The charm content of the proton

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Based on: arXiv 1510.00009, R. D. Ball, V. Bertone, M. Bonvini, S. Carrazza, S. Forte, P. G. Merrild, J. Rojo, LR
arXiv 1510.02491, R. D. Ball, M. Bonvini, LR
arXiv 1604.xxxxx, R. D. Ball, V. Bertone, M. Bonvini, S. Carrazza, S. Forte, A. Guffanti, N. P. Hartland, J. Rojo, LR

Charm in PDF fits

- Consistent heavy quark treatment is **essential** in modern PDF fits. PDF fits explore a wide range of scales Q^2. Two different cases:
  - $Q^2 \sim m_h^2$ **Heavy quark mass effects** are required for precision results
  - $Q^2 \gg m_h^2$ **Collinear logarithms** may become large -> **resummation** of collinear logs
- Use of **Variable Flavour Number Scheme** (**VFNS**): combinations of calculations valid close and far from threshold
- Assumption: heavy quark PDFs are **perturbatively** generated above the threshold

Light quarks: $m_l^2 \ll \Lambda^2_{\mathrm{QCD}}$
Heavy quarks: $m_h^2 \gg \Lambda^2_{\mathrm{QCD}}$

$m_c \sim 1.3$ GeV **The charm quark plays a special role**

- Possible presence of an ***intrinsic*** component in the charm PDF Brodsky et al.
- Significant dependence on the matching scale at low perturbative orders

Introduction of a fitted heavy quark PDF for the charm quark

NNPDF with fitted charm

Fit settings based on **NNPDF3.0** analysis

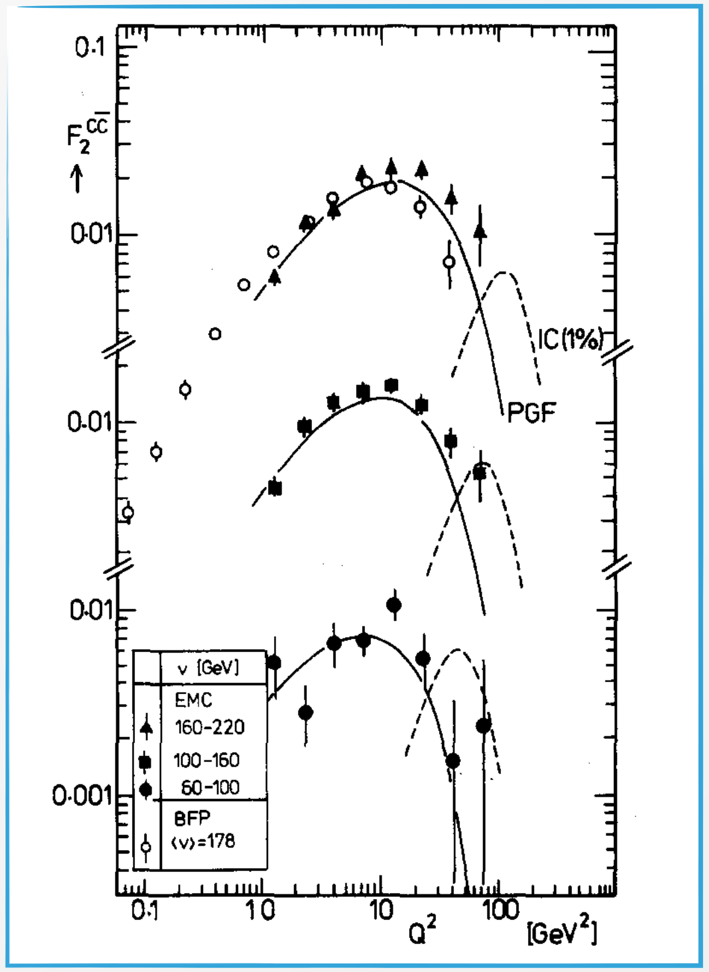
Some differences:

- **Dataset:**

  New **HERA legacy** data

  EMC charm structure functions →

  Stringent **cuts** on DY



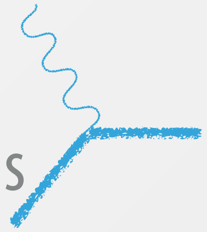
- **Methodology**

  PDF parameterization basis supplemented by c^+

  $$c^+(x, Q_0^2) = x^{-a}(1-x)^b \mathrm{NN}(x)$$ 37 free parameters

- **Theory**

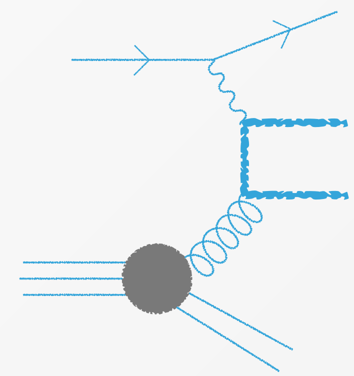
  FONLL scheme needs to be modified to include charm-initiated contributions



  Correction terms implemented in `APFEL` (benchmark with `massiveDISfunction`)

Most of this talk

3 and 4 flavour schemes



The quark mass acts as **IR regulator**

Renormalization: $\overline{\text{MS}}$ (light)
CWZ (heavy)

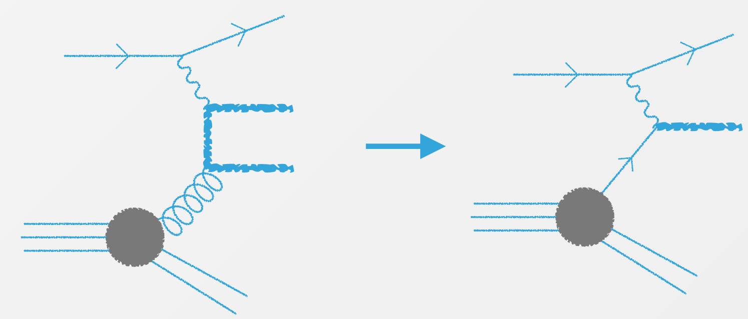
Two possible choices:

- **3 flavour scheme**: standard massless factorization for the light quarks and **massive collinear logs** in the coefficient functions

$$F^{(3)}(Q^2, m_c^2) = \sum_{i=g,q,\bar{q}} C_i^{(3)}\left(\frac{m_c^2}{Q^2}\right) \otimes f_i^{(3)}(Q^2) + \sum_{i=c,\bar{c}} C_i^{(3)}\left(\frac{m_c^2}{Q^2}\right) \otimes f_i^{(3)}$$

$$f_i^{(3)}(Q^2) = \sum_{j=g,q,\bar{q}} \Gamma_{ij}^{(3)}(Q^2, Q_0^2) \otimes f_i^{(3)}(Q_0^2)$$

- **4 flavour scheme**: collinear logarithms are **factorized** into the PDFs: introduction of an effective **heavy quark PDF**



$$F^{(4)}(Q^2, m_c^2) = \sum_{i=g,q,\bar{q},c,\bar{c}} \tilde{C}_i^{(4)}\left(\frac{m_c^2}{Q^2}\right) \otimes f_i^{(4)}(Q^2)$$

$$f_i^{(4)}(Q^2) = \sum_{j=g,q,\bar{q},c,\bar{c}} \Gamma_{ij}^{(4)}(Q^2, Q_0^2) \otimes f_i^{(4)}(Q_0^2)$$

Several formalisms which differ by terms which are subleading when charm is perturbatively generated: **ACOT**, **S-ACOT**, **FONLL**, **TR**, **BPT**

Massive collinear factorization: ACOT

- **ACOT** scheme based on a factorization scheme proved by Collins in 1998
- Coefficient functions obtained using standard massless collinear counter-terms for light partons and **massive collinear counter-terms** for heavy quarks

$$F^{(4)}(Q^2, m_c^2) = \sum_{i=g,q,\bar{q},c,\bar{c}} C_i^{(4)}\left(\frac{m_c^2}{Q^2}\right) \otimes f_i^{(4)}(Q^2)$$

Computation of the massive coefficient functions cumbersome ⟶ Fully available only at **NLO** hep-ph/9805233

S-ACOT simplification: *for hard-scattering processes with incoming heavy quarks or with internal on-shell cuts on a heavy quark line, the **heavy quark mass can be set to zero** for these pieces* hep-ph/0003035

$$C_i^{(4)}\left(\frac{m_c^2}{Q^2}\right) \longrightarrow C_i^{(4)}(0) \qquad i = c, \bar{c}$$

S-ACOT simplification exploits the factorization ambiguity present **when the heavy quarks evolve from gluons** $f_c(Q^2) \sim A_{cg}\left(\ln\frac{m_c^2}{Q^2}\right) f_g(Q^2)$ **no IC**

$$F(Q^2, m_c^2) \sim \left[C_c\left(\frac{m_c^2}{Q^2}\right) A_{cg}\left(\ln\frac{m_c^2}{Q^2}\right) + C_g\left(\frac{m_c^2}{Q^2}\right)\right] f_g(Q^2) + \mathcal{O}(\alpha_s^2)$$

No ambiguity to exploit if there is an intrinsic contribution in the heavy quark PDF

The FONLL scheme

Basic idea of the **FONLL** approach: combine **3FS** and **4FS** and subtract **double counting**

$$F_{\mathrm{FONLL}}(Q^2,m_c^2) = F^{(4)}(Q^2,0) + F^{(3)}(Q^2,m_c^2) - \mathrm{d.c.}$$

- No need to define new factorization schemes: only non-trivial part is the identification of the double counting
- The double counting is identified as the massless limit of the **3FS** result* (equivalently, fixed order expansion of **4FS**)

$$F^{(3,0)}(Q^2,m_c^2) = \sum_{i=g,q,\bar{q},c,\bar{c}} C_i^{(3,0)}\left(\frac{m_c^2}{Q^2}\right) \otimes f_i^{(3)}(Q^2)$$

*expressed in terms of the PDFs in the **4FS**

- The coefficient function $C_i^{(3,0)}$ contains only finite terms and collinear logarithms

Interpolation between the two limits

- $Q^2 \gg m_c^2$

$$F_{\mathrm{FONLL}}(Q^2,m_c^2) = F^{(4)}(Q^2,0) + \mathcal{O}(m_c^2/Q^2)$$

- $Q^2 \sim m_c^2$

$$F_{\mathrm{FONLL}}(Q^2,m_c^2) = F^{(3)}(Q^2,m_c^2) + \text{higher orders}$$

FONLL with and without IC

Final expression is written using **4FS** PDFs

- PDFs in the **3FS** must be expressed in terms of the PDFs in the **4FS**

$$f_j^{(4)} = \sum_{k=\text{light}} A_{jk}^{(4)}(m_c^2) \otimes f_k^{(3)} \quad + A_{jc}^{(4)}(m_c^2) \otimes f_c^{(3)}$$

Without IC there is freedom in the definition of the inverse

- Original **FONLL** (**FLNR**): 3FS PDFs in terms of **light flavours** only

$$f_j^{(3)} = \sum_{k=\text{light}} \left(\tilde{A}^{(4)}(m_c^2)\right)_{jk}^{-1} \otimes f_k^{(4)}, \qquad j = \text{light}$$

- New **FONLL** (**with IC**) need **all flavours**: no freedom

$$f_j^{(3)} = \sum_{k=\text{light+charm}} \left(A^{(4)}(m_c^2)\right)_{jk}^{-1} \otimes f_k^{(4)}, \qquad j = \text{light+charm}$$

Additional term to be added to FONLL (FLNR)

$$F_{\text{FONLL}}(Q^2, m_c^2) = F_{\text{FONLL}}(Q^2, m_c^2)\Big|_{\text{FLNR}} + \Delta F_{\text{FONLL}}(Q^2, m_c^2)$$

Intrinsic charm contribution is **subleading** without intrinsic charm

FONLL and ACOT

All-order equivalences between the two schemes arXiv 1510.02491

New **FONLL** (**with IC**) is equivalent to **ACOT**

- Consequence of the fact that there is no ambiguity
- Valid with and without IC

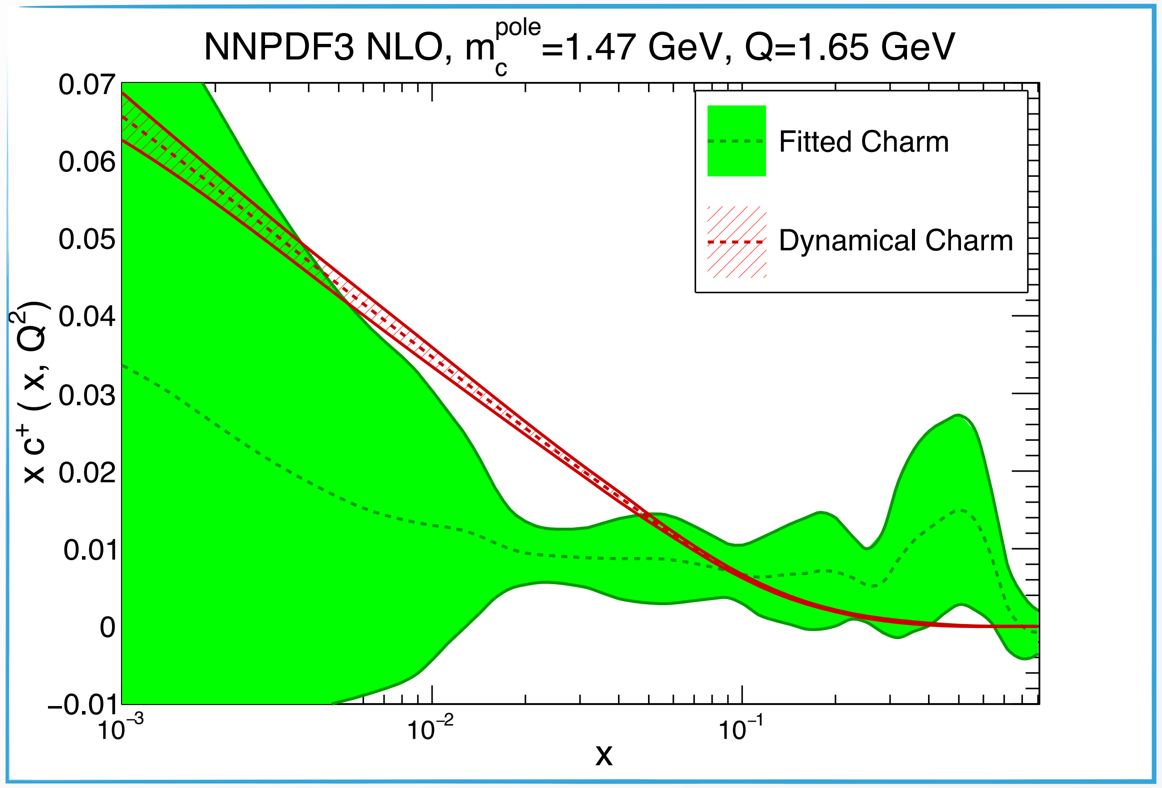
Original **FONLL** (**FLNR**) is equivalent to **S-ACOT**

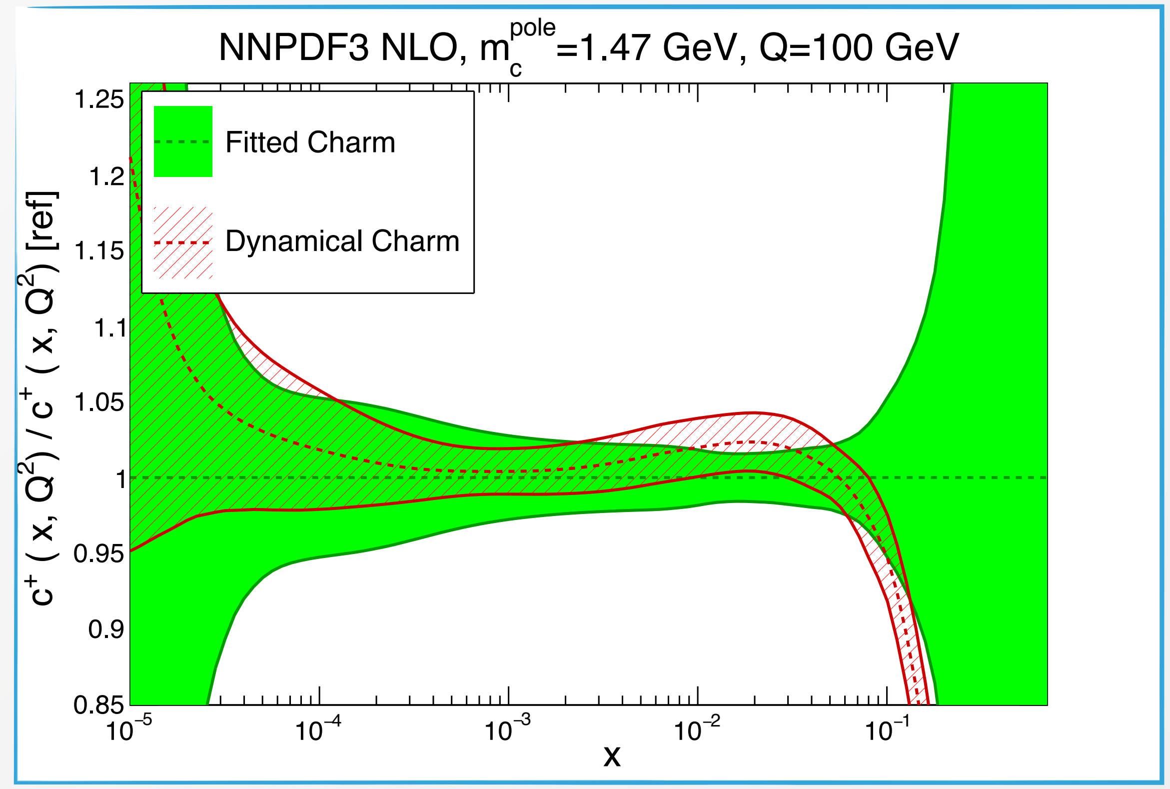
- Neglecting the mass dependence in the coefficient functions with incoming charm equivalent to the noIC result
- FONLL (FLNR) not possible with IC

Without IC the difference is subleading: simplified version (**FONLL** (**FLNR**) = **S-ACOT**) **convenient**

Calculations with fitted charm require new FONLL with IC (=ACOT)

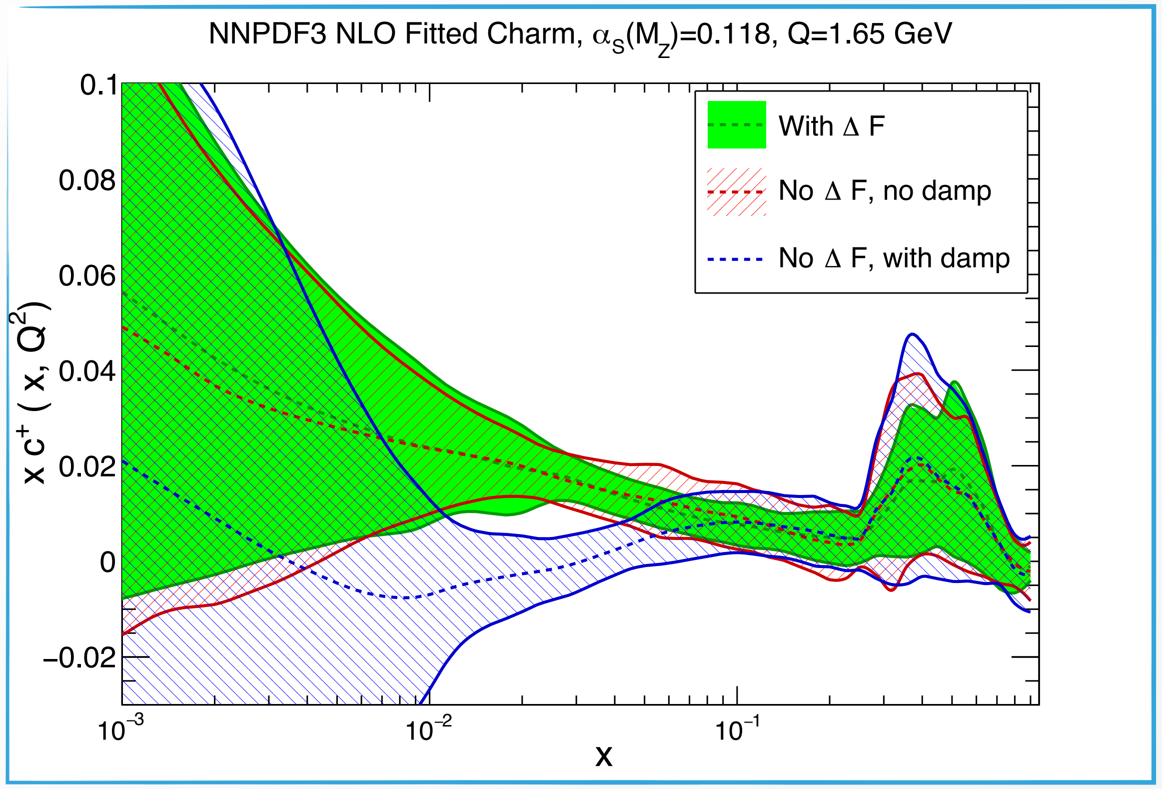
Fit results

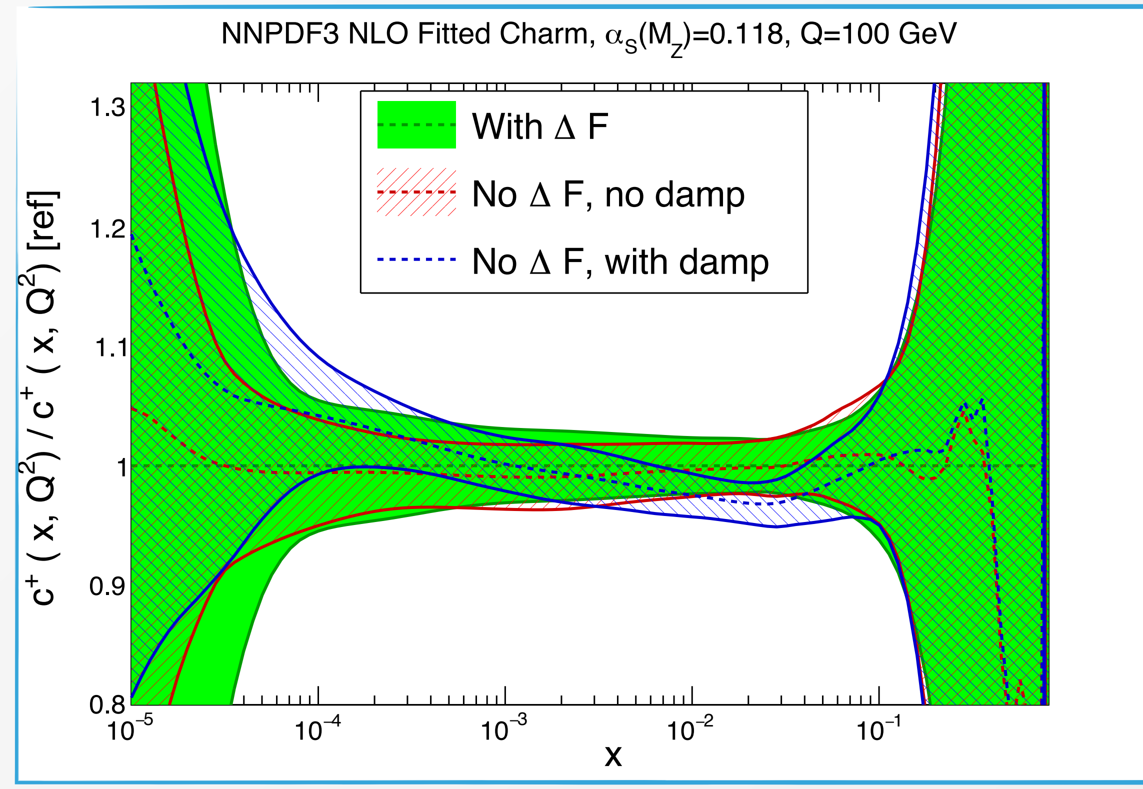


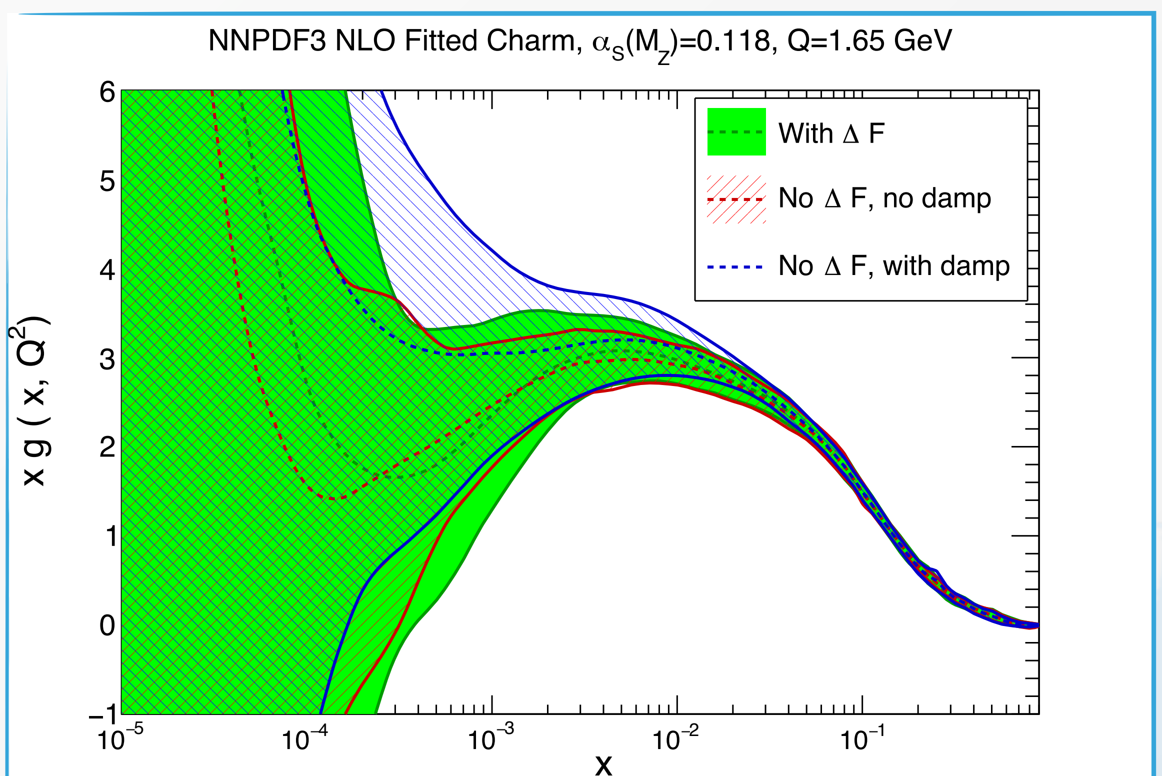


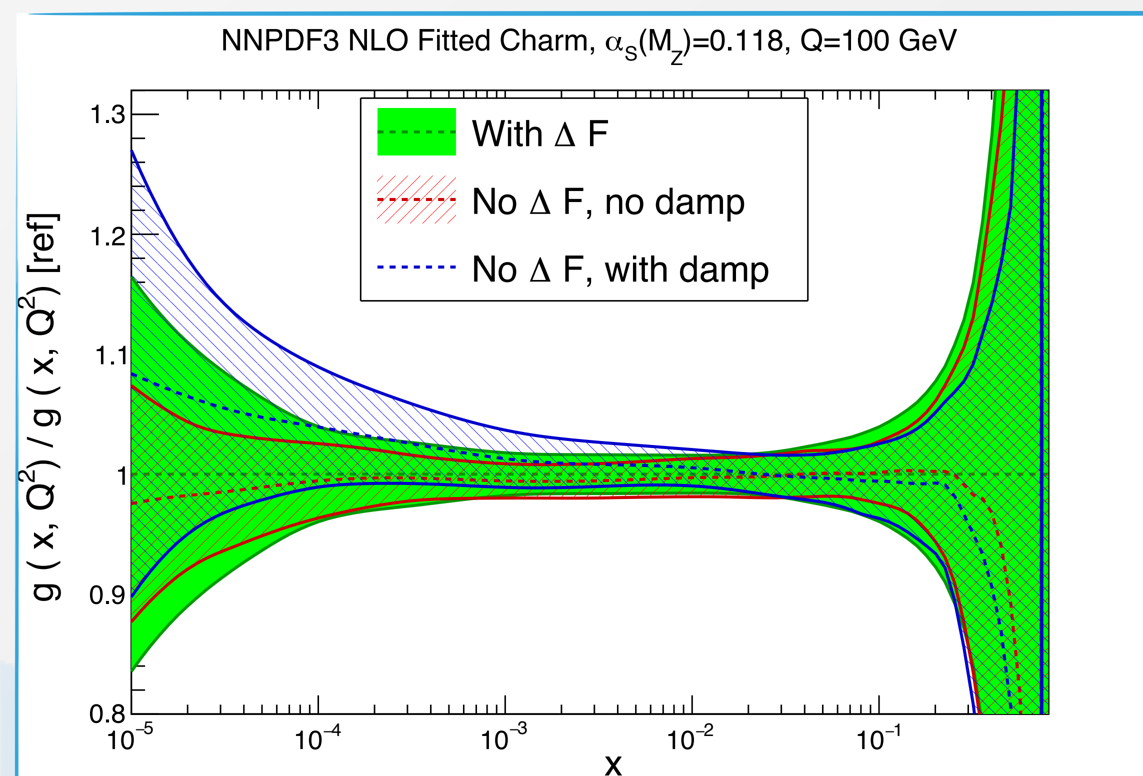
- Fitted Charm different from perturbatively generated charm at low scales
- Large uncertainties in the case of fitted charm, especially in the small-x region
- At large x fitted charm is larger than dynamical charm
- Agreement at 1σ level at Q=100 GeV
- Charm momentum can be as large as 1% within 68% C.L.

Scheme dependence

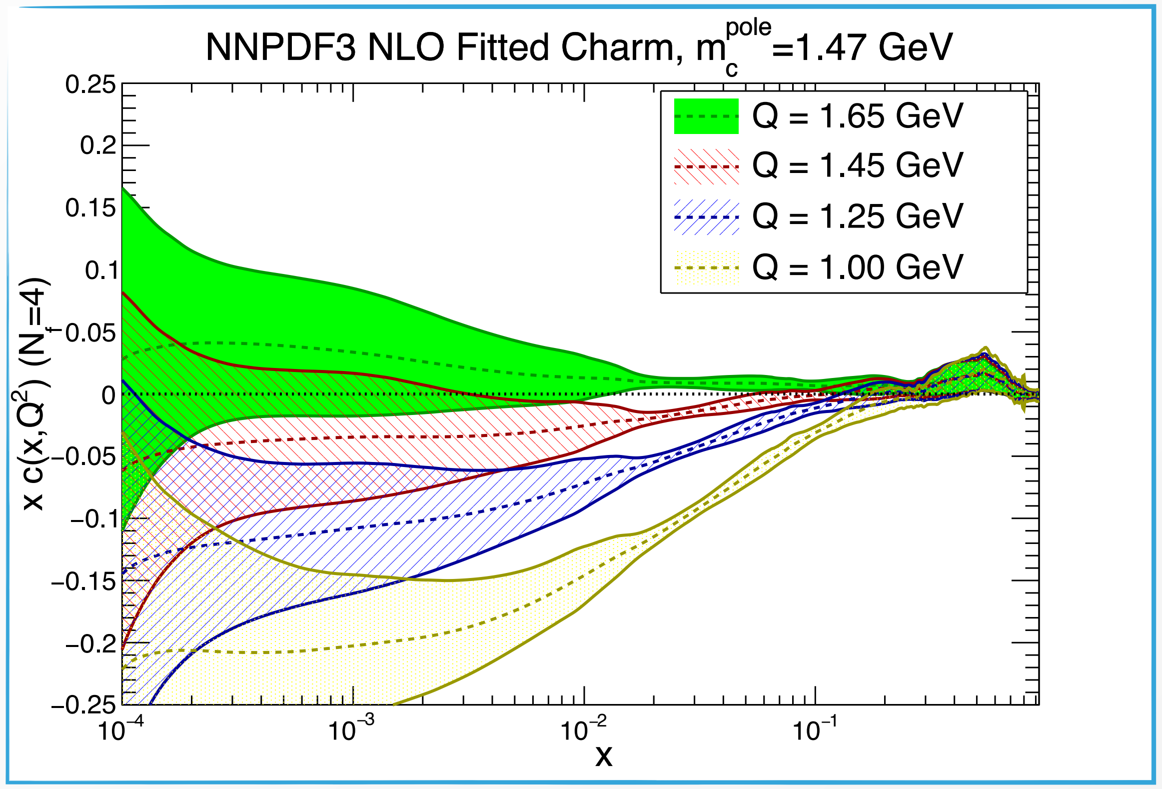


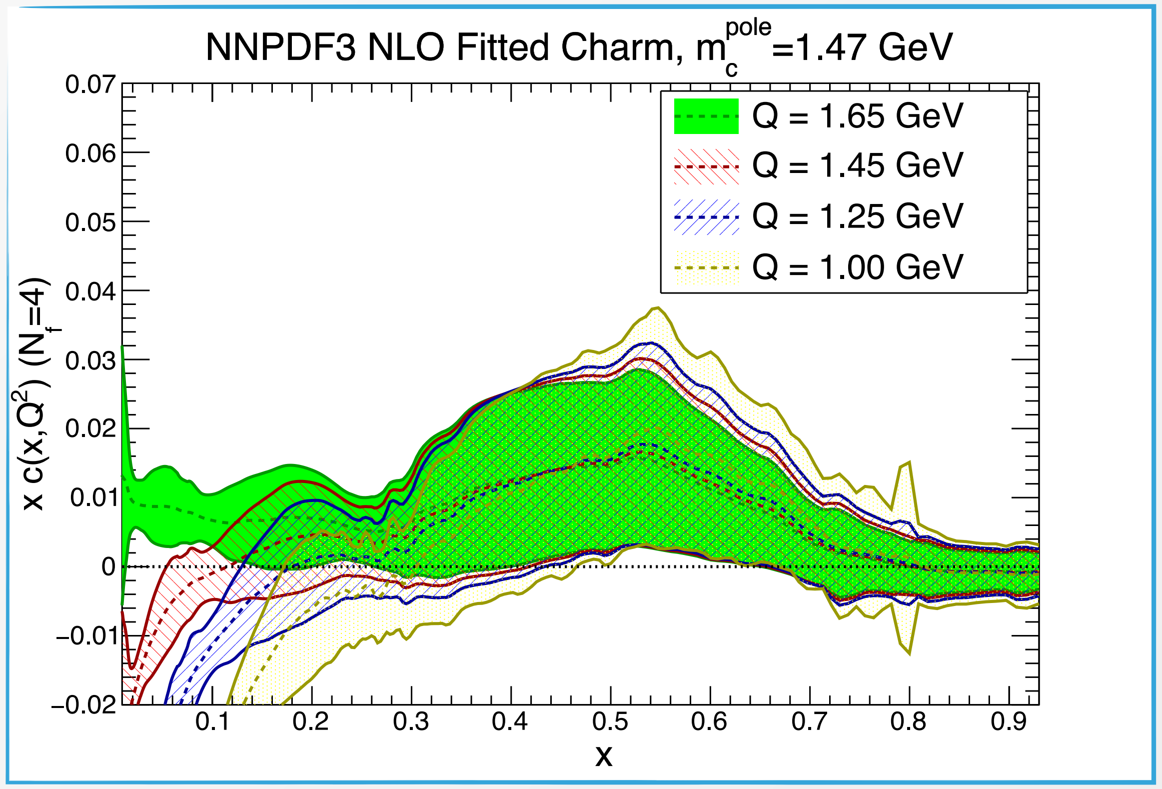






Intrinsic and non-perturbative contributions





- Hints of breakdown of the perturbative description at Q~1.5 GeV
- Large-x structure independent of the value of Q **Intrinsic charm?**

Summary

Determination of the charm content of the proton in the NNPDF approach

Extension of the FONLL scheme to include charm-initiated contributions

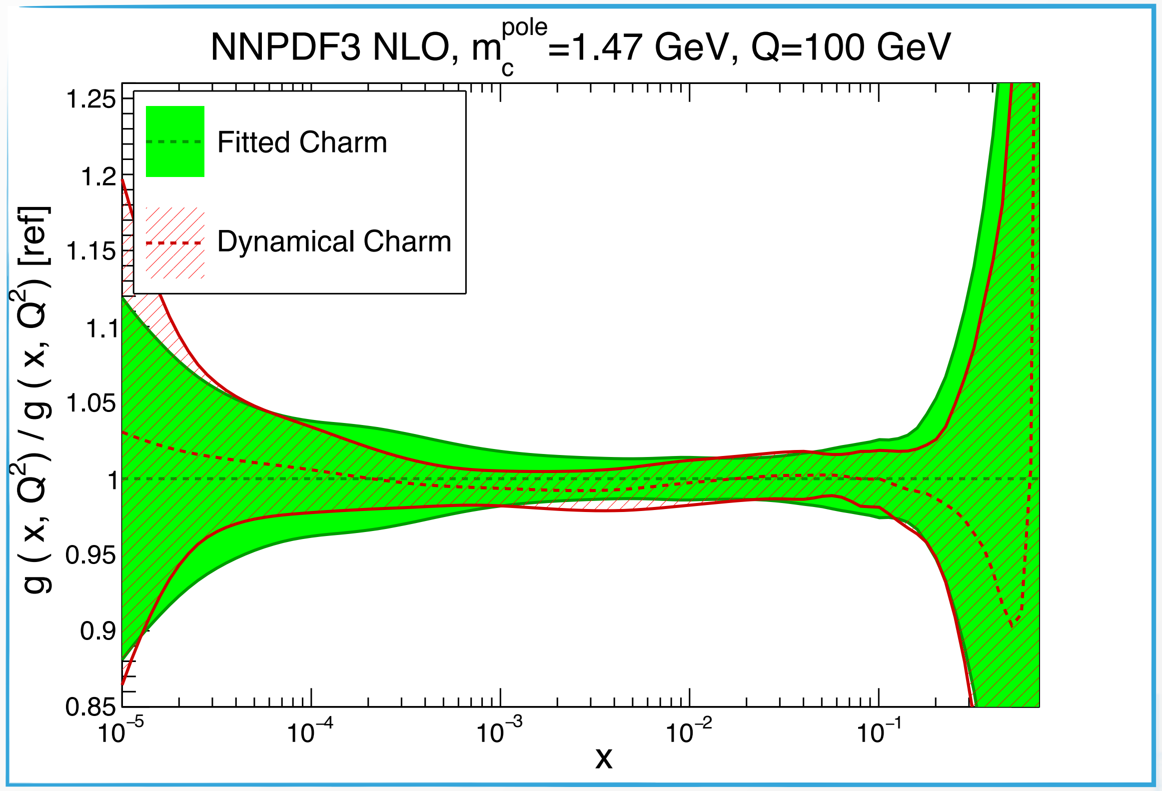
- new FONLL equivalent to ACOT
- FONLL (FLNR) equivalent to S-ACOT

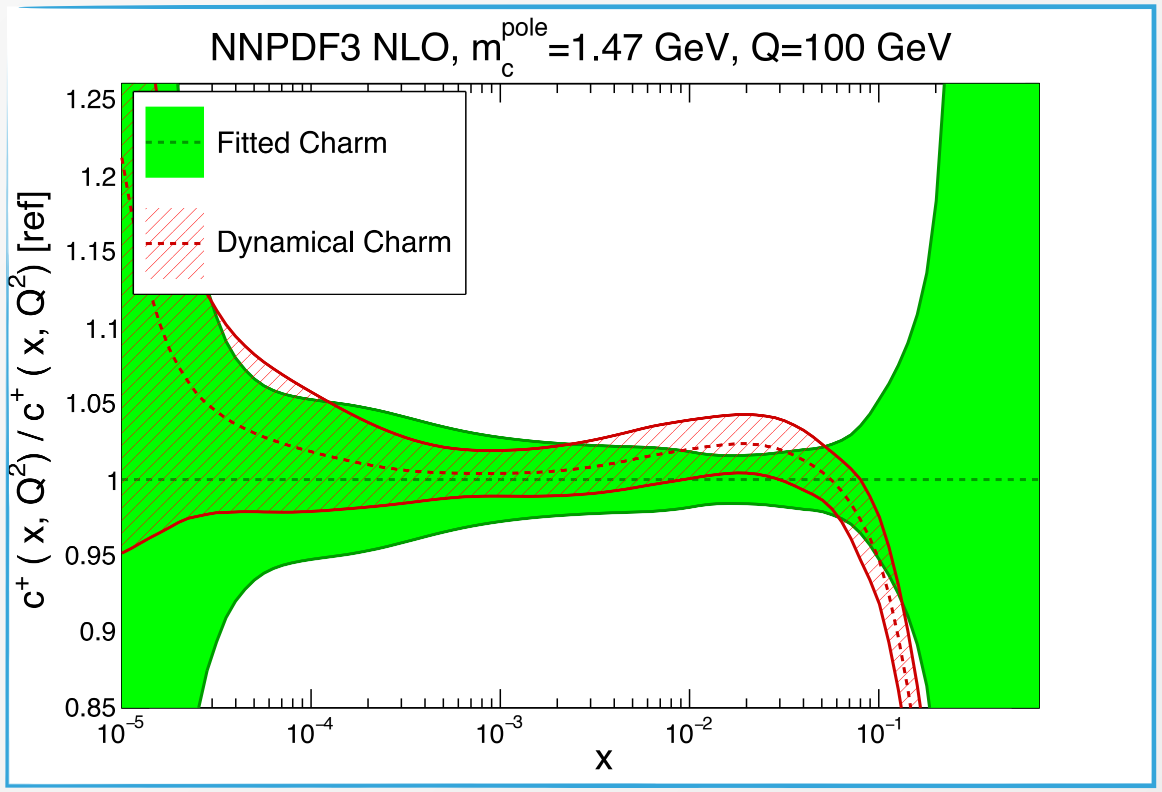
Larger uncertainties at low scales in the case of fitted charm

Limits of the perturbative description at $Q \sim m_c$

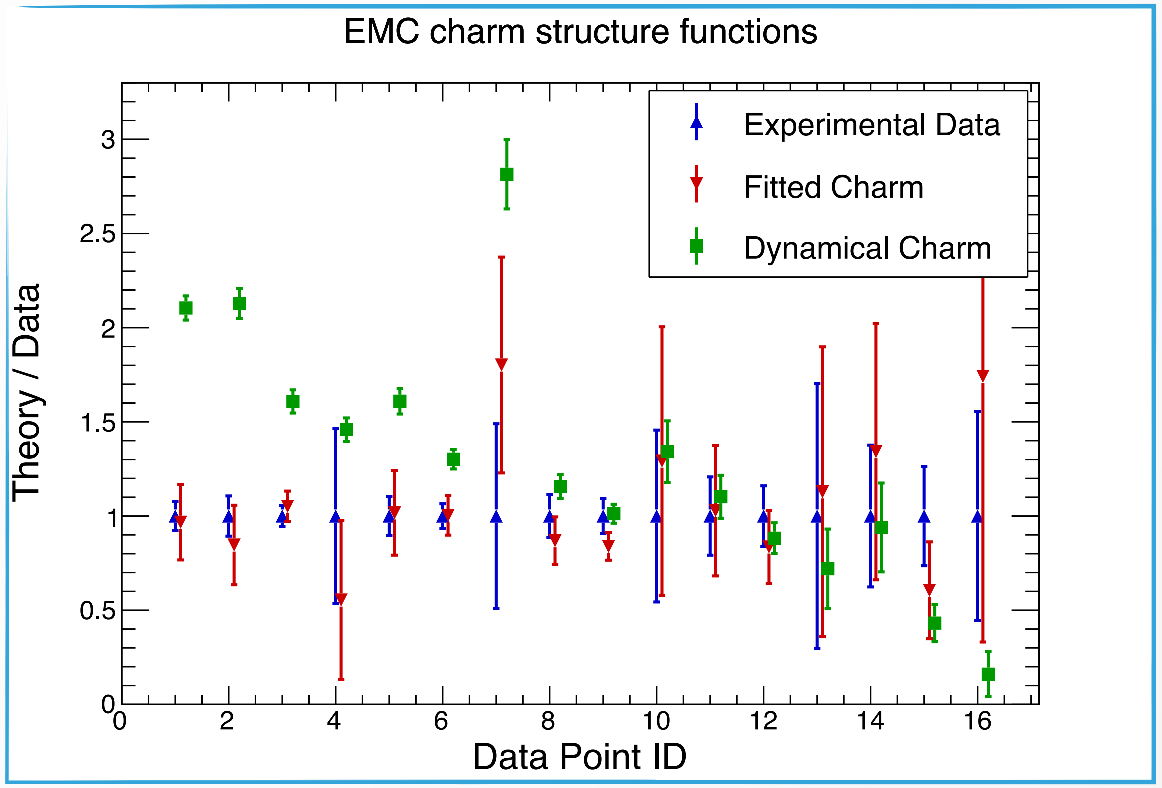
Back-up

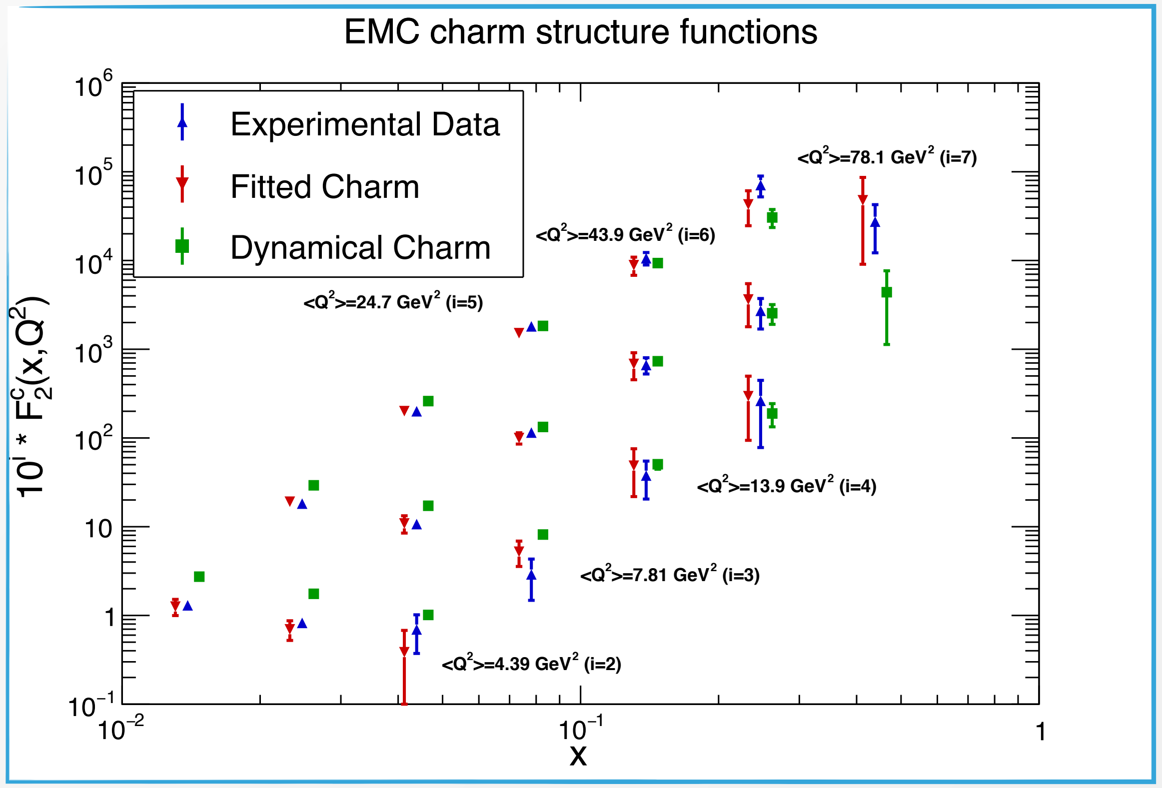
Fit results

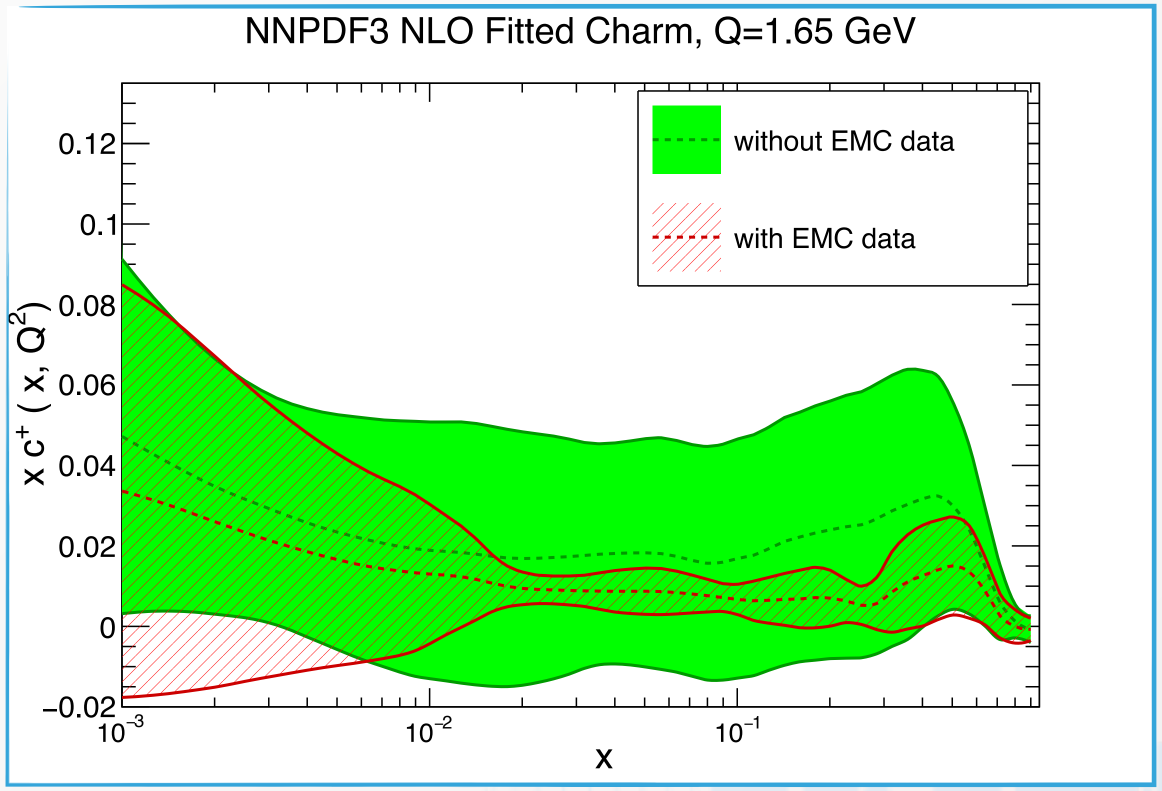

NNPDF3 NLO, m_c^{pole}=1.47 GeV, Q=100 GeV
Fitted Charm
Dynamical Charm
$g(x, Q^2) / g(x, Q^2)$ [ref]
x

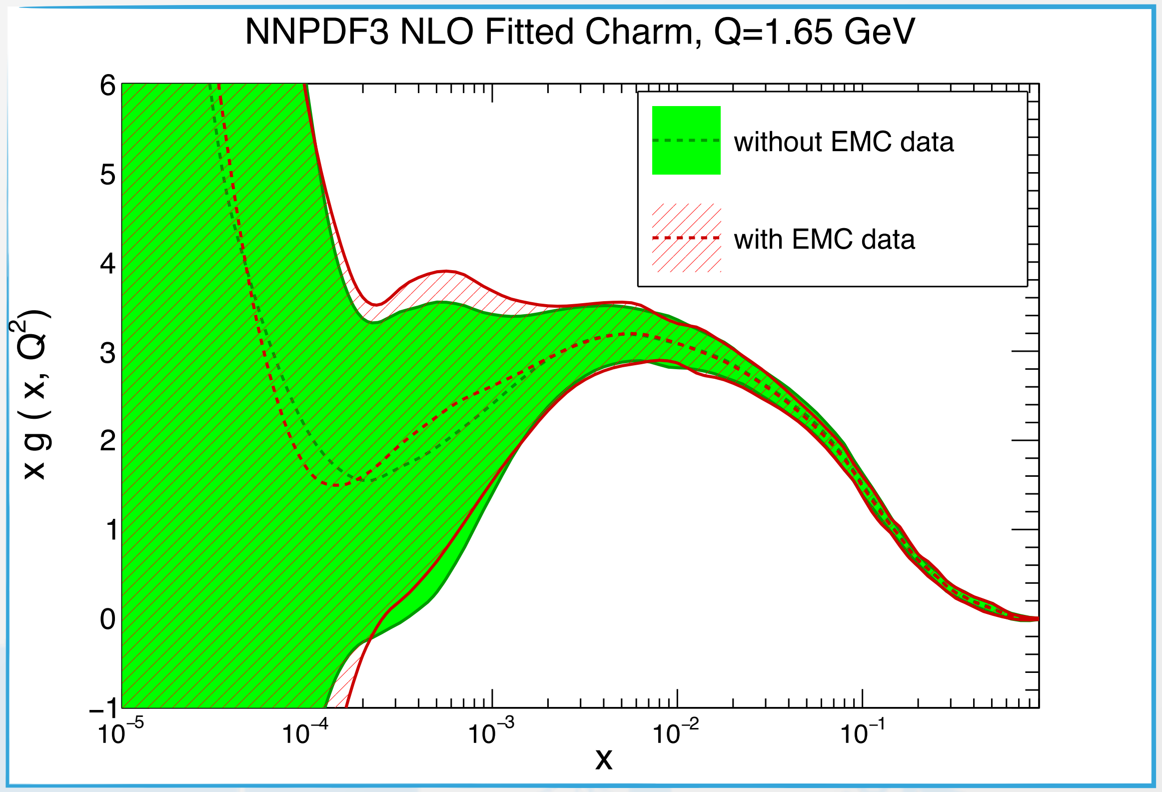

NNPDF3 NLO, m_c^{pole}=1.47 GeV, Q=100 GeV
Fitted Charm
Dynamical Charm
$c^+(x, Q^2) / c^+(x, Q^2)$ [ref]
x

Impact of EMC data

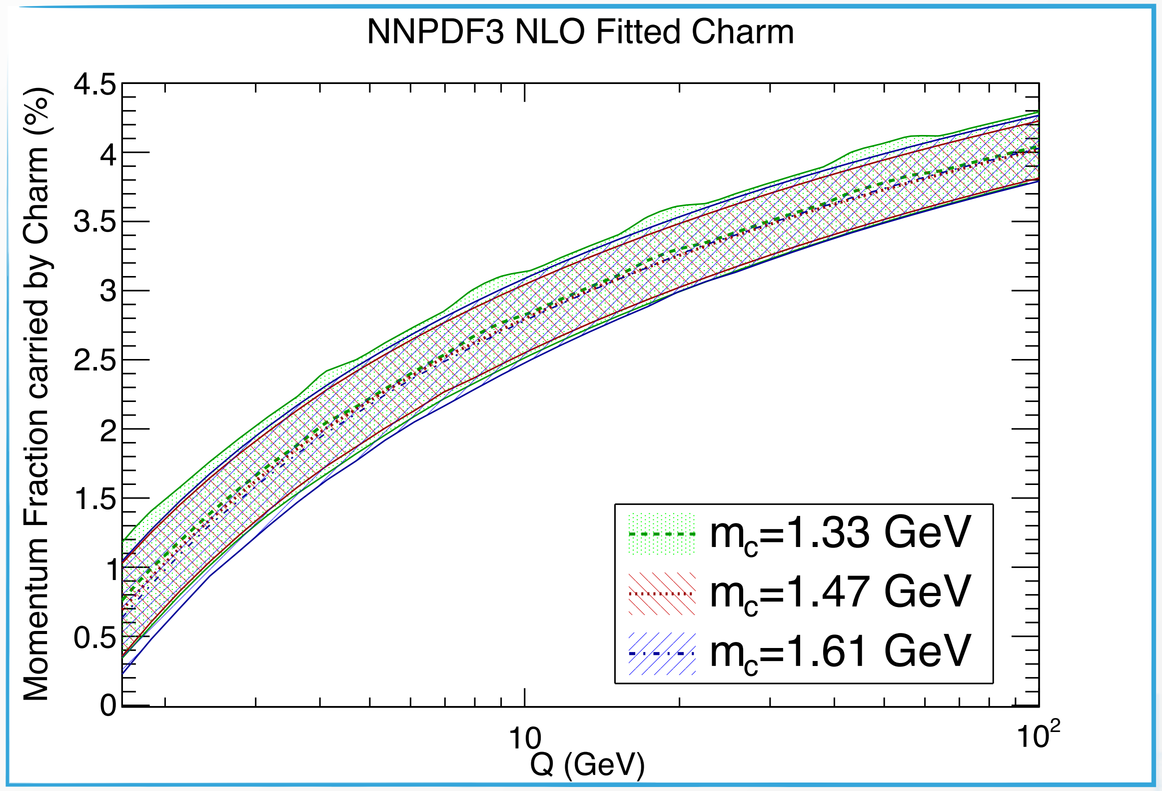


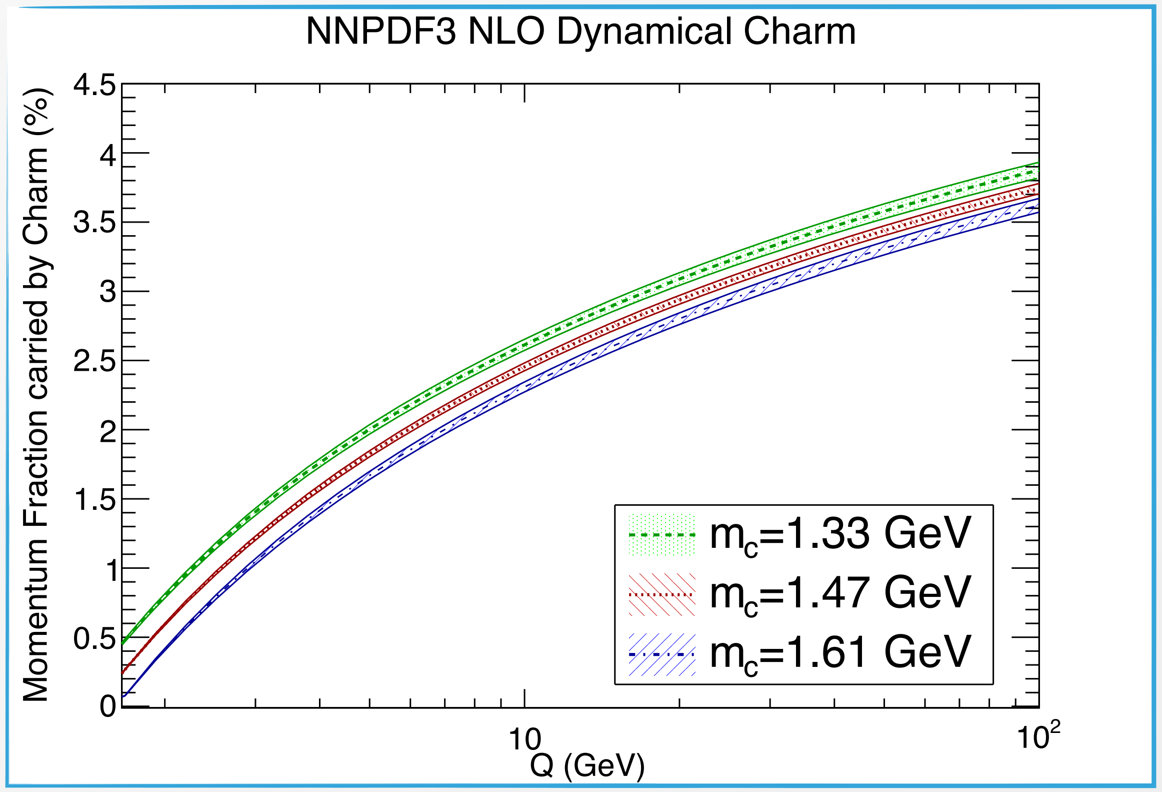




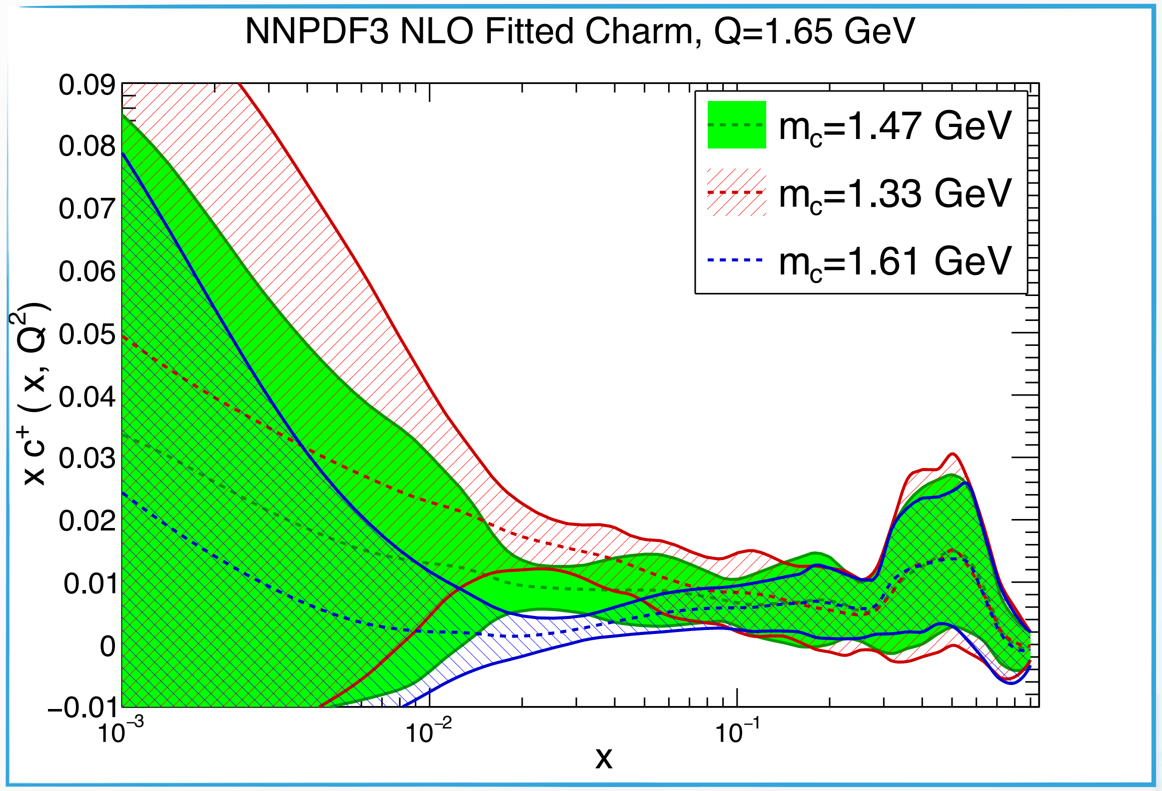


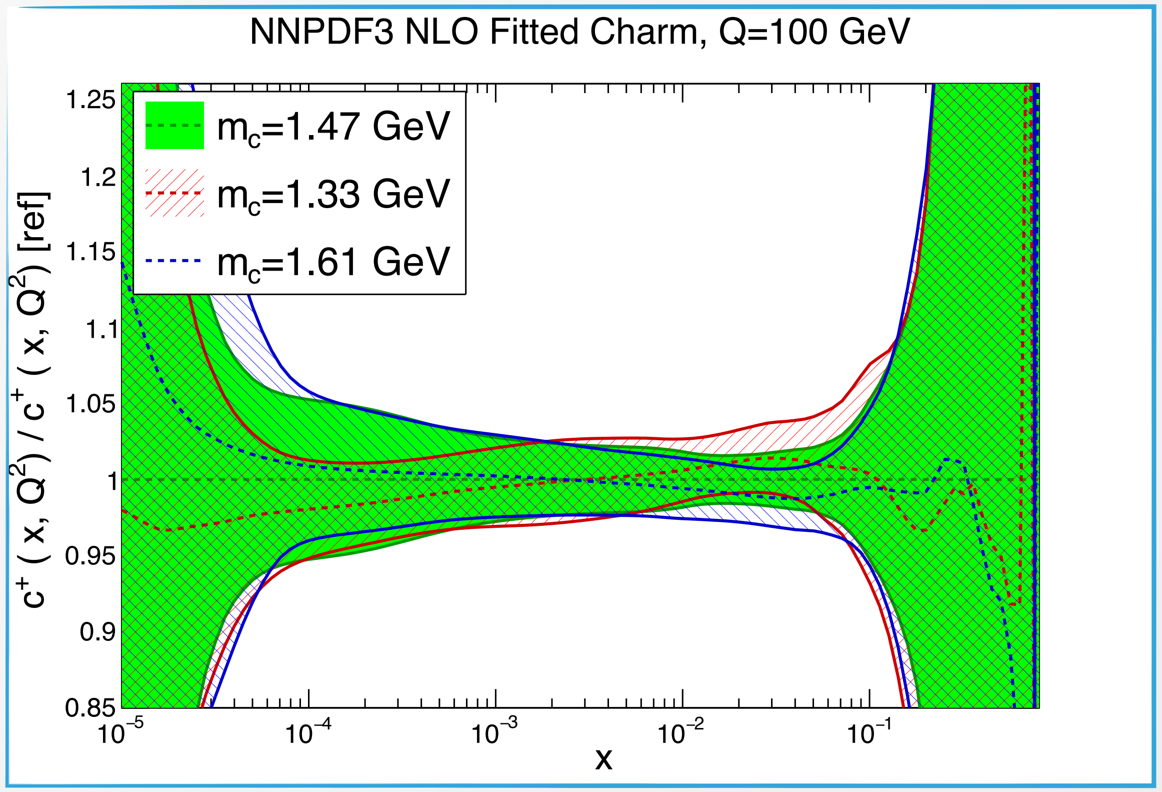
Fit results


NNPDF3 NLO Fitted Charm
Momentum Fraction carried by Charm (%)
Q (GeV)
m_c=1.33 GeV
m_c=1.47 GeV
m_c=1.61 GeV

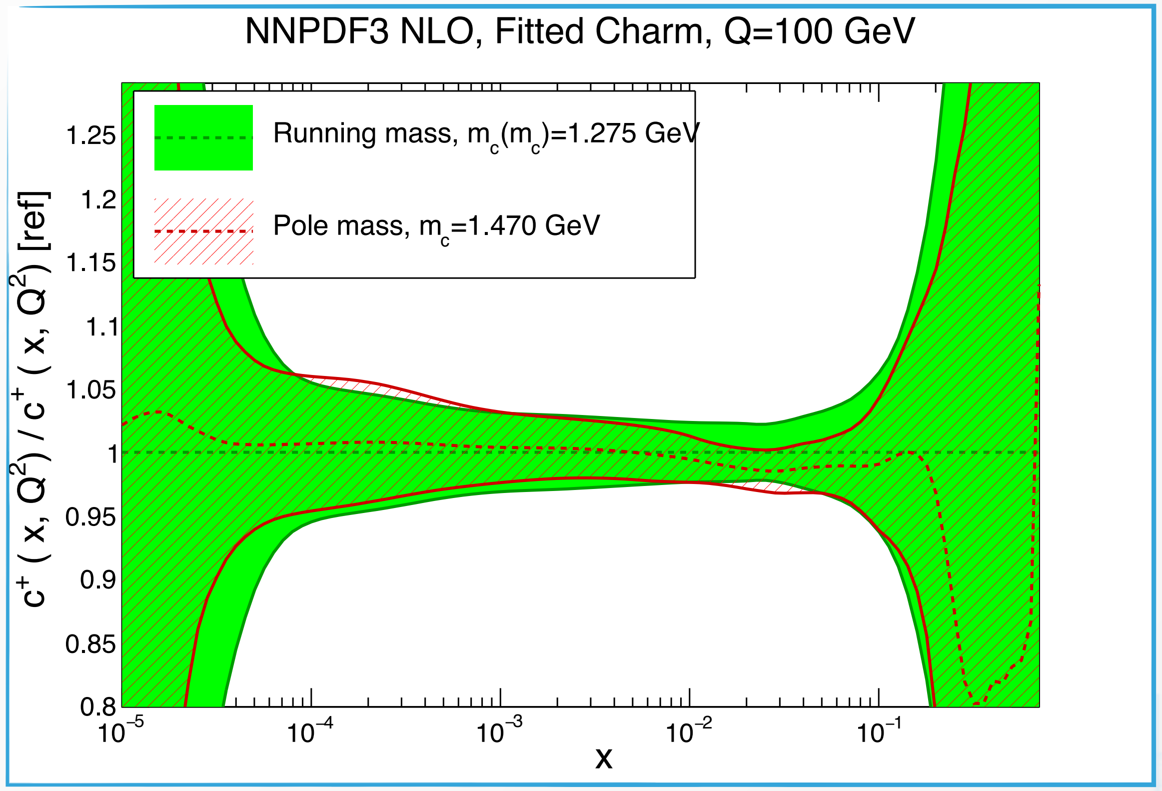

NNPDF3 NLO Dynamical Charm
Momentum Fraction carried by Charm (%)
Q (GeV)
m_c=1.33 GeV
m_c=1.47 GeV
m_c=1.61 GeV

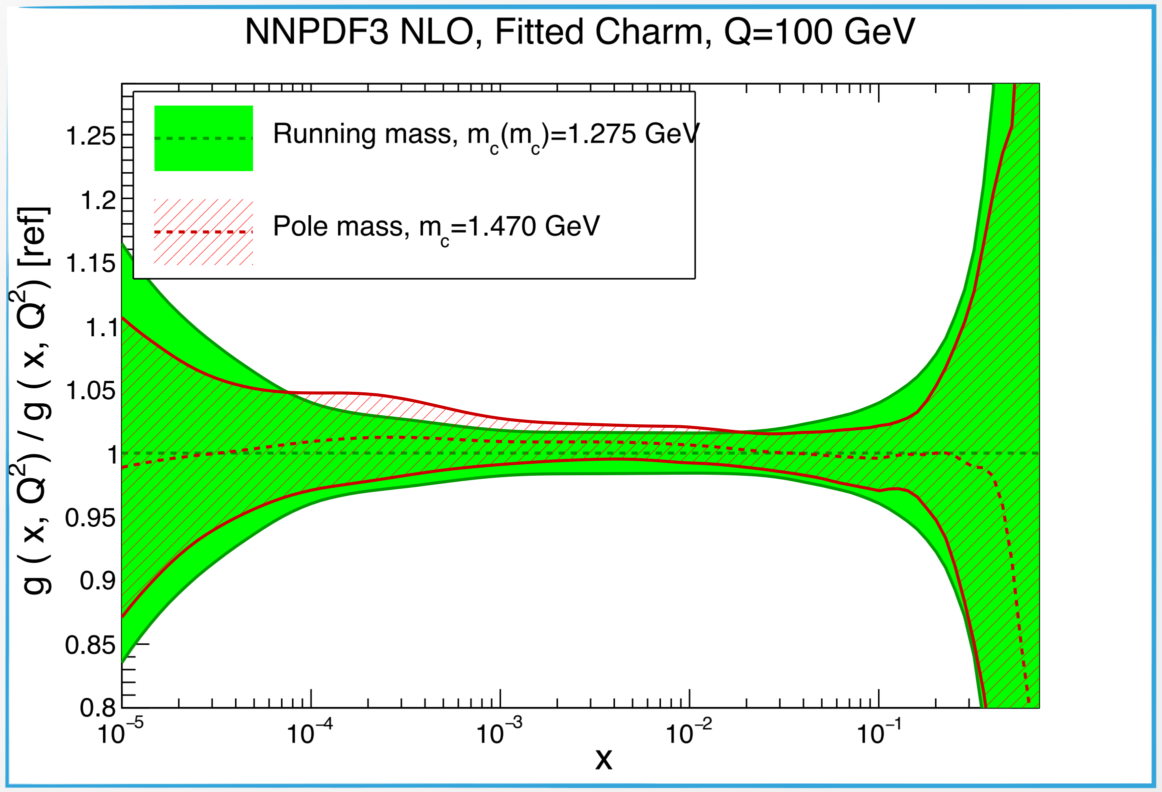
Fit results


NNPDF3 NLO Fitted Charm, Q=1.65 GeV
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−0.01
$x\, c^+(x, Q^2)$
10^{-3}
10^{-2}
10^{-1}
x
m_c=1.47 GeV
m_c=1.33 GeV
m_c=1.61 GeV

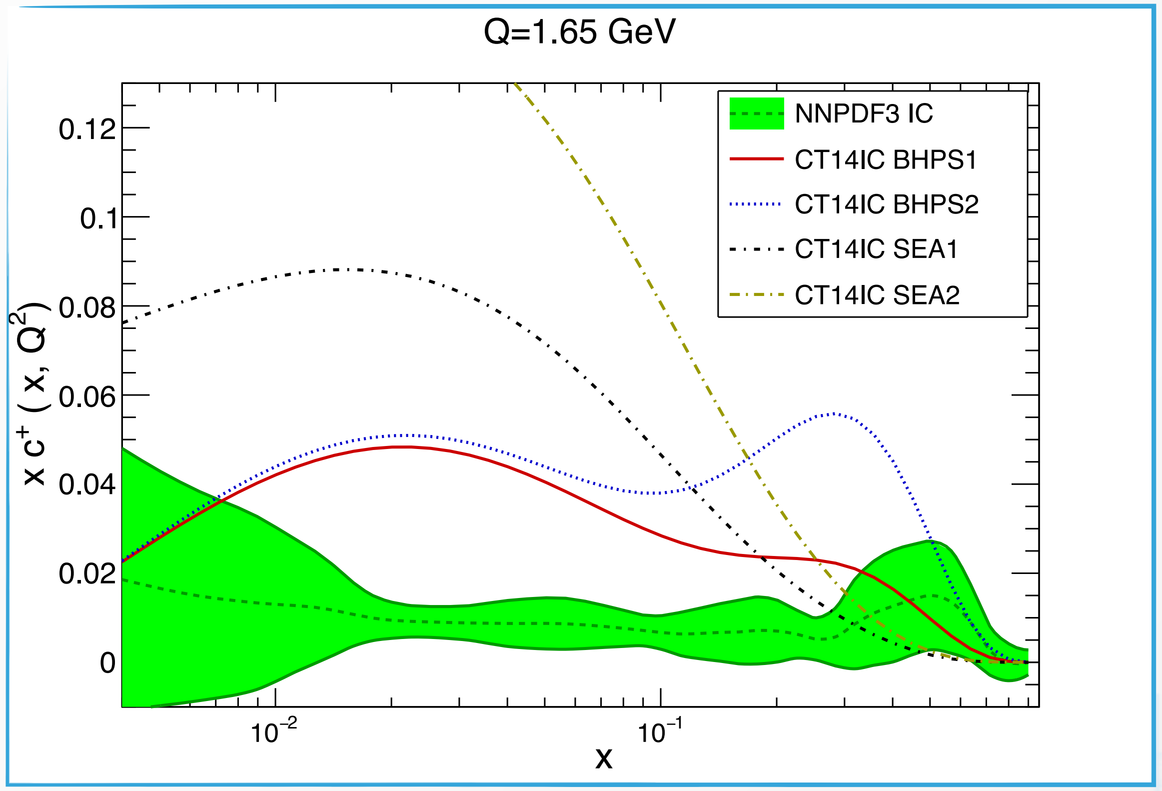

NNPDF3 NLO Fitted Charm, Q=100 GeV
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
$c^+(x, Q^2) / c^+(x, Q^2)$ [ref]
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x
m_c=1.47 GeV
m_c=1.33 GeV
m_c=1.61 GeV

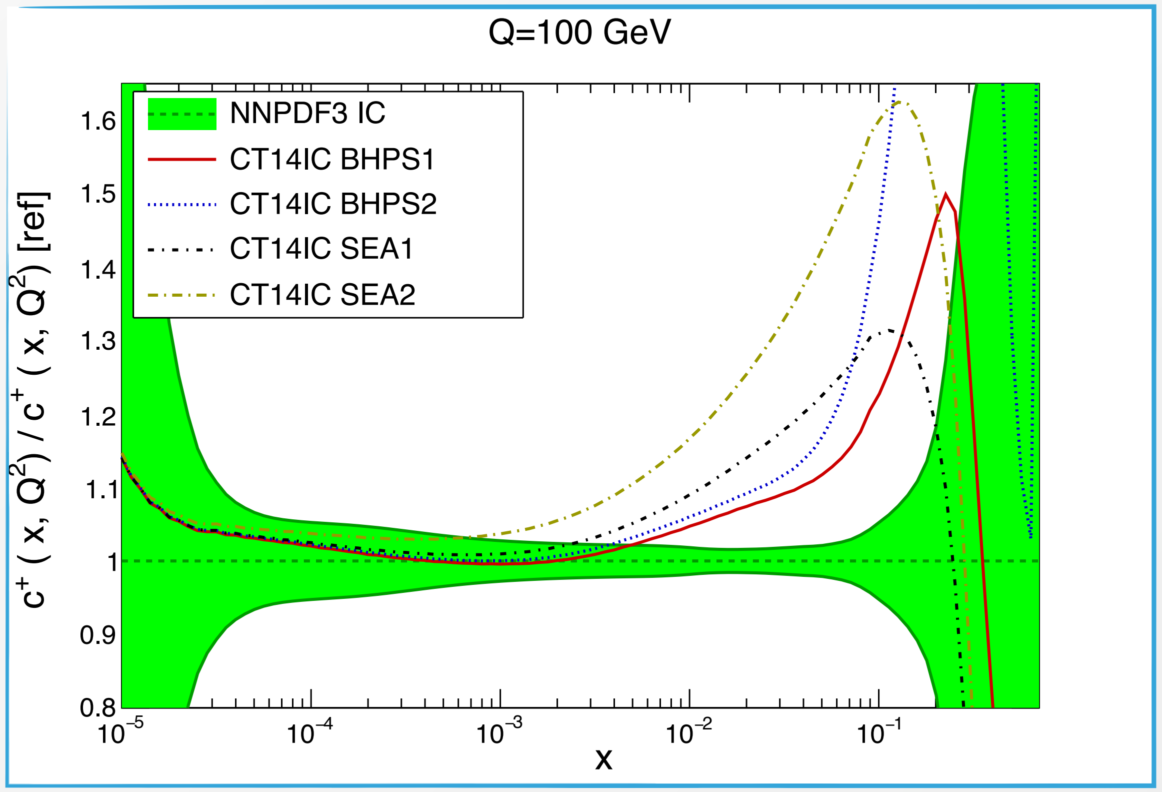
Fit results


NNPDF3 NLO, Fitted Charm, Q=100 GeV
Running mass, m_c(m_c)=1.275 GeV
Pole mass, m_c=1.470 GeV
c+ (x, Q2) / c+ (x, Q2) [ref]
x

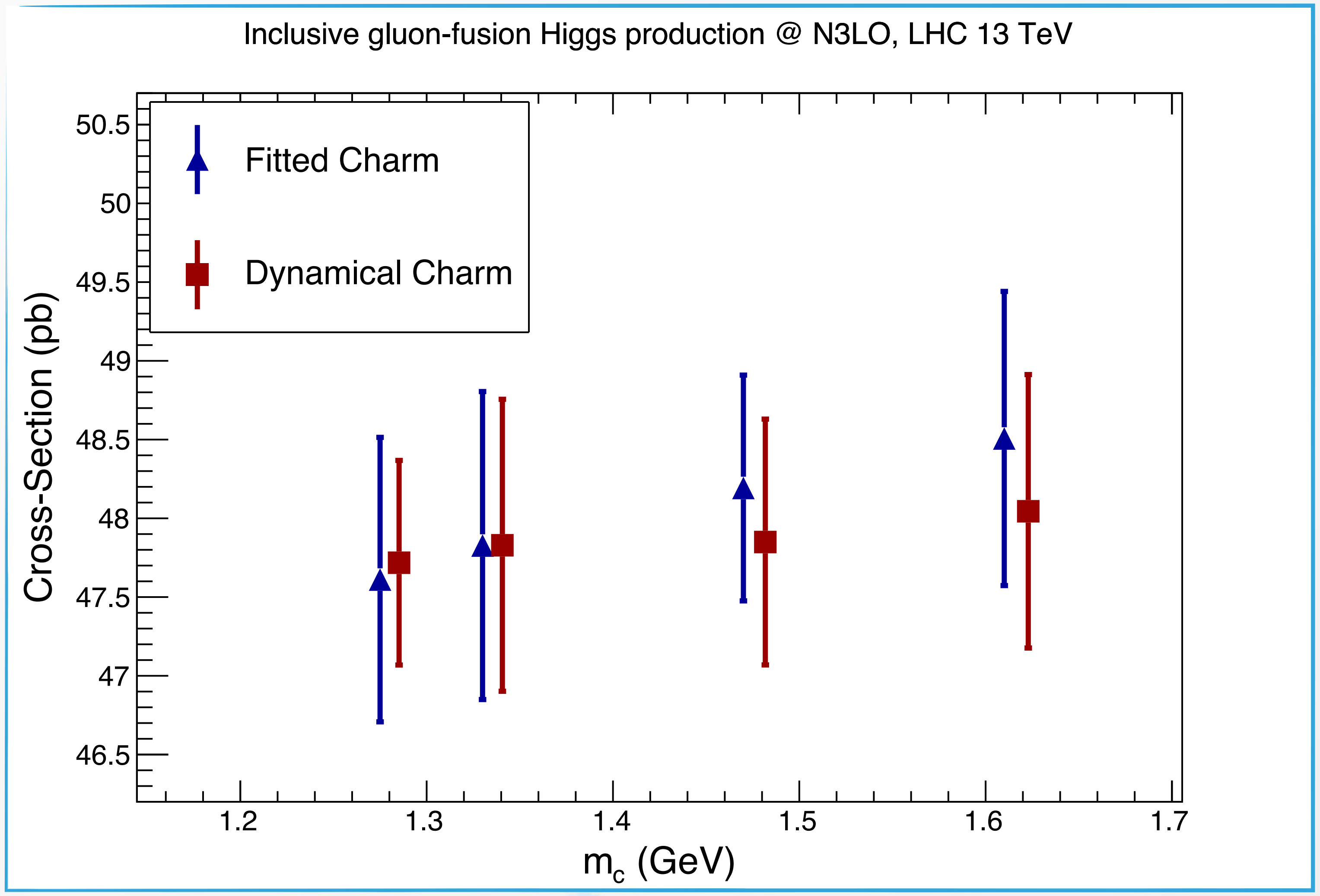

NNPDF3 NLO, Fitted Charm, Q=100 GeV
Running mass, m_c(m_c)=1.275 GeV
Pole mass, m_c=1.470 GeV
g (x, Q2) / g (x, Q2) [ref]
x

Fit results


Q=1.65 GeV
NNPDF3 IC
CT14IC BHPS1
CT14IC BHPS2
CT14IC SEA1
CT14IC SEA2
x c+ (x, Q2)
x


Q=100 GeV
NNPDF3 IC
CT14IC BHPS1
CT14IC BHPS2
CT14IC SEA1
CT14IC SEA2
c+ (x, Q2) / c+ (x, Q2) [ref]
x

Fit results


Inclusive gluon-fusion Higgs production @ N3LO, LHC 13 TeV
Fitted Charm
Dynamical Charm
Cross-Section (pb)
50.5
50
49.5
49
48.5
48
47.5
47
46.5
1.2
1.3
1.4
1.5
1.6
1.7
m_c (GeV)