

## DYNAMICAL ELECTROWEAK SYMMETRY BREAKING

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In theories of dynamical electroweak symmetry breaking, the electroweak interactions are broken to electromagnetism by the vacuum expectation value of a fermion bilinear. These theories may thereby avoid the introduction of fundamental scalar particles, of which we have no examples in nature. In this note, we review the status of experimental searches for the particles predicted in technicolor, topcolor, and related models. The limits from these searches are summarized in Table 1.

### *I. Technicolor*

The earliest models [1,2] of dynamical electroweak symmetry breaking [3] include a new asymptotically free non-abelian gauge theory (“technicolor”) and additional massless fermions (“technifermions” transforming under a vectorial representation of the gauge group) which feel this new force. The global chiral symmetry of the fermions is spontaneously broken by the formation of a technifermion condensate, just as the approximate chiral  $SU(2) \times SU(2)$  symmetry in QCD is broken down to  $SU(2)$  isospin by the formation of a quark condensate. If the quantum numbers of the technifermions are chosen correctly (*e.g.*, by choosing technifermions in the fundamental representation of an  $SU(N)$  technicolor gauge group, with the left-handed technifermions being weak doublets and the right-handed ones weak singlets), this condensate can break the electroweak interactions down to electromagnetism.

The breaking of the global chiral symmetries implies the existence of Goldstone bosons, the “technipions” ( $\pi_T$ ). Through the Higgs mechanism, three of the Goldstone bosons become the longitudinal components of the  $W$  and  $Z$ , and the weak gauge bosons acquire a mass proportional to the technipion decay constant (the analog of  $f_\pi$  in QCD). The quantum numbers and masses of any remaining technipions are model-dependent. There may be technipions which are colored (octets and triplets), as well as those carrying electroweak quantum

**Table 1:** Summary of the mass limits. Symbols are defined in the text.

Process	Excluded mass range	Decay channels	Ref.
$p\bar{p} \rightarrow \rho_T \rightarrow W\pi_T$	$170 < m_{\rho_T} < 215$ GeV and $80 < m_{\pi_T} < 115$ GeV for $M_V = 500$ GeV	$\rho_T \rightarrow W\pi_T$ $\pi_T^0 \rightarrow b\bar{b}$ $\pi_T^\pm \rightarrow b\bar{c}$	[24]
$pp \rightarrow \omega_T/\rho_T$	$130 < m_{\rho_T/\omega_T} < 180$ GeV for $50 < m_{\pi_T} < 480$ GeV	$\omega_T/\rho_T \rightarrow \ell^+\ell^-$	[36]
$pp \rightarrow \rho_T/a_T$	$m_{\rho_T/a_T} < 382$ GeV for $M(\pi_T) = \frac{3}{4}M(\rho_T) - 25$ GeV	$\rho_T \rightarrow WZ \rightarrow \ell\ell\nu$	[37]
	$m_{\rho_T/a_T} < 436$ GeV for $M(\rho_T) < M(\pi_T) + M_W$	$\rho_T \rightarrow WZ \rightarrow \ell\ell\nu$	[37]
$p\bar{p} \rightarrow \omega_T \rightarrow \gamma\pi_T$	$140 < m_{\omega_T} < 290$ GeV for $m_{\pi_T} \approx m_{\omega_T}/3$ and $M_T = 100$ GeV	$\omega_T \rightarrow \gamma\pi_T$ $\pi_T^0 \rightarrow b\bar{b}$ $\pi_T^\pm \rightarrow b\bar{c}$	[26]
$p\bar{p} \rightarrow \omega_T/\rho_T$	$m_{\omega_T} = m_{\rho_T} < 203$ GeV for $m_{\omega_T} < m_{\pi_T} + m_W$ or $M_T > 200$ GeV	$\omega_T/\rho_T \rightarrow \ell^+\ell^-$	[27]
	$m_{\omega_T} = m_{\rho_T} < 280$ GeV for $m_{\omega_T} < m_{\pi_T} + m_W$ or $M_T > 500$ GeV	$\omega_T/\rho_T \rightarrow \ell^+\ell^-$	[28]
$e^+e^- \rightarrow \omega_T/\rho_T$	$90 < m_{\rho_T} < 206.7$ GeV $m_{\pi_T} < 79.8$ GeV	$\rho_T \rightarrow WW,$ $W\pi_T, \pi_T\pi_T,$ $\gamma\pi_T, \text{hadrons}$	[29]
$p\bar{p} \rightarrow \rho_{T8}$	$260 < m_{\rho_{T8}} < 480$ GeV	$\rho_{T8} \rightarrow q\bar{q}, gg$	[31]
$p\bar{p} \rightarrow \rho_{T8}$	$m_{\rho_{T8}} < 510$ GeV	$\pi_{LQ} \rightarrow c\nu$	[34]
$\rightarrow \pi_{LQ}\pi_{LQ}$	$m_{\rho_{T8}} < 600$ GeV	$\pi_{LQ} \rightarrow b\nu$	[34]
	$m_{\rho_{T8}} < 465$ GeV	$\pi_{LQ} \rightarrow \tau q$	[33]
$p\bar{p} \rightarrow g_t$	$0.3 < m_{g_t} < 0.6$ TeV for $0.3m_{g_t} < \Gamma < 0.7m_{g_t}$	$g_t \rightarrow b\bar{b}$	[47]
$p\bar{p} \rightarrow Z'$	$m_{Z'} < 900$ GeV	$Z' \rightarrow t\bar{t}$	[48]
	$m_{Z'} < 835$ GeV for $\Gamma = 0.012m_{Z'}$	$Z' \rightarrow t\bar{t}$	[49]
	$m_{Z'} < 940$ GeV for $\Gamma = 0.03m_{Z'}$		
$pp \rightarrow Z'$	$m_{Z'} < 500 - 860$ GeV	$Z' \rightarrow t\bar{t}$	[50]
$p\bar{p} \rightarrow \text{Coloron}$	$m_{\text{Coloron}} < 775$ GeV for $\Gamma = 0.12m_{\text{coloron}}$ and $r=0.2$	$\text{Coloron} \rightarrow t\bar{t}$	[49]
$pp \rightarrow \text{Coloron}$	$320 < m_{\text{Coloron}} < 580$ GeV	$\text{Coloron} \rightarrow q\bar{q}$	[63]

numbers, and some color-singlet technipions are too light [4,3] unless additional sources of chiral-symmetry breaking are introduced. The next lightest technicolor resonances are expected to be the analogs of the vector mesons in QCD. The technivector mesons can also have color and electroweak quantum numbers and, for a theory with a small number of technifermions, are expected to have a mass in the TeV range [5].

While technicolor chiral symmetry breaking can give mass to the  $W$  and  $Z$  particles, additional interactions must be introduced to produce the masses of the standard model fermions. The most thoroughly studied mechanism for this invokes “extended technicolor” (ETC) gauge interactions [4,6]. In ETC, technicolor and flavor are embedded into a larger gauge group, which is broken at a sequence of mass scales down to the residual, exact technicolor gauge symmetry. The massive gauge bosons associated with this breaking mediate transitions between quarks/leptons and technifermions, giving rise to the couplings necessary to produce fermion masses. The ETC gauge bosons also mediate transitions among technifermions themselves, leading to interactions which can explicitly break unwanted chiral symmetries and raise the masses of any light technipions. The ETC interactions connecting technifermions to quarks/leptons also mediate technipion decays to ordinary fermion pairs. Since these interactions are responsible for fermion masses, one generally expects technipions to decay to the heaviest fermions kinematically allowed (though this need not hold in all models).

In addition to quark masses, ETC interactions must also give rise to quark mixing. One expects, therefore, that there are ETC interactions coupling quarks of the same charge from different generations. A stringent limit on these flavor-changing neutral current interactions comes from  $K^0-\bar{K}^0$  mixing [4]. These force the scale of ETC breaking and the corresponding ETC gauge boson masses to be in the 100-1000 TeV range (at least insofar as ETC interactions of first two generations are concerned). To obtain quark and technipion masses that are large enough then requires an enhancement of the technifermion condensate over that expected naively by scaling from QCD.

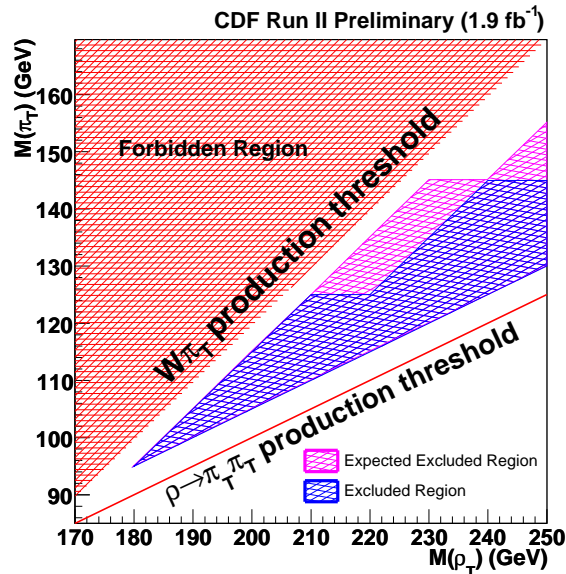
Such an enhancement can occur if the technicolor gauge coupling runs very slowly, or “walks” [7]. Some theories of walking technicolor incorporate many technifermions, implying that the technicolor scale and, in particular, the technivector mesons may be much lighter than 1 TeV [3,8].

It should be noted that there are no reliable analytical calculation techniques to analyze the properties of strongly-coupled gauge theories. Recently, however, progress has been made in simulating these theories using lattice gauge theory [9], including preliminary studies of condensate enhancement [10], precision electroweak parameters and parity doubling [11,12,13], and vector-boson scattering [14]. Progress has also been made in constructing a complete theory of fermion masses (including neutrino masses) in the context of extended technicolor [15].

In existing colliders, technivector mesons are dominantly produced when an off-shell standard model gauge boson “resonates” into a technivector meson with the same quantum numbers [16]. The technivector mesons may then decay, in analogy with  $\rho \rightarrow \pi\pi$ , to pairs of technipions. However, in walking technicolor the technipion masses may be increased to the point that the decay of a technirho to pairs of technipions is kinematically forbidden [8]. In this case the decay to a technipion and a longitudinally polarized weak boson (an “eaten” Goldstone boson) may be preferred, and the technivector meson would be very narrow. Alternatively, the technivector may also decay, in analogy with the decay  $\rho \rightarrow \pi\gamma$ , to a technipion plus a photon, gluon, or transversely polarized weak gauge boson. Finally, in analogy with the decay  $\rho \rightarrow e^+e^-$ , the technivector meson may resonate back to an off-shell gluon or electroweak gauge boson, leading to a decay into a pair of leptons, quarks, or gluons.

When comparing the various results presented in this review, one should be aware that the more recent analyses [23,24,27,29] make use of newer calculations [17] of technihadron production and decay, as implemented in PYTHIA [19] version 6.126 and higher [20]. The LHC analyses use the calculations given in reference [18] and PYTHIA [19] version 6.4. The results obtained with older cross section calculations are

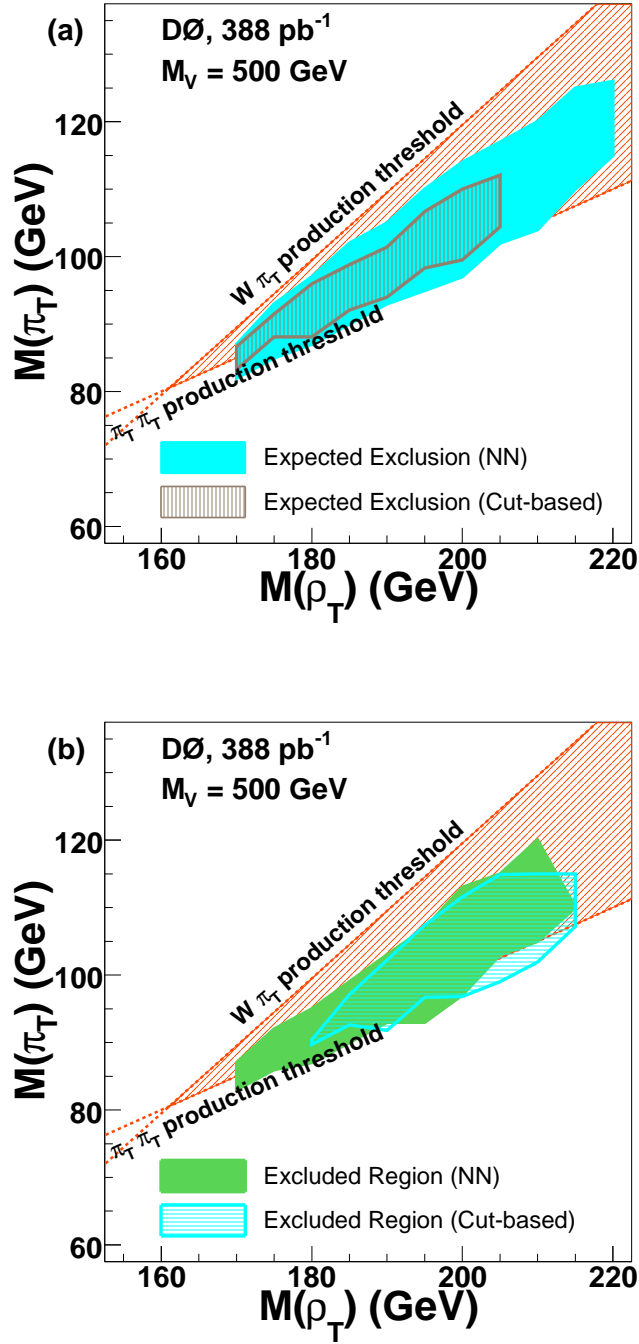
not generally directly comparable, and have only been listed in Table 1 when newer results are not available.



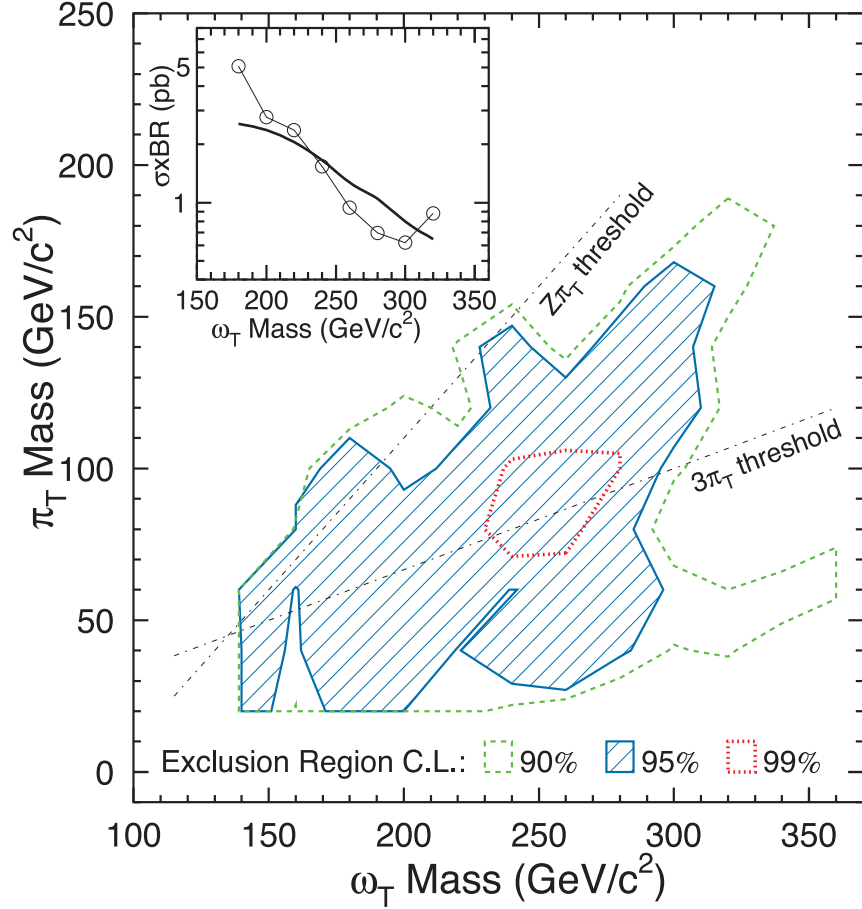
**Figure 1:** Search for a light technirho decaying to  $W^\pm$  and a  $\pi_T$ , and in which the  $\pi_T$  decays to two jets including at least one  $b$  quark [23]. Exclusion region at the 95% C.L. in the  $M(\rho_T), M(\pi_T)$  plane for  $\rho_T \rightarrow W\pi_T \rightarrow e\nu b\bar{b}(\bar{c})$  production. Kinematic thresholds from  $W\pi_T$  and  $\pi_T\pi_T$  are shown on the figure.

If the dominant decay mode of the technirho is  $W_L\pi_T$ , promising signal channels [21] are  $\rho_T^\pm \rightarrow W^\pm\pi_T^0$  and  $\rho_T^0 \rightarrow W^\pm\pi_T^\mp$ . If we assume that the technipions decay to  $b\bar{b}$  (neutral) and  $b\bar{c}$  (charged), then both channels yield a signal of  $W(\ell\nu) + 2$  jets, with one or more heavy flavor tags. The CDF collaboration carried out a search in this final state [22] based on Run I data and using PYTHIA version 6.1 for the signal simulation. Using  $1.9 \text{ fb}^{-1}$  of data from Run II, CDF [23] has published an update of this analysis. A large region of  $M(\rho_T) = 180\text{--}250 \text{ GeV}$  and  $M(\pi_T) = 95\text{--}145 \text{ GeV}$  are excluded at 95% CL, with the exact exclusion region displayed in Fig. 1.

The DØ [24] collaboration published an analysis based on  $388 \text{ pb}^{-1}$  of data from Run II and PYTHIA 6.22. The searches are sensitive to  $\sigma \cdot B \gtrsim 4 \text{ pb}$  and DØ finds mass combinations

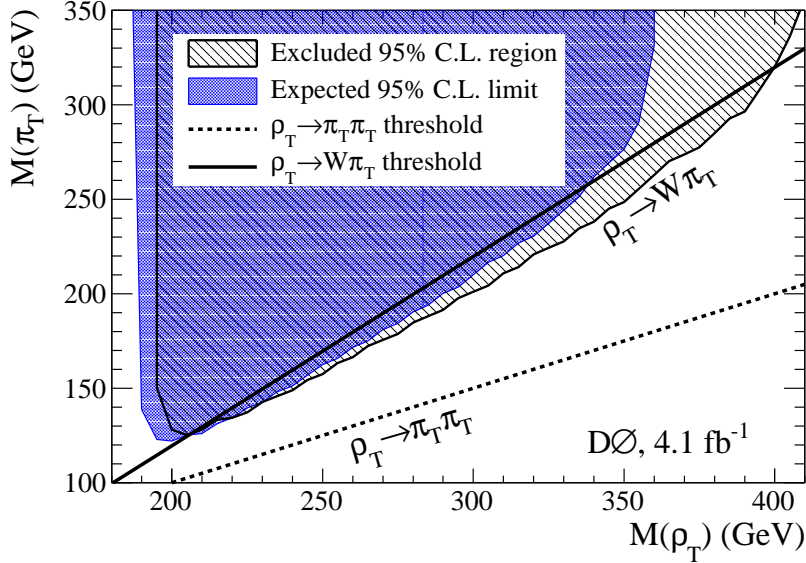


**Figure 2:** Search for a light technirho decaying to  $W^\pm$  and a  $\pi_T$ , and in which the  $\pi_T$  decays to two jets including at least one  $b$  quark [24]. Expected region of exclusion (a) and excluded region (b) at the 95% C.L. in the  $M(\rho_T)$ ,  $M(\pi_T)$  plane for  $\rho_T \rightarrow W\pi_T \rightarrow e\nu b\bar{b}(\bar{c})$  production with  $M_V = 500$  GeV. Kinematic thresholds from  $W\pi_T$  and  $\pi_T\pi_T$  are shown on the figures.



**Figure 3:** 95% CL exclusion region [26] for a light techniomega decaying to  $\gamma$  and a  $\pi_T$ , and in which the  $\pi_T$  decays to two jets, including at least one  $b$  quark. (Inset: cross section limit for  $m_{\pi_T} = 120$  GeV.)

up to  $m_{\rho_T} = 215$  GeV,  $m_{\pi_T} = 115$  GeV to be excluded for certain values of the model parameters. The expected sensitivity and the region excluded at 95% C.L. by the DØ analysis for  $M_V = 500$  GeV is shown in Fig. 2. For  $M_V = 100$  GeV, only a small region around  $M(\rho_T) = 190$  GeV and  $M(\pi_T) = 95$  GeV can be excluded. For an integrated luminosity of  $2 \text{ fb}^{-1}$ , the  $5\sigma$  discovery reach is expected to extend to  $m_{\rho_T} = 210$  GeV and  $m_{\pi_T} = 110$  GeV, while the 95% exclusion sensitivity will extend to  $m_{\rho_T} = 250$  GeV and  $m_{\pi_T} = 145$  GeV.

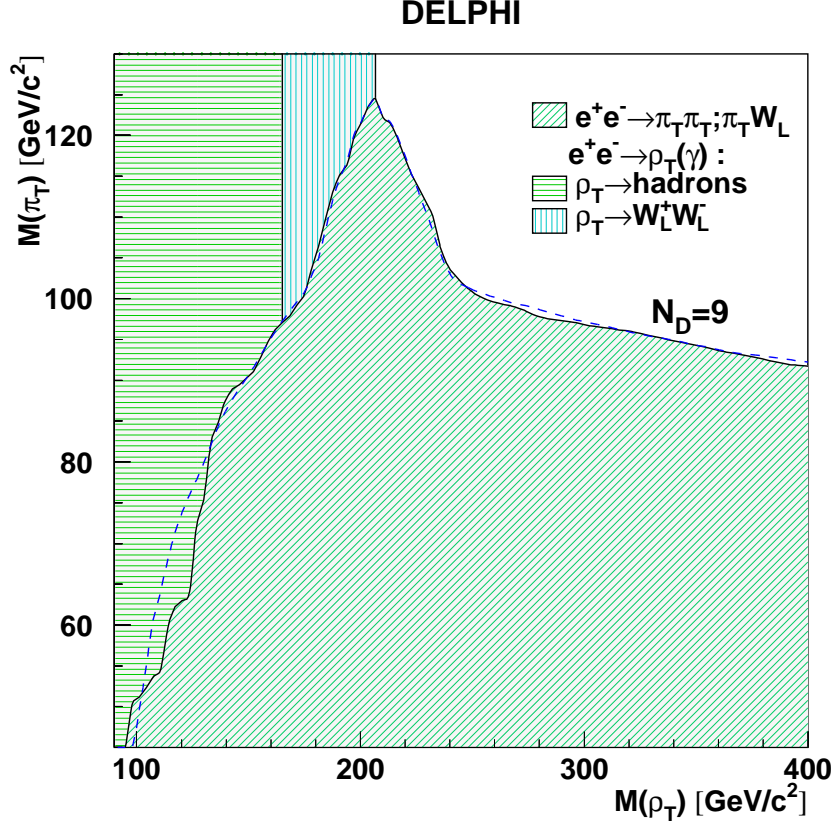


**Figure 4:** 95% CL exclusion region by the DØ experiment [25] in the  $M(\rho_T), M(\pi_T)$  plane for  $\rho_T \rightarrow WZ \rightarrow ll\nu$  (with  $l = e, \mu$ ) final state.

DØ has also performed a search for technihadrons decaying to  $WZ$  [25]. These decays can be searched in the tri-lepton final state, where the  $W$  decays into a lepton and neutrino and the accompanying  $Z$  decays to dileptons. With a dataset corresponding to a  $4.1 \text{ fb}^{-1}$  of integrated luminosity, DØ excludes  $\rho_T$  with mass between 208 and 408 GeV at 95% C.L. for  $M(\rho_T) < M(\pi_T) + M(W)$  as displayed in Fig. 4.

CDF also searched [26] in Run I for the process  $\omega_T^0 \rightarrow \gamma\pi_T^0$ , yielding a signal of a hard photon plus two jets, with one or more heavy flavor tags. The sensitivity to  $\sigma \cdot B$  is of order 1 pb. The excluded region is shown in Fig. 3 and is roughly  $140 < m_{\omega_T} < 290$  GeV at the 95% level, for  $m_{\pi_T} \approx m_{\omega_T}/3$ . The analysis assumes four technicolors,  $Q_D = Q_U - 1 = \frac{1}{3}$  and  $M_T = 100 \text{ GeV}/c^2$ . Here  $Q_U$  and  $Q_D$  are the charges of the lightest technifermion doublet, and  $M_T$  is a dimensionful parameter, of order  $100 \text{ GeV}/c^2$ , which controls the rate of  $\rho_T, \omega_T \rightarrow \gamma\pi_T$ .



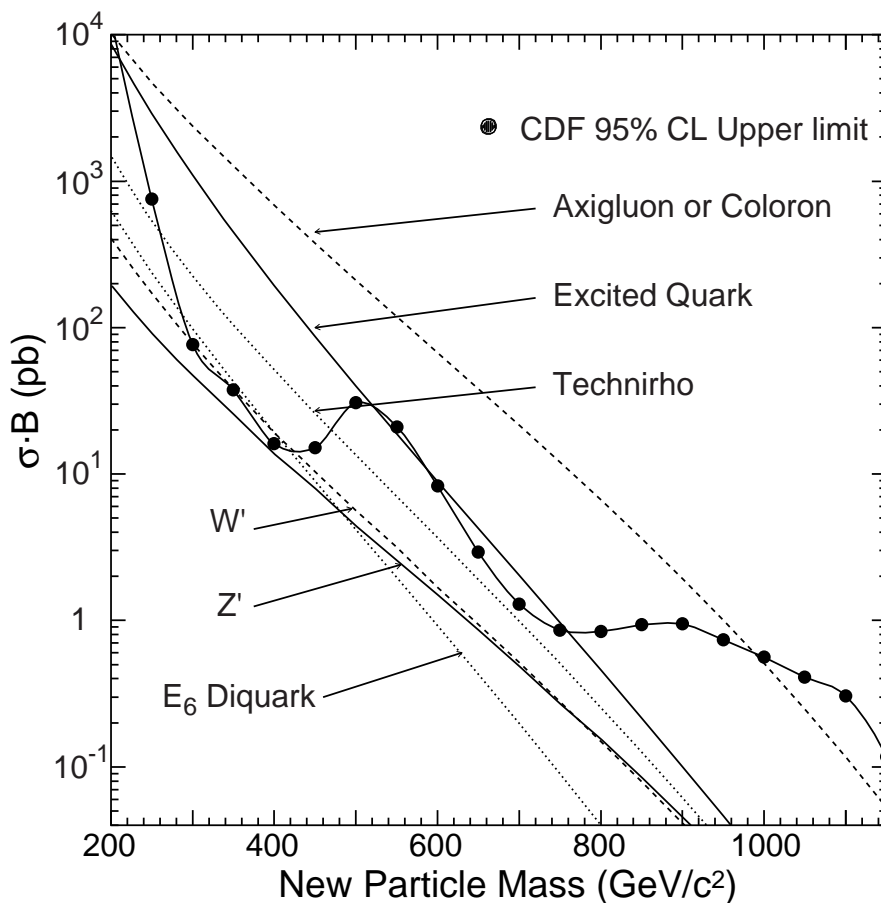


**Figure 5:** 95% CL exclusion region [29] in the technirho-technipion mass plane obtained from searches by the DELPHI collaboration at LEP 2, for nine technifermion doublets. The dashed line shows the expected limit for the 4-jet analysis.

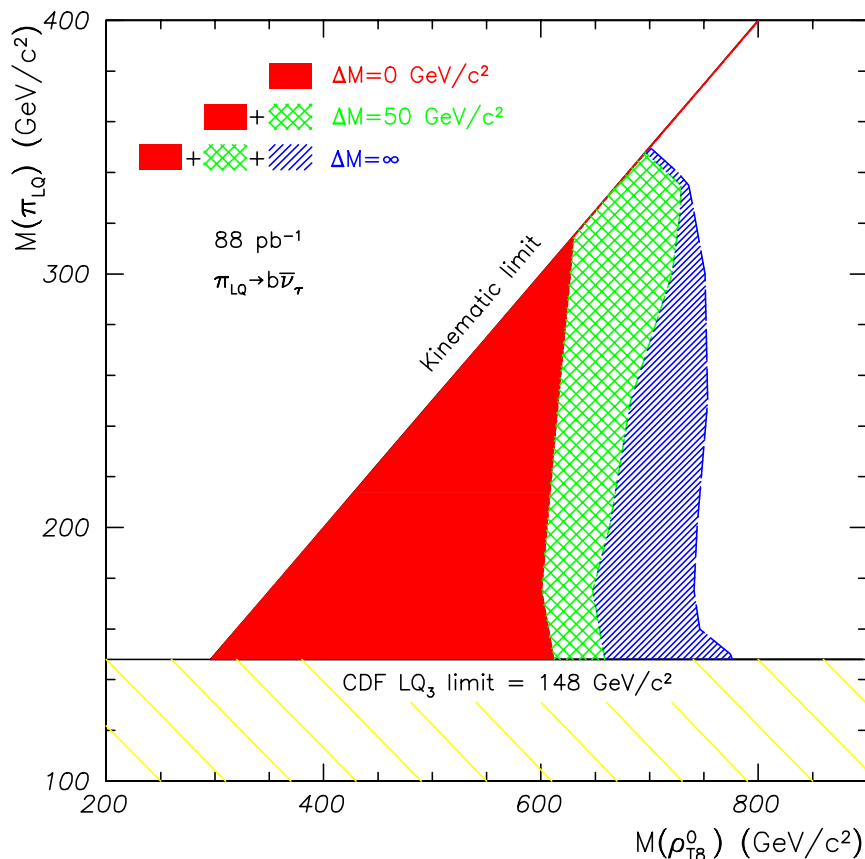
The  $D\bar{O}$  experiment has searched [27] for low-scale technicolor resonances  $\rho_T$  and  $\omega_T$  decaying to dileptons, using an inclusive  $e^+e^-$  sample from Run I. In the search, the  $\rho_T$  and  $\omega_T$  are assumed to be degenerate in mass. The absence of structure in the dilepton invariant mass distribution is then used to set limits. Masses  $m_{\rho_T} = m_{\omega_T} \lesssim 200$  GeV are excluded, provided either  $m_{\rho_T} < m_{\pi_T} + m_W$ , or  $M_T > 200$  GeV. The CDF experiment also performed a similar search with 200 pb<sup>-1</sup> of Run II data, and excluded equal  $m_{\rho_T} = m_{\omega_T}$  masses below 280 GeV for  $M_V = 500$  GeV and  $m_{\rho_T} < m_{\pi_T} + m_W$  at 95%

C.L. [28]. With  $2 \text{ fb}^{-1}$  of data, the sensitivity will extend to  $m_{\rho_T} = m_{\omega_T} \approx 500 \text{ GeV}$ .

DELPHI [29] has reported a search for technicolor production in  $452 \text{ pb}^{-1}$  of  $e^+e^-$  data taken between 192 and 208 GeV. The analysis combines searches for  $e^+e^- \rightarrow \rho_T(\gamma)$  with  $\rho_T \rightarrow W_L W_L$ ,  $\rho_T \rightarrow \text{hadrons}$  ( $\pi_T \pi_T$  or  $q\bar{q}$ ),  $\rho_T \rightarrow \pi_T \gamma$ , and  $e^+e^- \rightarrow \rho_T^* \rightarrow W_L \pi_T$  or  $\pi_T \pi_T$ . Technirho masses in the range  $90 < m_{\rho_T} < 206.7 \text{ GeV}$  are excluded, while technipion masses  $m_{\pi_T} < 79.8 \text{ GeV}$  are ruled out independent of the parameters of the technicolor model.



**Figure 6:** 95% CL Cross-section limits [31] for a technirho decaying to two jets at the Tevatron.



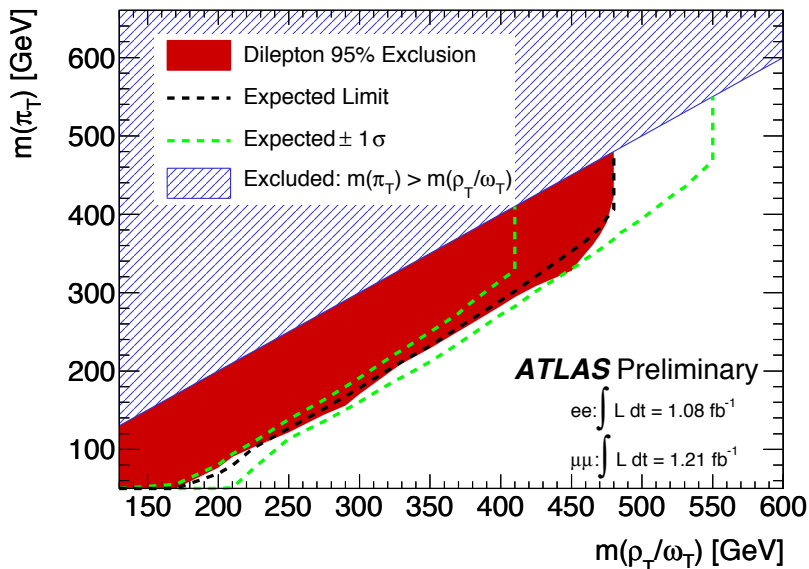
**Figure 7:** 95% CL exclusion region [34] in the technirho-technipion mass plane for pair produced technipions, with leptoquark couplings, decaying to  $b\nu$ .

Searches have also been carried out at the Tevatron for colored technihadron resonances [30,31]. CDF has used a search for structure in the dijet invariant mass spectrum to set limits on a color-octet technirho  $\rho_{T8}$  produced by an off-shell gluon, and decaying to two real quarks or gluons. As shown in Fig. 6, masses  $260 < m_{\rho_{T8}} < 480$  GeV are excluded; in Run II the limits will improve to cover the whole mass range up to about 0.8 TeV [32].

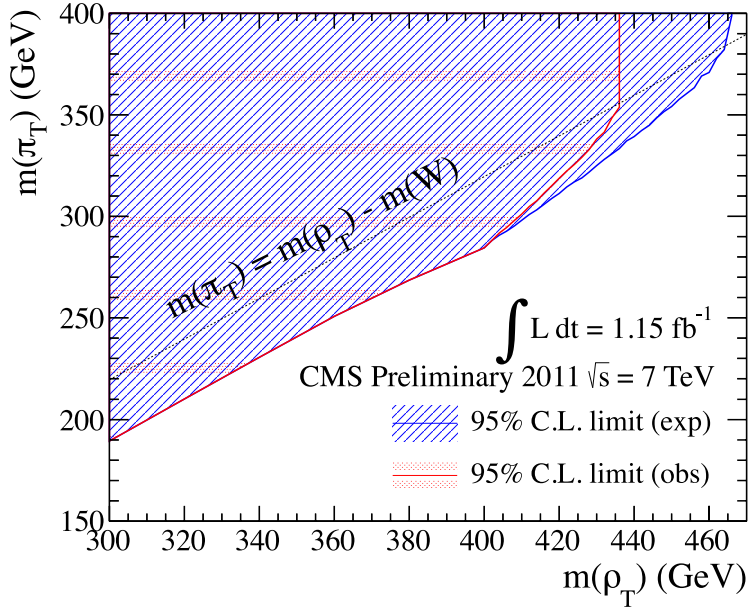
The CDF second- and third-generation leptoquark searches (see Refs. [33,34]) have also been interpreted in terms of the complementary  $\rho_{T8}$  decay mode:  $p\bar{p} \rightarrow \rho_{T8} \rightarrow \pi_{LQ}\pi_{LQ}$ . Here

$\pi_{LQ}$  denotes a color-triplet technipion carrying both color and lepton number, assumed to decay to  $b\nu$  or  $c\nu$  [34], or to a  $\tau$  plus a quark [33]. The searches exclude technirho masses  $m_{\rho_{T8}}$  less than 510 GeV ( $\pi_{LQ} \rightarrow c\nu$ ), 600 GeV ( $\pi_{LQ} \rightarrow b\nu$ ), and 465 GeV ( $\pi_{LQ} \rightarrow \tau q$ ) for technipion masses up to  $m_{\rho_{T8}}/2$ . Figure 7 shows the  $\pi_{LQ} \rightarrow b\nu$  exclusion region. (Leptoquark masses  $m_{\pi_{LQ}}$  less than 123 GeV ( $c\nu$ ), 148 GeV ( $b\nu$ ), and 99 GeV ( $\tau q$ ) are already ruled out by standard continuum-production leptoquark searches).

It has been demonstrated that there is substantial uncertainty in the theoretical estimate of the  $\rho_{T8}$  production cross section at the Tevatron and that the cross section may be as much as an order of magnitude lower than the naive vector meson dominance estimate [35]. To establish the range of allowed masses, these limits will need to be redone with a reduced theoretical cross section.

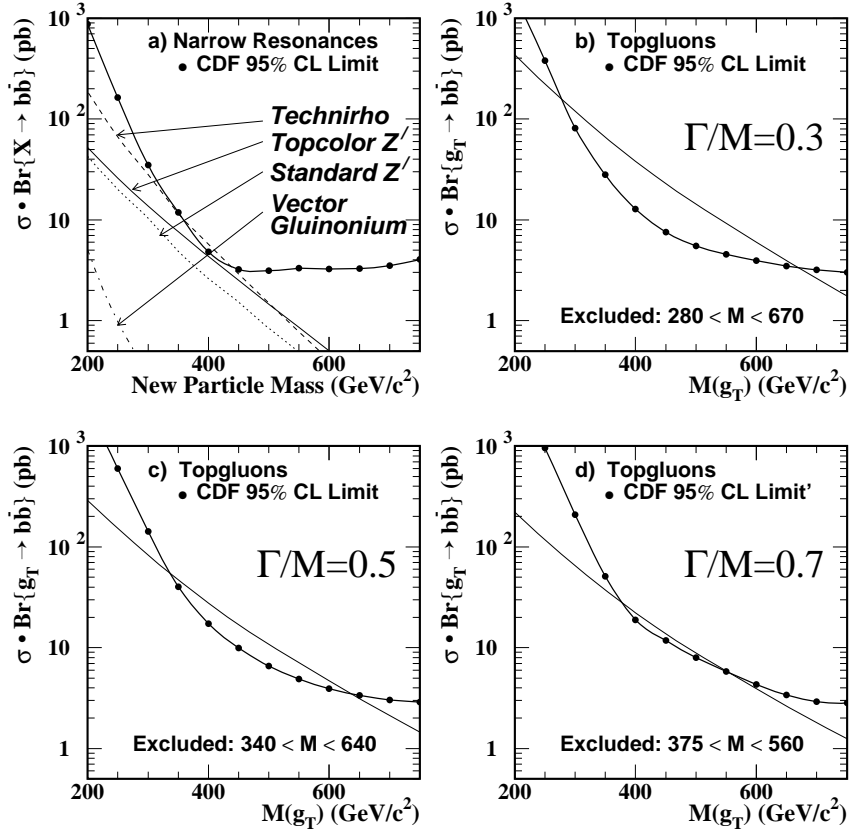


**Figure 8:** 95% CL excluded region by the ATLAS experiment [36] in the  $M(\rho_T), M(\pi_T)$  plane for  $\rho_T/\omega_T \rightarrow ll$  ( $l = e, \mu$ ).



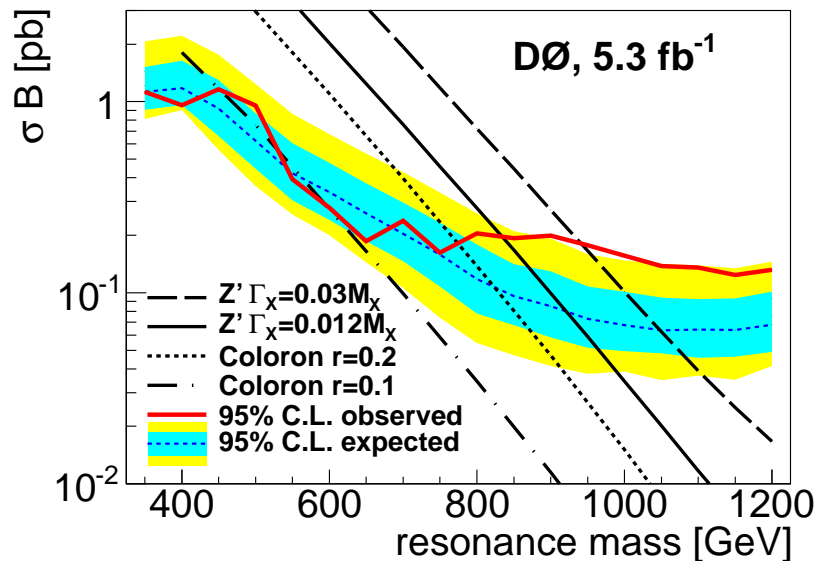
**Figure 9:** 95% CL Exclusion contour in the  $M(\rho_T), M(\pi_T)$  plane for  $\rho_T/a_T \rightarrow WZ \rightarrow ll\nu$  (with  $l = e, \mu$ ) final state by the CMS experiment [37].

Within the context of the model in reference [18], both the ATLAS and CMS experiments have carried out searches for technihadron production in proton-proton collisions at  $\sqrt{s} = 7$  TeV LHC running during 2011. An analysis of the process  $\rho_T$  and  $\omega_T$  decaying to  $\mu^+\mu^-$  and  $e^+e^-$  has been carried out by the ATLAS experiment [36]. This analysis based on  $1.08 \text{ fb}^{-1}$  ( $1.21 \text{ fb}^{-1}$ ) of integrated luminosity, for the  $e^+e^-$  ( $\mu^+\mu^-$ ) channel, as shown in Fig. 8, excludes  $\rho_T$  and  $\omega_T$  with masses in the range 130–480 GeV at 95% CL for  $\pi_T$  masses between 50–480 GeV. The CMS experiment has searched for  $\rho_T$  and its axial-vector partner,  $a_T$  production at  $\sqrt{s} = 7$  TeV using the  $\rho_T/a_T \rightarrow WZ \rightarrow ll\nu$  (with  $l = e, \mu$ ) final state [37]. Using a sample of  $1.15 \text{ fb}^{-1}$  of data, CMS excludes  $\rho_T$  with masses below 382 GeV in the parameter space  $M(\pi_T) = \frac{3}{4}M(\rho_T) - 25$  GeV. If  $M(\rho_T) < M(\pi_T) + M_W$ , then  $\rho_T$  with masses below 436 GeV are excluded. The exclusion contour in the  $\rho_T$  vs.  $\pi_T$  mass plane is shown in Fig. 9.



**Figure 10:** Tevatron limits [47] on new particles decaying to  $b\bar{b}$ : narrow resonances and topgluons for various widths.

LHC searches for Higgs Bosons in di-photon [40,41] or di-tau [42] decay modes place strong constraints [43] on the light top-pion state predicted in technicolor models that include colored technifermions. Compared with the standard Higgs Boson, the top-pions have an enhanced production rate (largely because the technipion decay constant is smaller than the weak scale) and also enhanced branching ratios into di-photon and di-tau final states (largely due to the suppression of  $WW$  decays of the technipions). These factors combine to make such technipions more visible in both channels than a standard model Higgs would be, though the precise bounds are model-dependent.



**Figure 11:** 95% CL exclusion limit on a narrow  $t\bar{t}$  resonance as a function of the resonance mass by the  $D\emptyset$  experiment [49].

## II. Top Condensate, Higgsless, and Related Models

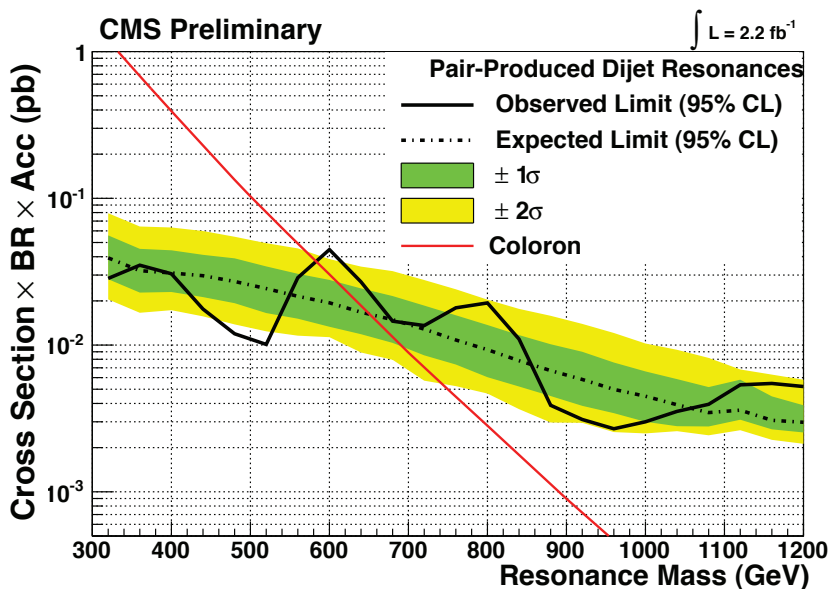
The top quark is much heavier than other fermions and must be more strongly coupled to the symmetry-breaking sector. It is natural to consider whether some or all of electroweak-symmetry breaking is due to a condensate of top quarks [3,44]. Top quark condensation alone, without additional fermions, seems to produce a top quark mass larger [45] than observed experimentally, and is therefore not favored. Topcolor-assisted technicolor [46] combines technicolor and top condensation. In addition to technicolor, which provides the bulk of electroweak symmetry breaking, top condensation and the top quark mass arise predominantly from “topcolor,” a new QCD-like interaction which couples strongly to the third generation of quarks. An additional, strong,  $U(1)$  interaction (giving rise to a topcolor  $Z'$ ) precludes the formation of a  $b$ -quark condensate.

CDF has searched [47] for the “topgluon,” a massive color-octet vector which couples preferentially to the third generation, in the mode  $p\bar{p} \rightarrow g_t \rightarrow b\bar{b}$ . The results are shown in Fig. 10.

Topgluon masses from approximately 0.3 to 0.6 TeV are excluded at 95% confidence level, for topgluon widths in the range  $0.3m_{gt} < \Gamma < 0.7m_{gt}$ . Results have also been reported by CDF [48] on a search for narrow resonances in the  $t\bar{t}$  invariant mass distribution. Using a data sample corresponding to  $4.8 \text{ fb}^{-1}$  integrated luminosity, CDF excludes a leptophobic topcolor  $Z'$  with masses less than 900 GeV, for the case where its width  $\Gamma = 0.012m_{Z'}$ . DØ has carried out a similar search, with greater sensitivity [49], and excludes a leptophobic topcolor  $Z'$  bosons at the 95% confidence level for masses below 835 GeV (940 GeV) if its width is 1.2% (3%) of its mass (see Fig. 11). A similar study by ATLAS searches for  $Z' \rightarrow t\bar{t}$  events, excludes leptophobic topcolor  $Z'$  with a width of 1.2% in the mass region 500–860 GeV [50]. The CMS experiment [51] quotes a 95% CL upper limit on the  $\sigma(pp \rightarrow Z') \times Z' \rightarrow t\bar{t}$  as a function of the invariant mass of the resonance. A limit of 2.51 pb is set for  $Z'$  mass of 1 TeV, resonance width 1%, and 0.62 pb or below for  $Z'$  mass above 2 TeV. A broad topgluon could also be detected in the same final state, though no results are yet available. In Run II, the Tevatron [32] should be sensitive to topgluon and topcolor  $Z'$  masses up to of order 1 TeV in  $b\bar{b}$  and  $t\bar{t}$  final states. A detailed theoretical analysis of  $B$ – $\bar{B}$  mixing and light quark mass generation in top-color-assisted technicolor shows that, at least in some models, the topgluon and  $Z'$  boson masses must be greater than about 5 TeV [53].

The top quark seesaw model of electroweak symmetry breaking [54] is a variant of the original top condensate idea which reconciles top condensation with a lighter top quark mass. Such a model can easily be consistent with precision electroweak tests, either because the spectrum includes a light composite Higgs [55], or because additional interactions allow for a heavier Higgs [56]. Such theories may arise naturally from gauge fields propagating in compact extra spatial dimensions [57].





**Figure 12:** 95% CL exclusion limit on pair production cross section of colorons by the CMS experiment [63]. Colorons with mass in the range 320-580 GeV are excluded.

A variant of topcolor-assisted technicolor is flavor-universal, in which the topcolor  $SU(3)$  gauge bosons, called colorons, couple equally to all quarks [58]. Flavor-universal versions of the seesaw model [59] incorporating a gauged flavor symmetry are also possible. In these models *all* left-handed quarks (and possibly leptons as well) participate in electroweak-symmetry-breaking condensates with separate (one for each flavor) right-handed weak singlets, and the different fermion masses arise by adjusting the parameters which control the mixing of each fermion with the corresponding condensate.

A prediction of these flavor-universal models is the existence of new heavy gauge bosons, coupling to color or flavor, at relatively low mass scales. The absence of an excess of high- $E_T$  jets in  $D\bar{O}$  data [60] has been used to constrain strongly coupled flavor-universal colorons (massive color-octet bosons coupling to all quarks). A mass limit of between 0.8 and 3.5 TeV is set [61] depending on the coloron-gluon mixing angle. Precision

electroweak measurements constrain [62] the masses of these new gauge bosons to be greater than 1–3 TeV in a variety of models, for strong couplings. A direct search for colorons has been performed in the proton-proton collisions at  $\sqrt{s} = 7$  TeV, during the 2011 running of the LHC. From analysis of dijet events, the CMS experiment excludes pair production of colorons with mass between 320 and 580 GeV at 95% CL, as shown in Fig. 12 [63]. A recent  $D\bar{O}$  analysis [49] of a resonance decaying to  $t\bar{t}$  can also be interpreted to search for colorons which would decay to  $t\bar{t}$  with a branching fraction of about 1/6 and have a width substantially below 1% of its mass. This study is performed for different values of the coupling to light quarks  $r=0.1$  and  $0.2$  [64]. This  $D\bar{O}$  analysis can exclude such a coloron for  $r=0.2$  with masses below 775 GeV (displayed in Fig. 11).

LHC searches for the standard model Higgs Boson in  $WW$  or  $ZZ$  decay modes [65,66] place strong constraints [67] on the top-Higgs state predicted in top-color models. Such a state couples strongly to top-quarks, and is therefore produced through gluon fusion at a rate enhanced relative to the rate for the standard model Higgs boson. A top-Higgs state with mass less than 300 GeV is excluded at 95% CL if the associated top-pion has a mass of 150 GeV, and the constraint is even stronger if the mass of the top-pion state exceeds the top-quark mass or if the top-pion decay constant is a substantial fraction of the weak scale.

A class [68] of composite Higgs model [69], dubbed “Little Higgs Theory,” has been developed which gives rise to naturally light Higgs bosons without supersymmetry [70]. Inspired by discretized versions of higher-dimensional gauge theory [71], these models are based on the chiral symmetries of “theory space.” The models involve extended gauge groups and novel gauge symmetry-breaking patterns [72]. The new chiral symmetries prevent large corrections to the Higgs boson mass, and allow the scale ( $\Lambda$ ) of the underlying strong dynamics giving rise to the composite particles to be as large as 10 TeV. These models typically require new gauge bosons and fermions, and

possibly additional composite scalars beyond the Higgs, in the TeV mass range [73].

Finally, “Higgsless” models [74] provide electroweak symmetry breaking, including unitarization of the scattering of longitudinal  $W$  and  $Z$  bosons, without employing a scalar Higgs boson. The most extensively studied models [75] are based on a five-dimensional  $SU(2) \times SU(2) \times U(1)$  gauge theory in a slice of Anti-deSitter space, and electroweak symmetry breaking is encoded in the boundary conditions of the gauge fields. Using the AdS/CFT correspondence [76], these theories may be viewed as “dual” descriptions of walking technicolor theories [7]. In addition to a massless photon and near-standard  $W$  and  $Z$  bosons, the spectrum includes an infinite tower of additional massive vector bosons (the higher Kaluza-Klein or  $KK$  excitations), whose exchange is responsible for unitarizing longitudinal  $W$  and  $Z$  boson scattering [77]. Depending on how these  $KK$  bosons couple to fermions, searches for the  $W'$  bosons decaying to  $WZ$  [37] may be used to place bounds in these theories.

Using deconstruction it has been shown [78] that a Higgsless model whose fermions are localized (*i.e.*, derive their electroweak properties from a single site on the deconstructed lattice) cannot simultaneously satisfy unitarity bounds and precision electroweak constraints. The [79] size of corrections to electroweak processes in Higgsless models may be reduced, however, by considering delocalized fermions, *i.e.*, considering the effect of the distribution of the wavefunctions of ordinary fermions in the fifth dimension (corresponding, in the deconstruction language, to allowing the fermions to derive their electroweak properties from several sites on the lattice). It has been shown [80] that, in an arbitrary Higgsless model, if the probability distribution of the delocalized fermions is related to the  $W$  wavefunction (a condition called “ideal” delocalization), then deviations in precision electroweak parameters are minimized. Phenomenological limits on delocalized Higgsless models may be derived [81] from limits on the deviation of the triple-gauge boson ( $WWZ$ ) vertices from the standard model, and current constraints allow for the lightest  $KK$  resonances

(which tend to be fermiophobic in the case of ideal fermion delocalization) to have masses of only a few hundred GeV. Such resonances would have to be studied using  $WW$  scattering [82].

An alternative approach to “Higgsless” models, dubbed “holographic technicolor” [83], incorporates a generalized extra-dimensional framework and allows for arbitrary couplings of the vector mesons to the light fermions, resulting in a wide variety of potential signatures at the LHC [84].

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