Complete NLO corrections to off-shell $t\bar{t}Z$ production at the LHC

Based on a work done by
A. Denner, DL and G. Pelliccioli (arXiv:2306.13535)

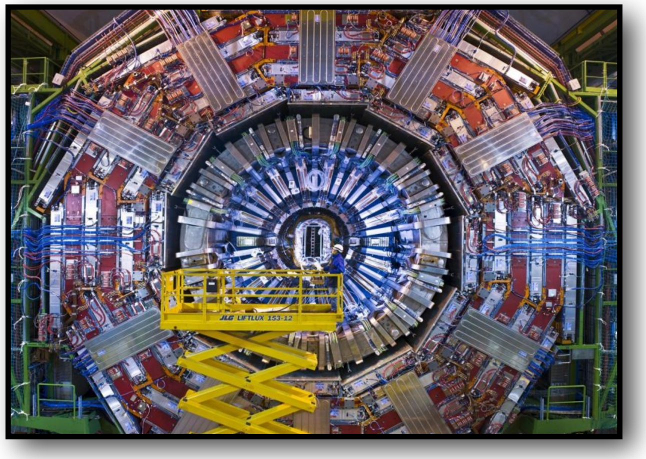
Presented by

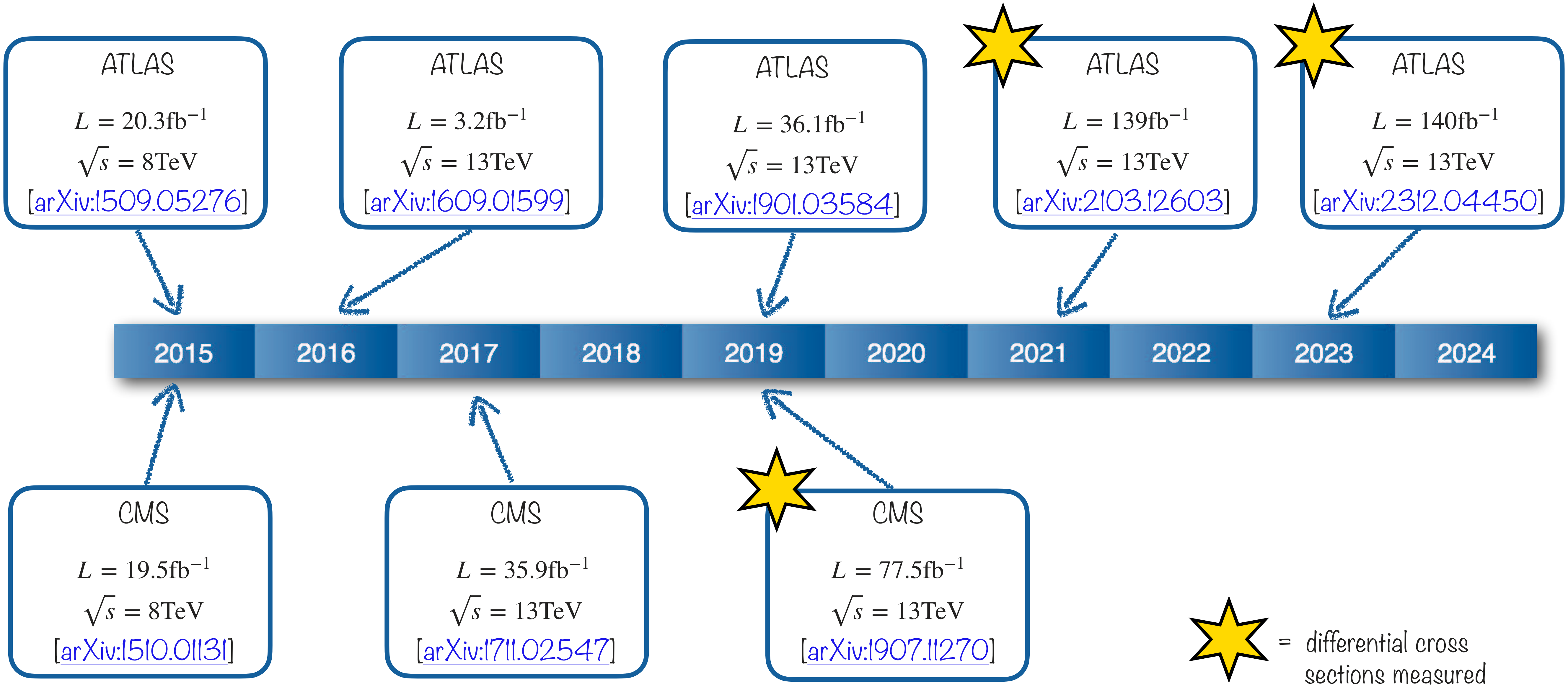
Daniele Lombardi

TOP2024 Workshop
(Saint-Malo)
Young Scientist Forum
September 25th, 2024

Search for $t\bar{t}Z$ production

- Important test of Standard Model (SM).
- Improved control on background for other processes (i.e $t\bar{t}H$, tZ, $t\bar{t}t\bar{t}$, ...).
- Better understanding of top-quark couplings to electroweak (EW) sector
  → beyond the SM physics?





ATLAS
$L = 20.3\text{fb}^{-1}$
$\sqrt{s} = 8\text{TeV}$
[arXiv:1509.05276]

ATLAS
$L = 3.2\text{fb}^{-1}$
$\sqrt{s} = 13\text{TeV}$
[arXiv:1609.01599]

ATLAS
$L = 36.1\text{fb}^{-1}$
$\sqrt{s} = 13\text{TeV}$
[arXiv:1901.03584]

★ ATLAS
$L = 139\text{fb}^{-1}$
$\sqrt{s} = 13\text{TeV}$
[arXiv:2103.12603]

★ ATLAS
$L = 140\text{fb}^{-1}$
$\sqrt{s} = 13\text{TeV}$
[arXiv:2312.04450]

CMS
$L = 19.5\text{fb}^{-1}$
$\sqrt{s} = 8\text{TeV}$
[arXiv:1510.01131]

CMS
$L = 35.9\text{fb}^{-1}$
$\sqrt{s} = 13\text{TeV}$
[arXiv:1711.02547]

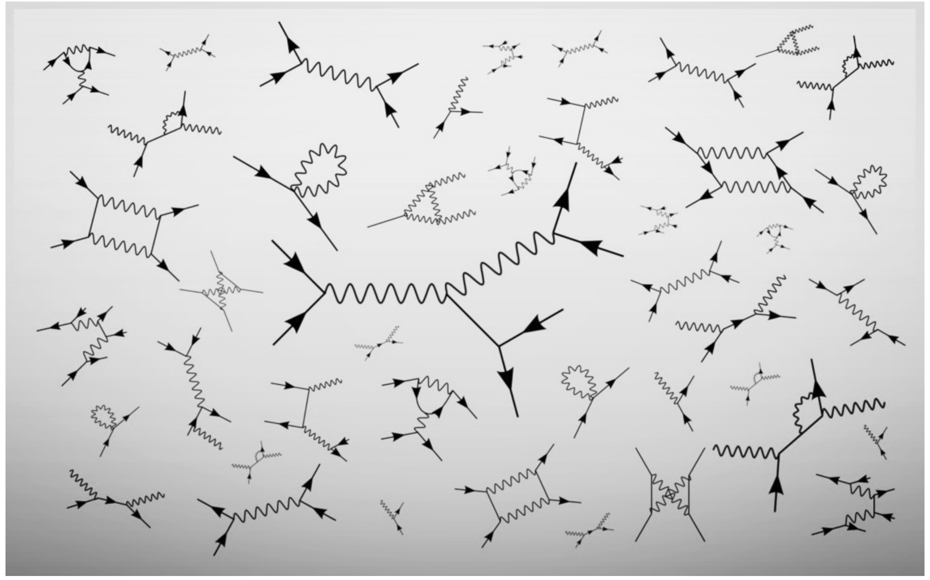
★ CMS
$L = 77.5\text{fb}^{-1}$
$\sqrt{s} = 13\text{TeV}$
[arXiv:1907.11270]

★ = differential cross sections measured

Theory predictions for $t\bar{t}Z$

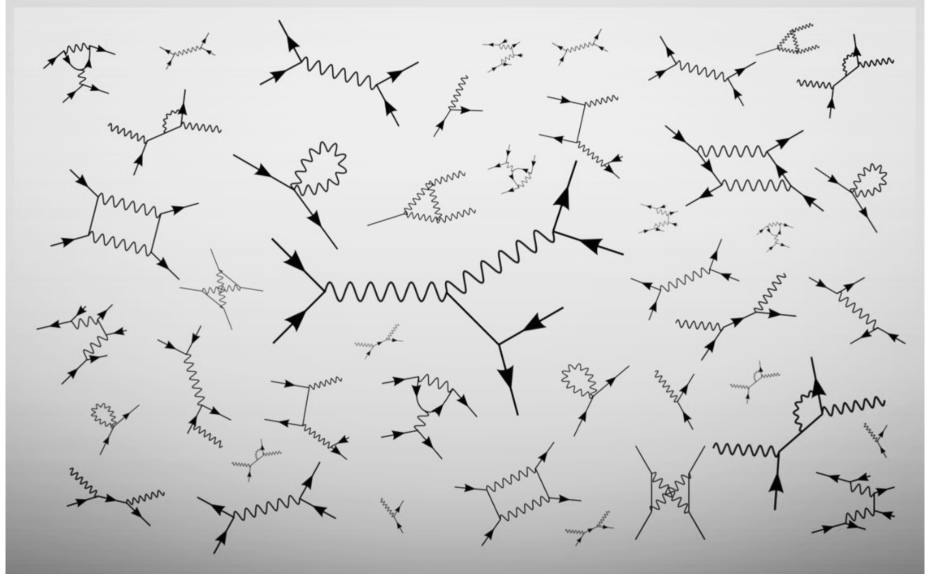
Fixed order (on-shell)

- ☑ **NLO QCD** predictions for on-shell top quark and Z boson [arXiv:0804.2220, arXiv:1111.0610].
  - ➡ NLO QCD corrections to top-quark decay in narrow-width approximation [arXiv:1404.1005].
- ☑ **NLO QCD+EW** predictions for on-shell top quark and Z boson with MadGraph5_aMC@NLO [arXiv:1504.03446, arXiv:1804.10017].



- ☑ **NLO QCD +PS** using MC@NLO [arXiv:1507.05640] and POWHEG [arXiv:1111.1444, arXiv:1208.2665], with narrow-width simulation of top-quark and Z-boson decays.
  - ➡ Inclusion of off-shell effects for Z-boson decay with POWHEG [arXiv:2112.08892].
- ☑ **NLO QCD +NNLL** results for on-shell top quark and Z boson [arXiv:1702.00800, arXiv:1812.08622], also including EW corrections [arXiv:1907.04343, arXiv:2001.03031].
- ☑ **NLO QCD** calculation for fully off-shell top quark and Z boson in HELAC-NLO for $Z \to \nu_\ell \bar{\nu}_\ell$ [arXiv:1907.09359] and $Z \to \ell\bar{\ell}$ [arXiv:2203.15688].
- ☐ **NLO QCD+EW** predictions for fully off-shell top quark and Z boson in the multi-lepton decay channel with MoCaNLO [arXiv:2306.13535].

Theory predictions for $t\bar{t}Z$



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All order (on-shell)

☑ **NLO QCD** calculation for fully off-shell top quark and Z boson in HELAC-NLO for $Z \to \nu_\ell \bar{\nu}_\ell$ [arXiv:1907.09359] and $Z \to \ell \bar{\ell}$ [arXiv:2203.15688].

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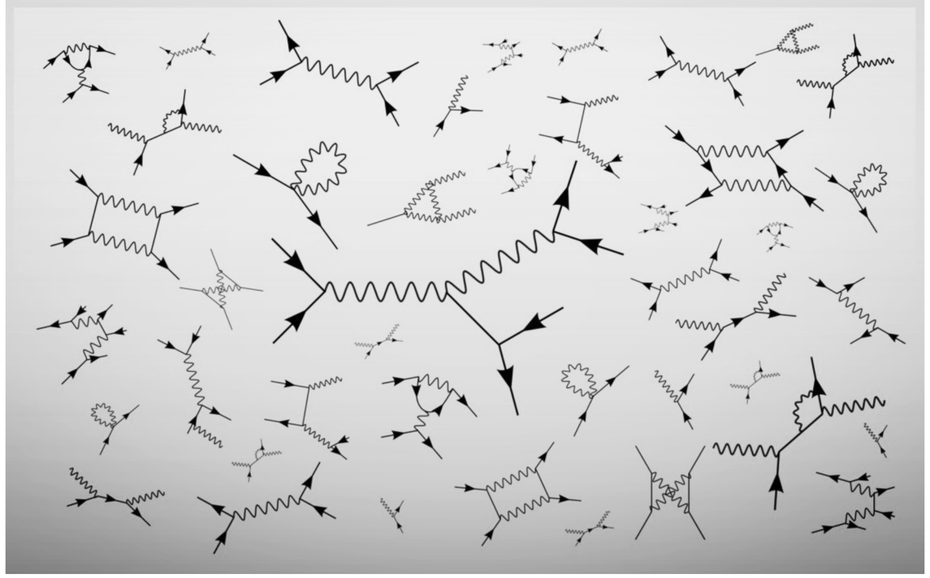
Theory predictions for $t\bar{t}Z$



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- ☐ **NLO QCD+EW** predictions for fully off-shell top quark and Z boson in the multi-lepton decay channel with MoCaNLO [arXiv:2306.13535].

Fixed order (off-shell)

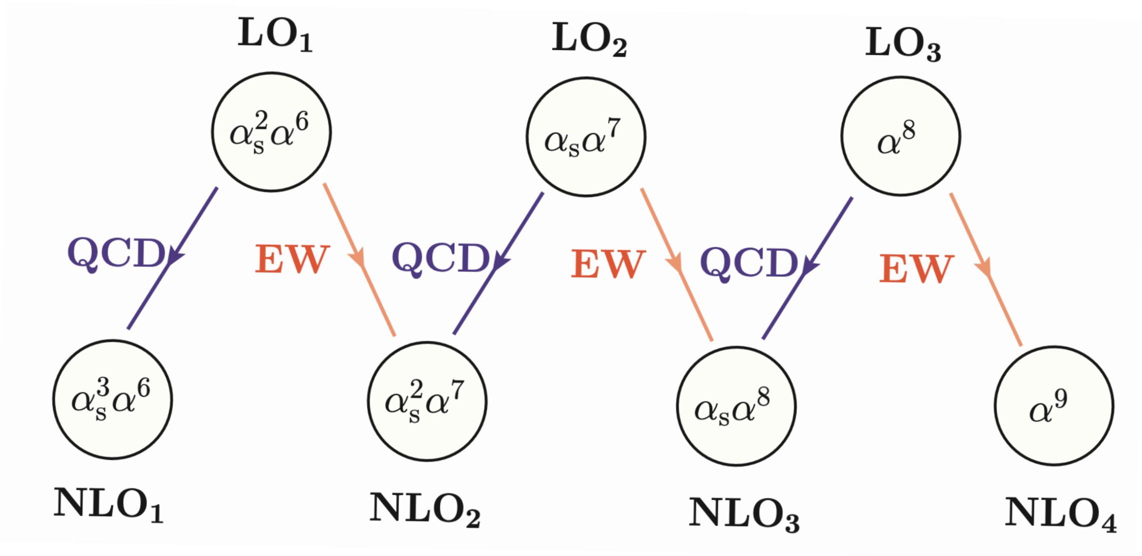
→ **This Talk!**

Structure of the calculation

A.Denner, DL, and G.Pellicciolli [arXiv:2306.13535]

NLO QCD and NLO EW corrections to fully off-shell $t\bar{t}Z$:

$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$$



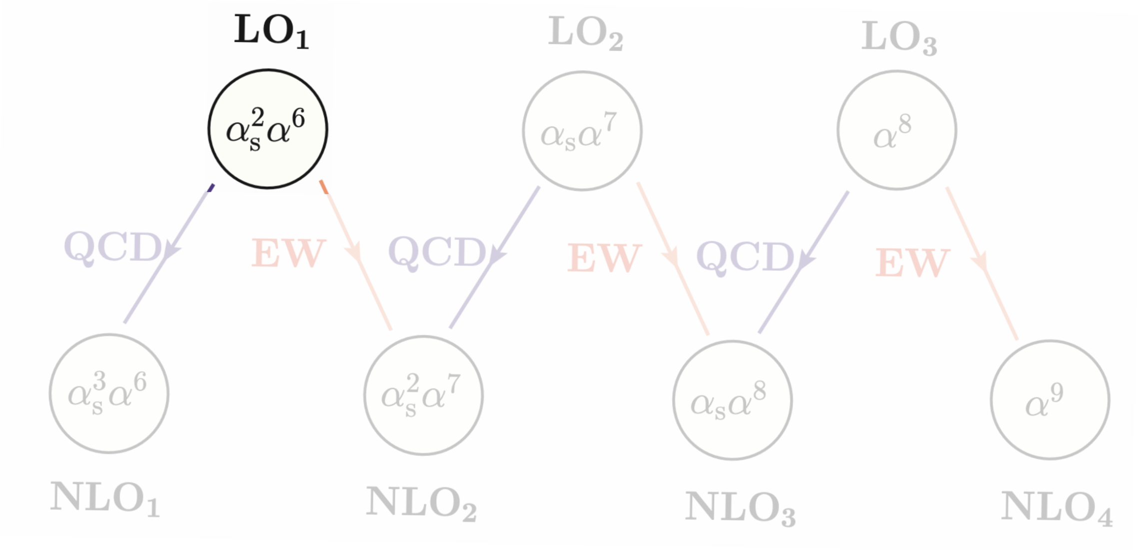
- ❖ Calculation performed with the in-house MoCaNLO program:
  - SM amplitudes computed with RECOLA (CKM matrix set to identity matrix);
  - Tensor reduction and evaluation of 1-loop integrals with COLLIER library.
- ❖ All light-quark- and gluon-induced partonic channels computed, together with:
  - Photon-induced channels;
  - Bottom-induced contributions → complete 5-flavour scheme.
- ❖ Inclusion of resonant and non-resonant terms (Higgs contribution included).
- ❖ Heavy-boson radiation at NLO EW neglected.

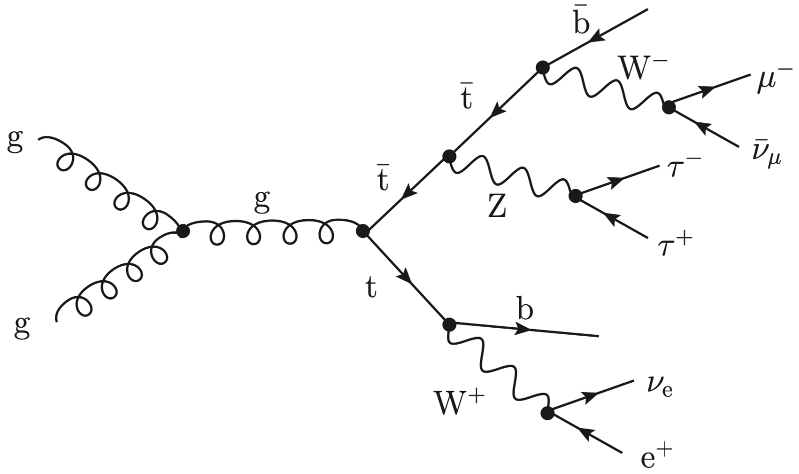
Structure of the calculation: LO_1 term

A.Denner, DL, and G.Pelliccioli [arXiv:2306.13535]

NLO QCD and NLO EW corrections to fully off-shell $t\bar{t}Z$:

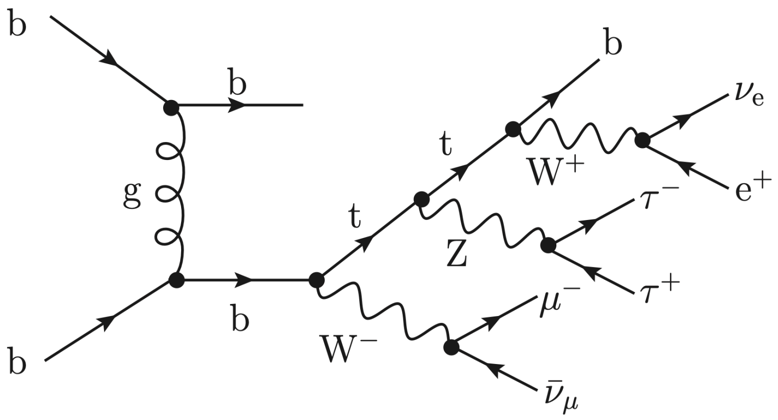
$$pp \;\to\; e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$$





- gg- and $q\bar{q}$-induced channels.
- Dominance of doubly-resonant $t\bar{t}$ topologies.

- Charge-blind b-jet tagging → sub-leading $\bar{b}\bar{b}$ and bb contributions included.

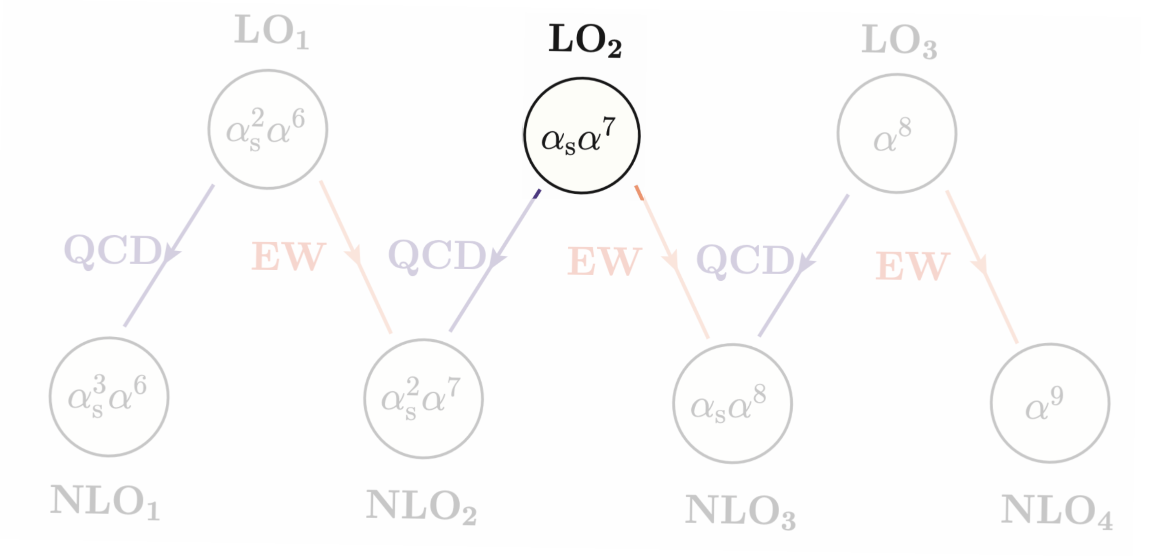


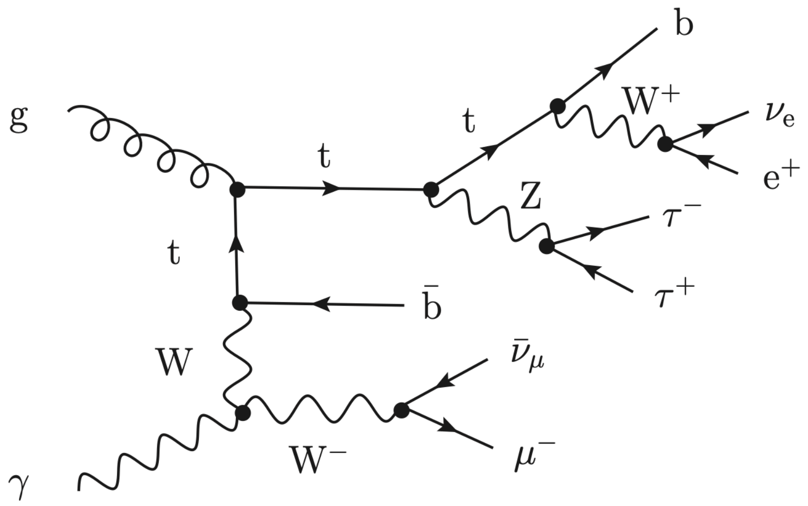
Structure of the calculation: LO_2 term

A.Denner, DL, and G.Pelliccioli [arXiv:2306.13535]

NLO QCD and NLO EW corrections to fully off-shell $t\bar{t}Z$:

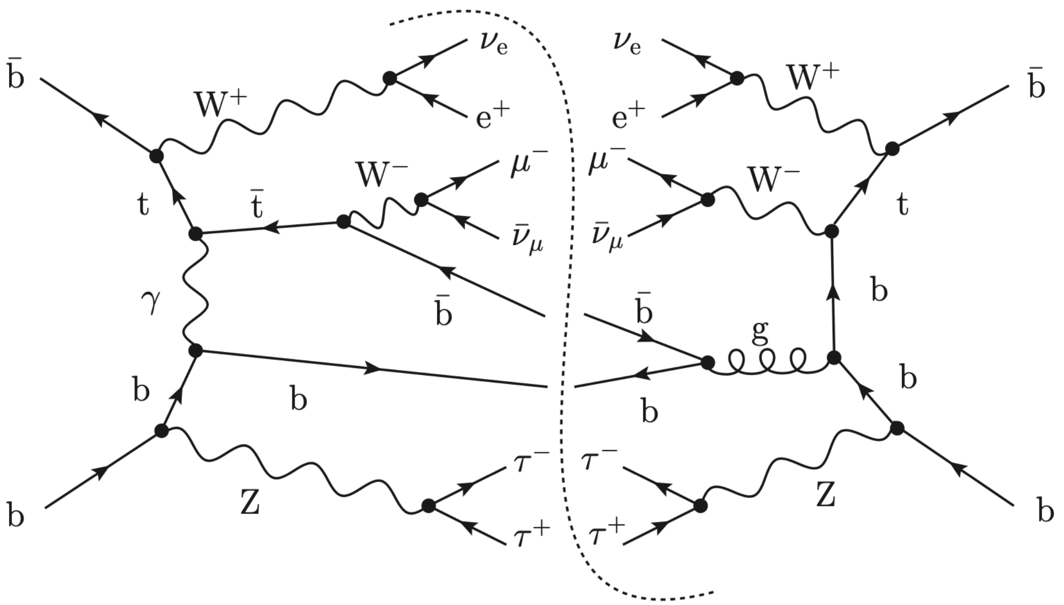
$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$$





- Light-quark interference terms vanish due to colour algebra.
- γg channel arises at this order.

- Non-vanishing bottom-interference terms.

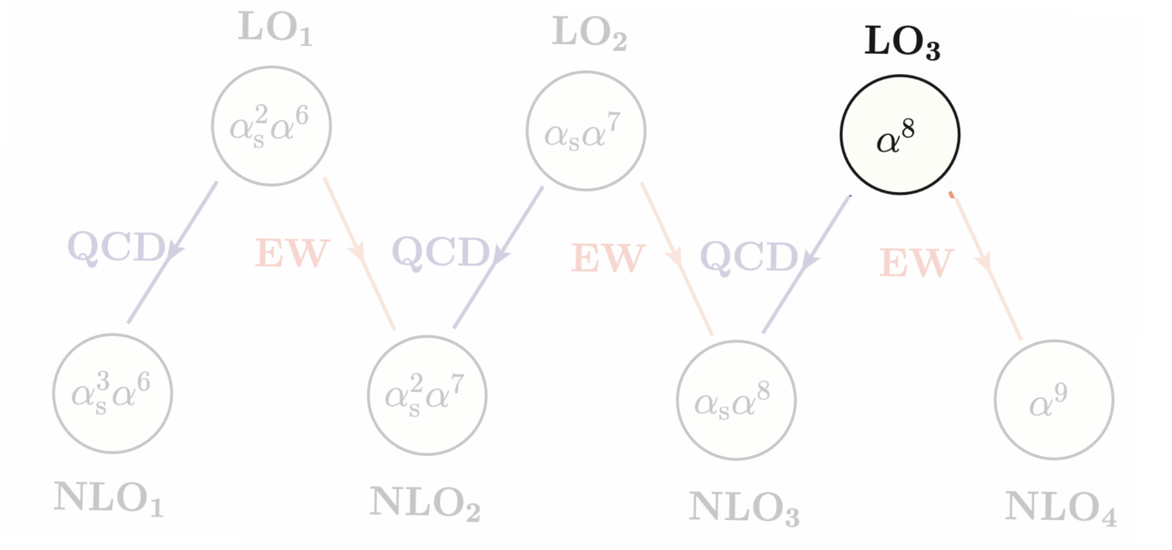


Structure of the calculation: LO_3 term

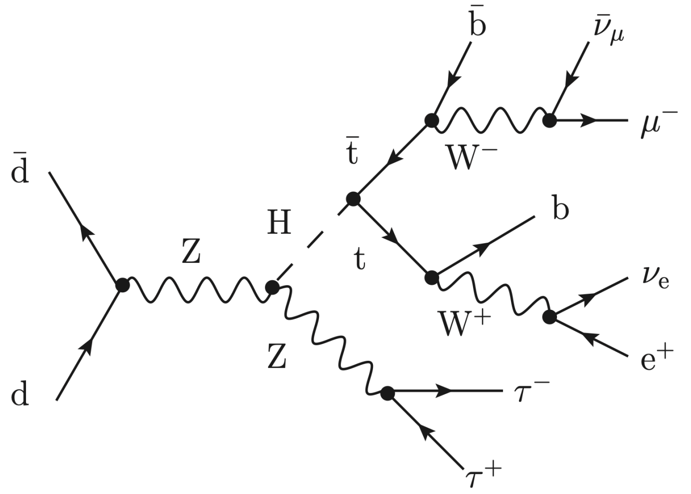
A.Denner, DL, and G.Pellicciolli [arXiv:2306.13535]

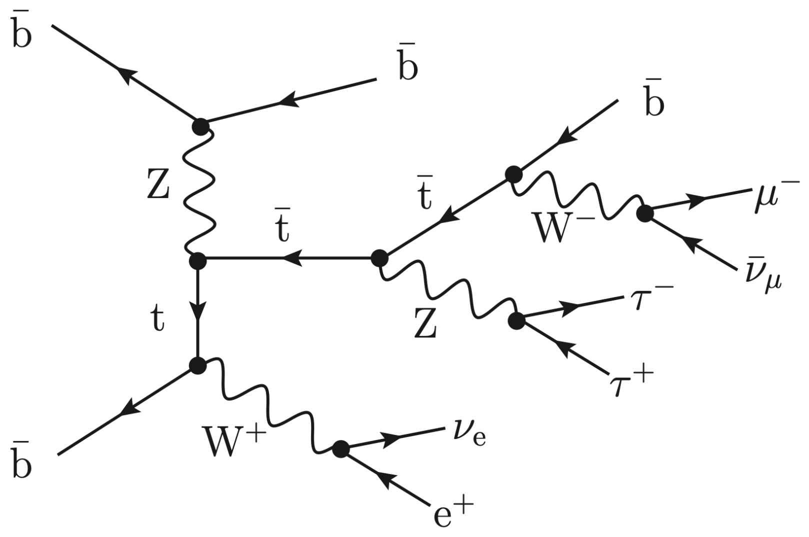
NLO QCD and NLO EW corrections to fully off-shell $t\bar{t}Z$:

$$pp \;\rightarrow\; e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$$



- Fully EW contribution → α/α_s-suppressed.
- $\gamma\gamma$ channel enters at this order.





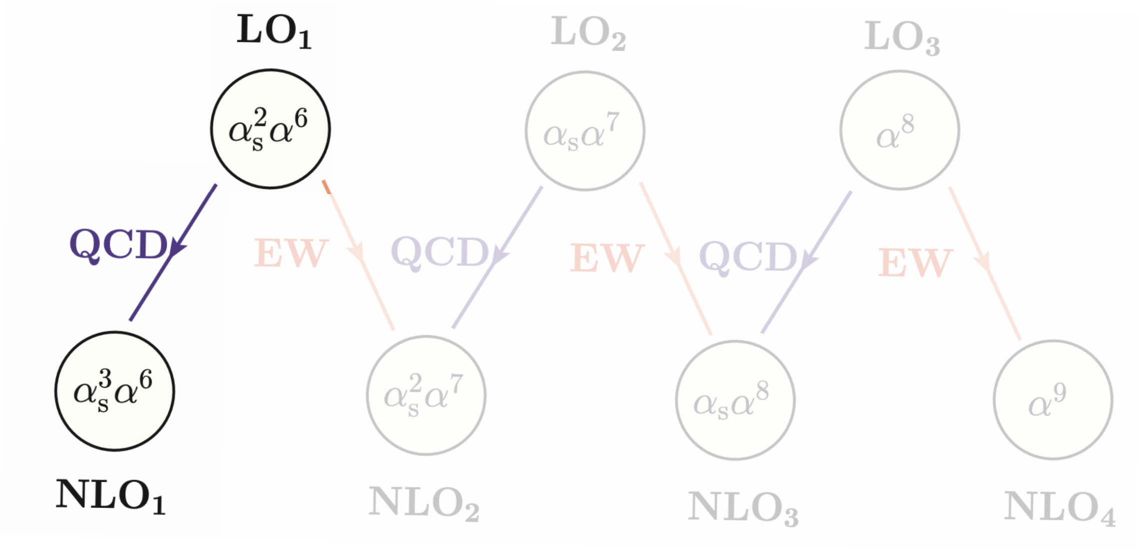
- New enhanced topologies for bottom-induced contributions.

Structure of the calculation: NLO_1 correction

A.Denner, DL, and G.Pellicciioli [arXiv:2306.13535]

NLO QCD and NLO EW corrections to fully off-shell $t\bar{t}Z$:

$$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$$



$$gg \rightarrow e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\,\bar{b}\,\tau^+\tau^-g\,,\quad q\bar{q} \rightarrow e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\,\bar{b}\,\tau^+\tau^-g\,,$$
$$g\bar{q} \rightarrow e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\,\bar{b}\,\tau^+\tau^-\bar{q}\,,\quad gq \rightarrow e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\,\bar{b}\,\tau^+\tau^-q\,.$$

- Dominant NLO correction.
- Validated against results obtained in HELAC-NLO framework [arXiv:2203.15688].

- Bottom-recombination rules crucial to avoid $g \rightarrow b\bar{b}$ singularity.

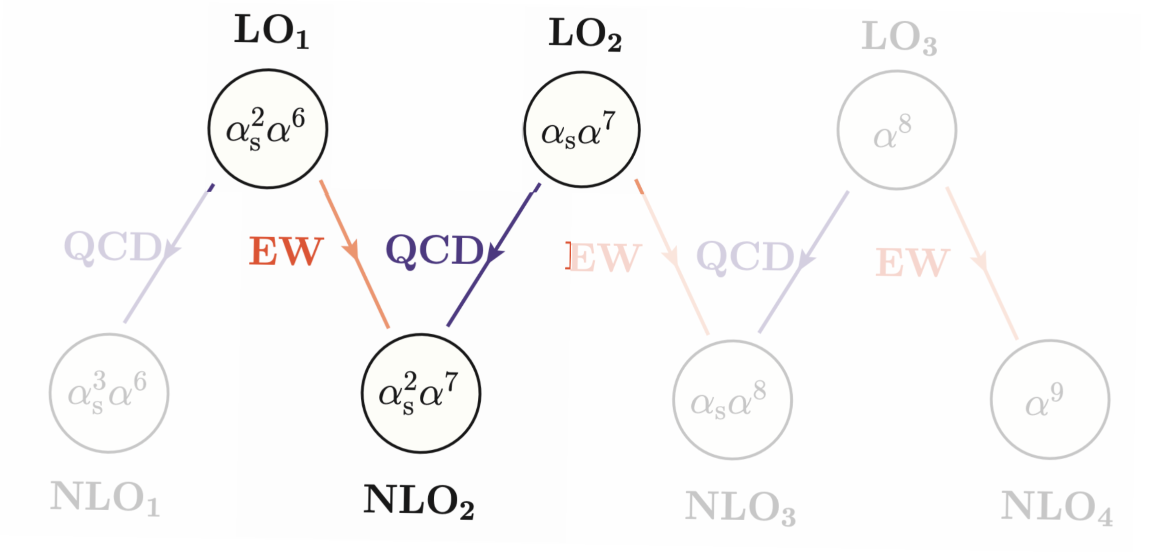
$$b\bar{b} \rightarrow e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\,\bar{b}\,\tau^+\tau^-g\,,$$
$$bb \rightarrow e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\,b\,\tau^+\tau^-g\,,\quad \bar{b}\bar{b} \rightarrow e^+\nu_e\,\mu^-\bar{\nu}_\mu\,\bar{b}\,\bar{b}\,\tau^+\tau^-g\,,$$
$$g\bar{b} \rightarrow e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\,\bar{b}\,\tau^+\tau^-\bar{b}\,,\quad gb \rightarrow e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\,\bar{b}\,\tau^+\tau^-b\,.$$

Structure of the calculation: NLO_2 correction

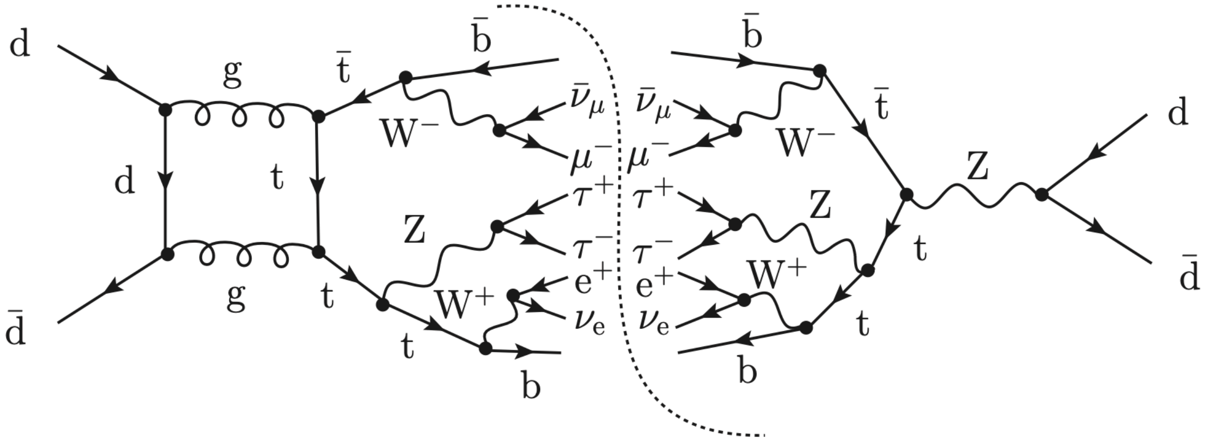
A.Denner, DL, and G.Pellicciioli [arXiv:2306.13535]

NLO QCD and NLO EW corrections to fully off-shell $t\bar{t}Z$:

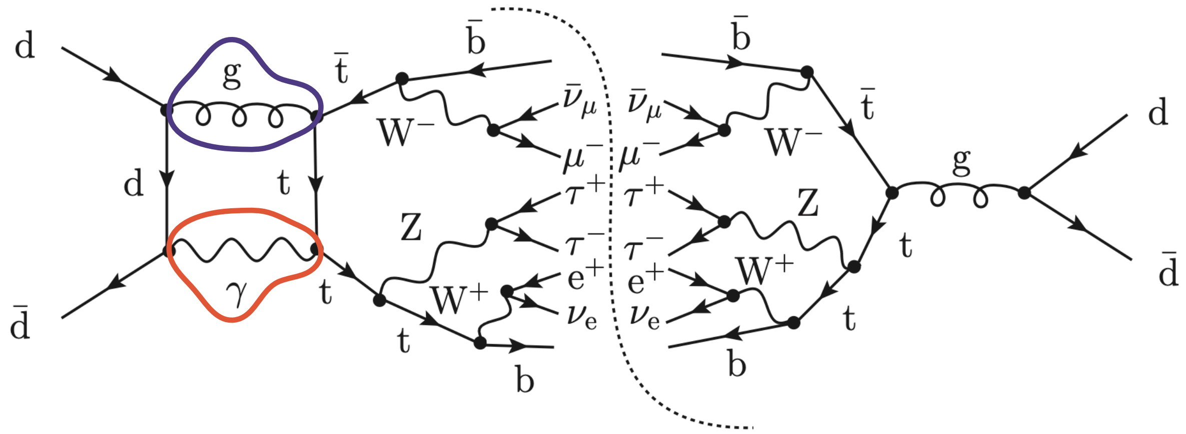
$$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$$



Two sources of corrections, distinguishable at the real-amplitude level, but not for the virtual contributions.



QCD correction to LO_2



QCD correction to LO_2

or

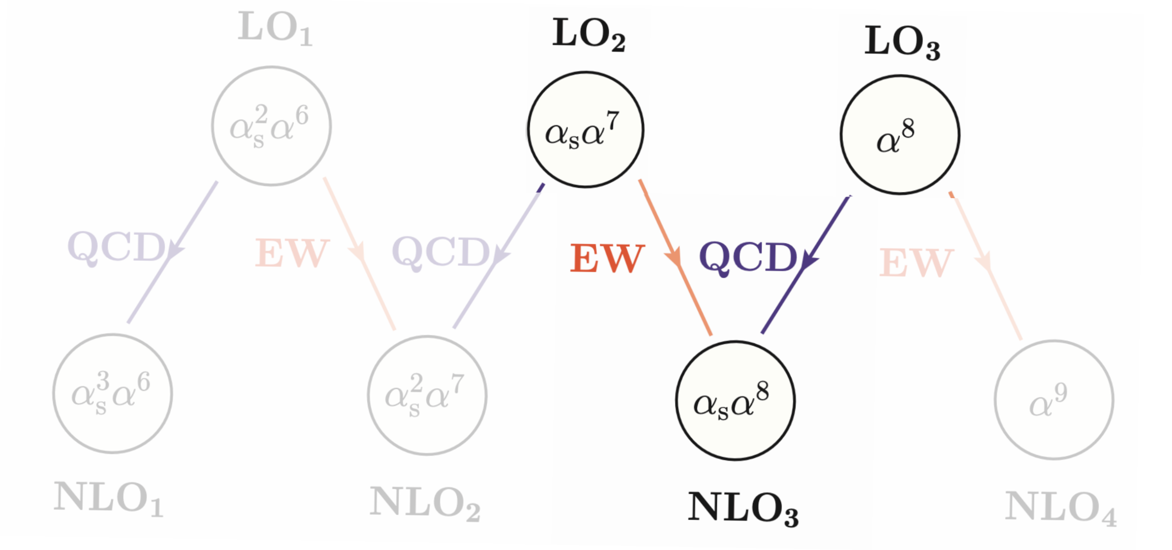
EW correction to LO_1 ?

Structure of the calculation: NLO_3 correction

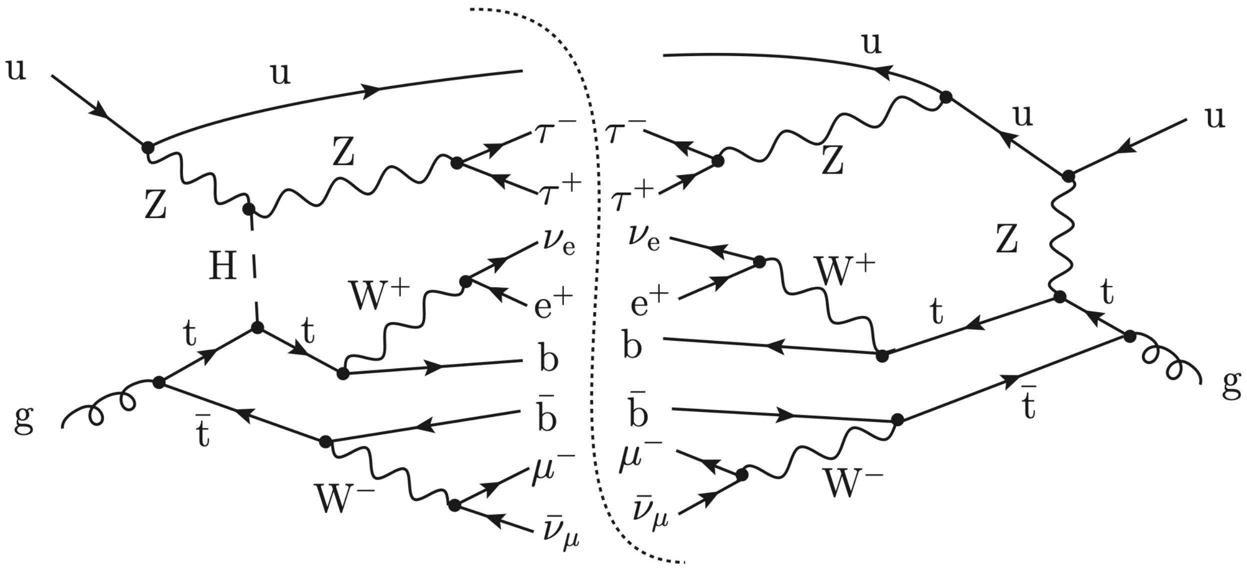
A.Denner, DL, and G.Pelliccioli [arXiv:2306.13535]

NLO QCD and NLO EW corrections to fully off-shell $t\bar{t}Z$:

$$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$$



- EW corrections to LO_2 for bottom- and γg-induced channels.
- Enhanced QCD corrections to LO_3 due to new scattering topologies in the light-quark + gluon channels.

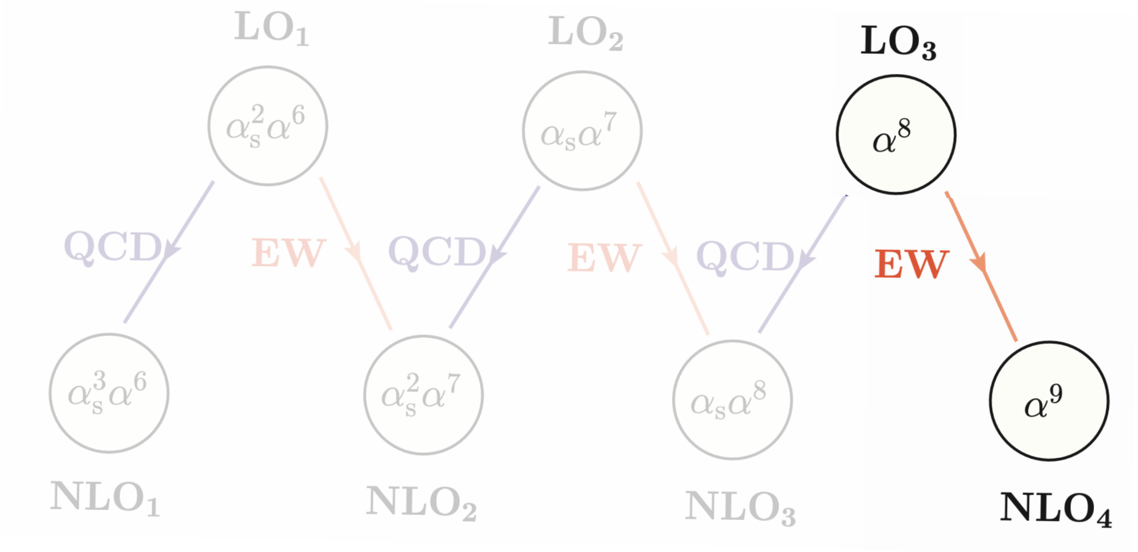


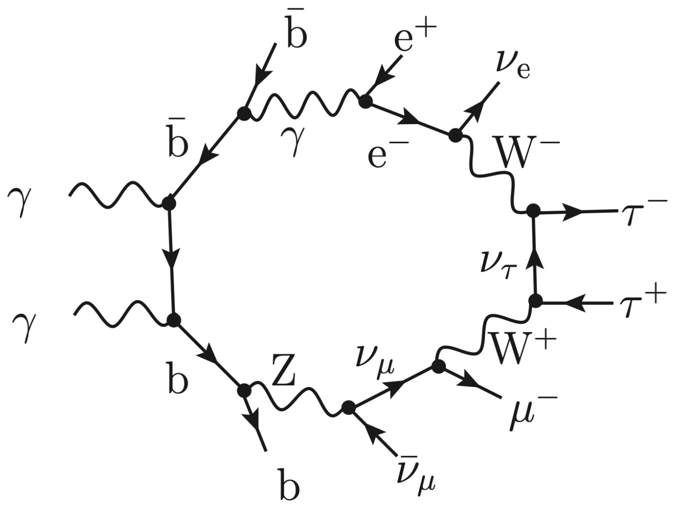
Structure of the calculation: NLO_4 correction

A.Denner, DL, and G.Pelliccioli [arXiv:2306.13535]

NLO QCD and NLO EW corrections to fully off-shell $t\bar{t}Z$:

$$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$$





- Contribution at the sub-per-mille level to the result.
- Computationally challenging virtual terms: high number of rank-6 10-point 1-loop functions to be evaluated!

Definition of the fiducial region

$$pp \;\to\; e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$$

- QCD partons with $|\eta| < 5$ are clustered into jets with anti-k_t clustering ($R = 0.4$).
  - Recombination rules: $j + j \to j, \qquad j_b + j \to j_b, \qquad j_b + j_b \to j.$
  - At least two b-jets are required: $p_{T,b} > 25\,GeV\,, \quad |\eta_b| < 2.5\,, \quad \Delta R_{bb} > 0.4\,.$
  - No cuts on additional light- or b-jet activity.
- Leptons are dressed with anti-k_t clustering ($R = 0.1$):
  - All leptons have to satisfy the cuts: $p_{T,\ell_i} > 20\,GeV\,, \quad |\eta_{\ell_i}| < 2.5\,, \quad \Delta R_{\ell_i \ell_j} > 0.4\,.$
- Missing transverse momentum cut: $p_{T,\,miss} > 40\,GeV\,.$

◆

- Renormalisation and factorisation scales set to:

$$\mu_0^{(d)} = \frac{1}{2}\left(m_{T,t}\, m_{T,\bar{t}}\right)^{1/2} = \frac{1}{2}\left(\sqrt{m_t^2 + p_{T,t}^2}\sqrt{m_t^2 + p_{T,\bar{t}}^2}\right)^{1/2}$$

Integrated Cross sections

perturbative order	σ_{nob} [ab]	$\frac{\sigma_{\mathrm{nob}}}{\sigma_{\mathrm{nob,\,LO_1}}}$	σ_{b} [ab]	$\frac{\sigma_{\mathrm{b}}}{\sigma_{\mathrm{nob,\,LO_1}}}$	σ [ab]	$\frac{\sigma}{\sigma_{\mathrm{LO_1}}}$
$\mathrm{LO_1}$	$107.246(5)^{+35.0\%}_{-24.0\%}$	1.0000	$0.31378(9)$	$+0.0029$	$107.560(5)^{+34.9\%}_{-23.9\%}$	1.0000
$\mathrm{LO_2}$	$0.7522(2)^{+11.1\%}_{-9.0\%}$	$+0.0070$	$-0.6305(2)$	-0.0059	$0.1217(3)$	$+0.0011$
$\mathrm{LO_3}$	$0.2862(1)^{+3.4\%}_{-3.4\%}$	$+0.0027$	$0.7879(2)$	$+0.0073$	$1.0742(3)^{+12.1\%}_{-14.9\%}$	$+0.0100$
$\mathrm{NLO_1}$	$-11.4(1)$	-0.1072	$0.518(3)$	$+0.0048$	$-10.9(1)$	-0.1016
$\mathrm{NLO_2}$	$-0.89(1)$	-0.0083	$0.051(3)$	$+0.0005$	$-0.84(1)$	-0.0078
$\mathrm{NLO_3}$	$1.126(4)$	$+0.0105$	$-0.089(4)$	-0.0008	$1.037(6)$	$+0.0096$
$\mathrm{NLO_4}$	$-0.0340(9)$	-0.0003	$-0.0180(9)$	-0.0002	$-0.052(1)$	-0.0005
$\mathrm{LO_1+NLO_1}$	$95.8(1)^{+0.4\%}_{-11.2\%}$	$+0.8933$	$0.832(3)$	$+0.0078$	$96.6(1)^{+0.4\%}_{-10.7\%}$	$+0.8984$
LO	$108.285(5)^{+34.7\%}_{-23.8\%}$	$+1.0097$	$0.4713(3)$	$+0.0044$	$108.756(5)^{+34.5\%}_{-23.7\%}$	$+1.0111$
LO+NLO	$97.0(1)^{+0.5\%}_{-11.2\%}$	$+0.9052$	$0.932(6)$	$+0.0087$	$98.0(1)^{+0.4\%}_{-10.7\%}$	$+0.9114$

Theoretical uncertainties from 7-point scale variation!

Integrated Cross sections: NLO_1 correction

perturbative order	$\sigma_{\rm nob}$ [ab]	$\frac{\sigma_{\rm nob}}{\sigma_{\rm nob,\,LO_1}}$	$\sigma_{\rm b}$ [ab]	$\frac{\sigma_{\rm b}}{\sigma_{\rm nob,\,LO_1}}$	σ [ab]	$\frac{\sigma}{\sigma_{\rm LO_1}}$
$\rm LO_1$	$107.246(5)^{+35.0\%}_{-24.0\%}$	1.0000	0.31378(9)	+0.0029	$107.560(5)^{+34.9\%}_{-23.9\%}$	1.0000
$\rm LO_2$	$0.7522(2)^{+11.1\%}_{-9.0\%}$	+0.0070	−0.6305(2)	−0.0059	0.1217(3)	+0.0011
$\rm LO_3$	$0.2862(1)^{+3.4\%}_{-3.4\%}$	+0.0027	0.7879(2)	+0.0073	$1.0742(3)^{+12.1\%}_{-14.9\%}$	+0.0100
$\rm NLO_1$	−11.4(1)	−0.1072	0.518(3)	+0.0048	−10.9(1)	−0.1016
$\rm NLO_2$	−0.89(1)	−0.0083	0.051(3)	+0.0005	−0.84(1)	−0.0078
$\rm NLO_3$	1.126(4)	+0.0105	−0.089(4)	−0.0008	1.037(6)	+0.0096
$\rm NLO_4$	−0.0340(9)	−0.0003	−0.0180(9)	−0.0002	−0.052(1)	−0.0005
$\rm LO_1+NLO_1$	$95.8(1)^{+0.4\%}_{-11.2\%}$	+0.8933	0.832(3)	+0.0078	$96.6(1)^{+0.4\%}_{-10.7\%}$	+0.8984
LO	$108.285(5)^{+34.7\%}_{-23.8\%}$	+1.0097	0.4713(3)	+0.0044	$108.756(5)^{+34.5\%}_{-23.7\%}$	+1.0111
LO+NLO	$97.0(1)^{+0.5\%}_{-11.2\%}$	+0.9052	0.932(6)	+0.0087	$98.0(1)^{+0.4\%}_{-10.7\%}$	+0.9114

Dominance of NLO_1 contribution:

- Roughly -10% correction of LO_1 ;
- Large reduction of scale uncertainties.

Theoretical uncertainties from 7-point scale variation!

Integrated Cross sections: Sub-leading contributions

perturbative order	σ_{nob} [ab]	$\frac{\sigma_{\text{nob}}}{\sigma_{\text{nob, LO}_1}}$	σ_{b} [ab]	$\frac{\sigma_{\text{b}}}{\sigma_{\text{nob, LO}_1}}$	σ [ab]	$\frac{\sigma}{\sigma_{\text{LO}_1}}$
LO_1	$107.246(5)^{+35.0\%}_{-24.0\%}$	1.0000	0.31378(9)	+0.0029	$107.560(5)^{+34.9\%}_{-23.9\%}$	1.0000
LO_2	$0.7522(2)^{+11.1\%}_{-9.0\%}$	+0.0070	−0.6305(2)	−0.0059	0.1217(3)	+0.0011
LO_3	$0.2862(1)^{+3.4\%}_{-3.4\%}$	+0.0027	0.7879(2)	+0.0073	$1.0742(3)^{+12.1\%}_{-14.9\%}$	+0.0100
NLO_1	−11.4(1)	−0.1072	0.518(3)	+0.0048	−10.9(1)	−0.1016
NLO_2	−0.89(1)	−0.0083	0.051(3)	+0.0005	−0.84(1)	−0.0078
NLO_3	1.126(4)	+0.0105	−0.089(4)	−0.0008	1.037(6)	+0.0096
NLO_4	−0.0340(9)	−0.0003	−0.0180(9)	−0.0002	−0.052(1)	−0.0005
LO_1+NLO_1	$95.8(1)^{+0.4\%}_{-11.2\%}$	+0.8933	0.832(3)	+0.0078	$96.6(1)^{+0.4\%}_{-10.7\%}$	+0.8984
LO	$108.285(5)^{+34.7\%}_{-23.8\%}$	+1.0097	0.4713(3)	+0.0044	$108.756(5)^{+34.5\%}_{-23.7\%}$	+1.0111
LO+NLO	$97.0(1)^{+0.5\%}_{-11.2\%}$	+0.9052	0.932(6)	+0.0087	$98.0(1)^{+0.4\%}_{-10.7\%}$	+0.9114

Sub-leading contributions:

- LO_2 + LO_3 ~ 1% of LO_1;
- NLO_2 + NLO_3 ~ 0.2% correction to LO_1.

Theoretical uncertainties from 7-point scale variation!

Integrated Cross sections: Bottom channels (at LO)

perturbative order	$\sigma_{\rm nob}$ [ab]	$\frac{\sigma_{\rm nob}}{\sigma_{\rm nob,\,LO_1}}$	$\sigma_{\rm b}$ [ab]	$\frac{\sigma_{\rm b}}{\sigma_{\rm nob,\,LO_1}}$	σ [ab]	$\frac{\sigma}{\sigma_{\rm LO_1}}$
$\rm LO_1$	$107.246(5)^{+35.0\%}_{-24.0\%}$	1.0000	0.31378(9)	+0.0029	$107.560(5)^{+34.9\%}_{-23.9\%}$	1.0000
$\rm LO_2$	$0.7522(2)^{+11.1\%}_{-9.0\%}$	+0.0070	−0.6305(2)	−0.0059	0.1217(3)	+0.0011
$\rm LO_3$	$0.2862(1)^{+3.4\%}_{-3.4\%}$	+0.0027	0.7879(2)	+0.0073	$1.0742(3)^{+12.1\%}_{-14.9\%}$	+0.0100
$\rm NLO_1$	−11.4(1)	−0.1072	0.518(3)	+0.0048	−10.9(1)	−0.1016
$\rm NLO_2$	−0.89(1)	−0.0083	0.051(3)	+0.0005	−0.84(1)	−0.0078
$\rm NLO_3$	1.126(4)	+0.0105	−0.089(4)	−0.0008	1.037(6)	+0.0096
$\rm NLO_4$	−0.0340(9)	−0.0003	−0.0180(9)	−0.0002	−0.052(1)	−0.0005
$\rm LO_1+NLO_1$	$95.8(1)^{+0.4\%}_{-11.2\%}$	+0.8933	0.832(3)	+0.0078	$96.6(1)^{+0.4\%}_{-10.7\%}$	+0.8984
LO	$108.285(5)^{+34.7\%}_{-23.8\%}$	+1.0097	0.4713(3)	+0.0044	$108.756(5)^{+34.5\%}_{-23.7\%}$	+1.0111
LO+NLO	$97.0(1)^{+0.5\%}_{-11.2\%}$	+0.9052	0.932(6)	+0.0087	$98.0(1)^{+0.4\%}_{-10.7\%}$	+0.9114

Role of the bottom-induced channels:

- Impact of LO bottom contributions at the sub-percent level on full *LO*;

Theoretical uncertainties from 7-point scale variation!

Integrated Cross sections: Bottom channels (at NLO)

perturbative order	$\sigma_{\rm nob}$ [ab]	$\frac{\sigma_{\rm nob}}{\sigma_{\rm nob,\,LO_1}}$	$\sigma_{\rm b}$ [ab]	$\frac{\sigma_{\rm b}}{\sigma_{\rm nob,\,LO_1}}$	σ [ab]	$\frac{\sigma}{\sigma_{\rm LO_1}}$
$\rm LO_1$	$107.246(5)^{+35.0\%}_{-24.0\%}$	1.0000	$0.31378(9)$	$+0.0029$	$107.560(5)^{+34.9\%}_{-23.9\%}$	1.0000
$\rm LO_2$	$0.7522(2)^{+11.1\%}_{-9.0\%}$	$+0.0070$	$-0.6305(2)$	-0.0059	$0.1217(3)$	$+0.0011$
$\rm LO_3$	$0.2862(1)^{+3.4\%}_{-3.4\%}$	$+0.0027$	$0.7879(2)$	$+0.0073$	$1.0742(3)^{+12.1\%}_{-14.9\%}$	$+0.0100$
$\rm NLO_1$	$-11.4(1)$	-0.1072	$0.518(3)$	$+0.0048$	$-10.9(1)$	-0.1016
$\rm NLO_2$	$-0.89(1)$	-0.0083	$0.051(3)$	$+0.0005$	$-0.84(1)$	-0.0078
$\rm NLO_3$	$1.126(4)$	$+0.0105$	$-0.089(4)$	-0.0008	$1.037(6)$	$+0.0096$
$\rm NLO_4$	$-0.0340(9)$	-0.0003	$-0.0180(9)$	-0.0002	$-0.052(1)$	-0.0005
$\rm LO_1+NLO_1$	$95.8(1)^{+0.4\%}_{-11.2\%}$	$+0.8933$	$0.832(3)$	$+0.0078$	$96.6(1)^{+0.4\%}_{-10.7\%}$	$+0.8984$
LO	$108.285(5)^{+34.7\%}_{-23.8\%}$	$+1.0097$	$0.4713(3)$	$+0.0044$	$108.756(5)^{+34.5\%}_{-23.7\%}$	$+1.0111$
LO+NLO	$97.0(1)^{+0.5\%}_{-11.2\%}$	$+0.9052$	$0.932(6)$	$+0.0087$	$98.0(1)^{+0.4\%}_{-10.7\%}$	$+0.9114$

Role of the bottom-induced channels:

- Impact of LO bottom contributions at the sub-percent level on full *LO*;
- Roughly +1% correction to the full result after including bottom-channels at LO and NLO.

Theoretical uncertainties from 7-point scale variation!

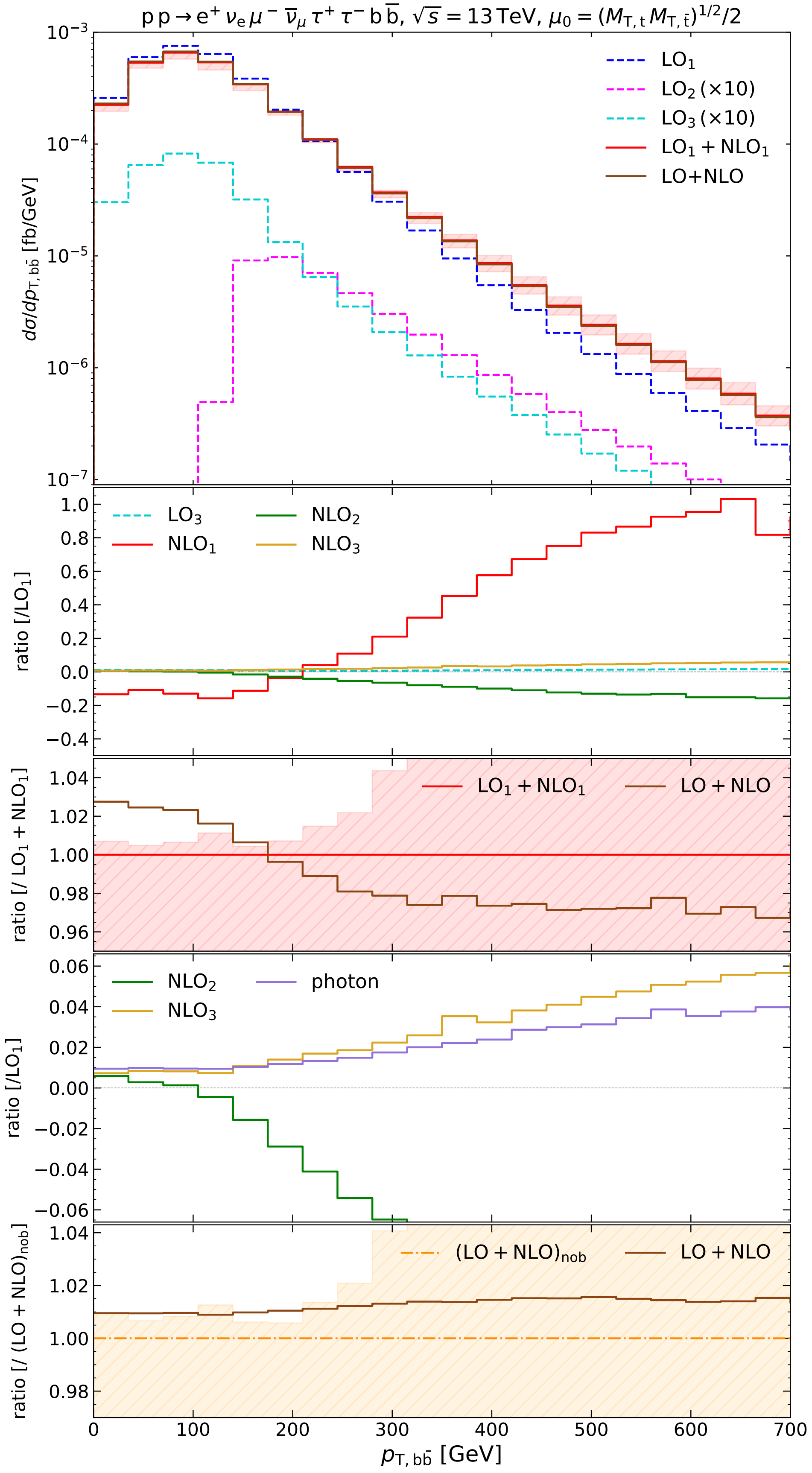
Integrated Cross sections: NLO_4 corrections

perturbative order	σ_{nob} [ab]	$\frac{\sigma_{\mathrm{nob}}}{\sigma_{\mathrm{nob,\,LO_1}}}$	σ_{b} [ab]	$\frac{\sigma_{\mathrm{b}}}{\sigma_{\mathrm{nob,\,LO_1}}}$	σ [ab]	$\frac{\sigma}{\sigma_{\mathrm{LO_1}}}$
$\mathrm{LO_1}$	$107.246(5)^{+35.0\%}_{-24.0\%}$	1.0000	0.31378(9)	+0.0029	$107.560(5)^{+34.9\%}_{-23.9\%}$	1.0000
$\mathrm{LO_2}$	$0.7522(2)^{+11.1\%}_{-9.0\%}$	+0.0070	−0.6305(2)	−0.0059	0.1217(3)	+0.0011
$\mathrm{LO_3}$	$0.2862(1)^{+3.4\%}_{-3.4\%}$	+0.0027	0.7879(2)	+0.0073	$1.0742(3)^{+12.1\%}_{-14.9\%}$	+0.0100
$\mathrm{NLO_1}$	−11.4(1)	−0.1072	0.518(3)	+0.0048	−10.9(1)	−0.1016
$\mathrm{NLO_2}$	−0.89(1)	−0.0083	0.051(3)	+0.0005	−0.84(1)	−0.0078
$\mathrm{NLO_3}$	1.126(4)	+0.0105	−0.089(4)	−0.0008	1.037(6)	+0.0096
$\mathrm{NLO_4}$	−0.0340(9)	−0.0003	−0.0180(9)	−0.0002	−0.052(1)	−0.0005
$\mathrm{LO_1{+}NLO_1}$	$95.8(1)^{+0.4\%}_{-11.2\%}$	+0.8933	0.832(3)	+0.0078	$96.6(1)^{+0.4\%}_{-10.7\%}$	+0.8984
LO	$108.285(5)^{+34.7\%}_{-23.8\%}$	+1.0097	0.4713(3)	+0.0044	$108.756(5)^{+34.5\%}_{-23.7\%}$	+1.0111
LO+NLO	$97.0(1)^{+0.5\%}_{-11.2\%}$	+0.9052	0.932(6)	+0.0087	$98.0(1)^{+0.4\%}_{-10.7\%}$	+0.9114

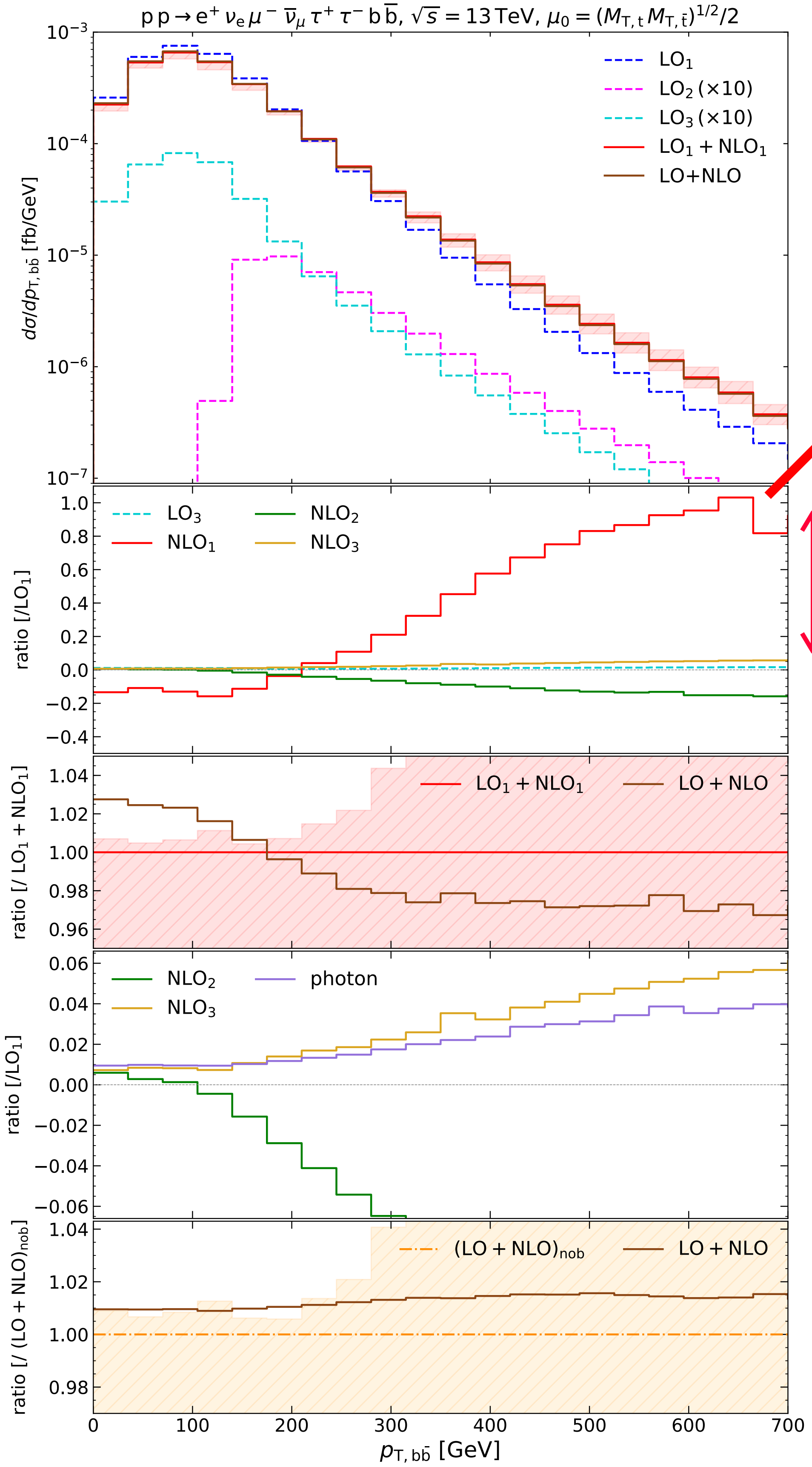
Fully off-shell NLO_4 corrections confirm to be negligible, so that omitting them is under good theoretical control.

Theoretical uncertainties from 7-point scale variation!

Differential Cross sections: $p_{T,b\bar{b}}$



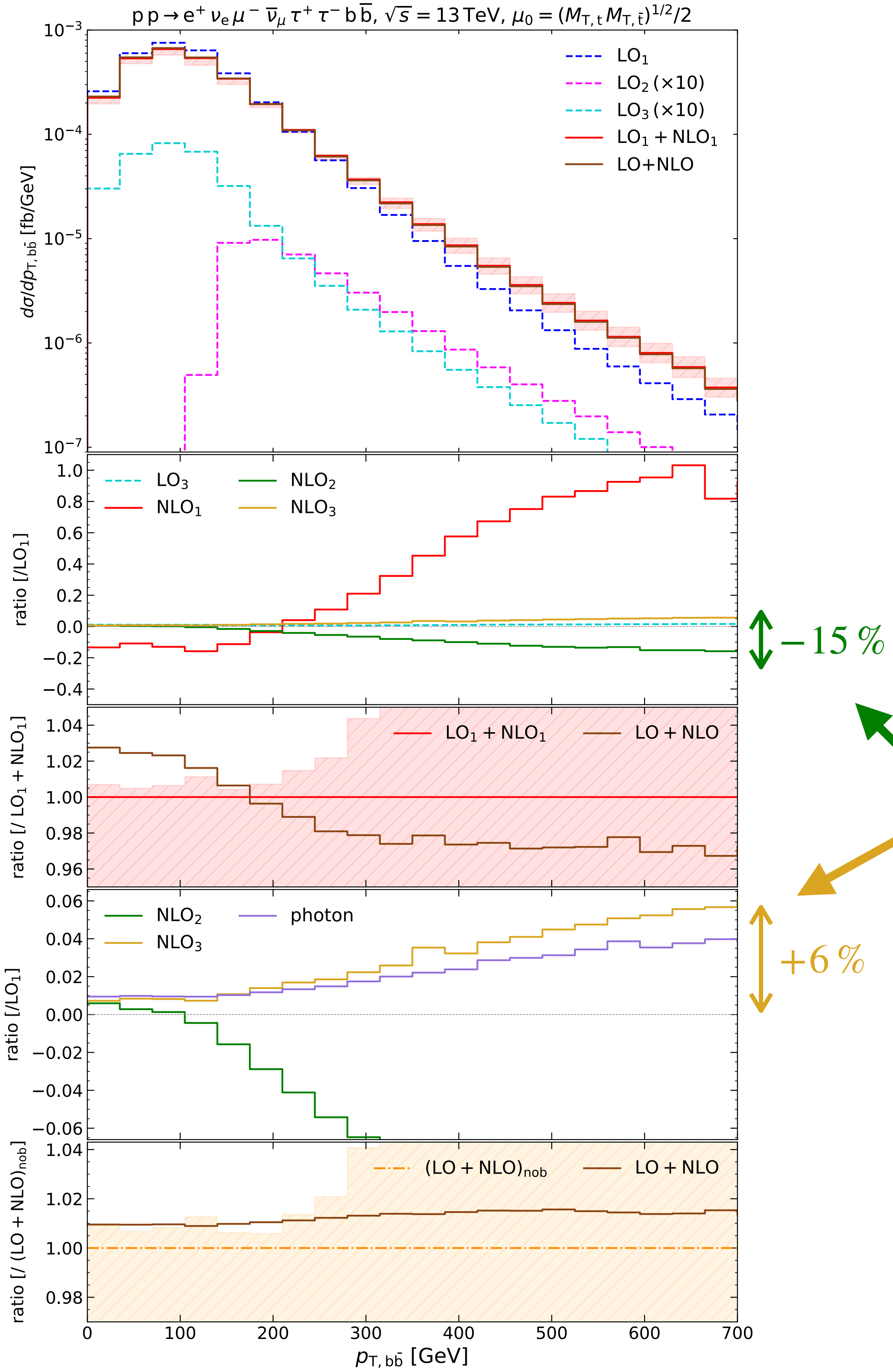
Differential Cross sections: $p_{T,b\bar{b}}$



$+100\,\%$

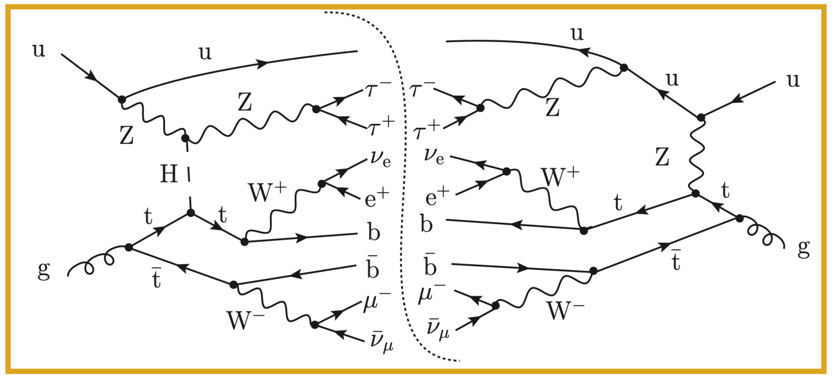
- Large NLO_1 corrections due to giant QCD K-factor.

Differential Cross sections: $p_{T,b\bar{b}}$

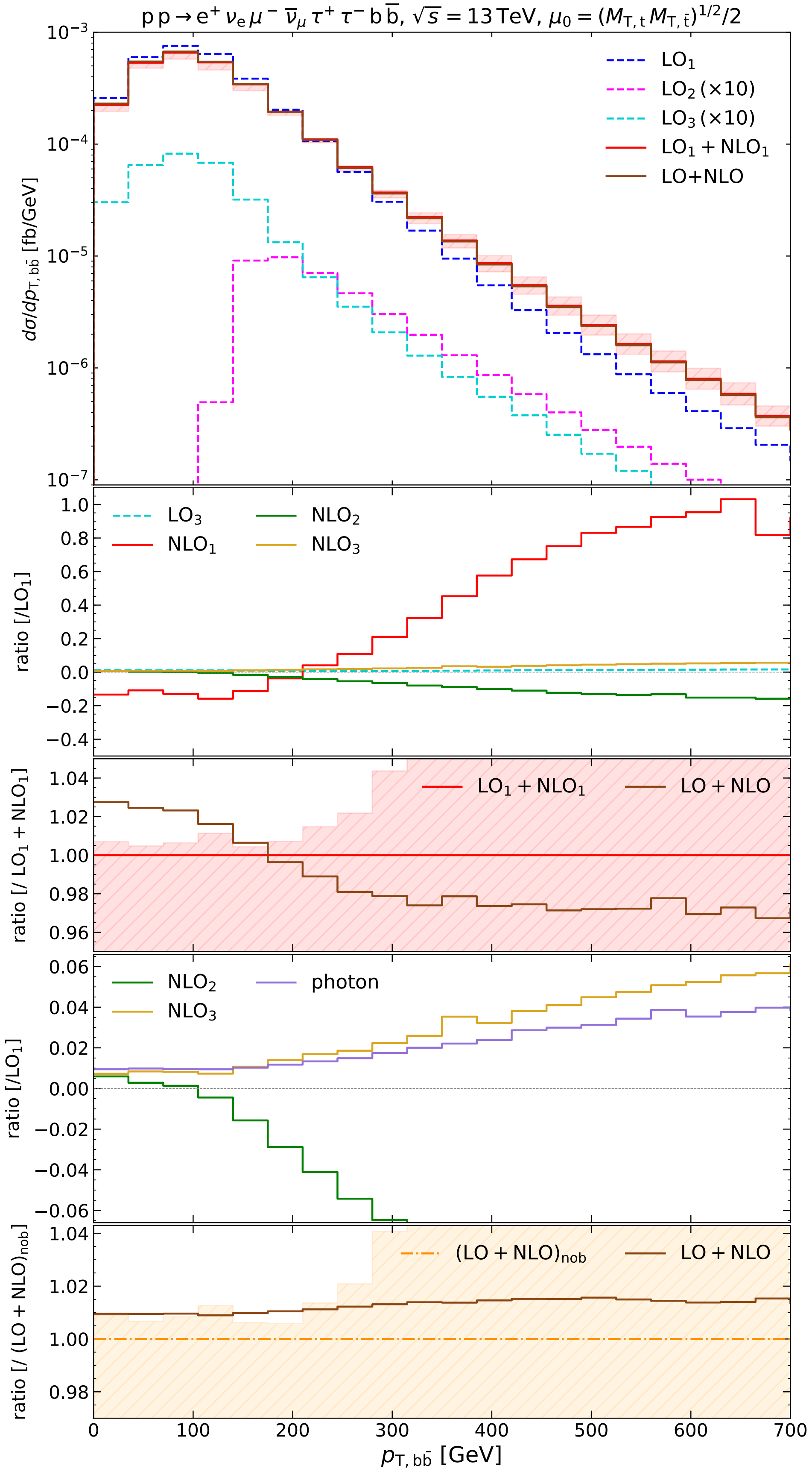


- Large NLO_1 corrections due to giant QCD K-factor.

- Interplay between NLO_2 corrections (EW Sudakov logarithms) and NLO_3 ones (dominance of real gluon-induced contributions).



Differential Cross sections: $p_{T,b\bar{b}}$

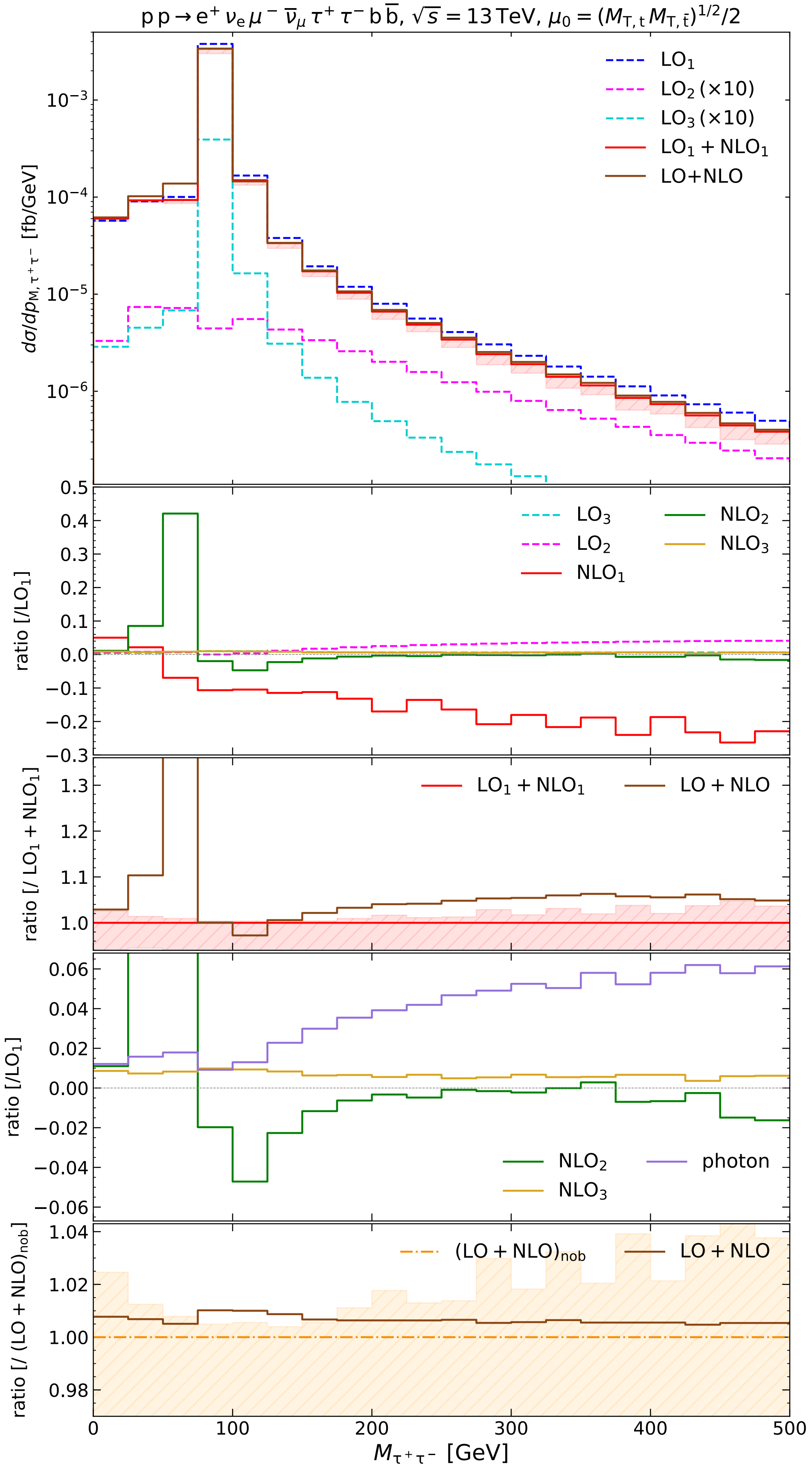


- Large NLO_1 corrections due to giant QCD K-factor.

- Interplay between NLO_2 corrections (EW Sudakov logarithms) and NLO_3 ones (dominance of real gluon-induced contributions).

- Moderate correction due to the inclusion of bottom channels.

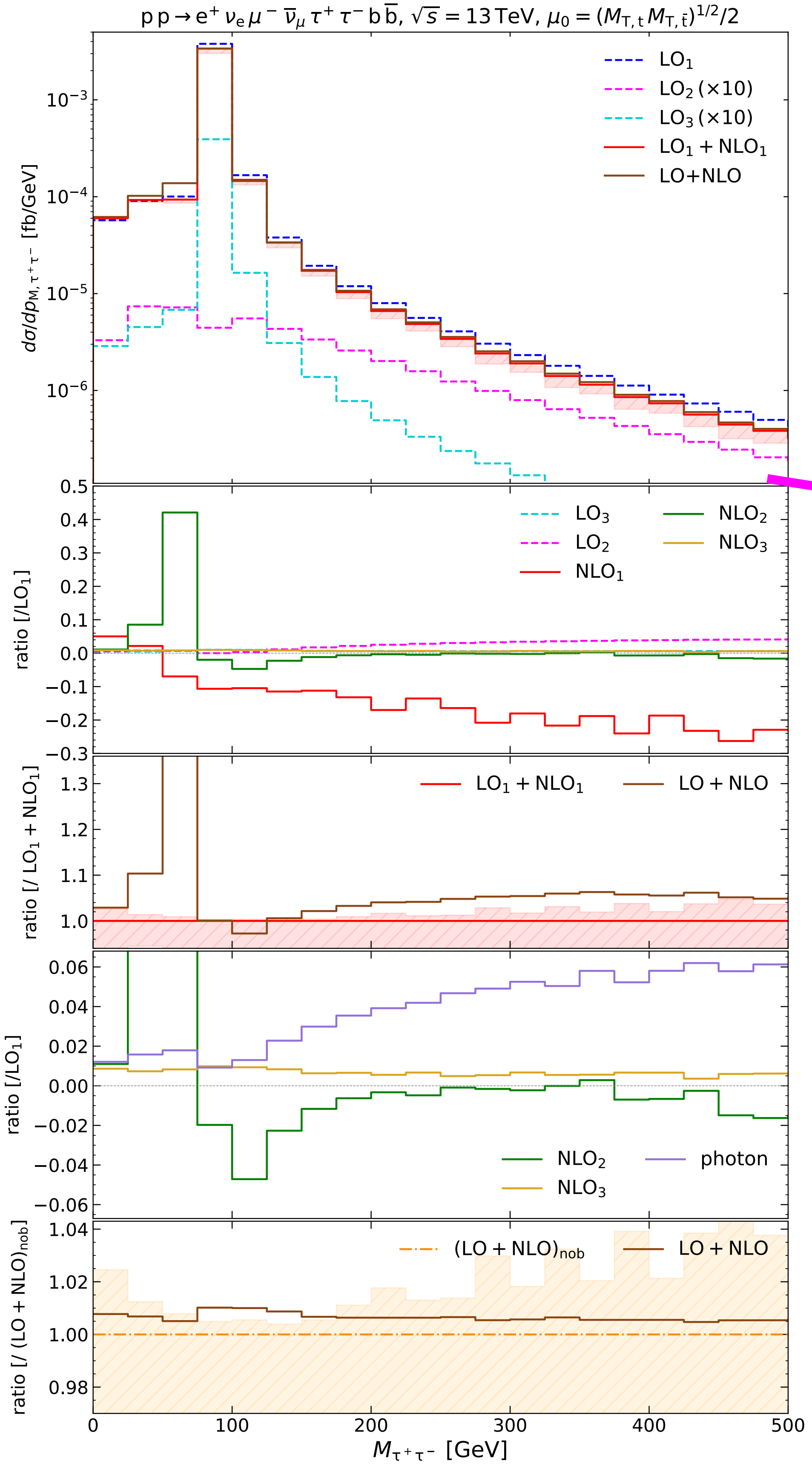
Differential Cross sections: $M_{\tau^+\tau^-}$



$-20\,\%$

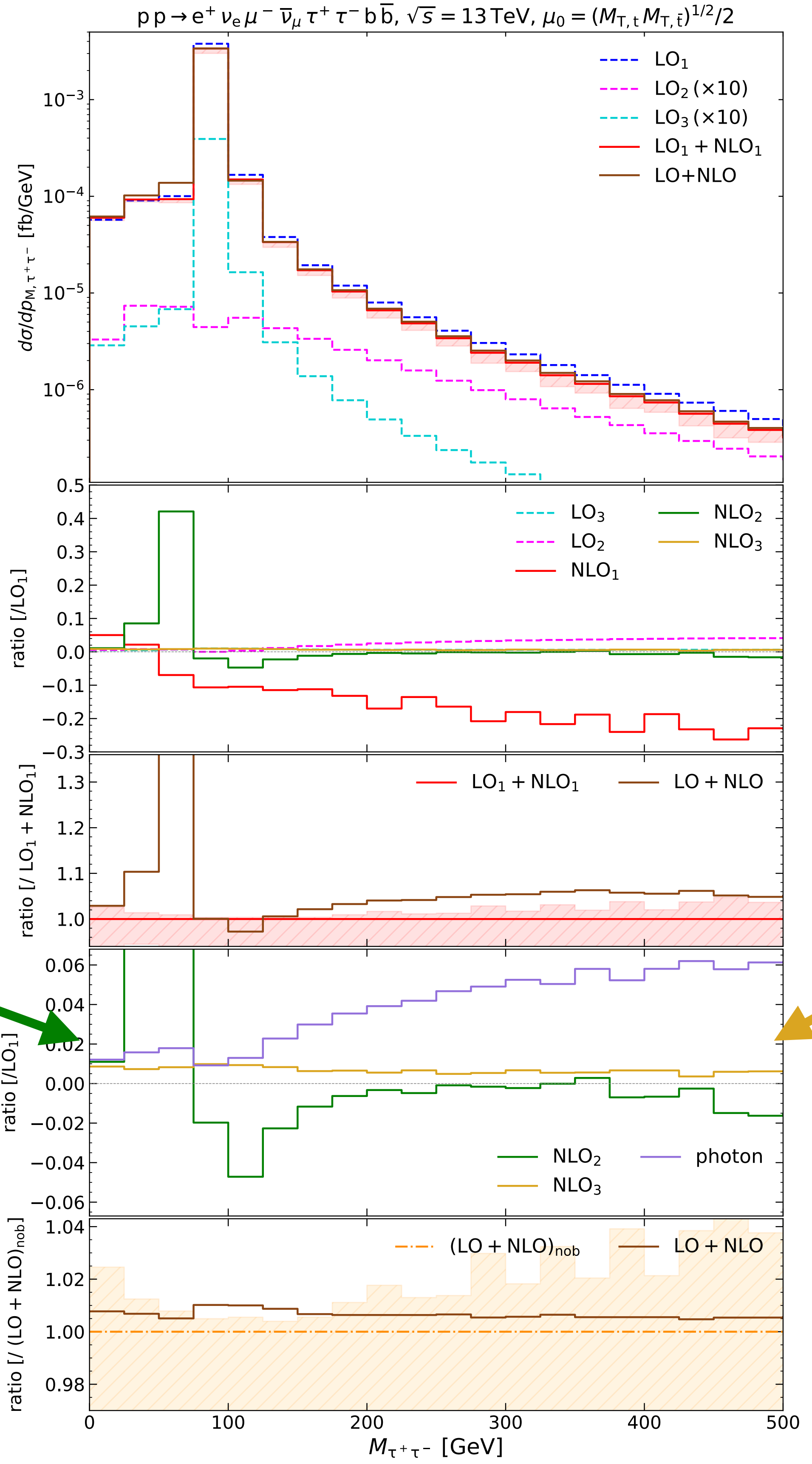
- Negative NLO_1 corrections in the far off-shell region.

Differential Cross sections: $M_{\tau^+\tau^-}$



- Negative NLO_1 corrections in the far off-shell region.
- LO_2 is the largest sub-leading contribution in the off-shell region, due to the γg channel.

Differential Cross sections: $M_{\tau^+\tau^-}$



- Negative NLO_1 corrections in the far off-shell region.
- LO_2 is the largest sub-leading contribution in the off-shell region, due to the γg channel.
- NLO_2 corrections are the dominant ones around the Z-mass pole (radiative return due to real photon radiation).
- Flat QCD-like corrections from NLO_3 terms.

Summary:

- Fully off-shell calculations for $t\bar{t}Z$ are important for a reliable description of the process both at the inclusive and at the differential level.

- NLO QCD corrections are the dominant NLO contributions:
  - At the inclusive level, sub-leading LO and NLO terms amount to less than a percent correction;
  - At the differential level, sub-leading terms are crucial for a correct description of the normalisation and the shape of many observables → non-trivial interplay among different corrections.

Summary:

- Fully off-shell calculations for $t\bar{t}Z$ are important for a reliable description of the process both at the inclusive and at the differential level.

- NLO QCD corrections are the dominant NLO contributions:
    - At the inclusive level, sub-leading LO and NLO terms amount to less than a percent correction;
    - At the differential level, sub-leading terms are crucial for a correct description of the normalisation and the shape of many observables → non-trivial interplay among different corrections.

Thank you for your attention

Backup

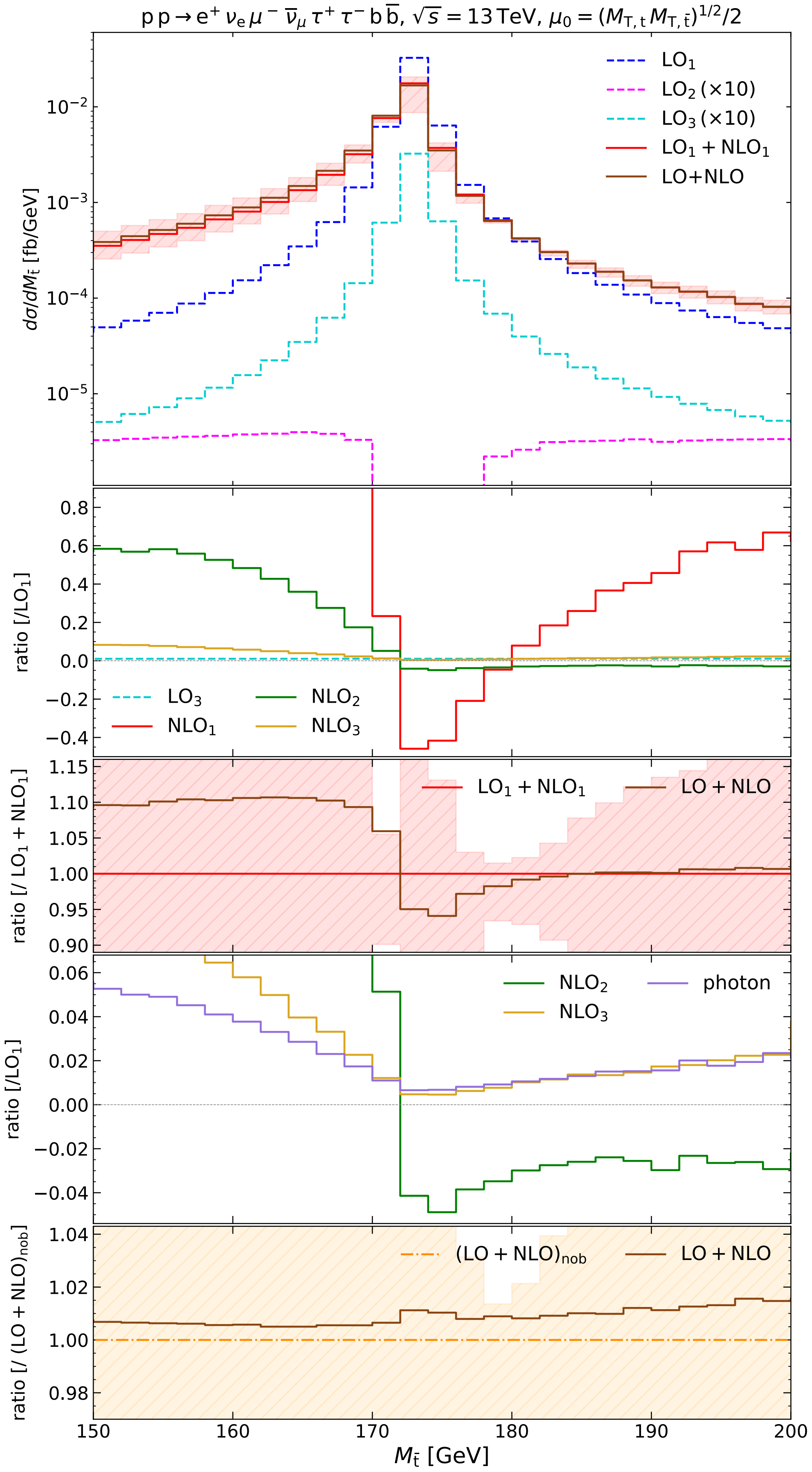
Fiducial Cross sections at LO: a channel-by-channel analysis

Channel	LO_1	LO_2	LO_3
gg	74.760(4)	-	-
$q\bar{q}$	32.486(3)	-	0.2848(1)
$\mathrm{b}\bar{\mathrm{b}}$	0.29208(9)	$-0.6330(2)$	0.7821(2)
$\bar{\mathrm{b}}\bar{\mathrm{b}}/\mathrm{bb}$	0.02171(2)	0.002516(9)	0.005817(9)
γg	-	0.7522(2)	-
$\gamma\gamma$	-	-	0.001431(6)
sum	107.560(5)	0.1217(3)	1.0742(3)

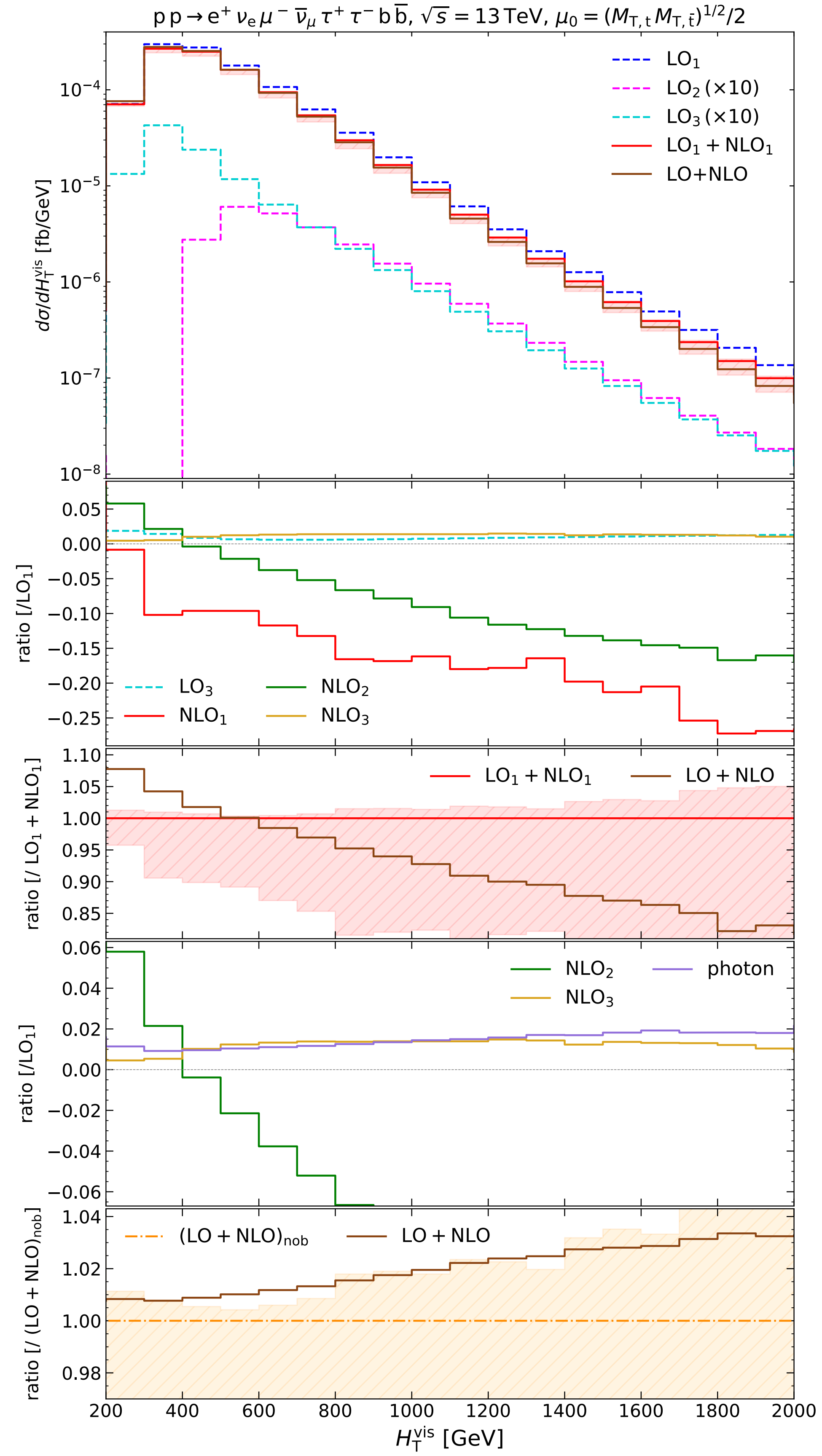
Fiducial Cross sections at NLO: a channel-by-channel analysis

Channel	NLO_1	NLO_2	NLO_3	NLO_4
gg	−14.9(1)	−0.107(9)	-	-
$q\bar{q}$	−12.35(7)	−1.177(6)	0.013(4)	−0.0380(9)
$\mathrm{b}\bar{\mathrm{b}}$	−0.106(2)	0.195(2)	−0.324(4)	−0.0194(9)
$\bar{\mathrm{b}}\bar{\mathrm{b}}/\mathrm{bb}$	0.00031(7)	−0.0016(1)	−0.0022(2)	−0.00059(2)
$\gamma\mathrm{g}$	-	−0.136(2)	0.0101(8)	-
$\gamma\gamma$	-	-	−0.00020(3)	−0.00010(2)
$\mathrm{g}q/\mathrm{g}\bar{q}$	15.77(3)	0.0570(5)	1.102(1)	-
$\mathrm{gb}/\mathrm{g}\bar{\mathrm{b}}$	0.624(2)	−0.146(2)	0.237(2)	-
$\gamma q/\gamma\bar{q}$	-	0.4774(8)	-	0.00403(2)
$\gamma\mathrm{b}/\gamma\bar{\mathrm{b}}$	-	0.00347(9)	−0.00026(1)	0.00194(1)
sum	−10.9(1)	−0.83(1)	1.037(6)	−0.052(1)

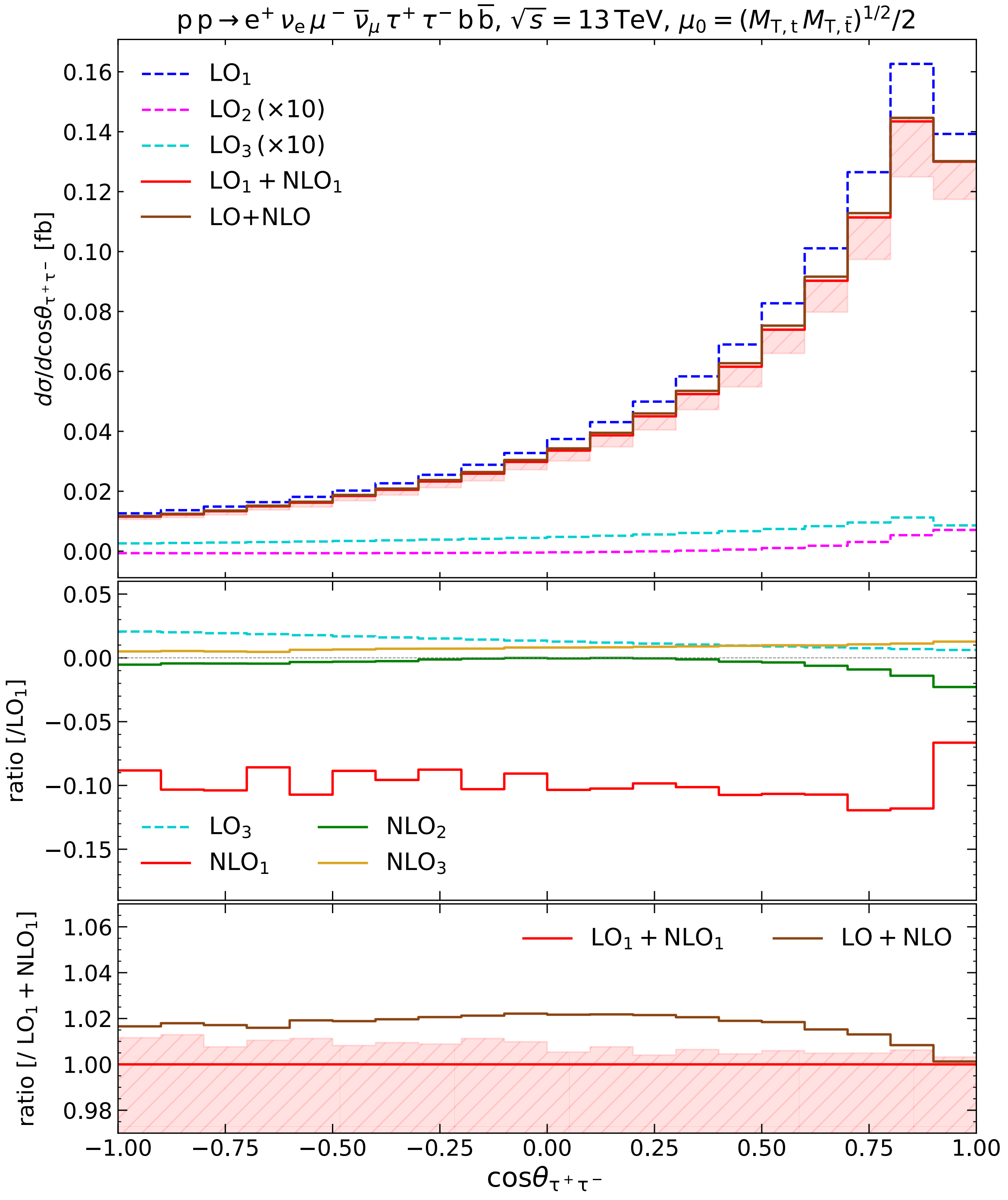
Differential Cross sections: $M_{\bar{t}}$

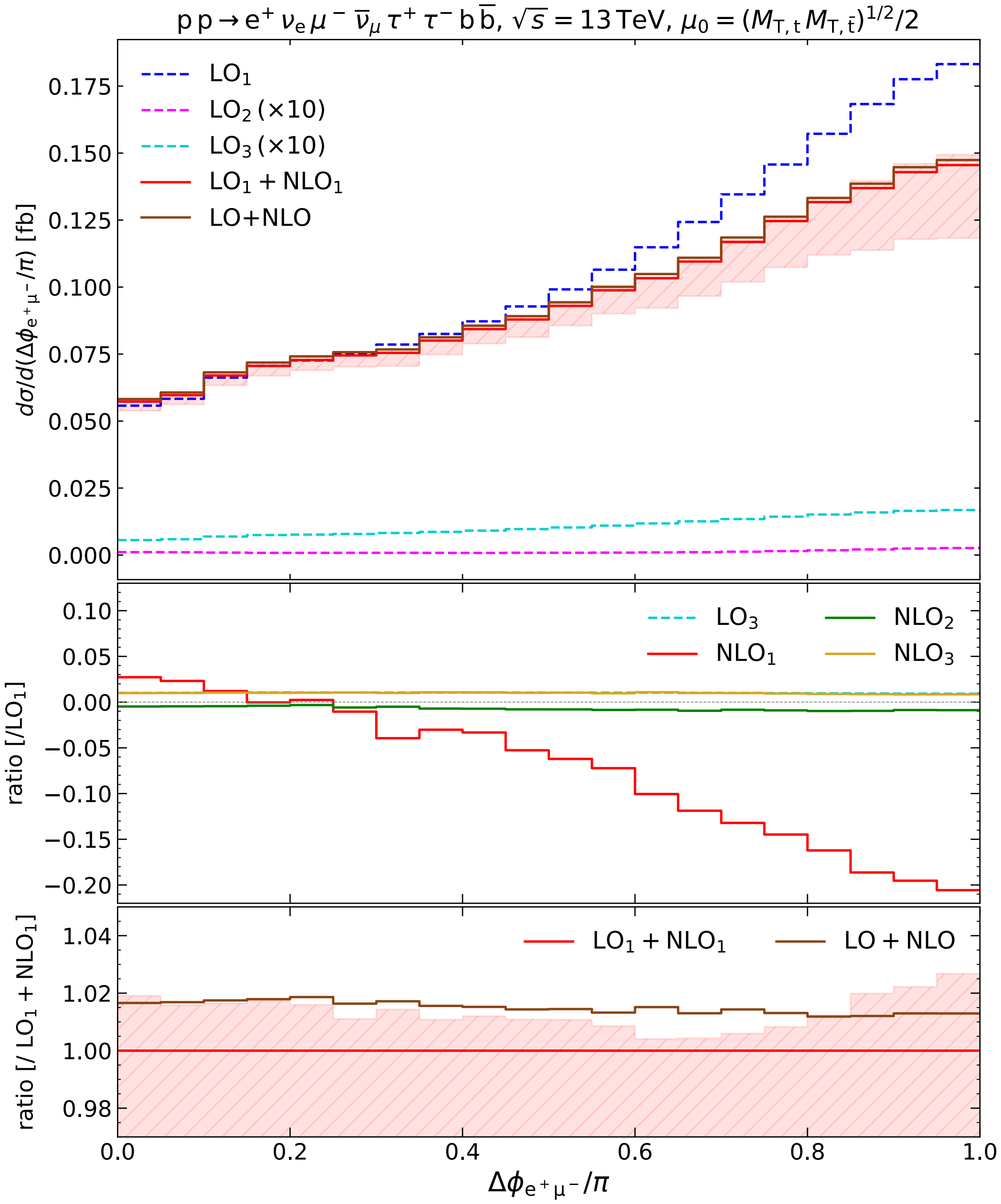


Differential Cross sections: H_T^{vis}

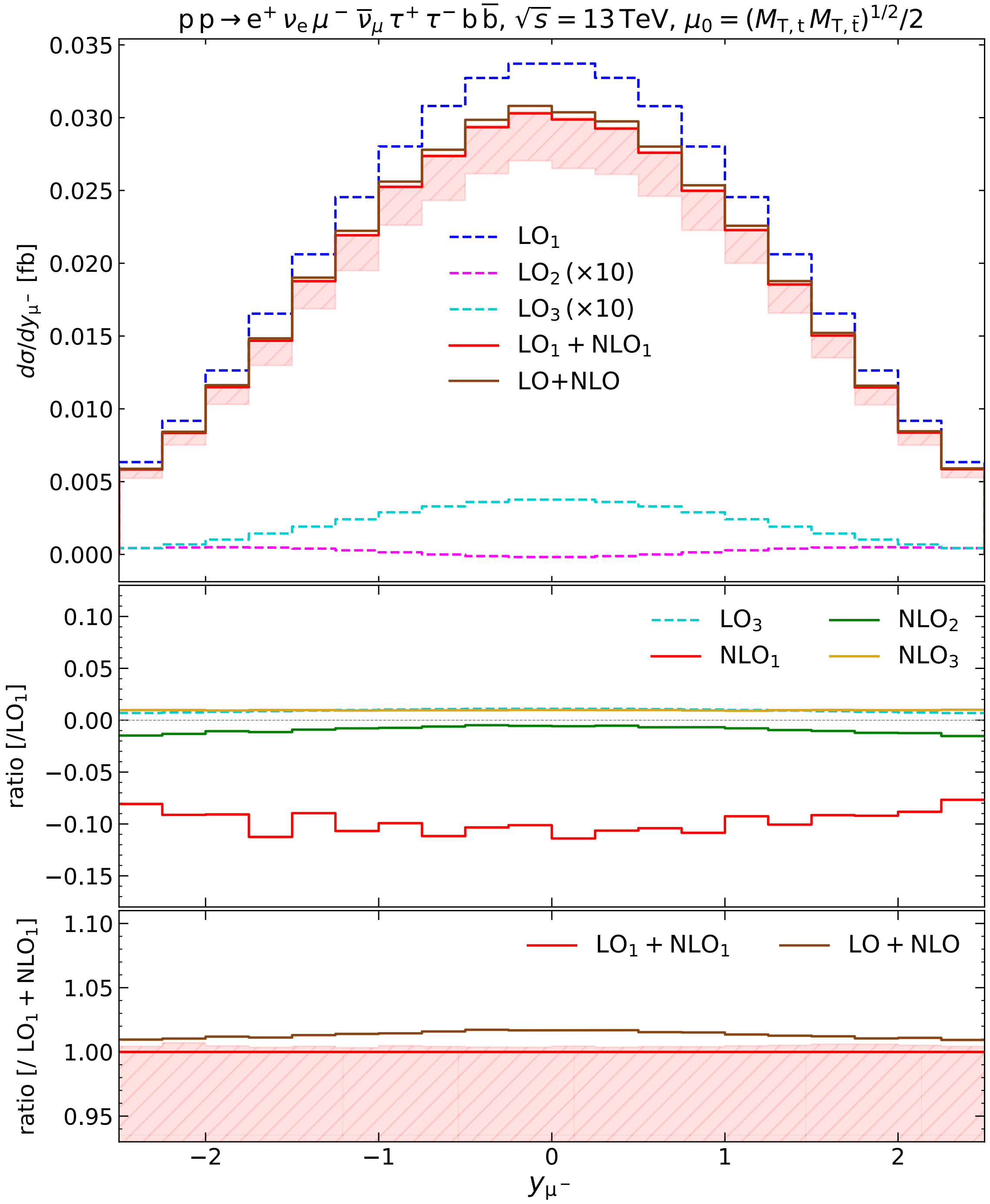


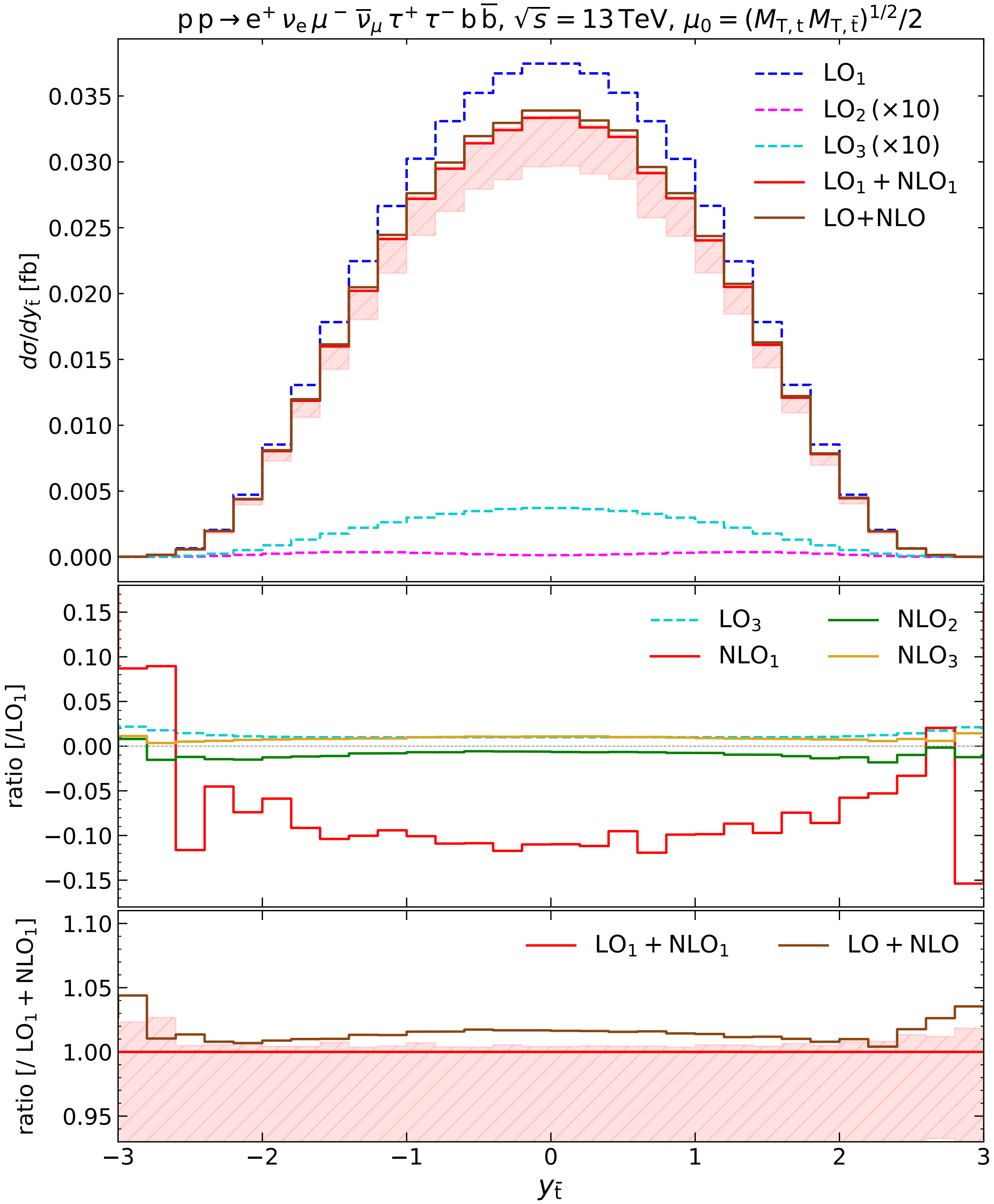
Differential Cross sections: Angular Observables





Differential Cross sections: Rapidity Distributions





Differential Cross sections: Transverse Momenta