APFEL

A PDF Evolution Library with QED Corrections

arXiv:1310.1394

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HERAFitter User's meeting

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SUMMARY

- Motivations
- Strategy
- Validation and Benchmark
- Conclusions and Outlook

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Motivations

- Need for **precision physics** at the LHC:
  - present PDF determination accuracy reaches NNLO in QCD.
- At this level of accuracy **QED corrections** become relevant.
  - Naive argument: $\frac{\alpha_s^2(M_Z)}{\alpha(M_Z)} \sim 1.8$
  - inclusion of QED corrections to **PDF evolution**,
  - extraction of a **photon PDF** from data.
- Need for an **accurate, flexible** and **public** code to perform PDF evolution that includes QED corrections.

APFEL

A PDF Evolution Library: arXiv:1310.1394

Motivations

Main Features of APFEL 1.0.0

- Accuracy:
  - PDF evolution up to NNLO in QCD and LO in QED,
  - FFNS and VFNS,
  - Pole and $\overline{\text{MS}}$ heavy quark masses.
- Flexibility:
  - Fortran, C/C++ and Python interfaces,
  - interface to LHAPDF (input/output).
- Publicly available from the HepForge webpage:

`http://apfel.hepforge.org/`

APFEL

Strategy

Solution of QCD and QED DGLAP Equations

- APFEL adopts a **decoupled** approach:

Different scales

$$\mu^2 \frac{\partial}{\partial \mu^2} \mathbf{q}(x,\mu,\nu) = \mathbf{P}^{\rm QCD}(x,\alpha_s(\mu)) \otimes \mathbf{q}(x,\mu,\nu)\,,$$

$$\nu^2 \frac{\partial}{\partial \nu^2} \mathbf{q}(x,\mu,\nu) = \mathbf{P}^{\rm QED}(x,\alpha(\nu)) \otimes \mathbf{q}(x,\mu,\nu)\,,$$

- whose **independent** solutions are:

$$\mathbf{q}(x,\mu_1,\nu) = \mathbf{\Gamma}^{\rm QCD}(x|\mu_1,\mu_0) \otimes \mathbf{q}(x,\mu_0,\nu)\,,$$

$$\mathbf{q}(x,\mu,\nu_1) = \mathbf{\Gamma}^{\rm QED}(x|\nu_1,\nu_0) \otimes \mathbf{q}(x,\mu,\nu_0)\,.$$

- Combination of $\mathbf{\Gamma}^{\rm QCD}$ and $\mathbf{\Gamma}^{\rm QED}$ to obtain the QCD+QED **combined evolution**... but how?

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Strategy

Combining QCD and QED Evolutions

- QCD and QED evolutions **do not commute**:

$$[\mathbf{\Gamma}^{\rm QCD}, \mathbf{\Gamma}^{\rm QED}] \neq 0$$

- In practice, QCD followed by QED or QED followed by QCD evolution lead to different results.

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Strategy

Combining QCD and QED Evolutions

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$$[\mathbf{\Gamma}^{\rm QCD}, \mathbf{\Gamma}^{\rm QED}] \neq 0$$

- In practice, QCD followed by QED or QED followed by QCD evolution lead to different results.

Is there anything wrong?

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Strategy

Combining QCD and QED Evolutions

- Solving the DGLAP QCD+QED evolution equations in Mellin space and expanding the solution, one finds:

$$[\mathbf{\Gamma}^{\mathrm{QCD}}, \mathbf{\Gamma}^{\mathrm{QED}}] = \mathcal{O}(\alpha\alpha_s)$$

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Strategy

Combining QCD and QED Evolutions

- Solving the DGLAP QCD+QED evolution equations in Mellin space and expanding the solution, one finds:

$$[\mathbf{\Gamma}^{\rm QCD}, \mathbf{\Gamma}^{\rm QED}] = \mathcal{O}(\alpha\alpha_s)$$

- Two **equivalent** possibilities:

1) $$\mathbf{\Gamma}^{\rm QCED}(\mu,\mu_0;\nu,\nu_0) \equiv \mathbf{\Gamma}^{\rm QED}(\nu,\nu_0) \otimes \mathbf{\Gamma}^{\rm QCD}(\mu,\mu_0)$$

2) $$\mathbf{\Gamma}^{\rm QECD}(\mu,\mu_0;\nu,\nu_0) \equiv \mathbf{\Gamma}^{\rm QCD}(\mu,\mu_0) \otimes \mathbf{\Gamma}^{\rm QED}(\nu,\nu_0)$$

Subleading

- whose perturbative expansions are:

$$\mathbf{\Gamma}^{\rm QCED} = 1 + \alpha \boldsymbol{A} + \alpha_s \boldsymbol{B} + \alpha\alpha_s \boldsymbol{C} + \dots$$

$$\mathbf{\Gamma}^{\rm QECD} = 1 + \alpha \boldsymbol{A} + \alpha_s \boldsymbol{B} - \alpha\alpha_s \boldsymbol{C} + \dots$$

- This suggests the **averaged** solution:

3) $$\mathbf{\Gamma}^{\rm QavD} \equiv \frac{\mathbf{\Gamma}^{\rm QCED} + \mathbf{\Gamma}^{\rm QECD}}{2}$$

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Strategy

Advantages of the APFEL Approach

- Possibility to treat QCD and QED **separately**:
  - optimized PDF evolution basis for each sector (not a common one),
  - better numerical efficiency.
- Possibility to explore different solutions differing by subleading terms (**QCED, QECD, QavD**):
  - estimate of the **theoretical error** due to the missing higher-order terms,
  - benchmark of the internal FastKernel code used by the NNPDF collaboration to obtain the NNPDF2.3 QED PDF sets [arXiv:1005.0397] which uses QECD.

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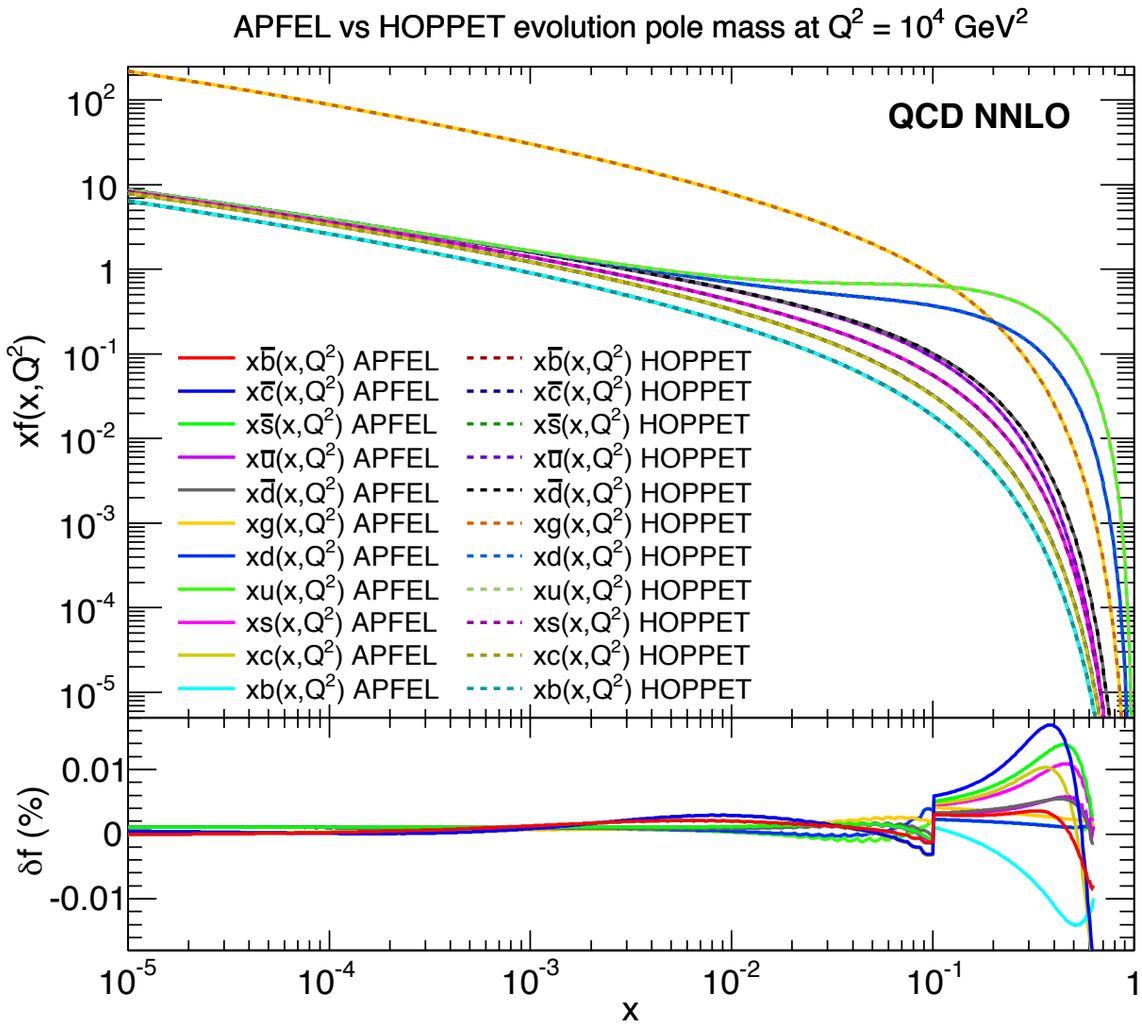
Validation and Benchmark

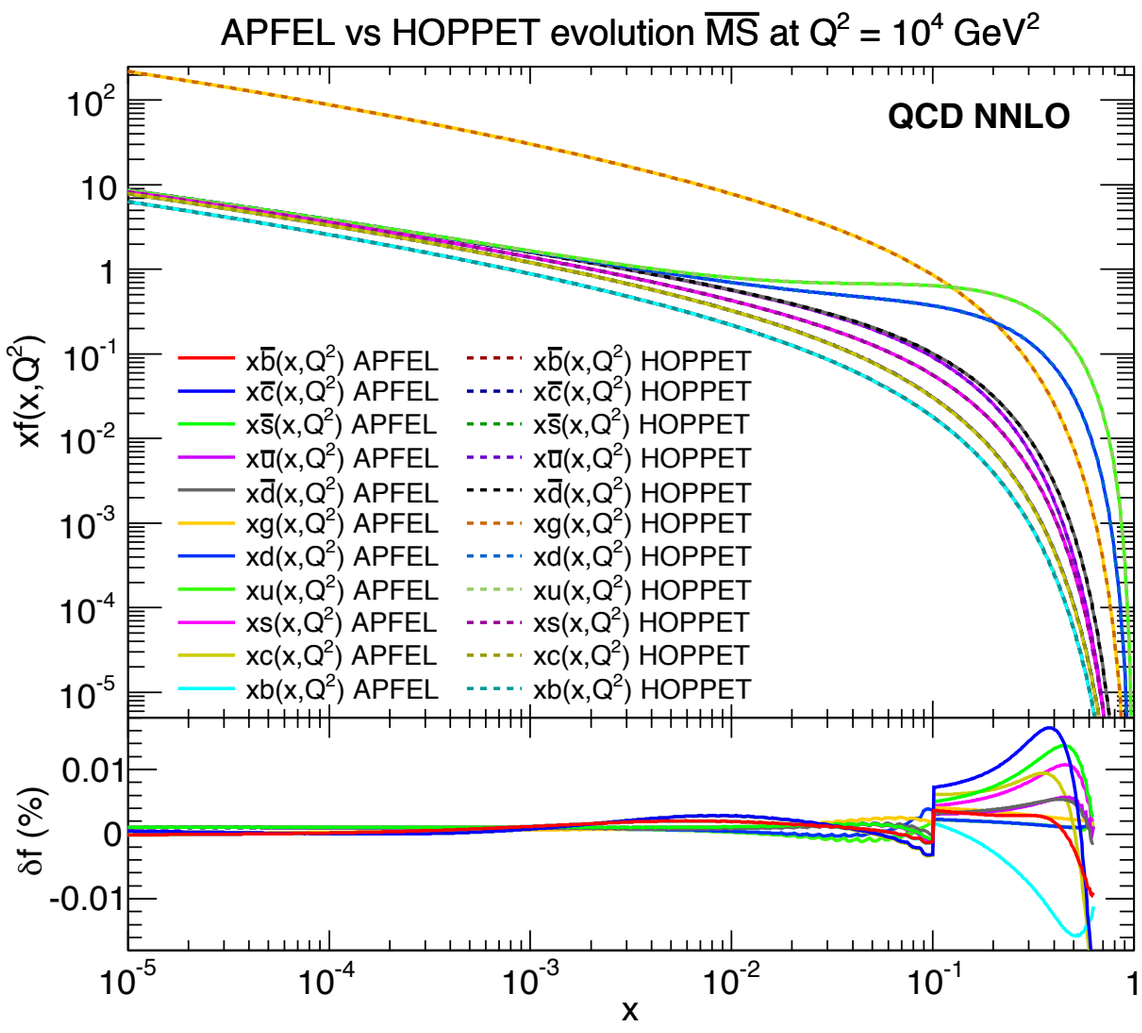
APFEL vs. HOPPET G. Salam and J. Rojo [arXiv:1005.0397]

- Benchmark of the **pure QCD** evolution at NNLO in the **VFNS**:

Pole masses



$\overline{\text{MS}}$ masses



Excellent agreement!

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Validation and Benchmark

APFEL vs. partonevolution

partonevolution (M. Roth and S. Weinzierl [hep-ph/0403200]) was the only public code implementing QED corrections in the PDF evolution.

Limitations of **partonevolution**:

- up to NLO in QCD,
- only FFNS,
- no possibility to interface it to an arbitary PDF set (*N*-space approach),
- slow and unpractical to use.

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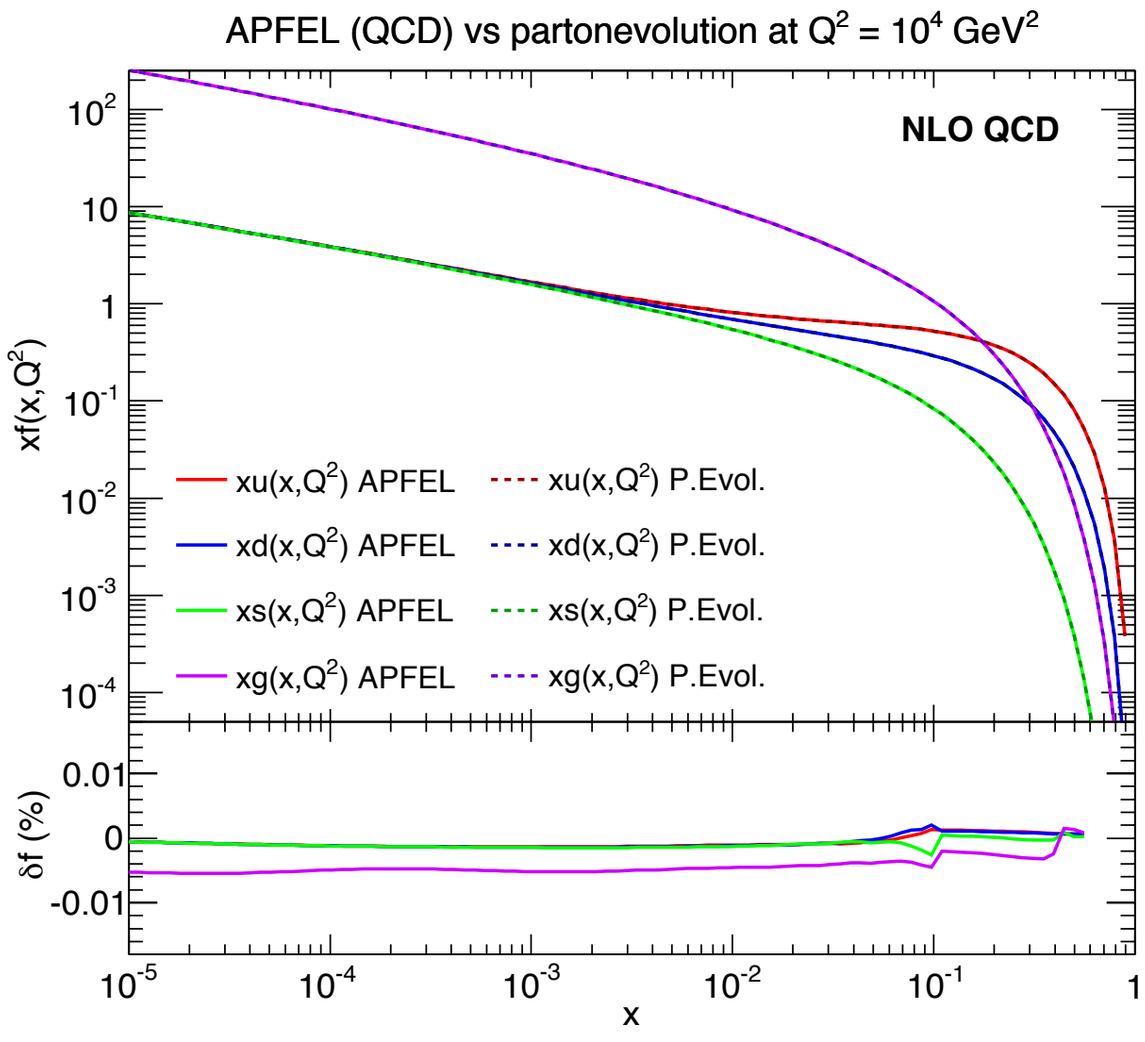
Validation and Benchmark

APFEL vs. partonevolution

- Check of the **pure QCD** evolution at NLO in the **FFNS**:
  - to disentangle the QED effects.



Very good agreement!

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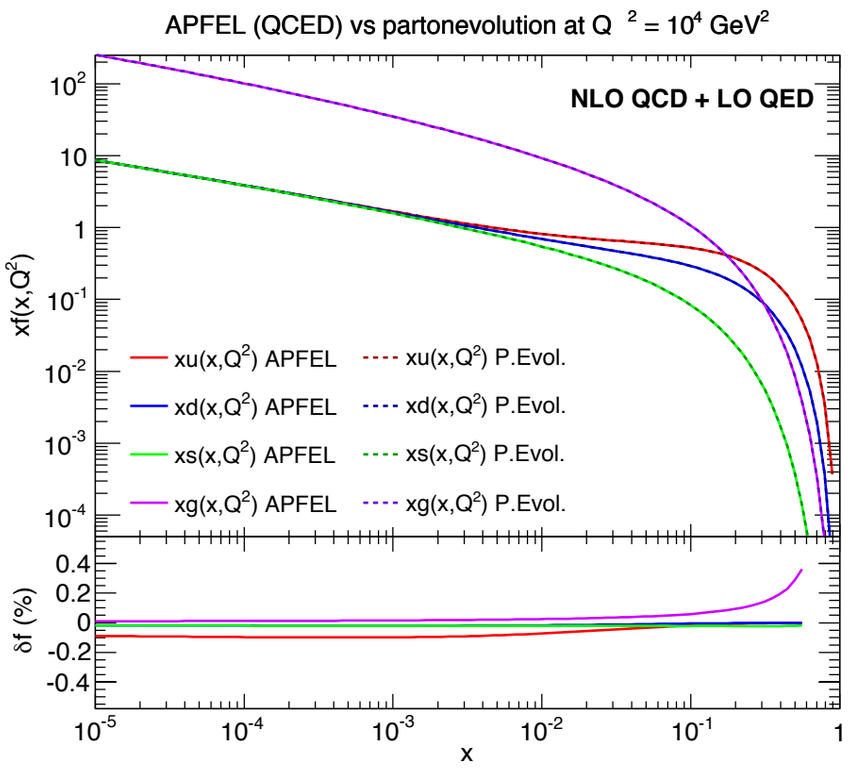
Validation and Benchmark

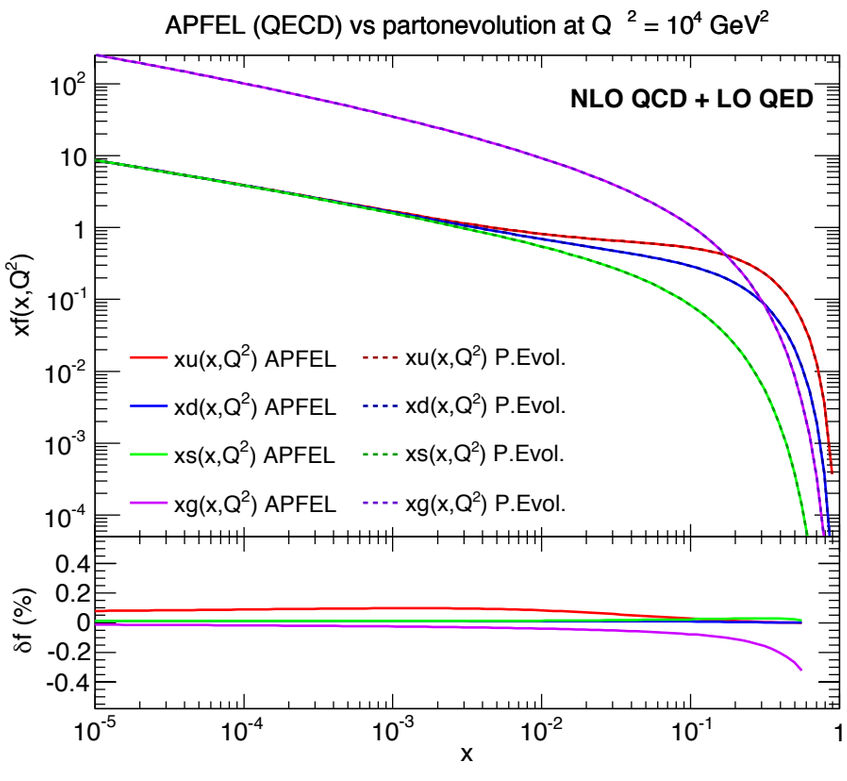
APFEL vs. partonevolution

- Test of the **QCD+QED evolution** in the **FFNS**:
  - APFEL provides **three different options** for the QCD+QED evolution:

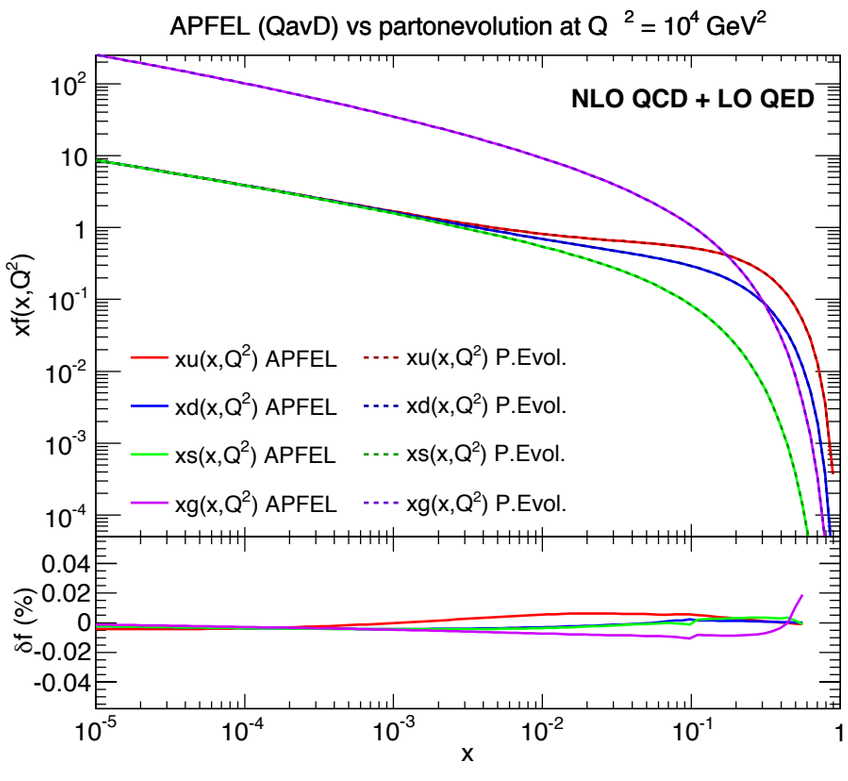
QCED



QECD



QavD



- **Quarks and gluon** are in good agreement for all the three options, though the **QavD** solutions ensures an even **better** agreement.

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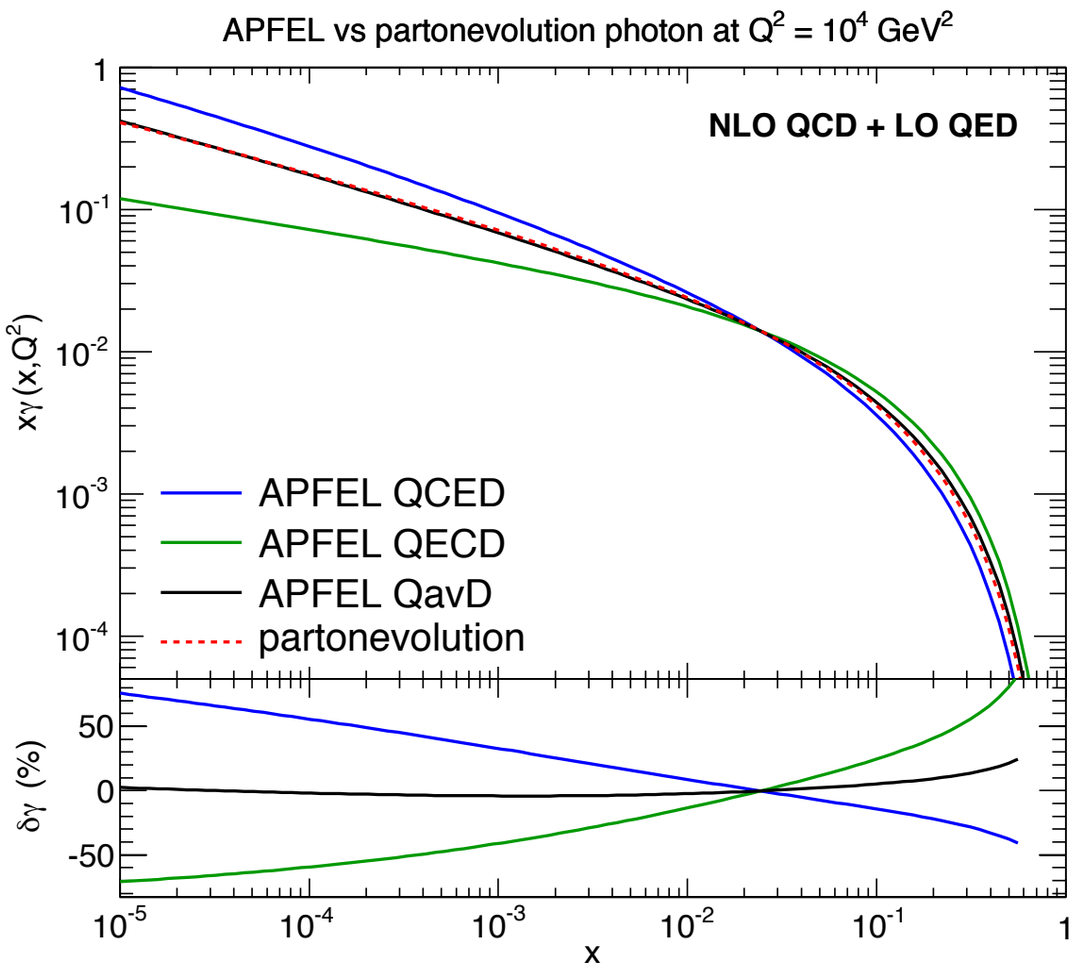
Validation and Benchmark

APFEL vs. partonevolution

- Test of the **QCD+QED evolution** in the **FFNS**:



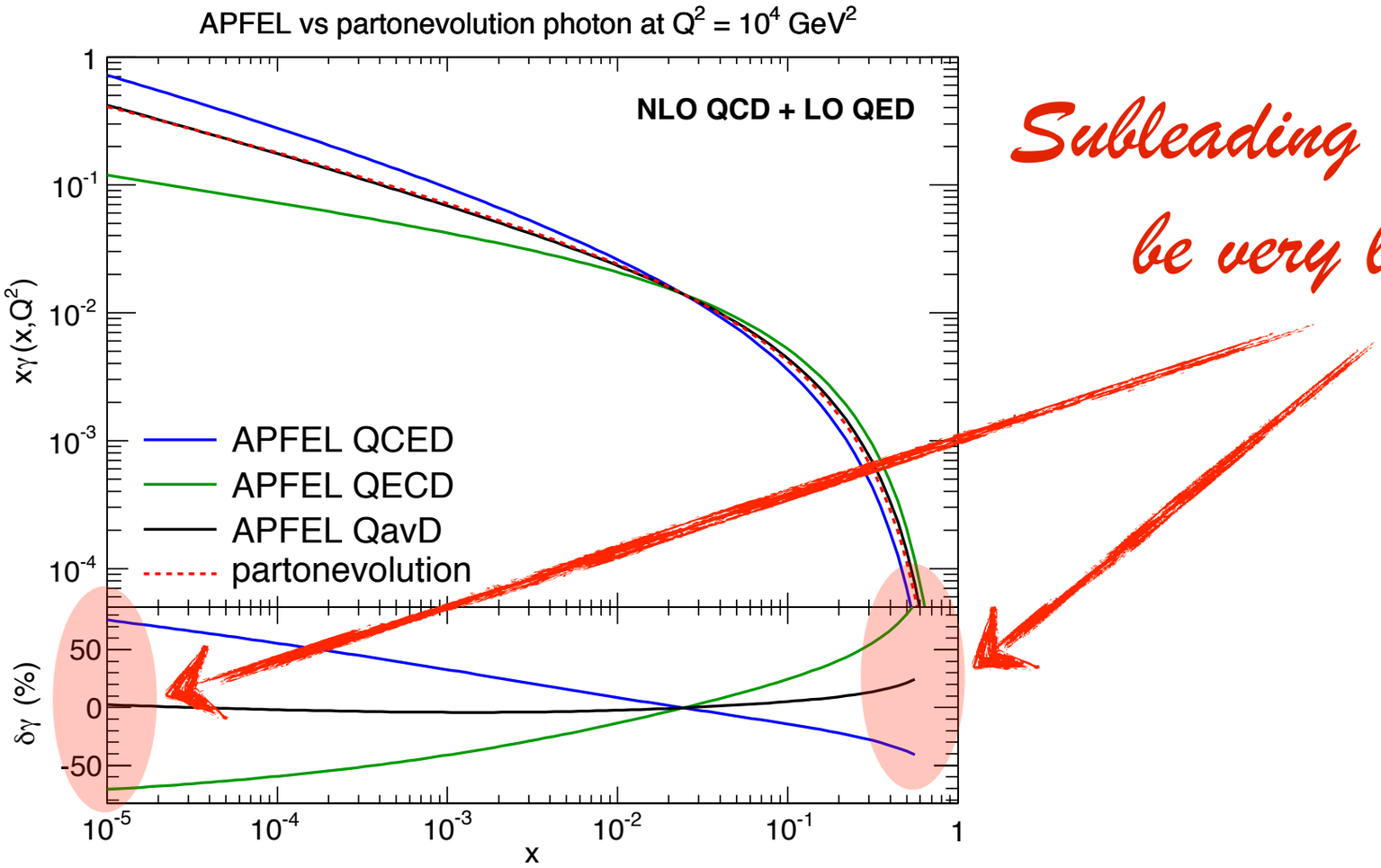
Photon PDF more sensitive to **higher-order corrections**:

- discrepancy between PE and APFEL(QCED/QECD) up to 60%,
- PE and APFEL(QavD) in good agreement at a few percent level.

Validation and Benchmark

APFEL vs. partonevolution

- Test of the **QCD+QED evolution** in the **FFNS**:



Subleading terms can be very large!

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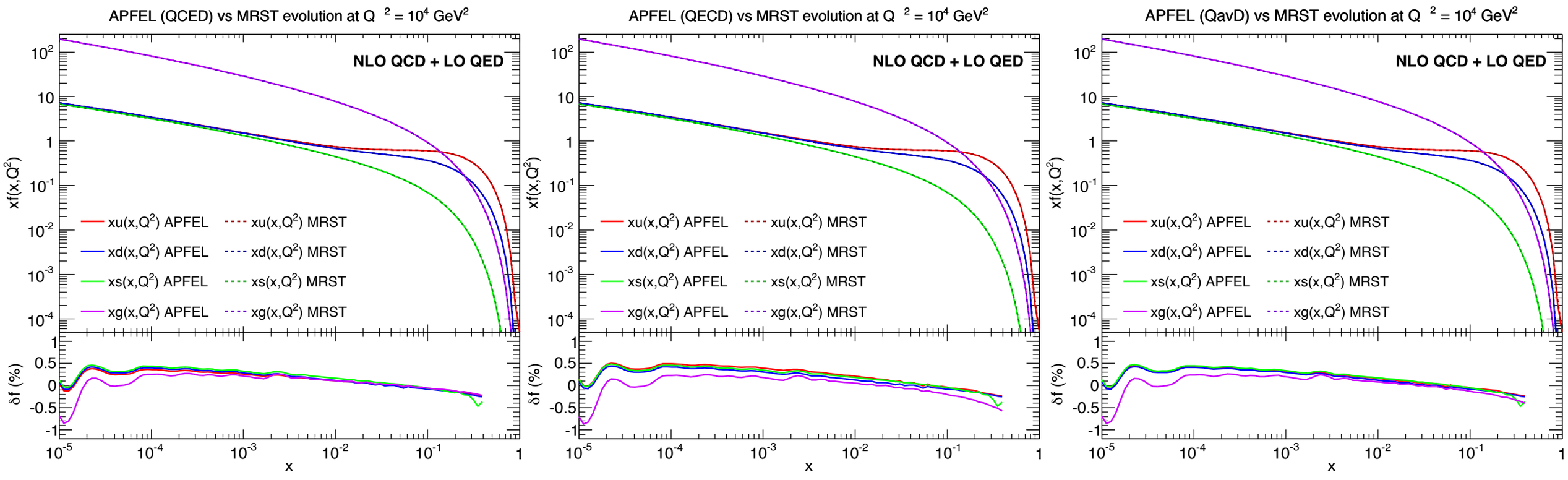
- PE and APFEL(QavD) in good agreement at a few percent level.

APFEL

Validation and Benchmark

APFEL vs. MRST2004QED A.D. Martin et al. [hep-ph/0411040]

- Test of the **QCD+QED evolution** in the **VFNS**:



- Same picture as for partonevolution:
  - Quark and gluon PDFs in good agreement

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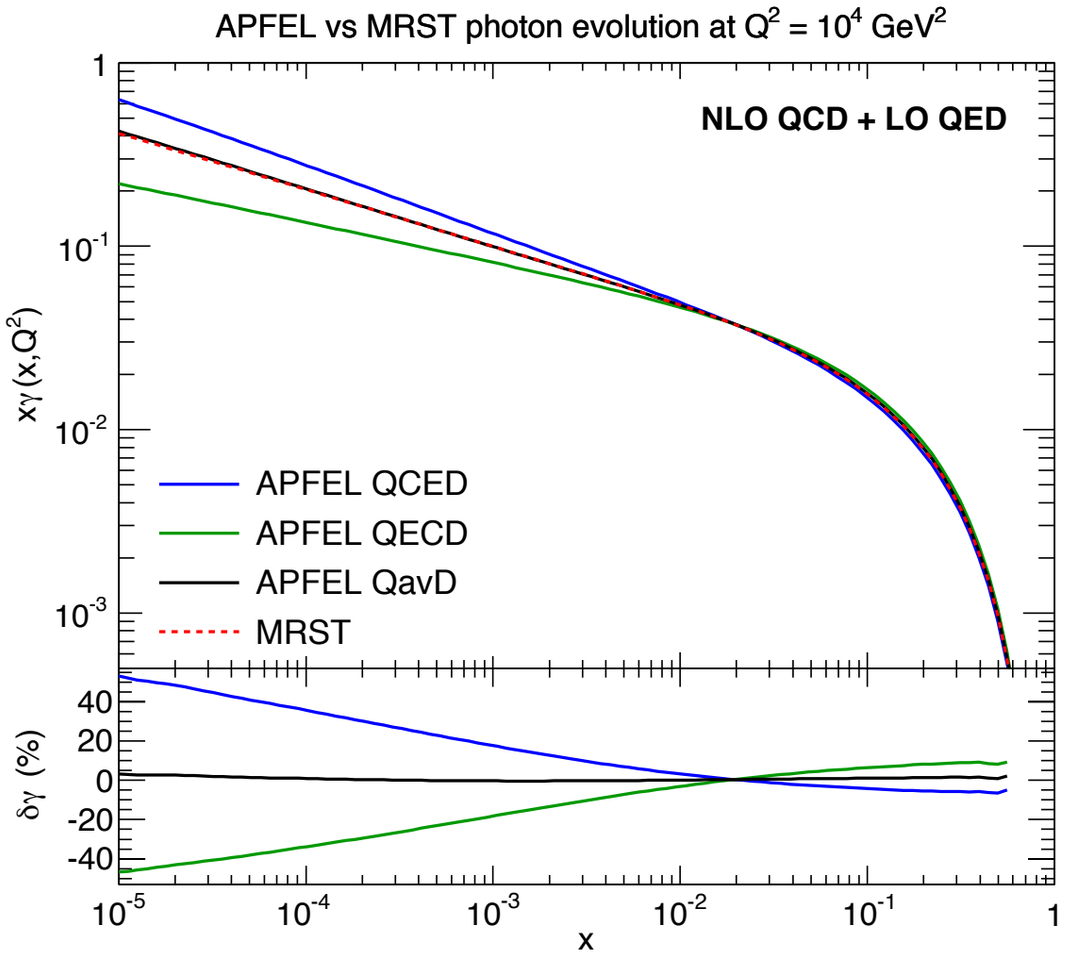
Validation and Benchmark

APFEL vs. MRST2004QED

- Test of the **QCD+QED evolution** in the **VFNS**:



- Same picture as for partonevolution:
  - Quark and gluon PDFs in good agreement
  - larger spread for the photon but good agreement for QavD

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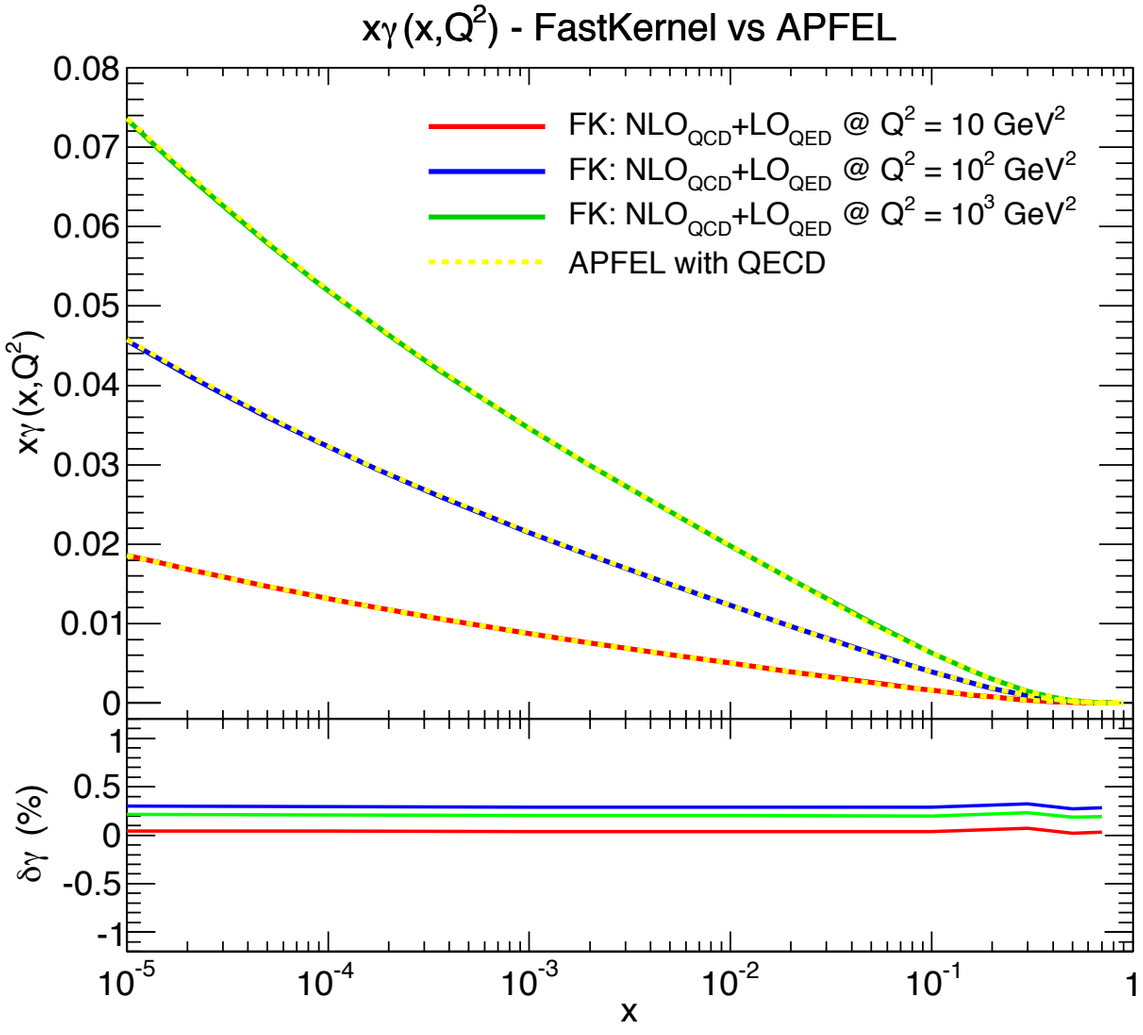
Validation and Benchmark

APFEL vs. FastKernel (NNPDF)

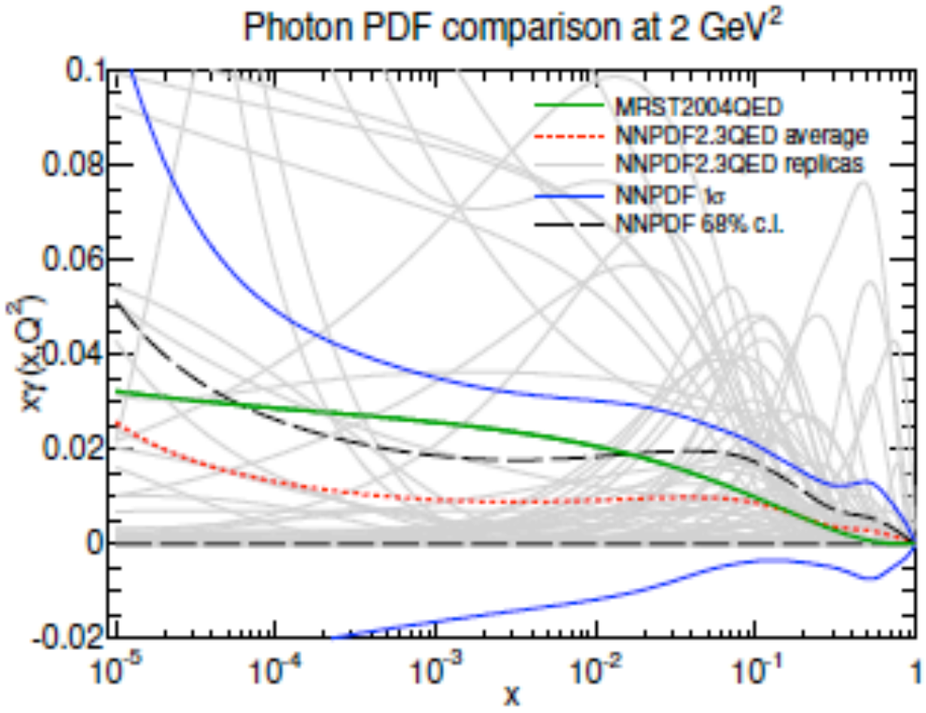
- APFEL has been employed to validate the **FastKernel** code used to produce the **NNPDF2.3 QED** sets:
  - whose evolution is equivalent to the **QECD solution**.

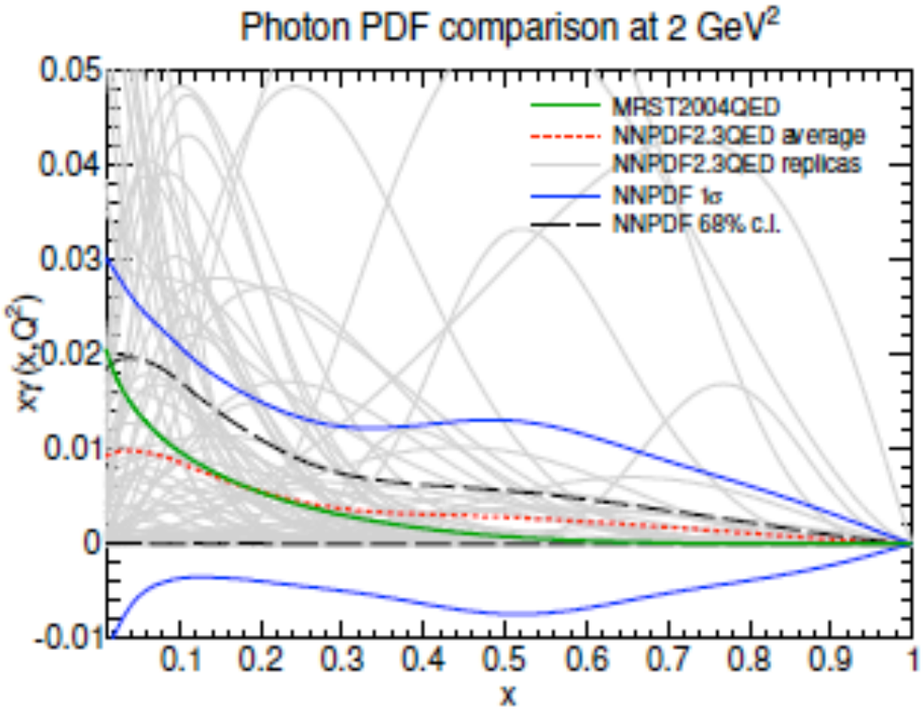


APFEL and NNPDF2.3QED

Motivation

- APFEL and NNPDF:
  - independent cross-check implementation of the FastKernel code
- QED evolution in new NNPDF2.3QED set:





- Photon PDF extracted from DIS data and LHC data.
  - LO in QED and up to NNLO in QCD ($\alpha_s = 0.117, 0.118, 0.119$)
  - public PDF sets available from LHAPDF $\geq$ 5.9.0.

Conclusions and Outlook

- APFEL is a public library for QCD+QED combined evolution:
  - up to NNLO in QCD and LO in QED,
  - FFNS and VFNS implemented,
  - Pole and $\overline{\text{MS}}$ heavy quark masses.
- Modern approach for PDF manipulation:
  - interface to LHAPDF.
- Good agreement with the existing public codes.

Outlook:

- time-like evolution (fragmentation functions),
- DIS factorization scheme,
- polarized evolution...

APFEL is available on: http://apfel.hepforge.org/

User support service included!

Contact us for any question.