**VV-fusion process to investigate EWSB; interplay LC-LHC**

G. Cerminara

*University and INFN Torino*

**Abstract.** The VV-fusion is a promising process to investigate the electroweak symmetry breaking (EWSB) mechanism. In fact the cross section for the scattering of longitudinally polarized vector bosons, in absence of a Higgs, violates unitarity at about 1.2 TeV. As a consequence, new physics must appear below this threshold. The LHC and the LC will be the machines which will explore the energy region where this new physics is expected. In the following the potential of the two accelerators for the study of this reaction is briefly reviewed and a preliminary study with the CMS detector at LHC is presented.

**Keywords:** VV-fusion, Electroweak Symmetry Breaking, LHC, LC

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**INTRODUCTION**

General arguments based on partial wave unitarity imply that, without a Higgs, the electroweak gauge bosons develop strong non-perturbative interactions at an energy scale of about $\sim 1.2$ TeV. Below this threshold new physics is therefore expected: in the Higgs case a resonance will be observed in the VV invariant mass spectrum at $m_H$; otherwise the cross section will deviate from the Standard Model (SM) prediction.

**Partial wave unitarity in the VV scattering**

In the SM the scattering of longitudinally polarized vector bosons, without a Higgs, violates the partial wave unitarity [1]. In fact, considering the Feynman diagrams for the W boson scattering not including the Higgs boson (Fig. 1) we would obtain a scattering amplitude

$$\mathcal{M}(L;L;L;L) \sim \sqrt{2} G_F (s + t)$$

where $t$ is the square of the four momentum transferred in the scattering process and $s$ is the square of the center of mass energy of the boson-boson system. Indeed this amplitude has a bad high energy behavior: the unitarity bound is violated at large $s$.

If we compute the amplitude for the W scattering considering also the terms from the exchange of a Higgs boson (Fig. 1) than we obtain:

$$\mathcal{M}(L;L;L;L) \sim -\sqrt{2} G_F m_H^2 \left( \frac{s}{s - m_H^2} + \frac{t}{t - m_H^2} \right).$$

The bad high energy behavior is therefore canceled for $\sqrt{s} \gg m_H$: the Higgs can remove the unitarity violation in the scattering of longitudinally polarized W bosons. If we consider the unitarity constraint in the limit $m_W^2 \leq s \leq m_H^2$ we can use eq. 2 to find the critical energy $\sqrt{s_c}$ which can be interpreted as an energy scale below which new physics, beyond the SM, must appear. This $s_c$ is the maximum value of $s$ allowed by tree-level unitarity for $m_H \rightarrow \infty$. It can be shown that this critical energy is:

$$s_c = \frac{4\pi \sqrt{2}}{G_F} = (1.2 \text{ TeV})^2.$$

For Higgs masses $m_H \gg \sqrt{s_c}$ the tree level unitarity breaks down and the effect of the Higgs boson on the scattering amplitude vanishes. This scenario is equivalent to a theory without the Higgs boson.

**VV scattering as a probe of EWSB**

The SM Higgs boson is not the only possibility for recovering tree level unitarity of scattering amplitude, nevertheless the above argument implies that a new sector of physics, associated with EWSB, must be revealed in the VV-fusion process before the threshold presented by eq. 3.

**VV-FUSION PROCESS AT LHC**

Thanks to its high center of mass energy and high luminosity the Large Hadron Collider (LHC) will be able to explore the high energy region beyond the unitarity violation threshold. The study of the VV-fusion process is therefore extremely promising: if no Higgs is found new physics is expected in this channel. If the Higgs boson exists, the study of this reaction can lead to interesting results. The fusion of longitudinally polarized vector bosons represents the second most important contribution to the cross section for the Higgs production and the WW/ZZ final state is one of the most clear signature for the Higgs decay.
A preliminary study of the VV-fusion process at CMS

An exploratory study [2, 3] has been performed in order to assess the possibility of probing the symmetry breaking mechanism through the VV-fusion process using the Compact Muon Solenoid (CMS) detector [4]. A model independent analysis was carried out with no assumptions on the mechanism restoring the unitarity in the scattering amplitude and without any degrees of freedom beyond the SM.

The analysis was focused on the semi-leptonic final state which offers a clear experimental signature, thanks to the presence of high $p_T$ leptons from the $W$ or $Z$ decays together with the highest branching ratio among the other final states which is possible to reconstruct in an hadronic environment. In particular the processes that were studied are:

$$pp \rightarrow qqWtWl + X \rightarrow qq\mu\nu qq + X,$$
$$pp \rightarrow qqZtWl + X \rightarrow qq\mu\mu qq + X,$$
$$pp \rightarrow qqZlZl + X \rightarrow qq\mu\mu qq + X.$$

In order to explore the sensitivity of the analysis method to the entire heavy Higgs mass spectrum, we analyzed Monte Carlo data sets produced using different Higgs masses: $m_H = 500$ GeV, $m_H = 750$ GeV and $m_H = 1000$ GeV. Moreover, we generated a sample with very high Higgs mass ($m_H = 10000$ GeV) which approximates the no-Higgs scenario and allows therefore to consider the VV-fusion cross section in a region where no resonance is present.

All the samples for this preliminary study were generated using PYTHIA [5] and the cross sections after minimal acceptance cuts are shown in Table 1.

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>$m_H = 500$ GeV</th>
<th>$m_H = 1000$ GeV</th>
<th>No Higgs case</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{pp\rightarrow qqWtWl}$</td>
<td>64.4</td>
<td>26.9</td>
<td>19.7</td>
</tr>
<tr>
<td>$\sigma_{pp\rightarrow qqZtWl}$</td>
<td>0.7</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>$\sigma_{pp\rightarrow qqZlZl}$</td>
<td>9.1</td>
<td>3.0</td>
<td>1.7</td>
</tr>
</tbody>
</table>

The signal topology (Fig. 2) is characterized by a six fermion final state; the four fermions from the $VV$ decay and the two quarks which radiated the vector bosons. These spectator quarks are scattered predominantly in the high pseudorapidity region and their presence is essential to tag the VV-fusion events (Fig. 3).

The most difficult backgrounds to the scattering of longitudinally polarized $V$ bosons are given by processes of the type: $pp \rightarrow VtVt + X$ and $pp \rightarrow VtVt + X$ with at least one of the two bosons transversely polarized. Contributions to these processes come from the scattering of transversally polarized vector bosons and from processes where the $V$ bosons are emitted by interacting quark lines. At the time of the preliminary work presented here, no appropriate generator was available to simulate the scattering of transverse bosons. Therefore only the production of unpolarized $WW$ and $ZZ$ pairs coming from quark anti-quark annihilation was considered. Also the production of $t\bar{t}$ pairs represents a difficult background; the top quark decays into a $W$ boson and a $b$-quark with a branching ratio of almost 100% giving a final state similar to that produced in VV-fusion events. Also the production of a vector boson in association with a pair of jets has been simulated. In fact this process, although it has a topology quite different from that of the signal, has a huge cross section which must be kept under control.

**Preliminary results**

The main goal of this exploratory study was to investigate the feasibility of the measurement of the VV-fusion...
cross section at CMS. A good sensitivity to all heavy Higgs mass resonances is achieved and also in the no Higgs scenario the $VV$ invariant mass spectrum is pretty well reconstructed (Fig. 4). A good reconstruction efficiency for the region of high $VV$ invariant masses is achieved, as shown in Fig. 5.

Thanks to this reconstruction efficiency the number of events obtained at the end of the selection is quite promising being about 120 events with $M_{WW} > 1$TeV for the $pp \rightarrow q\bar{q}WW \rightarrow q\bar{q}\mu\bar{\nu}qq + X$ channel (No Higgs) after 100fb$^{-1}$ of integrated luminosity. For the ZZ final state the efficiency at high invariant masses is about 35% and the number of expected events with $M_{ZZ} > 1$TeV is around 20. Also the signal-to-background ratio appears to be encouraging at high invariant masses. However it is worth remembering that the exact estimation of this quantity was far from being the main aim of the study. In fact at this stage only a limited set of backgrounds was considered and important irreducible processes were still missing.

**MC generators for six fermion final states and $VV$-fusion processes**

In order to explore the EWSB with the study of the $VV$-fusion process a precise knowledge of the cross section $\sigma_{VV}$ on the whole spectrum of $M_{VV}$ is essential. The choice of the MC generator to be used for the simulation is therefore a key aspect for this study. Results presented in the previous section were obtained using PYTHIA event generator. PYTHIA is a parton shower code which uses the Effective Vector Boson Approximation (EVBA)[7, 8] to compute the cross section for $VV$ scattering processes. In this approximation the $V$ bosons are treated as on-shell partons in the quarks: the fermion-fermion cross section is written as a product of the distri-
bution function of the vector boson inside the quark and the cross section for on-shell $VV$ scattering. Moreover PYTHIA can not simulate the scattering of transverse vector bosons which is the most important irreducible background.

Recently a new matrix element event generator was made available for this kind of studies: PHASE [9], a MC dedicated to SM processes with six fermions in the final state at the LHC. PHASE uses exact leading order matrix elements for the generation of unweighted events. Studies of the $VV$-fusion at CMS show important differences in the cross sections for the signal with respect to PYTHIA. PHASE also allows a more realistic background treatment since it can generate most of the irreducible backgrounds that were not available in the studies presented in the previous paragraph.

**VV-FUSION PROCESS AT LC**

A Linear Collider (LC) with a center of mass energy $\sqrt{s} = 500\text{GeV}$ or $\sqrt{s} = 1000\text{GeV}$ would be a powerful machine to investigate EWSB in $VV$ scattering. Even if no resonance will be observed in that energy range a precise analysis of the rising of the scattering processes in the sub-threshold region will significantly add information to data obtained at LHC.

At an $e^+ e^-$ collider the relevant processes are:

$$e^+ e^- \rightarrow \nu \bar{\nu} WW \rightarrow \nu \bar{\nu} VV,$$
$$e^+ e^- \rightarrow e^+ e^- ZZ \rightarrow e^+ e^- VV.$$  

All the possible $W$ and $Z$ decay channels (exception made for $Z \rightarrow \nu \bar{\nu}$) can be detected and the experimental environment of an $e^+ e^-$ collider will allow better signal to background ratio than at the LHC. Other clear experimetal advantages with respect to $pp$ machines will be the fact that the initial four-momenta of the interacting particles will not depend on the proton PDFs. Furthermore it will be possible to enhance the cross sections of all process involving $WW$ scattering polarizing the initial beams.

From the reactions mentioned above it will be possible to obtain informations about the anomalous couplings $\alpha_{4,5,6,7,10}$ which describe deviations form the SM in the four-point interactions of longitudinal gauge bosons in the electroweak effective Lagrangian. In particular, assuming $SU(2)$ invariance, $\alpha_4$ and $\alpha_6$ can be constrained with a better precision than what is achievable with LHC collider [10].

At the moment there is no complete study trying to combine the sensitivities of the two machines, but the LC could be important to interpret resonances in the $VV$-fusion cross section observed at LHC. For example measuring the TGC $\alpha_2$ and $\alpha_3$ at $\sqrt{s} = 500\text{GeV}$ the LC can help distinguish between vector and scalar resonances [11]; if $J = 1$ the measurement of $\alpha_2 + \alpha_3$ provides an indirect estimation of a 1TeV resonance mass with a precision of the order of the GeV. On the other side in case of a $J = 0$ resonance of $m = 1\text{TeV}$ the LC (with $\sqrt{s} = 800 - 1000\text{GeV}$) would be able to measure the mass, through the enhancement in the vector boson scattering cross section, with an accuracy of about 250GeV.

**CONCLUSIONS**

The $VV$-fusion will be an important channel to explore the EWSB especially in the case where no light Higgs boson is found. The LHC will be the machine able to explore the high energy region beyond the unitarity violation threshold. In case of new physics the LC can contribute to understand its nature and to improve the resolution on some of its parameters.

**REFERENCES**