

HIGH ENERGY PHYSICS

at the dawn of the L.H.C. era

J. Iliopoulos, ENS, Paris

Les Houches Summer School

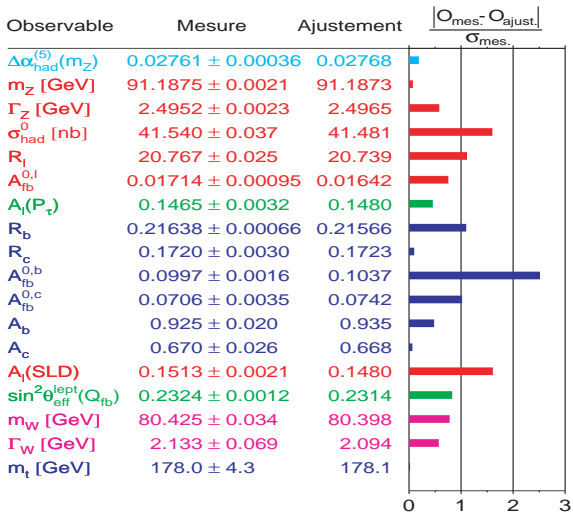
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- The long awaited experimental results are coming close.
- The last year of theoretical speculations.
- We feel quite confident that fundamental discoveries are ahead.
- A most exciting period to enter High Energy Physics.

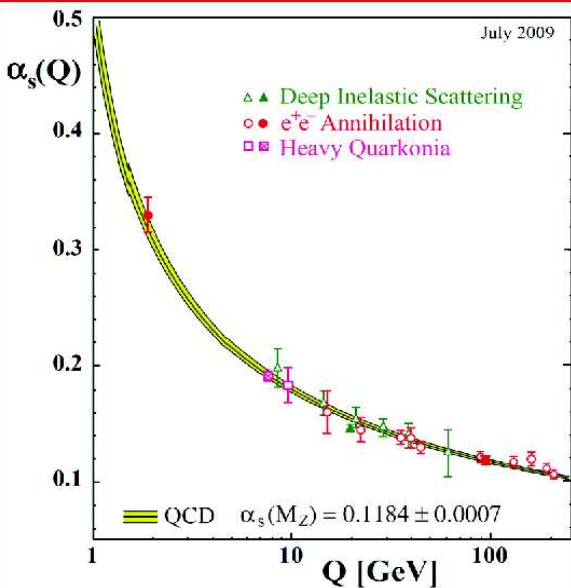
- We often say that revolutions in Physics come because an unexpected experimental result forces physicists to change their theoretical paradigms.
- This has often been the case in the past.
- But the revolution which linked permanently Physics and Geometry had a theoretical, even an aesthetic, motivation.
- It led to the formulation of the **STANDARD MODEL** in Particle Physics.
- It is a gauge theory based on the group $SU(3) \times SU(2) \times U(1)$ spontaneously broken to $SU(3) \times U(1)_{em}$.

THE STANDARD MODEL

HAS BEEN ENORMOUSLY SUCCESSFUL



July 2009



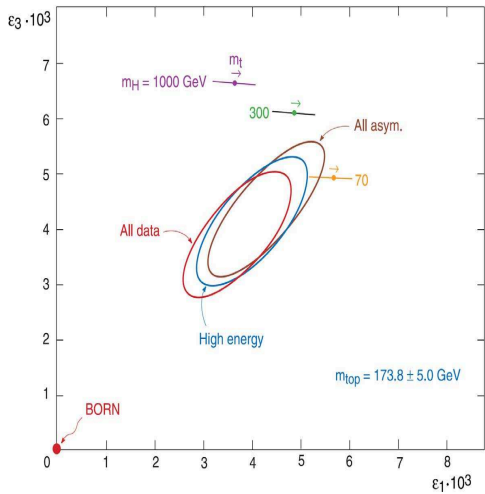
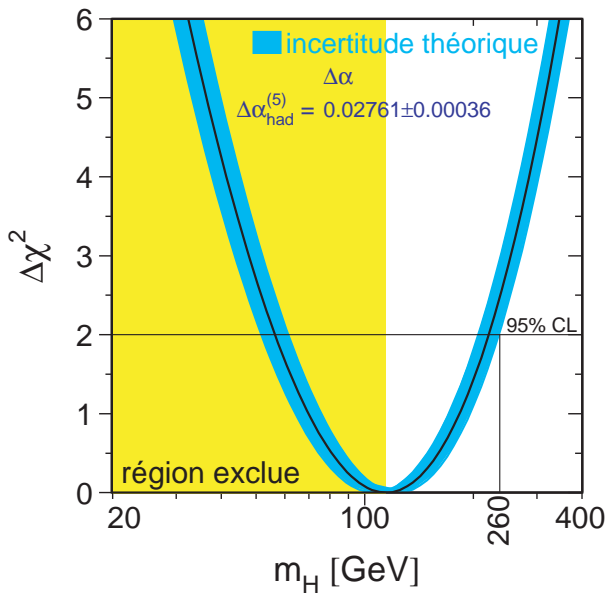


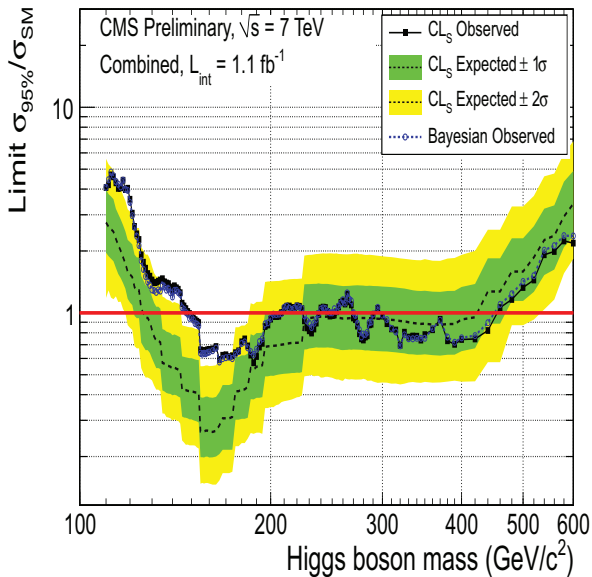
Figure 6: Data vs theory in the ϵ_3 - ϵ_1 plane (notations as in fig.5)

$$\epsilon_1 = \frac{3G_F m_t^2}{8\sqrt{2}\pi^2} - \frac{3G_F m_W^2}{4\sqrt{2}\pi^2} \tan^2 \theta_W \ln \frac{m_H}{m_Z} + \dots \quad (1)$$

$$\epsilon_3 = \frac{G_F m_W^2}{12\sqrt{2}\pi^2} \ln \frac{m_H}{m_Z} - \frac{G_F m_W^2}{6\sqrt{2}\pi^2} \ln \frac{m_t}{m_Z} + \dots \quad (2)$$

- All but one of the parameters of the Standard Model have been quite accurately determined by experiment.
- The precision of the measurements often led to successful predictions of new Physics. (Ex. Neutral currents, Charmed Particles, Gauge bosons, New quarks, etc)
- The last remaining parameter is the Higgs boson mass.
- Through the radiative corrections it enters into the determination of other physical quantities, but the dependence is only logarithmic. (Screening Theorem).





Limits on the Standard Model Higgs mass :

1) $160 \text{ GeV} \geq m_H \geq 114 \text{ GeV}$ (Exp.)

2) $m_H = 85_{-28}^{+39} \text{ GeV}$ (From global fit)

3) $m_H \leq \mathcal{O}(1\text{TeV})$ (Validity of perturbation)

4) $m_H \geq \mathcal{O}(130\text{GeV})$ (Vacuum stability)

$$m_H^2 \sim \lambda$$

$$\frac{d\lambda}{dt} = \frac{3}{4\pi^2} [\lambda^2 + 3\lambda h_t^2 - 9h_t^4 + \dots]$$

Validity of perturbation

The Landau pole does not occur up to Λ

$$\Lambda \sim 1 \text{ TeV} \rightarrow m_H \leq 0.8 \text{ TeV}$$

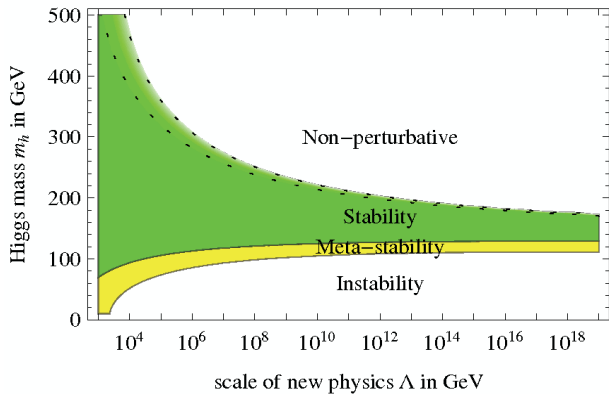
$$\Lambda \sim 10^{16} \text{ GeV} \rightarrow m_H \leq 180 \text{ GeV}$$

Vacuum stability

$$\lambda > 0$$

for $\Lambda \sim 10^{16} \text{ GeV}$

$$m_H \geq 110 - 120 \text{ GeV}$$



Can we “predict” the value of the Higgs mass?

$$m_Z/m_H = C \quad (3)$$

$$C = \frac{m_Z}{m_H} = \frac{\sqrt{g_1^2 + g_2^2}}{\sqrt{8\lambda}} \quad (4)$$

$$\begin{aligned}16\pi^2\beta_{g_1} &= g_1^3 \frac{1}{10} \\16\pi^2\beta_{g_2} &= -g_2^3 \frac{43}{6} \\16\pi^2\beta_\lambda &= 12\lambda^2 - \frac{9}{5}g_1^2\lambda - 9g_2^2\lambda + \frac{27}{100}g_1^4 + \frac{9}{10}g_1^2g_2^2 + \frac{9}{4}g_2^4\end{aligned}\tag{5}$$

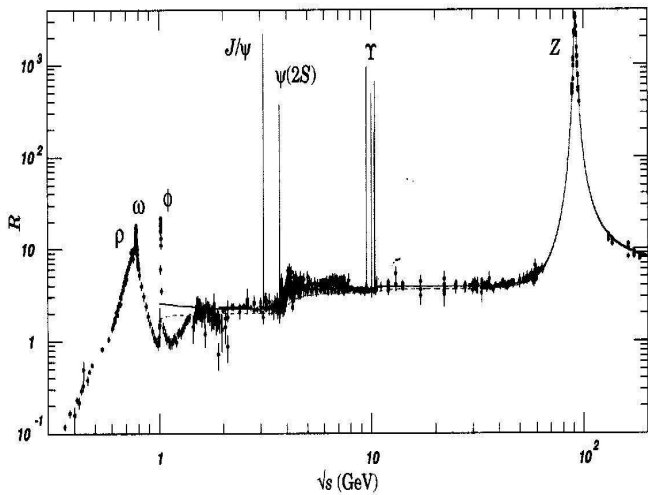
$$\begin{aligned}
\beta_z &= \beta_{\eta_1} + \beta_{\eta_2} = \\
&= \frac{-\lambda w}{16\pi^2 \rho z} \left[\left(\frac{27}{100} \rho^2 + \frac{9}{10} \rho + \frac{9}{4} \right) z^2 - \left(2\rho^2 + \frac{54}{5} \rho - \frac{16}{3} \right) z \right. \\
&\quad \left. + 12(\rho + 1)^2 \right]
\end{aligned} \tag{6}$$

$$\eta_1 = \frac{g_1^2}{\lambda} ; \quad \eta_2 = \frac{g_2^2}{\lambda} ; \quad z = \eta_1 + \eta_2 ; \quad \rho = \frac{\eta_1}{\eta_2} ; \quad w = \eta_1 \eta_2 \tag{7}$$

What we have learnt

Perturbation theory is remarkably reliable

Outside the region of strong interactions



Why?

-We do not really understand why.

Simple argument :

$$A_n \sim \alpha^n (2n - 1)!!$$

Perturbation theory breaks down when $A_n \sim A_{n+1}$

$$2n + 1 \sim \alpha^{-1}$$

For QED $n \gg 1$; For QCD???

General rule : Precision measurements at a given energy scale allow to guess new Physics at the next energy scale

Example : Yukawa's prediction of the π meson in 1934

The range of nuclear forces is of order 1 fermi ($\sim 10^{-13}$ cm).

The Physics was correct, the details were not !!

Example : The prediction for charmed particles in 1969

The absence, with very high accuracy, of certain weak decays

- Three decades of intense experimental effort, mainly at L.E.P., but also at the Tevatron, B -factories, ν -physics etc, have brought the agreement between the Standard Model and experiment to an impressive degree of accuracy.
- I want to exploit this experimental fact and argue that the available precision tests of the Standard Model allow us to claim with confidence that new physics is present at the TeV scale and the LHC can, probably, discover it.
- The argument assumes the validity of perturbation theory and it will fail if the latter fails. But, as we just saw, perturbation theory breaks down only when strong interactions become important. But new strong interactions imply new physics.

First task of LHC

Study the Higgs sector of the theory.

Possible (Predictable) LHC Results

1) A Light Higgs is found

The Standard Model is **complete**

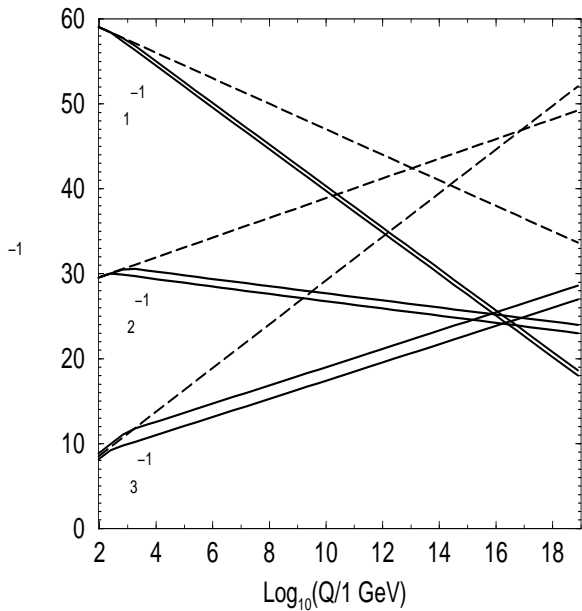
No new Strong Interactions \Rightarrow

Perturbation theory is reliable \Rightarrow

$m_H^2 \sim \alpha M^2 \Rightarrow$ **Hierarchy**

Possible Answers :

- Supersymmetry
- Possible solution of the dark matter problem
- Gauge coupling unification



- Theoretically very attractive
- Fermion-Boson connection
- Higgs-Gauge boson connection
- Non-renormalisation theorems
- Possible connection with Gravity
- BUT...The precise supersymmetry breaking mechanism is still unknown

Other answers to the hierarchy problem :

- Large extra dimensions
- Connection with Gravity
- More spectacular, less probable ??

Possible (Predictable) LHC Results

2) A Light Higgs is NOT found

- Seems unlikely, but...
- Perturbation theory breaks down
- \Rightarrow New Strong Interactions

Possible Answers :

- Technicolor

The Higgs boson is a bound state of new, heavy fermions

- Little Higgs

The Higgs boson is a pseudo-Goldstone boson of a new symmetry

THE ABSENCE OF A LIGHT HIGGS
IMPLIES NEW PHYSICS

BUT A LIGHT HIGGS IS UNSTABLE
WITHOUT NEW PHYSICS

CONCLUSIONS

THE TIME FOR SPECULATIONS WILL BE SOON OVER!

L.H.C. IS WORKING

NEVER BEFORE AN EXPERIMENTAL FACILITY WAS LOADED
WITH SO GREAT EXPECTATIONS