Vector Boson Fusion Higgs Analysis in the Compact Muon Solenoid Experiment

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This is the 3 Month Report on my PhD Progress. Theoretical and experimental motivations for a Vector Boson Fusion Standard Model Higgs Search are presented at the Compact Muon Solenoid Experiment and the plans for future analysis. A summary of the work already done on determining a working point for an invisible VBF Higgs Level 1 Trigger and the ongoing work on an inclusive VBF trigger are summarized. This results have been presented to the CMS Collaboration and will be used for 2012 data taking.

Keywords: High Energy Physics Experimental, Trigger Systems and Data Acquisition

I. INTRODUCTION AND MOTIVATION

A. Introduction

The current knowledge on the field of particle physics is summarized in the Standard Model (SM). It is known that this model is incomplete without the inclusion of a spontaneous symmetry breaking mechanism that would explain the observation that the electroweak bosons (the W and Z particles) have mass. The easiest way to introduce such a mechanism is with the Higgs Mechanism, which suggests the presence of new yet to be observed particle, the Higgs Boson.

After 2 years of successful operation the experiments built on the Large Hadron Collider (LHC) at European Organization for Nuclear Research (CERN) located near Geneva, Switzerland were already able to further narrow down the possible mass range allowed experimentally for a Standard Model like Higgs Boson. The CMS collaboration has excluded at a 95% confidence level the range 127-600 GeV. Some hits of a possible signal have already been seen around 124 GeV with a significance of 1.5σ (after look-elsewhere effect) but yet lack enough statistics to claim discovery [4]. Also, the ATLAS Collaboration have exclude at a 95% confidence level the mass ranges of 112.9–115.5 GeV, 131–238 GeV and 251–466 GeV and seen an excess of events around 126 GeV with a significance of 2.2σ (after look-elsewhere effect)[1].

With the running condition targeted for the year 2012 at the LHC, physicists are confident that enough data will be taken to discover or exclude a Standard Model Higgs.

B. Higgs Phenomenology

The main processes for Standard Model Higgs production are summarized at table I B.

The respective cross sections for each production process can be found in figure 1 [7]. It can be seen that the Gluon Fusion (GF) is the leading process by almost one order of magnitude higher than Vector Boson Fusion (VBF) which is the second most frequent process in the currently allowed experimental mass range for a Standard

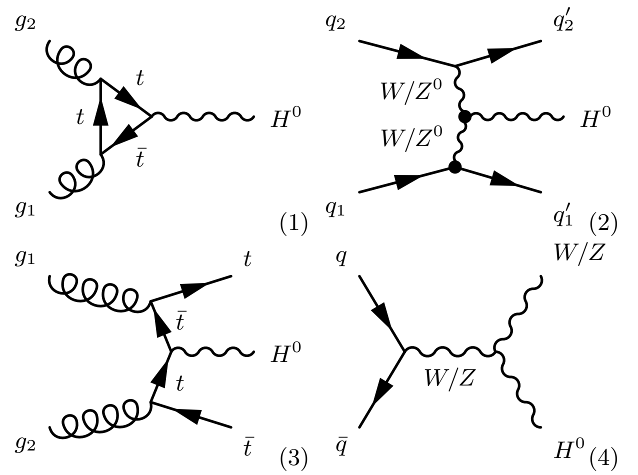

TABLE I. Main processes for Standard Model Higgs production ordered by highest cross section at the LHC. (1) Gluon Fusion, (2) Vector Boson Fusion, (3) $t\bar{t}$ Fusion and (4) W/Z associated production.

Model Higgs Boson. Both $t\bar{t}$ Fusion and Weak Boson associated productions have cross sections more than one order of magnitude lower than VBF in the same mass range.

The Higgs Boson will than decay with different probabilities to different objects depending on its mass, a plot of this probabilities can be found at figure 2 [7]. We can see that the allowed decay channels for the non-excluded experimental mass range are by order of likeliness $b\bar{b}$, $\tau\bar{\tau}$, $c\bar{c}$, gg, $\gamma\gamma$ and $Z\gamma$.

C. Motivation

The first theoretical motivations for looking for VBF Higgs events is obviously to observe and measure its cross section and each of the branching ratios for its decays. We can then calculate its coupling to the Week Bosons and to fermions (including the leptonic sector via $\tau\bar{\tau}$). From the couplings we may be able to differentiate between a SM Higgs or Beyond the Standard Model (BSM) Higgs like one of the Super Symmetric incarnations of

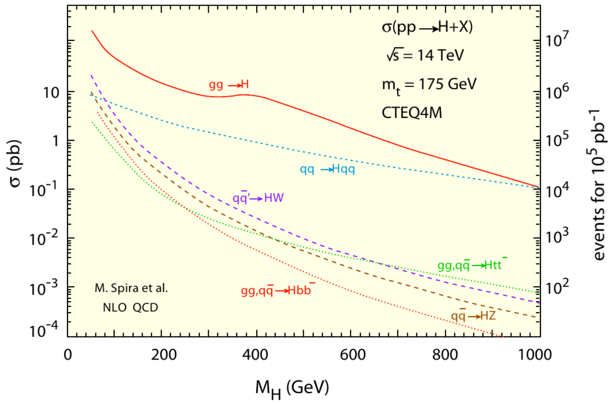

FIG. 1. Theoretical prediction of Standard Model Higgs productions cross sections for a $\sqrt(s) = 14\ TeV$ and assuming $m_{top} = 175\ GeV$.

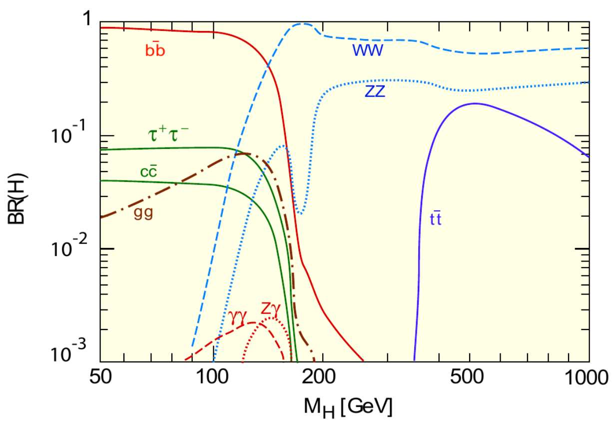

FIG. 2. Theoretical prediction of Standard Model Higgs branching rations as a function of its mass.

this boson[6, 8]. And, if the Higgs will only decay invisibly like it is predicted by Higgs Fermiophobic Models, VBF is the primary discovery channel.

From the experimental point of view, we can see from figure 1 that VBF has a cross section one order of magnitude lower than GF, but we should notice from diagram 2 in table I B that there are two forward jets produced along with the Higgs and we can use them for tagging. Also we can profit from the lack of colour exchange between the interacting quarks which will result in low hadronic activity in the central rapidity region. Since the Higgs visible decay products (if any) are most likely produced in the central rapidity region, this means that they will be likely isolated from the forward jets thus allowing better reconstruction/identification efficiency which should allow easier study of the Higgs properties.

II. THE LARGE HADRON COLLIDER

The Large Hadron Collider (LHC) is at this moment the world's largest and highest-energy particle accelerator in activity. It was built in a 27 kilometer circular tunnel, at an average depth of around 100 meters, under the Franco-Swiss border near Geneva, Switzerland[2].

The LHC is a synchrotron machine designed to accelerate and collide two opposing particle beams of particles. Particles are injected into the machine in bunches, which can be composed of protons or lead nuclei. For protons the maximum nominal energy that can be achieved per beam is 7 TeV, which represents 14 TeV in the center of mass frame for a single proton-proton collision. While for lead nuclei a maximum nominal energy of 574 TeV per nucleus (2.76 TeV per nucleon) per beam is planned. The running conditions for proton collisions during 2012 are predicted to be 8 TeV center of mass energy, with initially an average number pile up collisions of the order of 28 and a delivering instant luminosity of the order of $5 \times 10^{33}\ cm^{-2}s^{-2}$

III. THE COMPACT MUON SOLENOID EXPERIMENT

The Compact Muon Solenoid Experiment (CMS) is a general purpose experiment that is an integrating part of the LHC program. It was designed to study the collisions of two intersecting proton beams in its center [3]. This detector was planned with the intention of studying a broad spectrum of physics processes and is made of several subsystems, each one designed to take advantage of some characteristics of the particles produced in order to measure their energy, momentum and charge. The detector has classical onion structure with several layers, starting from the collision point outwards we have: Tracker System, Electromagnetic Calorimeter, Hadronic Calorimeter, Magnet, Muon System and Return Yoke.

At nominal conditions forty million collisions are produced in a single second and it would be impossible to register all of them. As collisions are uninteresting, the solution is having some kind of event selection already in the machine so we would only save the most interesting collisions. This is the role of the Trigger System, which over two levels (each one with more information of what happened), reduces the number of events to a manageable rate.

The overall dimensions of CMS detector are a length of 21.6 m, a diameter of 14,6 m, and total weight of 12500 *tons*.

IV. VBF SIGNATURE AT CMS

The Standard Model Higgs Vector Boson Fusion (VBF) signature main characteristic is the presence of two forward jets associated with the Higgs (see diagram

2 in table I B). This two forward jets have a reasonable p_T ($\gtrsim 30\ GeV$), high $\Delta\eta$ separation between them ($\gtrsim 3$) and low $\Delta\phi$ ($\lesssim 2.5$). The dijet pair also has a high invariant mass since it will be produced back-to-back to the Higgs Boson. Because there is no color exchange between the incoming quarks the hadronic activity between the jets is suppressed. On the other hand the Higgs decay products if any will be located at the central rapidity area which will be easier to study because of the low hadronic activity already described[5]. The distribution of the pseudo-rapidity for both forward jets and two τ coming form SM Higgs decay of simulated events at the CMS detector can be found in 3.

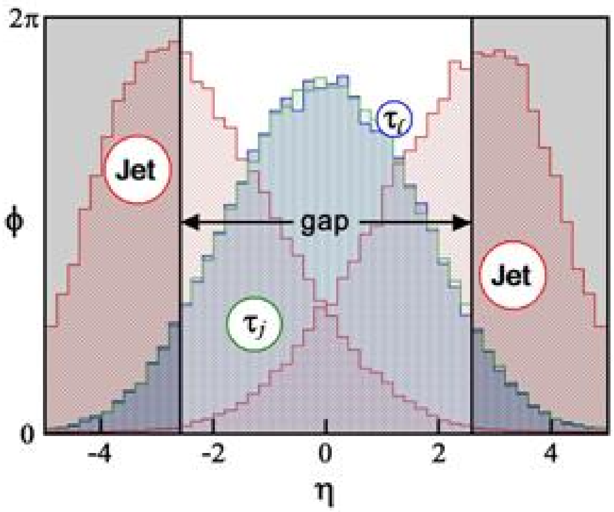

FIG. 3. Simultaneous plot of the η coordinate of both forward jets and the $\tau\bar{\tau}$ produced from simulated VBF Higgs decay. Super-imposed with 4 circle showing the possible positions of this 4 object in an hypothetical event.

The CMS detector is ideal for this type of searches since it is an 4π hermetic detector with calorimeter coverage from -5 to 5 in pseudo-rapidity, it also has very good capabilities of particle measurement and identification which can be used to identify the forward jets and Higgs decay products or in case of an invisible decay, compute the resulting missing transverse energy. An event display of a simulated Standard Model Higgs (which than decays to $\tau\bar{\tau}$) produced via VBF can be found at figure 4.

V. L1 TRIGGER STUDIES

A. Invisible Higgs Trigger

I have been involved in a study of a CMS Level 1 Trigger algorithm with the objective of efficiently selecting VBF Higgs to invisible decays. This study was based on real data from the High Pileup special run taken late 2012 and was aimed at making a proposal for a viable trigger algorithm to be used in the 2011 proton run.

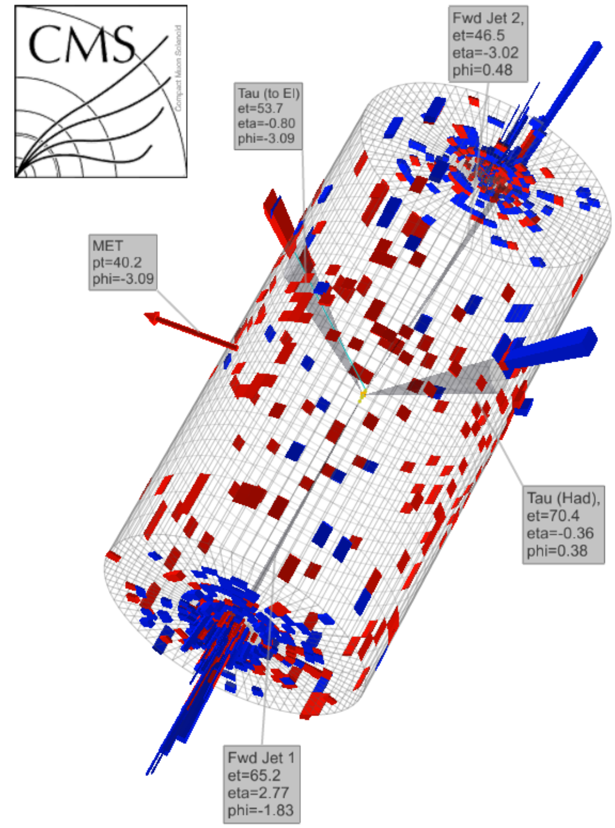

FIG. 4. Event display of a simulated event where a Standard Model Higgs is produced via Vector Boson Fusion which than decays to $\tau\bar{\tau}$ which in turn decay leptonically to electron (left) and hadronically (right).

MET [GeV] ($E_\perp(jj) > 20$ [GeV])				
$\Delta\phi$	no cut	2.5	2.1	1.8
10kHz	32	32	32	32
5kHz	35	35	35	35
2kHz	41	41	41	41
1kHz	47	47	47	46
500Hz	54	54	54	53

TABLE II. Cut thresholds to apply to MET assuming fixed dijet $E_\perp > 20$ [GeV] to obtain specif L1 Rates forced instant luminosity of $5e33$ and $< PU >= 28$. Highlighted in green is the working point suggested to the Tigger Studies Group for the L1 Trigger.

The algorithm was based on selecting missing transverse energy (MET) and two jets that would pass the test $\eta_{jet1} \times \eta_{jet2} < 0$ and would have a separation of $\Delta\eta_{jj} > 3$. An possible additional cut was also studied, a restriction on $\Delta\phi_{jj}$, tested points were no cut, < 2.5, < 2.1 and < 1.8. For the conditions expected on early 2012 (i.e. instant luminosity of $5e33$ and $< PU >= 28$) two tables were produced reporting the cuts necessary to achieve a give rate threshold, one assuming fixed dijet $E_\perp$ cut and varying MET (table II) and another assuming fixed MET cut and varying $E_\perp$ (table III).

$E_\perp(jj)$ [GeV] ($MET > 30$ [GeV])				
$\Delta\phi$	no cut	2.5	2.1	1.8
10kHz	28	28	24	24
5kHz	32	32	32	32
2kHz	52	48	44	44
1kHz	68	68	64	64
500Hz	92	92	88	88

TABLE III. Cut thresholds to apply to dijet $E_\perp$ assuming fixed dijet $MET > 30$ [GeV] to obtain specif L1 Rates forced instant luminosity of $5e33$ and $< PU >= 28$. Highlighted in green is the working point suggested to the Tigger Studies Group for the L1 Trigger.

MET [GeV] ($p_\perp(jj) > 20$ [GeV])				
$\Delta\phi$	no cut	2.5	2.1	1.8
10kHz	36	36	36	36
5kHz	40	40	40	40
2kHz	47	47	47	46
1kHz	54	54	54	54
500Hz	67	66	66	64

TABLE IV. Cut thresholds to apply to MET assuming fixed dijet $E_\perp > 20$ [GeV] to obtain specif L1 Rates forced instant luminosity of $7e33$ and $< PU >= 32$

Results were used to define working points for this trigger, which were already proposed to the Trigger Studies Group to be included on a future L1 Trigger Menus. Proposed trigger were:

- Dijet $E_\perp > 20\ GeV$ + fwd/bkwd + $\Delta\eta_{jj} > 3$ + $MET > 40\ GeV$
- Dijet $E_\perp > 50\ GeV$ + fwd/bkwd + $\Delta\eta_{jj} > 3$ + $MET > 30\ GeV$

Further studies were made for conditions predicted for late 2012 (i.e. instant luminosity of $7e33$ and $< PU >= 32$) and can be found on tables IV and V.

B. Inclusive Higgs Trigger

It would be desirable to have a dedicated inclusive L1 Trigger (i.e. Higgs decay independent). Such a trigger would allow to have a single trigger for all VBF signature analysis, which implies less systematics while comparing them and usually the more people using a trigger means it will become better understood by all.

$p_\perp(jj)$ [GeV] ($MET > 30$ [GeV])				
$\Delta\phi$	no cut	2.5	2.1	1.8
10kHz	32	32	32	32
5kHz	40	40	40	40
2kHz	64	60	60	56
1kHz	76	76	76	76
500Hz	100	100	96	92

TABLE V. Cut thresholds to apply to dijet $E_\perp$ assuming fixed dijet $MET > 30$ [GeV] to obtain specif L1 Rates forced instant luminosity of $7e33$ and $< PU >= 32$

By triggering only on the VBF signature we therefore have no dependence on the Higgs decay, which means we can get all possible decays with a single trigger, even those that are predicted by yet to be defined models. Thus, it would be a model independent trigger.

If it happens that we do not find any Higgs boson, this trigger can than be used for a WW scattering analysis, aimed at Standard Model exclusion, since the signature is similar.

For such a trigger to work it would have to be based only on the forward dijet present on the VBF signature. It was decided to study three variables: Invariant Mass, Transverse Invariant Mass (MT) and Scalar Sum of the Hadronic Energy (HT). Again, we always require a dijet with $\Delta\eta > 3$ and we study the effects of an additional cut on $\Delta\phi$, the points tested were no cut, < 2.5, < 2.1 and < 1.8).

1. *Invariant Mass*

This variable takes advantage from the very high invariant mass of the dijet system but it is not yet implemented on the L1 Hardware but it is in principle possible.

Unfortunately this variable was showed to be unusable. To get acceptable rates we would need to cut too high on Jet $p_\perp$ or M_{Inv} losing almost all signal efficiency.

2. *Transverse Invariant Mass*

This variable is better at suppressing QCD events, it is less pileup dependent and has lower error associated to it (only x-y dependence). It is also not yet implemented on the L1 Hardware but should also be possible to develop.

This variable showed to be promising. A possible working point for a Level 1 rate of 5kHz could be $MT > 50\ GeV$ no $\Delta\phi$ cut and dijet $p_\perp \sim 45\ GeV$ which should give a signal efficiency of $\lesssim 70\%$ (see R. Lane 3 Months PhD Report).

3. *HT (Scaler Sum of the Transverse Energy)*

Theoretically this is the best variable to separate signal from background and has the advantage of being already implemented on L1 Hardware.

This was showed to be the most promising variable. A possible working point for a Level 1 rate of 5kHz could be $HT > 100\ GeV$ no $\Delta\phi$ cut and dijet $p_\perp \sim 40\ GeV$ which should give a signal efficiency of $\lesssim 98\%$ (see R. Lane talk, 5 and 6).

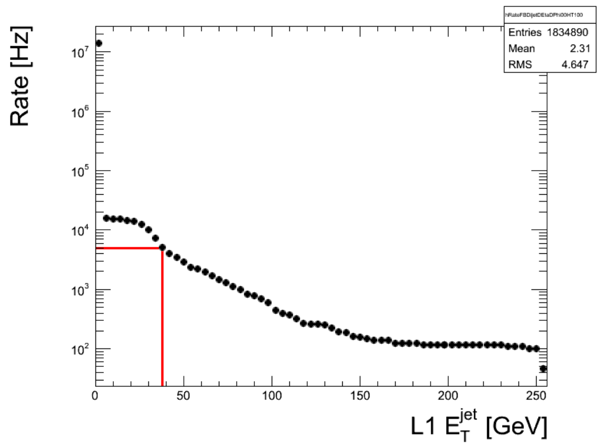

FIG. 5. Level 1 rate as a function of dijet $p_\perp$ while selecting events with $HT > 100\ GeV$. Results based on date from the High Pileup Special run taken late 2011.

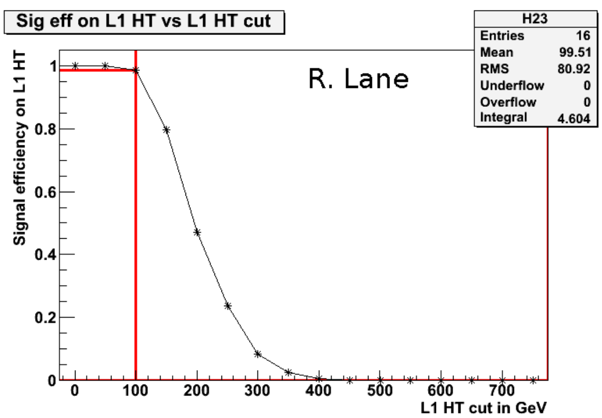

FIG. 6. Higgs to $\tau\bar{\tau}$ signal efficiency as a function of HT cut extracted from monte carlo simulation. Result from R. Lane.

VI. PLANS

My plans are, to participate on the L1-HLT inclusive VBF Trigger development, commissioning and maintenance. This trigger will be the basis of a data analysis of a VBF Higgs decay channel, which on a first stage will aim at observation and later at properties measurement.

In parallel I will participate on trigger related efforts like, Data Quality Monitoring (DQM), trigger upgrades development and other types of service work.

VII. CONCLUSIONS

There will be a VBF Higgs to Invisible dedicated trigger for 2012. Most likely an inclusive VBF trigger will be included soon, which should cover most of the 2012 data. The year of 2012 will be an exciting year for all the LHC experiments, where we may finally find hits of new physics and/or be forced the rethink our current knowledge of particle physics.

Imperial College CMS Group highly involved on the trigger efforts for a VBF analysis. This will evolve quickly with data to a full analysis effort aimed at publication of the (soon to be discovered) Higgs Boson properties.

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