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

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Top-quark pair production associated with a Z-boson

Relevance

- Direct probe of the top quark coupling to the Z
- Background for tZ and $t\bar{t}H$ associated production
- Background for other processes with multiple leptons and b-jets in final state

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)
- JHEP **03** (2020), arXiv:1907.11270 (CMS)

Experimental measurements are in agreement with the SM, but we still need to reduce uncertainties $\rightarrow$ theory:

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

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Existing calculations of $t\bar{t}Z$ production

- NLO QCD and EW calculation (on-shell Z)

  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]

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

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

- NNLL resummation (on-shell Z)

  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]

- $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$ @NLO QCD (off-shell Z and top quarks)

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

Existing calculations of $t\bar{t}Z$ production (cont.)

- 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]

Our work: arXiv:2112.08892

- NLO with PS matching using POWHEG
- Can study off-shell effects of Z in $Z \to \ell^+\ell^-$ and γ contributions
- Can include spin correlations of top decays

Implementation

Our work: arXiv:2112.08892

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

Two separate implementations in POWHEG BOX-V2 → available now!

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

Include matching to PYTHIA 8.2

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

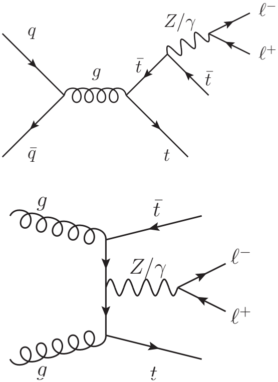
https://powhegbox.mib.infn.it

Process-dependent ingredients:

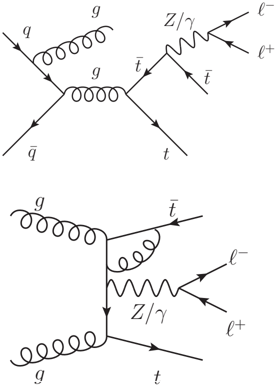
- LO matrix elements squared
- NLO virtual corrections, real-emission amplitudes squared
- flavor structure
- spin- and color-correlated amplitudes
- phase space parametrization

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

LO $\alpha_s^2\alpha^2$



NLO $\alpha_s^3\alpha^2$



Born + reals

→ `MadGraphII`

Virtuals

→ `NLOX 1.2`
one-loop provider

T. Stelzer and W. F. Long, Comput. Phys. Commun. **81** (1994) 9401258; J. Alwall et al., JHEP **09** (2007)

S. Honeywell, S. Quackenbush, L. Reina, C. Reuschle, Comput. Phys. Commun. **257** (2020)

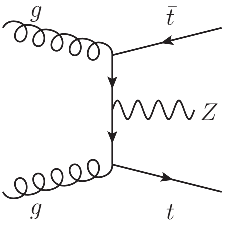
D. Figueroa, S. Quackenbush, L. Reina, C. Reuschle, Comput. Phys. Commun. **270** (2022)

The packages in comparison

$t\bar{t}Z$ implementation

- Stable Z-boson in final state, decayed by `PYTHIA 8.2`

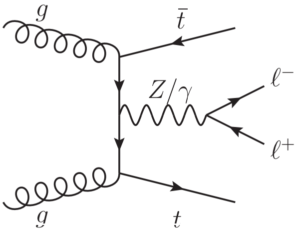
  $\rightarrow$ no off-shell effects



$t\bar{t}\ell^+\ell^-$ implementation

- Full matrix elements: Z and γ channels
- Necessary technical (generation) cut on lepton-pair inv. mass $M_{\ell^+\ell^-}$

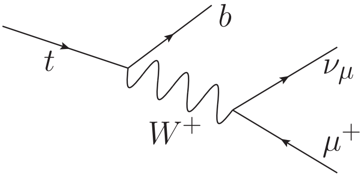
  $\rightarrow$ our default: $M^{\text{min}}_{\ell^+\ell^-} = 10$ GeV



Top-quark decays: two options

Spin-averaged

stable tops in POWHEG BOX, decayed by PYTHIA 8.2



With spin correlations

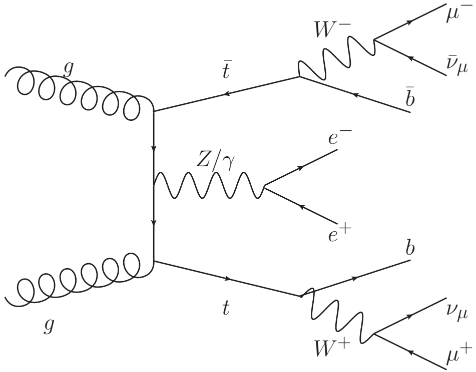
- NLO QCD with stable tops
- LO production of e.g. $(t \to \ell'^+ \nu_{\ell'} b)(\bar{t} \to \ell'^- \bar{\nu}_{\ell'} \bar{b})\, \ell^+ \ell^- (+\text{jet})$

  $\to$ spin correlations are retained

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

Numerical analysis

Here: e^+, e^- from Z/γ; μ^+, μ^- from $t, \bar{t}$:



Parameters

EW input parameters: G_μ scheme

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

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

Other parameters:

$$\Gamma_Z = 2.4952 \text{ GeV}, \quad \Gamma_W = 2.085 \text{ GeV},$$

$$m_t = 172.76 \text{ GeV}, \quad \Gamma_t = 1.42 \text{ GeV}.$$

PDF: CT18NLO

Renormalization and factorization scales: $\mu_\text{r} = \xi_\text{r} \mu_0$ and $\mu_\text{f} = \xi_\text{f} \mu_0$

$$\text{with} \quad \mu_0 = \frac{2m_t + m_Z}{2} \quad \text{(fixed)} \quad \text{or} \quad \mu_0 = \frac{M_T(Z) + M_T(t) + M_T(\bar{t})}{3} \quad \text{(dynamical)}$$

with $m_Z \leftrightarrow M(e^+e^-)$. Scale uncertainty estimated by 7-point variation: $\xi_\text{r}, \xi_\text{f} \in \{0.5, 1, 2\}$

Analysis cuts

- Cuts on the electrons/positrons:

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

- 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, $t \to \mu^+\nu_\mu b$ and $\bar{t} \to \mu^-\bar{\nu}_\mu\bar{b}$

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

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

NLO QCD corrections of $t\bar{t}e^+e^-$

Fixed order results

Total cross section, LO and NLO QCD:

Fixed scale:

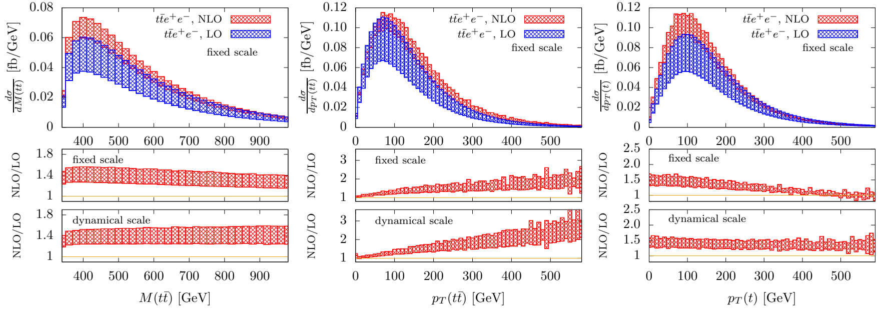
$$\sigma^{\mathrm{LO}}_{\mathrm{t\bar{t}e^+e^-}} = 15.9^{+5.1}_{-3.6}\ \mathrm{fb}$$

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

Dynamical scale:

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

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

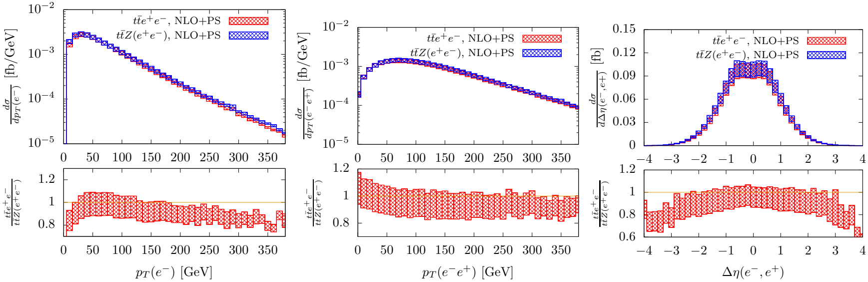


Off-shell effects of the e^+e^- system: $t\bar{t}e^+e^-$ vs $t\bar{t}Z(e^+e^-)$

NLO + PS

- effects of off-shell Z
- top-quarks decays by PYTHIA
- only 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

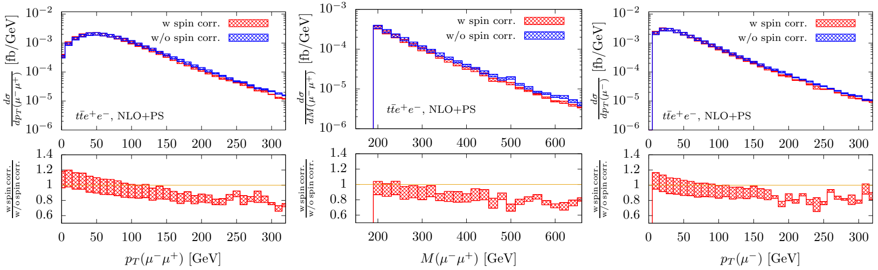


(fixed scale)

Spin-correlations in top decays: $t\bar{t}e^+e^-$

NLO + PS

- $t\bar{t}e^+e^-$ implementation
- tree-level NWA spin correlations *vs.* $t\bar{t}e^+e^-$ with spin-averaged top quarks decayed by PYTHIA 8.2
- Visible effects in the tails, 10-20% lower with spin correlations



(fixed scale)

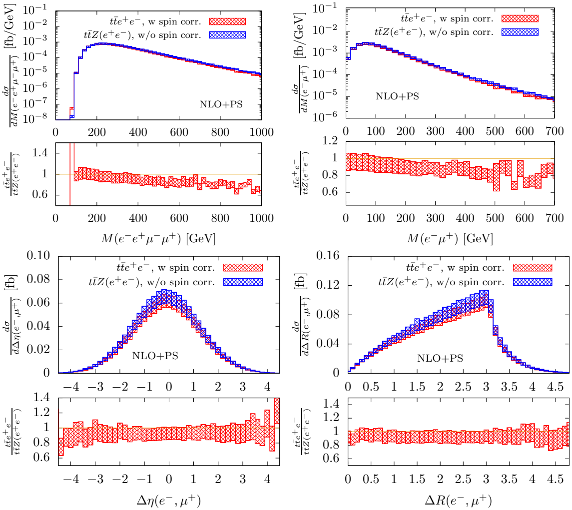
Summary

- I presented here our implementations of $t\bar{t}\ell^+\ell^-$ and $t\bar{t}Z$ in 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 pseudorapity distributions of the $\ell^+\ell^-$ system.
- Also considering tree-level spin correlations in top decays can cause effects of up to 10-20% in tails of distributions for transverse momenta and invariant masses of the Z and the top/antitop decay products.

Backup Slides

Mixed lepton observables

NLO + PS

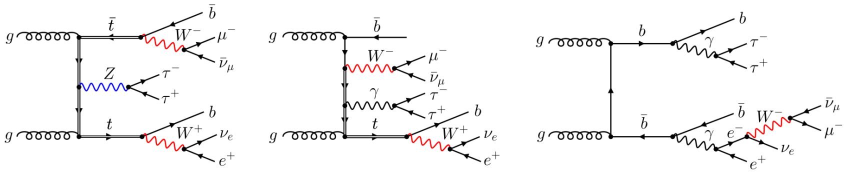


- Most accurate *vs.* most approximated prediction
- $M(e^+e^-\mu^+\mu^-)$ and $M(e^-\mu^+)$ distributions: 10-20% off-shell and spin-correlation effects at high invariant masses
- $e^\pm\mu^\mp$ angular distributions: no appreciable effect

(fixed scale)

Recent NLO QCD study

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



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

- Full top and Z/γ off-shell effects and spin correlations @NLO
- Double, single and non-resonant (top) diagrams

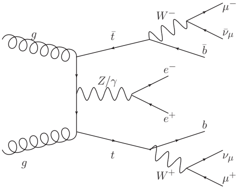
Top-decay algorithm, 1

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

They provide an upper bound $\mathcal{U}$ of the full (decayed) top-resonant matrix elements (ME) in terms of the undecayed ME times a process-independent prefactor C

$$\mathcal{U} = C \times |\mathcal{M}_{\text{undec}}|^2 \geq |\mathcal{M}_{\text{dec}}|^2$$

$\rightarrow$ a rejection-sampling procedure can be used to recover spin correlations



Top-decay algorithm, 2

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

First, integrate the undecayed ME and generate corresponding events. Then, for each event:

1. Generate momenta of decay products uniformly distributed in available phase space.
2. Compute $|\mathcal{M}_{\text{undec}}|^2$ and $|\mathcal{M}_{\text{dec}}|^2$ using the momenta from the event and from step 1.
3. Generate $r \sim U[0, 1]$ and accept momenta from 1. with probability $\mathcal{M}_{\text{dec}}/\mathcal{U}$.

Charge asymmetry of the $t\bar{t}$ system (fixed order)

Definitions:

$$A_c = \frac{\sigma(\Delta|y_{t\bar{t}}| > 0) - \sigma(\Delta|y_{t\bar{t}}| < 0)}{\sigma(\Delta|y_{t\bar{t}}| > 0) + \sigma(\Delta|y_{t\bar{t}}| < 0)} \qquad A_c^{ex} = A_c \, \frac{\sigma^{\mathrm{NLO}}_{\mathrm{t\bar{t}e^+e^-}}}{\sigma^{\mathrm{LO}}_{\mathrm{t\bar{t}e^+e^-}}}$$

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:

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

dynamical scale:

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