Top-quark pair production at NNLO QCD + NLO EW accuracy

Based on the work done in collaboration with
M. Czakon, D. Heymes, A. Mitov, I. Tsinikos, M. Zaro

Davide Pagani

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Louvain-la-Neuve
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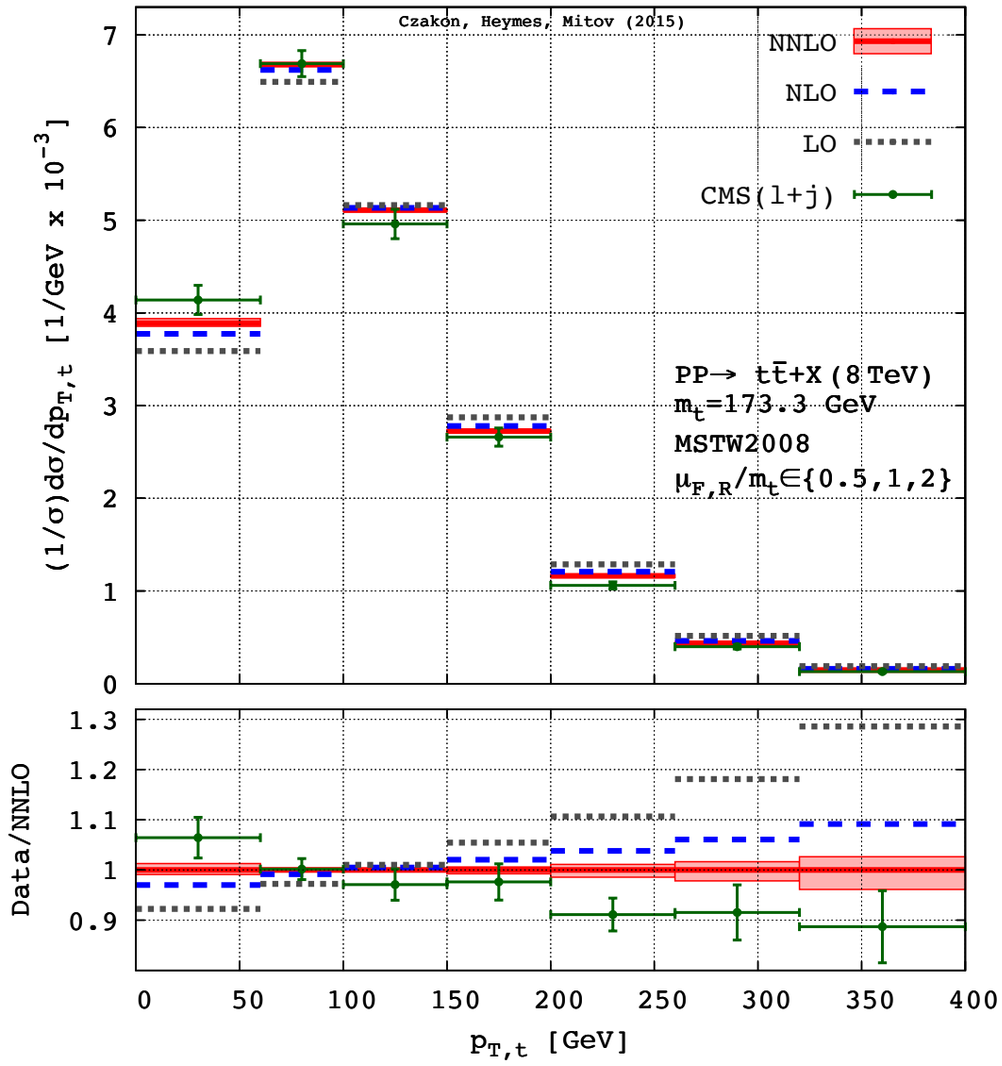
Motivation

The precision reached in ttbar measurements at the LHC has made both higher-order **QCD and EW corrections** unavoidable ingredients for a correct comparison of theory vs. experiment.

8 TeV data have shown a tension with NLO QCD predictions for pt(top) distributions, which is partially explained by **NNLO QCD** corrections.



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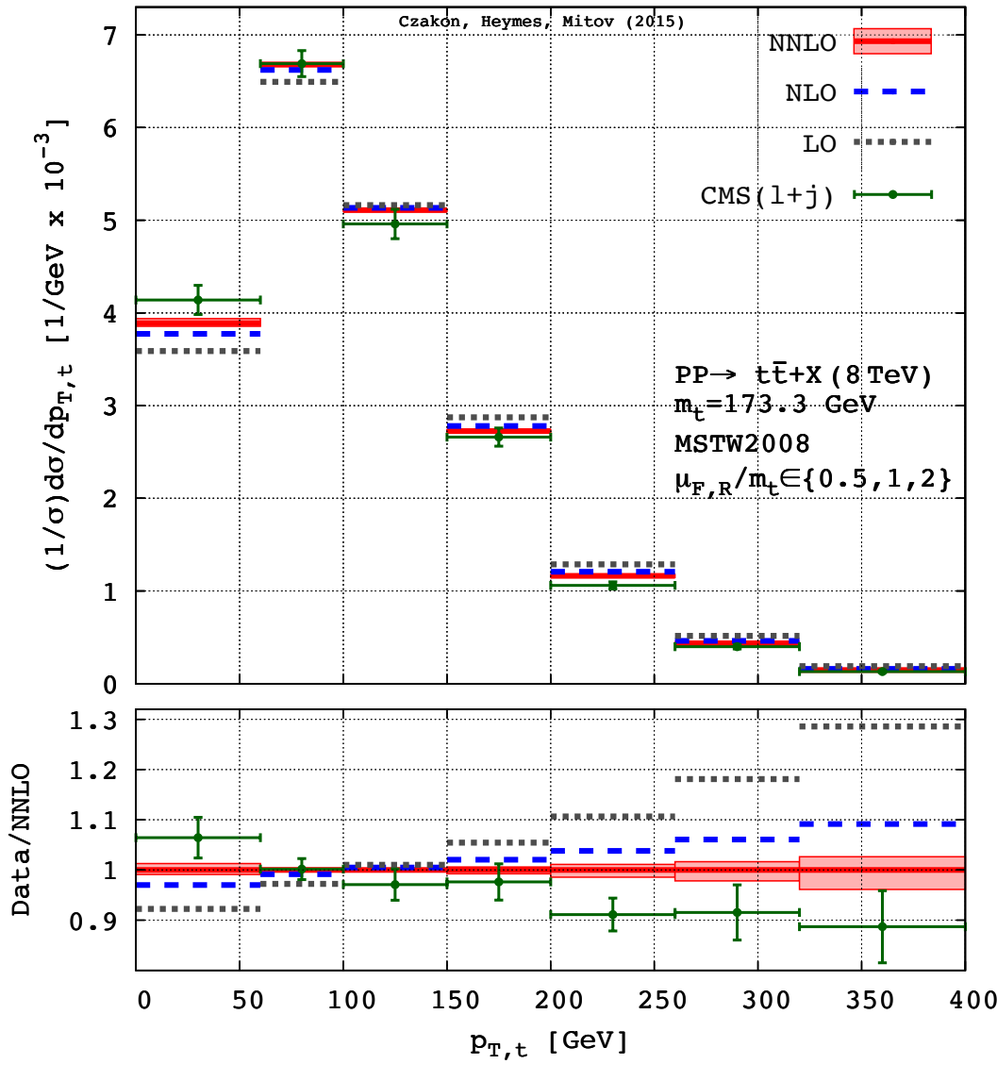

EW corrections have a similar size ($\alpha_s^2 \sim \alpha$), with **Sudakov enhancements** in the boosted regime. However, only a part of them is taken into account in experimental analyses, and no consistent combination with NNLO QCD (same input parameters, PDFs and scale) is yet available.

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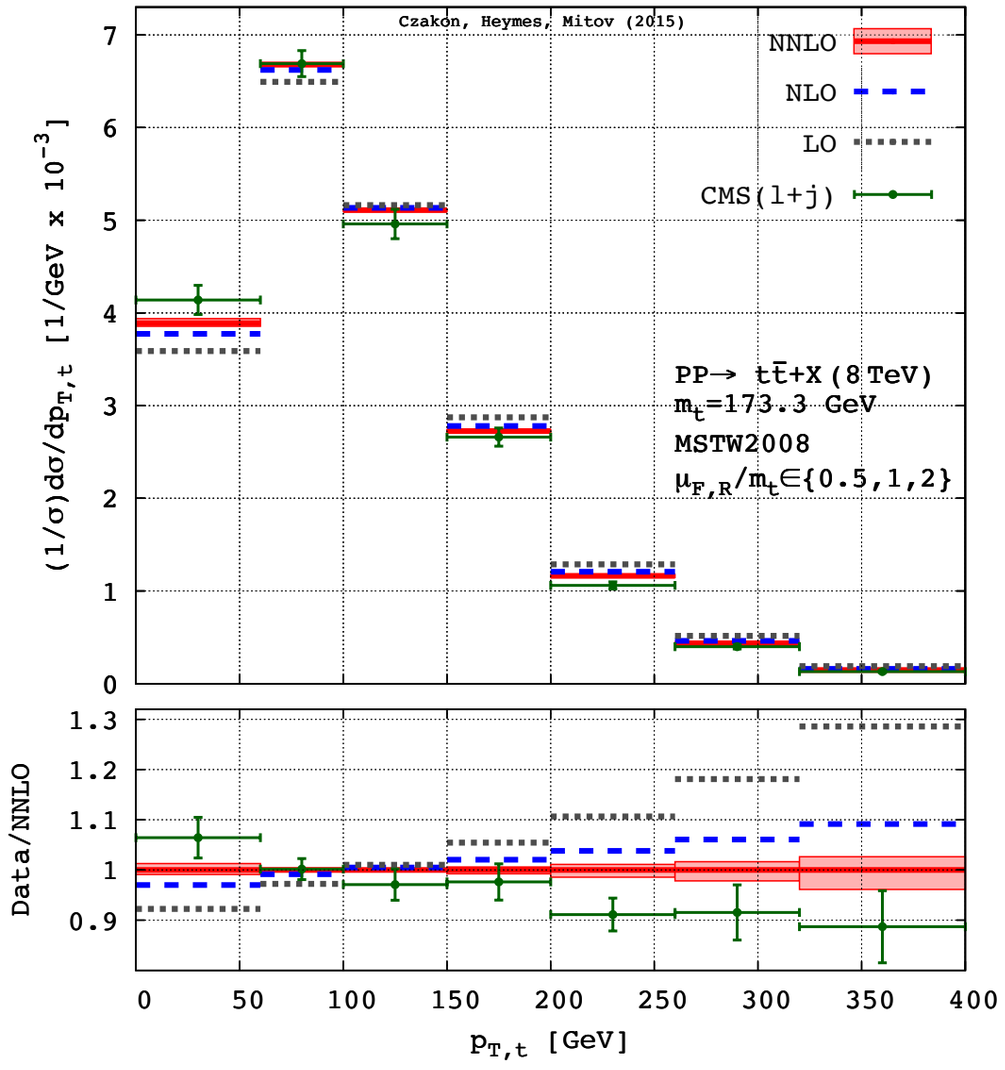

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We provide predictions at complete NLO accuracy including also NNLO QCD corrections for differential distributions in top-quark pair production at 8 and 13 TeV.

Motivation (part 2)

If you do not believe that NNLO QCD + NLO EW corrections are essential:
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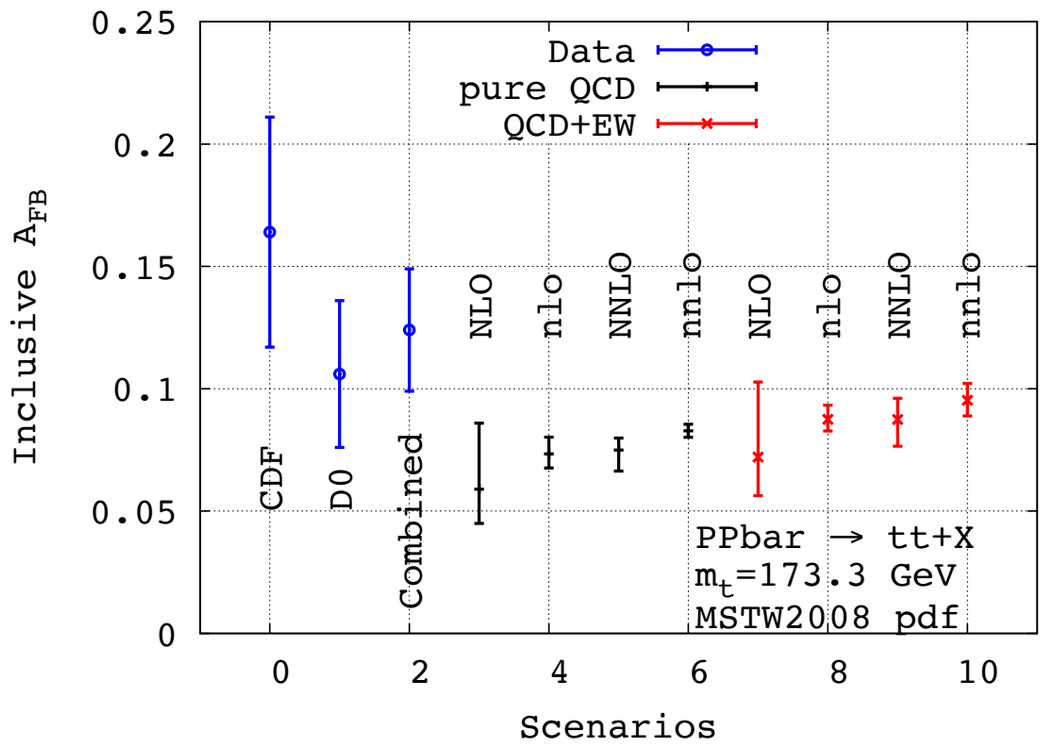


FIG. 1: The inclusive asymmetry in pure QCD (black) and QCD+EW[28] (red). Capital letters (NLO, NNLO) correspond to the unexpanded definition (2), while small letters (nlo, nnlo) to the definition (3). The CDF/DØ (naive) av-

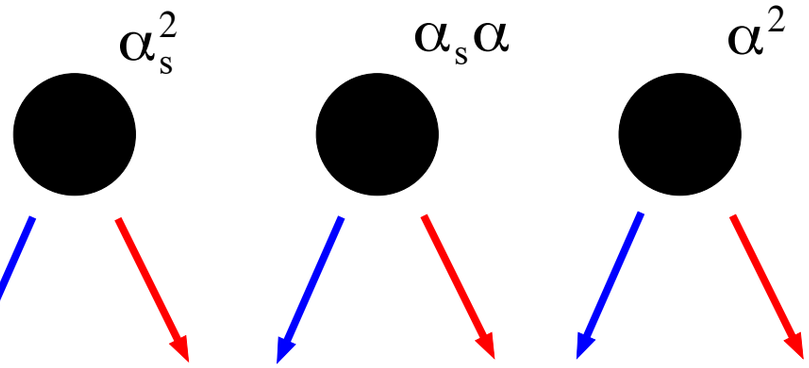
A posteriori,
it was realized that a large fraction of the discrepancy was due to the missing contributions from:
EW corrections
(*Hollik, DP '11*)
and
NNLO QCD corrections
(Czakon, Fiedler, Mitov '15)

Calculation framework

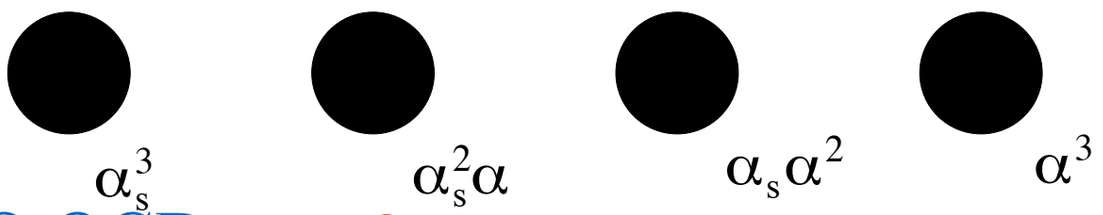
The calculation of **NNLO QCD** corrections is based on
Czakon, Fiedler, Mitov '15

The calculation of the **complete NLO** corrections is performed with the EW branch of **MadGraph5_aMC@NLO** (*Frixione, Hirschi, DP, Shao, Zaro '14,'15*).

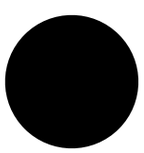
LO



NLO



NNLO



All these orders are taken into account, without any approximation.

Choice of input parameters

$m_t = 173.3\ \text{GeV}\,, \quad m_H = 125.09\ \text{GeV}\,, \quad m_W = 80.385\ \text{GeV}\,, \quad m_Z = 91.1876\ \text{GeV}\,.$

$G_\mu = 1.1663787 \cdot 10^{-5}\ \text{GeV}^{-2}$ for the parametrization of the EW couplings

Five-flavor-scheme for α_s

Which Factorization and Renormalization scale?

Which PDF set?

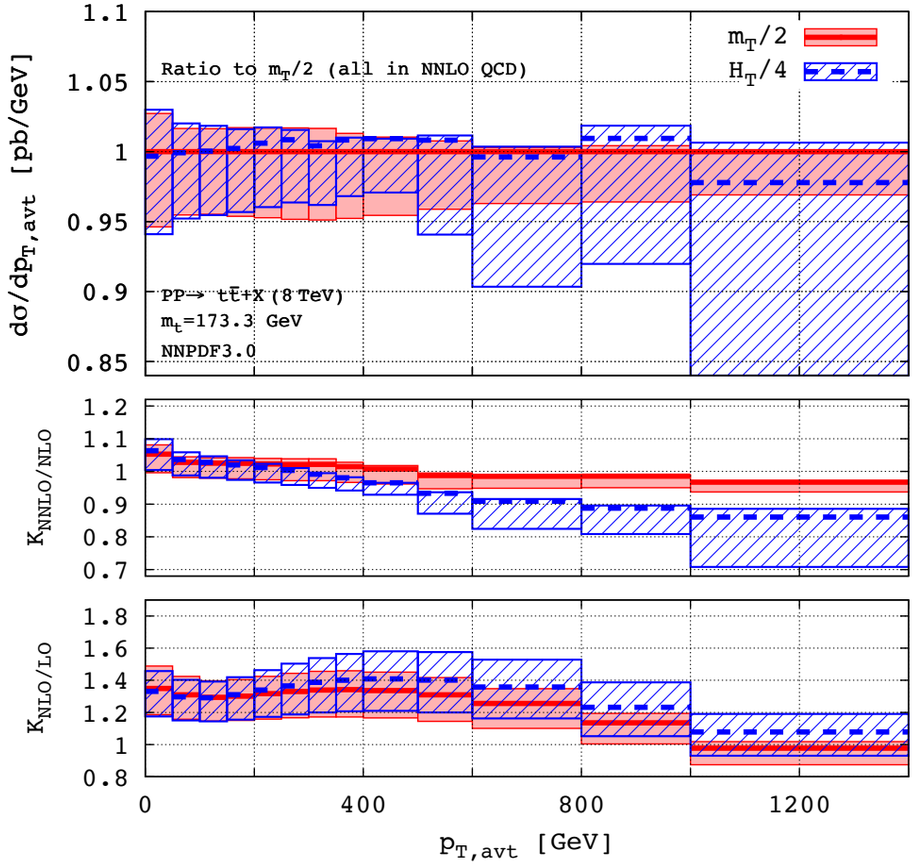
NNLO QCD: scale definition

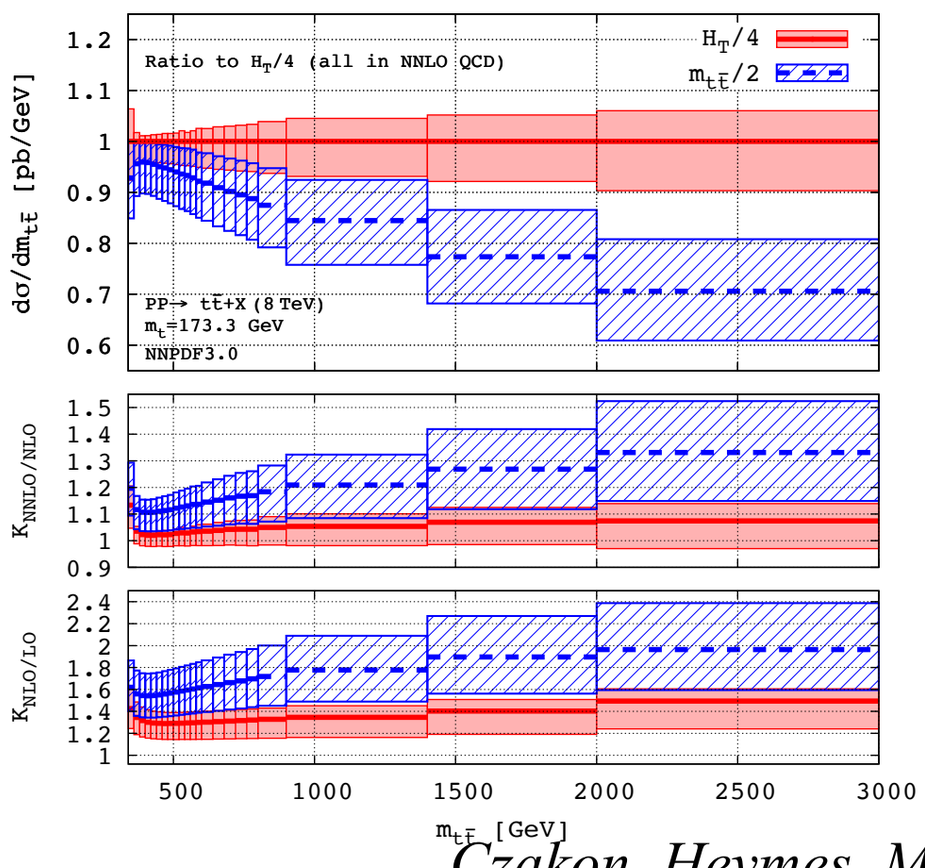
The dependence on the ren. and fac. scale is mainly due to QCD effects.

The scale that minimizes NLO and NNLO corrections can be chosen as optimal scale: **“Principle of fastest convergence”.**
The best-scale definition can also depend on the observable:

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

$$H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2}$$





Czakon, Heymes, Mitov ’16

EW corrections: PDFs choice

PDFs must have the same accuracy of the calculation of the matrix elements; not only NNLO QCD but also NLO QED accuracy is necessary.
The best on the market is NNLO QCD + LO QED:

NNPDF3.0QED *Bertone, Carrazza '16*
LUXQED *Manohar et al. '16*

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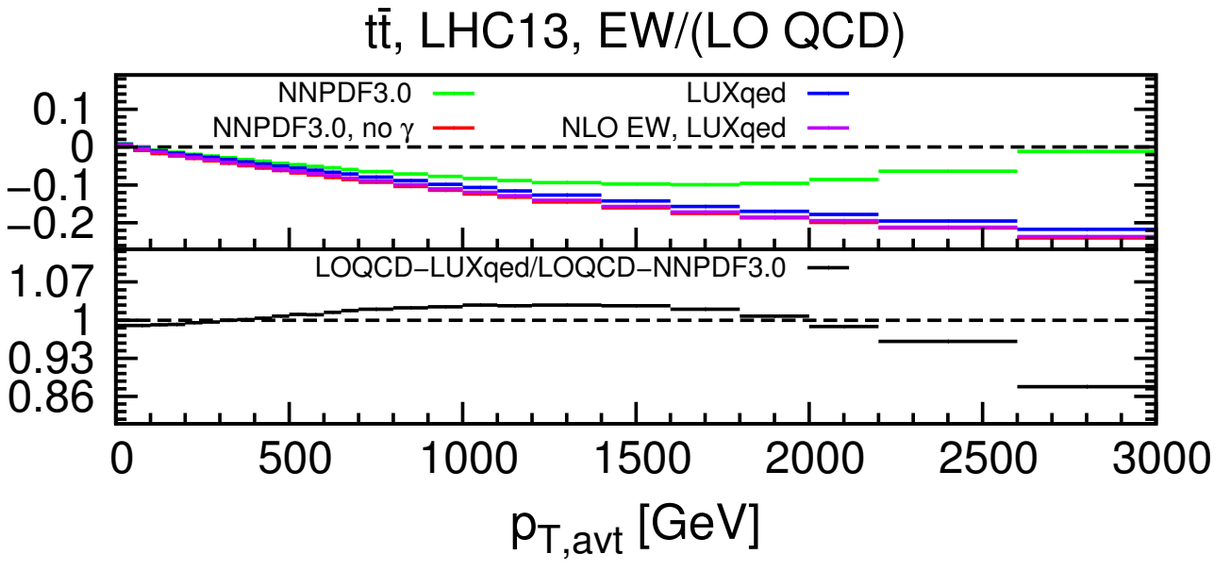
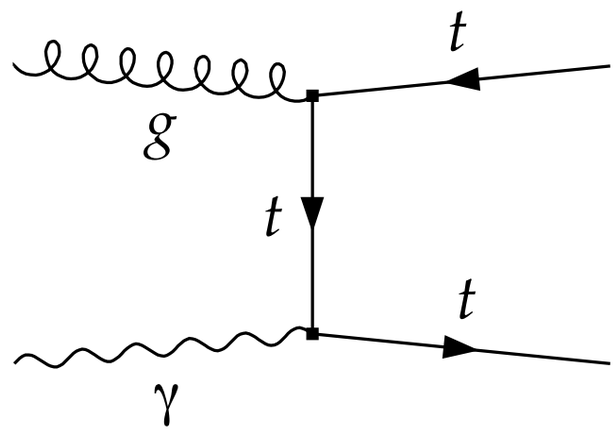
While the impact of the NNPDF photon PDF is huge in ttbar differential distributions (and with large uncertainties), in the case of LUXQED is small. Cancellation between Sudakov Logarithms and photon-induced results depends on the scale definition. *DP, Tsinikos, Zaro '16*

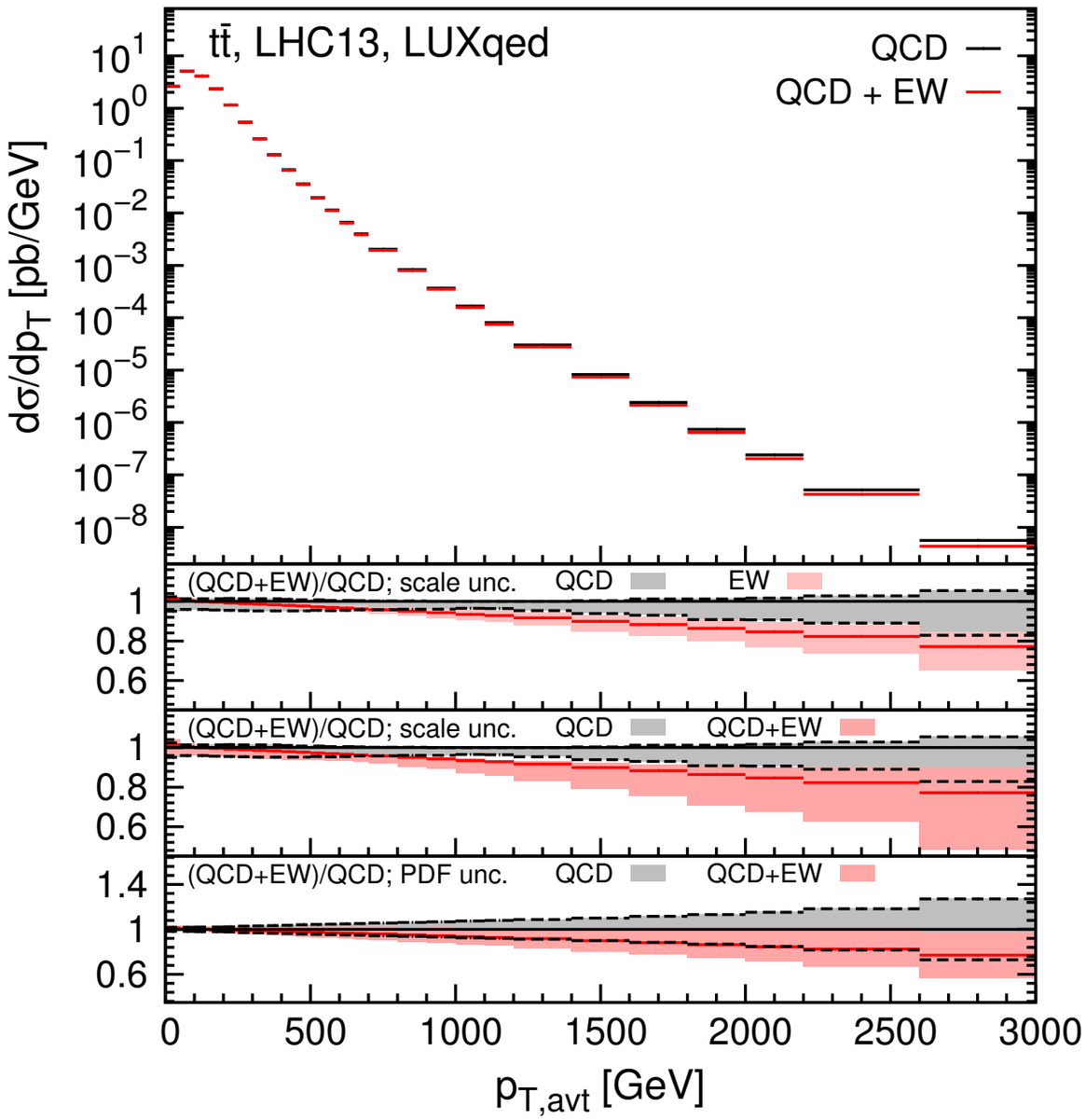




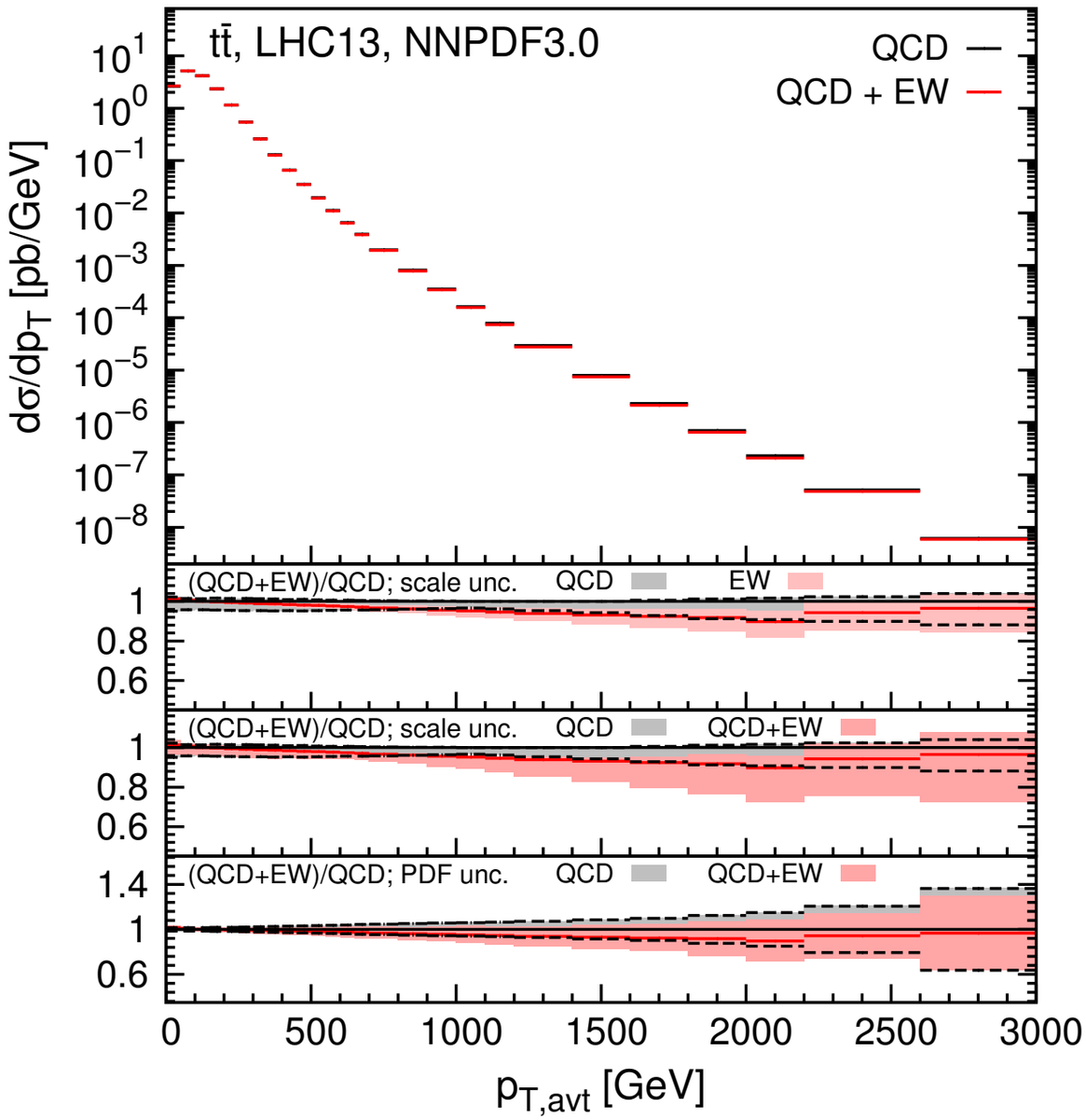
Results

13 TeV

$p_{T,\mathrm{avt}}$



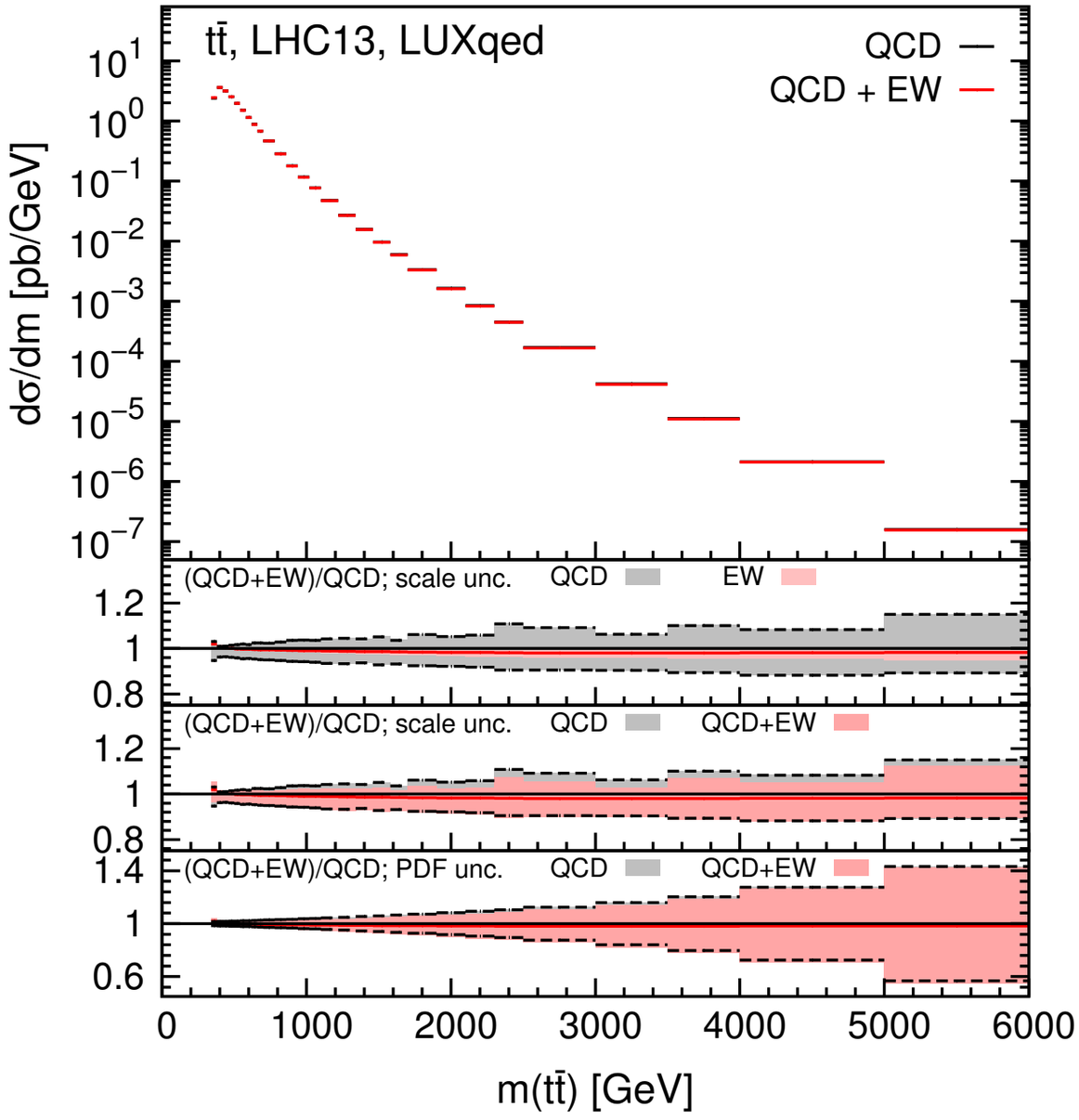
LUXQED



NNPDF3.0QED

$m(t\bar{t})$

13 TeV



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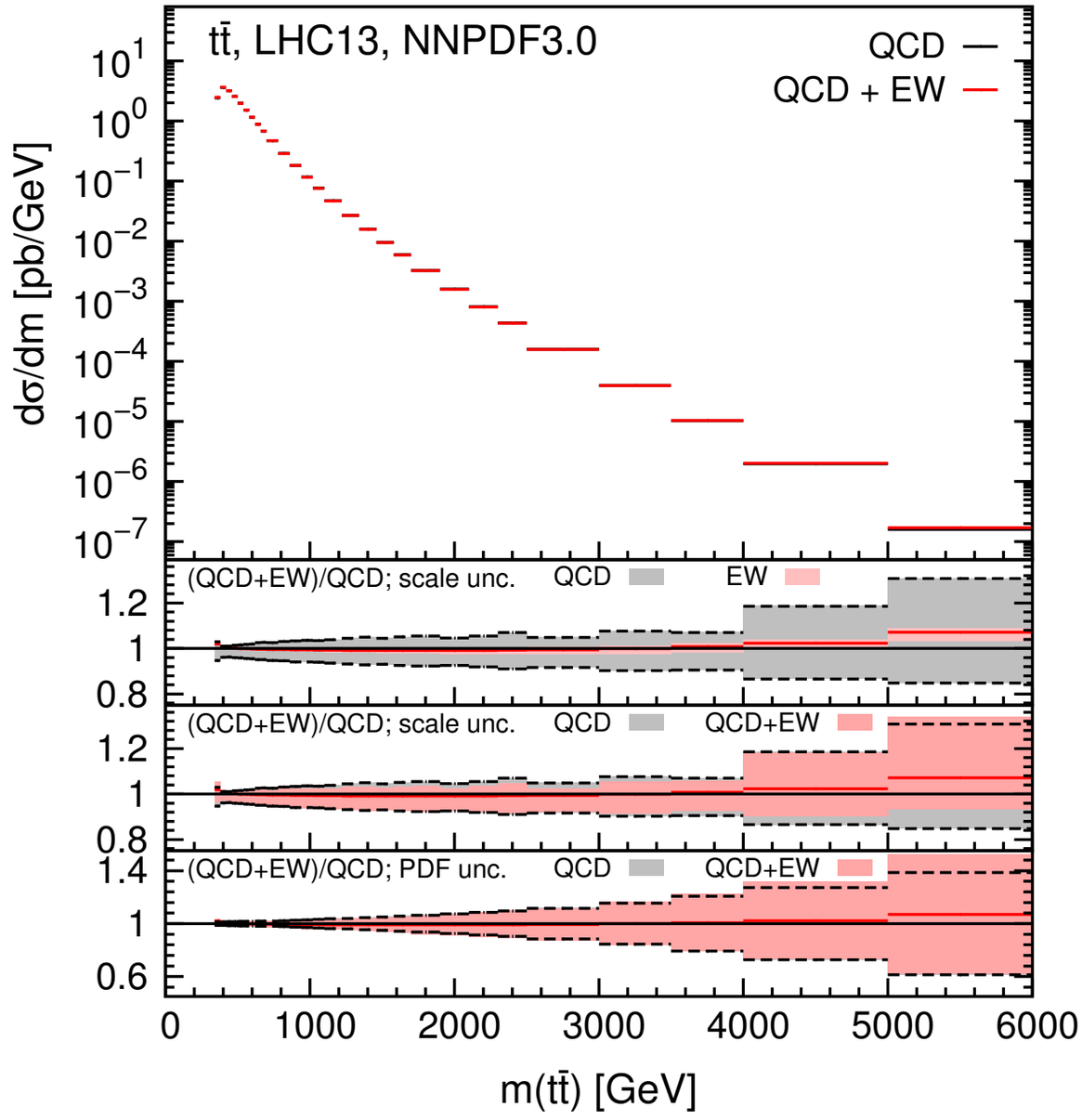
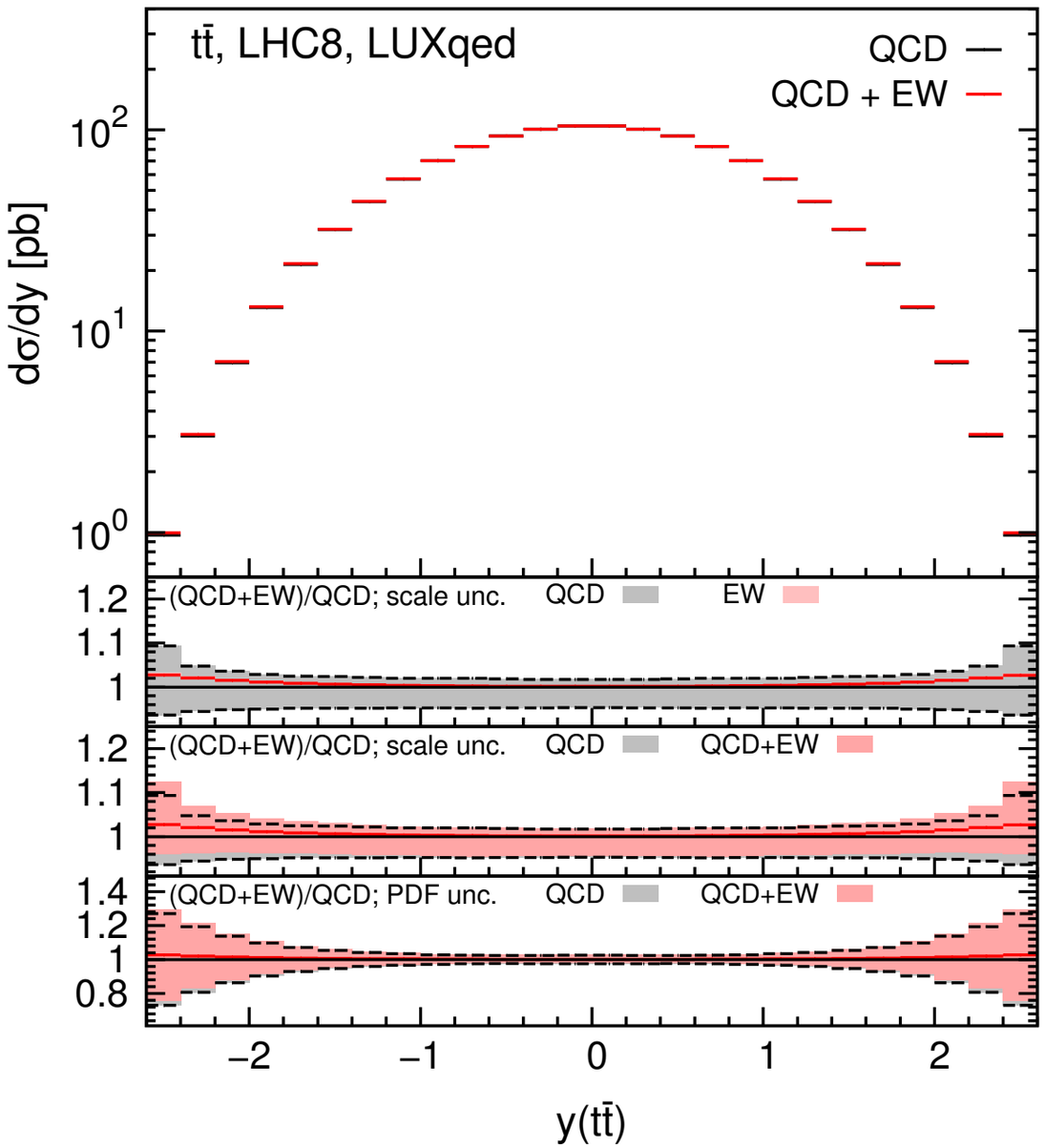


NNPDF3.0QED

$y(t\bar{t})$

8 TeV



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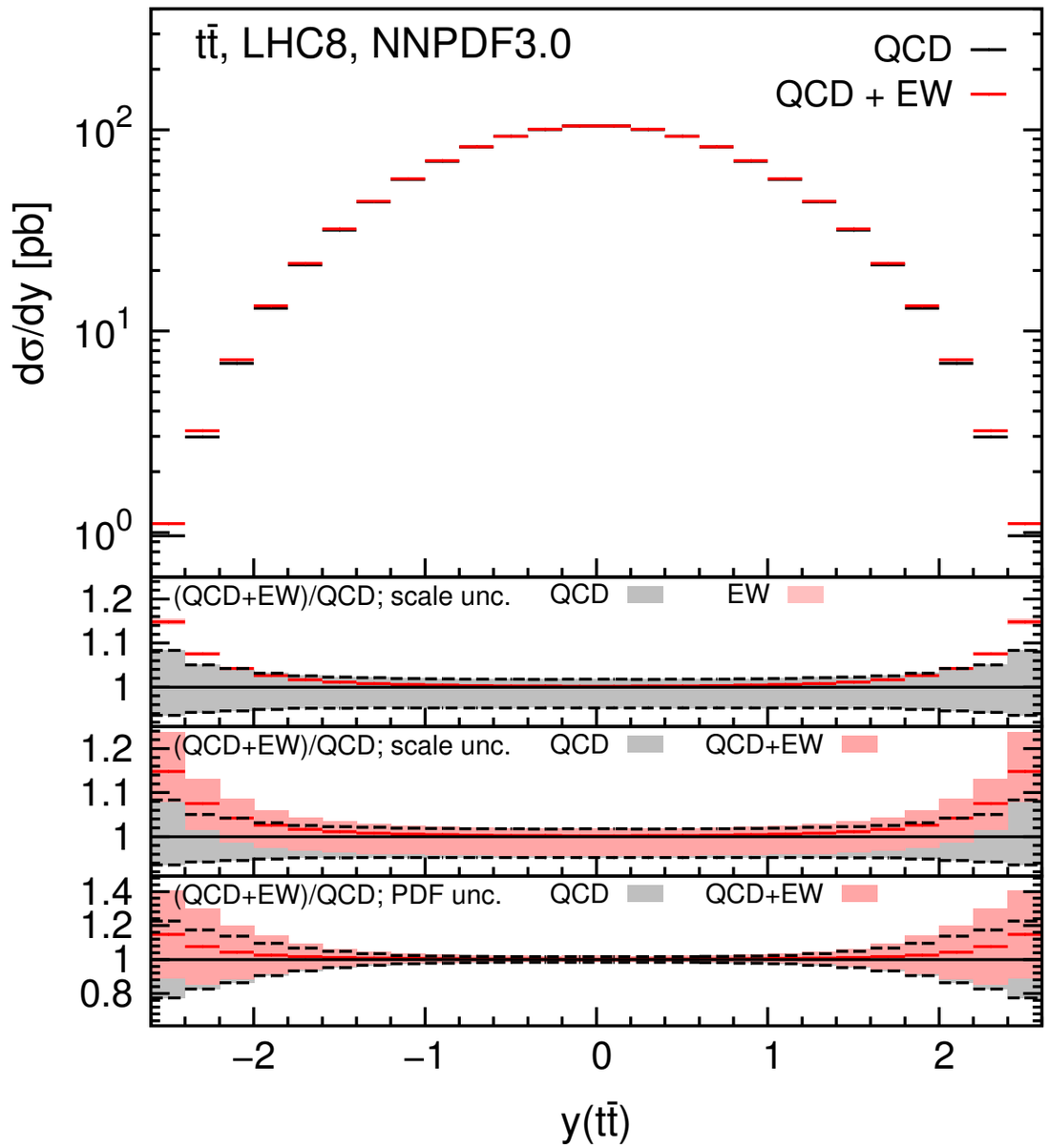

NNPDF3.0QED

Can we do better?

Can we estimate NNLO mixed QCD-EW effects?

Can we reduce the scale-dependence from NLO EW effects?

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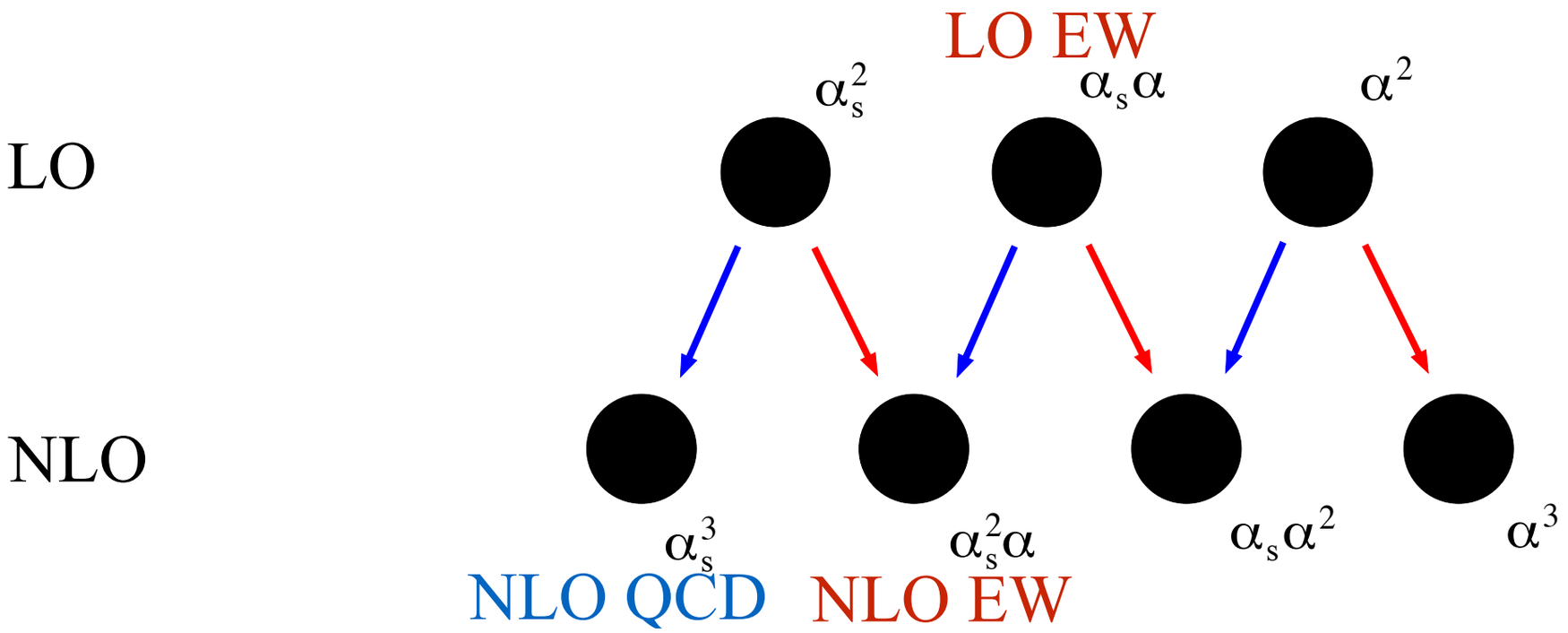
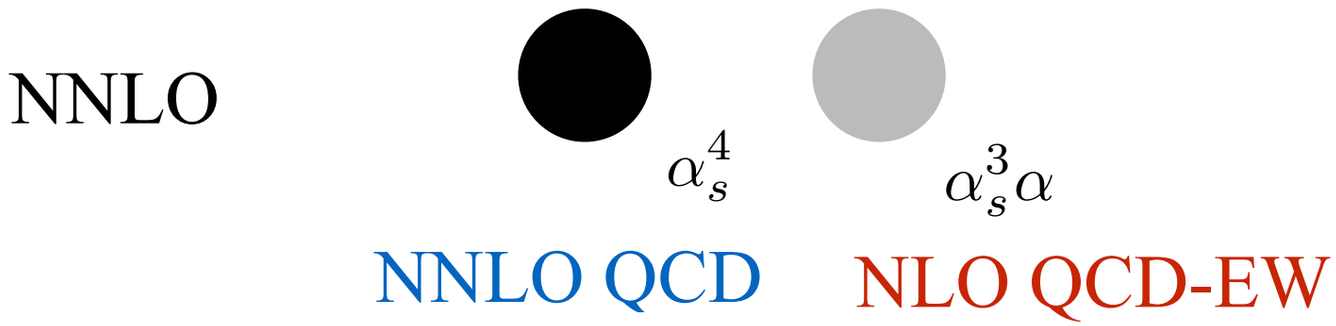
Combination of EW and QCD corrections in the multiplicative approach

When QCD and EW effects factorize (e.g. soft QCD and Sudakov Logarithms) multiplying NLO QCD with NLO EW is a good approximation for NNLO mixed QCD-EW effects.
In general, it can be used as an estimate of uncertainties due to mixed QCD-EW higher order effects.

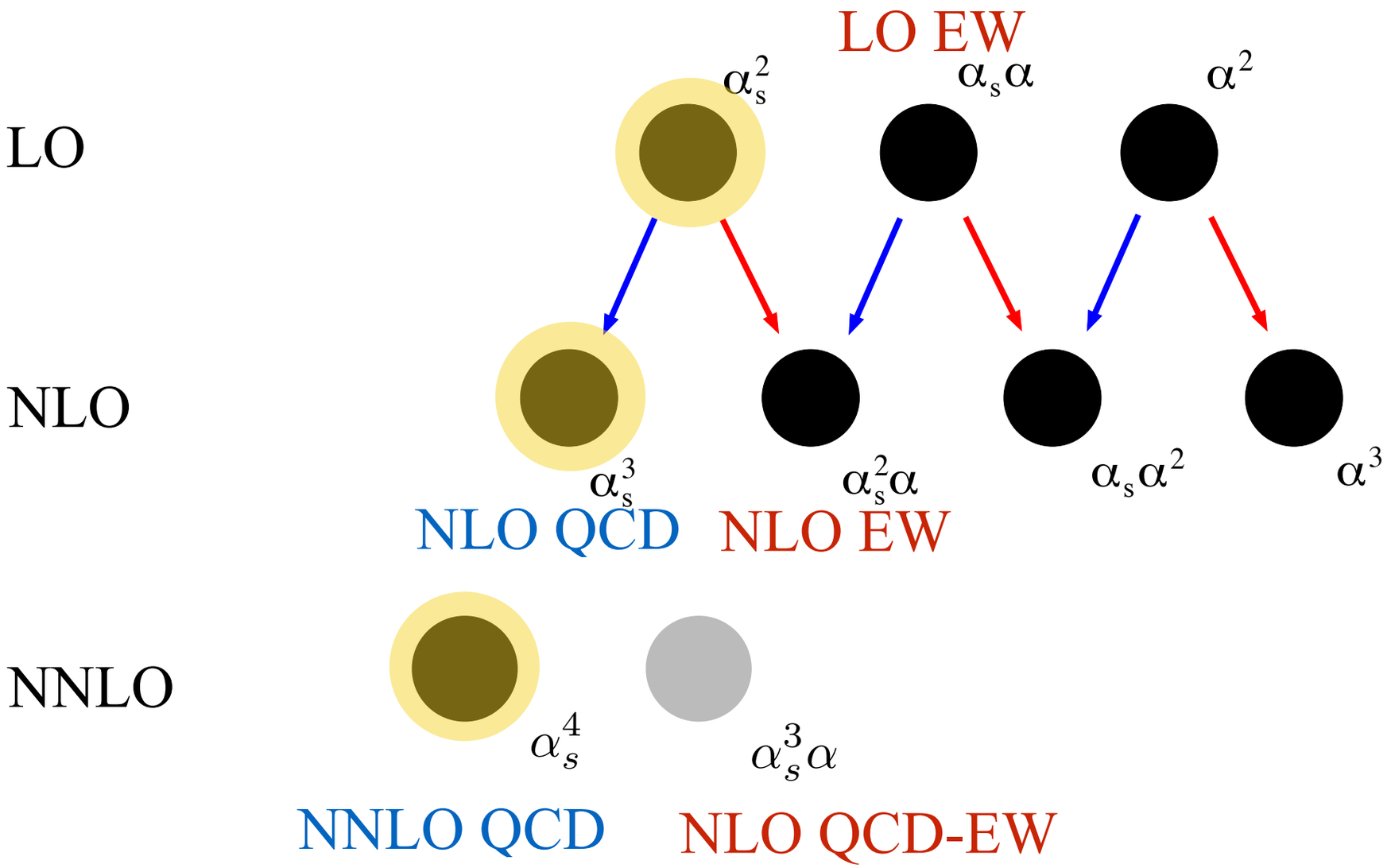
Multiplicative combination





$$\Sigma_{\mathrm{QCD}\times\mathrm{EW}} \equiv \Sigma_{\mathrm{QCD}} + K^{\mathrm{NLO}}_{\mathrm{QCD}}\,\Sigma_{\mathrm{NLO\ EW}} + \Sigma_{\mathrm{LO\ EW}} + \Sigma_{\mathrm{subleading}}$$

Multiplicative combination



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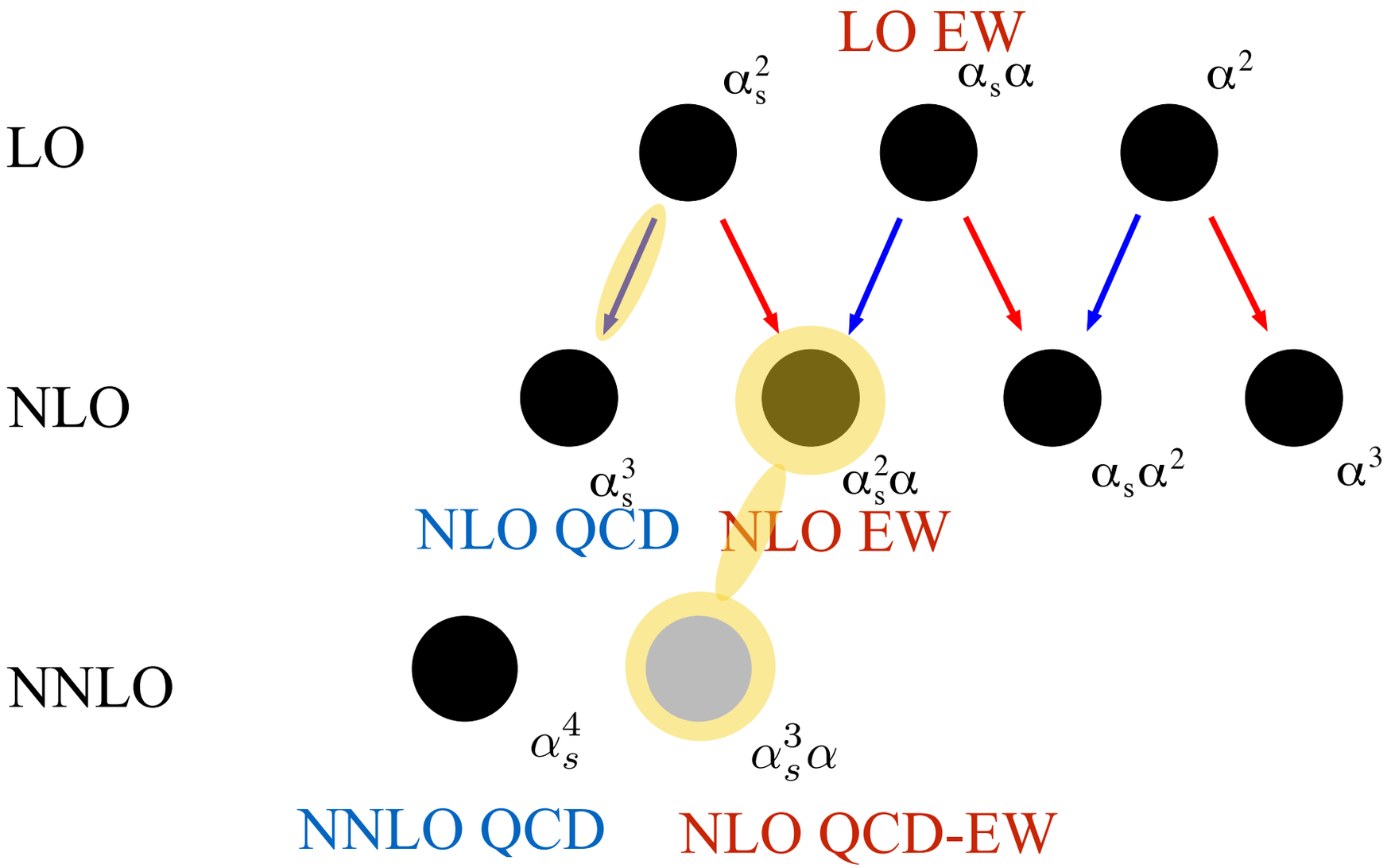

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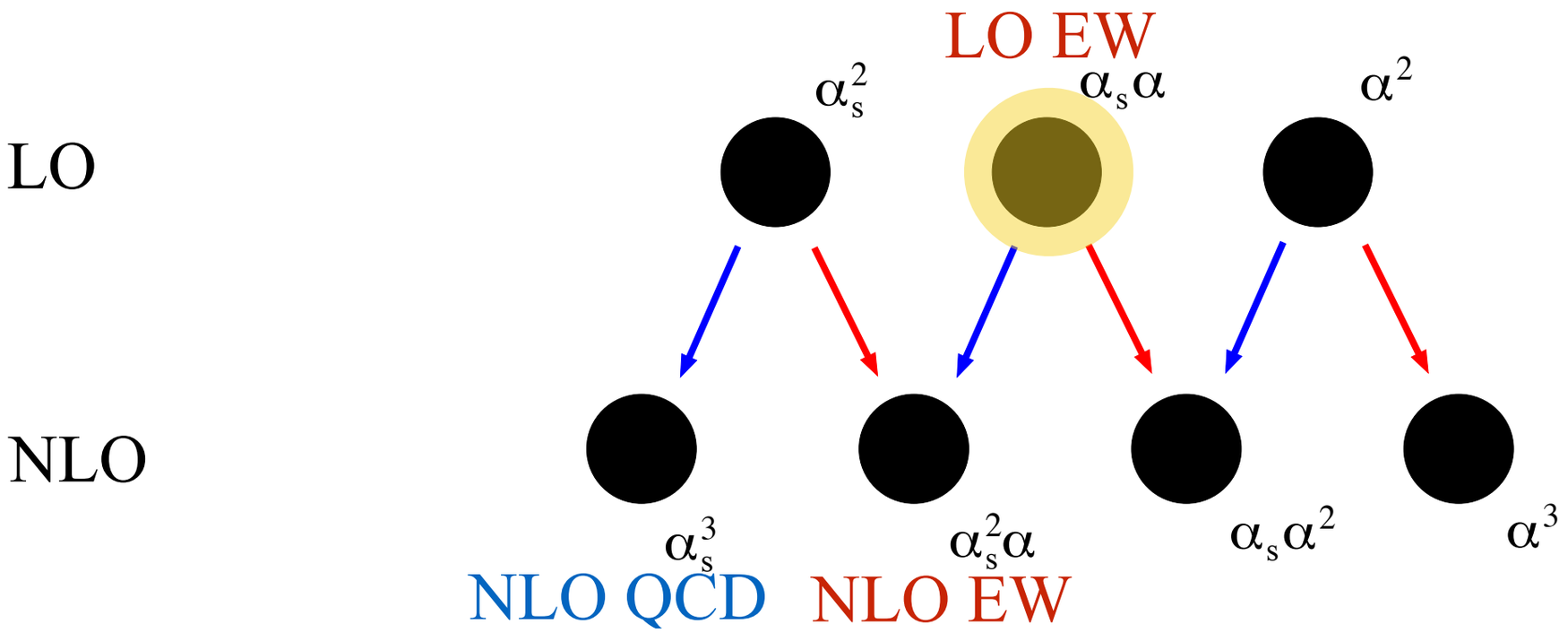

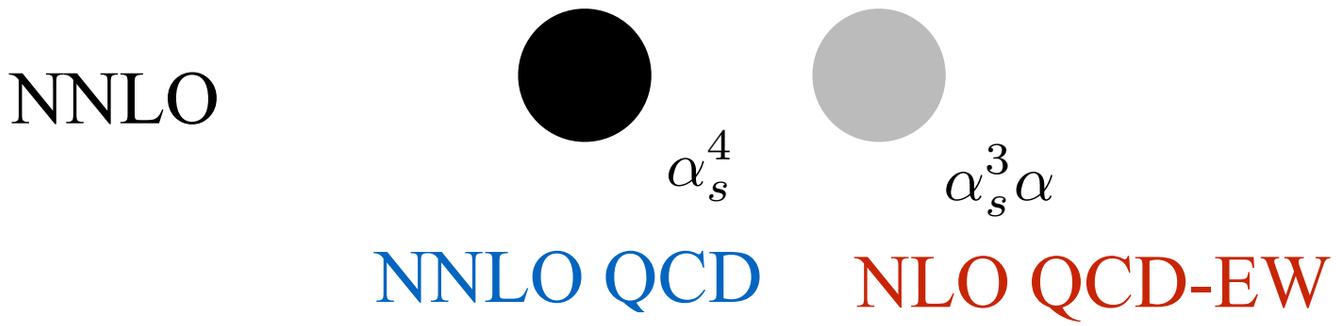

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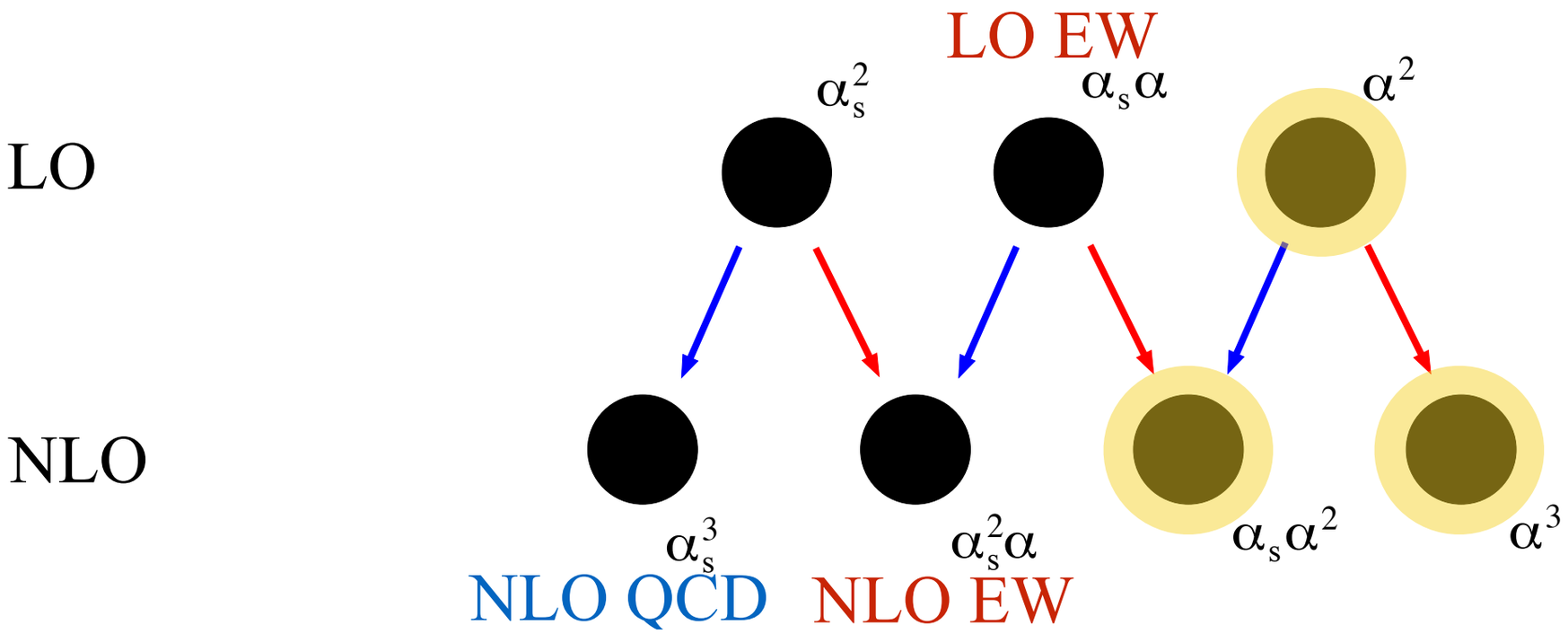

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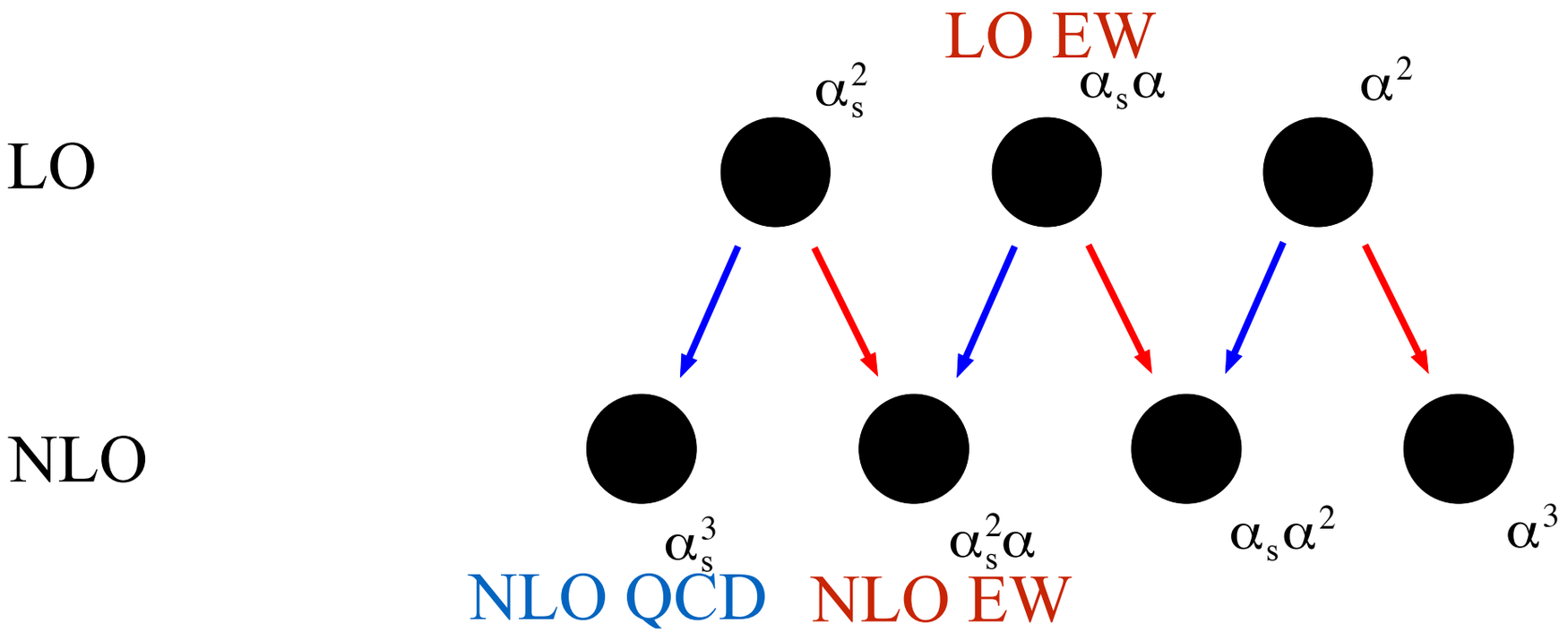

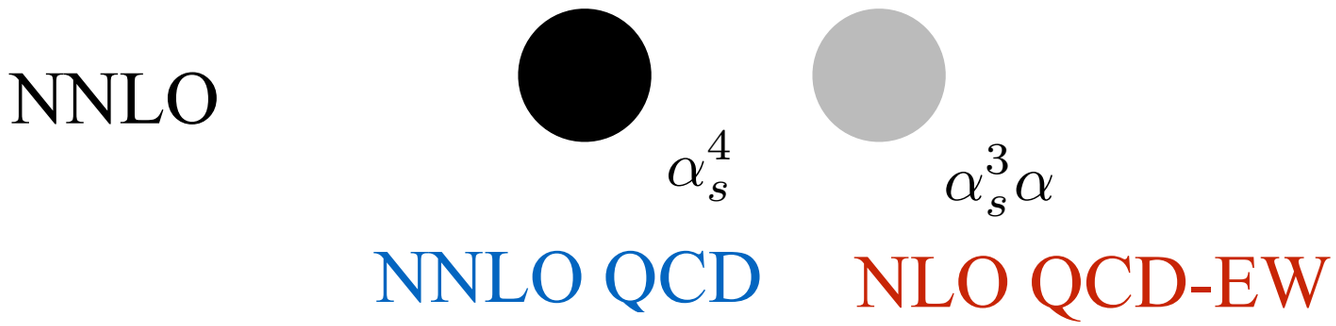

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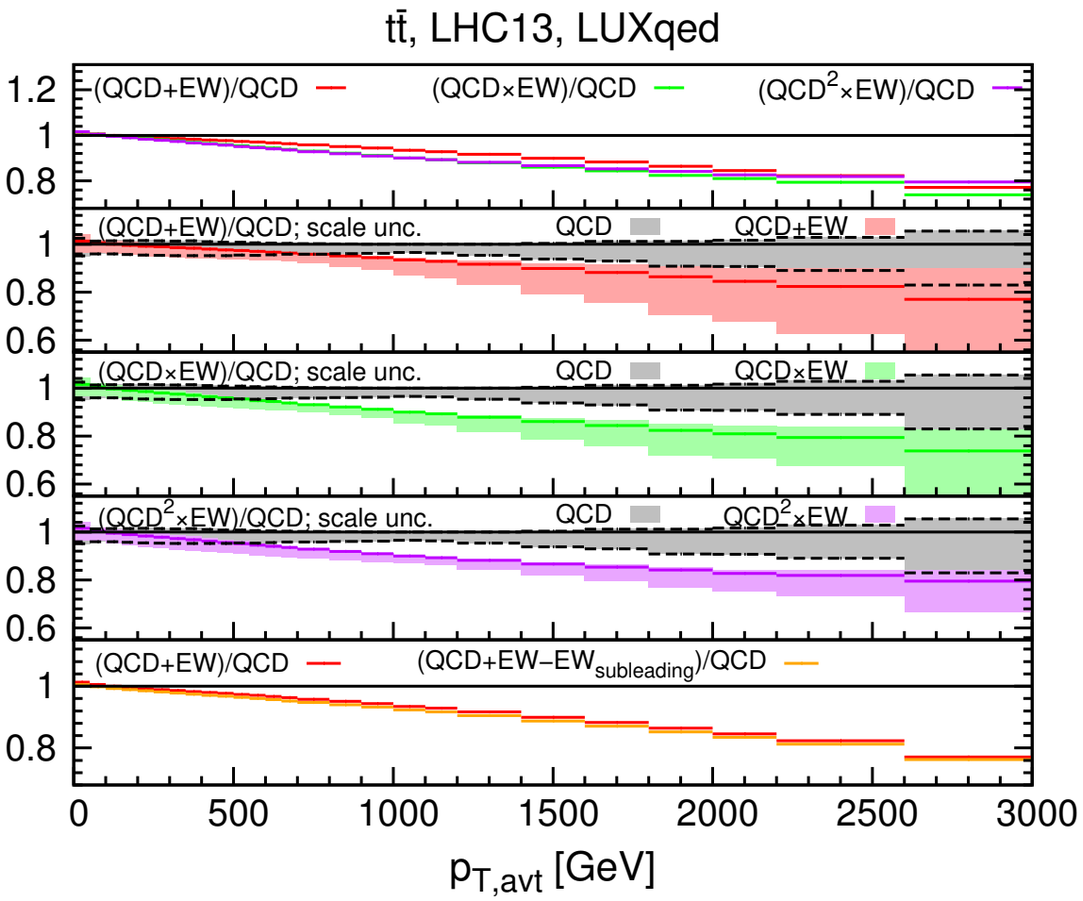
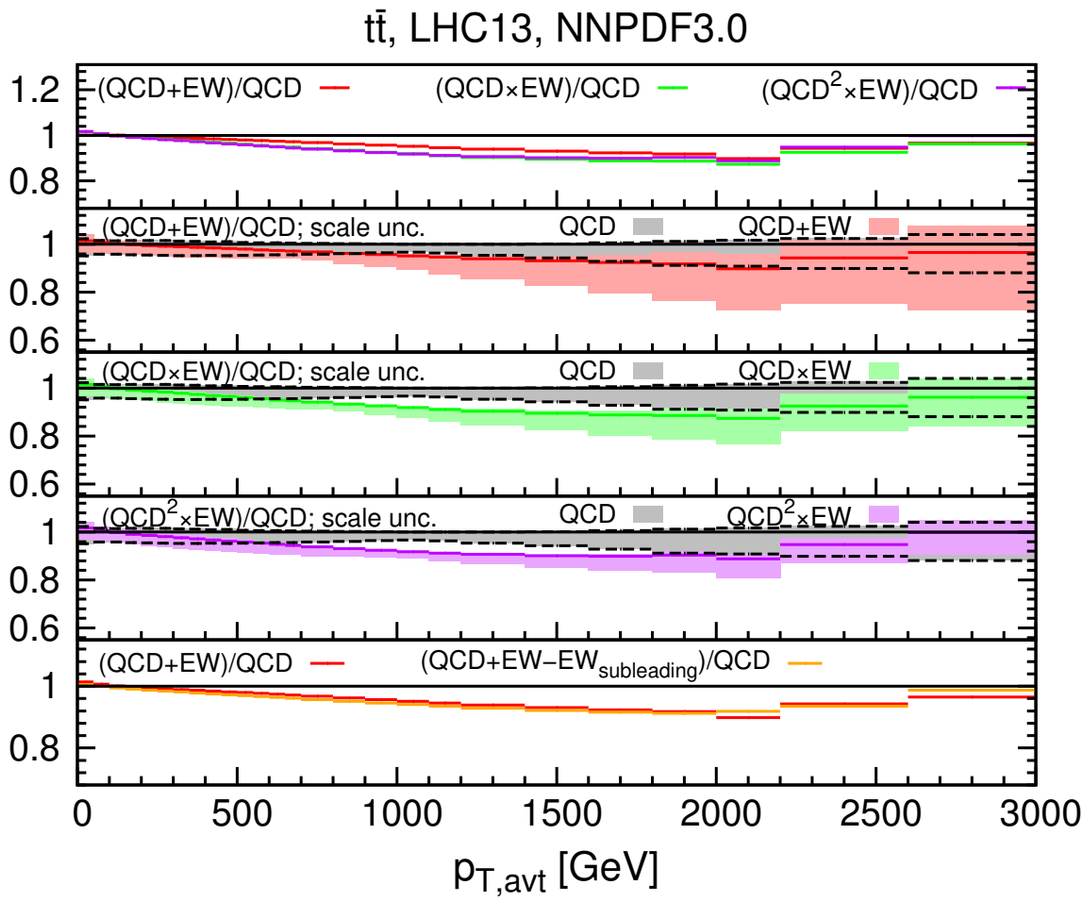
Results

$p_{T,\mathrm{avt}}$ 13 TeV

ADDITIVE (**EXACT**), MULTIPLICATIVE (**NLO**, **NNLO**)





LUXQED

NNPDF3.0QED

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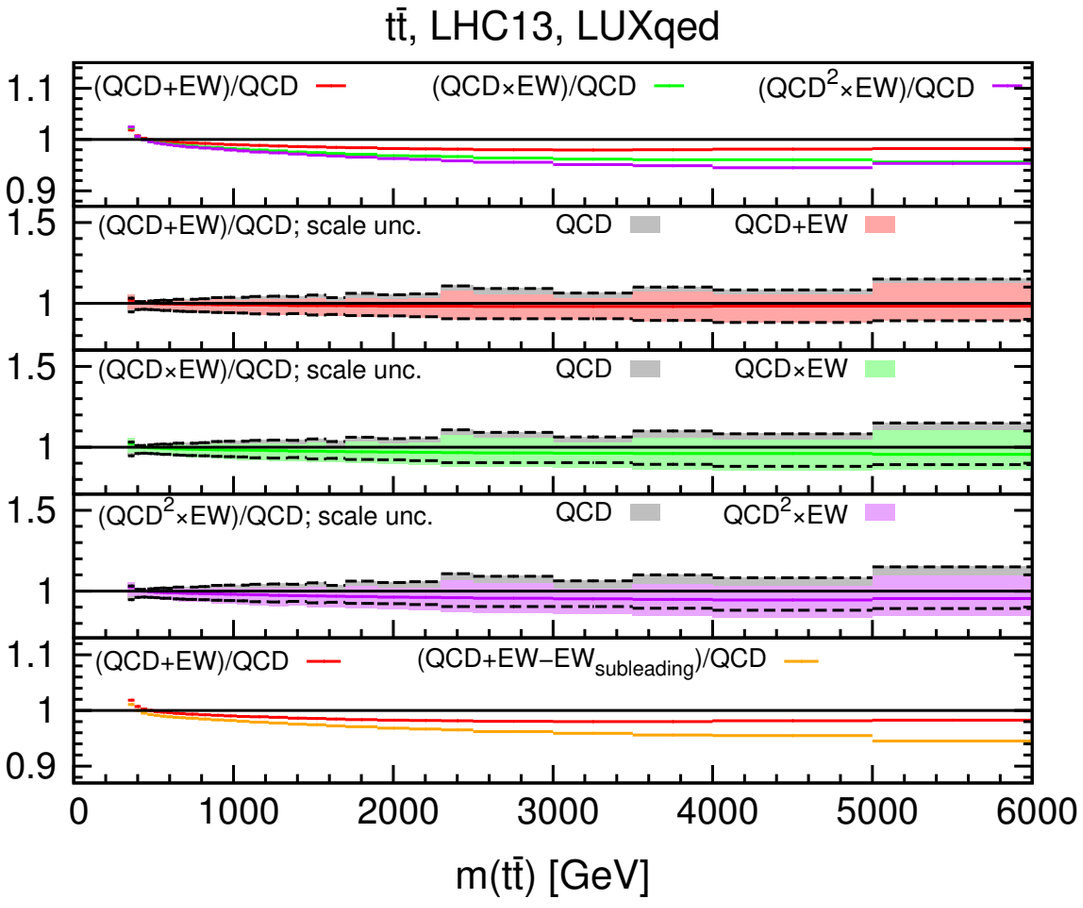

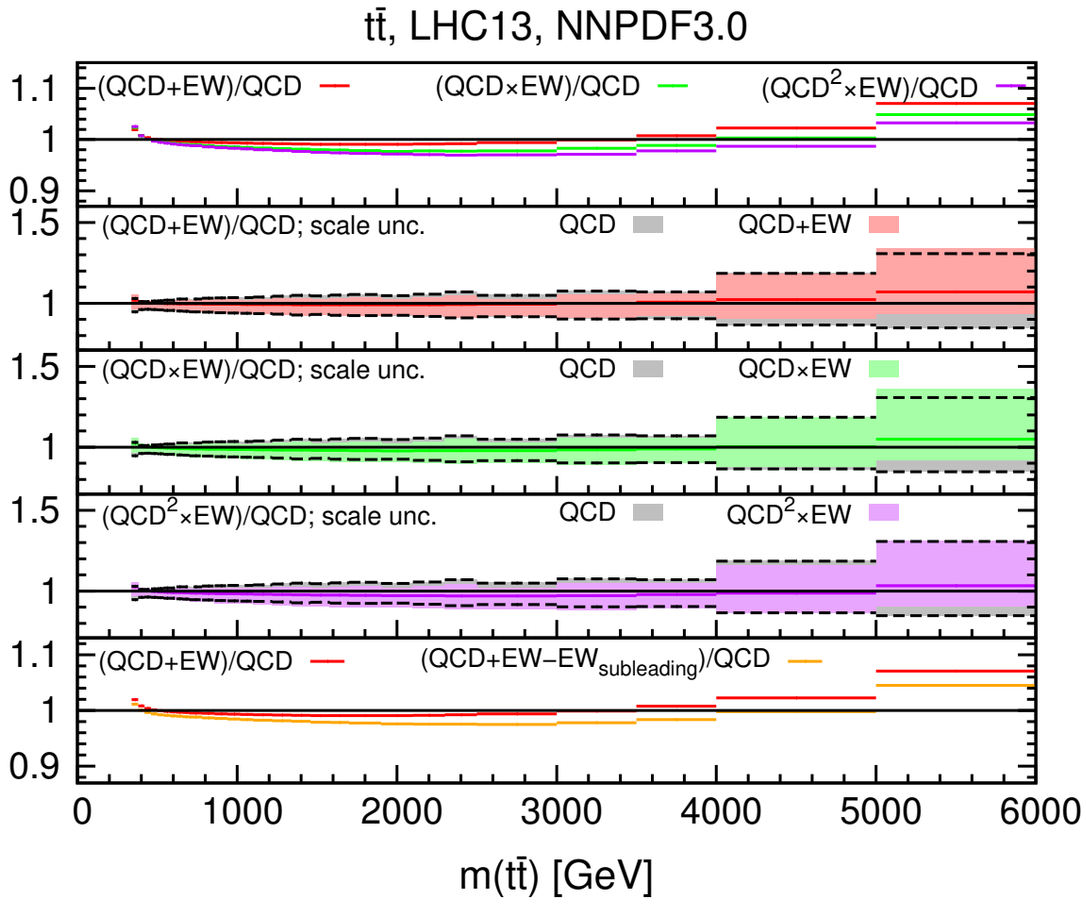

LUXQED

NNPDF3.0QED

$y(t\bar{t})$ 8 TeV

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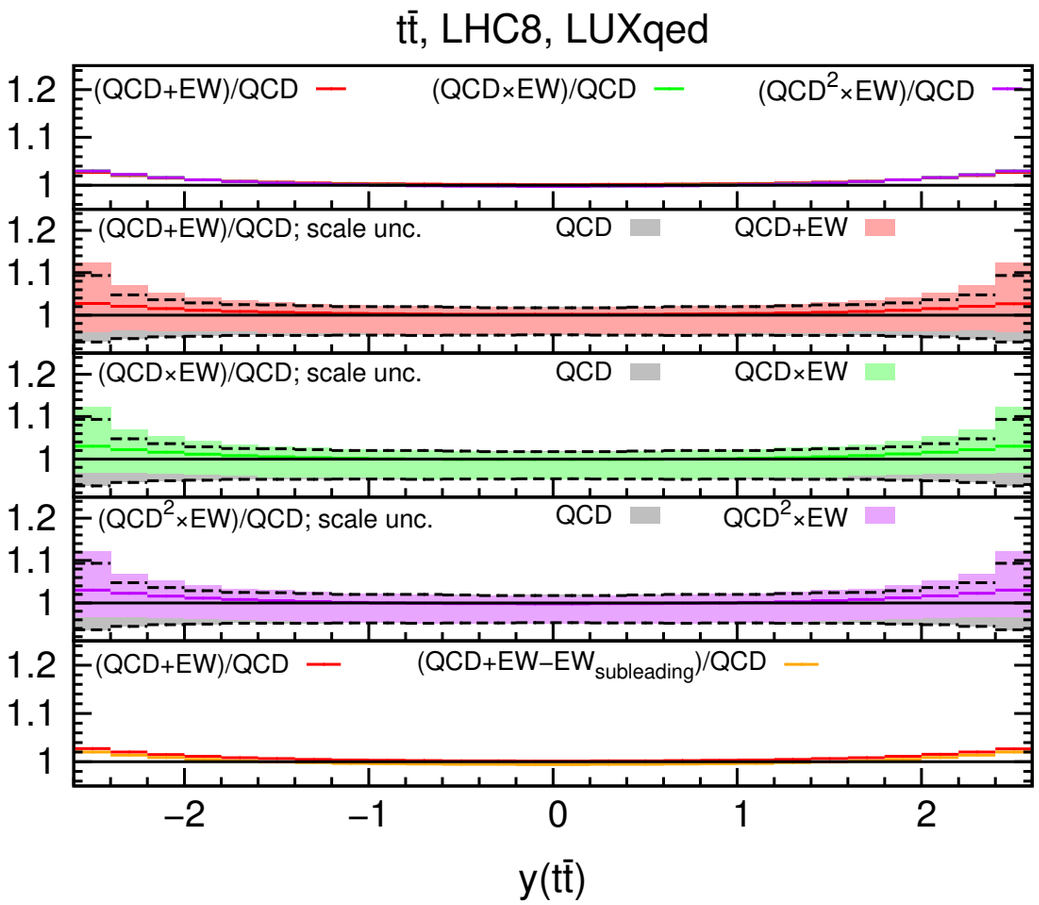
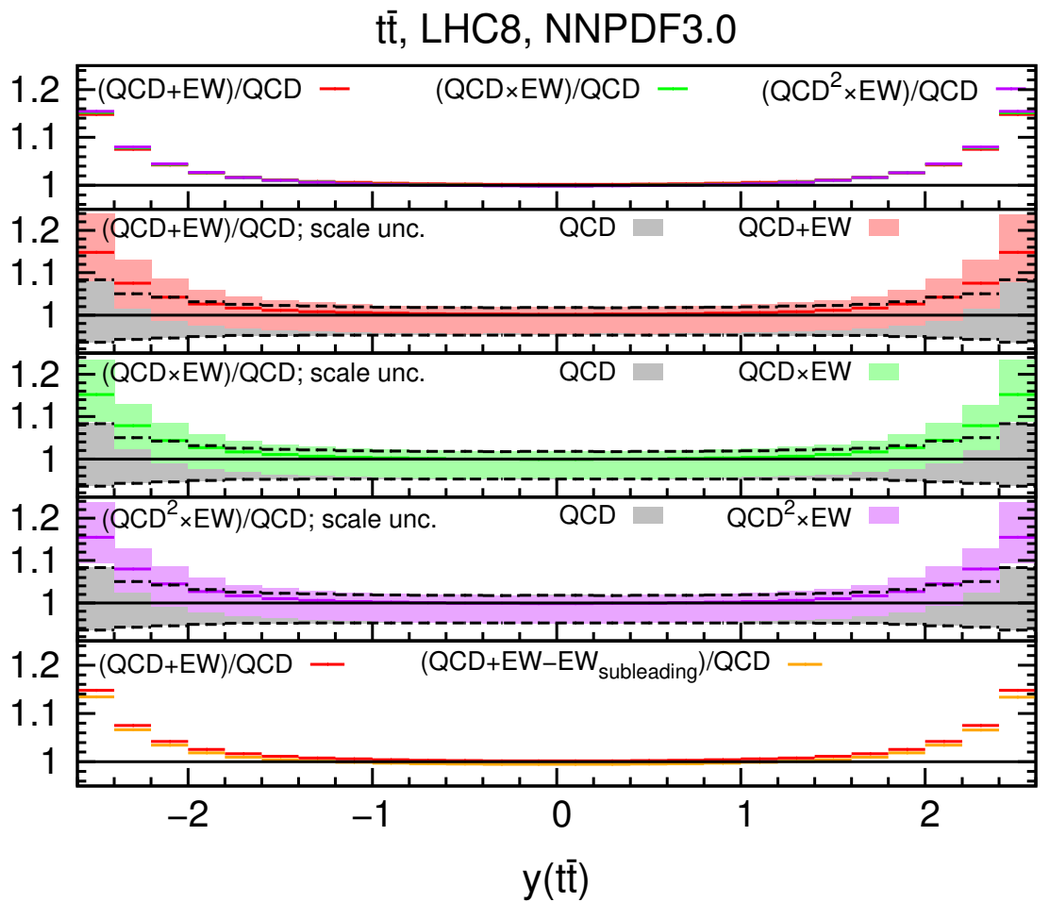




LUXQED

NNPDF3.0QED

Conclusion

We provided predictions at NNLO QCD + complete-NLO accuracy for ttbar production at the LHC (8, 13 TeV) with NNPDF3.0QED and LUXQED.

In pt distributions at 13 TeV EW corrections are outside the NNLO QCD scale-uncertainty band (for LUXQED, which has a small photon PDF). Including EW corrections, the total scale uncertainty is larger than with QCD only.

At 8 TeV, top and top-pair large rapidities are sensitive to the photon PDF á la NNPDF.

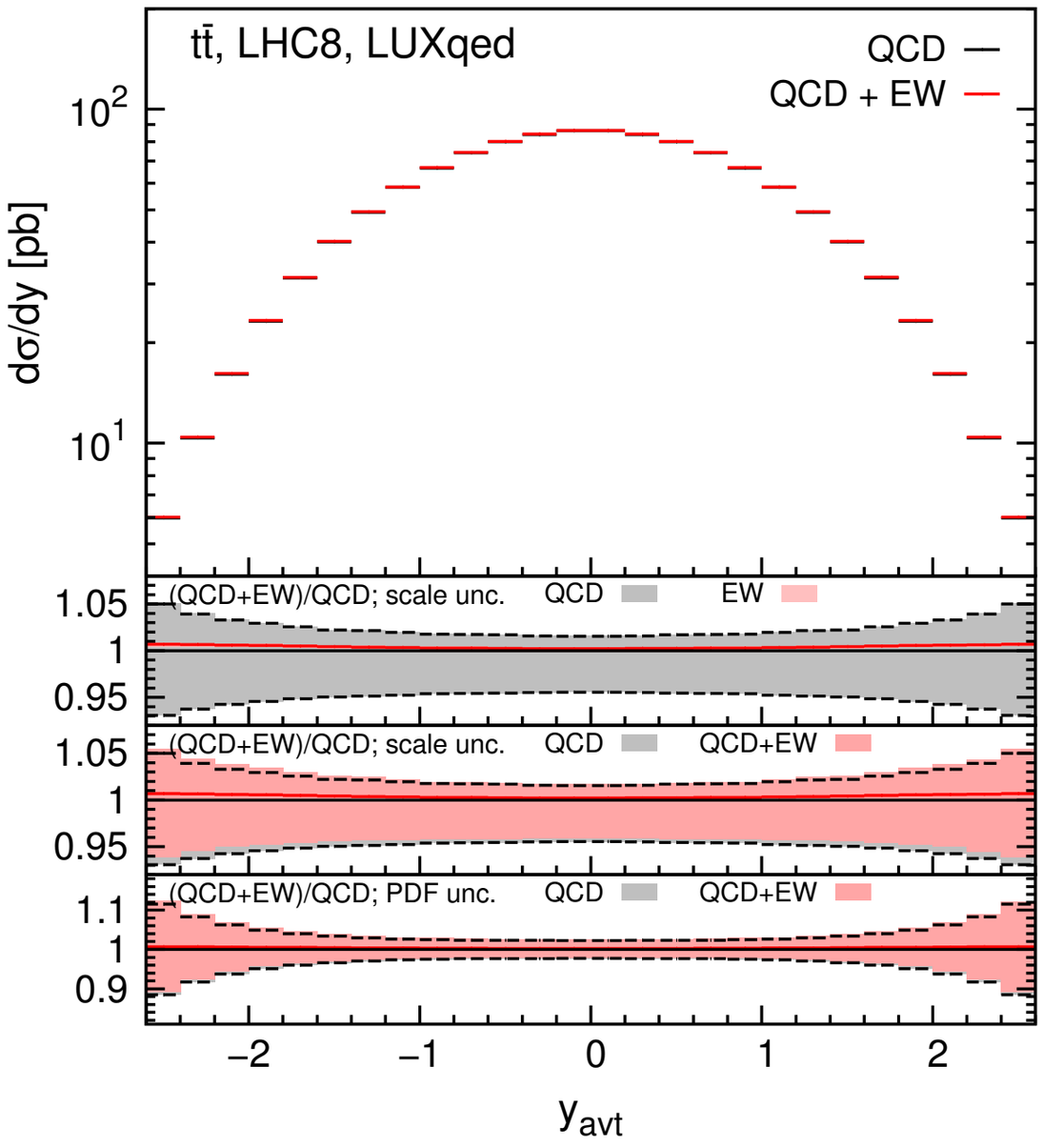
The combination in the multiplicative approach leads to a reduction of scale uncertainties.

We are producing results also for asymmetries at the LHC with this accuracy.

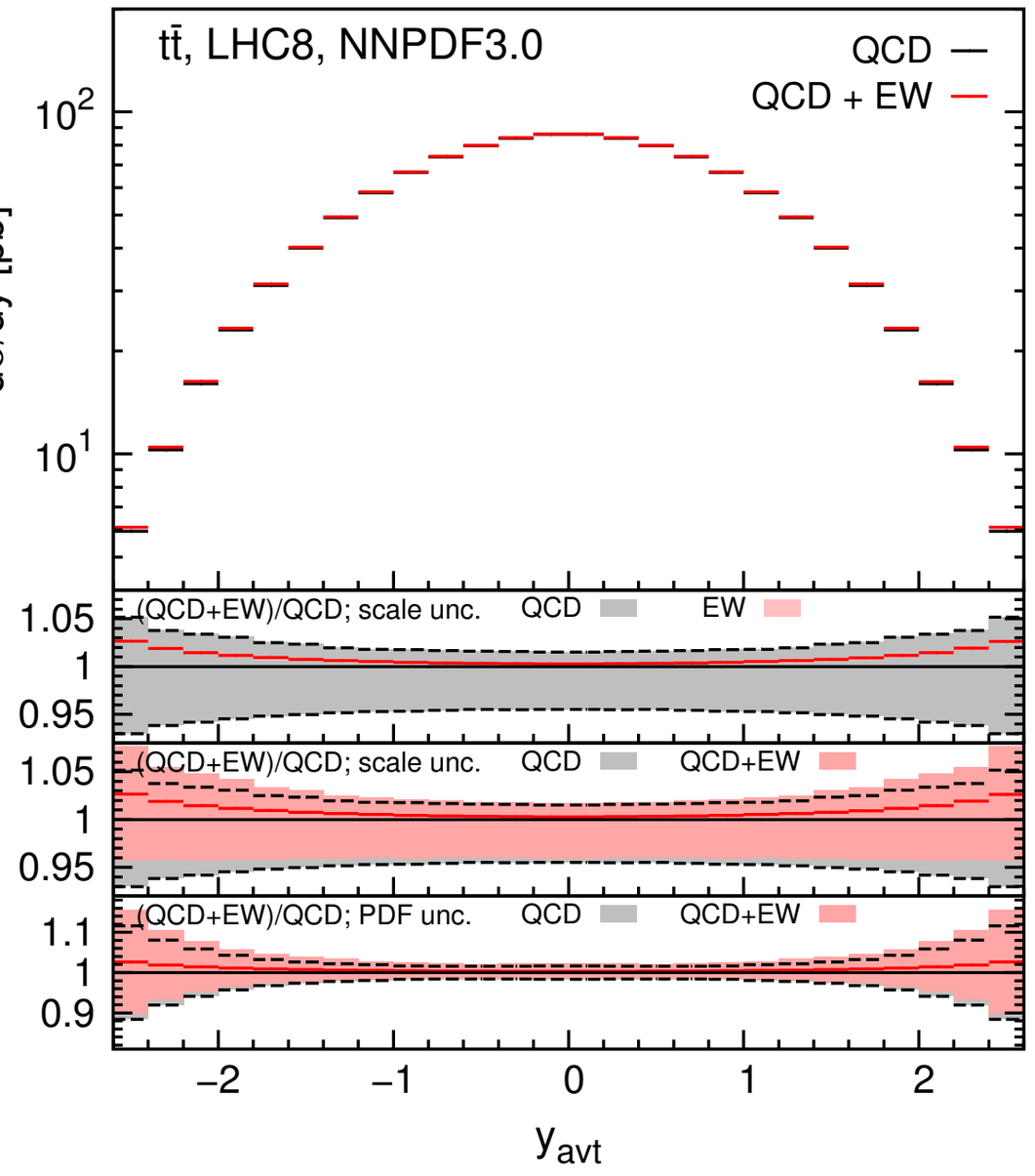
EXTRA SLIDES

8 TeV

y_{avt}



LUXQED



NNPDF3.0QED

y_{avt}

8 TeV

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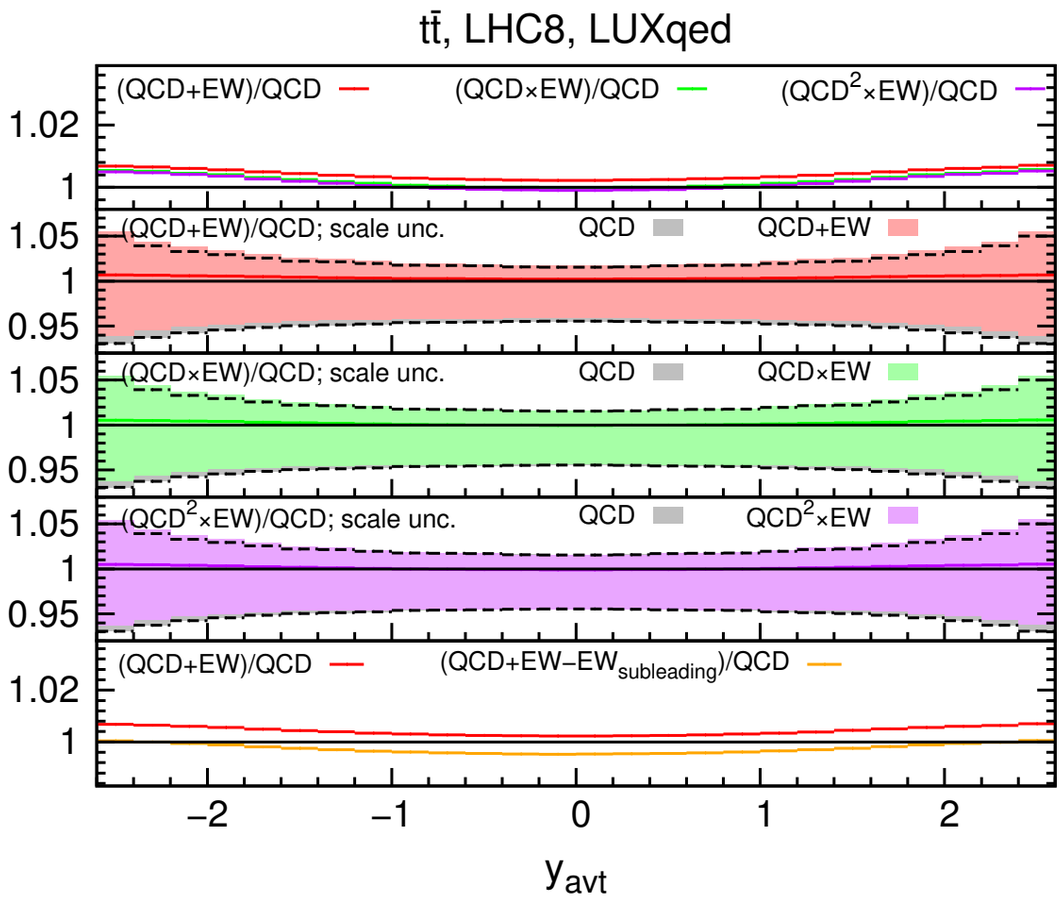
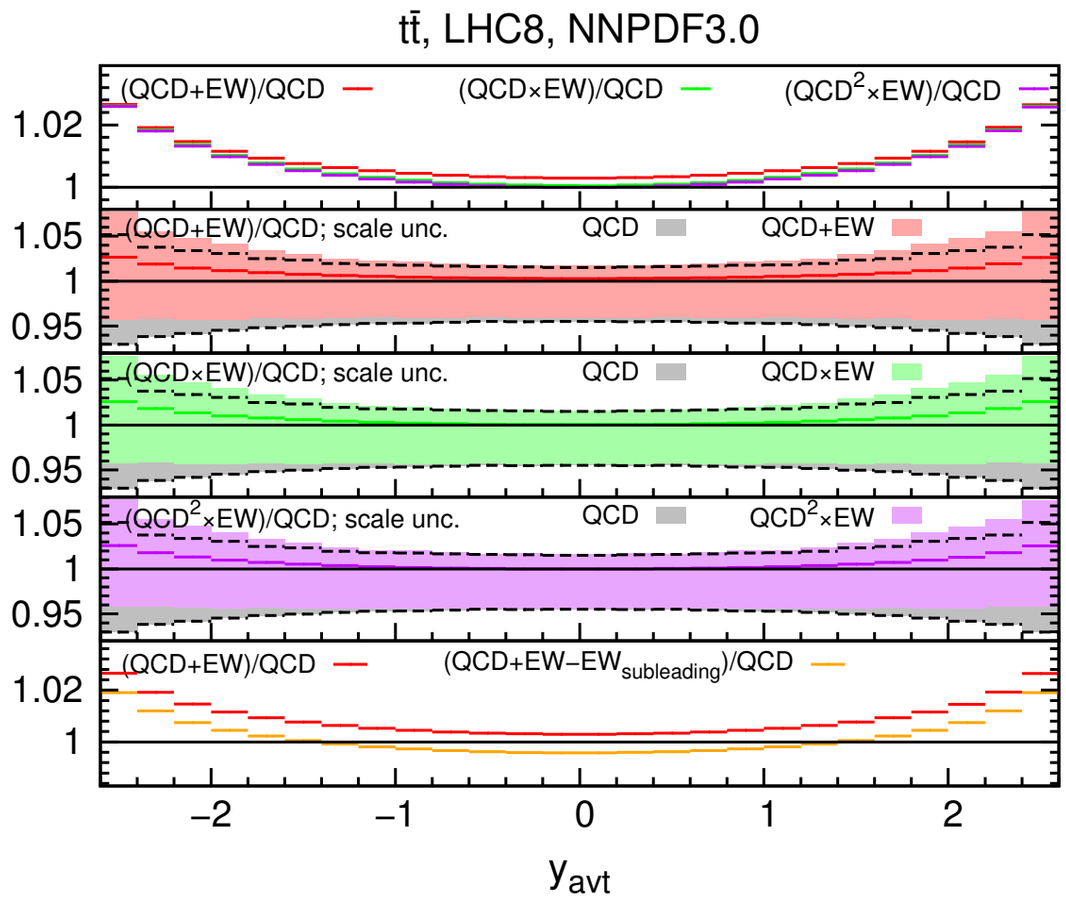
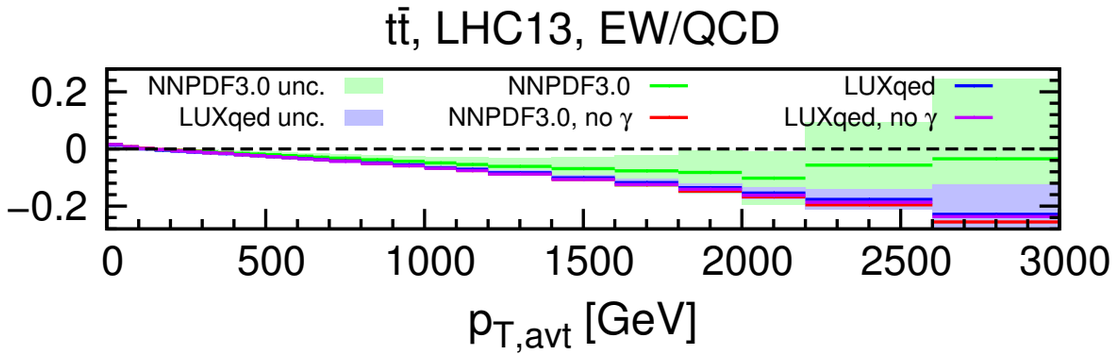


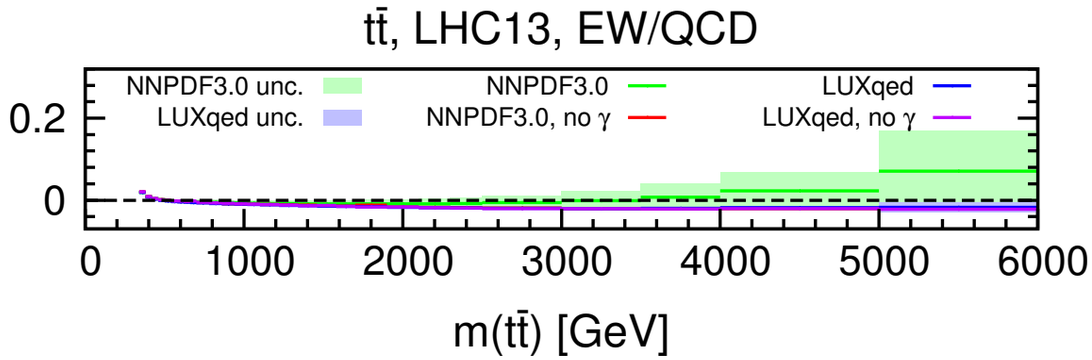


LUXQED

NNPDF3.0QED

13 TeV


tt̄, LHC13, EW/QCD
NNPDF3.0 unc.
LUXqed unc.
NNPDF3.0
NNPDF3.0, no γ
LUXqed
LUXqed, no γ
0.2
0
−0.2
0
500
1000
1500
2000
2500
3000
p_T,avt [GeV]


tt̄, LHC13, EW/QCD
NNPDF3.0 unc.
LUXqed unc.
NNPDF3.0
NNPDF3.0, no γ
LUXqed
LUXqed, no γ
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0
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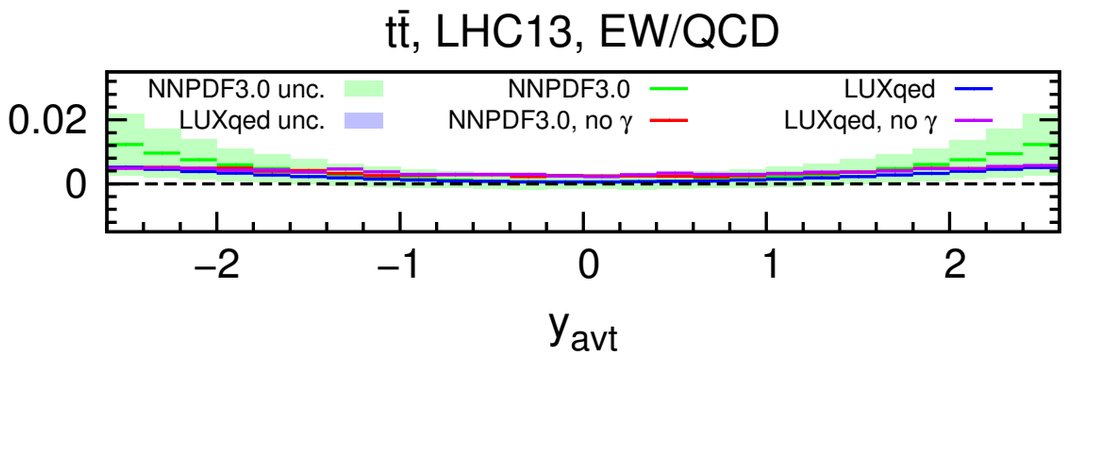
1000
2000
3000
4000
5000
6000
m(tt̄) [GeV]


tt̄, LHC13, EW/QCD
NNPDF3.0 unc.
LUXqed unc.
NNPDF3.0
NNPDF3.0, no γ
LUXqed
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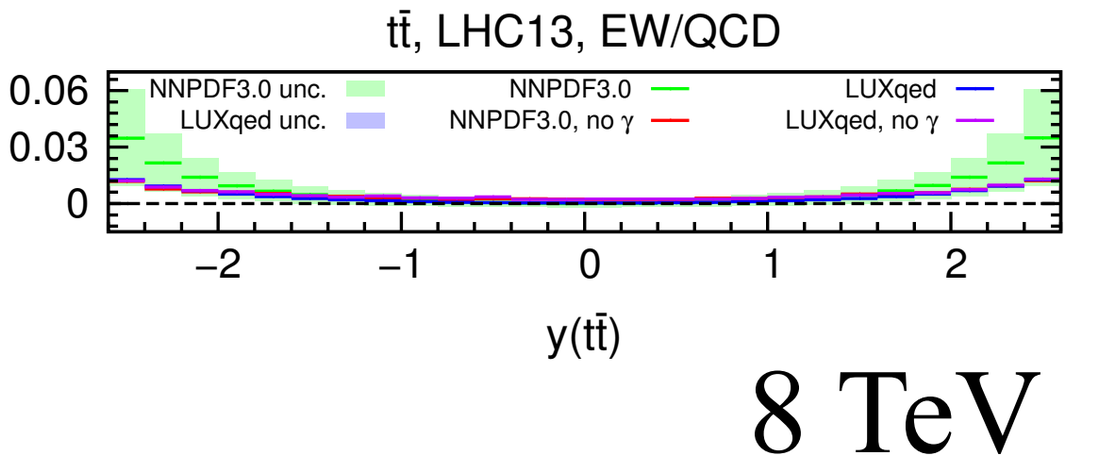
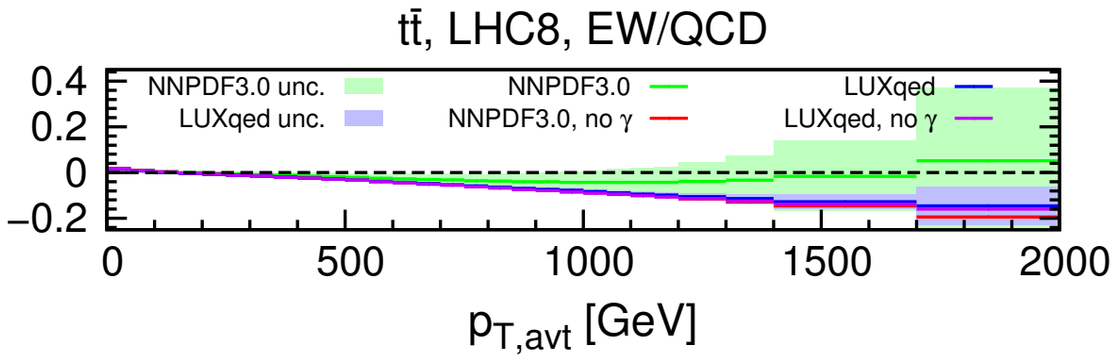
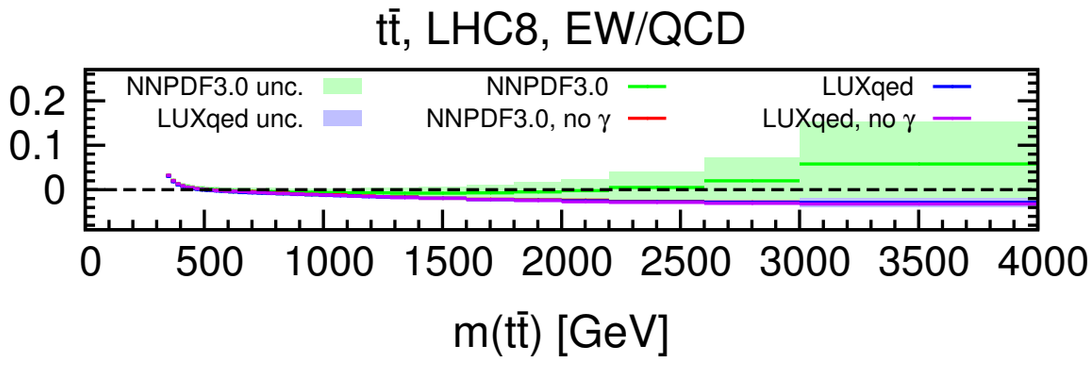
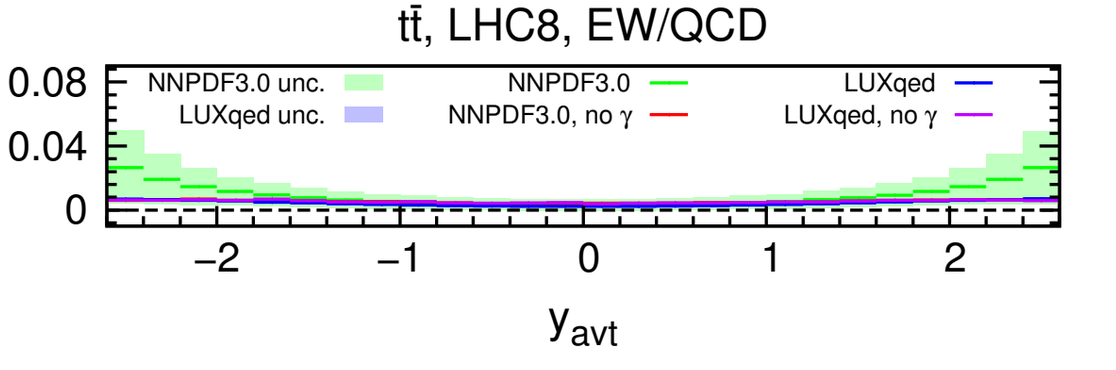
y_avt

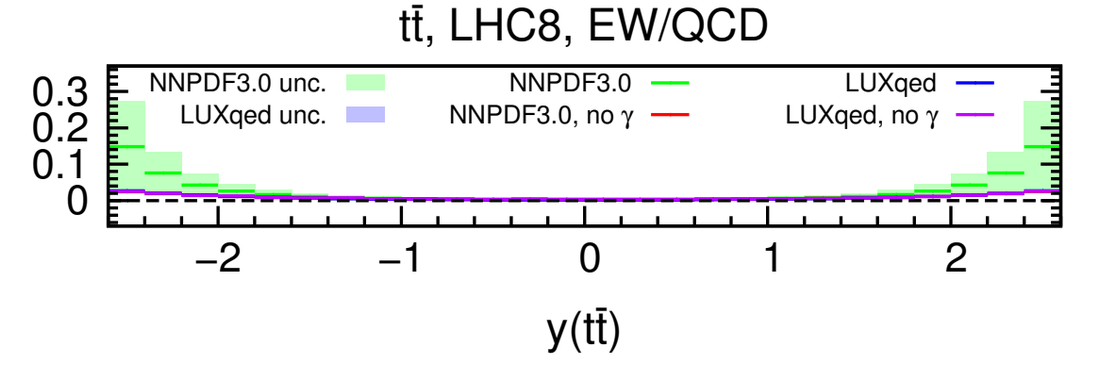

tt̄, LHC13, EW/QCD
NNPDF3.0 unc.
LUXqed unc.
NNPDF3.0
NNPDF3.0, no γ
LUXqed
LUXqed, no γ
0.06
0.03
0
−2
−1
0
1
2
y(tt̄)

8 TeV


tt̄, LHC8, EW/QCD
NNPDF3.0 unc.
LUXqed unc.
NNPDF3.0
NNPDF3.0, no γ
LUXqed
LUXqed, no γ
0.4
0.2
0
−0.2
0
500
1000
1500
2000
p_T,avt [GeV]

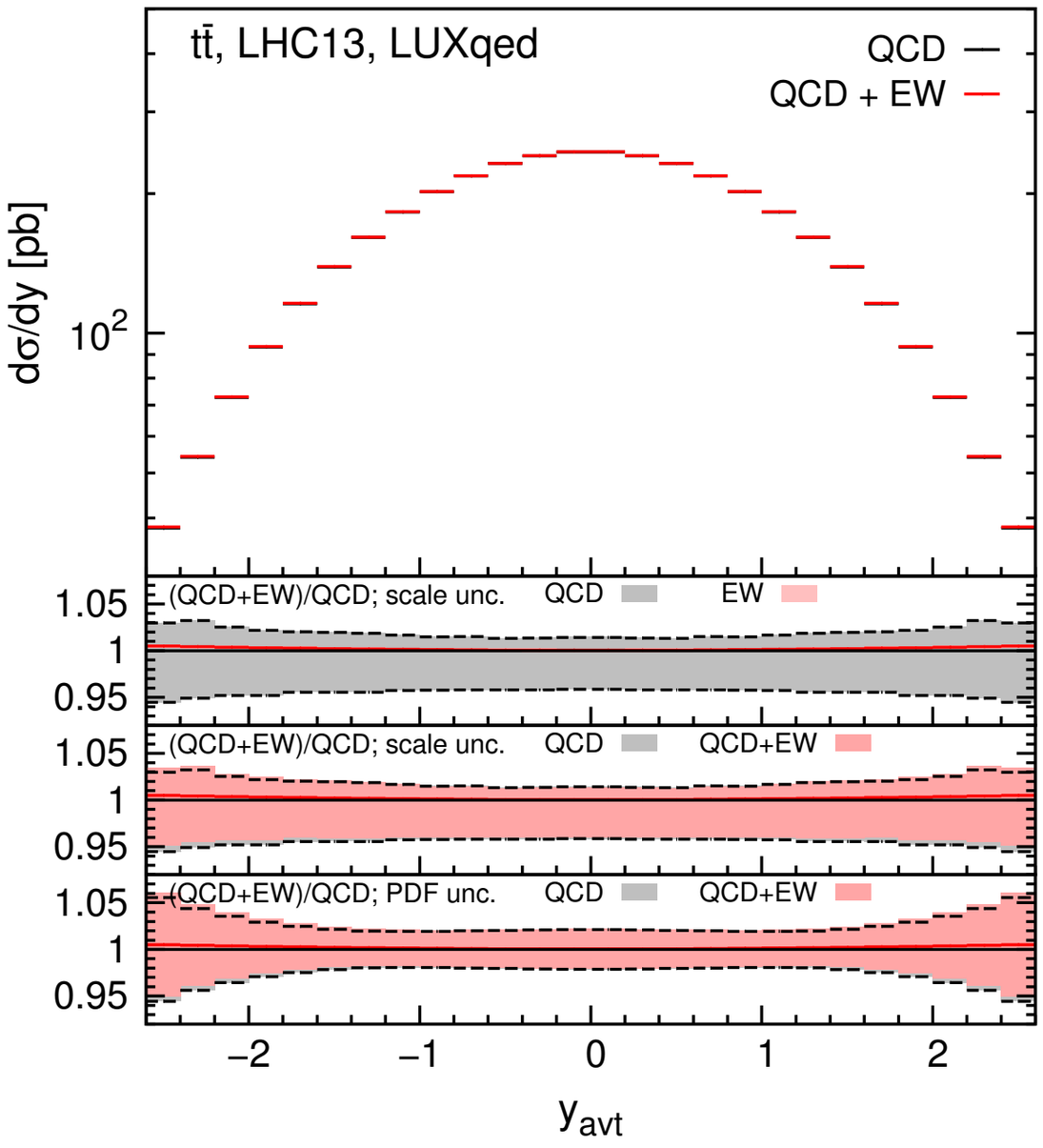

tt̄, LHC8, EW/QCD
NNPDF3.0 unc.
LUXqed unc.
NNPDF3.0
NNPDF3.0, no γ
LUXqed
LUXqed, no γ
0.2
0.1
0
0
500
1000
1500
2000
2500
3000
3500
4000
m(tt̄) [GeV]


tt̄, LHC8, EW/QCD
NNPDF3.0 unc.
LUXqed unc.
NNPDF3.0
NNPDF3.0, no γ
LUXqed
LUXqed, no γ
0.08
0.04
0
−2
−1
0
1
2
y_avt

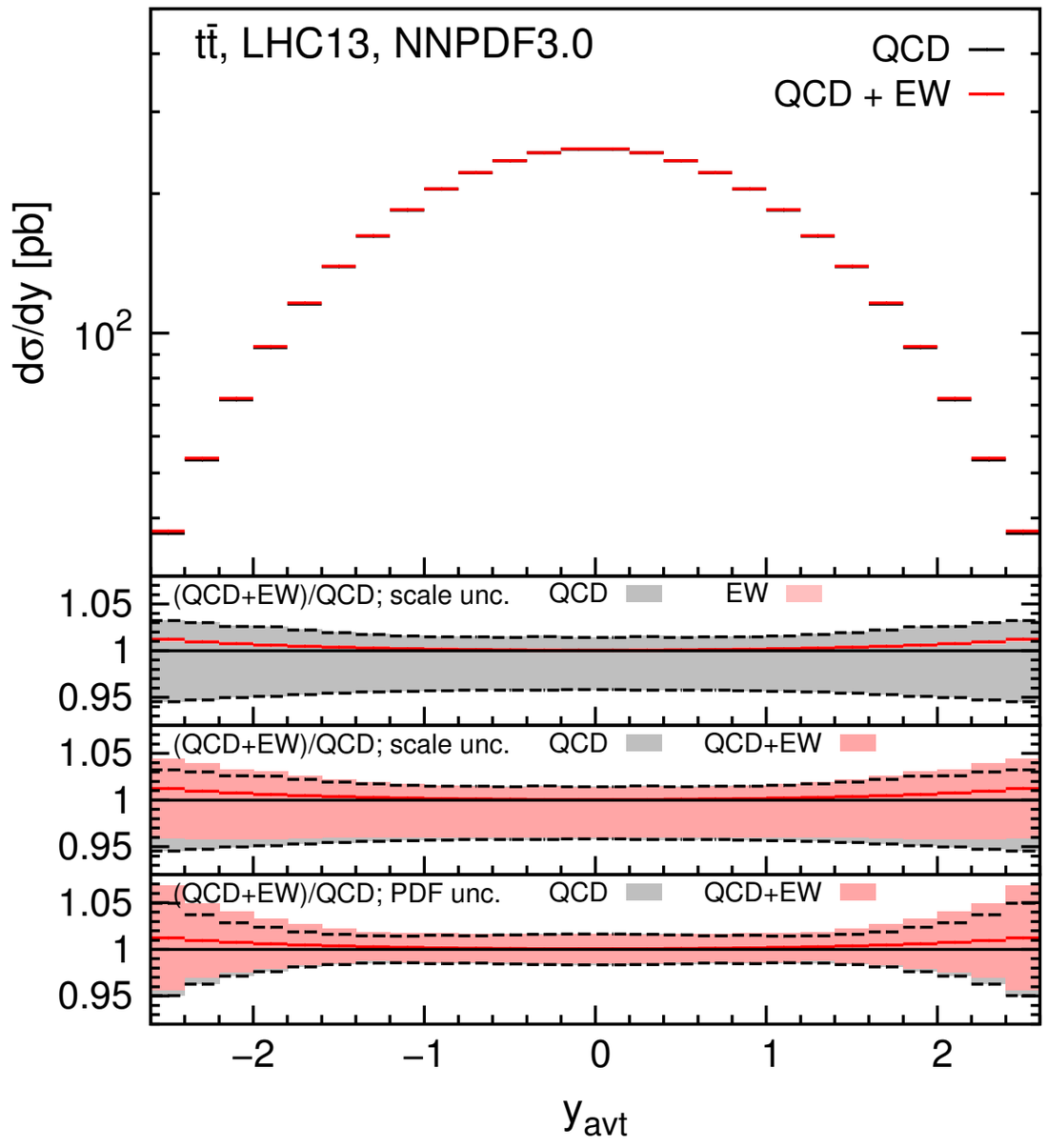

tt̄, LHC8, EW/QCD
NNPDF3.0 unc.
LUXqed unc.
NNPDF3.0
NNPDF3.0, no γ
LUXqed
LUXqed, no γ
0.3
0.2
0.1
0
−2
−1
0
1
2
y(tt̄)

13 TeV

y_{avt}



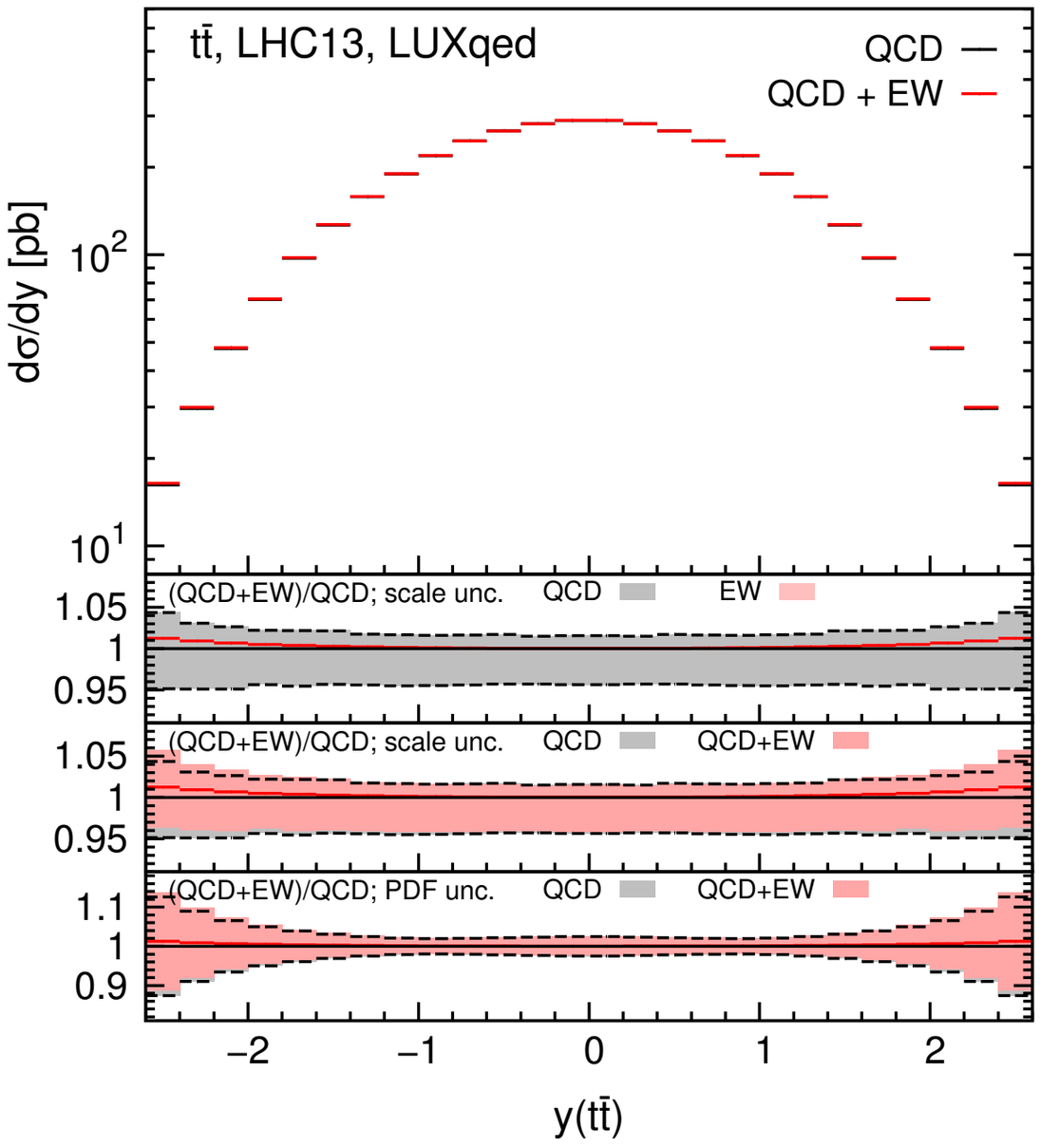
LUXQED



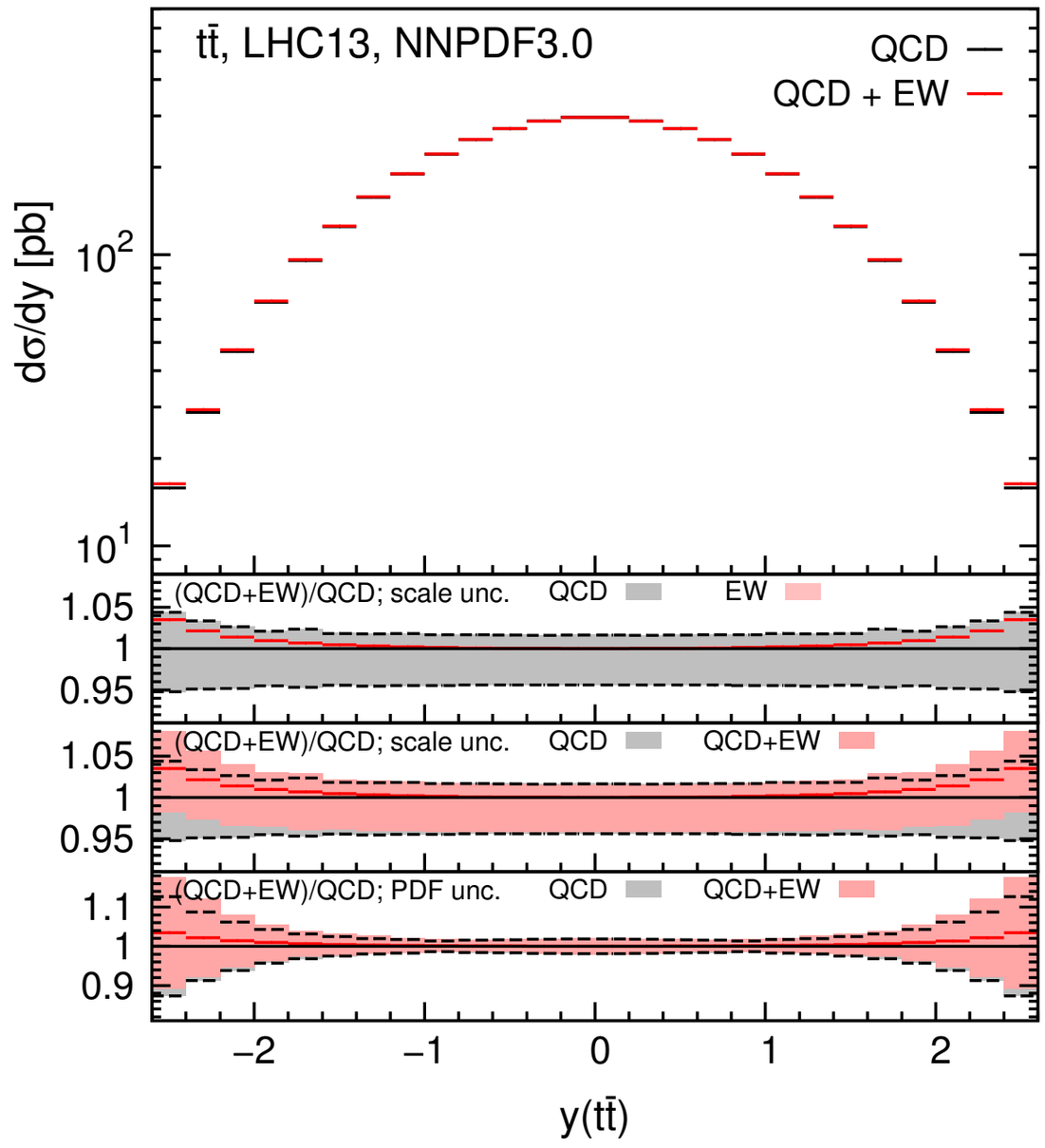
NNPDF3.0QED

$y(t\bar{t})$

13 TeV



LUXQED



NNPDF3.0QED

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*

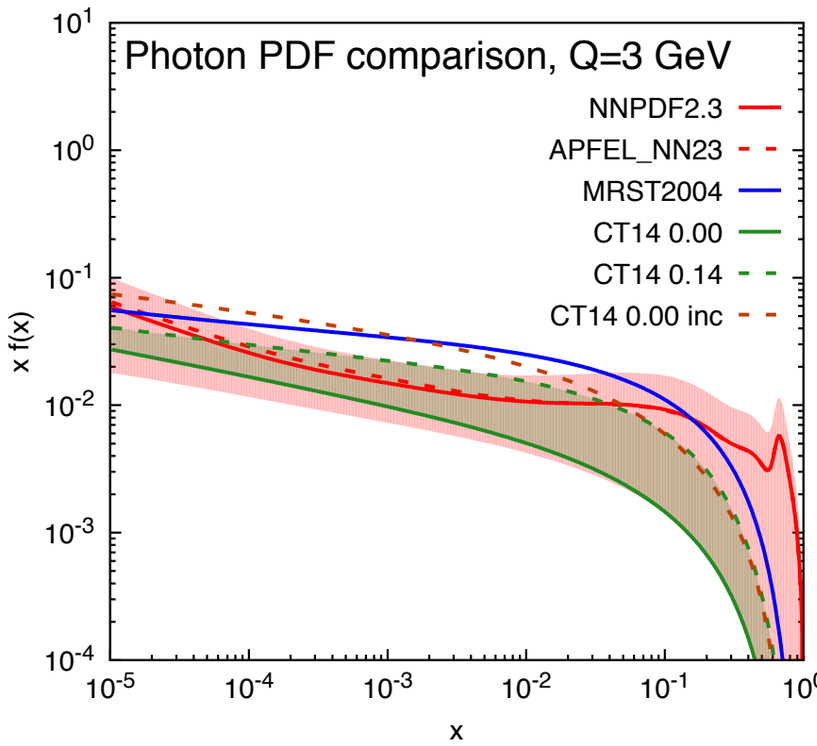
These PDF sets have at least NLO QCD + LO QED terms in the DGLAP evolution.

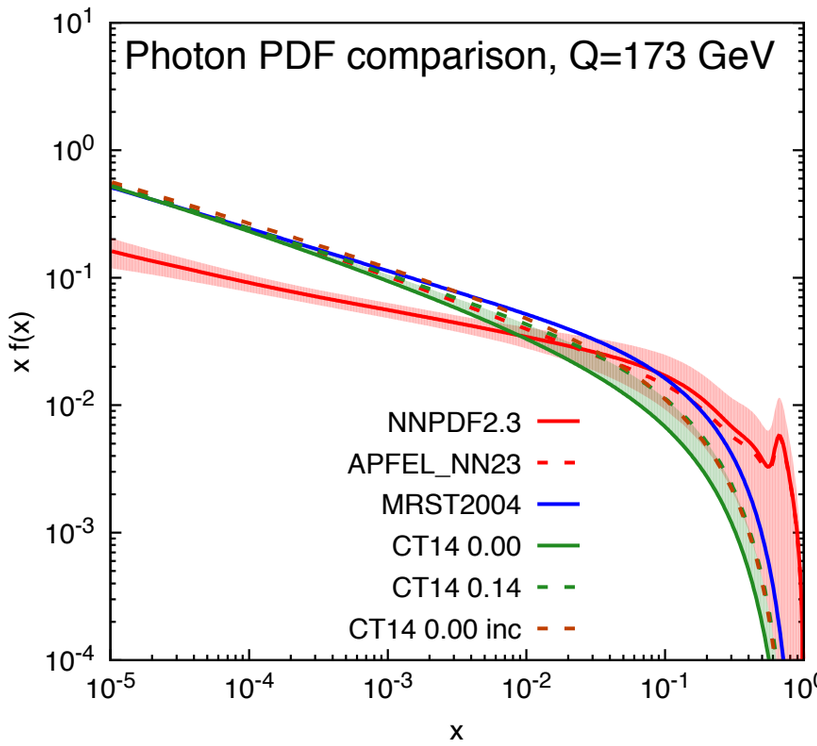
- The photon PDF determination is very different in the various sets.

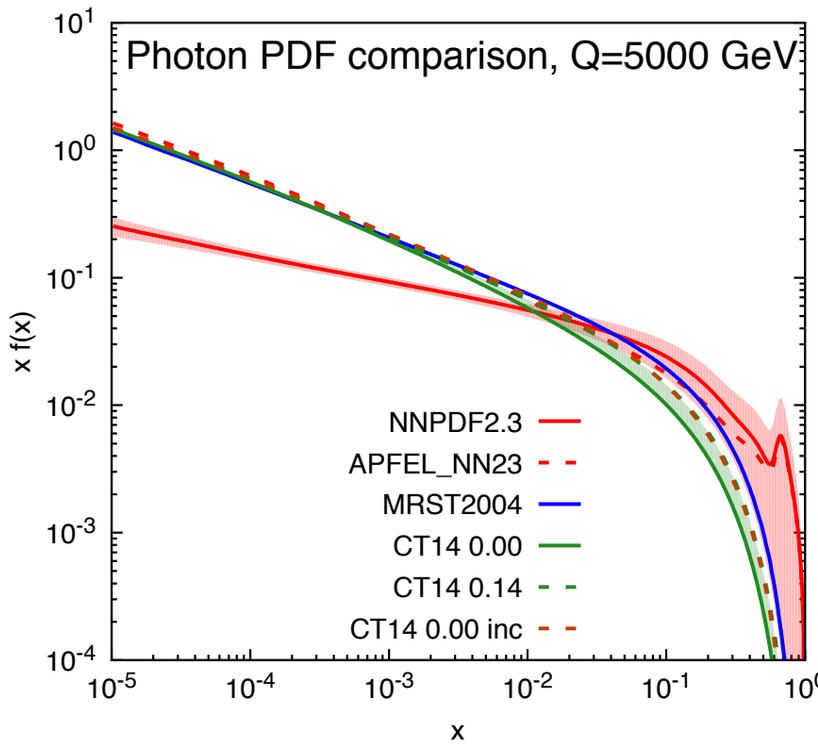
- The different treatment of the QED and QCD DGLAP evolution has a huge impact at small x and large Q (**NNPDF2.3QED**), but does **not** lead to visible effects in ttbar phenomenology.

- 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 …





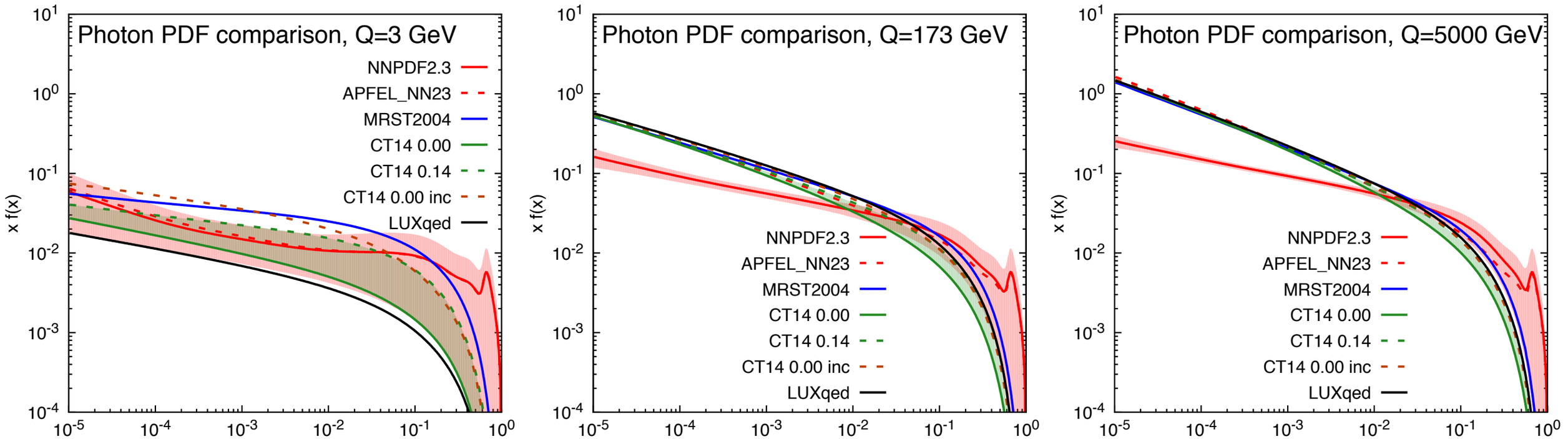


- **APFEL_NN23** (*Bertone, Carrazza, DP, Zaro '15*) is at the initial scale equivalent to **NNPDF2.3QED** for all the PDFs. But, the DGLAP QCD and QED running is consistent (similar to **NNPDF3.0QED**, where also quark and gluons have been updated to **NNPDF3.0**).

- 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**

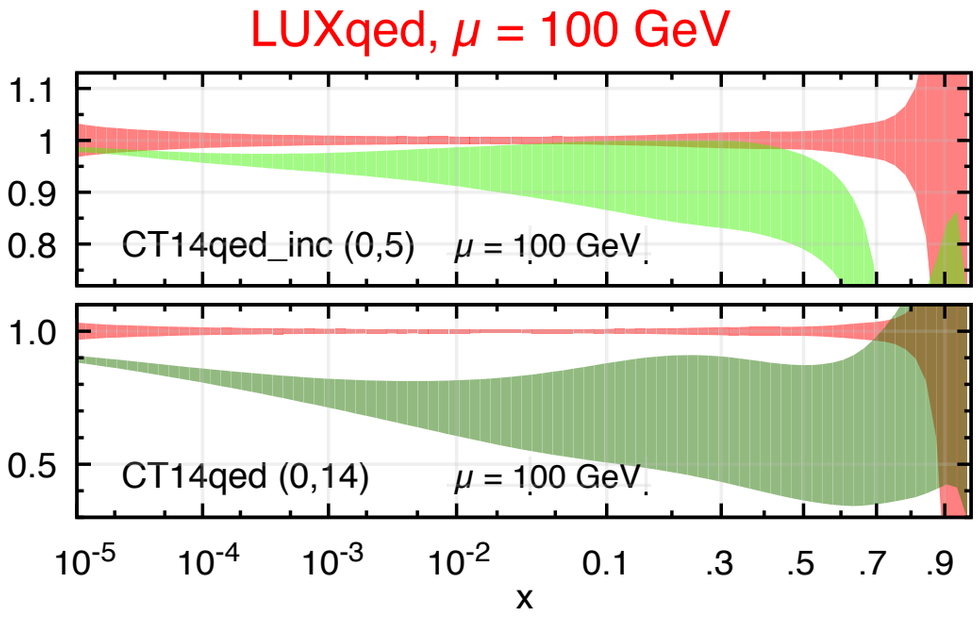
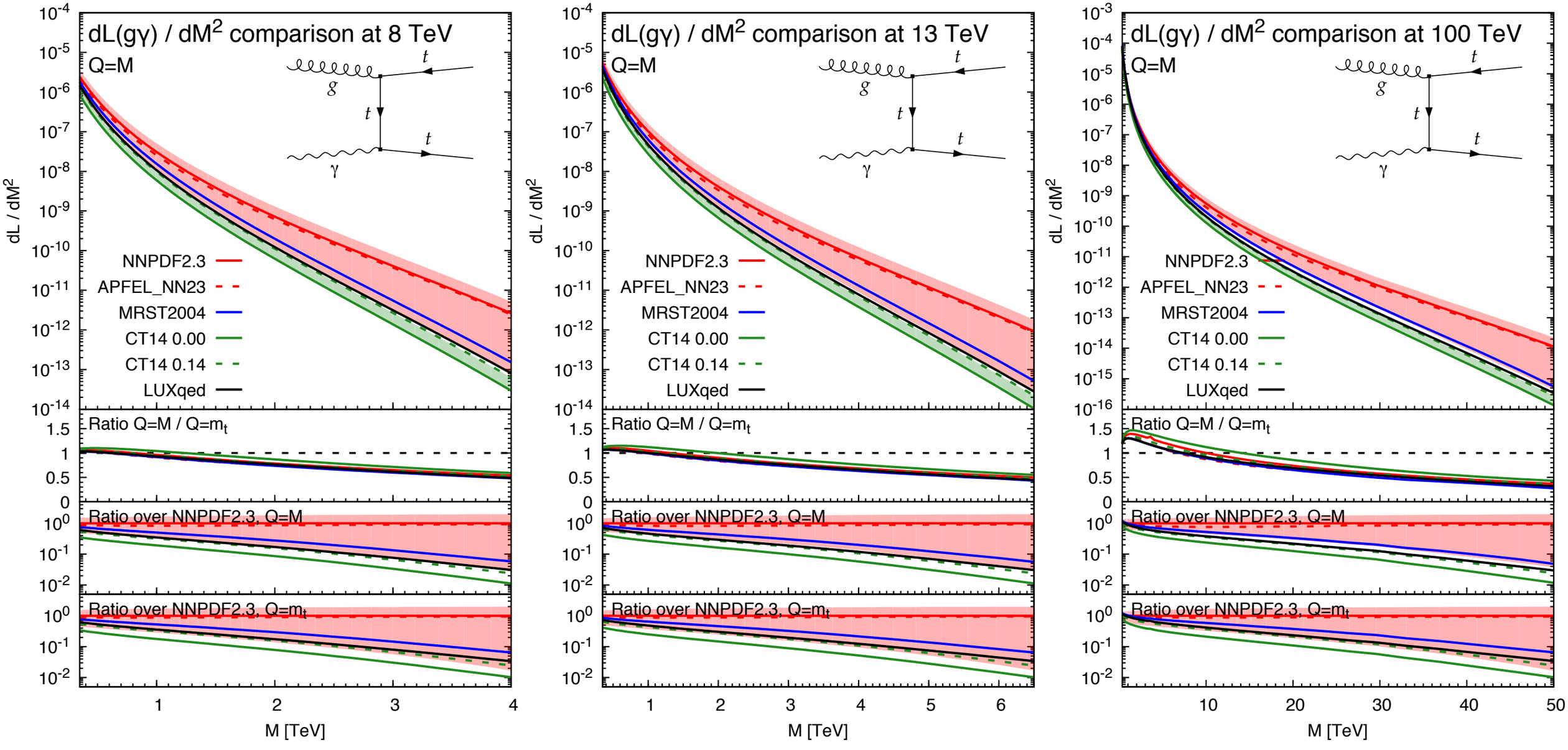


Image taken from Manohar, Nason, Salam, Zanderighi ’16 and adapted for this slide.

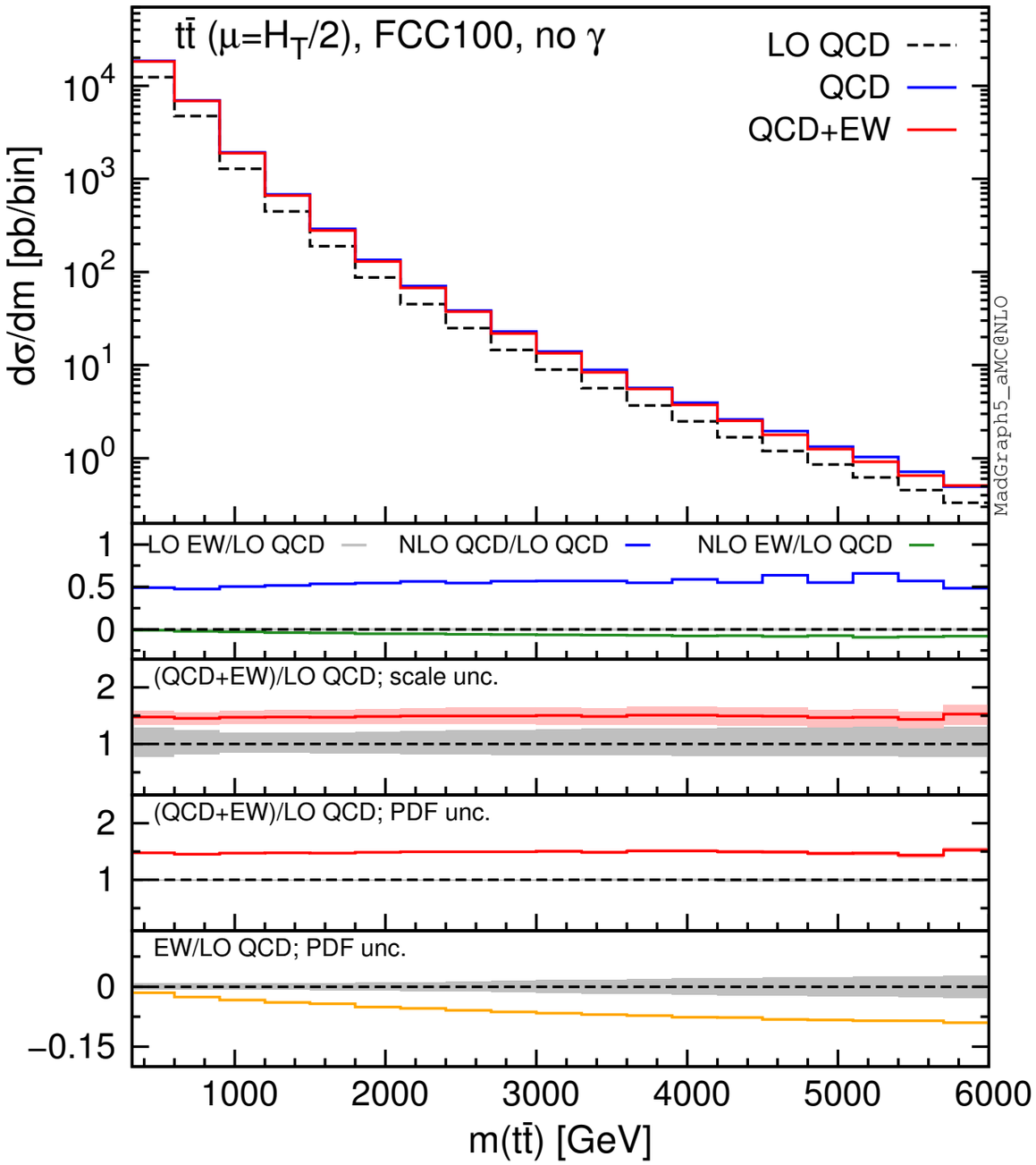
… and the different photon-gluon luminosities

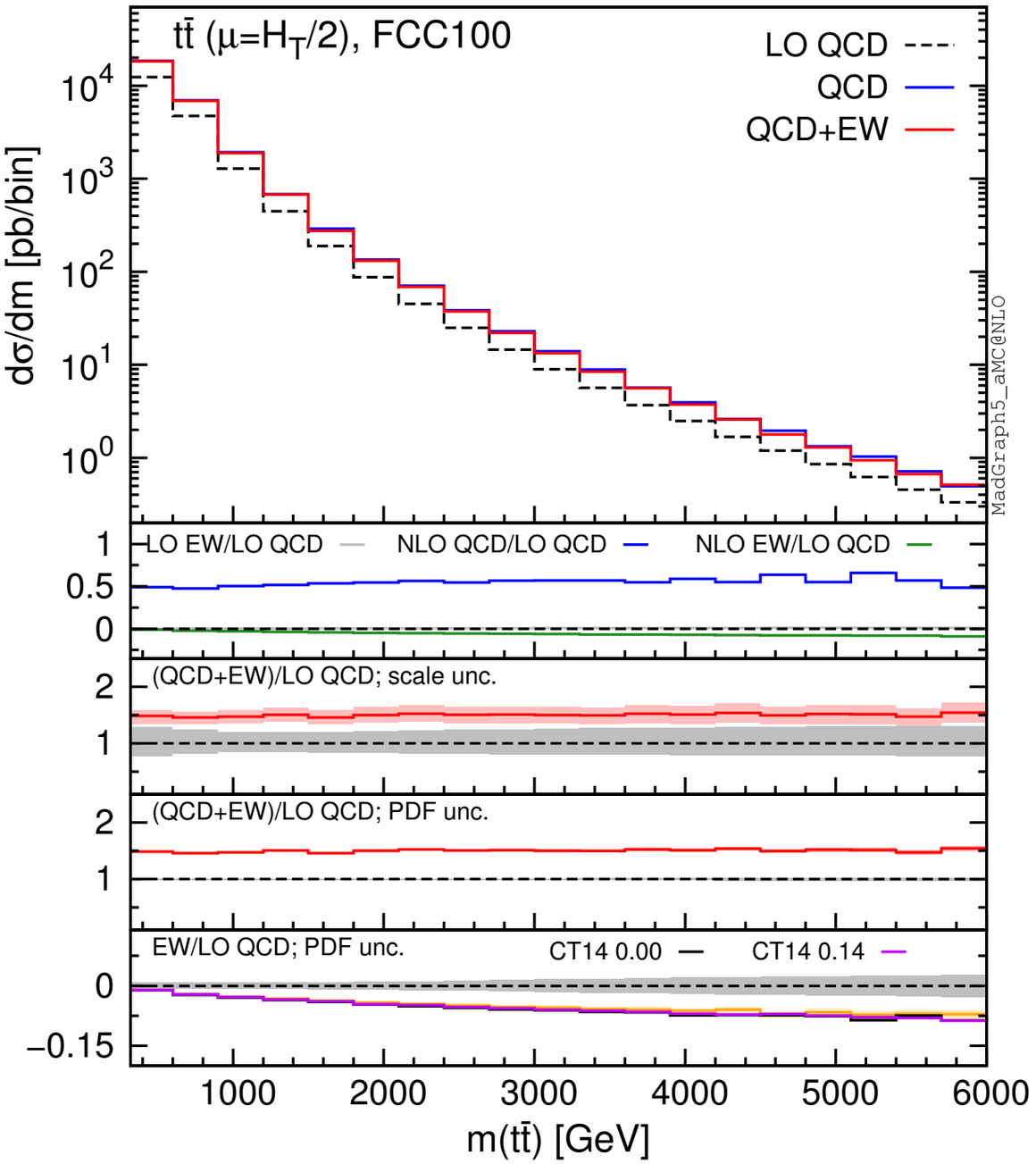


- **LUXQED** luminosity is very close to **CTEQ14QED**
- **NNPDF2.3QED** and **APFEL_NN23** are equivalent! (diff. running is not relevant)

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

100 TeV

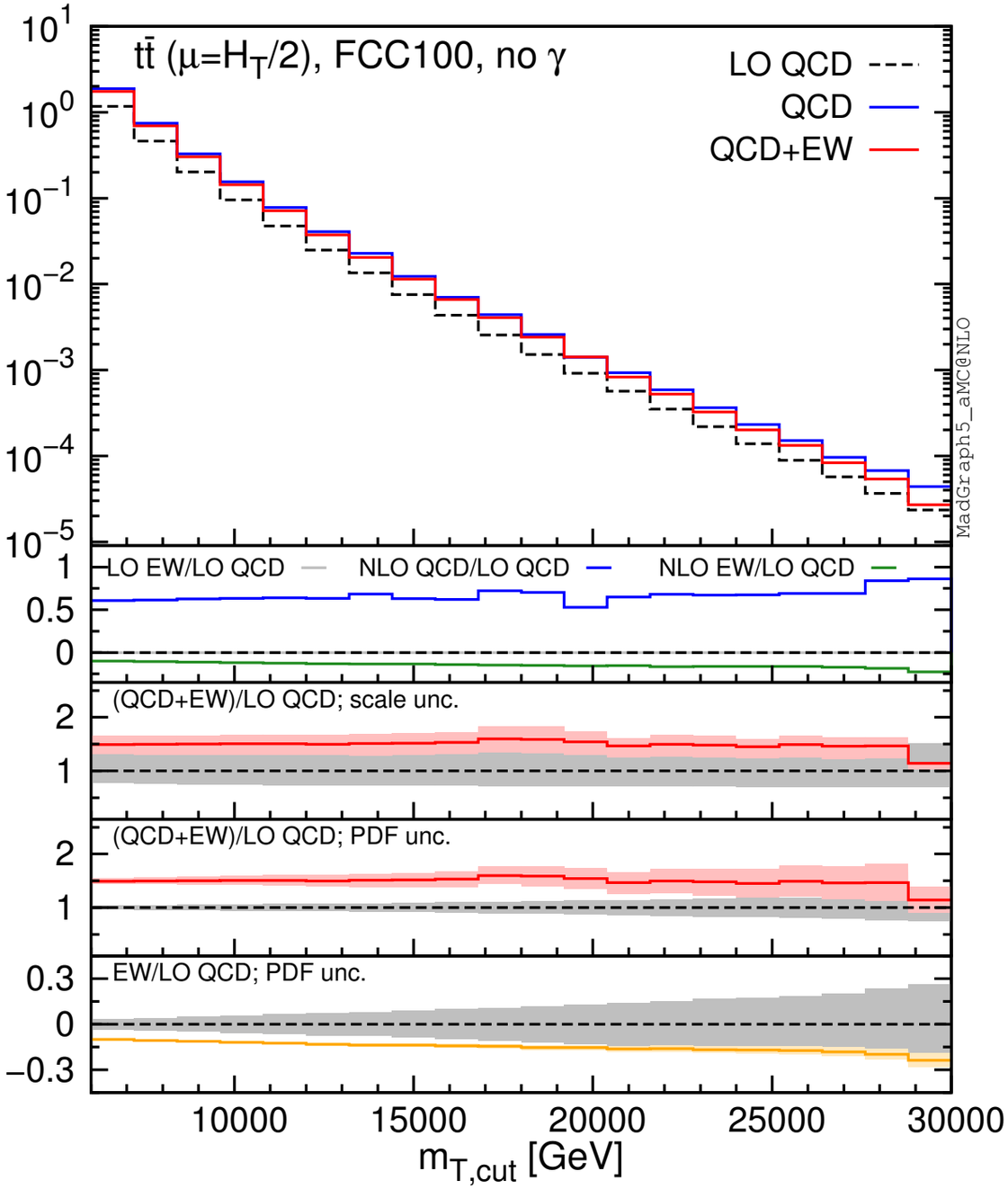




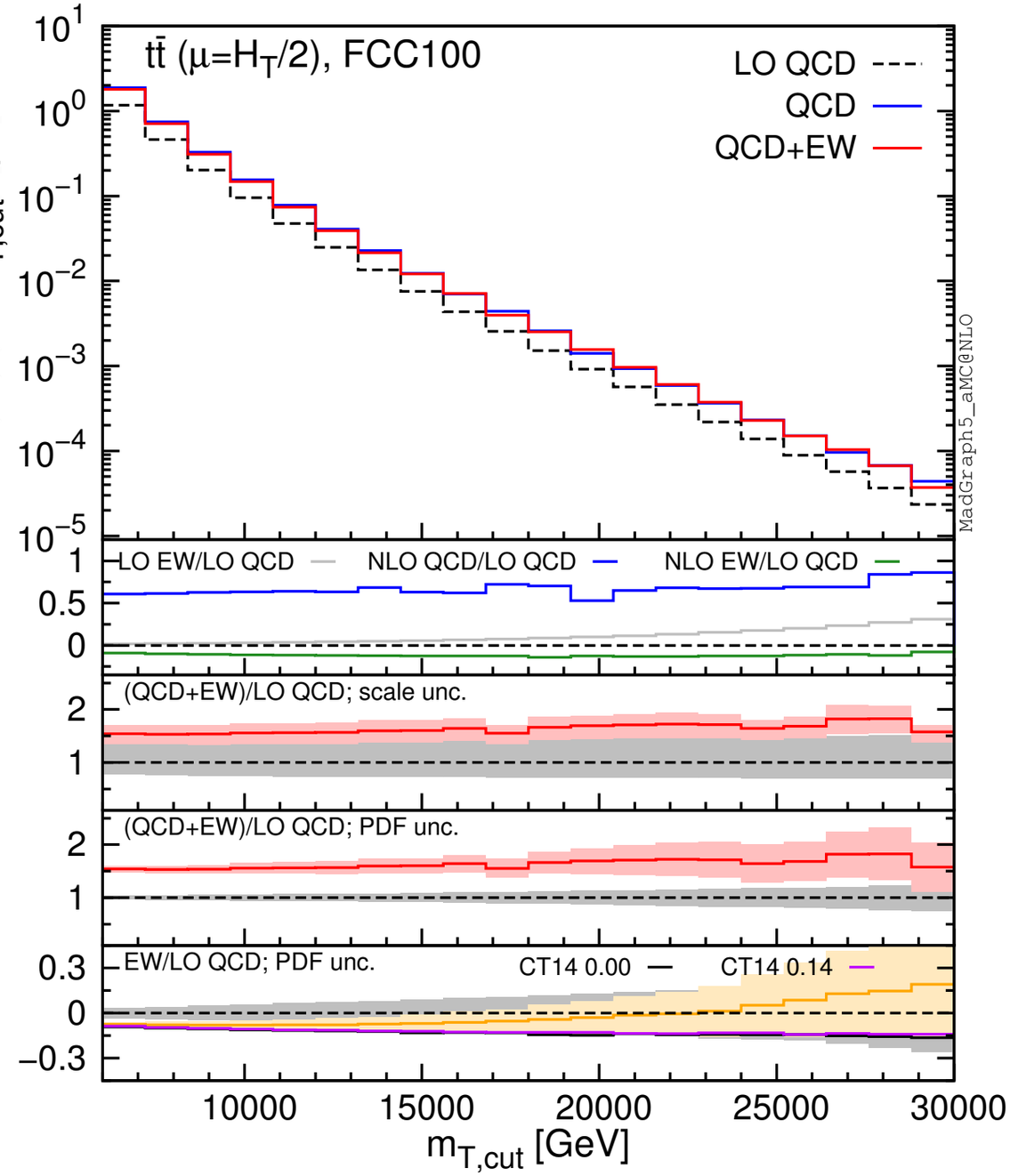
photon PDF **NO**

photon PDF **YES**

100 TeV



photon PDF **NO**



photon PDF **YES**

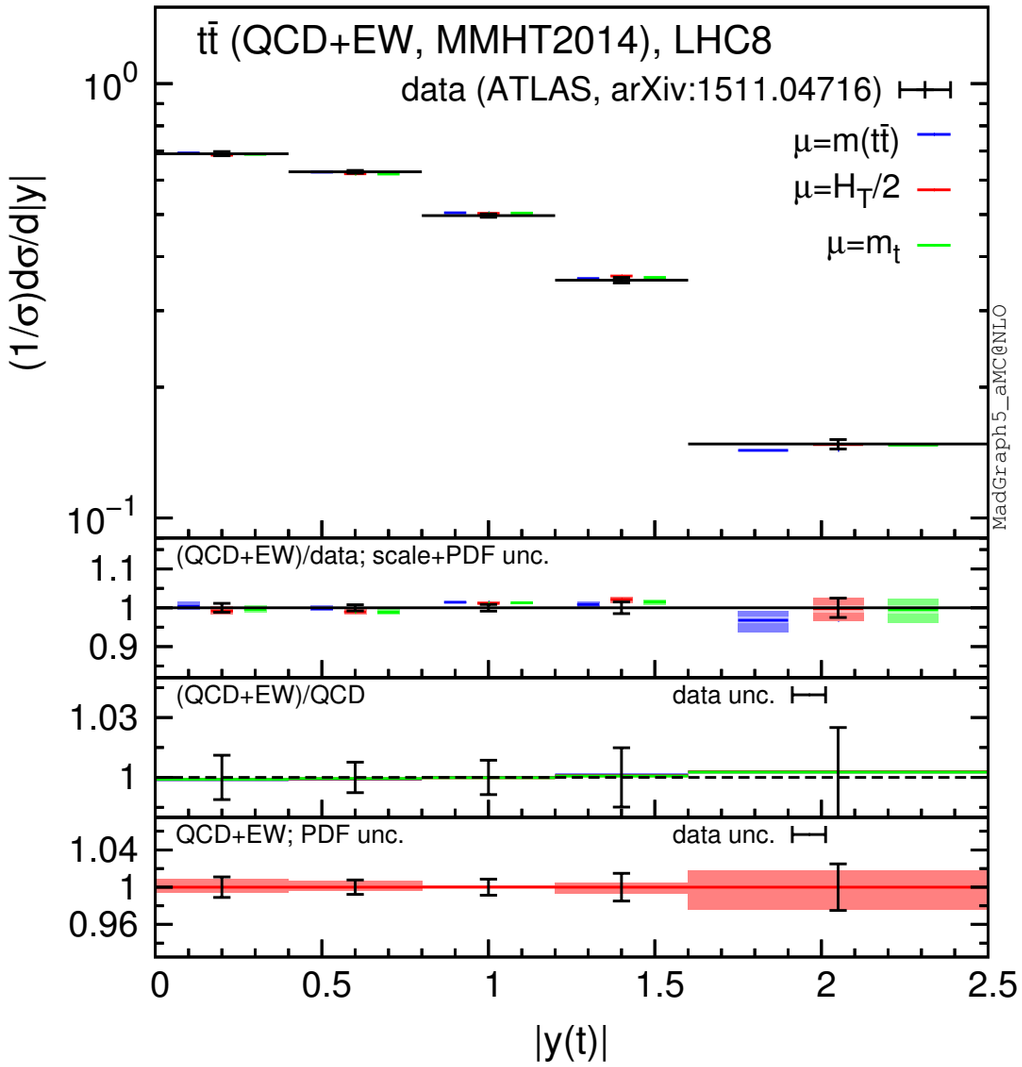
Measured (normalized) differential distributions at the LHC 8 TeV

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

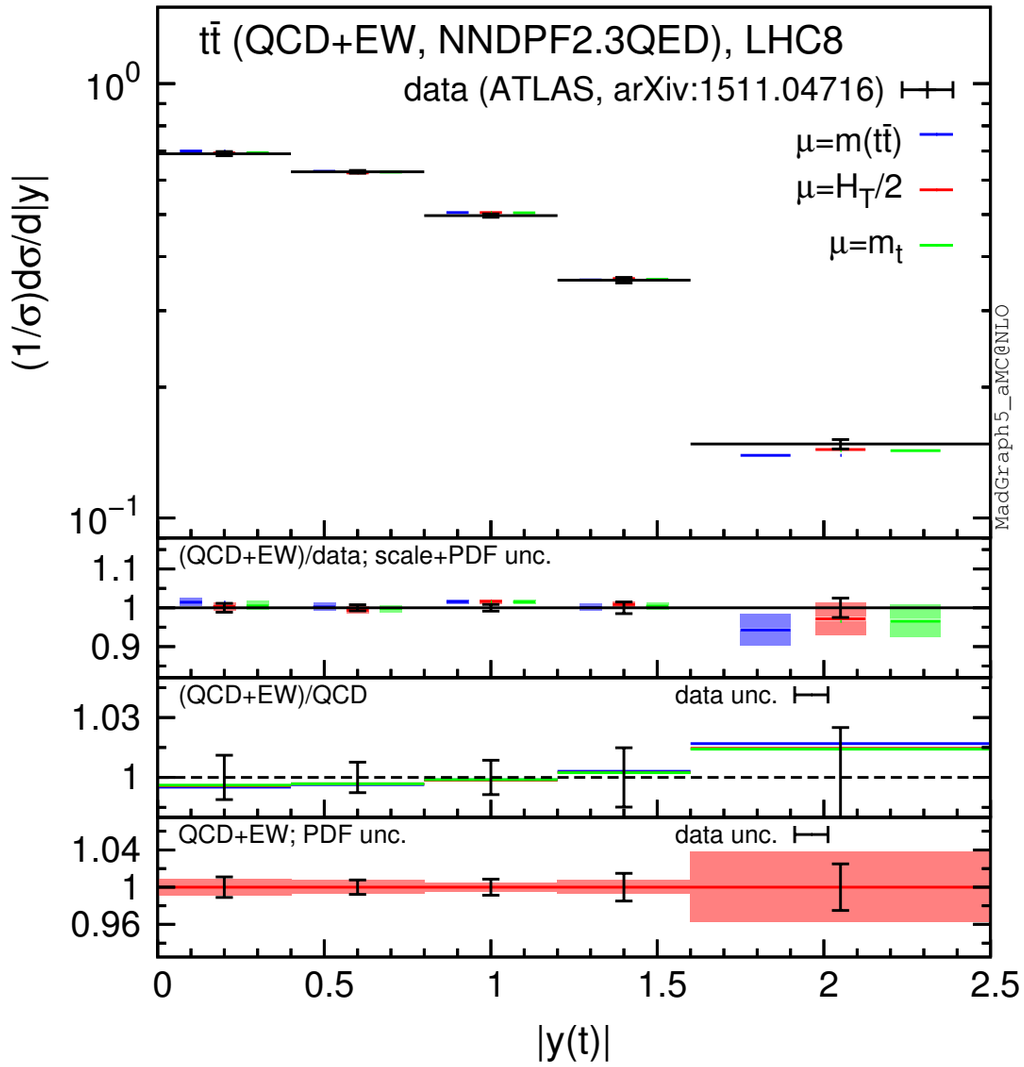
ATLAS data: *arXiv:1510.03818, arXiv:1511.04716*
CMS data: *arXiv:1505.04480*

8 TeV

comparison theo. unc. and exp. err.



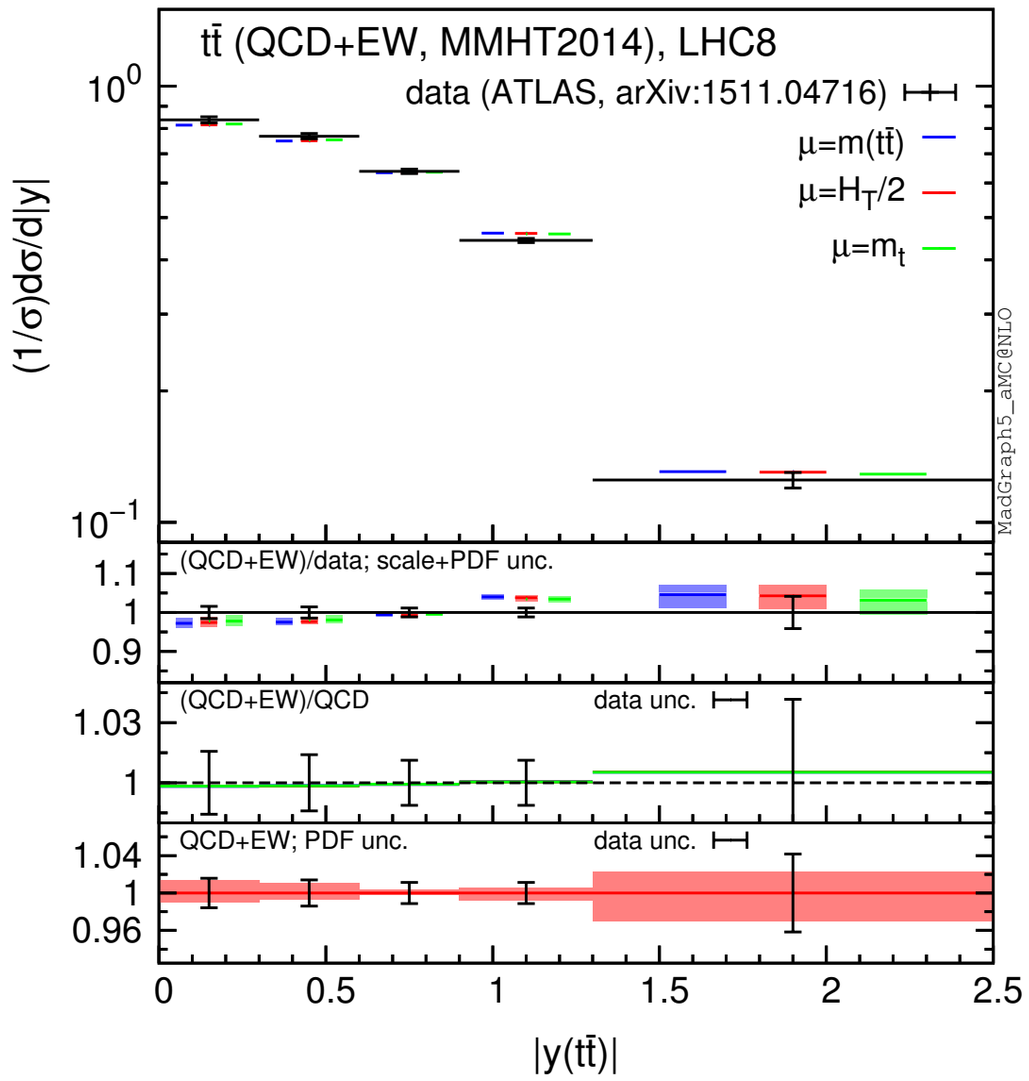
photon PDF **NO**

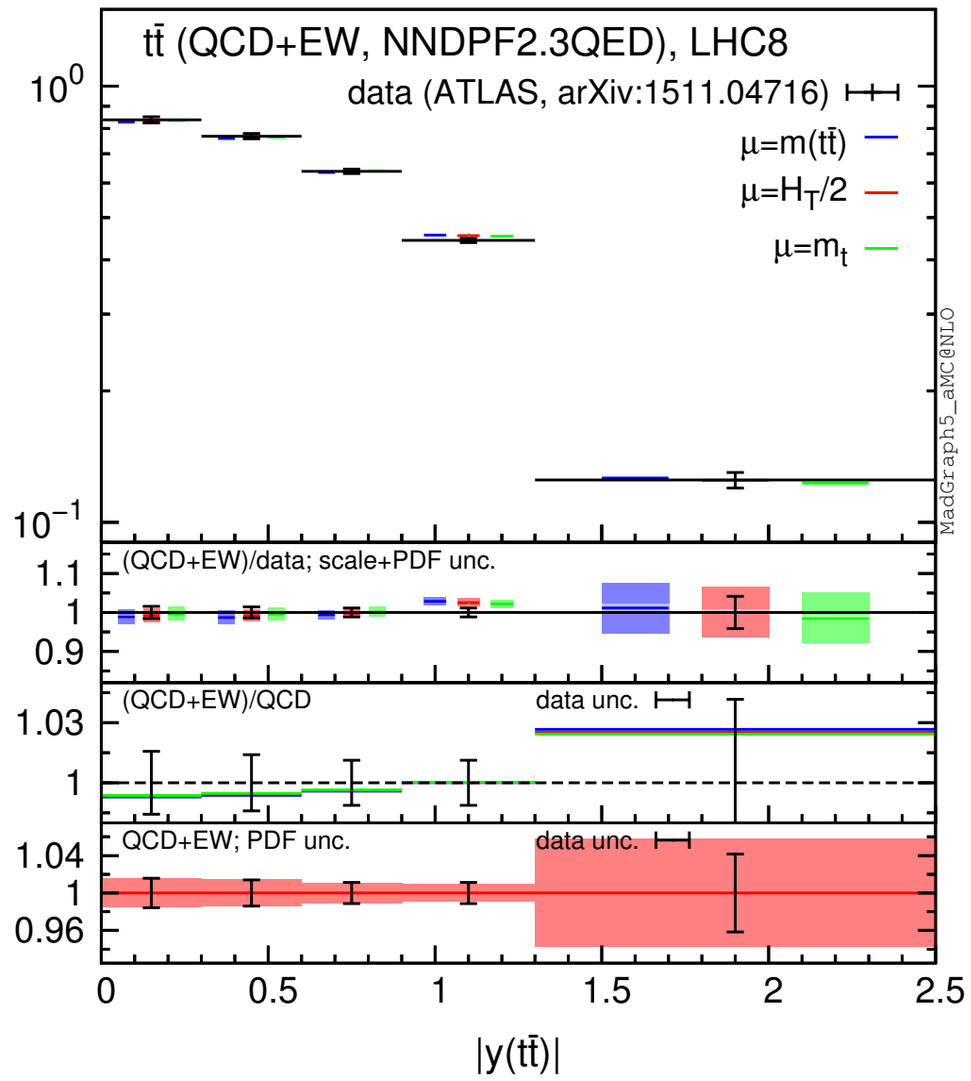


photon PDF **YES**

8 TeV

comparison theo. unc. and exp. err.



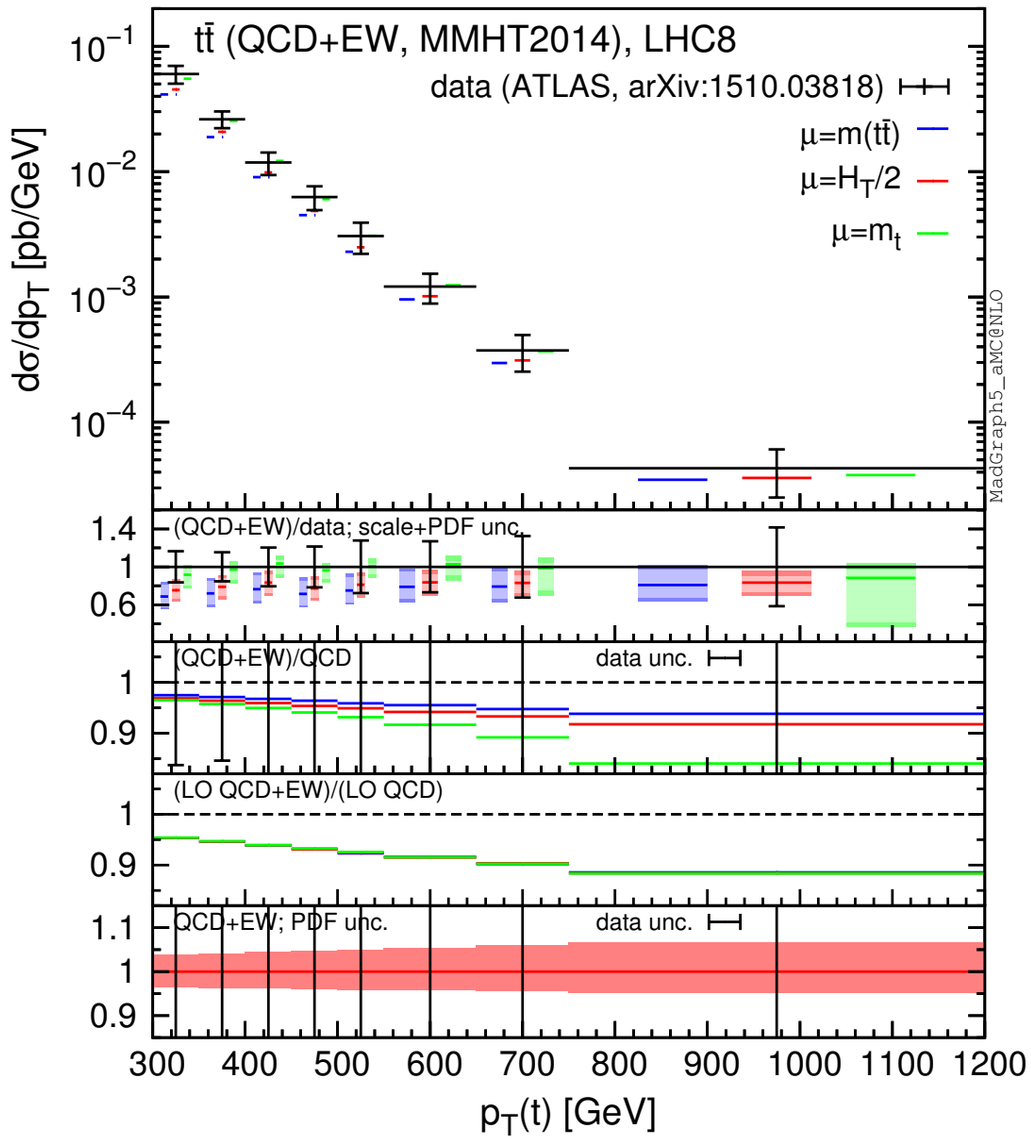


photon PDF **NO**

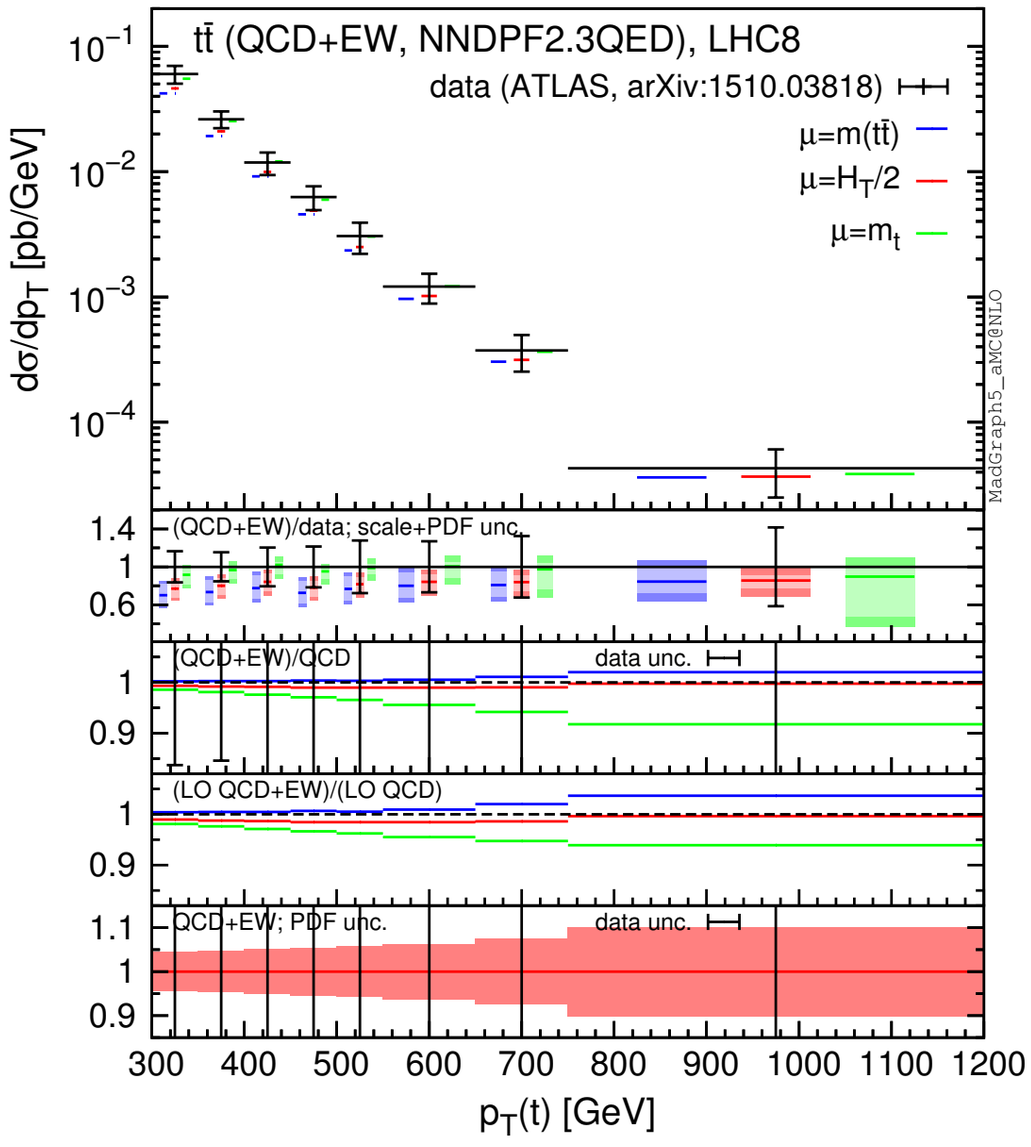
photon PDF **YES**

8 TeV

comparison theo. unc. and exp. err.



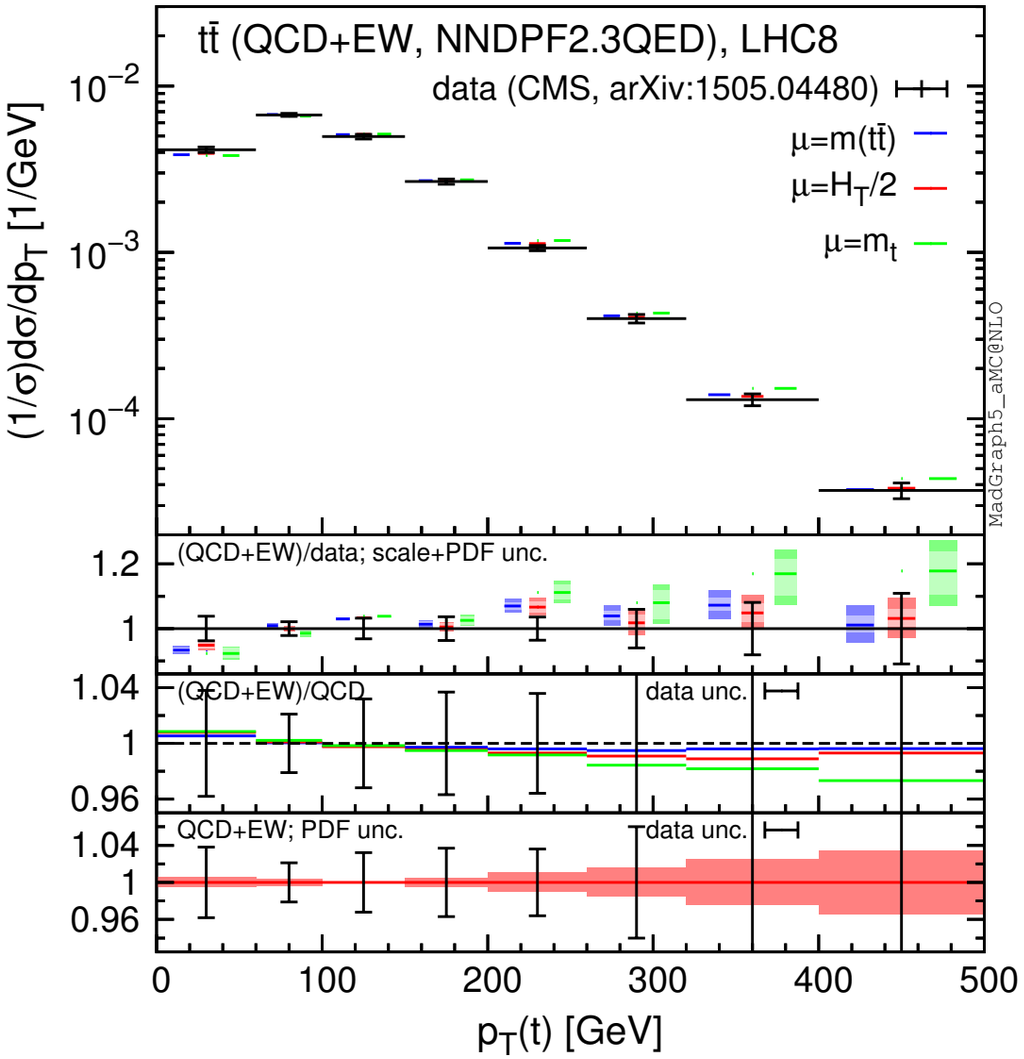
photon PDF **NO**

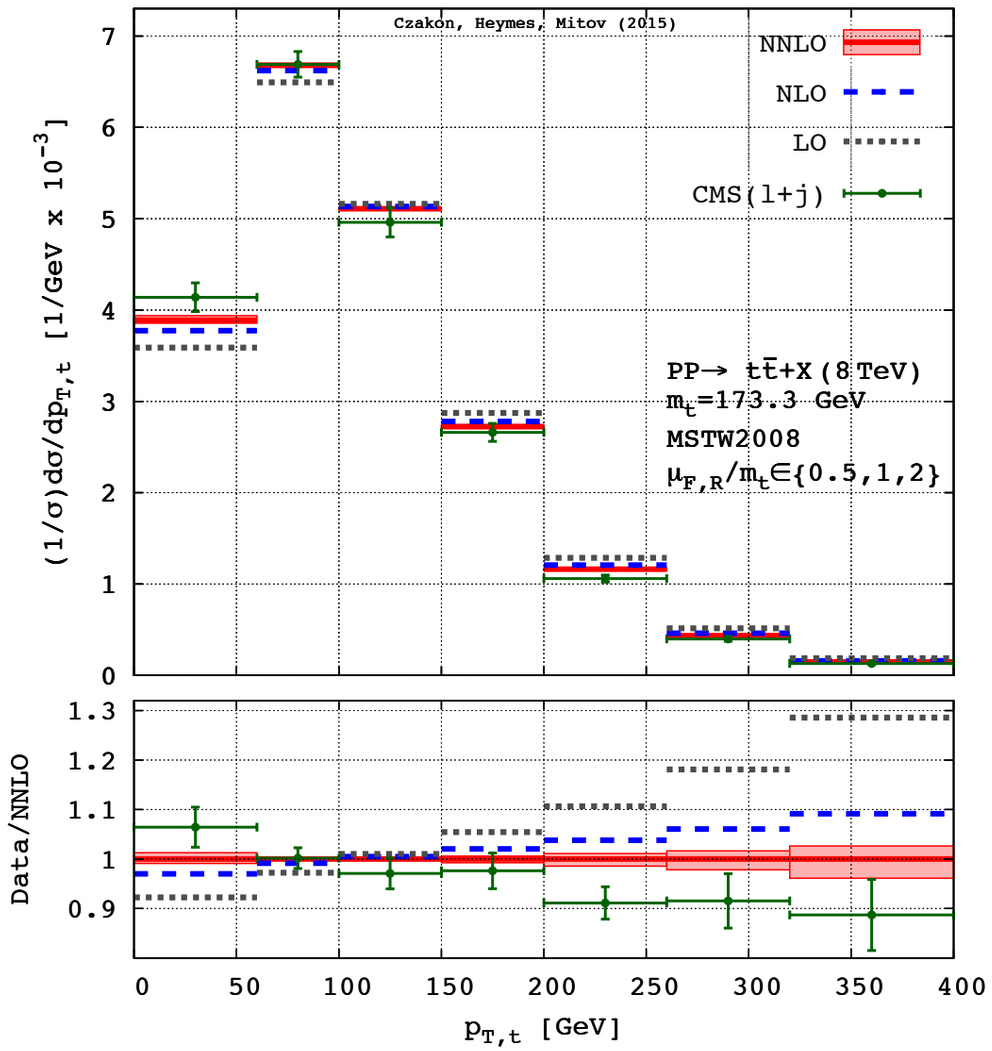


photon PDF **YES**

8 TeV

comparison theo. unc. and exp. err.





Czakon, Heymes, Mitov 2016

photon PDF **YES**

NNLO QCD