The Discovery of the Higgs Boson

New trends in Higgs Physics at LHC

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And CERN

HASCO Hadron Collider Physcis School

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

Disclaimer

The Higgs boson

“The” refers to the one discovered

Will use material from mainly all lectures

- General LHC detectors and physics (R. Schmidt, B. Clement, M. Weber and R. Schmidt)
  - Introduction to the Machine
  - The detectors
  - The Experimental challenges of object reconstruction in high PU
  - The Main processes at the LHC
- Elements of QCD and toolbox (S. Schumann and A. Robson)
  - Difficulties to compute predictions
  - How to compute certain processes
  - Jets
- Statistics (G. d'Agostini and L. Bellagamba)
  - How to compute a limit
  - What is the significance of an excess
- Electroweak Theory (V. Cavassini)
  - Construction of EW theory
  - Discovery of W and Z bosons at SPS
- Top physics (M. Owen)
- Introduction to SUSY and BSM (C. Clement and T. Lari)

2013 EPS-HEP Prize

European Physical Society
High Energy and Particle Physics Division

The 2013 High Energy and Particle Physics Prize, for an outstanding contribution to High Energy Physics, is awarded to the ATLAS and CMS collaborations, "for the discovery of a Higgs boson, as predicted by the Brout-Englert-Higgs mechanism", and to Michel Della Negra, Peter Jenni, and Tejinder Virdee, "for their pioneering and outstanding leadership rôles in the making of the ATLAS and CMS experiments".

HEP 2013
Stockholm
18-24 July 2013
(info@eps-hep2013.eu)

October 8, 2013…

?

Crowning of half a century of theoretical developments and Higgs Hunt ?

1964

Five pages that changed the course of the Standard Theory of particles…

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

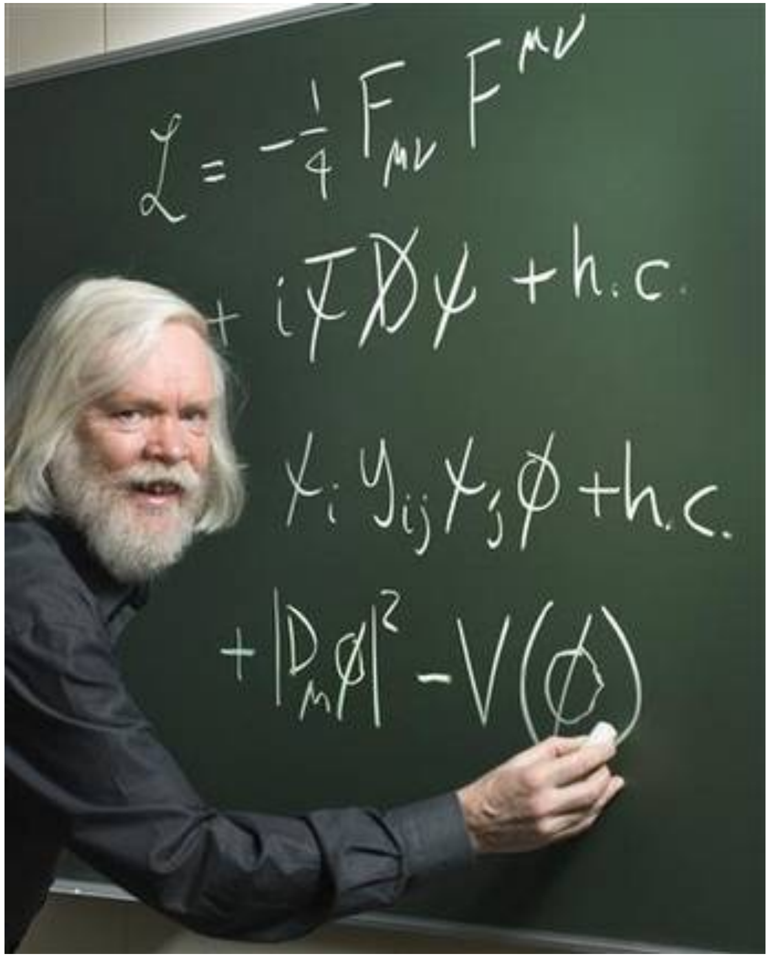
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

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



1976

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)
CERN -- Geneva

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

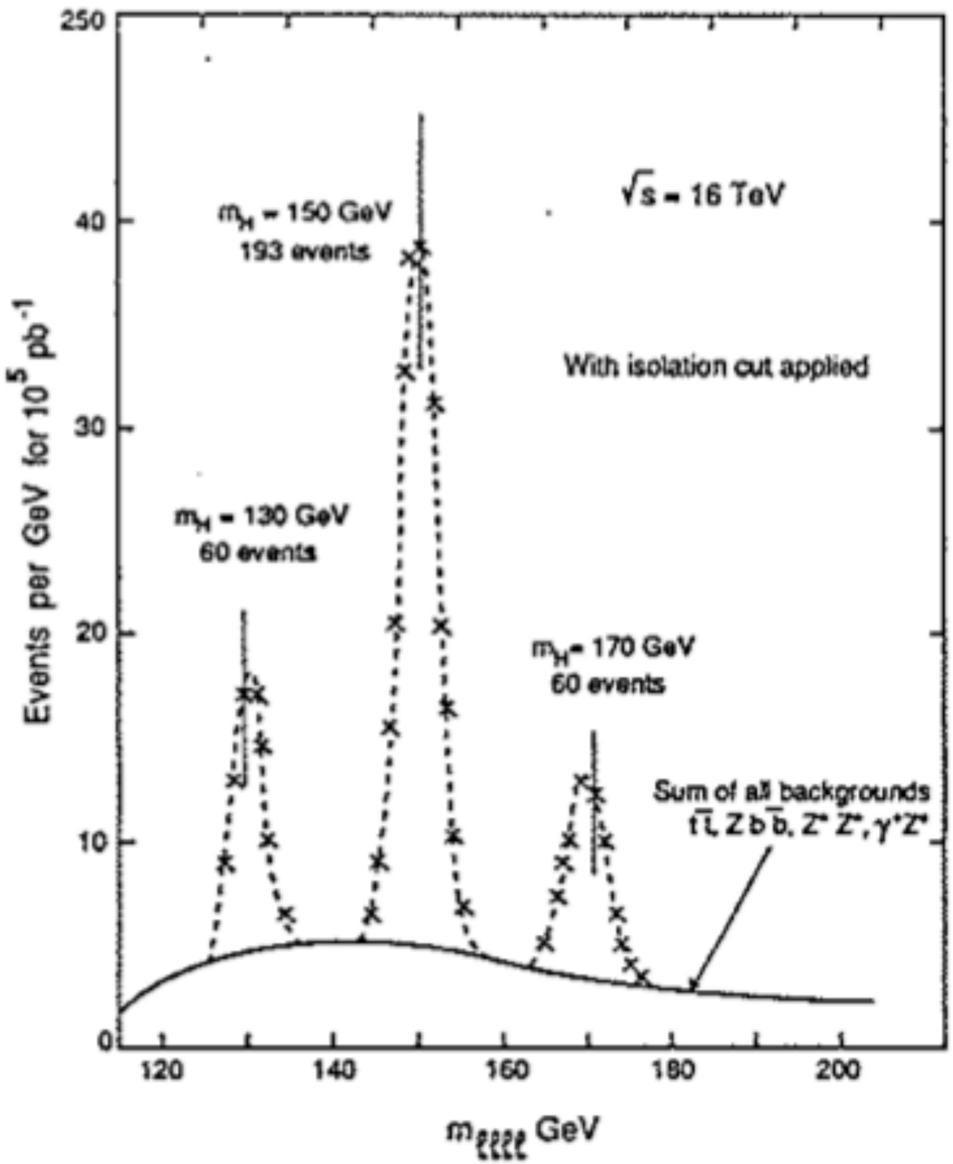
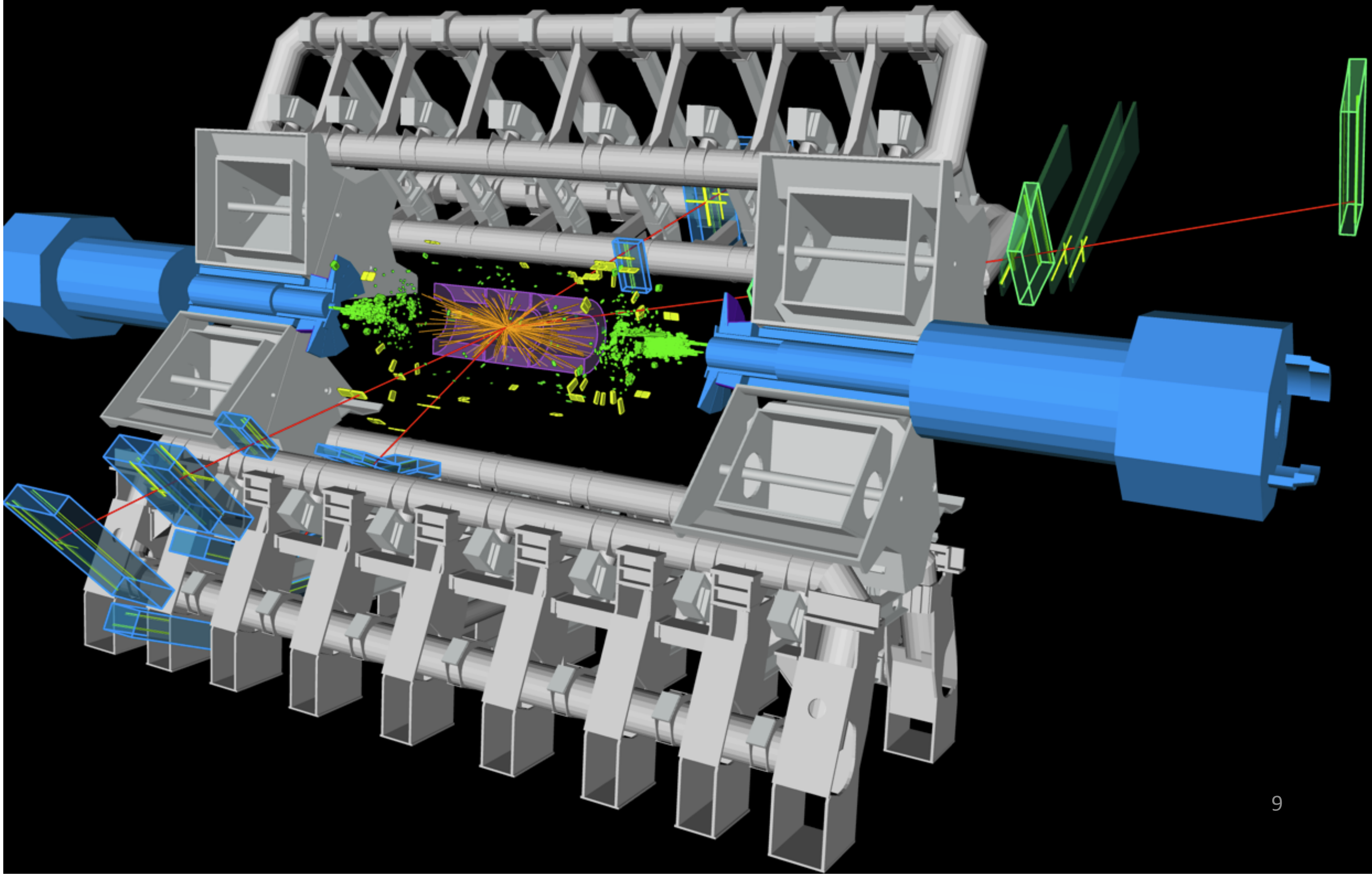


Fig. 10

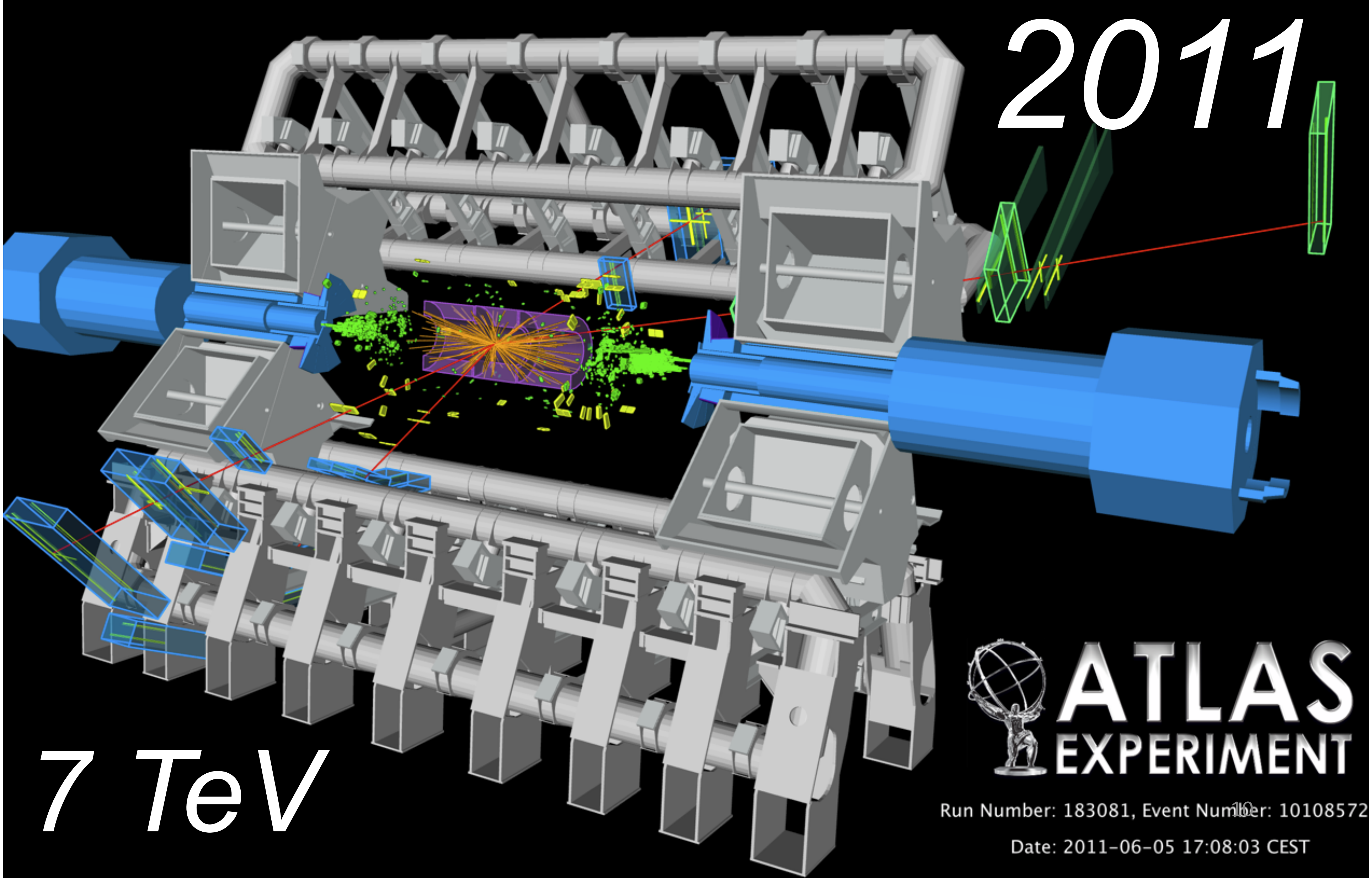
1990

Proceedings of LHC Workshop (Aachen, 1990): $\sqrt{s}$ = 16 TeV, 100 fb^{-1}

20 Years, projecting, constructing and Simulating…

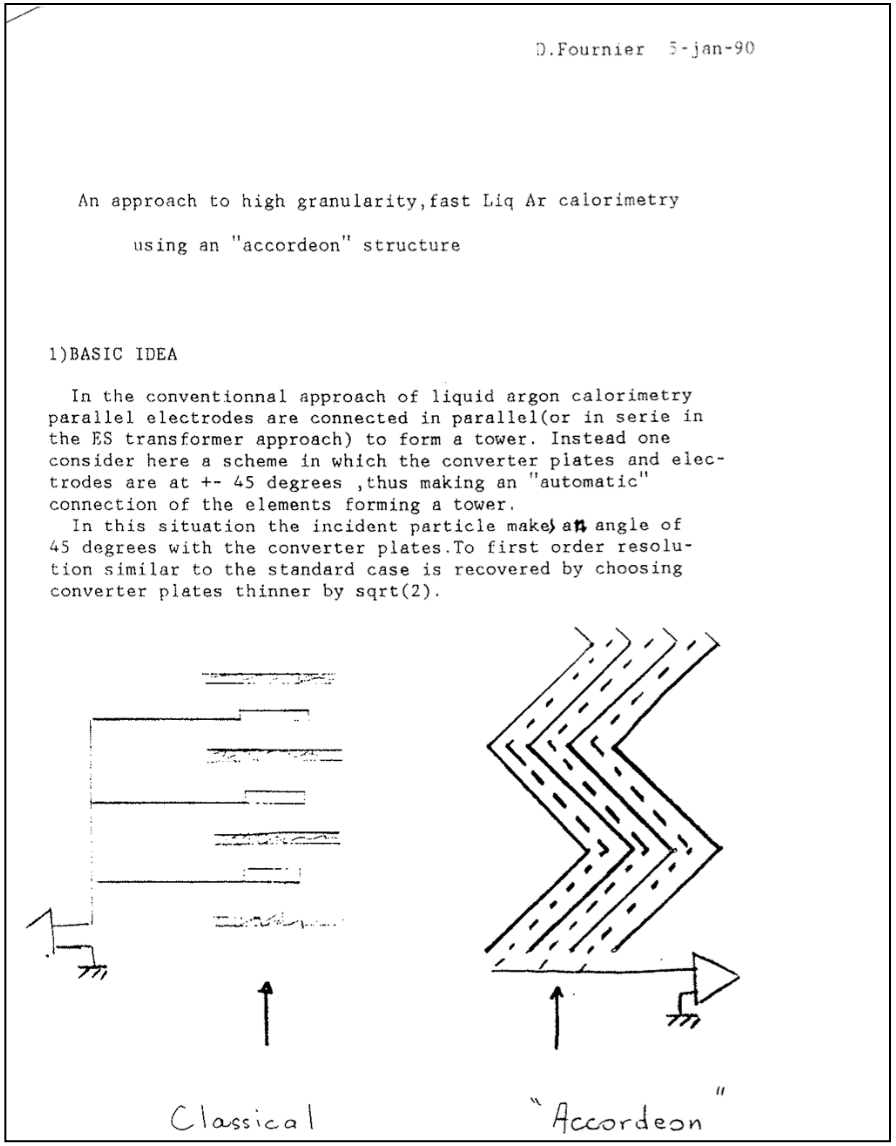


4 μ event … *Standard EW only or Higgs?*



ATLAS Electromagnetic Calorimeter

From RD3 to the LAr Calorimeter



D.Fournier 5-jan-90

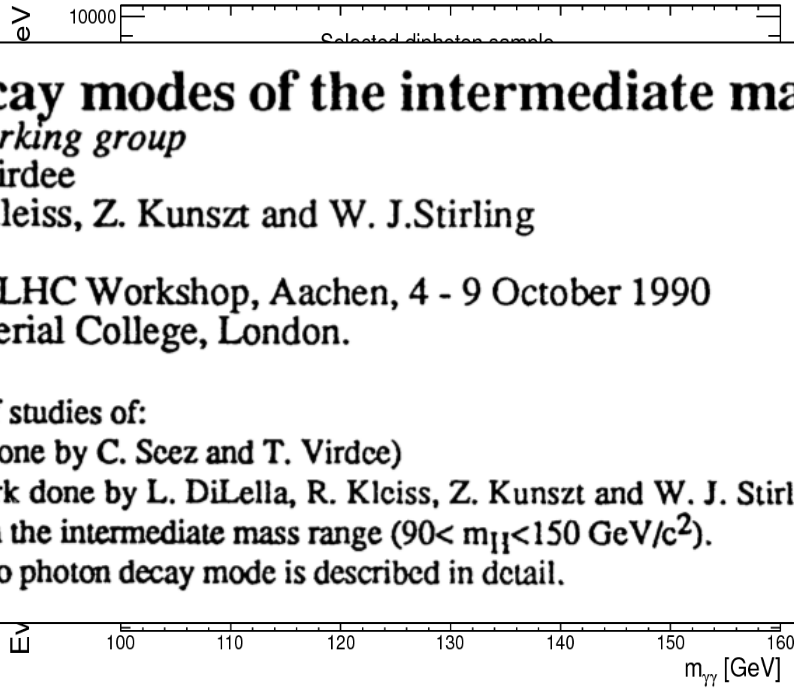
An approach to high granularity,fast Liq Ar calorimetry

using an "accordeon" structure

1)BASIC IDEA

In the conventionnal approach of liquid argon calorimetry parallel electrodes are connected in parallel(or in serie in the ES transformer approach) to form a tower. Instead one consider here a scheme in which the converter plates and electrodes are at +- 45 degrees ,thus making an "automatic" connection of the elements forming a tower.
In this situation the incident particle makes an angle of 45 degrees with the converter plates.To first order resolution similar to the standard case is recovered by choosing converter plates thinner by sqrt(2).

The Di-Photon Channel Historical Prospective



Photon decay modes of the intermediate mass Higgs

ECFA Higgs working group

C.Seez and T. Virdee

L. DiLella, R. Kleiss, Z. Kunszt and W. J.Stirling

Presented at the LHC Workshop, Aachen, 4 - 9 October 1990
by C. Seez, Imperial College, London.

A report is given of studies of:
(a) H -> $\gamma\gamma$ (work done by C. Seez and T. Virdee)
(b) W H -> $\gamma\gamma$ (work done by L. DiLella, R. Kleiss, Z. Kunszt and W. J. Stirling)
for Higgs bosons in the intermediate mass range (90< m_{H}<150 GeV/c^2).
The study of the two photon decay mode is described in detail.

1991 Analysis

Moriond 2013 Analysis

16 TeV, 100 fb^{-1}

7 - 8 TeV, ~25 fb^{-1}

First EAGLE (ATLAS) note

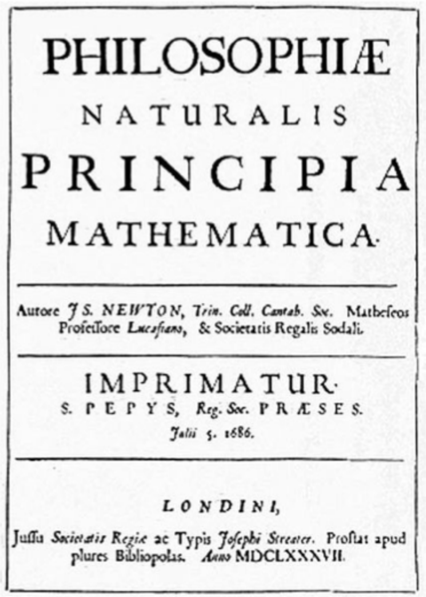
ATLAS diphoton channel

diphoton channel

L. Fayard
G. Unal
EAGLE Note
PHYSICS-NO-001
december 1991

July 4, 2012

… On the NY Times front Page!



Digression on the origin of Mass

- Gallilean and Newtonian concept of mass :

Inertial mass (F=ma) Gravitational mass (P=mg)

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 :

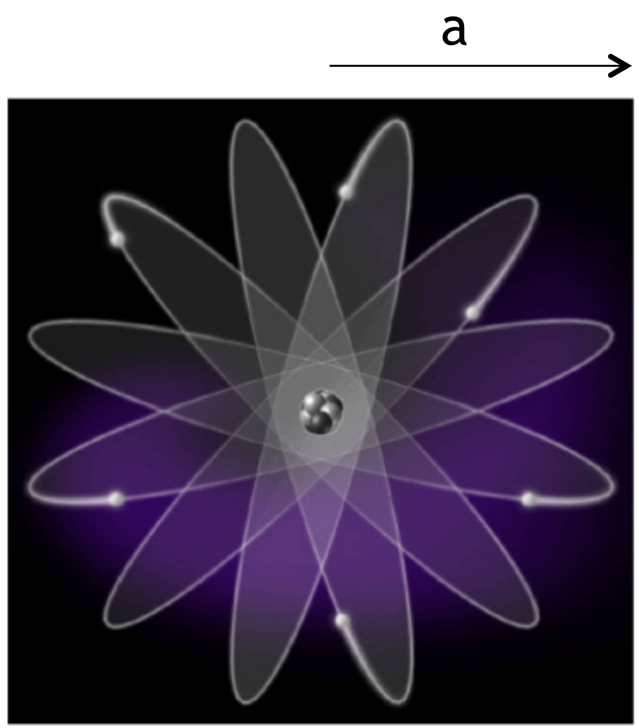
Understanding the origin of mass of gauge bosons and fermions

How Would it Be Without Elementary Particle Masses?

Electron mass (m_e = 511 keV)

Bohr Radius a = $1/(a_{EM}\ m_e)$ so :

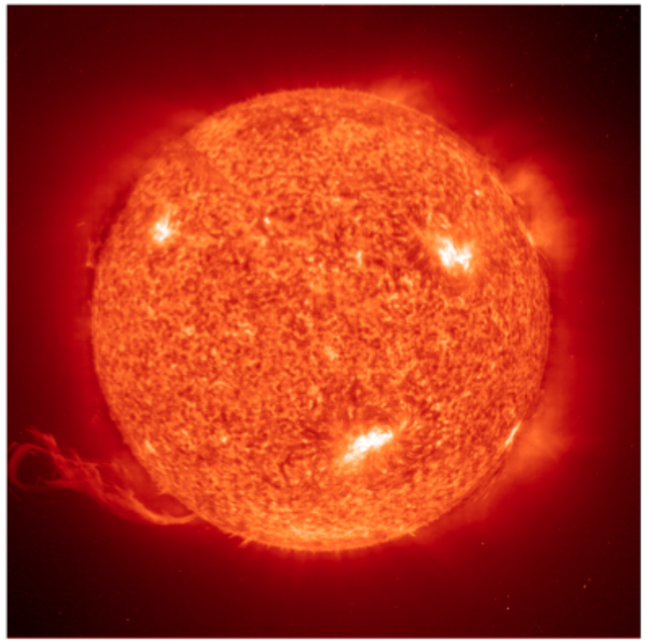
If m_e = 0 : Then no atomic binding



W boson mass (m_W = 81 GeV)

$$G_F \sim (M_W)^{-2}$$

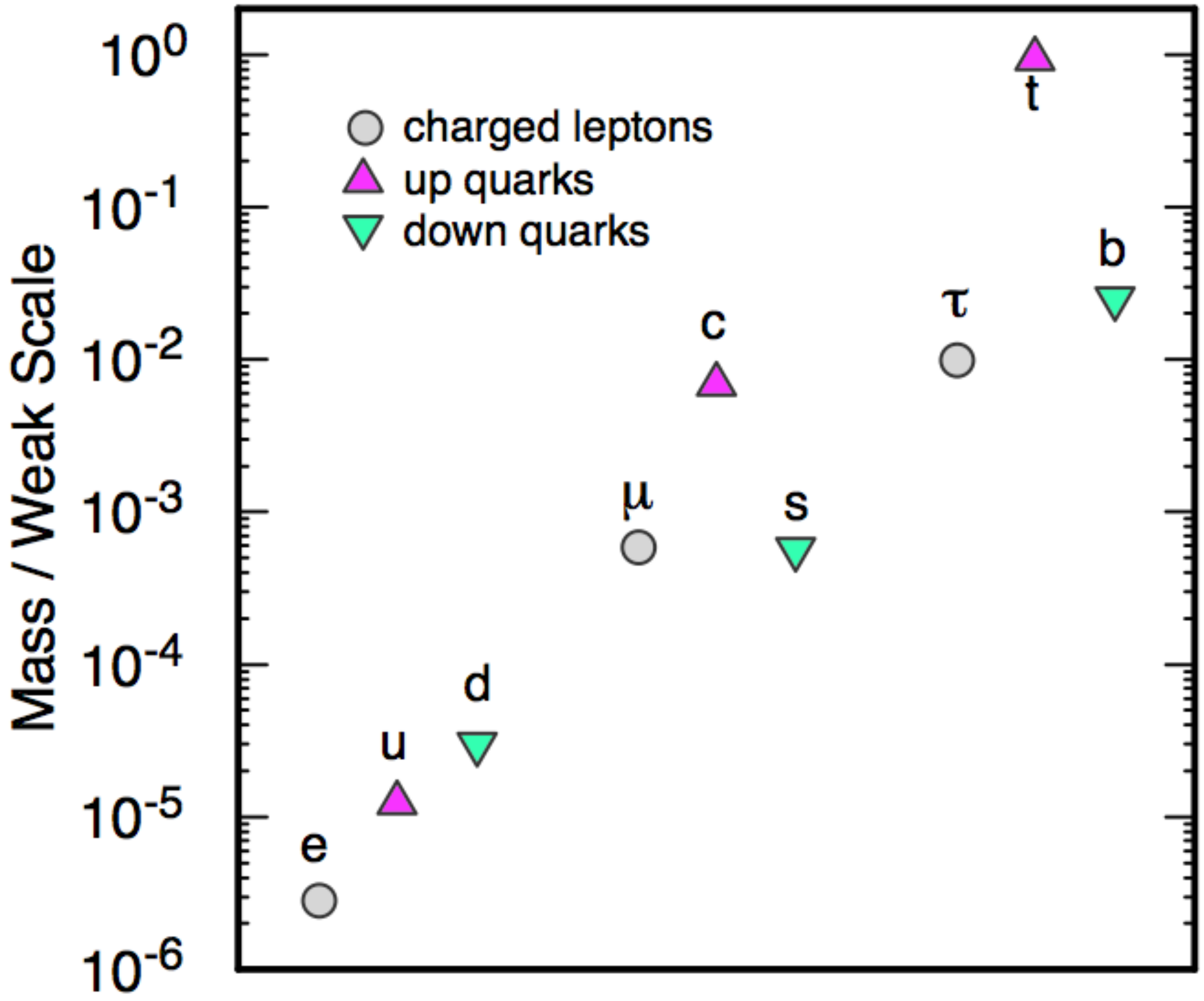
If no or lower W mass : shorter combustion time at lower temperature



Everything would be completely different!

The Flavor Hierarchy

Simple glance at the masses of Fermions



Not explained by the Higgs mechanism !

Preamble

Historical context and roots of the Standard Model and Higgs Mechanism

1864-1958 - Abelian theory of quantum electrodynamics

1933-1960 - Fermi model of weak interactions

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

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 …

$$SU(2)_L \times U(1)_Y$$

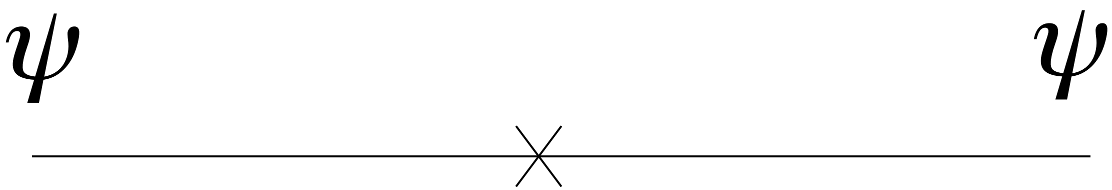
Caution, not unified in the sense of unified forces, only unique framework

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

How Does Mass Appear in a Lagrangian

$$m\bar{\psi}\psi$$

In Terms of Feynman Diagram



1960

Spontaneous Symmetry Breaking (SSB) - Global Symmetry

The Goldstone theorem is where it all began…

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

Originates from the work of Landau (1937)

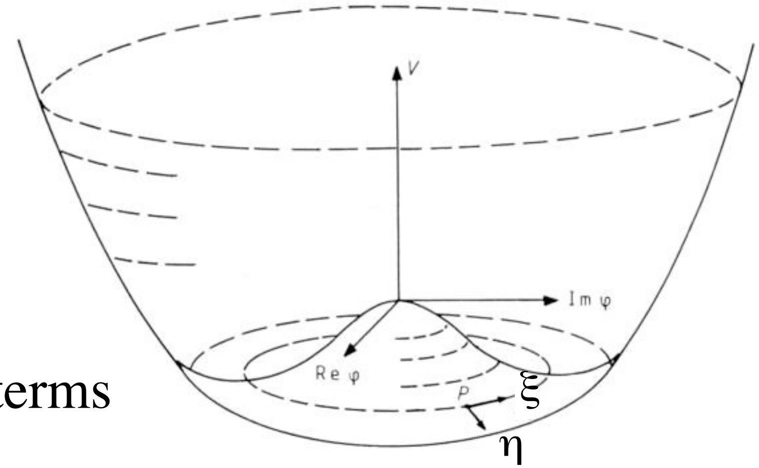
From a simple (complex) scalar theory with a U(1) symmetry

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

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

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

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.

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

Massless scalar

Massive scalar

Nice but what should we do with these massless salars?

Digression on Chiral Symmetry

In the massless quarks approximation : $SU(2)_L x SU(2)_R$ 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)

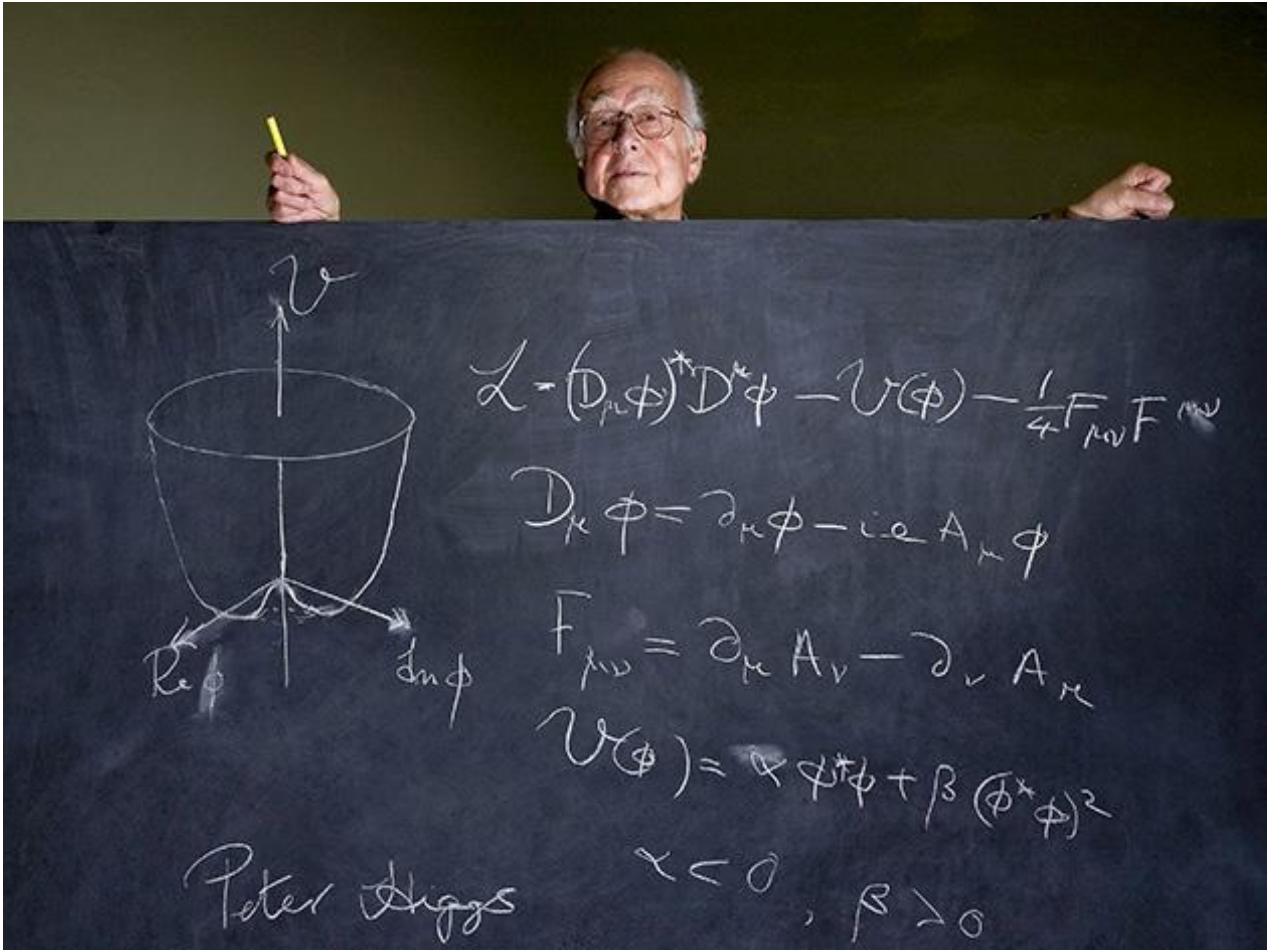
$$SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_V$$

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

And the massive scalar is also there : the sigma!

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

1964


V
$\mathcal{L} = (D_\mu\phi)^* D^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$D_\mu\phi = \partial_\mu\phi - ieA_\mu\phi$
$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
$V(\phi) = \alpha\,\phi^*\phi + \beta\,(\phi^*\phi)^2$
$\alpha < 0\ ,\ \beta > 0$
Re ϕ
Im ϕ
Peter Higgs

Spontaneous Symmetry Breaking (SSB) - Local Symmetry

All the players… in the same PRL issue

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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) Extended to Local Symmetry

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

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

α(x) now depends on the space-time x.

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

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

Mass term for the gauge field! But…

What about the field content?

A massless Goldstone boson ξ, a massive scalar η and a massive gauge boson!

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

Number of initial d.o.f. : 2 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 : $\varphi \to e^{-i\frac{\theta(x)}{v}}\varphi \qquad A_\mu \to A_\mu + \frac{1}{ev}\partial_\mu \theta$

$$L = \frac{1}{2}\partial_\nu h \partial^\nu h - \lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4$$ 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

The turning point : Bolting pieces together !

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

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

and on a right-hande

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

The larg
matic te
ian cons
on L, pl
right-ha
as we kn
tirely un
and the
gauge fi
metry w
massles
form ou
spin $\vec{T}$ a
$+\frac{1}{2}N_L$.

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

whose
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

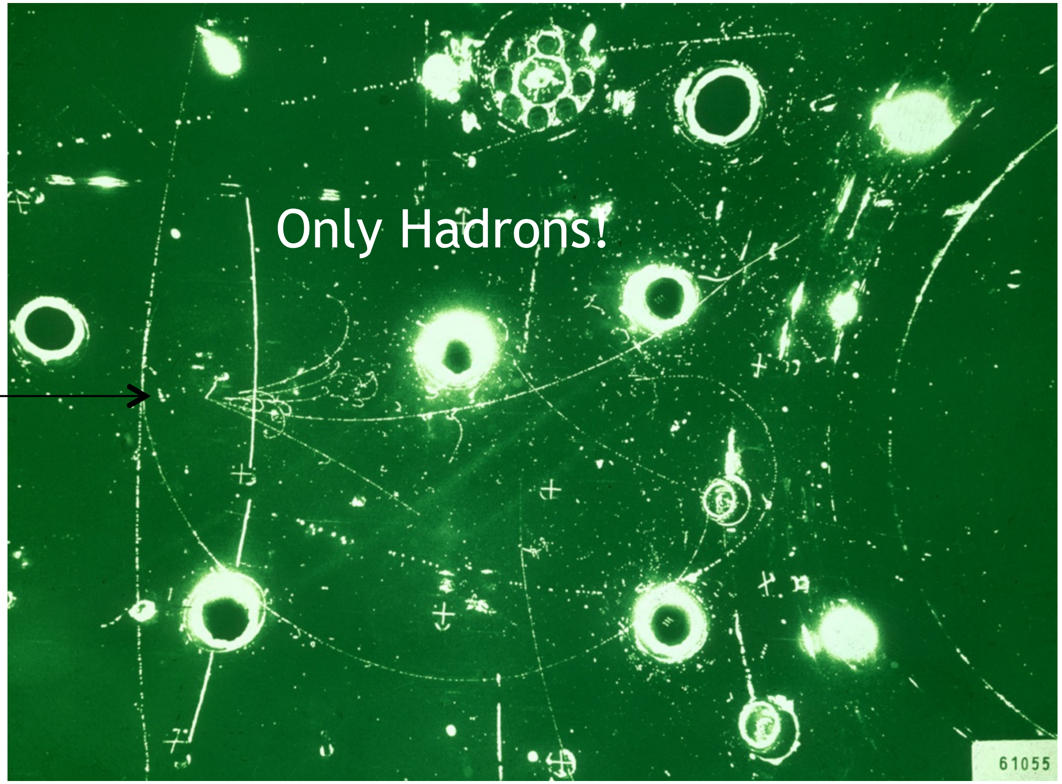
Milestone PRL 1967

The Neutral Currents

1973: neutral current discovery (Gargamelle experiment, CERN)

Evidence for neutral current events $\nu + N \rightarrow \nu + X$ in ν-nucleon deep inelastic scattering

ν_μ



1973-1982: $\sin^2\theta_W$ Measurements in deep inelastic neutrino scattering experiments (NC vs CC rates of νN events)

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 :

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

The next step is to develop the Lagrangian near : $< \phi > = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

Choosing the specific real direction of charge 0 of the doublet is not fortuitous :

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

In particular for a non charged vacuum

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 : $W_\mu^\pm = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}}$

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

For the mass terms only :

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

Explicit mixing of W^3 and B.

Finaly the full Lagrangian will then be written :

$$\begin{aligned}
\mathcal{L} \;=\; & \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4}H^4 \\
+ \; & \frac{1}{2}\left[\frac{g'^2 v^2}{4}B_\mu B^\mu - \frac{g g' v^2}{2}W^3_\mu B^\mu + \frac{g^2 v^2}{4}\vec{W}_\mu.\vec{W}^\mu\right] \\
+ \; & \frac{1}{v}\left[\frac{g'^2 v^2}{4}B_\mu B^\mu H - \frac{g g' v^2}{2}W^3_\mu B^\mu H + \frac{g^2 v^2}{4}\vec{W}_\mu.\vec{W}^\mu H\right] \\
+ \; & \frac{1}{2v^2}\left[\frac{g'^2 v^2}{4}B_\mu B^\mu H^2 - \frac{g g' v^2}{2}W^3_\mu B^\mu H^2 + \frac{g^2 v^2}{4}\vec{W}_\mu.\vec{W}^\mu H^2\right]
\end{aligned}$$

Massive scalar : The Higgs boson

Massive gauge bosons

Gauge-Higgs interaction

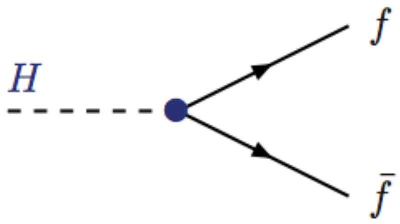
In order to derive the mass eigenstates :

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

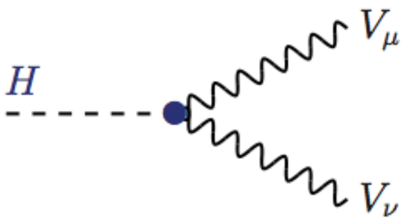
Where

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

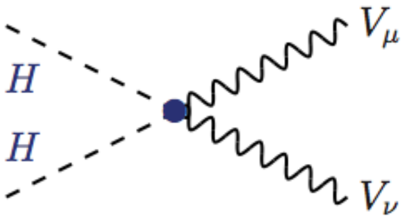
The Weinberg angle was actually first introduced by Glashow (1960)



$$g_{Hff} = m_f/v$$

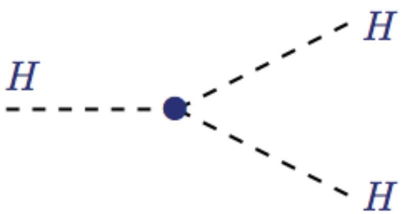


$$g_{HVV} = 2M_V^2/v$$

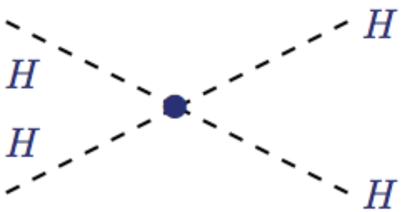


$$g_{HHVV} = 2M_V^2/v^2$$

Keep this in mind for the next lecture...



$$g_{HHH} = 3M_H^2/v$$



$$g_{HHHH} = 3M_H^2/v^2$$

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 describe 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

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

$$\rho = 1$$

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

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 crucial 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 any number of doublets is fine

Higher representations need to fine tune the vevs

Dynamical Symmetry Breaking and Technicolor

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

The experimental crowning glory of the model

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

1997 - Neutrino Oscillations

1998 – tau neutrino discovery

1999 - CP violation in B’s

Until last year the Standard Model is experimentally crowned, except…

The expected massive physical state

Open questions

Is it the Higgs boson of the Standard Model?

Is there a reason why is μ^2 should be negative?

What could explain the flavor mass hierarchy?

Is the mechanism responsible for the mass of gauge boson also responsible for fermion masses ?

What is dark matter made of?

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

In practice : all known processes can be computed in this framework

$$\rho = 1$$

However…

The Higgs sector somehow is the least elegant sector of the Standard Theory

- It accounts for most of the unknown parameters (fermion masses)
- There is no underlying gauge principle

…and wait!

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

Knowing the Higgs mass…

$$\lambda = 0.126$$

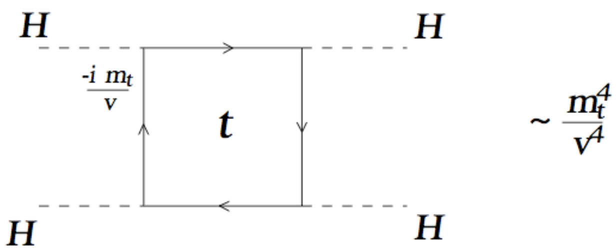
So what?

Running Quartic Coupling : Vacuum stability

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

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

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

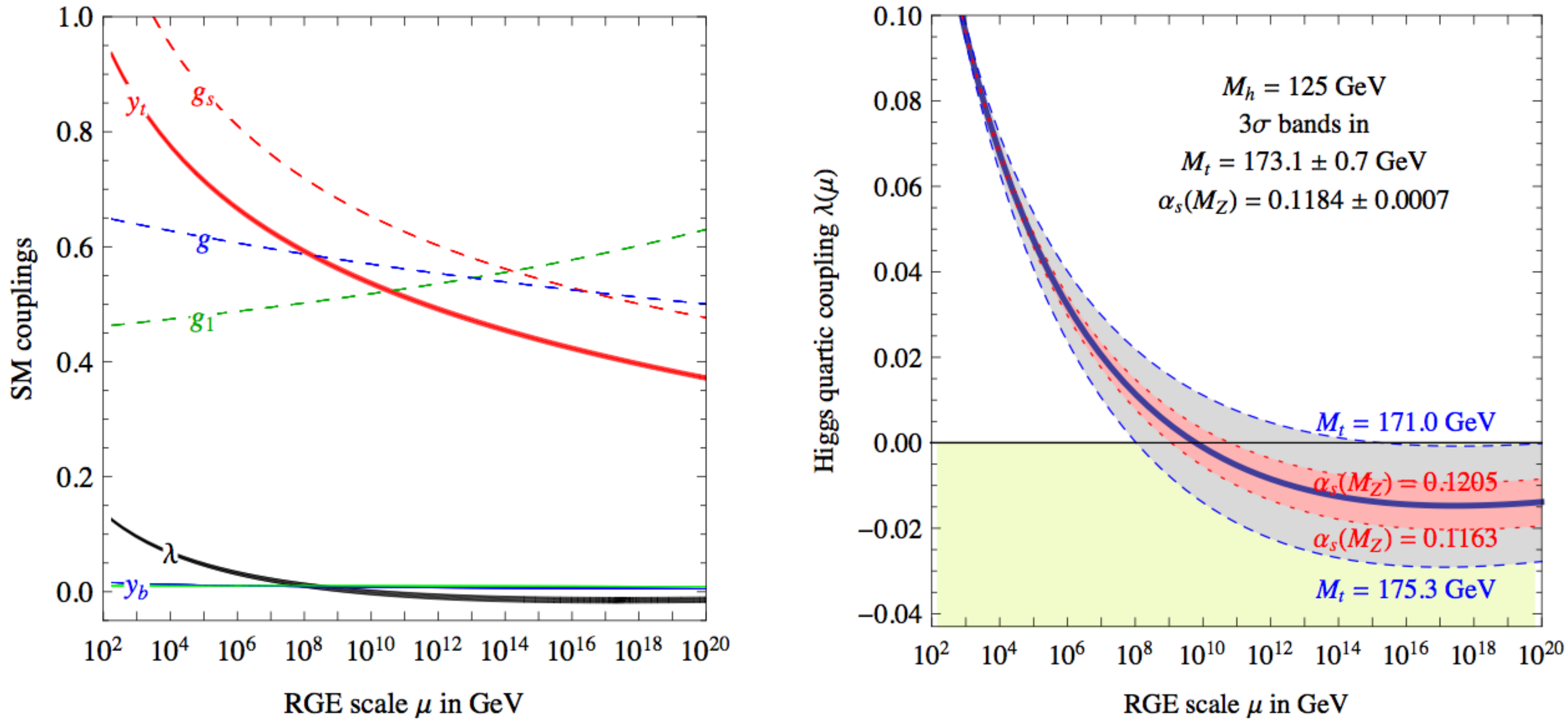


The equation is then very simply solved : $\lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2}y_t^2\log\left(\frac{\Lambda^2}{v^2}\right)$

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

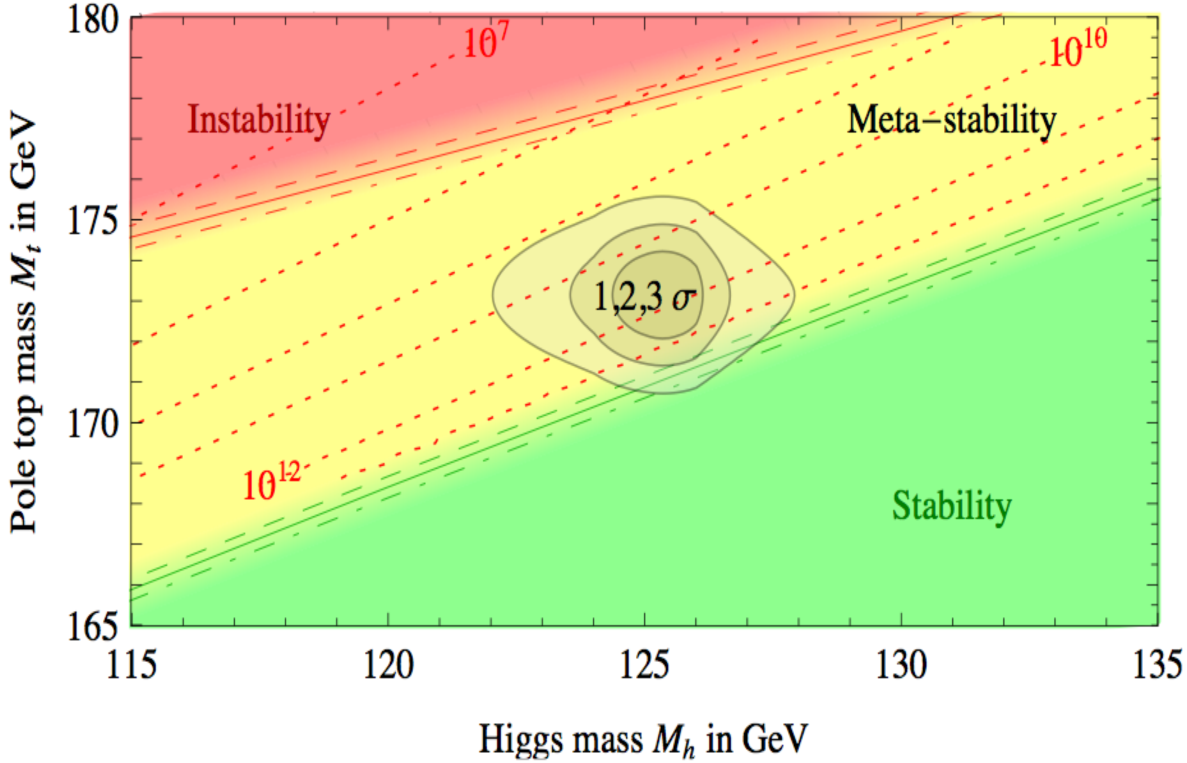
$\lambda(\Lambda) > 0$ then $\boxed{M_H^2 > \frac{3v^2}{2\pi^2}y_t^2\log\left(\frac{\Lambda^2}{v^2}\right)}$

Running of the Quartic Coupling



Large dependence on top mass and of
course Higgs boson mass

Metastability



$\lambda \sim 0$

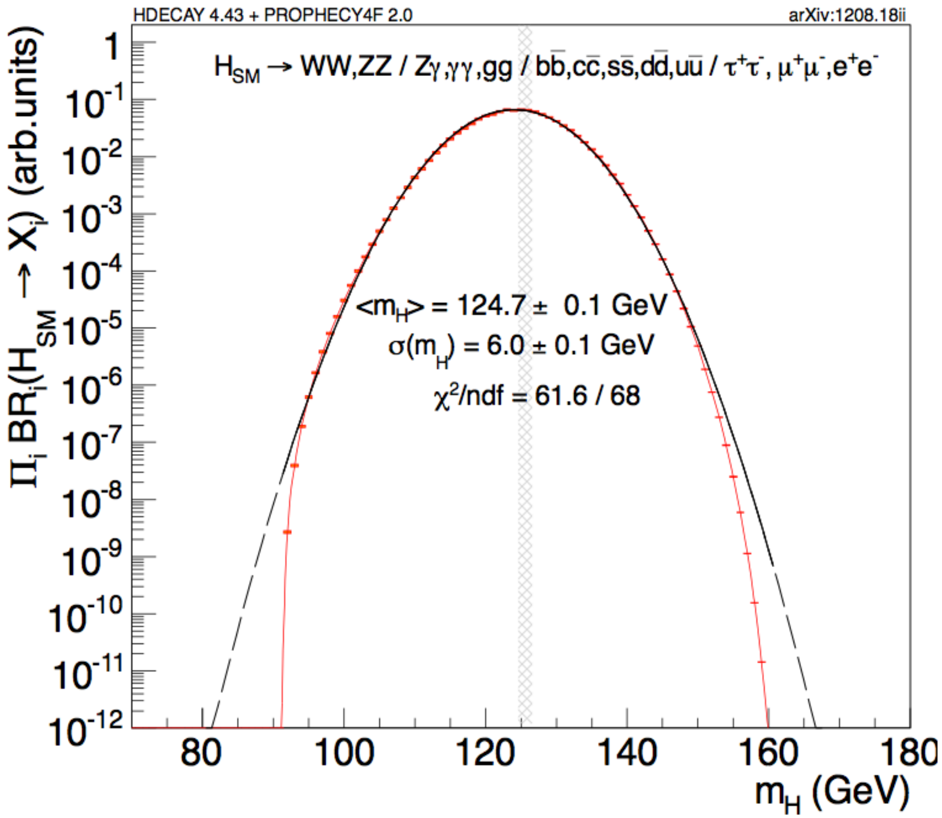
(at the high scale)

Intriguing (Amusing) Coincidences (?)

- $m_H = (m_W + m_W + m_Z)/2 = 126.0$ GeV (http://arxiv.org/abs/0912.5189)

- $m_H^2 = m_Z \times m_t \Rightarrow m_H = 125.8$ GeV (http://arxiv.org/pdf/1209.0474.pdf)

- Π BR peak at mH =124.7 GeV (http://arxiv.org/pdf/1208.1993.pdf)



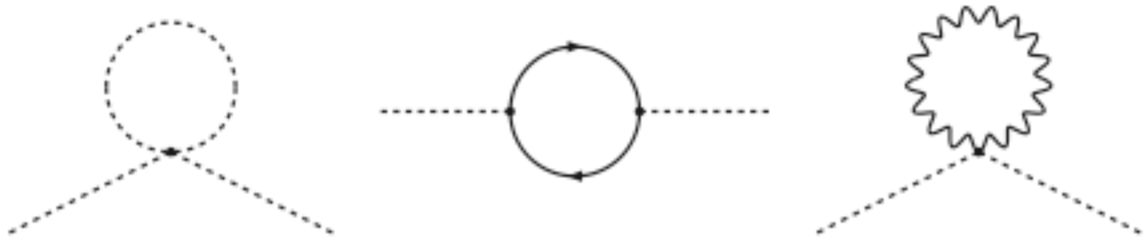
Gauge Hierarchy and Fine Tuning

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

$$m = m_0 + \Delta m + \ldots \text{ Higher orders}$$

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

This can be achieved by fine tuning our theory… Inelegant…

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

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 in a theory where for each fermion there are two scalar fields with

$$\lambda_s = |\lambda_f|^2$$

(which is fulfilled if the scalars have the same couplings as the fermions) quadratic divergencies will cancel

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 a SSB mechanism is far more complex than for the EWSB and 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…

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

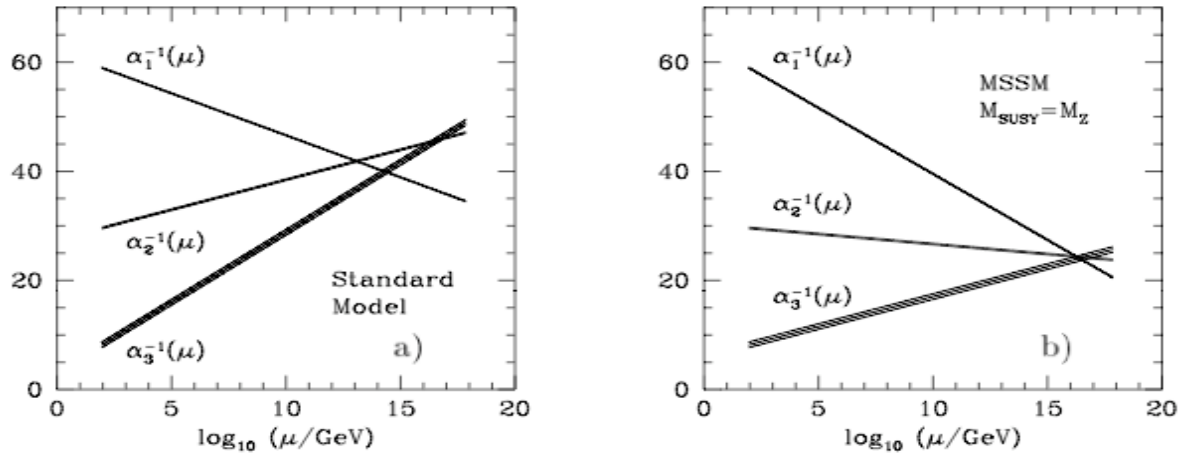
Interestingly similar relation to that of the general fine tuning one

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

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)
- Natural candidate for Dark Matter



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

- MSSM : 5 Higgs bosons
- Lightest mass < m_Z at tree level and smaller than ~130 GeV/c^2 w/ rad. Corr.

Naturalness

M_{Pl}

Electroweak Precision Data Indirect Constraints

The LEP and SLC legacies

Experimental Indirect Constraints : Electroweak Precision Data and the Higgs Mass

The standard model has 3 free parameters not counting the Higgs mass and the fermion masses and couplings.

Particularly useful set is :

1.- The fine structure constant : $\alpha = 1/137.035999679(94)$ 10^{-9}

Determined at low energy by electron anomalous magnetic moment and quantum Hall effect

2.- The Fermi constant : $G_F = 1.166367(5) \times 10^{-5}\ \mathrm{GeV}^{-2}$ 10^{-5}

Determined from muon lifetime

3.- The Z mass : $M_Z = 91.1876 \pm 0.0021\ \mathrm{GeV}$ 10^{-5}

Measured from the Z lineshape scan at LEP

Experimental Constraint : Electroweak Precision Data and the Higgs Mass

Taking the hypothesis of a Minimal Standard Model, the radiative corrections to numerous observables can be computed in order to assess the impact of certain particles e.g. the Higgs boson

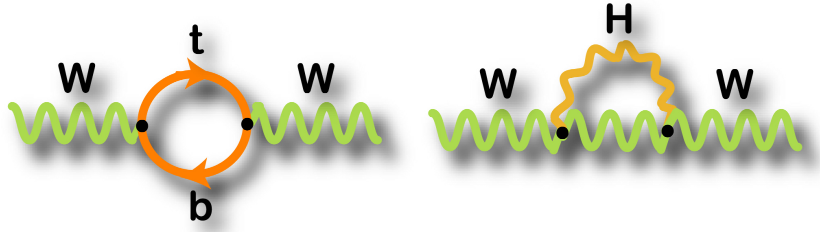
From the measurement of these observables a constraint is derived

For example the corrections to the Fermi coupling constant can be written as :

$$G_F = \frac{\pi \alpha_{QED}}{\sqrt{2} m_W^2 (1 - m_W^2/m_Z^2)} (1 + \Delta r)$$

With :

$$\begin{cases} \Delta r_t \propto m_t^2 \\ \Delta r_H \propto \log(m_H/m_W) \end{cases}$$



Essential ingredients top, W and Z masses and a_{QED}

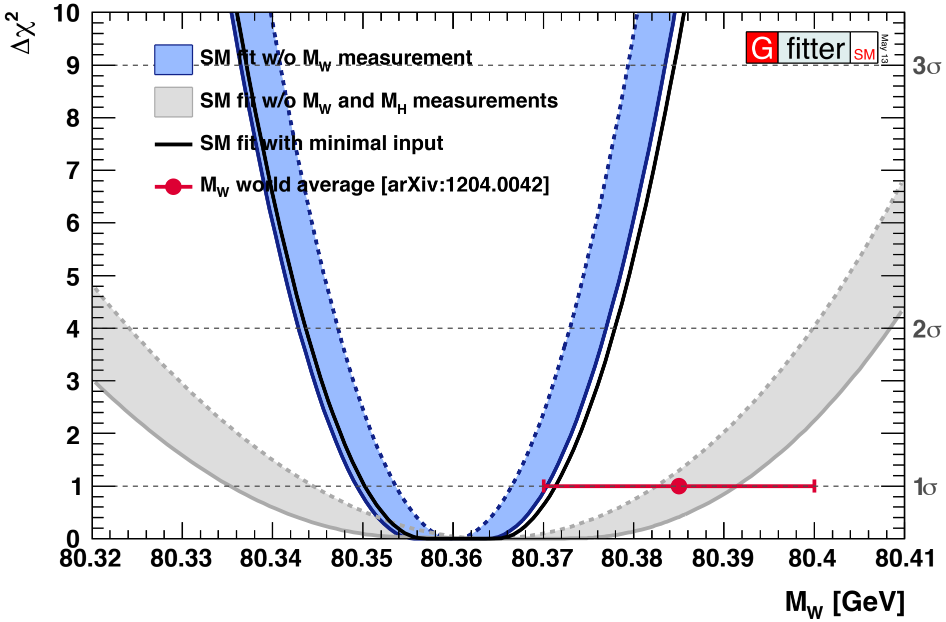
The Complete Data

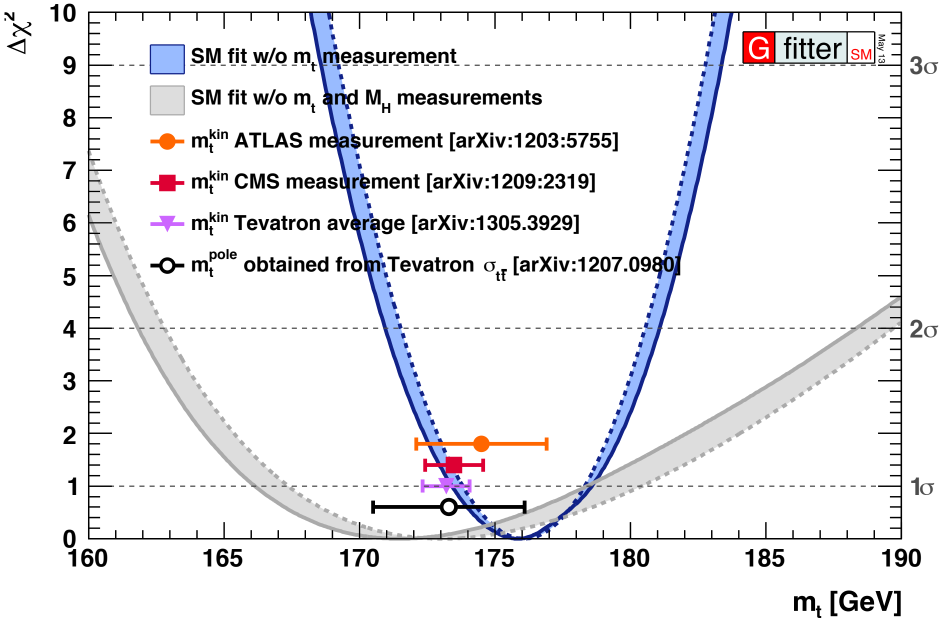
Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements	Fit without exp. input in line
M_H [GeV]°	125.7 ± 0.4	yes	125.7 ± 0.4	94.1^{+25}_{-22}	94.1^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367^{+0.006}_{-0.007}$	$80.380^{+0.011}_{-0.012}$	80.360 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1874 ± 0.0021	91.1983 ± 0.0115
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4953 ± 0.0014	2.4957 ± 0.0015	2.4949 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.480 ± 0.014	41.479 ± 0.014	41.472 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.739 ± 0.017	20.741 ± 0.017	20.713 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	$0.01627^{+0.0001}_{-0.0002}$	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1473^{+0.0006}_{-0.0008}$	$0.1477^{+0.0009}_{-0.0008}$	–
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23148^{+0.00011}_{-0.00007}$	$0.23143^{+0.00010}_{-0.00012}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6681^{+0.00021}_{-0.00042}$	$0.6682^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00005}_{-0.00007}$	$0.93468^{+0.00008}_{-0.00007}$	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0739^{+0.0003}_{-0.0005}$	$0.0740^{+0.0005}_{-0.0004}$	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	$0.1032^{+0.0004}_{-0.0006}$	$0.1036^{+0.0007}_{-0.0006}$	0.1034 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	$0.17222^{+0.00006}_{-0.00005}$	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21491 ± 0.00005	0.21492 ± 0.00005	0.21490 ± 0.00005
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	$4.20^{+0.17}_{-0.07}$	–
m_t [GeV]	173.20 ± 0.87	yes	173.49 ± 0.82	173.17 ± 0.86	$175.83^{+2.74}_{-2.42}$
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$ $^{(\dagger\triangle)}$	2756 ± 10	yes	2755 ± 11	2757 ± 11	2716^{+49}_{-43}
$\alpha_s(M^2_Z)$	–	yes	$0.1188^{+0.0028}_{-0.0027}$	$0.1190^{+0.0028}_{-0.0027}$	0.1188 ± 0.0027
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	yes	-1.4	4.7	–

$^{(\circ)}$Average of ATLAS ($M_H = 126.0 \pm 0.4$ (stat) ± 0.4 (sys)) and CMS ($M_H = 125.3 \pm 0.4$ (stat) ± 0.5 (sys)) measurements assuming no correlation of the systematic uncertainties. $^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements, used as two measurements in the fit. The fit w/o the LEP (SLD) measurement gives $A_\ell = 0.1474^{+0.0005}_{-0.0009}$ ($A_\ell = 0.1467^{+0.0006}_{-0.0004}$). $^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency.

- Numerous observables O(40)
- Numerous experiments (with different systematics)
- Within experiments numerous analyses (with different systematics)
- Various theoretical inputs

W and Top quark mass measurements





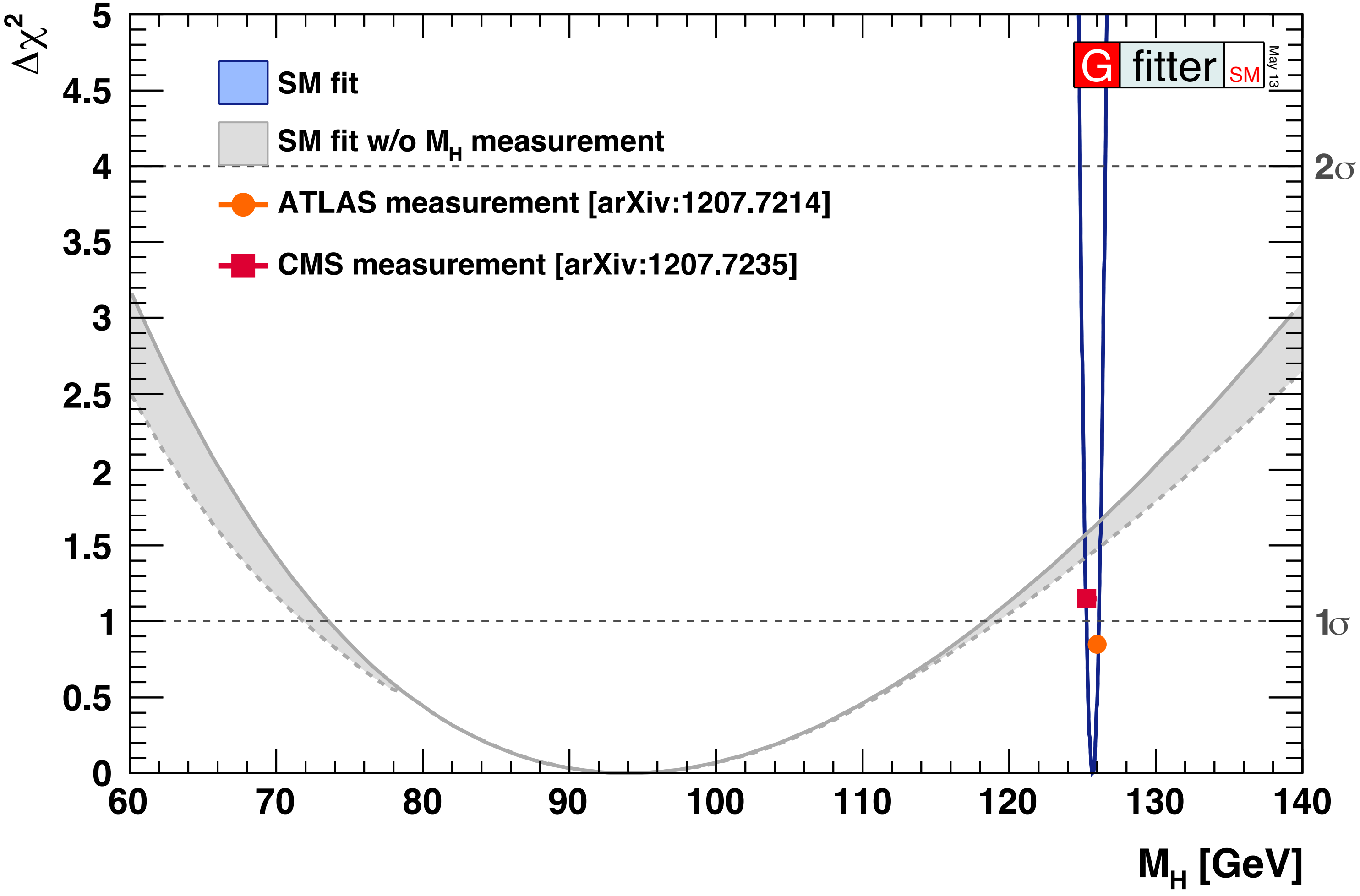
Precision of ~0.02%

- TeVatron reached ~15 MeV
- LHC should reach ~15 MeV or better

Precision of ~0.8%

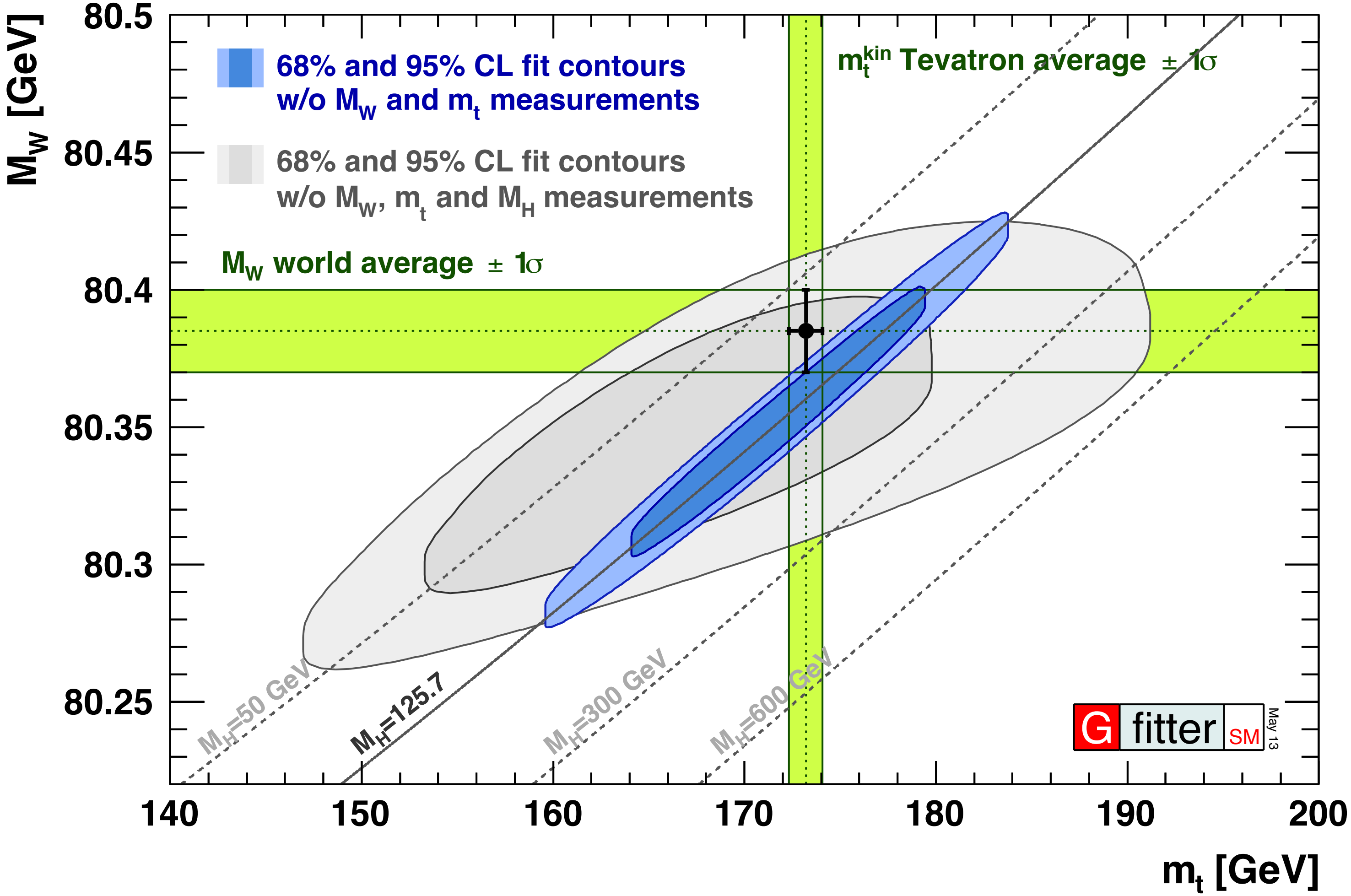
- TeVatron is aiming at ~ 0.9 GeV
- Not so clear that LHC will be able to do much better.

Indirect Measurement of Higgs Boson Mass



M_H [GeV] $^{(\circ)}$	95% CL limits	yes	$94^{+25[+59]}_{-22[-41]}$	–	$94^{+25[+59]}_{-22[-41]}$

Indirect Measurement of Higgs Boson Mass



M_H [GeV] $^{(\circ)}$	95% CL limits	yes	$94^{+25[+59]}_{-22[-41]}$	–	$94^{+25[+59]}_{-22[-41]}$

Additional Slides

The sector of Fermions (Fermionic neutral current)

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

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

In the lepton sector :

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

1.- Eliminate neutrino coupling to the photon : $g\sin\theta_W = -g'Y_L\cos\theta_W$

2.- Same coupling e_R and e_L to the photon : $g'Y_R = 2g'Y_L$

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

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

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

- 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

But wait…

The coupling to the Higgs fields is the following :

$$\lambda_d (\bar{u}_L, \bar{d}_L) \begin{pmatrix} 0 \\ v+h \end{pmatrix} d_R + H.C. = \lambda_d \bar{Q}_L \ \phi \, d_R$$

Can be seen as giving mass to down type fermions…

To give mass to up type fermions, need to use a slightly different coupling :

$$\phi^C = i\sigma_2 \phi^* \qquad \lambda_u Q_L \ \phi^C \ \bar{u}_R = \lambda_u (\bar{u}_L, \bar{d}_L) \begin{pmatrix} v+h \\ 0 \end{pmatrix} d_R + H.C.$$

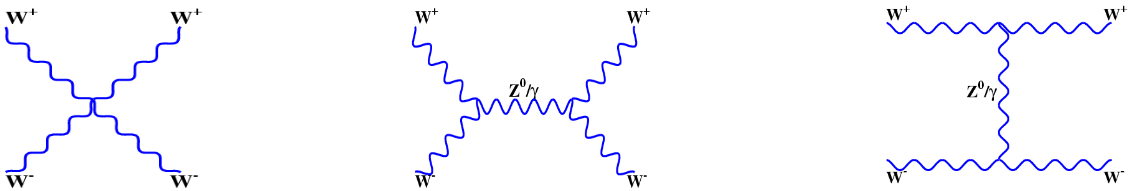
One doublet of complex scalar fields is sufficient to accommodate mass terms for gauge bosons and fermions !

... But not necessary.

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 PROVIDED 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…)

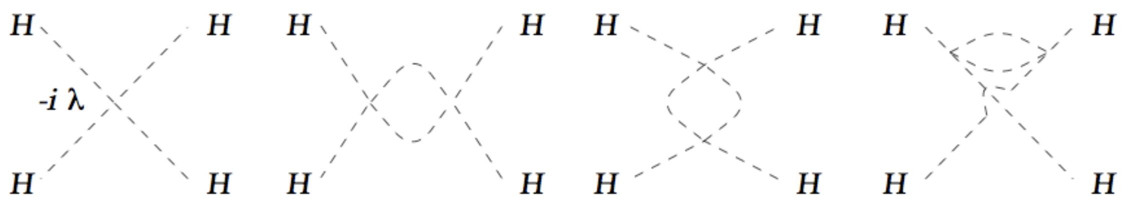
Running Quartic Coupling : Triviality

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 :



$$\frac{d\lambda(Q^2)}{dt} = \frac{3}{4\pi^2}\lambda^2(Q^2) \longrightarrow \frac{1}{\lambda(Q^2)} = \frac{1}{\lambda(Q_0^2)} - \frac{3}{4\pi^2}\ln\left(\frac{Q^2}{Q_0^2}\right)$$

If Q can be high at will eventually lead to Landau pole

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

Then

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