The Standard Model of Particle Physics and Beyond

or

The Universe of Elementary Particles

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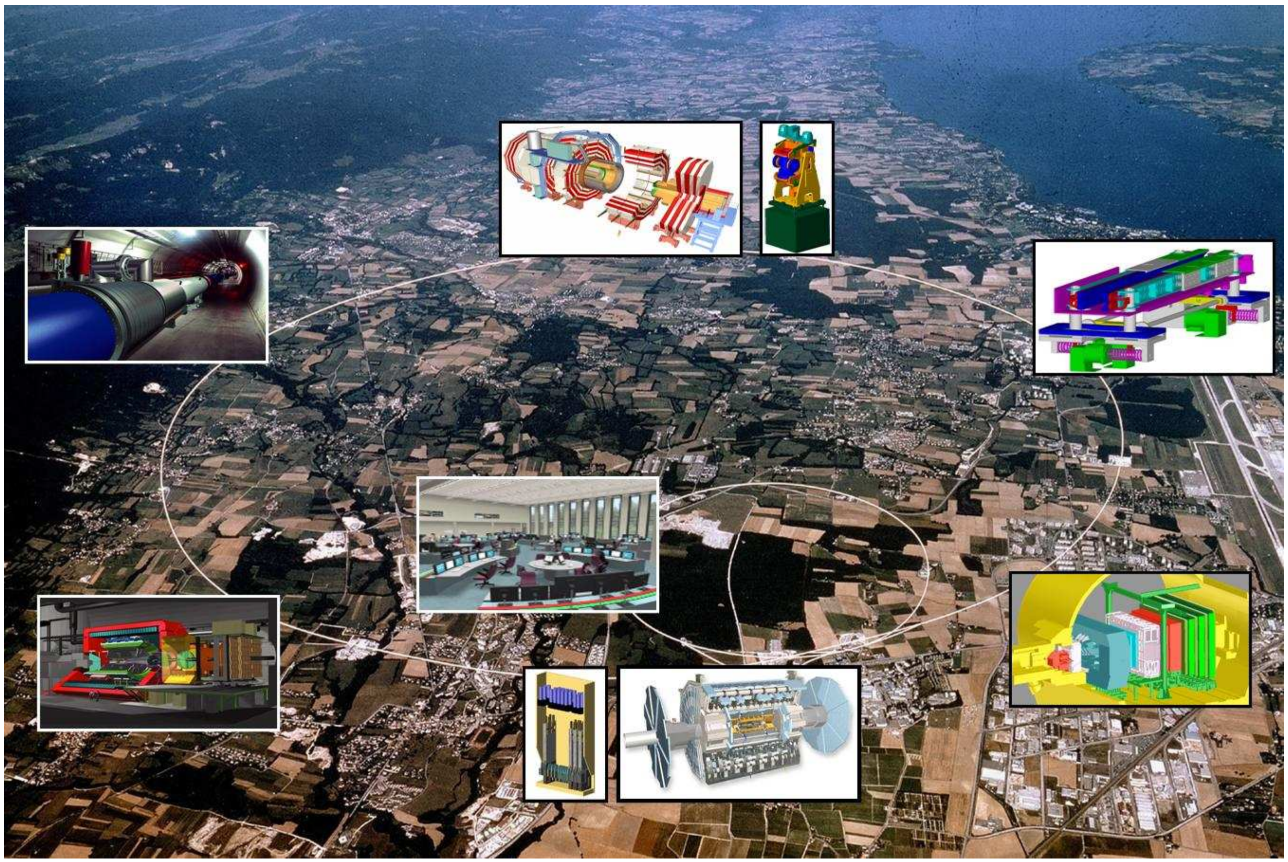
III.1 The LHC and the Higgs boson

The LHC: the largest/most complex scientific instrument ever built.

A proton-proton collider at CERN near Geneva: 27km long, 100m deep:

- energy at E=8–14 TeV ($10^4 m_P$), particles at c≈1, at 10^{-12}s from Big-Bang;
- 1232 magnets 15m long and 8.3 Tesla, 40.000t in liquid He at 1.9^0K (cold...);
- beams: 2800 bunches of 10^{11}protons of $10\mu m$ of diameter every 25ns!



III.1 The LHC and the Higgs boson

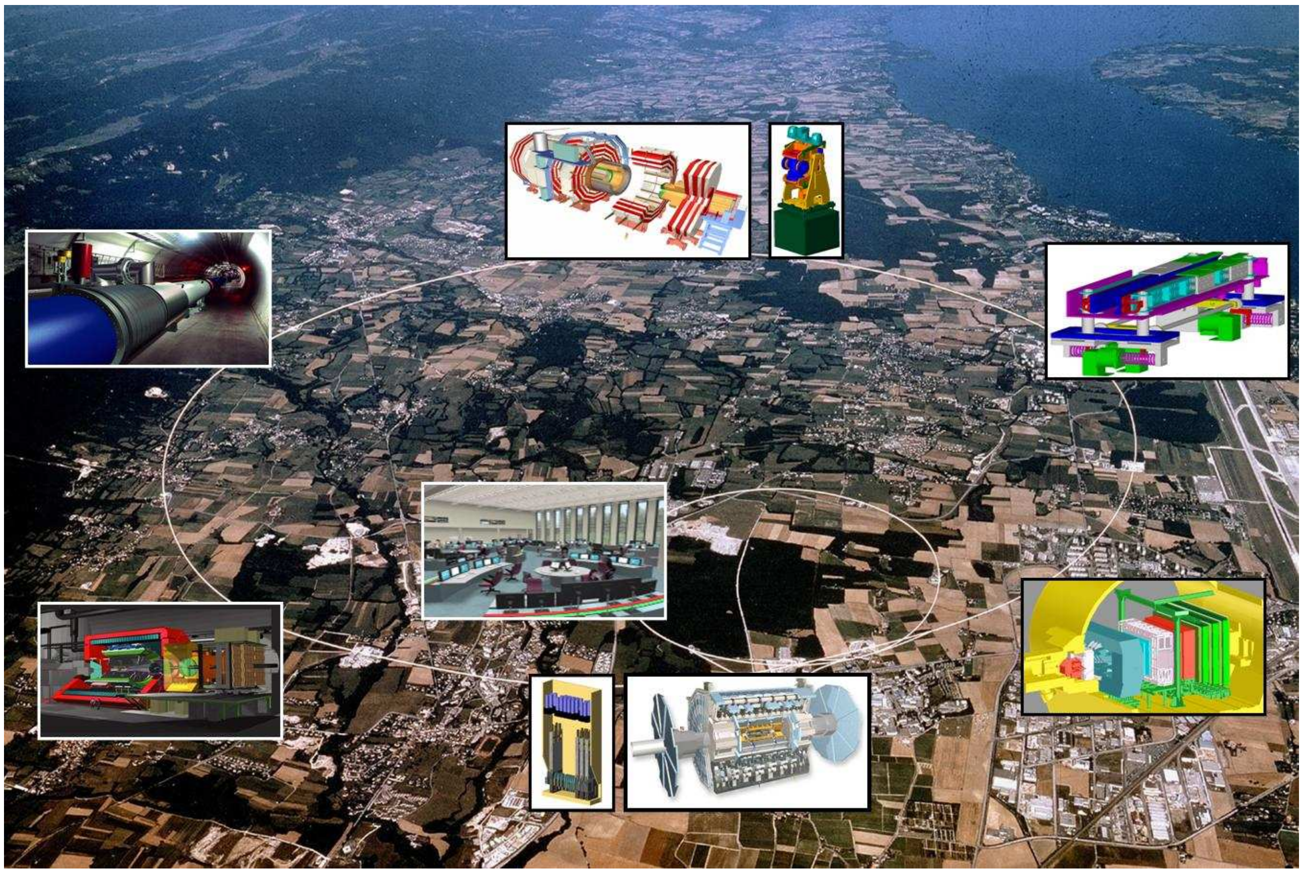
The LHC: the largest/most complex scientific instrument ever built.

2 general purpose detectors: ATLAS+CMS to pin down 10^9 interactions/sec.

– **ATLAS: 46m long, 25m diam, 7.000t; 3000 physicists of 175 labs/38 countries.**

– **CMS: 22m long, 15m diam, 12.500t; 3800 physicists of 182 labs/42 countries.**

– **Very complex, full of High Tech (mechanics, electronics, cryogenics, etc...).**



III.1 The LHC and the Higgs boson

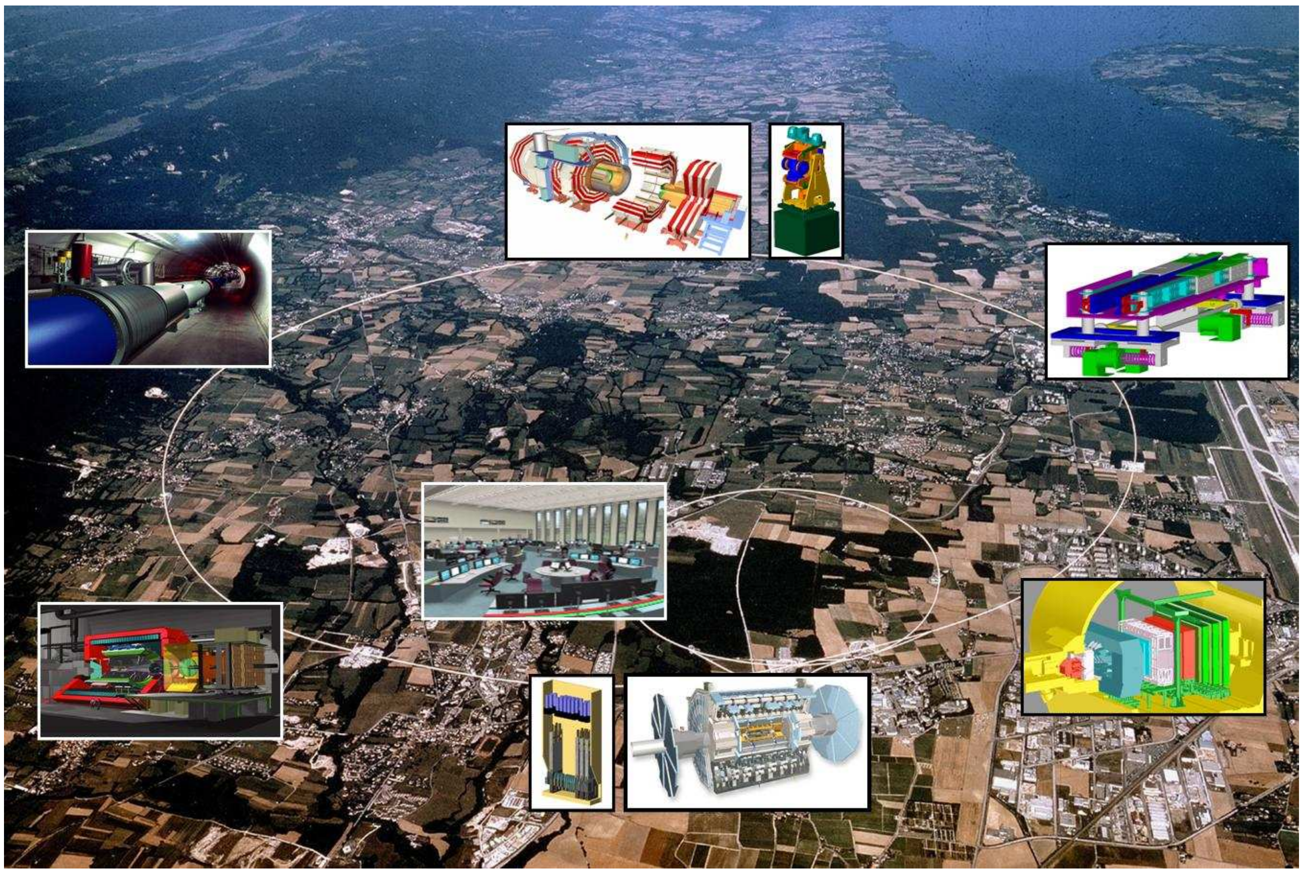
The LHC: the largest/most complex scientific instrument ever built.

Incredible computing power necessary $\Rightarrow$ "LHC Computing GRID".

– 10^9 collisions/s and 25 ev./col. $\Rightarrow 10^7$ Gbytes data/day (2×10^5 DVDs)..

– 10^7 PC in 140 centers in 33 countries; 30 millions jobs in January 2013.

– 8000 users linked via web (developed at CERN in 1989) by optical fibers.

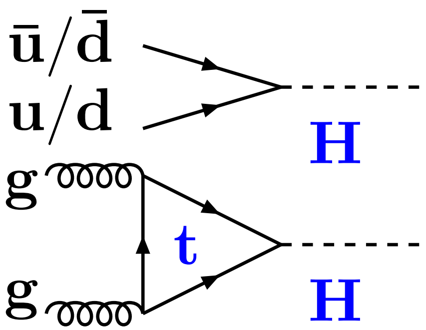


III.1 The LHC and the Higgs boson

5 billion euros worth question: how to produce and detect the H boson?

- **Only free parameter M_H: once known, all Higgs properties are fixed.**
- **Exploit the fact that the Higgs couples mostly to massive particles.**

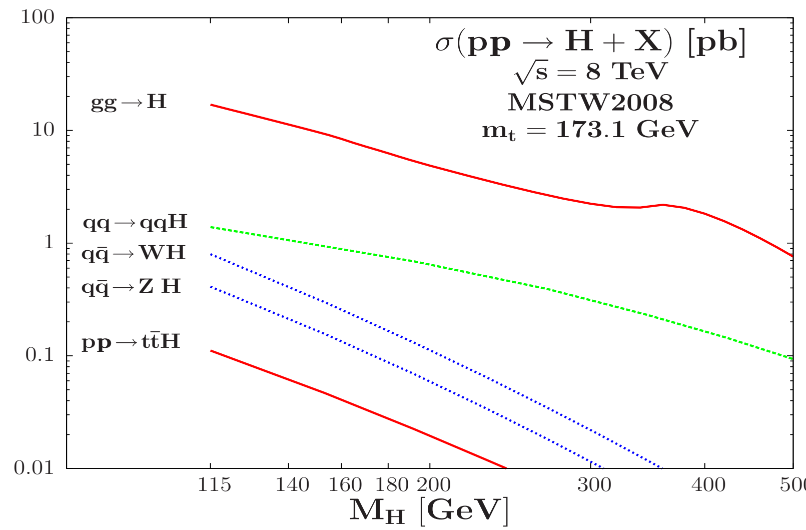
Higgs production processes:



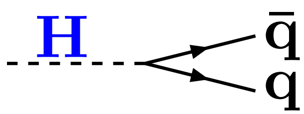
$\propto m^2_{u,d} \Rightarrow$ no!

$\propto m^2_{top} \Rightarrow$ yes!

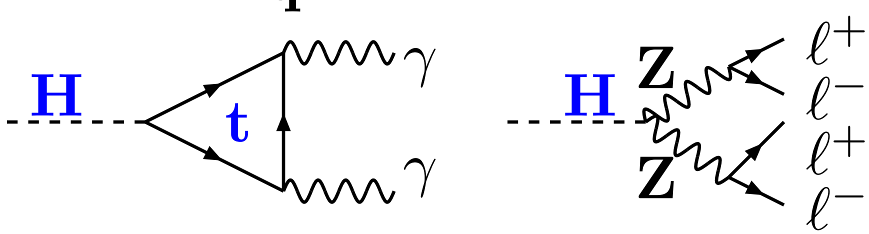
250.000 events/year at E=8 TeV.

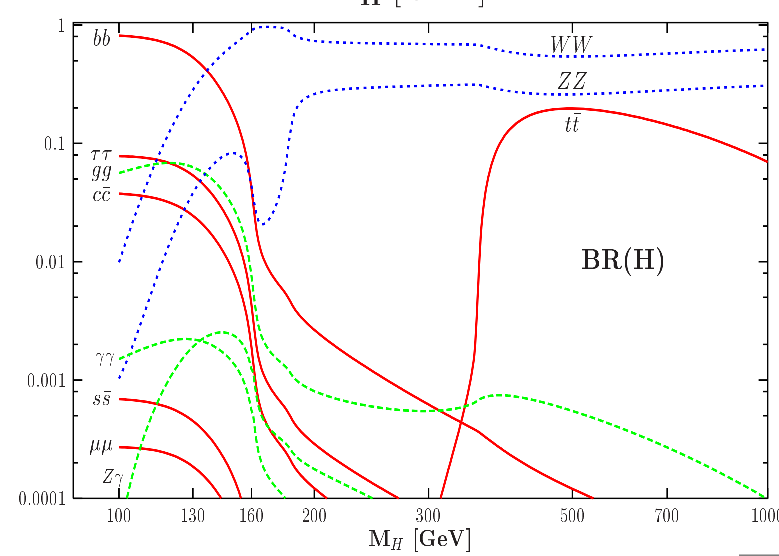


Higgs decay processes:



frequent/complicated





very rare: probability of ≈0.1%...

very small number of total events!

III.1 The LHC and the Higgs boson

Physics at a hadron machine: un nightmare.

- Proton non-elementary: hostile environment.
- Enormous production rates for backgrounds.
- Very small production rate for Higgs signal.

  S/B $\gtrsim 10^{10} \Rightarrow$ a needle in a haystack!
- Need severe criteria to discriminate S and B:

– trigger: eliminate uninteresting (low E) events,

– selection of clean modes: leptons/photons,..

– make use of specific properties of the Higgs.

- Combine $\neq$ production and decay channels

(and eventually data from the two experiments).

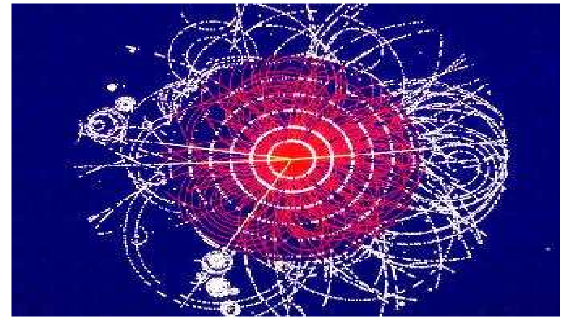
- Precise knowledge of signal and bkg essential

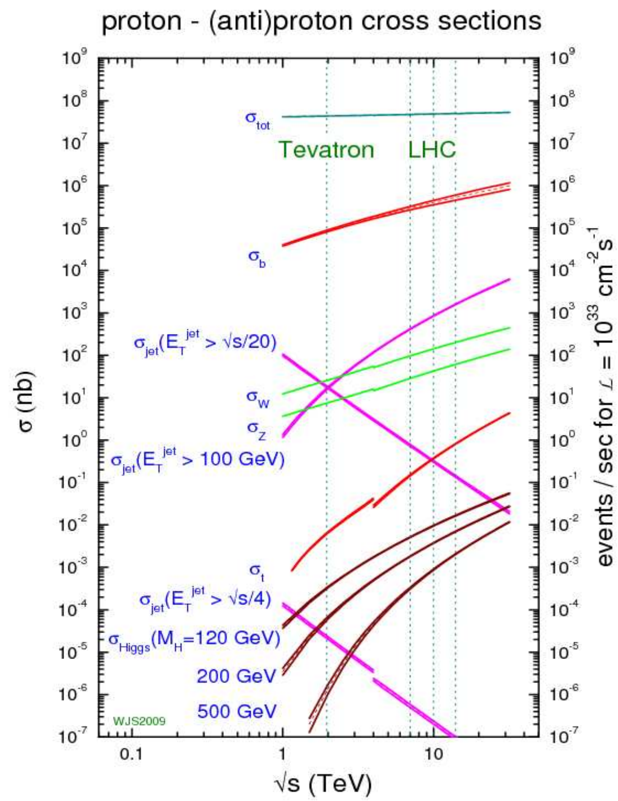
(higher order quantum effects $\approx$ factors of 2!).

- Gigantic experimental+theoretical effort/synerg

(and more than 30 years of extremely hard work!)

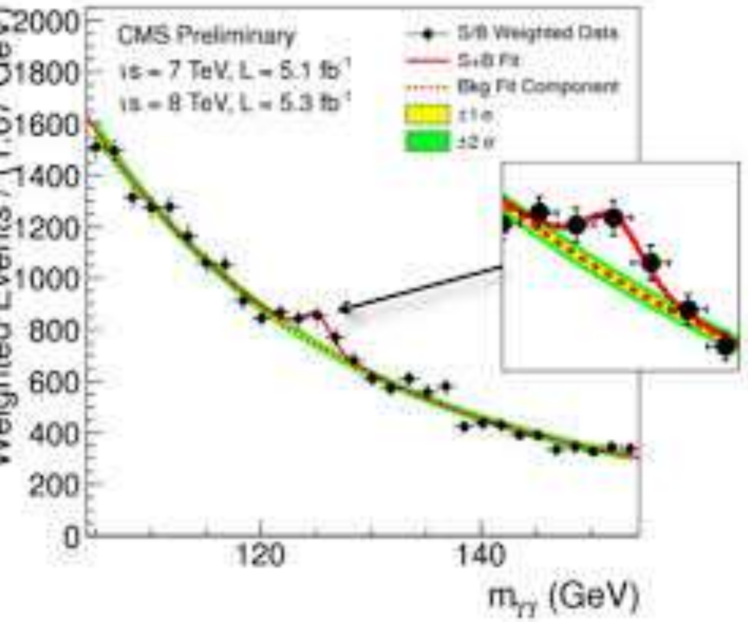
in order to leave no escape to the Higgs.

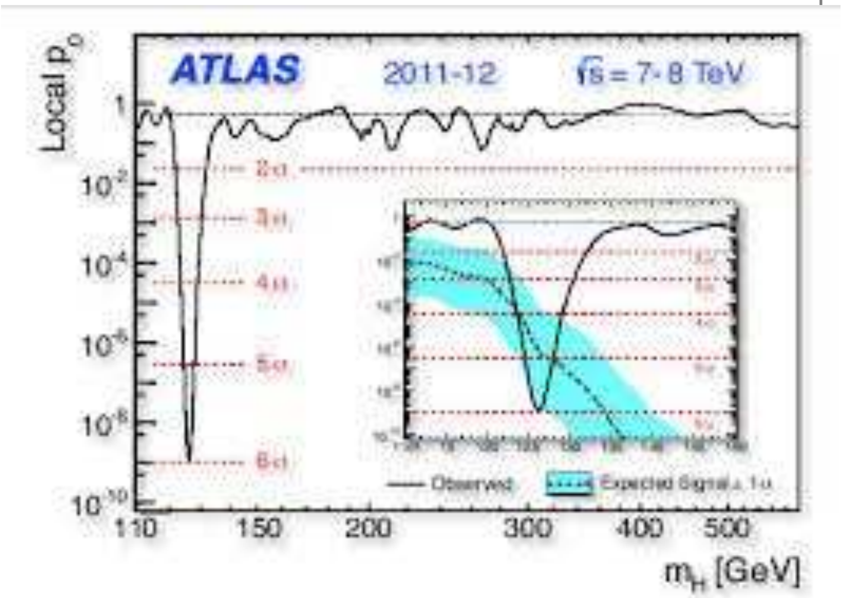




III.1 The LHC and the Higgs boson

... and the challenge was met on the 4th of July 2012: a Higgstorical day!...

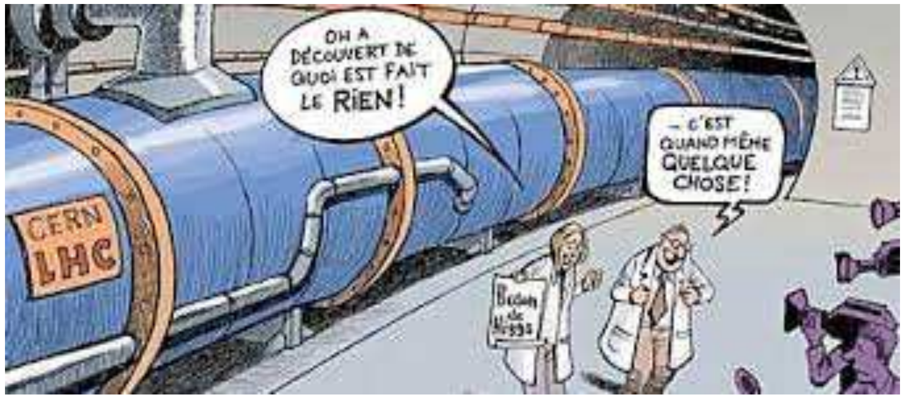




III.2 Beyond the Standard Model

Now that the Higgs is discovered and the SM is confirmed in a spectacular way, is Particle Physics closed? Should we just go to the Playa or Sierra Nevada?

Of course not!



Despite of its successes, the SM is not considered to be satisfactory/complete and is only an effective manifestation of a more fundamental/general theory...

... that cures certain serious problems that the SM left aside....

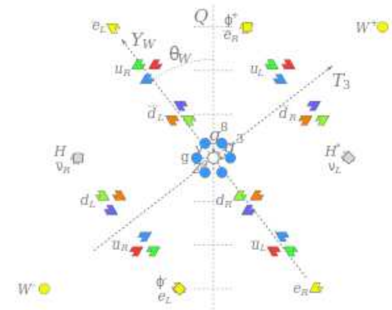
- **Problems of aesthetic nature: too complex and too many ingredients, we want a theory with a few parameters and basic ingredients/principles.**
- **Problems of experimental nature and non-conformity to the microcosm: the SM does not explain all the phenomena that are observed in Nature.**
- **Problems of theoretical consistency: the SM is not extrapolable up to the ultimate energies ⇒ we need a new paradigm to achieve this aim.**

III.2 Beyond the Standard Model

- **Problems of aesthetic nature: SM too complex and too many ingredients, we want a theory with a few parameters and basic ingredients/principles.**

- **Too many ingredients put by hand:**

– needs 19 parameters to describe everything;
– fermion masses very different from another;
– symmetry breaking is had-hoc/non-natural.

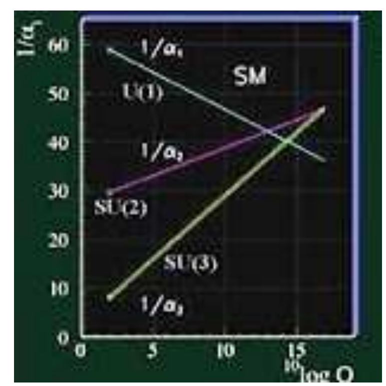


- **Does not include gravitation:**

– desirable at very high energies;
– but no quantum theory so far,
– graviton of spin 2 complicated.

- **Unification of interactions?**

– 3 gauge groups with 3 different couplings,
– better: only one group and one coupling,
– coupling unification at a high scale?
– the three couplings do not converge.

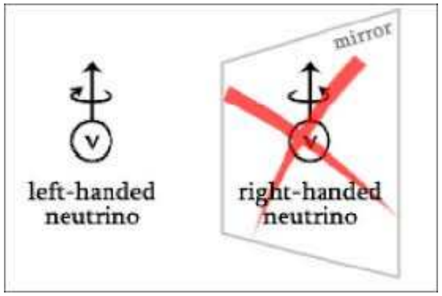


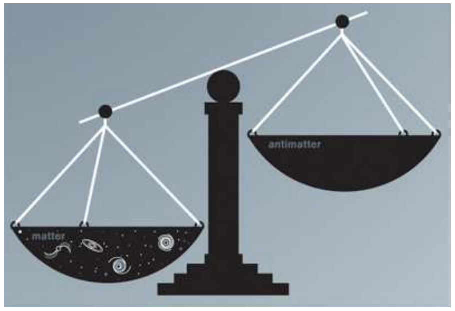
III.2 Beyond the Standard Model

• Problems of experimental nature and non-conformity to the microcosm: the SM does not explain all the phenomena that are observed in Nature.

• The neutrinos are massless:

– in the SM, neutrinos are left-handed,
– experiment: neutrinos oscillate $\Rightarrow$ massive;
– their mass is not coming from the Higgs,
– we need right-handed neutrinos ($\neq$ left).



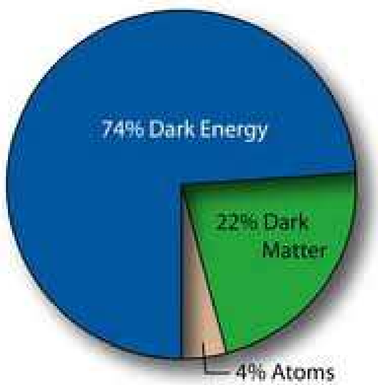


• No baryon asymmetry in the universe:

– there is a one billion p for a single $\bar{\mathrm{p}}$,
– but at early times, CP conserved and $\mathrm{n_p = n_{\bar{p}}}$,
– why there is such an asymmetry now?

• There is no Dark Matter particle:

– known matter makes $\approx$4% of energy of Universe;
– $\approx$ 25% of it is a dark or invisible matter;
– Astroparticle: must be massive and cold ($\mathrm{v \ll c}$);
– in the SM, there is not a particle which is: neutral, weakly interacting, massive and stable.



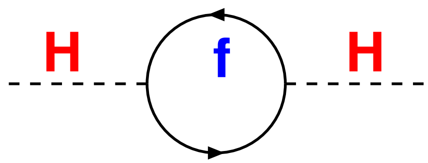
III.2 Beyond the Standard Model

● Problems of theoretical consistency: the SM is not extrapolable up to the ultimate energies ⇒ we need a new paradigm to achieve this aim.

● The Higgs should have mass of order of the W,Z masses i.e. $\mathcal{O}$(100 GeV):
– required by mathematical consistency, conservation of probabilities, etc...
– more natural to solve a problem at 100 GeV with "object" of 100 GeV mass.

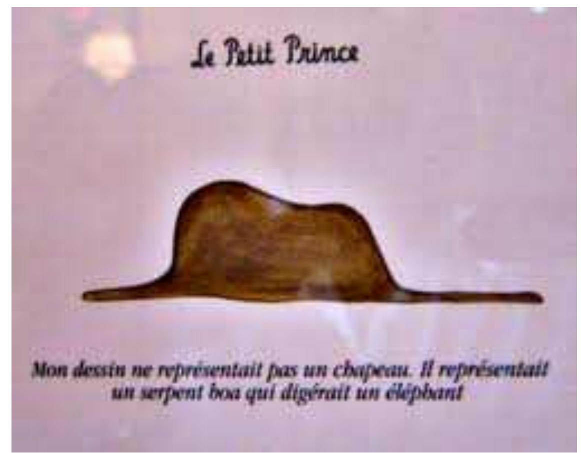
● But we should include all quantum corrections to the Higgs mass:
⇒ contributions to M_H of order M_P while they should be $\approx M_{W,Z}$...

$$\Delta M_H^2 \equiv$$



$$\propto \Lambda^2 \approx (10^{18}\ \mathrm{GeV})^2$$

– enormous hierarchy $M_P \gg M_{W,Z}$;
– this hierarchy seems very unnatural.



● No symmetry to protect M_H from high scales?
– gauge symmetry: protects the photon mass (vanishing corrections);
– L/R or chiral symmetry: protects fermion masses (small corrections).

Hierarchy problem: M_H prefers to be close to the high scale...

III.2 Beyond the Standard Model

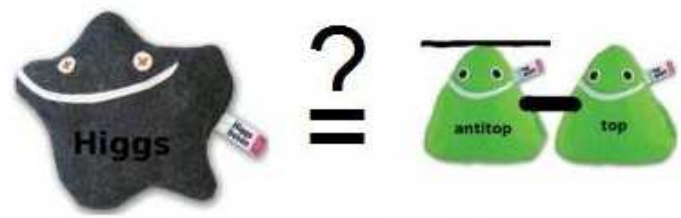
Three main avenues to solve the hierarchy problem of the SM.

I) The Higgs is not an elementary spin-0 particle, but it is composite.

The Higgs boson is the sole fundamental particle of spin equal to zero:
if the Higgs is not fundamental $\Rightarrow$ the hierarchy problem disappears.

- The Higgs is a bound state of two fermions:

one can have a bound state or condensate:
$s = \frac{1}{2} \oplus \frac{1}{2} = 0 \Rightarrow$ scalar (like the π meson).
but the particle should be rather massive.
Only option in SM: top-antitop condensate.



- Even more radical is Technicolor:

all SM particles are composite states
(here is another layer in the onion);
$\equiv$ QCD but at higher scale $\Lambda = 1$ TeV,
$\Rightarrow$ H bound state of two techni-fermions.

- In both cases $\Rightarrow$ Higgs properties $\neq$ of those of the standard H.

Both theories are of strong interaction $\Rightarrow$ constrained by experiment.

III.2 Beyond the Standard Model

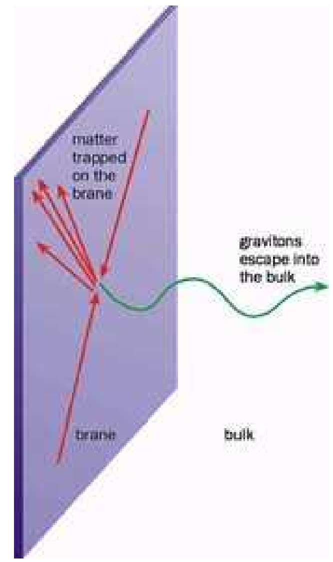
Three main avenues to solve the hierarchy problem of the SM.

II) Additional space-time dimensions at the scale of a few TeV?

We could have a 5th space-time dimension where at least the s=2 gravitons propagate.

Gravity: effective scale is $M_P^{\rm eff} \approx \Lambda \approx$ TeV, not $M_p = 10^{18}$GeV; gravity now in the game.

Several possibilities to realize the scenario: large, warped, universal extra dimensions, ...



Enormous impact on particle physics!

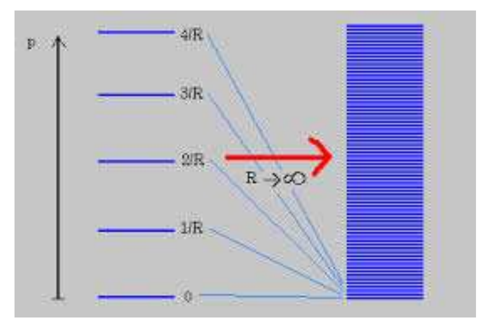
(with solutions to other SM problems).

- But we still need symmetry breaking:

– the same Higgs mechanism as in the SM,
– but also possibility of a Higgs-less world.

- Known particles are the zero modes of

– an infinite tower of Kaluza–Klein excitations,
– new heavy partners of the fermions/bosons.



Plenty of new exotic particles to discover and study at LHC and beyond!

III.2 Beyond the Standard Model

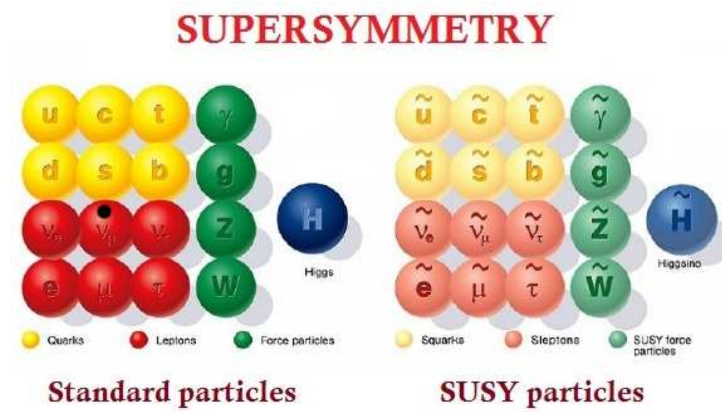
Three main avenues to solve the hierarchy problem of the SM.

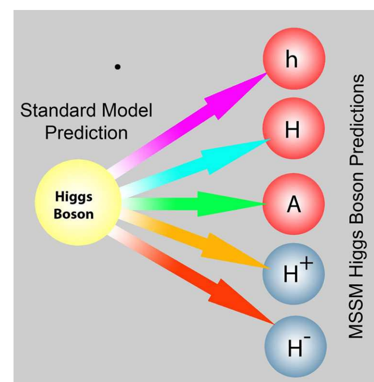
III) Supersymmetric theories (SUSY) or how to double the world.

Supersymmetry is considered to be the most attractive extension of the SM:

- relates the s=$\frac{1}{2}$ fermions to s=0,1 bosons;
- relates internal and space-time symmetries;
- if SUSY is made local, we recover gravity;
- is naturally present in Superstrings theory.
  - To each particle $\Rightarrow$ a superparticle (sfermions of s=0 and gauginos of s=$\frac{1}{2}$).
  - Enlarged Higgs sector: h,H,A,H^+, H^- (two doublets of scalar Higgs fields).
- Cancels divergences Λ^2 and hierarchy;
- $\mu^2 < 0$ naturally via quantum effects;
- leads to unification of gauge couplings;
- has the ideal candidate for Dark Matter...

A whole new continent to explore at the LHC!





III.3 Quo vadis? Conclusions

To recap again: the Standard Model is base on three pillars:

- **it is a theory that obeys to special relativity and quantum mechanics;**
- **a theory based on invariance with respect to gauge symmetries;**
- **uses the Higgs (or HEB, or EWSB) mechanism for mass generation.**

It predicted the existence of the Higgs particle with definite properties:
it was produced at the LHC and its properties agree with expectations!

- **Mathematically consistent theory $\Rightarrow$ extremely precise predictions.**
- **Multiple experiments since 5 decades $\Rightarrow$ tests with very high accuracy.**
- **Predictions match measurements at 0.01% $\Rightarrow$ very satisfactory theory!**

But the model has many shortocomings, and we discussed some of the problems which are of aesthetical, experimental and theoretical nature.

All these problems call for new physics beyond the Standard Model.

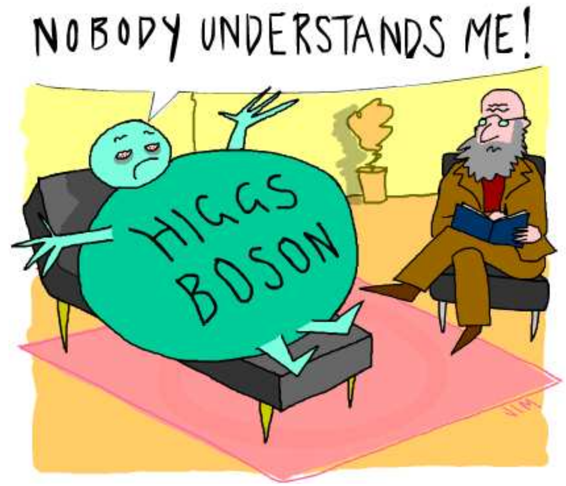
and we briefly discussed examples of bSMs addressing hierarchy problem:
composite models, models of extra-dimensions, supersymmetric theories.

III.3 Quo vadis? Conclusions

All these extensions of the SM imply a fascinating new physics:

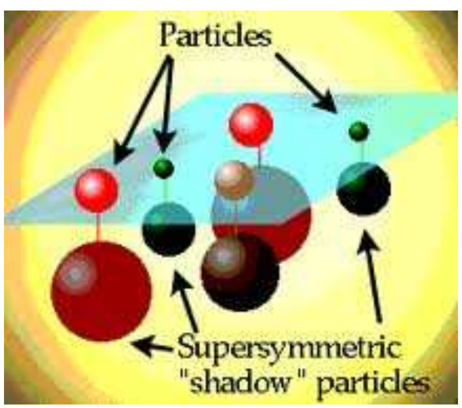
- **a Higgs sector that is slightly or completely different from the SM one,**
- **a large number of new particles with rather exotic properties,**

⇒ **attempt to discover the new predicted phenomena and study them!**



- **Via high precision tests of the Higgs boson:**

by measuring the properties of the observed H (mass, quantum number, couplings, etc..) and look for deviations with respect to SM that are induced by the new physics effects.



- **Via the production of the new particles:**

in a direct way at very high energies and, once these particles have been produced, study their properties in a detailed way.

A considerable work to be done!

III.3 Quo vadis? Conclusions

Although the Higgs was discovered, which apparently confirms the SM, Nature has not said its last word and the entire truth is still not known!

**"Now, this is not the end.
It is not even the beginning to the end.
But it is perhaps the end of the beginning."**

Sir Winston Churchill, November 1942
(after the battle of El-Alamein in Egypt...).

The journey (in the world of the two infinities...) will be certainly long, but we hope ardently that it will provide us with plenty of surprises!

**"Life has more imagination
than we carry in our dreams."**

Cristóbal Colón
(1492 in the Caribbean?)