Higgsless electroweak symmetry breaking at the LHC

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Abstract. While the Higgs model is the best studied scenario of electroweak symmetry breaking, a number strongly-coupled models exist, predicting new signatures. Recent studies of WW and WZ final states at the ATLAS and CMS experiments are summarized and expected sensitivities are presented within the frameworks of the technicolor straw-man model and the electroweak chiral Lagrangian.

1. Introduction
Understanding the dynamics of electroweak symmetry breaking (EWSB) will be a principal goal for the ATLAS and CMS experiments at the Large Hadron Collider (LHC). While the physics of the EWSB in the minimal Standard Model (perhaps extended by super-symmetry) is based on a purely weakly-interacting Higgs sector [1], there is no fundamental reason for the existence of a unique elementary scalar particle. The mechanism for the symmetry breaking might rely on strong dynamics.

Unitarity violation in the scattering of longitudinal massive gauge bosons sets the scale for such strong dynamics to $\Lambda \sim 4\pi M_W/g \sim 1.5$ TeV, where $g$ is the $SU(2)_L$ gauge coupling. While precision electroweak constraints disfavor strongly coupled physics at this scale, various new models postpone unitarity violation by introducing new weakly-coupled particles appearing at the TeV scale. This contribution reviews some of the recent experimental developments in the planned searches for these particles at the ATLAS and CMS detectors.

2. Technirho search at CMS
Technicolor (TC) is one of the earliest models of strong symmetry breaking. Analogous to quantum chromodynamics, it introduces new massless fermions (“technifermions”) whose chiral symmetry is spontaneously broken by the formation of a condensate, which is also responsible for the EWSB. Three of the Goldstone bosons (“technipions”) produced in the breaking of the chiral symmetry provide the masses for the $W^\pm$ and $Z^0$ bosons.

The masses of the Standard Model (SM) fermions can be introduced by embedding color, technicolor and flavor into a larger gauge group, whose breaking gives rise to massive gauge bosons that mediate transitions between SM fermions and technifermions. For such “extended TC” interactions not to lead to significant quark mixing that is inconsistent with limits from flavor-changing neutral currents, the technicolor gauge coupling is required to run very slowly (“walking TC”). This requirement is satisfied by having many technifermions, with lightest TC resonances appearing below 1 TeV [2].
The recent CMS study [3] examines one such technihadron, color-singlet $\rho_{TC}$, within the phenomenological framework of the “technicolor straw man model” [4]. The model assumes that (i) the lowest-lying bound states of the lightest technifermions can be considered in isolation, (ii) the isotriplet ($\Pi_{TC}^{\pm,0}$) comprised of the lightest pseudo-scalar bound states are two-state mixtures of the longitudinal $W_L^\pm$, $Z_L^0$ and mass-eigenstate pseudo-Goldstone technipions.

The particular channel studied is $\rho_{TC} \rightarrow \Pi_{TC} \Pi_{TC} \rightarrow W + Z \rightarrow 3\ell + \nu$, $\ell = e$ or $\mu$, which has a final state cross-section ($\sigma \times BR$) of $1 - 370$ fb, as obtained from Pythia [5] for 14 different selections of $(m(\rho_{TC}), m(\pi_{TC}))$ within the range $100 \leq m(\pi_{TC}) \leq 600$ GeV. The $\Pi_{TC} - W_L$ mixing is taken as $\sin \chi \sim 1/3$. The SM backgrounds from $W Z \rightarrow 3\ell + \nu$, $ZZ \rightarrow 4\ell$, $Z\overline{b}b \rightarrow 2\ell + X$ and $\overline{t}t$ pair production are considered, all generated with Pythia except for the $Z\overline{b}b$ process, for which the matrix elements are computed with CompHep [6]. The detector is simulated with the CMS fast simulation, FAMOS [7], validated against Geant4-based simulation.

The $Z$ boson is reconstructed from a pair of same flavor and opposite charge leptons, whose combined invariant mass is within 3 standard deviations ($3 \times 2.6$ GeV) of the nominal $Z$ mass. The $W$ boson is reconstructed from a third lepton and missing transverse energy in the event by solving a quadratic equation which uses the nominal mass of the $W$ as a constraint. The ambiguity in the longitudinal direction of the neutrino is resolved by choosing the solution with the lower absolute longitudinal momentum ($|p_Z|$) for the neutrino. All three leptons are required to have transverse momenta above certain minima ($p_T^{\ell(1,2,3)} > (30, 10, 10)$ GeV) and to be isolated in the detector – a requirement which particularly aims to reduce the $Z\overline{b}b$ and $\overline{t}t$ backgrounds.

As a final step to improve the signal to background ratio, kinematic selection criteria are applied on the reconstructed vector boson candidates: $p_T^{(W,Z)} > 30$ GeV and $|\eta^W - \eta^Z| < 1.2$. The latter requirement on the pseudorapidity difference is most useful to reduce the background from the SM $ZW$ production, and has been tested not to depend significantly on $m(\rho_{TC})$.

![Figure 1. $\rho_{TC}$ invariant mass distribution for 5 fb$^{-1}$ of data.](image1)

![Figure 2. Contours of $\rho_{TC}$ discovery at 5$\sigma$ significance, neglecting the systematic errors.](image2)

The invariant mass of the $\rho_{TC}$ candidate reconstructed from the selected vector boson candidates is shown in Fig. 1, for the signal generated with $(m(\rho_{TC}), m(\pi_{TC})) = (300, 300)$ GeV. To determine the significance of the signal above the background, a likelihood fit is performed with the signal modelled with a Gaussian probability density function (pdf) and the background with an exponential pdf. A comparison of the likelihoods for the signal-plus-background and background-only hypotheses provides the significance estimate as $S_L = \sqrt{2 \ln(L_{S+B}/L_B)}$. The expected value of the estimate is obtained by multiple “toy” Monte-Carlo experiments to be 7.7 for this particular choice of $(m(\rho_{TC}), m(\pi_{TC}))$.

The 5$\sigma$ discovery contours shown in Fig. 2 are obtained by repeating the same procedure for different signals. The sum of the systematic uncertainties from various detector effects is about 11%. Their effect on the contours is therefore small, with 5$\sigma$ significance still achievable with as low as 4 fb$^{-1}$ of data for certain parts of the phase space, after taking them into account.
3. Vector boson scattering at ATLAS

It is possible to study the EWSB in a model-independent way by removing the Higgs field from the SM Lagrangian and introducing an extra field with three degrees of freedom that will provide the masses of the $W^\pm$ and $Z^0$ bosons. This new field is chosen such that the Lagrangian is invariant under the full electroweak symmetry group. Prepared in analogy with low-energy QCD, the resulting effective theory is called the Electroweak Chiral Lagrangian (EWChL) [8].

The recent studies [9] by the ATLAS Collaboration implement the EWChL framework in the Pythia program to generate vector boson scattering (VBS) events. When the $W^\pm/Z^0$ are on-shell, their quasi-elastic scattering amplitude diverges at the lowest order unless there is some Higgs-like mechanism. Therefore VBS provides an excellent window to EWSB. Imposing CP-invariance and respecting precision electroweak constraints, one finds that among all possible dimension-four-or-lower operators that can be added to EWChL, only two contribute significantly to $W^\pm W^\pm$ and $W^\pm Z^0$ channels. The effective couplings for these terms, $\alpha_4$ and $\alpha_5$, determine if and where resonances should appear in the mass spectrum, after the unitarization of the scattering amplitudes.

The particular channel summarized in this contribution is $q_1q_2 \rightarrow q_3q_4 W^\pm W^\pm$, with one of the final-state $W$ bosons decaying leptonically, and the other hadronically. The bosons are accompanied by two “tag” jets (from $q_3q_4$) at high rapidity. The considered SM backgrounds are from $W$+jets and $t\bar{t}$, also generated with Pythia. ATLAS fast simulation program, ATLAST [10], is used for detector simulation. The jets are identified using the $k_T$ algorithm [11].

Since the $WW$ center-of-mass energy of interest is $\mathcal{O}(1 \text{ TeV})$, the bosons are produced at high transverse momenta ($p_T$). The leptonically decaying $W$ is reconstructed the same way as described in the previous section, while the hadronically decaying $W$ is identified as the highest-$p_T$ jet in the event. The invariant mass of this jet and the scale at which its constituents are resolved into two subjets are required to be consistent with the values expected from genuine $W$ decays [12]. The latter quantity, $p^2_T y_{21}$, is expected to be $\mathcal{O}(m_W^2)$ for the signal events, and the criterion $1.55 < \log(p^2_T \sqrt{y_{21}}) < 2.0$ can reduce the $W$+jets background by an additional 40% after a 2σ-mass-window requirement has been applied.

Both $W$ candidates are required to have $p_T > 320$ GeV. To reduce the $t\bar{t}$ background, each candidate is combined with any other jet in the event and events having combinations close to the top-quark mass are rejected. The tag jets are identified as the highest-$p_T$ jets forward and backward of the $W$ candidates, and required to have pseudorapidity $|\eta| > 2$ and energy $E > 300$ GeV. With all four final state objects identified, the total $p_T$ of the “hard scattering” system is expected to be close to zero, so events with $p_T(WW+\text{tagjets}) > 50$ GeV are rejected. Finally, events are rejected when they contain more than one jet with $p_T > 20$ GeV which lies between the two $W$s in pseudorapidity, since QCD radiation is suppressed in the central region in the signal with respect to the background.

![Figure 3](image_url)  
**Figure 3.** Reconstructed $WW$ mass distribution for five different signal scenarios (circles and downward triangles) and the two backgrounds (squares and upward triangles) after all cuts.

Fig. 3 shows the reconstructed $WW$ mass after all cuts for five different signal scenarios. In all cases, the signals are clearly observable above the $t\bar{t}$ and $W$+jets backgrounds for an integrated luminosity of 30 fb$^{-1}$. Even the non-resonant (continuum) signal with the lowest predicted cross-
section yields an expected significance of $S/\sqrt{B} \simeq 4.7$. Finally, the studies on $ZW$ scattering indicate that significant signals can also be observed with $100 \text{ fb}^{-1}$ in the $ZW \rightarrow \ell\nu qq$ channel and with $300 \text{ fb}^{-1}$ in the $ZW \rightarrow 3\ell + \nu$ channel.

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