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In Pursuit of Lepton Flavour Violation. A search for the $\tau \to \mu\gamma\gamma$ decay with ATLAS at $\sqrt{s}$ = 8 TeV.

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Summary

What are the fundamental building blocks of the universe? Which forces govern their behaviour? High energy physics is the branch of science that tries to answer these and other intriguing questions.

The theory known as the *Standard Model* successfully describes the elementary particles and their interactions. The particle content of the Standard Model, shown in Figure S.1, consists of twelve fermions, divided into six quarks and six leptons, four types of gauge bosons (photon, gluon, $W^{\pm}$ and Z bosons) and the scalar Higgs boson. The latter was discovered in 2012, completing this picture. The three interactions described by the Standard Model are the electromagnetic, weak and strong forces.

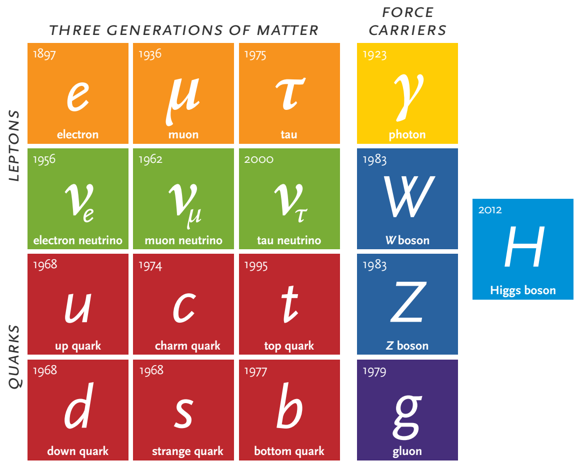

Fig. S.1 · Schematic view of the Standard Model with the three generations of fermions, the gauge bosons and the Higgs boson.

Despite the experimental confirmation of its predictions, the Standard Model does not explain everything. For example, gravity, which is the fourth fundamental force, is not included in the theory. Moreover, only about 5% of the universe is made of the particles of the Standard Model. What is the origin of the other 95%?

In addition, contrary to the original formulation of the Standard Model, the observation of *neutrino oscillations* implies that neutrinos are massive particles and can change from one flavour (electron, muon or tau neutrino) to another. It is natural to ask whether flavour violation can be observed also among the charged leptons (electron, muon and tau). In this sector, lepton flavour violating (LFV) processes are allowed in the Standard Model extension that includes massive neutrinos, but their rates are negligible. On the other hand, several scenarios of physics beyond the Standard Model predict rates within the reach of the experiments. Many searches have been performed during the years, through the investigation of several decay modes, but no evidence of charged LFV has been found so far.

In high energy physics, particle accelerators are employed to perform experimental searches. At the present time, the Large Hadron Collider (LHC) is the most powerful accelerator, designed to collide protons at the centre-of-mass energy of $\sqrt{s} = 14$ TeV. It is located at CERN, between France and Switzerland, in a tunnel of almost 27 km circumference. Four detectors are installed along the LHC ring to record the collisions delivered by the LHC. The ATLAS detector measures Standard Model observables and searches for physics beyond the Standard Model. It consists of several sub-detectors, each with specific properties, which are used to identify and measure the energy and momentum of the different particles produced in the collisions. Furthermore, the ATLAS detector employs a *trigger system* to reduce the amount of the LHC data and select the fraction of interesting events for physics analyses.

In this thesis, a search for the LFV $\tau \to \mu\gamma\gamma$ decay has been presented. It is based on the data collected with the ATLAS detector at $\sqrt{s} = 8$ TeV in 2012, during the first run (Run-1) of the LHC. The data sample corresponds to an integrated luminosity of 19.1 fb^{-1}. The tau leptons used in the analysis are produced by the $W \to \tau\nu$ decay.

Tau leptons provide good opportunities to search for LFV. Several decay channels, such as $\tau \to \mu\gamma$ and $\tau \to 3\mu$, have been studied by different experiments looking for a sign of physics beyond the Standard Model. The $\tau \to \mu\gamma\gamma$ channel represents a new probe of LFV. Theoretical frameworks, such as *supersymmetry* and *Higgs-mediated* LFV, indicate the possibility to investigate this decay, predicting sizeable rates. No experimental searches have been performed in the $\tau \to \mu\gamma\gamma$ channel before the one described here.

In any analysis, it is essential to enhance the *signal* under investigation, reducing the contribution from *background* processes. In the LFV $\tau \to \mu\gamma\gamma$ search, the background is estimated directly from data. Selection criteria are applied to target the decay of the W boson and the $\tau \to \mu\gamma\gamma$ candidate in each event. Several requirements are applied on physical quantities, such as the kinematic properties of photons and muons and the transverse mass of the W boson. Another step in the selection of the events is based on triggers. In particular, dedicated *muon+photon* triggers are used to select the combinations of objects in the final state of the $\tau \to \mu\gamma\gamma$ decay.

For a better discrimination between signal and background sources, key steps of the analysis rely on a multivariate approach. The identification of the pair of photons in the $\tau \to \mu\gamma\gamma$ decay is realized using the multivariate method called *Boosted Decision Tree* (BDT), based on detector characteristics of these objects. At a later stage, the same strategy is adopted to focus on the properties of the $W \to \tau\nu$

decay and target the remaining background, which consists mainly of decays of heavy quarks and $W \to \mu\nu$ decays.

The analysis is designed to be sensitive in the region where a signal excess over the background is expected. The *signal region* is selected relying on the distribution of the LFV tau candidate mass, which is given by the invariant mass of the three tau decay products (one muon and two photons). Figure S.2 shows the mass distribution of the tau candidate for the Monte Carlo *simulation* of the $\tau \to \mu\gamma\gamma$ sample (signal) and the data sample. The signal region is defined as an interval around the nominal tau mass between 1.6 and 2.0 GeV.

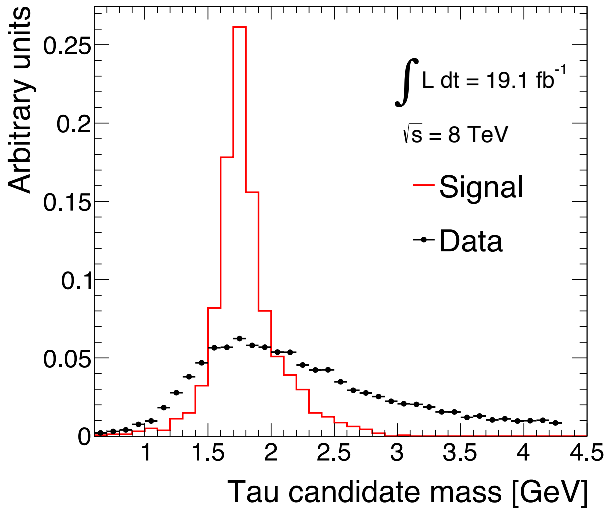

Fig. S.2 · Mass distribution of the LFV tau candidate for signal (red) and data (black dots) samples.

The expected number of background events in the signal region is compared to the number of observed data events in the same region. At the end of the selection, 293 data events are observed in the signal region. This value is compatible with the one obtained from the background estimation (278 expected events). No statistically significant excess with respect to the Standard Model background expectation is observed.

In the absence of a LFV signal, the results of this search are presented in terms of *upper limits* on the $\tau \to \mu\gamma\gamma$ branching fraction. The expected and observed exclusion limits are determined with a confidence level of 90%. The expected (median) upper limit is established to be

$$\mathrm{Br}(\tau \to \mu\gamma\gamma) = (1.14^{+0.57}_{-0.35}) \times 10^{-4}, \tag{S.1}$$

where its variations, expressed in terms of ± 1 standard deviation, are also indicated. The observed upper limit corresponds to

$$\mathrm{Br}(\tau \to \mu\gamma\gamma) = 1.49 \times 10^{-4}. \tag{S.2}$$

Exciting years are in front of us. The LHC is now in its second run (Run-2), which is characterized by an increased centre-of-mass energy of $\sqrt{s} = 13$ TeV. The larger datasets will allow to improve the results presented in this thesis. Looking at the bigger picture, the quest for lepton flavour violation among charged leptons will continue. Is it time for another breakthrough discovery in high energy physics?