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

Based on **arXiv:1705.04105** in collaboration with
M. Czakon, D. Heymes, A. Mitov, I. Tsinikos, M. Zaro

results and histograms available at
http://www.precision.hep.phy.cam.ac.uk/results/ttbar-nnloqcd-nloew/

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Shanghai
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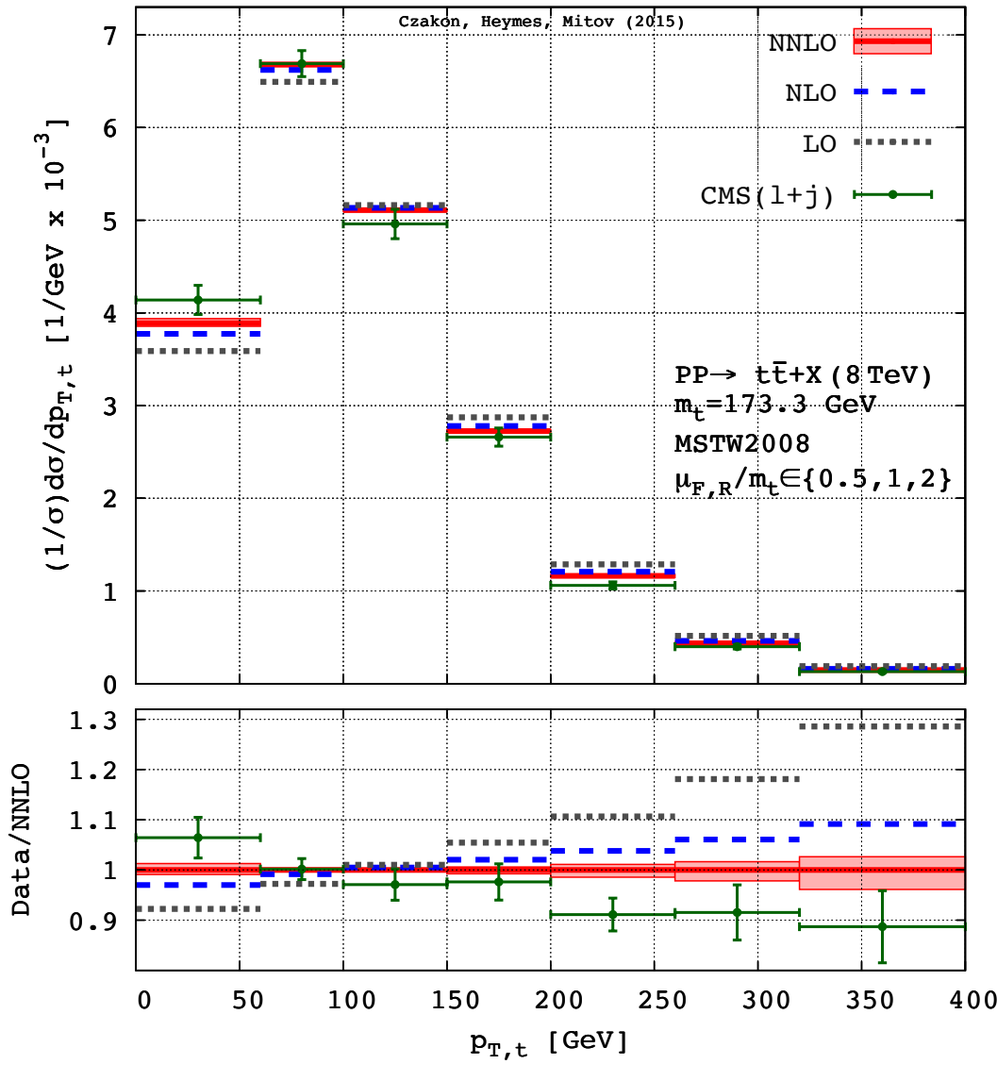
Motivation

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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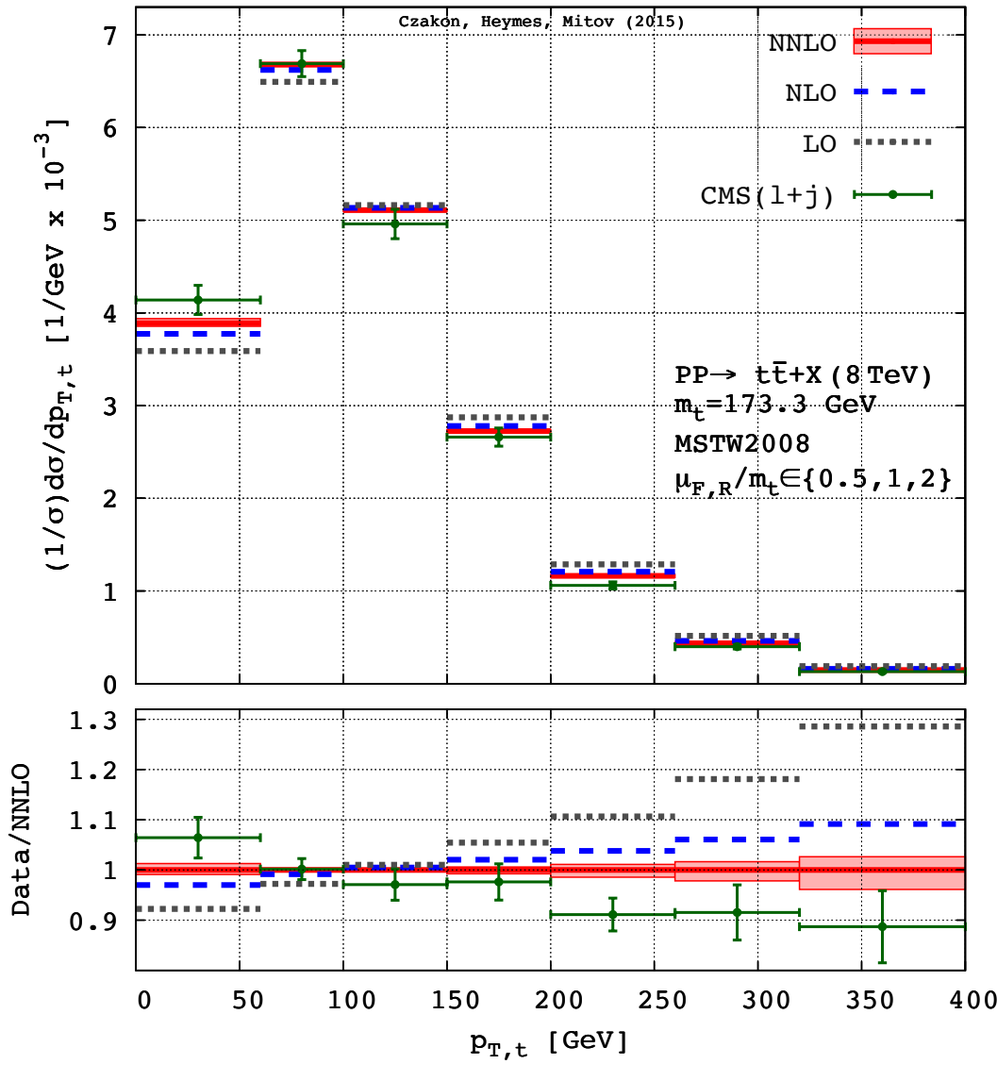

EW corrections have a similar size ($\alpha_s^2 \sim \alpha$), with **Sudakov enhancements** in the boosted regime. However, only a part of them is taken into account in experimental analyses, and no consistent combination with NNLO QCD (same input parameters, PDFs and scale) is yet available.

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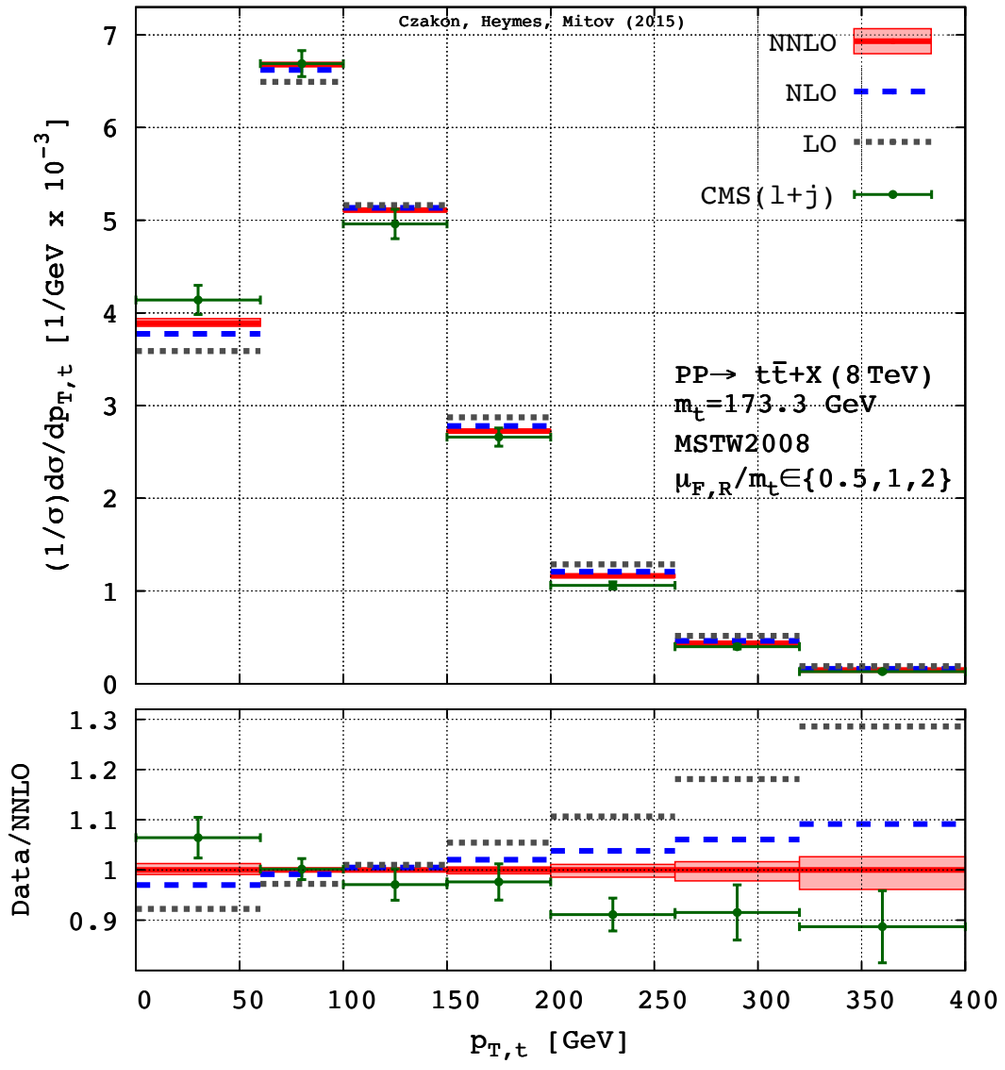

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We provide predictions at complete NLO accuracy including also NNLO QCD corrections for differential distributions in top-quark pair production at 8 and 13 TeV.

Motivation (part 2)

If you do not believe that NNLO QCD + NLO EW corrections are essential:
do you remember the forward-backward asymmetry at the Tevatron?

It is exactly the same process (top-quark production) at another hadron collider

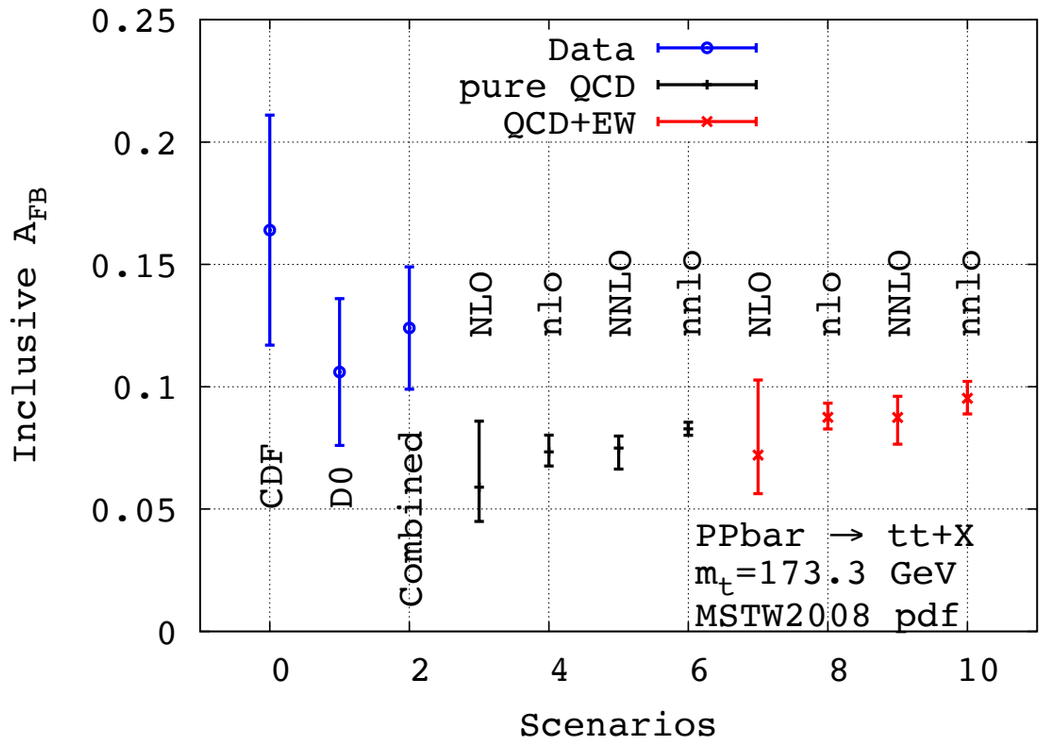


FIG. 1: The inclusive asymmetry in pure QCD (black) and QCD+EW[28] (red). Capital letters (NLO, NNLO) correspond to the unexpanded definition (2), while small letters (nlo, nnlo) to the definition (3). The CDF/DØ (naive) av-

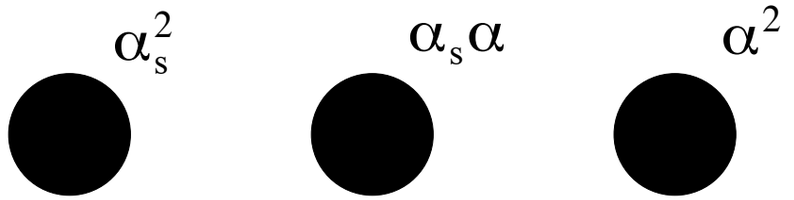
A posteriori,
it was realized that a large fraction of the discrepancy was due to the missing contributions from:
EW corrections
(*Hollik, DP '11*)
and
NNLO QCD corrections
(Czakon, Fiedler, Mitov '15)

Calculation framework

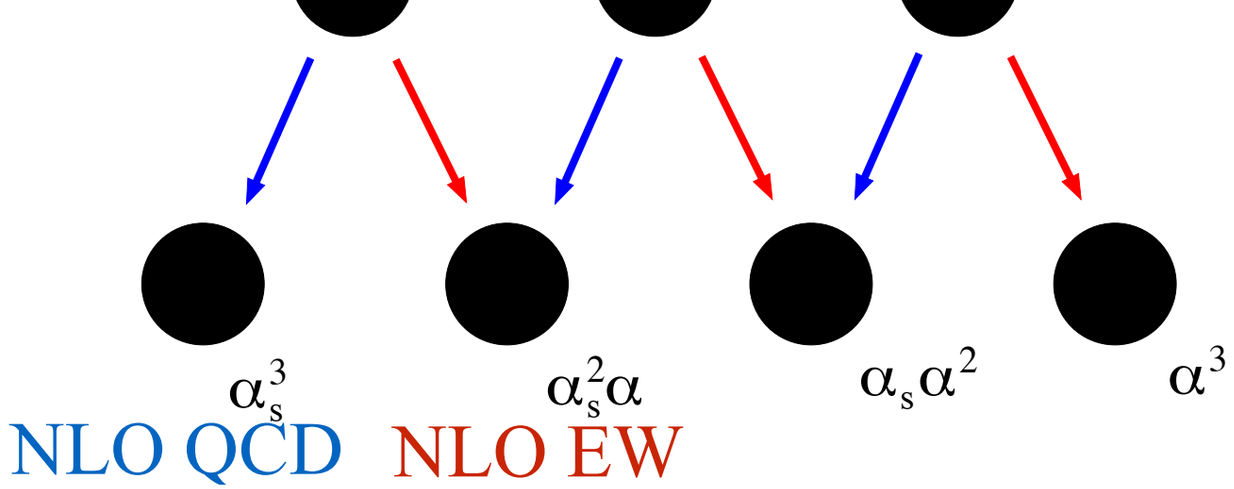
The calculation of **NNLO QCD** corrections is based on
Czakon, Fiedler, Mitov '15

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

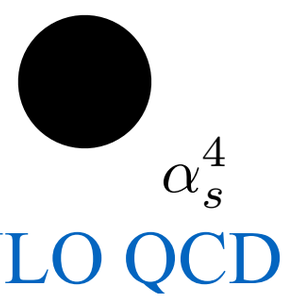
LO



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?

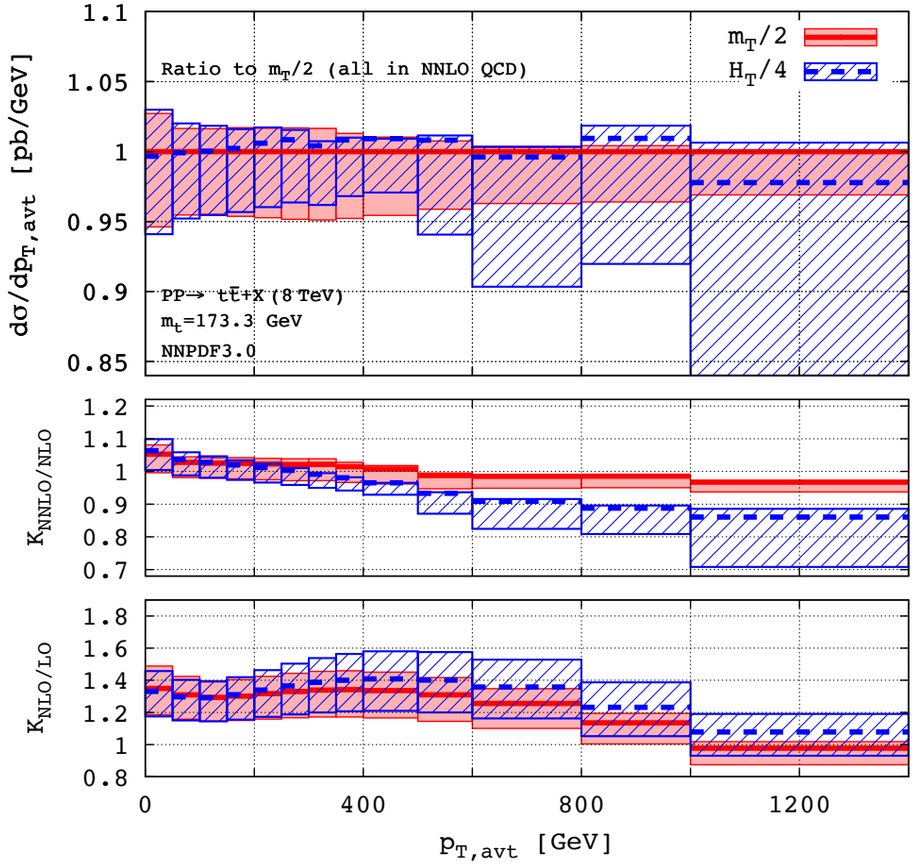
NNLO QCD: scale definition

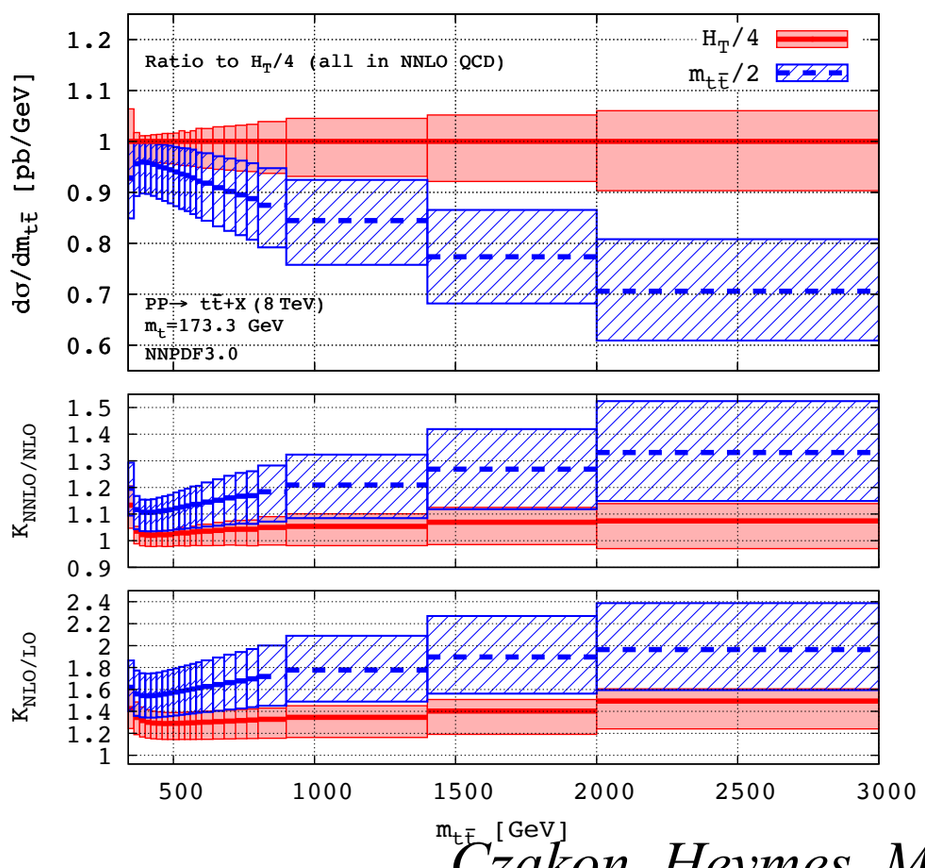
The dependence on the ren. and fac. scale is mainly due to QCD effects.

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*
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They both include a photon PDF!

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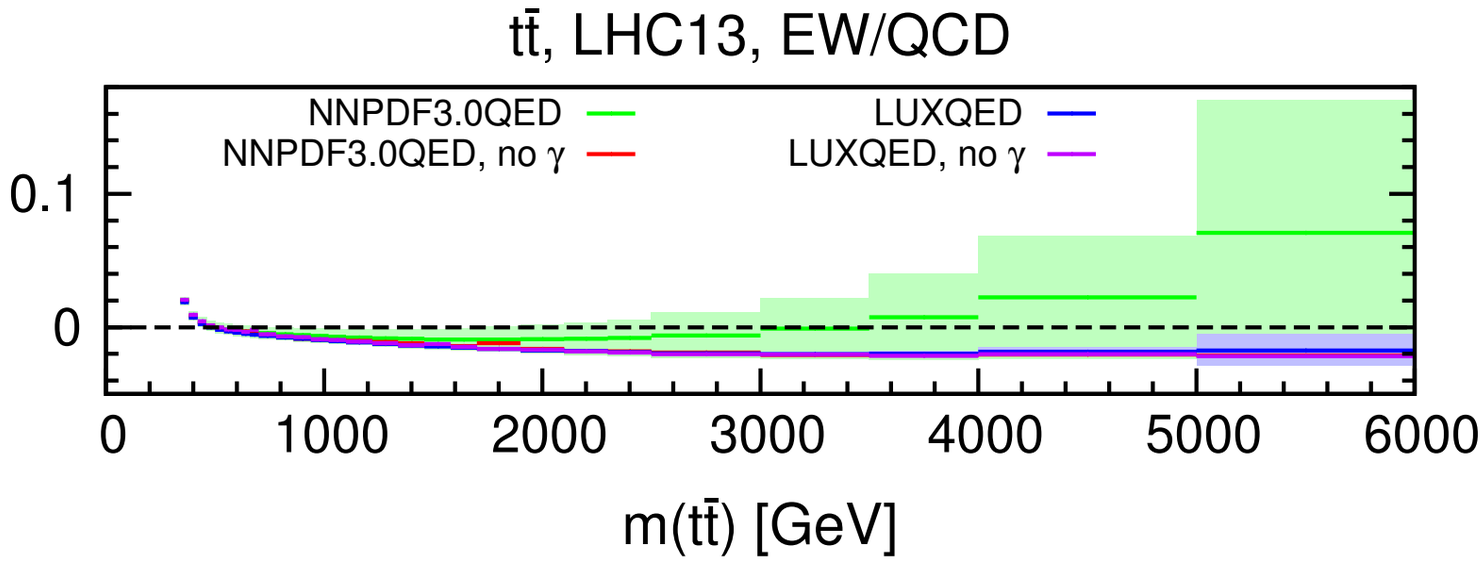
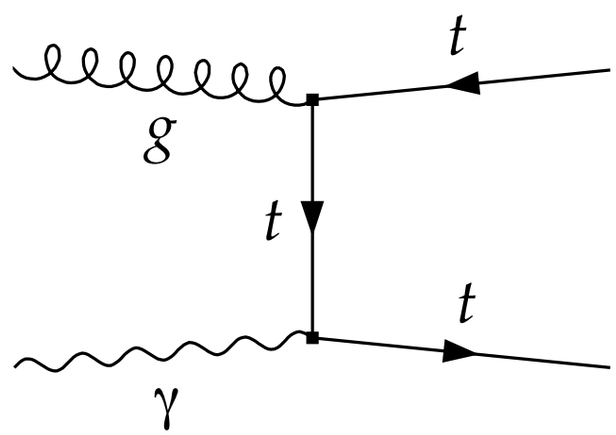
While the impact of the NNPDF photon PDF is huge in ttbar differential distributions (and with large uncertainties), in the case of LUXQED is small.
Cancellation between Sudakov Logarithms and photon-induced results depends on the scale definition. *DP, Tsinikos, Zaro '16*

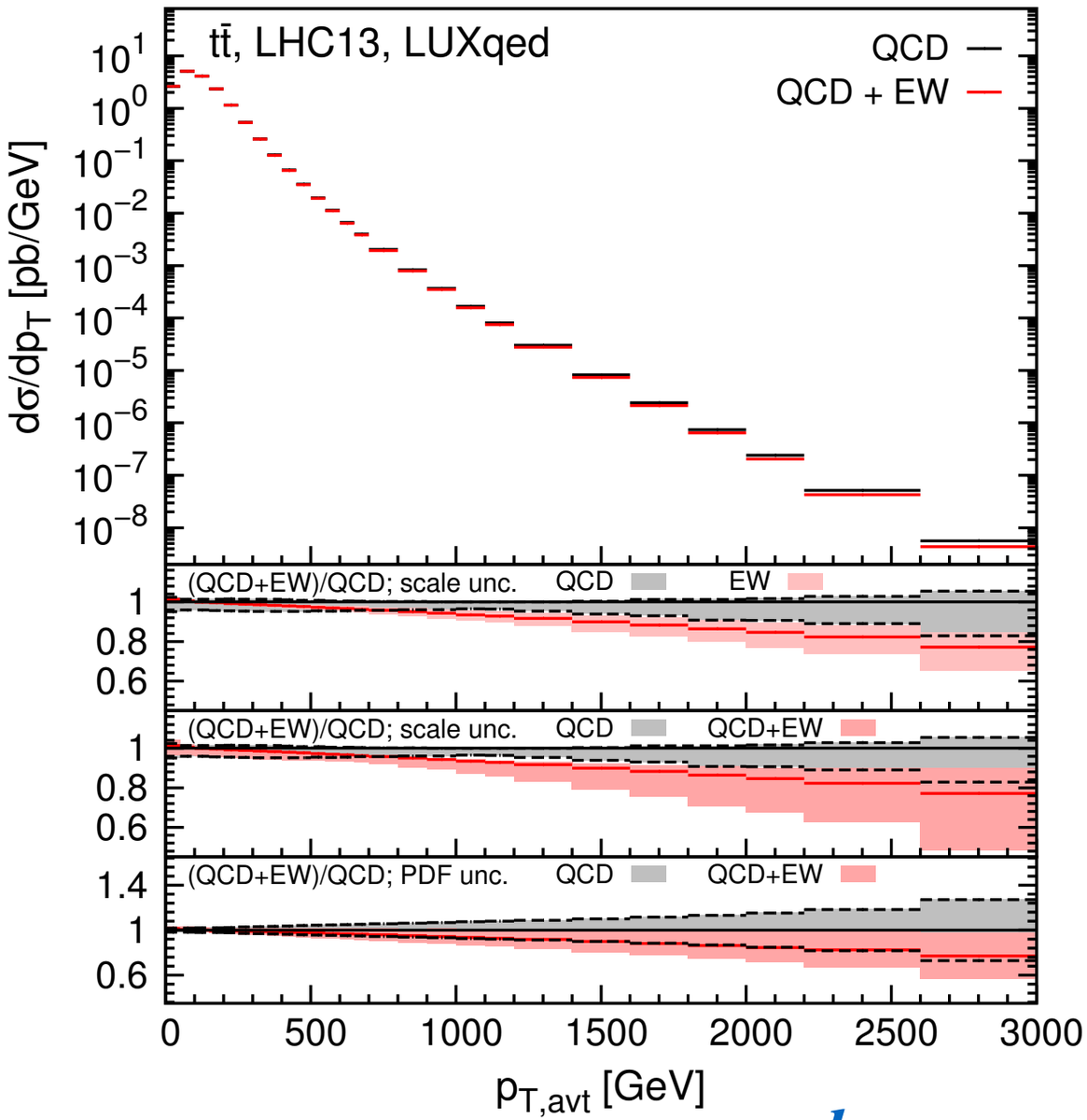


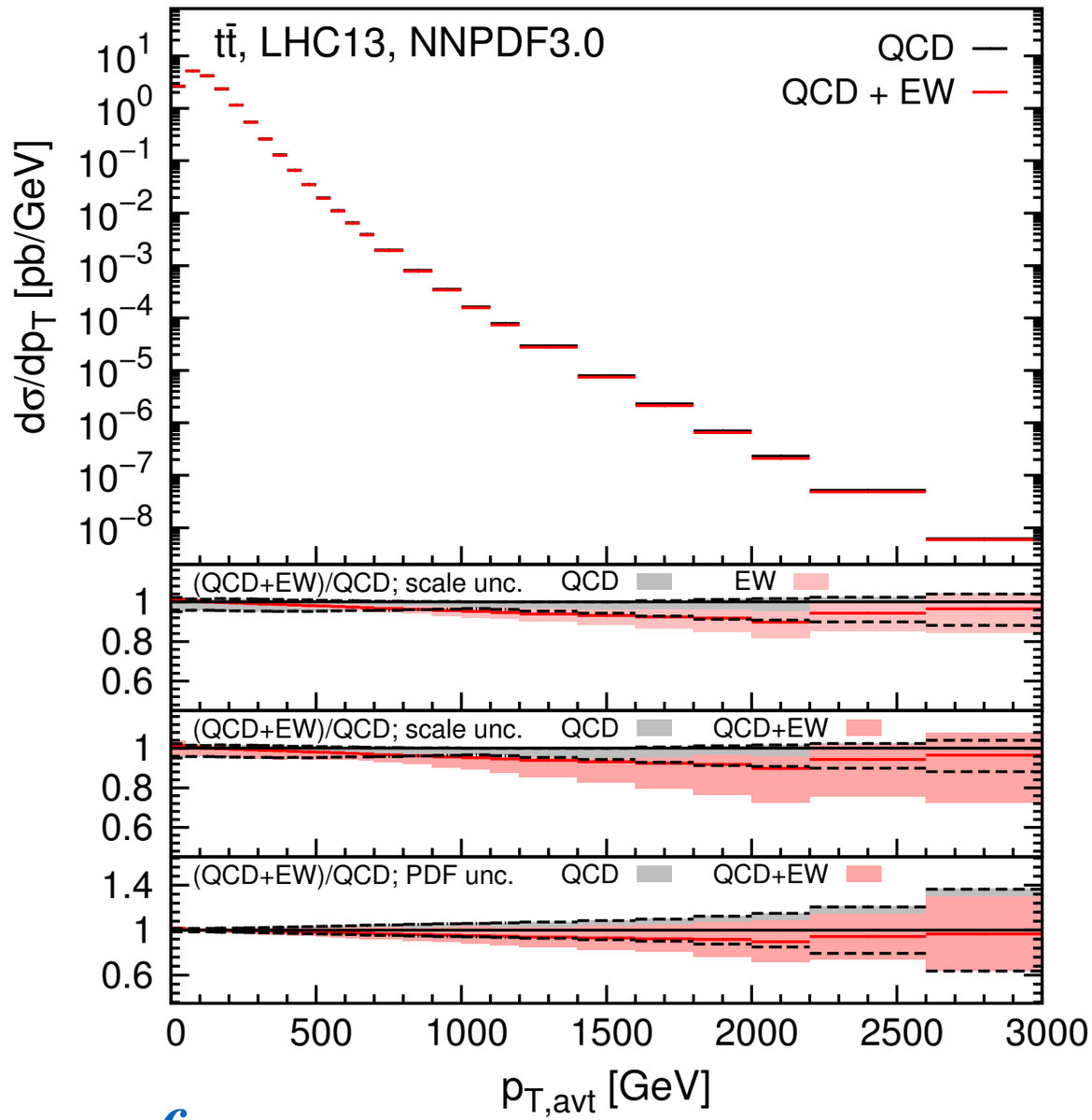


Results

13 TeV

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





large scale unc. from EW corrections

\+

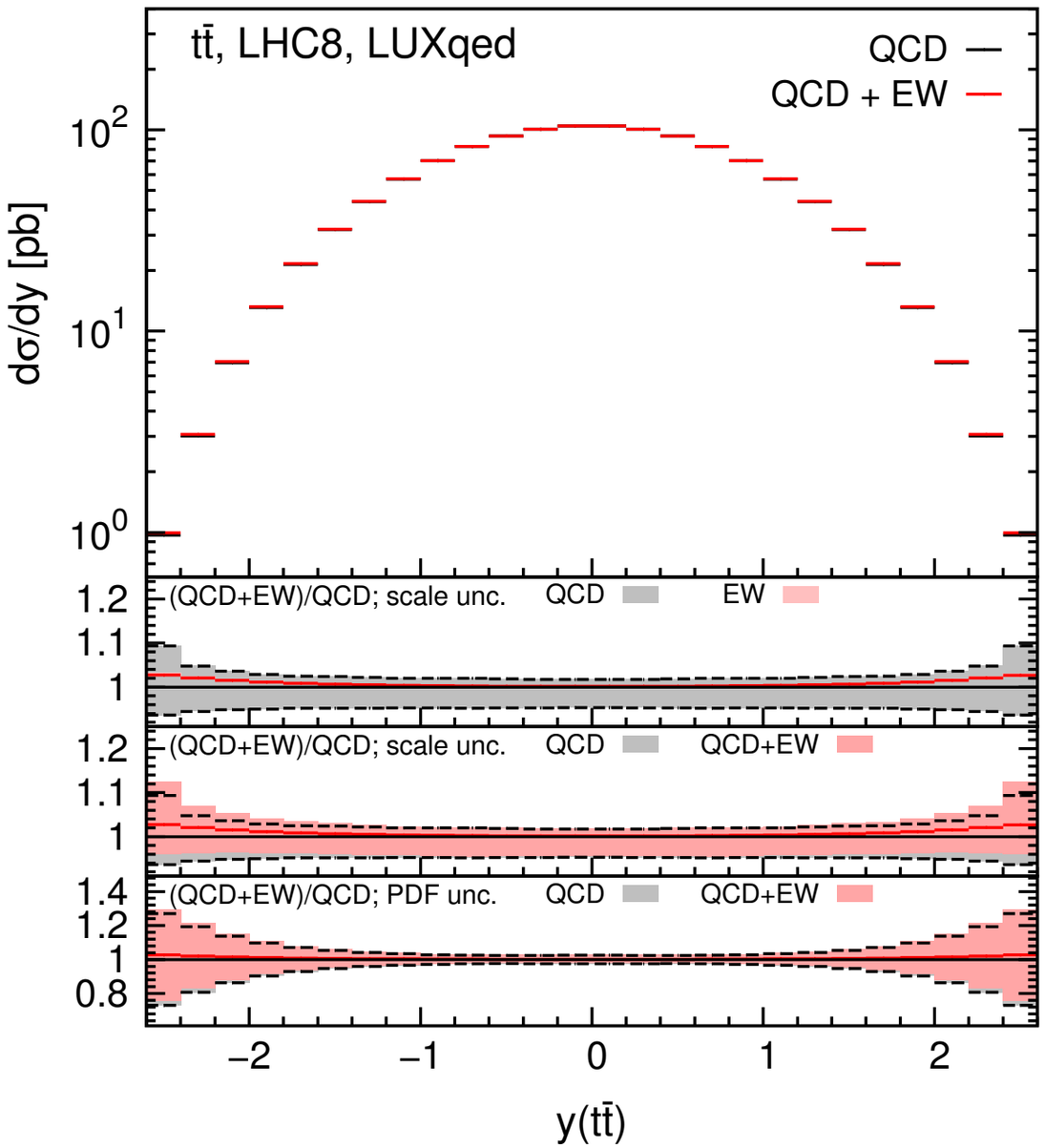
photon PDF relevant

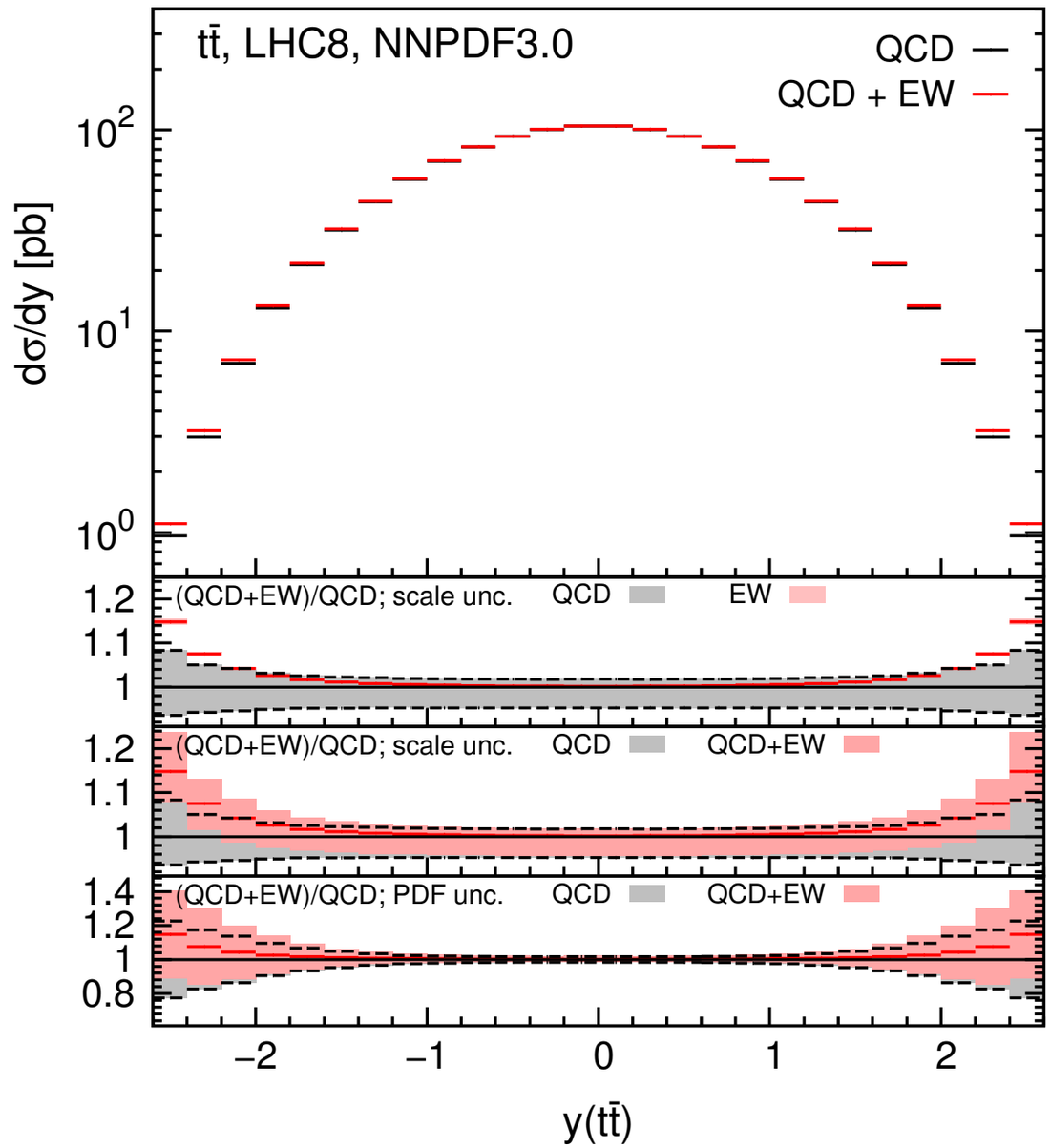
LUXQED

NNPDF3.0QED

$y(t\bar{t})$

8 TeV





LUXQED

photon PDF relevant at large rapidity

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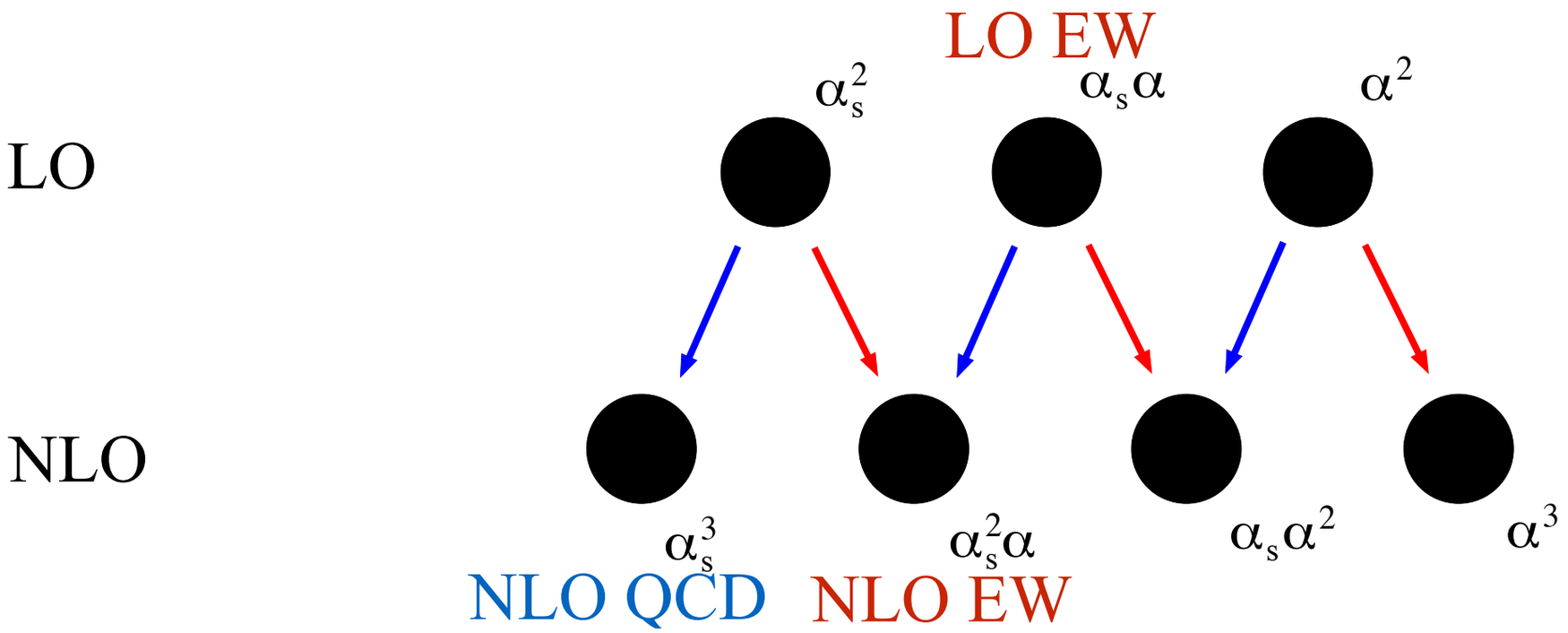
Can we reduce the scale-dependence from NLO EW effects?

Combination of EW and QCD corrections in the multiplicative approach

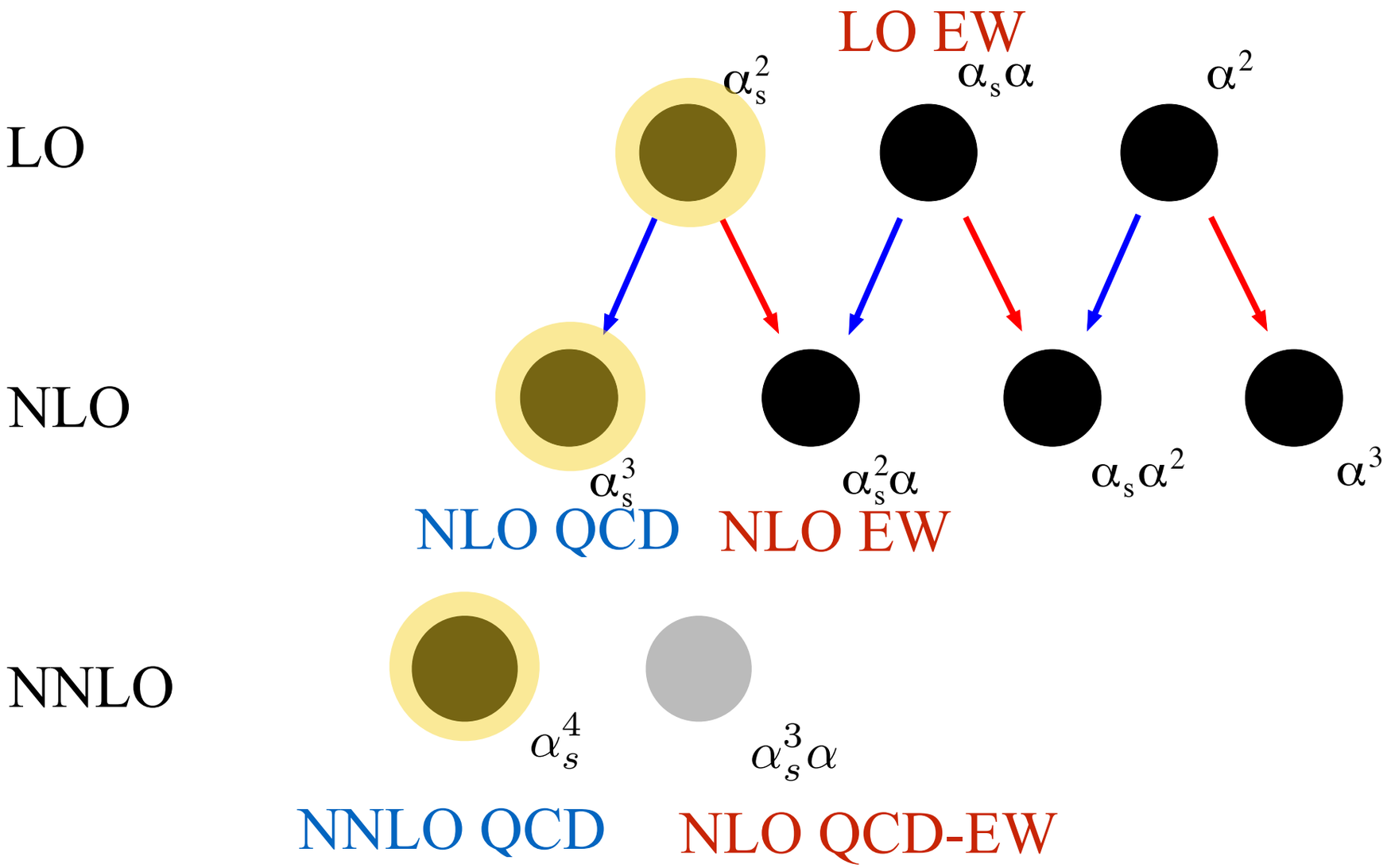
When QCD and EW effects factorize (e.g. soft QCD and Sudakov Logarithms) multiplying NLO QCD with NLO EW is a good approximation for NNLO mixed QCD-EW effects.
In general, it can be used as an estimate of uncertainties due to mixed QCD-EW higher order effects.

Multiplicative combination



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

Multiplicative combination



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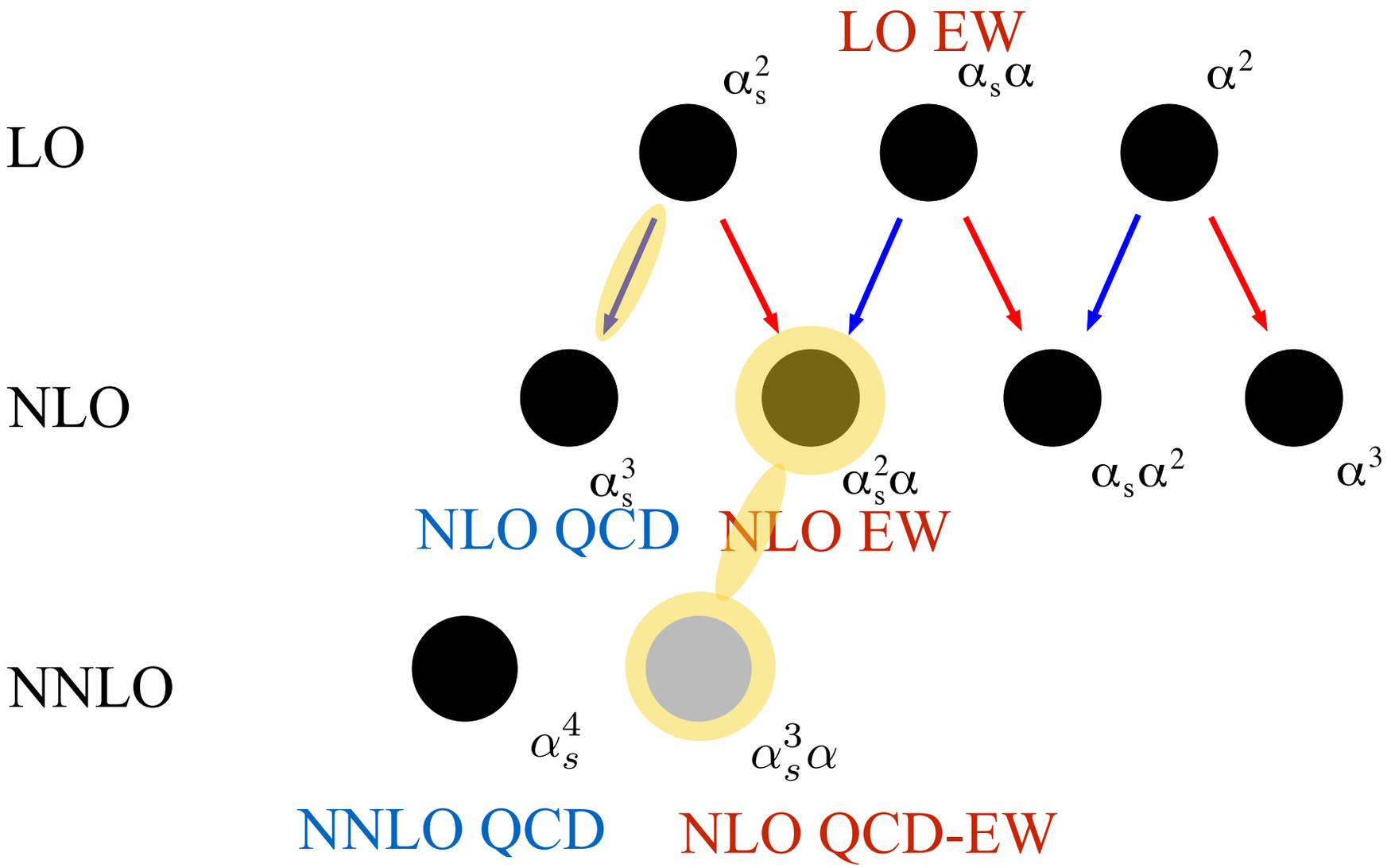

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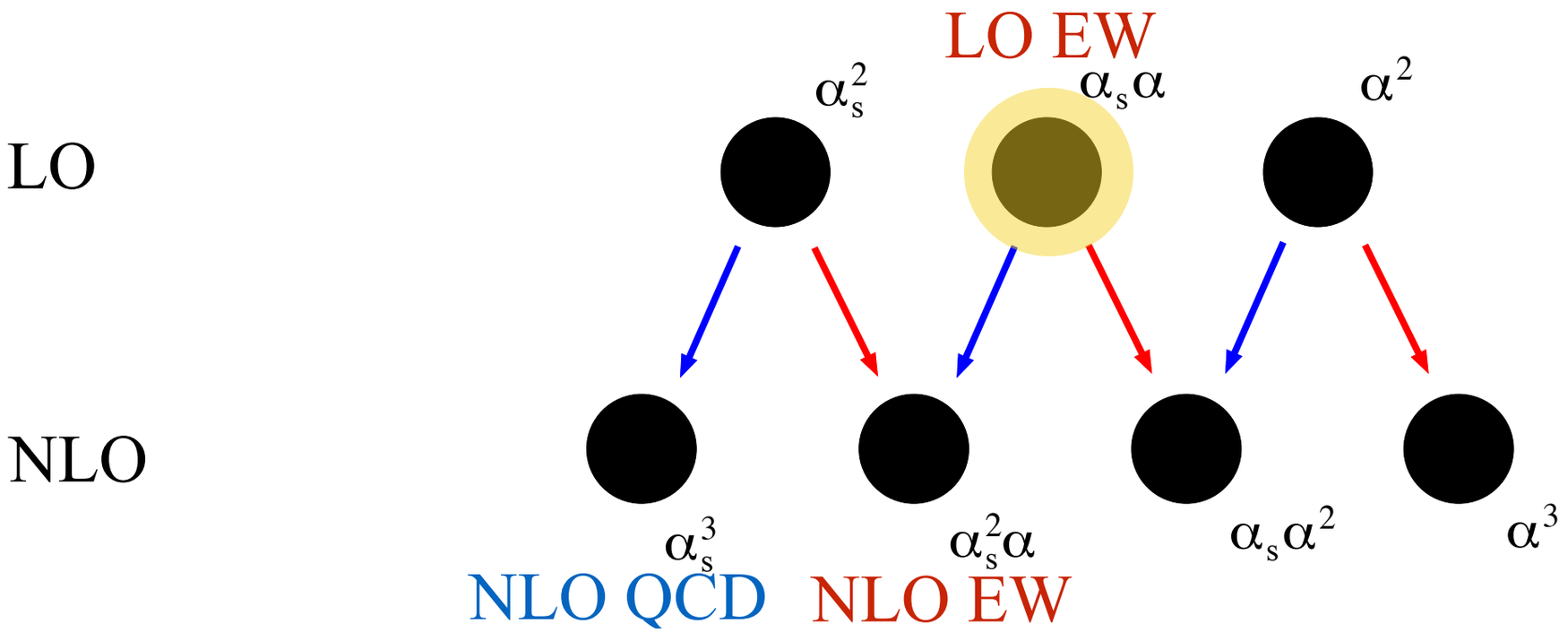

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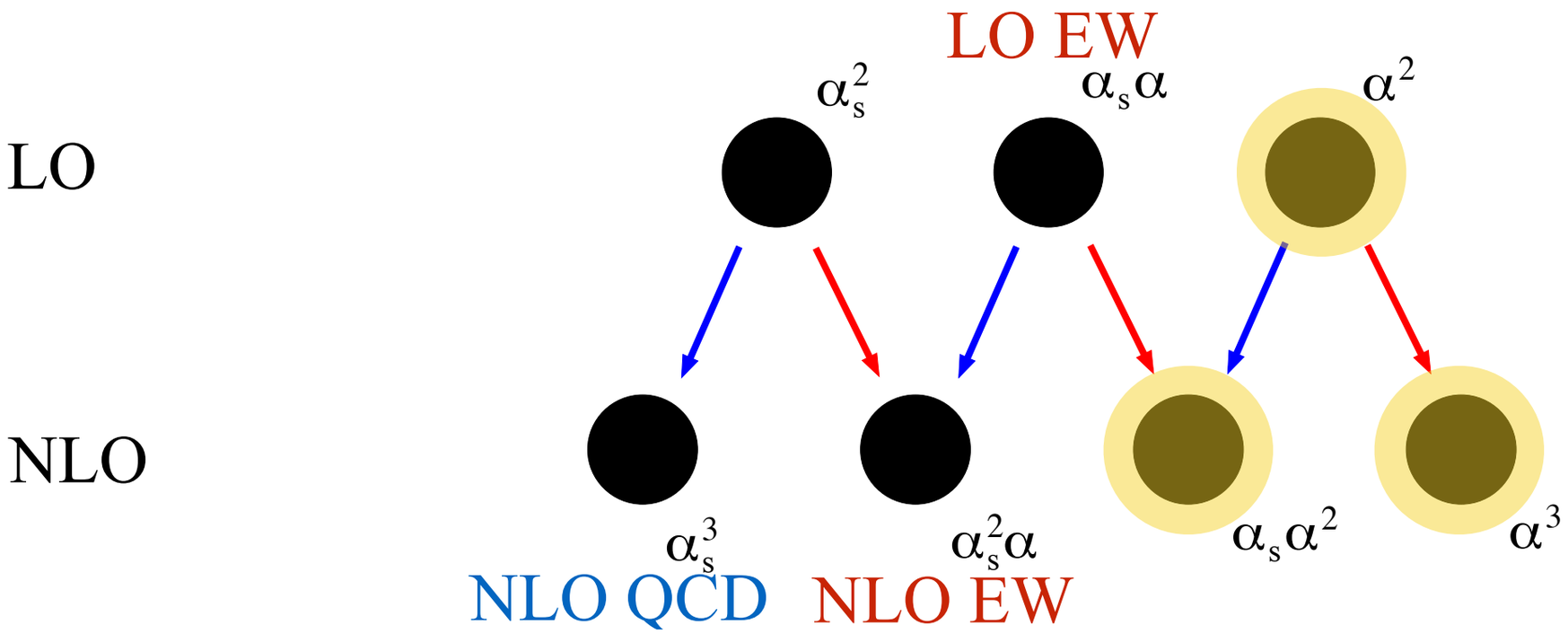

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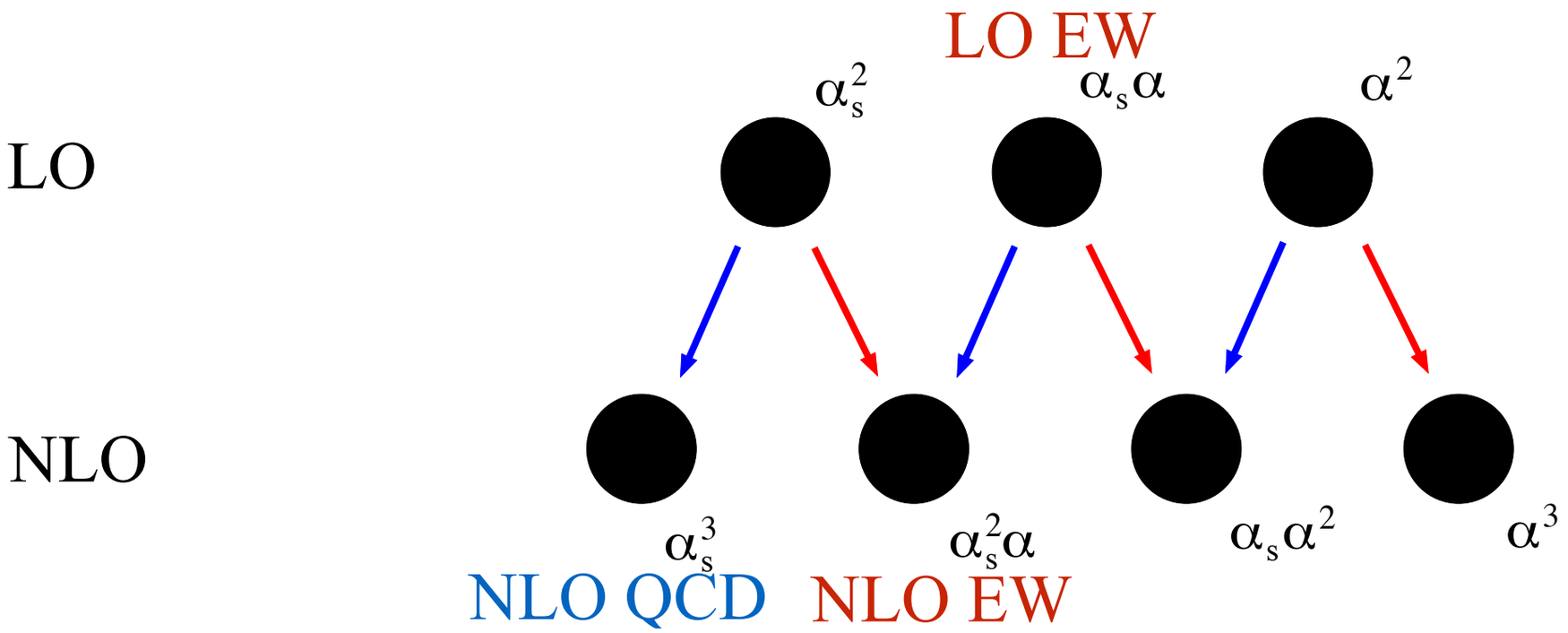

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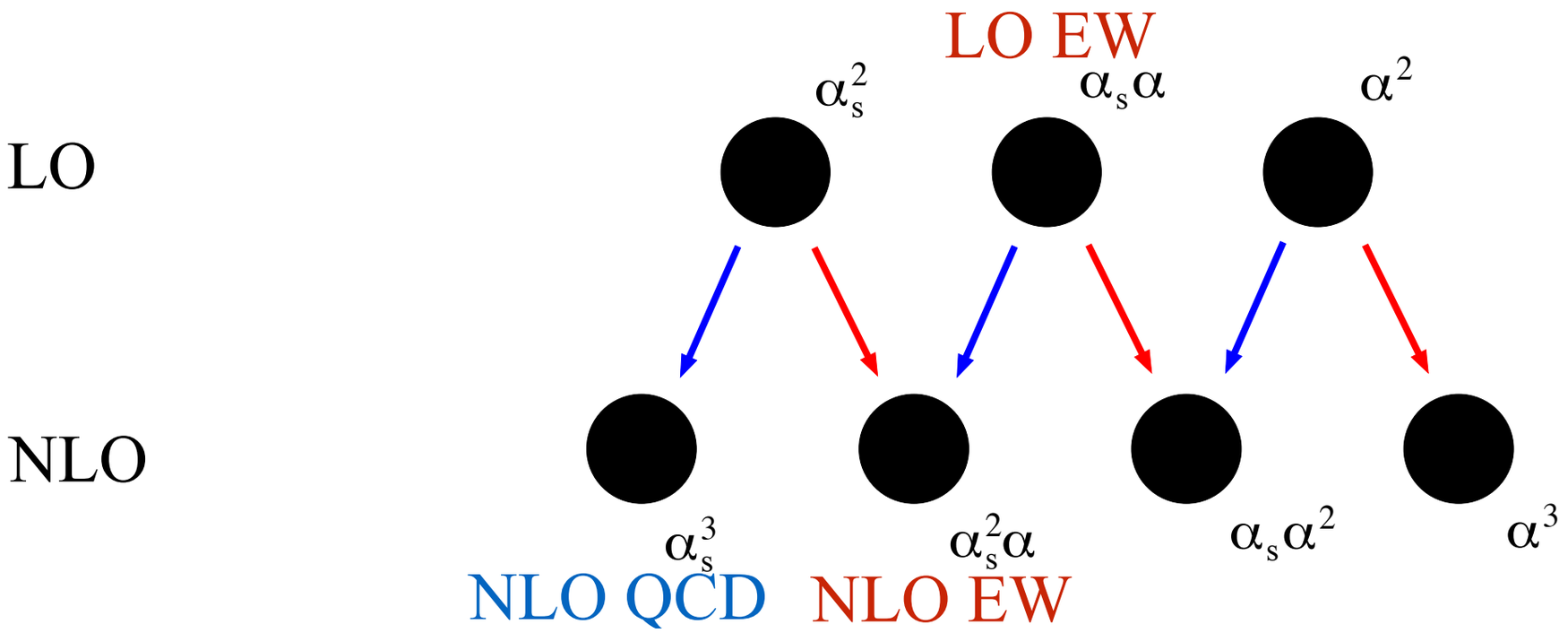
Multiplicative combination



MULTIPLICATIVE

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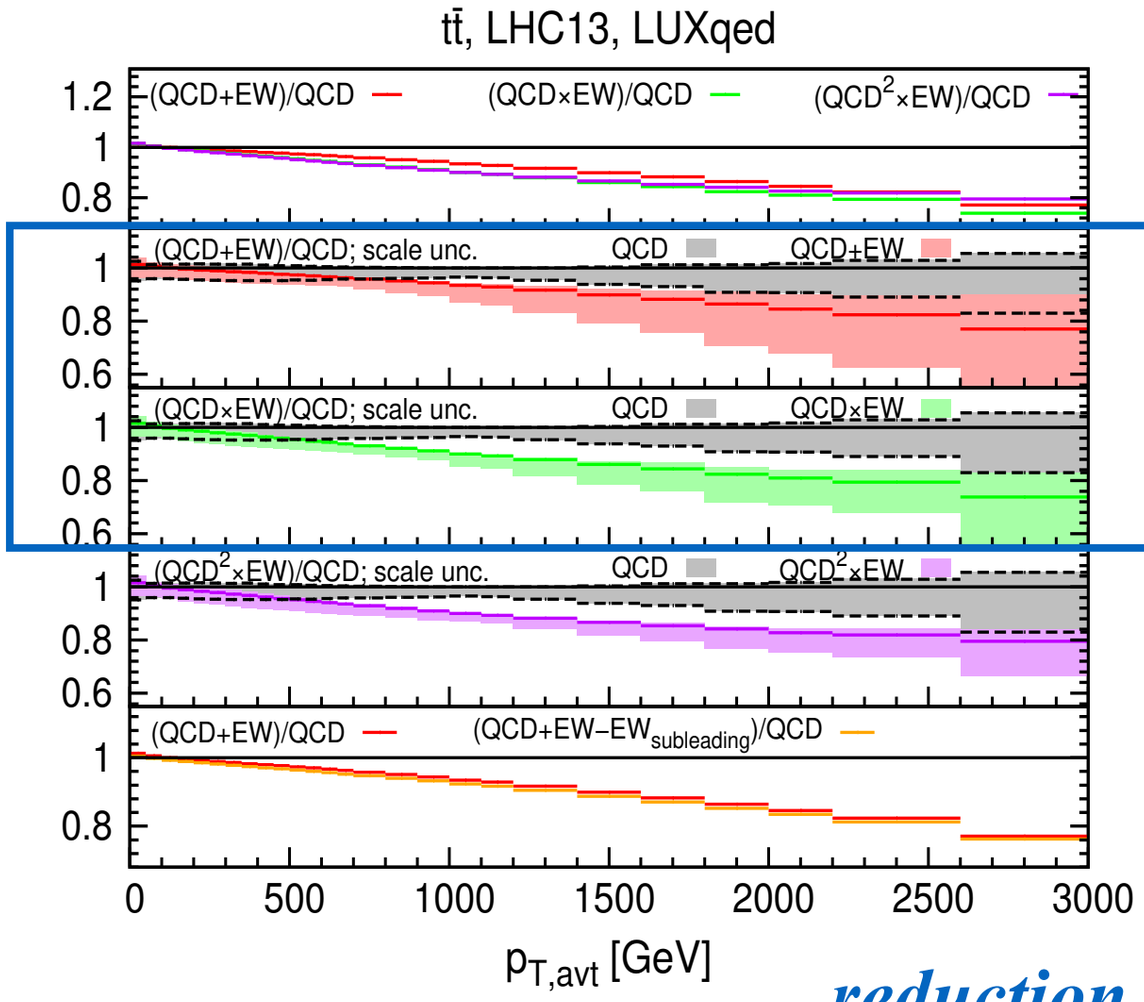
Results

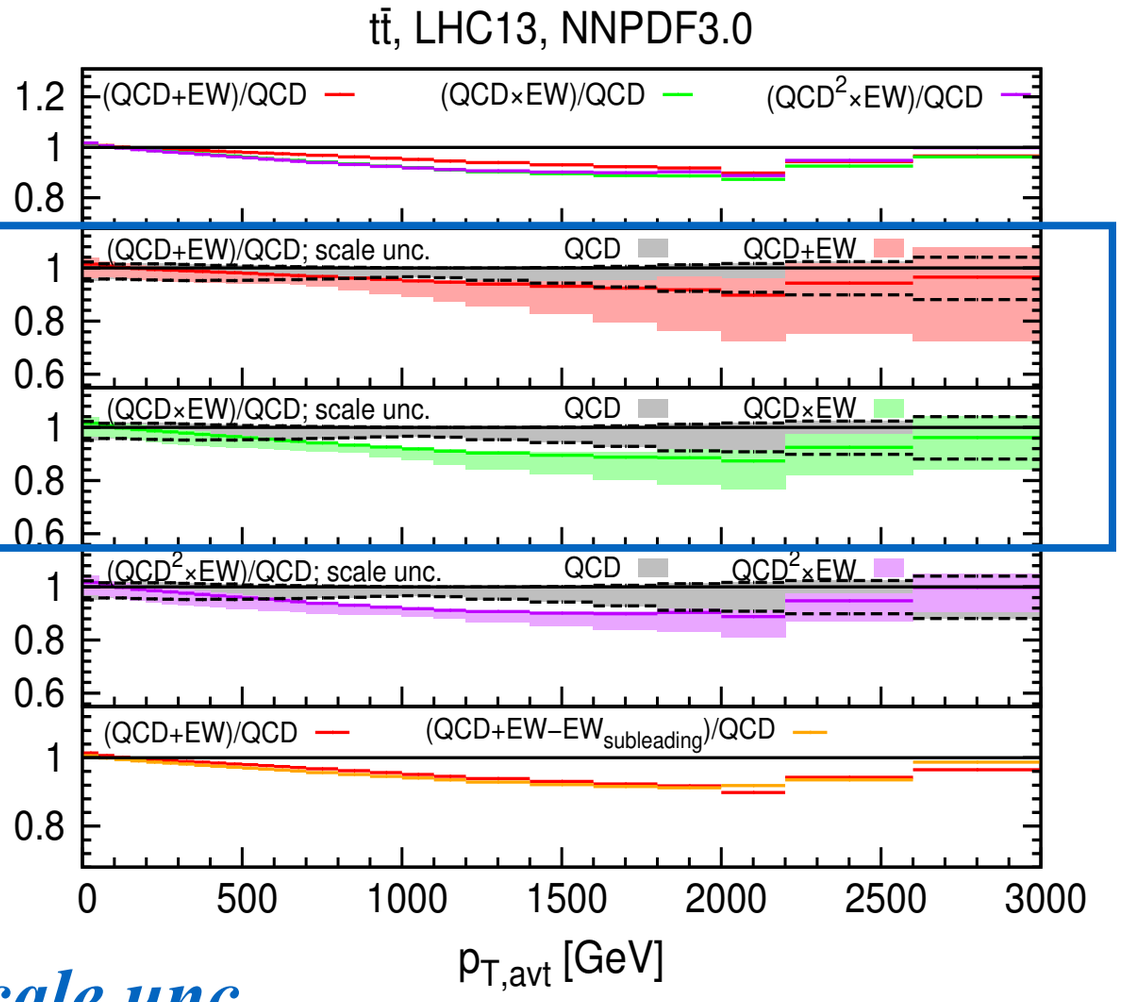
$p_{T,\mathrm{avt}}$

13 TeV

ADDITIVE

MULTIPLICATIVE





LUXQED

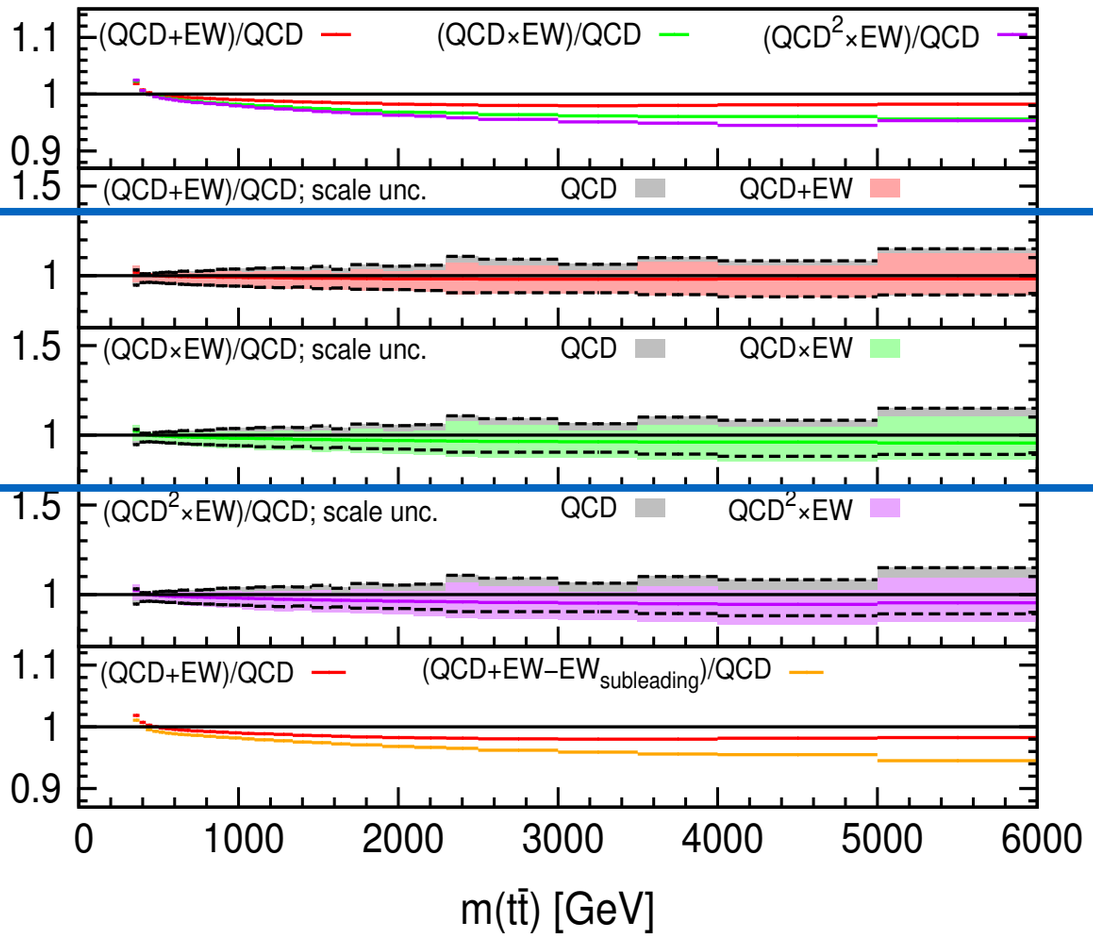
NNPDF3.0QED

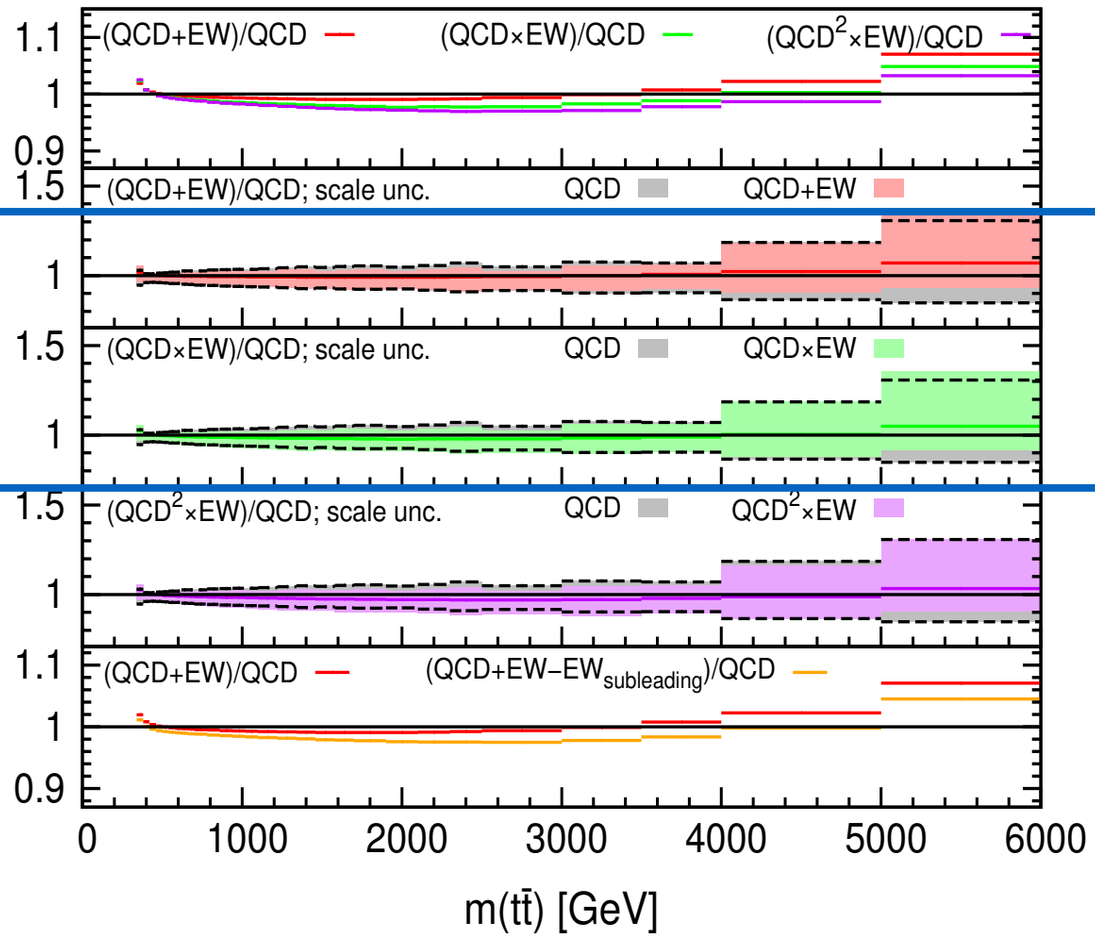
reduction of scale unc. due to EW corrections, QCD and QCDxEW do not overlap (with LUXQED)

$m(t\bar{t})$ 13 TeV

ADDITIVE

MULTIPLICATIVE





QCD+EW ~ QCDxEW

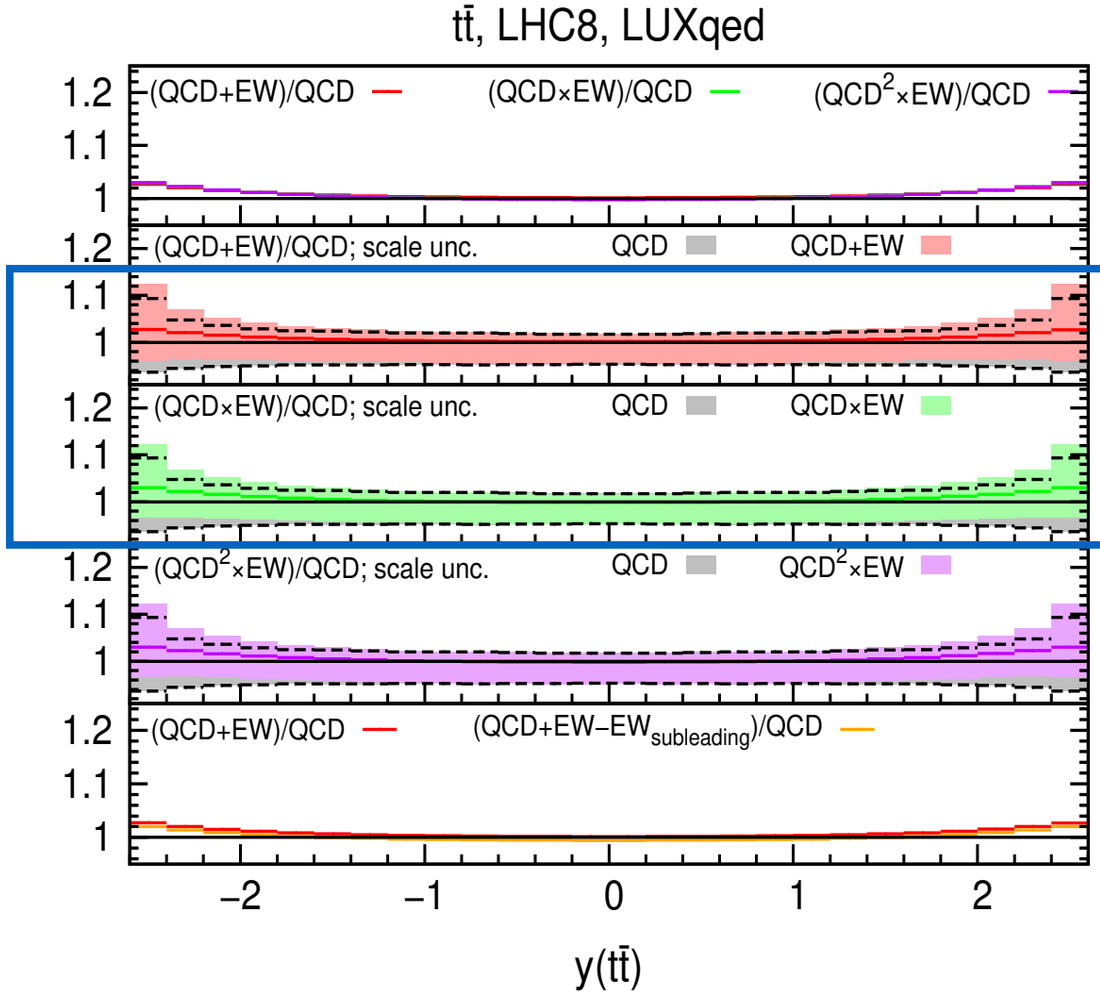
LUXQED NNPDF3.0QED

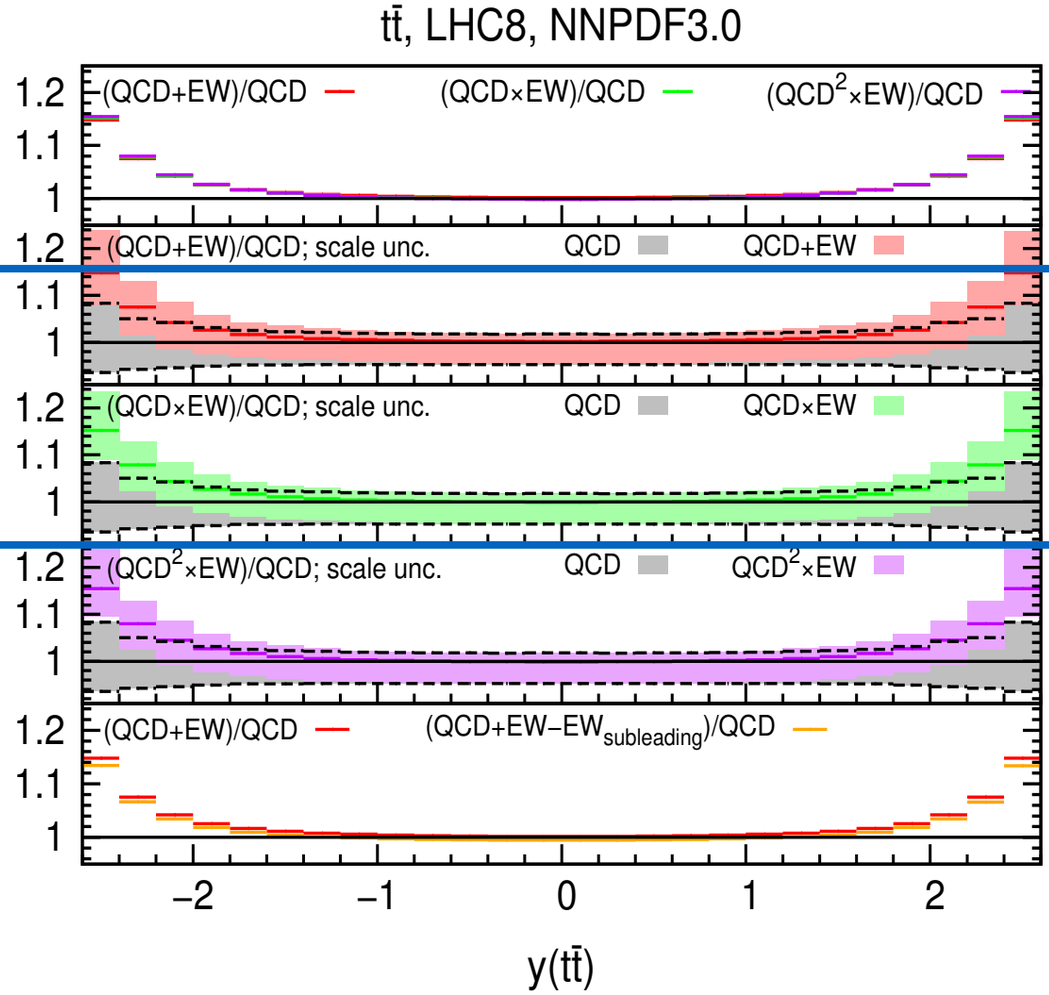
$y(t\bar{t})$

8 TeV

ADDITIVE

MULTIPLICATIVE





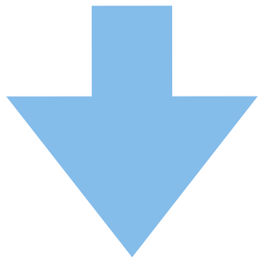
QCD+EW ~ QCDxEW

LUXQED

NNPDF3.0QED

Results

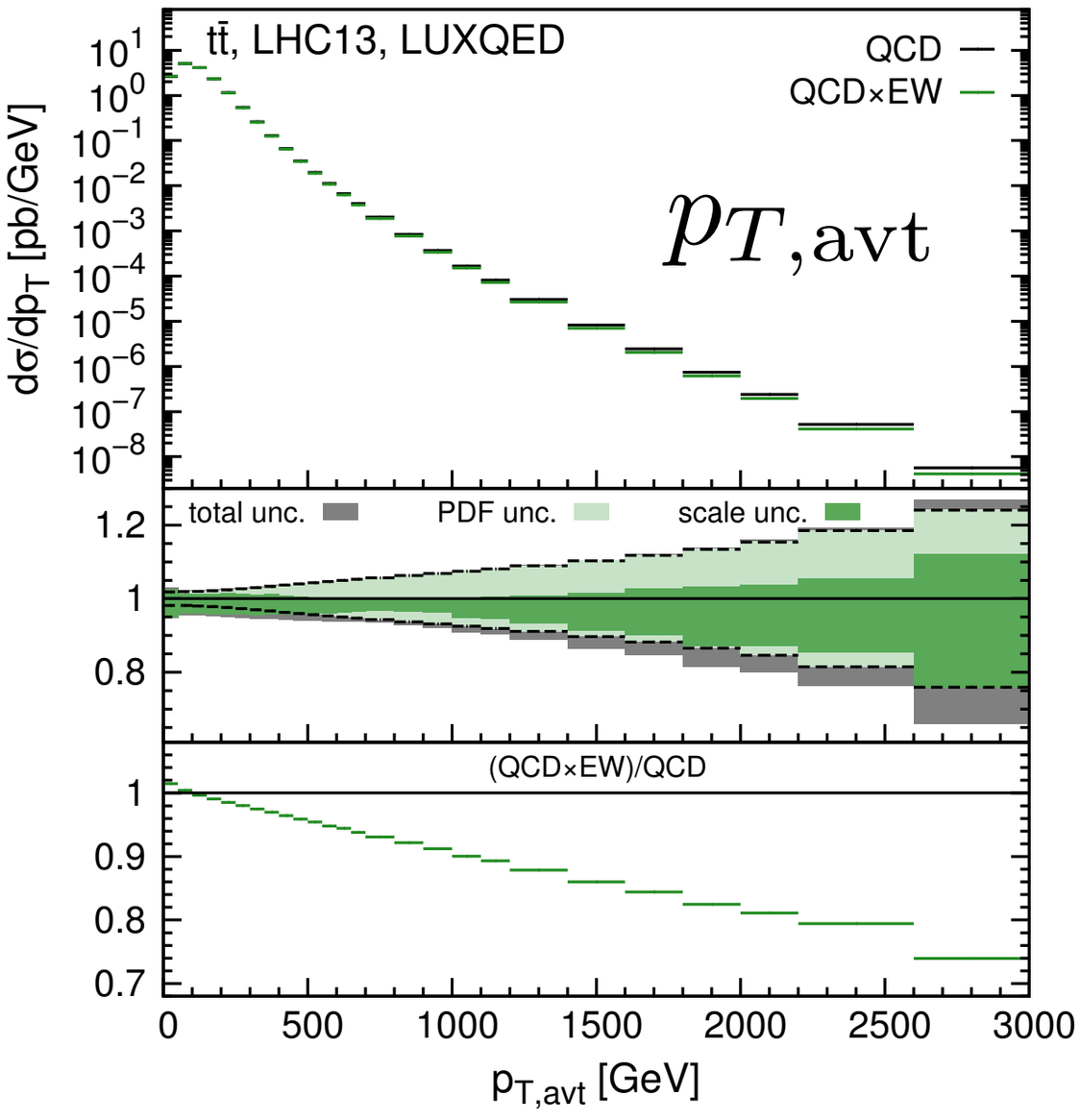
Best predictions

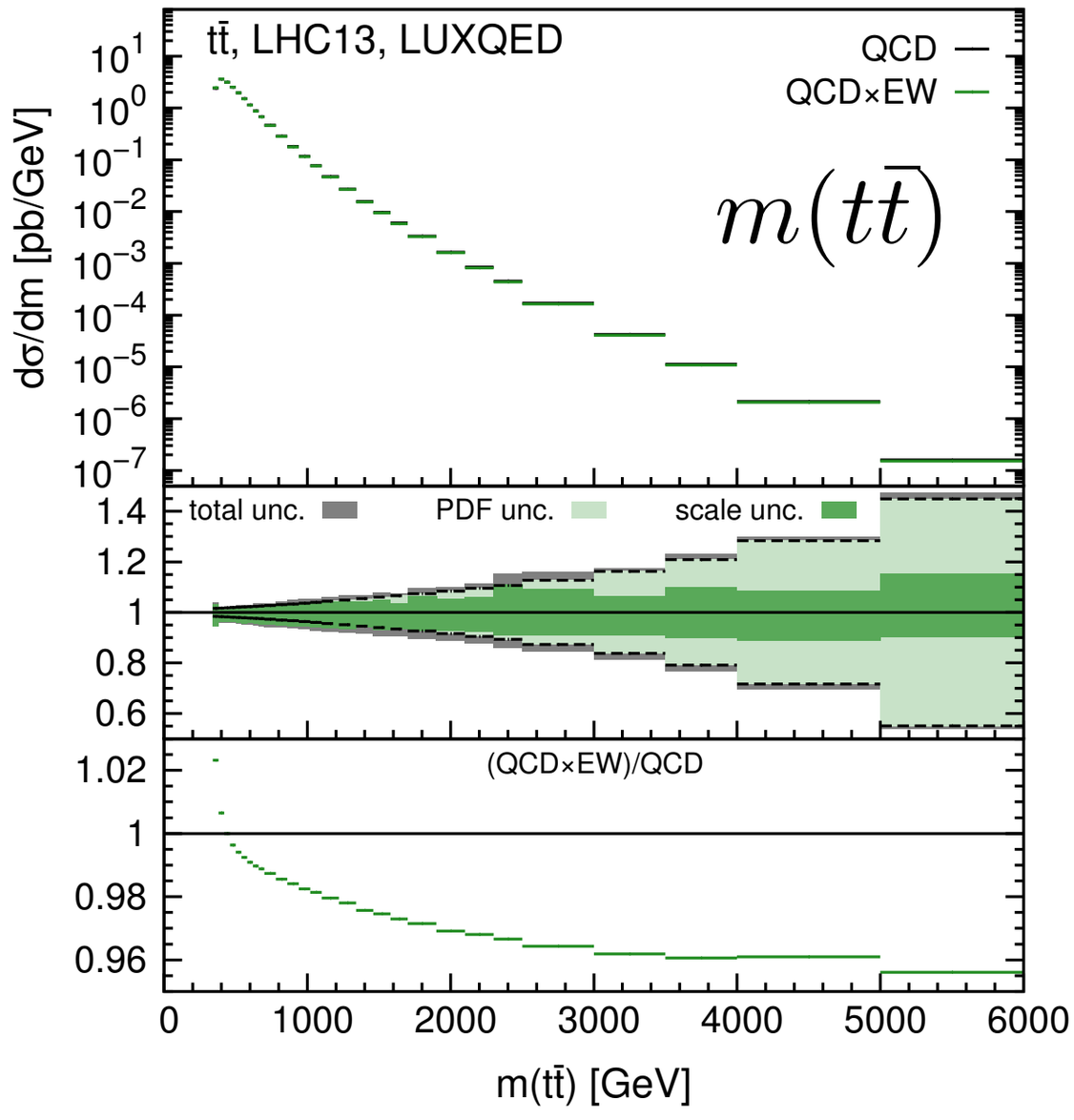


MULTIPLICATIVE
with LUXQED

13 TeV

MULTIPLICATIVE with LUXQED





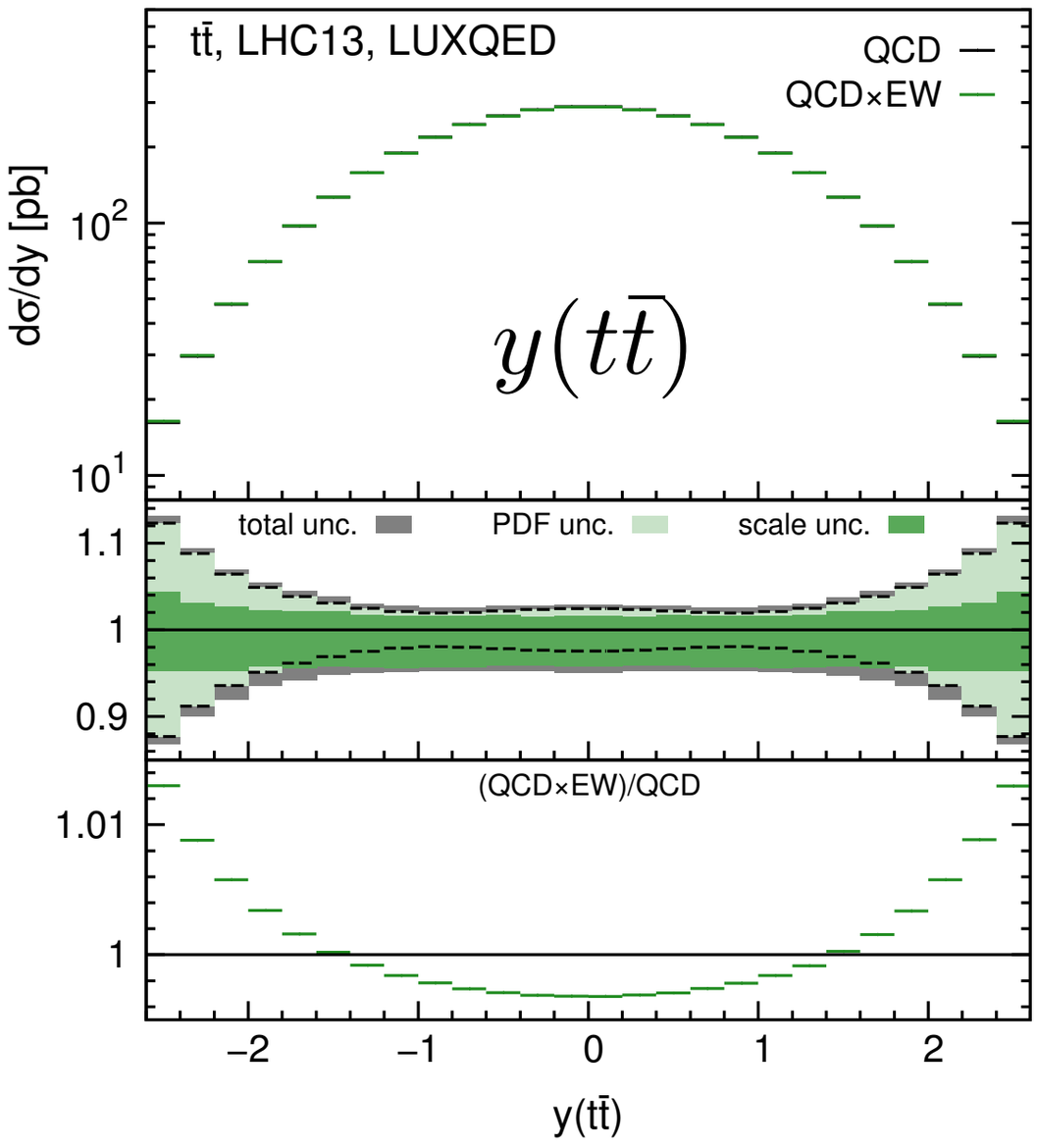
scale unc. ~ PDF unc

EW corrections ~ theory error

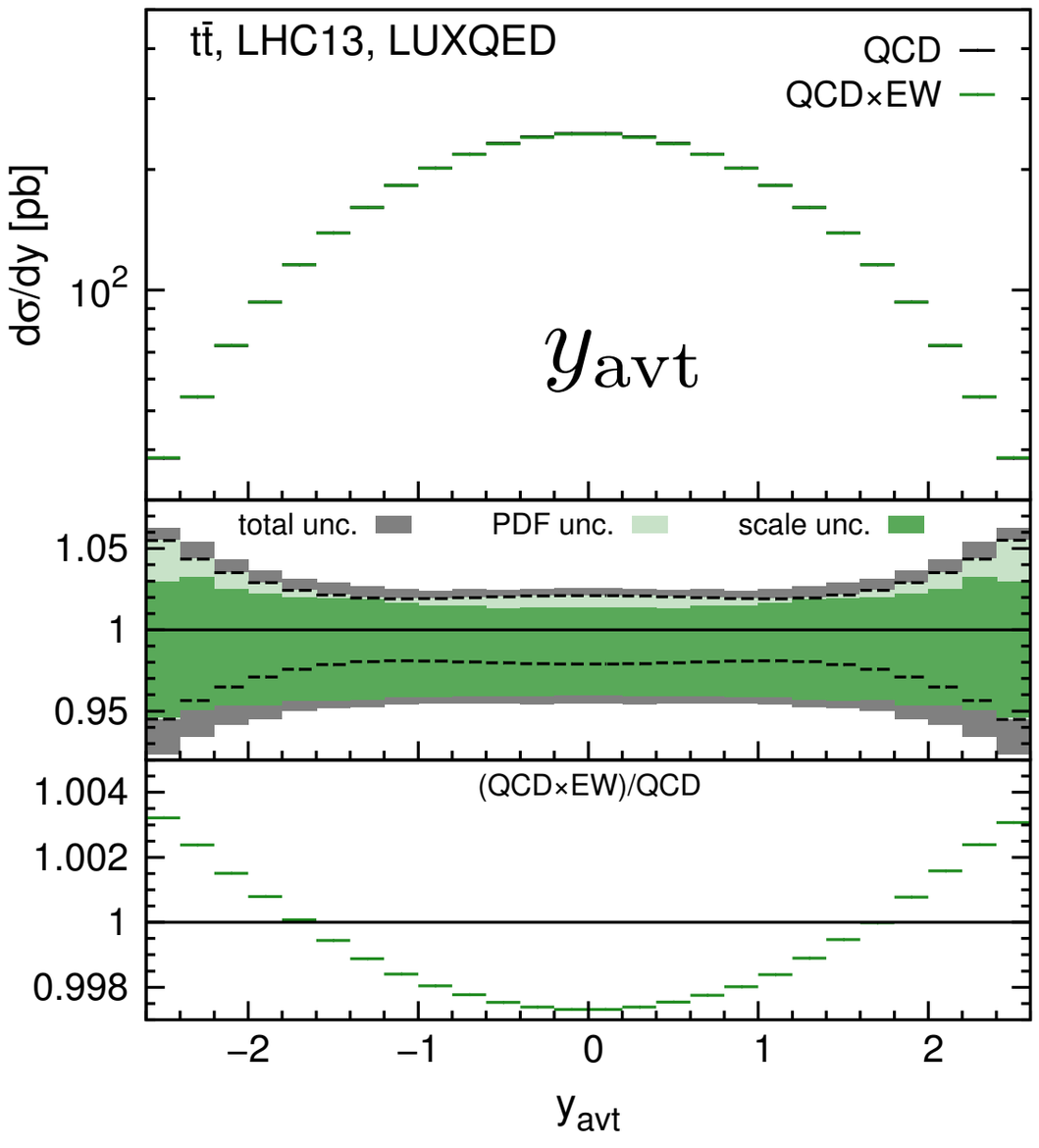
scale unc. < PDF unc

13 TeV

MULTIPLICATIVE with LUXQED



scale unc. ~ PDF unc, larger PDF unc. at large y



scale unc. ~ PDF unc,

Conclusion

We provided predictions at NNLO QCD accuracy and including EW corrections (complete-NLO) for ttbar production at the LHC (8, 13 TeV).

In pt distributions at 13 TeV EW corrections are outside the NNLO QCD scale-uncertainty band (for LUXQED). Additively combining EW corrections, the total scale uncertainty is larger than with QCD only.

Results are strongly affected by the photon PDF parametrization (LUXqed vs. NNPDF3.0) and LUXqed should be preferred.

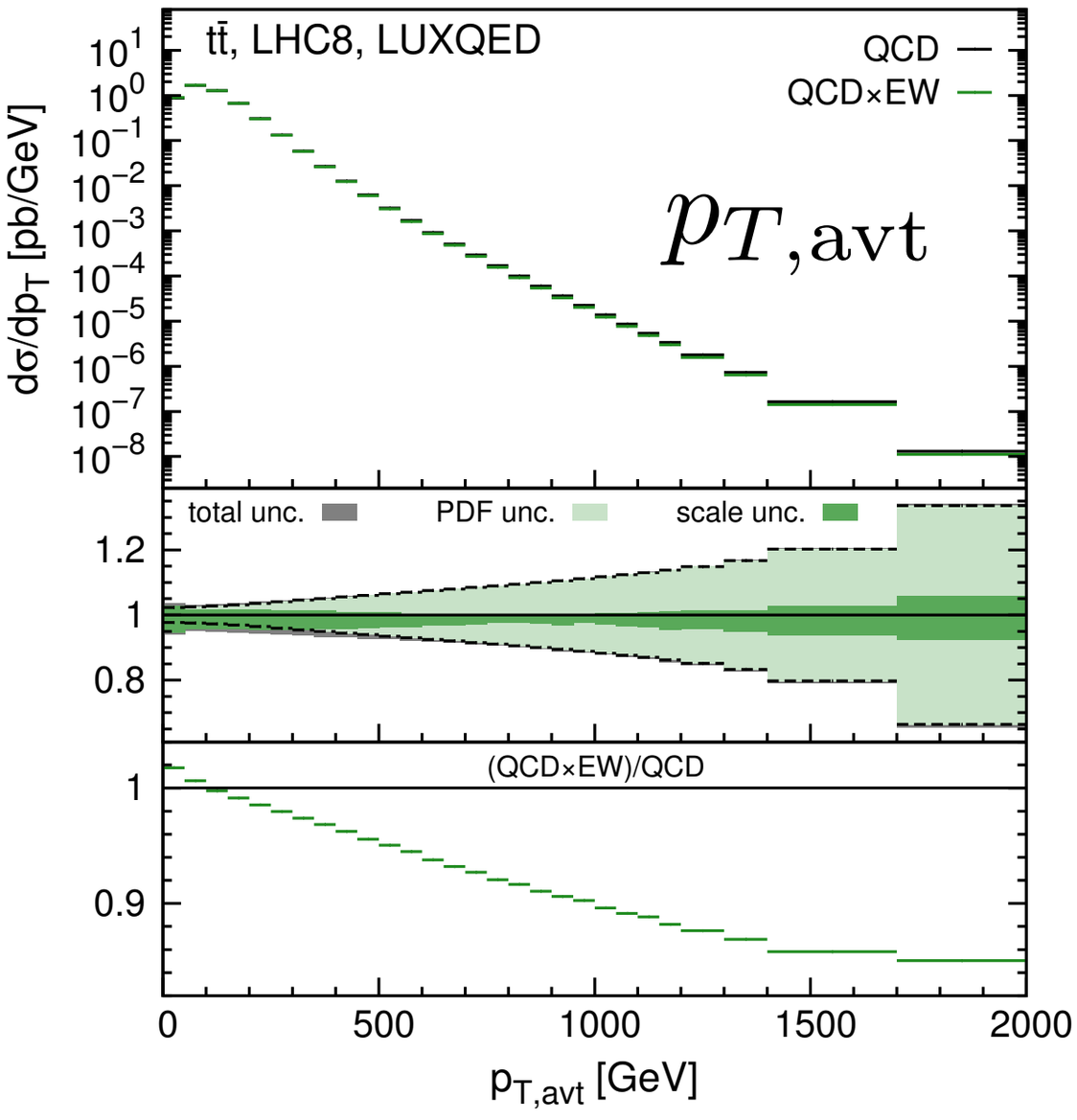
The combination in the multiplicative approach leads to a reduction of scale uncertainties. Still, in pt distribution, EW corrections are comparable to the total theory uncertainty (scale+PDF), and QCD and QCDxEW bands do not overlap.

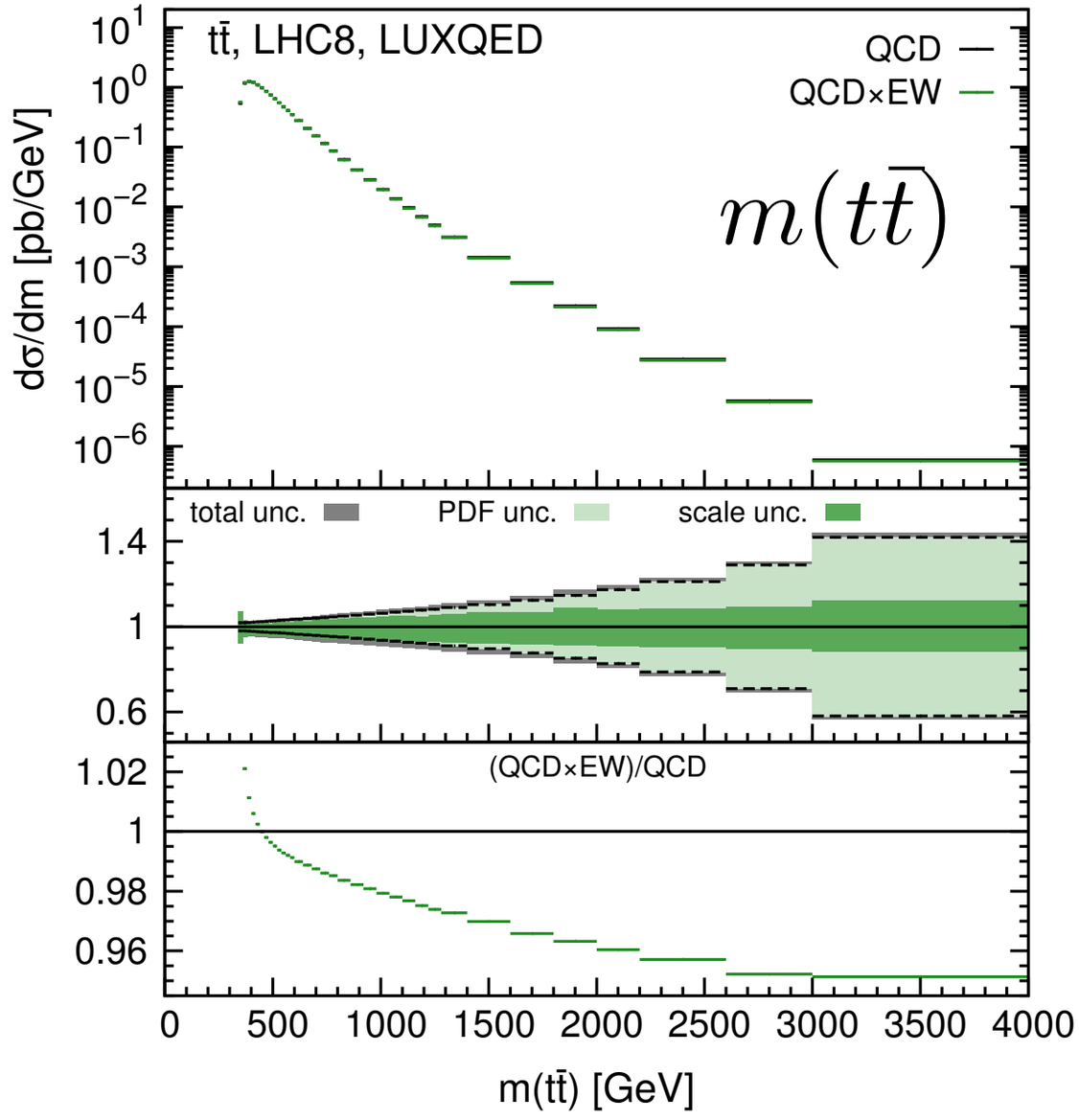
more results and histograms available at
http://www.precision.hep.phy.cam.ac.uk/results/ttbar-nnloqcd-nloew/

EXTRA SLIDES

8 TeV

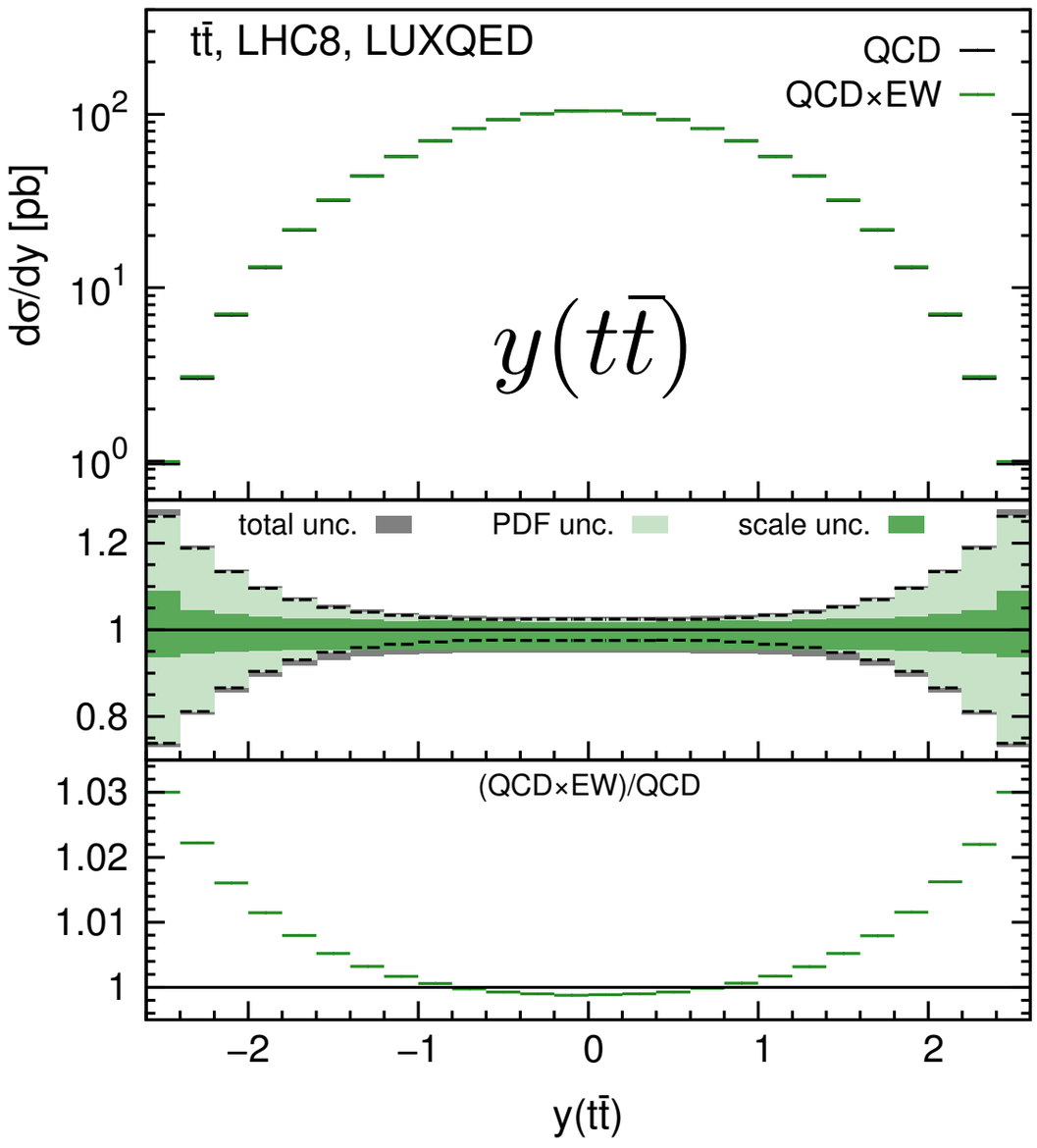
MULTIPLICATIVE with LUXQED

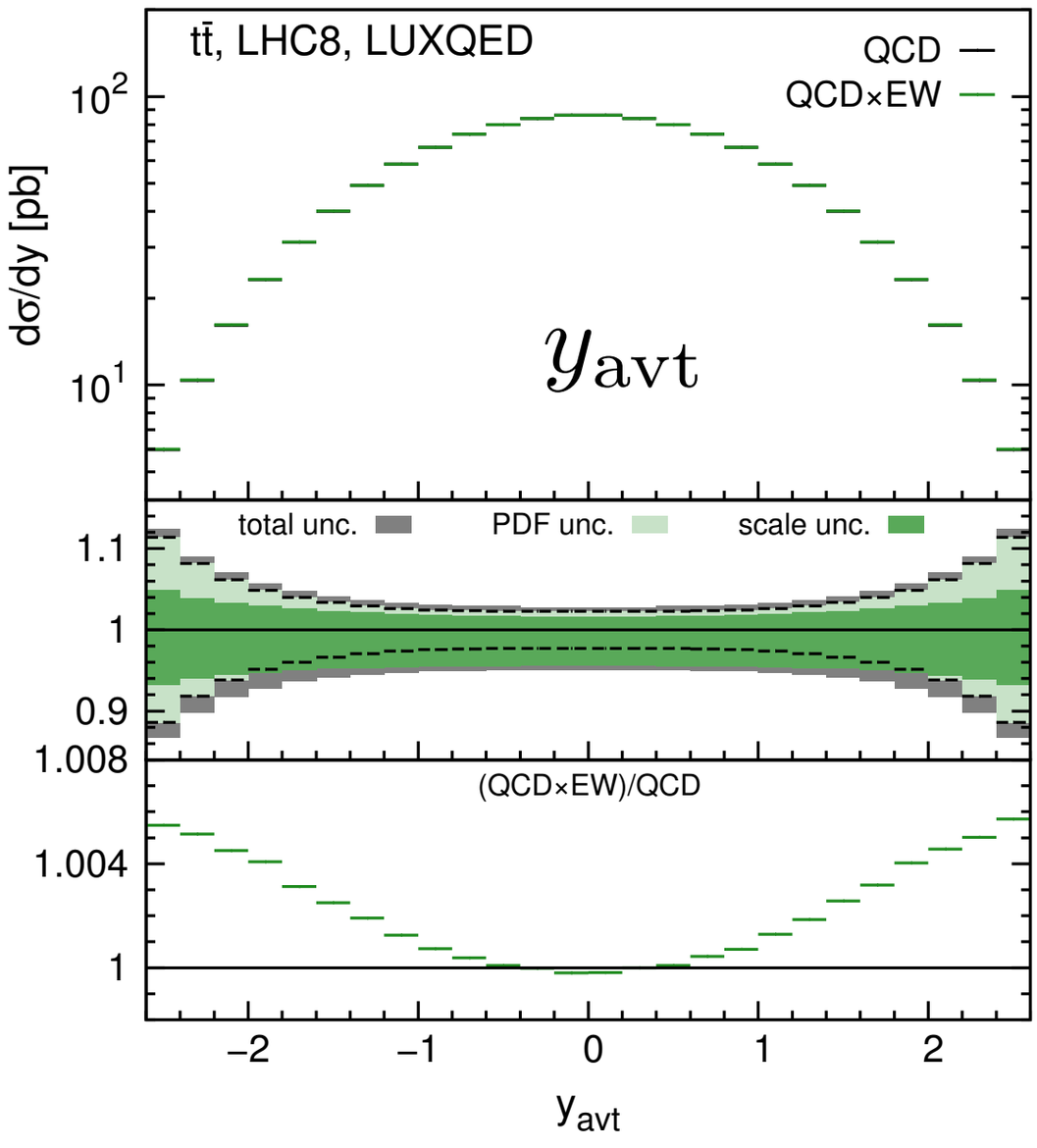




13 TeV

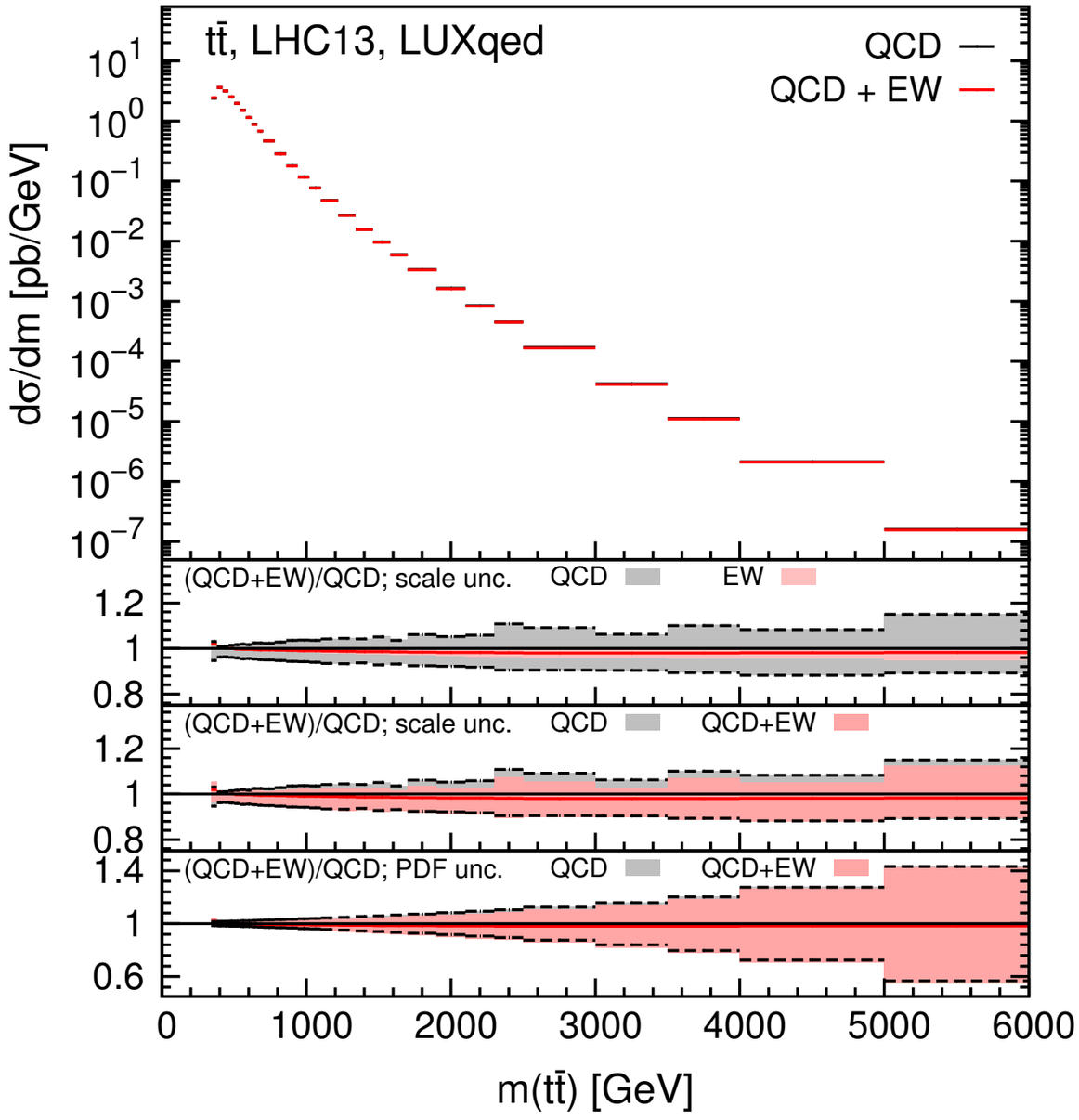
MULTIPLICATIVE with LUXQED



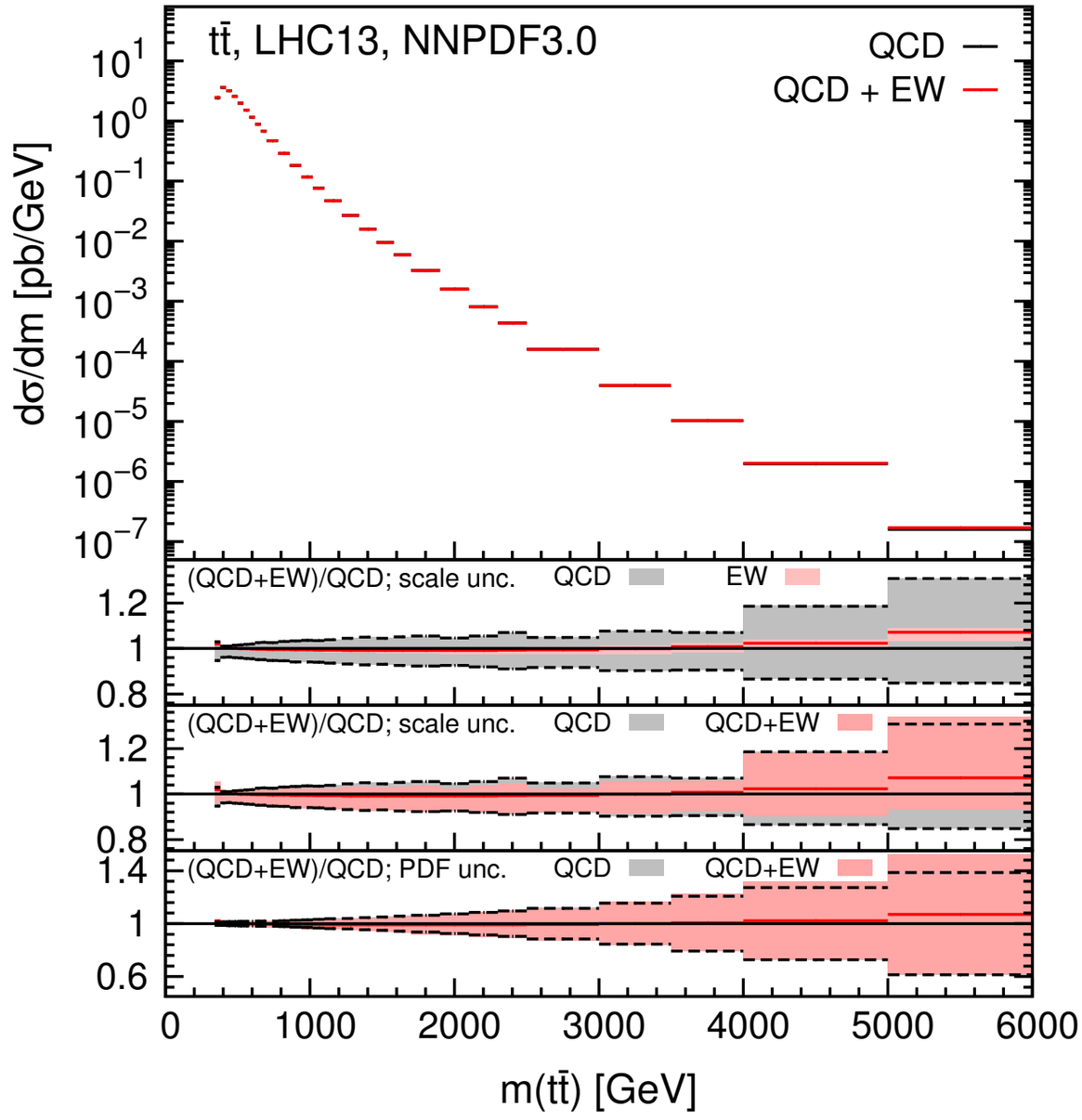


$m(t\bar{t})$

13 TeV



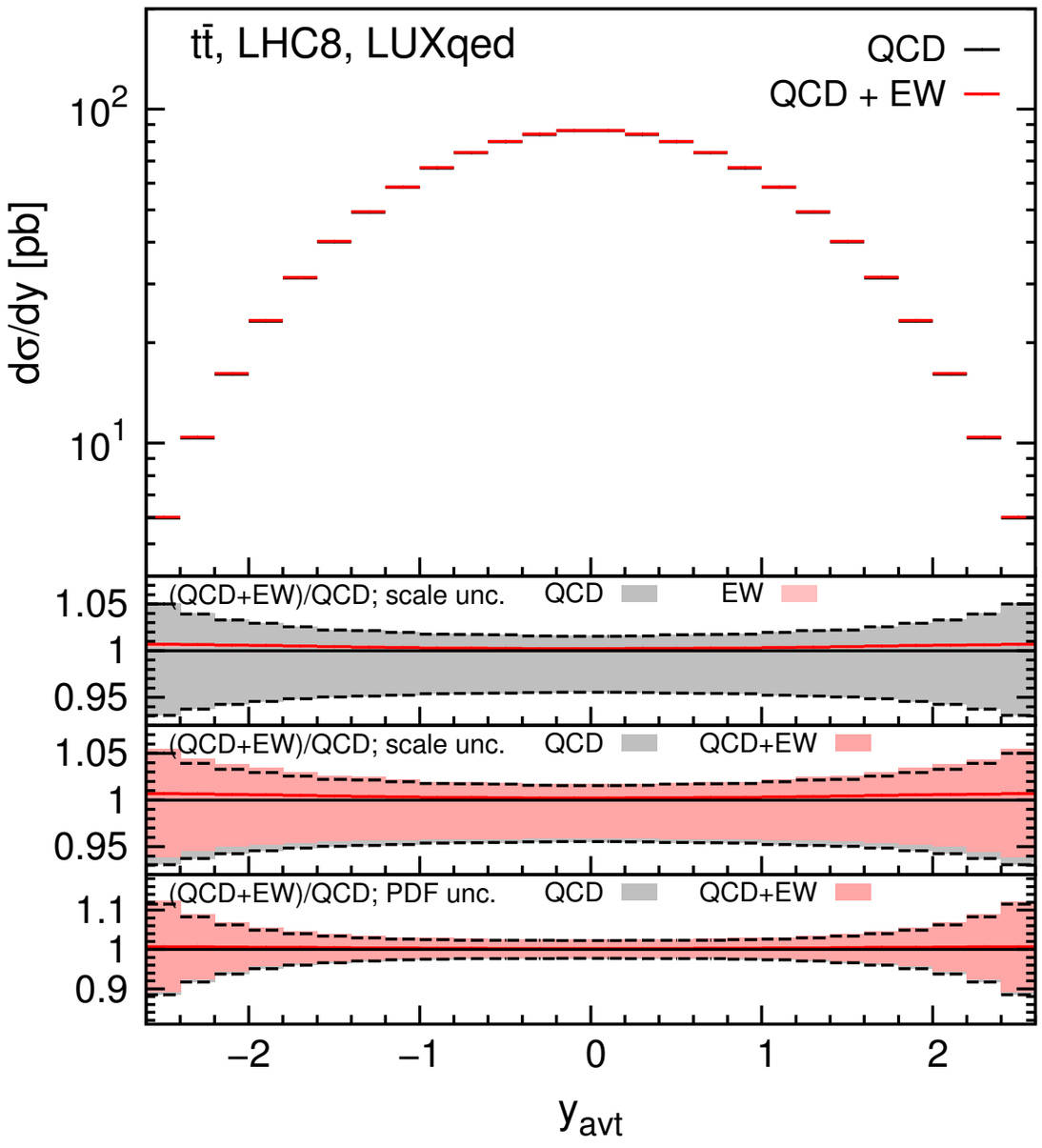
LUXQED



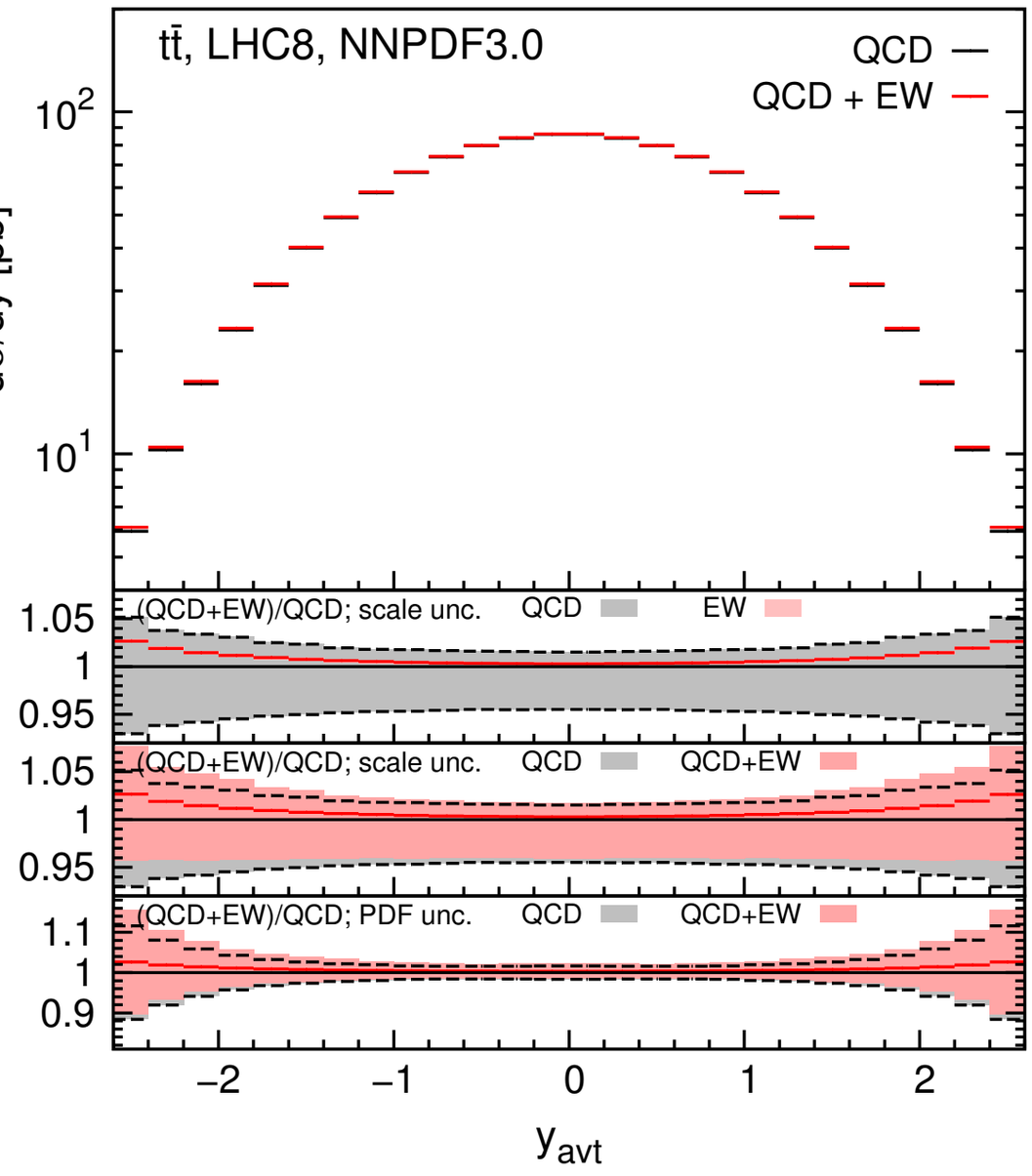
NNPDF3.0QED

8 TeV

y_{avt}

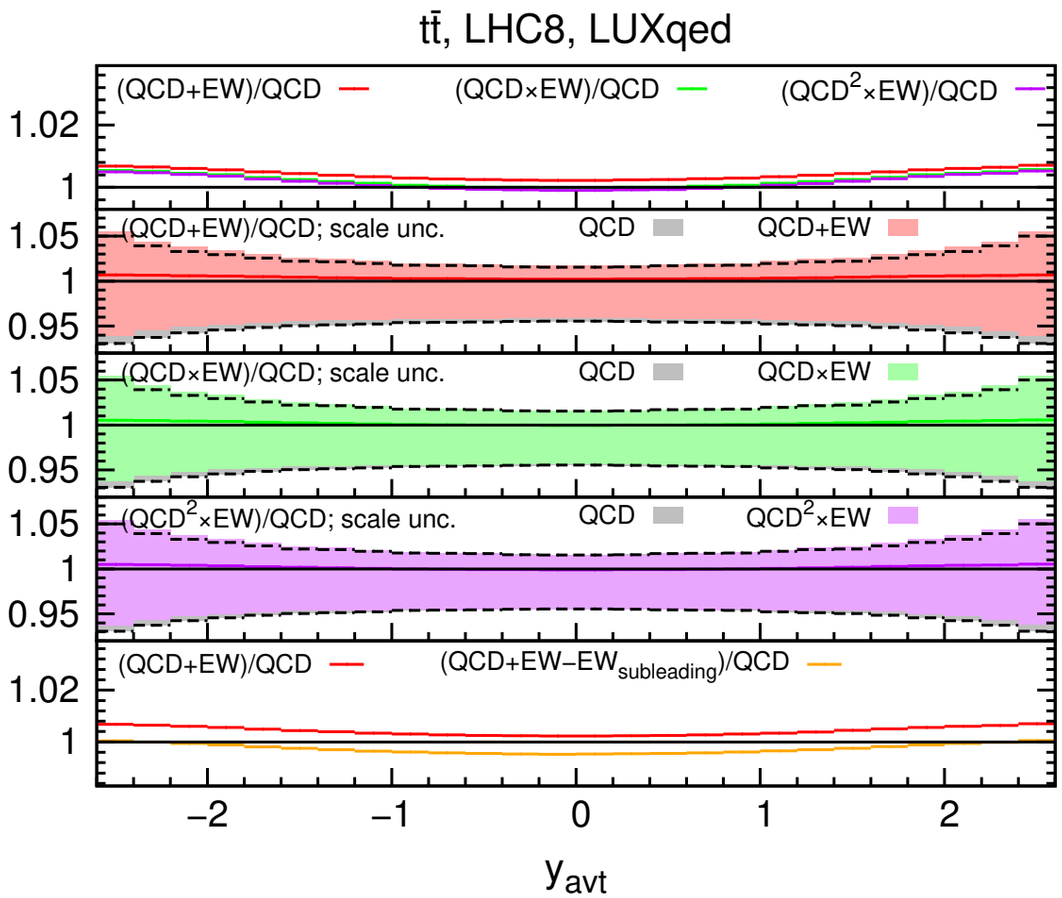


LUXQED

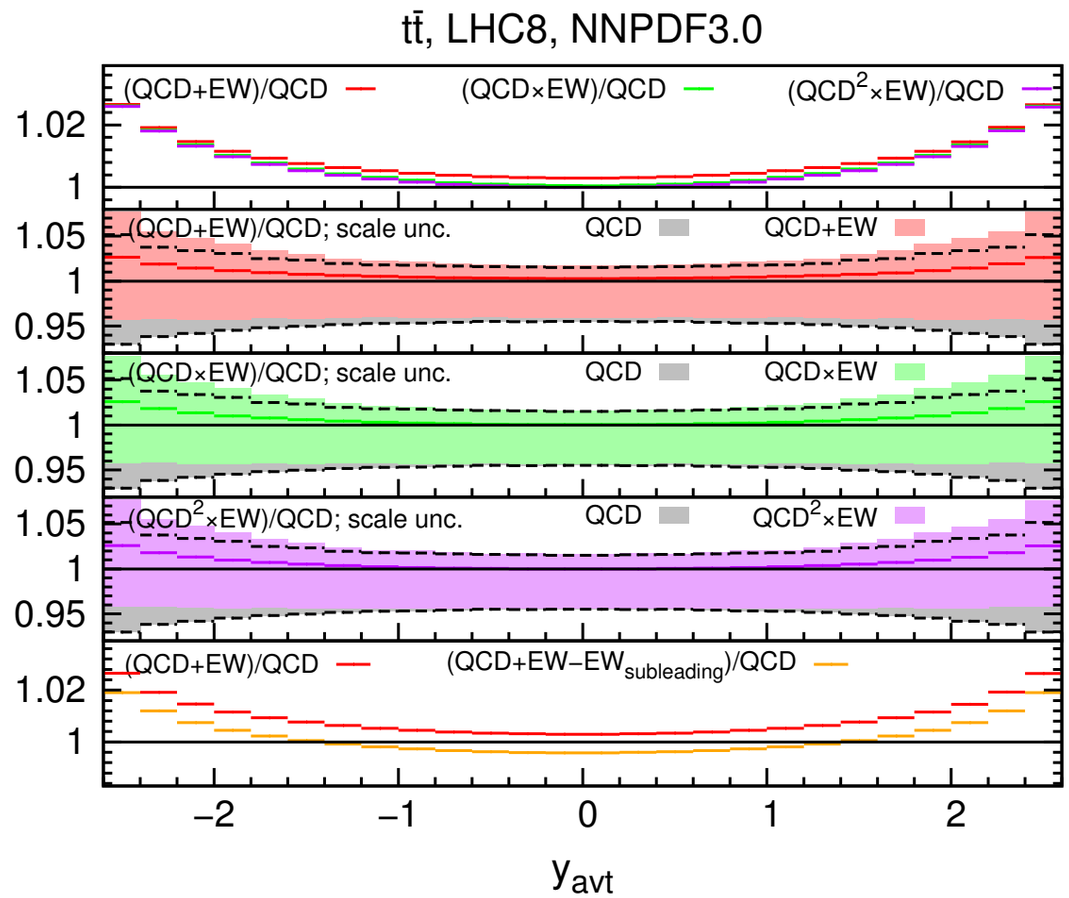


NNPDF3.0QED

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

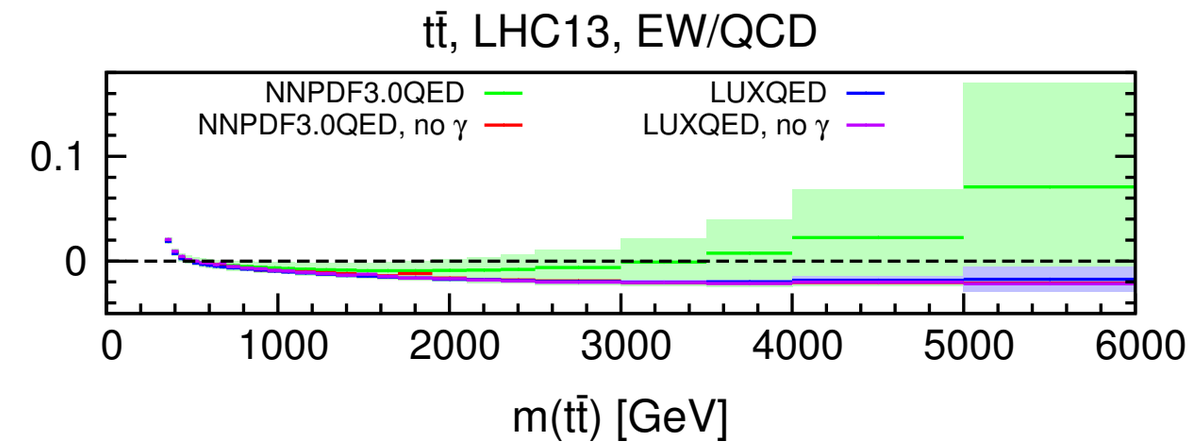


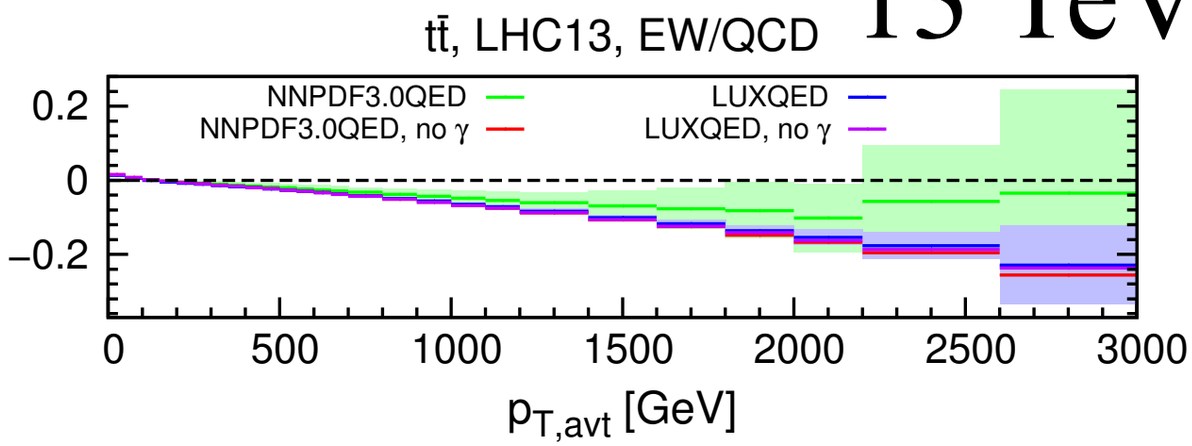
LUXQED

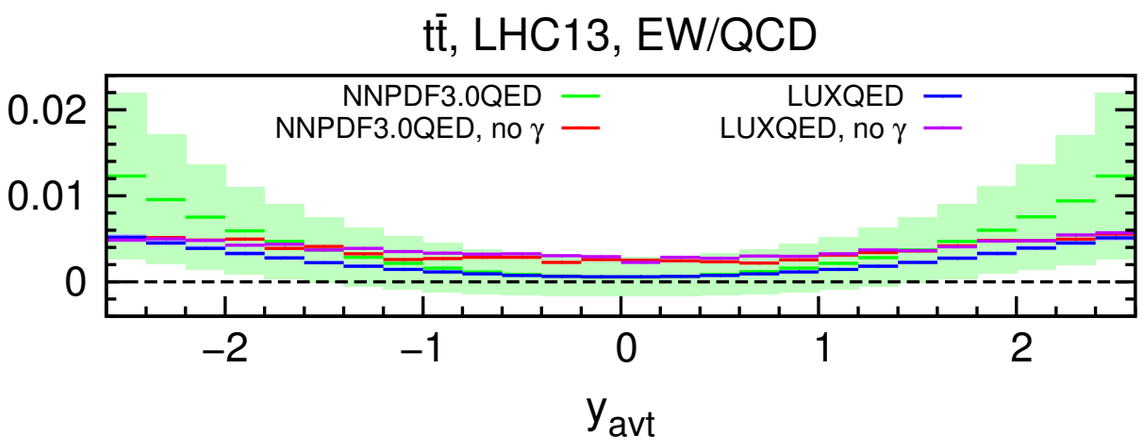


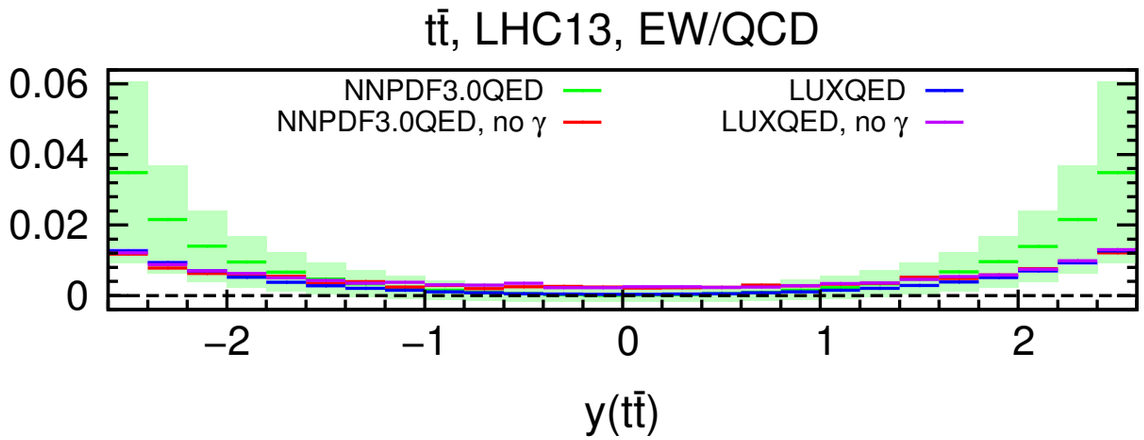
NNPDF3.0QED

13 TeV

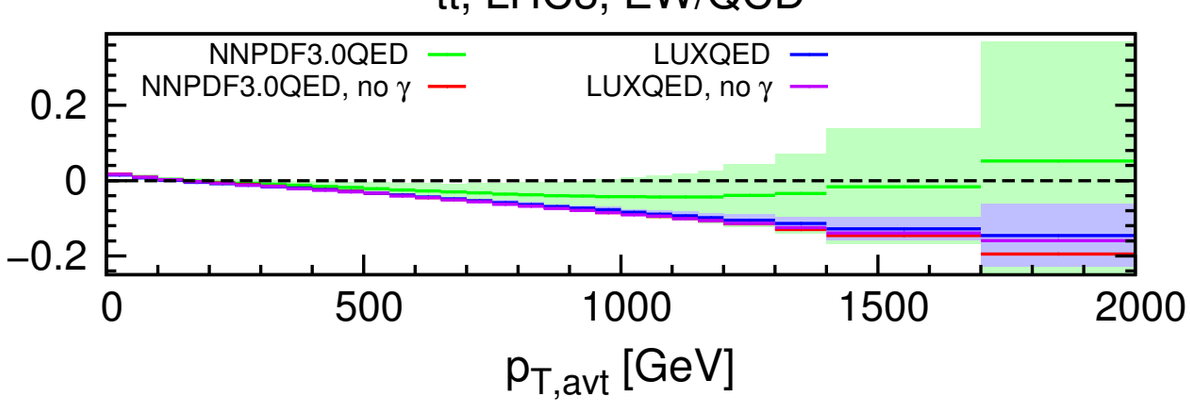

tt̄, LHC13, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.1
0
0
1000
2000
3000
4000
5000
6000
m(tt̄) [GeV]

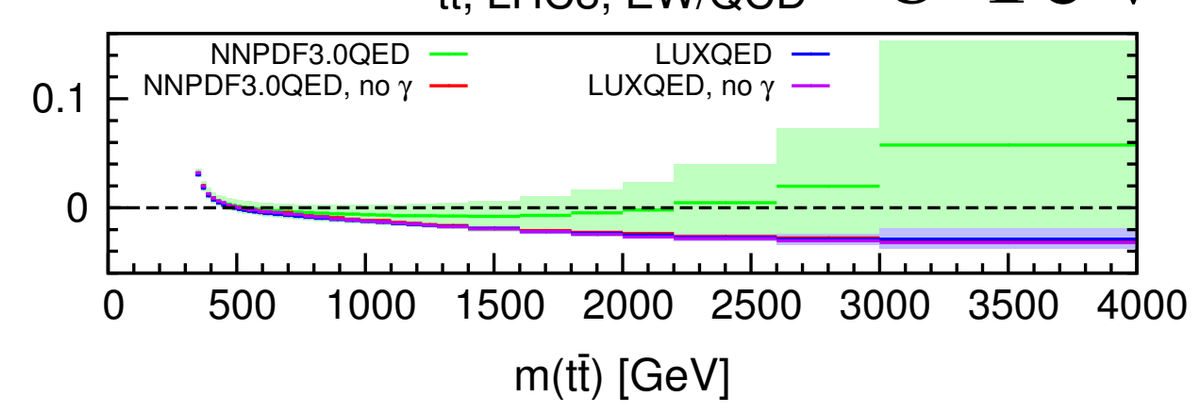

tt̄, LHC13, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.2
0
−0.2
0
500
1000
1500
2000
2500
3000
p_T,avt [GeV]

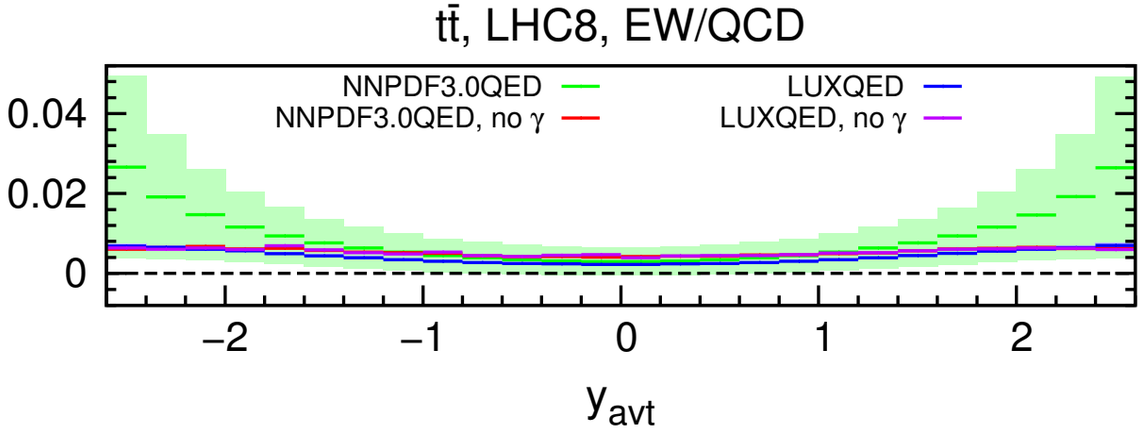

tt̄, LHC13, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.02
0.01
0
−2
−1
0
1
2
y_avt

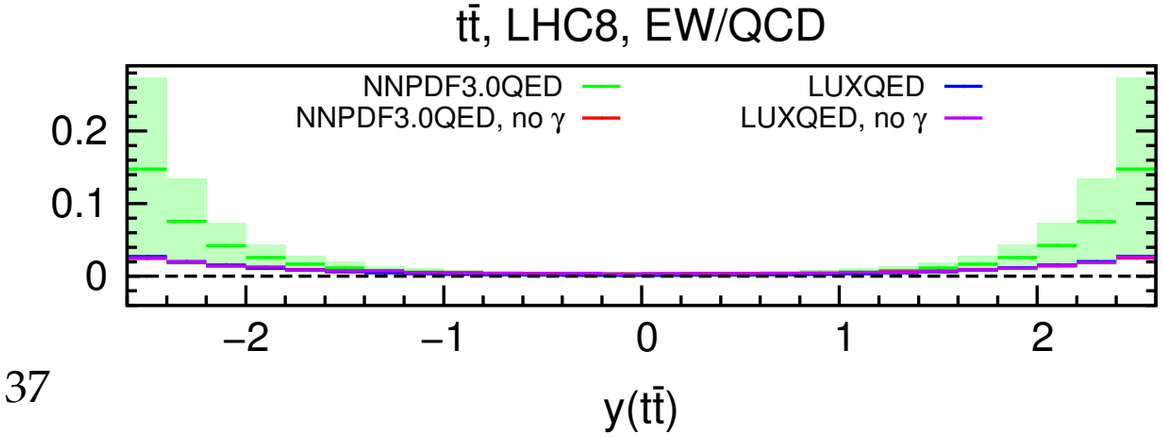

tt̄, LHC13, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.06
0.04
0.02
0
−2
−1
0
1
2
y(tt̄)

8 TeV


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

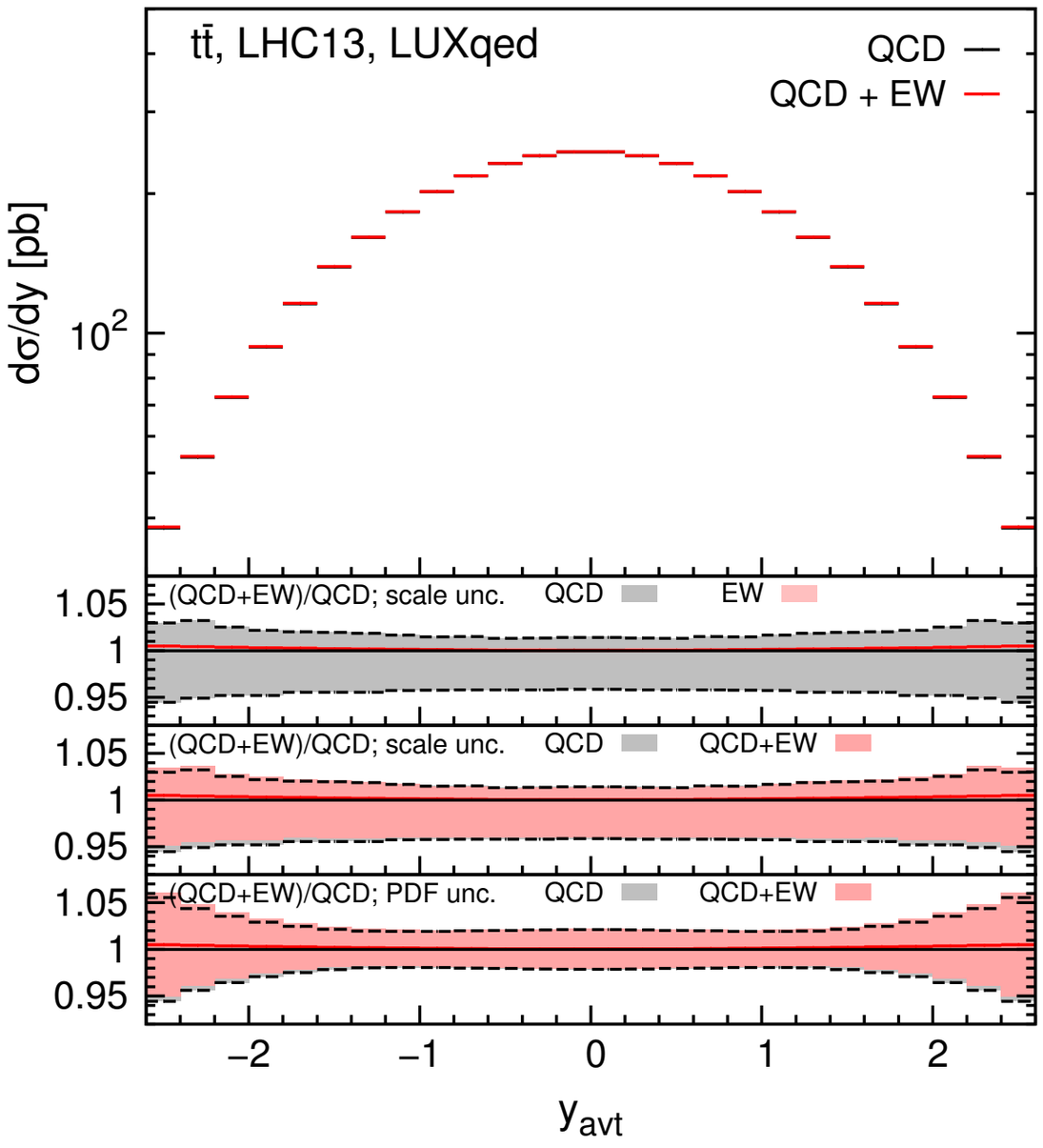

tt̄, LHC8, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.1
0
0
500
1000
1500
2000
2500
3000
3500
4000
m(tt̄) [GeV]


tt̄, LHC8, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.04
0.02
0
−2
−1
0
1
2
y_avt

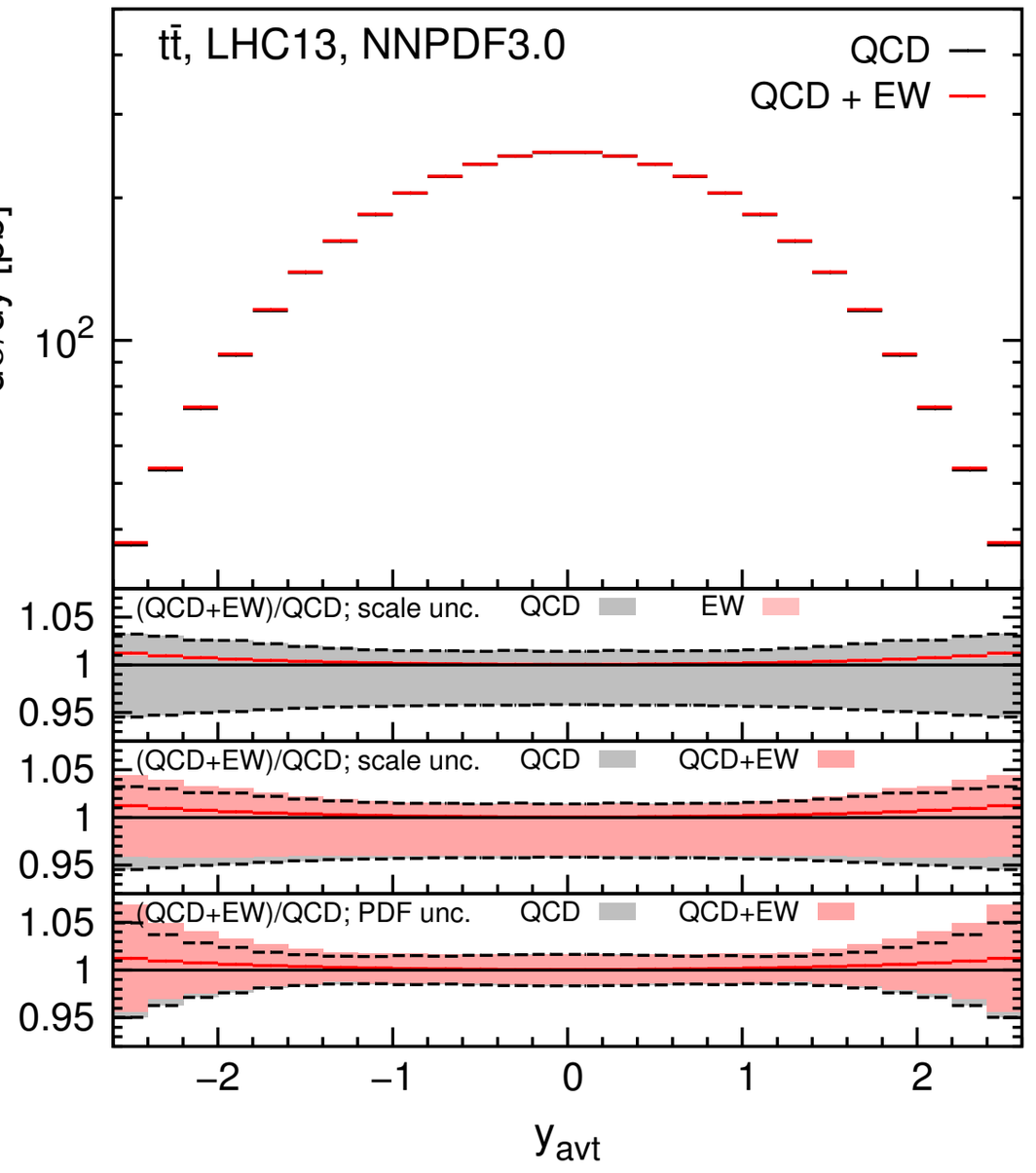

tt̄, LHC8, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.2
0.1
0
−2
−1
0
1
2
y(tt̄)

13 TeV

y_{avt}



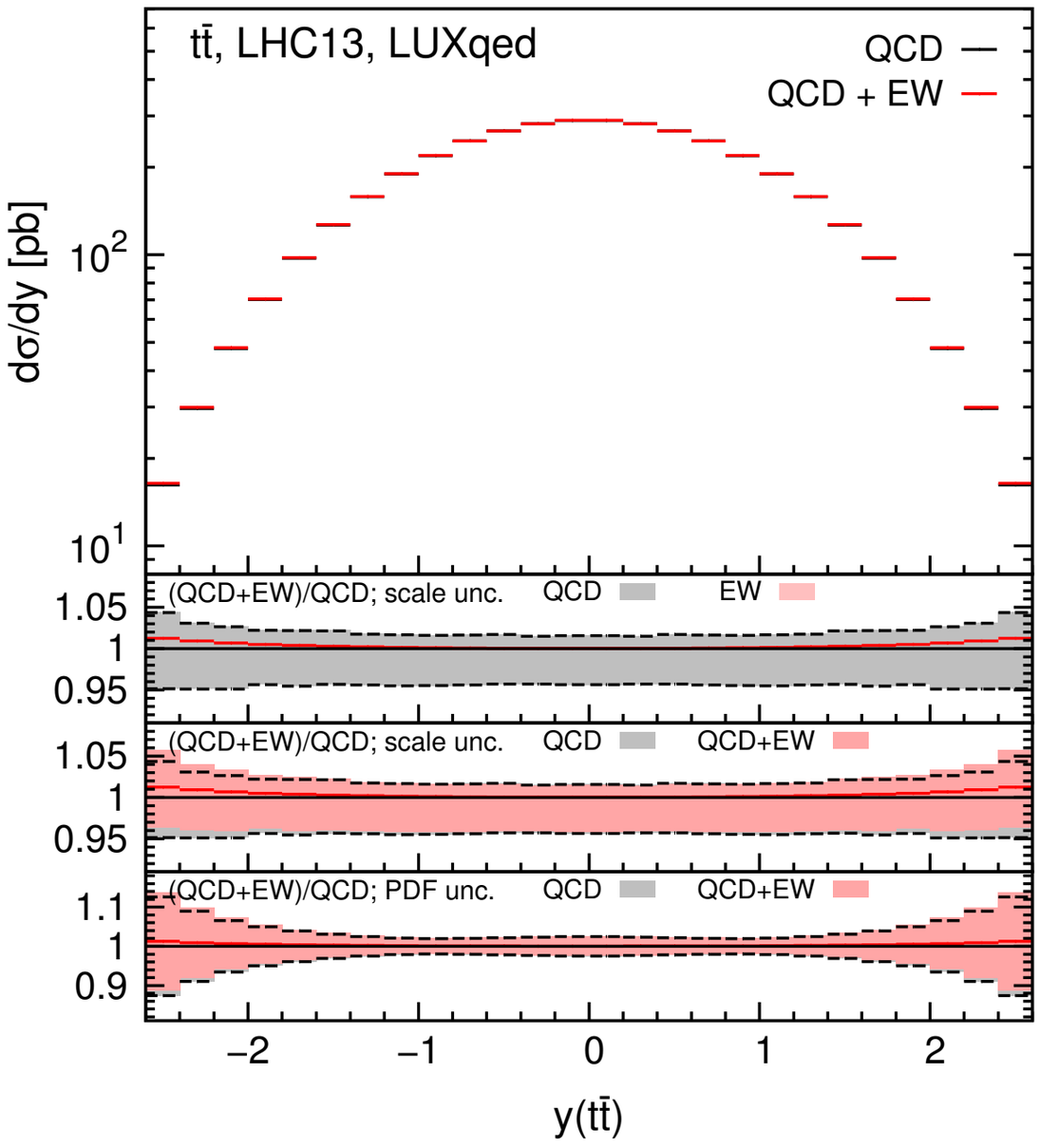
LUXQED



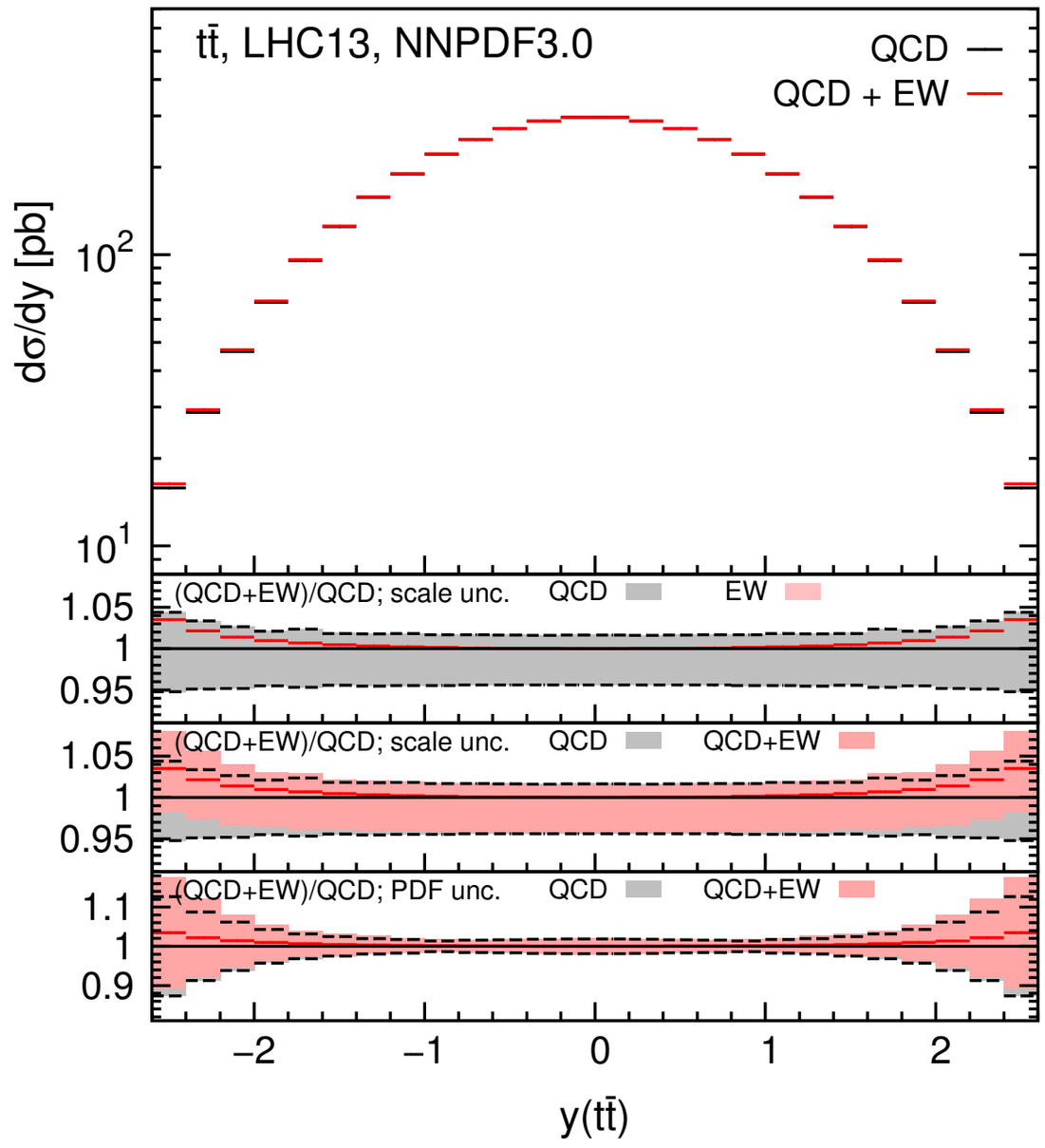
NNPDF3.0QED

$y(t\bar{t})$

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*

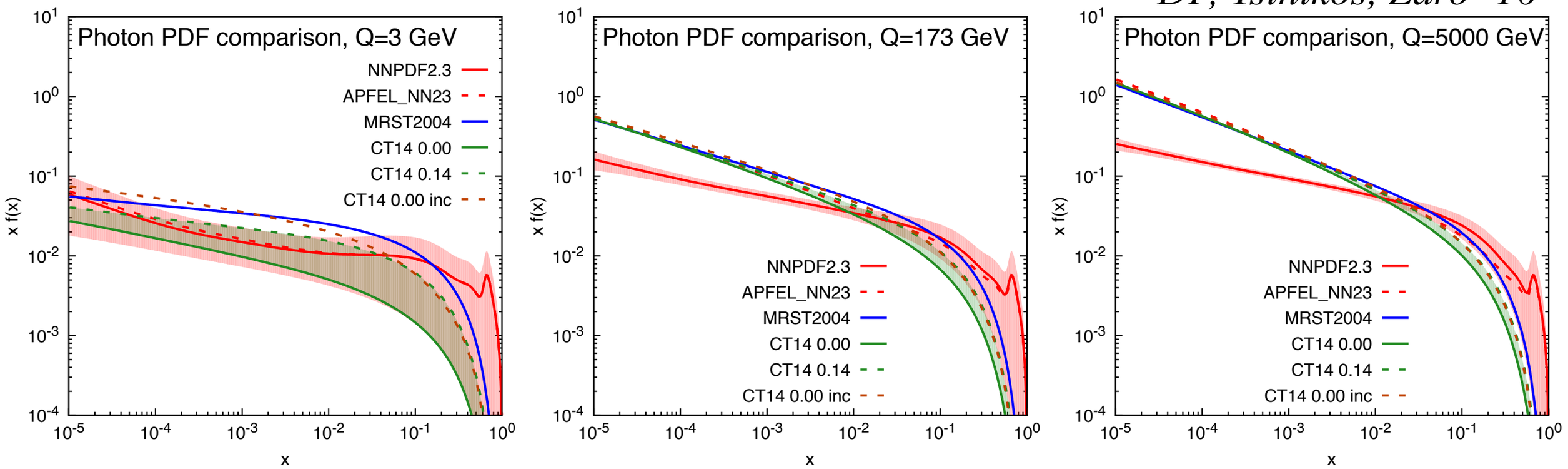
These PDF sets have at least NLO QCD + LO QED terms in the DGLAP evolution.

- 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.

The different photon PDFs …

DP, Tsinikos, Zaro '16



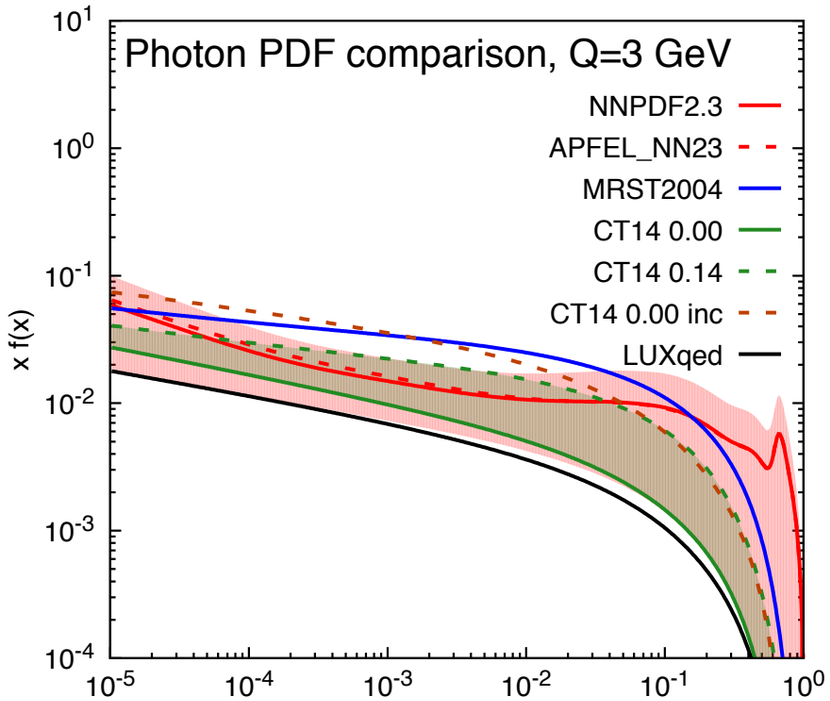
- APFEL_NN23 (*Bertone, Carrazza, DP, Zaro '15*) is at the initial scale equivalent to **NNPDF2.3QED** for all the PDFs. But, the DGLAP QCD and QED running is consistent (similar to **NNPDF3.0QED**, where also quark and gluons have been updated to **NNPDF3.0**).

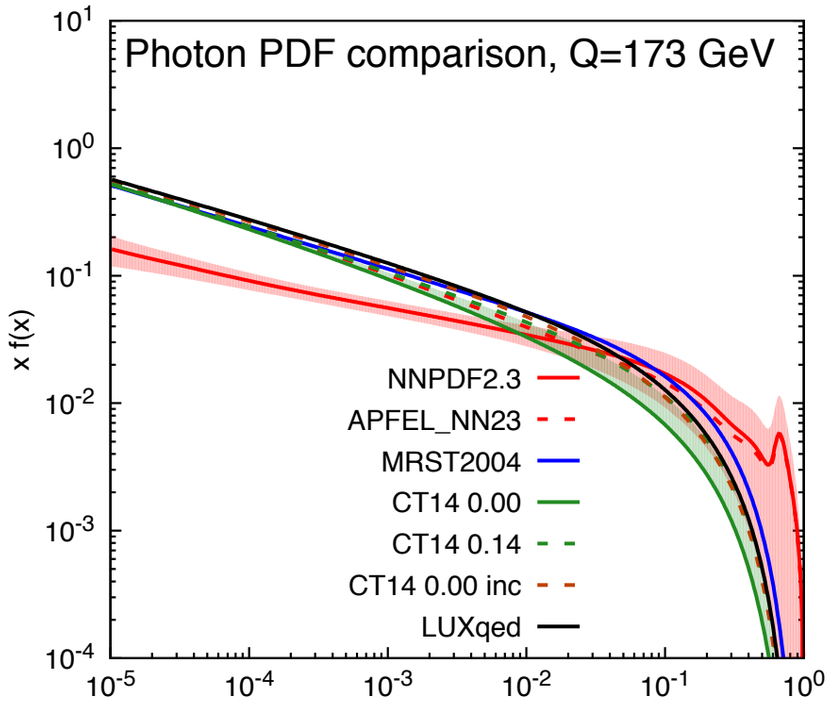
- At small Q: **APFEL_NN23** is like **NNPDF2.3QED.** At large Q: it is like **CTEQ14QED** at small x, while it is like **NNPDF2.3QED** at large x.

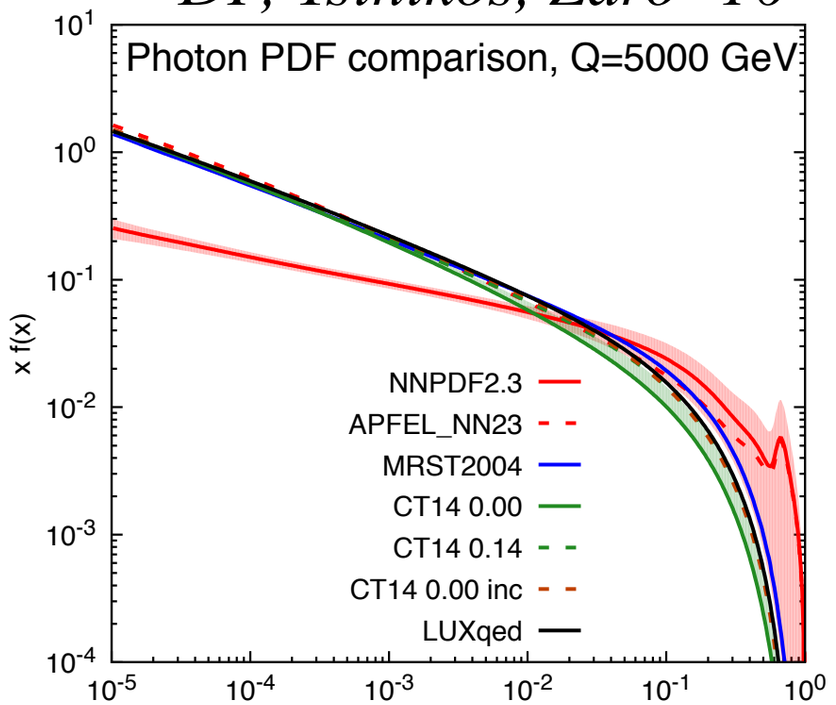
- CTEQ14QED is close to the upper edge of the **CTEQ14QEDinc** band.

The different photon PDFs …

DP, Tsinikos, Zaro '16







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

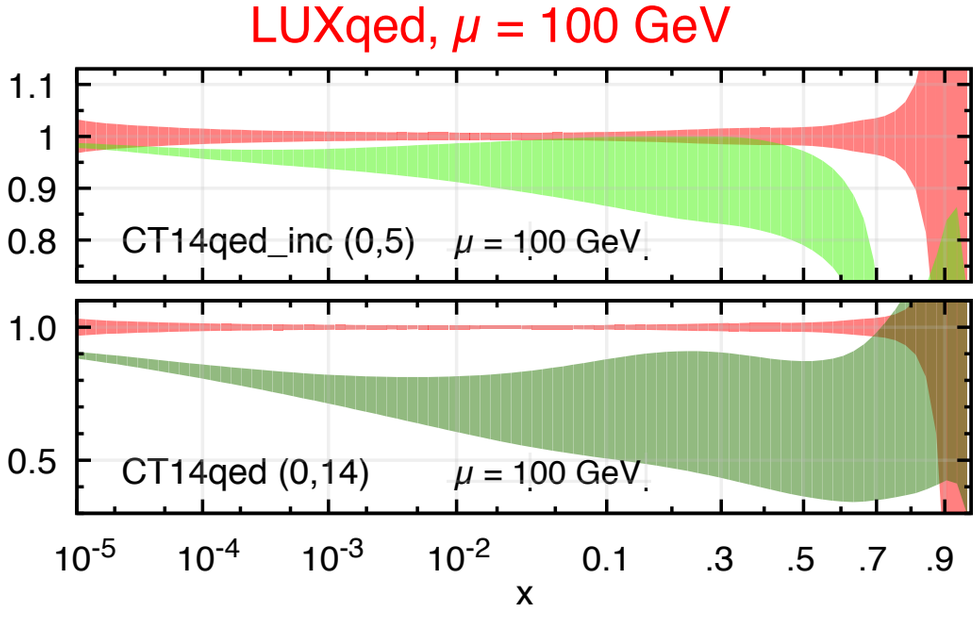
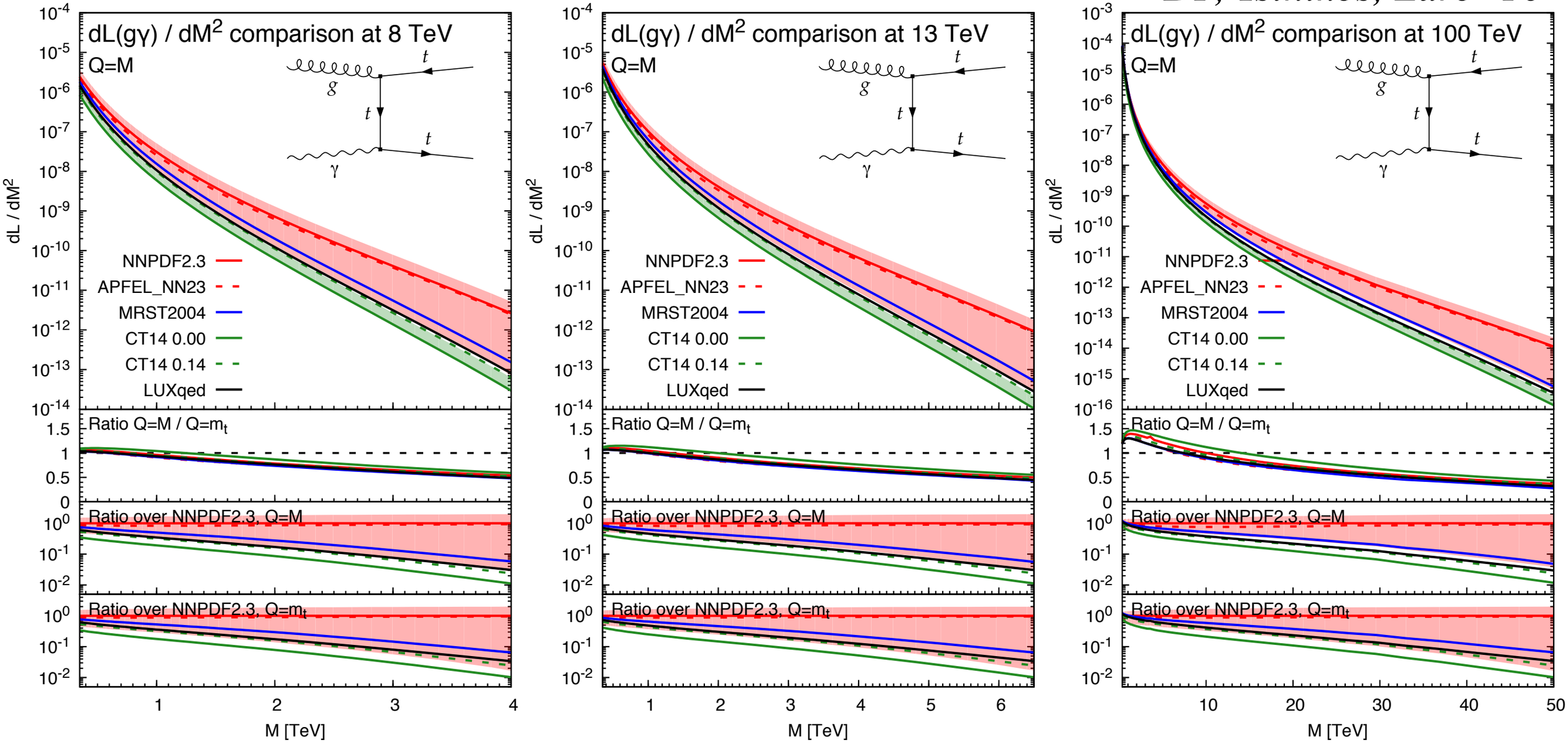


Image taken from Manohar, Nason, Salam, Zanderighi '16 and adapted for this slide.

… and the different photon-gluon luminosities

DP, Tsinikos, Zaro '16

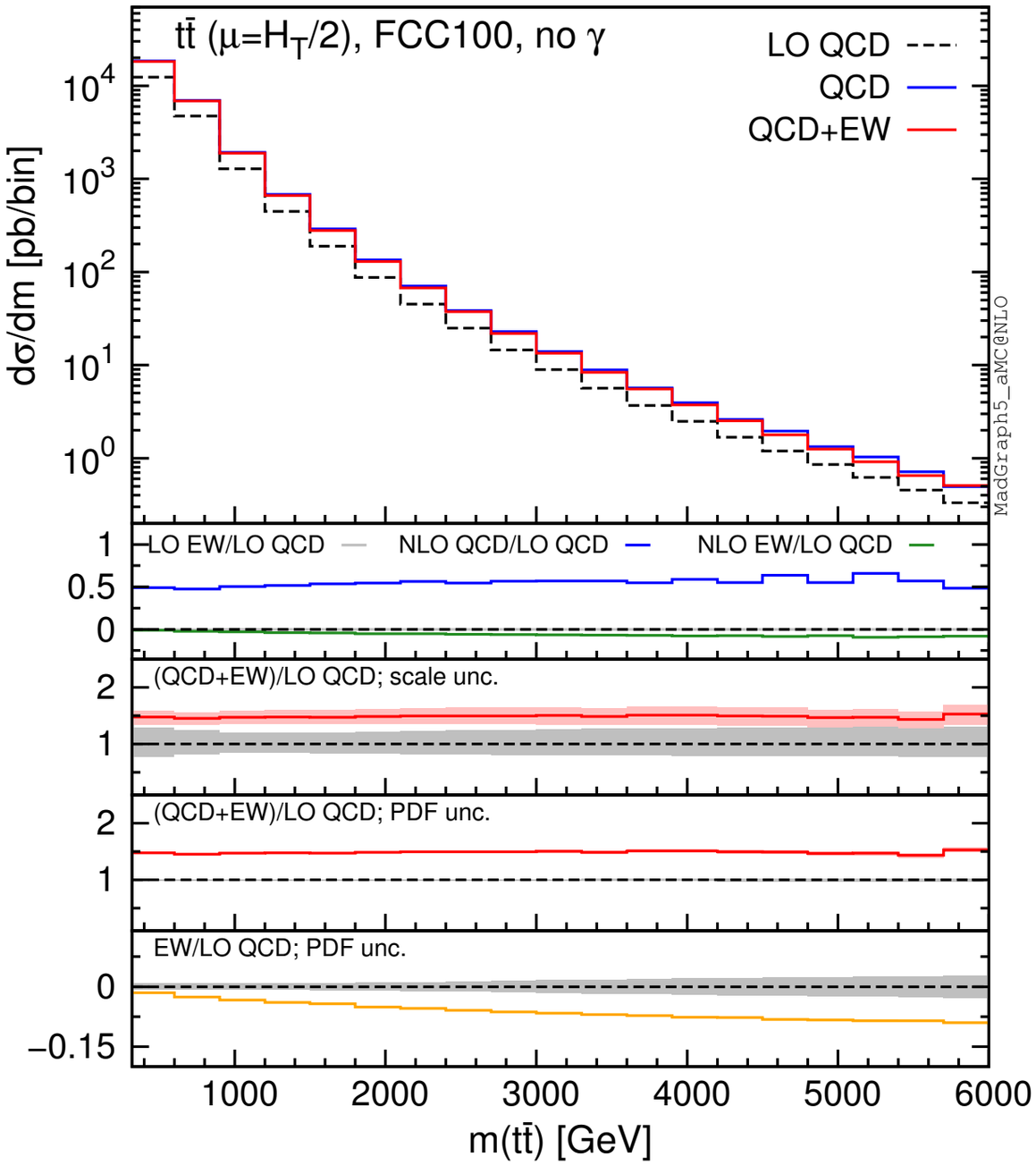


- **LUXQED** luminosity is very close to **CTEQ14QED**
- **NNPDF2.3QED** and **APFEL_NN23** are equivalent! (diff. running is not relevant)

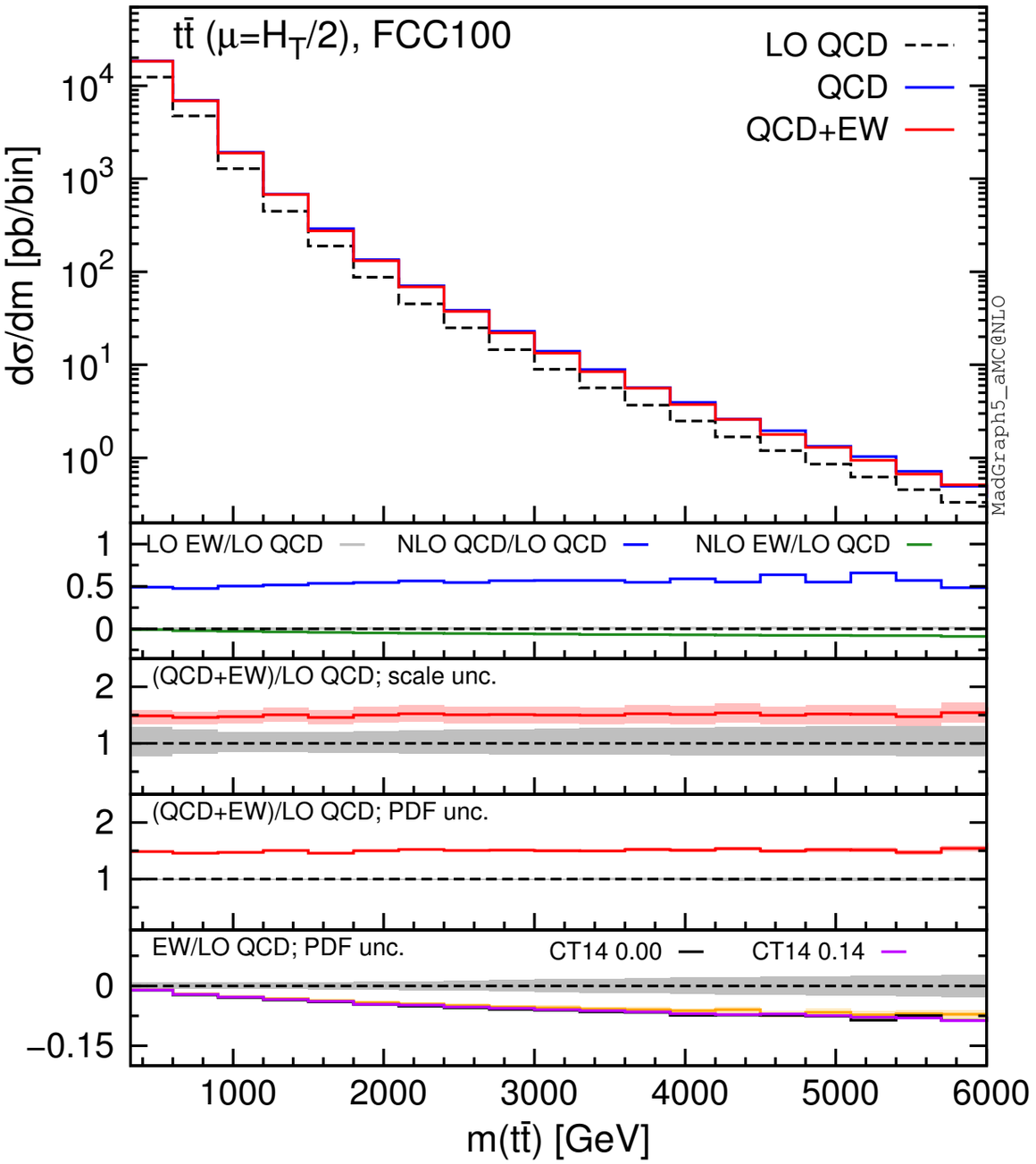
NNPDF2.3QED representative for **(NNPDF3.0QED, APFEL_NN23)**
CTEQ14QED representative for **(CTEQ14QEDinc, LUXQED)**

100 TeV

DP, Tsinikos, Zaro '16



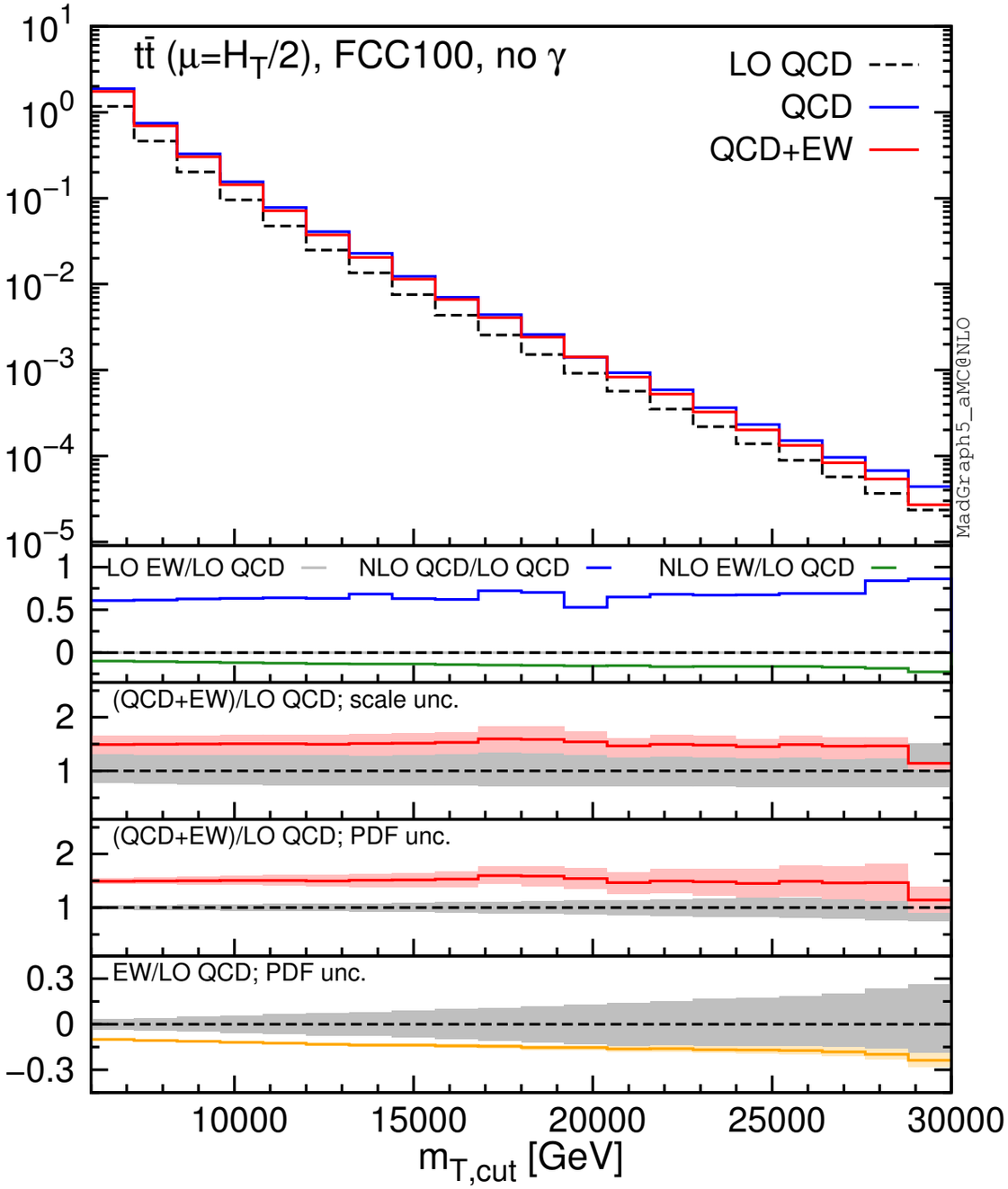
photon PDF **NO**



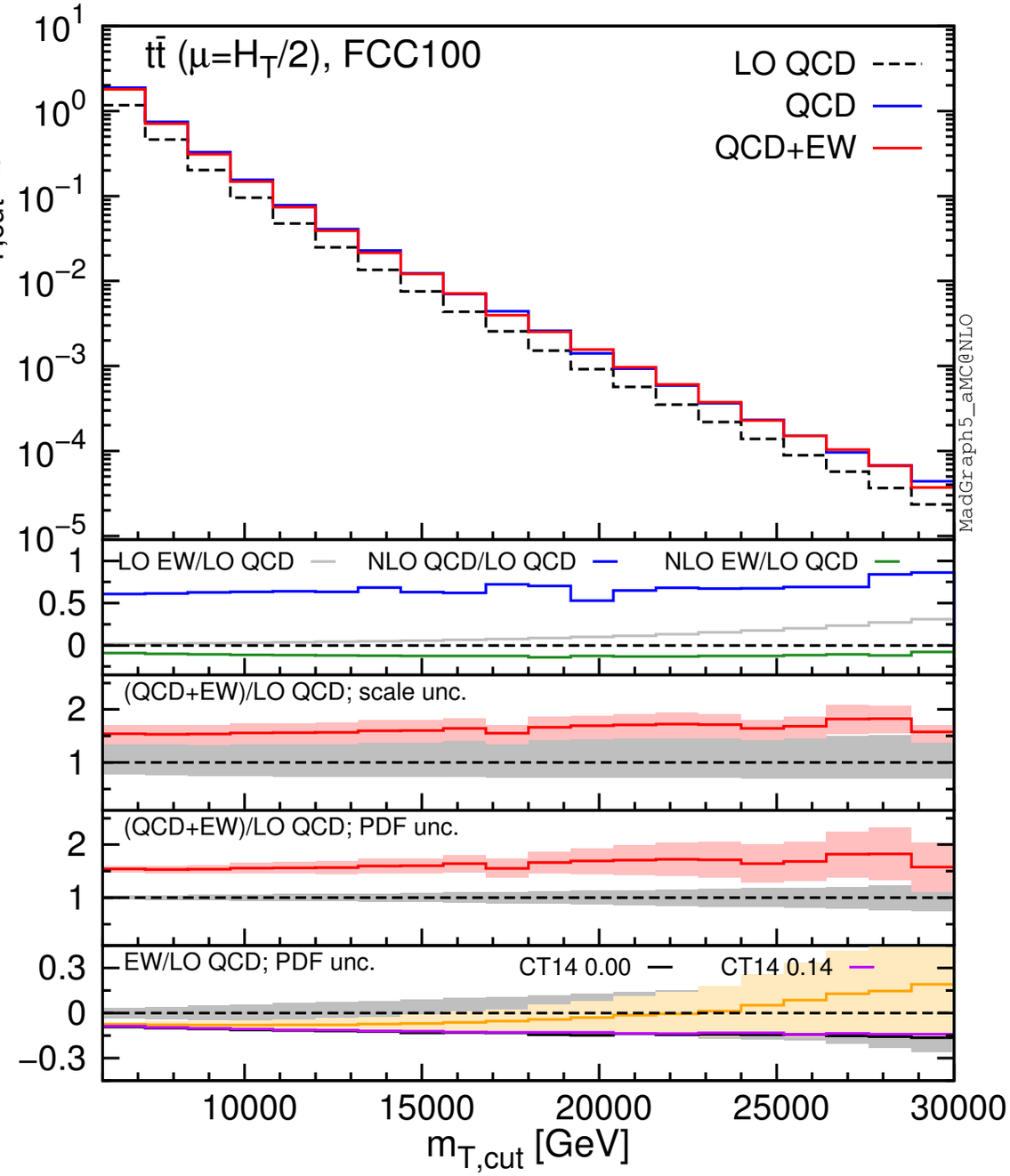
photon PDF **YES**

100 TeV

DP, Tsinikos, Zaro '16



photon PDF **NO**



photon PDF **YES**