Vector Boson Fusion Production of the Standard Model Higgs at the LHC

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The cross section measurements of the Higgs boson production in the vector boson fusion (VBF) process at the LHC followed by a Higgs boson decay into $\tau\tau$, $WW$ and $\gamma\gamma$ will significantly extend the possibility of Higgs boson coupling measurements. Prospective analyses with the CMS experiment are discussed for the $H \rightarrow \gamma\gamma$, $WW$ and $\tau\tau$ decay channels for an integrated LHC luminosity of 30 fb$^{-1}$. For a Higgs boson mass in the range 115 to 140 GeV, an observation with a significance above 2 standard deviations is expected in the $H \rightarrow \gamma\gamma$ channel, and above 3 standard deviations in the $H \rightarrow \tau\tau$ channel. The $H \rightarrow WW$ channel offers a discovery reach above 5 sigma in the mass range 140 to 200 GeV. A new complete strategy is presented for the control of systematics and early searches at very low luminosities of the order of 1 fb$^{-1}$. 

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1. Introduction

Vector Boson Fusion (VBF) Higgs boson production is the second largest production mechanism at the LHC. The cross section measurements of the VBF process, $VV \rightarrow H$ ($qq \rightarrow qqH$), followed by Higgs boson decays into $\tau\tau$, $WW$ and $\gamma\gamma$ will significantly extend the possibility of Higgs boson coupling measurements [1, 2].

2. Vector Boson Fusion Signature

Events produced by VBF are characterized by a distinct topology of the final state: two forward jets with little extra hadronic activity and the decay products of the Higgs boson. The rapidity distribution of the 3rd jet with respect to the two forward jets, $\eta_{j3}$, is shown in Fig. 1 (left) which shows a double-peak structure for the electroweak processes, including the VBF signal, and is more central for the QCD background samples. Applying a central jet veto (CJV) is a powerful rejection method against the QCD background. To avoid considering jets from pile-up events in the CJV, jets are associated to the signal vertex using tracks. For every extra jet one can define the quantity $\alpha_{j3} = \sum p_T^{trk}/E_T^{j3}$, where $p_T^{trk}$ is the $p_T$ of tracks from the signal vertex within the jet cone and $E_T^{j3}$ is the jet measured raw $E_T$. Figure 1 (right) shows $\alpha_{j3}$ tends to peak at low values for non-signal jets. The efficiency of the veto for the background samples versus the signal efficiency is shown in Figure 2 (left) for events containing a 3rd jet with $E_T$ larger than different threshold values. An optimal threshold where the signal process has $\sim$80% efficiency while the backgrounds are suppressed below 50% is used [3]. An alternative approach is to consider a track counting veto (TCV) [4], where the number of tracks between the two leading jets is counted with different $p_T$ thresholds. Figure 2 (right) shows the performance of the TCV algorithm, i.e. the efficiency of selecting the signal versus the background for events with an increasing cut on the track multiplicity and $p_T$. The black star indicates the performance of the CJV based on calorimeter jets. The TCV algorithm can reach similar discrimination power than the central jet veto.

Figure 1: The $\eta$ distribution of the 3rd jet with respect to the two forward jets (left). The distribution of $\alpha_{j3}$ which is used to match jets to the signal vertex (right).
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3. Vector Boson Fusion Higgs Discovery Potential

The observability of the VBF Higgs boson production has been studied with the full CMS detector simulation in the $H \rightarrow \tau\tau$, $\gamma\gamma$ and $WW$ decay channels [5]. VBF $H \rightarrow \tau\tau$ production has been studied in the Higgs mass range of 115 to 145 GeV in the lepton plus $\tau$jet final state. Figure 3 (left) shows the expected di-$\tau$ mass distribution using the collinear approximation [3] for a luminosity of 30 fb$^{-1}$. Figure 3 (right) shows the significance of the expected number of signal events for different Higgs masses. A statistical signal significance of 3.9$\sigma$ is expected for a Higgs mass of 135 GeV.

| $M_H$ [GeV] | 115 | 125 | 135 | 145 |
|-------------|-----|-----|-----|-----|
| $N_S$ (30 fb$^{-1}$) | 10.47 | 7.79 | 7.94 | 3.63 |
| $N_B$ (30 fb$^{-1}$) | 3.70 | 2.21 | 1.84 | 1.42 |
| $S_{CP}$ at 30 fb$^{-1}$ (no uncertainty) | 4.04 | 3.71 | 3.98 | 2.19 |
| $S_{CP}$ at 30 fb$^{-1}$ ($\sigma_B = 7.8\%$) | 3.97 | 3.67 | 3.94 | 2.18 |
| $S_{CP}$ at 60 fb$^{-1}$ ($\sigma_B = 5.9\%$) | 5.67 | 5.26 | 5.64 | 3.19 |

VBF $H \rightarrow WW$ production in the lepton plus two jet final state has been studied in the Higgs mass range between 120 and 250 GeV. Figure 4 (left) shows the signal significance expected with 30 fb$^{-1}$ for different central jet veto selections [6]. In the mass range between 140-200 GeV a 5$\sigma$ significance can be achieved. VBF $H \rightarrow \gamma\gamma$ production has also been studied in the Higgs mass range between 115 and 150 GeV [7]. Figure 4 (right) shows the signal significance expected with 30 and 60 fb$^{-1}$. With 60 fb$^{-1}$ of collected data a 3$\sigma$ significance can be achieved for a low mass Higgs in the range 115 to 130 GeV.
4. Search of Higgs → ττ → lepton + τjet with 1 fb⁻¹

A selection strategy for the search of VBF Higgs → ττ → lepton + τjet with 1 fb⁻¹ has been developed and is described in detail in [8]. The di-τ invariant mass will be analyzed to search for the presence of a Higgs boson in the region above the Z → ττ mass peak. It is important to know well the shape of the Z → ττ background. The dominant uncertainty comes from the modeling of the missing transverse momentum related to the effects of pile-up, underlying event and the calorimeter noise and response. A method to model the di-τ mass has been developed [4]. Z → μμ data events are selected and the muons are removed from the real event. Di-τ Monte Carlo events are generated with the same kinematics as the real muons and their detector response is fully simulated. Finally the real Z → μμ events with the muons removed and the simulated di-τ events are super-imposed to form one event, Z → μμττ, and the di-τ mass is calculated. The reconstructed di-τ mass for real and fake Z → ττ events for inclusive Drell-Yan and Z+jets events are shown in Fig. 5. A good agreement between the di-τ mass shapes is obtained.

The expected di-τ mass distribution for the background and the Higgs signal for 1 fb⁻¹ is shown in Fig. 6 (left). A profile likelihood method is used to evaluate the upper limit on the number of signal events. Figure 6 (right) shows the expected 95% CL limit on the cross section times branching ratio as a function of the Higgs boson mass.

Figure 4: Signal significance of VBF H → WW for 30 fb⁻¹. The high (low) curves correspond to full (loose) extra jet veto (left). Signal significance of VBF H → γγ for 30 and 60 fb⁻¹ (right).

Figure 5: Reconstructed di-τ mass for real and fake Z → ττ events for the final states (left) ττ → μνν + μνν from inclusive Drell-Yan events and (right) ττ → lνν + τjetν from Z+jets events.
5. Conclusion

A selection strategy for the Standard Model Higgs boson produced in vector boson fusion decaying to a pair of τ leptons with 1 fb$^{-1}$ of early CMS data at the LHC has been presented. No signal evidence is expected and upper limit on the cross section times branching ratio is evaluated. Prospective analyses for the $H \rightarrow \gamma\gamma$, $WW$ and $\tau\tau$ decay channels for a luminosity of 30 fb$^{-1}$ have also been discussed. For a Higgs boson mass in the range 115 to 140 GeV, an observation with a significance above 2 standard deviations is expected in the $H \rightarrow \gamma\gamma$ channel, and above 3 standard deviations in the $H \rightarrow \tau\tau$ channel. The $H \rightarrow WW$ channel offers a discovery reach above 5 sigma in the mass range of 140 to 200 GeV.

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