The generalized standard model Higgs field

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What would it mean if the LHC finds no evidence for the Higgs Boson ?

No Higgs at the LHC?

$$\Big\Downarrow$$

No Higgs at the LHC!

No lose scenario (M. Chanowitz 1986)
Building the SSC (now LHC) one will find the Higgs boson or new interactions that one can study.

This violates the "you can always lose" principle (van der Bij 1986)
Therefore(C. Quigg Moriond 2008)

The van der Bij conjecture (weak form)
Something bad could happen.

The van der Bij conjecture (strong form)
It already has.

A. de Roeck Moriond 2008
There are always killjoys.

Belen Gavela Moriond 2010
The van der Bij malediction
Can we miss the Higgs at the LHC? : Yes we can.

G. Altarelli EPS 2011
Catastrophic:
No Higgs, no new physics.

What do we know?

- Vectorbosons exist → a Higgs field exists.
- QFT is right → The Higgs field has a Källén-Lehmann spectral density.
- EW precision date → 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

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

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

Two Higgses with reduced couplings

$$D_{HH}(k^2) = \frac{sin^2\beta}{k^2 + m_+^2} + \frac{cos^2\beta}{k^2 + m_-^2}$$

This is sufficient to study Higgs signals (interaction basis).

The generalization to more fields is straightforward.

n Higgses H_i with couplings g_i.

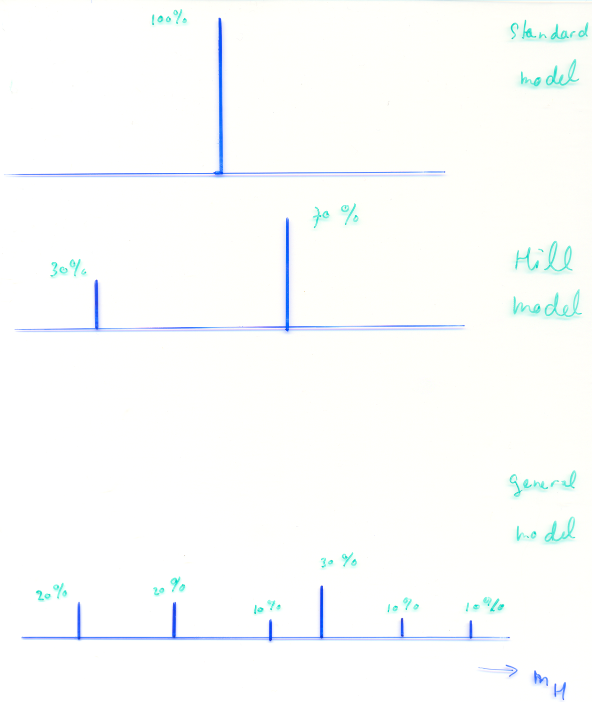
Sum rule:

$$\Sigma g_i^2 = g_{Standard\ model}^2$$

This can be generalized to a continuum.

$$\int \rho(s) ds = 1$$

Källén-Lehmann density.


100%
Standard model
70 %
30%
Hill model
general model
20%
20%
10%
30 %
10%
10%
m_H

HEIDI Models (with S. Dilcher and B. Puliçe)

Higher dimensional singlet ⇒ Few Parameters !

In terms of the modes H_i the Lagrangian is the following:

$$
\begin{aligned}
L &= -\frac{1}{2} D_\mu \Phi^\dagger D_\mu \Phi - \frac{M_0^2}{4} \Phi^\dagger \Phi - \frac{\lambda}{8} (\Phi^\dagger \Phi)^2 \\
&- \frac{1}{2} \sum (\partial_\mu H_k)^2 - \sum \frac{m_k^2}{2} H_k^2 \\
&- \frac{g}{2} \Phi^\dagger \Phi \sum H_k - \frac{\zeta}{2} \sum H_i H_j
\end{aligned}
$$

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

$$
S = \int d^{4+\gamma} x \prod_{i=1}^{\gamma} \delta(x_{4+i}) \Big(g_B H(x) \Phi^\dagger \Phi - \zeta_B H(x) H(x) \Big)
$$

Propagator

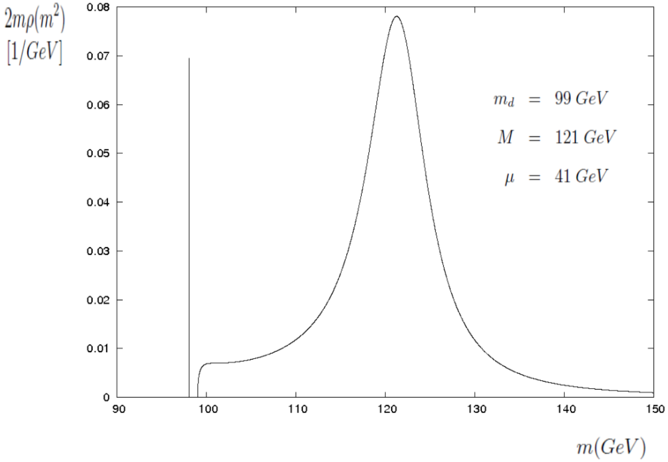
$$D_{HH}(q^2) = \left(q^2 + M^2 - \frac{\mu^{8-d}}{(q^2+m^2)^{\frac{6-d}{2}} \pm \nu^{6-d}} \right)^{-1}$$

This is renormalizable up to 6 dimensions, while

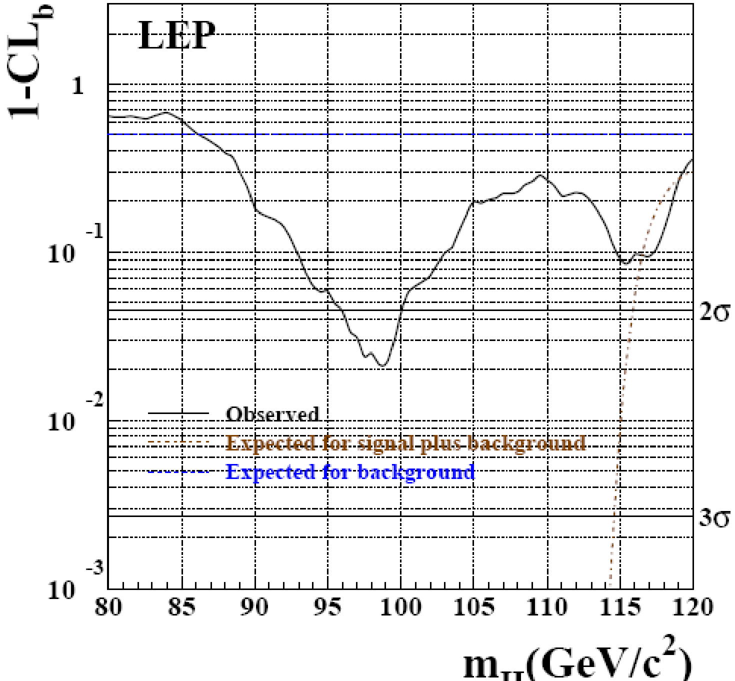
$$H\Phi^\dagger\Phi$$

is superrenormalizable in four dimensions

Corresponding Källén-Lehmann spectral density:
zero, one or two peaks plus continuum



$2m\rho(m^2)$
$[1/GeV]$
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
90
100
110
120
130
140
150
$m(GeV)$
$m_d = 99\,GeV$
$M = 121\,GeV$
$\mu = 41\,GeV$


LEP
1-CL_b
1
10^-1
10^-2
10^-3
2σ
3σ
Observed
Expected for signal plus background
Expected for background
80
85
90
95
100
105
110
115
120
m_H(GeV/c^2)

Interpretation of the data (one peak plus continuum).

- nothing below 95 GeV
- 2.3 sigma at 98 GeV
- 1.7 sigma at 115 GeV
- above 100 GeV above the background over the whole range

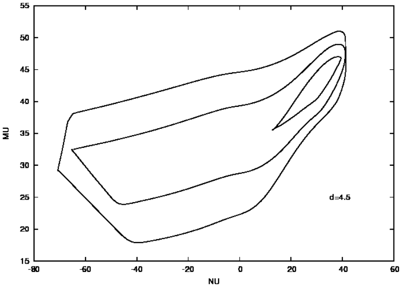
Impose conditions.

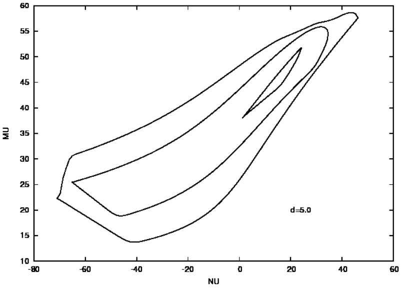
$$95\,GeV < m_{peak} < 101\,GeV$$

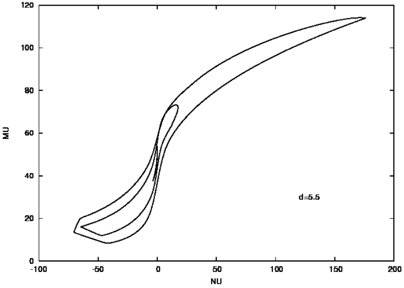
$$0.056 < g_{98}^2/g^2SM < 0.144$$

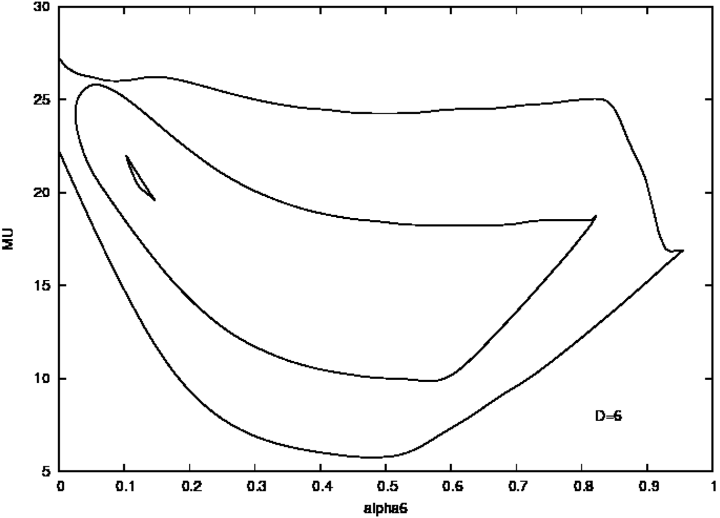
$$\int_{(100)^2}^{(110)^2} \rho(s)ds < 0.3$$

$$\int_{(110)^2}^{(120)^2} \rho(s)ds > 0.3$$


55
50
45
40
35
30
25
20
15
MU
-80
-60
-40
-20
0
20
40
60
NU
d=4.5


60
55
50
45
40
35
30
25
20
15
10
MU
-80
-60
-40
-20
0
20
40
60
NU
d=5.0


120
100
80
60
40
20
0
MU
-100
-50
0
50
100
150
200
NU
d=5.5



$$D_{HH}(q^2) = \left(q^2 + M^2 + \mu^2 \frac{\log((q^2+m^2)/m^2)}{1+\alpha_6 \log((q^2+m^2)/m^2)} \right)^{-1}$$

Conclusion

- The Higgs field has been found at LEP-200.
- Its properties are consistent with the electroweak precision data.
- A dark matter candidate can be included.
- The LHC will see no Higgs signal.

Caveats

Significance roughly 3.3 sigma but uncertain.
The data were not analyzed with this type of model in mind.

In the case of two peaks, the reduced peak at $115 GeV$ could possibly be seen with the design luminosity and energy of the LHC.

The two peak case.

Relax the precision data somewhat.
Example: 98 GeV (10%); 115 GeV (40%); continuum (50%)

- Can this be seen at the LHC?
  probably YES, with the full design parameters.
- How would you see this, at the LHC?
  A peak in γ, γ and a signal in WW, but no peak in $ZZ*$, roughly speaking
- Was LEP's energy large enough?
  NO.
- Should one build a linear e^+e^- collider?
  MAYBE.

A Higgs factory

Questions for the ILC

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

$$e^+e^- \to Z \quad H.$$

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

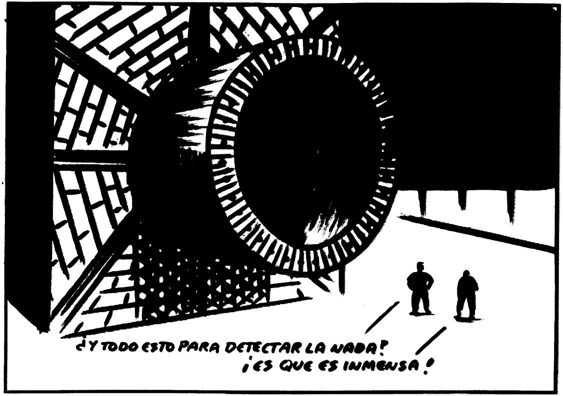
- Energy about 250-300 GeV
- High precision
- Theory: benchmark models
- Beam Strahlung: machine
- Resolution: detector
- Unfolding: analysis

Alternative: A muon collider. Science fiction ?
A large circular collider: LEP300. Fermilab ?

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 !



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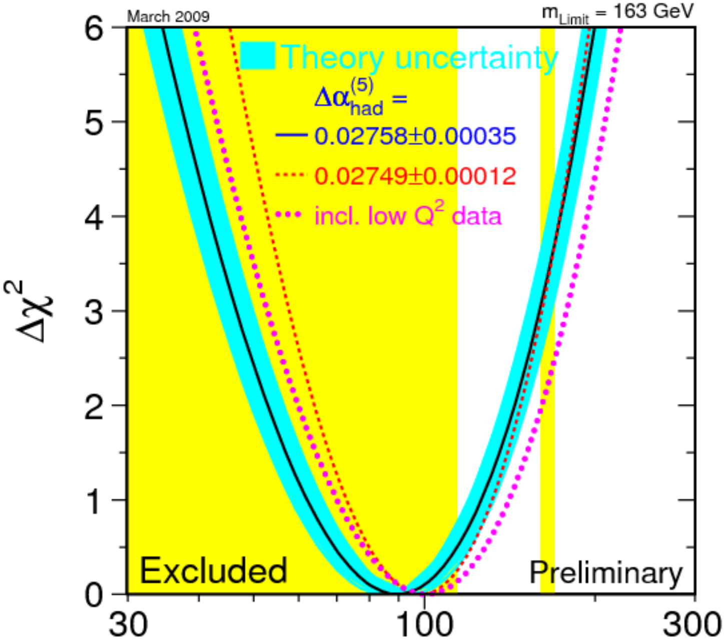
RESERVE


March 2009
m_{Limit} = 163 GeV
Theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
$\Delta\chi^2$
6
5
4
3
2
1
0
30
100
300
Excluded
Preliminary

Fits to the M_H mass

- **leptonic observables**

$$\left(\sin^2\theta_{eff}\right)_l = 0.23113 \pm 0.00020$$

$$M_H = 51^{+37}_{-22}\,\mathrm{GeV} \qquad M_H^{95} = 124\,\mathrm{GeV}$$

- **combined fit**

$$\left(\sin^2\theta_{eff}\right)_l \text{ and } M_W = 80.404 \pm 0.030\,\mathrm{GeV}$$

$$M_H = 51^{+30}_{-21}\,\mathrm{GeV} \qquad M_H^{95} = 109\,\mathrm{GeV}$$

- **hadronic observables**

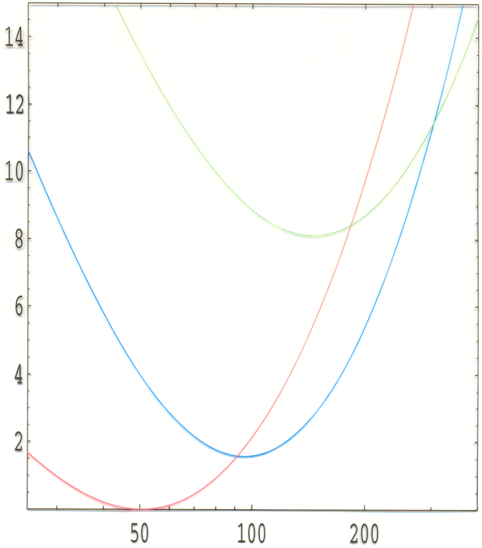
$$\left(\sin^2\theta_{eff}\right)_{\mathrm{bottom}} = 0.23222 \pm 0.00027$$

$$M_H = 488^{+426}_{-219}\,\mathrm{GeV} \qquad (M_H^{95})_{\mathrm{l.b.}} = 181\,\mathrm{GeV}$$

$$m_t = 172.5 \pm 2.3\,\mathrm{GeV} \;\; \Delta\alpha_h^{(5)} = 0.02758 \pm 0.00035$$

$$\alpha_s(M_Z) = 0.118 \pm 0.002$$

χ^2 for $\sin^2\theta^{lept}_{eff}$ and M_W as a function of M_H



The red line corresponds to $\sin^2\theta^{lept}_{eff}$ from leptonic

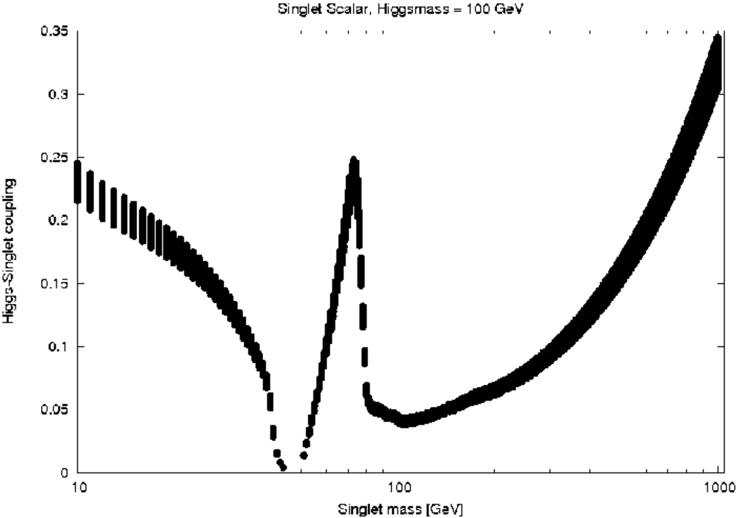
Stealth model (with T. Binoth)[†].

M(inimal) N(on) M(inimal) S(tandard) M(odel)

$$\begin{aligned}\mathcal{L} = \; & -\tfrac{1}{2}(D_\mu\Phi)^\dagger(D_\mu\Phi) - \tfrac{\lambda}{8}(\Phi^\dagger\Phi - f^2)^2 \\ & -\tfrac{1}{2}(\partial_\mu\vec{\phi})^2 - \tfrac{1}{2}m^2\vec{\phi}^2 - \tfrac{\kappa}{8}(\vec{\phi}^2)^2 \\ & -\tfrac{\omega}{2}\vec{\phi}^2\Phi^\dagger\Phi\end{aligned}$$

$\vec{\phi}$: N scalar fields; singlets under the standard model gauge group.

$O(N)$ symmetry unbroken ⇒ dark matter.

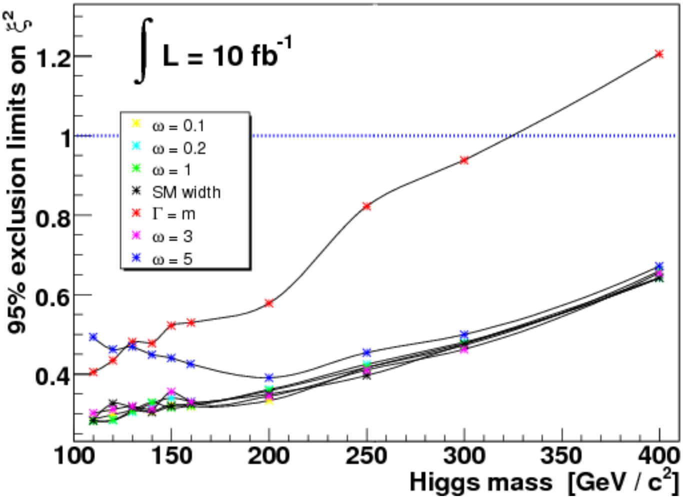

Singlet Scalar, Higgsmass = 100 GeV
Higgs-Singlet coupling
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10
100
1000
Singlet mass [GeV]

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.

$$H \;\rightarrow\; \vec{\phi}\;\vec{\phi}$$

$$\Gamma_H = \frac{\omega^2 N}{64\pi^2}\frac{v^2}{m_H}$$

$\omega^2\ N$ 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.



$\int L = 10\ fb^{-1}$
95% exclusion limits on ξ^2
Higgs mass [GeV / c^2]
ω = 0.1
ω = 0.2
ω = 1
SM width
Γ = m
ω = 3
ω = 5
0.4
0.6
0.8
1
1.2
100
150
200
250
300
350
400

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.