APFEL
Recent Developments

arXiv:1310.1394

Valerio Bertone

University of Oxford

xFitter external meeting

February 18 - 20, 2016, Dubna

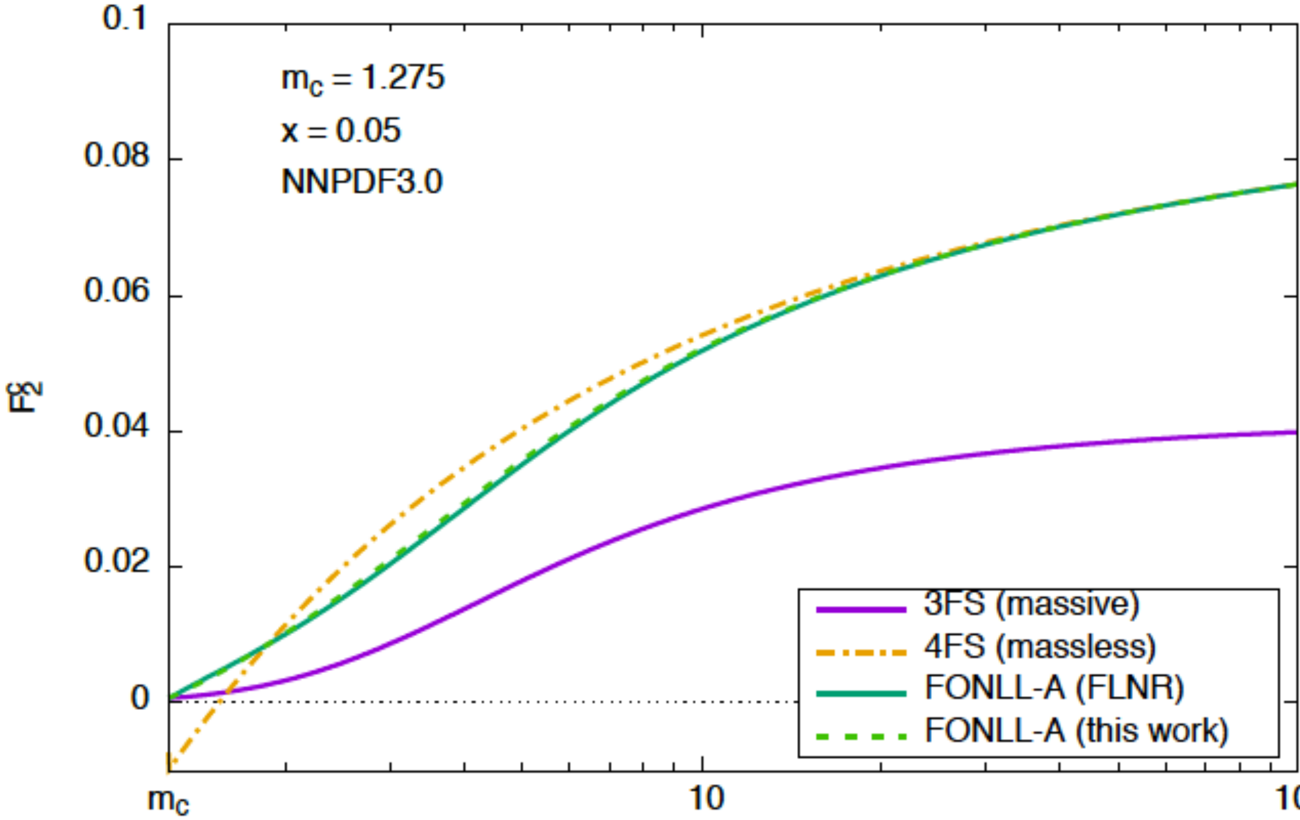
Recap on APFEL

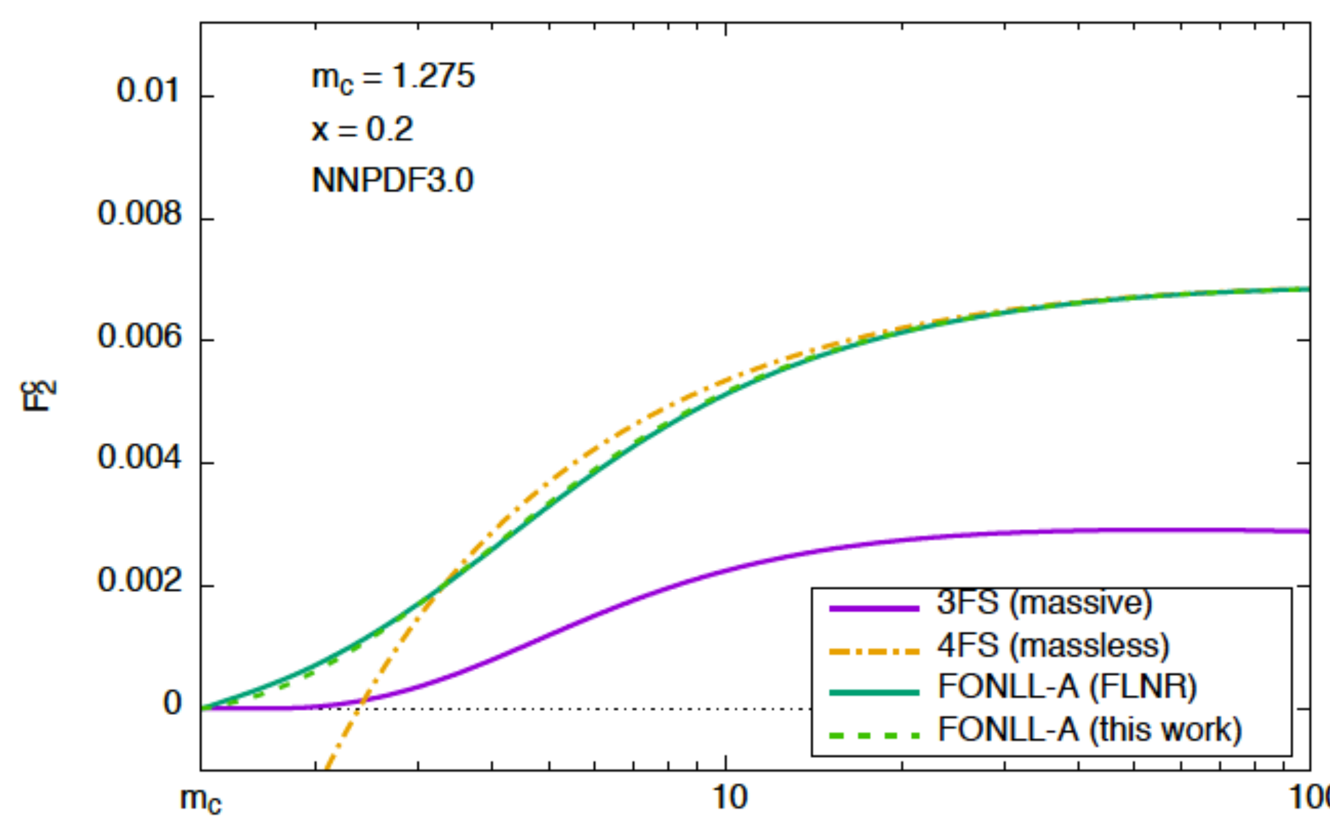
- APFEL is a **public** library for PDF evolution:
  - up to NNLO in QCD combined to LO QED corrections.
  - FFNS and VFNS.
  - Pole and $\overline{\mathrm{MS}}$ heavy quark masses.
  - Module for the fast computation of DIS NC and CC observables up to NNLO in different mass schemes (ZM-VFNS, FFNS and FONLL).
  - interfaces to FORTRAN, C/C++ and Python.
  - Amazing web interface available on http://apfel.mi.infn.it.
  - APFEL is available from http://apfel.hepforge.org/.
- Interfaced to xFitter and Alpos.
- Used for the next generation of the NNPDF fits.

Intrinsic Charm

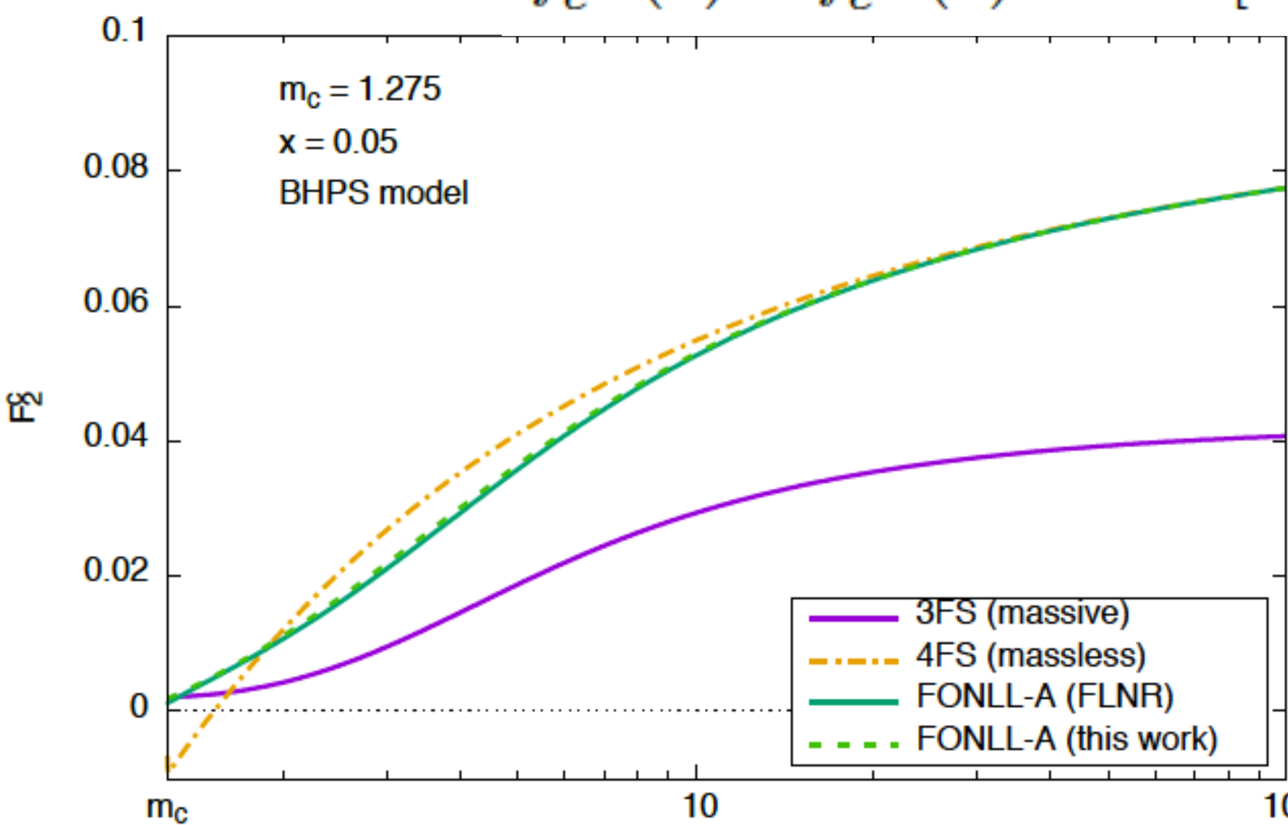
- Introducing an intrinsic charm (IC) component in the context of a GM-VFNS like FONLL (or ACOT, or TR) requires some care:
  - relax the assumption of pure perturbative generation of heavy quarks at the thresholds,
  - take into account charm-initiated diagrams both in the massive and in the massless sectors [arXiv:1510.00009].
- A full formulation of the FONLL scheme in the presence of IC has recently been achieved [arXiv:1510.02491]:
  - implemented in APFEL up to NLO both in the NC and CC sector and benchmarked against the public massiveDISsFuntion code (https://www.ge.infn.it/~bonvini/massivedis/).
  - Interestingly, it has been found that FONLL with IC is equivalent to full ACOT to all orders, while the standard FONLL (w/o IC) is instead equivalent to S-ACOT.

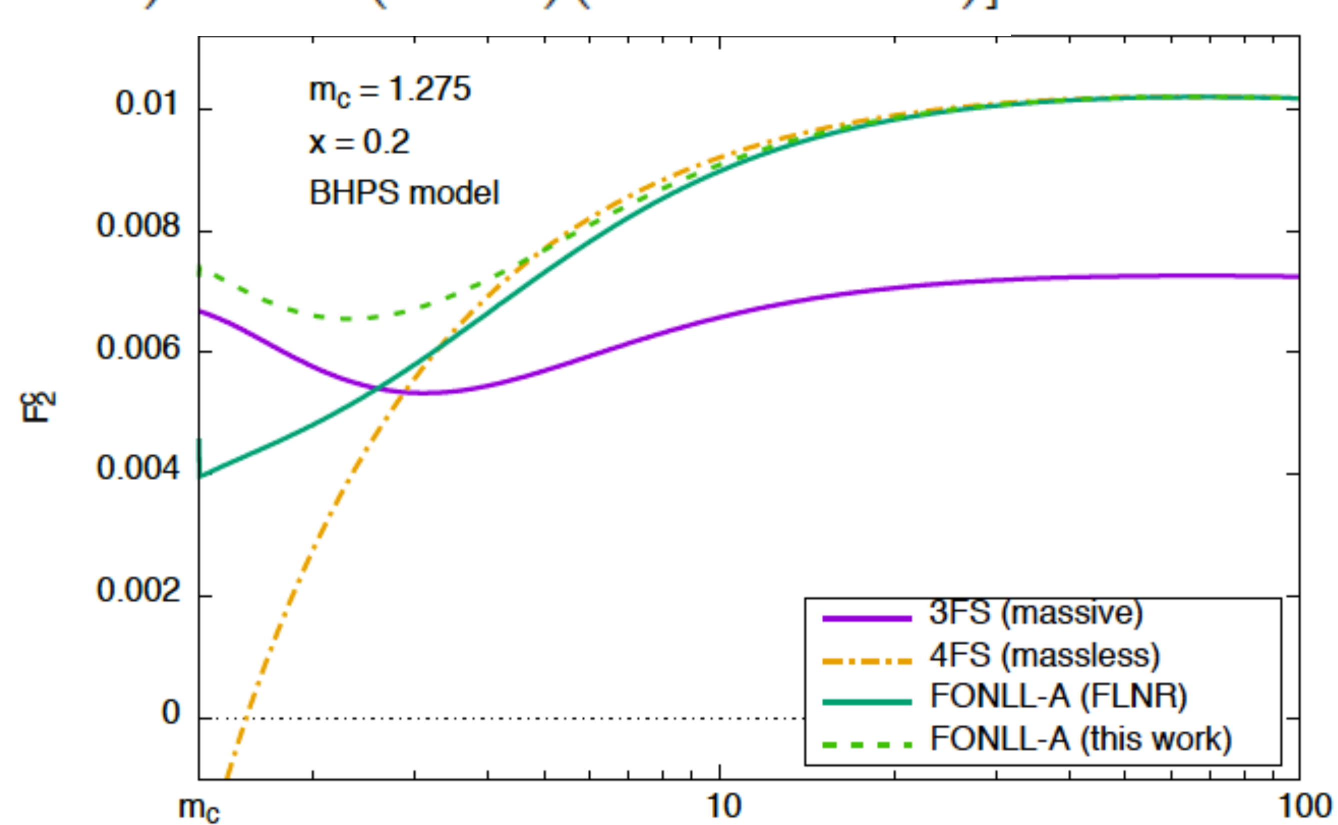
Intrinsic Charm



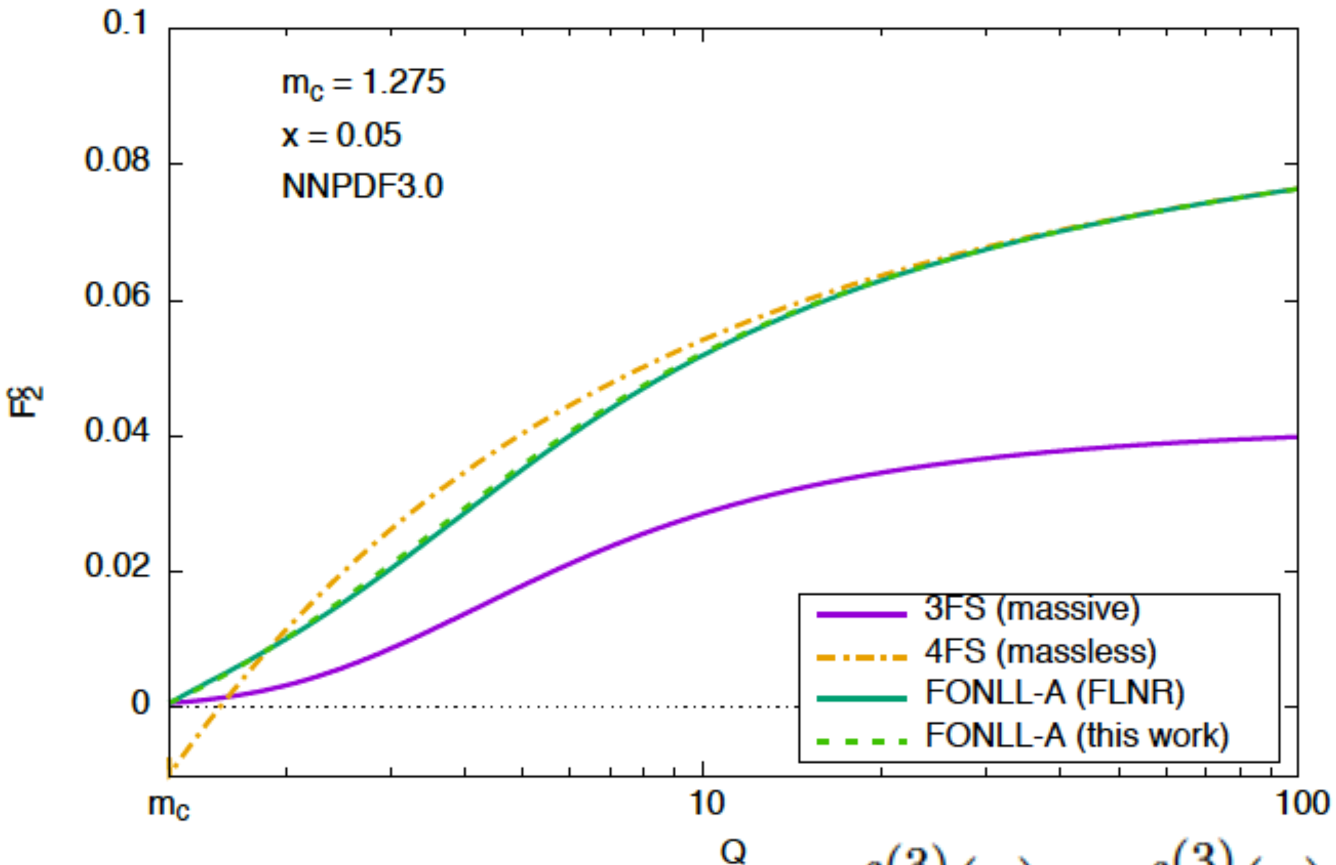


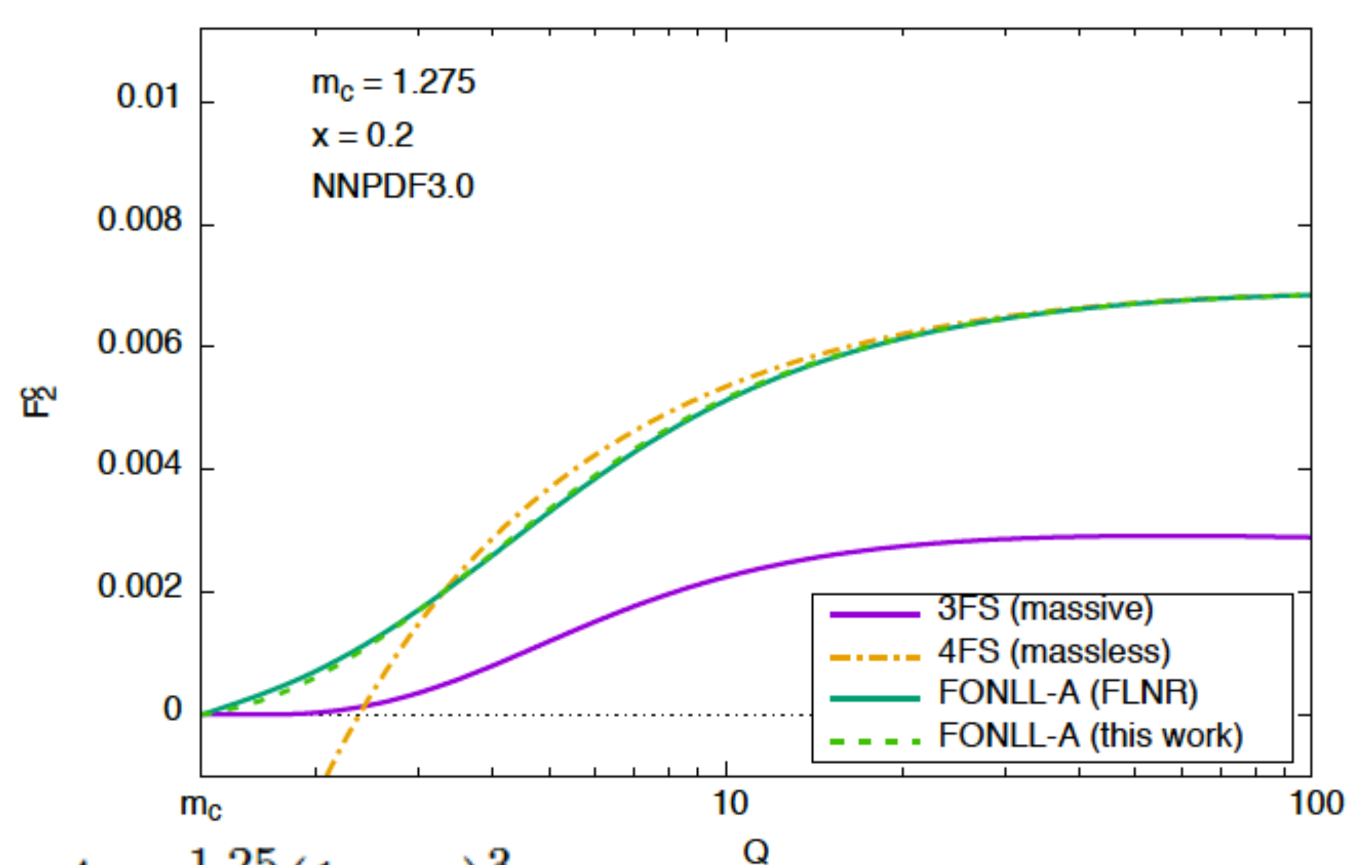
$$f_c^{(3)}(x) = f_{\bar{c}}^{(3)}(x) = A\, x^2[6x(1+x)\ln x + (1-x)(1+10x+x^2)]$$



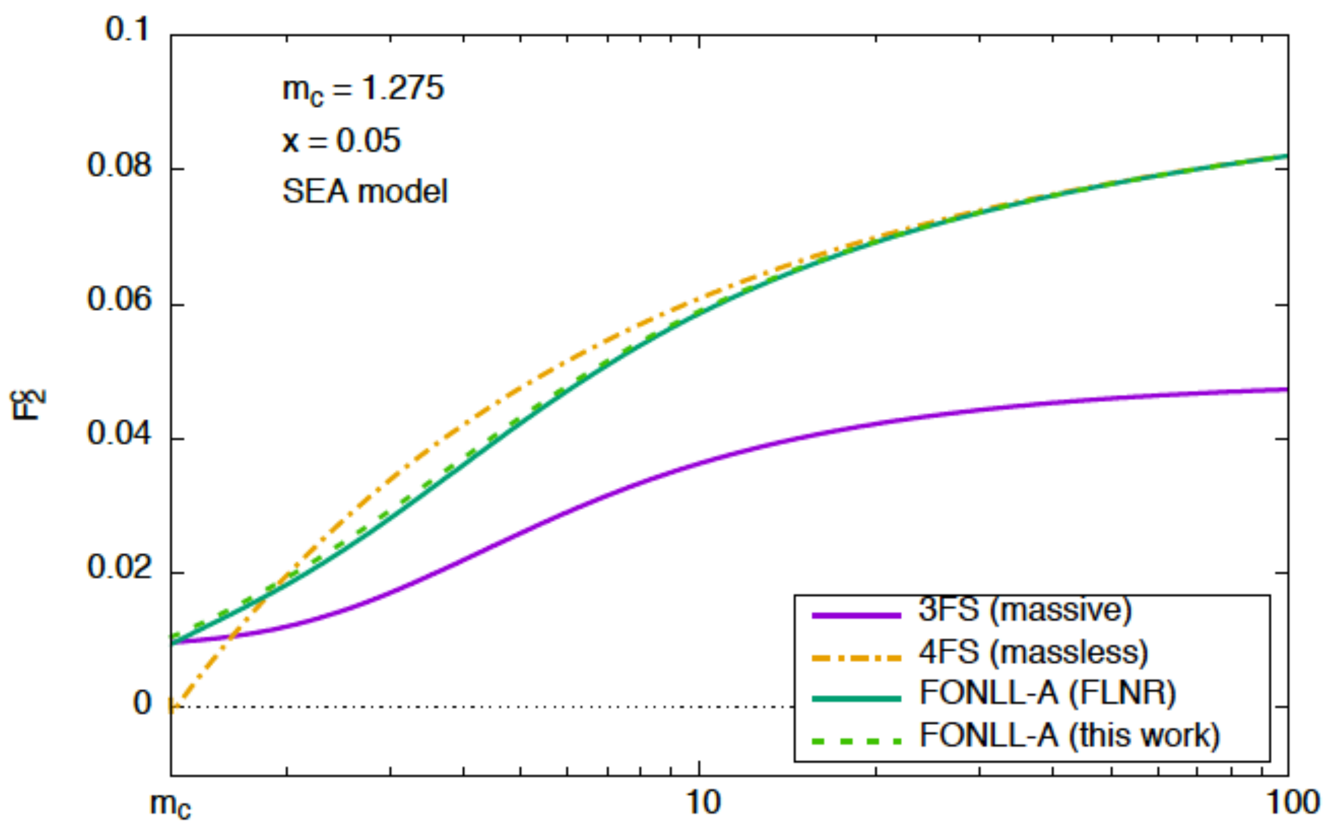


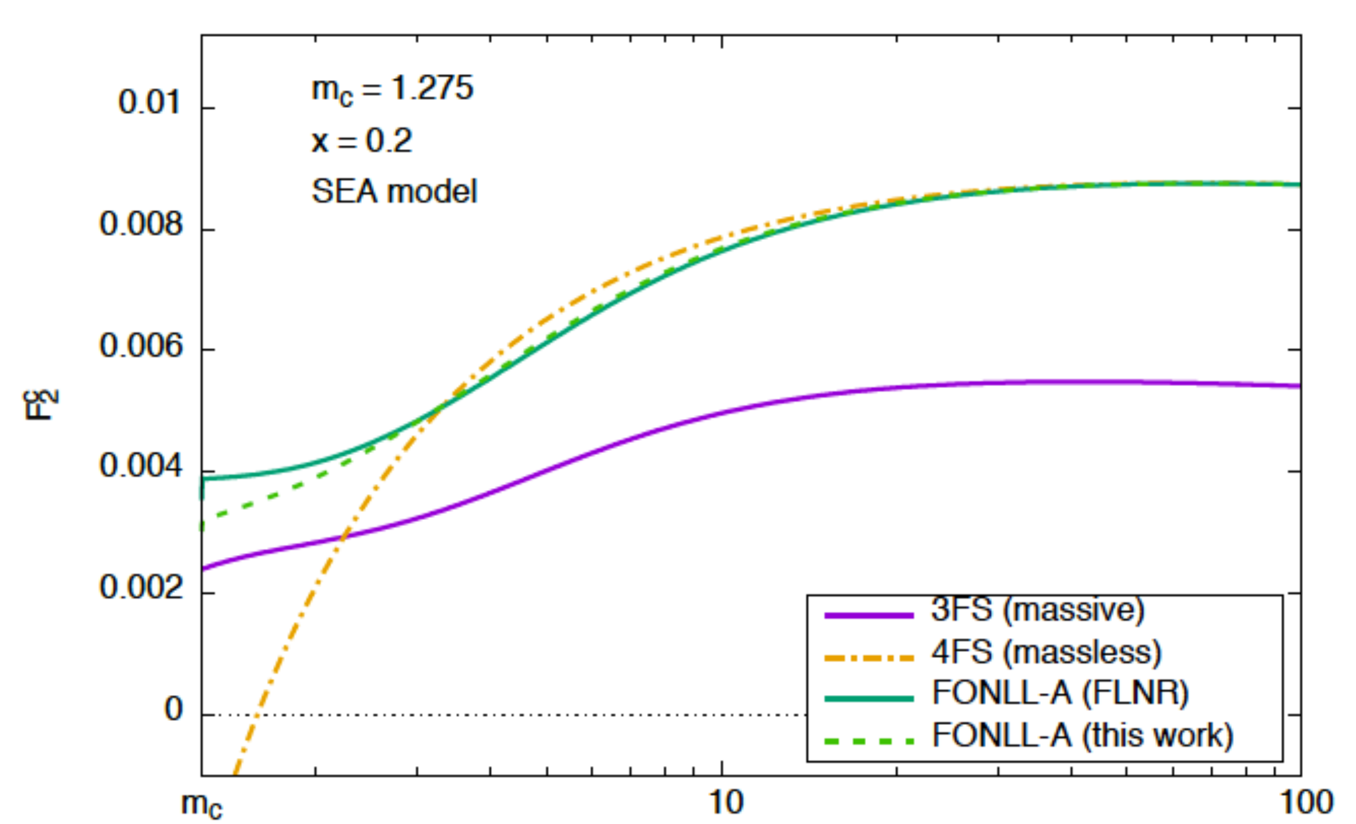
Intrinsic Charm





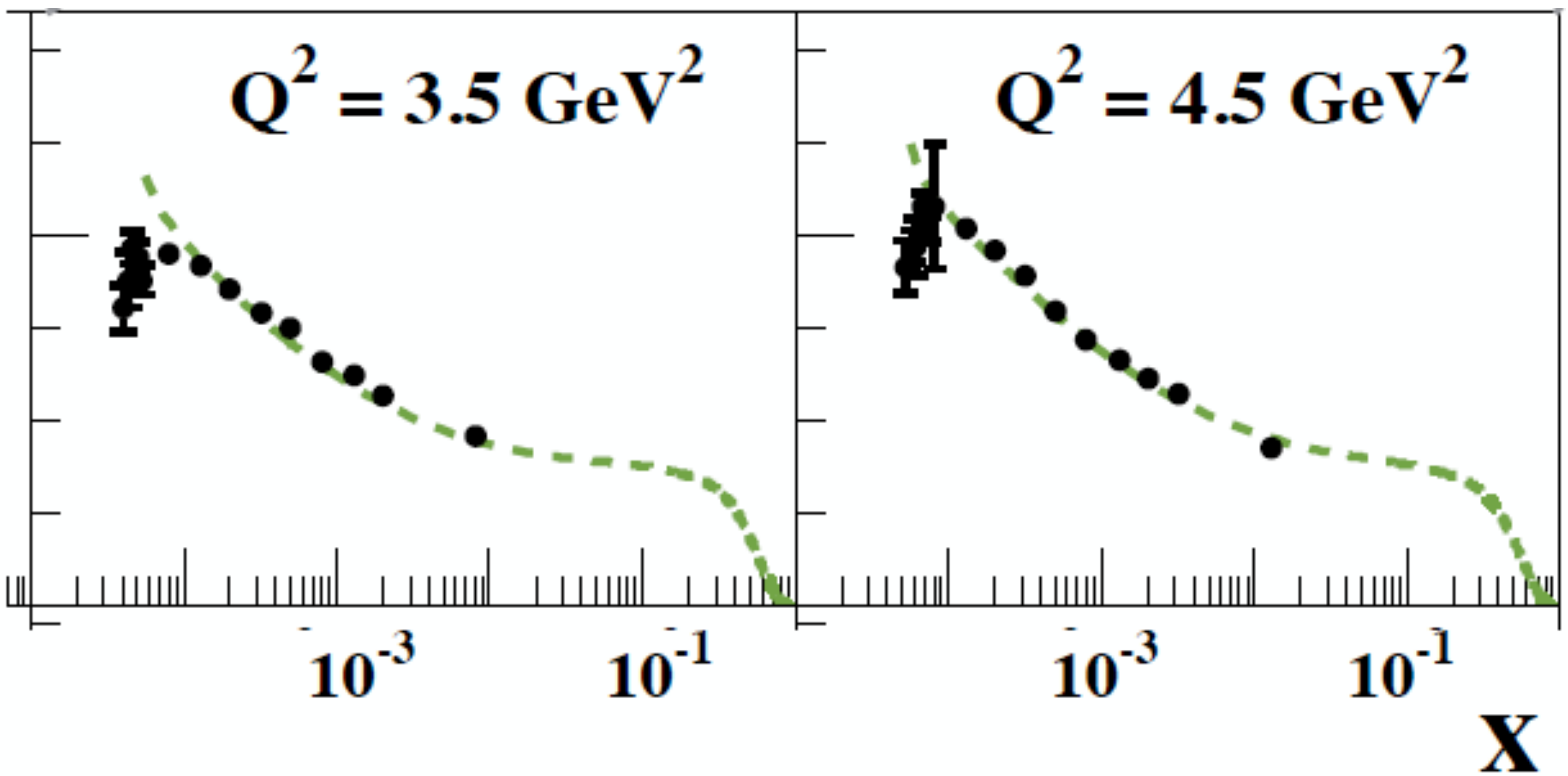
$$f_c^{(3)}(x) = f_{\bar{c}}^{(3)}(x) = A\, x^{-1.25}(1-x)^3$$





Small-x Resummation

- Some **tension** between fixed-order predictions and data in the low-x region reached by HERA:



From Eram Rizvi talk at QCD@LHC14

- A similar effect was observed some time ago in the NNPDF framework by F. Caola *et al.* [arXiv:1007.5405].

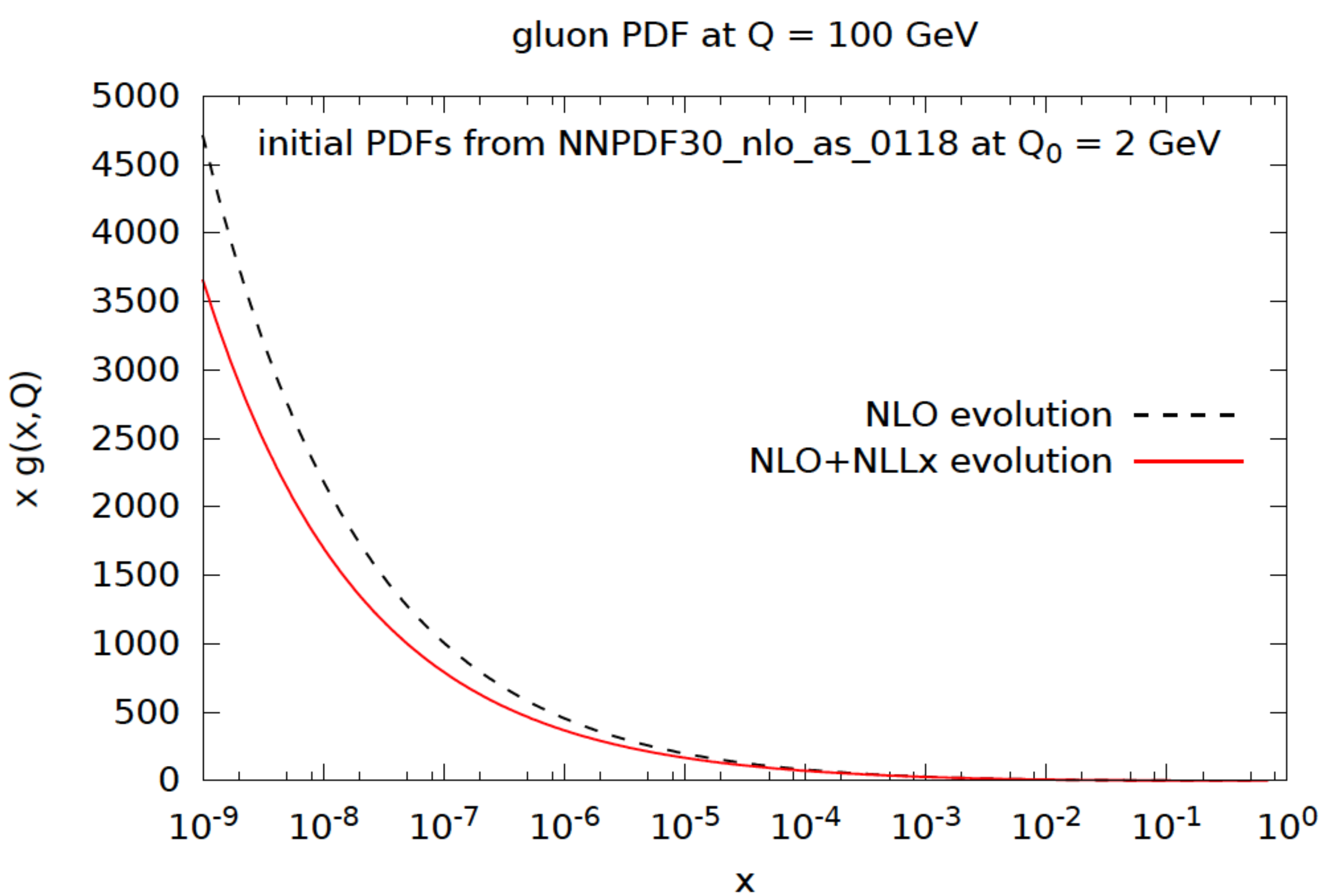
- Strong suggestion of the need for **small-x resummation**.

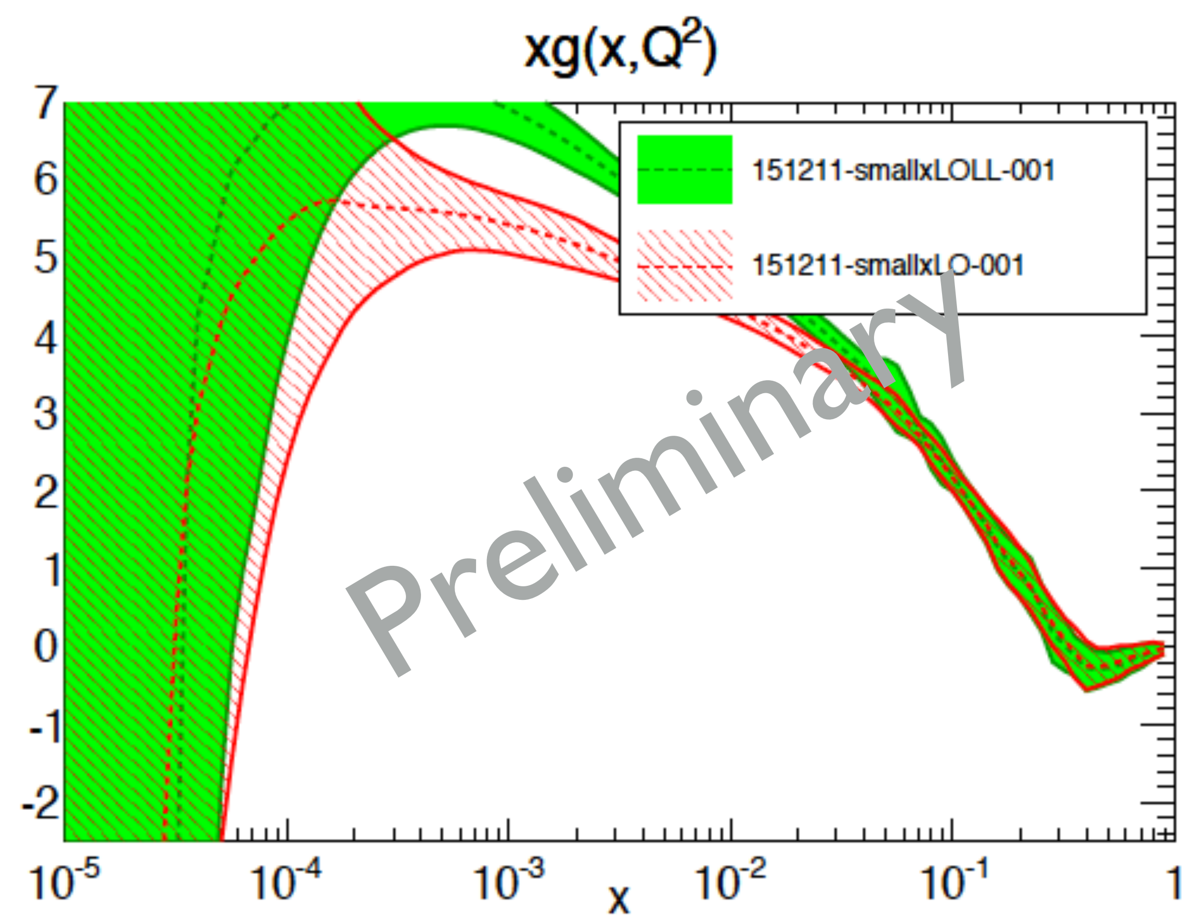
Small-x Resummation

- In collaboration with Marco Bonvini, quite some work has been done to interface to interface the **HELL** code to APFEL:
    - HELL implements small-x resummed splitting functions up to **NLL** accuracy based on the ABF approach [arXiv:0802.0032].
    - it will soon implement also small-x resummed DIS coefficient functions (Marco Bonvini, Luca Rottoli and Tiziano Peraro are presently working on that).
- The actual interface is **already in place** and fully operative.
- As a proof of concept, we have already run PDF fits with small-x resummed evolution obtaining encouraging results.
- A fully consistent PDF fit would require resummed coefficient functions which should be available in HELL within a few weeks.

Small-x Resummation

- Enhancement of the fitted gluon PDF at small values of x due to the relative suppression of the resummed evolution.
- Compensation expected when also resummed coefficient functions will be introduced.



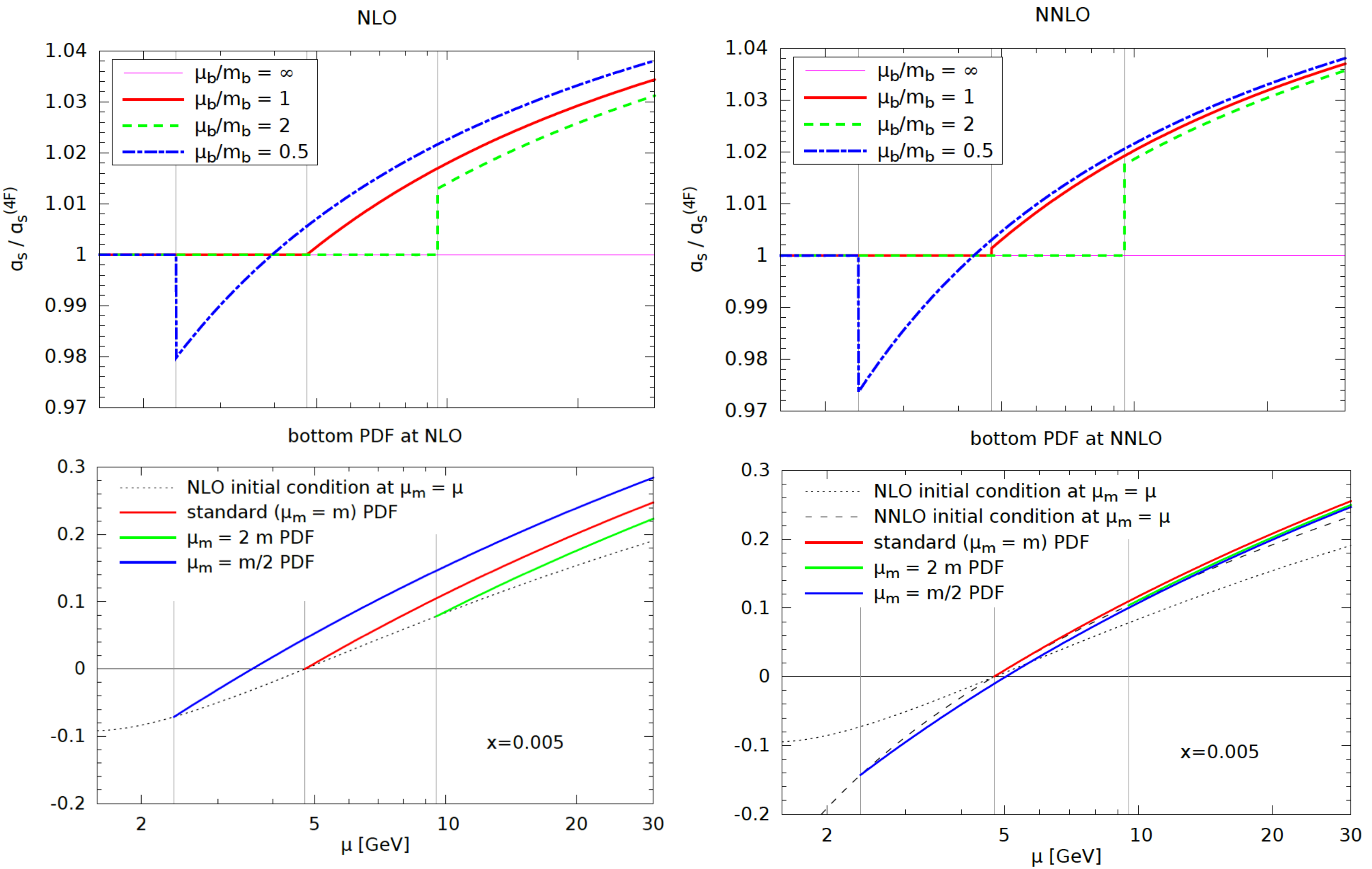


- Other PDFs mostly unchanged.

Displaced Heavy-Quark Thresholds

- The implementation of the VFNS evolution both for PDFs and α_s requires **matching** factorization schemes that differ in the number of active (light) flavours:
  - the scale at which two consecutive factorization schemes are matched are usually referred to as **heavy-quark thresholds**.
  - Heavy-quark thresholds are usually (and for convenience) identified with the heavy quark masses by means of the so-called **matching conditions** presently know up to $O(\alpha_s^2)$ [hep-ph/9612398].
  - However, heavy-quark thresholds are actually free parameters and can be chosen **arbitrarily**.
  - If masses and thresholds are taken to be different, the matching conditions need to be "generalized" including **logarithmic terms** that would vanish otherwise.
- APFEL now implements the possibility to set masses and thresholds to different values in a consistent way both in the pole mass and in the $\overline{\text{MS}}$ renormalization scheme.

Displaced Heavy-Quark Thresholds



APFELgrid

A fast(er) interface to hadron-collider observables

- While being an extremely useful tool, APPLgrid might not be appropriate to be directly employed in a global PDF fit where several thousands of iterations can be needed:
  - many tables need to be loaded with the concrete risk of exceeding the memory limit (pretty common on clusters).
  - Need to calculate PDF and α_s evolution in real time.
  - Not particularly fast convolution.
- In order to overcome this problems, in the NNPDF collaboration we have developed a tool (that we named APFELgrid) which, starting from an existing APPLgrid file, combines PDF evolution to the hard cross sections producing a derived interpolation tables (that we call FK tables):

Observable	APPLGRID	FK	optimized FK
W^+ production	1.03 ms	0.41 ms (2.5x)	0.32 ms (3.2x)
Inclusive jet production	2.45 ms	20.1 μs (120x)	6.57 μs (370x)

- APFELgrid will soon be made public in APFEL.

Other Recent Developments

- Polarized DGLAP evolution up to NNLO in QCD [arXiv:1409.5131].
- Time-like evolution + computation of SIA structure functions up to NNLO in QCD (getting ready to fit fragmentation functions).
- Independent factorization and renormalization scale variations both in the DIS structure functions and in the evolution.

In the Pipeline

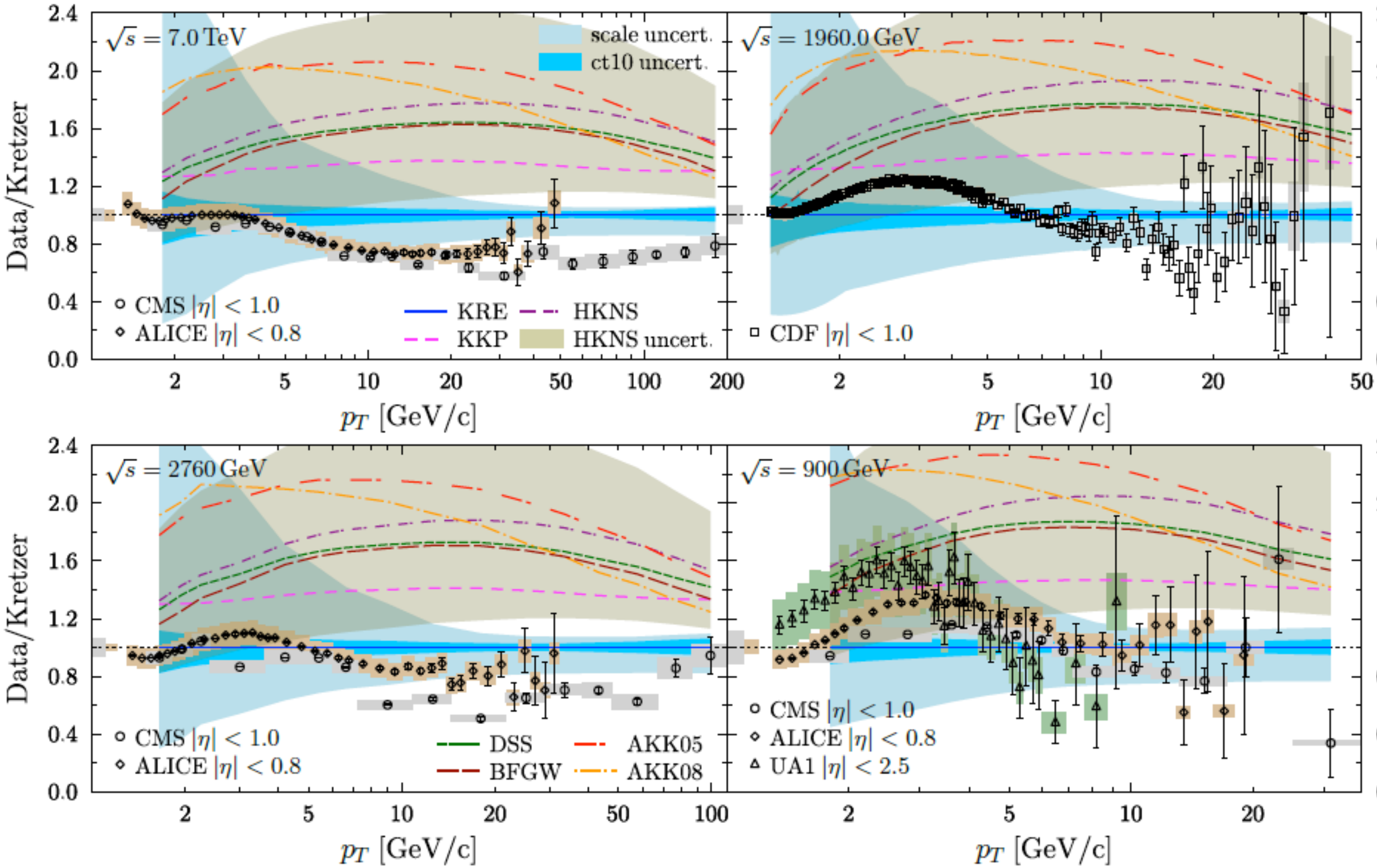
- Full NLO corrections to the PDF and α_s evolution (including the mixed QCD-QED corrections) [arXiv:1512.00612].
- Inclusion of the photon-initiated channels in DIS.
- Implementation of the polarized structure functions.

Tools for Determining FFs

- A faithful determination of fragmentation functions (FFs) is extremely important to study the universality of the QCD factorization theorem.
- The inclusive hadron measurements at the LHC, sensibly extending the previous kinematical coverage, are particularly useful for studying the FFs.
- Moreover, a good knowledge of FFs is functional to the determination of the **polarized PDFs**.
- The **spread between the different FFs** present on the market is currently very large.
- In addition, none of the existing FF sets can reproduce the experimental results optimally.

Tools for Determining FFs

- Inclusive charge-hadron spectrum:



d'Enterria *et al.* [arXiv:1311.1415]

Tools for Determining FFs

- APFEL implements the time-like evolution:
  - up to NLO in the VFNS,
  - up to NNLO in the FFNS (NNLO matching conditions missing).
- In collaboration with E. Nocera and S. Carrazza, we have performed a careful **benchmark** of the time-like evolution:
  - we are in contact with the people who calculated the time-like splitting functions: A. Mitov, S.O. Moch, A. Vogt.
- Single-inclusive e^+e^- annihilation (SIA) structure functions also implemented in APFEL up to NNLO:
  - partial benchmark against DSS implementation.
- APFEL can now effectively be used to fit FFs.

Improvements

A New Fast Evolution

- In the previous versions of APFEL the DGLAP evolution equations were written in terms of the **evolution operator**:

$$\mu^2 \frac{\partial}{\partial \mu^2} M_{ij}(\mu, \mu_0) = P_{ik}(\mu) \otimes M_{kj}(\mu, \mu_0) \quad \text{with} \quad f_i(\mu) = M_{ij}(\mu, \mu_0) \otimes f_j(\mu_0)$$

- This may be convenient because the evolution operator can be evaluated once and for all and convoluted with any initial PDF set.

- On the other hand, this requires solving numerically a big coupled system of ODEs, therefore it can be slow.

- Alternatively, one can directly solve the DGLAP equations in terms of **PDFs**:

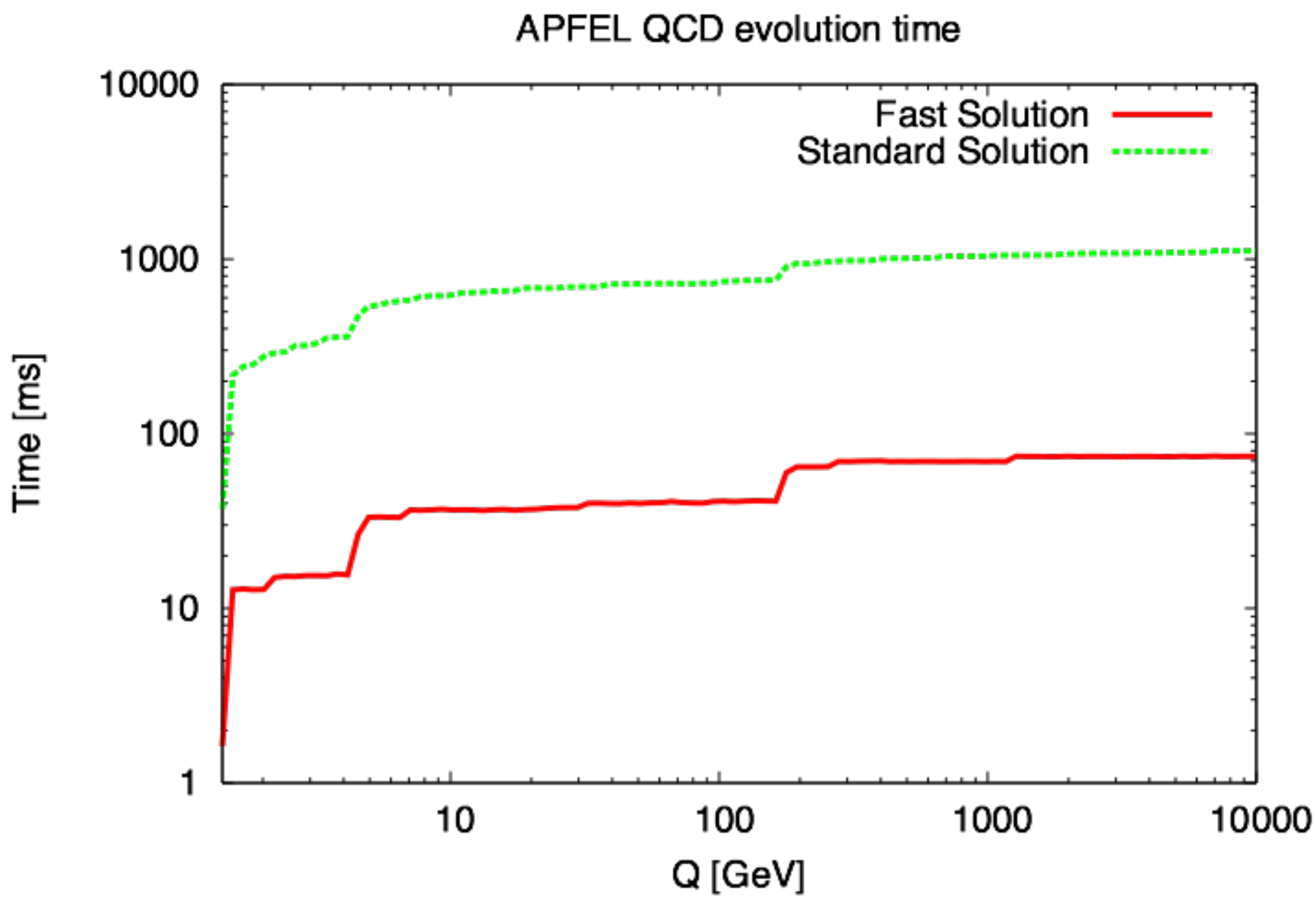
$$\mu^2 \frac{\partial}{\partial \mu^2} f_i(\mu) = P_{ij}(\mu) \otimes f_j(\mu)$$

- This requires the solution of a much smaller system of equations and is consequently much faster.

Improvements

A New Fast Evolution

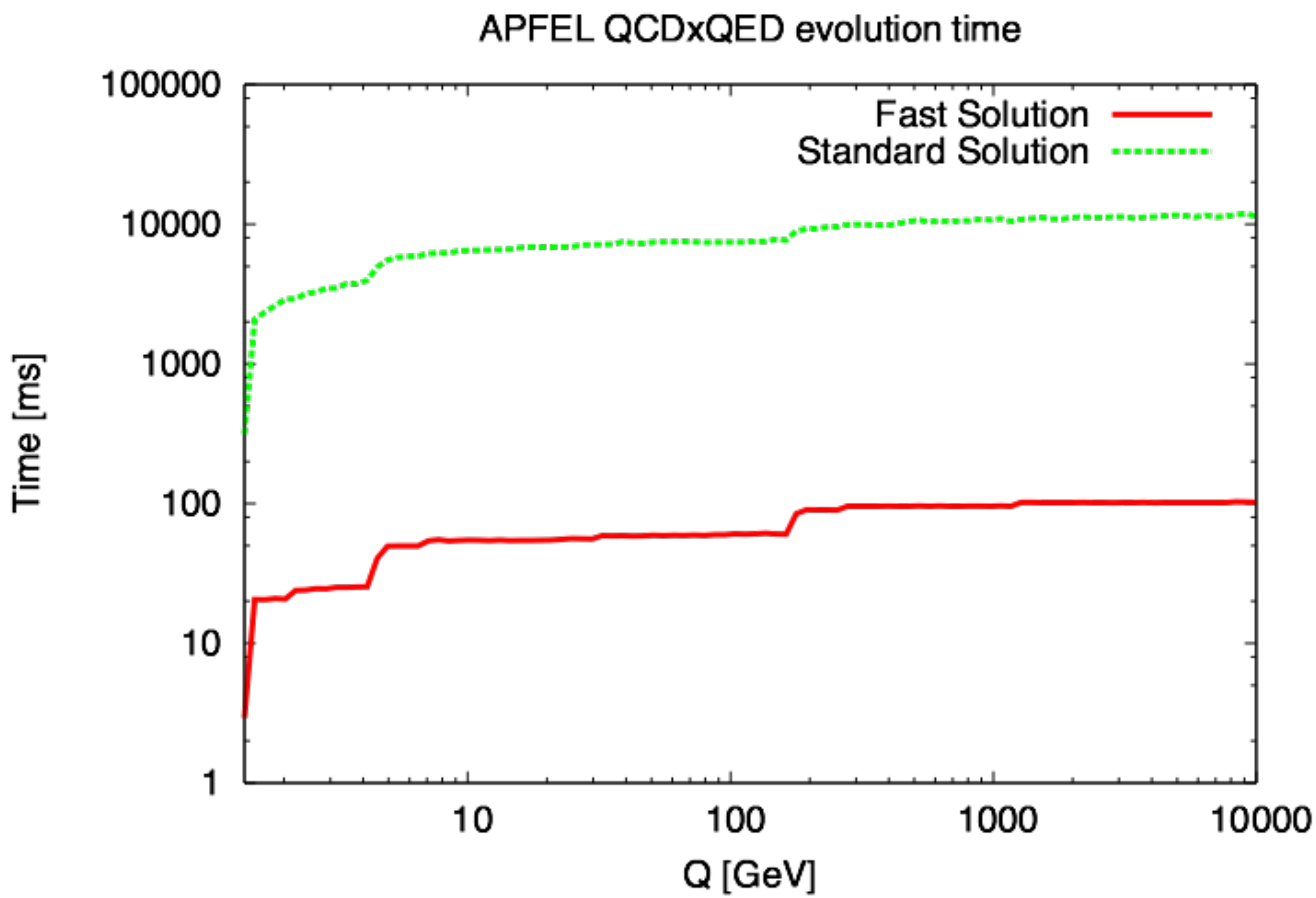
- Comparison between old (operatorial) and new (in terms of PDFs) solution for the QCD evolution:



Improvements

A New Fast Evolution

- Comparison between old (operatorial) and new (in terms of PDFs) solution for the QCD+QED evolution:



Improvements

A New QCD+QED Evolution

- In the previous versions of APFEL the QCD+QED evolution was performed by combining the **separate** QCD and QED evolution:
  - we showed that the differences, of a few % at most, with the standard implementations which evolve contemporaneously in QCD and QED were due to **subleading terms in $\boldsymbol{\alpha}$**.
- We have now implemented a new evolution basis which allows a **simultaneous diagonalization** of the QCD+QED evolution matrix:

1) g
2) γ
3) $\Sigma = \Sigma_u + \Sigma_d$
4) $\Delta_\Sigma = \Sigma_u - \Sigma_d$
5) $T_1^u = u^+ - c^+$
6) $T_2^u = u^+ + c^+ - 2t^+$
7) $T_1^d = d^+ - s^+$
8) $T_2^d = d^+ + s^+ - 2b^+$
9) $V = V_u + V_d$
10) $\Delta_V = V_u - V_d$
11) $V_1^u = u^- - c^-$
12) $V_2^u = u^- + c^- - 2t^-$
13) $V_1^d = d^- - s^-$
14) $V_2^d = d^- + s^- - 2b^-$

Improvements

A New QCD+QED Evolution

- In the previous versions of APFEL the QCD+QED evolution was performed by combining the **separate** QCD and QED evolution:
  - we showed that the differences, of a few % at most, with the standard implementations which evolve contemporaneously in QCD and QED were due to **subleading terms in α**.
- We have now implemented a new evolution basis which allows a **simultaneous diagonalization** of the QCD+QED evolution matrix:

Coupled:

1) g
2) γ
3) $\Sigma = \Sigma_u + \Sigma_d$
4) $\Delta_\Sigma = \Sigma_u - \Sigma_d$

9) $V = V_u + V_d$
10) $\Delta_V = V_u - V_d$

Decoupled:

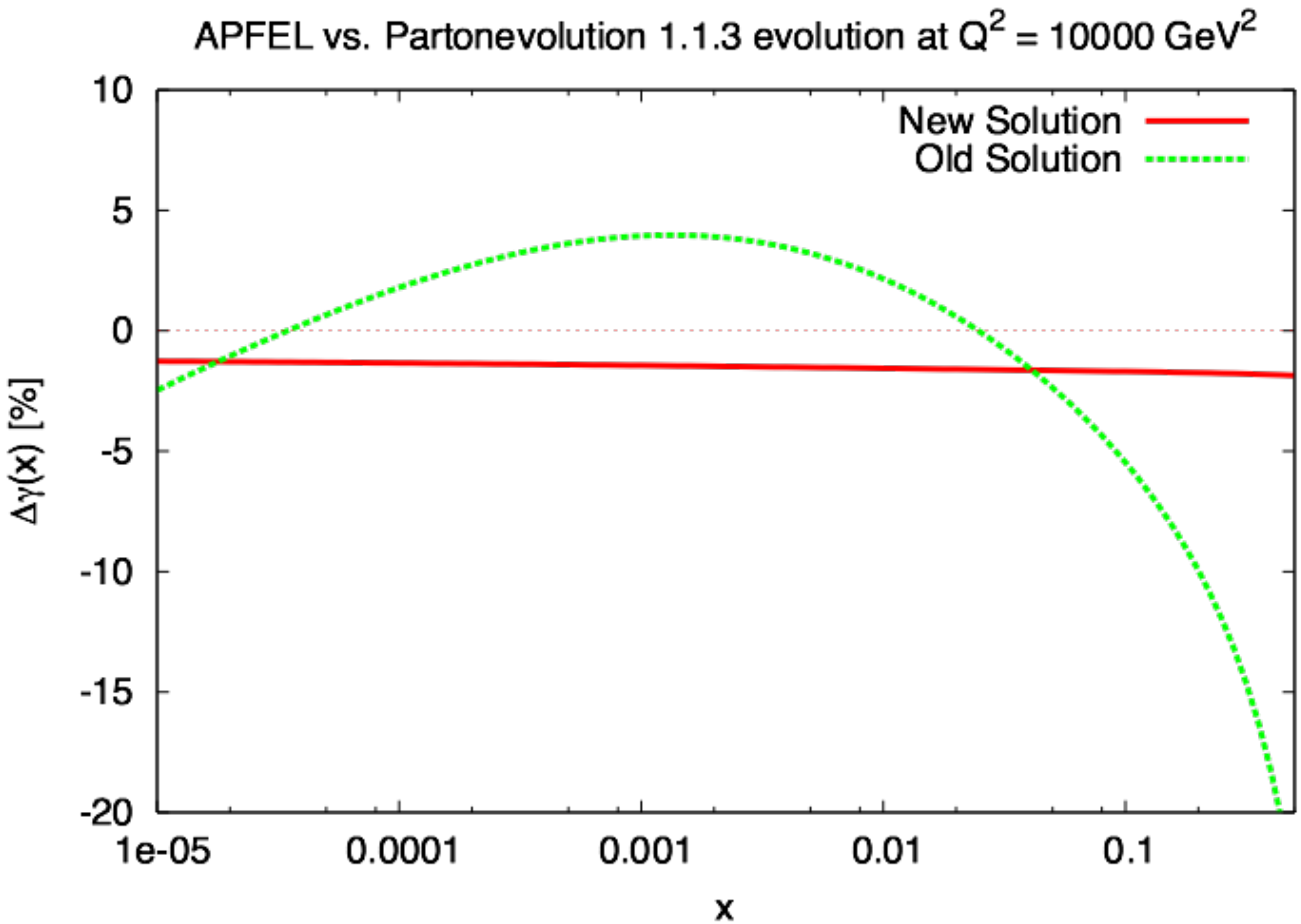
5) $T_1^u = u^+ - c^+$
6) $T_2^u = u^+ + c^+ - 2t^+$
7) $T_1^d = d^+ - s^+$
8) $T_2^d = d^+ + s^+ - 2b^+$

11) $V_1^u = u^- - c^-$
12) $V_2^u = u^- + c^- - 2t^-$
13) $V_1^d = d^- - s^-$
14) $V_2^d = d^- + s^- - 2b^-$

- This new basis is also suitable for an easy implementation of the mixed **higher order corrections** to the evolution.

Improvements
A New QCD+QED Evolution

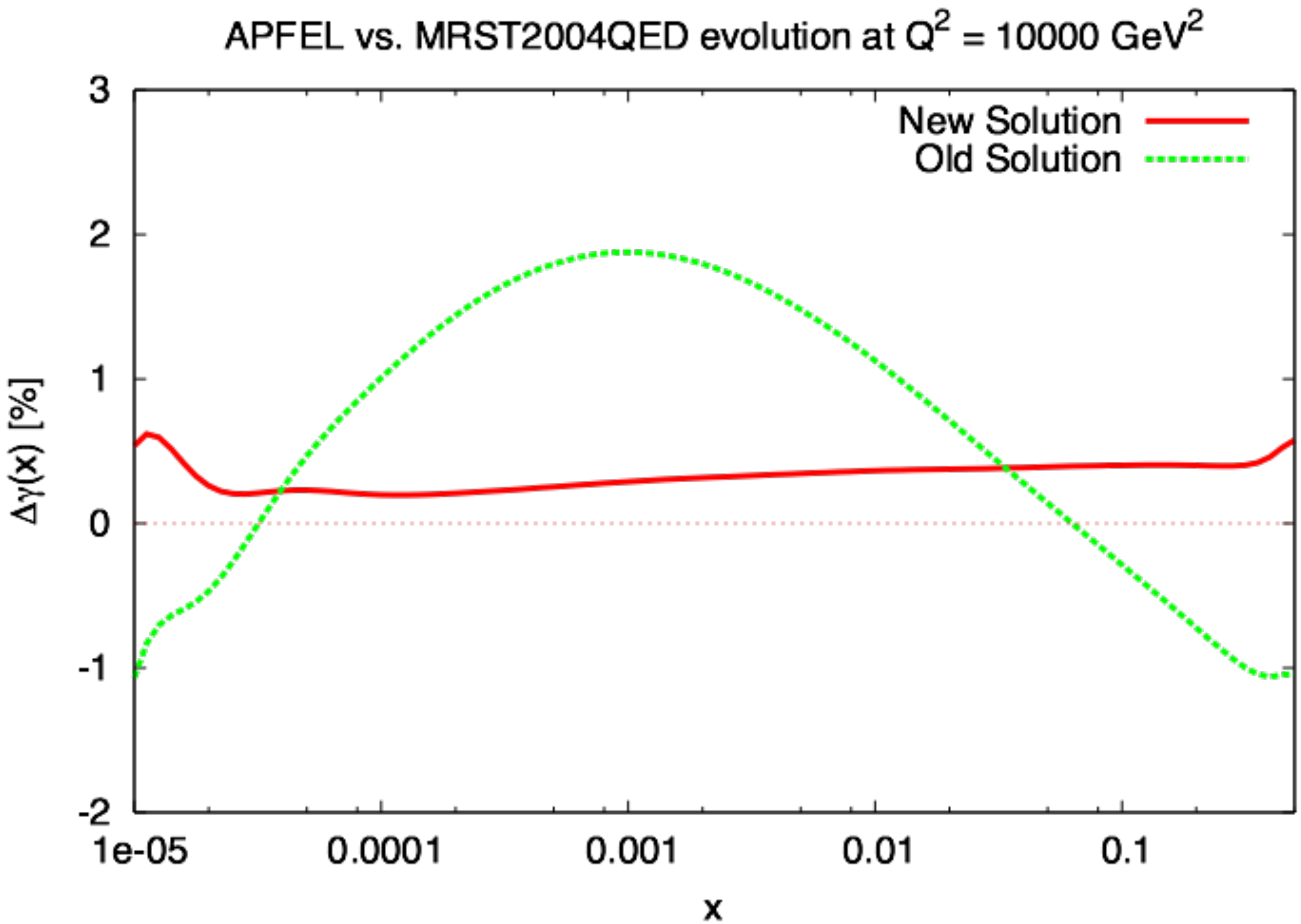
- Comparison of the photon against **Partonevolution** 1.1.3 in the FFNS:



- All the other PDFs are in excellent agreement.

Improvements
A New QCD+QED Evolution

- Comparison of the photon against **MRST2004QED** in the VFNS:



- All the other PDFs are in excellent agreement.