# Answering Very Short Distance Questions With A Very Big Gadget: Finding The Higgs Boson

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***Thanks to the San Juan Nature Institute***

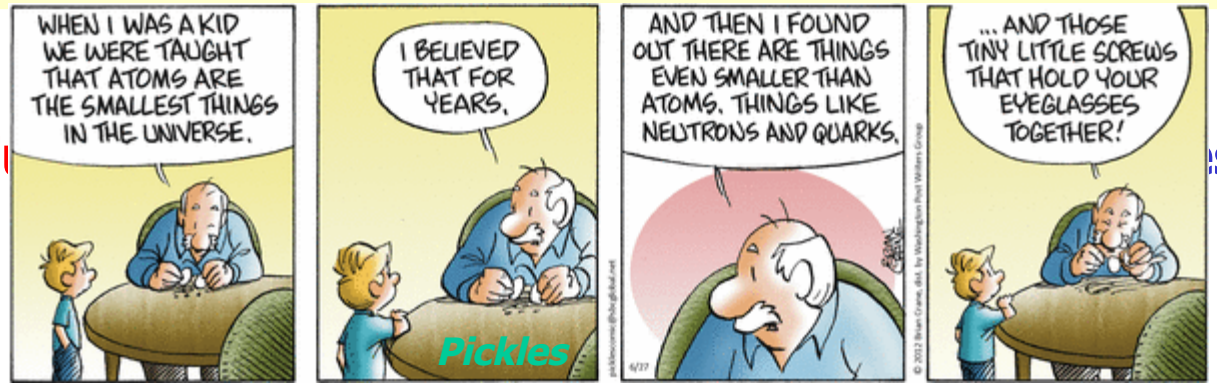
***2/27/14***


*Pronunciation note: boson = bos – on, ≠ bo-son =*

# Particle Physics
# or
# High Energy Physics

**Aims to answer two basic questions:**

- **What are the fundamental constituents of matter?**
- **What are the fundamental forces (rules) that control their behavior?**



# Warning!!!!

- **The correct language for the following discussion is Quantum Field Theory – i.e., during your second year of graduate school in physics!**

- **YouTube is filled with efforts to explain the Higgs without Quantum Field Theory. All "cheat" and oversimplify somewhere!**

- **I am no different, but sometimes I will tell you when I'm "cheating"!**

# The Physics Paradigm for Progress

**Theoretical Physics**

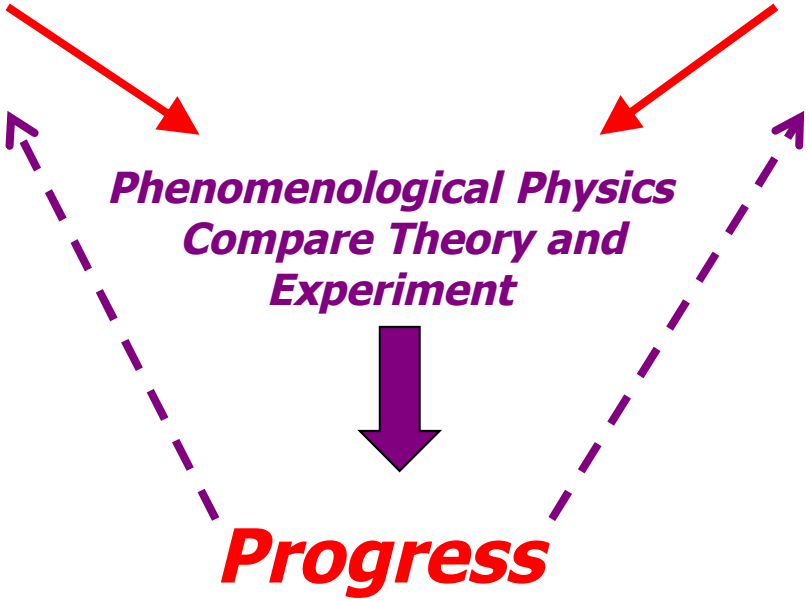
**Find *self-consistent* mathematical rules that describe how the universe works**

***Better Theories***

**Experimental Physics**

**Measure how the universe *actually* works in the laboratory**

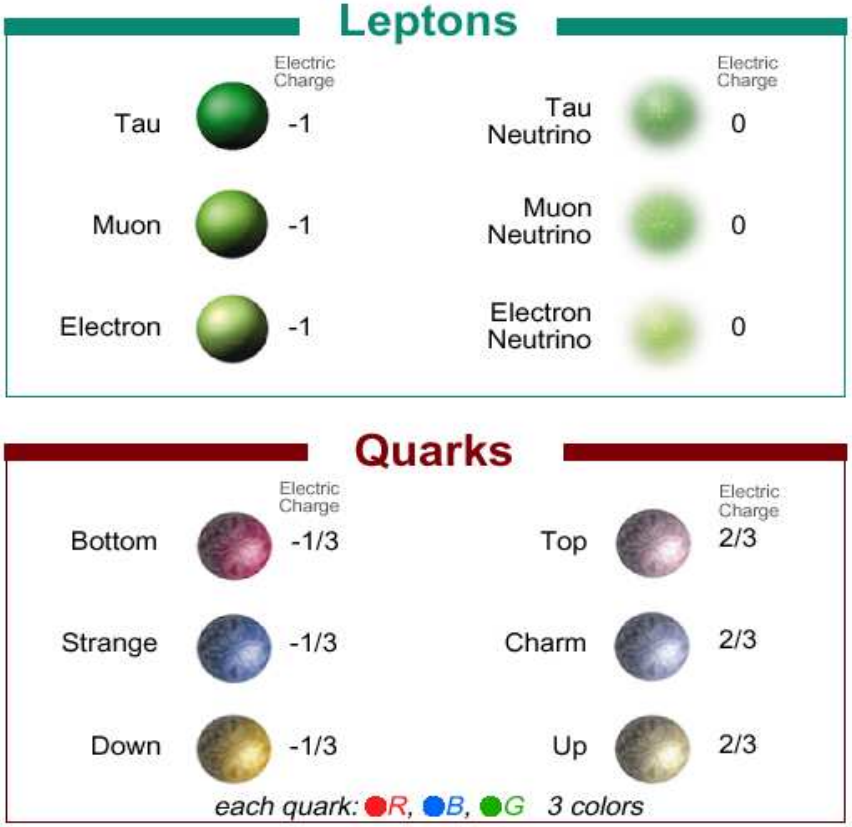
***Better Detectors***

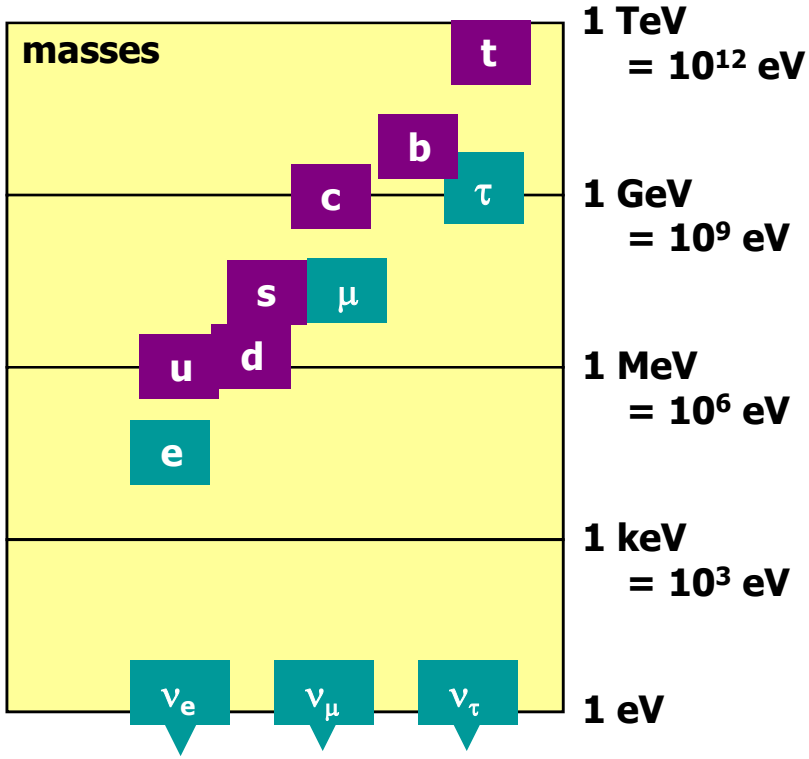



***The Higgs story is this process spread over 50 years, 1964 to 2014***

# Fundamental Matter Particles

← Separate by Interactions →



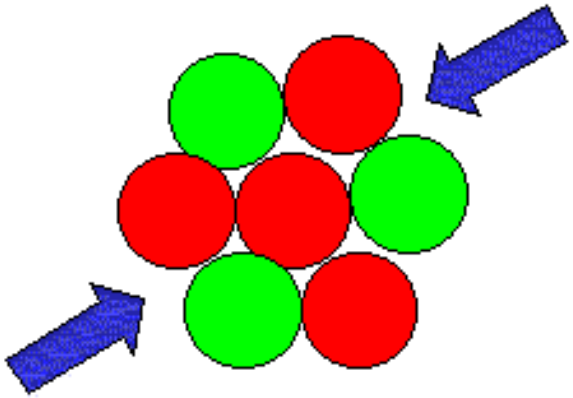

**Antiparticles: same mass but opposite charge as particles**

**Where do the masses of the particles come from?**

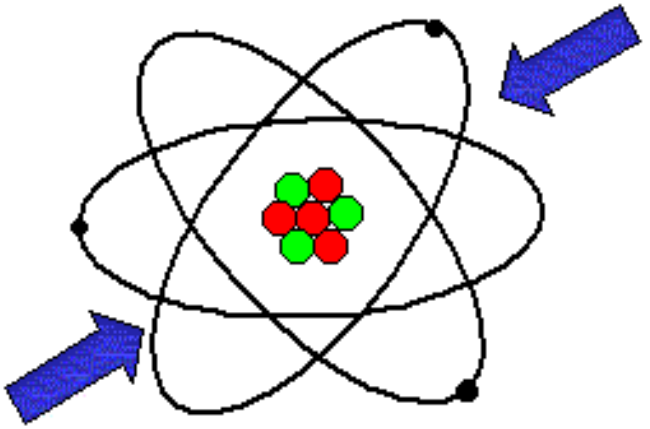
**All of these particles are "fermions" = spin ½!**

**1 GeV = mass of proton**

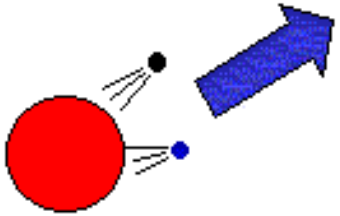
# Forces



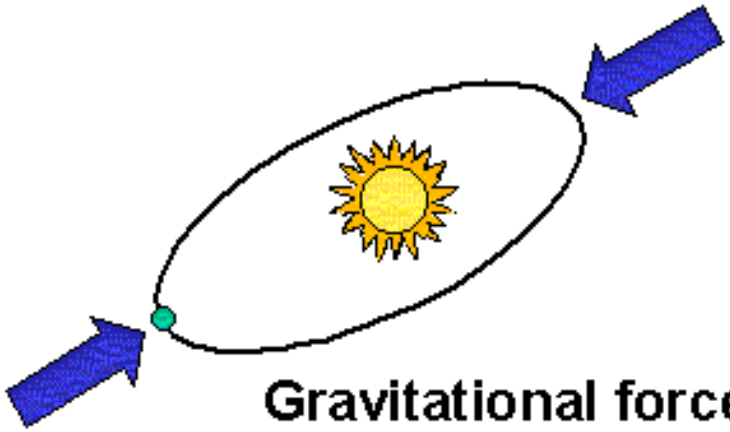
Strong force
binds the nucleus



Electromagnetic
force binds atoms



Weak force in
radioactive decay



Gravitational force
binds the solar system

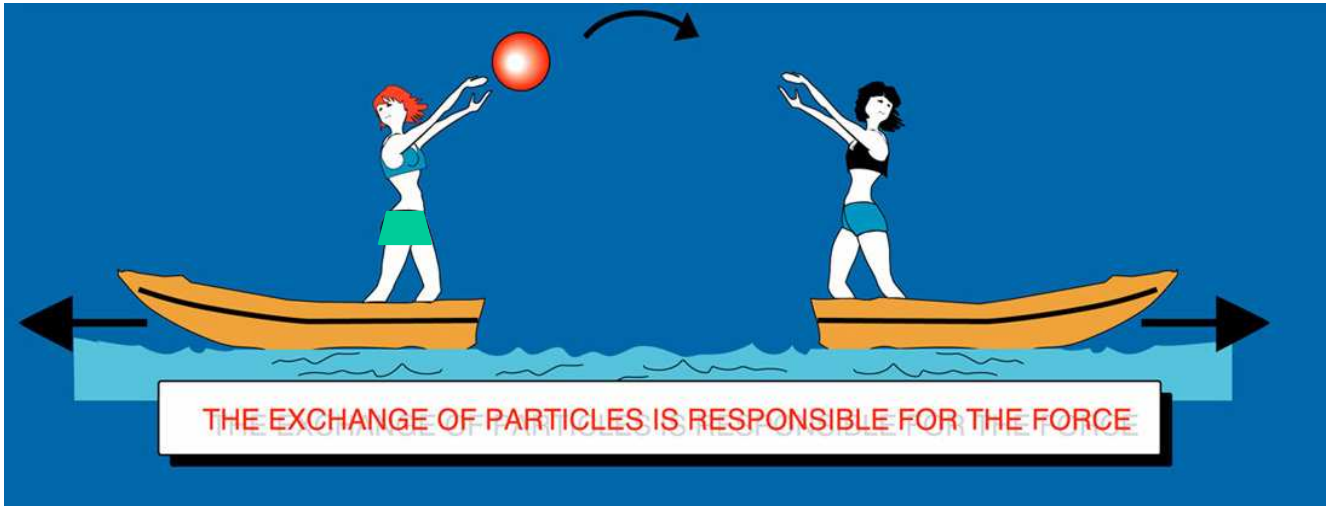
# How are forces felt?

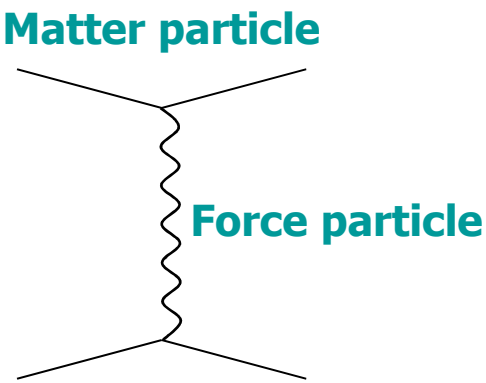
*Matter*

- **Particles interact at a distance, force is mediated through fields**
- **Fields can vibrate/oscillate**
- **Vibrations/oscillations/excitations are *quantized* → Particles**

*Force*

**Forces are mediated by the exchange of "force particles" between "matter particles"**




**"Feynman" diagram**

# Fundamental Forces


| | Gravity | Weak (Electroweak) | Electromagnetic (Electroweak) | Strong |
|---|---|---|---|---|
| Carried By | Graviton (not yet observed) | $W^+$ $W^-$ $Z^0$ | Photon | Gluon |
| Acts on | All | Quarks and Leptons and $W^+$ $W^-$ $Z^0$ | Quarks and Charged Leptons and $W^+$ $W^-$ | Quarks and Gluons |

It turns out (mathematically and verified experimentally) that the electromagnetic and weak forces are intimately related: the Electroweak force



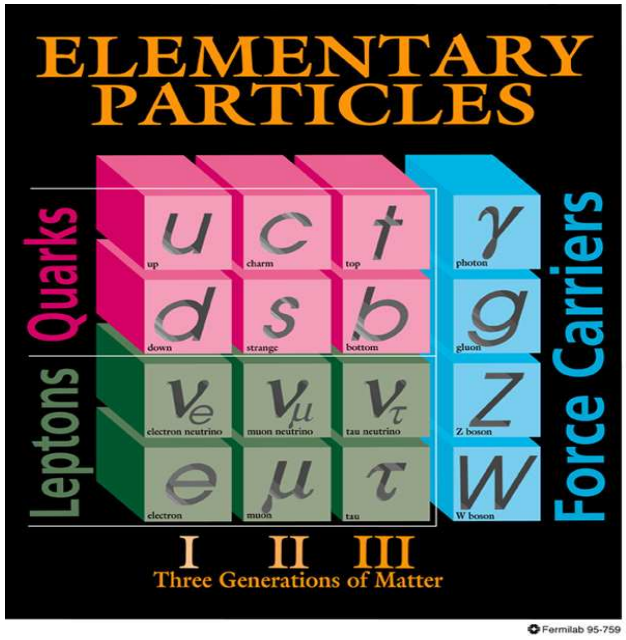
**The force carrier particles are "bosons" = integer spin (1 or 2).**

# Standard Model

**Verified to high precision**

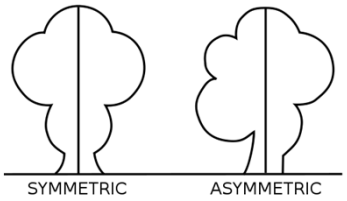
## Constituents

**elementary = fundamental**




**(SM does not incorporate Gravity)**

***Get ready – here comes the confusing bit!!!***




**For internal consistency *Theory* wants the mathematical description of the Standard Model to have as much *symmetry* as possible,**

**e.g., want all of the fundamental particles to start with the same mass = 0!**

**But *experiment* in 1960s already said W, Z and charged leptons are *MASSIVE* ⇒ Enter Higgs, et al.**

**Suggest: Keep the mathematical rules symmetric, but let the lowest energy state, the VACUUM, *break* the symmetry.**

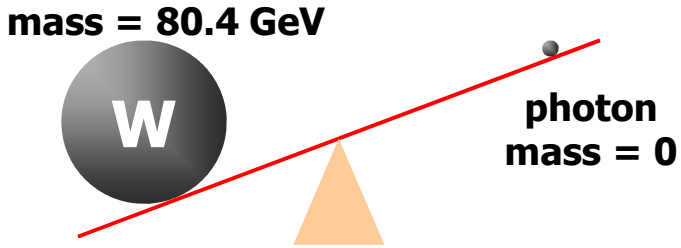
**Because the Higgs field is *NOT ZERO* in the vacuum!**

**That's right, the vacuum is not empty!!!**

**And the interaction of the elementary particles with the Higgs field in the vacuum gives them non-zero and different masses!!**

# In particular – "Higgs Field" Answers the Questions

## What gives mass to the W and Z bosons while the photon is massless?



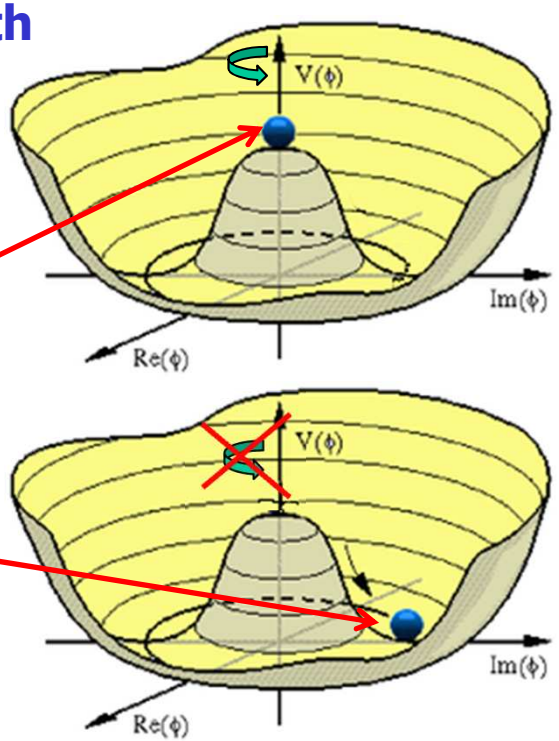

## What breaks the Electroweak Symmetry?

**WARNING: Only approximately 1 % of your mass comes from the Higgs via the quarks and leptons in your body! The rest (99 %) comes from the gluons in your protons and neutrons!**

**The Higgs plays no role in diets!**

# How can this happen - The Higgs mechanism

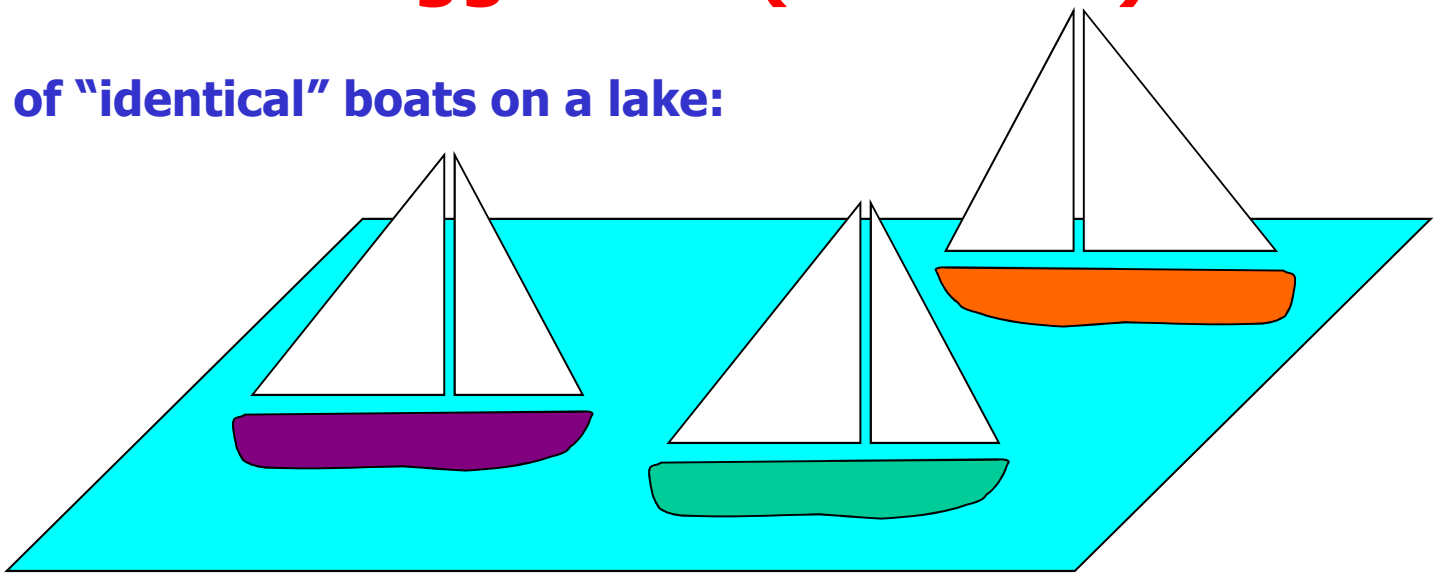
- All fundamental particles are massless to begin with
- Now add the Higgs field, which has a potential energy with a rotational symmetry
- Symmetric state at origin has higher energy. Low-energy state is not symmetric ⇒ choosing a particular low energy state "breaks" the symmetry "spontaneously"
- Higgs field is not at the symmetric origin ⇒ has NON-zero value EVERYWHERE in space-time



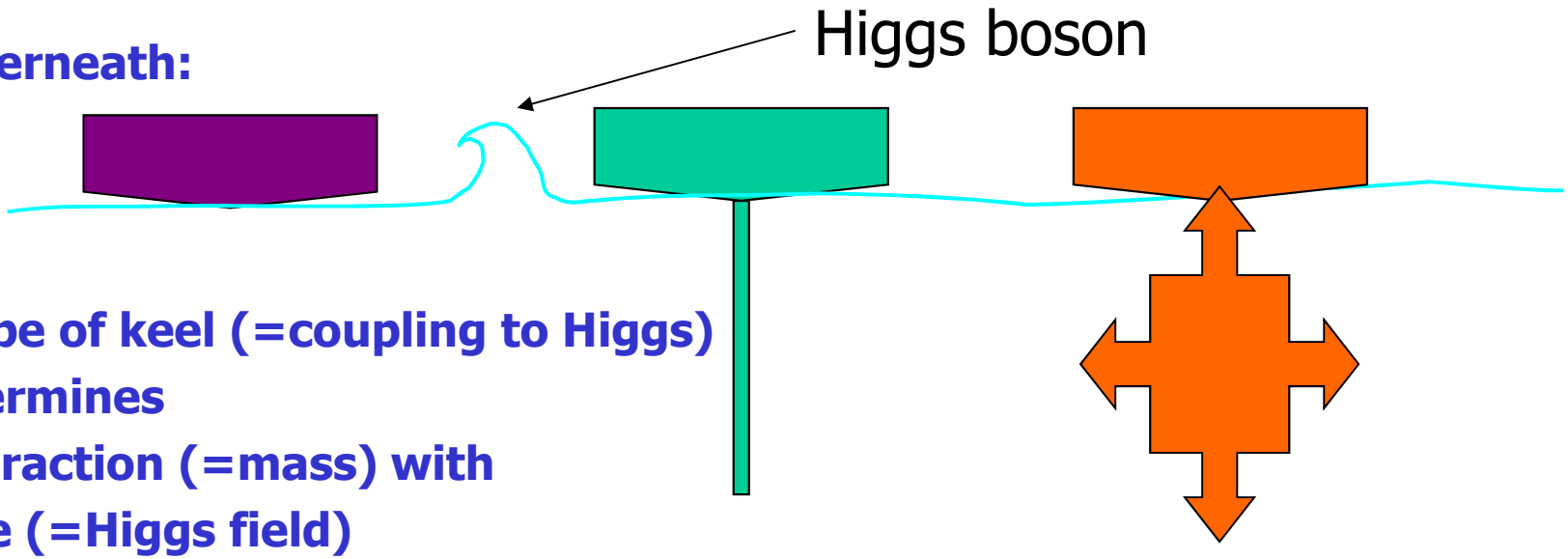

- Particles interacting with this field acquire mass – the stronger the interaction, the larger the mass
- The Higgs field is a quantum field – the quantum is the Higgs boson. Finding the Higgs particle establishes the presence of the field.

# The Higgs field (as a lake)

**Think of "identical" boats on a lake:**



**Underneath:**




**Shape of keel (=coupling to Higgs) determines Interaction (=mass) with Lake (=Higgs field)**

# Warning – lake is not a great analogy!

- **The real reason the interaction with the Higgs field (everywhere in the vacuum) really acts like a mass is because of the *DUCK THEOREM !***

- **The interaction specified in the Quantum Field Theory version of the Higgs mechanism**

  **looks like a mass!**

  **acts like a mass!**

  **quacks like a mass!**

  **So is a "mass", which vanishes in the symmetric (empty vacuum) theory.**

**Note: The Higgs scenario does NOT tell us what the masses are, only allows us to describe their NON zero values without breaking the underlying symmetric rules.**

**Hence the 50 year hunt for the Higgs Boson itself (we didn't know precisely where to look).**

# The Higgs at the LHC

**L = Large**

**H = Hadron = nuclear interactions = proton**

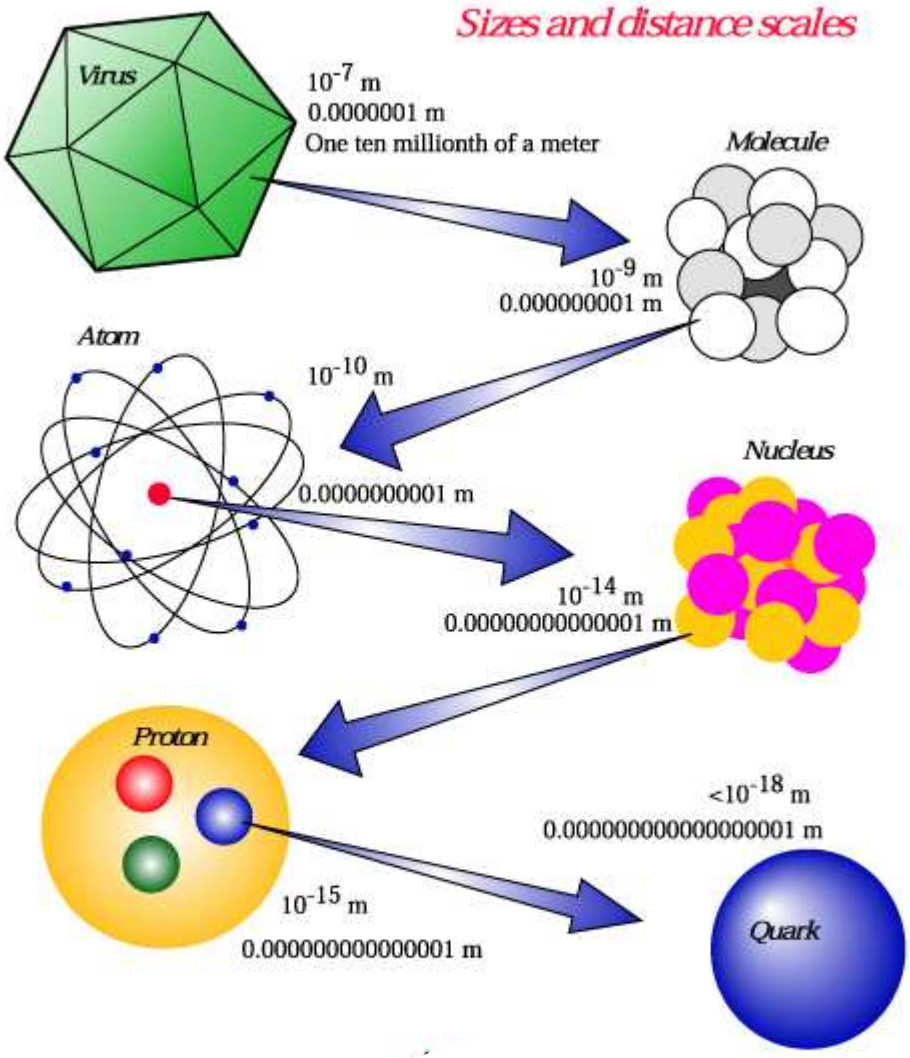
**C = Collider = 2 beams in opposite directions**

# Experimentalist's 'Microscope'

**Wavelength of radiation should be smaller than the object to be resolved**

Quantum Mechanics: $\lambda = \frac{\hbar}{p} = \frac{\hbar c}{E} <$ size

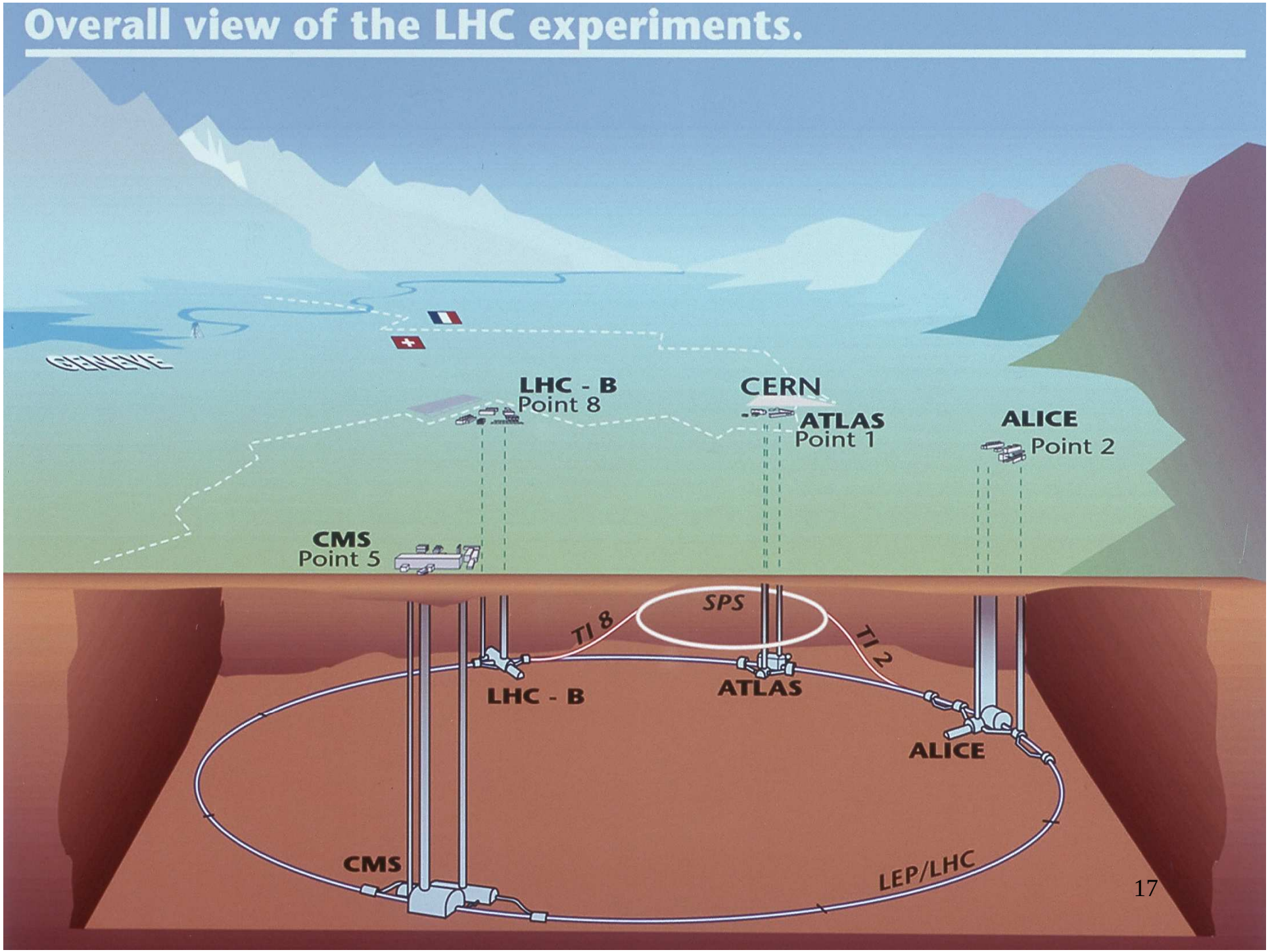
| Object | Size | Probing energy |
|---|---|---|
| Atom | $10^{-10}$ m | 0.00001 GeV |
| Nucleus | $10^{-14}$ m | 0.01 GeV |
| Proton | $10^{-15}$ m | 0.1 GeV |
| Quarks | $<10^{-18}$ m | >> 1 GeV |

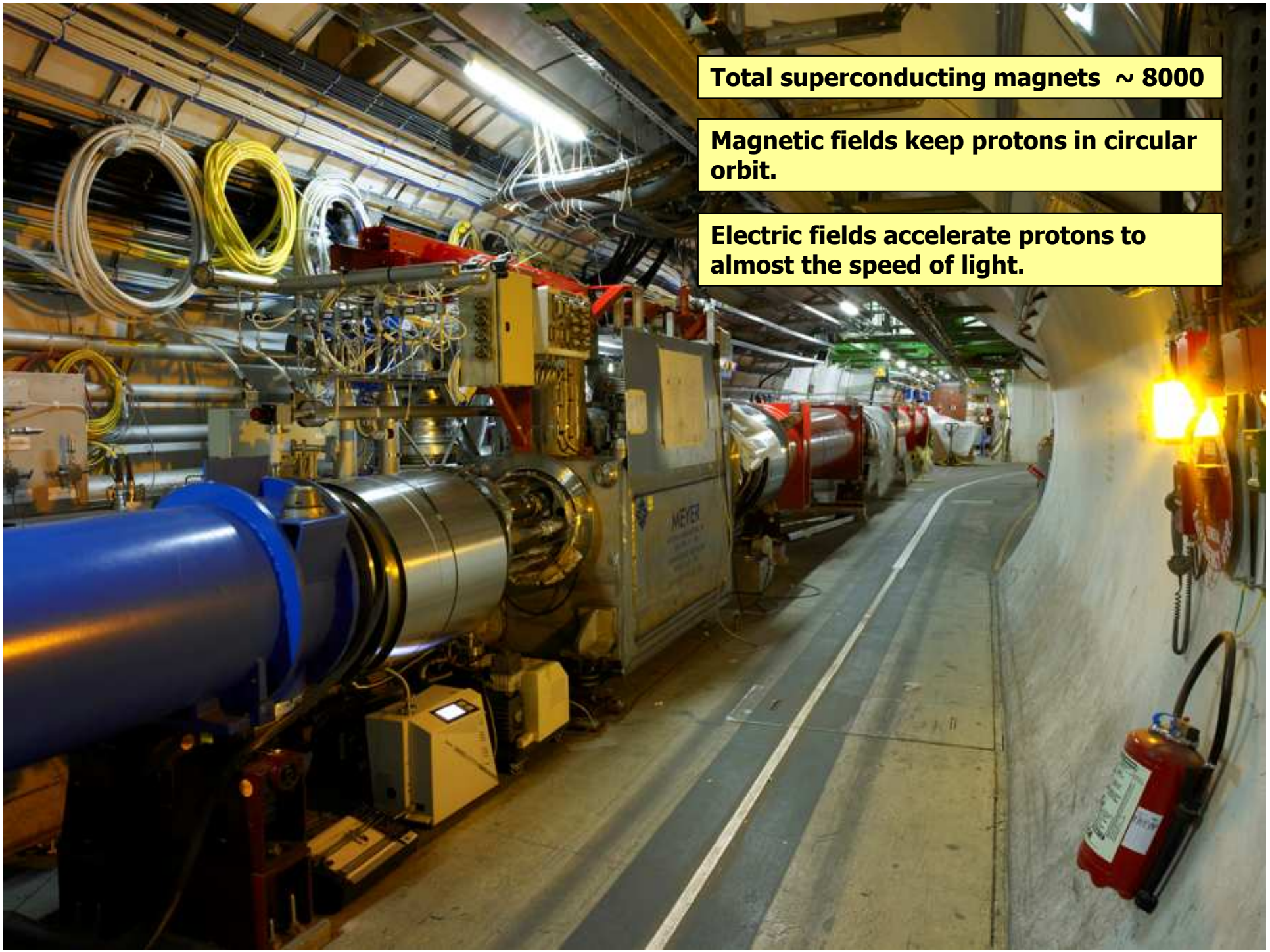



**Need accelerators for energies above 0.001 GeV!**

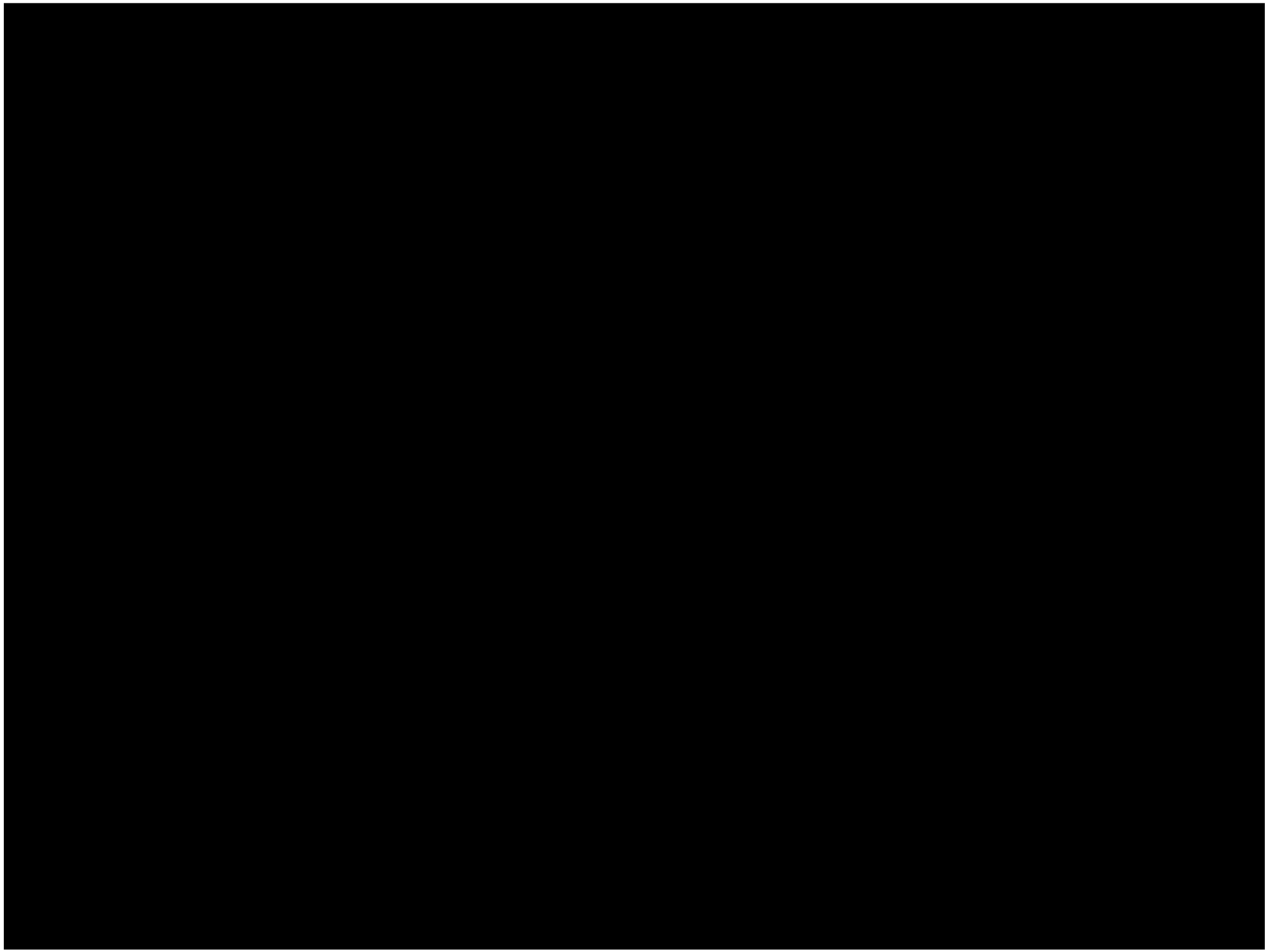
**The irony of quantum mechanics – for tiny distances need huge gadgets!**

# Large Hadron Collider (LHC)

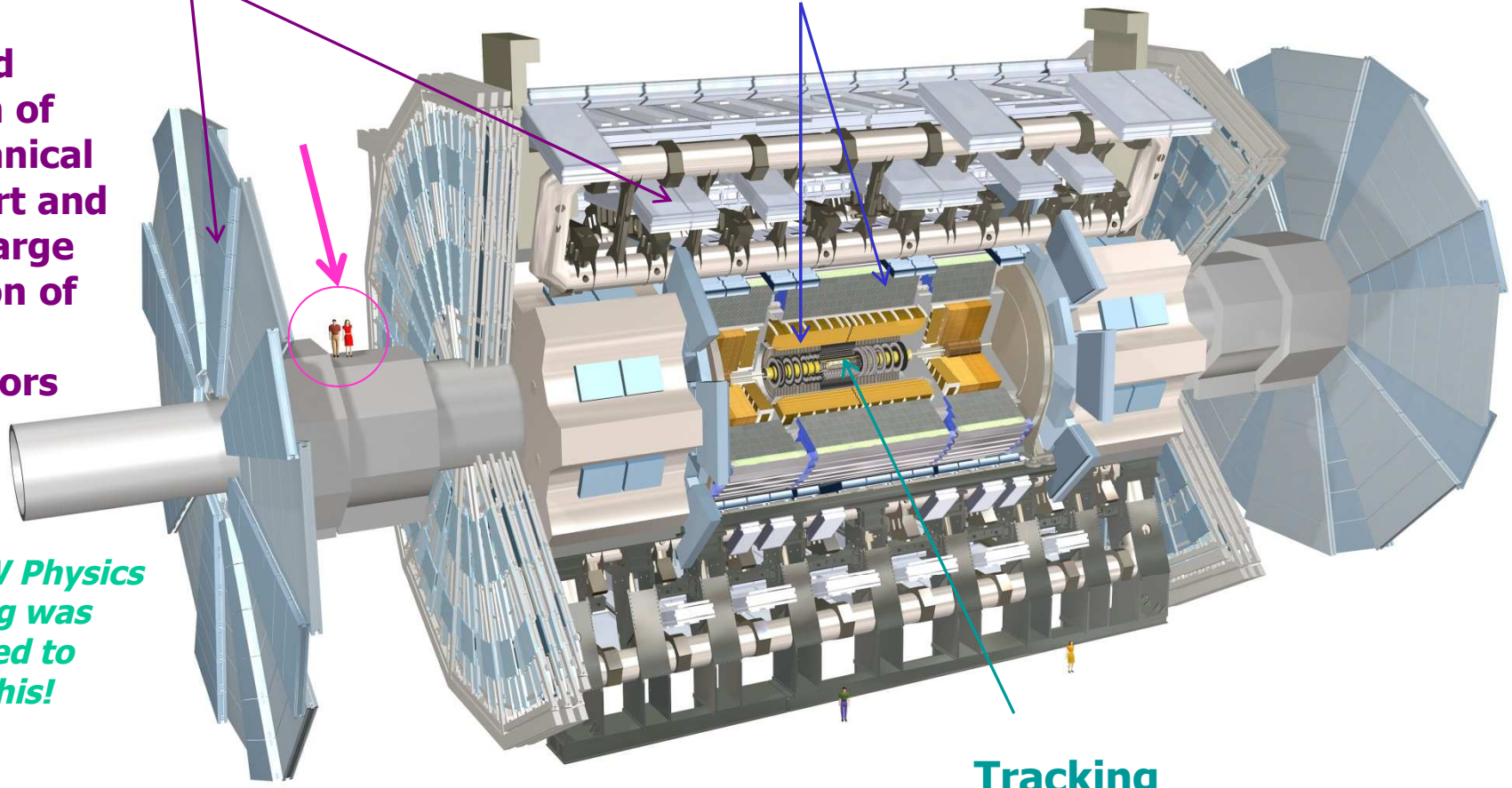

Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC


Total superconducting magnets ~ 8000
Magnetic fields keep protons in circular orbit.
Electric fields accelerate protons to almost the speed of light.

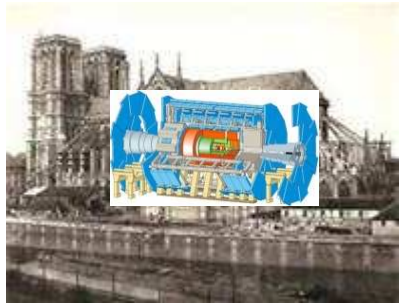
# LHC Video



# A Toroidal LHC Apparatus (ATLAS)

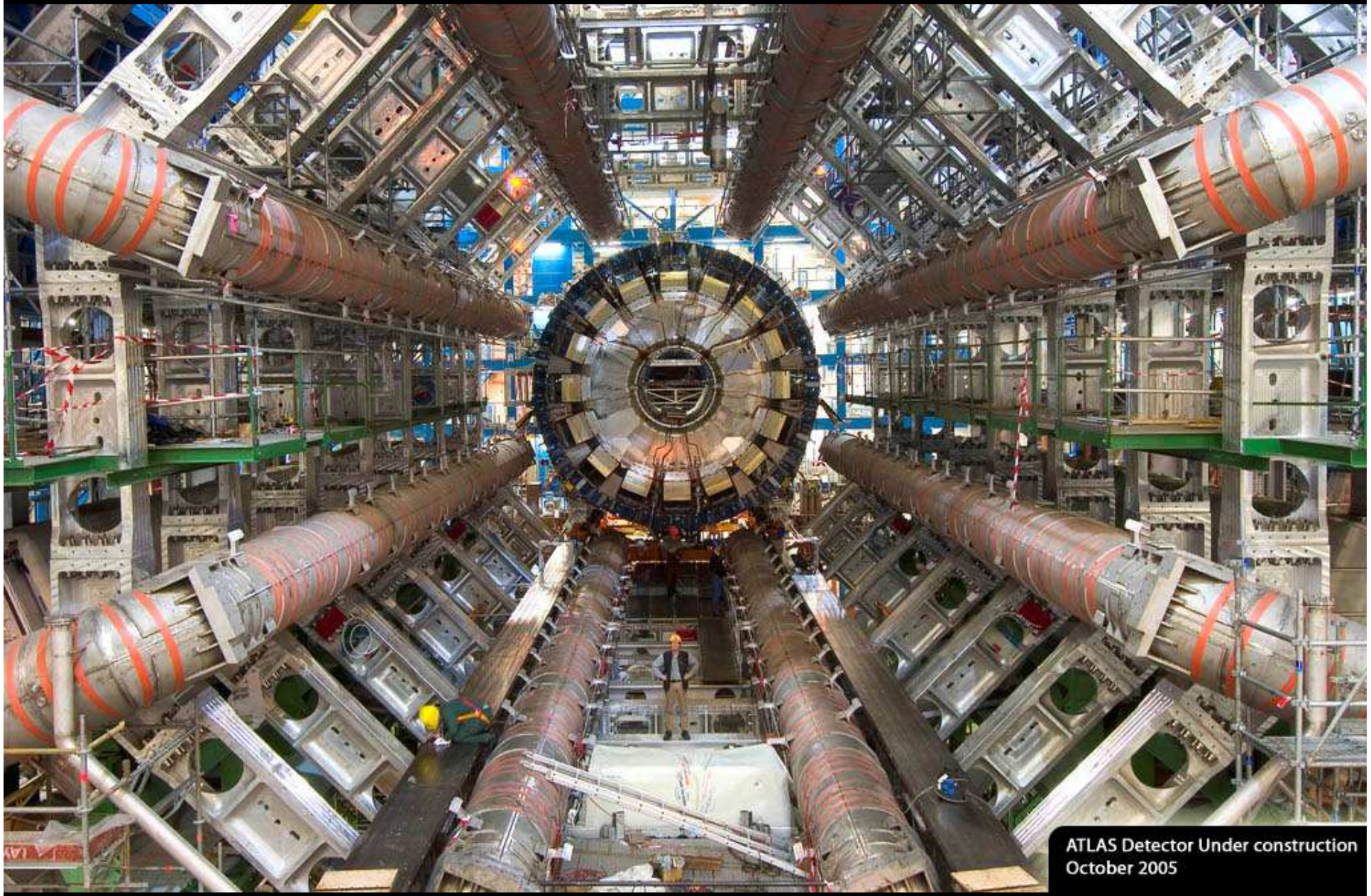


# Fun facts about the ATLAS detector

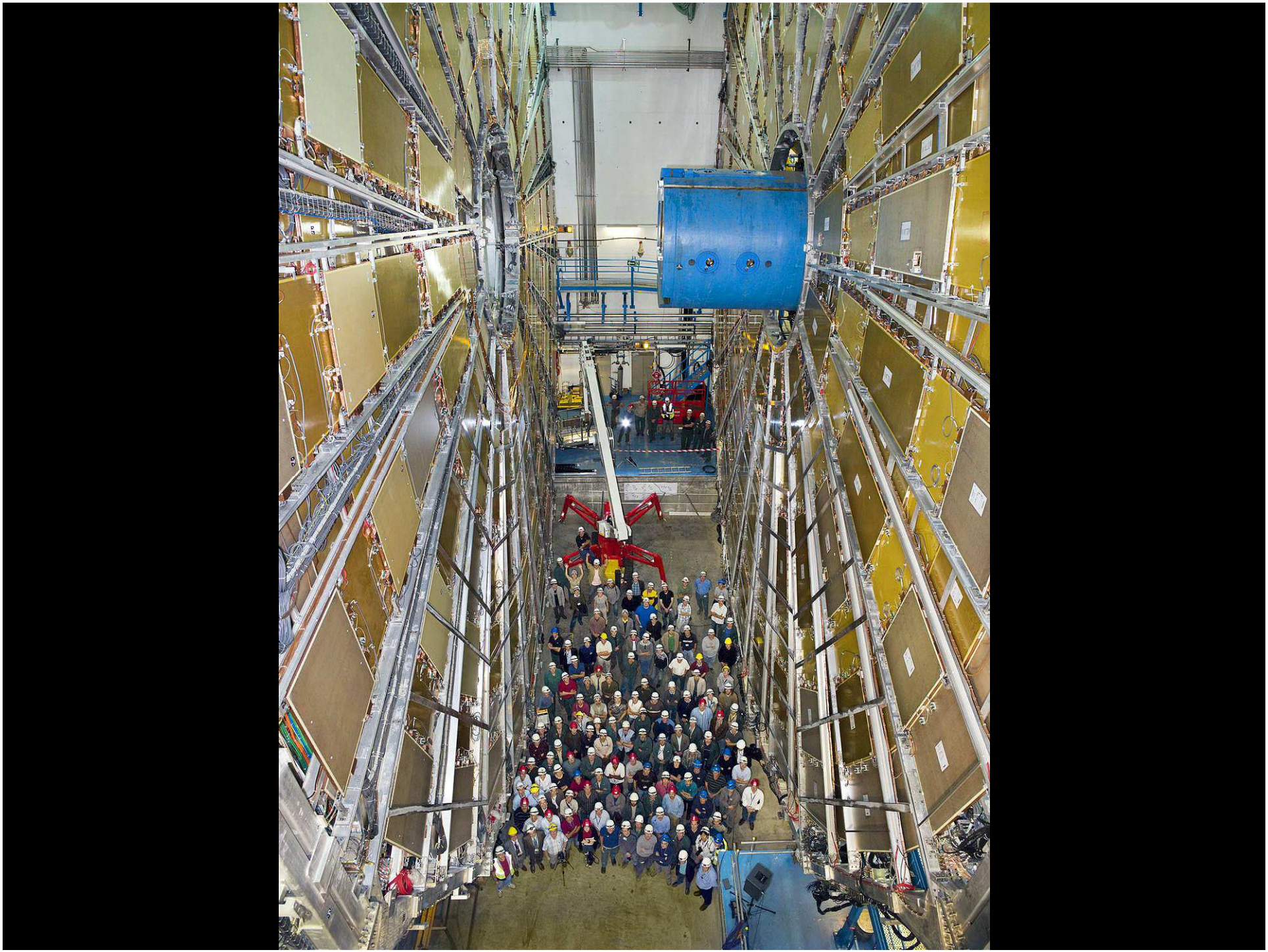


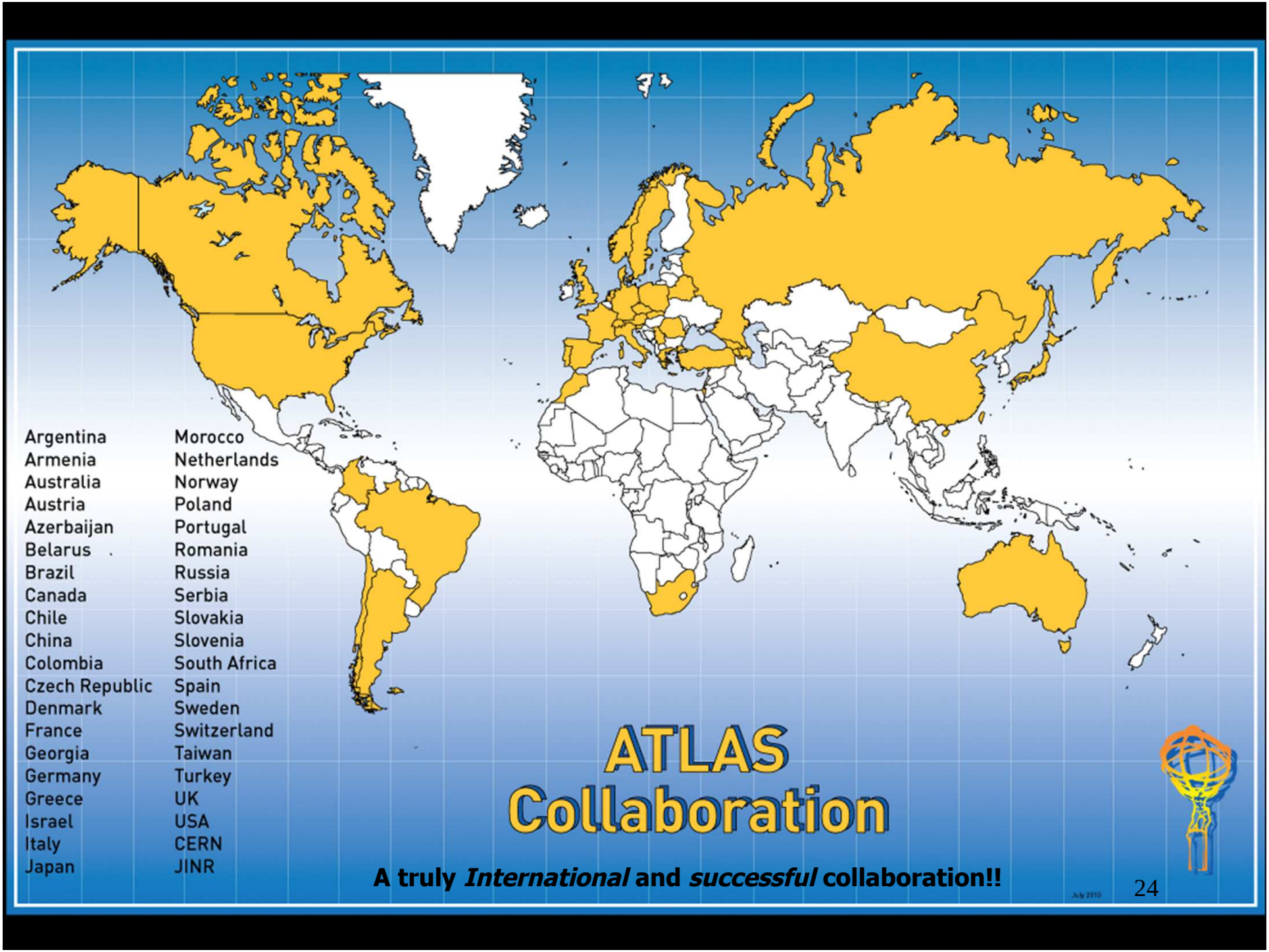
- Weighs 7000 tonnes, same as 100 Boeing 747 jets (empty)
- Half the size of the Cathedral of Notre Dame in Paris
- Can measure position with precision of 0.0004 inches
- Took 8 years to plan, 12 years to build
- At design LHC conditions:
  - About 1 billion proton-proton collisions/second occur in detector
  - One $H \rightarrow ZZ \rightarrow 4e$ produced every 2 hours and 48 minutes
  - If all data would be recorded, this would fill 100,000 CDs/second
  - Trigger selects for storage about 200 "interesting" events/second
- 3000 scientists (including 1000 graduate students) from 174 universities and labs from 38 countries built, operate, analyze data from the ATLAS detector

**As seen in the latest Muppet Movie.**



ATLAS Detector Under construction
October 2005

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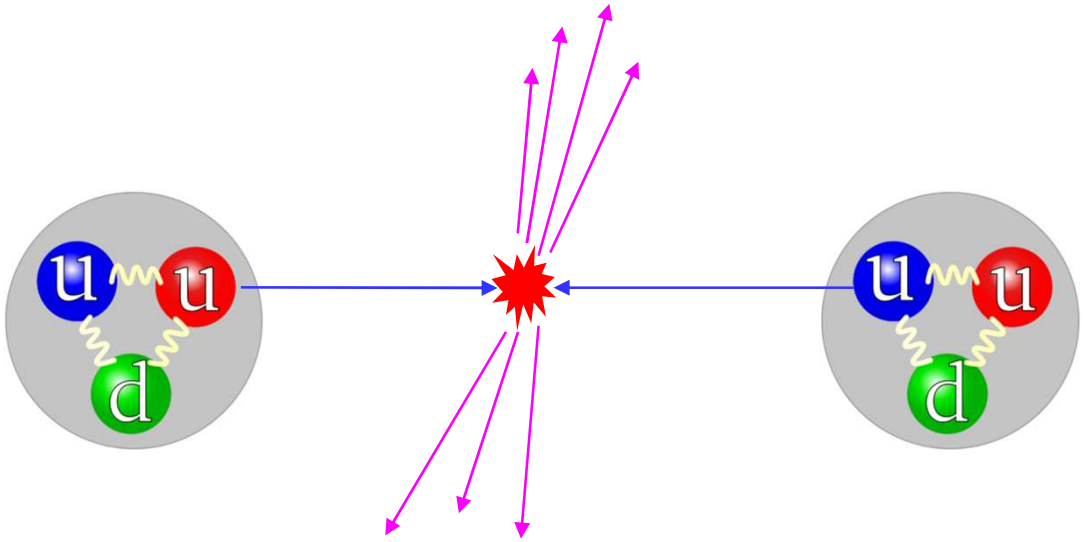
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR
ATLAS
Collaboration
A truly *International* and *successful* collaboration!!
July 2010

# Proton – proton Collisions

**The proton constituents (quarks and gluons) collide with each other.**

**The scattered quarks and gluons form new stable composite particles (hadrons) that move collimated along a direction (jets).**

**Sometimes rare particles are produced during a high energy collision, e.g., a W or Z boson (or a Higgs boson?). These live only for a tiny fraction of a second, then decay into quarks and/or leptons or photons.**




**Sophisticated trigger systems needed to select interesting events**

**Because protons are "big, floppy" particles, need energies about 100 times the mass of the fundamental particle you want to produce, 100 GeV → 10 TeV**

# Particles in the Detector

- **Particles moving out of the interaction point:**
  - **Photons**
  - **Electrons**
  - **Muons**
  - **Taus**

  } **Leptons**

  - **Jets of Hadrons (e.g., protons, neutrons, pions, etc.)**

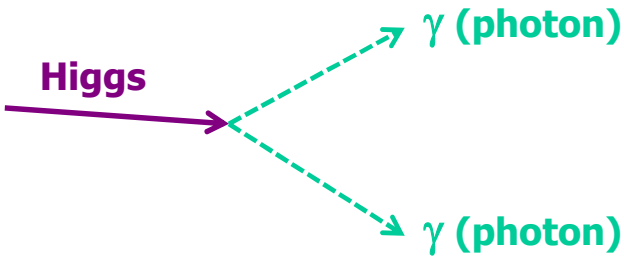
- **They interact with the matter of the detector and:**
  - **leave TRACKS (if electrically charged) in tracker**
  - **deposit their ENERGIES in calorimeters**

- **From the tracks and the energy deposits, we can reconstruct what happened during the collision.**

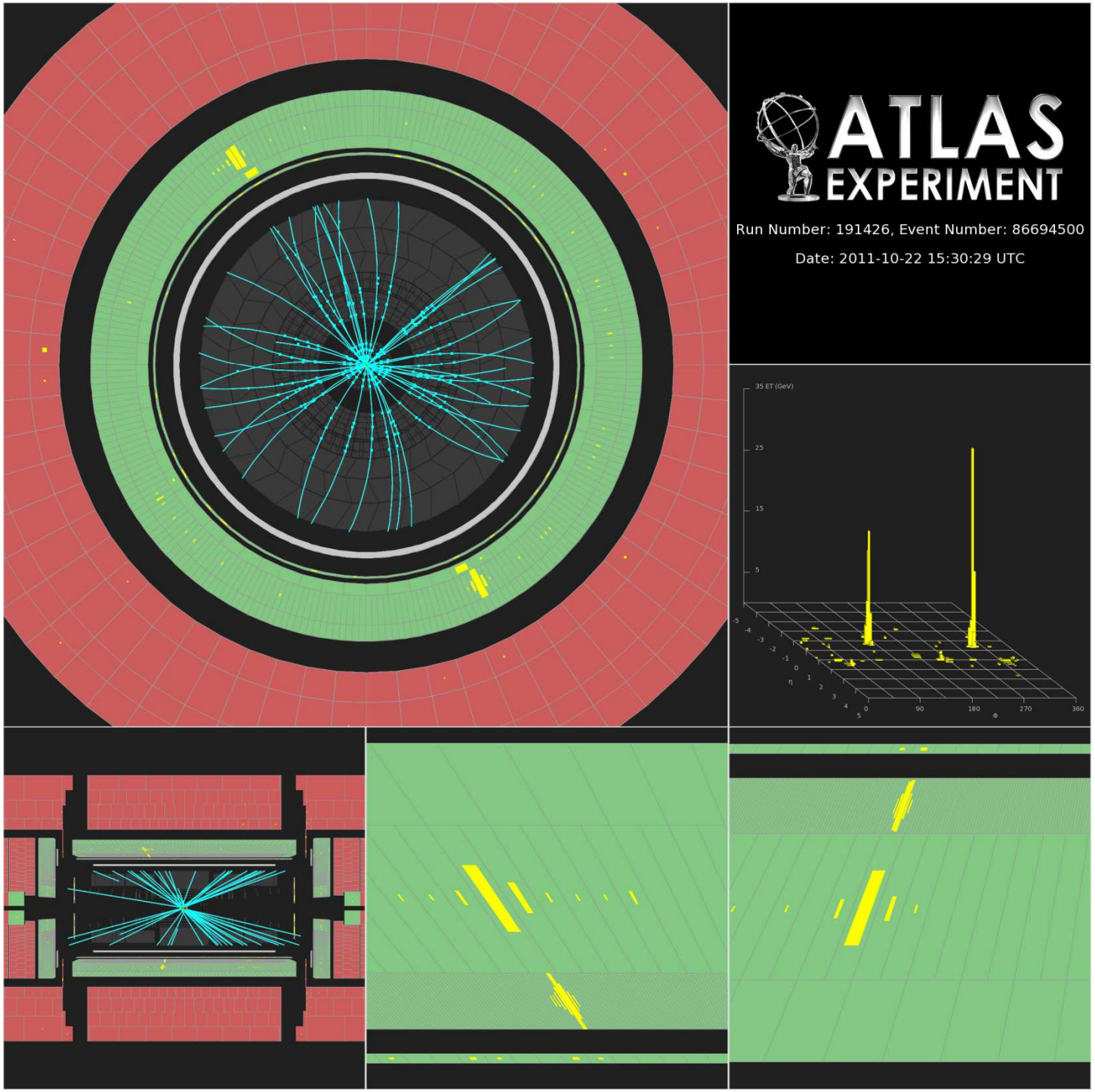
# How do we search for the Higgs?

**CSI ⇒ PSI (Physics Scene Investigation)**

- **Higgs lives only for $10^{-25}$ seconds**
- **Higgs decays into a pair of lighter particles:**
  - **pair of photons**
  - **pair of quarks or leptons**
  - **pair of W or Z bosons (which also decay very fast)**

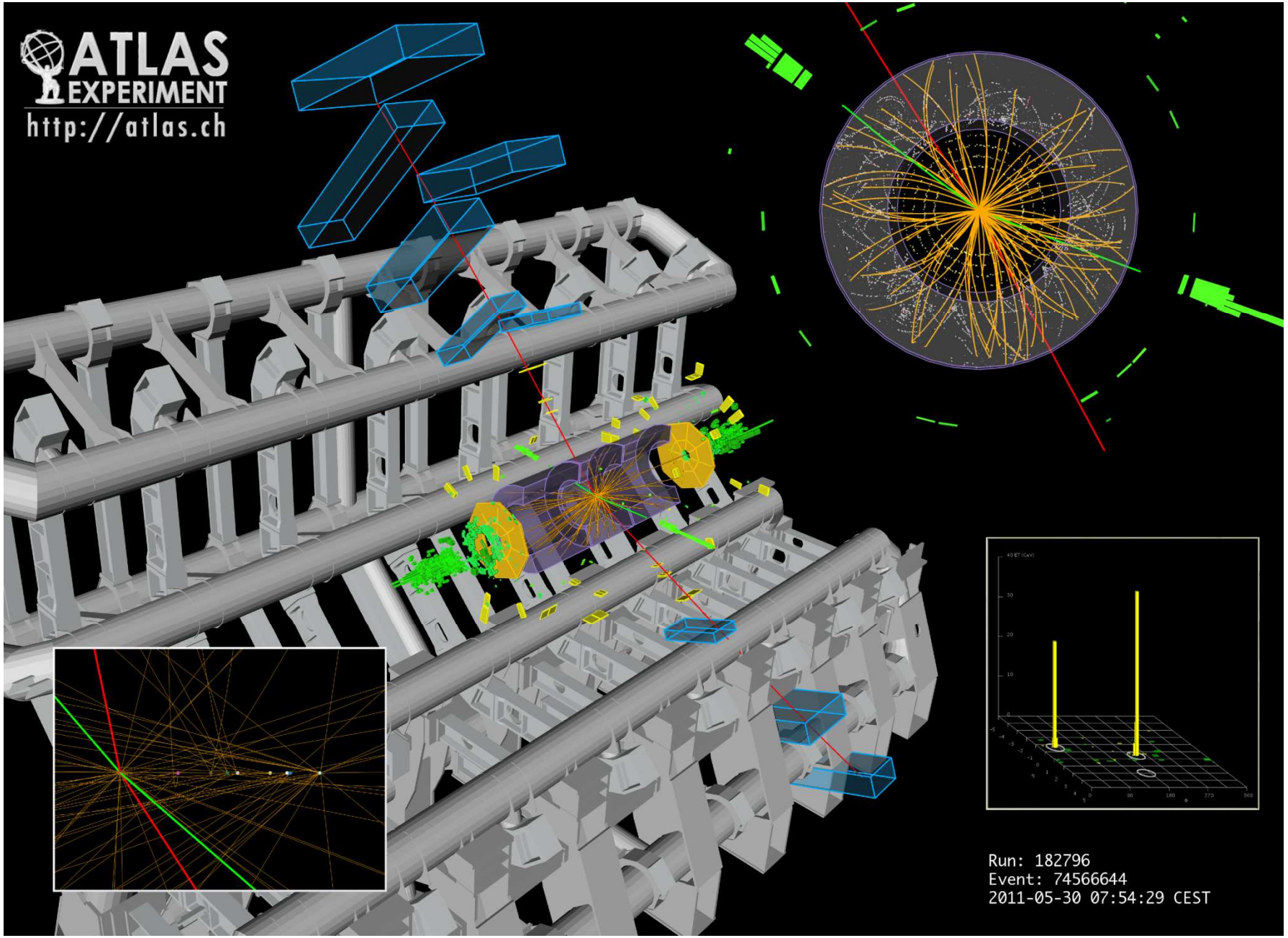



- **The Standard Model predicts how many decays of each type**
- **From the decay products, we can identify the Higgs boson**
- **Count events with a Higgs candidate, e.g., the "right" $\gamma\gamma$ mass**

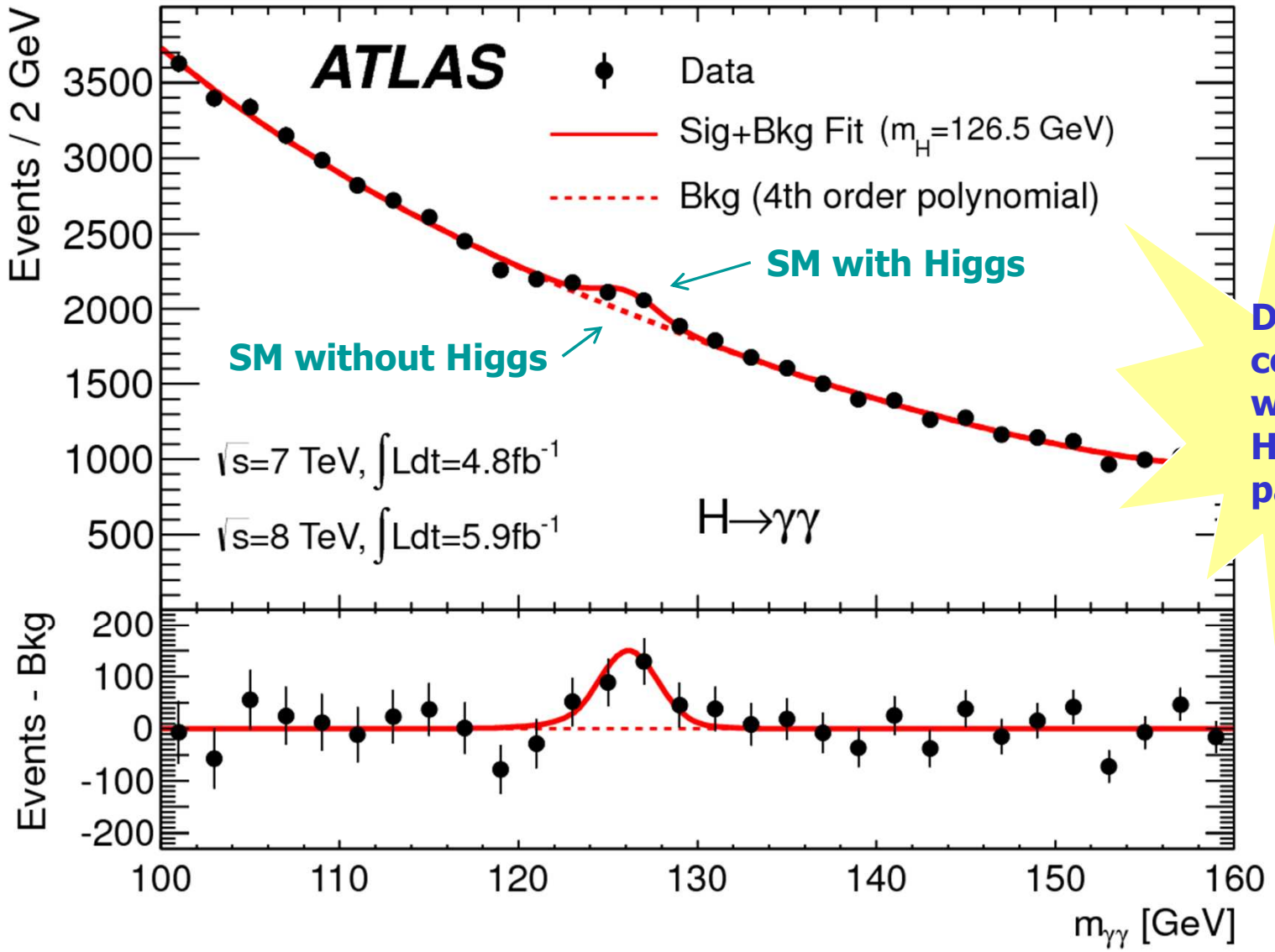



# Higgs →γγ candidate event

# Higgs → ZZ → eeμμ candidate event

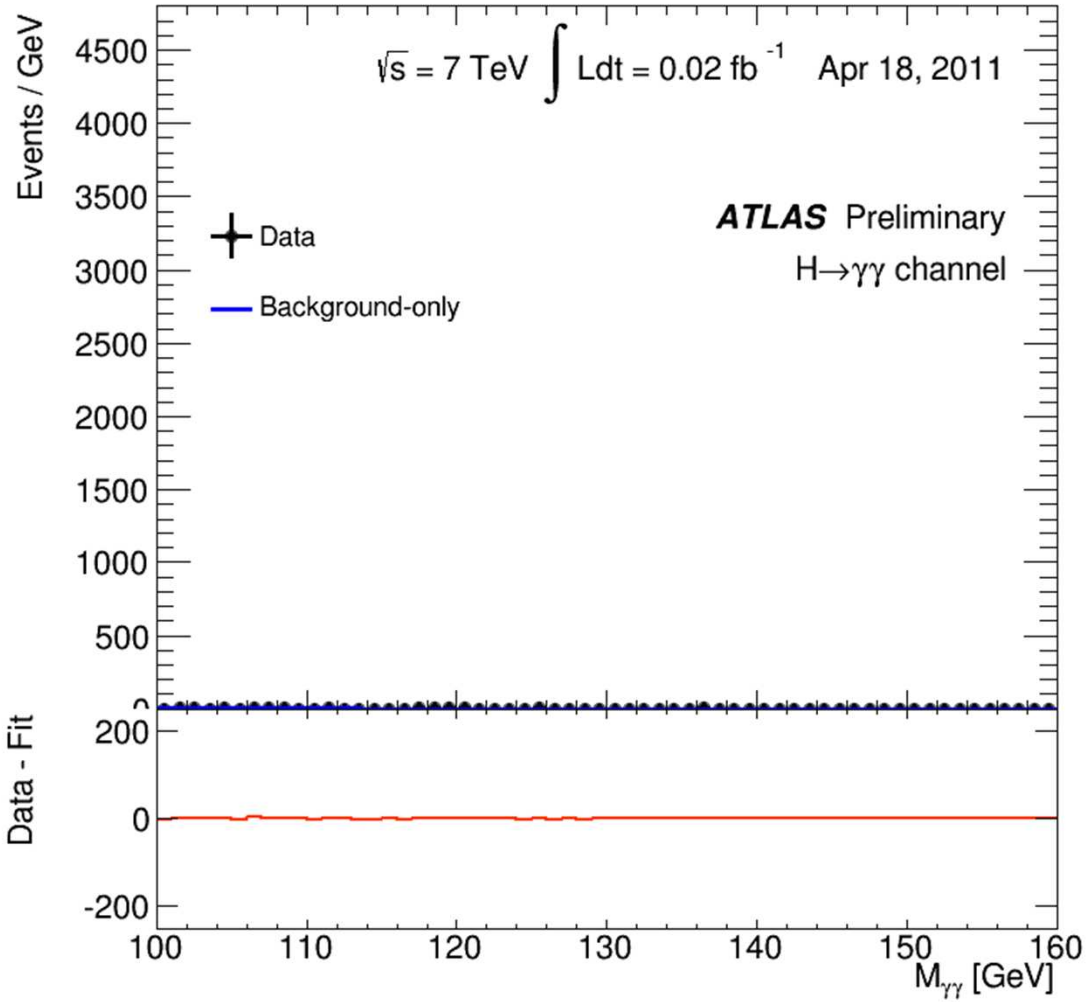


# Higgs → 2 photons




**Data consistent with Higgs-like particle!**

# Data accumulates!



# Conclusions and Outlook

- **The detailed properties of the new particle are now well (but not completely) tested as being those of the Standard Model Higgs**
- **Discovery of the Higgs boson is a verification of the value of the synergy between theory and experiment**
- **Provides an explanation of the masses of fundamental particles while maintaining the desired symmetries**
- **Explains the relationship of the ElectroMagnetic and Weak interactions**
- **Next for Exp: LHC (re)starting next year with twice the energy (~14 TeV), and (in about 3 years) 10 times the data!**
- **Next Theory: What sets the mass scale of 125 GeV? Need to connect with the Strong? With Gravity?**