Searches for diboson resonances in pp collisions

Literature Review

Jakub Malý

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1 Why study boson resonances?

Theories and frameworks that aim to extend the Standard Model (SM) often include new gauge bosons that couple to fields of the Standard Model. These bosons can decay into pairs of bosons and fermions that we can detect and explain as manifestations of new physics. In many cases, the mass scale of these predicted particles is within the range of the Large Hadron Collider (LHC) energies, and thus searching for resonances—or absence thereof—provides a model-independent way to test the viability of potential Standard Model extensions.

These extensions aim to address some of the shortcomings of the Standard Model which include: an absence of a theory describing gravity at a quantum scale; the matter-antimatter asymmetry; the lack of a common unification scale of couplings at high energies; and a prediction for the observed masses of particles (small neutrino masses; Higgs boson mass fine tuning; an explanation for the hierarchy of fermion masses).

2 Heavy bosons beyond the Standard Model

The Standard Model is described by a gauge structure $G_{SM} = U(1)_{SM} \times SU(2)_{SM} \times SU(3)_{SM}$. Each gauge group describes the symmetries for one of the fundamental forces: $U(1)$ for electromagnetic force; $SU(2)$ for weak force; and $SU(3)$ for the strong force of quantum chromodynamics (QCD). The interaction of fermion fields with the force fields is described by the exchange of gauge bosons of the Standard Model (photon γ, weak bosons $W^{\pm}$ and Z, the eight gluons g, and the Higgs boson H).

The simplest mathematical expression of an extended Standard Model can be made by adding an additional, spontaneously broken $U(1)'$ group to the gauge structure of the Standard Model G_{SM}: $G' = G_{SM} \times U(1)'$.[I] While this addition in itself does not solve any shortcomings of the Standard Model, it is a good example since $U(1)$ symmetries arise commonly from the breaking of larger non-Abelian (non-commutative) groups.[2] Furthermore, even this simple extension to the Standard Model would create a massive spin-1 Z' singlet due to symmetry breaking around the TeV scale. This singlet would couple to SM fields, and flavour-universal couplings to fermions would be assumed to avoid the problem of large Flavour-Changing Neutral Currents (FCNCs).

In practice, most theories include more than one heavy boson, but a common feature is to favour decay into a pair of SM bosons (W, Z, H), as can be seen in figure 1.[3] Therefore, boson resonances are a common manifestation of many extensions of the standard model.

[I] The concept of spontaneous symmetry breaking is somewhat of a misnomer. The process refers to a phenomenon in which a stable state of a system transforms non-trivially under symmetries of the theory.[1] Thus, it can be thought of as a hidden symmetry that causes breaking of a known symmetry.

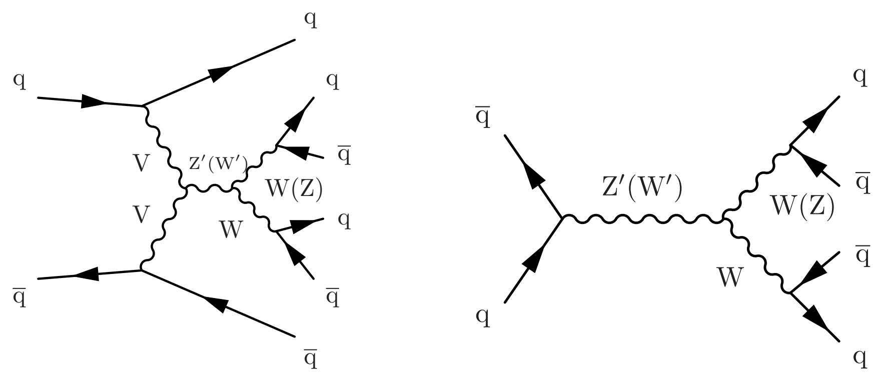

Figure 1: Feynman diagrams for production and decay of heavy bosons W' and Z' via the Vector Boson Fusion (VBF; left) and quark-antiquark fusion (Drell-Yan / DY; right) processes.[3]

Different frameworks have varying couplings to quarks, leptons, and SM vector bosons W/Z. The reason why we primarily focus on diboson resonances is that a lot of potential particles have strong couplings to a vector boson pair $B' \to VV$ (where VV is meant as the total decay for WW, WZ, or ZZ) or a vector boson and a Higgs boson $B' \to VH$.[II] While this report does not look at single boson resonances, there are models where the new boson B' can couple directly to fermions, and thus there are also searches for resonances corresponding to single boson decays.[4]. These models usually include a mechanism to suppress the coupling at low energies to match experimental observations.

2.1 Technicolour

Technicolour is a theory from the late 1970s which gives a dynamical explanation of electroweak symmetry breaking.[5] It predicts the existence of new particles called technifermions, which could generate the mass of the Standard Model W and Z bosons via their binding energy—analogous to how nucleons gain most of their mass via QCD interactions of gluons. This interaction is invariant under a $SU(N_T)$ gauge group, with the number of flavours $N_T = 3$ creating a QCD-like interaction at a much higher energy scale of $\Lambda_T \approx$ TeV compared to $\Lambda_{QCD} \approx 250$ MeV, and is set by the Nambu-Goldstone boson interactions.[III]

Moreover, the theory also predicts numerous bound states (π_T, ρ_T, a_T, ω_T) called technihadrons. These include dark matter candidates—Weakly Interacting Massive Particles (WIMPs)—since some technibaryons can be set up to be stable enough to survive through the evolution of the universe, but to couple weakly to SM particles.[6] Other technibaryons have possible decays to technipions π_T which then further couple to Standard Model fermions

[II] We use the B' notation instead of V' since the new physics bosons do not need to be a spin 1 vector (such as the graviton G and radion R of the Randall-Sundrum model mentioned in section 2.3).

[III] Nambu-Goldstone (NG) bosons are spinless bosons that appear in models exhibiting spontaneous breakdown of continuous symmetries, with one boson for each broken symmetry.

(hadron jets j, leptons l, and neutrinos ν), thus having the same experimental siganture as a diboson resonance (see figure 2).[7]

However, simple QCD-like models of technicolour were ruled out by the late 2000s by electroweak precision measurements—more specifically the Peskin-Takeuchi parameters S and T, which quantify the extent of corrections to the electroweak boson interaction in the presence of new physics.[8;9] Another issue for technicolour is that it is hard to justify the lack of resonances at all energies between the Higgs mass m_H at 125 GeV and the TeV scale, since many technicolour models predict a resonance peak well below 1 TeV.[7] Explaining this phenomenon would require an explicit mechanism to create this separation.[10]

$$\rho_T^{\pm} \to W^{\pm}\pi_T^0 \to l\nu jj$$
$$\rho_T^{0} \to W^{\pm}\pi_T^{\mp} \to l\nu jj$$
$$\omega_T, \rho_T^{0} \to \gamma\pi_T^0 \to l\nu jj$$
$$\omega_T, \rho_T^{0} \to ll$$

Figure 2: Technibaryon ρ_T, ω_T decays.

Yet more issues technicolour theories are similar to other composite Higgs models—technicolour can define the Higgs boson H as a composite particle, and can explain the electroweak scale with an alternative to the Higgs mechanism, but since H is no longer a fundamental particle, the model needs to provide an alternative to the Yukawa mechanism (Higgs-fermion interactions) to give mass to fermions. Since the Higgs boson was only a theoretical particle for the first decades of technicolour theories, many simpler models do not offer a satisfactory explanation.

2.2 Heavy Vector Triplets

It became clear very early on in the search beyond the Standard Model that we needed to find a way to standardise the search of the phase space via a model agnostic framework. To make testable predictions, physicists nowadays use a simplified model strategy—use a model that yields quantifiable manifestations of new physics, for example as a new resonance peak—instead of trying to fit data to any one specific model.

The Heavy Vector Triplet (HVT) is one such framework that encompasses a wide variety of models that predict the presence of a new boson triplet commonly called Z' and W'. It is a general vector (spin 1) boson framework that introduces a new $SU(2)'$ gauge group.[11] This boson triplet arises similarly to how the broken gauge symmetry of the Standard Model electroweak gauge group $U(1)_{SM} \times SU(2)_{SM}$ gives rise to a massive triplet $W^{\pm}$, Z^0.[IV] Also analogous to the bosons of the weak interaction, the new heavy boson triplet has coupling helicity—coupling to either right- or left-handed Standard Model fermions exclusively.[2]

The appeal of the HVT framework is that it can be described by just two parameters

[IV] In actuality, the electroweak bosons are the triplet $W^{\pm}$, W^0 (analogous to pions $\pi^{\pm}$ and π^0 in QCD, but coupling to weak isospin instead of colour), and a singlet boson B. The photon γ and Z boson are then expressed as $\gamma = W^0 + B/2$ and $Z^0 = W^0 - B/2$).[12]

commonly called $g_F = g^2 c_F / g_V$ and $g_H = g_V / c_H$ along with the mass scale of the almost degenerate vector triplet M_V. Here, g_V is the vector boson interaction strength; c_F the coupling to SM fermions; c_H the coupling to the Higgs boson H and polarised W, Z bosons; and g is the $SU(2)_{SM}$ coupling. This flexibility is why both ATLAS and CMS have adopted HVT as one of the main benchmark frameworks when searching for new resonances.[13;14]

Common HVT model benchmarks include Model A (boson interaction strength $g_V = 1$) where the vector bosons arise through the weak coupling to the Standard Model gauge group G_{SM} (describes theories such as the Sequential Standard Model (SSM)) and Model B ($g_V = 3$) where the bosons arise from a non-linear global symmetry of a $SO(5)/SO(4)$ gauge group (describes theories of strongly-coupled composite Higgs). In contrast to Model A's resonance peak, Model B's strong boson interaction $g_V = 3$ leads to wide-width boson resonances that are difficult to detect via localised searches for resonance peaks.[2]

2.3 Randall-Sundrum Model

Another common benchmark framework for diboson resonances is the Randall-Sundrum (RS) model. It is one of the Large Extra Dimension (LED) models that aim to solve the hierarchy problem—the disparity between the electroweak and Planck scales. It introduces a fifth spacetime dimension between two sub-spaces ("branes") which contain the Standard Model particles. These branes are separated by a 5-dimensional "bulk". This explains the weakness of gravity, since there is small overlap between the gravity boson wavefunction (which can extend into the bulk) with Standard Matter particles confined within the branes.[2;15] Since variations of Large Extra Dimensions (ADD/LED) predict tensor and scalar bosons instead of vectors, variations of the Randall-Sundrum model have become another common benchmark when searching for new physics.[13;14]

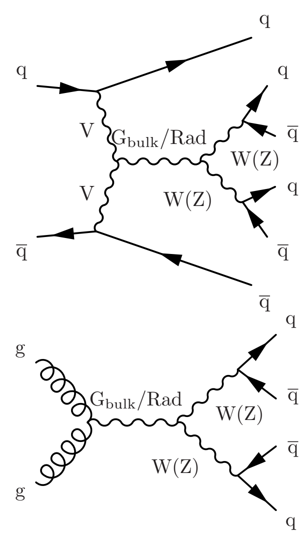

Figure 3: Feynman diagrams for production and decay of the bulk graviton G_{bulk} and the radion R via the Vector Boson Fusion (VBF; top) and gluon-gluon Fusion (ggF; bottom) processes.[3]

Unlike the regular RS graviton which mainly couples to photon and lepton pairs, the bulk RS gravitons G_{bulk} (spin 2) and radions R (spin 0) have fermion coupling reduced proportionally to the volume of the extra dimension, making boson decay favourable (see figure 3 for decay diagrams). Depending on the variant of the model, the graviton mass spectrum can be almost continuous. This means that instead of a single narrow resonance, we would expect higher boson pair cross sections at higher invariant masses.[2]

3 Experimental details

As we have seen, there are a lot of different ways new physics could manifest. The goal, then, is to search through the phase space and test several model-independent frameworks for possible discrepancies in experimental signatures ranging from new resonance peaks to increased cross sections. However, any new physics theory must conform to the observed data. A lot of times, this is achieved through weak couplings to the Standard Model. This means that we need very high experimental precision to be able to either set a hard exclusion limit or claim that there is a potential discovery. This section looks at a different experimental considerations and methods.

3.1 Simulations

Simulations have multiple uses in these experiments. When used directly, simulated events corresponding to both the Standard Model (no-signal hypothesis) and different frameworks are used to create templates. Indirectly, simulations can be used to get a better understanding of which background processes are the most relevant for each process of interest.

In both cases, the raw output of Monte Carlo (MC) simulations is convolved over with a detector-specific kernel to simulate real output. These kernels are used to account for real-world considerations such as detector resolution and geometry; nuisance parameters; and trigger efficiencies.[4] This output is then used to fit smooth functional forms to obtain theoretical predictions for results where no closed form solutions exist (templates).

However, while we can simulate next to leading order (NLO) or even next to next to leading order (NNLO) diagrams for some models, certain frameworks such as composite Higgs (and more specifically the near-conformal composite Higgs model) are extremely expensive to compute and therefore simulations are usually only done at leading order (LO).

3.2 Statistical limitations

Searches for signal are usually done by fitting the mass m_X distributions against a background-only signal from simulations. Various hypothesis testing procedures are then used to estimate the significance of the results as p-values.[V] The issue arising from looking for new phenomena is distinguishing a statistical fluctuation from a manifestation of new physics. A common issue is the look elsewhere effect—the chance for any histogram bin to have a significance of 5σ is small, but there are many bins to account for! Therefore, special care has to be taken

[V] p-values are usually converted to a number of standard deviations σ of a Gaussian distribution, beyond which the one-sided tail area equals p. The current heuristic standard for a new discovery in particle physics is set at 5σ, which corresponds to a p-value of $\approx 3 \times 10^{-7}$.

to convert results from local to global significance.

Another thing to take into account is that the p value only tests for the validity of the null hypothesis. A more robust way to look for new physics usually includes comparing two hypotheses via the likelihood ratio test or comparing their χ^2 goodness of fit.[16]

Combining results from multiple analyses provides their own set of issues. Each search has slightly different statistical and systematic errors—due to a variety of reasons ranging from different datasets; methodology used to estimate backgrounds; the specific simulations used; nuisance parameters for background and acceptance rates; et cetera. Moreover, depending on whether the analysis is done on the same or a different dataset, these errors may be correlated, and further care has to be taken when combining results.[16;17]

3.3 Final decay states

Another consideration is what final states we are looking for. In general, boson decays can be categorised as fully hadronic ($B'B' \to jjjj$); semi-leptonic ($B'B' \to jj\ell\ell$); and fully leptonic ($B'B' \to \ell\ell\ell\ell$),[VI] but VBF processes have two additional narrow jets. Since we are looking at decays of Standard Model bosons, we exclude decay into photon pairs since the decay of a vector particle (Z) into two vectors ($\gamma\gamma$) is prohibited by the Landau-Yang theorem.[18]

Each channel has their advantages and disadvantages. Leptonic decays are better for tagging and tracking accuracy since both CMS and ATLAS have very good e and μ resolutions. Decays with one neutrino are sometimes considered, but decays with 2 or more ν, or decays where $\not{E}_T$ does not match the vector boson mass are usually discarded.

On the other hand, the hadronic final states offer their own challenges—because the particles we are looking for often have mass in the TeV scale, their decay results in a highly boosted boson pair. This results in the jets being highly collimated, making it hard to differentiate between one wide and two narrow jets (see section 3.4).[19]

3.4 Multijet tagging

As mentioned in section 3.3, large mass particle decays lead to highly boosted bosons. While this is good, since we have a distinct experimental signature, the decay products are highly collimated. This is mostly an issue in hadronic decays, since it is hard to V-tag—determine whether a jet originated from a vector boson V or if it is a part of the large background of hadronising gluons and quarks.

During LHC run 1, the standard methodology at both ATLAS and CMS was to look for 2 high E jets (one for each vector boson decay $V \to jj$) using either the anti-k_t or the

[VI] Here, j refers to a jet and ℓ to either a lepton l or a neutrino ν.

Cambridge/Aachen (CA) sequential recombination algorithms with a large radius parameter R of 0.8 to 1.2.[20;21] The CA algorithm simply groups elements based on radial separation, while the anti-k_t algorithm adds the inverse of their momentum into the distance metric. In practice, this means that a hard particle will accumulate soft particles around itself, usually resulting in good performance in jet reconstruction.[22]

However, for collimated jets, the spatial separation is small enough such that even two hard particles are grouped under one jet since their distance is smaller than the distance to the beam line. In order to combat this, LHC run 2 analyses used new machine learning algorithms to analyse jet substructure.[3;23] These algorithms mostly focus on the point where two hard particles are grouped into a single jet and try to determine whether these should remain as two separate jets. Results show that these new methods significantly increased the efficiency of tagging a seeding particle as a $W/Z/H$.[2]

4 Current status

During LHC run 1 ($\sqrt{s} = 7$–8 TeV and $\int \mathcal{L} = 4$–$5\ \mathrm{fb}^{-1}$), there was some excitement about a potential discovery. Data from both CMS and ATLAS exhibited consistent fluctuations from the no-signal hypothesis around $m_X \approx 1.9$–2.0 TeV. A 2016 statistical analysis combining results from the two collaborations found deviations with global significance above 3σ.[17] However, even the preliminary data from LHC run 2 ($\sqrt{s} = 13$ TeV) with integrated luminosity of only $\int \mathcal{L} = 3.2\ \mathrm{fb}^{-1}$ showed that there was no excess in any of the three (hadronic, semileptonic, leptonic) channels, with largest deviations from the null hypothesis having local significance of no more than 2.5σ.[24]

Analyses of the full LHC run 2 dataset ($\sqrt{s} = 13$ TeV, $\int \mathcal{L} = 139\ \mathrm{fb}^{-1}$) have since confirmed that this fluctuation is most likely statistical in nature. The most recent results from both ATLAS and CMS, released in 2023, place stringent limits on common benchmark models up to the scale of a few TeV.[13;14] The ATLAS overview is shown in figure 4.

5 Conclusions

It is a well-understood fact that a larger volume of data improves statistical errors. Since most of the analyses to date have a negligible systematic error when compared to statistics, gathering more data would help better decouple signal from stochastic fluctuations—there are still local deviations up to 4σ in some analyses. At the same time, with a more prevalent use of machine learning algorithms in data analysis, larger datasets can help reduce systematic errors as well.

The limits that have been set at up to several TeV for different models, as well as several precision measurements, have ruled many simpler extensions to the Standard Model (such as QCD-like technicolour). These limits also make it clear that we need theories that can explain the energy scale gap between m_H and the TeV scale as well as the gap between the electroweak and Planck scales.

Going forwards, I believe that advancements in machine learning and computation (including quantum computing) can help us further reduce errors by improving both experimental apparatus performance (such as tagging efficiencies) as well as simulations. Therefore, while increasing energy would allow us to probe higher energy physics directly, there appears to still be potential to further probe new physics at current LHC centre-of-mass energies.

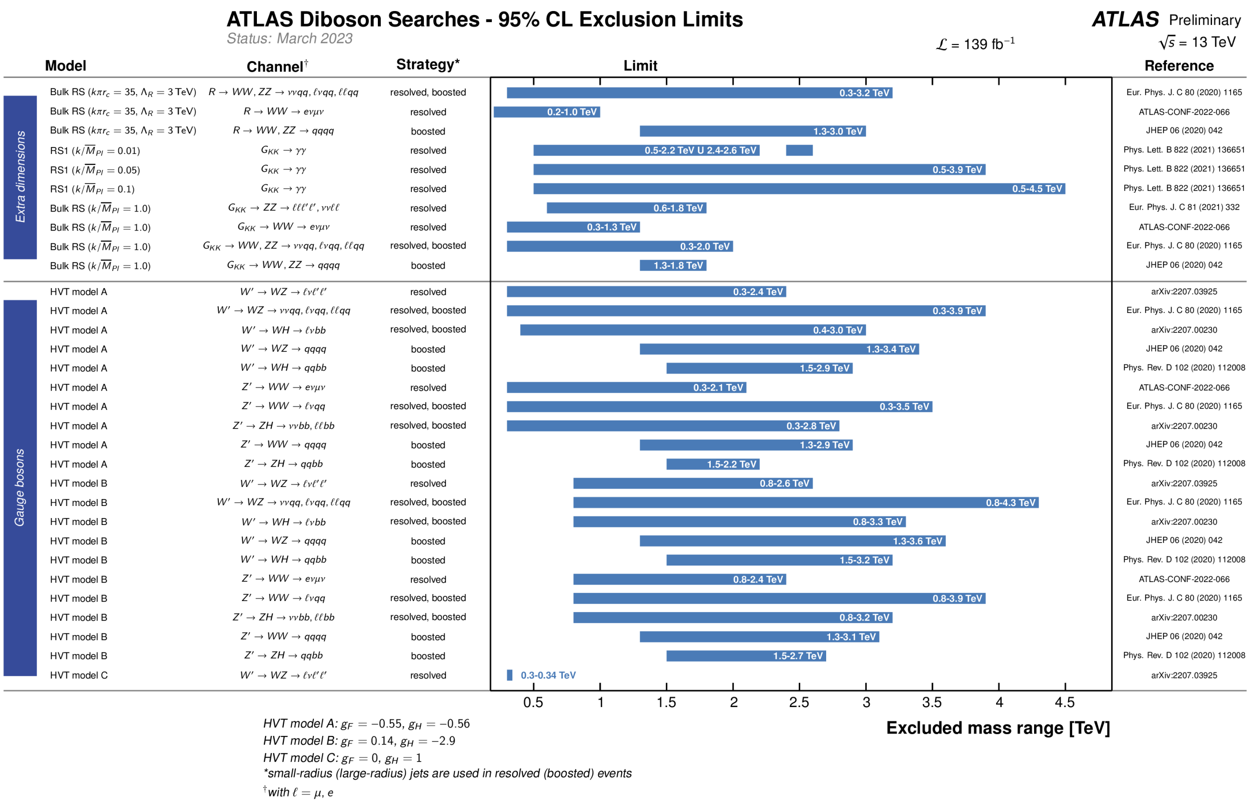

Figure 4: Mass exclusion limits at 95% confidence from diboson searches at ATLAS.[13]

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