APFEL
Improvements and Developments

arXiv:1310.1394

Valerio Bertone

CERN

HERAFitter User's meeting

01.10.2014

In collaboration with Stefano Carrazza and Juan Rojo

Recap on APFEL

- APFEL is a **public** library for QCD+QED combined evolution:
  - up to NNLO in QCD and LO in QED.
  - FFNS and VFNS.
  - Pole and $\overline{\text{MS}}$ heavy quark masses.
  - Module for the 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.
  - interfaced to LHAPDF 5 and 6.
  - Graphical User Interface (GUI).
  - APFEL is available from http://apfel.hepforge.org/.

Summary of the Talk

- Recent improvements and developments
- In the pipeline
- Plans for the future
- APFEL in HERAFitter

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.

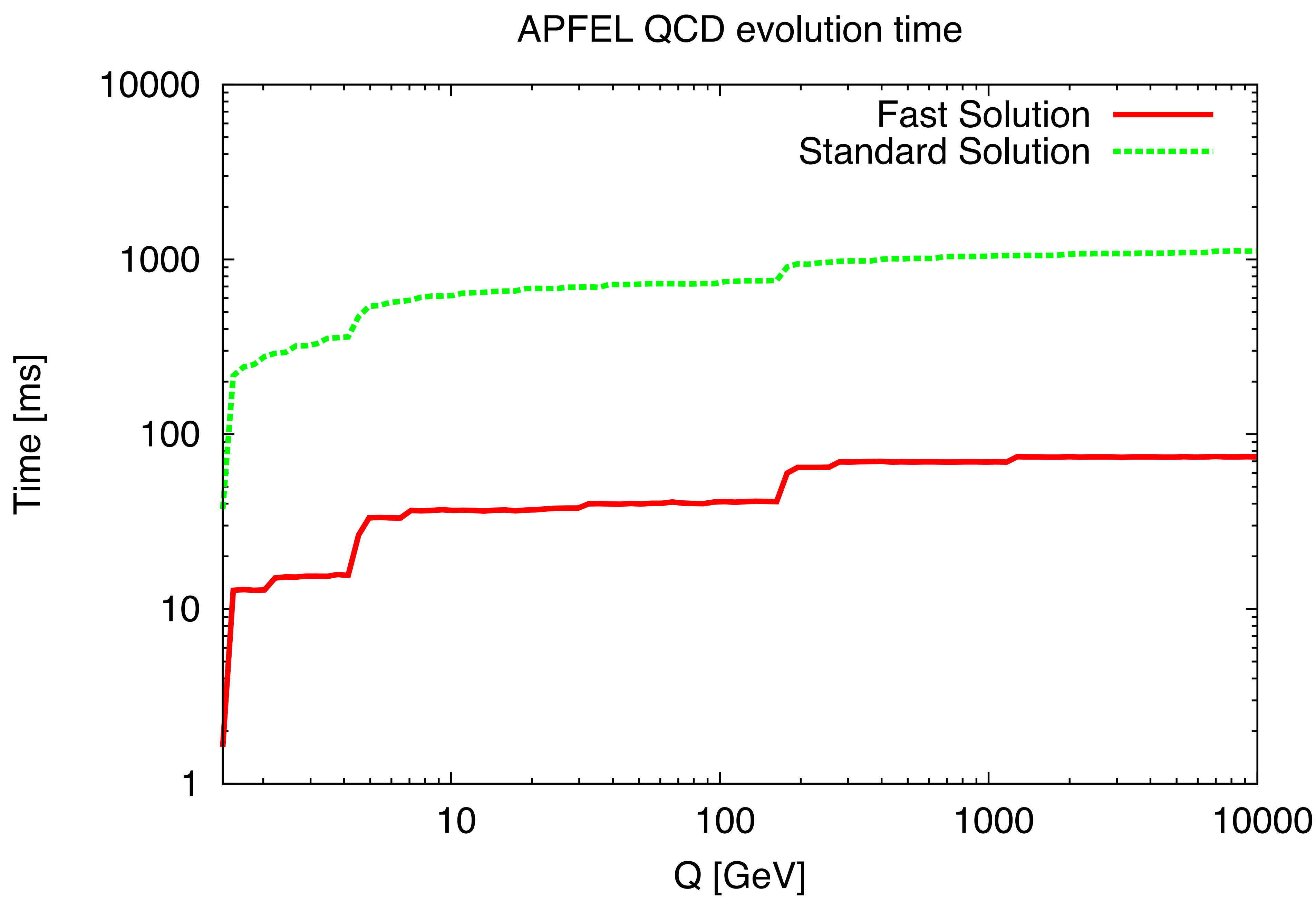
- Alternatively, one can directly solve the DGLAP equations in terms of **PDFs**:

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

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

Improvements
A New Fast Evolution

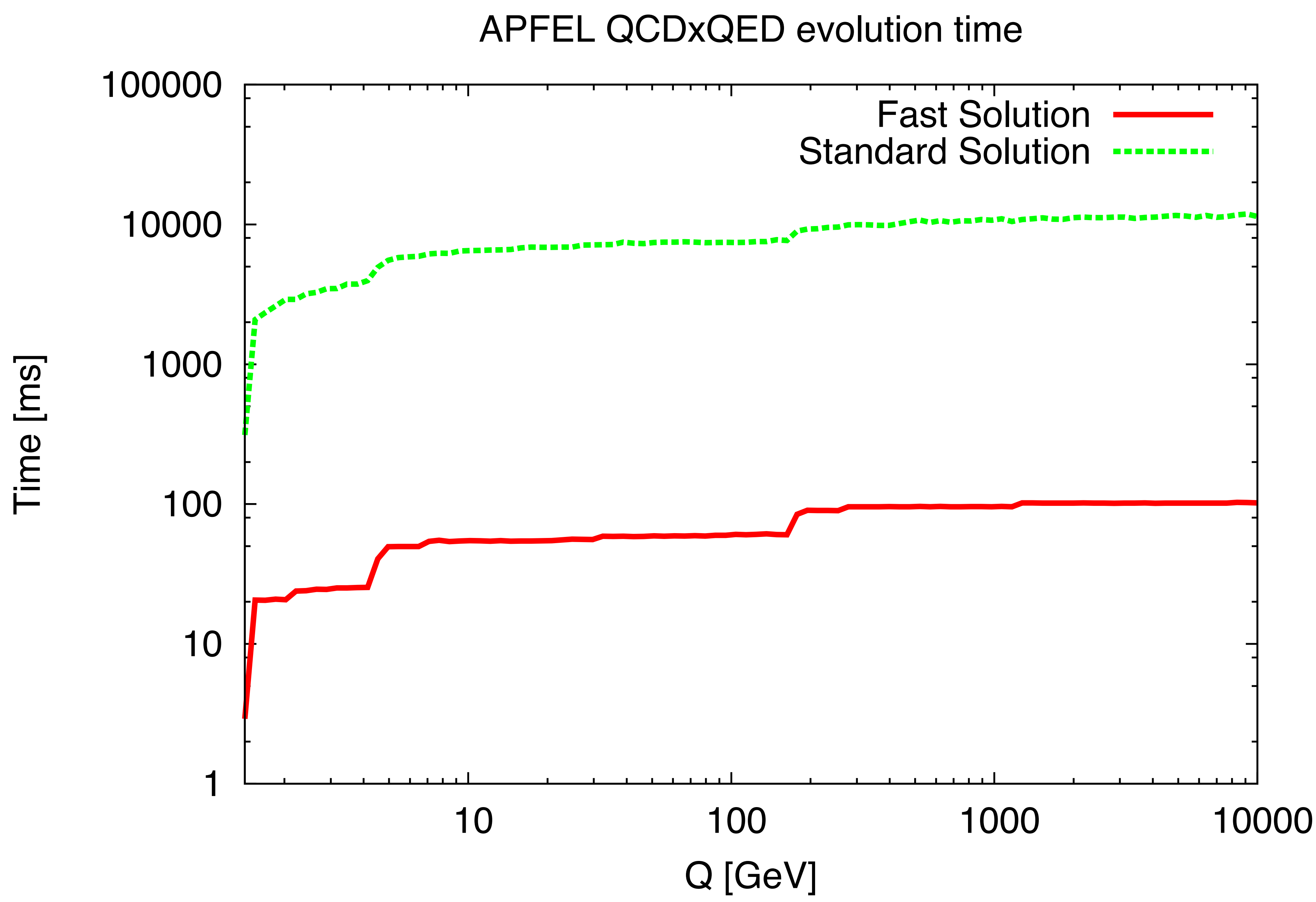
- Comparison between old (operatorial) and new (in terms of PDFs) solution for the QCD evolution:



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 α**.
- 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**.

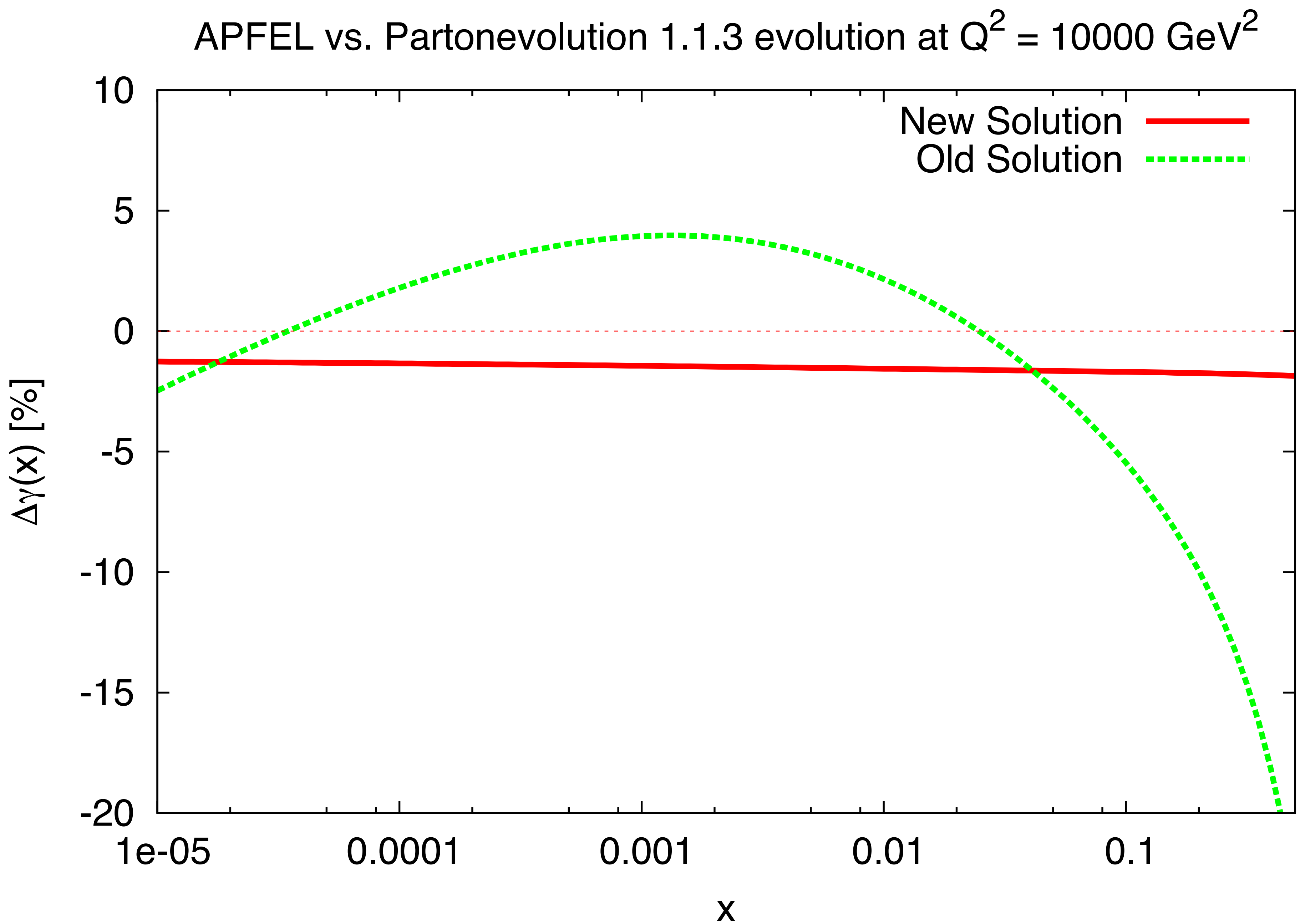
- We have now implemented a new evolution basis which allows a **simultaneous diagonalization** of the QCD+QED evolution matrix:

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

- 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:

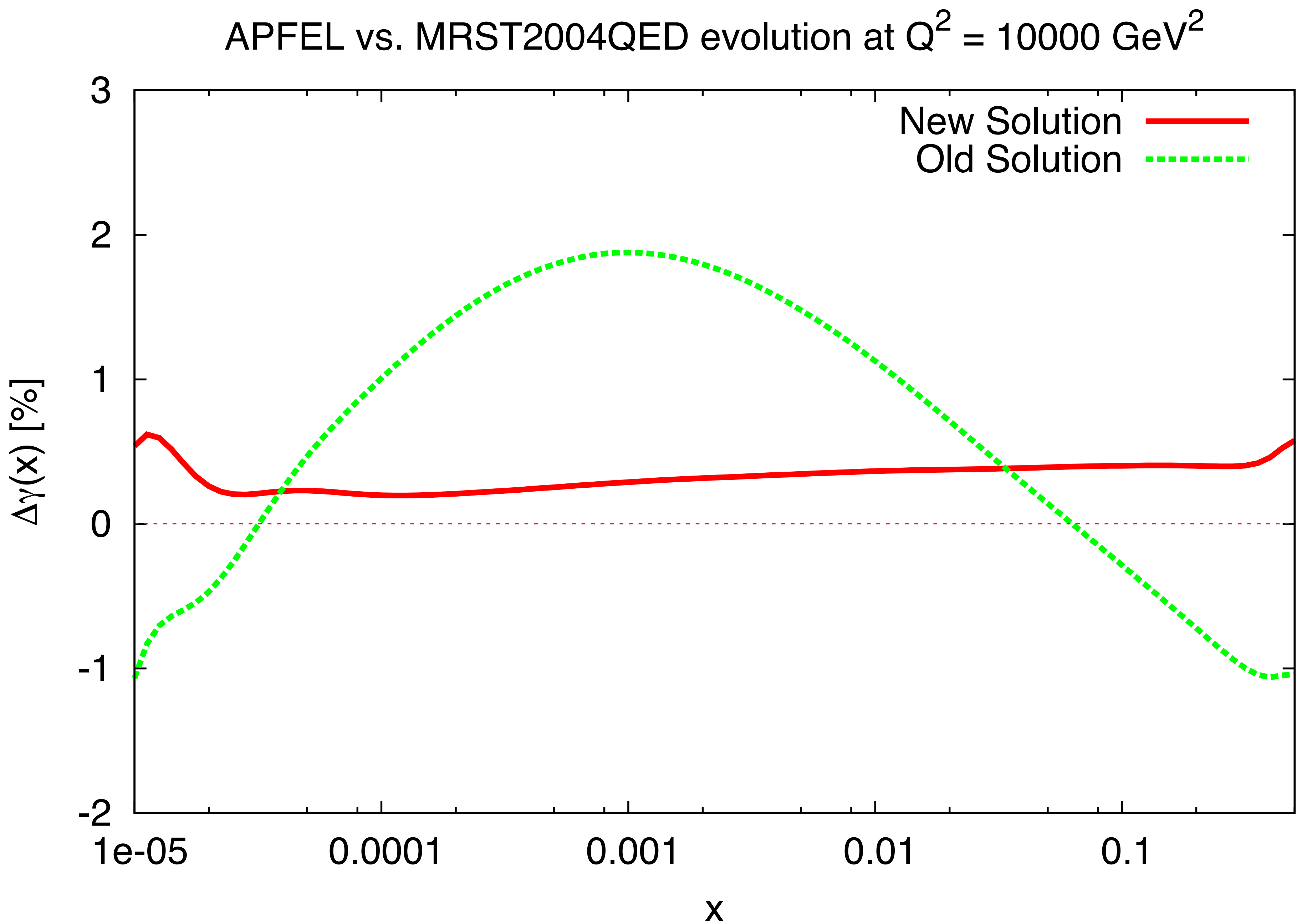


- All the other PDFs are in excellent agreement.

Improvements

A New QCD+QED Evolution

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

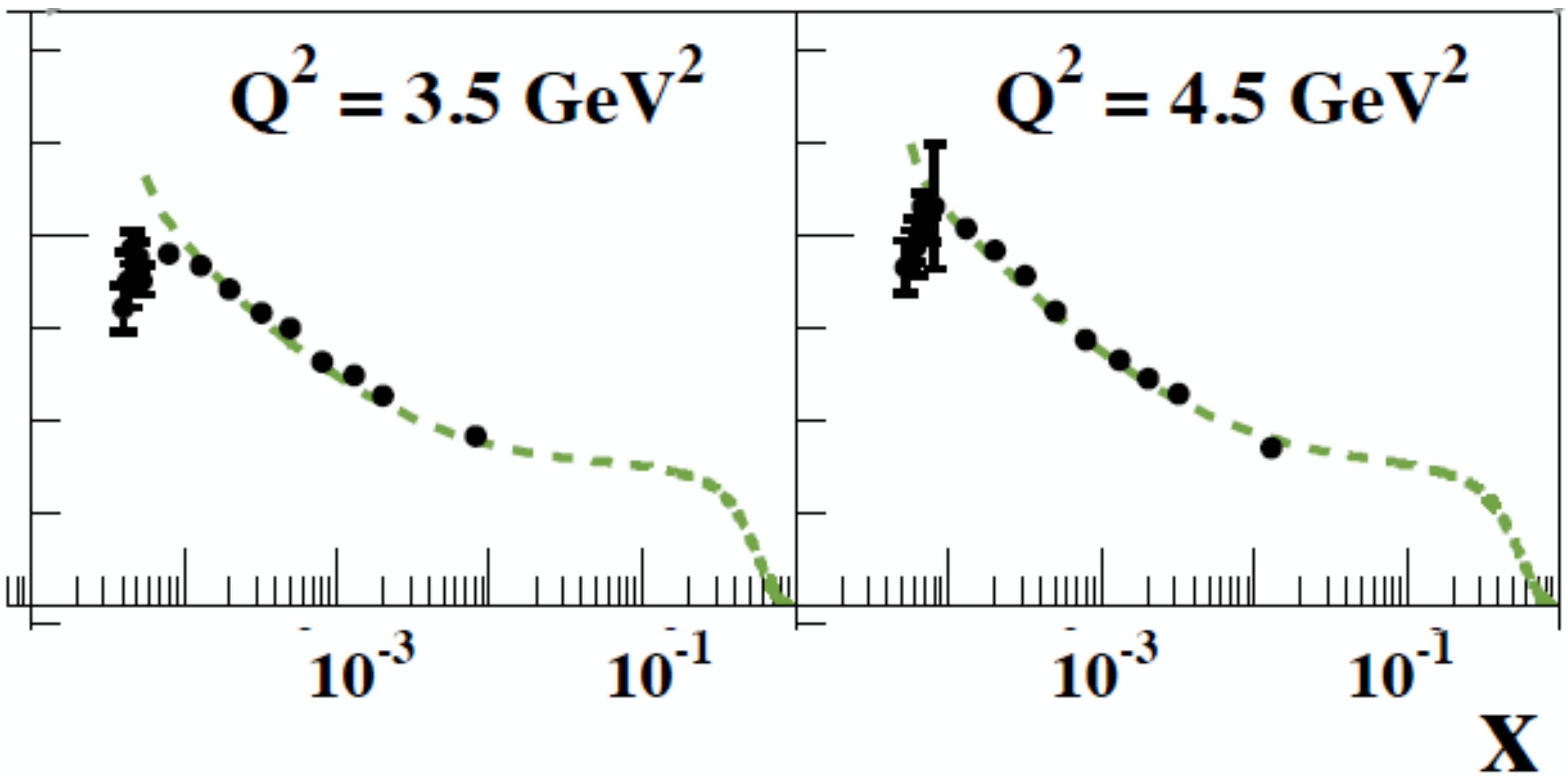


- All the other PDFs are in excellent agreement.

In the Pipeline

The Small-x Resummation

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



From Eram Rizvi talk at QCD@LHC14

- The same 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**.

In the Pipeline

The Small-x Resummation

- We are presently working to interface the Marco Bonvini's code (**HELL**) to APFEL:
  - HELL implements small-x resummed splitting functions up to **NLL** accuracy based on the ABF approach [arXiv:0802.0032].
  - HELL will soon implement also small-x resummed DIS coefficient functions.
- The actual interface is **already in place** and we are now in the process of debugging and tuning.
- We expect to be able to make the small-x resummed evolution available in APFEL by the next two/three months.
- Implementation on the small-x resummed DIS coefficient functions as soon as available in HELL (a few months).

In the Pipeline

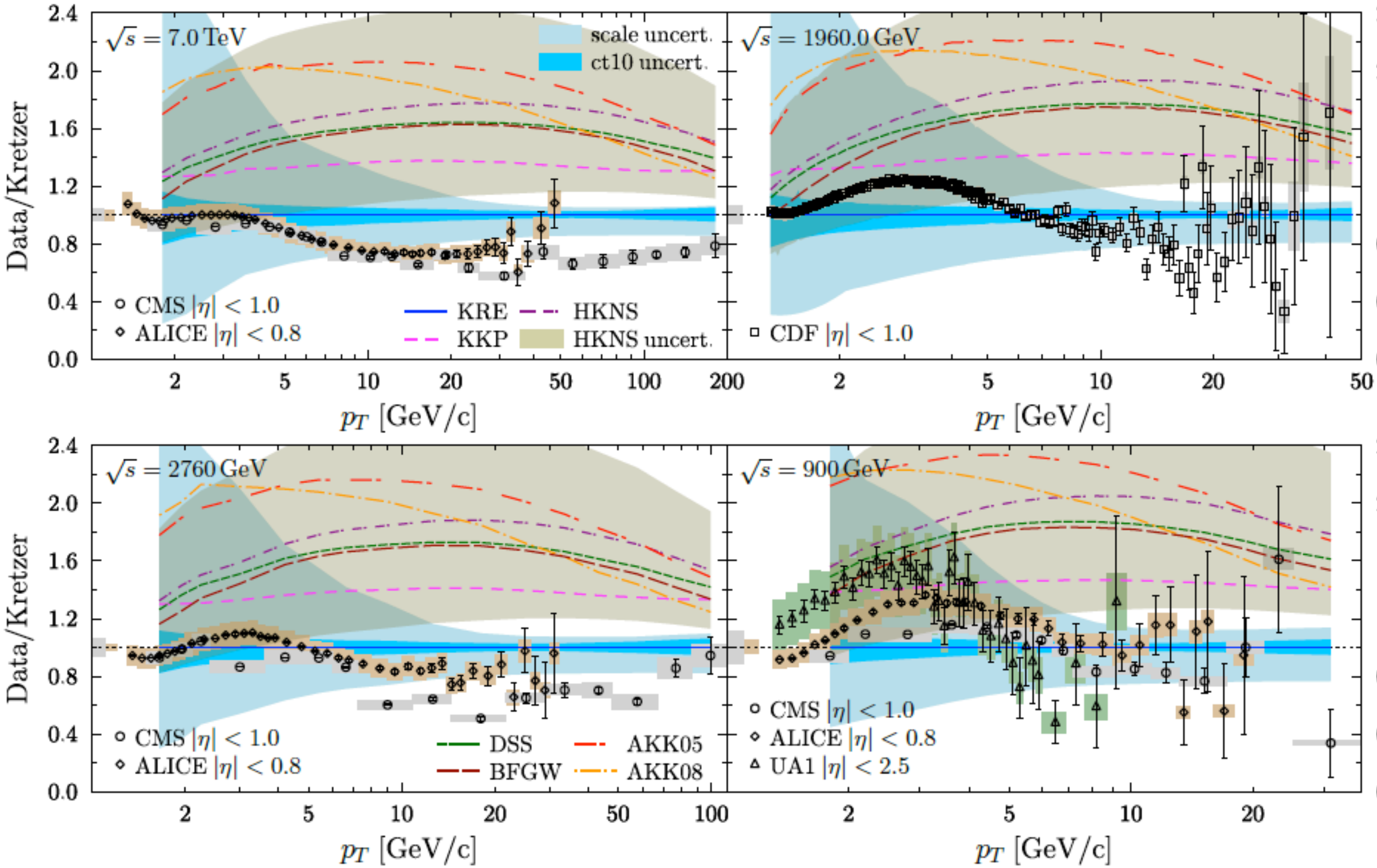
Time-Like Evolution for Fragmentation Functions

- 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.

In the Pipeline

Time-Like Evolution for Fragmentation Functions

- Inclusive charge-hadron spectrum:



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

In the Pipeline

Time-Like Evolution for Fragmentation Functions

- APFEL already 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, we are presently performing a careful **benchmark** of time-like evolution to finally define a standard:
  - we are in contact with the people who calculated the time-like splitting functions: A. Mitov, S.O. Moch, A. Vogt.
- The next step will be the implementation of the **observables** involving FFs (semi-inclusive e^+e^- annihilation, SIDIS, etc.).
- Soon the possibility to use APFEL to fit FFs.

In the Pipeline

... more Projects

- The **tensor gluon** evolution, in collaboration with G. Savvidy:
  - possibility to include in the PDF evolution a tensor gluon of **spin 2** according to the model described here [arXiv:1310.0856].
- A new **fast** module for the computation of the **DIS observables**:
  - based on the precomputation on a grid of the coefficient functions (same technology as in PDF evolution).
- Release of the APFEL **Web Graphical User Interface**:
  - All the APFEL GUI plotting and computational functionalities will be available from a public web site.
  - No need to bother about installing APFEL and running it locally.
  - Soon on line.

Plans for the Future

- Large-x (soft-gluon) resummed evolution:
  - resummation of terms $\alpha_s^{k+1}\ln^{2k}(1 - x)$ in the splitting functions.
- Polarized evolution:
  - recent computation of the three-loop (NNLO) splitting functions [arXiv:1409.5131]
- $O(\alpha\alpha_s)$ and $O(\alpha^2)$ corrections to the QCD+QED evolution.
- ...

APFEL in HERAFitter

... a Fruitful Collaboration

- APFEL implements (or will soon implement) a bunch of functionalities which, we think, could be of interest for HERAFitter as a framework to extract PDFs:
  - fast and accurate QCD and QCD+QED evolution:
    - Pole and $\overline{\mathrm{MS}}$ masses,
    - factorization/renormalization scale variation.
  - A module for the computation of DIS observables in the FONNL scheme (which will soon be improved).
  - Time-like evolution for the extraction of fragmentation functions.
  - Small-x (and large-x) resummed evolution.
  - Tensor gluon evolution.
  - Polarized evolution.