THESIS PROJECT PROPOSAL

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Title: Study of the Higgs boson production in association with a single top quark in proton collisions at the Large Hadron Collider.

Abstract: *The abstract*

1. BACKGROUND

-SM, Higgs, couplings, previous Higgs measurements, previous tH searches

The standard model (SM) of particle physics is so far the best theoretical model to describe the interaction of elementary particles using three of the four fundamental forces of nature which are electromagnetic force, strong nuclear force and the weak nuclear force. Gravitational force is neglected as the strength of this force is very weak at the scales over which elementary particle interact with each other. The standard model (SM) of particle physics is divided into two categories, bosonic sector and fermionic sector. Bosonic sector contain particles called bosons which mediate the fundamental forces of nature and the fermionic sector contain particles called fermions which make up all the matter in our universe. SM has three generations of matter (fermions) particles. The first generation of fermions consists of up (u) quark, down (d) quark, electron and electron neutrino, second generation consist of charm (c) quark, strange (s) quark, muon and muon neutrino and the third generation of matter particles has top (t) quark, bottom (b) quark, tau and tau neutrino. The bosonic sector consist of gauge bosons like gluon, photon, $W^{\pm}$, Z^0 which mediate strong force, electromagnetic force and weak force respectively. There is one more particle in the standard model called the Higgs Boson which gives mass to SM particles via electroweak symmetry breaking mechanism [1]. All the standard model particles are shown in Figure 1. Higgs boson can be produced at the particle colliders like the Large Hadron Collider (LHC) in Geneva, Switzerland.

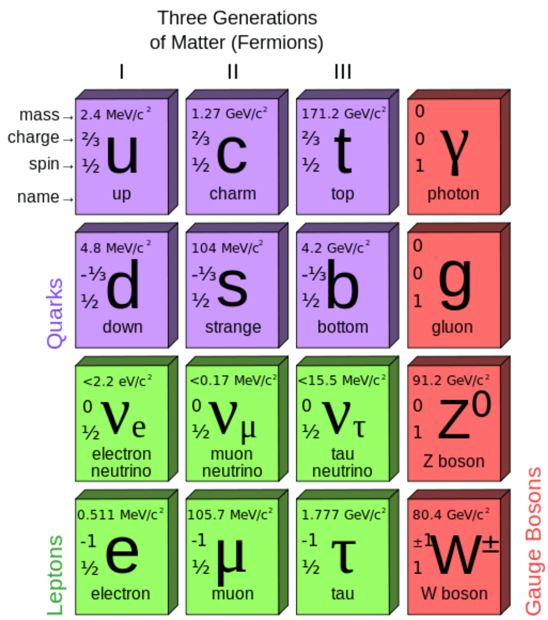

Figure 1: Elementary particles in standard model of particle physics with their mass, spin and charge.

There are various production modes of Higgs boson like the gluon gluon fusion (ggF), vector boson fusion (VBF), Higgs production in association with vector boson (VH, V = W or Z), Higgs production with top quark and top anti-quark ($t\bar{t}$H) and Higgs production with a single top quark and a quark jet (tHq). Each production channel has its own importance to probe the properties and the coupling strength of Higgs boson to fermions and bosons. The main production mode of Higgs bosons at LHC is gluon gluon fusion (ggF). As bosons like gluons and photons are massless, they do not interact directly with the Higgs boson and processes like ggF or Higgs boson decay to pair of photons are not possible at tree level and can only proceed via loop diagrams which involve W boson or top quark in the loop. The Higgs boson can also decay to other particles and these decay channels have different branching fractions. Higgs boson can decay to a pair of W bosons, Z bosons, photons, bottom quarks, muons and electrons. Higgs boson can also decay to Z boson and a photon. The important SM Higgs Boson production modes are shown in Figure 2. It is also interesting to investigate some invisible decay modes of Higgs boson which can be used to put upper bounds on dark matter-nucleon scattering cross section like in the Higgs-portal dark matter models.

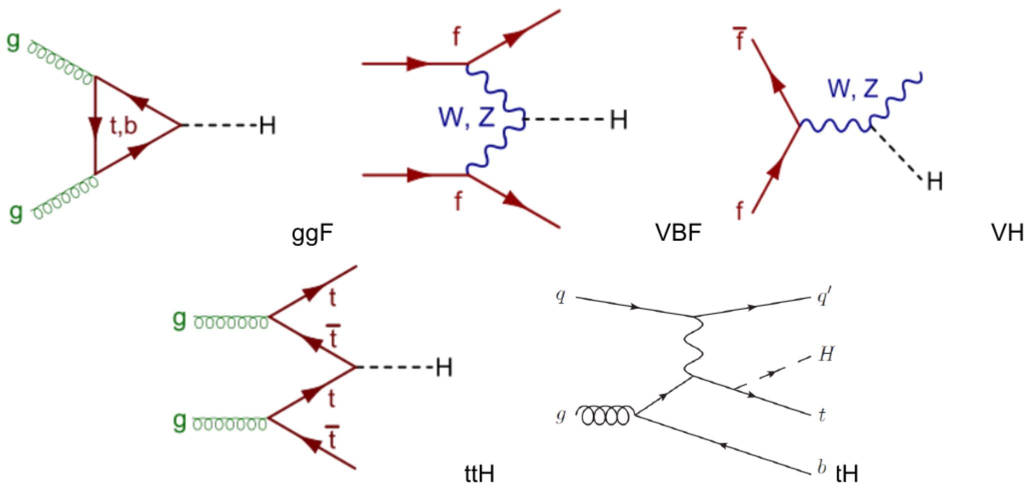

Figure 2: Important production processes of Standard model Higgs boson ggF, VBF, VH, ttH and tH in proton collisions.

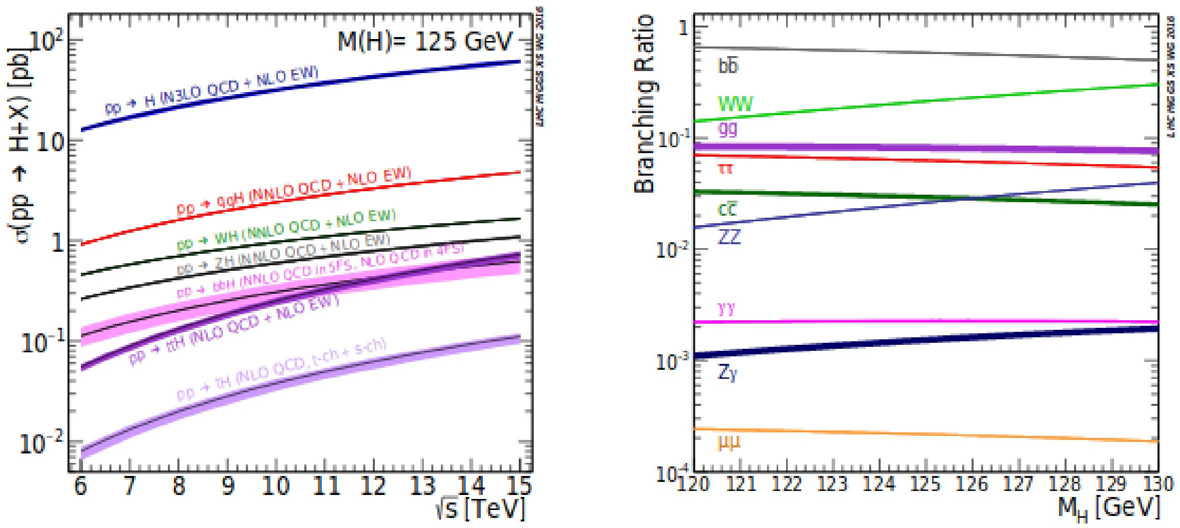

Figure 3: Standard model Higgs boson production cross section with center of mass energy and branching ratios for various decay channels.

The Standard Model (SM) of particle physics has successfully described most of the experimental data till now but a very large number of free-parameters like fine structure constant α, Weinberg angle or weak mixing angle θ_W, the coupling constant of strong interaction, electroweak symmetry breaking energy scale, Higgs potential self coupling or the Higgs mass, three mixing angles and the CP-violating phase of the CKM matrix which tells us how quarks of different color charge mix with each other, nine yukawa couplings which determine the mass of nine charged fermions and fine tunings related to the origin of masses robustly suggests new physics beyond Standard model (BSM). There are lot of specific BSM theories and most of these models involve heavy fields. In order to identify which new physics lies beyond the electroweak (EW) scale, the new parameters of such theories may be constrained by the actual, low energy, experiments. This approach requires studying each model individually, and calculating every possible observable. There is another approach immitating Fermi's treatment of beta decay which consists of considering the SM as the first order approximation of the actual theory and by completing it with a series of higher dimensional operators. When the electroweak symmetry breaking takes place well below the mass of the new particles, the BSM physics is taken into account at the EW scale and below by adding higher dimensional operators to the SM Lagrangian. They are built out of SM fields and supposed to be invariant under its gauge group. Those operators are the low-energy residue of the high energy theory. This approach does not pretend to guess the complete high-energy model and it is based solely on the symmetry of the theory. The operators are general and the only model dependence is encoded in the size of the operator coefficients, which is to be set from experiments.

The Higgs boson and fermions (quarks and leptons) coupling will deviate from the standard model predictions if these higher dimensional operators are present in low energy effective SM theory. We can consider anomalous Higgs and Higgs-gauge effective dimension 6 operators like $-\frac{1}{3}(\phi^\dagger\phi)^3$, $\frac{1}{2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$ and $(\phi^\dagger\phi)(D_\mu\phi)^\dagger(D^\mu\phi)$ to calculate the deviation of Higgs boson-fermion couplings from SM. The first operator shift the minimum of the Higgs potential. Also as there will be rescaling of the Higgs field due to the introduction of these operators in the potential term, Higgs-fermion (quarks and leptons) couplings are modified. In the effective standard model theory, there are dimension 5 and dimension 6 operators. Dimension 5 operators are odd under baryon minus lepton number symmetry and dimension 6 operator dominate baryon minus lepton number symmetry conservation processes.

The production of Higgs boson in association with single top quark is one of the rare Higgs boson production mode [2]. As the top quark is the heaviest fundamental particle in the standard model, due to its large mass, the top quark decay before hardronization which allow the possibility to reconstruct top quark from its decay products unlike the lighter quarks which undergo hardronization and are seen as bundles of particles in detector called jets. The most probable decay of top quark is into bottom (b) quark and W boson [3]. Using b-jet tagging algorithms, the jet originating from b-quark can be reconstructed to identity the top quark. In SM, the coupling of the Higgs boson to fermions like quarks and leptons is proportional to the mass of the fermions. Thus heavy quarks like top, bottom and charm couple strongly to Higgs boson which means that out of all known quarks, top quark couple most strongly to the Higgs boson. So, it has a large value of Yukawa coupling y_t [4]. That is why the Yukawa coupling of the top quark with the Higgs boson y_t has lot of importance as any deviation from standard model prediction might give an indication of new physics. The two processes at LHC which will allow us to directly probe the Yukawa coupling between Higgs Boson and top quark are Higgs boson production in association with top quark pair ($t\bar{t}$H) via strong interaction and the production of single top quark with a Higgs boson (tH). As tH occur via electroweak interaction, it is more rare than $t\bar{t}$H production [5]. The Higgs boson in the tH channel can be radiated off by a W boson or by a top quark as shown in Figure 4.

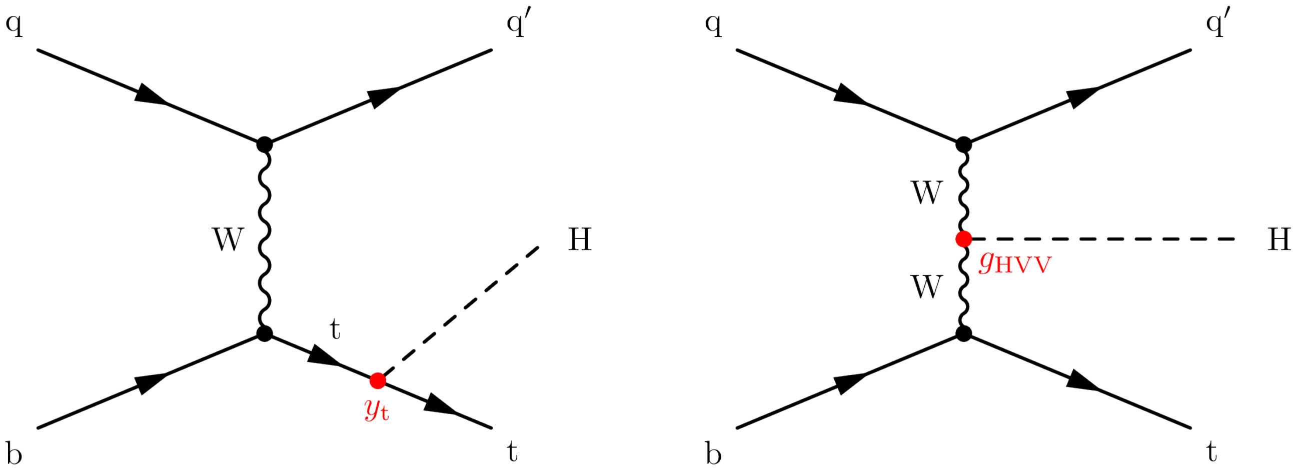

Figure 4: Leading order Feynman diagrams for the associated production of a single top quark and a Higgs boson in the t channel, where the Higgs boson couples either to the top quark (left) or the W boson (right).

These two processes in standard model have destructive interference which allow us to probe the relative sign between the coupling of top quark with Higgs boson y_t and the coupling of W boson to the Higgs boson [6]. If the Yukawa coupling between top quark and Higgs boson y_t deviate from the SM prediction or even if y_t has a negative sign, both would cause a strong increase in the tH production cross section which is a special property of tH production channel making it an interesting production channel to probe using LHC 2016, 2017 and 2018 data [7]. The coupling strength modifier κ_t is defined as $\kappa_t = \frac{y_t}{y_t^{SM}}$ which will tell us the deviation of y_t from the SM prediction as shown in Figure 5.

The LHC is sensitive to an anamolous Higgs coupling to the top quark in the Higgs boson-top quark associated production mode. The anomalous coupling will arise when we add interaction terms (dimension 6 operators in effective SM theory) in the Higgs potential. As there is strong destructive inteference in the t-channel for the standard model couplings, this production mode is sensitive to both the sign and the magnitude of any coupling beyond the SM between Higgs boson and top quark induced by higher dimensional operators in effective SM theory [8].

Until the 90's the existence of almost all the particles of the SM were confirmed except the top quark and the Higgs boson. These had eluded previous experiments due to difficulties in the production or reconstruction of its decays. The top quark was discovered in 1995 in the Tevatron collider of the Fermilab laboratory, this proton collider operated with a center of mass energy of 1.8 TeV untill 2010. The LHC collider at the CERN laboratory in Geneva, Switzerland, began its operations in 2010 colliding protons at 7 TeV increasing the colliding energies to 8 and 13 TeV in the subsequent years. The Compact Muon Solenoid (CMS) is based on the Large Hadron Collider (LHC) located at CERN. It is designed to detect particles known as muons very accurately. The CMS detector has the form of a cylindrical onion, with several concentric layers of components. Needed a powerful magnet to bend charged particles as they move away from the point of collision to identify the charge of the particles to bend them in opposite directions and measure your momentum. A silicon tracker, made of about 75 million electronic sensors individual arranged in concentric layers, identifies the routes taken by these charged particles bent with very high precision [9]. The muons are not detected by electromagnetic or hadron calorimeters, so special sub-detectors are outside to detect them once they have crossed the solenoid as shown in Figure 6. In 2012, the ATLAS and CMS collaborations, with detectors at two points where the protons collide in the LHC, announced the discovery of a new boson with a mass of 125 GeV. So far, all measurements of the properties of this boson are consistent with those of the Higgs boson of the standard model (SM).

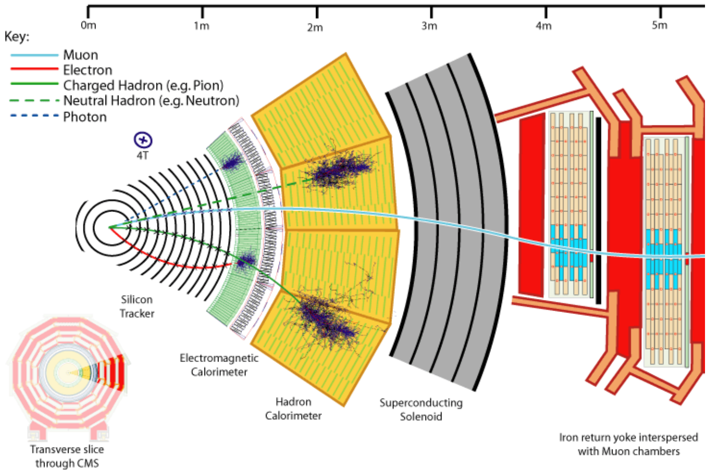

Figure 5: Transverse view of the CMS detector showing the silicon tracker, superconducting solenoid, electromagnetic calorimeter, hadron calorimeter and muon chambers.

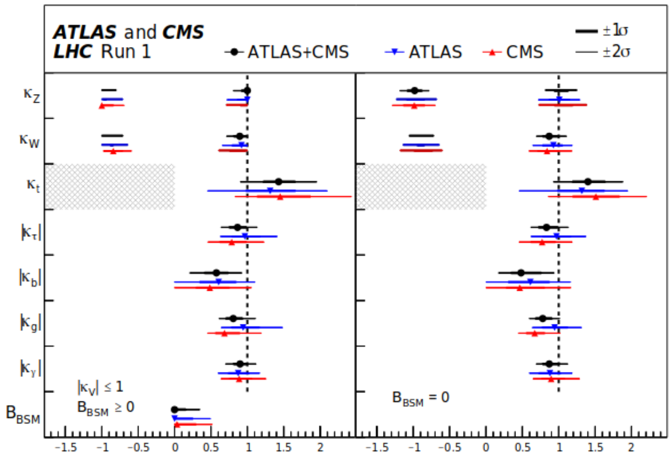

Figure 6: ATLAS-CMS combined measurements of coupling strength modifiers.

LHC during the first run in 2011 and 2012 reached a peak luminosity of 7.7×10^{33} $cm^{-2}s^{-1}$ which was more than 75% of its design luminosity and delivered an integrated luminosity of about 25 fb^{-1} to each ATLAS and CMS. The goal of subsequently run of LHC has been to obtain datasets at higher values of luminosities for precision measurements of the properties of Higgs boson, in order to test the Standard Model pattern of couplings to elementary particles. In order to minimize the machine downtimes and maximize the productive use of the LHC for physics, the replacement of the inner triplet magnets (the one responsible to squeeze the beam at collision) and of all hardware changes needed to enable an ambitious luminosity upgrade will take placein parallel during one shutdown, at around 2023-25 (Long shutdown 3), with some of the modification anticipated in 2019-2020 (LS2). This new phase of the LHC life has been named as High Luminosity LHC (HL-LHC) and has the scope of attaining the astonishing threshold of 3000 fb^{-1} in 10-12 years. All the hadron colliders in the world have so far produced a total integrated luminosity of about 10 fb^{-1}, while the LHC will deliver about 300 fb^{-1} in its first 10-12 years of life [10]. LHC will reach an integrated luminosity of about 300 fb^{-1} by 2023 as shown in Figure 8.

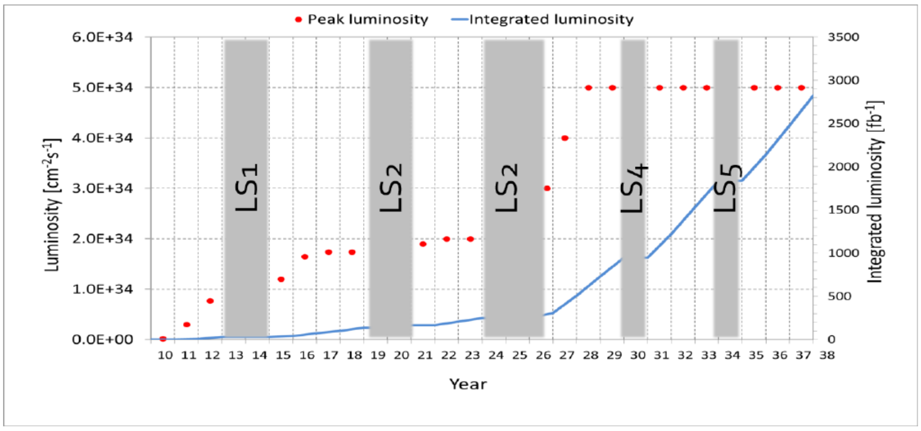

Figure 7: Projected performance of the LHC until 2038, which shows the preliminary dates for prolonged stops (LS) of the LHC and luminosities. Points show instant brightness while the line shows brightness accumulated.

Earlier searches for Higgs boson production production in association with single top quark have been studied to derive constraints on the magnitude and relative sign of Higgs boson couplings to top quarks and vector bosons. Constaints on κ_t can be derived using a likelihood ratio scan of $L(\kappa_t)/L(\hat{\kappa_t})$ where $\hat{\kappa_t}$ is the best fit value of κ_t as shown in Figure 9. Multilepton final state and final states with single lepton with a pair of bottom quarks were combined with Higgs decay to two photons to get the final result. The data favour positive value of top quark yukawa coupling for SM Higgs boson and excludes ranges of about [-0.9,-0.5] and [1.0,2.1] times y_t^{SM} at the 95 % confidence level.

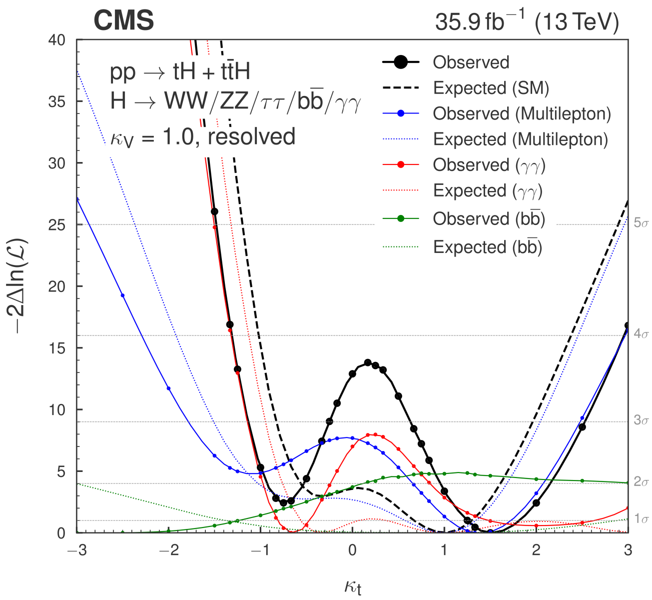

Figure 8: Scan of -2 Δ ln(L) versus κ_t for the data (black line) and the individual channels (blue, red, and green), compared to Asimov data sets corresponding to the SM expectations (dashed lines).

2. PROPOSAL

- what we will do: search for tH events, using which channels.

In this project, it is proposed to study the production channel of the Higgs boson associated with a single top quark in the Large Hadron Collider of the CERN laboratory. The measurement of this process complements other measurements of the yukawa coupling parameter of the top quark and Higgs boson. It is a part of the physics program of CMS international collaborations and ATLAS and it has not been observed so far. It is proposed to study sensitivity with the current data in the channel where the events are identified with two muons of the same sign. The impact of uncertainties will be studied and projections will be made to the future phases of the LHC. For these studies the data of the run two (2015-2018) of the LHC identifying the signal events with two muons from the same sign. It is also expected to estimate projections for the high brightness phase of the LHC (HL-LHC) that will begin in 2026.

3. GENERAL OBJECTIVE

- motivation, tH production crossection, sign of k_t, search for BSM, ..

There is currently a great enigma in physics since we know that ordinary matter comprises only 5% of the universe, another 27% includes what we call dark matter. Understanding the production of the Higgs boson, as well as its decays like the invisible decay modes are an important part of the physics program of CERN laboratory experiments to verify the Standard Model and look for new particles. Through this project we will investigate the production of the Higgs boson in association with a single top quark (tH) in proton-proton collisions with the CMS experiment of the LHC. We will study the distribution of events in one of the decay channels and the sensitivity that we get with the current data. The main objective is to search for new processes such as tH Higgs production mode in the CMS experiment which require to study different aspects such as the model of the noises that are made by simulation, techniques of adjustments to the data that incorporate the different noises and the signal, and estimates of statistical and systematic uncertainties. Some of the objectives in this project include:

- study one or more decay channels.
- verify that simulation of signal events is adequate.
- study the extraction of signal strength through adjustments to the data.
- study the impact of statistical and systematic uncertainties.

4. SPECIFIC OBJECTIVES

- details

5. HYPOTHESIS

- what we expect to find

Production studies in the tH channel have already started with the collaborations CMS and ATLAS with publications based on data from the 2011-2012 run and some data from the second run of 2015-2016. In these results it was not found signal evidence and upper limits have been set for the effective section. With the more sensitive analysis an upper limit is calculated for the effective section of a signal composed of tH and ttH that corresponds 3.1 times that expected in the SM. In this analysis the reconstruction methods do not allow to distinguish between tH and $t\bar{t}$H because the effective section of $t\bar{t}$H is much larger than that of tH and some events pass the selections designed for tH, the fraction of tH events over tH + $t\bar{t}$H is 5. In BSM models the fraction could change up to 50, for example with $\kappa_t = -1$. It could help to obtain better limits for the production of tH. The data that has been used so far correspond to only 20 of the final data of the run that which ends in 2018. The uncertainty for the signal in the current analysis is mostly statistical nature, therefore adding the total data in a new analysis the next year, sensitivity can be improved with an approximate factor of 2.2. Additionally, in subsequent phases of the LHC 2021-2023 and 2026-2038 the number of data fold and then multiply by 10 respectively. With these additions It is expected that the signal from the Higgs boson can be observed on the tH production channel. The current results can be used to project sensitivity in the third run and the high brightness phase and thus contribute to the planning of the updates of the detector.

6. METHODOLOGY

- methods used in the search: which dataset, lepton reconstruction, selections, jets, BDT, backgrounds, statistical analysis

Aspects of simulation of signal production are studied based on generators that simulate the interactions of quarks and gluons taking into account the probability distributions of each type of particle. These are packages of software that are controlled with configuration files that define various aspects of such as decay channels, energy in the center of mass and refinements in the development of the jets that are generated by the strong interaction of the quarks. The reconstruction and selection of tH events requires the use of central software of the CMS collaboration. This software contains the algorithms that reconstruct the charged and neutral particles starting from the energy deposits in the different parts of the detector. These particles include leptons, photons and hadrons which have a life time that allows them to leave the interaction region. These particles are used to identify the production of the top and the Higgs boson. In the case of the top quark, it usually decays to a bottom (b) quark and a W boson. Subsequently the W decays to two leptons or two quarks. Reconstruction requires finding a type b and two jet leptons. Improvements in this reconstruction can be done by studying the distributions of transverse momentum, the angular distributions of the different particles, and others properties.

7. EXPECTED RESULTS

- a limit, also predictions for future runs

The expected results of this project are the following: Improve data adjustments and study the effects of uncertainties. Improve the sensitivity to the tH signal in the data of the second CMS run. Limit calculations in the effective section incorporating data from the second run of the LHC. Calculate projections of signal sensitivity for the different phases of the LHC.

References

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Appendix A. SKILLS THAT WILL BE DEVELOPED

The following are skills that will be developed based on the work on this project: - understand particle physics from an experimental point of view. - analyze and manipulate data using modern programming languages such as C++, Python and ROOT. - data analysis techniques. - use high performance computing.

Appendix B. CALENDAR OF ACTIVITIES

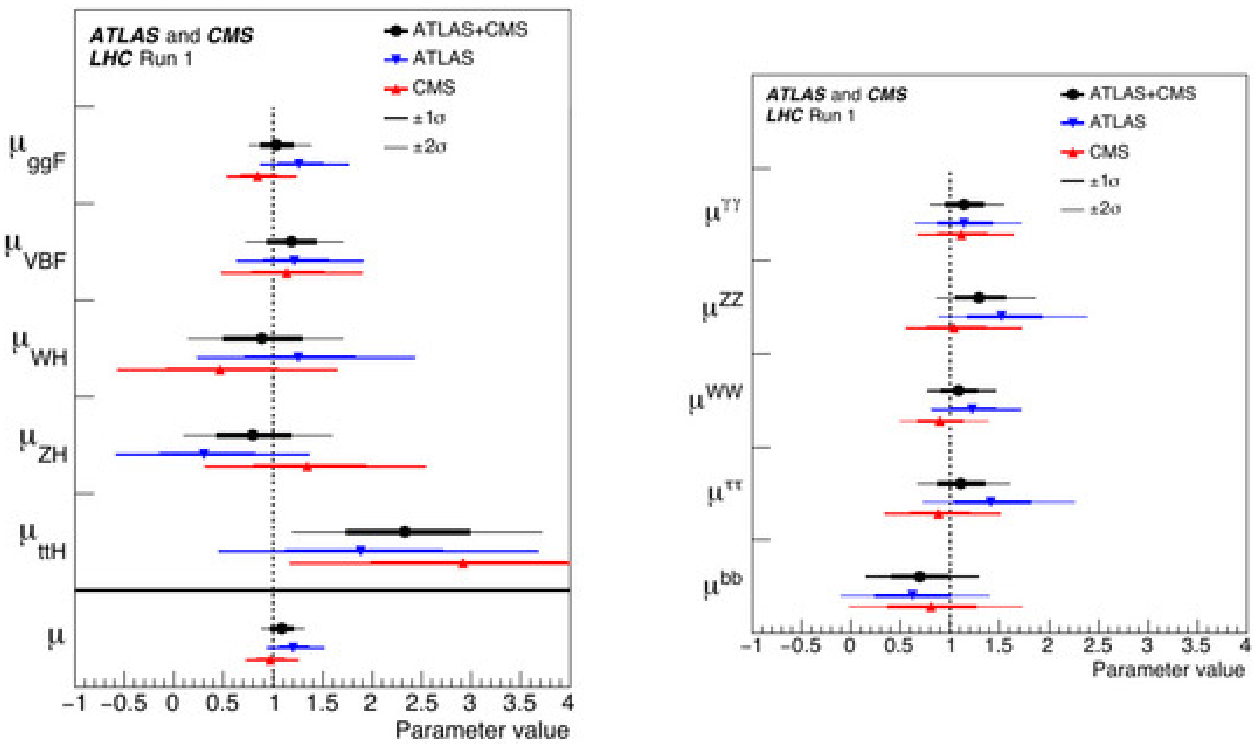

Figure B.9: Higgs boson signal strength modifier in various production modes and decay channels.

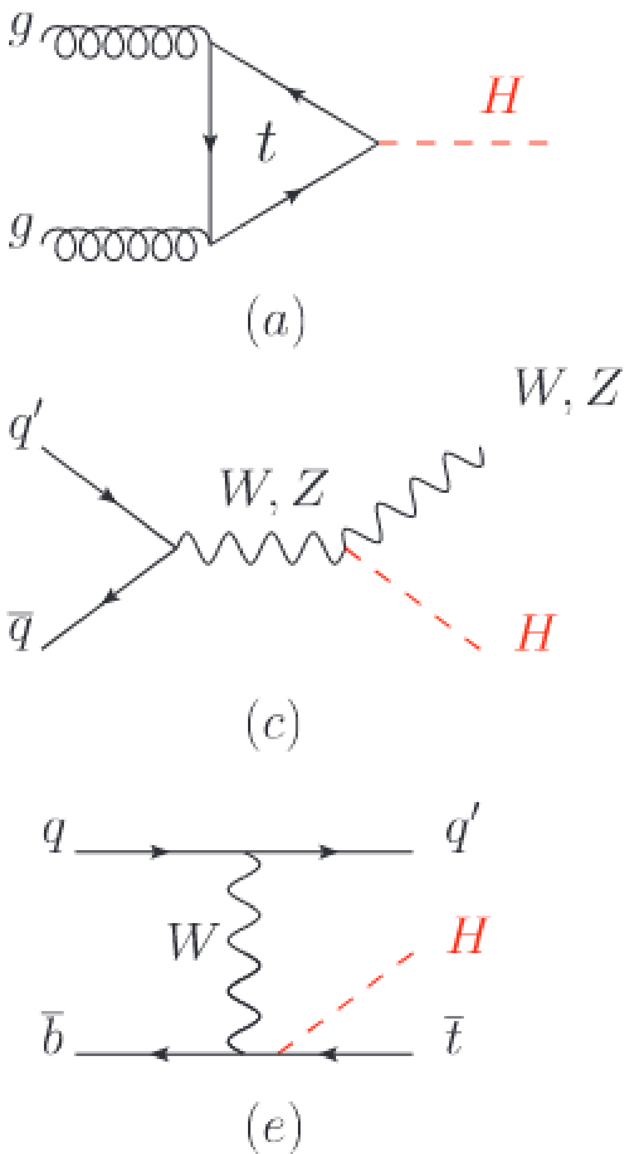

Figure B.10: Leading order Feynman Diagrams for various Higgs production modes.

$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+5\%}_{-5\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	19.1
8	$21.4^{+5\%}_{-5\%}$	$1.60^{+2\%}_{-2\%}$	$0.70^{+3\%}_{-3\%}$	$0.42^{+5\%}_{-5\%}$	$0.13^{+8\%}_{-13\%}$	24.2
13	$48.6^{+5\%}_{-5\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.50^{+9\%}_{-13\%}$	55.1
14	$54.7^{+5\%}_{-5\%}$	$4.28^{+2\%}_{-2\%}$	$1.51^{+2\%}_{-2\%}$	$0.99^{+5\%}_{-5\%}$	$0.60^{+9\%}_{-13\%}$	62.1

Figure B.11: Standard model Higgs boson production cross section in various production modes.

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.62×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.14×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.84×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.53×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$^{+6.0\%}_{-5.9\%}$

Figure B.12: Standard model Higgs boson branching ratios in various decay channels.

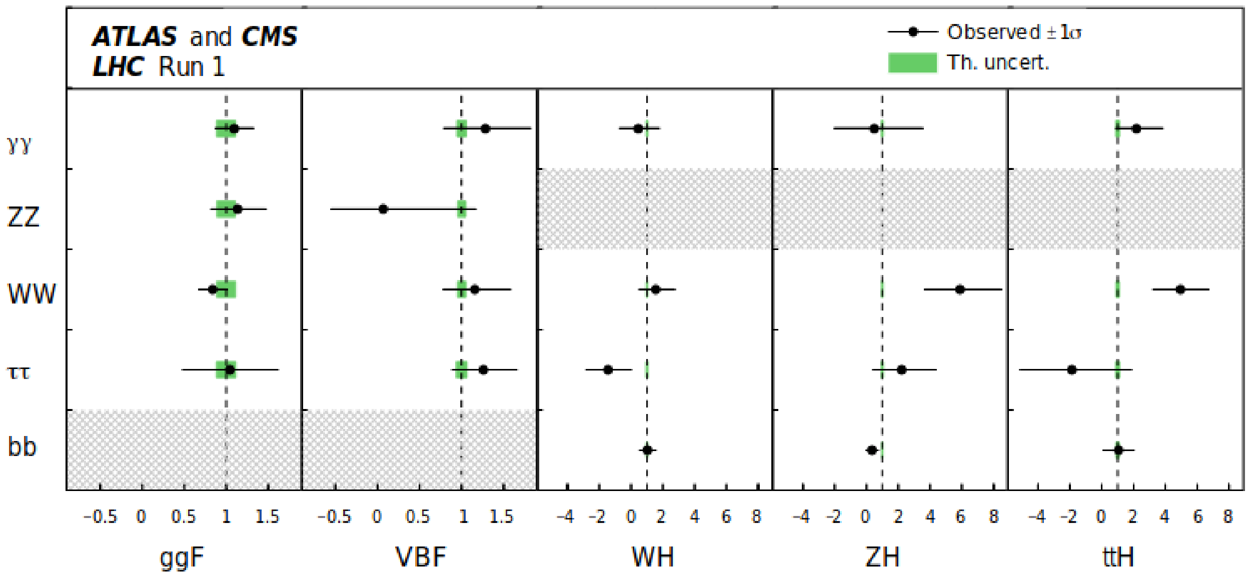

Figure B.13: Combined measurement of the products σ.BR for various production and decay channels of Standard model Higgs boson.

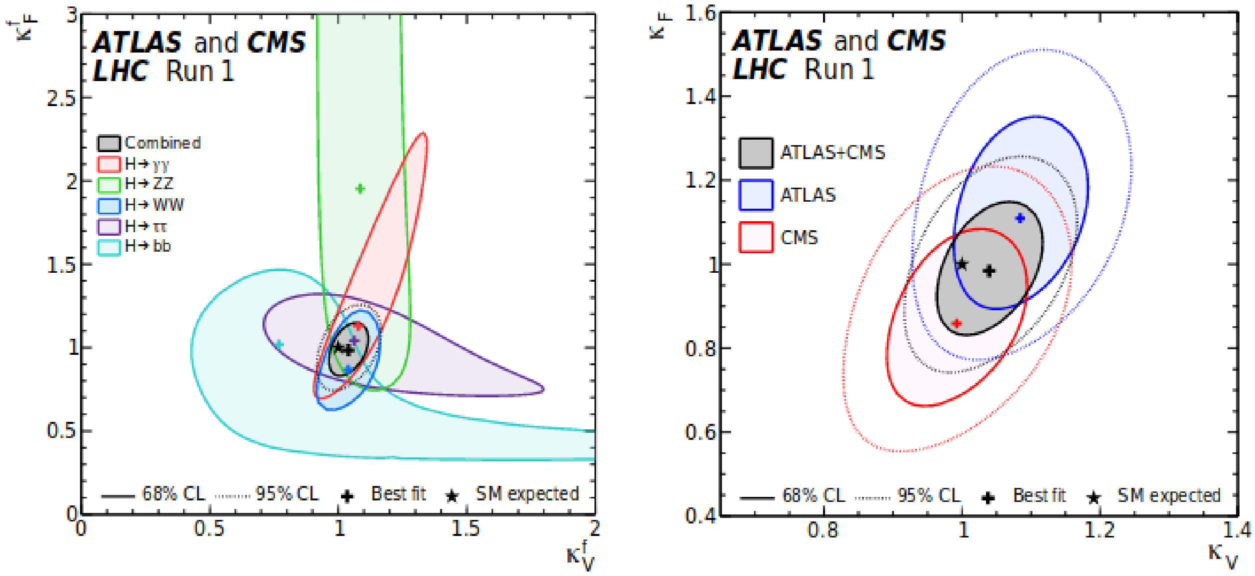

Figure B.14: Likelihood contours in the (κ_F,κ_V) plane and combined fit for all decay channels.

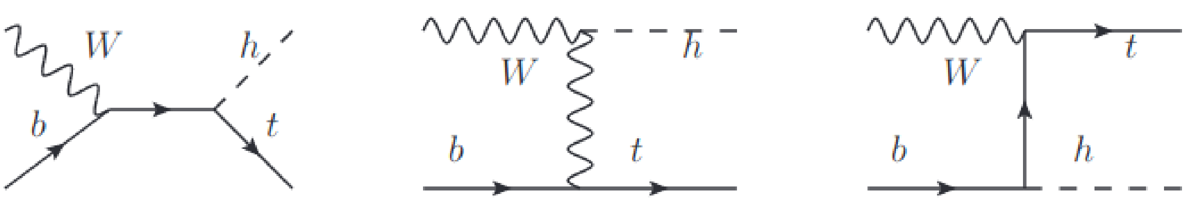

Figure B.15: Feynman diagrams contributing to the partonic process $W\ b -> tH$.

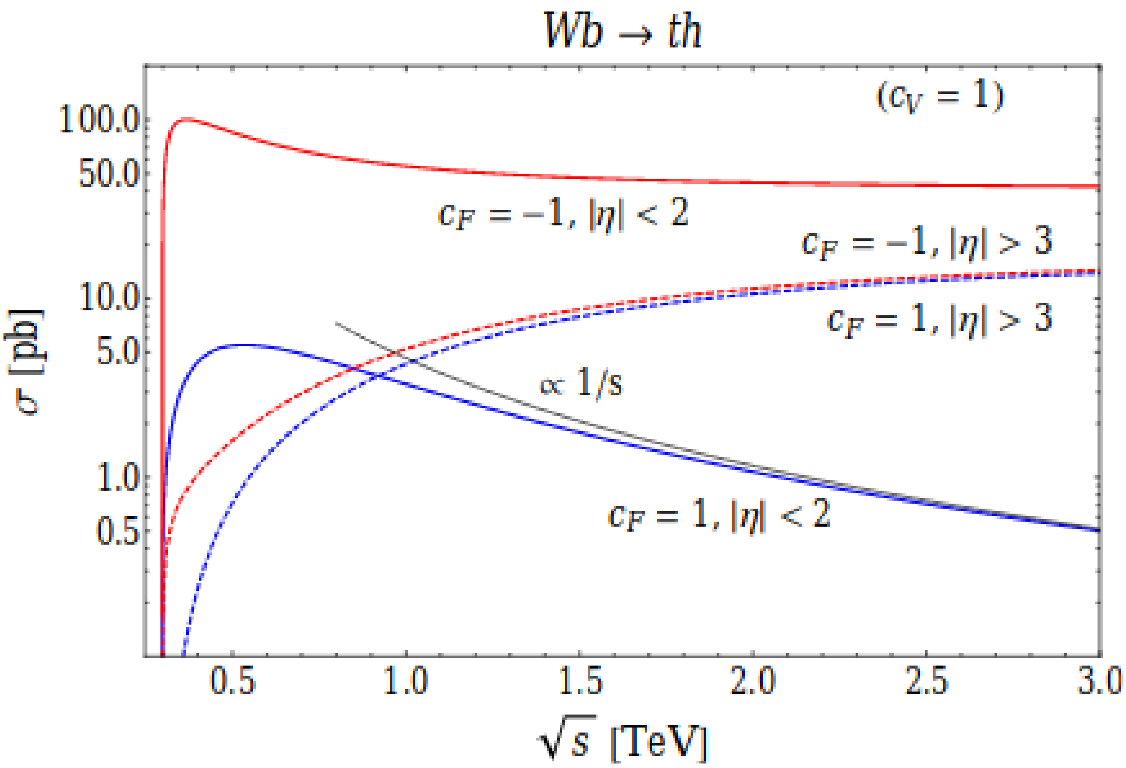

Figure B.16: Partonic cross sections for the process W b − > tH as a function of the center of mass energy.

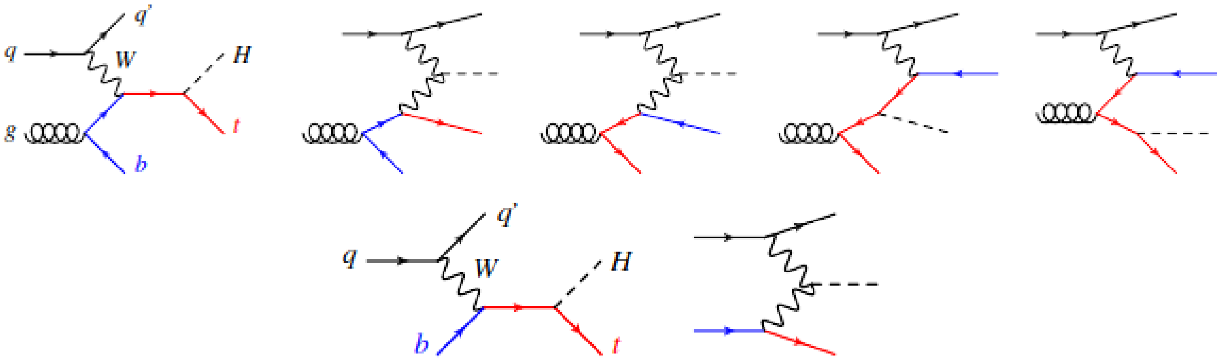

Figure B.17: Lowest order Feynman diagrams for t-channel tH production in the 4F scheme and in the 5F scheme.

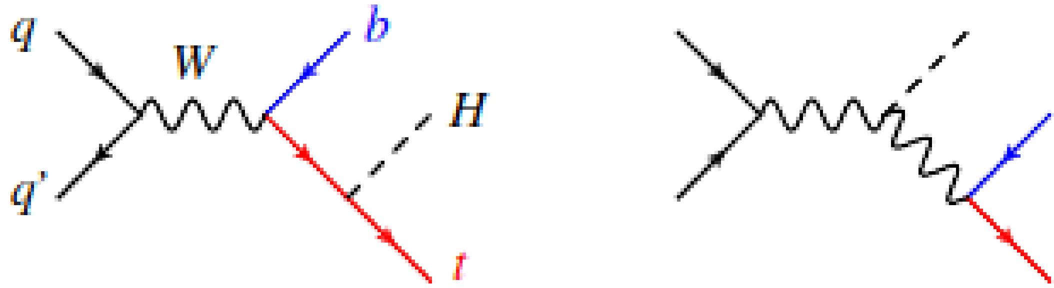

Figure B.18: Lowest order Feynman diagrams for s-channel tH production.