Multi-jet merged top-pair production including EW corrections¶

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IP3

Top Quark Physics at the Precision Frontier
Fermilab, 16.05.19

Top quark p_T

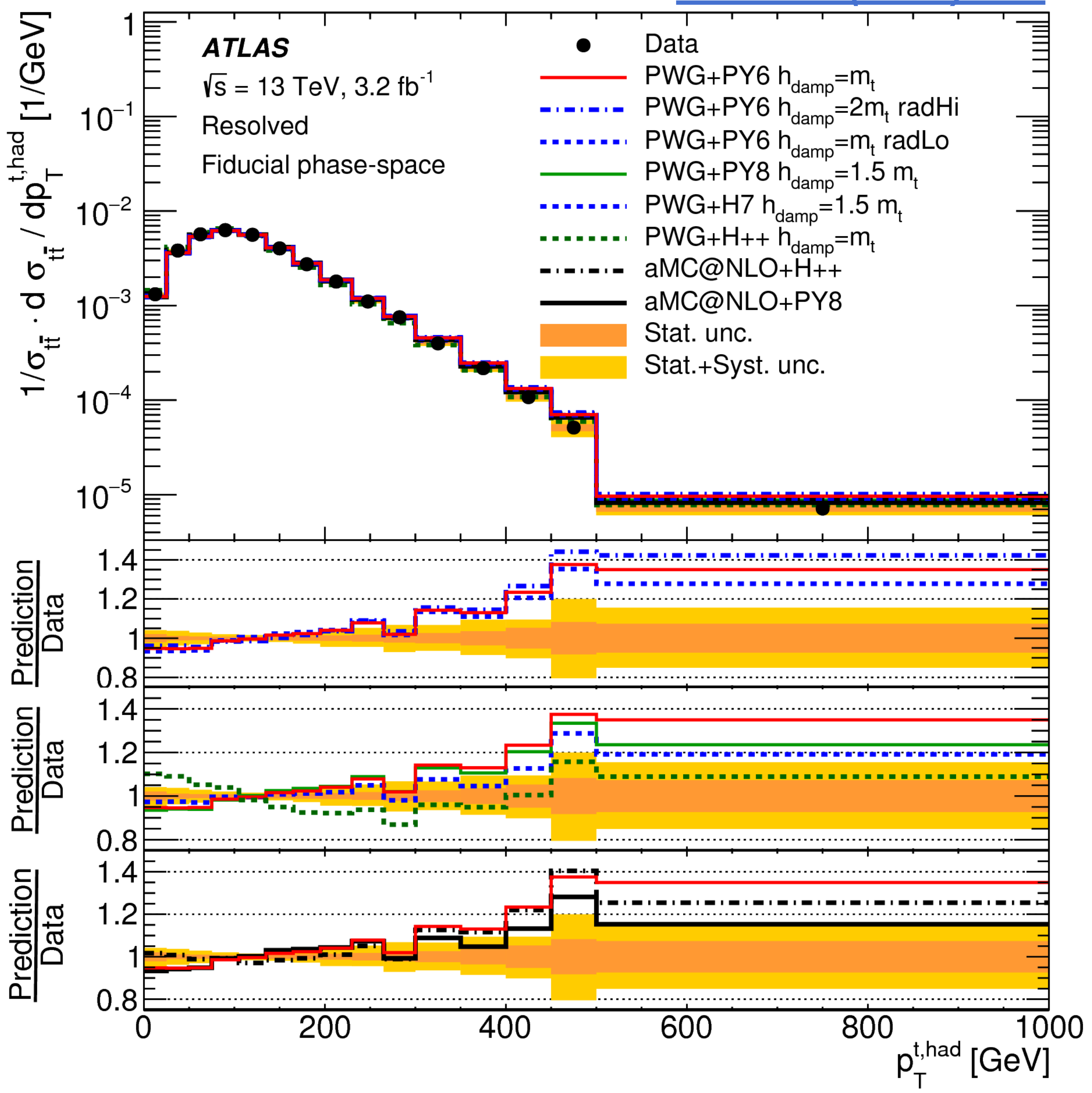
"the devil is in the tails"

[Yesterday's talk
by Riccardo Di Sipio]

Hadronic top
(single lepton channel)

Leptonic top
(dilepton channel)

JHEP 11 (2017) 191



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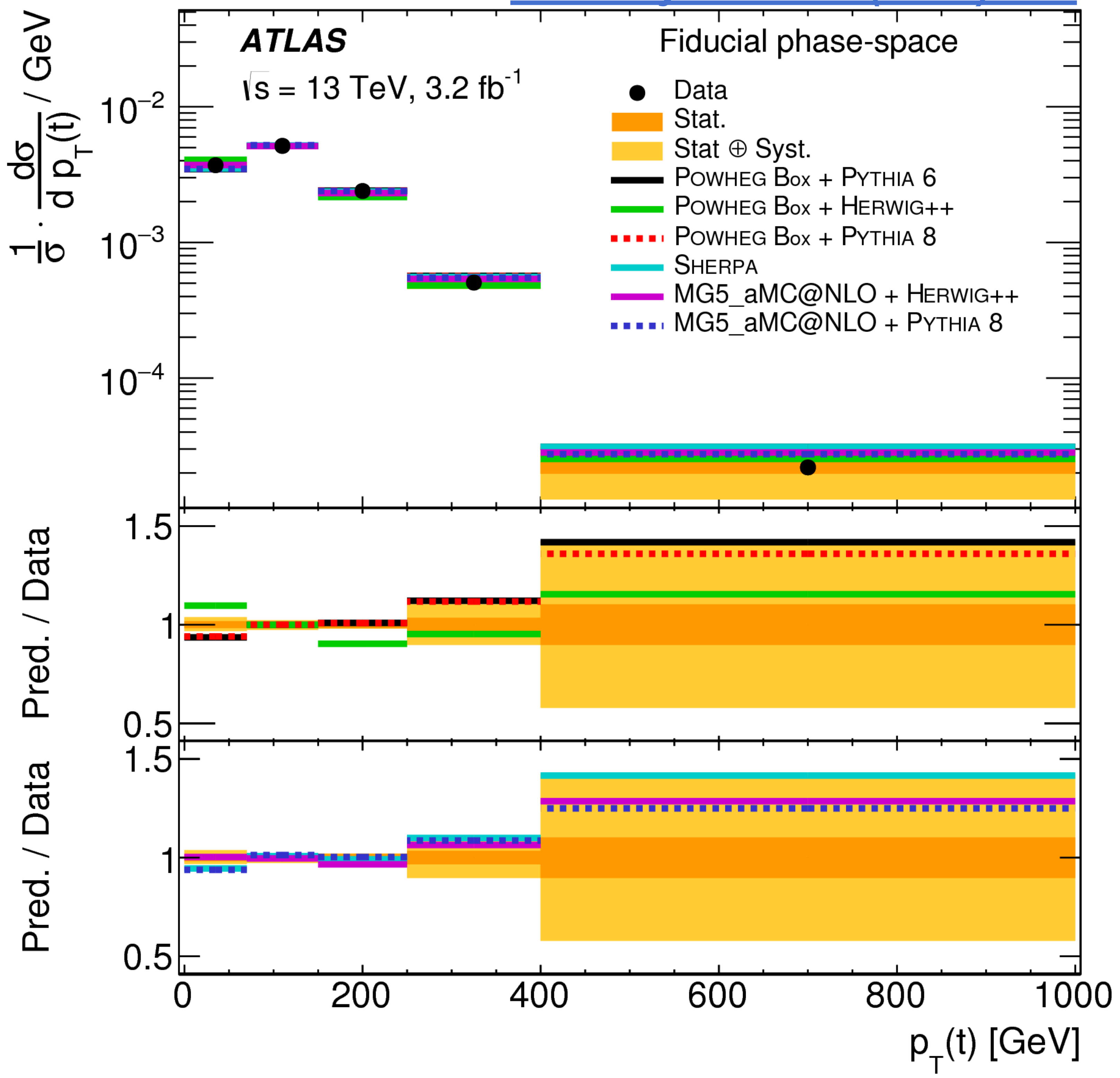
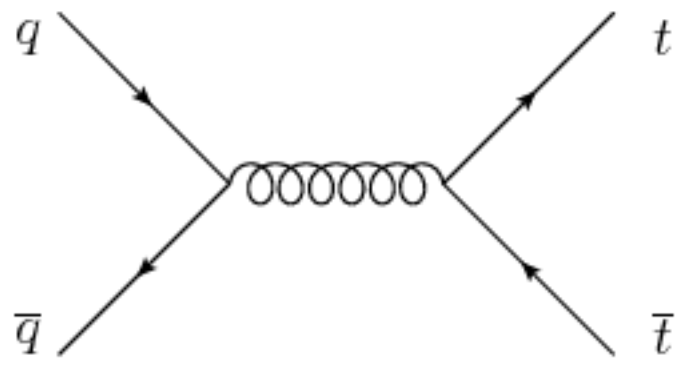


Upshot:

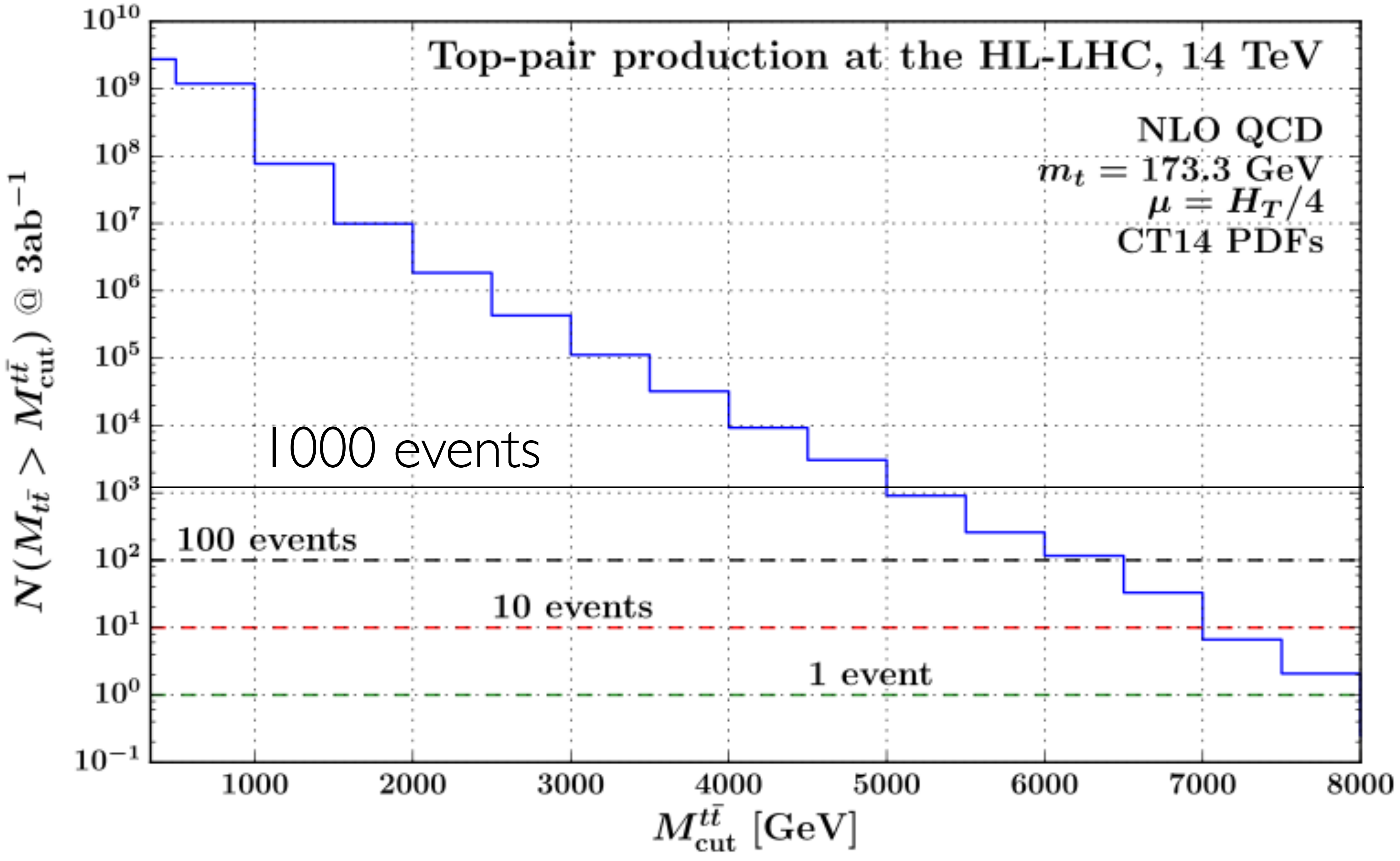
NNLO QCD + NLO EW corrections important
But do not fully explain discrepancy

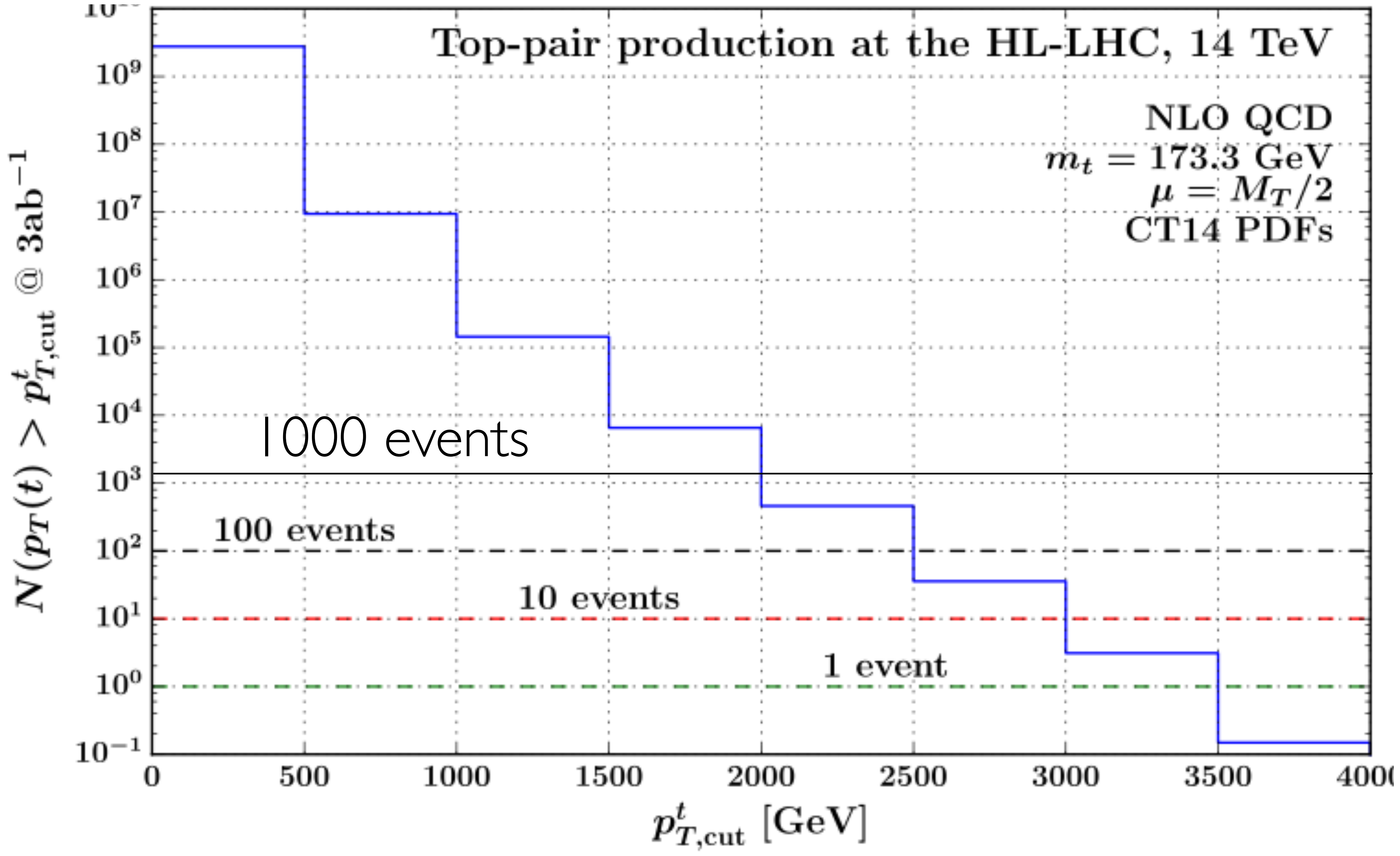
Tails of Tops



(b)

[M. Zaro, HL/HE LHC workshop, June 2018]



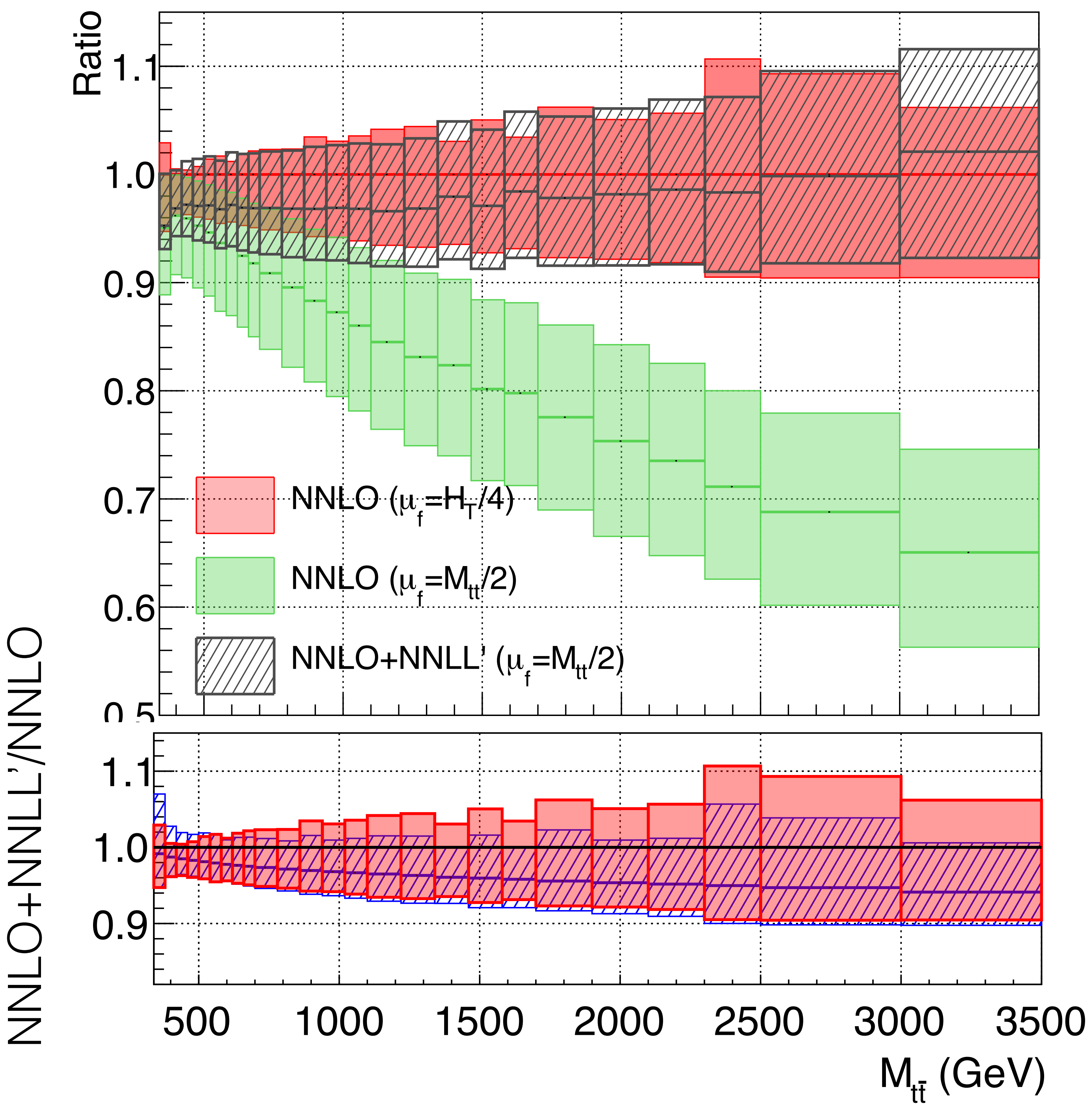


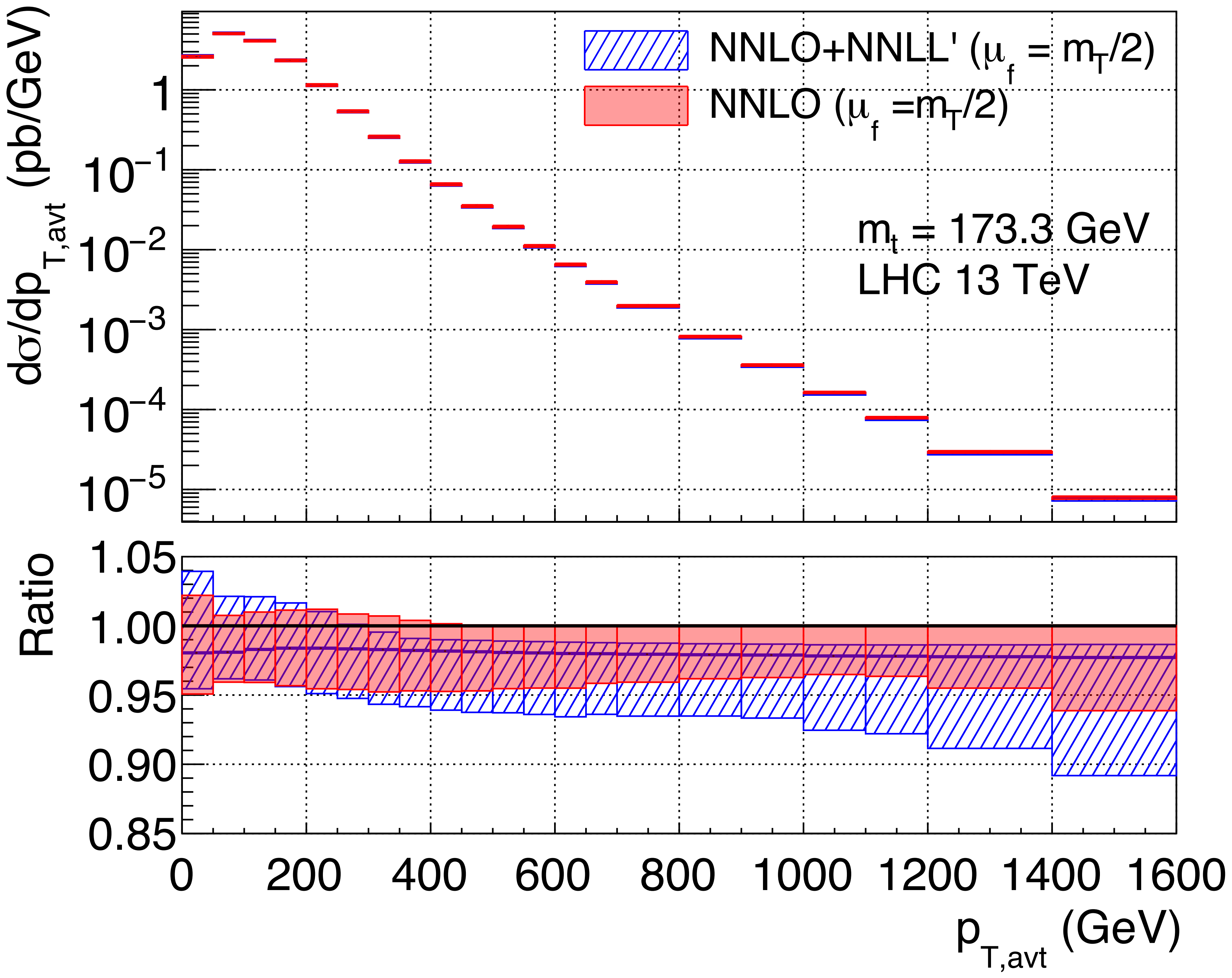
- 1-10% precision for M_{tt}=5000-6000 GeV
- 1-10% precision for pT_{top}=2000-2500 GeV

QCD precision for top tails

- 1-10% precision for M_{tt}=5000-6000 GeV
- 1-10% precision for pT_{top}=2000-2500 GeV

NNLO+NNLL′ for top-pair production [Czakon et. al.,'18]

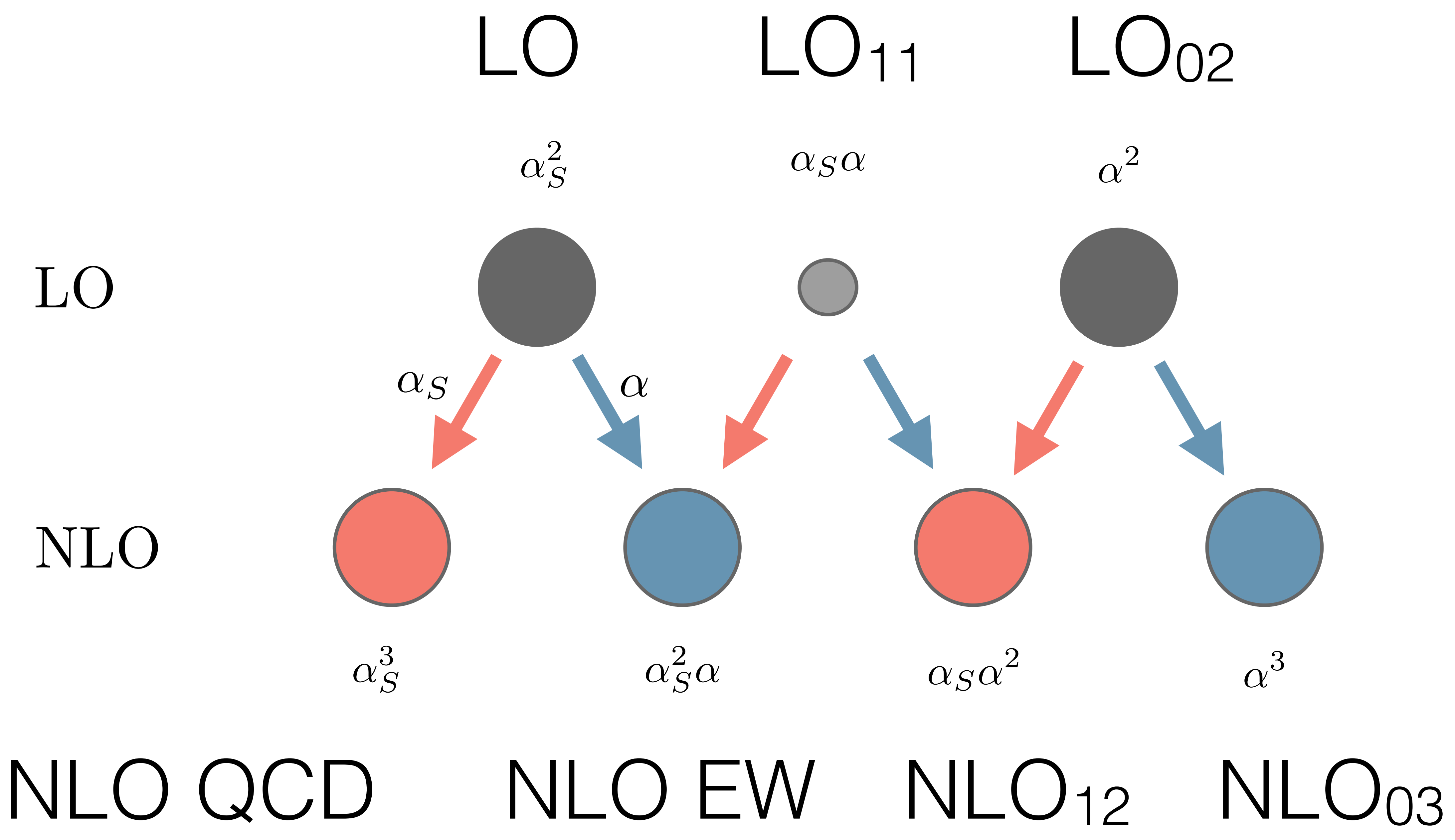




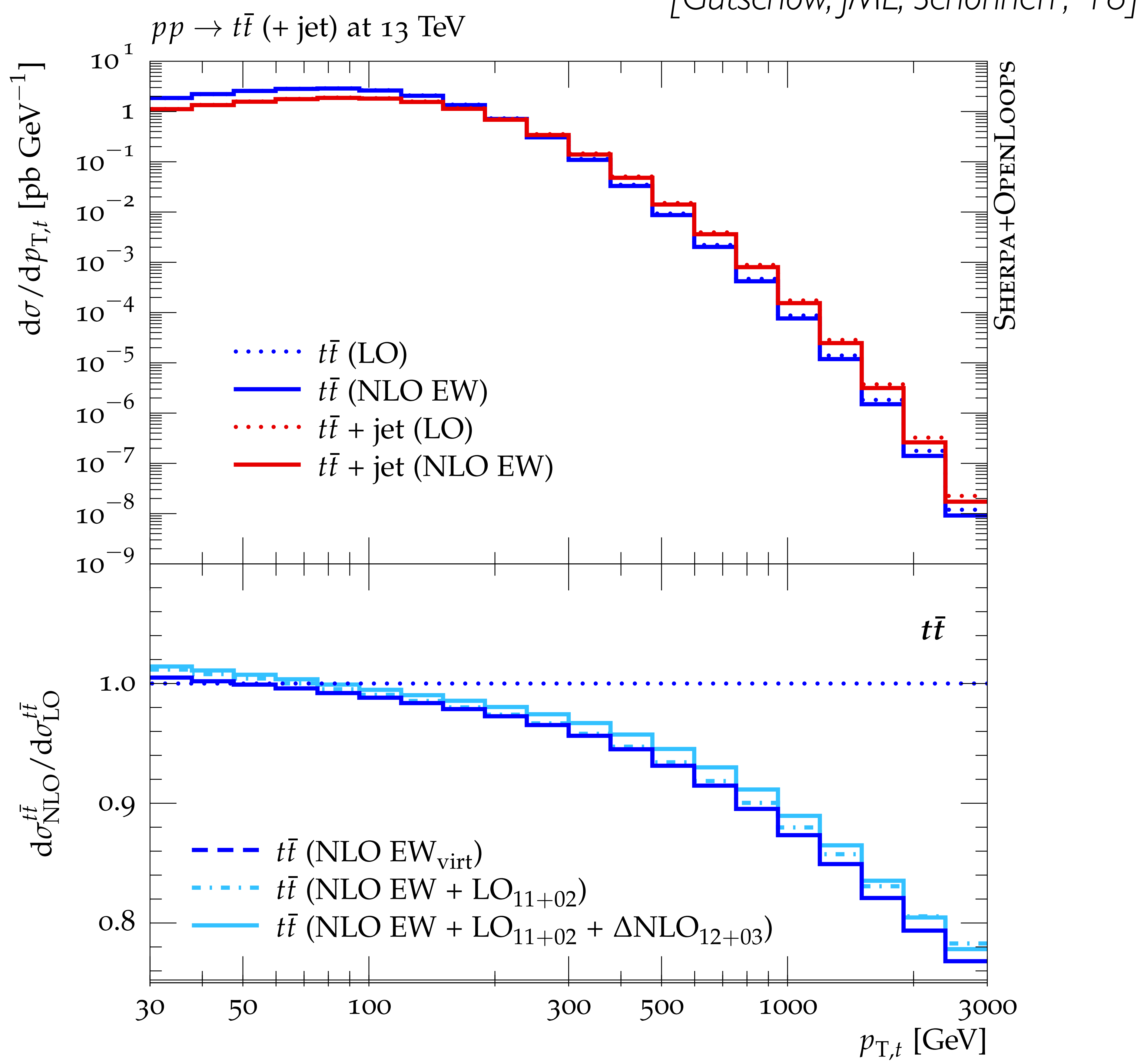
- most relevant hard scale is not M_{tt} itself but rather H_T
- remaining scale uncertainties at the level of 5%

- remaining scale uncertainties in the tail at the level of 5-10%

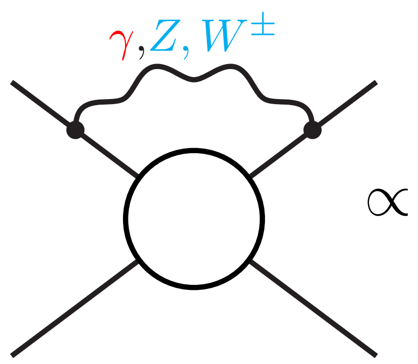
EW corrections for top-pair production



[Gütschow, JML, Schönherr; '18]



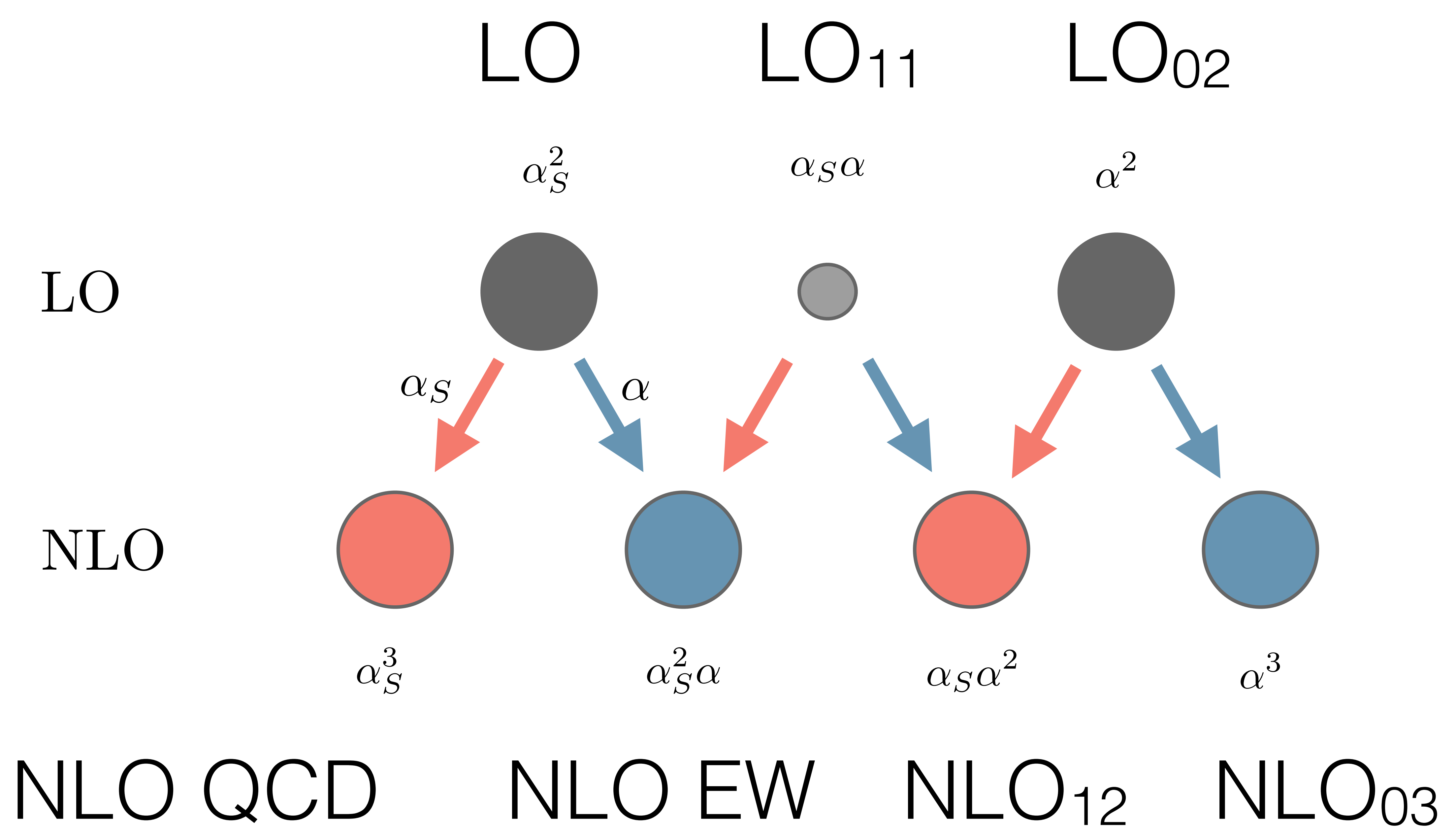
Origin: soft/collinear logs from virtual EW gauge boson (EW **Sudakov logarithms**)



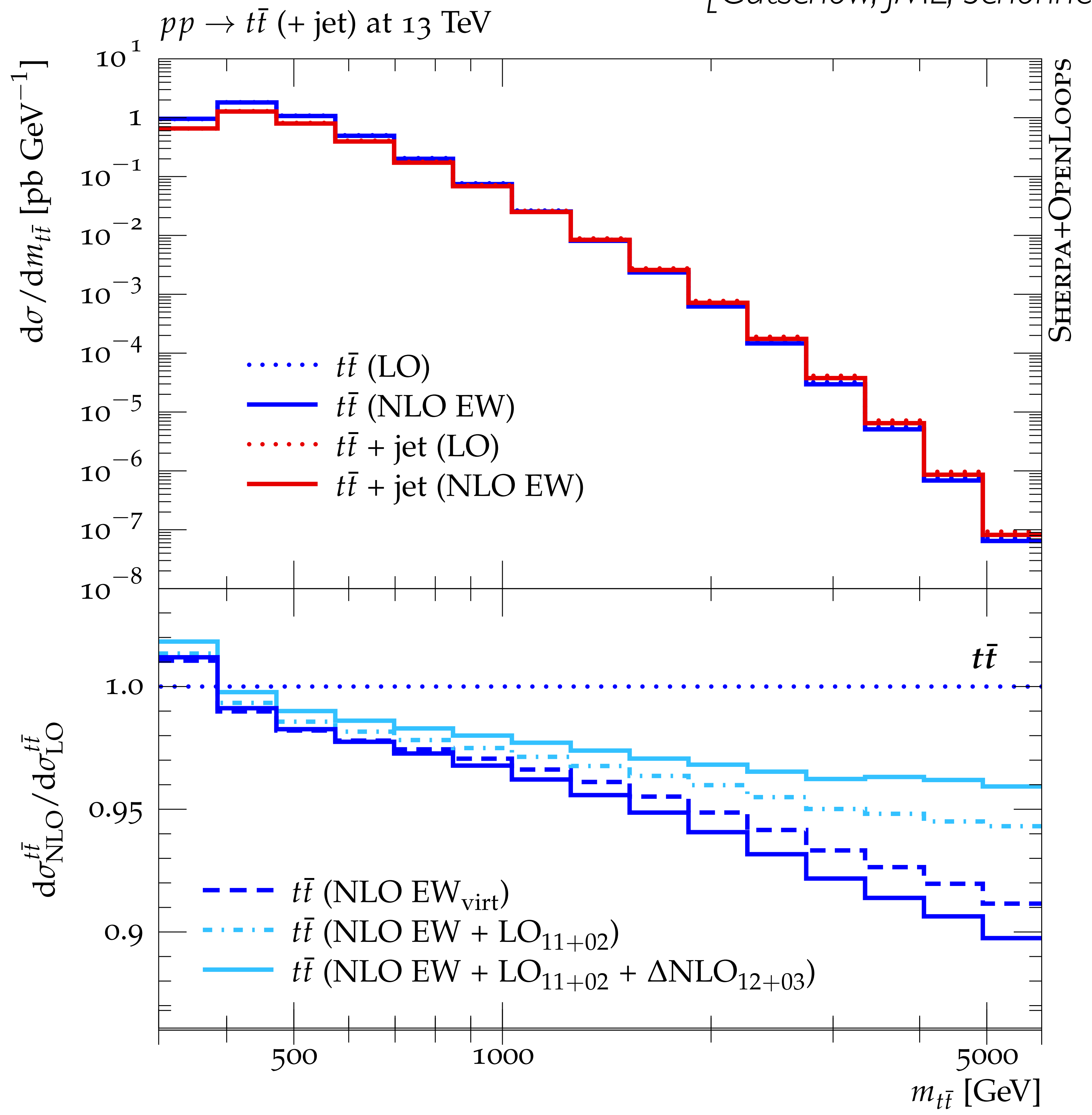
$\propto \ln^2\left(\frac{\hat{s}}{M_W^2}\right)\mathcal{M}_0$

- NLO EW: ~-12% at pT=1 TeV
- $LO_{11}+LO_{02}$: ~1%
- $NLO_{12}+NLO_{03}$: < 1%

EW corrections for top-pair production

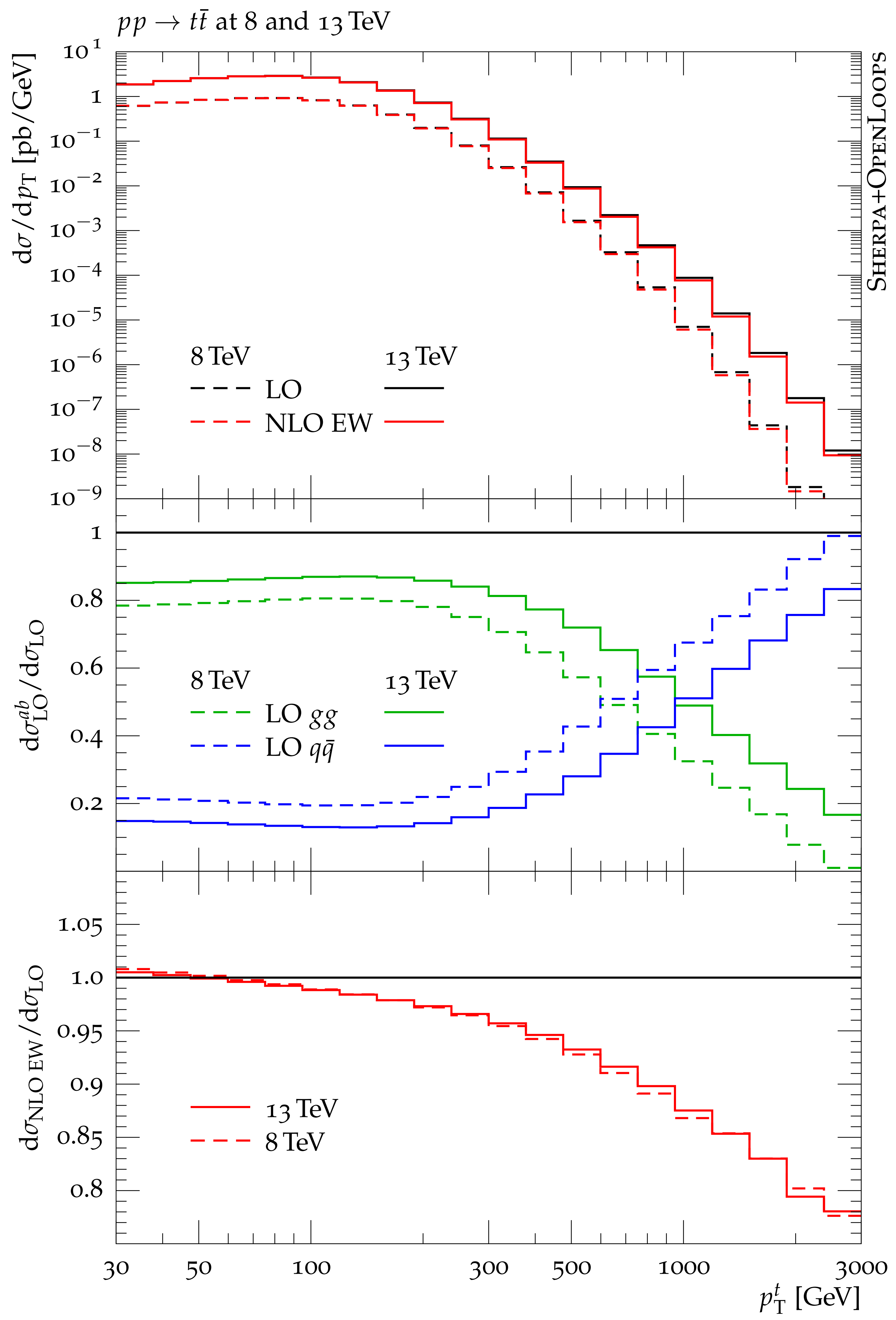


[Gütschow, JML, Schönherr; '18]



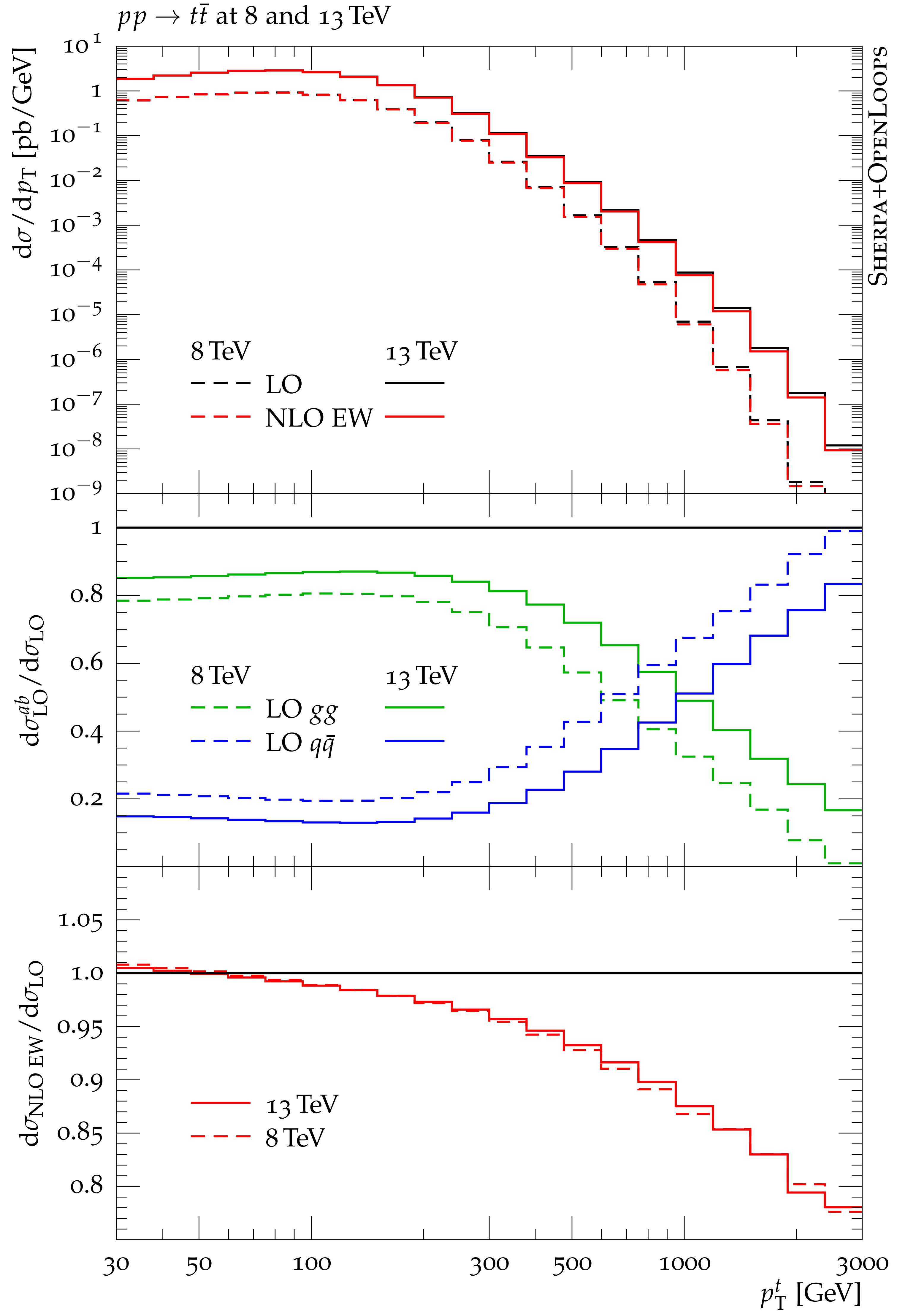
- NLO EW: ~-5% at Mtt=2 TeV
- LO11+LO02: ~2-3% at Mtt=2 TeV
- NLO12+NLO03: ~1% at Mtt=2 TeV

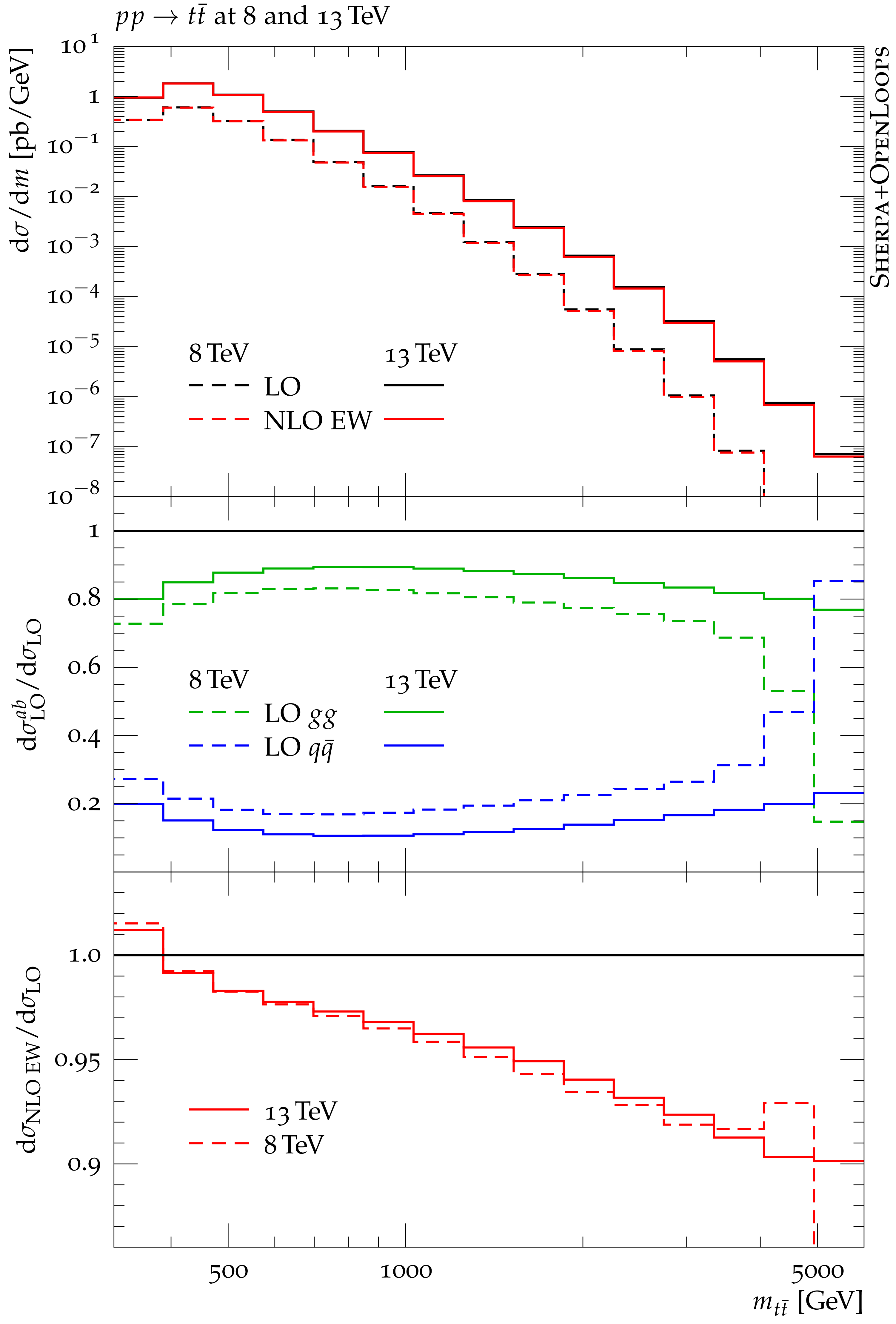
EW corrections: sqrtS dependence
8 TeV vs. 13 TeV



- gg channel receives smaller EW corrections in Sudakov limit than $q\bar{q}$ channel, at 1 TeV:
$$\delta^{q\bar{q}}_{\text{EW,sud}} \approx 1.5\, \delta^{gg}_{\text{EW,sud}}$$
- composition of total from gg vs $q\bar{q}$ channels changes
$\rightarrow$ NLO EW correction changes
$\rightarrow$ effect still small

EW corrections: sqrtS dependence
8 TeV vs. 13 TeV





Combination of QCD and EW corrections

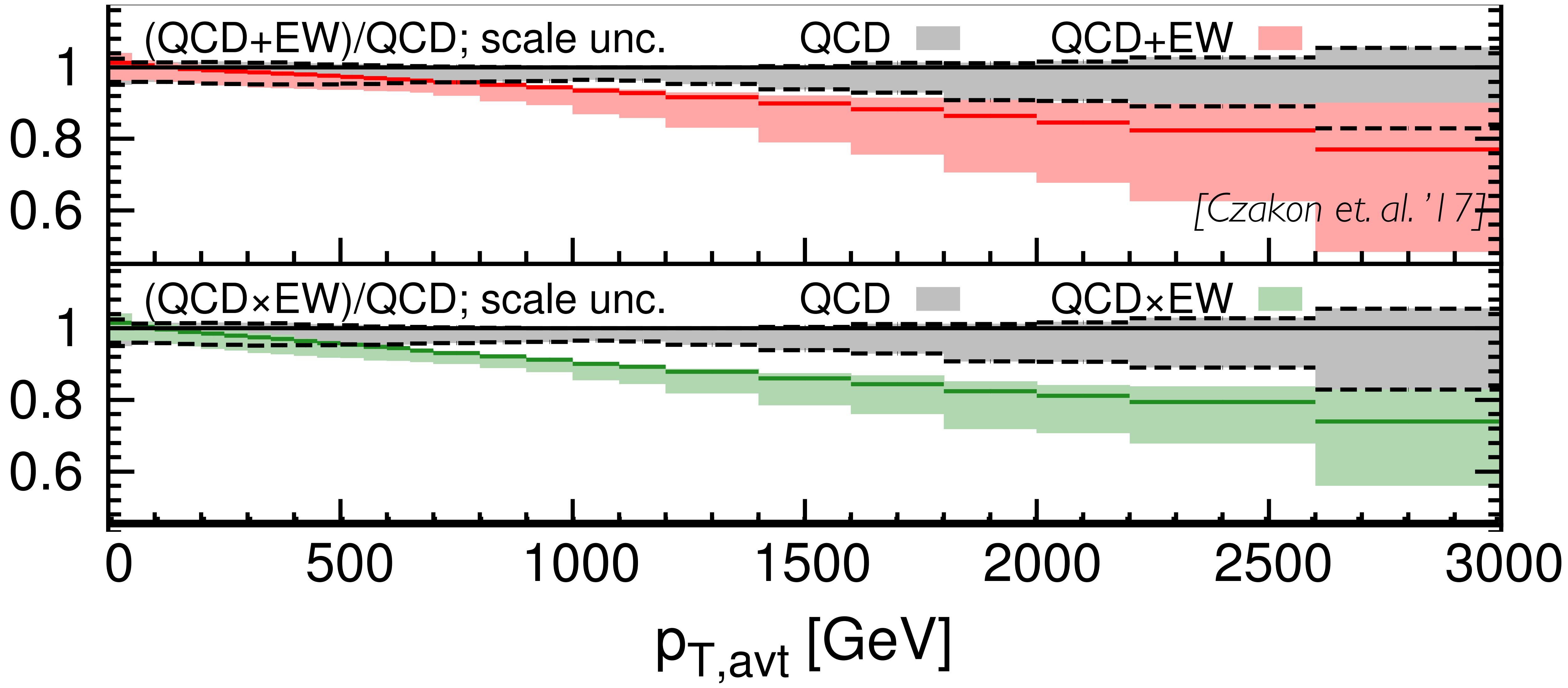
Additive combination

$$\sigma_{\mathrm{QCD+EW}} = \sigma^{\mathrm{LO}} + \delta^{\mathrm{NNLO}}_{\mathrm{QCD}} + \delta^{\mathrm{NLO}}_{\mathrm{EW}}$$

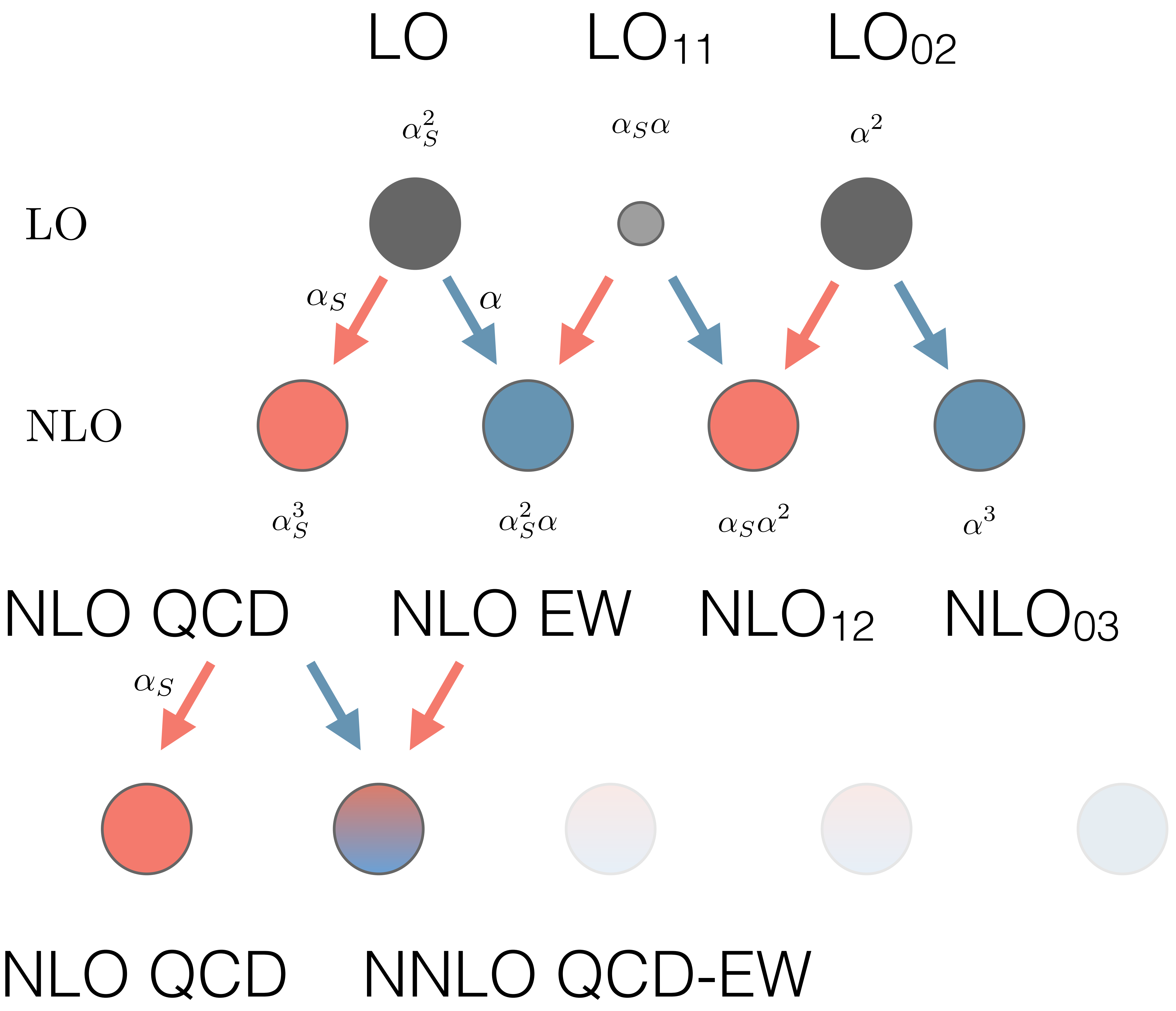
Multiplicative combination

$$\sigma_{\mathrm{QCDxEW}} = \sigma^{\mathrm{NNLO}}_{\mathrm{QCD}} \left(1 + \frac{\delta^{\mathrm{NLO}}_{\mathrm{EW}}}{\sigma^{\mathrm{LO}}}\right)$$

(try to capture some $\mathcal{O}(\alpha\alpha_s)$ contributions, e.g. EW Sudakov logs × soft QCD)

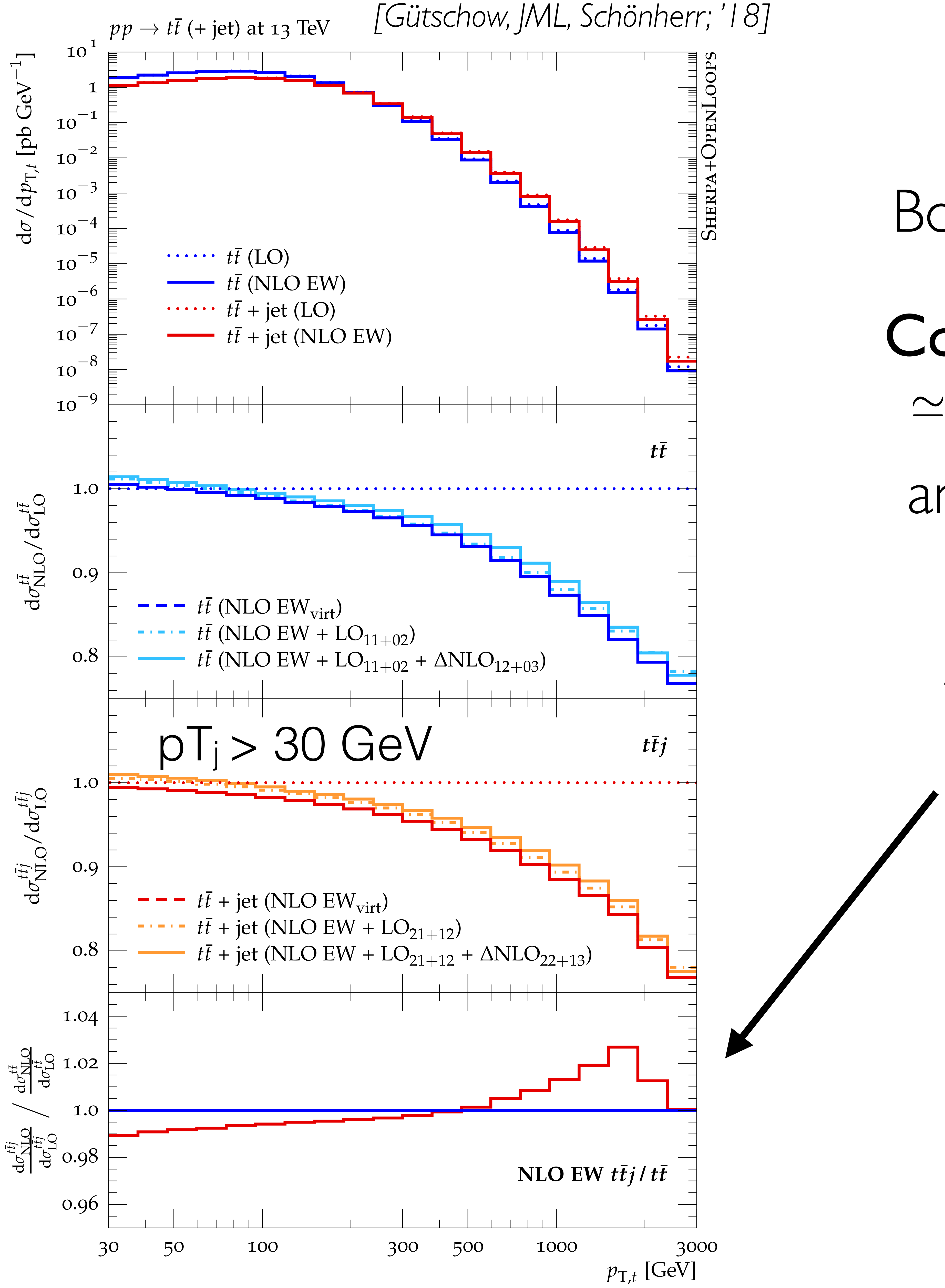


Difference between these two approaches indicates size of missing mixed EW-QCD corrections: few percent



Mixed QCD-EW uncertainties

[Gütschow, JML, Schönherr; '18]



Bold estimate:

Consider real $\mathcal{O}(\alpha\alpha_s)$ correction to tt+jet

$\simeq$ **NLO EW to tt+1jets**

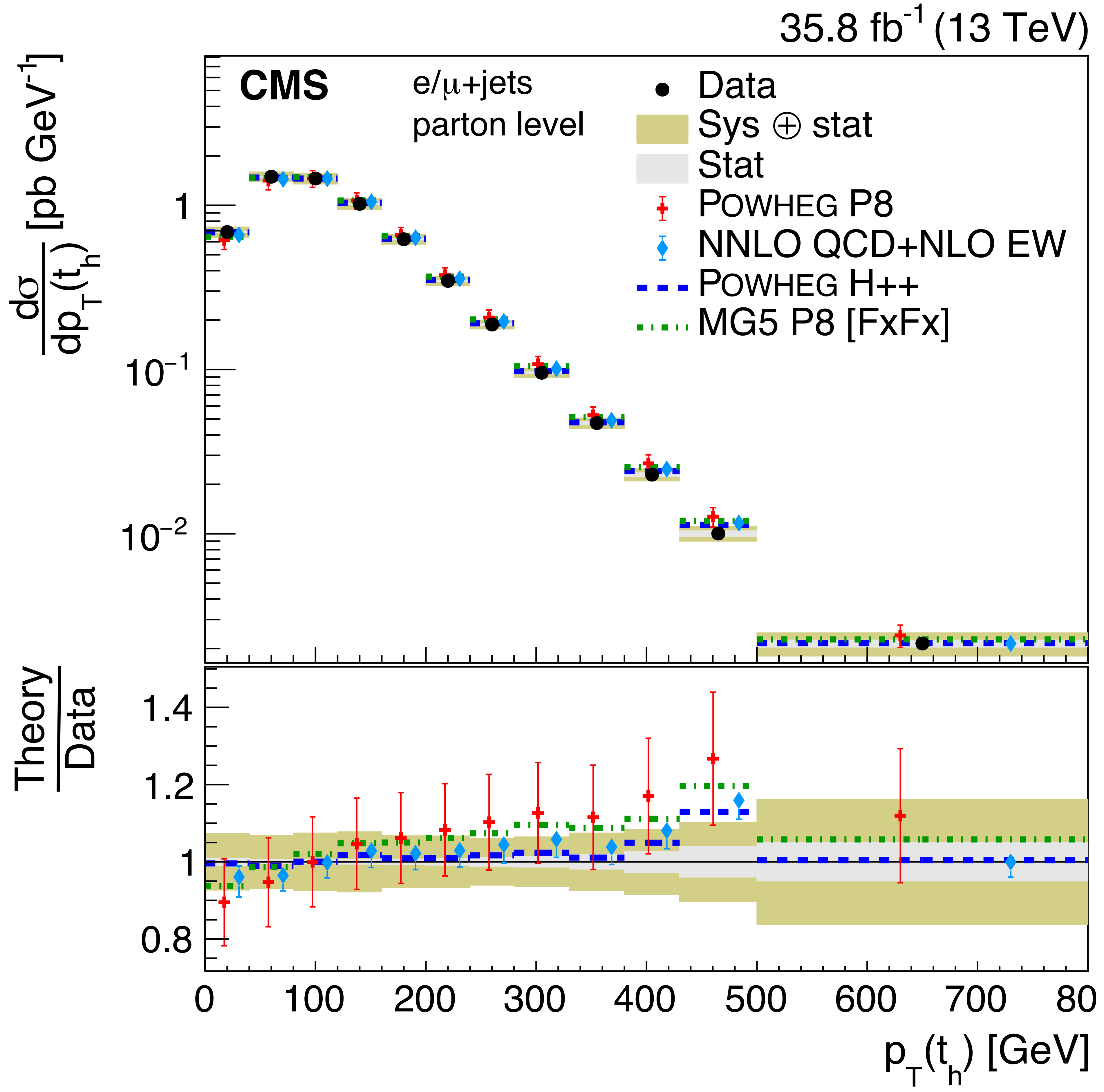
and we observe

$$\frac{d\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{d\sigma_{\mathrm{LO}}}\Big|_{t\bar{t}+1\mathrm{jet}} - \frac{d\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{d\sigma_{\mathrm{LO}}}\Big|_{t\bar{t}} \lesssim 2\%$$

strong support for

- factorization
- multiplicative QCD x EW combination

Comparison with data



arXiv:1803.08856

➡EW corrections alleviates tension with data

EW corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)

- modify MC@NLO B-function to include NLO EW virtual corrections and integrated approx. real corrections

optionally include subleading Born $\mathrm{LO}_{11}(+\mathrm{LO}_{02})$

$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$

exact virtual contribution

approximate integrated real contribution

EW corrections in particle-level event generation

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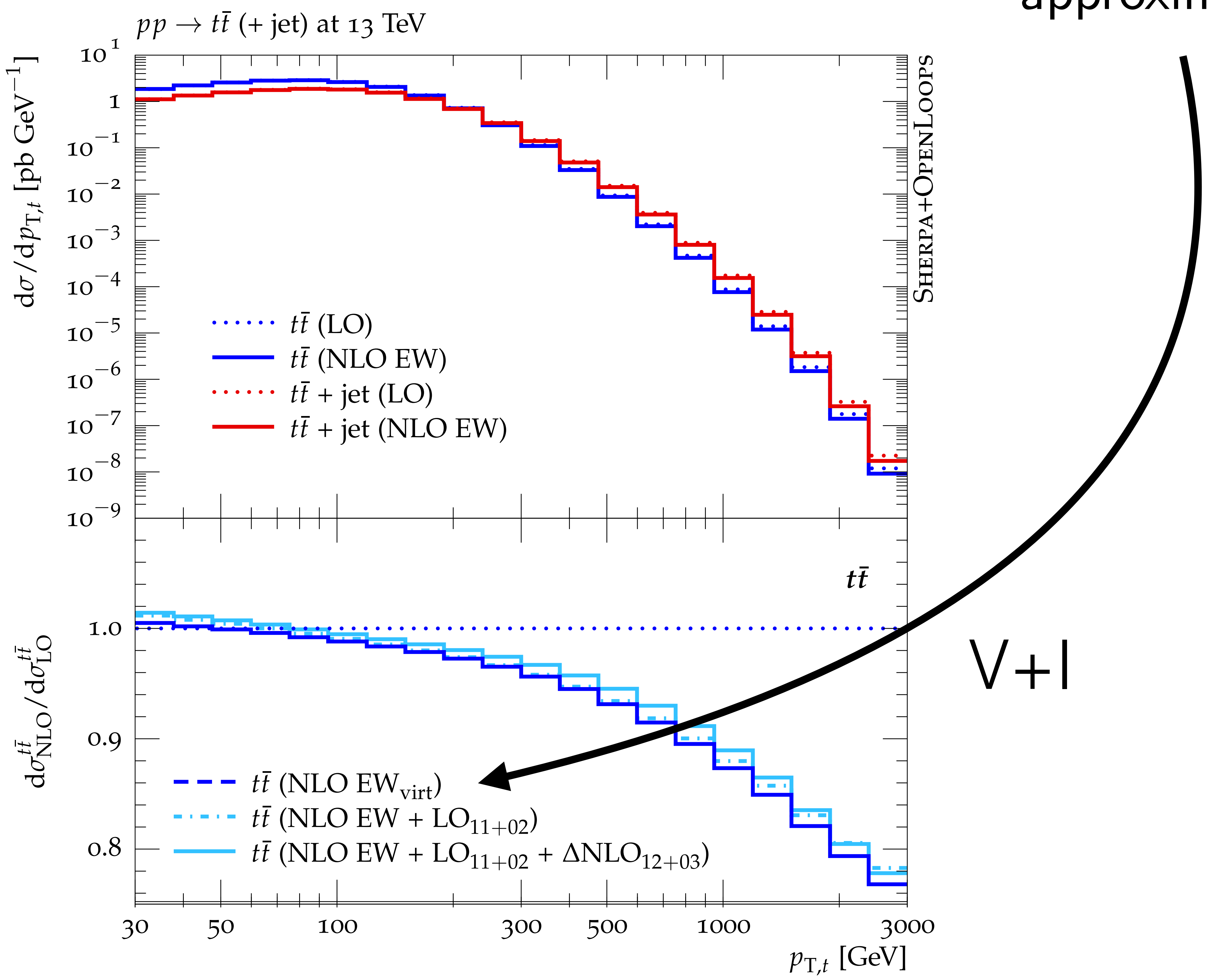
$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$

exact virtual contribution

approximate integrated real contribution

[Gütschow, JML, Schönherr; '18]



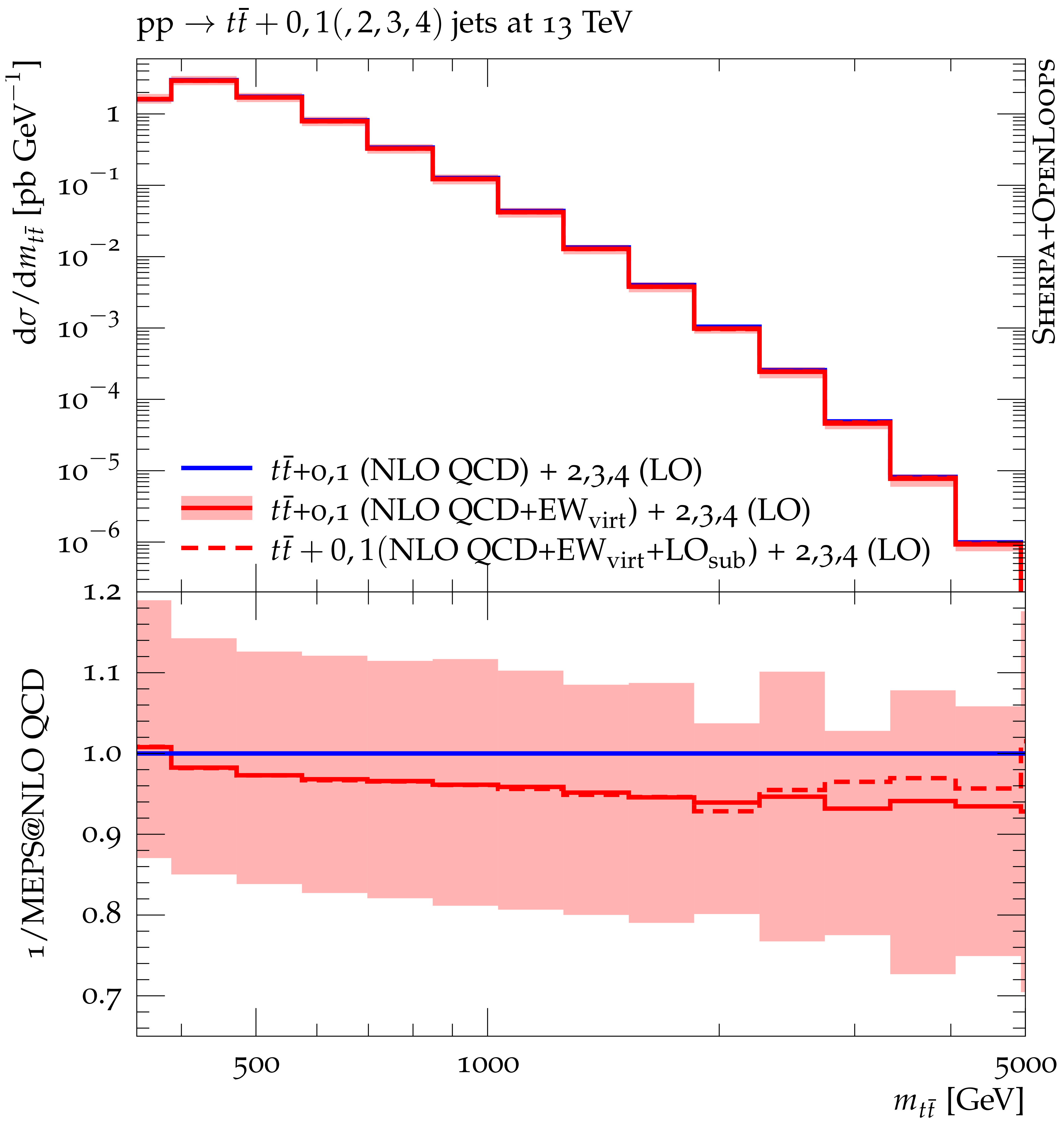
For pT-top: approximation reliable at 1%-level

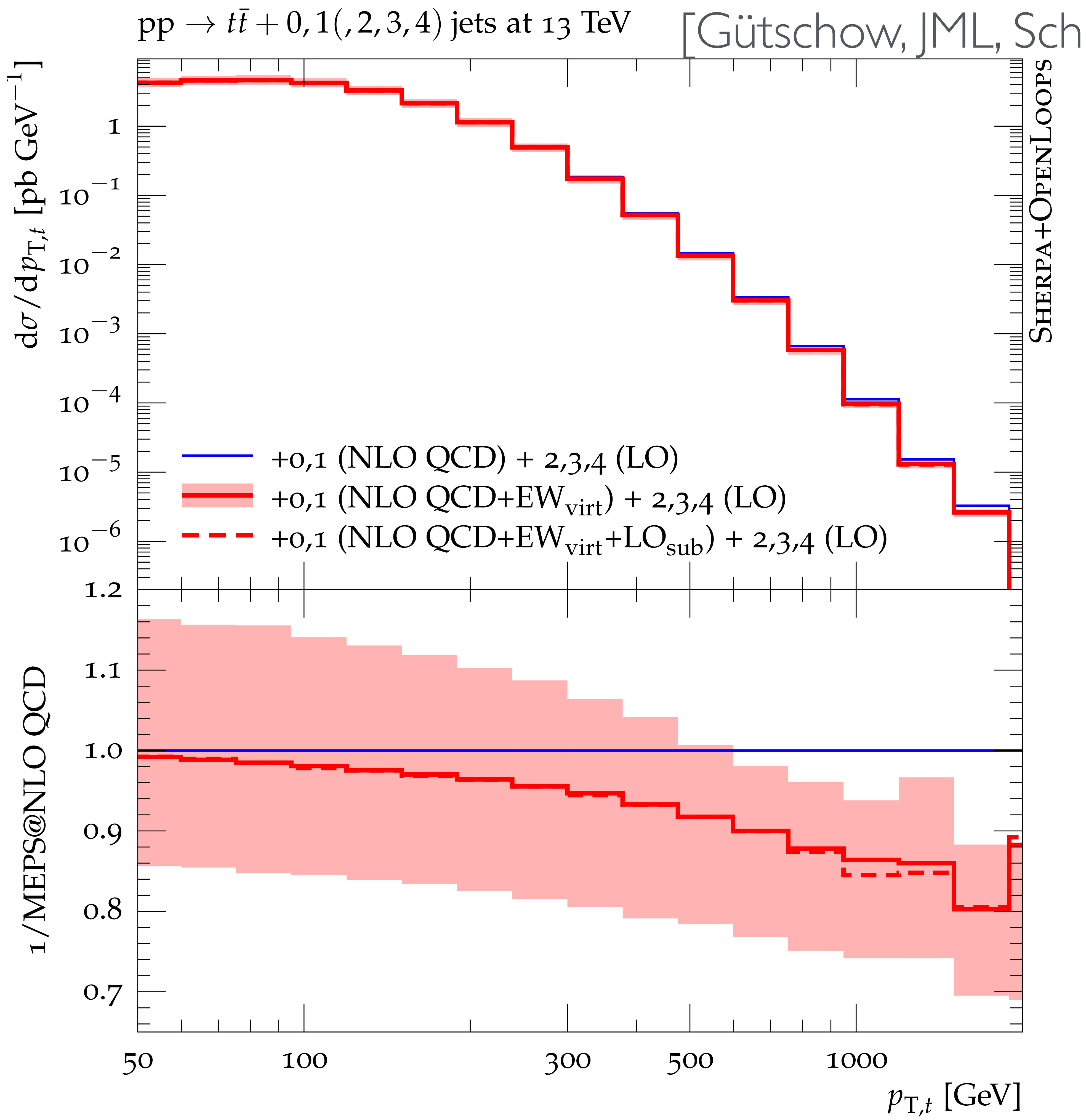
- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)

➡ simple stand-in for proper QCD+EW matching and merging (work-in-progress)

Results: ttbar+jets @ MEPS NLO QCD+EW$_{virt}$ (0,1jets merged)

[Gütschow, JML, Schönherr, '18]

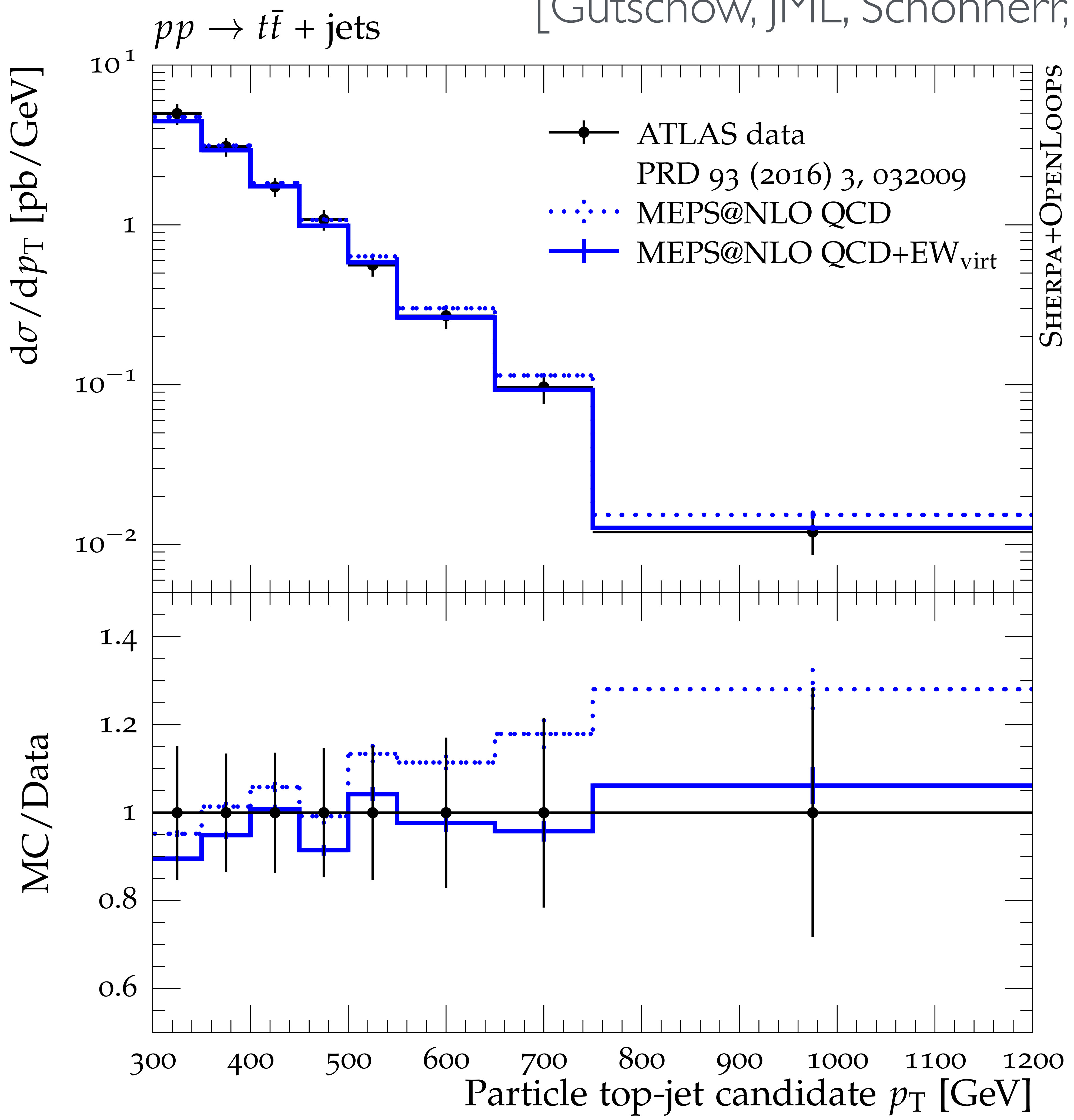




➡ reproduces well the corrections seen at fixed-order

Results: ttbar+jets @ MEPS NLO QCD+EW$_{virt}$ (0,1jets merged)

[Gütschow, JML, Schönherr,'18]



CKKW-scale with:

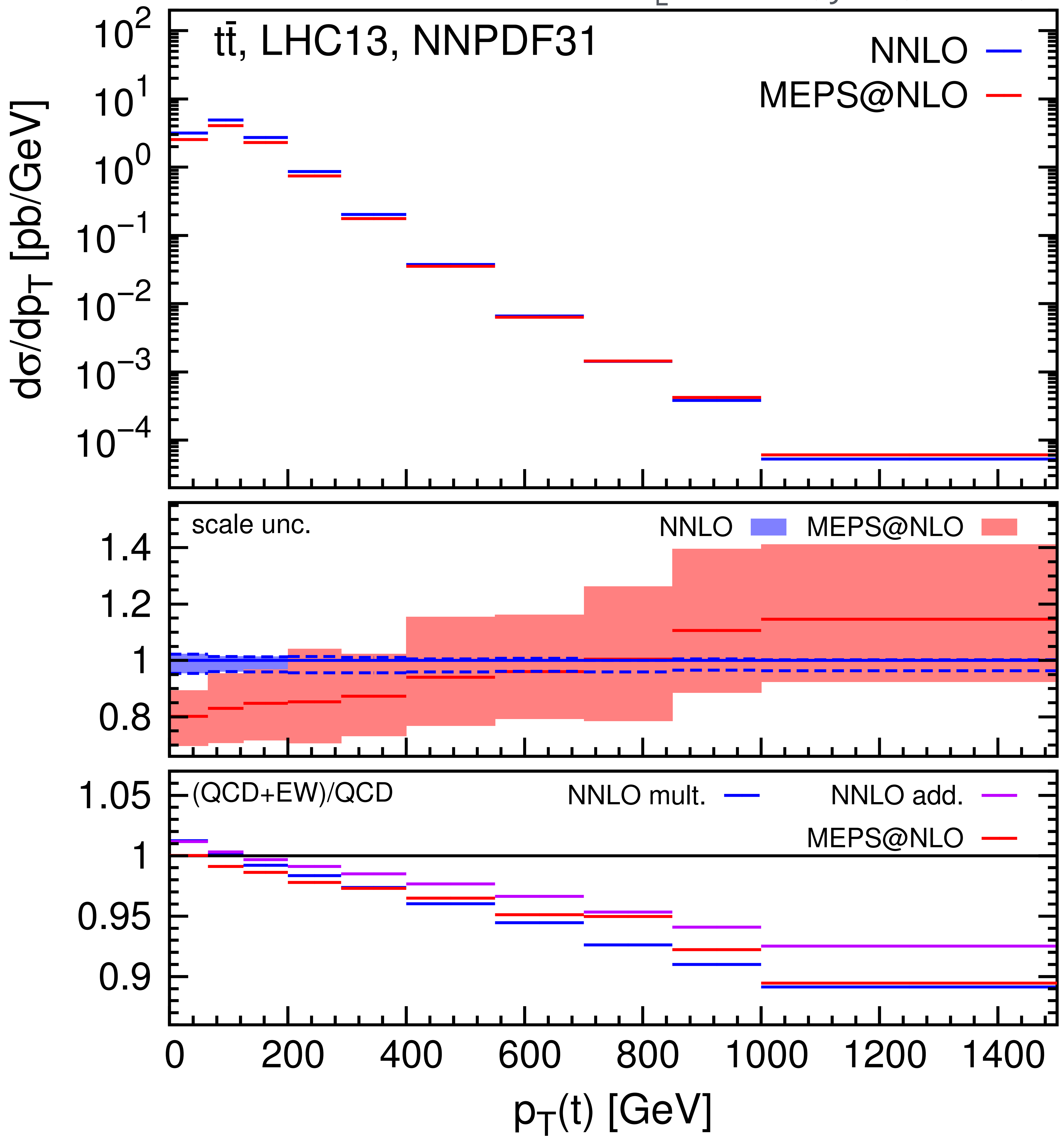
$$\mu_{\text{core}} = \frac{1}{2}\left(\frac{1}{\hat{s}} + \frac{1}{m_t^2 - \hat{t}} + \frac{1}{m_t^2 - \hat{u}}\right)^{-\frac{1}{2}}$$

- $pp \to t\bar{t} + 0, 1j$@NLO $+ 2, 3, 4j$@LO
- additional LO multiplicities inherit electroweak corrections through MENLOPS differential K-factor

  Höche, Krauss, MS, Siegert arXiv:1009.1127
- improved description of data

MEPS @ NLO vs. NNLO

[Czakon, JML, et. al.,'18]

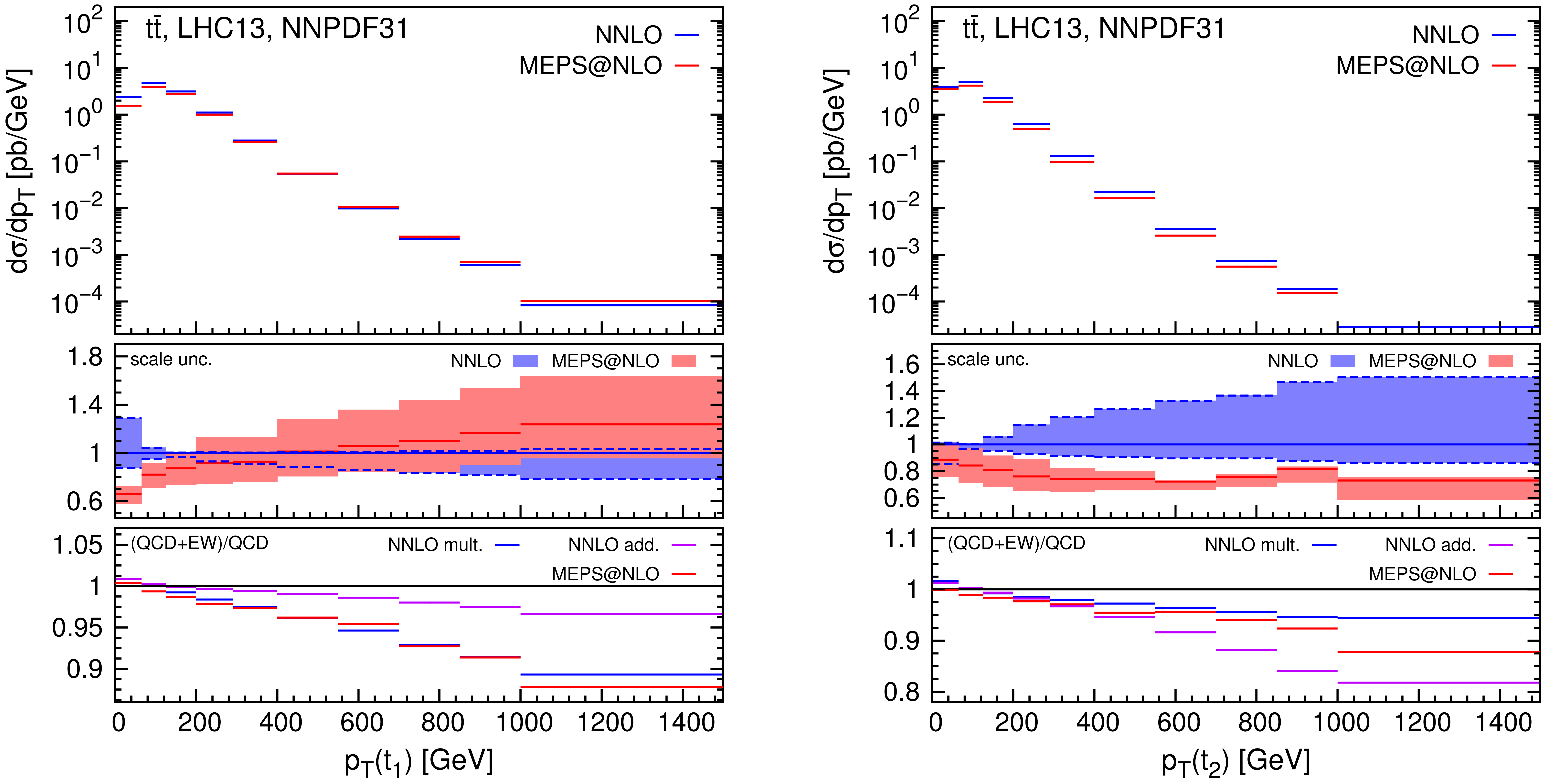


- MEPS@NLO and NNLO agree within uncertainties
- largely reduced uncertainties at NNLO
- shape differences

- EW corrections in MEPS NLO QCD+EW$_{virt}$ agree with NNLO QCDxEW

MEPS @ NLO vs. NNLO

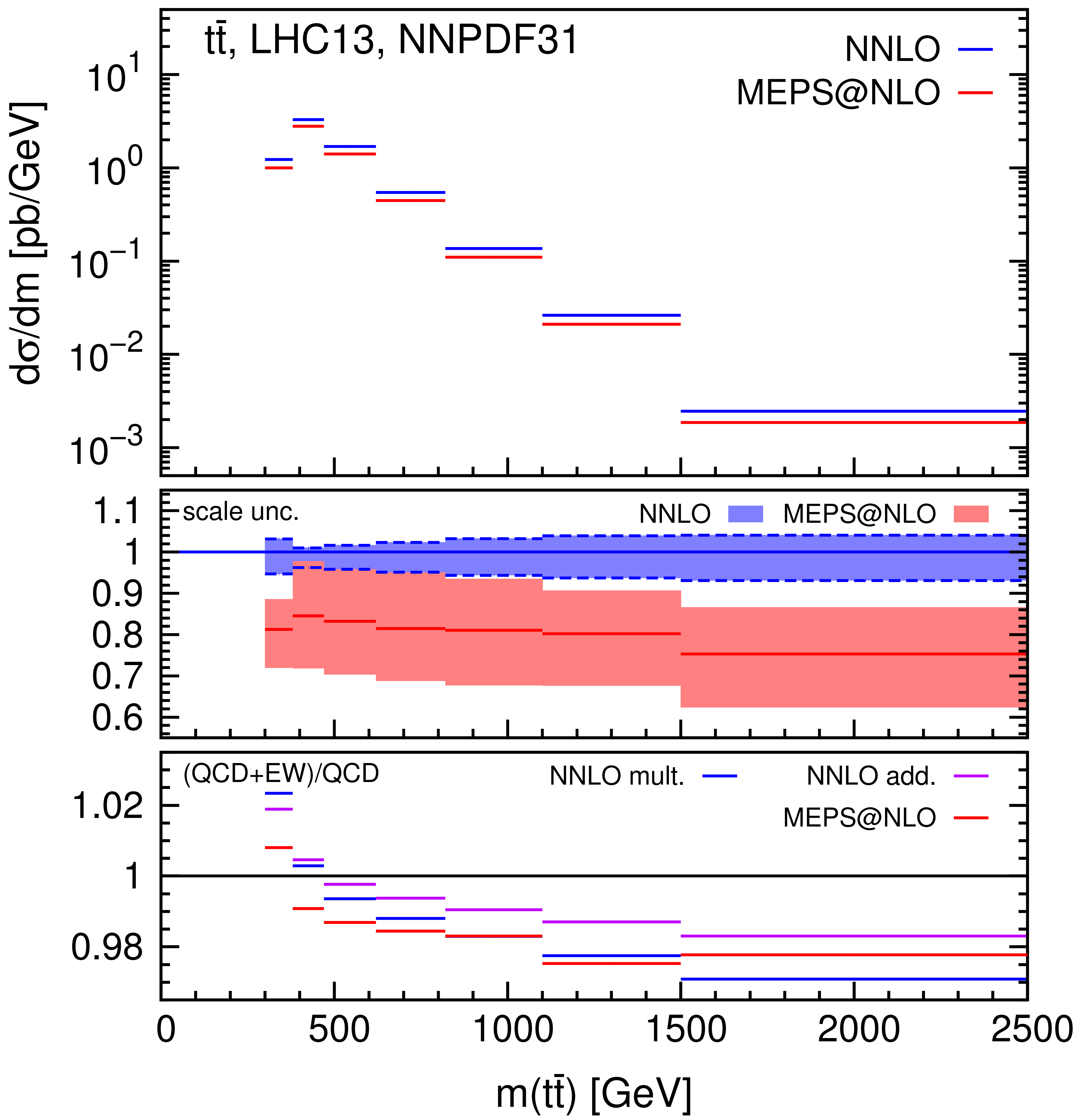
[Czakon, JML, et. al.,'18]

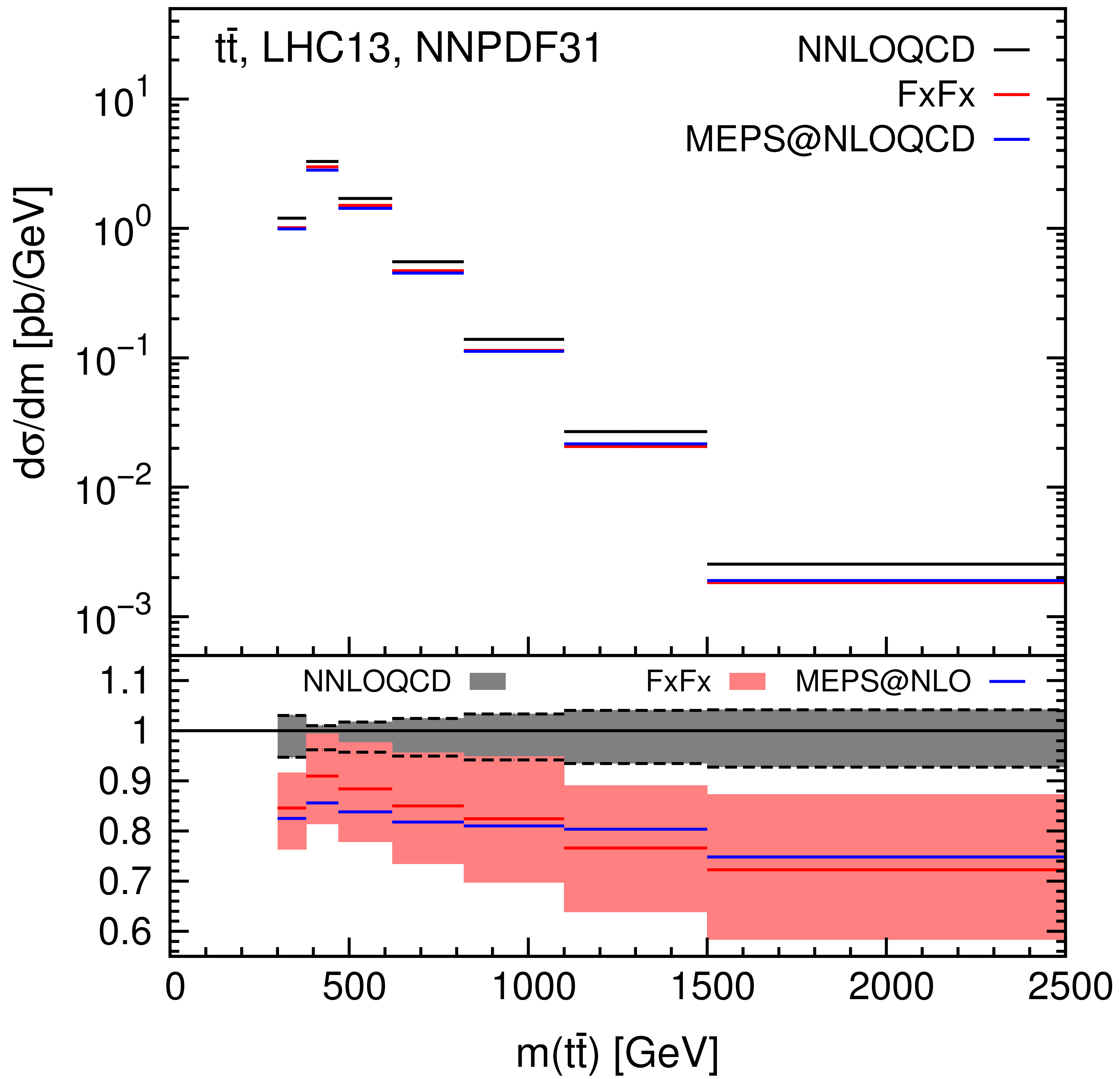


➡ for trailing top large uncertainties at fixed-order

MEPS @ NLO vs. NNLO

[Czakon, JML, et. al., '18]





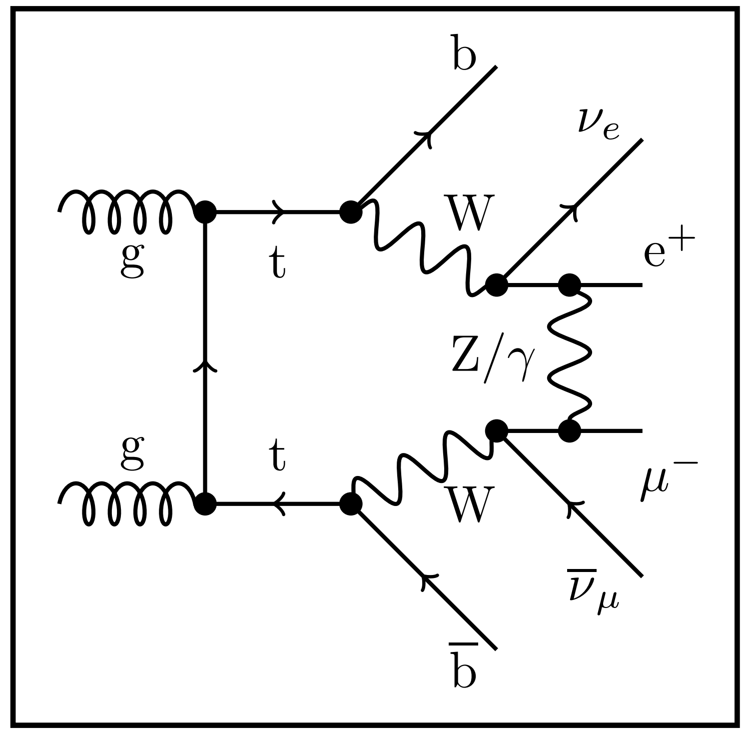
➡ relevant difference between MEPS@NLO and NNLO for Mtt

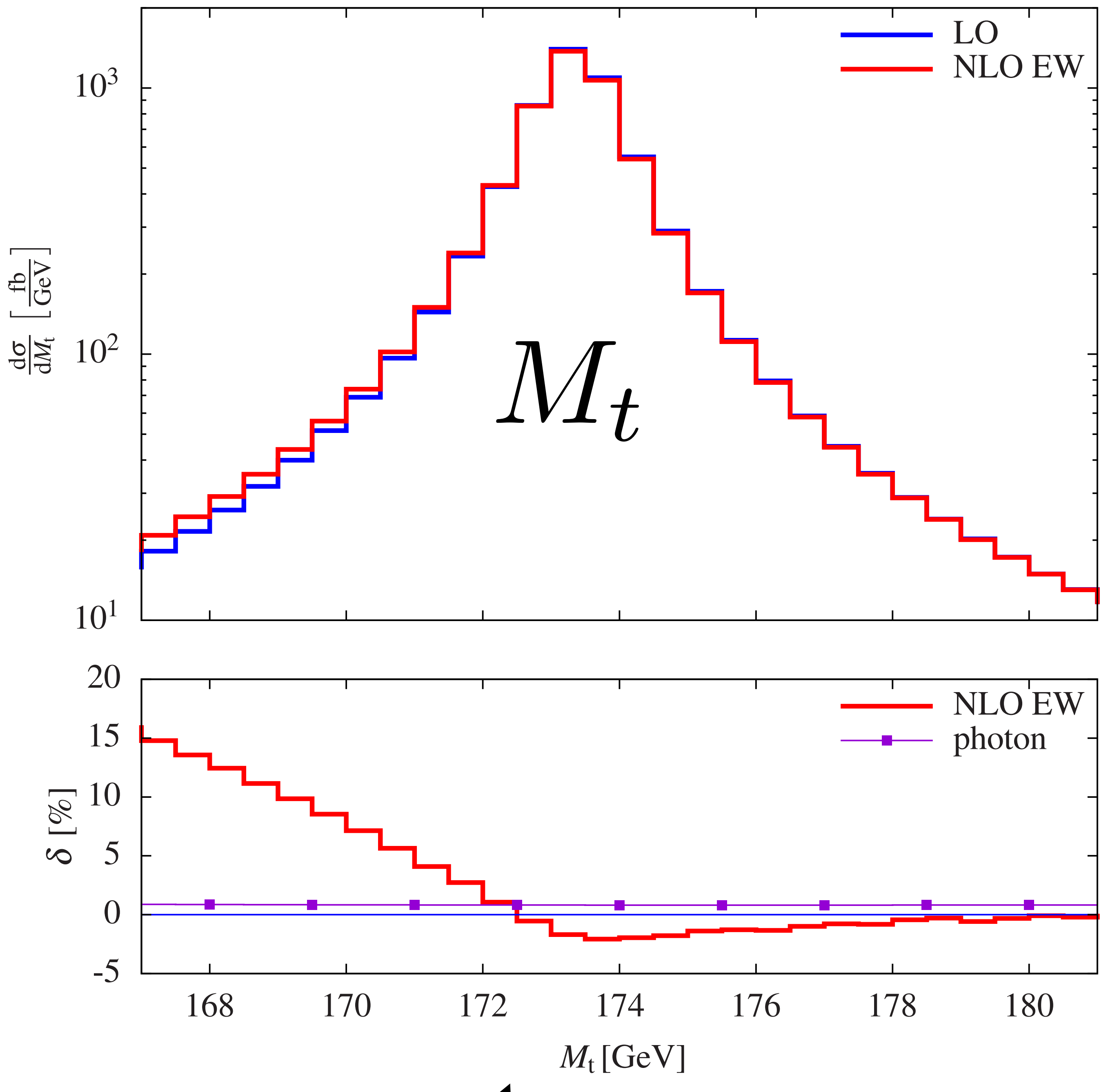
➡ MEPS@NLO (Sherpa) consistent with FxFx (MadGraph_aMC@NLO)

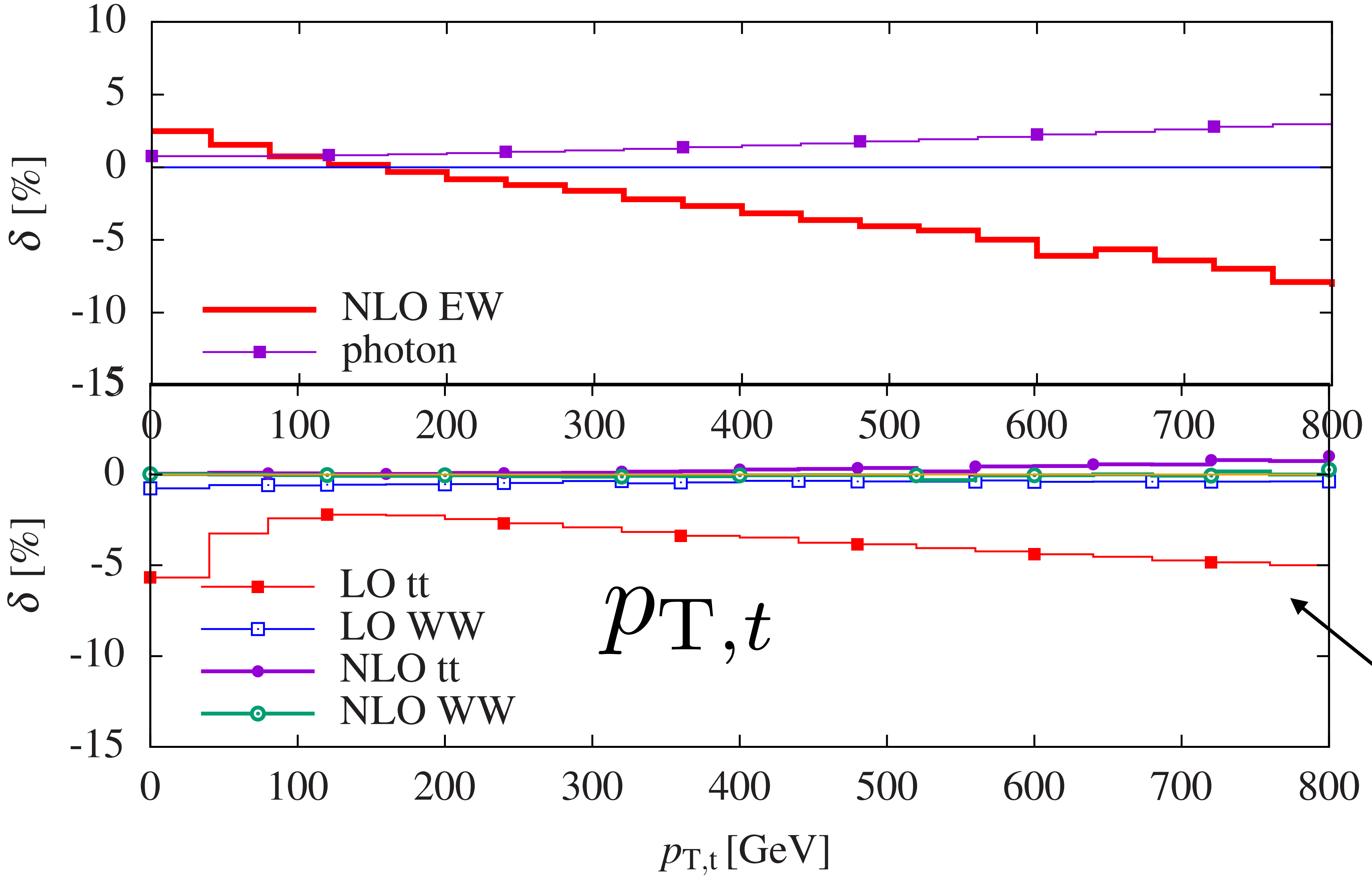
Top-pair: off-shell NLO EW

[Denner, Pellen; '16]

Technical challenge: full **2 →6 process**, i.e. pp → $\bar{b}b\, e^+\nu_e\mu^-\nu_\mu$ @ NLO EW (*)







- typical Sudakov behaviour O(10%) for pT,t = 800 GeV

- LO non-resonant: 5% for pT,t = 800 GeV

pole approximations/full

- O(2-5%) around top resonance
- possible relevance for top mass measurements

- non-resonant configurations can berelevant
- well described by WWbb approximation

Conclusions

- Theory predictions for differential top production very advanced:
  NNLO QCD x NLO EW
- EW corrections relevant for pT-tails (and eventually also Mtt)
- ttbar and ttbar+ j now known at NLO including all one-loop orders:
  universal corrections observed
- Inclusion of approximate EW corrections in MEPS@NLO available
- Improves data description for boosted top quarks already at 8 TeV
- MEPS@NLO vs. NNLO differences to be understood
- publically available in Sherpa-2.2.5 & OpenLoops2

Backup

Scale setting

NNLO

$$\mu = \frac{m_T(t)}{2} \quad \text{for the } p_T(t) \text{ distribution,}$$
$$\mu = \frac{m_T(\bar{t})}{2} \quad \text{for the } p_T(\bar{t}) \text{ distribution,}$$
$$\mu = \frac{H_T}{4} = \frac{1}{4}\big(m_T(t) + m_T(\bar{t})\big) \quad \text{for all other distributions,}$$

In MEPS@NLO CKKW-scale with:

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

$$\text{for } p_T(t) \to \infty \qquad \mu_{\text{core}} \Longrightarrow \frac{1}{2}\sqrt{\frac{4}{5}}p_T \sim \frac{p_T}{2}\,,$$
$$\text{for } E(t) \to \infty \text{ and } p_T(t)/E(t) \to 0 \qquad \mu_{\text{core}} \Longrightarrow \frac{m_T}{2} \sim \frac{H_T}{4}\,,$$
$$\text{for } E(t) \to 0 \qquad \mu_{\text{core}} \Longrightarrow \frac{1}{2}\sqrt{\frac{4}{5}}m_t \sim \frac{H_T}{4}\,,$$