The impact of the photon PDF and electroweak corrections on ttbar distributions

Mainly based on arXiv:1606.01915 (DP, Tsinikos, Zaro)

Preliminary NNLO QCD + NLO EW results (Czakon, Heymes, Mitov, DP, Tsinikos, Zaro)

Davide Pagani

QCD@LHC 2016

Zurich

23-08-2016

OUTLINE

NLO QCD + EW corrections to ttbar production

- Calculation framework, photon-induced contributions.

The different PDF sets with the photon

- Features of the photon PDFs and gluon-photon luminosity in ttbar production.

Distributions at 13 and 100 TeV

- Comparison **NNPDF2.3QED** (with and without photons) and **CTEQ14QED**

ATLAS and CMS measurements at 8 TeV

- Comparison of theory uncertainties and exp. errors

Preliminary results: NNLO QCD + NLO EW corrections

- Reduction of scale uncertainties and photon contributions in **NNPDF3.0QED**

Conclusions and Outlook

NLO EW corrections to ttbar

The reduction of the theory uncertainties from the calculation of higher-order QCD corrections and the precision reached in ttbar measurements at the LHC has made **EW corrections** an unavoidable ingredient for a correct comparison **THEORY** vs **EXPERIMENT**.

NLO EW corrections to ttbar

The reduction of the theory uncertainties from the calculation of higher-order QCD corrections and the precision reached in ttbar measurements at the LHC has made **EW corrections** an unavoidable ingredient for a correct comparison **THEORY** vs **EXPERIMENT**.

***Previous calculations*:**

NLO Weak: *Beenakker et al. '94; Kühn, Scharf, Uwer '06,'13*; *Bernreuther, Fücker, Si '06*

NLO QED: *Hollik, Kollar '08*

FB asymmetry: *Hollik, DP '11; Kühn, Rodrigo '12; Manohar, Trott '12; Bernreuther, Si '12*

NLO EW with decays: *Bernreuther, Si '10*

Photon-induced contributions had been calculated only at LO and only with the "old" **MRST2004QED** PDF set in *Hollik, Kollar '08*.

NLO EW corrections to ttbar

The reduction of the theory uncertainties from the calculation of higher-order QCD corrections and the precision reached in ttbar measurements at the LHC has made **EW corrections** an unavoidable ingredient for a correct comparison **THEORY** vs **EXPERIMENT**.

***Previous calculations*:**

NLO Weak: *Beenakker et al. '94; Kühn, Scharf, Uwer '06,'13*; *Bernreuther, Fücker, Si '06*

NLO QED: *Hollik, Kollar '08*

FB asymmetry: *Hollik, DP '11; Kühn, Rodrigo '12; Manohar, Trott '12; Bernreuther, Si '12*

NLO EW with decays: *Bernreuther, Si '10*

Photon-induced contributions had been calculated only at LO and only with the "old" **MRST2004QED** PDF set in *Hollik, Kollar '08*.

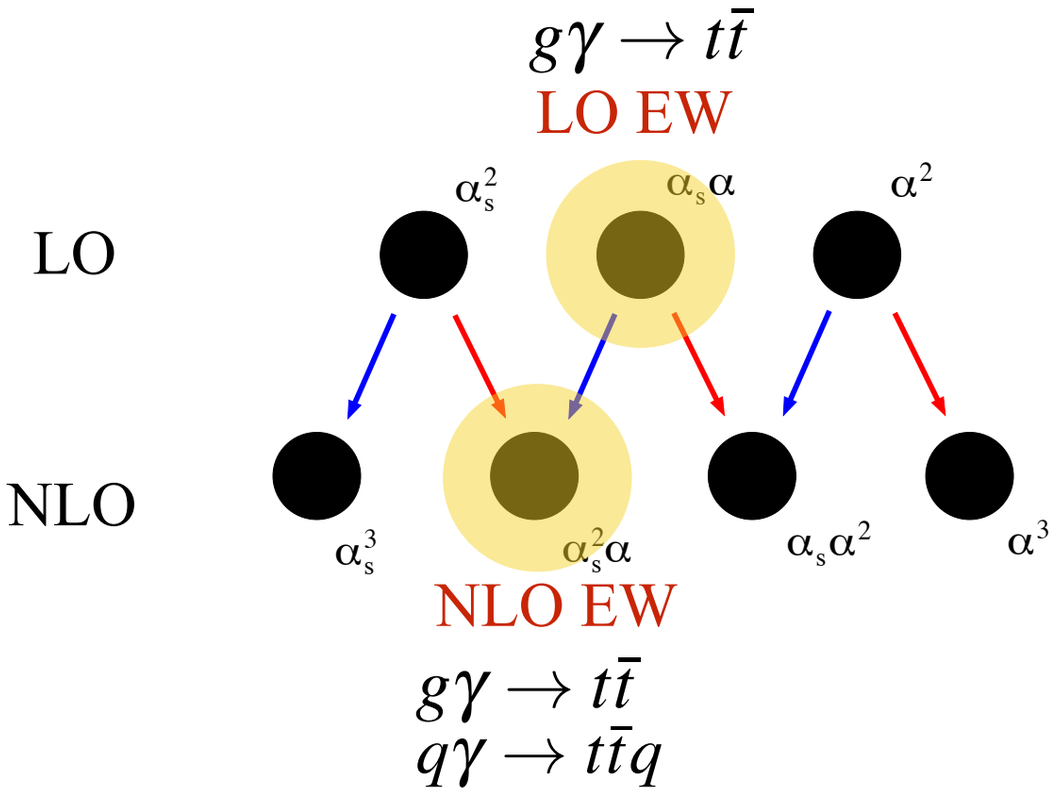
We (re)evaluated LO EW and NLO EW orders including **all the photon-induced channels** and we compared results obtained with **NNPDF2.3QED, CTEQ14QED**, two modern PDF sets including the photon density.

***Other very recent publications*:**

Denner, Pellen (**off-shell leptonic decays**), *Campbell, Wackeroth, Zhou* (**NLO Weak**)

Calculation framework

The calculation has been performed in a completely automated way via an extension of **MadGraph5_aMC@NLO** (*Frixione, Hirschi, DP, Shao, Zaro '14,'15*).
We take into account **LO QCD + LO EW + NLO QCD + NLO EW**.

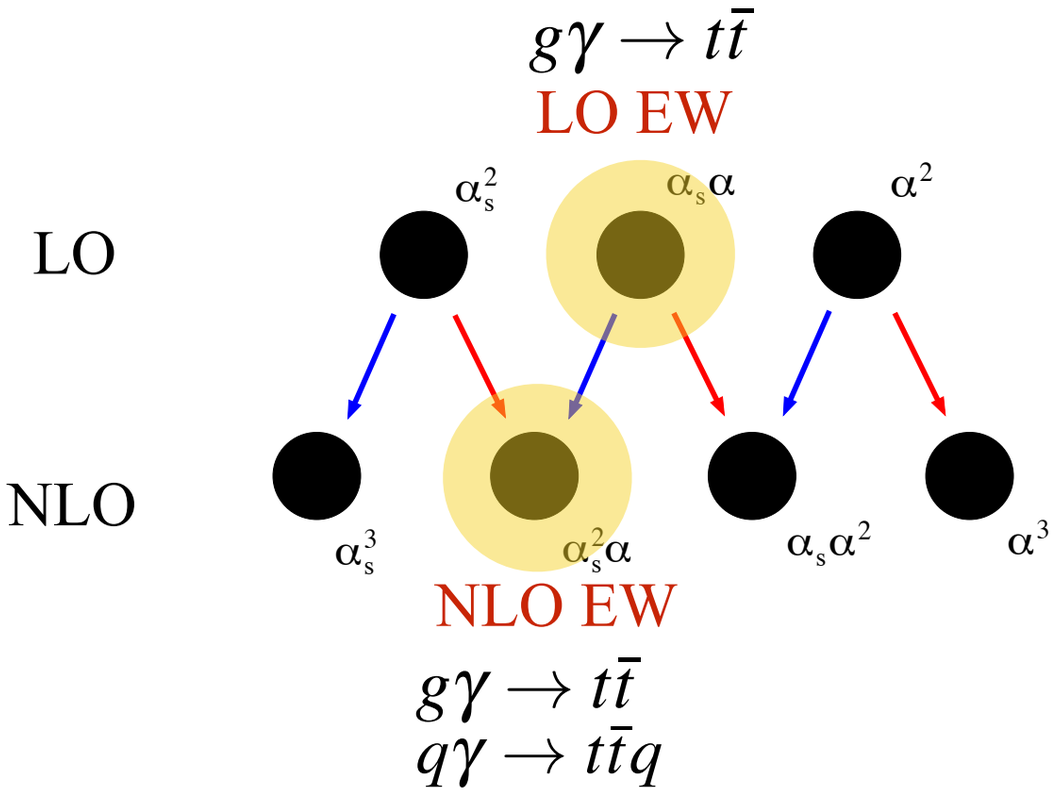


$$\Sigma_{\text{QCD}} \equiv \Sigma_{\text{LO QCD}} + \Sigma_{\text{NLO QCD}}\,,$$
$$\Sigma_{\text{EW}} \equiv \Sigma_{\text{LO EW}} + \Sigma_{\text{NLO EW}}\,,$$
$$\Sigma_{\text{QCD+EW}} \equiv \Sigma_{\text{QCD}} + \Sigma_{\text{EW}}\,.$$

In EW contributions, cancellations between Sudakov logs (NLO EW) and photon-induced processes (LO EW) are expected.

Calculation framework

The calculation has been performed in a completely automated way via an extension of **MadGraph5_aMC@NLO** (*Frixione, Hirschi, DP, Shao, Zaro '14,'15*).
We take into account **LO QCD + LO EW + NLO QCD + NLO EW**.



$$\Sigma_{\text{QCD}} \equiv \Sigma_{\text{LO QCD}} + \Sigma_{\text{NLO QCD}}\,,$$
$$\Sigma_{\text{EW}} \equiv \Sigma_{\text{LO EW}} + \Sigma_{\text{NLO EW}}\,,$$
$$\Sigma_{\text{QCD+EW}} \equiv \Sigma_{\text{QCD}} + \Sigma_{\text{EW}}\,.$$

In EW contributions, cancellations between Sudakov logs (NLO EW) and photon-induced processes (LO EW) are expected.

Input parameters:

$$m_t = 173.3\ \text{GeV}\,, \quad m_H = 125.09\ \text{GeV}$$
$$m_W = 80.385\ \text{GeV}\,, \quad m_Z = 91.1876\ \text{GeV}$$
$$G_\mu = 1.1663787 \cdot 10^{-5}\ \text{GeV}^{-2}$$

$$\mu = \frac{H_T}{2} = \frac{1}{2}\sum_i m_{T,i}$$

and the PDF set …

PDF sets with a photon density

MRST2004QED: *Martin et al. '04*
NNPDF2.3QED: *Ball et al. '13*
CTEQ14QED(inc): *Schmidt et al. '16*
NNPDF3.0QED: *Bertone, Carrazza '16*
LUXQED: *Manohar et al. '16*
MMHTQED? '16 ?
Additional Studies: *Harland-Lang, Khoze, Ryskin '16*

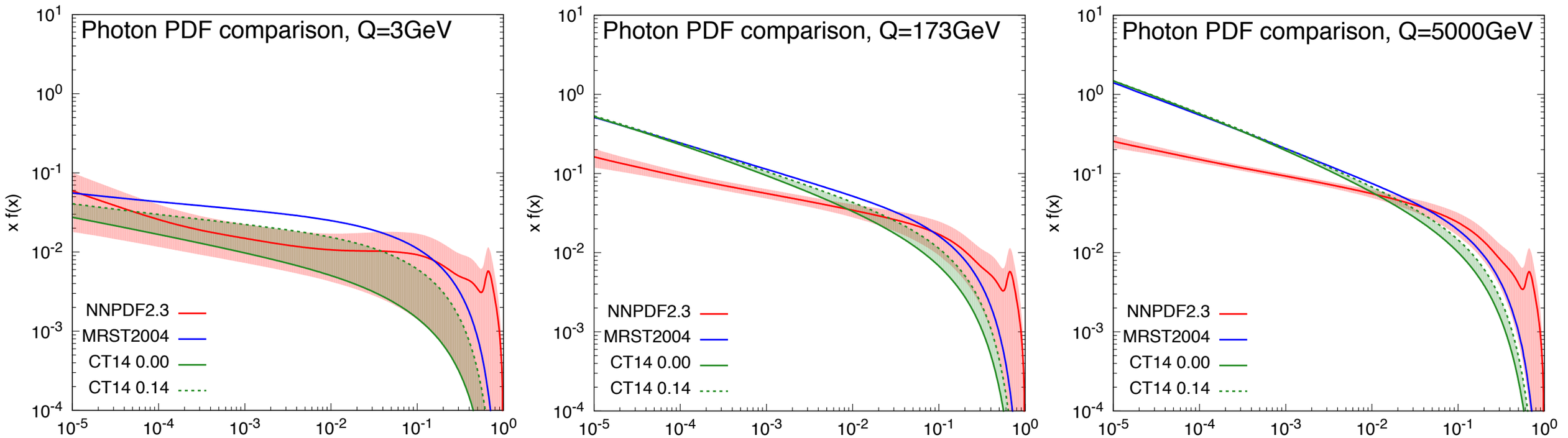
These PDF sets have at least NLO QCD + LO QED terms in the DGLAP evolution.

- The photon PDF determination is very different in the various sets.

- The different treatment of the QED and QCD DGLAP evolution has a huge impact at small x and large Q (**NNPDF2.3QED**), but does **not** lead to visible effects in ttbar phenomenology.

- We explicitly calculated EW corrections with **NNPDF2.3QED** and **CTEQ14QED**. All the others can be estimated, (**for ttbar**), from these two calculations.

The different photon PDFs …

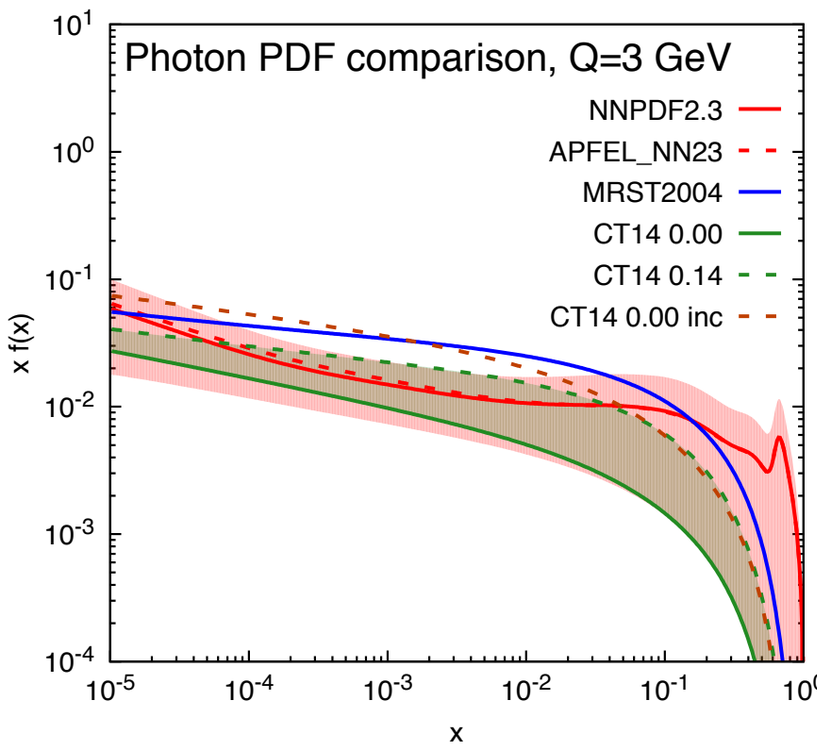


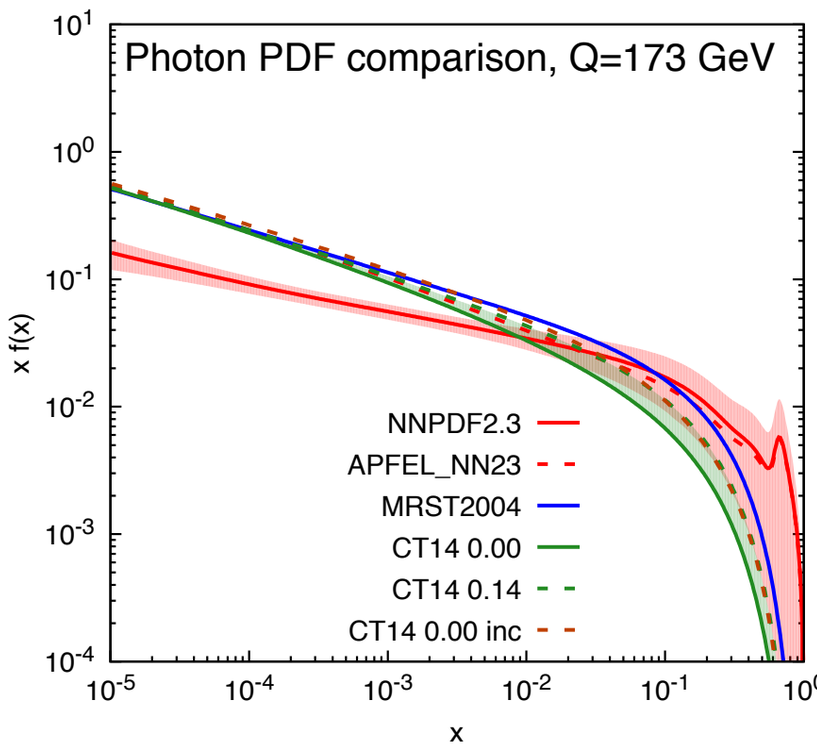
- **CTEQ14QED** and **NNPDF2.3QED** bands are compatible at Q = 3 GeV.

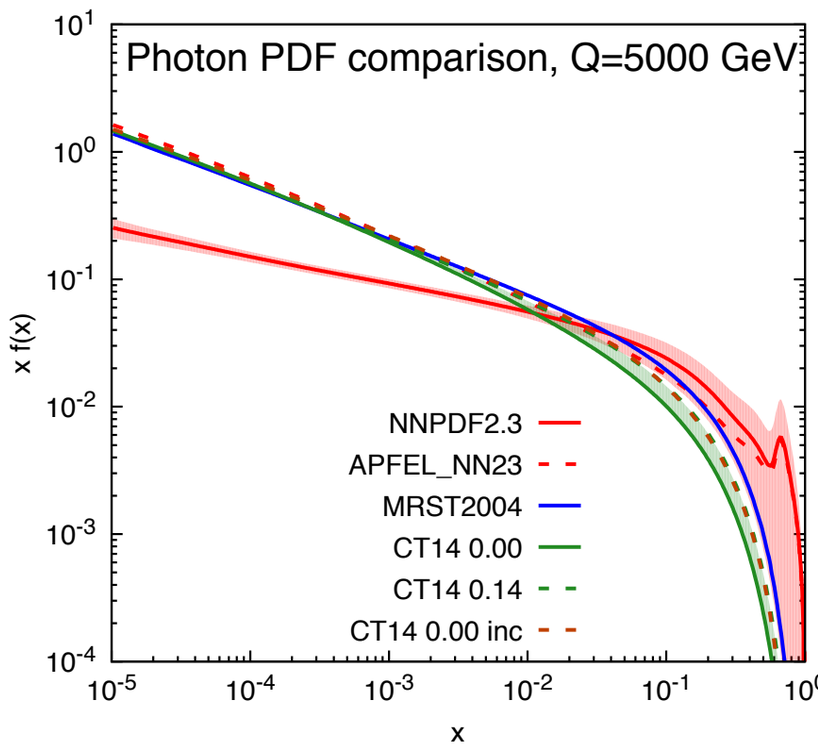
- **CTEQ14QED** and **NNPDF2.3QED** bands are not compatible at larger values of Q. **MRST2004QED** (current masses) slightly larger than **CTEQ14QED.**

- At large Q and low x **CTEQ14QED** and **NNPDF2.3QED** are very different due to the different DGLAP QCD and QED running.

The different photon PDFs …





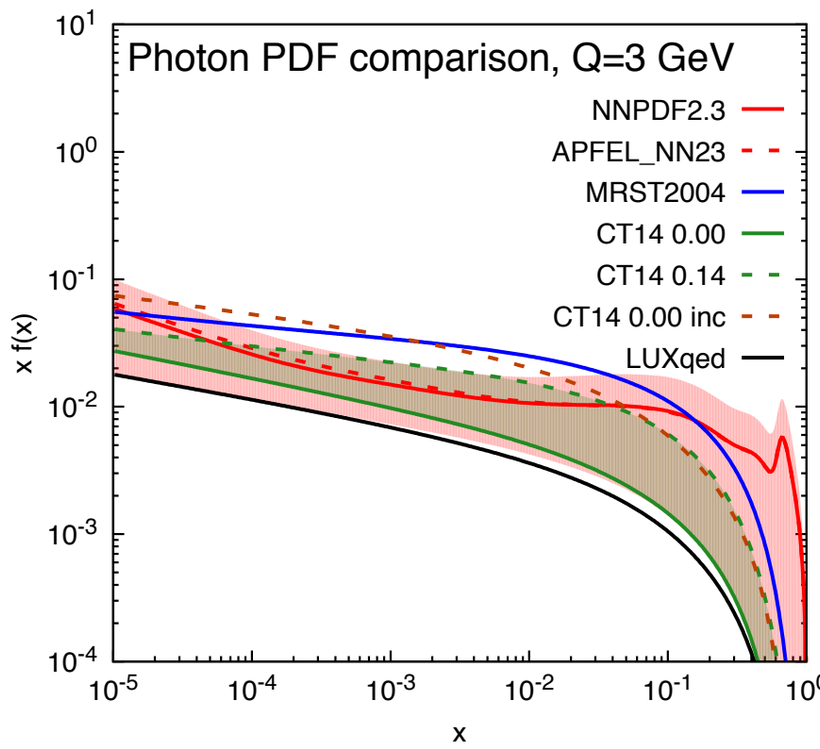


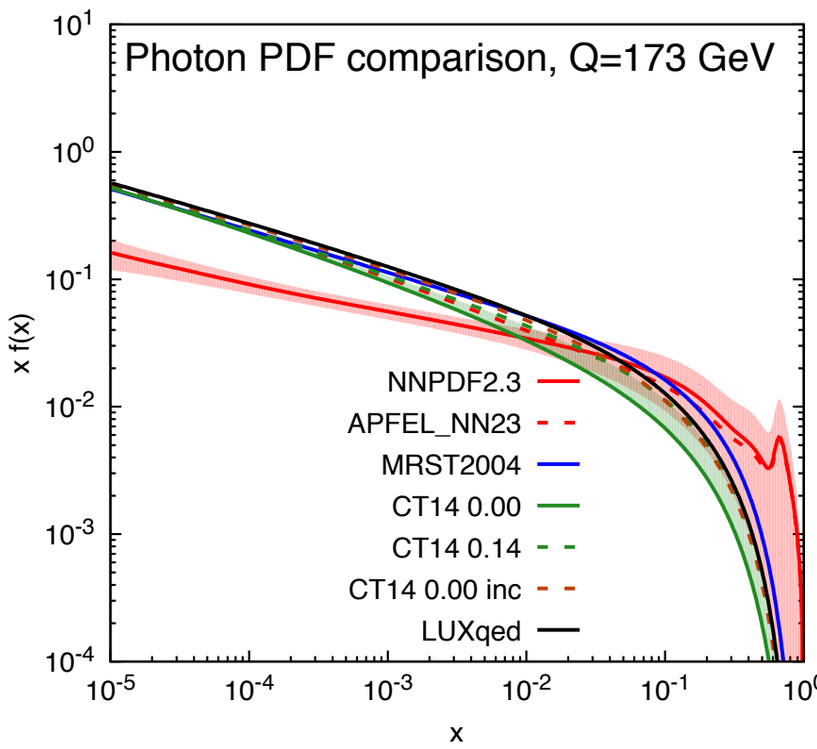
- **APFEL_NN23** (*Bertone, Carrazza, DP, Zaro '15*) is at the initial scale equivalent to **NNPDF2.3QED** for all the PDFs. But, the DGLAP QCD and QED running is consistent (similar to **NNPDF3.0QED**, where also quark and gluons have been updated to **NNPDF3.0**).

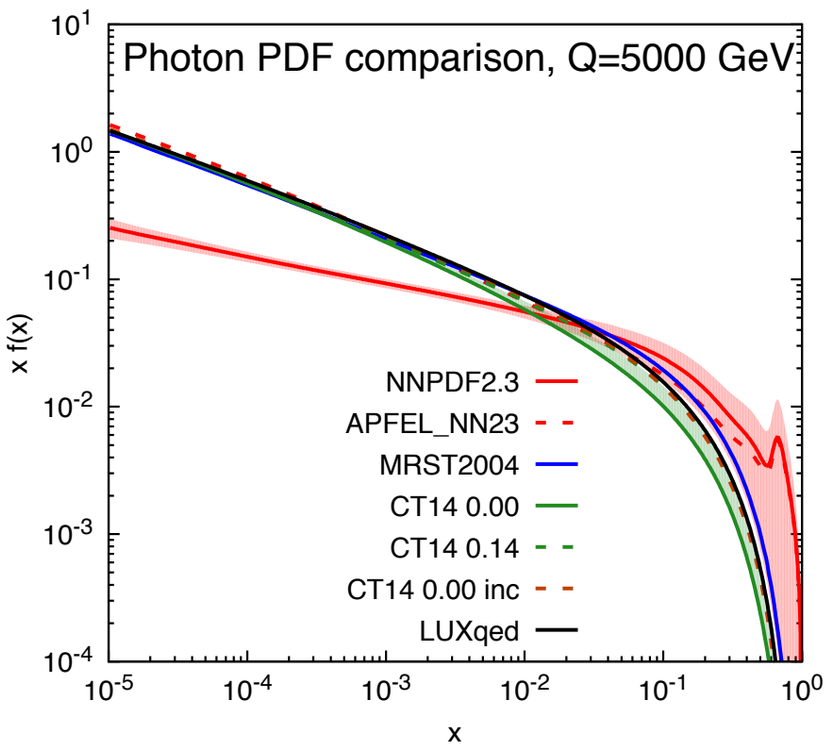
- At small Q: **APFEL_NN23** is like **NNPDF2.3QED.** At large Q: it is like **CTEQ14QED** at small x, while it is like **NNPDF2.3QED** at large x.

- **CTEQ14QED** is close to the upper edge of the **CTEQ14QEDinc** band.

The different photon PDFs …







- **LUXQED** is close to the upper edge of the **CTEQ14QED** band and to **CTEQ14QEDinc**

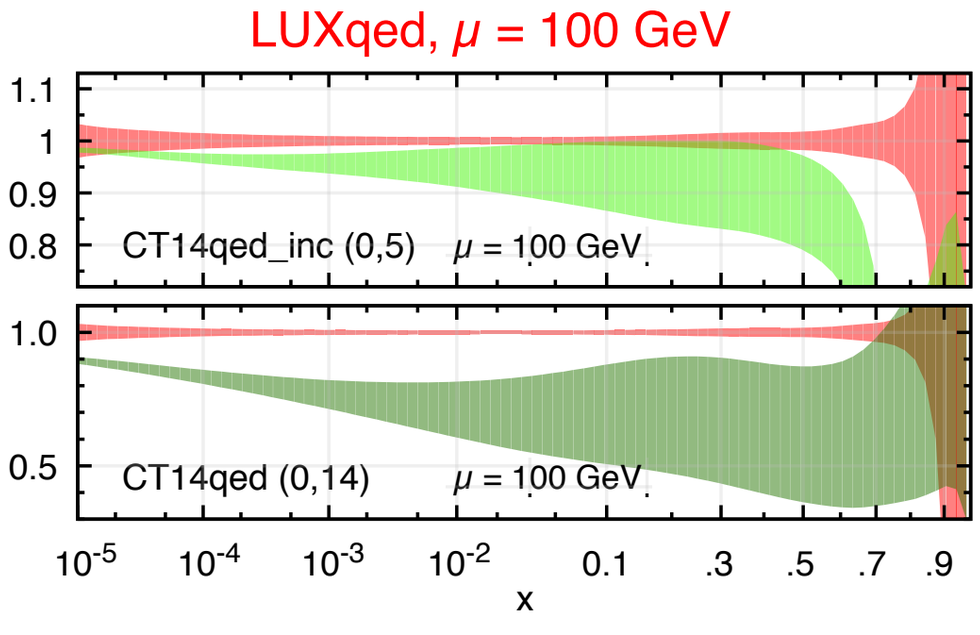
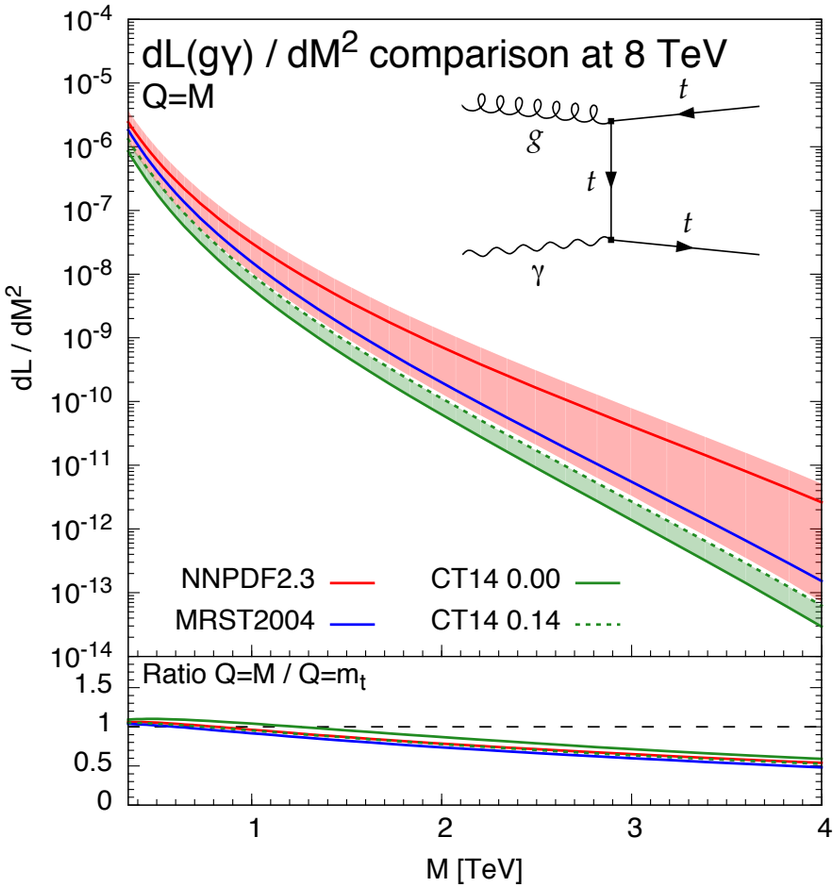
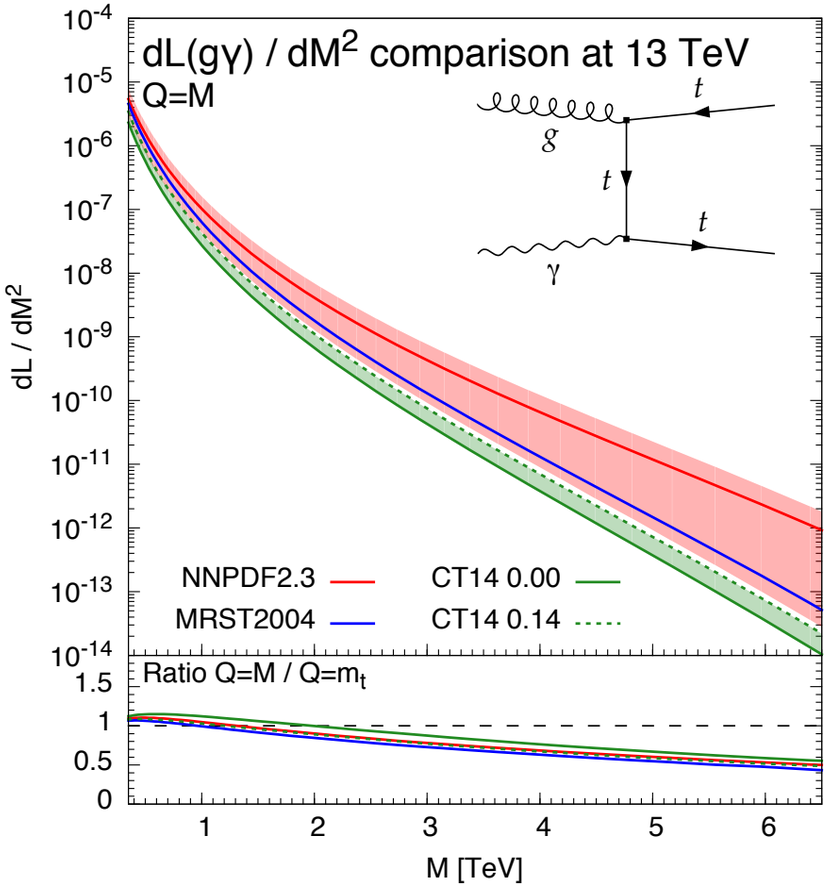
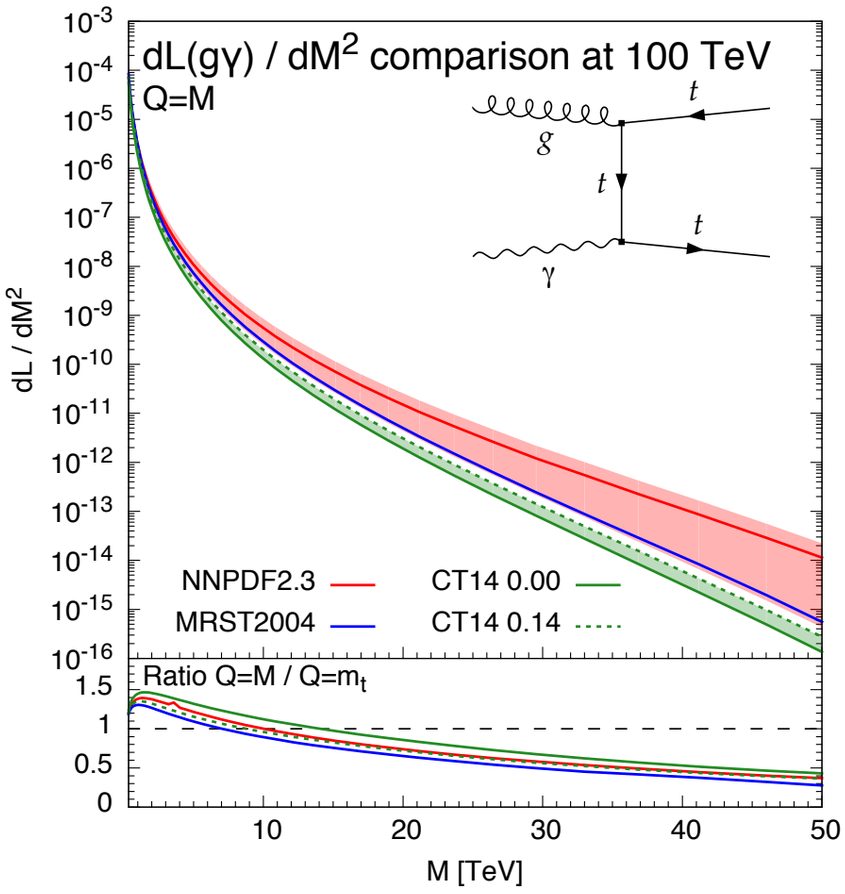


Image taken from Manohar, Nason, Salam, Zanderighi ’16 and adapted for this slide.

… and the different photon-gluon luminosities





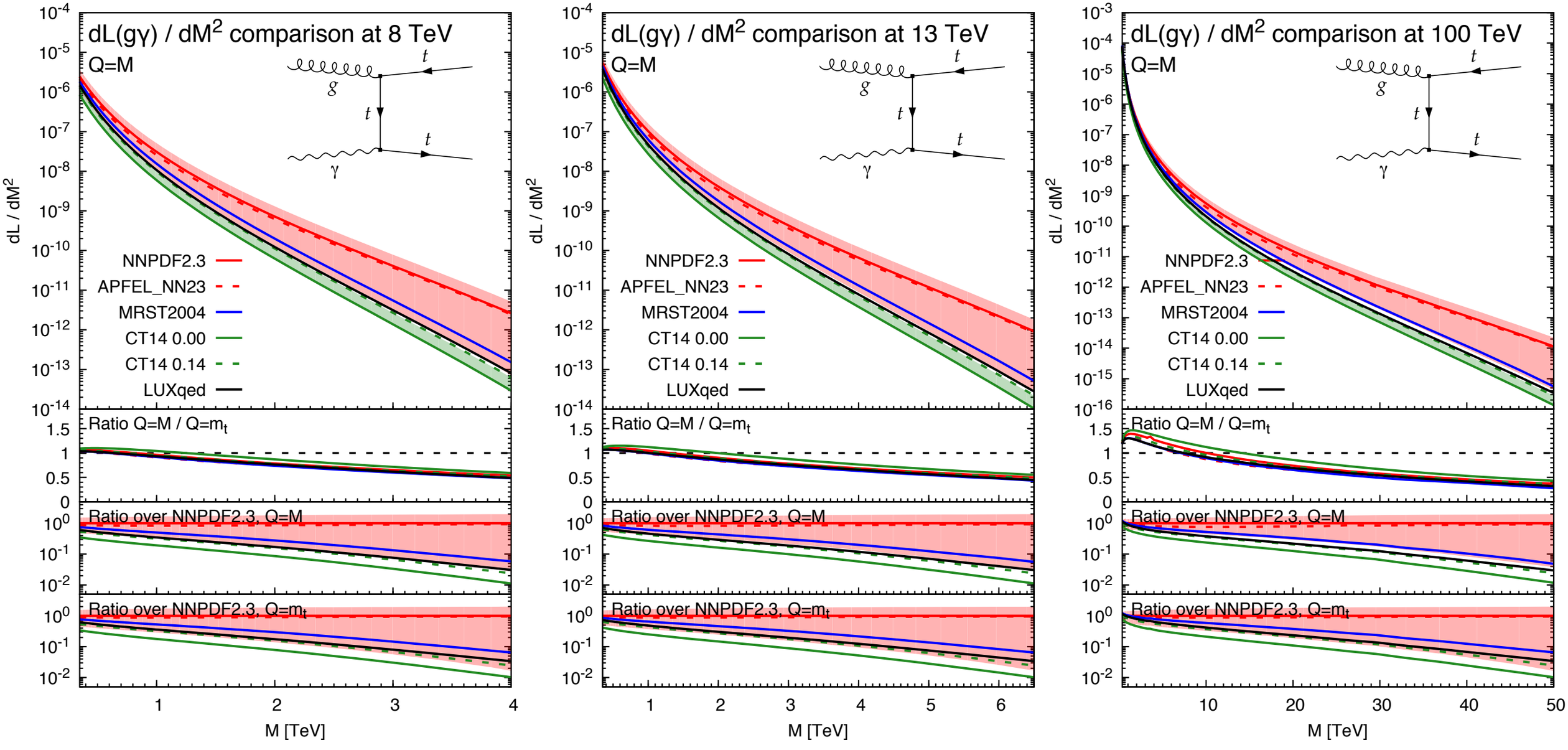


- At 8, 13, 100 TeV **CTEQ14QED** and **NNPDF2.3QED** photon-gluon luminosities are barely compatible (M < 1 TeV) or not compatible.

- **NNPDF2.3QED** central value and unc. band is much larger at large M.

- The value of the factorization scale is also relevant.

… and the different photon-gluon luminosities



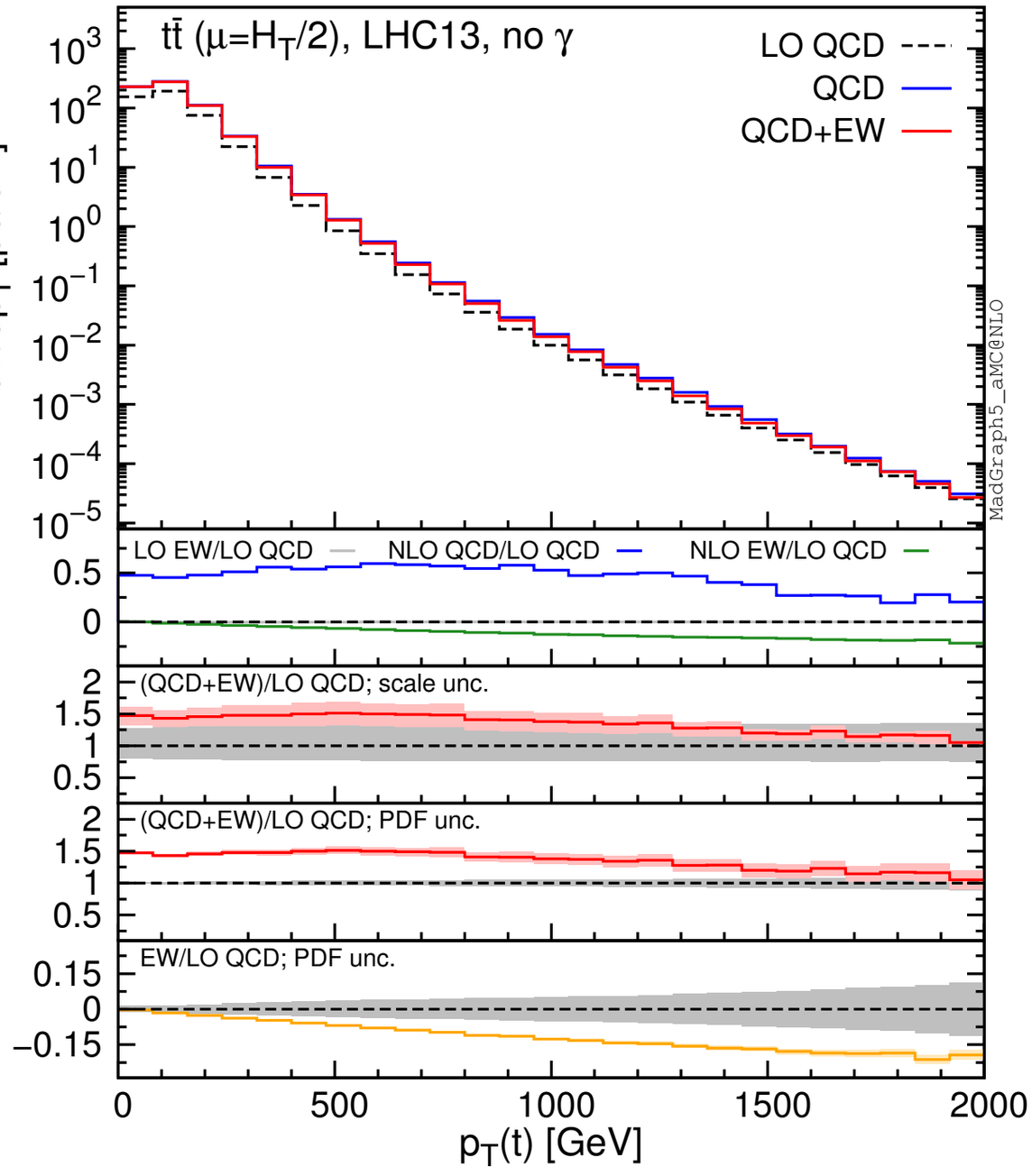
- **LUXQED** luminosity is very close to **CTEQ14QED**
- **NNPDF2.3QED** and **APFEL_NN23** are equivalent! (diff. running is not relevant)

NNPDF2.3QED representative for **(NNPDF3.0QED, APFEL_NN23)**
CTEQ14QED representative for **(CTEQ14QEDinc, LUXQED)**

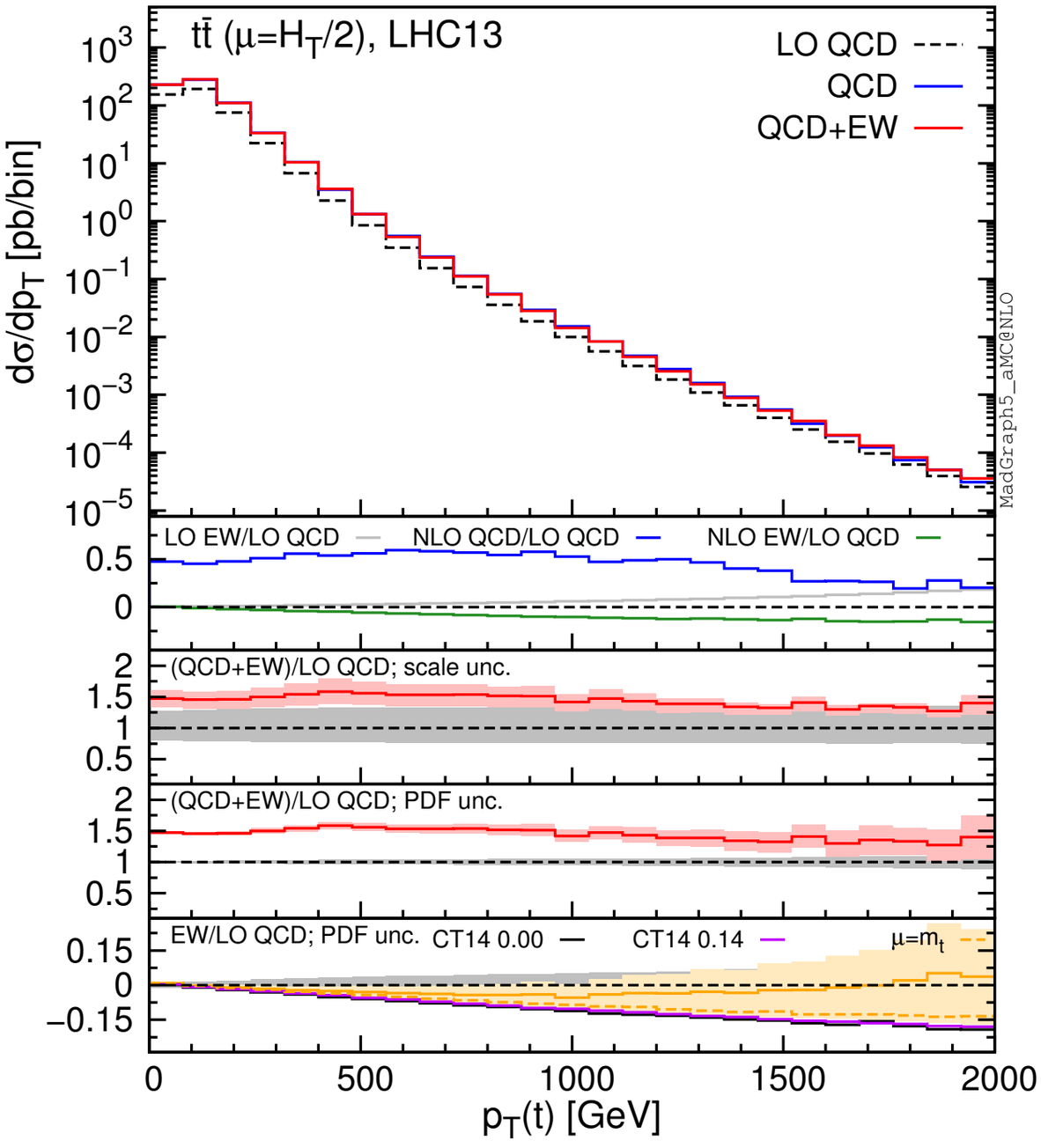
Differential distributions at the LHC 13 TeV

NNPDF2.3QED results with and without the photon PDF compared to the CTEQ14QED case.

13 TeV

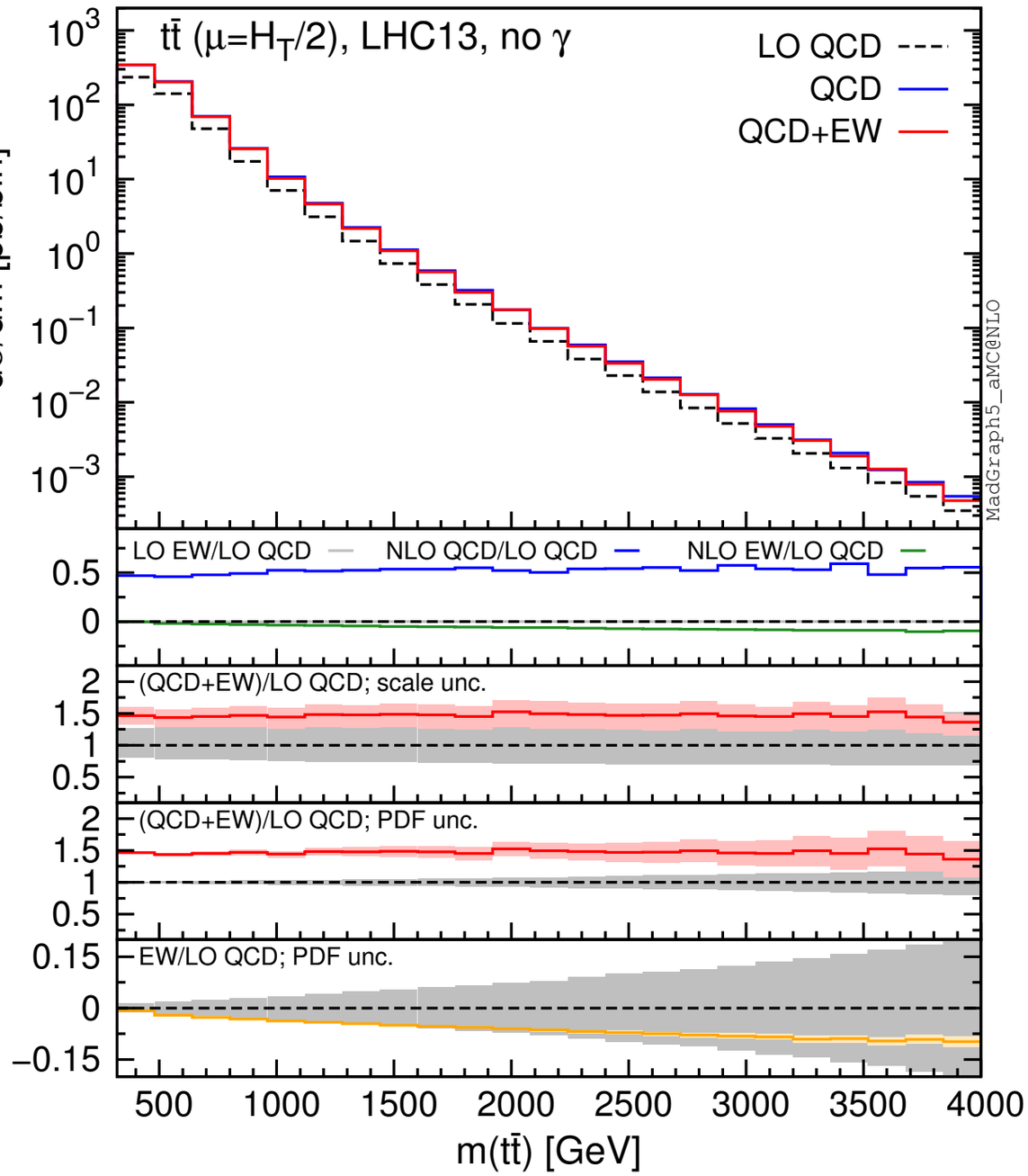


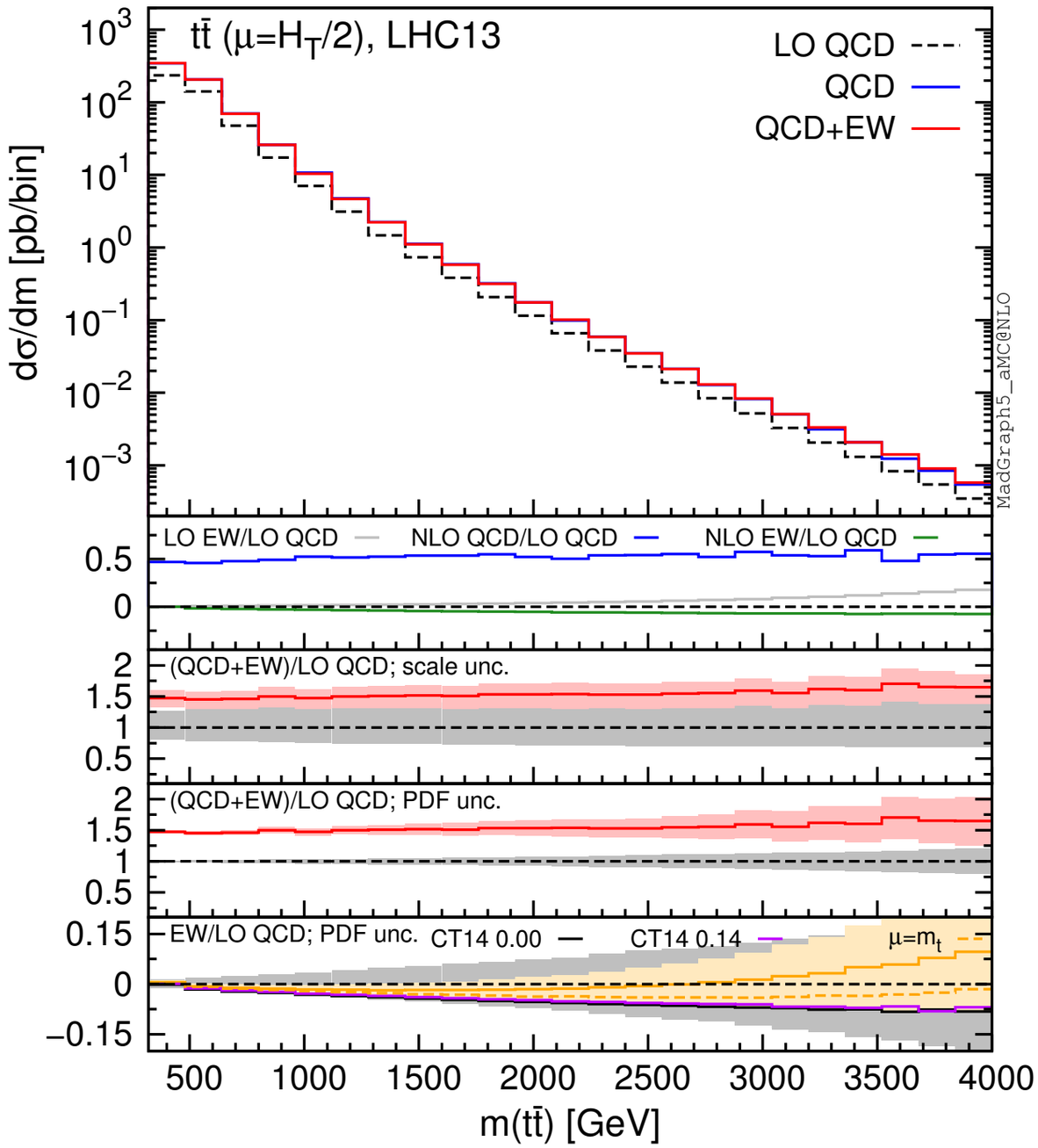
photon PDF **NO**



photon PDF **YES**

13 TeV

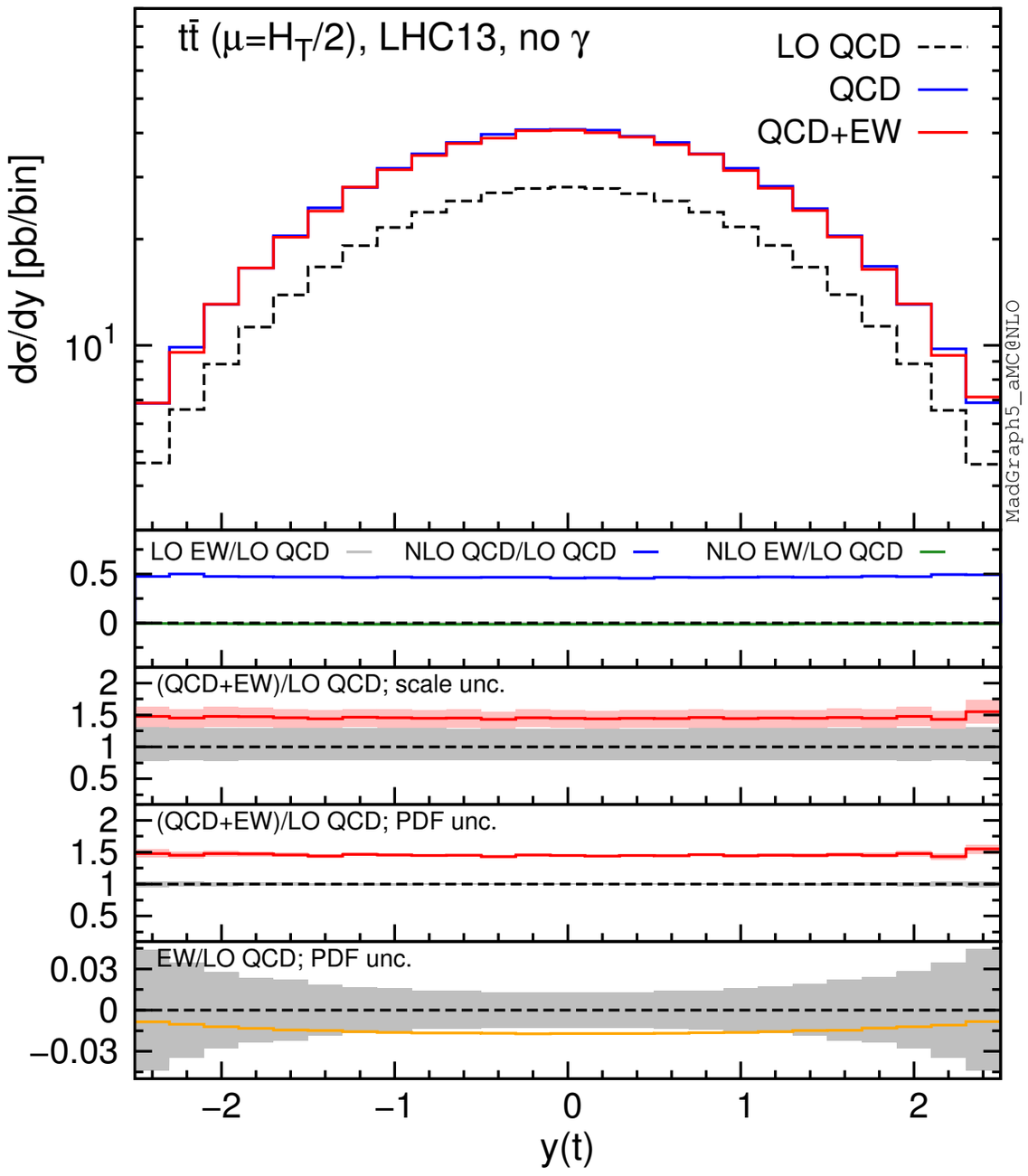




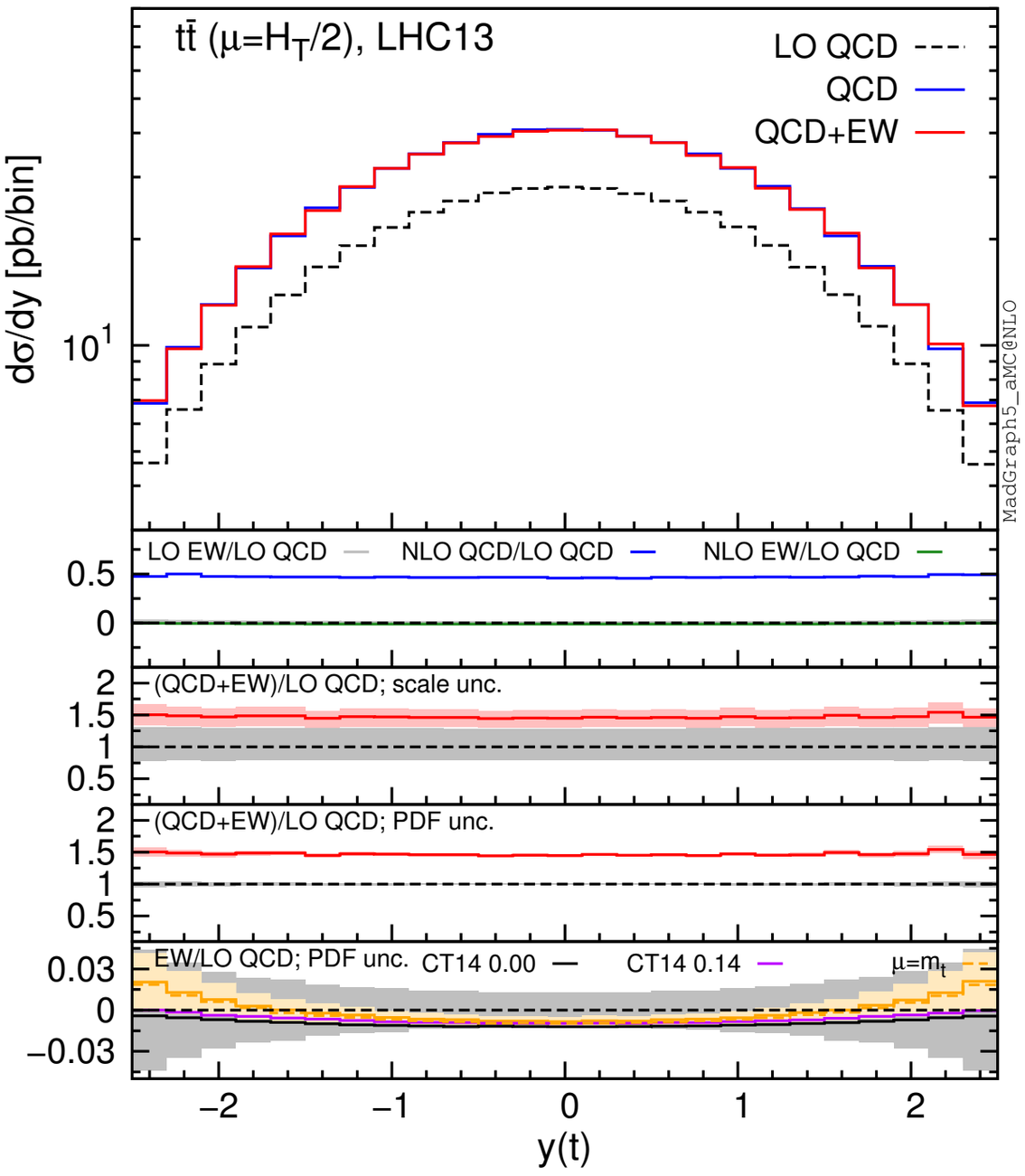
photon PDF **NO**

photon PDF **YES**

13 TeV

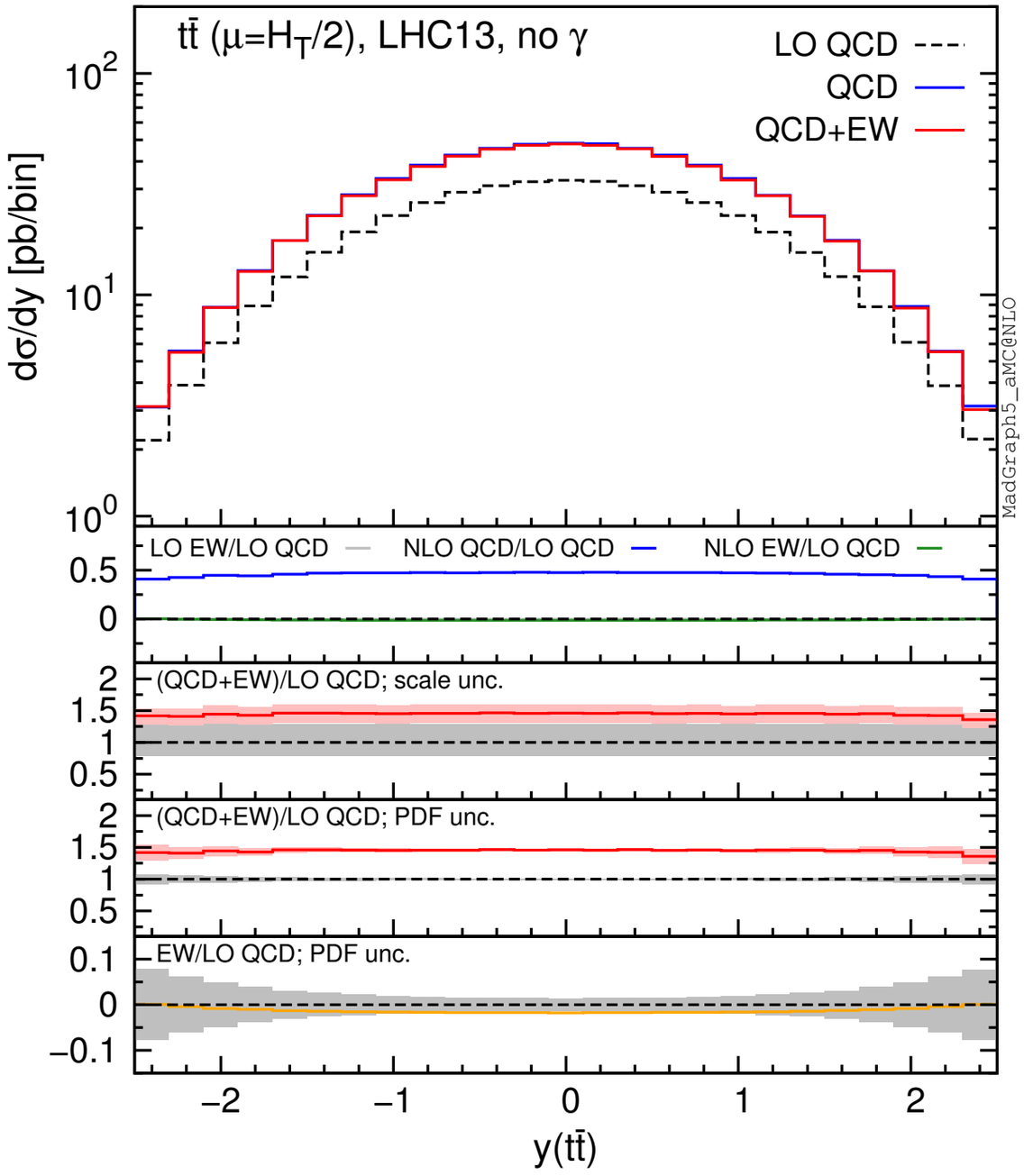


photon PDF **NO**

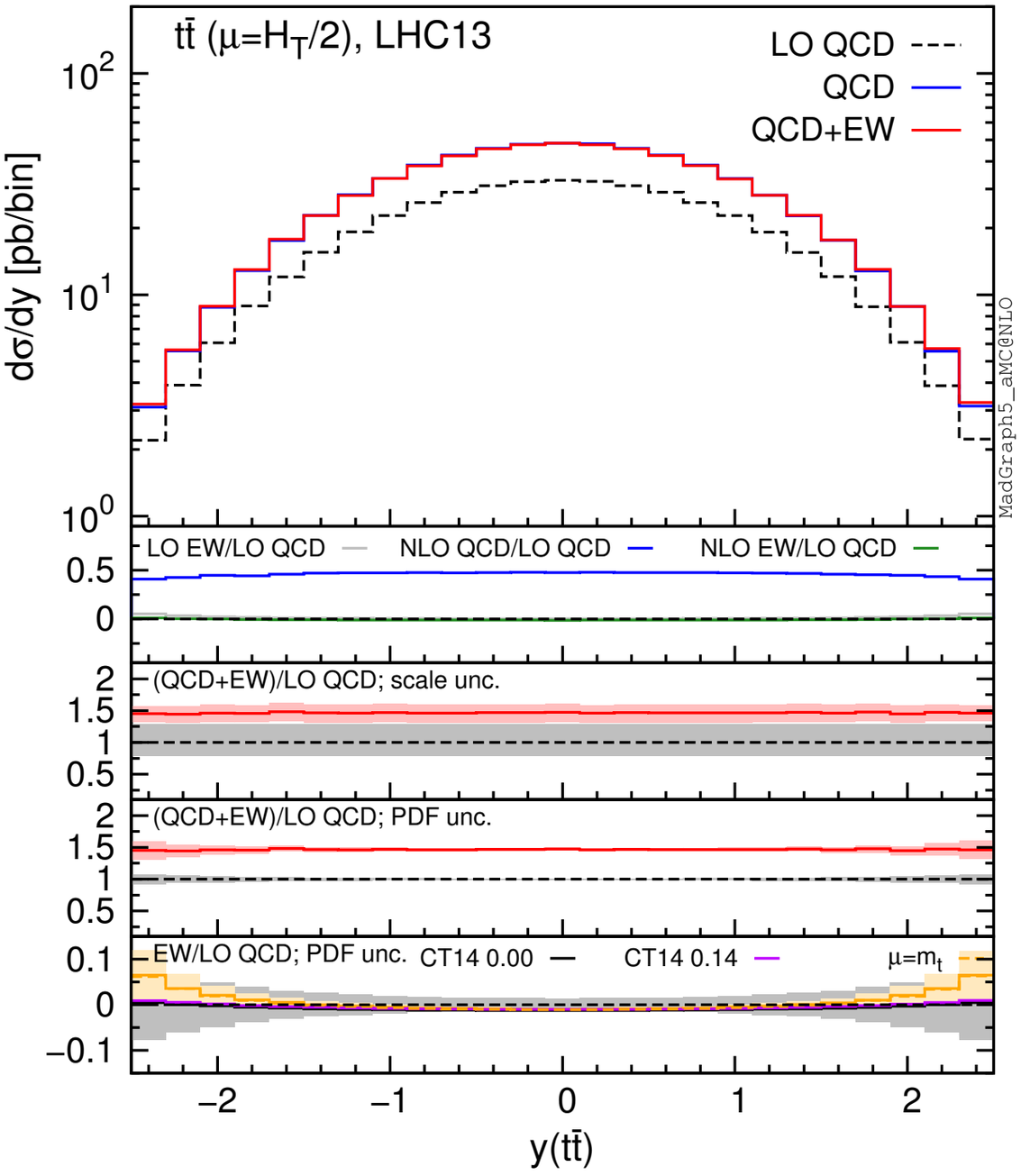


photon PDF **YES**

13 TeV



photon PDF **NO**



photon PDF **YES**

Comments

- Relative electroweak corrections for **CTEQ14QED** and for **NNPDF2.3QED with the photon PDF artificially set equal to zero** are equivalent!
In ttbar distributions the impact of the photon PDF is negligible for **CTEQ14QED** while it is large for **NNPDF2.3QED**

- In the transverse-momentum and invariant-mass distributions there are large cancellations between Sudakov logs and photon-induced contributions for **NNPDF2.3QED**.

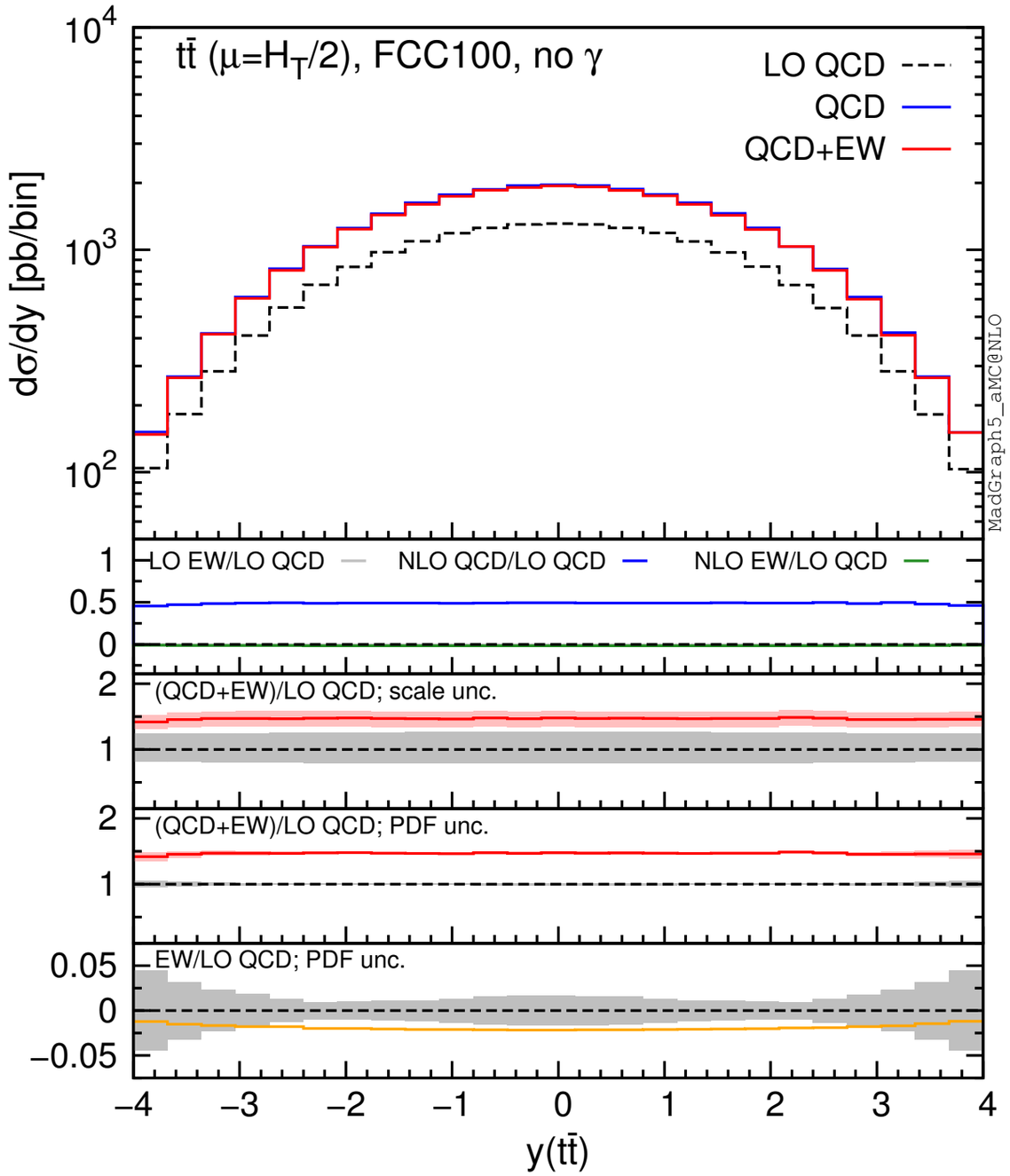
- At large top rapidities and especially top-pair rapidities the effects from the photon PDF is not negligible (**NNPDF2.3QED**).

- Photon PDF effects are almost completely due to the **LO EW** (gluon-photon initial state); the photon-induced **NLO EW** contribution (quark radiation via photon-quark initial state) is negligible. This was not obvious *a priori* and cannot be generalized to other processes, see e.g. the case of VV production (*Baglio, Ninh, Weber '13*).

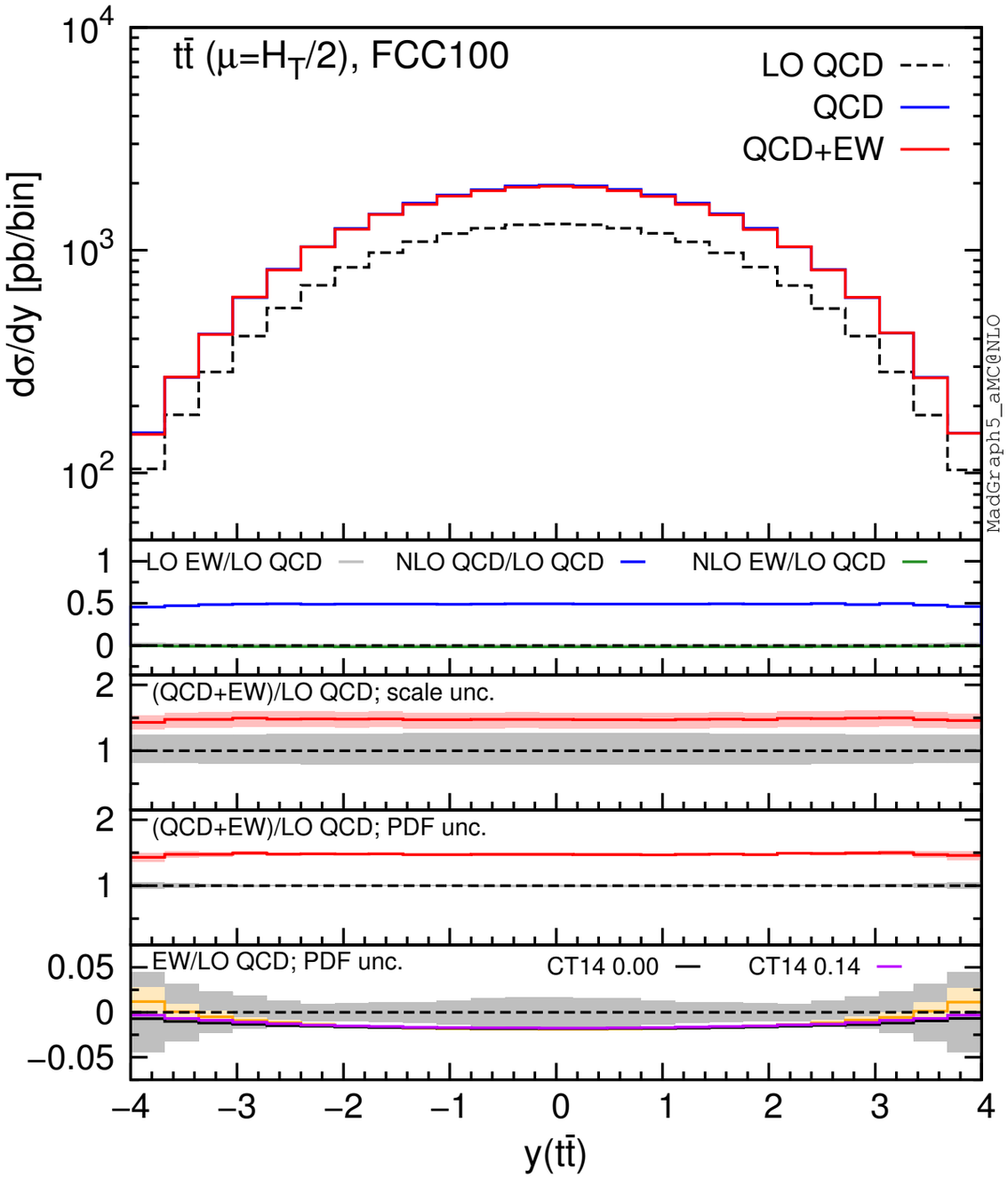
Differential distributions at 100 TeV

NNPDF2.3 results with and without the photon PDF compared to the CTEQ14QED case.

100 TeV

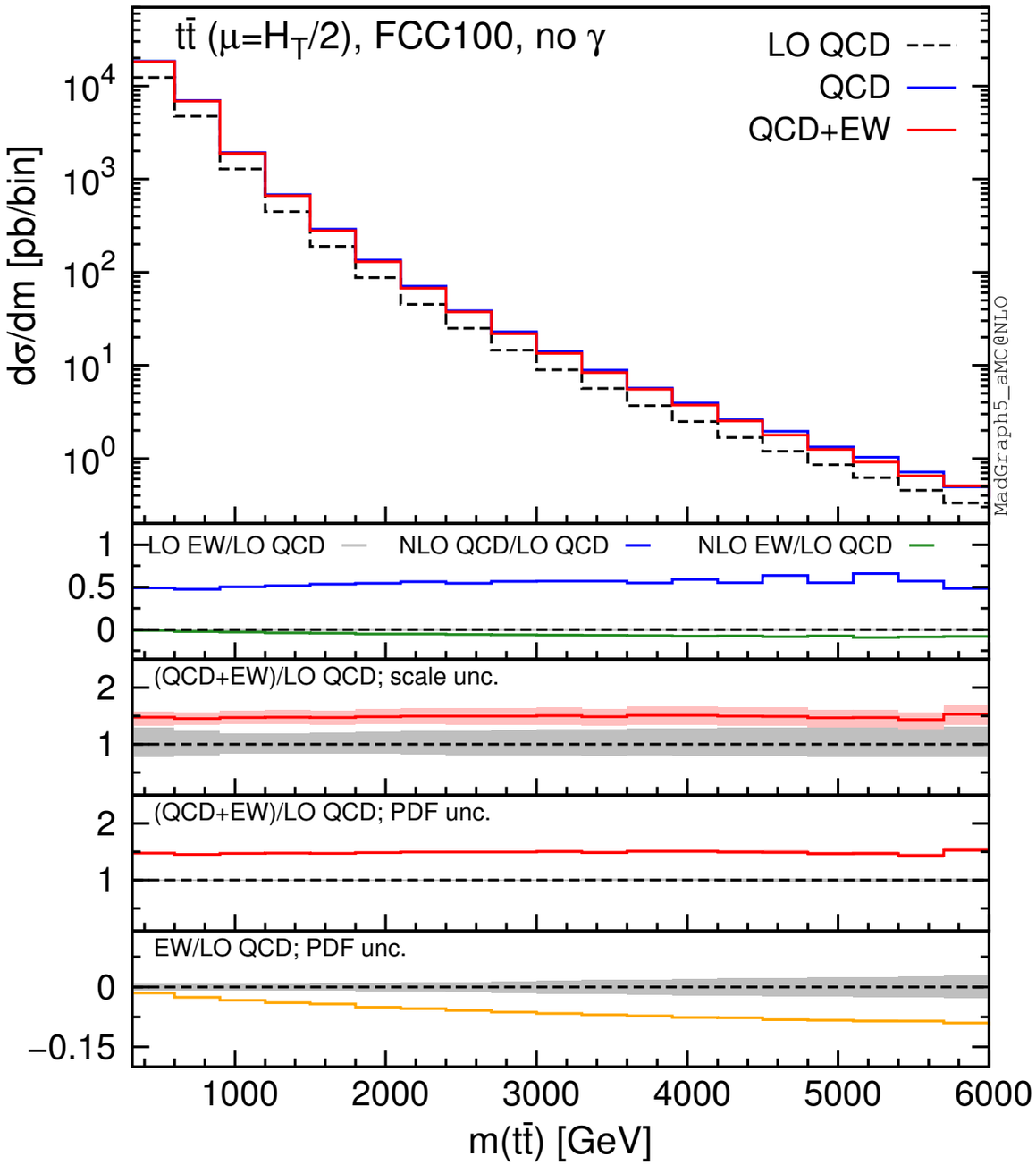


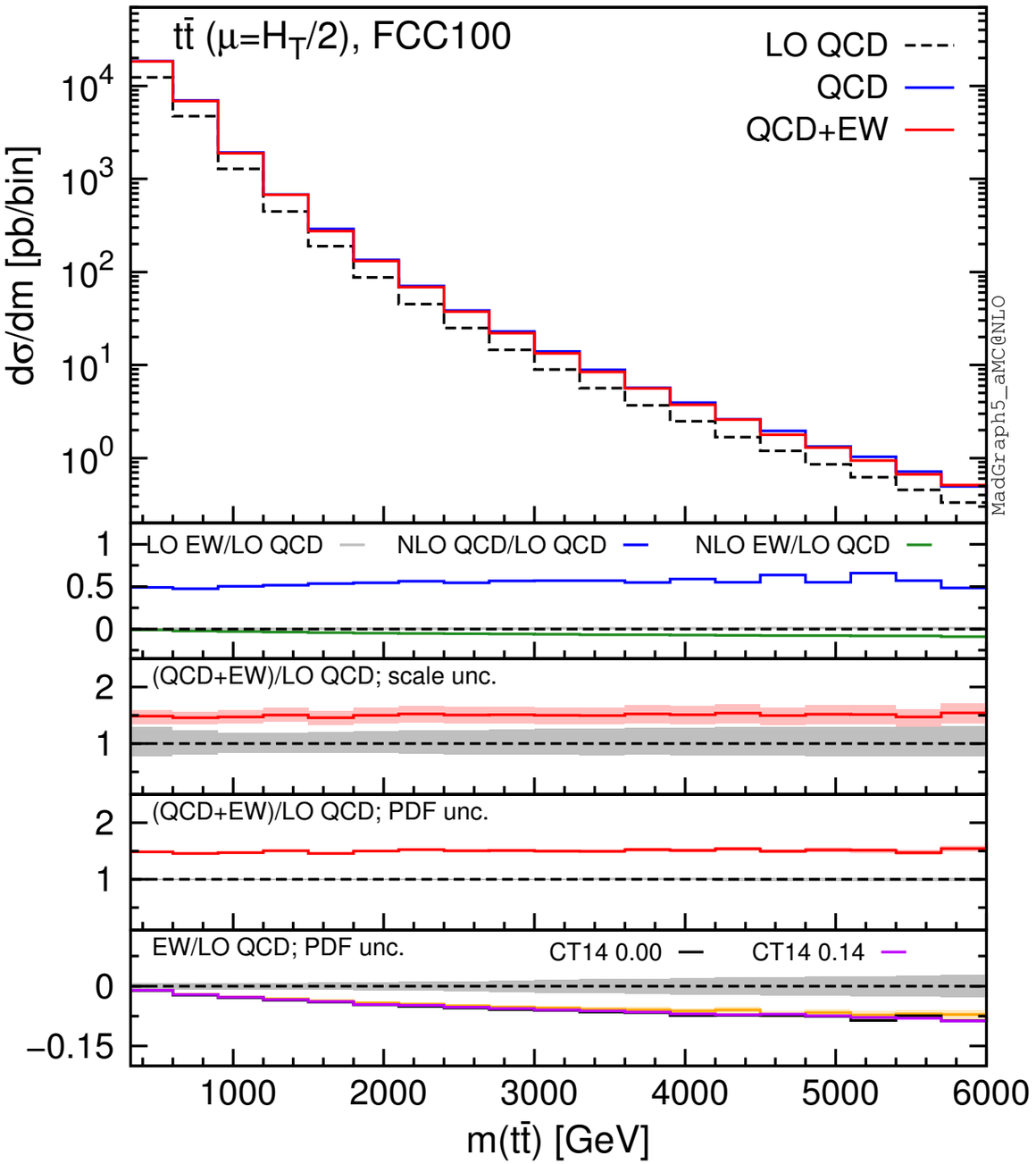
photon PDF **NO**



photon PDF **YES**

100 TeV

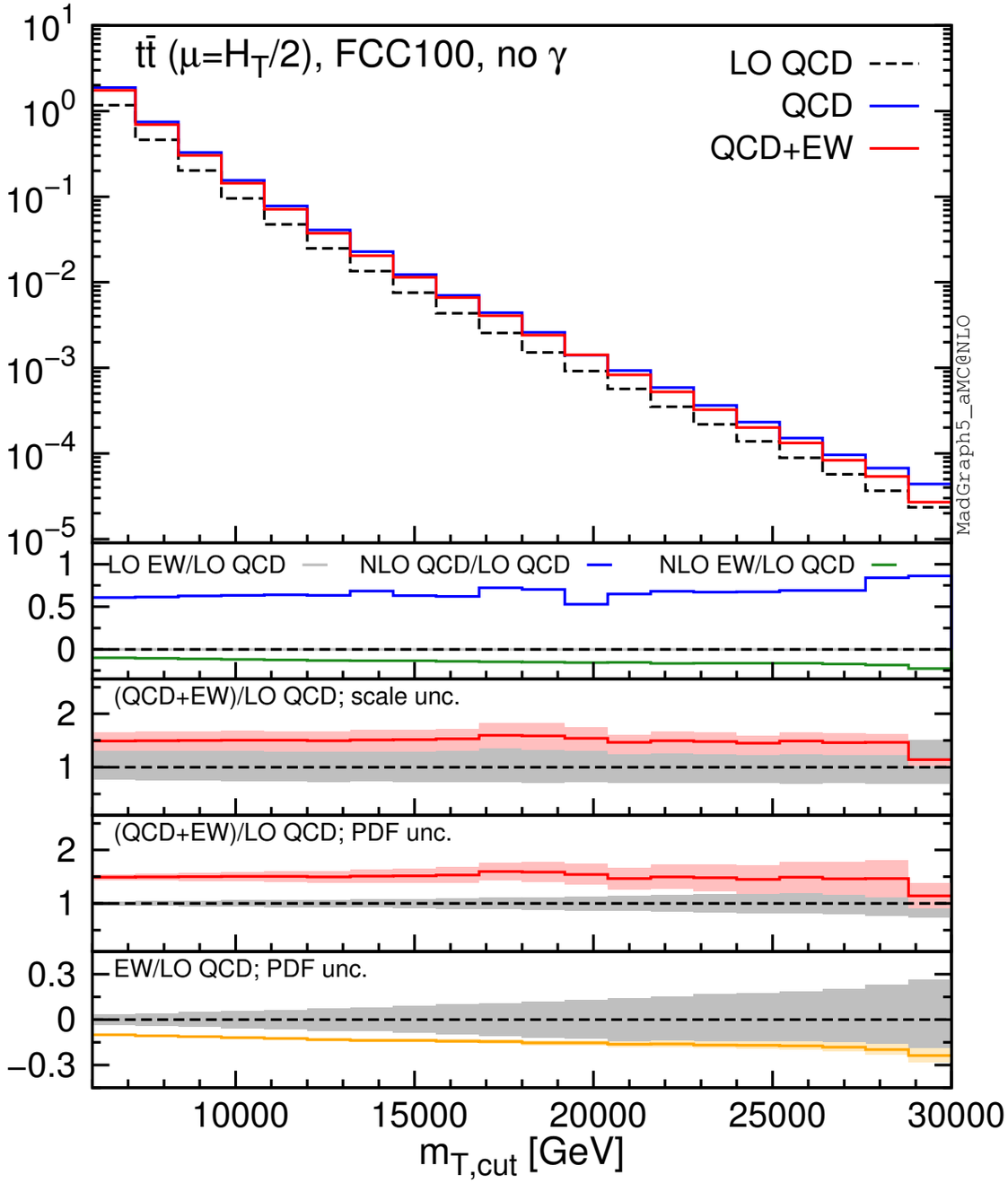




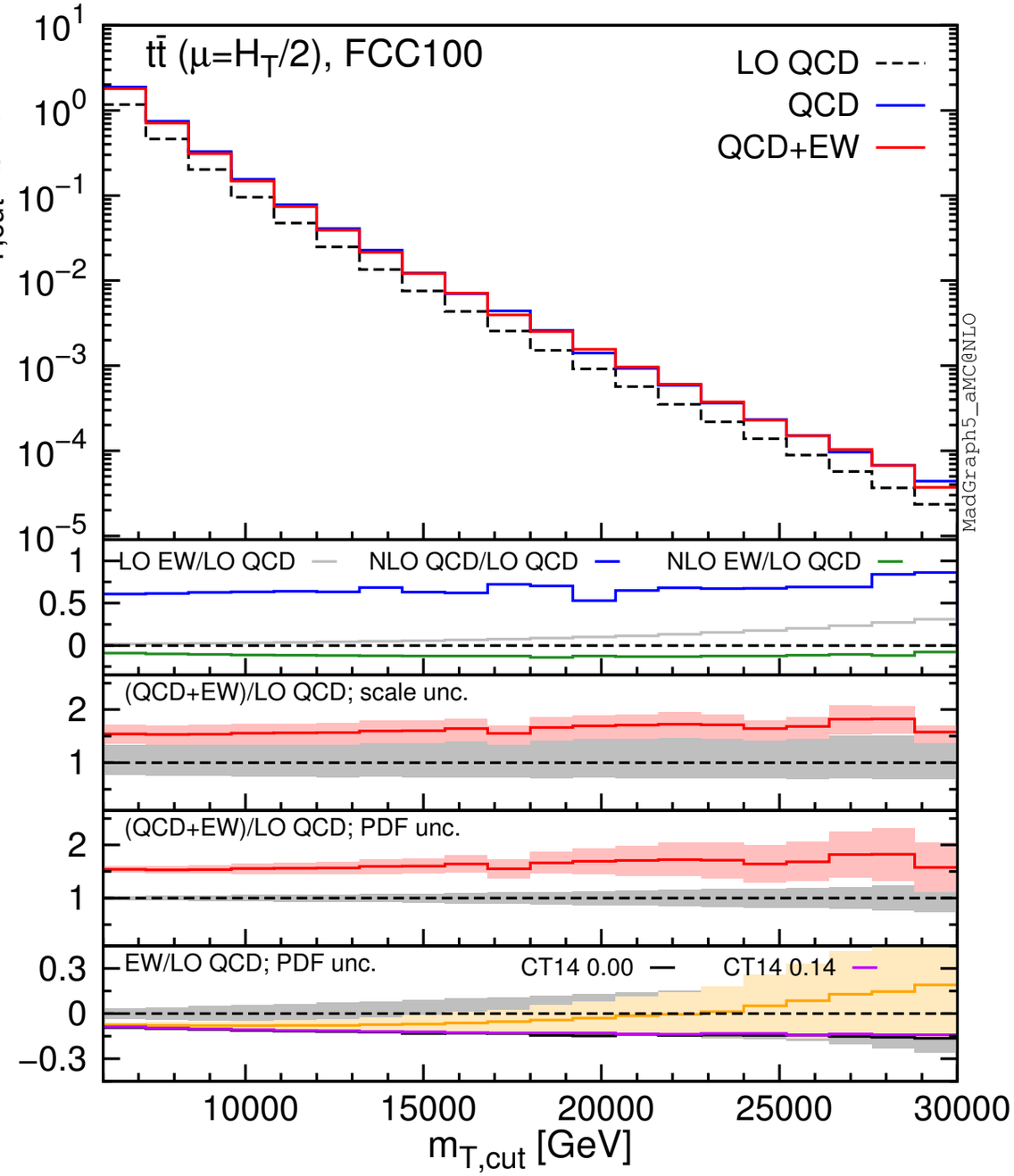
photon PDF **NO**

photon PDF **YES**

100 TeV



photon PDF **NO**



photon PDF **YES**

Comments

- At 100 TeV differential distributions are not sensitive to the photon-induced contributions. This **cannot be generalized** to other processes, see for example the case of VV and HV in the SM 100 TeV report (*Mangano, Zanderighi et al. '16*).

- Photon induced contributions are important at large τ —> smaller collider energy or larger ttbar invariant mass.

- At 100 TeV, photon PDF effects can be seen in ttbar production only imposing very hard cuts.

- Larger effects are expected at 8 TeV. On the other hand, the integrated luminosity and the total cross section are smaller. But we had already data …

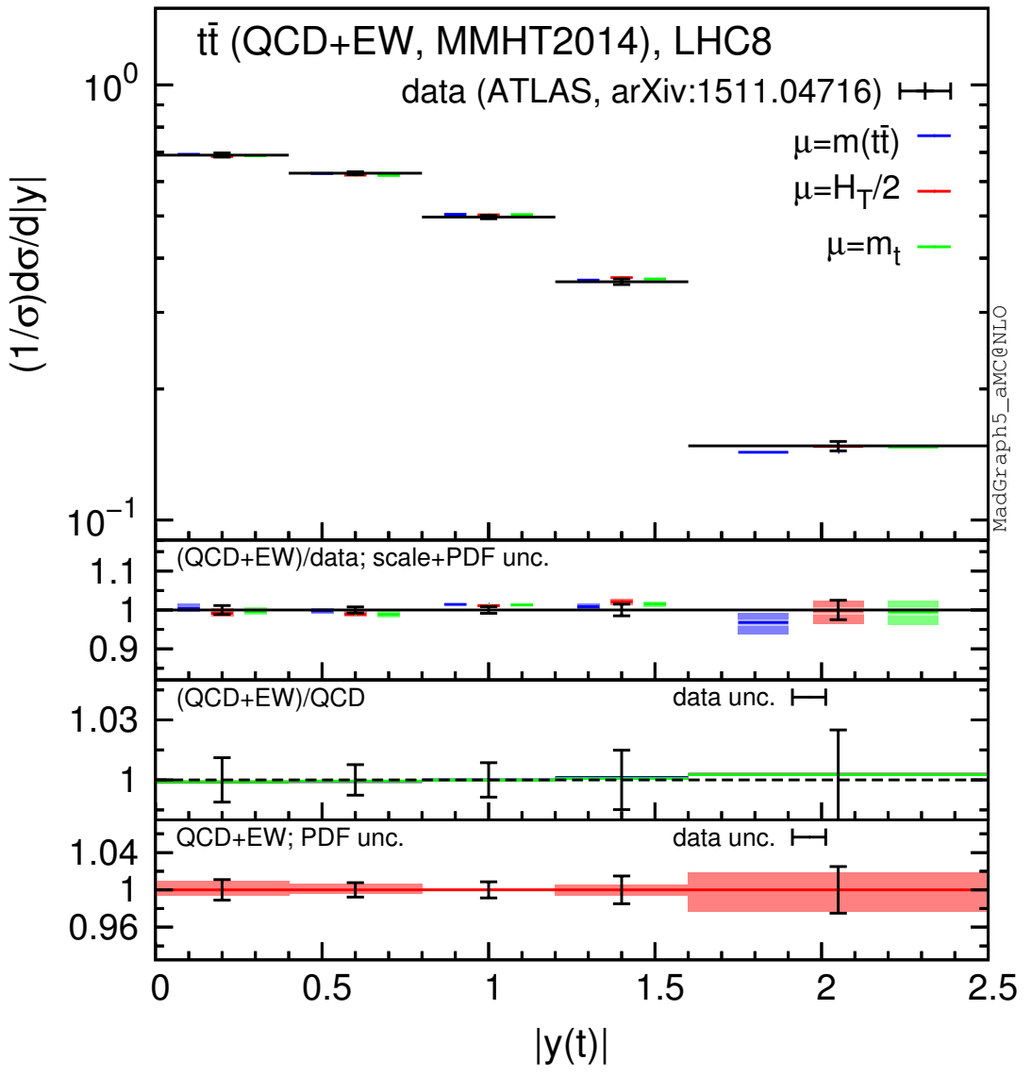
Measured (normalized) differential distributions at the LHC 8 TeV

Comparison of experimental errors and theory uncertainties with **NNPDF2.3QED** and **MMHT14** (no photon PDF and no LO QED running).

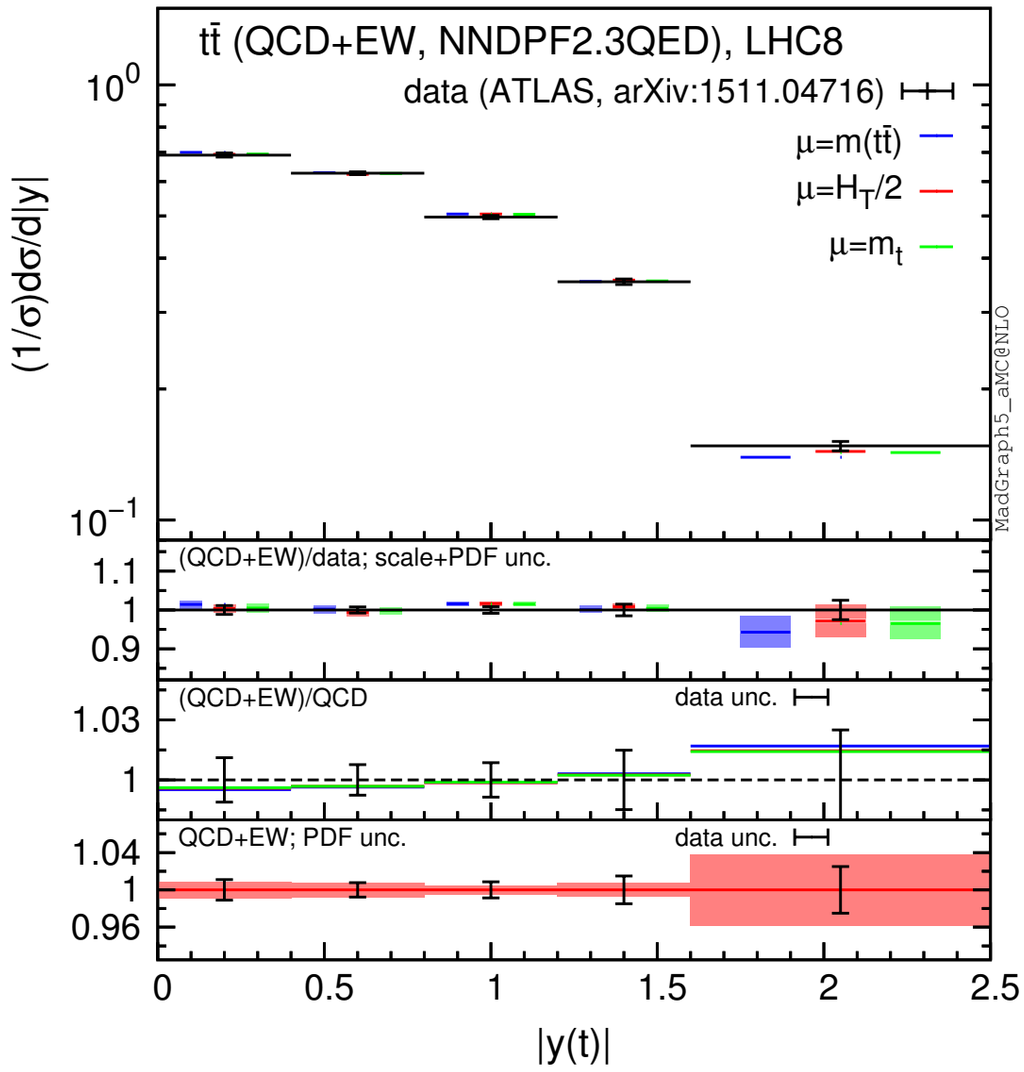
ATLAS data: *arXiv:1510.03818, arXiv:1511.04716*
CMS data: *arXiv:1505.04480*

8 TeV

comparison theo. unc. and exp. err.



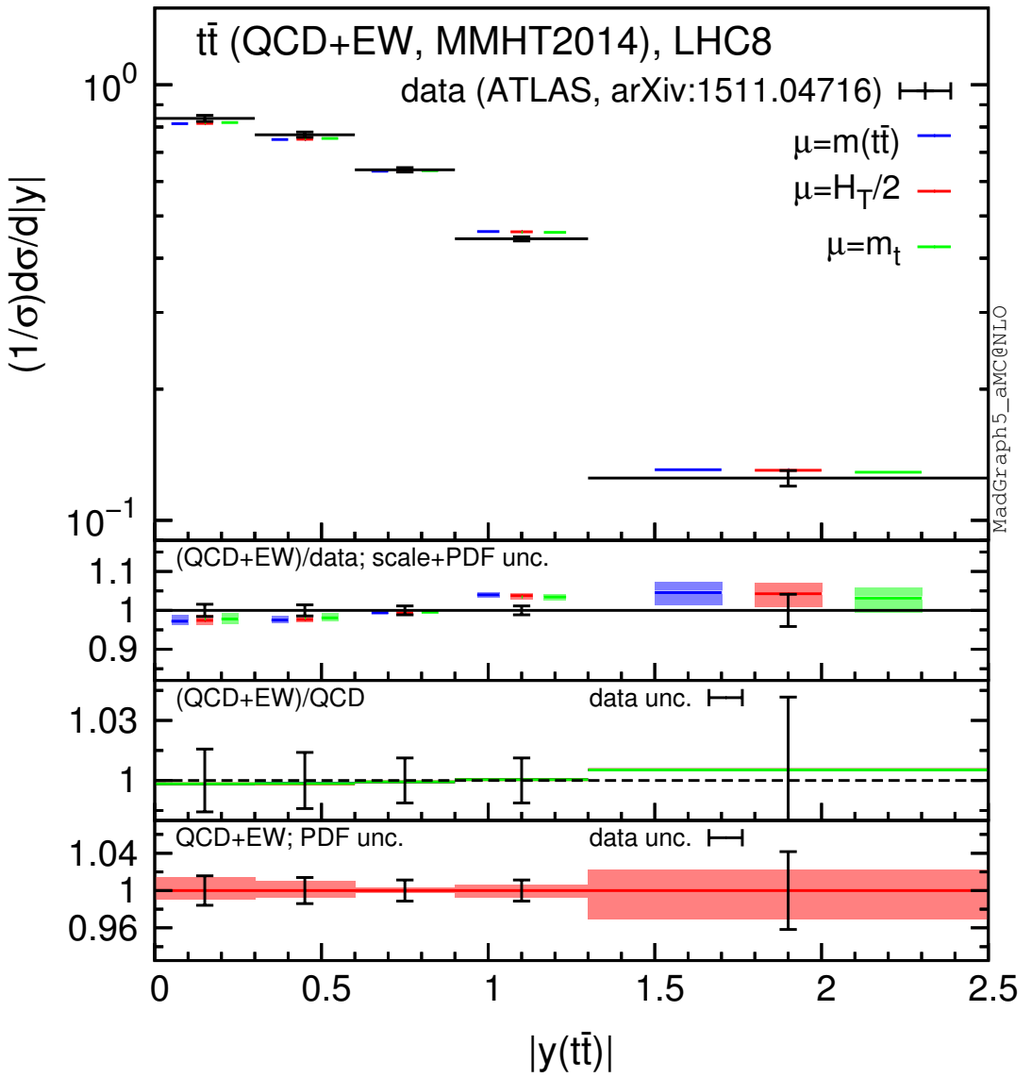
photon PDF **NO**



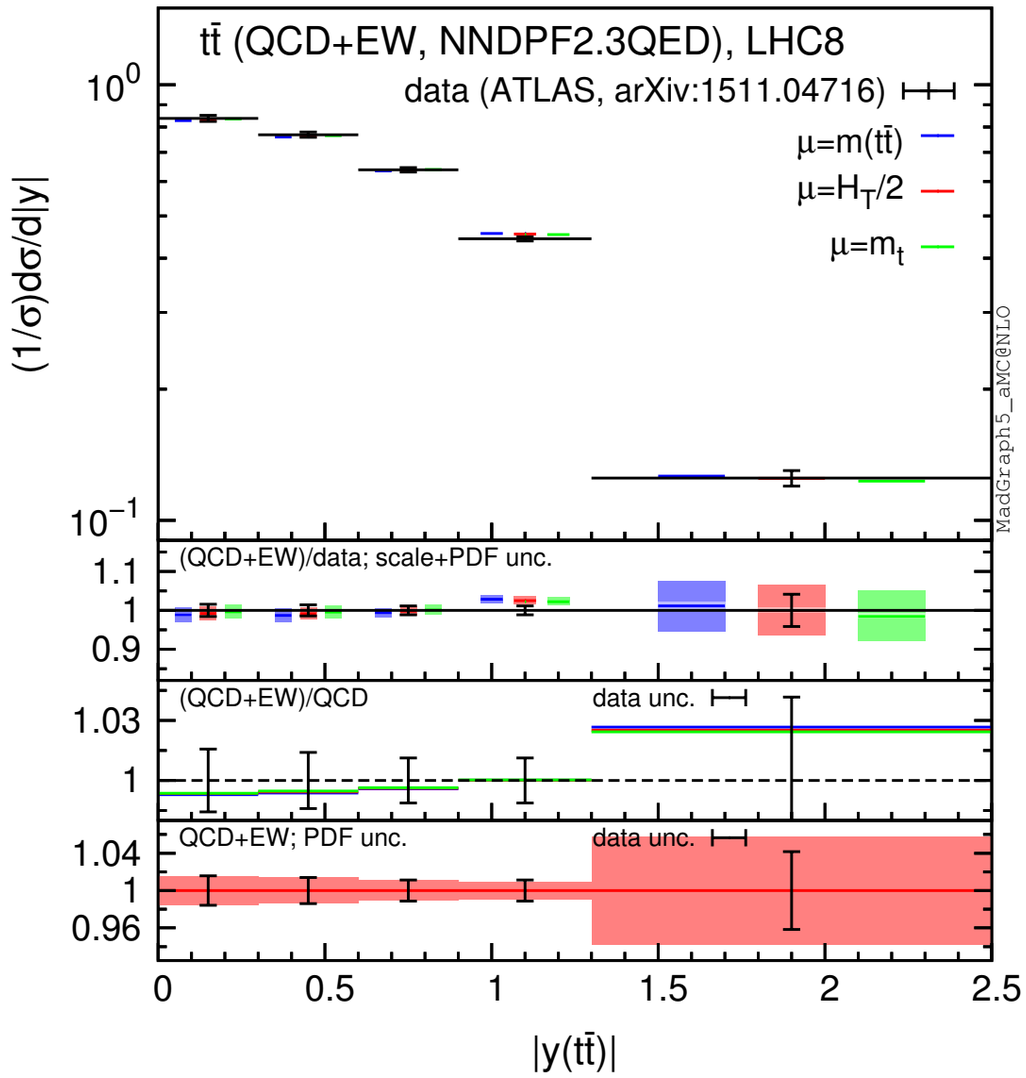
photon PDF **YES**

8 TeV

comparison theo. unc. and exp. err.



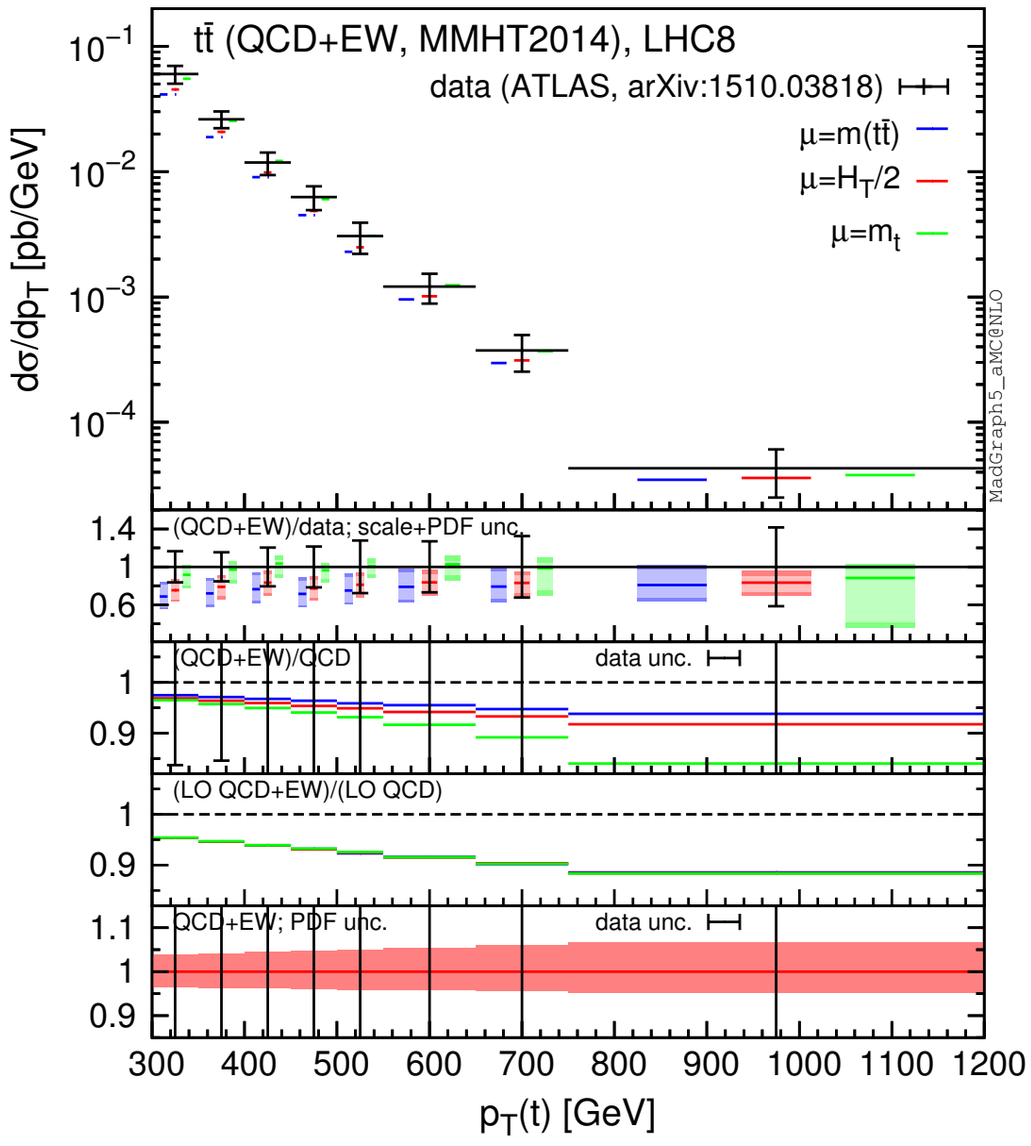
photon PDF **NO**



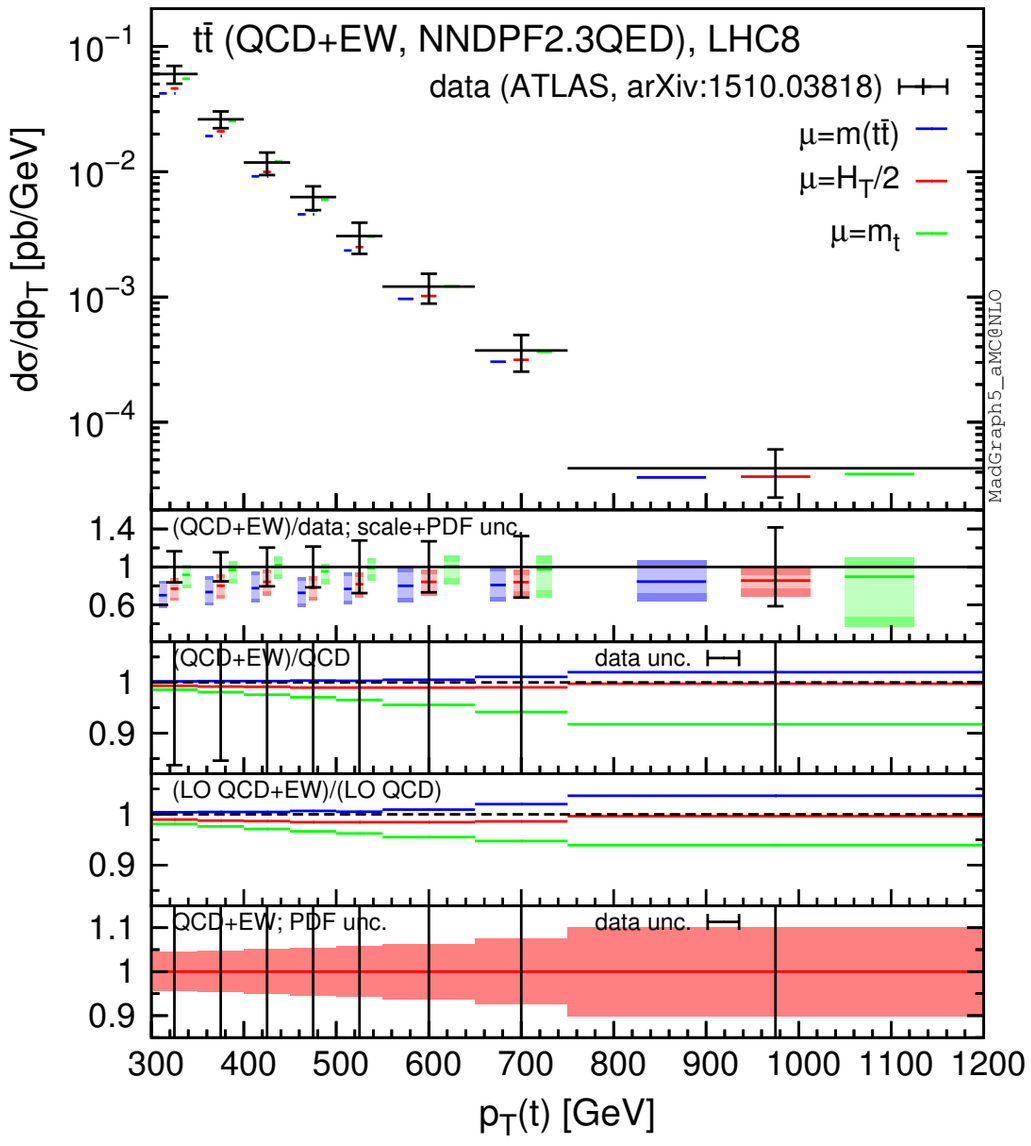
photon PDF **YES**

8 TeV

comparison theo. unc. and exp. err.



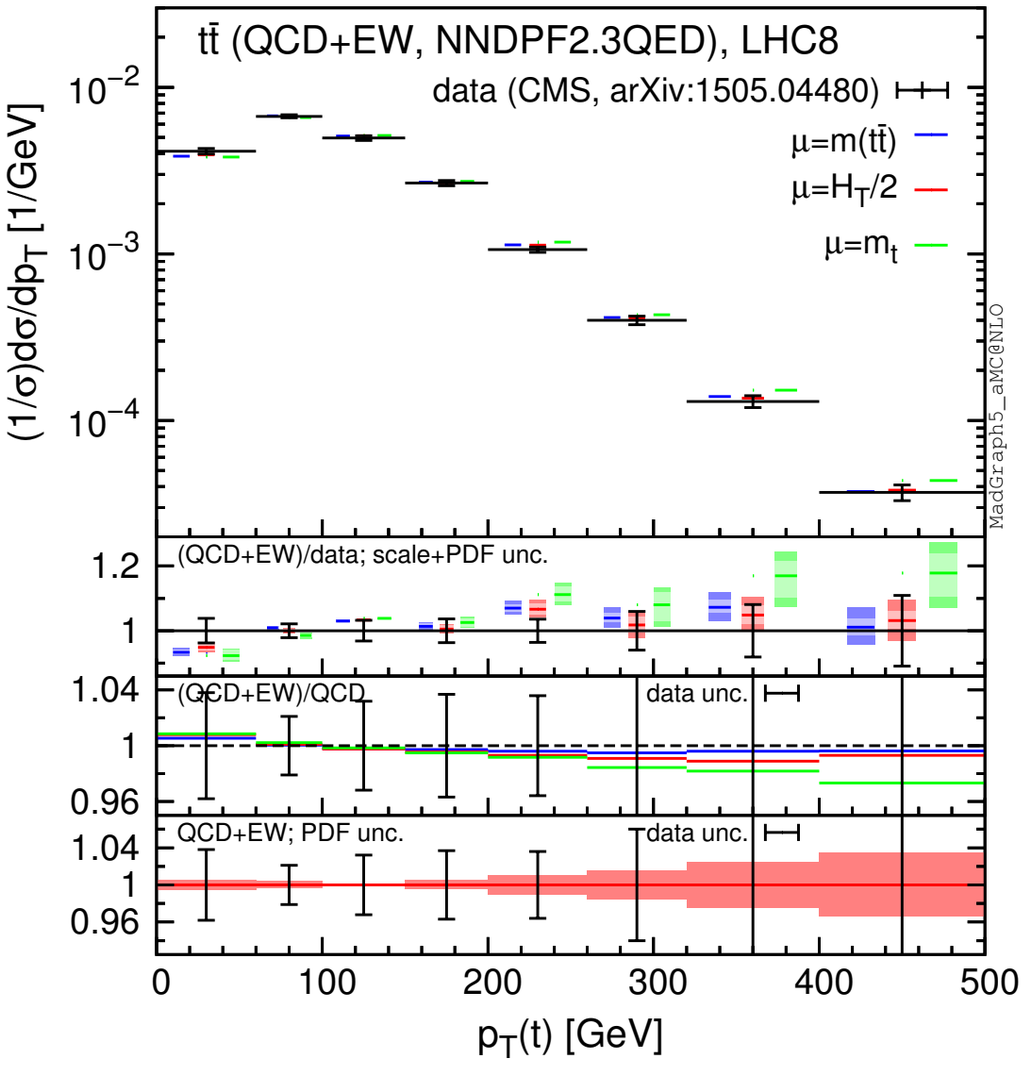
photon PDF **NO**

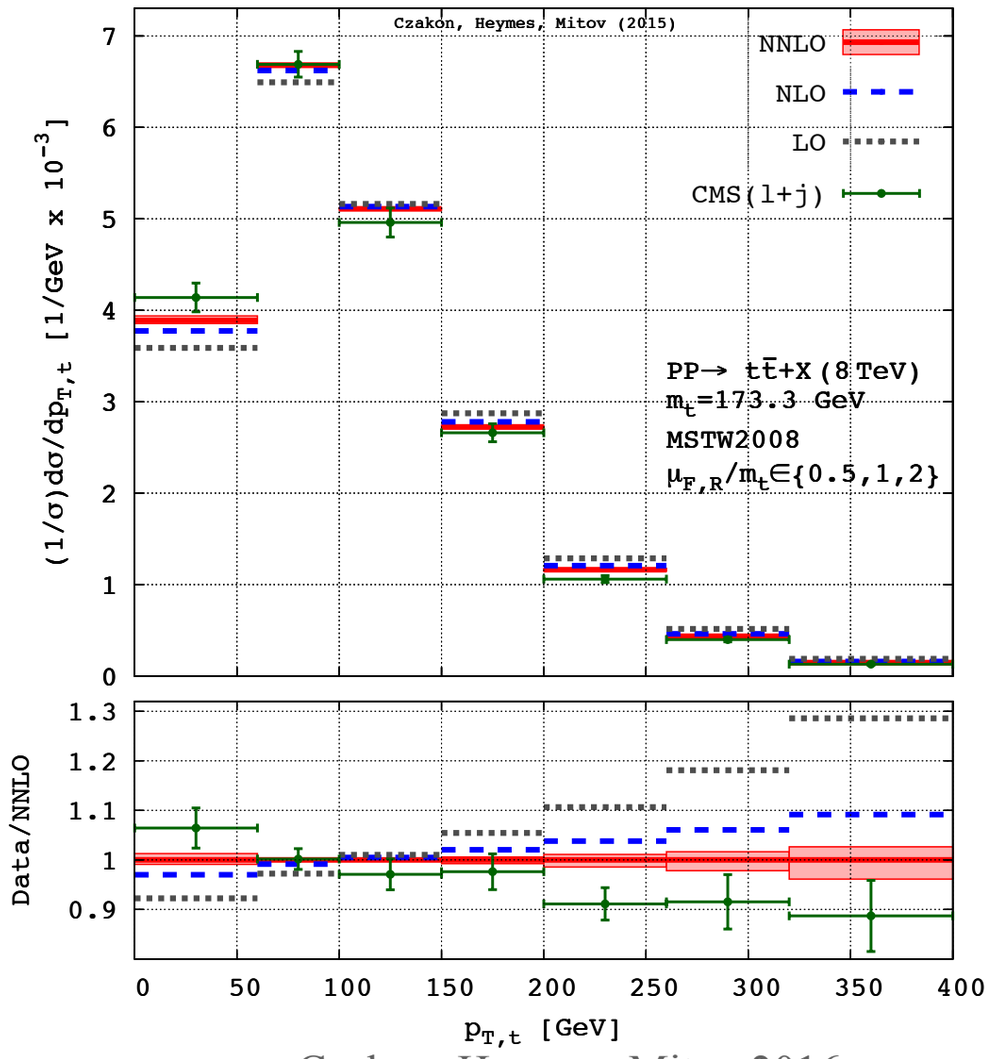


photon PDF **YES**

8 TeV

comparison theo. unc. and exp. err.





Czakon, Heymes, Mitov 2016

photon PDF **YES**

NNLO QCD

Comments

- In **normalized** distributions experimental errors are at 1% level for **rapidities** (top or top pair). Scale uncertainties are even smaller already at **NLO QCD** accuracy. The PDF uncertainties are larger and the impact of the photon PDF (**NNPDF2.3QED**) is visible at large rapidities.
Constraints on the photon PDF á la NNPDF can be set.

- In the transverse-momentum distributions the impact of the photon PDF (**NNPDF2.3QED**) is larger in the tail and compensates the effect of Sudakov logs. The size of the cancellation strongly depends on the scale definition.
On the other hand, experimental errors are larger than these effects and scale uncertainties (**at NLO QCD**) are larger than PDF uncertainties in normalized and unnormalized distributions.

- **For a reliable comparison THEORY vs EXPERIMENT** and possible constraints on the photon PDF at 13 TeV, **NNLO QCD corrections are necessary** for transverse-momentum distributions and in general for unnormalized distributions.

Differential distributions at NNLO QCD + EW accuracy

Preliminary results

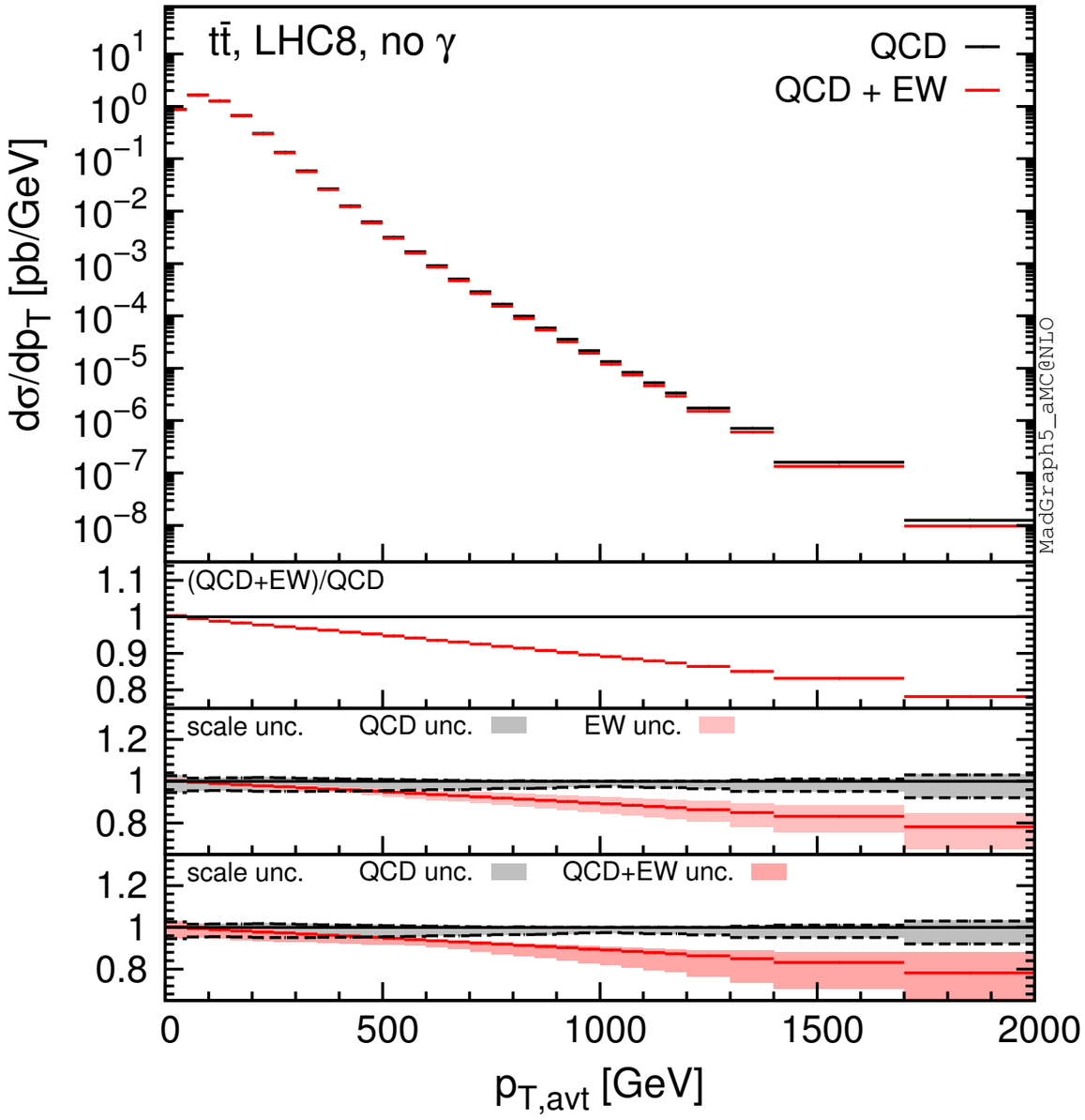
Czakon, Heymes, Mitov, DP, Tsinikos, Zaro arXiv:16xx.xxxx

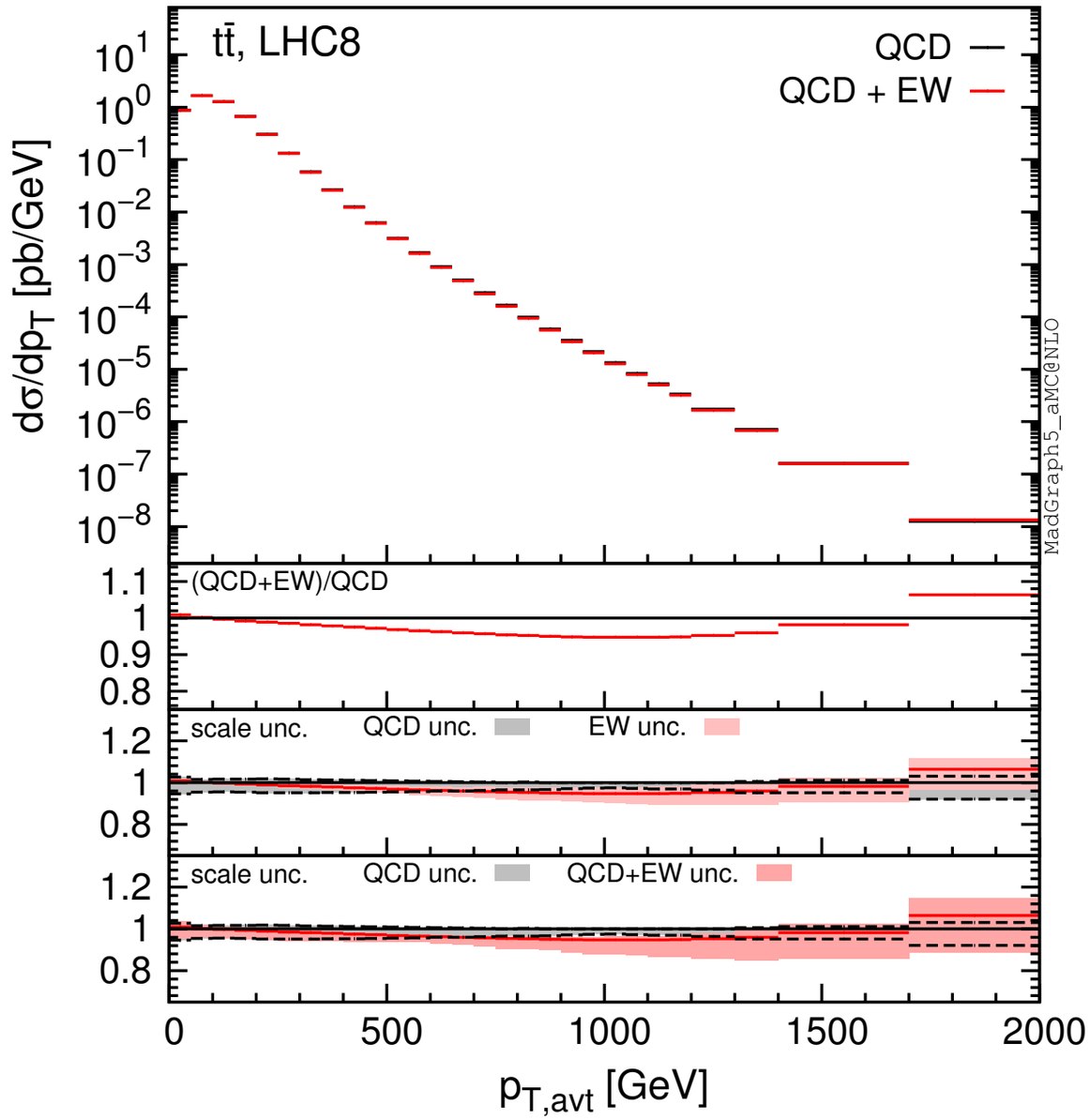
PDF: NNPDF3.0QED (NNLO),

Scale choice: $\mu_0 = \begin{cases} \frac{m_T}{2} & \text{for :} \quad p_{T,t},\ p_{T,\bar{t}} \text{ and } p_{T,t/\bar{t}}\,, \\ \\ \frac{H_T}{4} & \text{for :} \quad \text{all other distributions}\,. \end{cases}$

motivated from the study performed in: *Czakon, Heymes, Mitov: arXiv:1606.03350*

8 TeV

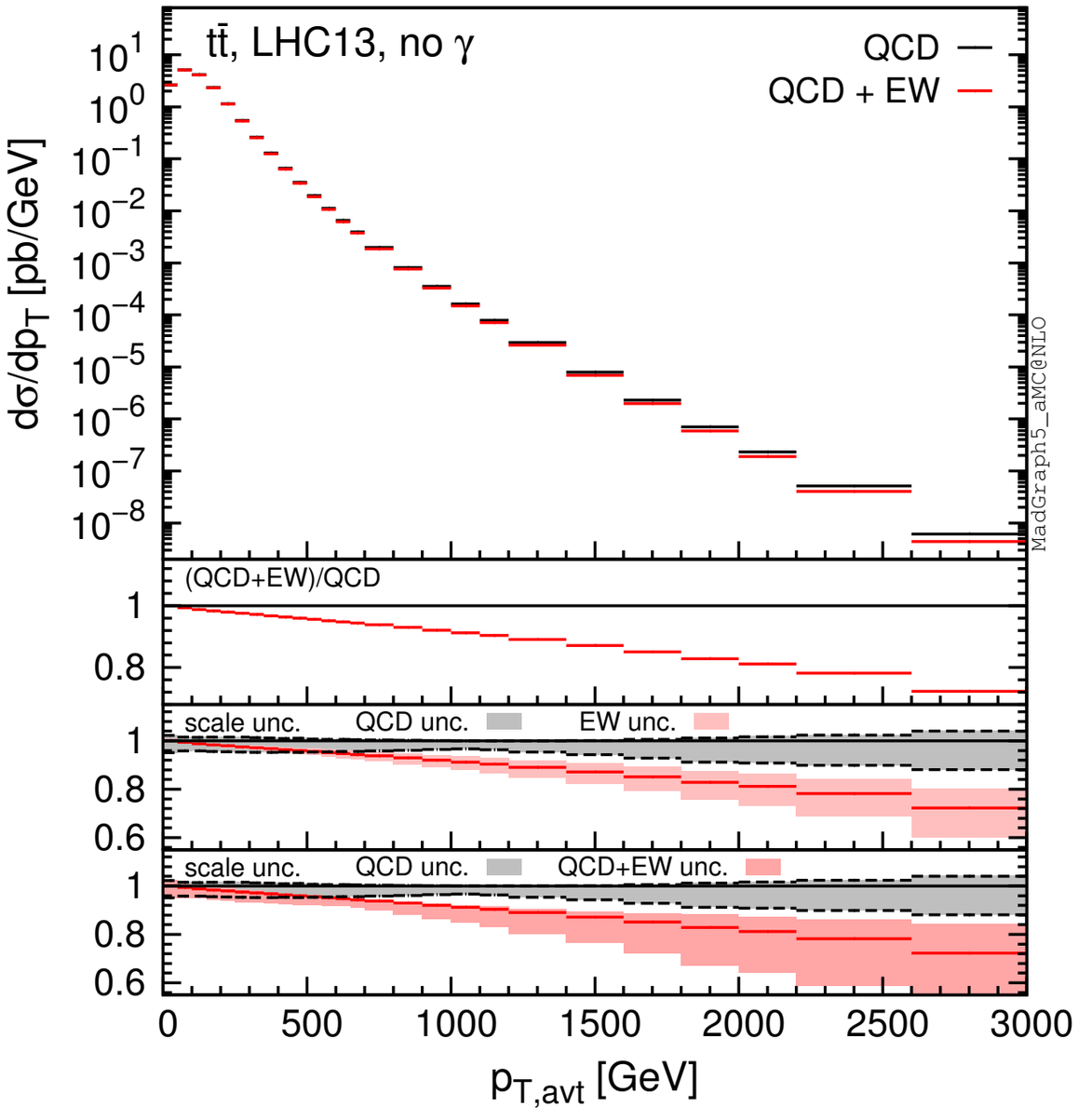




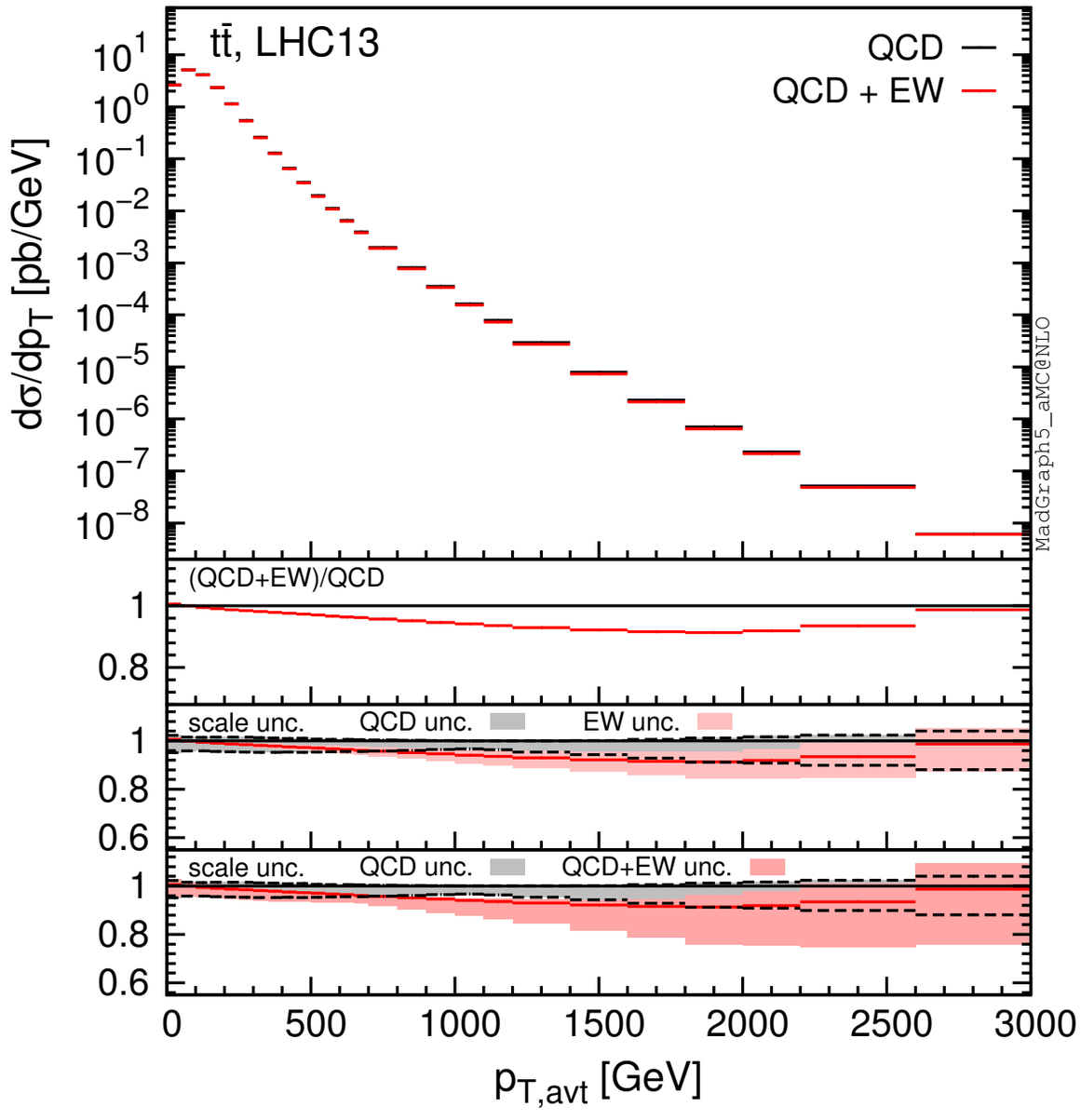
photon PDF **NO**

photon PDF **YES**

13 TeV

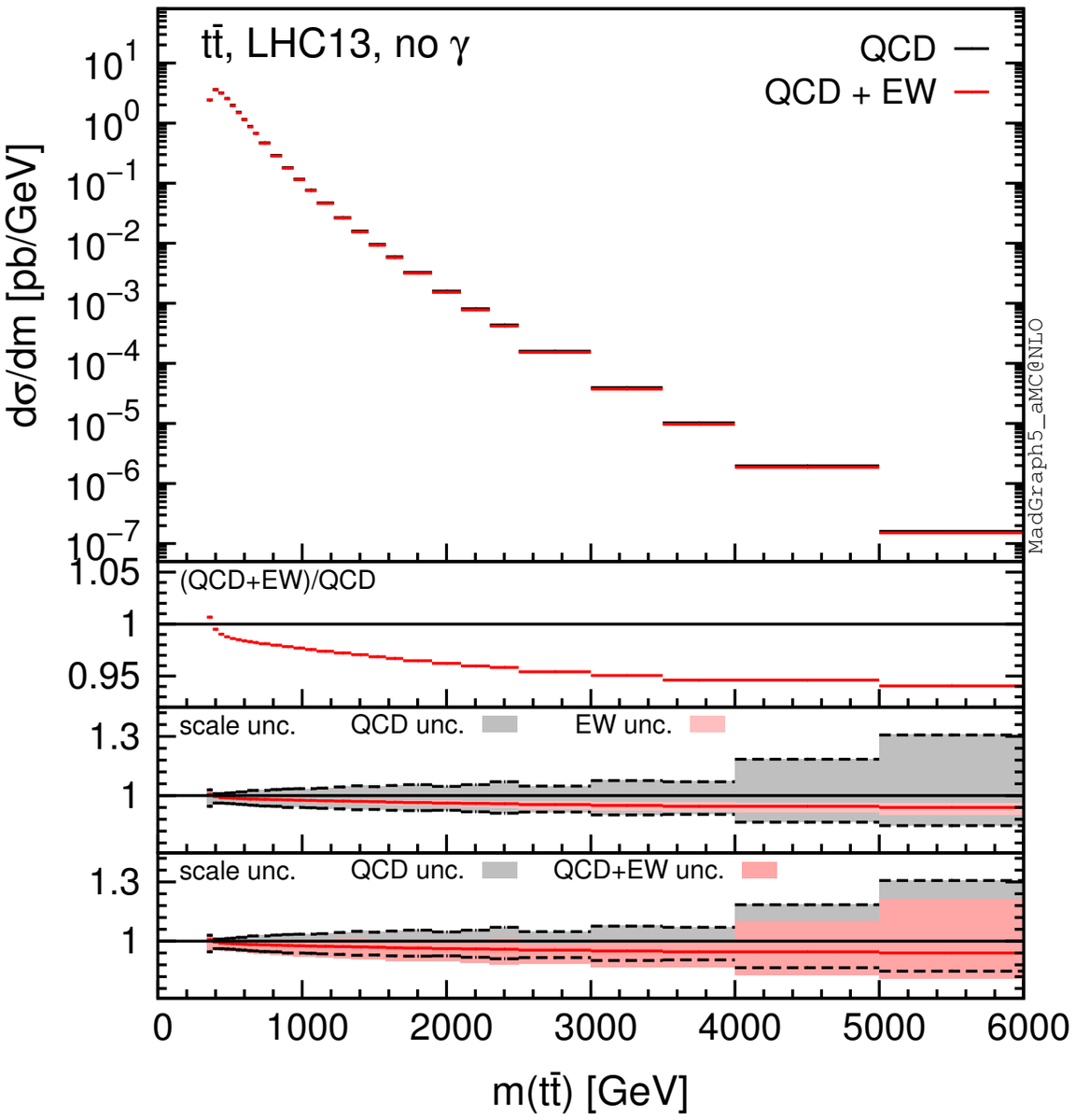


photon PDF **NO**

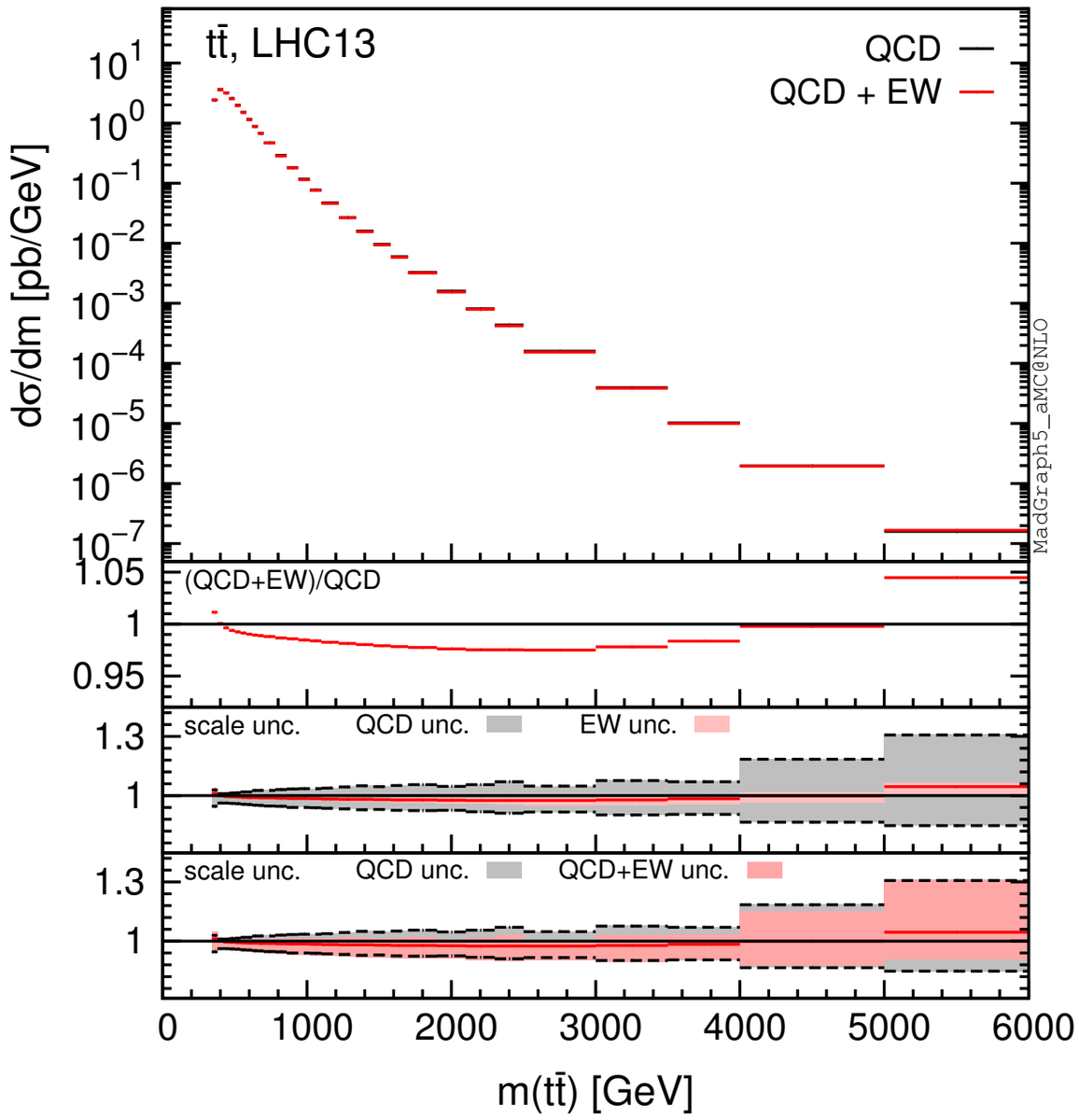


photon PDF **YES**

13 TeV

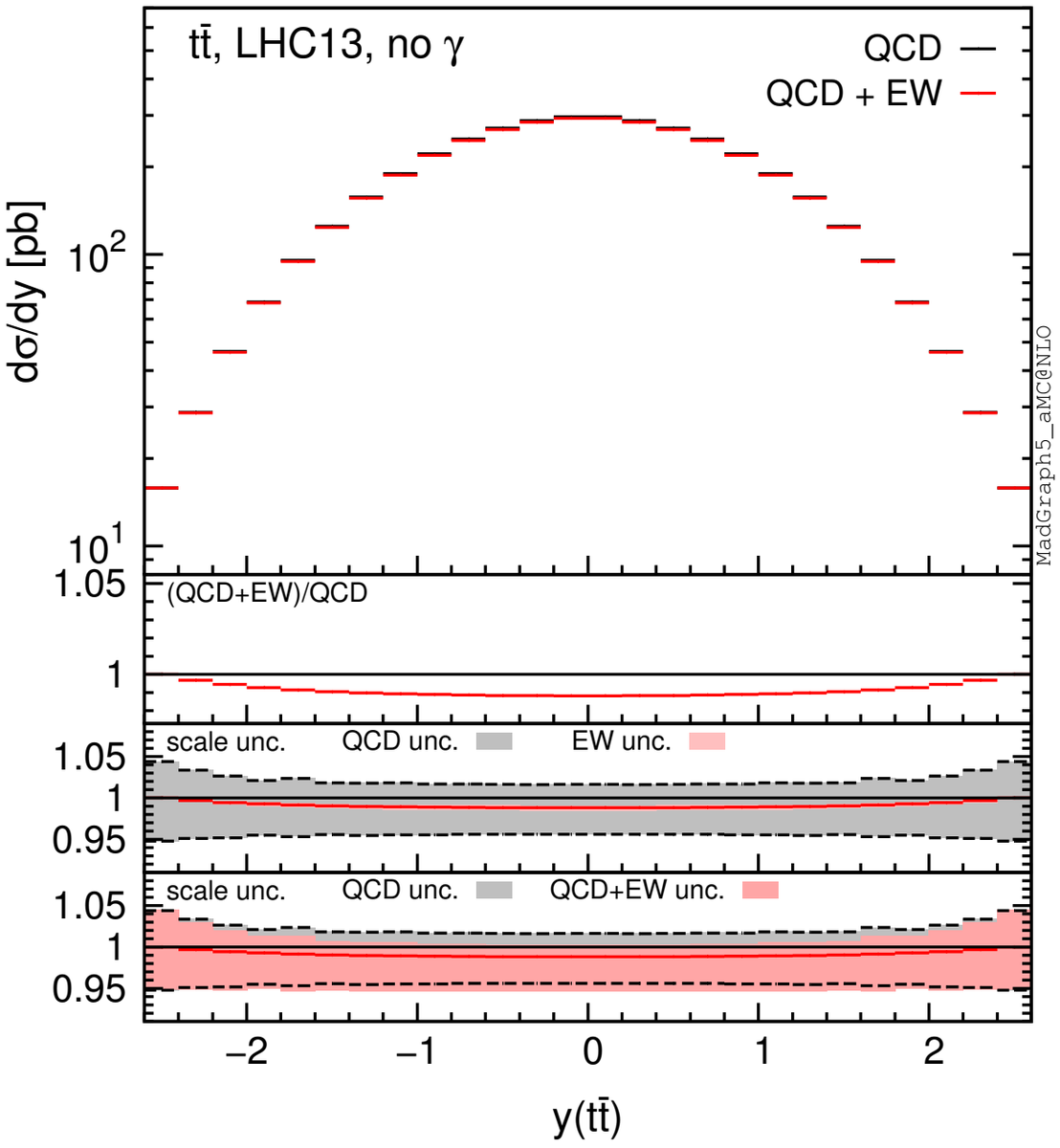


photon PDF **NO**

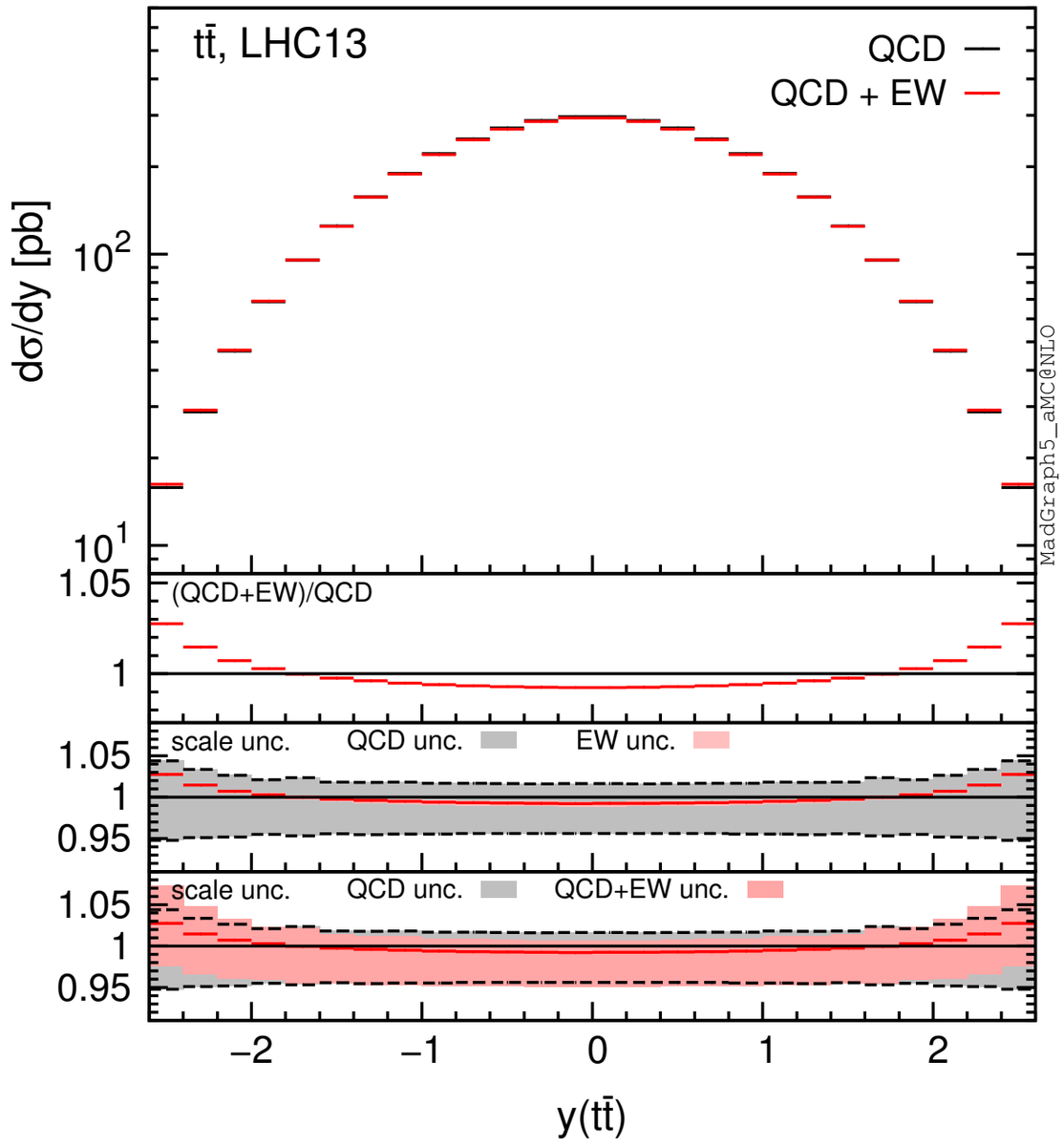


photon PDF **YES**

13 TeV



photon PDF **NO**



photon PDF **YES**

Comments

We have shown scale unc. bands, **not** PDF uncertainties (in progress).

- **NNLO QCD** corrections tremendously **reduce the scale dependence** also in the tails. In the case of the transverse momentum, the QCD scale unc. is even smaller than the one from EW corrections (large Sudakov logs), which may also be reduced via a "multiplicative combination" of QCD and EW corrections.

- The impact of the photon PDF (**NNPDF3.0QED**) at 13 TeV is reduced w.r.t. the 8 TeV case. In **unnormalized** rapidity distributions it is smaller than the scale unc. at NNLO.

-Depending on the integrated luminosity, at 13 TeV transverse momentum distributions may be more sensitive on the photon PDF **á la NNPDF** w.r.t. rapidity distributions.

Conclusion

Electroweak corrections to ttbar production feature possible cancellations between Sudakov Logs and photon induced contributions.

With **NNPDF**, photon induced contributions have large central values and uncertainties. On the contrary, with **CTEQ** or **LUXQED** their effect is not visible in ttbar phenomenology**.**

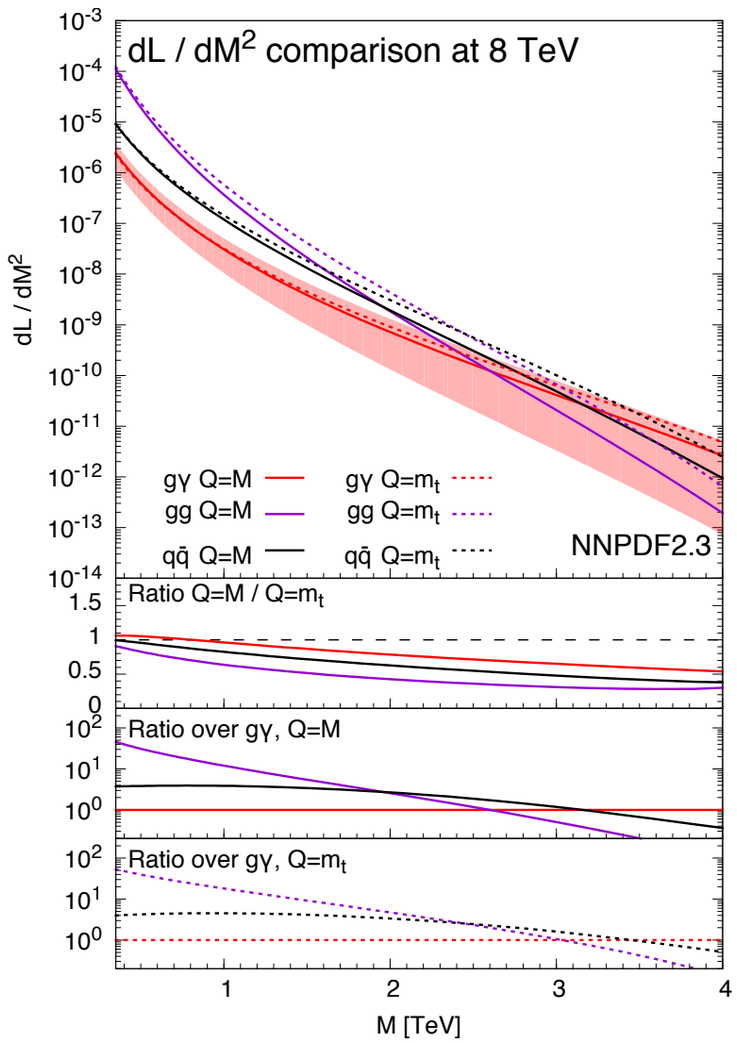
Even with **NNPDF**, photon induced contributions are negligible at 100 TeV, besides in the very hard regime.

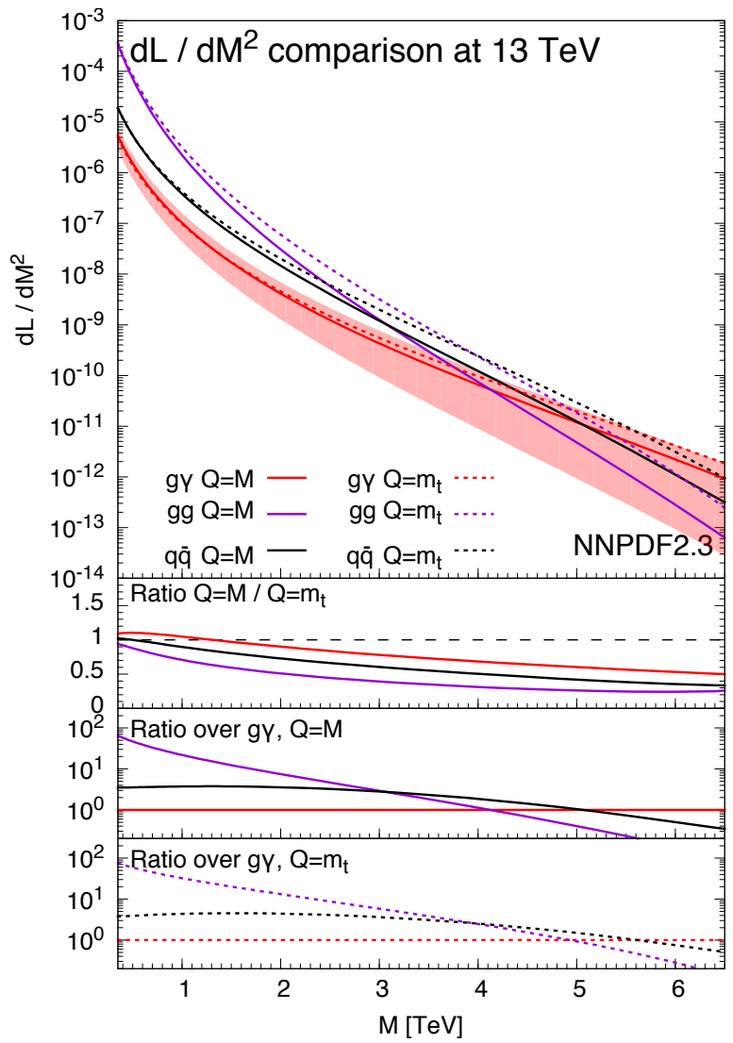
8 TeV data (normalized distributions) may be sensitive to the photon á la **NNPDF**, especially the top and top-pair rapidities distributions.

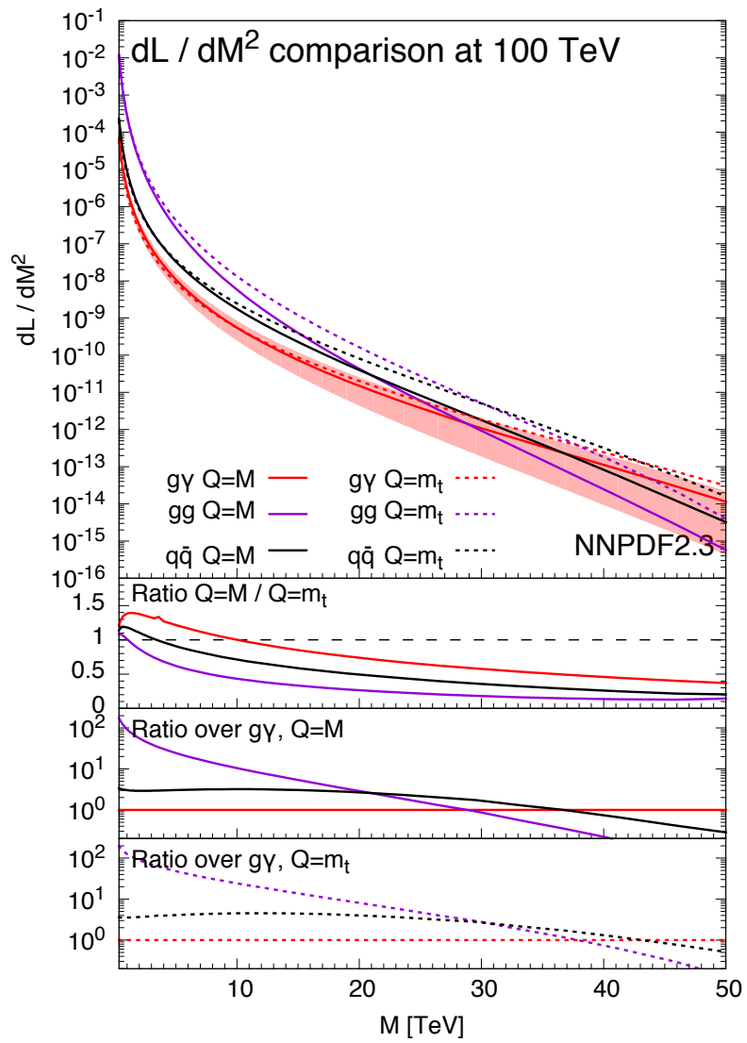
At 13 TeV, and in general for unnormalized distributions, NNLO QCD corrections are necessary for reducing scale uncertainties. Photon-induced contributions are smaller at 13 TeV, but they may be visible in pt distributions.

EXTRA SLIDES

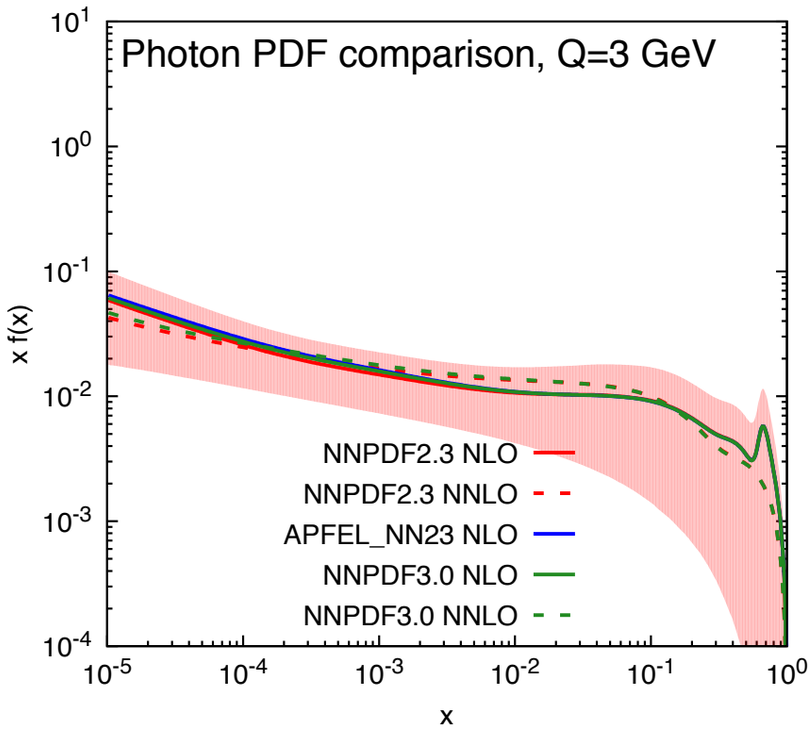
Comparison of the gg, qq and gγ luminosities

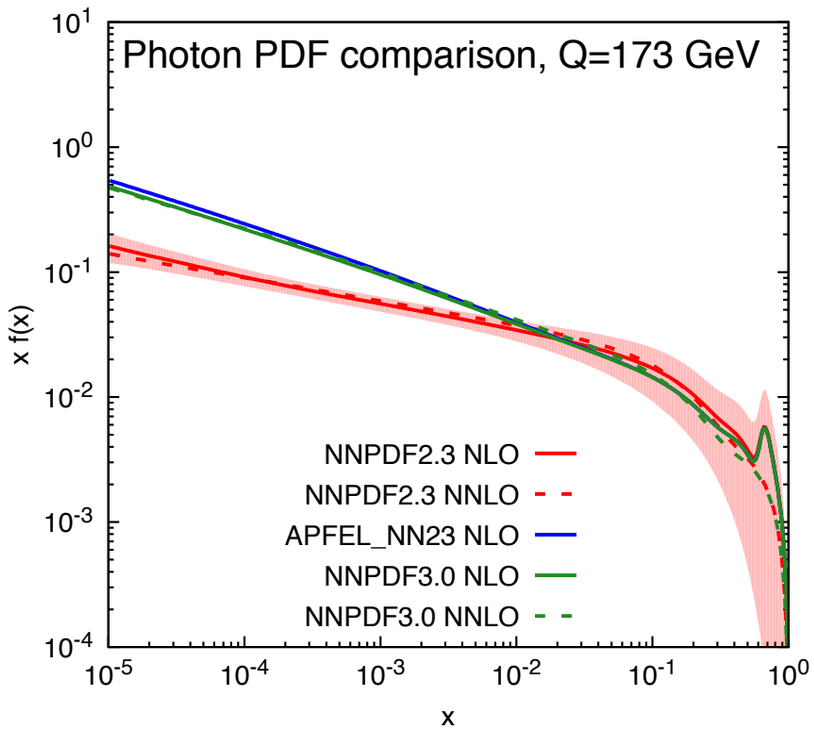


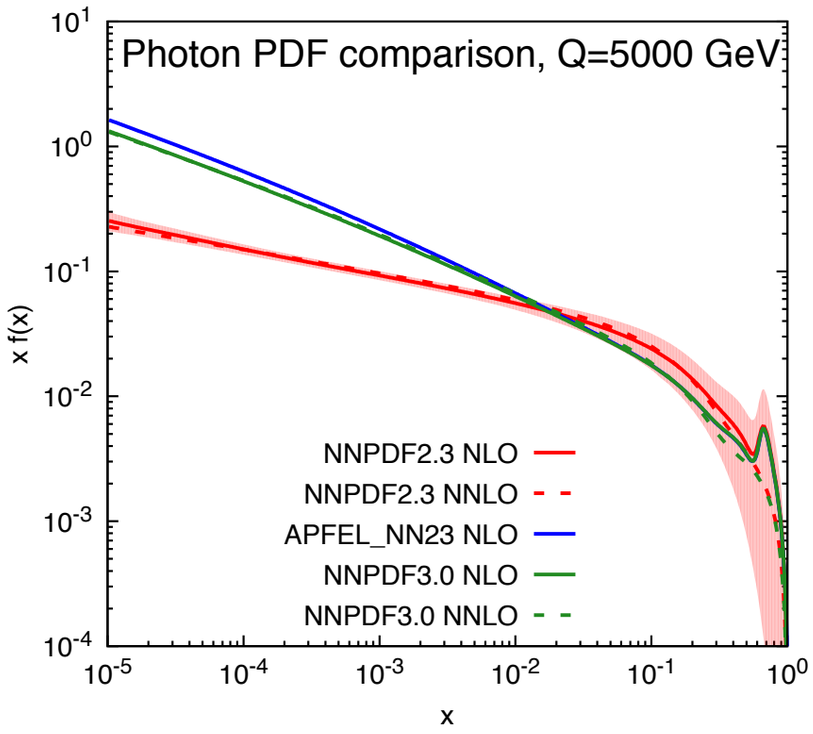




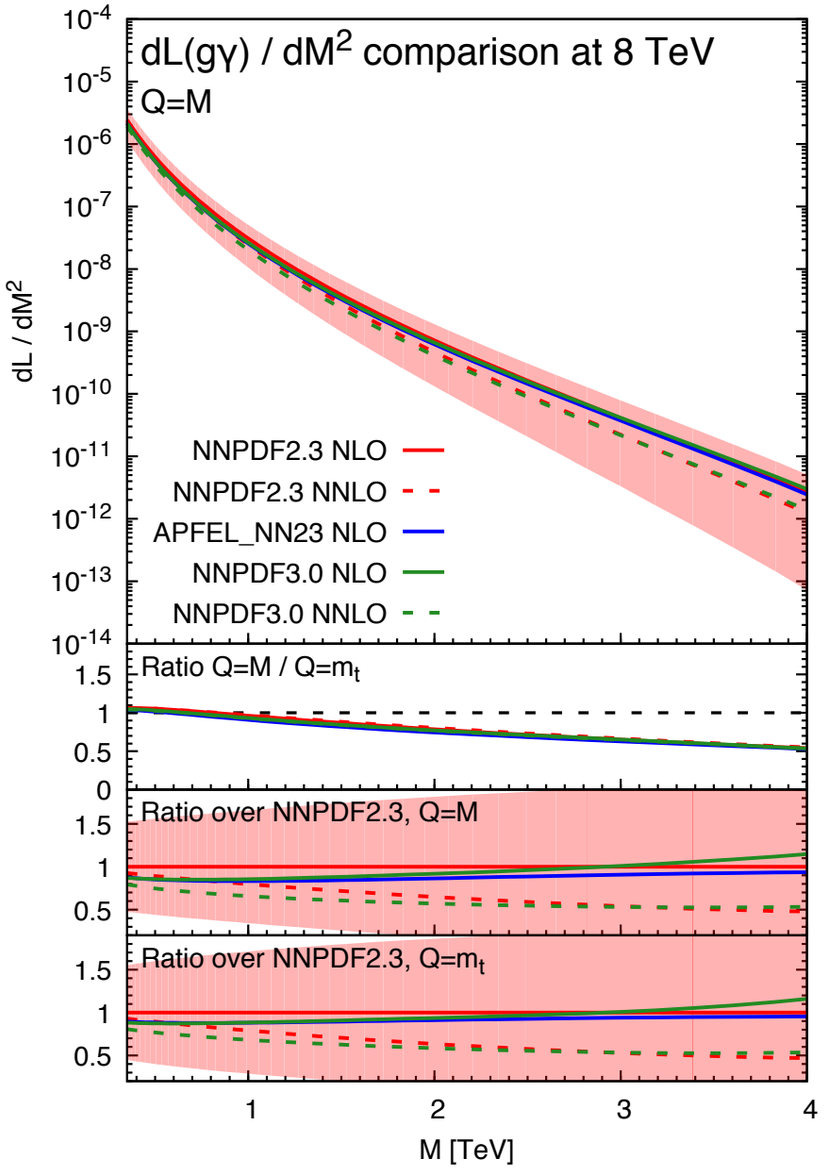
Comparison of NNPDF photon PDF

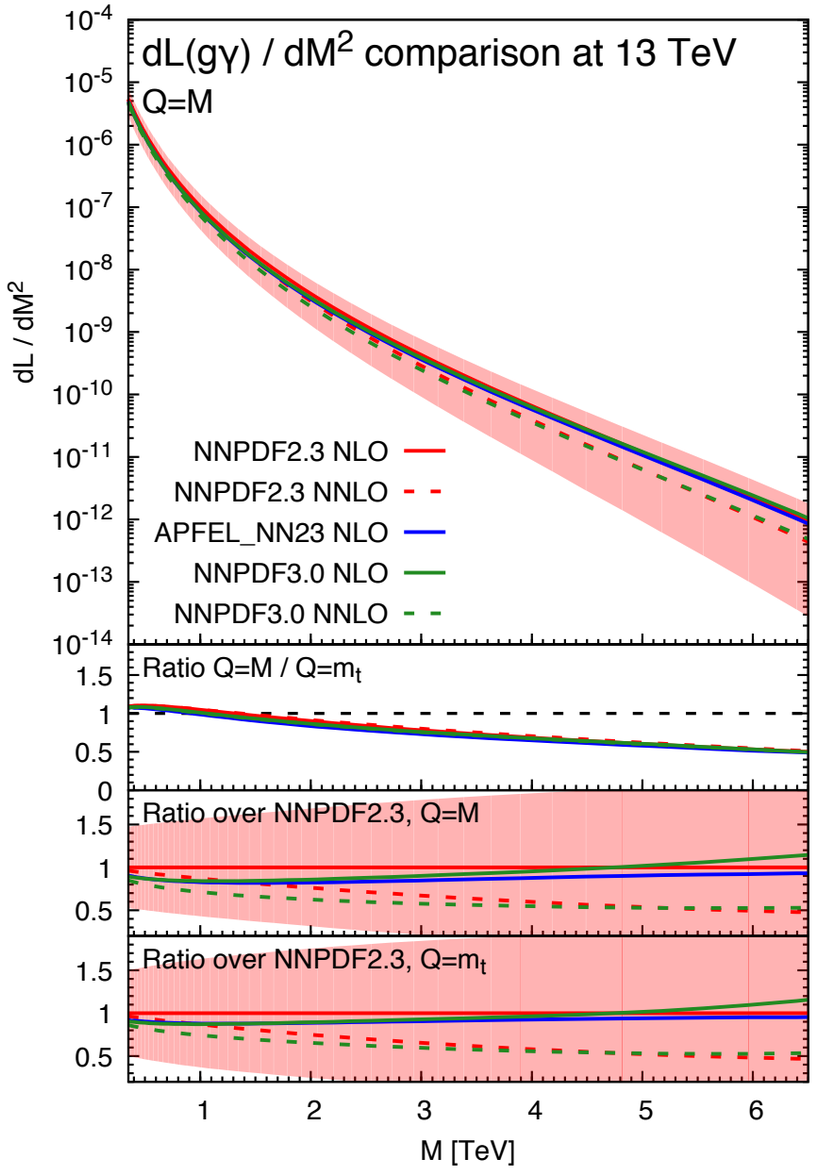


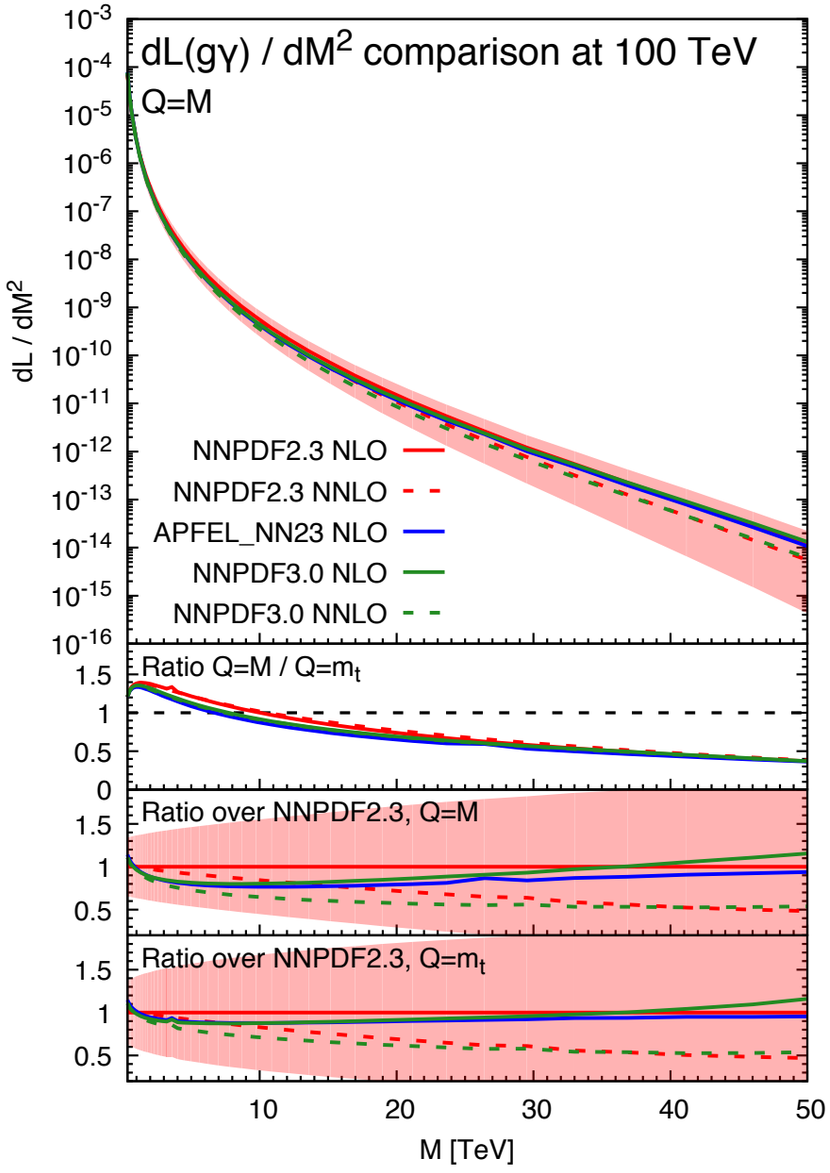




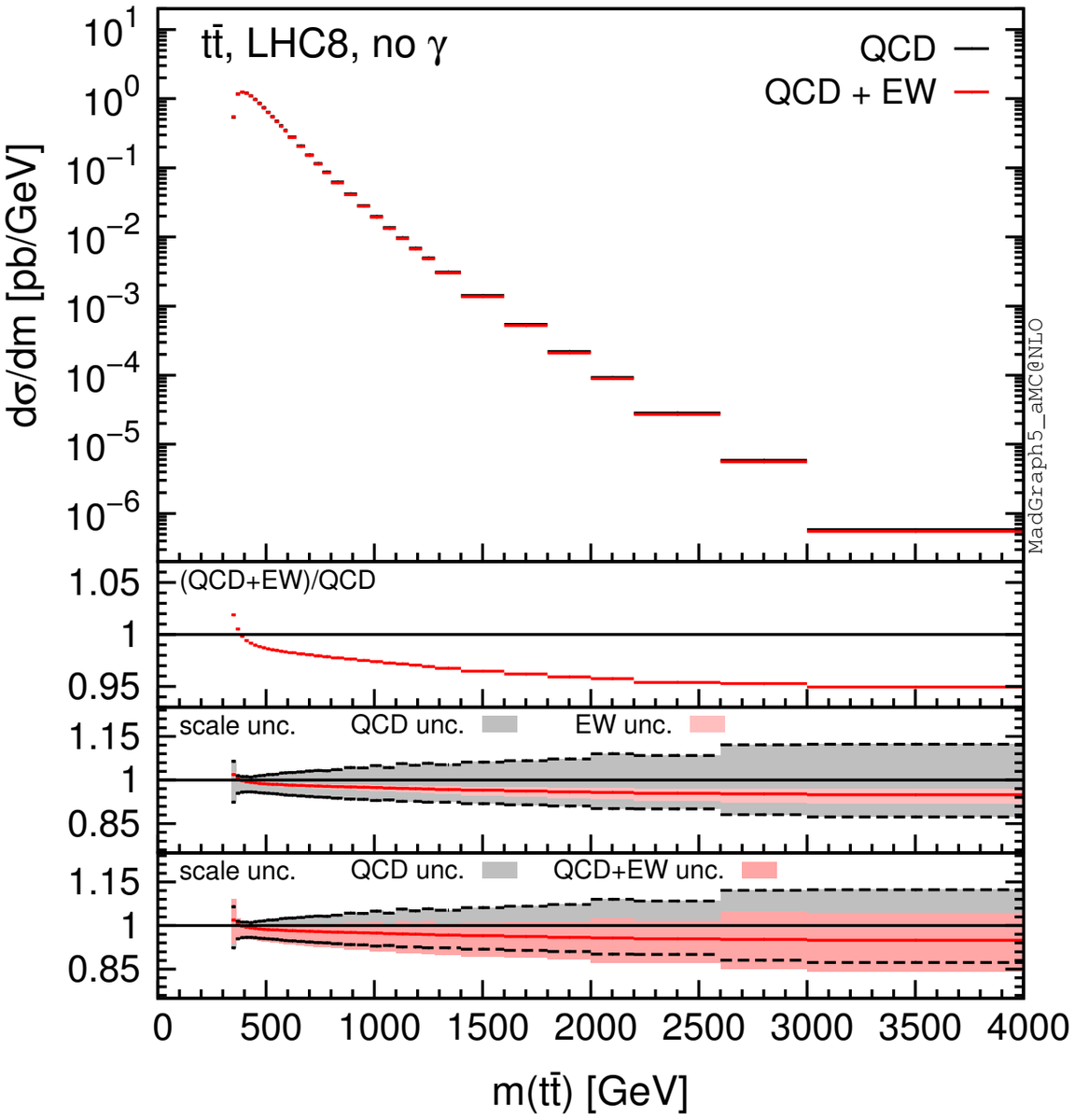
Comparison of NNPDF gluon-photon luminosities

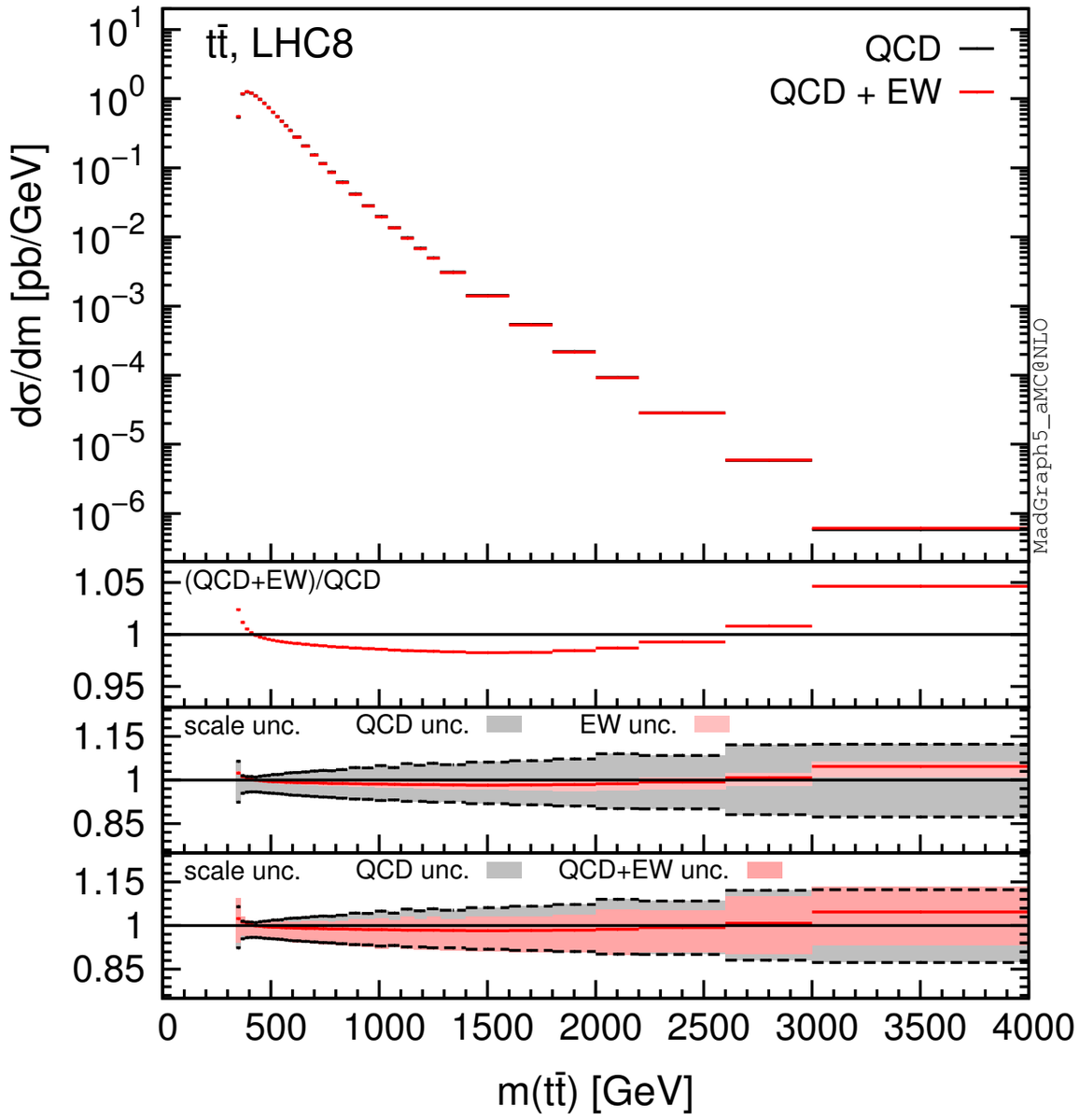






8 TeV

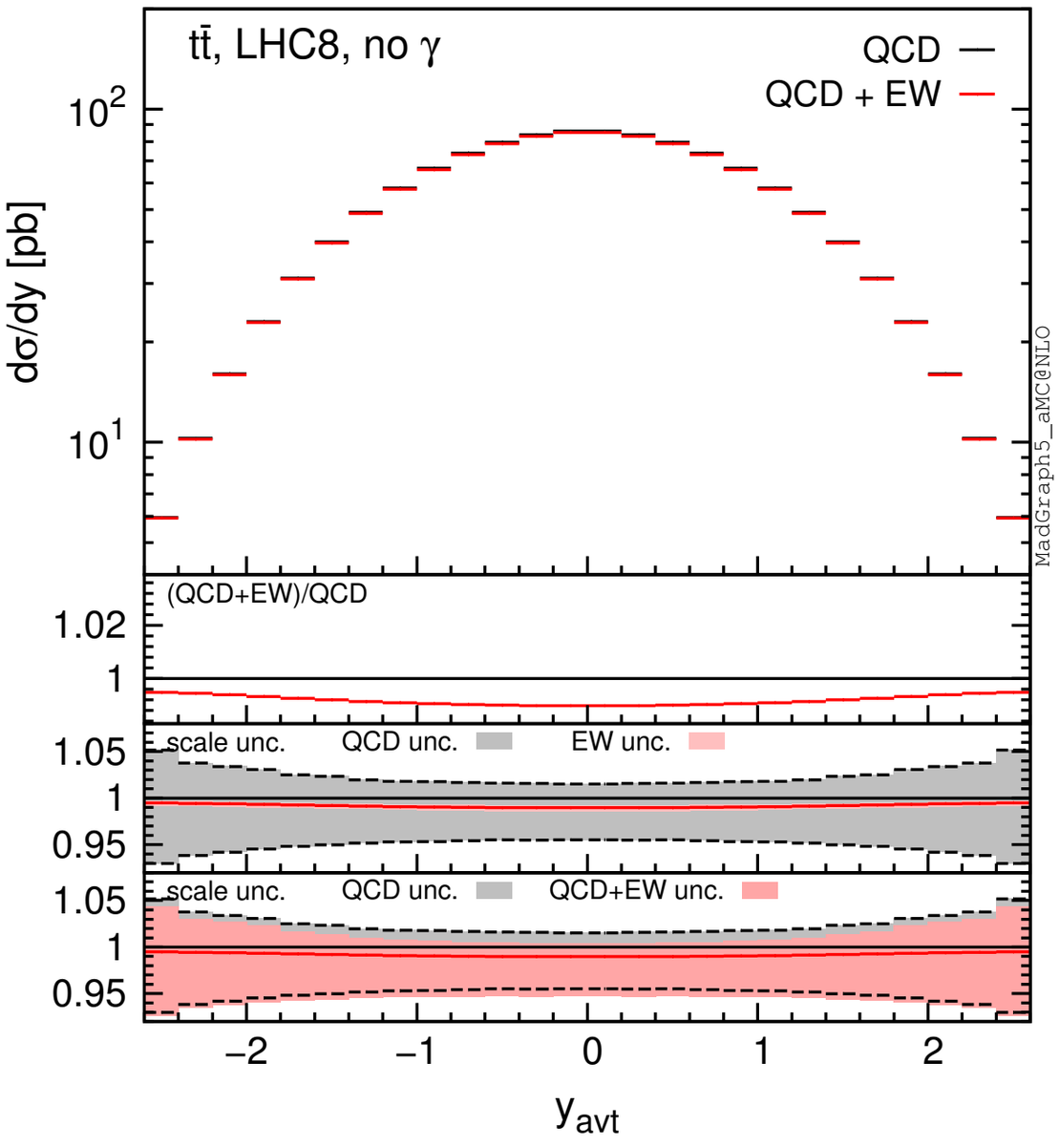




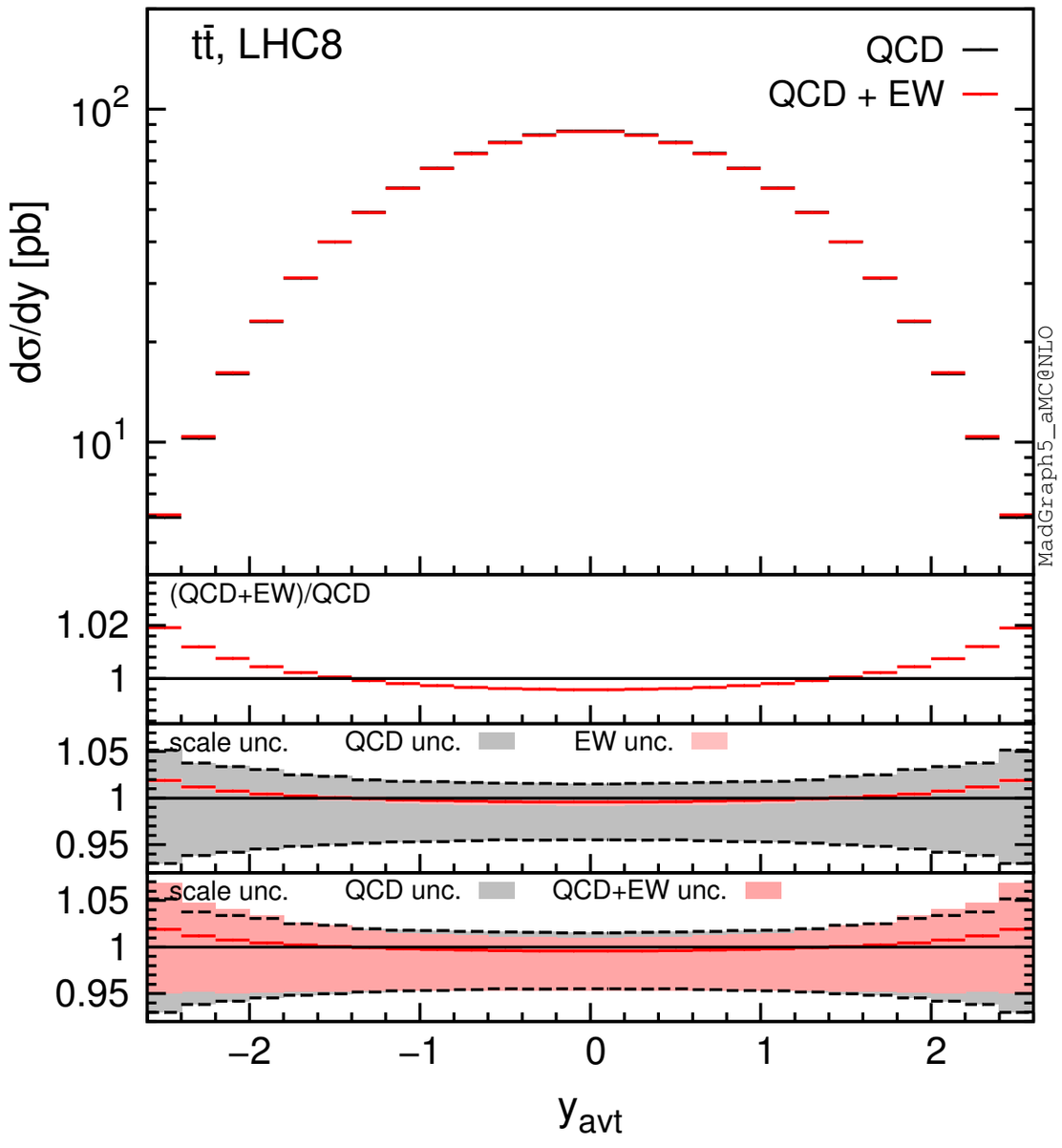
photon PDF **NO**

photon PDF **YES**

8 TeV

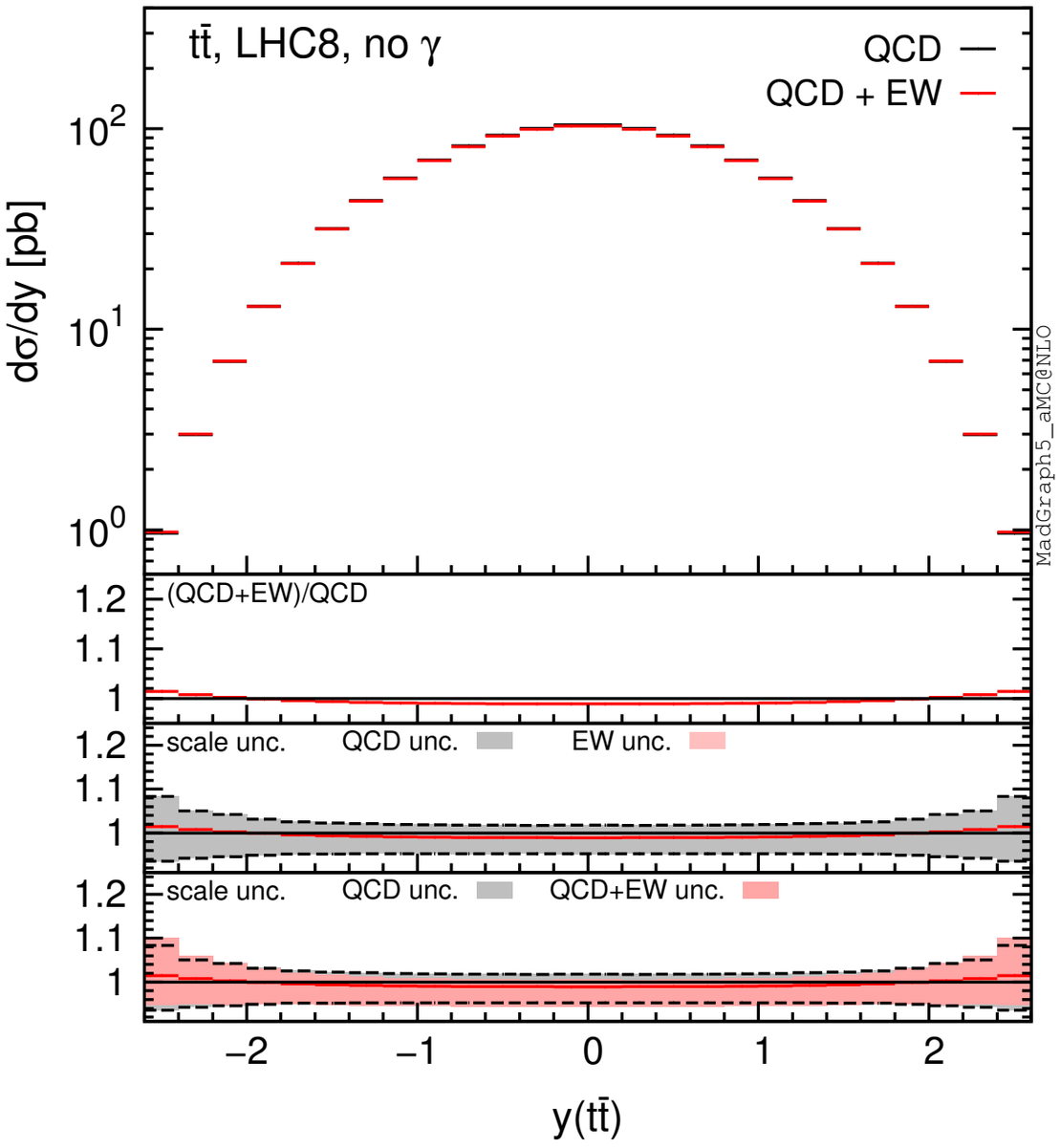


photon PDF **NO**

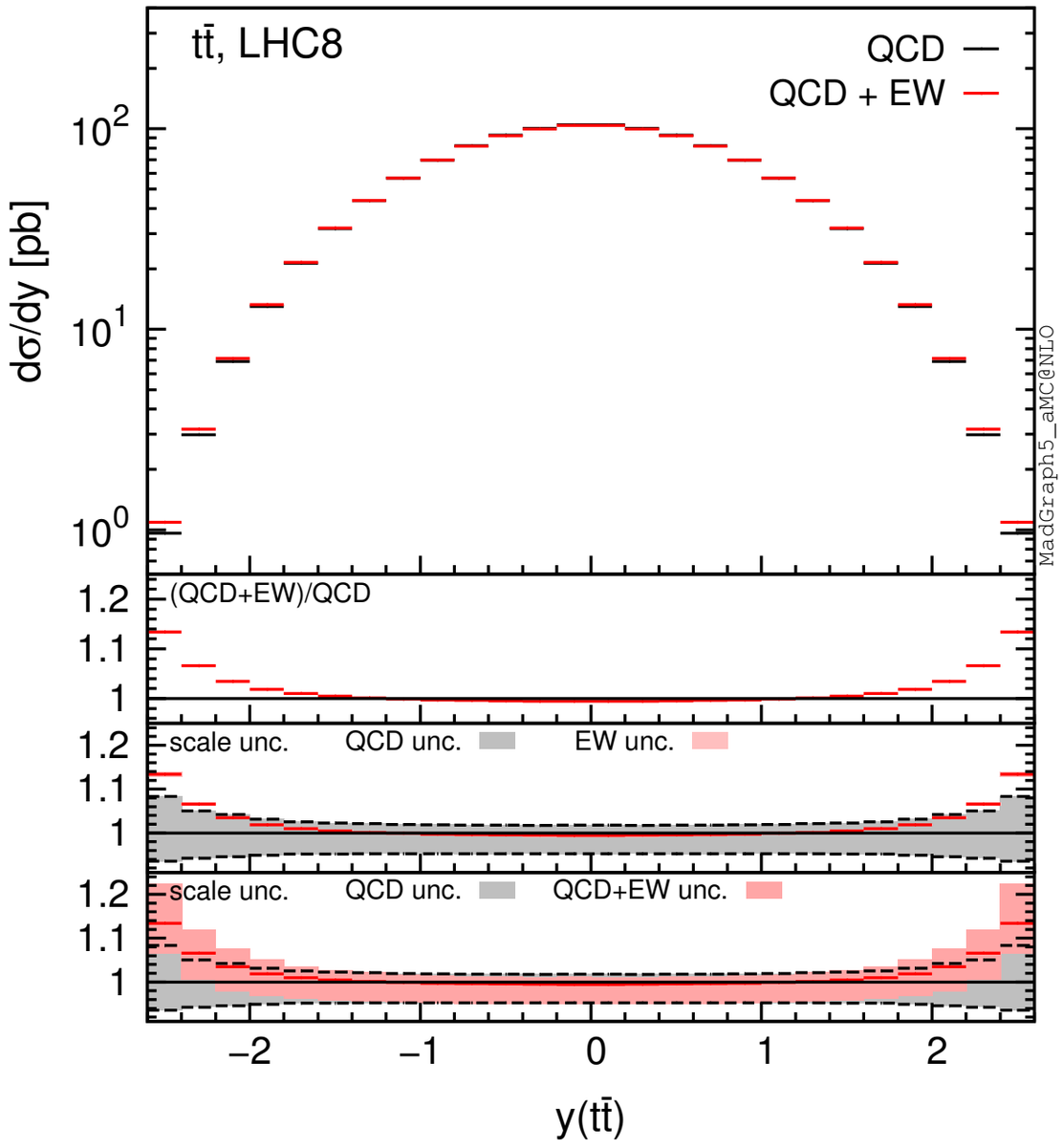


photon PDF **YES**

8 TeV

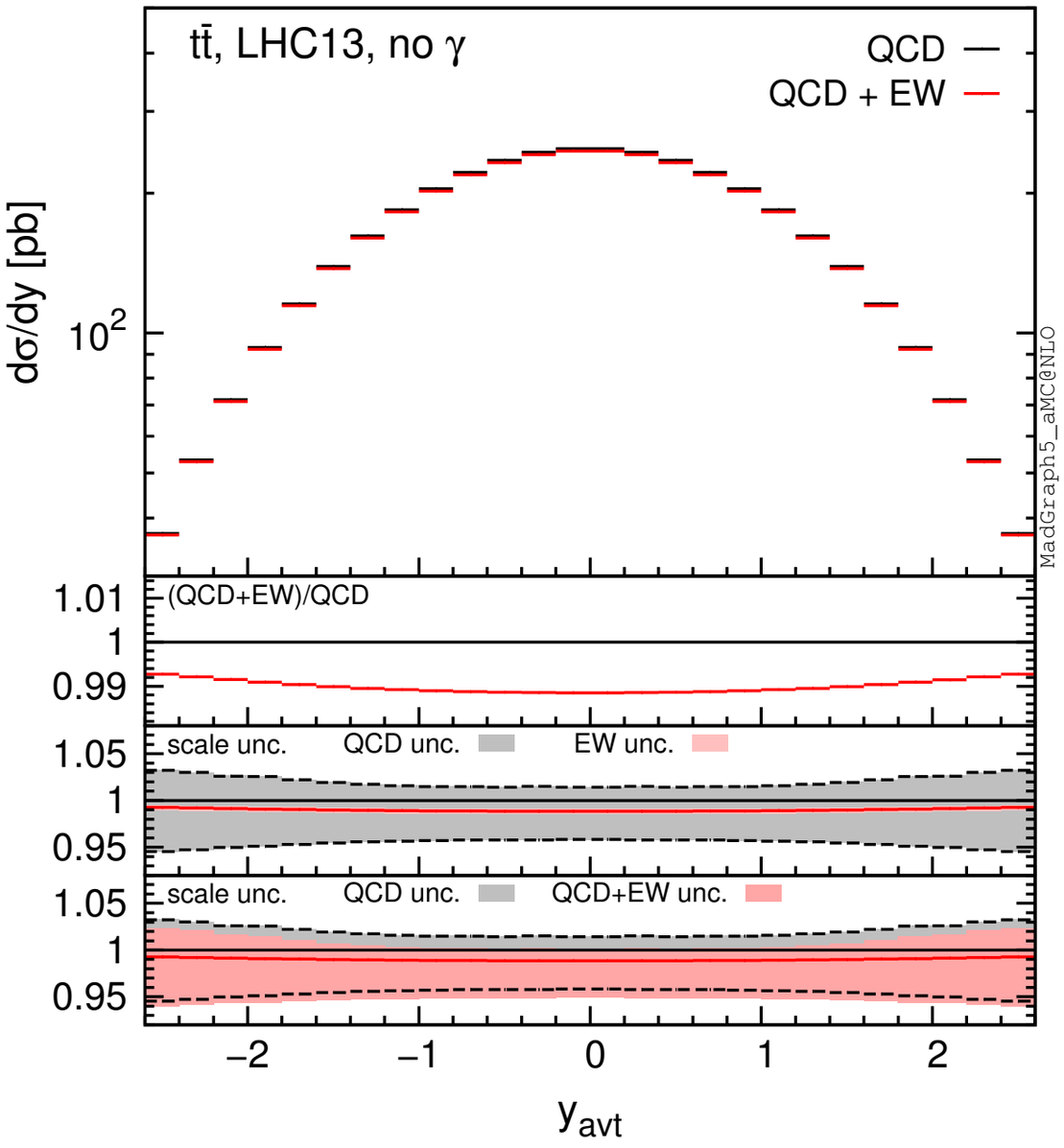


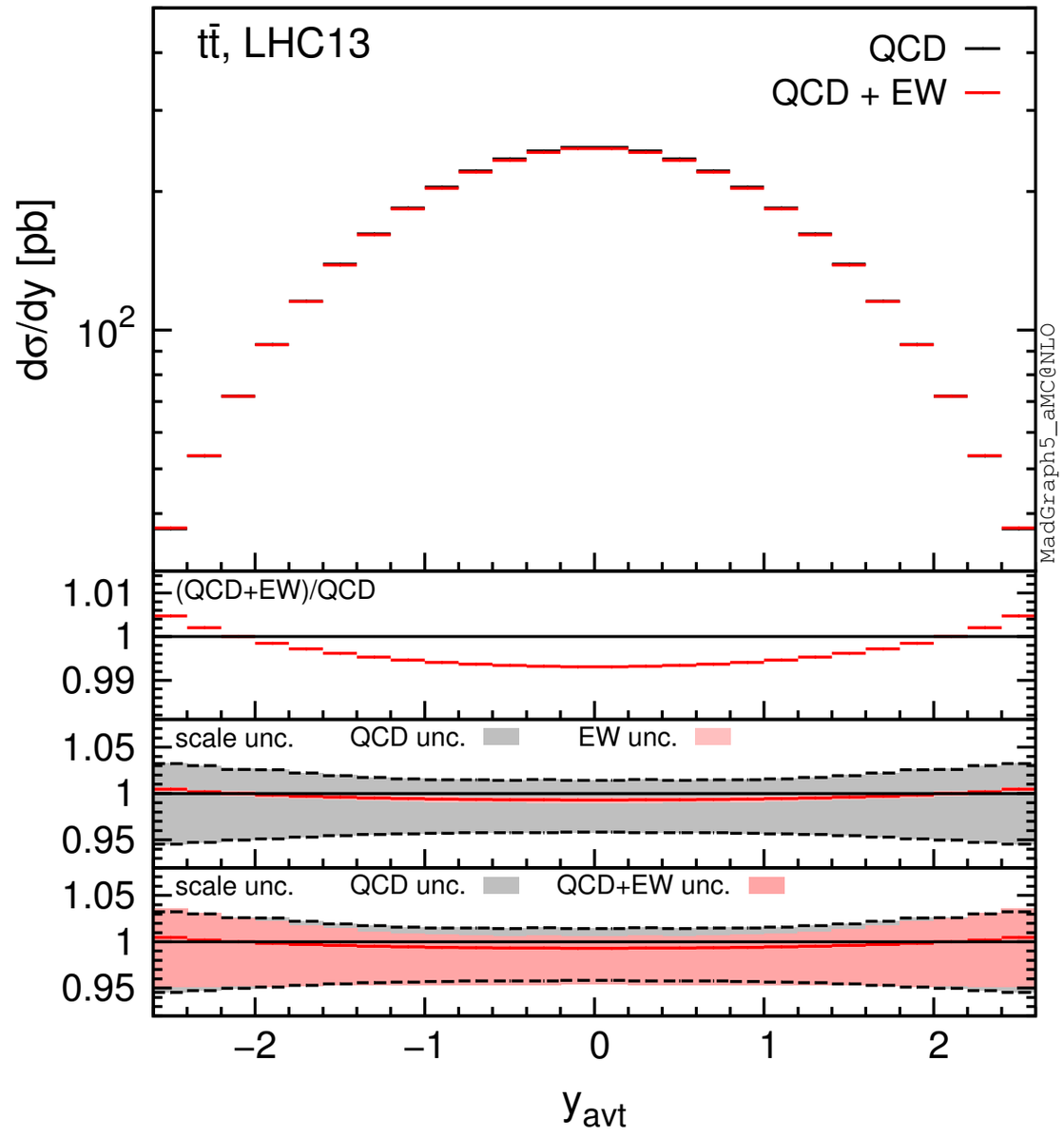
photon PDF **NO**



photon PDF **YES**

13 TeV





photon PDF **NO**

photon PDF **YES**

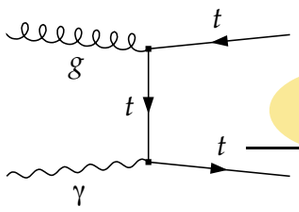
Why do we care about photons in the proton?

2 representative examples:

$t\bar{t}$

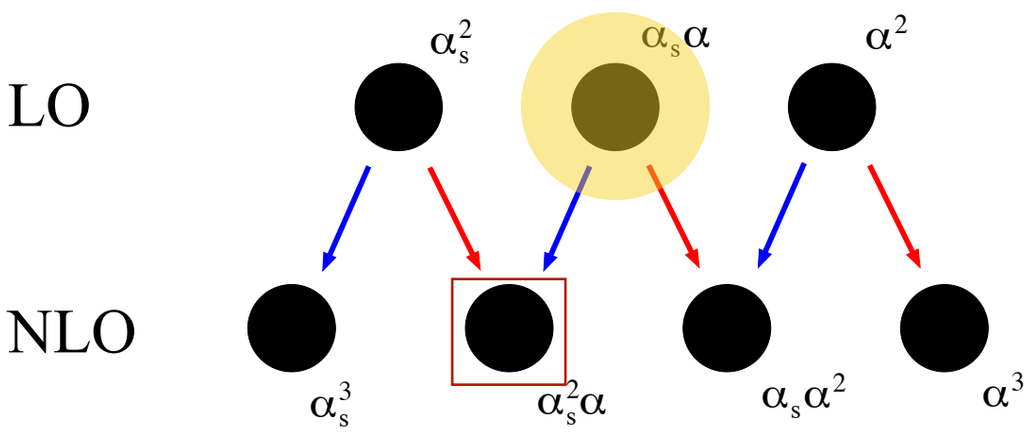
Process	σ_{tot} without cuts [pb]	
	Born	correction
$u\bar{u}$	34.25	-1.41
$d\bar{d}$	21.61	-0.228
$s\bar{s}$	4.682	-0.0410
$c\bar{c}$	2.075	-0.0762
gg	407.8	2.08
$g\gamma$		4.45
pp	470.4	4.78

NLO QED

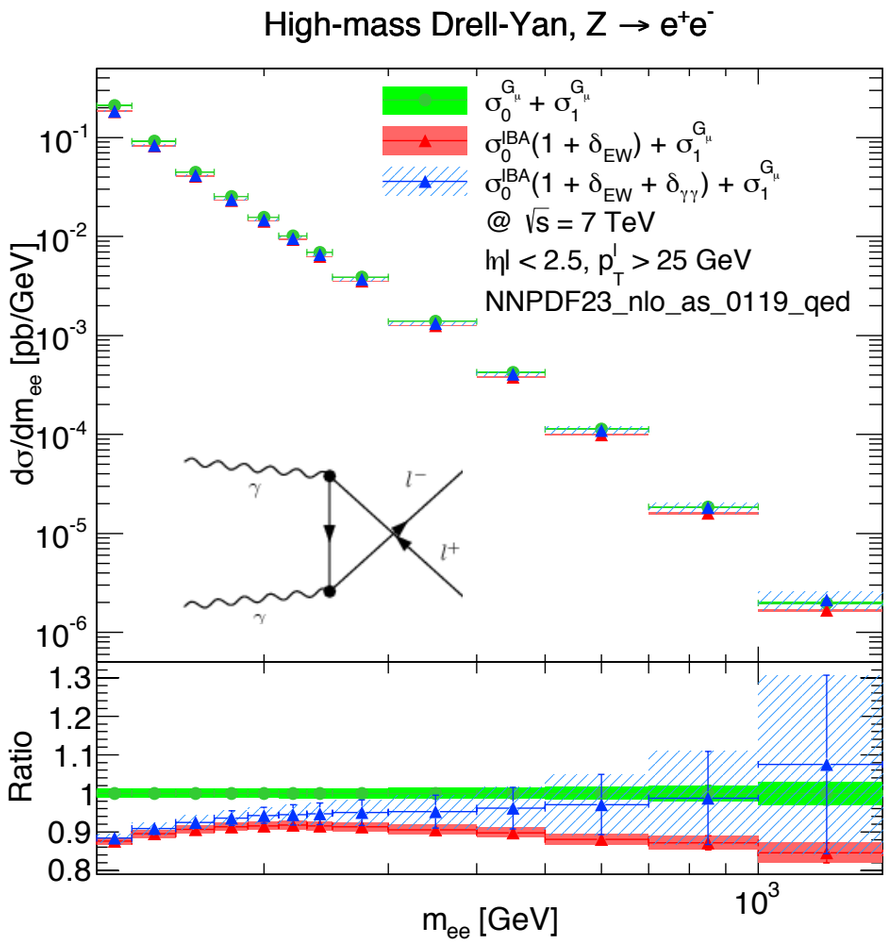


Integrated hadronic cross section for $t\bar{t}$ production at the LHC, at NLO QED

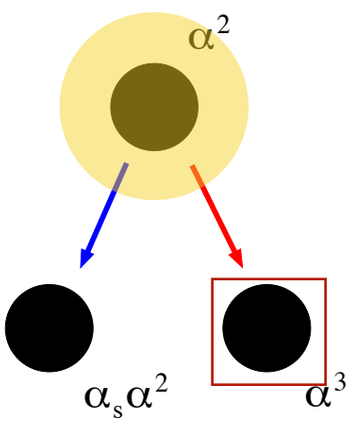
Hollik, Kollar '07 MRST2004QED



NLO EW



Carrazza '14 NNPDF2.3QED

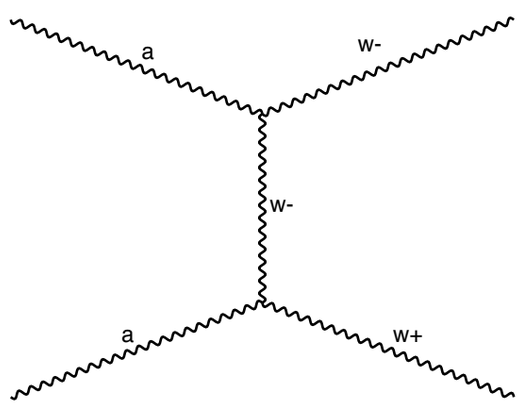


NLO EW

Set-up and photon-PDF perturbative orders

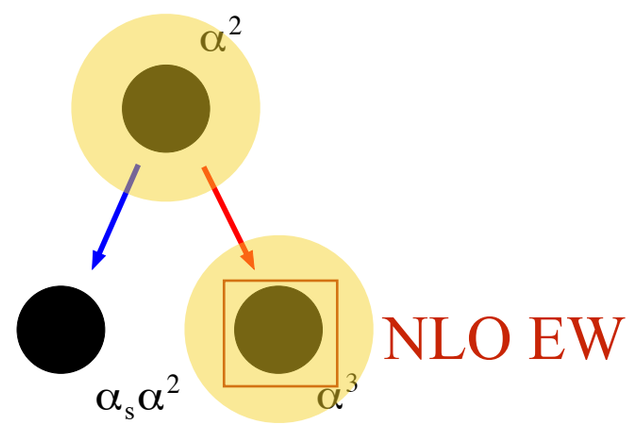
G_μ scheme, NNPDF2.3_QED, $\mu = \dfrac{H_T}{2}, \quad \dfrac{1}{2}\mu \leq \mu_R, \mu_F \leq 2\mu$

WW

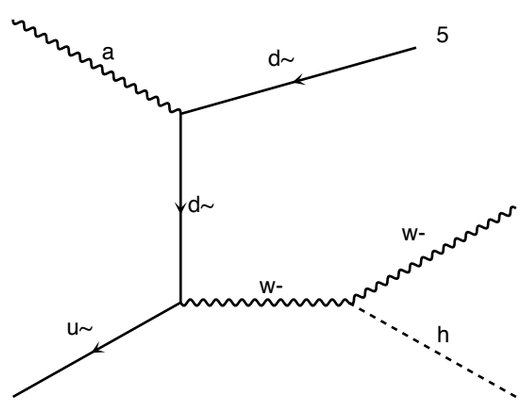


LO

NLO

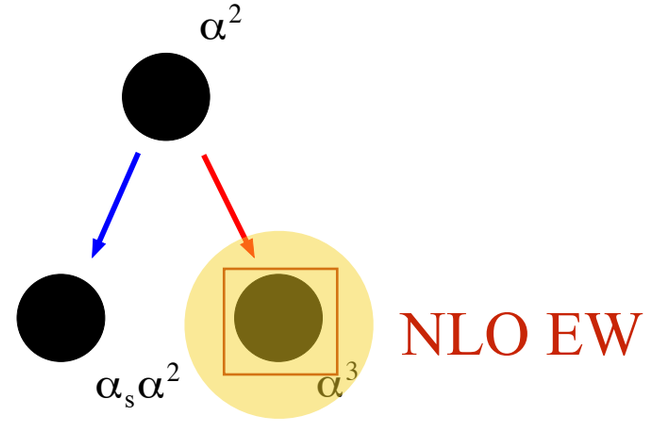


ZZ, ZW, HZ, HW

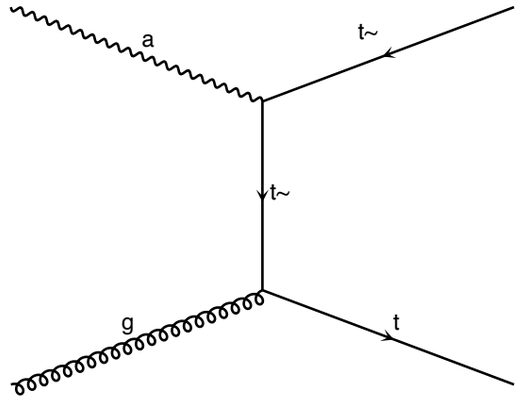


LO

NLO

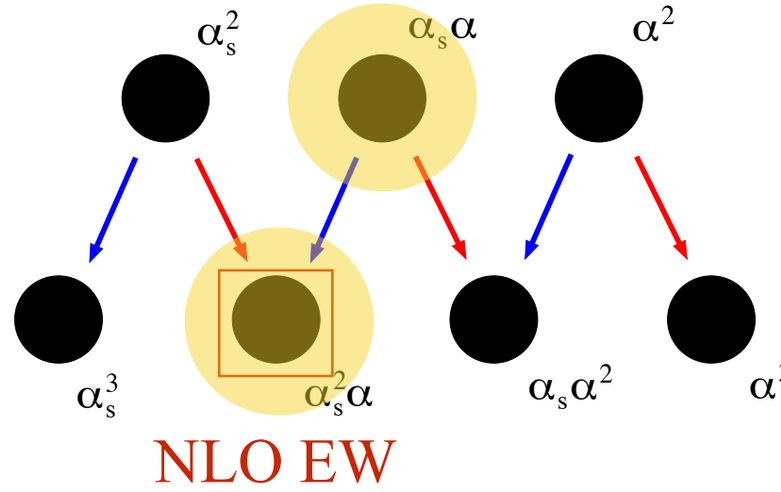


$t\bar{t}$



LO

NLO



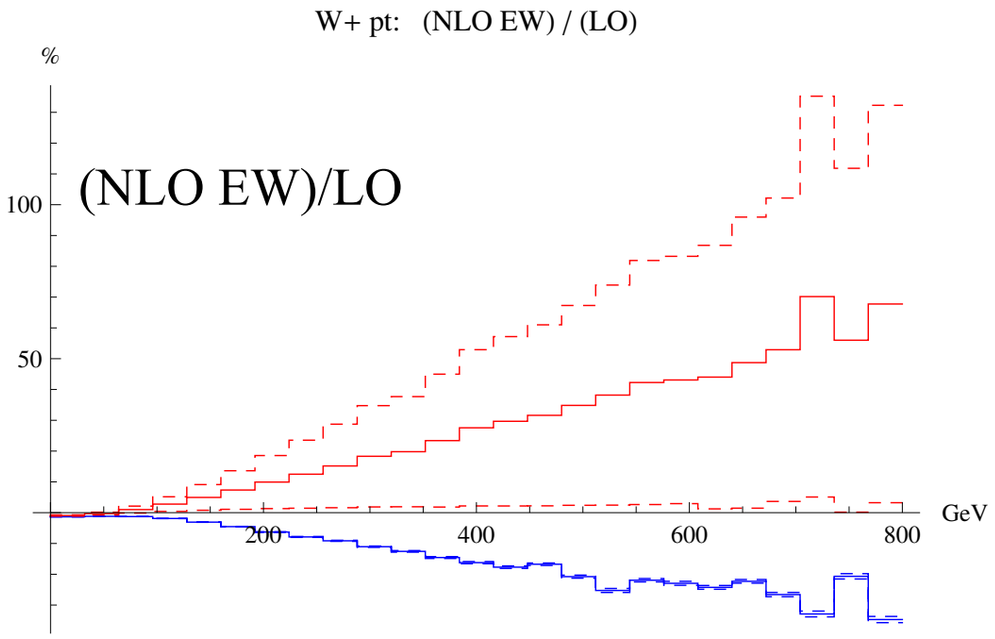
WZ

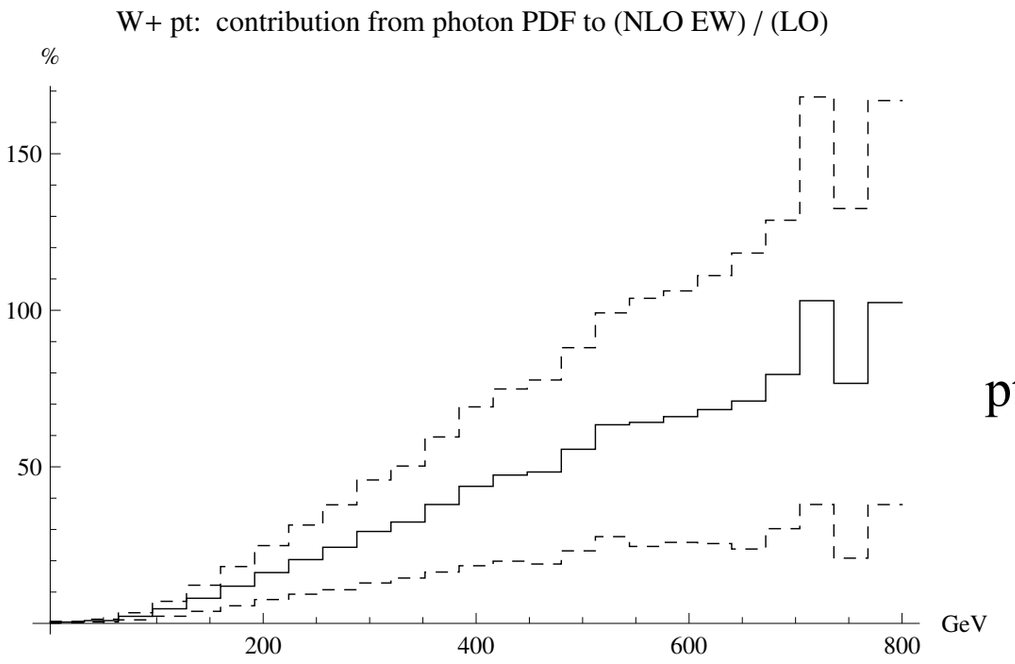
NLO EW in W+Z

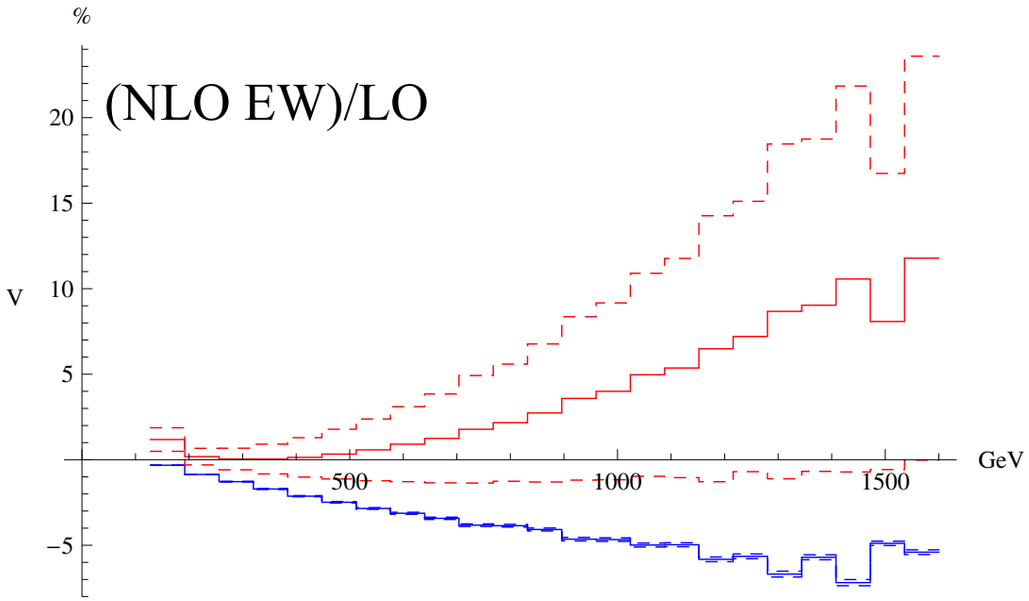
RED: with photon PDF

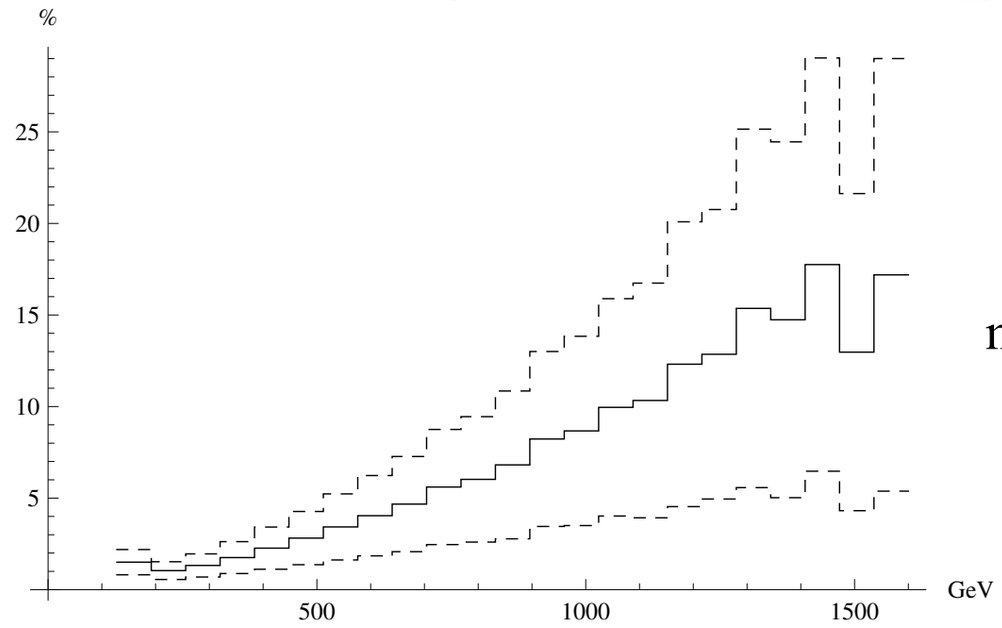
BLUE: photon PDF = 0

BLACK= RED - BLUE ~ γq contribution & PDF









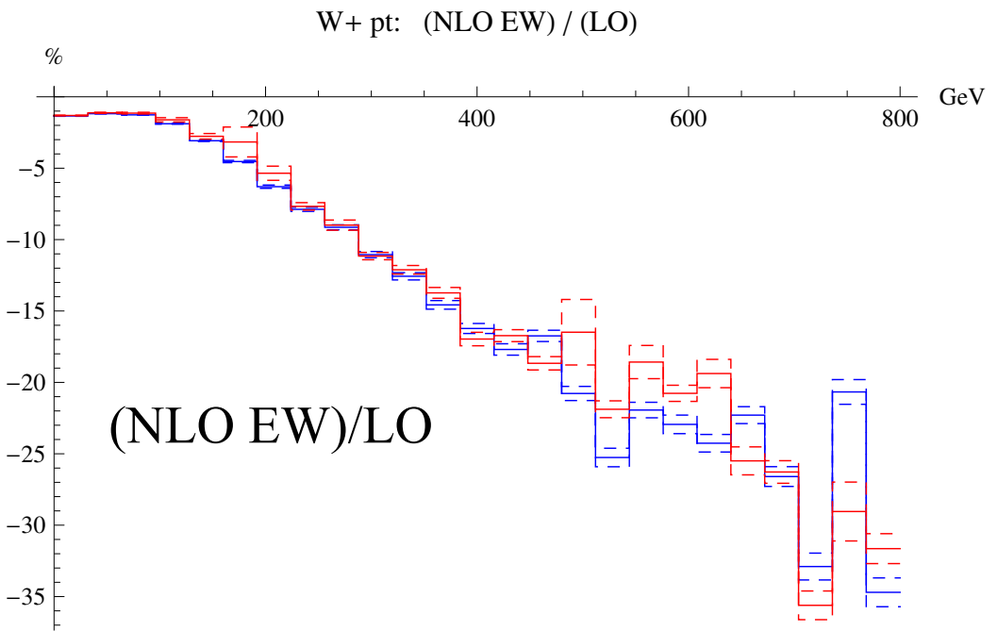
aMC@NLO_MadGraph5

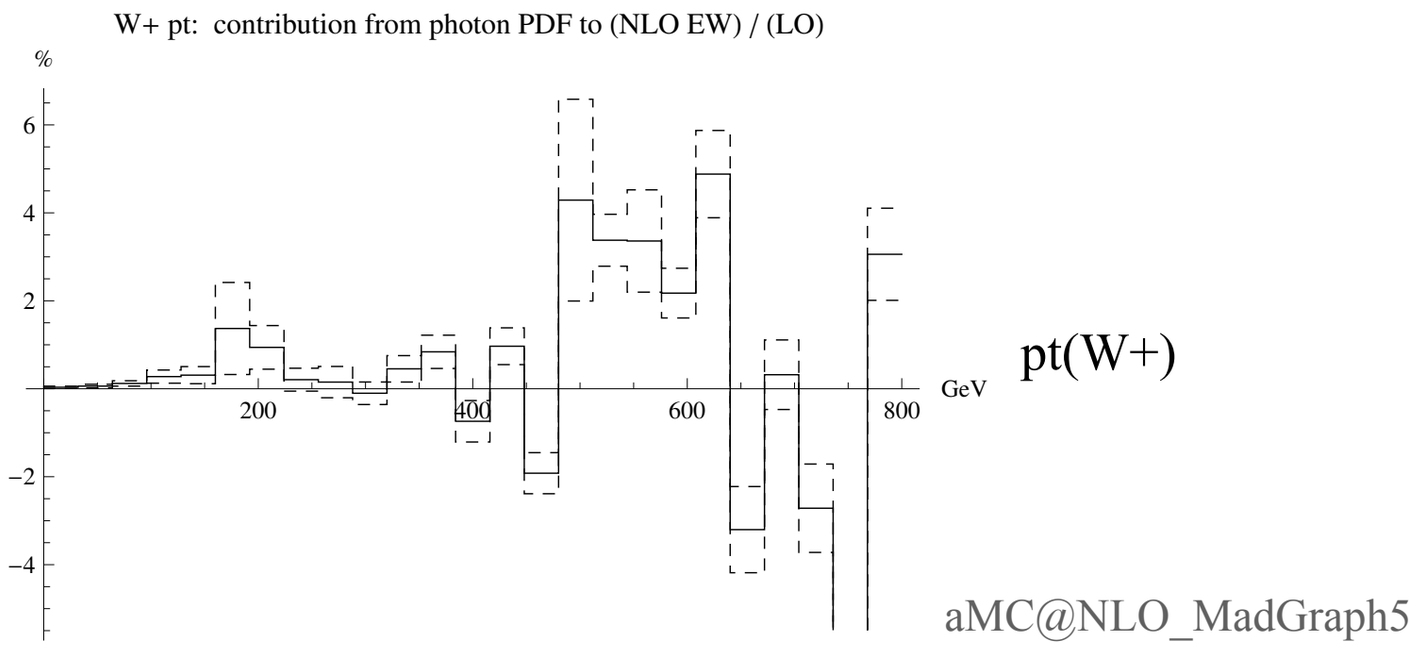
WZ

NLO EW in W+Z
RED: with photon PDF
BLUE: photon PDF = 0

BLACK= RED - BLUE ~ γq contribution & PDF

Now we impose a jet-veto for jets with pt(j) > 30 GeV:





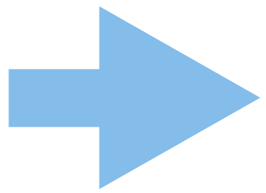
The jet veto kills γq contribution in pt(W+) distribution, the same effect is present also in the other distributions.

Automation of NLO corrections in Madgraph5_aMC@NLO

What do we mean with automation of EW corrections?

The possibility of calculating QCD and EW corrections for SM processes (matched to shower effects) with a process-independent approach.

```
generate process [QCD]
output process_QCD
```



```
generate process [QCD EW]
output process_QCD_EW
```

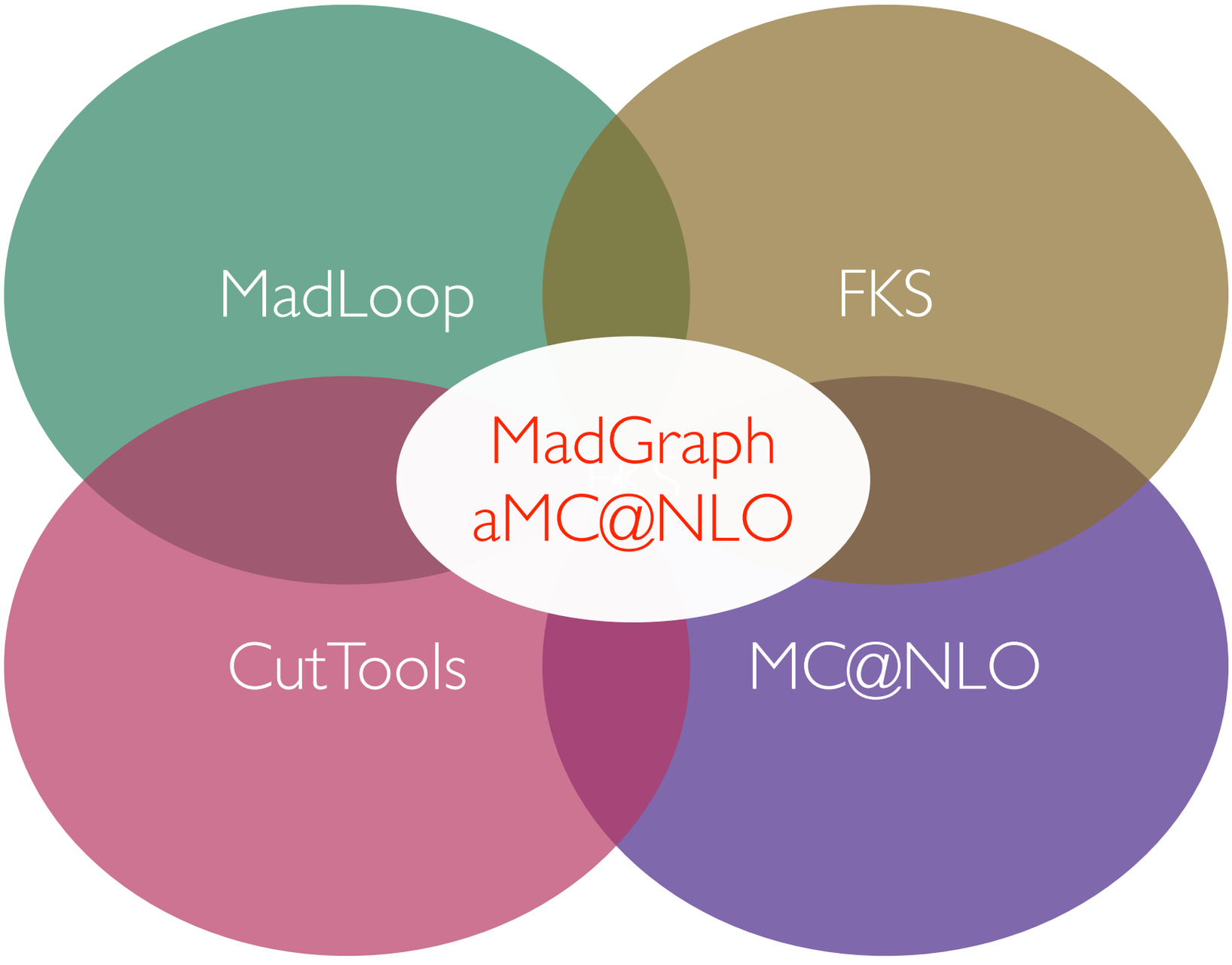
The automation of NLO QCD has been achieved, but we need higher precision to match the experimental accuracy at the LHC and future colliders.

- NNLO QCD automation is out of our theoretical capabilities at the moment.
- NLO EW corrections are of the same order ($\alpha_s^2 \sim \alpha$), the Sudakov logarithms can enhance their size. NLO QCD and EW corrections **can be automated.**

Automation of NLO corrections in Madgraph5_aMC@NLO

The **complete automation** for **QCD+EW** is in progress.

DONE!



DONE!

DONE!

in progress