The LHC and Discovery of the Higgs Boson - 50 years of Higgs'Mechanism

Christophe Royon IRFU-SPP, CEA Saclay, France

Colloquium at UFRJ, Rio de Janeiro, February 6 2014

Instituto de Física 50 ANOS
Universidade Federal do Rio de Janeiro

LHC: Exploration of a New Energy Frontier

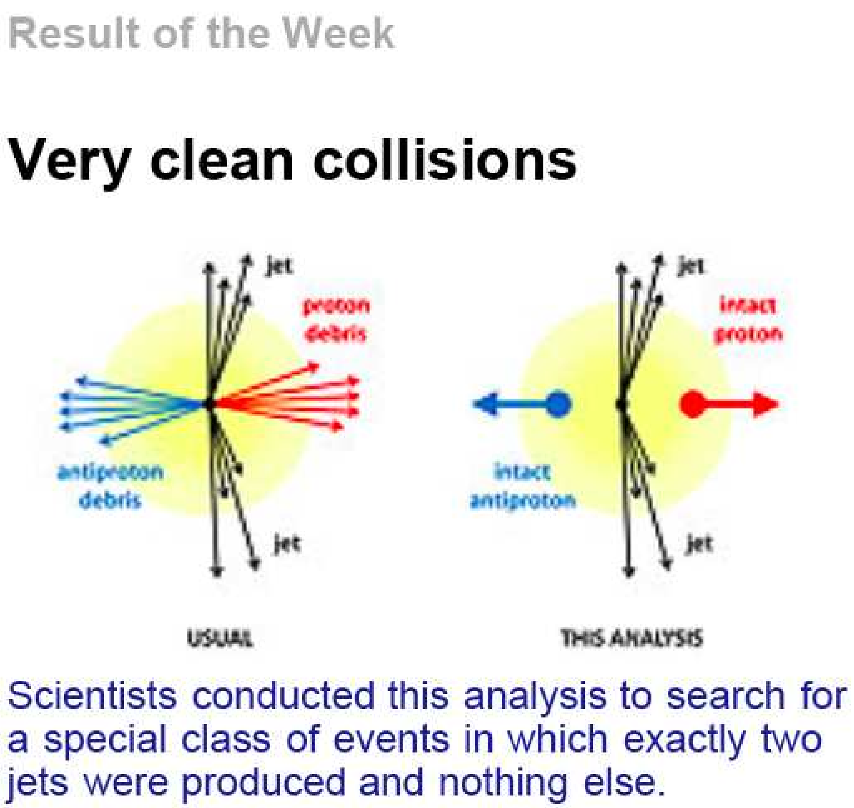
Physics exploitation for the next 20 years: The LHC will possibly answer some of the most fundamental questions in modern physics:

- **The origin of mass: The Higgs boson**
- Unification of fundamental forces
- Matter-Antimatter asymmetry
- New forms of matter (quark-gluon plasma...)
- Extra-dimensions of space time

Outline

- Introduction to particle physics
- A typical detector: the example of ATLAS
- What is particle physics: a few Physics results
- The Higgs boson discovery at the LHC
- Looking for extra-dimensions in the universe

CERN-Brazil and French-Brazil collaboration



Gilvan Alves
CBPF/LAFEX
Brazil

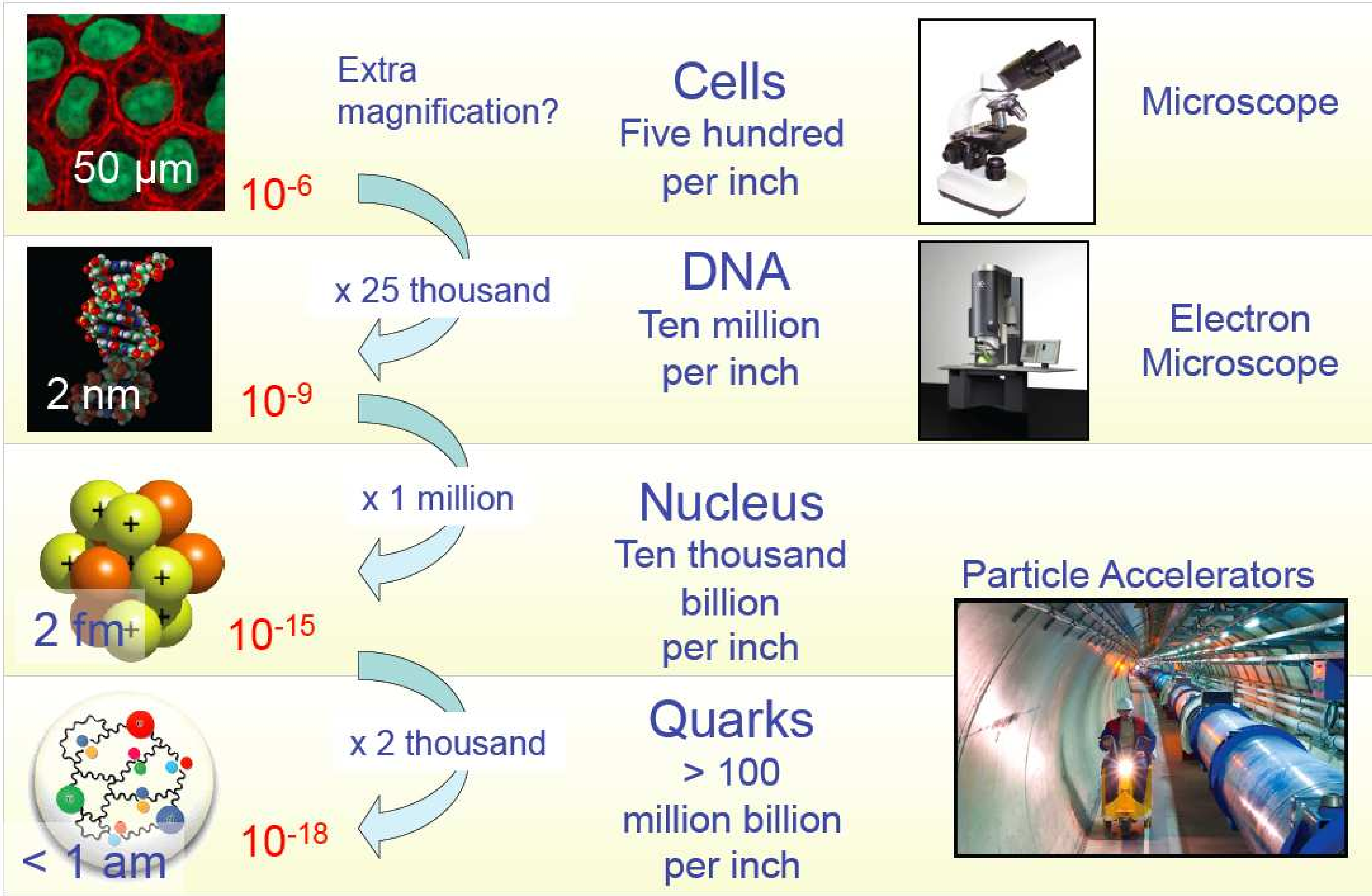
Jorge Barreto
IF/UFRJ
Brazil

Murilo Rangel
IN2P3/CNRS
France

Christophe Royon
Saclay
France

- Many people performed their PhD or post-doc in France, in Saclay for instance
- Long term collaboration in D0: as an example Result of the week of Fermilab in April 2010
- Presently, we have a COFECUB/CAPES collaboration between Saclay, Sao Paulo, Rio, Pelotas and Porto Alegre
- Brazil will be officially associated to CERN like USA, China... in a very near future

Scales and tools



Energy units

1 eV (electron volt) is the amount of energy gained by an electron, when accelerated by a 1 volt battery.

1.5 V

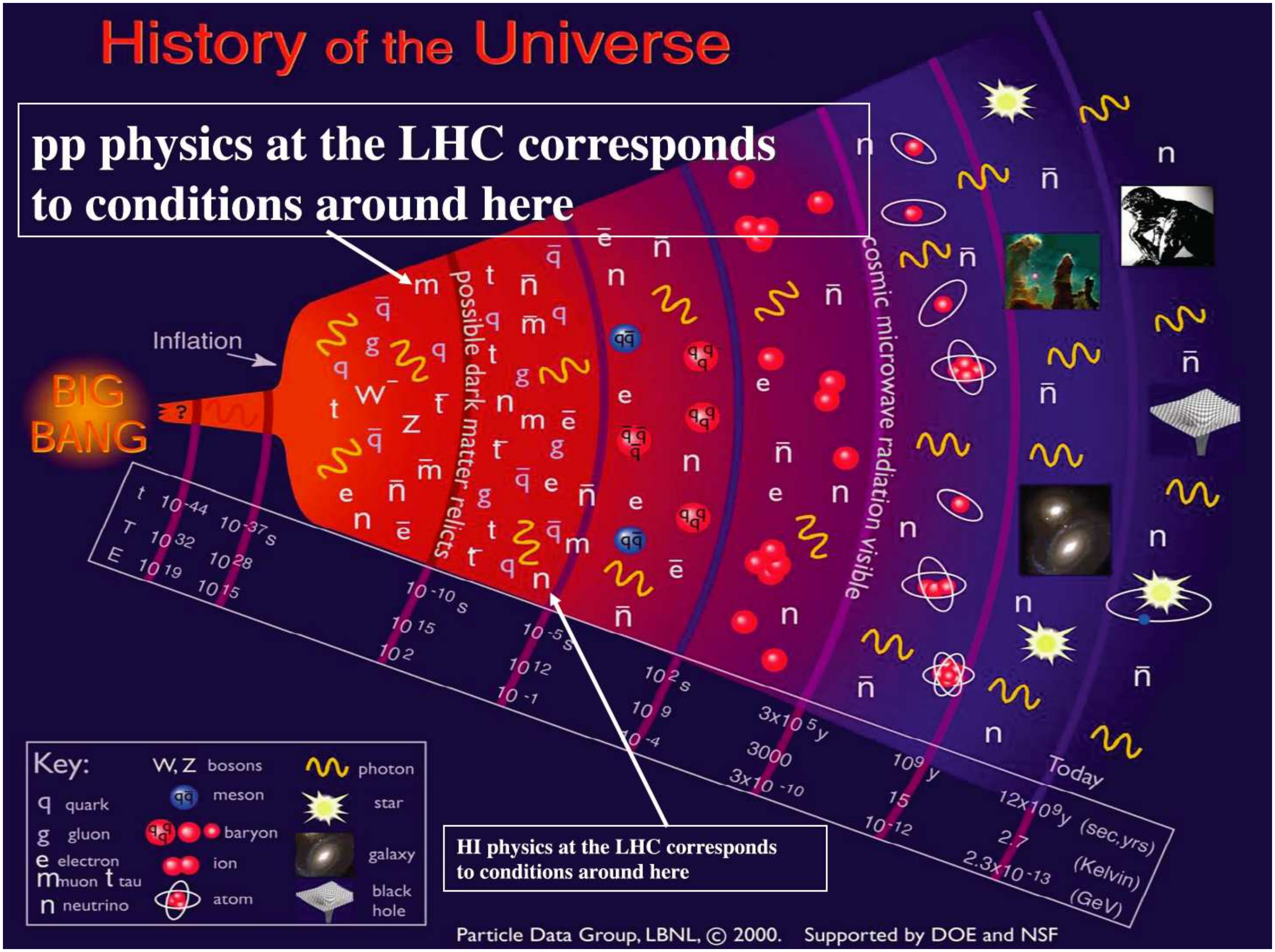
E_e = 1.5 eV

1 eV = 3.8×10^{-23} Calorie

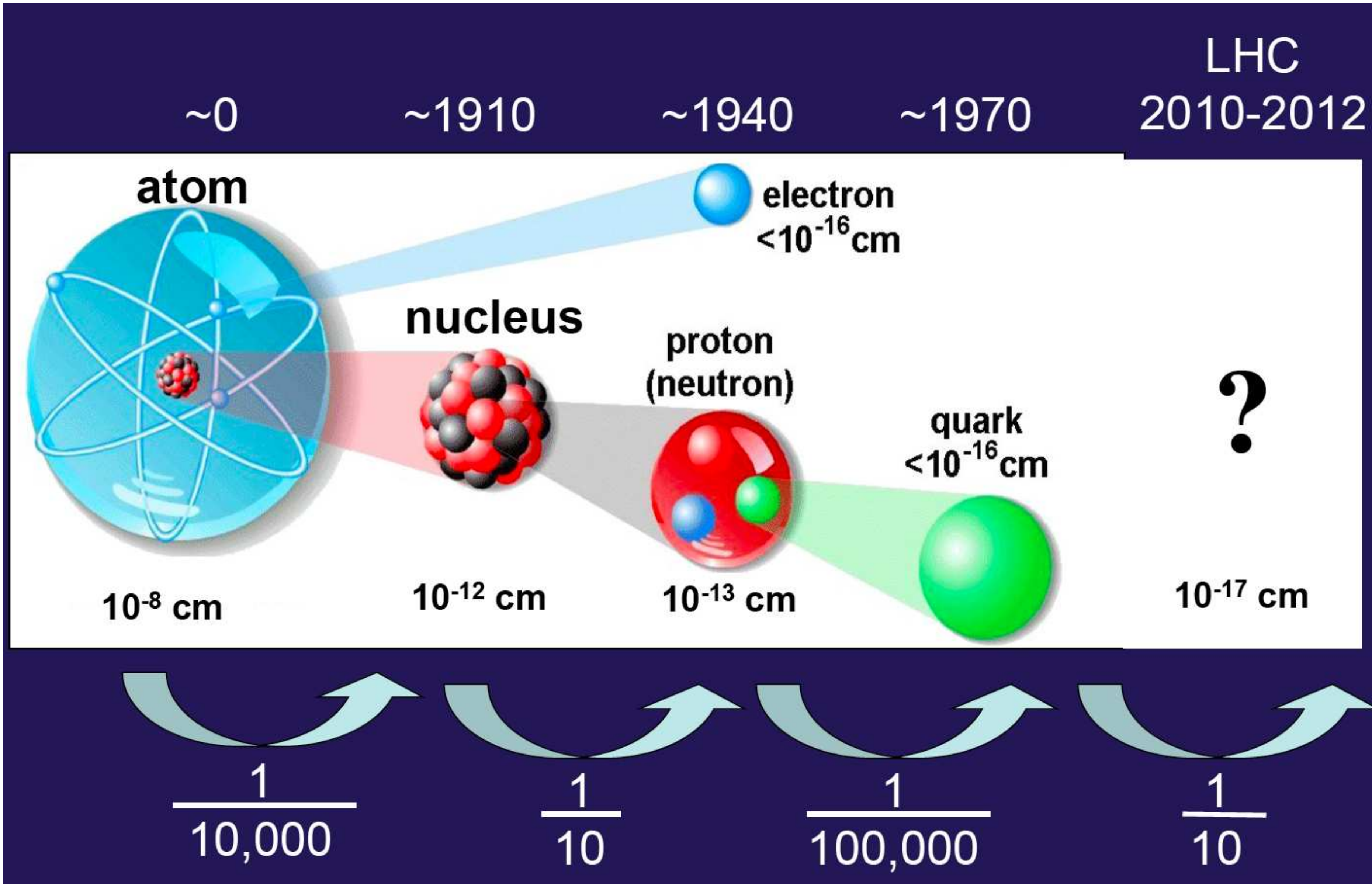
υ = 1,340,000 mph

1 keV (kilo electron volt)	10^3 (1,000) eV x-rays, TV
1 MeV (mega electron volt)	10^6 (1,000,000) Radioactivity
1 GeV (giga electron volt)	10^9 Cosmic rays &
1 TeV (tera electron volt)	10^{12} Accelerators

Energy and time



A long history: searching for fundamental particles



Starting point: Rutherford

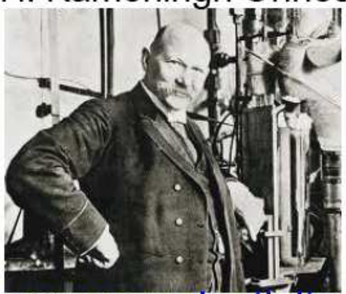
J.J. Thomson

electron

Henri Becqurel

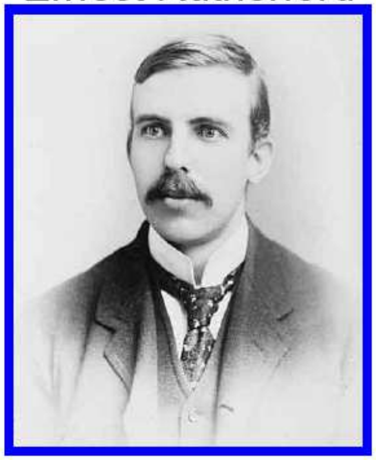
radioactivity

H. Kamerlingh Onnes



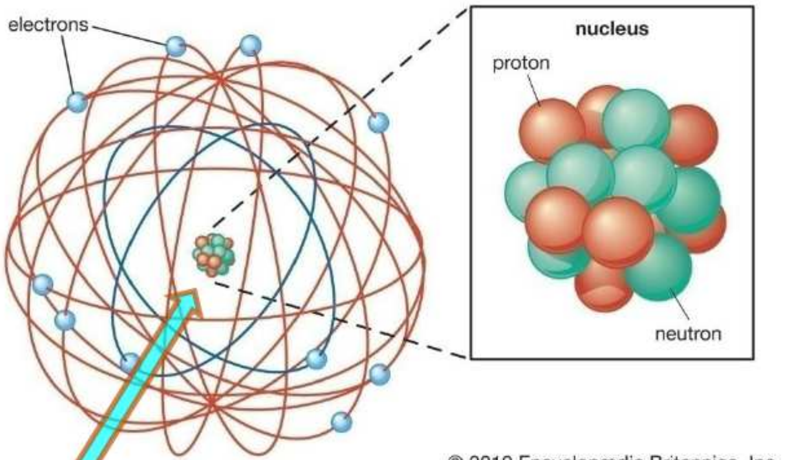
superconductivity

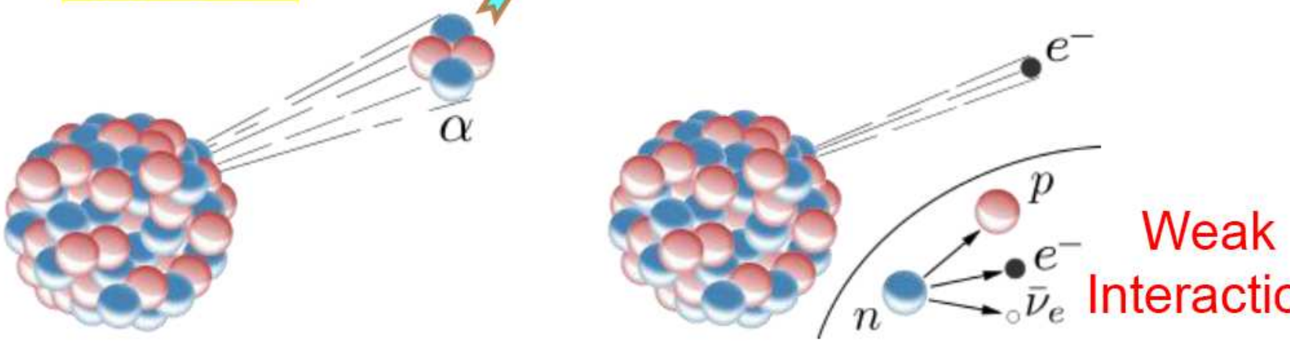
Ernest Rutherford



α, β, γ

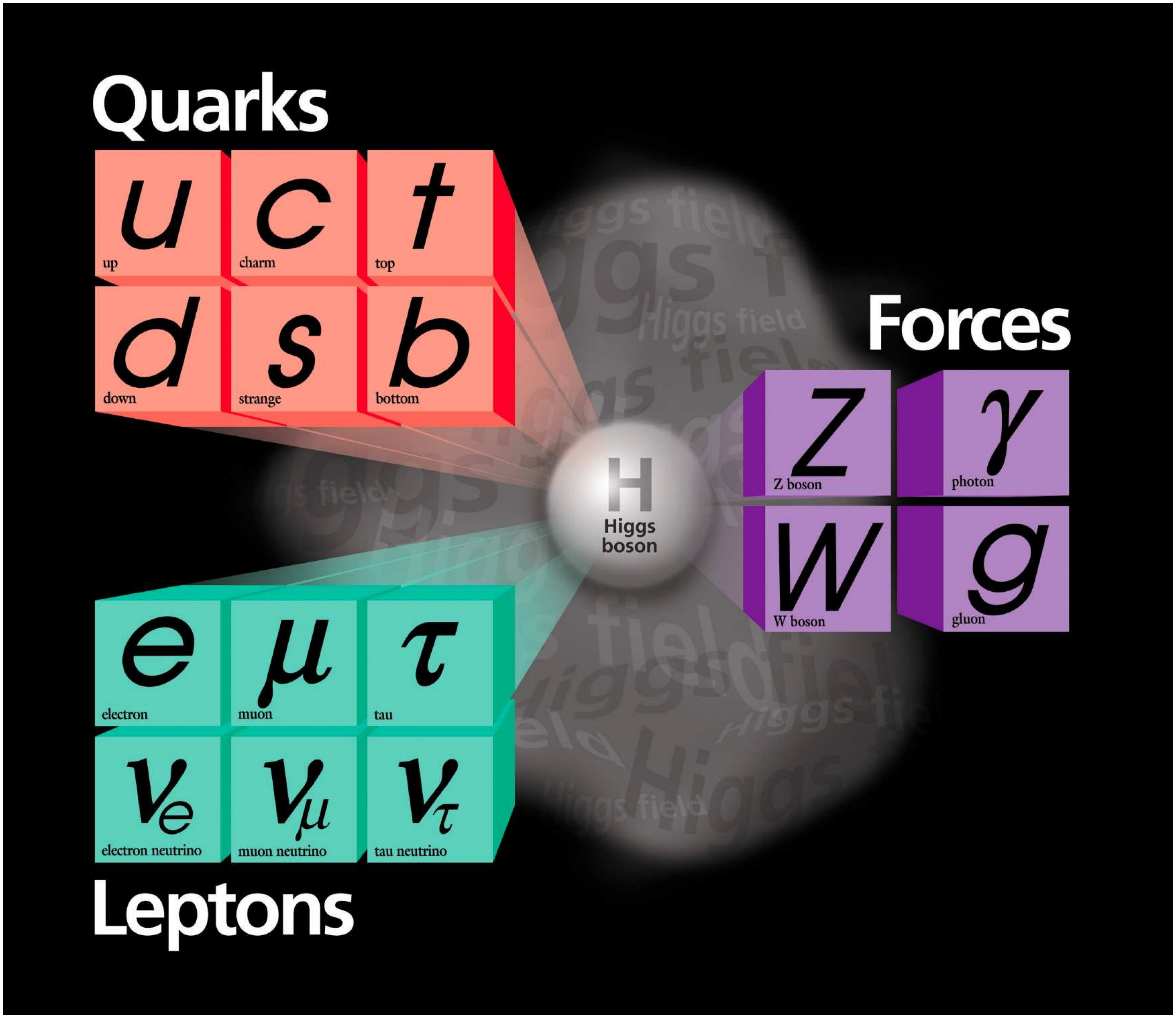
Our Common Heritage





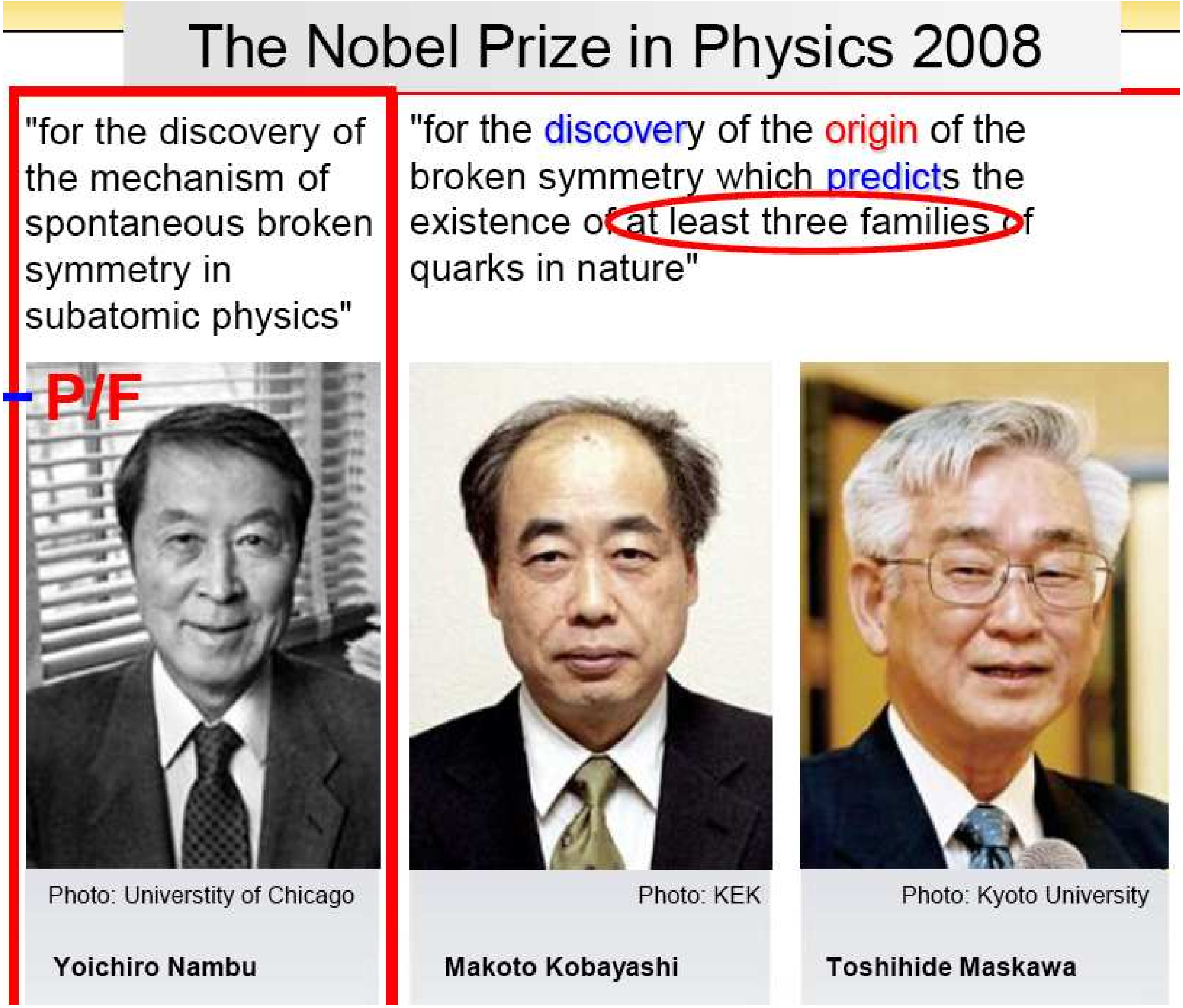
- The Rutherford team discovered the existence of the atomic nucleus
- α particles originating from radium directed onto a very thin gold foil, the α particles are scattered by the nuclei

Standard Model of particle physics



Three families of Quarks

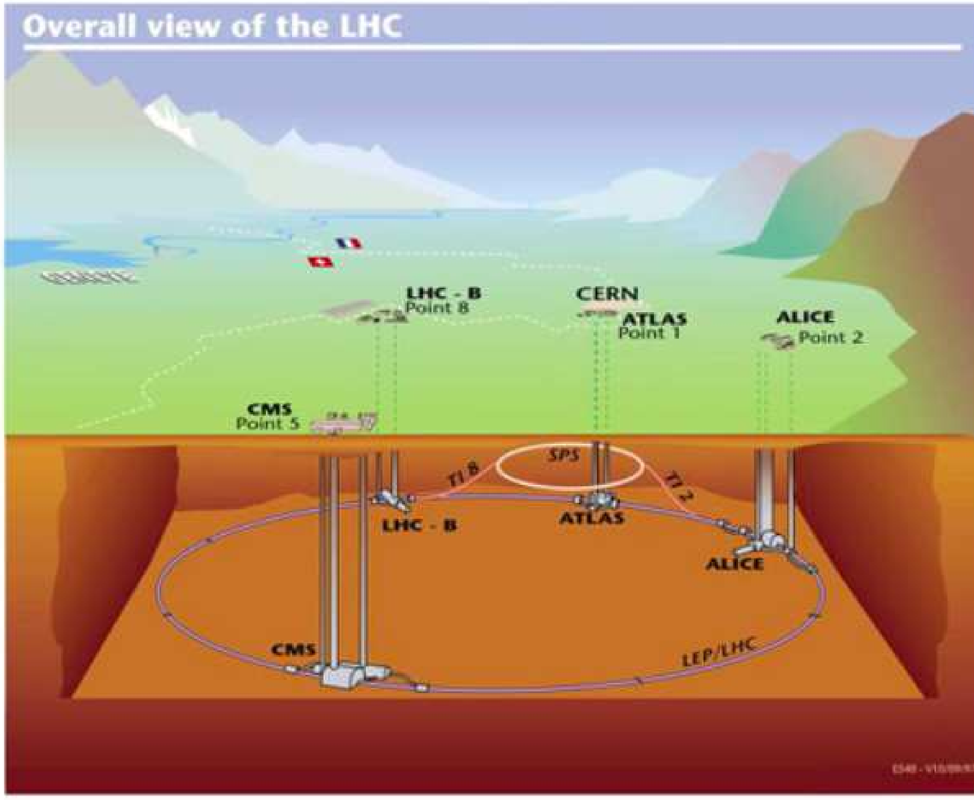
Three families of quarks in nature!



What do we use? The Large Hadron Collider

Circumference: 27 km (16.9 miles);

Underground: 50-100 meters;



Total weight:
  38,000 metric tons;

Beam energy:
  3.5 TeV now
  and 7 TeV later
  (speed: 0.99999999 c);

Magnetic field:
  8.3 Tesla;

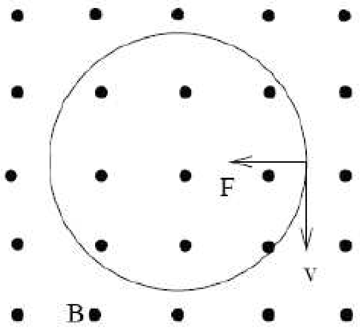
Energy per beam:
  E~400 MJ (1 MJ melts 2 kg Copper);

Power consumption: 120 MW (Ann Arbor: 190 MW in 2008)

LHC components

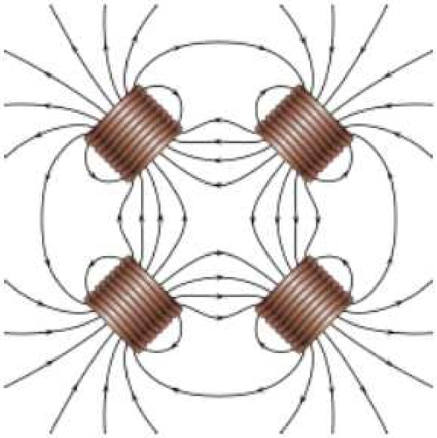
Dipole magnets

keep the beam in circular orbit



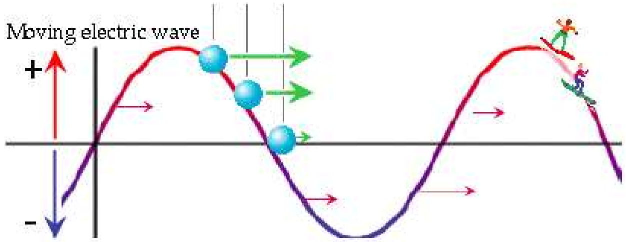
Quadrupole magnets

focus the beams



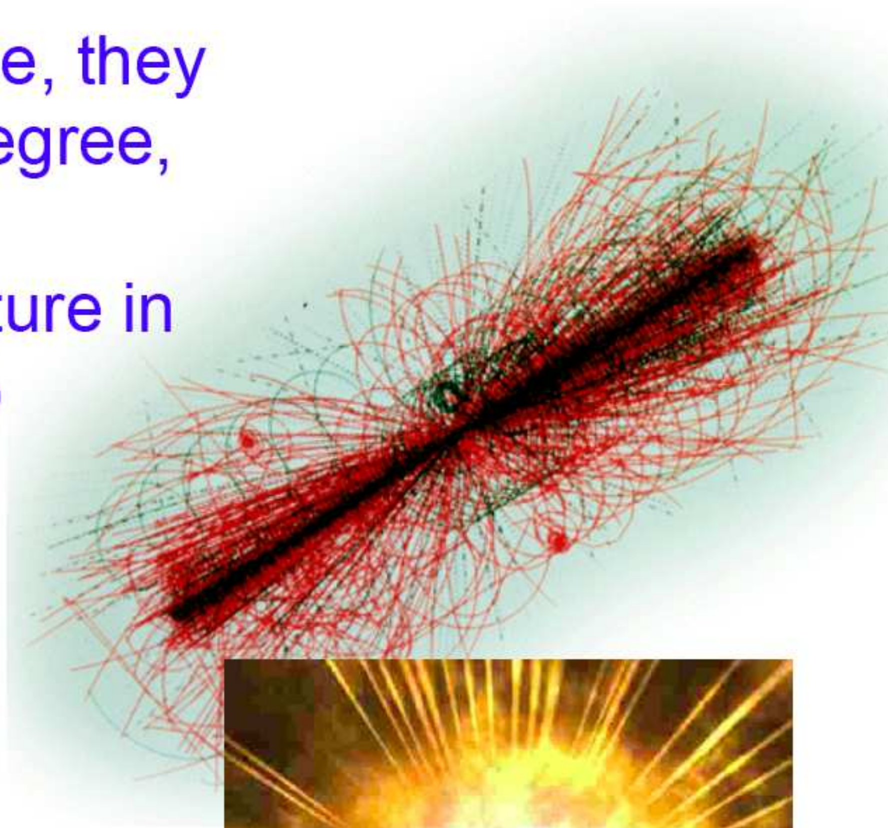
Radiofrequency cavity

accelerate the beam



LHC: one of the hottest spot in the universe!

When two proton beams collide, they reach a temperature of 10^{17} degree, albeit over a miniscule area.
(For comparison, the temperature in the Sun's core is $\sim 10^{7}$ degree)



It creates a condition similar to that 10^{-13} second after the Big Bang, right after the Universe was born.

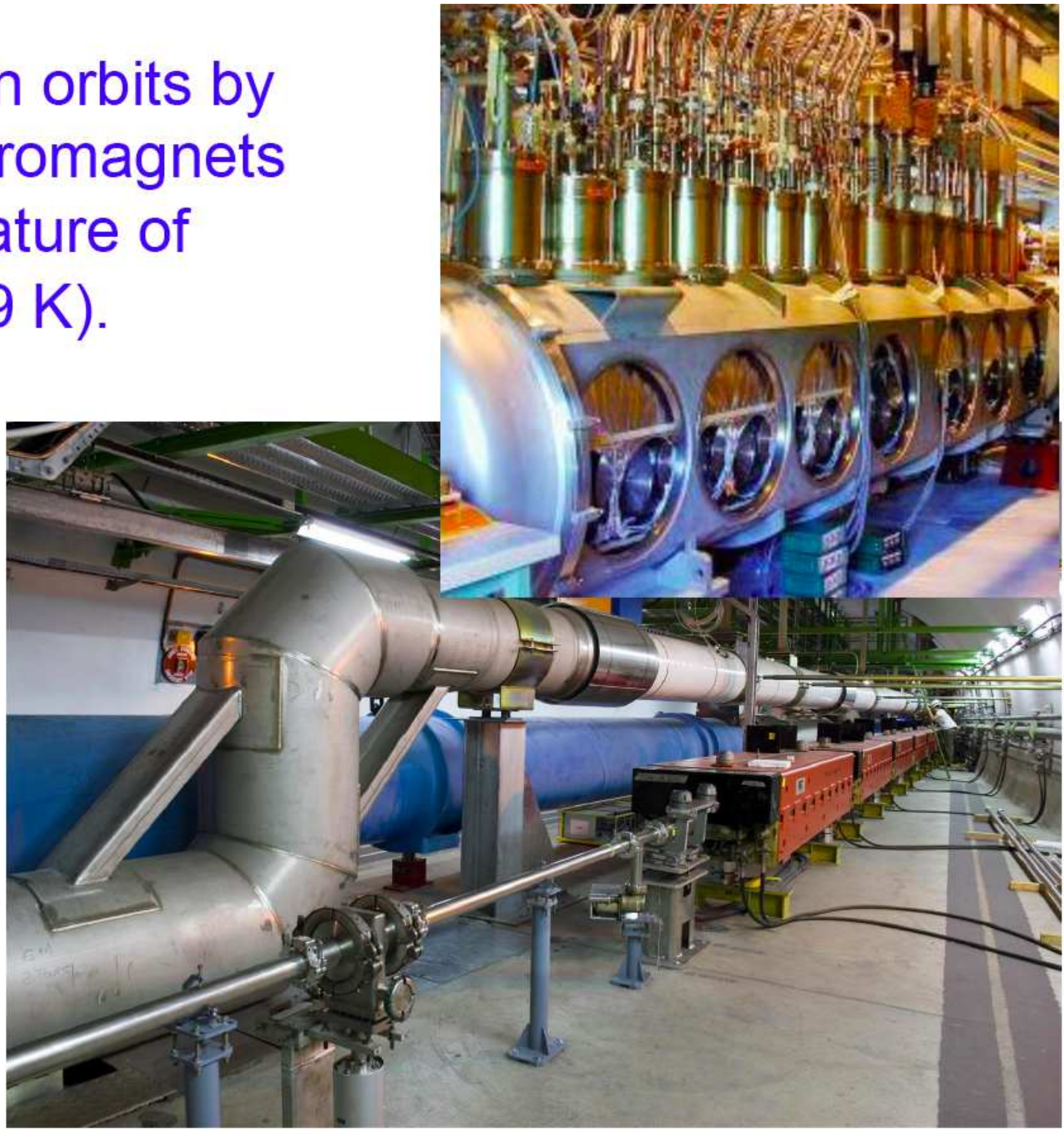
The hottest spots in the Universe today!

LHC: one of the coldest spot on earth!

LHC beams are kept in orbits by superconducting electromagnets operating at a temperature of -271 °C (-457 °F or 1.9 K).

It takes about a month to cool it down and needs ~10,000 tons of liquid nitrogen and ~100 tons of liquid helium to cool and to keep it cold.

The world's largest refrigerator !

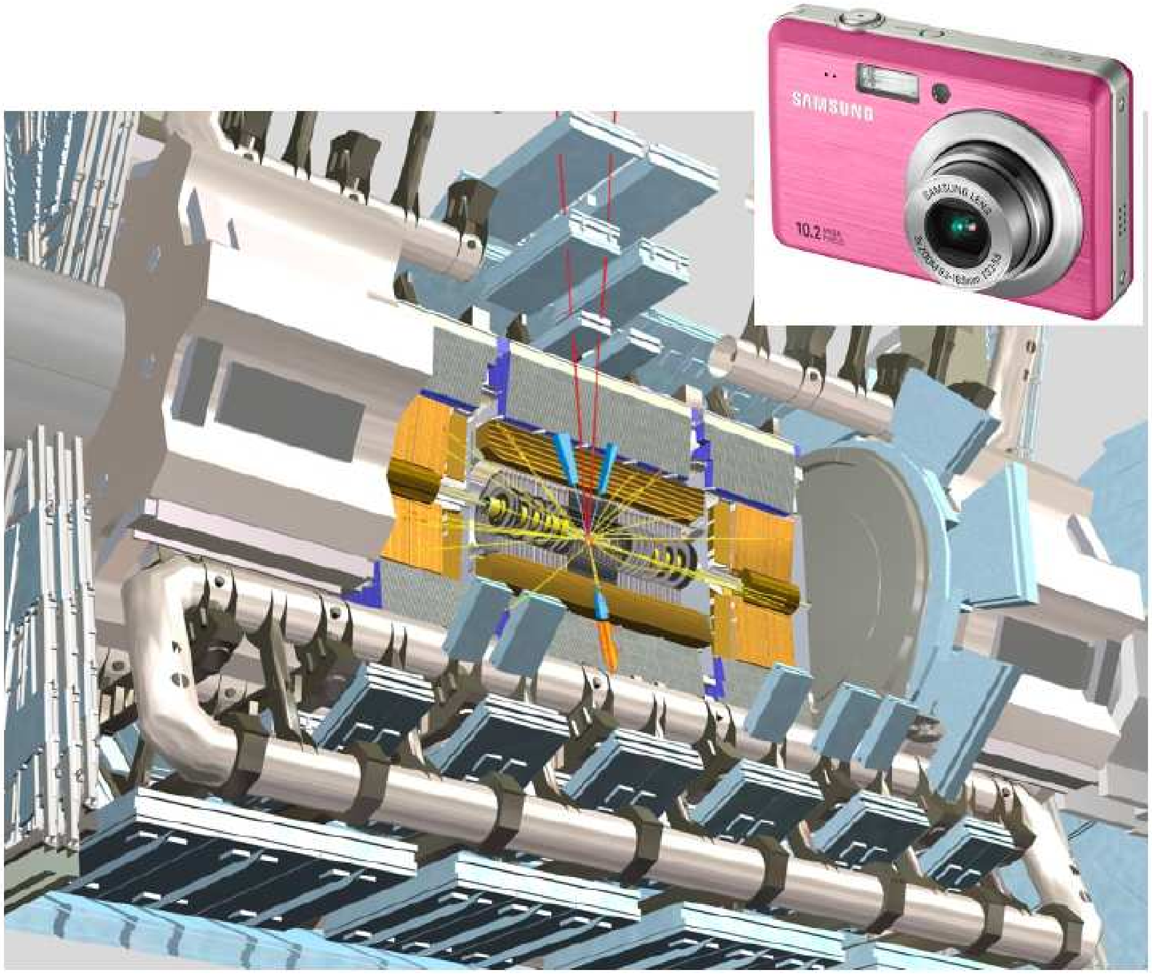


LHC: one of the largest instrument on earth!

Largest scientific instruments ever built to track particles with micron precision over ~50m length with ~100 million electronic readout channels.

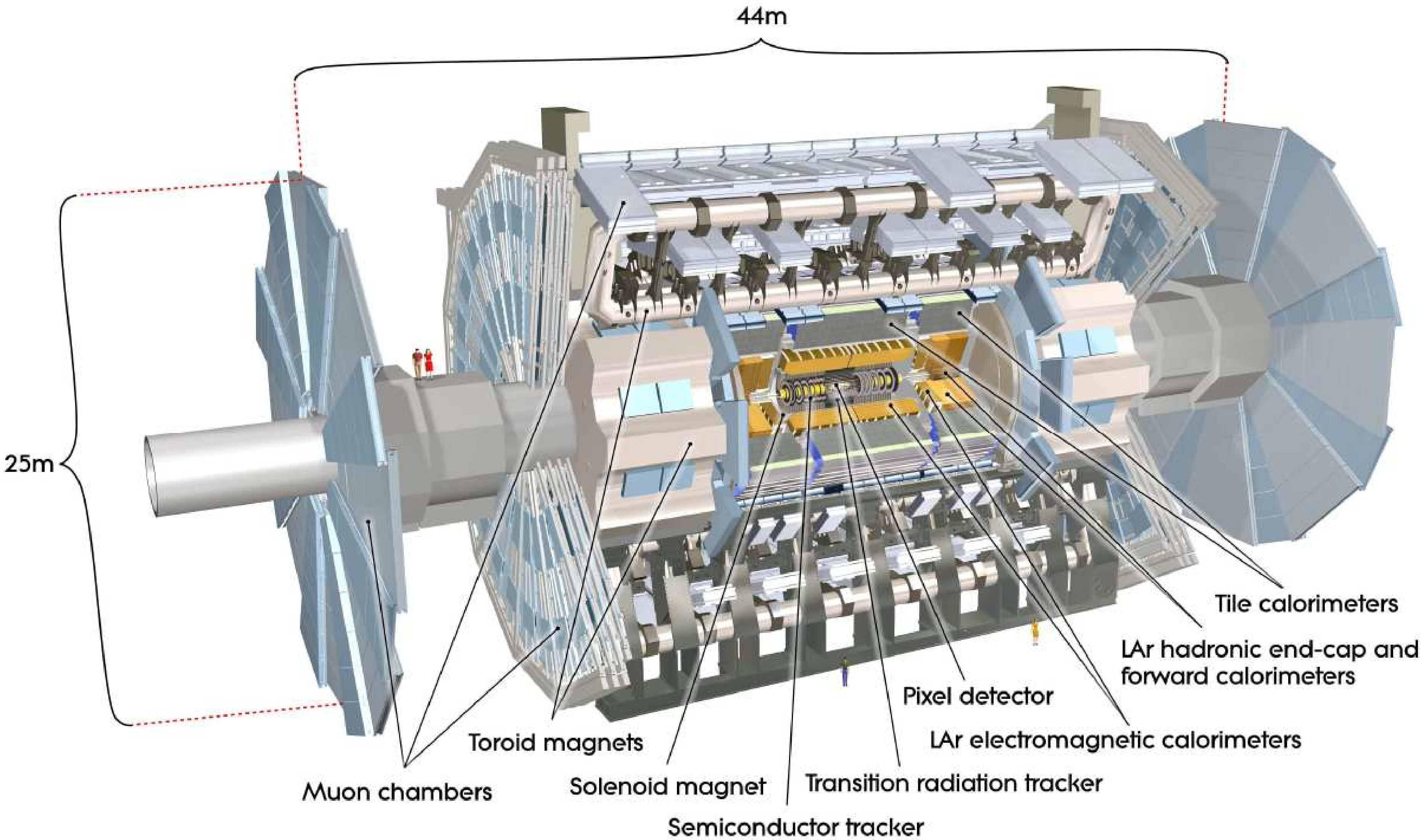
These detectors are similar to digital cameras, but taking pictures at a rate of 40,000,000 / second.

They are sensitive to light and all other radiations.



ATLAS ("A Toroidal LHC Apparatus") detector

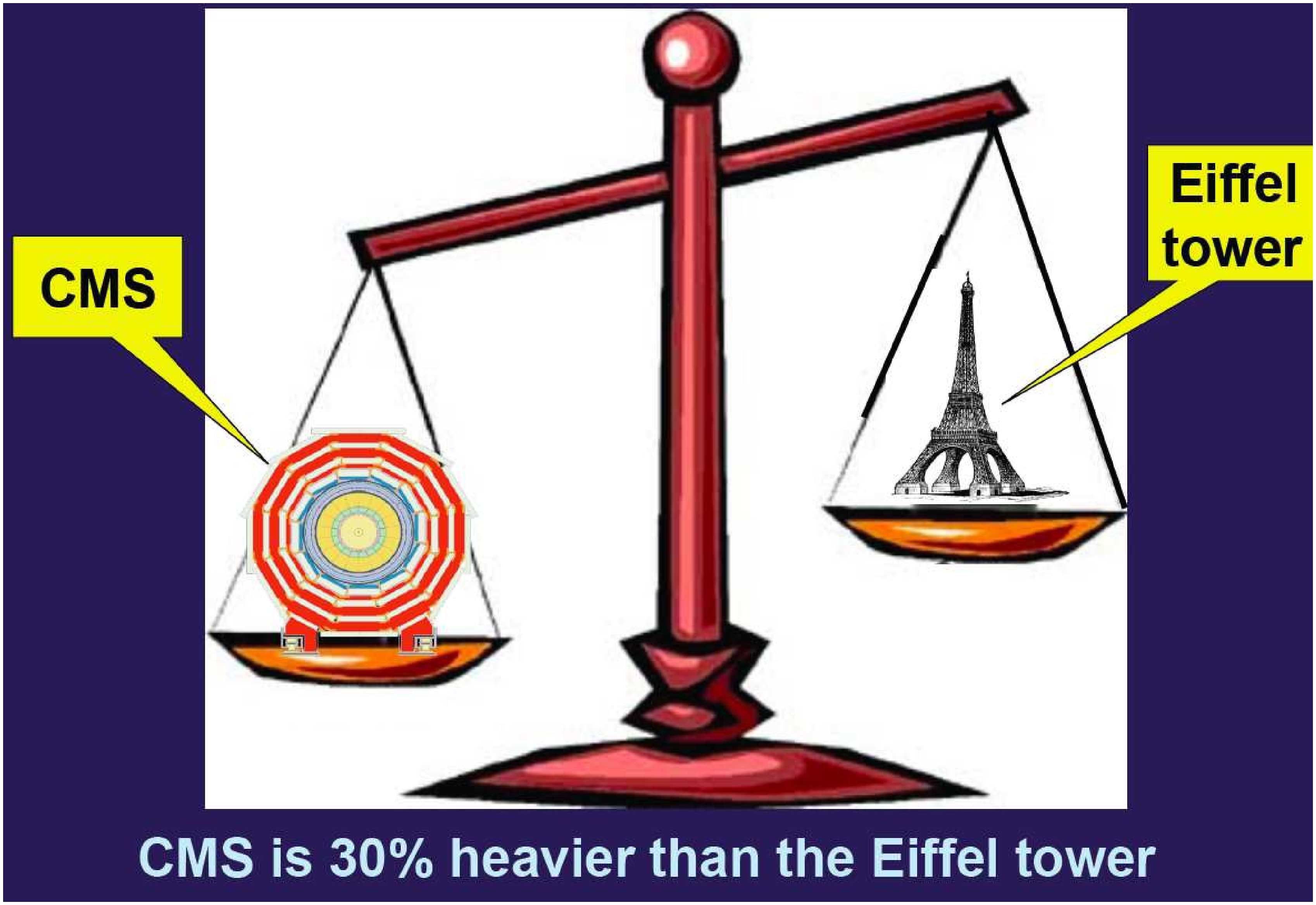
An example of a typical generic detector in high energy experiment (CMS is more compact)



Detector size

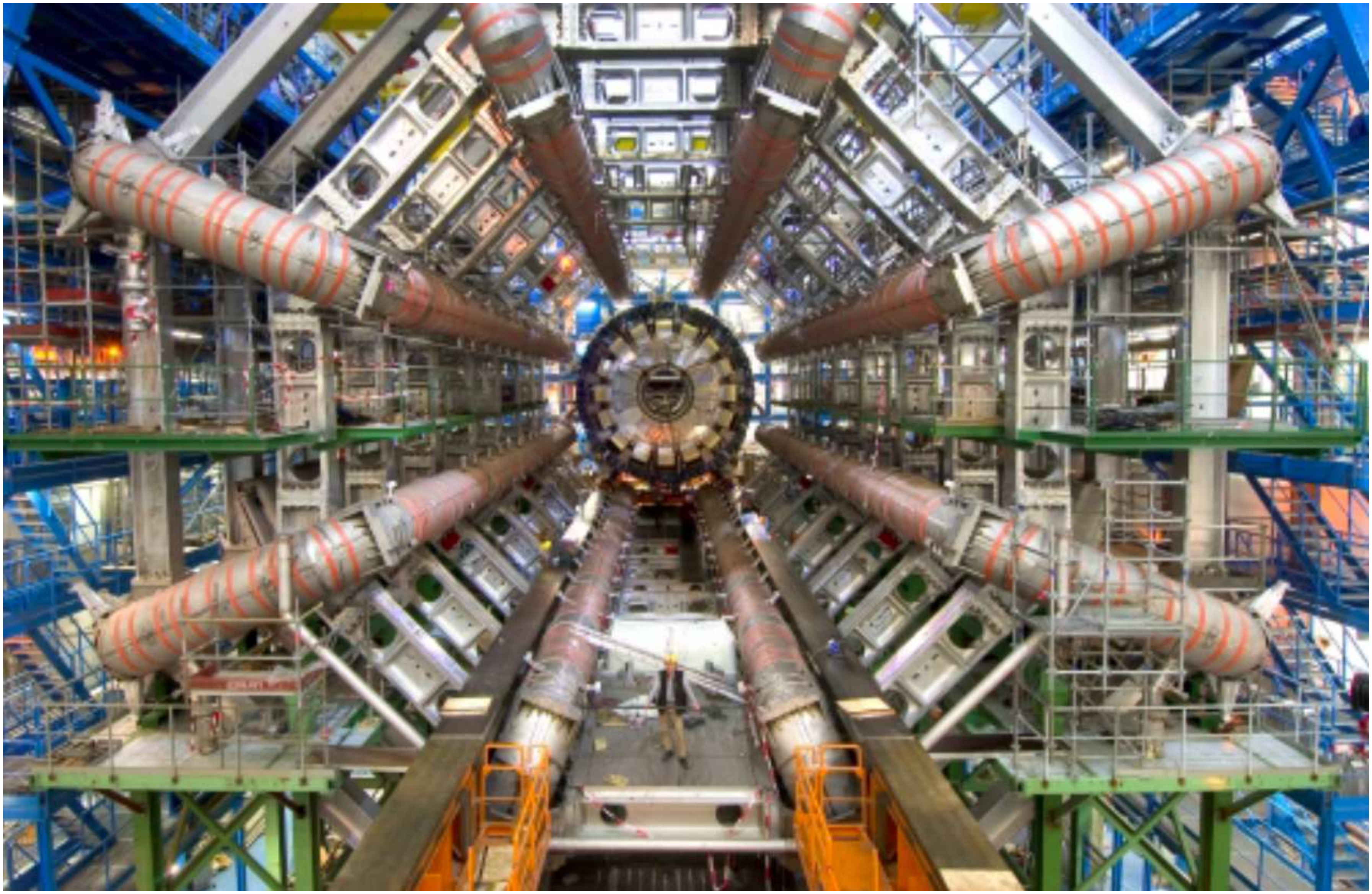
Two general experiments: ATLAS and CMS

Detector mass



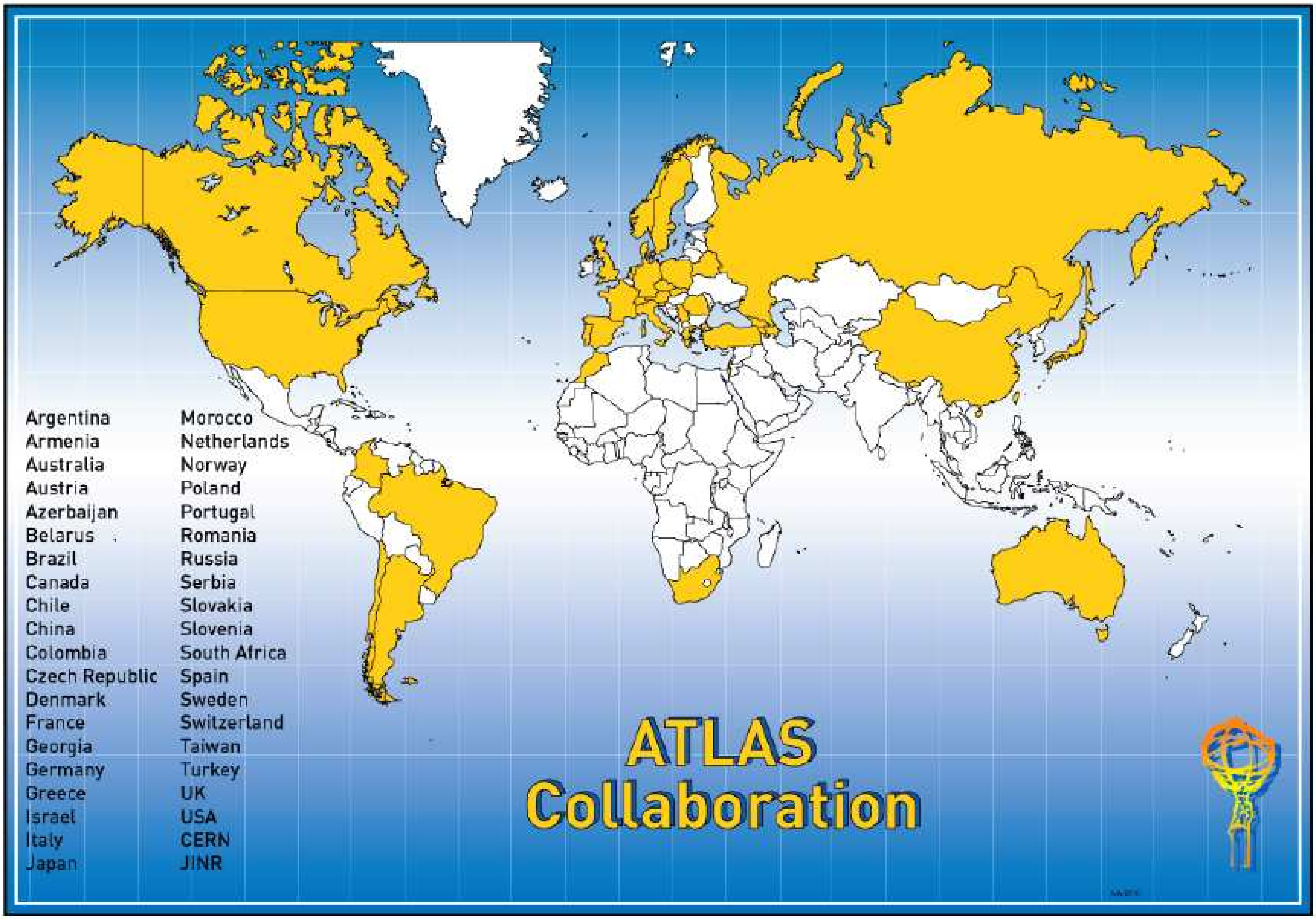
ATLAS ("A Toroidal LHC Apparatus") detector

An example of a typical generic detector in high energy experiment (CMS is more compact)



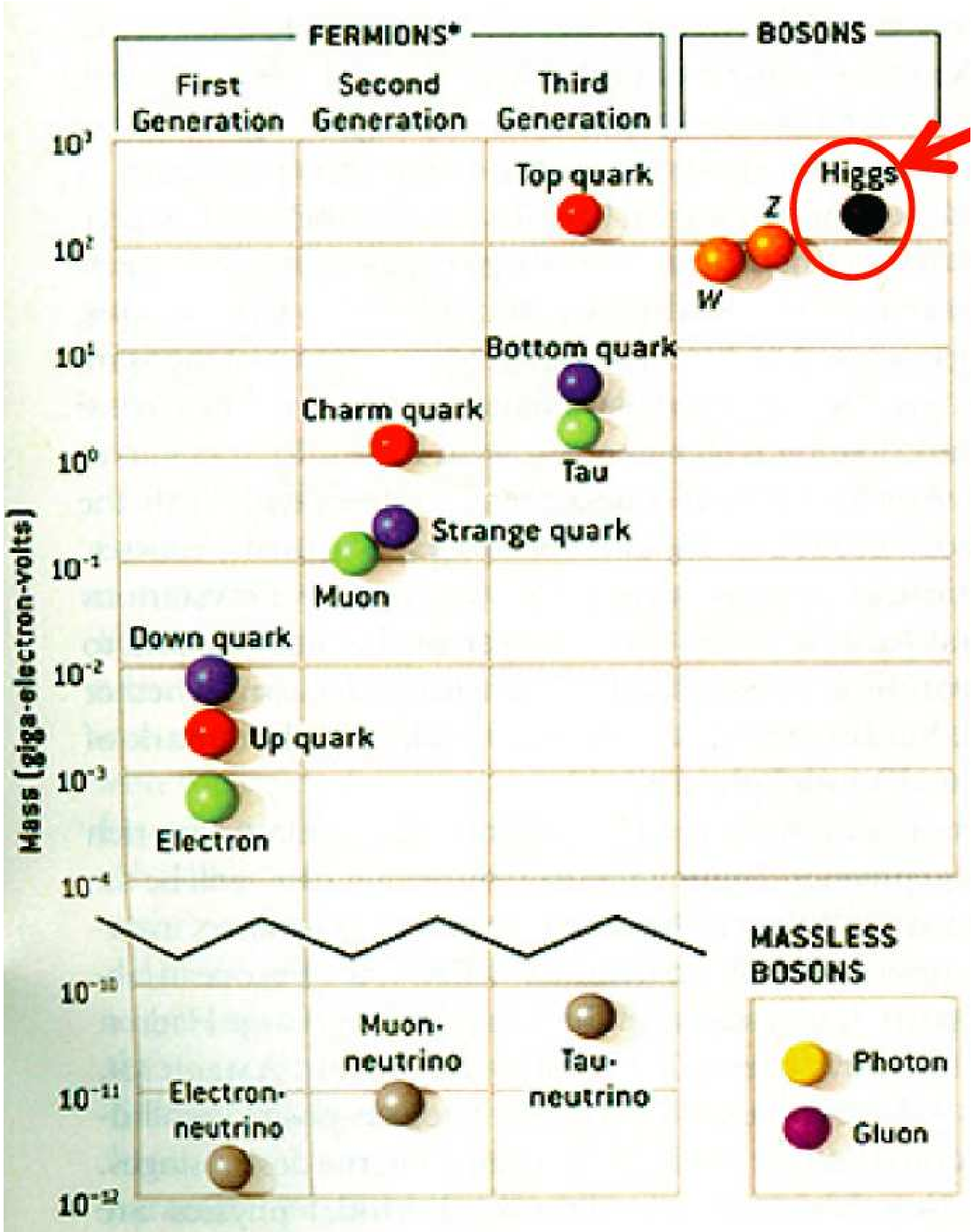
The ATLAS Collaboration

ATLAS: $\sim$ 3000 scientists from 174 institutes and 38 countries

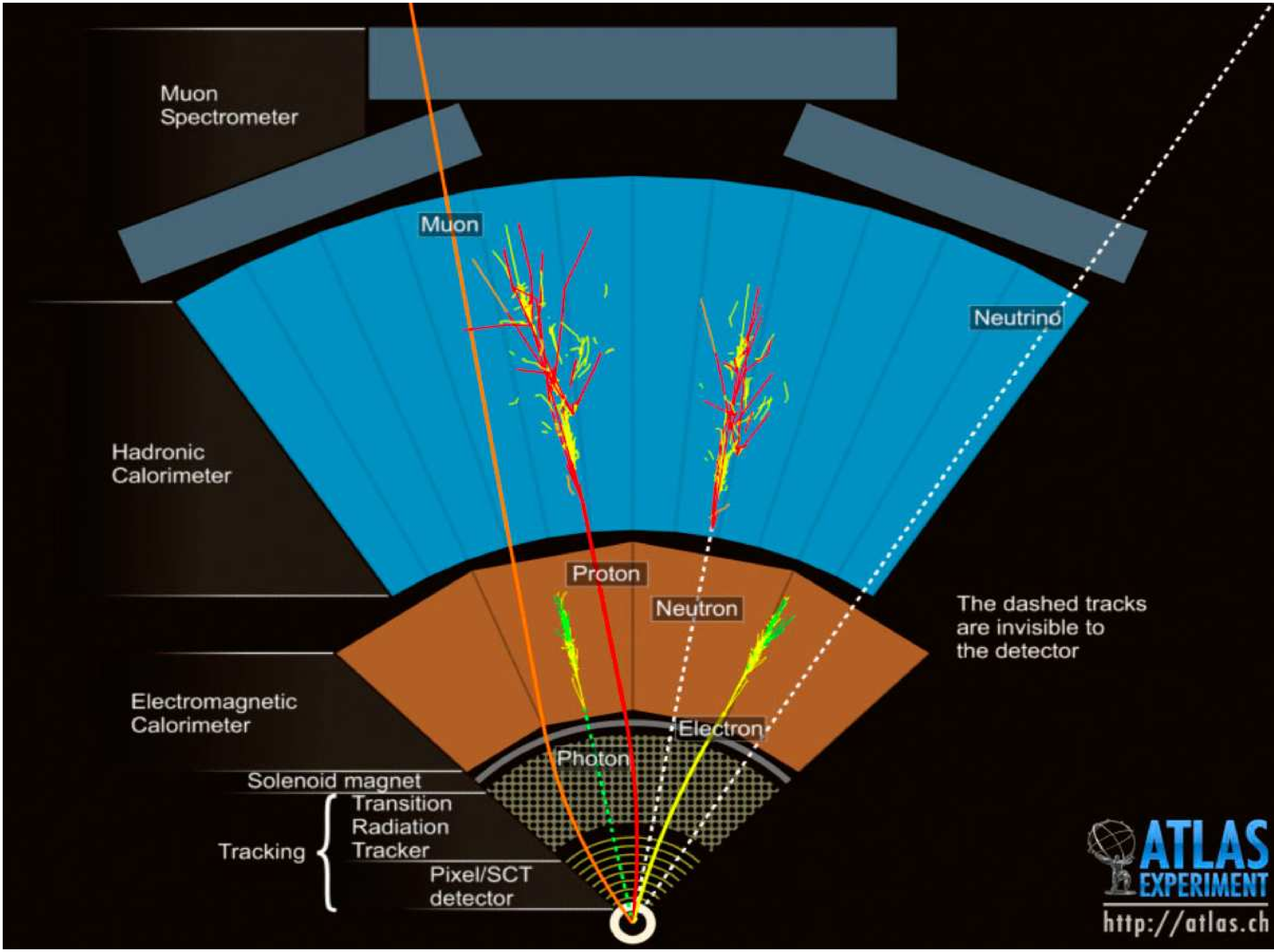


The elementary particle zoo

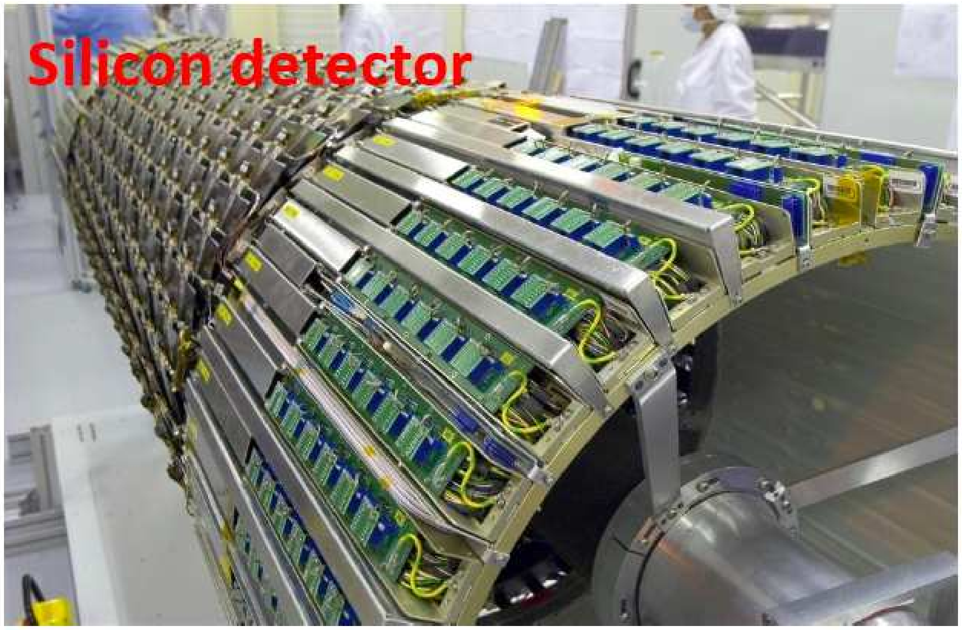
SM particles: What about Higgs boson?

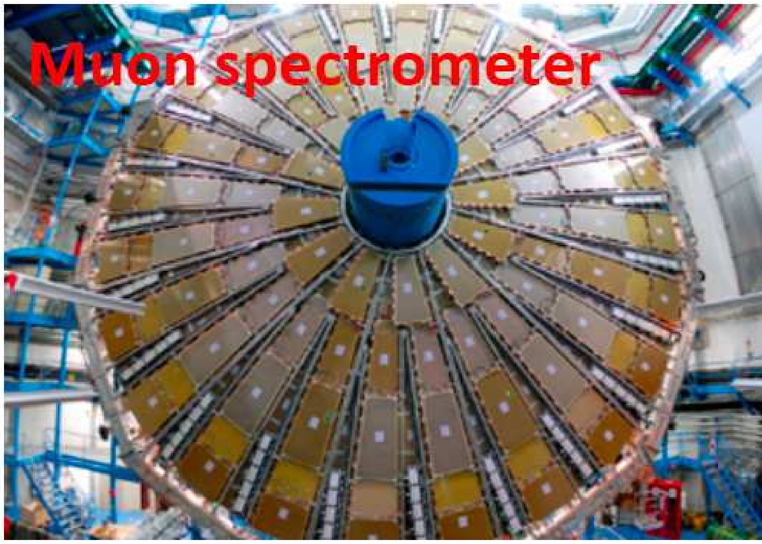


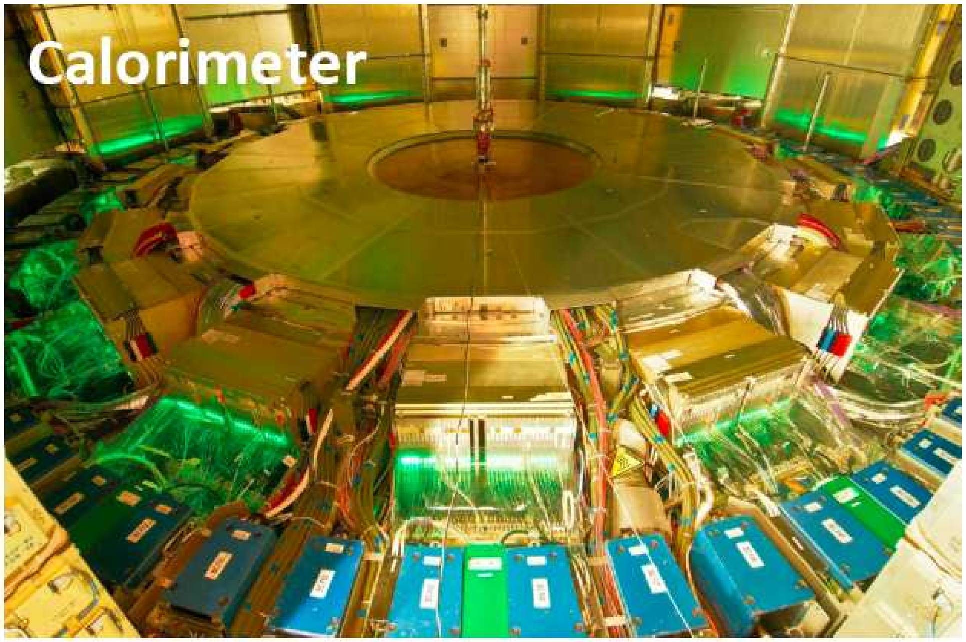
Particle signatures

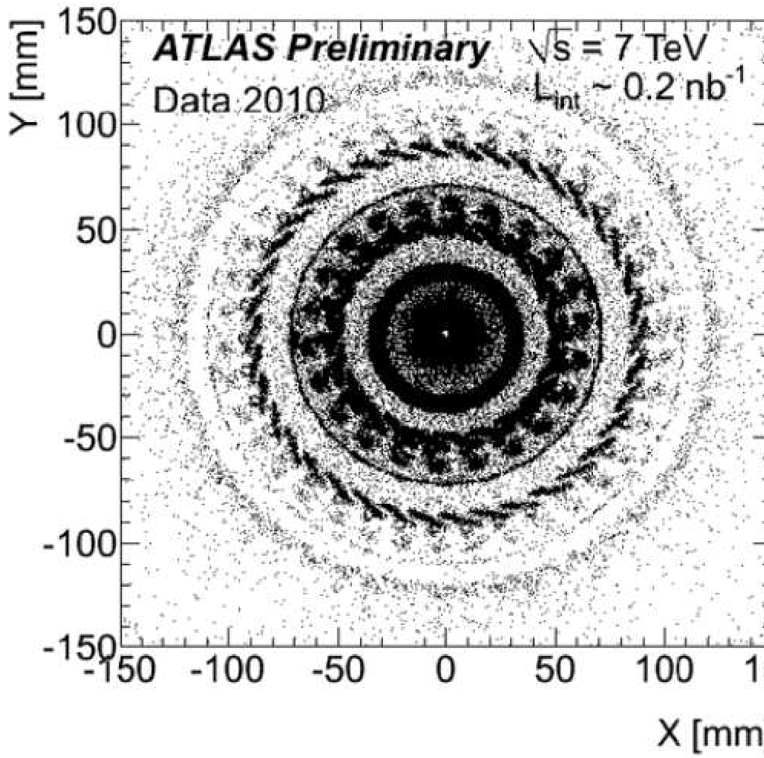


ATLAS by pictures



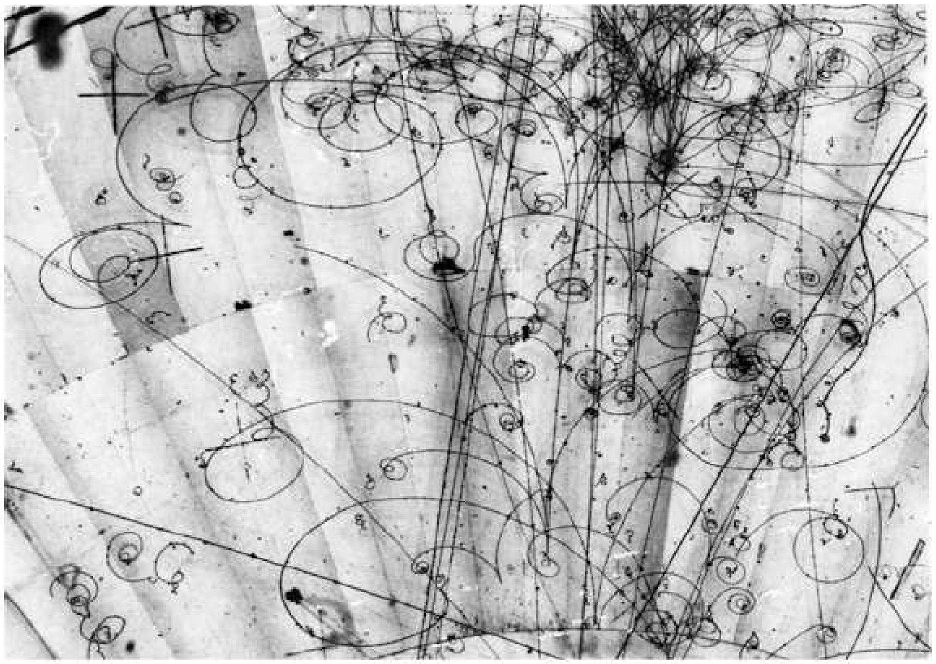


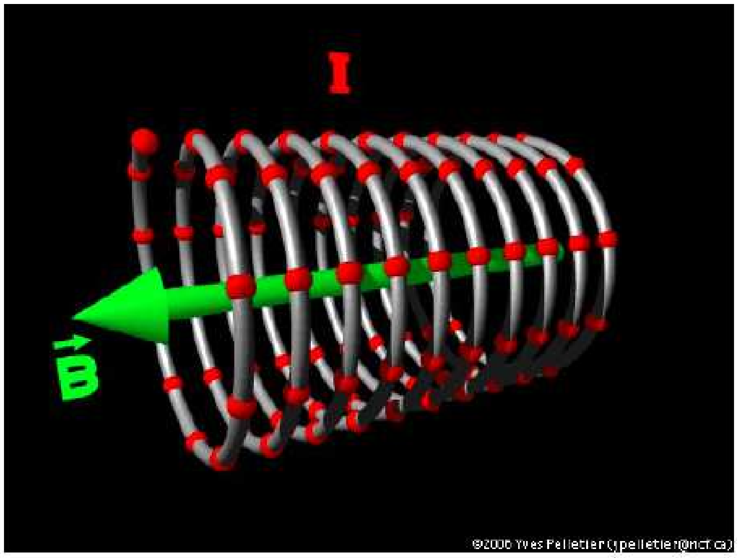




Magnetic spectrometer

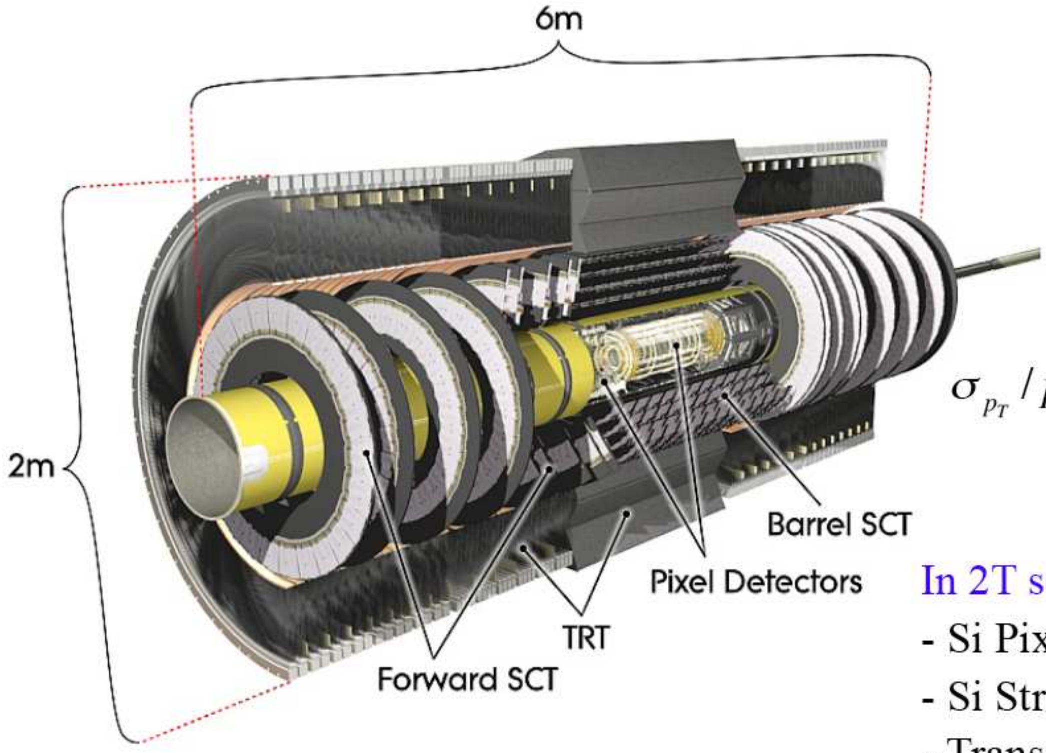
A device for measuring the momentum of charged particles by passing them through a magnetic field





A charged particle will move in a circle in a magnetic field. It's momentum can be measured from the radius.

ATLAS inner detector



$\eta = -\ln[\mathrm{tg}(\theta/2)]$

Precise Tracking

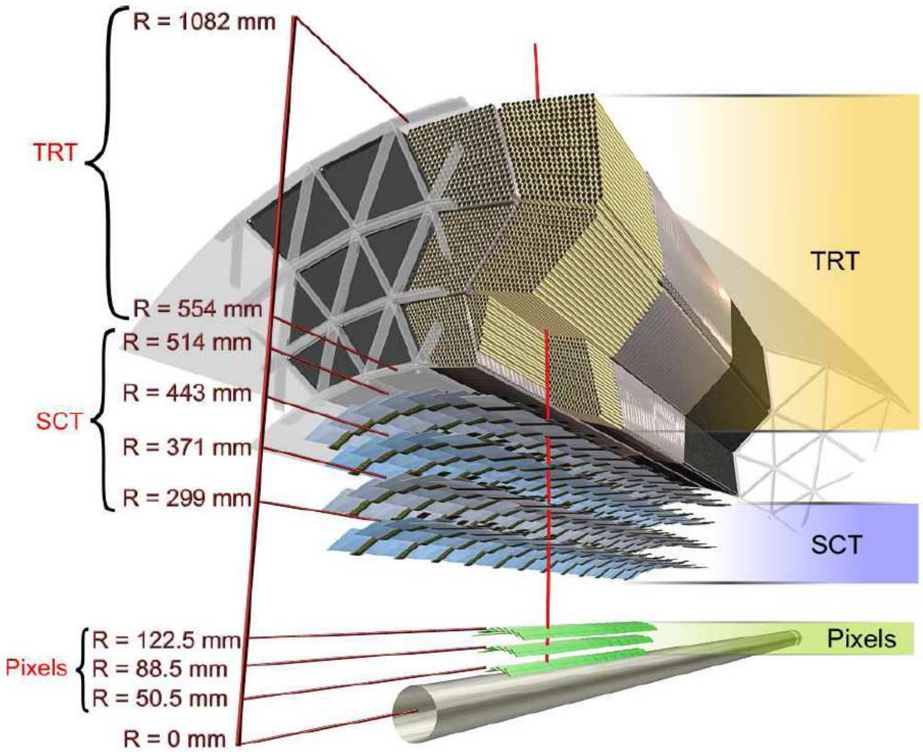
Precise Vertexing

e/π separation

$$\sigma_{p_T}/p_T \approx 3.8\times10^{-4}\,p_T(GeV)\oplus 0.015$$

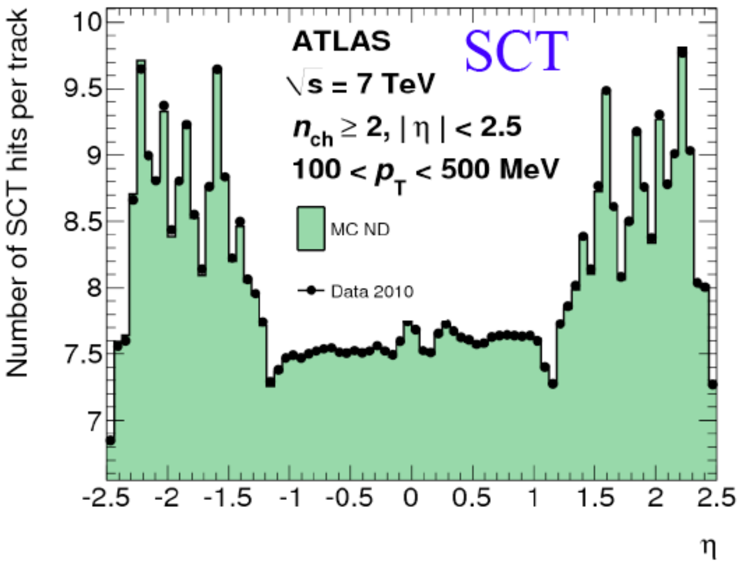
In 2T solenoidal field, $|\eta|<2.5$

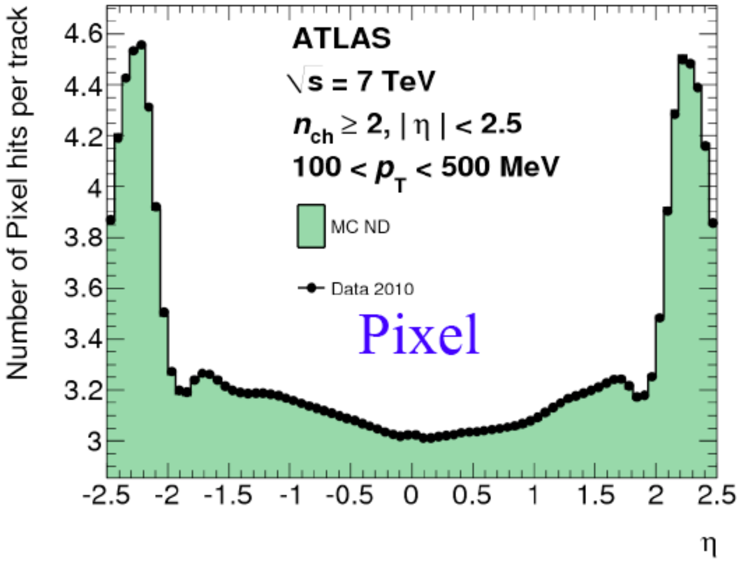
- Si Pixels: $\sigma_{r\phi}\sim10$ μm, $\sigma_Z\sim115$ μm
- Si Strips: $\sigma_{r\phi}\sim17$ μm, $\sigma_Z\sim580$ μm
- Transition Radiation tracker: $\sigma_{r\phi}\sim130$ μm

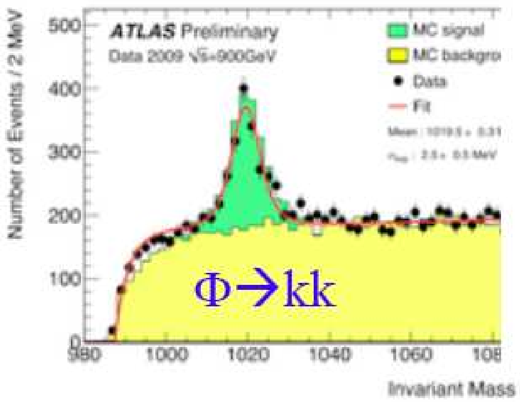


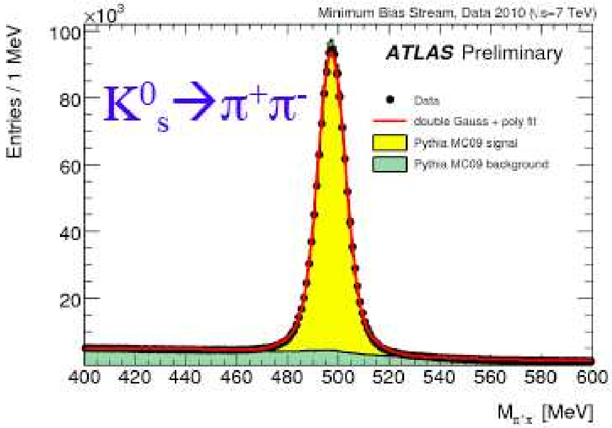
ATLAS performance: tracking and rediscovering resonances

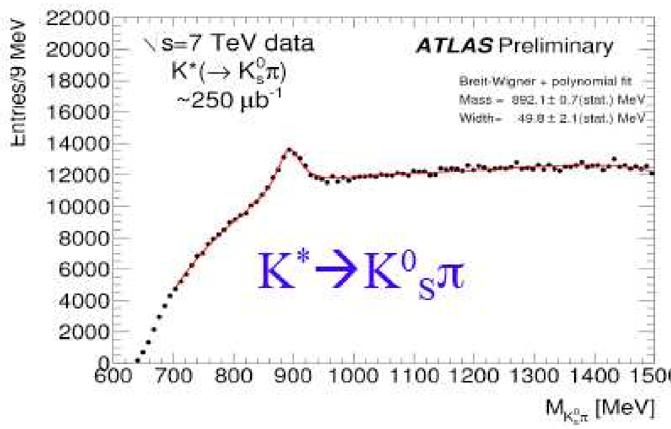
Excellent data/MC agreement for basic tracking quantities

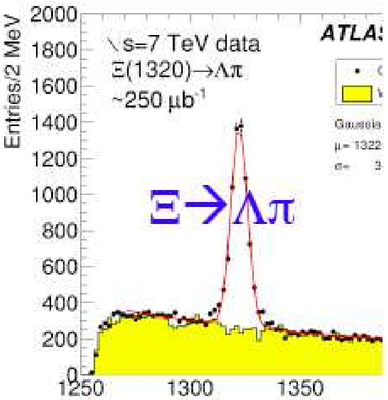


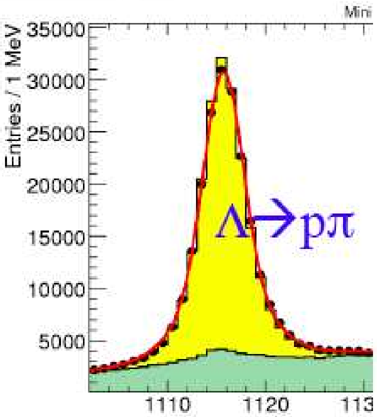


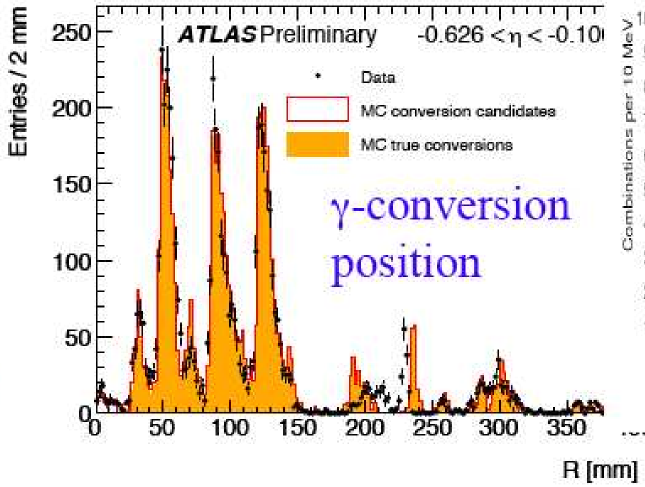


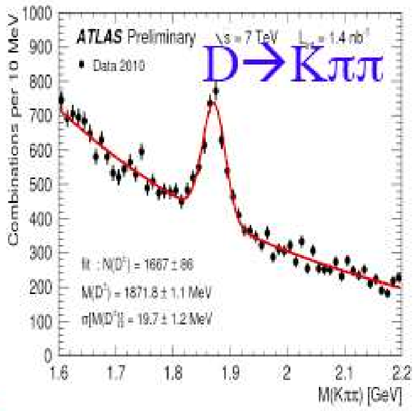








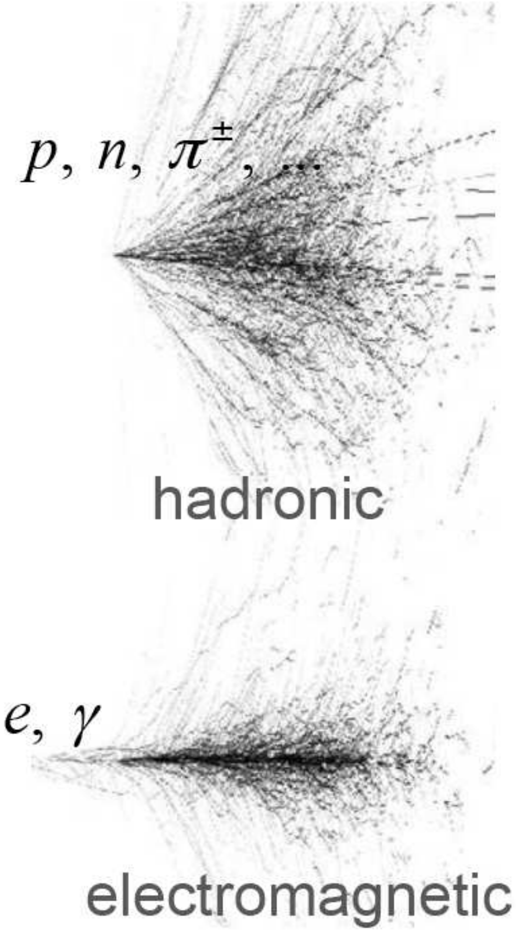


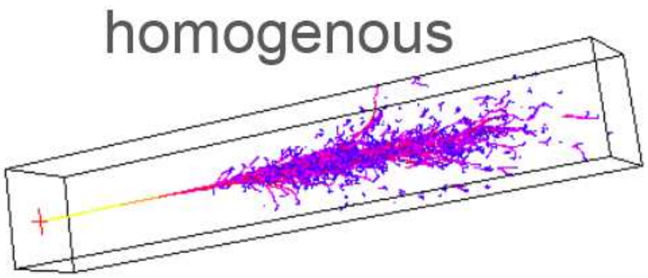


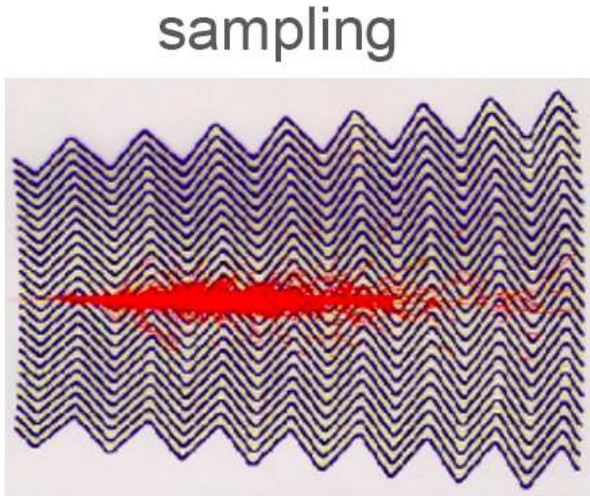
… and more

ATLAS Calorimeter

In particle physics, a calorimeter is a detector for measuring energies of both charged and neutral particles







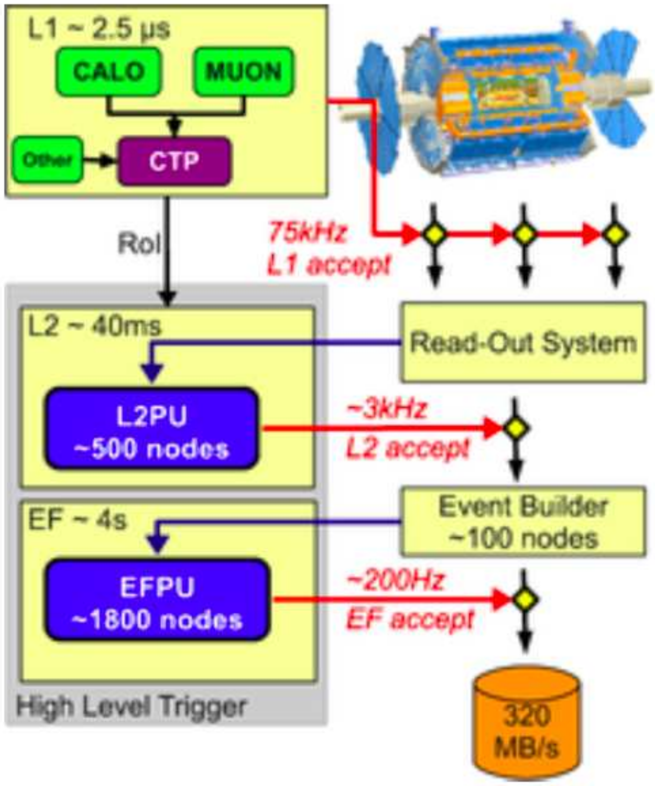
Purpose: Electromagnetic and hadronic
Design: Homogenous or sampling

The energy of incoming particles are determined from their cascade particles

ATLAS trigger

Protons collide at a rate of 40 MHz, 40,000,000 collisions per second. Among these, a tiny fraction (5×10^{-6}) is recorded:

- not all collisions are "interesting"
- not practical to record them all



The selection of interesting events is done through multi-level trigger system:

- Level 1: hardware, rate → 75 kHz;
- Level 2: firmware, rate → 3 kHz;
- Level 3: software, rate → 200 Hz

Huge raw data volume:

~ 320 MB per second

~ 3 PB a year (Peta Byte: 1,000,000,000,000,000 B=10^{15} B)

ATLAS trigger

- Trigger: Keep all interesting events (40 MHz nominal collision rate at the LHC)
- ATLAS different level trigger: ∼75 kHz at first level, >200 Hz output written on tape

Offline (GeV)	L1 thr (GeV)	L1 rate (kHz)	EF thr (GeV)	EF rate (Hz) @ 5 10^{33}
e > 25	18	17	24	70
μ > 25	15	8	24	45
dilepton	10-15	15	8-18	21
2γ 25-40	10-16	12	20-35	17
2τ 30-45	11-15	12	20-29	12
Jet > 360	75	2	2	5
MET 120	40	2	80	17

ATLAS computing

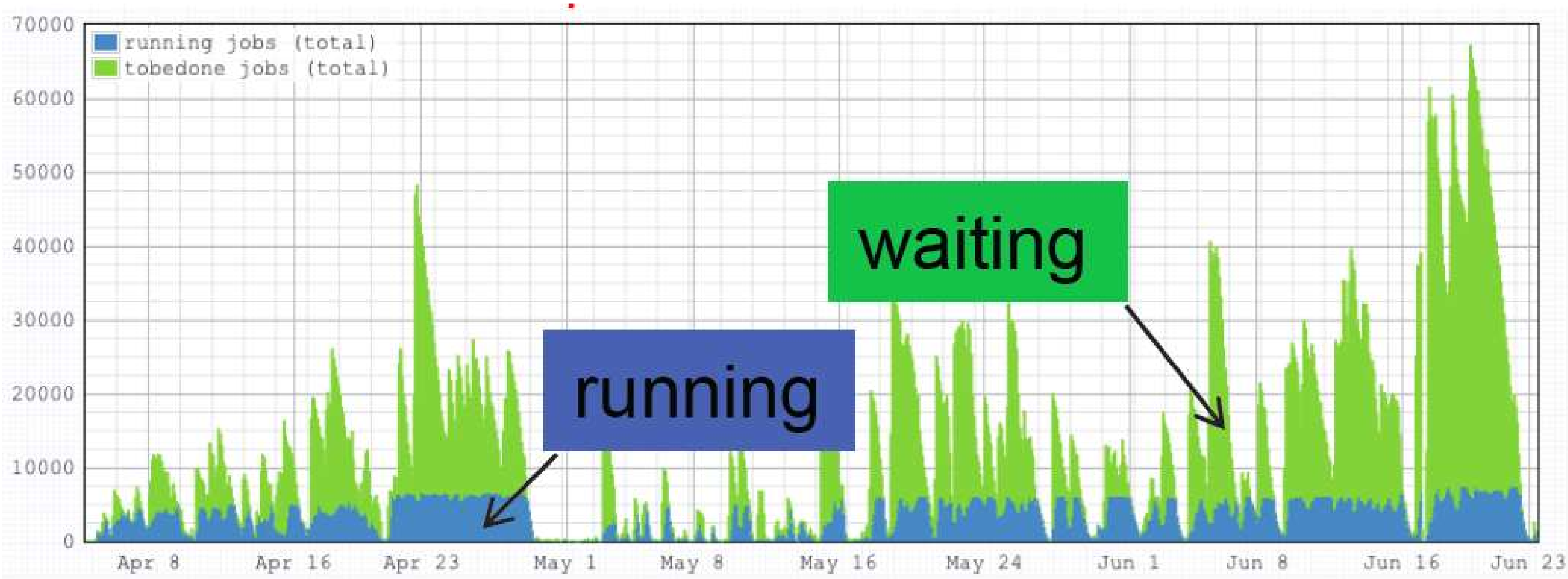
The data recorded by each LHC experiment will fill 2,000,000 DVDs (or 15,000,000 CDs) every year.

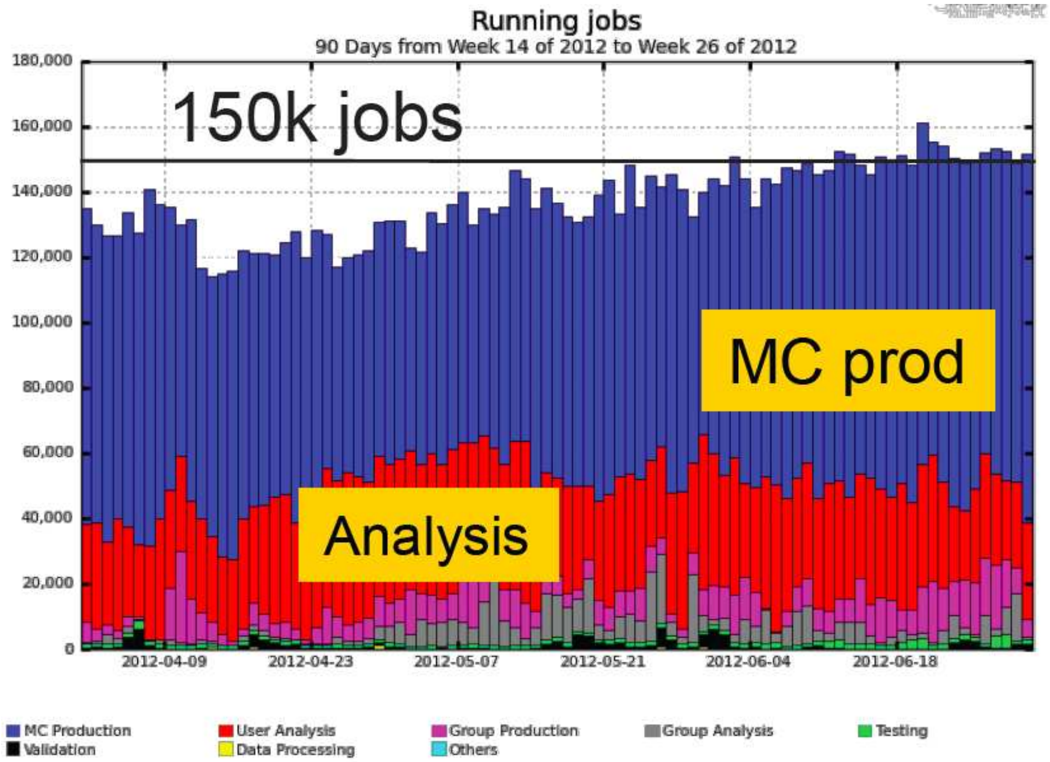
Hundreds of thousands of computers around the world are integrated together as a world-wide computing grid like the power grid

ATLAS computing

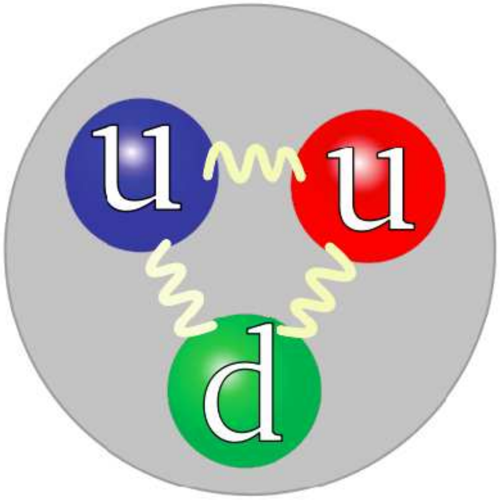
ATLAS computing

- GRID is essential: up to 150k jobs running in parallel
- Extra-resources up to 7.5k CPU cores



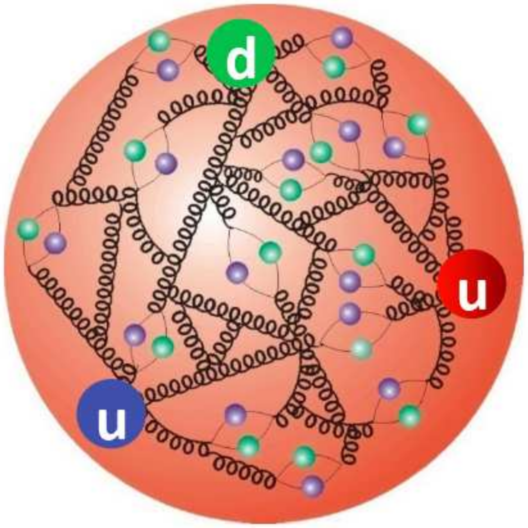


What is a proton?



LHC is a proton-proton collider,
so what are protons?

Protons are constituents of nuclei. They are small and have a size of $\sim 10^{-15}$ m (1 fermi) or about 1/1000 of the size of a hydrogen atom.

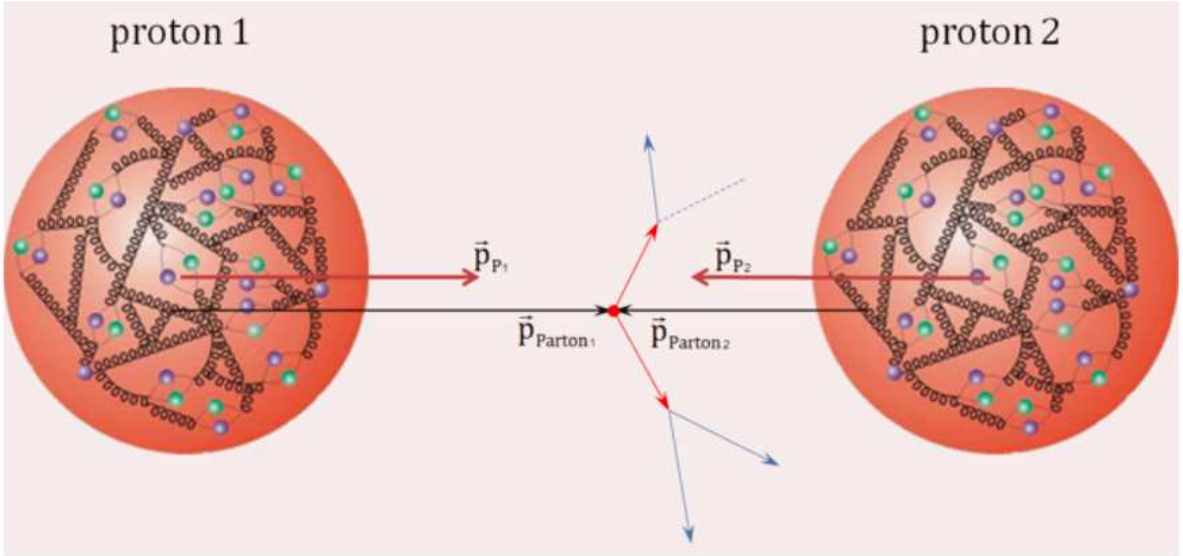


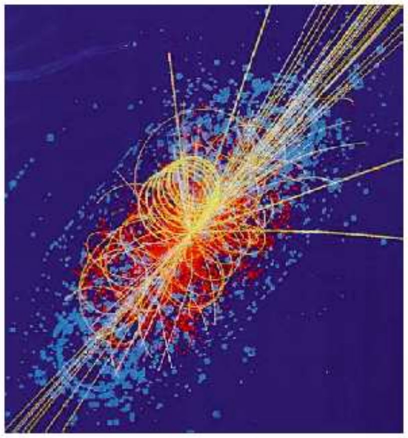
It "consists" three valence quarks and many gluons and sea quarks, bound together by nuclear (strong) interaction.

About half of the proton energy is carried by quarks while the other half by gluons.

Proton proton collisions

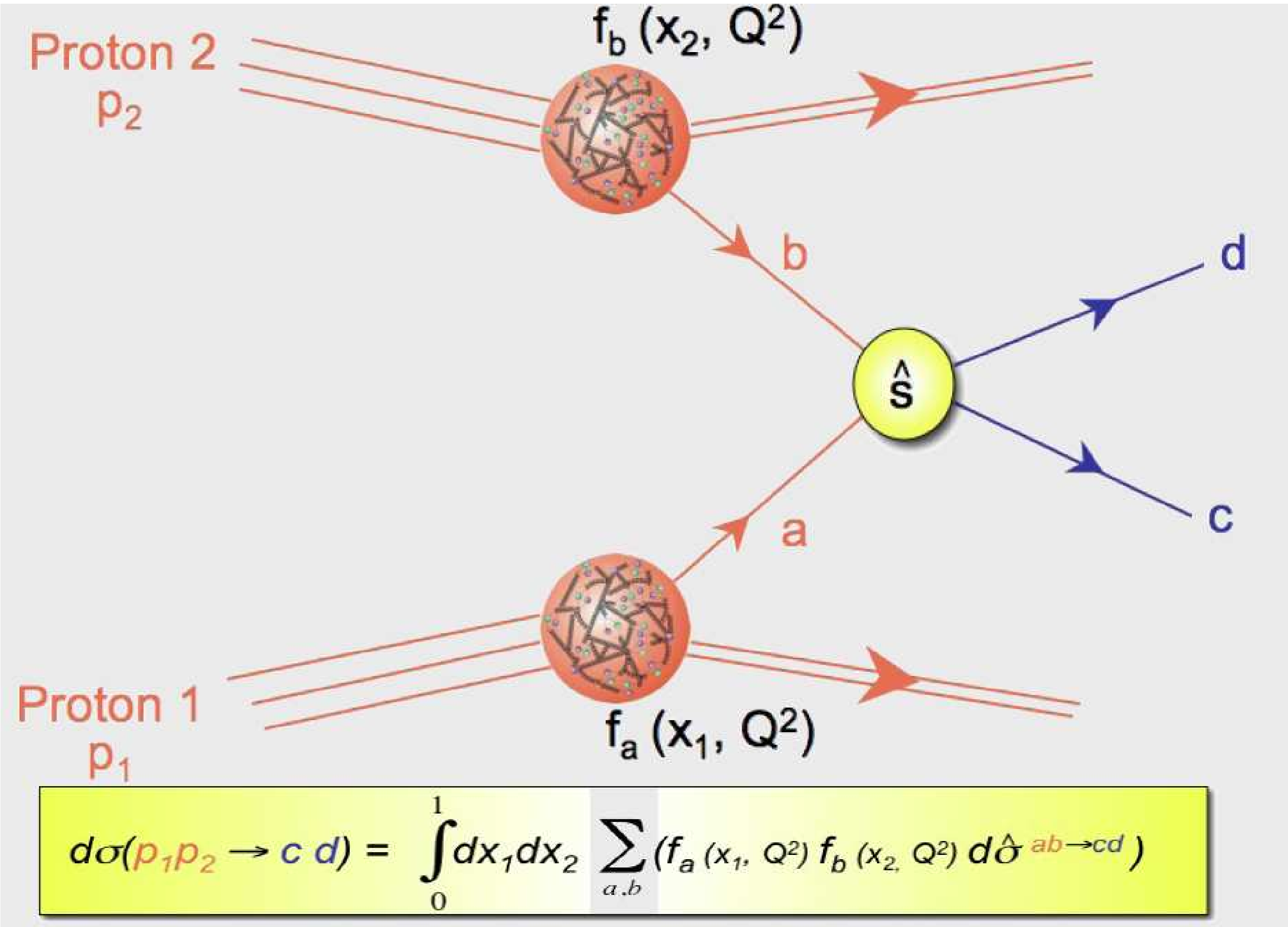
When a proton collides with another proton, the actual collision occurs between quarks and gluons





We have no control what process actually takes place! Our job is to figure out what actually happened.

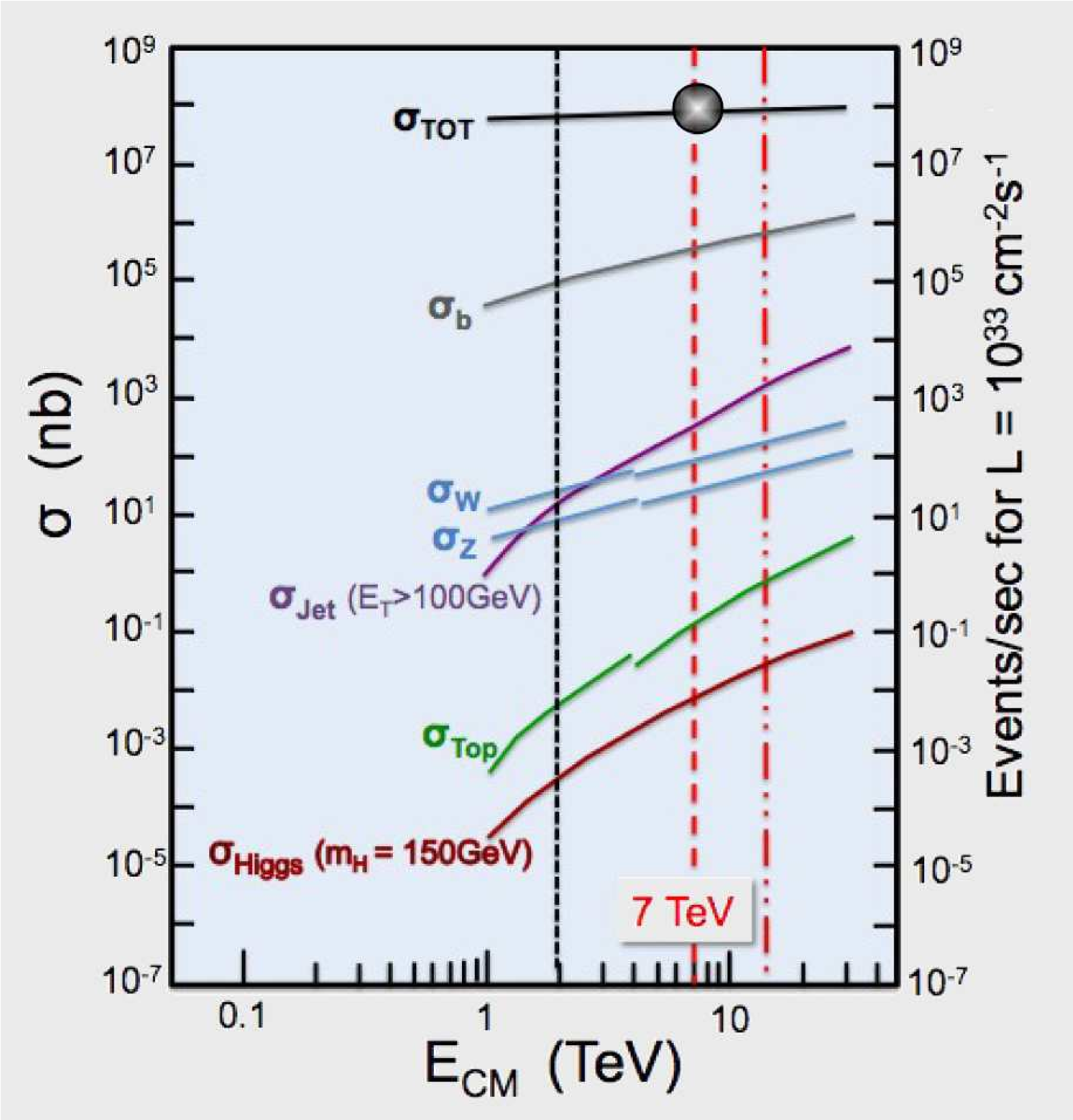
Basic processes at the LHC



- Hard scattering processes represent only a tiny fraction of the total inelastic and elastic pp cross sections
- Selection of interesting processes using triggers

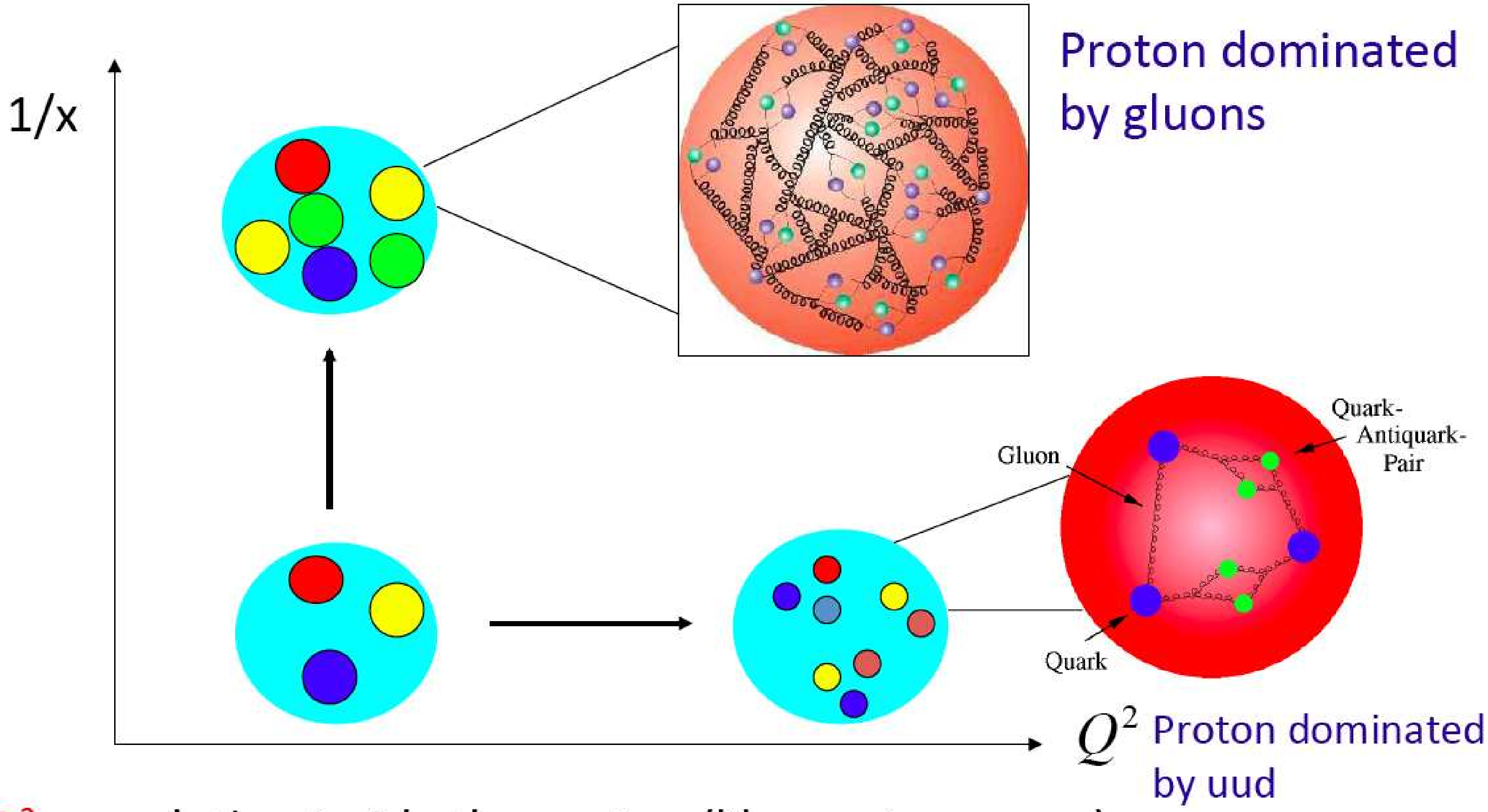
Different physics topics

Before looking for the Higgs boson: check the standard model



Understanding the proton structure

Aim: Understanding the proton structure (quarks, gluons)

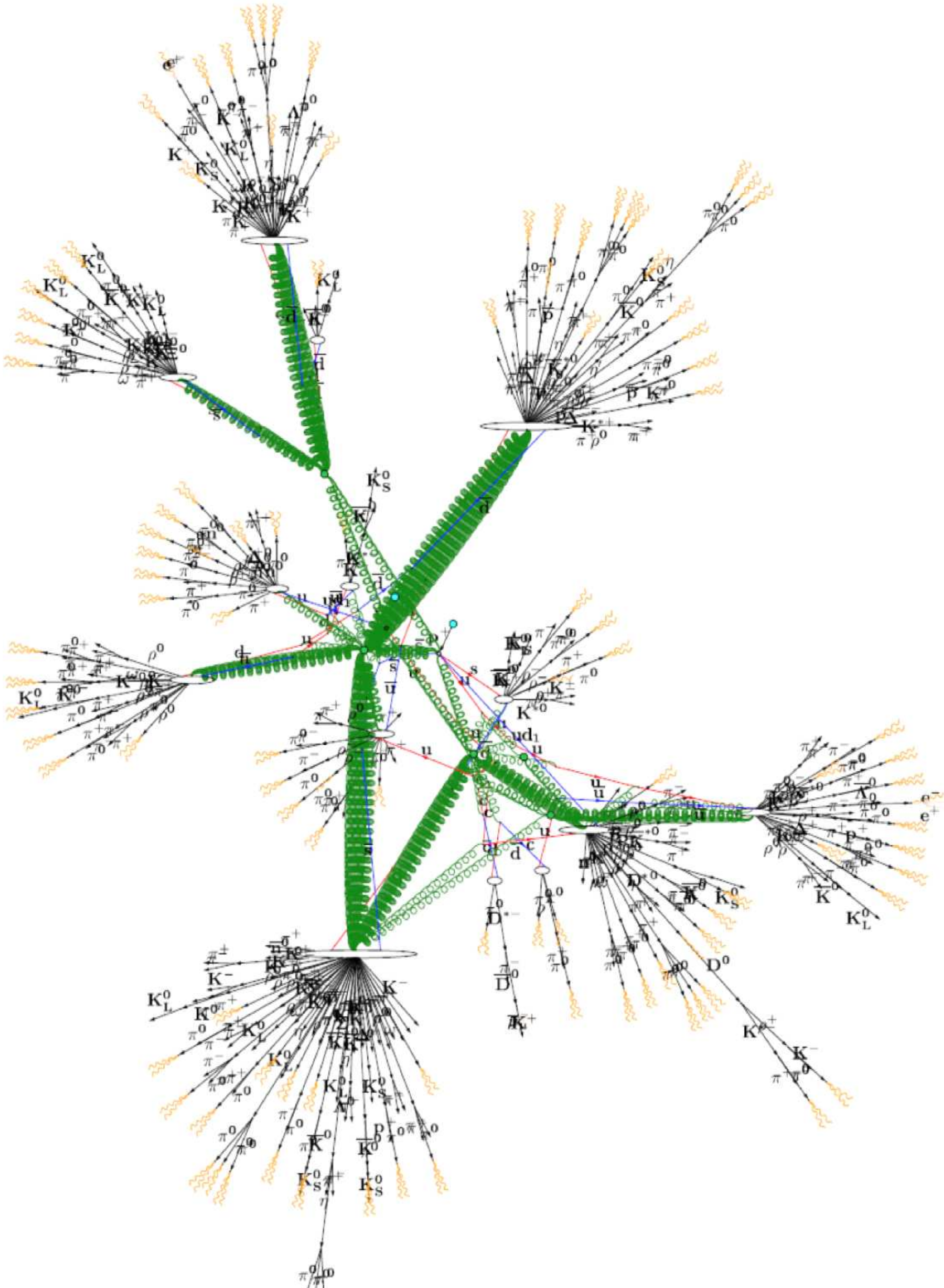


Q^2 : resolution inside the proton (like a microscope)

x :Proton momentum fraction carried away by the interacting quark

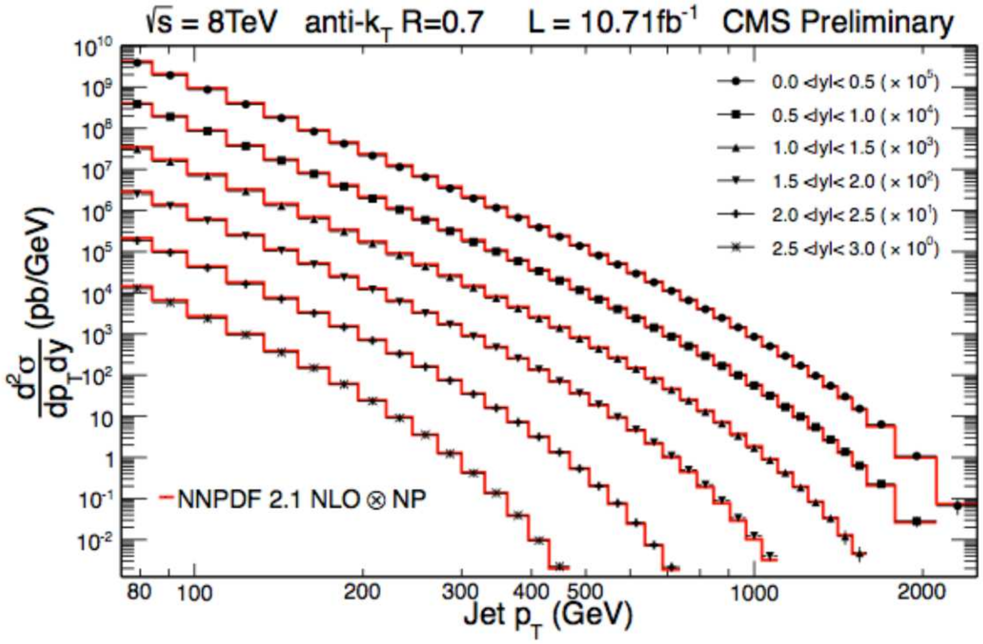
What happens when hadron collide?

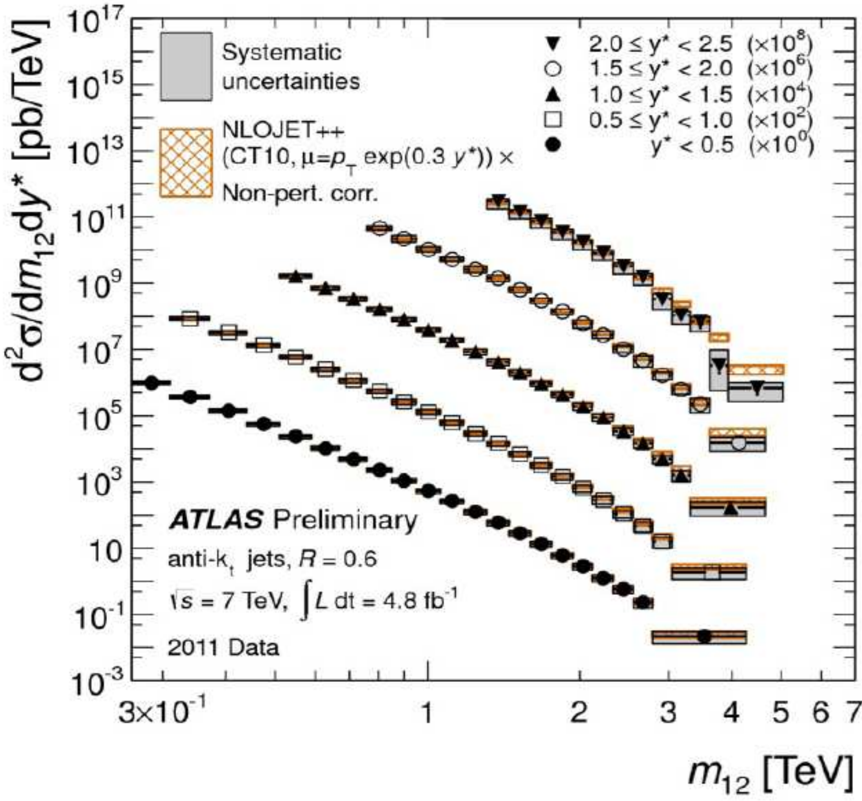
- Difficult to calculate: non-perturbative physics...: example of a "minimum bias" event at 7 TeV
- Fundamental aspects: confinement, hadronic mass generation...



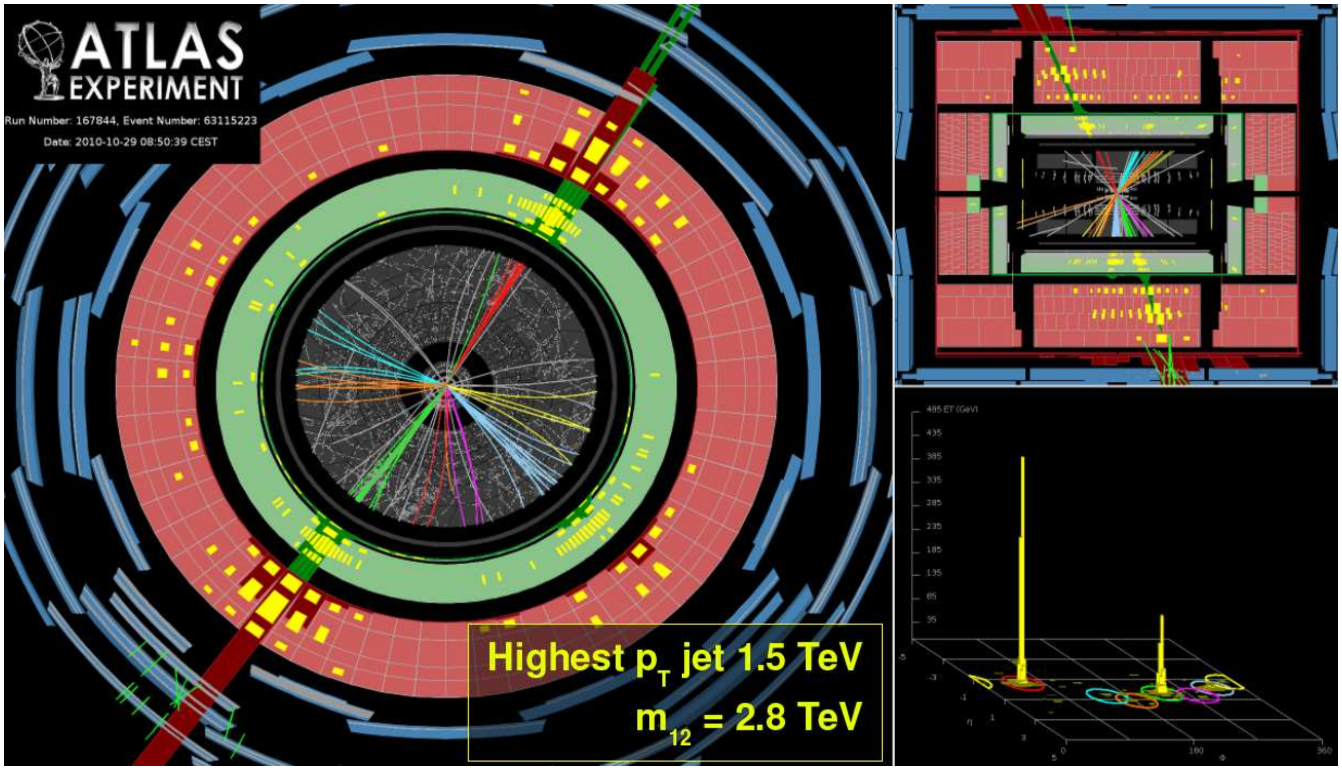
Jet production at 7 TeV: a new territory

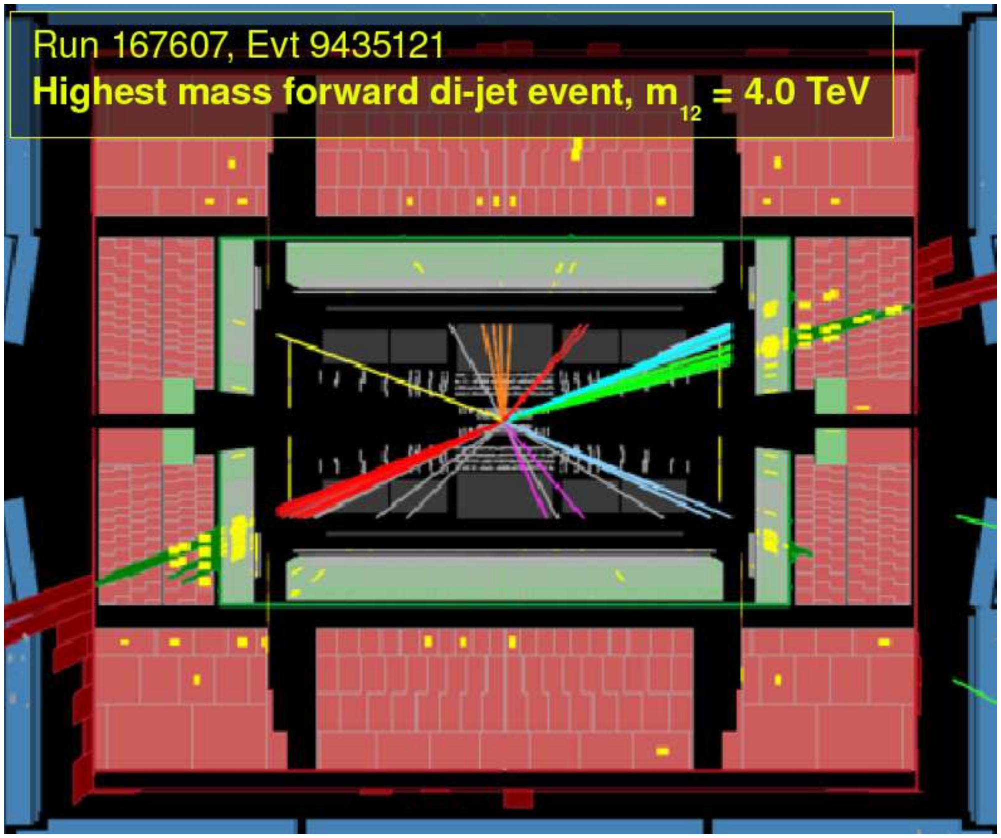
- Extension of measurement up to ∼2 TeV allows to probe standard model in a new territory and measure the proton structure in terms of quark and gluon densities
- Good agreement with Quantum Chromodynamics calculation



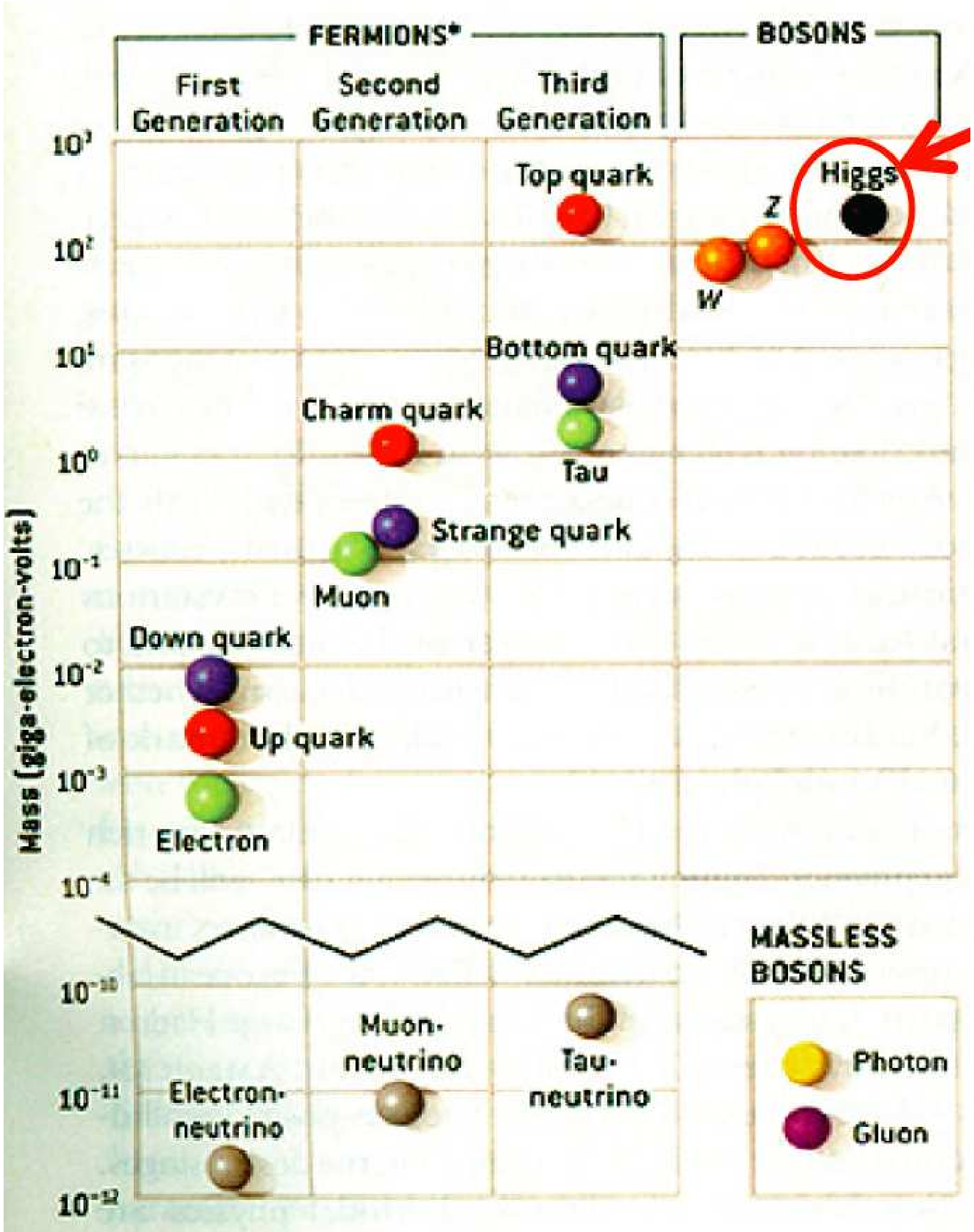


High p_T jet and dijet mass events

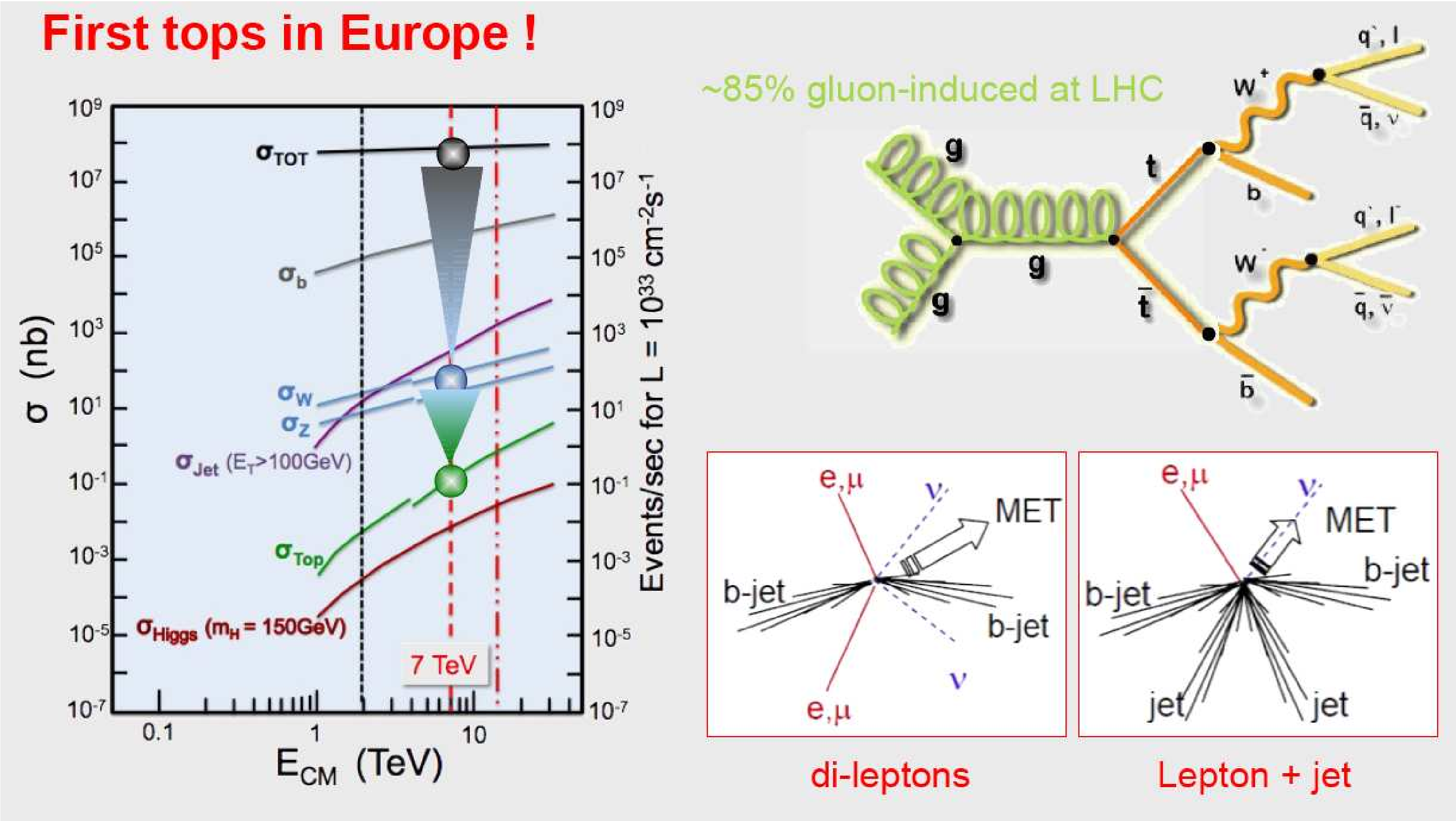




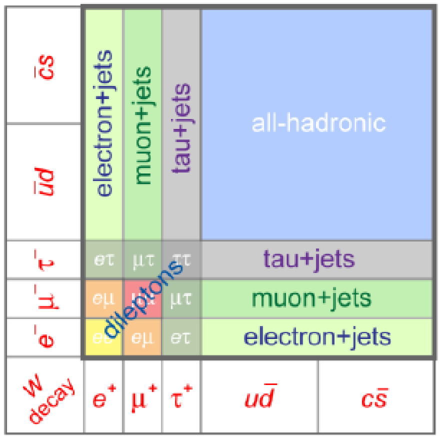
The elementary particle zoo: top quark



Rediscovering the Top quark

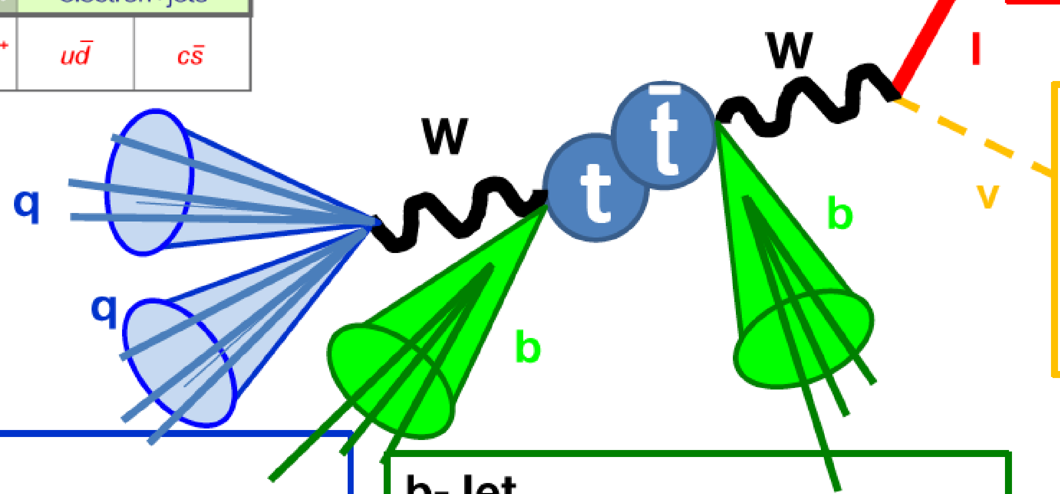


Selection of $t\bar{t}$ events



Electron
- Good isolated calo object
- Matched to track
- E_T>20 GeV
- $|\eta| \in [0;1.37][1.52;2.47]$

Muon
- Segments in tracker and muon detector
- Isolated track
- p_T > 20 GeV
- $|\eta|$ < 2.5



E_T^{miss}
- Vector sum of calo energy deposits
- Corrected for identified objects

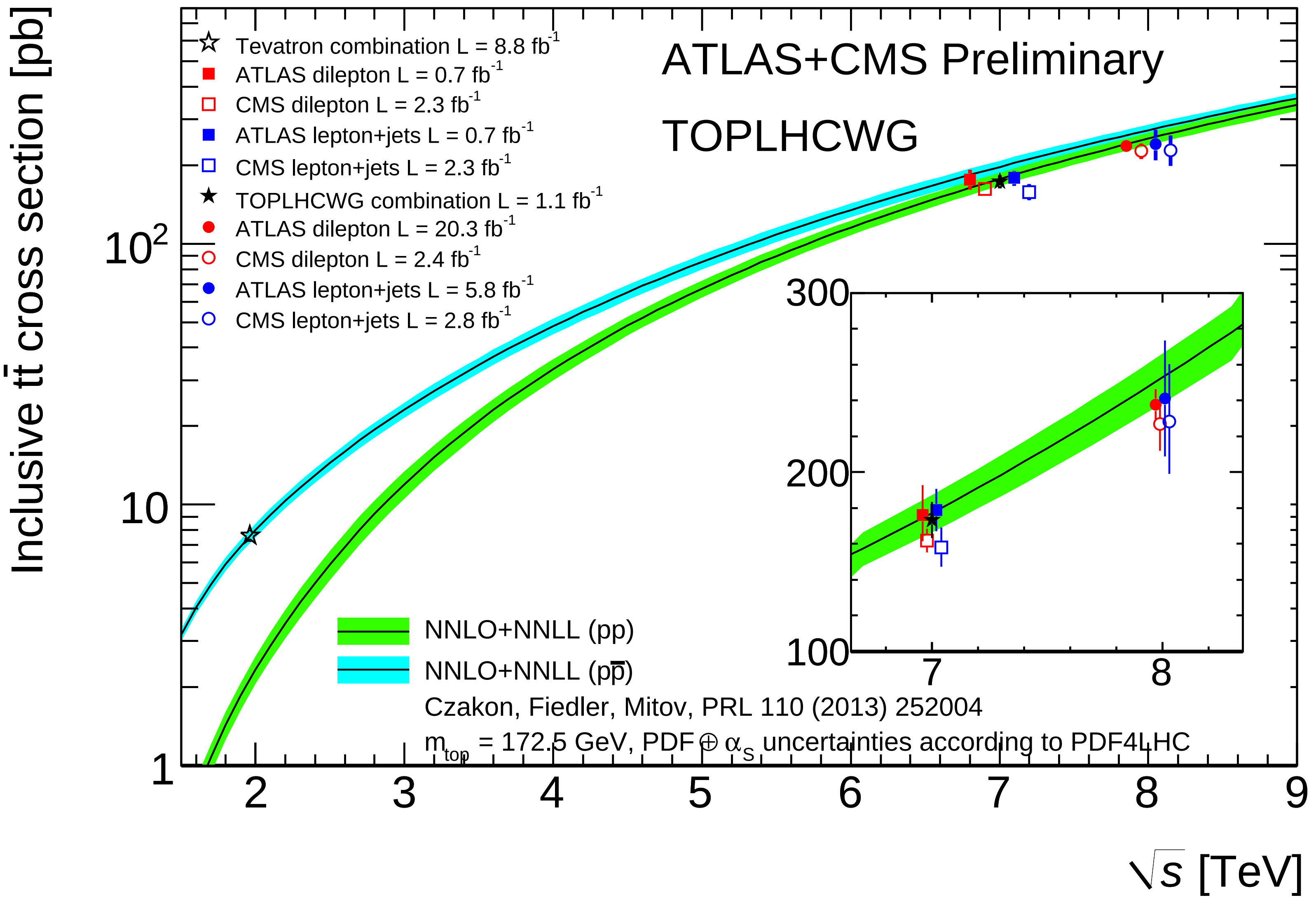
Jet
- Topological clusters
- Anti-k_T (R=0.4)
- MC-based calibration
- p_T > 25 (20) GeV
- $|\eta|$ < 2.5

b-Jet
- Displaced tracks or secondary lepton
- SV0: reconstruct sec.vertex
- JetProb: track/jet compatibility with primary vertex

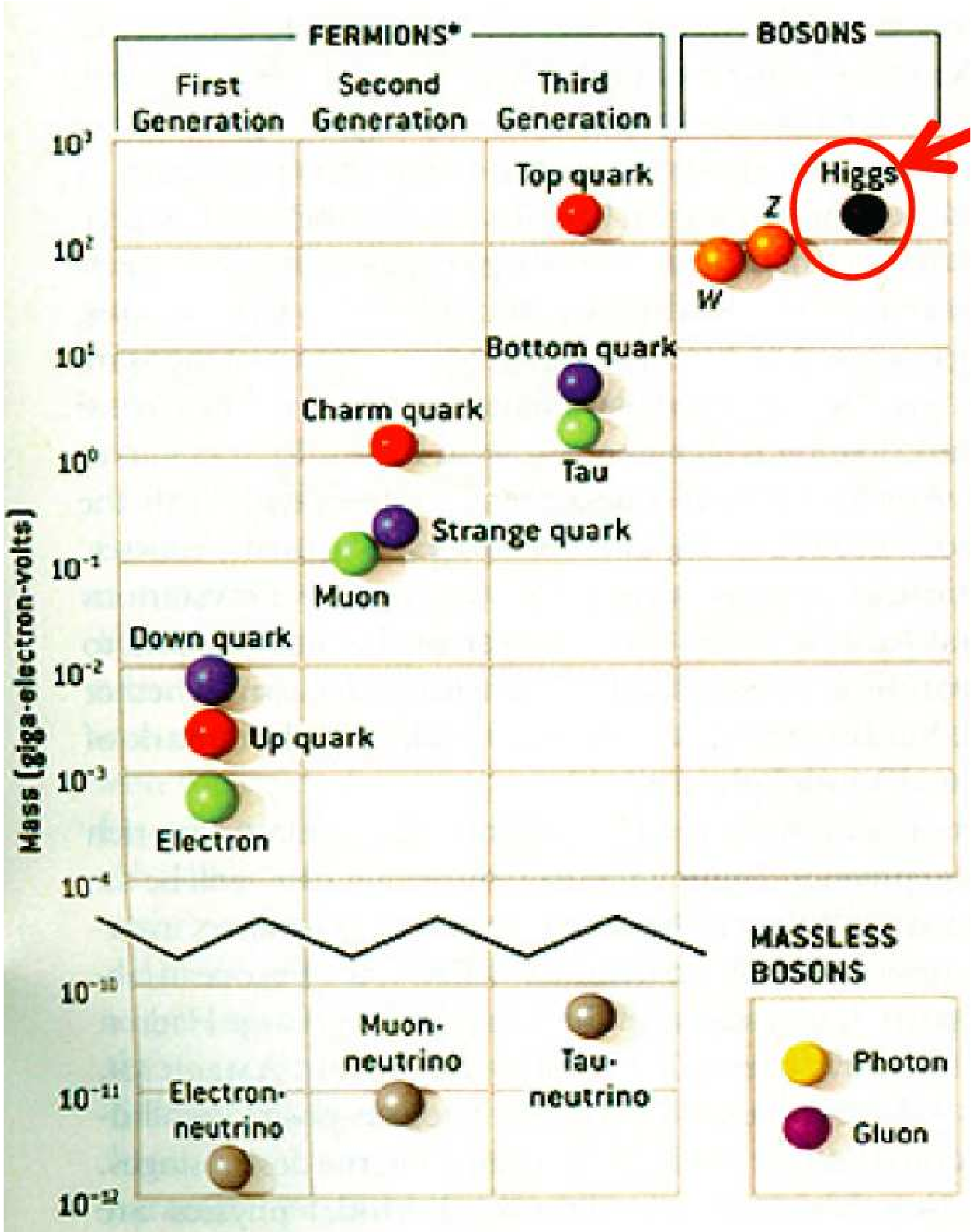
Event cleaning
- Good run conditions
- PV at least 5 tracks
- Bad jet veto
- Cosmic veto (μμ)

Measurement of $t\bar{t}$ cross section

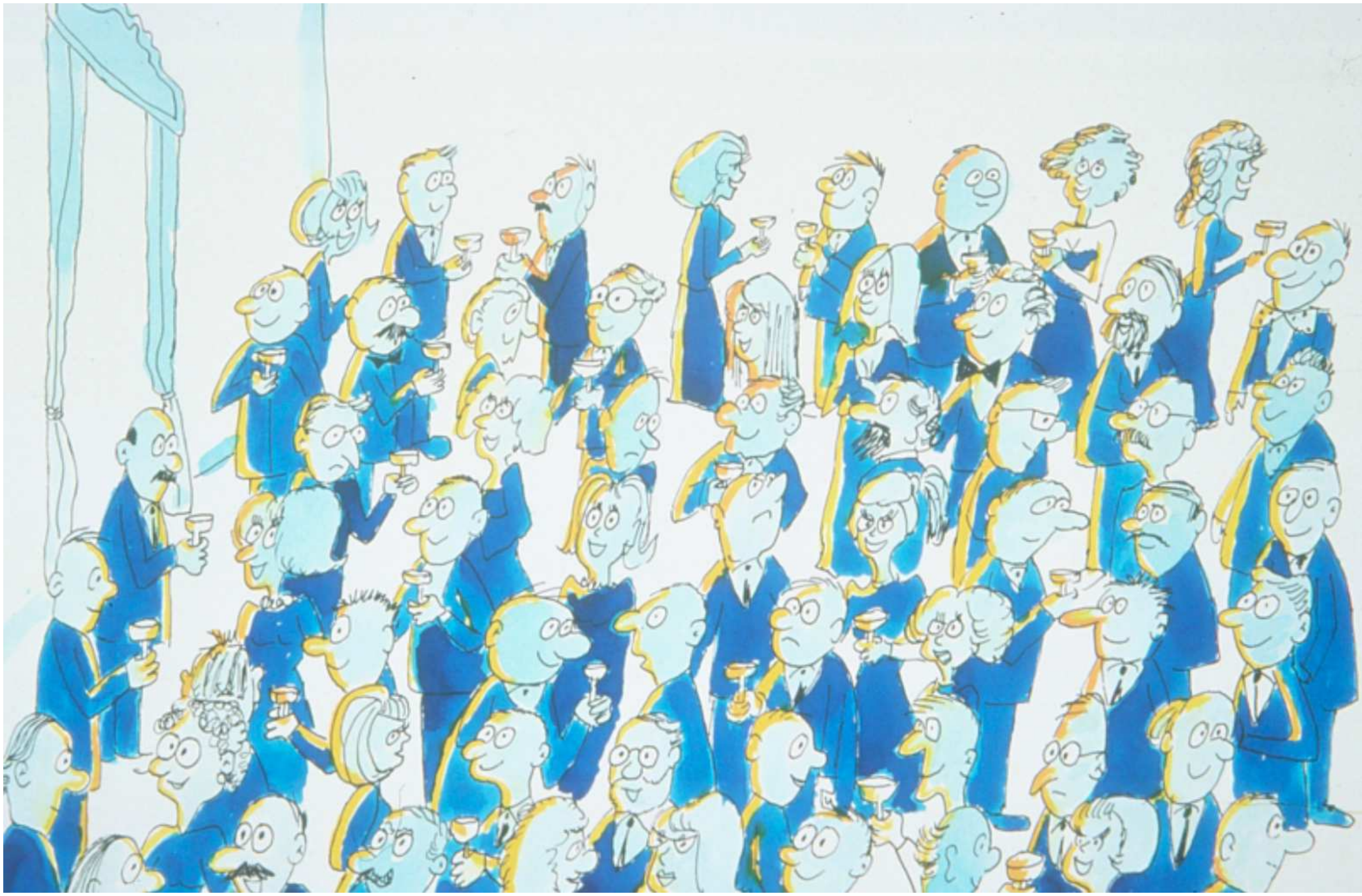
$t\bar{t}$ cross section in agreement with SM



The elementary particle zoo: Higgs boson

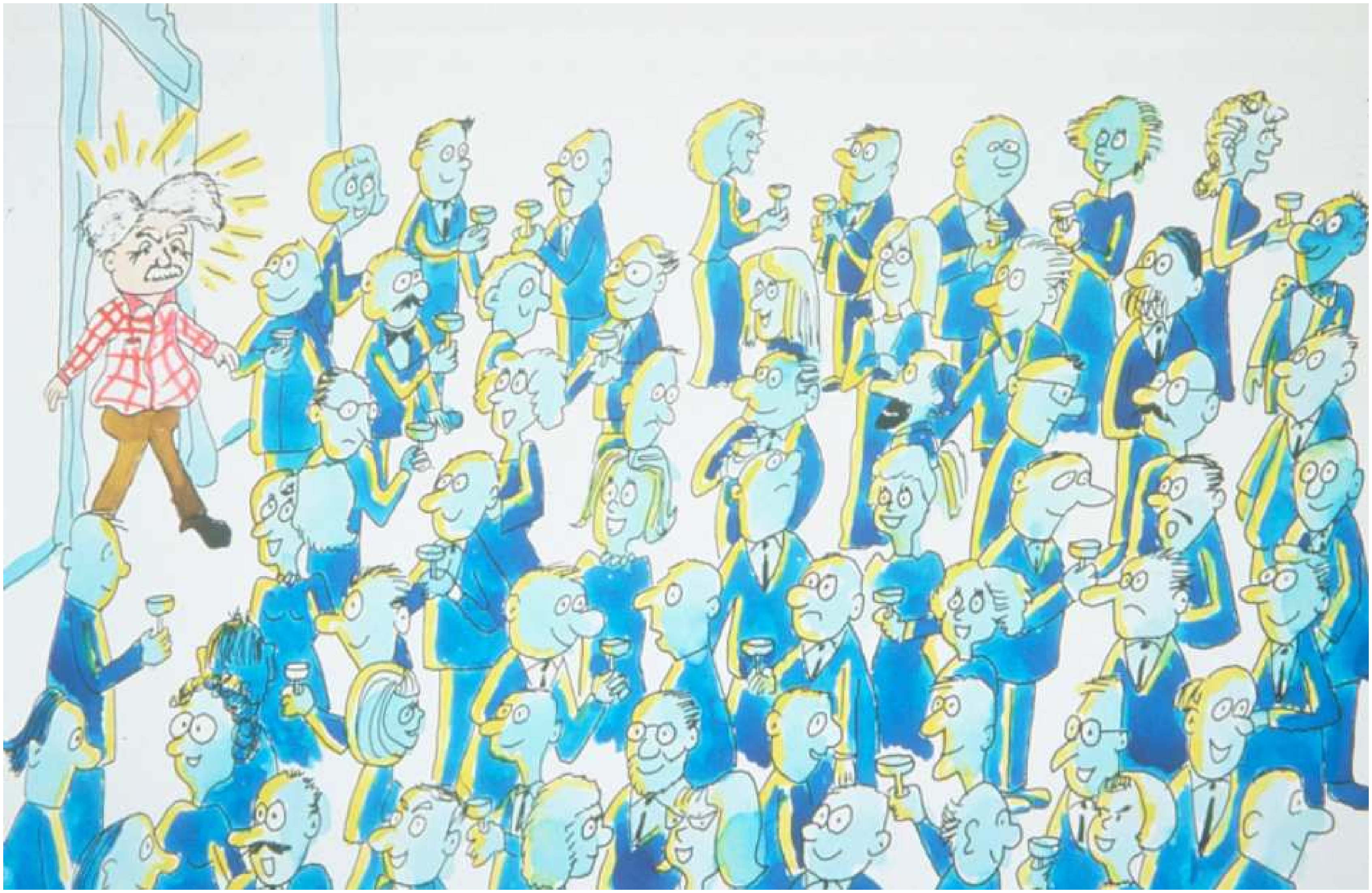


Higgs mechanism - part 1



Imagine a room full of journalists quietly chattering; it is like space filled only with the Higgs field

Higgs mechanism - part 2



A well-known person (President, Queen of England) enters in the room, This creates a disturbance as he moves through the room and attracts a group of journalists with each step

Higgs mechanism - part 3

This increases the resistance to movement of that famous person. In other words, he acquires mass just like a particle moving through the Higgs field

Higgs mechanism - part 4

Now something different: a rumour crosses the room, "the Higgs boson is discovered!" for instance

Higgs mechanism - part 5

It creates the same kind of clustering but this time between the journalists themselves. In this analogy, these clusters are the Higgs particles.

Higgs mechanism

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

Volume 12, number 2 PHYSICS LETTERS 15 September 1964

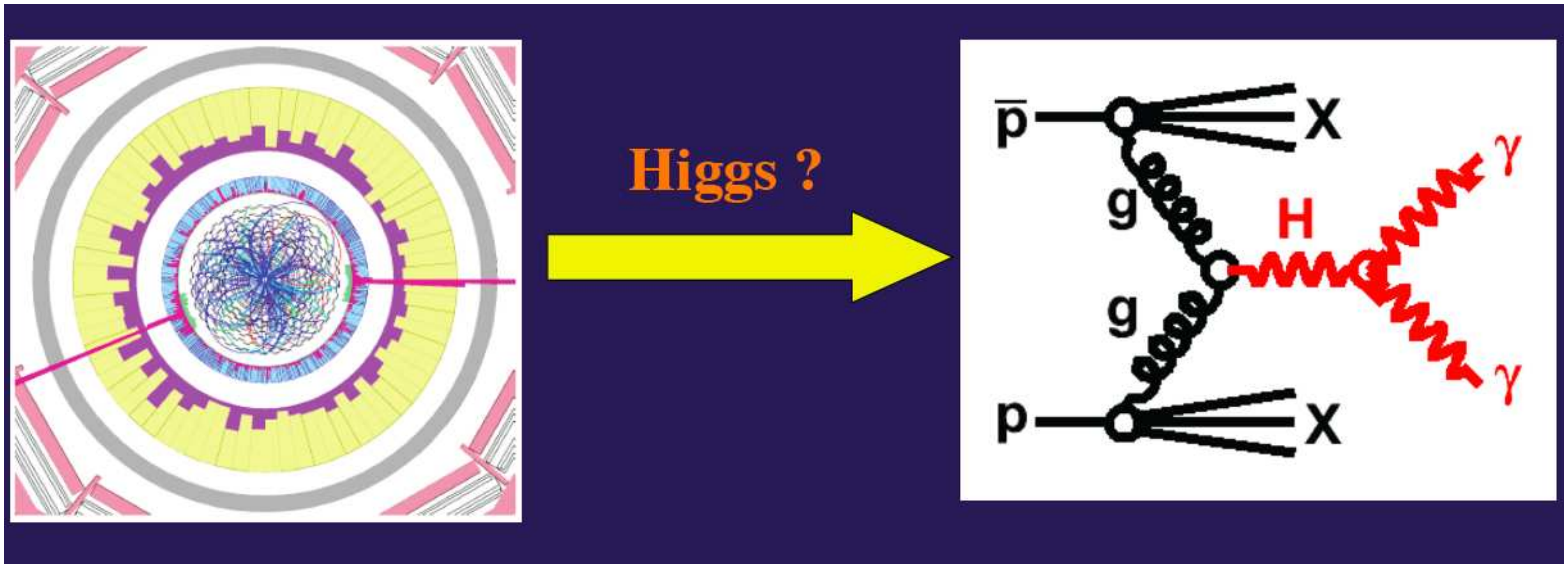
BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

1928 - 2011

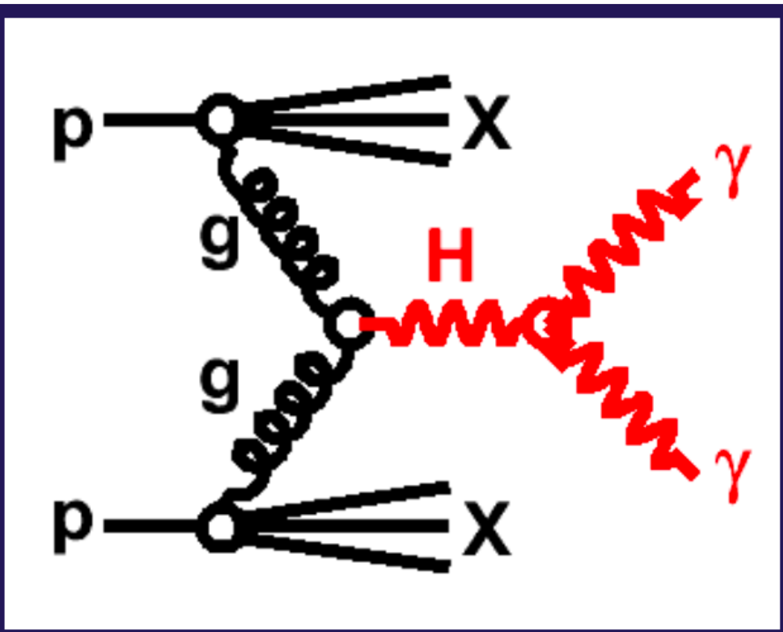
Born American, on Cornell faculty since 1953 with field in statistical physics and phase transitions. Englert was his postdoc at Cornell, 1959-1961, but when Englert returned to Brussels in 1961, Brout resigned from Cornell and moved to Brussels, becoming Belgian citizen eventually. [the 9/2008 LHC accident/delay really costed him]

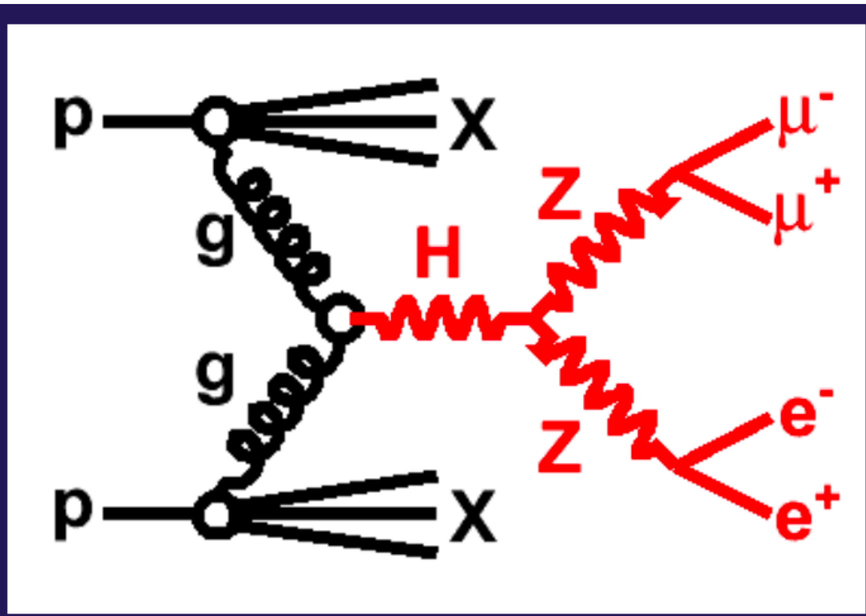
How the Higgs boson can be produced at the LHC?



- The Higgs boson can be produced via 2 gluons originating from the protons
- The Higgs boson can decay into two photons (one of the best signals to see the Higgs boson)

Two examples of decays of the Higgs boson

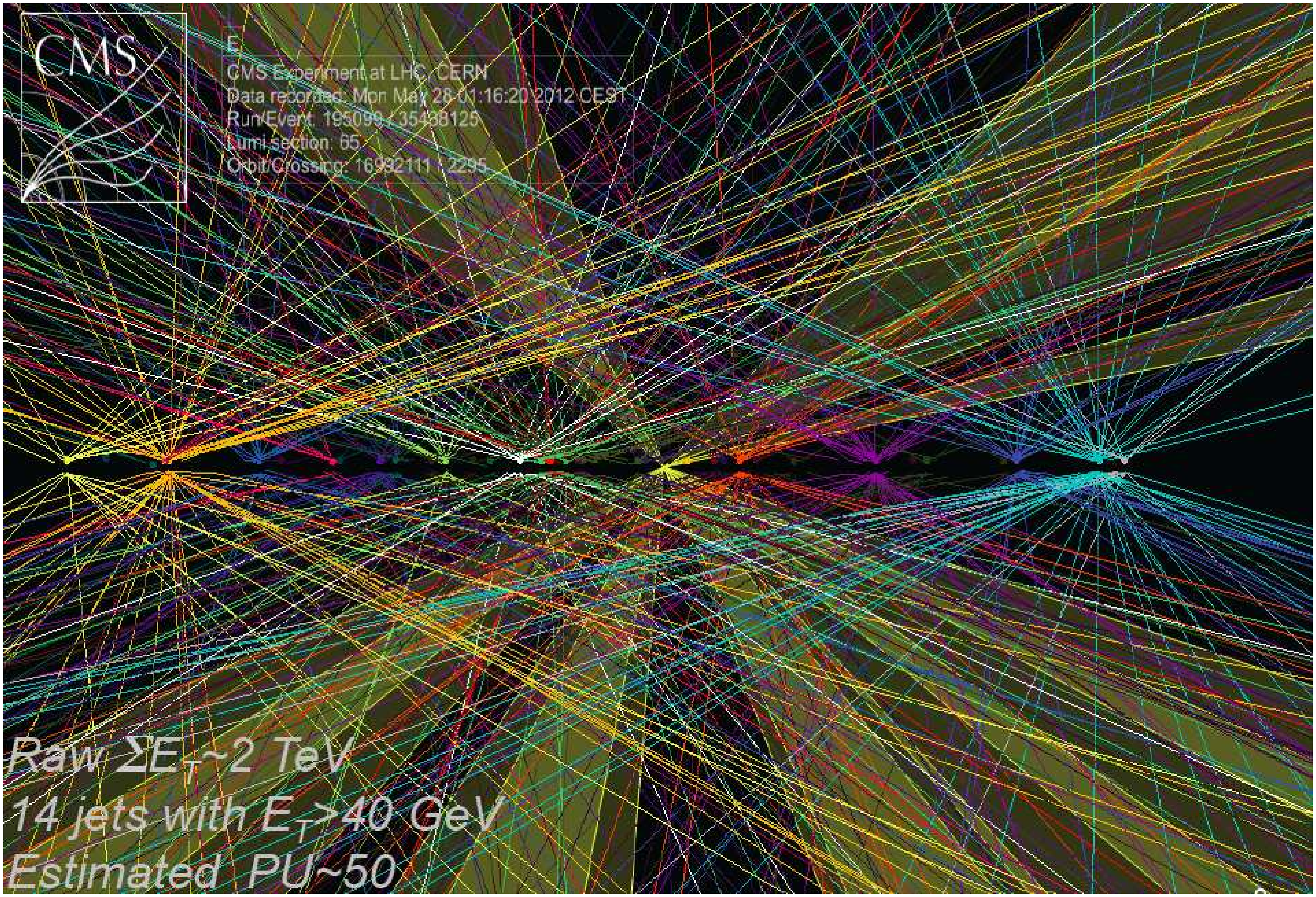




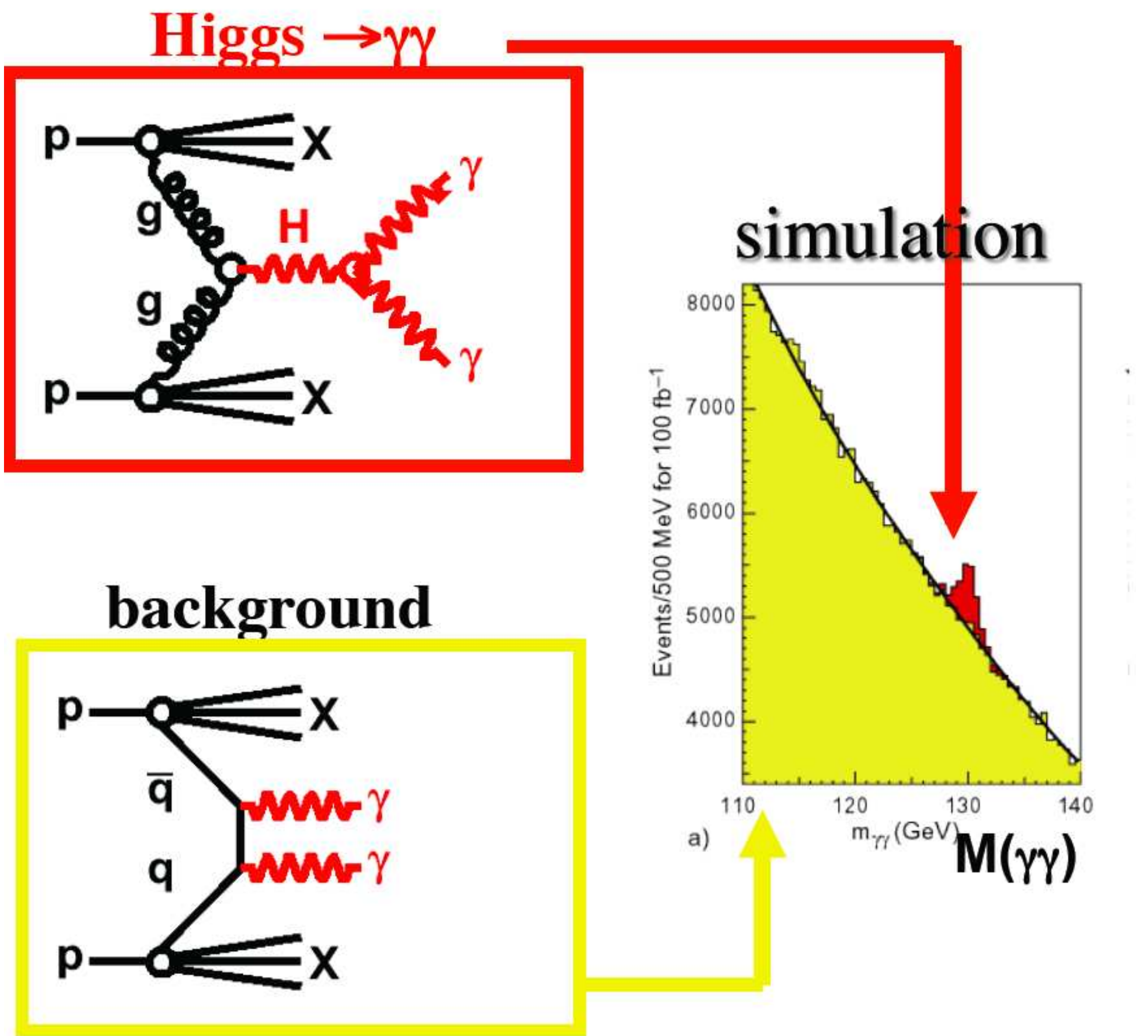
- Higgs boson is unstable and decays very quickly
  - 0.2% decay into **two photons**
  - 0.014% decay to **4 electrons or muons**
  - 99.8% of decays are harder to observe

Difficulty of the analysis: pile up!

Many interactions occur in the same bunch crossing

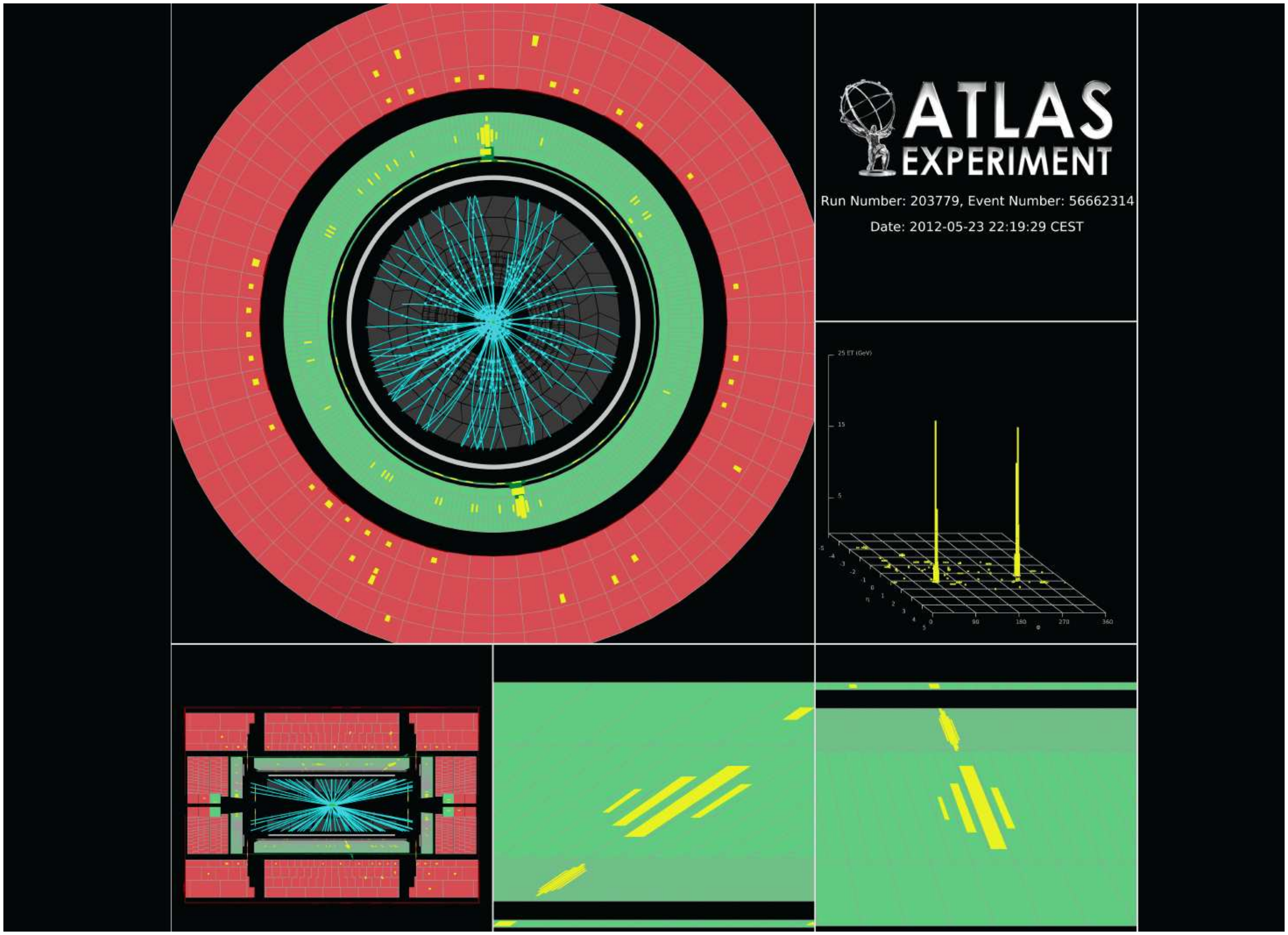


Looking for the Higgs boson decaying into two photons



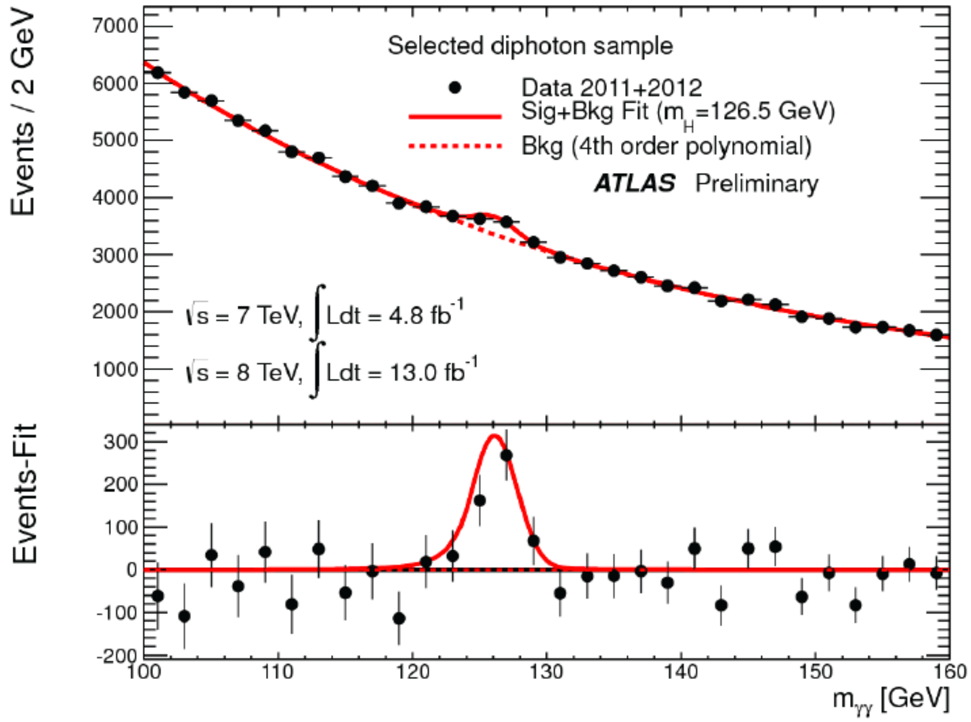
- Higgs boson decays to two high energetic photons: Higgs mass determined from energies and angles of photons
- Background processes look similar but creates no peak!

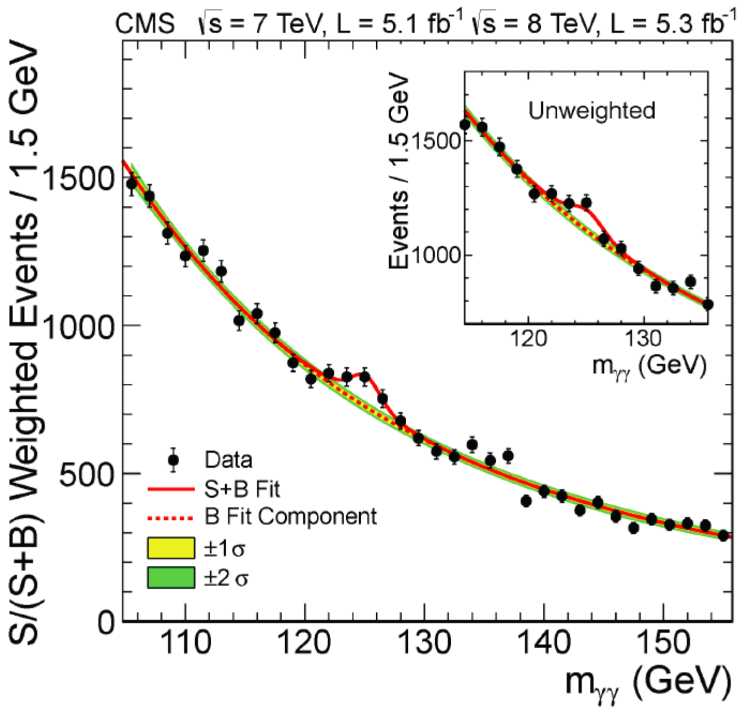
Higgs decaying into two photons



Higgs decaying into two photons

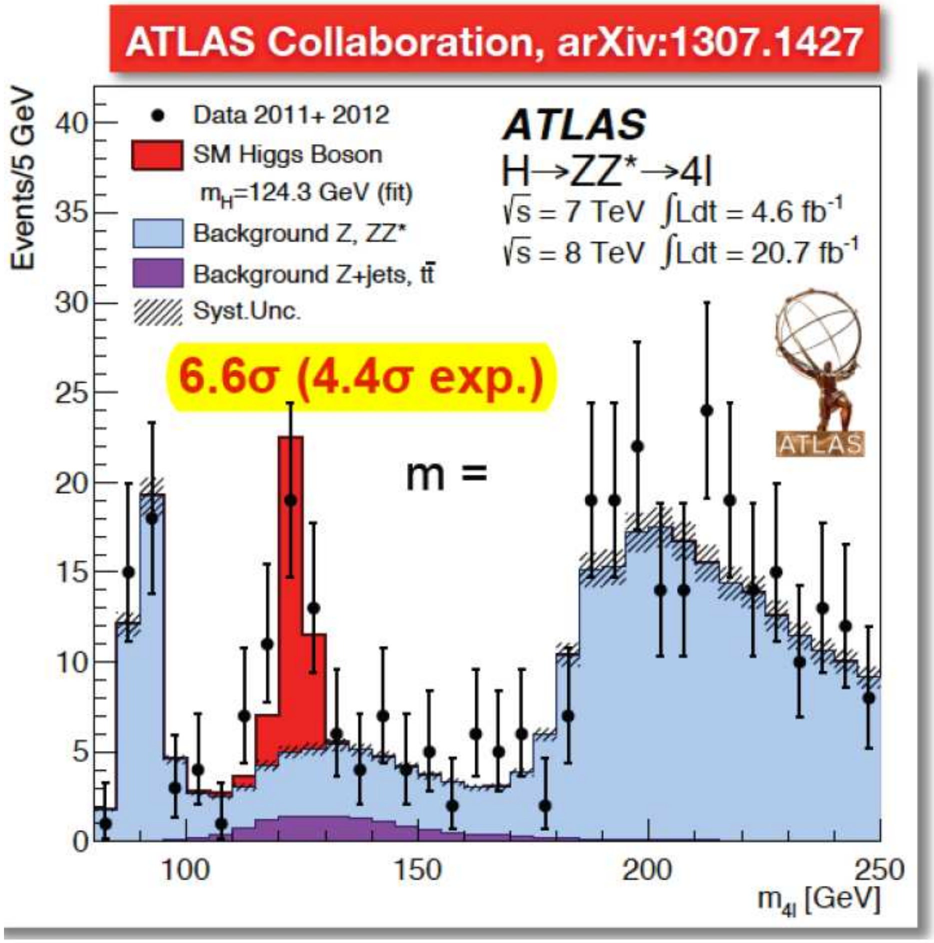
- Diphoton mass distributions
- Both CMS and ATLAS see a peak at about 126 GeV!

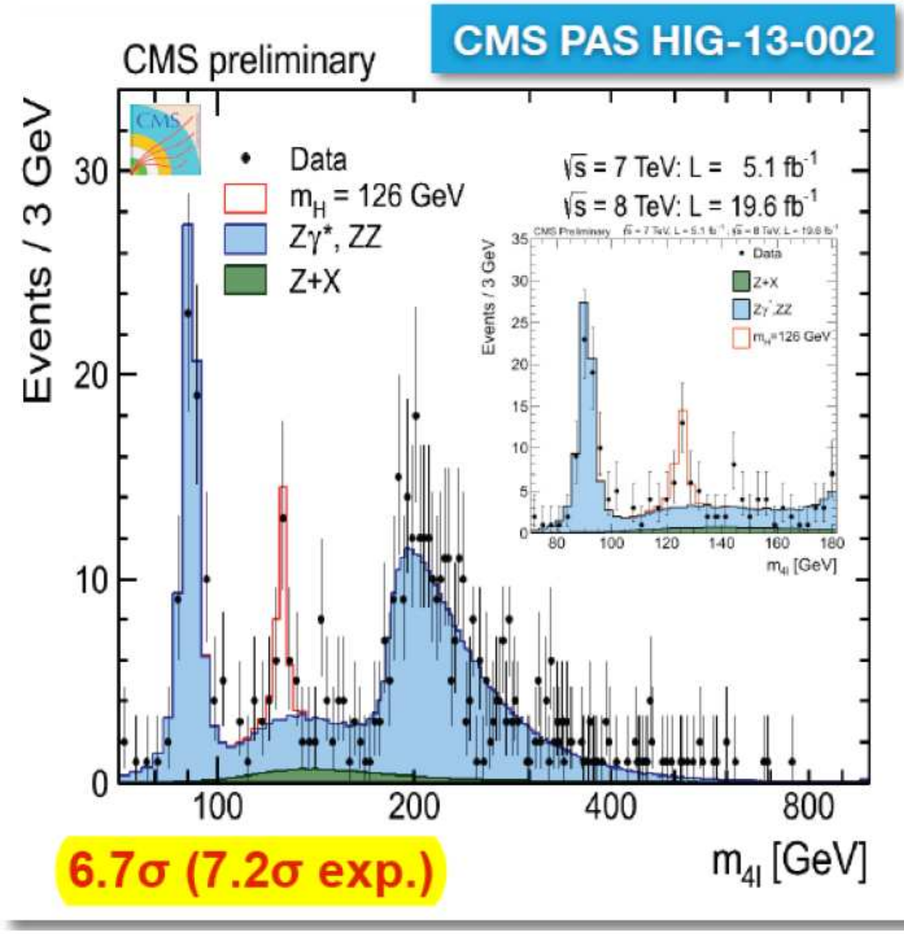




Higgs decaying into two Z bosons

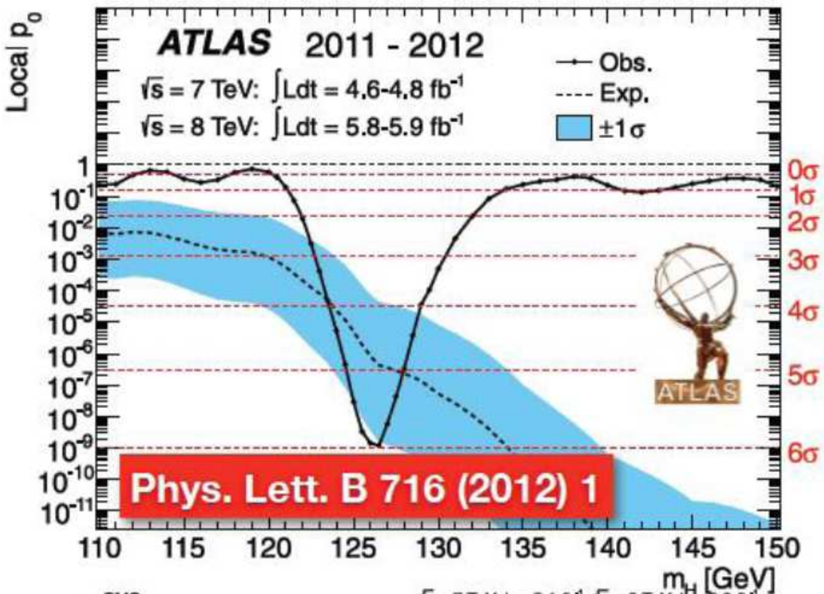
- Look in another channel: Higgs boson decaying into two Z bosons
- Many additional channels studied that show the same presence of the Higgs boson

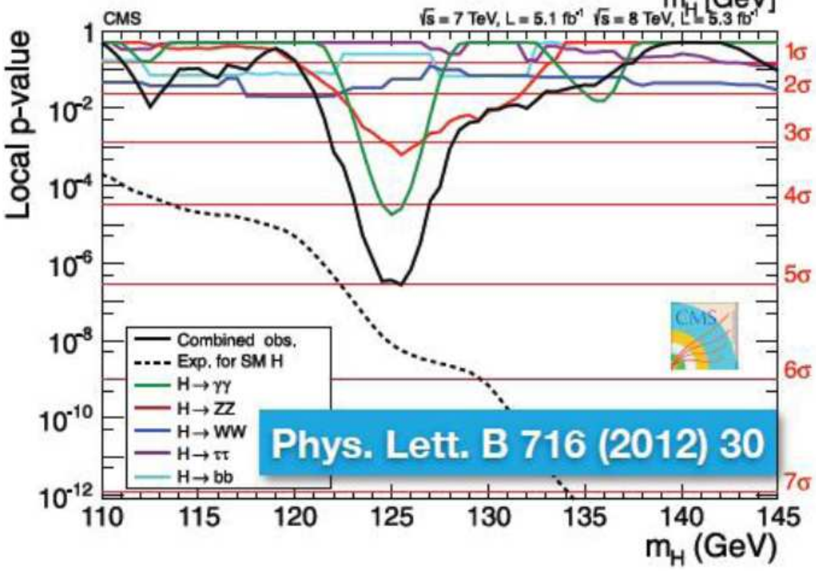


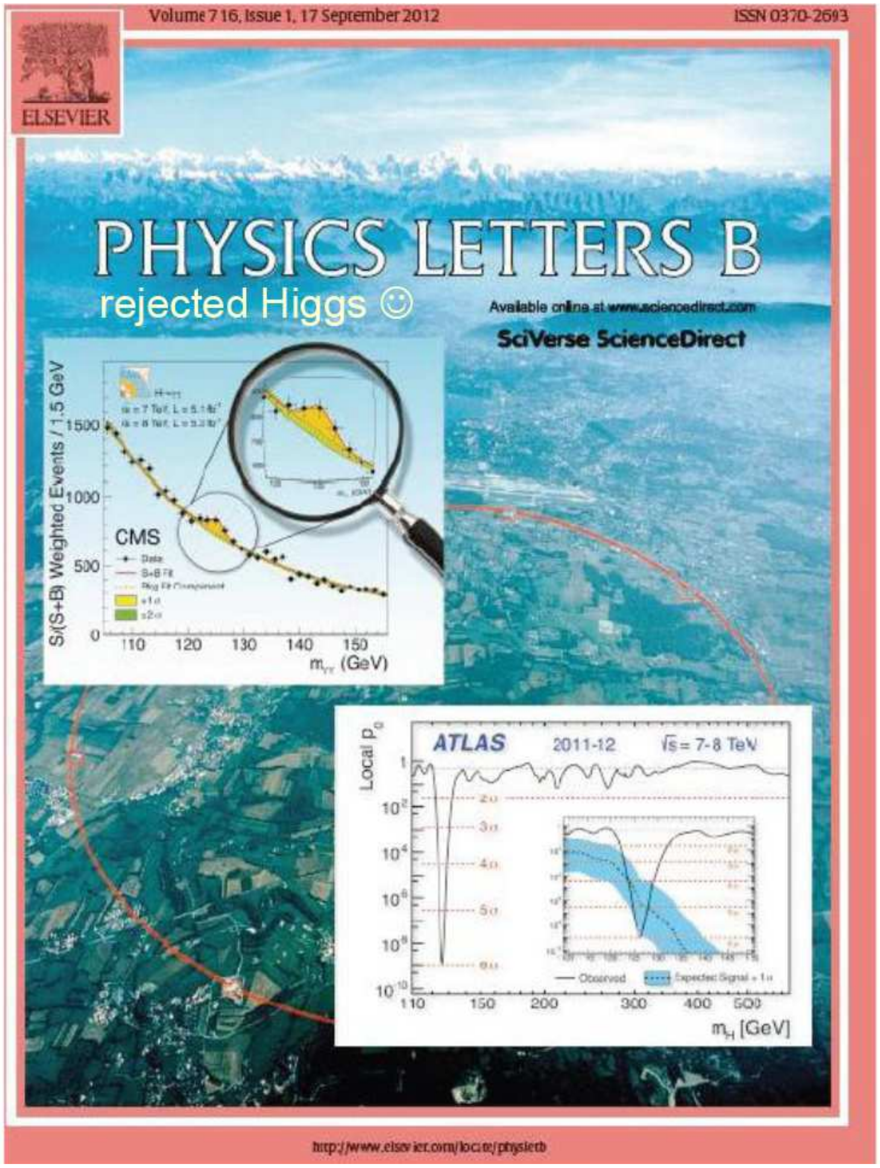


Higgs discovery paper

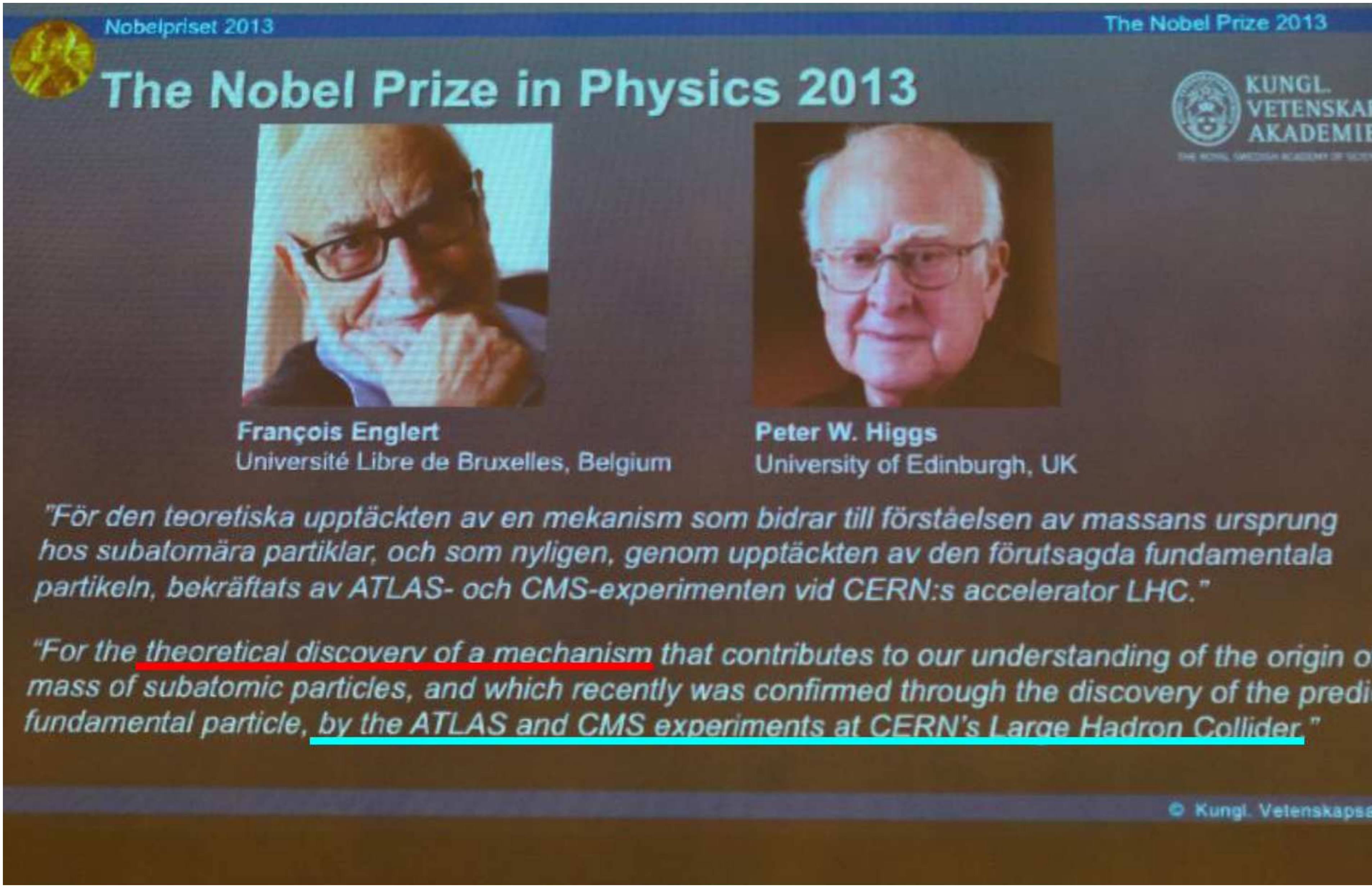
Leads to the Higgs discovery paper: already 2193 citations for atlas (2179 for CMS) in ∼1.5 year





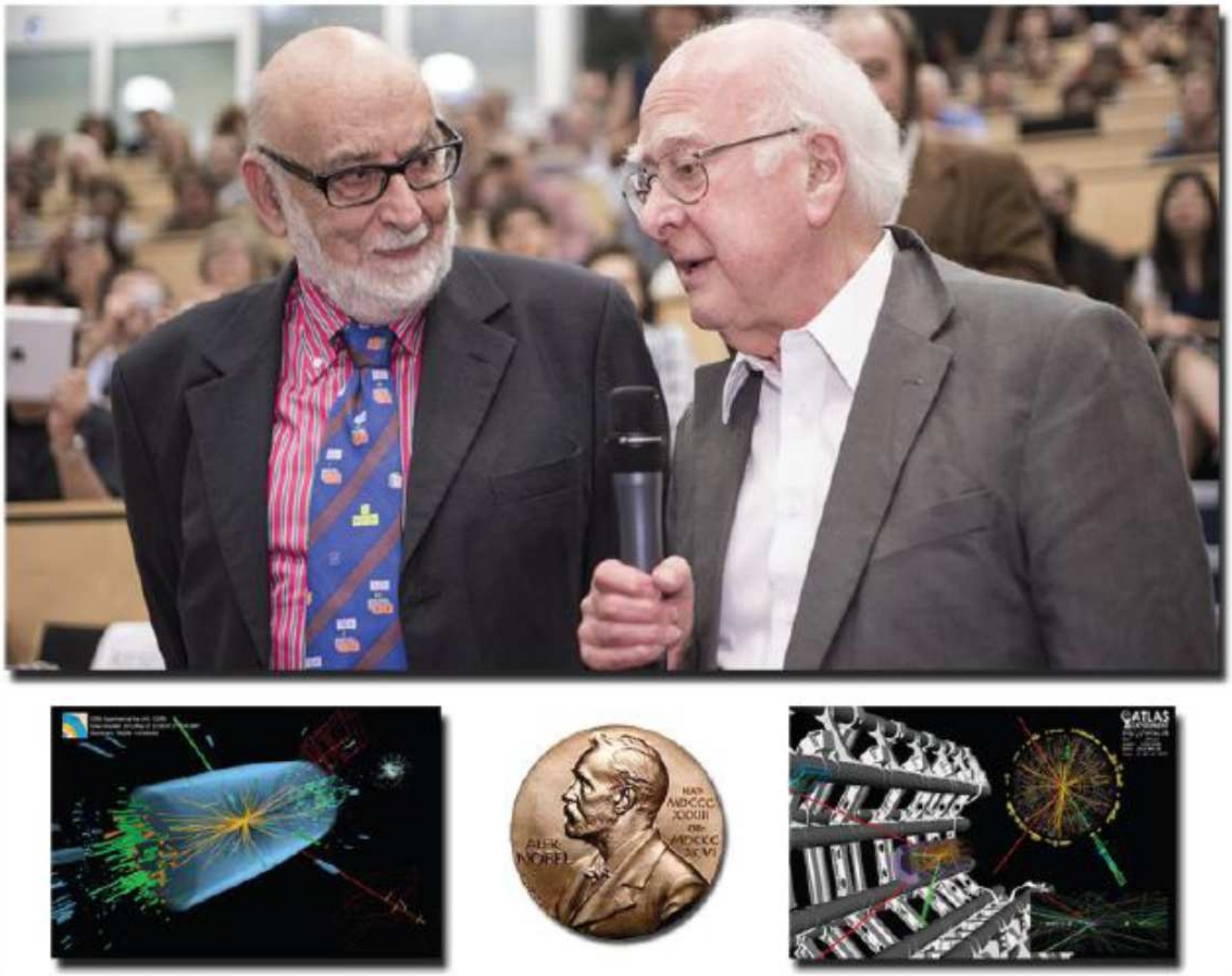


50 years of Higgs mechanism: Nobel Prize 2013



Higgs boson discovery

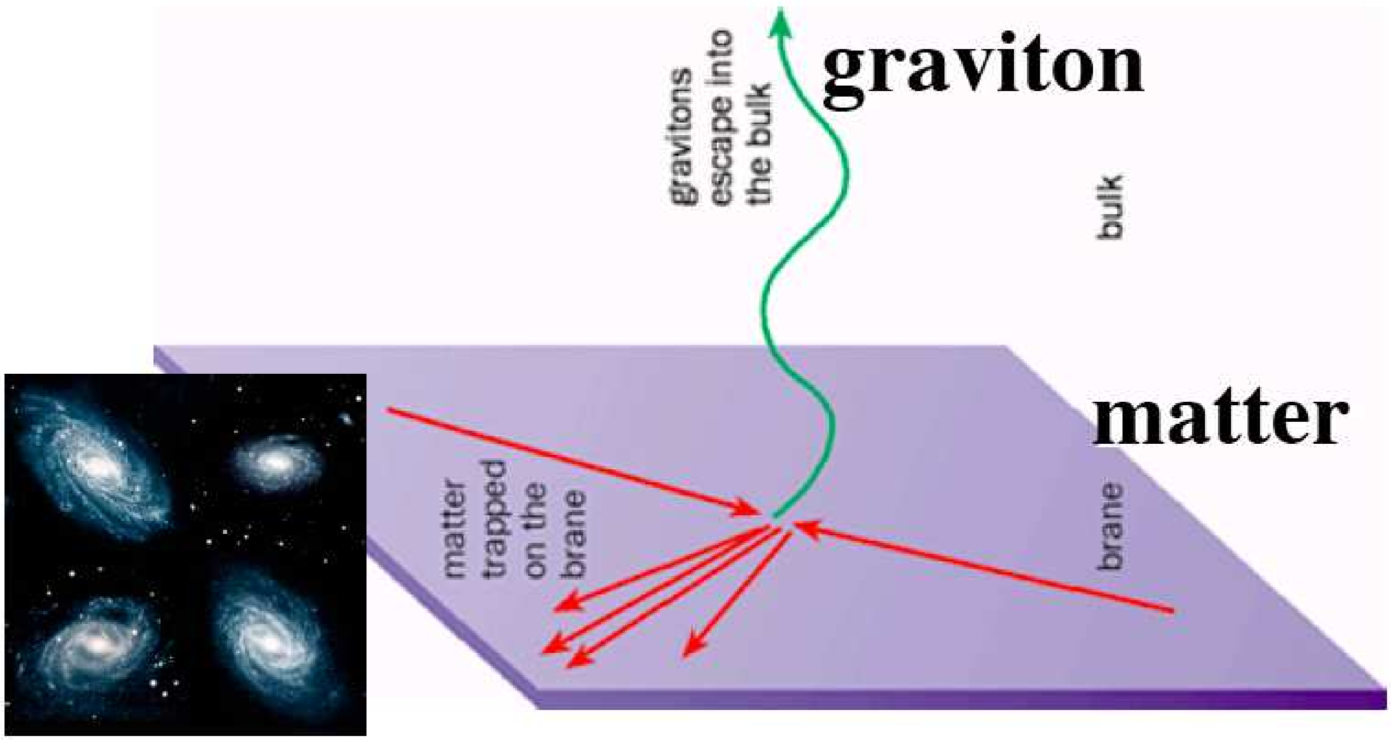
Meeting at CERN to celebrate the Nobel Prize



The ATLAS and CMS experiments at CERN congratulate Professors Francois Englert and Peter Higgs for their pioneering work in identifying the electroweak-symmetry-breaking mechanism. CMS and ATLAS independently announced the discovery of a new particle on 4 July 2012, later identified as a Higgs boson, confirming the predictions of Professors Higgs, Englert and others in seminal papers published in 1964. We join in this celebration of the triumph of human curiosity and ingenuity.

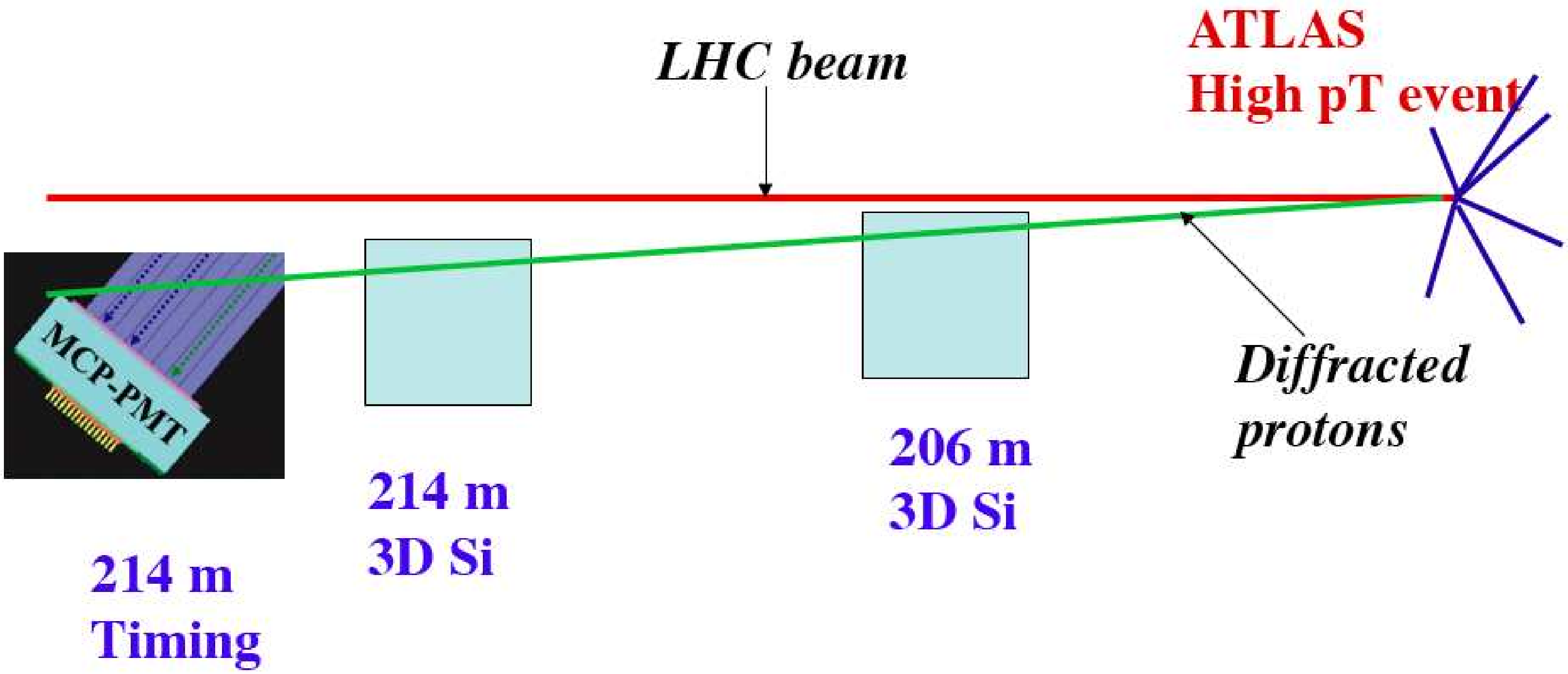
Special tribute to R. Brout who passed away in 2011

The future? Looking for extradimensions in the universe



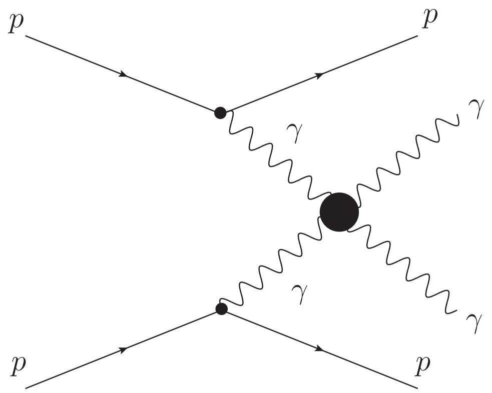
- We live in a 4 dimension space: time and space
- Gravity might live in extra-dimensions: exploration at the LHC for instance in looking for new couplings
- If discovered at the LHC, this might lead to major changes in the way we see the world

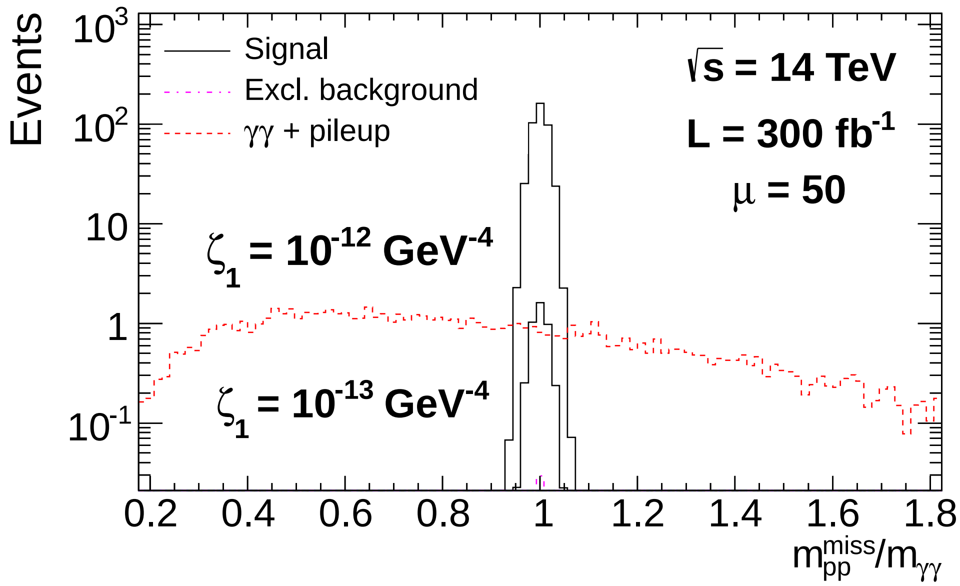
The future: tagging intact protons at high luminosity



- Very special events: the protons remain intact after interactions! (NB: analogy: accident between two big trucks, and not only the trucks remain intact but some cars are produced in addition in the final state!)
- Tagging intact protons allows to get one of the best methods to look for extra-dimensions in the universe

Looking for extradimensions

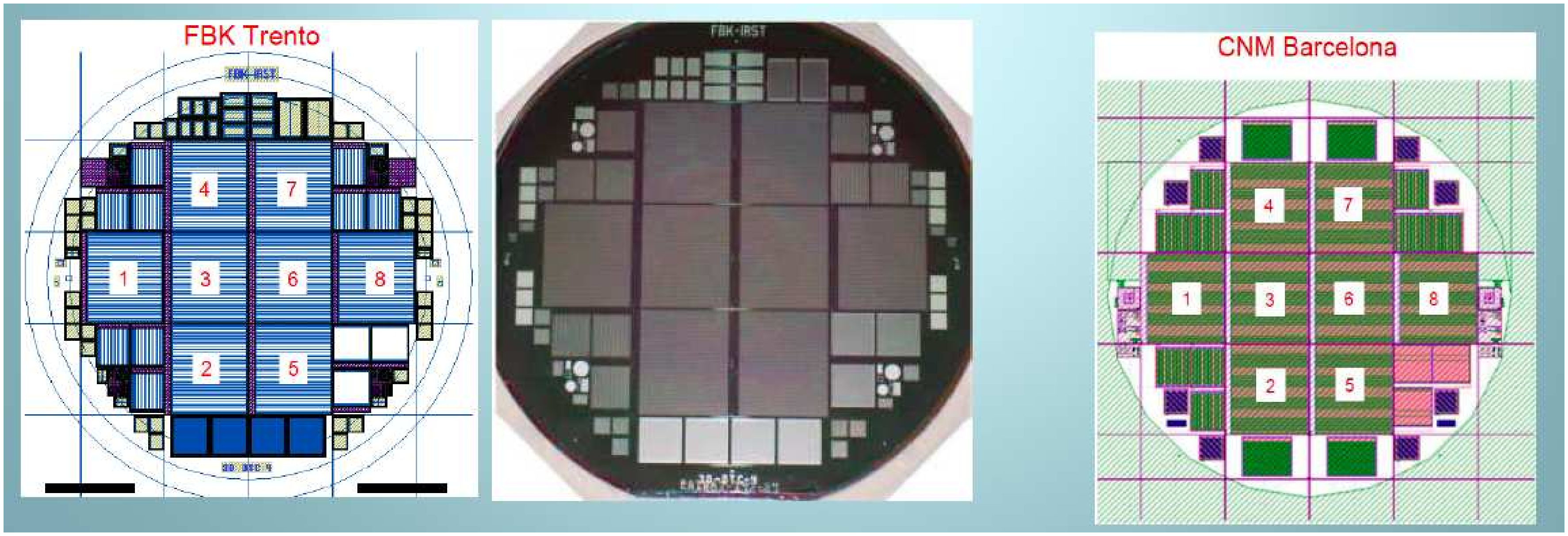


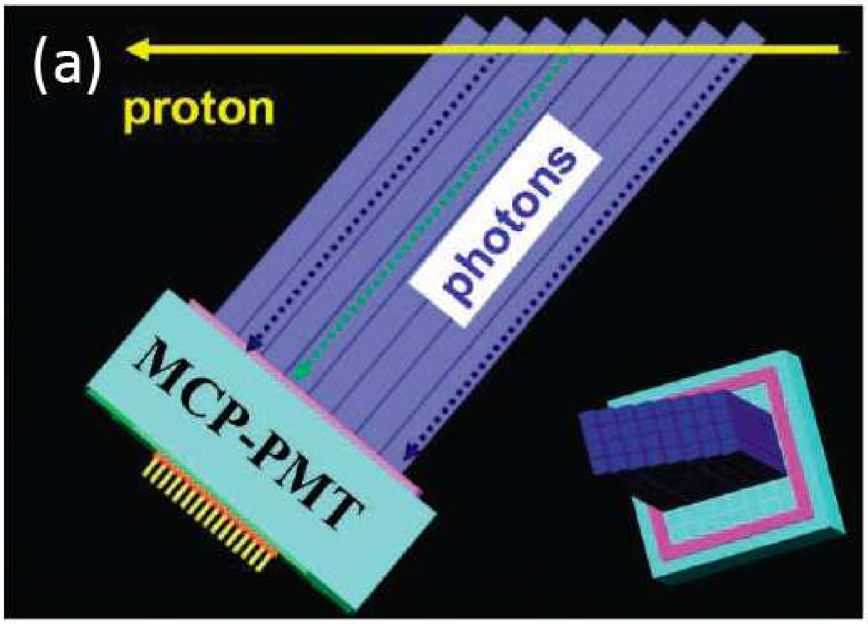


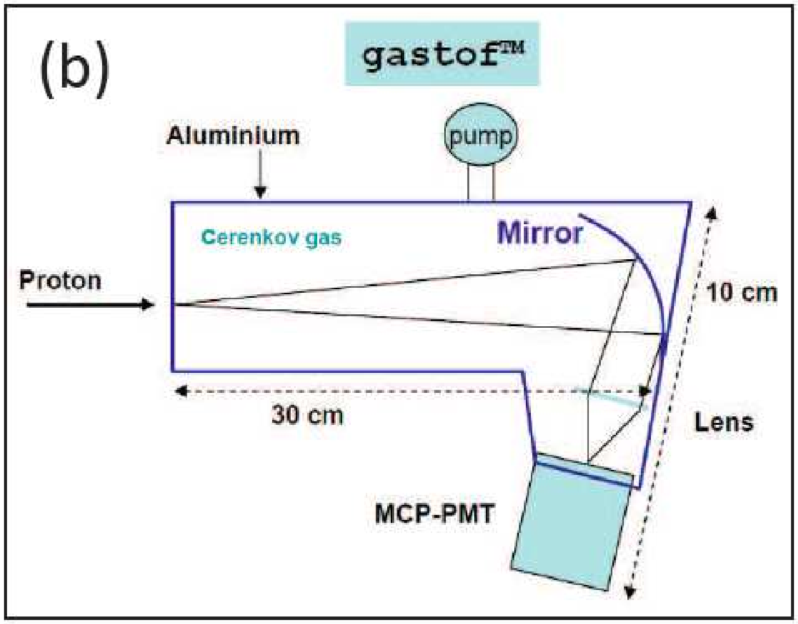
- Looking for instance for diphoton production with intact protons
- 4-photon coupling enhanced if extra-dimensions exist
- Background can be controlled by comparing the information from tagged protons and photons
- Might lead to important discoveries: stay tuned

Measuring the position and time-of-flight of protons

- Very precise measurement of the proton positions: 5-10 μm using Si technology
- Measurement of proton time-of-flight: $\sim$ 10 ps precision Many applications for instance in medicine: gain of about a factor 10 in resolution for PET imaging

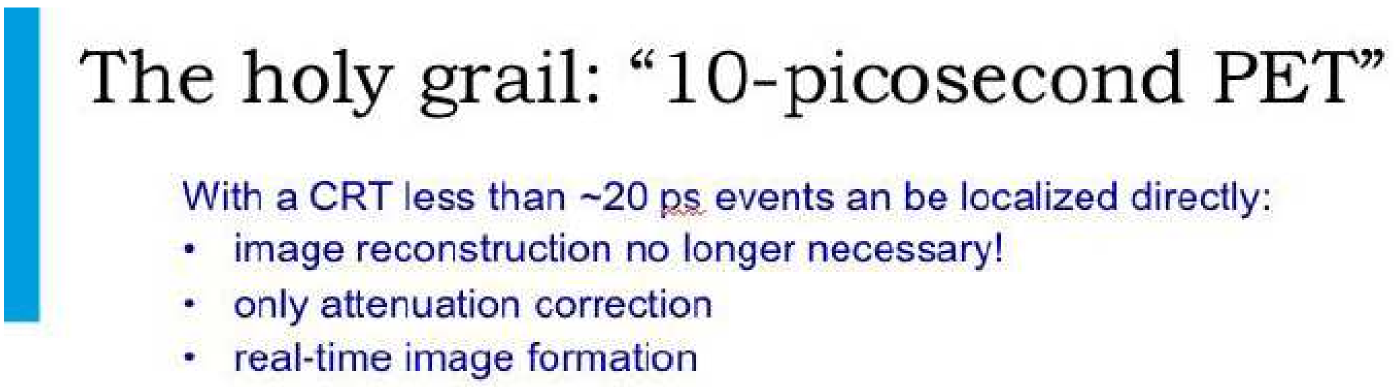






Conclusion

- “Rediscovering” the standard model of particle physics: detector well understood
- Nobel Prize 2013 in physics: Higgs boson discovery
- Exactly 40 years after the Higgs mechanism was invented by Brout, Englert and Higgs!
- Tagging protons in the final state: motivated for instance to probe extra-dimension in the universe; Position and timing detectors to be used
- Many devolopments performed/in progress for the project and extremly useful for the future in particle physics or medical applications: 3D Si, timing detectors
- Recall also that CERN was at the origin of WEB which everybody uses today
- Last but not least: Happy birthday for the physics institute, and best wishes for the ongoing collaboration between France and Brazil!




LHC is now in operation, stay tuned…
Thank you !