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A method for the study of the quantum interference between singly and doubly resonant top-quark production in proton-proton collisions at the LHC with the ATLAS detector

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Summary. — In this work, a method to be used for the measurement of the $WbWb$ production differential cross-section as a function of variables sensitive to $t\bar{t}/tW$ interference is presented: $t\bar{t}$ represents the doubly-resonant production, while tW is the singly-resonant one. This method is being used in the data sample collected by the ATLAS detector in 2015–2018 and corresponding to $\sqrt{s} = 13$ TeV and $\mathcal{L} = 139$ fb^{-1}. Single- and double-differential cross-sections extraction and comparison to theoretical predictions are described.

Introduction

The top quark is the heaviest known elementary particle of the *Standard Model*. It allows to explore unique physics domains, inaccessible otherwise. One of them is the quantum interference between singly- and doubly-resonant top-quark production processes, which can lead to identical $WbWb$ final states. Singly resonant process is given by next-to-leading-order (NLO) tW production with an extra b-quark in the final state while doubly resonant one is given by leading-order (LO) $t\bar{t}$, as explained in Sect. **1**.

In this work, a method is provided for the measurement of the particle-level $WbWb$ production cross-section, differential with respect to variables sensitive to $t\bar{t}/tW$ interference, using the full ATLAS Run-2 dataset, explained in Sect. **2**. Currently, the variables of interest are the invariant-mass of a b-jet and a lepton, m_{bl}^{minimax}, and the angular distance between the two b-jets, $\Delta R(b_1, b_2)$ and are fully defined in Sect. **3** within the method itself. With this technique, the single-differential cross-section will be measured as a function of both these variables, while the double-differential one will be measured as a function of one variable in bins of the other one, like m_{bl}^{minimax} in bins of $\Delta R(b_1, b_2)$. Results will than have to be compared to theoretical prediction schemes that model in a different way the $t\bar{t}/tW$ quantum interference description. The $WbWb$ cross-section as a function of m_{bl}^{minimax} has been measured only once, by ATLAS, using data collected in 2015 and 2016 [1].

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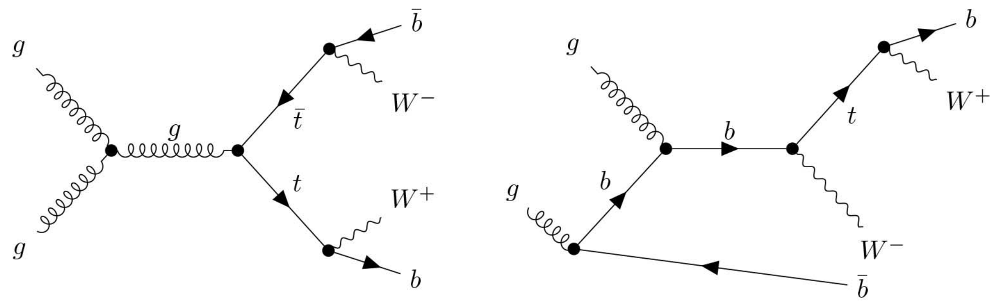

(a) Doubly-resonant diagram. (b) Singly-resonant diagram.

Fig. 1.: Examples of quantum-mechanical interfering LO doubly-resonant diagram (a) and NLO singly-resonant diagram (b).

The proposed method is of general validity and can be used by any experiment willing to measure such interference.

1. – $WbWb$ production processes

The inclusive production of a top quark, a W boson and a b quark from two α and β particles can be written as:

$$\alpha + \beta \to t + W + b. \tag{1}$$

This amplitude is given by:

$$\mathcal{A}_{\alpha\beta} = \mathcal{A}_{\alpha\beta}^{(tW)} + \mathcal{A}_{\alpha\beta}^{(t\bar{t})}. \tag{2}$$

At the NLO QCD corrections it holds:

$$\sigma_{WbWb} \propto |\mathcal{A}_{\alpha\beta}|^2 = \left|\mathcal{A}_{\alpha\beta}^{(tW)}\right|^2 + 2\Re\{\mathcal{A}_{\alpha\beta}^{(tW)}\mathcal{A}_{\alpha\beta}^{(t\bar{t})}\} + \left|\mathcal{A}_{\alpha\beta}^{(t\bar{t})}\right|^2, \tag{3}$$

where the first and third terms are respectively the NLO singly and the LO doubly resonant diagrams to the tW cross-section, while the second term describes the quantum interference between $t\bar{t}$ and tW. This latter term affects any computation that considers contributions beyond the first-order. Example of Feynman diagrams for these processes are shown in fig. 1. The interference is caused by the identical $WbWb$ final states of the singly- and doubly-resonant top-quark production.

The measurement of this cross-section targets the $WbWb$ dilepton final-state, characterized by the presence of a pair of oppositely charged leptons ($e^{\pm}e^{\mp}$, $e^{\pm}\mu^{\mp}$, $\mu^{\pm}\mu^{\mp}$) originating from W decays.

Comparisons between theoretical predictions and experimental results for the $WbWb$ cross-section in the dilepton channel require the merging of fixed NLO calculations with a parton shower (PS), resulting in NLO+PS calculations. The interference can be included into the amplitude of Eq. 3 at NLO+PS using two possible schemes:

- *Diagram Removal* (DR): where all the doubly resonant diagrams in the NLO tW process amplitude are removed.

- *Diagram Subtraction* (DS): where the NLO tW cross-section is modified by implementing a subtraction term designed to cancel only locally the $t\bar{t}$ contribution.

Where the interference is small, the predictions obtained with the DR and DS schemes are comparable, instead, where it is large, the difference between them is not negligible (typically of the order of $50-100\%$) [2]. This two methods are nowadays valid and the experimental studies will help understand how well they work.

2. – Dataset and event selection

The training of the method introduced before and explained in Sect. **3** is currently being applied to the full LHC Run-2 dataset collected by the ATLAS detector at $\sqrt{s}=13$ TeV and $\mathcal{L}=139$ fb^{-1} in order to probe its efficiency in the most accurate way.

ATLAS is a multipurpose detector composed by: a muon spectrometer, a magnetic system, an inner tracker, an electromagnetic calorimeter and an hadronic calorimeter [3].

For this analysis technique the dilepton channel (ee, $e\mu$ and $\mu\mu$) is considered and the following selection is applied to events that fire single-electron or single-muon triggers:

- $p_T^{\text{lepton}} > 28$ GeV, $p_T^{\text{jets}} > 25$ GeV and $|\eta| < 2.5$ for the jets.
- 2 b-tagged jets at 60%WP (working point) with veto on 3rd b-tagged jet at 85%WP.

The signal sample is obtained with Monte Carlo (MC) simulations of the $t\bar{t}$ and tW processes, while the background samples are obtained with MC simulations of other processes that lead to similar final states: Z+jets, diboson and $t\bar{t}V$ productions and non-prompt background. Several MC generators are used to describe both samples, namely: `MadGraph5_aMC@NLO` [4] and `Powheg` [5] interfaced with `Pythia` [6] or `Herwig` [7] and `Sherpa` [8] to account for the corresponding modelling uncertainties.

Particle-level objects are reconstructed using generator-level information from MC simulation: a fiducial region is defined with these objects replicating as close as possible the selection of an analysis with detector-level reconstructed objects. These requirements define the *particle-level fiducial region* and the measured observables have to be corrected to this phase space.

3. – Analysis strategy

The $WbWb$ production cross-section will be measured as a function of two interference-sensitive variables: the invariant mass of a b-jet and a lepton, m_{bl}^{minimax}, and the angular distance between the two b-jets, $\Delta R(b_1, b_2)$.

The former is chosen since it allows to well discriminate among the two samples:

$$m_{bl}^{\text{minimax}} \equiv \min\{\max(m_{b_1 l_1}, m_{b_2 l_2}), \max(m_{b_1 l_2}, m_{b_2 l_1})\}; \tag{4}$$

this particular definition exploits the fact that in tW production one of the two Wb pairs may be off-shell with respect to the top mass, providing good separation between doubly-resonant events where it holds $m_{bl}^{\text{minimax}} < \sqrt{m_t^2 - m_W^2}$, and singly-resonant events, where such endpoint doesn't exist. Due to the suppression of the doubly-resonant contribution the differential cross-section above this kinematic endpoint increases sensitivity to interference effects: the interference region starts to be significant for $m_{bl}^{\text{minimax}} > 155$ GeV and above 200 GeV the contribution of two on-shell top final-state is suppressed and interference effects become large.

The other variable is defined as follows:

$$\Delta R(b_1, b_2) = \sqrt{\Delta\eta^2(b_1, b_2) + \Delta\phi^2(b_1, b_2)} \tag{5}$$

where η is the pseudorapidity and ϕ is the azimuthal angle. The use of this latter variable is inspired by some past studies performed by the ATLAS collaboration [9].

The cross-sections will have to be extracted using an *unfolding* procedure(1). Unfolding is commonly used to correct data for the finite resolution and limited geometrical acceptance of the detector [10]. The unfolding technique used for this method is an iterative procedure, called *iterative Bayesian unfolding method*, using this equation [11]:

$$\frac{\mathrm{d}\sigma^{\mathrm{fid}}}{\mathrm{d}X^i} \equiv \frac{1}{\mathcal{L} \cdot \Delta X^i} \cdot \frac{1}{\epsilon^i} \cdot \sum_j M^{-1} \cdot f^j_{\mathrm{acc}} \cdot \left(N^j_{\mathrm{obs}} - N^j_{\mathrm{bkg}}\right), \tag{6}$$

where N^j_{obs} is the number of events observed in data in bin j, N^j_{bkg} is the background contribution, f^j_{acc} is the acceptance factor, ϵ^i is the inefficiency factor, the index j runs over bins of observable X at reconstruction level while the index i labels bins at particle level, ΔX^i is the bin width, $\mathcal{L}$ is the integrated luminosity and M^{-1} is the inverted *migration matrix* as obtained with the iterative unfolding procedure. From the Eq. 6 it is possible to obtain also the normalized differential cross-section:

$$\frac{d\sigma^{\mathrm{norm}}}{dX^i} = \frac{1}{\sigma^{\mathrm{fid}}} \cdot \frac{\mathrm{d}\sigma^{\mathrm{fid}}}{\mathrm{d}X^i}, \tag{7}$$

where σ^{fid} is the fiducial cross-section. Before unfolding, the binning of the different variables will have to be optimised with dedicated resolution studies and *closure tests* in order to ensure the stability of the unfolding procedure. The signal sample is used to perform this latter procedure: in this kind of tests, a reconstructed-level distribution generated with a given model is unfolded using corrections derived from an independent sample with the same model and then compared to a truth-level distribution obtained using the same model. Ideally, one should recover the original distribution, but the limited statistics and the choice of the regularization method usually have an effect on the unfolding results.

Uncertainties for the single- and double-differential cross-sections can be obtained; some of the most significant ones belong to the following categories:

- *Detector-level* systematics: lepton reconstruction efficiency, jet-vertex-tagger, b-tagging, pile-up reweighting, luminosity, jet energy scale and missing E^T_{miss}.

- *Signal modelling* systematics: choice of the removal scheme, finite-sample statistics of MC generators, matrix element and parton shower models, initial- and final-state QCD radiation for the signal sample and parton distribution functions.

- *Background modelling*: systematics on $Z+$jets, systematics on diboson and systematics on $t\bar{t}V$.

(1) Called also *deconvolution method* or *inverse-problem method*.

Each uncertainty caused by detector effects is evaluated before and after the unfolding procedure. Systematics are evaluated by unfolding the varied MC detector-level spectra with nominal corrections and then comparing the unfolded result with the particle-level distribution of the generator, corresponding to the detector-level spectrum which has been unfolded. The relative uncertainties evaluated with this procedure will be directly applied to the unfolded data.

Once the total fiducial cross-section and single- and double-differential cross-sections as a function of the previously mentioned variables will be extracted, they can be compared to predictions obtained with DR and DS schemes described in Sect. **1**.

4. – Conclusions

In this work, a method for the study of the quantum interference between singly and doubly resonant top-quark processes is reported through the measurement of the $WbWb$ production cross-section and its comparison with prediction schemes. The proposed method is of general validity and it is currently being exercised within the ATLAS collaboration on the dataset corrected during LHC Run 2 in 2015–2018 at $\sqrt{s} = 13$ TeV and corresponding to $\mathcal{L} = 139$ fb^{-1}.

With this technique, the particle-level $WbWb$ final-state cross-section, in the dilepton channel, can be measured as a function of $t\bar{t}/tW$ interference-sensitive variables, like the invariant-mass of a b-jet and a lepton, m_{bl}^{minimax}, and the angular distance between the two b-jets, $\Delta R(b_1, b_2)$, through an iterative Bayesian unfolding method and compared with the DR and DS schemes, two different models for quantifying the interference effects when simulating these physics processes.

In order to get information about the interference process, it will be finally necessary to understand which scheme better describes each cross-section as a function of the different variables.

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