tWZ associated production at the LHC in the SMEFT [to appear soon]

in collaboration with
Fabio Maltoni, Ken Mimasu, Marco Zaro

Hesham El Faham
hesham.elfaham@vub.be

Vrije Universiteit Brussel and Université Catholique de Louvain, Belgium

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Outline

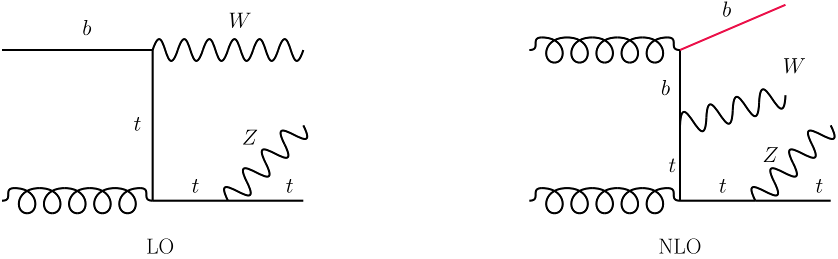
- Introduction
- The tWZ challenge at NLO
- tWZ in the SM
- tWZ in the SMEFT
- Summary

Introduction

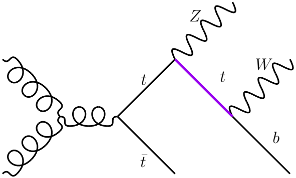
- The SM can not answer most of the pressing questions related to the top quark $\rightarrow$ **indications of answers might be manifested in new physics phenomena seen in the top-quark sector**
- *tWZ* is a rare EW process $\rightarrow$ **potential probe of EW couplings that are not well measured, so far**
- *tWZ* is sensitive to **unitarity-violating behaviour induced in its sub-amplitudes** via modified EW interactions [1904.05637] $\rightarrow$ can potentially serve as a test for the SM hypothesis
- New physics phenomena can be encapsulated in a higher dimensional operators $\rightarrow$ **SMEFT**
- Accurate theoretical predictions$\rightarrow$ **study *tWZ* at NLO**
- ***tWZ* at NLO is non-trivial due to its overlap with other processes**

tWZ from LO to NLO in QCD

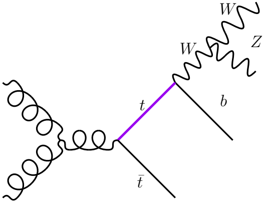
At NLO in QCD, the *tWZb* appears as a real emission final state



The *tWZ* challenge



ttZ



tt

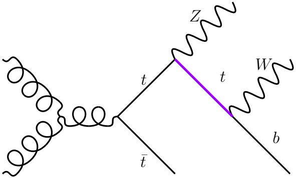
The ***tWZb*** final state can also have resonant contributions, from

$$ttZ,\, t \to Wb, \quad \text{or} \quad tt,\, t \to WZb$$

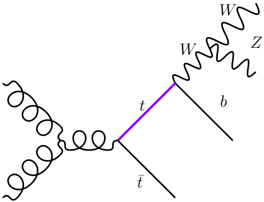
and not necessarily the non-resonant ***tWZb***

- These topologies **do not belong to the genuine *tWZ* final state process** but to the leading order ***ttZ*** and ***tt*** processes
- The underlying resonant structure can spoil the perturbative behaviour of the NLO expansion

The *tWZ* challenge



ttZ



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Suppress contributions from the resonant amplitude!

The *tWZ* challenge cont'd

The amplitude associated to the ***tWZ*** process can be expressed as

$$\mathcal{A}_{tWZ} = \mathcal{A}_{tWZ}^{\not{res}} + \mathcal{A}_{tWZ}^{res} \tag{1}$$

and thus the matrix element,

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

Two Diagram Removal (DR) schemes to handle the resonant part of the matrix element:

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Two Diagram Removal (DR) schemes to handle the resonant part of the matrix element:

- Keep ONLY the non resonant contribution → **DR1**

The *tWZ* challenge cont'd

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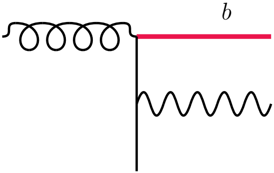
Two Diagram Removal (DR) schemes to handle the resonant part of the matrix element:

- Keep ONLY the non resonant contribution $\rightarrow$ **DR1**
- Keep ALSO interference term $\rightarrow$ **DR2**

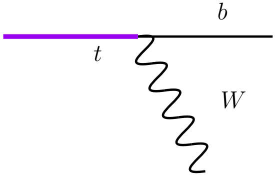
tWZ in the SM

- The current MG5 diagram removal plugin (`MadSTR`) does not handle $1 \to N$ decays where $N > 2$ → **DR1 and DR2 schemes are implemented by hand**
- The **resonant part of the phase space is suppressed by vetoing hard *b*-quarks** as they tend to have come from the decay of a top
- For SM predictions → both the ***ttZ*** and the ***tt*** overlaps are removed
- A good agreement between the DR1 and the DR2 schemes → **the non-resonant part of *tWZ* dominates the phase space**

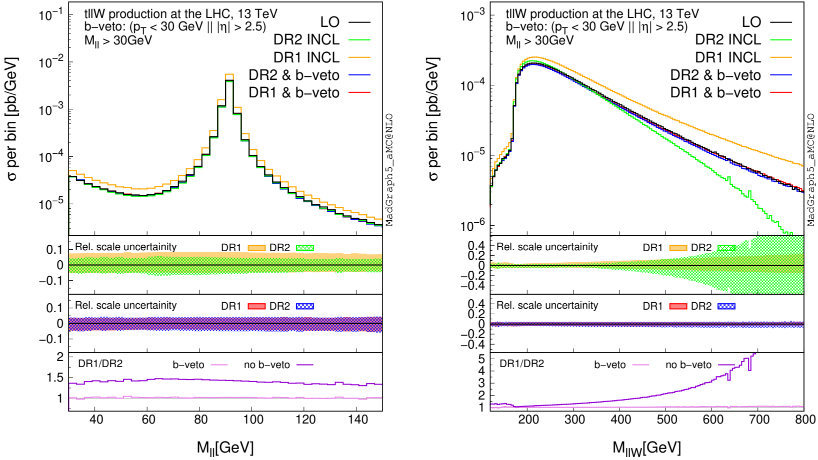
SOFT



HARD



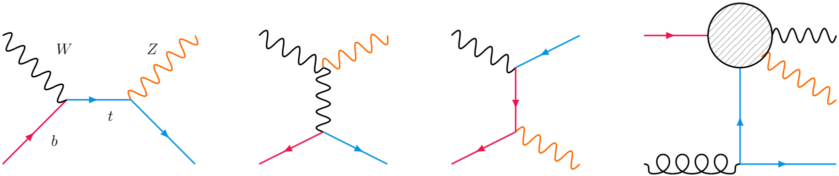
tWZ in the SM: differential results



The *b*-veto significantly improves the DR1-DR2 agreement

tWZ in the SMEFT

The $bW \to tZ$ sub-amplitude:



and therefore the operators included in the analysis are

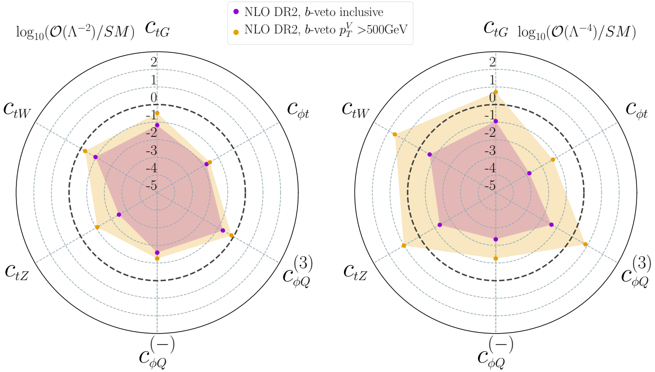
- $\mathcal{O}^{(3)}_{\varphi Q}$, $\mathcal{O}^{(-)}_{\varphi Q}$ $\to$ interaction of two fermions fields with the gauge bosons
- $\mathcal{O}_{\varphi t}$ $\to$ the right handed ***ttZ*** interaction
- $\mathcal{O}_{tW}$, $\mathcal{O}_{tZ}$ $\to$ interaction of the top with the weak isospin and the weak hypercharge gauge fields
- ($\mathcal{O}_{tG}$ $\to$ the gluon-top interaction)

Generic SMEFT predictions

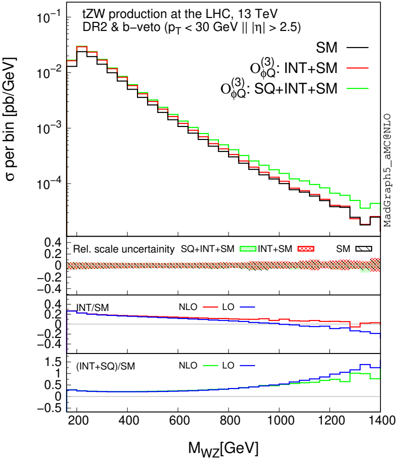
A generic observable in SMEFT can be expressed as

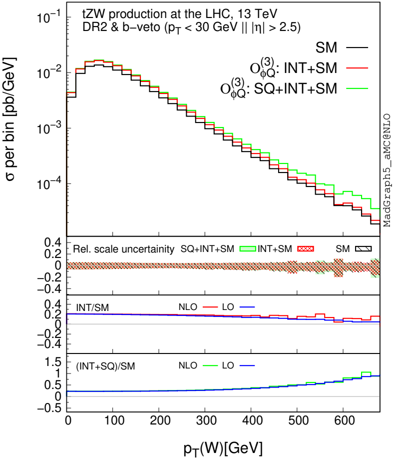
$$\sigma = \sigma_{SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\sigma_i + \sum_{ij} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4}\sigma_{ij} \quad (3)$$

- second term $\rightarrow$ interference contributions of dim-6 operators
- last term $\rightarrow$ squared contributions of dim-6 operators



tWZ in the SMEFT: differential results





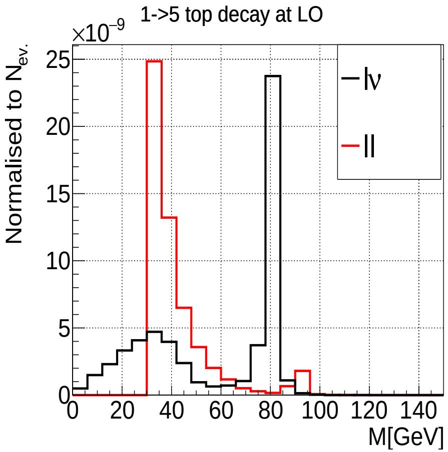
SMEFT impacts from LO to NLO accuracy are stable suggesting the DR treatment is correctly identifying the phase space of the *tWZ* process

Summary

- A study of ***tWZ*** production at NLO in QCD is presented in the context of the SM and SMEFT
- The overlap from ***tt*** and ***ttZ*** renders the ***tWZ*** at NLO a non-trivial process to study
- The resonant overlap is handled using the DR schemes at the amplitude-level
- Vetoing hard ***b***-quarks ensures the ***tWZ*** process dominates the phase space after the diagram removal
- The differential results presented suggest the DR treatment correctly identifies the phase space of the ***tWZ*** process
- The work presented lays the foundation for precision LHC interpretations of ***tWZ*** data in the SMEFT framework

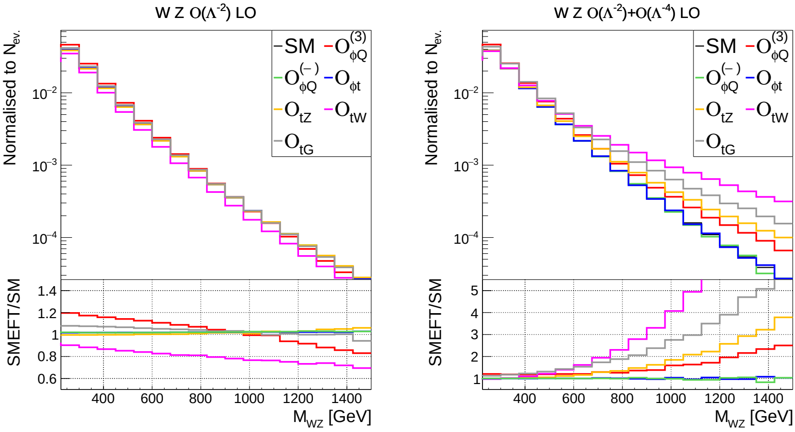
BACKUP SLIDES

Why decay the *Z* in the SM case?



- The $t \rightarrow lll\nu b$ decay is shown at LO
- This decay is what causes the overlap with *tt*
- The *Z* ‘likes’ to be off-shell more than the *W*
- To fairly treat the *tt* overlap, the *Z* should decay (keeping it on-shell suppresses the *tt* overlap)
- *Z* is kept stable in the SMEFT study as the overlap from *tt* there is irrelevant

tWZ in the SMEFT: differential results[2]



M_{WZ} is a proxy for the $bW \to tZ$ sub-amplitude scattering energy