Recent Developments in APFEL

[V. Bertone, *et al.*, Comput. Phys. Commun. 185, 1647 (2014)]

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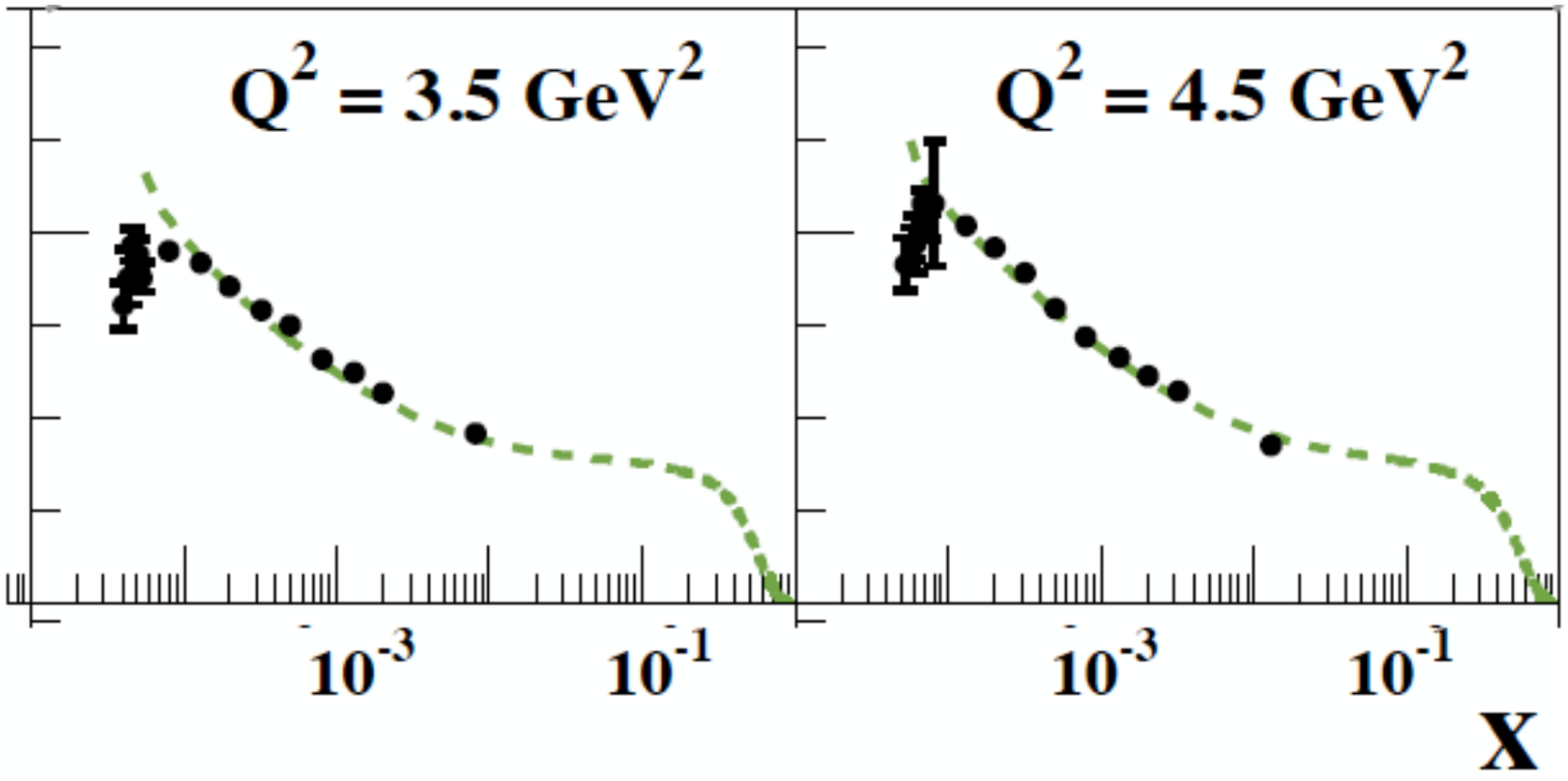
APFEL in a Nutshell

- APFEL is a **public** library for the computation of collinear PDF evolution and DIS structure functions:
  - up to NNLO in QCD combined to QED corrections up to NLO.
  - FFN and VFN schemes.
  - Pole and $\overline{\text{MS}}$ heavy-quark masses.
  - fast computation of DIS NC and CC observables in different mass schemes (ZM-VFNS, FFNS and FONLL).
  - Interfaces to FORTRAN, C/C++ and Python.
  - Web interface available on http://apfel.mi.infn.it.
  - available from http://apfel.hepforge.org/.
- Currently interfaced to **xFitter** and **Alpos**.
- Used for the next generation of the **NNPDF** fits (including FFs).

Small-x Resummation

- **Tension** between fixed-order predictions and data in the small-x region reached by HERA:



From Eram Rizvi talk at QCD@LHC14

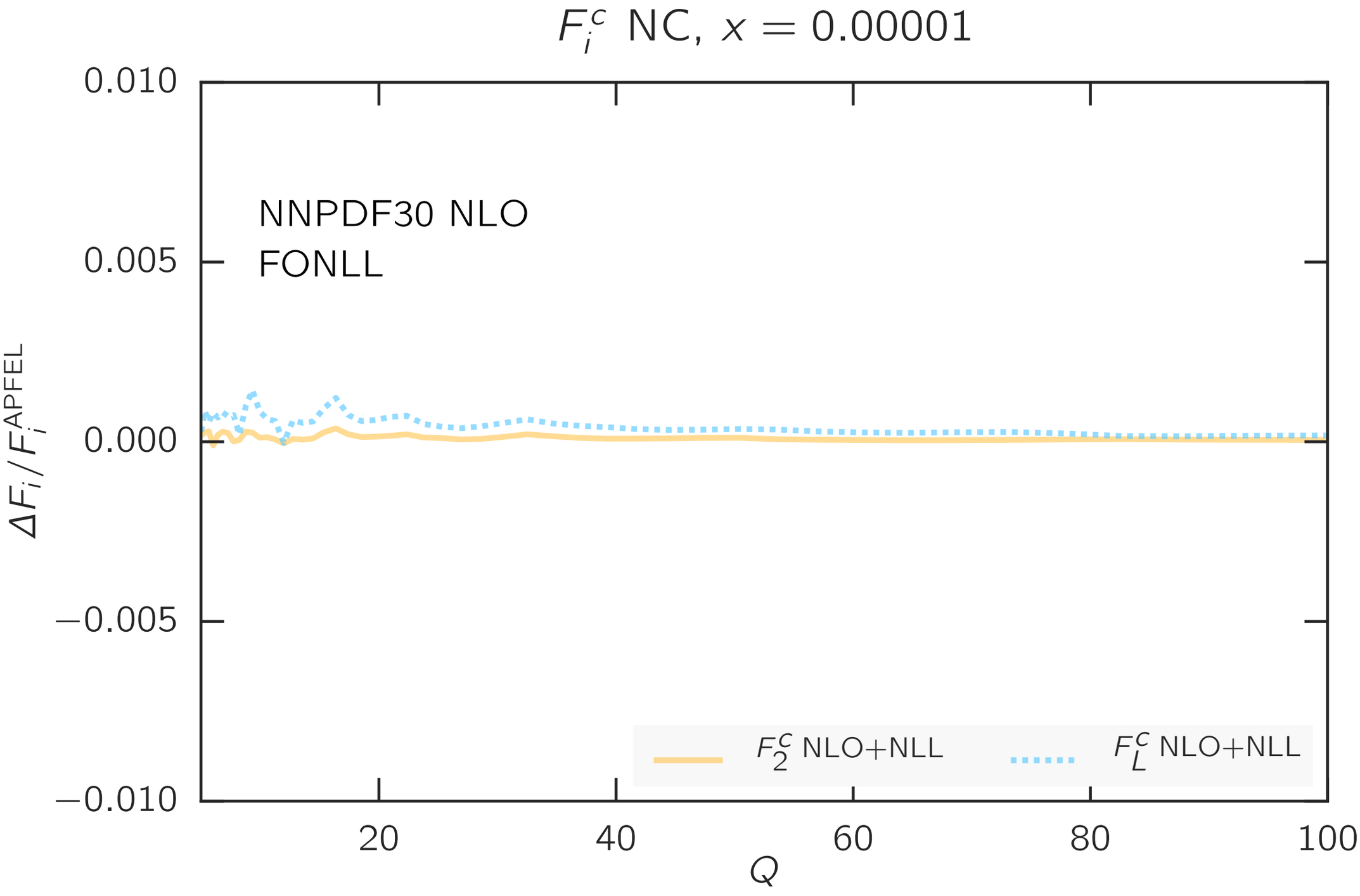
- A similar effect was observed some time ago in the NNPDF framework by F. Caola *et al.* [arXiv:1007.5405].

- Suggestion of the need for **small-x resummation**.

Small-x Resummation

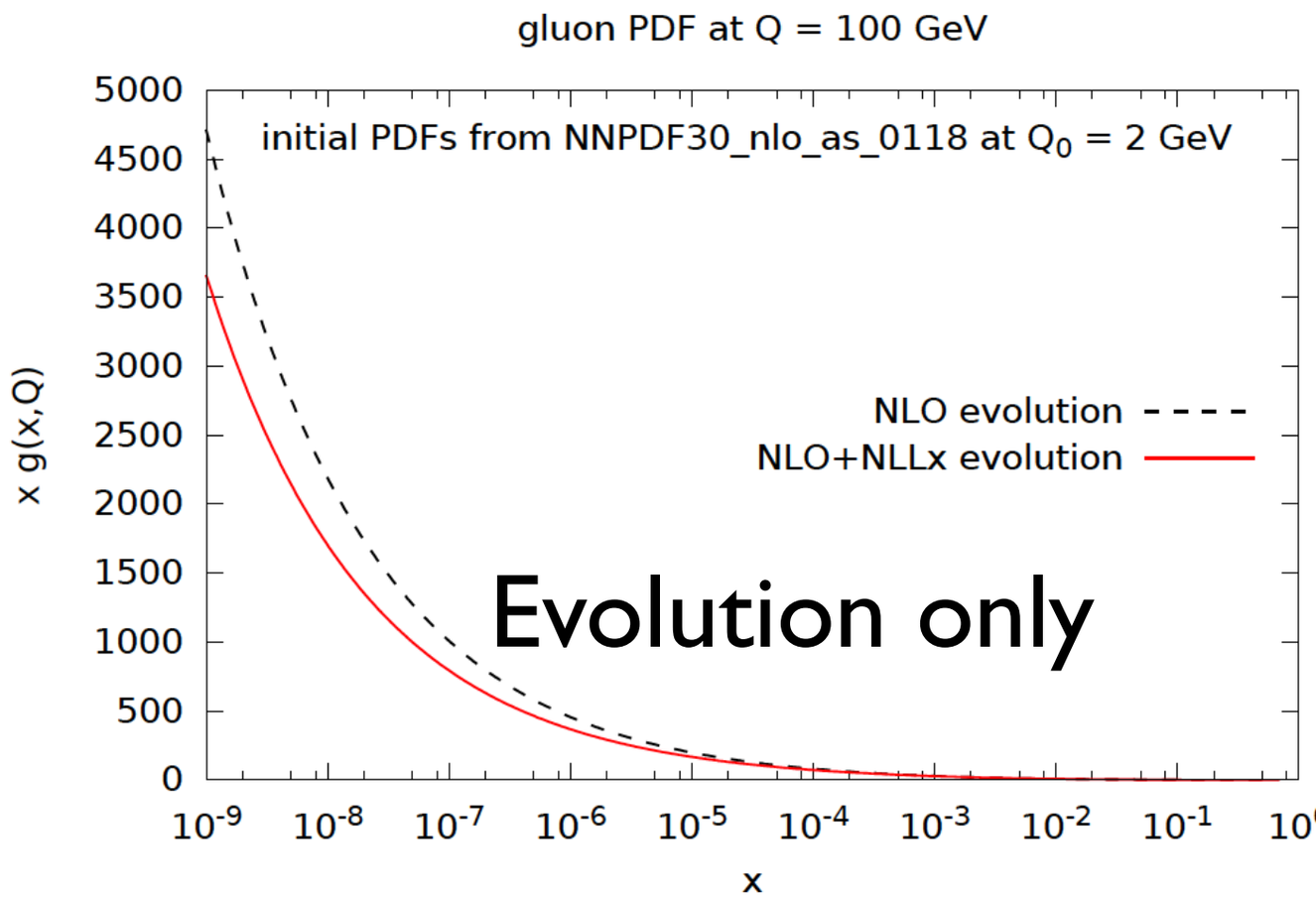
- The **HELL** code [arXiv:1607.02153] has been interfaced to APFEL:
  - based on the ABF formalism (e.g. see [hep-ph/9501231]).
  - Small-x **resummed splitting functions** up to **NLL** accuracy,
  - Small-x **resummed DIS coefficient functions** up to **NLL**:
    - massless,
    - massive.
  - **Resummed matching conditions**.
- It is now possible to compute structure functions in the FONLL GM-VFNS scheme including small-x resummation up to NLL.
- Forthcoming PDF fits in NNPDF.

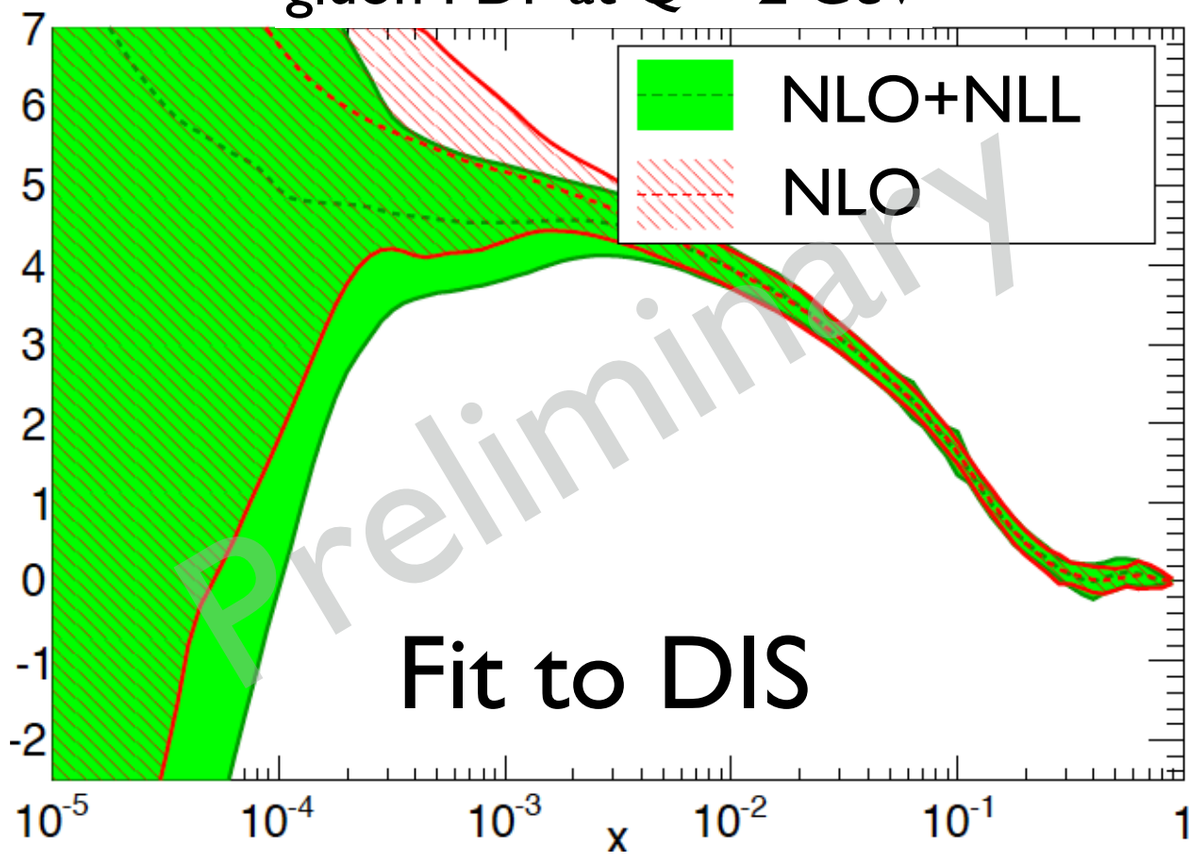
Small-x Resummation



🍏 Excellent agreement with `MassiveDIS` [Thanks to L. Rottoli]

Small-x Resummation





- Resummed evolution leads to a **suppression** of the **gluon PDF** at small values of x as compared to fixed order.
- **Compensation** when also resummed **coefficient functions** are introduced ⇒ effect on the small-x gluon PDF at the level of 1-σ.
- Other PDFs mostly unchanged.

NLO QCD+QED Corrections

Evolution

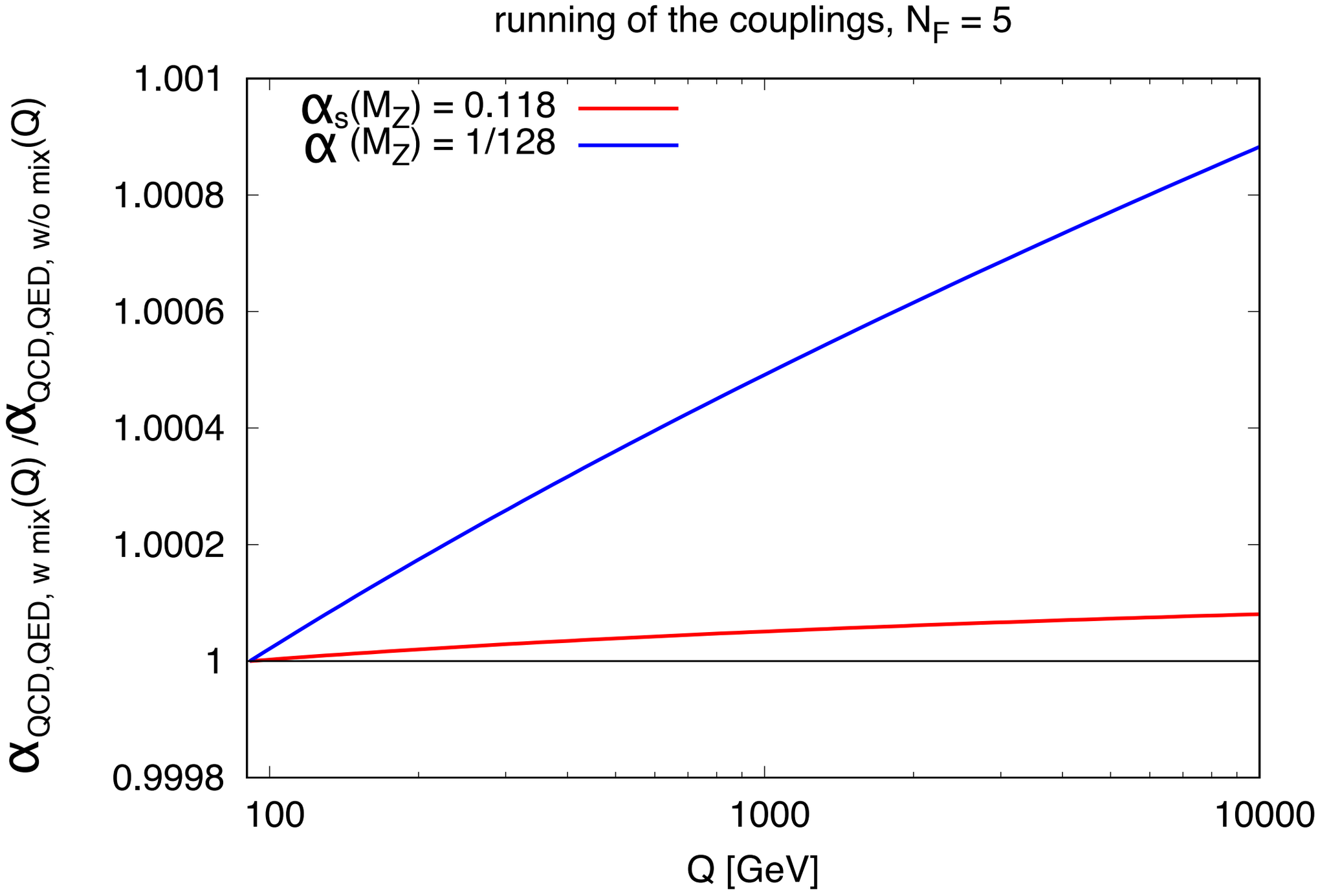
In order to implement the full NLO QCD+QED corrections in the DGLAP evolution two main steps are required:

1. Implementing the $O(\alpha_s^2\alpha)$, $O(\alpha^3)$, $O(\alpha^2\alpha_s)$ corrections to the **β-functions**:

   - running of α_s and α is coupled $\Rightarrow$ solve of a coupled ODE,
   - Numerical tests have shown that such terms lead to differences of $O(10^{-4})$ for α_s and $O(10^{-3})$ for α $\Rightarrow$ **unneeded complication**.

NLO QCD+QED Corrections

Coupling Evolution



- Mixed terms in the β-functions lead to negligible effects.

NLO QCD+QED Corrections

Evolution

In order to implement the full NLO QCD+QED corrections in the DGLAP evolution two main steps are required:

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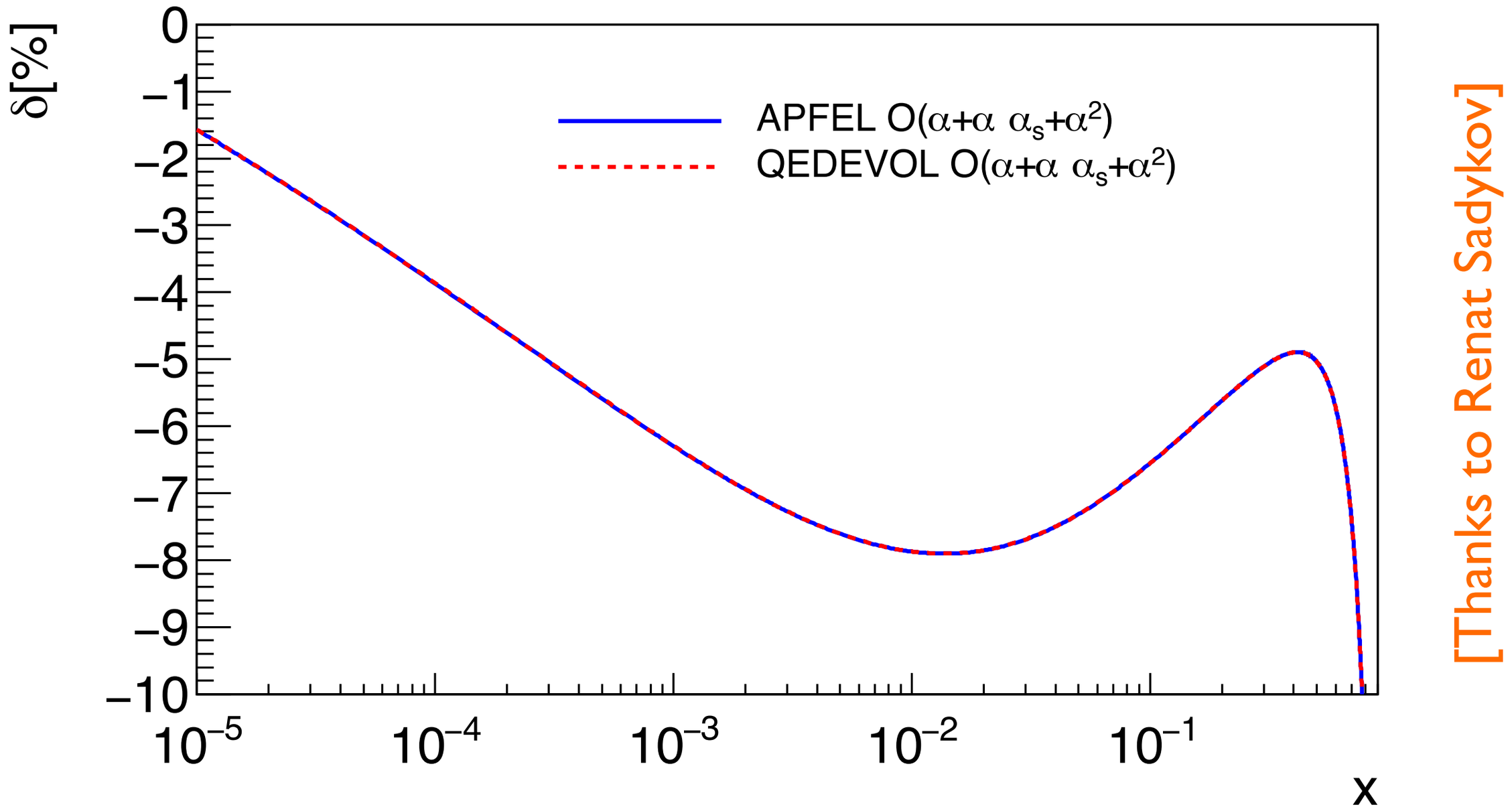
   - Numerical tests have shown that such terms lead to differences of $O(10^{-4})$ for α_s and $O(10^{-3})$ for α $\Rightarrow$ **unneeded complication**.

2. Implementing the $O(\alpha_s\alpha)$ and the $O(\alpha^2)$ corrections to the DGLAP **splitting functions** on top of the $O(\alpha)$ ones:

   - complication of the flavour structure due to the presence of terms promotional to e_q^2 and e_q^4 that break the isospin symmetry,
   - need for a more optimal evolution basis as compared to pure QCD.

NLO QCD+QED Corrections

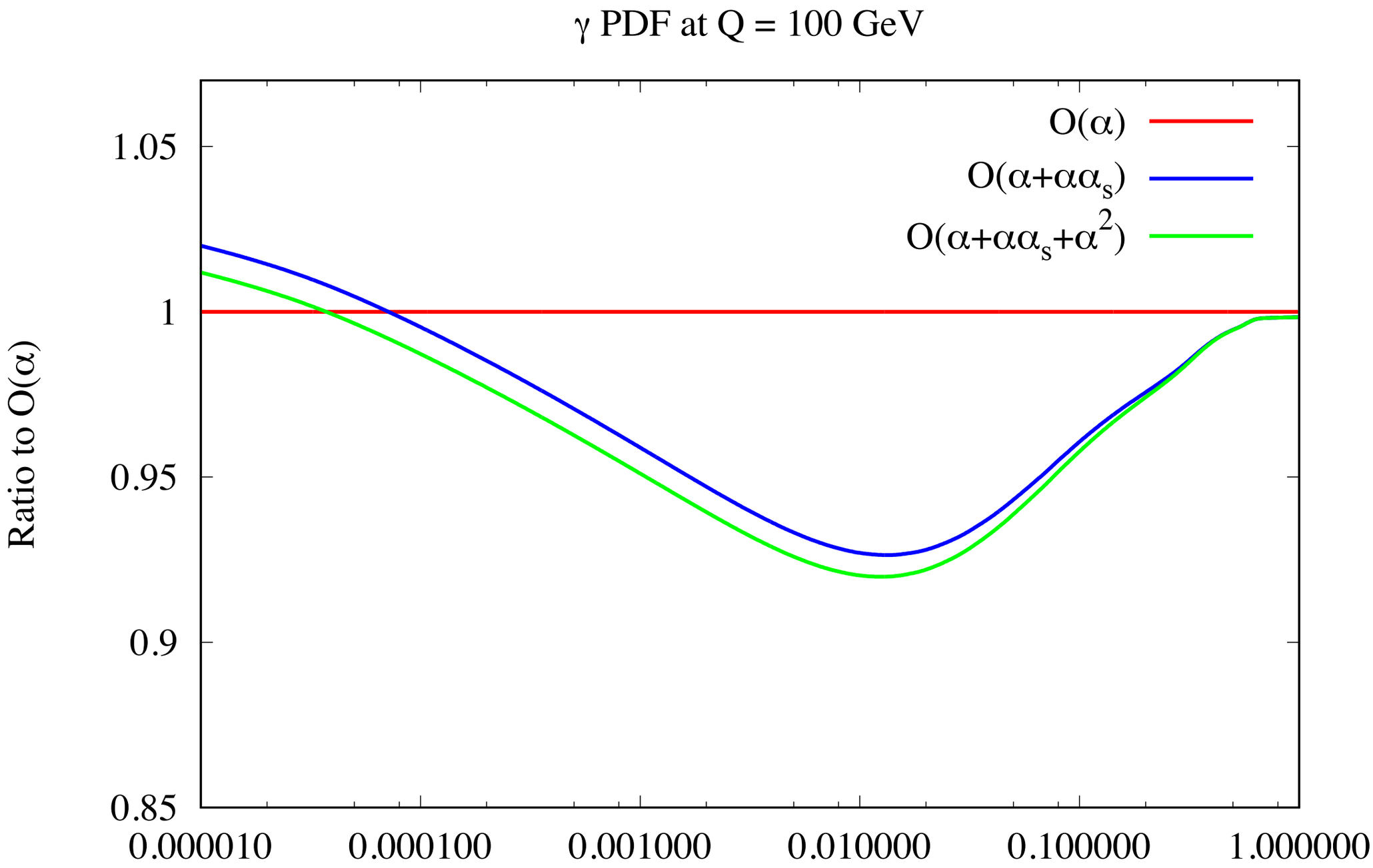
Benchmark against QEDEVOL



- Perfect agreement between APFEL and QEDEVOL.

NLO QCD+QED Corrections

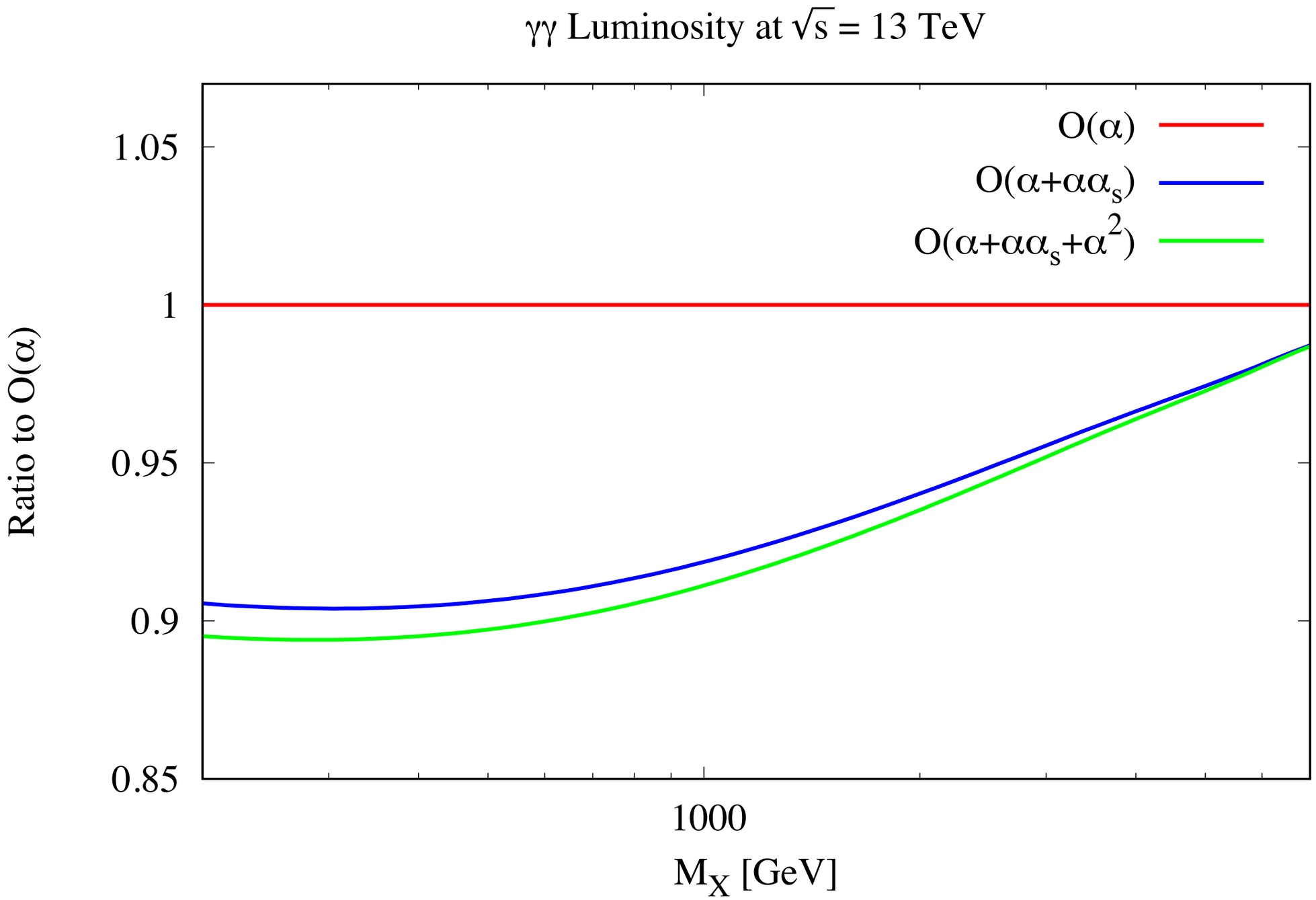
Photon PDF



- Effect on the photon PDF of the NLO corrns. at the level of 5%.

NLO QCD+QED Corrections

Photon Luminosity



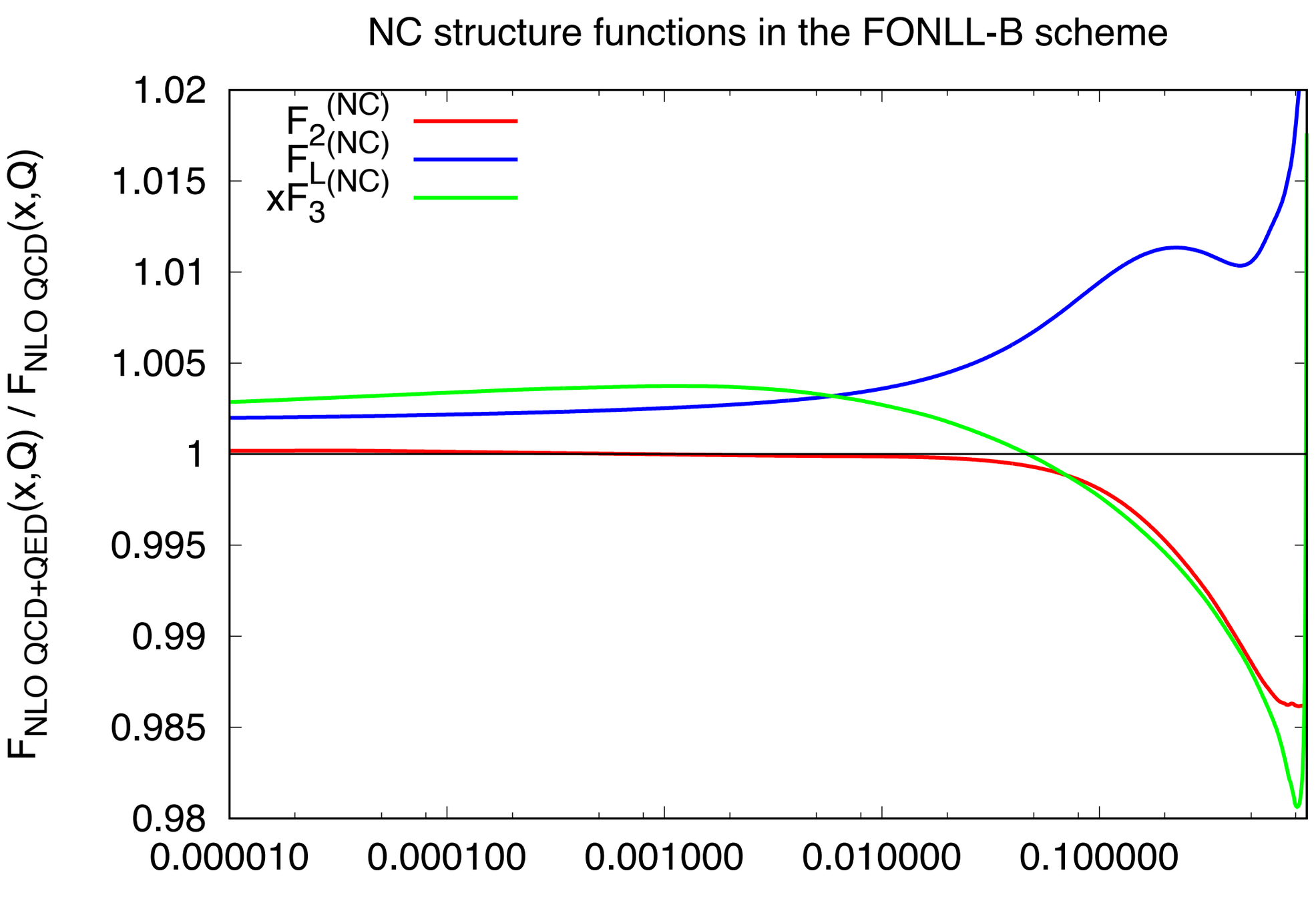
- More sizeable effect on the γγ luminosity.

NLO QCD+QED Corrections
DIS Structure Functions

- While at LO in QED no corrections to the DIS structure functions are required ($\gamma^* q \to q$ itself is the LO), at NLO in QED $O(\alpha)$ corrections need to be taken into account:
  - **new diagrams**: $\gamma^*\gamma \to q\overline{q}$ and $\gamma^* q \to q\gamma$,
    - easily derivable from the corresponding QCD diagrams.
- The additional diagrams offer a **direct handle** on the photon PDF in DIS observables:
  - at LO in QED the photon PDF was entirely driven by the evolution.
- Small contribution proportional to $\alpha\gamma \sim O(\alpha^2)$ but can be relevant in some kinematic regions:
  - typically at large x and large Q^2.

NLO QCD+QED Corrections

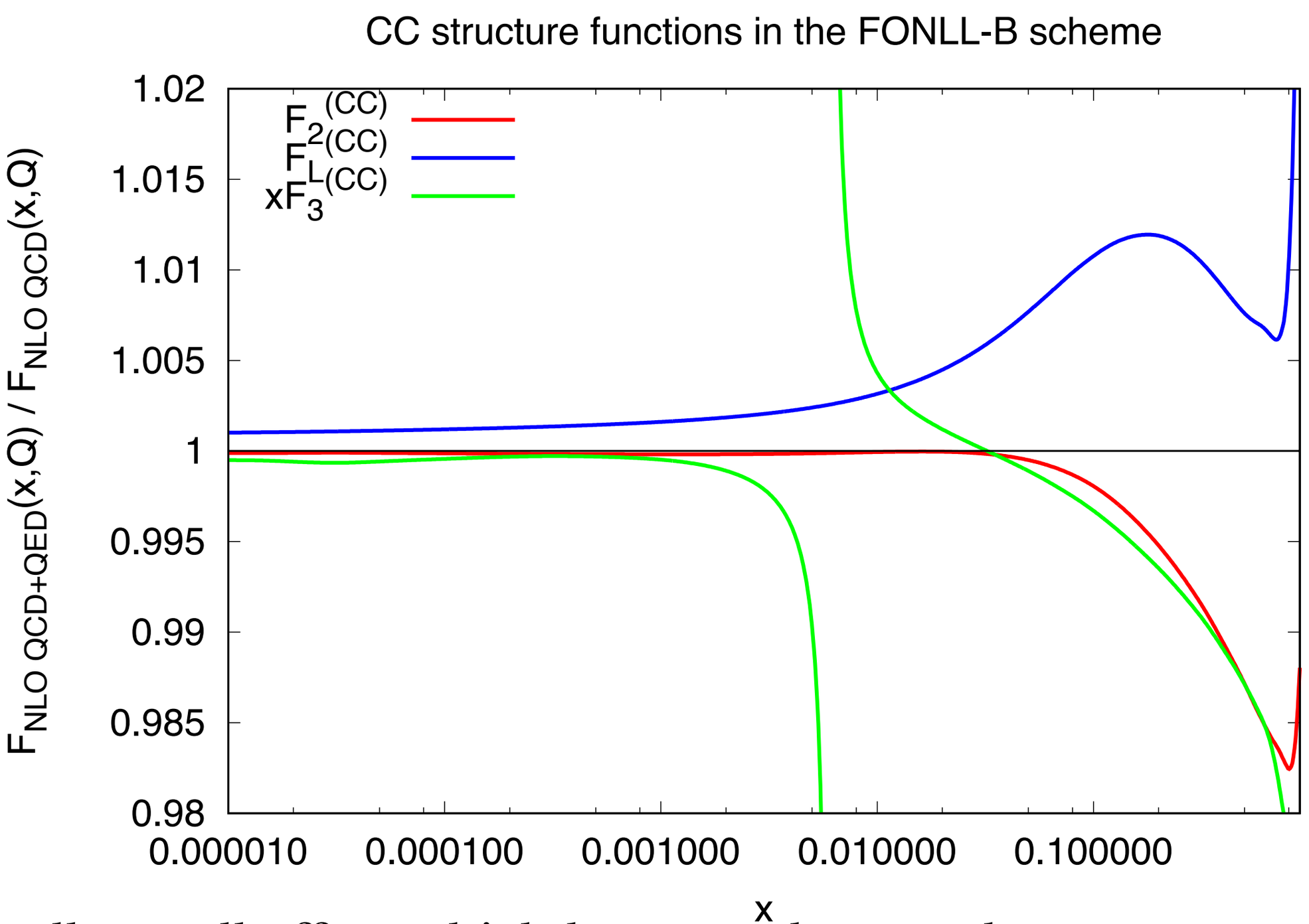
DIS Structure Functions (NC)



- Generally small effect which becomes large at large x.

NLO QCD+QED Corrections

DIS Structure Functions (CC)

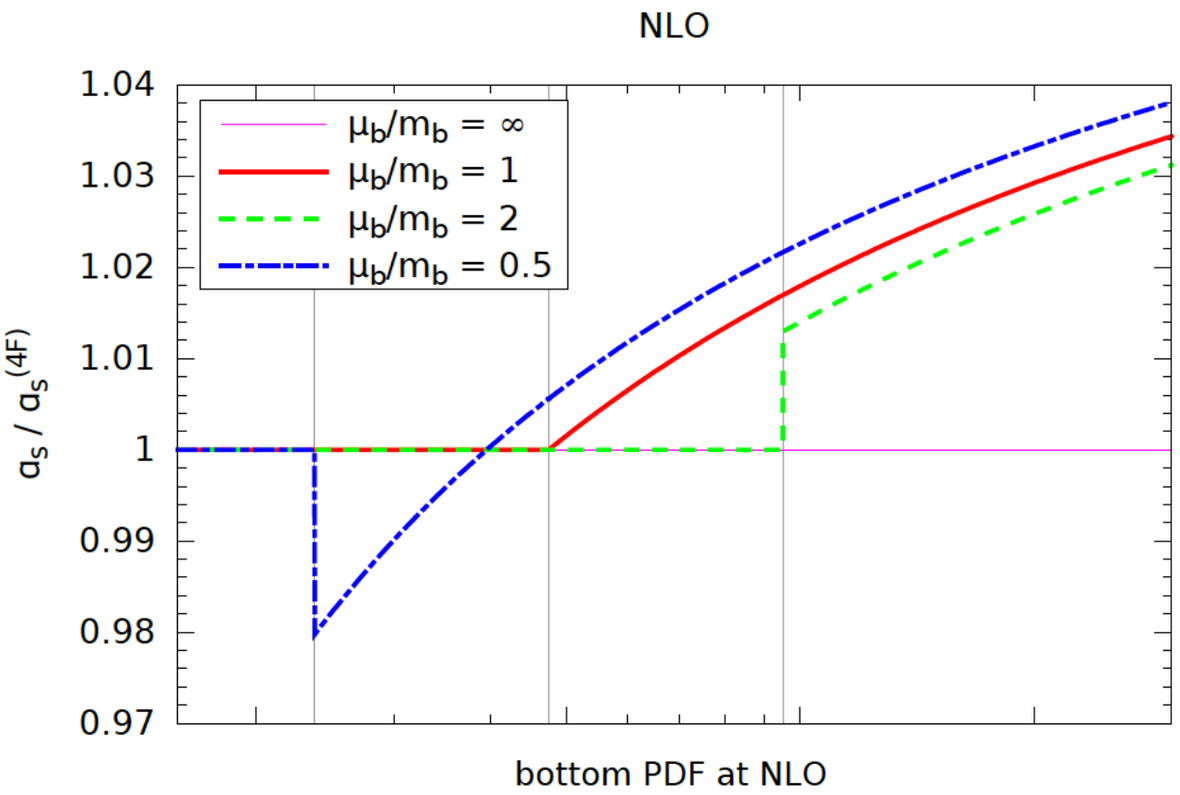


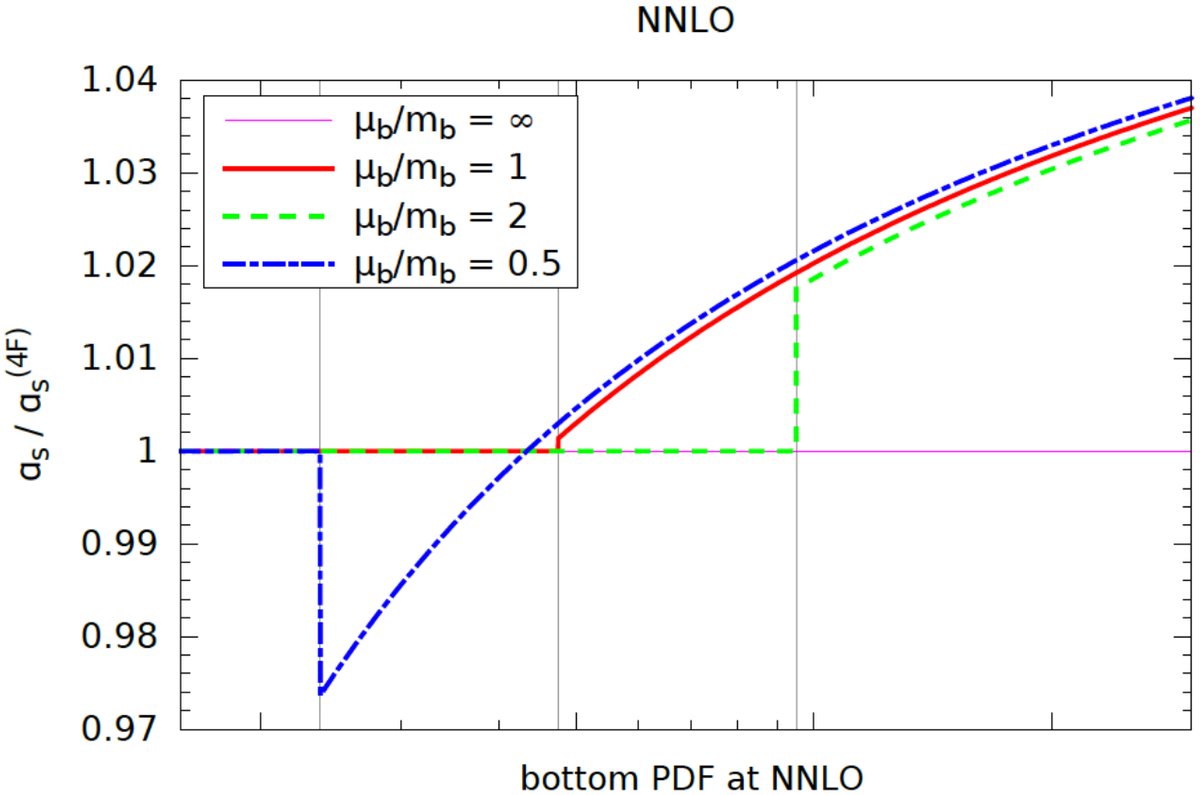
- Generally small effect which becomes large at large x.

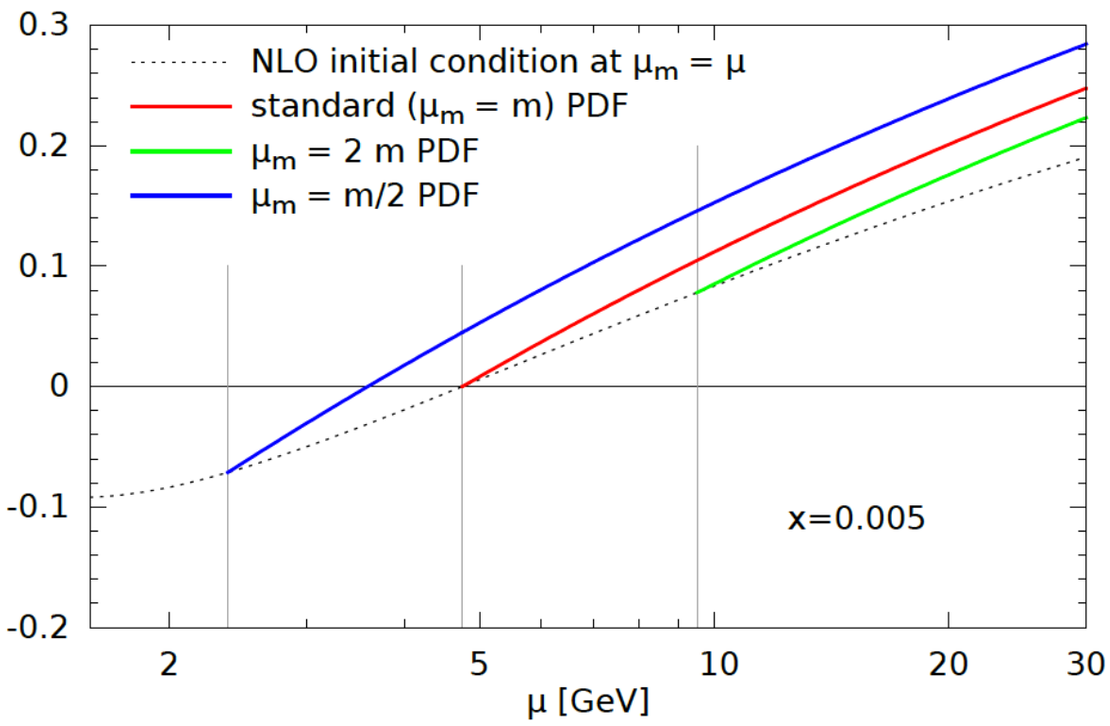
Displaced Heavy-Quark Thresholds

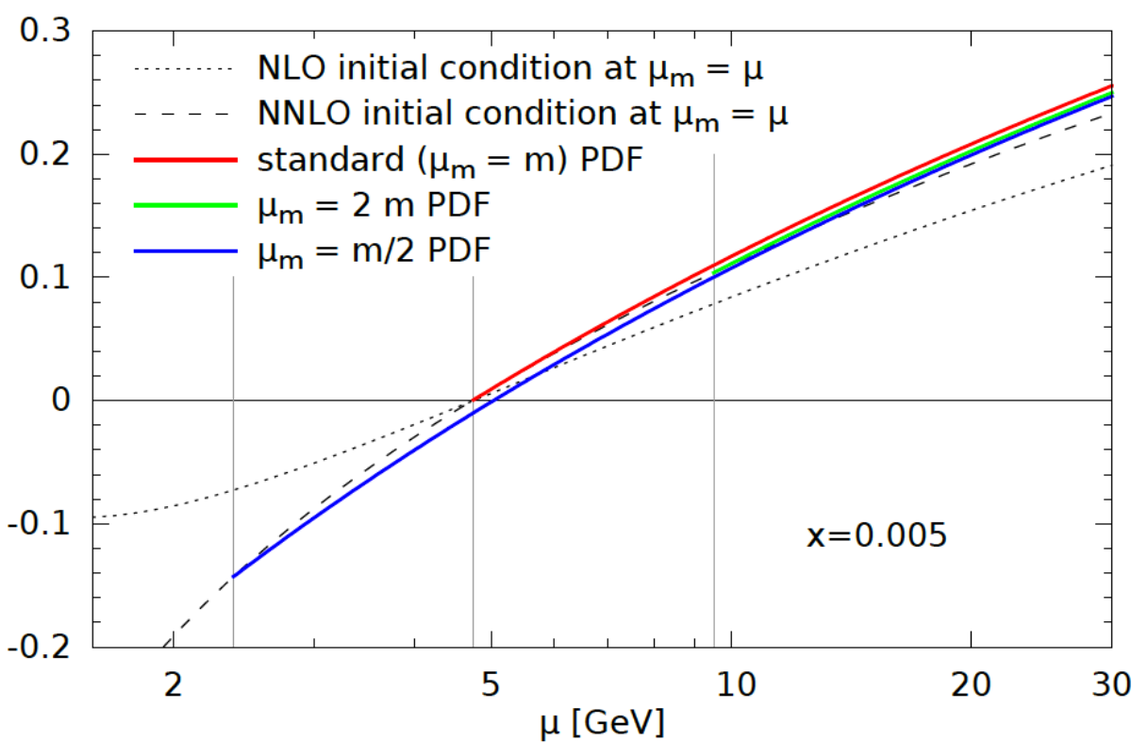
- The implementation of the VFNS evolution both for PDFs and α_s requires **matching** factorisation schemes differing in the number of active flavours:
  - the scale at which two consecutive factorisation schemes are matched are usually referred to as **heavy-quark thresholds**.
  - Heavy-quark thresholds 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 "generalised" including **logarithmic terms**.
- 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 $\overline{\text{MS}}$ renormalisation schemes.

Displaced Heavy-Quark Thresholds







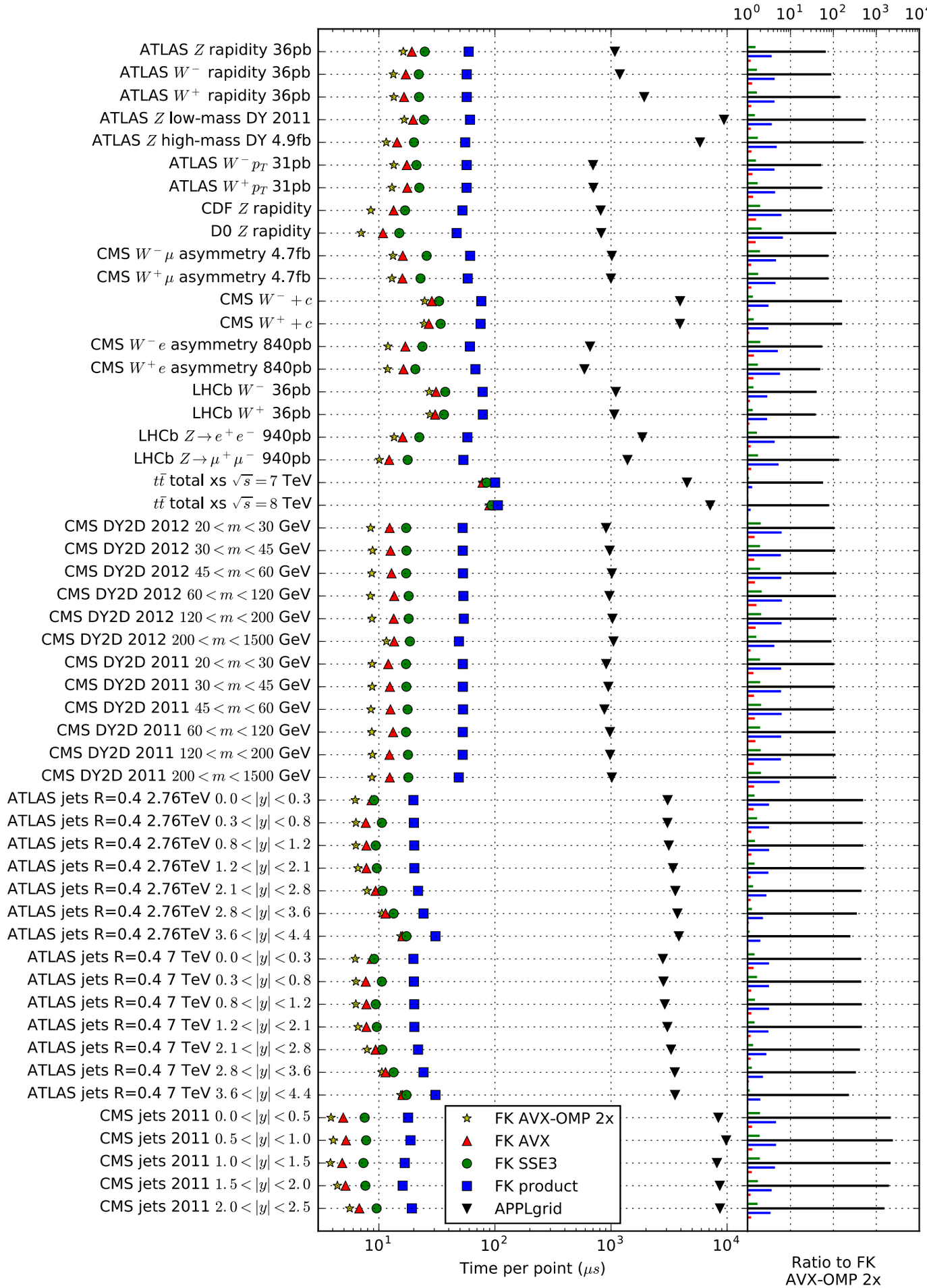


M. Bonvini et al. [arXiv:1508.03288]

APFELgrid

A fast(er) interface for PDF fits

- While being extremely useful tools, **APPLgrid** and **FastNLO** might not be appropriate to be directly employed in a global PDF fit where usually **thousands of iterations** are needed:
  - need to calculate PDF and α_s **evolution in real time**.
  - **not particularly fast** convolution.
    - many tables need to be loaded with the concrete risk of **exceeding the memory limit** (pretty common on clusters).
- We developed **APFELgrid** which, starting from an APPLgrid, combines the PDF evolution from APFEL to the hard cross sections producing *derived* tables (FK tables) to be directly convoluted with the initial scale PDFs.
- APFELgrid relies on the precomputation of the evolution of α_s and PDFs:
  - less flexible than APPLgrid as the evolution parameters (perturbative order, reference value of α_s, heavy-quark thresholds, etc.) cannot be changed.



[V. Bertone, S. Carrazza, N.P. Hartland, Comput.Phys.Commun. 212 (2017) 205-209]

APFEL++

An object oriented rewriting of APFEL

- APFEL core is currently based on **FORTRAN77**.
- It thus provides "**singleton objects**", *i.e.* it is not possible to instantiate different evolutions and/or structure functions with different parameters.
- It includes a **large number of features**:
  - limited modularity ⇒ **hard to maintain and extend**,
  - static memory management ⇒ **large memory footprint** to ensure appropriate accuracy for all foreseeable applications.
- **C++** provides a natural solution to these issues:
  - possibility to instantiate any number of evolutions and structure functions,
  - **modularity** ensured by the possibility to define objects,
  - optimal memory management,
  - based on C++11 standard (Lambda funcs., auto declaration, smart pointers, etc.)

APFEL++

An object oriented rewriting of APFEL

- A good excuse to do better:
  - improve integration procedure (faster and more accurate):

```
Initialization... elapsed time: 0.209144 seconds
Tabulation... elapsed time: 0.111195 seconds
```

  - improve interpolation procedure:

```
Interpolating 1000000 times PDFs on the (x,Q) grid... elapsed time: 0.604006 seconds
```

  - overload operators to make convolutions in an easy way:

```
//_____________________________________________________________________________
Set<Distribution> Dglap::Derivative(int const& nf, double const& t, Set<Distribution> const& f) const
{
  return _SplittingFunctions(nf, exp(t/2)) * f;
}
```

  - use the same technology for specific hadronic observables (*e.g.* double differential DY).
  - Exploit CPU acceleration techniques (AVX, SSE).

APFEL++

An object oriented rewriting of APFEL

vbertone@MacBook-Pro-di-Valerio.local: ~/Codes/apfelxx/tests — -b...

vbert...cern.ch | vberto...-bash | vberto...-bash ... | vbe...bash ... >>

```
Initialization... elapsed time: 0.212053 seconds
Evolution (4th order Runge-Kutta with 10 steps) from Q0 = 1.414214e+00 G
eV to Q = 1.000000e+02 GeV... elapsed time: 0.039274 seconds

AlphaQCD(Q) = 1.156047e-01

   x        u-ubar       d-dbar     2(ubr+dbr)     c+cbar        gluon
1.0e-05  3.1907e-03  1.9532e-03  3.4732e+01  1.5875e+01  2.2012e+02
1.0e-04  1.4023e-02  8.2749e-03  1.5617e+01  6.7244e+00  8.8804e+01
1.0e-03  6.0019e-02  3.4519e-02  6.4173e+00  2.4494e+00  3.0404e+01
1.0e-02  2.3244e-01  1.3000e-01  2.2778e+00  6.6748e-01  7.7913e+00
1.0e-01  5.4993e-01  2.7036e-01  3.8526e-01  6.4464e-02  8.5267e-01
3.0e-01  3.4622e-01  1.2833e-01  3.4600e-02  4.0132e-03  7.8898e-02
5.0e-01  1.1868e-01  3.0811e-02  2.3200e-03  2.3753e-04  7.6403e-03
7.0e-01  1.9486e-02  2.9901e-03  5.2355e-05  5.6022e-06  3.7082e-04
9.0e-01  3.3523e-04  1.6935e-05  2.5757e-08  4.3401e-09  1.1724e-06

vbertone@MacBook-Pro-di-Valerio:~/Codes/apfelxx/tests$
```

vbertone@lxplus037.cern.ch: ~/hoppet-qed/example_f90 — ssh vberton...

vbert...cern.ch | vberto...-bash | vberto...-bash ... | vbe...bash ... >>

```
WARNING in InitMTMNNLO: using parametrisation  (less accuracte) for A2PS
hg
Streamlined initialization completed!
Evolution done!

          Evaluating PDFs at Q =  100.000 GeV
   x        u-ubar       d-dbar     2(ubr+dbr)     c+cbar        gluon
1.0E-05  3.1907E-03  1.9532E-03  3.4732E+01  1.5875E+01  2.2012E+02
1.0E-04  1.4023E-02  8.2749E-03  1.5617E+01  6.7244E+00  8.8804E+01
1.0E-03  6.0019E-02  3.4519E-02  6.4173E+00  2.4494E+00  3.0404E+01
1.0E-02  2.3244E-01  1.3000E-01  2.2778E+00  6.6746E-01  7.7912E+00
1.0E-01  5.4993E-01  2.7035E-01  3.8526E-01  6.4466E-02  8.5266E-01
3.0E-01  3.4622E-01  1.2833E-01  3.4600E-02  4.0134E-03  7.8898E-02
5.0E-01  1.1868E-01  3.0811E-02  2.3198E-03  2.3752E-04  7.6398E-03
7.0E-01  1.9486E-02  2.9901E-03  5.2352E-05  5.6038E-06  3.7080E-04
9.0E-01  3.3522E-04  1.6933E-05  2.5735E-08  4.3368E-09  1.1721E-06
vbertone@lxplus037:~/hoppet-qed/example_f90$
vbertone@lxplus037:~/hoppet-qed/example_f90$
```

APFEL

HOPPET

- Perfect agreement between APFEL and HOPPET.

Other Recent Developments

- **Intrinsic-charm** in DIS *a la* FONLL.
- **Polarised DGLAP evolution** up to NNLO.
- Independent factorisation and renormalisation **scale variations** both in the DIS structure functions and in the evolution,
- framework for the **determination of FFs**.

In the Pipeline

- Implementation of **TMD evolution** and **SIDIS cross sections**,
- Implementation of the **polarised structure functions**,
- **mass corrections** to SIA structure functions.

TMD Evolution (PDFs)

$$
\begin{aligned}
F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) &= \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b) && : A \\
&\times \exp\left\{ K(b_*; \mu_b) \ln \frac{\sqrt{\zeta_F}}{\mu_b} + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_F}}{\mu'} \right] \right\} && : B \\
&\times \exp\left\{ g_{j/P}(x, b_T) + g_K(b_T) \ln \frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}} \right\} && : C
\end{aligned}
$$

TMD Evolution (PDFs)

$$F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) = \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b) \quad : A$$

$$\times \exp\left\{ K(b_*; \mu_b) \ln \frac{\sqrt{\zeta_F}}{\mu_b} + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_F}}{\mu'} \right] \right\} \quad : B$$

$$\times \exp\left\{ g_{j/P}(x, b_T) + g_K(b_T) \ln \frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}} \right\} \quad : C$$

- $b_T \ll 1/\Lambda_{QCD}$
- matching to the collinear region
- factorises as hard and non-perturbative
- numerically cumbersome
- precompute using the APFEL technology

- CS evolution
- perturbative

- matching between the small and large b_T
- non perturbative
- parametrised and fitted to data

TMDs in SIDIS

- In SIDIS, what enters the computation of the cross sections is:

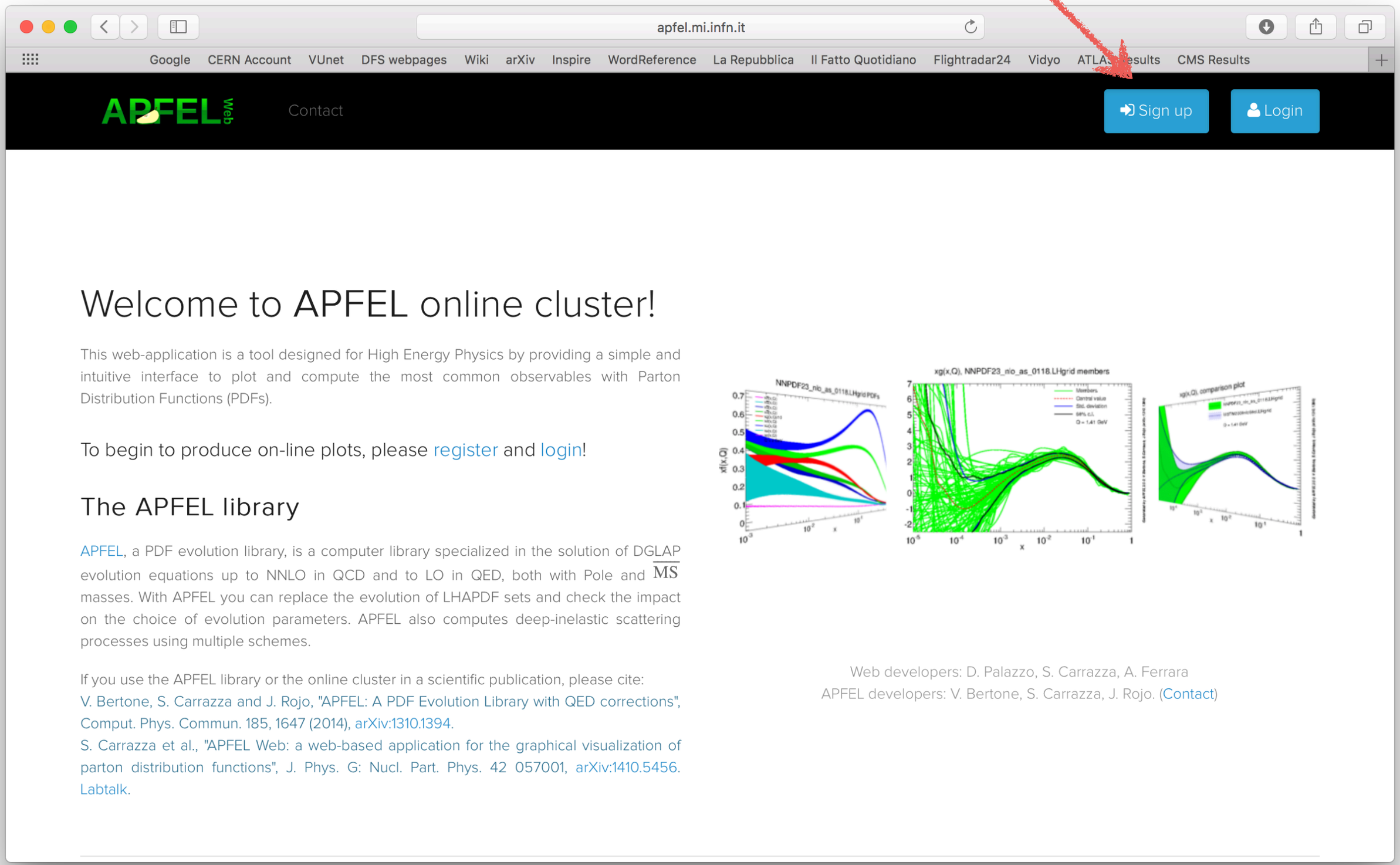
$$\mathcal{L}_{\rm SIDIS} = \int \frac{d^2\mathbf{b}_T}{(2\pi)^2} e^{-i\mathbf{q}_T\cdot\mathbf{b}_T} F_{f/P}(x,\mathbf{b}_T;\mu,\zeta_F) D_{H/f}(x,\mathbf{b}_T;\mu,\zeta_D)$$

Fourier transform PDFs FFs

- The ingredients are:
  - a set of evolved TMD-PDFs,
  - a set of evolved TMD-FFs,
  - the Fourier transform of its product.
- Complex set of tasks that have to be performed optimally
- APFEL provides the ideal environment for this computation:
  - fast and accurate interpolation techniques,
  - precomputation of the time consuming bits.

APFEL Web

Go to http://apfel.mi.infn.it and sign up



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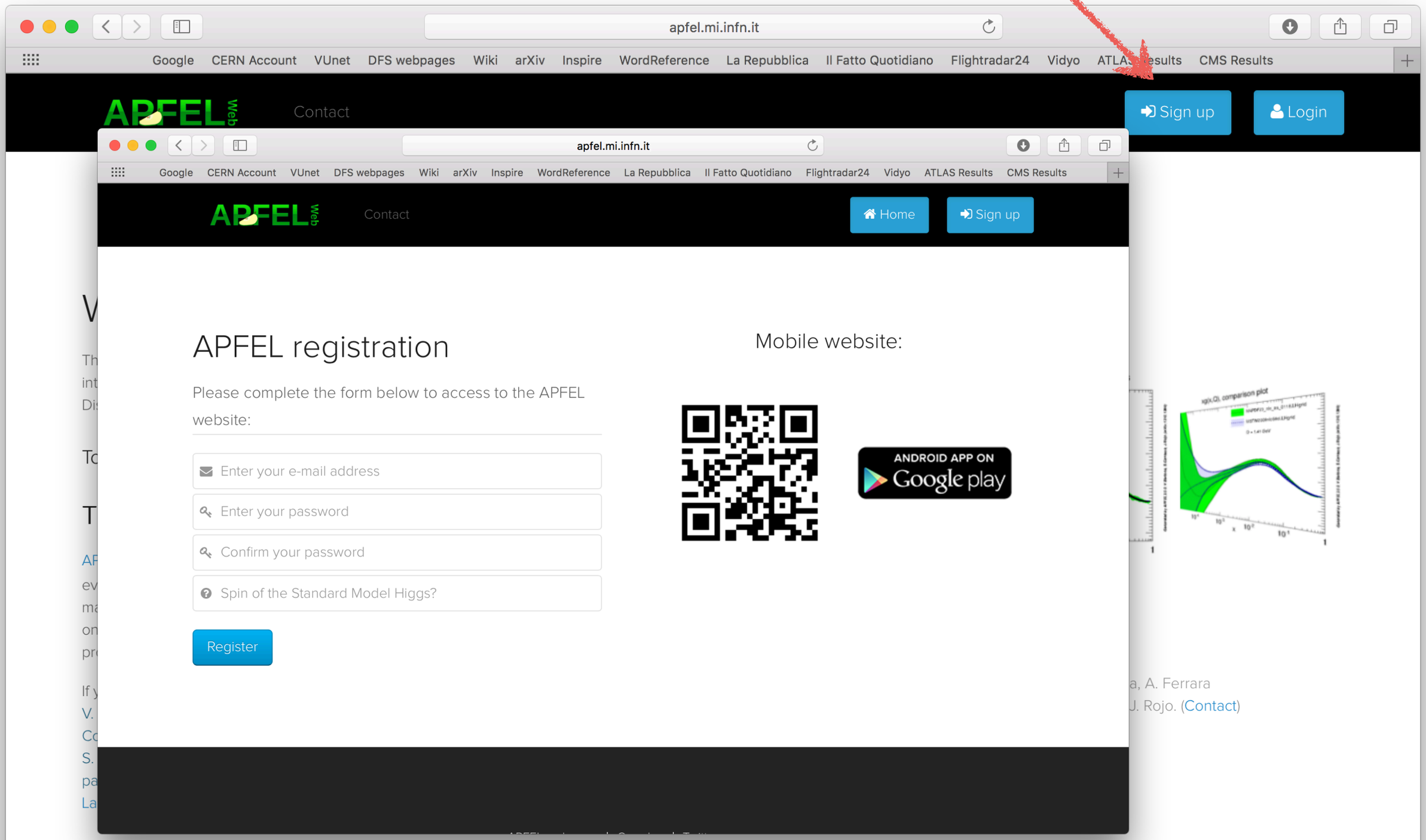
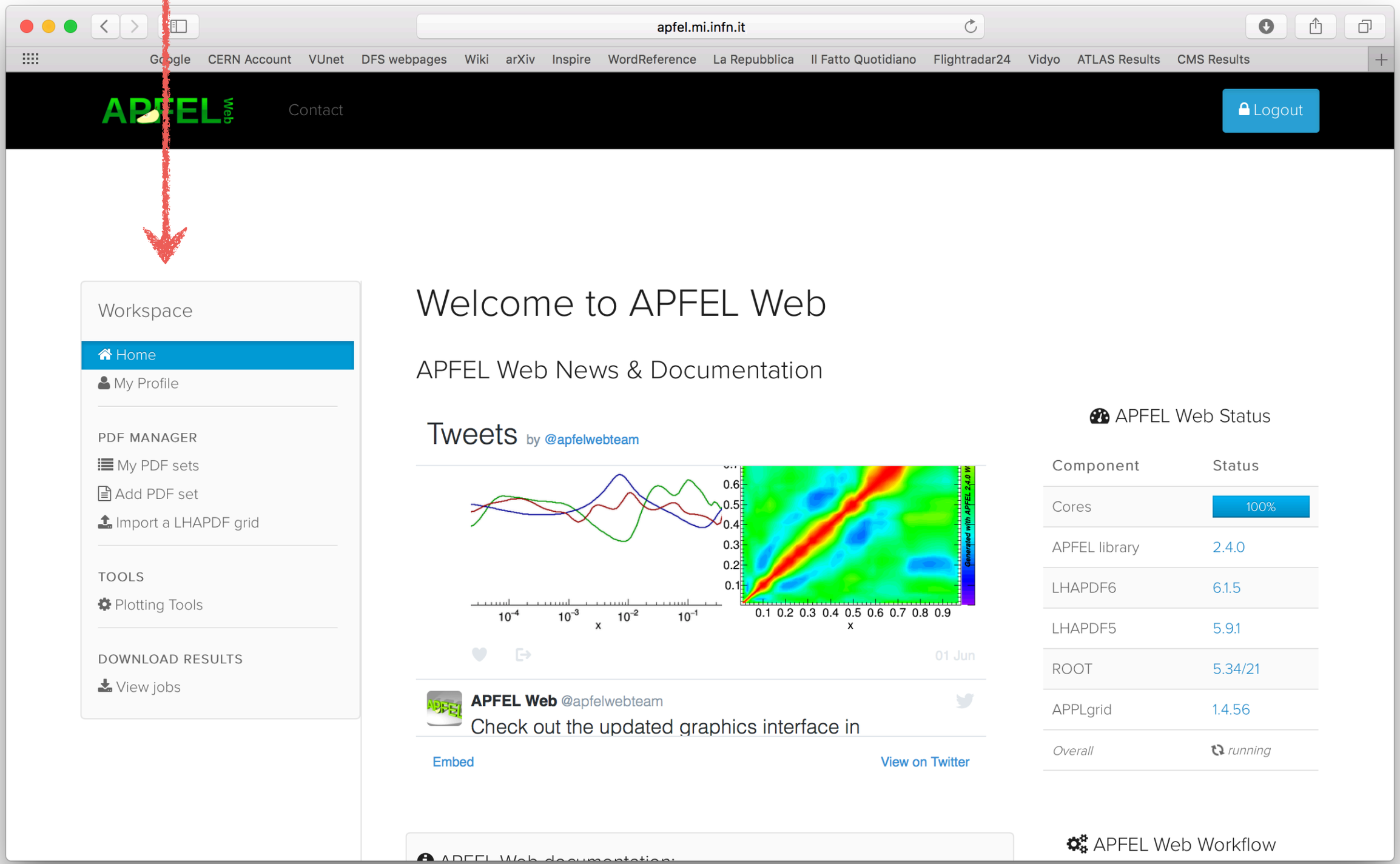


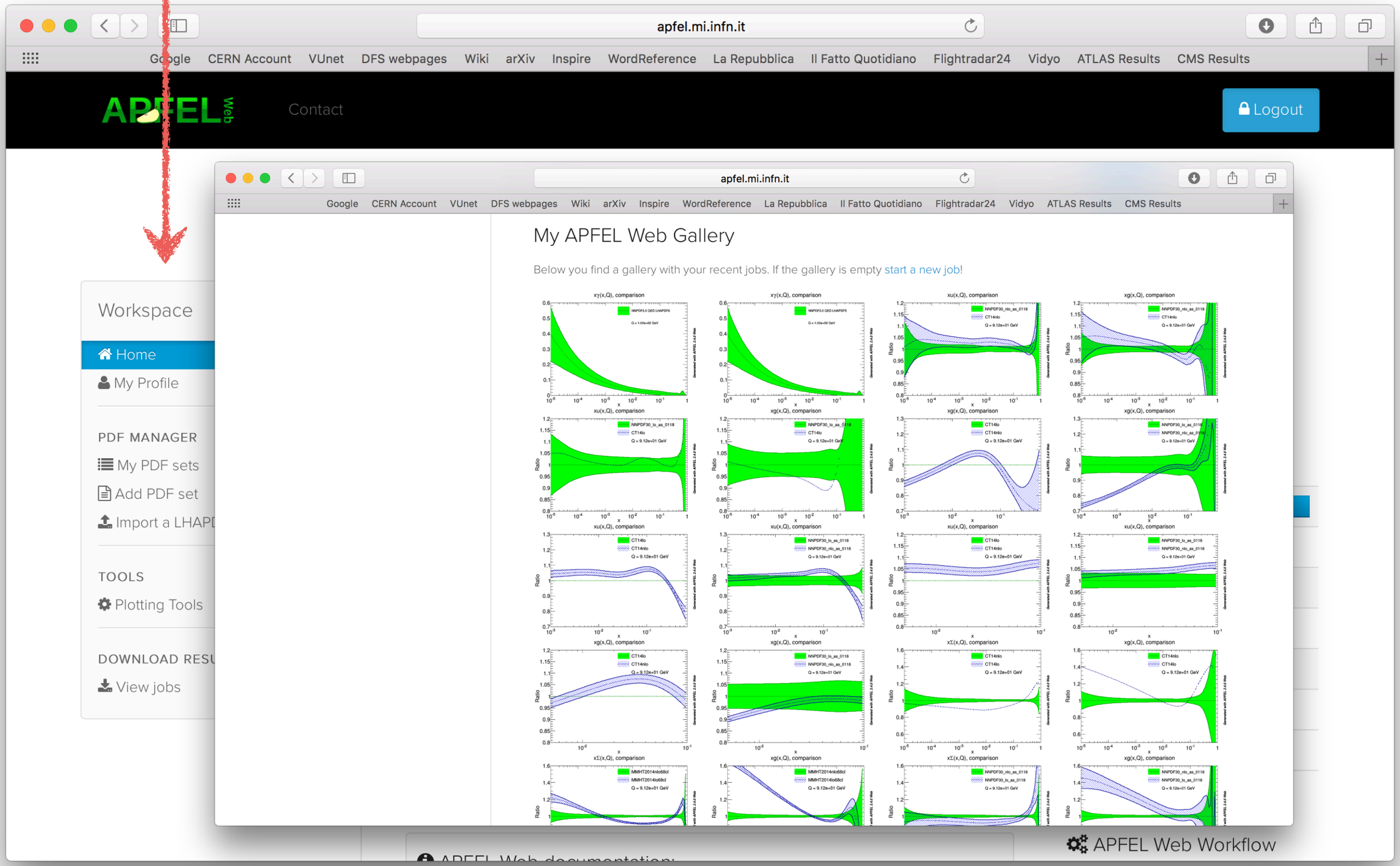
APFEL Web

Workspace



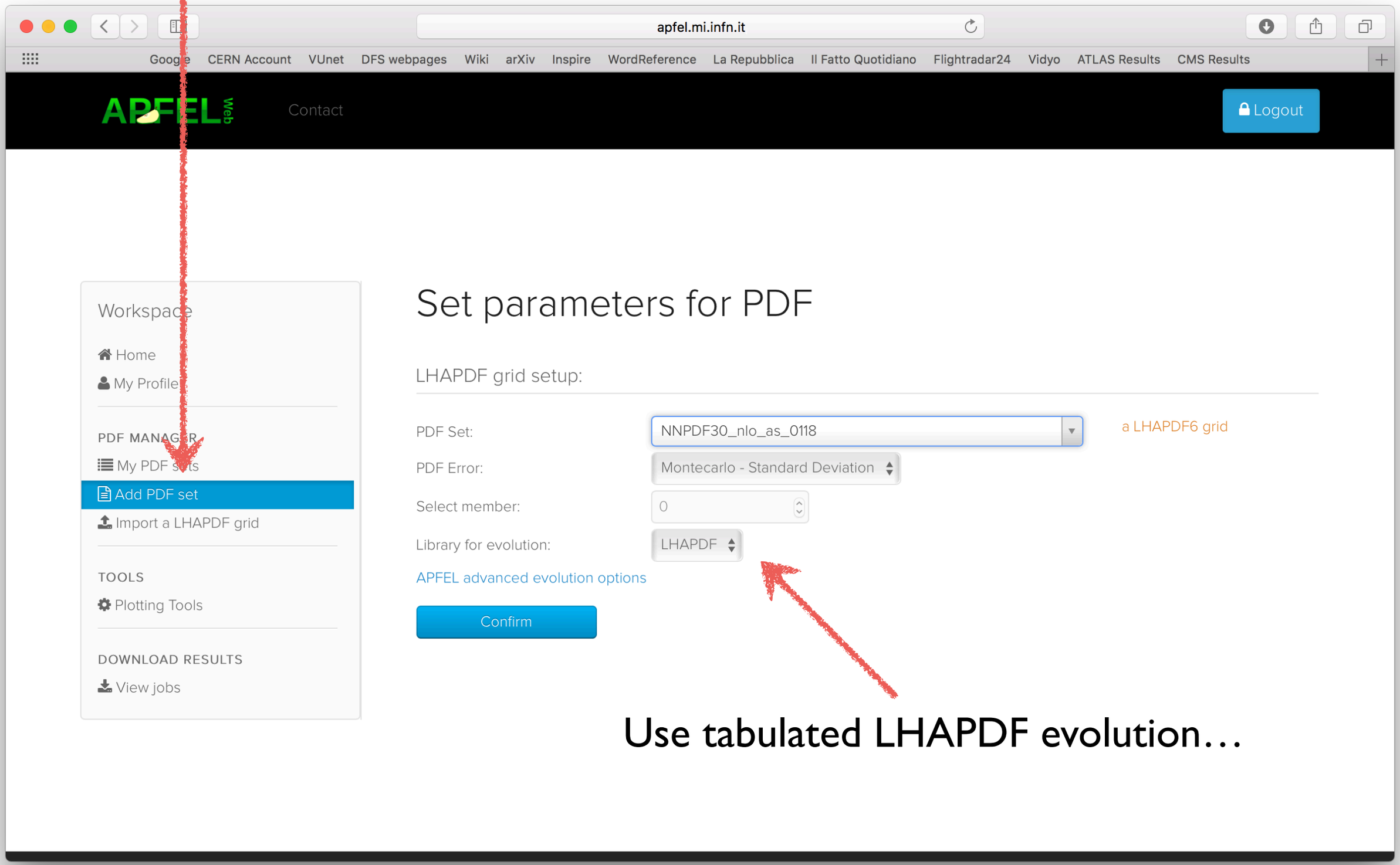
APFEL Web

Workspace



APFEL Web

Add a new PDF set



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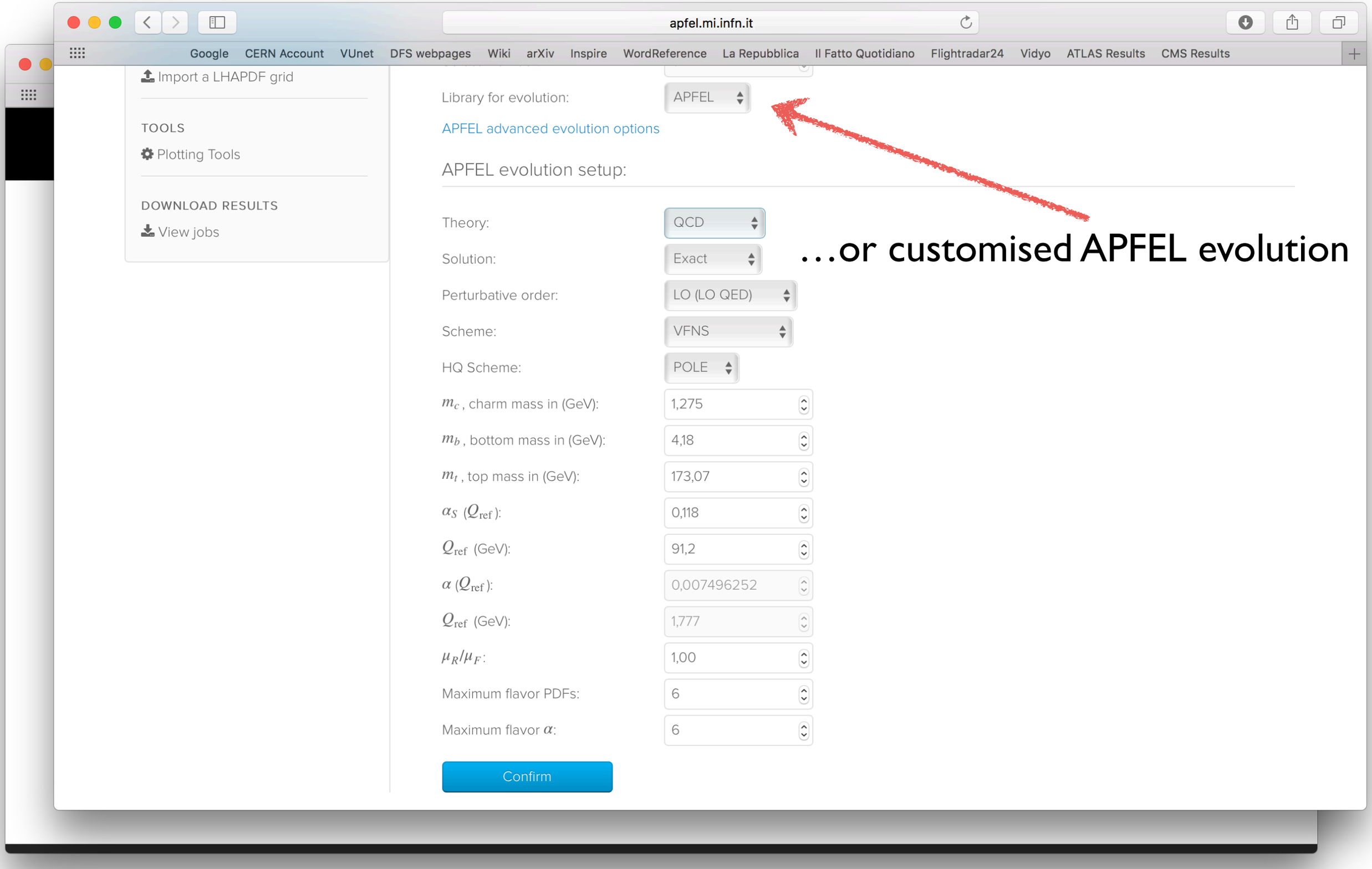


…or customised APFEL evolution

APFEL Web

Plotting tools

apfel.mi.infn.it

VUnet DFS webpages Wiki arXiv Inspire WordReference La Repubblica

Workspace

- Home
- My Profile

PDF MANAGER

- My PDF sets
- Add PDF set
- Import a LHAPDF grid

TOOLS

- Plotting Tools

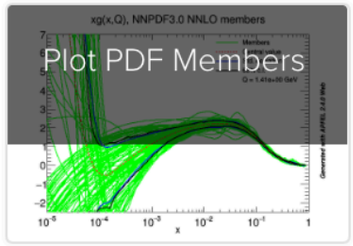
DOWNLOAD RESULTS

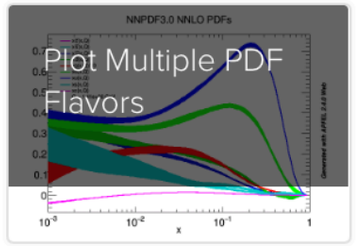
- View jobs

Choose a plotting tool and select your PDF set

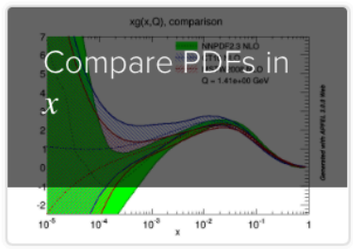
Some jobs, like PDF luminosities, require some time to be finalized. Check the job status at View jobs page.
The plotting tools can be used for both the LHAPDF libraries: LHAPDF5 and LHAPDF6.

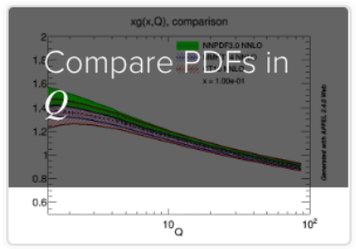
Tools for PDF basic plotting

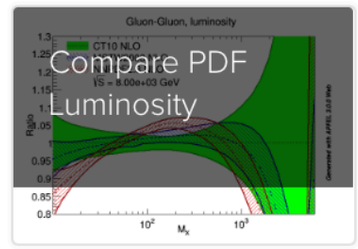


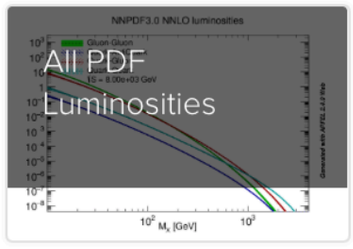


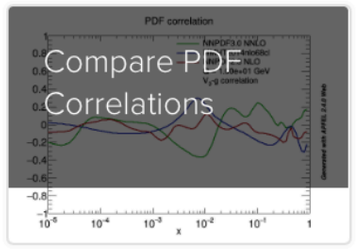
Tools for PDF analysis & comparisons

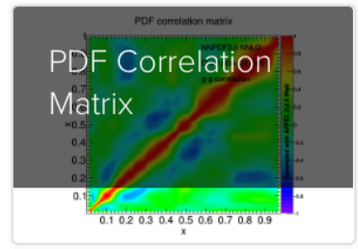




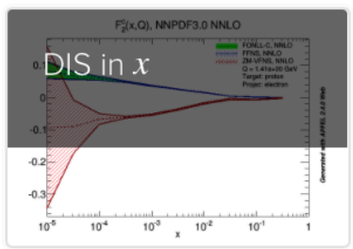


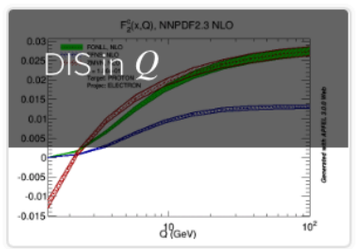


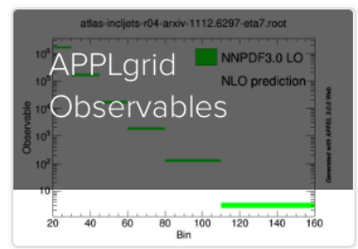




Tools for theoretical predictions from PDFs







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