Considerations on the Standard Model and the Higgs sector

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Triangle meeting Utrecht-Paris-Rome (Utrecht 1979)

Already then it was clear that the standard model is basically right, but people were dissatisfied.

- Naturalness, G. 't Hooft
- Simplicity, M. Veltman
- ► Fixed point, J. Iliopoulos

Old physics

- No BSM particles at the LHC
- ► No new plavour physics at the LHC
- The Higgs field has been found
- Agreement with precision data

New physics

- Dark matter
- Sterile neutrino
- ► (g 2)_µ

Given the fact that the standard model appears to be right, the LHC has become a Higgs discovery machine and a null-experiment for everything else. One should therefore maybe stop telling that there should be some new physics just around the corner, because we do not like the standard model. Instead one should probably try to explain why one has the standard model and not some other gauge theory. In particular why does one have three generations?

Is there a reason for the choice of gauge group and representations?

Phys. Rev. D76, 121702 (R) (2007);

General Relativity and Gravitation 43, 2467 (2011).

I. Rabi: Who ordered that? on the discovery of the muon

A. Einstein: Did God have a choice when He created the world?

Principle

Gravity is a geometrical theory. The Einstein equations allow for different topologies. The matter fields live in these geometrical backgrounds. The matter equations should be consistent with any form of compactification of spacetime consistent with the Einstein equations.

This allows for topological anomalies that can constrain the matter content!

Suggested topology of the universe $M_3 \times S_1$

 S_1 The radius may be too large to see the topology at the present time However a preferred direction may be visible

There appears to be an allignment of low multipoles along a preferred axis in the data

This could be explained in an inflationary Bianchi-I model

Three dimensional gravity $\mathcal{L} = -(1/\kappa^2)\sqrt{g}R - \frac{i}{4\kappa^2\mu}\epsilon^{\mu\nu\lambda}(R_{\mu\nu ab}\omega_{\lambda}^{ab} + \frac{2}{3}\omega_{\mu a}^{b}\omega_{\nu b}^{c}\omega_{\lambda c}^{a}).$ $q_{gr} = \frac{6\pi}{\mu\kappa^2} \text{ must be integer}$

Renormalization

$$q_{gr}^{ren} = q_{gr}^0 + rac{1}{8} N_g \, \, sign(m_g) - rac{1}{16} \, N_f \, sign(m_f)$$

 N_g is the number of vector bosons N_f is the number of fermions

assume $q_{gr} = 0$ (Einstein equations) consistency: $N_f \mp 2N_g = 0 \mod(16)$

Stronger conditions

isotropization: $q_{gr}^{ren} = 0$

vectors and fermions separately consistent:

 $N_g = 0 \mod(8)$ $N_f = 0 \mod(16)$ In combination vectors SU(5): 24 fermions SO(10): 16

$$2\times 24 - 3\times 16 = 0$$

Basically unique if also:

- 1) fermions automatically anomaly free, i.e. no SU(n):
- 2) fermions in fundamental representation

Speculations

Symmetry breaking: SU(5) decomposition: $16 = 10 + \overline{5} + 1$.

$$\begin{array}{cccc} SU(3) \rightarrow +, & SU(2) \rightarrow -, & U(1) \rightarrow + \\ & 10 \rightarrow +, & \overline{5} \rightarrow -, & 1 \rightarrow - \\ 2 \times (8 - 3 + 1) - 3 \times (10 - 5 - 1) = 0 \\ \text{possible: } SU(5) \rightarrow SU(3) \times SU(2) \times U(1) \\ \text{impossible: } SU(5) \rightarrow SU(4) \times U(1) \end{array}$$

more conditions

2

- other compactifications
- underlying structure
- quantum gravity

SU(5) Unification

Extra fields are needed, but multiple of 16. Solution: a Dirac **24**. Unification is easy, both **F** and **D** term of SU(5) possible. Dark matter candidate. A Dirac triplet with mass 1.9 TeV.

Predictions from 2007 (present status)

- No new chiral fermions at the LHC (confirmed)
- No new vector bosons at the LHC (confirmed)
- Presence of a preferred direction in the universe (sort of confirmed, but wait for Planck).
 2013 with Planck results still sort of confirmed.

Rabi's question: who ordered that? Answer: the early universe.

Einstein's question: did God have a choice?

Answer: no, because He has to use perfect symmetry.

However the devil may have had something to do with the Higgs sector, which brings us to this conference. Therefore if there is new physics at all, the Higgs sector is the most promising.

However there is no new flavour physics and the precision tests agree with the standard model. Thus only singlet extensions are safe.

It is reasonable to expect singlet fields to be present in the scalar sector, after all they exist in the fermion and in the gauge sector. Moreover they are the extensions of the standard model with the smallest number of parameters.

Since singlets do not change the basic gauge structure of the standard model it is a matter of taste whether such extensions still belong to the standard model. One could call it the non-minimal standard model (NMSM).

What do we know?

- Vectorbosons exist \rightarrow a Higgs field exists.
- ▶ QFT is right → The Higgs field has a Källén-Lehmann spectral density.
- EW precision data \rightarrow the field is light.
- LHC data \rightarrow most of the spectral density is around 126 GeV.

This does not mean the full Higgs field consists of a single particle peak only.

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.

In praxis this means measuring the Higgs lineshape (width) and looking for further peaks with a smaller than standard model signal strength.

Extended standard model (with A. Hill)^{\dagger}.

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

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

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

INTERMEZZO ! COMMENTS ON STRONG INTERACTIONS

Strong interactions:

$$\cos^2(lpha)m_-^2+\sin^2(lpha)m_+^2\geq rac{8\pi\sqrt{2}}{3G_F}.$$

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 $m_{-} \approx 115$ GeV and $m_{up} \approx 152$ GeV (blue-band).

Combine, $x = m_+^2/m_-^2$: $\frac{x-1}{\log(x)} \ge \frac{16\pi v^2 - 3m_-^2}{3m_-^2 \log(m_{up}^2/m_-^2)}.$

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

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

f_{LHC}	m_+ (GeV)	Γ_+ (GeV)	$sin^2(\alpha)$ (%)
0.0	3503	1730	8.1
0.1	3565	1761	7.9
0.2	3630	1792	7.6
0.3	3699	1826	7.3
0.4	3771	1861	7.0
0.5	3847	1898	6.8
0.6	3927	1937	6.5
0.7	4013	1979	6.2
0.8	4103	2022	5.9
0,9	4199	2069	5.7
1.0	∞	∞	0.0

END INTERMEZZO CONCLUSION: NO STRONG INTERACTIONS!

Hint for experimentalists: use the Hill model for 95% confidence exlcusion plots for heavier Higgs masses.

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.

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

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:

$$L = -\frac{1}{2}D_{\mu}\Phi^{\dagger}D_{\mu}\Phi - \frac{M_{0}^{2}}{4}\Phi^{\dagger}\Phi - \frac{\lambda}{8}(\Phi^{\dagger}\Phi)^{2}$$
$$- \frac{1}{2}\sum(\partial_{\mu}H_{k})^{2} - \sum\frac{m_{k}^{2}}{2}H_{k}^{2}$$
$$- \frac{g}{2}\Phi^{\dagger}\Phi\sum H_{k} - \frac{\zeta}{2}\sum H_{i}H_{j}$$

 $m_k^2 = m^2 + m_\gamma^2 \vec{k}^2$, 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

$$D_{HH}(q^2) = \left(q^2 + M^2 - rac{\mu^{8-d}}{(q^2 + m^2)^{rac{6-d}{2}} \pm
u^{6-d}}
ight)^{-1}$$

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







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.

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

 $0.056 < g_{98}^2/g_{5M}^2 < 0.144$
 $m > 116 GeV$
 $\int_{(130)^2}^{\infty}
ho(s) ds < 0.1$









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



Center point of the fits

The two peak case.

- continuum close to peak
- peak plus continuum unresolved at 125 GeV
- asymmetric lineshape



Without the LEP data the pure continuum case is also possible.

Conclusion

- The Higgs field has 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 not completely fixed.

Caveats

Significance roughly 2.3 sigma for the LEP data.

Questions for the LHC

- Constrain the height of the peak
- Get an upper (better a lower) limit on the width
- Go down to 90 GeV
- Check the branching ratios
- Improve the upper limit for further peaks

Beyond the LHC: A Higgs factory

The question is : of what kind?

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 (SM width 4 MeV!)
- Theory: benchmark models
- Beam Strahlung: machine
- Resolution: detector
- Unfolding: analysis

ILC

A muon collider: Science fiction ?

A large circular collider: VLLC or TLEP!

 m_{higgs} around 126 GeV is close to a scale invariance near the Planck scale.

 $\lambda = 0; \ \beta_{\lambda} = 0.$

A possible instability of the vacuum can be easily corrected through the presence of the extra singlet fields. We assume a two-peak HEIDI model with $m_H = 126 GeV$.



Conclusion: Higher dimensions may be hidden in the Higgs lineshape!

Where is Heidi hiding ?

Heidi is hidden

in the high-D Higgs Hill !

RESERVE



 $\label{eq:stealthmodel} \begin{array}{l} \mbox{Stealthmodel} & \mbox{(with T. Binoth)}^\dagger. \\ \mbox{M(inimal)} & \mbox{N(on)} & \mbox{M(inimal)} & \mbox{S(tandard)} & \mbox{M(odel)} \end{array}$

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

 $\vec{\phi}$: N scalar fields; singlets under the standard model gauge group. O(N) symmetry unbroken \Rightarrow 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.

$$H \rightarrow \vec{\phi} \ \vec{\phi}$$
$$\Gamma_H = \frac{\omega^2 N}{64\pi^2} \frac{v^2}{m_H}$$

 $\omega^2~N$ 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.



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 !