Parton Distributions with Intrinsic Charm

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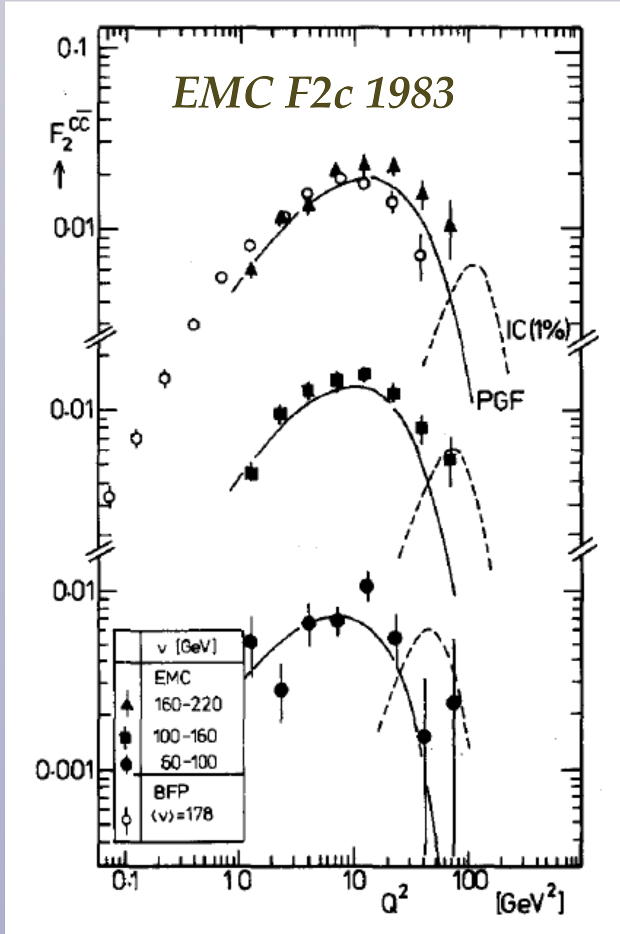
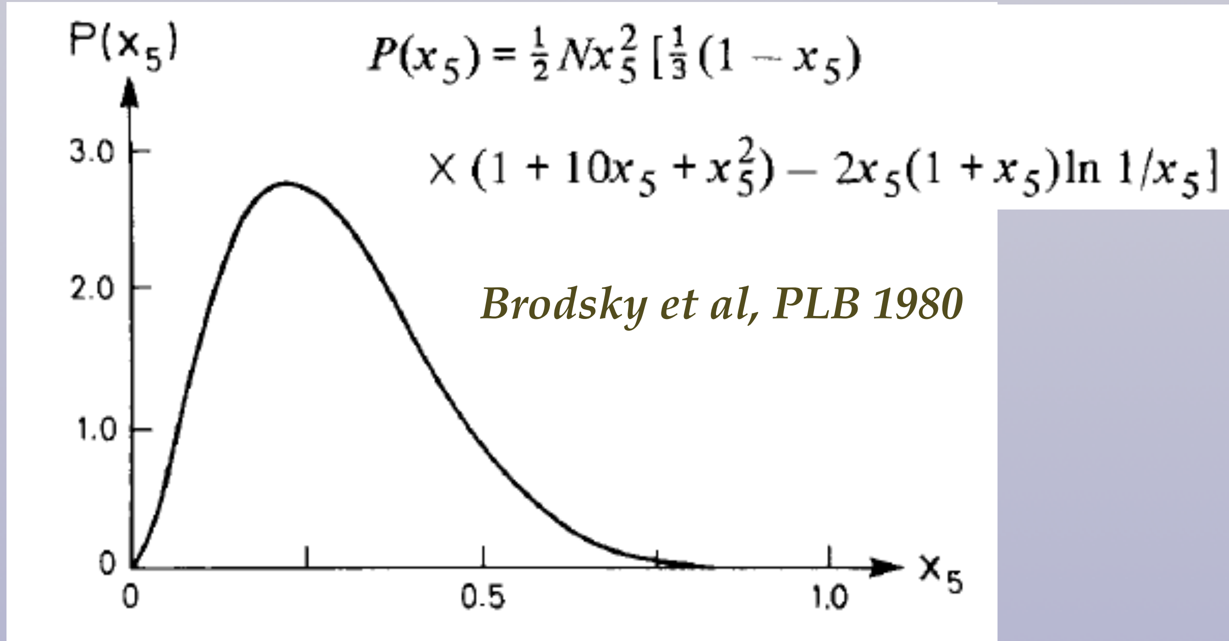
Why fitted charm?

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

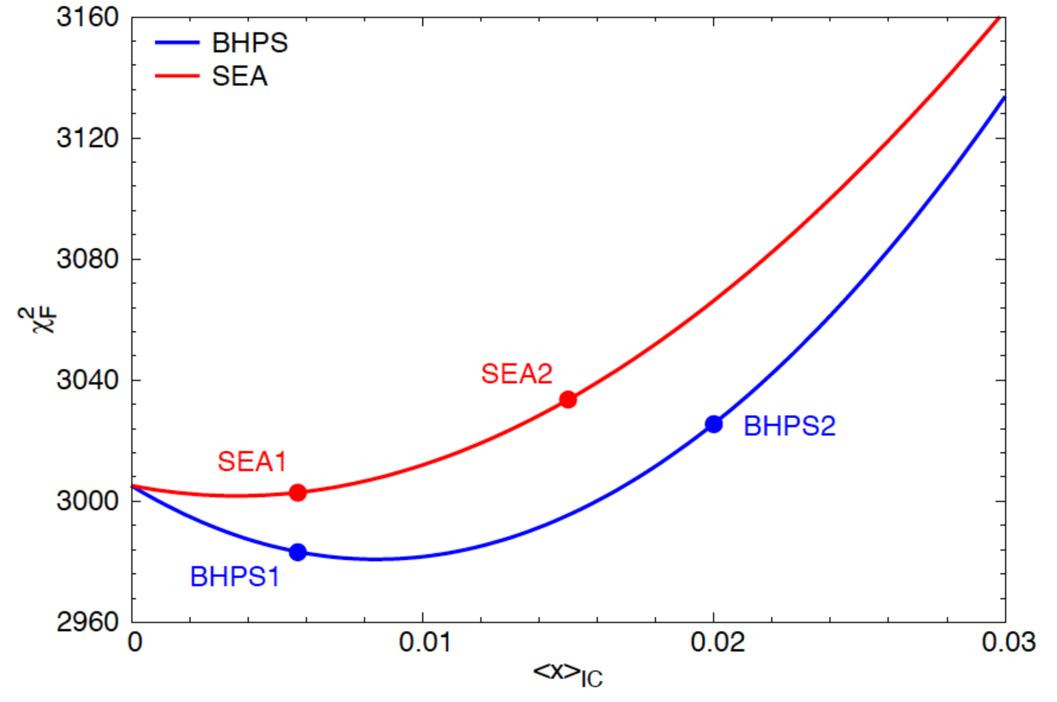




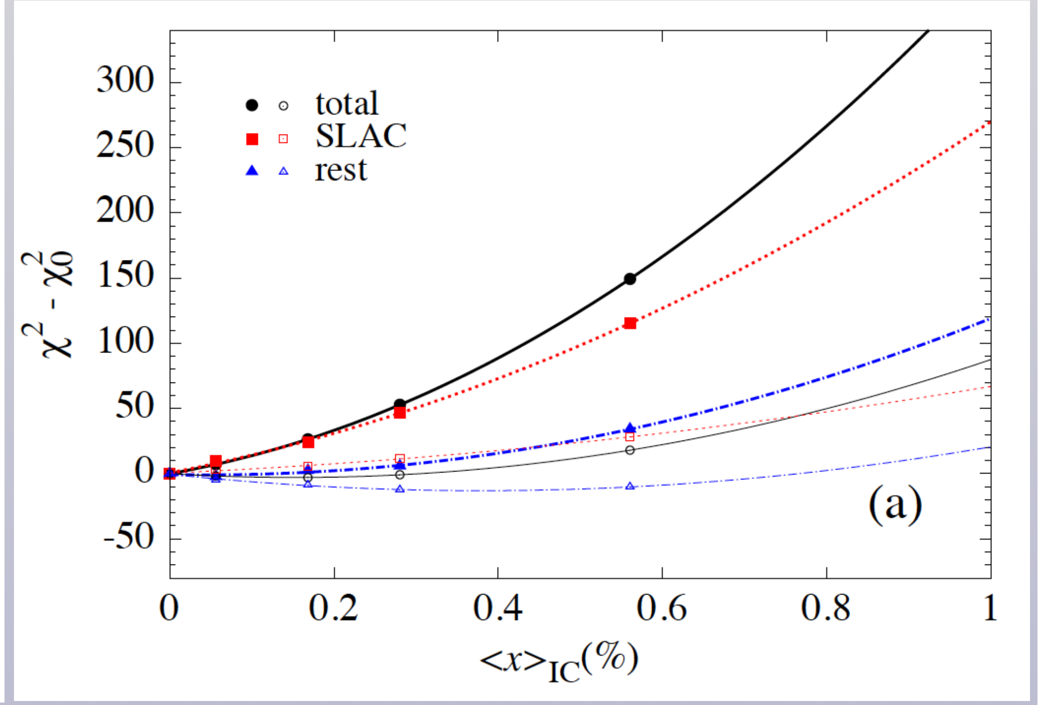
+30-years old conundrum of QCD!

Previous global PDF fits with IC

CT10 IC fit, arXiv:1309.0025



JLAB IC fit, arXiv:1408.1708



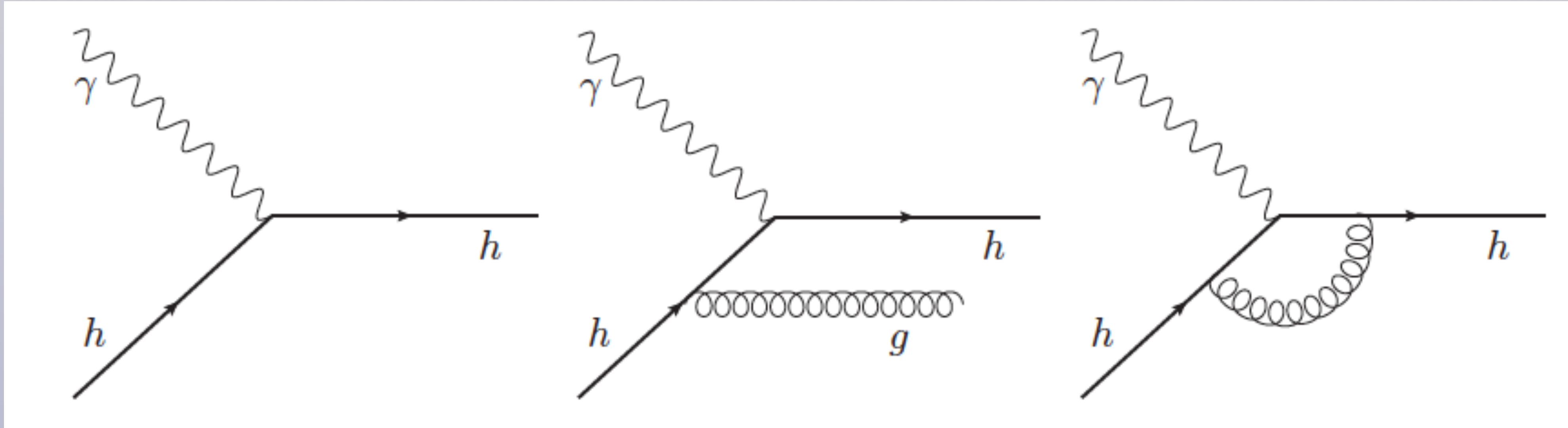
- Fitted charm with **standard S-ACOT structure functions,** without massive charm-initiated terms
- **Sizable charm** still allowed in global fit, though results depend on the **specific choice of model for fitted charm**, as well as **value of tolerance, $\Delta\chi^2$=100**

- Fitted charm in the **FFN scheme,** with massive charm-initiated terms
- Claims very stringent bounds on IC, also depends on **choice of tolerance (in this case $\Delta\chi^2$=1)**

Very restrictive charm PDF parametrizations in both cases

FONLL with fitted charm

- In a global PDF analysis with fitted charm, not enough to only 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, but NNLO not available yet

Hoffmann and Moore 83
Kretzer and Schienbein 98

FONLL with a fitted charm PDF

- The original FONLL structure functions can be modified to account for **massive charm-initiated contributions**

$$F(x,Q^2) = F^{\mathrm{FLNR}}(x,Q^2) + \Delta F(x,Q^2)$$

1) Ball, Bertone, Bonvini, Forte, Groth-Merrild, JR, Rottoli, arXiv:1510.01009
2) Ball, Bonvini, Rottoli, arXiv:1510.02491

- The new piece to be added to the **FONLL charm structure functions** is

$$\begin{aligned}
\Delta F_h(x,Q^2) = \sum_{i=h,\bar h} \Bigg\{ \Bigg[\left(C_i^{(3),0}\left(\frac{Q^2}{m_h^2}\right) - C_i^{(4),0} \right) \\
+ \alpha_s^{(4)}(Q^2)\left(C_i^{(3),1}\left(\frac{Q^2}{m_h^2}\right) - C_i^{(4),1} \right) \Bigg] \\
- \alpha_s^{(4)}(Q^2) C_i^{(3),0}\left(\frac{Q^2}{m_h^2}\right) \otimes \left(K_{hh}^{(1)}(m_h^2) + P_{qq}^{(0)} L \right) \Bigg\} \otimes f_i^{(4)}(Q^2) \\
- \alpha_s^{(4)}(Q^2) \sum_{i=h,\bar h} \left(C_i^{(3),0}\left(\frac{Q^2}{m_h^2}\right) - C_i^{(4),0} \right) \otimes P_{qg}^{(0)} L \otimes f_g^{(4)}(Q^2) + \mathcal{O}(\alpha_s^2).
\end{aligned}$$

- This correction **vanishes at large Q²** (since massless scheme unaffected by new contributions) and is **numerically tiny for a perturbative generated charm** (use equations of motion)

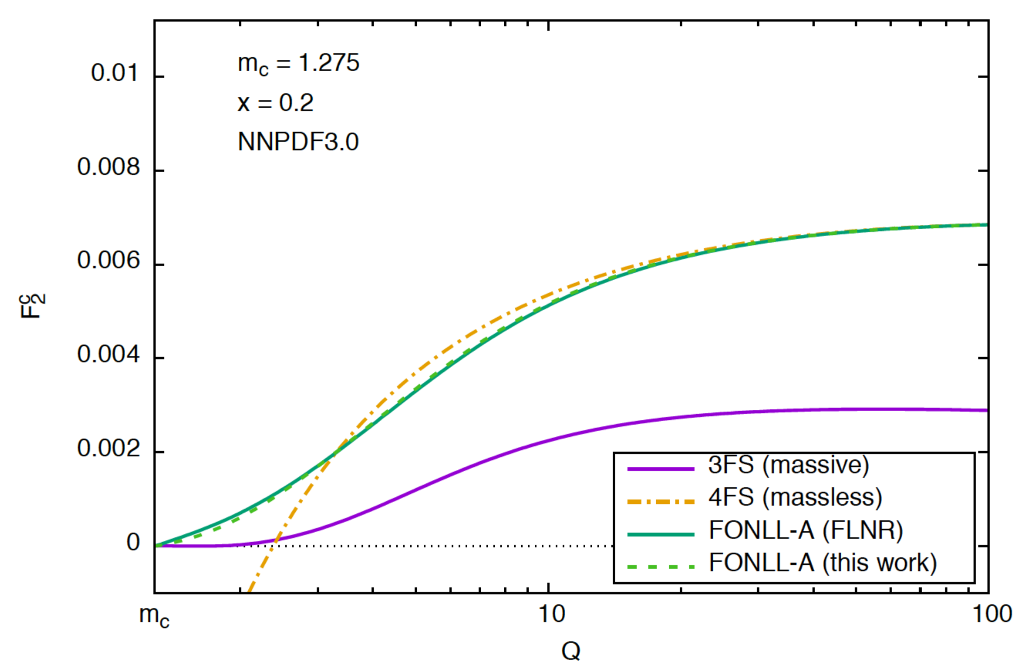
$$\begin{aligned}
f_h^{(3)} &= f_h^{(4)}(Q^2) \\
&- \alpha_s^{(4)}(Q^2)\left(K_{hh}^{(1)}(m_h^2) + P_{qq}^{(0)} L \right) \otimes f_h^{(4)}(Q^2) - \alpha_s^{(4)}(Q^2) L P_{qg}^{(0)} \otimes g^{(4)}(Q^2) + \mathcal{O}(\alpha_s^2).
\end{aligned}$$

FONLL with a fitted charm PDF

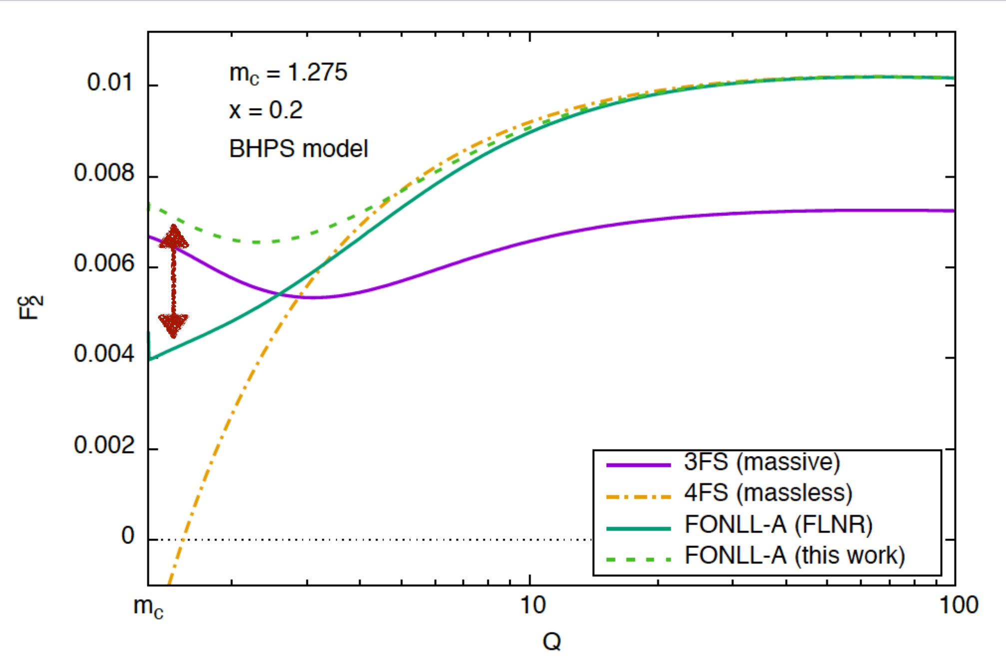
$$F(x,Q^2) = F^{\mathrm{FLNR}}(x,Q^2) + \Delta F(x,Q^2)$$

``This work"* *``FLNR"

Perturbatively generated charm PDF



Charm PDF from BHPS model, 0.5% mom fract

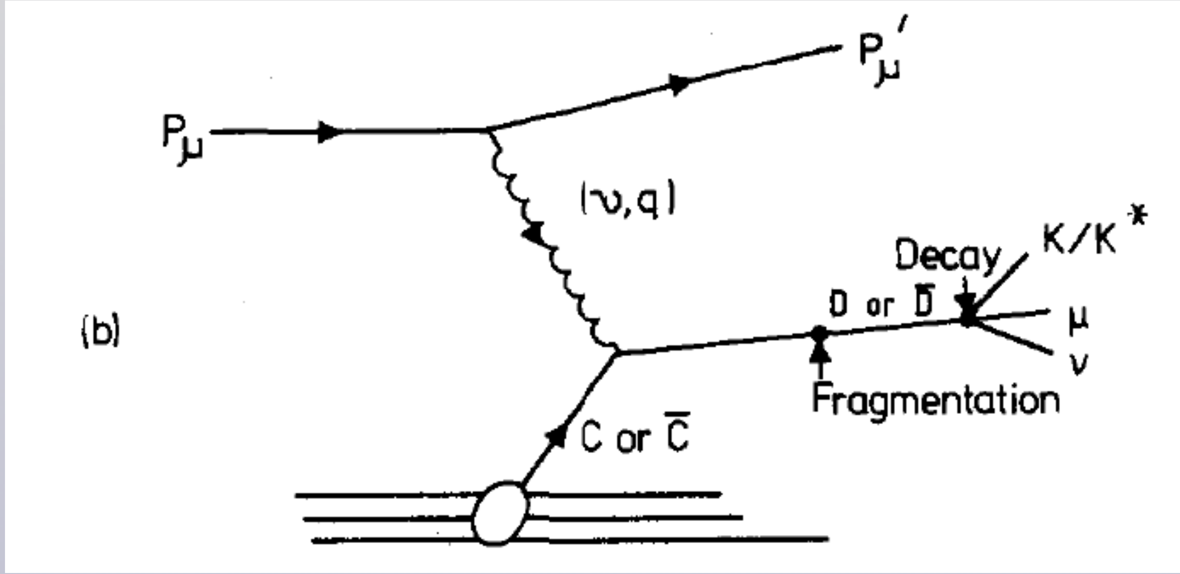


$$f_c^{(3)}(x) = f_{\bar{c}}^{(3)}(x) = A\,x^2[6x(1+x)\ln x + (1-x)(1+10x+x^2)]\,.$$

- For a **dynamically generated charm**, the new contributions have tiny numerical effects
- For **BHPS-like fitted charm**, substantial differences close to threshold at low scales

→ Use of **generalized GM-VFN scheme** crucial for any **realistic fit with charm PDFs**

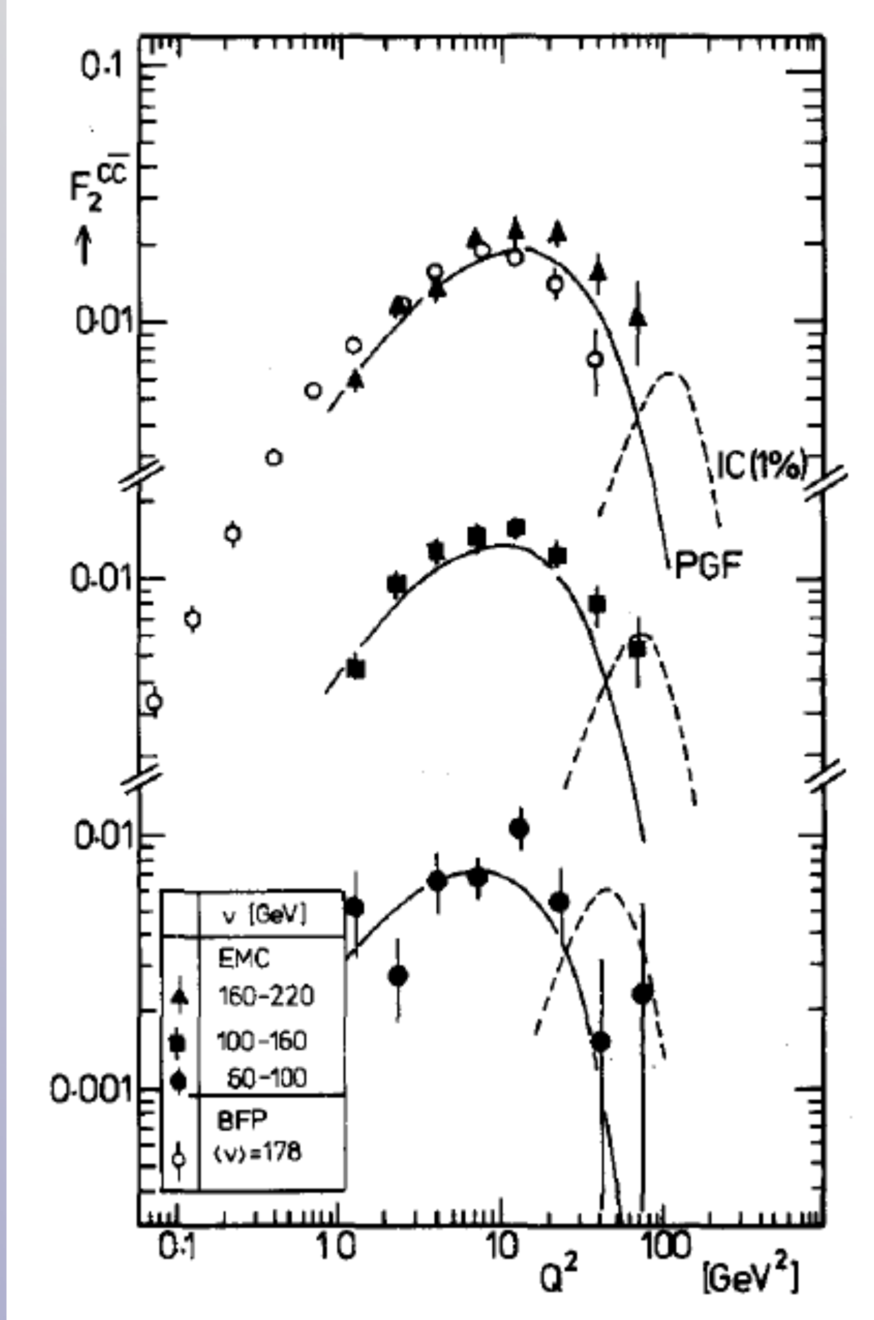
The EMC charm data



NPB213(31) 1983

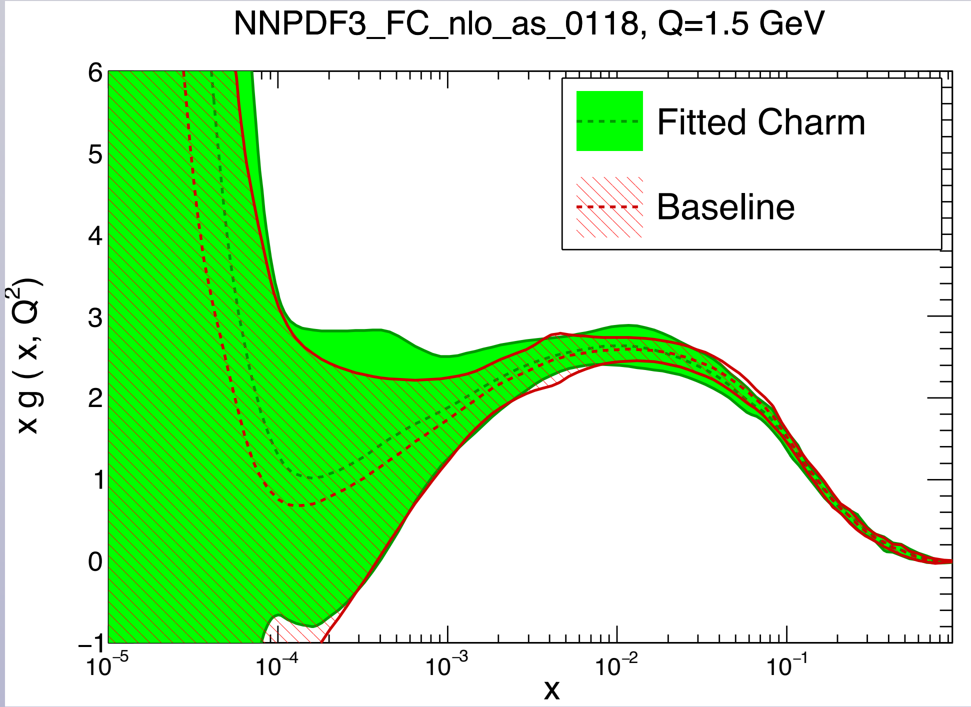
- Since more than 30 years, the EMC charm structure function data advocated as **evidence for intrinsic charm**
- However, previous global PDF fits with fitted charm **unable to achieve satisfactory description** of this experiment
- *Eg* **arXiv:1408.1708** (Jimenez-Delgado et al) finds χ^2/N_{dat}**=4.4**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

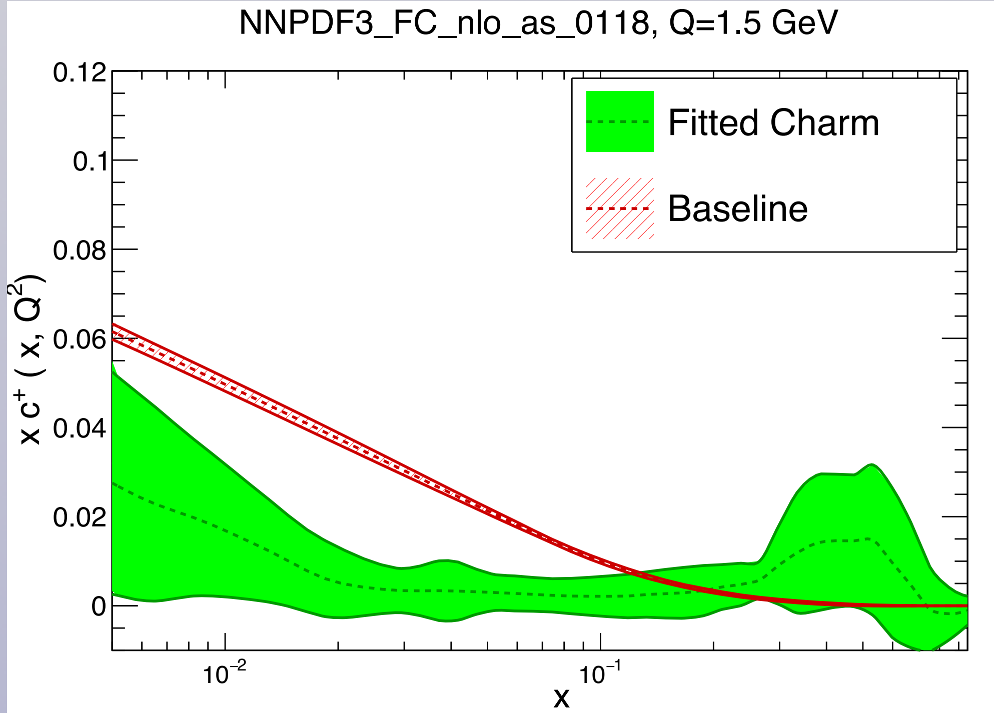
The **fitted charm** results shown in this talk include the **EMC charm production data**



NNPDF3 fits with intrinsic charm

- **Fit settings** based on the upcoming **NNPDF3.1 global analysis** (will be presented at **DIS16**)
- Same PDF input 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 very 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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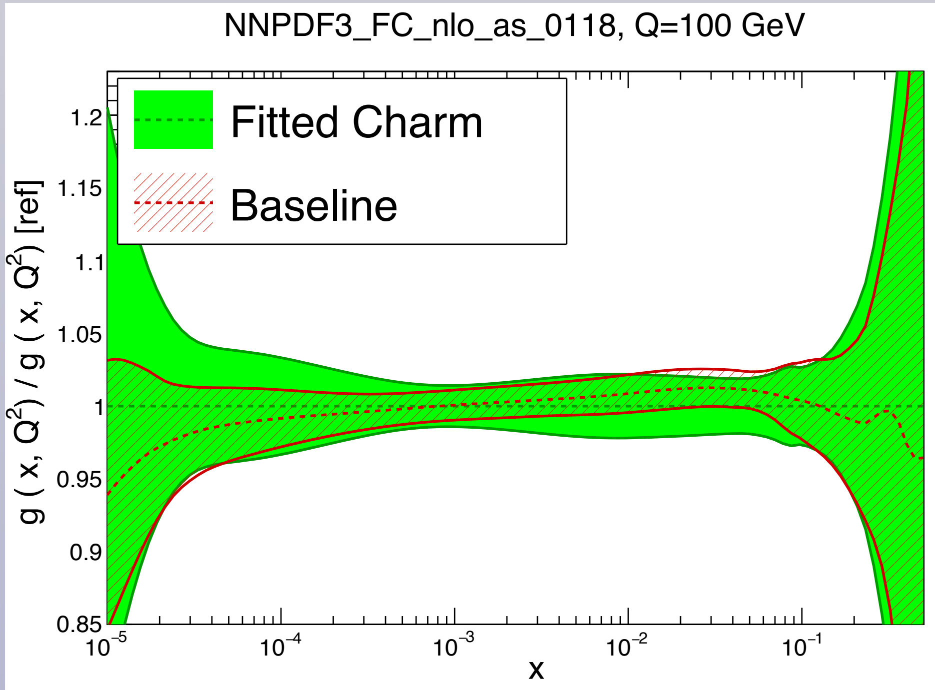
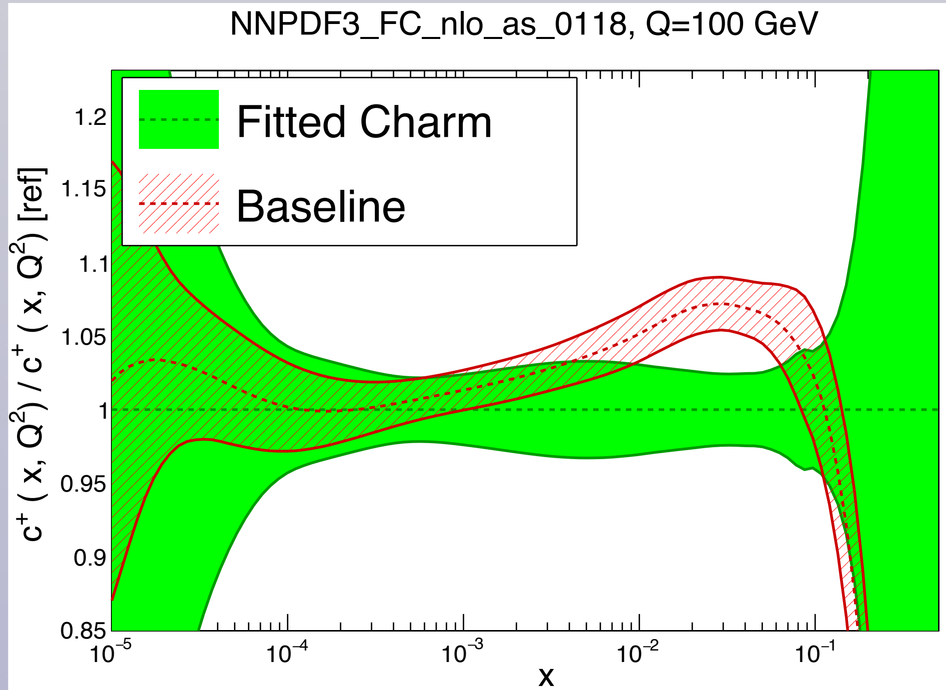




At high scales, **gluon PDF also very stable**, with moderate increase in PDF uncertainty

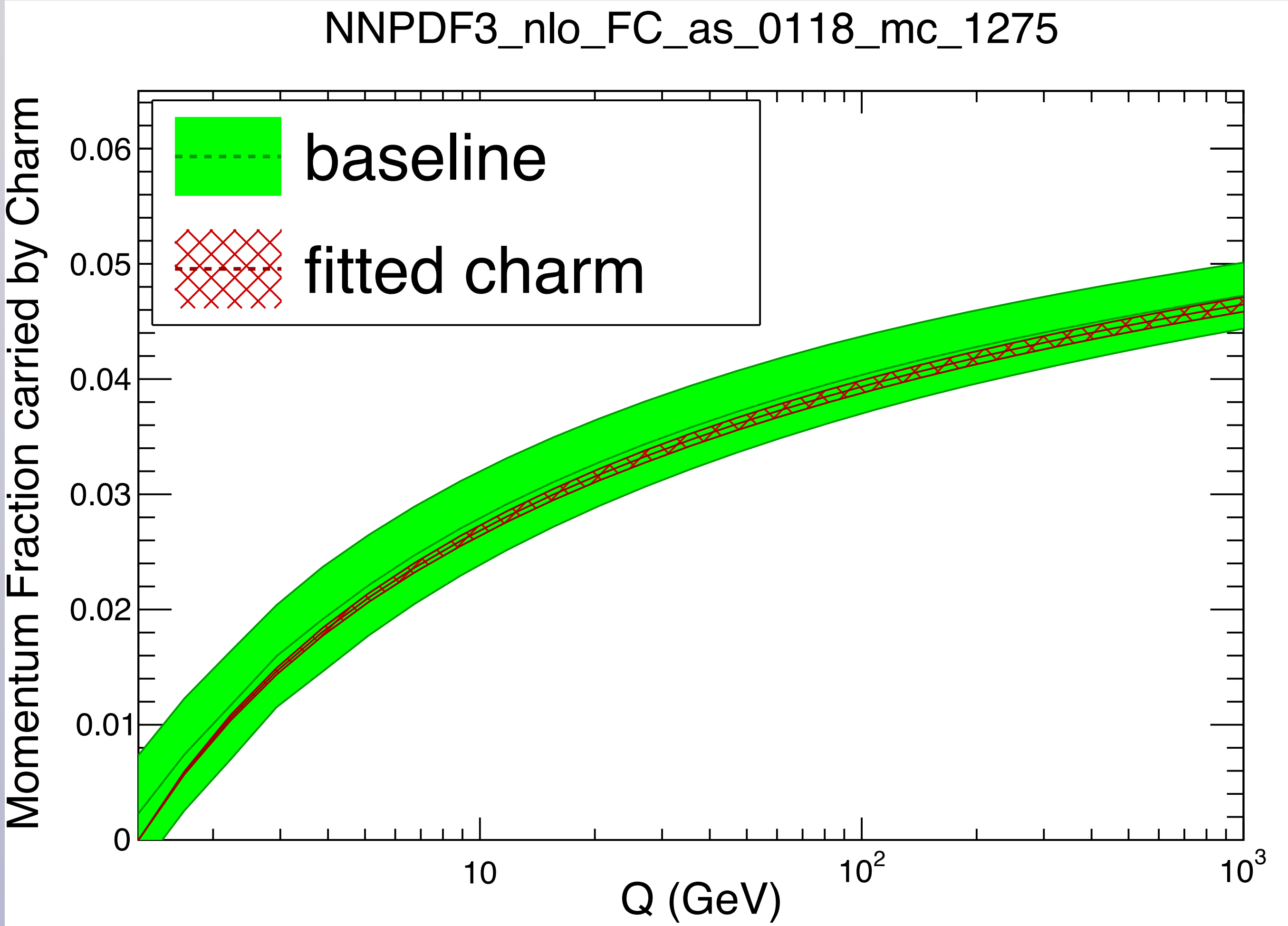
For the charm PDF, **good stability for x < 0.005,** where perturbative evolution dominates over initial conditions. Larger differences for **x> 0.01,** where boundary conditions dominate

Fit quality

χ	Fitted Charm	Baseline
Total	1.163	1.164
HERA I+II	1.20	1.20
HERA F2c	1.21	1.51
BCDMS	1.25	1.24
SLAC	1.28	1.24
CHORUS	1.05	1.11
ATLAS	1.45	1.45
CMS	1.10	1.08
LHCb	1.00	0.97

- The **fit quality** of the IC and baseline fits are **very similar**
- The most marked **improvements** in the IC fit correspond to the **HERA charm data** and the **CHORUS neutrino structure functions**
- For the **LHC datasets** the **fit quality is unchanged** when charm is fitted (within statistical fluctuations)

Charm contribution to the momentum integral



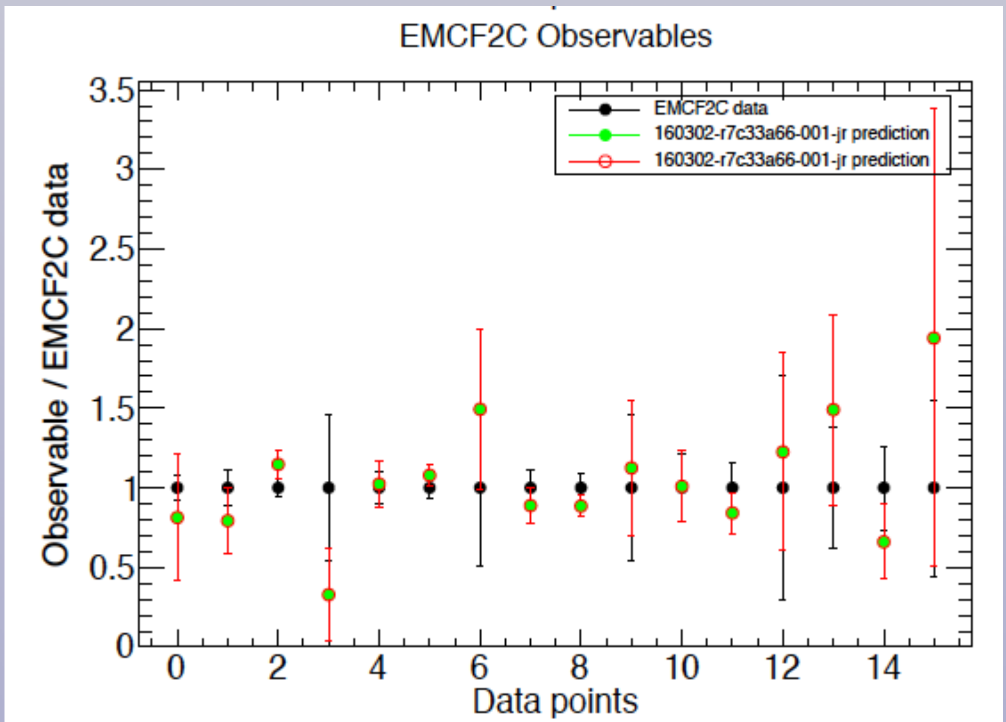
Charm mom fract	Q=Q	Q=100 GeV
Baseline	0%	(3.97 +- 0.06)%
Fitted Charm	(0.25+- 0.50)%	(4.1+-3.2)%

- At the input scale, **charm can carry up to 0.75% of the proton's momentum** at the 68% CL
- Good **overall consistency** between perturbative and fitted charm for $Q > Q_0$
- At **LHC scales**, central values in perfect agreement between the baseline and fitted charm PDFs, with larger uncertainties in the latter
- Important phenomenological implications for **charm-initiated processes** at the LHC

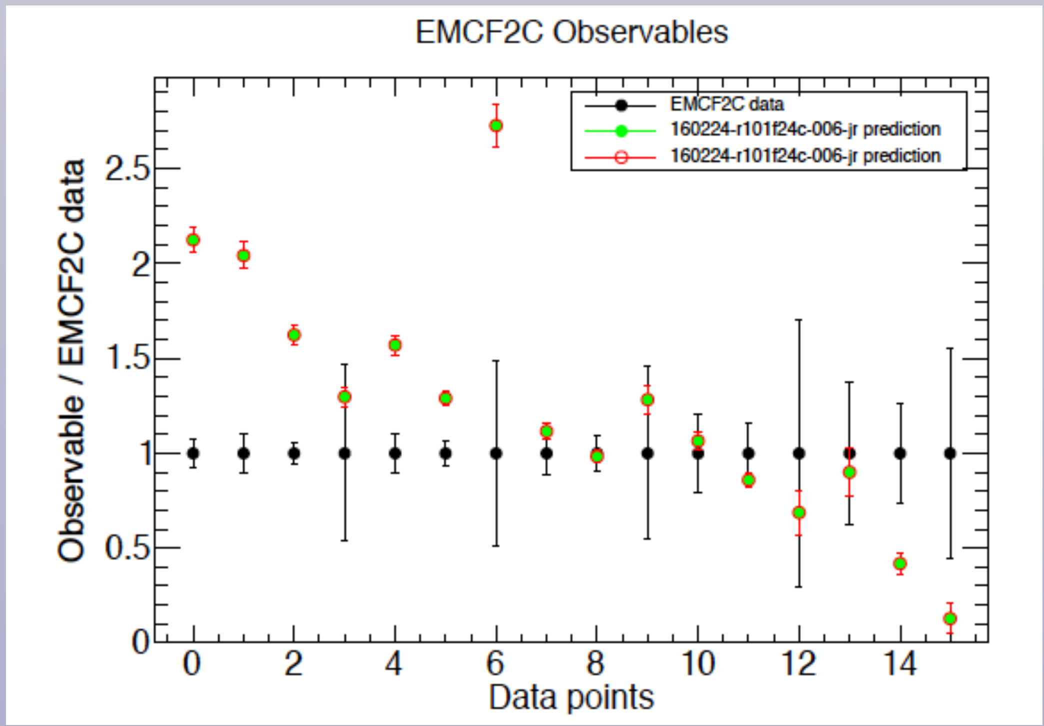
The EMC charm data

- Unlike previous IC fits, we find **satisfactory description of the EMC charm data** when charm is fitted
- Moreover, the EMC charm data is essential to **reduce the PDF uncertainties** in the fitted charm
- Improvements as compared to previous studies most likely related to the **more flexible charm PDF parametrization adopted**, not restricted to particular models

Fitted charm: χ^2/N_{dat}=1.9



Perturbative charm: χ^2/N_{dat}=31.9



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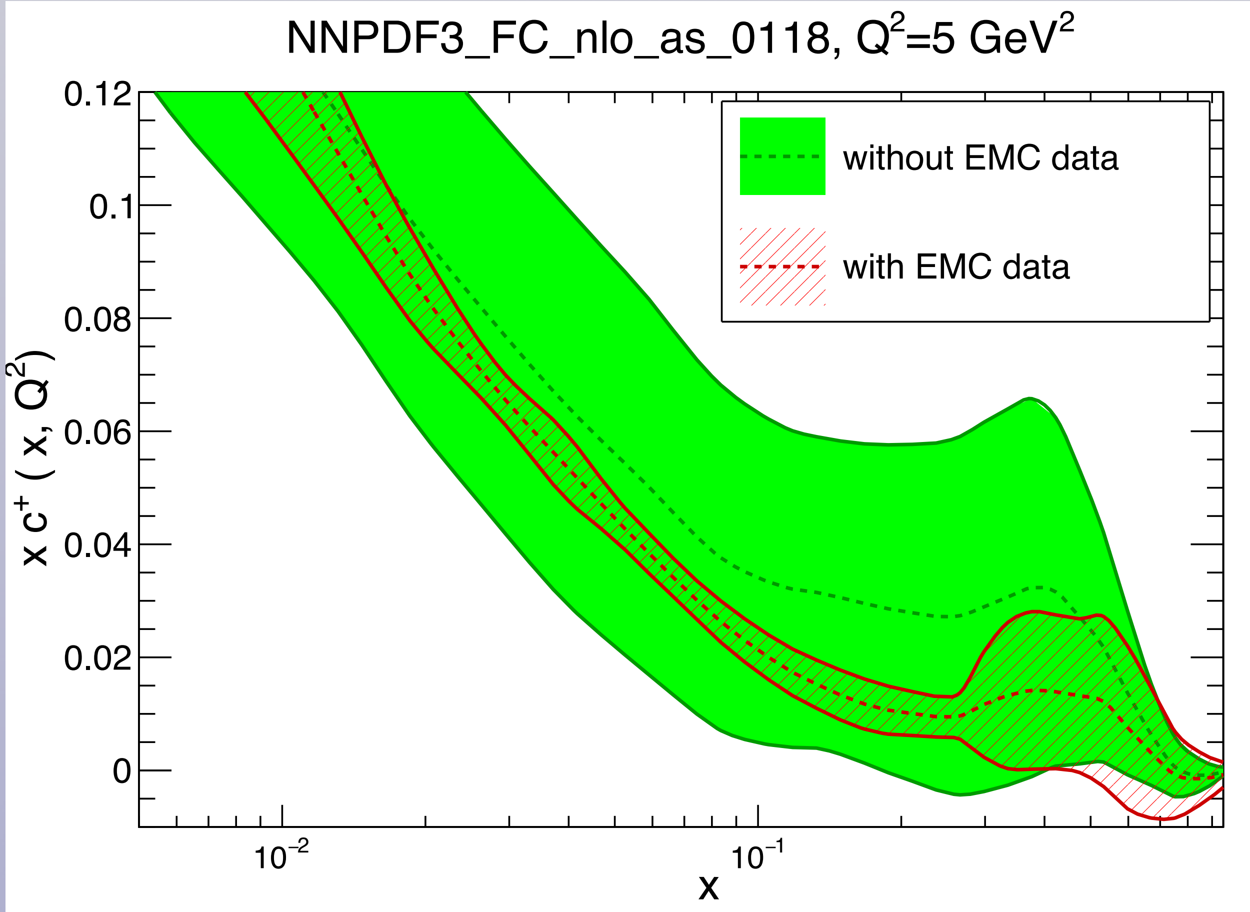
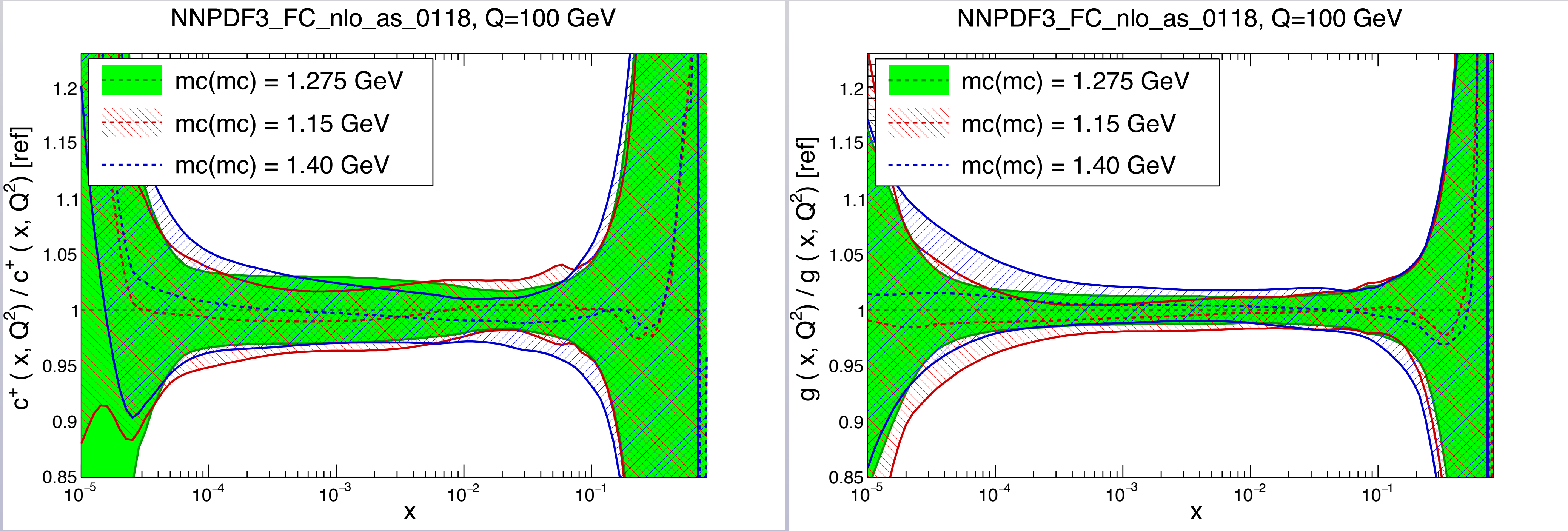


Stability with charm mass variations

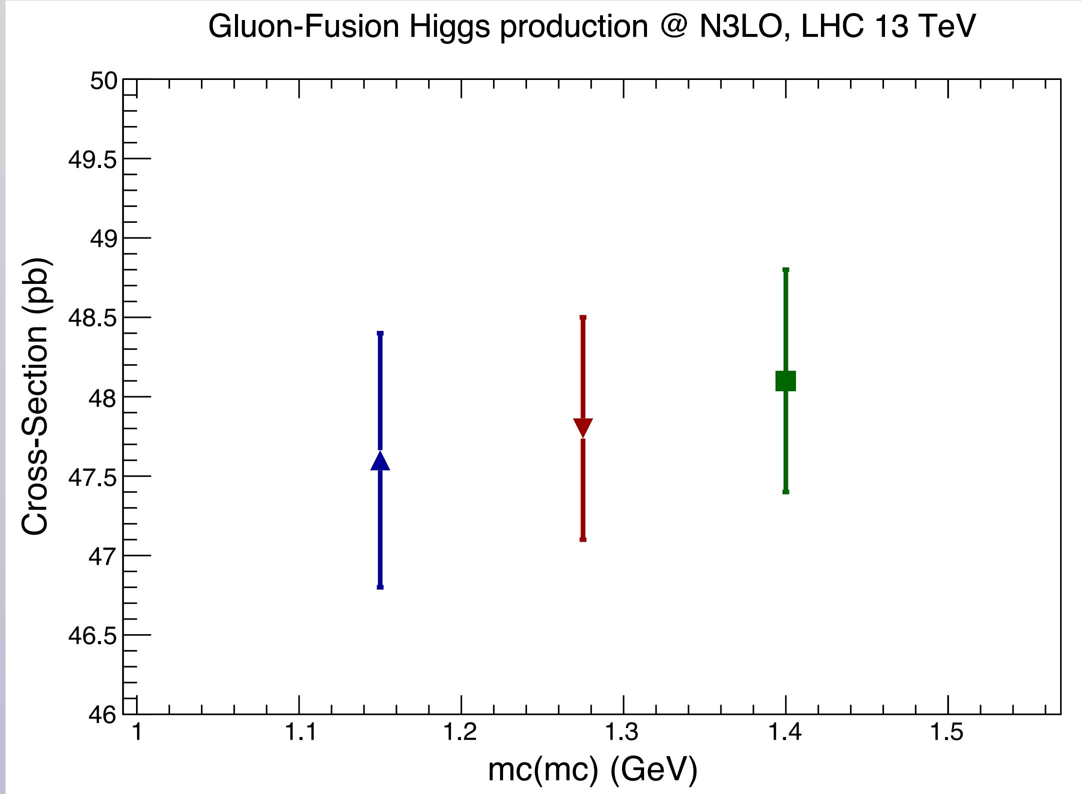
Charm

Gluon



- PDG 2016 average for running charm mass is **$m_c(m_c)$=(1.275 +- 0.025) GeV**
- Study stability of the IC fits by varying the charm mass by **+- 5 sigma** wrt the PDG value
- All PDFs, in particular **charm and gluon**, vary by **less than 1%** in the region relevant for precision phenomenology at the LHC

Stability with charm mass variations



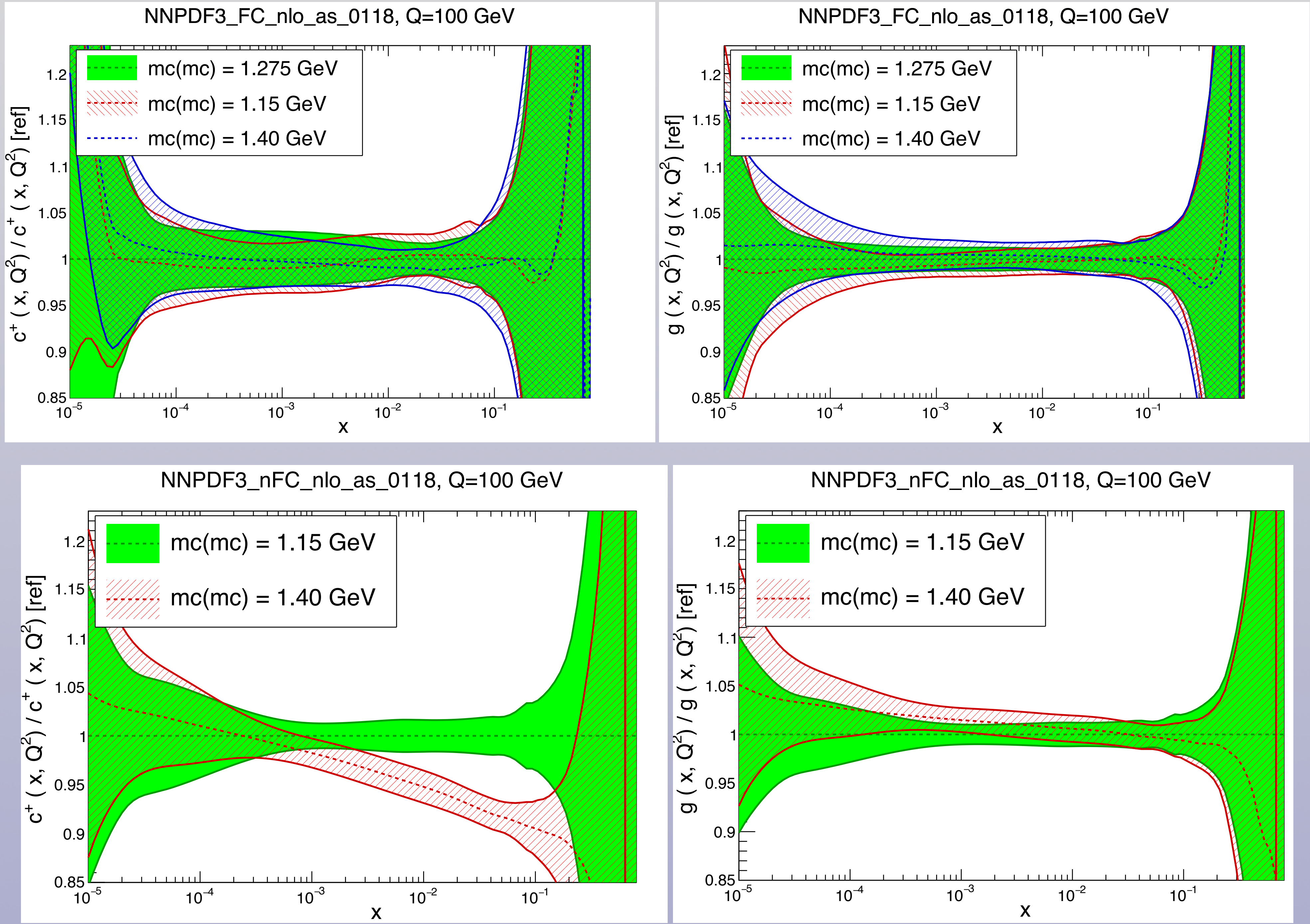
ggHiggs

mc(mc)	ggH N3LO
1.15 GeV	47.6 +- 0.8 pb
1.275 GeV	47.8 +- 0.7 pb
1.40 GeV	48.0 +- 0.7 pb

PDF uncertainties

- PDG 2016 average for running charm mass is **$m_c(m_c)$=(1.275 +- 0.025) GeV**
- Study stability of the IC fits by varying the charm mass by **+- 5 sigma** wrt the PDG value
- **N3LO Higgs cross-section** in gluon-fusion stable by less than **0.5%,** substantially smaller shift than the PDF uncertainty, in the case of fitted charm
- Calculation performed with **ggHiggs v3.0** and baseline theory settings

Stability with charm mass variations



Stability with charm mass variations

ggHiggs

mc(mc)	ggH N3LO (Fitted Charm)	ggH N3LO (baseline)
1.15 GeV	47.6 +- 0.8 pb	47.4 +- 0.7 pb
1.275 GeV	47.8 +- 0.7 pb	47.8 +- 0.7 pb
1.40 GeV	48.0 +- 0.7 pb	48.2 +- 0.8 pb

PDF uncertainties

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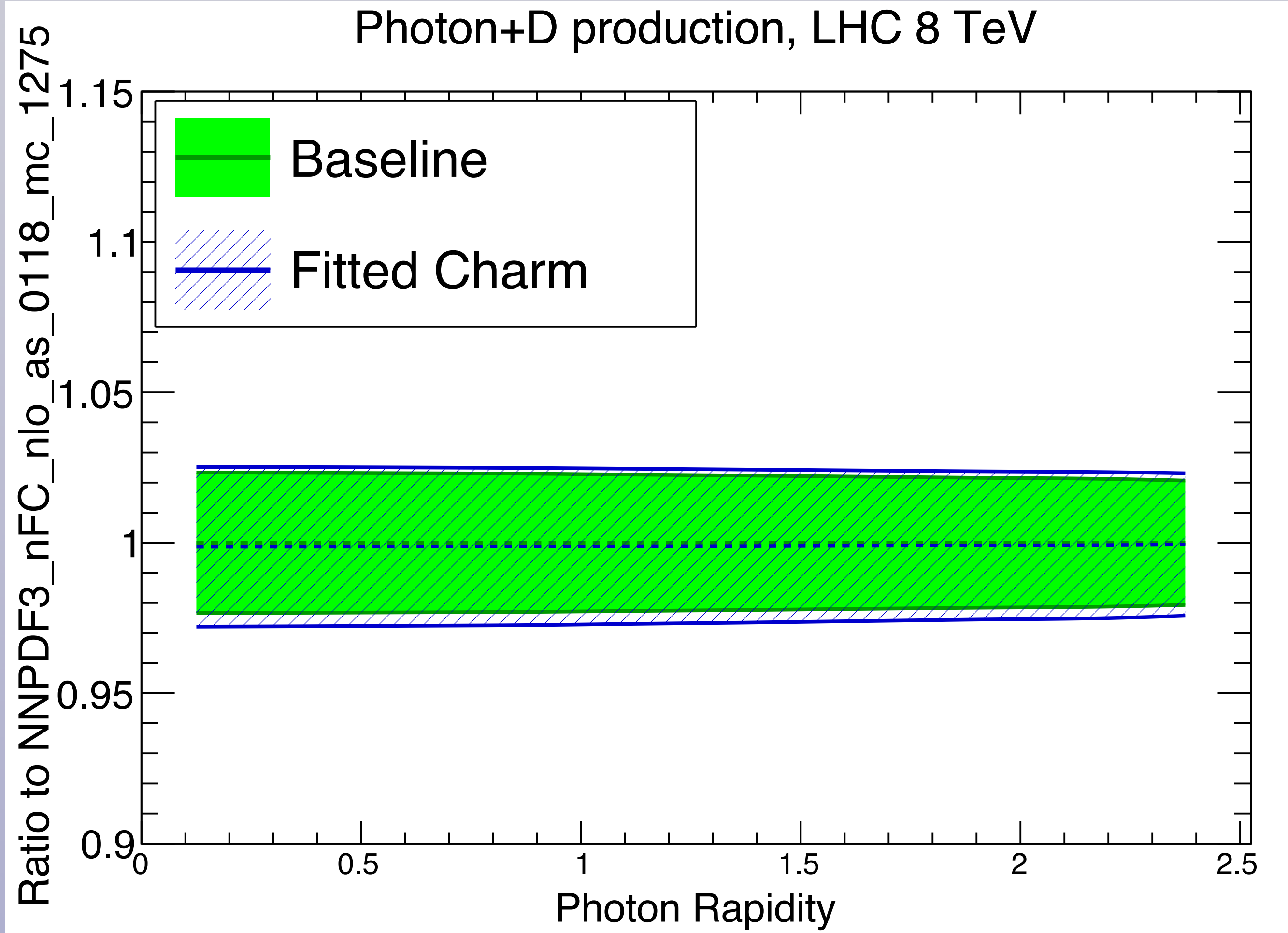
- **N3LO Higgs cross-section** in gluon-fusion stable by less than **0.5%,** substantially smaller shift than the PDF uncertainty, in the case of fitted charm
- Results with **perturbative charm more sensitive** to the choice of charm mass

Phenomenological implications @ LHC

- The differences between **fitted charm** and **perturbative charm** can be explored using a variety of LHC observables: **D meson production** at large pT, **Z+charm** at large rapidities etc

- Now quantifying this LHC sensitivity to intrinsic charm in the proton using **MCFM/APPLgrid** and **aMC@NLO/aMCfast**

- The **more forward and larger pT the measurement**, the more sensitive to the large-x charm PDF



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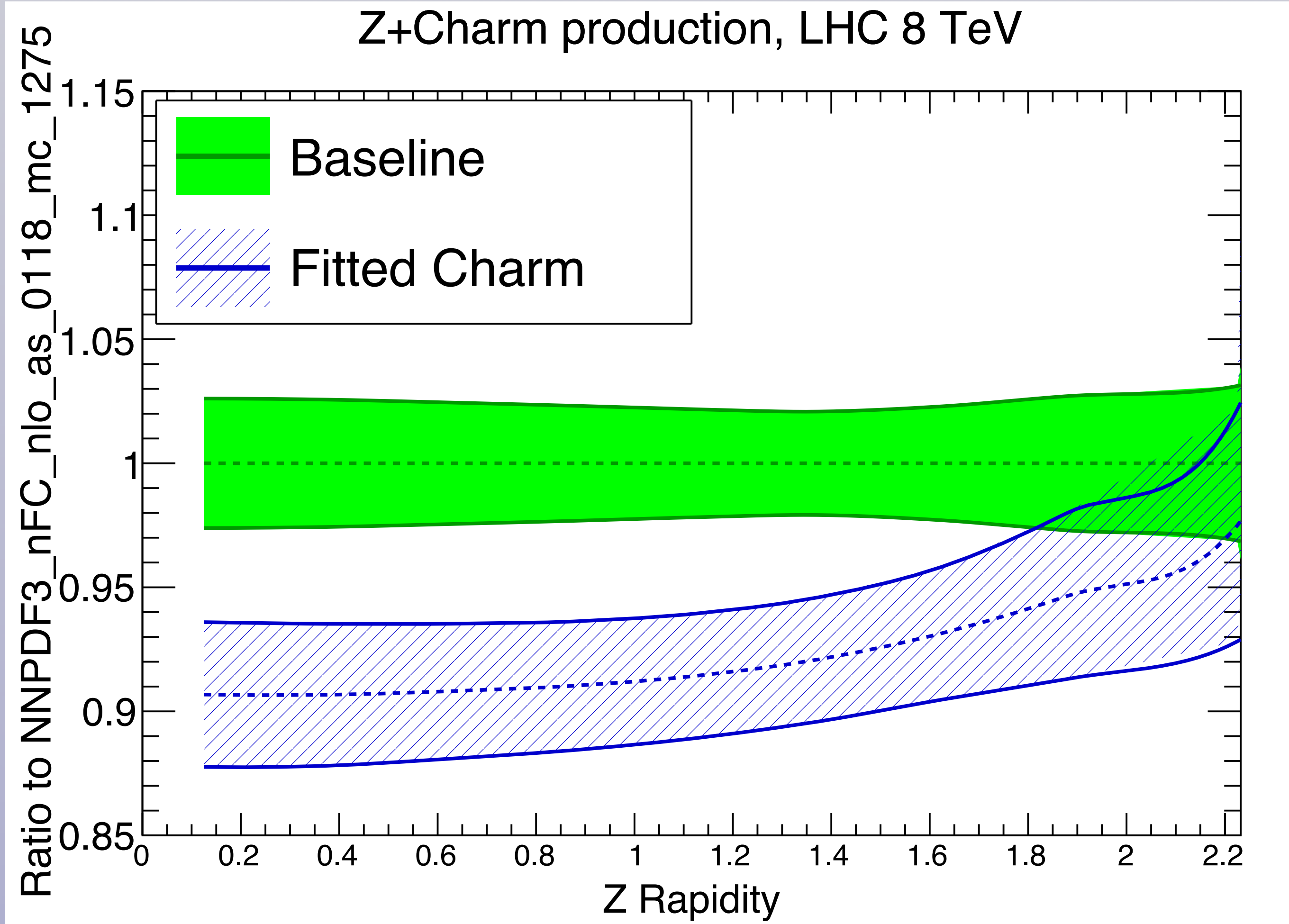

Summary and outlook

First determination of a fitted charm PDF in the NNPDF global analysis framework

- **Stability of PDFs and cross-sections** upon substantial variations of the charm mass
- Satisfactory description of the **EMC charm structure function data**
- At low scales, **charm can carry up to 0.75% of the total proton momentum** (at the 68%CL)
- Important phenomenological implications at the LHC for **charm-initiated processes**
- The NNPDF fitted charm allows detailed comparisons with n**on-perturbative QCD models**

Towards a resolution of the Intrinsic Charm conundrum: substantial fitted charm is allowed by the global QCD analysis (and required to fit EMC charm data), but **more data from the LHC needed to reach a robust unambiguous conclusion**

Delivery

First determination of a fitted charm PDF in the NNPDF global analysis framework

- **LHAPDF6 grids** will be made available from the **NNPDF HepForge website**
- Both fitted charm sets, and the corresponding baseline without fitted charm, for a range of (running) charm masses (pole mass fits also available)

NNPDF3_IC_nlo_as_0118_mc_1275
NNPDF3_IC_nlo_as_0118_mc_1400
NNPDF3_IC_nlo_as_0118_mc_1150

NNPDF3_nIC_nlo_as_0118_mc_1275
NNPDF3_nIC_nlo_as_0118_mc_1400
NNPDF3_nIC_nlo_as_0118_mc_1150

- These sets should **not** be used **in general-purpose applications**, only for s**tudies related to intrinsic/fitted/non-perturbative charm**, and the fitted charm PDFs should always be consistently compared with the corresponding baseline sets
- **Full-fledged fitted charm PDF sets** will be provided with the **new NNPDF3.1 global analysis**