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Search for non-standard and rare decays of the Higgs boson with the ATLAS detector

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At the LHC, searches for rare and exotic decays of the Higgs boson constitute an excellent opportunity to look for new physics. Some theories predict exotic decays that are heavily suppressed in the Standard Model, such as the ones violating lepton flavor conservation. Other theories predict enhanced branching ratios for rare decay modes, such as the ones to a photon and a Z boson, or to a photon and a meson. Recent searches performed with $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV pp collisions recorded by the ATLAS detector are presented.

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1. Introduction

The CMS and ATLAS collaborations have studied in great detail the 125 GeV boson whose discovery they announced on the 4th of July, 2012. So far, this particle has shown all the characteristics of a Standard Model (SM) Higgs boson. In particular, its couplings to heavy particles have been probed through its decays to $\tau\tau$, bb, WW, and ZZ, and they were found to be consistent with the SM prediction.

The fit to obtain the coupling constants to SM fermions and gauge bosons can constrain, with some dependence on the assumptions made in the fit, the branching ratio (Br) for invisible or undetected Higgs boson decays. From this fit, the 95% CL upper limit on the Br of the Higgs boson decaying to invisible or undetected final states can be as large as $\approx 30\%$ [1]. Such a loose constraint leaves open the possibility that the SM rare decays that have not been observed yet could be anomalously enhanced, or the possibility that unforeseen exotic decays might have sizeable branching ratios.

Several theories beyond the SM—including SUSY, Higgs doublet models, composite Higgs models—predict such exotic decays or such anomalous enhancements. Since the current constraint leave ample room for both phenomena, direct searches for exotic and rare decays of the Higgs boson constitute a very powerful approach to look for physics beyond the SM. We report here searches performed with pp collision data recorded by the ATLAS detector [2] at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV.

2. Searches for Exotic Decays Violating Lepton Flavor Conservation

Lepton-flavor-violating (LFV) decays are usually translated in a Lagrangian

$$\mathscr{L}_Y = Y_{ij}\left(\bar{f}^i_L f^i_R\right) h + h.c. + \ldots$$

where, following the notation used in Ref. [3] the Yukawa terms Y_{ij} are diagonal in the SM, and the off-diagonal elements are non-zero in several theories beyond the SM. When that is the case, diagrams corresponding to LFV processes arise. The amplitude of these diagrams, or of the corresponding Yukawa terms Y_{ij}, are constrained by experimental searches for several low-energy LFV processes. These constraints are described in detail in the paper [3] by Harnik *et al.* The $e\mu$ Yukawa term is constrained by the upper limits from the $\mu \to e\gamma$ searches, allowing Br($H \to \mu e$) to be at most $\approx 10^{-8}$. The constraints from $\tau \to \mu\gamma$ and $\tau \to e\gamma$ are much weaker, allowing for Br($H \to \mu\tau$) and Br($H \to e\tau$) to be as large as $\approx 10\%$. In fact, in the paper [3] by Harnik *et al.* the most stringent constraints on these decays are obtained recasting the ATLAS $H \to \tau\tau$ search [4].

ATLAS has performed searches [5, 6] for the decays $H \to \tau\mu$ and $H \to \tau e$ using both $\tau \to \ell\nu\bar{\nu}$ and $\tau \to$ hadrons. Two different search strategies are used in the hadronic channel and in the leptonic one.

In the hadronic channel, events are selected by requiring some missing transverse momentum $E_T^{\rm miss}$, one light lepton ℓ, and one hadronic tau $\tau_{\rm had}$. The lepton and the tau are required to be well-separated and to have opposite charge. Based on the values of the two transverse masses $m_T\left(\tau, E_T^{\rm miss}\right)$ and $m_T\left(\ell, E_T^{\rm miss}\right)$, events are categorised in a control region used to normalise the W+jets background, and two signal regions populated by different background components. The

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backgrounds are modelled with a combination of data-driven techniques and simulation: the former for the $Z/\gamma^* \to \tau\tau$ and multi-jet processes, and the latter for all the other processes. The mass of the Higgs boson candidate is estimated with the Missing Mass Calculator algorithm [7], whose output is used as a discriminant.

In the leptonic channel, events are selected by requiring two opposite-sign, different-flavor leptons $e^{\pm}\mu^{\mp}$, as well as angular cuts between the leptons and the missing transverse energy. Events are split into categories based on the number of jets in the event; this provides signal regions populated by different Higgs production mechanisms. All backgrounds are estimated with data-driven techniques, including the asymmetry method proposed in Ref. [8]. The collinear mass, computed from the two leptons and the missing transverse momentum, is used to discriminate signal events from the background ones.

Combining the hadronic channel with the leptonic one, the 95% CL upper limit on Br($H \to \tau e$) is found to be 1.04% (1.21% expected), and the one on Br($H \to \tau\mu$) is found to be 1.43% (1.01% expected). The upper limits for each channel and for their combination are summarised in Figure 1.

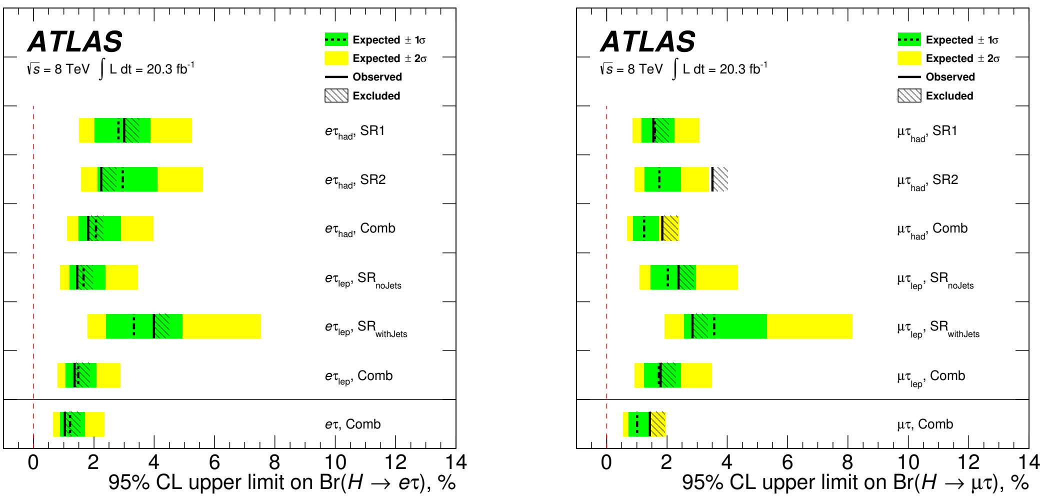

Figure 1: Upper limits on LFV decays of the Higgs boson from Ref. [6]. On the left: limits on Br($H \to \tau e$) are computed under the assumption that Br($H \to \tau\mu$)=0. On the right: limits on Br($H \to \tau\mu$) are computed under the assumption that Br($H \to \tau e$)=0.

3. Searches for Rare Decays of the Higgs Boson

ATLAS has performed several searches for rare SM decays of the Higgs boson. Some of them have been shown at this conference in dedicated presentations—see for example the one on $H \to \mu\mu$ by Christian Grefe. In this contribution we consider the searches for decays having final states with $\gamma + X$. In the $Z\gamma$ final state, the photon comes directly from the decay of the Higgs boson; in the $Q + \gamma$ final state the photon is radiated by one of the quarkonium's quarks.

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The search for the rare decay $H \to Z\gamma$ is performed using $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ events recorded at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. Events are categorised based on the lepton flavor, the rapidity difference between the Z candidate and the photon, and the Higgs boson candidate p_T. The Z-boson mass constraint is used in a kinematic fit to estimate the mass of the Higgs boson candidate, which is used as the discriminating variable between signal and background. This search is currently sensitive to a branching ratio about ten times larger than the SM one, as shown in Figure 2.

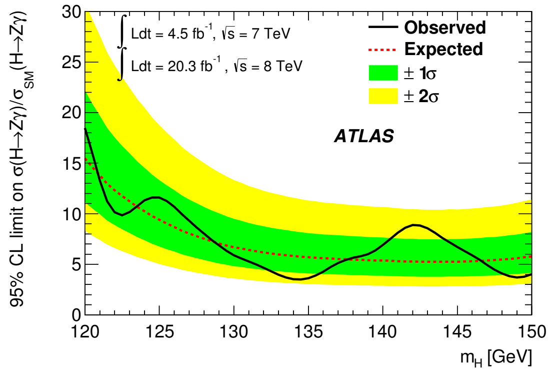

Figure 2: Upper limits at 95% CL on the decays of the Higgs boson to a photon and a Z boson, from Ref. [9].

Searches for decays of the Higgs boson to a quarkonium and a photon are interesting because they make it possible to probe the couplings of the boson to the c, s, and b quarks. ATLAS has performed searches for $H \to J/\Psi\gamma$, $H \to \Upsilon\gamma$, and $H \to \phi\gamma$. The strategy for these searches is to look for events with the quarkonium recoiling against a high-p_T photon. This strategy also makes it possible to search for the rare decays $Z \to J/\Psi\gamma$, $Z \to \Upsilon\gamma$, and $Z \to \phi\gamma$, which have not been observed yet.

In the searches for $H \to J/\Psi\gamma$ and $H \to \Upsilon\gamma$ the quarkonium is reconstructed as a $\mu^+\mu^-$ pair. The events, that were recorded in pp collisions at $\sqrt{s} = 8$ TeV, are categorised based on whether the photon converted within the inner detector, and on the pseudorapidity of the muons. A simultaneous unbinned fit is performed on the $p_T(\mu\mu)$ and $m(\mu\mu\gamma)$ distributions; for $\Upsilon\gamma$ candidates the $m(\mu\mu)$ distribution is also used in the fit to discriminate between the three $\Upsilon(nS)$ states. The $m(\mu\mu\gamma)$ distribution provides discrimination between signal and background. As shown in Figure 3, no significant excess is observed in any of the hypotheses considered in this search. For all hypotheses, the 95% CL upper limits are larger than the ones predicted by the SM; the process whose sensitivity is nearest to the SM expectation is $H \to Q\gamma$, for which the upper limit is set to be 540 times the expected rate.

Recently ATLAS has also performed a search [11] for the Higgs boson decaying to a photon and ϕ meson. In this search the ϕ meson is reconstructed through its decay to K^+K^- that are identified as two high-p_T isolated collinear tracks with opposite charge. The 13 TeV dataset used in this study was recorded at $\sqrt{s} = 13$ TeV using a dedicated trigger requiring an isolated high-p_T photon and a pair of tracks with an invariant mass consistent with m_ϕ. The invariant mass $m(K^+K^-\gamma)$, whose distribution is shown in Figure 4, provides discrimination between signal and background, which is estimated using a non-parametric data-driven template technique similar to

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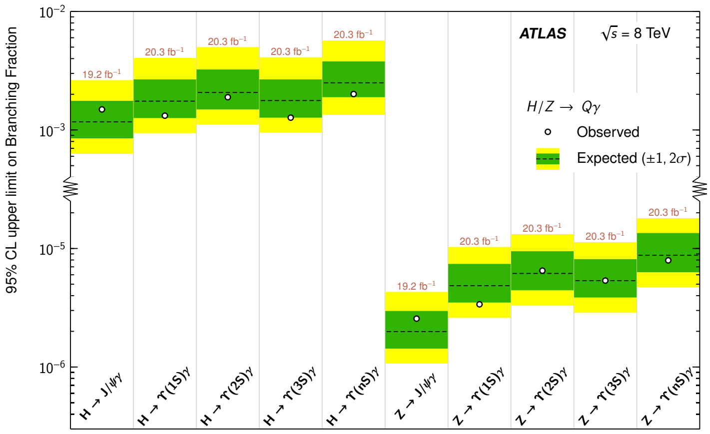

Figure 3: Upper limits on the decays of the Higgs boson and of the Z boson to a photon and a J/Ψ, or a photon and $\Upsilon\gamma$, from Ref. [10].

the one used in the search [10] for $H \to \mathrm{J}/\Psi\gamma$ and $H \to \Upsilon\gamma$. This approach makes it possible to probe not only the decay $H \to \phi\gamma$ but also the decay $Z \to \phi\gamma$, which has not been unobserved yet. The 95% CL upper limit set on $\mathrm{Br}(H \to \phi\gamma)$ is about 600 times larger than the expected SM Br. The 95% CL upper limit set on $\mathrm{Br}(Z \to \phi\gamma)$ is about 700 times larger than the expected SM Br.

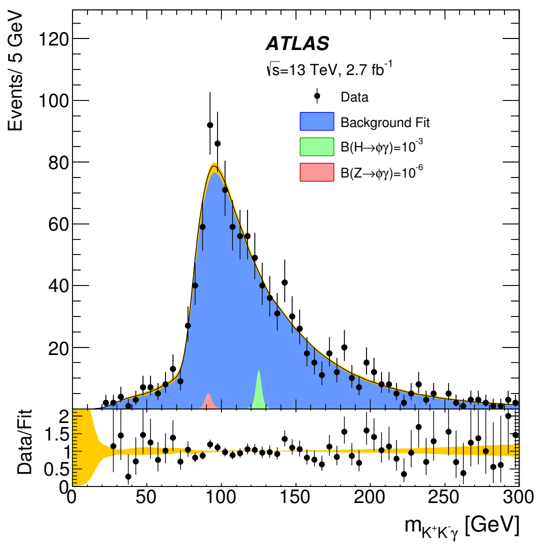

Figure 4: From Ref. [11], $m(K^+K^-\gamma)$ distribution of the $\phi\gamma$ candidates used in the search for $H \to \phi\gamma$ and $Z \to \phi\gamma$. The bottom plot illustrates the agreement of data with the background-only model.

4. Conclusion

Using pp collision data recorded at the LHC at $\sqrt{s} = 8$ and $\sqrt{s} = 13$ TeV, ATLAS has carried

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out several searches for exotic and rare decays of the Higgs boson and of the Z boson. The former include: $H \to \tau e$ and $H \to \tau\mu$. The latter include: $H \to Z\gamma$, $H/Z \to \mathrm{J}/\Psi\gamma$, $H/Z \to \Upsilon\gamma$, $H/Z \to \phi\gamma$. In none of these searches a significant excess was observed. The resulting upper limits allow to constrain several theories beyond the SM. Larger datasets will be needed to reach the sensitivity required to probe the Br predicted by the SM for rare decays of the Higgs boson and of the Z boson.

5. Acknowledgements

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