HIGGS τ-LEPTON YUKAWA COUPLING MEASUREMENT AND THE τ EMBEDDING METHOD FOR BACKGROUND ESTIMATION*

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To measure the $H \to \tau\tau$ Yukawa coupling the full dataset of the LHC Run 1 period recorded by the ATLAS experiment at the LHC during 2011 and 2012 has been analysed. The data correspond to integrated luminosities of 4.5 fb^{-1} and 20.3 fb^{-1} at centre-of-mass energies of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively. Evidence for the coupling of the Higgs boson to tau leptons at 4.5 (3.4) sigma significance was observed (expected). Recently, the combination of the CMS and ATLAS datasets has been published, raising the observed significance to discovery level at 5.5 sigma. One crucial ingredient in the search for the $H \to \tau\tau$ decay is the embedding method, which is a data-driven technique to estimate the large and irreducible background from $Z \to \tau\tau$ decays that cannot be obtained directly from data control samples. In this paper, the ATLAS search for the Higgs boson decaying to tau leptons is discussed and a detailed explanation of the embedding method is given. Other use cases of the embedding method are also mentioned.

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1. Introduction

The experimental confirmation of the Brout–Englert–Higgs mechanism, and, more generally, the investigation of the origin of electroweak symmetry breaking, was one of the main goals of the physics programme at the Large

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Hadron Collider (LHC). With the discovery of the particle with a mass of approximately 125 GeV by the ATLAS [1] and CMS [2] collaborations, this goal has been achieved. All of the performed measurements of the discovered particle's properties are consistent with the predictions for the Standard Model (SM) Higgs boson.

However, these measurements are based predominantly on studies of the bosonic decay modes, $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$. These are governed by different terms in the SM Lagrangian than the ones giving masses to fermions. Hence, it is clear that we can only establish the mass generation mechanism for fermions, as implemented in the SM, by measuring the direct coupling of the Higgs boson to fermions.

The ideal situation would be to measure all couplings to fermions. Unfortunately, due to very low signal strength for decays into light quarks and light leptons, this is currently unfeasible. Since the Yukawa couplings of the SM Higgs to fermions are proportional to their masses, the most promising candidate decay modes are the decays into tau leptons, $H \rightarrow \tau\tau$, and bottom quarks (b-quarks), $H \rightarrow b\bar{b}$. Among these two possibilities more favourable signal-to-background conditions are expected for $H \rightarrow \tau\tau$ decays [3]. The search for decays to $b\bar{b}$ is, due to the high QCD background, restricted to Higgs bosons produced in modes with a more distinct signature but a lower cross section, *e.g.*, H production with an associated vector boson. The smaller rate of such processes in the presence of still considerable background makes their detection challenging.

2. Background: Embedding

The crucial part of any searches of new physics in the LHC is to determine as precisely as possible all the relevant backgrounds from the SM processes. The different final-state topologies of the three analysis channels, arising from three main processes for Higgs boson production at the LHC: gluon–gluon Fusion (ggF), Vector Boson Fusion (VBF), and associated VH production, have different background compositions which necessitate different strategies for background estimation. In the analysis described in Ref. [3], mixture of a data-driven method and simulations was used.

The need for a data-driven technique comes from existence of the dominant and largely irreducible $Z/\gamma^* \rightarrow \tau\tau$ background. It is modelled using the so-called embedding technique, which is using $Z/\gamma^* \rightarrow \mu\mu$ events from data, where the muon tracks and associated energy depositions in the calorimeters are replaced by the corresponding simulated signatures of the final-state particles of the tau decay. The main advantage of this approach is that the essential features such as the modelling of the kinematics and of the hadronic activity of the event (jets and underlying event) as well as contributions from pile-up are taken from data. This minimizes the dependence on the simulations, since only the τ decays and the detector response to the tau-lepton decay products are based on simulation.

The embedding procedure is presented in the form of a flowchart in Fig. 1, intuitively showing the subsequent steps [4]. Firstly, by requiring two isolated, high-energy muons with opposite charge and a dimuon invariant mass satisfying $m_{\mu\mu} > 40$ GeV, $Z \to \mu\mu$ events can be selected from the data with high efficiency and purity. To replace the muons in the selected events, all tracks associated with the muons are removed and calorimeter cell energies associated with the muons are corrected by subtracting the corresponding energy depositions in a single simulated $Z \to \mu\mu$ event with the same kinematics. The calorimeter isolation energy in a cone of $\Delta R = 0.3$ around the muons from data before and after embedding are compared in Fig. 2 (a). Finally, both the track information and the calorimeter cell energies from a simulated $Z \to \tau\tau$ decay are added to the data event. The decays of the tau leptons are simulated by Tauola [5]. The tau-lepton kinematics are matched to the kinematics of the muons they are replacing, including polarisation and spin correlations [6], and the mass difference between the muons and the tau leptons is accounted for [3]. As an example, the reconstructed invariant mass for the $\tau\tau$ final state, $m_{\tau\tau}^{\mathrm{MMC}}$, is shown in Fig. 2 (b).

The remaining background processes are simulated using different generators, each interfaced to PYTHIA [7, 8] or Herwig [9, 10] to provide the parton shower, hadronisation and the modelling of the underlying event.

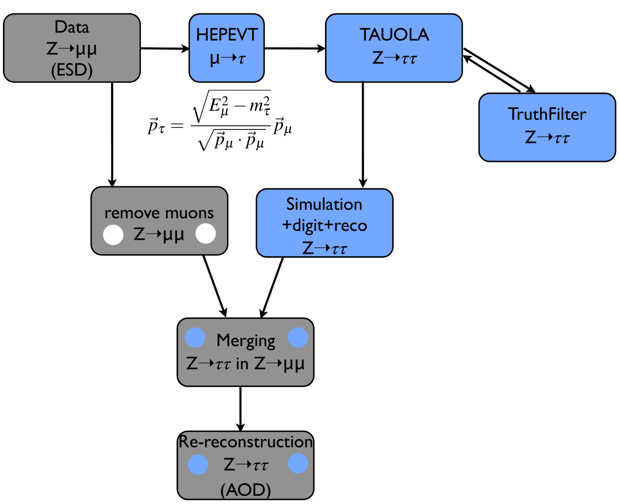

Fig. 1. The flowchart of the embedding procedure.

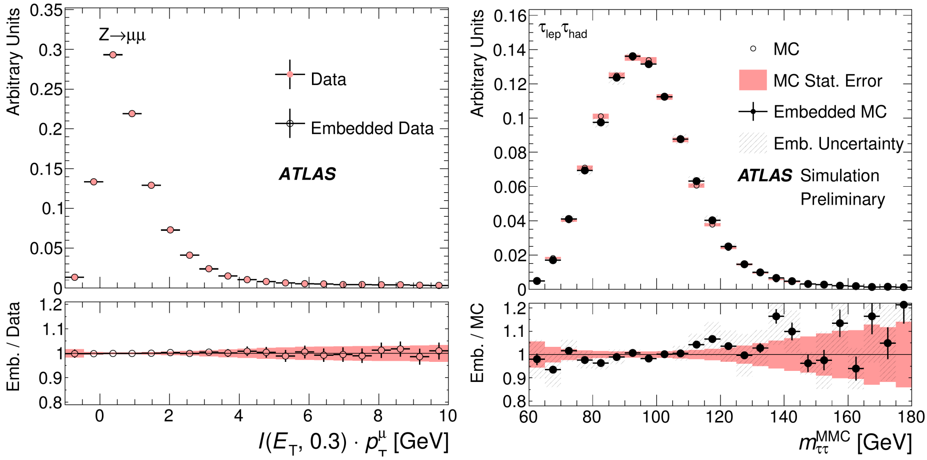

Fig. 2. (Left) The distribution of the calorimeter isolation energy $I(E_{\rm T}, 0.3) \times p_{\rm T}^{\mu}$ within a cone of radius $\Delta R = 0.3$ around the muons in $Z \to \mu\mu$ events from data, before and after the embedding of simulated muons. (Right) The distribution of the reconstructed invariant $\tau\tau$ mass, $m_{\tau\tau}^{\rm MMC}$, in the $\tau\tau$ final state, for simulated $Z \to \tau\tau$ events, compared to the one obtained from simulated $Z \to \mu\mu$ events after tau embedding. The ratios of the values before and after the embedding and between the embedded $Z \to \mu\mu$ and $Z \to \tau\tau$ events are given in (left) and (right) respectively. The errors in (left) and (right) on the ratios (points) represent the statistical uncertainties, while the systematic uncertainties are indicated by the hatched bands in (right). The shaded bands represent the statistical uncertainties from the $Z \to \mu\mu$ data events in (left) and from the $Z \to \tau\tau$ simulation in (right). Taken from Ref. [3].

It is worth mentioning that the embedding method was also successfully used in Run 1 in searches for charged Higgs in the $H \to \tau\nu$ channel [11]. In this case, it is used to distinguish the charged Higgs signatures from the SM process $W \to \tau\nu$, the dominant part of the irreducible background in the $t\bar{t} \to bH(\tau\nu)\bar{b}W$ channel.

3. Results

An excess of events over the expected background from other Standard Model processes then $H(125) \to \tau\tau$ is found with an observed significance of 4.5σ. It provides evidence for the direct coupling of the Higgs boson to fermions. The measured signal strength[1], normalised to the Standard Model

[1] $\mu =$ ratio of observed coupling of H to pair of tau leptons to the coupling of H to $\tau\tau$ in the Standard Model.

expectation, of

$$\mu = 1.43^{+0.27}_{-0.26}(\text{stat.})^{+0.32}_{-0.25}(\text{syst.}) \pm 0.09 \tag{1}$$

is consistent with the predicted Yukawa coupling strength in the Standard Model.

Additionally, the distribution of the invariant mass for the pair of tau leptons is peaked around the measured Higgs mass value, see Fig 3.

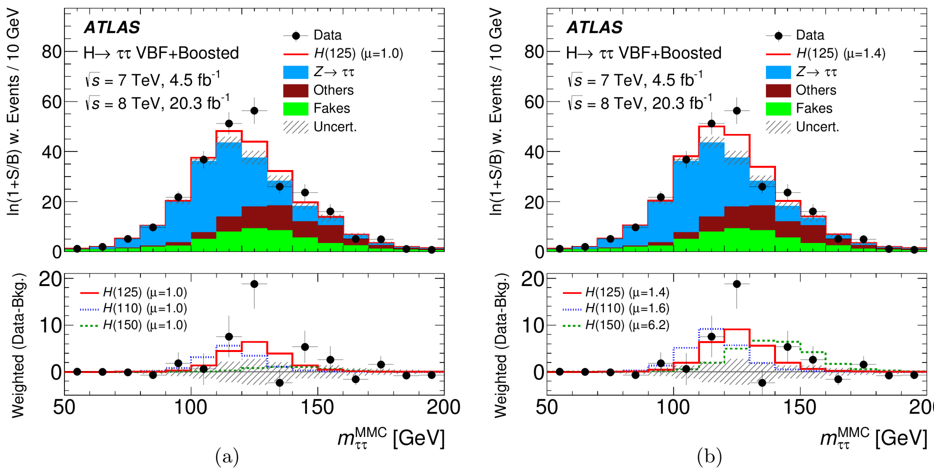

Fig. 3. (Colour on-line) Distributions of the reconstructed invariant $\tau\tau$ mass, $m_{\tau\tau}^{\text{MMC}}$, where events are weighted by $\ln(1 + S/B)$ for all channels, (S — signal, B — background). The bottom panel in each plot shows the difference between weighted data events and weighted background events (black points), compared to the weighted signal yields. The background predictions are obtained from the global fit with the $m_H = 125$ GeV signal hypothesis (signal strength $= 1.4$). The $m_H = 125$ GeV signal is plotted with a solid/red line, and, for comparison, signals for $m_H = 110$ GeV (thin dotted/blue) and $m_H = 150$ GeV (thick dotted/green) are also shown. The signal normalisations are taken from fits to data with the corresponding signal mass hypotheses, and the fitted μ values are given in the figure. The signal strengths are shown for the Standard Model expectations ($\mu = 1$) in (a), while in (b) the best-fit values are used. Taken from Ref. [3].

4. Conclusions

Evidence for decays of the Higgs boson into pairs of tau leptons was presented. The measured signal strength, normalised to the Standard Model expectation, is compatible with one. The embedding method, described in this paper, plays an important role in the background estimation for the reported analysis.

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