

Z' , Z_{KK} , Z^* and all that: current bounds and theoretical prejudices on heavy neutral vector bosons.

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Abstract. – I review the current experimental bounds and theoretical predictions for different kinds of heavy neutral vector bosons.

1. – The case of a “standard” Z'

Heavy neutral vector bosons appear in the particle content of many extensions of the Standard Model (SM), and their detection in dilepton channels is often mentioned as one example of early discovery mode at the Large Hadron Collider (LHC). In this talk I will briefly review the theoretical lore and the present experimental bounds on these heavy particles.

The interaction of a heavy Z' with the Standard Model fermions and Higgs boson can be parametrized in terms of the overall coupling strengths $g_{Z'}^{[\Psi]}$, $g_{Z'}^{[H]}$, and of (quantized) charges z_a , z_H :

$$\mathcal{L}_{Z'} = -\frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + g_{Z'}^{[\Psi]} \sum_a Z'_\mu \bar{\Psi}_a z_a \gamma^\mu \Psi_a + g_{Z'}^{[H]} H^\dagger z_H Z'_\mu i D^\mu H + h.c., \quad (1)$$

where $a = Q, d, u, L, e$ runs over all $SU(2)_L$ SM representations. The last term, in particular, leads to $Z' - Z$ mixing after electroweak symmetry breaking (EWSB).

A natural possibility is that the Z' is the gauge field of a new local symmetry broken at high energies, so that $g_{Z'}^{[\Psi]} = g_{Z'}^{[H]} = g_{Z'}$. To avoid large flavor-changing neutral currents, it is also commonly assumed in the literature that the couplings of the Z' to the SM fermions are flavor universal. I will refer to this case as that of a “standard” Z' [1]. Examples are: a heavy $B - L$ gauge boson; a Z_ψ from E_6 Grand Unified Theories, where $E_6 \rightarrow SO(10) \times U(1)_\psi$ at the unification scale ($g_{Z'} = g_2 \tan \theta_W$ and charge equal to $\sqrt{5/72}$ ($-\sqrt{5/72}$) for all left-handed (right-handed) SM fermions); a heavy replica of the SM Z , ($g_{Z'} = g_2 / \cos \theta_W$ and charges given by $(T_{3L} - Q \sin^2 \theta_W)$); a heavy replica of the hypercharge.

The main indirect bounds on the Z' mass and couplings come from LEP experiments. A tree-level exchange of a heavy Z' affects both the off-pole LEP2 observables, through the generation of four-fermion contact interactions $\propto g_{Z'}^{[\Psi]^2}$, and the Z -pole

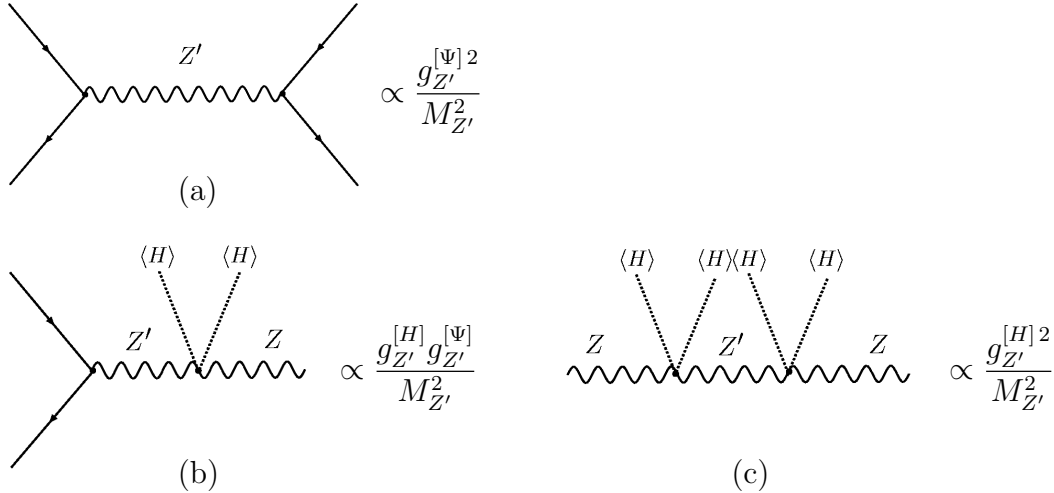


Figure 1: Corrections to LEP observables from the tree-level exchange of a heavy Z' : contact interactions (a); vertex corrections (b); corrections to the ρ parameter (c).

LEP1 observables via the $Z' - Z$ mixing, see figure 1. In the case of the latter, it is useful to distinguish between vertex corrections $\propto g_{Z'}^{[H]} g_{Z'}^{[\Psi]}$, and corrections to the ρ parameter $\propto g_{Z'}^{[H]^2}$. These corrections are said to be oblique, or universal, if they can be recast as pure modifications of the SM gauge boson self energies by making a suitable redefinition of fields. In this case it has been shown that all LEP observables can be expressed in terms of only four parameters, or form factors: \hat{S} , \hat{T} , W , Y [2]. For example, a heavy hypercharge leads to oblique corrections, while a heavy $B - L$, a Z_ψ or a heavy Z are not oblique. Notice that the oblique basis does not usually coincide with the mass-eigenstates basis. Besides LEP indirect constraints, direct exclusion limits on the Drell-Yan production $q\bar{q} \rightarrow Z' \rightarrow l^+l^-$, $l = e, \mu$ come from DØ and CDF experiments [3].

The left plot of figure 2 shows the bounds on a heavy $B - L$ with mass $M_{Z'}$ and arbitrary coupling strength $g_{Z'}$. The (darker) blue region is excluded by the CDF RunII results of [3], which were derived collecting 1.3 fb^{-1} of data. The exclusion region in (lighter) gray is instead obtained using the fit to the LEP electroweak data of reference [4].¹

For a Z' coupling strength equal to the SM value, $g_{Z'} = g' = g_2 \tan \theta_W$, CDF excludes masses up to $\sim 950 \text{ GeV}$, while the bound from LEP is $M_{Z'} \gtrsim 1.65 \text{ TeV}$. Even for such latter values of the mass, the Drell-Yan production rate $pp \rightarrow Z' \rightarrow l^+l^-$ ($l = e, \mu$) at the LHC is still large, $\sigma \times BR \simeq 200 \text{ fb}$, corresponding to a discovery luminosity of $\sim 100 \text{ pb}^{-1}$, see figure 2 and [6]. Similar results hold for a Z_ψ , a heavy

¹The plots in figure 2 and 3 have been obtained computing the Z' production cross section with the approximate formula in eq.(3.16) of reference [5]. This gives a reasonably accurate result except for low masses, where it slightly underestimates the cross section.

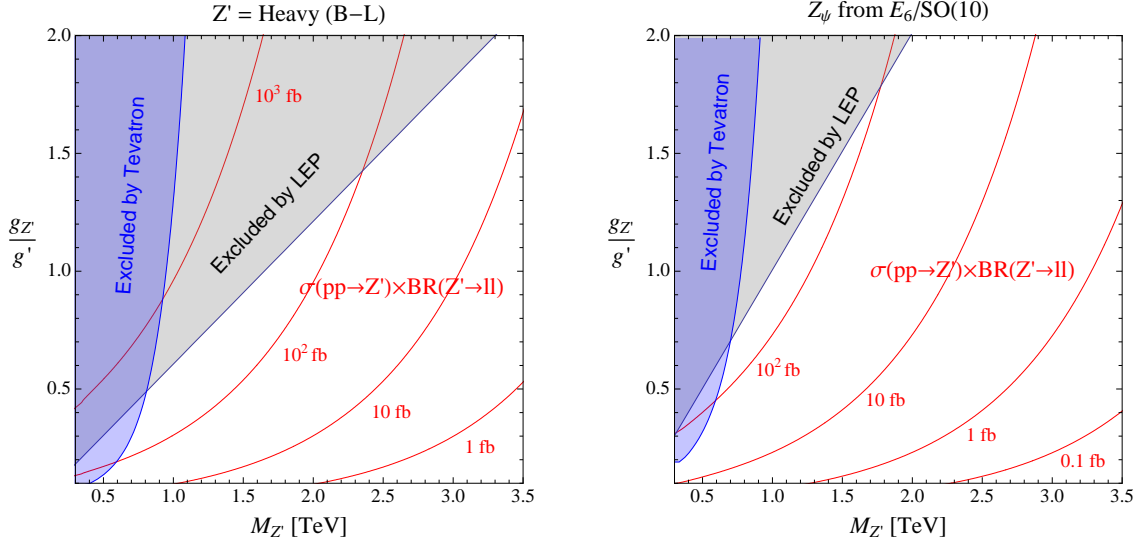


Figure 2: Constraints on the mass and the coupling strength of a heavy $B - L$ (left plot) and a Z_ψ from $E_6/SO(10)$ (right plot). The coupling strengths are expressed in units of the SM value $g' = g_2 \tan \theta_W$. The red curves report the production rate $\sigma(pp \rightarrow Z' \rightarrow l^+l^-)$, with $l = e, \mu$.

hypercharge and a heavy Z . The case of the Z_ψ is shown in the right plot of figure 2.

Larger values of $g_{Z'}$ are more constrained by LEP, requiring larger integrated luminosities for a discovery. In particular, a strongly coupled Z' ($1 \ll g_{Z'} < 4\pi$) is excluded by LEP unless it has a very large mass. The most robust constraint comes from the contact interactions of fig.1(a), which are proportional to $g_{Z'}^{[\Psi]2}$: for generic charges $z_a \sim \mathcal{O}(1)$ the ratio $(g_{Z'}^{[\Psi]}/M_{Z'})$ cannot be too large. On the other hand, the tree-level correction to the ρ parameter will vanish if the Z' originates from a new sector that preserves a custodial symmetry after EWSB [7]. In this case, the only other constraint comes from the vertex correction of fig.1(c), leaving the possibility of a large value of $g_{Z'}^{[H]}$ provided $g_{Z'}^{[\Psi]}$ is small. In fact, different coupling strengths $g_{Z'}^{[H]}$ and $g_{Z'}^{[\Psi]}$ can naturally emerge in theories where both the heavy vector and the Higgs field are bound states of a new strongly-interacting dynamics.

2. – Strongly coupled Z^*

Particularly attractive and theoretically motivated is the possibility that the SM gauge fields themselves have some degree of compositeness: they could arise as admixtures of an elementary field A_μ with a tower of resonances of the strong sector, $\hat{\rho}_\mu$. In complete analogy with the photon- ρ mixing occurring in QCD, the $A_\mu - \hat{\rho}_\mu$

mixing can proceed via a mass term

$$\mathcal{L}_{mix} = \frac{M_*^2}{2} \left(\frac{g_{el}}{g_*} A_\mu - \hat{\rho}_\mu \right)^2, \quad (2)$$

where g_{el} and g_* denote respectively the gauge coupling of A_μ and the coupling strength among three composite states. It is natural to assume $1 \ll g_* < 4\pi$, and $g_{el} \lesssim 1$. Due to \mathcal{L}_{mix} , the combination $(g_{el}A_\mu - g_*\hat{\rho}_\mu)$ acquires a mass M_* , while the orthogonal one – to be identified with the SM gauge field – remains massless. After rotating from the elementary/composite basis to the mass-eigenstates basis, one has:

$$\begin{aligned} |\text{SM}\rangle &= \cos\theta |A_\mu\rangle + \sin\theta |\hat{\rho}_\mu\rangle \\ |\text{heavy}\rangle &= -\sin\theta |A_\mu\rangle + \cos\theta |\hat{\rho}_\mu\rangle \end{aligned} \quad \tan\theta = \frac{g_{el}}{g_*}, \quad g_{\text{SM}} = \frac{g_{el}g_*}{\sqrt{g_{el}^2 + g_*^2}} \simeq g_{el}. \quad (3)$$

Here θ parametrizes the degree of compositeness of the SM field. While the Higgs in such a scheme is a full composite (solving in this way the SM hierarchy problem via dimensional transmutation), the SM fermions can also be partial composites as a consequence of their mixing with a tower of fermionic resonances of the strong sector. Theories with a warped extra dimension, with their 4-dimensional dual description, are explicit realizations of this scenario (see, for example, [8]). In particular, the tower of heavy resonances in the mass eigenstate basis is interpreted as the Kaluza-Klein (KK) modes of the higher-dimensional theory.

The phenomenology of a heavy neutral vector Z^* that is the result of the elementary/composite mixing of eq.(3) – or, equivalently, that of a KK in a warped extra-dimensional theory – is rather different from the phenomenology of a “standard” Z' . The LEP2 precision tests imply that the degree of compositeness of the light fermions has to be very small. On the other hand, the large top quark mass can find a natural explanation if the top is mainly composite. This means that the Drell-Yan production of Z^* will mostly proceed via the interaction of its elementary component with the light partons of the proton. The coupling strength for this scattering is $\sim g_{el} \sin\theta = g_{\text{SM}} \tan\theta$, implying a suppression factor $\tan\theta = g_{el}/g_* \ll 1$ compared to the SM value. Moreover, the same factor will also suppress the decay rate to light quarks and leptons. The Z^* will instead couple strongly, via its composite component, to all the SM particles with a sizable degree of compositeness: the Higgs, the longitudinally polarized W and Z 's, the top and bottom quarks. In other words, the Z^* will mainly decay to hZ_L , $W_L^+ W_L^-$, $t\bar{t}$ or $b\bar{b}$, while the branching ratio to a pair of electrons or muons will be quite small. For example, the decay rates of a

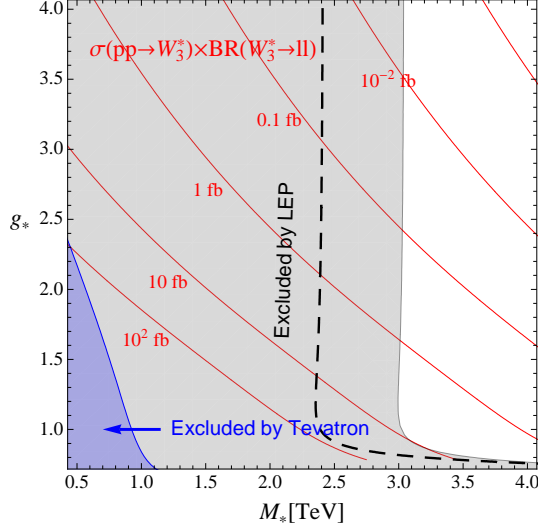


Figure 3: Constraints on the mass and the coupling strength of vectorial resonances in the adjoint of $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ (see text). The red curves report the production rate of the neutral W_3^* to two charged leptons: $\sigma(pp \rightarrow W_3^* \rightarrow l^+l^-)$, with $l = e, \mu$.

heavy W_3^* (the neutral component of a heavy $SU(2)_L$ triplet) are [8]

$$\begin{aligned} \Gamma(W_3^* \rightarrow q\bar{q}) &= 3\Gamma(W_3^* \rightarrow l\bar{l}) \simeq \frac{g_2^2 \tan^2 \theta}{32\pi} M_* \\ \Gamma(W_3^* \rightarrow t_L \bar{t}_L) &= \Gamma(W_3^* \rightarrow b_L \bar{b}_L) = (\sin^2 \varphi_L \cot \theta - \cos^2 \varphi_L \tan \theta) \frac{g_2^2}{32\pi} M_* \quad (4) \\ \Gamma(W_3^* \rightarrow Z_L h) &= \Gamma(W_3^* \rightarrow W_L^+ W_L^-) = \frac{g_2^2 \cot^2 \theta}{192\pi} M_* , \end{aligned}$$

where $\sin \varphi_L$ is the degree of compositeness of t_L and b_L . For $M_* = 3$ TeV, $\tan \theta = 1/6$, $\sin \varphi_L = 0.4$, one has a total decay rate $\Gamma_{tot}(W_3^*) = 170$ GeV and $BR(ee, \mu\mu) = 0.1\%$, $BR(tt, bb) = 5\%$.

The plot of figure 3 shows the experimental constraints on a strong sector with an $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ global invariance and vectorial resonances (two charged and three neutral states) in the adjoint representation.

The larger symmetry is required to have an unbroken custodial invariance after EWSB and protect the ρ parameter from large tree-level corrections. At the same time, however, it leads to several massive vectors, which makes the constraint from the vertex corrections in fig.1(c) stronger. The (lighter) gray region represents the portion of the (M_*, g_*) plane excluded by the LEP precision measurements. The LEP2 constraint on contact interactions becomes negligible for $g_* \gtrsim 1$, since the coupling of the heavy vectors to the light SM fermions scales as $g_{Z^*}^{[W]} = g_{SM} \tan \theta \simeq g_{SM}(g_{SM}/g_*)$. In that limit the dominant constraint comes from the \hat{S} parameter, which does not

depend on g_* since $g_{Z^*}^{[H]} = g_{SM} \cot \theta \simeq g_{SM}(g_*/g_{SM})$, hence $g_{Z^*}^{[\Psi]} g_{Z^*}^{[H]} = g_{SM}^2 = \text{constant}$. The dashed curve shows how much the LEP bound is relaxed by adding a correction $\Delta\rho = \Delta\hat{T} = 1 \times 10^{-3}$, which might come, for example, from the 1-loop contribution of new heavy fermions. The blue area is the region excluded by the CDF data of reference [3].

Superimposed in red are the curves reporting the production rate of the neutral W_3^* in the dilepton channel. One can see that in most of the region allowed by LEP the rate is quite small, so that the observation of this channel will probably require very large integrated luminosities. On the other hand, a discovery can come earlier from the other final states. According to the analysis of reference [9], a Z^* with mass $M_* = 2 \text{ TeV}$ (3 TeV) and $g_* \simeq 3.9$ can be discovered in the Zh channel with $\sim 100 \text{ fb}^{-1}$ (1 ab^{-1}). Observing the W^+W^- channel will instead require more integrated luminosity.

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I would like to thank Slava Rychkov and Alessandro Strumia for interesting discussions and useful comments.

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