Multi-jet merged top-pair production including electroweak corrections versus NNLO

talk based on JHEP 1710 (2017) 186 and Eur.Phys.J. C78 (2018) no.4, 317
and further work in collaboration with M. Czakon, C. Gütschow, J. M. Lindert, A. Mitov, A. Papanastasiou, M. Schönherr, I. Tsinikos and M. Zaro.

Davide Pagani

Top 2018
Bad Neuenahr
17-09-2018

OUTLINE

NNLO QCD combined with the Complete NLO of QCD and EW origin

Merged $t\bar{t}$ and $t\bar{t}+\text{jet}$ at Complete NLO

Comparisons between the two approximations

Conclusion

NNLO QCD combined with Complete NLO of QCD and EW origin

NNLO QCD combined with complete-NLO

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** (*Frederix, Frixione, Hirschi, DP, Shao, Zaro '18*).
Now public in the v3 of the code: https://launchpad.net/mg5amcnlo

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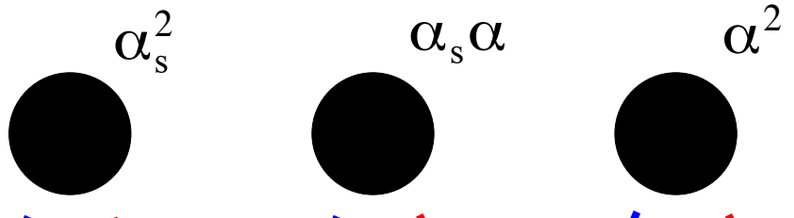
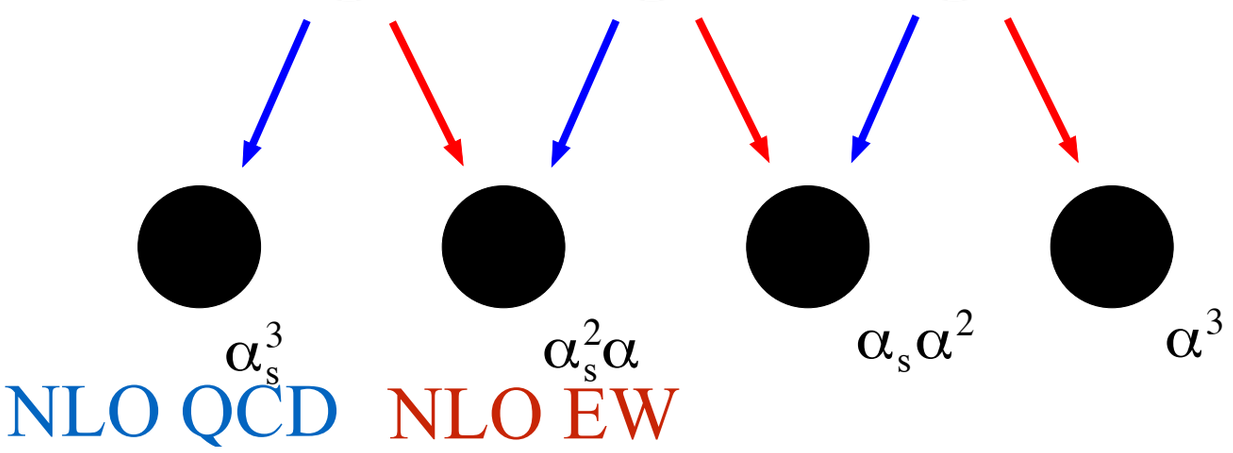
LO

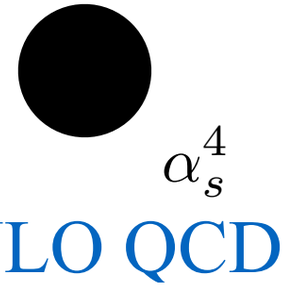


Czakon, Heymes, Mitov, DP, Tsinikos, Zaro '17

NLO



NNLO



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

NNLO QCD combined with complete-NLO

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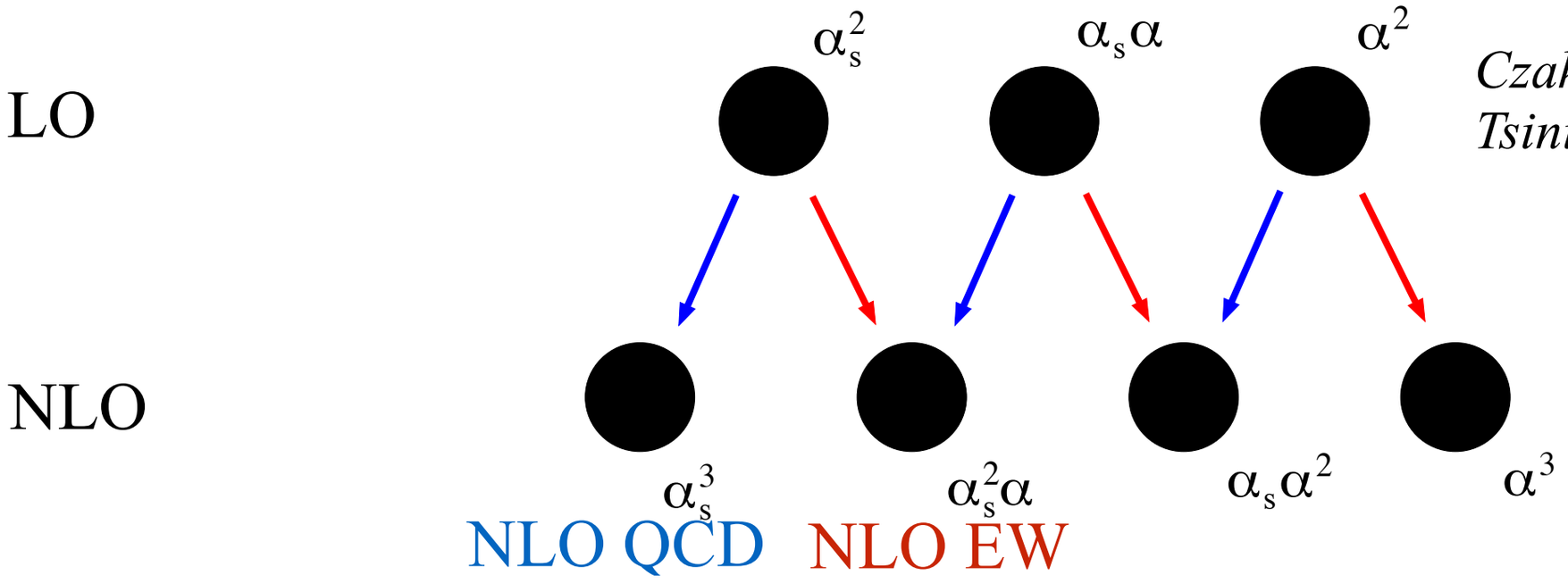

Czakon, Heymes, Mitov, DP, Tsinikos, Zaro '17

and this second NNLO term is approximated via the combination of NLO QCD and NLO EW in the multiplicative approach.

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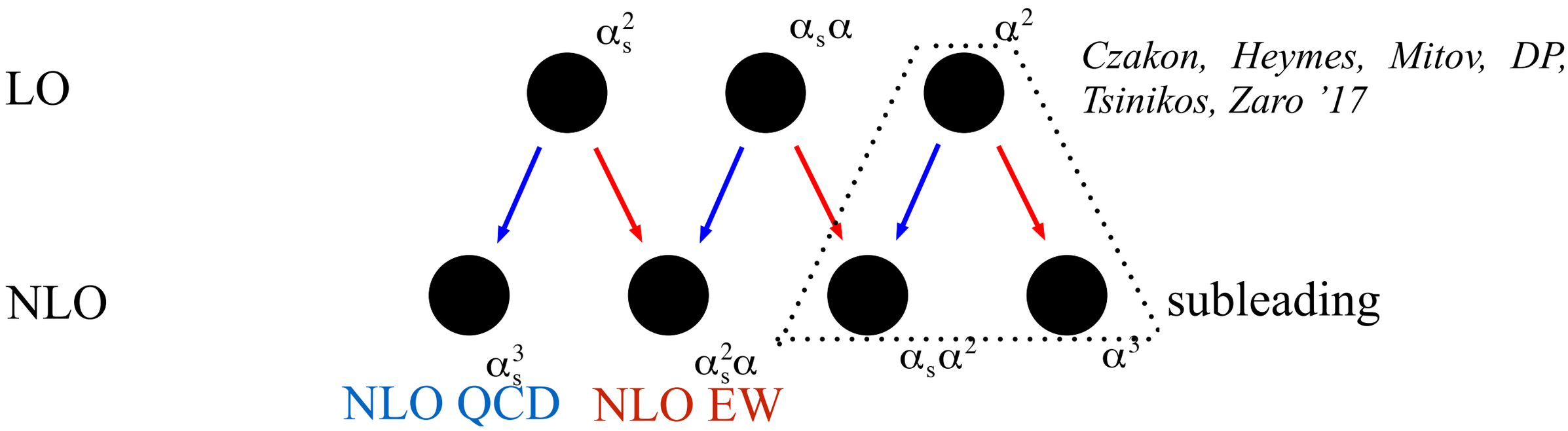


and this second NNLO term is approximated via the combination of NLO QCD and NLO EW in the multiplicative approach.

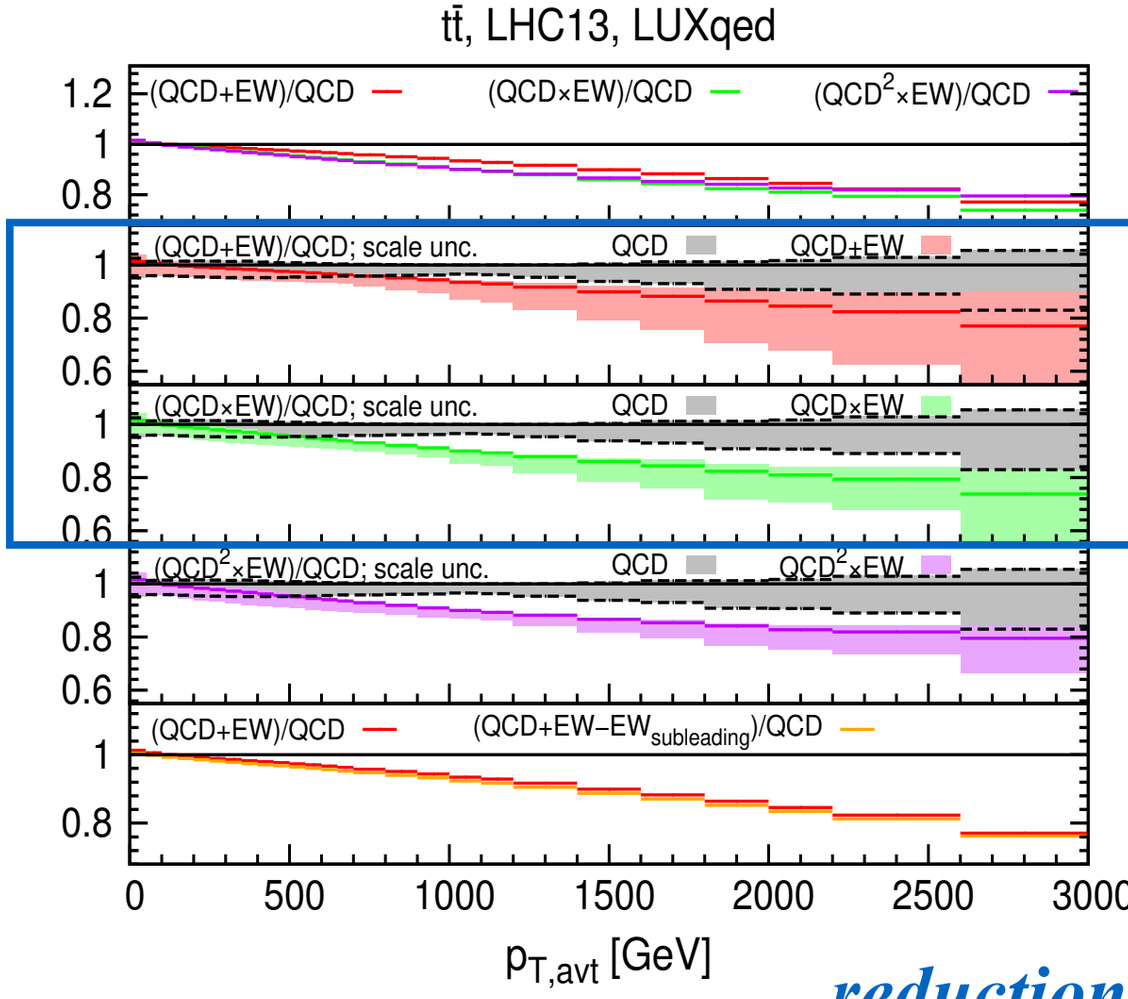
Czakon, Heymes, Mitov, DP, Tsinikos, Zaro '17

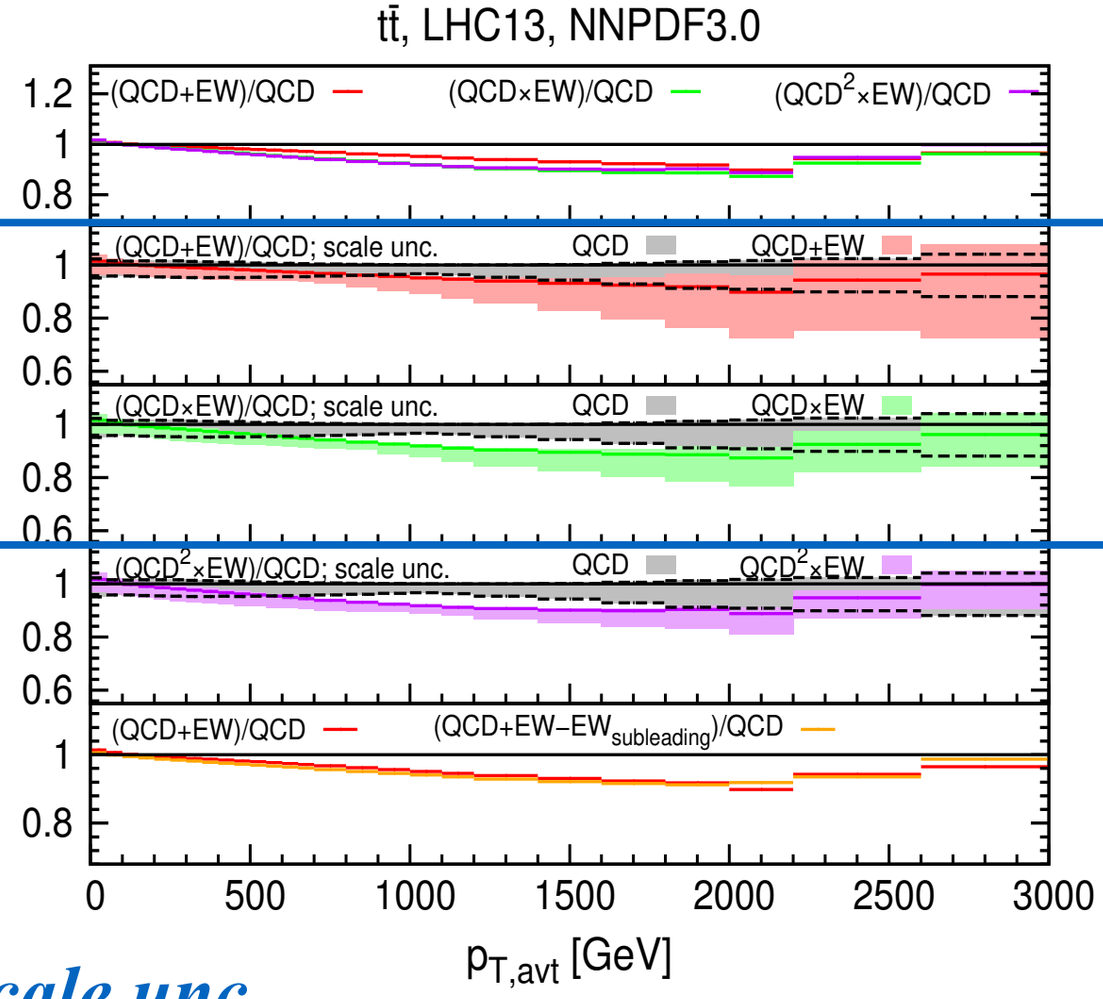
$p_{T,\mathrm{avt}}$

13 TeV

ADDITIVE

MULTIPLICATIVE





LUXQED

NNPDF3.0QED

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

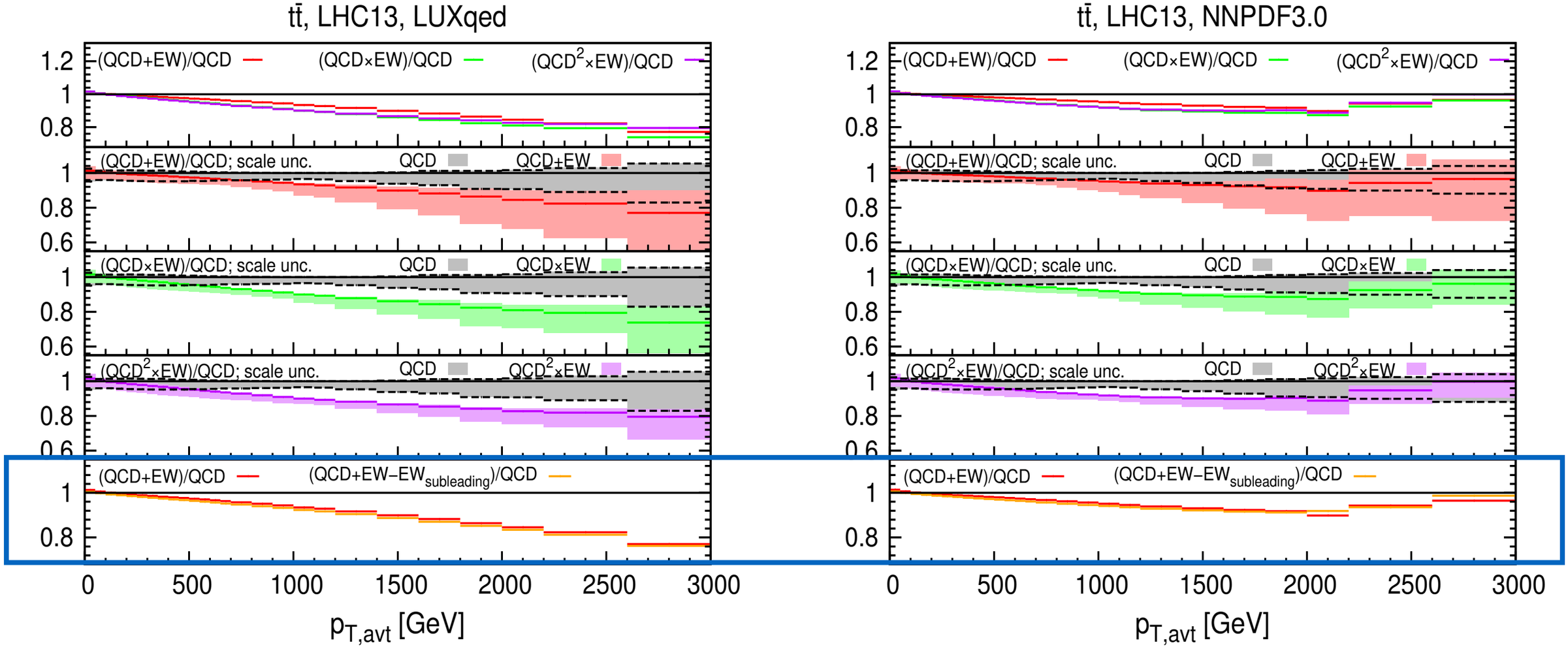
Czakon, Heymes, Mitov, DP, Tsinikos, Zaro '17

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

13 TeV

ADDITIVE

MULTIPLICATIVE



LUXQED

Subleading terms are negligible

NNPDF3.0QED

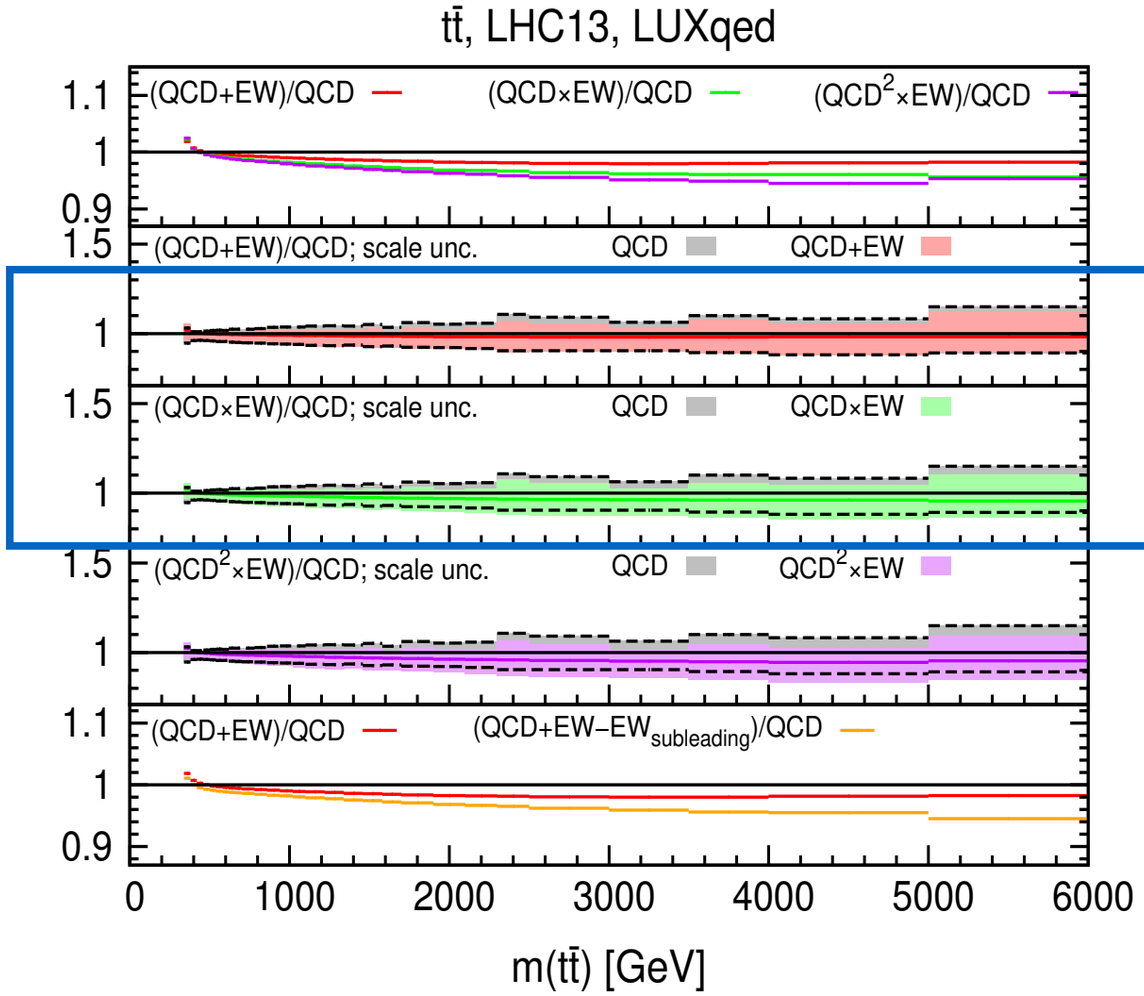
Czakon, Heymes, Mitov, DP, Tsinikos, Zaro '17

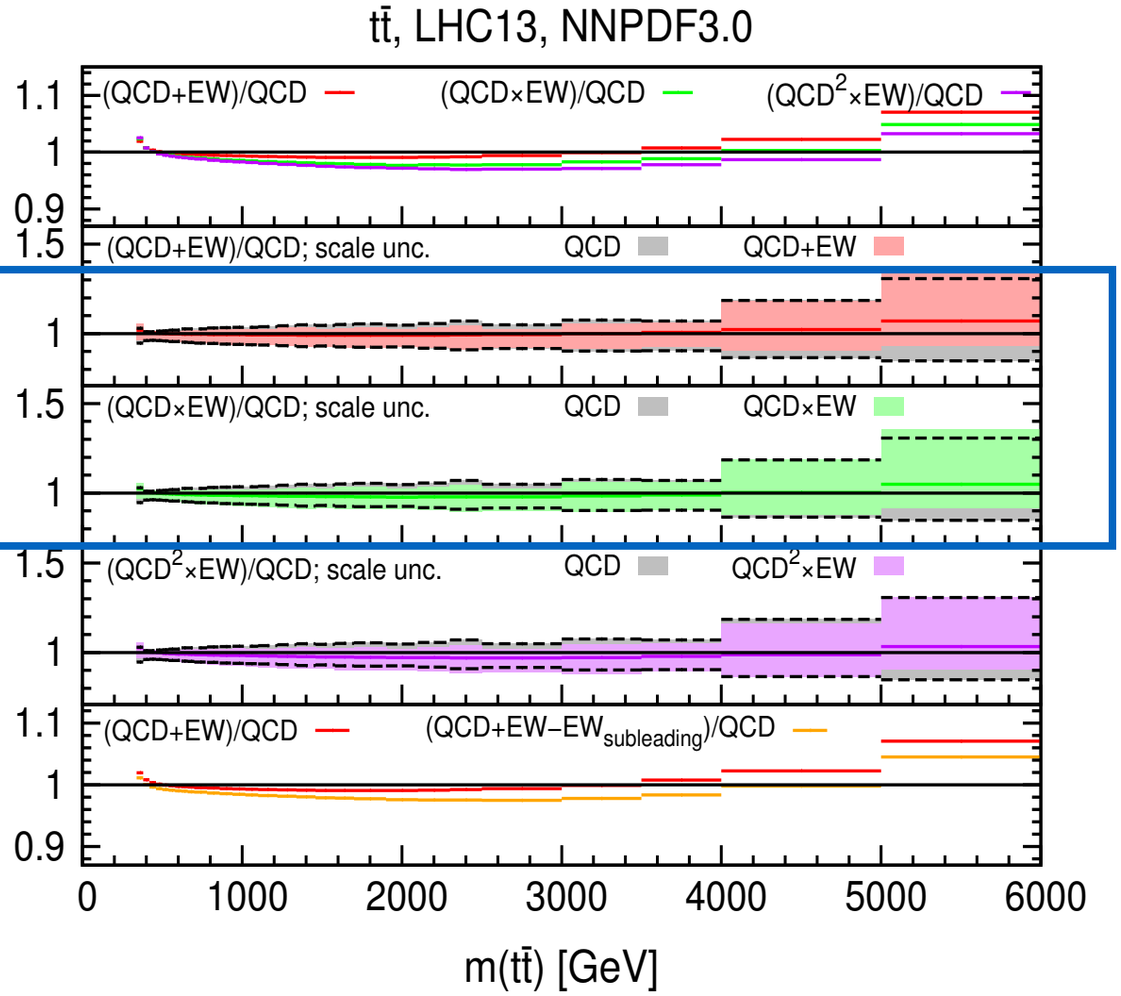
$m(t\bar{t})$

13 TeV

ADDITIVE

MULTIPLICATIVE





QCD+EW ~ QCDxEW

LUXQED NNPDF3.0QED

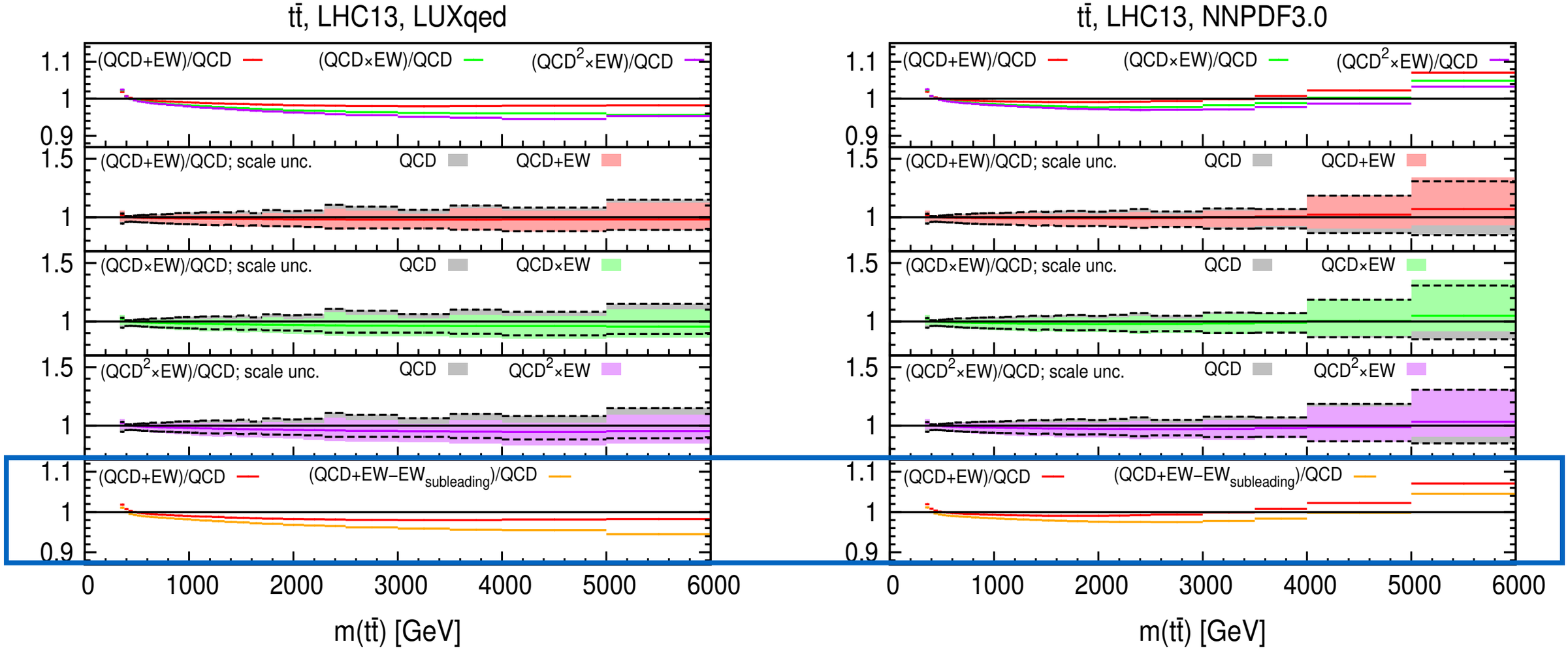
Czakon, Heymes, Mitov, DP, Tsinikos, Zaro '17

$m(t\bar{t})$

13 TeV

ADDITIVE

MULTIPLICATIVE



LUXQED

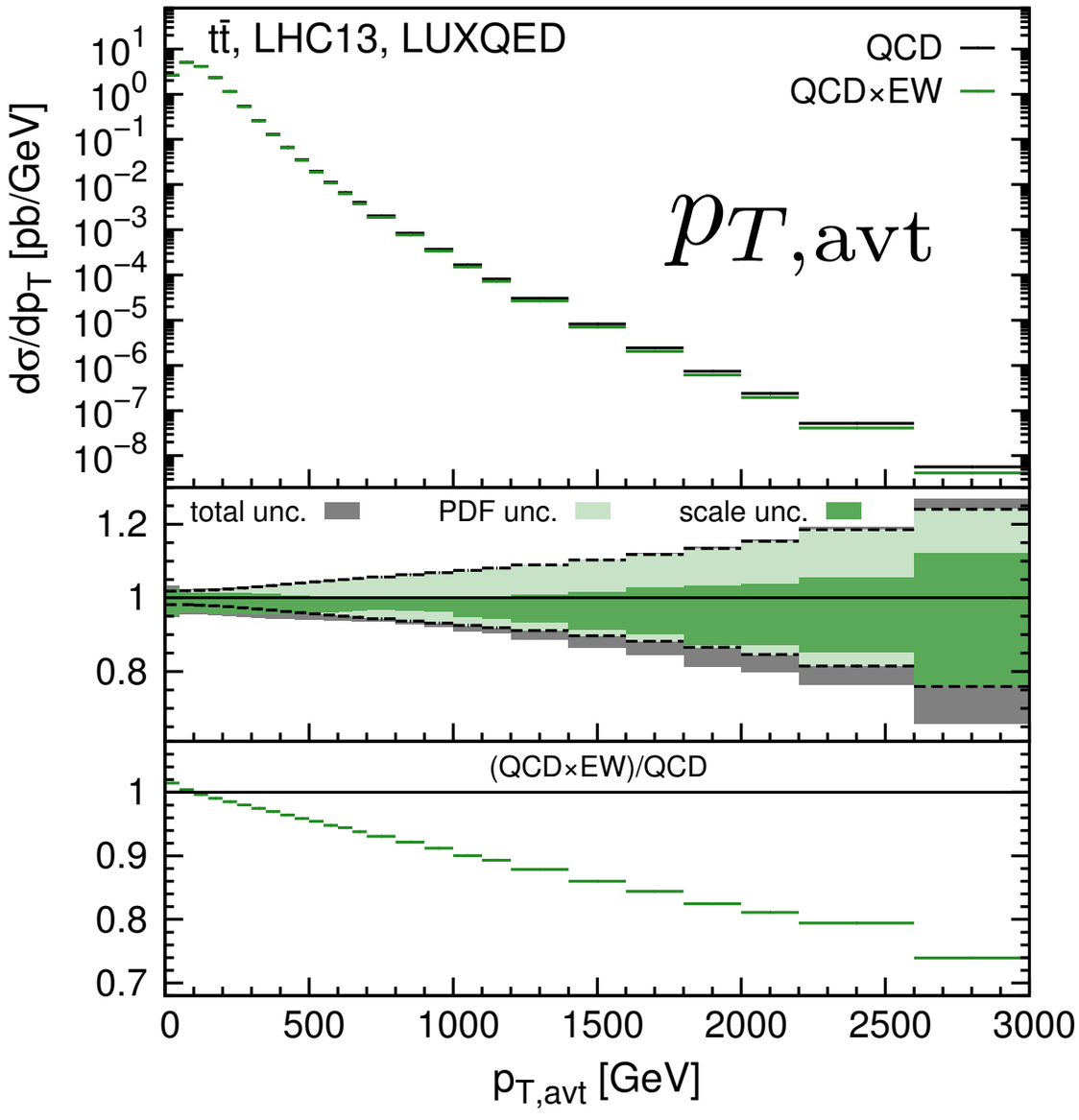
Subleading terms are ~ 2% (only in the far tail)

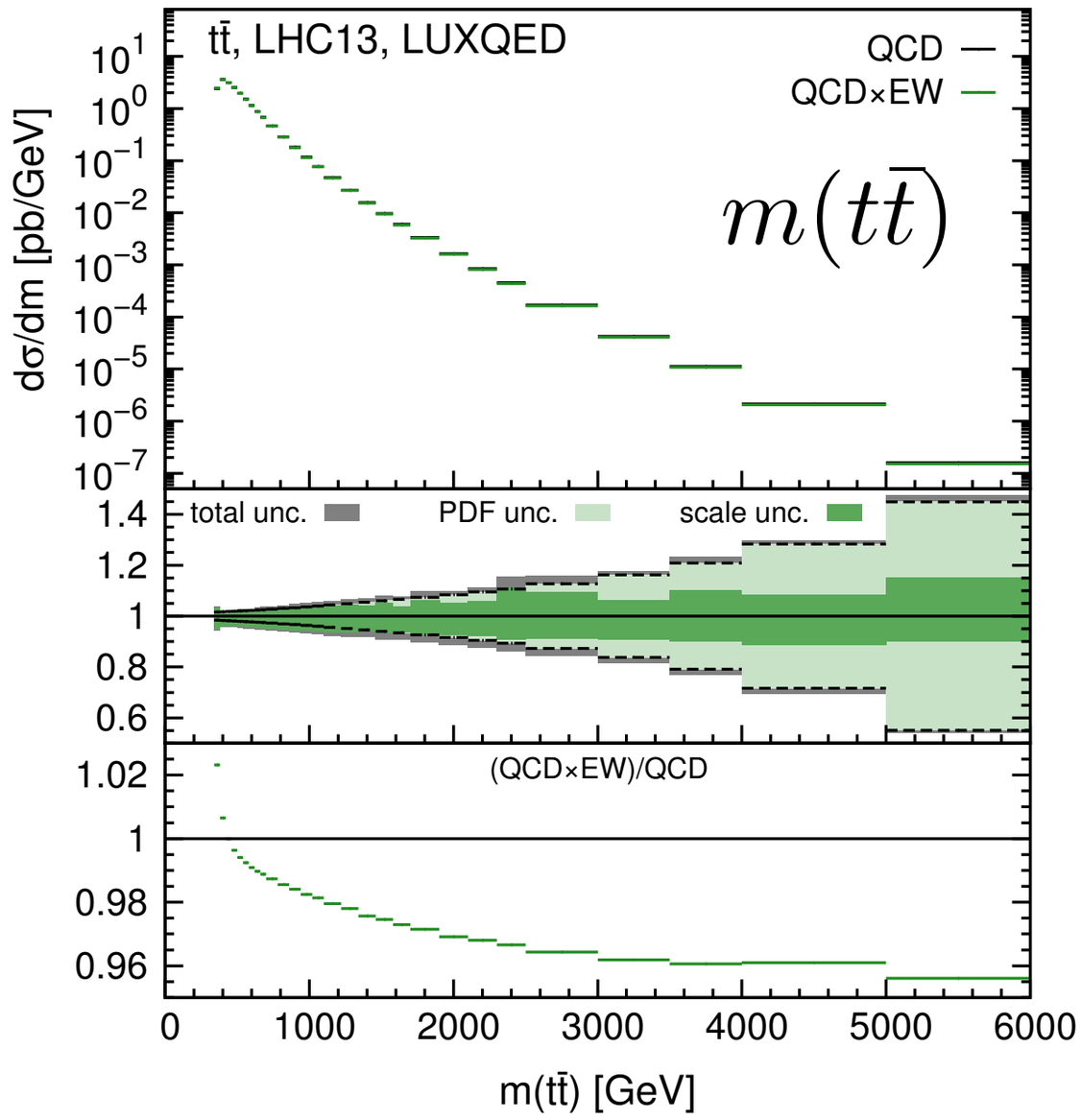
NNPDF3.0QED

Czakon, Heymes, Mitov, DP, Tsinikos, Zaro '17

MULTIPLICATIVE with LUXQED

13 TeV



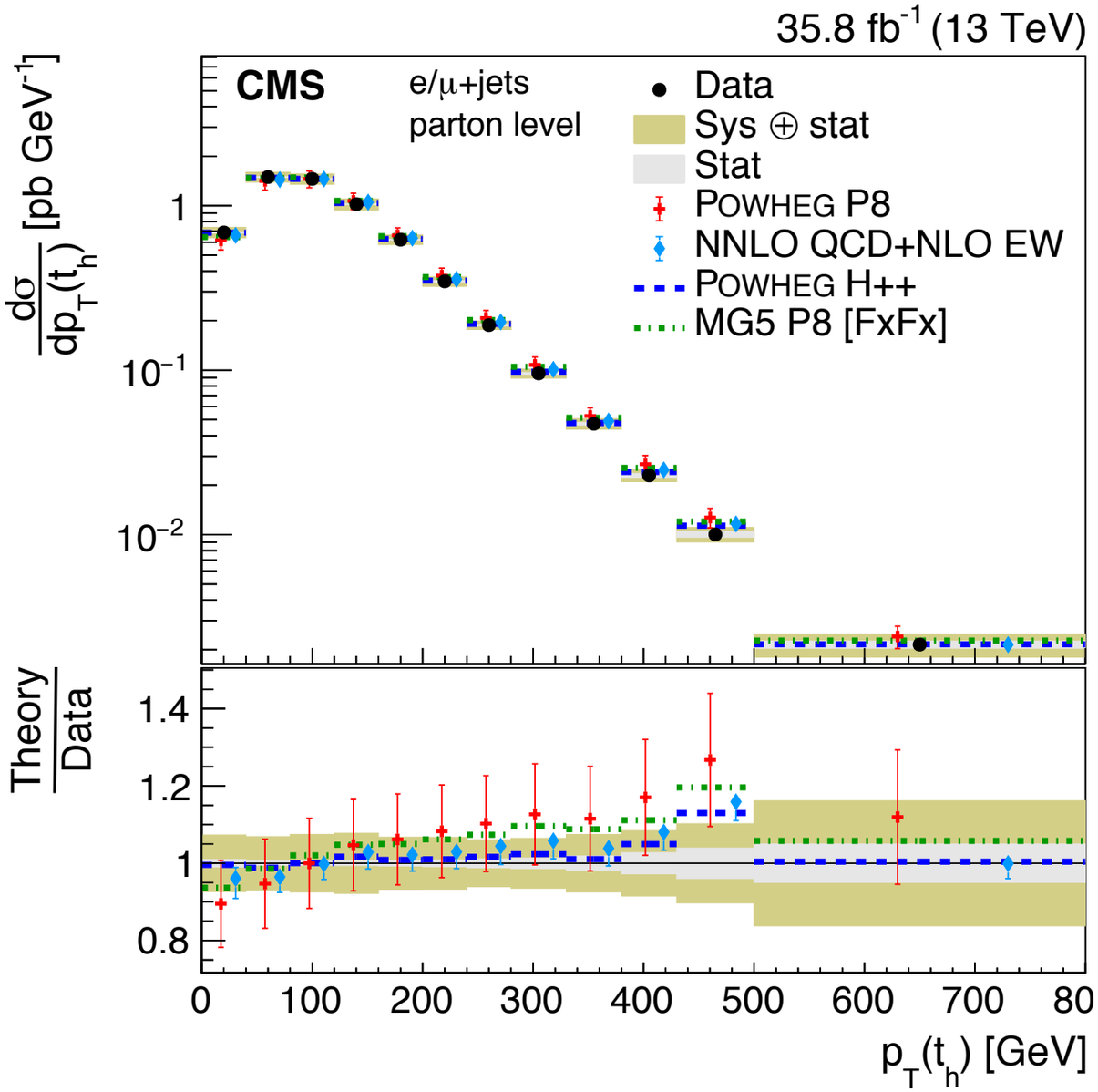


scale unc. ~ PDF unc

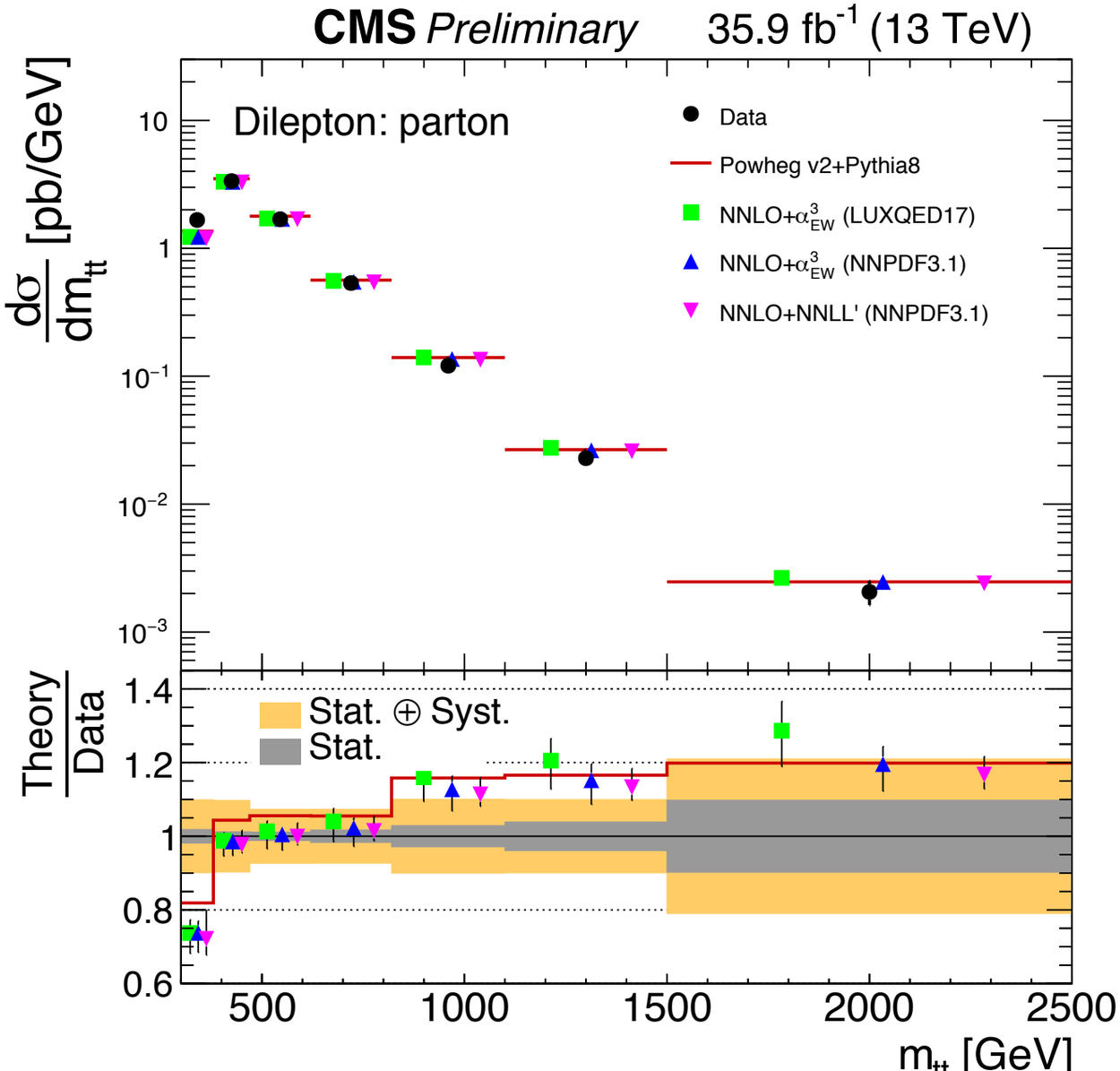
EW corrections ~ theory error

scale unc. < PDF unc

Comparison with data



arXiv:1803.08856



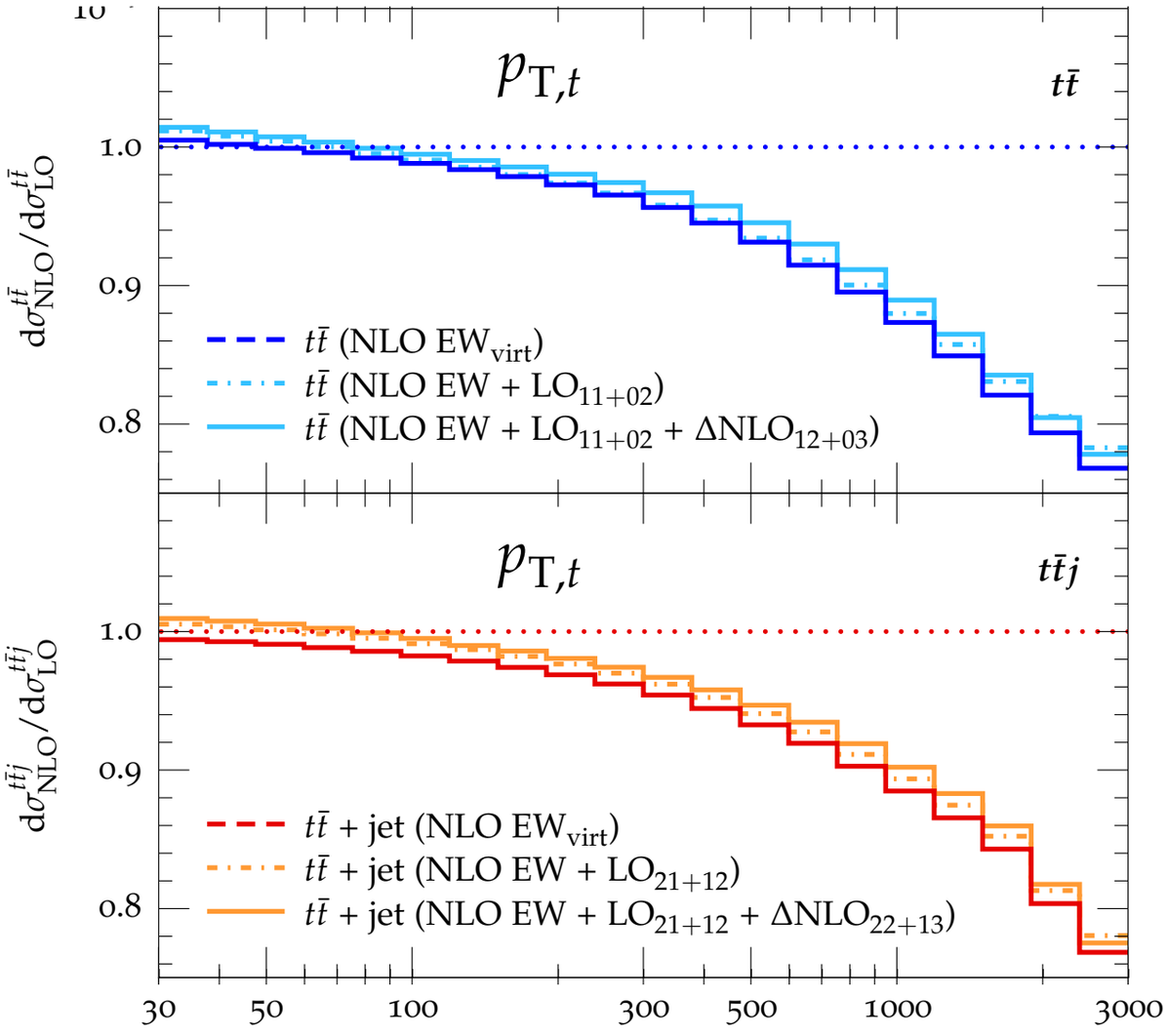
PAS TOP-17-014

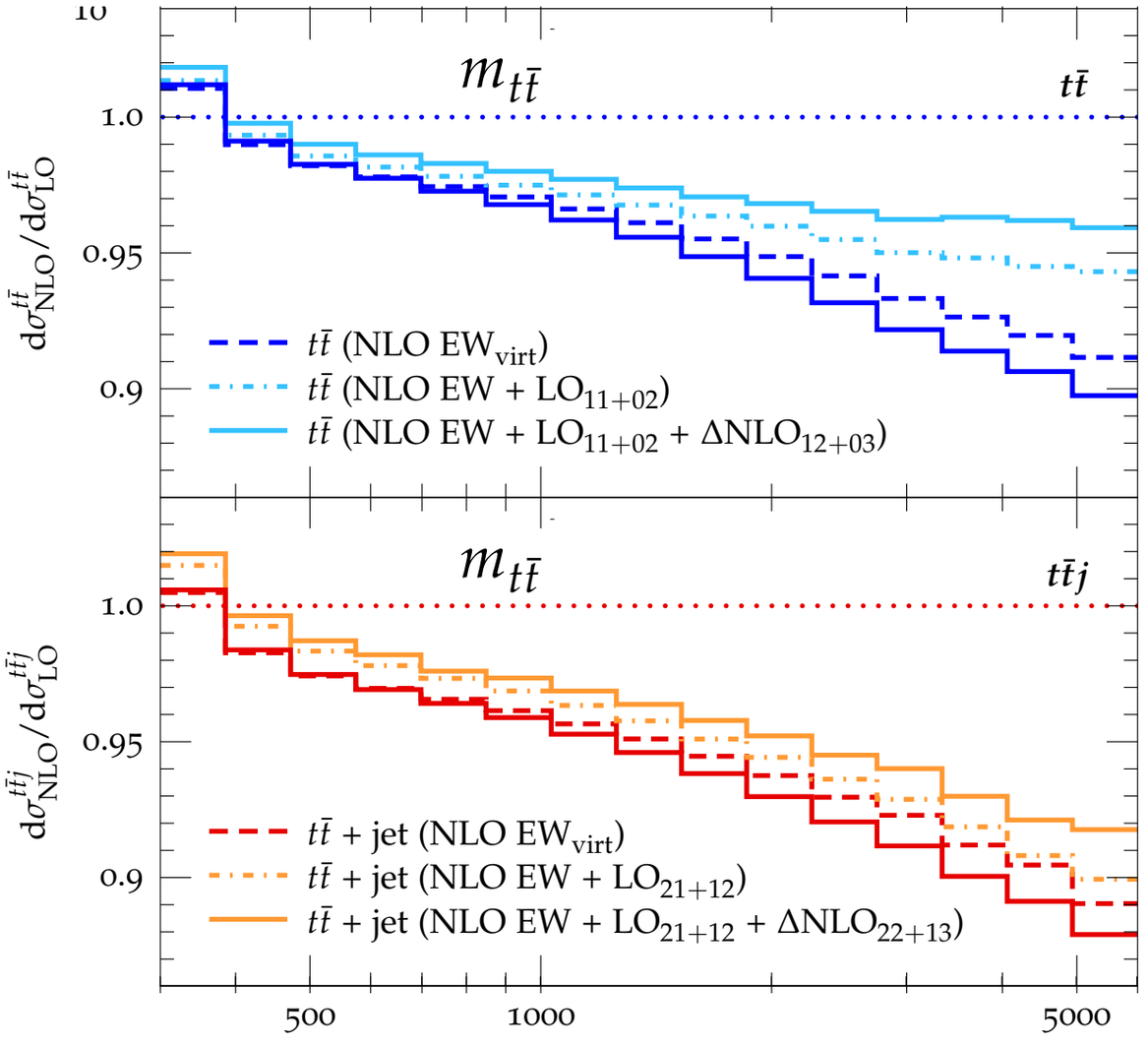
Merged $t\bar{t}$ and $t\bar{t}+$jet at Complete NLO

Merged $t\bar{t}$ and $t\bar{t}+$jet at Complete-NLO

Gütschow, Lindert, Schönherr '18

With an approximation for the QED effects (Virtual+YFS) $t\bar{t}$ and $t\bar{t}+$jet production are merged via the MEPS@NLO framework of Sherpa combined with Openloops. Sudakov logs and other weak effects exactly taken into account.

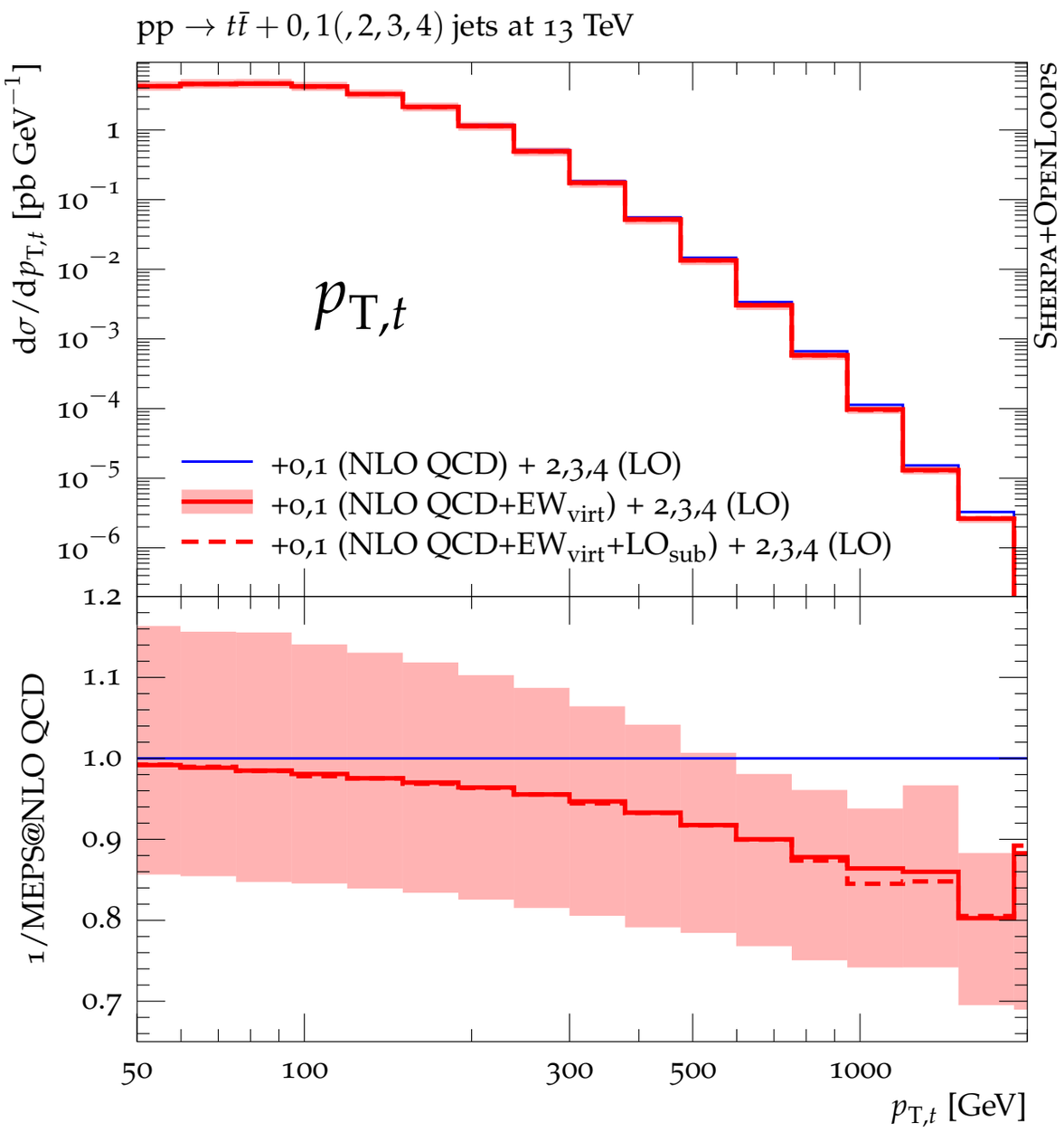


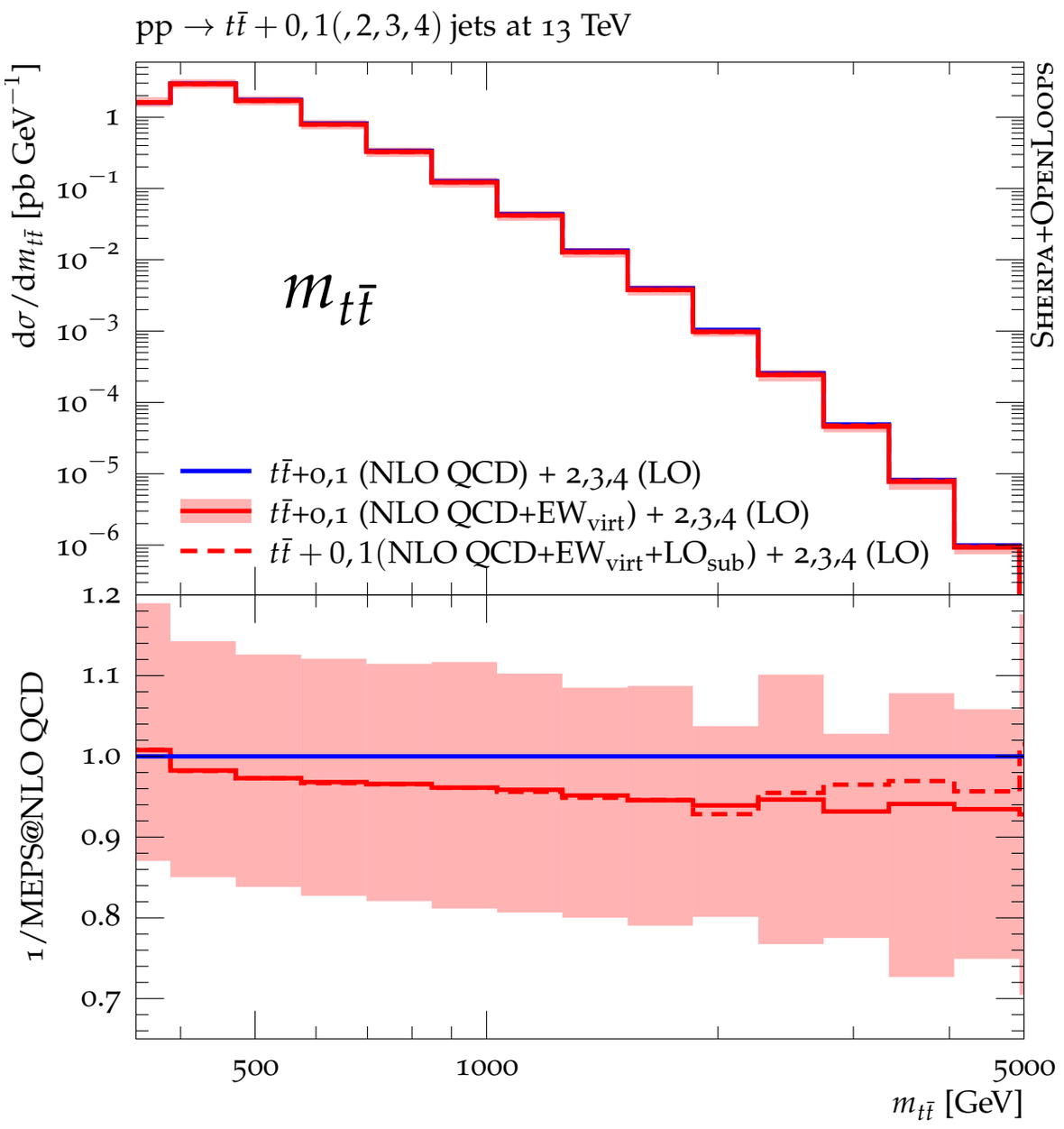


This approximation works at % level for these observables.
EW corrections factorise jet activity, supporting the multiplicative approach.

Comparison with NLO QCD merging

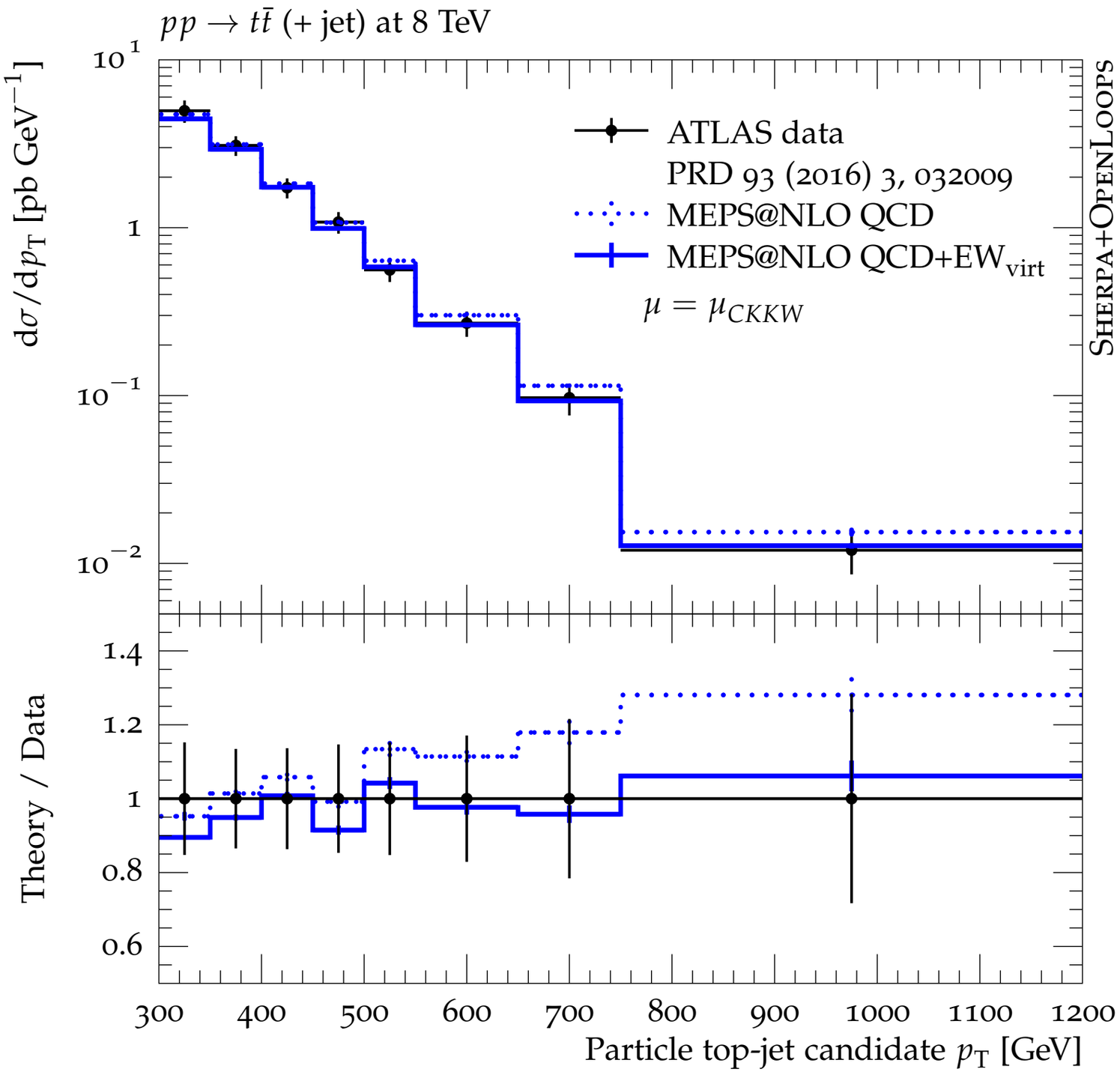
Gütschow, Lindert, Schönherr '18





Comparison with data

Gütschow, Lindert, Schönherr '18



Comparison to ATLAS data at 8 TeV.

Full particle-level predictions including spin-correlated top quark decays in the semileptonic decay channel, non-perturbative effects and higher-order QED effects are included.

EW effects are again shown to be relevant.

Comparison between the two different approximations

preliminary results

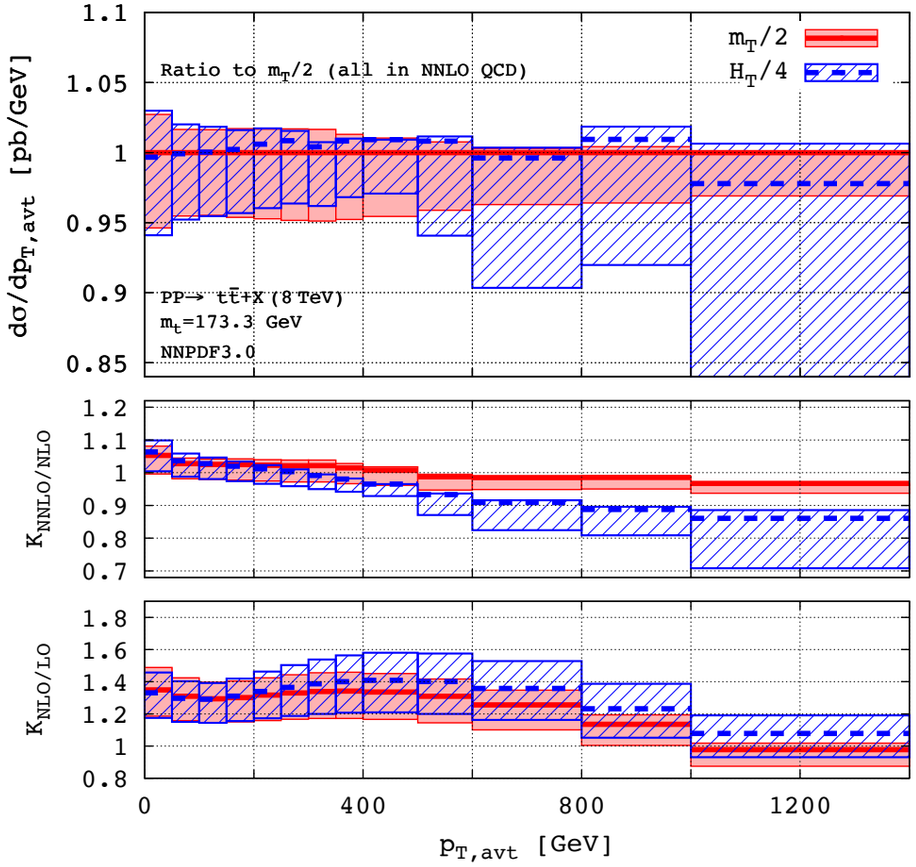
NNLO QCD: scale definition

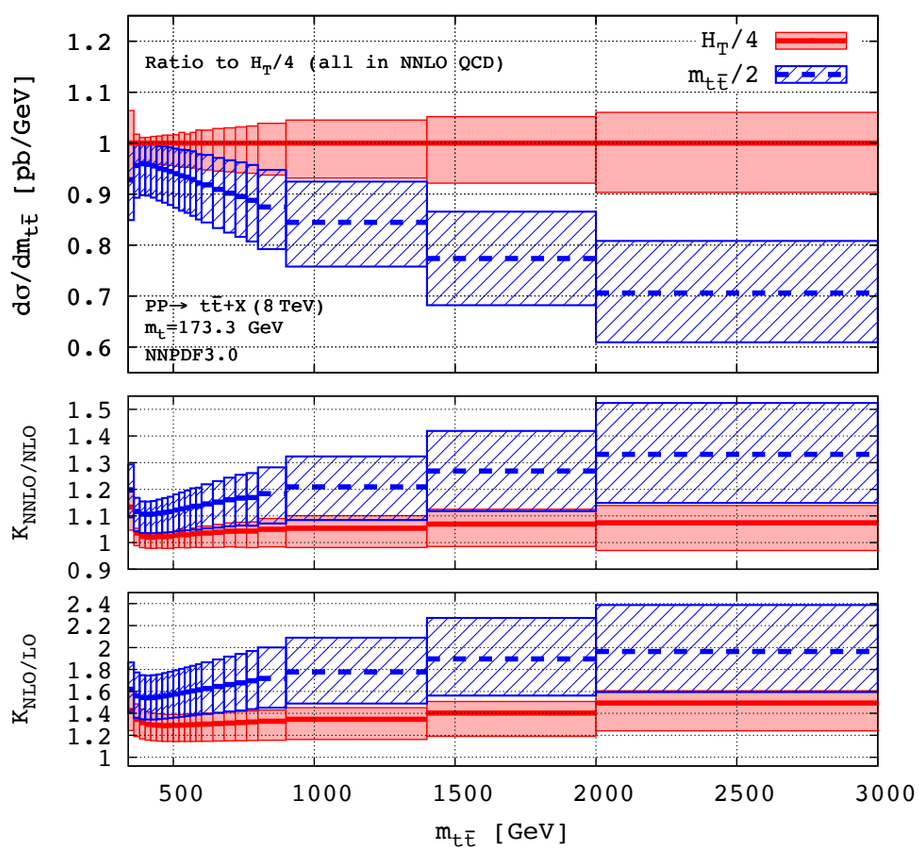
The dependence on the ren. and fac. scale is mainly due to QCD effects.

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

Merging: scale definition

Gütschow, Lindert, Schönherr '18

CKKW scale chosen on the base of the color flow in the process

$$\alpha_s^{2+n}(\mu^2_{\text{CKKW}}) = \alpha_s^2(\mu^2_{\text{core}}) \cdot \alpha_s(t_1) \cdots \alpha_s(t_n)$$

$$\mu_{\text{core}} = \frac{1}{2}\left(\frac{1}{\hat{s}} + \frac{1}{m_t^2 - \hat{t}} + \frac{1}{m_t^2 - \hat{u}}\right)^{-\frac{1}{2}}$$

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large p_T	large $M_{t\bar{t}}$	threshold
$p_T \to \infty$	$E \to \infty$ $p_T \to 0$	$E \to 0$
$\mu_{\text{core}} \to \frac{1}{2}\sqrt{\frac{4}{5}} p_T \sim \frac{p_T}{2}$	$\mu_{\text{core}} \to \frac{m_T}{2}$	$\mu_{\text{core}} \to \frac{1}{2}\sqrt{\frac{4}{5}} m_t \sim \frac{m_t}{2}$

Merging: scale definition

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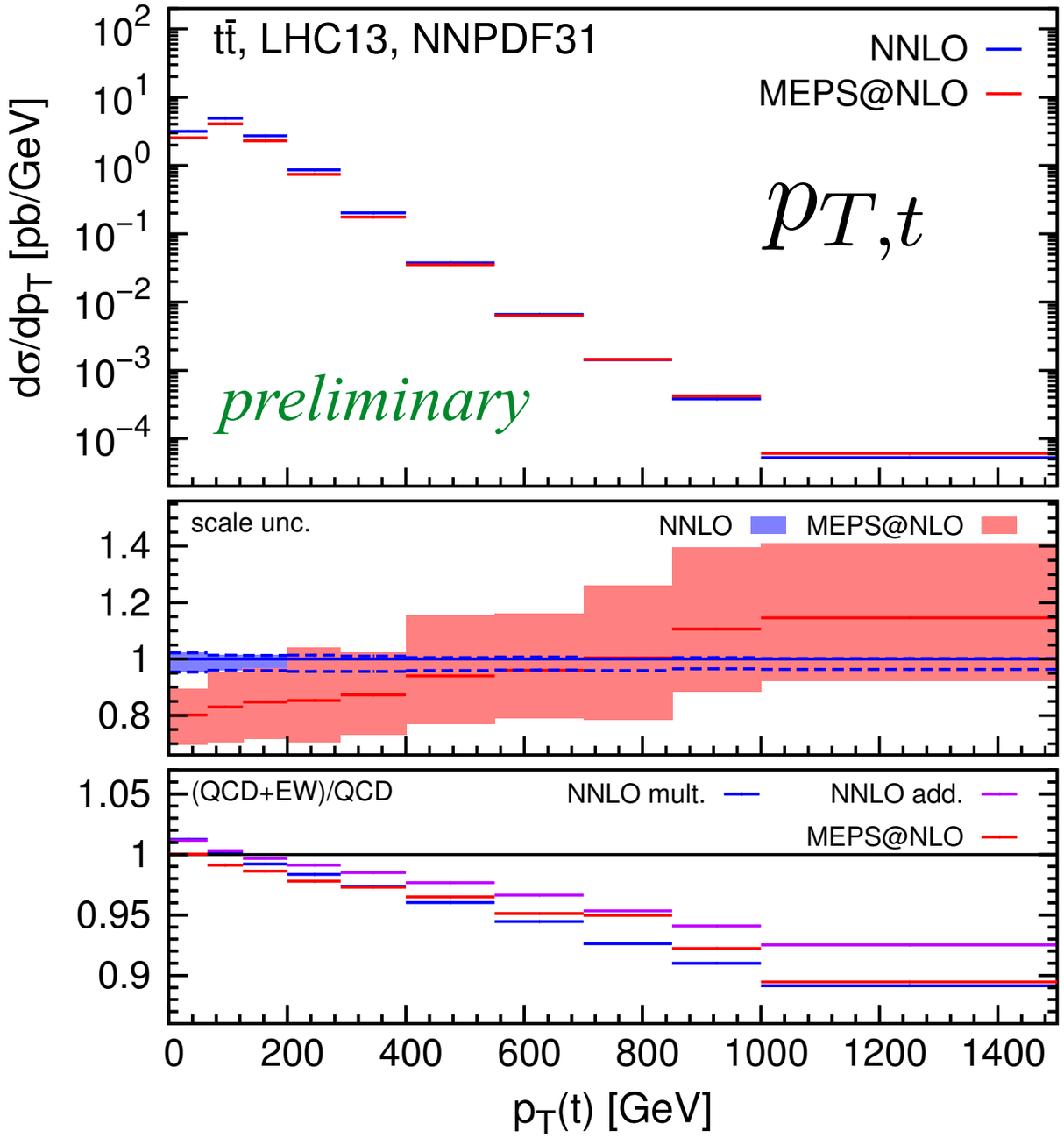
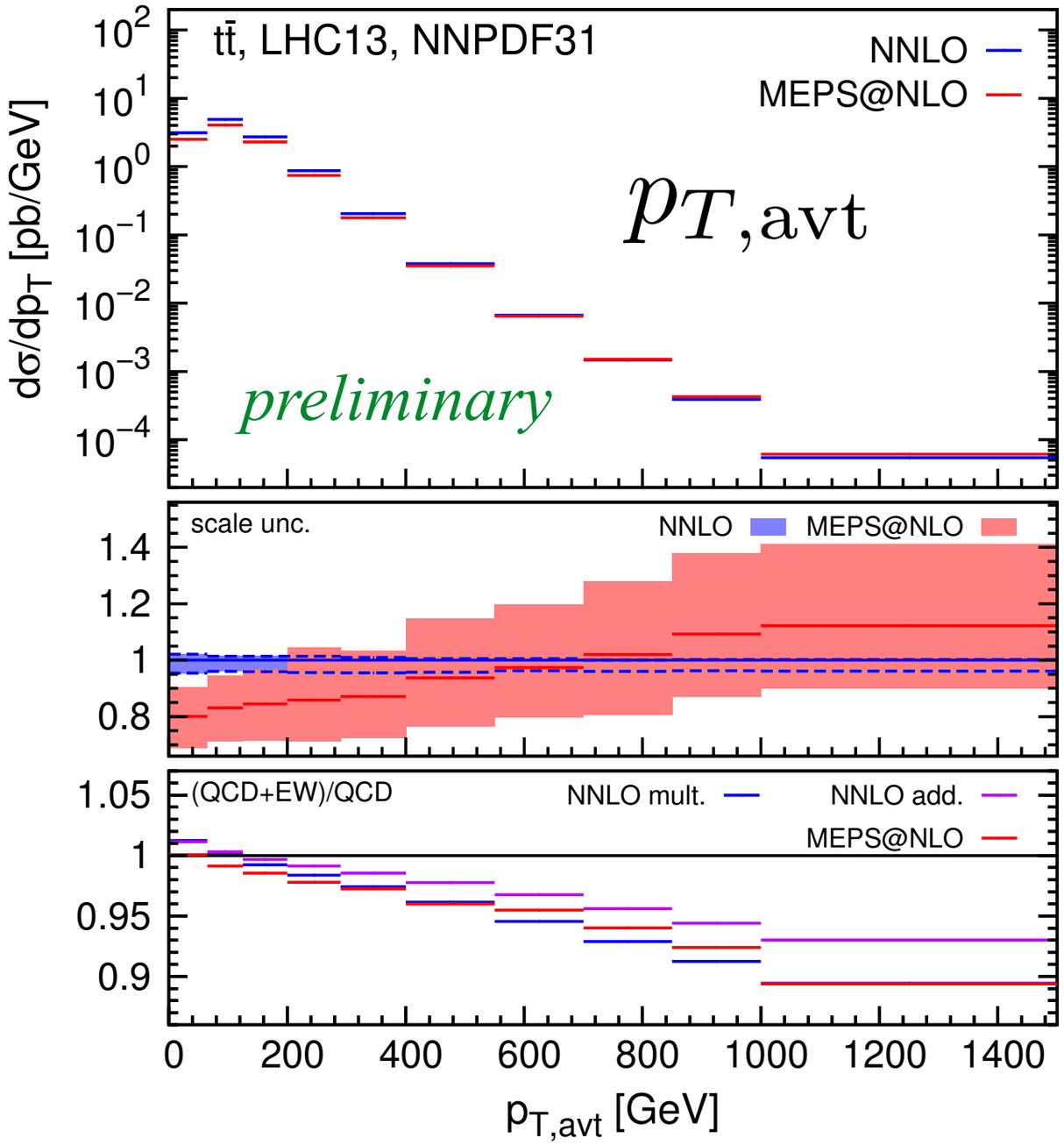
Although motivated by **different principles**, the scale **definitions** in the two approaches are, to a large extent, **equivalent**.

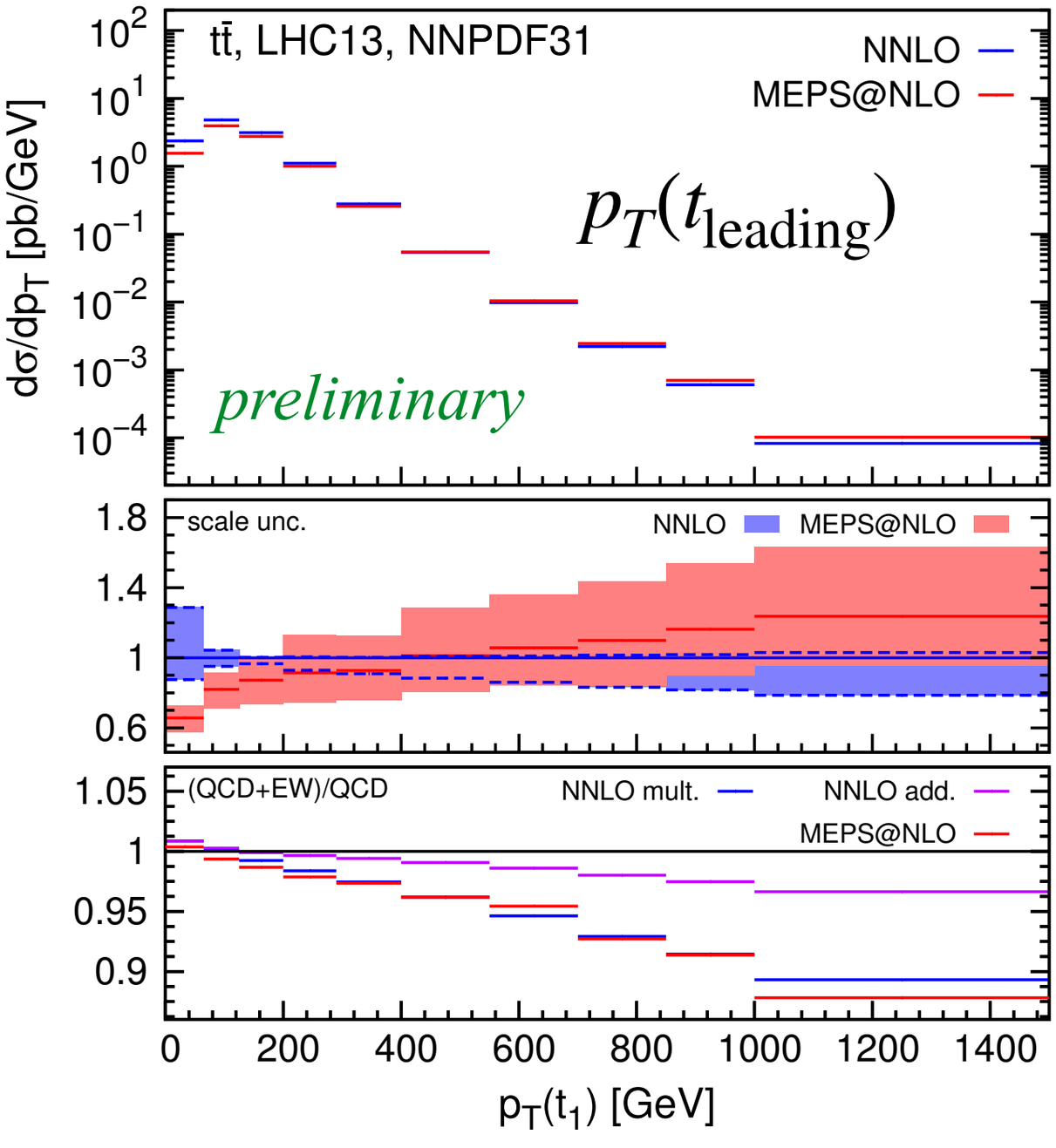
NNLO vs MEPS@NLO, including Complete NLO

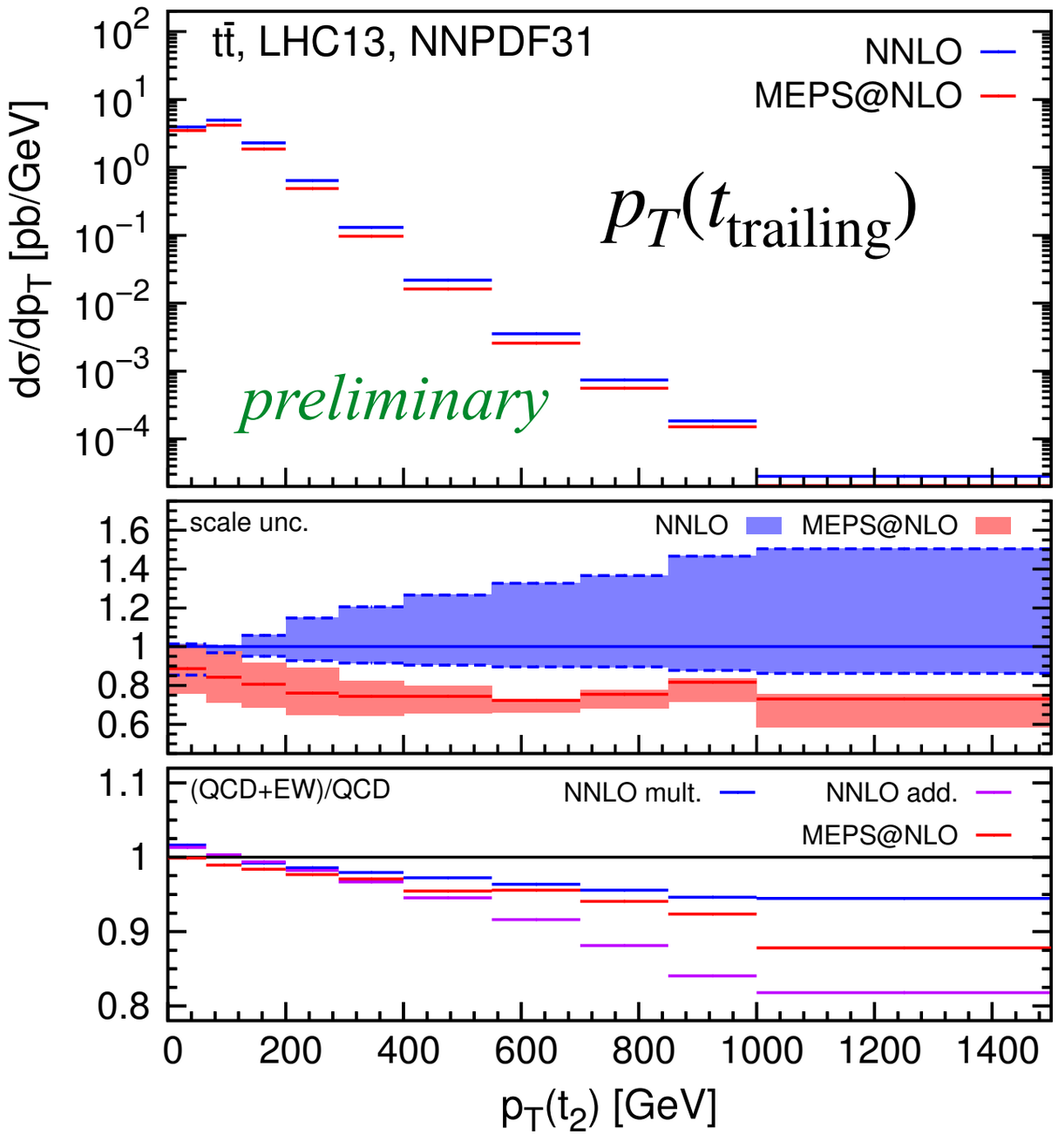




Predictions are **compatible**, with a **smaller scale unc.** for the **NNLO** case.
MEPS@NLO further **supports** the **multiplicative** approach.

NNLO vs MEPS@NLO, including Complete NLO





The **pt distribution** for the **softest top** and the region with **small values for the hardest top** are **pathological** at fixed order: **MEPS@NLO cures this problem**. See also backup slides.

Conclusion

Precise predictions in top-quark physics must take into account both QCD and EW effects in order to correctly identify possible BSM effects.

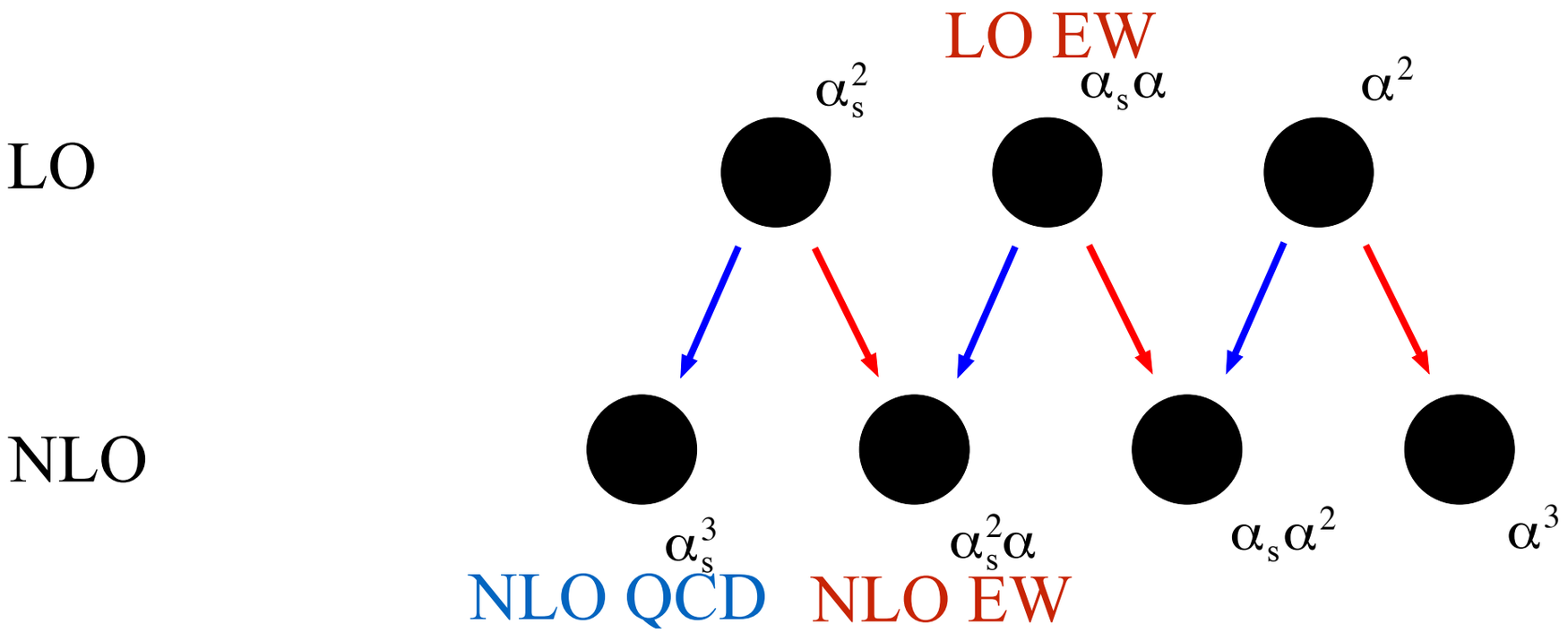
NNLO QCD and MEPS@NLO, both including Complete NLO, are in agreement for (anti)top pt distributions.

The NNLO QCD prediction has a scale uncertainty that is much smaller than MEPS@NLO for the pT of the (anti)top, but it is pathological for the pt of the trailing top and for soft leading tops

MEPS@NLO scale uncertainty is not small for the pT of the (anti)top, but this approximation cures the fixed-order pathologies for the trailing top and for soft leading tops. Full decays and analyses at the detector level are possible.

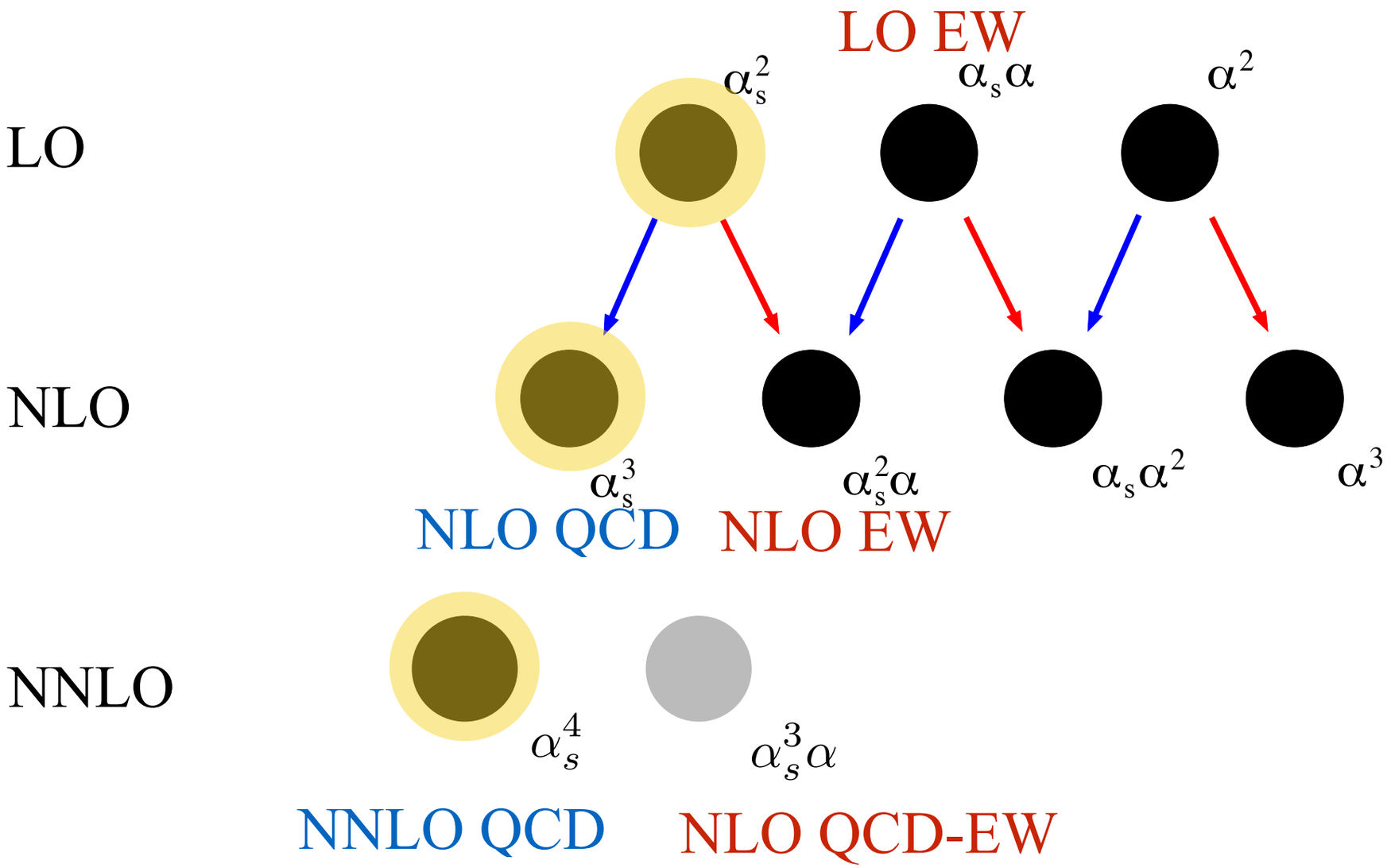
EXTRA SLIDES

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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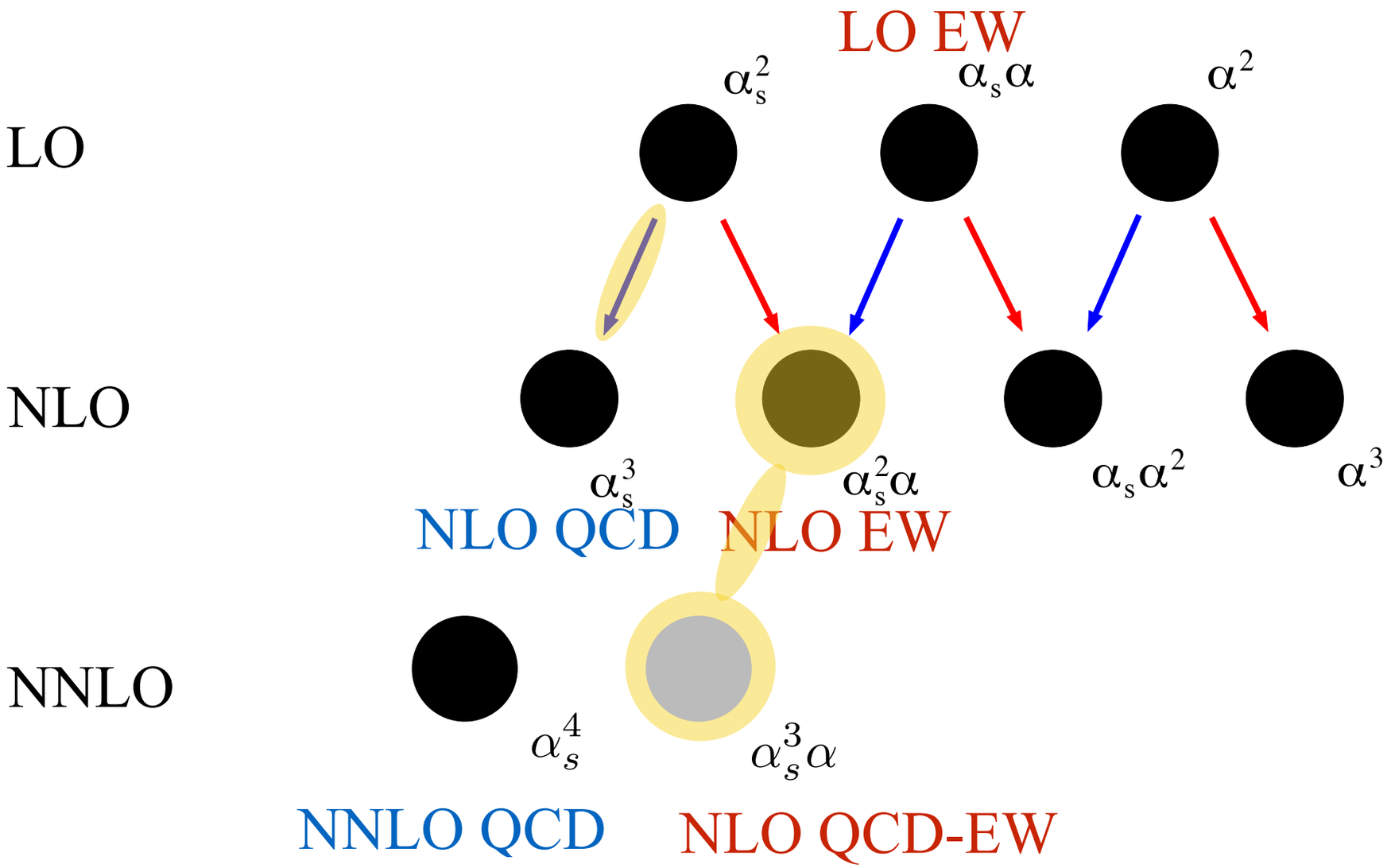
Multiplicative combination



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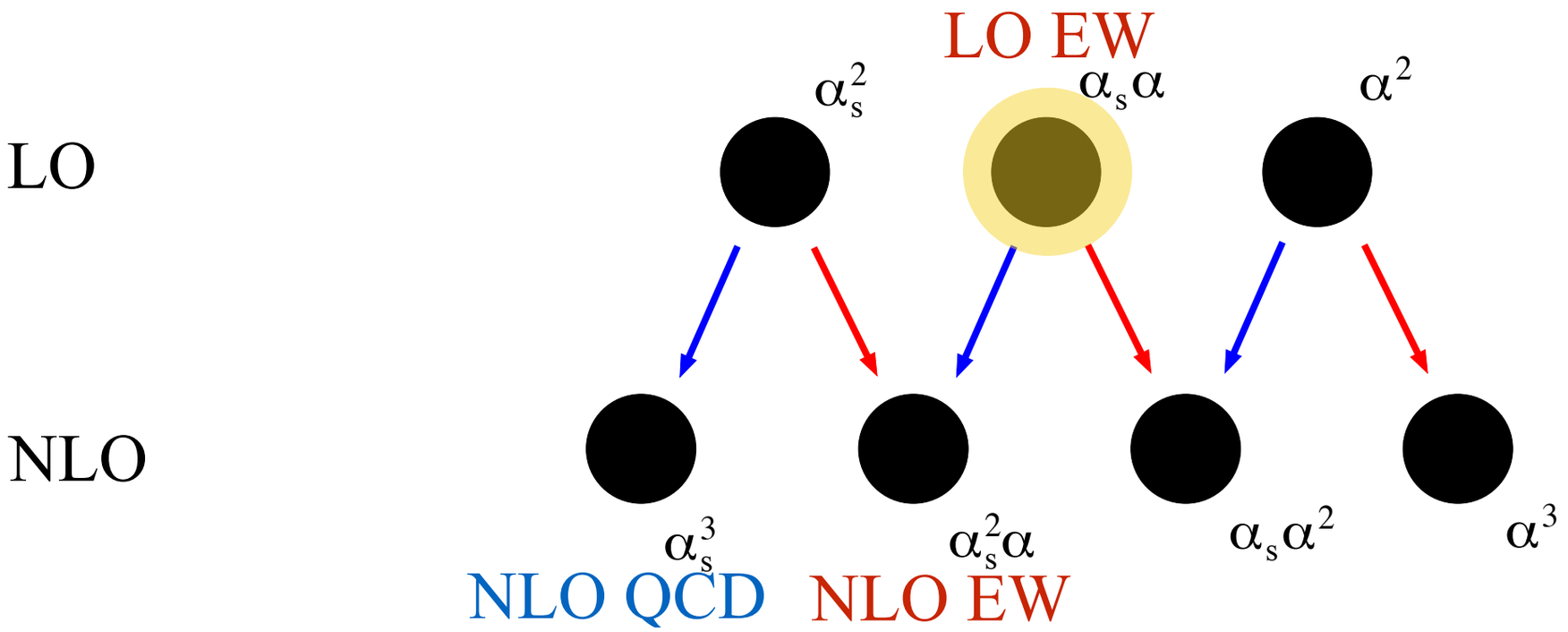
Multiplicative combination



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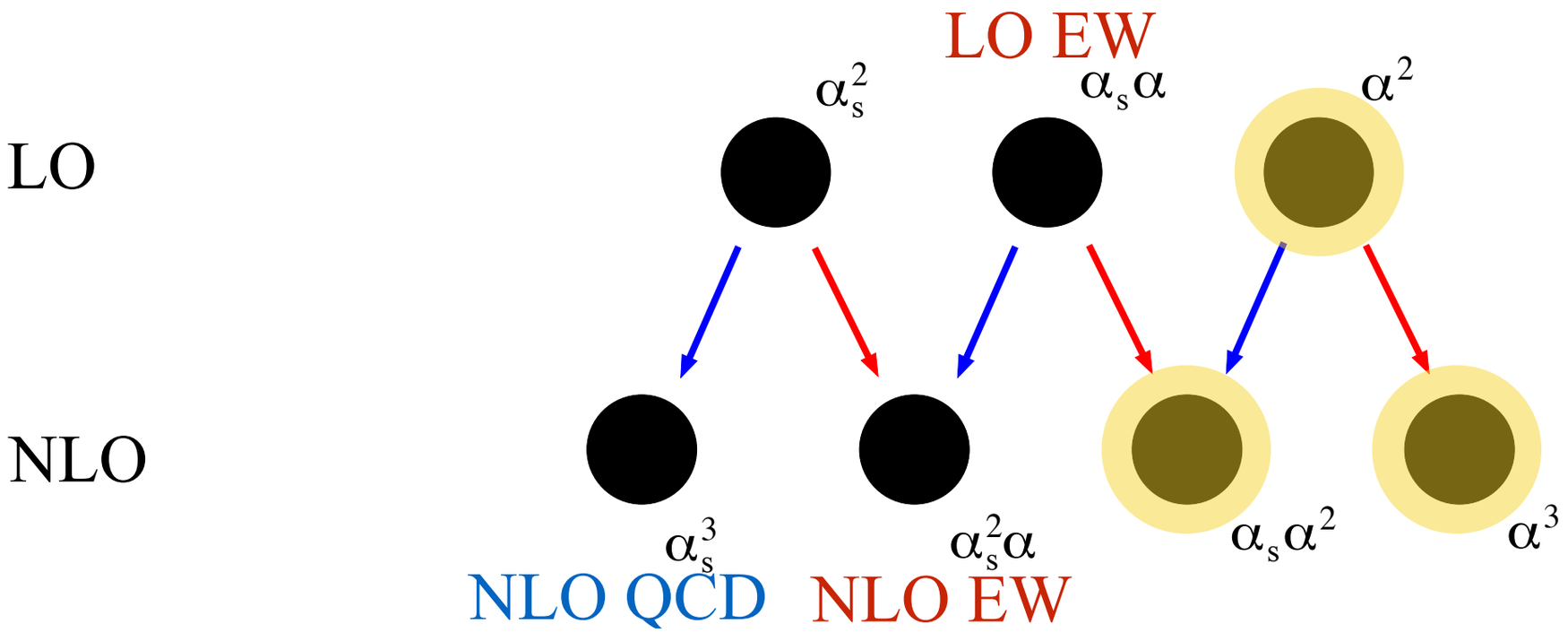
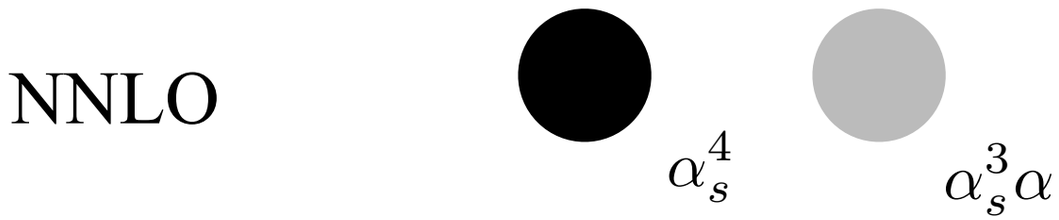
Multiplicative combination





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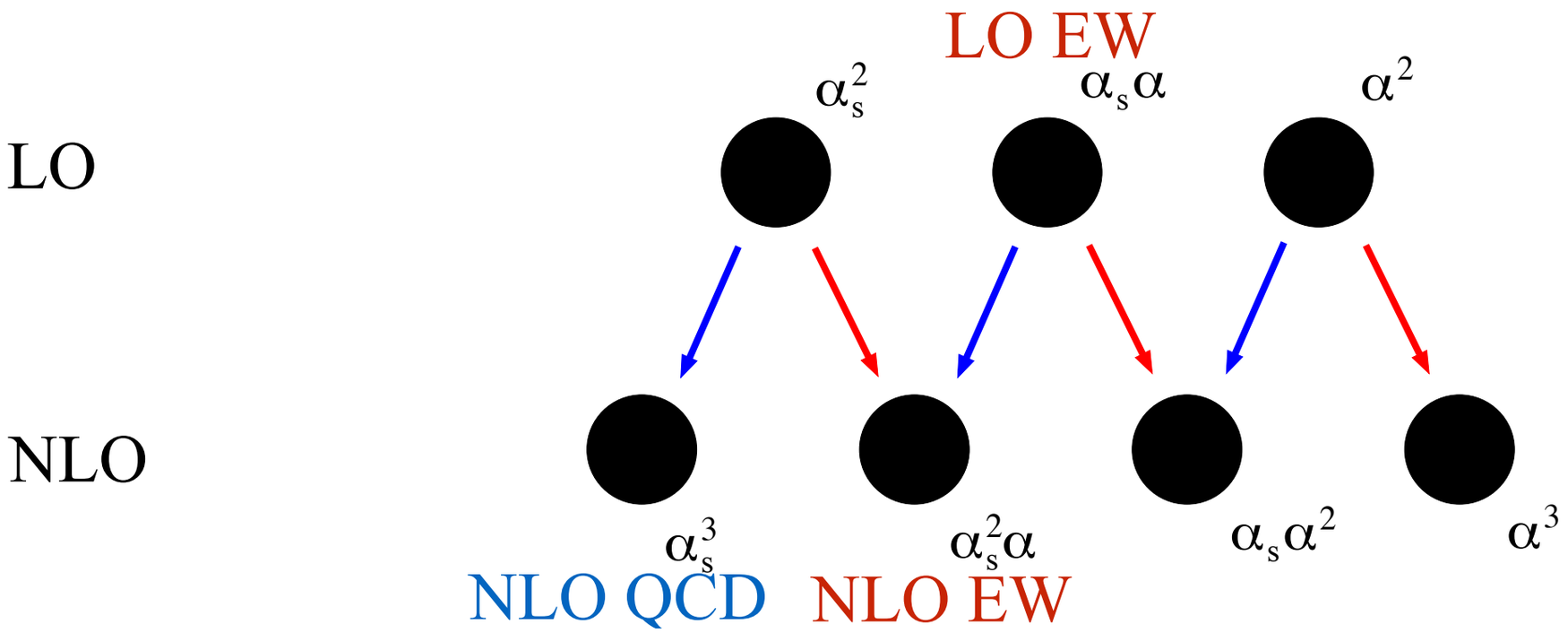
Multiplicative combination



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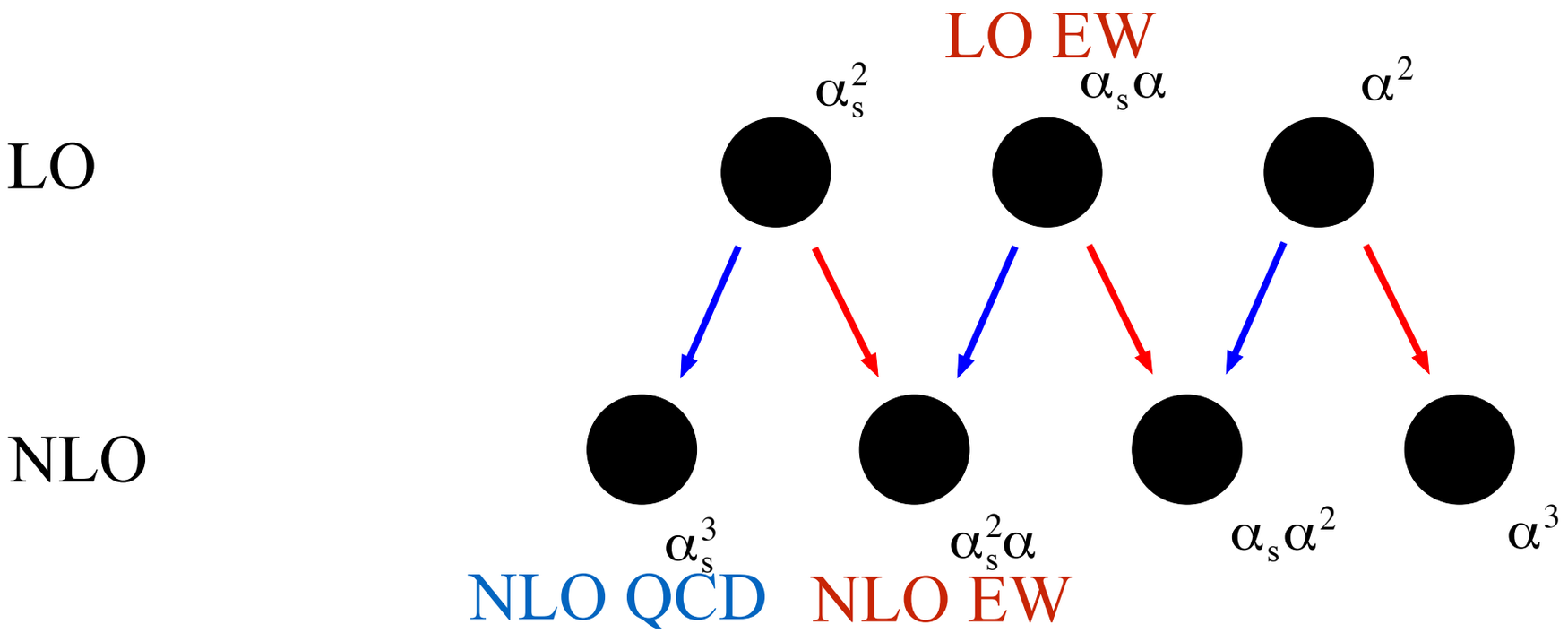
Multiplicative combination



MULTIPLICATIVE

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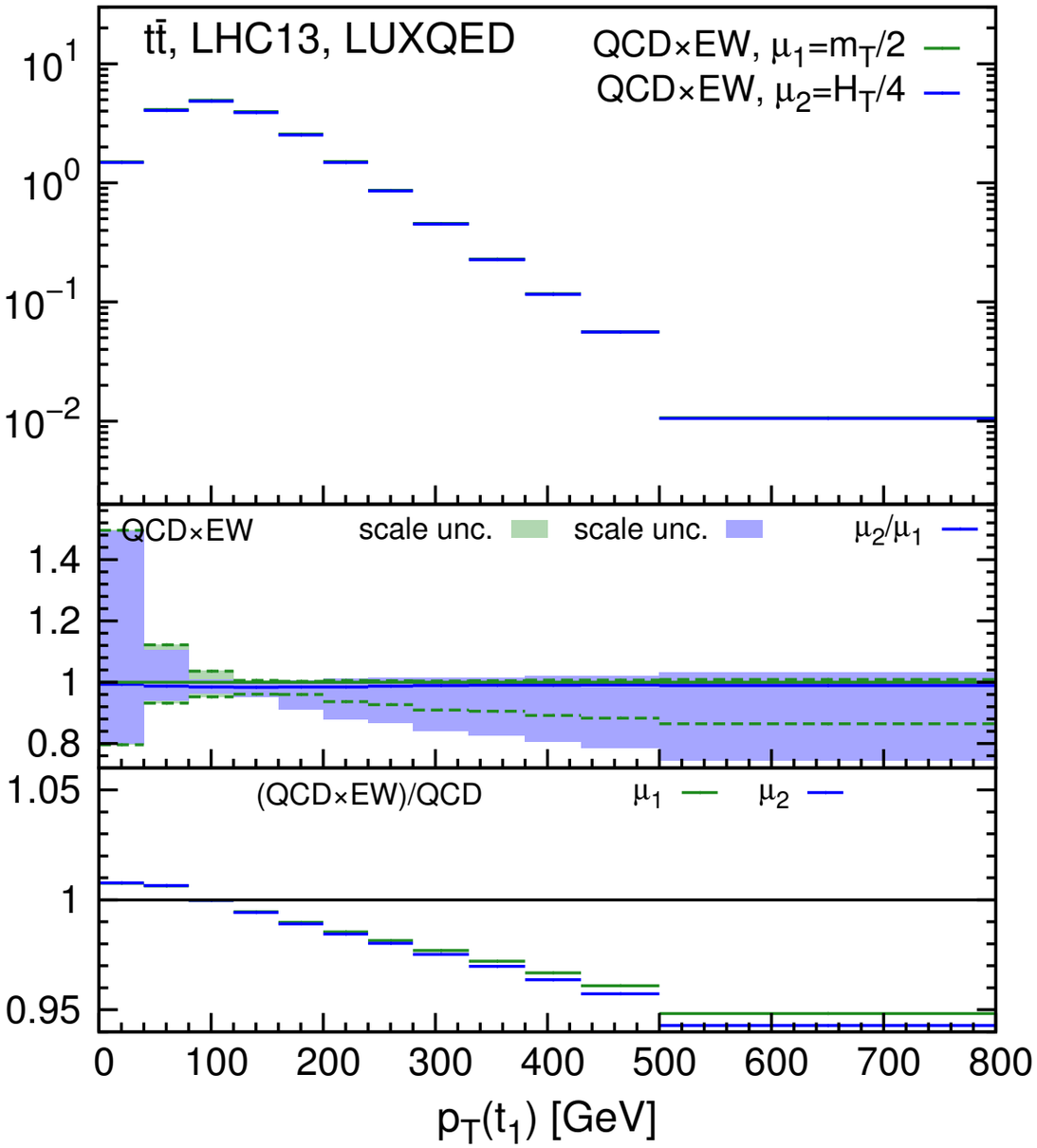
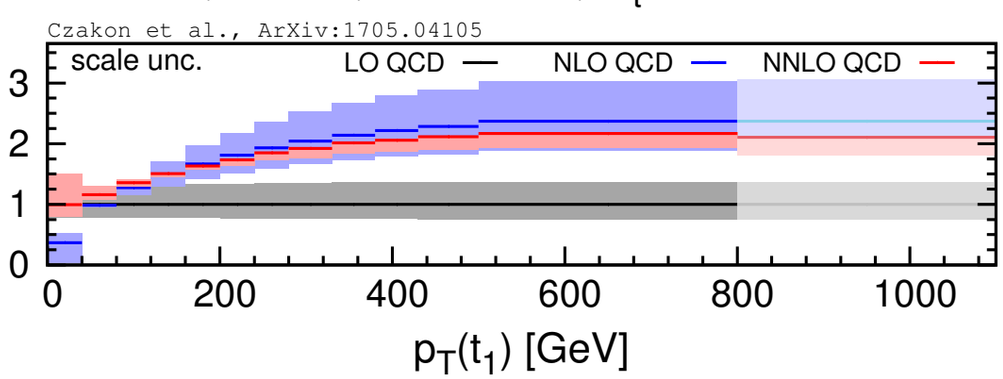
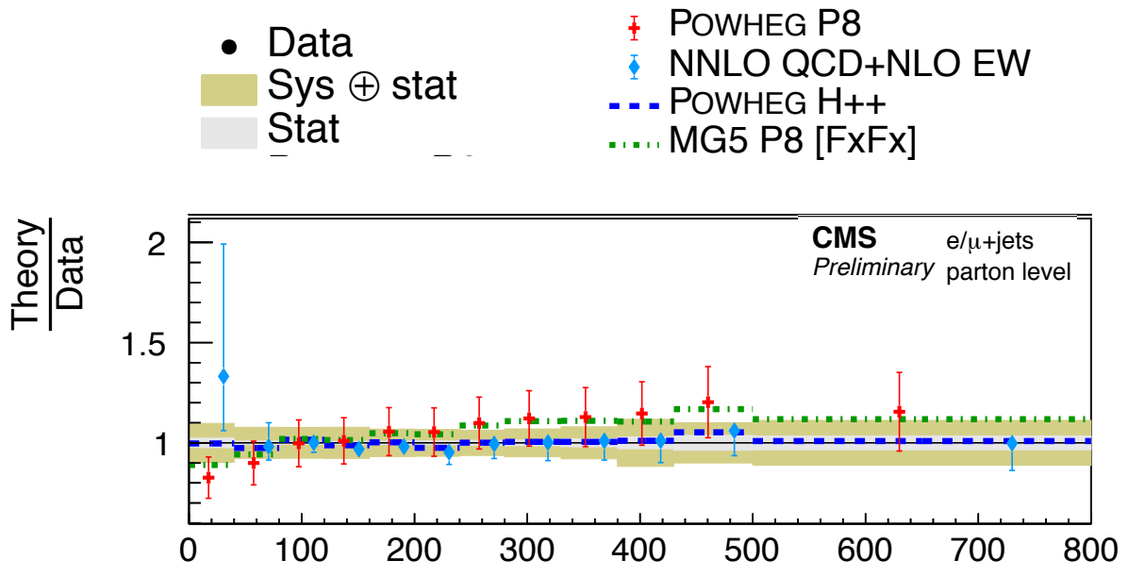
$$\Sigma_{\mathrm{QCD}^2\times\mathrm{EW}} \equiv \Sigma_{\mathrm{QCD}} + K_{\mathrm{QCD}}^{\mathrm{NNLO}}\,\Sigma_{\mathrm{NLO\ EW}} + \Sigma_{\mathrm{LO\ EW}} + \Sigma_{\mathrm{subleading}}$$

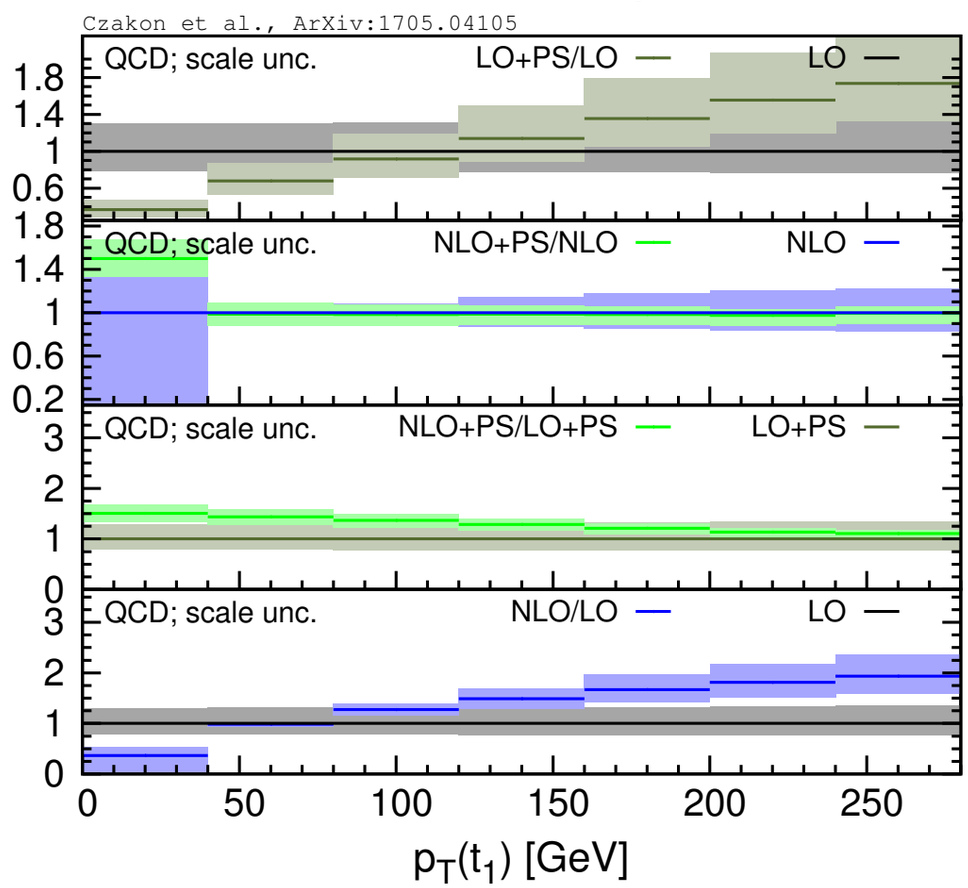
Leading-PT Top



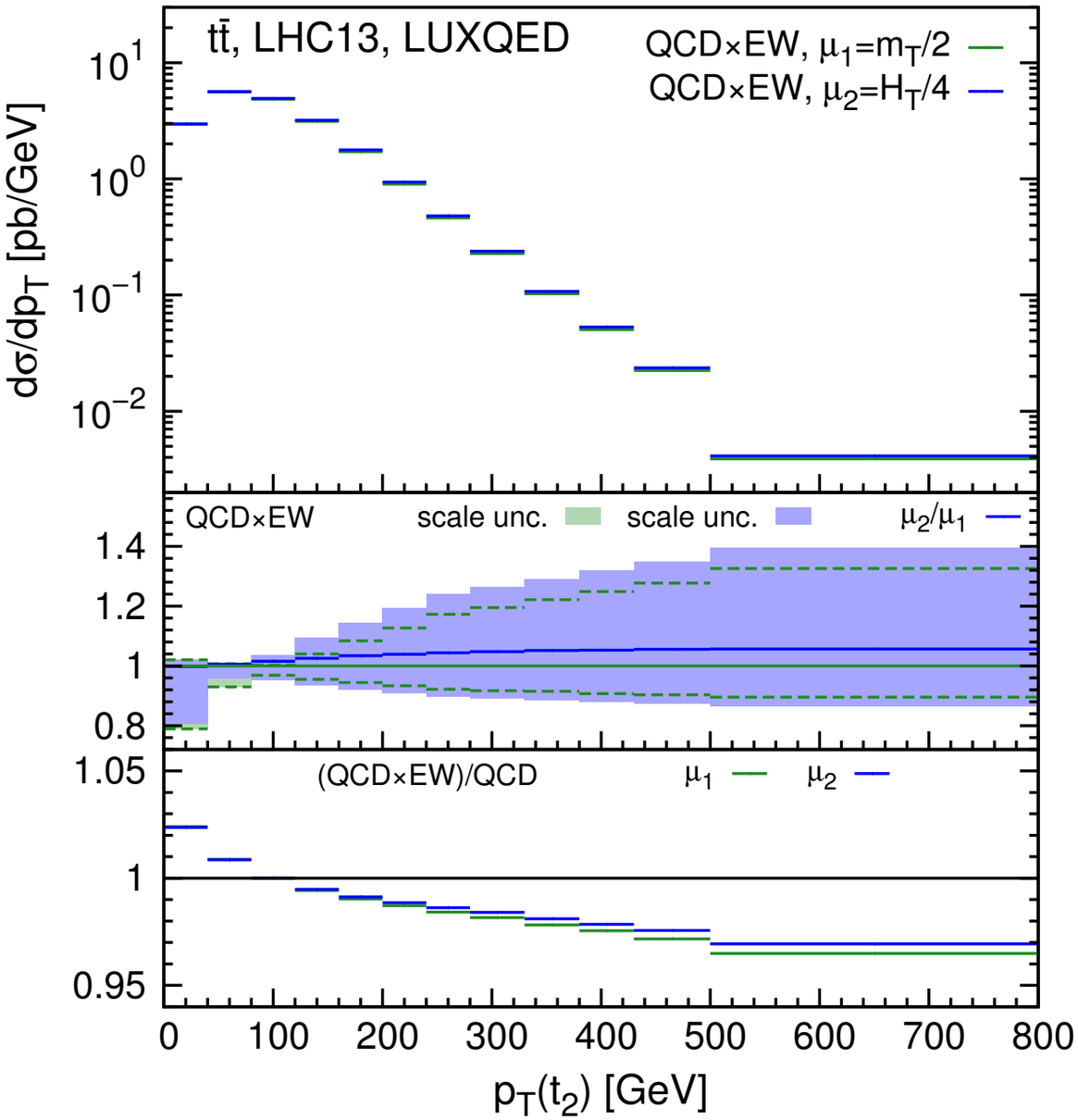


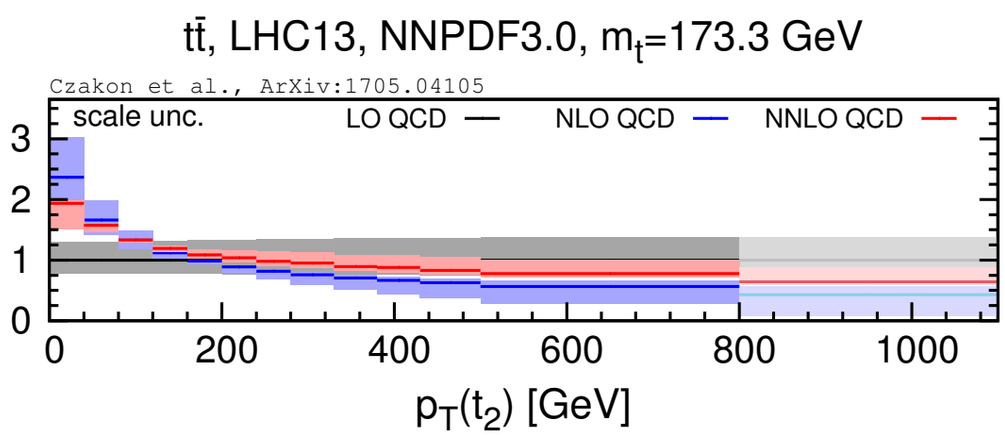


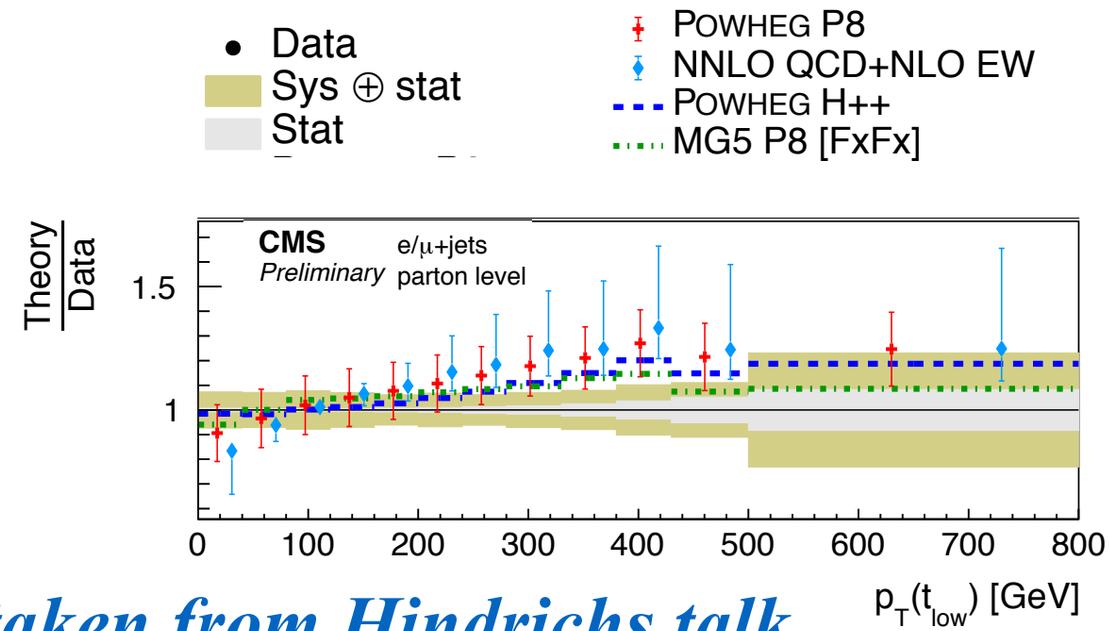
taken from Hindrichs talk Top20017



Trailing-PT Top



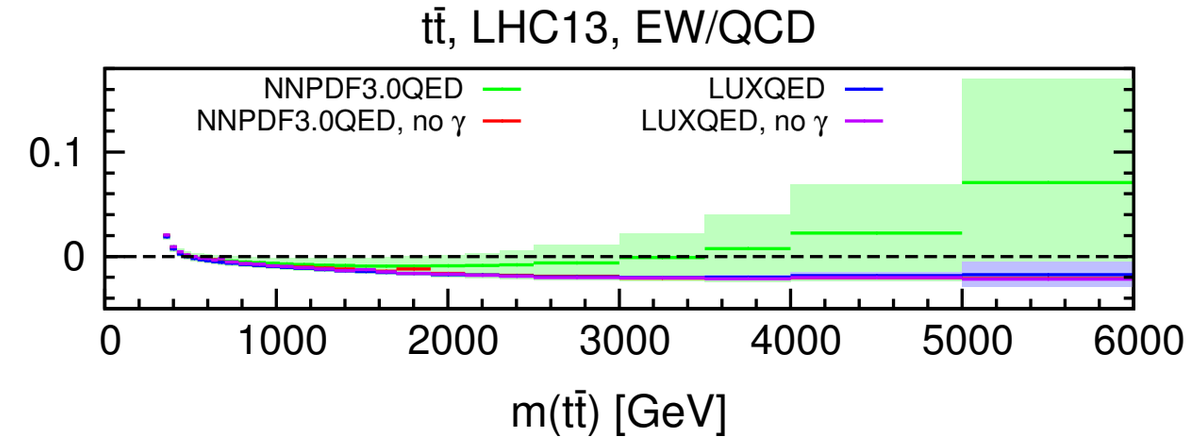


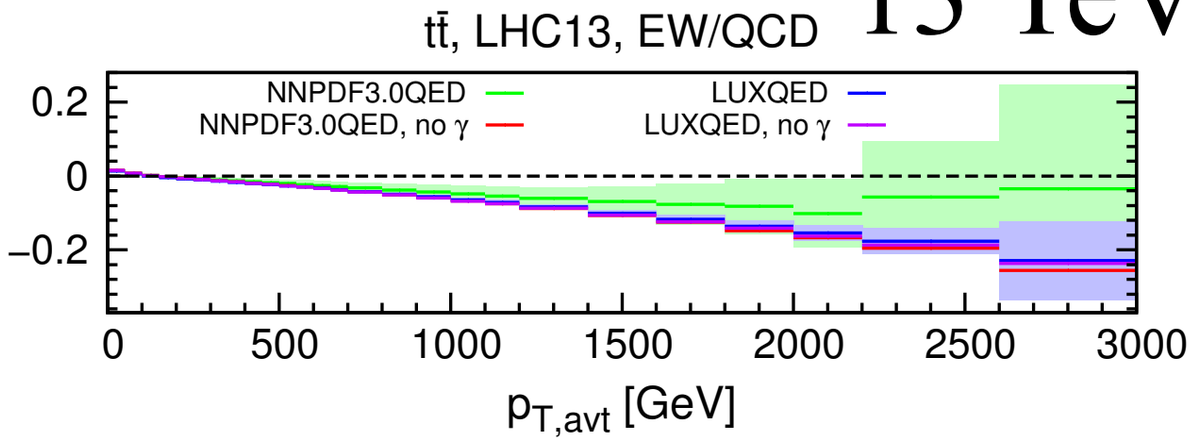


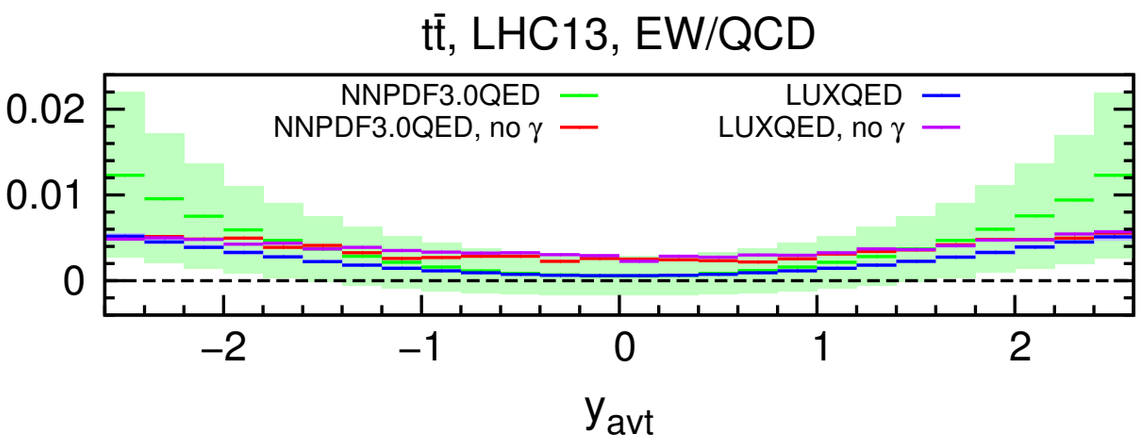
taken from Hindrichs talk Top20017

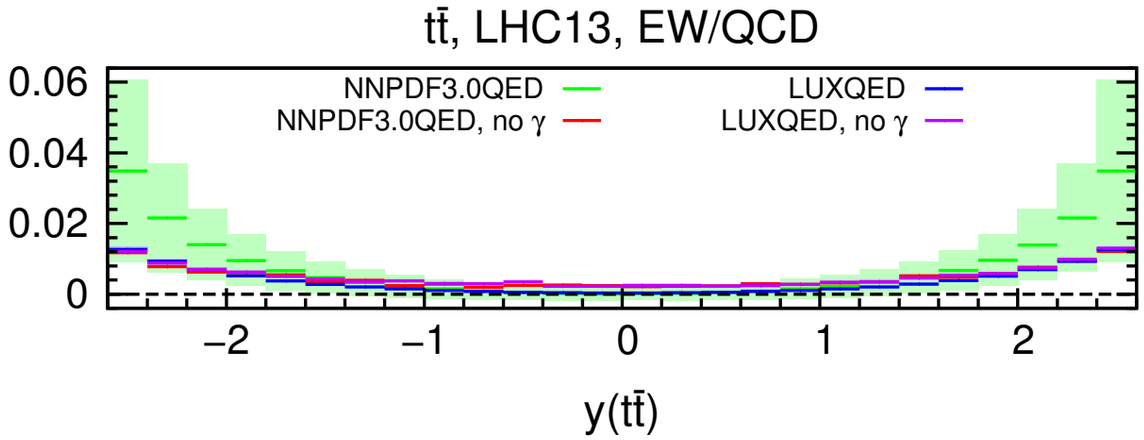
In the limit of a very hard **trailing top,** the same effects observed in the limit of very soft **leading top** are expected: **pathologies** at **fixed order.**
They are **not present** in the **average-pt** distribution.

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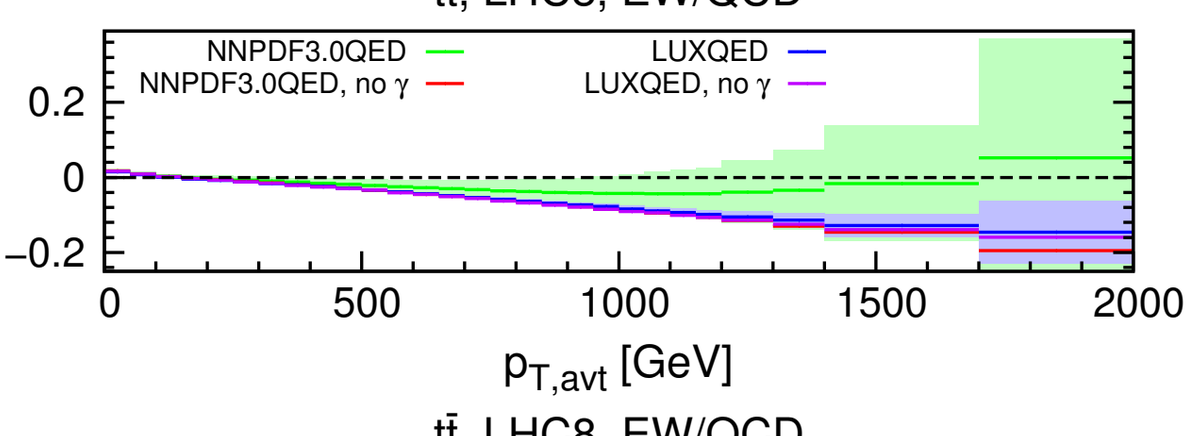
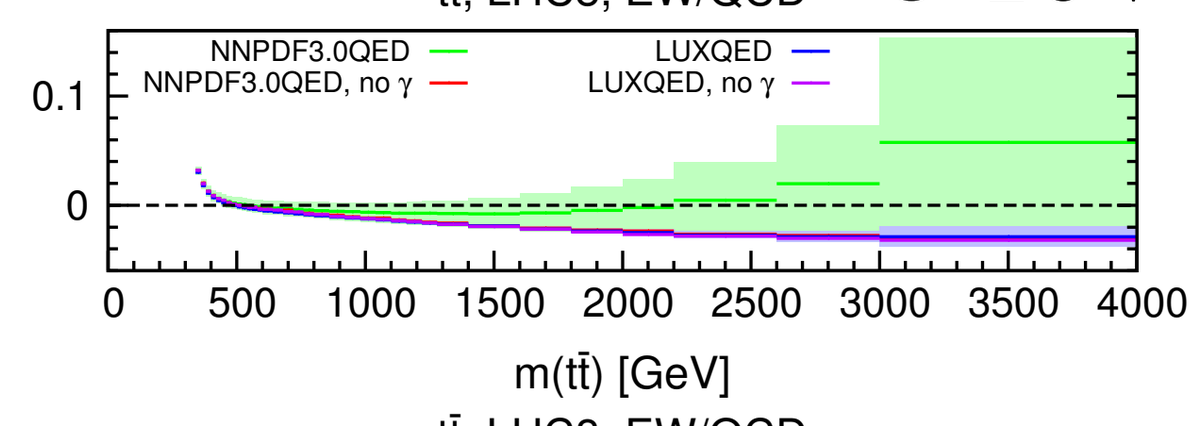
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.06
0.04
0.02
0
−2
−1
0
1
2
y(tt̄)

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
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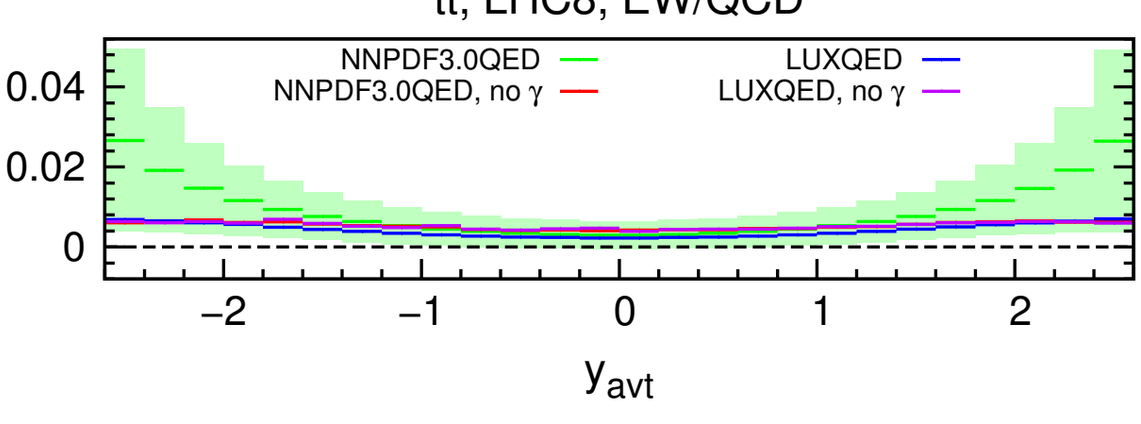
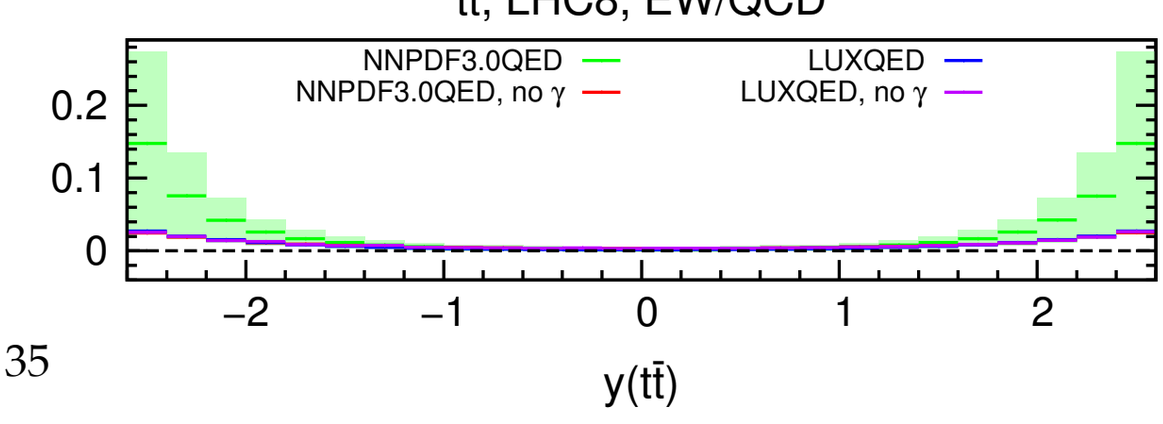
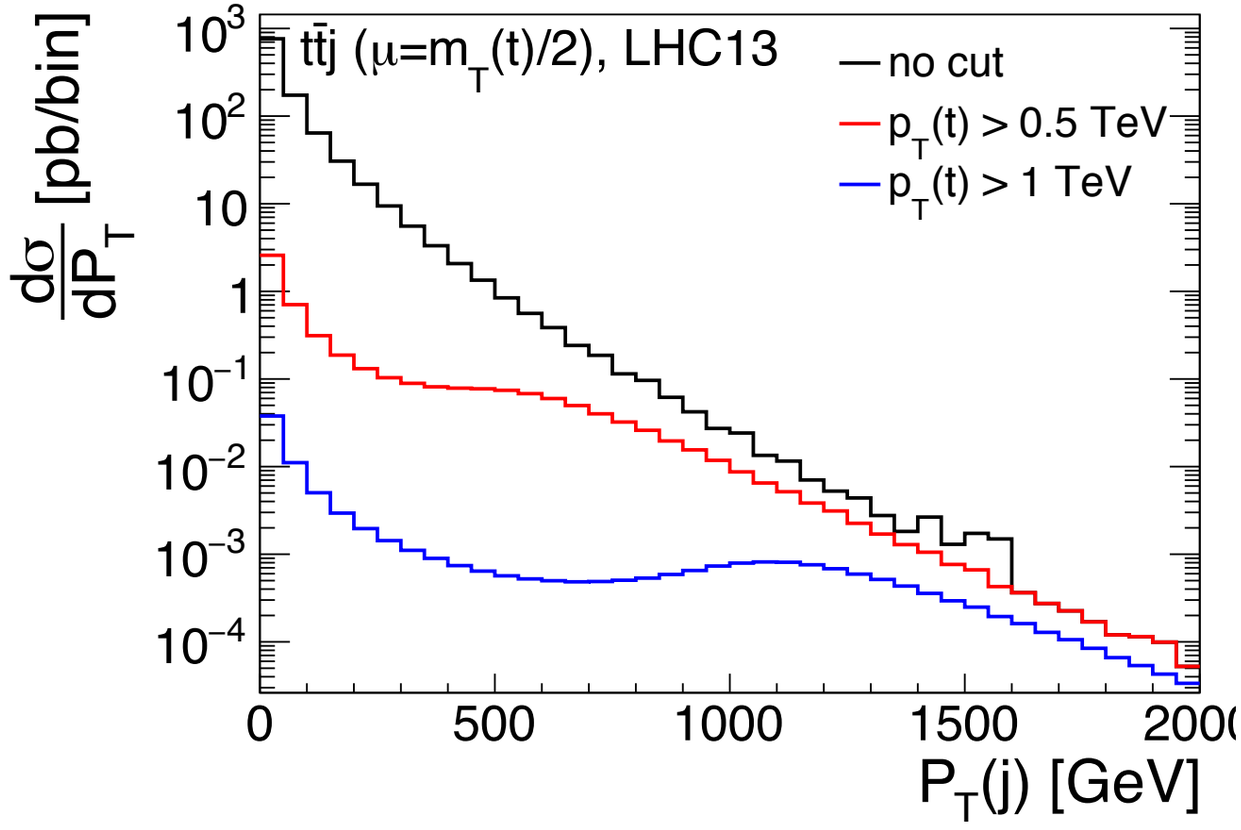
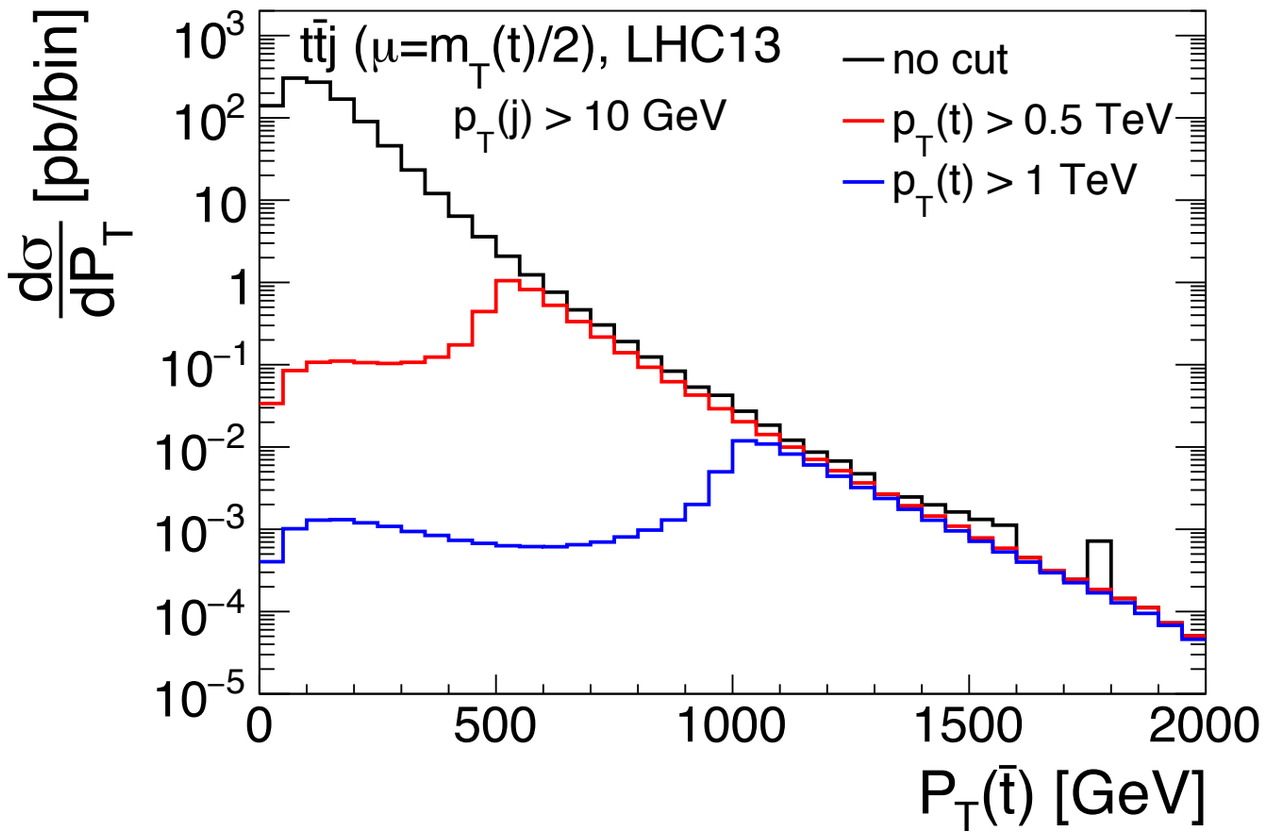
500
1000
1500
2000
2500
3000
3500
4000
m(tt̄) [GeV]


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

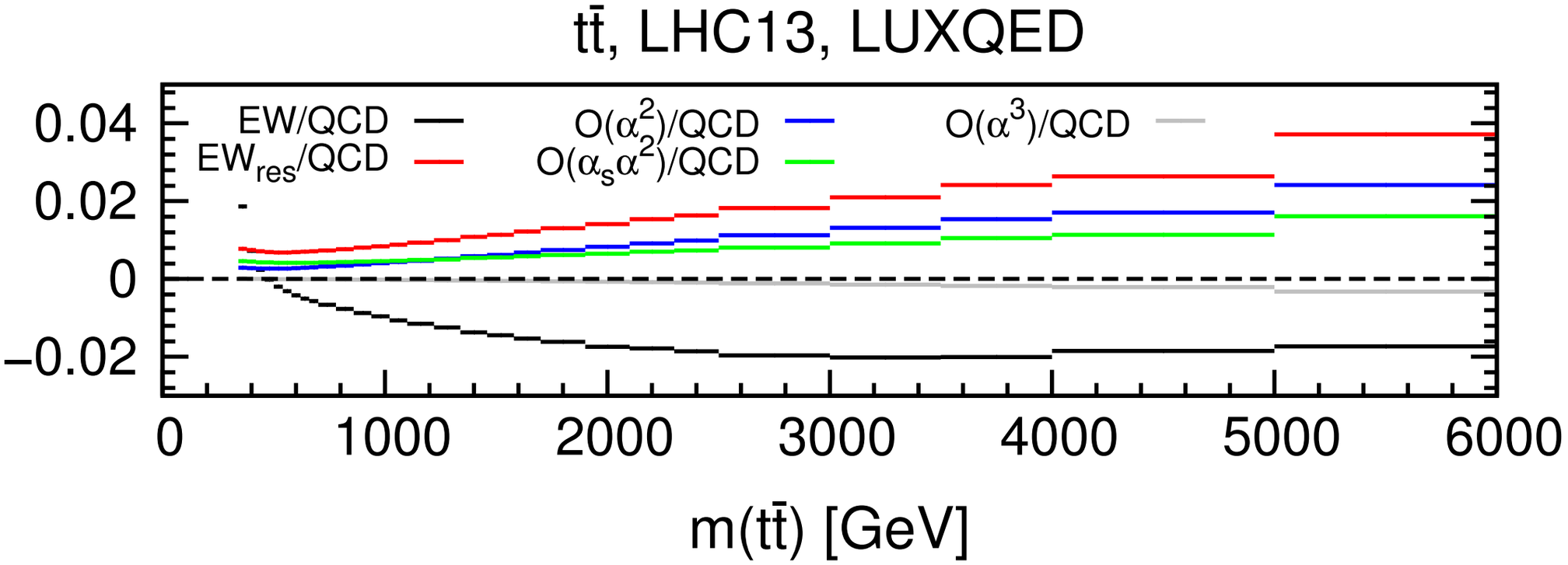

tt̄, LHC8, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.2
0.1
0
−2
−1
0
1
2
y(tt̄)

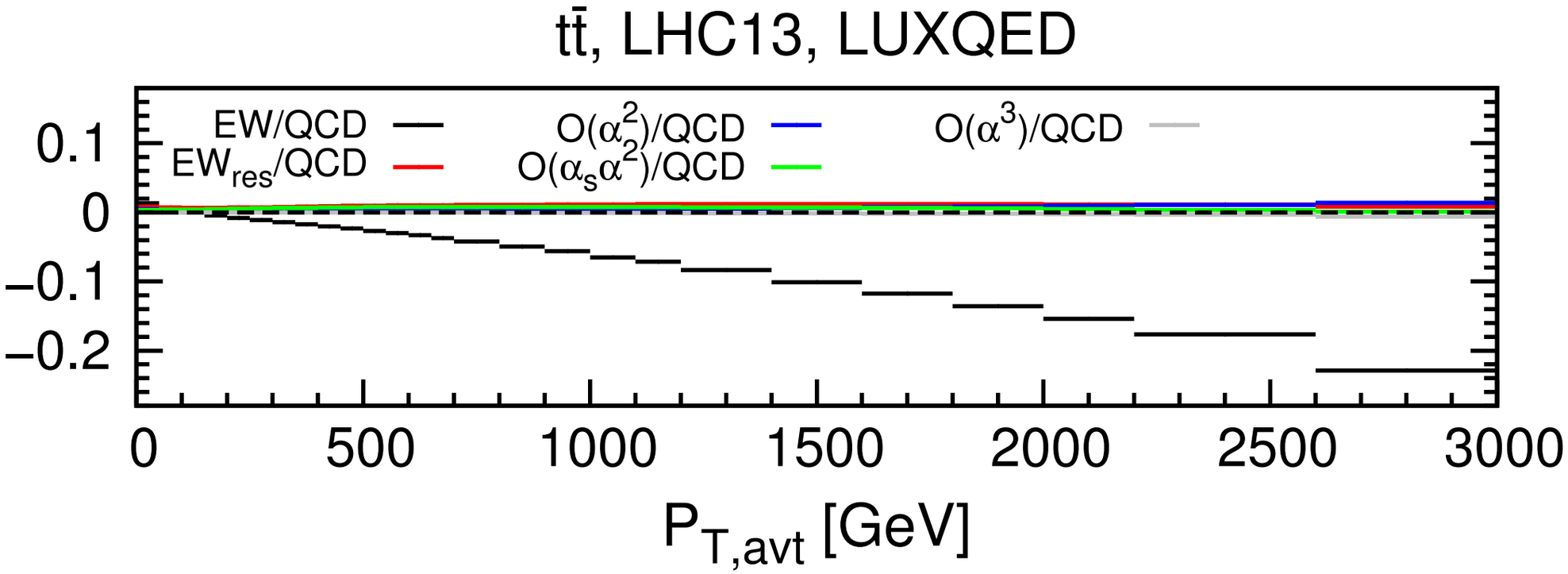
Checks EW and QCD factorisation





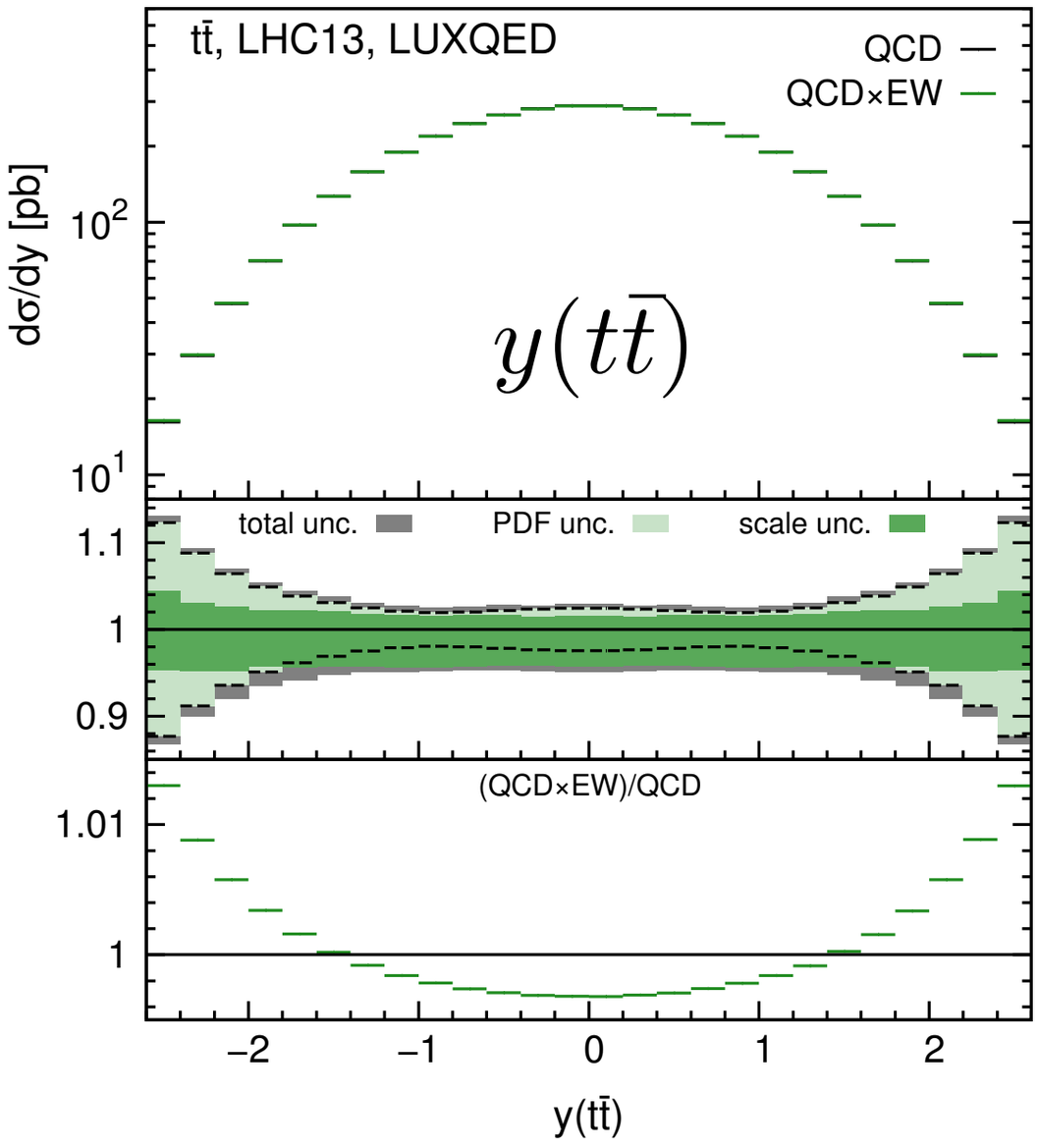
Individual subleading contributions

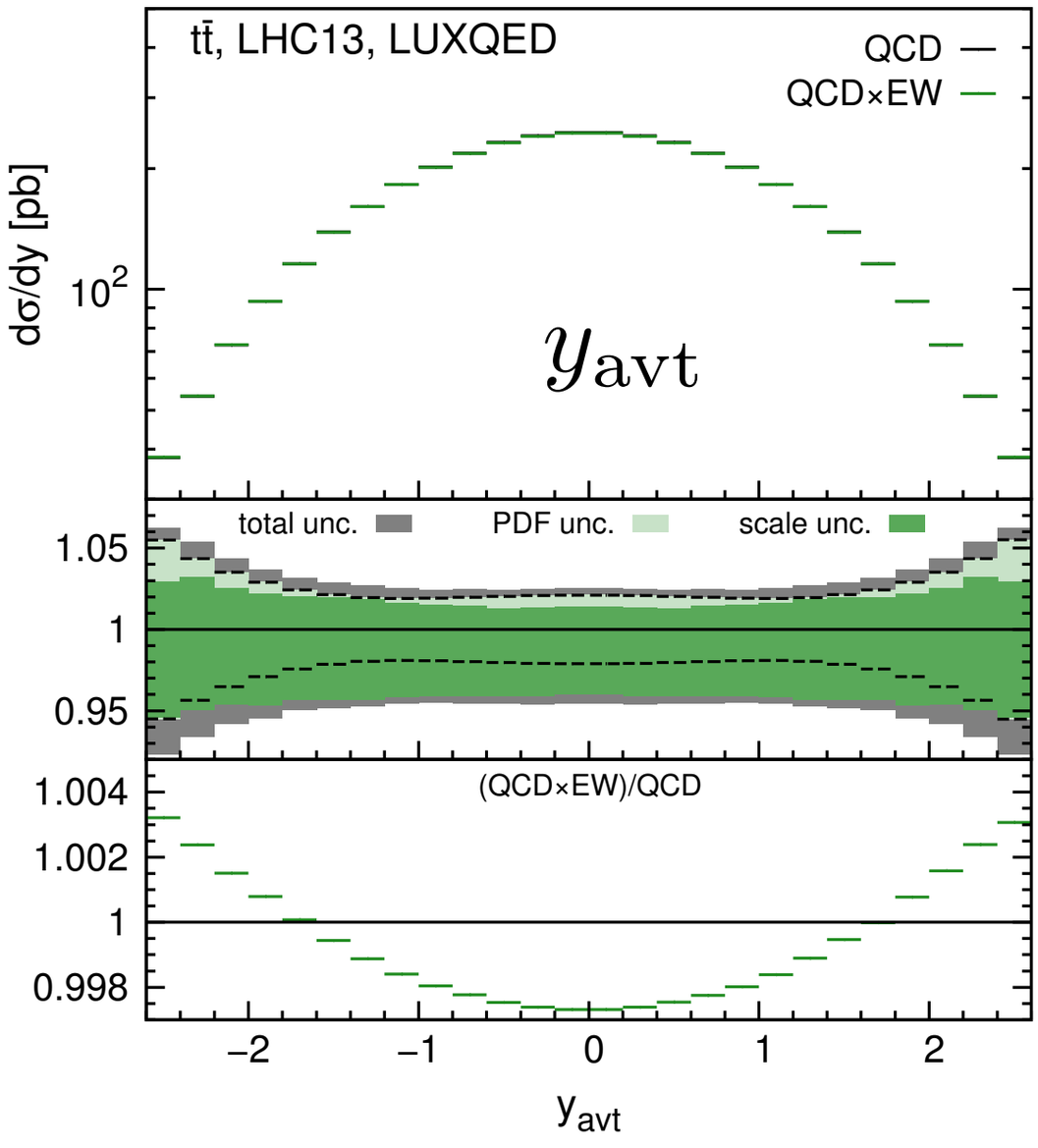




13 TeV

MULTIPLICATIVE with LUXQED



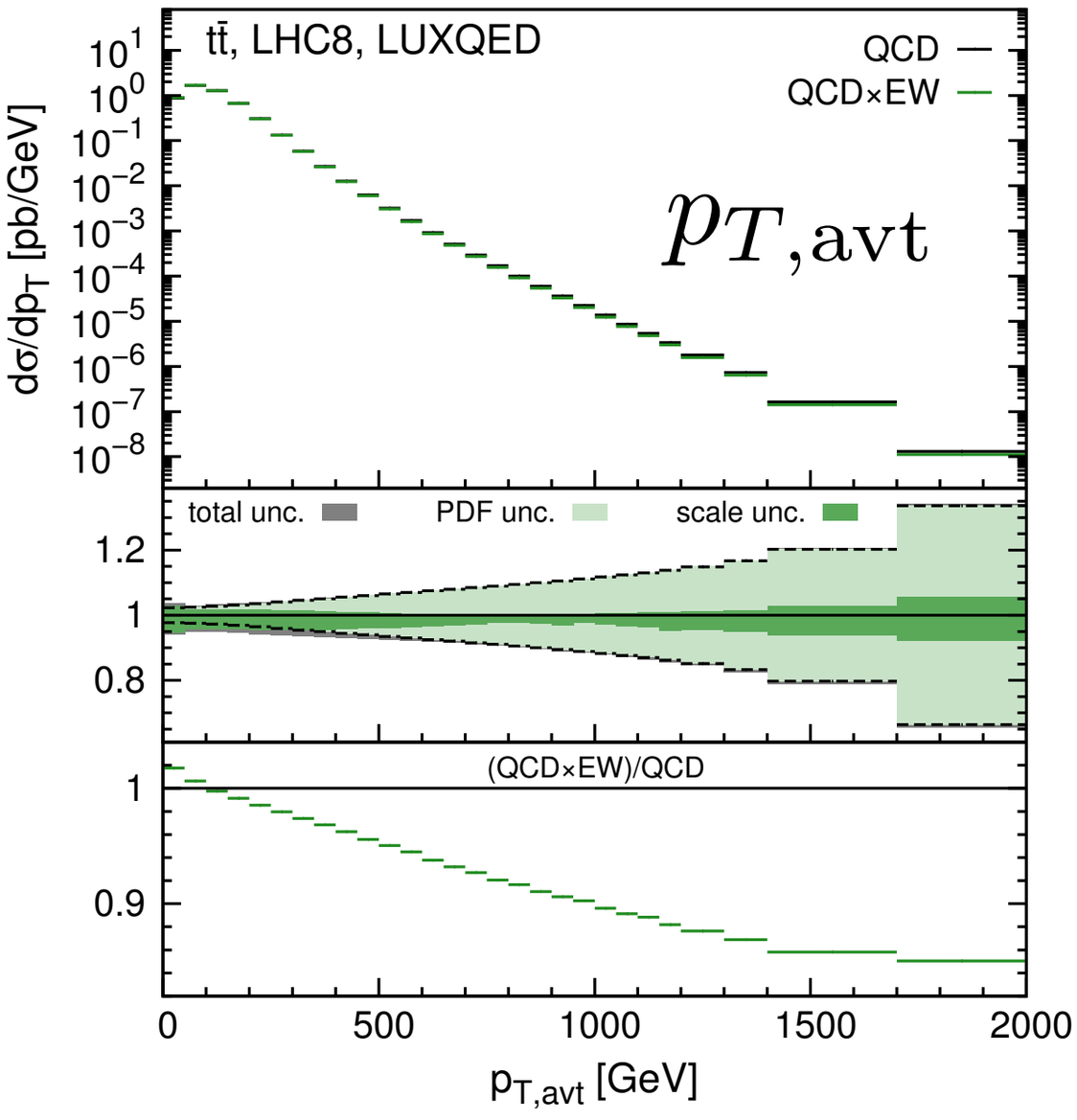


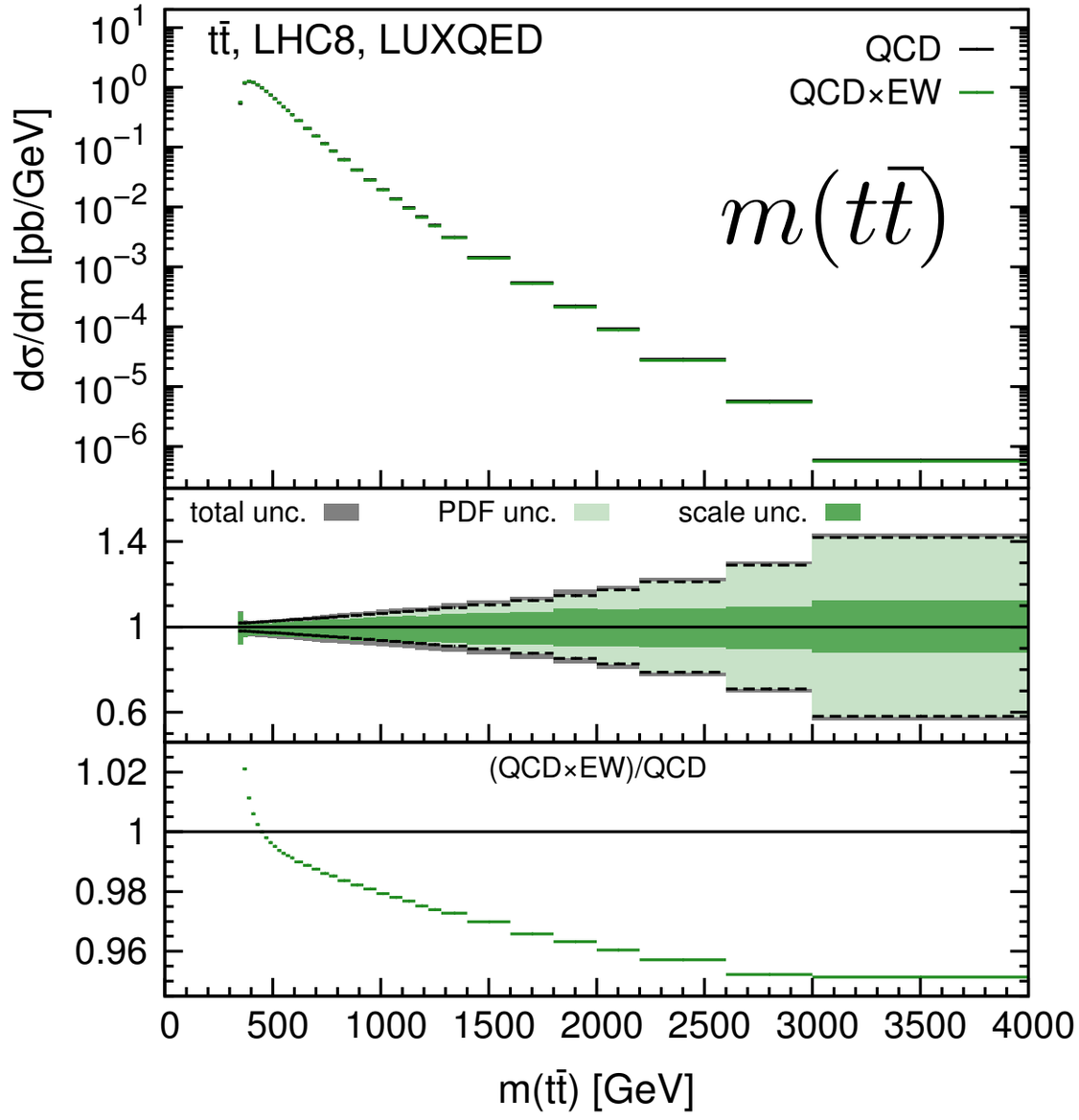
scale unc. ~ PDF unc, larger PDF unc. at large y

scale unc. ~ PDF unc,

8 TeV

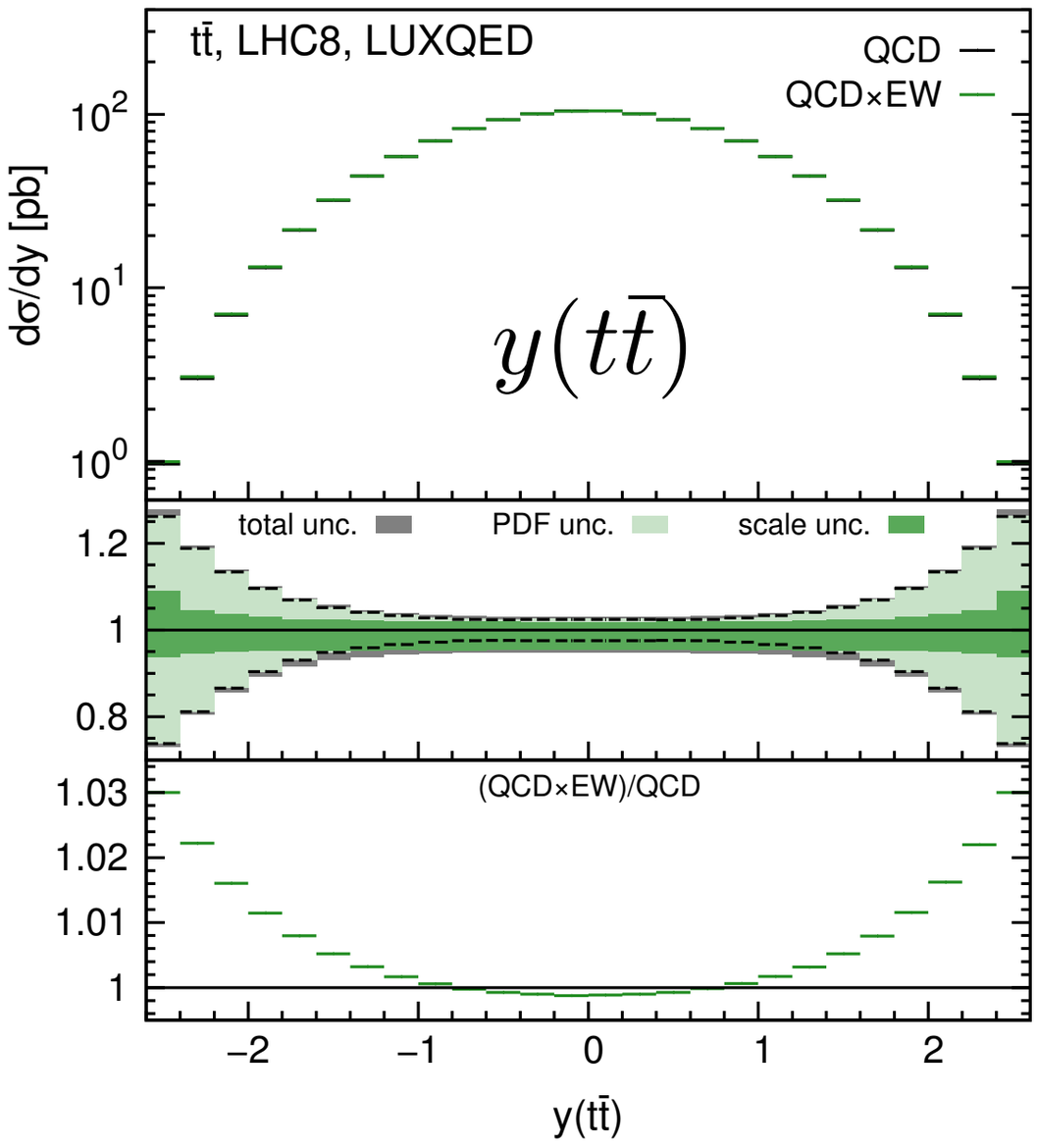
MULTIPLICATIVE with LUXQED

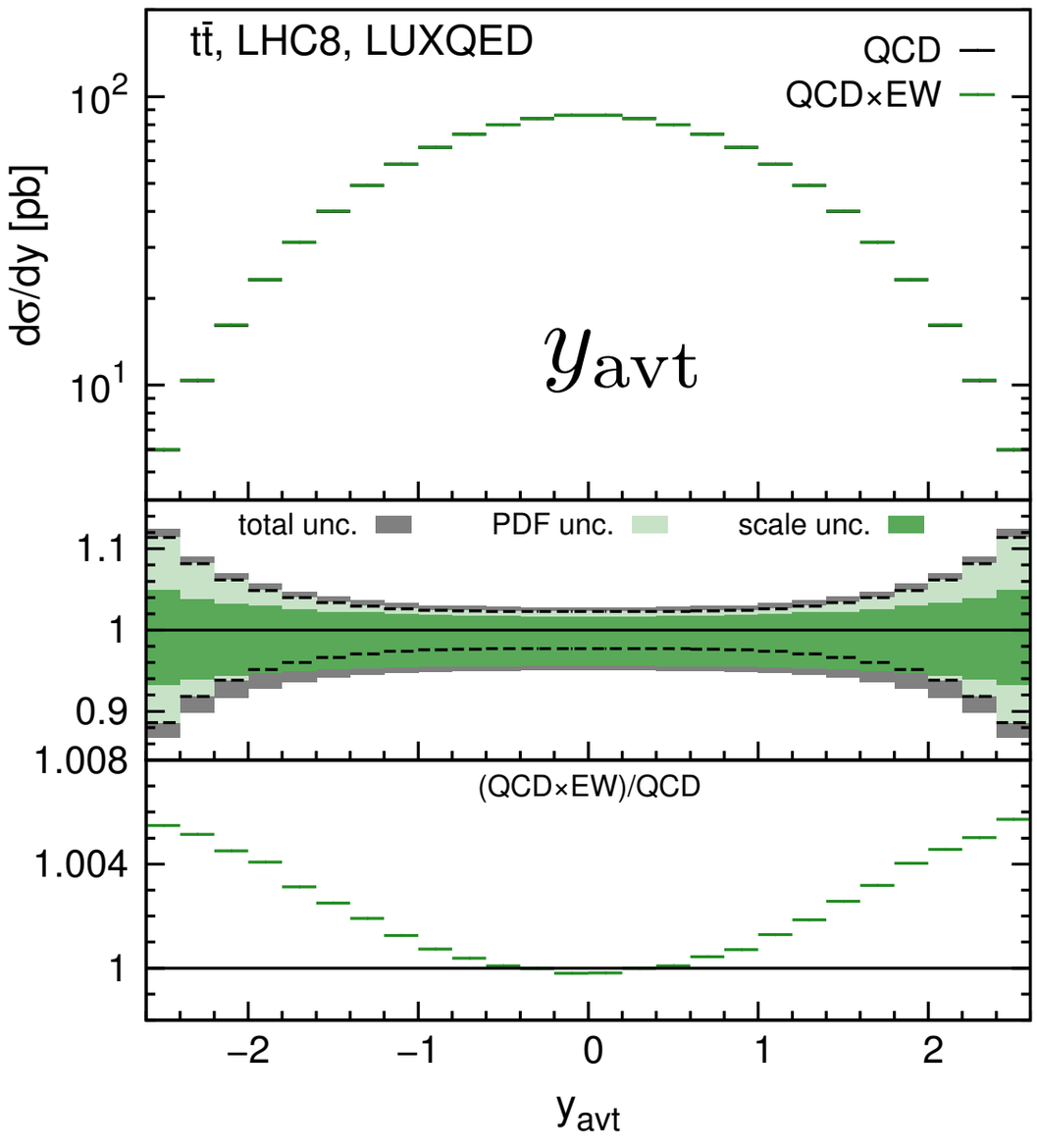




8 TeV

MULTIPLICATIVE with LUXQED

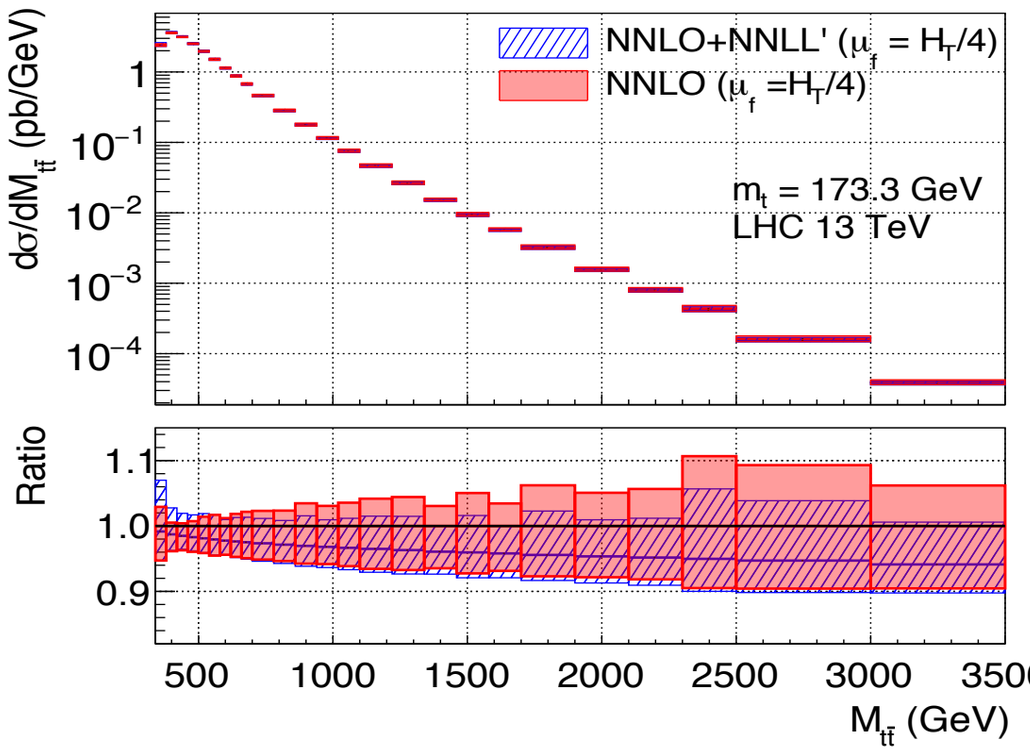


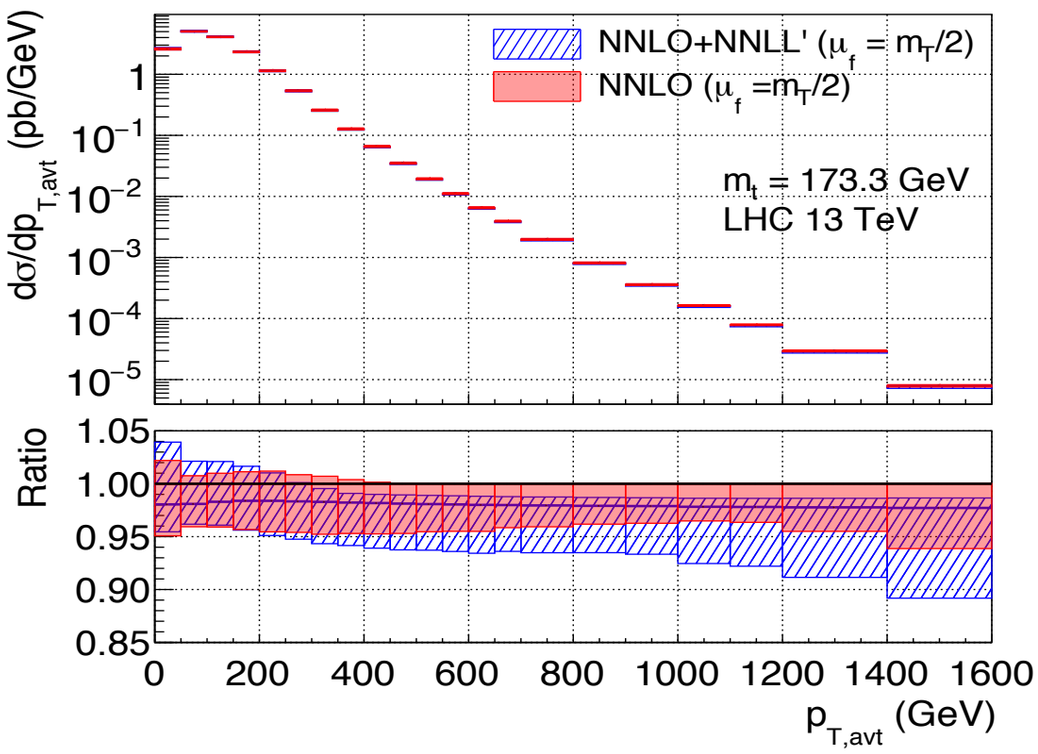


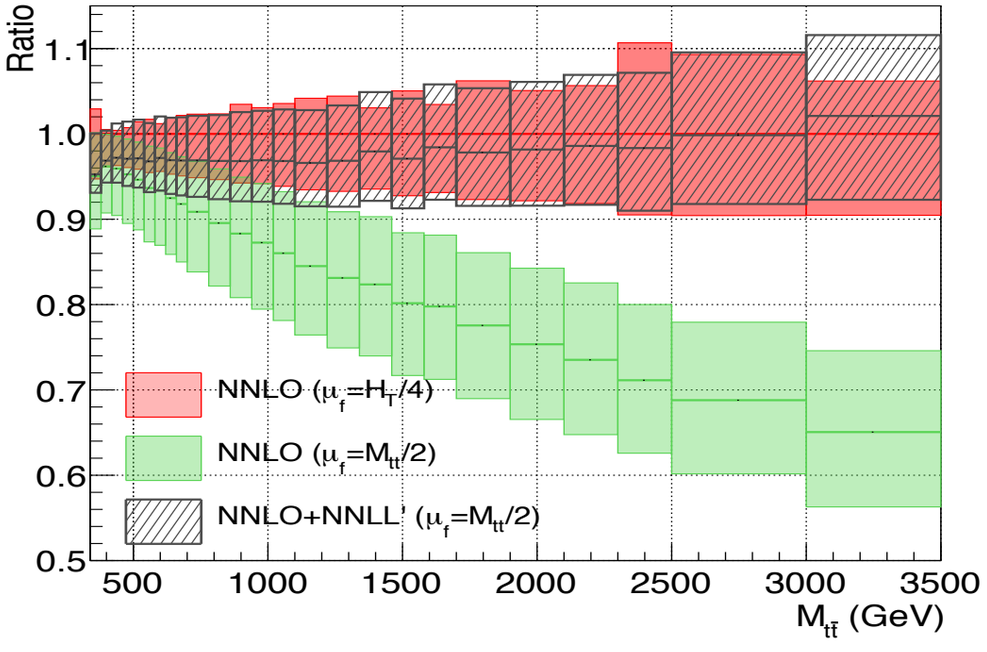
NNLO + NNLL`

NNLO matched to resummation of logs from soft gluons and quasi-collinear emissions from boosted top-quarks.

Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, Yang '18





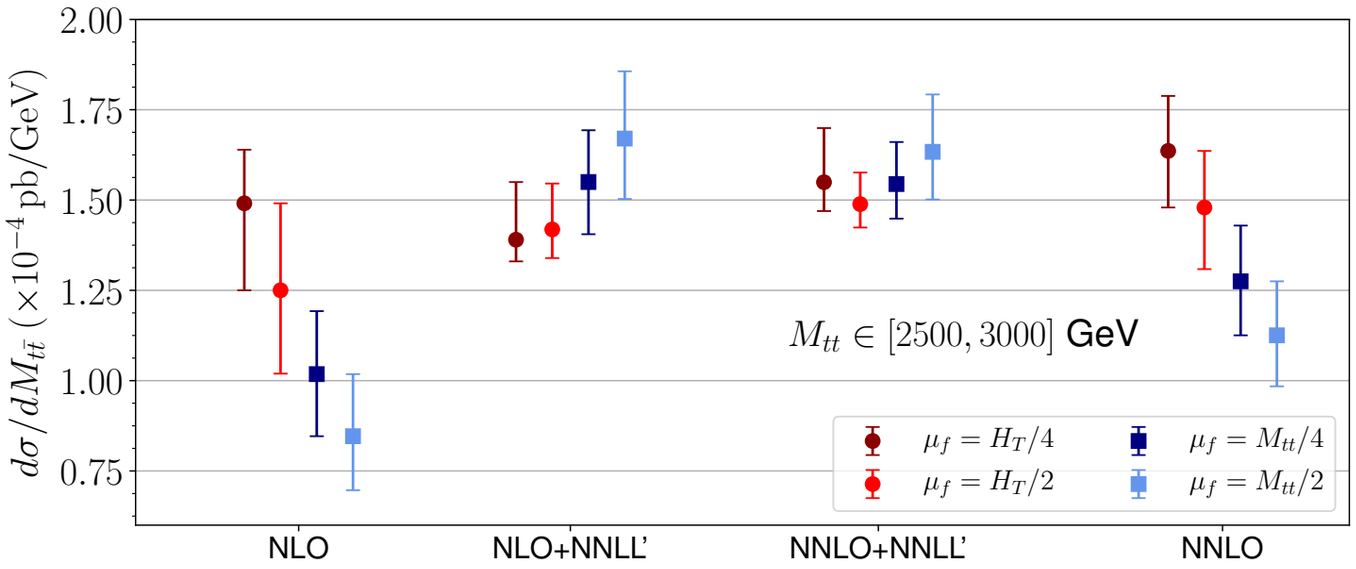


In the tail of the M_{tt} distribution the most relevant hard scale is not M_{tt} but H_T.

The consistency between NNLO and NNLO+NNLL` supports the previous scale choices.

NNLO + NNLL`

$$d\sigma^{\text{(N)NLO+NNLL}'} = d\sigma^{\text{NNLL}'_{b+m}} + \left(d\sigma^{\text{(N)NLO}} - d\sigma^{\text{NNLL}'_{b+m}}\Big|_{\substack{\text{(N)NLO} \\ \text{expansion}}} \right)$$



$\boldsymbol{M_{t\bar{t}}}$	$\mu_h = H_T/2$ and $\mu_s = H_T/\bar{N}$
$\boldsymbol{p_T}$	$\mu_h = m_T$ and $\mu_s = 2m_T/N$

Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, Yang '18

$$t\bar{t}W^{\pm}$$

Cross sections: order by order

$$\delta_{(\mathrm{N})\mathrm{LO}_i}(\mu) = \frac{\Sigma_{(\mathrm{N})\mathrm{LO}_i}(\mu)}{\Sigma_{\mathrm{LO}_{\mathrm{QCD}}}(\mu)}$$

Number in parentheses refer to the case of a jet veto $p_T(j) > 100$ GeV and $|y(j)| < 2.5$ is applied

13 TeV

$\delta[\%]$	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$
LO_2	-	-	-
LO_3	0.8	0.9	1.1
NLO_1	34.8 (7.0)	50.0 (25.7)	63.4 (42.0)
NLO_2	−4.4 (−4.8)	−4.2 (−4.6)	−4.0 (−4.4)
NLO_3	11.9 (8.9)	12.2 (9.1)	12.5 (9.3)
NLO_4	0.02 (−0.02)	0.04 (−0.02)	0.05 (−0.01)

Naive estimate

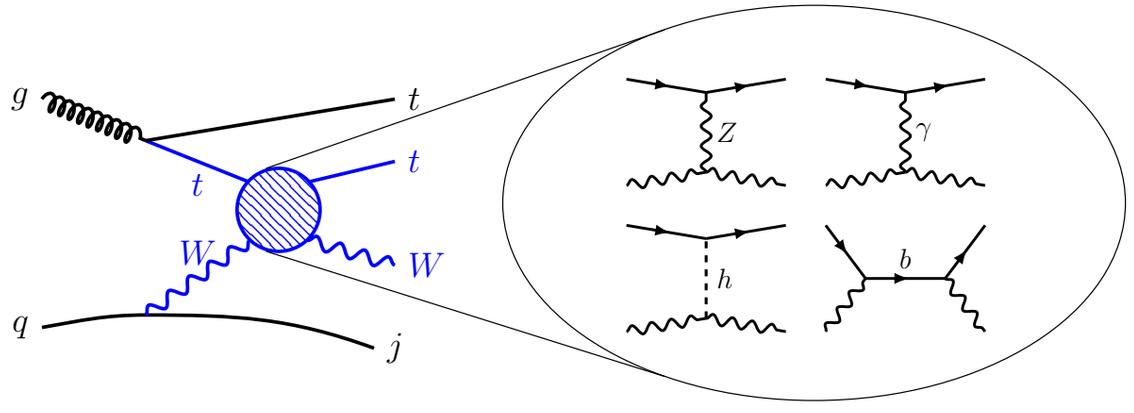
10
1
10
1
0.1
0.01

100 TeV

$\delta[\%]$	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$
LO_2	-	-	-
LO_3	0.9	1.1	1.3
NLO_1	159.5 (69.8)	149.5 (71.1)	142.7 (73.4)
NLO_2	−5.8 (−6.4)	−5.6 (−6.2)	−5.4 (−6.1)
NLO_3	67.5 (55.6)	68.8 (56.6)	70.0 (57.6)
NLO_4	0.2 (0.1)	0.2 (0.2)	0.3 (0.2)

NLO_3 is large and it is not suppressed by the jet veto (number in parentheses) as much as NLO QCD corrections.

NLO QCD corrections depend on the scale, while NLO EW and NLO_3 do not.



Frederix, DP, Zaro '17

$t\bar{t}t\bar{t}$

Cross sections

Naive estimate

13 TeV

$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-26.0	-28.3	-30.5
LO_3	32.6	39.0	45.9
LO_4	0.2	0.3	0.4
LO_5	0.02	0.03	0.05
NLO_1	14.0	62.7	103.5
NLO_2	8.6	-3.3	-15.1
NLO_3	-10.3	1.8	16.1
NLO_4	2.3	2.8	3.6
NLO_5	0.12	0.16	0.19
NLO_6	< 0.01	< 0.01	< 0.01
$NLO_2 + NLO_3$	-1.7	-1.6	0.9

10
1
0.1
0.01
10
1
0.1
0.01
0.001
0.0001

100 TeV

$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-18.7	-20.7	-22.8
LO_3	26.3	31.8	37.8
LO_4	0.05	0.07	0.09
LO_5	0.03	0.05	0.08
NLO_1	33.9	68.2	98.0
NLO_2	-0.3	-5.7	-11.6
NLO_3	-3.9	1.7	8.9
NLO_4	0.7	0.9	1.2
NLO_5	0.12	0.14	0.16
NLO_6	< 0.01	< 0.01	< 0.01
$NLO_2 + NLO_3$	-4.2	-4.0	2.7

Frederix, DP, Zaro '17

LO_2 and LO_3 are large and have also large cancellations.

NLO_2 and NLO_3 are mainly given by 'QCD corrections' on top of them, so they are large and strongly depend on the scale choice, at variance with standard EW corrections.

Accidentally, relatively to LO_1 , NLO_2+NLO_3 scale dependence almost disappear.

What happens if BSM enters into the game? Anomalous y_t ?