Vector Boson Fusion at CMS

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Abstract
The processes of boson-boson scattering and of Higgs production in boson-boson fusion hold the key to electroweak symmetry breaking. A preliminary study has been performed using a fast simulation of the CMS detector. The results are encouraging and suggest that, after few years of data taking at LHC, the region above 1 TeV can be explored, which is interesting if the Higgs is not found.

1 Vector Boson Fusion at CMS

1.1 Introduction

The Standard Model predicts that, without the Higgs boson, the scattering amplitude of the *longitudinally polarized vector boson* (V_L) fusion process violates unitarity at about 1-1.5 TeV. The longitudinal polarization of the *V* arises from the *V* getting massive, i.e. when the symmetry breaks spontaneously. The cross section as a function of the $V_L V_L$ invariant mass will show a resonance at M($V_L V_L$)=M(H) if the Higgs is there; otherwise, the cross section will deviate from the Standard Model prediction at high values of M(VV). Therefore, *VV* scattering can probe the Electroweak Symmetry Breaking with or without the assumption the Higgs mechanism.

1.2 The Signal Selection

Two channels have been studied using *Pythia* [1] and the *CMS Fast Simulation* [2]:

- $pp \to \mu\mu jjjj$ [3] through the processes:
  - $pp \to V_L V_L jj \to Z_L Z_L jj \to \mu\mu jjjj$,
  - $pp \to Z_L W_L jj \to Z_L W_L jj \to \mu\mu jjjj$.
- $pp \to \mu\nu jjjj$ [4] through the process:
  - $pp \to V_L V_L jj \to W_L W_L jj \to \mu\nu jjjj$.

The study has been done for high Higgs masses: $m_H = 500$ GeV and $m_H = 1000$ GeV, and for the no-Higgs scenario. The latter has been simulated in Pythia by setting $m_H = 10000$ GeV (the Higgs exchange diagram is suppressed by a m_H^2 term in the denominator of the Higgs propagator). The cross sections of the signal processes are shown in Table 1.

Table 1: Signal cross section (in fb) for different Higgs masses.

Processes	$m_H = 500$ GeV	$m_H = 1000$ GeV	$m_H = 10\,000$ GeV
$pp \to Z_L Z_L jj \to \mu\mu jjjj$	9.1	3.0	1.7
$pp \to Z_L W_L jj \to \mu\mu jjjj$	0.7	1.0	1.5
$pp \to W_L W_L jj \to \mu\nu jjjj$	64.4	26.9	19.7

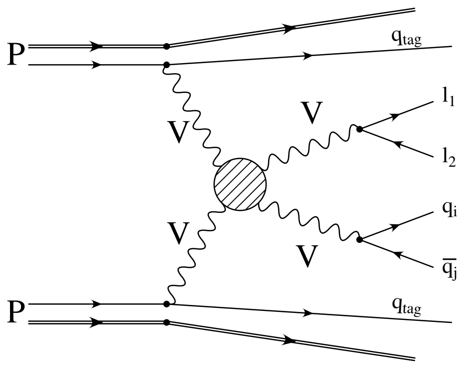

Fig. 1: The signal topology. l_1 and l_2 can be $\mu^{\pm}$ or μ and ν.

The signal has a well defined topology (see Figure 1):

- one μ^+ and one μ^- (or one μ and one ν) in the final state, with high p_T and low η coming from the *Z* (*W*) boson;
- two jets with high p_T and low η, coming from the vector boson decay;
- two energetic jets with high p_T, in the forward-backward regions (large η and $\Delta\eta$).

The aim of the work is to reconstruct the invariant mass of the *VV*-fusion system in both the channels and estimate its resolution. We also attempted a first estimate of the signal to background ratio assuming that the main background processes are:

- $t\bar{t}$ *background*: a six fermion final state, like the signal, but the jets are mainly in the central region; therefore, by requiring two jets at high η and with a large $\Delta\eta$ between them this kind of background can be rejected.
- *VV associated production*: a four fermion final state; it needs however to be kept under control in the case in which one boson decays leptonically since there are several jets from gluon radiation in the final state. The most effective variables to distinguish this background from the signal are the transverse momenta of the jets and of the leptons.
- *V plus one and two hard jets*: it is simple to reject this background because it has a topology not very similar to that of the signal and the additional jets have a very low p_T (since they are generated by the parton shower). However it is fundamental to keep it under control since it has a very large cross section.

The cross section of the background processes are shown in Table 2.

Table 2: Background cross section (in fb).

Background	Cross Section [fb]	**Background**	Cross Section [fb]
$t\bar{t}$, 1 μ	$622 \cdot 10^3$	$t\bar{t}$, 1 μ^- and 1 μ^+	$620 \cdot 10^3$
$ZZ \to \mu^-\mu^+jj$	653	$ZW \to \mu^-\mu^+jj$	663
$WW \to \mu\nu^+jj$	$11 \cdot 10^3$	$W + jj \to \mu\nu jj$	$77 \cdot 10^3$
$Z + jet \to \mu^-\mu^+j$	$13 \cdot 10^6$	$W + j \to \mu\nu j$	$184 \cdot 10^6$

1.3 The Results

A set of cuts has been applied to enhance the signal with respect to the background. A good resolution (estimated using MC info) on the most important observables has been achieved. In particular:

– $Z \rightarrow \mu\mu$ invariant mass: $R_z \sim 1.5\%$;
– $V \rightarrow jj$ invariant mass, $\mu\mu jjjj$ channel: $R_v \sim 13\%$;
– $V \rightarrow jj$ invariant mass, $\mu\nu jjjj$ channel: $R_v \sim 10\%$.

The difference between the two latter resolutions reflects the fact that for the $jjjj\mu\mu$ channel the pile-up has been considered whereas in the $jjjj\mu\nu$ it was not. The resolution on the energy scale of the process ($M_{inv}(VV)$) is:

– 4% for the $pp \rightarrow \mu\mu jjjj$ channel;
– 8% for the $pp \rightarrow \mu\nu jjjj$ channel.

The difference is due to the worse resolution on the neutrino p_T and p_z reconstruction. The resulting background efficiency is lower than one percent while the signal efficiency reaches 30% for the $jjjj\mu\mu$ channel and 50% for the $jjjj\mu\nu$ channel. A high significance ($S/\sqrt{B}$) has been achieved for an integrated luminosity of $100 fb^{-1}$: for the $\mu\mu jjjj$ samples it is about 8 in the interval $M_{inv}^{VV} \in [0, 1]$ TeV for the Higgs mass set to 500 GeV and about 10 for $M_{inv}^{VV} > 1$ TeV for the no-Higgs scenario. Similar values have been obtained for the $\mu\nu jjjj$ channel: a significance of about 5, in the interval $M_{inv}^{VV} \in [0, 1]$ TeV, for the Higgs mass set to 500 GeV and about 2.4 in the interval $M_{inv}^{VV} > 1$ TeV for the no-Higgs scenario. In Figs. 2 (no-Higgs scenario) and 3 ($m_H = 500$ GeV) the number of reconstructed events and the selection efficiency as a function of the *VV* invariant mass are shown.

1.4 Future Plans

Further studies are in progress, since for those presented here the Pythia generator was used, which only simulates a subset of the relavant diagrams, and cannot simulate the full set of background processes (notably not the scattering of transversely polarised vector bosons). To better describe the signal (and the background as well) a *Matrix Element Monte Carlo* must be used. *Phase* [5] is the best candidate, since it simulates all processes that lead to a six fermion final state, at order α_{QED}^6. Up to now only the channel $pp \rightarrow \mu\nu jjjj$ has been computed; therefore for the the $\mu\mu jjjj$ final state the *MadGraph* [6] event generator was used. This can simulate the $2l4j$ final state through the production (in Narrow Width Approximation) of intermediate vector bosons and their subsequent semileptonic decay.

Moreover it is crucial to redo the analysis, processing the events through the *Full Simulation* [7] of the CMS detector in order to properly take into account the detector resolution.

1.5 Summary

In conclusion, Electroweak Symmetry Breaking can be probed through the fusion of longitudinally polarized vector bosons with the CMS detector at LHC. The signal reconstruction and the background rejection algorithms have been successfully tested with the Fast Simulation. In the near future the study will be repeated with the Full Simulation of the detector and with dedicated generators.

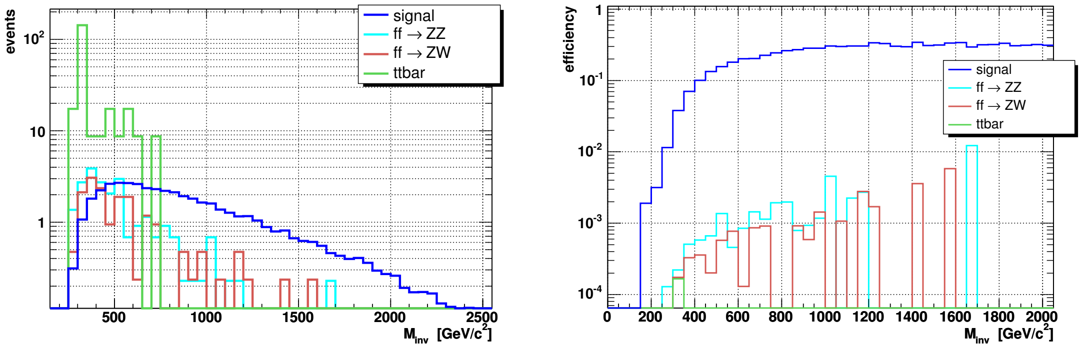

Fig. 2: (Left) Number of reconstructed events as a function of the *VV* invariant mass and (Right) the selection efficiency as a function of the invariant mass of the VV-fusion process; both for the $\mu\mu jjjj$ final state in the no-Higgs scenario and an integrated luminosity of 100 fb^{-1}.

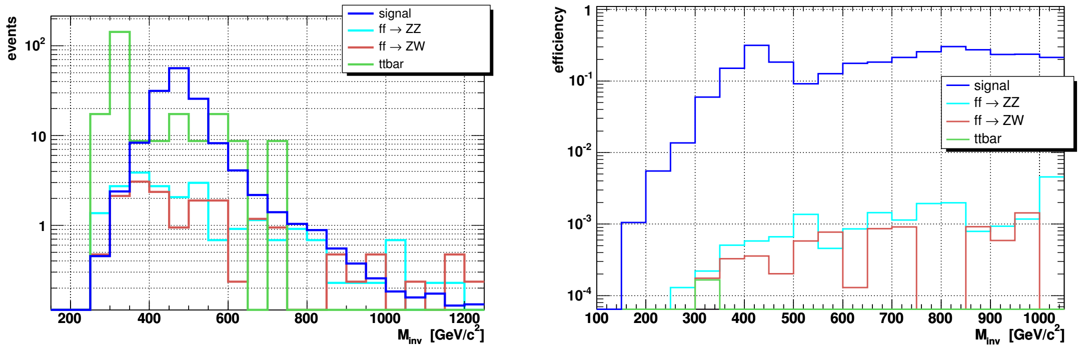

Fig. 3: (Left) Number of reconstructed events as a function of the *VV* invariant mass and (Right) the selection efficiency as a function of the invariant mass of the VV-fusion process; both for the $\mu\mu jjjj$ final state for $m_H =$ 500 GeV and an integrated luminosity of 100 fb^{-1}.

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