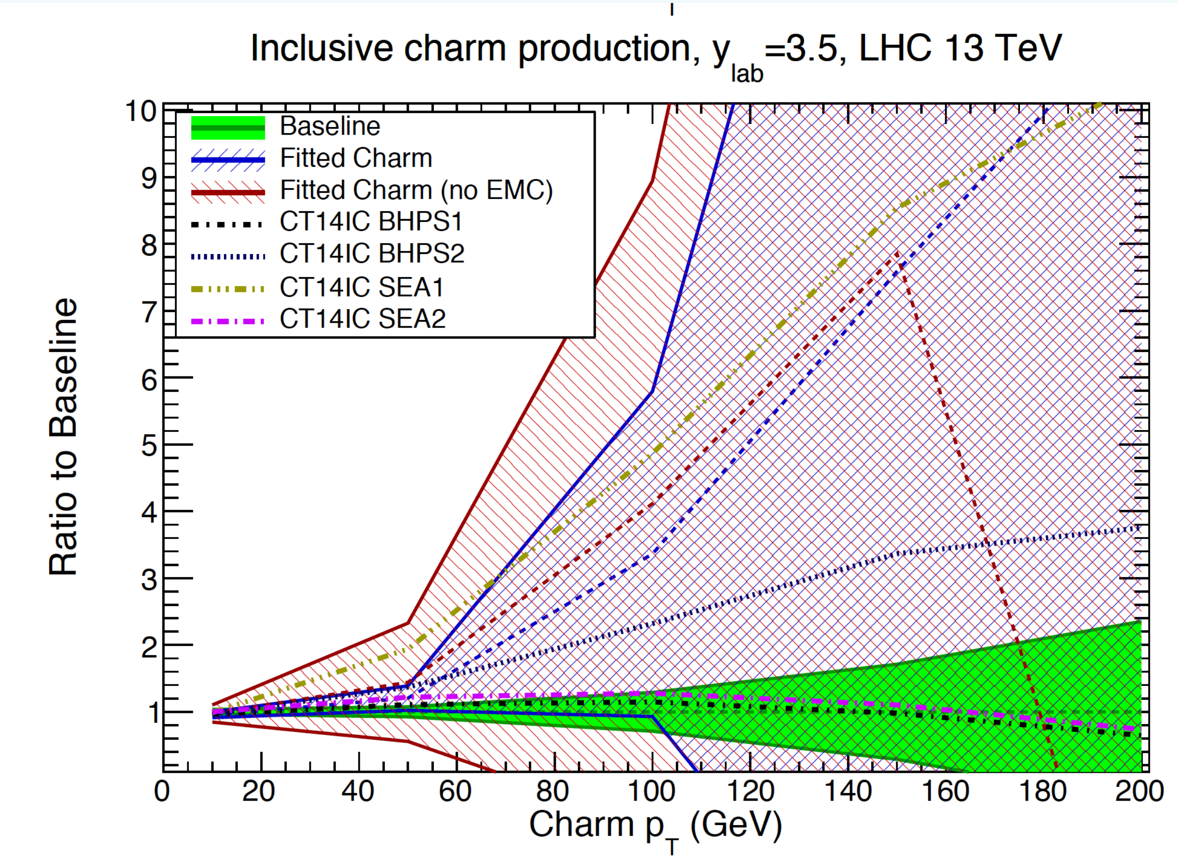


Phenomenological implications @ LHC

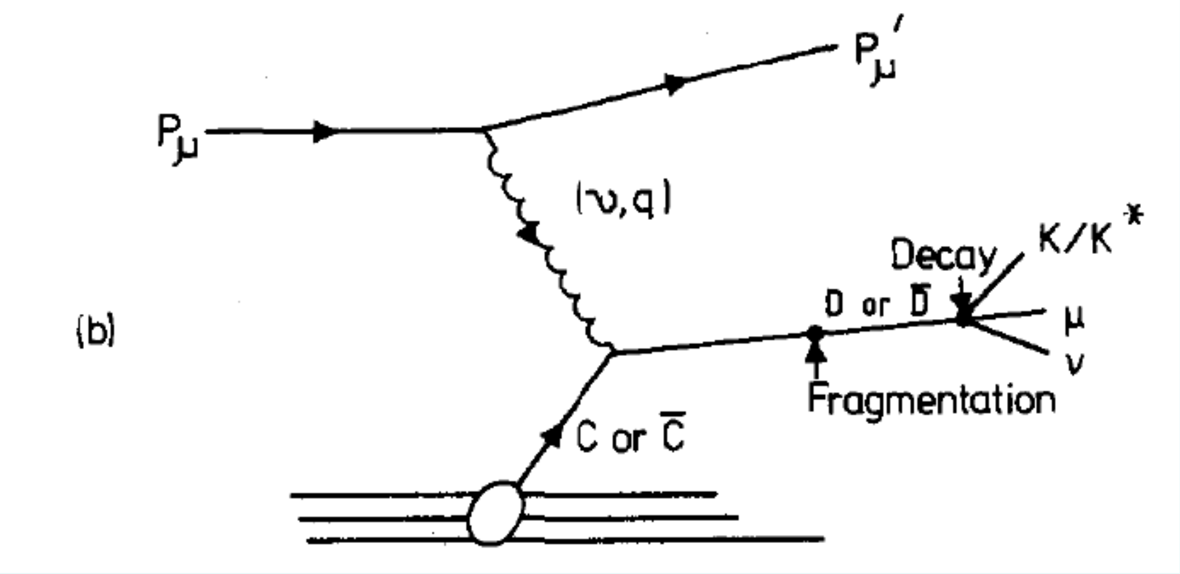
- The differences between **fitted charm** and **perturbative charm** can be explored using a variety of LHC observables such as **D meson production and Z+charm** production
- The **more forward and larger p_T the measurement**, the more sensitive to the large-x charm PDF, and thus to the differences between fitted and dynamical charm

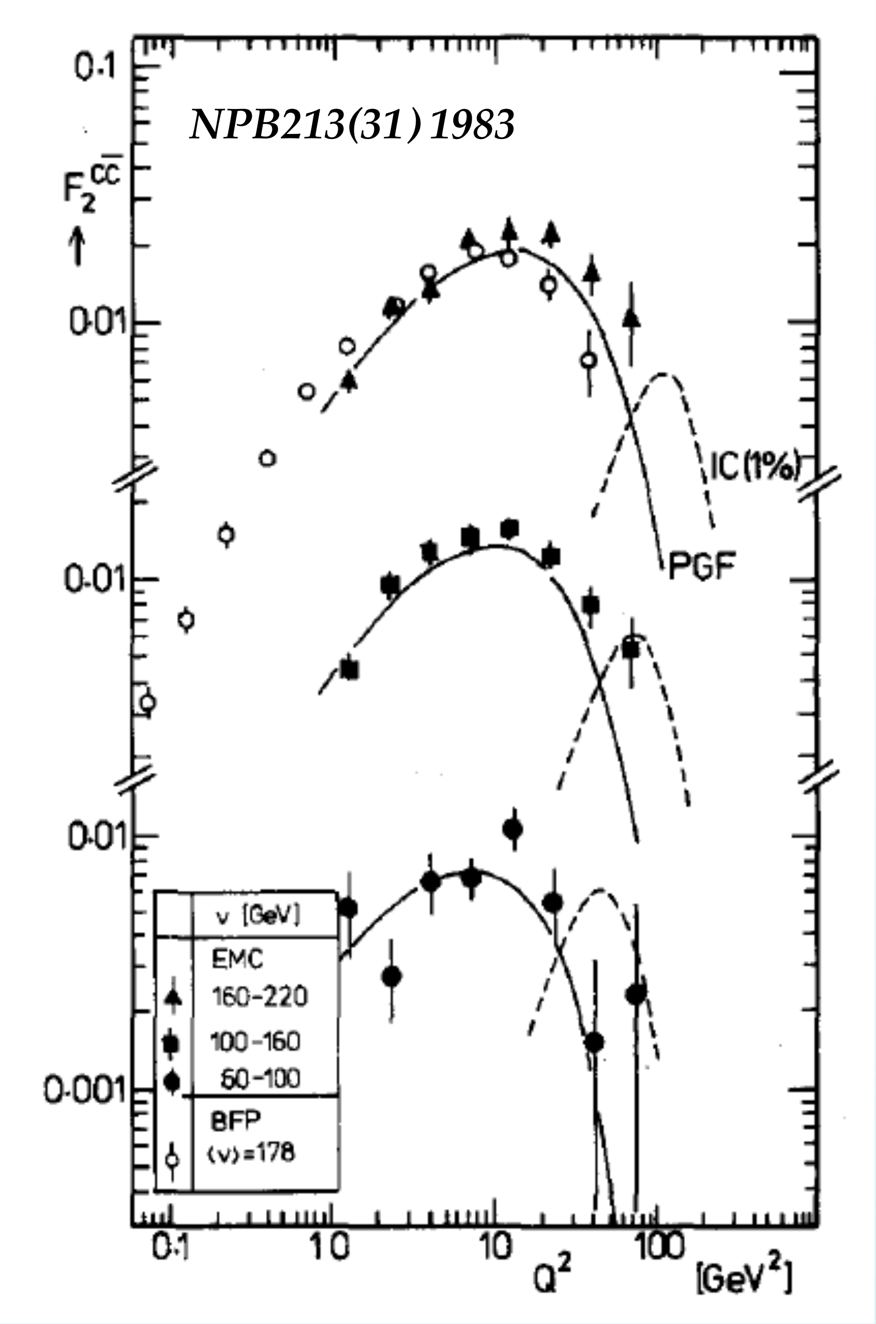
Charm pair production





The EMC charm data




NPB213(31) 1983

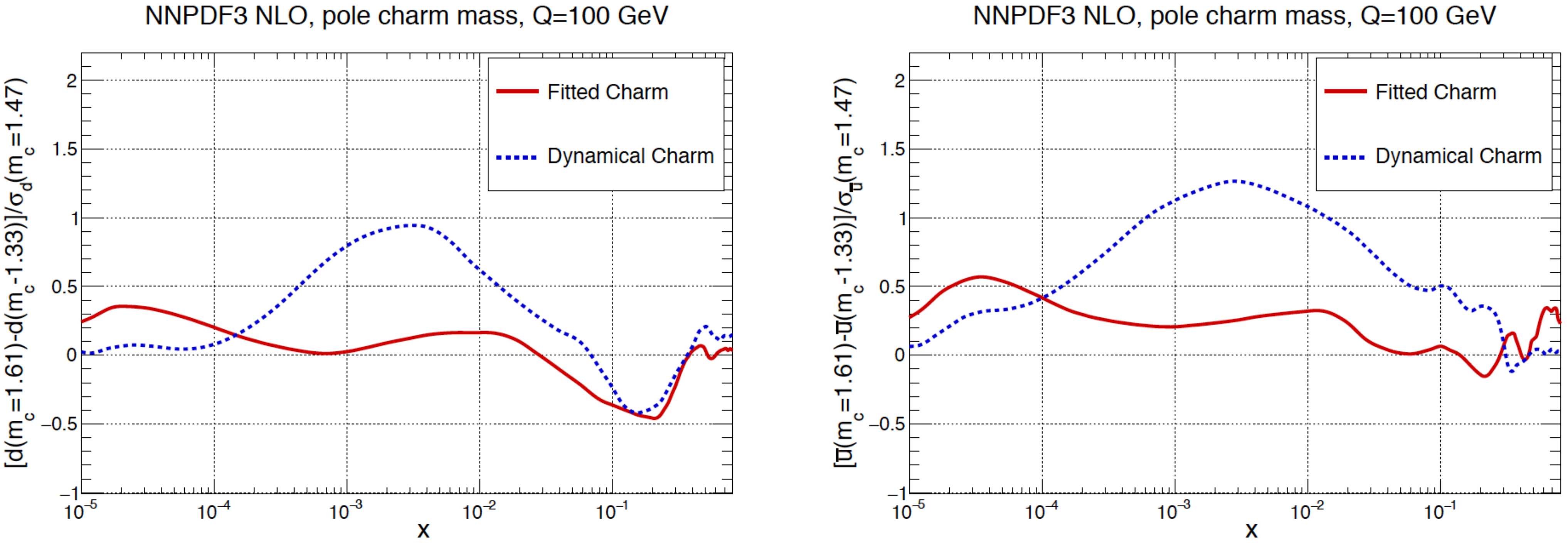
- Since more than 30 years, the EMC charm structure function data advocated as **evidence for intrinsic charm**
- However, previous global PDF fits with fitted charm **unable to achieve satisfactory description** of this experiment
- **arXiv:1408.1708** (Jimenez-Delgado et al) finds χ^2/N_{dat}**=4.4**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

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