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

$$\mathcal{L} = -\frac{1}{2}(D_\mu\Phi)^\dagger(D_\mu\Phi) - \lambda_1/8(\Phi^\dagger\Phi - f_1^2)^2 - \frac{1}{2}(\partial_\mu H)^2 - \frac{\lambda_2}{8}(2f_2H - \Phi^\dagger\Phi)^2$$

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 Higgses H_i with couplings g_i.

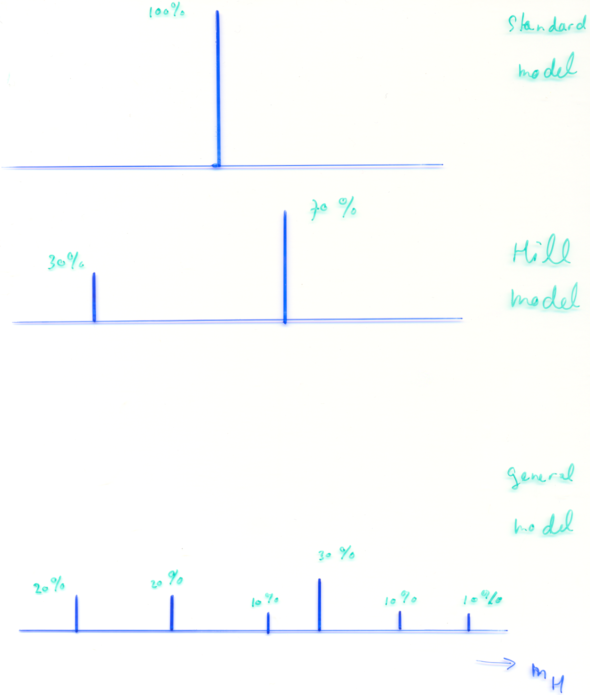
Sum rule:

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

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.

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

Propagator

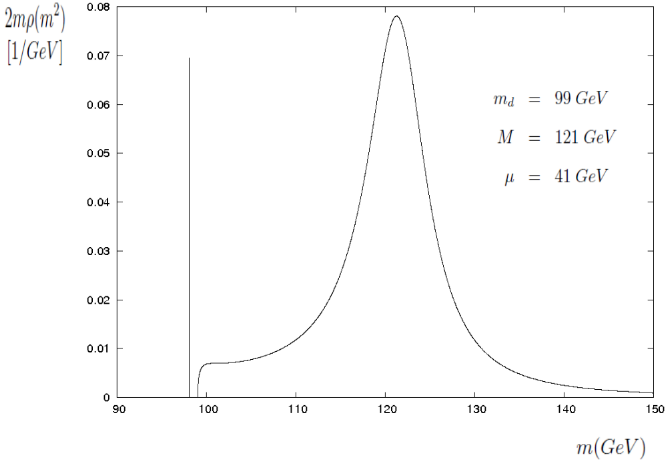
$$D_{HH}(q^2) = \left(q^2 + M^2 - \frac{\mu^{8-d}}{(q^2+m^2)^{\frac{6-d}{2}} \pm \nu^{6-d}} \right)^{-1}$$

This is renormalizable up to 6 dimensions, while

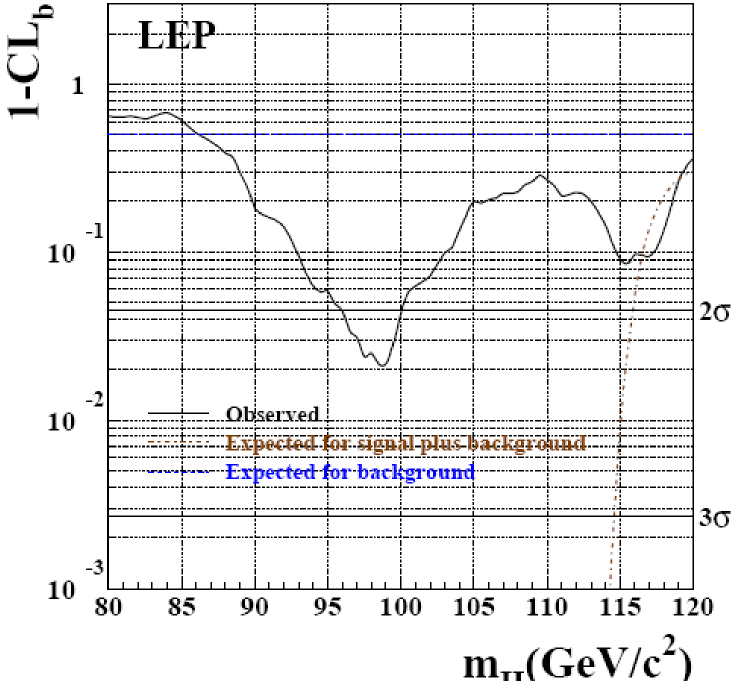
$$H\Phi^\dagger\Phi$$

is superrenormalizable in four dimensions

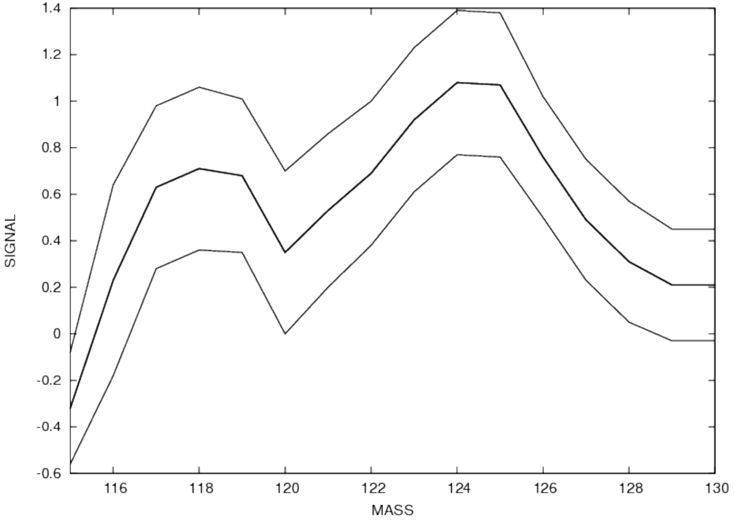
Corresponding Källén-Lehmann spectral density:
zero, one or two peaks plus continuum



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



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
$m_H(GeV/c^2)$



1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
SIGNAL
116
118
120
122
124
126
128
130
MASS

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

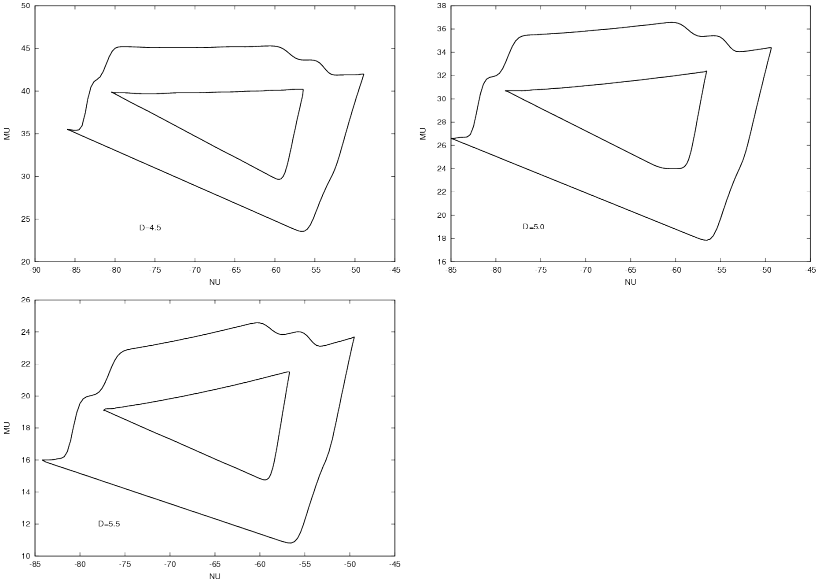
Impose conditions.

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

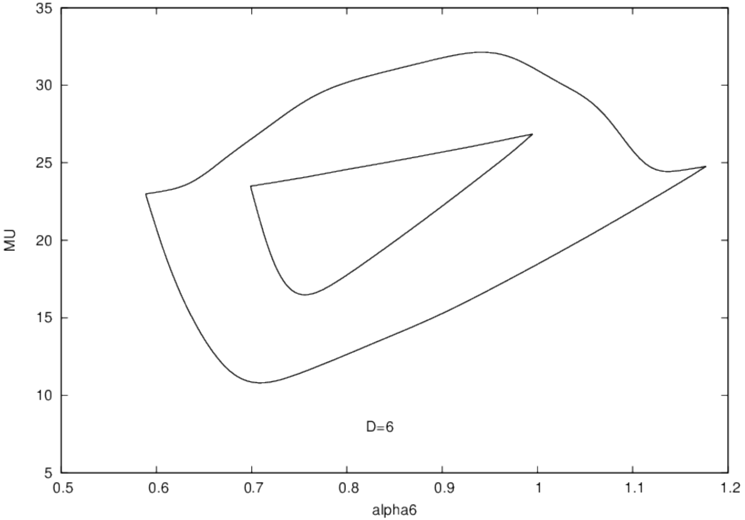
$$0.056 < g_{98}^2/g_{SM}^2 < 0.144$$

$$m > 116\,GeV$$

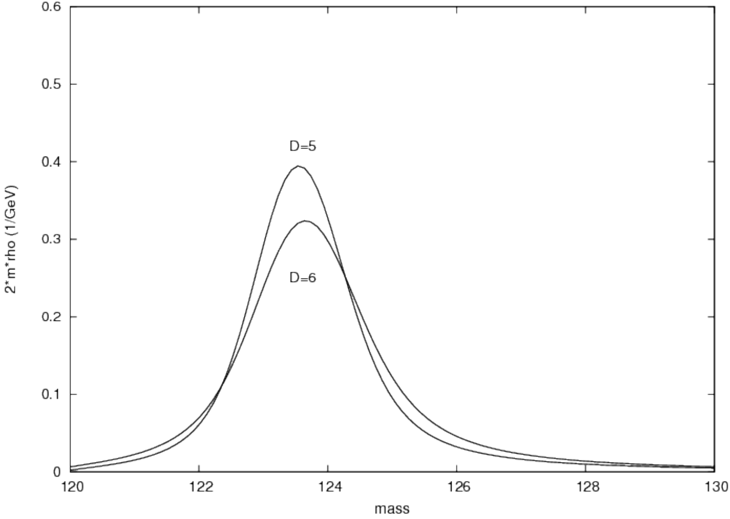
$$\int_{(130)^2}^{\infty} \rho(s) ds < 0.1$$



MU
NU
D=4.5
D=5.0
D=5.5



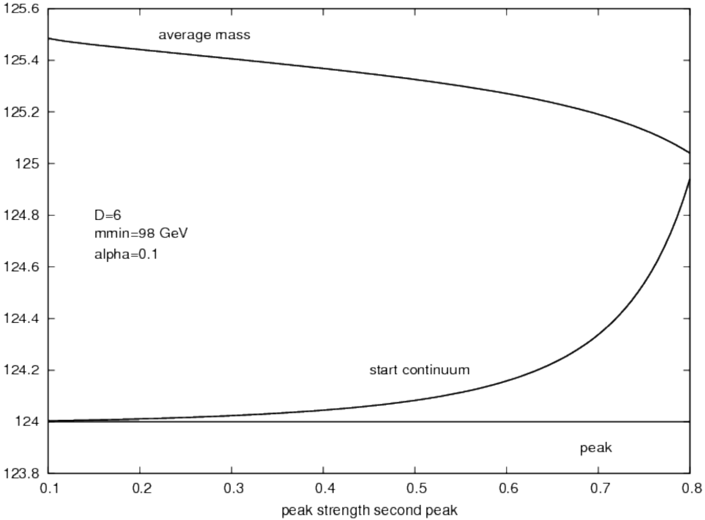
$$D_{HH}(q^2) = \left(q^2 + M^2 + \mu^2 \frac{\log((q^2+m^2)/m^2)}{1 + \alpha_6 \log((q^2+m^2)/m^2)} \right)^{-1}$$



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?

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

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

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 $m_- \approx 115 \quad GeV$ and $m_{up} \approx 157 \quad GeV$ (blue-band).

Combine, $x = m_+^2/m_-^2$:

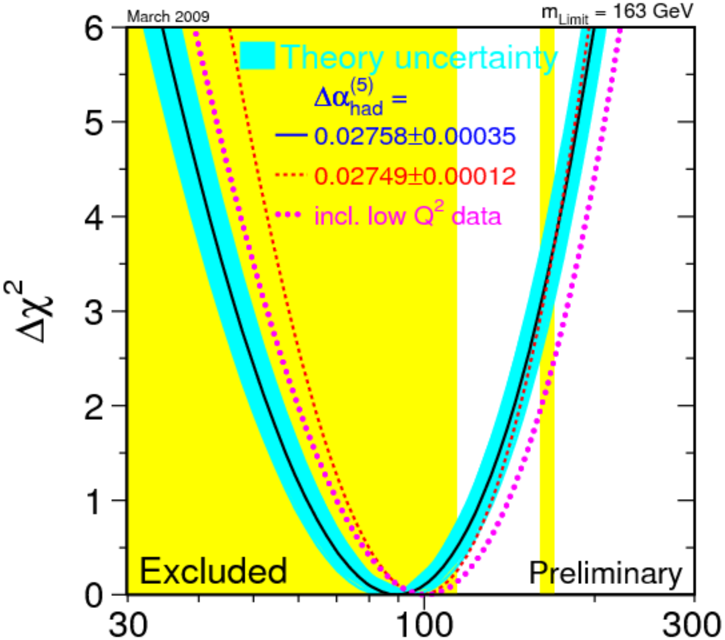
$$\frac{x-1}{\log(x)} \;\geq\; \frac{16\pi v^2 - 3m_-^2}{3m_-^2\,\log(m_{up}^2/m_-^2)}.$$

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

$$\frac{x-1}{\log(x)} \;\geq\; \frac{16\pi v^2 - 3(1-f)m_-^2 - 3\;fm_{LHC}^2}{3m_-^2\,(\log(m_{up}^2/m_-^2) - f\log(m_{LHC}^2/m_-^2))}.$$

f_{LHC}	m_+ (GeV)	Γ_+ (GeV)	$sin^2(\alpha)$ (%)
0.0	3285	1623	9.3
0.1	3337	1648	9.0
0.2	3391	1674	8.7
0.3	3448	1702	8.4
0.4	3508	1731	8.1
0.5	3571	1762	7.8
0.6	3636	1794	7.6
0.7	3705	1827	7.3
0.8	3778	1862	7.0
0.9	3854	1900	6.7
1.0	∞	∞	0.0

RESERVE



March 2009
m_Limit = 163 GeV
6
5
4
3
2
1
0
Δχ²
Theory uncertainty
Δα_had^(5) =
0.02758±0.00035
0.02749±0.00012
incl. low Q² data
Excluded
Preliminary
30
100
300

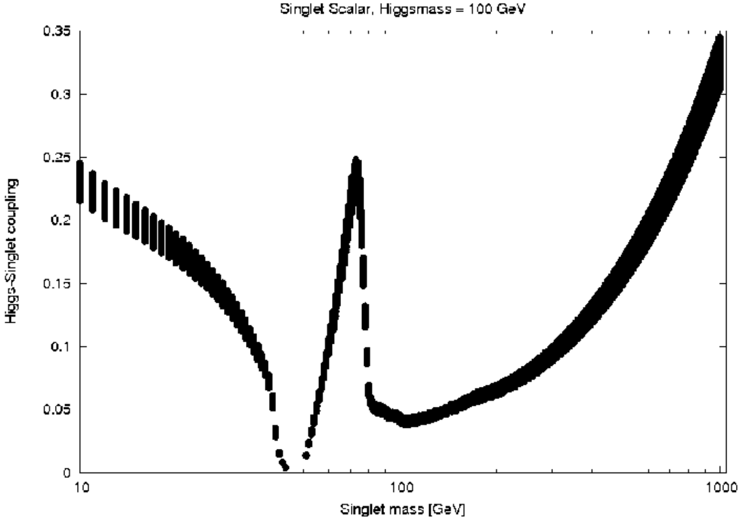
Stealth model (with T. Binoth)†.

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 $\Rightarrow$ dark matter.

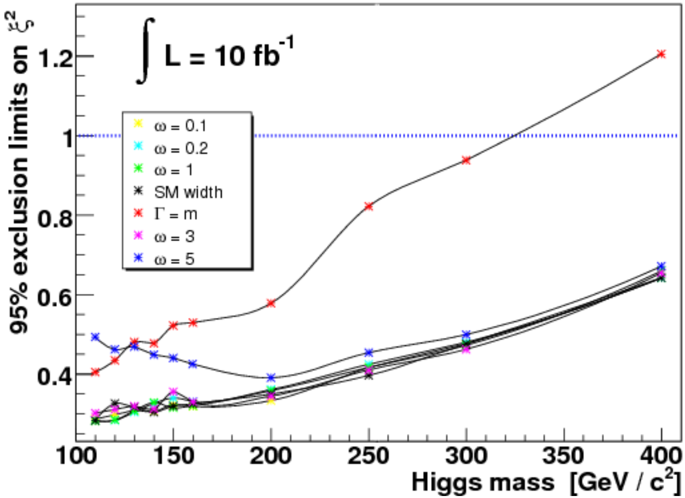

Singlet Scalar, Higgsmass = 100 GeV
Higgs-Singlet coupling
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10
100
1000
Singlet mass [GeV]

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}
ω = 0.1
ω = 0.2
ω = 1
SM width
Γ = m
ω = 3
ω = 5
95% exclusion limits on ξ^2
1.2
1
0.8
0.6
0.4
100
150
200
250
300
350
400
Higgs mass [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 !