PROCEEDINGS OF SCIENCE

Higgs boson with top quarks: searches and measurements from the LHC

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Owing to its large mass, the top quark is expected to play a special role in the electroweak symmetry breaking of the Standard Model. The measurement of the Higgs boson coupling to the top quark is therefore of the highest theoretical relevance, but is also experimentally rather challenging. In this review, results from the ATLAS and CMS collaborations on the searches for the production of a Standard Model Higgs boson in association with top quarks are discussed, including the latest results from the Run 2 of the LHC.

VII Workshop italiano sulla fisica pp a LHC
16-18 Maggio 2016
Pisa, Italy

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PoS(PP@LHC2016)013

1. Introduction

The Standard Model (SM) of particle physics becomes a fully predictive theory once the mass of the Higgs boson is specified. The tensor and flavour structure of the interactions between the Higgs doublet, Φ, and the quark fields, $Q = (u_L, d_L), u_R, d_R$, are determined in the form of Yukawa interactions, whose only allowed dimension-four combinations are:

$$-\sum_{i,j}[Y^U_{ij}\bar{Q}_i i\sigma_2\Phi^* u^R_j + Y^D_{ij}\bar{Q}_i\Phi d^R_j] + h.c., \tag{1.1}$$

where $Y^{U,D}$ are arbitrary matrices in flavour space. After electroweak symmetry breaking, the quark Yukawa sector in the quark-mass basis reads

$$\sum_{q=u,d,c,s,b,t} y_q[\bar{q}_L q_R H + \bar{q}_R q_L H], \tag{1.2}$$

where H is the physical Higgs boson and $y_q = -\frac{\sqrt{2}m_q}{v}$. Equation 1.2 implies that i) the coupling strength is proportional to the quark mass, thus inducing a strong hierarchy on the Yukawa couplings, with $y_t \approx 1$ and $y_{q\neq t} \ll 1$, and ii) there are no tree-level flavour changing neutral currents (FCNC).

At the LHC, only production cross section times branching ratio, $\sigma_{i\bar{i}\to H}\times$ BR$(H \to f\bar{f})$, can be measured for two-body decays of the Higgs boson. These rates can be parametrised as $\kappa_i^2\kappa_f^2 \cdot \kappa_H^{-2}$ times the corresponding SM prediction, where $\kappa_{i,f}$ are real-valued modifiers that shift the corresponding coupling strengths with respect to their SM expectation (*i.e.* $y_q = \kappa_q \cdot y_q^{\rm SM}$), while κ_H shifts the overall Higgs boson width. By measuring the signal rates for enough channels, it is possible to measure the individual κ's or, in a more model-independent approach, ratios of them. In general, the cross sections are insensitive to the phase of the coupling (*i.e.* its sign, if the coupling is real). However, in a few cases the phase of the coupling matters due to the interference between different amplitudes, and a measurement of the sign becomes possible.

The Large Hadron Collider (LHC) will offer a unique chance of measuring the top quark Yukawa coupling (y_t) in the next decades, and will likely reach an accuracy of about 5% per experiment with the amount of data collected at the future upgrade of the machine, the so-called High-Luminosity LHC (HL-LHC). Unlike the coupling strengths with other SM particles, y_t cannot be directly determined through the study of the Higgs boson decay rates, due to the too large top-quark mass. Its experimental determination is therefore to be assessed either in an indirect way through the loop-induced gluon-gluon fusion production ($gg \to H$) and di-photon decay processes ($H \to \gamma\gamma$) or in a direct way through its associated production with a single or pair of top quarks ($pp \to tH$ and $pp \to t\bar{t}H$). The latter ones are the only processes which are sensitive to y_t at tree level, allowing its determination independently of further assumptions on the absence of new heavy particles entering the production or decay loop processes described above. As already mentioned, the absence of tree-level FCNC in the $q\bar{q}'H$ vertex implies the suppression of the top-quark decay to a Higgs boson plus a up-type quark ($t \to Hq$, with $q = c, u$) to a level which is far below the reach of any conceivable experiment. Therefore, the observation of such processes would provide an unambiguous evidence of Physics Beyond the Standard Model (BSM).

In the following, the latest measurements performed by the ATLAS and CMS experiments at the LHC in searching for an evidence of the $t\bar{t}H$ and tH production and of new physics in $t\bar{t}H$-like final states, including the FCNC $t \to Hq$ decay, are presented, with special attention to the determination of the main background processes to these searches, namely the $t\bar{t}$ production in association with heavy-flavour jets from QCD processes ($t\bar{t}$+HF) and with massive vector bosons W or Z ($t\bar{t}V$).

2. Searches for $t\bar{t}H$

The $t\bar{t}H$ production processes can give rise to a wide variety of final states depending on the decay modes of the Higgs boson and of the top-quark pair. Experimental searches try to take advantage of the possible final states with different analysis strategies depending on the Higgs boson decay channel in particular, giving rise to three main channels, namely:

- $H \to b\bar{b}$ channel, targeting final states with zero, one or two charged leptons with opposite electric charge and a high number of b- and light-jets;
- 'multi-lepton' channel, where events with two same-sign (or more) charged leptons and many (b-)jets are selected for being sensitive to $H \to \tau\tau$, $H \to WW$ and $H \to ZZ$;
- $H \to \gamma\gamma$ channel, where a peak in the di-photon invariant mass spectrum is looked for in events with additional jets, b-jets and eventually charged leptons from the $t\bar{t}$ decay.

The $t\bar{t}H \to b\bar{b}$ channel is characterised by a relatively large statistics but a large amount of irreducible background mainly from $t\bar{t}$+HF. The analysis strategy in this channel is based on an event categorisation depending on the number of jets and b-tagged jets and on the usage of sophisticated techniques to reconstruct the $t\bar{t}$ system and multivariate analysis (MVA) discriminators. With this setup, a simultaneous profile-likelihood fit on discriminating variables in the different categories is able to constrain *in-situ* the systematic uncertainties related to the modeling of the $t\bar{t}$+jets background and to the performances of the jet energy determination (mainly the jet energy scale) and jet-flavour tagging (b-tagging). The latest results from ATLAS in this channel, using the Run 1 LHC pp collision data at $\sqrt{s} = 8$ TeV are published in Ref. [1] and in Ref. [2] for the single- and di-lepton final states and for the all-hadronic final states respectively. In particular, the single- and di-lepton final state analysis performs a simultaneous fit in 15 different categories. In the most signal-rich categories, tha analysis makes use of an artificial neural network (ANN) technique to build a MVA discriminating variable to separate the $t\bar{t}H$ signal from the $t\bar{t}$+HF background using several kinematical variables, including the outputs of a $t\bar{t}$ system reconstruction algorithm based on the matrix-element-method (MEM). The analysis of the fully-hadronic final state, despite providing a less sensitive result due to the larger reducible background from QCD multi-jet production, is combined with the leptonic final states, further improving the result. The CMS collaboration, beside having provided similar analyses based on the Run 1 data-set (see Ref. [3, 4]), has released a preliminary result based on the data collected by the LHC in Run 2 during 2015 at $\sqrt{s} = 13$ TeV [5]. The analysis, targeting the single-lepton and the di-lepton final states uses a MVA discriminant to split the most signal-rich event categories, where an analytical MEM discriminant is finally fitted. Moreover, this analysis includes an additional 'boosted' event category, built with single-lepton events where a large cone size jet is tagged as boosted top-quark jet and another one as a boosted Higgs-boson jet.

The multi-lepton channel targets final states with two same-sign (or more) charged leptons (electrons, muons or hadronically decaying τ leptons), which can result from the Higgs-boson decay to a pair of τ leptons or a pair of W or Z bosons, at least one of which decaying leptonically, together with one or more charged leptons and a number of b- and light-jets from the $t\bar{t}$ decay. Differently from the $t\bar{t}H \to b\bar{b}$ one, this channel is characterised by lower available statistics due to the more rare leptonic days of the Higgs boson, but by a much reduced amount of irreducible background, mainly from $t\bar{t}V$ events. The analysis strategies from the two collaborations have in common the categorisation of the selected events depending on the charged lepton number and flavour, but follow two different guidelines. The ATLAS analysis relies on event counting in the different categories after optimised event selections for each of them, while CMS strategy is based on the usage of MVA discriminants after looser event selections. The latest results from ATLAS, based on the $\sqrt{s} = 8$ TeV data, are published in Ref. [8], while CMS analysed both $\sqrt{s} = 8$ TeV data [9] and $\sqrt{s} = 13$ TeV data [10].

The di-photon channel is characterised by an even smaller statistics with respect to the multi-lepton channel, but has the advantage of a very clean signature, both in terms of size of expected background and in terms of presence of a well resolved invariant mass distribution, not suffering from ambiguities in the choice of the decay products. The analysis strategy is based on a tight selection on the two photons in the event, compensated by a looser selection requirements of additional jets and leptons from the $t\bar{t}$ decay. Two different categories are defined depending on the number of leptons and jets: the leptonic category with at least one charged lepton and a minimum number of jets and b-tagged jets, and a hadronic category, with no charged leptons but a tighter cut on the jet and b-jet multiplicity. The relatively loose event selection in terms of additional leptons and jets, necessary to keep the signal selection efficiency large enough, leaves the Higgs-boson production through other mechanisms such as $gg \to H$ and VH as one of the most important irreducible backgrounds. The rest of the background is estimated from data thanks to the combined usage of the di-photon invariant mass spectrum side-bands and of dedicated event selections enriched in reducible background events. The results from ATLAS based on the Run 1 data [6] and from CMS both on the Run 1 [3] and Run 2 data [7] are still statistically limited, but with higher accumulated data in the next years this channel is expected to drive the $t\bar{t}H$ search and measurement results.

The results in the different channels by each experiment on the Run 1 data are combined [2, 3], and the combination results in terms of fitted signal strength are shown in Figure 1. These results are also used as inputs for the combined measurement of the Higgs boson couplings between ATLAS and CMS [11]. A small excess in the measured signal strength is seen by both experiments, mainly driven by an excess of events in the multi-lepton channel (in particular in the same-sign di-lepton categories), resulting in observed signal significances of 2.3 σ and 3.4σ by ATLAS and CMS respectively, with 1.5σ and 1.2σ being expected in the SM hypothesis. However, the first results from LHC Run 2 don't seem to confirm this excess.

2.1 Background modeling for $t\bar{t}H$ searches

As mentioned before, the knowledge of the irreducible backgrounds in the $t\bar{t}H \to b\bar{b}$ and multi-lepton channels is of great relevance for the analyses, and might become a limiting factor for

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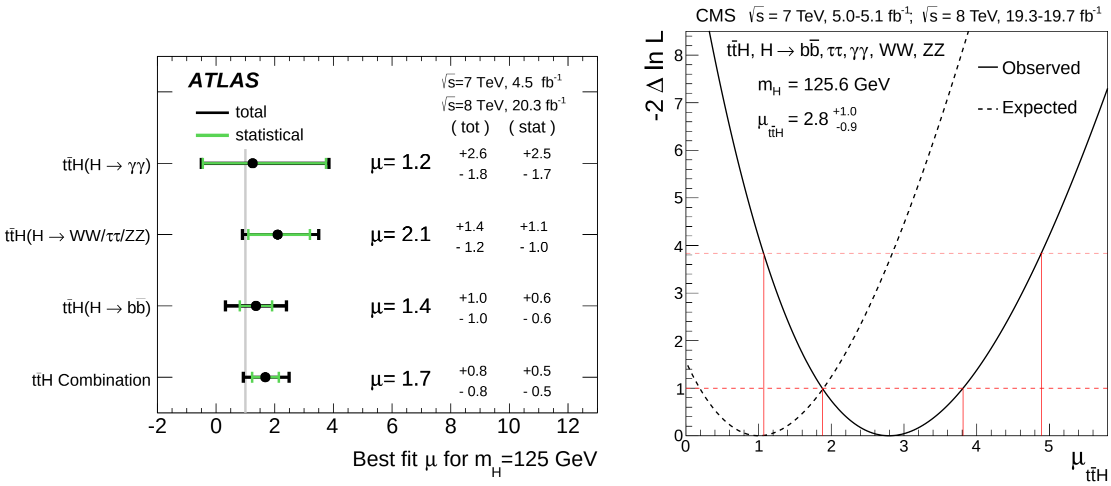

Figure 1: Left: summary of the measurements of the signal strength μ for the individual $t\bar{t}H$ channels and for their combination [2]. Right: the 1D test statistic $q(\mu_{t\bar{t}H})$ scan vs. the signal strength parameter for $t\bar{t}H$ processes, profiling all other nuisance parameters [3].

the precision of the direct measurement of y_t from $t\bar{t}H$ production with the increasing available statistics from the LHC. These backgrounds come from the associated production of a $t\bar{t}$ pair and either a massive vector boson (W or Z) or a pair of b-jets from QCD processes, the former being more relevant in the case of the multi-lepton channel, the latter entering as irreducible background in the case of the $t\bar{t}H \to b\bar{b}$ channel.

The production cross sections of the SM processes $t\bar{t}W$ and $t\bar{t}V$ have been measured by the ATLAS and CMS experiments at $\sqrt{s} = 8$ TeV [13, 14] and first results at $\sqrt{s} = 13$ TeV are already available from both experiments based on the data collected in 2015 [15, 16]. The analyses target mostly the leptonic decays of the W and Z bosons which, together with the leptonic decay of at least one of the top quarks, give rise to final states with two same-sign charged leptons, three leptons or four leptons, in association with two b-jets and eventually other light jets, final states similar to the $t\bar{t}H$ multi-lepton channel. For both experiments the analysis strategy is based on the categorisation of the selected events according to the number and flavour of the charged leptons, the number of (b-)jets and the invariant masses of the lepton pairs being close the Z mass (in the case of three and four lepton events). The main backgrounds in most of the categories come from events from fake or non-prompt leptons or with mis-identified electric charge. By mean of a simultaneous fit of the event counts (or MVA discriminant, in the case of the categories with higher statistics) in all the categories, the production cross sections of both $t\bar{t}W$ and $t\bar{t}Z$ are extracted. Figure 2 shows the results of the ATLAS and CMS Run 1 analyses compared to the SM predictions. At $\sqrt{s} = 8$ TeV, both the $t\bar{t}W$ and the $t\bar{t}Z$ processes where observed with a significance of at least 5 standard deviations. The measured $t\bar{t}Z$ cross section was found to be in good agreement with the SM predictions, while in the case of $t\bar{t}W$ a small tension started to appear, with both experiments measuring a cross section approximately a factor of two higher than the next-to-leading-order (NLO) prediction, at the limit of the experimental uncertainty. At $\sqrt{s} = 13$ TeV, despite the smaller accumulated data statistics and the simplified analyses with respect to Run 1, the results already show a comparable precision of 30-50%, with no tension with the SM predictions.

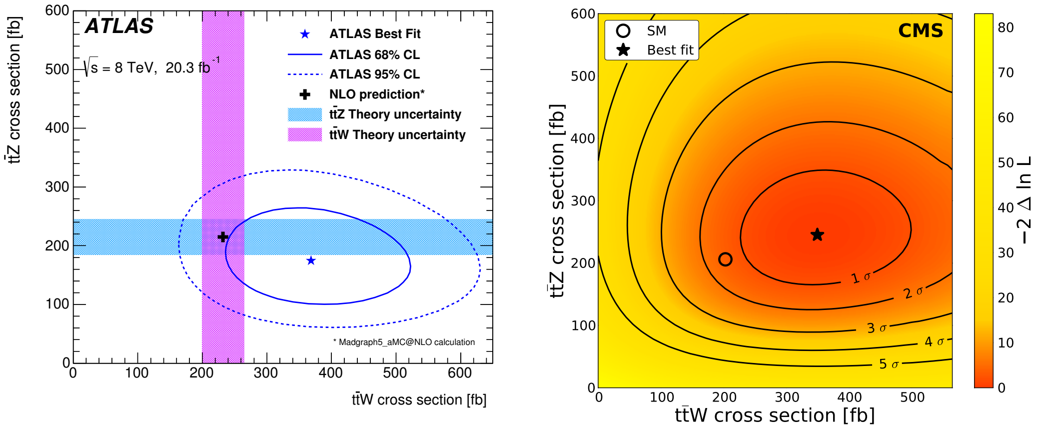

Figure 2: Left: The result of the simultaneous fit to the $t\bar{t}W$ and $t\bar{t}Z$ cross sections in the ATLAS Run 1 $t\bar{t}V$ analysis, along with the 68% and 95% confidence-level uncertainty contours, compared to the SM prediction with its uncertainties (including renormalisation and factorisation scale uncertainties as well as PDF uncertainties) indicated by the shaded areas. Right: Results of the CMS $\sqrt{s} = 8$ TeV $t\bar{t}V$ analysis in terms of profile likelihood as a function of the $t\bar{t}W$ and $t\bar{t}Z$ production cross sections, with lines denoting the 1 to 5 standard deviation confidence-level contours, the black star the best fit point and the open circle the SM theoretical prediction.

Concerning the main irreducible background process for the $t\bar{t}H \to b\bar{b}$ search, namely the $t\bar{t}$+$b\bar{b}$ QCD production, dedicated measurements have been performed at $\sqrt{s} = 8$ TeV by the two experiments [17, 18, 19, 20]. The analyses are based on similar event selection as the $t\bar{t}H \to b\bar{b}$ single- and di-lepton channels. The results are presented in a fiducial phase space[1], both as absolute cross sections and relative to the $t\bar{t}$ plus two jets ($t\bar{t}$+jj) ones and are compared to various theory predictions up the NLO precision in QCD. The results from CMS also include differential cross section measurements as a function of the jet multiplicity and the jet kinematics in the events. Despite being affected by large systematic uncertainties, the measured cross sections are systematically larger, by approximately a factor of 1.5. This result is still in agreement with what was observed in the Run 1 searches for $t\bar{t}H \to b\bar{b}$ and on some of the analyses mentioned in Ref. 4. From the first Run 2 analyses performed by ATLAS, again in the context of searches affected by this background (see for example Ref. [24, 25]), the effect seems to be even stronger at the new centre-of-mass energy, with the expectation underpredicting the data by almost a factor of two when selecting phase spaces dominated by the $t\bar{t}$+$b\bar{b}$ process. However, the situation seen by CMS (for instance in the $t\bar{t}H \to b\bar{b}$ analysis [5]) is different, with the data in good agreement with the prediction at high b-tag multiplicities. It seems likely that the opposite results mainly arise from the different settings used for the simulation. This fact highlights the importance of the development of theoretical predictions and tools for simulating the $t\bar{t}$+$b\bar{b}$ production in the most accurate possible way, an effort which is growing thanks to the collaboration between theoretical and experimental physicists. In particular, the "Yellow Report 4" of the LHC Higgs cross section working group which will be shortly made

[1]The fiducial phase space is defined as a visible phase space in which all selected final-state objects are produced within the detector acceptance and are thus measurable experimentally.

public will include the comparison of different simulations for the full $t\bar{t}$+$b\bar{b}$ process at the NLO precision in QCD, usable as an alternative to the prediction from simulations of the inclusive $t\bar{t}$ production where the $t\bar{t}$+$b\bar{b}$ final state is produced by the parton shower evolution.

3. Searches for tH

The single-top quark production in association with a Higgs boson has a rather small cross section ($\approx$ 18 fb at $\sqrt{s} = 8$ TeV). The dominant production mechanism through t-channel exchange of a W boson is suppressed by the negative interference between amplitudes containing the $W_\mu W^\mu H$ and $t\bar{t}H$ vertices. The destructive interference is close to maximal for $\kappa_{t,W} = 1$, implying that large deviations from the SM expectation can be obtained also for values of κ_t of order one, in particular for $\kappa_t \sim -1$. A more extensive review of the tH channel at the LHC can be found in Ref. [27].

The ATLAS Collaboration has performed an inclusive search for top quark(s) plus Higgs bosons in the $t\bar{t}H \to \gamma\gamma$ final states [6]. Figure 3 shows the effect of including the tH production in the coupling fit combination. Owing to its non-trivial dependence on κ_t, this channel has the unique feature of lifting the sign degeneracy of the likelihood. The CMS Collaboration has carried out dedicated searches for tH, targeting Higgs boson decays into two photons, two bottom quarks, and multi-lepton final states [12]. Differently from the analysis documented in Ref. [6], the CMS analyses are specifically optimised to separate the tH signal from the other Higgs production mechanisms, in particular from $t\bar{t}H$. The observed (expected) cross section exclusion limit at the 95% CL is shown in Figure 3, and amounts to 2.8 (2.0) times the SM expectation for a flipped-sign hypothesis ($\kappa_t = -1$). These measurements are included in the *grand combination* of Ref. [11].

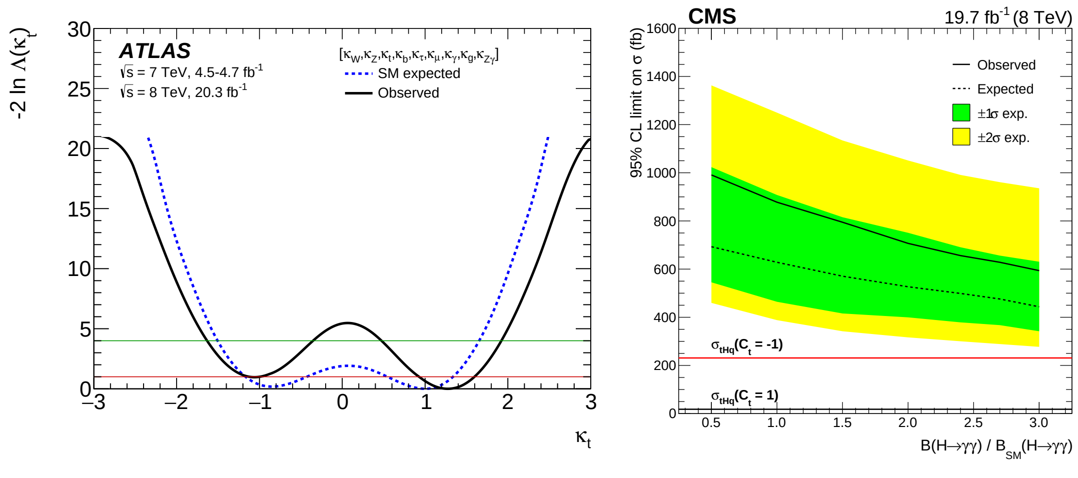

Figure 3: Left: the ATLAS likelihood scan as a function of κ_t as obtained from an analysis of di-photon events with additional jets [6]. Right: the 95% CL upper limits on σ_{tH} as a function of $\mu^{\gamma\gamma}$, as obtained from a combination of three independent searches for tH production [12].

4. New Physics in $t\bar{t}H$-like final states

A number of exotic processes result in final states with the same particle content of a $t\bar{t}H$ event. Searches for such reactions have been pursued by both ATLAS and CMS experiments, resulting in analyses that follow very closely the strategy of the corresponding SM $t\bar{t}H$ search, and are therefore affected by the same sources of systematic uncertainty (Section 2.1). Examples of such searches include i) anomalous four-top production [21, 23, 25], ii) scenarios where vector-like quarks are produced in pairs, $gg \to T\bar{T}$ [21, 22, 24], or single-produced via electroweak scattering (e.g. $qg \to q'Tt$), and subsequently decay to $T \to tH, bW$ giving rise to $t\bar{t}H$- or tH-like final states, and iii) heavy charged Higgs bosons produced in association with a top-bottom pair, and decaying via $H^{\pm} \to tb$ [26].

As mentioned in Section 1, FCNC in the Higgs sector are heavily suppressed in the SM, with branching ratios for the flavour-violating decay $t \to qH$ of the order of 10^{-15}. However, flavour violation naturally occurs in several BSM extensions, both at tree-level (e.g. 2HDM, Q-singlets) and as a result of loop-induced enhancements (e.g. MSSM). The typical signature of FCNC in the Higgs sector consists in the search for the decay $t \to cH$ in $t\bar{t}$ events. The subsequent decay of the Higgs boson into $\gamma\gamma$, WW, and $b\bar{b}$ final states offers a sample of distinctive signatures that can be used to differentiate such events from the overwhelming $t \to W^+b$ decays. A combination of different searches for FCNC decays of the top quark has been published by ATLAS in Ref. [28], yielding an upper limit at 95% CL of 0.46% on the branching ratio $t \to cH$, compatible with the background-only expectation of 0.25%. Similar searches have been performed by the CMS Collaboration; their results are reported in Ref. [29, 30, 31], and are summarised in Figure 4.

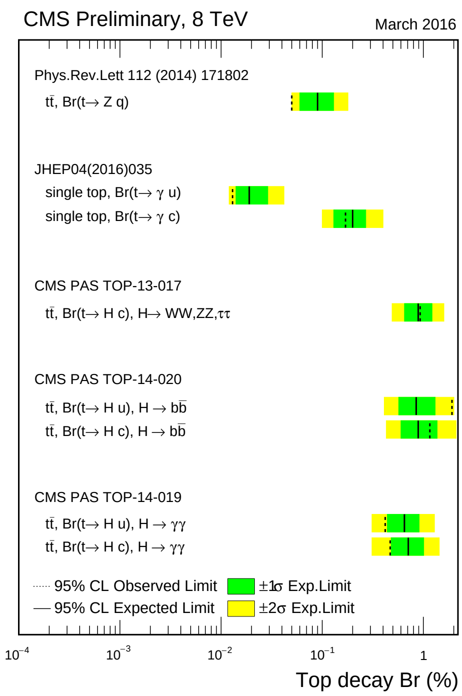

Figure 4: Summary of FCNC branching ratios from CMS searches at 8 TeV [29, 30, 31]. This summary figure is taken from Ref. [32].

5. Summary

The Run 1 results on the search for Higgs bosons produced in association with top quarks have been reviewed. The $t\bar{t}H$ channel remains the flagship to provide a direct measurement of the top quark Yukawa coupling, and a firm evidence of such process is still missing. The tH channel offers another channel to measure non-standard values of the coupling, in particular to break the sign degeneracy which affects the measurement of the $t\bar{t}H$ cross section. However, the sensitivity of the measurements is still far from what is needed to observe the SM tH production. The search for $t\bar{t}H$ and tH events can be reinterpreted in terms of search for exotic processes with top quarks and Higgs bosons in the final state, including anomalous four-top production, vector-like T quarks decaying to tH final states, and flavour-changing decays of the top quark via $t \to cH$. No evidence of deviations from the SM expectation has been found so far. All of these measurements rely on a solid understanding of the irreducible SM backgrounds, in particular $t\bar{t}+\mathrm{HF}$ and $t\bar{t}V$.

With the analysis of the 8 TeV LHC data close to completion, the new results at 13 TeV recently released by the two experiments are already approaching, if not exceeding, the Run 1 sensitivity.

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