PhD Progress 18 Months Report

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This is the 18 month report on my PhD progress. Theoretical and experimental motivations are presented for the analysis in which I am involved at the Compact Muon Solenoid experiment, the standard model Higgs on the $\gamma\gamma$ decay channel analysis and vector boson fusion produced Higgs with invisible decay products analysis. A summary of the service work already performed is also given.

Keywords: Experimental high energy physics, trigger systems and data acquisition

I. 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 a new particle, the Higgs boson.

After 3 years of successful operation, the experiments built on the Large Hadron Collider (LHC) at European Organization for Nuclear Research (CERN) located near Geneva, Switzerland observed of a new boson. Measurements of properties of this new particle are compatible within uncertainties with what would be expected for a SM Higgs boson.

The Compact Muon Solenoid experiment (CMS) published results where the best-fit signal strength for a SM Higgs boson mass hypothesis of 125 GeV is $\sigma_{SM} = 0.87 \pm 0.23$. The excess is most significantly seen in the $\gamma\gamma$ and in the ZZ decay channel, which together are the channels with best mass resolution. A fit to these signals gives a mass of $125.3 \pm 0.4(stat.) \pm 0.5(syst.)$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from 1[3].

The ATLAS collaboration also presented simultaneously similar results and claim of a new neutral boson with a measured mass of $126.0 \pm 0.4(stat.) \pm 0.4(syst.)$ GeV [1].

A. Higgs phenomenology

The main processes for Standard Model Higgs production are summarized in figure I A.

The respective cross sections for each production process can be found in figure 2 [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)

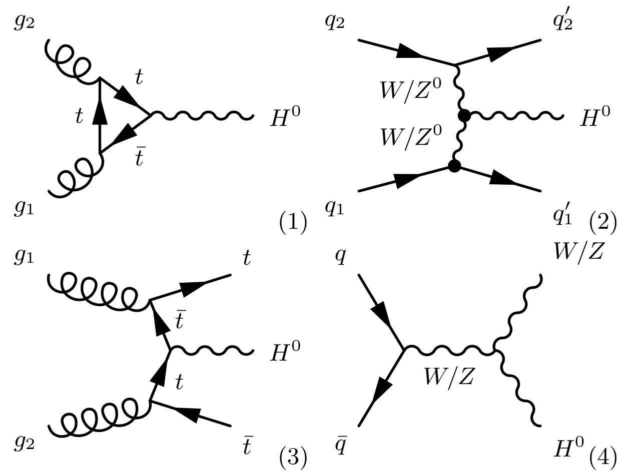

Figure 1. Main processes for standard model Higgs production ordered by highest cross section at the LHC. (1) gluon fusion,(2) vector boson fusion, (3) $t\bar{t}$ fusion and (4) W/Z associated production.

which is the second most frequent process in the currently allowed experimental mass range for a Standard 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 then decay with different probabilities to different objects depending on its mass; a plot of these probabilities can be found at figure 3 [7].

B. Higgs to $\gamma\gamma$

The $H \to \gamma\gamma$ channel main production mechanism is gluon fusion. This process compared with the other possible production mechanisms and decays is the one that presents the biggest potential for discovery at low masses, since its clean signature and amount of background on the signal area make this channel the most promising.

In the $H \to \gamma\gamma$ analysis a search is made for a narrow peak in the diphoton invariant mass distribution in the range 110–150 GeV. This signal is sitting on a large irreducible background from QCD production of two photons and reducible background where one or more of the

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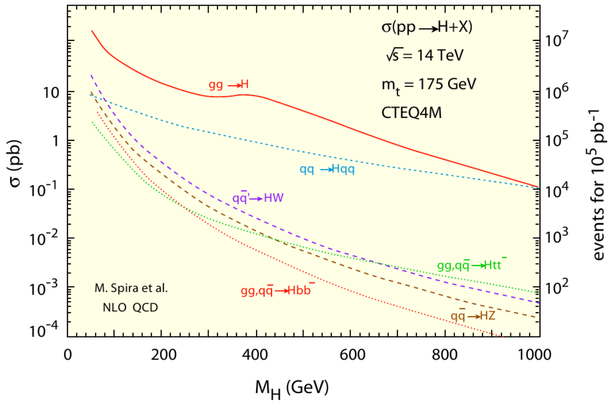

Figure 2. Theoretical prediction of standard model Higgs productions cross sections for a $\sqrt(s) = 14\, TeV$ and assuming $m_{top} = 175\ GeV$.

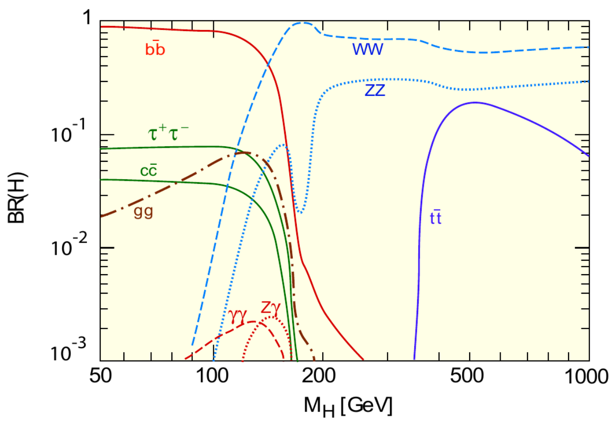

Figure 3. Theoretical prediction of standard model Higgs branching ratios as a function of its mass.

reconstructed photons originate from misidentification of jet fragments.

C. Vector boson fusion Higgs to invisible

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 weak 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 such as one of the super symmetric incarnations of this boson[6, 8]. Also for models where the Higgs would only decay invisibly, VBF is the primary discovery channel.

From the experimental point of view, we can see from figure 2 that VBF has a cross section one order of magnitude lower than GF, but we should notice from diagram 2 in figure I A 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 coming from the main interaction. 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.

In the case of an invisible decay we can profit from the large Z to invisible decay branching ratio. On the other hand we do not have the Higgs decay products to reconstruct its mass, so we have to rely only on the missing energy and tagged jets to identify these events.

II. EXPERIMENTAL INTRODUCTION

A. 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. 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. 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 8 TeV center of mass energy, with an initial average number pile up collisions of the order of 28 and a delivering instant luminosity of the order of $5 \times 10^{33}\ cm^{-2}s^{-2}$

B. Compact Muon Solenoid

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 centre [4]. 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: pixel system, tracker system, electromagnetic calorimeter, hadronic calorimeter, magnet, muon systems 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 almost all collisions are uninteresting, the solution is to have an event selection already in the machine so we would only save the most interesting events. This is the role of the trigger system, which is split into two levels, where the second level benefits from the extra time from the selection at first level to access more information of what happened. Using this approach by stages we are able to reduce the number of events to a more manageable rate between of under 1500 Hz.

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

C. Trigger

During 2012, LHC is being run with 50 ns bunch separations leading to a maximum bunch crossing rate of 20 MHz. Data from only about 10^3 $events/sec$ can be written to archival media; hence, the trigger system has to achieve a rejection factor of $\sim 2 \times 10^5$ by selecting what may be the most interesting events. The CMS trigger and data acquisition system consists of: the detector electronics, the Level-1 trigger processors (calorimeter, muon, and global), the readout network, and an online event filter system (processor farm) that executes the software for the High-Level Trigger (HLT).

D. Level 1 trigger

The size of the LHC detectors and the underground caverns imposes a minimum transit time for signals from the front-end electronics to reach the services cavern housing the Level-1 trigger logic and return back to the detector front-end electronics. The total time allocated for the transit and for reaching a decision to keep or discard data from a particular beam crossing is 3.2 μs. During this time, the detector data must be held in buffers while trigger data is collected from the front-end electronics and decisions are reached. This decision allows to discard a large fraction of events while retaining the small fraction of interactions of interest (nearly 1 crossing in 1000) at hardware level. Of the total latency, the time allocated to Level-1 trigger calculations is less than 1 μs.

1. *Level 1 Trigger Data Quality Monitoring*

The CMS Experiment developed a central data quality monitoring (DQM) System. This system provides online monitoring for the experiment, offline data certification and software release validation.

The online DQM system runs in real time in parallel with the data taking and produces plots based on the analysis of a fraction (typically 5% not considering parked data) of the events recorded in stream A (data for prompt reconstruction). The results are shown in an online interface accessible with a normal internet browser.

The offline DQM system runs over the full non parked data in the next few days after it has been recorded in order to produce plots with the full statistics available, thus providing a good handle to determine data quality and allow certification.

Like other systems on CMS the level 1 trigger also has online and offline DQM tools which are crucial to monitor its proper functioning and provide information for data certification specific for this subsystem.

III. DATA ANALYSIS

A. Higgs to $\gamma\gamma$

The Higgs to $\gamma - \gamma$ analysis searches for a peak on the diphoton mass spectrum. Candidate diphoton events are separated into mutually exclusive categories of different expected signal-to-background ratios. This selection is based on the properties of the reconstructed photons and on the presence of two jets satisfying criteria aimed at selecting events in which a Higgs boson is produced through the VBF process. The analysis uses multivariate techniques for the selection and classification of the events.

1. *Background fit function choice systematics study*

In order to extract the signal yield we must perform mass fit to the background in order to estimate its contribution to the signal region. In the side band analysis this fit is done excluding the signal region in order to perform a fit unbiased by the presence of signal.

This choice of function introduces a systematic error since we do not know the underlying function in the processes produce and smear our data. Thus implies the need to study how much this choice changes our background estimation. To perform this study we need to choose which candidate functions or function classes are adequate to fit our background. For applicability and simplicity and function classes of polynomials, exponentials and power laws were selected.

If we assume the we are fitting our data with function A and want to study function classes 1,2 and 3, the step of the study are:

1. Fit A to the data excluding the signal region and obtain a signal estimation.

2. Generate toys based on the fit made from A with the same number of events seen in data (all window).

3. Fit each toy with every selected function from class 1, 2 and 3. Calculate the number of events in the signal region. Compare the obtained value with the initial prediction of A over the data and plot them for each selected. These plots should have a Gaussian distribution where the mean is the difference between A and the selected function, which will contribute to the global systematic of the signal choice, and the sigma is the statistical error associated from the initial dataset. An example of such plot can be seen at figure 4.

4. We can combine the plots produced in the previous step by weighting them by the $p-$value of that fit to the initial data (implying that the functions that fit the data worse will have less weight).

5. We can now extract the global mean, which is an approximation of the systematic error associated with the choice of function and global RMS which is an approximation of the statistical error associated with the initial data.

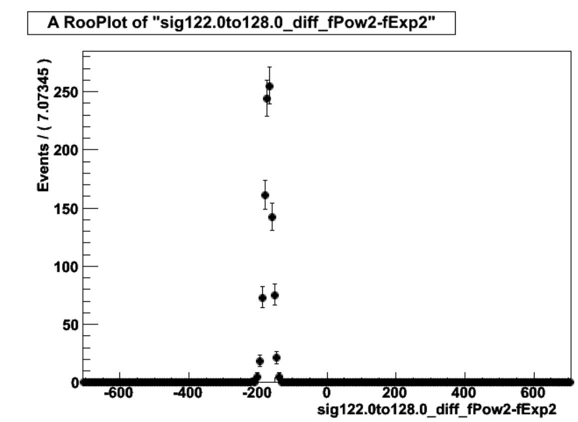

Figure 4. Plot of the diference of estimation of background contribution on the signal area, made by fitting toys from a generating power law of the second degree function and fitting with a exponential of the second degree. The mean for the gaussian fit to that distribution is -169.95 ± 0.55 (systematic error of choosing power law over exponential) and the RMS is 10.89 ± 0.39 (statistical error associated with the data initial statistics).

2. *Spin analysis*

With the observation of a new boson, now the focus turns to properties measurement. One of the important properties to measure is the spin of the new particle. We know from the decay channel where it was observed, $\gamma\gamma$ and Z^0Z^0, that it must have even value.

The SM Higgs is spin 0 but there are other models that predict particles with Spin 2 like the RS Graviton model.

To measure the spin we need to look into a variable that is sensitive to it. It was chosen to use $cos(\theta^*)$ which is the angle between the diphoton on the SM Higgs rest frame and a specific z-direction.

For this feasibility study we started from the events selected by the benchmark analysis that was used for claiming discovery of the new boson. Specifically, events that pass the diphoton BDT cut with a score of -0.05 or more.

To determine which is the best frame to measure $cos(\theta^*)$ we compared MC samples of SM Higgs and RS graviton. The following reference frames were analysed: Collins-Soper, Helicity, Perpendicular Helicity, Gottfried-Jackson and Vector Addition. It was determined that the best frame to use would be the Collins-Soper, as it shows better the difference between the two models 5.

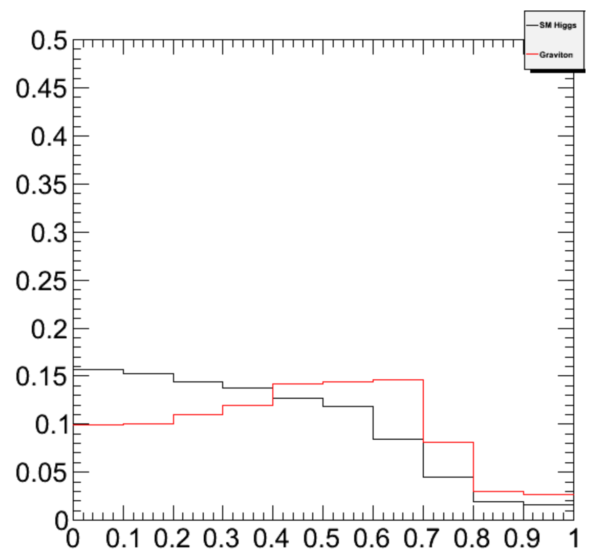

Figure 5. Plot for the absolute value of $cos(\theta^*)$ for both Monte-Carlo samples of standard model Higgs and RS graviton. Both distributions are normalized to 1.

It was decided to use the categories already present at the reference analysis and further split them in two by defining a threshold in $cos(\theta^*)$. The split point was chosen in the crossing point of each sample $cos(\theta^*)$ distribution when normalized to one, which make the sum of absolute differences between sample yields maximal.

Now we can create a signal model from Monte-Carlo by fitting each category, and extract signal yields from data by combining the signal models with an adequate background model.

Several methods for calculating signal significance/exclusion are now being investigated, which attempt to make use of not only the yield but also the relative amount of signal in each bin.

B. Vector Boson Higgs to Invisible

1. VBF Signature at CMS

The VBF SM Higgs signature main characteristic is the presence of two forward jets associated with the Higgs (see diagram 2 in figure I A). These 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 lower hadronic activity coming from the main interaction already described[5].

To illustrate this separation of the SM Higgs decay products let's look at VBF Higgs decay to a pair of τ. The distribution of the pseudo-rapidity for both forward jets and two τ coming from SM Higgs decay of simulated events at the CMS detector can be found in figure 6.

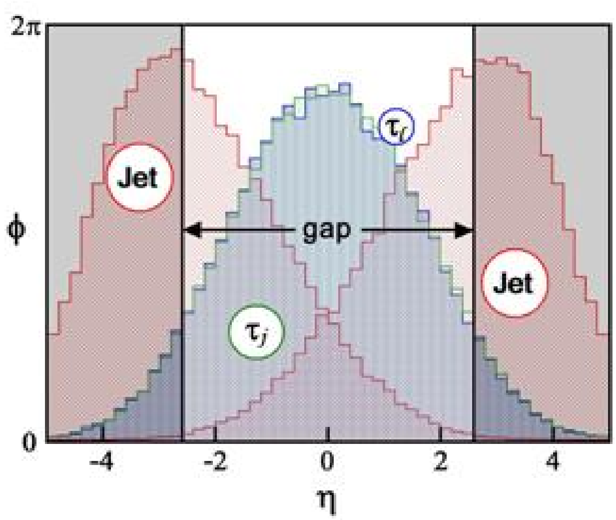

Figure 6. Simultaneous plot of the η coordinate of both forward jets and the $\tau\bar{\tau}$ produced from simulated VBF Higgs decay. Super-imposed with 4 circles showing the possible positions of these 4 objects in a hypothetical event.

The CMS detector is ideal for these types of searches since it is a 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 then decays to $\tau\bar{\tau}$) produced via VBF can be found in figure 7.

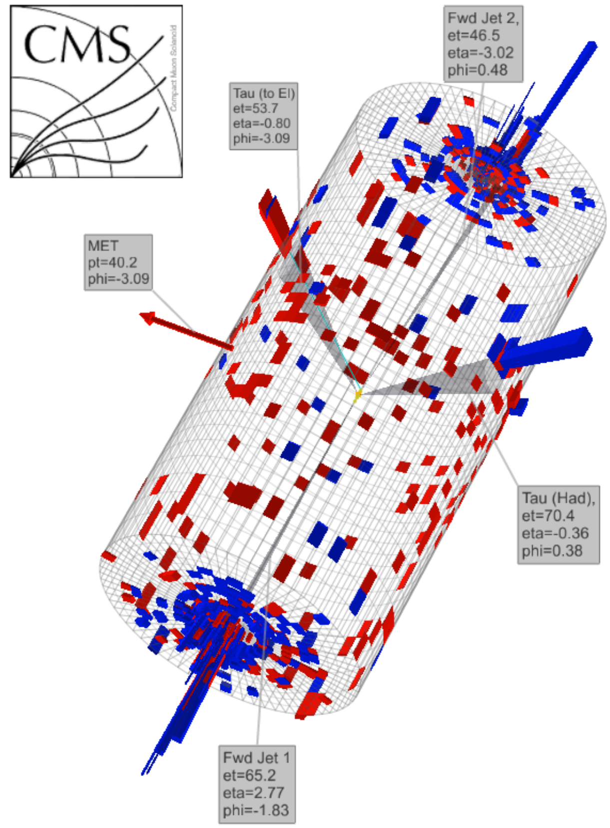

Figure 7. Event display of a simulated event where a standard model Higgs is produced via vector boson fusion which then decays to $\tau\bar{\tau}$, this in turn decay leptonically to an electron (left) and hadronically (right).

2. L1 Trigger Studies

The first step of any analysis is defining or selecting a trigger to collect data. This trigger should have a high signal efficiency while recording an acceptable background.

At the beginning of 2012 the possibility of recording data without prompt reconstruction it was introduced, thus allowing to record up to 1500 Hz of data where only 300 Hz are promptly reconstructed. This is now know as *parked data*; this data was reconstructed after the beginning of *Long Shutdown 1* already in 2013.

A study was initiated on the possibility to use this extra bandwidth to make a set of triggers that would cover record VBF events regardless of final state.

3. 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 2011 and was aimed at making a proposal for a viable trigger algo-

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 I. Cut thresholds to apply to MET assuming fixed dijet $E_\perp > 20$ [GeV] to obtain specific 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.

$E_\perp(jj)$ [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 II. Cut thresholds to apply to dijet $E_\perp$ assuming fixed dijet $MET > 30$ [GeV] to obtain specific 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 III. Cut thresholds to apply to MET assuming fixed dijet $E_\perp > 20$ [GeV] to obtain specific L1 rates forced instant luminosity of $7e33$ and $< PU >= 32$

$p_\perp(jj)$ [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 IV. Cut thresholds to apply to dijet $E_\perp$ assuming fixed dijet $MET > 30$ [GeV] to obtain specific L1 rates forced instant luminosity of $7e33$ and $< PU >= 32$

rithm to be used in the 2012 proton run. 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 $\Delta\eta_{jj} > 3$. A possible additional cut was also studied: a restriction on $\Delta\phi_{jj}$, and tested points were not cut, < 2.5, < 2.1 and < 1.8. For the conditions expected at this point for early 2012 (i.e. instant luminosity of $5e33$ and $< PU >= 28$) two tables were produced reporting the cuts necessary to achieve a given rate threshold, one assuming fixed dijet $E_\perp$ cut and varying MET (table I) and another assuming fixed MET cut and varying $E_\perp$ (table II).

Results were used to define working points for this trigger, which were already proposed to the Trigger Studies Group to be included on future L1 Trigger Menus. Proposed trigger options 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 in tables III and IV.

4. Inclusive Higgs trigger

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

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

This trigger can also be used for a WW scattering analysis, aimed at standard model without a new symmetry breaking mechanism exclusion, since the signature is similar.

For such a trigger to work it would have to be based only on the forward dijet which is the defining characteristic of the VBF signature. It was decided to study two variables of the dijet system: invariant mass and transverse invariant mass (MT); and an event variable, scalar sum of the hadronic energy (HT). For this study we always require a dijet with $\Delta\eta > 3$ and we look at the effects of an additional cut on $\Delta\phi$, the points tested were no cut, < 2.5, < 2.1 and < 1.8.

5. Dijet 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; according to trigger experts it is in principle possible to implement with the current hardware.

Unfortunately, using this variable alone to is not enough. To get acceptable rates we would need to cut too high on jet $p_\perp$ or M_{Inv} losing almost all signal efficiency.

6. *Dijet transverse invariant mass*

This variable is better at suppressing QCD events, it is less pileup-dependent and has lower error associated with it (only x-y dependence). It is also not yet implemented on the L1 Hardware but according to trigger experts it is in principle possible to implement with the current hardware.

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).

7. *Event 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 shown 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 Figures 8 and 9).

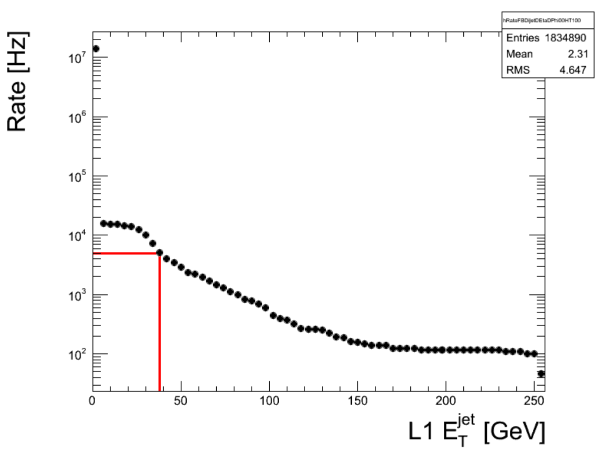

Figure 8. Level 1 rate as a function of dijet $p_\perp$ while selecting events with $HT > 100$ GeV. Results based on data from the high pileup special run taken late 2011.

C. Study of variables for QCD suppression

One of the most difficult background to estimate in the VBF Higgs to invisible analysis is QCD. This is mostly due to the lack of Monte Carlo sample statistics which are very difficult to produce because of the enormous quantity of events necessary to replicate enough signal like QCD.

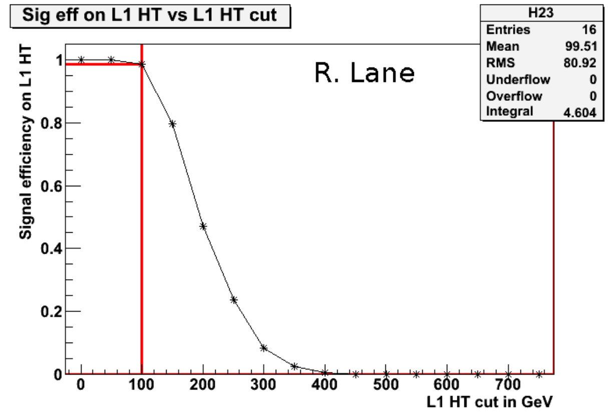

Figure 9. Higgs to $\tau\bar{\tau}$ signal efficiency as a function of HT cut extracted from monte carlo simulation. Result from R. Lane.

A possible approach is to try to reduce QCD levels where it can be considered negligible. In an attempt to use this approach we started to look for possible new variables that with a minimal signal impact would reduce QCD event yields by several orders of magnitude.

Three new variables were studied which try to exploit the correlations of the dijet plus MET system: Scalar Tri-Object Sum, Dijet pT fraction and Vector Tri-Object Sum.

1. *Scalar Tri-Object Sum*

This variable is defined as $|pT(jet1)| + |pT(jet2)| + |MET|$ which is similar to HT but only applied to our objects of interest. This implies that the higher it is, the better the average relative object resolution. This variable can also be used to relax constraints on individual object while still enforcing a global minimum transverse energy of the combined system.

2. *Dijet p_T fraction*

This variable is defined as $p_T(dijet)/(p_T(dijet) + MET)$. It reflects the balance of the dijet plus MET system. For signal it should peak strongly around 0.5 while this should not be the case for QCD in the case MET is faked.

3. *Vector Tri-Object Sum*

This variable is defined as $|VectorSum(pT(jet1) + pT(jet2) + MET)|$. It also reflects the balance of the dijet plus MET system. In this case, value of the variable for signal should concentrate around zero with the spread defined by the jet and MET resolution. The possibility of using jet and MET resolution as an input to this variable is being studied.

4. *Combining variable*

Based on the method of some CMS SUSY analysis that use an HT cut in conjunction with the α_T variables, a study was performed to evaluate the possibility of combining the scalar tri-object sum with each of dijet plus MET variables. Two dimensional plots for the signal monte carlo after the MET cut on the official VBF to invisible analysis can be seen in fig 10 for dijet p_T fraction versus scalar tri-Object sum and fig 11 for vector tri-object sum versus scalar tri-object sum.

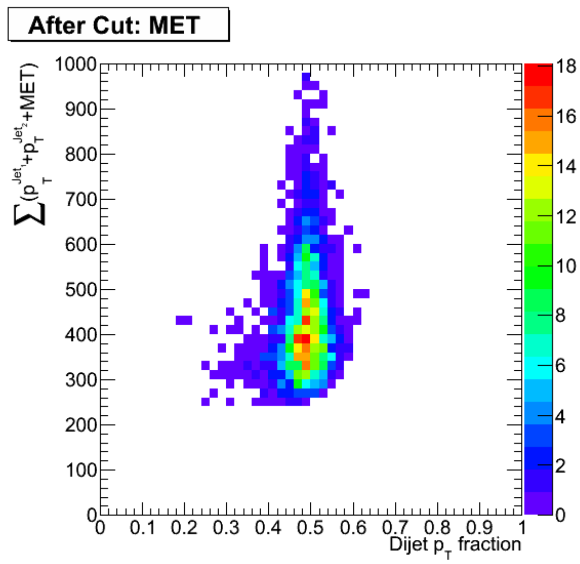

Figure 10. Plot of dijet p_T fraction versus scalar tri-object sum for signal monte carlos $m_H = 120$ GeV after the MET cut of the official VBF to invisible analysis.

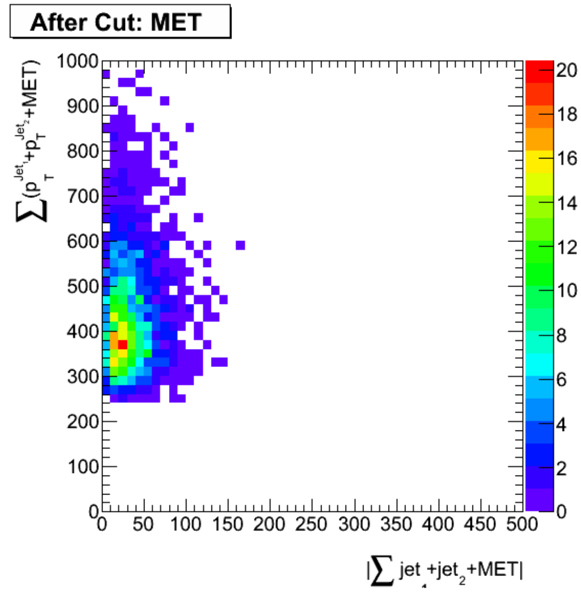

Figure 11. Plot of vector tri-object sum versus scalar tri-object sum for signal monte carlos $m_H = 120$ GeV after the MET cut of the official VBF to invisible analysis.

Preliminary studies show that by defining a 2D cut on these pairs of variables could yield a reduction of a factor of 2.5 on QCD, Z+Jet and W+Jets with a signal loss of less than 30%.

These studies may prove especially valuable for use in parked data, since by applying constraints on this type of system variables we may be able to relax cut on jet p_T and MET and therefore increase signal yield making use of the lower trigger thresholds for these individual objects, while keeping or even improving signal to background ratio.

IV. SERVICE WORK

At the CMS collaboration one of the requirements of authorship is to provide a given amount of *service work* for the experiment. It is possible to do service work in several ways, from providing direct contribution to the operation of the experiment to developing hardware upgrades to future implementation on the experiment itself.

My service work for 2012 and 2103 is being done in three ways: by doing central shifts, coordination of the L1 tigger data quality monitoring group and finally, development of monitoring tools for the L1.

A. Central shifts

The shifts taken were week long in the role of level 1 trigger detector on call (L1T DoC). This is the on call contact person for the L1 trigger, who is responsible for supporting the online operation of this subsystem. In the case of any problem arising in the trigger systems, the L1T DoC provides expertise to solve the issue or passes the information to the relevant experts.

B. L1 trigger data quality monitoring

Before I started my PhD at Imperial College, I worked as a developer for the level 1 trigger data quality monitoring (L1T DQM). Building upon this previous experience I took over the coordination of the central L1T DQM software starting June 2012. This role involves coordinating the L1T DQM developers in all the stages of the software cycle of the L1TDQM cycle, from planning to deprecation. I am also the contact person for the L1 trigger system on the CMS monitoring upgrade taskforce.

1. *Development of Monitoring for L1 Trigger System*

Continuing the work I developed before the start of my PhD, I have maintained or updated some of the tools used to monitor the online running and data quality certification of the L1 Trigger, and even created some new monitoring tools at the request of the L1 trigger management.

The developed tools monitor the several aspects of the L1 trigger operation:

- Rate: by comparing current rates with fits from previous runs using instantaneous luminosity as the independent variable.

- Synchronization: by comparing when the L1 trigger fires against the LHC bunch structure.

- Occupancy: by using detector symmetry we are able to detect dead or hot areas on the system.

- BPTX: the Beam Pickup for Timing for the eXperiments monitoring (BPTX) is used to veto events of the trigger and therefore its monitoring is necessary, similarly to the synchronization tools we compare it to the LHC bunch structure.

- : Summary plots: several summary plots are automatically made to allow the online shifter of certification expert to quickly find problems and their reasons.

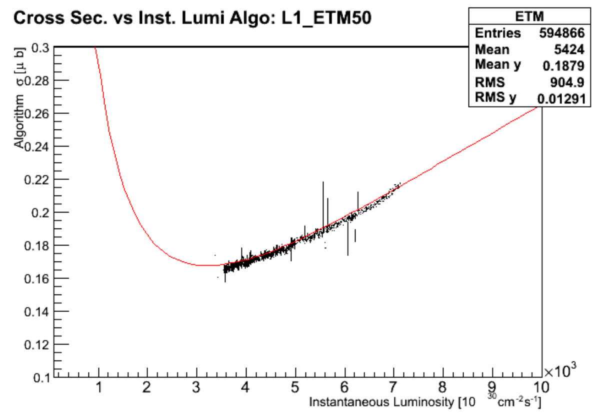

Figure 12. Monitoring plot produced by the L1TRate tool for L1 E_T^{miss} object category, which is automatically monitoring algorithm L1_ETM50 for the run 207099. In the plots data points are the calculated trigger cross section as a function of instant luminosity and the line is the reference fit done from previous runs.

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