The photon PDF from high-mass Drell Yan data at the LHC

[xFitter developers' team and F. Giuli, arXiv: 1701.08553]
Recently accepted for publication in EPJC.

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PHOTON 2017

May 24, 2017, CERN

The xFitter Project

xFitter (former HERAFitter) provides a **unique open-source** framework available from:

https://www.xfitter.org/xFitter

that allows the users to:

- **extract PDFs** from a large variety of experimental data,
- assess the **impact** of data **on PDFs**,
- check the **consistency** of experimental data,
- test different **theoretical** and **methodological assumptions**.

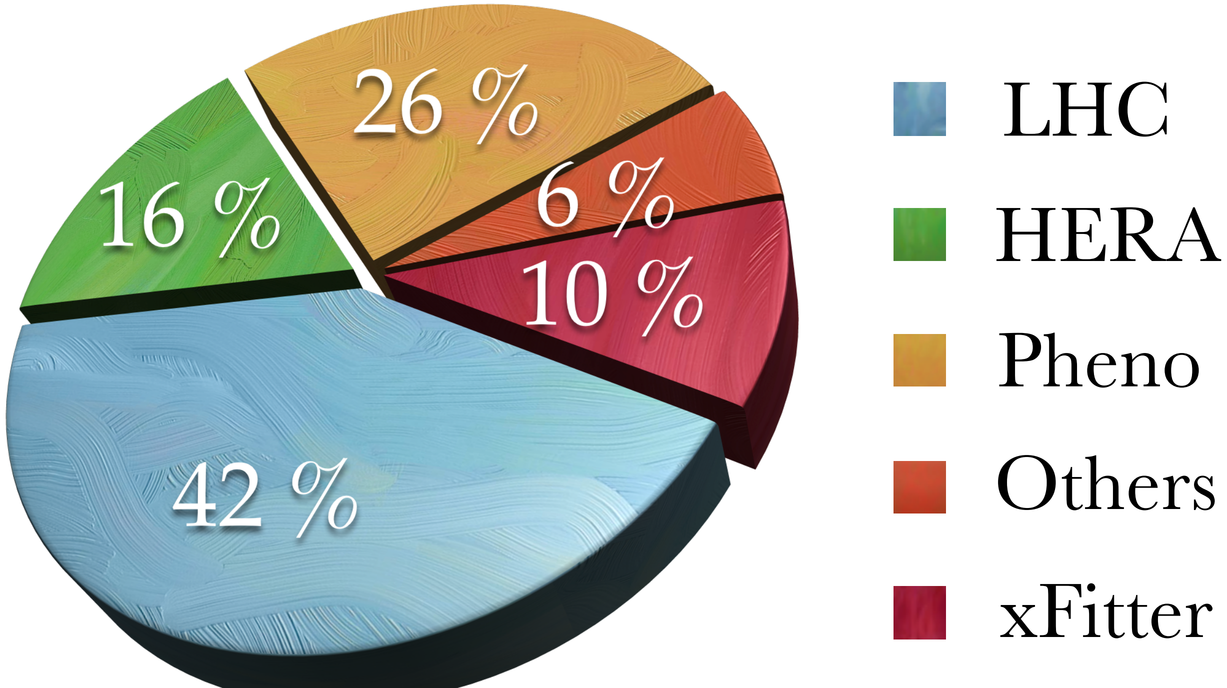
Latest release **xFitter 2.0.0 FrozenFrog** (first release distributed via *git*).

Around **30 active developers**:

- theorists and experimentalists.

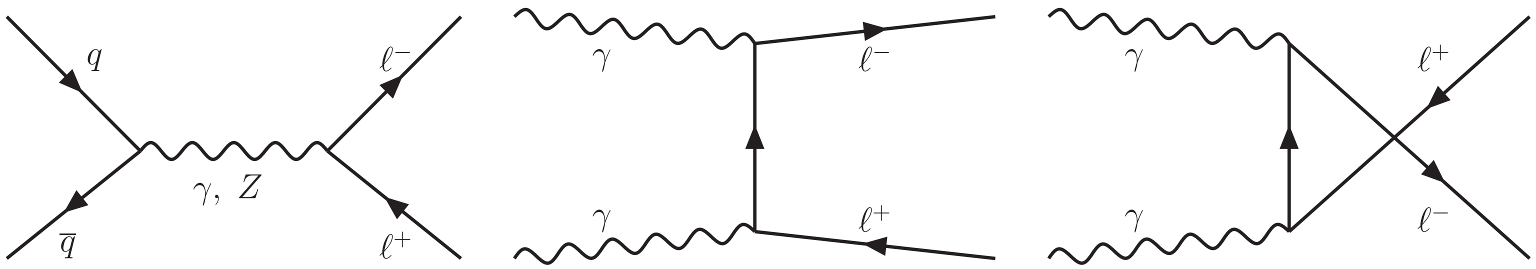
More than **40 publications** based on xFitter:

- I will discuss one of them in which I was directly involved.

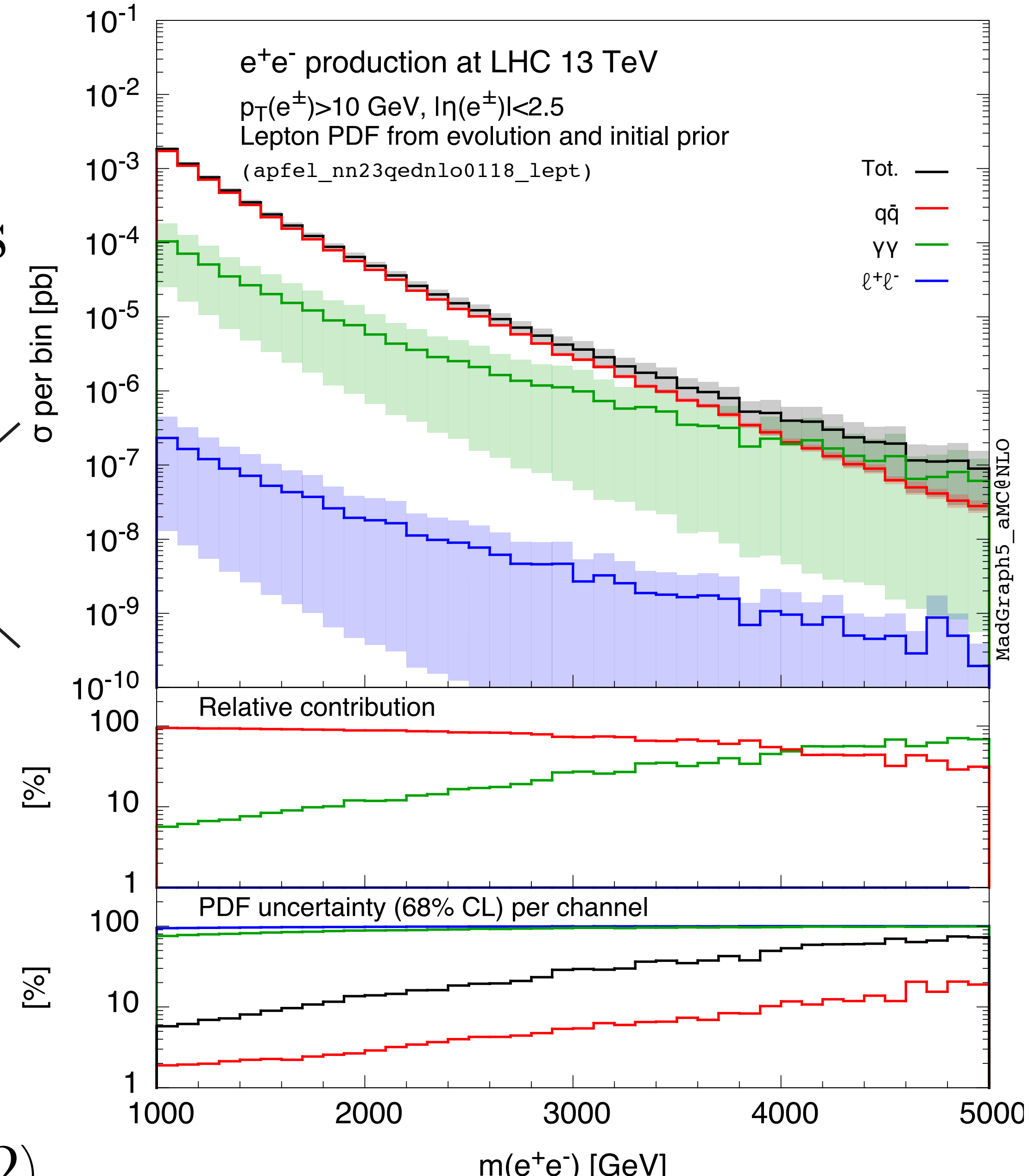


Motivation

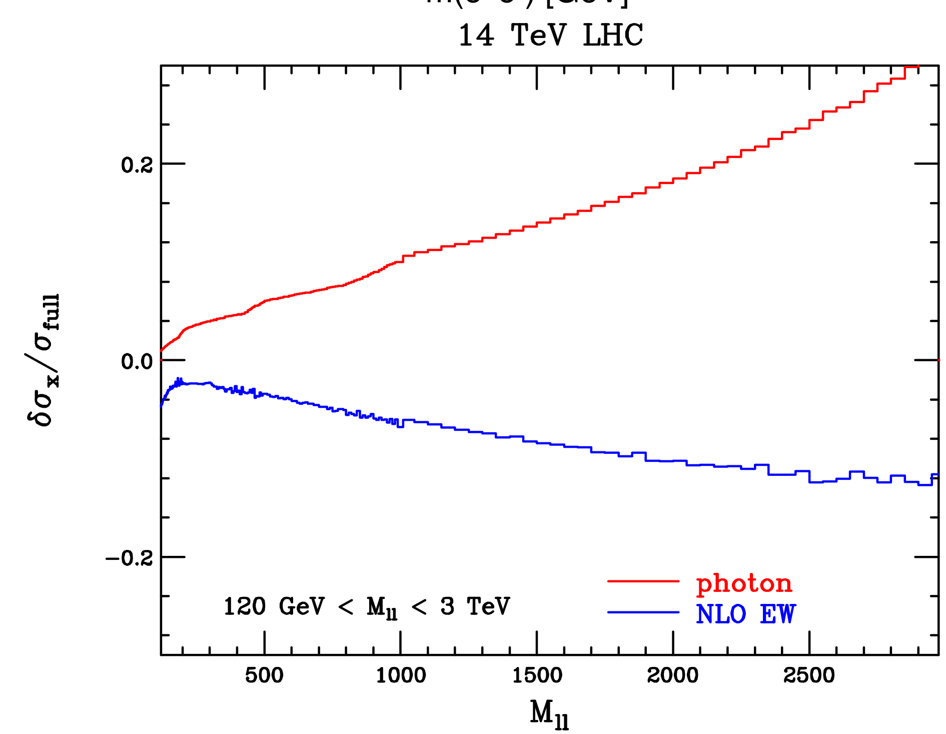
- The **Drell-Yan** process ($pp \to l^+l^-$) receives photon-initiated contributions at LO:



- **High-invariant-mass** region gets large photon contribution:
  - up to the same order or even larger than the QCD contribution.
  - probe the **large-*x* photon PDF** ($x \gtrsim 0.02$).
- Experimental data in this region can provide a constraint on the **photon PDF**:
  - ATLAS high-mass DY data.
    [G. Aad et al., JHEP 08 , 009 (2016)]
- Need for accurate predictions: **QED/EW corrections to NLO**.



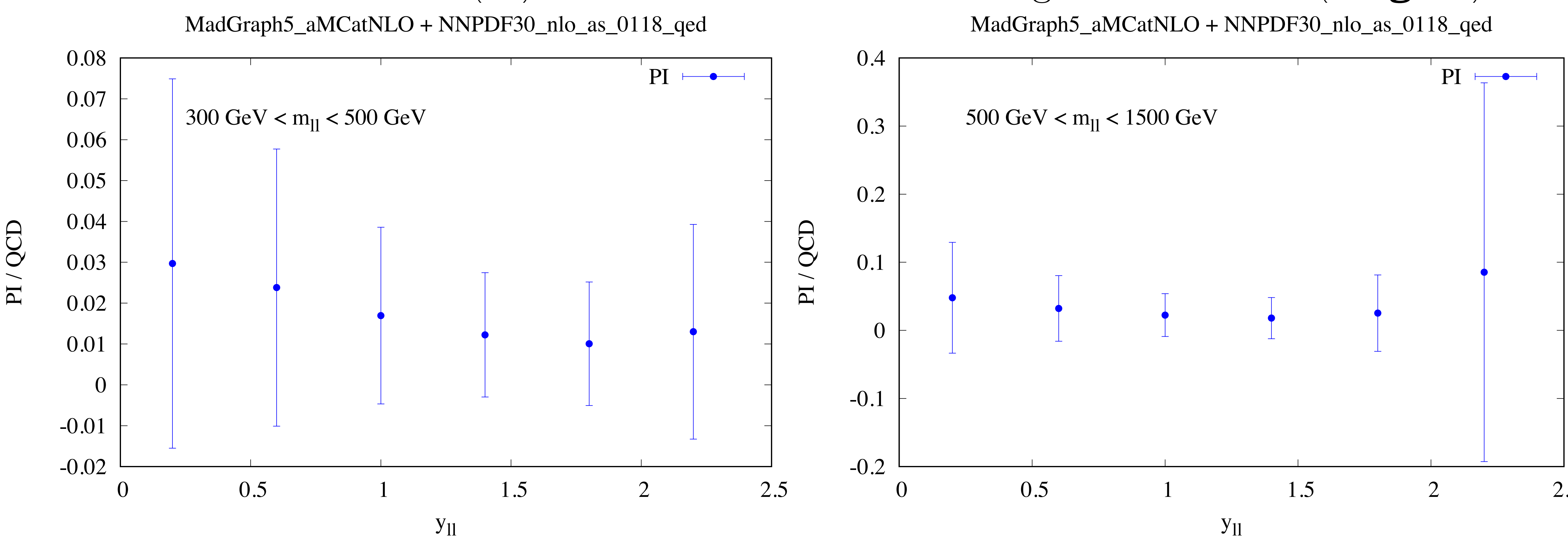
[V. Bertone et al., JHEP11(2015)194]



[R. Boughezal et al., P.R. D 89 (2014)]

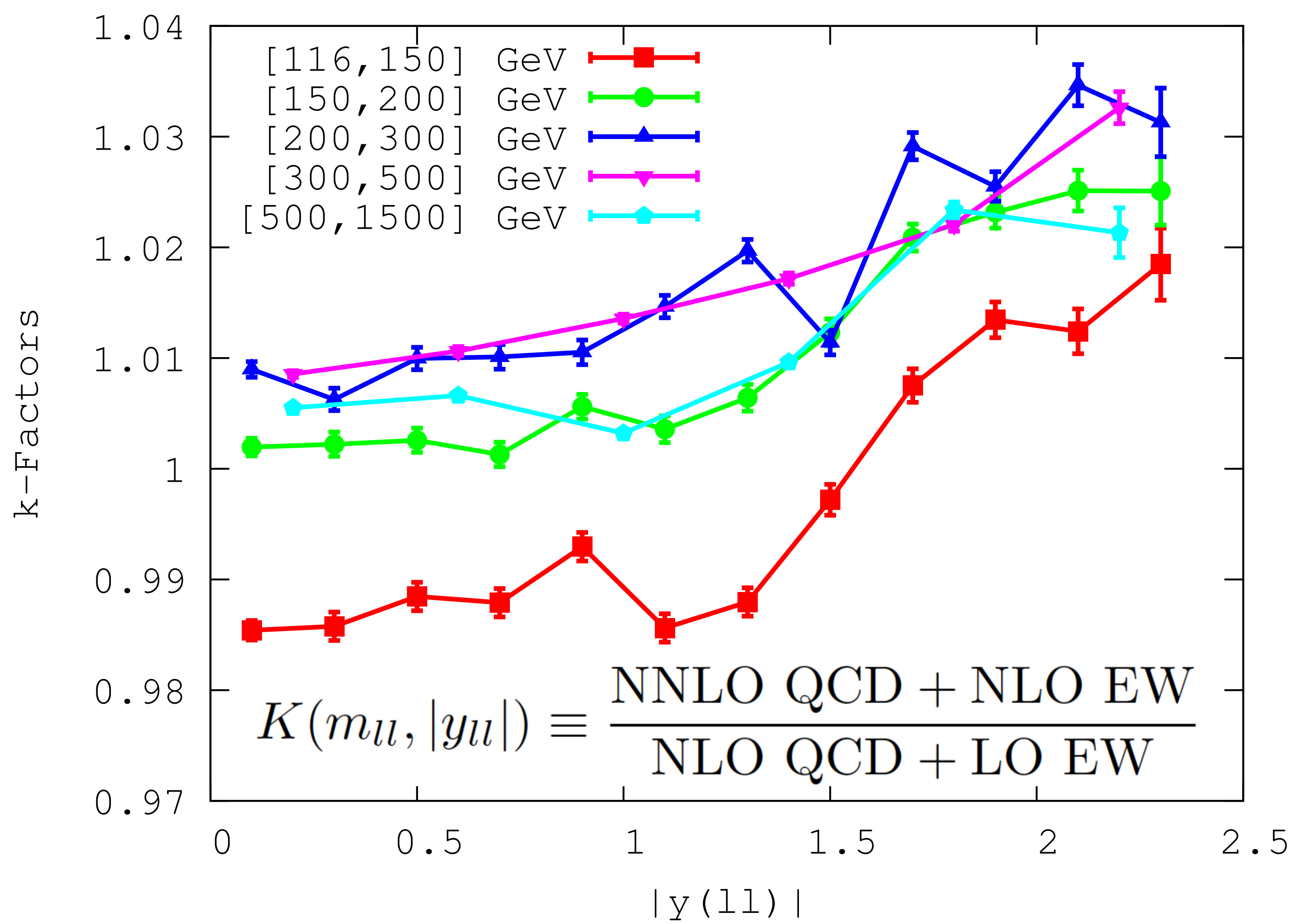
Data Set

- **HERA I+II DIS** inclusive data:
  - constraint on **quark** and **gluon PDFs**,
  - cut on $Q^2 \geq Q_{min}^2 = 7.5$ GeV^2.
- **ATLAS high-mass DY** data at 8 TeV ⇒ **photon PDF**:
  - double differential distributions in di-lepton mass m_{ll} and rapidity y_{ll},
  - 48 data points in 5 m_{ll} ranges: [116-150], [150-200], [200-300], [300-500], [500-1500] GeV,
  - kinematic cuts: $m_{ll} \geq 116$ GeV, $\eta_{ll} \leq 2.5$, $p_T(l_1) \geq 40$ GeV, $p_T(l_2) \geq 30$ GeV.
  - Photon-induced (PI) contribution sizeable at large values of m_{ll} (**large *x***).



Electroweak Corrections
Drell Yan

- **DY** cross sections calculated via **MadGraph5_aMC@NLO**:
  - includes the **photon-initiated** (PI) **diagrams**,
  - interfaced to **APPLgrid** (tailored to account for PI diagrams) via **aMCfast**.
  - this provides the NLO QCD + LO EW (QED) computation.
- NNLO QCD+NLO EW corrections obtained using **FEWZ** via K-factors.



Electroweak Corrections

Evolution

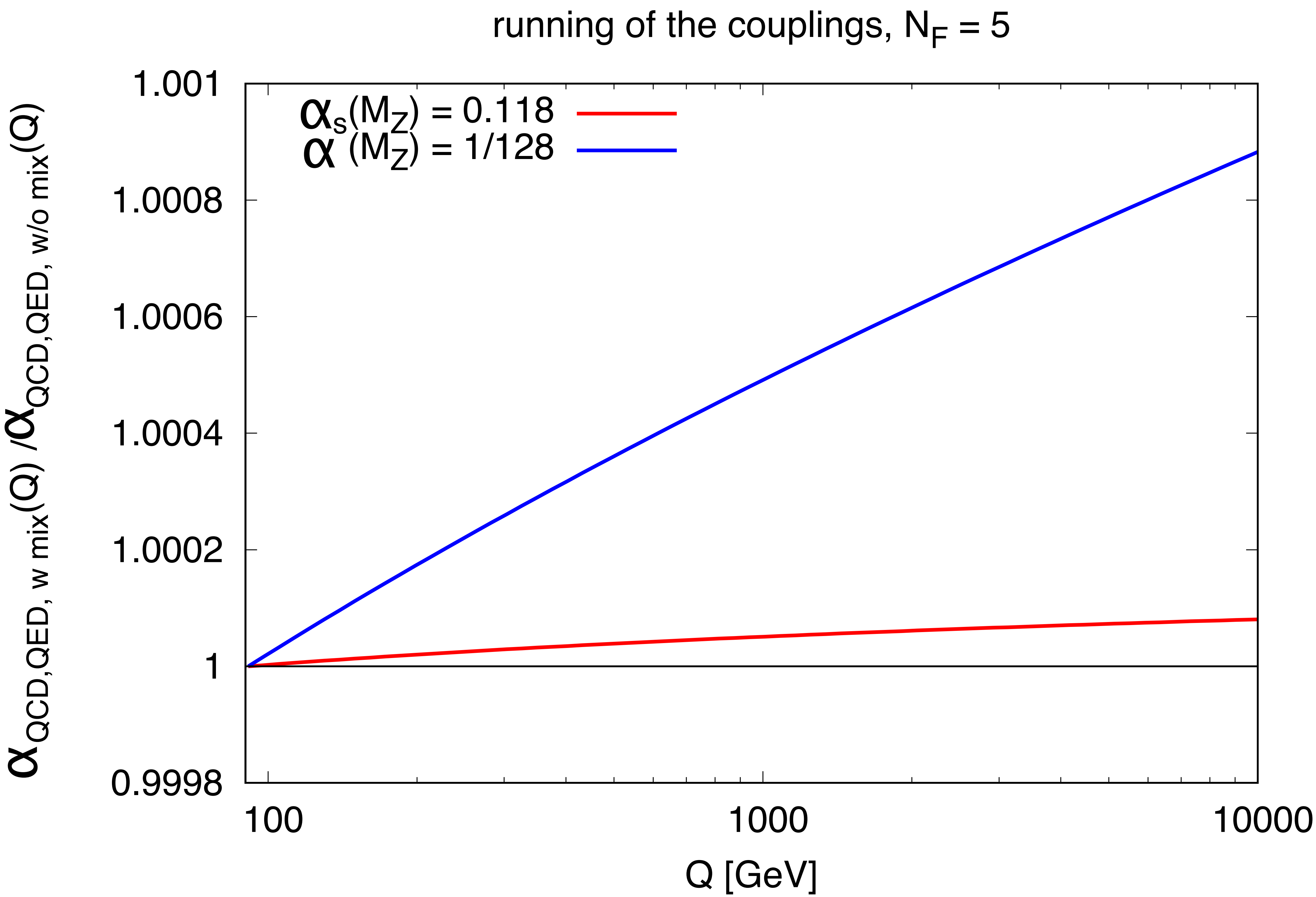
In order to implement the full NLO QED corrections in the DGLAP evolution **two main steps** are required:

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**.

Electroweak Corrections

Coupling Evolution



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

Electroweak Corrections

Evolution

In order to implement the full NLO 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**:

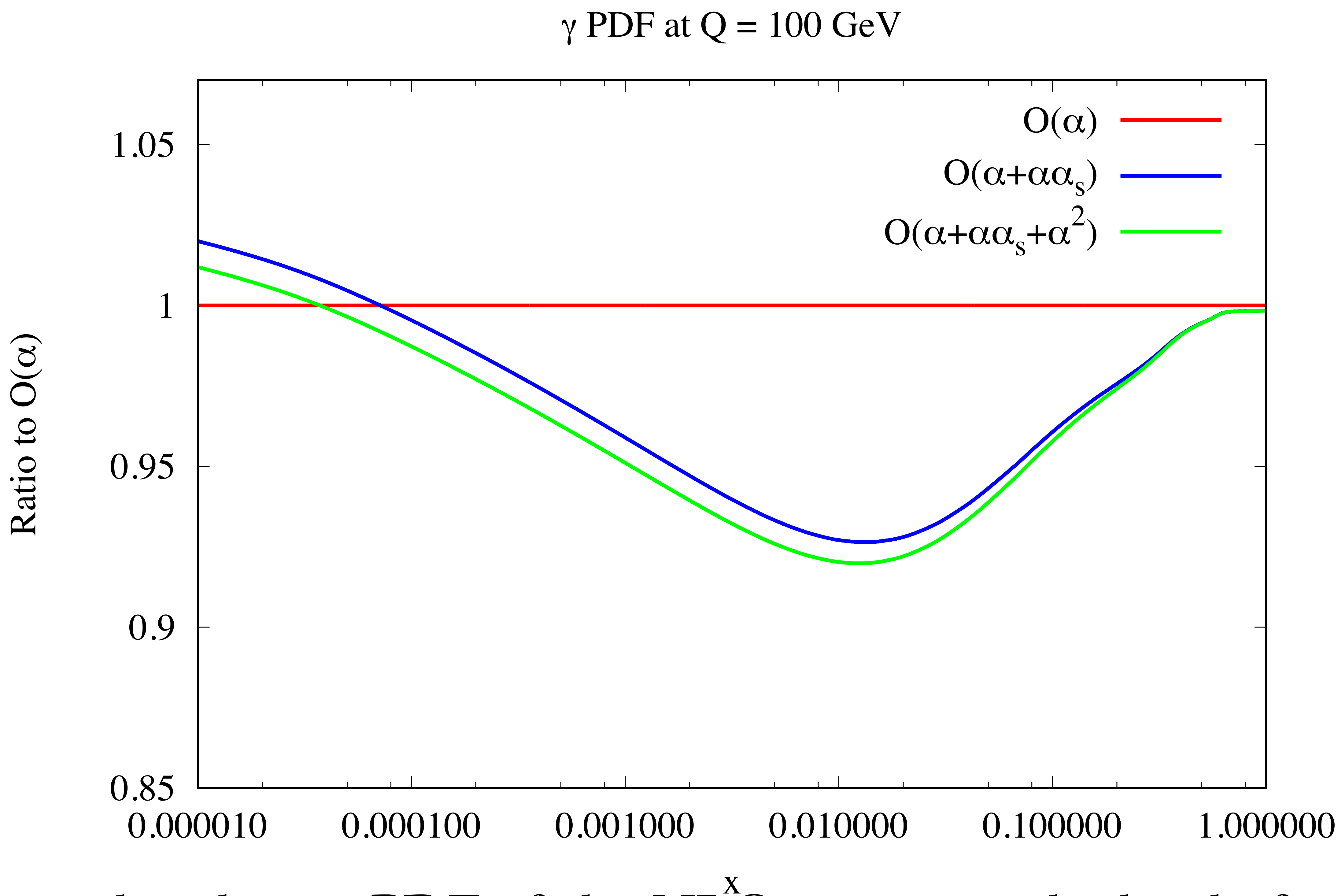
   - running of α_s and α is coupled ⇒ solve of a coupled ODE,
   - Numerical tests have shown that such terms lead to differences of $O(10^{-4})$ for α_s and $O(10^{-3})$ for α ⇒ **unneeded complication**.

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.

Electroweak Corrections

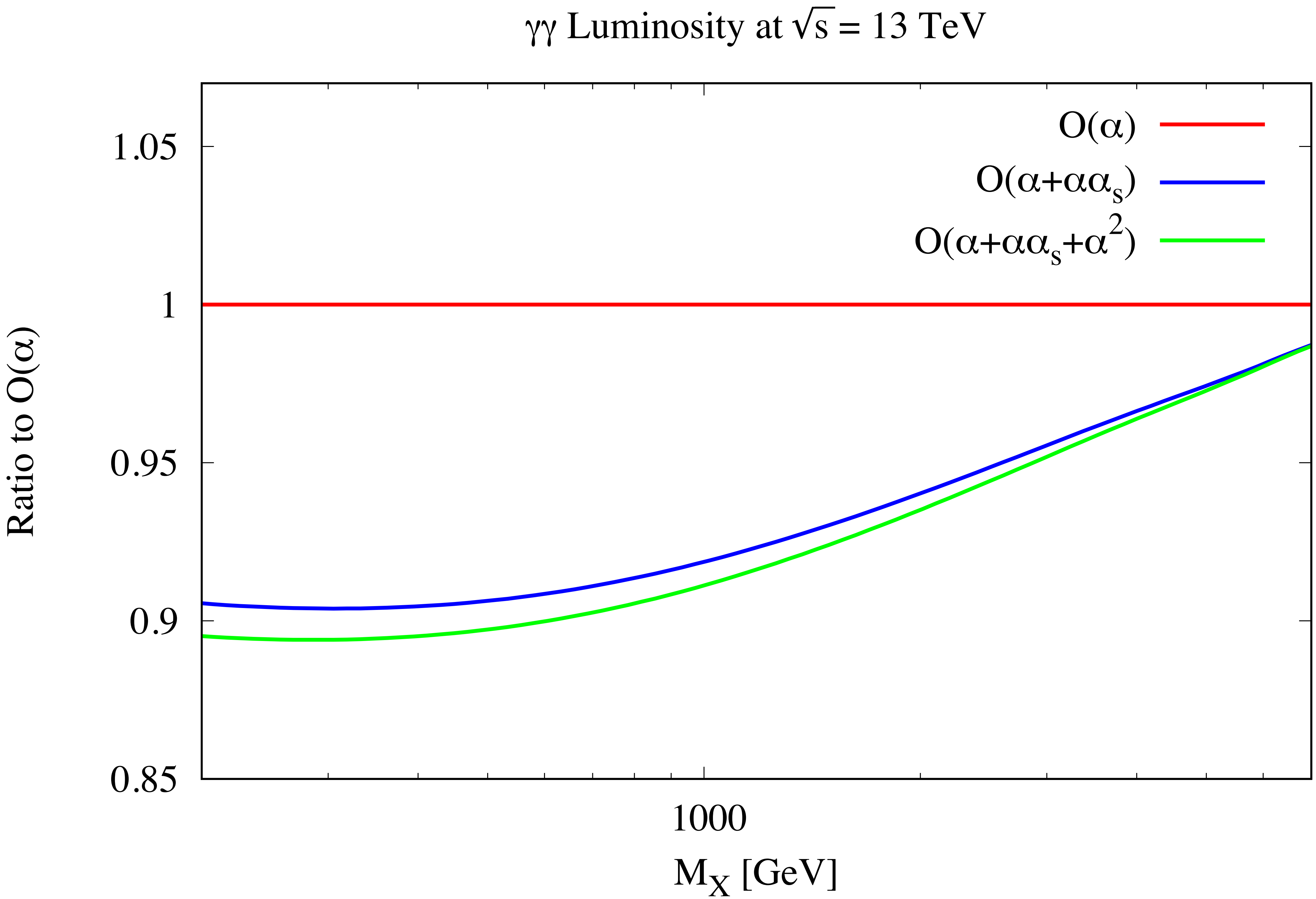
DGLAP Evolution: The Photon PDF



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

Electroweak Corrections

DGLAP Evolution: The $\gamma\gamma$ Luminosity



- More sizeable effect on the $\gamma\gamma$ luminosity.

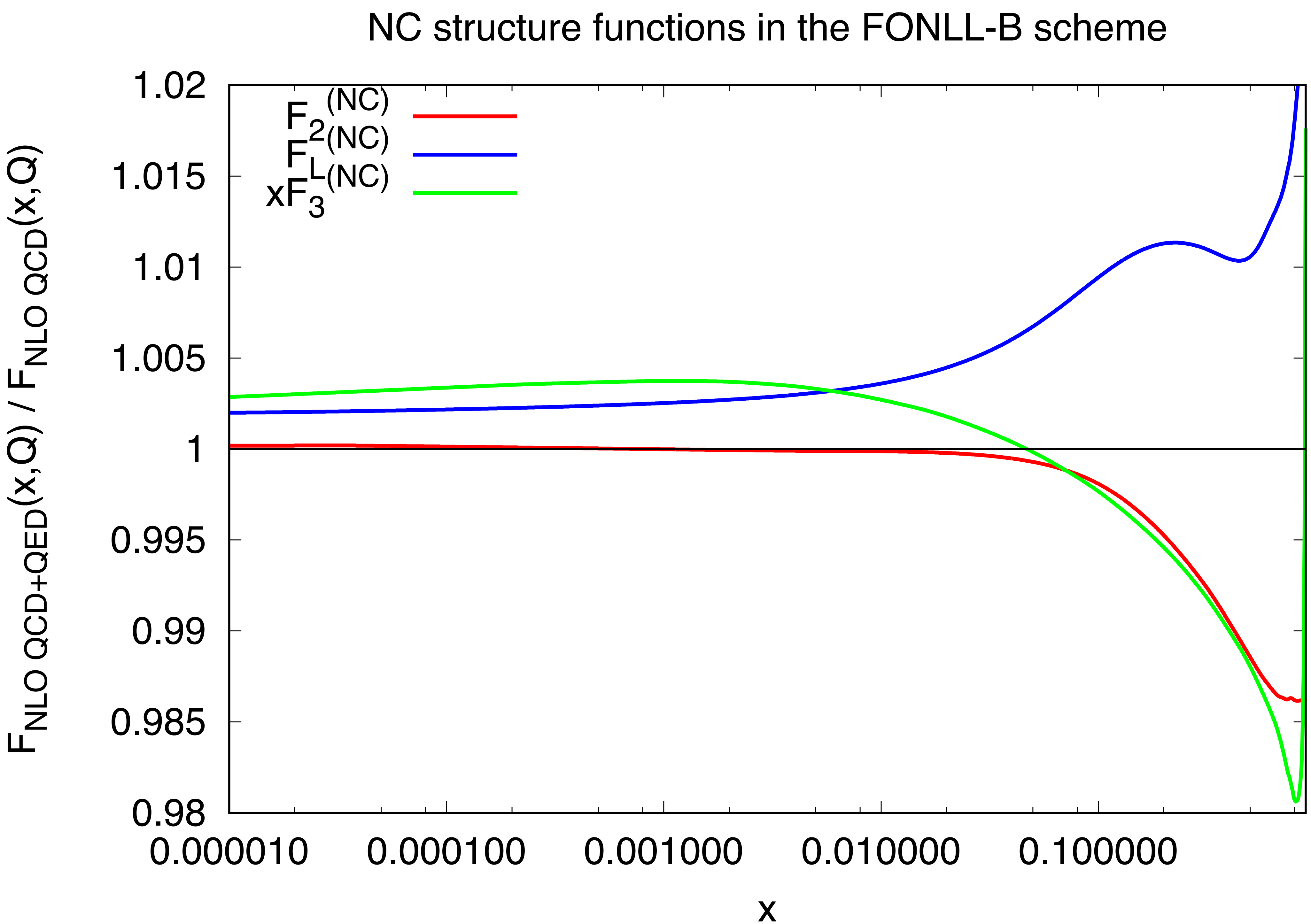
Electroweak Corrections

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**.

Electroweak Corrections

DIS Structure Functions



- Generally small effect which becomes larger at large x.

Fit Settings

- PDF **parameterisation**:

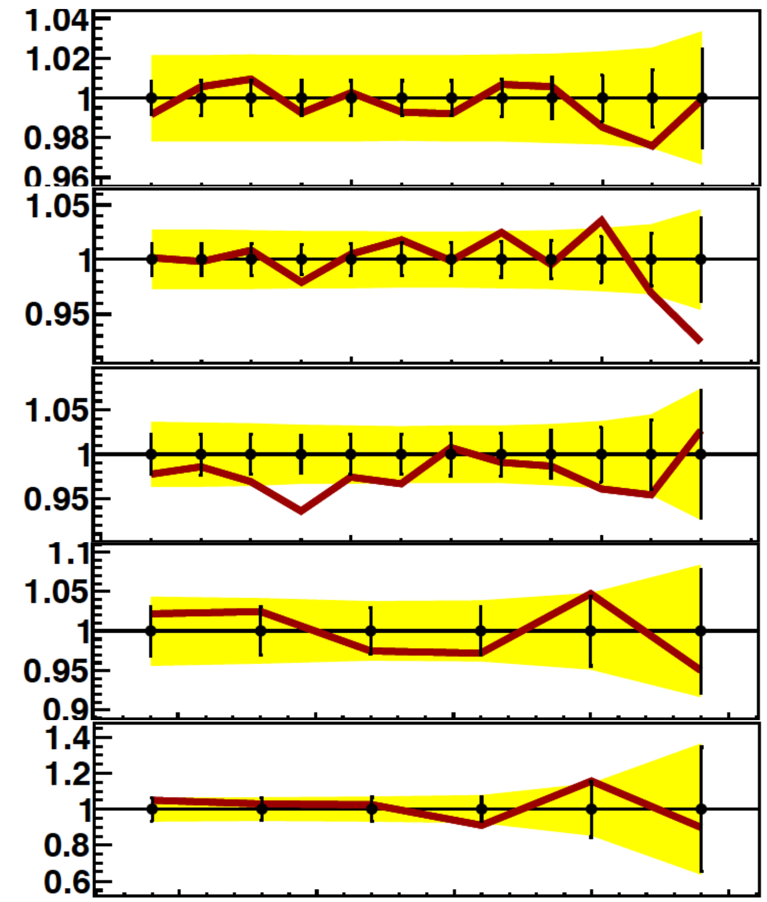
$$
\begin{aligned}
xu_v(x) &= A_{u_v} x^{B_{uv}} (1-x)^{C_{uv}} (1+E_{u_v}x^2)\,, \\
xd_v(x) &= A_{d_v} x^{B_{dv}} (1-x)^{C_{dv}}\,, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}}\,, \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}\,, \\
xg(x) &= A_g x^{B_g} (1-x)^{C_g} (1+E_g x^2)\,, \\
x\gamma(x) &= A_\gamma x^{B_\gamma} (1-x)^{C_\gamma} (1+D_\gamma x + E_\gamma x^2)\,.
\end{aligned}
$$

- with the conditions $x\bar{s}(x,Q_0^2) = x\bar{d}(x,Q_0^2)$ ($r_s = 1$) and $A_{\bar{U}} = 0.5 A_{\bar{D}}$
- DIS struct. funcs. computed in the FONLL-C scheme (NNLO) with APFEL.
- **Heavy-quark** masses and **couplings**:
    - $m_c = 1.47$ GeV, $m_b = 4.5$ GeV, $\alpha_s(M_Z) = 0.118$, $\alpha(M_Z) = 1/128$.
- PDF are parametrised at $Q_0 = \sqrt{7.5}$ GeV:
    - **larger than usual** to ensure a stable photon PDF at the Q_0,
    - $Q_0 > m_c$ but dynamically generated charm:
        - coped with by **displacing the charm threshold** to above Q_0.

Results

Fit Quality

Dataset	χ^2 / $N_{\rm dat}$
HERA I+II	1236/1056
high-mass DY 116 GeV $\leq m_{ll} \leq$ 150 GeV	9/12
high-mass DY 150 GeV $\leq m_{ll} \leq$ 200 GeV	15/12
high-mass DY 200 GeV $\leq m_{ll} \leq$ 300 GeV	14/12
high-mass DY 300 GeV $\leq m_{ll} \leq$ 500 GeV	5/6
high-mass DY 500 GeV $\leq m_{ll} \leq$ 1500 GeV	4/6
Total (high-mass DY) $\chi^2/N_{\rm dat}$	48/48
Combined HERA I+II and high-mass DY $\chi^2/N_{\rm dof}$	1284/1083

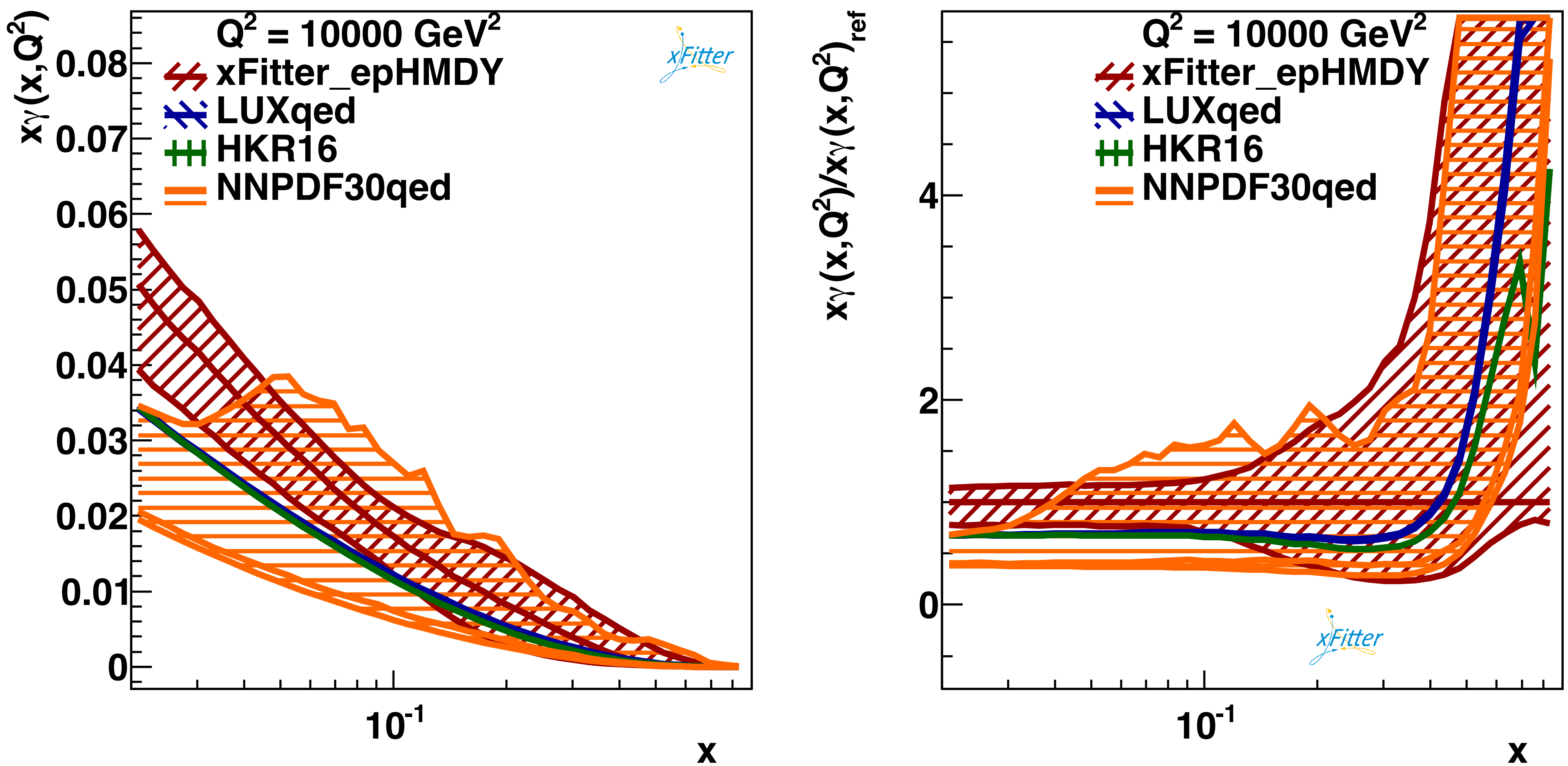


- Good description of the full data set.
- Remarkably DY data $\chi^2/N_{\rm dat}$ = 48/48.
- Good agreement between data and predictions despite the small experimental uncertainties.

Results

The Photon PDF

- Comparison with other determinations of the photon PDF:

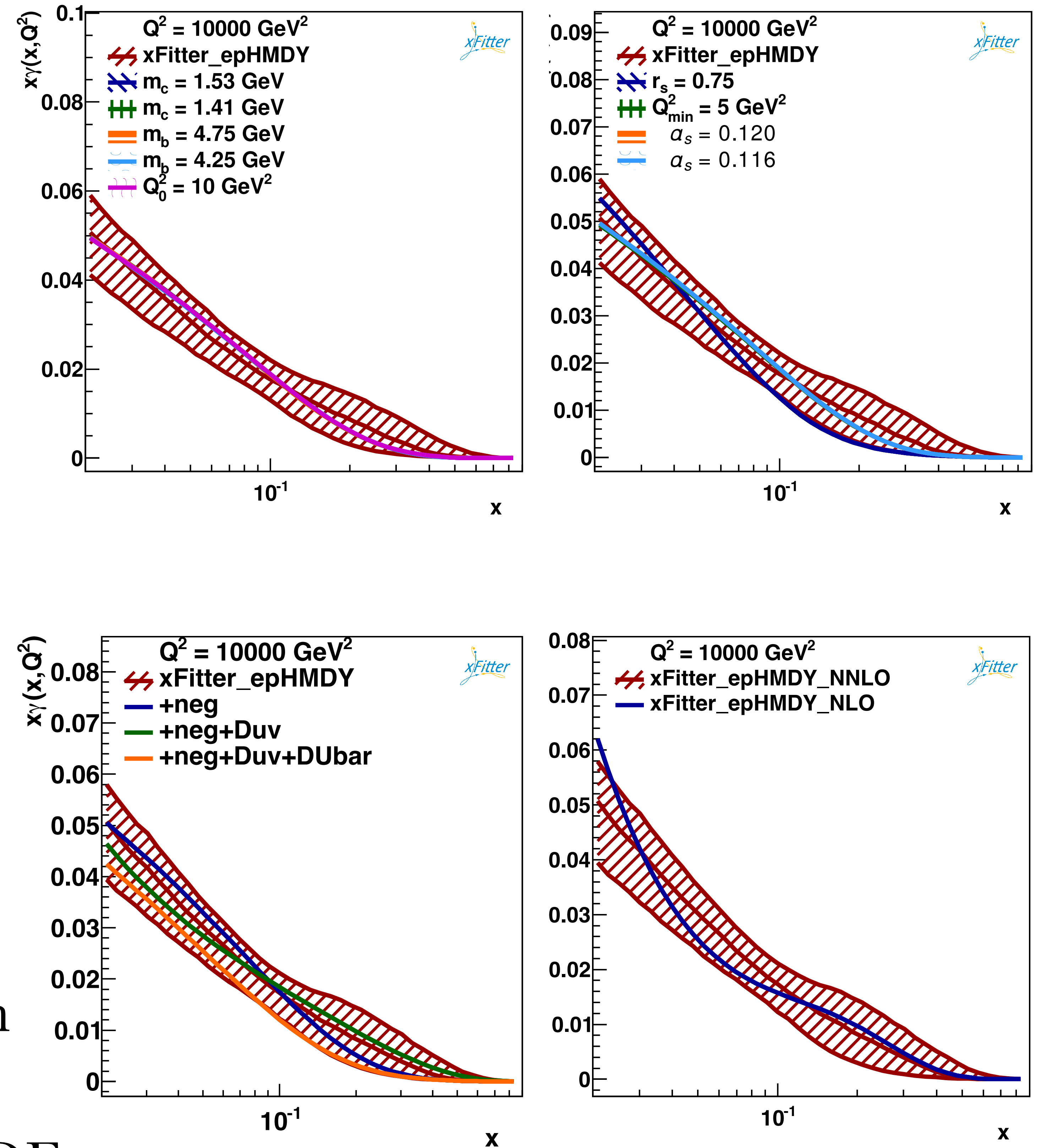


- Agreement within uncertainties for all determinations for $x > 0.1$.
- For $x < 0.1$ LUXqed and HKR16 are softer than `xFitter_epHMDY`:
    - agreement at the 2-σ level.
- Smaller uncertainty as compared to NNPDF3.0 (~30% below x = 0.1):
    - consequence of the constraining power of the ATLAS 8 TeV data.

Results

Fit Stability

- Variations of the **input** params:
  - $\delta\alpha_s = \pm\, 0.002$,
  - $r_s = 0.75$ (default 1),
  - $\delta m_c = \pm\, 0.05$ GeV,
  - $\delta m_b = \pm\, 0.25$ GeV,
  - $Q_0^2 = 10\ \mathrm{GeV}^2$ (default 7.5),
  - $Q_{min}^2 = 5\ \mathrm{GeV}^2$ (default 7.5).
- **Parametrisation** variations:
  - allow negative photon PDF,
  - more flexible quark PDFs.
- **NLO vs. NNLO**.
- All variations are contained within the **1-σ uncertainty band**.
- **Solid** extraction of the photon PDF.



Summary

- Extraction of the **photon PDF** in **xFitter** using:
    - the **HERA I+II** combined DIS data,
    - the ATLAS 8 TeV **High-Mass DY** data.
    - sensitivity to the photon in the large-x region ($\boldsymbol{x} \gtrsim \mathbf{0.02}$).
- Predictions accurate to **NNLO** in **QCD** and to **NLO** in **QED/EW**.
- Full control on the **fit stability**:
    - reliable extraction on the photon PDF.
- Fair **agreement** with the models provided by **LUXqed** and **HKR16**.
- Reduction of the uncertainty as compared to **NNPDF3.0QED**.

Backup Slides

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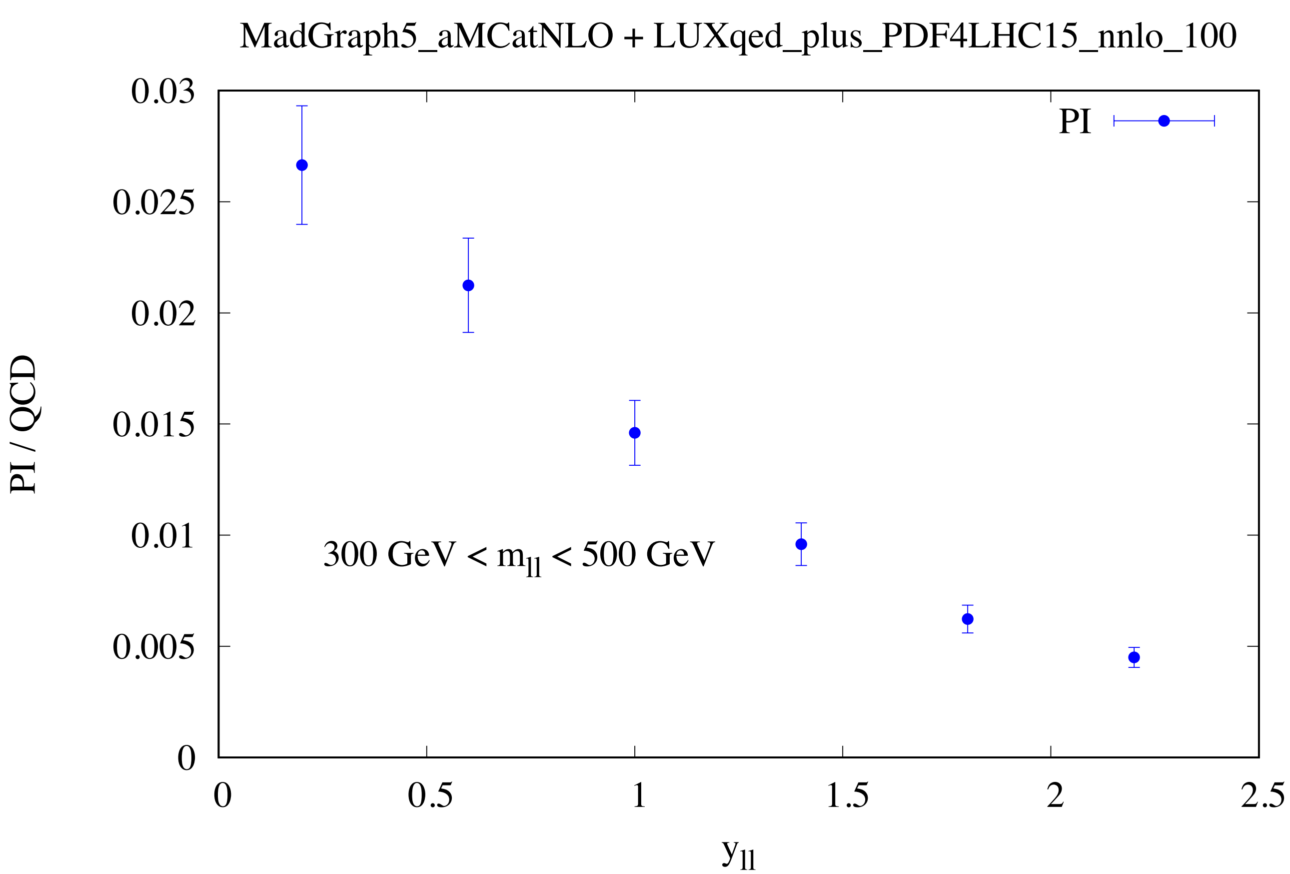
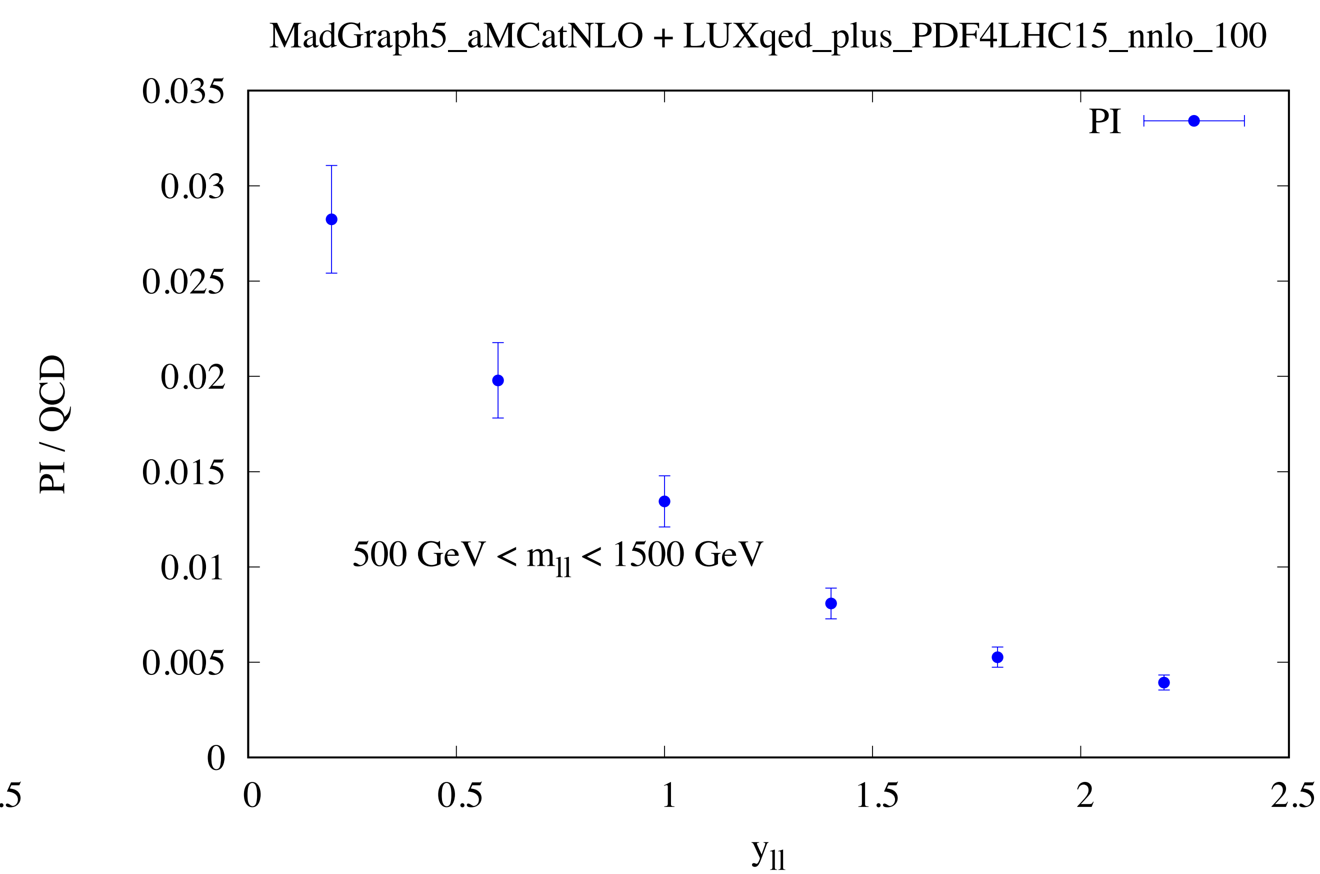
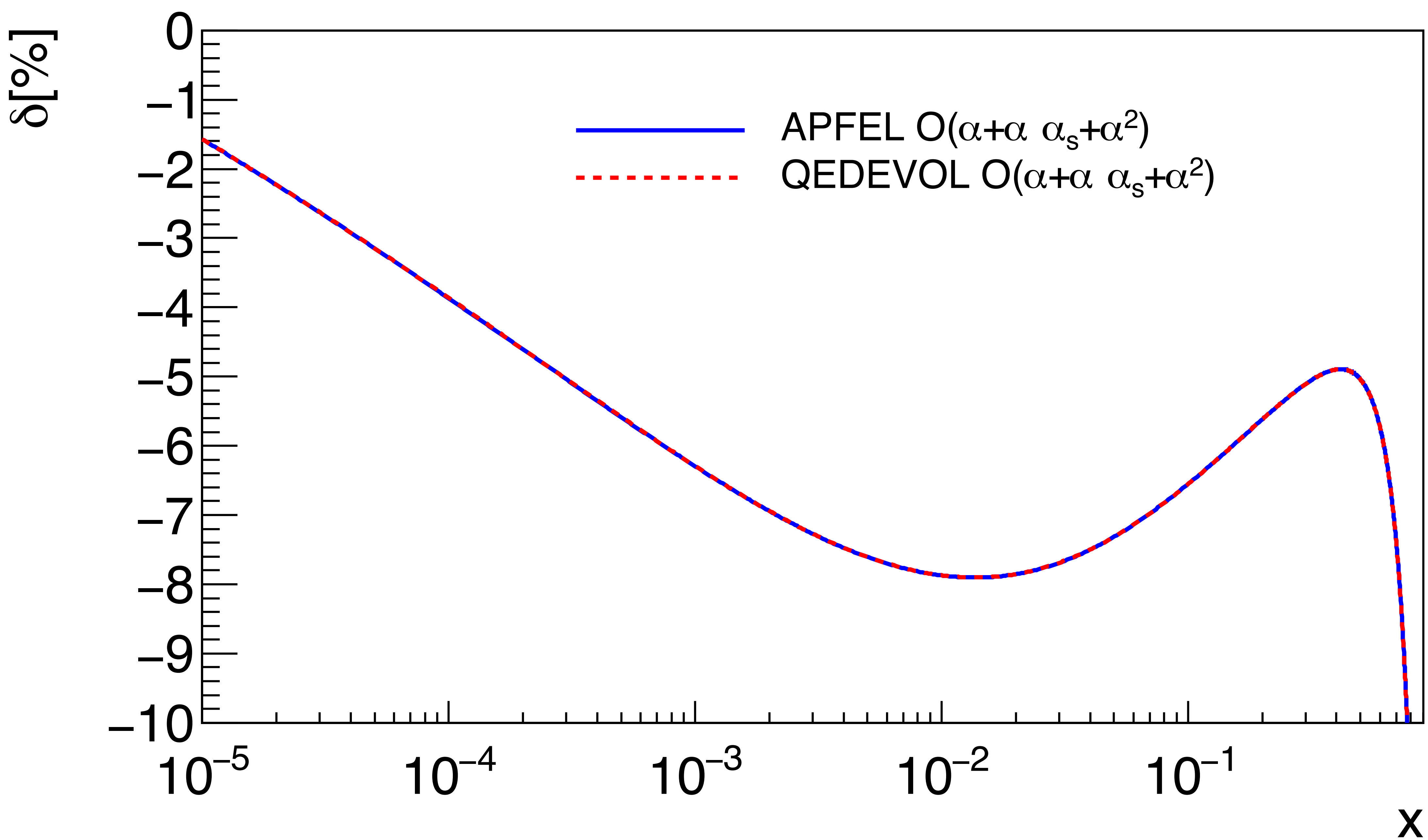




NLO QCD+QED Corrections

Benchmark against QEDEVOL

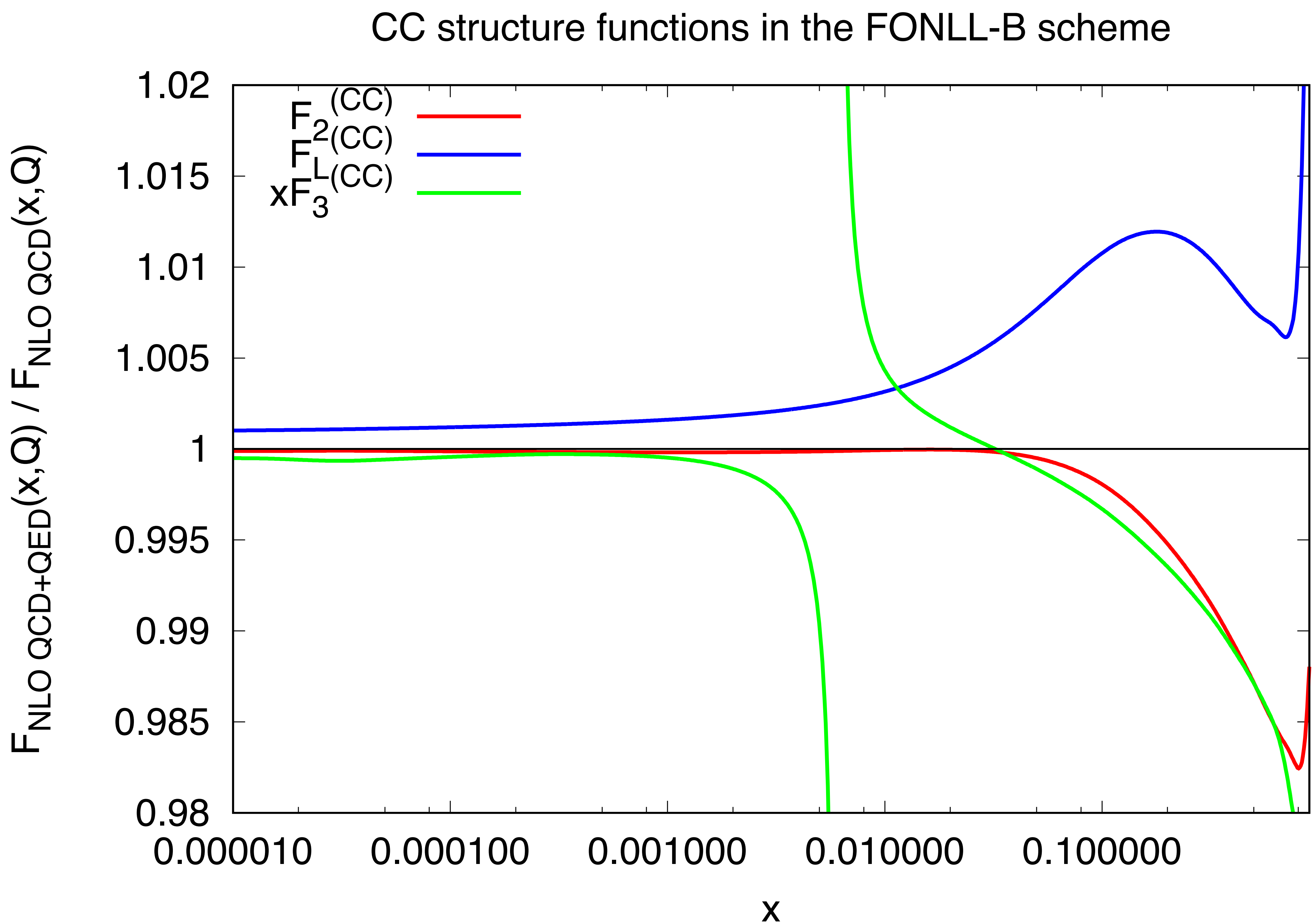


[Thanks to Renat Sadykov]

- Perfect agreement between APFEL and QEDEVOL.

NLO QCD+QED Corrections

DIS Structure Functions (CC)



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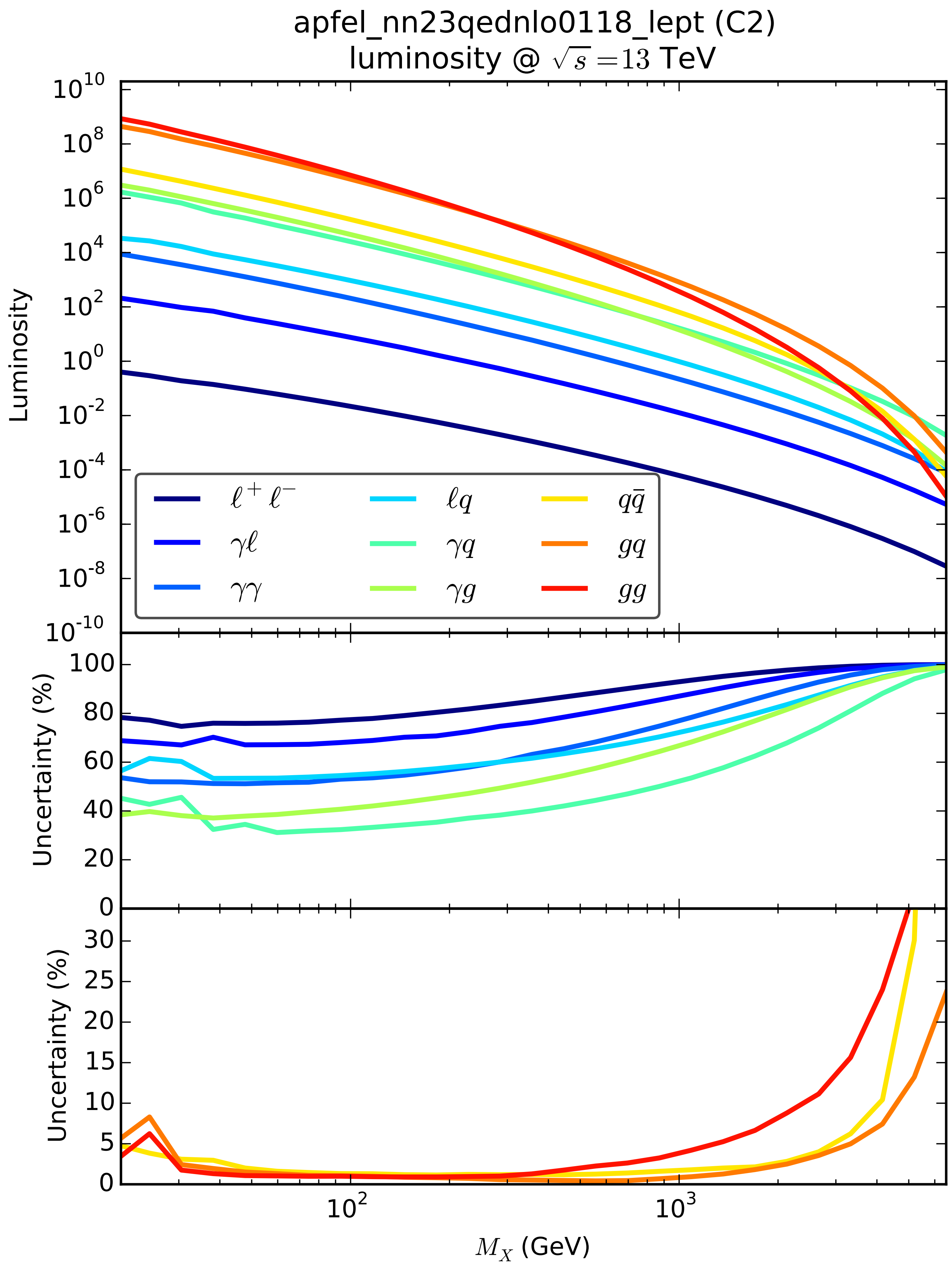

apfel_nn23qednlo0118_lept (C2)
luminosity @ $\sqrt{s} = 13$ TeV
Luminosity
Uncertainty (%)
Uncertainty (%)
M_X (GeV)
$\ell^+\ell^-$
$\gamma\ell$
$\gamma\gamma$
ℓq
γq
γg
$q\bar{q}$
gq
gg