PhD thesis:

Search for the Higgs boson decaying to two photons and produced in association with a pair of top quarks in the CMS experiment

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The thesis should start in September 2014. The deadline to apply for french fundings (from doctoral schools or CEA) is usually around the end of april.

The 4th of July 2012, the ATLAS and CMS experiments at LHC at CERN observed a new boson, with a dataset of proton-proton collisions of about 10 fb^{-1} at the centre of mass energy of 7 to 8 TeV [1, 2]. This particle is compatible with the Higgs boson predicted by the Standard Model of particle physics (SM) [3–6]. Its mass, of order 125 GeV, is in good agreement with indirect constraints from electroweak precision measurements [7]. It was observed via its decays to two photons and to four leptons, the two most sensitive decay channels at this mass. The precise measurement of its properties (its spin, its parity and its couplings to other particles) is now one of the major goal in particle physics.

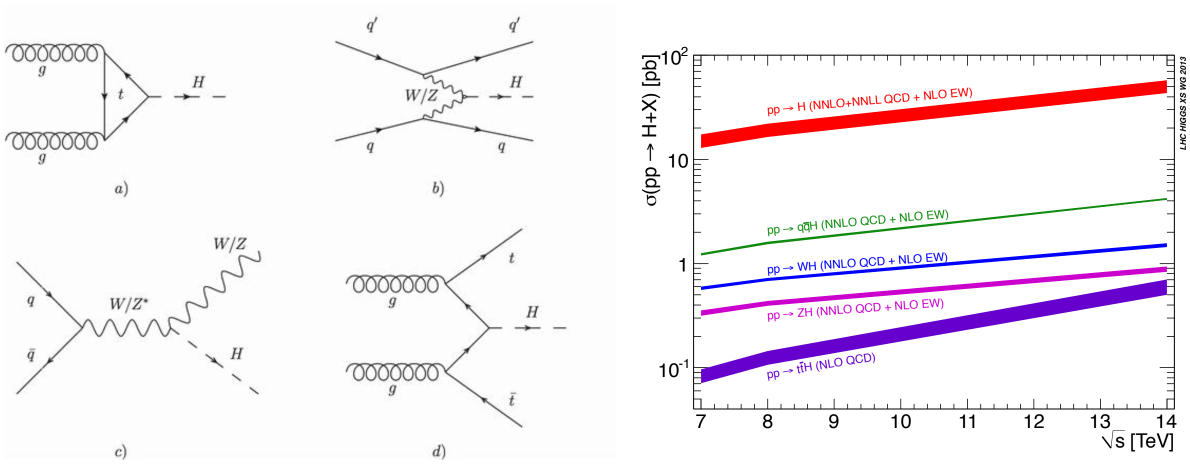

Figure 1: Left: dominant Higgs boson production mechanisms at the LHC. Right: production cross sections as a function of the centre of mass energy at m_H =125 GeV. The $t\bar{t}H$ production is smaller by two orders of magnitude than the dominant production by gluon fusion. The $t\bar{t}H$ production is about 4 times larger at 13 TeV than at 8 TeV.

The measurement of $t\bar{t}H$ production is the only direct access to the top quark Yukawa coupling, fundamental parameter of the SM. $t\bar{t}H$ production is a very rare process, two orders of magnitude smaller than the dominant Higgs boson production by gluon fusion. At 13 TeV, the $t\bar{t}H$ production is however about 4 times larger than at 8 TeV. First searches of $t\bar{t}H$ production have been performed by the CMS and ATLAS experiments with 7 and 8 TeV data in various decay modes. The present statistics does not allow an observation. CMS results are depicted on figure 2 (left). The present limits at 95% of confidence level on the $t\bar{t}H$ production cross section [9, 10] in the two photons decay channel are::

$$\frac{\sigma}{\sigma_{\mathrm{SM}}}(t\bar{t}H) \quad < \quad 5.4 \ (5.3 \text{ expected}) \qquad \text{CMS}$$
$$\frac{\sigma}{\sigma_{\mathrm{SM}}}(t\bar{t}H) \quad < \quad 5.3 \ (6.4 \text{ expected}) \qquad \text{ATLAS}$$

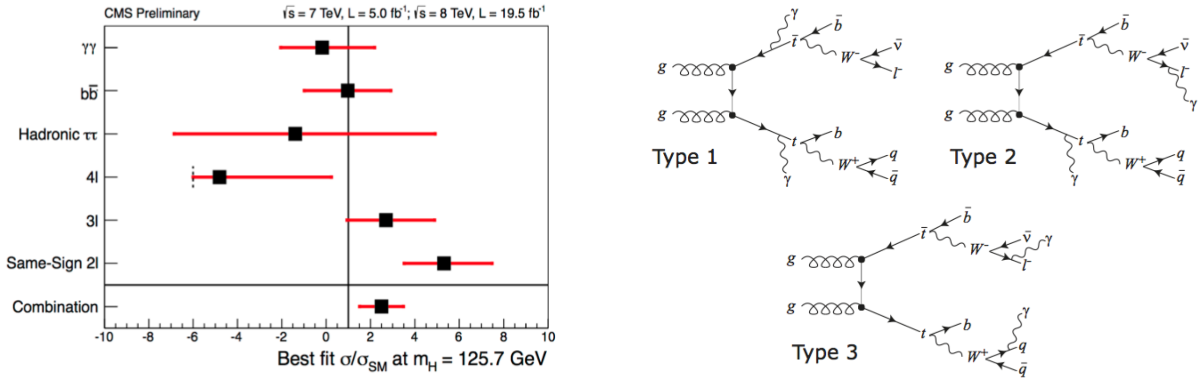

Figure 2: Left: CMS results on $t\bar{t}H$ production for different Higgs boson decay channels. The constraints on cross sections are divided by the cross sections expected in the SM, for m_H =125.7 GeV. Note that uncertainties are still very large. The diphoton decay mode is already competitive with other modes. Right: irreducible background $t\bar{t}\gamma\gamma$.

Despite a very small branching ratio (only about 0.2%), the two photons decay channel of the Higgs boson is very promising, because of its excellent mass resolution (about 1%). Moreover, its signature in the detector is very clear: two isolated energetic photons, that is to say two isolated energy deposits in the electromagnetic calorimeter, with no associated particle in the tracker. The diphoton decay channel is also of particular interest as it is the only channel allowing the study of all production modes (gluon fusion, vector boson fusion, associated productions with a W or a Z, or with a top quark pair, see figure 1). Although limited by statistical uncertainties at the beginning, this channel will be the most precise to measure the $t\bar{t}H$ coupling on the longer term, as many systematic uncertainties vanish in cross-sections ratio. Preliminary studies [8] show that an excess at 3 σ should be observed in the $t\bar{t}H$ with $H \to \gamma\gamma$ channel with about a hundred fb^{-1}.

The final state considered here is more constrained than in the inclusive channel, as there are, on top of the two photons, two b quarks and two W bosons[1]. Backgrounds are thus easier to reject. Two decay channels can be studied: the hadronic channel, where the W decays in jets, and the leptonic channel, where at least one of the Ws decays leptonically $W \to \ell\nu$ with ℓ =e, μ. The main backgrounds are $\gamma\gamma$+jets and γ+jets productions, QCD multijets production, top, $V\gamma\gamma$ and VV productions (with $V = Z$ or $W^{\pm}$). The irreducible background is the $t\bar{t}\gamma\gamma$ production (cf figure 2).

[1]The top quark decays to Wb.

Different variables can be used to discriminate backgrounds. In the presence of top quarks, the event multiplicity is larger (numbers of jets and b-tagged jets), it can be used to fight QCD background. Moreover, the photons p_T tend to be larger for the boosted signal. In the leptonic channel, the presence of one isolated high p_T lepton helps to reject QCD background and to determine precisely the interaction vertex. Transverse missing energy due to the presence of neutrinos in the leptonic channel can also help to reduce backgrounds.

The PhD thesis will follow the schedule below:

1. 2014-2015 (during the LHC shutdown):
   - A study related to electromagnetic calorimeter (ECAL) upgrades for LHC phase II, high luminosity period which should allow to reach the ultimate precision on $t\bar{t}H$ coupling. The ECAL electronics will have to be changed for phase II and the new electronics has to be defined and studied to minimize the worsening of the detector performances due to high luminosity.
   - A detailed study of the expected sensitivity to the $t\bar{t}H$ coupling in the $H \to \gamma\gamma$ channel at 13 TeV, at middle and long term, using realistic simulations including high pileup conditions and detector upgrades.
2. 2015-2016 (collisions at 13 TeV, 30 fb^{-1} expected at the end of 2015):
   The analysis of 13 TeV data, with a first limit on $t\bar{t}H$ production at 13 TeV and a first publication.
3. 2016-2017 (collisions at 13 TeV, 80 fb^{-1} expected at the end of 2016):
   - The analysis of the final dataset, which should allow a first measurement of the $t\bar{t}H$ coupling with $H \to \gamma\gamma$ and a second publication.
   - The last 4 to 6 months should be dedicated to the thesis writing and the search for a post-doctoral position

During this thesis, the student will have to understand many aspects of data analysis: photon energy measurement in the ECAL, measurement of the angle between the two photons and of the primary vertex position, identification of photons, electrons, muons, measurement of the jet energy scale, missing energy, b jets tagging.
The Saclay CMS group has a great expertise in photon energy measurement, as it has been involved in the ECAL construction and design and has a leading role in its calibration. The team was also involved in the $H \to \gamma\gamma$ analysis for the Higgs boson discovery and is now working on the properties measurements with this channel. The student will thus be directed by a group with the needed expertise and tools.

References

[1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716** (2012) 1.

[2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716** (2012) 30.

[3] S. L. Glashow, Nucl. Phys. **22** (1961) 579; S. Weinberg, Phys. Rev. Lett. **19** (1967) 1264; A. Salam, Proceedings of 8th Nobel Symposium - Lerum - Sweden (19-25 May 1968) 367.

[4] S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. **D2** (1970) 1285.

[5] P. W. Higgs, Phys. Rev. Lett. **13** (1964) 508 et Phys. Rev. **145** (1966) 1156; F. Englert, R. Brout, Phys. Rev. Lett. **13** (1964) 321; G. S. Guralnik, C. R. Hagen, T. W. B. Kibble, Phys. Rev. Lett. **13** (1964) 585; T. W. B. Kibble, Phys. Rev. **155** (1967) 1554.

[6] G. 't Hooft, Nucl. Phys. **B33** (1971) 173 et Nucl. Phys. **B35** (1971) 167; G. 't Hooft, M. J. G. Veltman, Nucl. Phys. **B44** (1972) 189.

[7] [ALEPH, DELPHI, L3, and OPAL Collaborations, LEP electroweak and SLD electroweak and heavy flavor working groups], Phys. Rept. **427** (2006) 257.

[8] G. L. Bayatian *et al.* [CMS Collaboration], J. Phys. G **34** (2007) 995.

[9] [CMS Collaboration], CMS PAS HIG-13-015 (2013).

[10] [ATLAS Collaboration], ATLAS-CONF-2013-080 (2013).