HOW TO RULE OUT LITTLE HIGGS
(AND CONSTRAIN MANY OTHER MODELS) AT THE LHC

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In this talk I describe how to discover or rule out the existence of $W'$ bosons at the CERN Large Hadron Collider as a function of arbitrary couplings and $W'$ masses. If $W'$ bosons are not found, I demonstrate the 95% confidence-level exclusions that can be reached for several classes of models. In particular, $W'$ bosons in the entire reasonable parameter space of Little Higgs models can be discovered or excluded in 1 year at the LHC.

1 Introduction

Significant attention has been paid to the recent class of models of electroweak symmetry breaking known as “Little Higgs” models. The purpose of Little Higgs models is to provide a natural mechanism to cancel quadratic divergences that appear in the calculation of the Higgs mass without resorting to supersymmetry (cf. Ref. 1 for a nice review). The cancellation of divergences occurs by a clever alignment of vacuua, and the addition of several new particles — several scalars, $Z'$ and $W'$ bosons, and vector-like top quarks. While the detailed mass-spectrum and couplings are very model-dependent, some features generic to all of the models can be tested to high precision at the Large Hadron Collider (LHC) at CERN.

The key to probing the Little Higgs spectrum is the search for the $W'$ bosons. For each SU(2) gauge symmetry that is broken there will be a new massive charged vector-boson with a typical mass\(^2\)

\[
M_{W'} < 6 \text{ TeV} \left( \frac{m_H}{200 \text{ GeV}} \right)^2.
\]  

These $W'$ bosons will each introduce a new term to the Lagrangian of the form

\[
\mathcal{L} = \frac{g'}{2\sqrt{2}} V_{ij} W'_{\mu} q^i \gamma^\mu (1 - \gamma_5) q^j ,
\]
with the opening of a new channel (see Ref. 4 for details). decrease, however the branching fraction to the final state examined below can actually increase effect on the width unless $g''_W$ will contribute to the overall width of the $W'$ boson. In general these have a small numerical effect on the width unless $g'$ is very small. In that case, the branching fractions to fermions decrease, however the branching fraction to the final state examined below can actually increase with the opening of a new channel (see Ref. 4 for details).

An essential constraint on the individual couplings $g_i$ comes from their relationship to $g_{SM}$:

$$\frac{1}{g_1} + \frac{1}{g_2} + \cdots + \frac{1}{g_n} = \frac{1}{g_{SM}^2} \approx \frac{1}{0.427}$$

must hold, which implies $1.02g_{SM} < g_1, g_2, \ldots, g_n < \sqrt{4\pi}$. The upper limit is determined by a requirement of perturbativity. Hence, for all Little Higgs models there will be at least one $W'$ boson with $0.187 < g'/g_{SM} < 5.34$, and a preference for $g'/g_{SM} \sim 1$ in more complicated scenarios.

It was demonstrated in Ref. 5 that the best method to look for $W'$ bosons is to search for a resonant mass peak in the top-quark/bottom-quark decay channel. A limit in this search method applies equally to left or right-handed $W'$ bosons, whereas the handedness of the $W'$ boson can be determined from the spin-correlations of the final state. The model-independent search for this peak structure can then be translated directly into bounds on any model with $W'$ bosons by using the equations in Ref. 5. The CDF Collaboration has used this method to set lower mass bounds on $W'$ bosons of 536(566) GeV assuming SM-like couplings, where decays to right-handed neutrinos are (not) allowed. For pure left-handed $W'$ bosons (like those that appear in Little Higgs models), the current best bound is 786 GeV. In this brief summary, I will demonstrate obtainable exclusion limits at the LHC for arbitrary couplings and for several specific models, including Little Higgs.

2 Searching for $W'$ bosons at the LHC

The $s$-channel production of single top quarks via $W'$ bosons can occur at an extremely large rate at the LHC. In Fig. 2a, the cross section for this channel is shown for SM-like couplings as a function of $W'$ mass up to 10 TeV. The dotted line denotes the production of 1 $W'$ boson decaying into $t\bar{b}$ or $\bar{t}b$ per low-luminosity (10 fb$^{-1}$) year at the LHC. In high-luminosity (100 fb$^{-1}$) years there could be 50 $W'$ bosons produced with masses of 10 TeV that decay into this channel. The question is, can these be observed over the background?

In order to address this question, a full analysis of the signal and background has been performed. The signal is evaluated using PYTHIA run through the SHW detector simulation.
predict a Kaluza-Klein tower of right-handed $W_{1.5}^g$ which is bounded from below by roughly the $W^g$ that can be placed at the LHC as a function of coupling are the predictions of several classes of models. Generic to p-flavor models $13$ of the detector parameters within the range of variation quoted in Ref. $10$. Nothing in the analysis above is specific to Little Higgs models. In fact, these results are generic to all models with a charged vector-like boson. For this summary I show results assuming $3$ Numerical Results

In order to extract the signal from the backgrounds I make the cuts listed in Table $1$. Demanding at least $1$ $b$-tag removes most of the $Wjj$ background. An additional constraint that the second-highest-$E_T$ jet combine with the lepton and missing energy to produce a mass not too far from the top-quark mass can be useful for eliminating any residual $Wjj$ backgrounds. In this case, the neutrino is constructed from the missing energy by using the $W$-mass constraint, and choosing the smaller of the two possible rapidities. Jets are reconstructed using a $k_T$-clustering algorithm with $R = 1$ (similar to a cone size of $0.7$). For this summary I chose a mass window which is bounded from below by roughly the $W'$ mass or $3$ TeV, whichever is smaller.

3 Numerical Results

Nothing in the analysis above is specific to Little Higgs models. In fact, these results are generic to all models with a charged vector-like boson. For this summary I show results assuming that the width is composed entirely of decays to fermions (see Ref. $4$ for the general case) so that $(g'/g_{SM})^2$ is proportional to the width. $5$ In Fig. $2a$ we see the $95\%$ confidence-level exclusion that can be placed at the LHC as a function of coupling $g'/g_{SM}$ and $W'$ mass for a few integrated luminosities. A $W'$ with SM-like couplings can be ruled out up to $5.5$ TeV! Overlaid on this plot are the predictions of several classes of models. Generic top-flavor models $13,14$ predict $0.65 < g'/g_{SM} < 1.04$, whereas top-flavor see-saw models $15$ conspire to predict a coupling of $g'/g_{SM} = 1.34$. Another interesting class of models are orbifolded left-right symmetric models $16$ which predict a Kaluza-Klein tower of right-handed $W'$ bosons with an effective coupling $g'/g_{SM} = \sqrt{2}$. In general there is an upper limit on any model with perturbative couplings of $g'/g_{SM} \sim 5.34$, and a lower limit for models with ratios of couplings of $\sim 0.187$. Now it is time to turn specifically to Little Higgs. Little Higgs is one of the theories that is supposed to be perturbative at all stages, and hence has the absolute limits on the couplings quoted before. However, there is an additional relationship between $M_W'$ and $f$ the pseudo-Goldstone boson decay constant. To find upper bounds on the allowed $W'$ mass it is sufficient to look at the Littlest Higgs, where the relationship is

$$M_W' \approx \frac{f}{2} \sqrt{g_1^2 + g_2^2}. \quad (4)$$

Solving for $g'$ in terms of $f$ and the mass leads to the maximally allowed region of parameter

Table 1: Cuts used to reconstruct the $M_{jj\not{E}_T}$ invariant mass. Demand at least 2 jets (with at least 1 $b$-tag), 1 isolated lepton, and missing energy $E_T$.

| Cut | Requirement |
|-----|-------------|
| $E_{Tj1}$ | $\max[200$ GeV, $\min(10\%M_W', 500$ GeV)] |
| $E_{Tj2}$ | $\min(10\%M_W', 150$ GeV) |
| $E_{T\ell}$ | $> 30$ GeV |
| $\not{E}_T$ | $> 50$ GeV |

with parameters updated to match the ATLAS detector. $10$ The final state of interest contains a lepton ($e$ or $\mu$), $2$ $b$-jets, and missing energy. The backgrounds come from $t\bar{t}$, $t$-channel single-top-quark production (i.e. $tj$), $Wjj$, $Wcj$, $Wb\bar{b}$, $Wc\bar{c}$, $WZ$, $Wt$, and $s$-channel single-top-quark production. As is apparent from Fig. $1b$, the most important of these are $t\bar{t}tj$, $t\bar{t}$, and $Wjj$. The cross section for the backgrounds falls exponentially with $M_{jj\not{E}_T}$ the reconstructed invariant mass, and drops to less than one event above $3$ TeV.

Unfortunately, the event generators do not currently model the $tj$ background correctly. Hence, I have used a matrix-element calculation $11$ normalized to the correct fully-differential NLO calculation of the $tj$ cross section. $12$ The resulting jets and leptons are run through the SHW efficiency routines. I have checked that the results are completely insensitive to variations of the detector parameters within the range of variation quoted in Ref. $10$. In order to extract the signal from the backgrounds I make the cuts listed in Table $1$. Demanding at least $1$ $b$-tag removes most of the $Wjj$ background. An additional constraint that the second-highest-$E_T$ jet combine with the lepton and missing energy to produce a mass not too far from the top-quark mass can be useful for eliminating any residual $Wjj$ backgrounds. In this case, the neutrino is constructed from the missing energy by using the $W$-mass constraint, and choosing the smaller of the two possible rapidities. Jets are reconstructed using a $k_T$-clustering algorithm with $R = 1$ (similar to a cone size of $0.7$). For this summary I chose a mass window which is bounded from below by roughly the $W'$ mass or $3$ TeV, whichever is smaller.
Figure 2: 95% confidence-level exclusion reach as a function of $W'$ mass at the LHC for arbitrary $g'/g_{SM}$. Superimposed are the predictions of (a) various classes of perturbative models, and (b) Little Higgs. The short dot-dashed contours denote the maximally allowed parameter space for a given $f$. The solid contours denote the perturbative parameter space ($\alpha_i = g_i^2/(4\pi) < 1/\pi \approx 0.32$).

space shown by the triple-dashed contours of Fig. 2b.

When examining Fig. 2b it should be questioned whether the theory is really perturbative if one of the couplings is $\sqrt{4\pi}$. A more reasonable perturbative bound of $\alpha_i = g_i^2/(4\pi) < 1/\pi \approx 0.32$ is shown via solid contours in Fig. 2b. The figure stops for $f = 4$ TeV, since it becomes increasing unnatural for $f$ to be larger than 1 TeV in Little Higgs scenarios. However, even $f$ as large as 6–8 TeV can be mostly covered in the central perturbative region ($g'/g_{SM} \sim 1$) which is favored for more complicated models. The conclusion to be drawn is that the $W'$ bosons appearing in Little Higgs models should either be seen or excluded in the first year of running at the LHC.

Acknowledgments

This work is supported by the U. S. Department of Energy under contract No. DE-AC02-76CH03000.

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