Implications of LHC results for TeV-scale physics: other signatures of BSM physics

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Editors: C. Grojean, G. Isidori, D. Martínez, J. Santiago, P. Savard, S. Worm
Contributing authors: J. de Blas[1]*, M. Pérez-Victoria*[2]*, R. Torre*[3]
[1] Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA
[2] Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, E-18071 Granada, Spain
[3] Instituto de Física Teórica UAM/CSIC, Universidad Autónoma de Madrid, Cantoblanco, E-28049, Spain

1 New Vector Bosons

1.1 Model-independent description and current limits

Theories beyond the Standard Model (SM) contain extra fields, which can give rise to new particles that can be produced at large colliders. These particles can be classified by their Lorentz and gauge quantum numbers. In this section we consider new particles of spin 1, i.e. vector bosons. We will also make a few comments about extra scalars. New vector bosons appear frequently in extensions of the SM. They are usually associated to an extended, spontaneously broken gauge group, as for instance in Grand Unified Theories (GUT), Little Higgs models or models in extra dimensions, and can also appear as composite resonances of a strongly interacting sector. In all cases a gauge boson interpretation is possible. To evade current bounds, these new particles should be heavy or interact very weakly with the SM fields.

For phenomenological purposes, the new vector bosons can be described in a model-independent fashion by a lowest order effective Lagrangian. The Lagrangian must be invariant under the full SM gauge group, H. This greatly restricts the possible interactions of the new fields. Another important consequence of gauge invariance is that the new vector bosons appear in multiplets of the color and isospin group factors, with definite hypercharge. The general effective Lagrangian for one of these multiplets, V_μ, has the form

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_V + \mathcal{L}_{V-\mathrm{SM}} + \text{ nonlinear}, \tag{1}$$

with $\mathcal{L}_{\mathrm{SM}}$ the SM Lagrangian,

$$\mathcal{L}_V = -D_\mu V_\nu^\dagger D^\mu V^\nu - D_\mu V_\nu^\dagger D^\nu V^\mu + M_V^2 V_\mu^\dagger V^\mu, \tag{2}$$

and

$$\mathcal{L}_{V-\mathrm{SM}} = -V^{\mu\dagger} \sum_k g_V^k j_\mu^{Vk} + \mathrm{h.c.} \tag{3}$$

We are using matrix notation to write the product of two multiplets. The derivatives D_μ are covariant with respect to the SM gauge group H, and the sum in k runs over currents j_μ^{Vk} made with SM fields, with the same quantum numbers as V. To have sizable effects, they should have scaling dimension 3. Finally, "nonlinear" refers to additional interaction terms that contain two or more extra fields. These are usually less relevant for collider searches, and we will neglect them in the following[1]. Then, a vector multiplet is fully characterized by its mass M_V and its couplings g_V^k to the possible SM currents (plus, possibly, the width, see footnote 1). Ignoring the flavour structure, a full singlet has six independent couplings, whereas the other multiplets the number of couplings ranges from one to three.

The existing limits on these vectors come mainly from flavor observables, electroweak precision tests (including observables below, on and above the Z pole), and direct searches at hadron colliders. Flavor physics, and in particular the absence of flavor changing neutral currents, impose very strict limits on the flavor structure of the couplings g_V^k. These limits can be satisfied assuming, depending on the

[1] These terms could give rise to an enhancement of the width, if the new vector can decay into non-standard particles. This effect can be easily parameterized leaving the width as a free parameter.

type of vector boson, either family universality (possibly only for the first two families) or couplings to just one family. Electroweak precision data are very sensitive to lepton couplings and to couplings to the Higgs field, which induce a mixing with the SM gauge bosons. They require that the new vector bosons are very heavy or leptophobic to a certain degree. In this sense, it is worthwhile observing that some of the vector multiplets are necessarily leptophobic due to the SM gauge invariance. On the other hand, a light Higgs implies that the mixing can only be sizable if there are cancellations between the new degrees of freedom. These cancellations can be guaranteed by a custodial symmetry. For leptonic and quark couplings of electroweak size, the limits from precision observables on the mass of the extra vector bosons are typically in the range 1-3 TeV. Finally, the best direct limits are set by the Atlas and CMS searches at the LHC. They come from a variety of final states: dilepton, dijet, lepton+MET, $t\bar{t}$, diboson. For example, for electroweak-size couplings, the limits on new vectors from searches of dilepton resonances are at present around 2.5 TeV, but these numbers keep raising as more and more data are collected and analyzed.

1.2 Expectations from classes of models

Let us discuss briefly the expectations on the properties of the new vector bosons in the different theoretical models that have been proposed. First of all, the actual multiplets that appear in a given model depend on the pattern of symmetry breaking $G \to H$, where G is the gauge group of the complete theory. For instance, whenever $G = H \times F$, the gauge bosons associated to the factor F are singlets under H. This is the case of the popular Z' bosons in GUT. To have other multiplets, a non-trivial embedding of H in G is required. For instance, models with gauge bosons in extra dimensions can be interpreted as having a gauge group that is an infinite product of four-dimensional gauge groups, and always contain replicas of the SM gauge bosons that are isosinglets, isotriplets and color-octets. As a second example, models with a custodially-symmetric extended sector predict charged vectors that couple to right-handed fermions ($\mathrm{W'}_{\mathrm{R}}$). It is also important to bear in mind that each model often contains several extra vector boson multiplets.

Different classes of models also provide rough generic predictions about the sizes of couplings and masses:

- In GUT, the couplings of the extra vector bosons are fixed by the requirement of unification. They are typically a bit weaker than the ones of the electroweak gauge bosons. The masses of non-singlet vectors, such as leptoquarks, is large due to the size of the unification scale and to bounds from proton decay. Therefore, in these models only the singlets (Z') can be at the reach of present and future colliders.
- In models with new vectors that provide solutions to the hierarchy problem, such as Little Higgs or Randall-Sundrum models, the masses are expected at the TeV scale.
- If the couplings of the recently discovered Higgs boson turn out to be different from the ones of the SM, new vector bosons at the TeV scale could contribute to a perturbative unitarization of the theory. For this, they should have sizable couplings to the Higgs and SM gauge bosons, so they will give rise to diboson final states. This is the case of composite Higgs models.
- Models with fermion partial compositeness, which can be realized in warped extra dimensions, link the masses of the different fermions to the size of their couplings to new vector bosons from the composite sector (or extra dimension). Thus, they predict small couplings to leptons and light quarks, and large couplings to gauge bosons, the Higgs boson and the top quark. Therefore, these vector bosons are better searched for in top-pair final states (and possibly multiboson), and in any case their observation is challenging due to the suppressed Drell-Yan production.
- Models like universal extra dimensions or little Higgs with T parity have a discrete symmetry that implies vanishing values of the couplings g_V^k of the lightest new vector bosons to the SM fermions. Obviously, this weakens significantly the electroweak precision bounds, but also forbids single production at colliders.

1.3 LHC: discovery

In the following we would like to assess the potential of different upgrades of the LHC to discover extra vector bosons, and to compare the relative importance of an increase in energy and an increase in luminosity. We focus on the most sensitive searches, which involve resonant production of a single, narrow state. Furthermore, we restrict ourselves to Drell-Yan production and, among the possible final states, we study decays into dileptons and dijets. As we will see these illustrate different behaviours in terms of luminosity. To allow for dilepton production, we consider colorless neutral vector bosons Z', which could be singlets, neutral components of multiplets or admixtures of these[2]. Finally, to be able to present the results in a (partially) model-independent manner, we make use of the narrow width approximation[3] Our strategy here is similar to the $c_u - c_d$ formalism. The interaction of the Z' with the light quarks is given by

$$\mathcal{L}_{\rm prod}^{Z'} = \frac{g_{Z'}}{2} Z'_\mu \left(\bar{u}_i \gamma^\mu \frac{1-\gamma_5}{2} u^i + \bar{d}_i \gamma^\mu \frac{1-\gamma_5}{2} d^i \right). \tag{4}$$

We have assumed, for definiteness, universal, left-handed couplings and same couplings to up and down quarks. These assumptions do not affect significantly the plots below (up to a rescaling of $g_{Z'}$). We present results for the expected reach in the plane $(g_{Z'}\sqrt{{\rm BR}\,(Z' \to l^+ l^-)}, M_{Z'})$ of the LHC at 14 TeV with 300 fb^{-1} and 3 ab^{-1} of integrated luminosity and for the SLHC at 33 TeV with 300 fb^{-1} of integrated luminosity on a new Z' vector.

Let us start from the dilepton channel. In this case we can assume negligible background at high invariant masses ($M_{l^+l^-} > 300$ GeV) of the lepton pair and according to a Poissonian statistics the discovery simply corresponds to the observation of $N_{\rm min} = 5$ events. This can be written in formula as

$$\sigma_{\bar{q}q}^{Z'}(s, M_{Z'}, g_{Z'}) \times \mathcal{A}_{l^+l^-}(M_{Z'}) \times \epsilon_{l^+l^-} \times {\rm BR}\left(Z' \to l^+ l^-\right) \times L > N_{\rm min}\,, \tag{5}$$

where σ is the production cross section, $\mathcal{A}$ is the acceptance corresponding to the kinematic cuts $p_T^l >$ 30 GeV and $|\eta_l| < 2.5$, ϵ is the detector efficiency for the di-lepton final state and L the integrated luminosity. This relation allows us to define the minimum accessible coupling for a given energy and luminosity as a function of the Z' mass according to

$$g_{Z'}^2 \times {\rm BR}\left(Z' \to l^+ l^-\right) = \frac{N_{\rm min}}{\sigma_{\bar{q}q}^{Z'}(s, M_{Z'}, g_{Z'} = 1) \times \mathcal{A}_{l^+l^-}(M_{Z'}) \times \epsilon_{l^+l^-} \times L}. \tag{6}$$

In the left panel of Figure 1 we show the reach on the product of the production coupling times the square root of the decay branching ratio as a function of the Z' mass for different collider configurations: LHC14 with 300 fb^{-1} and 3 ab^{-1} and the SLHC33 with 300 fb^{-1}. We have taken $\epsilon_{l^+l^-} = 1$, so our limits are a bit optimistic.

Let us now consider the di-jet final state. In this case the background cannot be neglected and assuming a Gaussian statistics Eq. (5) takes the form

$$\sigma_{\bar{q}q}^{Z'}(s, M_{Z'}, g_{Z'}) \times \mathcal{A}_{jj}(M_{Z'}) \times \epsilon_{jj} \times {\rm BR}\left(Z' \to jj\right) \times L > \mathcal{S}\sqrt{\sigma_{\rm B}(s) \times \mathcal{A}_{\rm B}(s) \times \epsilon_{\rm B} \times L}\,, \tag{7}$$

where $\sigma_{\rm B}$, $\mathcal{A}_{\rm B}$ and $\epsilon_{\rm B}$ correspond to the di-jet background and $\mathcal{S}$ is the statistical significance. Discovery corresponds to $\mathcal{S} = 5$. In this case, the reach corresponding to Eq. (6), is given by

$$g_{Z'}^2 \times {\rm BR}\left(Z' \to jj\right) = \frac{\mathcal{S}\sqrt{\sigma_{\rm B}(s) \times \mathcal{A}_{\rm B}(s) \times \epsilon_{\rm B} \times L}}{\sigma_{\bar{q}q}^{Z'}(s, M_{Z'}, g_{Z'} = 1) \times \mathcal{A}_{jj}(M_{Z'}) \times \epsilon_{jj} \times L}. \tag{8}$$

The reach corresponding to this relation is shown in the right panel of Figure 1 for the same collider configurations shown in the di-lepton case. Again, we have taken the efficiencies for signal and background

[2]The results for dijet production also apply to colored resonances with a simple rescaling of the coupling by a color factor.

[3]This approximation actually fails for some of the masses and couplings we include in the plots. Our limits in these regions should be considered as an optimistic extrapolation of a simplified calculation. Nevertheless, we believe that the approximation correctly captures the impact of luminosity and energy upgrades of the LHC.

equal to 1. It is worth noting that the dependence on the integrated luminosity in the case of negligible and non negligible background is different. In the former case the quantity $g_{Z'}^2 \times \mathrm{BR}\,(Z' \to l^+l^-)$ scales like L^{-1} while in the latter case it scales like $L^{-1/2}$, changing the relative importance of an energy vs luminosity upgrade. Both figures show clearly that higher energy is crucial to explore heavy vector bosons, whereas higher luminosity is required to be sensitive to weak couplings.

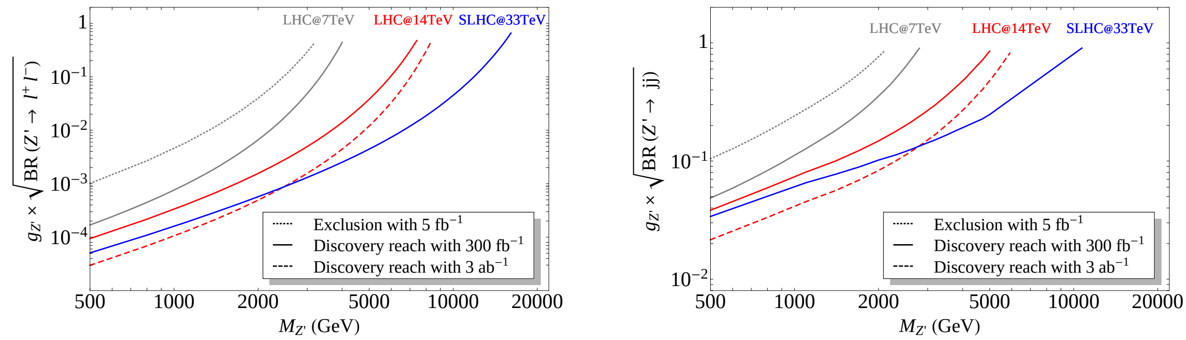

Fig. 1: Discovery reach in the plane $(g_{\mathrm{prod}}\sqrt{\mathrm{BR}\,(Z' \to l^+l^-)}, M_{Z'})$ in the di-lepton (left) and di-jet (right) channels.

1.4 LHC: measurement of properties

The measurement of the total cross section allows to detect extra resonances but it is not sufficient to determine their properties. Let us discuss briefly the expectations for these measurements for the LHC at 14 TeV with 100 fb^{-1} of integrated luminosity. We use again a Z' as a representative vector boson and, for definiteness, assume typical GUT values of the couplings. Analyzing the angular distribution in the $\ell^+\ell^-$ channel, the spin of a Z' boson can be determined for $M_{Z'} \lesssim 3-4$ TeV. The leptonic forward-backward asymmetry[4] and other observables would allow, in principle, to determine the Z' couplings, and thus to distinguish between different models. For instance, it should be possible to determine how the Z' couples to u and d quarks in the proton, using the rapidity distribution of the Z'. For the given values of center of mass energy, luminosity and approximate coupling size, the most popular models will only be distinguishable for $M_{Z'} \lesssim 2-2.5$ TeV. But the current CMS limit on, for instance, the Z'_ψ model is 2260 GeV. Therefore, it is clear that, if such a new boson is discovered, measuring its couplings will require more luminosity, an upgrade of the LHC in luminosity and/or energy, or a linear collider.

1.5 Linear Collider

Extra neutral vector bosons coupling to leptons can be efficiently produced at future e^+e^- linear colliders, such as the ILC ($\sqrt{s} = 0.5 - 1$ TeV, $\mathcal{L}_{\mathrm{int}} = 0.5 - 1$ ab^{-1}). However, unless the new vectors do not couple significantly to the first families of quarks, the LHC already provides limits beyond the production threshold of such machines. On the other hand, the much cleaner environment of an e^+e^- collider offers the possibility of performing high-precision measurements. Thus, in case of observing a discrepancy with the SM prediction, such measurements could unveil the existence of extra particles even if their masses are out of the reach of the collider. Deviations from the SM are only sensitive to the different Z' coupling to mass ratios. For typical GUT values of the couplings, the ILC should be sensitive to Z' effects for masses up to $\sim 10 \cdot \sqrt{s}$ for the highest luminosity.

With the possibility of controlling the polarization of the beam, the ILC is well suited to obtain information about the spin and Z' couplings, by studying the angular distributions of different polarized observables. In this regard, the ILC should be able to distinguish Z' models within the mass region where the LHC is able to detect the new vectors but not to identify its couplings. Moreover, the knowledge of

[4] This cannot be directly measured at the LHC for, in principle, one does not know which proton is the origin of the q and $\bar{q}$ in the interaction. However, the q direction can be inferred from the dilepton rapidity distribution.

its mass from the LHC could be used as an input to substantially improve the distinction of different models with the ILC data. This shows the synergy of the LHC and future linear colliders results in the study of new vector bosons. For the case of extra charged vectors, the proccess $e^+e^- \to \nu\bar{\nu}\gamma$ could be used to determine the W' leptonic couplings.

Finally, let us stress that it is possible that the new vectors be either leptophobic or hadrophobic. In fact, for several multiplets this is imposed by SM gauge invariance. In this regard, a lepton linear collider and the LHC are complementary, and both are necessary to cover the different kinds of vector bosons. In particular, linear colliders can discover relatively light new particles with small hadronic couplings, which could escape LHC searches.

1.6 Left out

- Vector boson fusion
- Other decay modes
- Broad resonances
- Pair production
- Scalars

2 References

Use `report.bib` file and BibTex-style for bibliography [**?**]. I suggest we keep the bibliography to a bare minimum, to save space.