New spectra in the HEIDI models

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What do we know?

- Vectorbosons exist $\rightarrow$ a Higgs field exists.
- QFT is right $\rightarrow$ The Higgs field has a Källén-Lehmann spectral density.
- EW precision data $\rightarrow$ the field is light.
Everything else is conjecture.

In particular the idea that there is a single Higgs particle peak is an assumption, for which there is no basis in theory or experiment. Newton: Non fingo hypotheses.

Since the Higgs field is in some way different from other fields, a non-trivial density is quite natural.

The scientific goal regarding EW symmetry breaking is therefore to measure the Källén-Lehmann spectral density of the Higgs propagator. For this the LHC is less than optimal.
Extended standard model (with A. Hill)†.

Higgs Sector

\[ \mathcal{L} = -\frac{1}{2} (D_{\mu} \Phi)^\dagger (D_{\mu} \Phi) - \lambda_1 / 8 (\Phi^\dagger \Phi - f_1^2)^2 - \frac{1}{2} (\partial_{\mu} H)^2 - \frac{\lambda_2}{8} (2 f_2 H - \Phi^\dagger \Phi)^2 \]

N.B. no \( H^4 \) coupling: pure mixing model.
Renormalizable !!

Two Higgses with reduced couplings

\[ D_{HH}(k^2) = \frac{\sin^2 \alpha}{k^2 + m^2_+} + \frac{\cos^2 \alpha}{k^2 + m^2_-} \]

This is sufficient to study Higgs signals (interaction basis).
The generalization to more fields is straightforward.

\[ n \text{ Higgses } H_i \text{ with couplings } g_i. \]

**Sum rule:**

\[ \sum g_i^2 = g_{\text{Standard model}}^2 \]

This can be generalized to a continuum.

\[ \int \rho(s) ds = 1 \]

Källén-Lehmann density.
HEIDI Models  (with S. Dilcher and B. Puliçe)

Higher dimensional singlet \( \Rightarrow \) Few Parameters !

In terms of the modes \( H_i \) the Lagrangian is the following:

\[
L = -\frac{1}{2} D_\mu \Phi^\dagger D^\mu \Phi - \frac{M_0^2}{4} \Phi^\dagger \Phi - \frac{\lambda}{8} (\Phi^\dagger \Phi)^2 \\
- \frac{1}{2} \sum (\partial_\mu H_k)^2 - \sum \frac{m_k^2}{2} H_k^2 \\
- \frac{g}{2} \Phi^\dagger \Phi \sum H_k - \frac{\zeta}{2} \sum H_i H_j
\]

\( m_k^2 = m^2 + m_\gamma \vec{k}^2 \), where \( \vec{k} \) is a \( \gamma \)-dimensional vector, \( m_\gamma = 2\pi/L \)
and \( m \) a \( d \)-dimensional mass term for the field \( H \).

\[
S = \int d^{4+\gamma} x \prod_{i=1}^{\gamma} \delta(x_{4+i}) \left( g_B H(x) \Phi^\dagger \Phi - \zeta_B H(x) H(x) \right)
\]
Propagator

\[ D_{HH}(q^2) = \left( q^2 + M^2 - \frac{\mu^{8-d}}{(q^2 + m^2)^{\frac{6-d}{2}} \pm \nu^{6-d}} \right)^{-1} \]

This is renormalizable up to 6 dimensions, while

\[ H\Phi^\dagger\Phi \]

is superrenormalizable in four dimensions

Corresponding Källén-Lehmann spectral density:
zero, one or two peaks plus continuum
$2m\rho(m^2)$

$[1/GeV]$

$m_d = 99 \text{ GeV}$

$M = 121 \text{ GeV}$

$\mu = 41 \text{ GeV}$

$m(\text{GeV})$
Interpretation of the data (one peak plus continuum).

**LEP + LHC**

- nothing below 95 GeV
- 2.3 sigma at 98 GeV
- no further signal below 116 GeV
- bulk of the spectrum between 116 GeV and 130 GeV

Impose conditions.

\[
95 \text{GeV} < m_{peak} < 101 \text{GeV}
\]

\[
0.056 < g_{98}^2 / g_{SM}^2 < 0.144
\]

\[
m > 116 \text{GeV}
\]

\[
\int_{(130)^2}^{\infty} \rho(s) ds < 0.1
\]
\[ D_{HH}(q^2) = \left( q^2 + M^2 + \mu^2 \frac{\log((q^2 + m^2)/m^2)}{1 + \alpha_6 \log((q^2 + m^2)/m^2)} \right)^{-1} \]
Center point of the fits
The two peak case.

- continuum close to peak
- no fit with two peaks, 115 and 119 GeV
  plus continuum at 125 GeV
Without the LEP data the pure continuum case is also possible.
Conclusion

- The Higgs field has probably been found at the LHC and possibly at LEP-200.
- Its properties are consistent with the electroweak precision data.
- A dark matter candidate can be included.
- The spectrum is uncertain.

Caveats

Significance roughly 3 sigma, somewhat less for LEP.
Questions for the LHC this year

- Confirm the peak
- Go down to 95 GeV
- ”model-independent” analysis

Example: divide 116-130 GeV in 7 bins of 2 GeV. Allow for Higgs spectral densities in steps of 1/6. This give 1716 models.

Longer term
- branching ratios
- width
Beyond the LHC: A Higgs factory

Questions for the ILC

Obviously a lepton collider is needed, but how well can one do?

\[ e^+ e^- \rightarrow Z \ H. \]

Measurement of line-shape and invisible decay BR’s.

- Energy about 250-300 GeV
- High precision
- Theory: benchmark models
- Beam Strahlung: machine
- Resolution: detector
- Unfolding: analysis

ILC: no mandate from ICFA for 300 GeV
A muon collider: Science fiction ?
A large circular collider: VLLC !
Where is Heidi hiding?

Heidi is hidden in the high-D Higgs Hill!
EXTRA!
COMMENTS ON STRONG INTERACTIONS
Strong interactions:

\[ \cos^2(\alpha)m_-^2 + \sin^2(\alpha)m_+^2 \geq \frac{8\pi\sqrt{2}}{3G_F}. \]

Precision tests:

\[ \delta_{EW} \approx \log(m_-^2/m_Z^2) + \sin^2(\alpha) \log(m_+^2/m_-^2). \]

This must then be smaller than the limit for the standard model

\[ \delta_{EW} \leq \log(m_{up}^2/m_Z^2). \]

We take \( m_- \approx 115 \text{ GeV} \) and \( m_{up} \approx 157 \text{ GeV} \) (blue-band).
Combine, \( x = m_+^2/m_-^2 \):

\[
\frac{x - 1}{\log(x)} \geq \frac{16\pi v^2 - 3m_-^2}{3m_-^2 \log(m_{up}^2/m_-^2)}.
\]

The LHC has shown evidence for the presence of a Higgs at 125 GeV with a fraction \( f \) of the signal:

\[
\frac{x - 1}{\log(x)} \geq \frac{16\pi v^2 - 3(1 - f)m_-^2 - 3 fm_{LHC}^2}{3m_-^2 \left( \log(m_{up}^2/m_-^2) - f \log(m_{LHC}^2/m_-^2) \right)}.
\]
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RESERVE
March 2009
$m_{\text{Limit}} = 163 \text{ GeV}$

$\Delta \alpha_{\text{had}}^{(5)} =$

- $0.02758 \pm 0.00035$
- $0.02749 \pm 0.00012$

incl. low $Q^2$ data

Excluded

Preliminary
Stealth model \, (with T. Binoth)†.

\[ \mathcal{L} = -\frac{1}{2}(D_\mu \Phi)^\dagger(D_\mu \Phi) - \frac{\lambda}{8}(\Phi^\dagger\Phi - f^2)^2 \]
\[ -\frac{1}{2}(\partial_\mu \vec{\phi})^2 - \frac{1}{2}m^2 \vec{\phi}^2 - \frac{\kappa}{8}(\vec{\phi}^2)^2 \]
\[ -\frac{\omega}{2}\vec{\phi}^2 \Phi^\dagger \Phi \]

\vec{\phi} : \, N \text{ scalar fields; singlets under the standard model gauge group.} \\
O(N) \text{ symmetry unbroken } \Rightarrow \text{ dark matter.}
After spontaneous symmetry breaking of the electroweak group this leads to an invisible decay mode of the Higgs boson if the dark matter particles are light enough.

\[ H \rightarrow \phi \bar{\phi} \]

\[ \Gamma_H = \frac{\omega^2 N \nu^2}{64\pi^2 m_H} \]

\( \omega^2 N \) can be large, so the Higgs boson resonance can be wide and invisible. Therefore very difficult at the LHC, but there would be a measurable excess in missing energy signals in the vectorboson fusion channel.
\[ \int L = 10 \text{ fb}^{-1} \]

95% exclusion limits on $\xi^2$ vs. Higgs mass in [GeV / c$^2$]

- $\omega = 0.1$
- $\omega = 0.2$
- $\omega = 1$
- $\omega = 3$
- $\omega = 5$
- SM width
- $\Gamma = m$

Higgs mass range 100 to 400 GeV / c$^2$
General singlet extensions allow for invisible decay (dark matter). There are two arbitrary functions:

- Line shape.
- Invisible branching ratio.

Unchanged are the relative branching fractions to standard model particles.

Examples

- Visible peak unequal to Standard Model.
- Completely invisible decay.
- Spread-out Higgs.
- Singlets too heavy for the Higgs to decay into.
Theory or scenario?

- philosophical argument
- plausibility argument
- cosmological indications
- experimental support
- simplicity
- consistency at the quantum level
- a prediction that can be refuted

So this is a theory, not a scenario!