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Measurements of Higgs boson production cross-section and CP violation in the $H \to \tau\tau$ decay channel with the ATLAS detector

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Summary. — The $H \to \tau\tau$ decay is an important decay mode of the Higgs boson as it allows to measure directly the Higgs coupling to fermions. This paper presents the measurement of the $H \to \tau\tau$ cross-section and a test of CP invariance in the Higgs boson production performed in the same channel. The results achieved using the data collected by the ATLAS experiment during the Run 1 of the LHC (2011–2012), corresponding to 20 fb^{-1}, are shown and future perspectives for the Run 2 are described as well.

1. – Introduction

The Higgs boson was discovered by the ATLAS [1] and CMS Collaborations in July 2012 [2, 3]. All the measurements performed so far have not shown any significant deviation from the Standard Model (SM) expectation. The $H \to \tau\tau$ decay mode is the most promising channel for measuring the Higgs coupling to fermions due to its larger signal-background separation with respect to the other fermionic decay modes. In addition, it can play a role for other Higgs properties measurements such as the measurement of its CP properties.

The $H \to \tau\tau$ decay channel has a complex signature as the visible decay products of the τ can be either leptons or hadrons and they are always produced together with neutrinos. We can identify three subchannels: a channel where both of the two taus decay leptonically, the notation $\tau_{\text{lep}}\tau_{\text{lep}}$ will be used in the paper, a channel where one tau decays leptonically and the other hadronically with the notation $\tau_{\text{lep}}\tau_{\text{had}}$ and in the end a channel where both the taus decay hadronically, with the notation $\tau_{\text{had}}\tau_{\text{had}}$. This paper summarizes the two important results for the $H \to \tau\tau$ cross-section [4] and the test of CP invariance in the Higgs boson production via vector boson fusion (VBF) [5] performed with the Run 1 data at $\sqrt{s} = 8\,\text{TeV}$ (2011–2012) collected by the ATLAS experiment corresponding to $20\,\text{fb}^{-1}$. In addition, the perspectives from the data coming from the Run 2 of the LHC are described.

2. – Cross-section measurement

For each of the $H \to \tau\tau$ subchannels two exclusive analysis categories are defined: the VBF and the Boosted category. The VBF category is characterized by two high-p_{T} jets well separated in rapidity, while the Boosted contains events that fails VBF selection and have a high-p_{T} Higgs boson candidate and it is dominated by events produced via gluon-gluon fusion (ggF). Once the events are selected in these two categories, a multivariate analysis is performed for separating signal from background. The multivariate technique uses the Boosted Decision trees (BDT) algorithm to extract the Higgs signal in each category. Among the variables used for the BDT the most discriminating ones are the reconstruced mass of the Higgs $m_{\tau\tau}^{MMC}$, $\Delta R(\tau_1, \tau_2)$, and $\Delta\eta(j_1, j_2)$.

The signal strength obtained with the Run 1 data corresponding to $20\,\mathrm{fb}^{-1}$ of integrated luminosity is $\mu = 1.43^{+0.27}_{-0.26}$ (stat) $^{+0.32}_{-0.25}$ (syst) ± 0.09 (theory syst.) with an observed (expected) significance of 4.5σ (3.4σ) [4]. This result has proved the evidence for the decay of the Higgs boson into pairs of tau leptons and combined with the CMS Run 1 measurement led to the discovery of the Higgs decay to tau leptons: the combined signal strength is $\mu = 1.12\pm^{+0.25}_{-0.23}$ with an observed significance of 5.5σ [6].

There is currently an ongoing analysis which is performing a cross-section measurement of the Higgs boson production using data coming from the Run 2 of the LHC. The integrated luminosity at the end of the run should be of $100\,\mathrm{fb}^{-1}$, as planned by the LHC official schedule [7], 5 times higher than the integrated luminosity reached during Run 1. In addition, the center-of-mass energy has been brought from 8 TeV to 13 TeV. This leads to a huge improvement of the statistics and specifically to an increase of number of events by a factor ∼11–12 for VBF and ggF. With the increase of statistics the statistical uncertainty will become less relevant compared to the systematics uncertainties. A crucial issue of the Run 2 analysis will be then the evaluation and monitoring of the systematic uncertainties.

The theory uncertaities are one of these systematics which are particularly relevant in the $H \to \tau\tau$ measurements. They are related to the Higgs production mode and we can identify three main sources of theory uncertainties: QCD scale, parton distribution functions (PDF) and parton shower. In the $H \to \tau\tau$ analysis the QCD scale uncertainties are ∼1% for the VBF process and ∼10% for ggF, the PDF uncertainties are less significant compared to the other sources, ∼1% for VBF and ∼3% for ggF. Finally the parton shower uncertainties affect the most this analysis and in some signal regions they also have a higher impact than the experimental uncertainties. These parton shower uncertainties are obtained by directly comparing Pythia and Herwig, the two main available Monte Carlo programs for parton shower modelling. The differences between the two programs are mainly due the different showering algorithm used and the different modelling of the hadronization process. For the $H \to \tau\tau$ this leads to ∼10% uncertainty for the VBF sample and ∼20% for ggF.

3. – Test of *CP* invariance

It is of paramount importance to establish whether the Higgs boson discovered by the ATLAS and CMS experiments is really the particle predicted by the Standard Model (SM) and, in order to verify it, one has to measure its properties. An analysis performed in the $H \to \tau\tau$ channel with the Run 1 data looked in particular for *CP* violation in this channel [5]. The presence of *CP* violation would be an unequivocal sign of new physics Beyond the Standard Model (BSM).

The measurement performed is the first direct test of *CP* invariance in the Higgs boson production via VBF. In principle the method is applicable to any Higgs decay but the $H \to \tau\tau$ allows to select a sizeable amount of VBF events.

In the context of effective field theories we can write a generic matrix-element for a *CP*-violating process as the sum of the SM term and a *CP*-odd term:

$$\mathcal{M}_{non\text{-}SM} = \mathcal{M}_{SM} + \tilde{d}\mathcal{M}_{CP\text{-}odd} \tag{1}$$

where $\tilde{d}$ is a parameter derived from the effective Lagrangian framework which quantifies the amount of *CP* violation.

We can then write the squared matrix-element:

$$|\mathcal{M}_{non\text{-}SM}|^2 = |\mathcal{M}_{SM}|^2 + \tilde{d} \cdot 2\mathcal{R}\rceil(\mathcal{M}^*_{SM}\mathcal{M}_{CP\text{-}odd}) + \tilde{d}^2 \cdot |\mathcal{M}_{CP\text{-}odd}|^2 \tag{2}$$

and from this it is possible to define an observable, sensitive to the presence of a *CP*-odd contribution, as follows:

$$O_1 = \frac{2\mathcal{R}\rceil(\mathcal{M}^*_{SM}\mathcal{M}_{CP\text{-}odd})}{|\mathcal{M}_{SM}|^2}. \tag{3}$$

The O_1 is called the first-order Optimal Observable [8], it has $\langle O_1 \rangle = 0$ and a symmetric distribution for the SM, while it has $\langle O_1 \rangle \neq 0$ and an asymmetric distribution if a *CP*-odd contribution is present.

This study has been performed on the Run 1 dataset and it is essentialy based on the $H \to \tau\tau$ cross-section analysis, therefore, it uses the same region definition and the same technique. The main difference is that only the VBF selection is applied but for further enhancing the signal-to-background ratio, a BDT is performed, identifing the final signal regions and the O_1 is used in all regions as observable. A maximum-likelihood fit is then performed to the Optimal Observable in each signal region. The likelihood is evaluated for different $\tilde{d}$ hypothesis using the different signal samples but the same background model. This allows to derive exclusion intervals on $t\tilde{d}$, resulting in excluding $\tilde{d} < -0.11$ and $\tilde{d} > 0.05$ at 68% C.L. [5].

4. – Conclusions

The $H \to \tau\tau$ is a promising channel which can allow to measure the Higgs coupling to fermions and the Higgs boson properties. The measurements presented have shown the potential of this channel which will surely benefit from the Run 2 data that will be collected by the ATLAS experiment either for the cross-section measurement and for the *CP* measurement with the usage of the innovative technique of the Optimal Observable. It will then be particularly important to limit as much as possible the effect of systematics uncertainties.

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