SEARCHES FOR THE STANDARD MODEL HIGGS BOSON DECAY TO τ LEPTON PAIRS AT THE CMS EXPERIMENT*

Andrzej Pyskir†

on behalf of the CMS Collaboration

Institute of Experimental Physics, Faculty of Physics, University of Warsaw
Pasteura 5, 02-093 Warszawa, Poland

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We present results of searches for the Standard Model Higgs boson decaying to tau lepton pairs at the CMS experiment with data collected during the LHC Run 1. We also present some insight into the analysis with Run 2 data. CP sensitive variables are described and an experimental method of probing CP of the Higgs boson is presented.

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1. Introduction

A new particle at mass around 125 GeV has been discovered by the CMS [1, 2] and ATLAS [3] collaborations in 2012 during searches for the SM Higgs boson. The particle has been observed in decays into vector boson pairs: $\gamma\gamma$, WW^*, ZZ^*. Data collected during the LHC Run 1 allowed also for determination of the particle properties [4]. The total cross section has been established to be 1.09 ± 0.11 relative to the SM prediction for the Higgs boson, and CP parity has been determined to be 0^+ [5]. This justifies a statement that the particle is a Standard Model Higgs boson. Significance of the signal in the three above-mentioned channels exceeded 5σ in both experiments individually. Search in $\tau\tau$ decay channel has also been performed. The channel is very promising due to a high branching ratio — 6.27% [6] — and direct coupling to fermions, which enables the

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Yukawa coupling measurement. The significance of signal in the $\tau\tau$ channel observed (expected) in each experiment was 3.4 (3.7)σ at CMS and 4.4 (3.3)σ at ATLAS [4]. A combination of results from both experiments leads to the significance observed (expected) equal to 5.5 (5.0)σ. Obtaining the significance above 5σ is the goal of both experiments in Run 2, as well as getting some insight into CP nature of the Higgs boson in $H \to \tau\tau$ decay mode.

2. Run 1 $H \to \tau\tau$ analysis overview

Since τ lepton is unstable, in $H \to \tau\tau$ analysis, we can consider a few final states. These include $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$, ee and $\mu\mu$, where τ_h means reconstructed hadronic decay of the τ lepton. In this article, we focus on the $\mu\tau_h$ final state. The baseline selection for this final state contains the following requirements:

— trigger requiring opposite sign of a pair of μ with transverse momentum $p_{\mathrm{T}}^{\mu} > 12$–$18$ GeV and τ_h with transverse momentum $p_{\mathrm{T}}^{\tau_h} > 10$–$20$ GeV, thresholds depending on instantaneous luminosity,

— $p_{\mathrm{T}}^{\mu} > 17$–$20$ GeV, threshold depend on trigger threshold, $|\eta_\mu| < 2.1$,

— $p_{\mathrm{T}}^{\tau_h} > 30$ GeV, $|\eta_{\tau_h}| < 2.4$,

— relative μ isolation $R^\mu < 0.1$, τ_h isolation $I^{\tau_h} < 1.5$ GeV,

— transverse mass $m_{\mathrm{T}} < 30$ GeV.

For definitions of I^{τ_h}, R^μ and m_{T}, see [7]. Events in each final state are split into mutually exclusive categories to enhance sensitivity. Categories differ with each other in the jet multiplicity (0-jet, 1-jet, 2-jet called "vbf") and some other kinematical variables, like $p_{\mathrm{T}}^{\tau_h}$ or invariant mass of jet pair (m_{jj}) in the case of 2-jet category. For more details, see [7]. In the $\mu\tau_h$ final state, signal extraction is performed using the distribution of invariant mass of τ pair ($m_{\tau\tau}$).

3. $H \to \tau\tau$ background estimation

Background sources depend mostly on the considered final state. The main source of irreducible background is Drell–Yan production of Z boson, that decays into τ pairs, except for the $e\mu$ final state, where the $t\bar{t}$ is a dominant contribution. Reducible backgrounds are QCD parton scattering processess and W + jets production with jet misidentified as τ_h. Distribution of the $\tau\tau$ system mass reconstructed with the likelihood method [8] is presented in figure 1.

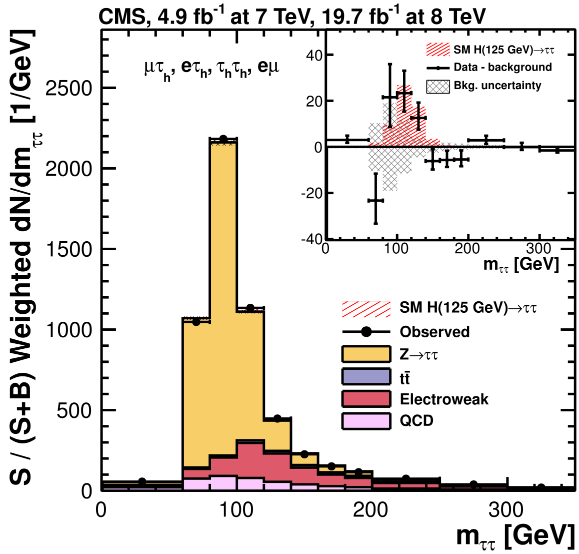

Fig. 1. Distribution of reconstructed invariant mass of tau lepton pairs in four final states using data from the LHC Run 1 [7].

3.1. Drell–Yan Z production

$Z \to \tau\tau$ background can be slightly reduced by requiring additional jet in the event, since jet production associated with Z falls off more steeply than associated with the Higgs boson. A method, called "embedding", of estimating this background is based on $Z \to \mu\mu$ events from data. Reconstructed muons are removed from the real data event and replaced with visible tau decay products simulated in $Z \to \tau\tau$ events before reconstruction of missing transverse energy, jets, τ_h candidates and lepton isolation. Then the yield of the events is normalised to the observed yield of $Z \to \mu\mu$ events.

3.2. W + jets processes

These processes significantly contribute to background in $\mu\tau_h$ and $e\tau_h$ final states, where W decays leptonically and jet is reconstructed as a τ_h. The shape of this background is modelled with a simulation performed using MadGraph generator [9], but the yield is taken from data using high m_{T} region, where W + jets events dominate.

3.3. QCD

The main source of background in these processes are jets misidentified as τ_h. The core of estimating this background is the fact that charge combinations of reconstructed muon and τ_h are random, therefore, mass distribution for pairs of same-sign (SS) and opposite-sign (OS) should be similar. One has to take mass distribution in data using SS selection and subtract all other backgrounds. The resulting distribution is said to be QCD contribution in SS region. After multiplication by a scale factor, one obtains QCD background in OS region. The scale factor is derived from a control region with inverted isolation requirements, where QCD processess are dominating.

3.4. $t\bar{t}$ processes

The $t\bar{t}$ background shape is estimated from simulation and the yield is obtained using a control region rich in $t\bar{t}$ events. This control region is obtained by requiring b-tagged jets in the final state.

4. CP study in $H \to \tau\tau$ analysis

CP nature of a Higgs boson in decay to two τ leptons manifests in τ spin correlations [10]. In $H \to \tau\tau \to \pi\nu\pi\nu$ decays, the τ spin correlations result in different distributions of angle ϕ between τ decay planes for CP-even (denoted as H) and CP-odd (denoted as A) Higgs boson. In the boson's rest frame, those distributions obey the following formula [10]:

$$\frac{\mathrm{d}\Gamma_{H/A}}{\Gamma_{H/A}\mathrm{d}\phi} = \frac{1}{2\pi}\left(1 \mp \frac{\pi^2}{16}\cos\phi\right) .$$

4.1. Observables: impact parameter method

In order to obtain distribution of the ϕ angle, one should reconstruct τ rest frames, which is almost impossible at CMS. Berge *et al.* [11] proposed to use impact parameter vector $\vec{n}_{\mathrm{PCA}}$ instead of τ momentum together with charged decay product momentum to construct the τ decay plane. The angle between two planes measured in the rest frame of the two charged decay products is the new angle ϕ^*. The distribution of ϕ^* is given by a formula [11]

$$\frac{\mathrm{d}\Gamma_{H/A}}{\Gamma_{H/A}\mathrm{d}\phi^*} = \frac{1}{2\pi}\left(1 \mp \frac{\pi^2}{16}\kappa_1\kappa_2\cos\phi^*\right) ,$$

where κ_1 and κ_2 are strongly dependent on τ decay mode and can be even negative. For $\tau \to \pi\nu$, the factor $\kappa = 1$ and for $\tau \to \mu\nu\bar{\nu}$, it is $\kappa = -0.33$, therefore, in the $\mu\tau_h$ final state, the distributions for H and A will give opposite contribution to the ones from the $\tau_h\tau_h$ final state.

A precise measurement of $\vec{n}_{\mathrm{PCA}}$ is very difficult. Figure 2 shows the distribution of the impact parameter and the τ flight length for τs from the Standard Model Higgs boson decay. The resolution of reconstruction of impact parameters in CMS are of the order of 10 μm in the direction transverse to the beam and 30 μm in the longitudinal direction, whereas mean impact parameter is of the order of 100 μm [12].

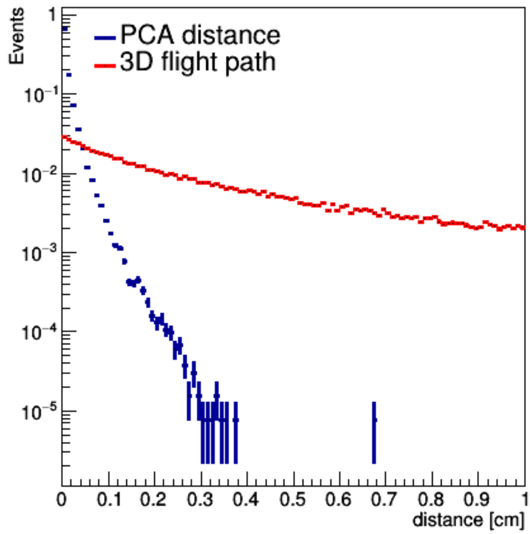

Fig. 2. Distributions of impact parameter's length and tau lepton's flight length for events after baseline selection (private work with PYTHIA 8.1).

4.2. Observables: ρ decay method

Tau leptons can decay into a charged ρ meson and a neutrino. The branching ratio for this decay is around 25%, so this is a very important decay mode. Bower *et al.* [13] proposed an observable that is sensitive to Higgs boson's parity in this decay channel. Let us assume that each ρ decays into one charged and one neutral pion.

The relevant observable is the acoplanarity angle $\phi^{\rho *}$ between ρ mesons decay planes measured in $\rho^+\rho^-$ rest frame. This frame is easy to reconstruct because ρ mesons decay into visible particles. This angle can also be measured in $\pi^+\pi^-$ rest frame and be combined with ϕ^* from the impact parameter method.

5. Summary and outlook

A brief description of $H \to \tau\tau$ searches in Run 1 was presented. In Run 2, the CMS detector collected 35.87 fb^{-1} of data with the center-of-mass energy equal to 13 TeV. This is much more than in the whole Run 1 (4.9 fb^{-1} with 7 TeV and 19.7 fb^{-1} with 8 TeV), and the cross section for

Higgs boson production was higher than in Run 1 due to an increase in collision energy. The analysis will be similar to what was done in Run 1, but with different, simpler categorisation. Therefore, we expect to reach the desired 5σ signal significance observed.

As far as CP parity is concerned, two observables that are sensitive to the parity of the Higgs boson were presented. Our plan is to take advantage of machine learning techniques such as Boosted Decision Trees (BDT's) and Artificial Neural Networks (ANN) to combine those, and possibly other observables. There will be also a possibility to use information about the precision of the reconstruction of the variables, *e.g.* the impact parameter length for the ϕ^*. Basing on the output of the above-mentioned techniques, we expect to make predictions about the amount of data needed to determine CP of the Higgs boson with 5σ significance.

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