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The electroweak symmetry breaking Higgs boson in models with top-quark condensation

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Abstract

The top quark may get its large mass not from a fundamental scalar but a Nambu-Jona-Lasinio mechanism involving a strongly coupled gauge sector that triggers top-quark condensation. Forbidding a large hierarchy in the gap equation implies that top quark condensation is a spectator to electroweak symmetry breaking, which must be accomplished mainly by another sector. The properties of the electroweak symmetry breaking scalars are identified. Production mechanisms and decay modes are studied. Unlike the standard model, the scalar degree of freedom most relevant to electroweak symmetry breaking can only be produced by its gauge interactions. An $e^\pm e^\pm \mu^\mp + \mu^\pm \mu^\pm e^\mp$ signal is proposed to help unambiguously detect the presence of such a gauge-coupled Higgs if it is light. Other useful modes of detection are also presented, and a summary is made of the search capabilities at LEPII, Tevatron and LHC.

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1 Finetuning and the top-quark gap equation

As it became clear that the top quark is very massive attention was naturally turned to top-quark condensate models [1, 2, 3] which rely on the gauged Nambu-Jona-Lasinio (NJL) model [4]. Starting with a four fermion interaction

$$L = L_{kin} + G\bar{\psi}_L t_R \bar{t}_R \psi_L \quad \text{where} \quad \psi_L = (t_L, b_L) \tag{1}$$

a gap equation can be formulated for the dynamical top quark mass

$$G^{-1} = \frac{N_c}{8\pi^2}\left(\Lambda^2 - m_t^2 \log\frac{\Lambda^2}{m_t^2}\right). \tag{2}$$

Furthermore, in the fermion bubble approximation, with the above gap equation enforced, zeros of the inverse gauge boson propagators are found at non-zero momentum. This gives mass to the gauge bosons and corresponds [5, 3, 6] to a decay constant of

$$f_{\pi_t}^2 \simeq \frac{N_c}{16\pi^2} m_t^2 \log\frac{\Lambda^2}{m_t^2}. \tag{3}$$

This relation is often referred to as the Pagels-Stokar formula. In order for the top-quark condensate to account for all of electroweak symmetry breaking, f_{π_t} needs to be equal to $v = 175\,\text{GeV}$. The currently measured top quark mass is $m_t = 175 \pm 6\,\text{GeV}$ [7], which means that Λ would have to be about thirteen orders of magnitude above m_W to account for all of electroweak symmetry breaking, an uninspiring result for pure top-quark condensate models.

The Pagels-Stokar relation is logarithmically sensitive to the condensate scale, and provides only a relationship between the decay constant and dynamical quark mass, not the overall scale of these parameters. The gap equation, on the other hand, sets the overall scale of m_t and therefore f_{π_t}. The quadratic sensitivity to the condensate scale induces a large hierarchy problem for the weak scale (m_t and f_{π_t}) if Λ is above a few TeV. For large Λ the four-fermion coupling G must be tuned to one part in Λ^2/m_t^2. For a condensate scale in the multi-TeV region, this finetuning is greater than one part in 10^3. It will be assumed here that finetunings much above this are unnatural, and are probably not maintained by nature [8]. Therefore, from the Pagels-Stokar relation the decay constant associated with top-quark condensation is $f_{\pi_t} \lesssim 60\,\text{GeV}$, implying that top-quark condensation is a spectator to electroweak symmetry breaking (EWSB). That is, top-quark condensation mainly provides the top quark its mass, but another sector mainly provides the W and Z bosons their masses.

The above argument have led to the conception of top-quark condensate assisted models such as those discussed in Refs. [9, 10, 11, 12]. Much emphasis and study have been devoted to the boundstate scalars and gauge bosons associated with top-quark condensation in these models [9]-[14]. Attention is given here to the degrees of freedom which bear the most burden for electroweak symmetry breaking. In the following, a single electroweak symmetry breaking doublet is postulated to give mass to the W, Z and all light fermions, and perhaps a small contribution to the top and bottom quarks. The production and decay modes of this doublet are detailed. The results will be significantly different than the standard model doublet, since unlike the standard model the resulting scalar field has a small coupling to the top quark. The complexity of the electroweak symmetry breaking sector will have little effect on the detectability of the scalars associated with electroweak symmetry breaking.

2 Top-quark condensate scalars

Top-quark condensation only requires a critical four-fermion coupling in a lagrangian such as that given in Eq. 1. Explaining the origin of such a strong interaction is a more difficult question. Topcolor is one such explanation [15, 9, 10, 12], which is used as an example here. Upon integrating out the heavy vector bosons from the topcolor gauge group and the "tilting" $U(1)$ gauge group, one obtains the following NJL interaction lagrangian:

$$L = L_{kin} + G_t \bar{\psi}_L t_R \bar{t}_R \psi_L + G_b \bar{\psi}_L b_R \bar{b}_R \psi_L. \tag{4}$$

Tuning the couplings of the different gauge interactions which formed this four fermion interaction lagrangian, one can obtain $G_t > 8\pi^2/N_c\Lambda^2 > G_b$, which induces a $\langle t\bar{t}\rangle$ condensate but not a $\langle b\bar{b}\rangle$ condensate.

It is convenient to introduce auxiliary fields ϕ_t and ϕ_b and rewrite the above lagrangian as

$$L = L_{kin} - (\bar{\psi}_L \phi_t t_R + \bar{\psi}_L \phi_b b_R + h.c.) - G_t^{-1}\phi_t^\dagger \phi_t - G_b^{-1}\phi_b^\dagger \phi_b. \tag{5}$$

Renormalization group evolution [3, 12, 16] below Λ makes the scalar fields ϕ_t and ϕ_b dynamical, and it induces a vacuum expectation value for ϕ_t (not ϕ_b) in accord with the gap equation. The pion decay constant of ϕ_t can be solved via the Pagels-Stokar formula of Eq. 3 given particular values of m_t and Λ. For the purposes of this paper we will assume the numerical value $f_{\pi_t} \simeq 50\,\mathrm{GeV}$ ($\Lambda \simeq 1.5\,\mathrm{TeV}$).

In the approximation that $f_{\pi_t}^2 \ll v^2$ (v is normalized to $175\,\mathrm{GeV}$) top condensation is merely a spectator to electroweak symmetry breaking (in analogy to chiral symmetry breaking among the light quarks) and so they do not mix into the longitudinal components of the W and Z. Therefore, all the component states of ϕ_t and ϕ_b are physical eigenstates to a good approximation,

$$\phi_t = \begin{pmatrix} f_{\pi_t} + \frac{1}{\sqrt{2}}(h_t^0 + i a_t^0) \\ h_t^\pm \end{pmatrix}, \qquad \phi_b = \begin{pmatrix} h_b^\pm \\ \frac{1}{\sqrt{2}}(h_b^0 + i a_b^0) \end{pmatrix}. \tag{6}$$

In the fermion bubble approximation the scalar $t\bar{t} \to t\bar{t}$ scattering amplitude has a pole at $p^2 = 4m_t^2$ which can be identified with the mass of the h_t^0. Other masses are dependent upon details of the underlying model and can vary from about 150 to $350\,\mathrm{GeV}$ [9, 11, 12]. The top quark gets almost all its mass by a large Yukawa coupling to ϕ_t, and it can be assumed that the bottom quark gets almost all its mass from topcolor instanton effects [9, 12].

In addition to these boundstate topcolor scalars, there needs to be degrees of freedom that break $SU(2) \times U(1)_Y$. To do this we introduce another doublet, ϕ_{ew}, whose vacuum expectation value is such that

$$f_{\pi_t}^2 + f_{\pi_{ew}}^2 = v^2 = (175\,\mathrm{GeV})^2. \tag{7}$$

We also assume that this doublet is a fundamental scalar and gives a small mass to all the light fermions in the theory in addition to breaking electroweak symmetry. Even though the following assumes a fundamental scalar breaking electroweak symmetry, it might be that $SU(2) \times U(1)_Y$ is broken by some other strongly interacting sector which produces a narrow resonance composite ϕ_{ew} which has very similar properties to the fundamental Higgs state discussed below.

It will be convenient later to introduce a "top-quark condensate spectator angle" θ_t, which is defined as

$$\begin{aligned} f_{\pi_{ew}} &= v \sin\theta_t \\ f_{\pi_t} &= v \cos\theta_t. \end{aligned}$$

Using the numerical value of $f_{\pi_t} = 50\,\mathrm{GeV}$, one obtains

$$\cos\theta_t = \frac{50\,\mathrm{GeV}}{175\,\mathrm{GeV}} \simeq 0.3\,. \tag{8}$$

The pseudoscalar and charged Higgs fields in the ϕ_{ew} doublet all get eaten by the $W^\pm$ and Z bosons, and what remains physical is a single scalar field h^0_{ew}, whose mass cannot be determined *a priori*. Note also that since $f_{\pi_t} \ll v$, and since h^0_{ew} does not couple to tops (or couples very weakly), then h^0_{ew} is a mass eigenstate.

The assumption of just one scalar providing electroweak symmetry breaking is not important for the qualitative results below. The most important assumption is that a $t\bar{t}$ condensate gives the top quark its large mass. If we added more condensing scalar fields to the spectrum, it is possible to have large Yukawa couplings of these scalars to the light quark fields. However, in this case these additional fields would also have to be spectators to electroweak symmetry breaking, just as ϕ_t is, and there would remain the necessity of a scalar(s) with large vacuum expectation values which have small Yukawa interactions with the fermions.

If the electroweak symmetry breaking sector were more complicated, more angles would need to be introduced. For example, if a two Higgs doublet model were involved then a new angle, β, would need to be introduced which specifies the ratios of the vevs of these two fields. Defining $\tan\beta \equiv \langle\phi_{ew,2}\rangle/\langle\phi_{ew,1}\rangle$, then

$$\begin{aligned} f_{\pi_t} &= v\cos\theta_t \\ f_{\pi_{ew,1}} &= v\sin\theta_t\cos\beta \\ f_{\pi_{ew,2}} &= v\sin\theta_t\sin\beta. \end{aligned}$$

This angle β does not enhance the coupling of the neutral scalars to the top-quark but does reduce the coupling to gauge bosons by a factor of $\sin^2(\beta-\alpha)$ or $\cos^2(\beta-\alpha)$ where α is the mass eigenstate mixing angle between $h^0_{ew,1}$ and $h^0_{ew,2}$. The argument generalizes to an arbitrarily complex electroweak symmetry breaking sector with doublets to show that Yukawa production processes are negligibly affected by additional complexity in the EWSB sector, and gauge production processes can only be *reduced.* Thus, production modes for the scalars will decrease with additional complexity. Higher dimensional $SU(2)$ representations such as triplets are not considered since they explicitly break custodial $SU(2)$ symmetry. Barring finetuned cancellations, triplets are incapable of providing a substantial fraction of EWSB due to the current ρ parameter constraints [17]. Since our conclusion will be that the gauge-coupled EWSB scalars are extremely difficult to reconstruct at the LHC, it is most conservative to maximize the gauge boson couplings of the EWSB scalar(s) by postulating one single ϕ_{ew} which breaks electroweak symmetry, and analyzing the consequences of this assumption.

3 Decays of the h^0_{ew}

The decay of the h^0_{ew} (the neutral scalar component of ϕ_{ew}) has a few inherent uncertainties. The most important uncertainty is how much of the b quark mass is derived from $f_{\pi_{ew}}$. This sets the coupling of the ϕ_{ew} to the b quark, which in turn sets the partial width of $h^0_{ew} \to b\bar{b}$. The instanton induced b quark mass [9, 12] can be substantial and provide the b quark with all of its mass, leaving a very small (if any) residual b quark mass contribution from ϕ_{ew}. Furthermore, the hierarchy of masses generated by ϕ_{ew} need not be in descending order of generations. That is, the b quark mass induced by ϕ_{ew} could be much smaller than the strange quark. The working assumption will be that the b quark coupling to ϕ_{ew} is negligible. However, it cannot be ruled out that all of the b quark mass comes from ϕ_{ew} and this possibility will be commented on later.

In the standard model all the couplings to the gauge bosons and fermions are set without ambiguity, and the decay branching fractions can be calculated [18, 19, 20]. In Fig. 1 the decay branching fractions of the standard model are displayed for $50\,\mathrm{GeV} < m_{h^0_{sm}} < 200\,\mathrm{GeV}$. Above 200 GeV the WW and ZZ branching fractions dominate in a ratio of 2 to 1 for a Higgs mass well above the ZZ threshold. Above the $t\bar{t}$ threshold the branching ratio to $t\bar{t}$ reaches its maximum of 20% at $m_{h^0_{sm}} = 500\,\mathrm{GeV}$ and slowly reduces to 10% at $m_{h^0_{sm}} = 1\,\mathrm{TeV}$. ($m_t = 175\,\mathrm{GeV}$ is assumed throughout this discussion.) Note the dominance of the $b\bar{b}$ final state up to $m_{h^0_{sm}} \lesssim 135\,\mathrm{GeV}$. Above this, the branching fraction into WW becomes dominate.

The branching fractions of h^0_{ew} can likewise be calculated once the angle $\cos\theta_t$ is known, and the b quark coupling to h^0_{ew} is specified. In Fig. 2 the decay branching fractions are shown for $\cos\theta_t = 0.3$ and negligible b quark coupling to h^0_{ew}. The $\tau^+\tau^-$ and $c\bar{c}$ final states are more important for h^0_{ew} than for h^0_{sm}. Furthermore the WW^* branching fraction is much enhanced despite the $\sin^2\theta_t$ suppression of the partial width to WW^*. The branching fractions of h^0_{ew} are much different than the standard model Higgs for $m_{h^0_{ew}} \lesssim 140\,\mathrm{GeV}$.

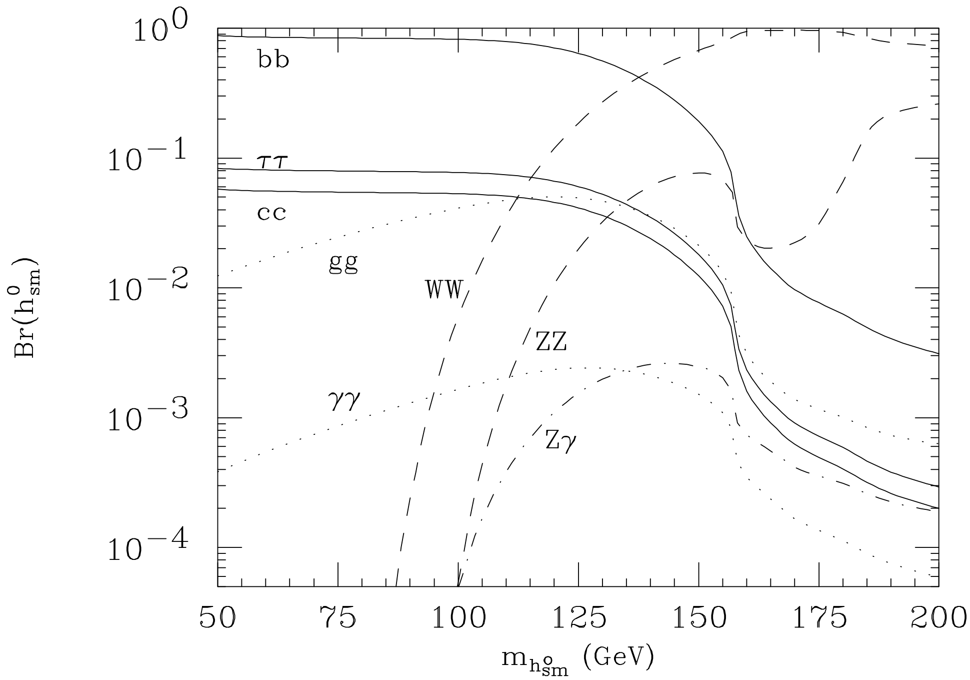

Figure 1: Branching fractions of h^0_{sm} versus its mass.

Above 140 GeV the h^0_{ew} branching fractions are similar to the standard model except that $h^0_{ew} \to t\bar{t}$ always has a negligible rate. A further important distinction from the standard model is the substantially lower production rate of h^0_{ew} compared to h^0_{sm} at a hadron collider discussed in the next section.

4 Production of h^0_{ew}

The production modes of a standard model Higgs boson can be broken up into three categories:

- Gauge processes: $q\bar{q} \to Zh^0_{sm}$, $q\bar{q}' \to W^{\pm}h^0_{sm}$, $WW(ZZ) \to h^0_{sm}$, $e^+e^- \to Zh^0_{sm}$, $e^+e^- \to e^+e^-h^0_{sm}$.
- Yukawa processes: $q\bar{q} \to t\bar{t}h^0_{sm}$, $gg \to h^0_{sm}$, $e^+e^- \to t\bar{t}h^0_{sm}$,
- Gauge or Yukawa processes: $\gamma\gamma \to h^0_{sm}$.

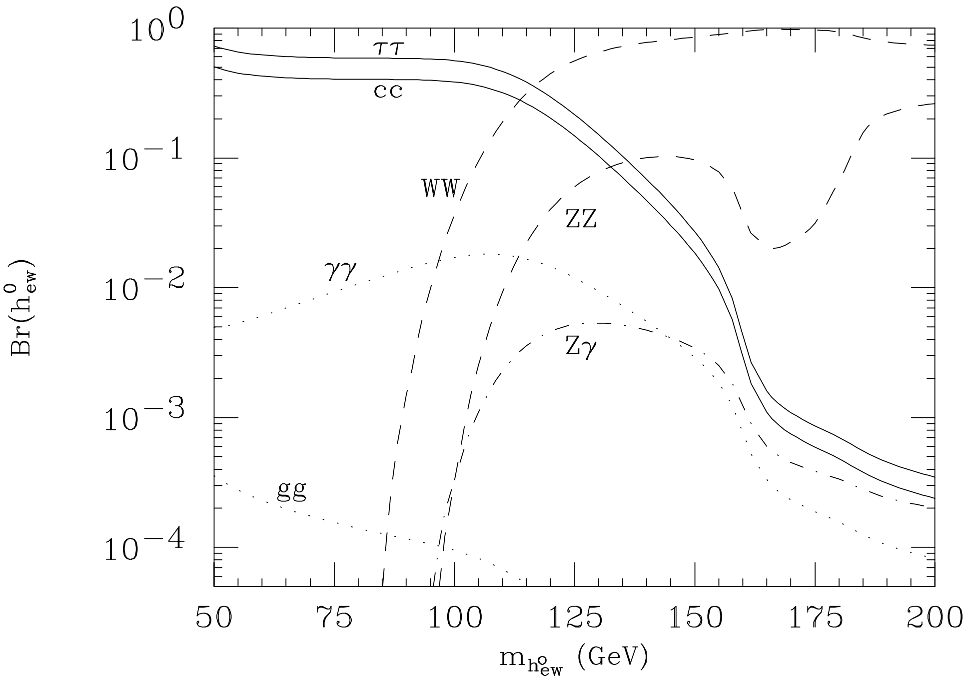

Figure 2: Branching fractions of h^0_{ew} versus its mass for $\cos\theta_t = 0.3$ and negligible b quark coupling to h^0_{ew}.

The $gg \to h^0_{sm}$ production mechanism is called a "Yukawa process" because it has a non-negligible rate due to the large top Yukawa coupling of the h^0_{sm} to the top quark in the loop. The $\gamma\gamma \to h^0_{sm}$ is called a "Gauge or Yukawa process" since it has non-negligible contributions from both W and top loops.

The scalars in top-quark condensate models [9, 11, 12, 14] generally either get produced by gauge processes *or* by Yukawa process. For example, the top Higgs, h^0_t, has a small gauge production process suppressed relative to the standard model by $\cos^2\theta_t \simeq 0.08$. On the other hand, its production via Yukawa processes is enormous due to the large Yukawa coupling of the top quarks to ϕ_t. The bottom Higgs, h^0_b, has approximately zero production cross section via gauge processes, however, it has a reasonable Yukawa induced cross section from $gg \to h^0_b$ and even $qq(e^+e^-) \to b\bar{b}h^0_b$.

The electroweak symmetry breaking scalar, h^0_{ew}, has negligible production cross section due to Yukawa processes. It must be produced via gauge interactions, which are slightly suppressed compared to the gauge interactions of the standard model Higgs boson. The cross sections are related to the standard model cross sections by

$$\sigma_{gauge}(h^0_{ew}) = \sin^2\theta_t \sigma_{gauge}(h^0_{sm}) \tag{9}$$

where $\sigma_{gauge}(h)$ is either $\sigma(Wh)$, $\sigma(Zh)$ or $\sigma(WW(ZZ) \to h)$, etc. For $f_{\pi_t} = 50\,\mathrm{GeV}$ the suppression factor is merely $\sin^2\theta_t \gtrsim 0.92$.

The lack of Yukawa production processes for h^0_{ew} is a severe handicap for a search at the LHC. The dominant production cross section for the standard model Higgs is $gg \to h^0_{sm}$. In Fig. 3 the cross sections for jjh^0_{ew}, Wh^0_{ew}, and Zh^0_{ew} at the LHC ($\sqrt{s} = 14\,\mathrm{TeV}$) are shown. The jjh^0_{ew} cross section is from $WW(ZZ) \to h^0_{ew}$ where the two jets are the ones which radiate the W's and are generally at high rapidity. We see that the total production rate for h^0_{ew} is much smaller than for h^0_{sm} due to lack of the $gg \to h^0_{ew}$ Yukawa mode. The $h^0_{ew} \to \gamma\gamma$ signal for $100\,\mathrm{GeV} \lesssim m_{h^0_{ew}} \lesssim 140\,\mathrm{GeV}$ is no longer as viable since the total rate of Higgs production is not entirely compensated by the somewhat enhanced branching fraction into two photons. Detecting h^0_{ew}, if it is possible, must rely on the smaller gauge production cross sections.

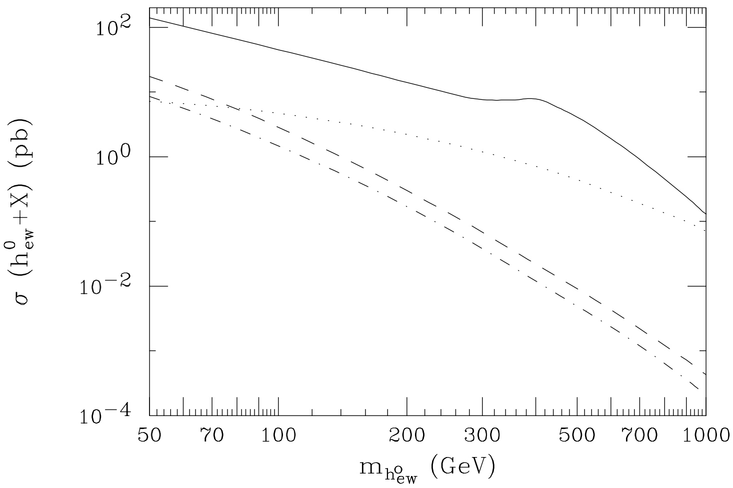

Figure 3: Cross sections for jjh^0_{ew} (dotted), Wh^0_{ew} (dashed), and Zh^0_{ew} (dot-dashed) at the LHC (14 TeV) for $\cos\theta_t = 0.3$. Also, the standard model Yukawa production cross section $gg \to h^0_{sm}$ (solid) is shown to demonstrate the relatively low instrinsic rate of the gauge production cross sections.

5 Detecting the h^0_{ew}

The search for the standard model Higgs boson has been well studied and the strategy is well mapped [18]. LEPII running at $\sqrt{s} = 192\,\mathrm{GeV}$ will be able to see the Higgs boson up to about 95 GeV with $150\,\mathrm{pb}^{-1}$ per experiment. Above this, the LHC experiments should be able to see the standard model Higgs through $gg \to h^0_{sm} \to \gamma\gamma$ up to about 140 GeV, and through $gg \to h^0_{sm} \to ZZ^{(*)}$ if $140\,\mathrm{GeV} \lesssim m_{h^0_{sm}} \lesssim 700\,\mathrm{GeV}$. For scalar resonances above about 700 GeV the concept of a perturbatively coupled Higgs boson becomes more tenuous, and longitudinal W scattering analyses become more important.

The common thread among all the searches described above is the $gg \to h^0_{sm}$ Yukawa production mode. In the standard model this process dominates the production rate for Higgs bosons. Some studies have been performed on the ability to detect the Higgs boson via Wh^0_{sm} [21, 22, 23, 24], which is a gauge-coupled production mode. The hope is that with two tagged b quarks from h^0_{sm} and a high p_T lepton tag from the W, the small rate of Wh^0_{sm} could still be pulled out from the background (WZ, $Wb\bar{b}$, $t\bar{t}$, etc.). At the LHC it was concluded by [23] that this mode could be useful if $80\,\mathrm{GeV} \lesssim m_{h^0_{sm}} \lesssim 100\,\mathrm{GeV}$, whereas [24] finds that $m_{h^0_{sm}} \lesssim 130\,\mathrm{GeV}$ are detectable in this mode with excellent bottom jet identification.

For the h^0_{ew} state, the LEPII capability should not be altered. The τ branching fraction of the Higgs will be large and the backgrounds from ZZ where one Z decays to $\tau^+\tau^-$ will be relatively small since that branching fraction is only about 3%. Searches at the LHC with $m_{h^0_{ew}} \gtrsim 100\,\mathrm{GeV}$ are more difficult. In the range from $100\,\mathrm{GeV} \lesssim m_{h^0_{sm}} \lesssim 135\,\mathrm{GeV}$ the branching ratio to $\tau^+\tau^-$ is greater than 8%. The signal $pp \to W h^0_{sm}$ where $W \to jj$ and $h^0_{sm} \to \tau^+\tau^-$ has been studied in Ref. [22]. It was concluded that a significant signal at the LHC could not be found in this mode for a standard model Higgs boson. However, such a signal might be possible in this $\tau^+\tau^-$ decay mode at the Tevatron running at $\sqrt{s} = 2\,\mathrm{TeV}$ with $30\,\mathrm{fb}^{-1}$ of integrated luminosity. Turning back to the h^0_{ew}, the $\tau^+\tau^-$ decay branching fraction is much increased. The significance of the standard model $\tau^-\tau^+$ signal now should be multiplied by a factor of $Br(h^0_{ew} \to \tau^+\tau^-)/Br(h^0_{sm} \to \tau^+\tau^-) \simeq 6$. It therefore might be possible to detect the light h^0_{ew} at the Tevatron with compelling significance if $m_{h^0_{ew}} \lesssim 130\,\mathrm{GeV}$. Furthermore, this signal might also be detectable at the LHC with sufficient luminosity.

Earlier we postulated that h^0_{ew} does not couple to the b quarks. If we now relax that assumption and assume the opposite extreme, that all the b quark mass comes from ϕ_{ew}, then the branching fraction of h^0_{ew} into fermions for $m_{h^0_{ew}} \lesssim 130\,\mathrm{GeV}$ will be almost identical to the standard model. Then the analyses of the Wh^0_{ew} signal will become most important, and from studies in the standard model (especially [24]) it can be concluded that a b quark coupled h^0_{ew} is detectable at the LHC with as low as 10 fb^{-1} of data. The Tevatron probably could not detect this b-coupled Higgs state above the LEPII limit of 95 GeV in the $b\bar{b}$ mode alone [21, 23], but could possibly be detected up to 130 GeV using both the $b\bar{b}$ and $\tau^+\tau^-$ modes [22].

If $m_{h^0_{ew}} \gtrsim 130\,\mathrm{GeV}$ then it appears that the Tevatron and LHC will have difficulty seeing a signal and reconstructing the h^0_{ew} mass. In this range h^0_{ew} will decay to WW^* most of the time. Since the production rate for h^0_{ew} is small the $ZZ^{(*)}$ decay cannot be separated from backgrounds to construct a signal. Without this mode at our disposal it appears near impossible to measure the Higgs mass since the $WW^{(*)}$ decay mode does not allow the Higgs mass to be reconstructed.

However, it might be possible to detect a Higgs signal without being able to reconstruct the mass. If the Higgs decays to W^+W^- (either on-shell or off-shell) then the $pp \to W^\pm h^0_{ew}$ produces a three lepton plus $\not{E}_T$ signal if all the W's decay leptonically. This signal is relatively clean in a hadron collider environment and has been proposed as a search tool for supersymmetric gaugino production of $\widetilde{W}\widetilde{Z}$ with subsequent leptonic decays into three leptons plus missing energy carried away by the stable lightest supersymmetric particle [29]. Because of this potentially large supersymmetric rate, it may be difficult to tell the difference between a $Wh^0_{ew} \to lll + \not{E}_T$ signature as opposed to a $\widetilde{W}\widetilde{Z} \to lll + \not{E}_T$ signature.

Some permutations of these trilepton decays yield a like-sign dilepton signal with missing energy and little background [21]. Potential backgrounds to like-sign dileptons include WZ production where one lepton comes from the W and one lepton comes from the Z. Cutting out $m_{l^+l^-} \simeq m_Z$ reduces this background. Another background comes from $t\bar{t}$ production where one lepton comes from a W decay in the t decay and the like-sign lepton comes from a b decay in the $\bar{t}$ decay. This background can be greatly reduced by an effective jet veto of the hadronic activity of the b quark, requiring no tagged b quark in the event, and also requiring that all the leptons be isolated. Here, we propose a more discerning signal of like-sign dileptons with a different flavor third lepton. Using just the first two generations of leptons, the signal for the presence of a Higgs boson is $e^\pm e^\pm \mu^\mp$ and $\mu^\pm\mu^\pm e^\mp$, with all leptons isolated. This is a useful signal to distinguish Wh^0_{ew} production as opposed to the supersymmetric $\widetilde{W}\widetilde{Z}$ production since like-sign dileptons from the latter require all three leptons to be of the same flavor. The branching fraction into $WW^{(*)}$ is given in Fig. 2. Using the production cross section from Fig. 3 the total number of signal events in 100 fb^{-1} of data is displayed in Fig. 4.

The main background from $t\bar{t}$ can be estimating using the geometric acceptance of leptons ($|\eta| < 2.5$) and jets ($|\eta| < 5$), the combinatorics of the decays which yield $e^\pm e^\pm \mu^\mp$ and $\mu^\pm\mu^\pm e^\mp$ signal events, and the total inclusive $t\bar{t}$ cross section at LHC, which will be conservatively bounded at 2 nb. The number of background events estimated from $t\bar{t}$ is approximately 100 for 100 fb^{-1} of data. (Note that there are no background events from WZ.) After applying the same lepton acceptance cuts to the signal, a 5σ effect would require at least 100 signal events (using $S/\sqrt{B}$ for significance). Thus, the electroweak symmetry breaking Higgs, h^0_{ew}, could be detected in the range $110\,\mathrm{GeV} \lesssim m_{h^0_{ew}} \lesssim 175\,\mathrm{GeV}$ by this process. This estimate is based solely on parton level calculations and is only meant to demonstrate that this signal could be useful at the LHC. Estimates of non-physics backgrounds such as mis-identification, and full jet-level Monte Carlo simulation could diminish the significance found here. However, it is likely that additional cuts not studied here could further distinguish the $Wh^0_{ew} \to WWW$ topology over $t\bar{t} \to WWbb$, thereby increasing the

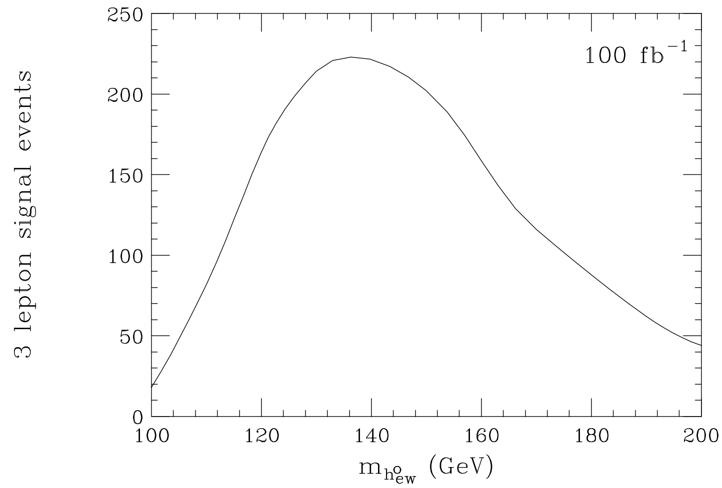

Figure 4: The total event rate of $e^\pm e^\pm \mu^\mp + \mu^\pm \mu^\pm e^\mp$ expected from $pp \to W h^0_{ew} \to WWW^{(*)}$ production with $100\,\mathrm{fb}^{-1}$ of data collected at the LHC with center of mass energy 14 TeV. A 5σ signal above background requires at least 100 signal events.

significance of the signal. Also, using the τ final states could help somewhat since b decays to τ's are kinematically suppressed.

From Fig. 3 we can see that the $WW(ZZ) \to h^0_{ew}$ vector boson fusion provides the highest production rate for h^0_{ew}. Along with the Higgs boson comes two high rapidity jets corresponding to the quark lines which radiated the initial vector bosons. For low mass Higgses, where $h^0_{ew} \to ZZ^{(*)}$, the signal would be four leptons with high invariant masses, $m_{l^+l^-}$ from each decay. The standard model background is dominated by continuum $Z\gamma^*$ production with enhancement at small invariant $m_{l^+l^-}$. Identifying the $Z^{(*)}$ as the lower mass $m_{l^+l^-}$ and placing a cut on how low this invariant mass very effectively removes the background while retaining almost all of the signal [18]. It might be possible to detect the light h^0_{ew} from vector boson fusion with as low as 40 signal events (before cuts) in this mode [18]. The signal rate for $VV \to h^0_{ew} \to ZZ^{(*)} \to l^+l^-l'^+l'^-$ $(l, l' = e$ or $\mu)$ is shown in Fig. 5. In the ZZ^* region, the detectability requirement of 40 signal events corresponds to a Higgs mass range of $120\,\mathrm{GeV} \lesssim m_{h^0_{ew}} \lesssim 155\,\mathrm{GeV}$.

The region between the WW and ZZ threshold is much more difficult. The $h^0_{ew} \to ZZ^*$ branching fraction is greatly reduced in this region because $h^0_{ew} \to WW$ is above threshold and rapidly increasing. Therefore, $VV \to h^0_{ew} \to ZZ^*$ is not viable. From above it appears that it might be possible to see $pp \to W h^0_{ew} \to WWW$ up to about 175 GeV. However, above

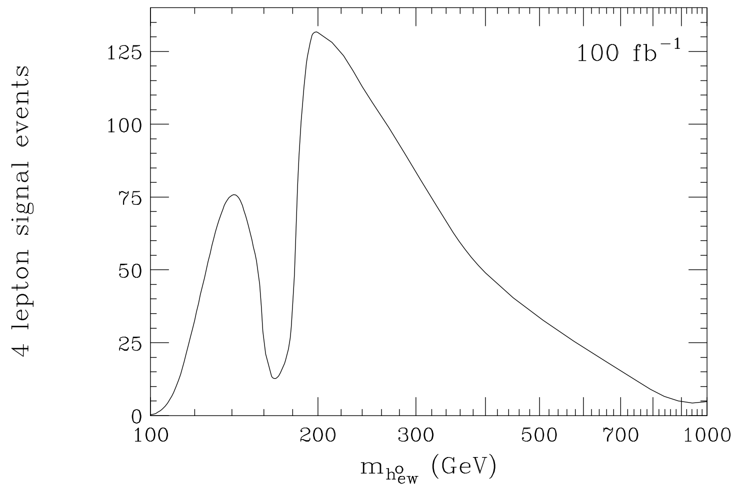

Figure 5: The total event rate of $e^+e^-\mu^+\mu^-$ expected from $VV \to h^0_{ew} \to ZZ^{(*)}$ production with $100\,\mathrm{fb}^{-1}$ of data collected at the LHC with center of mass energy 14 TeV. A 5σ signal above background from this mode is estimated to be possible for the mass ranges $120\,\mathrm{GeV} \lesssim m_{h^0_{ew}} \lesssim 155\,\mathrm{GeV}$ and $200\,\mathrm{GeV} \lesssim m_{h^0_{ew}} \lesssim 400\,\mathrm{GeV}$.

175 GeV the trilepton signal runs out. Thus, the small region between $175\,\mathrm{GeV} \lesssim m_{h^0_{ew}} \lesssim 180$ must rely on the difficult task of seeing a resonant enhancement in $VV \to h^0_{ew} \to WW$. In the standard model, the large $gg \to h^0_{sm}$ rate allows for the possibility of seeing the Higgs in the $h^0_{sm} \to WW$ channel for the range $155\,\mathrm{GeV} \lesssim m_{h^0_{sm}} \lesssim 180\,\mathrm{GeV}$ [25, 26]. It has been estimated that with $5\,\mathrm{fb}^{-1}$ a signal with greater than 5σ significance could be observed in this mass range for the standard model Higgs using the $h^0_{sm} \to WW \to l\nu l'\nu'$ decay mode [26]. The gauge-coupled Higgs h^0_{ew} does not get produced by gg fusion but rather $WW(ZZ)$ fusion. In this mass range the total cross section is more than a factor of six lower than the gg cross section. Taking this into account and scaling the significance result of [26] up to $100\,\mathrm{fb}^{-1}$ there is an 8σ signal available in the range $155\,\mathrm{GeV} \lesssim m_{h^0_{sm}} \lesssim 180\,\mathrm{GeV}$. It should be pointed out, however, that some of the cuts employed to reduce background may not be as effective if the underlying signal event is produced mainly by $WW(ZZ)$ fusion rather than gg fusion. For example, the $|\cos\theta_{l^+l^-}| < 0.8$ cut to reduce continuum $q\bar{q} \to W^+W^-$ background may not be as useful. However, it might be possible to gain significance by tagging the high p_T, high rapidity jets which radiate the initial vector bosons [27]. A central mini-jet veto [28] which takes advantage of the different color flow of the signal compared to background may also be helpful. Again, confusion with a supersymmetric signal is possible,

especially for slepton and chargino pair production which both can yield $ll' + \not{E}_T$ signatures at high rates. The spectator jet tags would be especially useful to eradicate this potential confusion.

Above the $h^0_{ew} \to ZZ$ threshold the Higgs signal would be a Higgs bump in the ZZ invariant mass spectrum in the total ZZ production cross section. Again, the Z's are required to decay into leptons. Fig. 5 give the total rate above the ZZ threshold and can be compared with the total ZZ production cross section for sensitivity of this invariant mass peak [30]. The resonant Higgs signal is smeared according to the detector's electromagnetic resolution, which is taken to be $15\%/\sqrt{E_T}$. Taking into consideration lepton acceptance, the significance is calculated for signal events in a bin centered on $m_{ZZ} = m_{h^0_{ew}}$ with a width determined by the two standard deviation smearing of the Higgs resonance corresponding to the resolution factor given above. The significance reaches a peak of about 7σ at $m_{h^0_{ew}} = 220\,\mathrm{GeV}$ and falls below 5σ for $m_{h^0_{ew}} \gtrsim 400\,\mathrm{GeV}$. This estimate is based only on the $h^0_{ew} \to ZZ \to e^+e^-\mu^+\mu^-$ mode. Using all lepton permutations at the expense of potential lepton pairing ambiguity should extend the search range well above $400\,\mathrm{GeV}$. Again, a realistic detector simulation is required to obtain a precise range. Nevertheless, it appears possible to discern a Higgs peak up to high mass scales with $100\,\mathrm{fb}^{-1}$.

In short, top-quark condensate models may imply at least one scalar degree of freedom, h^0_{ew}, which breaks electroweak symmetry and has negligible Yukawa production modes. The LEPII search range should not be different than the standard model. The Tevatron h^0_{ew} search is even enhanced over the standard model Higgs search range. On the other hand, it will be more challenging at the LHC to demonstrate that such a gauge-coupled Higgs like h^0_{ew} can be detected, and most especially that its mass can be reconstructed. However, over most of the perturbative Higgs mass range detection should be possible with $100\,\mathrm{fb}^{-1}$ of data.

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