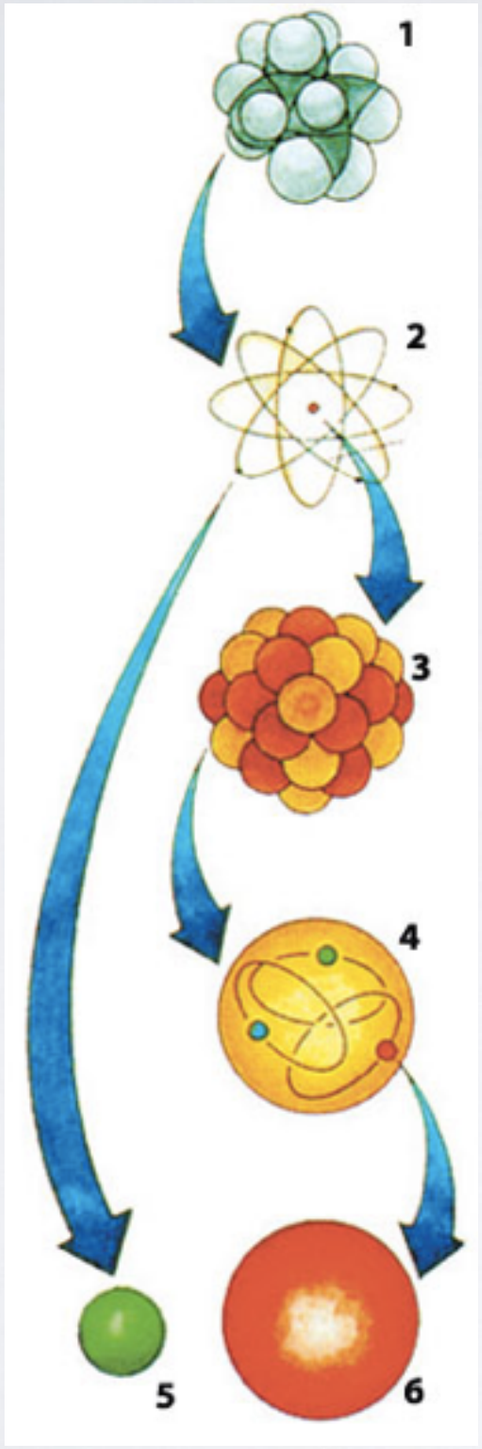
News from NBIA
17th of November, 2014

The Higgs was discovered
- what's next?

Christine Hartmann

Let's zoom in...



Molecule

Atom

Nucleon

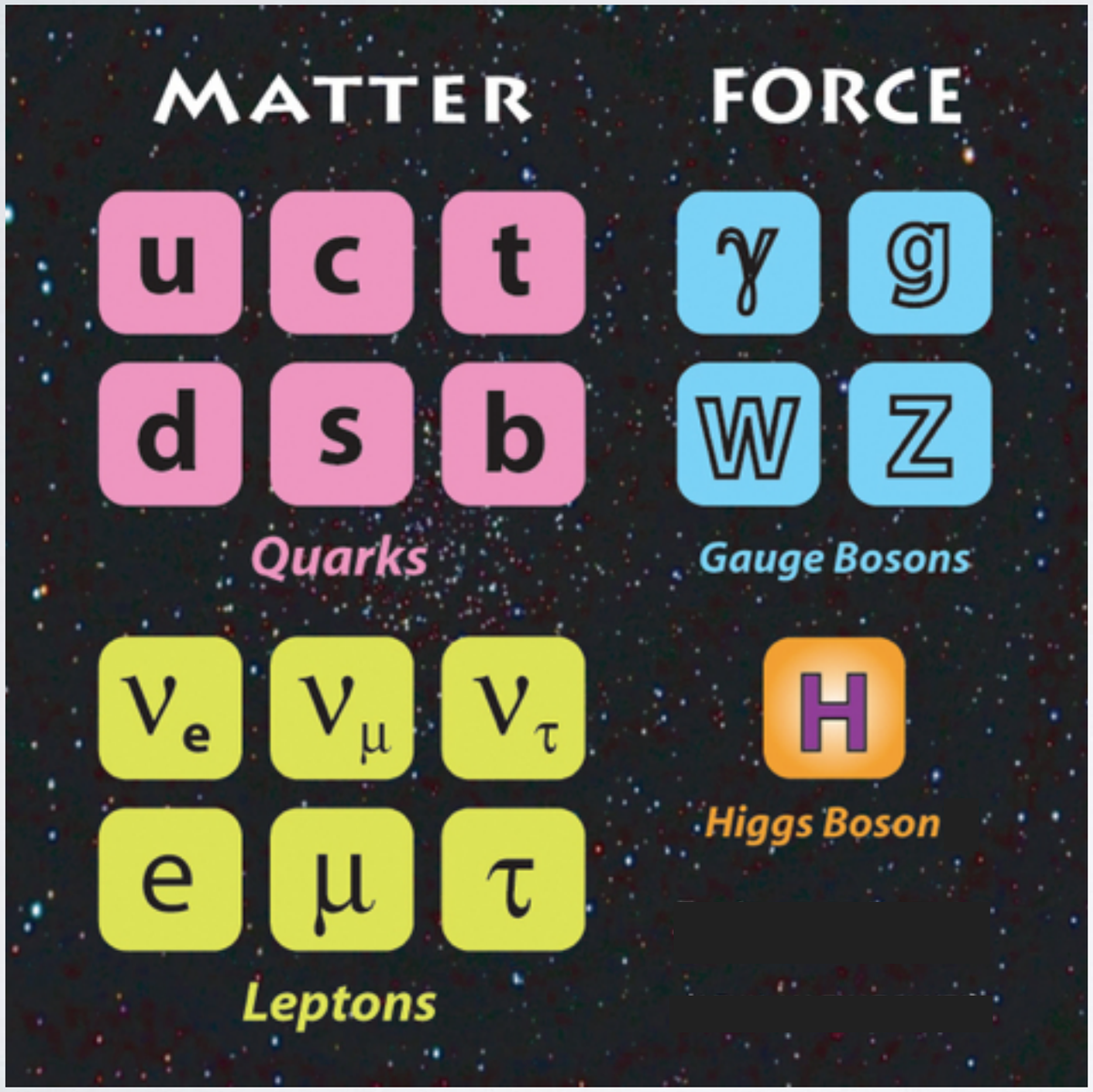
Proton/Neutron

Electron

Quark

Standard model

Classification of *elementary* particles



Credit: GridPP.ac.uk

- Particles
- Interactions
- Masses
- Charges
- Forces

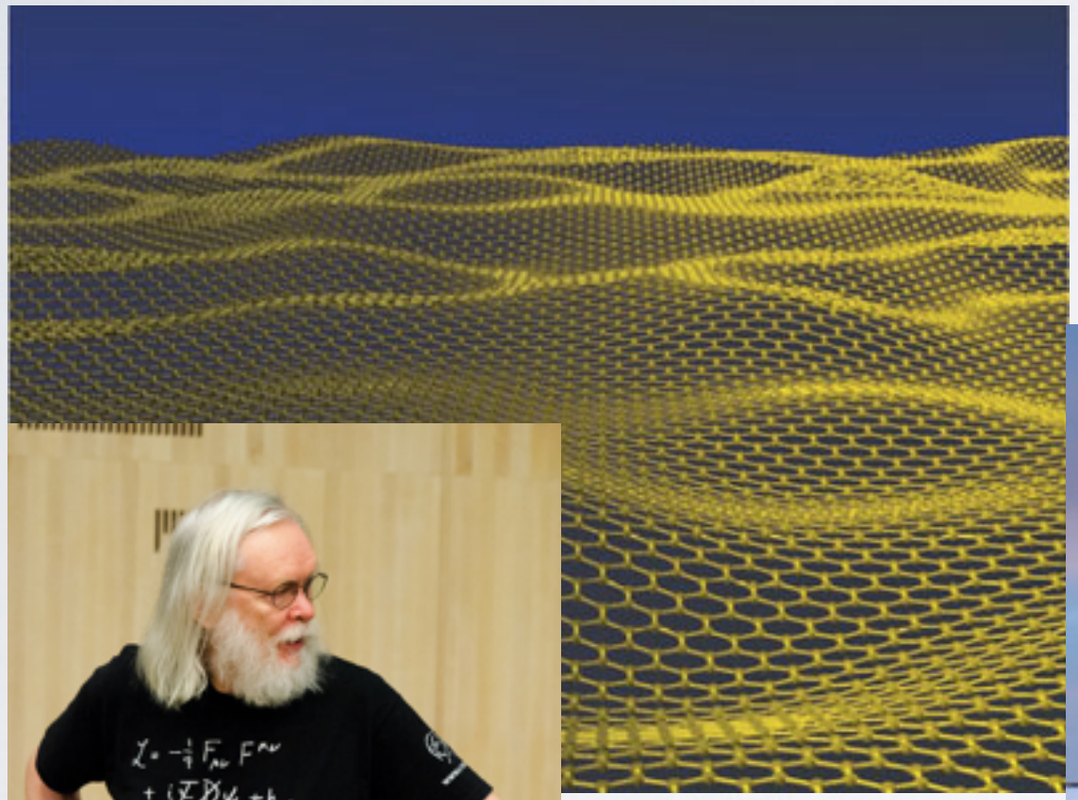
Described what had not been discovered!

The Higgs:

- the carrier of mass.

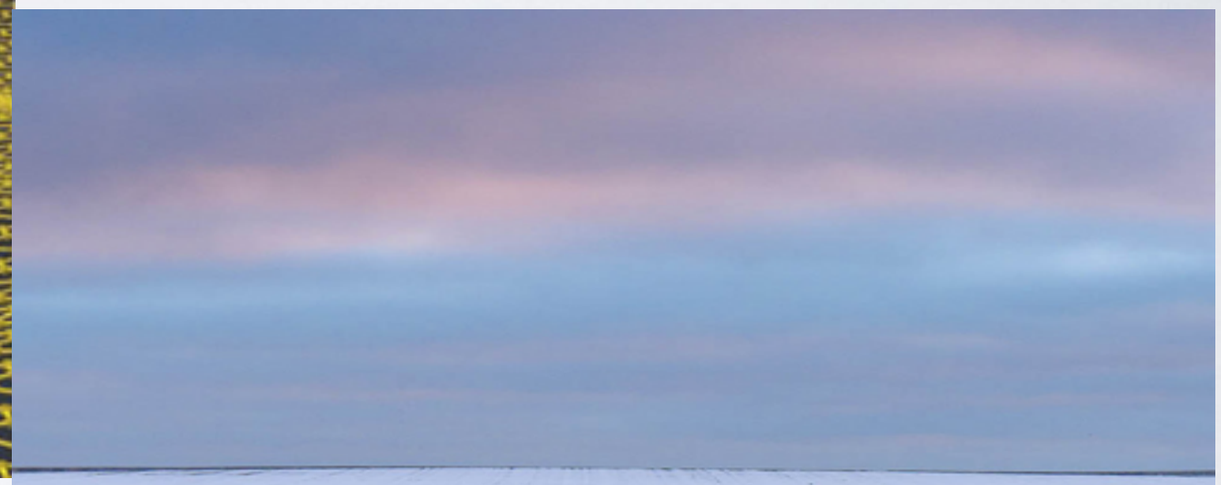
The Higgs

The last missing piece of the Standard Model puzzle



The Higgs field permeates everything.

John Ellis:
Like a snow field.



The more particles interact with the Higgs field, the more massive they become!

The Ellis Higgs snow field

Skier: Slides over Higgs snow field with almost no resistance.

Snowboots: More interaction, slower.

Walker: Very hard to get through - very slow.

Bird: No interaction at all - no resistance from the slow field.

The Ellis Higgs snow field

Higgs field
- the snow field

Higgs boson
- the snow flake

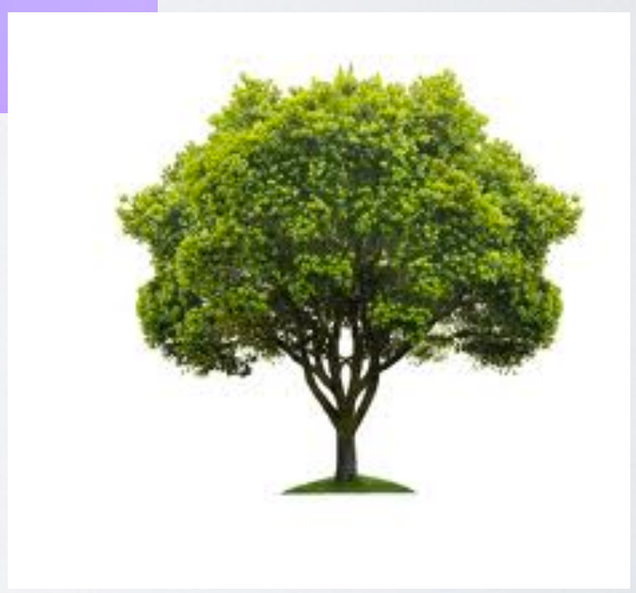
Symmetries

Occur in nature.

Employed throughout the Standard Model.

Classify observables, determine properties

→ Predictivity.



Natural to use symmetries as a guideline…

… and their breaking

In nature…

… and in the Standard Model.

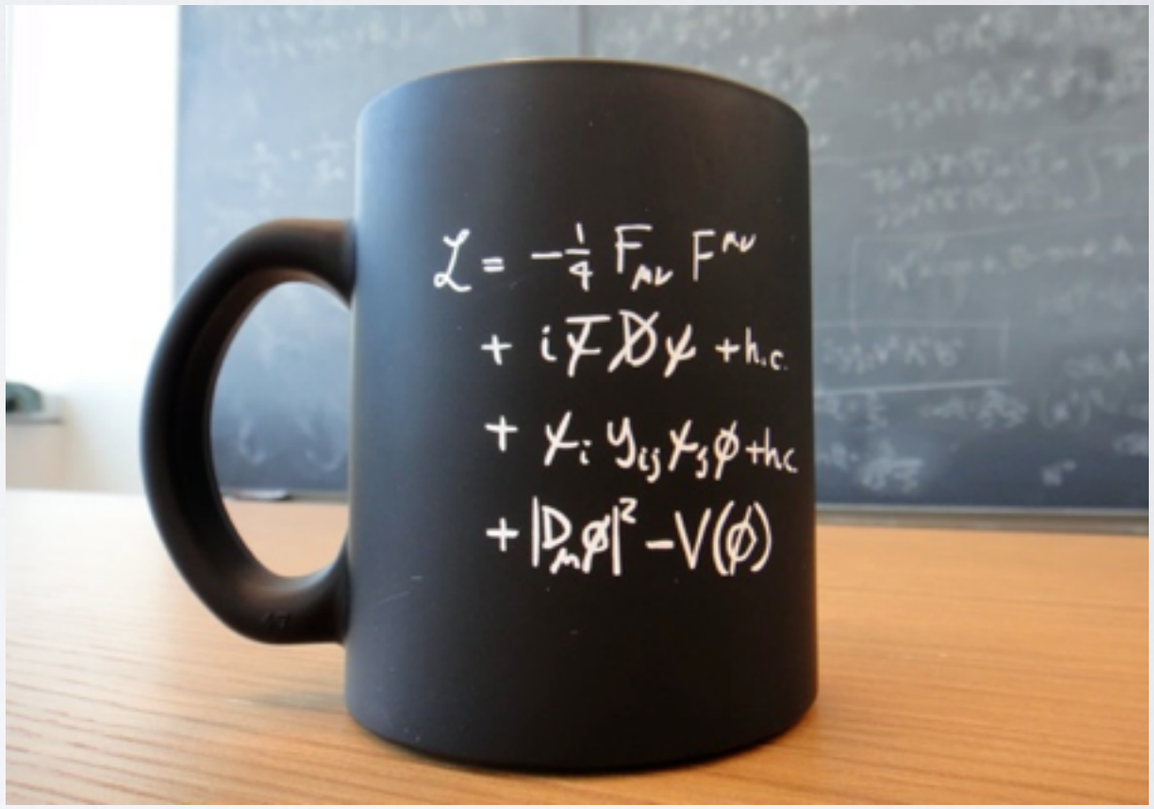
Very interesting
- and least understood part…

Why and *how* are symmetries broken?

Theoretical perspective

Standard model on a mug from *CERN*

The Lagrangian



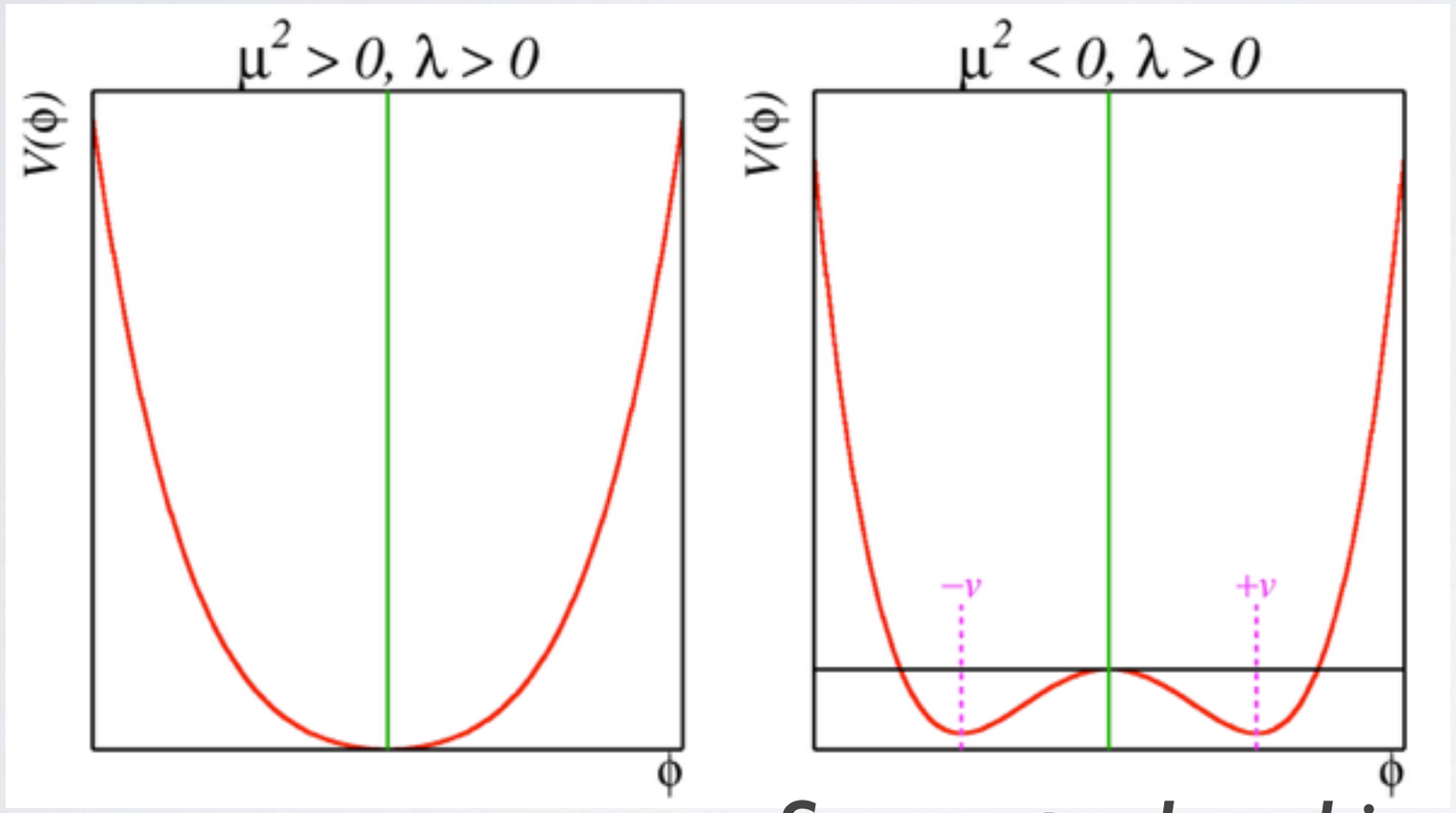
Important part:

Potential:

$$V = \mu^2 \phi^2 + \lambda \phi^4$$

Spontaneous symmetry breaking in a nutshell

Potential: $V = \mu^2\phi^2 + \lambda\phi^4$



Symmetry:

$$\phi \to -\phi$$

Minimise the potential

Symmetry breaking:

$$\phi = \pm v$$

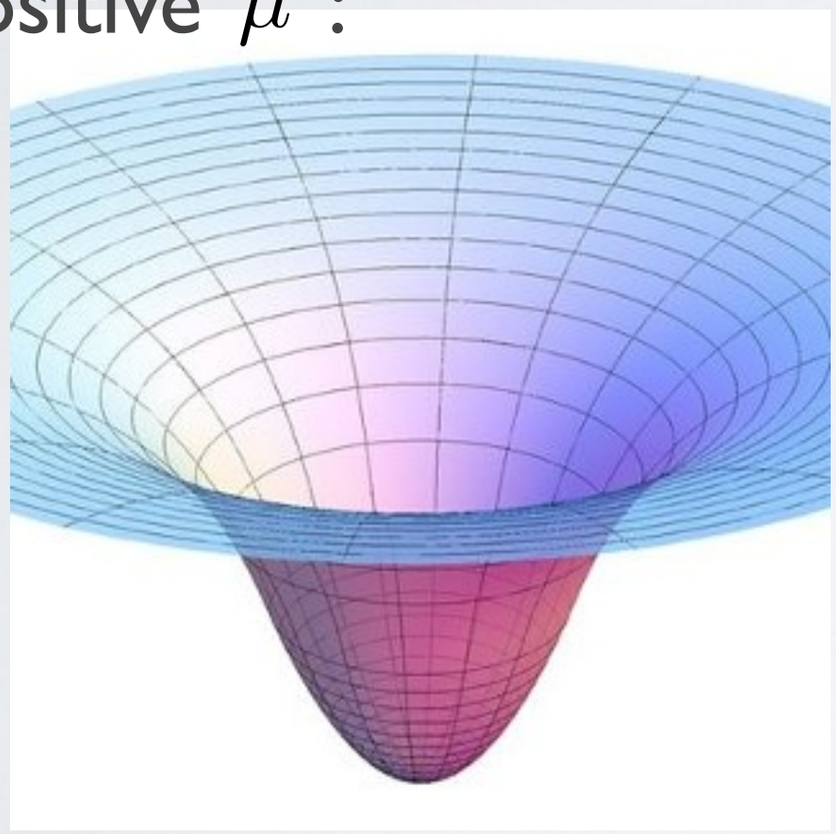
$$\phi \to v + \eta$$

More complex...

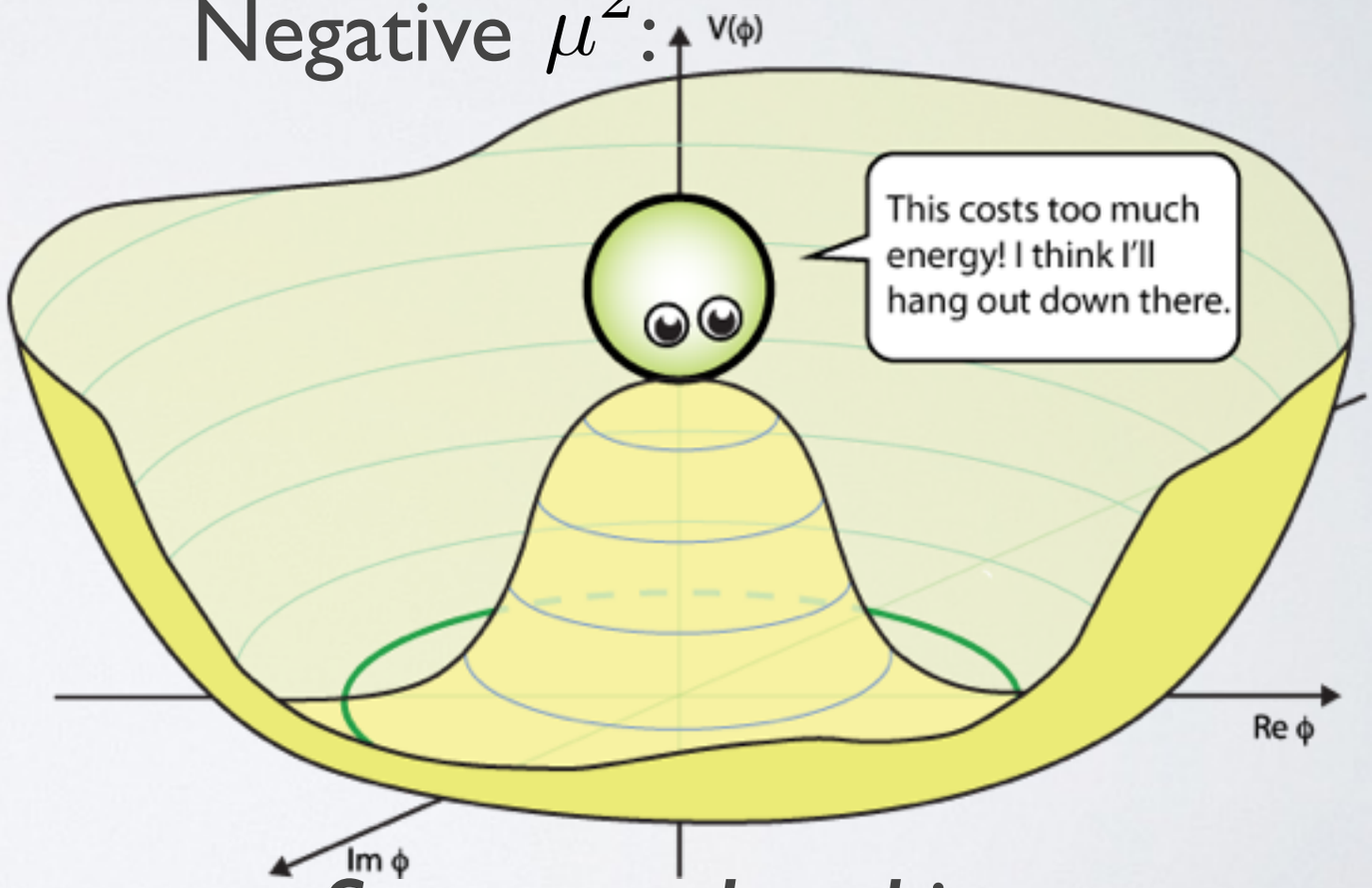
$$V = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2$$

➡ Same thing - continuous: $\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$

Positive μ^2:



Negative μ^2:



Symmetry breaking:

$$\phi = \frac{1}{\sqrt{2}}(v + \eta + i\xi) \qquad \phi_1^2 + \phi_2^2 = v^2$$

The Higgs mechanism

Continuous symmetry breaking ➡ massless particles

- not seen in nature!!!

Solution: ***Higgs mechanism:***
Other particles "eat" massless ones

➡ **obtain masses.**

Massless particles - part of Higgs field

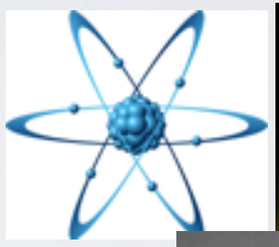
- **without these - particles will not have mass.**

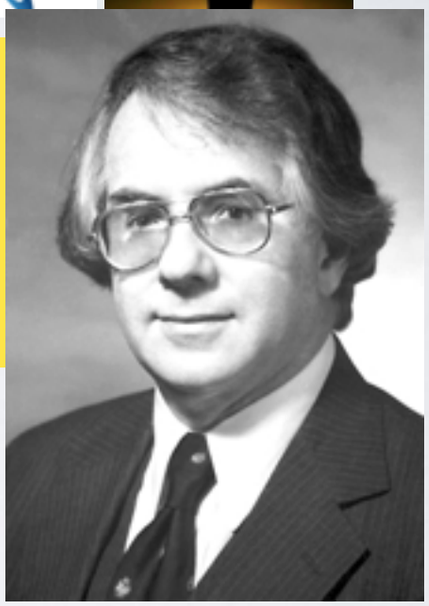
In fact, part of the Higgs particle was discovered a long time ago…

History perspective

60's: (Schwinger), Glashow:
Electroweak unification.

Electromagnetism: *Atoms held together, light*





Sheldon Glashow

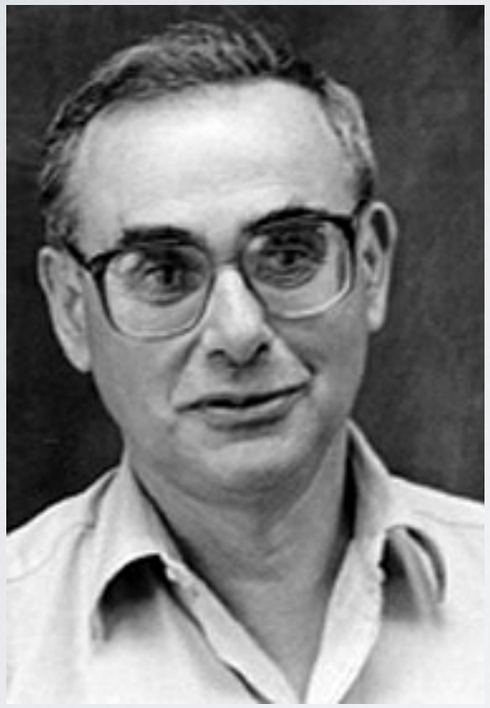
Weak interactions: *Beta decay, radioactivity*

Problem number 1: Carriers of weak interactions have big masses.

1983: 3 weak carrier bosons were discovered at CERN accelerator LEP.

Symmetry breaking

1960: Nambu: *Mechanism of spontaneous symmetry breaking. (Chiral symmetry)*



Jeffrey Goldstone
MIT webpage

1962: Goldstone: A method of **losing symmetry** is... highly desirable in particle physics, but these theories will not do this without introducing **non-existent massless bosons**... If use is to be made of these solutions, **something more complicated** than the simple models considered in this paper will be necessary.

→ *Nambu-Goldstone massless bosons*

Problem number 2:
Where did the massless particles go?

Yoichiro Nambu
Antimatter

Combining the problems

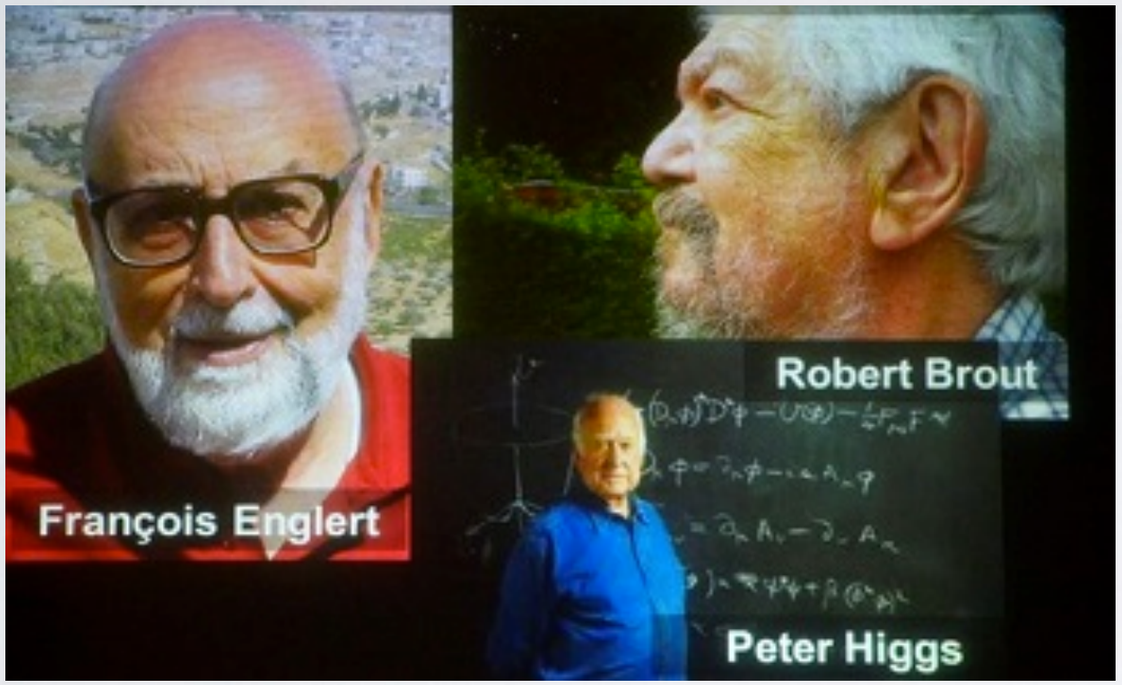
1962: Anderson: Two types of massless particles:
Goldstone bosons + *weak force carriers*
➡ ***massive particles.***

Used in superconductivity: Relativity and calculations were still missing as was the Higgs particle.

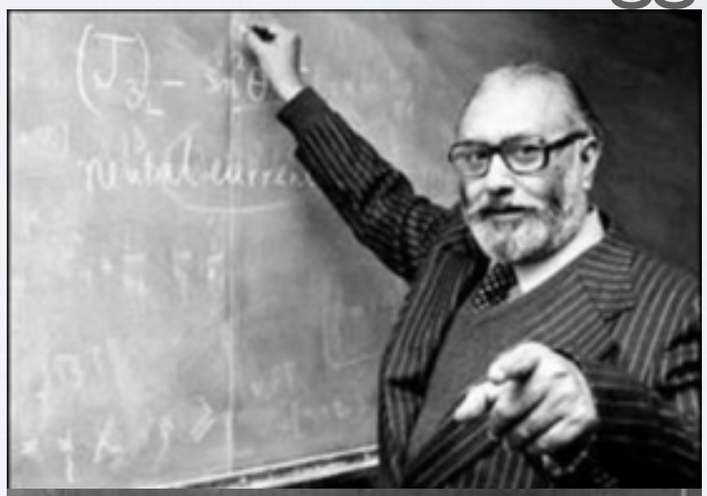
Solution to both problems?

Philip Anderson

Higgs mechanism



1964: Higgs, Englert and Brout independently:
Particles get their masses coupling to the Higgs field!
➡ needed Higgs particle!



Abdus Salam
Gizmodo

Steven Weinberg
Gizmodo

1967: Salam, Weinberg:
Higgs mechanism applied to electroweak unification.

Quantum electrodynamics

CERN - LHC

One experiment

- all of particle physics depending on it

Some facts:

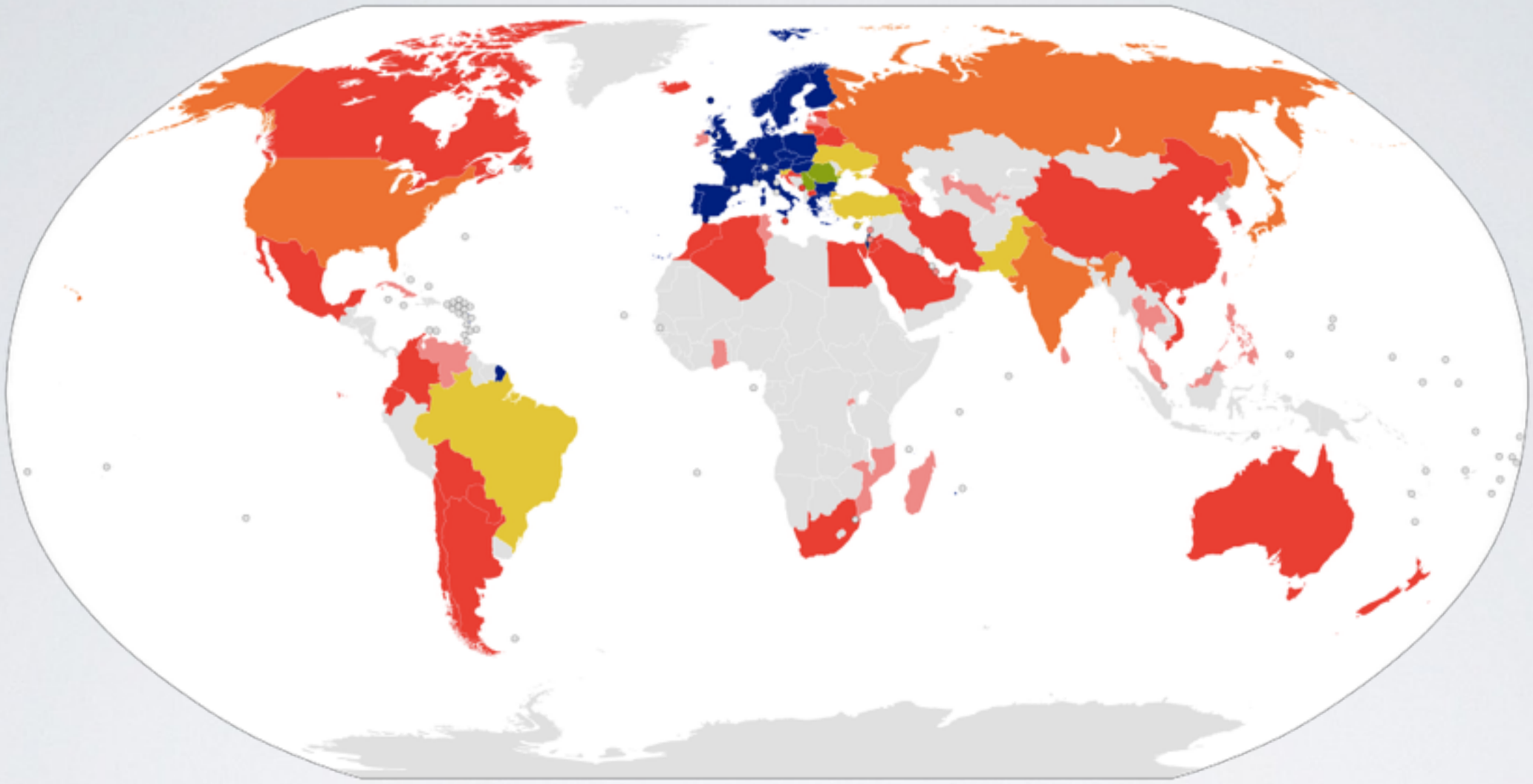
~ 30 km in circumference.

~ 175 meter under ground.

> 99.9999991 % of speed of light.

~ 11.000 rounds per second.

World collaboration

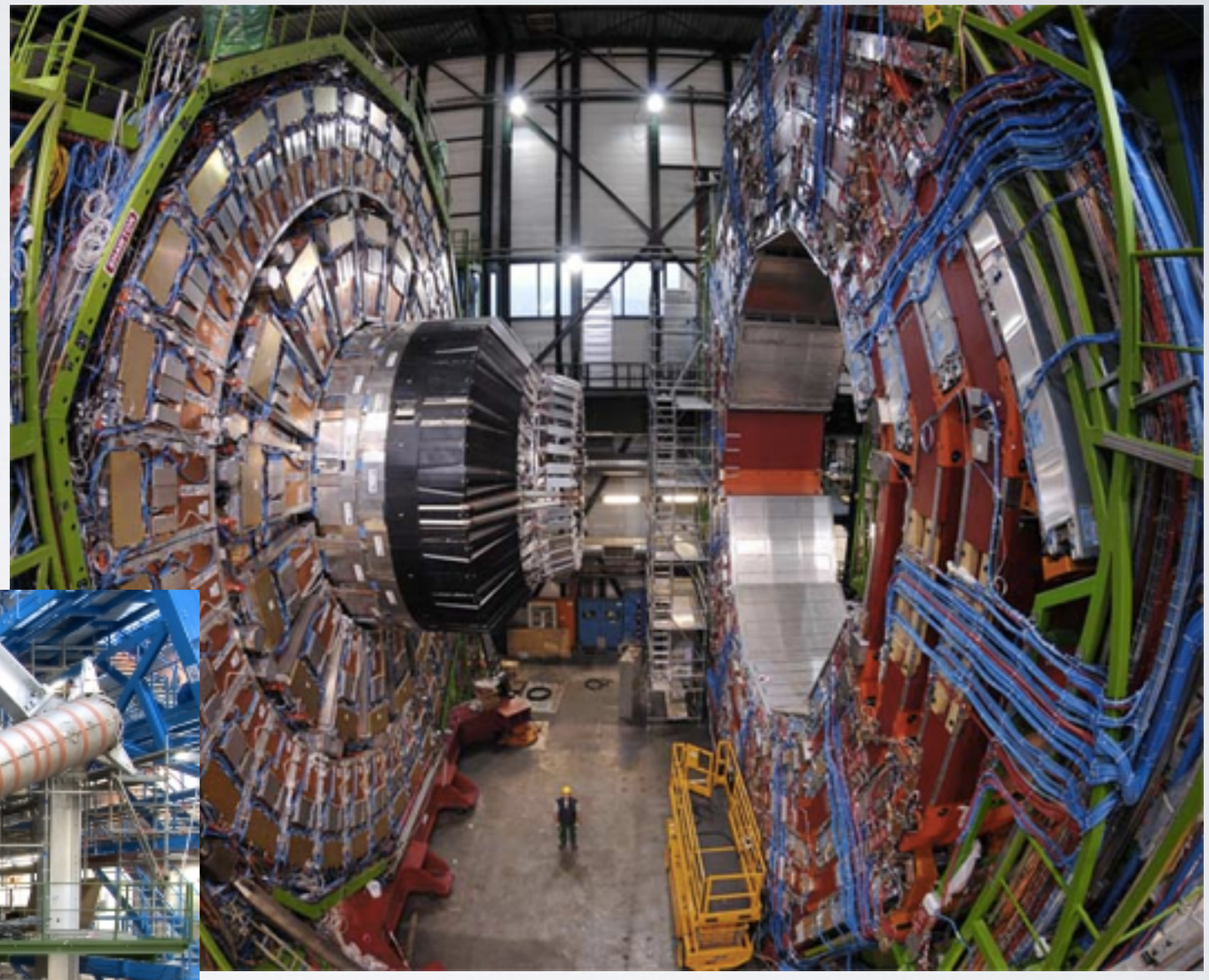


- CERN member states: 21 c.
- Accession in progress: 3 c.
- Declared intent to join: 2 c.
- Observers: 4 c. + EU
- Cooperation agreement: 35 c. + Slovenia, Cyprus, Turkey
- Scientific contacts: 19 c.

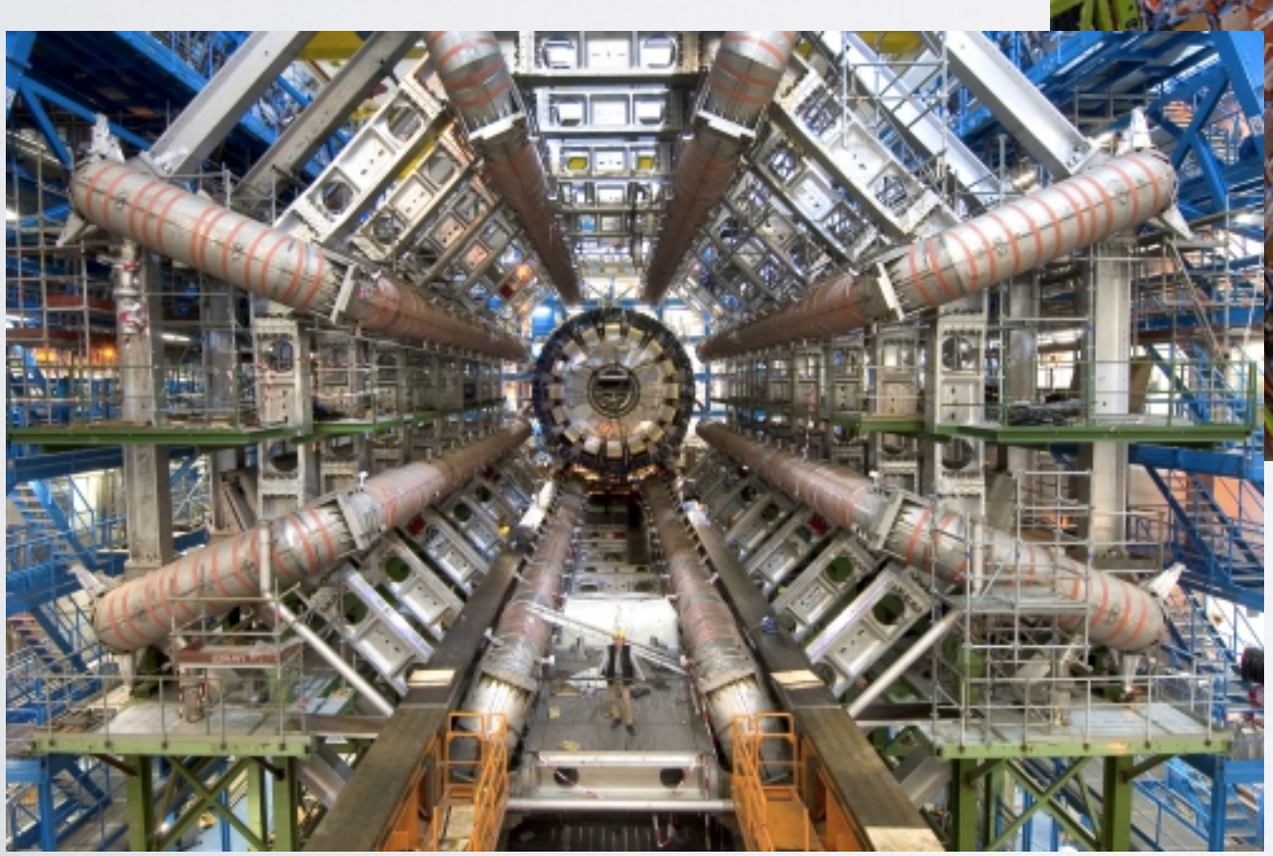
Even countries in conflict…

Detectors
- searching for the Higgs

40 million protons colliding per second in 4 detectors.



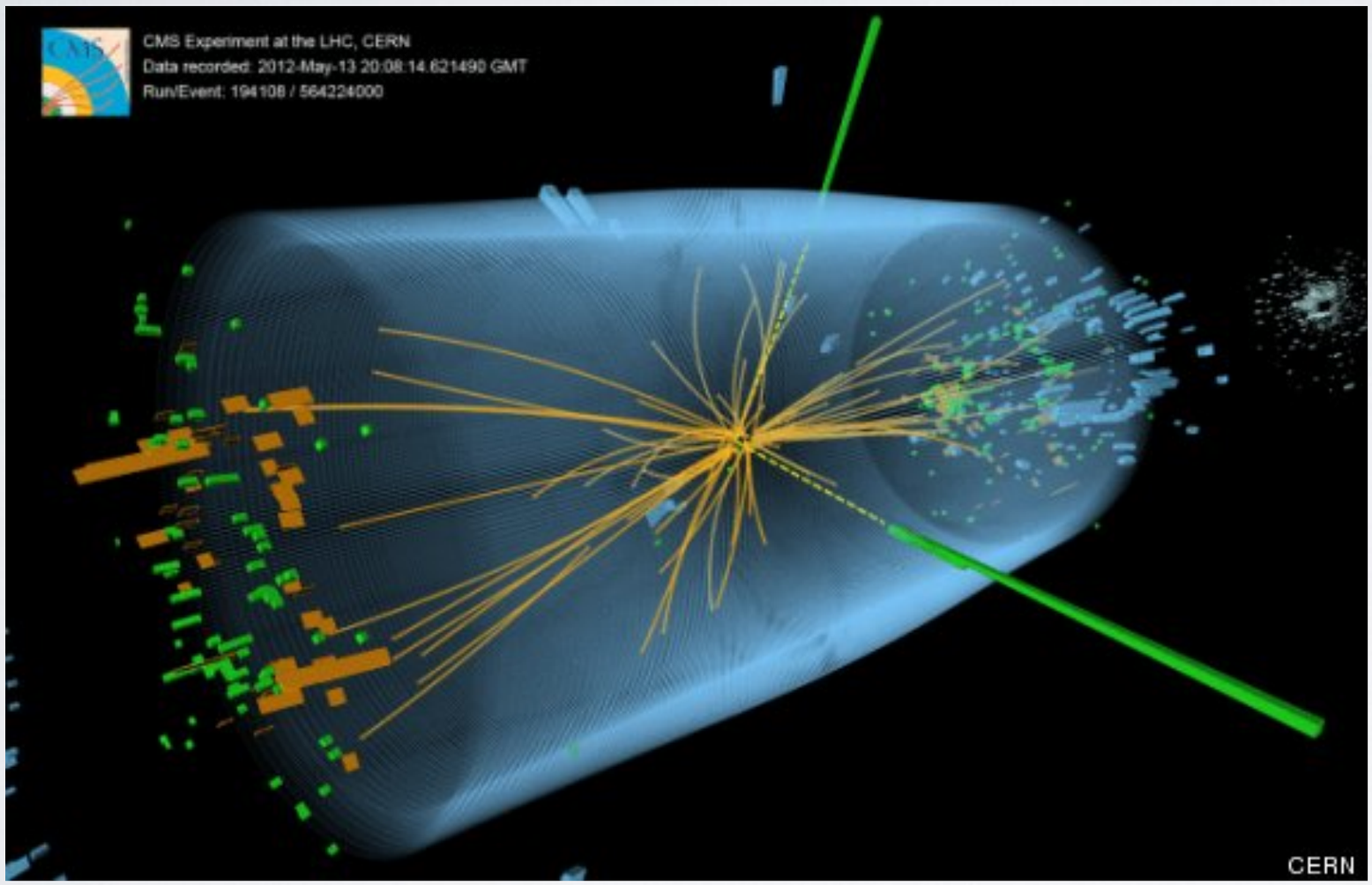
CMS detektor

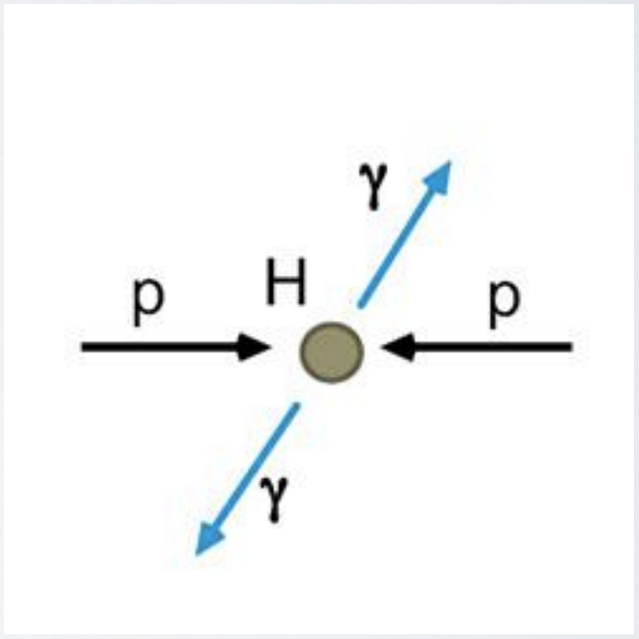


ATLAS detektor

The creation of the Higgs

Higgs field disturbed → Higgs particle created

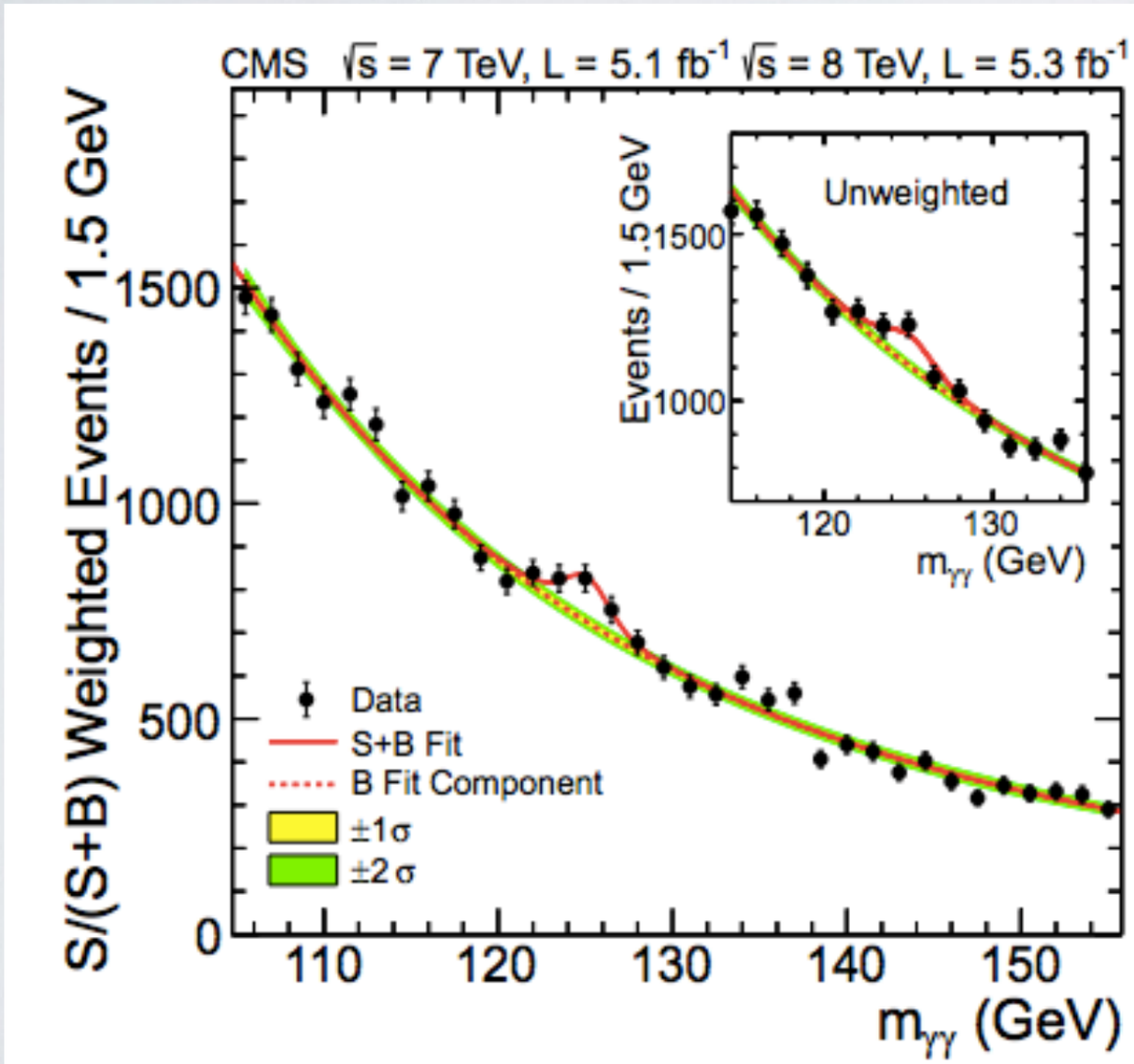


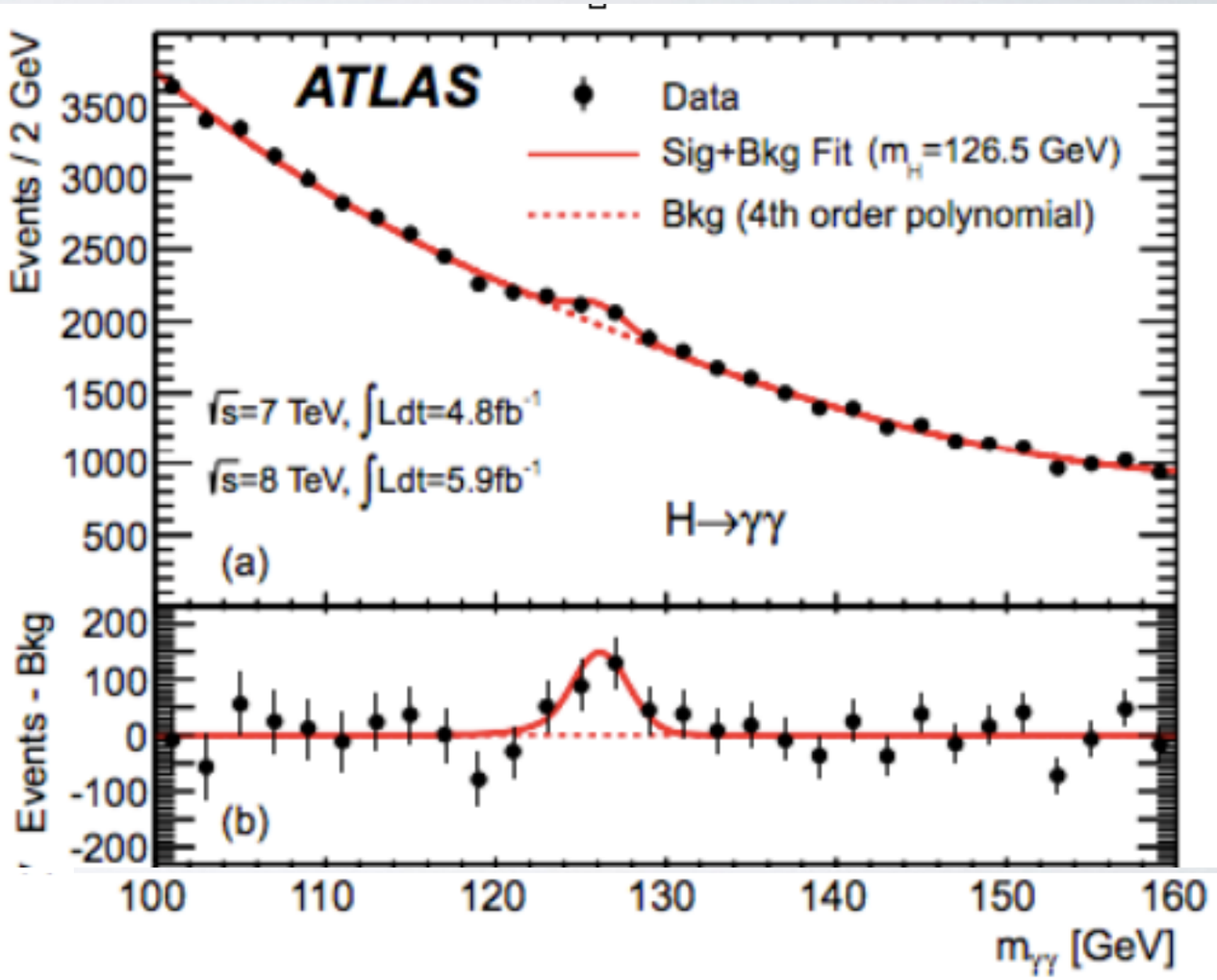


Decay into two photons - unlikely channel but clear signal:
Two very energetic photons.

The bump

Bump seen at a mass around 125 GeV.





Celebration!

4th of July, 2012

5 sigma confidence level:
Probability of error less than 0.0001%
➡ Discovery!

God particle?

It is quite extraordinary…

Crucial part of Standard model

Responsible for structure in atom, particle masses.

But *God particle* is probably overrated…

What's next?

LHC will be operating again after 2 years of shutdown! Operating at *14 TeV* - double energy

What to expect from the future?

What is there, besides more precise measurements?

To be continued… (After the break)

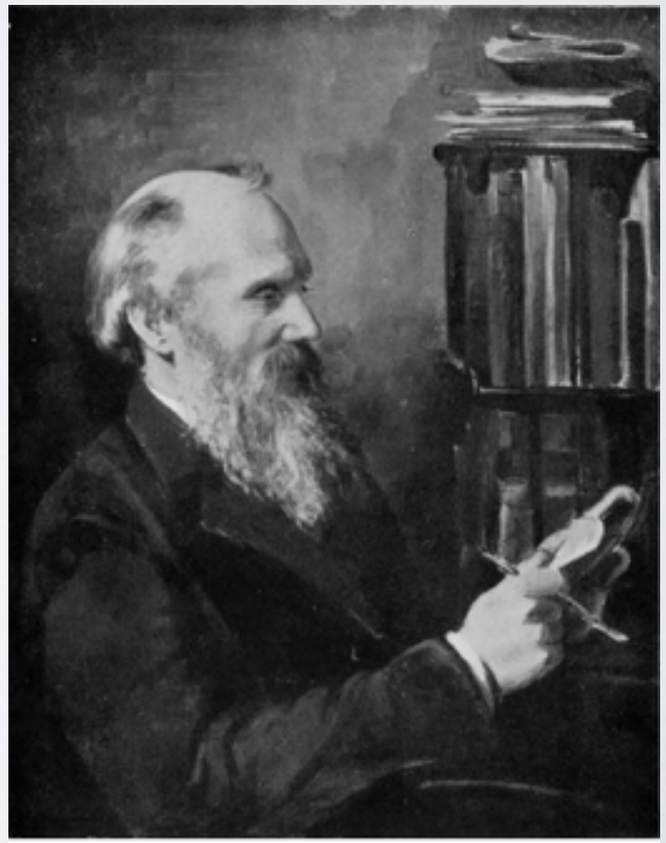
Historical predictions

The more **important fundamental laws and facts of physical science** have **all been discovered**, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote . . . **Our future discoveries must be looked for in the sixth place of decimals**.

~ Albert A. Michelson, 1894

There is **nothing new to be discovered** in physics now. All that remains is more and more **precise measurement**.

~ William Thomson (Lord Kelvin), 1900

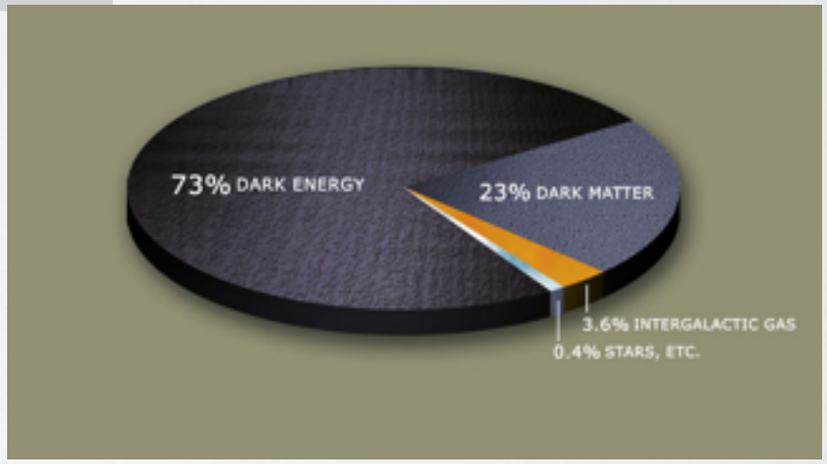


Why beyond the Standard Model?

There must be more to the story, to account for:

- Neutrino masses!

- Dark matter/energy, 96 % of universe!



- Gravity!

Other technical problems

Hierarchy problem, *naturalness.*

Force carriers associated with weak scale
- exist at Fermi scale. W and Z bosons.

Expect force carriers associated with gravity
- to exist at Planck scale.

Weak force: 10^{32} times stronger than Gravity!

Why?

The hierarchy problem

70's: Hierarchy problem even more serious…

Particles at Planck scale contribute to Higgs mass!

➞ Light Higgs disfavoured
Should be 10^{16} bigger than it is!

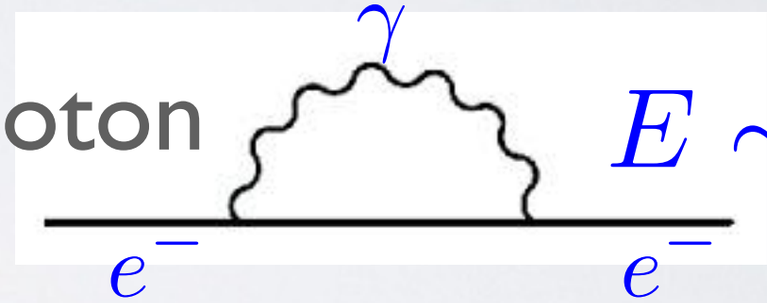
Just aesthetics? Maybe not serious…

Solved before!

Classical electromagnetism: *Electron hierarchy problem*

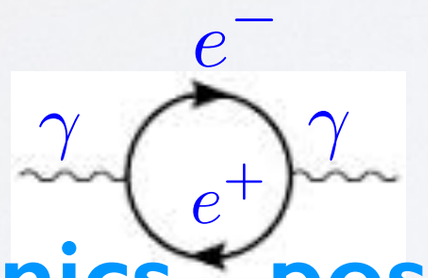
Coulomb electric field around electron

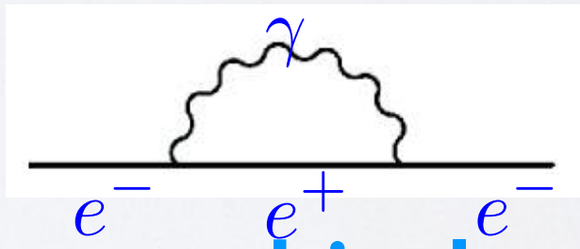
Energy emission/absorption: photon



Need cancellation of this contribution.

Solution:





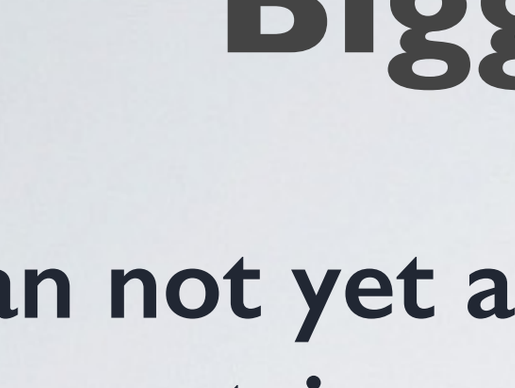
Quantum mechanics - positron, chiral symmetry.

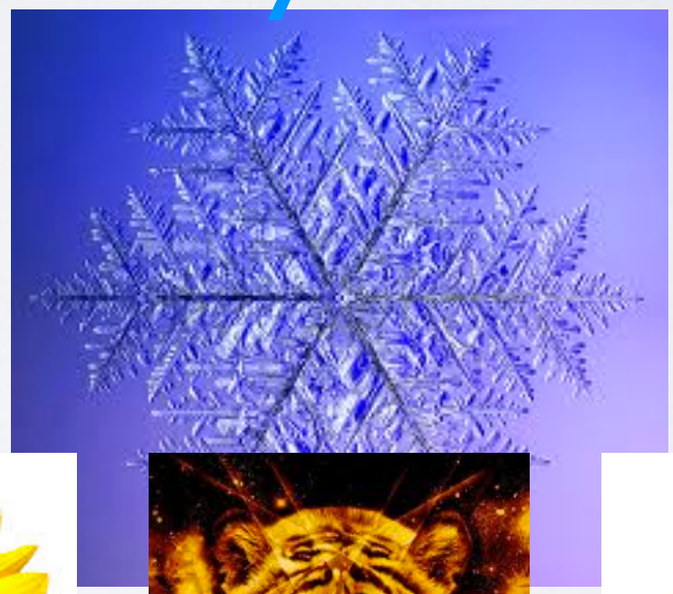
Alternative solution: New particles and symmetries

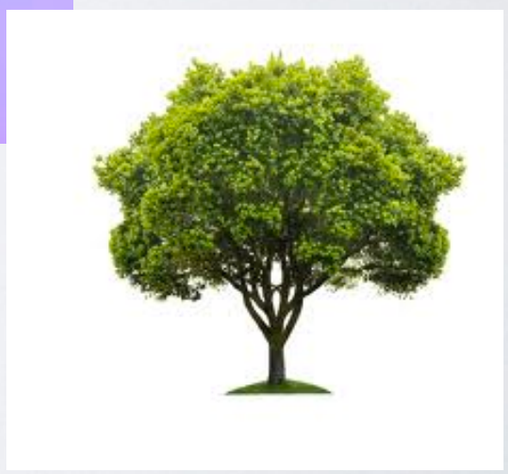
Bigger symmetries?

Can not yet account for whole universe with used symmetries.

Which symmetries have we not yet seen?







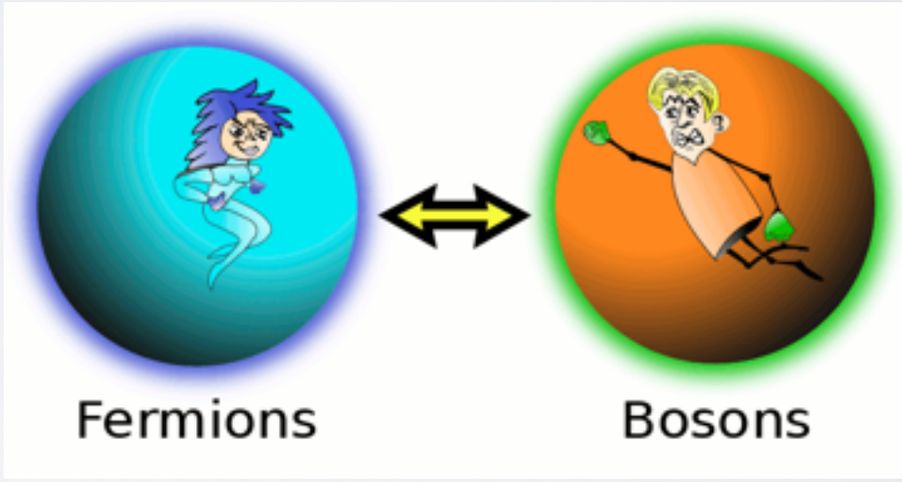
Or understood?

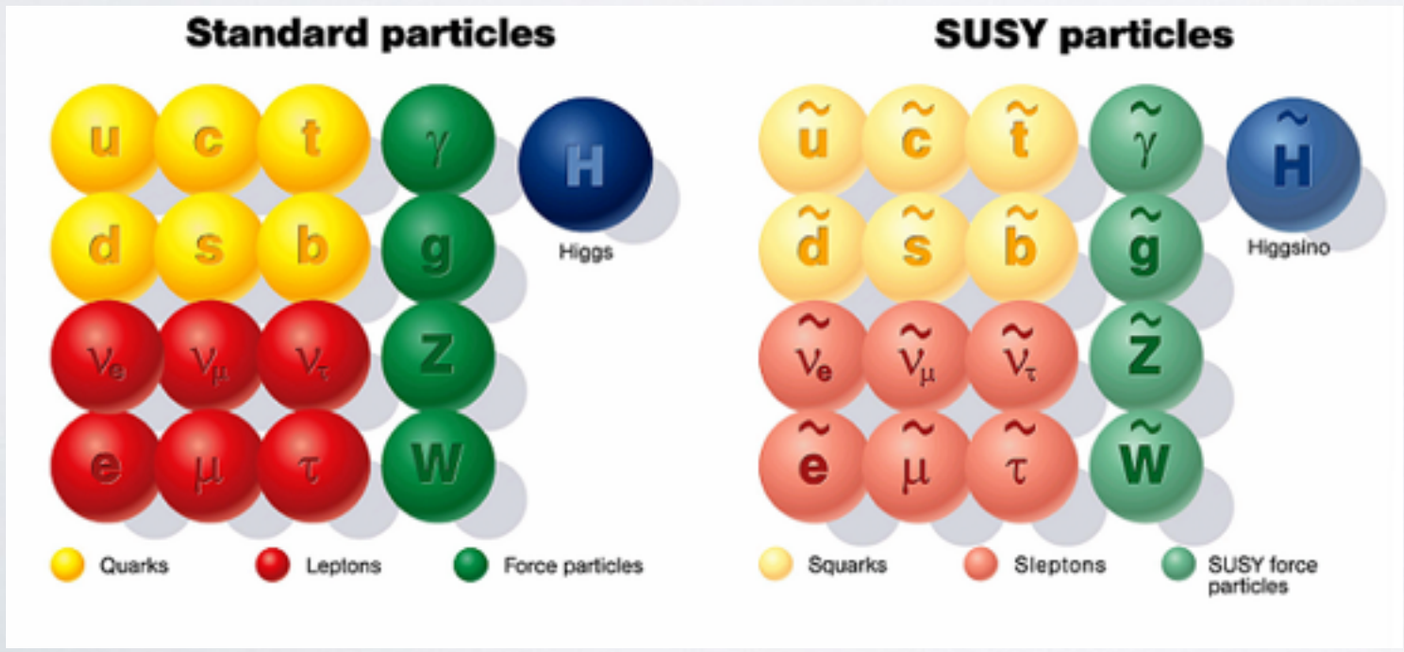
Supersymmetry

Could be the answer to many of the Standard Model problems!

... and maybe the next discovery at the LHC!

New symmetry between fermions and bosons.





All particles get a superpartner.

Composite Higgs

Also provides answers to many of the Standard Model problems!

→ *too heavy!*

Sally Appleby

Breaking of a symmetry → Goldstone bosons (*massless particles*).

Symmetry not exact to begin with - already broken
→ pseudo Goldstone bosons (*light particles*).

→ Make Higgs a *pseudo-Goldstone boson.* It becomes *naturally light!*

How to proceed beyond?

Discovery of Higgs → search for properties!

Two areas to look for new Higgs physics:

- New particles associated with the Higgs
- Higgs couplings to other fields.

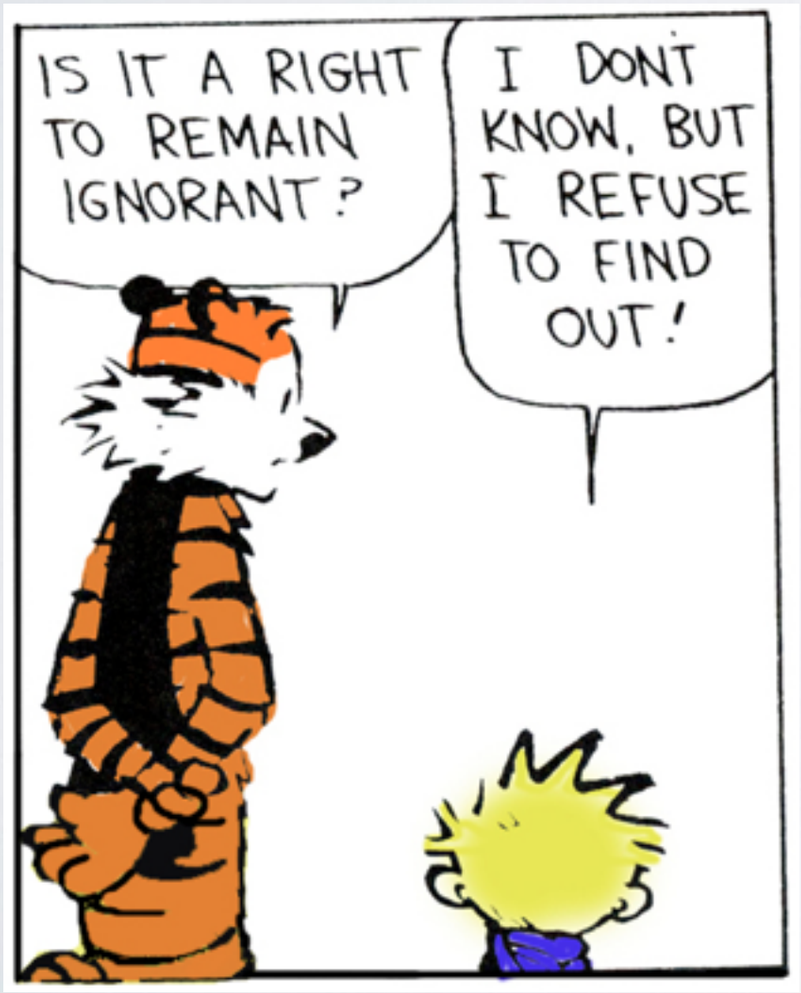
Two questions to ask when looking:

- Is the Higgs elementary or composite?
- Is it weakly or strongly interacting?

Effective field theory

Method: Ignore details of the new physics and the particles within it.

This leaves traces at the low energy scale....



These are for us to find!

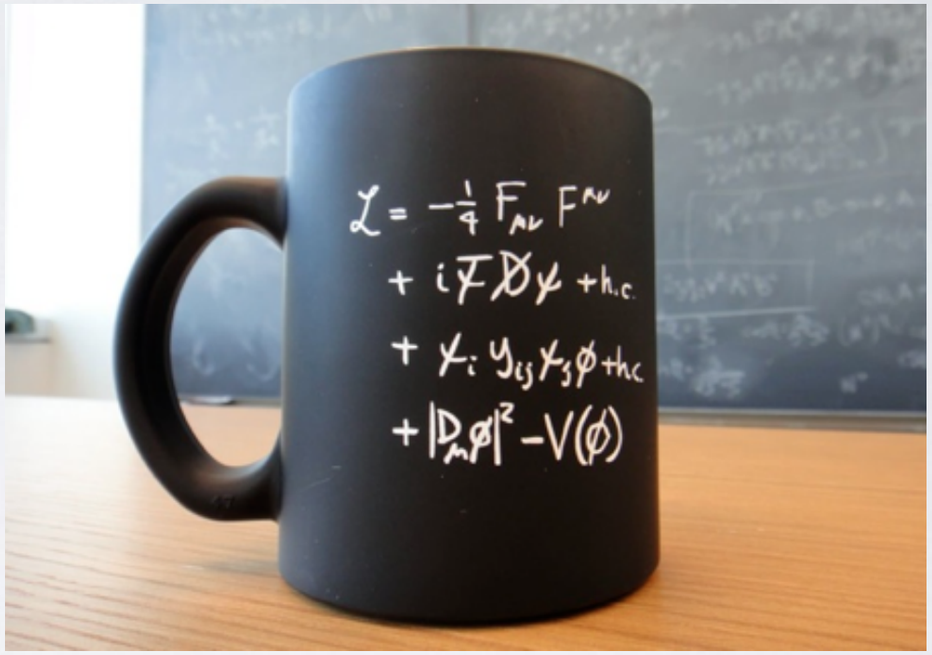
Result: New terms introduced.

- Higher dimensional operators.

They just need to be written up...

Extending the Lagrangian

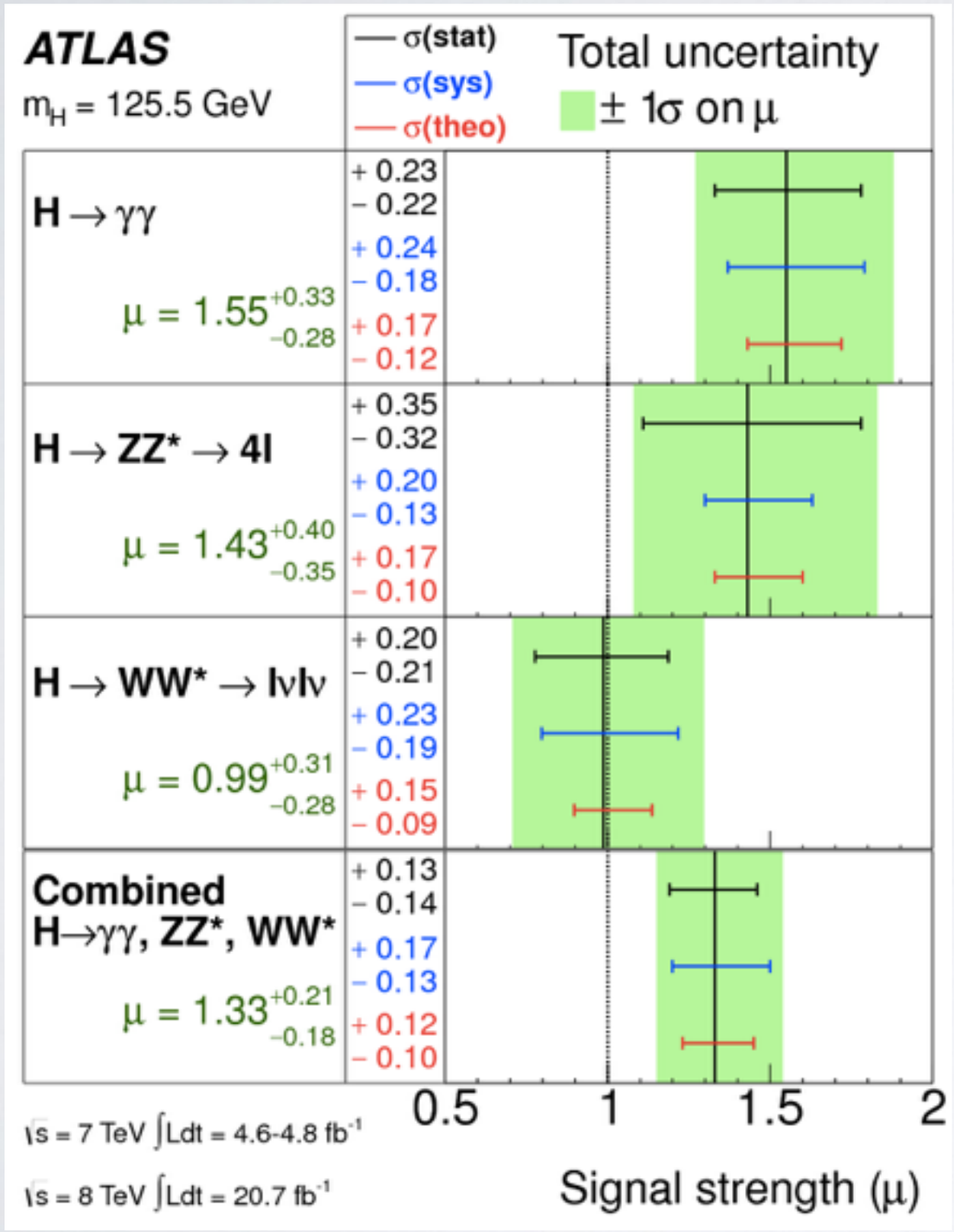
The *Standard model* can easily fit on a mug from *CERN*...



59 new terms entering at next level!

- CERN would need to launch a bigger cup!
- The need for coffee would scale the same way...

Data

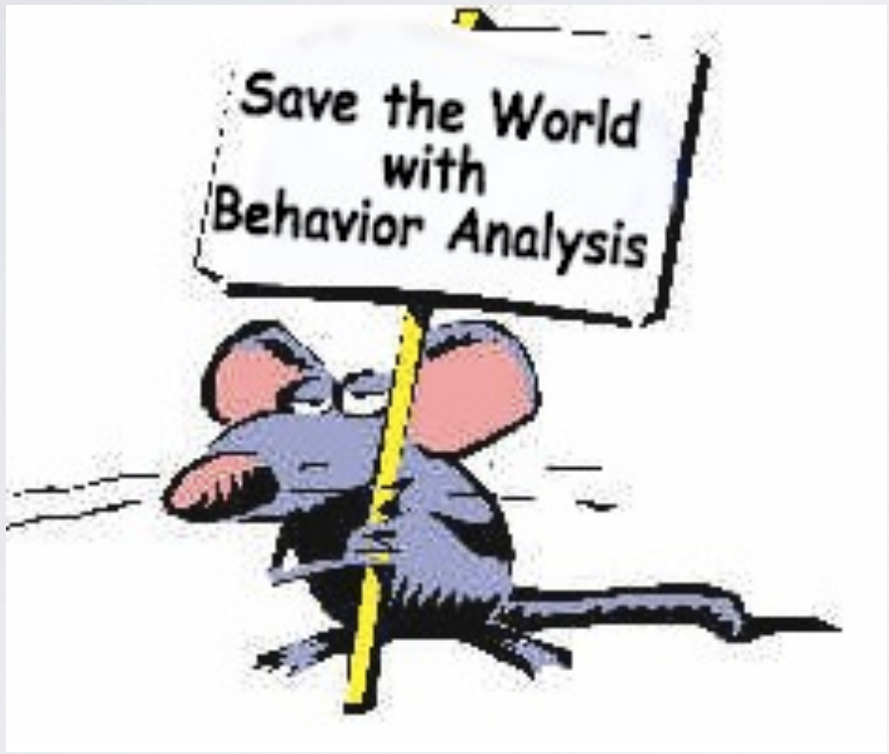


Current status of $H \to \gamma\gamma$ decay

Still room for new physics!

Precision important!

Now that we found the Higgs - need behavior analysis



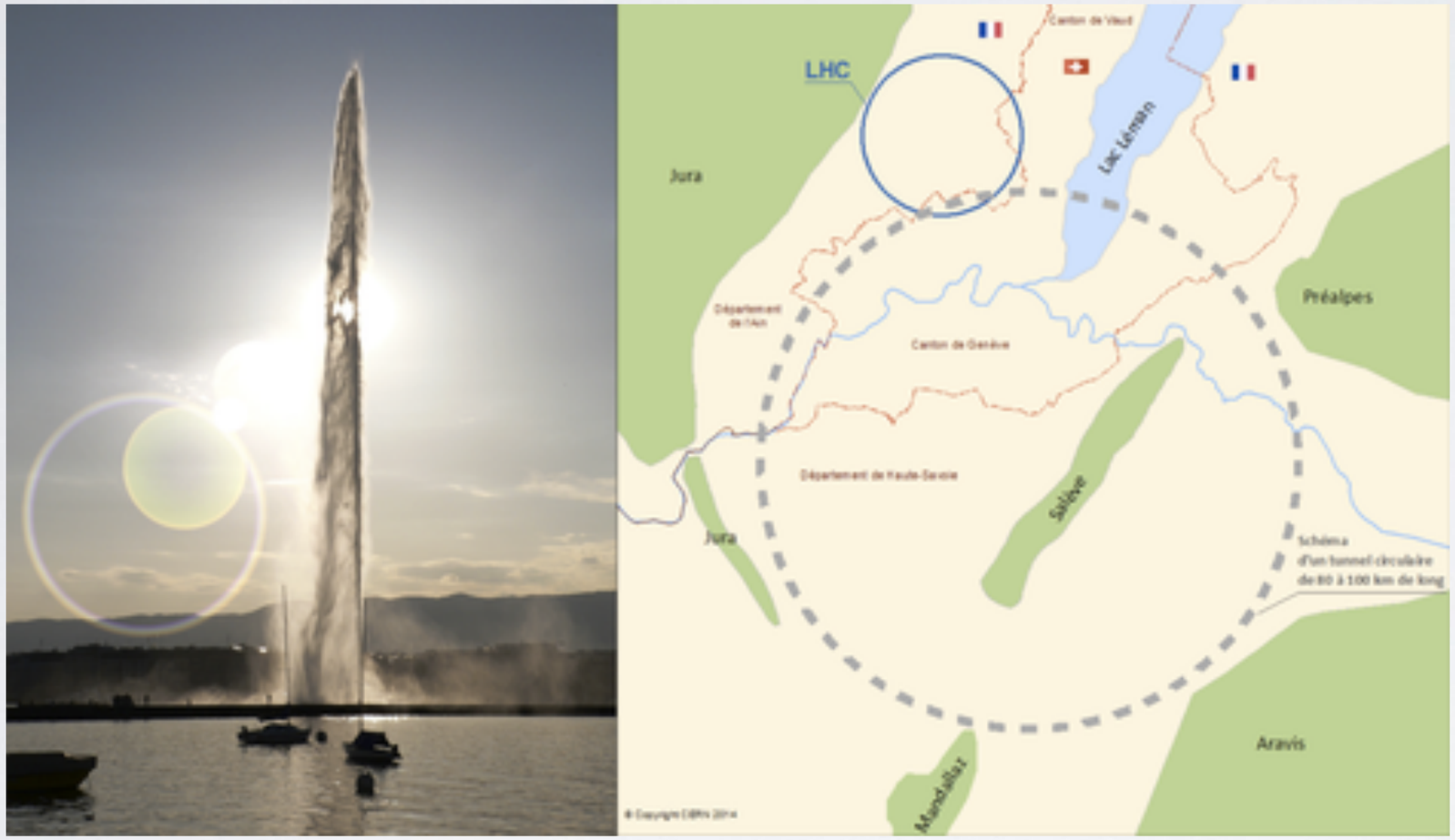
- How does it interact?
- What is it made of?
- How important is it?

But we might stumble over new physics in the search for accuracy…

A glimpse of the future

Future circular colliders! Even bigger

- surrounding mountains.



80-100 km ring
(compared to 30 km)
100 TeV energy
(compared to 14 TeV)

Intermediate step: 90-400 GeV lepton collider.

What have we learned?

- Discovery of Higgs field and theory behind - a worldwide effort

- Higgs not a God particle - but close to being it

- Never believe that there is nothing more to be discovered!

- SUSY and composite Higgs models - few of the ways you can go

- Data still leave room for new physics!

- We are still in a very exciting era of particle (Higgs) physics!