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APFEL update

NLO QED corrections - Preliminary APFEL 3.0.0 Braeburn

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Motivation

Motivation for a new release:

- No **public code** for DGLAP evolution with $\mathcal{O}(\alpha + \alpha_s\alpha + \alpha^2)$.
- **Quantitative** description of these corrections.
- Incomplete **benchmark** available for these evolutions.
- Similar issues for **DIS** structure functions.

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New features in APFEL 3.0.0 Braeburn (preliminary):

- QED corrections up to NLO with QCD corrections up to NNLO
  - for **DGLAP** evolution and **DIS** structure functions.

Braeburn?

Origin: Nelson, New Zealand, 1950s

DGLAP evolution

NLO QED corrections in the DGLAP evolution (preliminary)

The inclusion of NLO QED corrections requires the implementation of:

- $\mathcal{O}(\alpha_s\alpha)$ and $\mathcal{O}(\alpha^2)$ corrections to the DGLAP **splitting functions** on top of the $\mathcal{O}(\alpha)$ (*De Florian et al.*, arXiv:1606.02887)
  - complication of the flavor structure due to the presence of terms proportional to e_q^2 and e_q^4 that break the isospin symmetry.
  - need of a more optimal evolution basis as compared to pure QCD (appendix of *Bertone et al.*, arXiv:1508.07002).

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- $\mathcal{O}(\alpha_s^2\alpha)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_s\alpha^2)$ corrections to the β-**functions**:
  - running of α_s and α is coupled $\Rightarrow$ solve a coupled ODE.
  - numerical tests show that such terms lead to differences of $\mathcal{O}(10^{-4})$ for α_s and $\mathcal{O}(10^{-3})$ for α $\Rightarrow$ negligible effects.

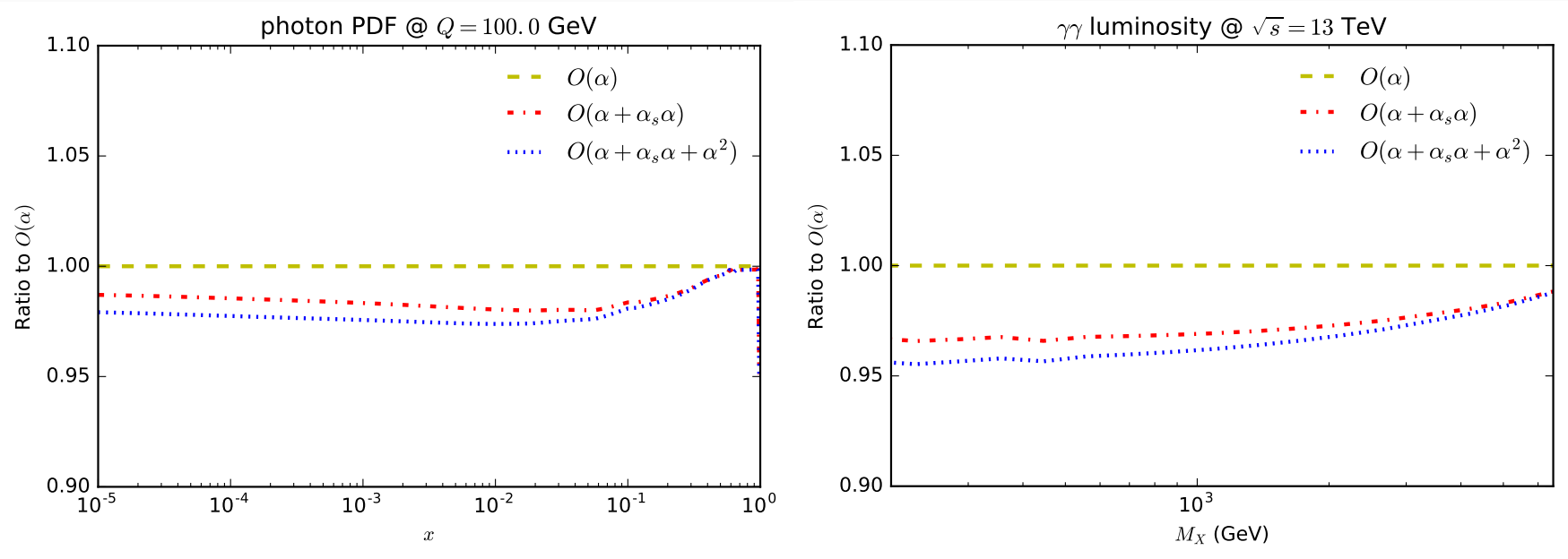
Mixed corrections to the β-functions **are not included** in APFEL 3.0.0.

NLO QED corrections in the DGLAP evolution (preliminary)

Preliminary exercise:

- take the **central value** of NNPDF3.0QED NLO and **re-evolve** with $\mathcal{O}(\alpha_s\alpha)$ and $\mathcal{O}(\alpha^2)$ corrections and compare to $\mathcal{O}(\alpha)$.

Some results for the **photon PDF** and **photon-photon luminosity**:

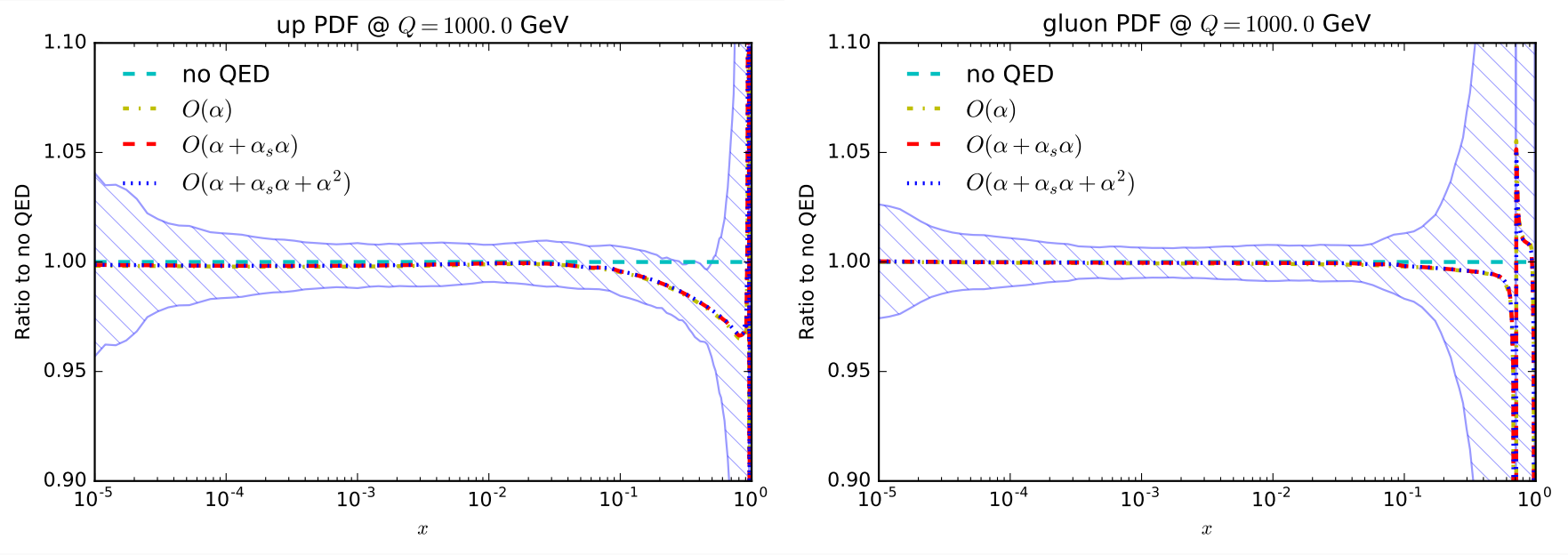


$\Rightarrow$ Relevant differences only if the photon PDF uncertainty is small.

NLO QED corrections in the DGLAP evolution (preliminary)

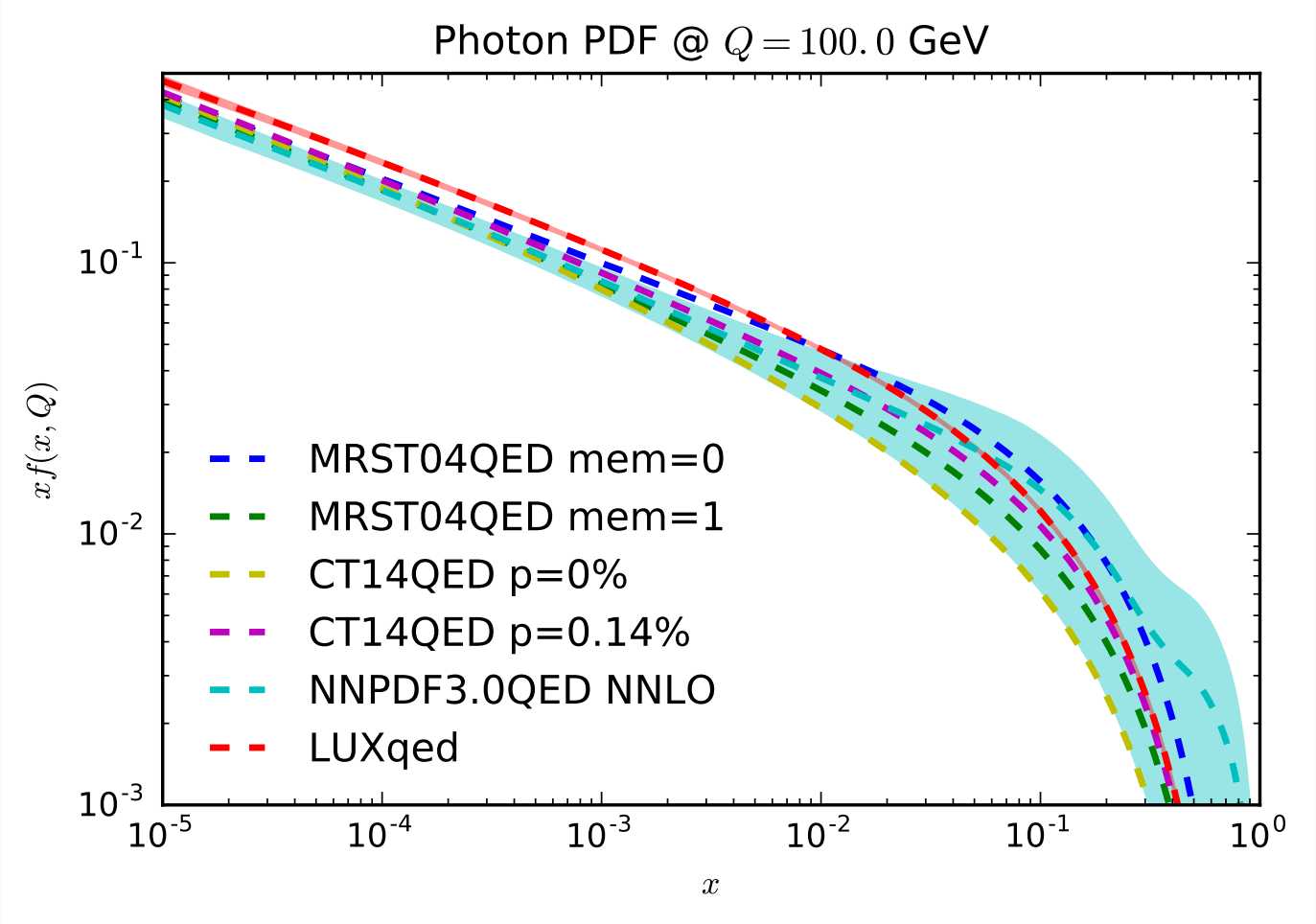
Negligible effect on QCD partons:

- visible differences between **"no QED"** and **"LO QED"** corrections for large values of x within uncertainties.
- LO vs NLO QED corrections are different $< 0.1\%$ for QCD partons.



Benchmark status

Since 2004 some photon PDF determinations are available:



where QED corrections are:

$$\mathcal{O}(\alpha)\text{: MSRT, NNPDF, CT} \quad \Longleftrightarrow \quad \mathcal{O}(\alpha + \alpha_s\alpha) \text{ : LUXqed}$$

Benchmark status

We have performed several benchmarks:

- Pure QCD: *Carrazza*, arXiv:1509.00209
  - HOPPET vs. APFEL (*sect. 2.4.1*)
- $\mathcal{O}(\alpha)$:
  - MRST vs. APFEL (*sect. 2.4.2*)
  - QCDNUM vs. APFEL (*sect. 2.4.2*)
  - partonevolution vs. APFEL (*sect. 2.4.2*)
- $\mathcal{O}(\alpha_s\alpha)$: TODO
  - LUXqed vs. APFEL

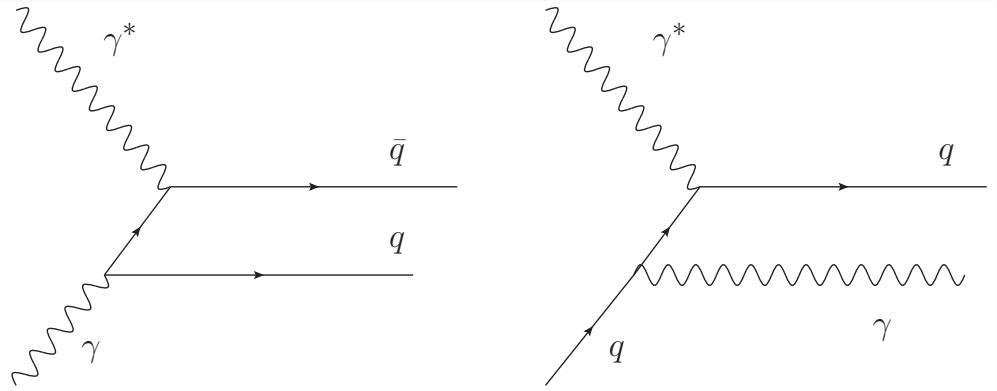
We think that a systematic benchmark of QCD+QED evolution codes is important and required today, as it was years ago for pure QCD evolution.

DIS Structure Functions

DIS Structure Functions (preliminary)

While at LO in QED no corrections to the DIS structure functions are required ($\gamma^* q \to \bar{q}$ is LO), at NLO in QED corrections need to be taken into account:

- new diagrams: $\gamma^*\gamma \to \bar{q}q$ and $\gamma^* q \to q\gamma$,
- easily derivable from the corresponding QCD diagrams.

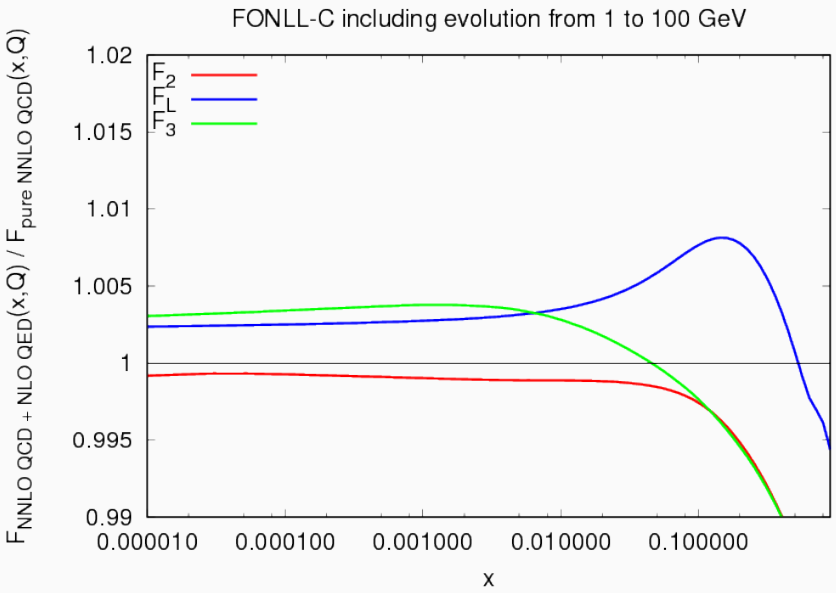


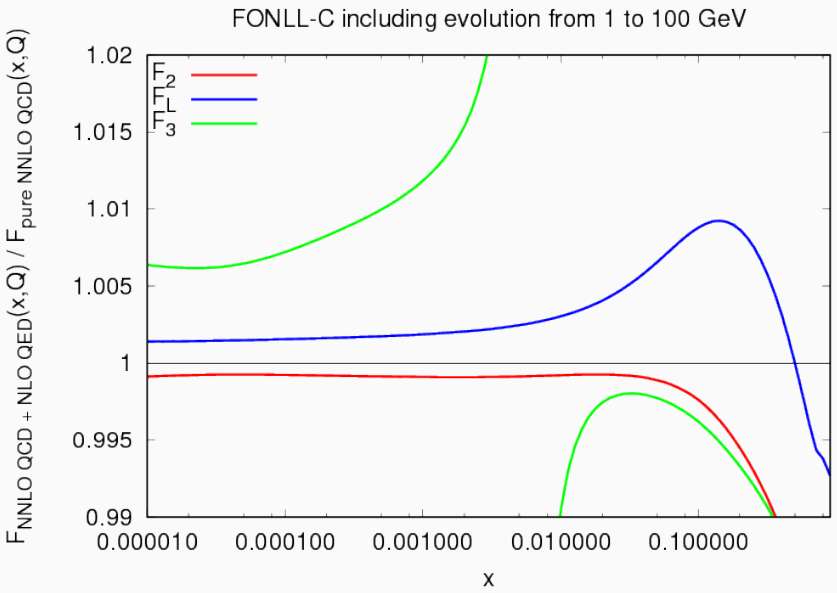
The additional diagrams offer a direct handle on the photon PDF in DIS observables.

Small contribution proportional to $\alpha\gamma \sim \mathcal{O}(\alpha^2)$ but can be relevant in some kinematic regions $\Rightarrow$ typically at large x and large Q^2.

DIS Structure Functions (preliminary)

NC and **CC** structure functions computed at NNLO QCD + NLO QED:





- **NC:** differences below 1% for $x < 0.1$, more pronounced effects for F_L and F_3.
- **CC:** differences below 1% at $x < 0.1$ for F_L and F_3, larger effects for F_2.

Summary

APFEL 3.0.0 Braeburn is available at:

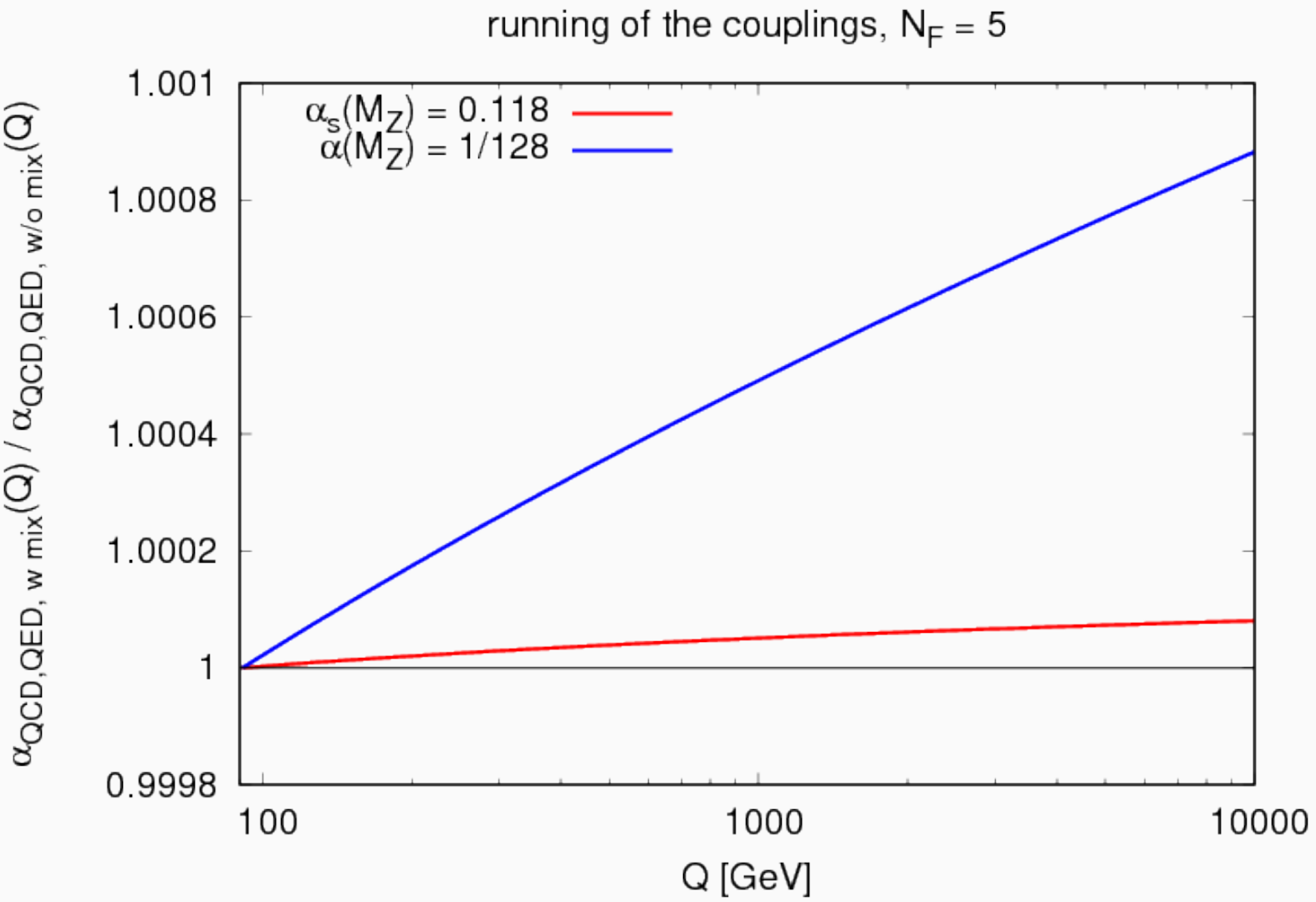
https://github.com/scarrazza/apfel [master]

Code example of NLO QED corrections in APFEL 3.0.0:

```
#!/usr/bin/env python
import apfel

# enable QCD+QED O(a) evolution
apfel.SetTheory('QUniD')

# enable QED O(a+a*as+a^2)
apfel.EnableNLOQEDCorrections(True)

"""APFEL with NLO QED corrections enabled"""
```

Thanks for your attention!

Backup


running of the couplings, $N_F = 5$
$\alpha_s(M_Z) = 0.118$
$\alpha(M_Z) = 1/128$
1.001
1.0008
1.0006
1.0004
1.0002
1
0.9998
100
1000
10000
Q [GeV]
$\alpha_{QCD,QED,\ w\ mix}(Q)\ /\ \alpha_{QCD,QED,\ w/o\ mix}(Q)$