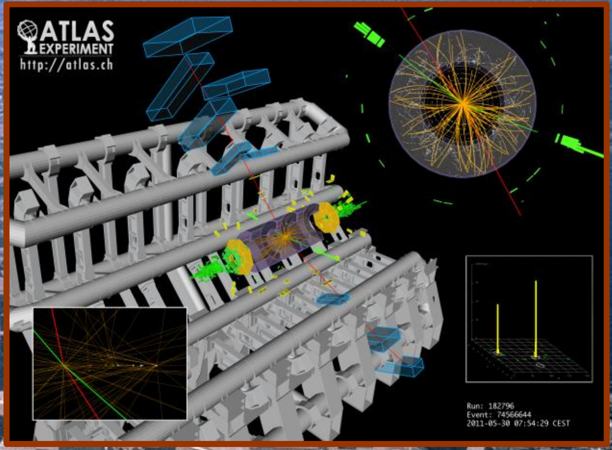
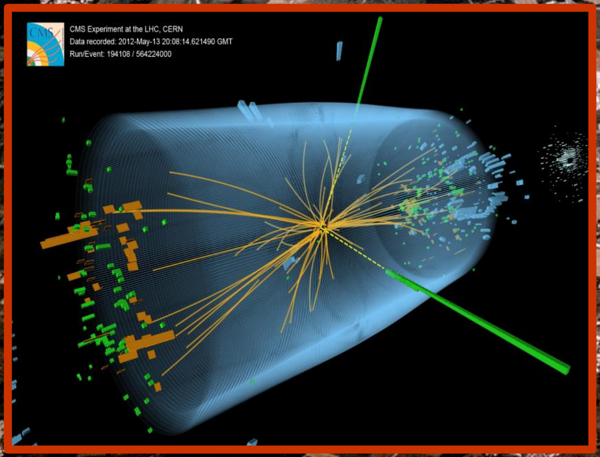


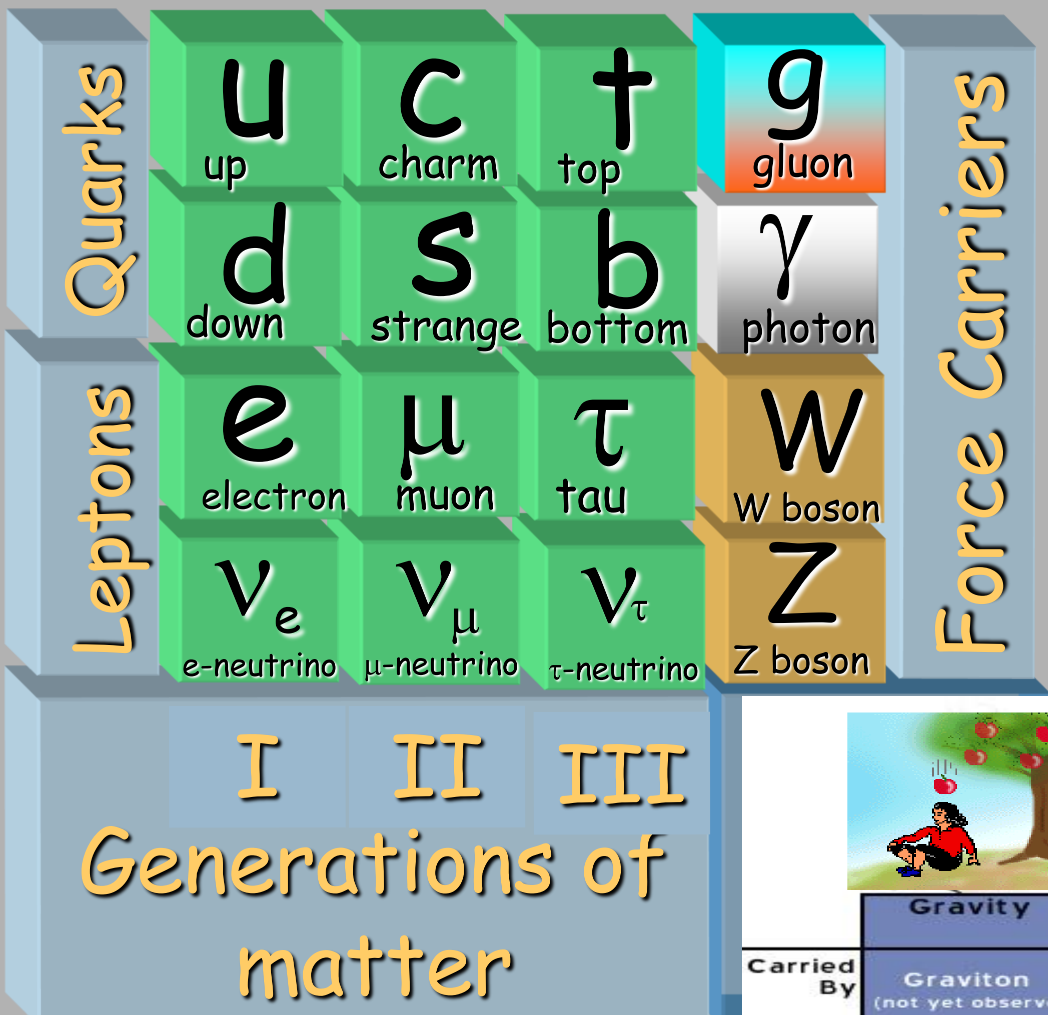
Status and prospects of high-energy physics

Fabiola Gianotti, CERN, Physics Department

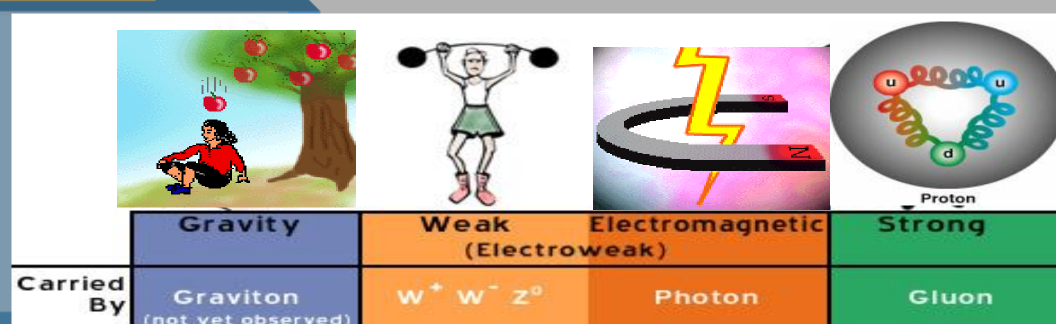


The world of elementary particles before the LHC (4 July 2012)

The elementary particles and their interactions are described by a very successful theory: the Standard Model. Before the LHC, all particles (but one) foreseen by the SM had been observed, and the SM predictions had been verified with extremely high precision by experiments at CERN and other labs all over the world (over 50 years)



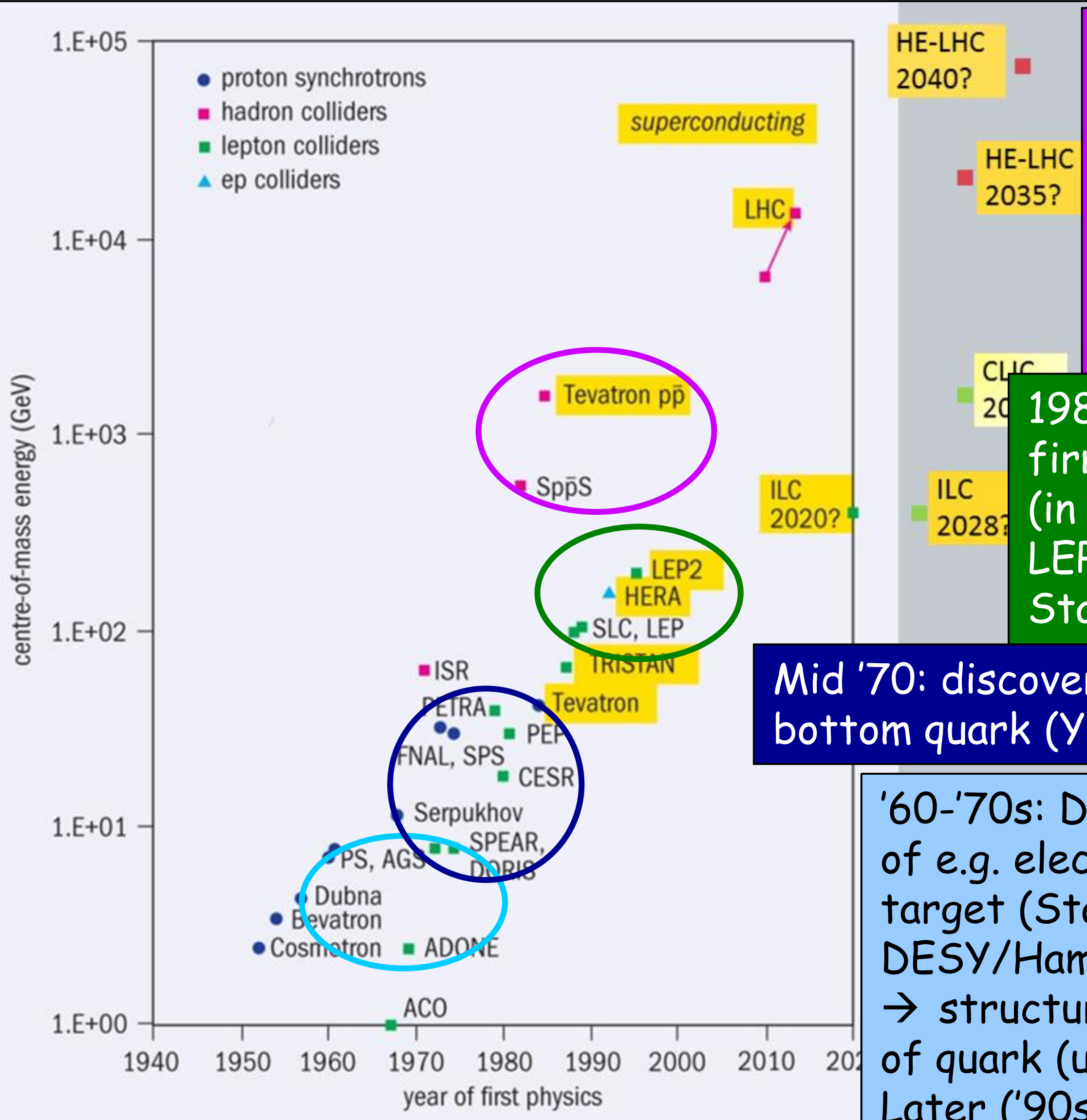
Particles and forces



The role of accelerators

'30s-'50s: particle physics based mainly cosmic ray observations → discovery of e^+, μ, ..

Accelerator-based particle physics starts in the '50s: here only very few examples



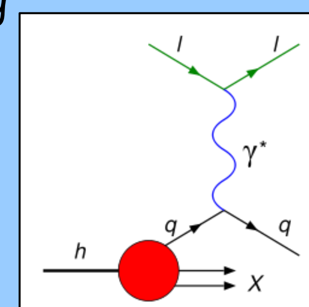
1983: Discovery of W, Z bosons (m ~ 100 GeV) at CERN p-antip collider ($\sqrt{s} \leq 630$ GeV)

1995: Discovery of the top quark (the heaviest elementary particle ever) at the Tevatron p-antip collider ($\sqrt{s} \leq 2$ TeV) at Fermilab/Chicago

1989-2000: Standard Model put on very firm grounds by precision measurements (in particular of Z boson) at e^+e^- colliders: LEP at CERN ($\sqrt{s}$ → 209 GeV) and Stanford Linear Collider ($\sqrt{s}$ ~ 90 GeV)

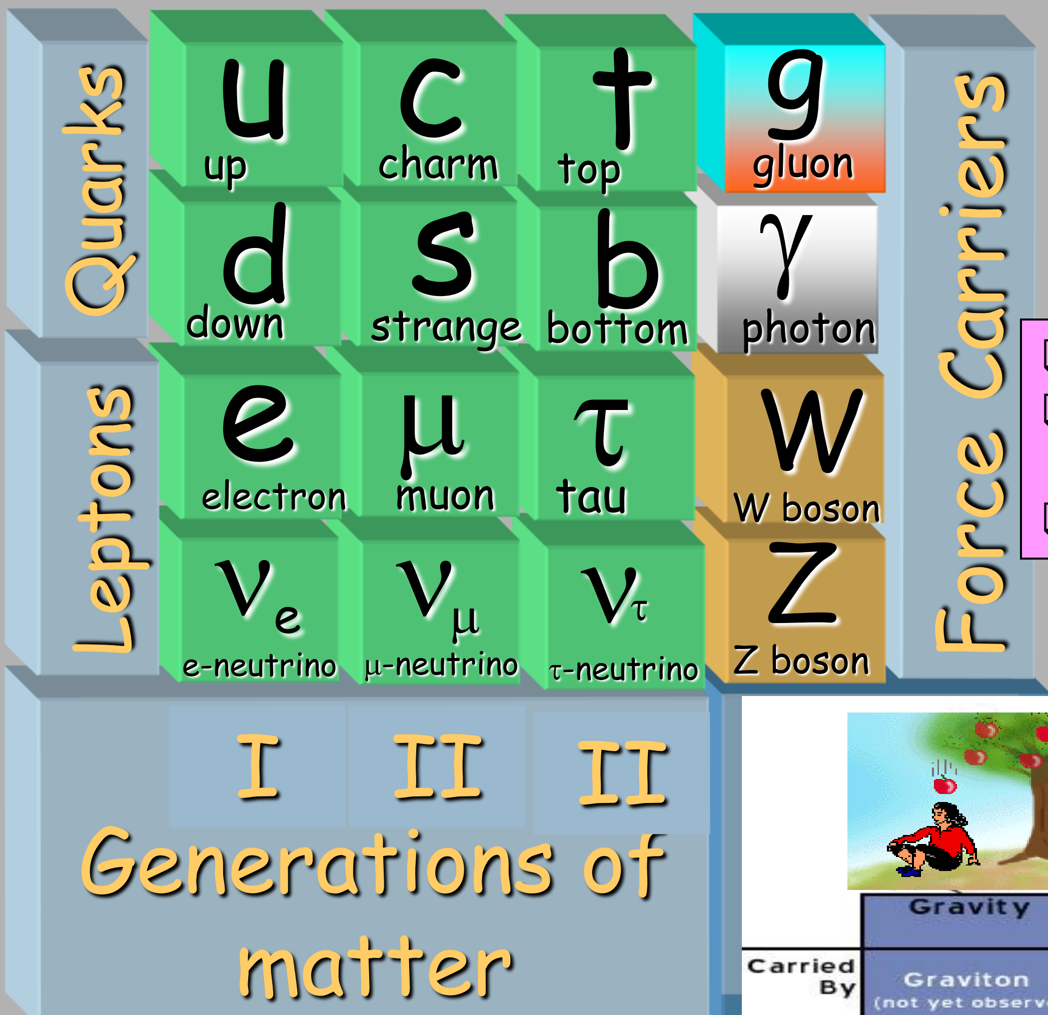
Mid '70: discovery of charm quark ($J/\psi = c\bar{c}$ BNL, SLAC), bottom quark ($\Upsilon = b\bar{b}$, FNAL), τ-lepton (SLAC)

'60-'70s: Deep inelastic scattering of e.g. electron beams on fixed target (Stanford, DESY/Hamburg, etc.):
→ structure of n and p in terms of quark (u, d) constituents
Later ('90s): HERA ep collider



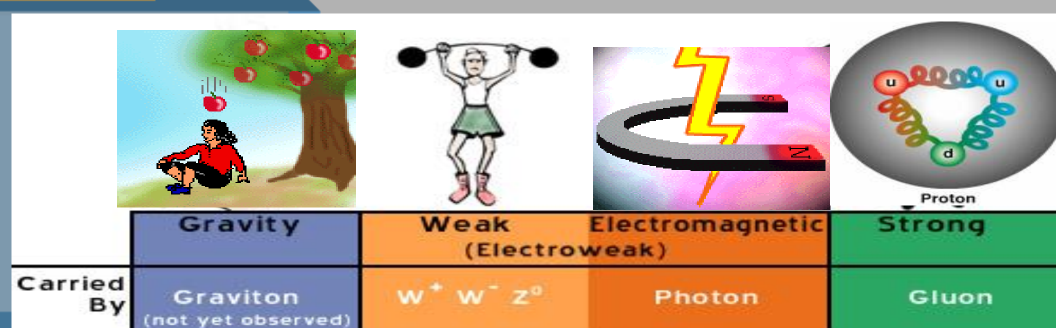
The world of elementary particles before the LHC (4 July 2012)

The elementary particles and their interactions are described by a very successful theory: the Standard Model. Before the LHC, all particles (but one) foreseen by the SM had been observed, and the SM predictions had been verified with extremely high precision by experiments at CERN and other labs all over the world (over 50 years)



Particles and forces

- Matter particles: why 3 generations ?
- Force carriers: why some massless and some massive ?
- Why is gravity so weak ?



The outstanding questions before the LHC

What is the origin of the particle masses ?
→ Related to the Higgs boson

What is the nature of the Universe dark matter ?

Note: New Physics beyond the Standard Model is needed in most cases. Experimental data and theoretical arguments indicate that this New Physics could manifest itself at the ~ TeV energy scale being explored by the LHC

permeating the Universe ~10 μs after the Big Bang ?

LHC built to address these and other fundamental questions

Why is gravity so weak ? Are there additional (microscopic) space dimensions ?

Etc. etc.

ATLAS, CMS

ATLAS, CMS

LHCb

ALICE

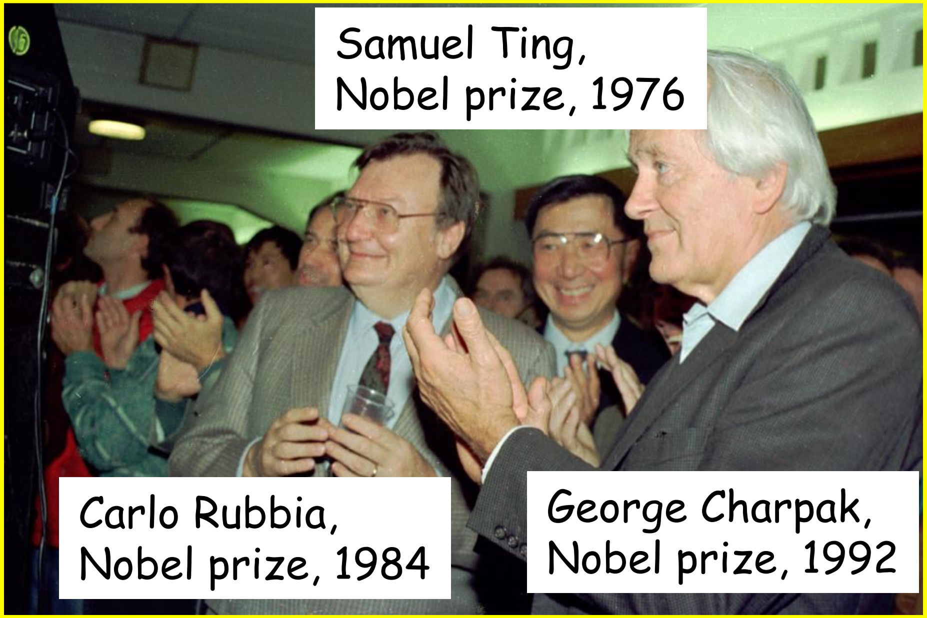
ATLAS, CMS

CERN : European Organization for Nuclear Research
The world's largest particle physics laboratory

More than 50 years of:

- fundamental research and discoveries (and Nobel prizes …)
- technological innovation and technology transfer to society
  (e.g. the World Wide Web: 20^{th} anniversary on 30 April)
- training and education (young scientists, school students and teachers)
- bringing the world together (10000 scientists from > 60 countries)

CERN staff member T. Berners-Lee, inventor of the WEB, with Kofi Annan and CERN DG Luciano Maiani



Samuel Ting, Nobel prize, 1976

Carlo Rubbia, Nobel prize, 1984

George Charpak, Nobel prize, 1992

CERN was founded 1954: 12 European States
Today: 20 Member States

Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

Observers: India, Japan, the Russian Federation, United States of America, Turkey, the European Commission and UNESCO

Associate, in the pre-stage to membership: Israel

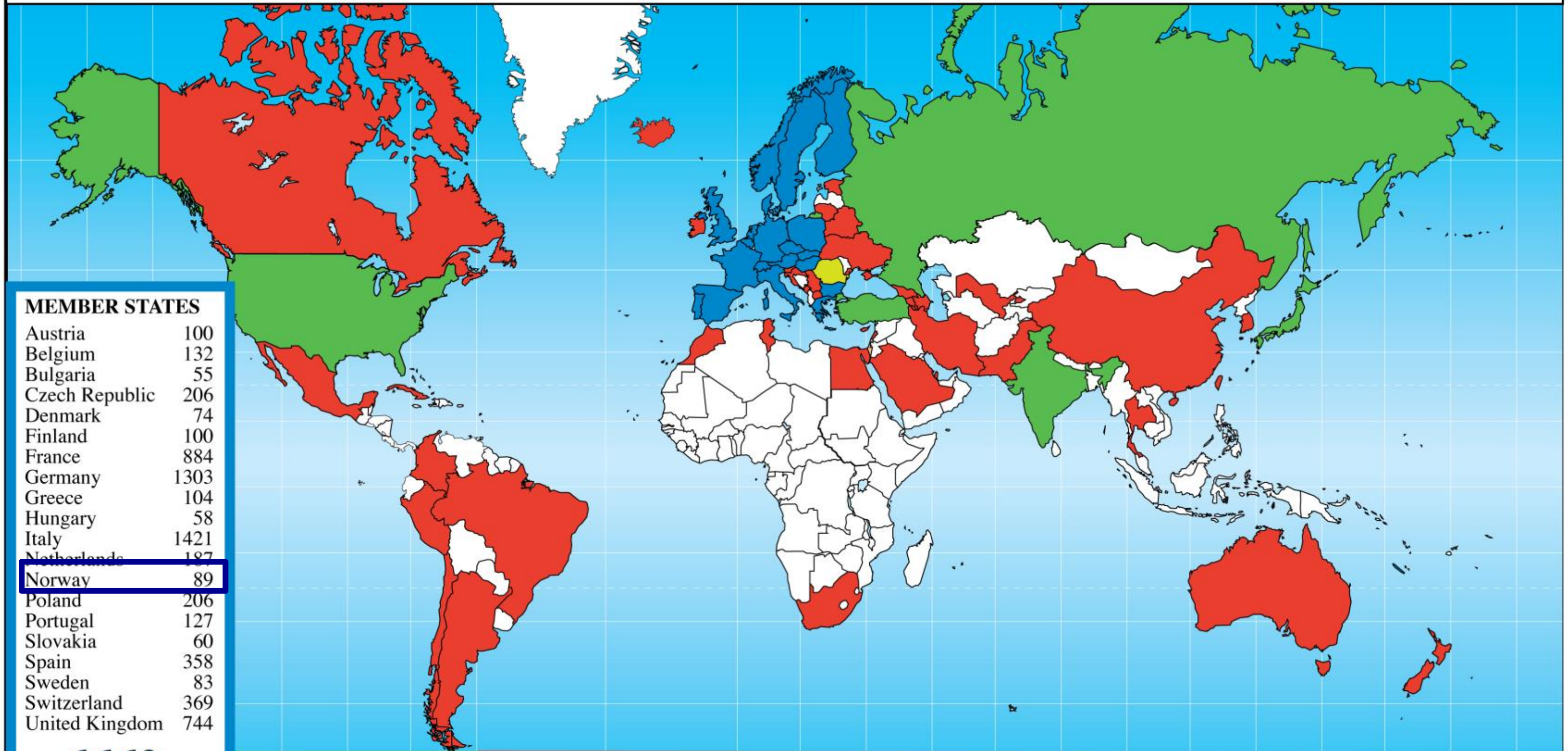
~ 2300 staff

> 10000 users

Budget (2012) ~1000 MCHF (→ about 1 cappuccino/citizen): each Member State contributes in proportion to its income: **Norway: ~ 2.5% (~ 25 MCHF)**

More than 10000 users from > 60 countries

Distribution of All CERN Users by Nation of Institute on 9 January 2012



MEMBER STATES

Austria	100
Belgium	132
Bulgaria	55
Czech Republic	206
Denmark	74
Finland	100
France	884
Germany	1303
Greece	104
Hungary	58
Italy	1421
Netherlands	187
Norway	89
Poland	206
Portugal	127
Slovakia	60
Spain	358
Sweden	83
Switzerland	369
United Kingdom	744

6660

CANDIDATE FOR ACCESSION

Romania	75

ASSOCIATE MEMBER IN THE PRE-STAGE TO MEMBERSHIP

Israel	62

OBSERVERS

India	115
Japan	225
Russia	856
Turkey	77
USA	1708

2981

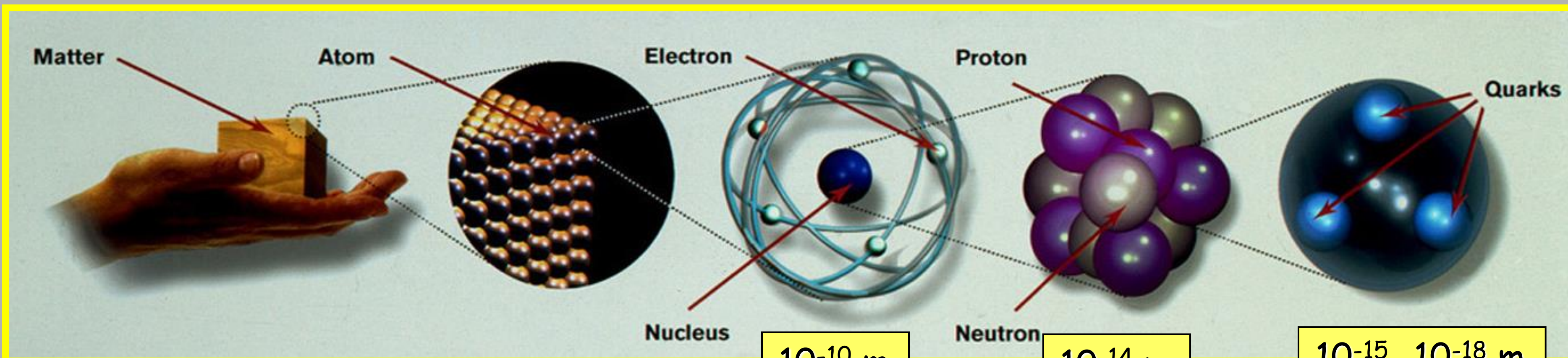
OTHERS

Argentina	18
Armenia	12
Australia	24
Azerbaijan	1
Belarus	22
Brazil	93
Canada	167
Chile	4
China	95
China (Taipei)	67
Colombia	10
Croatia	17
Cuba	4
Cyprus	9
Egypt	7
Estonia	18
Georgia	10
Iceland	3
Iran	14
Ireland	10
Korea	89
Lebanon	1
Lithuania	12
Malta	1
Mexico	43
Montenegro	1
Morocco	5
New Zealand	11
Pakistan	19
Peru	2
Qatar	1
Saudi Arabia	3
Serbia	26
Slovenia	37
South Africa	21
Thailand	5
T.F.Y.R.O.M.	2
Tunisia	1
Ukraine	21
Uzbekistan	1

907

CERN's primary mission is SCIENCE

Study the elementary particles (e.g. the building blocks of matter: electrons and quarks) and the forces that control their behaviour at the most fundamental level



10^{-10} m

10^{-14} m

10^{-15} -10^{-18} m

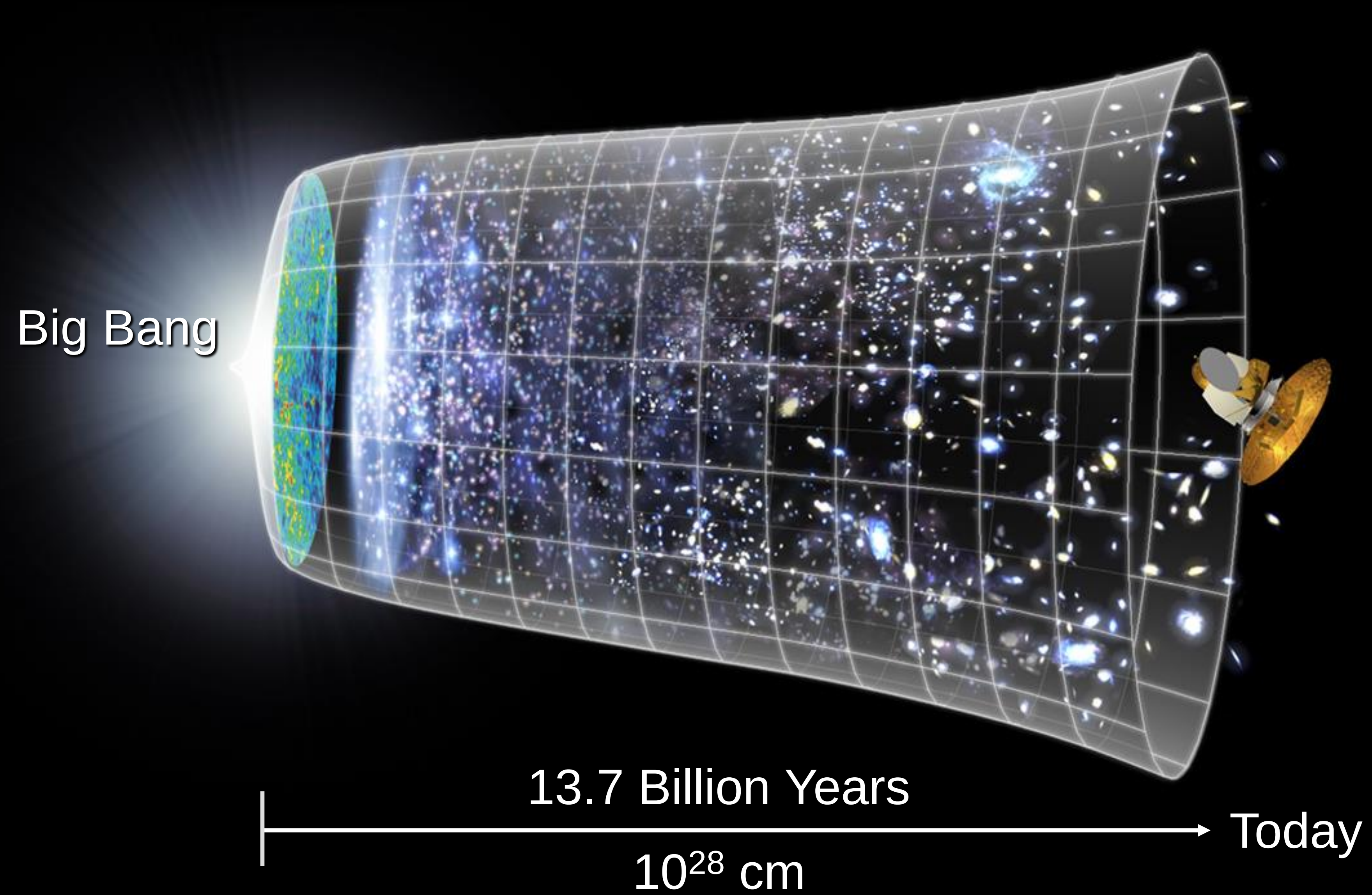
Particle physics at modern accelerators allows us to study the fundamental laws of nature on scales down to 10^{-18} m

→ insight also into the structure and evolution of the Universe

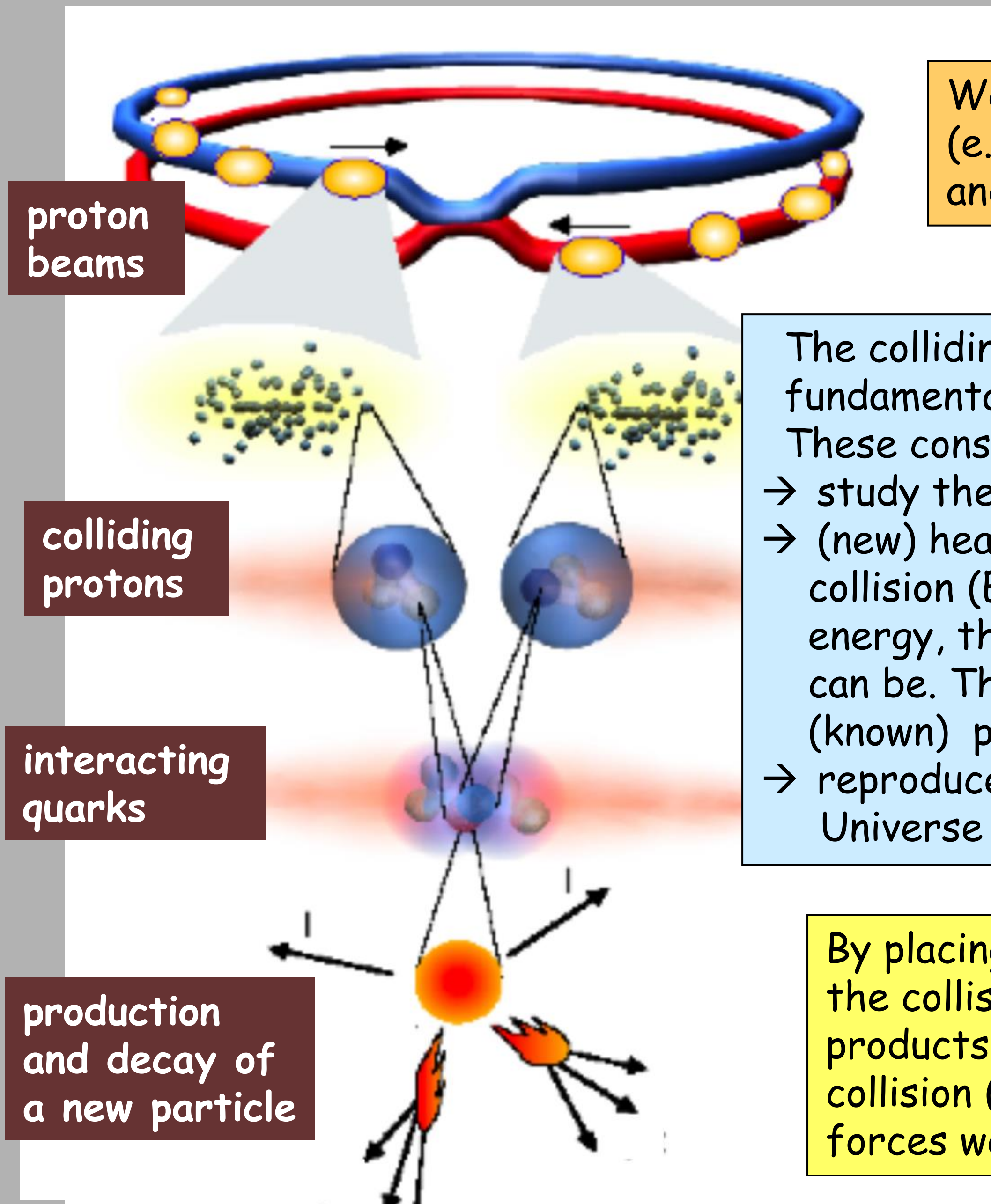
→ from the very small to the very big …

F. Gianotti, CAS, Trondheim, 28/8/2013

Evolution of the Universe



To study the elementary particles and their interactions:



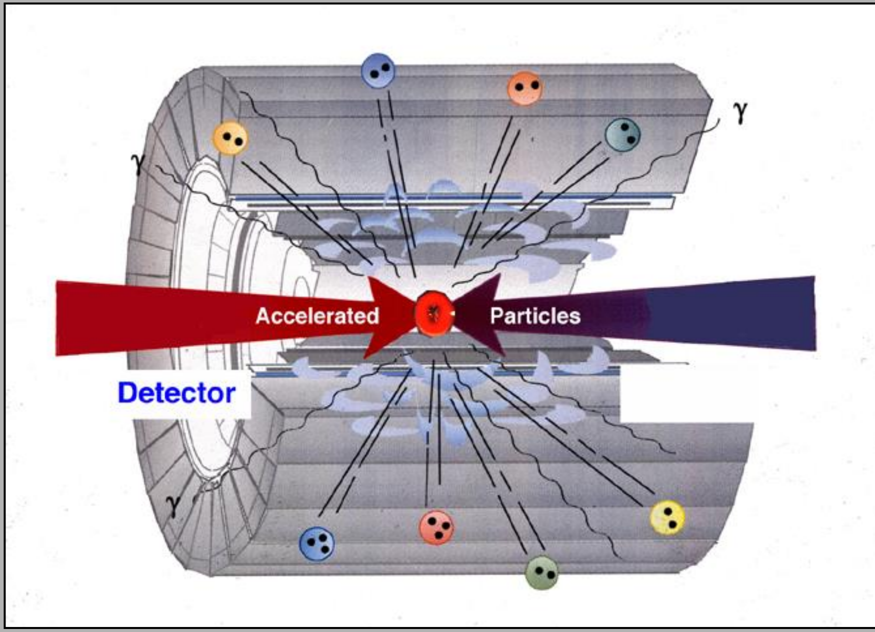
We accelerate two beams of particles (e.g. protons) close to the speed of light and make them collide

The colliding protons break into their fundamental constituents (e.g. quarks)
These constituents interact at high energy:
→ study the way fundamental matter behave
→ (new) heavy particles can be produced in the collision ($E=mc^2$). The higher the accelerator energy, the heavier the produced particles can be. These particles then decay into lighter (known) particles: electrons, photons, etc
→ reproduce the temperature (~10^{16} K) of the Universe a few instants (10^{-11} s) after the Big Bang

By placing high-tech powerful detectors around the collision point we can detect the collision products and reconstruct what happened in the collision (which phenomena, which particles and forces were involved, etc.)

Therefore, we need three things:

Accelerators: underground tunnels (usually rings) containing electric fields to accelerate particles to very high energy (incrementally at each turn), and magnets to bend the beams inside the ring and bring them into collision
Powerful giant microscopes to explore the smallest constituents of matter !



Detectors: massive instruments which register the collision products and allow to identify the produced particles and measure their energy and trajectory.

Computing: to store, distribute and analyse the vast amount of data produced by the detectors and thus reconstruct the "event" occurred in the collision.

The Large Hadron Collider (LHC) at CERN

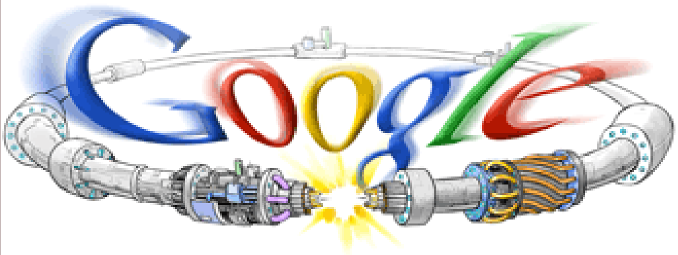
the most powerful accelerator

.... and also ....

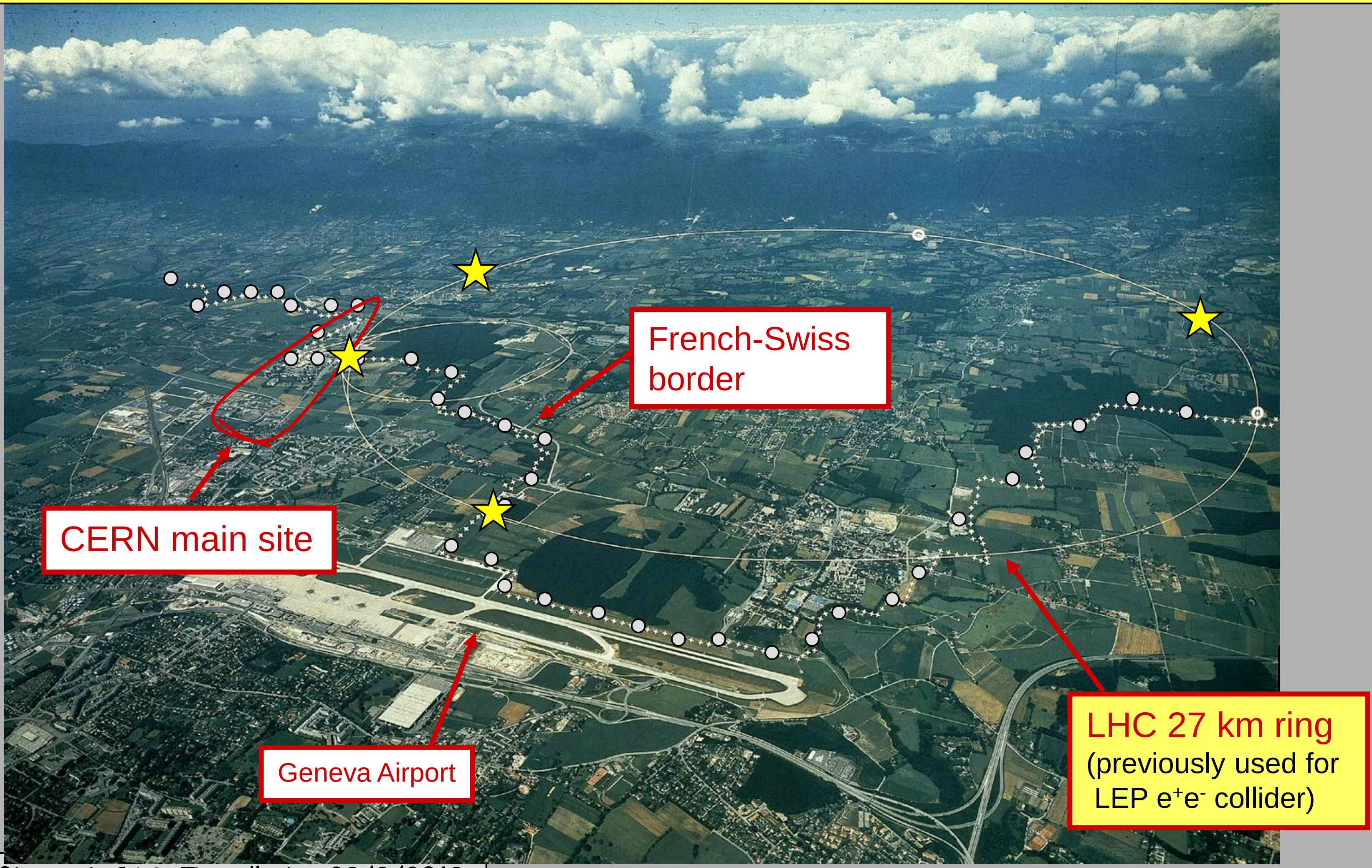
the most high-tech and complex detectors
the most advanced computing infrastructure
the most innovative concepts and technologies
(cryogenics, new materials, electronics, data transfer and storage, etc. etc…)
the widest international collaborations

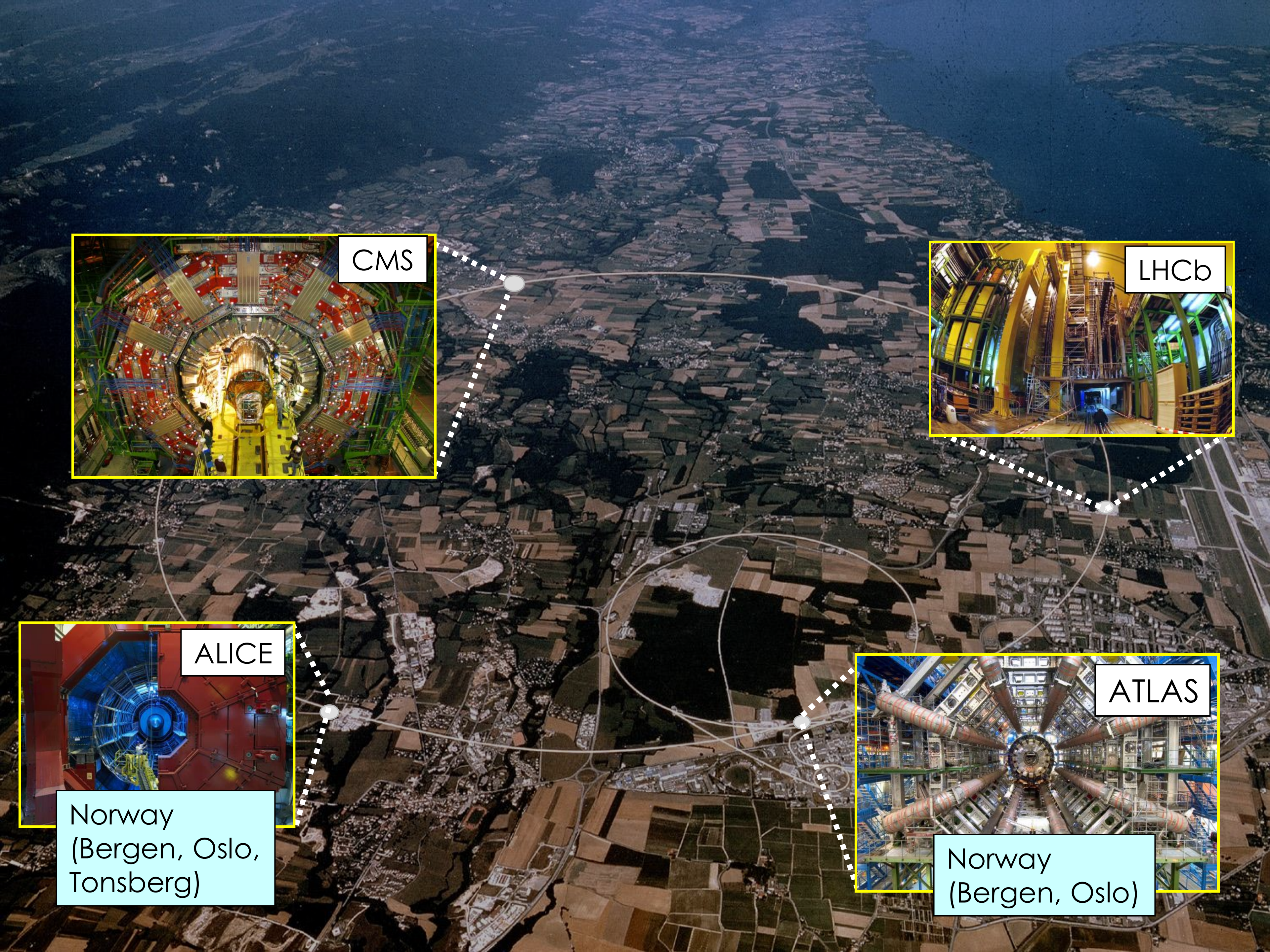
ever achieved in accelerator-based particle physics.
One of the most ambitious projects in science in general.

Operation started 20 November 2009
(> 20 years from concept to start of operation)
→ End of first data-taking period: February 2013



The LHC is a 27 km ring, 100 m below ground, across France/Switzerland
Over the last three years, two high-energy proton beams have been circulating in opposite directions and colliding at 4 points, where 4 big experiments had been installed.
Unprecedented collision energy: 8 TeV (4 times larger than the Tevatron collider, Fermilab)



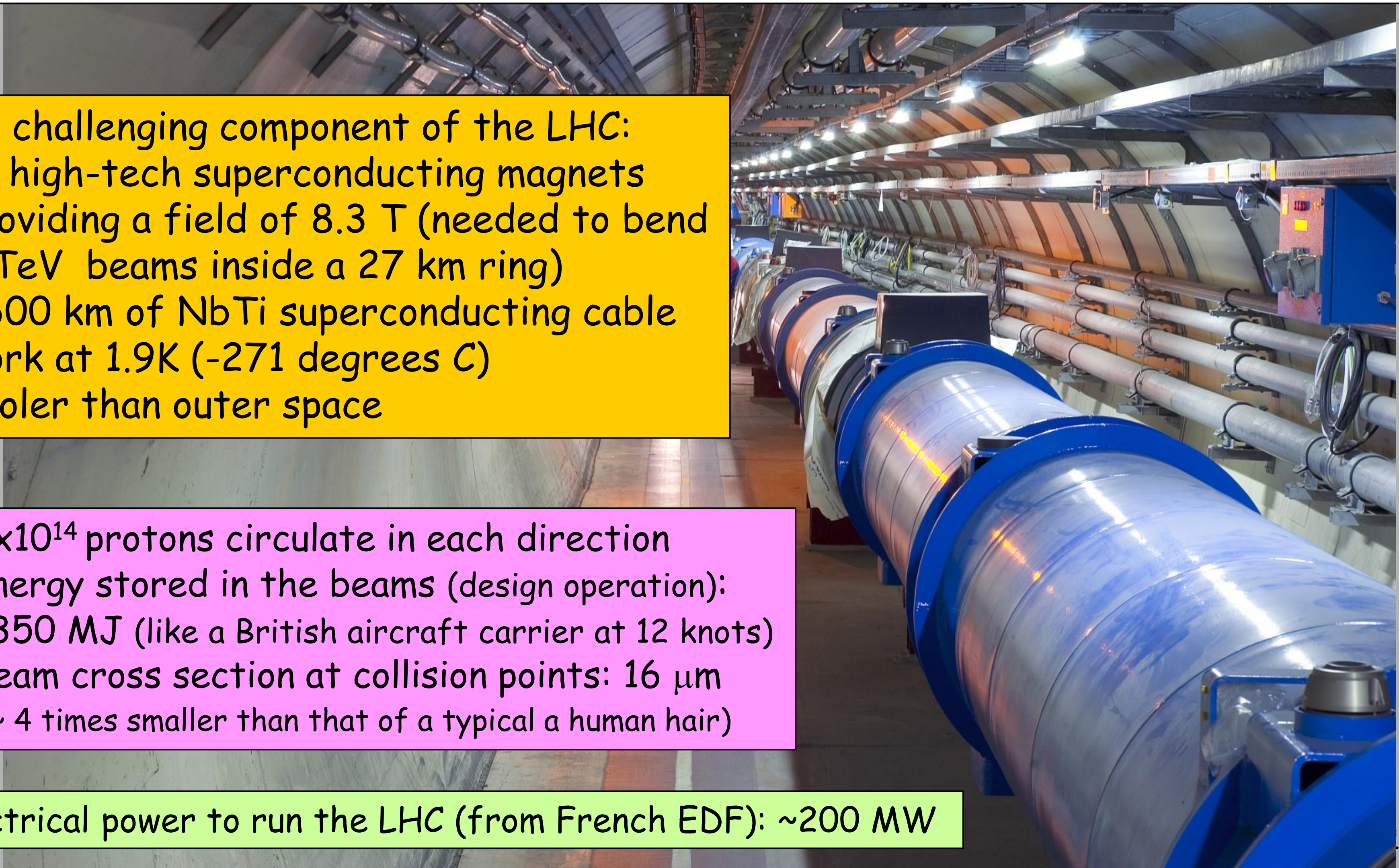

CMS
LHCb
ALICE
Norway (Bergen, Oslo, Tonsberg)
ATLAS
Norway (Bergen, Oslo)

Unprecedented energy: 4 TeV per beam particle → collision energy = 8 TeV

(1 TeV= 10^{-7} Joule)

2015 → collision energy to ~ 14 TeV

Note: huge amount of energy concentrated in the collision point
(14 TeV corresponds to 10^{14} times the temperature in this room)
However: small energy on macroscopic scale (1 μJoule is just enough to swat a mosquito)



Most challenging component of the LHC:
1232 high-tech superconducting magnets

- ❑ providing a field of 8.3 T (needed to bend 7 TeV beams inside a 27 km ring)
- ❑ 7600 km of NbTi superconducting cable
- ❑ work at 1.9K (-271 degrees C)

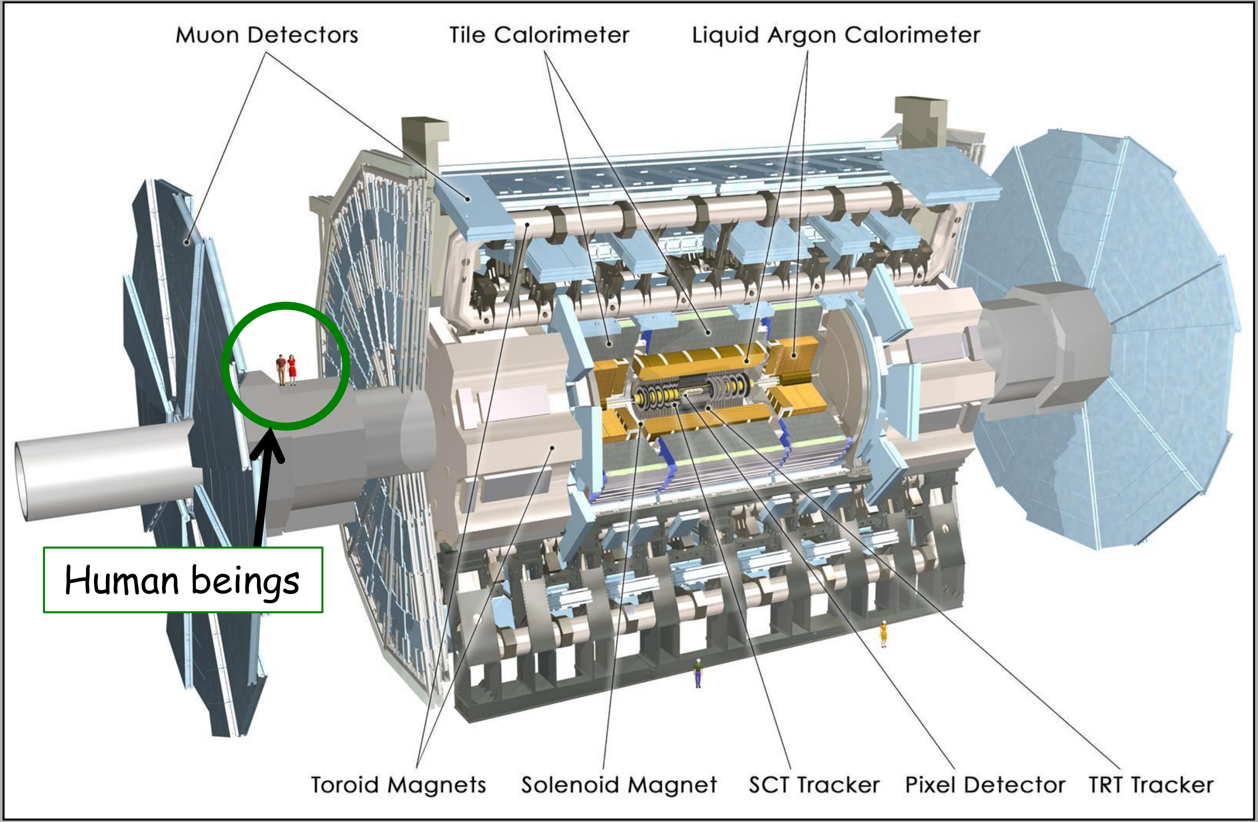
→ cooler than outer space

- ❑ 2×10^{14} protons circulate in each direction
- ❑ energy stored in the beams (design operation): ~350 MJ (like a British aircraft carrier at 12 knots)
- ❑ Beam cross section at collision points: 16 μm (~ 4 times smaller than that of a typical a human hair)

Electrical power to run the LHC (from French EDF): ~200 MW

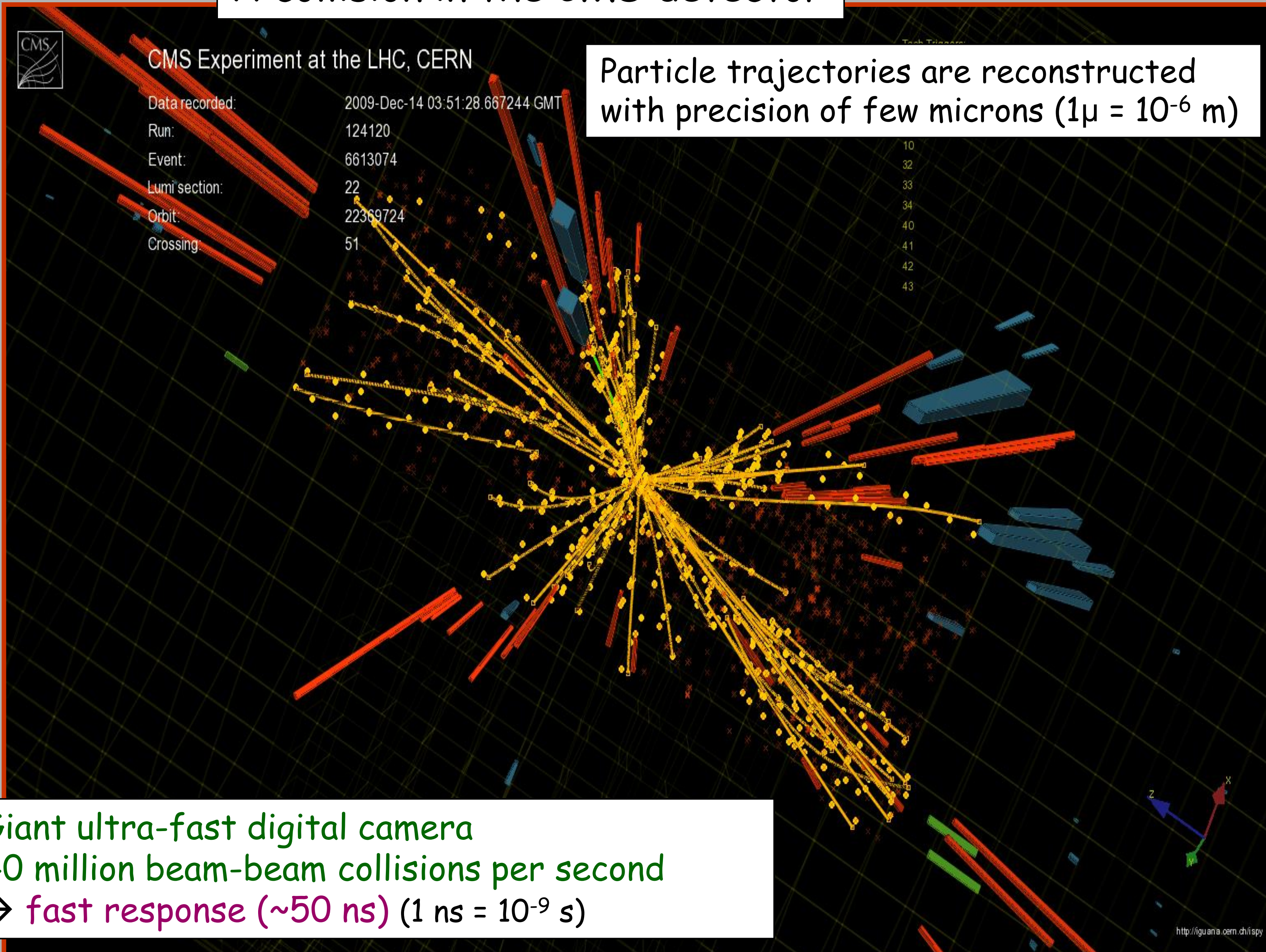
ATLAS

LHC detectors are much more complex, performing and challenging than those at previous/present accelerators
→ a big jump in concepts and technologies



- Size (length 45m, diameter 25m): to measure and absorb high-energy particles
- 10^8 sensors ("individual signals"): to track ~1000 particles per event and reconstruct their trajectories with ~10 μm precision (1 μm=10^{-6} m)

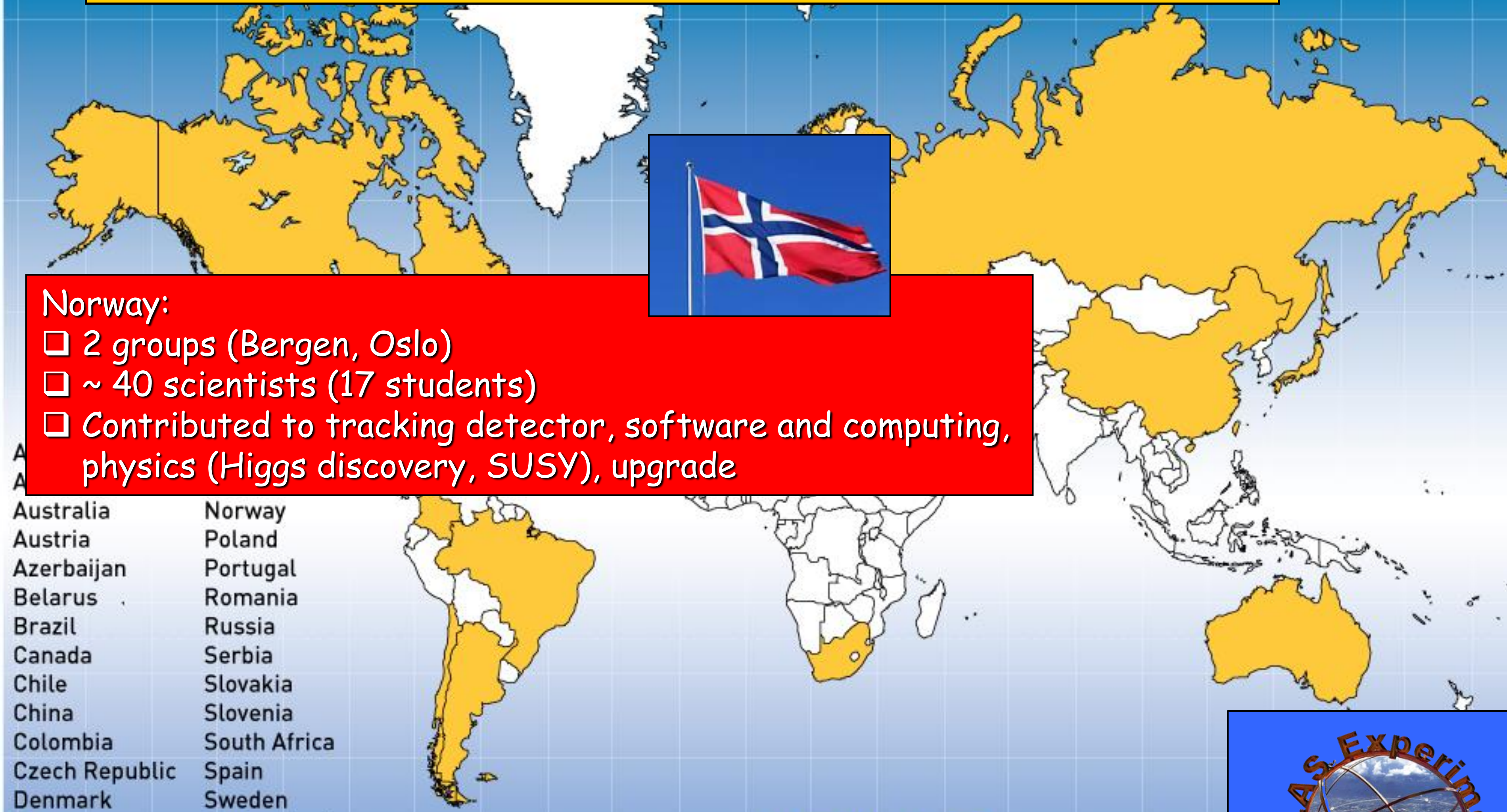
A collision in the CMS detector



Particle trajectories are reconstructed with precision of few microns (1μ = 10^{-6} m)

Giant ultra-fast digital camera
40 million beam-beam collisions per second
→ fast response (~50 ns) (1 ns = 10^{-9} s)

~ 3000 scientists from 177 Institutions from 38 Countries



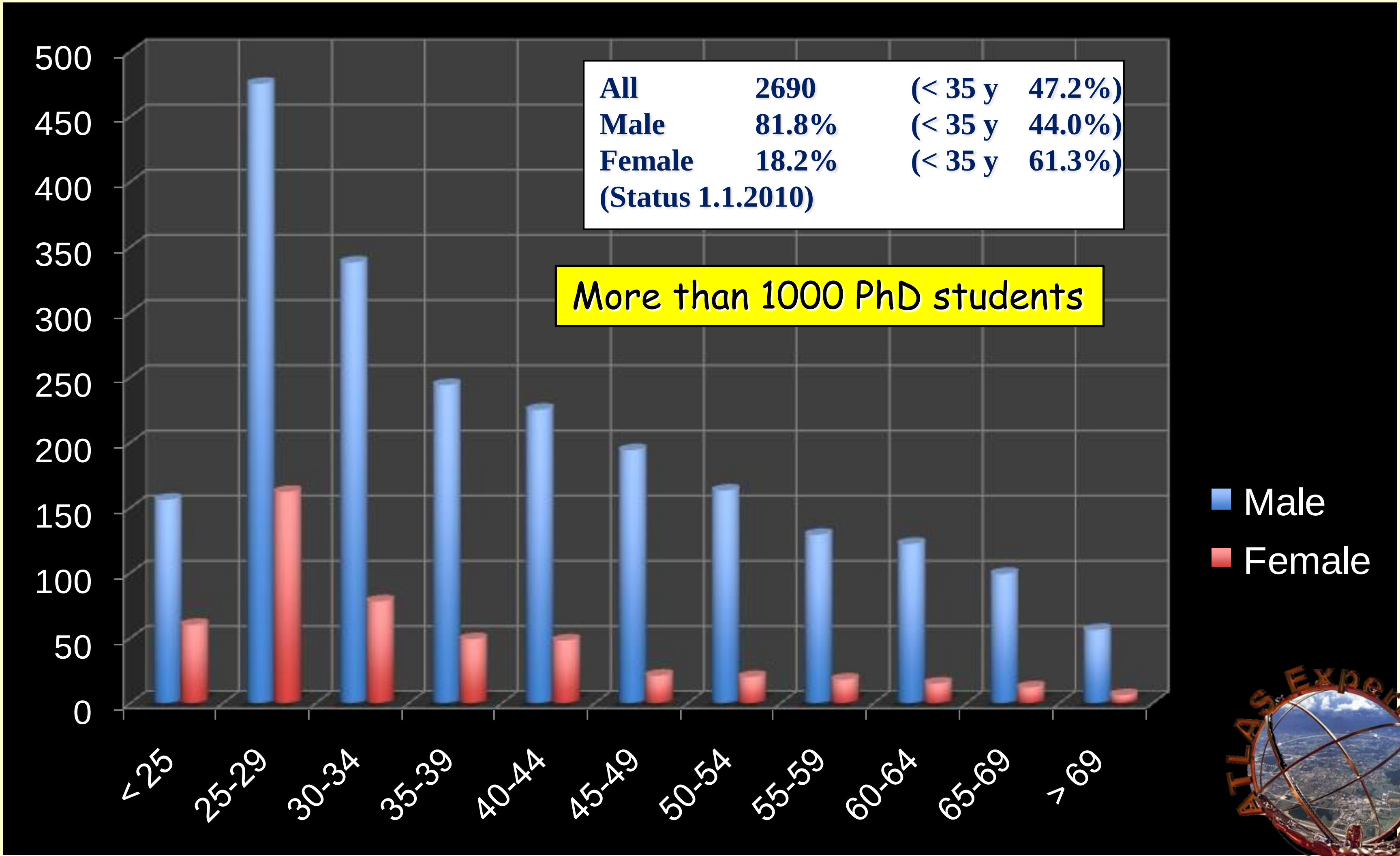
Norway:
- 2 groups (Bergen, Oslo)
- ~ 40 scientists (17 students)
- Contributed to tracking detector, software and computing, physics (Higgs discovery, SUSY), upgrade

Australia	Norway
Austria	Poland
Azerbaijan	Portugal
Belarus	Romania
Brazil	Russia
Canada	Serbia
Chile	Slovakia
China	Slovenia
Colombia	South Africa
Czech Republic	Spain
Denmark	Sweden
France	Switzerland
Georgia	Taiwan
Germany	Turkey
Greece	UK
Israel	USA
Italy	CERN
Japan	JINR

ATLAS Collaboration

ATLAS Experiment

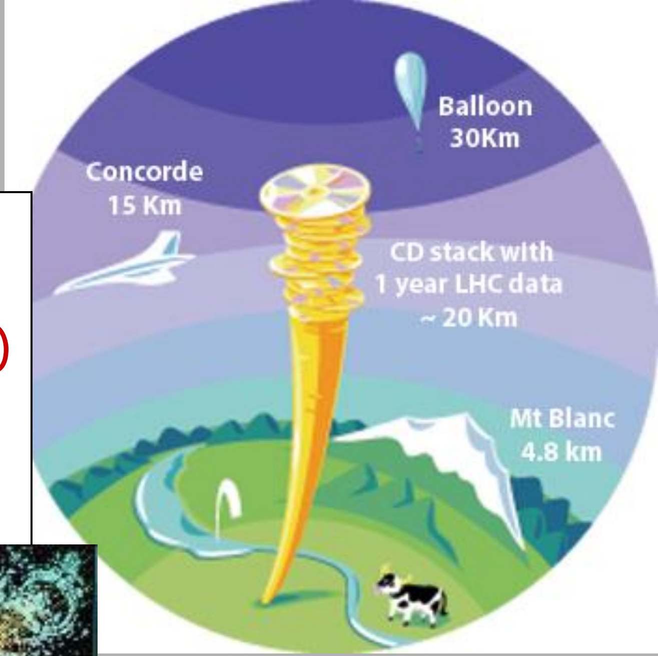
Age distribution of the ATLAS population



All	**2690**	**(< 35 y**	**47.2%)**
Male	**81.8%**	**(< 35 y**	**44.0%)**
Female	**18.2%**	**(< 35 y**	**61.3%)**
(Status 1.1.2010)			

More than 1000 PhD students

Computing

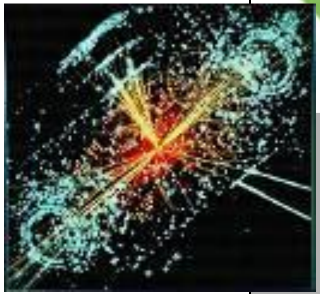


Each LHC experiment produces ~ 10 PB of data per year

1 PB=10^6 GB

This corresponds to ~ 20 million DVD (a 20 km stack …)

Data analysis requires computing power equivalent to ~100 000 today's fastest PC processors.



The experiment international Collaborations are spread all over the world → computing resources must be distributed.

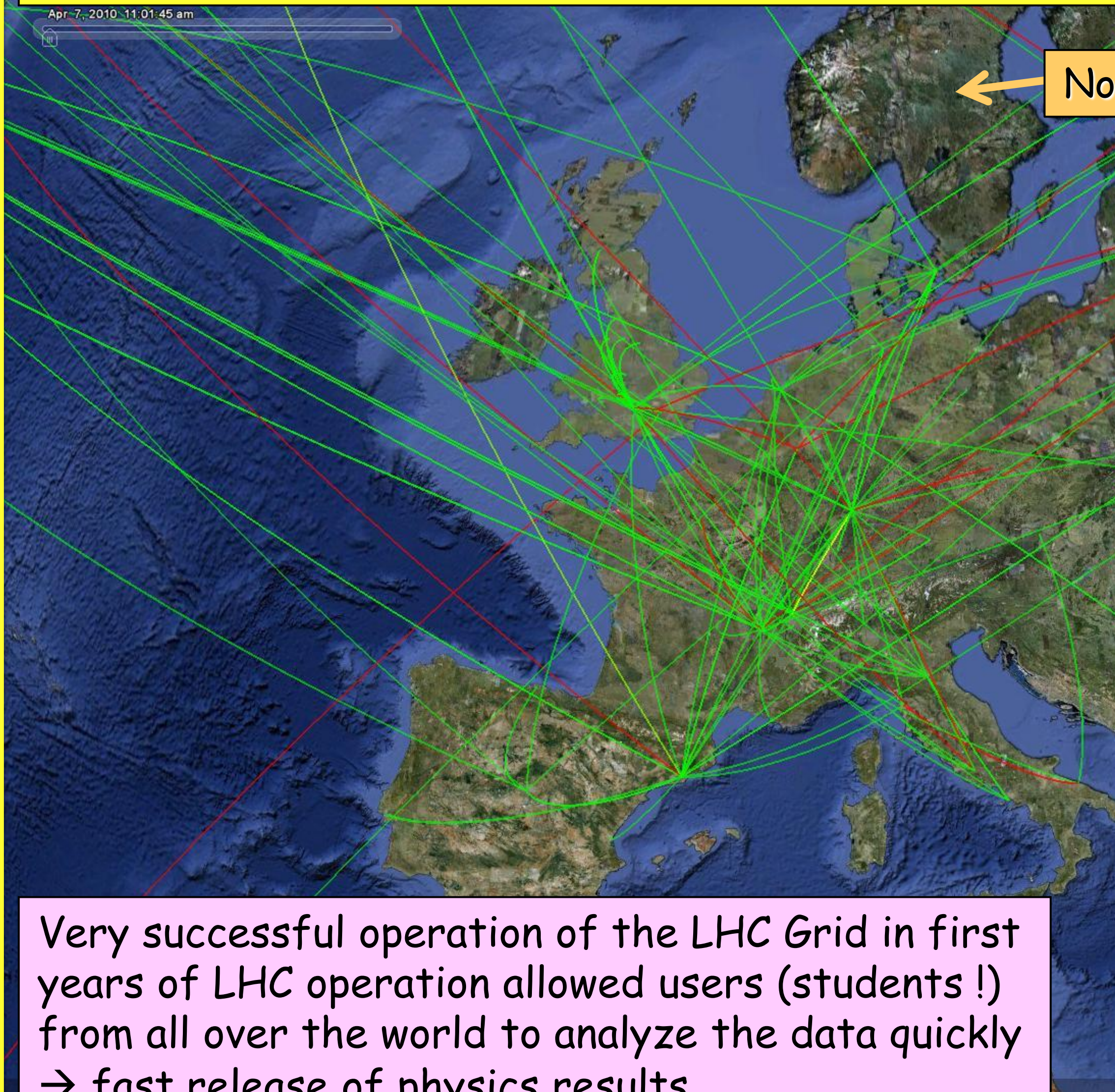
↓

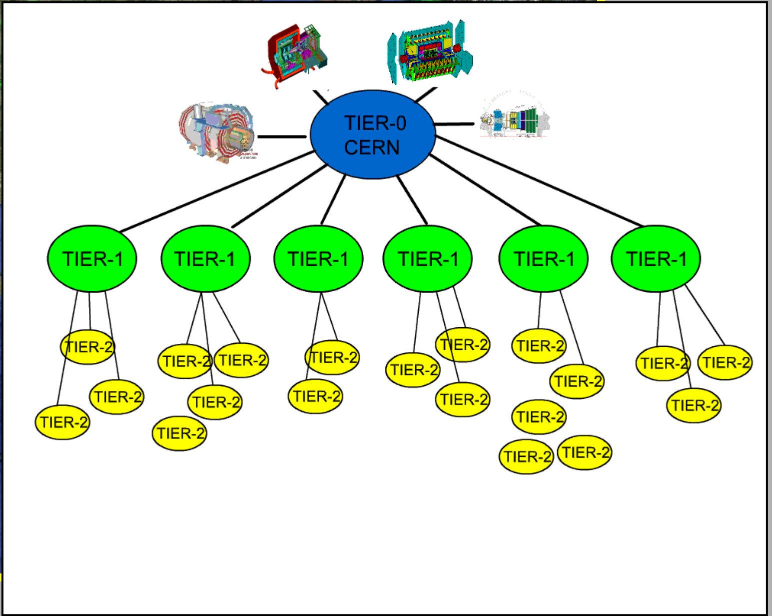
Cooperation of many computer centres all over the world is needed →

Grid

The Grid provides seamless access to computing power and data storage capacity distributed over the globe

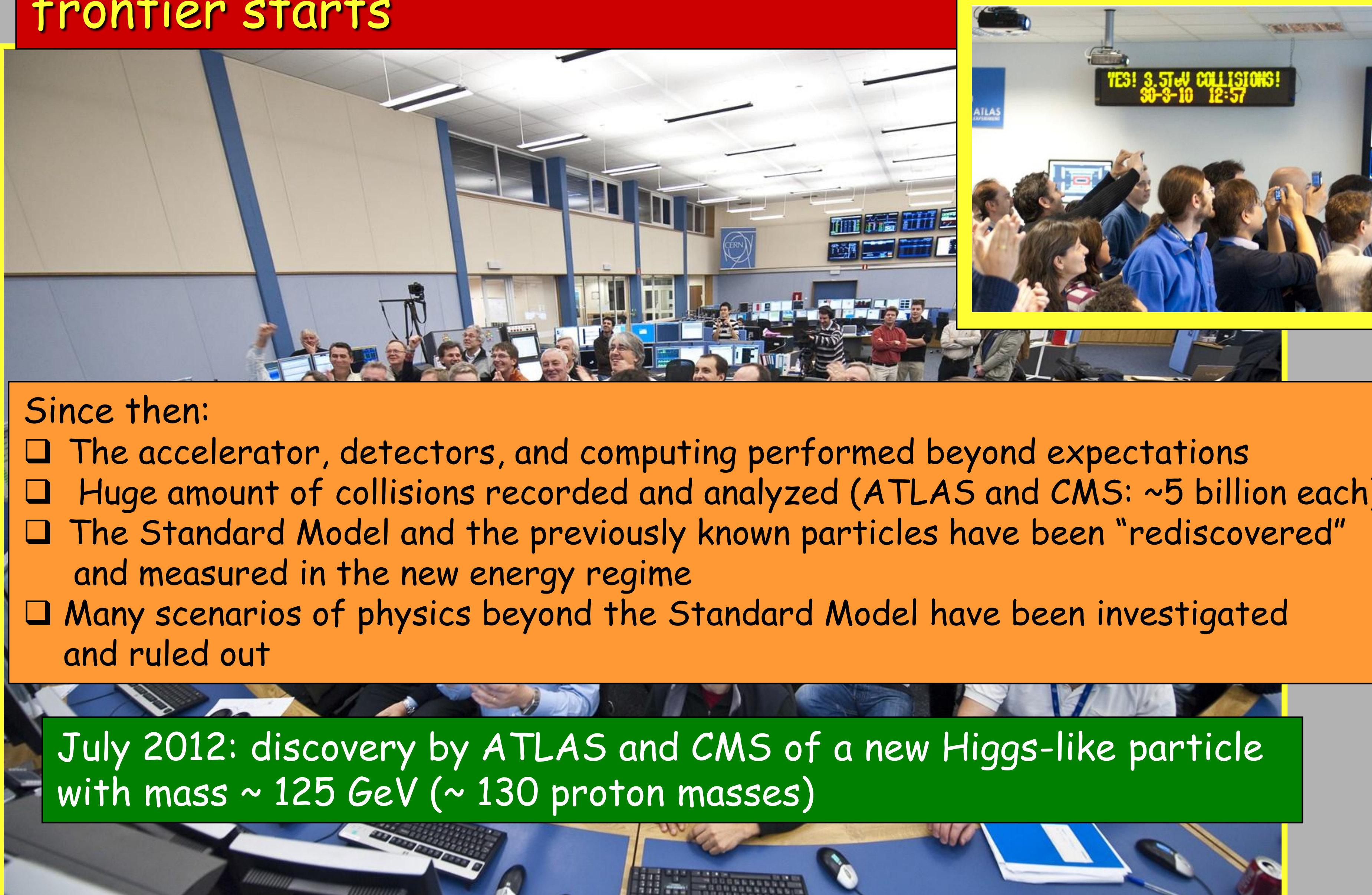
Worldwide LHC Computing Grid (WLCG): ~ 150 computing centres, ~ 35 countries





Very successful operation of the LHC Grid in first years of LHC operation allowed users (students !) from all over the world to analyze the data quickly → fast release of physics results

30 March 2010: first proton-proton collisions at an unprecedented energy → exploration of a new energy frontier starts

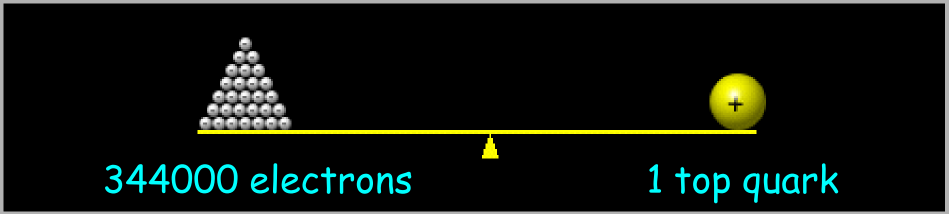


Since then:

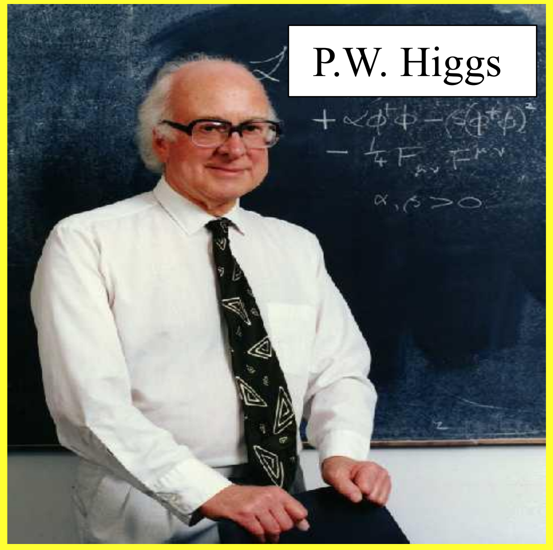
- ❑ The accelerator, detectors, and computing performed beyond expectations
- ❑ Huge amount of collisions recorded and analyzed (ATLAS and CMS: ~5 billion each)
- ❑ The Standard Model and the previously known particles have been "rediscovered" and measured in the new energy regime
- ❑ Many scenarios of physics beyond the Standard Model have been investigated and ruled out

July 2012: discovery by ATLAS and CMS of a new Higgs-like particle with mass ~ 125 GeV (~ 130 proton masses)

What is the origin of the particle masses ?



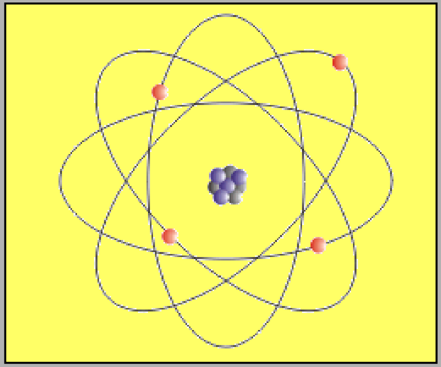
Mass of top quark (heaviest elementary particle observed) ≈ mass of Gold atom
Electron mass is ~350000 times smaller: why ???



Proposed solution (Brout, Englert, Guralnik, Hagen, Higgs, Kibble):
"Higgs mechanism": origin of masses ~ 10^{-11} s after the Big Bang, when "Higgs field" became active → particles acquired masses proportional to the strength of their interactions with the Higgs field

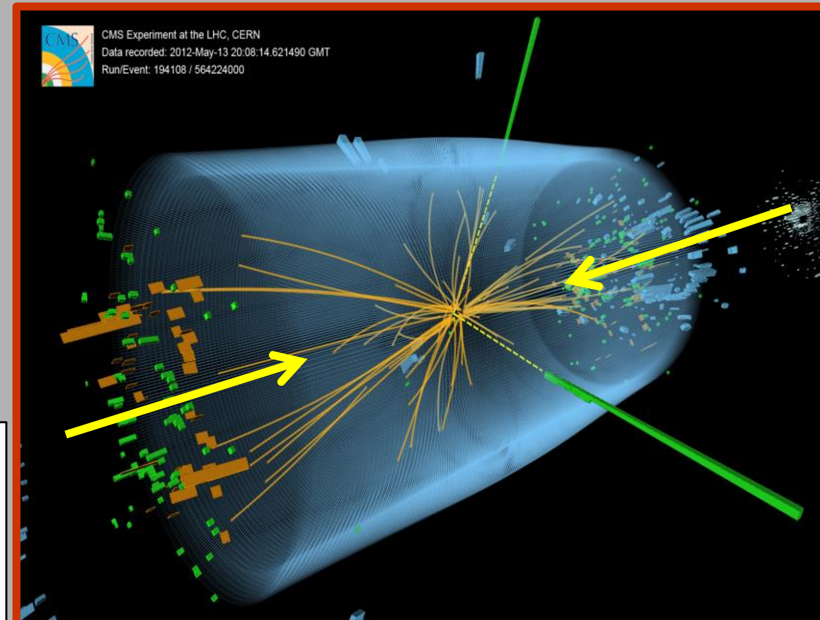
Consequences: existence of a **Higgs boson**
This particle has been searched for > 30 years at accelerators all over the world
→ finally found at the LHC !

Note: a world without "Higgs" would be a very strange one !
Atoms may not exist, and the Universe would be very different

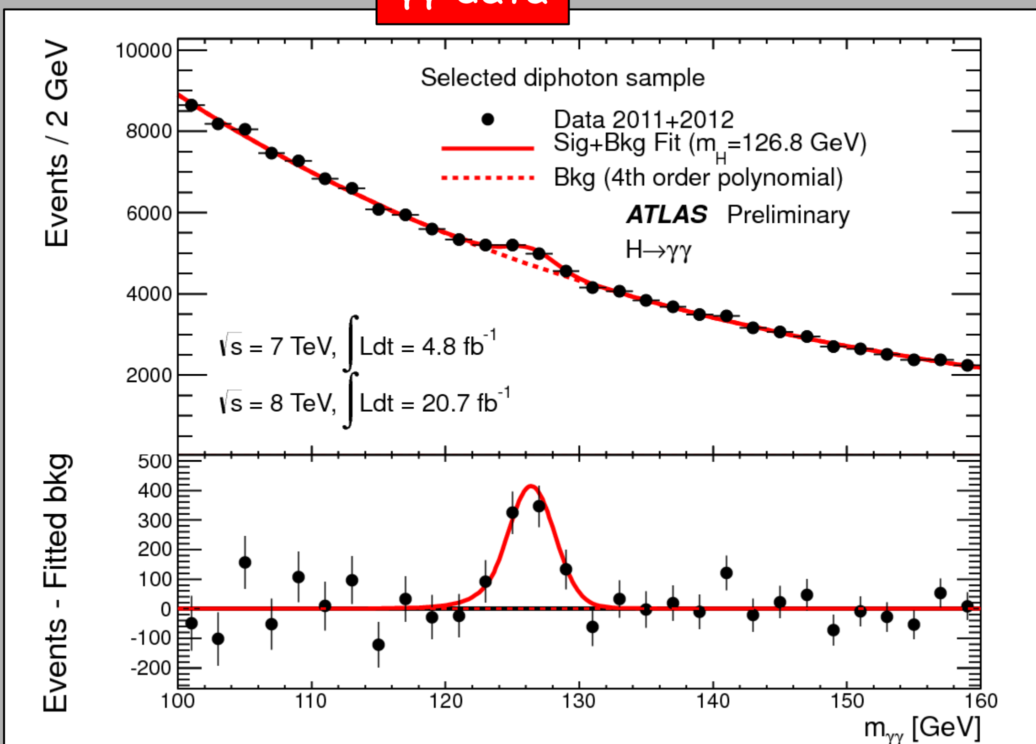


What did we observe ?

Once produced the Higgs boson is expected to disintegrate ("decay") into known particles, for instance into two photons → looked at the γγ spectrum in our data

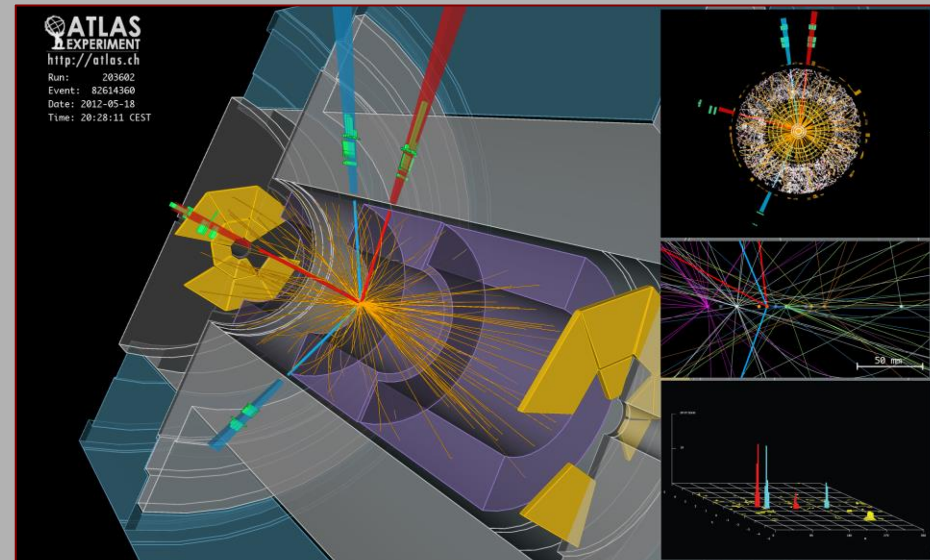


γγ data

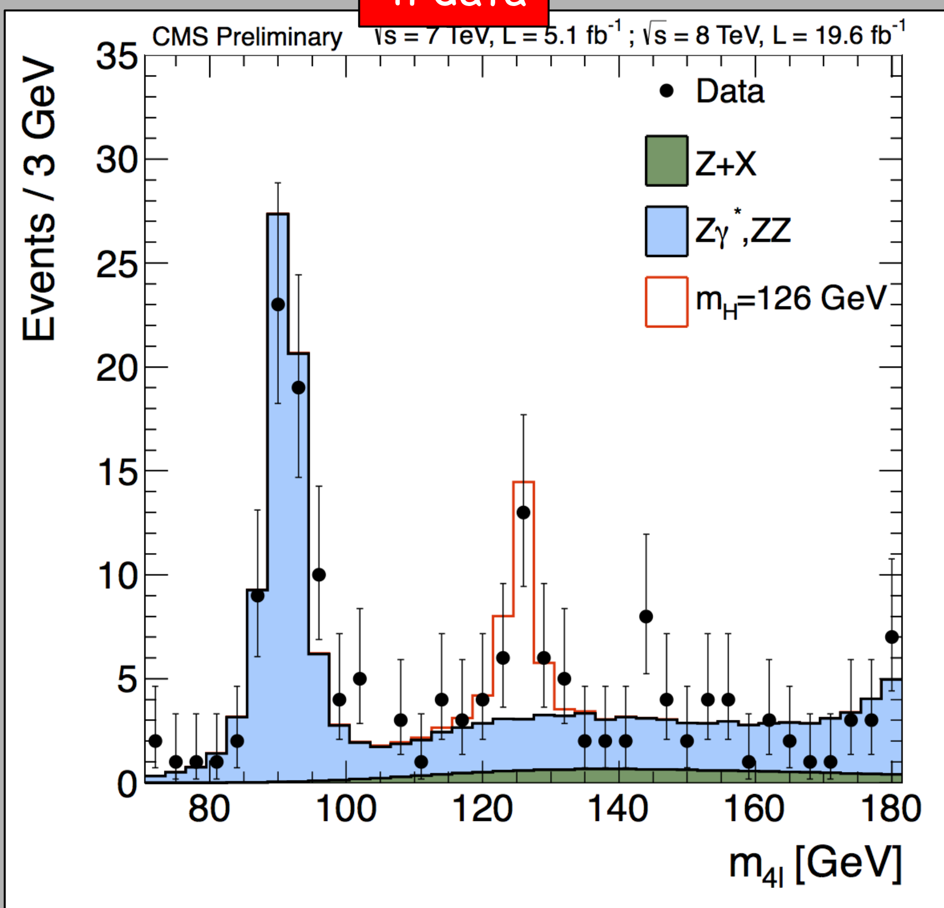


Peak ("resonance") at $m_{\gamma\gamma}$ around 125 GeV indicates the production of a (new) heavy particle

Higgs boson can also decay into 4 leptons (electrons, muons) :
→ looked at 4e, 4μ, 2e2μ spectrum in our data



4l data



A peak is observed also in this case at m_{4l} around 125 GeV

Higgs boson can also decay into 4 leptons (electrons, muons) :
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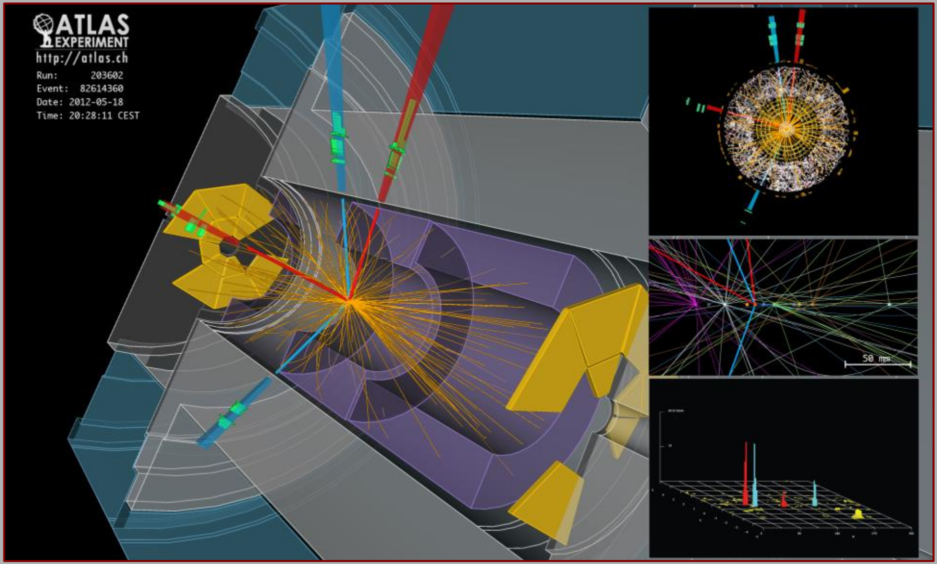
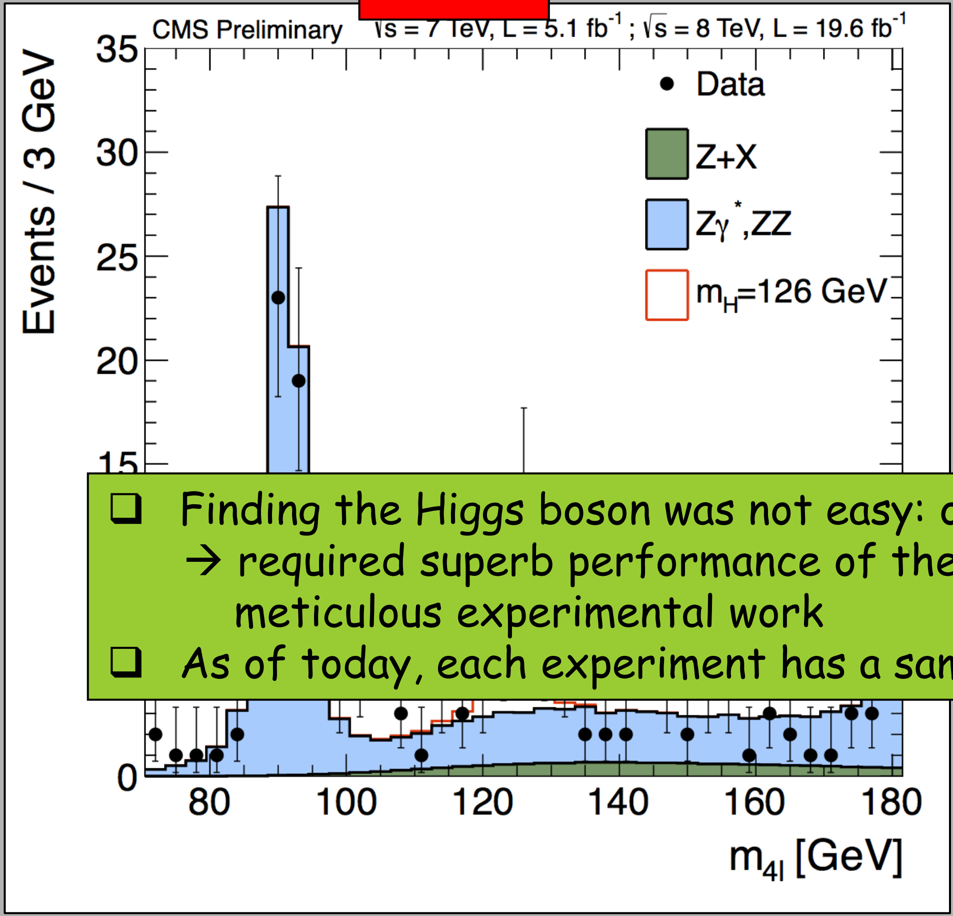


4l data

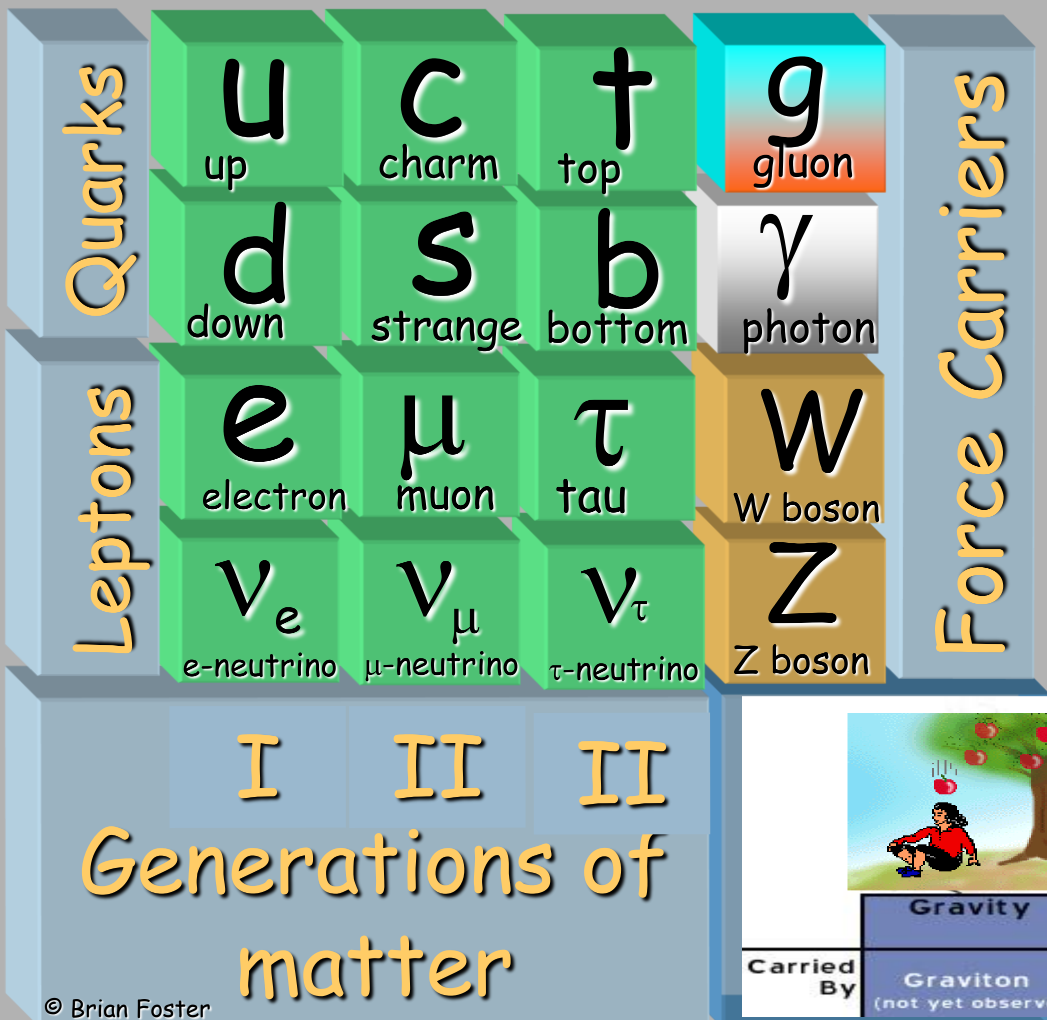


A peak is observed also in this case at m_{4l} around 125 GeV

- Finding the Higgs boson was not easy: one H→ 4e produced every 10^{13} pp collisions
  → required superb performance of the LHC, ideas, and a huge amount of meticulous experimental work
- As of today, each experiment has a sample of about 600 Higgs events

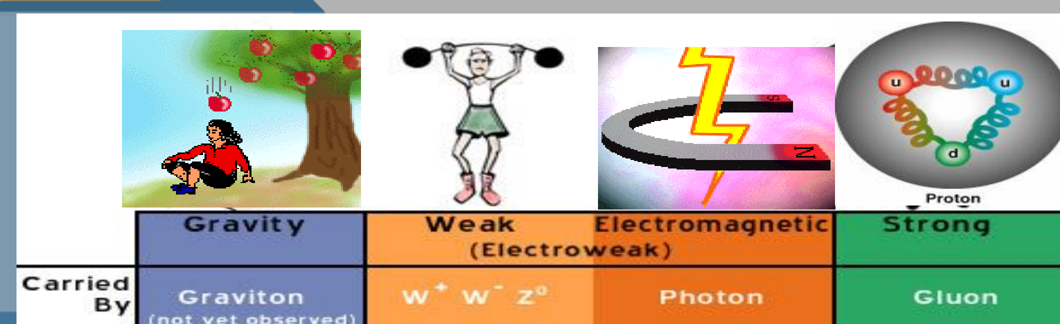
Is this a Higgs boson ?

A Higgs boson is a very special particle ..



H

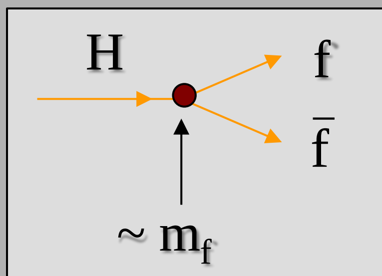
Particles and forces



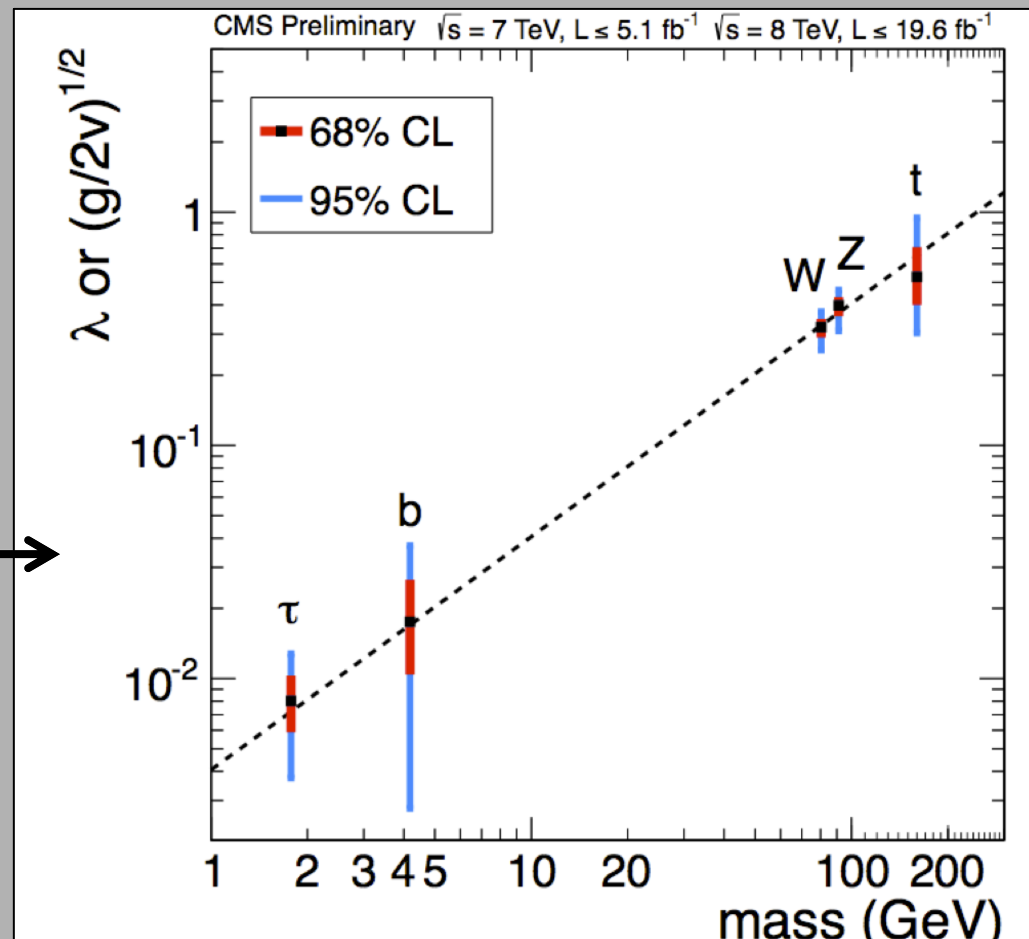
F. Gianotti, CAS, Trondheim, 28/8/2013

Two "fingerprints" distinguish the Higgs boson from all other particles

1) To accomplish its job (providing mass) it interacts with other particles with strength proportional to their masses, as predicted by the "Higgs mechanism"



Couplings of the new particle to several known particles (W, Z, top-quark, b-quark, τ-lepton) vs particle mass (over a factor of 100 !)

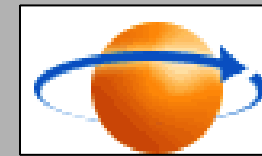


2) It has spin zero ("scalar")

None of the other SM elementary particles has spin zero:

-- Matter particles (electrons, quarks, …): spin $\frac{1}{2}$

-- Force carriers (photons, W, Z, ..): spin 1



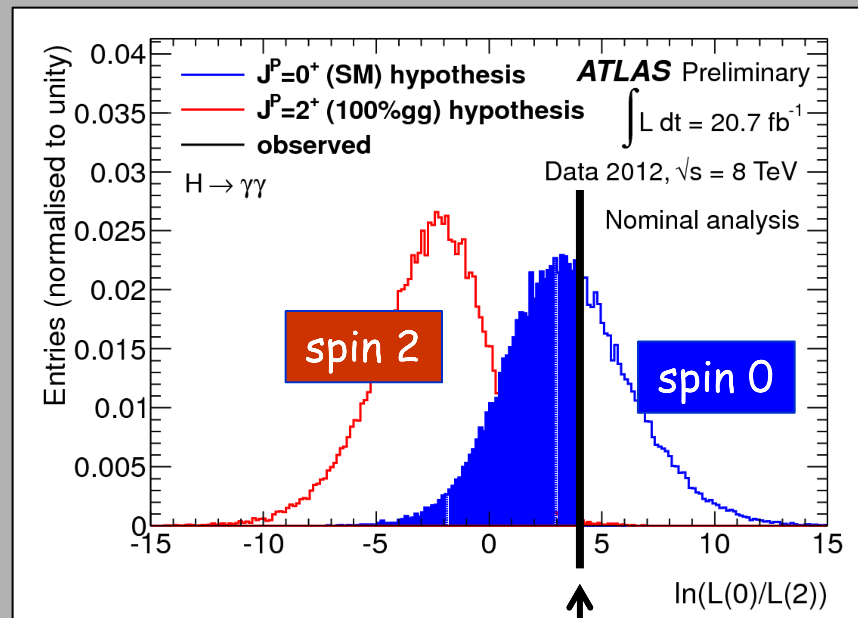
What is the spin of the newly discovered particle ?

Spin can be determined from the angular distribution of the decay products of the particle (here for events where the new particle decays to γγ)

Red : expected distribution for spin 2

Blue : expected distribution for spin 0

Vertical black line: ATLAS data



ATLAS data

→ (likely) the first elementary scalar observed in Nature

→ consequences also for Universe evolution (according to cosmology, inflation was triggered by a scalar field)

Note: until now, fermions (c, b, t, τ) discovered in US, bosons (W, Z, H) in Europe ..!

Three Frequently-Asked-Questions

1) Is this new particle the Standard Model Higgs boson ?

Present LHC measurements say it's A Higgs boson (it has both fingerprints)
However, too early to draw definite conclusions → we will need to measure its properties in detail in the months/years to come with present/future data to understand e.g. if it is THE SM Higgs boson or a more exotic object of a more general theory → LHC upgrade and possibly a new (e^+e^- ?) accelerator

2) Is the task of the LHC over ?

No, this is just the beginning of the LHC exploration phase: the LHC was built to address many more questions (dark matter, etc.), not only to find the Higgs boson

3) Will the Higgs boson change our day-by-day life ?

It did already !

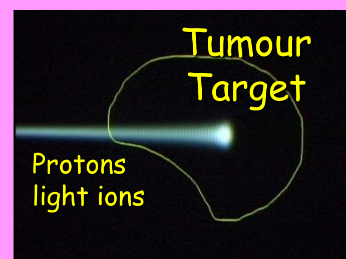
From fundamental science to everyone's life

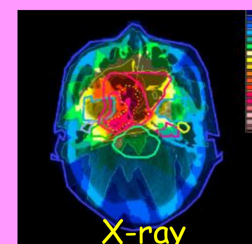
Extreme performance required in particle physics → cutting-edge technologies developed at CERN (and collaborating Institutes) and other HEP laboratories, and then transferred to society.

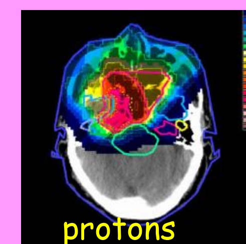
Applications: medical imaging (e.g. PET), cancer therapy, materials science, airport scanners, cargo screening, food sterilization, nuclear waste transmutation, analysis of historical relics, etc. …not to mention the WEB ..

Accelerating particle beams
~30'000 accelerators worldwide
~17'000 used for medicine

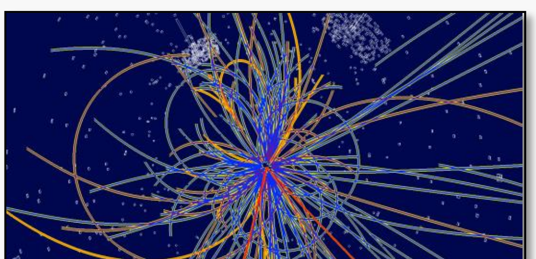
Hadron Therapy







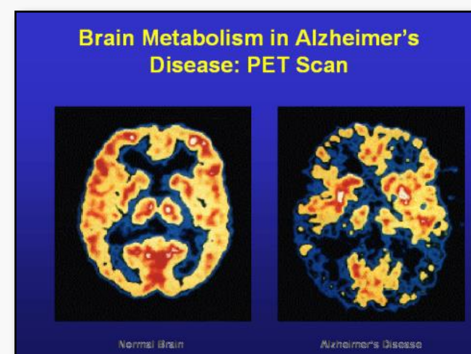
> 90000 patients treated worldwide (30 facilities)



Detecting particles

Imaging

e.g. PET scanner



The outstanding questions after the 1st LHC run

What is the origin of the particle masses ? ✔
→ Related to the Higgs boson

What is the nature of the Universe dark matter ?

Why 3 generations of matter particles ?
Why is there so little antimatter in the Universe ?
(Nature's favouritism allowed us to exist …)

What are the features of the primordial plasma permeating the Universe ~10 μs after the Big Bang ?

Are there other forces in addition to the known four ?

Why is gravity so weak ? Are there additional (microscopic) space dimensions ?

Etc. etc.

ATLAS, CMS

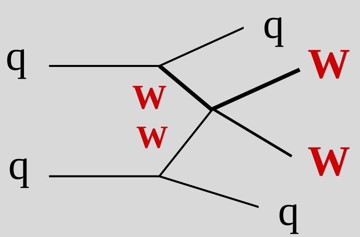
ATLAS, CMS

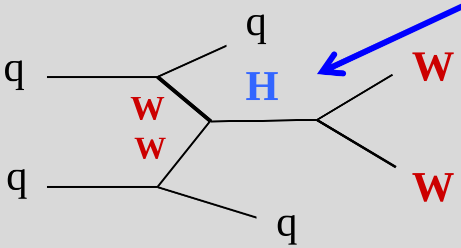
LHCb

ALICE

ATLAS, CMS

Two additional questions (from the Higgs boson itself ..)





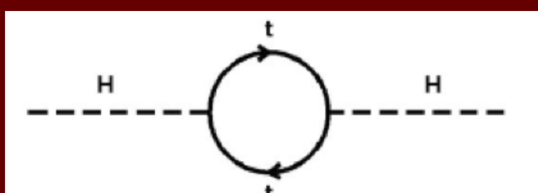
Does this new particle fix the SM problems at high energy ?

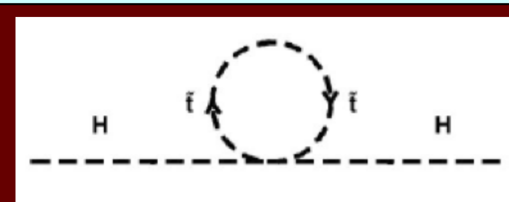
This process becomes unphysical (cross section diverges):
$\sigma \sim E^2$ at $m_{WW} \sim$ TeV
if this process does not exist

→ Important to verify that the new particle accomplishes this task → a "closure test" of the SM
→ Need LHC upgrade to verify

Why is the Higgs so light ?

Need new physics (close-by, ~TeV scale) to "stabilize" the divergent Higgs mass





In the SM, this correction to m_H diverges as ~ Λ^2 (energy scale up to which the SM is valid)

E.g. the supersymmetric partner of the top (stop) gives rise to the same diagram with opposite sign
→ cancellation
Only works if mass difference stop-top small (few hundreds GeV) → motivation for SUSY at TeV scale

Conclusions

The discovery of the Higgs boson is a giant leap in our understanding of fundamental physics and the structure and evolution of the universe

This accomplishment is the result of > 20 years of talented work and extreme dedication of those involved in the LHC project. More in general, it's the result of the ingenuity, vision and painstaking work of the HEP community (theory, accelerators, computing, experiments)

After 50 years of theory and experimental work, the Standard Model is now complete
However: it is not the ultimate theory of particle physics, as many unanswered questions remain:

- Why is the Higgs boson so light ("naturalness" problem) ?
- What is the the nature of dark matter and dark energy (95% of the universe!) ?
- What is the origin of the matter-antimatter asymmetry in the universe ?
- Why is gravity so weak and "fundamental scales" so different ("hierarchy problem") ?
- ....

More powerful accelerators will be needed in the future to address these and other questions, requiring new ideas, ingenuity, new developments in order to provide higher energy at affordable costs.

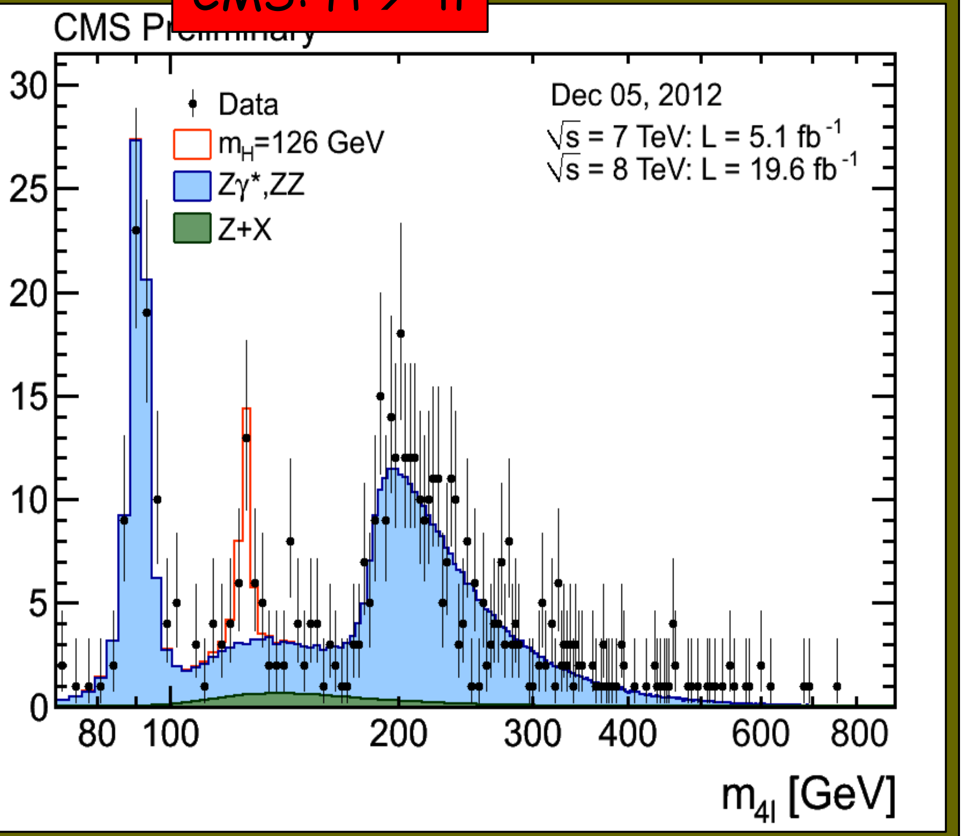
As in the past, the benefits to society are expected to be HUGE.

THANK YOU !

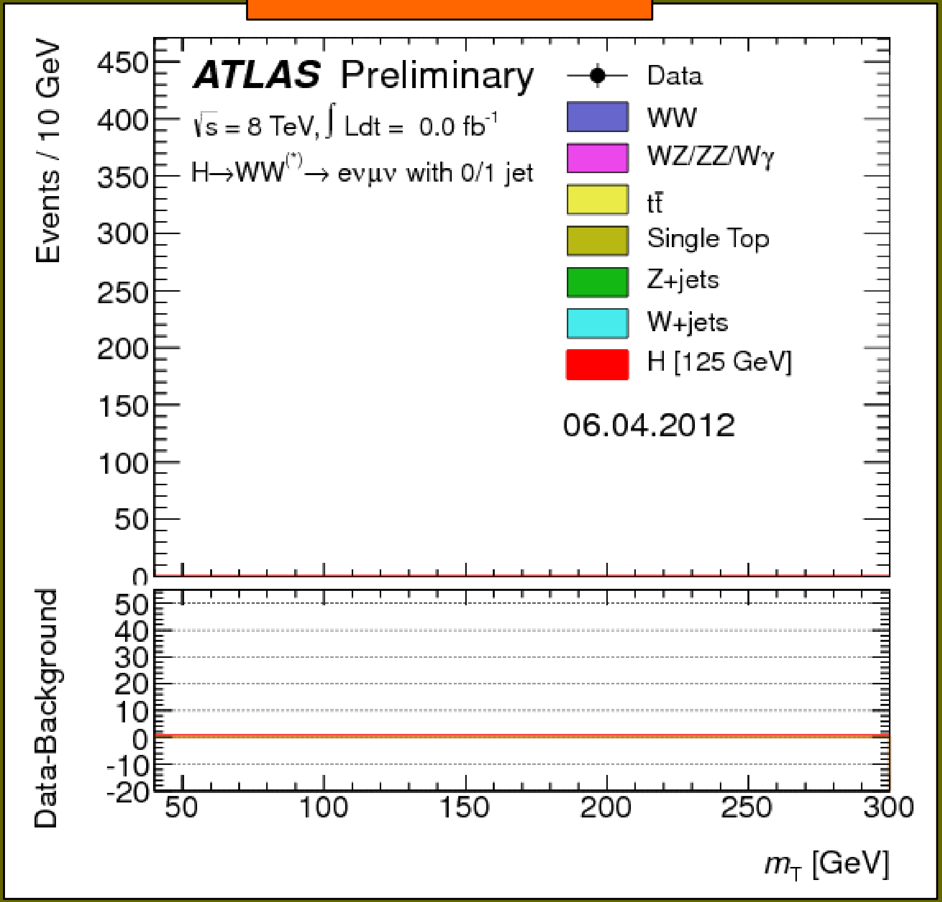

caglecartoons.com
ELEMENTARY PARTICLE RESPONSIBLE FOR MASS
CERN
AMERICAN OBESITY
See! IT'S NOT MY FAULT- I WAS BORN WITH TOO MANY HIGGS BOSONS.
INTOON.COM 7·6·12

Birth and evolution of a signal

CMS: H→ 4l



ATLAS: H→ lvlv

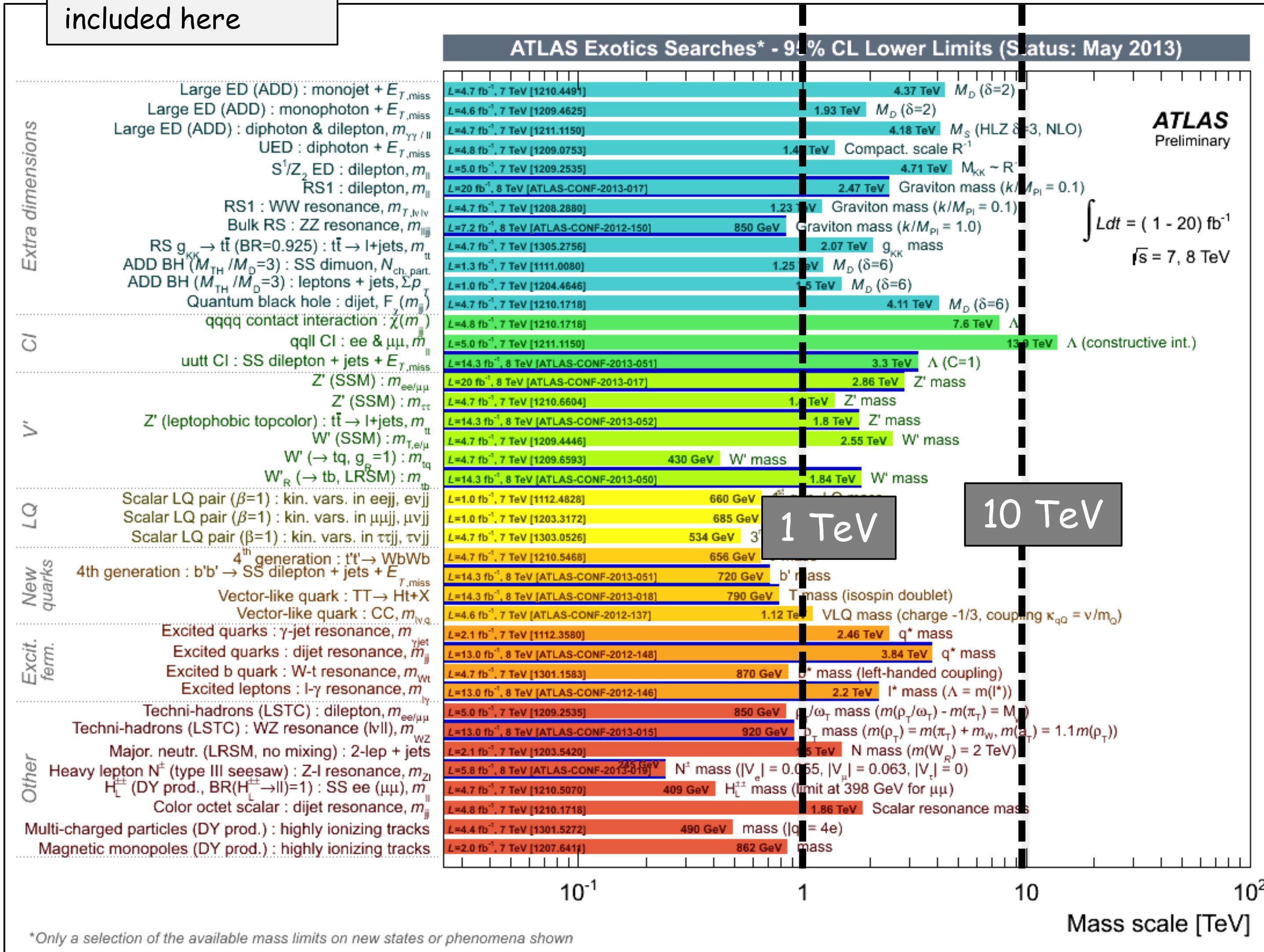


SPARES

Searches for physics beyond the Standard Model

Huge number of scenarios and topologies investigated

SUSY searches not included here



Exotics Models:

Extra dimensions:
- RS KK Graviton
  - (dibosons, dileptons, diphotons)
- RS KK gluons (top antitop)
- ADD (monojets, monophotons,
  - dileptons, diphotons)
- KK Z/gamma boosns (dileptons)

Grand Unification symmetries
- (dielectons, dimuons, ditaus)
- Leptophobic topcolor Z' boson
  - (dilepton ttbar, l+j, all had)

S8- color octet scalars (dijets)

String resonance (dijets,)

Benchmark Sequential SM Z', W'

W' (lepton+MET, dijets, tb)

W* (lepton+MET, dijets)

Quantum Black Holes (dijet)

Black Holes (l+jets, same sign leptons)

Technihadrons (dileptons, dibosons)

Dark Matter
- WIMPs (Monojet, monophotons)

Excited fermions
- q*, Excited quarks (dijets, photon+jet)
- l*, excited leptons (dileptons+photon)

Leptoquarks (1st, 2nd, 3rd generations)

Higgs -> hidden sector
- (displaced vertices, lepton jets)

Contact Interaction
- llqq CI
- 4q CI (dijets)

Doubly charged Higgs (
- multi leptons, same sign leptons)

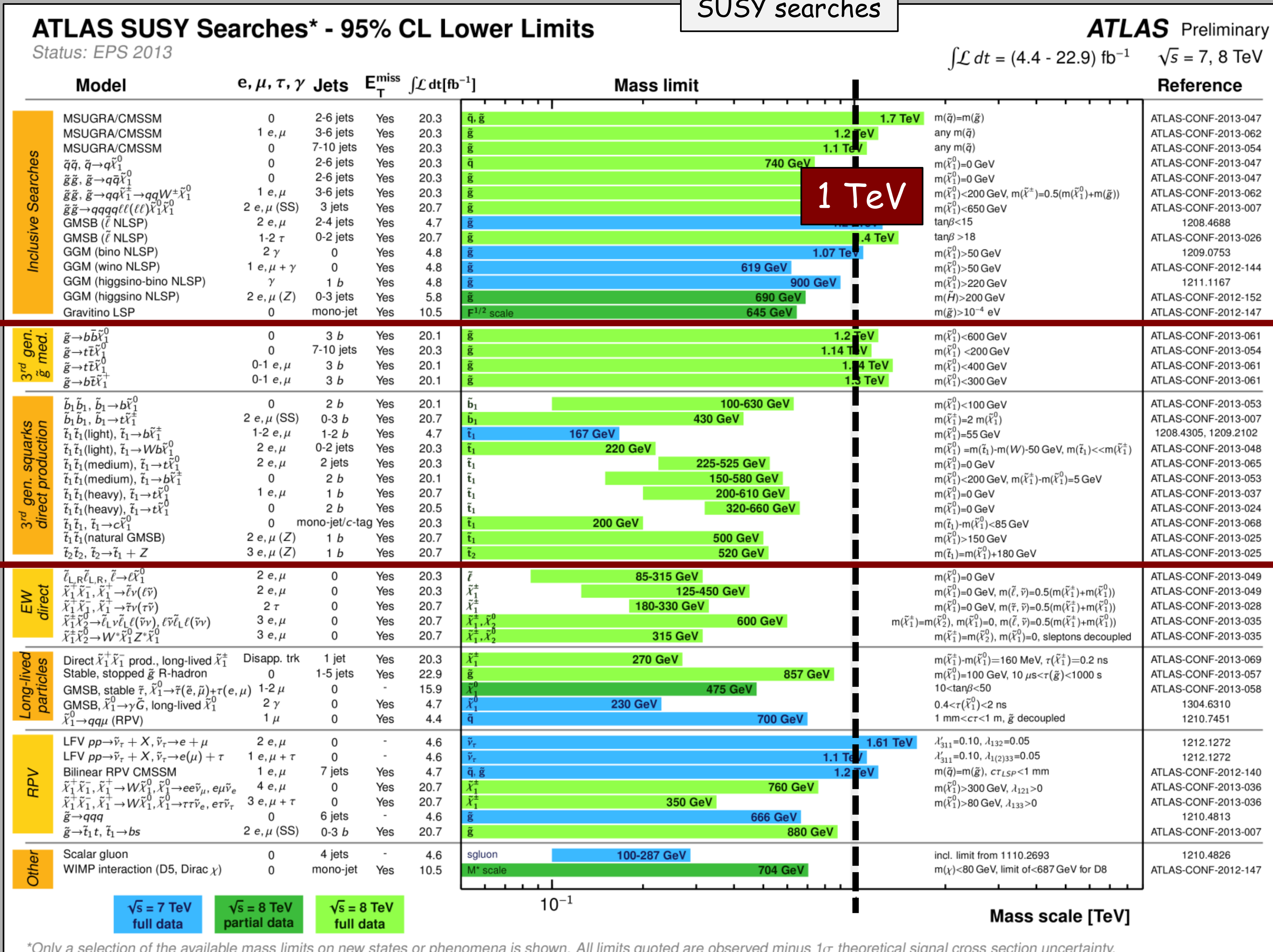
4th generation
- t'->Wb, t'->ht, b'-Zb, b'->Wt
  - (dileptons, same sign leptons, l+J)

VLQ-Vector Like quarks

Magnetic Monopoles (and HIP)

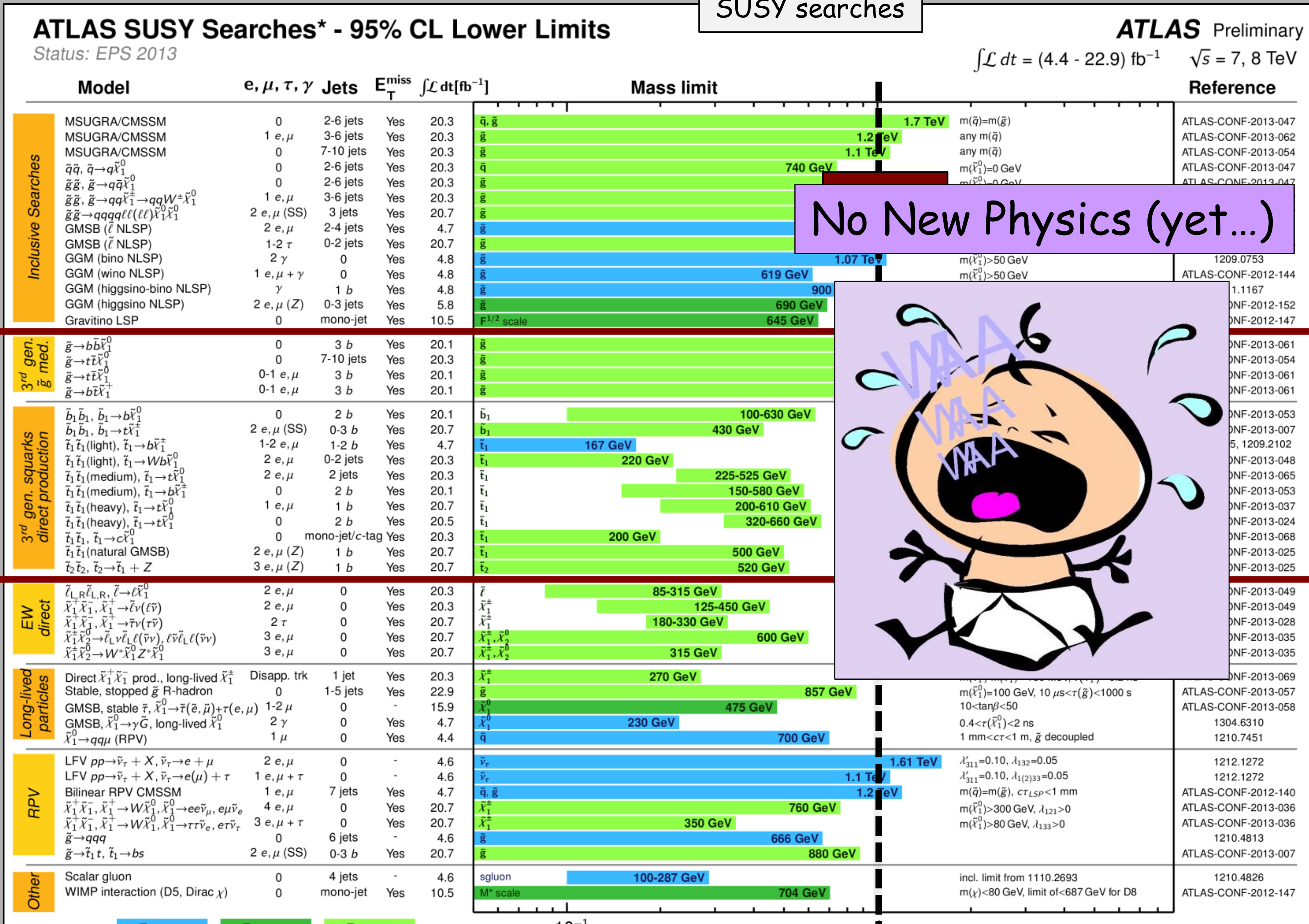
Heavy Majorana neutrino and RH W

SUSY searches



F. Gianotti, CAS, Trondheim, 28/8/2013

SUSY searches



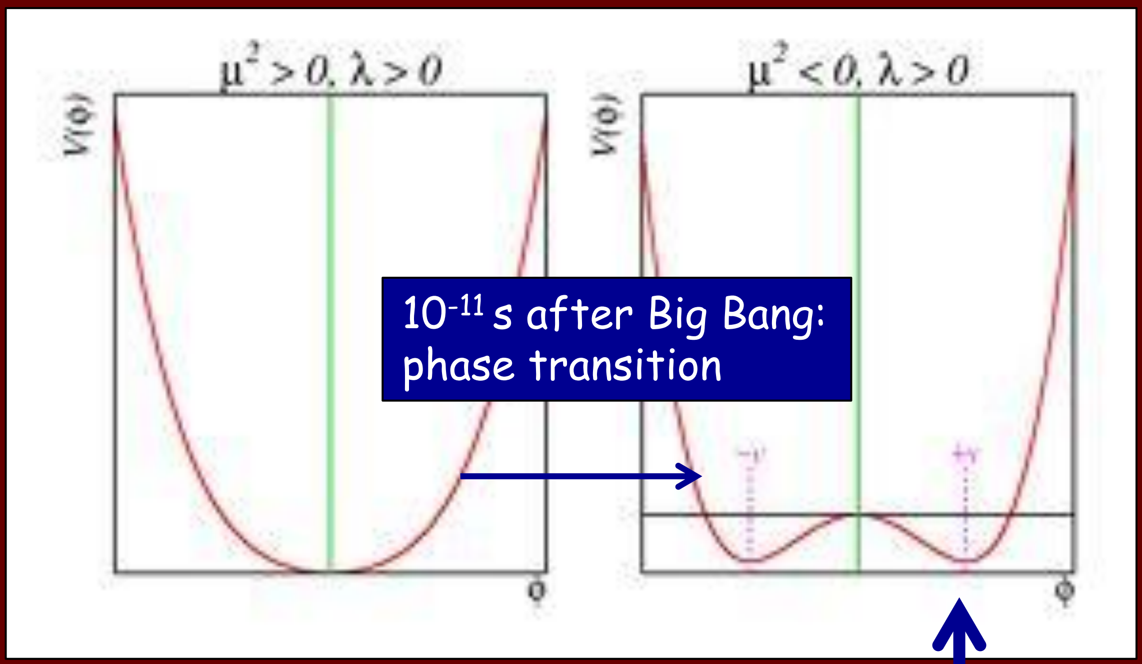
No New Physics (yet…)

But

- ❑ searches far from being complete → surprises may hide in present data
- ❑ √s today ~ 1.7 smaller than design value and integrated luminosity ~12 smaller → 2015++

How does the Higgs mechanism work ? An over-simplified picture …

At the time of the Big Bang particles were all massless (→ were moving at speed of light) and Higgs field was there as an "non-interacting ether" (minimum of Higgs potential = 0).



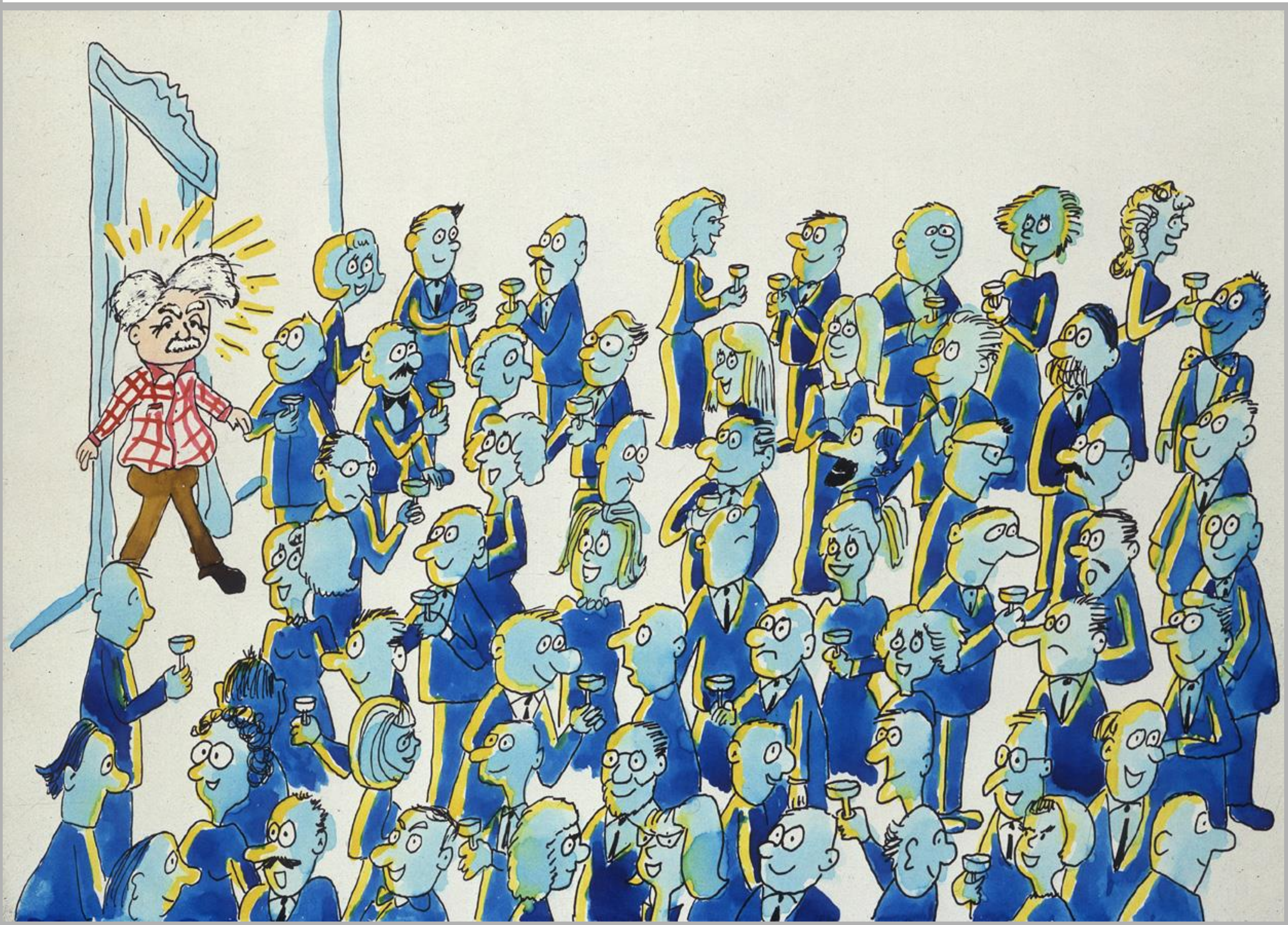
10^{-11} s after Big Bang: phase transition

About 10^{-11} s after the Big Bang → temperature became low enough for phase transition (→ minimum of Higgs potential became negative) → ether becomes "molasses" → particles interacting with "molasses" acquire a mass and are slowed down

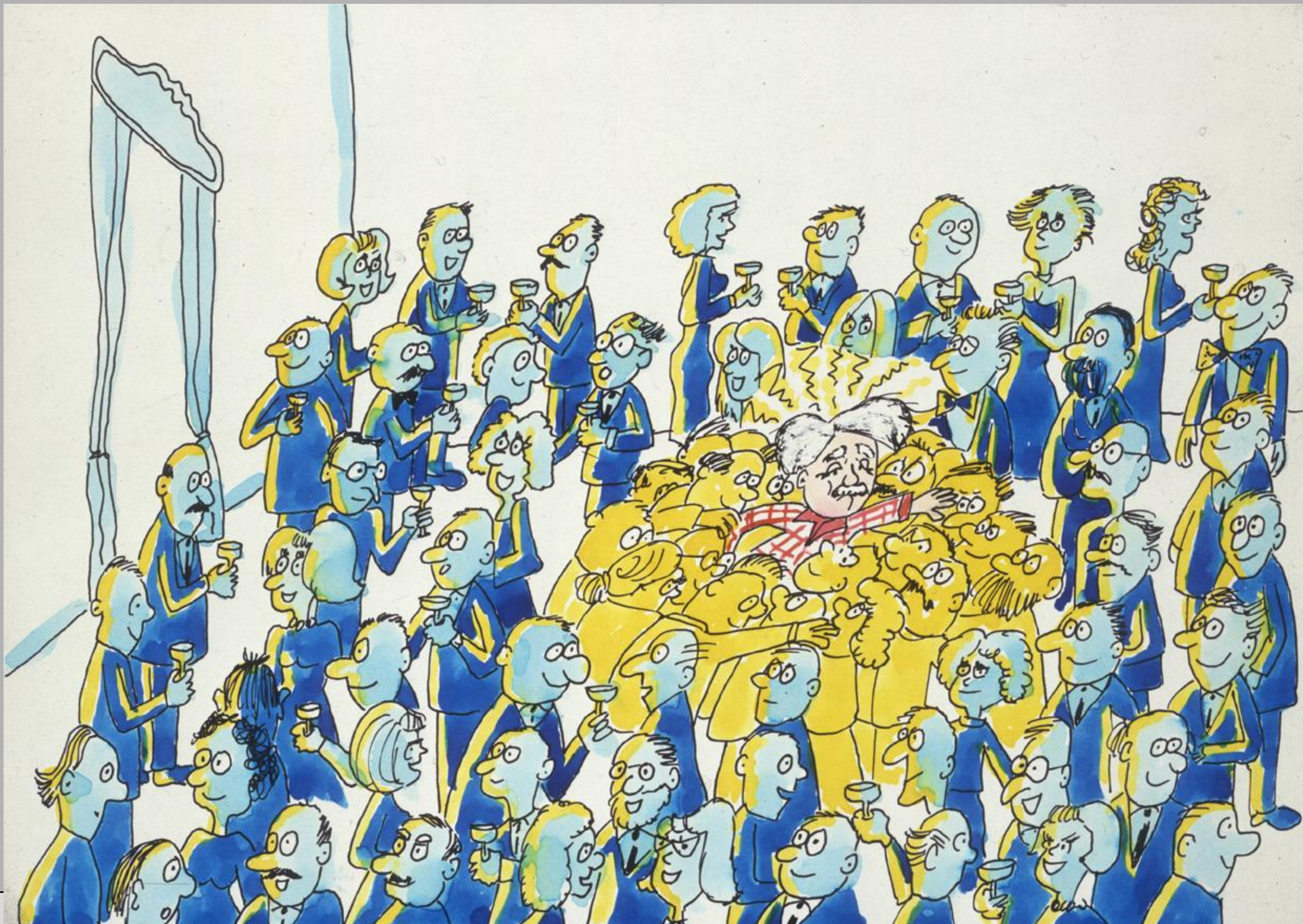
The Higgs mechanism … as exemplified by Prof. David Miller

Imagine a room full of people quietly chattering … this is like space filled only with the Higgs field ...

a well known actor walks in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step ... the actor is like a particle traversing the Higgs field



this increase his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field ...



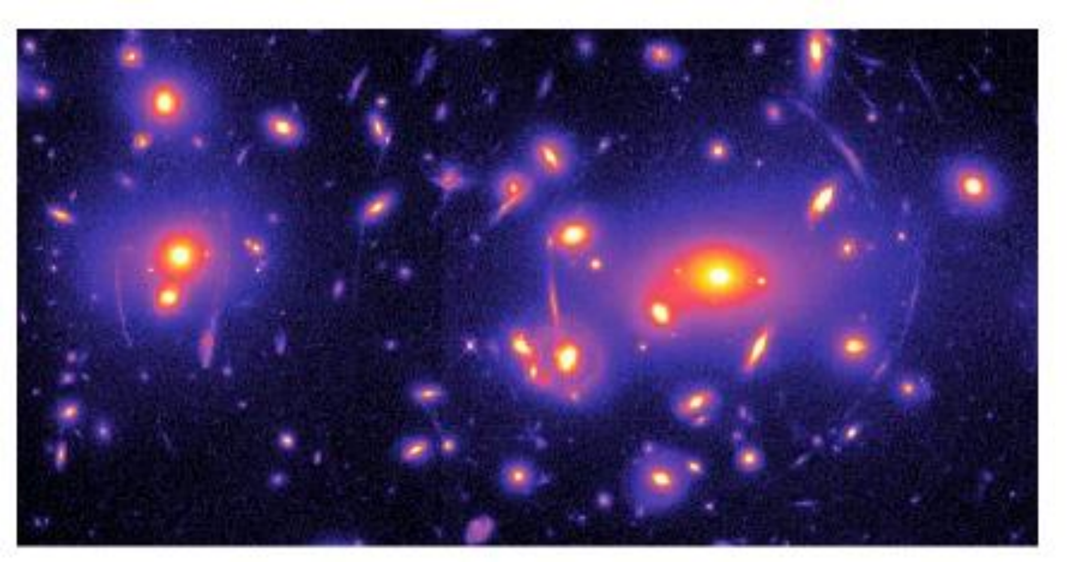
... Imagine now that a rumour crosses the room ...

it creates the same kind of clustering, but this time among the people in the room. In this analogy, these clusters are the Higgs particle.

What is the nature of the Universe Dark Matter ?

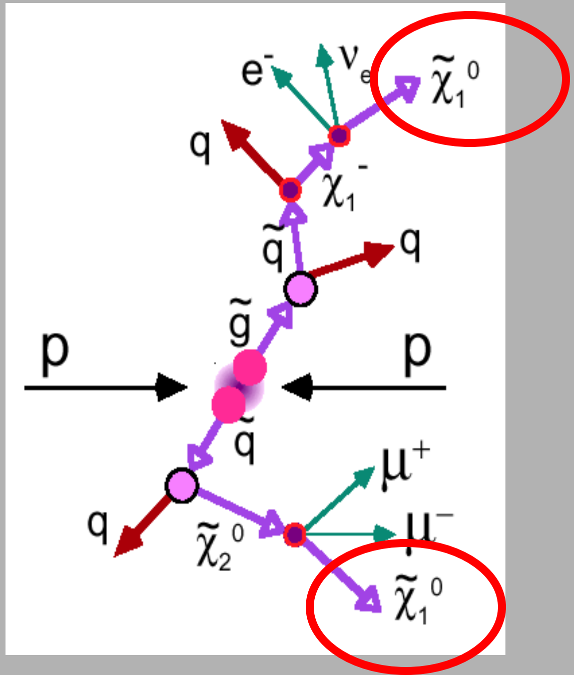
Recent astrophysical measurements indicate that the Universe is made of:

- 5% of known matter
- 25 % of "dark matter" (no known particle can explain it)
- 70% of "dark energy"

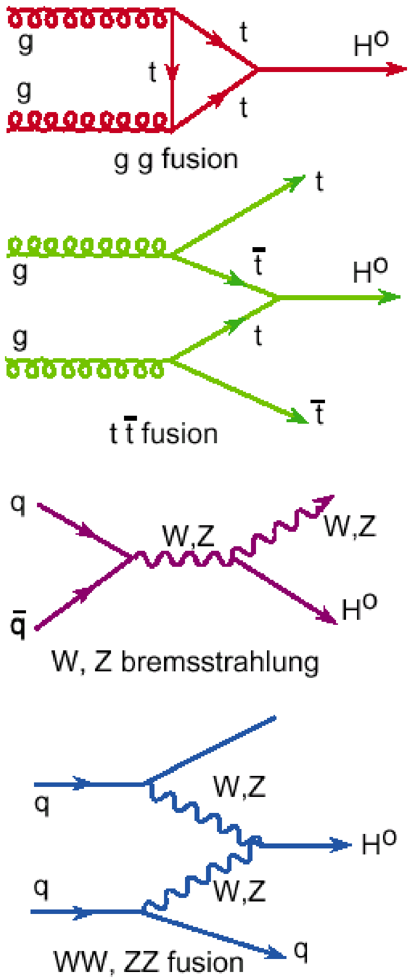


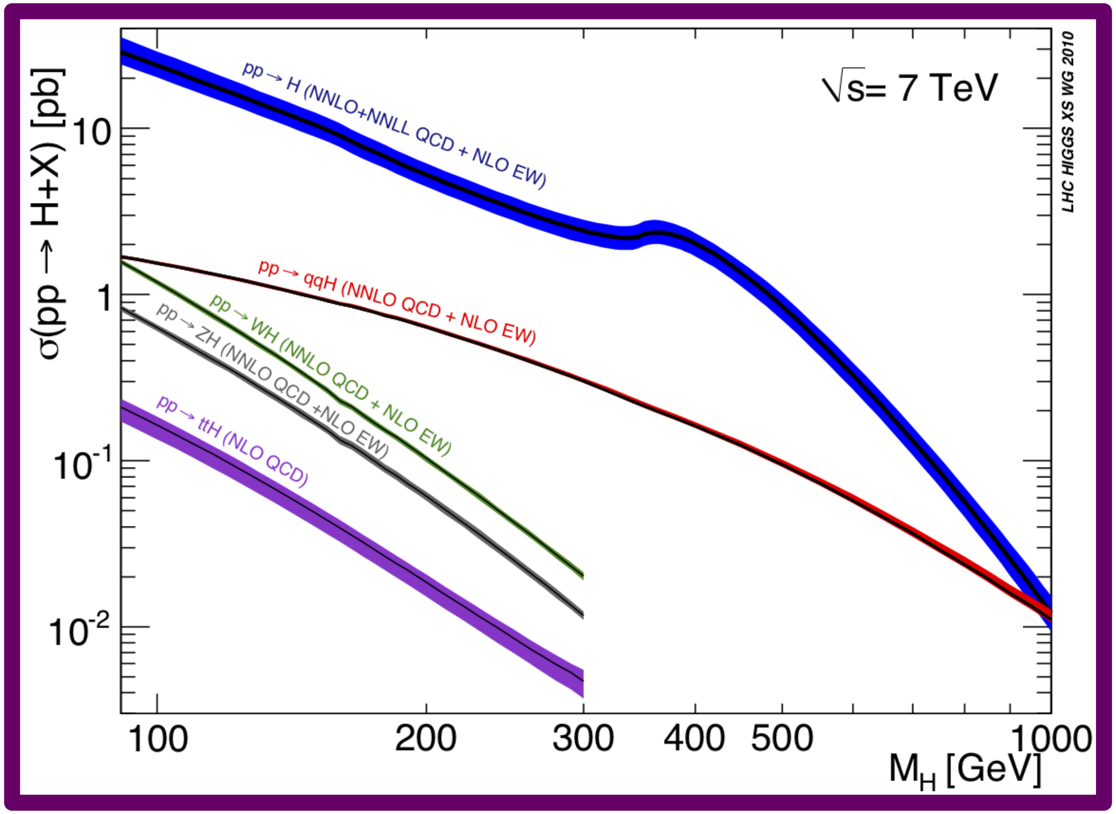
Today we understand <u>only 5%</u> of the Universe composition

Supersymmetry (a particle physics theory) predicts new (heavy) elementary particles, not yet observed. Among them the neutralino, our present best candidate for the Universe dark matter (its predicted features are in agreement with astrophysics observations and cosmological predictions).
It is expected to be light enough to be produced abundntly at the LHC



SM Higgs production cross section at LHC …

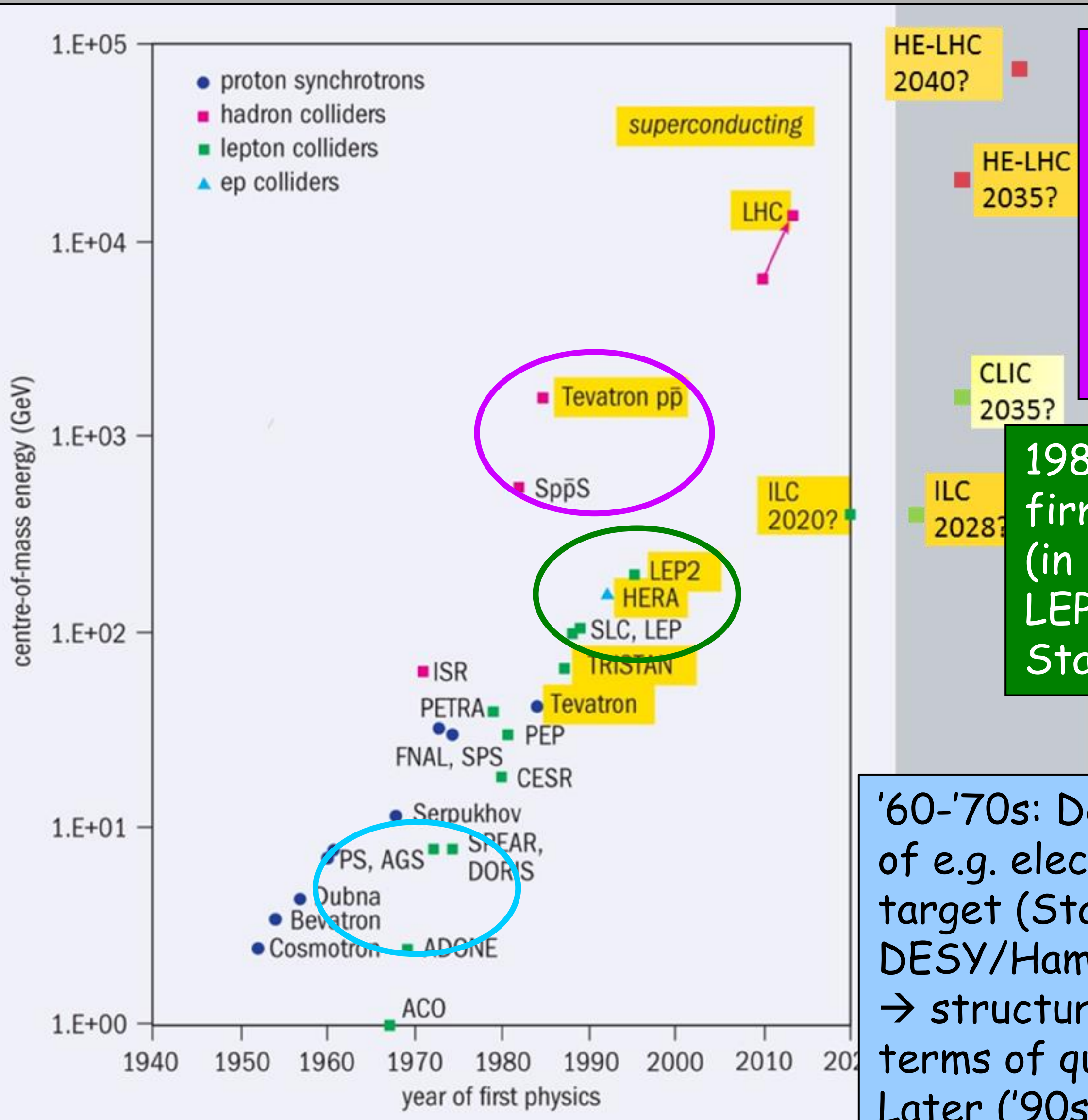




The role of accelerators

'30s-'50s: particle physics based mainly cosmic ray observations → discovery of e^+, μ, ..

Accelerator-based particle physics starts in the '50s: here only very few examples



1983: Discovery of W, Z bosons (m ~ 100 GeV) at CERN p-antip collider ($\sqrt{s} \leq$ 630 GeV)
1995: Discovery of the top quark (the heaviest elementary particle ever) at the Tevatron p-antip collider ($\sqrt{s} \leq$ 2 TeV) at Fermilab/Chicago

1989-2000: Standard Model put on very firm grounds by precision measurements (in particular of Z boson) at e^+e^- colliders: LEP at CERN ($\sqrt{s}$ → 209 GeV) and Stanford Linear Collider ($\sqrt{s}$ ~ 90 GeV)

'60-'70s: Deep inelastic scattering of e.g. electron beams on fixed target (Stanford, DESY/Hamburg, etc.):
→ structure of n and p in terms of quark constituents
Later ('90s): HERA ep collider