STRATEGY FOR AN EARLY OBSERVATION OF THE ZZ$^{(*)}$ DI-BOSON PRODUCTION IN FOUR-LEPTON FINAL STATES

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The study of the production of two Z bosons at the TeV scale constitutes an important test of the Standard Model and it is a necessary step towards the discovery of new physics and new particles like the Higgs boson. We investigate the CMS potential for the observation and study of pp $\to$ ZZ $\to 4\ell$ reaction at LHC centre of mass energies, using fully simulated signal and background samples. It is shown that these processes are accessible with early CMS data. Data driven methods are developed for the background determination.

1 Introduction

The measurement of the ZZ di-boson production at the LHC is fundamental in the physics program of the CMS experiment [1]. Many signals of new physics beyond the Standard Model (SM) can show as enhancements in the ZZ production. Moreover, the pp $\to$ ZZ $\to 4\ell$ ($\ell = e, \mu$) process is the main irreducible background in searches for the SM Higgs boson via its "golden" decay mode, H $\to$ ZZ$^{(*)} \to 4\ell$. Thus an early observation of the ZZ $\to 4\ell$ process is an important step towards the discovery of the Higgs boson.

With the same analysis developed in CMS for the H $\to$ ZZ$^{(*)} \to 4\ell$ channel [2], also the ZZ $\to 4\ell$ cross section can be directly measured with the very first data. In order to be more suitable for first data, some of the criteria used in the original analysis need to be simplified.

The analysis has been developed using fully simulated signal and background samples at the nominal LHC centre of mass energy of 14 TeV. Methods for the measurement of backgrounds and for the estimation of systematic uncertainties from data have also been investigated. In the following sections, the general strategy will be outlined starting from the original Higgs analysis. The results and plots shown are also taken from the Higgs analysis, to underline the similar kinematics of Higgs and ZZ signals. In the last section, the expected signal significance is obtained for an integrated luminosity of 1 fb^{-1}, but projections for lower luminosities and for centre of mass energies of 10 and 7 TeV are also provided.

2 Signal and background

Dedicated signal and background samples have been produced using different Monte Carlo generators (PYTHIA [3] and CompHEP [4] for 14 TeV analysis, MadGraph [5] and PYTHIA for analyses at lower energies). The ZZ signal is simulated at leading order (LO) via $qq \rightarrow$ ZZ process, then normalised to next-to-leading order (NLO) with a mass dependent k-factor. A further 20% enhancement is introduced to take into account the $gg \rightarrow$ ZZ mode. The main backgrounds, $t\bar{t}$ and Z$b\bar{b}$, plus a large variety of electroweak and QCD processes (Z+jets, W+jets, multi-jet events) are simulated at LO and brought to NLO using constant k-factors.

3 Trigger, skimming and pre-selection

The trigger and the preliminary off-line selection steps are in common with the Higgs analysis [2].

The *trigger* selection of signal events is ensured by the presence of at least one or two high p_T leptons in the final state. Several High Level Trigger (HLT) sequences for electrons and muons are combined with a logical OR, in order to maximise the signal efficiency: single and double muon/electron triggers, with or without isolation requirements.

A *skimming* is applied to the primary data streams emerging from the HLT in order to reduce the total amount of data, dominated by QCD events, to a more manageable volume. The skimming selection requires at least two leptons with $p_T > 10$ GeV/c and one additional lepton with $p_T > 5$ GeV/c.

A set of *pre-selection* cuts is applied to suppress the contribution from "fake leptons". The goal is to bring the QCD multi-jets and Z/W+jets contributions to a level comparable to or below the contribution of the main backgrounds. The pre-selection consists of cuts on the p_T of leptons and invariant mass of 2-lepton and 4-lepton combinations.

Fig. 1 (*left*) shows the expected number of remaining events after each trigger, skimming and pre-selection step in $4e$ final state. All the backgrounds are reduced by several orders of magnitude and the QCD is almost totally suppressed. Also the ZZ signal is reduced by two orders of magnitude, due to the rejection of off-shell Z bosons and photons.

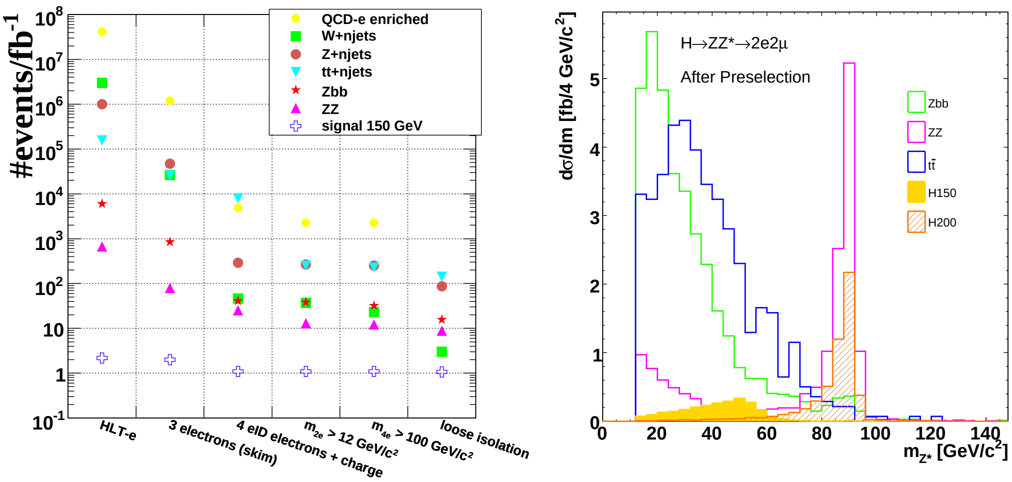

Figure 1: (*left*) number of remaining events after trigger, skimming and pre-selection cuts in the $4e$ channel and (*right*) invariant mass of the second lepton pair (the further from nominal Z mass) in $2e2\mu$ channel.

4 Analysis selection

After the pre-selection, the remaining background is dominated by $t\bar{t}$ and $Zb\bar{b}$, plus Z+jets in the $4e$ channel.

To discriminate against these processes, the invariant mass of both lepton pairs is required to be consistent with the nominal Z mass. This cut also rejects the residual contribution from off-shell Z bosons (Fig. 1 *right*).

In all the backgrounds, two leptons are produced inside jets and are thus expected not to be isolated. An *isolation variable* is then defined combining the momenta of the tracks and the energy of the calorimetric deposits inside a cone surrounding the lepton. The two least isolated leptons can be used to select signal events (Fig. 2 *left*). With the first data, this variable can be simplified by using only the track based isolation.

In $t\bar{t}$ and $Zb\bar{b}$ processes, the leptons coming from b-jets are expected to have a higher *impact parameter* (IP) compared to the primary muons from Z decay. The IP significance ($S_{IP} = IP/\sigma_{IP}$) is thus used to further reduce these backgrounds (Fig. 2 *right*).

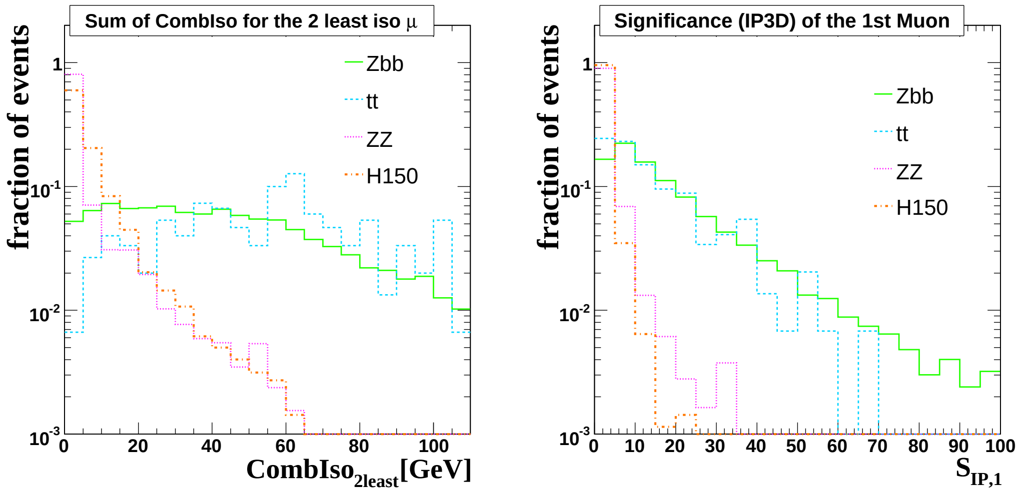

Figure 2: (*left*) sum of the isolation variables of the two least isolated leptons and (*right*) IP significance of the first (i.e. highest S_{IP}) lepton in the 4μ channel.

After the previous cuts, mostly the $Zb\bar{b}$ background is left, in particular in 4μ and $2e2\mu$ channels. The bidimensional distribution of the isolation variable versus the p_T of the third or forth lepton (sorted by decreasing p_T) shows an excellent separation between signal and $Zb\bar{b}$ background (Fig. 3). This distribution can be used both as a selection cut and to provide a signal-free region where the $Zb\bar{b}$ background can be measured directly from data. Using Monte Carlo simulations, the measurement in this control region can be extrapolated to the signal region to estimate the remaining contamination. With the first data, when the systematics and correlations between the different observables are not fully understood yet, the bidimensional cut can be replaced by a sequence of separate cuts on each observable, with little significance loss.

5 Conclusions

Applying the described analysis, with a realistic estimation of the systematic uncertainties, an observation of $ZZ \rightarrow 4\ell$ can be expected with about 130 pb^{-1} at a centre of mass energy of 14 TeV.

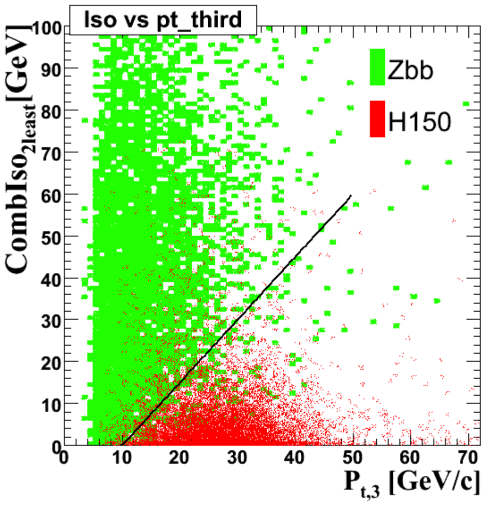

Figure 3: Isolation variable *vs* p_T of the third lepton (sorted by decreasing p_T) in the 4μ final state. Here an example of Higgs signal is shown in red, but the distribution for the ZZ signal is very similar.

For lower energies, an approximate projection can be obtained by simply rescaling the significance with the signal and background cross sections. In such a way, at 10 and 7 TeV, observations can be foreseen with about 190 and 300 pb^{-1} respectively.

Acknowledgments

The author would like to thank Laura Nervo and Chiara Mariotti for their active participation in preparing this paper and the related presentation; Juan Alcaraz, Michael Schmitt and Gautier Hamel De Monchenault for their useful corrections; Martijn Mulders for his suggestions about the talk.

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