The Universe of Elementary Particles

or

The Standard Model of Particle Physics and Beyond

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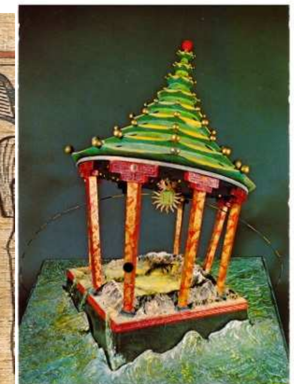
Contents:

1. Particle physics as an explanation of the world

Always, mankind has tried to understand the world that surrounds it:

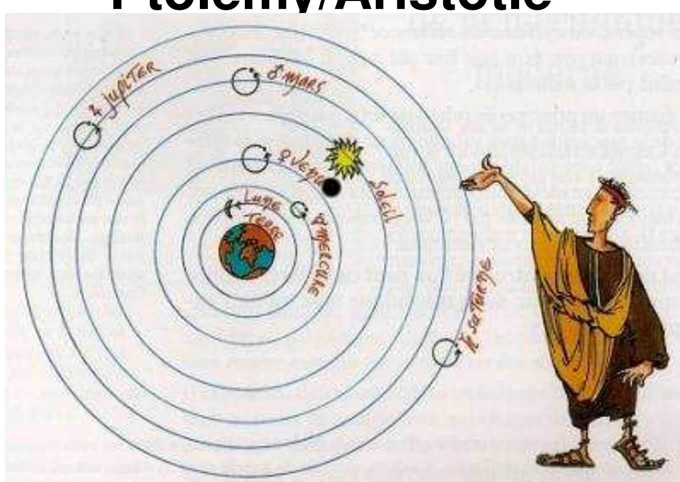
How did it form? How is it organized? What will it become?

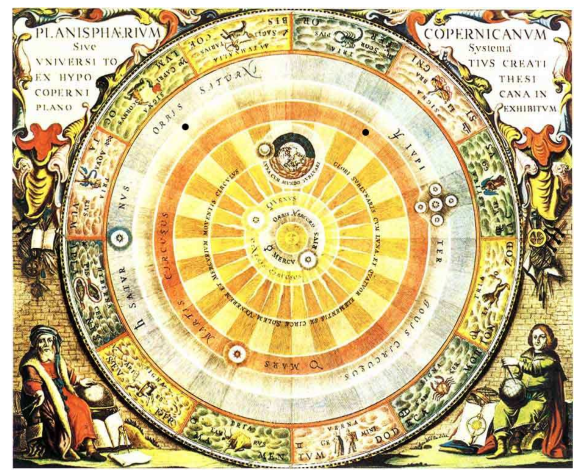
Mesopotamia **Egypt** **China**



Heaven, Earth, Hell?

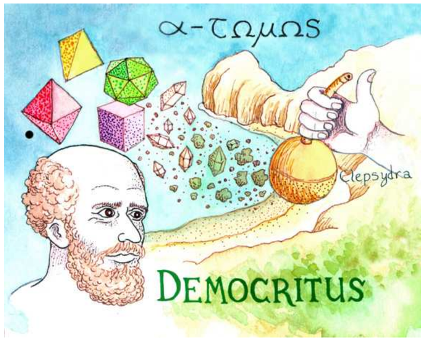
Homer **Ptolemy/Aristotle** **Aristarque of Samos**

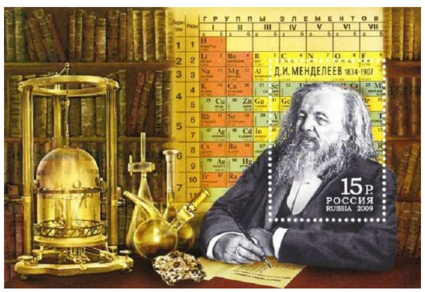


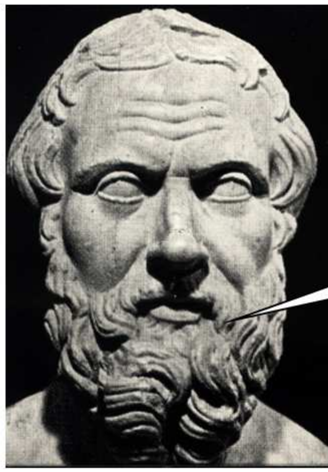


1. Particle physics as an explanation of the world

The antique Greeks started to give some naive but plausible answers:



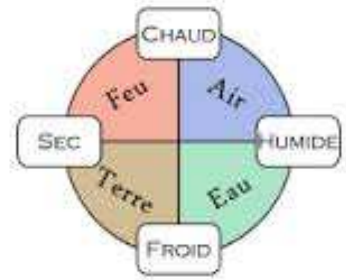




DEMOCRITE

IV^{ème} siècle AVJC

La matière est constituée de corpuscules invisibles à cause de leur extrême petitesse, indivisibles et éternels.



ARISTOTE

IVème siècle AVJC

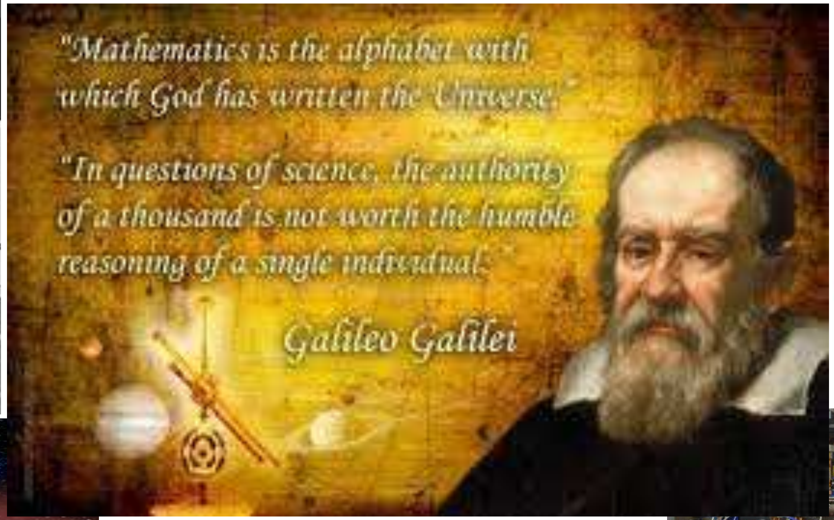
Mais non ! On sait tous que la matière est constituée des quatre éléments: l'eau, la terre, le feu et l'air…

1. Particle physics as an explanation of the world

But at least since Galileo, we know the language to answer these questions
Galileo (among others) also gave us the two instruments which help to do it.

The Telescope

Mathematics



The Pisa experiment

+
Experiment
=
"Physics"

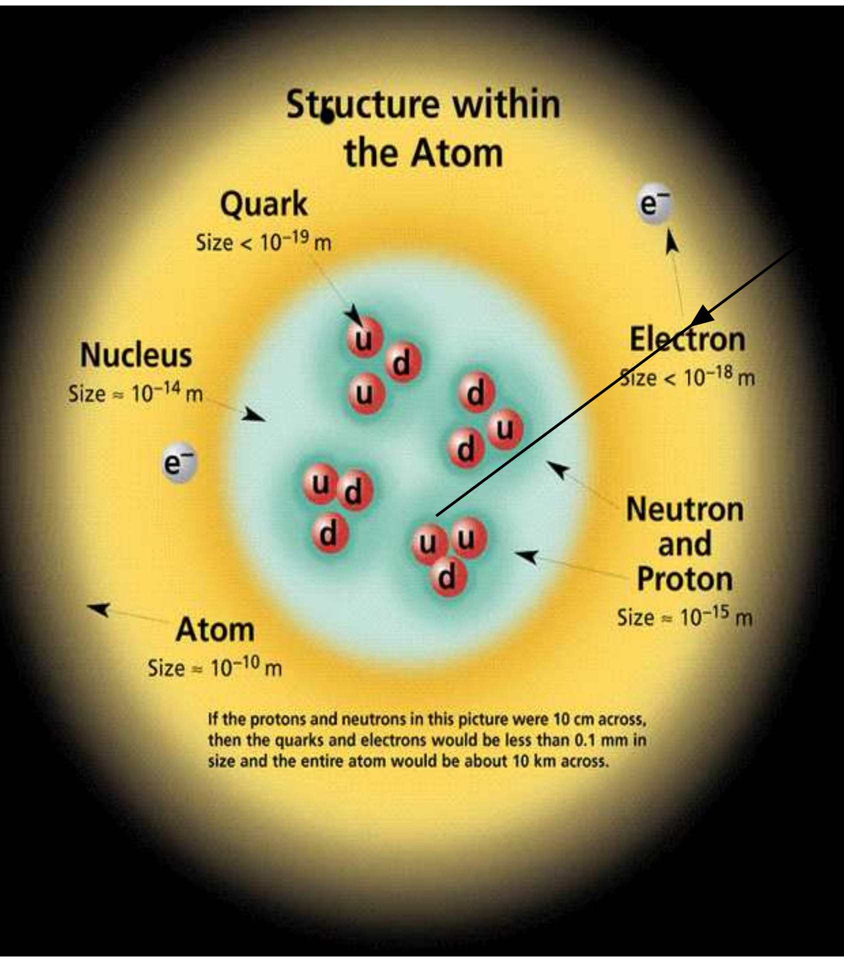
The Planck satellite

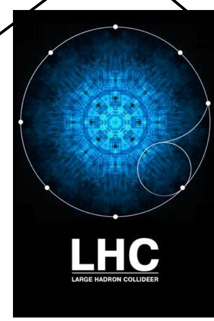
Le LHC accelerator

1. Particle physics as an explanation of the world

The experiment in Laboratory, from Galileo to the LHC led to:

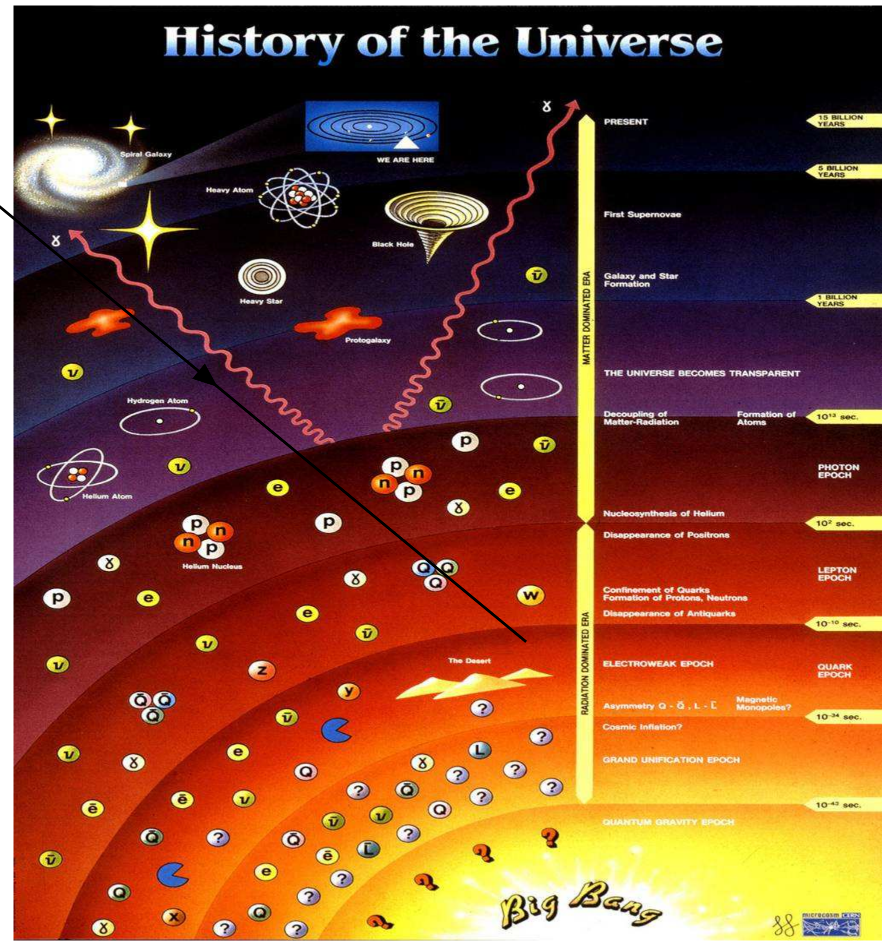
The observation of the sky from then to the Planck satellite led to:





1 TeV

$$\approx 10^{-12}\,\mathrm{s} \approx 10^{16}\,\mathrm{K}$$

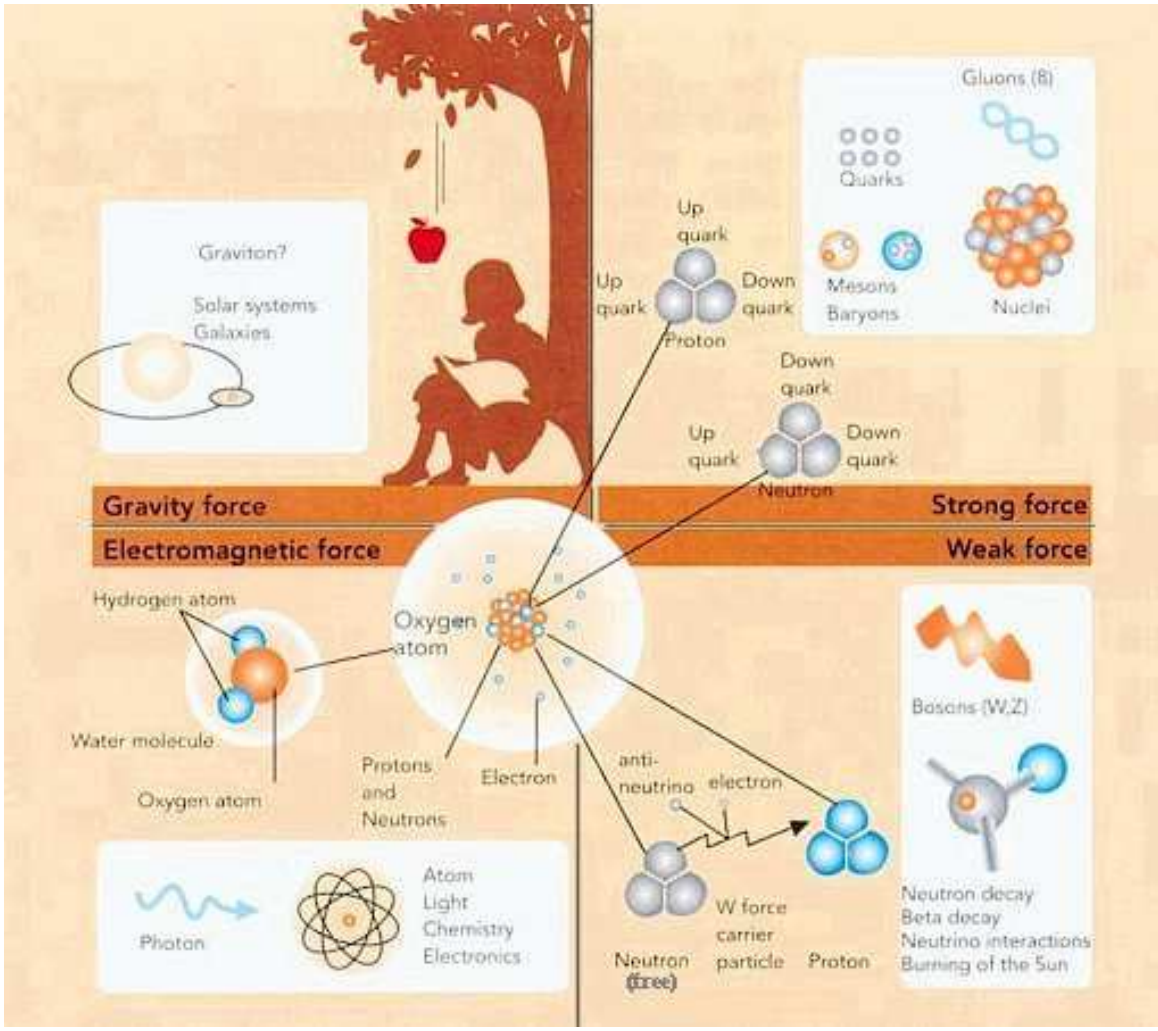


.. and the two – the infinitely small and infinitely big – meet...

2. The elementary particles and their interactions

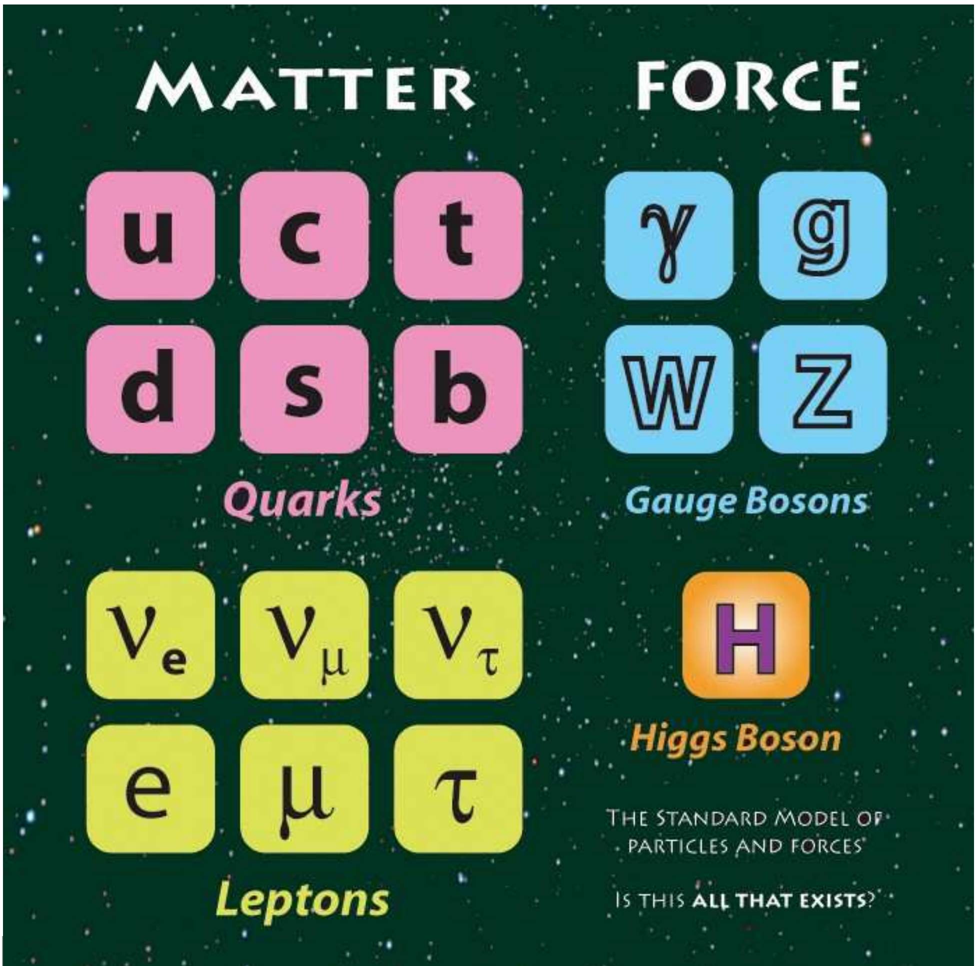
We have observed only four fundamental interactions in Nature:

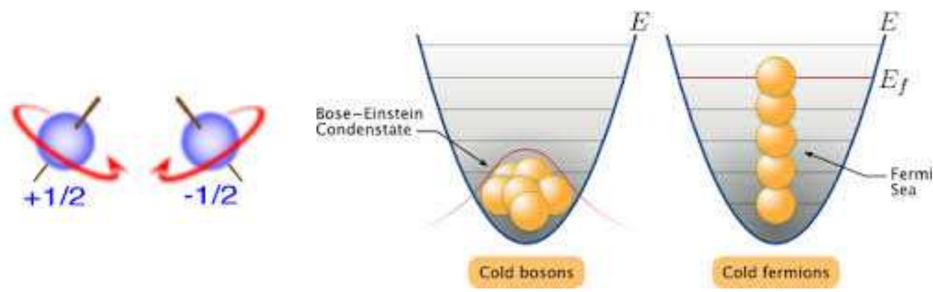
the gravitational, electromagnetic, nuclear strong and nuclear weak forces.

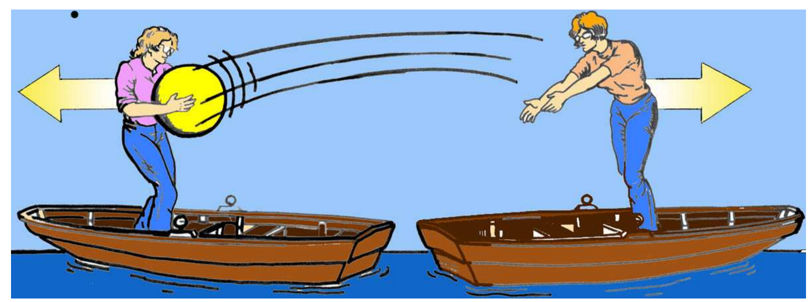


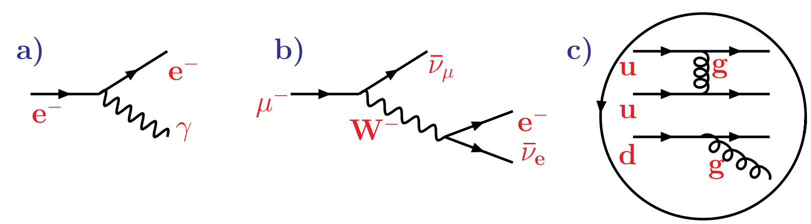
2. The elementary particles and their interactions

We have a theory, the Standard Model (SM), that describes this microcosm:
three of fundamental interactions in Nature (excluding the gravitational one):
interactions of matter particles (s=$\frac{1}{2}$) via exchange of force particles (s=1).





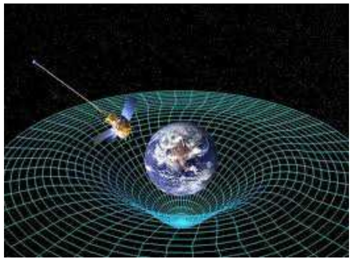


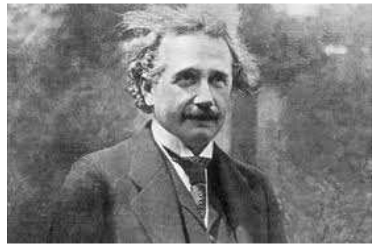


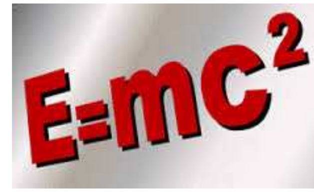
2. The elementary particles and their interactions

The SM uses the language of Mathematics and three pillars of Physics:

A. The theory obeys the laws of Einstein's special relativity (1905).







- The physical laws are the same in any inertial frame of reference (not subject to an acceleration): there is no absolute/privileged frame.
- The speed of light in vacuum, denoted by c, is a universal constant:

  c = 300.000 km/s (or 1 billion km/h) and cannot be exceeded.

  It has major implications for physics; here are some of them:

- the end of absolute time and absolute space: space-time vector x=($\vec{x}$, t),
- at very high speed, close to c, time dilatation and length contraction,
- only particles without a mass, like the photon, can travel at v=c,
- equivalence between the mass and the energy; at rest, one has E=mc^2.

$\Rightarrow$ at high energies (LHC), elementary particles travel at a speed v$\approx$c.

2. The elementary particles and their interactions

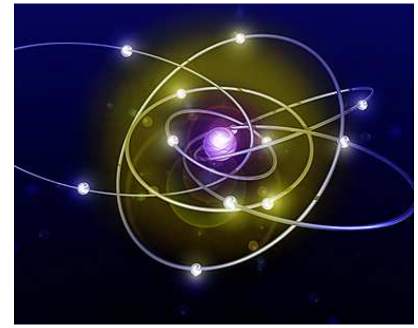
B. The theory obeys the laws of Quantum Mechanics (years 1920–1930).

- **The wave particle duality: fields**

– **electron:** $\mathbf{e} \Rightarrow \mathbf{\Psi}(\vec{x},t) \equiv \mathbf{\Psi}(\mathbf{x})$

– **photon :** $\gamma \Rightarrow \mathbf{A}(\vec{x},t) \equiv \mathbf{A}(\mathbf{x})$

Particles non-localized: probabilistic view.
Schrödinger's cat: dead and alive?



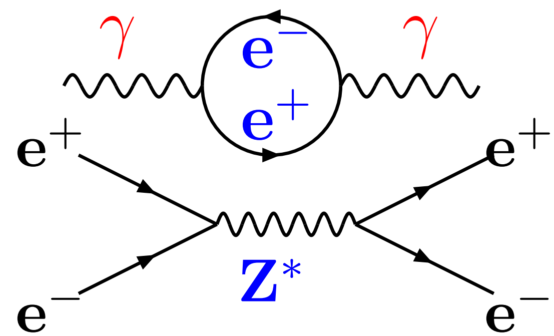
- **Heisenberg uncertainty principle :**

$$\left.\begin{array}{l}\Delta\vec{x}\Delta\vec{p} \geq \frac{1}{2}\hbar \\ \Delta t \Delta E \geq \frac{1}{2}\hbar\end{array}\right. \Rightarrow \mathbf{\Delta x \cdot \Delta p} \geq \frac{\mathbf{1}}{\mathbf{2}}\hbar$$

large uncertainty possible on x, p**.**

- **Quantum fluctuations:**

during an infinitesimal time ($\mathbf{\Delta}\mathrm{t} \ll \frac{\mathbf{1}}{\mathbf{2}}\hbar$**)**
possible violation of conservation laws
for energy ($\mathbf{\Delta}\mathrm{E} \gg \frac{\mathbf{1}}{\mathbf{2}}\hbar$**) and momentum.**



Quantum corrections: emission and absorption of very heavy particles;
whatever happens in intermediate state is called virtual effect or state.

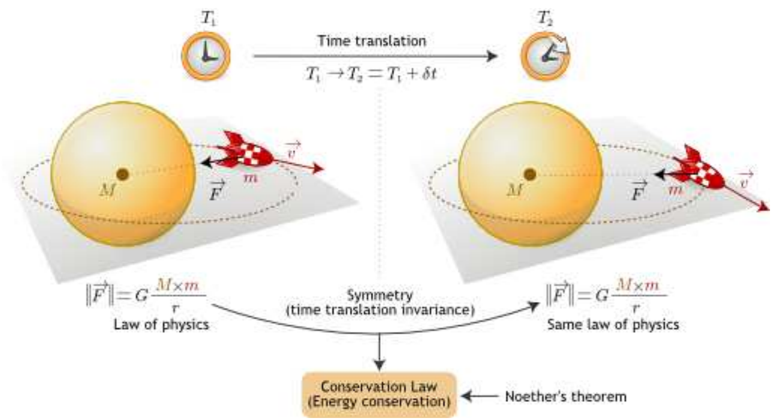
2. The elementary particles and their interactions

C. The theory makes extensive use of the symmetries of Nature (aesthetic).

At least three types of symmetries that play an important role in the SM:

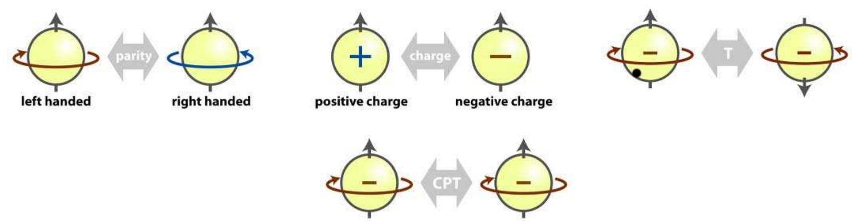
- **Space-time symmetries:**

translations $(\mathrm{t}, \vec{\mathrm{x}})$, rotations, etc..
known continuous symmetries.
Noether: conservation of $\mathrm{E}, \vec{\mathrm{p}}, \vec{\omega}$, ...



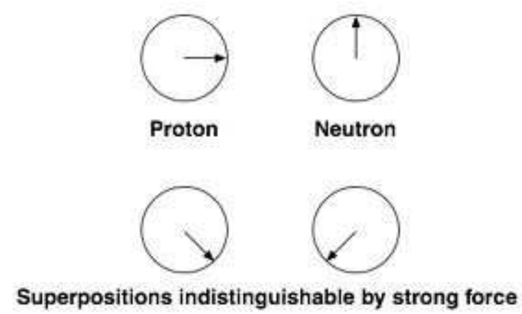
- **Discrete symmetries:**

parity-P, charge-C et T-reversal;
quantum number conservation.
CPT is always conserved.



- **Internal symmetries:**

"rotations" in an internal space,
ex: proton$\equiv$neutron for strong force;
same physics in interchange of p$\leftrightarrow$n;
isospin symmetry: doublet $\mathrm{N} \equiv \binom{\mathrm{p}}{\mathrm{n}}$.



2. The elementary particles and their interactions

C. The theory makes extensive use of the symmetries of Nature (aesthetic).

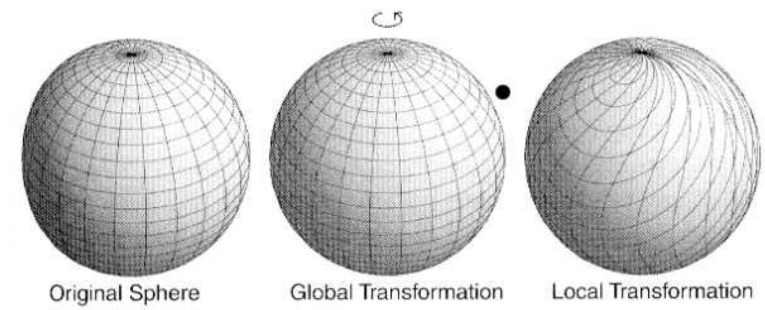
- **Gauge symmetries:**

isospin: global internal transformation

transf. x dependent $\Rightarrow$ local symmetry

$$\Psi(x) \to \Psi'(x) = T(x)\Psi(x)$$

more general and has a huge impact.



The prototype of a gauge symmetry: Quantum Electro-Dynamics (QED).

Invariance under local phase transformations of the U(1)$_Q$ group:

- **transformation of electron field:** $\Psi(x) \to \Psi'(x) = e^{iQ\alpha(x)}\Psi(x)$,
- **transformation of photon field:** $A(x) \to A'(x) = A(x) - \frac{1}{Q}\partial_\mu \alpha(x)$.

$\Rightarrow$ **the physics (or system) is invariant under these transformations,**

$\Rightarrow$ **the quantity conserved by the symmetry is the electric charge Q,**

$\Rightarrow$ **once symmetry group chosen: interaction and number of bosons fixed,**

$\Rightarrow$ **the invariance implies massless gauge bosons (like photons).**

Gauge Theories: aesthetical/geometry, simplicity/minimality, predictivity;

should possibly be extended to all known interactions!

3. The Standard Model of Particle Physics

The Standard Model describes electromagnetic, weak and strong interactions:

The electromagnetic interaction (QED):

– subjects: electrically charged particles,
– mediator: the massless photon,
– conserves P, C, T... and of course Q.

The strong nuclear interaction (QCD):

– quarks appear in triplets q, q , q,
– interact via the exchange of color,
– mediators: eight massless gluons,
– conserves P,C,T and color number;
– color = attraction $\Rightarrow$ confinement!

Nuclear weak interaction:

– subjects: all known s=1/2 fermions;
– mediators: the massive W^+, W^-, Z (only interaction with short range),
– does not conserve parity: $f_L \neq f_R$; (ex: there is no $\nu_R \Rightarrow \nu$ massless);
– does not conserve CP: $n_P \gg n_{\bar{P}}$.

Particules de: matière (s=1/2) force (s=1)

3 familles de fermions — bosons-jauge

c→ Q→ m→	quark up ^{3}u $+2/3$ $\sim$5 MeV	quark charm ^{3}c $+2/3$ 1.6 GeV	quark top ^{3}t $+2/3$ 172 GeV	gluon ^{8}g 0 0
	quark down ^{3}d $-1/3$ $\sim$5 MeV	quark strange ^{3}s $-1/3$ 0.2 GeV	quark bottom ^{3}b $-1/3$ 4.9 GeV	photon γ 0 0
	neutrino e ν_e 0 ~ 0	neutrino μ ν_μ 0 ~ 0	τ neutrino ν_τ 0 ~ 0	boson Z Z^0 0 91.2 GeV
	electron e -1 0.5 MeV	muon μ -1 0.1 GeV	tau τ -1 1.7 GeV	bosons W $W^\pm$ ±1 80.4 GeV

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

3. The Standard Model of Particle Physics

Standard Model based on $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ gauge symmetry.

- The local $\mathrm{SU(3)_C}$ symmetry group describes the strong interactions:
  - strong interaction between q,q,q which are color triplets of SU(3),
  - mediated by 8 gluons, which correspond to 8 generators of SU(3).
- $\mathrm{SU(2)_L \times U(1)_Y}$ is for the unified electromagnetic+weak interactions:
  - acts on quarks/leptons of isospin Left (doublets) and Right (singlets),

$$\binom{\nu}{\mathrm{e}}_{\mathrm{L}} \, , \; \mathrm{e_R^-} \, , \; \binom{\mathrm{u}}{\mathrm{d}}_{\mathrm{L}} \, , \; \mathrm{u_R} \, , \; \mathrm{d_R} \, , \; \cdots$$

idem for the other families; neutrinos are massless $\Rightarrow$ there are no ν_{R};

- mediated by the bosons W$_1$, W$_2$, W$_3$ generators of SU(2) and B of U(1):

(W$_1$,W$_2$) and (W$_3$,B) then combine to form the (W$^+$,W$^-$) and (Z,γ) bosons.

Major problem: the photon is massless but the weak bosons are massive!

Naive inclusion of a mass for W/Z bosons and also fermions breaks invariance with respect to gauge symmetry and loss of nice theory properties.

Former major problem of Particle Physics: how to generate these masses?

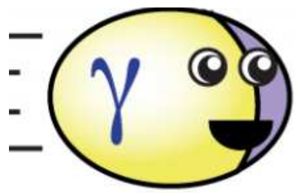
$\Rightarrow$ the Higgs-Englert-Brout mechanism of electroweak symmetry breaking!

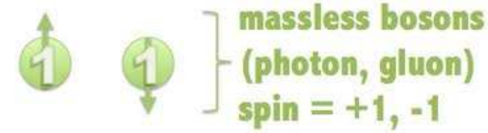
3. The Standard Model of Particle Physics

How to make a gauge boson massive without violating gauge symmetry?

Recall:

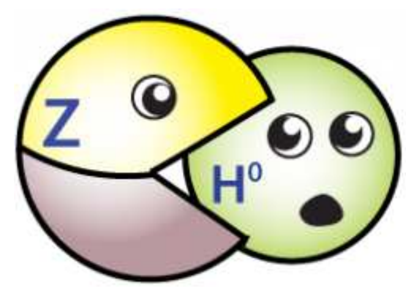
- **Photon: massless spin–1:** two degrees of freedom $\mathrm{P_x}$, $\mathrm{P_y}$, or transverse polarizations.
- **Massive boson of spin–1:** three degrees of freedom (x,y,z): i.e. + longitudinal polarization.
- **Scalar boson of spin–0:** has no polarization at all: only one degree of freedom.





"Trick":

to make a massive spin–1 state (with three degrees of freedom): make absorb a scalar (one dof) to a massless spin–1 (two dof). The "longitudinal" components of W/Z bosons can be scalars.



All this is done without altering the symmetry properties of the theory.

3. The Standard Model of Particle Physics

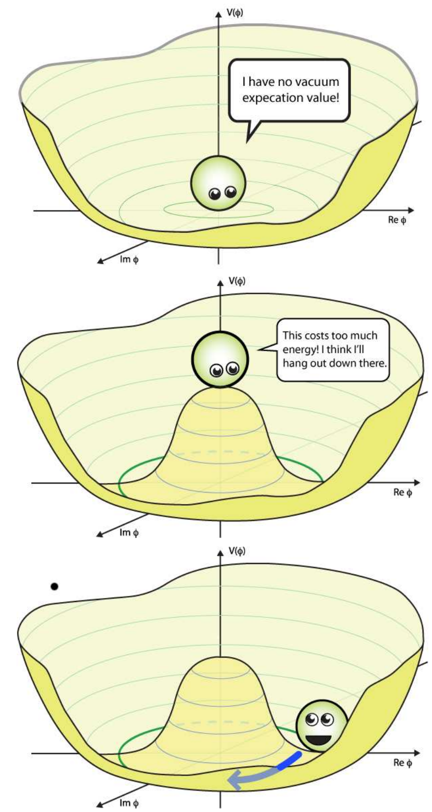
Question: how can one do that in practice for the weak interactions?

– Total energy of a system = kinetic energy plus potential energy.
– Least action: minimal energy $\Rightarrow$ at rest and minimum of potential.

- In general, the potential is a well:
the minimum of Φ is called "vacuum"
(at the bottom of the well in this case).
Everything is still symmetric...

- Imagine now a different potential,
like, for instance, this Mexican hat:
symmetry $\Rightarrow$ Φ on top of the bump;
non-minimal and costs some energy.

- Potential energy minimal $\Rightarrow$
Φ at bottom of the potential well.
Minima in a circle of radius v called
non-zero vacuum expectation value:
"spontaneously" broken symmetry.



- Look at phenomena from the point of equilibrium $\equiv$ true vacuum.
zero vev or symmetric phase: Φ is real and the "photon" is massless.
non-zero or asymmetric phase: Φ absorbed and "photon" is massive!

3. The Standard Model of Particle Physics

Application to the weak interaction:

- we have an SU(2)xU(1) symmetry,
1 gauge boson for U(1): one B field,
3 gauge bosons for SU(2): W$_1$,W$_2$,W$_3$,
all four bosons are non-massive.

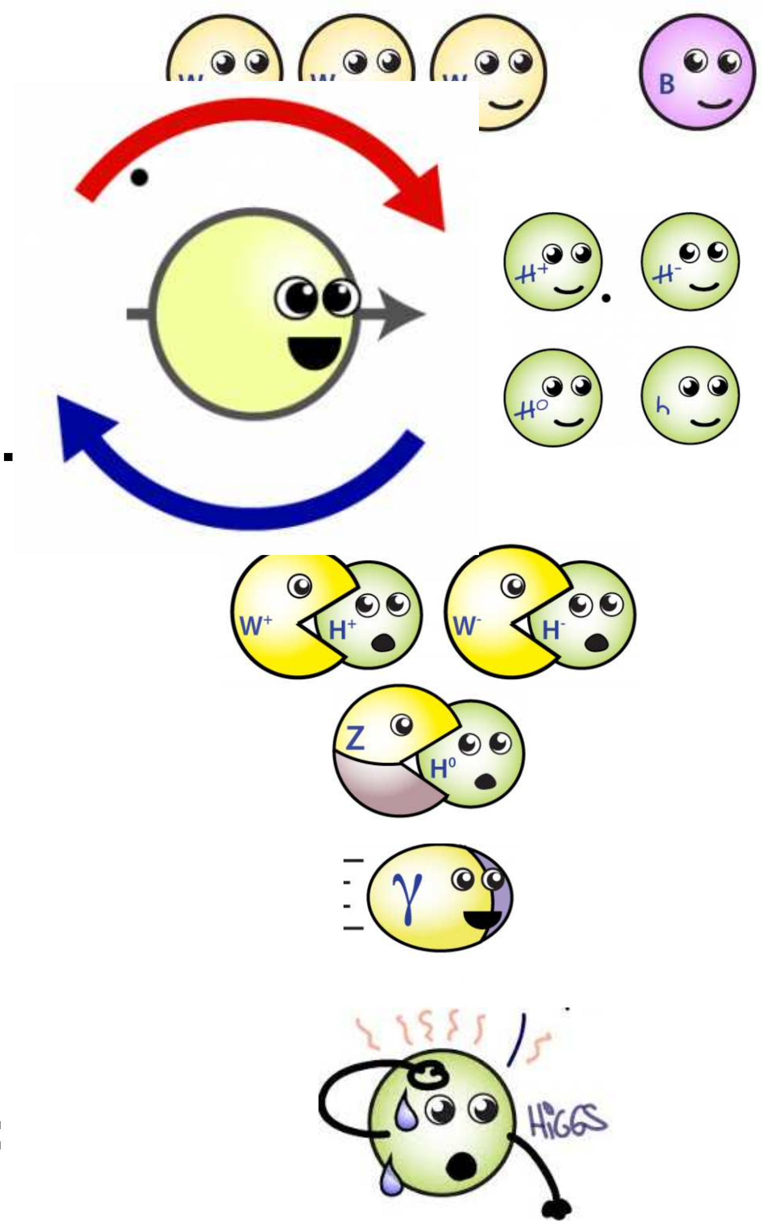
- We need 3 spin-1 massive bosons:
i.e. ≥ 3 degrees of freedom more.
Most economical: scalar complex field.
SU(2) doublet: 4 degrees of freedom.

$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} = \begin{pmatrix} H^+ + iH^- \\ h \ + iH^0 \end{pmatrix}$$

- Spontaneous symmetry breaking:
$\Rightarrow$ some scalar fields are absorbed
we have W$_1$, W$_2$ $\oplus$ H$^+$, H$^-$ $\Rightarrow$ W$^+$, W$^-$
combination of W$_3$,B $\oplus$ H^0 $\Rightarrow$ Z
combination of W$_3$,B still hungry $\Rightarrow \gamma$

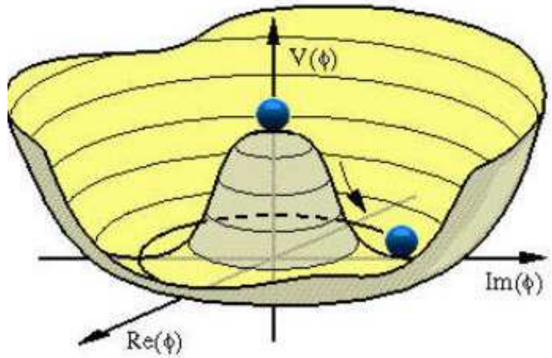
- But one scalar field is not absorbed,
it remains a physical field, a new state:

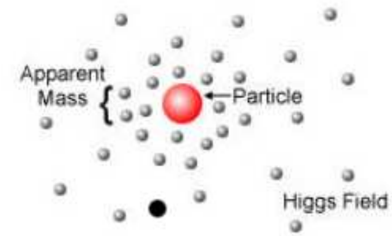
$\Rightarrow$ **it is the Higgs boson!**



3. The Standard Model of Particle Physics

Another (more "colorful") way to see things:

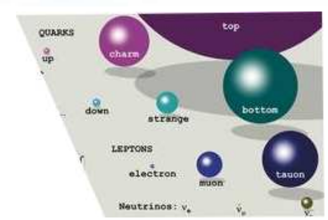




The field Φ fills all space: (exp.value$\neq$0 in vacuum) — **gives inertia,** (slows down) — **confers a mass!** (inertia = mass)

- **The field Φ and the gauge bosons:**
  - interacts more with $W^{\pm}$, Z $\Rightarrow$ very massive!
  - does not interact with $\gamma \Rightarrow$ stays massless.

- **It does the same thing with the fermions:**
  - interacts more with 3d than 2d than 1st families;
  - interacts much more with top quark: very heavy;
  - interacts little with the electron: extremely light;
  - does not interact with neutrinos: non–massive.



- **The Higgs boson also interacts with itself:**
  - the Higgs boson is a massive particle,
  - but the theory does not predict its mass.

3. The Standard Model of Particle Physics

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 5 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!

4. The LHC and the Higgs boson

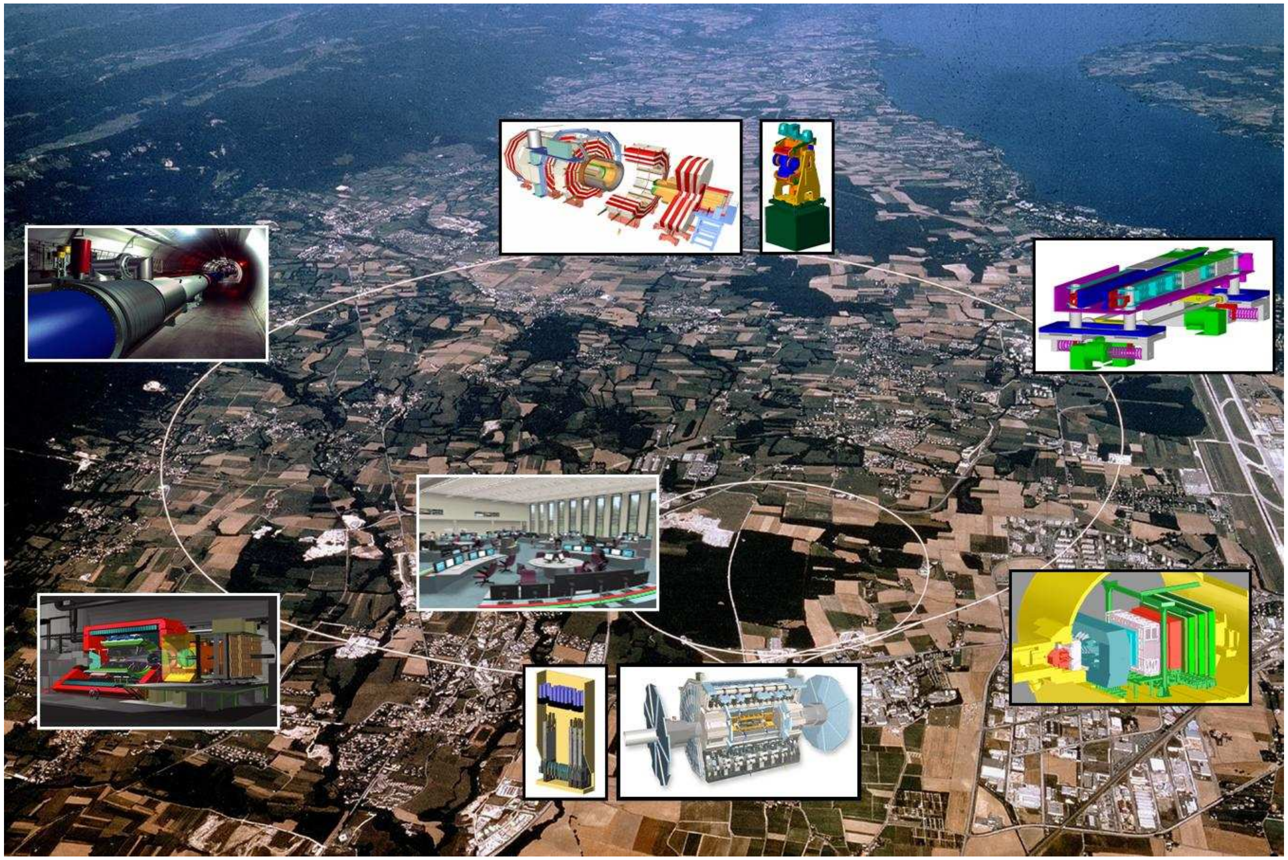
The LHC: the largest/most complex scientific instrument ever built.

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$\approx$1, at 10^{-12}s from Big-Bang;

– 1232 magnets 15m long and 8.3 Tesla, 40.000t in liquid He at 1.9°K cold;

– beams: 2800 bunches of 10^{11}protons with 10μm of diameter every 25ns!

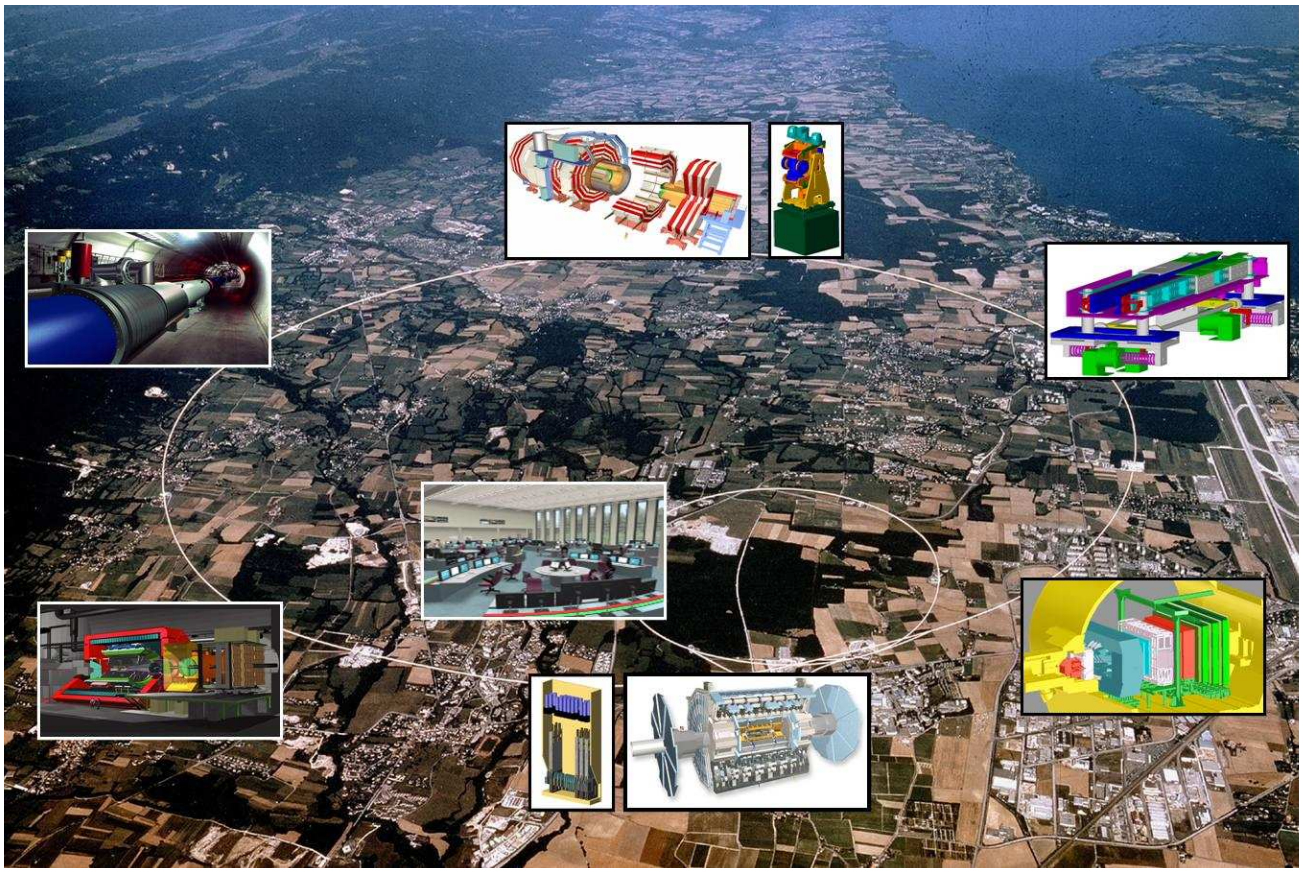


4. The LHC and the Higgs boson

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 technology (mechanics, electronics, cryogenics...)**



4. The LHC and the Higgs boson

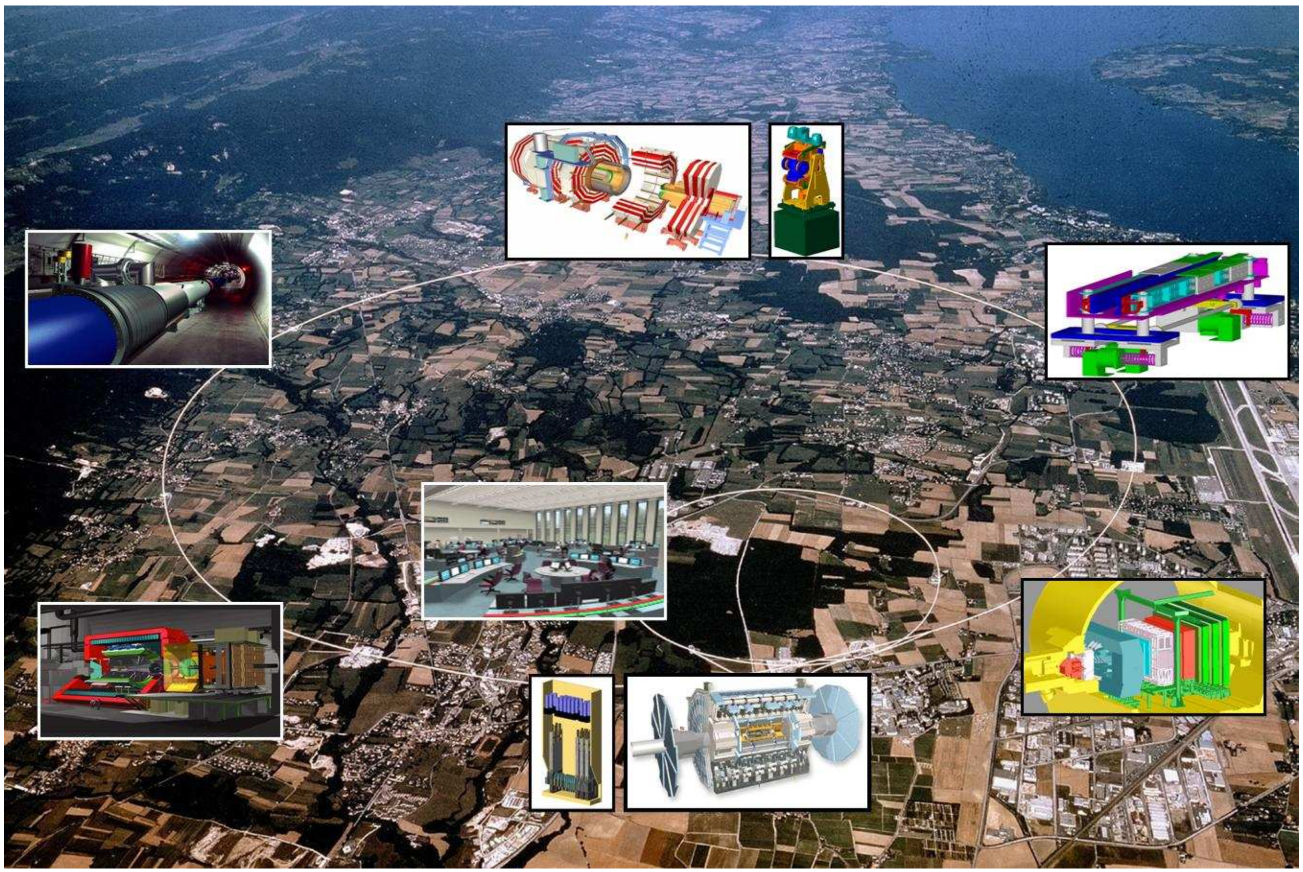
The LHC: the largest/most complex scientific instrument ever built.

Incredible computing power necessary $\Rightarrow$ "the 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.

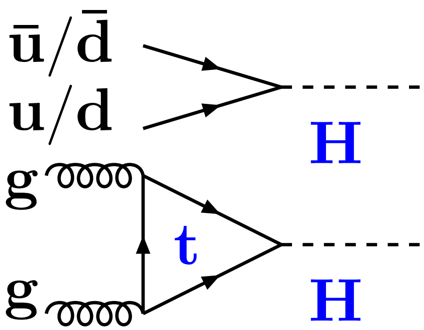


4. The LHC and the Higgs boson

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.**

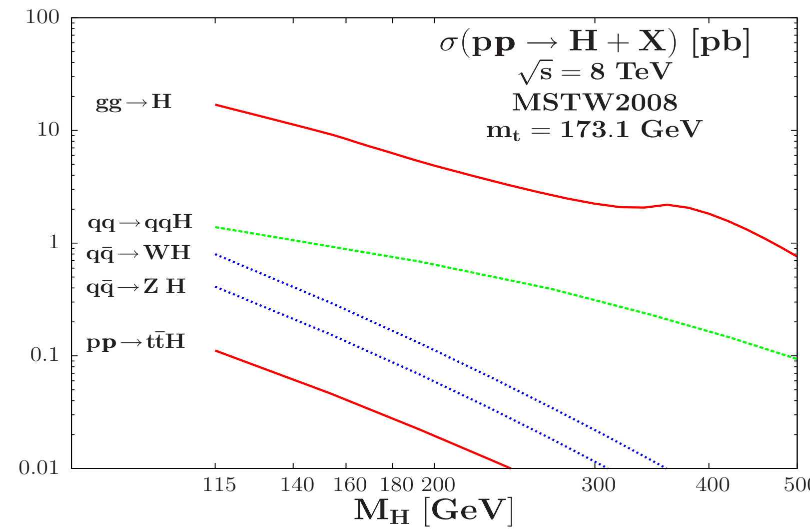
Higgs production processes:



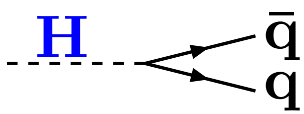
$\propto m_{u,d}^2 \Rightarrow$ no!

$\propto m_{top}^2 \Rightarrow$ yes!

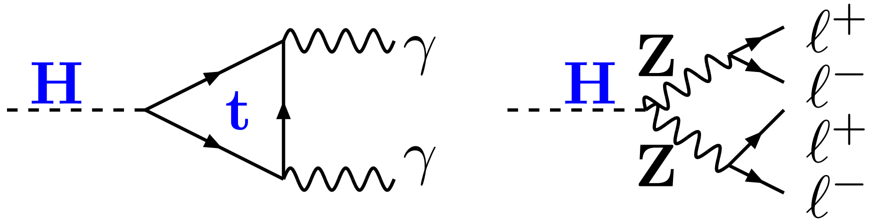
250.000 events/year at E=8 TeV.

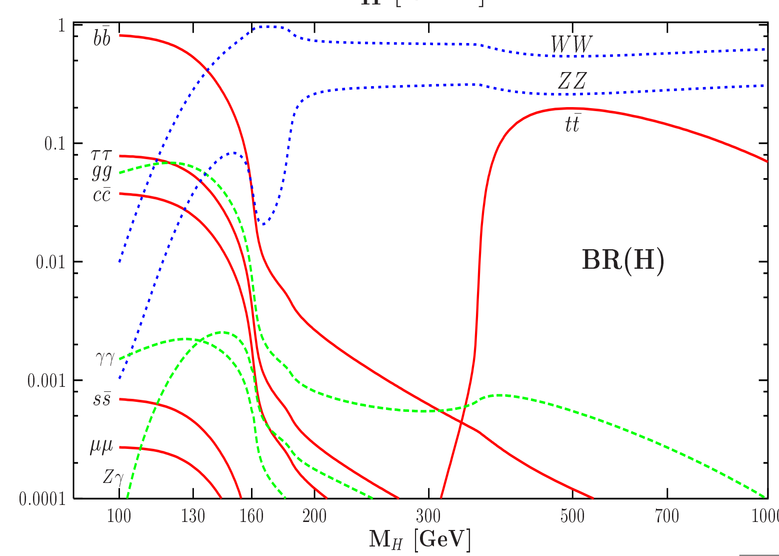


Higgs decay processes:



frequent/complicated





very rare: probability of ≈0.1%...

Very small number of total events!

4. 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).

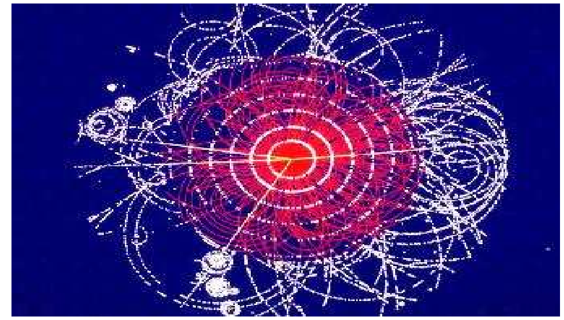
- Precise knowledge of signal and bkg essential

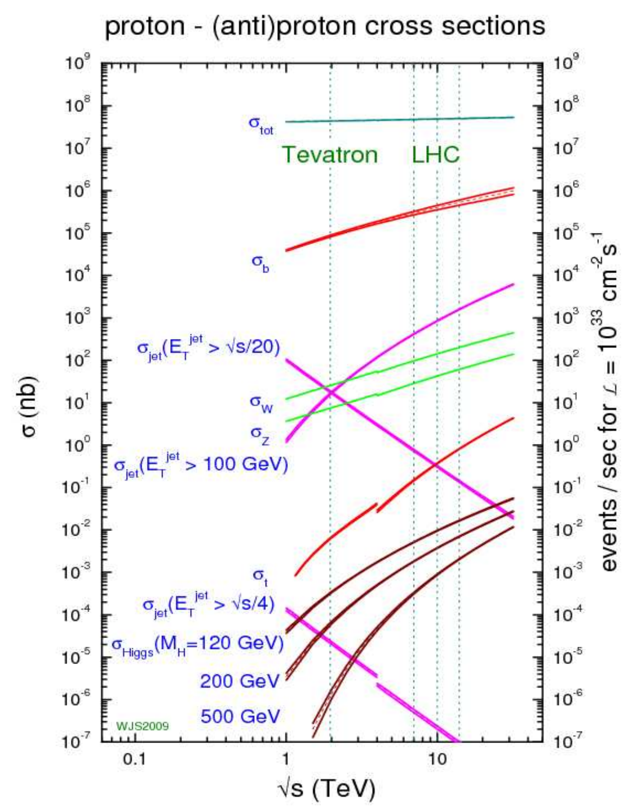
(higher order quantum effects $\approx$ factors of 2!).

- Gigantic experimental+theory effort/synergy

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

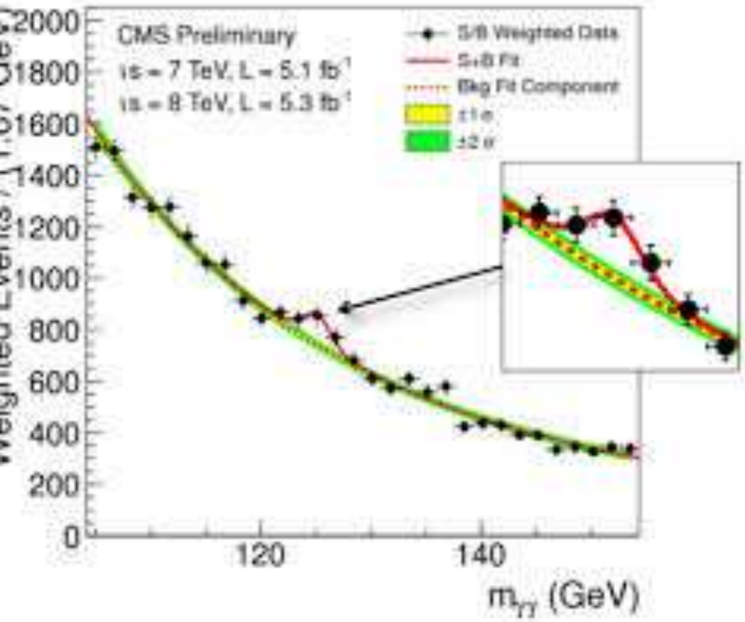
in order to leave no escape to the Higgs.

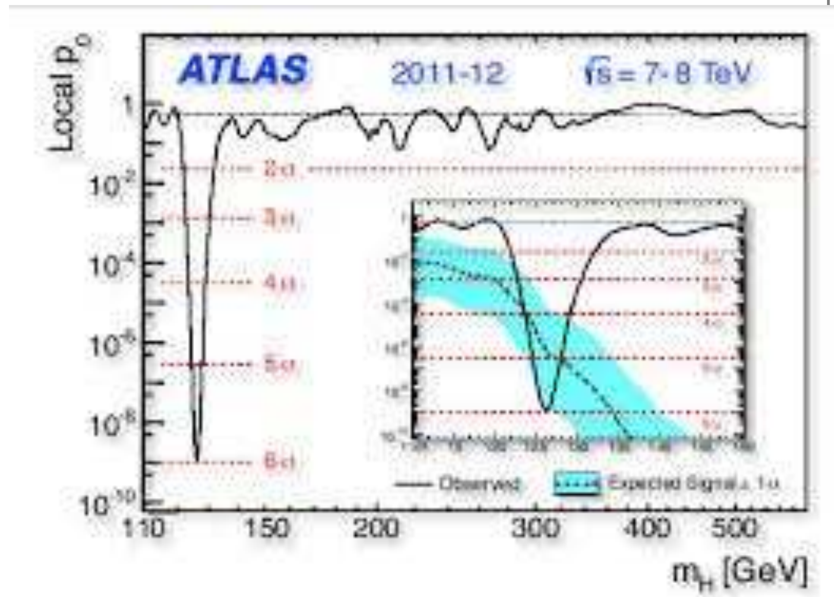




4. The LHC and the Higgs boson

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

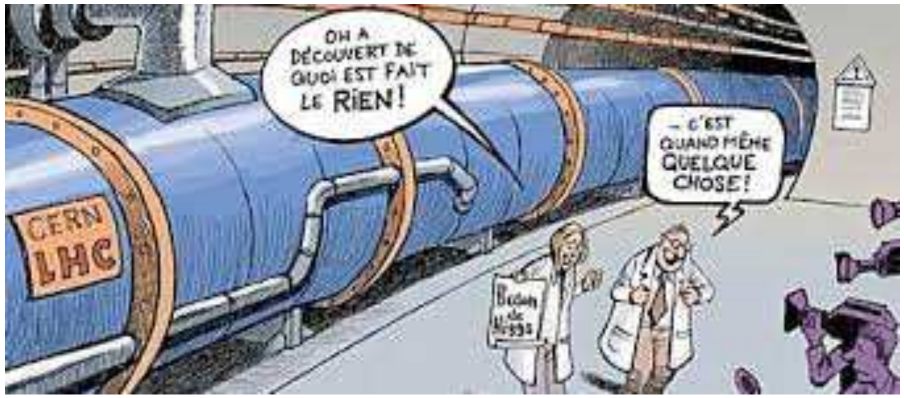




5. Quo Vadis? Beyond the SM

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 to 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....

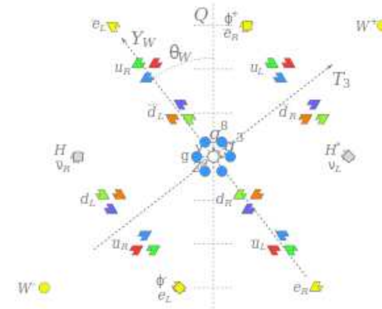
- Problems of aesthetic nature: too complex and too many ingredients, we want a theory with a few parameters and basic ingredients/principles.
- Problems of experimental nature and non-conformity to the microcosm: the SM does not explain all the phenomena that are observed in Nature.
- Problems of theoretical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

5. Quo Vadis? Beyond the SM.

● 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.

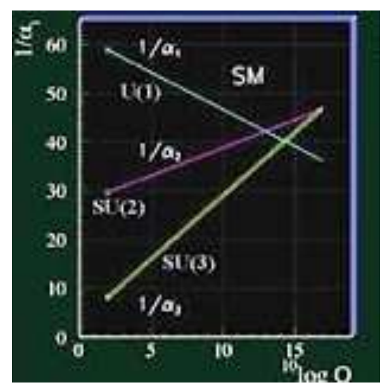


● Does not include gravitation:

– 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.

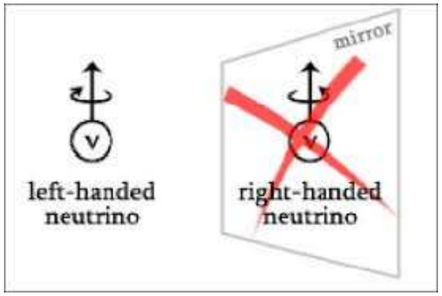


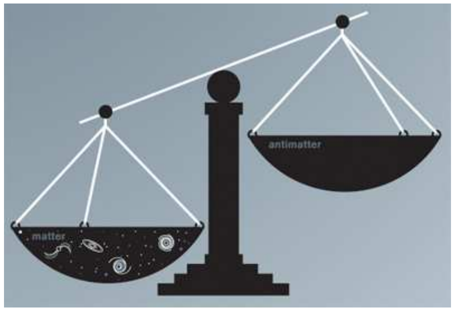
5. Quo Vadis? Beyond the SM

• 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).



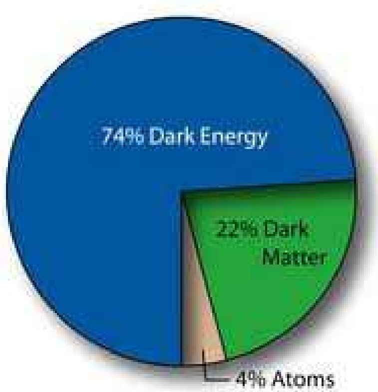


• No baryon asymmetry in the universe:

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



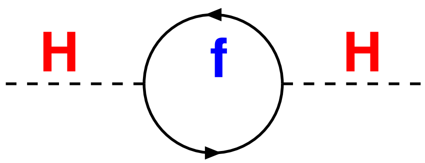
5. Quo Vadis? Beyond the SM

• **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.**

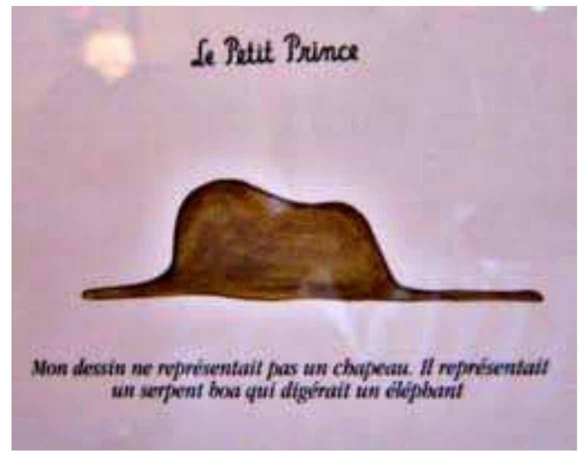
• **But we should include all quantum corrections to the Higgs mass:**
⇒ **contributions to M_H of order M_P while they should be $\approx M_{W,Z}$.**

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



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

– **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.

5. Quo Vadis? Beyond the SM

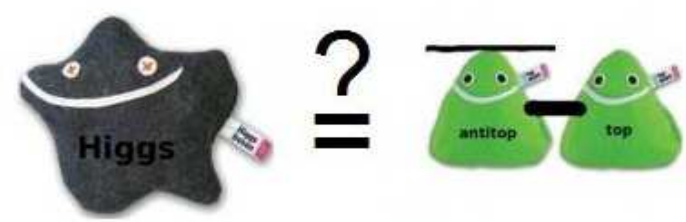
Three main avenues to solve the hierarchy problem of the SM.

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.

5. Quo Vadis? Beyond the SM

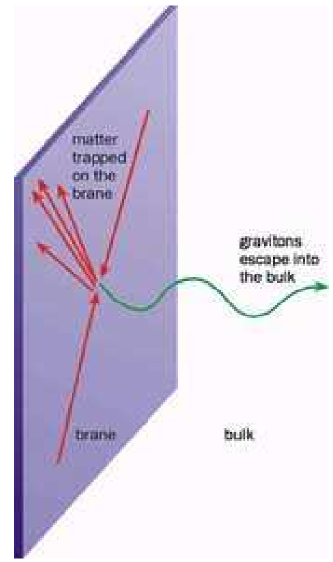
Three main avenues to solve the hierarchy problem of the SM.

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!

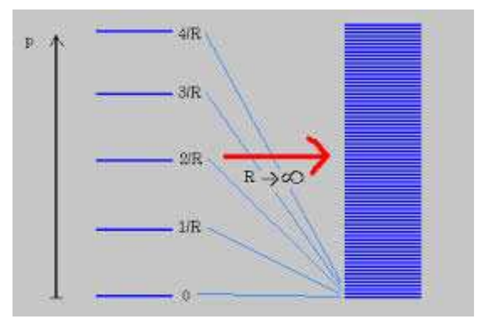
(with solutions to other SM problems).

- 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.

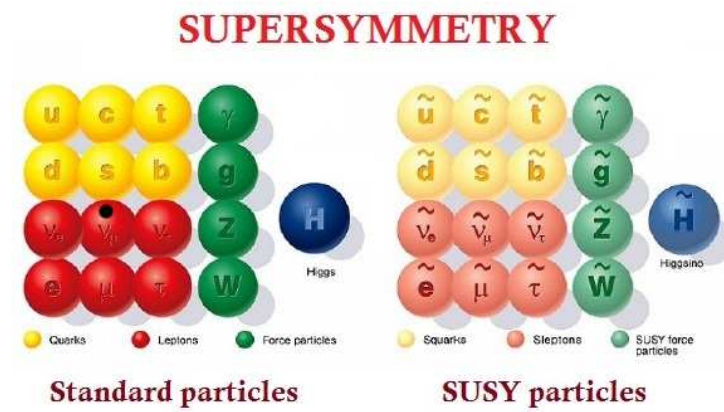
5. Quo Vadis? Beyond the SM

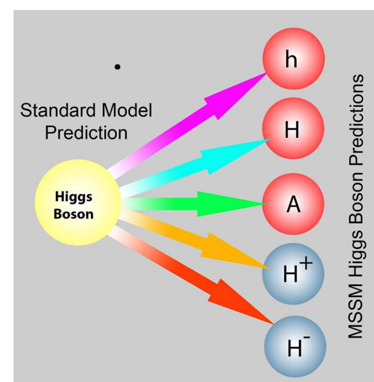
Three main avenues to solve the hierarchy problem of the SM.

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.





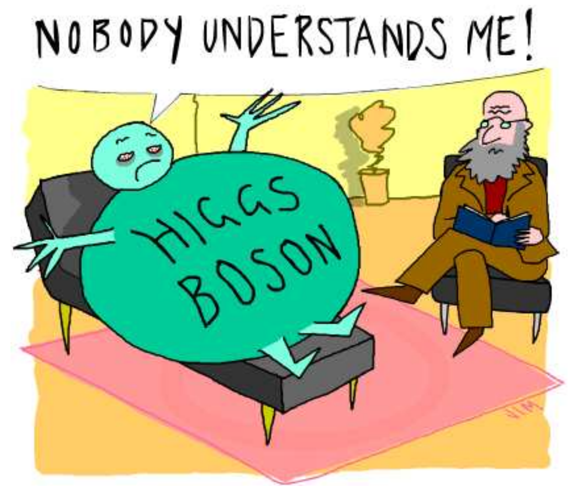
A whole new continent and with a rich phenomenology to explore at LHC!

6. Conclusions

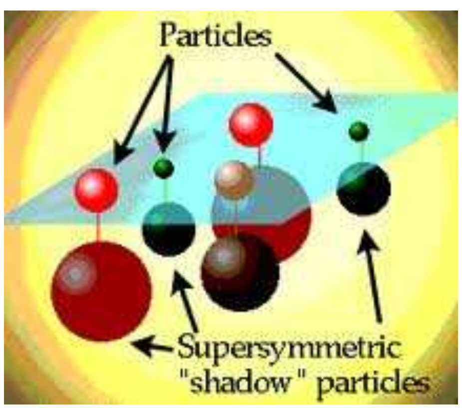
All these extensions of the SM imply a fascinating new physics:

- 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 (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!

6. 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?)