

Hadronic production of $t\bar{t}Z$ in the POWHEG BOX framework

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The $t\bar{t}Z$ associate production

- Probe of the top quark coupling to the Z
- background for $t\bar{t}H$ associate production
- background for other processes involving final states with multiple leptons and b -jets

Cross section measured by ATLAS and CMS at $\sqrt{s} = 13$ TeV.

Most recent references:

- Eur. Phys. J. C 81 (2021) 737, arXiv:2103.12603 (ATLAS)
- CMS-PAS-TOP-18-009 (CMS)

Experimental measurements are in agreement with the SM, but affected by large uncertainties → theory uncertainties

- unknown higher-order perturbative corrections
- estimate of non-perturbative effects
- intrinsic uncertainties of the simulation programs used

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The $t\bar{t}Z$ associate production: theory

State of the art of calculations of $t\bar{t}Z$:

- NLO QCD and EW calculation

Lazopoulos, McElmurry, Melnikov and Petriello, Phys. Lett. B 666 (2008) 62 [0804.2220]

Kardos, Trocsanyi and Papadopoulos, Phys. Rev. D 85 (2012) 054015 [1111.0610]

Maltoni, Pagani and Tsinikos, JHEP 02 (2016) 113 [1507.05640]

Frixione, Hirschi, Pagani, Shao and Zaro, JHEP 06 (2015) 184 [1504.03446]

- NNLL resummation

Broggio, Ferroglia, Ossola, Pecjak and Sameshima, JHEP 04 (2017) 105 [1702.00800]

Kulesza, Motyka, Schwartländer, Stebel and Theeuwes, Eur. Phys. J. C 79 (2019) 249 [1812.08622]

Broggio, Ferroglia, Frederix, Pagani, Pecjak and Tsinikos, JHEP 08 (2019) 039 [1907.04343]

Kulesza, Motyka, Schwartländer, Stebel and Theeuwes, Eur. Phys. J. C 80 (2020) 428 [2001.03031]

- off-shell top quarks and Z (matrix elements)

Bevilacqua, Hartanto, Kraus, Nasufi and Worek, arXiv:2203.15688

The $t\bar{t}Z$ associate production: theory

State of the art of calculations of $t\bar{t}Z$ (2nd part):

- NLO QCD + parton shower

Garzelli, Kardos, Papadopoulos and Trocsanyi, Phys. Rev. D 85 (2012) 074022 [1111.1444]

Garzelli, Kardos, Papadopoulos and Trocsanyi, JHEP 11 (2012) 056 [1208.2665]

Missing:

- full study of off-shell effects of $Z \rightarrow \ell^+\ell^-$ with parton shower
- spin correlations in top decays

→ our work [arXiv:2112.08892](https://arxiv.org/abs/2112.08892)

Our work: arXiv:2112.08892

M. Ghezzi, S. Lopez Portillo Chavez, B. Jäger, L. Reina, D. Wackerroth

2 implementations in POWHEG BOX-V2 → **available soon!**

- $pp \rightarrow t\bar{t}\ell^+\ell^-$
- $pp \rightarrow t\bar{t}Z$

The POWHEG BOX framework:

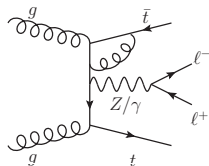
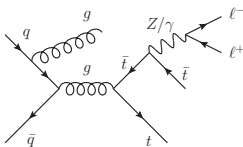
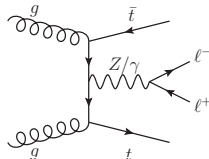
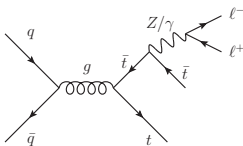
- general **process-independent** framework
- matching of **NLO QCD** calculations to **parton showers**
- constructs infrared subtraction terms according to the **FKS** scheme

<https://powhegbox.mib.infn.it>

Process-dependent ingredients:

- LO matrix elements squared
- NLO virtual corrections, real-emission amplitudes squared
- flavour structure
- spin- and color-correlated amplitudes
- phase space

$$pp \rightarrow t\bar{t}\ell^+\ell^-$$



LO contributions at order $\alpha_s^2\alpha^2$;
NLO at order $\alpha_s^3\alpha^2$

● Born+reals \rightarrow Madgraph

● virtuals \rightarrow NLOX

Possibilities for top quark decays

e.g. $t \rightarrow W^+ b \rightarrow \ell^+ \nu_\ell b$

- **spin-averaged:** stable tops in POWHEG BOX, decayed by Pythia 8
- **with spin correlations:** in POWHEG BOX
 - NLO QCD with stable tops
 - LO production of $(t \rightarrow \ell'^+ \nu_{\ell'} b)(\bar{t} \rightarrow \ell'^- \bar{\nu}_{\ell'} \bar{b}) \ell^+ \ell^- (+\text{jet})$
 - spin correlations are then retained at LO

Frixione, Laenen, Motylinski and Webber, JHEP 04 (2007) 081, hep-ph/0702198

The Z in the $t\bar{t}Z$ case

- stable in POWHEG BOX, decayed by PYTHIA 8

The $\ell^+ \ell^-$ pair in the $t\bar{t}\ell^+ \ell^-$ case

- full matrix elements: Z and γ channels
- generation cut: $M_{\ell^+ \ell^-}^{\min} = 10 \text{ GeV}$

Parameters

EW input parameters: G_μ scheme

$$m_Z = 91.1876 \text{ GeV}, \quad m_W = 80.379 \text{ GeV}, \quad G_\mu = 1.166378 \times 10^{-5} \text{ GeV}^{-2}.$$

electromagnetic coupling constant: $\alpha = \frac{\sqrt{2}G_\mu m_W^2}{\pi} \left(1 - \frac{m_W^2}{m_Z^2}\right).$

Other parameters:

$$\begin{aligned} \Gamma_Z &= 2.4952 \text{ GeV}, & \Gamma_W &= 2.085 \text{ GeV}, \\ m_t &= 172.76 \text{ GeV}, & \Gamma_t &= 1.42 \text{ GeV}. \end{aligned}$$

PDF: CT18NLO

Renormalization and factorization scales: $\mu_r = \xi_r \mu_0$ and $\mu_f = \xi_f \mu_0$

with $\mu_0 = \frac{2m_t + m_Z}{2}$ (fixed) or $\mu_0 = \frac{M_T(e^+e^-) + M_T(t) + M_T(\bar{t})}{3}$ (dynamical)

Analysis cuts

- Cuts on the electrons/positrons:

$$p_T^e > 10 \text{ GeV}, \quad |\eta^e| < 2.5$$

- Cut on invariant mass of the e^+e^- system (window around the Z -boson):

$$m_Z - 10 \text{ GeV} \leq M_{e^+e^-} \leq m_Z + 10 \text{ GeV}$$

- When top/anti-top quarks are decayed, $t \rightarrow \mu^+ \nu_\mu b$ and $\bar{t} \rightarrow \mu^- \bar{\nu}_\mu \bar{b}$

$$p_T^\mu > 10 \text{ GeV}, \quad |\eta^\mu| < 2.5$$

Notice: here e^+e^- from the Z/γ ; $\mu^+\mu^-$ from t, \bar{t} .

Fixed order results - NLO QCD

Total cross section, LO and NLO QCD:

Fixed scale:

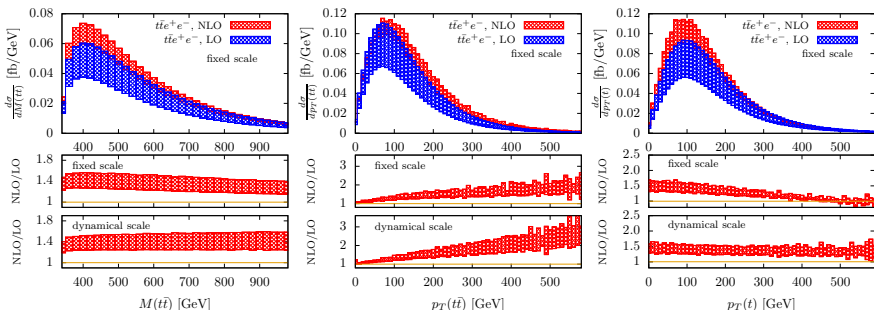
$$\sigma_{t\bar{t}e^+e^-}^{\text{LO}} = 15.9^{+5.1}_{-3.6} \text{ fb}$$

$$\sigma_{t\bar{t}e^+e^-}^{\text{NLO}} = 21.9^{+2.0}_{-2.4} \text{ fb}$$

Dynamical scale:

$$\sigma_{t\bar{t}e^+e^-}^{\text{LO}} = 15.8^{+5.0}_{-3.5} \text{ fb}$$

$$\sigma_{t\bar{t}e^+e^-}^{\text{NLO}} = 22.1^{+2.2}_{-2.5} \text{ fb}$$



Fixed order results - Charge asymmetry of the $t\bar{t}$ system

Definitions:

$$A_c = \frac{\sigma(\Delta y_{t\bar{t}} > 0) - \sigma(\Delta y_{t\bar{t}} < 0)}{\sigma(\Delta y_{t\bar{t}} > 0) + \sigma(\Delta y_{t\bar{t}} < 0)} \quad A_c^{\text{ex}} = A_c \frac{\sigma_{t\bar{t}e^+e^-}^{\text{NLO}}}{\sigma_{t\bar{t}e^+e^-}^{\text{LO}}}$$

with $\Delta y_{t\bar{t}} = |y_t| - |y_{\bar{t}}|$.

Czakon et al., Phys. Rev. D 98 (2018) 014003, arXiv:1711.03945

Results:

fixed scale:

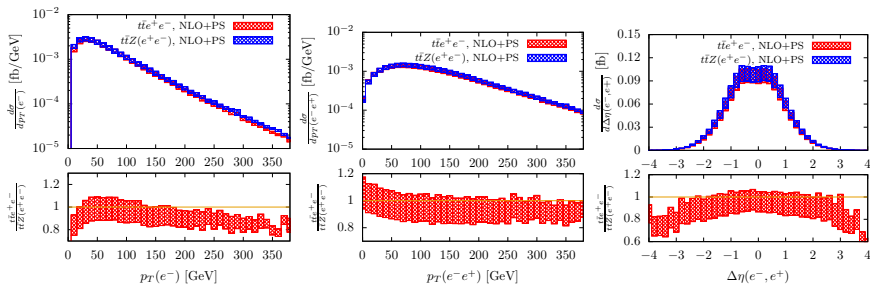
$$A_c = 0.84_{-0.19}^{+0.28} \% \quad , \quad A_c^{\text{ex}} = 1.15_{-0.18}^{+0.11} \% ,$$

dynamical scale:

$$A_c = 0.74_{-0.18}^{+0.25} \% \quad , \quad A_c^{\text{ex}} = 1.04_{-0.17}^{+0.20} \% .$$

Off-shell effects of the e^+e^- system

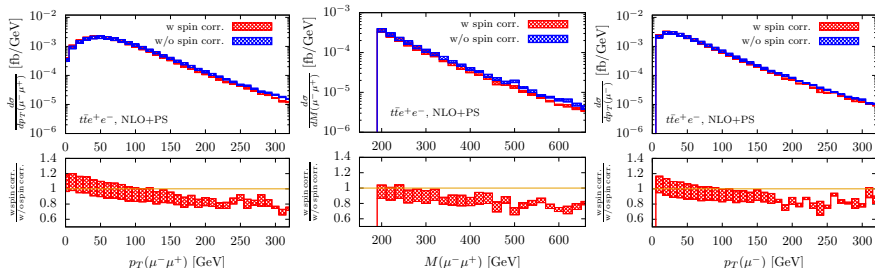
- top quarks are stable
- effects of off-shell Z
- e^+e^- spin correlations
- 10-20% effect in the high- $p_T(e^-)$ region and in the large absolute-value region of the pseudorapidity difference



(fixed scale)

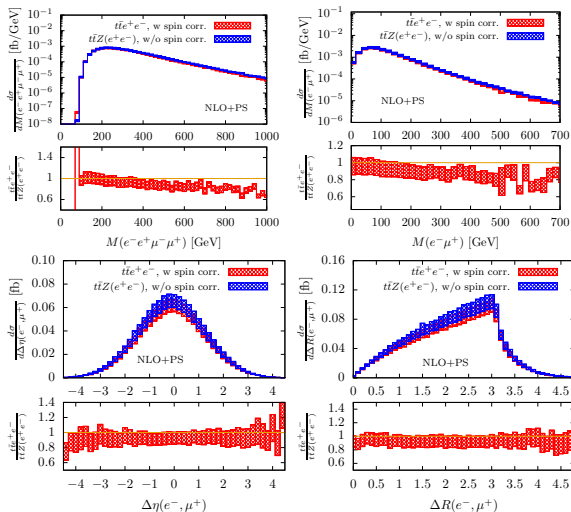
Spin-correlations in top decays

- $t\bar{t}e^+e^-$ implementation
- tree-level NWA spin correlations vs. $t\bar{t}e^+e^-$ with spin-averaged top quarks decayed by PYTHIA
- Visible effects in the tails, 10-20% lower with spin correlations



(fixed scale)

Mixed lepton observables



- Most accurate vs. most approximated prediction
- $M(e^+e^-\mu^+\mu^-)$ and $M(e^-\mu^+)$ distributions: 10-20% off-shell and spin-correlation effects at high invariant masses
- $e^\pm\mu^\mp$ angular distributions: no appreciable effect

(fixed scale)

Summary

- I presented here our implementations of $t\bar{t}\ell^+\ell^-$ and $t\bar{t}Z$ in the **POWHEG BOX, NLO QCD + PS**, with the option of including spin correlations in the top decays.
- We studied the phenomenology at the LHC with $\sqrt{s} = 13$ TeV.
- We studied the effects of an **off-shell Z**, finding 10-20% effects in the tails of the leptons' transverse-momentum distributions, as well as in the transverse momentum and pseudorapidity distributions of the $\ell^+\ell^-$ system.
- Also considering tree-level **spin correlations** in top decays can bring up to 10-20% effect in tails of distributions for transverse momenta and invariant masses of the Z and the top/antitop decay products.