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Where is Heidi hiding ?
Heidi is hidden
in the high-D Higgs Hill !

A higher dimensional explanation of the excess of Higgs-like events at CERN LEP

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Abstract

Searches for the SM Higgs boson by the four LEP experiments have found a $2.3\,\sigma$ excess at $98\,\text{GeV}$ and a smaller $1.7\,\sigma$ at around $115\,\text{GeV}$. We interpret these excesses as evidence for a Higgs boson coupled to a higher dimensional singlet scalar. The fit implies a relatively low dimensional mixing scale $\mu_{lhd} < 50\,\text{GeV}$, which explains the low confidence level found for the background fit in the range $s^{1/2} > 100\,\text{GeV}$. The data show a slight preference for a five-dimensional over a six-dimensional field. This Higgs boson cannot be seen at the LHC, but can be studied at the ILC.

With the latest developments from high energy colliders like LEP and the Tevatron the standard model (SM) has been established up to the loop level. The main missing ingredient is the direct detection of the SM Higgs boson. The four LEP experiments ALEPH, DELPHI, L3 and OPAL have extensively searched for the Higgs boson. The final combined result has been published in [1]. The absence of a clear signal has led to a lower limit on the Higgs boson mass of 114.4 GeV at the 95% confidence level. Although no clear signal was found the data have some intriguing features, that can be interpreted as evidence for Higgs bosons beyond the standard model. There is a $2.3\,\sigma$ effect seen by all experiments at around 98 GeV. A somewhat less significant $1.7\,\sigma$ excess is seen around 115 GeV. Finally over the whole range $s^{1/2} > 100\,\text{GeV}$ the confidence level is less than expected from background.

Within the minimal supersymmetric standard model (MSSM) and other extensions [2-5], the excesses at 98 GeV and 115 GeV were interpreted as evi-

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dence for the presence of two Higgs bosons H_i with couplings reduced by a factor α_i to matter $g_i^2 = \alpha_i\, g_{SM-Higgs}^2$. We will call such Higgs bosons fractional Higgses in the following. The excess at 98 GeV is well described by a 10% fractional Higgs. More precisely [2] gives limits $0.056 < \alpha_{98} < 0.114$ and a mass range $95\,\text{GeV} < m_{Higgs} < 101\,\text{GeV}$. The second peak at 115 GeV is then interpreted as a second Higgs boson with $\alpha_{115} = 0.9$. The first peak at 98 GeV is rather convincing. The second one at 115 GeV is compatible with the data, but not really preferred as the data at 115 GeV are also compatible with pure background with a similar confidence level. The data correspond roughly to background plus one half of a Higgs boson, however with a large uncertainty. The MSSM fit is therefore not completely satisfactory and it is natural to look for other extensions to describe the data.

Actually the precision measurements leave only very little space for extensions, as these tend to spoil the agreement with experiment due to a variety of effects, one of the most important of which is the appearance of flavor-changing neutral currents. Even the MSSM has to finely tune a number of parameters. This leaves only one type of extensions that are safe, namely the singlet extensions. Experimentally right handed neutrino's appear to exist. Since these are singlets a natural extension of the SM is the existence of singlet scalars too. These will only have a very limited effect on radiative corrections, since they appear only in two-loop calculations. For a mini-review on singlet extensions see [7].

In this letter we will try to fit the data within the specific model of a SM Higgs boson coupled to a higher dimensional ($d = 5, 6$) singlet scalar, where we assume that the higher dimensions are open and flat. This leads to a Higgs propagator of the form:

$$D_{HH}(q^2) = \left[q^2 + M^2 - \mu_{lhd}^{8-d}(q^2 + m^2)^{\frac{d-6}{2}} \right]^{-1}. \tag{1}$$

The masses M, m and μ_{lhd} are the free parameters of the model and are defined more precisely later. The scale μ_{lhd} stands for low-to-high-dimensional mixing mass and measures the coupling of the high-d singlet scalar and the 4-d doublet. The propagator contains a particle peak and a continuum. This model has, like the MSSM, three free parameters to fit the data. We will take the excess at 98 GeV at face value and interpret it as the delta-peak in the propagator. The excess at 115 GeV is interpreted as an enhancement due to the continuum of the Higgs propagator. Because of the uncertainty of this excess we will only demand that a Higgs integrated spectral density $\int \rho(s)ds > 30\%$ is present in the range $110\,\text{GeV} < s^{1/2} < 120\,\text{GeV}$. We will find that with these conditions one gets a relatively small highdimension-lowdimension mix-

ing scale $\mu_{lhd} < 50\,\mathrm{GeV}$. This result has a non-trivial consequence. It implies that the continuum starts very close to the delta-peak. This would therefore explain why in the range $s^{1/2} > 100\,\mathrm{GeV}$ the confidence level of the data is less than expected for background. This cannot be explained by the MSSM.

The effects of singlets appear in two forms, one is the mixing with the SM Higgs, the other is invisible decay. In this paper we are interested in pure mixing models. It is actually possible to have a Higgs model that has only Higgs-mixing. If one starts with an interaction of the form $H\Phi^\dagger\Phi$, where H is the new singlet Higgs field and Φ the SM Higgs field, no interaction of the form H^3 or H^4 is generated with an infinite coefficient [6]. Therefore one can leave the H^3 and H^4 interactions out of the Lagrangian without violating renormalizability. This type of model can easily be extended to more fields H_i. The situation becomes quite interesting, when one allows for an infinite number of fields, in particular when one assumes the field H to be moving in $d = 4 + \delta$ dimensions. Normally speaking this would lead to a nonrenormalizable theory. However since the only interaction is of the form $H\Phi^\dagger\Phi$, which is superrenormalizable in four dimensions, the theory stays renormalizable. An analysis of the power counting of divergences shows that one can associate the canonical dimension $1 + \delta/2$ to the H-field. This means that the theory stays renormalizable as long as $\delta \leq 2$. When one assumes, that the extra dimensions are compact, for instance a torus, with radius $R = L/2\pi$, one can simply expand the d-dimensional field $H(x)$ in terms of Fourier modes:

$$H(x) = \frac{1}{\sqrt{2}\,L^{\delta/2}} \sum_{\vec{k}} H_{\vec{k}}(x_\mu)\, e^{i\frac{2\pi}{L}\vec{k}\vec{x}}, \qquad H_{\vec{k}} = H_{-\vec{k}}^* \quad . \qquad (2)$$

Here x_μ is a four-vector, $\vec{x}$ is δ-dimensional and the δ components of $\vec{k}$ take only integer values.

One then finds a Lagrangian of the form:

$$L = -\frac{1}{2}D_\mu\Phi^\dagger D_\mu\Phi - \frac{1}{2}\sum(\partial_\mu H_k)^2 + \frac{M_0^2}{4}\Phi^\dagger\Phi - \frac{\lambda}{8}(\Phi^\dagger\Phi)^2 - \sum \frac{m_k^2}{2}H_k^2 - \frac{g}{2}\Phi^\dagger\Phi\sum H_k \; .$$
$$(3)$$

The masses of the H_k fields are given by $m_k^2 = m_0^2 + m_d^2\vec{k}^2$. Here $\vec{k}$ is a δ-dimensional vector and m_0 is a d-dimensional mass term for the field H. This term is necessary to insure stability of the vacuum. The last term can be written as a so-called brane-bulk term

$$S = \int d^{4+\delta}x \prod_{i=1}^{\delta} \delta(x_{4+i}) H(x)\Phi^\dagger\Phi. \qquad (4)$$

This Lagrangian leads to spontaneous symmetry breaking. Both the Φ-field

and the H_k-fields will receive a vacuum expectation value, which we call v respectively h_k. In the unitary gauge we write $\Phi = v + \phi$ and $H_k = h_k + x_k$.

The conditions for the minimum of the potential $V' = 0$ read:

$$\frac{\partial V}{\partial \Phi}\Big|_{v,h_k} = \frac{\lambda}{2}v^3 - \frac{M_0^2}{2}v + gv\sum_k h_k = 0, \tag{5}$$

$$\frac{\partial V}{\partial H_k}\Big|_{v,h_k} = m_k^2 h_k + \frac{gv^2}{2} = 0, \tag{6}$$

$$\Rightarrow v^2 = \frac{M_0^2}{\lambda - g^2\sum_k \frac{1}{m_k^2}} \;\; ; \;\; h_k = \frac{-gM_0^2}{2m_k^2(\lambda - g^2\sum_k \frac{1}{m_k^2})}. \tag{7}$$

From the second derivatives one then finds the mass matrix :

$$L_{mass} = \frac{-M^2}{2}\phi^2 - \sum_k \frac{m_k^2}{2}x_k^2 + gv\phi\sum_k x_k, \tag{8}$$

with $M^2 = \frac{3}{2}\lambda v^2 - \frac{M_0^2}{2} + g\sum_k h_k = \lambda v^2$.

One can derive the Higgs propagator without knowing the eigenstates explicitly by inverting the matrix:

$$D_{ij}(q^2)^{-1} = \begin{pmatrix} q^2 + M^2 & -gv & \cdots \\ -gv & q^2 + m_i^2 & 0 \\ \vdots & & 0 & \ddots \end{pmatrix}. \tag{9}$$

First we define the auxiliary quantity Q:

$$Q = 1 - \sum_k \frac{g^2v^2}{(q^2 + M^2)(q^2 + m_k^2)}. \tag{10}$$

$D_{ij}(q^2)$ is found to be:

$$D_{ij}(q^2) = \frac{1}{Q}\begin{pmatrix} \frac{1}{q^2+M^2} & \frac{gv}{(q^2+M^2)(q^2+m_j^2)} \\ \frac{gv}{(q^2+M^2)(q^2+m_i^2)} & \left(\frac{Q}{q^2+m_i^2}\delta_{ij} + \frac{g^2v^2}{(q^2+M^2)(q^2+m_i^2)(q^2+m_j^2)}\right) \end{pmatrix}. \tag{11}$$

In the continuous case the Higgs propagator, which corresponds to the (1,1)

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component of D, becomes:

$$D_{HH}(q^2) = \left[q^2 + M^2 - g^2 v^2 \frac{\Gamma(1-\delta/2)}{(4\pi)^{\delta/2}}(q^2 + m_0^2)^{\frac{\delta-2}{2}}\right]^{-1}. \qquad (12)$$

After redefining variables this becomes:

$$D_{HH}(q^2) = \left[q^2 + M^2 - \mu_{lhd}^{8-d}(q^2 + m^2)^{\frac{d-6}{2}}\right]^{-1}. \qquad (13)$$

We will now consider in more detail the two cases $d = 5$ and $d = 6$ separately and compare these with the data. Other values of d are in principle possible, but have no simple physical interpretation as higher dimensional fields.

First we consider the case $d = 5$. The propagator becomes of the form:

$$D_{HH}(q^2) = \left[q^2 + M^2 - \mu_{lhd}^{3}(q^2 + m^2)^{-1/2}\right]^{-1}. \qquad (14)$$

This corresponds to a Källén-Lehmann spectral density:

$$\begin{aligned}
\rho(s) = {} & \theta(m^2 - s)\,\frac{2(m^2 - s_{peak})^{3/2}}{2(m^2 - s_{peak})^{3/2} + \mu_{lhd}^{3}}\,\delta(s - s_{peak}) \\
& + \frac{\theta(s - m^2)}{\pi}\,\frac{\mu_{lhd}^{3}\,(s - m^2)^{1/2}}{(s - m^2)(s - M^2)^2 + \mu_{lhd}^{6}},
\end{aligned} \qquad (15)$$

where s_{peak} satisfies:

$$s_{peak} - M^2 + \mu_{lhd}^{3}(m^2 - s_{peak})^{-1/2} = 0. \qquad (16)$$

The peak always exists at a positive value of s_{peak} as long as $\mu_{lhd}^{3} < mM^2$, which we assume satisfied, since this corresponds to the condition that we expand around a minimum of the potential. Actually this form of the spectral density is only correct as long as $M > m$. In the case $m > M$ in principle more peaks can appear, however this would imply for the residue at the pole $\alpha_{98} > 1/3$, which is not allowed by the data.

We now consider the case $d = 6$. This case is special, since it corresponds to the limiting dimension, where the theory is still renormalizable. In the limit $d \to 6$ one notices that the propagator has a logarithmic singularity. This is because the coupling constant becomes dimensionless and is running as a function of the renormalization scale. In contrast to normal four-dimensional models, the

running appears already at the tree level of the theory. Specializing to this case and expanding the Γ-function around $d = 6$ the propagator can be written as:

$$D_{HH}(q^2) = \left[q^2 + M^2 + \mu_{lhd}^2 \log(\frac{q^2 + m^2}{\mu_{lhd}^2}) \right]^{-1}. \tag{17}$$

The spectrum contains a pole term for a positive mass as long as:

$$M^2 + \mu_{lhd}^2 \log(m^2/\mu_{lhd}^2) > 0. \tag{18}$$

When this condition is not fulfilled the pole becomes a tachyon. The reason is as before in the $d = 5$ case, that in this case the potential due to the attractive H-exchange dominates over the repulsive $\lambda\phi^4$ term and the vacuum is not stable.

The corresponding Källén-Lehmann spectral density is:

$$\rho(s) = \qquad \theta(m^2 - s) \, \frac{m^2 - s_{peak}}{m^2 + \mu_{lhd}^2 - s_{peak}} \, \delta(s - s_{peak})$$
$$+ \theta(s - m^2) \, \frac{\mu_{lhd}^2}{[\, s - M^2 - \mu_{lhd}^2 \, \log((s - m^2)/\mu_{lhd}^2) \,]^2 + \pi^2 \, \mu_{lhd}^4}. \tag{19}$$

With these formulas we now try to describe the LEP data. We start with the case $d = 5$. The delta-peak will be assumed to correspond to the peak at 98 GeV, with a fixed value of α_{98}. Ultimately we will vary the location of the peak between $95 \, \mathrm{GeV} < m_{peak} < 101 \, \mathrm{GeV}$ and $0.056 < \alpha_{98} < 0.144$. After fixing α_{98} and m_{peak} we have one free variable, which we take to be μ_{lhd}. If we also take a fixed value for μ_{lhd} all parameters and thereby the spectral density is known. We can then numerically integrate the spectral density over selected ranges of s. The allowed range of μ_{lhd} is subsequently determined by the data at 115 GeV. Since the peak at 115 GeV is not very well constrained, we demand here only that the integrated spectral density from $s_{down} = (110 \, \mathrm{GeV})^2$ to $s_{up} = (120 \, \mathrm{GeV})^2$ is larger than 30%. This condition, together with formula (15), which implies:

$$\rho(s) < \frac{(s - m^2)^{1/2}}{\pi \, \mu_{lhd}^3}, \tag{20}$$

leads to the important analytical result:

$$\frac{2}{3\pi \, \mu_{lhd}^3} [\, (s_{up} - m_{peak}^2)^{3/2} - (s_{down} - m_{peak}^2)^{3/2} \,] > 0.3 \tag{21}$$

This implies $\mu_{lhd} < 53 \, \mathrm{GeV}$. Using the constraint from the strength of the delta-peak, it follows that the continuum starts very close to the peak, the

difference being less than 2.5 GeV. This allows for a natural explanation, why the CL for the fit in the whole range from 100 GeV to 110 GeV is somewhat less than what is expected by pure background. The enhancement can be due to a slight, spread-out Higgs signal. Actually when fitting the data with the above conditions, one finds for small values of μ_{lhd}, that the integrated spectral density in the range 100 GeV to 110 GeV can become rather large, which would lead to problems with the 95% CL limits in this range. We therefore additionally demand that the integrated spectral density in this range is less than 30%. There is no problem fitting the data with these conditions. As allowed ranges we find:

$$
\begin{aligned}
95\,\mathrm{GeV} &< m < 101\,\mathrm{GeV} \\
111\,\mathrm{GeV} &< M < 121\,\mathrm{GeV} \\
26\,\mathrm{GeV} &< \mu_{lhd} < 49\,\mathrm{GeV}
\end{aligned}
\tag{22}
$$

As a final consistency check we notice that the results are in agreement with the upper limit on the Higgs boson mass from precision measurements $m_H < 190\,\mathrm{GeV}$. The integrated spectral density above 190 GeV is less than 1%. This upper limit on the Higgs mass is actually so large, because of the measurement of the b-asymmetry, which is away from the other measurements, that are very close together. One can follow the analysis from [8] with the latest data and finds at the 95% CL $m_H < 124\,\mathrm{GeV}$ from the leptonic data on $\sin^2_\theta(lept)$, $m_H < 144\,\mathrm{GeV}$ from m_W and $m_H < 109\,\mathrm{GeV}$ from the two combined. Even this limit is not inconsistent with our model, which may be taken as additional confirmation. One can actually allow for the integrated spectral density in the low mass region to be larger than given in our analysis, if one allows for a fraction of invisible decays of the Higgs boson. Indeed if this strong limit is valid, a low mass spread-out Higgs boson appears to be the only possibility consistent with experiment.

We now repeat the analysis for the case $d = 6$. The analytic argument gives the result:

$$
\frac{s_{up} - s_{down}}{\pi^2\,\mu_{lhd}^2} > 0.3
\tag{23}
$$

which implies $\mu_{lhd} < 28\,\mathrm{GeV}$. Because of this low value of μ_{lhd} it is difficult to get enough spectral weight arond 115 GeV and one also tends to get too much density below 110 GeV. So the fit was only possible in a restricted range. We found the following limits:

$$
\begin{aligned}
95\,\mathrm{GeV} &< m < 101\,\mathrm{GeV} \\
106\,\mathrm{GeV} &< M < 111\,\mathrm{GeV} \\
22\,\mathrm{GeV} &< \mu_{lhd} < 27\,\mathrm{GeV}
\end{aligned}
\tag{24}
$$

As far as the limit from the precision data there is no problem here either. The spectral weight above 190 GeV is a bit larger, because the six-dimensional spectrum falls off somewhat more slowly at high values of s, however is still less than 4%. Though not quite ruled out, the six-dimensional case therefore seems to be somewhat disfavoured compared to the five-dimensional case.

From the discussion it is clear that the data can be well described by the assumption of a higher dimensional Higgs field. The model is renormalizable and contains only two parameters beyond the SM. The relevant mass scales are all comparable to each other and no fine tuning is present. The model obviously fits the data better than pure background or the MSSM, due to the fact that fractional Higgses are possible at 98 GeV and 115 GeV. Also it provides an explanation for the slight discrepancy in the range 100 GeV to 110 GeV, that is not explained by another model. What is not clear is how significant the overall results are. For this an analysis of the confidence level on a bin by bin basis would be necessary. From the discussion given in [1] we cannot reliably extract this significance. This can only be done by the experimental groups. Assuming independence in the different mass ranges a very rough estimate gives a $3.5\,\sigma - 4\,\sigma$ overall signal.

If this model is indeed true, what are the consequences for the Higgs search at the LHC? The situation appears to be essentially hopeless. Most of the spectral density is tied up in the low Higgs mass region. In this region the Higgs search is performed at the LHC in the rare decay modes $H \to \gamma\gamma$ and $H \to ZZ^* \to l^+l^-l^+l^-$, both of which heavily rely on an excellent mass resolution in order to extract the Higgs signal. Since now there is no mass peak, these signals do not work. In the range 150 GeV-180 GeV one can try to use the dominant $H \to W^*W^*$ decay mode. However this does not work either, because the integrated spectral density in this region is less than 2% for the $d = 5$ case and less than 6% for the $d = 6$ case. Also the golden decay modes above the Z threshold are too small, since the integrated spectral density above 190 GeV is less than 4%. The only possibility to study this type of Higgs boson appears to be the international linear collider (ILC), where the Higgs signal can be studied independently of its decay modes. The spectral density can be reconstructed from the Bjorken process $e^+e^- \to ZH$, by looking at the invariant mass of the Higgs boson, that can be extracted, if one knows the Z momentum precisely. Since backgrounds and signal can be calculated and measured very precisely, this model presents no particular problem for the ILC.

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