After the Standard Model: New Resonances at the LHC

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Experiments will soon start taking data at CERN’s Large Hadron Collider (LHC) with high expectations for discovery of new physics phenomena. Indeed, the LHC’s unprecedented center-of-mass energy will allow the experiments to probe an energy regime where the standard model is known to break down. In this article, the experiments’ capability to observe new resonances in various channels is reviewed.

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1. Introduction

The standard model of particle physics has proven to be a remarkably accurate framework for the description of the interactions of particles at energies up to almost 1 TeV\(^1\). At 1.7 TeV, however, the standard model longitudinal W boson scattering cross-section violates the unitarity bound\(^2\). One solution to this problem is the introduction of the so-called Higgs boson\(^3\), which in the standard model can also generate the fermion masses. The latter allows the decoupling of the mechanism responsible for fermion masses from the standard model interactions. However, quadratically divergent radiative corrections suggest the standard model Higgs boson mass is close to the limit of validity of the theory, and experimental constraints\(^4\) imply its mass is less than approximately 200 GeV. This suggests the scale of new physics is at or below 1 TeV, although in principle, if one accepts a high level of fine-tuning, with the addition of a \(m_H = 150\) GeV Higgs boson the list of existing particles could be “complete”, in analogy with Mendeleev’s table in chemistry. No new physics would then appear below the Planck scale of \(10^{19}\) GeV.

In addition to these “technical” issues in the standard model, it is good to re-emphasize that it is a theory of interactions, in which the properties of the interaction bosons in terms of couplings (to fermions and each other), propagation and masses are linked and testable, but the properties of fermions are inputs. The
standard model does not give any information regarding the nature of particles and leaves many fundamental questions unanswered. For example: What is color? Or electric charge? Why are they quantized? Are these dynamic or static properties of particles? Are there only three generations? Why are there no neutral, colored fermions? Is there a link between particle and nucleon masses?

There are many models of physics beyond the standard model that address at least the technical issues, including supersymmetry, little Higgs, and models with additional space dimensions. Most of these predict the existence of new particles that should be produced and detected at the LHC. Hopefully, the observation of such new particles and the measurement of their properties will also help us understand the patterns observed in the properties of the standard model fermions.

Looking at the three currently known generations of fermions, it appears that within a generation, the more a fermion interacts, the larger its mass: colored particles are heavier than their color-neutral counterparts; up-type quarks, with electric charge $|q| = 2/3$ are heavier than bottom-type quarks of charge $|q| = 1/3$; charged leptons are heavier than neutral leptons. This pattern suggests that the fermion masses might be related to a more complex mechanism leading to an indirect link between masses and standard model interactions. In that case, the Higgs boson might only be relevant to the unitarization of massive vector boson scattering, which would relax the existing constraints on its mass.

2. Signals of Parity Restoration

Maximal violation of parity in weak interactions is "catastrophic" since for massive fermions helicity depends on the reference frame. Therefore, a deeper understanding of the nature of fermion spin, and thus the weak interaction would allow progress similar to the discovery of a Higgs boson: the mechanism of restoration of parity symmetry might lead to an understanding of fermion masses.

The primary signals of parity restoration would be the presence of a $W$-like boson coupling to right-handed fermions with weak coupling strength. As in the standard model, the neutral member of such a triplet could mix with the other neutral electroweak bosons and have a different mass than its charged companions. We generically denote these extra bosons as $W'$ and $Z'$. At energies much larger than $m_{W'}, m_{Z'}$, the left- and right-handed interactions have the same strength and the symmetry is restored.

$W'$ and $Z'$ bosons are predicted to exist not just in left-right symmetric models, but also many constructions inspired by grand unification. The production cross-sections and decay branching ratios (and widths) depend on the specific model

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*a A recent paper explores the consequences of modifying hypercharge to allow for such particles.

*b This is if the tau lepton and tau neutrino are part of the same generation as the top and bottom quarks, and similarly for muon, muon neutrino, and charm and strange quarks, as is usually assumed.
through the couplings \( \mathcal{L} \), but in most cases the \( Z' \) boson decay to a pair of leptons remains the “golden” signature.

### 2.1. \( Z' \) Boson Decays To Leptons

The most promising decay channels are \( Z' \rightarrow e^+e^- \) and \( Z' \rightarrow \mu^+\mu^- \), where the only irreducible background comes from the Drell-Yan continuum, and instrumental backgrounds from misidentification of jets as leptons are typically significantly smaller. Current limits from searches for such objects at the Fermilab Tevatron imply masses larger than approximately 1 TeV for couplings identical to the standard model \( Z \) boson \(^{15,16} \). Figure 1 (left) shows the production cross-section times branching ratio folded with detector efficiency and resolution for a \( m_{Z'} = 1 \) TeV \( E_6 \)-inspired \( Z'_\chi \) boson as a function of the invariant mass of the reconstructed electron-positron pair, as obtained in a full simulation of the ATLAS detector \(^{17} \). The luminosity needed to discover such a resonance is shown as a function of the resonance mass in Fig. 1 (right) for a few models. Tens of inverse picobarns of data at a center-of-mass energy of 14 TeV suffice to extend the reach beyond the Fermilab Tevatron limits, and with 10 fb\(^{-1}\) a \( m_{Z'} = 3 \) TeV resonance will be observable. Thanks to the excellent performance of the detectors, the sensitivity is similar in the muon channel \(^{18} \). The ultimate LHC sensitivity is expected to be in the range of 5–6 TeV for most models.

One difficulty with these searches originates in the a priori unknown mass of the resonance. The data analysis therefore often uses a moving “window” in the invariant mass distribution to compare the data with the expectation from standard model backgrounds, either by counting events or comparing a signal plus background...
distribution to a background-only one. When using such a strategy, it is important to factor in the number of mass windows in which the search is conducted, as was done by CDF\cite{19}. An alternative is to use a maximum likelihood fit where masses, cross-sections and widths are free parameters. Toy simulations show that the real sensitivity is typically about 20% lower compared to cases where the “look elsewhere” effect is ignored\cite{17}.

Once a signal is established, its nature can be determined by measuring not only its production cross-section and width (if larger than the detector resolution), but also its spin and couplings to fermions. By measuring the angle between one of the leptons and the beam direction, the spin of a Randall-Sundrum graviton can be determined with 90% confidence in 100 fb$^{-1}$ for a resonance mass up to 1720 GeV\cite{20}. In case of a vector resonance, the couplings can be determined by measuring the forward-backward asymmetry. For a mass of 1 (3) TeV, an integrated luminosity of 10 (400) fb$^{-1}$ allows the distinction between various E$_6$ model points or a left-right symmetric signal with a significance larger than 3$\sigma$\cite{21}.

2.2. Other $Z'$ Boson Decays

$Z'$ boson decays to light quarks are significantly more difficult to detect given the much larger backgrounds from QCD dijet production and an energy resolution which is significantly worse for jets than leptons. Such signals are observable however, but with a sensitivity which is typically one or two orders of magnitude worse than in the dilepton channel\cite{22}. Decays to pairs of top quarks require specialized techniques and will be discussed later.

Another possibility in left-right symmetric models is that the $Z'$ boson decays to right-handed neutrinos, provided these are light enough. The right-handed neutrino can then decay to a lepton and two jets: $N_R \rightarrow \ell W_R^*, W_R^* \rightarrow q\bar{q}'$. In this case the final state contains two leptons and four jets, and since the right-handed neutrino is a Majorana particle, the final state leptons can have the same sign. If furthermore the right-handed neutrino is relatively light, it will be highly boosted and the collimation of the lepton and the jets from its decay will lead to the lepton being embedded in the jets. This decay chain has been studied and, depending on the mass of the heavy neutrino, discovery can be achieved for $Z'$ boson masses up to 5 TeV in 300 fb$^{-1}$ of data\cite{23}. Other decay chains are possible: if there is a mass hierarchy between different flavors of right-handed neutrinos for example, additional leptons will probably be present.

2.3. $W'$ Boson Production and Decay

The total $W'$ boson production rate at the LHC is not very dependent on the boson’s helicity couplings to fermions, however the interference with the standard model $W$ boson, which shapes $d\sigma/dM$, is key to the determination of these couplings\cite{21} and has so far rarely been included in experimental studies. A $W'$ boson can be searched for in the very clean $W' \rightarrow \ell\nu$ channel by studying the transverse mass
distribution in events with a single isolated lepton and missing transverse energy. If such a decay mode is open, resonances of mass up to approximately 3 (4.5) TeV can be discovered with as little as 1 (10) fb$^{-1}$ of data. Transverse mass spectra for a few signal points and dominant backgrounds are shown in Fig. 2. Even though the resolution function is very different between muons and electrons, because of very low backgrounds the sensitivity is very similar in both channels. However, in

![Figure 2](image)

**Fig. 2.** Transverse mass spectrum in $W' \rightarrow e\nu_R$ decays in a full simulation of ATLAS data after requiring that the reconstructed event contain a single isolated lepton with $p_T > 50$ GeV, missing transverse energy $> 50$ GeV, and a “lepton fraction” $\sum_{\text{leptons}} p_T / (\sum_{\text{leptons}} p_T + \sum E_T) > 0.5$.

a purely left-right model for example, this decay is forbidden.

If the right-handed neutrino ($N_R$) mass is smaller than that of the $W'$ boson, the $W' \rightarrow \ell N_R$ channel opens up. Of course, if the $N_R$ neutrino is stable on the scale of the detector, the signature from $W' \rightarrow \ell N_R$ is very similar to the classical one. The decay chain $N_R \rightarrow \ell W'^* \rightarrow q\bar{q}'$ may also be observable. The final state contains at least two hard leptons and two hard jets. Note that depending on the mass differences between the $W'$ and the heavy neutrino $N_R$, one of the leptons could be very close to one of the jets. The dominant standard model backgrounds to these searches are $t\bar{t}$ production, production of $Z/\gamma^*$ in association with hard jets, and diboson production. These are effectively suppressed by cuts on the summed transverse energy of the two leptons and two jets ($S_T$), and the invariant mass of the two leptons. This is illustrated in Fig. 3 for both signal and backgrounds from a study of the dimuon channel based on a full simulation of the ATLAS detector. After these cuts, the candidate $N_R$ neutrino mass can be reconstructed by taking the invariant mass of the two jets with each of the leptons separately. In the analysis shown here, the combination with the smallest invariant mass is kept as the $N_R$ candidate. The other lepton can then be added to form the $W'$ boson. Both invariant mass distributions are shown in Fig. 4 for the muon channel. With this analysis, the signal point with $m_{W'} = 1500$ GeV, $m_{N_R} = 500$ GeV can be discovered with as little as 20 pb$^{-1}$ of data, while the $m_{W'} = 1800$ GeV,
Fig. 3. Sum of the transverse energies of the two muons and two leading jets ($S_T$) (a), and dilepton invariant mass (b) for backgrounds and two signal points in the search for $W'$ bosons decaying following the chain $W' \rightarrow \mu N_R, N_R \rightarrow \mu W''$, $W'' \rightarrow q\bar{q}'$. The signal points LRSM$_{18\_3}$ and LRSM$_{15\_5}$ correspond to masses $m_{W'} = 1800$ GeV, $m_{N_R} = 300$ GeV and $m_{W'} = 1500$ GeV, $m_{N_R} = 500$ GeV respectively.

$m_{N_R} = 300$ GeV point requires almost 200 pb$^{-1}$. Since these results were obtained by counting events above background after cuts, a further increase in the sensitivity should be attainable with a more sophisticated analysis technique based on shapes of distributions.

Another promising channel is the decay chain $W' \rightarrow WZ \rightarrow \ell
\nu\ell\ell$, where again
the transverse mass distribution, but now built with three charged leptons, is key in the analysis. This distribution is shown for various $W'$ boson masses and for the standard model backgrounds for 300 fb$^{-1}$ of ATLAS data in Fig. 5. In a dataset that size, a $W'$ boson with couplings identical to the standard model $W$ boson is observable for masses up to 2.8 TeV$^{25}$. If after the $W' \rightarrow WZ$ decay one allows one of the $W$ or $Z$ bosons to decay hadronically, the overall branching ratio goes up along with the backgrounds. Since the $W$ or $Z$ boson is highly boosted, the quarks from the decay are collimated and form a single hadronic jet. This jet can however be distinguished from a light quark jet through its mass splitting scale, which will be explained in detail below. The backgrounds from $W/Z+$jet production are not well known, and no reliable estimates of sensitivity exist at this time.

Identification of the $W'^+ \rightarrow \bar{t}\bar{b}$ decay (and its charge conjugate) requires high-$p_T$ $b$- and top-tagging, the specifics of which will be discussed later. Early studies show that $W'$ bosons from little Higgs models can be discovered in this channel for masses up to 2.5 TeV in as little as 30 fb$^{-1}$ of data$^{26}$.

2.4. Exotic Quarks

In most cases, the existence of $Z'$ bosons requires the existence of new exotic quarks or leptons$^{27}$. Such quarks could be pair-produced and decay to a standard model gauge boson and quark. For down-type quarks one would for example have $pp \rightarrow D\bar{D}$, with $D \rightarrow Wu$ or $D \rightarrow Zd$. The sensitivity of the ATLAS experiment to such quarks in final states with at least two leptons has been investigated$^{28}$, showing that these quarks can be discovered up to masses of about 1 TeV with 100 fb$^{-1}$ of data.
Fig. 6. Invariant $Z$ boson plus jet mass spectra for both signal and background in the search for the exotic quark decay $D \rightarrow Zd$ in the $D\bar{D} \rightarrow ZdZ\bar{d} \rightarrow \ell\ell j\nu\nu j$ channel for two different $D$ quark masses: (a) $m_D = 600$, (b) $m_D = 1000$ GeV.

data. Figure 6 shows the $Z$ boson plus jet invariant mass spectra that are obtained by combining the leptonically decaying $Z$ boson with each of the hard jets in events with two isolated leptons, two hard jets and substantial missing transverse energy, as expected from the $D\bar{D} \rightarrow ZdZ\bar{d} \rightarrow \ell\ell j\nu\nu j$ decay chain.

3. Extra Dimensions

A promising approach to quantum gravity consists in supposing the existence of extra space dimensions, a strategy known as string theory. To explain that these additional space dimensions are not observed, string theorists hypothesize that they are compactified, i.e. folded on themselves at a length scale much smaller than what is accessible in experiments. This compactification scale is typically assumed to be the scale of gravity, i.e. $10^{19}$ GeV. However, in the late 90’s people realized this scale may actually be much lower, in reach of current or near-future experiments.

3.1. “ADD” Extra Dimensions

In the so-called “ADD” model, after Arkani-Hamed, Dimopoulos and Dvali, standard model fields are confined to a $3 + 1$ dimensional subspace (“brane”) and gravity is allowed to propagate in the “bulk” space of extra dimensions. The extra dimensions have a flat metric, and the reason gravity appears very weak to us is that it is only felt when the graviton goes through the standard model brane.

The edges of the compactified extra dimensions are identified, leading to boundary conditions on the wave functions of particles propagating along these directions. Momentum along the extra dimensions is therefore quantized, and appears as mass to observers in the standard model brane. Gravitons thus acquire a “mass” proportional to their extra-dimensional momentum. In the ADD model, the mass splittings between these different states, commonly called “excitations”, are small, and the “tower” of graviton excitations appears as a continuous distribution in mass. While
the coupling to a single graviton remains extremely weak, there are a very large number of accessible states leading to a very large phase space, and observable cross-sections. Furthermore, since the graviton couples to energy-momentum, all processes are affected.

At colliders, searches for evidence for the presence of such extra dimension have been conducted in two categories of events: those where a graviton is directly produced and immediately disappears into the bulk, and those where gravitons interfere with a standard model process. At hadron colliders, the former lead to signatures with a single hard jet or gauge boson accompanied by a large amount of missing transverse energy due to the escaping graviton. The predicted signal consists of an excess of events at high transverse momentum. Searches at the Fermilab Tevatron result in lower limits on the compactification scale of the order of 1 TeV \[30\] \[31\].

The most sensitive process to study in the second category appears to be Drell-Yan production of charged lepton pairs. In addition to the high mass tail, the angular distribution of the leptons can be used to increase the sensitivity to the presence of a spin-2 particle. Based on this technique, the DØ experiment has set limits \[32\] on the compactification scale between 1 and 2 TeV depending on the number of extra dimensions.

### 3.2. Warped Extra Dimensions

Randall and Sundrum proposed \[13\] a model in which the hierarchy between the electroweak and Planck scale is generated by a warped metric in an extra dimension. In this model there are two branes, with the standard model fields confined to one, and the metric between the two warped by \(e^{-2kr_c\phi}\), where \(k\) is the warp factor, \(r_c\) the compactification radius, and \(\phi\) the coordinate along the extra dimension. With \(kr_c \approx 50\), a hierarchy of \(10^{15}\) is created between the branes located at \(\phi = 0\) and \(\pi\), allowing the generation of TeV-scale masses from the \(10^{19}\) GeV Planck scale. In this scenario, instead of an almost continuous tower, a small number of heavy graviton excitations \(G\) exist, but these couple with electroweak strength and are therefore individually observable. They are widely spaced resonances decaying mainly to pairs of standard model particles. Searches at the Tevatron have set limits between a few hundred GeV and one TeV on the mass of such excitations, depending on the magnitude of the warp factor \(k\) \[33\]. The LHC experiments should be able to cover the entire region of interest (i.e. where this solution generates the hierarchy between the Planck and electroweak scales), as shown in a CMS study \[18\] of \(G \rightarrow \mu^+\mu^-\) in Fig. 7.

An interesting variation on this model has the standard model fermions located along the extra dimension \[34\] \[35\]. The fermion masses and mixings are then generated by geometry, and the heavier fermions as well as gauge boson excitations are located close to the “TeV” brane. The most promising channels for discovery then become the direct production of gauge boson excitations, and in particular the first excitation of the gluon. This is expected to have a mass larger than about 2 TeV.
based on constraints from precision electroweak measurements. However, even though the object is strongly interacting, the production cross-section is relatively small because of the small overlap of its wavefunction in the extra dimension with the light fermions’ wavefunctions. Correspondingly, the dominant branching ratio is to pairs of top quarks or longitudinal W or Z bosons, and the width can be large.

The decay of a heavy resonance \((m \gg m_{\text{top}})\) to one or more top quarks leads to a new experimental phenomenology: because of the large top quark momentum, its decay products will be collimated, leading to a merger of the decay products into a single high transverse momentum jet, with possibly an embedded charged lepton. The angular distance \(\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}\) between the decay products as a function of top quark transverse momentum is shown in Fig. For top quark transverse momenta larger than about 400 GeV, a large fraction of the quarks from hadronic W boson decay are separated by \(\Delta R < 0.5\), the typical jet radius. When the top quark transverse momentum exceeds 600 GeV, the \(b\)-jet is usually merged with the \(W\) boson decay products. New techniques are therefore necessary to distinguish jets from high transverse momentum top quark decays from those originating from light quarks or gluons.

Even though with standard reconstruction techniques we observe a single, hard jet, it originated from a massive particle decaying to two or three hard partons. Therefore, if it were possible to measure each of the partons perfectly, the direct daughter partons and the originator’s invariant mass could be reconstructed. Of course, quarks hadronize, leading to “cross-talk”, and the detectors are not able to resolve all individual hadrons. Nevertheless, the fine granularity of the LHC
experiments’ calorimeters can be used to try to resolve the objects inside the jets. Various techniques have been proposed \[39\]–\[44\] and tested in fast simulations. In the following, results \[47\] obtained using the full simulation of the ATLAS detector \[48\] are presented.

A simple discriminating variable is the jet mass, i.e. the invariant mass of all the jet constituents. At the detector level, these constituents are typically calorimeter cells or proto-clusters made from a small number of cells. (The latter approach allows for improved noise suppression and reduces sensitivity to pile-up and underlying event contributions.) The jet mass for “top monojets”, i.e. hadronically decaying top quarks in which all decay products are reconstructed as a single jet, is shown in Fig. 9 as a function of jet transverse momentum. This plot is based on simulated \[Z’\] bosons with masses \[m_{Z’} = 2\] and 3 TeV. Events cluster in a band going from \[m_{\text{jet}} \approx 180\text{ GeV}\] for jets of 600 GeV transverse momentum, to \[m_{\text{jet}} \approx 200\text{ GeV}\] at 1400 GeV. There is a slow increase in the jet mass as a function of transverse momentum due to increased radiation, but the discrimination power is large since for a given transverse momentum jets from light quarks or gluons have a mass following a negative exponential distribution. Jet mass, however, is insensitive to a potential anisotropy in the jet energy distribution, as would be expected when jets from a few hard partons are merged together.

\[k_\perp\]-type jet reconstruction algorithms are well suited to identify substructure in a jet. As opposed to the cone-type algorithms which seek to maximize energy in a cone in \((\eta, \phi)\)-space, \[k_\perp\] algorithms are “nearest neighbor” clusterers: they combine nearby clusters into a jet if their energy-weighted distance is smaller than a certain quantity. If a \[k_\perp\] jet is formed from multiple decay products of a heavy particle, the energy scale at which it splits from one into two (and two into three, etc.) jets,

\[4\text{New techniques} \[45\]–\[48\] which have been proposed to reduce this dependency are being studied in fully simulated events.
sometimes called “Y-scale”, is related to the mass of that particle. Figure 10 shows the scales at which top monojets split into two or three jets, for both the $m_{Z'} = 2$

Fig. 10. Scales at which top monojets split into (a) two, and (b) three jets. Jets from the $m_{Z'} = 2$ (3) TeV $Z'$ boson samples are drawn as a solid (dashed) line.

and 3 TeV simulated $Z'$ boson samples. Again, the distributions are very similar, showing the value of these variables in identifying high transverse momentum top quarks in a wide range of momenta. The scale for splitting into two jets is close to half the top quark mass, and for the next splitting it is close to half the $W$ boson mass, as expected. For light quark and gluon jets, these distributions are all negative exponentials.

The correlation between jet mass and splittings into two, three and four jets can be exploited to discriminate between top and light quark and gluon jets. This is shown for splitting in two jets and jet mass in Fig. 11. The efficiencies resulting from
Fig. 11. Correlation between $Y$ scale values and jet mass for splitting into two jets for (a) top monojets and (b) light quark and gluon jets.

Simple two-dimensional cuts in these variables for signal and background are shown in Fig. 12. Further studies are underway and an improvement in signal/background of a factor of three or more is expected. In the lepton-plus-jets channel, this will make QCD production of $t\bar{t}$ pairs the dominant background in the search for heavy resonances decaying to top quarks pairs. $t\bar{t}$ invariant mass resolution then becomes the most critical aspect in isolating a signal.

4. Final Remarks

Many models of new physics predict the existence of resonances which will be detectable at the LHC. The sensitivity of the experiments to a number of these has been exposed in this paper. Significant information on the underlying physics will
be available immediately through the observed production cross-section and decay mode(s) of the discovery signal, but this will need to be followed up by searches in complementary channels and detailed measurements of signal properties. Hopefully, this will allow us to learn something about the origins of the properties of fermions, in addition to opening a window on physics at the TeV scale and beyond.

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The author would like to thank the authors of all the studies presented in this review. Understanding of the capabilities of the LHC detectors and the corresponding discovery reach is not only important for model builders, but also a crucial part in preparing for the real data analysis. This review will hopefully be useful for both newcomers to the field as well as more advanced particle physicists.

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