

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

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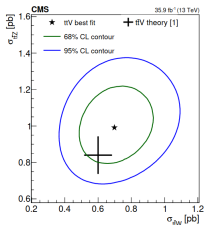
Based on [JHEP 11 \(2020\) 069 \[2007.12089\]](#) and [EPJC 81 \(2021\) 4, 354 \[2102.03246\]](#).

Motivations

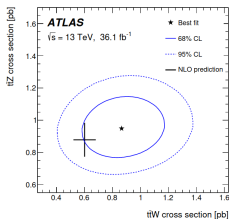
Hadro-production of $t\bar{t}W^\pm$ at the LHC, an optimal process for studying

- ▶ $t\bar{t}V$ coupling in or beyond the SM, new-physics effects (EFT, SUSY, ...) [Dror et al. 1511.03674, ...], particularly in the fully-leptonic channel
- ▶ charge asymmetries [Maltoni et al. 1406.3262, Bevilacqua et al. 2012.01363]: gg-channel opens up at NNLO QCD
- ▶ important background to $t\bar{t}H$ [Maltoni et al. 1507.05640]

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



[CMS 1711.02547]



[ATLAS 1901.03584]

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].

Improved theory modeling required → 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 × decay:

NLO QCD [Campbell Ellis 1204.5678].

NLO + PS, production × 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, Bevilacqua et al. 2109.15181] matched to parton-shower.

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, Frederix Tsinikos 2108.07826].

NLO, 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.

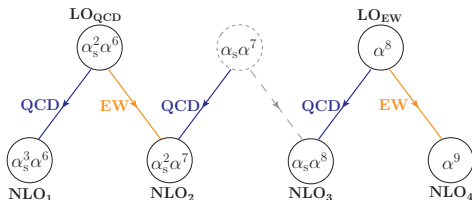
Details of the calculation: perturbative orders

LHC process:

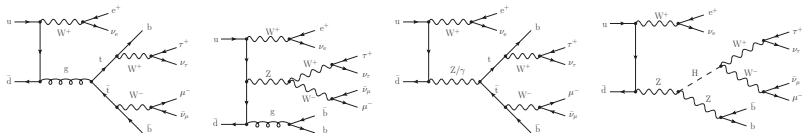
$$pp \rightarrow b \bar{b} e^+ \nu_e \mu^- \bar{\nu}_\mu \tau^+ \nu_\tau + X$$

at **NLO** accuracy

→ several contributions.



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

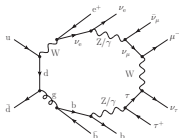


NLO₁: genuine **NLO QCD** to **LO QCD** (expected to be dominant NLO contribution), up to **7-point functions** in virtual corr., challenging real corr. (**high-multiplicity**). Real partonic channels with initial states $q\bar{q}, gq$.

Details of the calculation: contributions

NLO₂: EW corrections to LO QCD plus QCD corrections to LO interference.

Up to 10-point functions in virtuals.

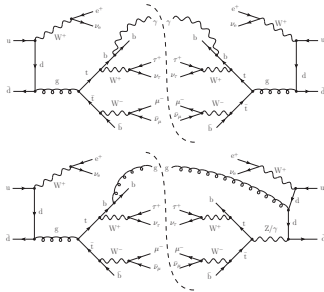
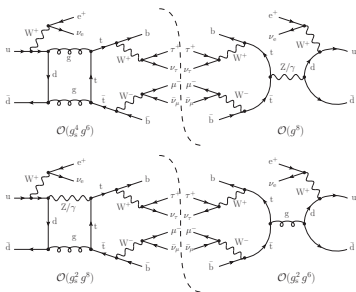


High-multiplicity reals (2 → 9) and large number of IR-singular configurations.

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.

Two contributions:



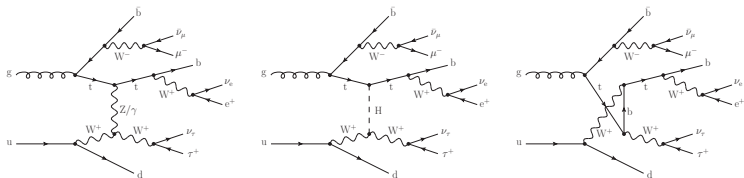
Virtual IR poles for $\mathcal{O}(g_s^2 g^8) \times \mathcal{O}(g_s^2 g^6)$ are cancelled by both classes of reals: only the sum of all contributions is IR safe!

Details of the calculation: contributions

NLO₃: pure QCD corrections to LO EW (EW corrections do not change color structure of LO interference) → enable simple matching to QCD PS (as NLO₁).

Expected to be subleading but larger than NLO₂ (already for on-shell production [Frederix et al. 1711.02116 & 1804.10017]).

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



NLO₄: EW corrections to LO_{EW}, amount at 0.04% of LO_{QCD} already at inclusive level [Frederix et al. 1711.02116]. Out of reach in a fiducial phase-space even at HL-LHC → neglected here.

Details of the calculation: setup

[Denner GP 2102.03246]

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

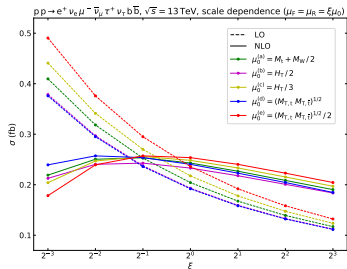
- full tree-level and one-loop amplitudes: RECOLA1 [Actis et al. 1605.01090]
- 1-loop tensor-integral reduction and evaluation: COLLIER [Denner et al. 1604.06792]
- multi-channel integration with MoCANLO in-house Monte Carlo
- dipole subtraction of IR singularities both for EW and QCD real radiation [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, $p_{T,b} > 25$ GeV, $|\eta_b| < 2.5$),
3 ch. leptons ($p_{T,\ell} > 27$ GeV, $|\eta_\ell| < 2.5$, $\Delta R_{\ell b} > 0.4$).

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 $\mu^0 = H_T/3$ ($H_T = p_T^{\text{miss}} + \sum_{i=b,\ell} p_{T,i}$);
- ▶ 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 $\Gamma_t^{(N)LO\text{QCD}}$ 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
$\mu_0^{(d)} = (M_{T,t} M_{T,\bar{t}})^{1/2}$	0.1920(1) $^{+23.0\%}_{-17.5\%}$	0.2394(6) $^{+5.4\%}_{-7.2\%}$	1.25
$\mu_0^{(e)} = (M_{T,t} M_{T,\bar{t}})^{1/2} / 2$	0.2360(1) $^{+24.9\%}_{-18.7\%}$	0.2535(8) $^{+3.4\%}_{-5.2\%}$	1.07 ← best

Combining NLO EW and QCD: integrated cross-sections

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

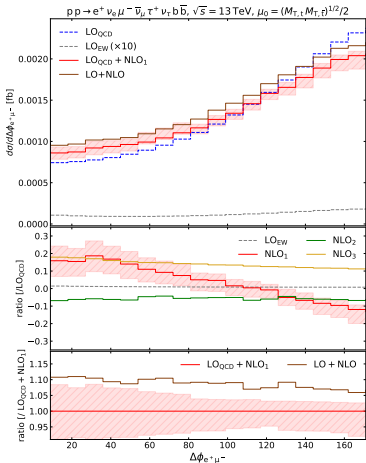
order	$\mu_0^{(c)}$		$\mu_0^{(d)}$		$\mu_0^{(e)}$	
	σ (fb)	ratio	σ (fb)	ratio	σ (fb)	ratio
LO _{QCD} ($\alpha_s^2 \alpha^6$)	0.2218(1) ^{+25.3%} _{-18.8%}	1	0.1948(1) ^{+23.9%} _{-18.1%}	1	0.2414(1) ^{+26.2%} _{-19.3%}	1
LO _{EW} (α^8)	0.002164(1) ^{+3.7%} _{-3.6%}	0.010	0.002122(1) ^{+3.7%} _{-3.6%}	0.011	0.002201(1) ^{+3.7%} _{-3.6%}	0.009
NLO ₁ ($\alpha_s^3 \alpha^6$)	0.0147(6)	0.066	0.0349(6)	0.179	0.0009(7)	0.004
NLO ₂ ($\alpha_s^2 \alpha^7$)	-0.0122(3)	-0.055	-0.0106(3)	-0.054	-0.0134(4)	-0.056
NLO ₃ ($\alpha_s \alpha^8$)	0.0293(1)	0.131	0.0263(1)	0.135	0.0320(1)	0.133
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
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
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

- ▶ NLO₁-corr. impact depends a lot on scale choice (from +0.5% to +18%)
- ▶ NLO₂ and NLO₃ relative corr. are scale-independent: -5% and +13% resp.
- ▶ LO_{EW} is 1% of LO_{QCD}, NLO₃ corr. 10 times larger than its LO (tW scattering)
- ▶ scale-uncertainties dominated by NLO₁: $\approx \pm 5\%$ for combined NLO result

In a very inclusive setup (only $M_{bb} > 5$ GeV): similar NLO₂ corrections ($\approx -3\%$) as in on-shell calculation ($\approx -4\%$ in [Frederix et al. 1804.10017]).

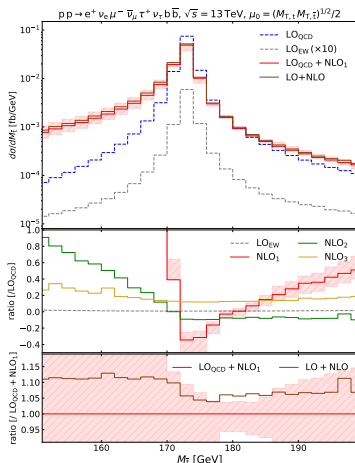
Combining NLO EW and QCD: angular & invariant-mass distributions

Azimuthal separation between e^+ and μ^-



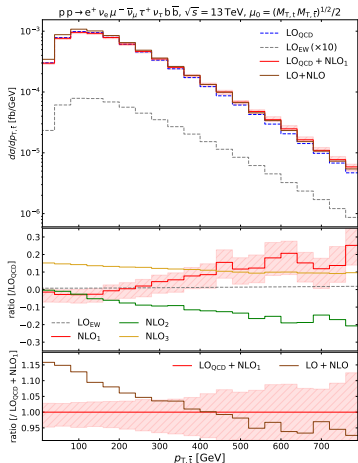
- ▶ NLO_1 diminish with constant slope, $NLO_2 + NLO_3$ give a rather flat correction to $LO + NLO_1$.

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



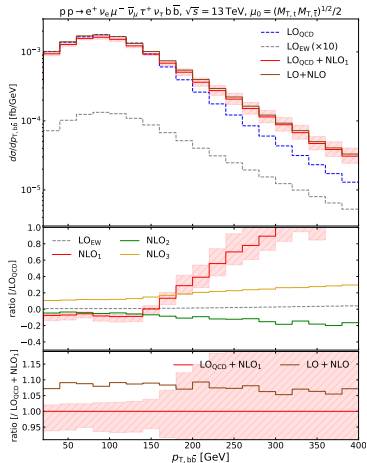
- ▶ Large radiative tail at low mass both for NLO_2 and NLO_1 . NLO_3 corrections are flatter.

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



- ▶ Negative growth of NLO₂ (−20% at 800 GeV): large EW Sudakov logs. NLO₃ flat, NLO₁ increases by 25%.

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



- ▶ Very large NLO₁ correction for $p_{T,b\bar{b}} > 150 \text{ GeV}$. 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 $t\bar{t}W^\pm$ (in the 3ℓ channel).

Essential theory progress towards **realistic final states** modelling.

- ▶ 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 NLO_1 .
- ▶ 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.
- ▶ NLO_3 corr. are **large (+10% to +25%)** and also **rather scale-independent**, dominated by the qg channels that embed tW scattering.
- ▶ **Combined NLO predictions exceed the scale-uncertainties of the NLO_{QCD} results**: NLO_2 and NLO_3 necessary for a correct modelling of $t\bar{t}W$.
- ▶ **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 $t\bar{t}W$ production.