Strong Electroweak Symmetry Breaking and Spin-0 Resonances

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We argue that theories of the strong electroweak symmetry breaking sector necessarily contain new spin 0 states at the TeV scale in the $\bar{t}t$ and $\bar{t}b/\bar{b}t$ channels, even if the third generation quarks are not composite at the TeV scale. These states couple sufficiently strongly to third generation quarks to have significant production at LHC via $gg \to \varphi^0$ or $gb \to t\varphi^-$. The existence of narrow resonances in QCD suggests that the strong electroweak breaking sector contains narrow resonances that decay to $\bar{t}t$ or $\bar{t}b/\bar{b}t$, with potentially significant branching fractions to 3 or more longitudinal W and Z bosons. These may give new ''smoking gun'' signals of strong electroweak symmetry breaking.

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Introduction.—One of the most important questions to be addressed at the LHC is whether the interactions that break electroweak symmetry are strongly or weakly coupled. Precision electroweak data are in good agreement with the standard model containing a light Higgs boson, but mild cancellations may allow a good fit to precision electroweak data in strongly coupled models. Direct searches are essential to settle this question.

One direct test of the nature of electroweak symmetry breaking is of course the search for the Higgs boson. However, even if a light Higgs-like particle is discovered at the LHC, it is important to make sure that it is ''the'' Higgs boson, namely, the state that unitarizes VV scattering, where $V = W, Z$. There are other types of scalars that naturally have couplings to gauge bosons and fermions similar to Higgs bosons even though they are not responsible for electroweak symmetry breaking, for example, radions [1] and dilatons [2]. In principle one can measure the couplings of the scalar to electroweak gauge bosons and compare with the values needed to unitarize VV scattering, but this requires very high integrated luminosity at LHC [3]. Conversely, if the standard Higgs search does not lead to a discovery, it does not follow that electroweak symmetry breaking is strongly coupled. For example, there may be a light Higgs with new physics modifying its decays, making Higgs discovery difficult at LHC [4].

It is therefore important to carry out direct searches for a strongly coupled electroweak symmetry breaking sector, independently of the status of the search for the Higgs boson. The classic signal is strong VV scattering [5], which is directly related to the absence of a light Higgs boson by unitarity. However, this also requires very high integrated luminosity at LHC [6].

We argue that there is another generic signature in models with strong VV scattering: new $J = 0$ states in the $\bar{t}t$, $\bar{b}t$, and $\bar{t}b$ channels, with masses of order a TeV. These states must couple to the top quark sufficiently strongly to change the $\bar{t}t$, $\bar{b}t$, and $\bar{t}b$ cross sections by order 100% at energies of order TeV.

The existence of such resonances is already expected in models where the top quark is composite (as in ''topcolor'' models [7]) and in extradimensional models that are ''dual'' to strongly coupled theories with a composite top quark [8]. We argue that such states also exist in models where the top quark is an elementary particle perturbatively coupled to a strong electroweak symmetry breaking sector. These states give rise to new signatures that may provide a ''smoking gun'' for strong electroweak symmetry breaking.

Strong electroweak breaking and the top quark.—We focus on models where the top quark mass arises from coupling to an operator Φ with the quantum numbers of a Higgs doublet:

$$\Delta \mathcal{L} = \frac{c}{\Lambda_t^{d-1}} \bar{Q}_L \Phi t_R + \text{H.c.} \tag{1}$$

Here d is the scaling dimension of the operator Φ above the TeV scale, and Λ_t is a mass scale that parametrizes the strength of the coupling. The dimensionless constant c is chosen so that Λ_t is the scale where this operator becomes strongly coupled (see below). Another possibility not discussed here is that the top quark couples to a fermionic operator with quantum numbers conjugate to the top itself [9]. In order for the top to be weakly coupled to the electroweak breaking sector at the TeV scale, we want d to be as small as possible, e.g., $d = 1 + 1/\text{few}$. On the other hand, naturalness requires that the operator $\Phi^\dagger \Phi$ be irrelevant; i.e., its dimension must be larger than 4. The possibility of models satisfying these requirements was pointed out in Ref. [10]. Rigorous inequalities on dimensions in conformal field theories allow this scenario [11]. Models based on QCD in the conformal window were described in Ref. [12].

The basic point is that the operator Φ creates states in the strong sector, so Eq. (1) couples the top quark to the strong sector. As we now show, this coupling is sufficiently strong to make an order 100% change in the scattering cross sections with initial states $\bar{t}t$, $\bar{t}b$, and $\bar{b}t$ for $E \gtrsim$ TeV, where the electroweak symmetry breaking sector gets strong. For simplicity, we will discuss the electrically neutral $\bar{t}t$ channel below, but the same arguments apply to the $\bar{t}b$ and $\bar{b}t$ channels. For $m_t \ll E \ll \Lambda_{\rm EW}$ the chirality-violating top quark scattering cross section does not fall off at large energy [13]:

$$\sigma(\bar{t}_L t_R \to VV) \sim \frac{1}{4\pi}\frac{m_t^2}{v^4}. \tag{2}$$

We now compare this to scattering amplitudes for $E \sim \Lambda_{\rm EW}$. The leading contribution to the amplitude for chirality-violating top interactions involves one insertion of the interaction Eq. (1). The cross section for producing a state X with mass of order $\Lambda_{\rm EW}$ is then of order

$$\sigma(\bar{t}_L t_R \to X) \sim \frac{(4\pi)^3}{\Lambda_{\rm EW}^2}\left(\frac{\Lambda_{\rm EW}}{\Lambda_t}\right)^{2(d-1)}. \tag{3}$$

The normalization can be most easily understood in the limit $\Lambda_t \to \Lambda_{\rm EW}$, where there is no suppression of the cross section and we expect $\sigma \sim (4\pi)^3/\Lambda_{\rm EW}^2$. For example, 2-to-2 scattering of particles of mass $\Lambda_{\rm EW}$ with quartic coupling $\sim(4\pi)^2$ (so that loop and tree effects are the same size) gives a cross section of this size. This is an example of "naïve dimensional analysis" (NDA) [14], counting powers of 4π in a strongly coupled theory by assuming that loop and tree effects are the same order of magnitude. To compare this with Eq. (2) we note that NDA also gives

$$m_t \sim \Lambda_{\rm EW}\left(\frac{\Lambda_{\rm EW}}{\Lambda_t}\right)^{d-1} \tag{4}$$

and $\Lambda_{\rm EW} \sim 4\pi v$, so the cross sections in Eqs. (2) and (3) are comparable.

NDA may not be quantitatively reliable, so we give an independent argument that does not rely on NDA. For $E \gg \Lambda_{\rm EW}$ the energy dependence of the total chirality-violating cross section to create hadrons in the strongly coupled theory is fixed by scale invariance:

$$\sigma(\bar{t}_L t_R \to \text{hadrons}) \sim \left(\frac{E^{d-2}}{\Lambda_t^{d-1}}\right)^2. \tag{5}$$

For $d \neq 2$, this has a different energy dependence than at low energy [see Eq. (2)]. This means that the strong sector gives a correction to the cross section that is order 100% at the matching scale $\Lambda_{\rm EW} \sim$ TeV. This argument does not imply a large change in the cross section if $d \simeq 2$, but the most phenomenologically interesting case is $d < 2$, as discussed above.

Both arguments above also hold for the chirality-violating channels $\bar{t}_R b_L$ and $\bar{b}_L t_R$, which also get contributions from the operator Eq. (1).

Resonances and phenomenology.—We now discuss the nature of the new states in the $\bar{t}t$, $\bar{t}b$, and $\bar{b}t$ channels at the TeV scale. The most spectacular signals arise if these states include narrow resonances. The only strongly interacting theory for which we have data is QCD, which tells us that strongly interacting theories can have narrow resonances. For example,

$$\frac{\Gamma(\rho \to \pi\pi)}{m_\rho} \simeq 0.2, \tag{6}$$

$$\frac{\Gamma(\omega \to \pi\pi\pi)}{m\omega} \simeq 10^{-2}. \tag{7}$$

This is much narrower than an estimate from NDA and large-N_c counting [15]:

$$\left.\frac{\Gamma(n\text{-body})}{m}\right|_{\rm NDA} \sim \frac{\pi}{N_c^{n-1}}. \tag{8}$$

This estimate is for direct n-body decays, i.e., those without intermediate on-shell particles. This tells us that NDA is not quantitatively reliable for all quantities, and that narrow resonances are plausible in strongly coupled theories. On the other hand, NDA is more accurate for inclusive quantities such as those discussed in the previous section.

Because Φ is a Lorentz scalar, the resonances created by the interaction Eq. (1) are spin 0. The resonances will fall into representations of a custodial $SU(2)$ symmetry, required to avoid large corrections to the ratio m_W/m_Z. Assuming the standard custodial symmetry breaking pattern $SU(2)_L \times SU(2)_R \to SU(2)_C$, the operator Φ transforms as $(\mathbf{2},\mathbf{2}) \to \mathbf{3} \oplus \mathbf{1}$. We therefore expect $SU(2)_C$ singlet and triplet states.

The mass of these resonances will be of order TeV. The coupling to $\bar{t}t$, $\bar{t}b$, and $\bar{b}t$ for these resonances will be of order $y_t \sim 1$. This coupling allows production of these states at LHC. Electrically neutral states can be produced via $gg \to \varphi$ via a top loop, and electrically charged states

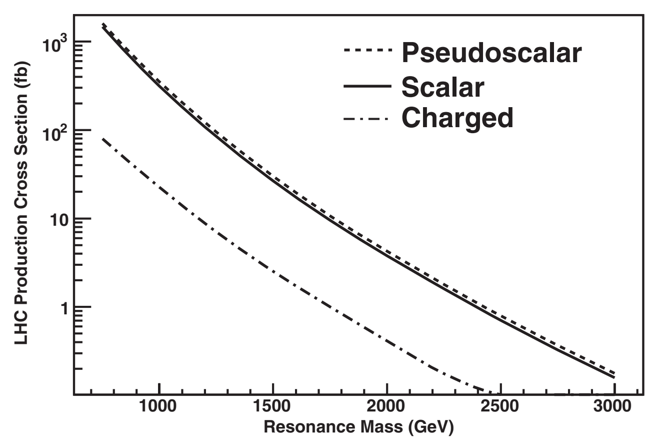

FIG. 1. Cross section for spin-0 resonance production at LHC via $gg \to \varphi^0$ (solid and dashed lines) and $gb \to t\varphi^-$ (dash-dotted line). We assume $g_{\bar{t}t\varphi^0} = g_{\bar{b}t\varphi^-} = y_t$. Cross sections are tree level with no K factor. Scalar and pseudoscalar cross sections are nearly equal for the charged case, and are not shown separately.

can be produced via $gb \to t\varphi^-$. The production rate for these states at the LHC is shown in Fig. 1.

These resonances can decay to top quarks via $\varphi^0 \to \bar{t}t$ or $\varphi^- \to \bar{t}b$ via the coupling Eq. (1). For $m_\varphi \gg m_t$ we have

$$\frac{\Gamma(\varphi \to \bar{t}t \text{ or } \bar{t}b)}{m_\varphi} = \frac{3(g_{\bar{t}t\varphi,\bar{t}b\varphi})^2}{16\pi} \sim 10^{-1}. \qquad (9)$$

These resonances also have strong decays to longitudinal W's and Z's, which can be identified with the Nambu-Goldstone bosons π of the strong sector. In the absence of additional symmetries, isospin singlets will decay strongly to $\pi\pi$ with a large width, similar to the TeV standard model Higgs. A spin-0 isospin triplet cannot decay to $\pi\pi$, so the leading strong decay is generally $\pi\pi\pi$. If the three-body strong decay is direct, scaling from QCD gives $\Gamma/m_\varphi \sim 10^{-2}$, corresponding to a branching ratio of order 10%. Observation of a direct three-body decay with such a large branching ratio is a "smoking gun" for strong dynamics, since a perturbative three-body decay would have $\Gamma/m \sim 10^{-4}$ due to three-body phase space suppression. Examination of the invariant mass distributions is required to exclude the possibility of a two-body chain decay.

Other interesting possibilities can arise if the strong sector has additional discrete symmetries. As an example, we consider a strong $SU(N)$ gauge theory in which the operator Φ in Eq. (1) is a "techniquark" bilinear $\Phi = \bar{\psi}_L \psi_R$. The strong sector then preserves C and P, and the lowest-lying resonances are expected to have the quantum numbers of techniquark bilinears. In addition, the resonances will conserve weak isospin I associated with the custodial $SU(2)_C$. As in QCD, it is convenient to introduce G parity by $G = Ce^{i\pi I_2}$. The operator Φ has the decomposition

$$I^{PG} = 0^{++} \oplus 0^{-+} \oplus 1^{+-} \oplus 1^{--}, \qquad (10)$$

so we may expect resonances in any of these channels. We emphasize that a theory of this type need not be a scaled-up version of QCD. For example the theory may have additional techniquarks that make the theory conformal above the TeV scale [12]. The 0^{-+} resonance in QCD-like technicolor theories was previously discussed in Ref. [16], but not the crucial role of the top quark coupling.

The 0^{++} resonance has the quantum numbers of the QCD σ. It has a two-body strong decay to $\pi\pi$, and is therefore expected to be broad. Here π is the composite eaten Nambu-Goldstone boson that makes up the longitudinal polarization of the W or Z.

The 0^{-+} has the quantum numbers of the QCD η', and we call it the η. Its most plausible strong decays are $\eta \to \rho\pi\pi$ (followed by $\rho \to \pi\pi$) or $\pi\pi\pi\pi$. Here ρ is the spin-1 $I^{PG} = 1^{++}$ particle, the quantum numbers of the QCD ρ. The strong decay to $VVVV$ can plausibly compete with the perturbative $\bar{t}t$ decay, especially if the $\eta \to \rho\pi\pi$ decay is open, leading to interesting observable signals at the LHC. For example, assuming $\Gamma/m_\eta \sim 10^{-2}$ for the strong decay, we obtain a cross section for like-sign electrons or muons of order 1 fb for a TeV resonance. In QCD, $\eta \to \rho\pi\pi$ is kinematically forbidden, but even if we scale up QCD, the decay is allowed because

$$\frac{m_W}{m_\rho} \sim 10^{-1} \frac{m_\pi}{m_\rho}\bigg|_{\text{QCD}}. \qquad (11)$$

This scaling predicts $m_\eta \simeq 2.5$ TeV, $m_\rho \simeq 2$ TeV, giving a very small production cross section. However, this may be very misleading because the dynamics is not expected to be QCD-like.

Another interesting case is the spin-0 $I^{PG} = 1^{--}$ resonance, which we call the π'. Its plausible strong decays are $\pi' \to \pi\pi\pi$ or $\pi' \to \rho\pi$ (followed by $\rho \to \pi\pi$). These possibilities correspond, respectively, to either a narrow resonance with a possibly significant branching ratio to $\pi\pi\pi$, or a broad resonance decaying dominantly to $\pi\pi\pi$. Finally, the $I^{PG} = 1^{+-}$ resonance has plausible strong decays $\eta\pi$ (followed by $\eta \to \bar{t}t$), $\rho\pi\pi\pi$ (followed by $\rho \to \pi\pi$), and $\pi\pi\pi\pi\pi$. The last two cases potentially give an observable rate for a $VVVVV$ final state!

Conclusions.—We have shown that the top quark coupling to strong electroweak symmetry breaking provides a production mechanism for TeV-scale spin-0 resonances, and that these resonances are a generic signature for strong electroweak symmetry breaking. The processes $\bar{t}t \to \varphi^0$ and $gb \to \varphi^- t$ may give significant numbers of events at the LHC, and can result in the production of both narrow and broad resonances. (By comparison, WW scattering can only produce resonances with two-body strong decays, which are therefore broad.) These resonances always have decays to third generation quarks via $\varphi^0 \to \bar{t}t$, $\varphi^- \to \bar{t}b$, but may also have substantial branching fractions to multi-V final states, where $V = W, Z$. Whether or not these modes are observable at the LHC depends sensitively on their mass: as can be seen from Fig. 1, the production cross section drops by 3 orders of magnitude as the resonance mass varies from 1 to 3 TeV. However, besides strong WW scattering this is the only generic signal for strong electroweak symmetry breaking observable at LHC, and should be pursued vigorously. We do not know the masses of the lightest resonances, so broad-based search strategies are required. We leave the detailed investigation of phenomenology for future work.

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