A first trip to the world of particle physics

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invisibles
neutrinos, dark matter & dark energy physics
SEVENTH FRAMEWORK PROGRAMME
MARIE CURIE ACTIONS

INFN
Istituto Nazionale di Fisica Nucleare

Itinerary

1. The forces in Nature
2. Quantum field theory
3. The "Standard" Model
4. The mystery of the Higgs
5. Beyond the Standard Model?

1

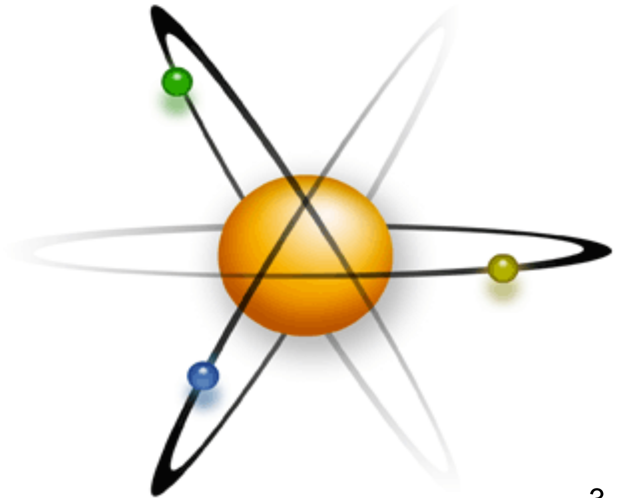
The forces in Nature

The 4 fundamental interactions

- **Electromagnetic**
- Weak
- Strong
- Gravitational

Electromagnetic interactions:

- **Hold atoms and molecules together**
- **Explain all em & optics**
- **Infinite range**
- **Mediated by the photon (QED)**



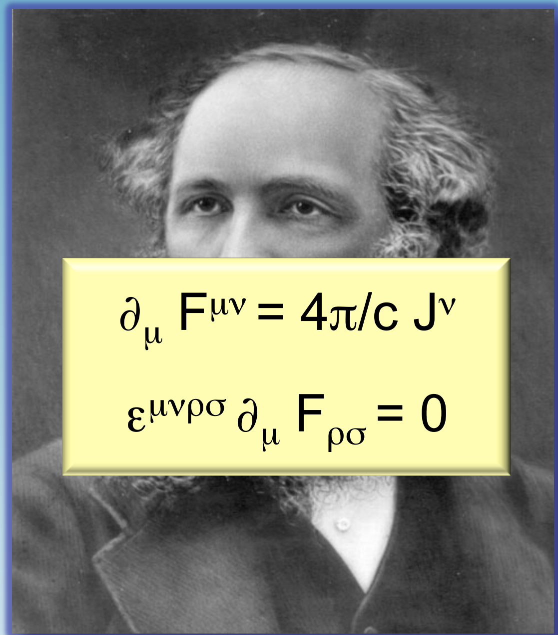
EM: Maxwell equations

I. $\nabla \cdot \boldsymbol{E} = \frac{\rho}{\epsilon_0}$

II. $\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$

III. $\nabla \cdot \boldsymbol{B} = 0$

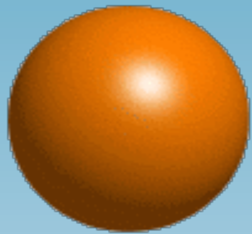
IV. $c^2 \nabla \times \boldsymbol{B} = \frac{\boldsymbol{j}}{\epsilon_0} + \frac{\partial \boldsymbol{E}}{\partial t}$



Unifying electricity and magnetism, Maxwell explained the nature of light: optics became a branch of electromagnetism.

These equations mark the beginning of the departure of physics from Mechanism.

Weak interactions



β **decays**

Muon decay

Weak interactions:

- **Are at the origin of natural radioactivity**
- **Are weak, but only at low energy**
- **Mediated by W and Z (masses ~80 and ~90 times the proton mass)**
- **Distinguish between left- and right-handed particles (violate parity)**

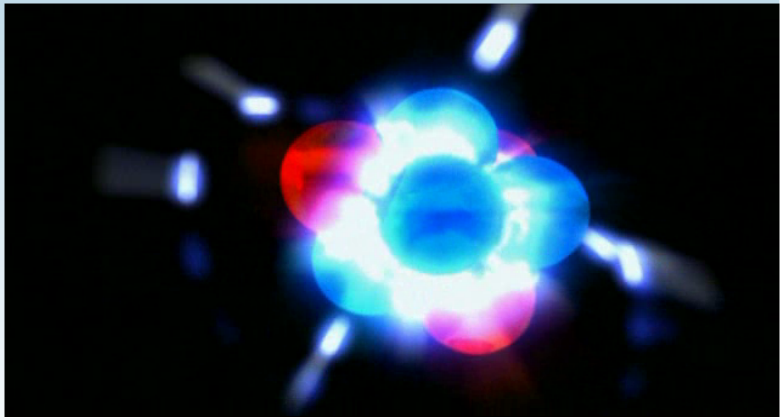
The 4 fundamental interactions

- Electromagnetic
- Weak
- Strong
- Gravitational

(Electromagnetic and Weak: } Electroweak)

The strong interactions:

- hold atomic nuclei together
- confine quarks in protons and neutrons
- are mediated by “gluons” (QCD)
- are weak at short distances



The 4 fundamental interactions

- Electromagnetic
- Weak
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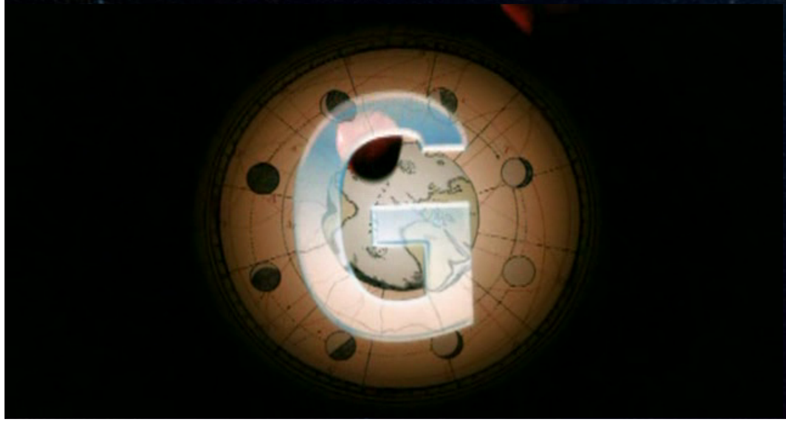
General relativity
Einstein 1916

Are much, much weaker than the other interactions!



We do not have a consistent quantum theory of gravitation

The 4 fundamental interactions

- EM
- Weak
- Strong
- Gravitational

EM + Weak → Electroweak

EM, Weak, Strong: The "Standard" Model

The "Standard" Model → GUTs ?

GUTs + Gravitational → Strings ??

All interactions are determinated by a symmetry principle (*gauge symmetry*)

Is it possible to unify all forces using larger symmetries?

2

Quantum Field Theory

Quantum Field Theory

- Combines 3 foundations of modern physics:

    Quantum mechanics

    The theory of relativity

    The concept of "field"

- Together with the symmetry principle, it describes the interactions of elementary particles.

Quantum Mechanics

Describes the world of extremely small objects characterized by:

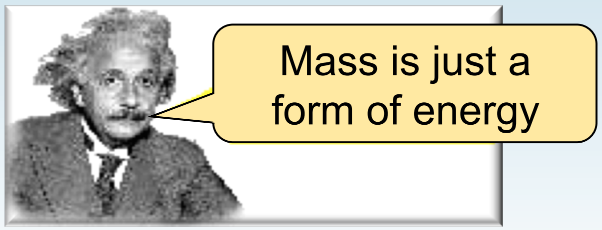
- **Intrinsic uncertainty**: there is a limit to the precision that can be reached in the simultaneous measurement of some observables. For example, if you measure an object, and determine the component $p_x = mv_x$ of its momentum with an uncertainty Δp_x, you won't be able, at the same time, to know its position x more accurately than $\Delta x = (h/2\pi) / \Delta p_x$. This is Heisenberg's (famous) uncertainty principle. The constant $h = 6.626 \cdot 10^{-34}$ J·s is called the Planck constant.
- **Common interpretation of waves and particles**: the former can behave like the latter, and vice versa.

Theory of special relativity

Describes the motion of an object modifying the predictions of Newtonian mechanics when its speed gets close to the speed of light:

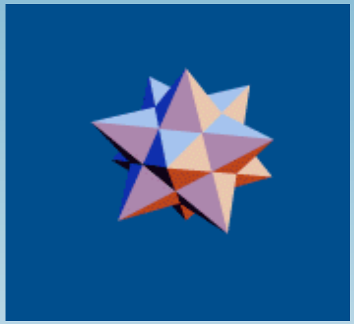
c ~ 300000 km/sec

- **The speed of light in vacuum c is finite and does not depend on the motion of its source. It's the maximum speed.**
- **The "effective" mass increases with speed.**
  Energy and mass are the same thing.

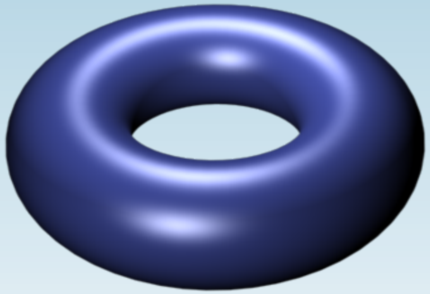


Symmetries

In physics we speak of *symmetry* when a system is invariant under a certain transformation (e.g. of the coordinates).
Symmetries can be *discrete*,



or *continuous*



Each continuous symmetry is associated with a conserved quantity. The space-time symmetries determine the constants of the motion (for example: translational invariance → conservation of momentum).

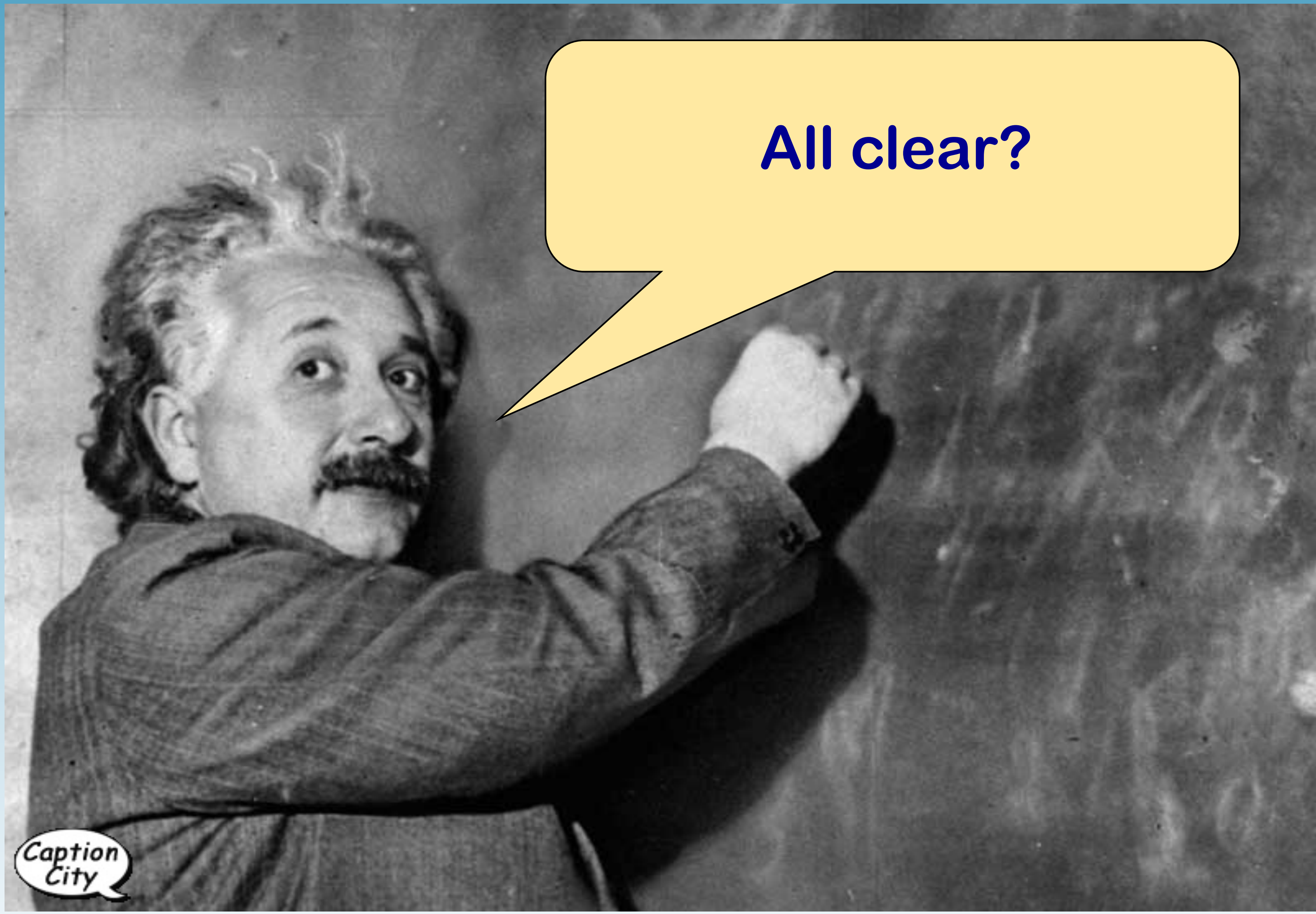
“Symmetries determine the interactions”

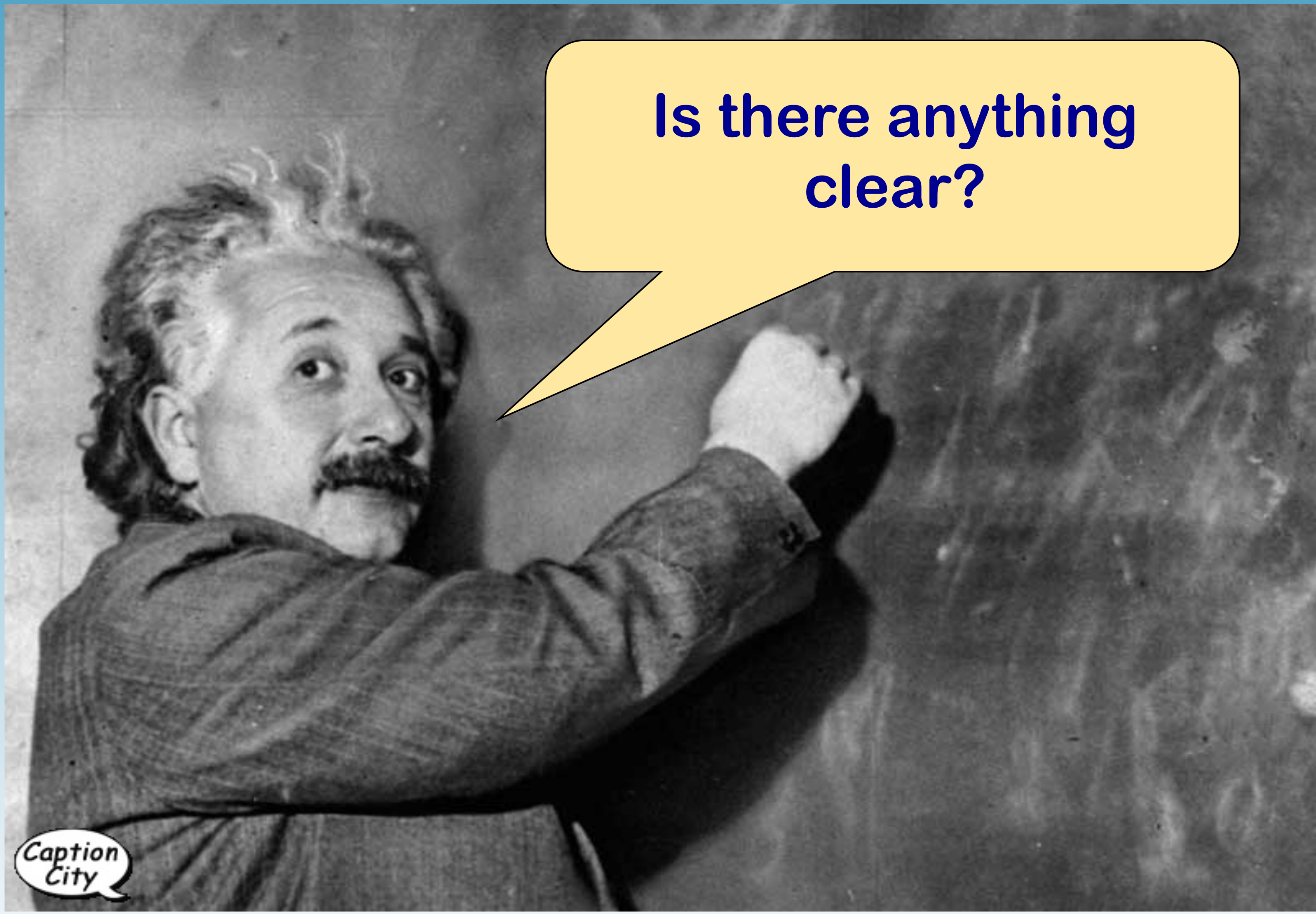
C.N. Yang

Today we believe that symmetries determine the fundamental laws of physics

The modern theory of interactions of elementary particles is a quantum theory of
“*gauge*”
fields whose invariance is with respect to local generalized rotations in an “internal” space

General relativity is based on a similar idea

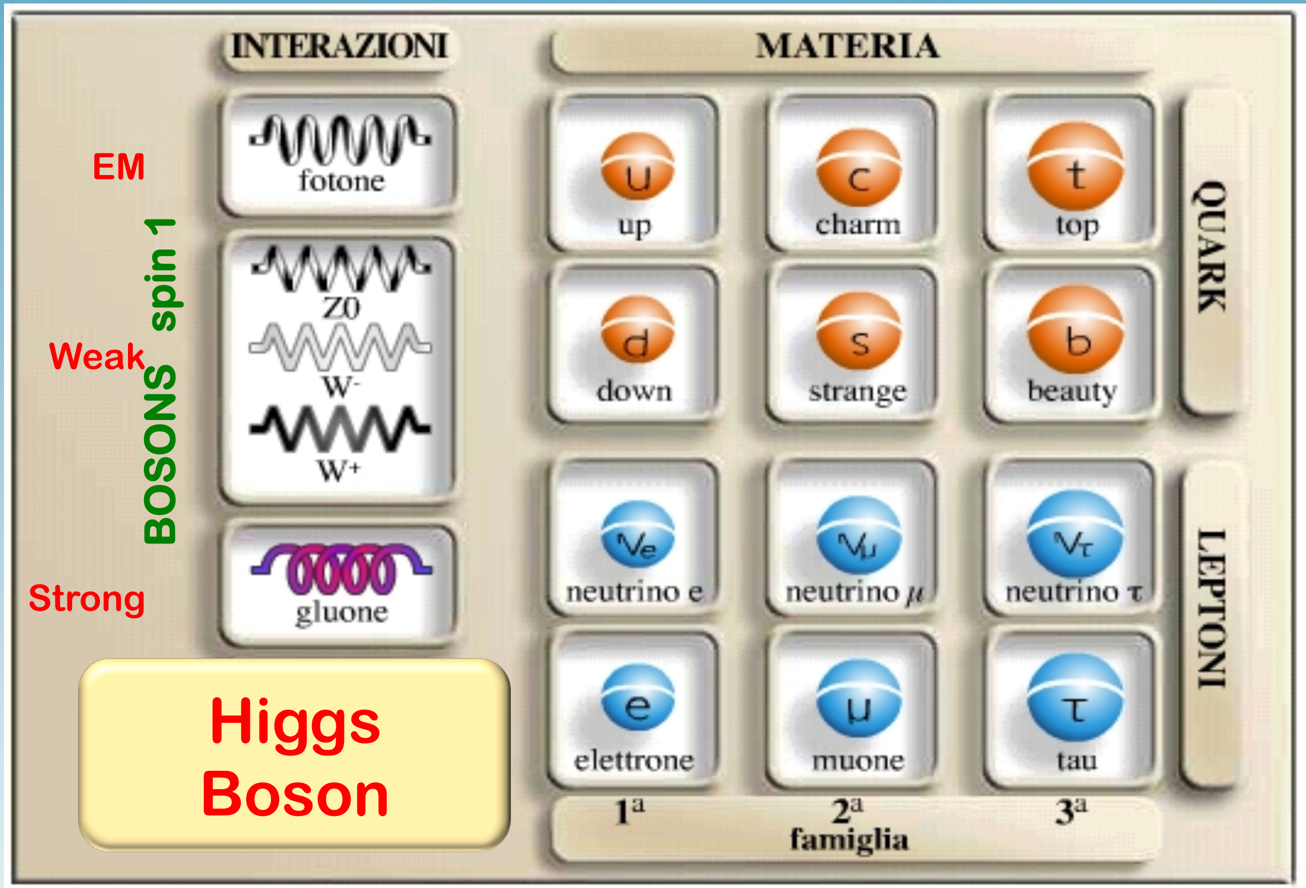

All clear?
Caption City


Is there anything clear?
Caption City

3

The “Standard” Model

The "Standard" Model



(there is no evidence, up to now, of any lepton or quark structure)

Three generations:

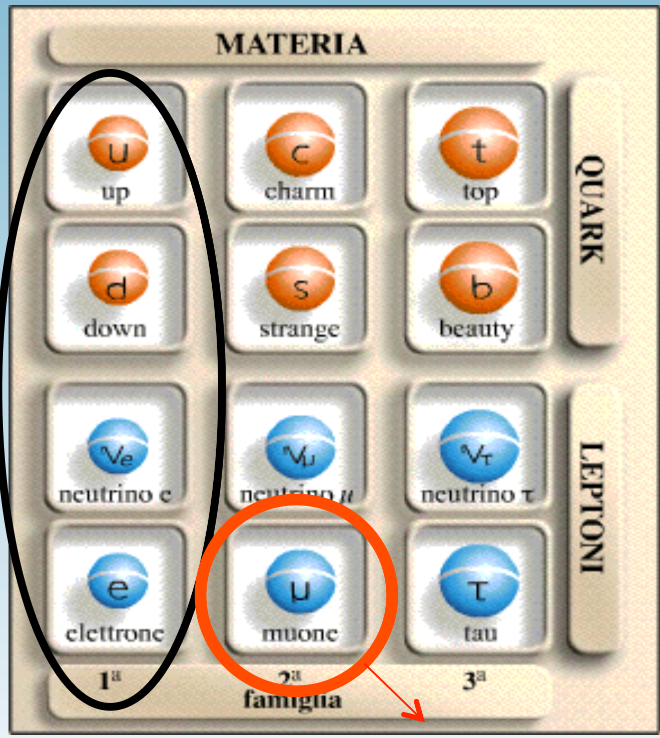
the particle zoo reduced to fundamental ingredients

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

At first sight, only the first family shows up in everyday life



in cosmic rays

The basic unit of energy is the electron Volt (eV): it is the variation of potential energy of a single electron that crosses a difference of potential of 1 Volt.

To observe the heaviest building blocks we need accelerators

New particles? 2 complementary ways:

Direct production
"relativistic way"

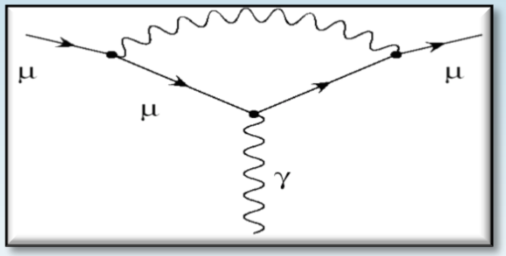
but also

Indirect research
"quantum way"

Heavy particles induce virtual effects ("quantum" corrections) which are very tiny, but very useful too:

Example: the anomalous magnetic moment of the muon, measured with the fantastic precision of 0.5 parts per million (!), is sensitive to possible effects of physics beyond the SM

Feynman diagram →



Sometimes indirect signals have anticipated direct discoveries. Eg: the top quark

Precision tests and the top quark

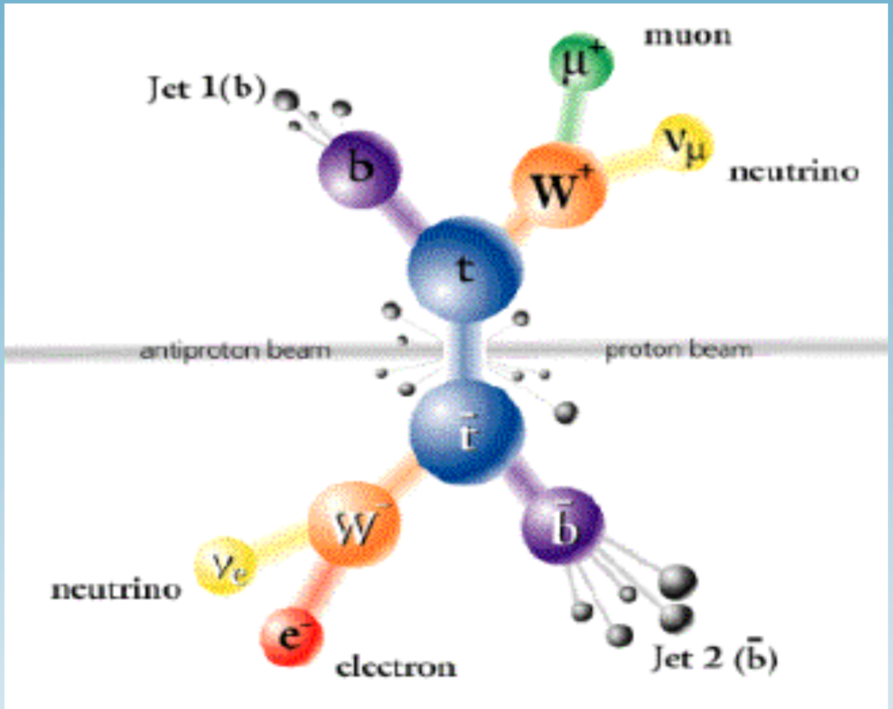
Nov 1994: fits to precision measurements predict:

$M_{top} = 178 \pm 11^{+18}_{-19}$ GeV

March '95: Fermilab discovers the top quark. Today it is:

$M_{top} = 173.1 \pm 1.3$ GeV

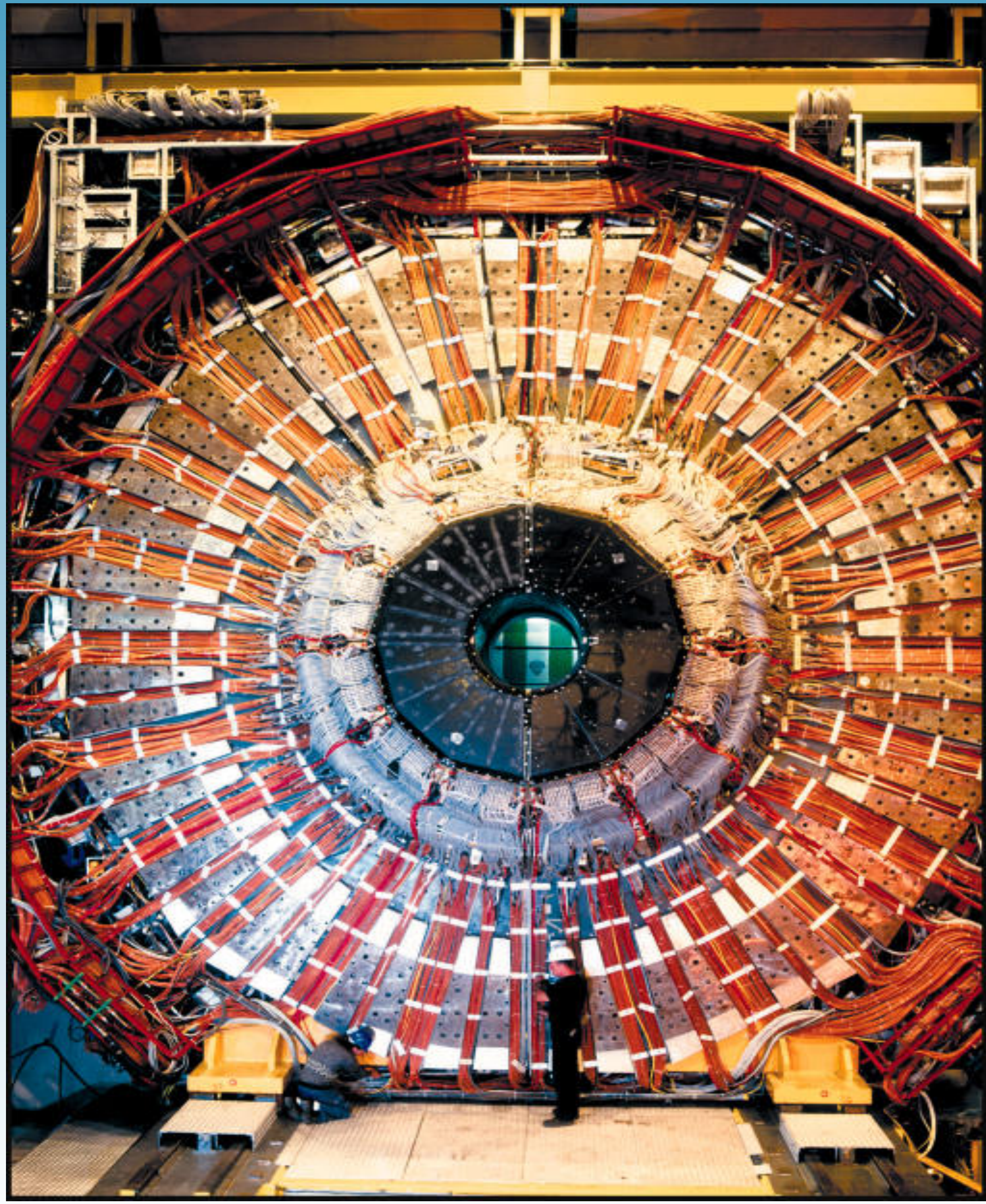
Great success of SM and experimental program!



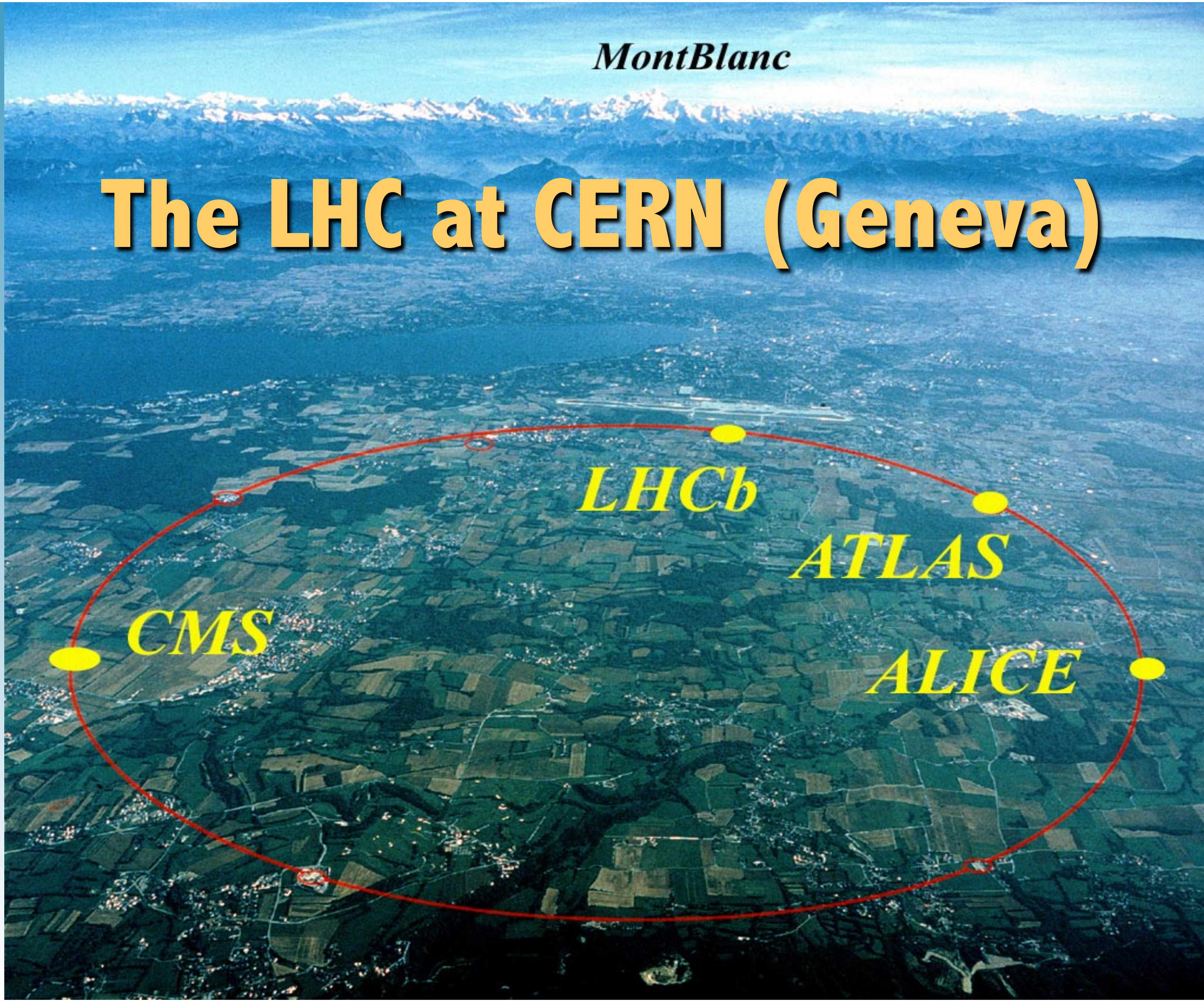
Can we repeat this analysis with the Higgs boson? Yes, but the sensitivity to its mass is much weaker. More later…

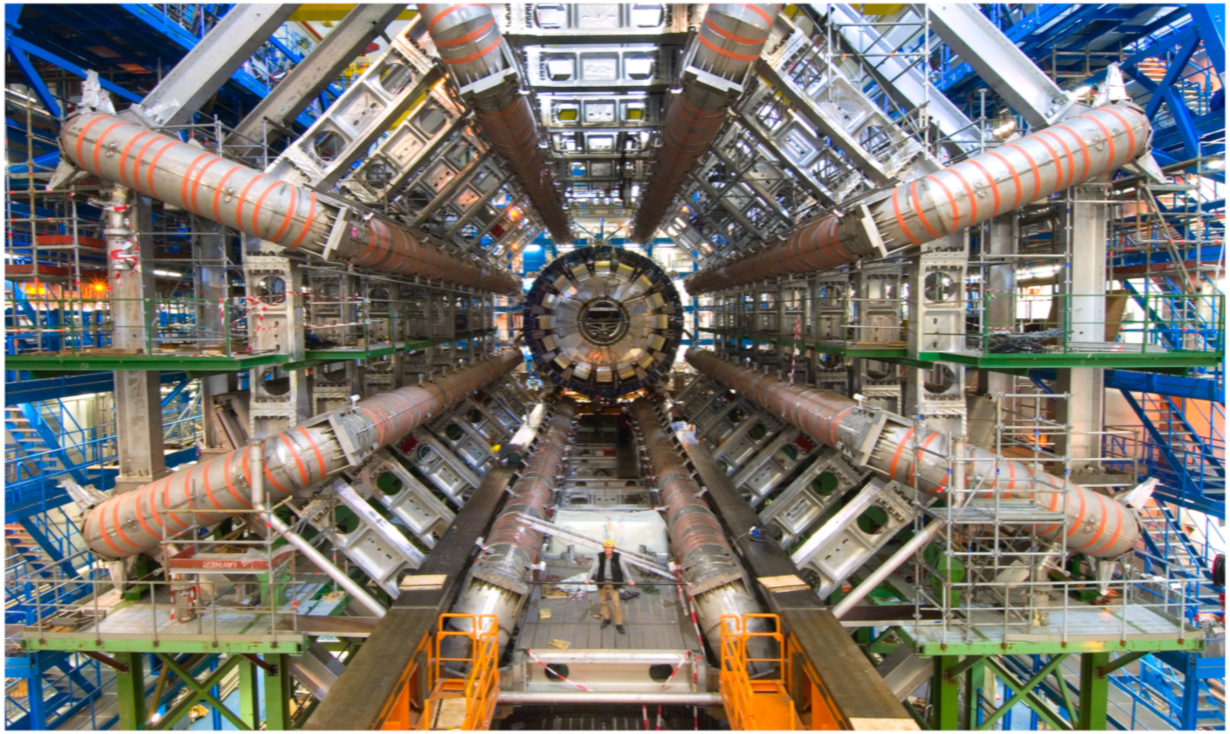
The lesson of LEP

The Large Electron–Positron Collider (LEP) (1989-2000) at CERN did not discover new particles but confirmed the SM gauge interactions with a fantastic precision: 0.1%!



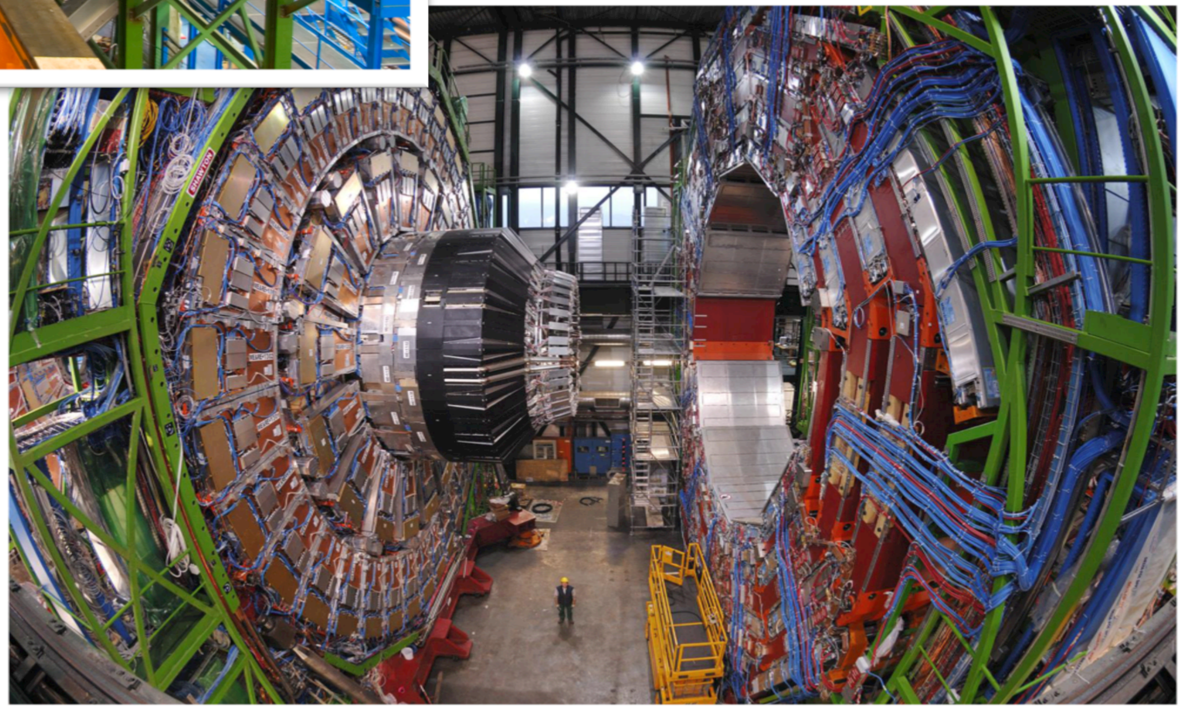
The LHC at CERN (Geneva)

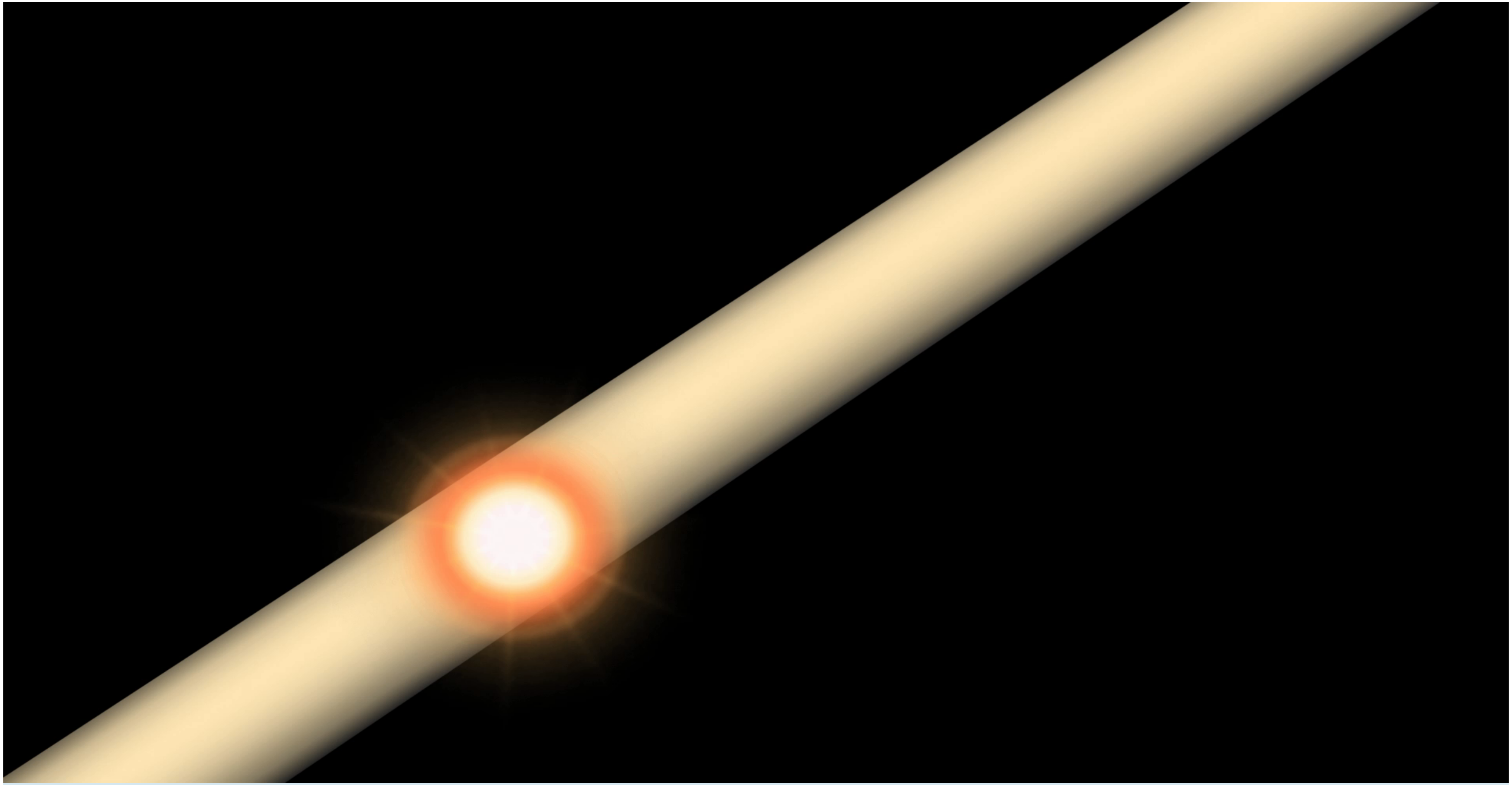




ATLAS

CMS

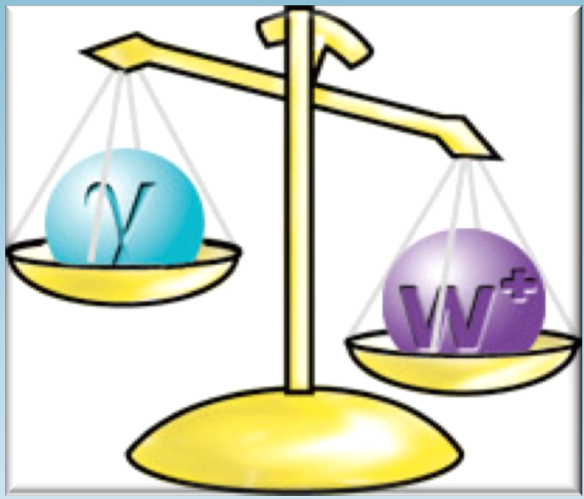




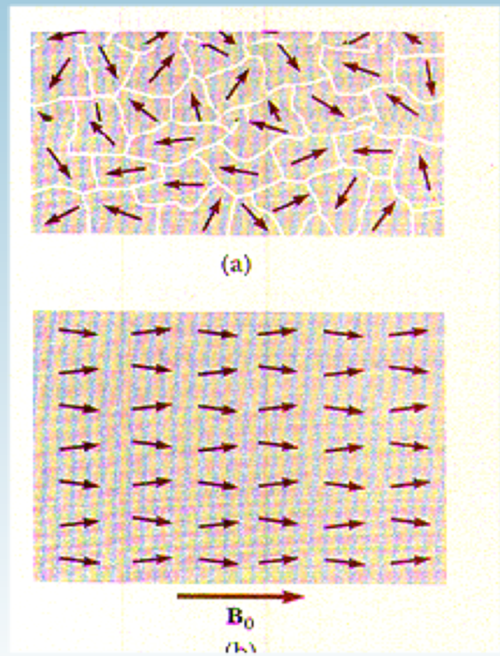
ATLAS: Animation of a real proton collision occurred in 2011. The two photons produced in the collision are indicated by their energy cluster (in green). ATLAS Experiment © 2012 CERN.

Broken symmetries

The SM unifies weak and electromagnetic interactions. If they are "unified", why do they appear so different to us? Their range is very different. We believe that…

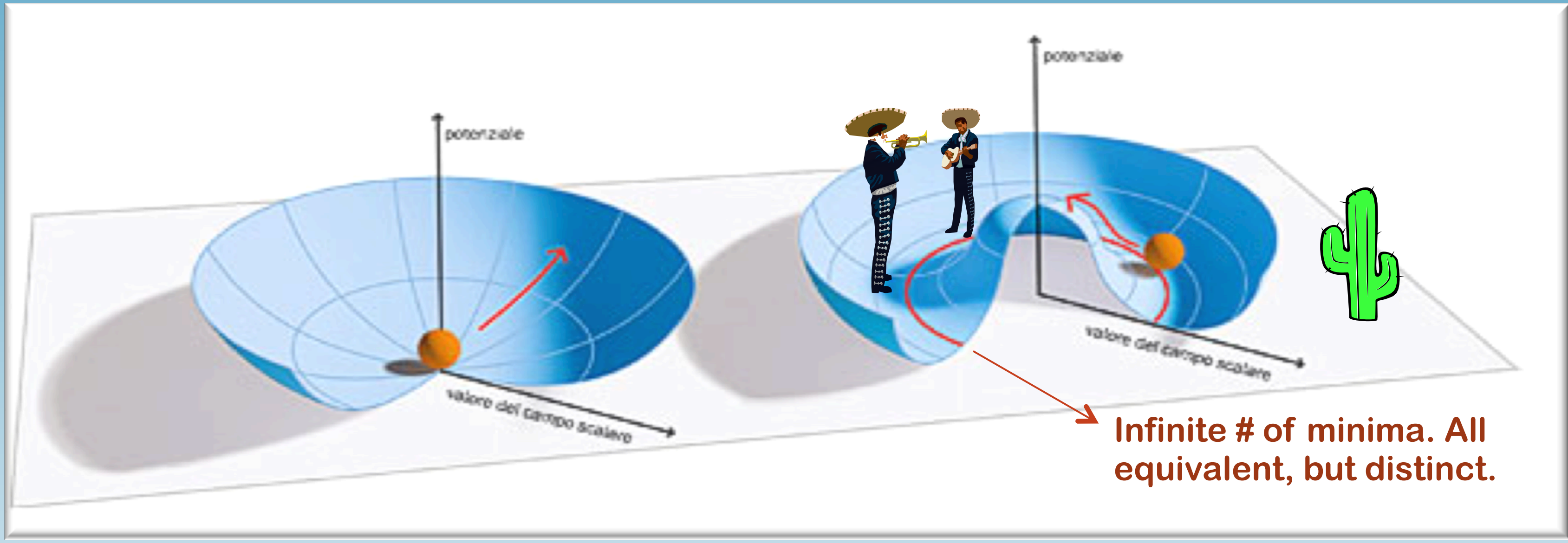


… the symmetry that unifies them is "broken", i.e, the state of minimum energy (the "vacuum") is not symmetric.



In nature it is not uncommon to have non symmetric states of minimum energy: for example, a ferromagnet. The (broken) symmetry manifests itself in the equivalence of the breaking options.

Spontaneous symmetry breaking

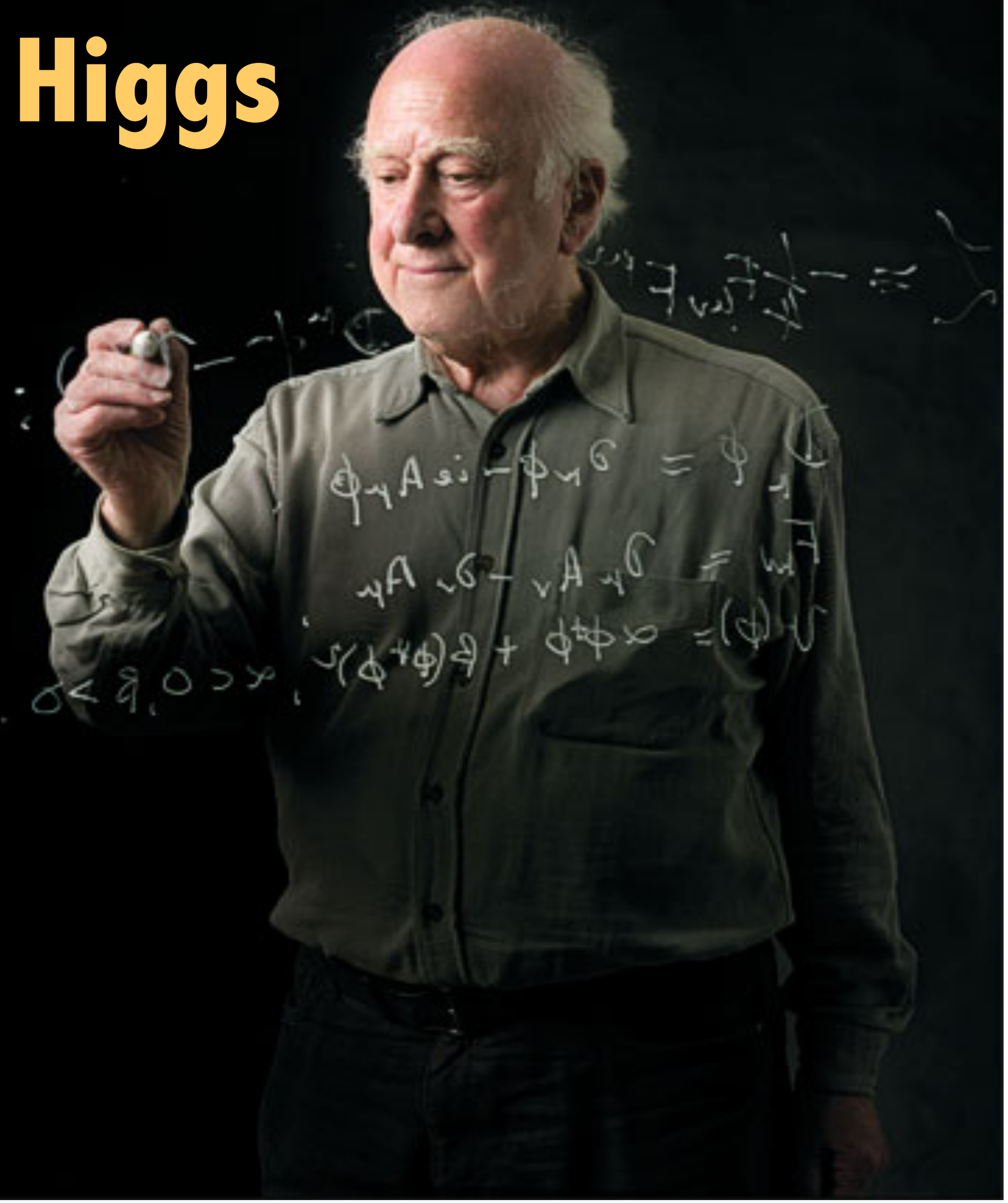


We believe that this process of "spontaneous" symmetry breaking is at the origin of the mass of the particles → there are good chances that the LHC will help us understand it better.

4

The mistery of the Higgs

The mystery of the Higgs



Peter Higgs

The Higgs boson

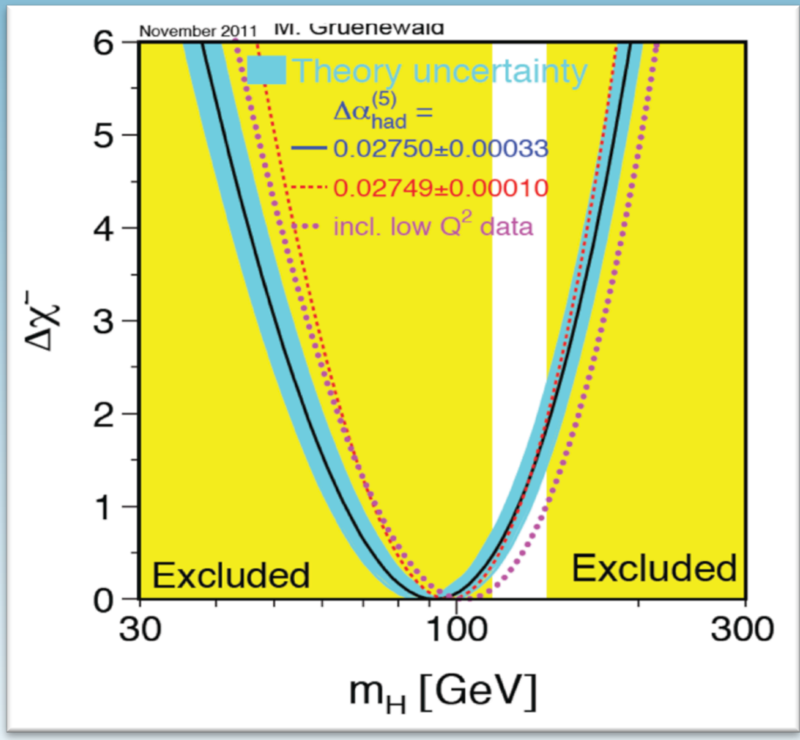
There must exist something that breaks the symmetry of the "vacuum"and, interacting with the particles, gives them their masses.

It could be an elementary field: the HIGGS boson (or the manifestation of something more elaborate)

Today, the electroweak symmetry breaking mechanism is the central problem of particle physics

What did we know about the Higgs a few years ago?

Direct searches at LEP: its mass is
$M_H > 114.4$ GeV



Comparing the experimental measurements with the SM predictions that depend on M_H we obtained indirect information on M_H: clear preference for a "light" Higgs (below ~150 GeV)

The Higgs has been found! (or not?)

July 2012: ATLAS and CMS announce the discovery of a new particle with mass of about 125 GeV (*) and properties consistent with those of the Higgs boson predicted by the SM:

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Physics Letters B

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ELSEVIER

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

A R T I C L E I N F O

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A B S T R A C T

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Physics Letters B 716 (2012) 30–61

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

A R T I C L E I N F O

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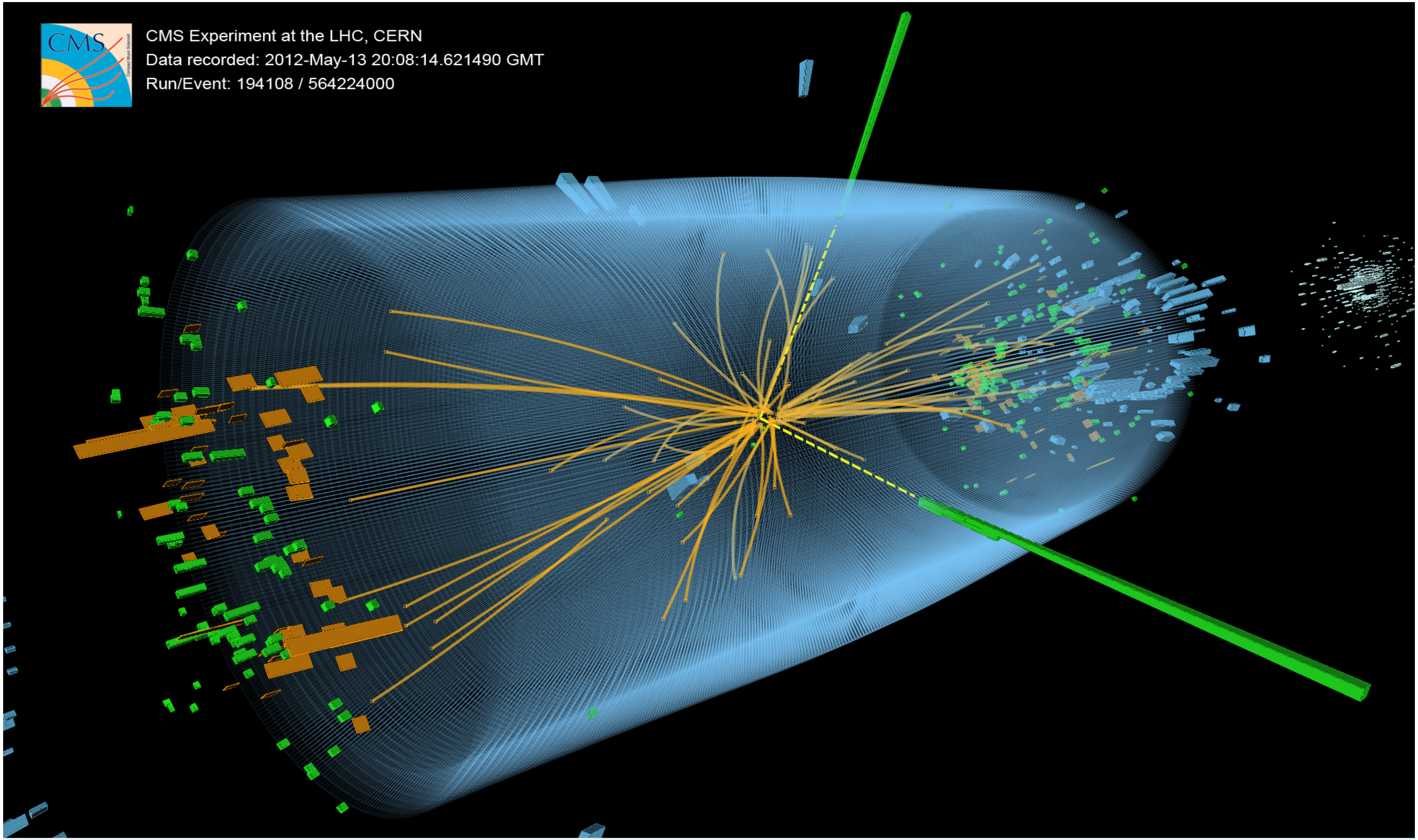
A B S T R A C T

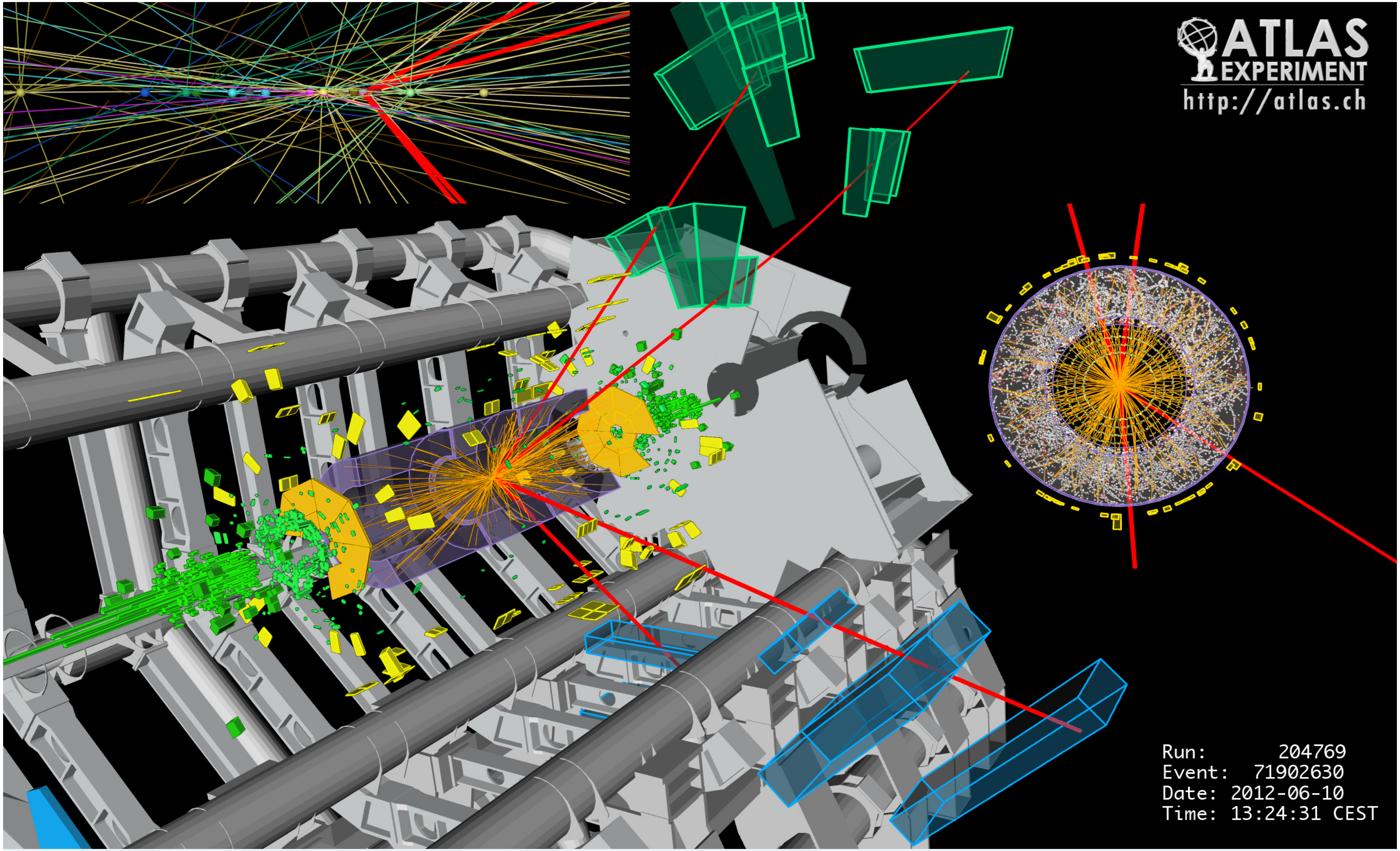
Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of 125.3 ± 0.4(stat.) ± 0.5(syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

Is it really the SM Higgs? It's too early to say, but the LHC data will tell us!

(*) the mass of the proton is about 1GeV



CMS: The event shows characteristics expected from the decay of the SM Higgs boson to a pair of photons (dashed yellow lines and green towers). The event could also be due to known SM background processes. CMS Experiment © 2012 CERN.



ATLAS: Candidate event for the decay of a SM Higgs boson into 4 muons (in red). The origin of the 4 muons is a common primary vertex. ATLAS Experiment © 2012 CERN.

5

Beyond the Standard Model?

Why don't we believe in the SM??

The discovery of the Higgs is part of a more ambitious project to understand the origin of the symmetry breaking that generates the masses, and the nature of the electroweak scale.

The Standard Model passed so many tests, however:

- **Too many parameters. Why 3 families?**
- **Incomplete: what about gravity? Why is it so weak?**
- **Doesn't explain the smallness of neutrino masses**
- **Doesn't explain the observed dark matter (and energy), nor baryogenesis.**

The SM must have a completion that we still don't know. Supersymmetry? Extra dimensions ….. ??


The LHC just started exploring…