tWZ at NLO in QCD

ongoing work in collaboration with Fabio Maltoni, Ken Mimasu, and Marco Zaro

Hesham El Faham

Nov 2020

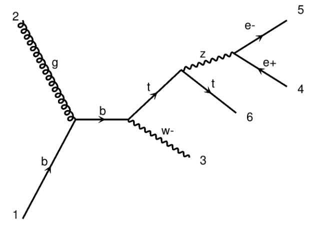
Centre for Cosmology, Particle Physics and Phenomenology (CP3),
Université Catholique de Louvain, Belgium

Inter-University Institute for High Energies (IIHE),
Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium

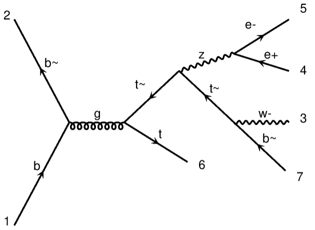
Introduction

arxiv 1904.05637

- tWZ is a rare EW top production process $\rightarrow$ **it can be a potential probe of the weak couplings of the top quark that are relatively poorly measured.**
- Studying tWZ process at NLO in QCD is 'tricky' because of its 'interference' with $t\bar{t}Z$ and $t\bar{t}$ at LO $\rightarrow$ tWZ **needs to be understood better.**
- tWZ is sensitive to unitarity-violating behaviour induced in its sub-amplitudes through modified EW interactions $\rightarrow$ **study tWZ in SMEFT.**



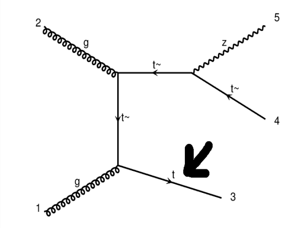
born diagram QCD=1, QED=3



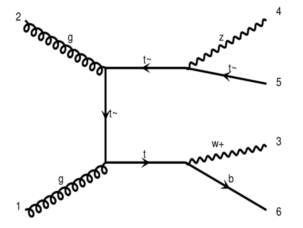
real diagram QCD=2, QED=3

The 'interference'

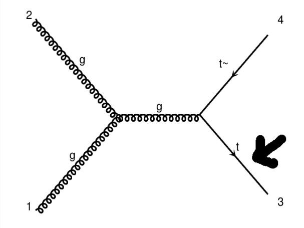
arxiv 1907.04898



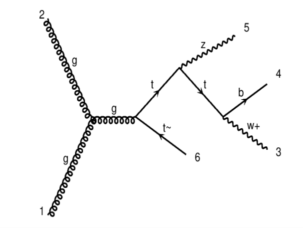
Example diagram of *ttZ* at LO by MG5.



Example diagram of *tWZ* at NLO (real) by MG5.



Example diagram of *tt* at LO by MG5.



Example diagram of *tWZ* at NLO (real) by MG5.

The underlying resonant structure of $t\bar{t}Z$ followed by $t \to Wb$ or $t\bar{t}$ followed by rare $t \to WZb$ **can spoil the perturbative behaviour of the NLO expansion in** tWZ**.**

Diagram Removal

arxiv 1907.04898

The amplitude associated to the tWZ process (at NLO in QCD with real emissions) can be expressed as:

$$\mathcal{A}_{tWZ} = \mathcal{A}_{tWZ}^{r\not{e}s} + \mathcal{A}_{tWZ}^{res} \quad (1)$$

and thus the matrix element,

$$|\mathcal{A}_{tWZ}|^2 = |\mathcal{A}_{tWZ}^{r\not{e}s}|^2 + 2\Re\left(\mathcal{A}_{tWZ}^{r\not{e}s}\mathcal{A}_{tWZ}^{\dagger res}\right) + |\mathcal{A}_{tWZ}^{res}|^2 \quad (2)$$

Two schemes to handle the resonant part of the matrix element is to:

- drop the resonant contribution to the matrix element and use non-resonant cross section as a measurable quantity to compare to experimental results, this is called **DR/DR1.**
- include the interference term for a better approximation of the cross section, this is called **DR+I/DR2.**

Diagram Removal is automated in MG5 via the MadSTR plugin. However MadSTR doesn't handle $1 \to 3$ decays $\to$ we do DR manually.

SM analysis and preliminary results

arxiv 0805.3067

- In practice, we are studying tWl^+l^-, the two leptons can be coming from a Z or a γ decay. Our aim is to **identify a region in the phase space in which the non-resonant part of tWZ dominates.**

- We have two DR scenarios $\rightarrow$ either remove ttZ+tt overlap, or only remove the ttZ overlap. We here show results from the former scenario.

- We then look at cross section rates at DR1 and DR2 schemes $\rightarrow$ our results show DR1/DR2 ratio of $\sim$ 1.50. This means that the interference with the resonant part of the matrix element is significant.

$$|\mathcal{A}_{tWZ}|^2 = |\mathcal{A}_{tWZ}^{r\not{e}s}|^2 + 2\Re\left(\mathcal{A}_{tWZ}^{r\not{e}s}\mathcal{A}_{tWZ}^{\dagger res}\right) + |\mathcal{A}_{tWZ}^{res}|^2 \tag{3}$$

- The resonant part can be suppressed by a cutting on the pT of the extra b quark $\rightarrow$ hard b quarks tend to have come from the decay of a top. Requiring an upper limit on $pT(b)$, $pT(b) < 30GeV$ $\rightarrow$ DR1/DR2 ratio $\sim$ 1.10.

SM analysis and preliminary results

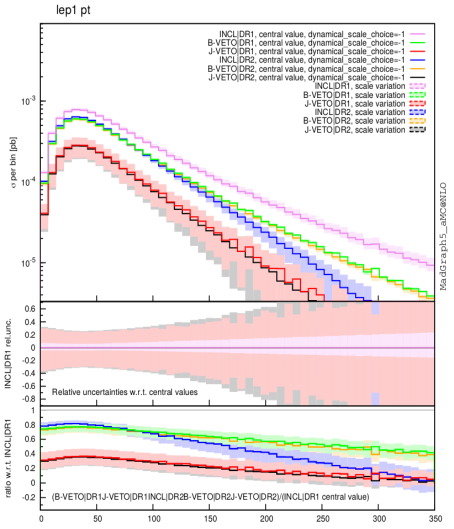


Figure 1: $pT(l_1)$

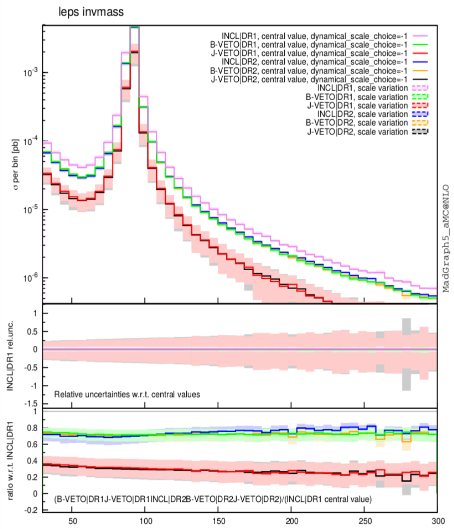
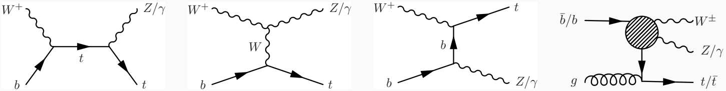


Figure 2: $m(l^+l^-)$

To SMEFT: relevant operators

- tWZ is sensitive to unitarity-violating behaviour through modified EW interactions $\rightarrow$ probing the high-energy phase space of tWZ can therefore serve as a test for the SM hypothesis.



Three diagrams to the left are SM diagrams for the $bW \rightarrow tZ$ subprocess. Last diagram to the right is the embedding of the $bW \rightarrow tZ$ sub-amplitude into tWZ production. arxiv 1904.05637

- We therefore use the following SMEFT operators in our study:

Operator	Definition .
$\mathcal{O}_{tW}$	$i\big(\bar{Q}\tau^{\mu\nu}\,\tau_I\,t\big)\,\tilde{\varphi}\,W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tB}$	$i\big(\bar{Q}\tau^{\mu\nu}\,t\big)\,\tilde{\varphi}\,B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tG}$	$ig_S\,\big(\bar{Q}\tau^{\mu\nu}\,T_A\,t\big)\,\tilde{\varphi}\,G^A_{\mu\nu} + \text{h.c.}$
$\mathcal{O}^{(1)}_{\varphi Q}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\,\varphi\big)\big(\bar{Q}\,\gamma^\mu\,Q\big)$
$\mathcal{O}^{(3)}_{\varphi Q}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\,\tau_I\varphi\big)\big(\bar{Q}\,\gamma^\mu\,\tau^I Q\big)$
$\mathcal{O}_{\varphi t}$	$i\big(\varphi^\dagger\,\overleftrightarrow{D}_\mu\,\varphi\big)\big(\bar{t}\,\gamma^\mu\,t\big)$

.. the interaction of the top with the weak isospin and the weak hypercharge gauge fields, the chromo-magnetic dipole operator, the interaction of two fermions fields with gauge bosons, and the Yukawa coupling modification.

SMEFT analysis and preliminary results

- We start the SMEFT analysis by looking at tWZ with stable Z.
- We start by looking at the gain for each operator from considering tWZ at NLO, see the given table.
- We work in the dim6top implementation, i.e. SMEFTatNLO. Some operators in the Warsaw basis are expressed as linear coefficients of the dim6top operators shown below.

op.	σ_i^{LO}(pb)	σ_{ij}^{LO}(pb)	σ_i^{NLO}(pb)	σ_{ij}^{NLO}(pb)	$(\sigma_{NLO}/\sigma_{LO})_i$	$(\sigma_{NLO}/\sigma_{LO})_{ij}$
`cpt`	2.0e-03	2.2e-04	2.2e-03	2.3e-04	1.10	1.04
`cpqm`	2.5e-03	5.2e-04	3.6e-03	6.4e-04	1.44	1.23
`cpq3`	2.2e-02	6.0e-03	2.9e-02	7.0e-03	1.32	1.16
`ctw`	-1.3e-02	2.9e-02	-1.6e-02	3.3e-02	1.23	1.13
`ctz`	-3.4e-04	6.4e-03	-3.5e-04	7.0e-03	1.03	1.09
`ctg`	9.0e-03	1.9e-02	10.0e-03	2.0e-02	1.22	1.05

- On the level of total rates, we don't seem to gain much from considering the NLO correction $\rightarrow$ **look at differential distributions.**

Summary

- Being a rare EW top production process makes tWZ is an interesting process to study.
- Diagram removal is essential when studying tWZ at NLO in QCD because of the overlap with ttZ and tt processes at LO.
- The resonant structure of ttZ and tt can spoil the convergence of tWZ at NLO in QCD.
- In our SM analysis, by vetoing hard b quarks, we were able to identify a region in the phase space in which the non-resonant part of the tWZ dominates.
- In our SMEFT analysis, we are assessing the significance of relevant operators to tWZ at NLO, it is still an ongoing work.