NLO EW and QCD corrections to off-shell ttW production at the LHC

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Based on JHEP 11 (2020) 069 [2007.12089] and EPJC 81 (2021) 4, 354 [2102.03246].

Motivations

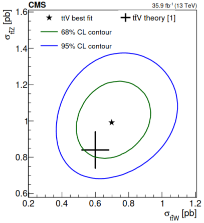
Hadro-production of $t\bar{t}W^{\pm}$ at the LHC give access to $t\bar{t}V$ couplings in the SM, new-physics effects and charge asymmetries.

Important background to $t\bar{t}H$.

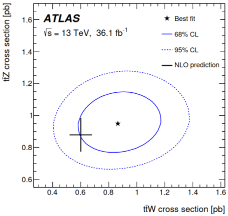
Measured with Run-2 dataset [ATLAS 1609.01599 & 1901.03584, CMS 1711.02547].

Tension between data and SM predictions, in both direct [CMS 1711.02547, ATLAS 1901.03584] and $t\bar{t}H$ measurements [ATLAS 1806.00425, CMS 1804.02610].

Excess of $t\bar{t}W$ events over SM confirmed in improved analyses [ATLAS-CONF-2019-045, CMS-PAS-HIG-19-008].



[CMS 1711.02547]



[ATLAS 1901.03584]

Theory status

Improved theory modeling required $\rightarrow$ towards realistic final states.

NLO, on-shell: NLO QCD [Maltoni et al. 1406.3262] and subleading NLO orders [Frixione et al. 1504.03446, Frederix et al. 1711.02116 & 1804.10017].

NLO, production $\times$ decay: NLO QCD [Campbell Ellis 1204.5678].

Resummation & merging, on-shell: NLO QCD and EW + NNLL [Broggio et al. 1907.04343, Kulesza et al. 2001.03031], multi-jet merging at NLO [von Buddenbrock et al. 2009.00032].

NLO + PS, production $\times$ decay: NLO QCD to LO QCD [Garzelli et al. 1208.2665] and NLO QCD to LO EW [Frederix Tsinikos 2004.09552, Cordero et al. 2101.11808] matched to parton-shower.

NLO, full off-shell: NLO QCD [Bevilacqua et al. 2005.09427 & 2012.01363, Denner GP 2007.12089] and subleading NLO orders [Denner GP 2102.03246] in the 3ℓ channel.

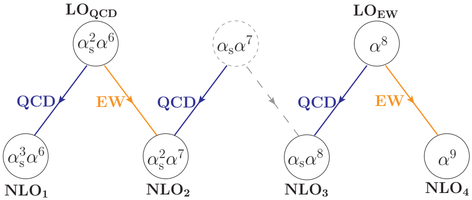
Details of the calculation: perturbative orders

LHC process:

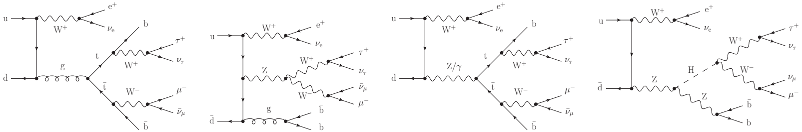
$\mathrm{p\,p} \to \mathrm{b\,\bar{b}\,e^+}\nu_\mathrm{e}\,\mu^-\bar{\nu}_\mu\,\tau^+\nu_\tau\ + X$

at NLO accuracy

$\to$ several contributions.



LO: double-resonant ($\mathrm{t\bar{t}}$), single-resonant (t or $\mathrm{\bar{t}}$), non-resonant diagrams. Interference of order $\mathcal{O}(\alpha_s\alpha^7)$ vanishes (if CKM is unit matrix).

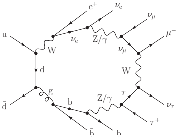


NLO$_1$: genuine NLO QCD to LO QCD (expected to be dominant NLO contribution), up to 7-point functions in virtual corr., challenging real corr. (high-multiplicity). Real partonic channels with initial states $q\bar{q}$, gq.

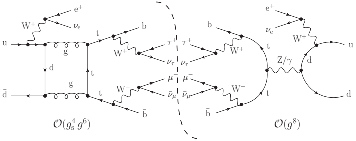
Details of the calculation: contributions

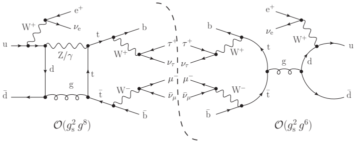
NLO$_2$: EW corrections to LO QCD plus QCD corrections to LO interference.

Up to 10-point functions in virtuals.



Two contributions:

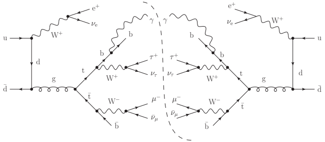


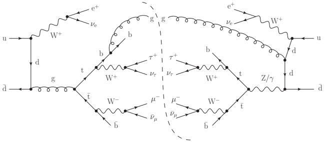


High-multiplicity reals ($2 \to 9$) and large number of IR-singular configurations.

Channels: $q\bar{q}, \gamma q, gq$ (γq suppressed by PDFs).

QCD real corr. to LO interf. is non-zero if gluon is emitted by the initial state and absorbed by final state.





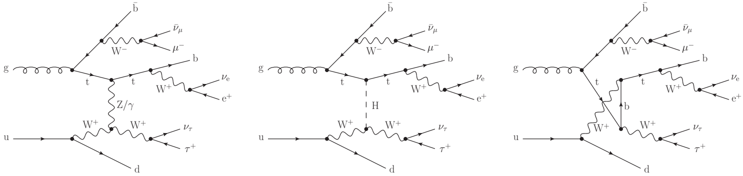
Virtual IR poles for $\mathcal{O}(g_s^2 g^8) \times \mathcal{O}(g_s^2 g^6)$ are cancelled by both classes of reals: only the sum of all contributions is IR safe!

Details of the calculation: contributions

NLO$_3$: pure QCD corrections to LO EW (EW corrections do not change color structure of LO interference) $\rightarrow$ enable simple matching to QCD PS (as NLO$_1$).

Expected to be subleading but larger than NLO$_2$ (already for on-shell production [Frederix et al. 1711.02116 & 1804.10017]).

Dominated by *gq*-channel contribution, that embeds $tW^+ \rightarrow tW^+$ scattering:



NLO$_4$: EW corrections to LO$_{\text{EW}}$, amount at 0.04% of LO$_{\text{QCD}}$ already at inclusive level [Frederix et al. 1711.02116]. Out of reach in a fiducial phase-space even at HL-LHC $\rightarrow$ neglected here.

Details of the calculation: setup

[Denner GP 2102.03246]

$\mathrm{pp} \to \mathrm{b}\,\bar{\mathrm{b}}\,\mathrm{e}^+\nu_\mathrm{e}\,\mu^-\bar{\nu}_\mu\,\tau^+\nu_\tau + \mathrm{X}$ at $\mathcal{O}(\alpha_\mathrm{s}^3\alpha^6)$, $\mathcal{O}(\alpha_\mathrm{s}^2\alpha^7)$, $\mathcal{O}(\alpha_\mathrm{s}\alpha^8)$

- full tree-level and one-loop amplitudes: RECOLA1 [Actis et al. 1605.01090]
- 1-loop tensor-integral reduction and evaluation: COLLIER [Denner et al. 1604.06792]
- multi-channel integration with MoCaNLO in-house Monte Carlo
- dipole subtraction of IR singularities [Catani Seymour 9605323, Dittmaier 9904440]
- complex-mass scheme [Denner et al. 9904472] for W, Z, top
- NNPDF3.1 NLO LUXQED PDFs (photon included, [Bertone et al. 1712.07053]) for both LO and NLO simulations; $N_F = 5$
- Both LO and NLO simulation: Γ_t computed including NLO QCD+EW corrections [Basso et al. 1507.04676]

Selections, mimic those of [ATLAS 1901.03584]:

2 b-jets (anti-k_t, $R = 0.4(0.1)$ for jet (photon) clustering, $p_{\mathrm{T,b}} > 25$ GeV, $|\eta_\mathrm{b}| < 2.5$),
3 ch. leptons ($p_{\mathrm{T},\ell} > 27$ GeV, $|\eta_\ell| < 2.5$, $\Delta R_{\ell\mathrm{b}} > 0.4$).

Three central-scale choices: $\mu_0^{(\mathrm{c})} = H_\mathrm{T}/3$, $\mu_0^{(\mathrm{d})} = \sqrt{M_{T,\mathrm{t}} M_{\mathrm{T},\bar{\mathrm{t}}}}$, $\mu_0^{(\mathrm{e})} = \sqrt{M_{T,\mathrm{t}} M_{\mathrm{T},\bar{\mathrm{t}}}}/2$.

Combining NLO EW and QCD: integrated cross-sections

Total cross-sections in the fiducial setup [Denner GP 2102.03246]:

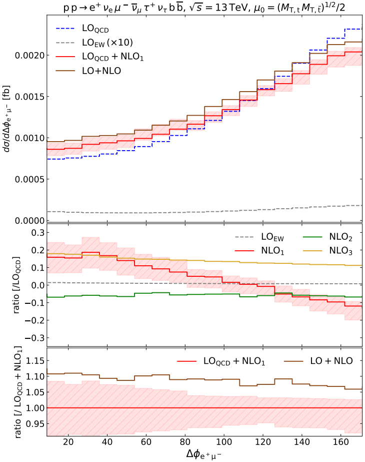
	$\mu_0^{(c)}$		$\mu_0^{(d)}$		$\mu_0^{(e)}$	
order	σ (fb)	ratio	σ (fb)	ratio	σ (fb)	ratio
$\mathrm{LO_{QCD}}$ ($\alpha_s^2\alpha^6$)	$0.2218(1)^{+25.3\%}_{-18.8\%}$	1	$0.1948(1)^{+23.9\%}_{-18.1\%}$	1	$0.2414(1)^{+26.2\%}_{-19.3\%}$	1
$\mathrm{LO_{EW}}$ (α^8)	$0.002164(1)^{+3.7\%}_{-3.6\%}$	0.010	$0.002122(1)^{+3.7\%}_{-3.6\%}$	0.011	$0.002201(1)^{+3.7\%}_{-3.6\%}$	0.009
$\mathrm{NLO_1}$ ($\alpha_s^3\alpha^6$)	0.0147(6)	0.066	0.0349(6)	0.179	0.0009(7)	0.004
$\mathrm{NLO_2}$ ($\alpha_s^2\alpha^7$)	−0.0122(3)	−0.055	−0.0106(3)	−0.054	−0.0134(4)	−0.056
$\mathrm{NLO_3}$ ($\alpha_s\alpha^8$)	0.0293(1)	0.131	0.0263(1)	0.135	0.0320(1)	0.133
$\mathrm{LO_{QCD}+NLO_1}$	$0.2365(6)^{+2.9\%}_{-6.0\%}$	1.066	$0.2297(6)^{+5.5\%}_{-7.3\%}$	1.179	$0.2423(7)^{+3.5\%}_{-5.2\%}$	1.004
$\mathrm{LO_{QCD}+NLO_2}$	$0.2094(3)^{+25.0\%}_{-18.7\%}$	0.945	$0.1840(3)^{+23.8\%}_{-17.9\%}$	0.946	$0.2277(4)^{+25.9\%}_{-19.2\%}$	0.944
$\mathrm{LO_{EW}+NLO_3}$	$0.03142(4)^{+22.2\%}_{-16.8\%}$	0.141	$0.02843(6)^{+20.5\%}_{-15.6\%}$	0.146	$0.03425(7)^{+22.8\%}_{-17.0\%}$	0.142
LO+NLO	$0.2554(7)^{+4.0\%}_{-6.5\%}$	1.151	$0.2473(7)^{+6.3\%}_{-7.6\%}$	1.270	$0.2628(9)^{+4.3\%}_{-5.9\%}$	1.089

- $\mathrm{NLO_1}$-corr. impact depends a lot on scale choice (from +0.5% to +18%)
- $\mathrm{NLO_2}$ and $\mathrm{NLO_3}$ relative corr. are scale-independent: −5% and +13% resp.
- $\mathrm{LO_{EW}}$ is 1% of $\mathrm{LO_{QCD}}$, $\mathrm{NLO_3}$ corr. 10 times larger than its LO (tW scattering)
- scale-uncertainties dominated by $\mathrm{NLO_1}$: $\approx \pm 5\%$ for combined NLO result

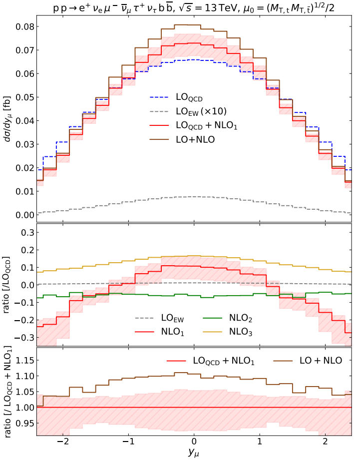
In a very inclusive setup (only $M_{bb} > 5$ GeV): similar $\mathrm{NLO_2}$ corrections ($\approx -3\%$) as in on-shell calculation ($\approx -4\%$ in [Frederix et al. 1804.10017]).

Combining NLO EW and QCD: angular & rapidity distributions

Azimuthal separation between e^+ and μ^-



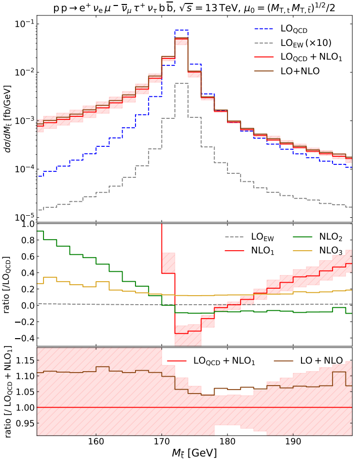
Rapidity of μ^-



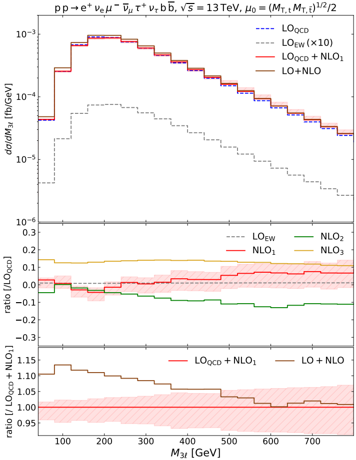
- NLO_1 diminish with constant slope, NLO_2+NLO_3 give a rather flat correction to LO+NLO_1.
- NLO_1 large variation (35%), NLO_2 rather flat, NLO_3 diminish from +16% (central) to +8% (forward)

Combining NLO EW and QCD: invariant-mass distributions

Invariant mass of the $\bar{b}\mu^-\bar{\nu}_\mu$ system



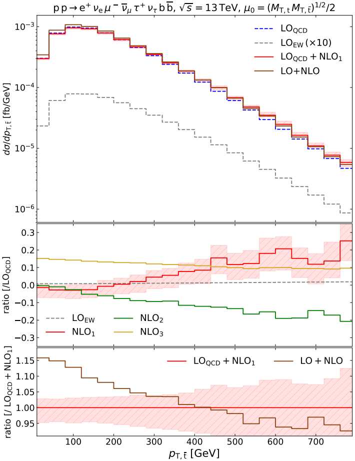
Invariant mass of the 3ℓ system



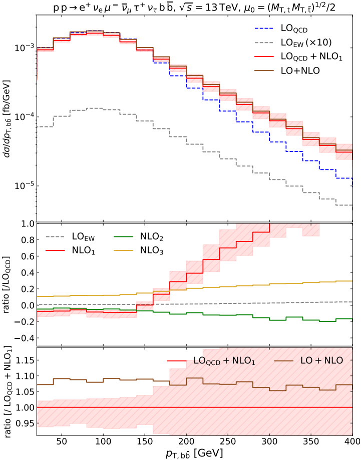
- Large radiative tail at low mass both for $\mathrm{NLO_2}$ and $\mathrm{NLO_1}$. $\mathrm{NLO_3}$ corrections are flatter.
- Rather flat QCD corrections, $\mathrm{NLO_2}$ corrections diminish down to -11% at 800 GeV.

Combining NLO EW and QCD: transverse-momentum distributions

Transverse momentum of $\bar{b}\mu^-\bar{\nu}_\mu$ system



Transverse momentum of $b\bar{b}$ system



- Negative growth of NLO_2 (-20% at 800 GeV): large EW Sudakov logs. NLO_3 flat, NLO_1 increases by 25%.
- Very large NLO_1 correction for $p_{\text{T,bb}} > 150$ GeV. Small NLO corrections in the soft region.

Conclusions & outlook

First calculations including complete off-shell effects at NLO QCD ($\alpha_s^3\alpha^6$) and subleading NLO orders ($\alpha_s^2\alpha^7$, $\alpha_s\alpha^8$) now available for $\mathrm{t\bar{t}W^{\pm}}$ (in the 3ℓ channel).

Essential theory progress towards realistic final states modelling.

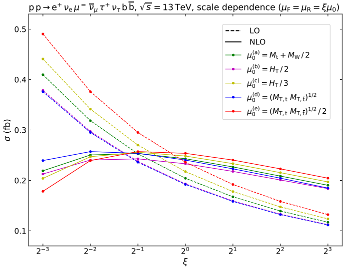
- $\mathrm{NLO_1}$ corr. range between 0.5% and 18%, depending on central scale.
- Scale uncertainties reduced from 25% (LO) to 5% (NLO), mostly due to $\mathrm{NLO_1}$.
- $\mathrm{NLO_2}$ corr. are negative (-5%) and almost scale-independent and become large (down to -20%) in the tail of p_T and invariant-mass distributions.
- $\mathrm{NLO_3}$ corr. are large ($+10\%$ to $+25\%$) and also rather scale-independent, dominated by the $q\mathrm{g}$ channels that embed tW scattering.
- Combined NLO predictions exceed the scale-uncertainties of the $\mathrm{NLO_{QCD}}$ results: $\mathrm{NLO_2}$ and $\mathrm{NLO_3}$ necessary for a correct modelling of $\mathrm{t\bar{t}W}$.
- Off-shell effects are important in the tails of several distributions. For inclusive variables, spin-correlated production$\times$decay is a good approximation.
- All NLO corr. change distribution shapes (even angular ones).

Ultimate target: NLO+PS for off-shell $\mathrm{t\bar{t}W}$ production.

Backup

NLO QCD results: scale dependence

The inclusion of NLO QCD corrections reduces scale-uncertainties from 25% to 5%.



[Denner GP 2007.12089]

Comparison among different central scale choices:

- fixed $\mu_0 = M_W + M_t/2$;
- dynamical, resonance-blind $\mu_0 = H_T/2$, or $\mu^0 = H_T/3$ ($H_T = p_T^{miss} + \sum_{i=b,\ell} p_{T,i}$);
- dynamical, resonance-aware $\mu_0 = \sqrt{M_{T,t} M_{T,\bar{t}}}$ or $\mu_0 = \sqrt{M_{T,t} M_{T,\bar{t}}}/2$ ($M_{T,t} = \sqrt{M_t^2 + p_{T,t}^2}$).

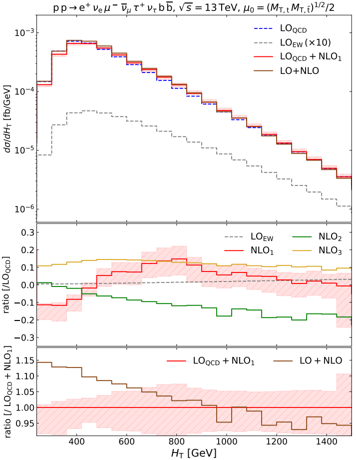
K-factors range between 1.07 to 1.25: QCD corrections are at the 10-20% level.

Note: (N)LO QCD understands $\Gamma_t^{(N)LO\,QCD}$ and (N)LO NNPDF3.1 PDFs.

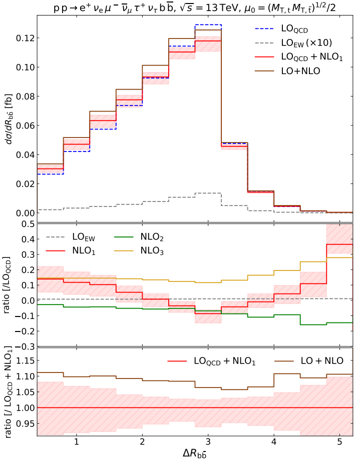
central scale	LO	NLO QCD	K-factor	
$\mu_0^{(a)} = M_t + M_W/2$	$0.2042(1)^{+23.8\%}_{-18.0\%}$	$0.2452(7)^{+4.5\%}_{-6.8\%}$	1.20	
$\mu_0^{(b)} = H_T/2$	$0.1931(1)^{+23.0\%}_{-17.5\%}$	$0.2330(9)^{+4.2\%}_{-6.5\%}$	1.21	
$\mu_0^{(c)} = H_T/3$	$0.2175(1)^{+24.2\%}_{-18.2\%}$	$0.2462(8)^{+2.8\%}_{-5.8\%}$	1.13	
$\mu_0^{(d)} = \left(M_{T,t} M_{T,\bar{t}}\right)^{1/2}$	$0.1920(1)^{+23.0\%}_{-17.5\%}$	$0.2394(6)^{+5.4\%}_{-7.2\%}$	1.25	
$\mu_0^{(e)} = \left(M_{T,t} M_{T,\bar{t}}\right)^{1/2}/2$	$0.2360(1)^{+24.9\%}_{-18.7\%}$	$0.2535(8)^{+3.4\%}_{-5.2\%}$	1.07	← best

NLO EW and QCD: more distributions (1)

H_T variable

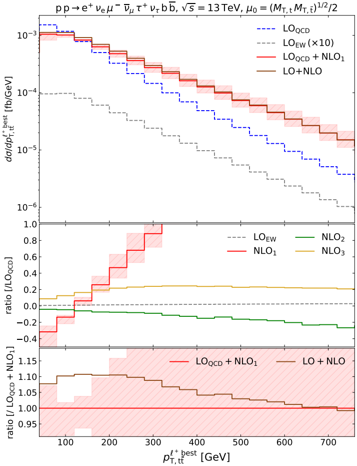


R-distance between the two b-jets



NLO EW and QCD: more distributions (2)

Transverse momentum of the $t\bar{t}$ system



Transverse momentum of the positron