Physics Beyond the Standard Model

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1. The Standard Model and the Higgs boson

To recap: the Standard Model is based 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;

and before the advent of LHC, had only one unknown: the H boson mass.

- The theory is mathematically consistent:

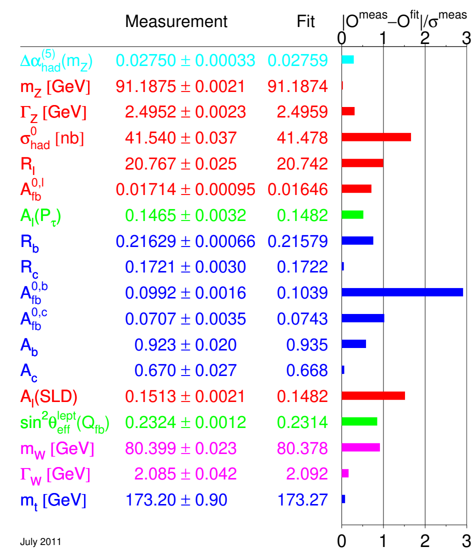
$\Rightarrow$ can make extremely precise predictions.

- Multiple experiments since five decades,

$\Rightarrow$ tested with extremely high accuracy.

- Predictions match measurements at 0.01%

$\Rightarrow$ **an extremely satisfactory theory!**



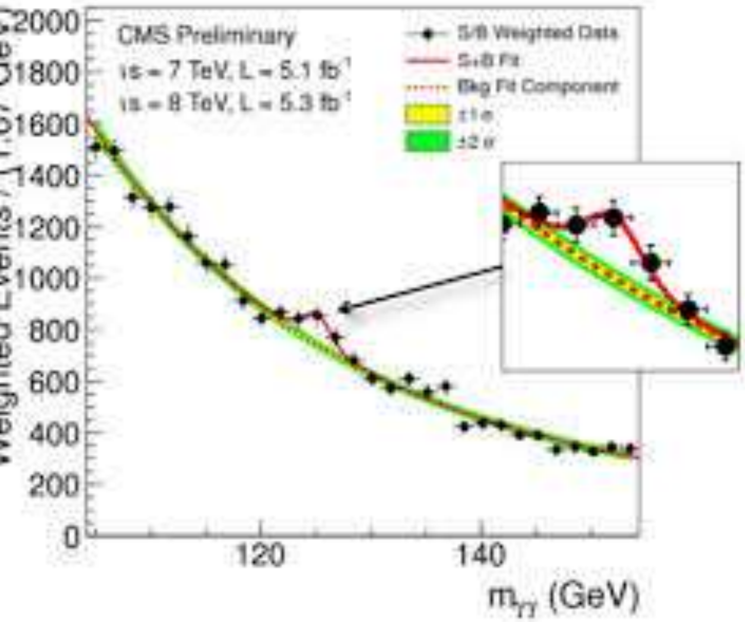
10 years ago, only remaining problem:

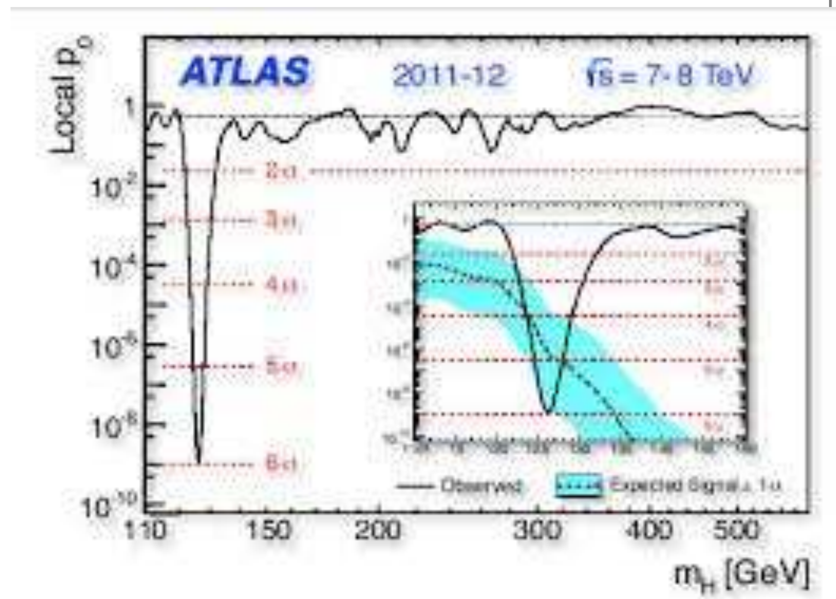
- verify the Higgs mechanism,
- discover the famous Higgs boson
- or the ingredient that does its job....

LHC was just devised for that!

1. The Standard Model and the Higgs boson

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

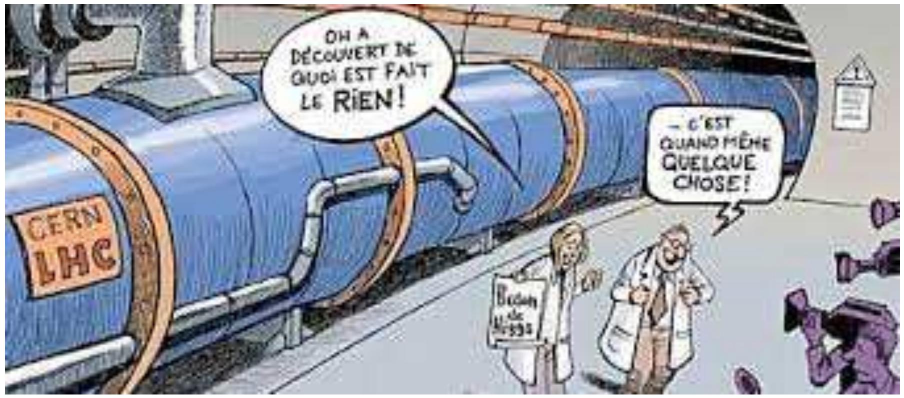




1. The Standard Model and the Higgs boson

Now that the Higgs is discovered and the SM is confirmed in a spectacular way, is Particle Physics closed? Should we stop physics and go for vacations?

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 $\Rightarrow$ we need a new paradigm to achieve this aim.**

2. Shortcomings of the Standard Model

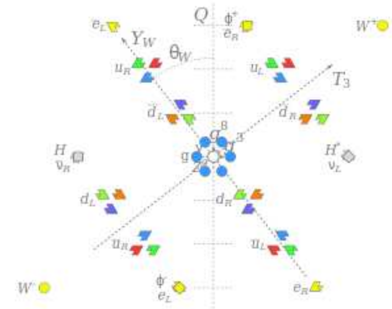
• Problems of aesthetic nature: SM too complex and too many ingredients, we want a theory with a few parameters and basic ingredients/principles.

• 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.

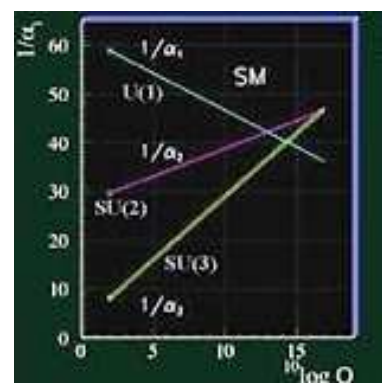
• Unification of teh gauge interactions?

– 3 gauge groups with 3 different couplings,

– better: only one group and one coupling,

– coupling unification at a very high scale?

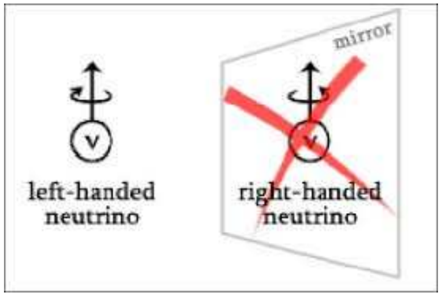
– the three gauge couplings do not converge.



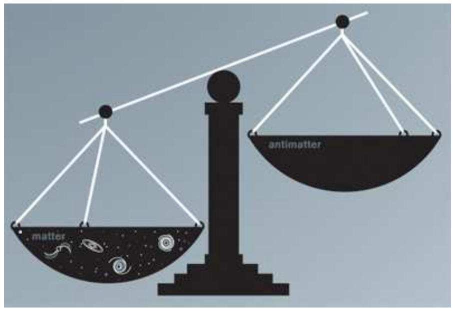
2. Shortcomings of the Standard Model

• 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:



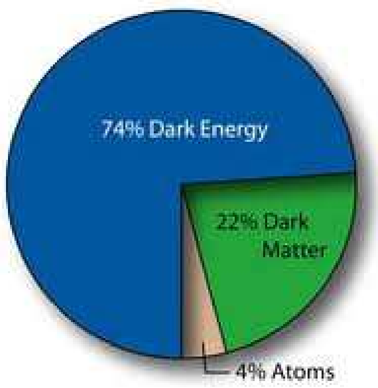
– in the SM, the neutrinos are left-handed;
– nature: neutrinos oscillate $\Rightarrow$ massive;
– their mass is not coming from the Higgs;
– we need right-handed neutrinos ($\neq$ left).



• No baryon asymmetry in the universe:

– there is a one billion p for a single $\bar{\mathrm{p}}$,
– at early times, CP conserved and $\mathrm{n_p} = \mathrm{n_{\bar{p}}}$;
– 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 formed by dark or invisible matter;
– Astroparticle: must be massive and cold ($\mathrm{v} \ll \mathrm{c}$);
– in the SM, there is not such a particle which is: neutral, weakly interacting, massive and stable.

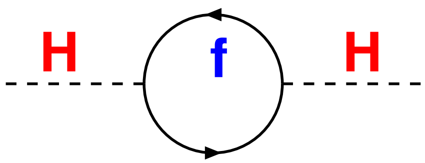
2. Shortcomings of the Standard Model

• 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.

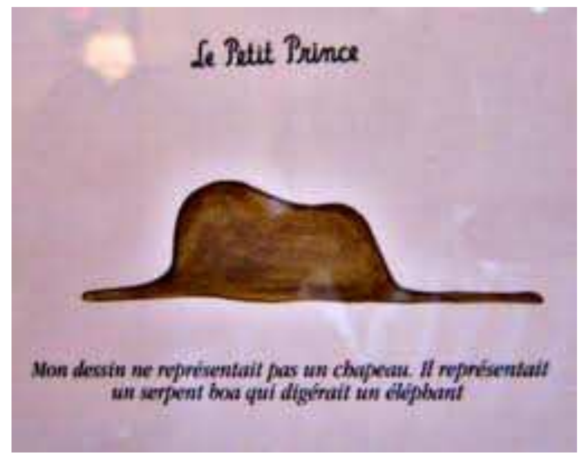
• But we should include all quantum corrections to the Higgs mass:
⇒ contributions to M_H of order M_P while they should be $\approx M_{W,Z}$.

$$\Delta M_H^2 \; =$$



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

– 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 closer to the high scale.

3. Three avenues for beyond the Standard Model

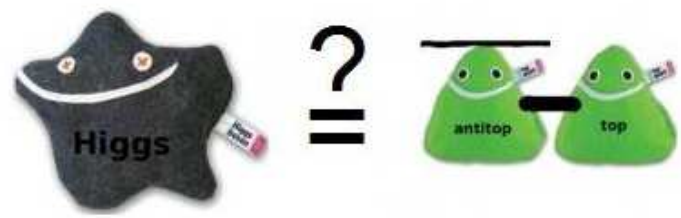
Three main avenues to solve the hierarchy problem of the SM.

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
(there 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 $\neq$ from those of the standard H.

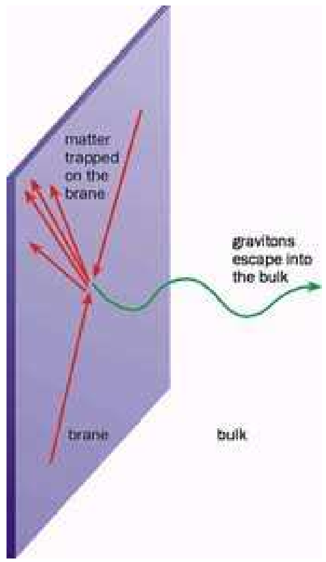
Both theories are of strong interaction $\Rightarrow$ constrained by experiment.

3. Three avenues for 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 $\mathrm{M_P^{eff}} \approx \Lambda \approx$ TeV,
not $\mathrm{M_p} = 10^{18}$GeV; gravity now in the game.
Several possibilities to realize the scenario:
large, warped, universal extra dimensions, ...



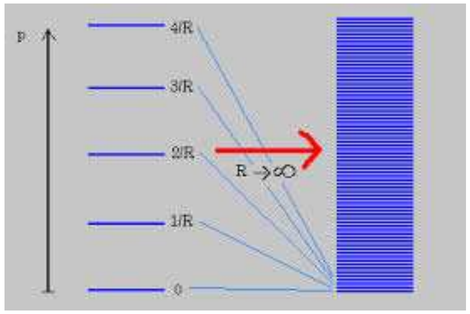
Enormous impact on particle physics!
(with solutions to other SM problems).

- But we still need a 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.

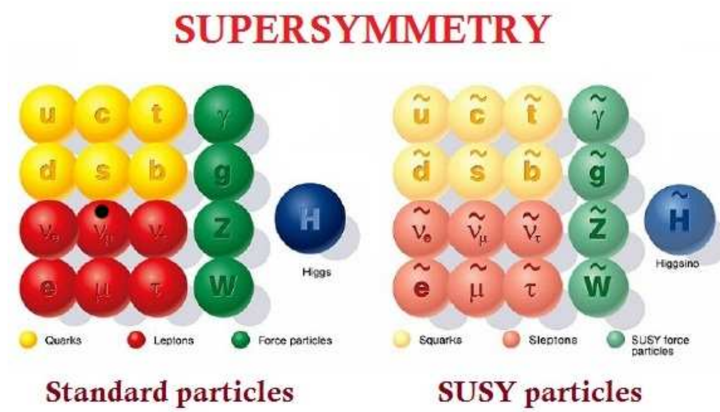
3. Three avenues for beyond the Standard Model

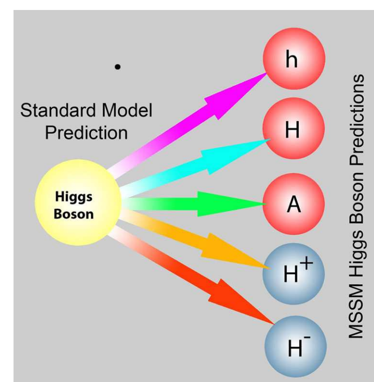
Three main avenues to solve the hierarchy problem of the SM.

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 Λ^2 divergences and hierarchy;
- $\mu^2 < 0$ naturally via quantum effects;
- leads to unification of gauge couplings;
- has the ideal candidate for Dark Matter.





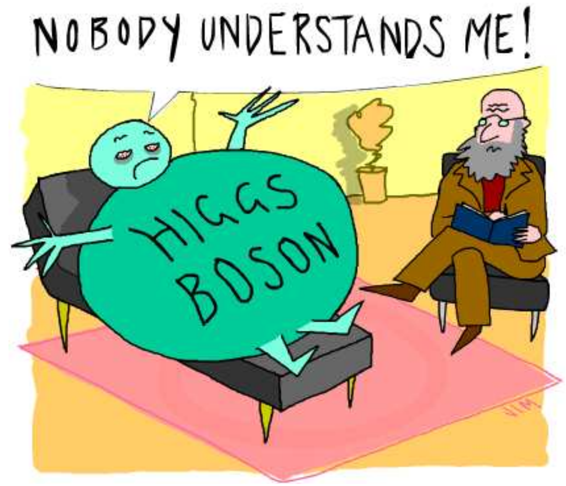
A whole new continent and with a rich phenomenology to explore at LHC!

4. Conclusions

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

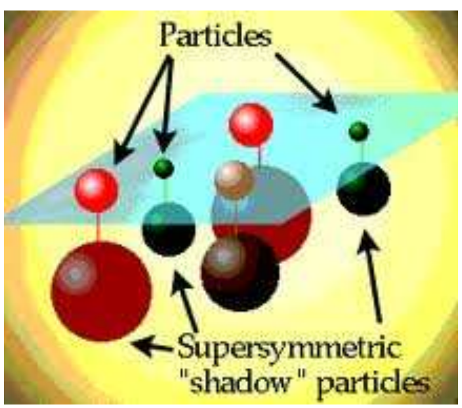
- a Higgs sector that is slightly or completely different from the SM one,
- a large number of new particles with rather exotic properties,

$\Rightarrow$ 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 (its mass, quantum number, couplings, etc) and look for deviations with respect to the SM which 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!

4. 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?)