WW Fusion in Higgsless Models

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Abstract

Recently several Higgsless models of electroweak symmetry breaking have been proposed in which
unitarity of $W, Z$ scattering amplitudes is partially restored through a tower of massive vector gauge
bosons. These massive states are expected to couple mainly to $W$ and $Z$ and should appear as resonances
in $WW$ and $WZ$ fusion at the CERN Large Hadron Collider (LHC). We study the LHC discovery reach
for the first neutral state, $V_0^1$, through the reaction $W^+W^- \rightarrow V_1^0 \rightarrow W^+W^- \rightarrow e^\pm\mu^\mp + E_T$. The
background from $t\bar{t}$, $\tau^+\tau^-$ and $W$ pair production is calculated and dual forward jet tagging as well as
a mini-jet veto in the central detector region are applied. The maximal $P_T(e, \mu)$ distribution is found
to have a fat tail for large $P_T$ that rises above the backgrounds and allows $5\sigma$ discovery for $V_0^1$ masses
above 1 TeV and total integrated luminosity of 300 fb$^{-1}$.

1 Introduction

Though the Standard Model (SM) has been very successful in explaining a range of observations at hadron
colliders and LEP, the exact mechanism for electroweak symmetry breaking (EWSB) remains a mystery.
However, in most models of new physics, a Higgs scalar is assumed to be responsible for EWSB as it also
preserves the unitarity of $WW$ and $WZ$ scattering amplitudes [1, 2].

Recently some alternative methods for EWSB have been proposed in models containing more than
4 dimensions [3] and in the so-called deconstructed theories [4]. In the extra-dimensional models, the
boundary conditions on fields in the extra dimensions result in constraints on the masses and ordering of
Kaluza Klein (KK) modes such that the lowest set of modes looks like the Standard Model. At the same
time, violation of unitarity in $WW$ and $WZ$ scattering is delayed to $\Lambda \sim 5 \sim 10$ TeV due to exchange of a
KK tower of massive vector bosons. We denote these bosons by $V_0^N$ and $V_+^N$; where $N = 0, 1, 2, ...$
represents the KK level of the state. The $N = 0$ modes are the familiar $W^\pm$ and $Z$ bosons.

Such Higgsless models initially faced serious challenges from Precision Electroweak Constraints (PEC)
as they predicted a positive $S$ parameter [5]. These issues were resolved recently in warped space Higgsless
models by fermion delocalization [6] which also results in vanishing overlap between wavefunctions of the
higher ($N > 0$) KK modes and those of the SM fermions. Hence the primary couplings of the KK vector
boson states would be between themselves and the $W, Z$ particles. Other remaining issues concern the top
quark mass, which are currently under active investigation [7] and have been resolved in some models.

As Higgsless theories have now matured into viable models of new physics at the TeV scale, it is
important to investigate their phenomenological signatures at the LHC. In this paper we concern ourselves
with $WW$ scattering where the $W$s are radiated off initial state quarks. Fig. 1(a-c) shows the $WW \rightarrow WW$
scattering diagrams involving intermediate $V_0^N$ particles. Normally, without a Higgs boson or the KK modes,
the $WW \rightarrow WW$ scattering amplitude has terms that grow as $E^2$ or $E^4$. If there is a Higgs boson, then
these terms are identically zero. However, in Higgsless extra-dimensional models, the terms are cancelled by
the KK modes provided certain identities between their masses and couplings to $W, Z$ bosons. These are:

\[ g_{WWWW} = g_{WWZ}^2 + g_{WW\gamma}^2 + \sum_{N=1}^{\infty} (g_{WWV}^N)^2 \]

and

\[ 4g_{WWWW} M_W^2 = 3g_{WWZ}^2 M_Z^2 + 3 \sum_{N=1}^{\infty} (g_{WWV}^N M_N^0)^2 \]
where \( g_{WWV}^N \) is the trilinear \( WWV_0^N \) coupling and \( M_N^0 \) is the mass of \( V_0^N \). As shown in [8], considerations of series convergence as well as a survey of Higgsless models show that the sum rules are nearly saturated by the first \( N = 1 \) mode. In that case Eqns. (1,2) reduce to

\[
g_{WWV}^1 \approx g_{WVZ} \frac{M_Z}{\sqrt{3}M_1^0} \]  

which gives us the approximate coupling of the first mode to \( W \) bosons. From Fig. 1(c) it is clear that the \( V_0^N \) should show up as resonances in pair production of \( W \)s. Also, the final state decay rate \( V_0^N \to WW \) should be close to 100\%, assuming the \( V_0^N \) decouple from SM fermions.

A similar resonance in \( WZ \to WZ \) scattering was exploited in [8] to show that the lightest \( V_1^\pm \) particles can be discovered at the LHC with masses up to 1 TeV using about 60 fb\(^{-1}\) of integrated luminosity. The purely leptonic decay of the final state \( WZ \) allows for a clean observation of the first \( V_1^\pm \) state, including mass reconstruction. The rest of the KK modes are not expected to be observable due to their heavier masses and smaller couplings to \( WZ \).

In the case of \( V_0^0 \) however, the \( WW + 2 \) forward jets final state is much more difficult to separate from the background, especially given the approximately 800 pb of \( tt \) production cross-section expected at the LHC [9]. Mass reconstruction is only possible in the \( WW \to 2j + \ell \nu \) or \( WW \to 4j \) channels, which results in a minimum of 4 jets in the final state once the forward jets are counted. We concentrate on the much cleaner leptonic channel \( WW \to e\mu + E_T \) where mass reconstruction is not possible but appropriate cuts can be made to reveal an excess.

To enhance the signal significance we employ the technique of minijet veto which has been shown to be promising for the case of intermediate and heavy Higgs production via \( W \) fusion i.e. the Higgs discovery reaction \( WW \to H \to WW \to e\mu + E_T \) [10].

## 2 Physics Background

The dominant physics backgrounds to the final state of 2 "forward jets" + \( e^\pm \mu^\mp + E_T \) come from \( pp \to tt + X \) production, followed by \( pp \to WW + 2j \). We define “forward jets” as having transverse momentum \( P_T > 20 \) GeV and pseudorapidity \( 2 < |\eta| < 4 \), with one jet having positive and the other negative \( \eta \).

### 2.1 \( tt \) background

The main physics background to the \( e^\pm \mu^\mp + E_T \) signal arises from \( tt+jets \) production, due to its nearly 800 pb of cross section at the LHC. Top pair production at the LHC is strongly dominated by the gluon fusion channel, \( gg \to tt \), while the \( q\bar{q} \to tt \) channel is less than 10% of the total. Emission of additional quarks or gluons leads to \( tt + j \) and \( tt + 2j \) events.

Figure 1: Feynman diagrams for \( WW \to WW \) scattering. In Higgsless models we only have diagrams (a-c). In the Standard Model however, all diagrams contribute, with the \( V_0^N \) replaced by the \( Z \) boson only.
If no additional partons are emitted, the $b$ quarks from the decaying tops are required to be in the forward jet configuration. Then, the $tt + j$ cross-section, where the $b$ quarks are required to be forward, allows us to estimate the minijet activity in the central region. To estimate minijet activity in $tt + j$, for the configuration where the final-state light quark or gluon, and one of the $b$ quarks are identified as forward tagging jets, we calculate $tt + 2j$. Lastly, we also calculate $pp \rightarrow tt + 2j$, where the final state light quarks or gluons are the two tagging jets and the $b$ quarks from top decay must pass the minijet cuts (next section). Overall the methodology is very similar to that used in [10]. The matrix elements for all three processes were obtained using CompHEP. The narrow-width approximation is used for top and $W$ decays. A $K$ factor of 2 is chosen which normalizes total $t\bar{t}$ production to 800 pb for our renormalization and factorization scale $\mu_R = \mu_F = 2M_{top}$.

2.2 $WW + 2j$ background

This background consists of (a) radiation of $W^+, W^-$ during quark anti-quark scattering and (b) QCD corrections to $W^+W^-$ production. Normally, (b) is higher than (a), but (a) includes $WW$ fusion diagrams, which give final states very similar to the signal. Therefore, in the final analysis, (a) turns out to be larger than (b). We also calculate the $WW + 3j$ cross section to estimate minijet activity. A similar factorization scale is chosen as for the signal process $V^\pm + 2j$, which is the invariant mass of the final state $W$s i.e. $\mu_R = \mu_F = M_{WW}$. Variation of scale by a factor of 2 results in uncertainties as high as 30%, which means that in the absence of NLO calculations, experimental calibration might be necessary. CompHEP is used here also to generate matrix elements.

2.3 $\tau^+\tau^- + 2j$ background

The $e\mu + 2j$ final state can be obtained from $\tau\tau + 2j$ production due to the leptonic decay of $\tau$ leptons. We use the collinear approximation for $\tau$ decay [11]. However, the $e, \mu$ from $\tau$ decay are comparatively soft and we see later that in most cases this background turns out to be insignificant ($< 1\%$) in comparison to the two described above.

3 Analysis

We define "forward jets" as final state partons satisfying the following selection criterion

$$P_T > 20 GeV; \, 2 < |\eta| < 4 \quad (4)$$

Furthermore, the two forward jets need to be on opposite ends of the beam-line. The leptons are required to satisfy

$$P_T > 20 GeV; |\eta| < 2.5 \quad (5)$$

as well as isolation from the jets

$$\Delta R_{j,l} > 0.7 \quad (6)$$

to suppress the background from semi-leptonic decays of QCD $b$ quark production. With these cuts, the two types of $WW + 2j$ backgrounds are already comparable in magnitude, which is due to the fact that Standard Model $WW$ fusion processes (not including the Higgs boson) pass the forward jet cut (4) naturally. This technique of isolating $WW$ fusion processes is well established in the literature [12, 13, 14].

The $W$ pairs from decay of the heavy $V_{0}^{0}$ are close to being back-to-back as the $V_{0}^{0}$ are slow-moving for higher masses. Also, the $W$’s are boosted enough that the $e\mu$ pair from their decay has a large separation angle i.e. $\cos \theta_{e\mu}$ is predominantly negative. For the $tt$ and the $WW$ backgrounds however, the $\cos \theta_{e\mu}$ distribution is roughly uniform. Therefore, we employ the following cut

$$\cos \theta_{e\mu} < 0.1 \quad (7)$$
which keeps \( \sim 85\% \) of the signal, but removes more than 50\% of the background.

We use real \( \tau \) reconstruction to reduce the \( \tau\tau + 2j \) background. In the collinear approximation, if \( x_1, x_2 \) are the \( \tau \) momentum fractions carried by \( e, \mu \) respectively, then we have the equations

\[
(1 - \frac{1}{x_1})P^1_T + (1 - \frac{1}{x_2})P^2_T = E_T
\]

where \( P^1,^2_T \) are the original transverse momenta vectors of the \( \tau \) leptons that give rise to \( e, \mu \) respectively. These two equations for \( x, y \) coordinates can be solved simultaneously to yield \( x_{1,2} \). If the \( e, \mu \) really did come from a pair of \( \tau \)s, then it must be true that

\[
0 < x_{1,2} < 1
\]

Furthermore, we can use the \( x_{1,2} \) to reconstruct the invariant mass of the \( \tau \)s, \( M_{\tau\tau} \), and then veto events that fall near the \( Z \) pole as that is where most of the \( \tau\tau \) pairs originate. Finally, events that satisfy condition (9) and

\[
M_Z - 30 \text{GeV} < M_{\tau\tau} < M_Z + 30 \text{GeV}
\]

are vetoed. This cuts down the \( \tau\tau \) background by a factor of 7 while leaving the signal and other backgrounds almost untouched.

The most problematic background is the \( W^+W^- \) pairs from \( t\bar{t} + X \) production. The first step in controlling this is a veto on \( b \) or \( \bar{b} \) jets with \( P_T > 20 \) GeV in the region between the two forward jets. It is to be noted that \( b \) tagging is not required here, just rejection of events with a central jet. This by itself cuts down the \( t\bar{t} \) background by a factor of 15. It is still the largest background by far, but now of the same order of magnitude as the other backgrounds.

Besides this, a cut on the invariant mass, \( M_{JJ} \), of the two forward jets

\[
M_{JJ} > 650 \text{GeV}
\]

is useful in reducing the \( t\bar{t} \) background by about 60\% with little effect on the signal. This is because QCD processes at the LHC typically occur at lower invariant masses than the signal. Similarly QCD corrections to \( WW \) production are also reduced by about the same factor.

The minijet veto on jets with \( P_T > 20 \) GeV in the region between the forward jets is applied, to match the \( b \) veto condition above. We follow the procedure given in [10] which has been shown to be useful for Higgs discovery in the \( WW \) fusion channel extensively in the literature [15, 16]. For our cuts, this procedure shows a survival probability of 90\% for signal events, but only 32\% for the \( t\bar{t} \) background and 53\% for the \( WW + 2j \) background.

In the \( V^0_1 \to WW \to e\mu + E_T \) decay channel, explicit reconstruction of the invariant mass of the two \( W \)'s is not possible as there are two neutrinos. Nor are the \( W \)'s boosted enough to permit a collinear
approximation for their decay products. However, the maximal $P_T$ between the $e, \mu$ does have a peak at an energy that increases monotonically with the mass of the $V_1^0$. We do not employ a "window" cut though around the peak as there are too few signal events. Instead, we note that the transverse momentum distribution of the lepton carrying the higher $P_T$, hereafter denoted by $P_T^{\text{max}}(e, \mu)$, has a fat tail towards higher momenta that rises above the background. We then demand that $P_T^{\text{max}}(e, \mu)$ be greater than a lower threshold which is chosen for each $M_{V_1}$ such that the signal significance is maximized.

We find that the optimal threshold for $P_T^{\text{max}}(e, \mu)$ varies roughly linearly between 100 and 350 GeV for $M_{V_1}$ between 400 and 1200 GeV. However, we also ask that there be at least 10 signal events, which does not always allow this threshold to be used.

The step-by-step effect of the cuts is shown in Fig. (2).

4 Results

We calculate signal significance over the background as a function of the mass of $V_1^0$ for integrated luminosities of $L = 30, 100, 300$ fb$^{-1}$, as shown in Fig. (3). For low luminosity running (30 fb$^{-1}$), the 5σ discovery potential is poor, with only masses below $\sim 300$ GeV being accessible. However, for high luminosity running (300 fb$^{-1}$), $V_1^0$ as heavy as 1.35 TeV can be discovered. As shown in the figure, between
$M_V = 800 - 1000$ GeV the discovery potential actually improves for this luminosity because more energetic $V_1^0 \rightarrow WW$ decays lead to higher transverse momenta for the final state $e, \mu$. This offsets to some extent the effect of the lower $VWW$ coupling (which falls off as $1/M_V$), and the more restricted phase space.

Our requirement that there be a minimum of 10 signal events implies that for low luminosities we cannot always use the most optimal lower cutoff on $P^\text{min}_T(e, \mu)$. Therefore, the signal significance drops sharply beyond a point for all three luminosities considered.

A minijet veto could be challenging to realise. If this cut is not used, the discovery potential is still quite substantial, up to $M_V = 900$ GeV, for $L = 300$ fb$^{-1}$.

It is clear therefore that both $V_1^\pm, V_0^1$ particles, which are the key signatures of extra-dimensional (and deconstructed) Higgsless models, are within reach of the LHC. While discovery of the $V_1^\pm$ would provide a smoking gun [8], searches for the $V_0^1$ would provide important confirmation, and can be conducted in the same channels as those for a heavy Higgs.

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