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Prima facie evidence against spin-two Higgs impostors

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ABSTRACT

The new particle X recently discovered by the ATLAS and CMS Collaborations is widely expected to have spin zero, but this remains to be determined. The leading alternative is that X has spin two, presumably with graviton-like couplings. We show that measurements of the X particle to pairs of vector bosons constrain such scenarios. In particular, a graviton-like Higgs impostor in scenarios with a warped extra dimension of AdS type is *prima facie* excluded, principally because they predict too small a ratio between the X couplings to WW and ZZ, compared with that to photons. The data also disfavour universal couplings to pairs of photons and gluons, which would be predicted in a large class of graviton-like models.

1. Introduction and summary

The ATLAS [1] and CMS [2] Collaborations have discovered a new particle X with mass ~ 125 to 126 GeV during their searches for the Higgs boson at the LHC. Supporting evidence for X production in association with massive vector bosons $V \equiv W, Z$ at the TeVatron has been provided by the CDF and D0 Collaborations [3]. If it is indeed a/the Higgs boson of the Standard Model, the X particle must have spin zero. Since it has been observed to decay into pairs of photons, we already know that the X particle cannot have spin one, but spin two is still an open possibility at the time of writing.

In view of the importance of determining the 'Higgs' spin, and the strong presumption that it has spin zero, it is particularly important to take an unbiased, approach to its measurement. Indeed, there is an extensive literature on possible strategies to distinguish the spin-parity J^P of the X particle, based on the kinematic characteristics of its production and decays [4,5]. Examples include correlations between the momenta of particles produced in X decays into $\gamma\gamma$, WW^* and ZZ^*, and the $V + X$ invariant mass when it is produced in association with a massive vector boson V [6]. It is generally expected that significant evidence on the possible spin of the X particle will shortly be provided by analyses of the existing TeVatron and 2012 LHC data.

In this Letter we explore the extent to which the available data on X production and decay already provide *prima facie* evidence that it is not a spin-two particle with graviton-like couplings in the frameworks of some popular models.[1] As we recall in Section 2, the couplings $c_{g,\gamma}$ of a Higgs impostor X to gluon pairs and photon pairs must be equal in many models with a compactified extra dimension, and hence

$$\Gamma(X \to gg) = 8\Gamma(X \to \gamma\gamma). \quad (1)$$

This relation is completely different from the case of a Higgs-like spin-zero particle, for which the Xgg and $X\gamma\gamma$ couplings are induced by loop diagrams, and $\Gamma(X \to gg) = \mathcal{O}(\alpha_s/\alpha_{EM})^2\Gamma(X \to \gamma\gamma)$. Numerically, at the one-loop level for the Higgs boson H in the Standard Model in the limit $m_H \ll 2m_t, 2m_W$ one has

$$\Gamma(H \to gg) \simeq 37\Gamma(H \to \gamma\gamma). \quad (2)$$

Various analyses have shown that the current data are compatible with the X particle being a Standard Model Higgs boson [8,9], and in particular with (2).

Here we argue that the present data on X production and decay disfavour the graviton-like spin-two prediction (1), providing some *prima facie* evidence against the spin-two hypothesis. However, some graviton-like spin-two interpretations of the X particle encounter more serious problems. For example, in models with a warped fifth dimension of AdS type one expects the following hierarchy of couplings to the energy-momentum tensors of different particle species:

$$c_b \simeq c_t \gtrsim c_W \simeq c_Z = \mathcal{O}(35) \times (c_g = c_\gamma > c_u, c_d). \quad (3)$$

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[1] The spirit of this analysis is similar to that of [7], where *prima facie* evidence was presented that the 'Higgs' particle is not a pseudoscalar.

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As we show later, the hierarchy between $c_{W,Z}$ and $c_{g,\gamma}$ predicted in (3) is in strong tension with the available data, which indicate a much greater hierarchy.

In the rest of this Letter, we first review in Section 2 the couplings of a graviton-like spin-two boson, emphasizing the model-independence of the prediction (1) and discussing the motivations for the more model-dependent predictions (3). We then discuss the current data in Section 3, and the problems they raise for the predictions (1) and (3). Finally, in Section 4 we summarize our conclusions and discuss the prospects for gaining further insight into the nature of the X particle.

2. Spin-two Boson couplings to Standard Model particles

It was pointed out in [10] that dimension-four couplings of a massive spin-two particle to a pair of Standard Model particles are forbidden by Lorentz invariance and gauge symmetry. The flavour and CP symmetries of the Standard Model then imply that the leading dimension-five terms should be proportional to their energy-momentum tensors $T^i_{\mu\nu}$, so that the couplings take the forms

$$\mathcal{L}_{int} = -\frac{c_i}{M_{eff}} G^{\mu\nu} T^i_{\mu\nu}. \tag{4}$$

In scenarios with extra dimensions, $M_{eff} \simeq \mathcal{O}$ (TeV) is the effective Planck mass, whereas in composite models M_{eff} would be a scale related to confinement. These two scenarios are, in general, related by some suitable extension of the AdS/CFT correspondence, and we consider here the formulation in terms of an extra dimension.

If the new strongly-interacting sector were not to conserve the Standard Model flavour structure and CP symmetry, there would be a new type of tensor structure involving fermions and the spin-two field, namely $\bar{\Psi}\gamma_\mu\gamma_5\partial_\nu\Psi$, with all combinations of fermions changing flavour indices. Some of the strong constraints one would obtain from allowing these structures were discussed in [10]. In light of those constraints, here we assume that CP and flavour are approximately conserved by the strongly-interacting sector.

We consider general warped geometries of the form

$$ds^2 = w^2(z)\left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right), \tag{5}$$

where $w(z) = 1$ for a flat extra dimension, and in the case of warping *à la* AdS one has $w(z) = z_{UV}/z$. In general, $w(z)$ is a positive constant or decreasing function of z.

In such a scenario, the Kaluza–Klein (KK) decomposition for spin-one particles leads to an equation of motion for the wave-function of the nth KK mode, $f_n(z)$, of the following form [11]:

$$\partial_z\left(w(z)\partial_z f_n(z)\right) = -m_n^2 w(z) f_n(z). \tag{6}$$

If the four-dimensional gauge symmetry is preserved by the compactification, as is the case for the SU(3) of QCD and the U(1) of electromagnetism, then the spin-one field has a massless zero mode, i.e., the lowest-lying KK mode has $m_0 = 0$, implying

$$w(z)\partial_z f_0(z) = \text{constant}. \tag{7}$$

Taking into account the Neumann boundary conditions on the boundary branes, there is only one solution, namely

$$f_0(z) = C, \tag{8}$$

where the constant C is determined by requiring the canonical normalization for the four-dimensional gauge field.

Obviously, the graviton is not the source of electroweak symmetry breaking (EWSB). Instead, one may think that EWSB is triggered by a condensate of new fermions induced by new strongly-interacting gauge fields, as in technicolor models [12], a heavy Higgs, or, in the language of models with extra dimensions, by boundary conditions [13]. The graviton would couple to this source of EWSB, which we can parametrize by a field Σ that is a doublet under $SU(2)_L$, that could be spurious or dynamical and satisfies $\langle\Sigma\rangle = v$. In view of the small values of the T and $\Delta\rho$ parameters [14], the field Σ should respect an approximate custodial symmetry, and couple to the graviton via an effective interaction of the form

$$\frac{c_\Sigma}{M_{eff}} G_{\mu\nu} D^\mu \Sigma D^\nu \Sigma, \tag{9}$$

where

$$D^\mu \equiv \partial^\mu + igW^\mu + igB^\mu. \tag{10}$$

Gauge invariance implies that the graviton couples to the gauge eigenstates W^a universally in (4), i.e., $c_W = c_Z$ as $g' \to 0$. Once EWSB occurs, the graviton would feel the effect through couplings induced via (10), which also respect custodial symmetry.

The next issue is the relation between $c_{\gamma,g}$ and $c_{W,Z}$. If it is assumed that electroweak symmetry is broken by boundary conditions on the IR brane,[2] the support of the wave-functions of the transverse components of the W and Z is suppressed near this brane, so that $c_{W_t,Z_t} < c_{g,\gamma}$. However, the wave-functions of the longitudinal components of the W and Z are localized near the IR brane, as are the wave-functions of the massive fermions b and t, so that $c_{W_L,Z_L,b,t} > c_{g,\gamma}$. On the other hand, the wave-functions of light fermions such as the u and d are expected to be concentrated closer to the UV brane, so that $c_{u,d} \ll c_{g,\gamma}$.

One can estimate the hierarchy between $c_{\gamma,g}$ and $c_{W,Z}$ by accounting for the suppression due to the difference between localization on the IR brane, where the graviton has most of its support, and delocalization in the bulk. The couplings of the massive graviton to the massless gauge bosons, i.e., the gluons and photon, are suppressed by the effective volume of the extra dimension, namely [15]

$$c_{g,\gamma} \simeq 1\Big/\int_{z_{UV}}^{z_{IR}} w(z)\,dz, \tag{11}$$

and are therefore universal, leading to the result (1). If the extra dimension is of AdS type, $w(z) = 1/kz$, and the suppression is by a factor $\log M_{Pl}/\text{TeV} \simeq 35$. In other metrics, one could get a different degree of suppression. For example, one could introduce deviations from conformal invariance in AdS (or condensates of canonical dimension d in the dual picture), by introducing metrics of the form [16]

$$w(z) = \frac{1}{kz}\left(1 + c_d\left(\frac{z}{z_{IR}}\right)^{2d}\right). \tag{12}$$

Such effects would not change the AdS result $c_{W,Z}/c_{\gamma,g} \lesssim \mathcal{O}(35)$ by more than a factor $\mathcal{O}(1)$, since $c_{g/\gamma}$ as calculated by plugging (12) into (11) would receive corrections suppressed by z/z_{IR}. On the other hand, one could obtain a larger difference by postulating a metric that is not asymptotically AdS.

In the dual picture, metrics of the form (12) correspond to theories which become scale-invariant at high energies. This is a very attractive feature of a strongly-coupled theory, as one can relate

[2] This assumption is commonly used in model building, inspired by the AdS/CFT interpretation of this extra-dimensional scenario. However, one could imagine a situation in which electroweak symmetry breaking and the IR brane are unrelated, in which case this discussion would apply.