



Englert, C., Jäger, B., Worek, M., and Zeppenfeld, D. (2009) Observing strongly interacting vector boson systems at the CERN Large Hadron Collider. *Physical Review D*, 80(3), 035027.

Copyright © 2009 American Physical Society

A copy can be downloaded for personal non-commercial research or study, without prior permission or charge

Content must not be changed in any way or reproduced in any format or medium without the formal permission of the copyright holder(s)

<http://eprints.gla.ac.uk/106787/>

Deposited on: 28 May 2015

Enlighten – Research publications by members of the University of Glasgow
<http://eprints.gla.ac.uk>

Observing Strongly Interacting Vector Boson Systems at the CERN Large Hadron Collider

C. Englert¹, B. Jäger^{2,3}, M. Worek^{1,4}, D. Zeppenfeld¹

¹ ITP, Universität Karlsruhe, 76128 Karlsruhe, Germany

² Institut für Theoretische Physik und Astrophysik, Universität Würzburg,
97074 Würzburg, Germany

³ KEK Theory Division, 305-0801 Tsukuba, Japan

⁴ Institute of Physics, University of Silesia, 40-007 Katowice, Poland

Abstract

We explore the potential of the CERN Large Hadron Collider to access a strongly interacting electroweak symmetry breaking sector via weak boson scattering with W^+W^-jj , $ZZjj$ and $W^\pm Zjj$ final states. As examples of models with scalar or vector resonances we concentrate on a scenario with a heavy Higgs boson and on a Warped Higgsless Kaluza-Klein model of narrow spin-one resonances. The signal and the most prominent background processes are evaluated using exact tree-level matrix elements including full off-shell and finite width effects for final states with two tagging jets and four leptons. Using double forward jet-tagging techniques, we derive dedicated cuts on the observable jets and charged leptons to suppress Standard Model backgrounds. We demonstrate that the LHC has substantial sensitivity to strong interactions in the electroweak symmetry breaking sector.

September 3, 2009

1 Introduction

An essential goal of the CERN Large Hadron Collider (LHC) [1, 2] is gaining information on the mechanism which breaks the electroweak symmetry. Particularly promising means for probing electroweak symmetry breaking are provided by weak boson scattering reactions, $VV \rightarrow VV$ (with V denoting a W^\pm or Z boson). The respective scattering amplitudes for longitudinally polarized vector bosons grow with energy, thus violating unitarity beyond about 1 TeV [3–5], when Feynman graphs with vector bosons only are considered. Taming of this unphysical growth can be attained by a SM Higgs boson [6–8], but also strong couplings among the gauge bosons may serve to cure the growth of the VV scattering amplitudes at high energies [9–11]. Various models have been suggested in which the unitarization of these scattering amplitudes is realized by new excitations stemming from the compactification of extra-dimensional theories [12–14], based on the ideas of [15]. At the LHC, weak boson scattering can be accessed via vector boson fusion (VBF) reactions, where the quarks emerging from the scattering protons emit t -channel weak bosons which in turn scatter off each other. A Higgs boson as predicted by the Standard Model (SM) would manifest itself as a relatively low mass resonance in this reaction, but the VBF cross section would remain perturbatively small at di-boson masses well above the Higgs boson mass. In the case of strongly interacting gauge bosons, the production rate of longitudinally polarized gauge boson pairs $V_L V_L$ is significantly enhanced at $m_{VV} \approx 1$ TeV, before unitarizing effects reduce the scattering amplitudes.

Signal events from strong $V_L V_L$ scattering processes via $qq \rightarrow qqVV$ in VBF exhibit unique signatures. The decay leptons of the gauge bosons emerge almost back-to-back in the central region of the detector with large transverse momenta and high invariant mass. The scattered quarks give rise to highly energetic jets of relatively low transverse momenta in the forward and backward regions. Due to the colorless weak boson exchange, the hadronic jet activity in the central regions is very low. These distinctive features can be exploited to efficiently reduce background processes with respect to the $V_L V_L$ signals.

The goal of this study is to refine the analyses of Refs. [16–19] for strongly interacting electroweak symmetry breaking. Instead of using single forward jet tagging, as in these early analyses, we will consider the boost invariant double forward jet-tagging techniques which have proven highly efficient for the search of a light Higgs boson in VBF [20–23]. These more efficient jet-tagging techniques will allow us to relax the cuts on the VV decay leptons as compared to Ref. [19]. A second refinement is in the level of signal and background simulation. We use parton-level calculations for the processes $pp \rightarrow VVjj$ at $\mathcal{O}(\alpha^6)$ and $\mathcal{O}(\alpha^4\alpha_s^2)$ including leptonic decays of the weak bosons, as well as a simulation of the $t\bar{t}$, $t\bar{t}j$, and $t\bar{t}jj$ background processes at $\mathcal{O}(\alpha^4\alpha_s^2)$, $\mathcal{O}(\alpha^4\alpha_s^3)$, and $\mathcal{O}(\alpha^4\alpha_s^4)$, respectively. This corresponds to tree-level amplitudes for all processes and includes full off-shell effects for top-quark decays $t \rightarrow Wb$ and for the leptonic decays of the weak bosons in all signal and background processes. While comparable accuracy of the simulations has been discussed in the literature for individual reactions (see, e.g., Refs. [24–26]), an analysis of VBF signal and background processes with full leptonic decay correlations and off-shell effects is new. Phenomenological studies for other production modes of extra vector resonances have recently been performed in [27–31].

For the signal processes, we consider two different models for the strongly interacting electroweak symmetry breaking. We model unitarity conservation with a heavy and broad Standard Model scalar Higgs resonance, which we take as a prototype for models with strong VV scattering. As a model with extra vector resonances, we adapt a Warped Higgsless scenario where unitarity violation is postponed by the exchange of additional spin-one Kaluza-Klein (KK) resonances. On the basis of these two distinct examples, we show that independent of whether the unitarity-restoring interactions are of a scalar or vector nature, our set of cuts and signal processes provides a clear signature with a large signal to background ratio.

Our paper is organized as follows: Section 2 outlines the theoretical setup for the two signal scenarios which we consider. The framework of the phenomenological analysis is described in Sec. 3 and here we also give details on the Monte Carlo calculation of the various signal and background processes. In Sec. 4 we present the numerical results for expected cross sections at the LHC. Section 5 contains our conclusions.

2 Theoretical Setup

Strongly-coupled theories have a long history as extensions of the Standard Model [32–34]. In these models the additional degrees of freedom, needed to unitarize longitudinal gauge boson scattering, originate from a strongly-interacting sector that produces scalar and vectorial composites. While electroweak symmetry breaking is stabilized at the electroweak scale, the compositeness scale is in principle a free parameter. The unitarizing mass spectrum can be rather heavy and broad, due to strong couplings in the composite sector. As such models are intrinsically non-perturbative, there are large theoretical uncertainties on the theory’s parameters that can only roughly be estimated by Naive Dimensional Analysis [35]. This poses a huge challenge for modelling LHC phenomenology. For this reason we use unitarity of longitudinal VV scattering at the TeV scale as key ingredient to model the strongly interacting sector, focusing on two distinct scenarios: In the first one, we adapt a heavy and broad scalar resonance, while in the second one, longitudinal gauge boson scattering is unitarized by vectorial resonances in the Warped Higgsless Model of Refs. [12, 13].

2.1 Scalar Resonance

Within the SM, unitarization of longitudinal VV scattering is achieved by adding the contributions of a scalar resonance of zero isospin, the Higgs boson, to the gauge boson exchange graphs which are mandated by the gauge symmetry. Working within the SM, precision data, in particular the results of LEP and SLC on various four-fermion processes combined with the direct Higgs search at LEP, constrain the mass of the SM Higgs boson to lie inside the 100 to 200 GeV region [36, 37]. Strictly within the SM, a heavy scalar resonance, with a mass of order 1 TeV, is ruled out as a model for unitarized weak boson scattering.

These SM Higgs boson mass bounds might be misleading, however, if other new physics

contributions to four-fermion amplitudes (partially) cancel the virtual contributions of a heavy Higgs boson to the S and T parameters [38–41], thus mitigating the constraints from precision experiments. Since the precision observables, with their strong focus on four fermion-amplitudes, and weak boson scattering amplitudes are independent entities in sufficiently general models of new physics, we ignore the constraints from precision data in the following and consider, as a phenomenological model, unitarization of weak boson scattering by a scalar resonance with quantum numbers and couplings identical to a heavy SM Higgs boson. We include s -, t - and/or u -channel channel exchange of this resonance and use $m_H = 1$ TeV and a fixed width $\Gamma_H = 0.5$ TeV as a toy-model for demonstration purposes. This fixed width is included for time-like and space-like propagators, in analogy to the complex mass scheme for the gauge boson propagators. More general model parameters of a heavy scalar resonance can easily be implemented in the VBFNLO program [42] which we use for all signal simulations.

2.2 Vectorial Resonances

As an example of unitarization with vectorial resonances we consider a phenomenological version of the Warped Higgsless model of Refs. [43, 44]. Using the AdS/CFT correspondence [45–47], the Warped Higgsless scenario can be considered as a particular type of a strongly-interacting Walking Technicolor theory [46], yet being calculable by perturbative means from a bulk-gauged effective theory defined on a slice of a five dimensional Anti-de Sitter space. In these scenarios the growth of the amplitude in longitudinal gauge boson scattering is tamed by the exchange of heavy spin-1 Kaluza-Klein excitations, W_k^\pm and Z_k . Demanding sum rules for the quartic and triple vector boson couplings [27, 48],

$$g_{W_1 W_1 W_1 W_1} = \sum_{k \geq 0} g_{W_1 W_1 Z_k}^2, \quad (1)$$

$$4m_{W_1}^2 g_{W_1 W_1 W_1 W_1} = 3 \sum_{k \geq 1} m_{Z_k}^2 g_{W_1 W_1 Z_k}^2, \quad (2)$$

$$g_{W_1 W_1 Z_1 Z_1} = \sum_{k \geq 1} g_{W_k W_1 Z_1}^2, \quad (3)$$

$$2(m_{Z_1}^2 + m_{W_1}^2) g_{W_1 W_1 Z_1 Z_1} = \sum_{k \geq 1} g_{W_k W_1 Z_1}^2 \left(3m_{W_k}^2 - \frac{(m_{Z_1}^2 - m_{W_1}^2)^2}{m_{W_k}^2} \right), \quad (4)$$

results in good high energy behaviour of the $V_L V_L$ scattering amplitude. In (1)-(4) k labels the Kaluza-Klein states, and $k = 0, 1$ identifies the massless and massive gauge bosons of the SM, respectively. We focus on a scenario where the new additional massive vector bosons have vanishing couplings to SM-fermions, and include states up to W_4 and Z_6 .

Higgsless symmetry breaking has already been studied in various realizations [12–14, 27–31, 49–51]. In this paper we do not attempt to construct a realistic model of Higgsless symmetry breaking, but we solely use the quoted sum rules as a phenomenological paradigm of unitarization with iso-vectorial resonances. For a more detailed discussion on the implementation of the sum rules and the KK mass spectrum, we refer the reader to a separate publication [44].

3 Framework of the Analysis

Throughout this study, we consider vector boson pair production in association with two tagging jets, $pp \rightarrow VVjj$, with subsequent leptonic decays of the gauge bosons in proton-proton collisions at the LHC with a center-of-mass energy of 14 TeV. If strong interactions among longitudinally polarized vector bosons are realized in nature, $V_L V_L \rightarrow V_L V_L$ scattering is expected to be enhanced at large invariant mass. In contrast, the scattering of transversely polarized gauge bosons V_T is dominated by the same weak gauge interactions as in the SM light Higgs boson scenario and, thus, remains perturbative throughout the entire VV invariant mass range. The $V_T V_T \rightarrow V_T V_T$ and $V_L V_T \rightarrow V_L V_T$ contributions to vector boson scattering must be considered as an irreducible background to the signature of strong gauge boson interactions, which we wish to isolate. We thus define the VBF “signal” in EW $pp \rightarrow VVjj$ production as the enhancement of the cross section over the SM prediction with a light Higgs boson. In the heavy Higgs boson scenario this is

$$\sigma_S \equiv \sigma_{SM}(m_H = 1 \text{ TeV}) - \sigma_{SM}(m_H = 100 \text{ GeV}). \quad (5)$$

As an alternative realization of electroweak symmetry breaking we consider the Warped Higgsless Kaluza-Klein model described in Sec. 2.2. In this context we define

$$\sigma_S \equiv \sigma_{KK} - \sigma_{SM}(m_H = 100 \text{ GeV}). \quad (6)$$

Backgrounds arise from QCD-induced and non-resonant electroweak (EW) reactions with the same final-state configuration as the signal, at $\mathcal{O}(\alpha^4 \alpha_s^2)$ and $\mathcal{O}(\alpha^6)$, respectively. For the $W^+ W^- jj$ channel, the production processes $t\bar{t}$, $t\bar{t}j$ and $t\bar{t}jj$ at $\mathcal{O}(\alpha^4 \alpha_s^2)$, $\mathcal{O}(\alpha^4 \alpha_s^3)$, and $\mathcal{O}(\alpha^4 \alpha_s^4)$, respectively, have to be considered as copious background sources also. Via their decay chains, the $t\bar{t}$ pairs give rise to the same combination of charged leptons in the final state as the VBF signal process.

Since the principle subject of this study is the investigation of strongly interacting gauge boson systems, we do not consider signal processes deriving from Yukawa couplings of the Higgs boson to fermions, such as gluon-induced Hjj production.

3.1 Details of the Calculation

The calculation of cross sections and kinematic distributions for all signal and background processes introduced above is performed with two independent computer programs featuring full tree-level matrix elements:

- Results for all but Kaluza-Klein signal reactions are generated with HELAC-PHEGAS, a completely automatic Monte-Carlo event generator [52–56], which calculates matrix elements through Dyson-Schwinger off-shell recursive equations. The package provides events for arbitrary parton-level processes in the most recent Les Houches Accord format [57] and has successfully been tested for scattering reactions at a future linear collider [58] and at the LHC [59].
- The EW VBF and Kaluza-Klein signal and background processes are tackled with the tree-level version of VBFNLO [42], a parton-level Monte-Carlo program for

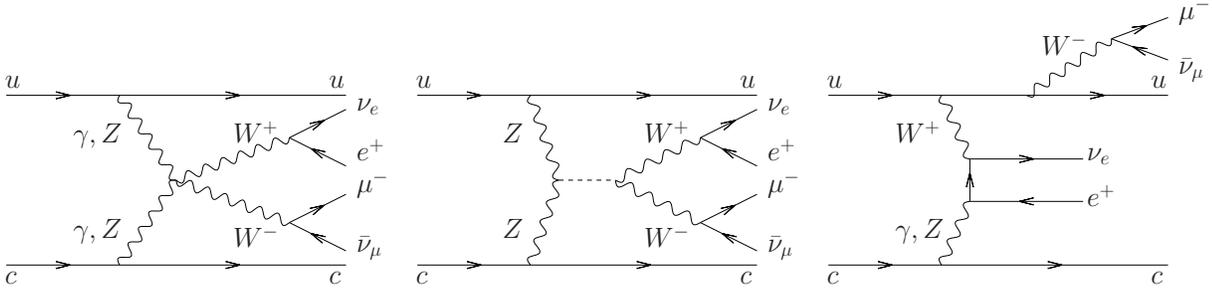


Figure 1: *Examples of Feynman-graph topologies contributing to EW W^+W^-jj production at $\mathcal{O}(\alpha^6)$.*

VBF-type reactions. For the QCD $VVjj$ processes, we implemented MADGRAPH-generated amplitudes [60, 61] into the framework of VBFNLO. Results for the $t\bar{t}$, $t\bar{t}j$, and $t\bar{t}jj$ reactions are generated with the codes of Ref. [24].

Making sure that the different programs yield the same results provides an excellent check of our calculation. In particular, HELAC-PHEGAS agrees at least at the level of 1% with the top-backgrounds of Ref. [24], and even better with the MADGRAPH-type implementation of the QCD $VVjj$ backgrounds in VBFNLO, irrespectively of the cuts applied.

For our numerical studies we use the CTEQ6L1 parton distribution functions [62, 63] at leading order (LO) with $\alpha_s(M_Z) = 0.130$. We have chosen $M_Z = 91.188$ GeV, $M_W = 80.423$ GeV, and $G_F = 1.166 \times 10^{-5}/\text{GeV}^2$ as electroweak input parameters. The other parameters, α and $\sin^2\theta_W$, are computed thereof via LO EW relations. The masses of the top and bottom quarks are set to $m_t = 172.5$ GeV and $m_b = 4.4$ GeV, respectively. Contributions from b - and t -quarks in the initial state are neglected throughout. In HELAC-PHEGAS, finite width effects in massive vector boson and top quark propagators are taken into account by the complex mass scheme of Refs. [64–66]. Both, in VBFNLO and in the code of Ref. [24], unstable particles are treated via modified versions [67, 68] of the complex mass scheme. Spin and color correlations of the final state particles are taken into account without any approximations. Final state partons are recombined into jets according to the k_T algorithm [69–71] with resolution parameter 0.7. In the following, we outline the process-specific settings of our analysis.

3.1.1 EW $VVjj$ production

EW $VVjj$ production mainly proceeds via the fusion of weak bosons in the t -channel in quark-(anti)quark scattering processes like $qq' \rightarrow qq'VV$. In experiment, however, leptons rather than vector bosons are identified. We therefore focus on the reactions

$$\begin{aligned}
 pp &\rightarrow \ell^+ \nu_\ell \ell'^- \bar{\nu}_{\ell'} jj, \\
 pp &\rightarrow \ell^+ \ell'^- \ell'^+ \ell'^- jj, \\
 pp &\rightarrow \ell^+ \ell'^- \nu_{\ell'} \bar{\nu}_{\ell'} jj,
 \end{aligned}
 \tag{7}$$

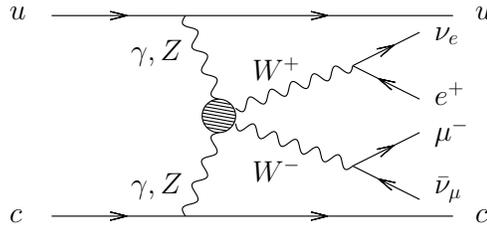


Figure 2: *Modified weak boson fusion topology. The shaded area contains different Kaluza-Klein intermediate states.*

$$\begin{aligned}
 pp &\rightarrow \ell^+ \nu_\ell \ell'^+ \ell'^- jj, \\
 pp &\rightarrow \ell^- \bar{\nu}_\ell \ell'^+ \ell'^- jj
 \end{aligned}$$

at $\mathcal{O}(\alpha^6)$, which include the resonant $VVjj$ production processes with subsequent leptonic decays and additional single- and non-resonant diagrams, see Fig. 1. We only simulate decays of the weak bosons to different lepton generations, e.g. $W^+W^- \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu$. Same-generation lepton interference effects as occurring in $W^+W^- \rightarrow e^+\nu_e e^-\bar{\nu}_e$ are neglected for all production channels. However, we adjust counting factors to correspond to the production of all combinations of charged leptons of the first two generations. In case of $Z \rightarrow \nu_\ell\bar{\nu}_\ell$ we sum over three neutrino generations, i.e. $\nu_\ell\bar{\nu}_\ell = \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$. For brevity, we will refer to these reactions as EW W^+W^-jj , $ZZjj \rightarrow 4\ell jj$, $ZZjj \rightarrow 2\ell 2\nu jj$, W^+Zjj , and W^-Zjj production, respectively, even though we are always considering leptonic final states.

As discussed in Refs. [72–75], compared to the dominant t -channel configurations, contributions from s -channel electroweak boson exchange and identical fermion effects are negligible in the phase-space regions where $VVjj$ production is observed experimentally. They are therefore disregarded for our analysis. In Ref. [74] it has been demonstrated that next-to-leading order (NLO) QCD effects can be well approximated also in distributions by a proper choice of the factorization scale, μ_F , in the LO calculation: for each fermion line choose the momentum transfer Q between the respective initial- and final-state quarks. We therefore set $\mu_F = Q$ for all EW $VVjj$ processes.

3.1.2 Higgsless $VVjj$ production

The implementation of the Kaluza-Klein scenario described in Sec. 2.2 into the VBFNLO framework is described in detail in Refs. [43,44]. The leptonic tensors for subamplitudes such as $ZZ \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu$ in Fig. 2 have been extended by the different Kaluza-Klein intermediate states. We discard interactions of non-SM Kaluza-Klein gauge bosons with the light SM fermions. The coupling of the Kaluza-Klein W_k and Z_k to the W_1 and Z_1 steeply drops off with the Kaluza-Klein index k . For $k \geq 3$, contributions of Kaluza-Klein excitations to cross sections and distributions are tiny [44]. In our studies we include all Kaluza-Klein states up to W_4 and Z_6 with the masses and widths as given in Tab. 1.

Gauge boson pair production in the presence of Kaluza-Klein excitations proceeds analogously to Higgs-mediated $VVjj$ production. In order to absorb the dominant NLO-QCD effects we therefore use the same factorization scales as for EW $VVjj$ production,

| Particle | m [GeV] | Γ [GeV] |
|----------|-----------|----------------|
| W_2 | 700 | 13.7 |
| Z_2 | 695 | 8.7 |
| Z_3 | 718 | 6.4 |
| W_3 | 1106 | 31.0 |
| Z_4 | 1112 | 26.5 |
| W_4 | 1585 | 56.5 |
| Z_5 | 1580 | 31.7 |
| Z_6 | 1605 | 24.1 |

Table 1: *Masses and widths of the Kaluza-Klein resonances used in the simulation. The spectrum corresponds to a Planck brane localization $R = 9.75 \times 10^{-9}$ GeV $^{-1}$.*

i.e. $\mu_F = Q$ [43, 44].

3.1.3 QCD $VVjj$ production

QCD-induced $VVjj$ production calculated at order $\mathcal{O}(\alpha^2\alpha_s^2)$ includes the production processes

$$qq \rightarrow qqVV, \quad qg \rightarrow qgVV, \quad (8)$$

with subsequent leptonic decays, and all crossing-related reactions.

For these processes we use $\mu_F = \min(p_{Tj_1}, p_{Tj_2})$. The renormalization scale is chosen such that the strong coupling factor takes the form $\alpha_s^2 = \alpha_s(p_{Tj_1}) \cdot \alpha_s(p_{Tj_2})$, i.e. the transverse momentum of each parton is taken as the relevant scale for its production.

3.1.4 $t\bar{t}$ + jets production

Due to the large top quark production rate at the LHC and because the branching ratio $B(t \rightarrow Wb)$ is essentially 100%, $t\bar{t}$ + jets processes constitute a major background to EW W^+W^-jj production. We consider the reactions $pp \rightarrow t\bar{t}$, $t\bar{t}j$, and $t\bar{t}jj$ which include full off-shell and finite width top and W effects and take into account the double-resonant, single-resonant and non-resonant contributions at order $\mathcal{O}(\alpha^2\alpha_s^2)$, $\mathcal{O}(\alpha^2\alpha_s^3)$ and $\mathcal{O}(\alpha^2\alpha_s^4)$, respectively. To avoid double counting, the top-quark backgrounds are separated into three categories, depending on whether two, one or zero $b(\bar{b})$ quarks are identified as tagging jets and are referred to as $t\bar{t}$, $t\bar{t}j$ and $t\bar{t}jj$ background, respectively. When

combining these processes, we proceed as follows: For $t\bar{t}jj$ production both tagging jets are required to arise from massless partons, while in the $t\bar{t}j$ case exactly one tagging jet is allowed to emerge from a b or \bar{b} quark. For $t\bar{t}$ production both tagging jets stem from b quarks [22, 23]. When presenting cross sections and kinematic distributions, the three $t\bar{t} + \text{jets}$ backgrounds are combined for clarity even though their individual distributions are slightly different.

In all cases, the factorization scale is chosen as $\mu_F = \min(m_{T_i})$ of the top quarks and additional jets, where each m_{T_i} is given by the transverse momentum and mass of the respective entity i as

$$m_{T_i} = \sqrt{p_{T_i}^2 + m_i^2}. \quad (9)$$

The overall strong coupling factors for the $t\bar{t} + n$ jets cross section are calculated as $(\alpha_s)^{n+2} = \prod_{i=1}^{n+2} \alpha_s(m_{T_i})$.

3.2 Selection Cuts

In order to suppress the backgrounds with respect to the signal processes, the design of dedicated selection cuts is essential. For our analysis we have developed various sets of cuts, which are given as follows:

- I. **INCLUSIVE CUTS:** Basic selection cuts need to be introduced to render our calculation of the production cross sections of all signal and background processes finite. This is achieved by identifying all final state massless partons with high transverse momentum jets. The two jets of largest transverse momentum are called “tagging jets” and are required to carry

$$p_{T_j}^{\text{tag}} > 30 \text{ GeV}. \quad (10)$$

All jets need to lie in the rapidity-range accessible to the detector,

$$|\eta_j| < 4.5, \quad (11)$$

and are supposed to be well-separated,

$$\Delta R_{jj} = \sqrt{(\eta_{j_1} - \eta_{j_2})^2 + (\phi_{j_1} - \phi_{j_2})^2} > 0.7, \quad (12)$$

with η_j denoting the jet rapidity and ΔR_{jj} the separation of any pair of jets in the rapidity-azimuthal angle plane. For all $VVjj$ production processes, the tagging jets are identified with the massless final-state partons of the reaction. For the $t\bar{t} + \text{jets}$ backgrounds, the tagging jets can stem from a massless quark or gluon, or from the decay products of the top quarks.

In order to ensure well-observable isolated charged leptons in the central-rapidity region, we require

$$p_{T_\ell} > 20 \text{ GeV}, \quad |\eta_\ell| < 2.5, \quad \Delta R_{\ell j} > 0.4, \quad (13)$$

where $\Delta R_{\ell j}$ stands for the separation of a charged lepton from any jet. Since any b -quark close to a charged lepton is very likely to also spoil lepton isolation, we require $\Delta R_{\ell b} > 0.4$ even if the b -quark is too soft to qualify as a jet. Finally, a cut on the invariant mass $m_{\ell\ell}$ of two charged leptons of the same flavor is applied to avoid virtual photon singularities stemming from quasi-collinear $\gamma^* \rightarrow \ell^+\ell^-$ decays,

$$m_{\ell\ell} > 15 \text{ GeV}. \quad (14)$$

II. **VBF CUTS:** VBF events are characterized by two tagging jets in the far forward and backward regions of the detector, while the leptonic decay products of the vector bosons are typically located in the central-rapidity range between the jets. To favor such configurations, we demand that the charged leptons fall between the tagging jets,

$$\eta_{j,\min}^{\text{tag}} < \eta_{\ell} < \eta_{j,\max}^{\text{tag}}, \quad (15)$$

which are well-separated in rapidity,

$$\Delta\eta_{jj} = |\eta_{j_1}^{\text{tag}} - \eta_{j_2}^{\text{tag}}| > 4, \quad (16)$$

and occupy opposite detector hemispheres,

$$\eta_{j_1}^{\text{tag}} \times \eta_{j_2}^{\text{tag}} < 0. \quad (17)$$

Furthermore, the tagging jets are required to have a large invariant mass,

$$m_{jj} > m_{jj}^{\text{min}}, \quad (18)$$

where $m_{jj}^{\text{min}} = 1000 \text{ GeV}$ for the W^+W^-jj signal and background processes and $m_{jj}^{\text{min}} = 500 \text{ GeV}$ for all other channels.

To illustrate the significance of the m_{jj} cut, the invariant mass distribution of the two tagging jets in $pp \rightarrow W^+W^-jj$ is shown in Fig. 3, after applying the cuts of Eqs. (10)-(17) and requiring $p_T(\ell) > 100 \text{ GeV}$. For reducing the $t\bar{t}$ +jets backgrounds, additionally a b -veto and a central jet veto have been imposed, as discussed below. While large invariant masses of the tagging jets are characteristic for VBF processes, QCD-induced reactions tend to peak at small values of m_{jj} . Requiring $m_{jj} > 1000 \text{ GeV}$ thus efficiently suppresses contributions from $t\bar{t}$ + jets and QCD $VVjj$ production with respect to the signal processes.

III. **LEPTONIC CUTS:** In all channels, the signal processes feature energetic leptons of high p_T and large invariant mass. The decay products of the backgrounds are less back-to-back in the transverse plane and are characterized by lower transverse momenta. These features suggest the application of extra selection cuts specific to each decay channel:

- $ZZjj \rightarrow 4\ell jj$:

$$\begin{aligned} m_{ZZ} &> 500 \text{ GeV}, \\ p_T(\ell\ell) &> 0.2 \times m_{ZZ}. \end{aligned} \quad (19)$$

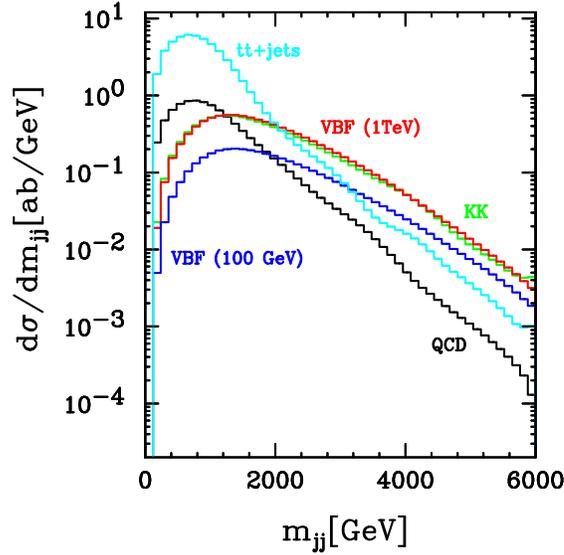


Figure 3: *Invariant mass distribution of the two tagging jets for $pp \rightarrow W^+W^-jj$ after imposing the cuts of Eqs. (10)-(17), a b -veto, a CJV , and requiring $p_T(\ell) > 100$ GeV. Plotted are results for the heavy Higgs boson scenario, the Higgsless Kaluza-Klein model, and the relevant SM backgrounds.*

Here, m_{ZZ} is the invariant mass of the four-lepton system, and $p_T(\ell\ell)$ the transverse momentum of two same-flavor charged leptons.

- $ZZjj \rightarrow 2\ell 2\nu jj$:

$$\begin{aligned} m_T(ZZ) &> 500 \text{ GeV}, \\ p_T^{miss} &> 200 \text{ GeV}, \end{aligned} \quad (20)$$

with p_T^{miss} being the transverse momentum of the neutrino system and

$$m_T^2(ZZ) = [\sqrt{m_Z^2 + p_T^2(\ell\ell)} + \sqrt{m_Z^2 + (p_T^{miss})^2}]^2 - [\vec{p}_T(\ell\ell) + \vec{p}_T^{miss}]^2. \quad (21)$$

- $W^\pm Zjj$:

$$\begin{aligned} m_T(WZ) &> 500 \text{ GeV}, \\ p_T^{miss} &> 30 \text{ GeV}, \end{aligned} \quad (22)$$

where

$$m_T^2(WZ) = [\sqrt{m^2(\ell\ell) + p_T^2(\ell\ell)} + |p_T^{miss}|]^2 - [\vec{p}_T(\ell\ell) + \vec{p}_T^{miss}]^2, \quad (23)$$

with $m(\ell\ell)$ and $p_T(\ell\ell)$ denoting the invariant mass and transverse momentum of the charged-lepton system, respectively.

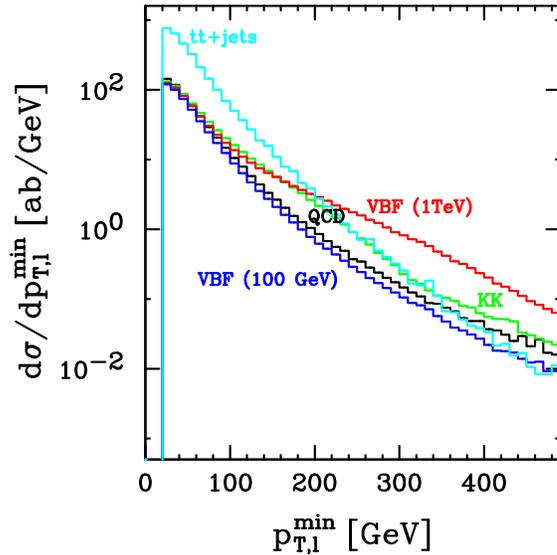


Figure 4: *Transverse momentum distribution of the softest charged lepton for $pp \rightarrow W^+W^-jj$ after imposing the cuts of Eqs. (10)-(18), a b -veto, and a CJV. Plotted are results for the heavy Higgs boson scenario, the Higgsless Kaluza-Klein model, and the relevant SM backgrounds.*

- W^+W^-jj :

$$\begin{aligned}
 p_{T\ell} &> 100 \text{ GeV} , \\
 \Delta p_T(\ell\ell) &= |\vec{p}_{T,\ell_1} - \vec{p}_{T,\ell_2}| > 250 \text{ GeV} , \\
 m_{\ell\ell} &> 200 \text{ GeV} , \\
 \min(m_{\ell j}) &> 180 \text{ GeV} ,
 \end{aligned} \tag{24}$$

where $\Delta p_T(\ell\ell)$ is the difference between the transverse momenta of the two charged decay leptons, and $\min(m_{\ell j})$ the minimum invariant mass of a tagging jet and any charged lepton.

To motivate this set of selection cuts, we show representative distributions for the $pp \rightarrow W^+W^-jj$ channel in the following. In Fig. 4, the transverse momentum distribution of the softest charged lepton is shown after imposing the cuts of Eqs. (10)-(18), a b -veto, and a central jet veto. While the heavy-Higgs and the Kaluza-Klein distributions can barely be distinguished from the QCD and EW backgrounds at low transverse momenta, the signal cross sections start to deviate from the EW $WWjj$ background at about $p_{T\ell} \approx 100$ GeV. Removing events with $p_{T\ell} < 100$ GeV therefore helps to suppress irreducible backgrounds from SM-like W^+W^-jj production processes. For reducing the still sizeable $t\bar{t} + \text{jets}$ cross sections, additional cuts are necessary.

Figure 5 (a) displays the invariant mass distribution of the two charged final-state leptons after all inclusive and VBF cuts have been applied, and a b -veto, a central jet veto, $p_T(\ell) > 100$ GeV and $\min(m_{\ell j}) > 180$ GeV have been imposed. In

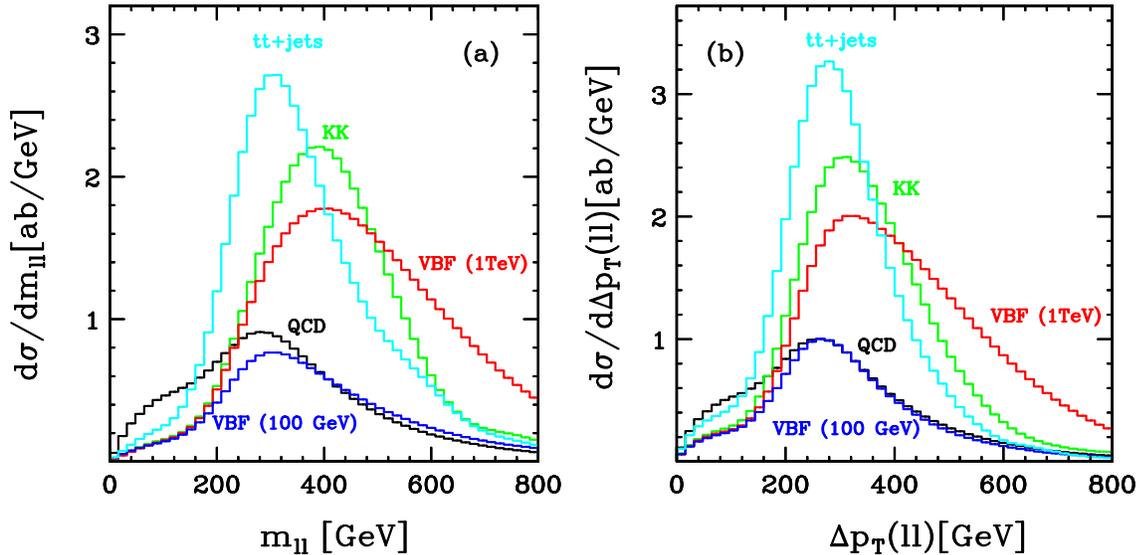


Figure 5: *Invariant mass distribution of the two charged leptons (a) and difference between their transverse momenta (b) for the $pp \rightarrow W^+W^-jj$ process after imposing the cuts of Eqs. (10)-(18), a b -veto, a CJV, and requiring $p_T(\ell) > 100$ GeV and $\min(m_{l_j}) > 180$ GeV. Plotted are results for the heavy Higgs boson scenario, the Higgsless Kaluza-Klein model, and the relevant SM backgrounds.*

the heavy-Higgs and Kaluza-Klein signal processes, the invariant mass distribution peaks at rather large values of $m_{\ell\ell}$, while smaller invariant masses are preferred by the background processes, which therefore can be reduced considerably by requiring $m_{\ell\ell} > 200$ GeV.

Choosing the cut on the difference in the transverse momenta of the decay leptons is a subtle issue, as the peaks of the signal and background distributions are located rather closely in $\Delta p_T(\ell\ell)$, see Fig. 5 (b). Selecting events with $\Delta p_T(\ell\ell) > 250$ GeV turns out to be a reasonable choice, however, which suppresses contributions from the $t\bar{t}$ +jets and the QCD $VVjj$ processes, while the Kaluza-Klein and heavy-Higgs cross sections are retained to a large extent.

The cut on the minimum invariant mass of the tagging jet and any charged lepton, depicted in Fig. 6, is particularly effective in reducing the $t\bar{t}$ and $t\bar{t}j$ backgrounds, i.e. the cases where at least one of the tagging jets arises from a b -quark which is a top decay product. For top quarks which are almost on mass-shell, this b -quark must have an invariant mass with the charged lepton from the same top-quark decay of $m_{\ell j} < m_t$. The $\min(m_{\ell j})$ cut will thus reduce the $t\bar{t}$ +jets background to mostly its $t\bar{t}jj$ component. At the same time, the signal processes are only slightly affected, as their $m_{\ell j}$ shapes are peaking well above 200 GeV.

The powerful sets of selection cuts introduced so far exploit the characteristic features of VBF processes and the fact that we are looking for the decay products of massive objects or, more precisely, for low partial waves in high energy vector boson

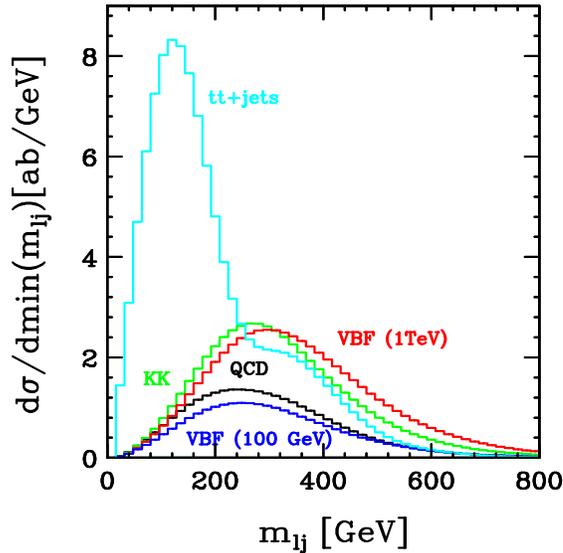


Figure 6: Minimum invariant mass distribution of a tagging jet and a charged lepton for the $pp \rightarrow W^+W^-jj$ process after imposing the cuts of Eqs. (10)-(18), a b -veto, a CJV, and requiring $p_T(\ell) > 100$ GeV. Plotted are results for the heavy Higgs boson scenario, the Higgsless Kaluza-Klein model, and the relevant SM backgrounds.

scattering. We did not impose further leptonic cuts for the $ZZjj$ and $W^\pm Zjj$ channels, because the amount of improvement in the significance of the signal would be marginal. However, in the case of $pp \rightarrow W^+W^-jj$ additional measures are necessary to suppress the overwhelming $t\bar{t} + \text{jets}$ backgrounds.

VI. CENTRAL JET VETO: QCD-induced processes tend to exhibit more jet activity in the central rapidity region than VBF reactions with colorless weak boson exchange in the t -channel. A central jet veto (CJV) can therefore be applied to reduce QCD backgrounds by eliminating events where in addition to the tagging jets at high rapidity secondary jets with a high transverse momentum are found in the central regions of the detector.

We veto any such activity by discarding all events with an extra veto jet of

$$p_{T_j}^{\text{veto}} > 25 \text{ GeV}, \quad (25)$$

located in the gap region between the two tagging jets,

$$\eta_{j,\text{min}}^{\text{tag}} < \eta_j^{\text{veto}} < \eta_{j,\text{max}}^{\text{tag}}. \quad (26)$$

In our simulations we do not yet model extra QCD radiation which might be subject to the central jet veto. Such refinements are beyond the scope of the present work. However, the $t\bar{t}j$ and $t\bar{t}jj$ background processes typically have additional b -quark jets from top-quark decay in the central region. The CJV thus is very effective in reducing these backgrounds.

| $p_{T_j}^{veto}$ [GeV] | $1.4 < \eta_j^{veto} < 2.4$ | $ \eta_j^{veto} < 1.4$ |
|------------------------|-------------------------------|-------------------------|
| 30 - 50 | 60% | 70% |
| 50 - 80 | 65% | 75% |
| 80 - 120 | 70% | 80% |
| 120 - 170 | 70% | 80% |
| > 170 | 65% | 75% |

Table 2: Assumed b -tagging efficiencies as functions of the transverse momentum of the jet for different rapidity ranges.

V. b -TAGGING JET VETO: Discrimination between jets originating from b -quarks and those emerging from light quarks or gluons by efficient b -tagging helps additionally to suppress $t\bar{t}$ + jets backgrounds in the W^+W^-jj channel: we eliminate any events where at least one of the tagging jets is identified as arising from a b -quark. We use the results of a CMS analysis [76] for our assumptions on b -veto efficiencies and mis-tagging probabilities. For a 10% mis-tagging probability per jet one finds b -veto efficiencies in the range 60% – 80%, depending on the transverse momentum and pseudorapidity of the jet as listed in Tab. 2.

4 Results and Discussion

We now turn to a discussion of numerical results for the signal and background processes of the scenarios discussed in the previous sections. In all cases the cross sections correspond to two generations of charged leptons and three neutrino species for $Z \rightarrow \bar{\nu}\nu$. They are listed in Tables 3–7 for all processes contributing to a specific leptonic final state, after different sets of selection cuts have been applied. The impact on inclusive cross sections of only the VBF cuts or only the leptonic cuts is shown in the lines labeled “INC. + VBF” and “INC. + LEP.”, respectively. In each case, we consider the QCD $VVjj$ background, EW $VVjj$ production assuming a light or a heavy Higgs boson, and a Warped Higgsless scenario with additional spin-one resonances. For the W^+W^-jj channel also the $t\bar{t}$ + jets background is given and the impact of CJV and b -veto cuts on the cross section after inclusive and VBF cuts is also shown. In Table 8, results for $t\bar{t}$, $t\bar{t}j$, and $t\bar{t}jj$ production are listed separately to better illustrate the impact of the individual contributions.

In all channels, VBF cuts reduce the QCD $VVjj$ backgrounds efficiently, decreasing inclusive production rates by factors of 25 – 85 as shown in the respective second lines of Tables 3–7. VBF cuts are even more efficient in the case of the $t\bar{t}$, $t\bar{t}j$ and $t\bar{t}jj$ background processes, as illustrated by Table 8. At the same time, rates for the heavy and light Higgs boson scenarios as well as for the Higgsless Kaluza-Klein model have decreased by a factor of 2 – 3 only.

Imposing leptonic cuts, on the other hand, helps to suppress EW backgrounds, while

| Level of cuts | QCD | VBF $m_H = 100 \text{ GeV}$ | VBF $m_H = 1 \text{ TeV}$ | KK |
|-------------------|---------|--------------------------------|------------------------------|---------|
| INCLUSIVE | 3.83 | 0.2323 | 0.3101 | 0.2725 |
| INC. + VBF | 0.0752 | 0.0883 | 0.1503 | 0.11152 |
| INC. + LEP. | 0.3755 | 0.02827 | 0.08302 | 0.04227 |
| INC. + VBF + LEP. | 0.00951 | 0.01171 | 0.05948 | 0.02147 |

Table 3: *Cross sections (in fb) for various $ZZjj \rightarrow 4\ell jj$ production processes with different Higgs boson masses and the Higgsless Kaluza-Klein scenario, after different levels of selection cuts have been applied, as defined in Section 3. Statistical errors in all cases are well below 0.5%.*

the respective signal processes remain substantial, as apparent from the third rows of Tables 3–7. Combining the leptonic and VBF cuts one finds sufficient background suppression for the $ZZjj$ and $WZjj$ final states, as shown in the fourth rows of Tables 3–6. For the $t\bar{t}$ + jets backgrounds to W^+W^-jj final states the impact of the leptonic cuts is even more pronounced than the effect of the VBF cuts. However, total rates are still much higher for the backgrounds than for the corresponding signal process. Thus, additional cuts have to be applied for the W^+W^-jj production mode. In order to reduce the large $t\bar{t}$ + jets backgrounds we make use of a b -veto and a CJV. We discard all events where one or both tagging jets can be identified as b jets, allowing for an overall mis-tagging probability of 10% for light partons with $p_T > 30 \text{ GeV}$ and $|\eta| < 2.4$. This results in a reduction of less than 10% for the signal and all backgrounds apart from $t\bar{t}$ + jets. The b -veto reduces these top-induced backgrounds by a factor of 2 – 4. The CJV is particularly efficient for the $t\bar{t}jj$ process. In this case, an additional reduction factor of 18 is obtained. The last row of Table 8 shows that after the application of all cuts the $t\bar{t}$ + jets background rates are comparable in size to those of the other individual backgrounds.

In Tables 9 and 10, the signal and combined background cross sections σ_S and σ_B are listed together with the ratios S/B , S/\sqrt{B} , and $S/\sqrt{S+B}$, where S and B denote signal and background rates, respectively. They are calculated for a luminosity of 300 fb^{-1} from the cross sections tabulated in Tables 3–8, after all selection cuts have been applied, with the signal defined according to Eqs. (5) and (6). The W^-Zjj channel exhibits features very similar to the related W^+Zjj mode, while its production rates are always smaller by approximately a factor of 2, which is due to the size of the parton distribution functions of the dominant subprocesses for the respective production modes. In Tables 9 and 10 we therefore combine the W^+Zjj and the W^-Zjj channels to enhance the statistical significance of the $W^\pm Zjj$ mode.

Considering the SM with a heavy Higgs boson as a prototype for scenarios with a broad scalar, iso-scalar resonance, an indicator for the LHC sensitivity is provided by the cross section enhancement in the $ZZjj$ and W^+W^-jj channels for VBF with $m_H = 1 \text{ TeV}$.

| Level of cuts | QCD | VBF $m_H = 100$ GeV | VBF $m_H = 1$ TeV | KK |
|-------------------|--------|------------------------|----------------------|---------|
| INCLUSIVE | 36.13 | 1.961 | 2.482 | 2.260 |
| INC. + VBF | 0.867 | 0.7788 | 1.196 | 0.9531 |
| INC. + LEP. | 1.717 | 0.1163 | 0.4230 | 0.1852 |
| INC. + VBF + LEP. | 0.0518 | 0.04907 | 0.3194 | 0.09883 |

Table 4: Cross sections (in fb) for various $ZZjj \rightarrow 2\ell 2\nu jj$ production processes with different Higgs boson masses and the Higgsless Kaluza-Klein scenario, after different levels of selection cuts have been applied. Statistical errors in all cases are well below 0.5%.

| Level of cuts | QCD | VBF $m_H = 100$ GeV | VBF $m_H = 1$ TeV | KK |
|-------------------|--------|------------------------|----------------------|--------|
| INCLUSIVE | 54.96 | 1.834 | 1.897 | 2.718 |
| INC. + VBF | 2.189 | 0.6933 | 0.7382 | 1.273 |
| INC. + LEP. | 4.301 | 0.2382 | 0.2599 | 0.9161 |
| INC. + VBF + LEP. | 0.1719 | 0.0888 | 0.1077 | 0.5435 |

Table 5: Cross sections (in fb) for various W^+Zjj production processes with different Higgs boson masses and the Higgsless Kaluza-Klein scenario, after different levels of selection cuts have been applied. Statistical errors in all cases are well below 0.5%.

| Level of cuts | QCD | VBF $m_H = 100 \text{ GeV}$ | VBF $m_H = 1 \text{ TeV}$ | KK |
|-------------------|--------|--------------------------------|------------------------------|--------|
| INCLUSIVE | 37.48 | 1.1072 | 1.1445 | 1.5863 |
| INC. + VBF | 1.304 | 0.3798 | 0.4048 | 0.6784 |
| INC. + LEP. | 2.385 | 0.1233 | 0.1344 | 0.4828 |
| INC. + VBF + LEP. | 0.0838 | 0.04324 | 0.05272 | 0.2758 |

Table 6: Cross sections (in fb) for various W^-Zjj production processes with different Higgs boson masses and the Higgsless Kaluza-Klein scenario, after different levels of selection cuts have been applied. Statistical errors in all cases are well below 0.5%.

| Level of cuts | $t\bar{t} + \text{jets}$ | QCD | VBF $m_H = 100 \text{ GeV}$ | VBF $m_H = 1 \text{ TeV}$ | KK |
|---------------------|--------------------------|-------|--------------------------------|------------------------------|-------|
| INCLUSIVE | 28710 | 504.5 | 16.76 | 18.55 | 19.80 |
| INC. + VBF | 228.667 | 5.918 | 5.063 | 6.165 | 6.536 |
| INC. + LEP. | 27.4090 | 6.72 | 0.828 | 1.620 | 1.702 |
| INC. + VBF + b-VETO | 64.055 | 5.473 | 4.77 | 5.86 | 6.22 |
| INC. + VBF + CJV | 43.197 | — | — | — | — |
| ... + b-VETO | 24.025 | 5.47 | 4.772 | 5.856 | 6.217 |
| ... + LEPTONIC | 0.381644 | 0.202 | 0.1969 | 0.7011 | 0.588 |

Table 7: Cross sections (in fb) for various W^+W^-jj production processes with different Higgs boson masses and the Higgsless Kaluza-Klein scenario after different levels of selection cuts have been applied. Also given is the sum of the $t\bar{t}$, $t\bar{t}j$ and $t\bar{t}jj$ backgrounds for $m_t = 172.5 \text{ GeV}$ and $m_H = 100 \text{ GeV}$. Statistical errors are well below 0.5% for the W^+W^-jj processes and below 1% for $t\bar{t} + \text{jets}$.

| Level of cuts | $t\bar{t}$ | $t\bar{t}j$ | $t\bar{t}jj$ | Sum ($t\bar{t} + \text{jets}$) |
|---------------------|------------|-------------|--------------|----------------------------------|
| INCLUSIVE | 13850 | 13260 | 1600 | 28710 |
| INC. + VBF | 1.967 | 131.4 | 95.3 | 228.667 |
| INC. + LEP. | 0.0490 | 3.02 | 24.34 | 27.4090 |
| INC. + VBF + b-VETO | 0.915 | 38.57 | 24.57 | 64.055 |
| INC. + VBF + CJV | 1.967 | 35.82 | 5.41 | 43.197 |
| ... + b-VETO | 0.915 | 18.24 | 4.87 | 24.025 |
| ... + LEPTONIC | 0.000844 | 0.0518 | 0.329 | 0.381644 |

Table 8: Cross sections (in fb) for the $t\bar{t} + nj$ production processes, where $n = 0, 1, 2$, with $m_t = 172.5$ GeV and $m_H = 100$ GeV, after different levels of selection cuts have been applied. Statistical errors in all cases are well below 1%.

| Process | σ_S | σ_B | S/B | S/\sqrt{B} | $S/\sqrt{S+B}$ | N_{signal}^{SM} | $N_{\text{bkgd.}}$ |
|------------------------------|------------|------------|-------|--------------|----------------|--------------------------|--------------------|
| $ZZjj \rightarrow 4\ell jj$ | 0.048 | 0.021 | 2.2 | 5.7 | 3.1 | 14 | 6 |
| $ZZjj \rightarrow 2l2\nu jj$ | 0.27 | 0.10 | 2.7 | 14.8 | 7.7 | 81 | 30 |
| W^+W^-jj | 0.51 | 0.78 | 0.6 | 10.0 | 7.8 | 153 | 234 |
| $W^\pm Zjj$ | 0.031 | 0.386 | 0.1 | 0.9 | 0.8 | 9 | 116 |

Table 9: Cross sections for the heavy Higgs boson signal and overall background for various channels (in fb) after all selection cuts have been applied. Also listed are several ratios for signal and background rates together with the number of signal and background events for an assumed integrated luminosity of 300 fb^{-1} at the LHC.

| Process | σ_S | σ_B | S/B | S/\sqrt{B} | $S/\sqrt{S+B}$ | N_{signal}^{SM} | $N_{\text{bkgd.}}$ |
|----------------------------------|------------|------------|-------|--------------|----------------|--------------------------|--------------------|
| $W^\pm Zjj$ | 0.68 | 0.39 | 1.7 | 18.9 | 11.4 | 204 | 117 |
| W^+W^-jj | 0.40 | 0.78 | 0.5 | 7.9 | 6.4 | 120 | 234 |
| $ZZjj \rightarrow 4\ell jj$ | 0.009 | 0.021 | 0.4 | 1.1 | 0.9 | 3 | 6 |
| $ZZjj \rightarrow 2\ell 2\nu jj$ | 0.05 | 0.10 | 0.5 | 2.7 | 2.2 | 15 | 30 |

Table 10: Cross sections for the Higgsless Kaluza-Klein scenario and overall background for various channels (in fb), after all selection cuts have been applied. Also listed are several ratios for signal and background rates together with the number of signal and background events for an assumed integrated luminosity of 300 fb^{-1} at the LHC.

These two channels provide excellent possibilities for the study of strongly interacting gauge boson systems via scalar resonances, see Table 9. Particularly encouraging is the signal rate for the $ZZjj \rightarrow 2\ell 2\nu jj$ mode. The absence of a significant enhancement in the $WZjj$ channel is a crucial factor in identifying the iso-scalar character of such a resonance.

A 5σ statistical significance, defined here as $S/\sqrt{B} = 5\sigma$, for a signal with a heavy Higgs boson can already be obtained with an integrated luminosity of 240 fb^{-1} , 35 fb^{-1} , and 75 fb^{-1} , respectively, for the $ZZjj \rightarrow 4\ell jj$, the $ZZjj \rightarrow 2\ell 2\nu jj$, and the W^+W^-jj processes. It should be noted, however, that event rates for $ZZ \rightarrow 4$ charged leptons are very small, and Poisson significances would be substantially smaller. $W^\pm Zjj$ production, with heavy Higgs boson contributions entering via t - and u -channel exchange diagrams only, is hardly affected by the Higgs resonance. No significant deviation from background is expected in this channel for the heavy Higgs scenario.

In contrast, the Warped Higgsless Kaluza-Klein model with a tower of additional vector resonances can be studied most easily via the $W^\pm Zjj$ and W^+W^-jj modes, as shown in Table 10. In the $W^\pm Zjj$ channel, the first of the W_k resonances, W_2 , can be observed. Two Z_k resonances, which are difficult to disentangle, Z_2 and Z_3 , are accessible in the W^+W^-jj process. A 5σ statistical significance for the Higgsless signal, calculated using the same formula as in the heavy Higgs boson case, can be obtained with a minimal integrated luminosity of 25 fb^{-1} and 125 fb^{-1} , respectively, for the $W^\pm Zjj$ and the W^+W^-jj processes for our choice of the model parameter $R = 9.75 \times 10^{-9}$. The two $ZZjj$ channels are much less sensitive to this model, since in these production modes the W_k Kaluza-Klein excitations occur only in t - and u -channel exchange diagrams. A similar study for the W^+W^-jj channel in the context of a Higgsless Kaluza-Klein scenario has been performed in Ref. [77], yielding a signal significance of comparable size.

Altogether, a reasonable number of signal events can be achieved at the LHC for an integrated luminosity of 300 fb^{-1} , see Tables 9 and 10. Our cuts have considerably

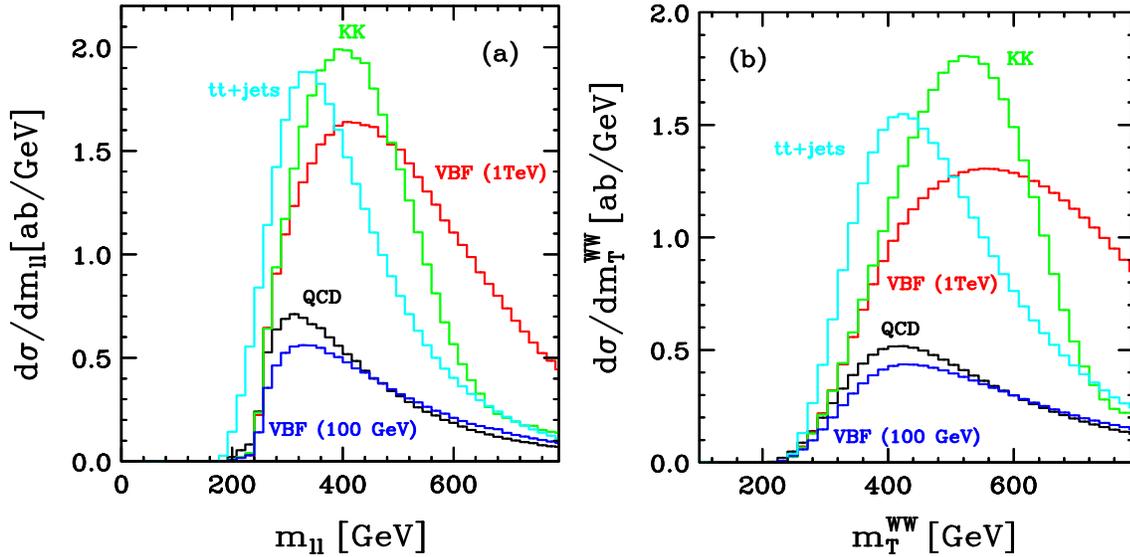


Figure 7: *Invariant mass distribution of the two charged leptons (a) and cluster transverse mass distribution of the W^+W^- system (b) for the $pp \rightarrow W^+W^-jj$ process after imposing all levels of cuts.*

reduced backgrounds, so that even a relatively small number of excess signal events should be observable. The $W^\pm Zjj$ channel per se is not sensitive to a scalar resonance like a 1 TeV Higgs boson. Similarly, the $ZZjj$ mode is barely sensitive to the W^\pm KK mode. It is however the combined analysis of all channels that eventually allows to select between the models as distinct realizations of electroweak symmetry breaking.

In addition to the signal and background rates listed above, we have studied various kinematic distributions for each production process. Representative results are presented in the following, with histograms corresponding to the cross sections listed in Tables 3–7. Due to the large $t\bar{t}$ + jets cross sections, the W^+W^-jj mode constitutes the biggest challenge. In Fig. 5 (a), we have shown the invariant mass distribution of the two charged leptons in $pp \rightarrow W^+W^-jj$ after the application of general selection cuts. At this level of cuts, the $t\bar{t}$ + jets background was still sizeable. If additionally all process-specific cuts of Eq. (24) are imposed, the $t\bar{t}$ + jets cross sections can be further reduced, while the signal distributions are barely affected, cf. Fig. 7 (a). In Fig. 7 (b), the cluster transverse mass of the produced W^+W^- system, defined by

$$m_T^2(WW) = [\sqrt{m^2(\ell\ell) + p_T^2(\ell\ell)} + |p_T^{miss}|]^2 - [\vec{p}_T(\ell\ell) + \vec{p}_T^{miss}]^2, \quad (27)$$

is shown. Similar to the $m_{\ell\ell}$ distribution, QCD and EW $VVjj$ backgrounds are small, and $t\bar{t}$ + jets is well under control. The Kaluza-Klein scenario we consider exhibits a pronounced resonance peak, well above the backgrounds. The heavy Higgs cross section is distributed more broadly in $m_T(WW)$, but still well distinguishable.

The heavy Higgs scenario can also be well identified in the $ZZjj$ production modes, which are, however, less sensitive to Kaluza-Klein resonances as discussed above. Figure 8 (a) shows the invariant mass distribution of the four charged leptons in $pp \rightarrow$

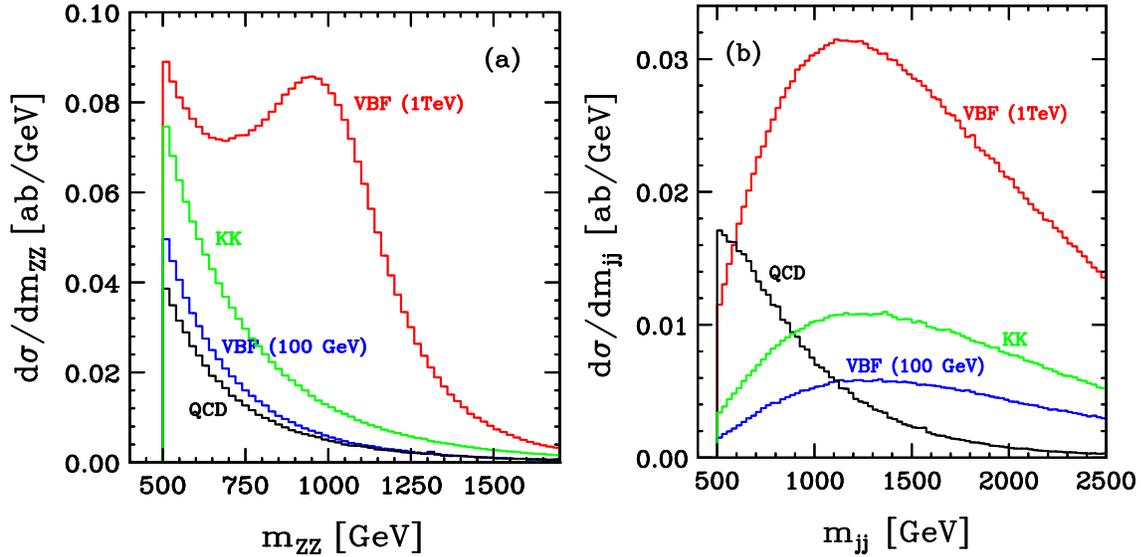


Figure 8: *Invariant mass distribution of the four charged leptons (a) and of the two tagging jets (b) for the $pp \rightarrow ZZjj \rightarrow 4\ell jj$ process after imposing all levels of cuts.*

$ZZjj \rightarrow 4\ell jj$ after all process-specific selection cuts have been applied. The impact of the heavy Higgs resonance is evident at $m_{ZZ} = 1000$ GeV, where all backgrounds are small. The Kaluza-Klein cross section exceeds the QCD and continuum EW results, but does not exhibit a characteristic resonance behavior. The Higgsless model's excess over the EW continuum can be understood from the absence of an iso-scalar exchange contribution to weak gauge boson scattering, which in the SM enters with an amplitude of opposite phase as the gauge boson exchange graphs. Another distinction can be observed in the invariant mass distribution of the tagging jets displayed in Fig. 8 (b). The excess events from enhanced VBF production correlate with large dijet invariant masses, while the QCD background mostly resides at $m_{jj} < 1$ TeV and rapidly falls off as m_{jj} increases.

This behavior is completely independent of the gauge boson decay, as illustrated by Fig. 9 (a), where the m_{jj} distribution is shown for the $ZZjj \rightarrow 2\ell 2\nu jj$ mode. Apparently, the shapes of the invariant mass distribution are identical to the $ZZjj \rightarrow 4\ell jj$ case. The overall normalization differs due to the $Z \rightarrow \nu\bar{\nu}$ branching ratio exceeding the one for $Z \rightarrow \ell^+\ell^-$. Fig. 9 (b) illustrates the cluster transverse mass of the ZZ system in the $2\ell 2\nu jj$ decay mode. Similar to the m_{ZZ} distribution in $pp \rightarrow ZZjj \rightarrow 4\ell jj$, the heavy Higgs cross section dominates over all backgrounds. However, the Higgs resonance does not manifest itself in a pronounced peak, but is smeared out over a large range in $m_T(ZZ)$.

The most distinctive signatures of iso-vector Kaluza-Klein excitations are observed in the $W^\pm Zjj$ mode, since these heavy spin-one states contribute to resonant $W^\pm Z$ scattering, which does not occur in scenarios with a scalar Higgs boson. This is illustrated by Fig. 10 (a), which shows the cluster transverse mass distribution for the $W^+ Zjj$ case. The $m_T(WZ)$ distribution exhibits a characteristic peak at about 700 GeV due to the impact of the first massive Kaluza-Klein excitation W_2 . The QCD and EW backgrounds as well as the heavy Higgs cross section are smoothly distributed over $m_T(WZ)$. As

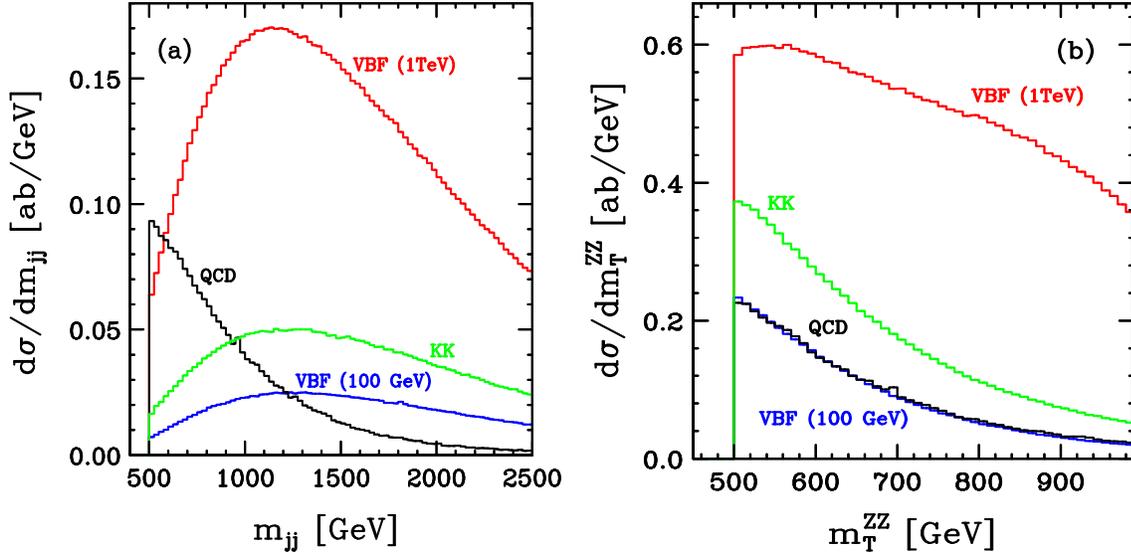


Figure 9: Invariant mass distribution of the two tagging jets (a) and cluster transverse mass distribution of the ZZ system (b) for the $pp \rightarrow ZZjj \rightarrow 2\ell 2\nu jj$ process after imposing all levels of cuts.

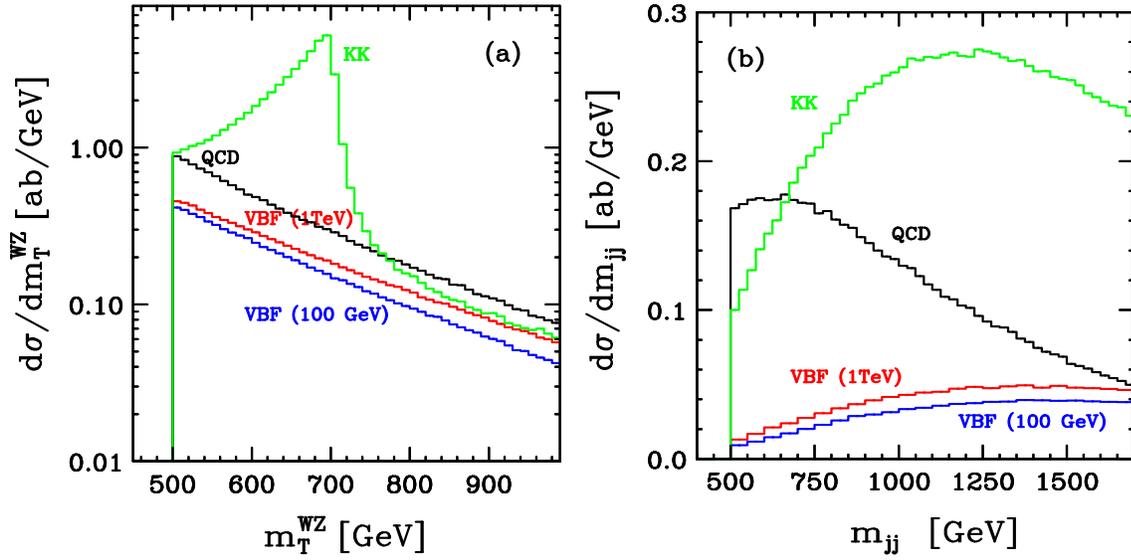


Figure 10: Cluster transverse mass distribution of the W^+Z system (a) and invariant mass distribution of the two tagging jets (b) for the $pp \rightarrow W^+Zjj$ process after imposing all levels of cuts.

expected, the VBF cross sections for the $m_H = 100$ GeV and the $m_H = 1$ TeV case are very similar, because the scalar Higgs boson contributes to W^+Z scattering only via non-resonant diagrams. Also for W^+Zjj production, the invariant mass distribution of the two tagging jets, as shown in Fig. 10 (b) shows the characteristic distinction between QCD backgrounds and VBF processes. Shapes for W^-Zjj production are almost identical to the W^+Zjj case and therefore not displayed here.

In summary, signatures of a heavy Higgs boson scenario as well as of Kaluza-Klein excitations should be observable in gauge boson scattering processes at the LHC. While an iso-scalar resonance like a heavy Higgs boson manifests itself most distinctively in the W^+W^-jj and the $ZZjj$ channels, a Higgsless scenario with iso-vector resonances, such as the Kaluza-Klein model which we have considered, can be studied best in the $W^\pm Zjj$ channel. A multivariate analysis with full detector simulation might yield a slightly different shape of the distributions and total rates. However, our conclusions on the observability of strong interaction signatures should remain valid.

5 Conclusions

The origin of electroweak symmetry breaking is still unknown. While a perturbative Higgs sector with a light SM-like Higgs boson is a preferred solution at present, experimental tests are needed to probe other scenarios where new strong interactions are responsible for the weak gauge boson masses. With the luminosity and energy available at the LHC the search for such scenarios becomes feasible via studies of weak boson scattering as realized in vector boson fusion processes.

We have performed a broad study of the possibility to probe the strongly interacting electroweak symmetry breaking sector in gauge boson scattering reactions leading to $ZZjj$, $W^\pm Zjj$ and W^+W^-jj final states at the LHC, using only leptonic decay modes. By performing full tree-level simulations of the dominant backgrounds, at a level where double forward jet-tagging acceptances can be reliably calculated, we have established selection cuts which allow to isolate the strong weak boson scattering signals. We have found that, for each of the models we considered, an observable excess of events occurs in at least one of the production modes, after three years of running with an annual luminosity of 100 fb^{-1} . As compared to Ref. [19], higher signal rates for a SM-like 1 TeV Higgs boson could be obtained with loosened leptonic cuts by tagging two jets of high transverse momenta. Defining such high acceptance signal regions for the various vector boson fusion channels and providing realistic background estimates in these regions was a second goal of our work. These results can now be used for further studies, be it of other scenarios for weak boson scattering, for the assessment of higher order QCD corrections, or for refinements such as improved central jet veto techniques. We should stress that our analysis has been conservative, as a central jet veto offers promising prospects for a further enhancement of the signal-to-background ratio. From related studies on $pp \rightarrow Z + 2\text{jets}$ and $pp \rightarrow H + 2\text{jets}$ [78, 79] one expects additional suppression of the QCD backgrounds by about 70%, while around 90% of the VBF signal are retained when a central jet veto is imposed.

In the search regions defined in Sec. 3, ignoring improvements from a central jet veto on the QCD backgrounds, even the SM light Higgs scenario yields weak boson fusion signal cross sections which are of the same order as the QCD backgrounds, with signal to background ratios of 1:1 for $ZZjj$ final states, 1:2 for the higher statistics $WZjj$ mode and 1:3 for W^+W^-jj . With expected statistical samples of 36, 116 and 234 signal plus background events, respectively, in 300 fb^{-1} of data, an increase of the VBF cross section by a factor of two in any of these channels should be observable at the LHC. Our conclusions are thus valid beyond the details of the models considered and will certainly apply to any scalar or vector resonances of sufficient size but general peak location.

Should a light Higgs boson be found rather than first signatures of strong gauge boson interactions, the precise measurement of event rates at high invariant mass is essential to ensure that the Higgs boson indeed cures the bad high energy behavior of gauge boson scattering processes as predicted by the SM. Given the results mentioned above, a measurement of the high vector boson pair invariant mass cross section in several vector boson fusion channels, with a statistical accuracy of order 30%, seems possible after several years of LHC running. Improvements on this result appear feasible, in particular with a more realistic calculation of central jet veto acceptances for QCD induced background events, which make use of the elevated level of central soft gluon radiation in such events. We leave such refinements to future work.

Acknowledgments

We are grateful to N. Kauer for making his computer code for $t\bar{t}$ +jets available for comparison with the HELAC-PHEGAS package. We furthermore would like to thank G. Klämke for interesting discussions.

Our work was supported by the Japan Society for the Promotion of Science (JSPS) and by the Deutsche Forschungsgemeinschaft via the Sonderforschungsbereich/Transregio SFB/TR-9 “Computational Particle Physics”. M. W. was funded in part by the RTN European Programme MRTN-CT-2006-035505 HEPTOOLS - Tools and Precision Calculations for Physics Discoveries at Colliders, B. J. by the Initiative and Networking Fund of the Helmholtz Association, contract HA-101 (“Physics at the Terascale”), and C. E. by “CETA Strukturiertes Promotionskolleg”.

References

- [1] **ATLAS** Collaboration, “ATLAS detector and physics performance”. Technical design report. Vol. 2, . CERN-LHCC-99-15.
- [2] **CMS** Collaboration, G. L. Bayatian et. al., “CMS technical design report, volume II: Physics performance”, *J. Phys.* **G34** (2007) 995.
- [3] M. J. G. Veltman, “Second Threshold in Weak Interactions”, *Acta Phys. Polon.* **B8** (1977) 475.

- [4] B. W. Lee, C. Quigg and H. B. Thacker, “The Strength of Weak Interactions at Very High-Energies and the Higgs Boson Mass”, *Phys. Rev. Lett.* **38** (1977) 883.
- [5] B. W. Lee, C. Quigg and H. B. Thacker, “Weak Interactions at Very High-Energies: The Role of the Higgs Boson Mass”, *Phys. Rev.* **D16** (1977) 1519.
- [6] F. Englert and R. Brout, “Broken Symmetry and the Mass of Gauge Vector Mesons”, *Phys. Rev. Lett.* **13** (1964) 321.
- [7] P. W. Higgs, “Broken Symmetries and the Masses of Gauge Bosons”, *Phys. Rev. Lett.* **13** (1964) 508.
- [8] G. S. Guralnik, C. R. Hagen and T. W. B. Kibble, “Global Conservation Laws and Massless Particles”, *Phys. Rev. Lett.* **13** (1964) 585.
- [9] M. S. Chanowitz and M. K. Gaillard, “Multiple Production of W and Z as a Signal of New Strong Interactions”, *Phys. Lett.* **B142** (1984) 85.
- [10] M. S. Chanowitz and M. K. Gaillard, “The TeV Physics of Strongly Interacting W’s and Z’s”, *Nucl. Phys.* **B261** (1985) 379.
- [11] M. S. Chanowitz, “Electroweak Symmetry Breaking: Unitarity, Dynamics, Experimental Prospects”, *Ann. Rev. Nucl. Part. Sci.* **38** (1988) 323.
- [12] C. Csaki, C. Grojean, H. Murayama, L. Pilo and J. Terning, “Gauge theories on an interval: Unitarity without a Higgs”, *Phys. Rev.* **D69** (2004) 055006, [[hep-ph/0305237](#)].
- [13] C. Csaki, C. Grojean, L. Pilo and J. Terning, “Towards a realistic model of Higgsless electroweak symmetry breaking”, *Phys. Rev. Lett.* **92** (2004) 101802, [[hep-ph/0308038](#)].
- [14] K. Agashe, A. Delgado, M. J. May and R. Sundrum, “RS1, custodial isospin and precision tests”, *JHEP* **0308** (2003) 050, [[hep-ph/0308036](#)].
- [15] L. Randall and R. Sundrum, “A large mass hierarchy from a small extra dimension”, *Phys. Rev. Lett.* **83** (1999) 3370, [[hep-ph/9905221](#)].
- [16] V. D. Barger, K. Cheung, T. Han and D. Zeppenfeld, “Single forward jet tagging and central jet vetoing to identify the leptonic WW decay mode of a heavy Higgs boson”, *Phys. Rev.* **D44** (1991) 2701.
- [17] V. D. Barger, K. Cheung, T. Han and D. Zeppenfeld, “Finding the leptonic WW decay mode of a heavy Higgs boson at hadron supercolliders”, *Phys. Rev.* **D48** (1993) 5433, [[hep-ph/9305277](#)].
- [18] J. Bagger et. al., “The Strongly interacting WW system: Gold plated modes”, *Phys. Rev.* **D49** (1994) 1246, [[hep-ph/9306256](#)].

- [19] J. Bagger et. al., “LHC analysis of the strongly interacting WW system: Gold plated modes”, *Phys. Rev.* **D52** (1995) 3878, [hep-ph/9504426].
- [20] D. L. Rainwater and D. Zeppenfeld, “Searching for $H \rightarrow \gamma\gamma$ in weak boson fusion at the LHC”, *JHEP* **9712** (1997) 005, [hep-ph/9712271].
- [21] D. L. Rainwater, D. Zeppenfeld and K. Hagiwara, “Searching for $H \rightarrow \tau\tau$ in weak boson fusion at the LHC”, *Phys. Rev.* **D59** (1998) 014037, [hep-ph/9808468].
- [22] D. L. Rainwater and D. Zeppenfeld, “Observing $H \rightarrow W^{(*)}W^{(*)} \rightarrow e^\pm\mu^\mp\not{p}_T$ in weak boson fusion with dual forward jet tagging at the CERN LHC”, *Phys. Rev.* **D60** (1999) 113004, [hep-ph/9906218].
- [23] N. Kauer, T. Plehn, D. L. Rainwater and D. Zeppenfeld, “ $H \rightarrow W^+W^-$ as the discovery mode for a light Higgs boson”, *Phys. Lett.* **B503** (2001) 113, [hep-ph/0012351].
- [24] N. Kauer, “Top pair production beyond double-pole approximation: $pp, p\bar{p} \rightarrow 6$ fermions and 0, 1 or 2 additional partons”, *Phys. Rev.* **D67** (2003) 054013, [hep-ph/0212091].
- [25] E. Accomando, A. Ballestrero, S. Bolognesi, E. Maina and C. Mariotti, “Boson boson scattering and Higgs production at the LHC from a six fermion point of view: Four jets + $l\nu$ processes at $O(\alpha_{em}^6)$ ”, *JHEP* **0603** (2006) 093, [hep-ph/0512219].
- [26] A. Alves, O. J. P. Eboli, M. C. Gonzalez-Garcia and J. K. Mizukoshi, “Deciphering the spin of new resonances in Higgsless models”, [0810.1952].
- [27] A. Birkedal, K. Matchev and M. Perelstein, “Collider phenomenology of the Higgsless models”, *Phys. Rev. Lett.* **94** (2005) 191803, [hep-ph/0412278].
- [28] H.-J. He et. al., “LHC Signatures of New Gauge Bosons in Minimal Higgsless Model”, *Phys. Rev.* **D78** (2008) 031701, [0708.2588].
- [29] H. Davoudiasl, J. L. Hewett, B. Lillie and T. G. Rizzo, “Higgsless electroweak symmetry breaking in warped backgrounds: Constraints and signatures”, *Phys. Rev.* **D70** (2004) 015006, [hep-ph/0312193].
- [30] K. Agashe et. al., “LHC Signals for Warped Electroweak Neutral Gauge Bosons”, *Phys. Rev.* **D76** (2007) 115015, [0709.0007].
- [31] K. Agashe, S. Gopalakrishna, T. Han, G.-Y. Huang and A. Soni, “LHC Signals for Warped Electroweak Charged Gauge Bosons”, [0810.1497].
- [32] E. Farhi and L. Susskind, “Technicolor”, *Phys. Rept.* **74** (1981) 277.
- [33] D. B. Kaplan, H. Georgi and S. Dimopoulos, “Composite Higgs Scalars”, *Phys. Lett.* **B136** (1984) 187.

- [34] D. B. Kaplan and H. Georgi, “SU(2) \times U(1) Breaking by Vacuum Misalignment”, *Phys. Lett.* **B136** (1984) 183.
- [35] A. Manohar and H. Georgi, “Chiral Quarks and the Nonrelativistic Quark Model”, *Nucl. Phys.* **B234** (1984) 189.
- [36] J. Erler and P. Langacker, “Electroweak Physics”, *Acta Phys. Polon. B* **39** (2008) 2595, [0807.3023].
- [37] R. Barate et al. “Search for the standard model Higgs boson at LEP”, *Phys. Lett. B* **565** (2003) 61, [hep-ex/0306033].
- [38] M. E. Peskin and T. Takeuchi, “A New constraint on a strongly interacting Higgs sector”, *Phys. Rev. Lett.* **65** (1990) 964.
- [39] M. E. Peskin and T. Takeuchi, “Estimation of oblique electroweak corrections”, *Phys. Rev.* **D46** (1992) 381.
- [40] R. Barbieri, A. Pomarol, R. Rattazzi and A. Strumia, “Electroweak symmetry breaking after LEP1 and LEP2”, *Nucl. Phys. B* **703** (2004) 127, [hep-ph/0405040].
- [41] M. E. Peskin and J. D. Wells, “How can a heavy Higgs boson be consistent with the precision electroweak measurements?”, *Phys. Rev. D* **64** (2001) 093003, [hep-ph/0101342].
- [42] K. Arnold et al., “VBFNLO: A parton level Monte Carlo for processes with electroweak bosons”, [0811.4559];
<http://www-itp.particle.uni-karlsruhe.de/~vbfnlweb/>.
- [43] C. Englert, “Spin 1 Resonances in Vector Boson Fusion in Warped Higgsless Models”, Diploma Thesis, Karlsruhe University 2007:
<http://www-itp.particle.uni-karlsruhe.de/diplomatheses.en.shtml>.
- [44] C. Englert, B. Jager and D. Zeppenfeld, “QCD Corrections to Vector-Boson Fusion Processes in Warped Higgsless Models”, *JHEP* **0903** (2009) 060, [0812.2564].
- [45] J. M. Maldacena, “The large N limit of superconformal field theories and supergravity”, *Adv. Theor. Math. Phys.* **2** (1998) 231, [hep-th/9711200].
- [46] N. Arkani-Hamed, M. Porrati and L. Randall, “Holography and phenomenology”, *JHEP* **0108** (2001) 017, [hep-th/0012148].
- [47] R. Rattazzi and A. Zaffaroni, “Comments on the holographic picture of the Randall-Sundrum model”, *JHEP* **0104** (2001) 021, [hep-th/0012248].
- [48] R. S. Chivukula, H. J. He, M. Kurachi, E. H. Simmons and M. Tanabashi, “General Sum Rules for WW Scattering in Higgsless Models: Equivalence Theorem and Deconstruction Identities,” *Phys. Rev. D* **78** (2008) 095003, [arXiv:0808.1682].

- [49] N. Arkani-Hamed, A. G. Cohen and H. Georgi, “Electroweak symmetry breaking from dimensional deconstruction,” *Phys. Lett. B* **513** (2001) 232, [[hep-ph/0105239](#)].
- [50] G. Cacciapaglia, C. Csaki, C. Grojean and J. Terning, “Curing the ills of Higgsless models: The S parameter and unitarity”, *Phys. Rev.* **D71** (2005) 035015, [[hep-ph/0409126](#)].
- [51] R. Sekhar Chivukula, E. H. Simmons, H.-J. He, M. Kurachi and M. Tanabashi, “Ideal fermion delocalization in Higgsless models”, *Phys. Rev.* **D72** (2005) 015008, [[hep-ph/0504114](#)].
- [52] A. Kanaki and C. G. Papadopoulos, “Helac: A package to compute electroweak helicity amplitudes”, *Comput. Phys. Commun.* **132** (2000) 306, [[hep-ph/0002082](#)].
- [53] C. G. Papadopoulos, “Phegas: A phase space generator for automatic cross-section computation”, *Comput. Phys. Commun.* **137** (2001) 247, [[hep-ph/0007335](#)].
- [54] C. G. Papadopoulos and M. Worek, “Multi-parton cross sections at hadron colliders”, *Eur. Phys. J.* **C50** (2007) 843, [[hep-ph/0512150](#)].
- [55] A. Cafarella, C. G. Papadopoulos and M. Worek, “Helac-Phegas: a generator for all parton level processes”, [[0710.2427](#)].
- [56] <http://helac-phegas.web.cern.ch/helac-phegas/>.
- [57] J. Alwall et. al., “A standard format for les houches event files”, *Comput. Phys. Commun.* **176** (2007) 300, [[hep-ph/0609017](#)].
- [58] T. Gleisberg, F. Krauss, C. G. Papadopoulos, A. Schälicke and S. Schumann, “Cross sections for multi-particle final states at a linear collider”, *Eur. Phys. J.* **C34** (2004) 173, [[hep-ph/0311273](#)].
- [59] J. Alwall et. al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J.* **C53** (2008) 473, [[0706.2569](#)].
- [60] F. Maltoni and T. Stelzer, “Madevent: Automatic event generation with Madgraph”, *JHEP* **0302** (2003) 027, [[hep-ph/0208156](#)].
- [61] J. Alwall et. al., “MadGraph/MadEvent v4: The New Web Generation”, *JHEP* **0709** (2007) 028, [[0706.2334](#)].
- [62] J. Pumplin et. al., “New generation of parton distributions with uncertainties from global QCD analysis”, *JHEP* **0207** (2002) 012, [[hep-ph/0201195](#)].
- [63] D. Stump et. al., “Inclusive jet production, parton distributions, and the search for new physics”, *JHEP* **0310** (2003) 046, [[hep-ph/0303013](#)].

- [64] A. Denner, S. Dittmaier, M. Roth and D. Wackerroth, “Predictions for all processes $e^+e^- \rightarrow 4\text{fermions} + \gamma$ ”, *Nucl. Phys.* **B560** (1999) 33, [[hep-ph/9904472](#)].
- [65] A. Denner, S. Dittmaier, M. Roth and L. H. Wieders, “Electroweak corrections to charged-current $e^+e^- \rightarrow 4$ fermion processes: Technical details and further results”, *Nucl. Phys.* **B724** (2005) 247, [[hep-ph/0505042](#)].
- [66] A. Denner and S. Dittmaier, “The complex-mass scheme for perturbative calculations with unstable particles”, *Nucl. Phys. Proc. Suppl.* **160** (2006) 22, [[hep-ph/0605312](#)].
- [67] C. Oleari and D. Zeppenfeld, “Next-to-leading order QCD corrections to W and Z production via vector-boson fusion”, *Phys. Rev.* **D69** (2004) 093004, [[hep-ph/0310156](#)].
- [68] N. Kauer and D. Zeppenfeld, “Finite-width effects in top quark production at hadron colliders”, *Phys. Rev.* **D65** (2001) 014021, [[hep-ph/0107181](#)].
- [69] S. Catani, Y. L. Dokshitzer and B. R. Webber, “The k-perpendicular clustering algorithm for jets in deep inelastic scattering and hadron collisions”, *Phys. Lett.* **B 285** (1992) 291.
- [70] S. Catani, Y. L. Dokshitzer and B. R. Webber, “Longitudinally invariant k(t) clustering algorithms for hadron hadron collisions”, *Nucl. Phys.* **B 406** (1993) 187.
- [71] S. D. Ellis and D. E. Soper, “Successive combination jet algorithm for hadron collisions”, *Phys. Rev.* **D48** (1993) 3160, [[hep-ph/9305266](#)].
- [72] B. Jäger, C. Oleari and D. Zeppenfeld, “Next-to-leading order QCD corrections to W^+W^- production via vector-boson fusion”, *JHEP* **0607** (2006) 015, [[hep-ph/0603177](#)].
- [73] B. Jäger, C. Oleari and D. Zeppenfeld, “Next-to-leading order QCD corrections to Z boson pair production via vector-boson fusion”, *Phys. Rev.* **D73** (2006) 113006, [[hep-ph/0604200](#)].
- [74] G. Bozzi, B. Jäger, C. Oleari and D. Zeppenfeld, “Next-to-leading order QCD corrections to W^+Z and W^-Z production via vector-boson fusion”, *Phys. Rev.* **D75** (2007) 073004, [[hep-ph/0701105](#)].
- [75] M. Ciccolini, A. Denner and S. Dittmaier, “Electroweak and QCD corrections to Higgs production via vector-boson fusion at the LHC”, *Phys. Rev.* **D77** (2008) 013002, [[0710.4749](#)].
- [76] C. Weiser, “A Combined Secondary Vertex Based B-Tagging Algorithm in CMS”, *CMS NOTE* 2006/014.
- [77] R. Malhotra, “WW fusion in Higgsless models”, [[hep-ph/0611380](#)].

- [78] D. L. Rainwater, R. Szalapski and D. Zeppenfeld, “Probing color-singlet exchange in $Z + 2$ -jet events at the LHC”, *Phys. Rev.* **D54** (1996) 6680, [[hep-ph/9605444](#)].
- [79] D. L. Rainwater, “Intermediate-mass Higgs searches in weak boson fusion”, [[hep-ph/9908378](#)].