Higgs Physics

Lecture 1

Fundamental Concepts

ÉCOLE DE PHYSIQUE
LES HOUCHES

Fundamental Concepts through an Illustrated History of the Standard Model

Trying to follow the thread starting from five decades ago

1864-1958 - Abelian theory of quantum electrodynamics

1933-1960 - Fermi model of weak interactions

1954 - Yang-Mills theories for gauge interactions...

Follow in retrospect the story of a person… like you, starting a PhD...

TOWARDS A UNIFIED THEORY - THREADS IN A TAPESTRY

SHELDON LEE GLASHOW
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In 1956, when I began doing theoretical physics, the study of elementary particles was like a patchwork quilt. Electrodynamics, weak interactions, and strong interactions were clearly separate disciplines, separately taught and separately studied. There was no coherent theory that described them all. Developments such as the observation of parity violation, the successes of quantum electrodynamics, the discovery of hadron resonances and the appearance of strangeness were well-defined parts of the picture, but they could not be easily fitted together.

1957-59 – Schwinger, Bludman and Glashow introduce W bosons for the weak charged currents…

…birth of the idea of unified picture for the electromagnetic and weak interaction in $SU(2)_L \times U(1)_Y$ …

… Although local gauge symmetry forbids gauge bosons and fermion masses.

Which wasn't a real show stopper as they could be boldly set by hand in the theory (Schwinger even explicitely mentionned the idea of mass generation through interaction with a non empty-vacuum Ann. Phys. **2** (1957) 407) :

> Schwinger, as early as 1956, believed that the weak and electromagnetic interactions should be combined together into a gauge theory. [9] The charged massive vector intermediary and the massless photon were to be the gauge mesons. As his student, I accepted this faith. In my 1958 Harvard thesis, I wrote: "It is of little value to have a potentially renormalizable theory of beta processes without the possibility of a renormalizable electrodynamics. We should care to suggest that a fully acceptable theory of these interactions may only be achieved if they are treated together. . ."

As Schwinger and Glashow stated very early the key point isn't really only the masses of gauge bosons but the renormalizability of the theory.

The classical picture of how the problem was solved nevertheless contains most of the predictions and consequences of the theory.

Spontaneous Symmetry Breaking (SSB) - Global Symmetry

The Goldstone theorem is where it all begun…

Massless scalars occur in a theory with SSB (or more accurately where the continuous symmetry is not apparent in the ground state).

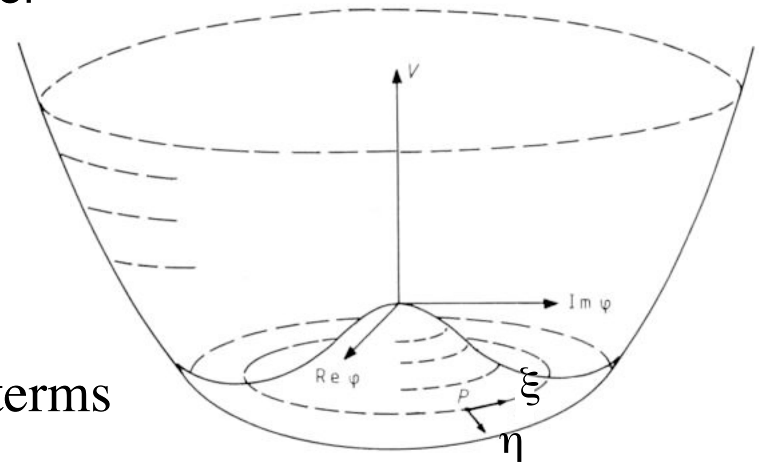
Le us illustrate it with a simple scalar theory with a symmetry U(1) :

$$\varphi = \frac{\phi_1 + i\phi_2}{\sqrt{2}} \qquad L = \partial_\nu \varphi^* \partial^\nu \varphi - V(\varphi) \qquad V(\varphi) = \mu^2 \varphi^* \varphi + \lambda (\varphi^* \varphi)^2$$

The Lagrangian is invariant under : $\varphi \to e^{i\alpha}\varphi$

$$v = -\frac{\mu^2}{\lambda}$$

Shape of the potential if $\mu^2<0$ and $\lambda>0$ necessary for SSB and be bounded from below.



Change frame to local minimum frame :

$$\varphi = \frac{v + \eta + i\xi}{\sqrt{2}}$$

No loss in generality.

$$L = \underbrace{\frac{1}{2}\partial_\nu \xi \partial^\nu \xi}_{\text{Massless scalar}} + \frac{1}{2}\partial_\nu \eta \partial^\nu \eta + \mu^2 \eta^2 + \text{interaction terms}$$

Nice but what should we do with these massless salars?

Digression on Chiral Symmetry

In the massless quarks approximation : $SU(2)_L x SU(2)_R$ v.i.z. the chiral symmetry is an (approximate) global symmetry of QCD

While conserving the diagonal group $SU(2)_V$ symmetry, the chiral symmetry is broken by means of coherent states of quarks (which play a role similar to the cooper pairs in the BCS superconductivity theory)

$$SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_V$$

It is thus a Dynamical Symmetry Breaking where the pseudo-goldstone bosons are the π^+,π^0,π^- mesons

This is the basis of the construction of an effective field theory ChPT allowing for calculations strong interaction calculations at rather low energy

Spontaneous Symmetry Breaking (SSB) - Local Symmetry

Those who answered this question… in the same PRL issue

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

2 pages

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

1 page

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

2 pages

1964 –The Higgs mechanism : How gauge bosons can acquire a mass.

Spontaneous Symmetry Breaking (SSB) - Local Symmetry

Let the aforementioned continuous symmetry U(1) be local :

α(x) now depends on the space-time x.

$$\varphi \rightarrow e^{i\alpha(x)}\varphi$$

The Lagrangian can now be written : $L = (D_\nu \varphi)^* D^\nu \varphi - V(\varphi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$

In terms of the covariant derivative : $D_\nu = \partial_\nu - ieA_\nu$

The gauge invariant field strength tensor : $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$

And the Higgs potential : $V(\varphi) = \mu^2 \varphi^* \varphi + \lambda(\varphi^* \varphi)^2$

Here the gauge field transforms as : $A_\mu \rightarrow A_\mu + \frac{1}{e}\partial_\mu \alpha$

Again translate to local minimum frame : $\varphi = \dfrac{v + \eta + i\xi}{\sqrt{2}}$

$$L = \frac{1}{2}\partial_\nu \xi \partial^\nu \xi + \frac{1}{2}\partial_\nu \eta \partial^\nu \eta + \mu^2 \eta^2 - v^2 \lambda \eta^2 + \frac{1}{2}\underbrace{e^2 v^2 A_\mu A^\mu} - evA_\mu \partial^\mu \xi - F^{\mu\nu} F_{\mu\nu} + \mathrm{ITs}$$

Mass term for the gauge field! But…

What about the field content?

A massless Goldstone boson ξ, a massive scalar η and a $\underbrace{\text{massive gauge boson!}}$

Number of d.o.f. : 1 1 3

Number of initial d.o.f. : 4 Oooops… Problem!

But wait! Halzen & Martin p. 326 The term $evA_\mu \partial^\mu \xi$ is unphysical

The Lagrangian should be re-written using a more appropriate expression of the translated scalar field choosing a particular gauge where h(x) is real :

$$\varphi = (v + h(x))e^{i\frac{\theta(x)}{v}}$$

Gauge fixed to absorb θ

Then the gauge transformations are : $\varphi \rightarrow e^{-i\frac{\theta(x)}{v}}\varphi \qquad A_\mu \rightarrow A_\mu + \frac{1}{ev}\partial_\mu \theta$

$$L = \frac{1}{2}\partial_\nu h \partial^\nu h - \lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4$$ Massive scalar : The Higgs boson

$$+(1/2)e^2 v^2 A_\mu A^\mu - F^{\mu\nu}F_{\mu\nu}$$ Massive gauge boson

$$+(1/2)e^2 A_\mu A^\mu h^2 + ve^2 A_\mu A^\mu h$$ Gauge-Higgs interaction

The Goldstone boson does not appear anymore in the Lagrangian

1968 – Glashow, Salam and Weinberg : Electroweak theory. Introduce two yet undiscovered particles : the Z and Higgs boson.

2 pages

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L=[\tfrac{1}{2}(1+\gamma_5)]\binom{\nu_e}{e} \qquad (1)$$

and on a right-hande

$$R=[\tfrac{1}{2}(1-\gamma_5)]e. \qquad (2)$$

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ cou

and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec{T}$ and Y gauge transformations is

The conclusions of the paper…

Is this model renormalizable? We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our Z_μ and W_μ mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning. Indeed, the model Lagrangian we start from is probably renormalizable

Of course our model has too many arbitrary features for these predictions to be taken very seriously

Milestone PRL 1967

The Weinberg Salam model (classical)

Before applying the Higgs mechanism to the $SU(2)_L$ x U(1) gauge symmetry

Let us have a short discussion on the fundamental choice of the gauge group is needed

Why $SU(2)_L$ x U(1) ? And not $SU(2)_L$ only?

In order to describe the weak and electromagnetic interactions with a unique gauge group, Q the photon should be among the three generators of $SU(2)_L$

… then the electric charges of the multiplets must add up to 0. Which is not the case for the simple electron-neutrino doublet.

The ways out are$_{\text{Cheng and Li p.341}}$:

(i) Add an additional U(1) thus introducing an additional gauge boson

(ii) Add new fermions to form a triplet with charges adding up to 0

Georgi and Glashow followed (ii) in 1972 but their model was ruled out later in 1973 by a major discovery…

Let us follow (i)…

Assuming a third weak gauge boson the initial number of gauge boson d.o.f. is 8, to give mass to three gauge bosons at least one doublet of scalar fields is necessary (4 d.o.f.) :

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^o \end{pmatrix}$$

Setting aside the gauge kinematic terms the Lagrangian can be written :

$$\mathcal{L} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi) \qquad \begin{cases} D_\mu = \partial_\mu - ig\vec{W}_\mu . \vec{\sigma} - ig' \frac{Y}{2} B_\mu \\ V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \end{cases}$$

Then by developing the Lagrangian near its non null VEV : $< \phi >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

Choosing the specific real direction of charge 0 of the doublet :

$$\phi = e^{-i\vec{\sigma}.\vec{\xi}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix}$$

Again choosing the gauge that will absorb the Goldstone bosons ξ...

Then developing the covariant derivative for the Higgs field :

Just replacing the Pauli matrices :

$$D_\mu\varphi = \partial_\mu\varphi - \frac{i}{2}\begin{pmatrix} gW_\mu^3 + g'B_\mu & g(W_\mu^1 - iW_\mu^2) \\ g(W_\mu^1 + iW_\mu^2) & -gW_\mu^3 + g'B_\mu \end{pmatrix}\varphi$$

Then using : $W_\mu^\pm = \dfrac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}}$

$$D_\mu\varphi = \partial_\mu\varphi - \frac{i}{2}\begin{pmatrix} gW_\mu^3 + g'B_\mu & \sqrt{2}gW_\mu^+ \\ \sqrt{2}gW_\mu^- & -gW_\mu^3 + g'B_\mu \end{pmatrix}\varphi = \begin{pmatrix} 0 \\ \partial_\mu h \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \sqrt{2}gvW_\mu^+ + \sqrt{2}ghW_\mu^+ \\ -gvW_\mu^3 + g'vB_\mu - ghW_\mu^3 + g'hB_\mu \end{pmatrix}$$

For the mass terms only :

$$(D_\mu\varphi)^+ D^\mu\varphi = \partial_\mu h\partial^\mu h + \frac{1}{4}g^2v^2W_\mu^+W^{-\mu} + \frac{1}{8}(W_\mu^3 \quad B_\mu)\begin{pmatrix} g^2v^2 & -gg'v^2 \\ -gg'v^2 & g'^2v^2 \end{pmatrix}\begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix}$$

Explicit mixing of W^3 and B.

Finaly the full Lagrangian will then be written :

$$\mathcal{L} = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4}H^4$$ Massive scalar : The Higgs boson

$$+ \frac{1}{2}\left[\frac{g'^2 v^2}{4}B_\mu B^\mu - \frac{g g' v^2}{2}W_\mu^3 B^\mu + \frac{g^2 v^2}{4}\vec{W}_\mu.\vec{W}^\mu\right]$$ Massive gauge bosons

$$\left.\begin{aligned} &+ \frac{1}{v}\left[\frac{g'^2 v^2}{4}B_\mu B^\mu H - \frac{g g' v^2}{2}W_\mu^3 B^\mu H + \frac{g^2 v^2}{4}\vec{W}_\mu.\vec{W}^\mu H\right] \\ &+ \frac{1}{2v^2}\left[\frac{g'^2 v^2}{4}B_\mu B^\mu H^2 - \frac{g g' v^2}{2}W_\mu^3 B^\mu H^2 + \frac{g^2 v^2}{4}\vec{W}_\mu.\vec{W}^\mu H^2\right] \end{aligned}\right\}$$ Gauge-Higgs interaction

In order to derive the mass eigenstates :

Diagonalize the mass matrix $\frac{1}{4}\begin{pmatrix} g^2 v^2 & -g g' v^2 \\ -g g' v^2 & g'^2 v^2 \end{pmatrix} = \mathcal{M}^{-1}\begin{pmatrix} m_Z^2 & 0 \\ 0 & 0 \end{pmatrix}\mathcal{M}$

Where

$$\mathcal{M} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \qquad \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}} \qquad \cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}}$$

The Weinberg angle was actually first introduced by Glashow (1960)

The first very important consequences of this mechanism :

1.- Two massive charged vector bosons :

$$m_W^2 = \frac{g^2 v^2}{4}$$

Corresponding to the observed charged currents

Thus v = 246 GeV

Given the known W mass and g coupling

2.- One massless vector boson : $m_\gamma = 0$

The photon correponding to the unbroken $U(1)_{EM}$

3.- One massive neutral vector boson Z :

$$m_Z^2 = (g^2 + g'^2) v^2 / 4$$

4.- One massive scalar particle : The Higgs boson

Whose mass is an unknown parameter of the theory as the quartic coupling λ

$$m_H^2 = \frac{4\lambda(v) m_W^2}{g^2}$$

Which of these consequences are actually predictions ?

1.- The theory was chosen in order to describ the weak interactions mediated by charged currents.

2.- The masslessness of the photon is a consequence of the choice of developing the Higgs field in the neutral and real part of the doublet.

3 & 4.- The appearance of massive Z and Higgs bosons are actually predictions of the model.

One additional very important prediction which was not explicitly stated in Weinberg's fundamental paper… although it was implicitly clear :

There is a relation between the ratio of the masses and that of the couplings of gauge bosons :

$$\frac{M_W}{M_Z} = \frac{g^2}{g^2 + g'^2} = \cos^2\theta_W$$

or

$$\boxed{\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1}$$

The sector of Fermions (Fermionic neutral current)

Taking a closer look at the neutral current interaction part of the Lagrangian :

$$L_L = -\frac{1}{2}\overline{\psi}_L\gamma_\mu\begin{pmatrix} gW_3^\mu + \widehat{g}_L B^\mu & 0 \\ 0 & -gW_3^\mu + \widehat{g}_L B^\mu \end{pmatrix}\psi_L \qquad L_R = -\frac{1}{2}\overline{\psi}_R\gamma_\mu\begin{pmatrix} \widehat{g}_L B^\mu & 0 \\ 0 & 0 \end{pmatrix}\psi_R$$

In the lepton sector :

$$\begin{aligned} -2L_{NC}^{leptons} &= \overline{\nu}_L\gamma_\mu\left[(c_W g - s_W\widehat{g}_L)Z^\mu + (s_W g + c_W\widehat{g}_L)A^\mu\right]\nu_L \\ &+ \overline{e}_L\left[(-c_W g - s_W\widehat{g}_L)Z^\mu + (-s_W g + c_W\widehat{g}_L)A^\mu\right]e_L \\ &+ \overline{e}_R\gamma_\mu\left[-s_W\widehat{g}_R Z^\mu + c_W\widehat{g}_R A^\mu\right]e_R \end{aligned}$$

1.- Eliminate neutrino coupling to the photon : $g\sin\theta_W = -\widehat{g}_L\cos\theta_W$

2.- Same coupling e_R and e_L to the photon : $\widehat{g}_R = 2\widehat{g}_L$

3.- Link to the EM coupling constant *e* : $g\sin\theta_W = e$

4.- Absorb the inelegant notation $\widehat{g}_R$ and $\widehat{g}_L$ by : $\widehat{g}_R = Y_R g' \qquad \widehat{g}_L = Y_L g'$

Y the hypercharge is chosen to verify the Gell-Mann Nishijima formula : $Q = I_3 + \frac{Y}{2}$

The picture is now almost complete…

	Field	I_3	Y	Q	$SU(2)_L x U(1)_Y$	$SU(3)_C$
Leptons	(ν_L, e_L)	(1/2,-1/2)	-1	(0,-1)	(2,-1)	1
	e_R	0	-2	-1	(1,-2)	1
Quarks	(u_L, d_L)	(1/2,-1/2)	-1	(2/3,-1/3)	(2,1/3)	3
	u_R	0	4/3	2/3	(1,4/3)	$\bar{3}$
	d_R	0	-2/3	-1/3	(1,-2/3)	$\bar{3}$
IVB	B	0	0	-	(1,0)	1
	W	(1,0,-1)	0	-	(3,0)	1
	g	0	0	-	(1,0)	8
Higgs	H	(1/2,-1/2)	1	-	(2,1)	1

The Minimal Standard Model

Jean Iliopoulos

The sector of Fermions (kinematic)

Another important consequence of the Weinberg Salam Model :

A specific $SU(2)_L x U(1)_Y$ problem : $m\overline{\psi}\psi$ manifestly not gauge invariant

$$m\overline{\psi}\psi = m\overline{\psi}(\frac{1}{2}(1-\gamma^5) + \frac{1}{2}(1+\gamma^5))\psi = m(\overline{\psi}_R\psi_L + \overline{\psi}_L\psi_R)$$

- neither under $SU(2)_L$ doublet and singlet terms together
- nor under $U(1)_Y$ do not have the same hypercharge

Fermion mass terms are forbidden

Not the case when using Yukawa couplings to the Higgs doublet

Then after SSB one recovers :

$$\frac{\lambda_\psi v}{\sqrt{2}}\overline{\psi}\psi + \frac{\lambda_\psi}{\sqrt{2}}H\overline{\psi}\psi$$

Which is invariant under $U(1)_{EM}$

Very important : The Higgs mechanism DOES NOT predict fermion masses

…Yet the coupling of the Higgs to fermions is proportional to their masses

The Weinberg Salam model (quantum)

Renormalizability of the Weinberg Salam Model : 't Hooft and Veltman 1971

Again, in 1970, Iliopoulos and I showed that a wide class of divergences that might be expected would cancel in such a gauge theory.[19] We showed that the naive divergences of order $(\alpha\Lambda^4)^n$ were reduced to "merely" $(\alpha\Lambda^2)^n$, where Λ is a cut-off momentum. This is probably the most difficult theorem that Iliopoulos or I had even proven. Yet, our labors were in vain. In the spring of 1971, Veltman informed us that his student Gerhart 't Hooft had established the renormalizability of spontaneously broken gauge theory.

In pursuit of renormalizability, I had worked diligently but I completely missed the boat. The gauge symmetry is an exact symmetry, but it is hidden. One must not put in mass terms by hand. The key to the problem is the idea of spontaneous symmetry breakdown: the work of Goldstone as extended to gauge theories by Higgs and Kibble in 1964.[20] These workers never thought to apply their work on formal field theory to a phenomenologically relevant model. I had had many conversations with Goldstone and Higgs in 1960. Did I neglect to tell them about my SU (2)xU (1) model, or did they simply forget?

Sheldon Glashow… (Nobel Lecture)

<u>Key thread in the tapestry...</u>   <u>But still some pieces missing</u>

The experimental crowning glory of the model

1973 - Discovery of neutral currents in neutrino interactions

1974 - Discovery of the c quark

1975 - Discovery of the tau lepton

1977 - Discovery of the b quark

1979 - Discovery of the gluon

1983 - Discovery of the W and Z bosons

1990 - Determination of the number of light neutrino families

1991 - Precise tests of the internal coherence of the theory and top mass prediction

1993 - Top quark discovery

$\boxed{\rho \text{ measured} = 1}$

$\text{Wilczek}_{\text{LEP celebration}}$: The Higgs mechanism is corroborated at 75%

When I was a pre-doctoral student like you… (previous century in the mid-nineties)

Our teacher FLDB told us that there are still four important discoveries to be made in the Standard Model

He then gave us the list in growing order of importance :

1.- Tau neutrino discovery — $\boxed{1998}$

2.- CP violation in the B system — $\boxed{2000}$

3.- Neutrino oscillations — $\boxed{1997}$

$\boxed{\text{4.- The discovery of the Higgs boson}}$

Custodial Symmetry

Turning again to the chiral symmetry which is also a symmetry of the Higgs sector :

$$SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_V$$

It is very interesting to note that under the $SU(2)_V$ symmetry, the weak gauge bosons (W^1,W^2,W^3) transform as a triplet

Meaning that after EWSB all W^i's are mass degenerate

This directly implies that ρ=1

Under this crutial condition does any Higgs sector work for this purpose?

For N iso-multiplets :
$$\rho = \frac{\sum_{k=1}^{N} v_k^2[I^k(I^k+1) - (I_3^k)^2]}{\sum_{k=1}^{N} 2v_k^2(I_3^k)^2}$$

For the condition to be fulfilled either need any number of doublets is fine

Higher representations need to fine tune the vevs

Dynamical Symmetry Breaking and Technicolor

Turning yet once again to the chiral symmetry which is also a symmetry of the Higgs sector :

$$SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_V$$

Could the pions dynamicaly break the EW symmetry?

Nice - Custodial symmetry protects $\rho = 1$

No
- Disappear from the physical spectrum (longitudinal components of gauge bosons)
- insufficient mass generaion e.g. : m_W = 30 MeV (vev too small, set for pion interactions)

In order to generate sufficiently high gauge boson masses with a dynamical EWSB, need :

Technicolor
- Additional fermions
- Larger group : strong interaction at EW scale

No fundamental scalars in the theory as the EWSB is dynamically done by fermion condensates… (very appealing)

Most simple models of technicolor are disfavored by EW precision data

What have we learned?

Higgs mechanism

- Allows gauge bosons to acquire a mass
- Allows fermion masses
- Interpretation of EW interactions (not unification)
- Enables renormalizability of EW gauge theory

Legitimates $SU(2)_L xU(1)_Y$ as a gauge theory of electroweak interaction which is now known as the Standard Model

In other words : all known processes can be calculated in this framework

It predicts $\rho = 1$ which has been measured

Predicts the existence of a Higgs boson which is still not discovered

At this Point What is there Still to be Learned?

Is there a reason why is μ^2 negative?

What could explain the flavor mass hierarchy?

Does the Higgs boson exist?

Digression on the origin of Mass

- Gallilean and Newtonian concept of mass :

$$\underbrace{\text{Inertial mass (F=ma)} \qquad \text{Gravitational mass (P=mg)}}_{\text{Single concept of mass}}$$

Conserved intrinsic property of matter where the total mass of a system is the sum of its constituents

- Einstein : Does the mass of a system depend of its energy content?

Mass = rest energy of a system or $m_0=E/c^2$

  - Atomic level : binding energy ~O(10eV) which is ~10^{-8} of the mass
  - Nuclear level : binding energy ~2% of the mass
  - Nucleus parton level : binding energy ~98% of the mass

Most of the (luminous) mass in the universe comes from QCD confinement energy

- The insight of the Higgs mechanism :

New element in trying to understand the origin of mass of gauge bosons and fermions

Theoretical Constraints on The Higgs Boson Mass

Self consistency arguments to derive lower and upper Higgs boson mass boundaries

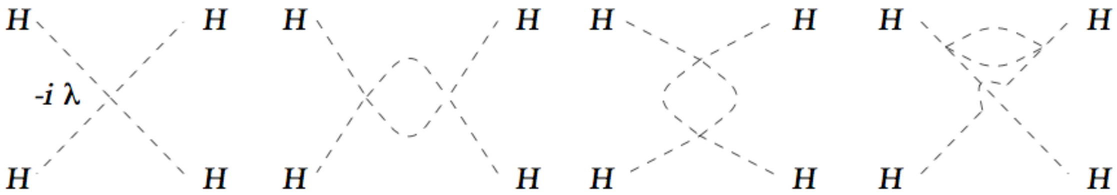
Running Quartic Coupling : Triviality

The (non exhaustive though rather complete) evolution of the quartic coupling :

$$32\pi^2 \frac{d\lambda}{dt} = \boxed{24\lambda^2} - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 24y_t^4 + \cdots$$

In the case where the Higgs mass is large (large λ) : $M_H^2 = 2\lambda v^2$

The first term of the equation is dominant and due to diagrams such as :



When integrated : $\lambda(Q) = \dfrac{\lambda(Q_0)}{1 - \frac{3}{4\pi^2}\lambda(Q_0)\ln\left(\frac{Q^2}{Q_0^2}\right)}$ A pole may appear at high Q

Triviality condition to avoid such pole : $1/\lambda(Q) > 0$

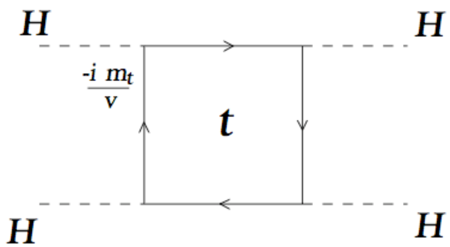
Then $$\boxed{M_H^2 < \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}}$$

Running Quartic Coupling : Vacuum stability

Looking closer into the limit where the Higgs boson mass is small :

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - \boxed{24y_t^4} + \cdots$$

The last term of the equation is dominant and due to diagrams such as :



$\sim \frac{m_t^4}{v^4}$

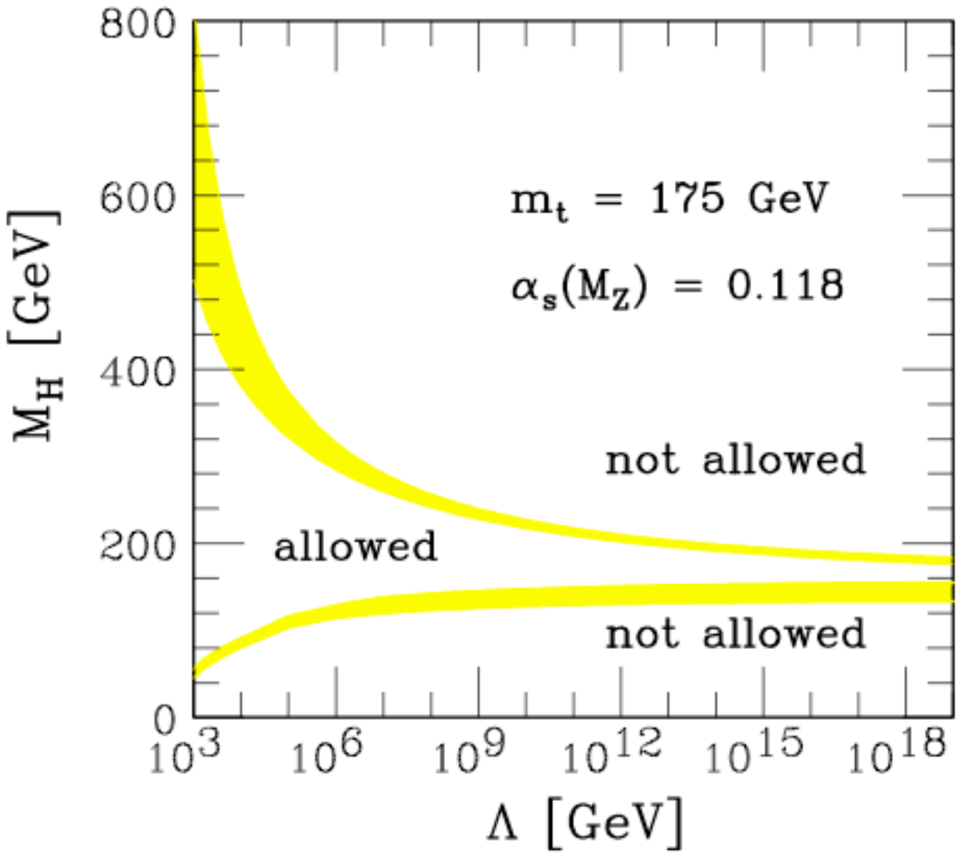
The equation is then very simply solved : $\lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2} y_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)$

Requiring that the solutions are stable (non-negative quartic coupling) :

$\lambda(\Lambda) > 0$ then $\boxed{M_H^2 > \frac{3v^2}{2\pi^2} y_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)}$

Vacuum Stability and Triviality Constraints Summary

More acurate analysis yields :



What do we learn from these constraints?

If a Higgs boson exists it should be found at LHC!

If it is very heavy new physics should occur at a low scale

If the SM is valid at any scale the Higgs mass is quite precisely predicted

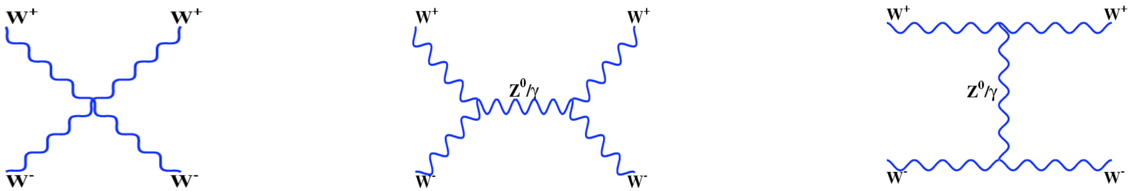
If the Higgs is rather light new physics should also be at a rather low energy

However it does not motivate the very existence of a Higgs boson…

Unitarity or why a Higgs Boson is Highly Desirable

The cross section for the thought scattering process :

$$W^+W^- \to W^+W^-$$



Does not preserve perturbative unitarity.

Introducing a Higgs boson ensures the unitarity of this process <u>PROVIDED</u> that its mass be smaller than :

$$\sqrt{4\pi\sqrt{2}/3G_F}$$ v.i.z. approximately 1 TeV

This is not only a motivation for the Higgs mechanism but is also a strong experimental constraint on its mass… if you believe in perturbative unitarity…

If you don't the electroweak interaction should become strong at the TeV scale and one would observe non perturbative effects such as multiple W production, WW resonances… (Technicolor…)

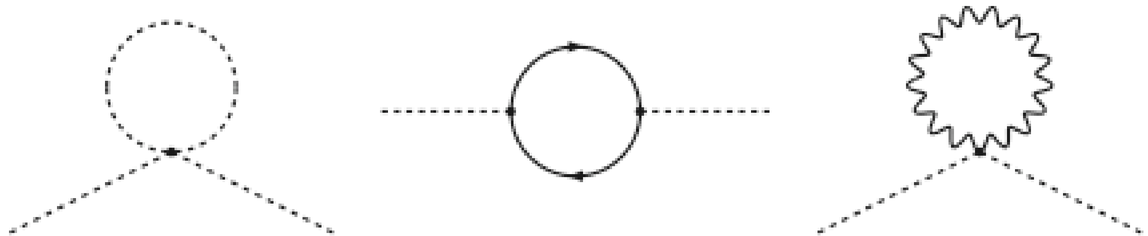
Gauge Hierarchy and Fine Tuning

How the Higgs boson may not only SOLVE problems

The Hierarchy Problem

The Higgs potential is fully renormalizable, but…

Loop corrections to the Higgs boson mass…



…are quadratically divergent : $$\Delta m^2 \propto \int^{\Lambda} \frac{d^4k}{(2\pi)^4} \frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi^2}$$

If the scale at which the standard model breaks down is large, the Higgs natural mass should be of the order of the cut-off. e.g. the Planck scale

$$m = m_0 + \Delta m + \ldots$$ Higher orders

…but if the Higgs boson exists it should have a low mass!

This will be possible by fine tuning your theory… Inelegant…

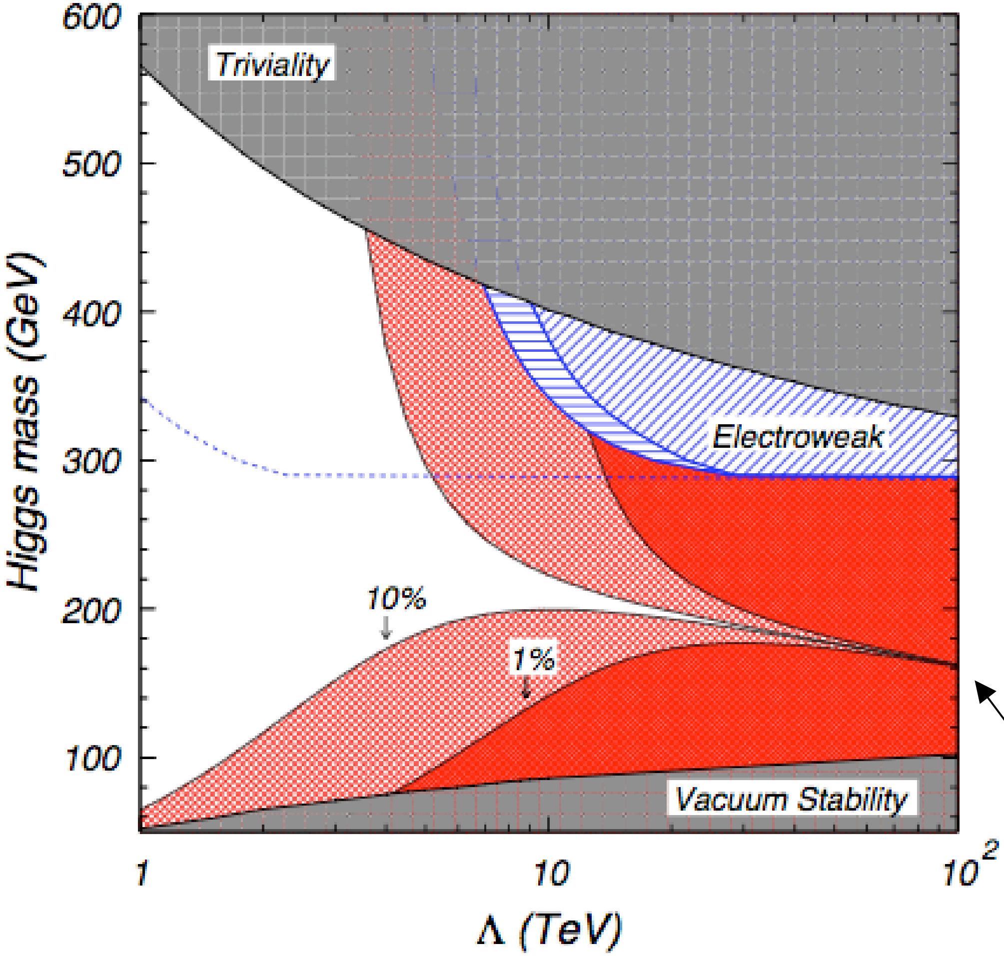
(you can note that technicolor models are not concerned by this problem)

Fine Tuning : can you leave with it?

Is fine tuning really necessary? The improved Veltman condition :

$$\bar{\mu}^2 = \mu^2 + \Lambda^2 \sum_{n=0}^{\infty} \underbrace{c_n(\lambda_i)\log^n(\Lambda/Q)}$$

Not if this vanishes…



At the essentially two loop level (n_{max}=1) the condition:

$$\sum_{n=0}^{n_{max}} c_n(\lambda_i)\log^n(\Lambda/m_h) = 0$$

Translates into Higgs mass limits when requiring a certain level of fine tuning :

$$\mathcal{F} \equiv \left|\frac{\delta m_W^2}{m_W^2}\right| = \left|\frac{\delta v^2}{v^2}\right| = \left|\frac{\delta \mu^2}{\mu^2}\right| = \left|\frac{\delta m_h^2}{m_h^2}\right|$$

$$= \frac{2\Lambda^2}{m_h^2}\left|\sum_n c_n \log^n(\Lambda/m_h)\right|$$

Large scale allowed?
(disfavored at HO)

Supersymmetry

The Hierarchy problem is not only a problem of esthetics : If the difference is imposed at tree level, the radiative corrections will still mix the scales and destabilize the theory.

One may note that :

$$\Delta m_H^2 \sim \frac{|\lambda_f|^2}{16\pi^2}(-2\Lambda^2 + 6m_f^2 \ln \frac{\Lambda}{m_f} + ...) \longrightarrow \text{Contribution of fermions}$$

$$\Delta m_H^2 \sim \frac{\lambda_s}{16\pi^2}(\Lambda^2 + 2m_f^2 \ln \frac{\Lambda}{m_s} + ...) \longrightarrow \text{Contribution of scalars}$$

Therefore a theory where for each fermions there are two scalar fields with $\lambda_s = |\lambda_f|^2$

(which is fulfilled if the scalars have the same couplings as the fermions)

Will not display quadratic divergencies

The field content of the standard model is not sufficient to fulfill this condition

A solution is given by supersymmetry where each fermionic degree of freedom has a symmetrical bosonic correspondence

In supersymmetry the quadratic divergences naturally disappear but…

Immediately a problem occurs : Supersymmetry imposes $m_{boson} = m_{fermion}$

Supersymmetry must be broken!

But in the case of SUSY an SSB mechanism is far more complex than for the EWSB no satisfactory SSB solution exists at this time…

…However an explicit breaking "by hand" is possible provided that it is softly done in order to preserves the SUSY good UV behavior…

$$\Delta m_H^2 \propto m_{soft}^2 (\ln \frac{\Lambda}{m_{soft}} + ...)$$

Interestingly similar relation to that of the general fine tuning one

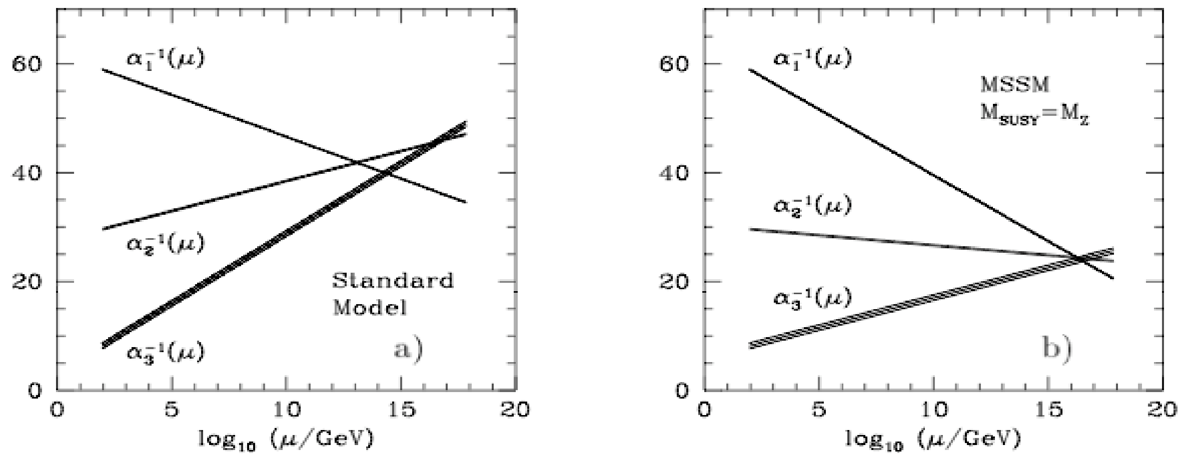
Implies that the m_{soft} should not exceed a few TeV

Many more details to come in S. Lavignac's presentation

The Minimal Supersymmetric Standard Model's Higgs Sector

In a tiny nut shell

Additional motivations for supersymmetry :
- Allows the unification of couplings
- Local SUSY: spin 3/2 gravitino (essential ingredient in strings)



The Higgs Sector : Two doubets with opposite hypercharges are needed to cancel anomalies (and to give masses independently to different isospin fermions)

What you should know :

- MSSM : 5 Higgs bosons
- Lightest mass < m_z at tree level and smaller than ~140 GeV/c^2 w/ rad. Corr.

The Higgs sector yields the strongest constraints on the MSSM

What have we learned

1.- A Higgs boson is highly desirable for the self consistency (unitarity) of the theory and should have a mass lower than about 1 TeV

2.- If it exists the running of the quartic coupling yields interesting bounds on its mass (triviality and vacuum stability)

3.- The existence of a Higgs boson is a key to investigate theories beyond the standard model (fine tuning)

4.- It highly motivates supersymmetry

5.- It even gives indication on the mass scale of SUSY particles

The Higgs mechanism is yielding way more than what it was initially introduced for