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

mainly based on **arXiv:1705.04105** and work in collaboration with
M. Czakon, D. Heymes, A. Mitov, A. Papanastasiou, 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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TOP2017
Braga
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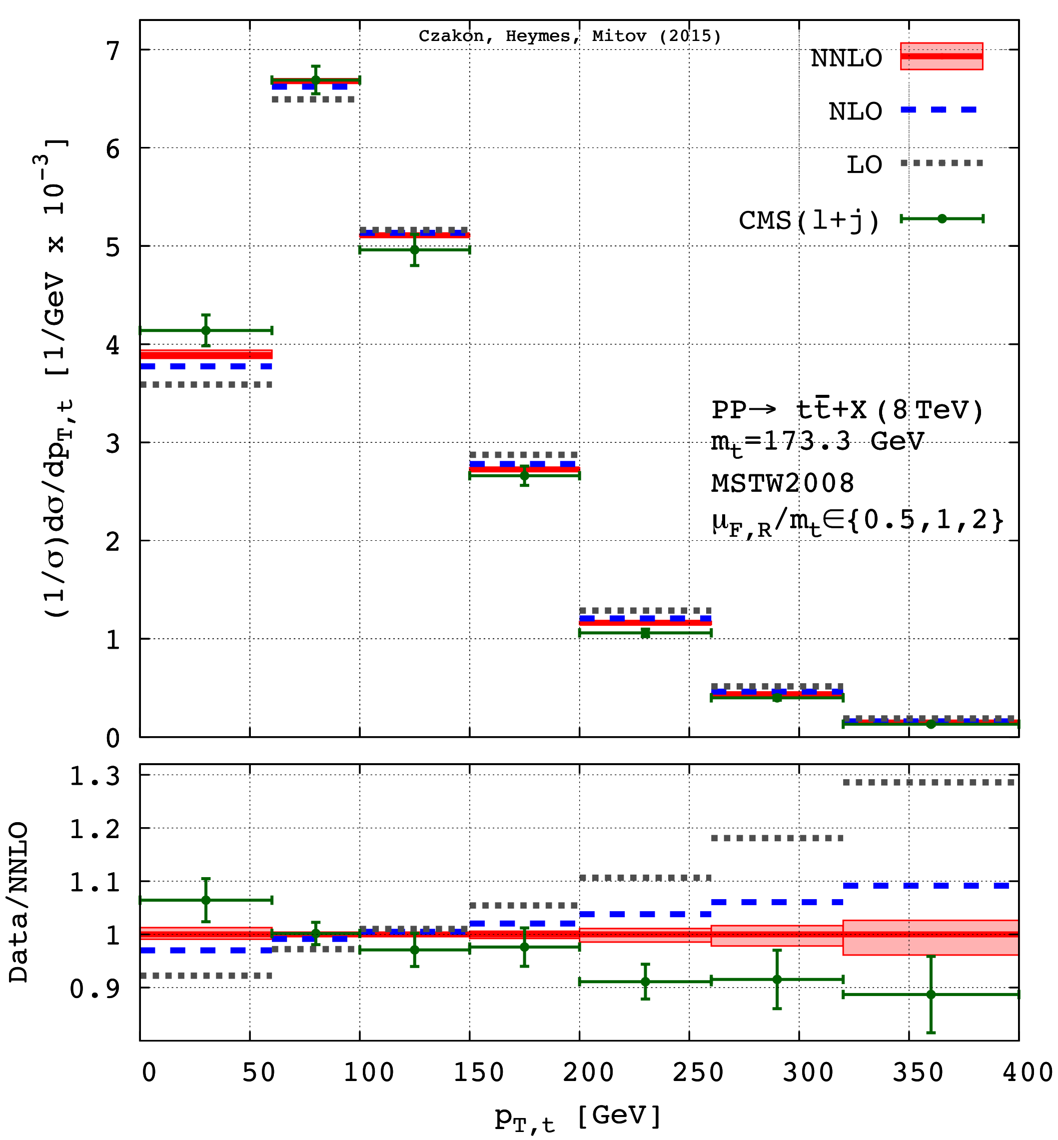
Motivation

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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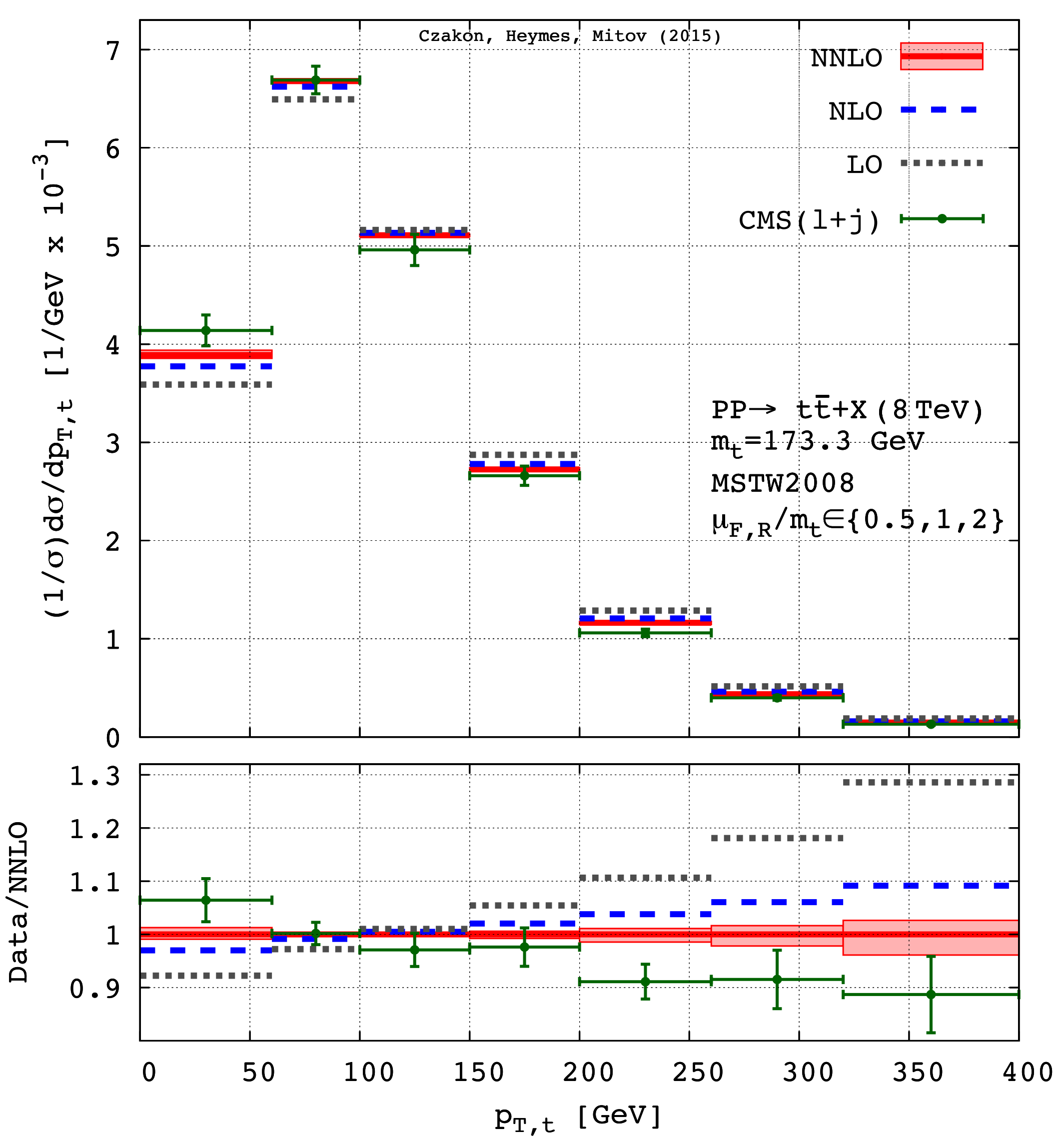

EW corrections have a similar size ($\alpha_s^2 \sim \alpha$), with **Sudakov enhancements** in the boosted regime. However, only a part of them has been taken into account in experimental analyses, and no consistent combination with NNLO QCD (same input parameters, PDFs and scale) was available till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

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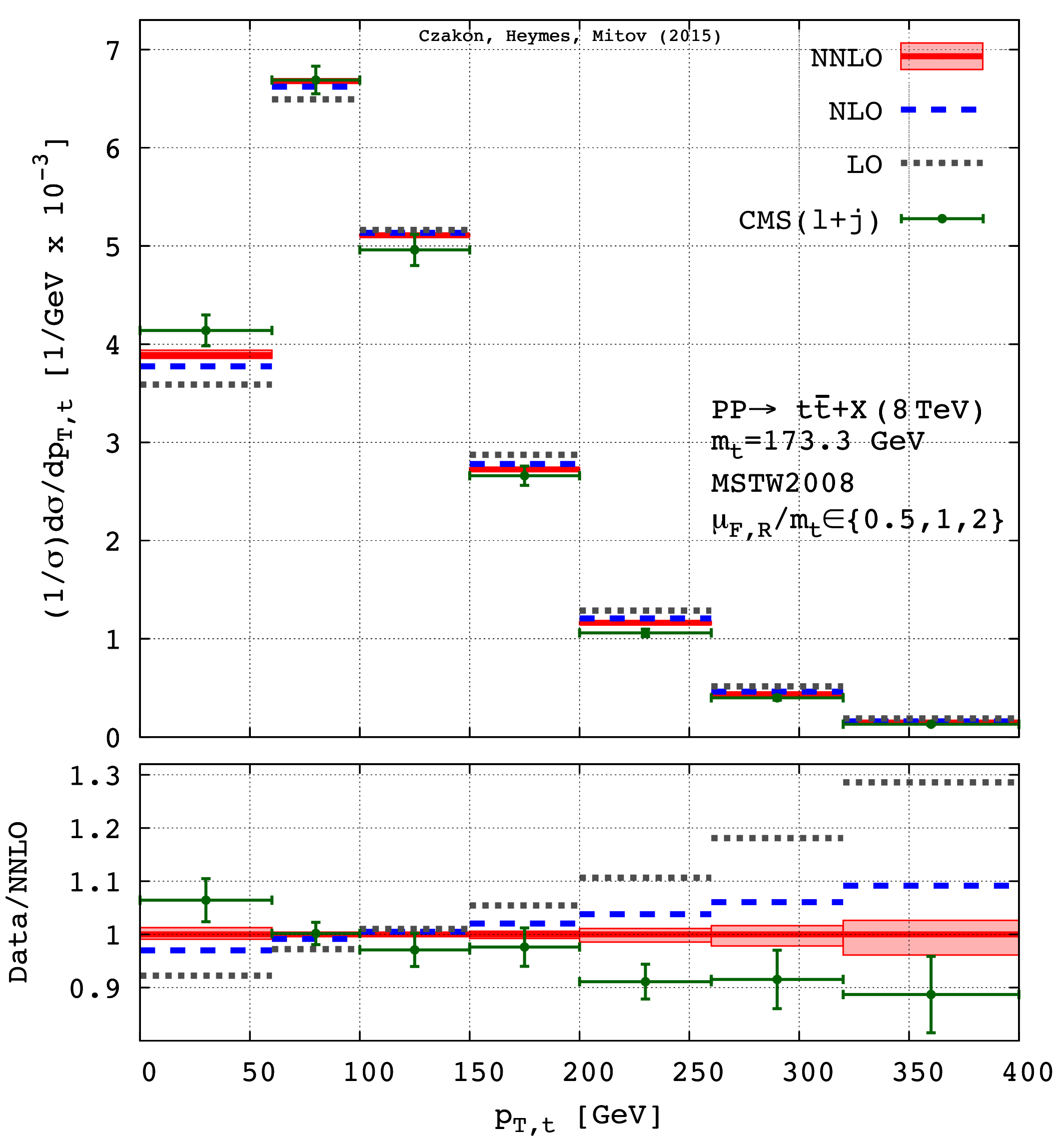

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We provided predictions at complete NLO accuracy including also NNLO QCD corrections for differential distributions in top-quark pair production at 8 and 13 TeV.

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, at another hadron collider.

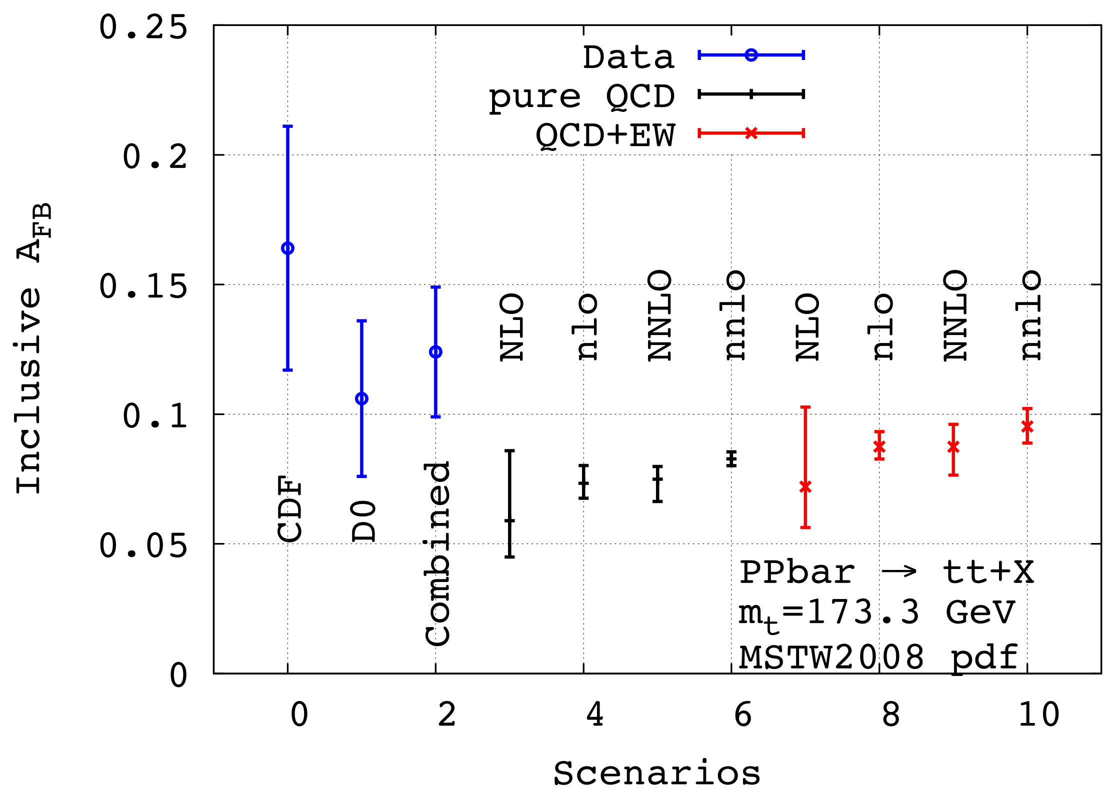

FIG. 1: The inclusive asymmetry in pure QCD (black) and QCD+EW[28] (red). Capital letters (NLO, NNLO) correspond to the unexpanded definition (2), while small letters (nlo, nnlo) to the definition (3).

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
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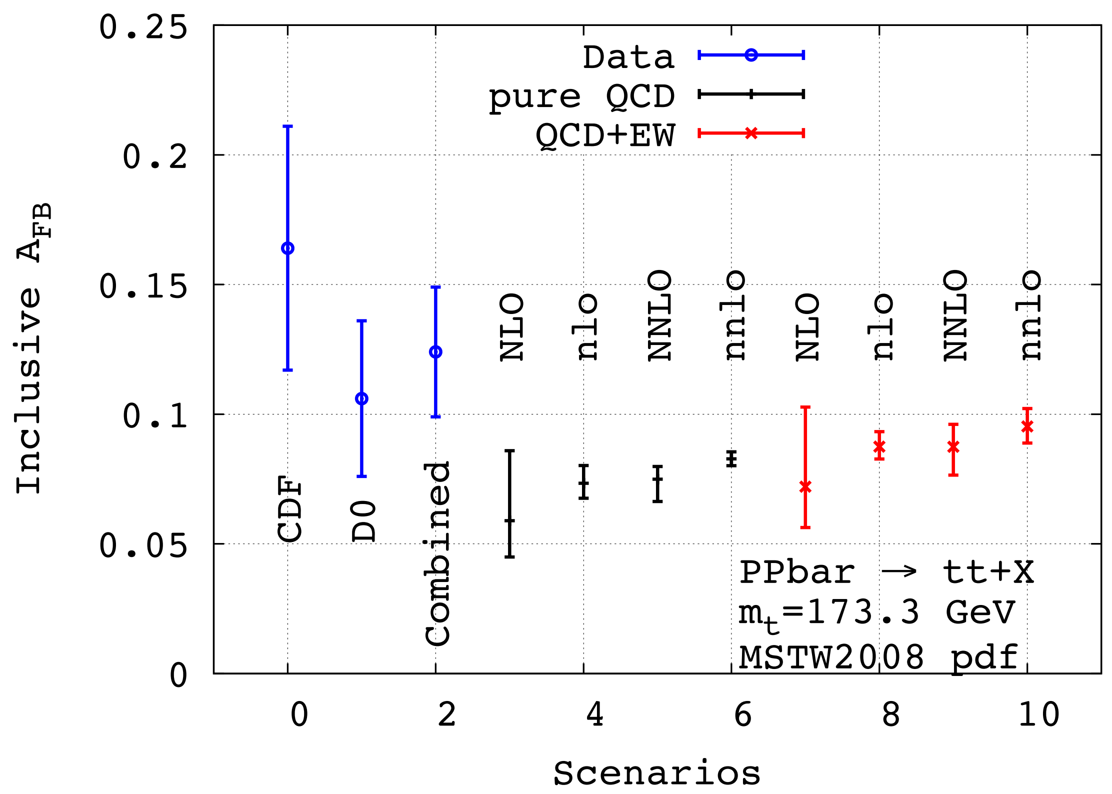

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NEW PRELIMINARY RESULTS LATER IN THIS TALK!

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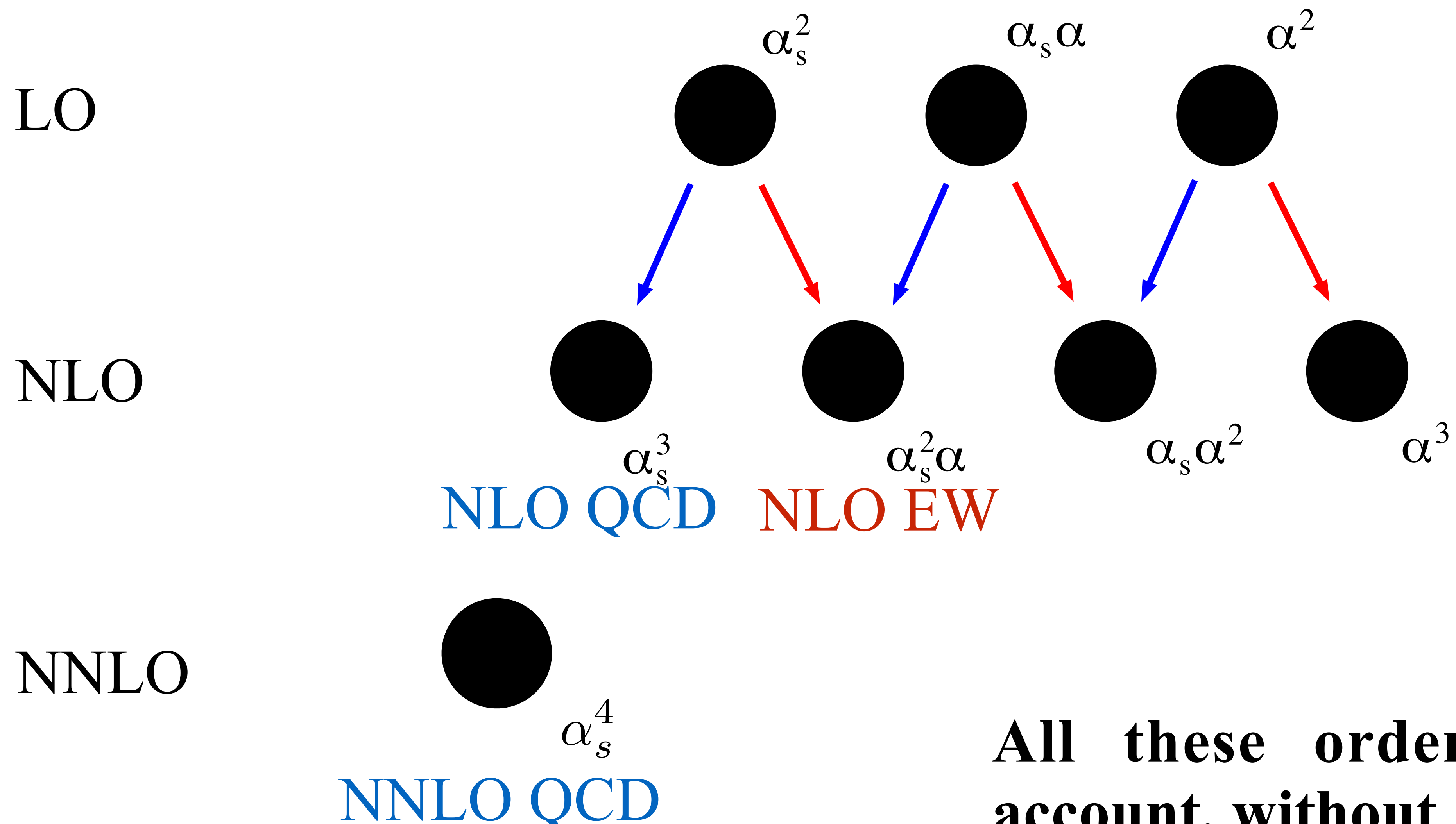
Calculation framework

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*).



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?

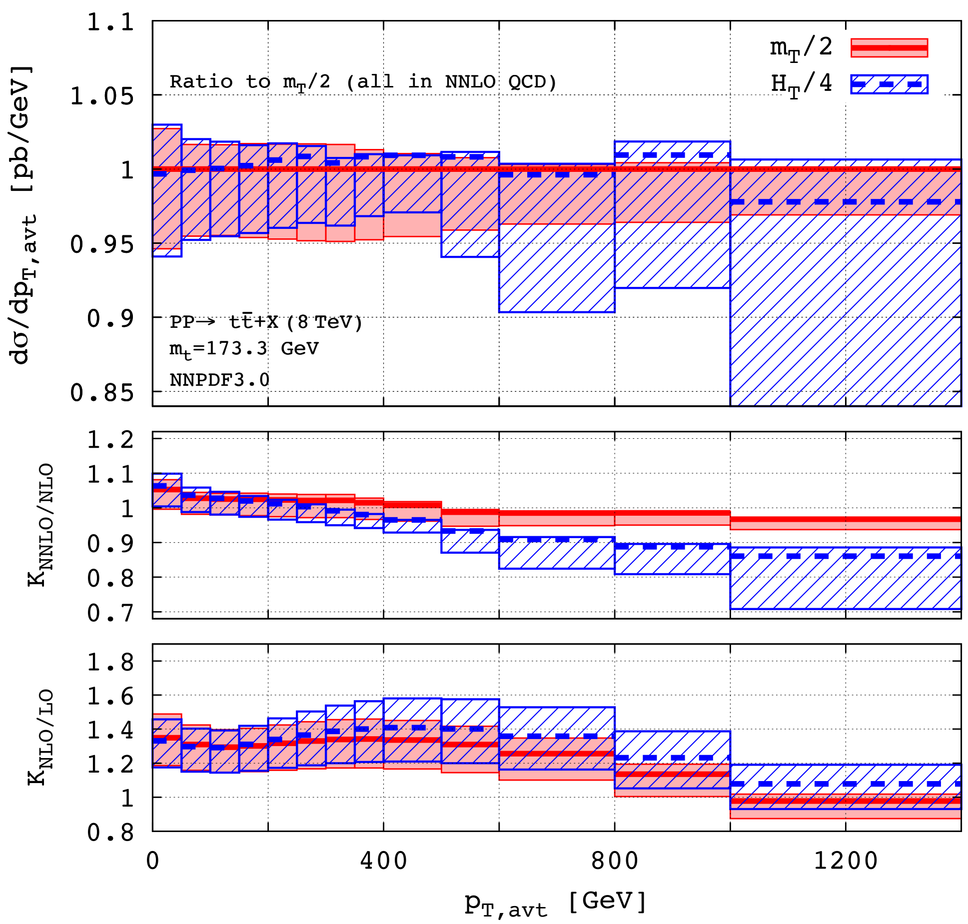
NNLO QCD: scale definition

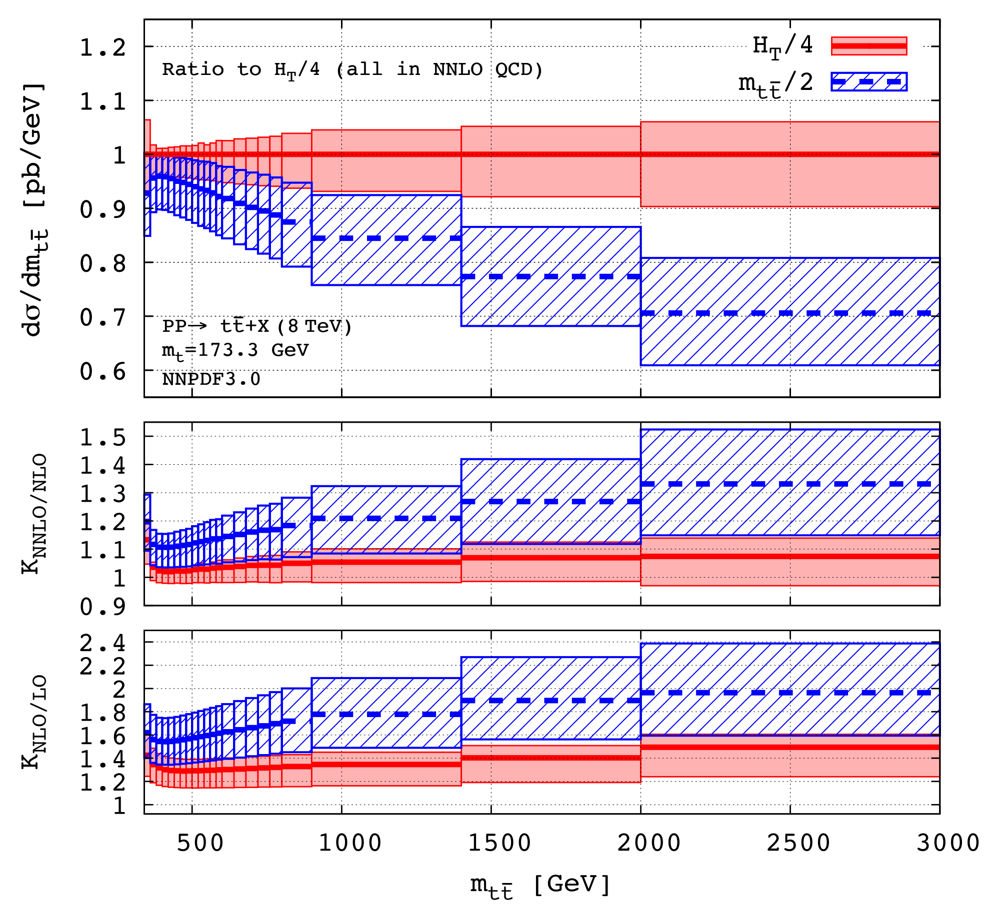
The dependence on the ren. and fac. scale is mainly due to QCD effects.

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 + (N)LO QED:

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

They both include a photon PDF!

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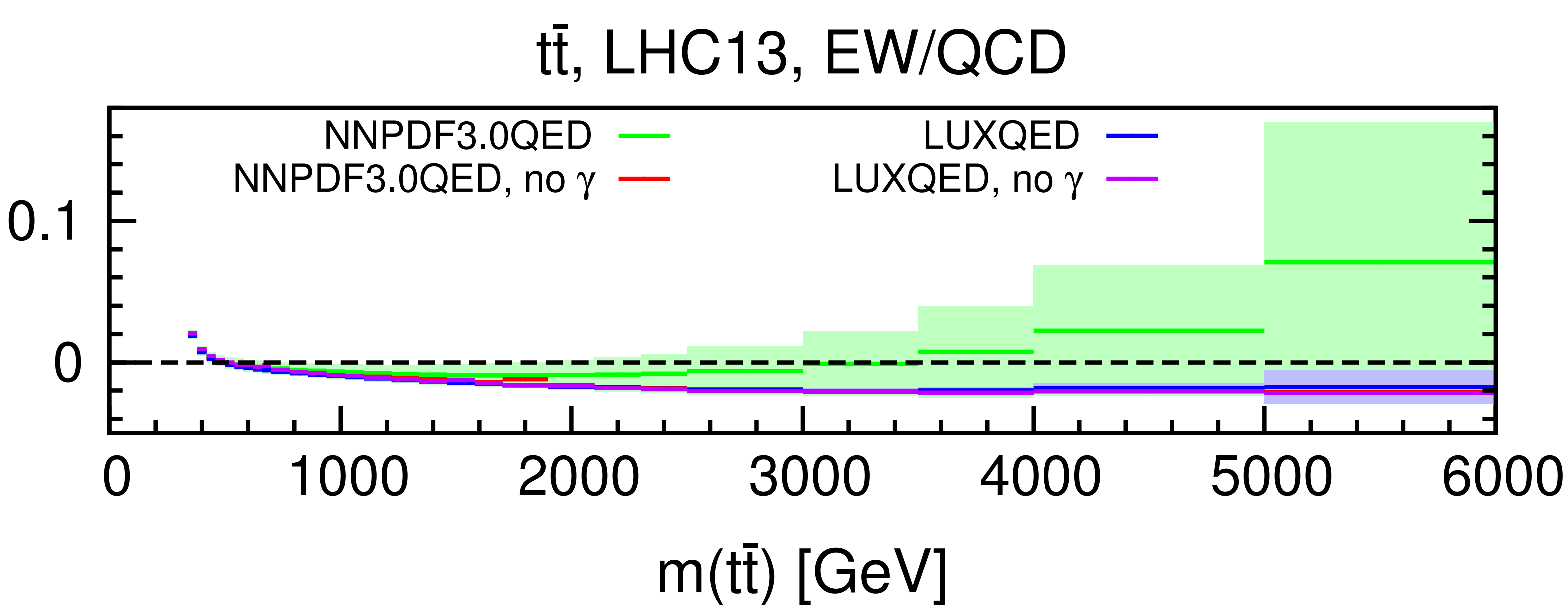
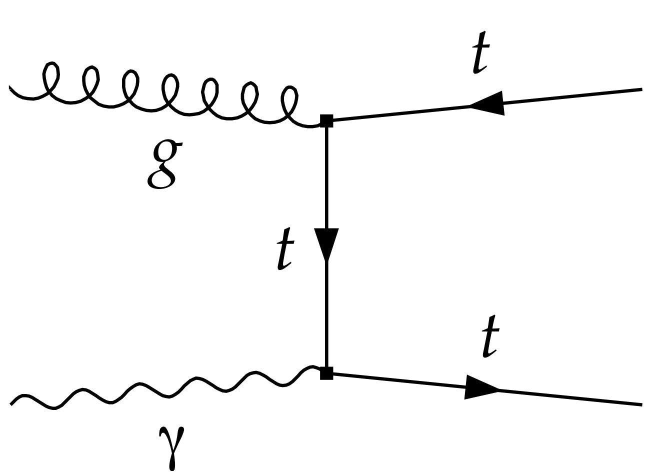
While the impact of the NNPDF photon PDF is huge in ttbar differential distributions (and with large uncertainties), in the case of LUXQED is small.
Cancellation between Sudakov Logarithms and photon-induced results depends on the scale definition. *DP, Tsinikos, Zaro '16*

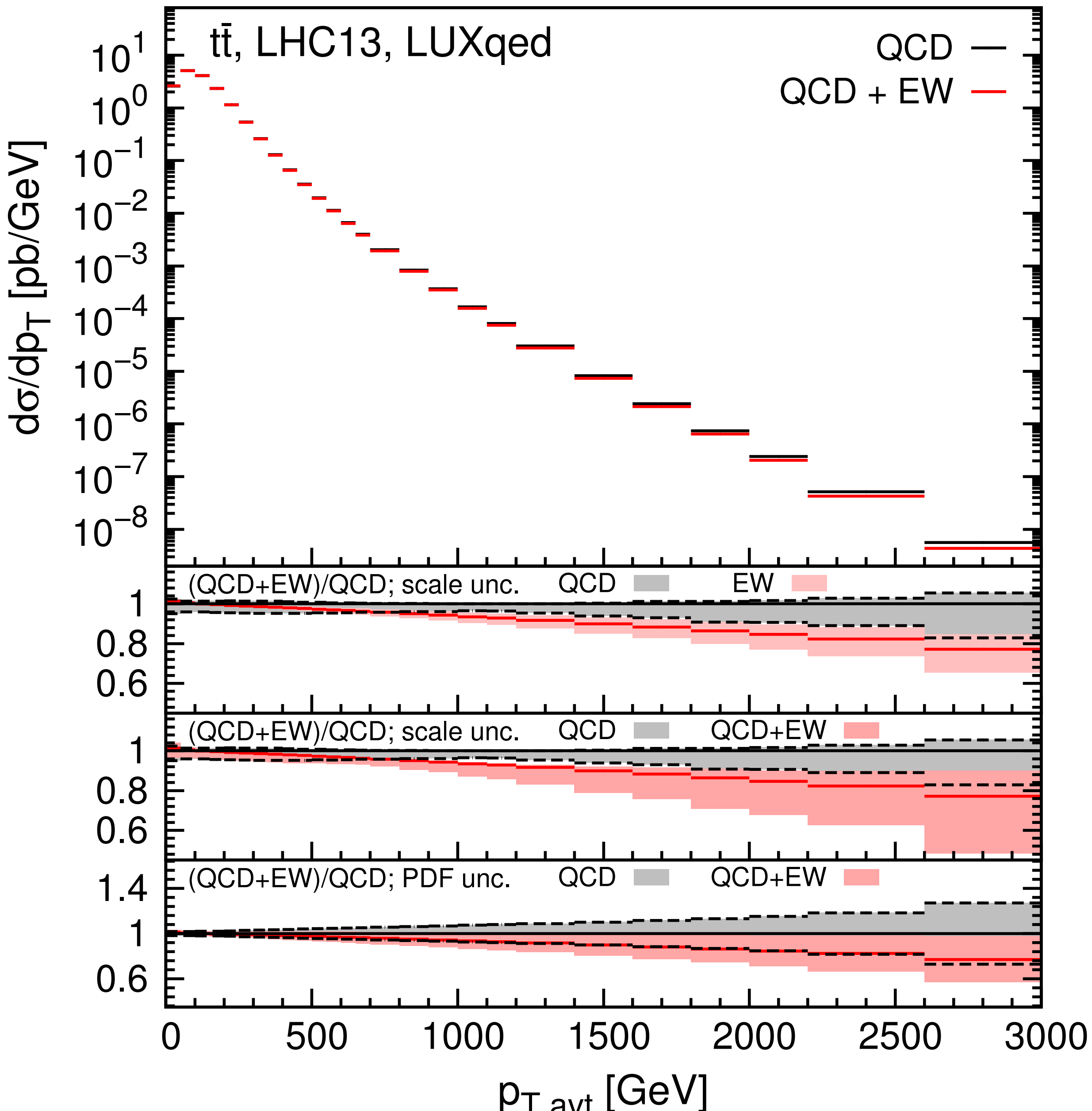


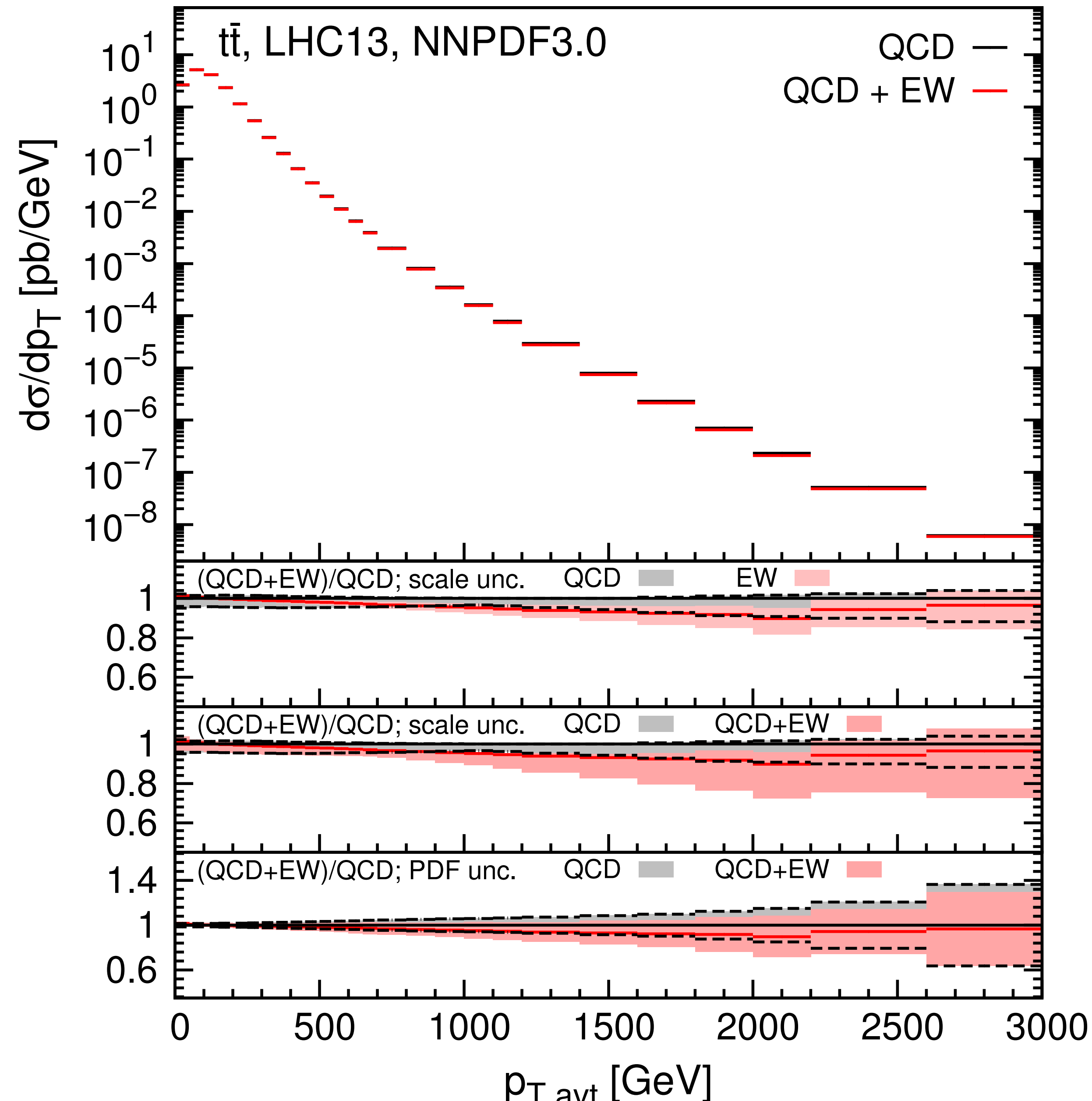


Results

13 TeV

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





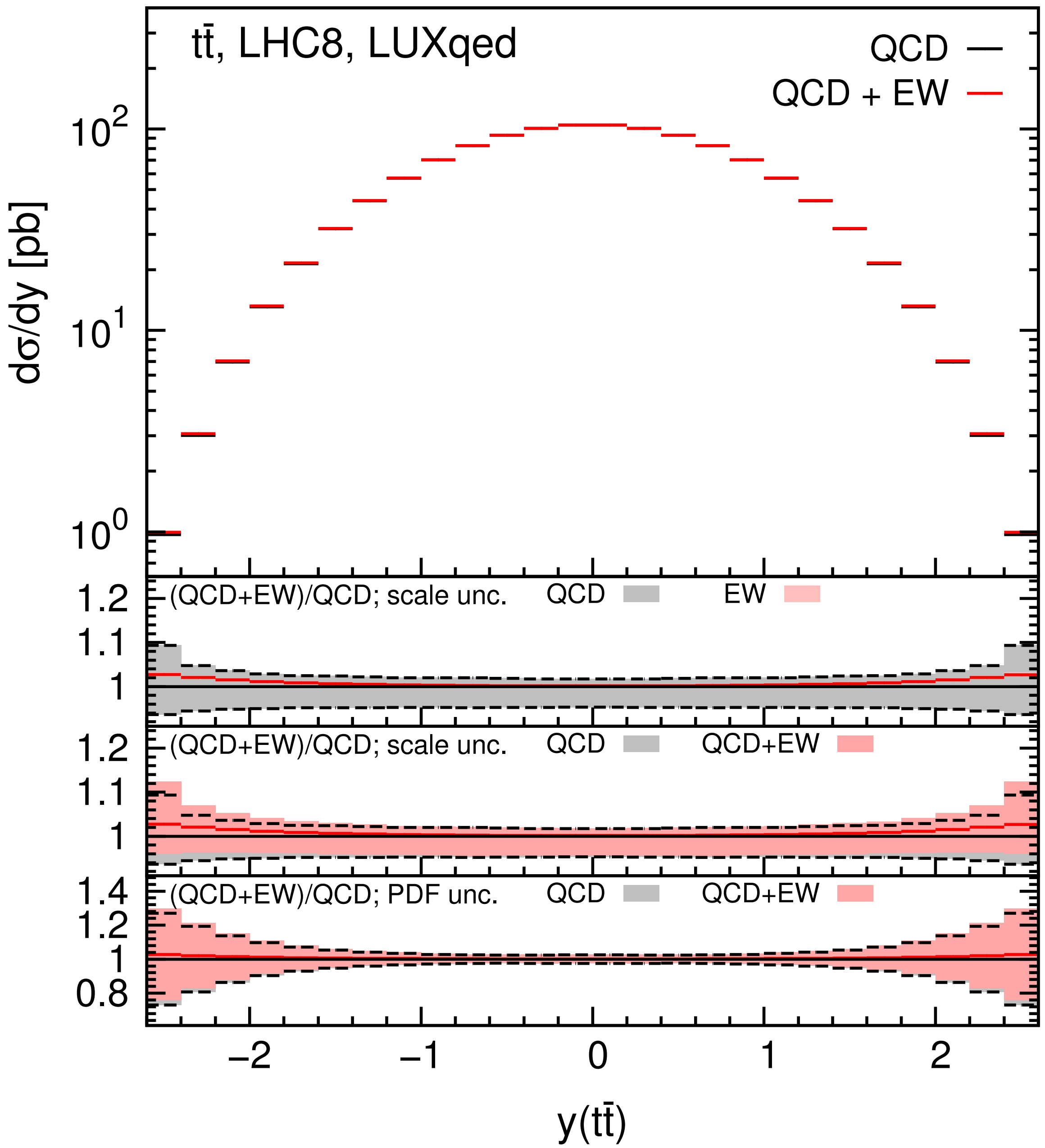
LUXQED

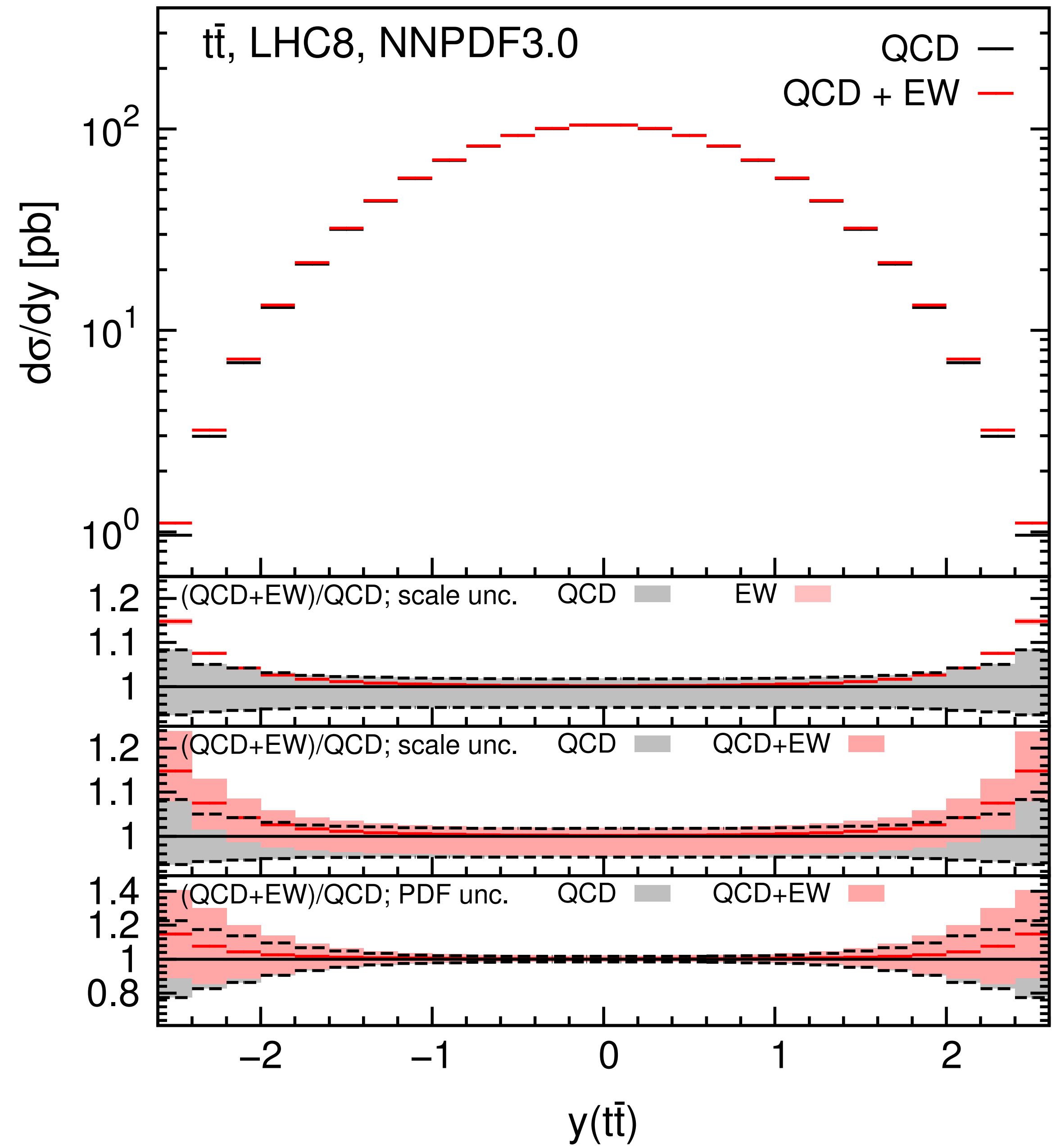
NNPDF3.0QED

large scale unc. from EW corrections + photon PDF relevant

8 TeV

$y(t\bar{t})$





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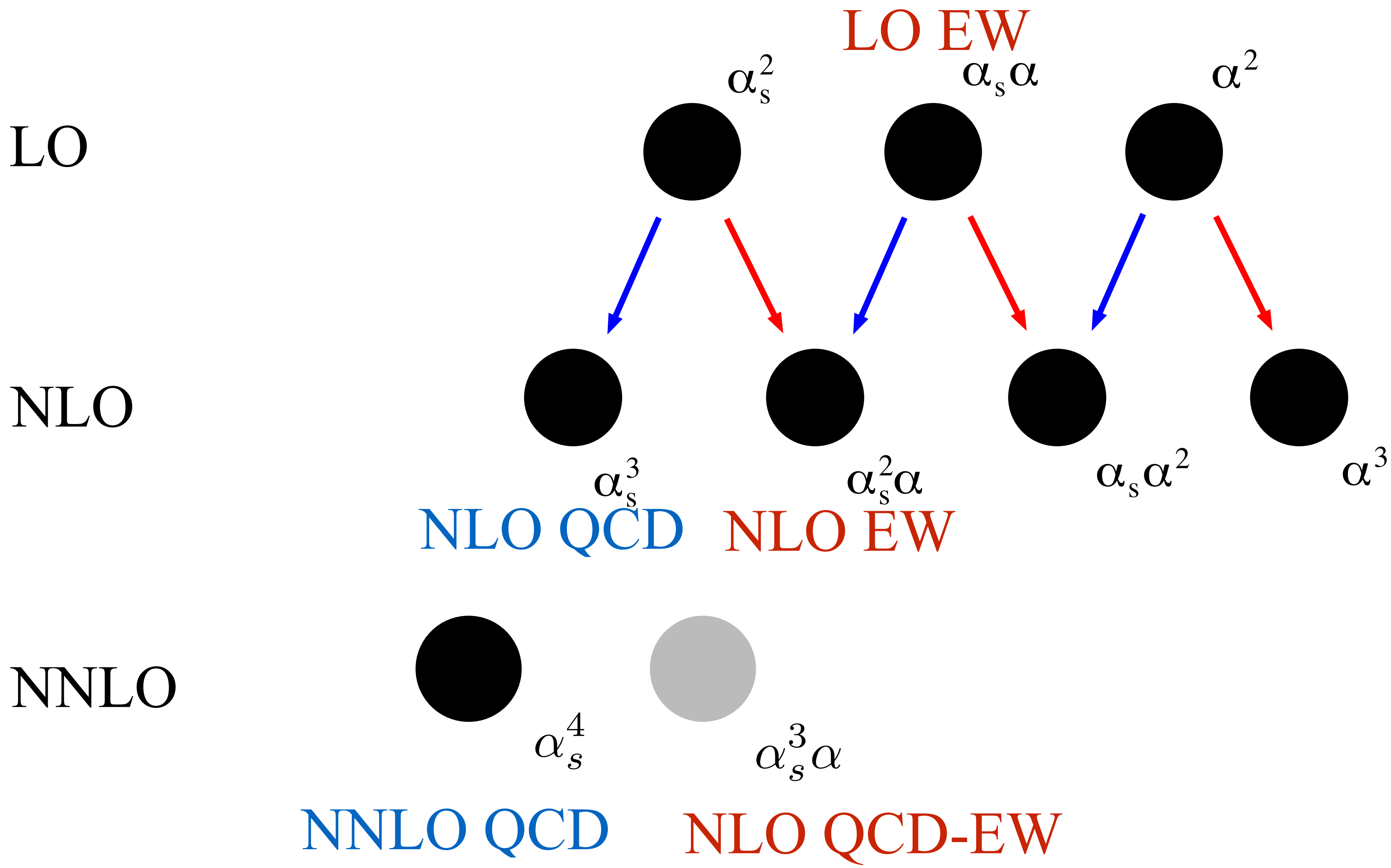
Can we reduce the scale-dependence from NLO EW effects?

Combination of EW and QCD corrections in the multiplicative approach

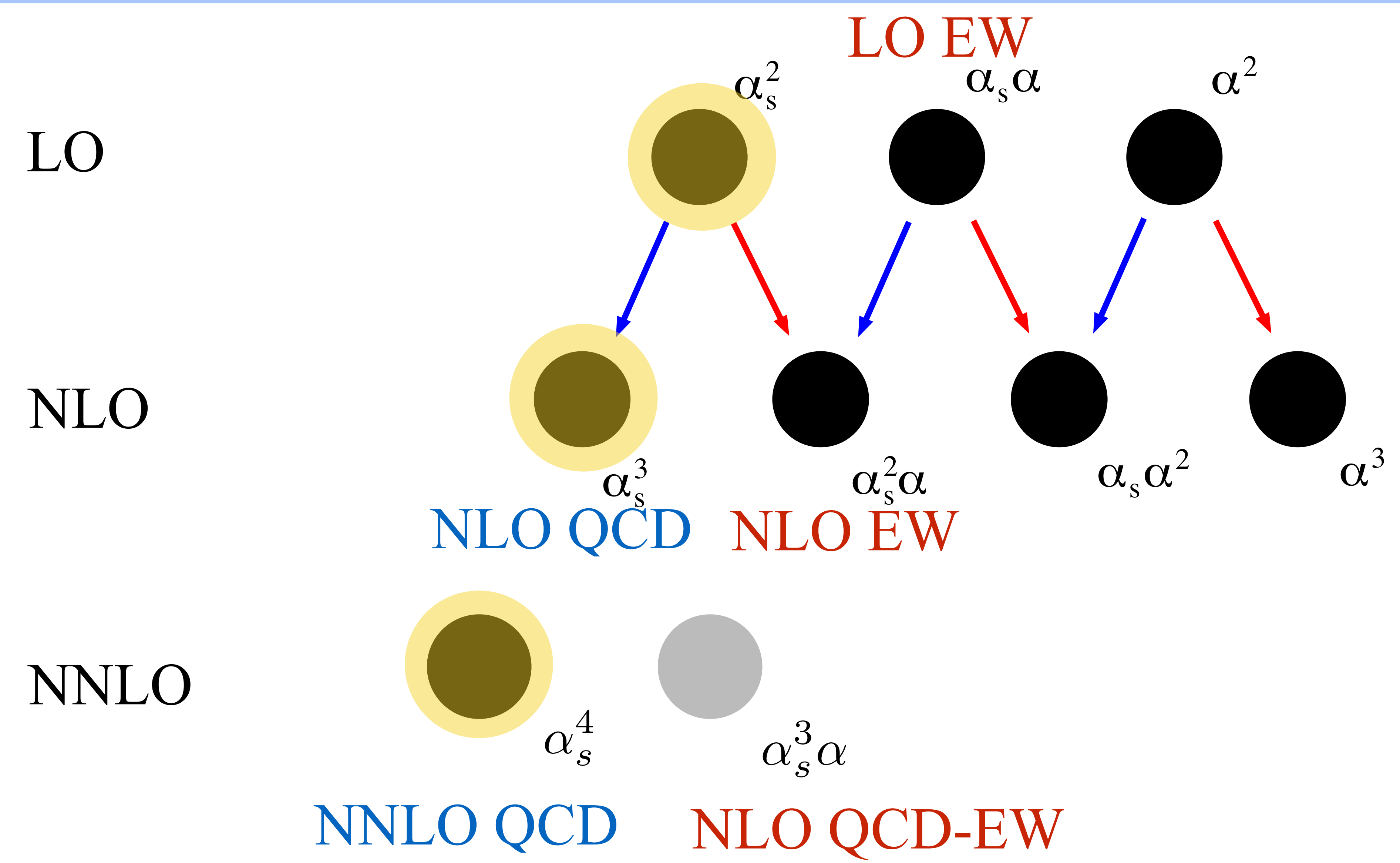
When QCD and EW effects factorize (e.g. soft QCD and Sudakov Logarithms) multiplying NLO QCD with NLO EW is a good approximation for NNLO mixed QCD-EW effects.
In general, it can be used as an estimate of uncertainties due to mixed QCD-EW higher order effects.

Multiplicative combination



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

Multiplicative combination



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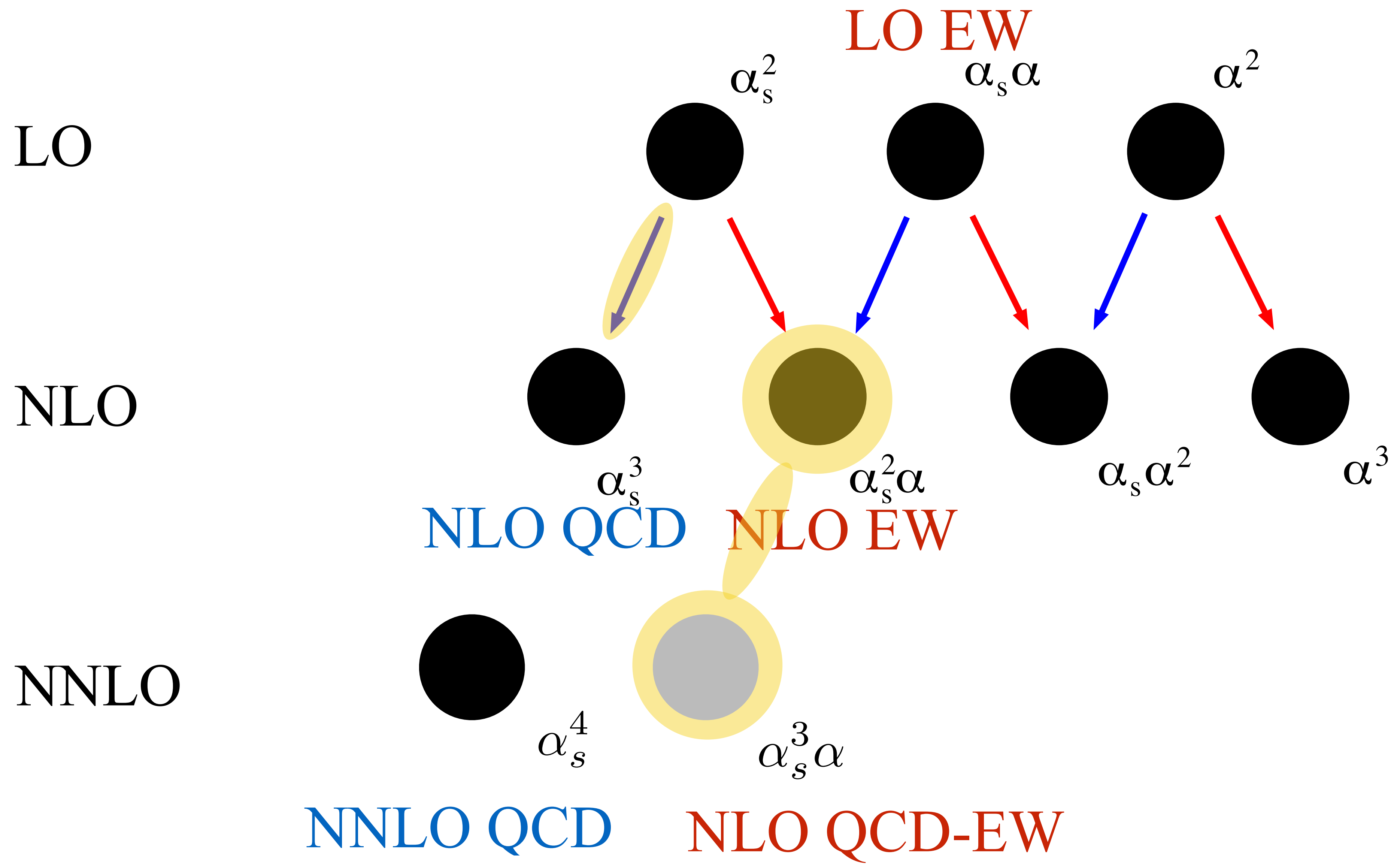

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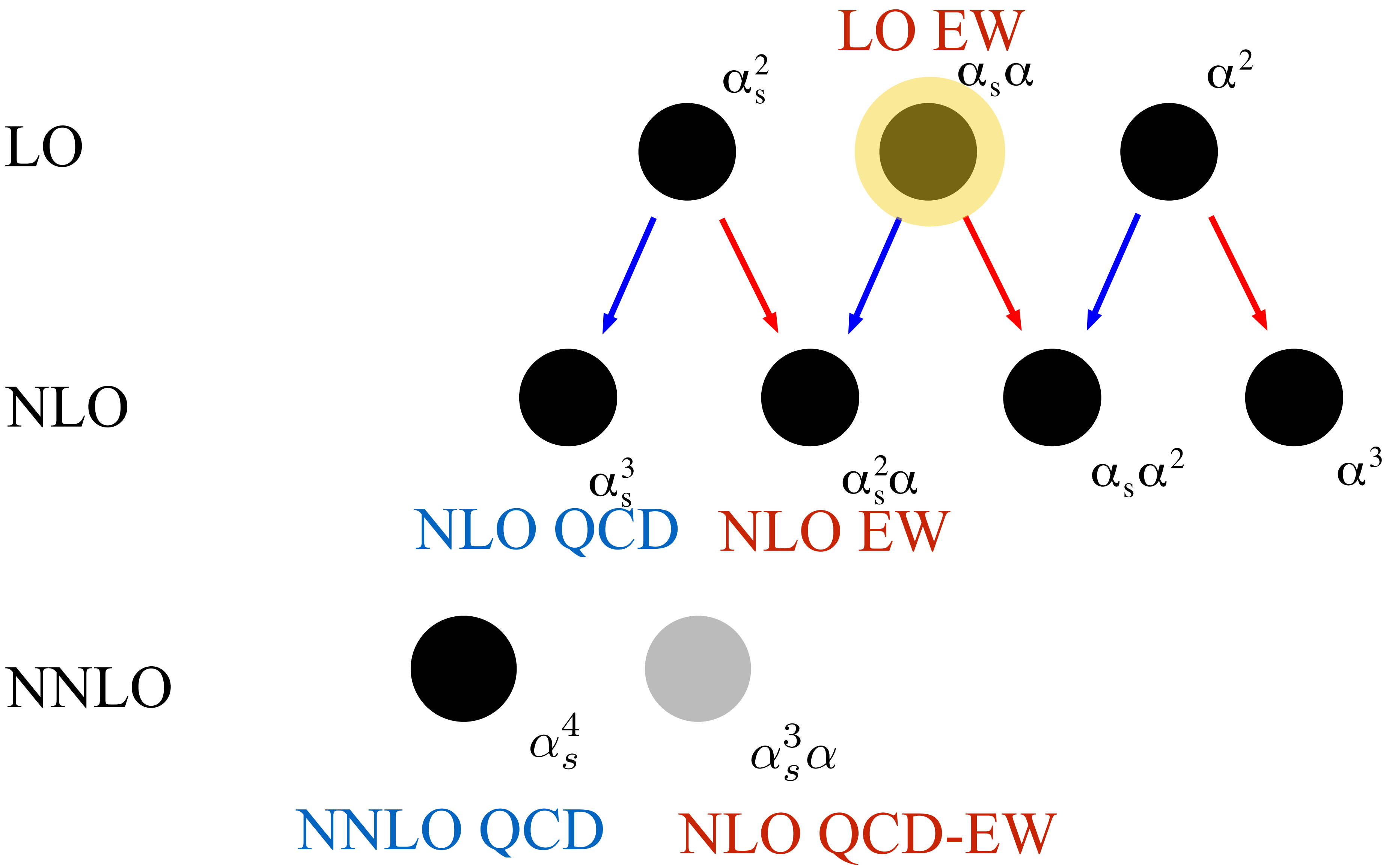

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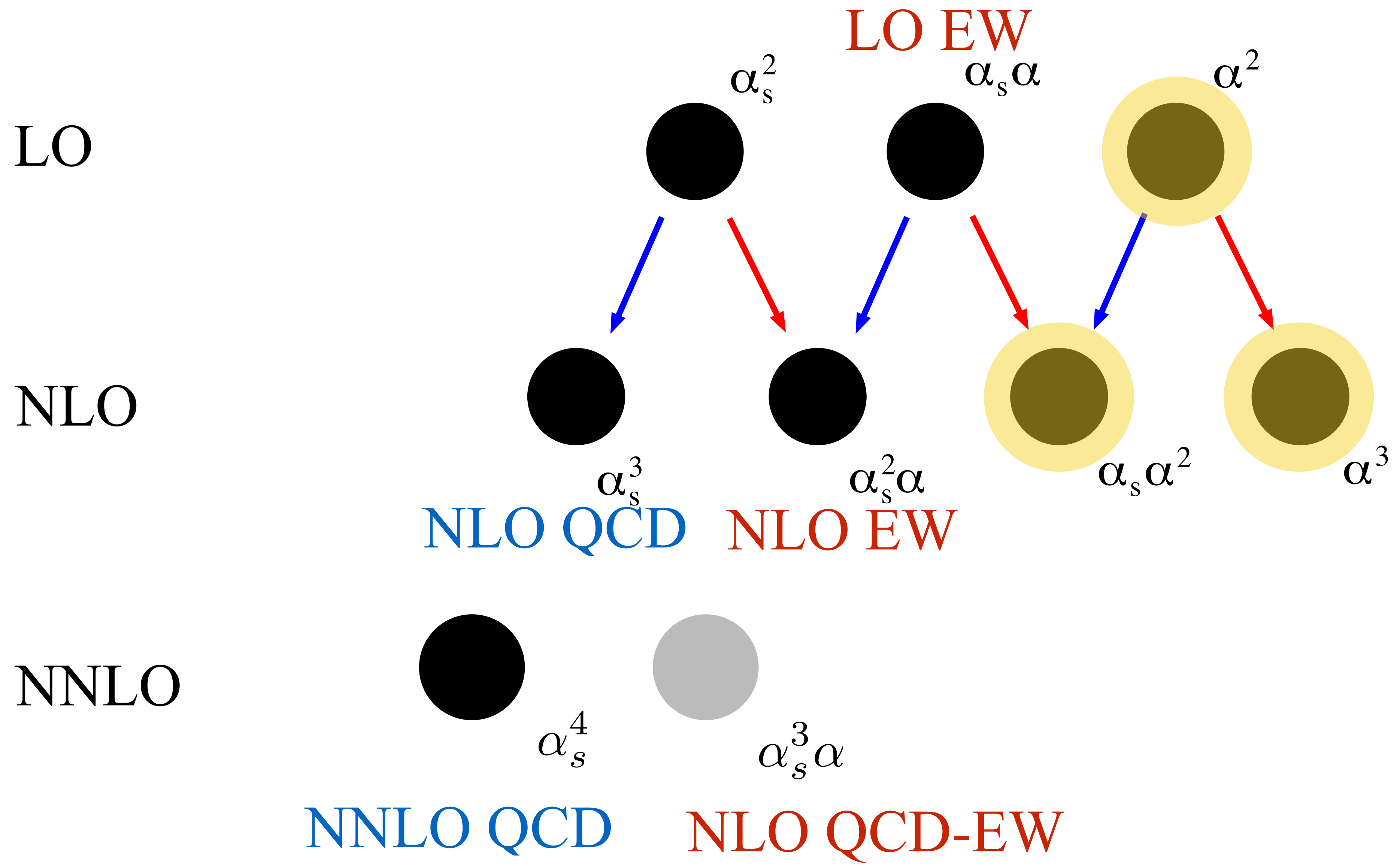
Multiplicative combination



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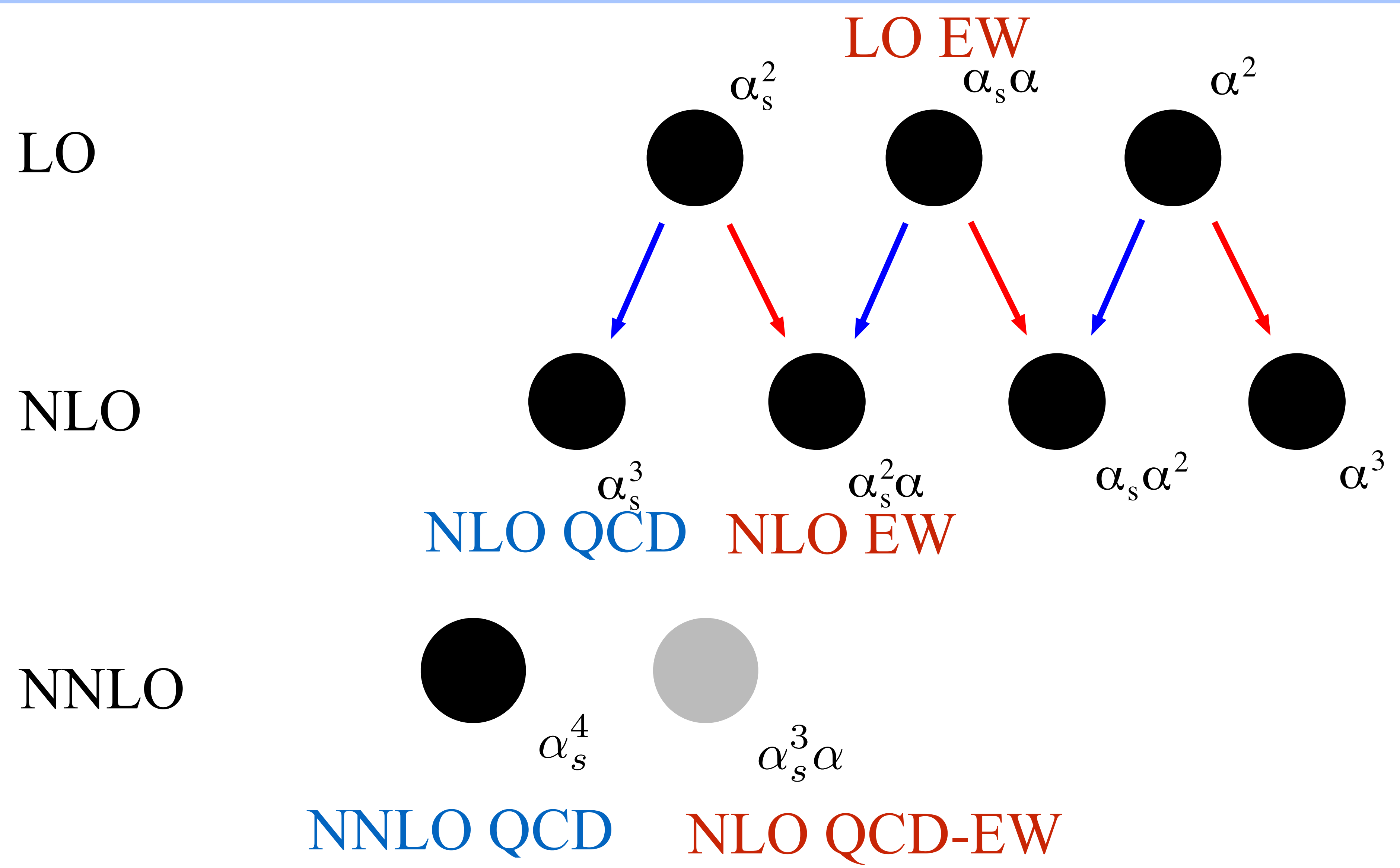

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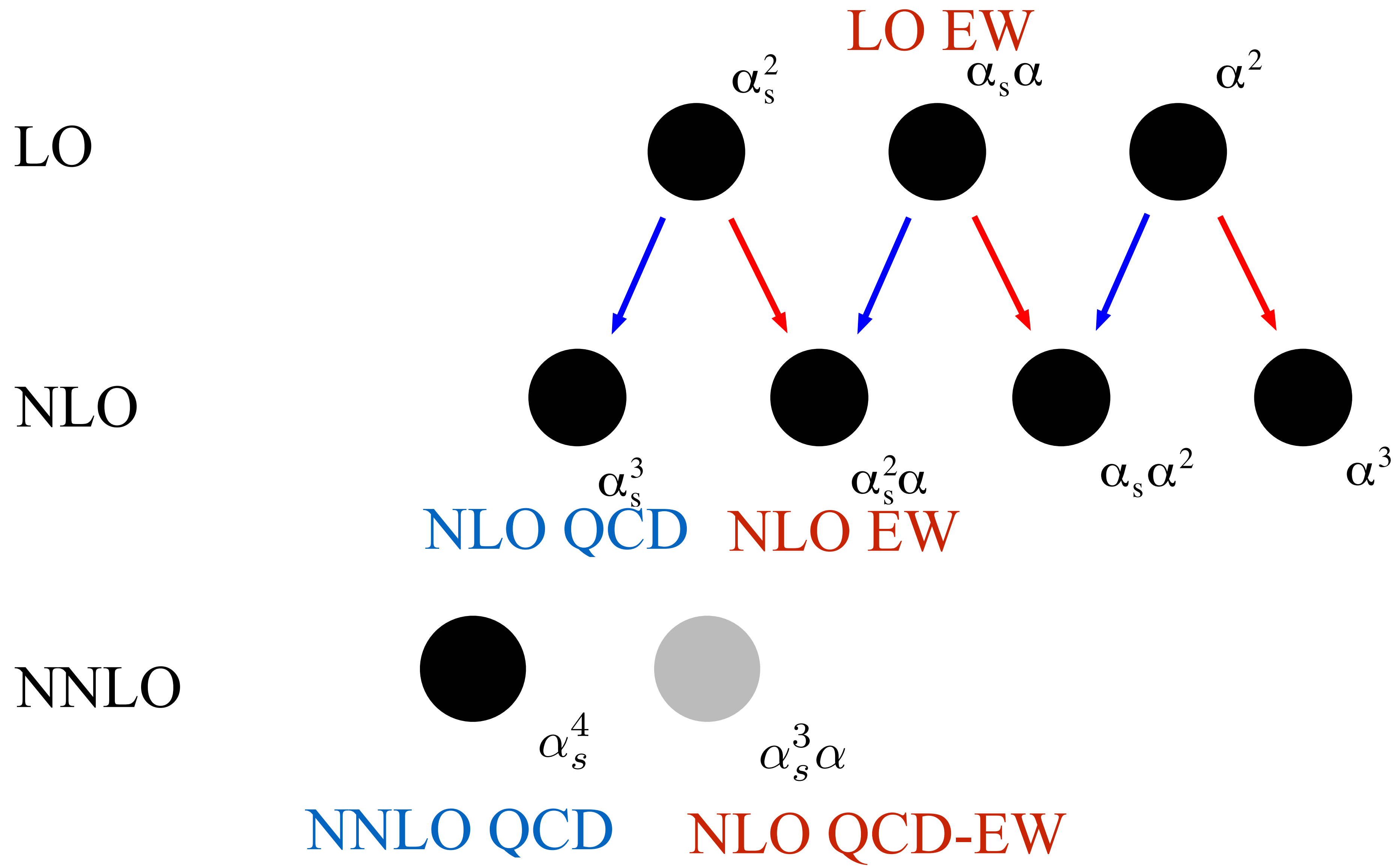

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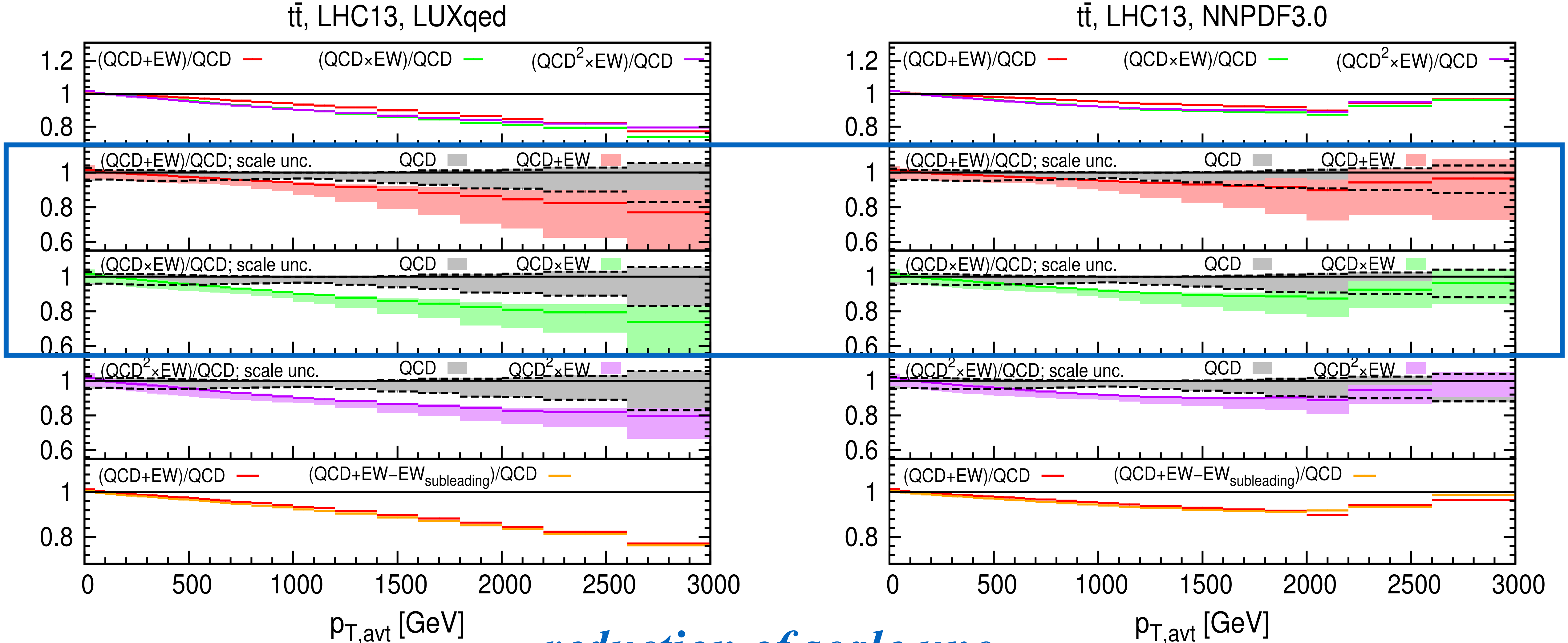
Results

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

13 TeV

ADDITIVE

MULTIPLICATIVE



LUXQED

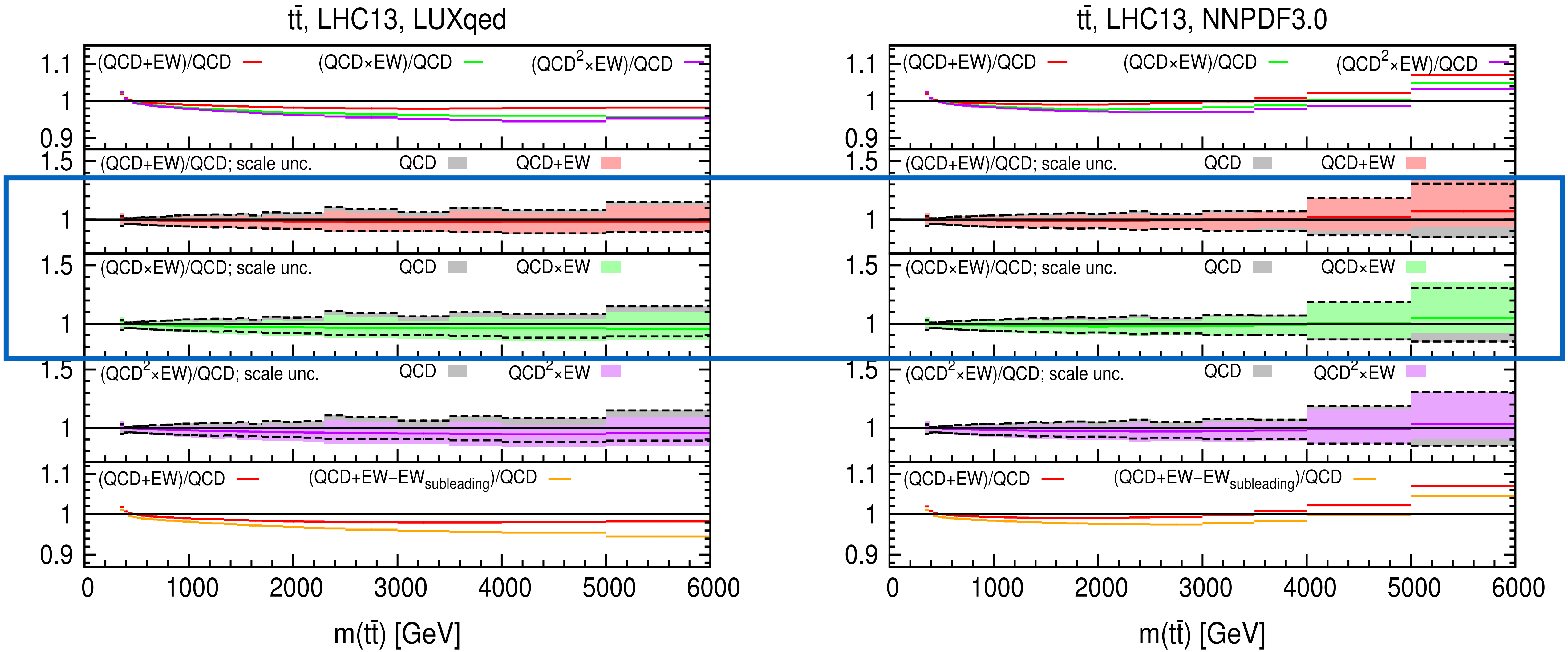
reduction of scale unc. due to EW corrections, QCD and QCDxEW do not overlap (with LUXQED)

NNPDF3.0QED

$m(t\bar{t})$

13 TeV

ADDITIVE
MULTIPLICATIVE



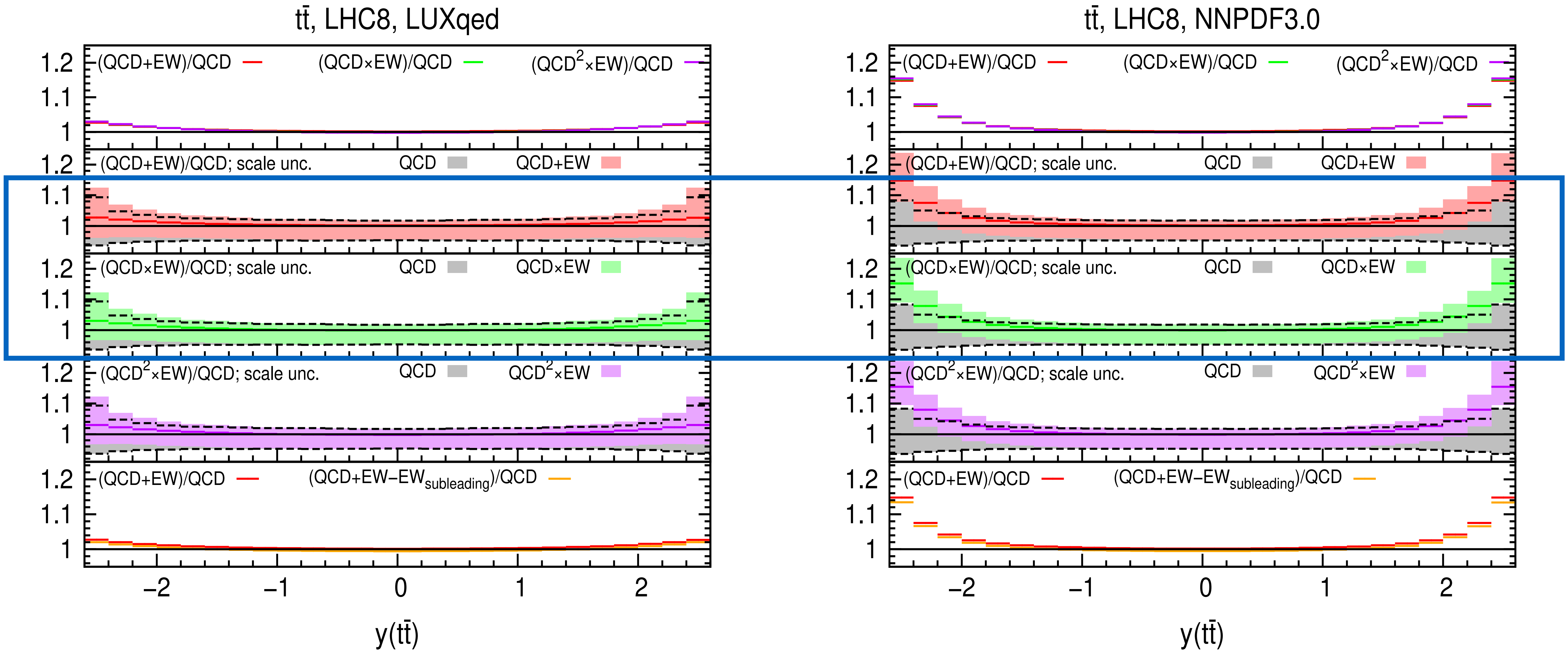
QCD+EW ~ QCDxEW

LUXQED

NNPDF3.0QED

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

ADDITIVE
MULTIPLICATIVE



QCD+EW ~ QCDxEW

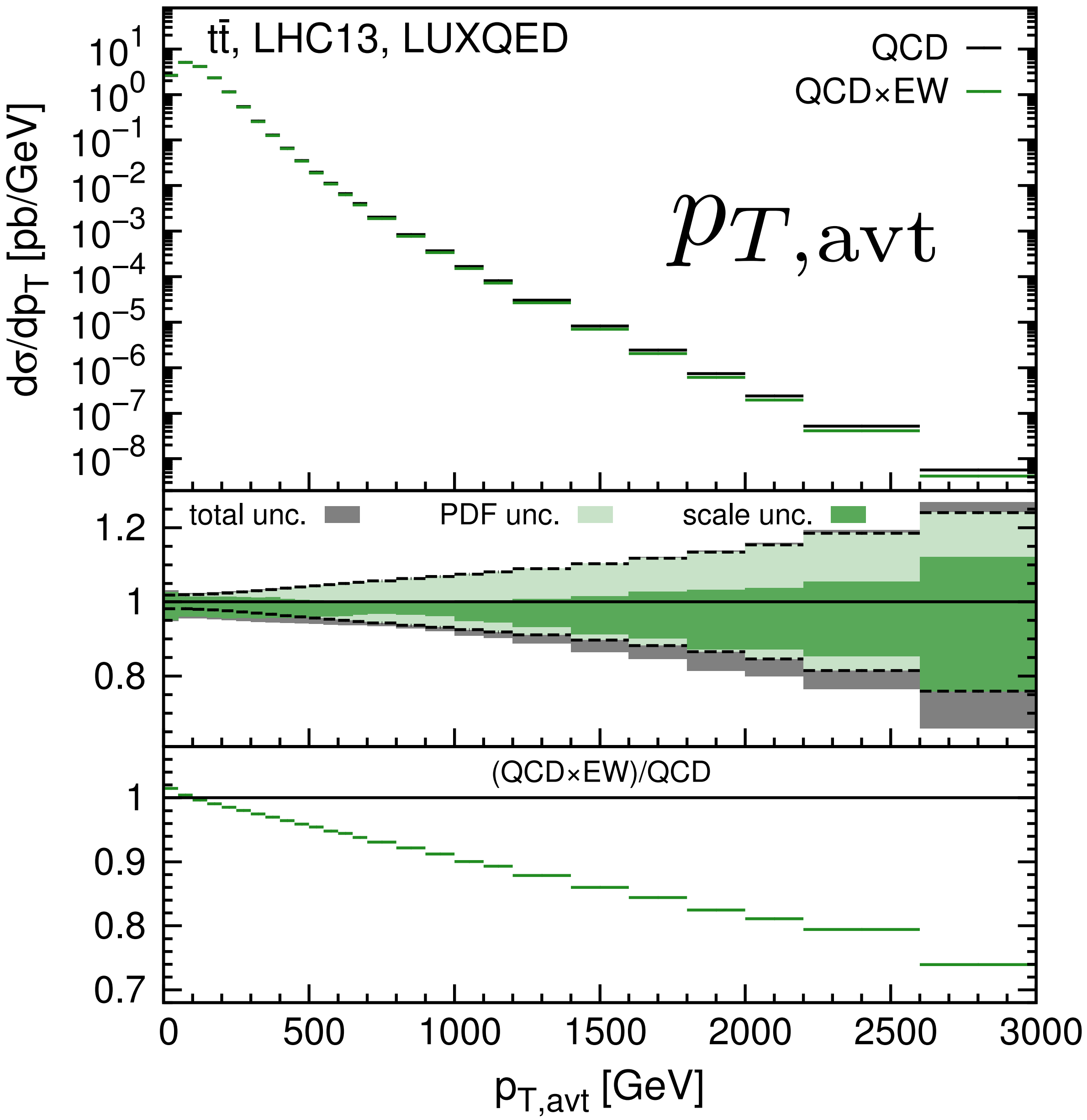
LUXQED NNPDF3.0QED

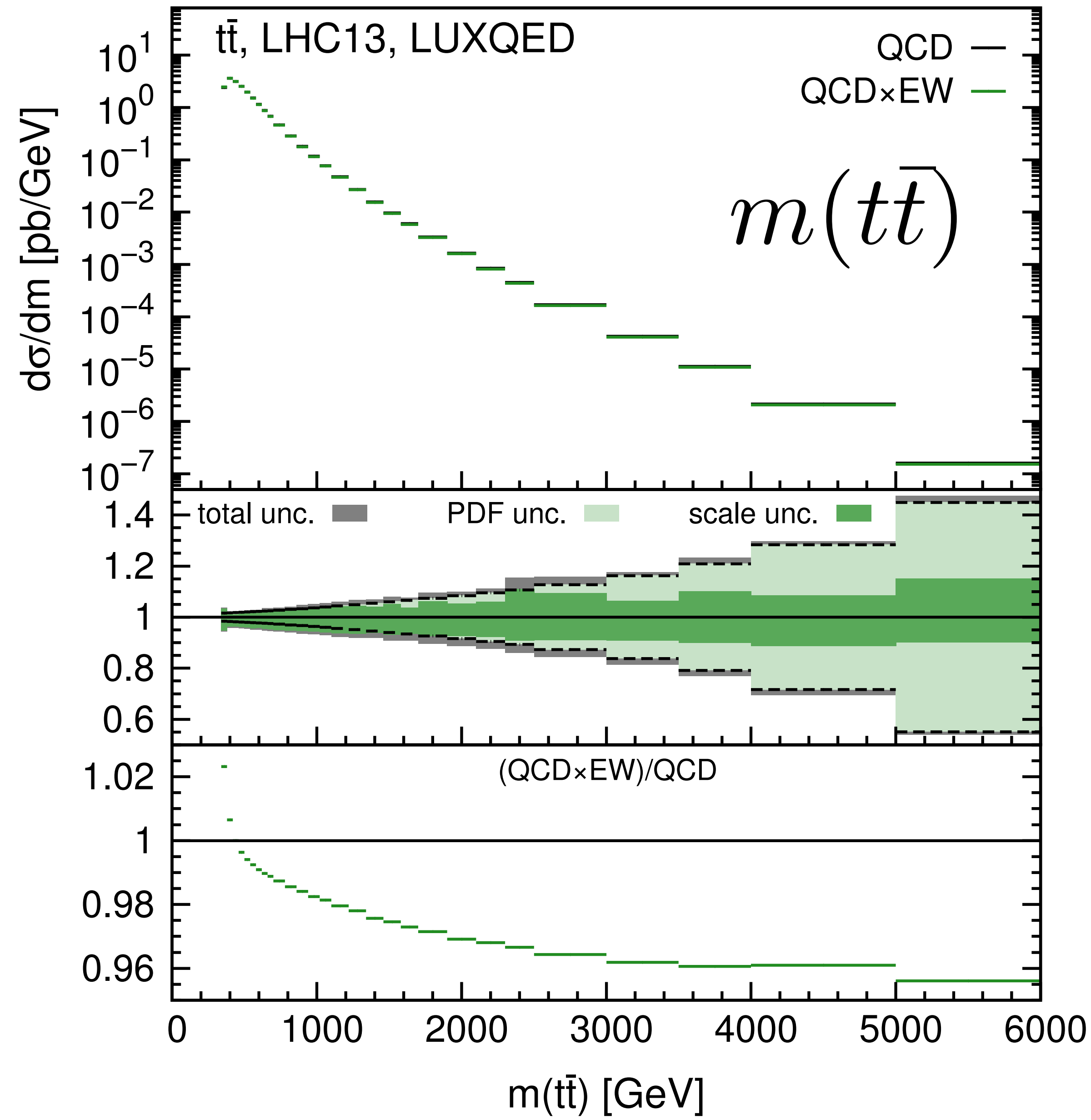
Results

Best predictions

MULTIPLICATIVE
with LUXQED

MULTIPLICATIVE with LUXQED





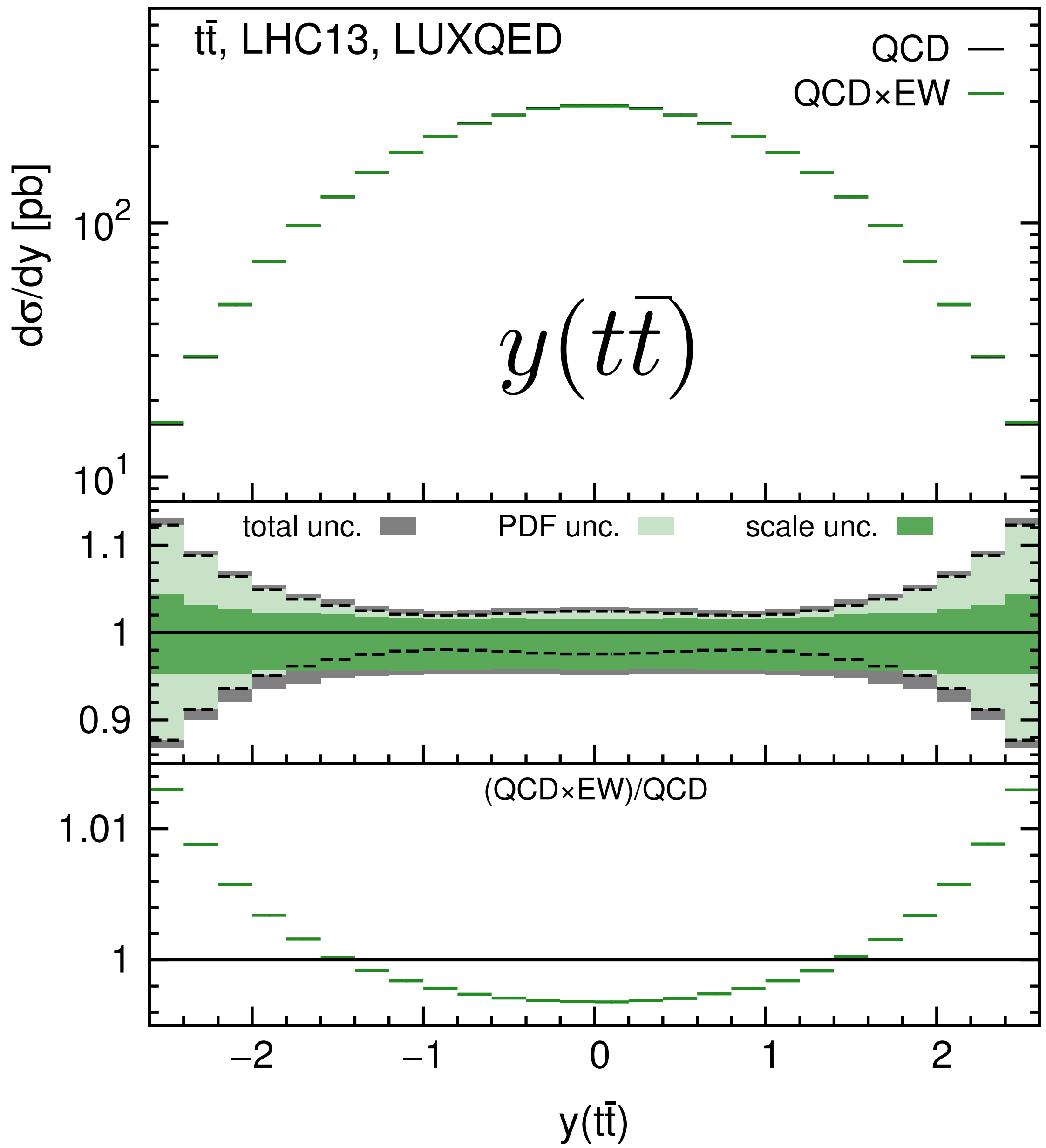
scale unc. ~ PDF unc

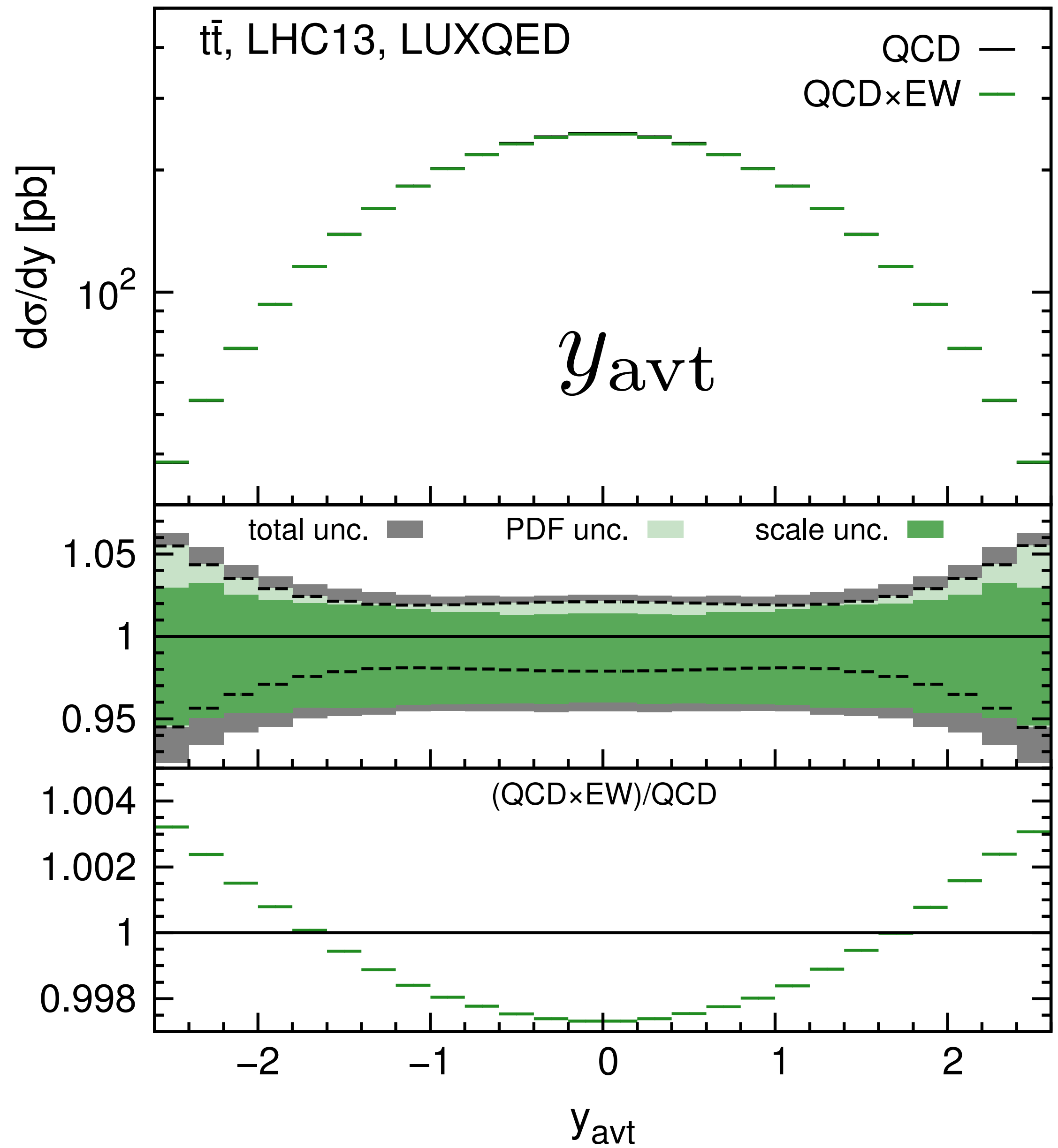
EW corrections ~ theory error

scale unc. < PDF unc

13 TeV

MULTIPLICATIVE with LUXQED



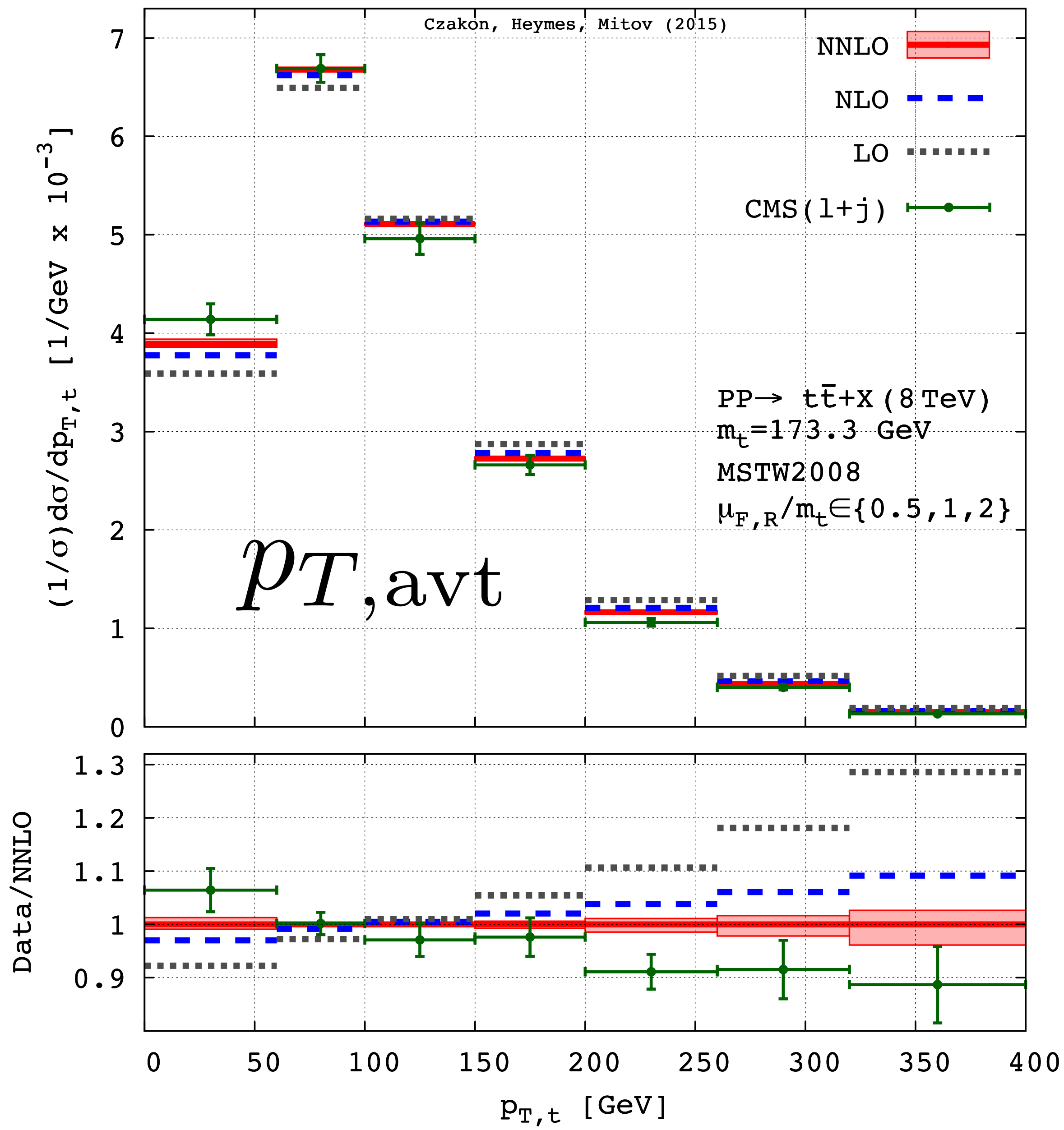


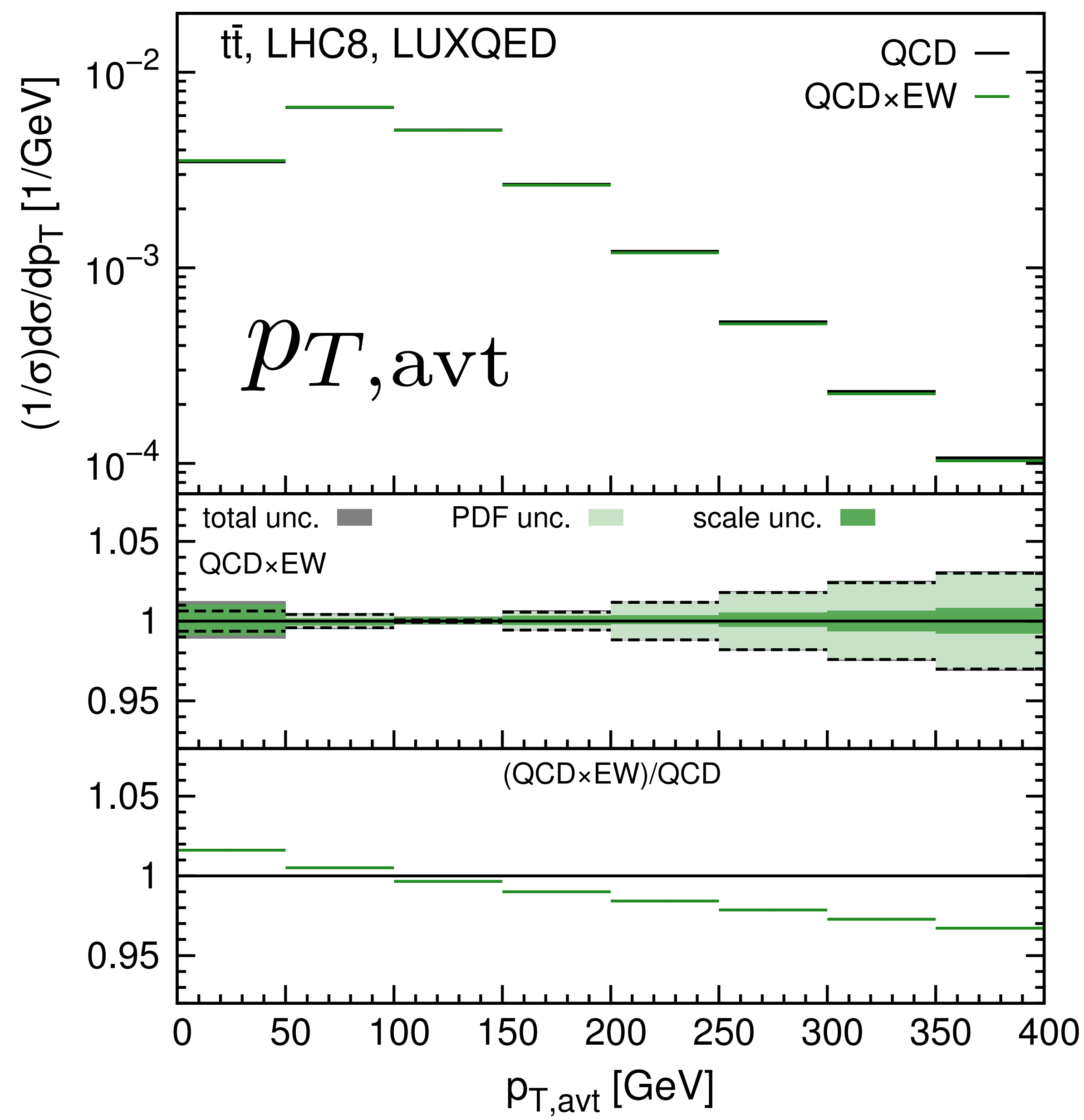
scale unc. ~ PDF unc, larger PDF unc. at large y

scale unc. ~ PDF unc,

8 TeV

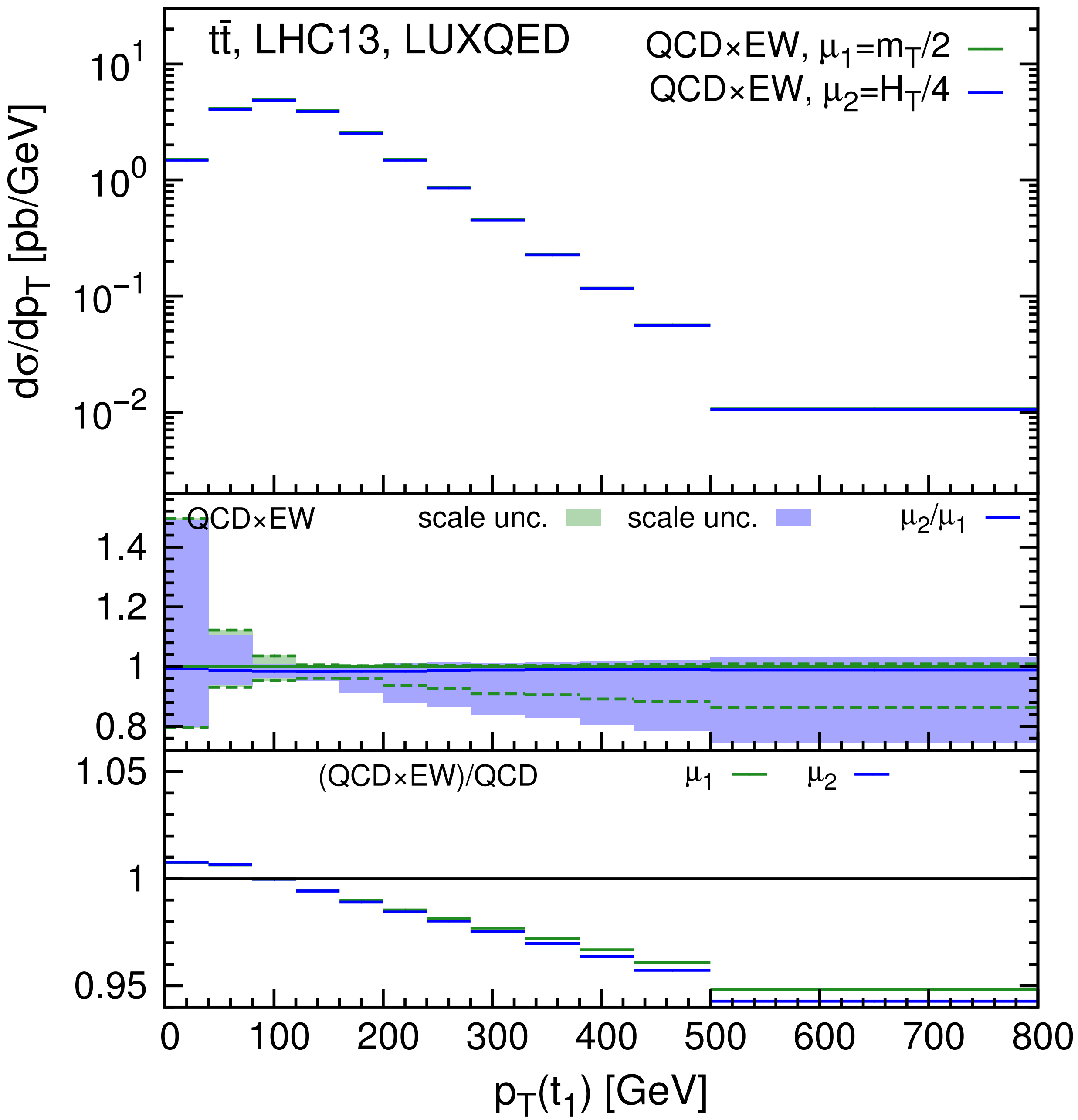
MULTIPLICATIVE with LUXQED

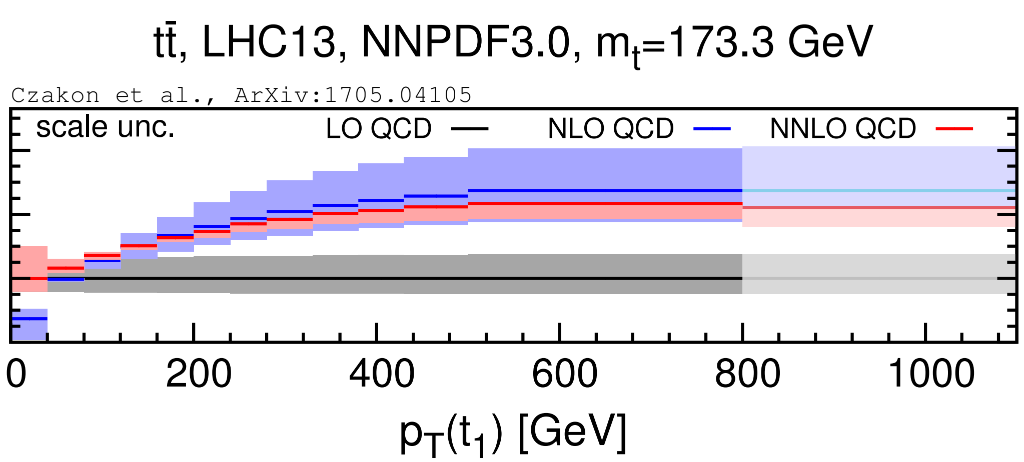


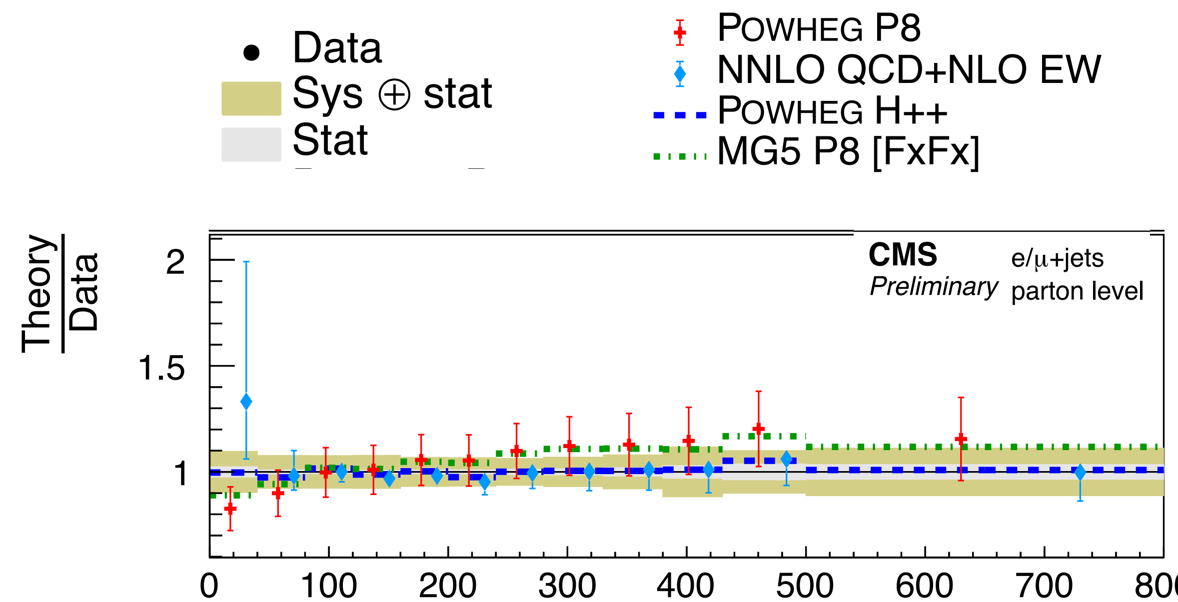


Normalised distribution with smaller range

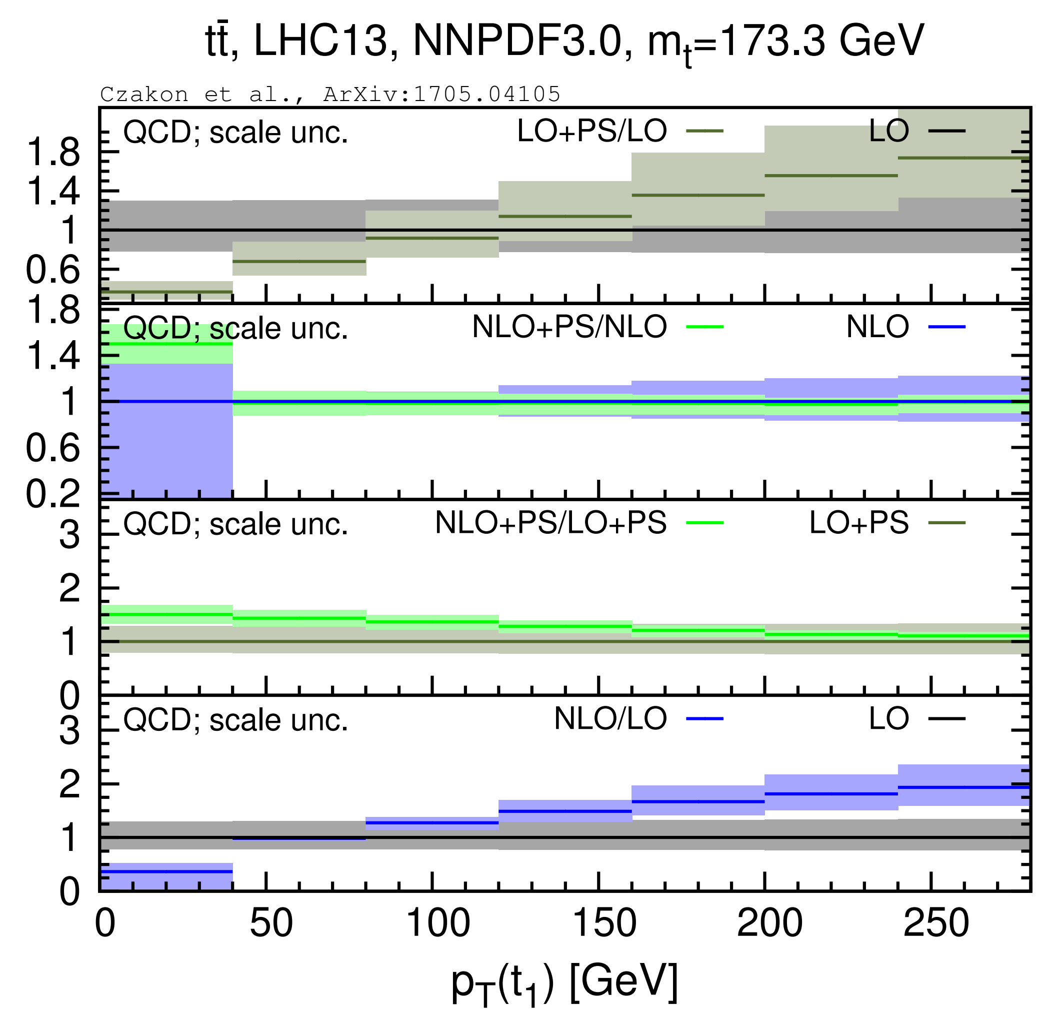
Leading-PT Top



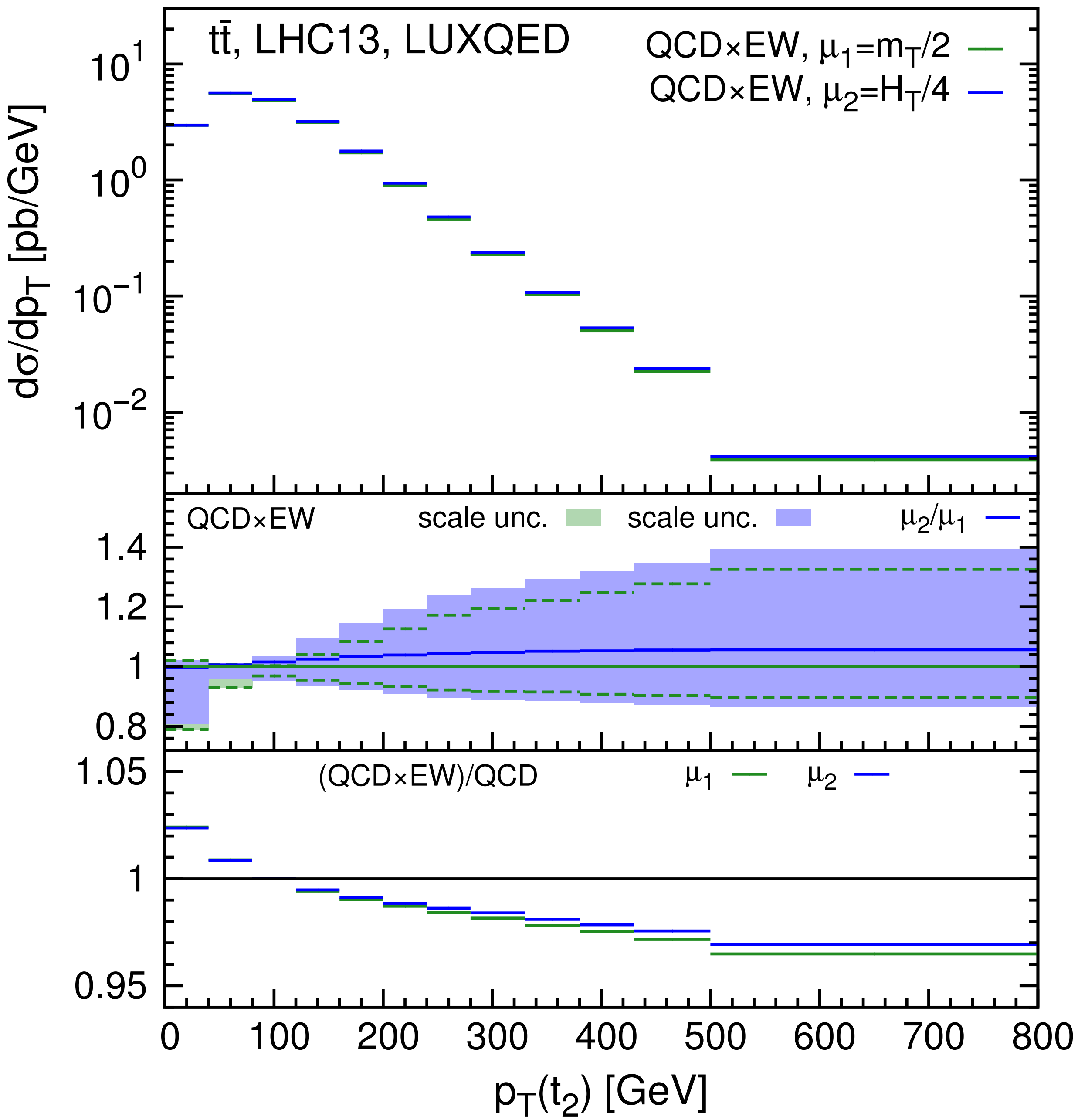


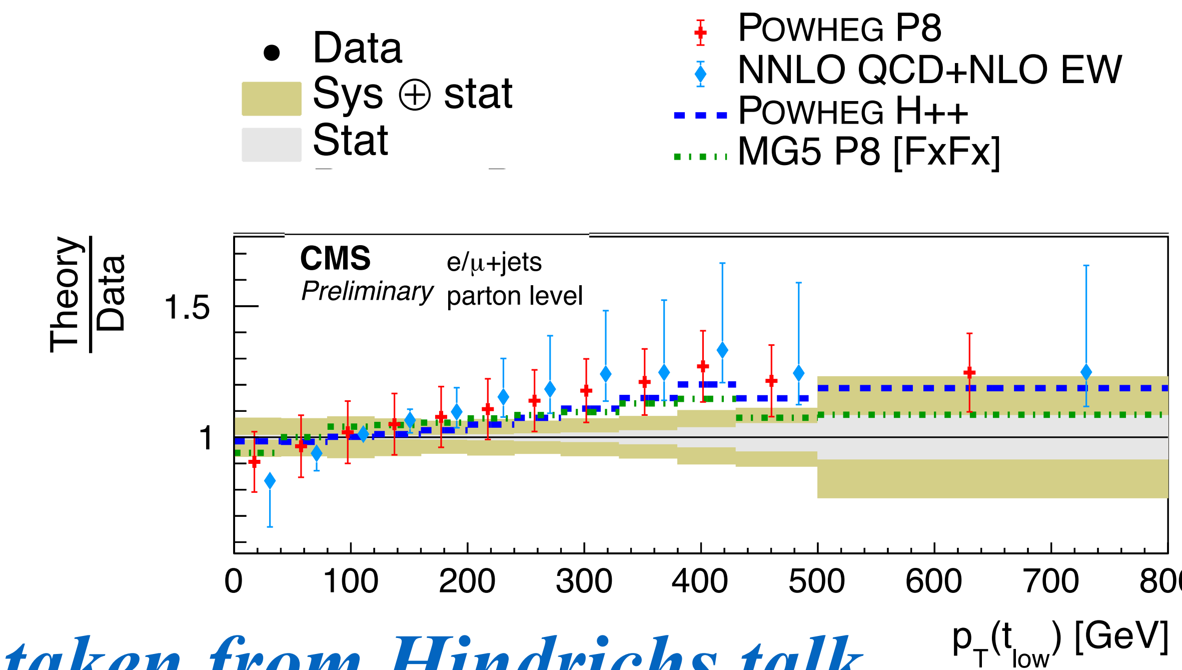


taken from Hindrichs talk



Trailing-PT Top





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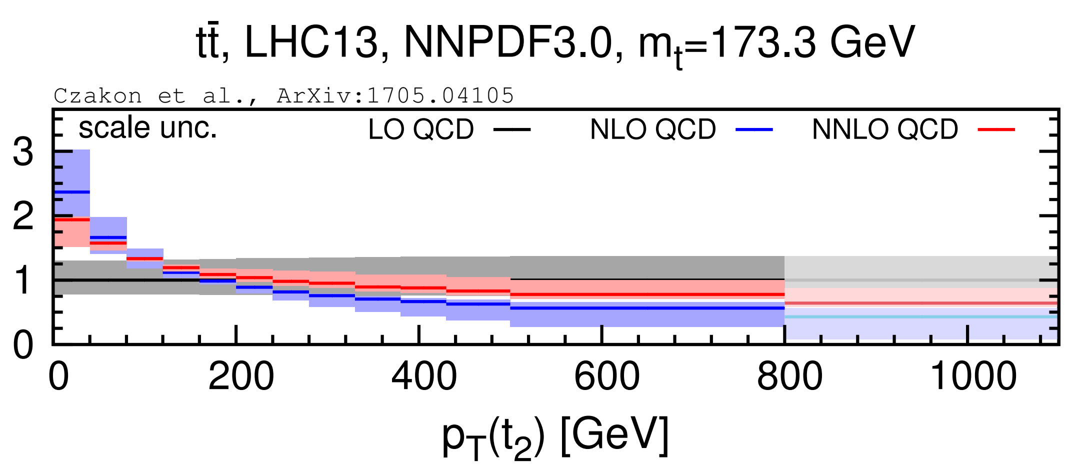
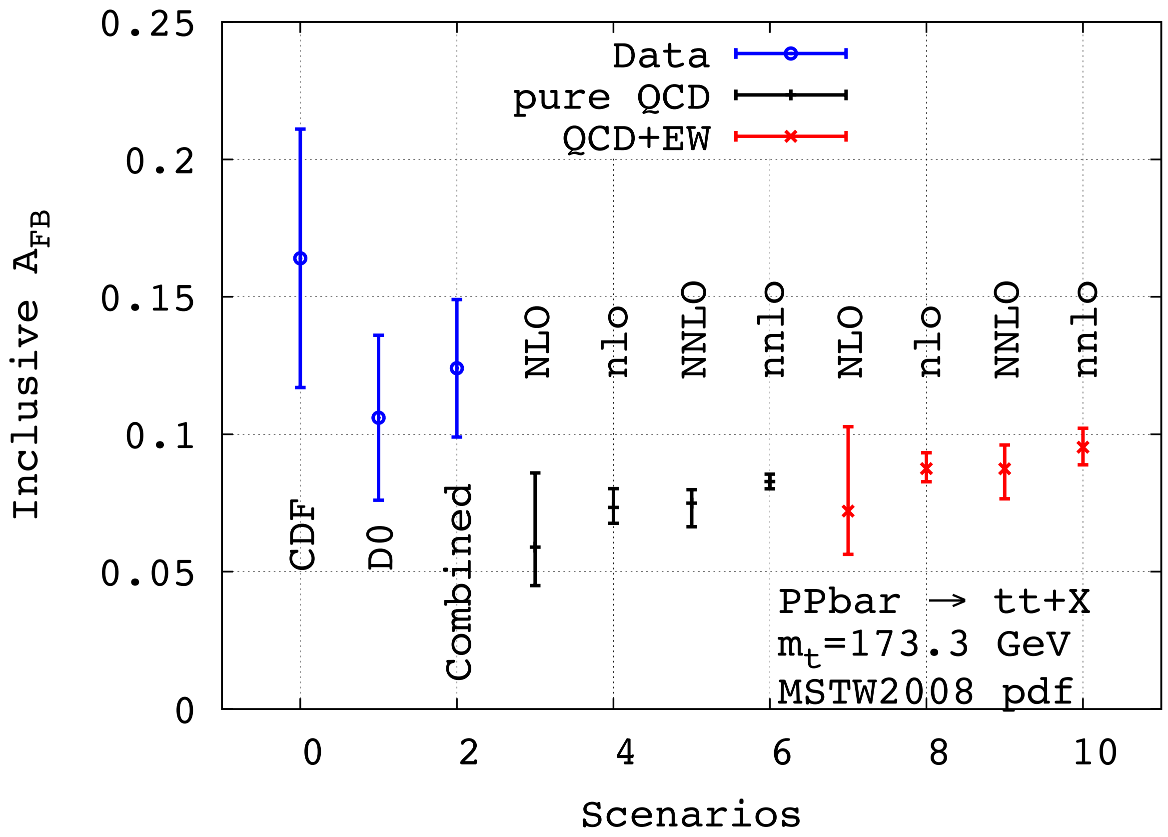


In the limit of a very hard **trailing top,** the same effects observed in the limit of very soft **leading top** are expected: **pathologies** at **fixed order.** They are **not present** in the **average-pt** distribution.

Charge Asymmetry

What is already known:



Capital:	unexpanded
Small:	expanded
Red:	QCD+EW (approximation)
Black:	QCD

No EW corrections in the denominator of:

$$A_{t\bar{t}} = \frac{N(y_t > y_{\bar{t}}) - N(y_{\bar{t}} > y_t)}{N(y_t > y_{\bar{t}}) + N(y_{\bar{t}} > y_t)}$$

Czakon, Fiedler, Mitov '14

- EW contribution is relevant.
- NLO≠NNLO, nlo~nnlo.
- |NNLO-nnlo| < |NLO-nlo|

The bulk of EW corrections is **not** a Sudakov effect, it is of QED origin and it can easily be obtained from NLO QCD calculation.
Hollik, DP '11

$$R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}$$

PDF uncertainties are negligible; there are large cancellations in the ratio.

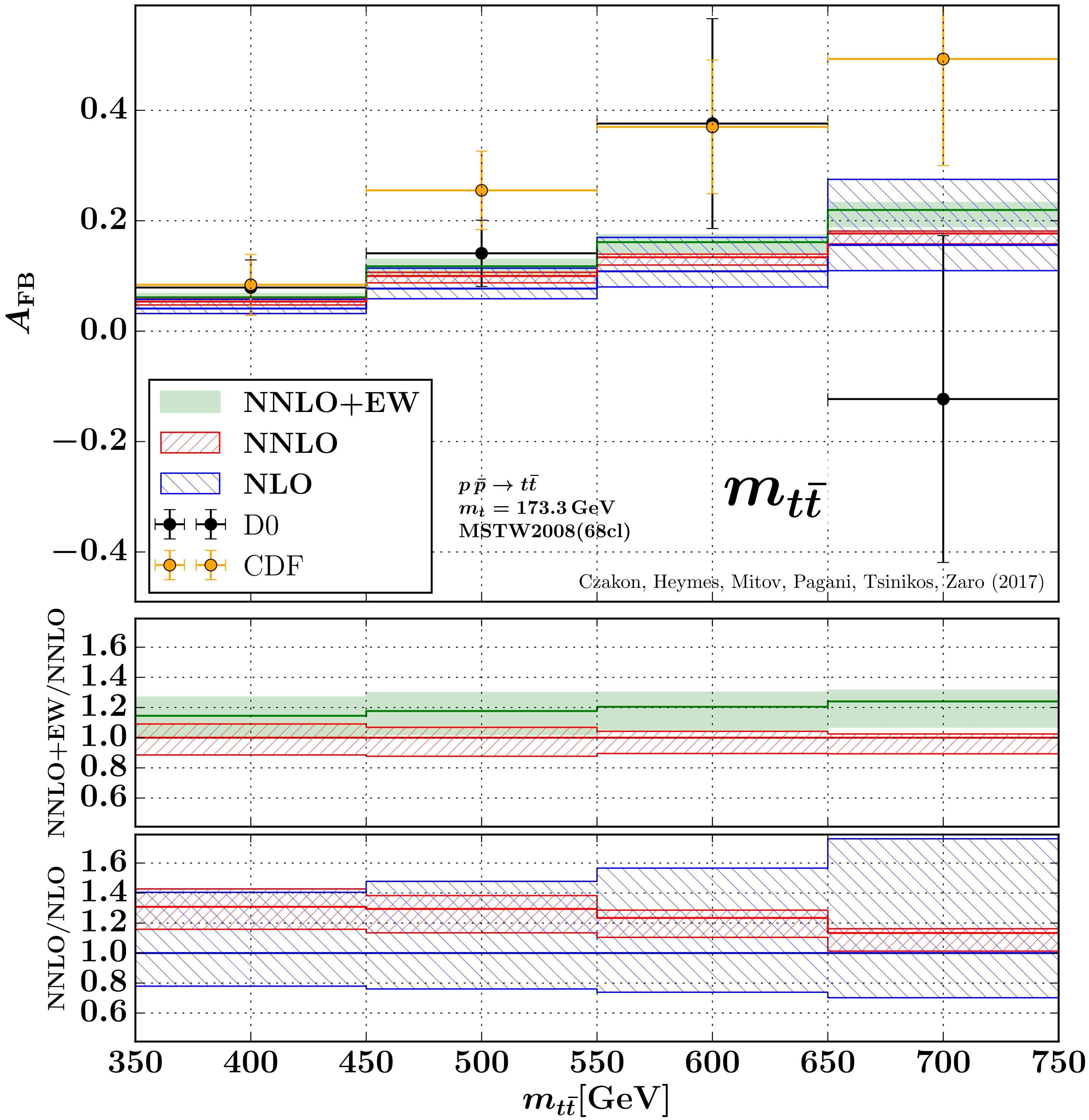
Preliminary results

Differential distributions

Additive approach (QCD +EW, all LO and NLO included)

Unexpanded definition for the asymmetry

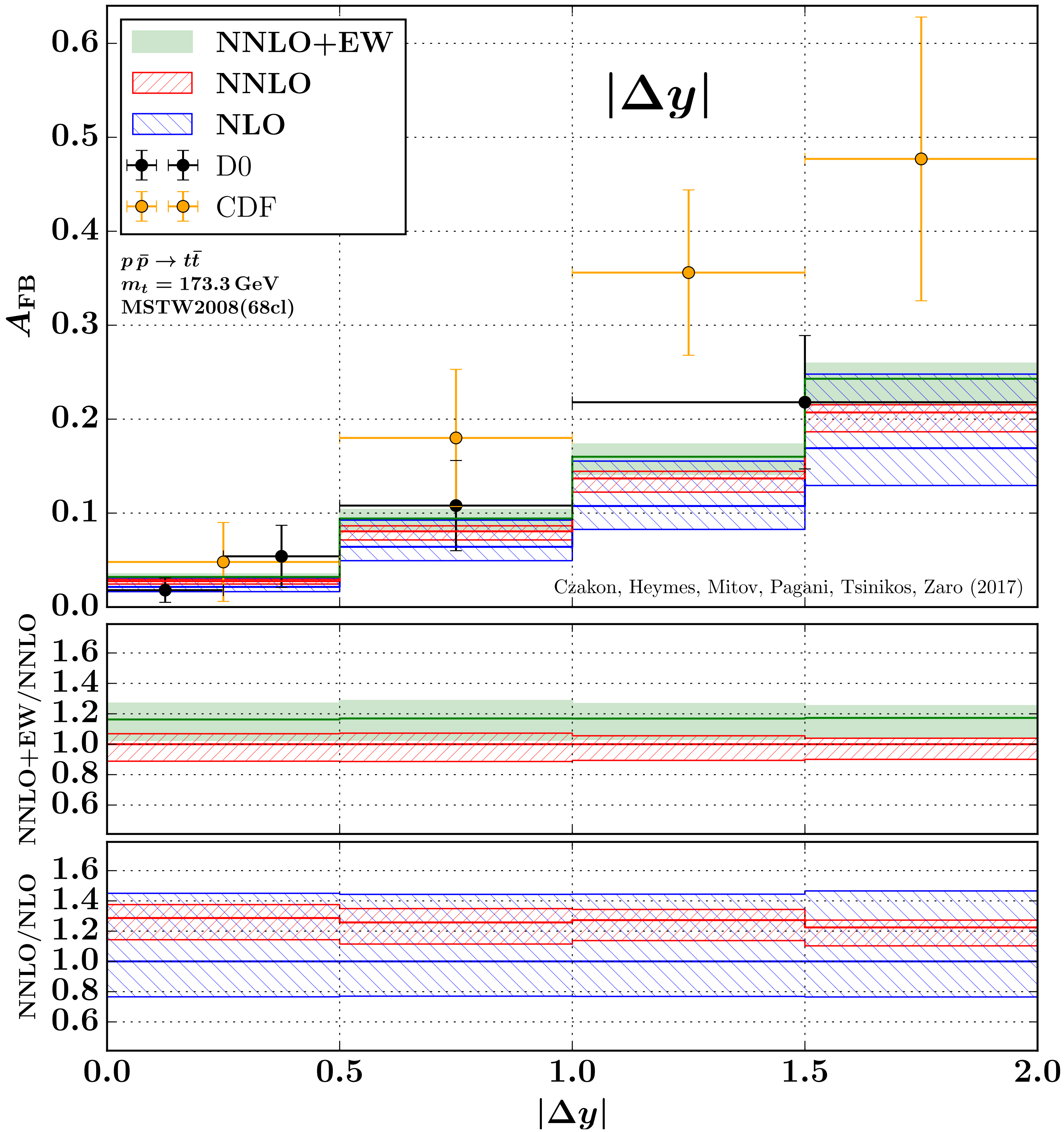
$$A_{\rm FB} = \frac{\sigma^{+}_{\rm QCD+EW} - \sigma^{-}_{\rm QCD+EW}}{\sigma^{+}_{\rm QCD+EW} + \sigma^{-}_{\rm QCD+EW}}$$



Tevatron

EW corrections are larger than the NNLO QCD scale uncertainty

The theory uncertainty is much smaller than experimental errors.



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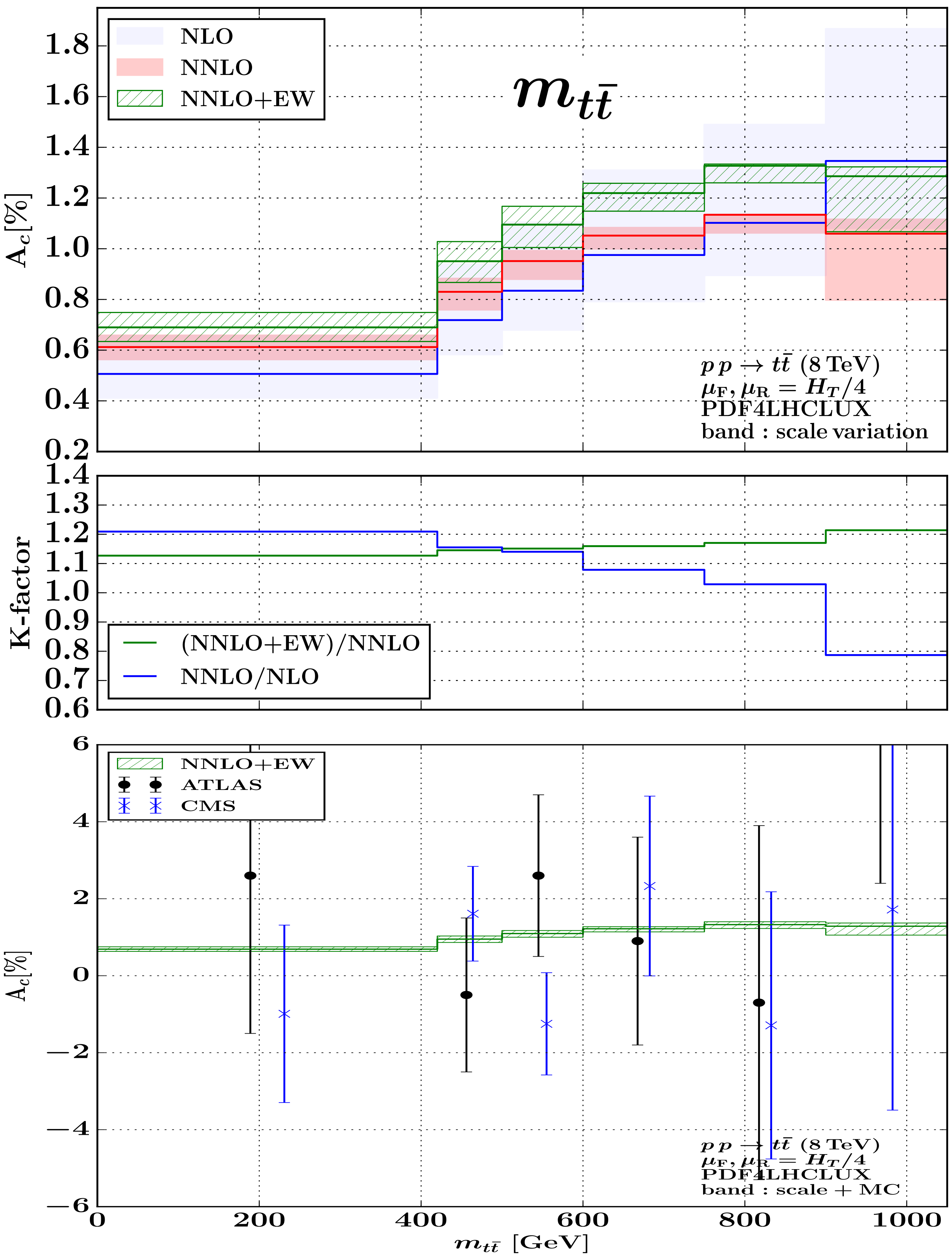


LHC 8 TeV

Central asymmetry

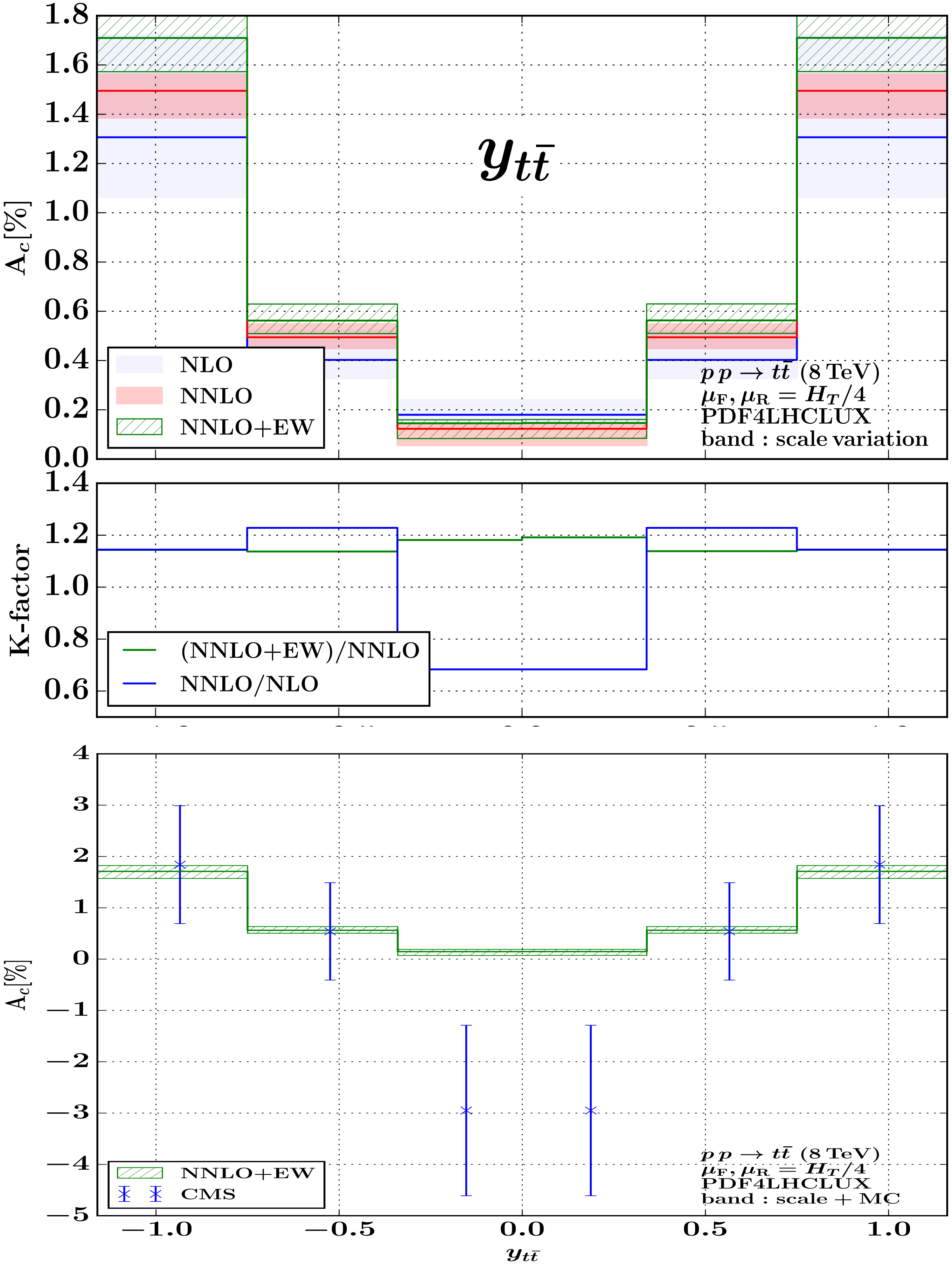
As at the Tevatron, EW corrections are larger than the NNLO QCD scale uncertainty and the theory uncertainty is much smaller than experimental errors.

$$A_C^{t\bar{t}} = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

LHC 8 TeV

Central asymmetry



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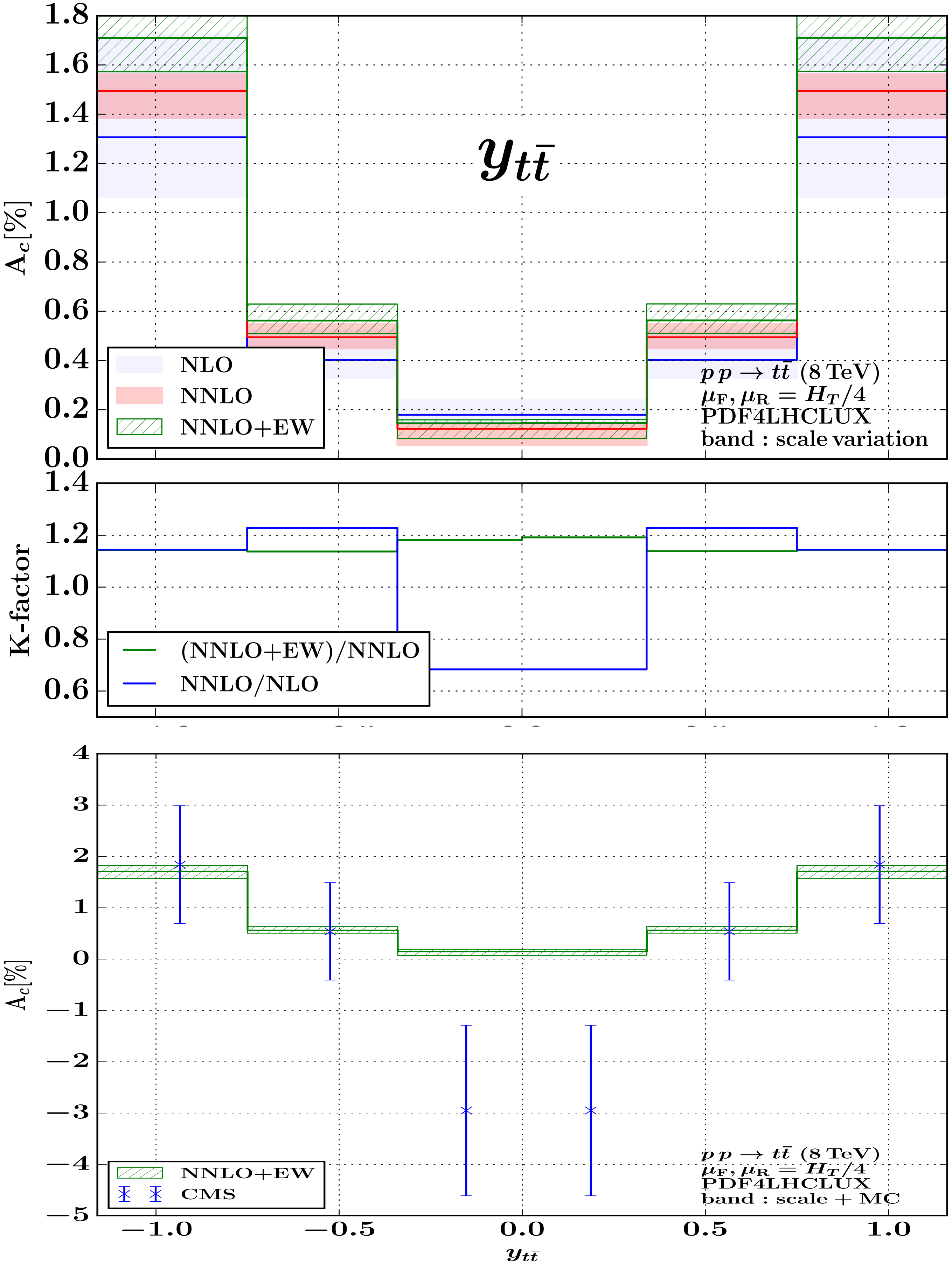
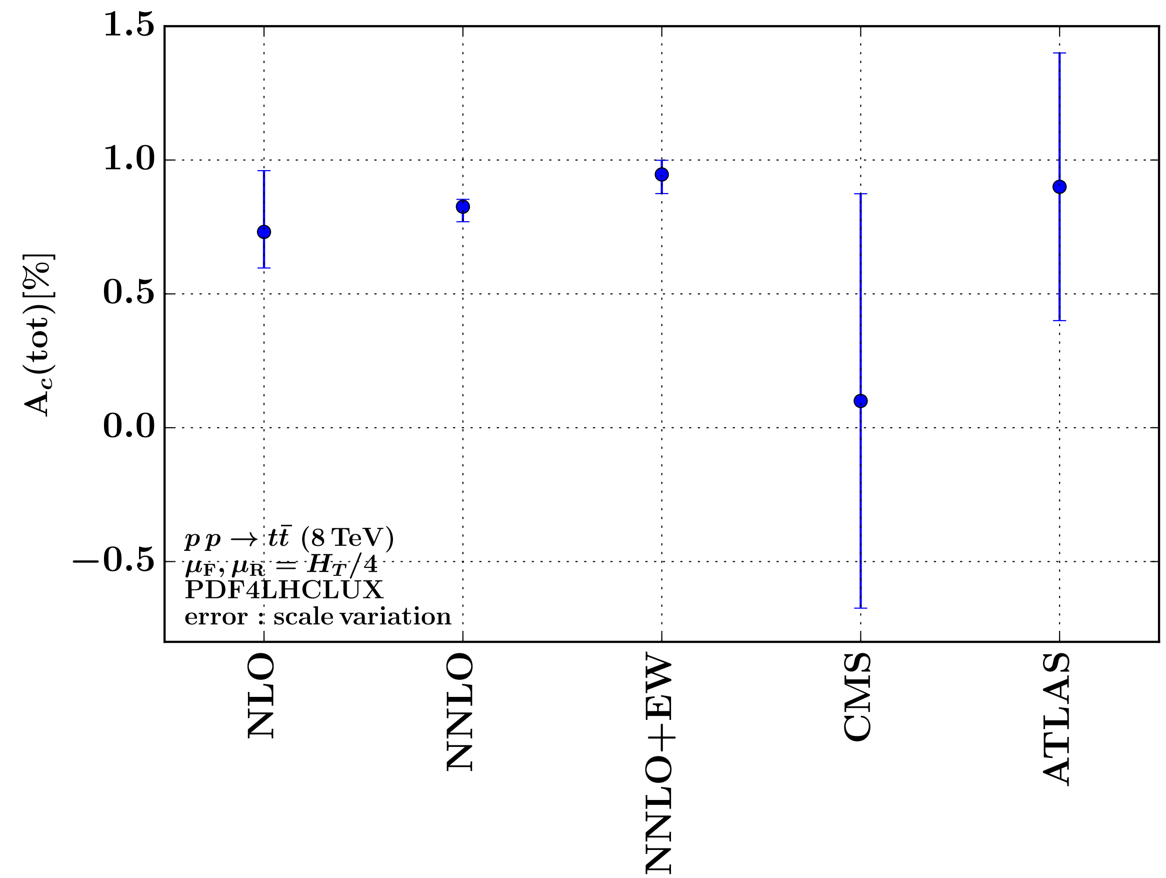
LHC 8 TeV

Central asymmetry

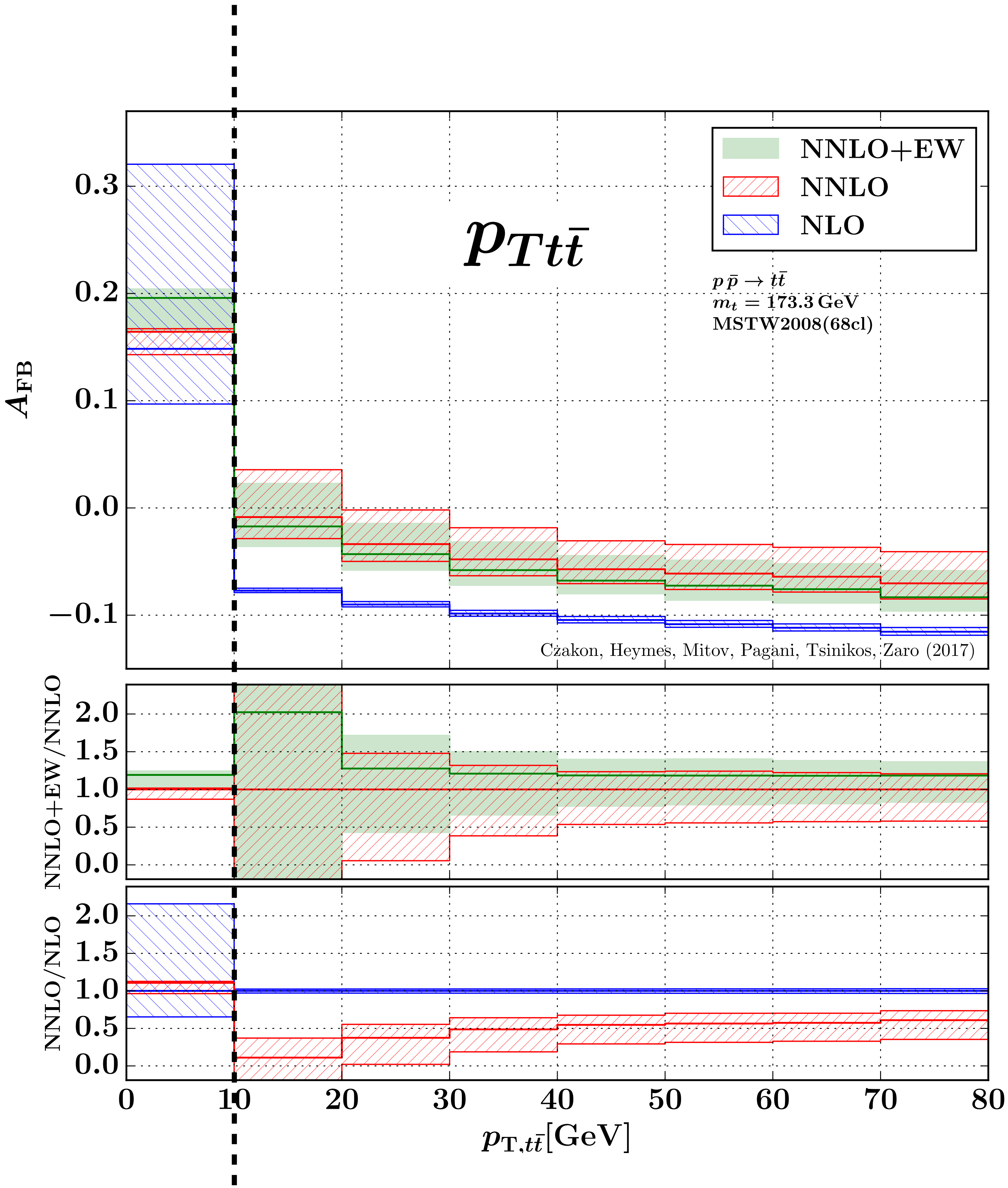


$$A_C^{t\bar{t}} = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



Total asymmetry

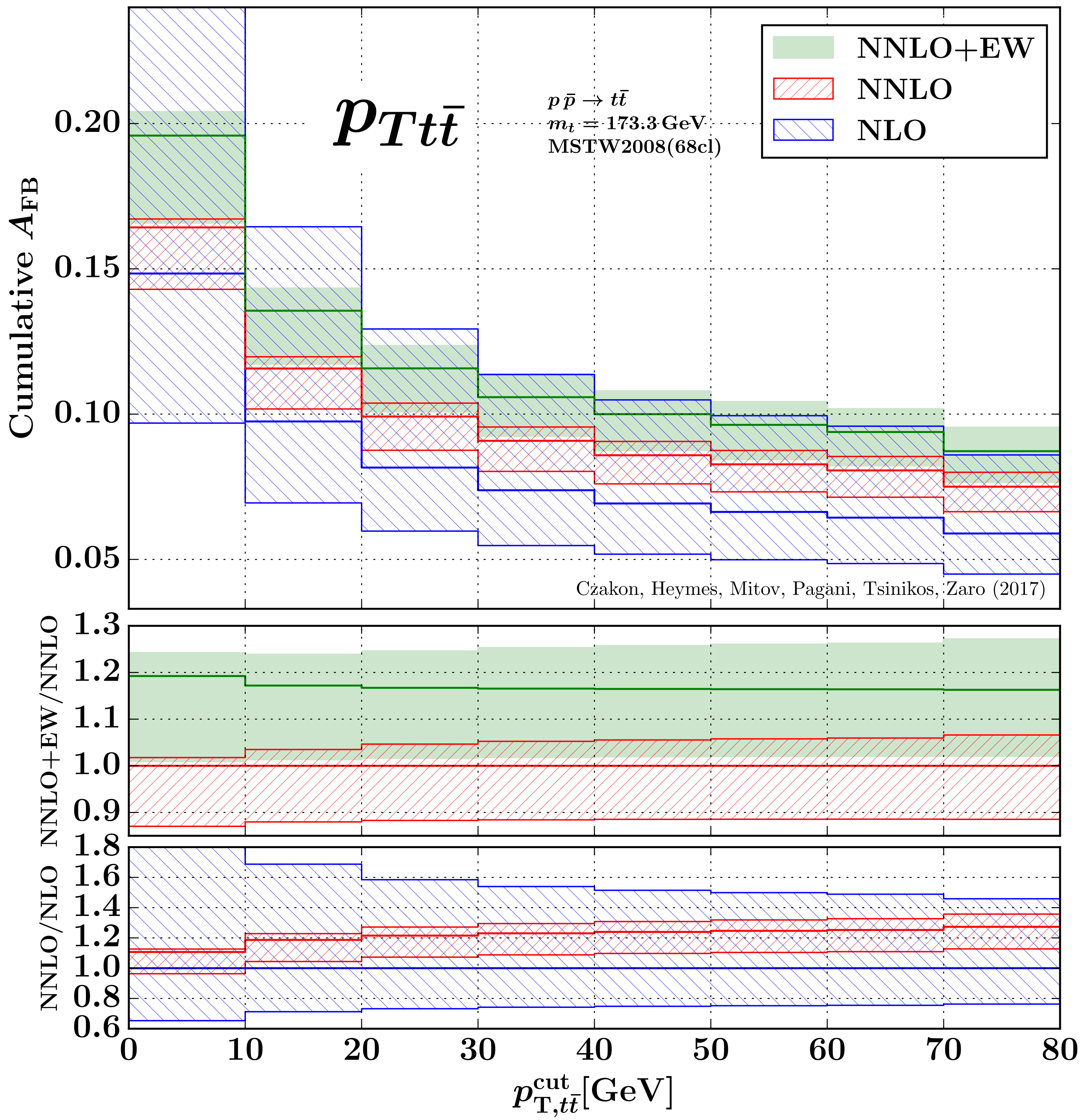


back to

Tevatron

NNLO accuracy is present **only** in the first bin.

EW corrections are large w.r.t. the "NNLO" results. They are within the "NNLO" scale uncertainty **only from** the second bin on.



back to

Tevatron

NNLO accuracy is present in all bins.

EW corrections are large. They are **outside** the NNLO scale uncertainty band.

$$A_{\mathrm{FB}}(p_{T,t\bar{t}} < p_{T,t\bar{t}}^{\mathrm{cut}})$$

Conclusion

We provided predictions at **NNLO QCD** accuracy and including **EW** corrections (complete-NLO) for ttbar production at the LHC (**8, 13 TeV**).
Both **differential distributions** and **asymmetries** have been considered.

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.

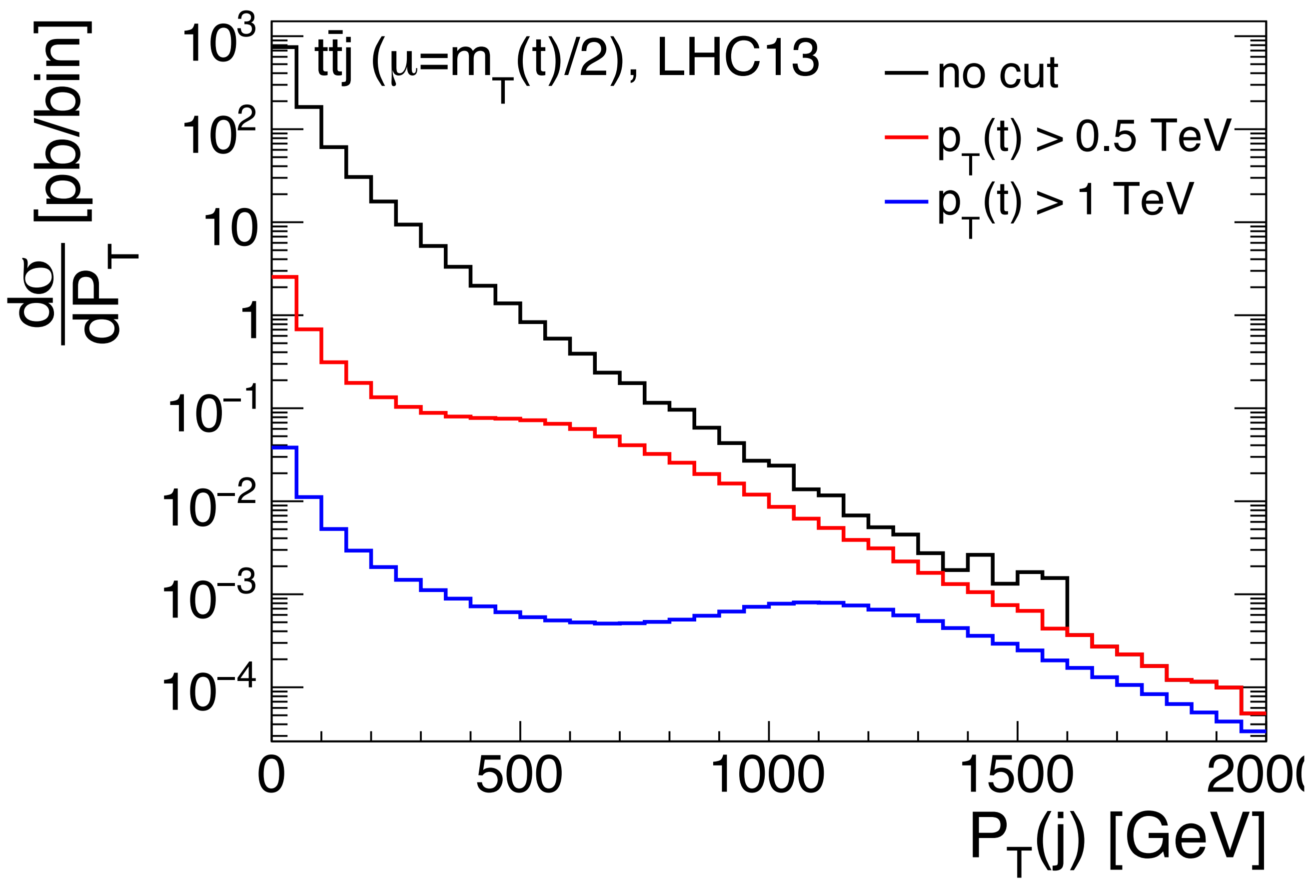
Results are strongly affected by the photon PDF parametrization (LUXqed vs. NNPDF3.0) and LUXqed should be preferred.

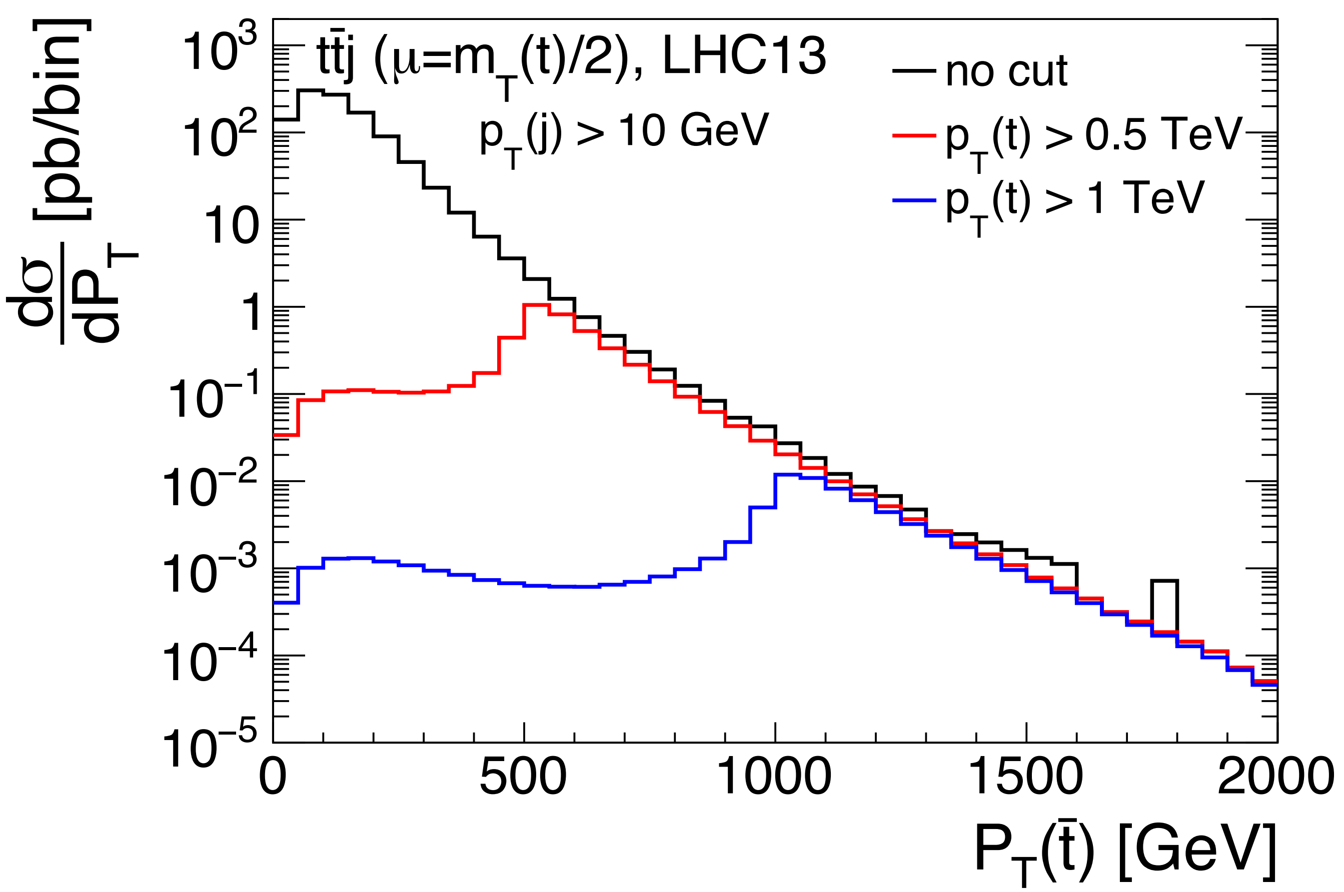
The combination in the multiplicative approach leads to a reduction of scale uncertainties. Still, in pt distribution, EW corrections are comparable to the total theory uncertainty (scale+PDF), and QCD and QCDxEW bands do not overlap.

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

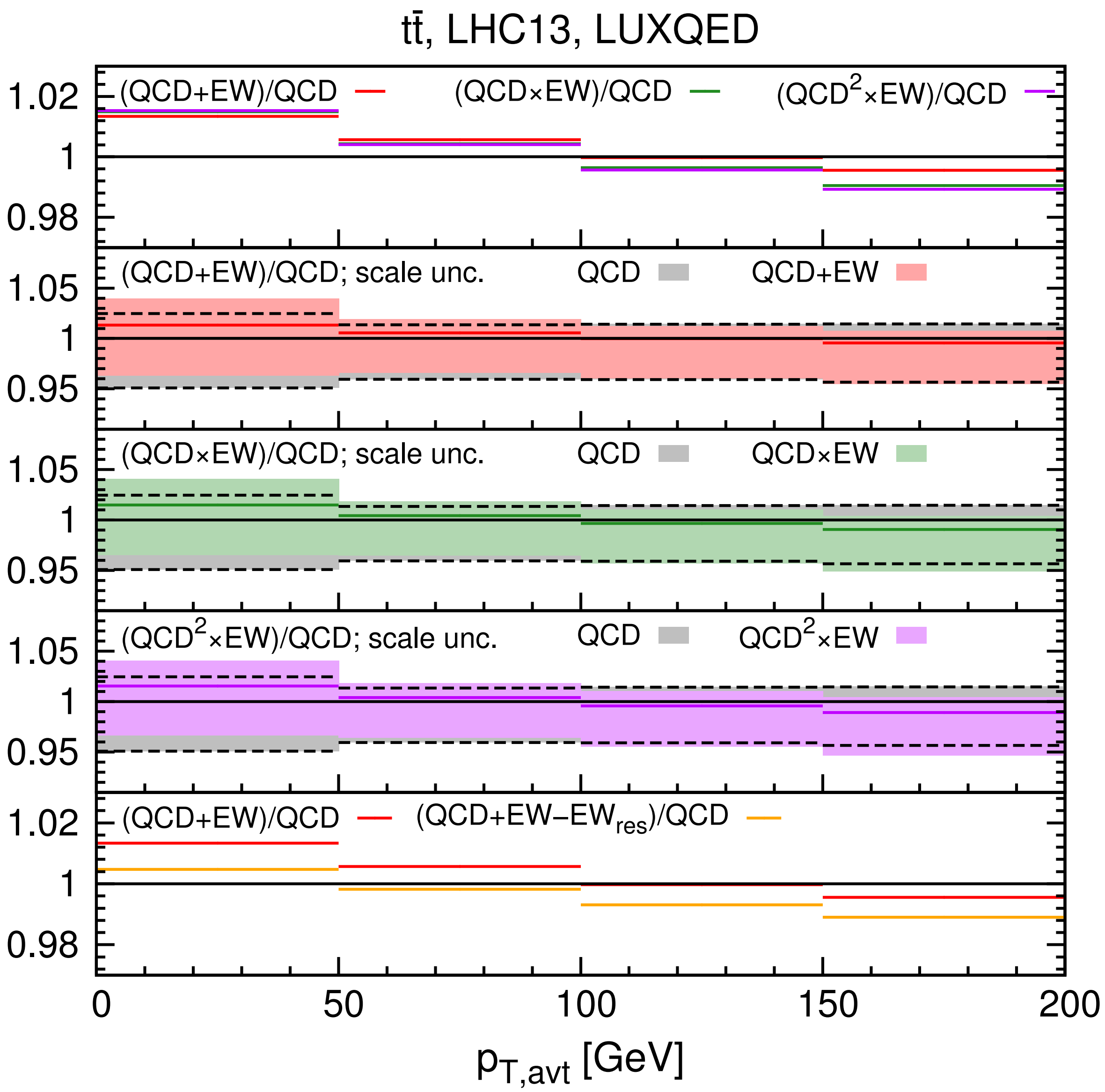
EXTRA SLIDES

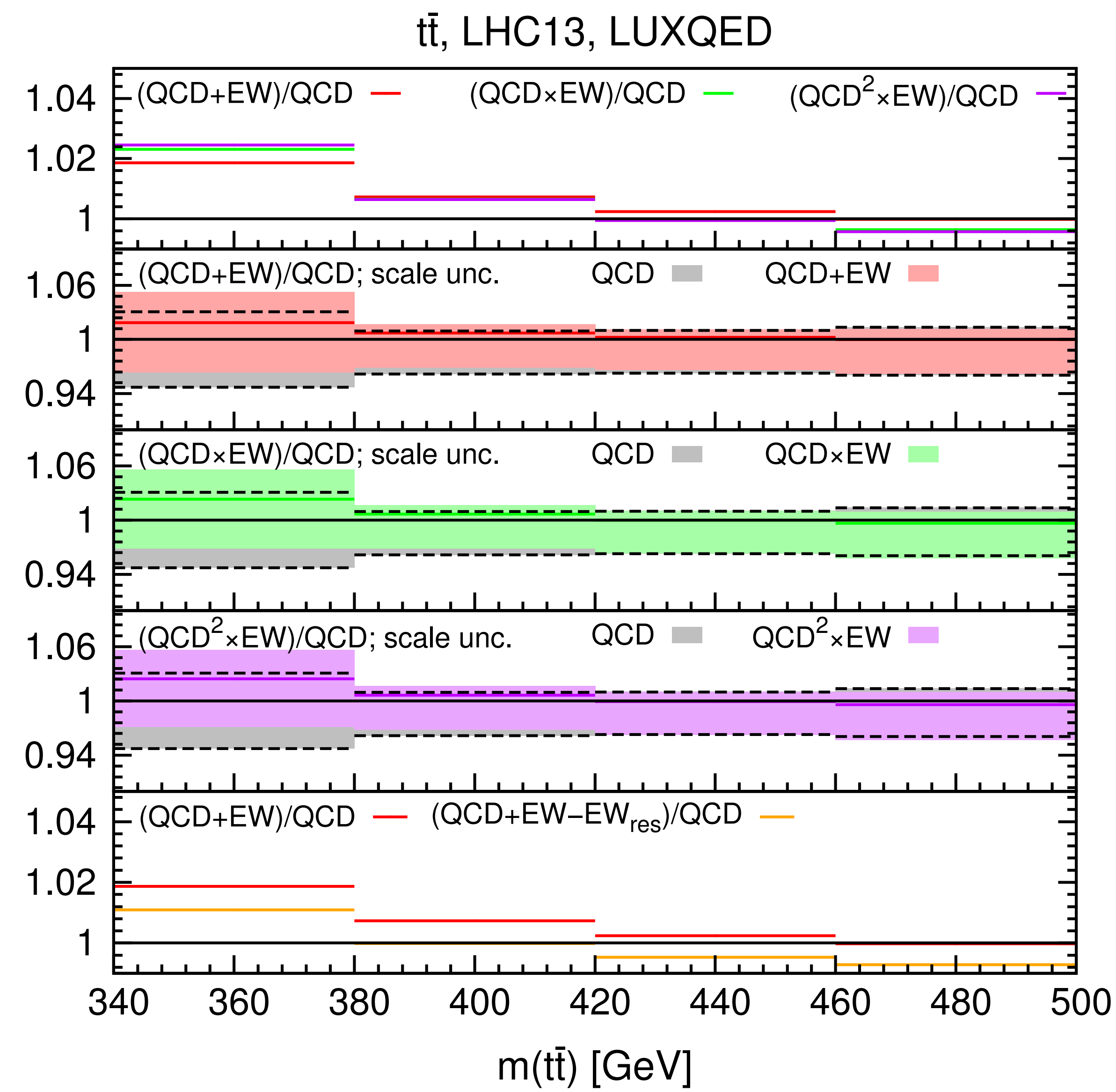
Checks EW and QCD factorisation



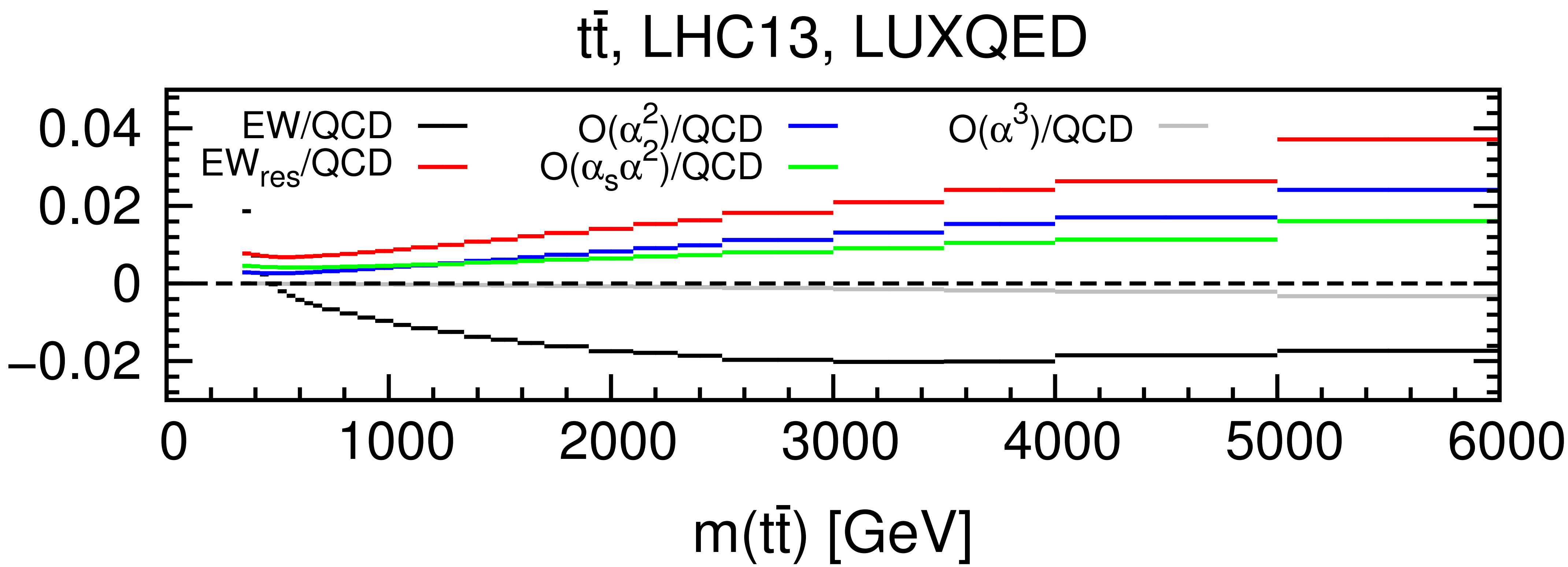


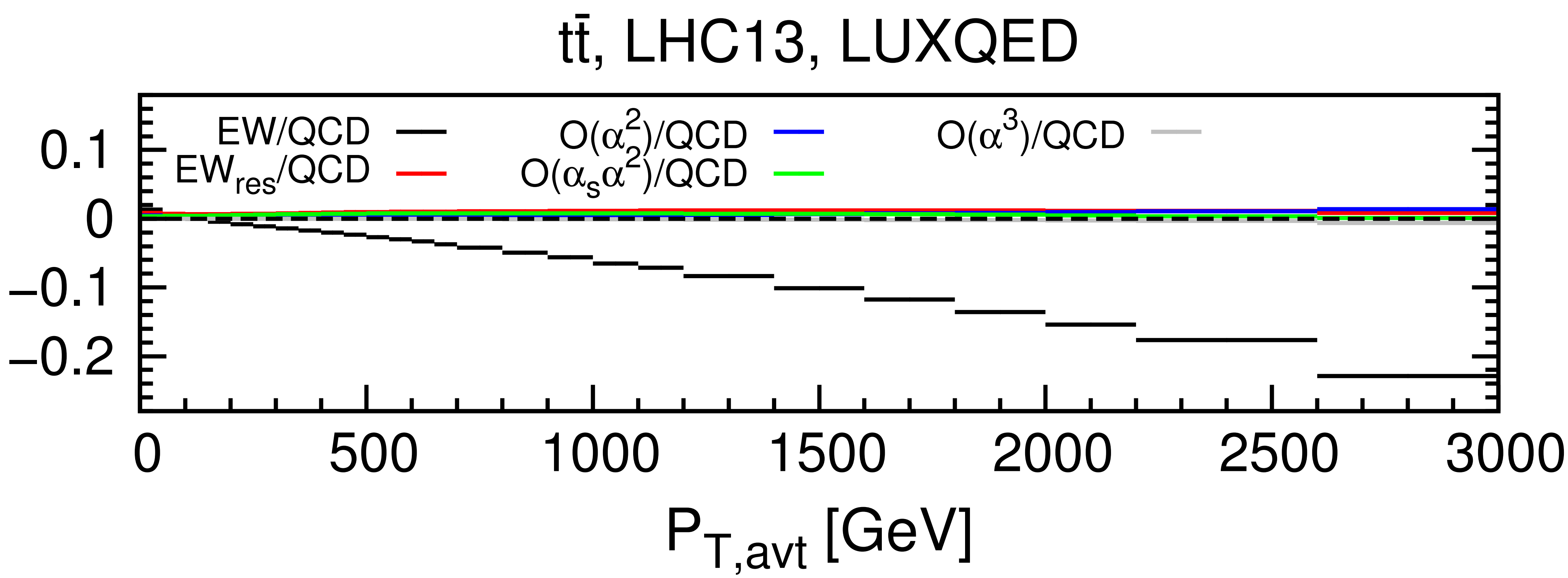
Checks EW and QCD factorisation

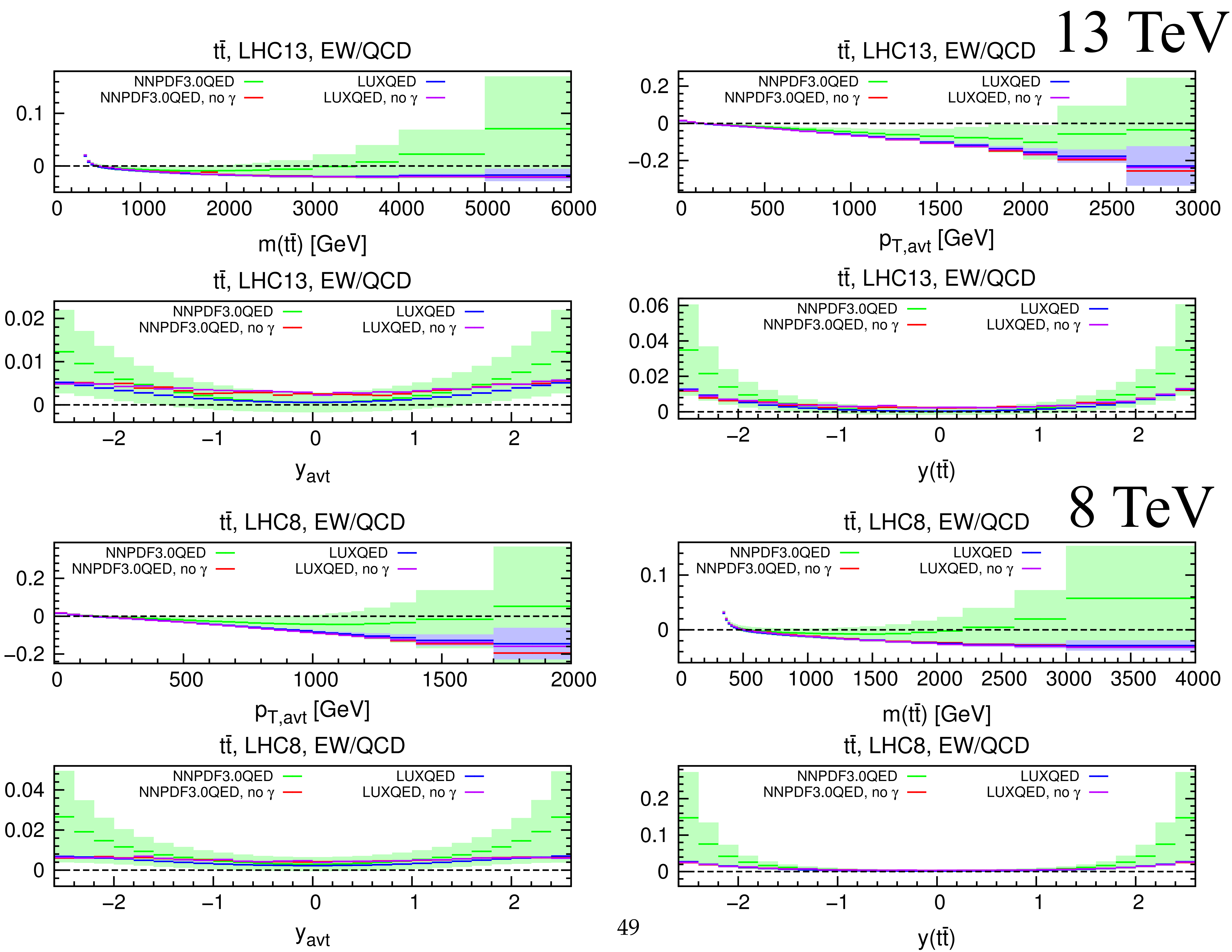


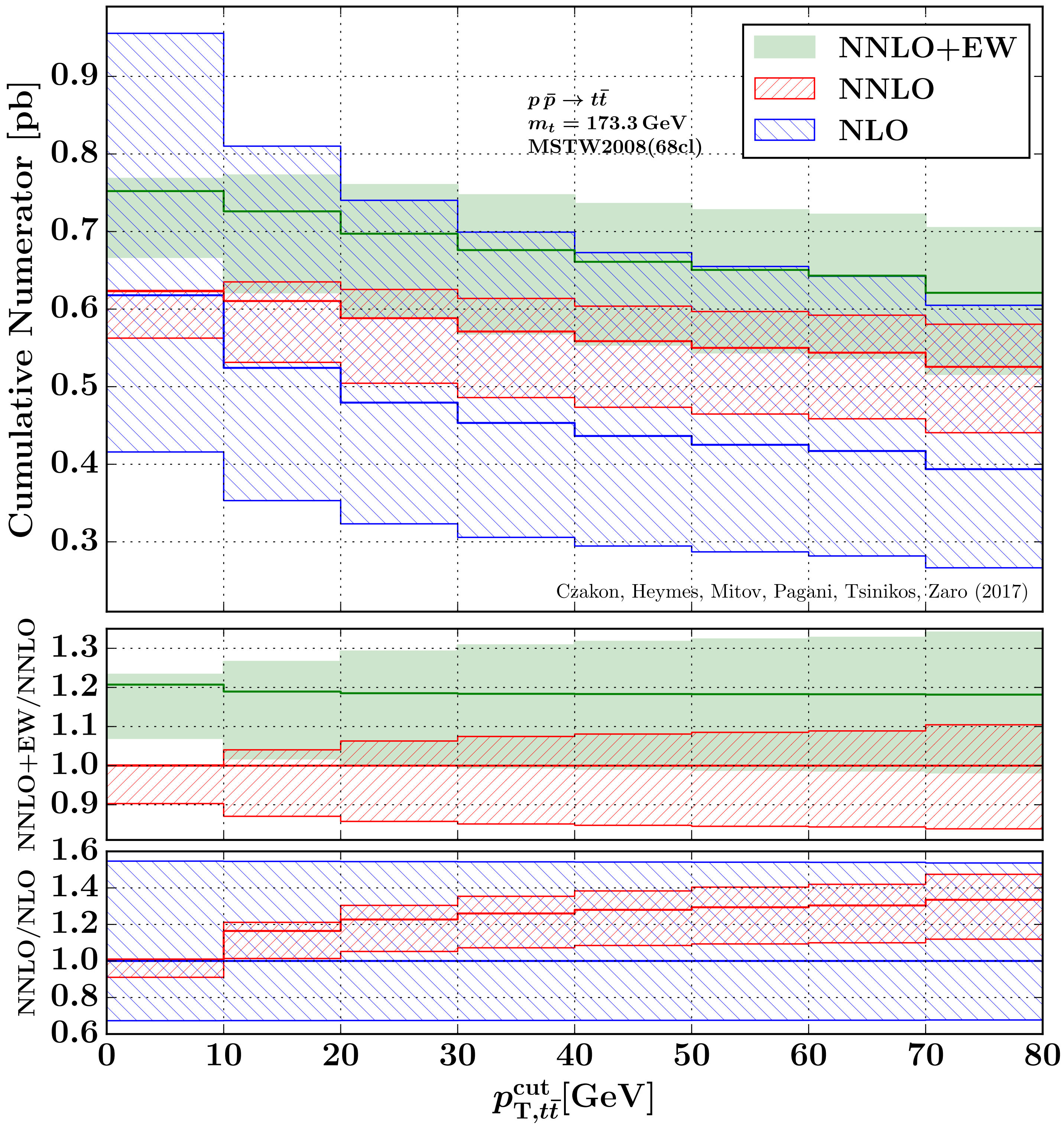


Individual subleading contributions



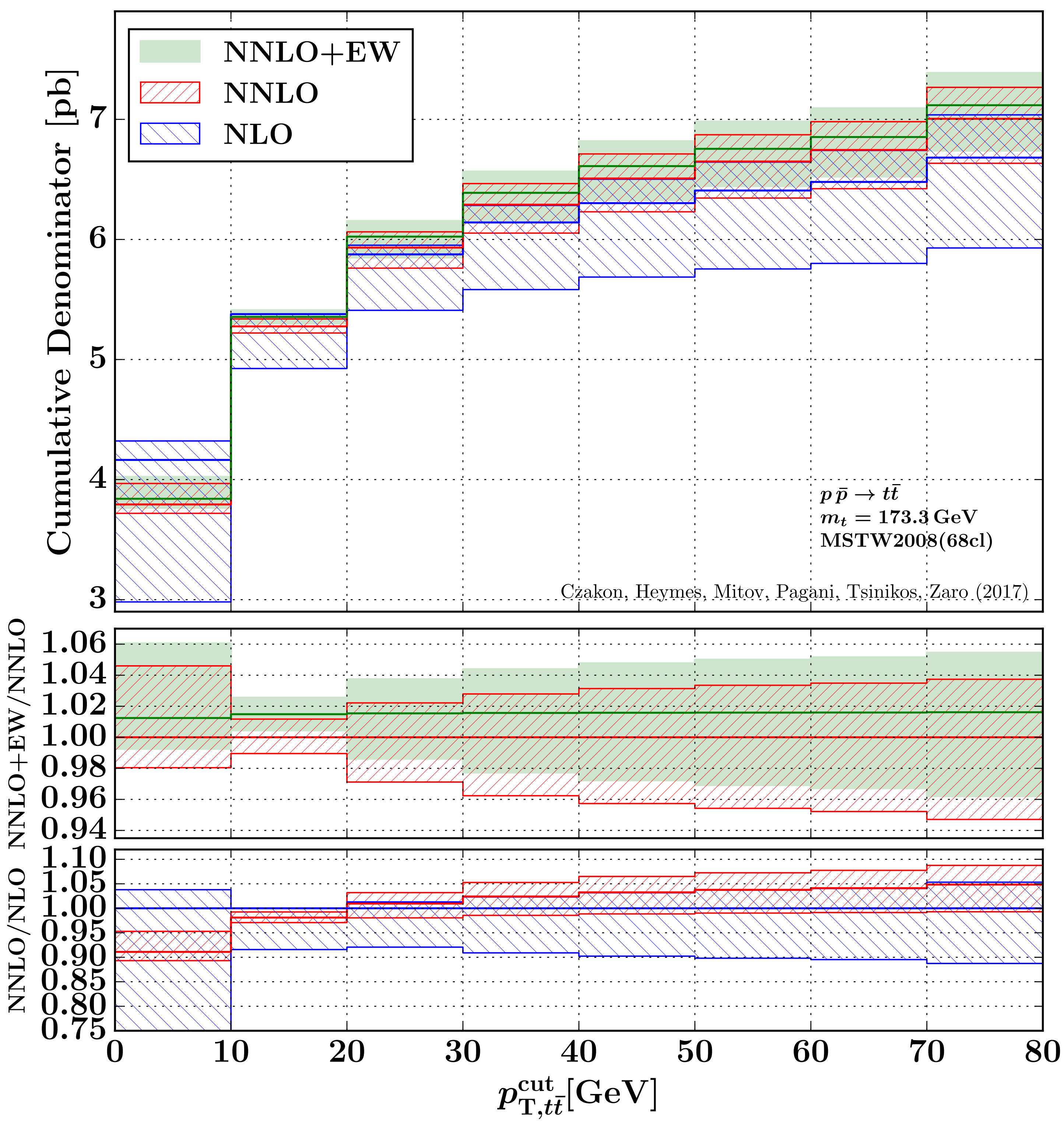



13 TeV
tt̄, LHC13, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
m(tt̄) [GeV]
$p_{T,avt}$ [GeV]
y_{avt}
y(tt̄)
8 TeV
tt̄, LHC8, EW/QCD
$p_{T,avt}$ [GeV]
m(tt̄) [GeV]
y_{avt}
y(tt̄)



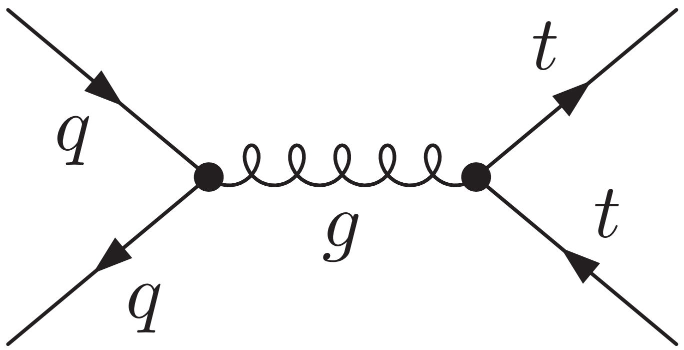
Tevatron

Numerator pT(tt) asymmetry



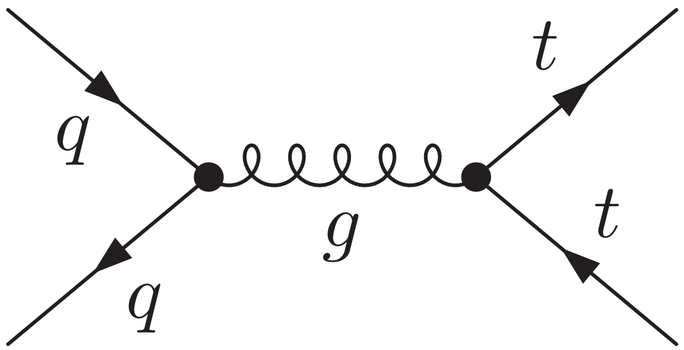
Tevatron

Denominator pT(tt) asymmetry



At LO partonic processes are not asymmetric.
QCD produces the asymmetry only at NLO!
NLO in the cross-section, LO in A_{FB}

$$A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$



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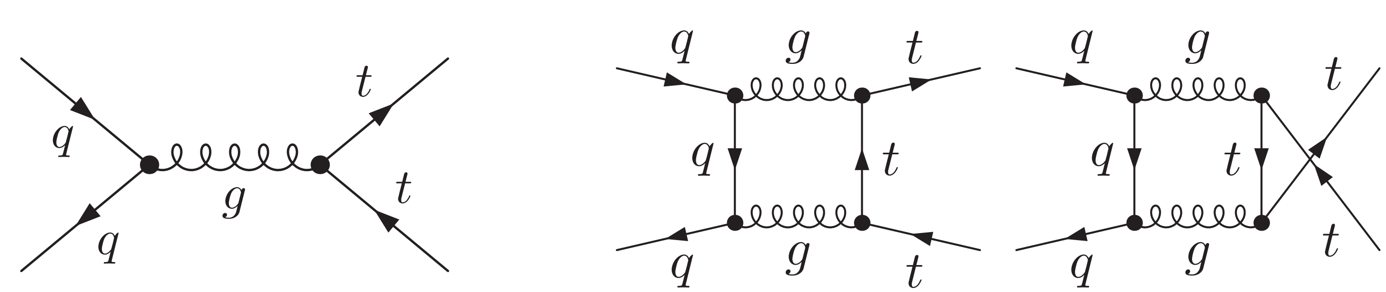
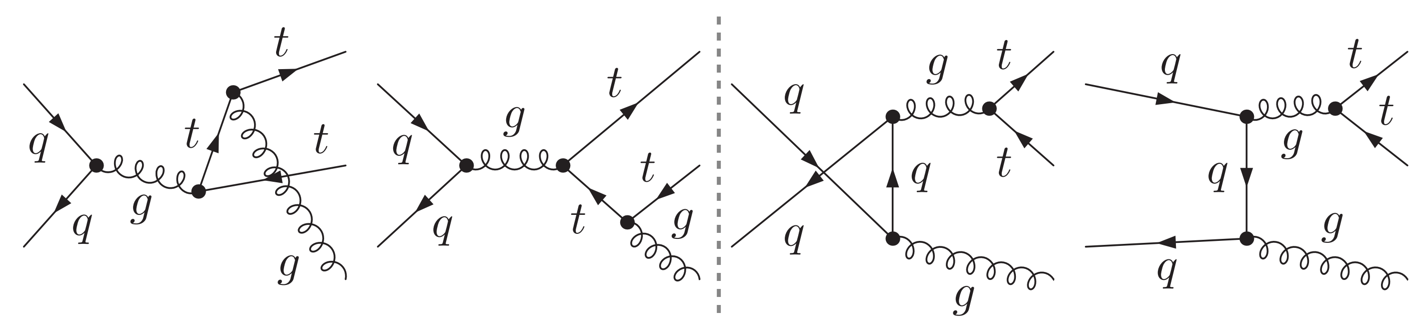
gg initial state doesn't contribute to Tevatron and LHC asymmetry numerator!
q-qbar QCD contribution only from interaction between initial and final state!

$$\alpha_s \frac{N_1}{D_0}$$

VIRTUAL (Only Boxes)
NO UV, NO Coll. Div.
Only IR



REAL
Only interference of initial and final gluon emission is asymmetric.



Final Initial

Kuhn, Rodrigo '99

$\alpha \frac{\tilde{N}_1}{D_0}$

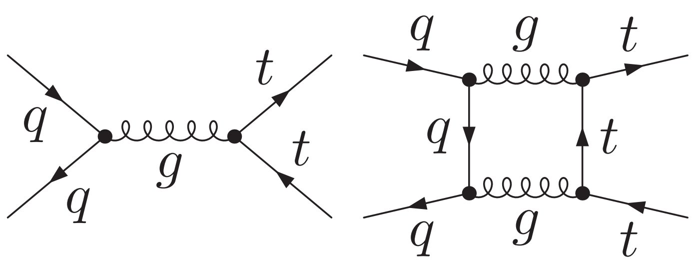
It's useful to divide electroweak contribution into QED (photon) and weak (Z) part.

QED

QED can be easily obtained from QCD calculation and the substitution of one gluon into one photon in the squared amplitudes.

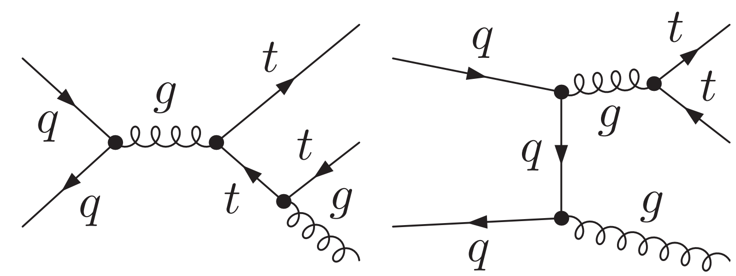
$q\bar{q} \to t\bar{t}$

$\overline{|\mathcal{M}^{t\bar{t}}|}^2_{\mathcal{O}(\alpha_s^3)}$



$q\bar{q} \to t\bar{t}g$

$\overline{|\mathcal{M}^{t\bar{t}g}|}^2_{\mathcal{O}(\alpha_s^3)}$



$$\alpha\frac{\tilde{N}_1}{D_0}$$

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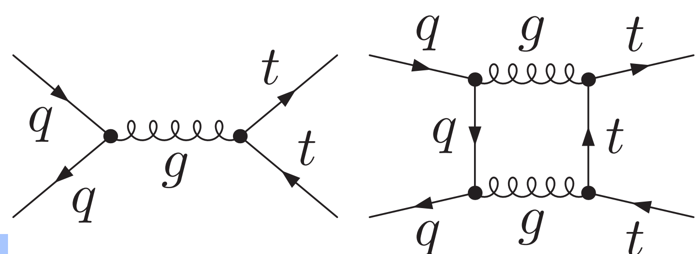
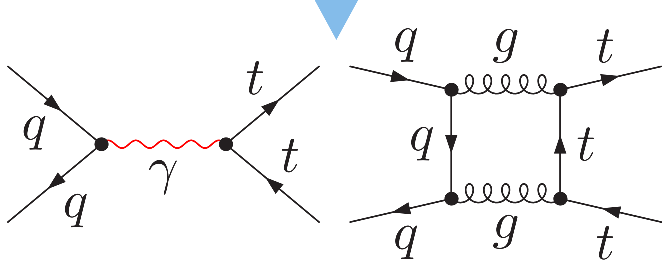
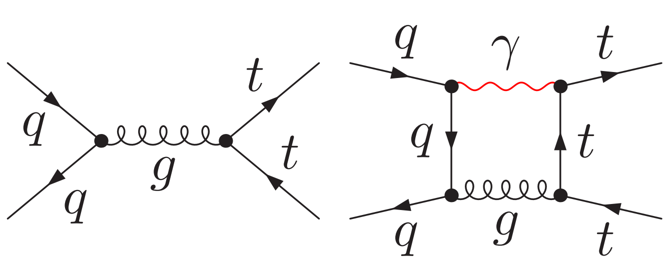
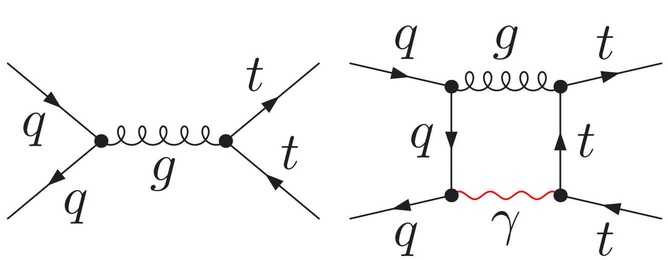


#(QED diagrams) = 3 #(QCD diagrams)



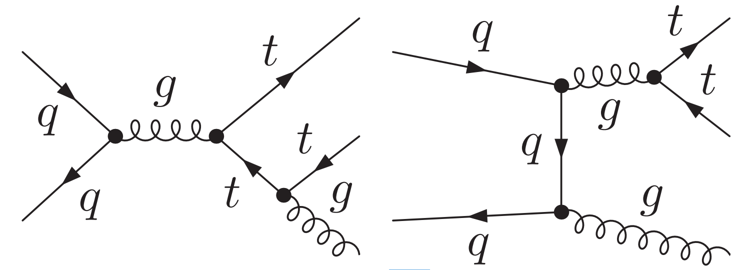
$\overline{|\mathcal{M}^{t\bar{t}}|}^2_{\mathcal{O}(\alpha_s^2\alpha)}$



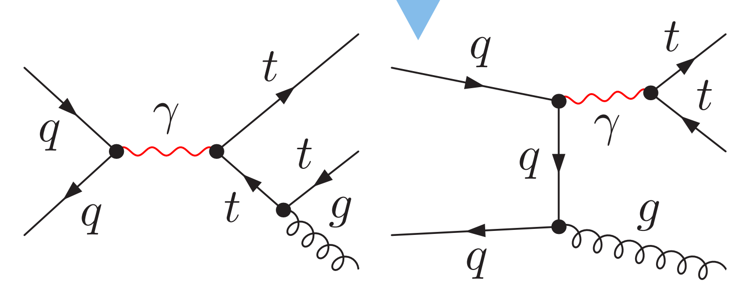


$q\bar{q} \to t\bar{t}g$

$\overline{|\mathcal{M}^{t\bar{t}g}|}^2_{\mathcal{O}(\alpha_s^3)}$

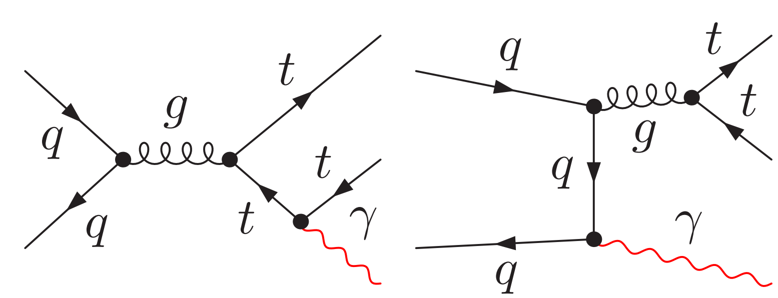


$\overline{|\mathcal{M}^{t\bar{t}g}|}^2_{\mathcal{O}(\alpha_s^2\alpha)}$



$q\bar{q} \to t\bar{t}\gamma$

$\overline{|\mathcal{M}^{t\bar{t}\gamma}|}^2_{\mathcal{O}(\alpha_s^2\alpha)}$



DIFFERENCES:
Only couplings and color factor!

$$A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$

Hollik, D.P. '11

$$R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}$$

QED correction can be obtained from QCD × R_{QED}

$$A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$

Hollik, D.P. '11

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QED correction can be obtained from QCD × R_{QED}

Weak

The same diagrams as QED part, but γ → Z.

Z is not massless → If we write Weak=QCD × R_{Weak}.
R_{Weak} does not depend only on couplings and color factor

$$A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$

Hollik, D.P. '11

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The same diagrams as QED part, but $\gamma \rightarrow Z$.

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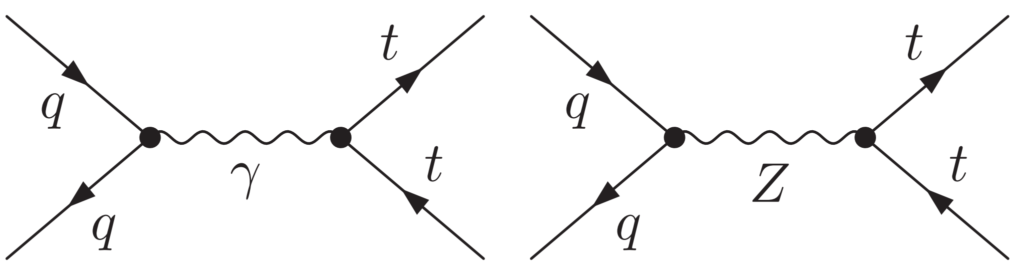
R_{Weak} does not depend only on couplings and color factor

$$\frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$



Different couplings for different chiralities produce asymmetric terms in the cross-section

$$\frac{d\sigma_{asym}}{d\cos\theta} = 2\pi\alpha^2 \cos\theta \left(1 - \frac{4m_t^2}{s}\right) \left[\kappa \frac{Q_q Q_t A_q A_t}{(s - M_Z^2)} + 2\kappa^2 A_q A_t V_q V_t \frac{s}{(s - M_Z^2)^2}\right]$$

Forward-backward asymmetry

(a) $A_{FB}^{t\bar{t}}$

EW CORRECTIONS

$A_{FB}^{t\bar{t}}$		$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$
$\mathcal{O}(\alpha_s^3)$	$u\bar{u}$	7.01%	6.29%	5.71%
$\mathcal{O}(\alpha_s^3)$	$d\bar{d}$	1.16%	1.03%	0.92%
$\mathcal{O}(\alpha_s^2\alpha)_{QED}$	$u\bar{u}$	1.35%	1.35%	1.35%
$\mathcal{O}(\alpha_s^2\alpha)_{QED}$	$d\bar{d}$	-0.11%	-0.11%	-0.11%
$\mathcal{O}(\alpha_s^2\alpha)_{weak}$	$u\bar{u}$	0.16%	0.16%	0.16%
$\mathcal{O}(\alpha_s^2\alpha)_{weak}$	$d\bar{d}$	-0.04%	-0.04%	-0.04%
$\mathcal{O}(\alpha^2)$	$u\bar{u}$	0.18%	0.23%	0.28%
$\mathcal{O}(\alpha^2)$	$d\bar{d}$	0.02%	0.03%	0.03%
tot	$p\bar{p}$	9.72%	8.93%	8.31%

$R_{QED}^{u\bar{u}} = (0.192, 0.214, 0.237)$

$R_{QED}^{d\bar{d}} = (-0.096, -0.107, -0.119)$

- R_{QED} depend only on the renormalization scale, not on A_{FB} definitions and cuts.
(with fixed scales)

Hollik, DP '11

$\mathcal{O}(\alpha_s^2\alpha)$ QED is the dominant contribution of the electroweak corrections. It is stable under factorization and renormalization scale variation.

u and d have different charges: contributions of opposite sign for $\mathcal{O}(\alpha_s^2\alpha)$

Charge asymmetry

At the LHC same partonic processes, but different partonic luminosities.

The gluon-gluon luminosity is larger, so the asymmetry is smaller.
Gluon-quark initial states start to be “interesting” (per mill).

The ratio of integrated luminosities $u\bar{u}/d\bar{d}$ at the Tevatron(LHC) is 4(2).
The cancellation between QED contributions is bigger. The EW contribution at the LHC is in general smaller (~ 15%, 20% of QCD contribution).

$$R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}$$

$\sqrt{s}$		$M_c = 2m_t$	0.5 TeV	0.7 TeV	1 TeV
7 TeV	QCD: $A_C^{\Delta\|y\|}$ (%)	1.07 (4)	1.27 (4)	1.68 (4)	2.06 (5)
	QCD + EW: $A_C^{\Delta\|y\|}$ (%)	1.23 (5)	1.48 (4)	1.95 (4)	2.40 (6)
8 TeV	QCD: $A_C^{\Delta\|y\|}$ (%)	0.96 (4)	1.14 (4)	1.48 (4)	1.85 (4)
	QCD + EW: $A_C^{\Delta\|y\|}$ (%)	1.11 (4)	1.33 (5)	1.73 (5)	2.20 (5)

		$M_c = 2m_t$	0.5 TeV	1 TeV	2 TeV
14 TeV	QCD: $A_C^{\Delta\|y\|}$ (%)	0.58 (3)	0.74 (3)	1.11 (5)	1.72 (10)
	QCD + EW: $A_C^{\Delta\|y\|}$ (%)	0.67 (4)	0.86 (5)	1.32 (8)	2.12 (10)

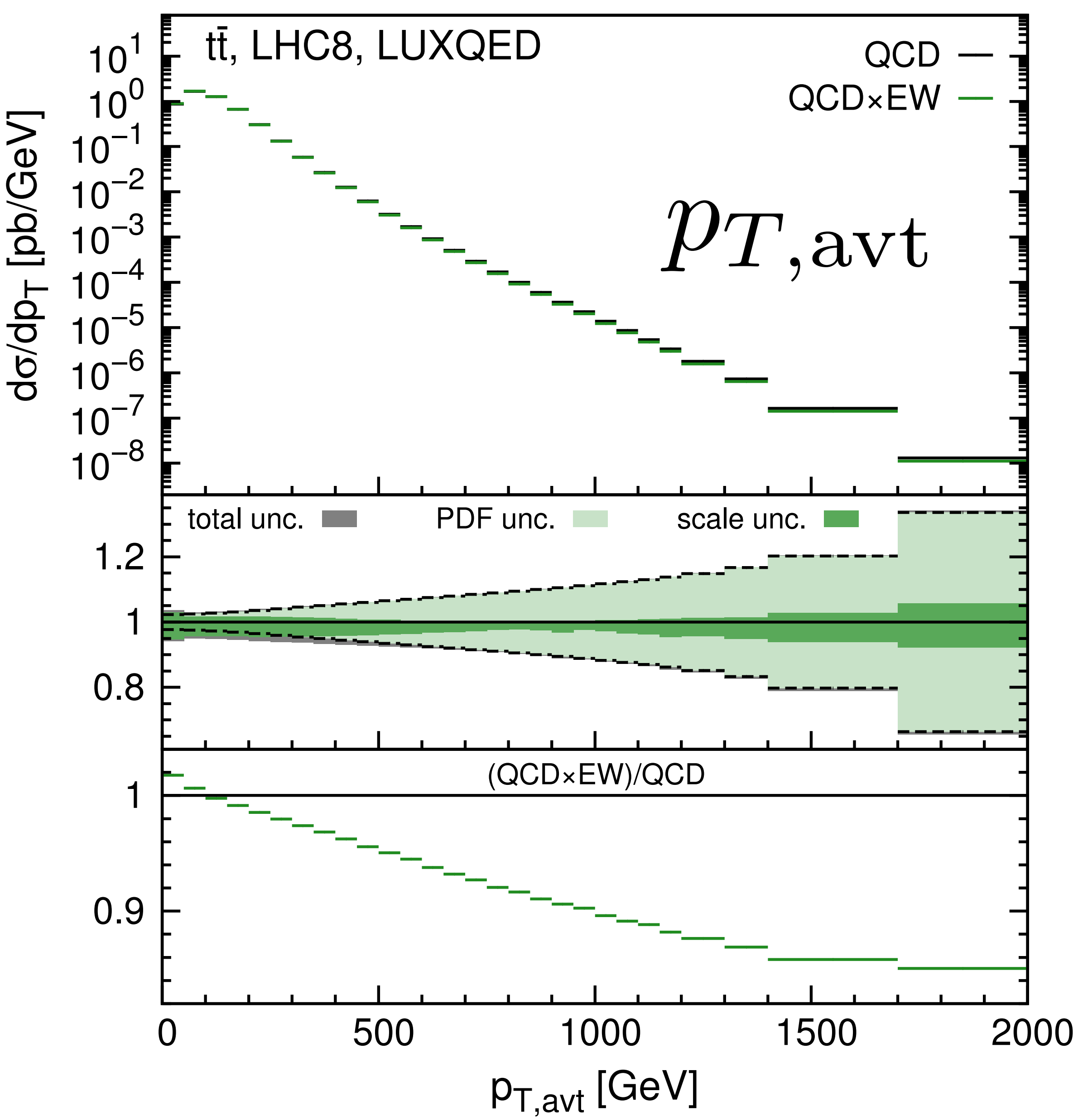
Bernreuther, Si ’12

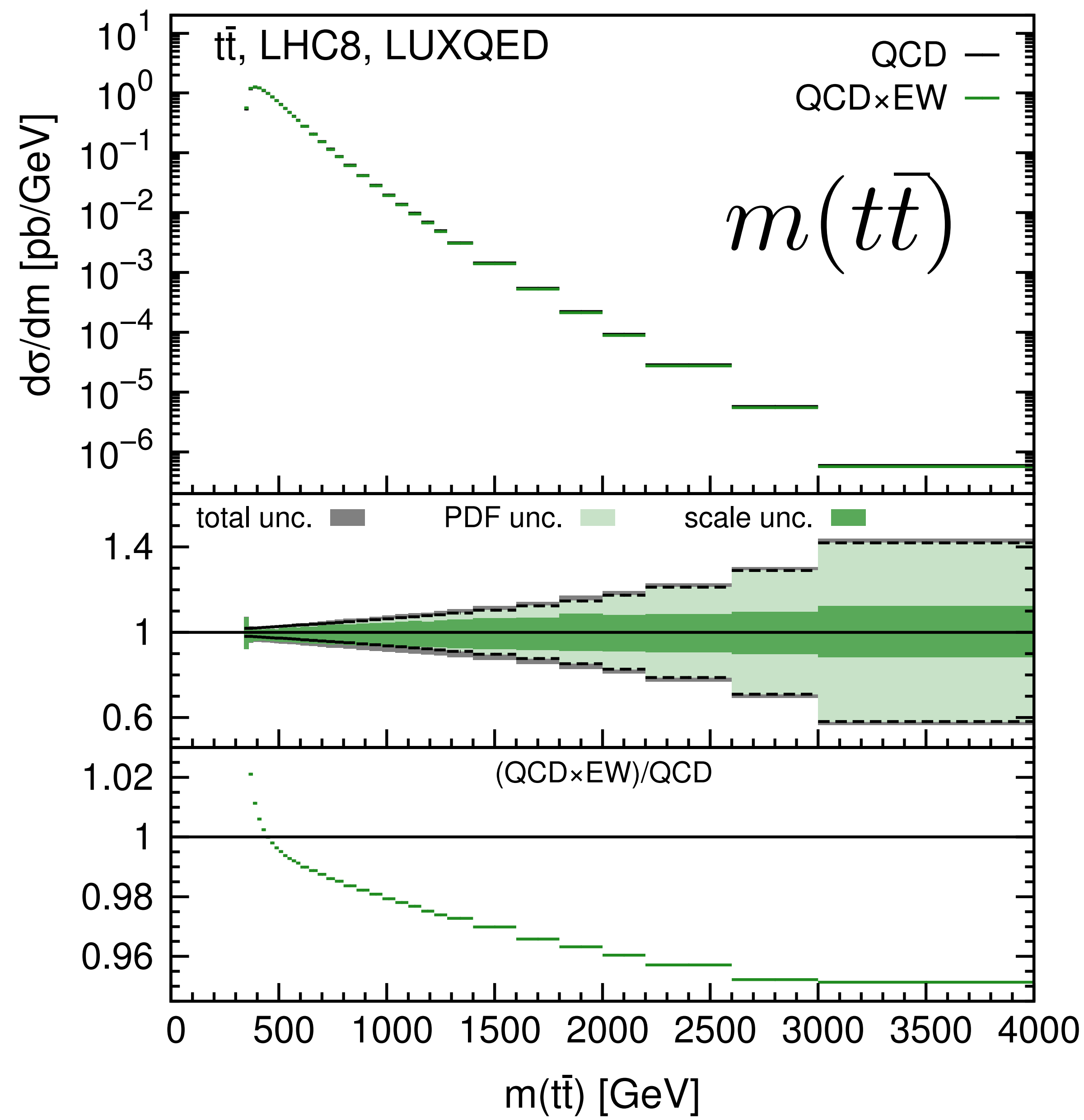
$m_{t\bar{t}}$[GeV]	$\mathrm{A_{FB}(m_{t\bar{t}})}$	
	NLO	NNLO
[350 ; 450]	$4.10^{+1.66+0.07+1.66}_{-0.90-0.10-0.91} \times 10^{-2}$	$5.36^{+0.49+0.09+0.50}_{-0.61-0.07-0.62} \times 10^{-2}$
[450 ; 550]	$7.71^{+3.69+0.09+3.69}_{-1.85-0.34-1.88} \times 10^{-2}$	$9.98^{+0.68+0.15+0.70}_{-1.23-0.17-1.24} \times 10^{-2}$
[550 ; 650]	$1.08^{+0.61+0.09+0.62}_{-0.28-0.00-0.28} \times 10^{-1}$	$1.34^{+0.06+0.03+0.06}_{-0.14-0.02-0.14} \times 10^{-1}$
[650 ; 750]	$1.56^{+1.19+0.03+1.19}_{-0.46-0.03-0.47} \times 10^{-1}$	$1.77^{+0.04+0.03+0.06}_{-0.19-0.02-0.19} \times 10^{-1}$

Table 11. $m_{t\bar{t}}$ dependent $\mathrm{A_{FB}}$ in NLO and NNLO QCD. The format is $central \pm scales \pm pdf \pm total$. The lowest and highest bins contain spillover events.

8 TeV

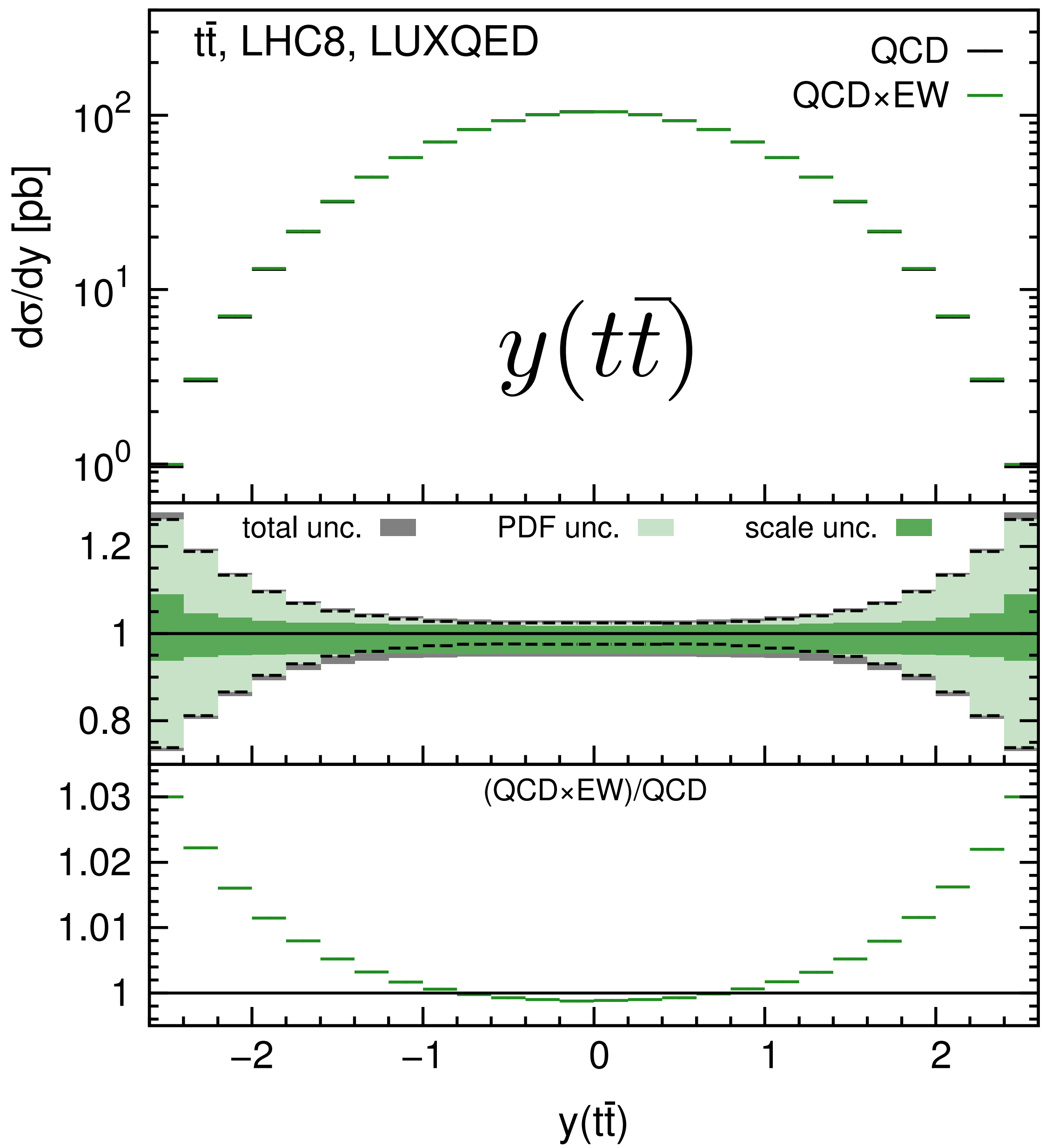
MULTIPLICATIVE with LUXQED

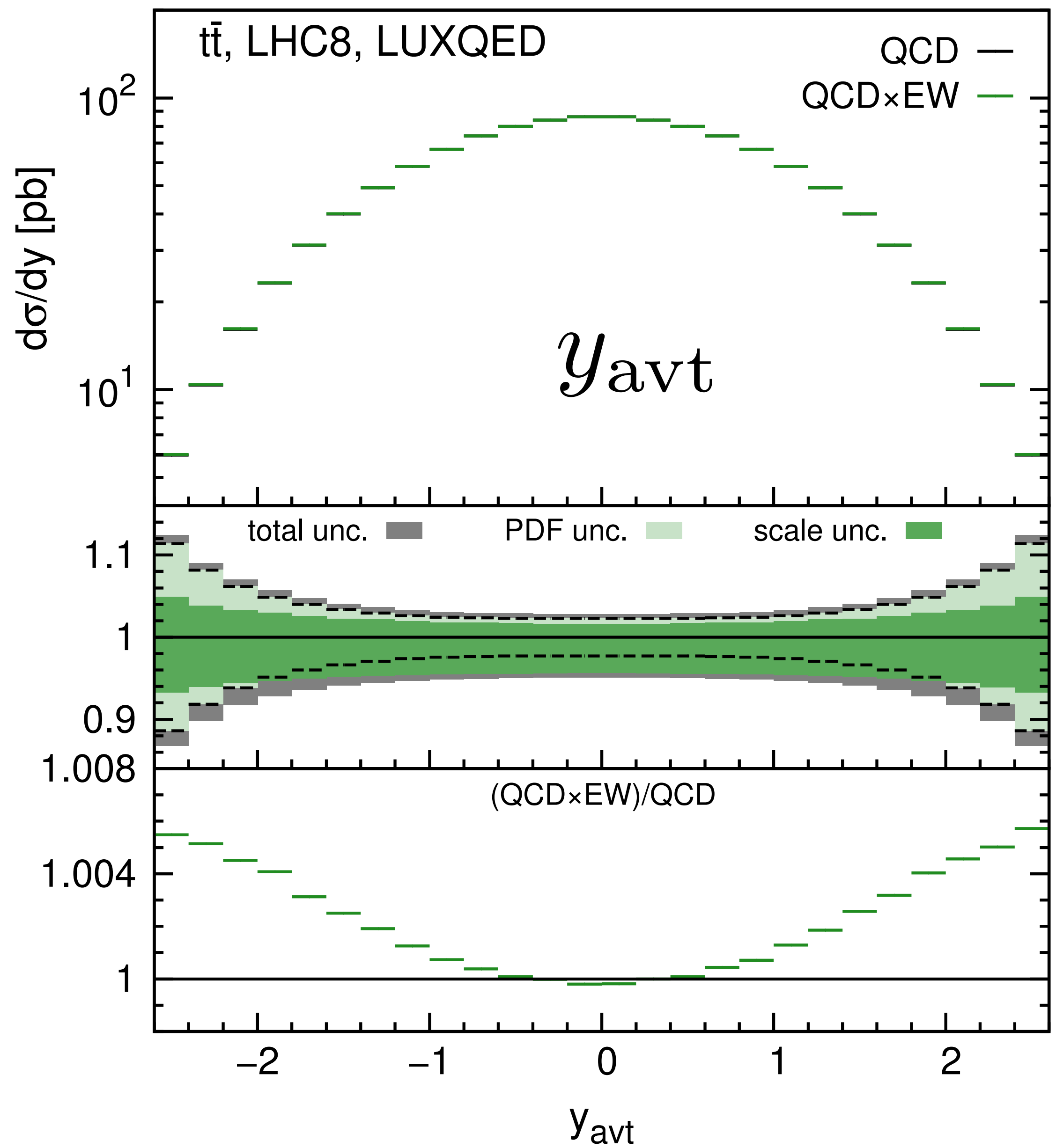




8 TeV

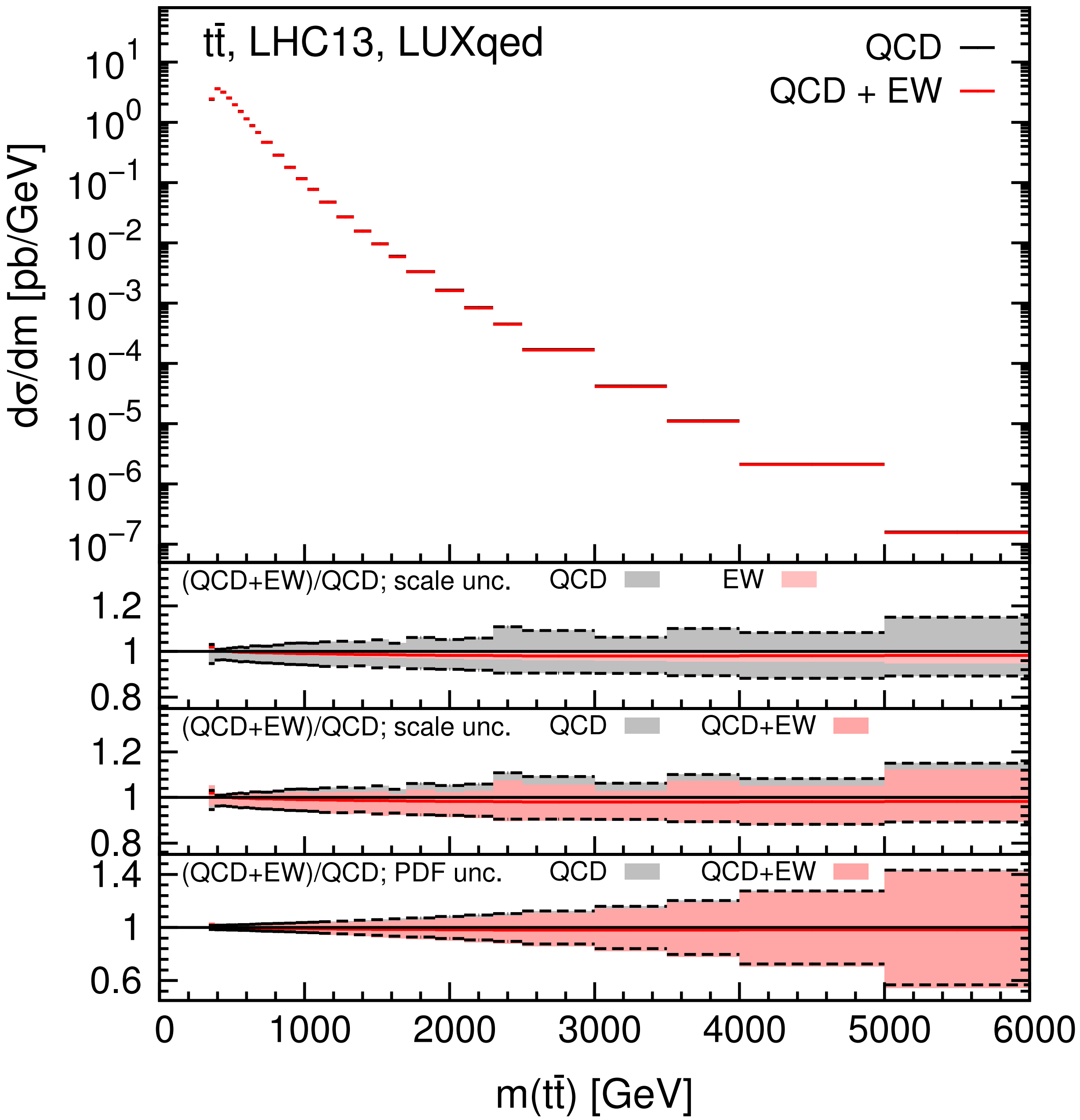
MULTIPLICATIVE with LUXQED



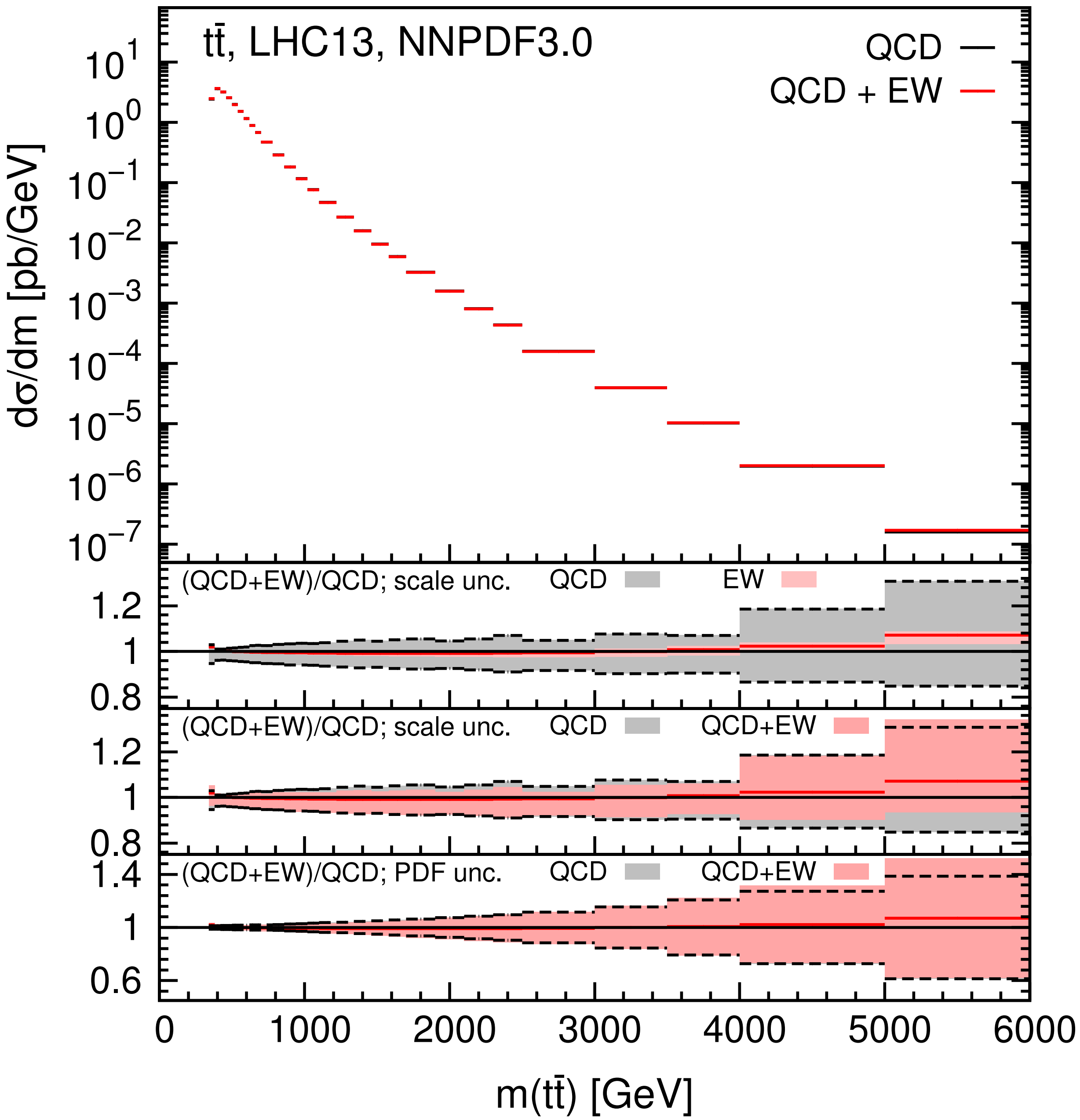


13 TeV

$m(t\bar{t})$



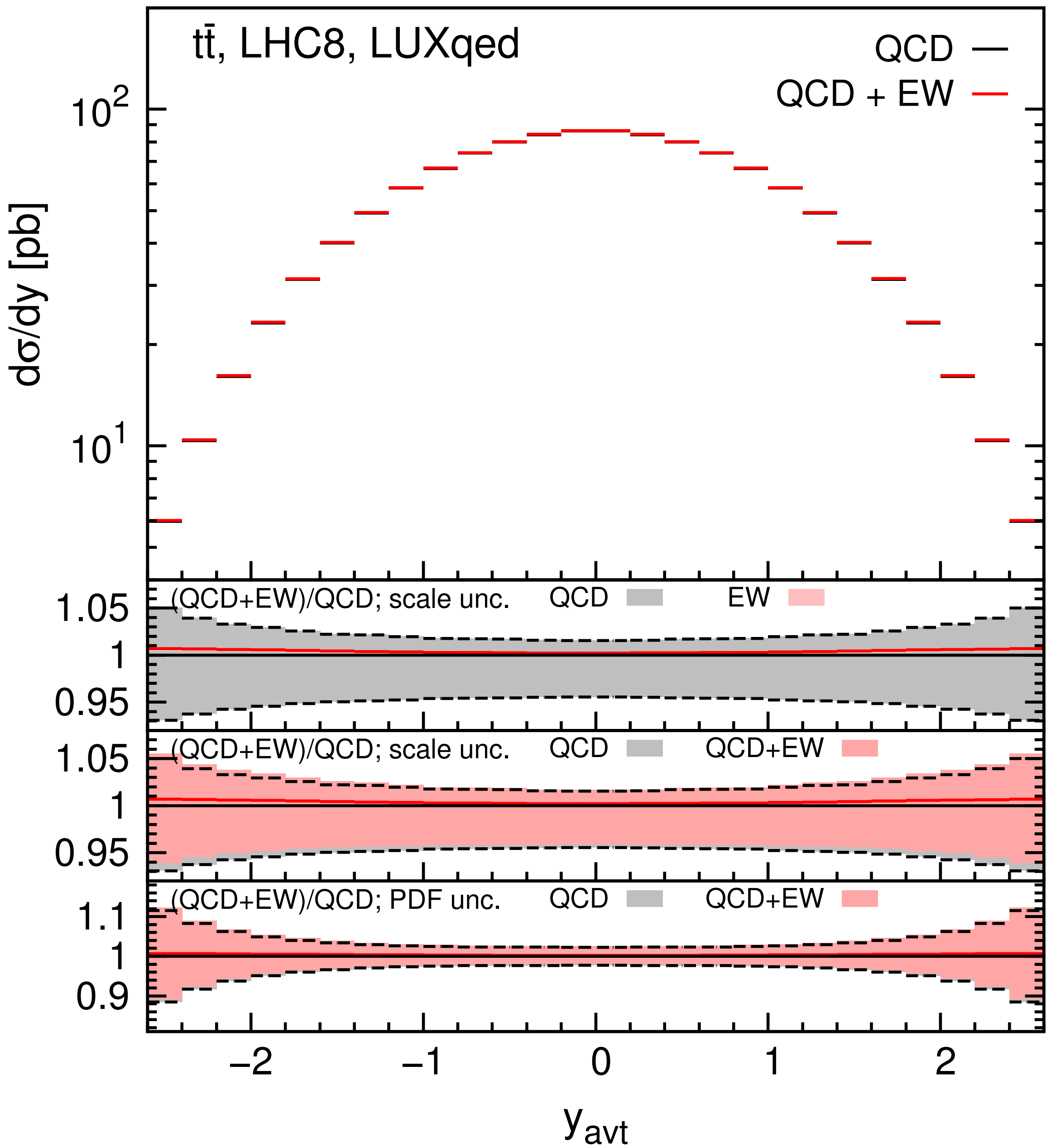
LUXQED



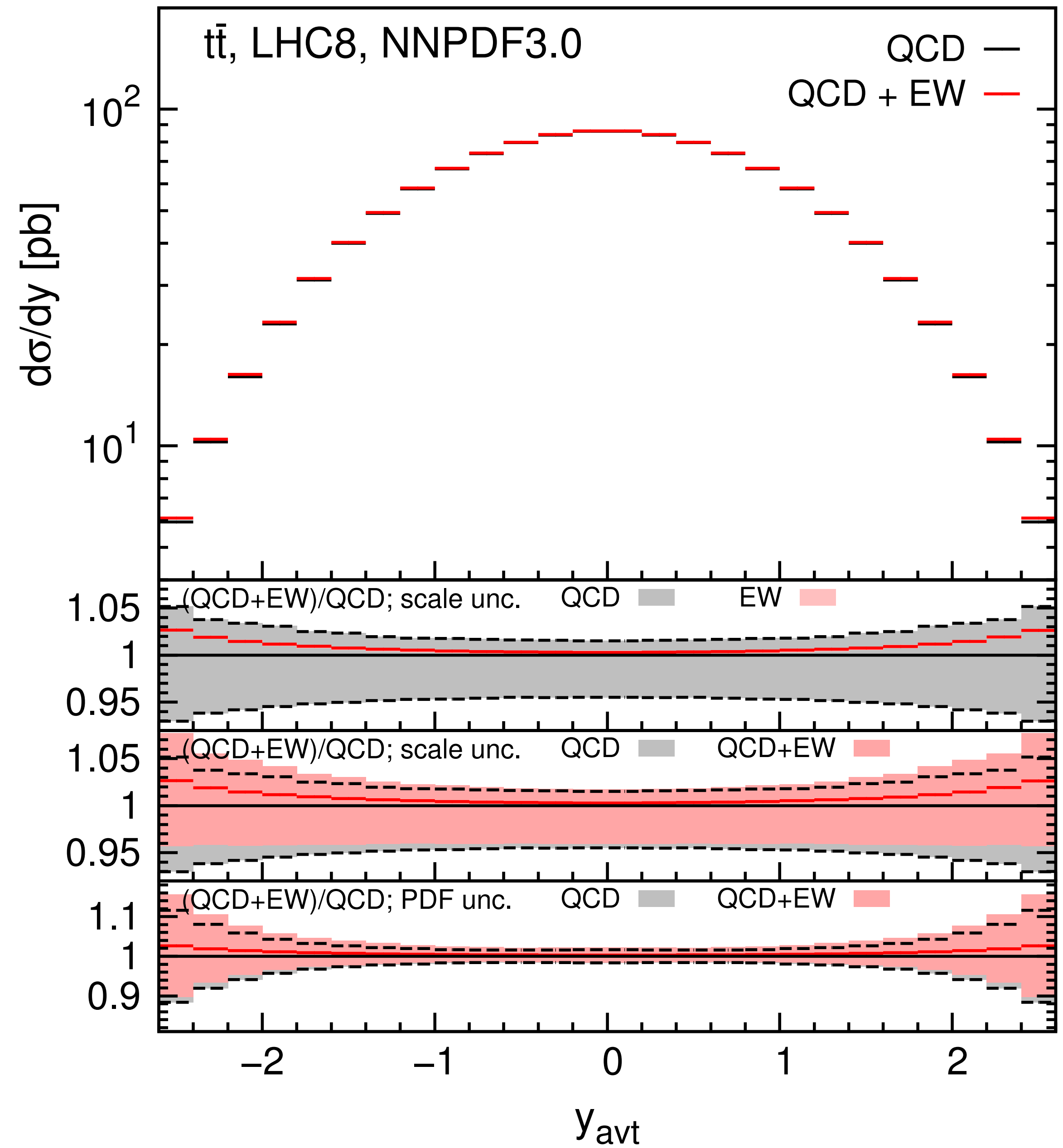
NNPDF3.0QED

8 TeV

$y_{\rm avt}$



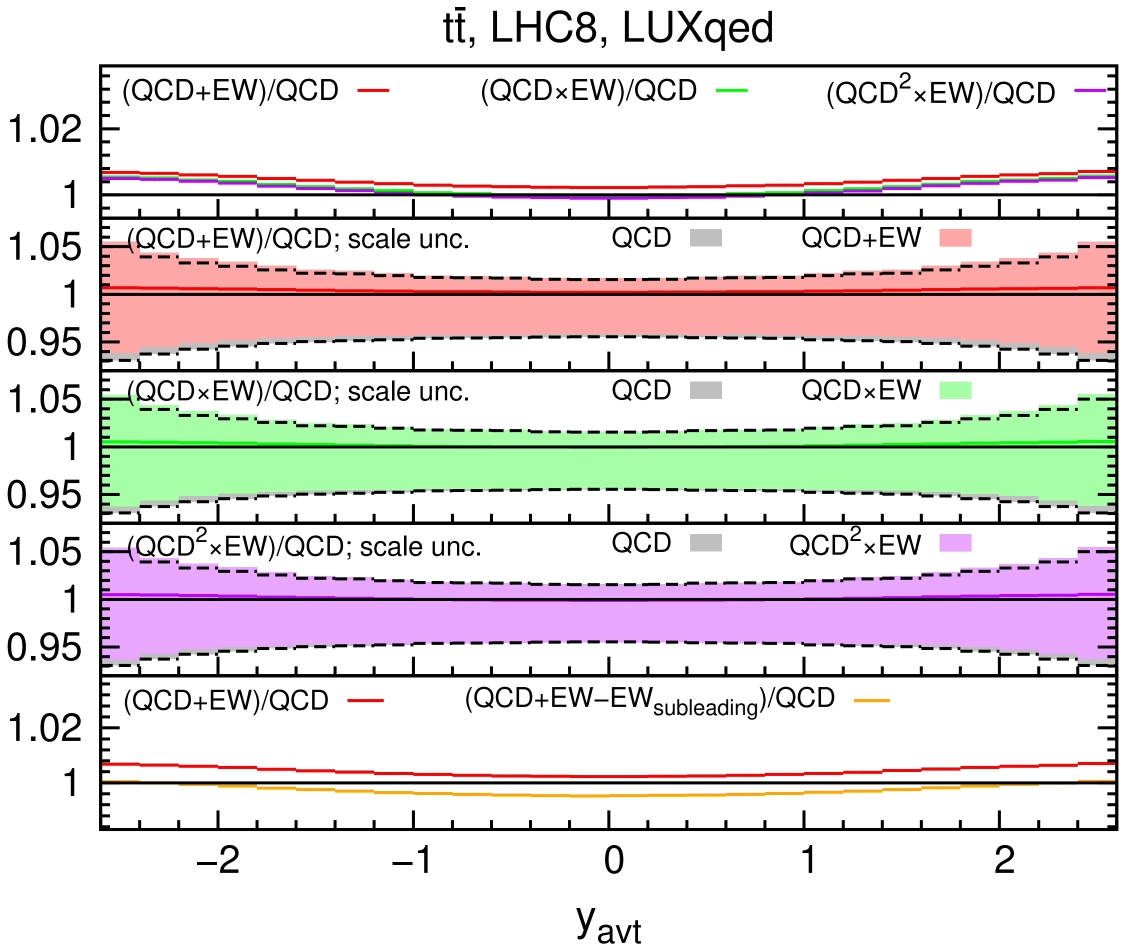
LUXQED

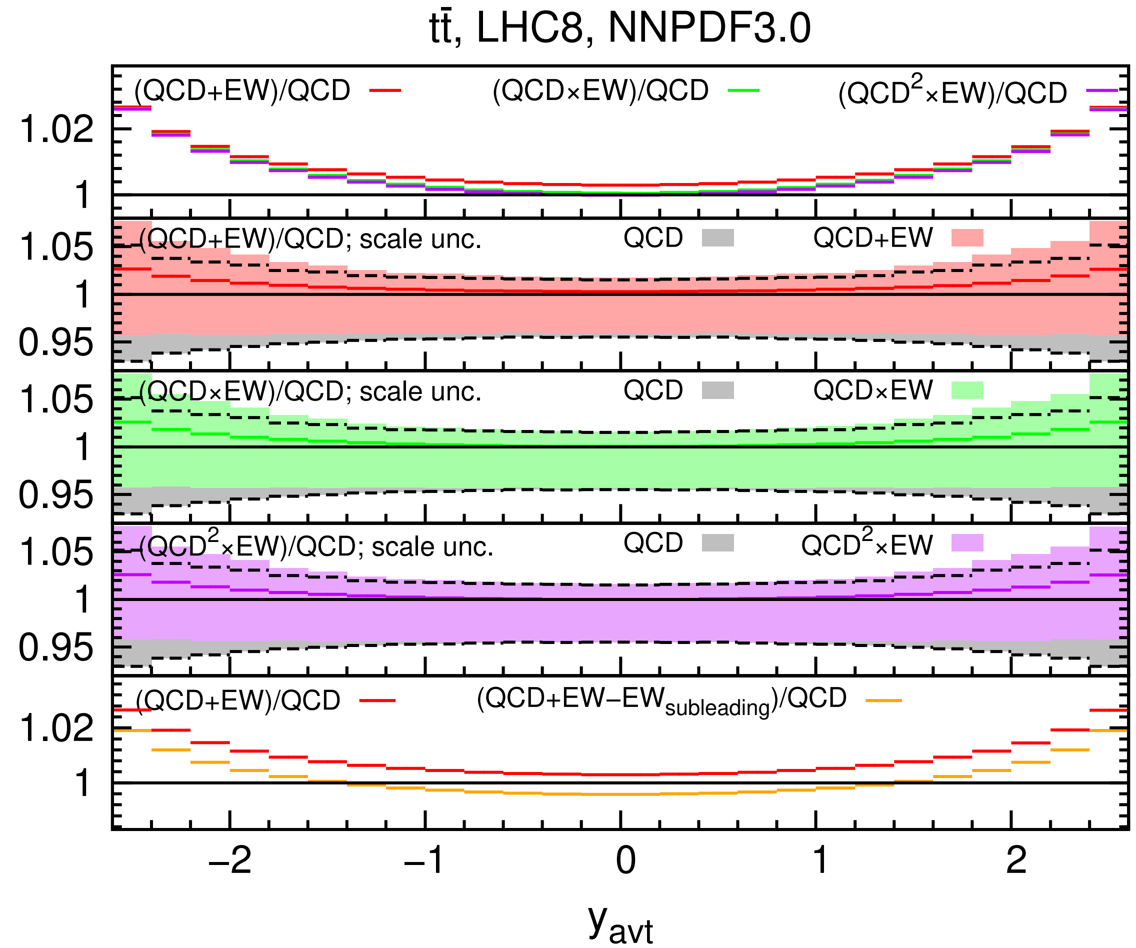


NNPDF3.0QED

y_{avt} 8 TeV

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

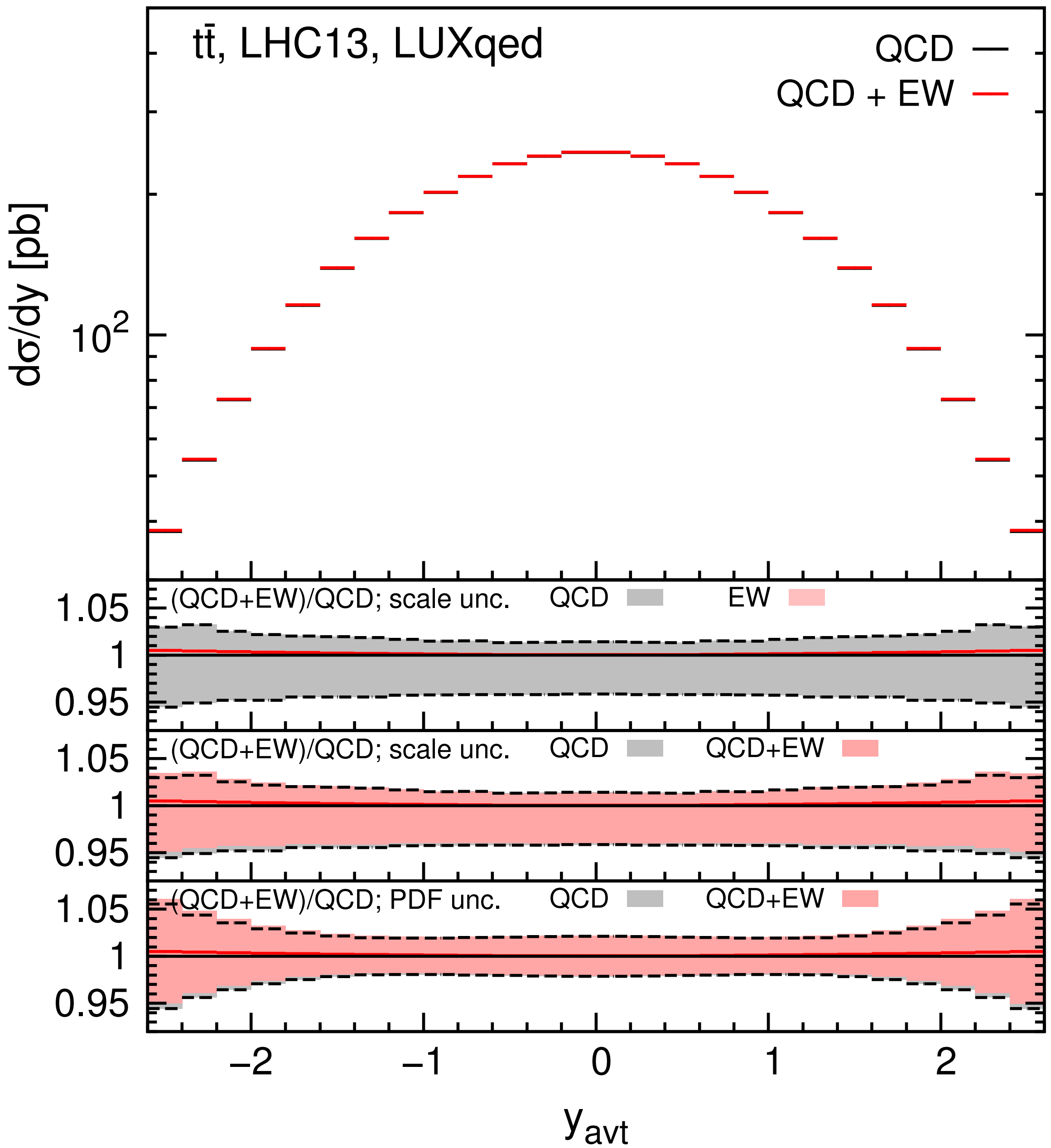




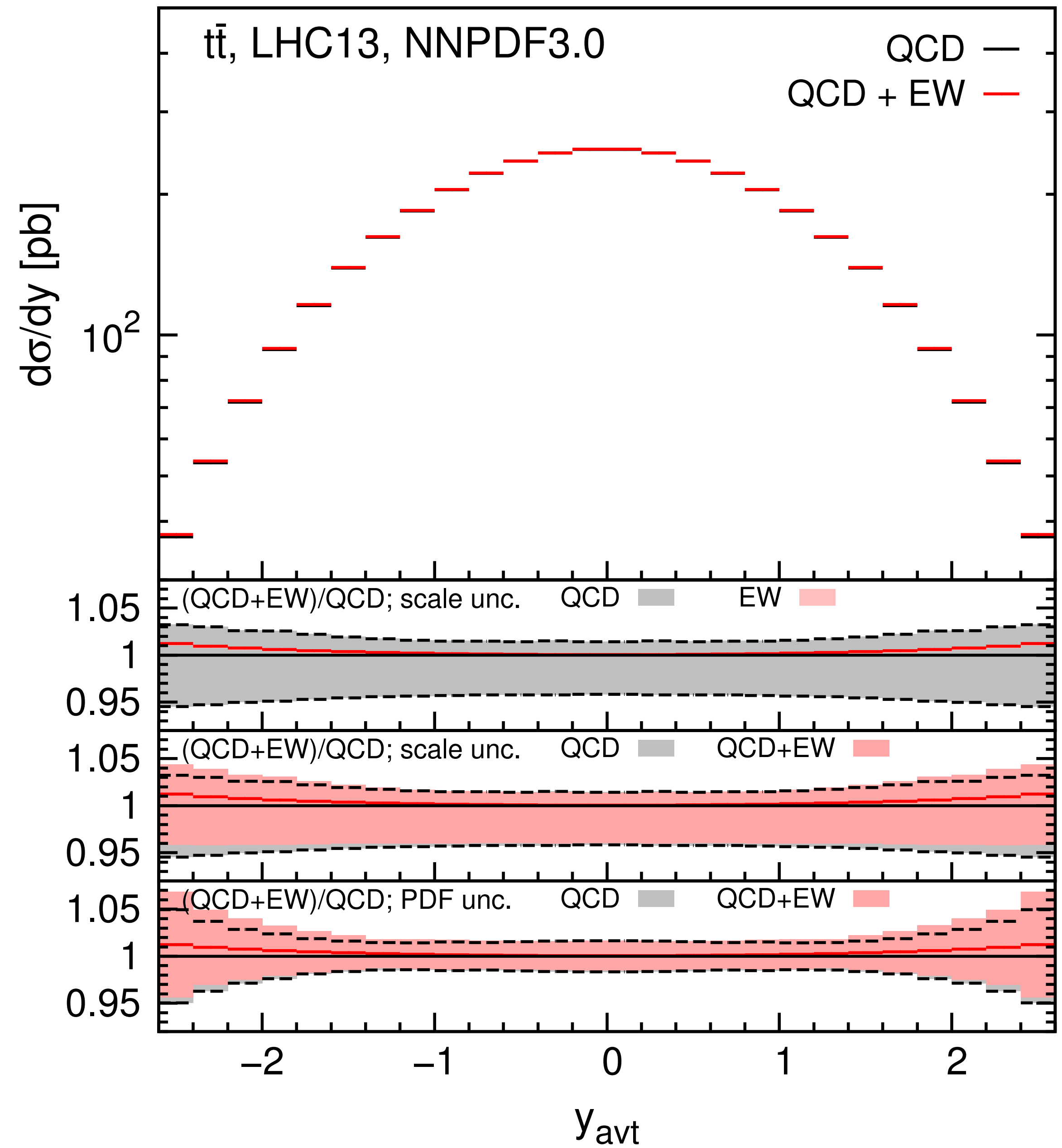
LUXQED NNPDF3.0QED

13 TeV

$y_{\rm avt}$



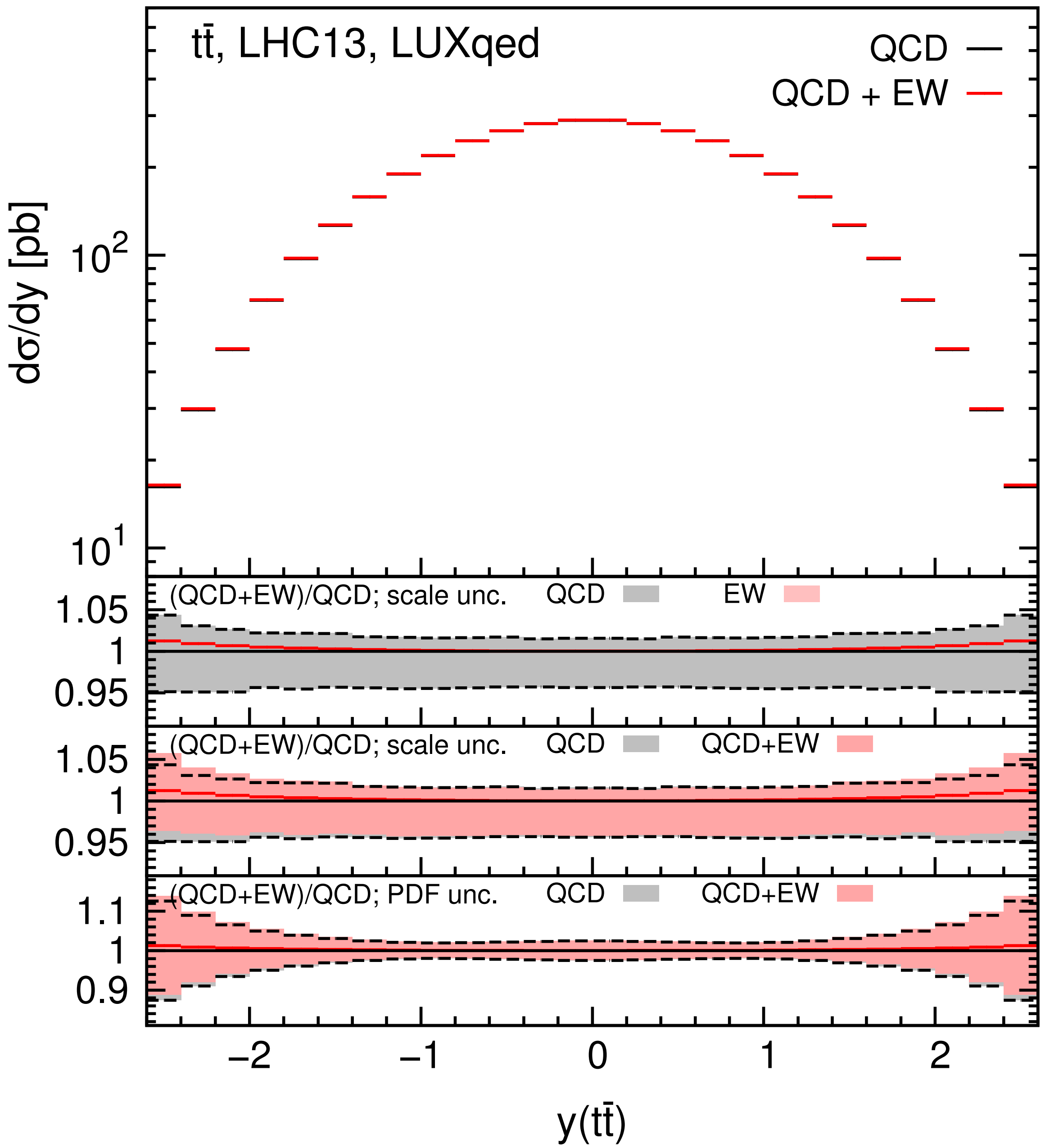
LUXQED



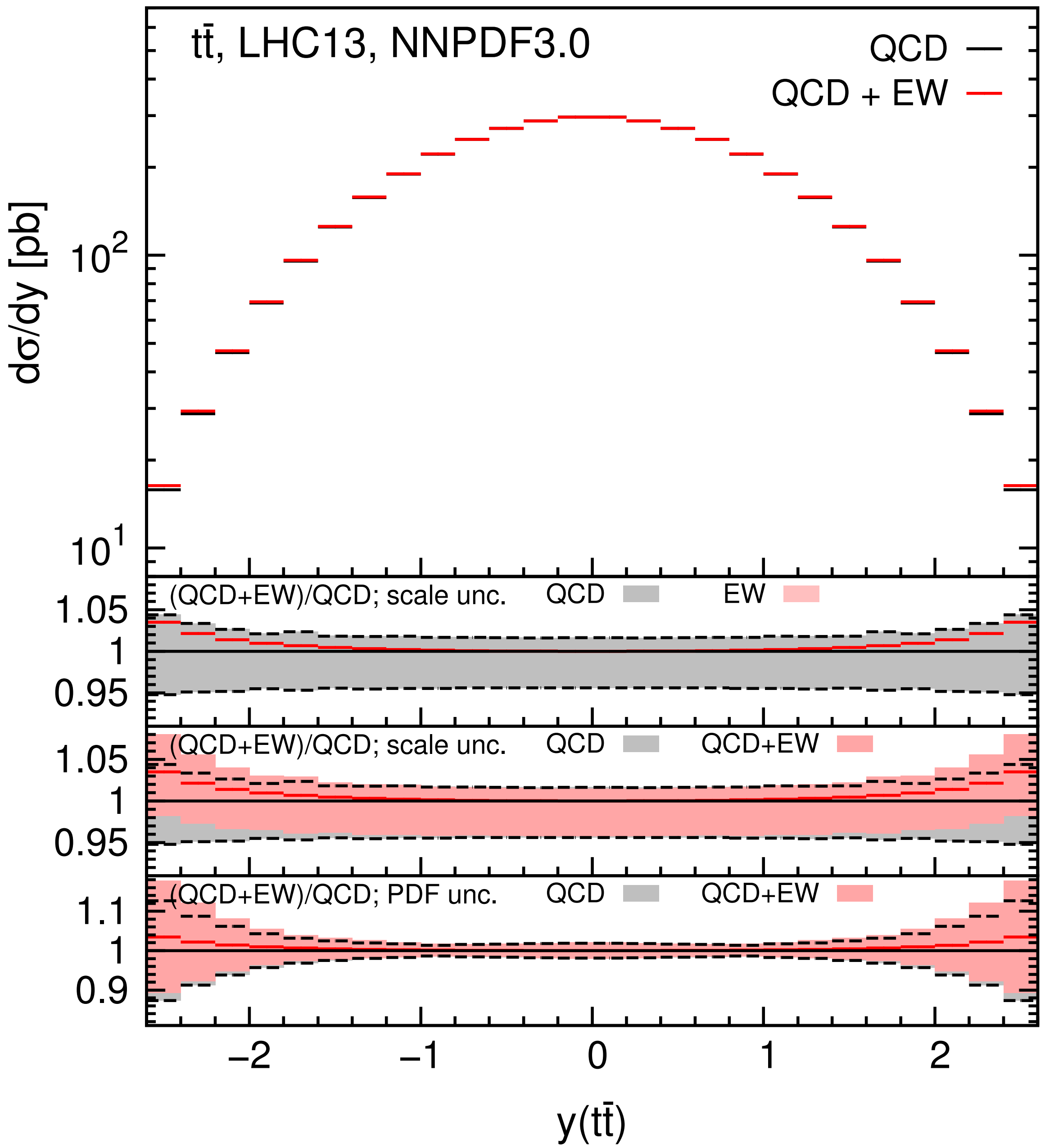
NNPDF3.0QED

13 TeV

$y(t\bar{t})$



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*

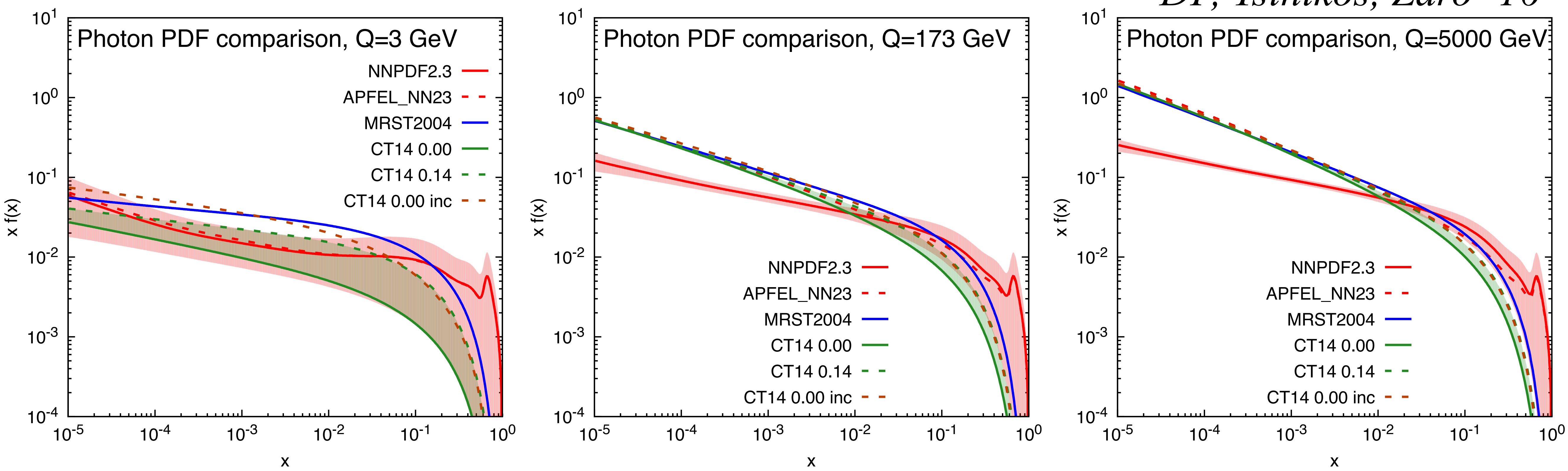
These PDF sets have at least NLO QCD + LO QED terms in the DGLAP evolution.

- 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



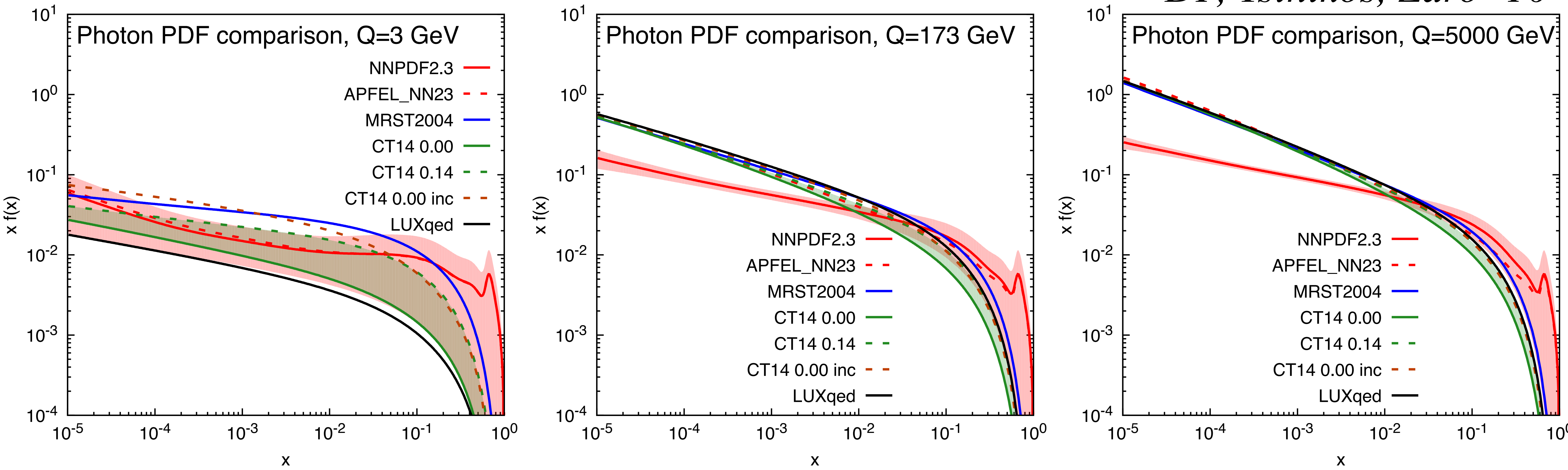
- **APFEL_NN23** (*Bertone, Carrazza, DP, Zaro ‘15*) is at the initial scale equivalent to **NNPDF2.3QED** for all the PDFs. But, the DGLAP QCD and QED running is consistent (similar to **NNPDF3.0QED**, where also quark and gluons have been updated to **NNPDF3.0**).

- 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**

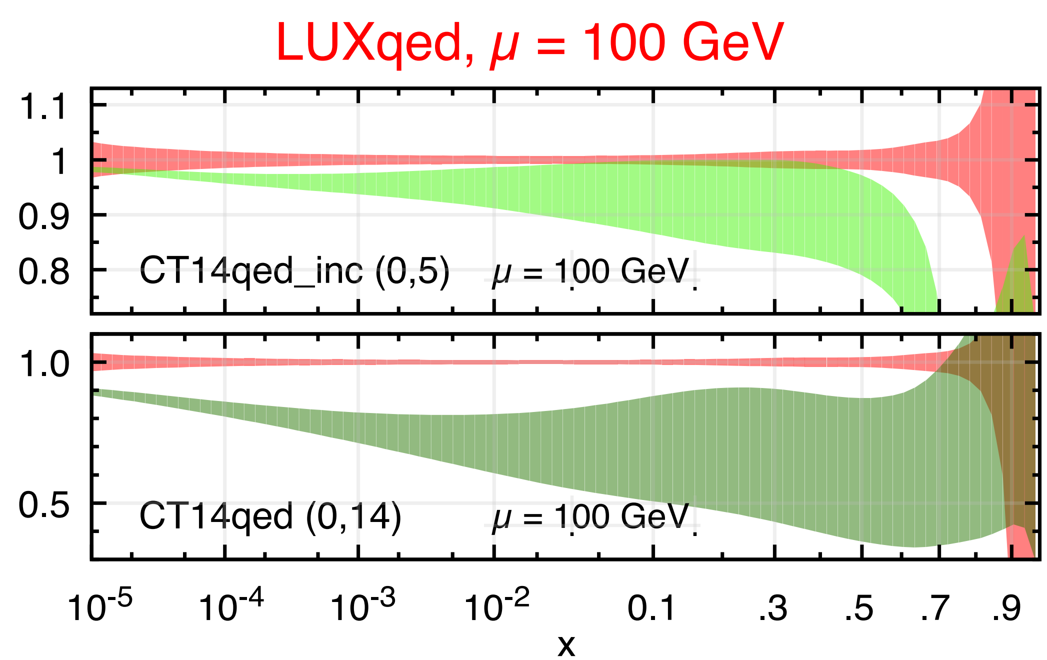
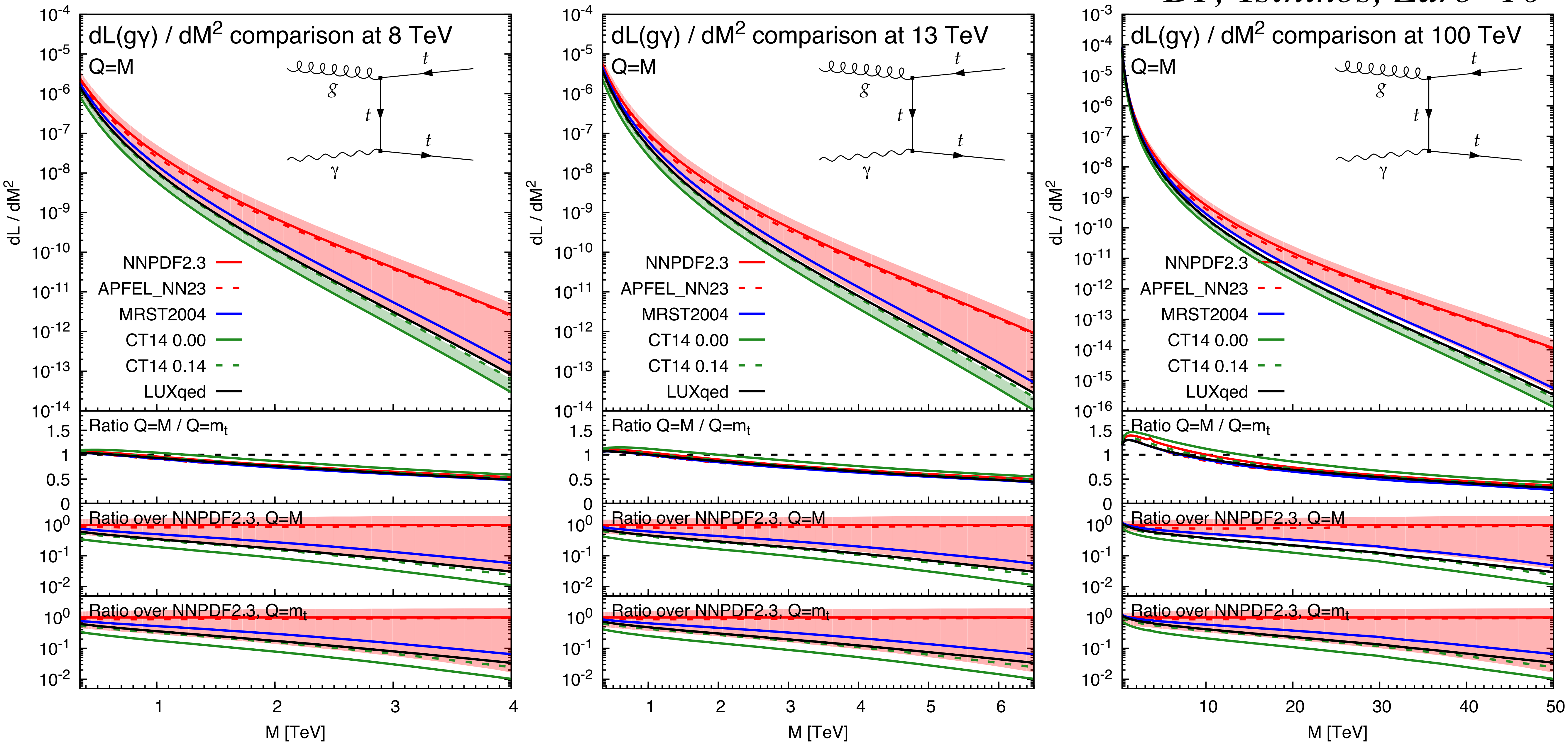


Image taken from Manohar, Nason, Salam, Zanderighi '16 and adapted for this slide.

… and the different photon-gluon luminosities

DP, Tsinikos, Zaro '16

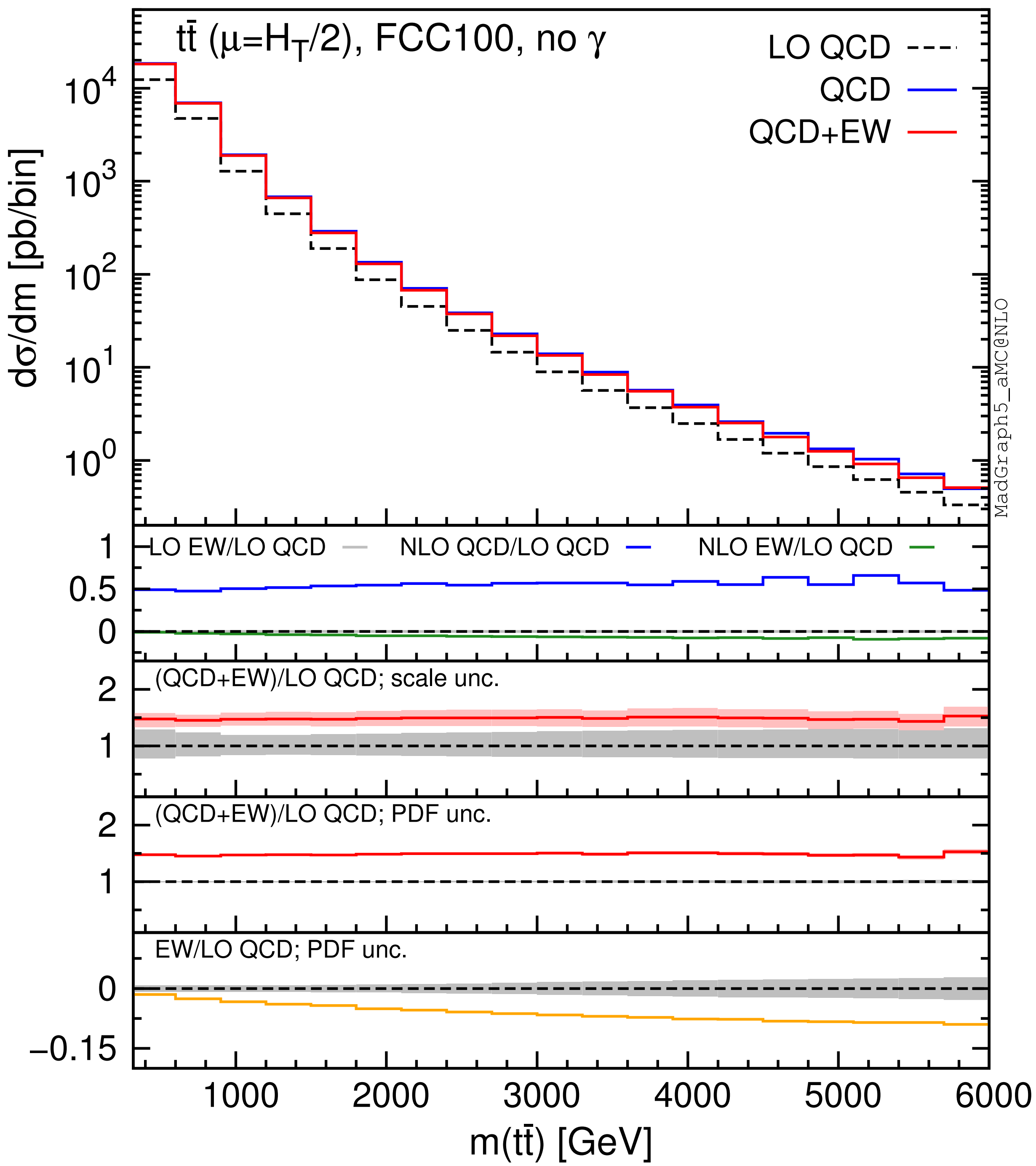


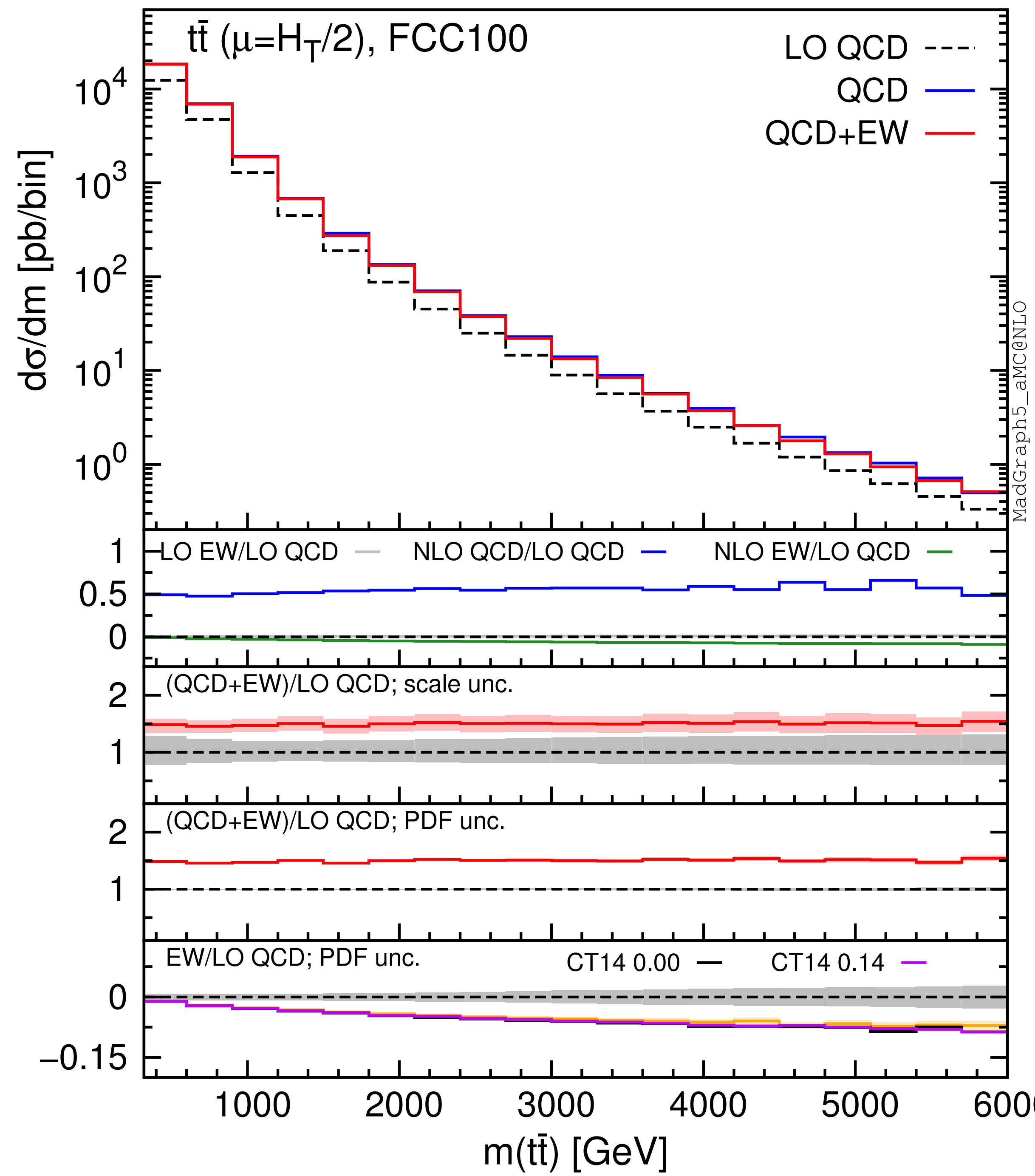
- **LUXQED** luminosity is very close to **CTEQ14QED**
- **NNPDF2.3QED** and **APFEL_NN23** are equivalent! (diff. running is not relevant)

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

100 TeV

DP, Tsinikos, Zaro '16



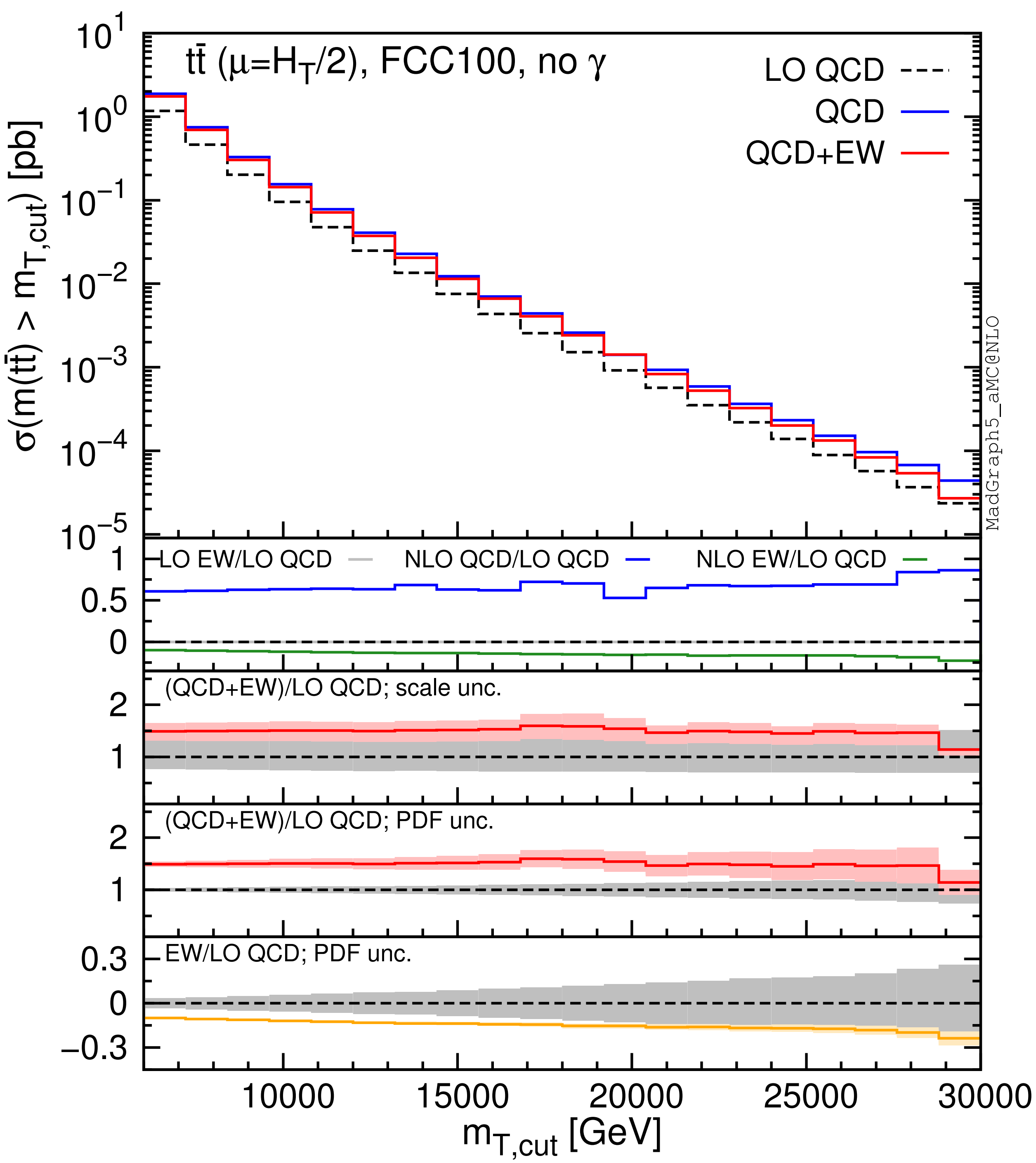


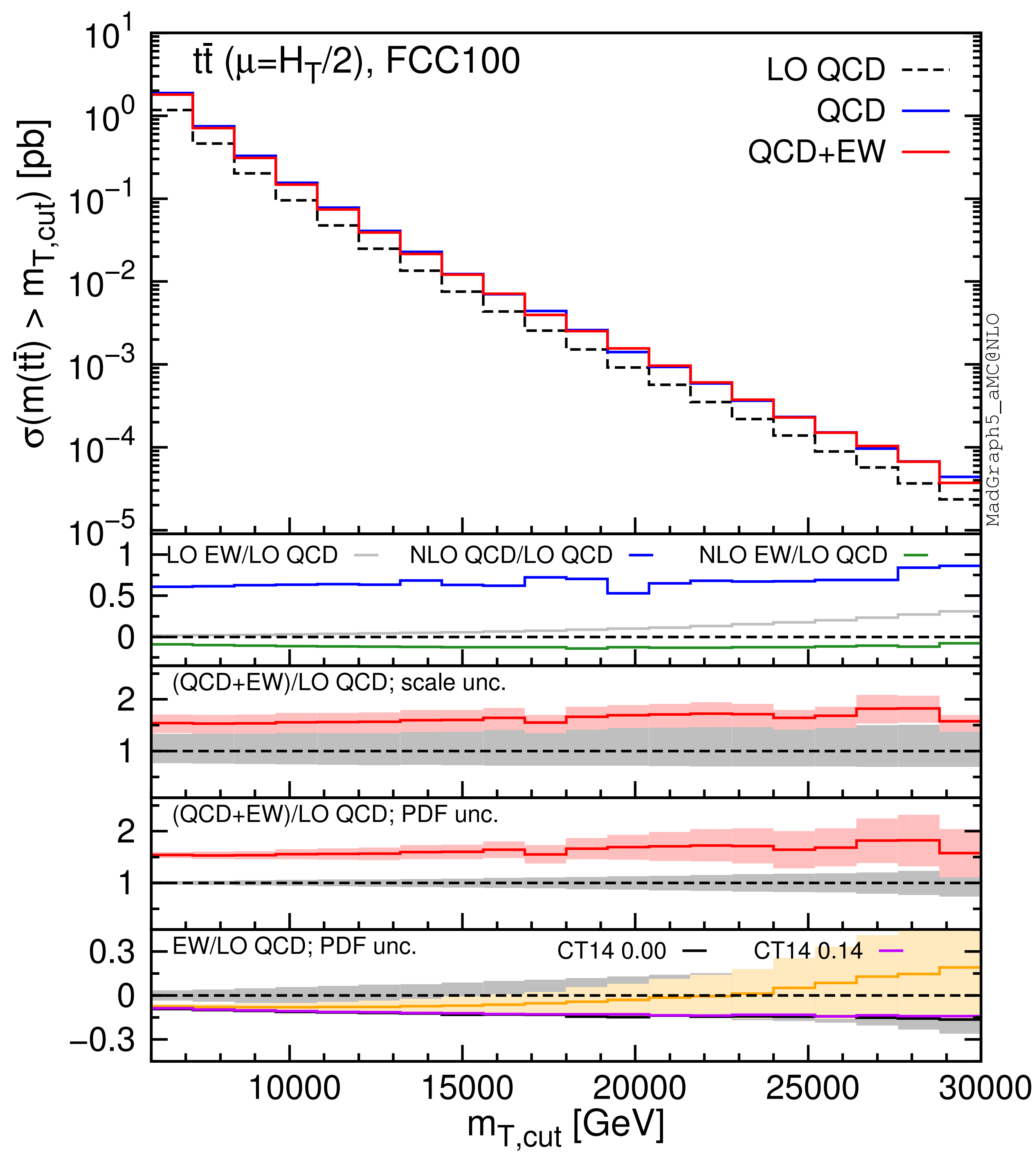
photon PDF **NO**

photon PDF **YES**

100 TeV

DP, Tsinikos, Zaro '16





photon PDF **NO** photon PDF **YES**