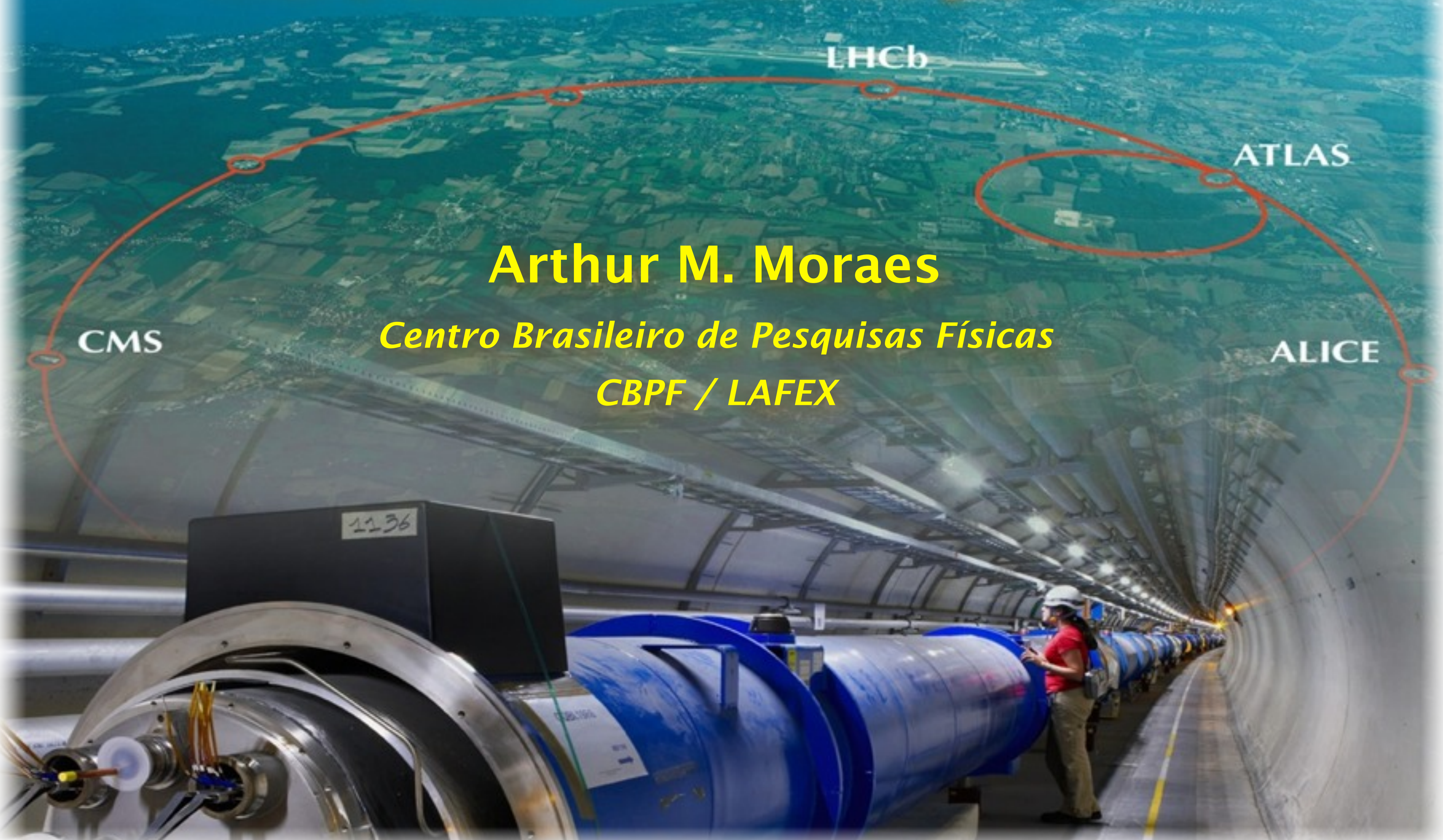
On the trail of LHC discoveries: scientific advances that accelerate more than sub-atomic particles



Arthur M. Moraes

Centro Brasileiro de Pesquisas Físicas

CBPF / LAFEX

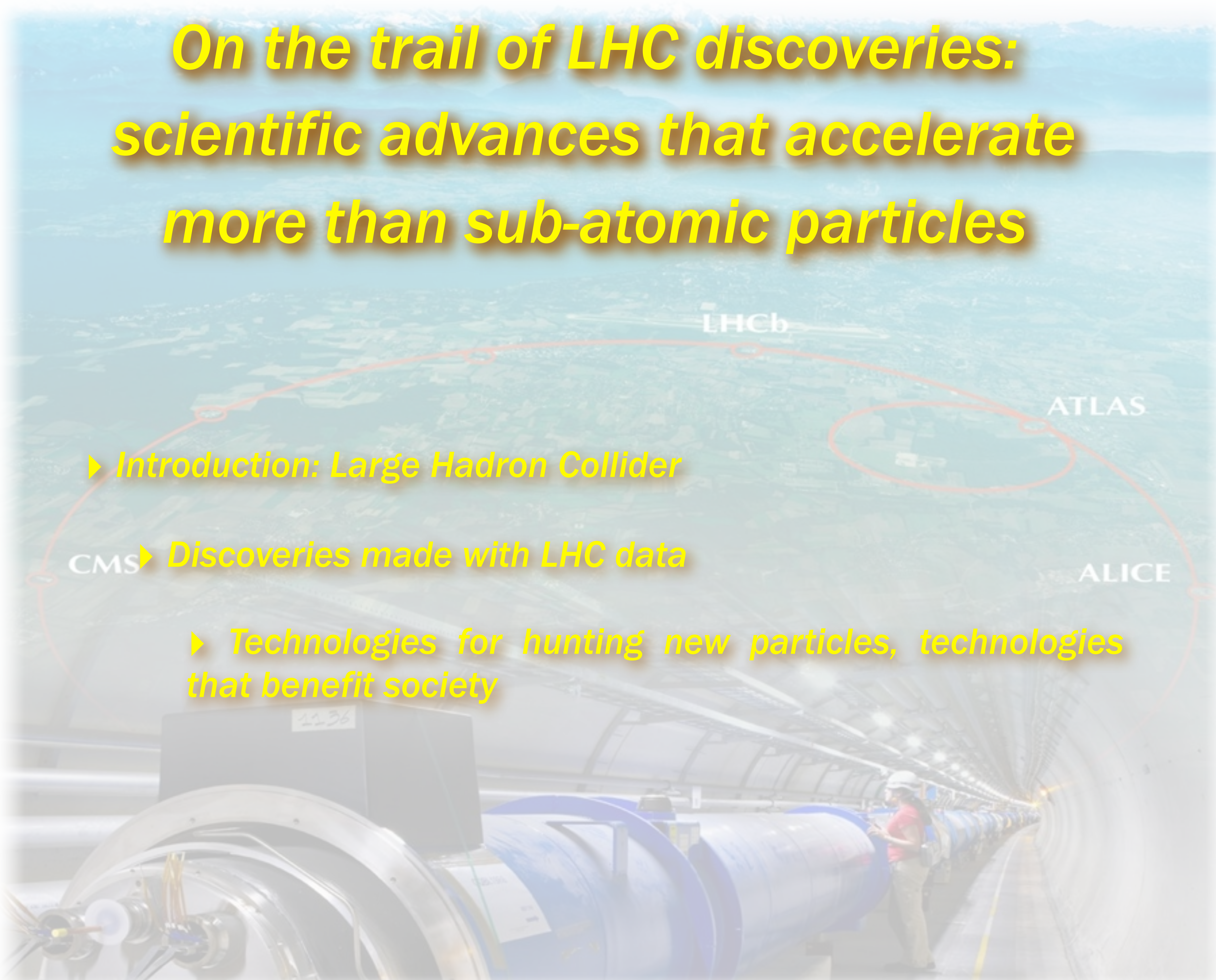
CBPF
Centro Brasileiro de Pesquisas Físicas

The Academy of Sciences of the Czech Republic - Institute of Physics

Fyzikální ústav
Akademie věd ČR, v. v. i.

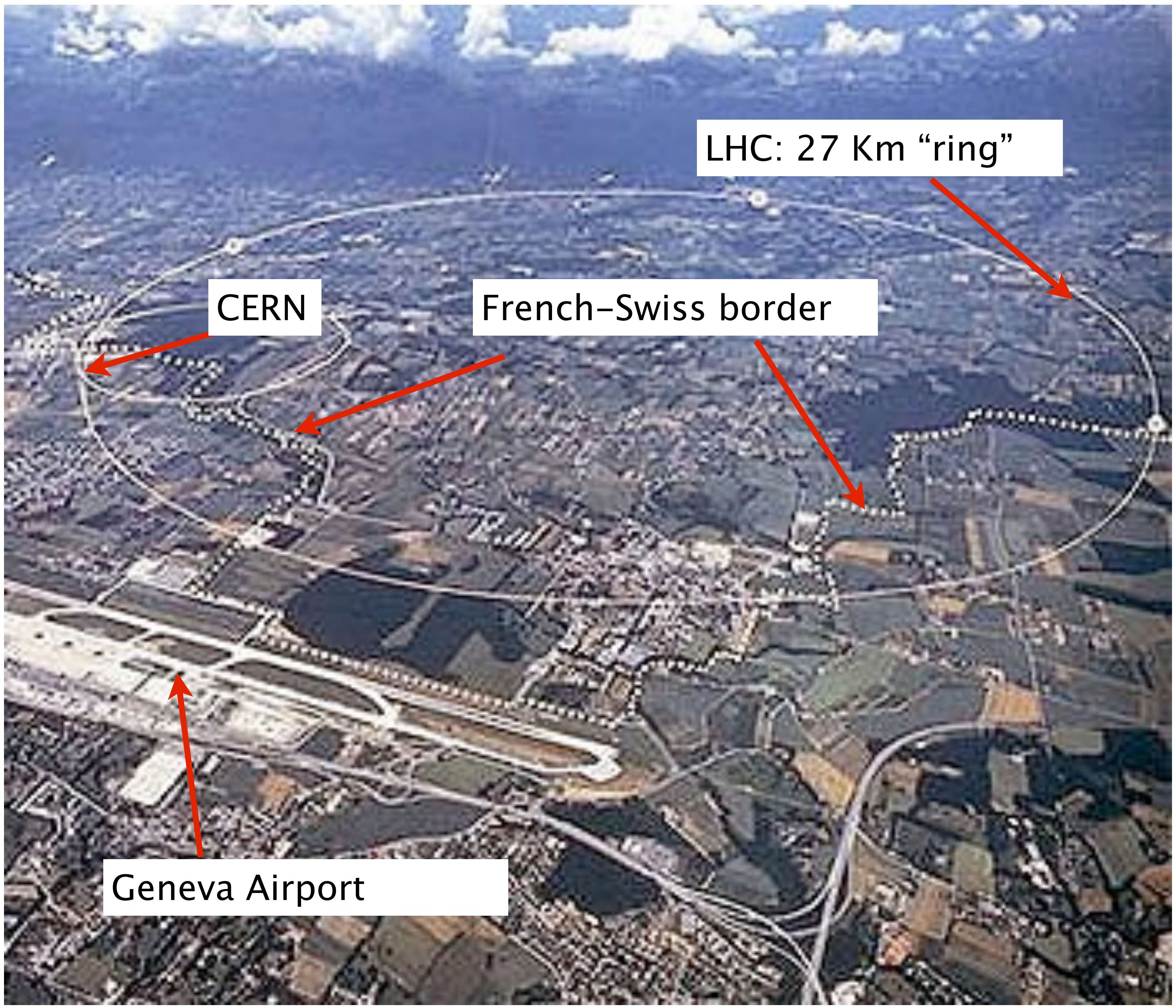
19th June 2013

On the trail of LHC discoveries: scientific advances that accelerate more than sub-atomic particles

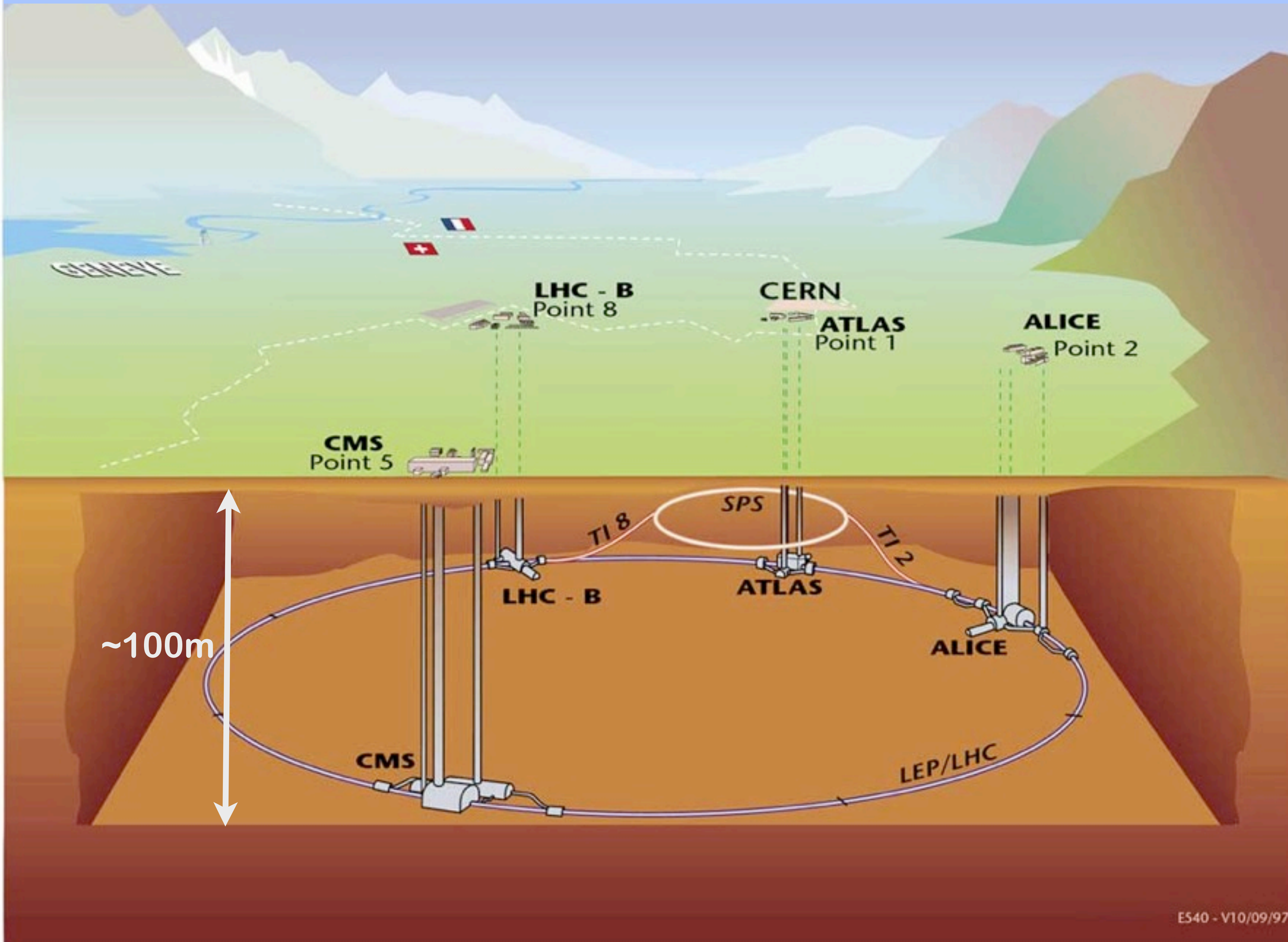


- *Introduction: Large Hadron Collider*
- *Discoveries made with LHC data*
- *Technologies for hunting new particles, technologies that benefit society*

- The LHC is a circular accelerator built in an underground tunnel, ~100m deep, under the French-Swiss border.
  - Two proton beams are accelerated in opposite directions, close to the speed of light.
    - The proton beams are brought together in 4 crossing points where detectors record the collision products.



Four experiments are analysing the collision products at the LHC: ATLAS, CMS, ALICE and LHCb



The Large Hadron Collider - CERN


Image courtesy of CERN

- Energy of centre-of-mass in proton collision: 14TeV !

  ~7 times greater than what had been achieved in previous accelerators

- Trillions of protons race through a 27km tunnel

  ~11.000 laps per second!

  99.999999% of the light speed!

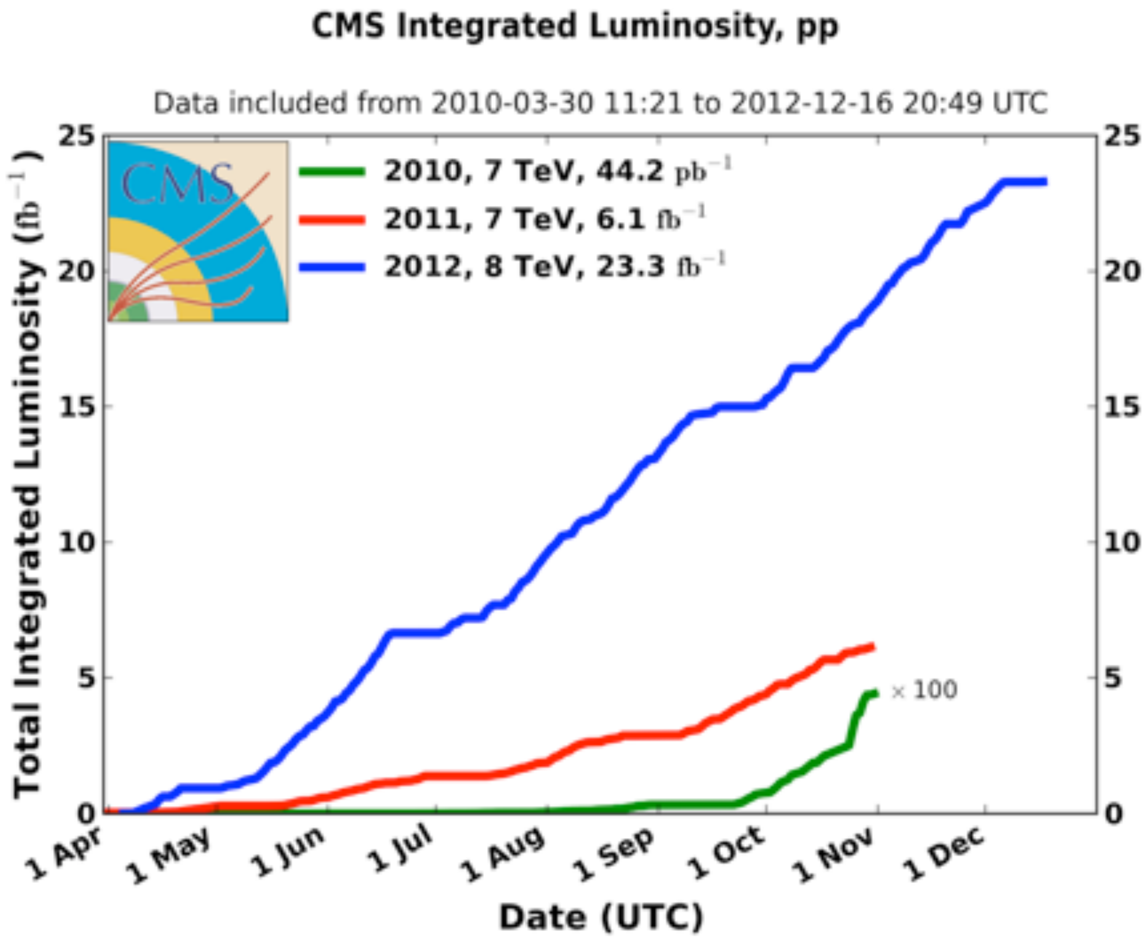
- The biggest and most complex detectors ever built will study the smallest particles with the highest precision.

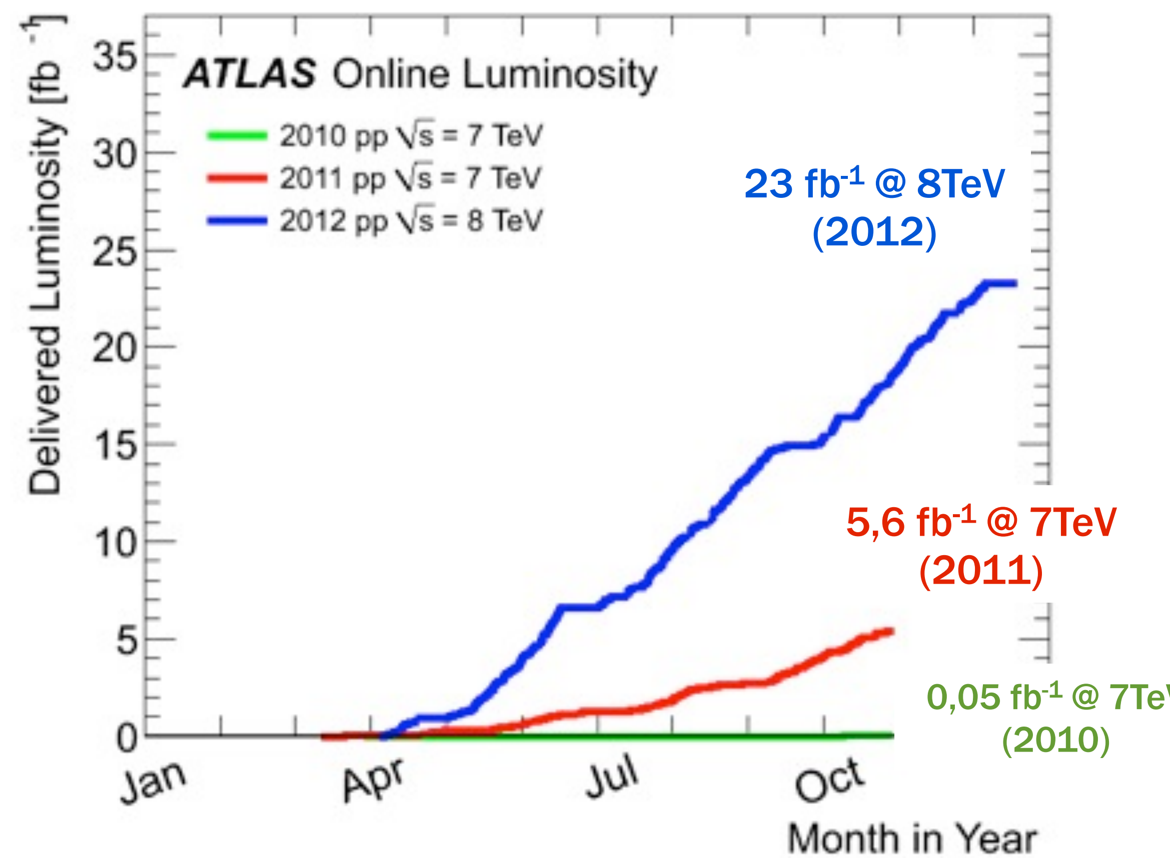
- The coldest place in the Galaxy: -271°C

- Hotter than the stars: proton collisions generate temperatures thousands of times hotter than those found in the centre of our Sun.

- A global adventure: more than 10,000 scientists coming from 70 countries. An investment that cost over 10 billion US dollars over 20 years.

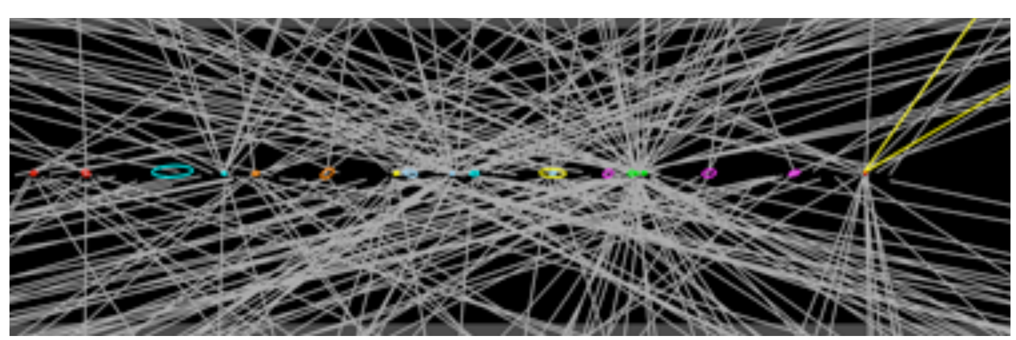
LHC proton collisions: exploring the energy frontier





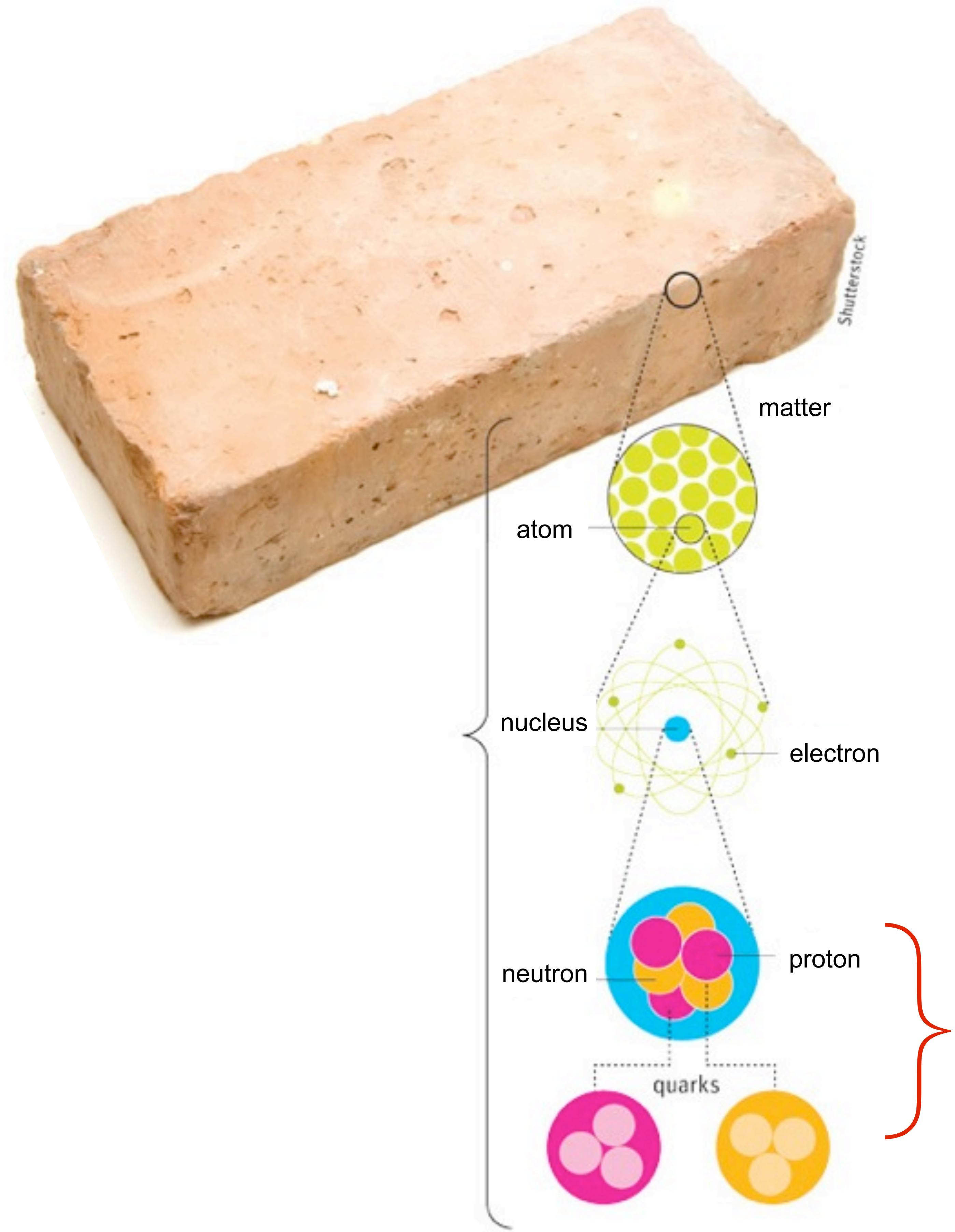
~5 billion collisions registered (by each experiment)

~120 PB of data ("actual" data and simulated events in each experiment!)



Pile-up of collisions

Main goal of the LHC: advance science!

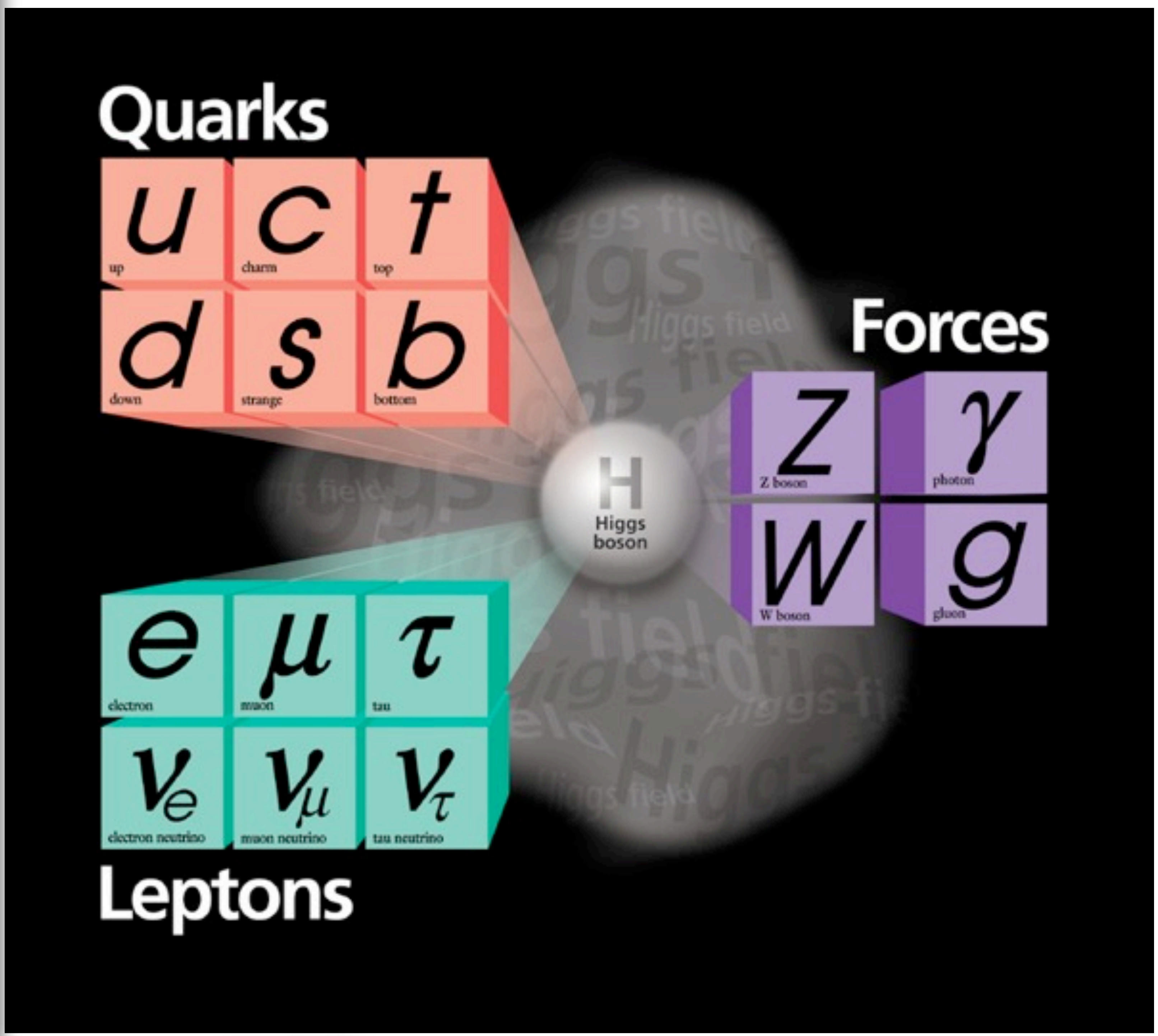


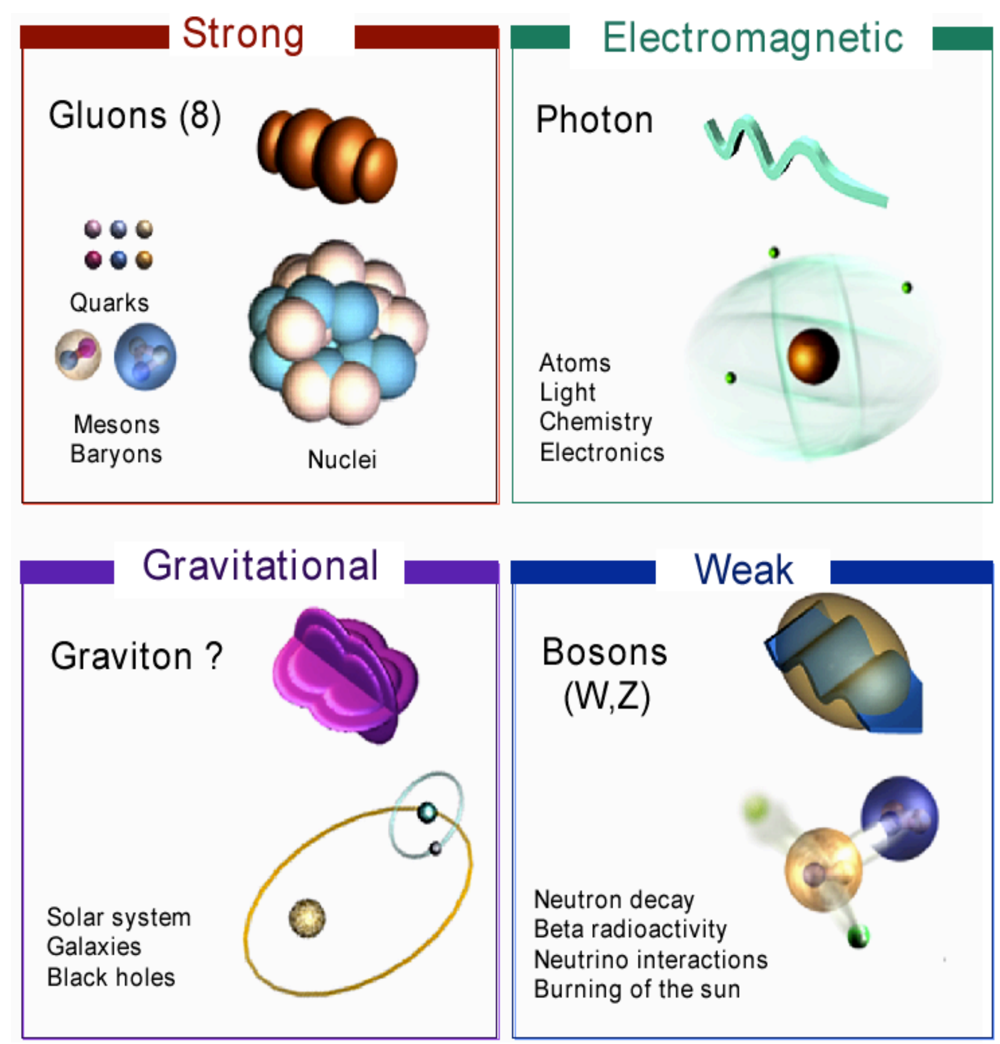
Particle accelerators are necessary to investigate the inner structure of the atom.

– particle accelerators operate like giant microscopes

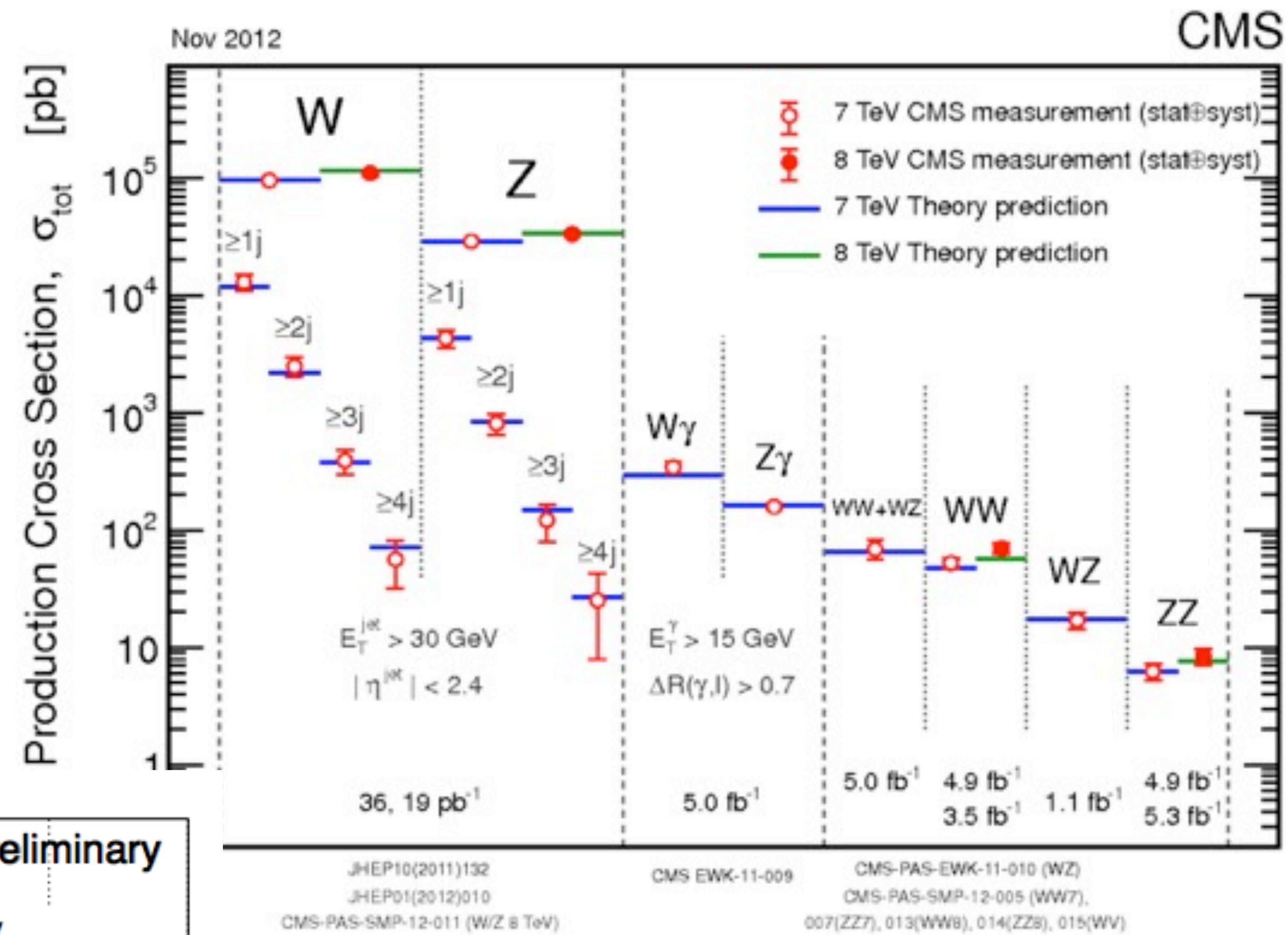
Elementary particles and interactions

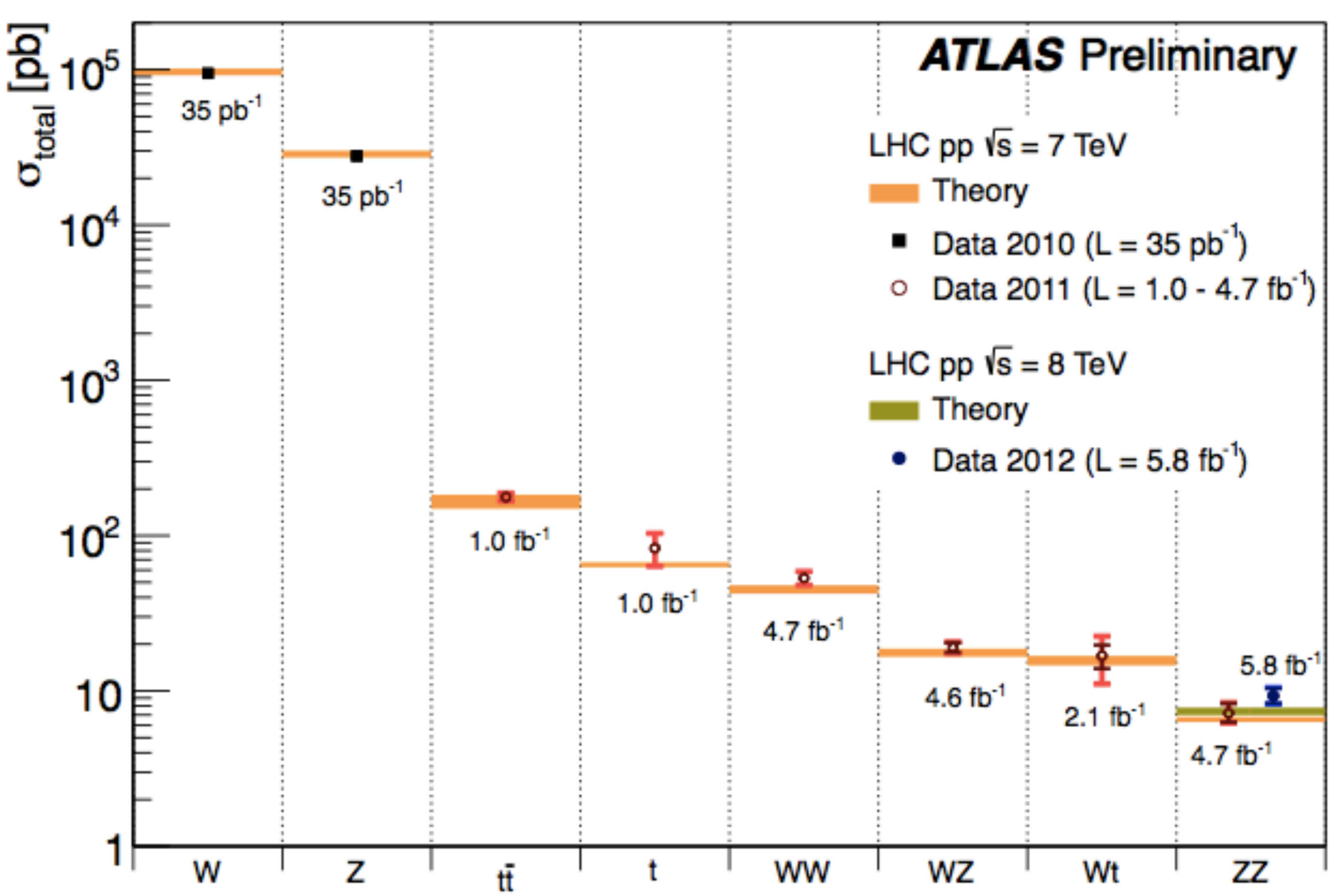
▸ The elementary particles and their interactions are described by a theory, known as the “Standard Model”, which has been experimentally verified with extreme precision by various laboratories.





▸ Standard Model predictions have been confirmed again and again by many generations of experiments over the past 40 years (including LHC experiments...)



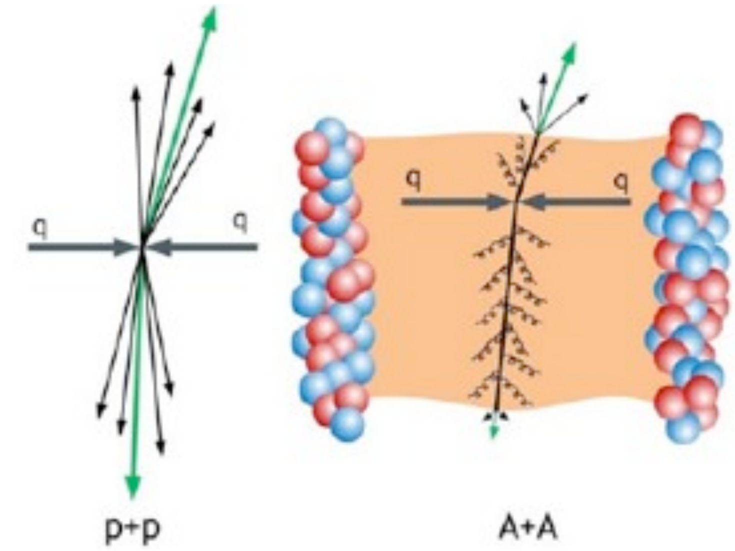


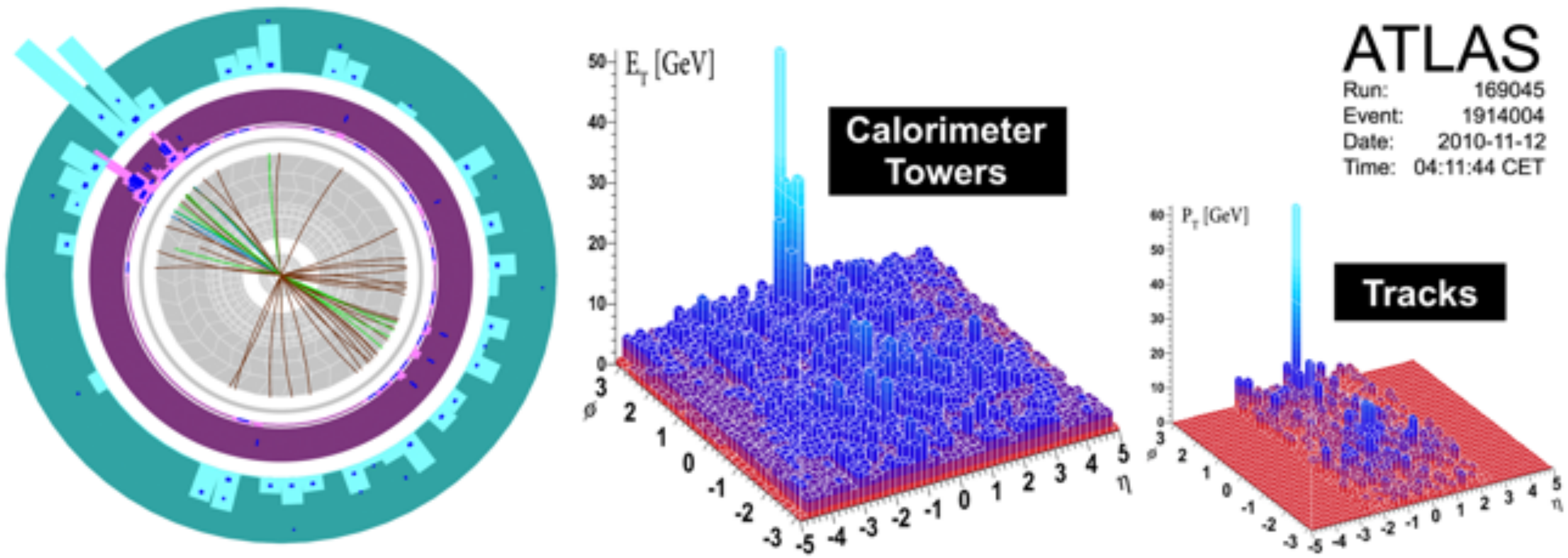
Over 800 scientific papers have now been published by the LHC's experimental collaborations: results confirm the SM predictions!

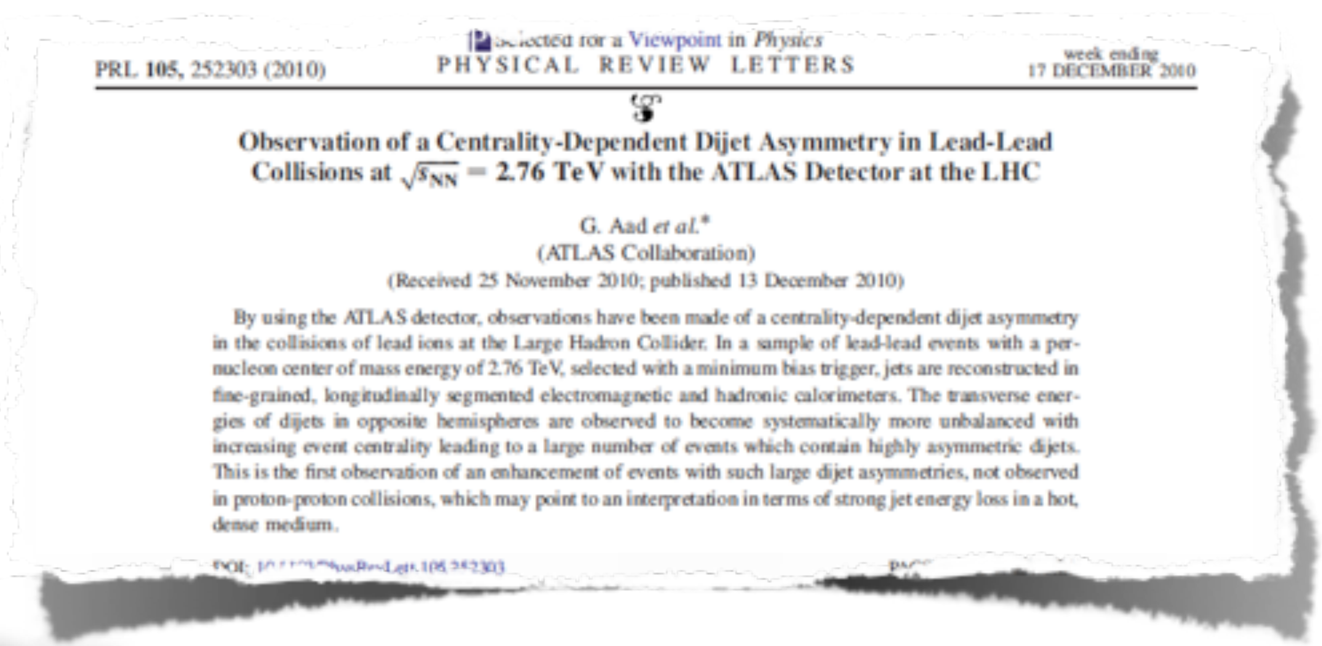
Some discoveries made with LHC data...

An unknown sub-atomic particle waiting to be discovered.

November 2010: first direct observation of "jet quenching" in heavy-ion collisions






Selected for a Viewpoint in Physics
PRL 105, 252303 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC

G. Aad *et al.**
(ATLAS Collaboration)
(Received 25 November 2010; published 13 December 2010)

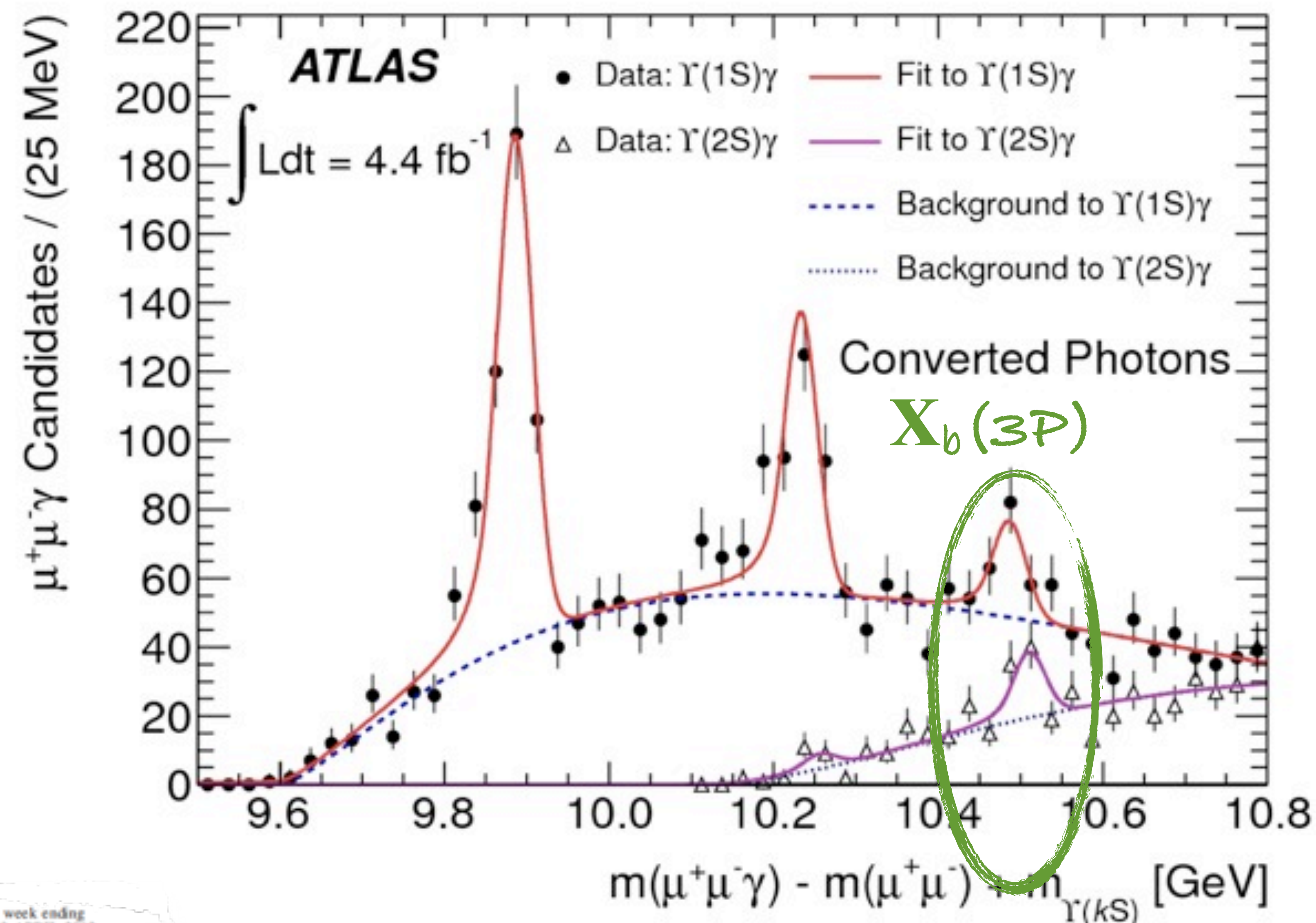
By using the ATLAS detector, observations have been made of a centrality-dependent dijet asymmetry in the collisions of lead ions at the Large Hadron Collider. In a sample of lead-lead events with a per-nucleon center of mass energy of 2.76 TeV, selected with a minimum bias trigger, jets are reconstructed in fine-grained, longitudinally segmented electromagnetic and hadronic calorimeters. The transverse energies of dijets in opposite hemispheres are observed to become systematically more unbalanced with increasing event centrality leading to a large number of events which contain highly asymmetric dijets. This is the first observation of an enhancement of events with such large dijet asymmetries, not observed in proton-proton collisions, which may point to an interpretation in terms of strong jet energy loss in a hot, dense medium.

November 2011: new particle discovered at the LHC

Quarkonium

$\chi_b(3P) \rightarrow \Upsilon(1S, 2S)\gamma \rightarrow \mu^+\mu^-\gamma$

(meson)



PRL 108, 152001 (2012) PHYSICAL REVIEW LETTERS week ending 13 APRIL 2012

Observation of a New χ_b State in Radiative Transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$ at ATLAS

G. Aad *et al.**
(ATLAS Collaboration)

(Received 21 December 2011; revised manuscript received 18 February 2012; published 9 April 2012)

The $\chi_b(nP)$ quarkonium states are produced in proton-proton collisions at the Large Hadron Collider at $\sqrt{s} = 7$ TeV and recorded by the ATLAS detector. Using a data sample corresponding to an integrated luminosity of 4.4 fb^{-1}, these states are reconstructed through their radiative decays to $\Upsilon(1S, 2S)$ with $\Upsilon \rightarrow \mu^+\mu^-$. In addition to the mass peaks corresponding to the decay modes $\chi_b(1P, 2P) \rightarrow \Upsilon(1S)\gamma$, a new structure centered at a mass of $10.530 \pm 0.005(\text{stat}) \pm 0.009(\text{syst})$ GeV is also observed, in both the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ decay modes. This structure is interpreted as the $\chi_b(3P)$ system.

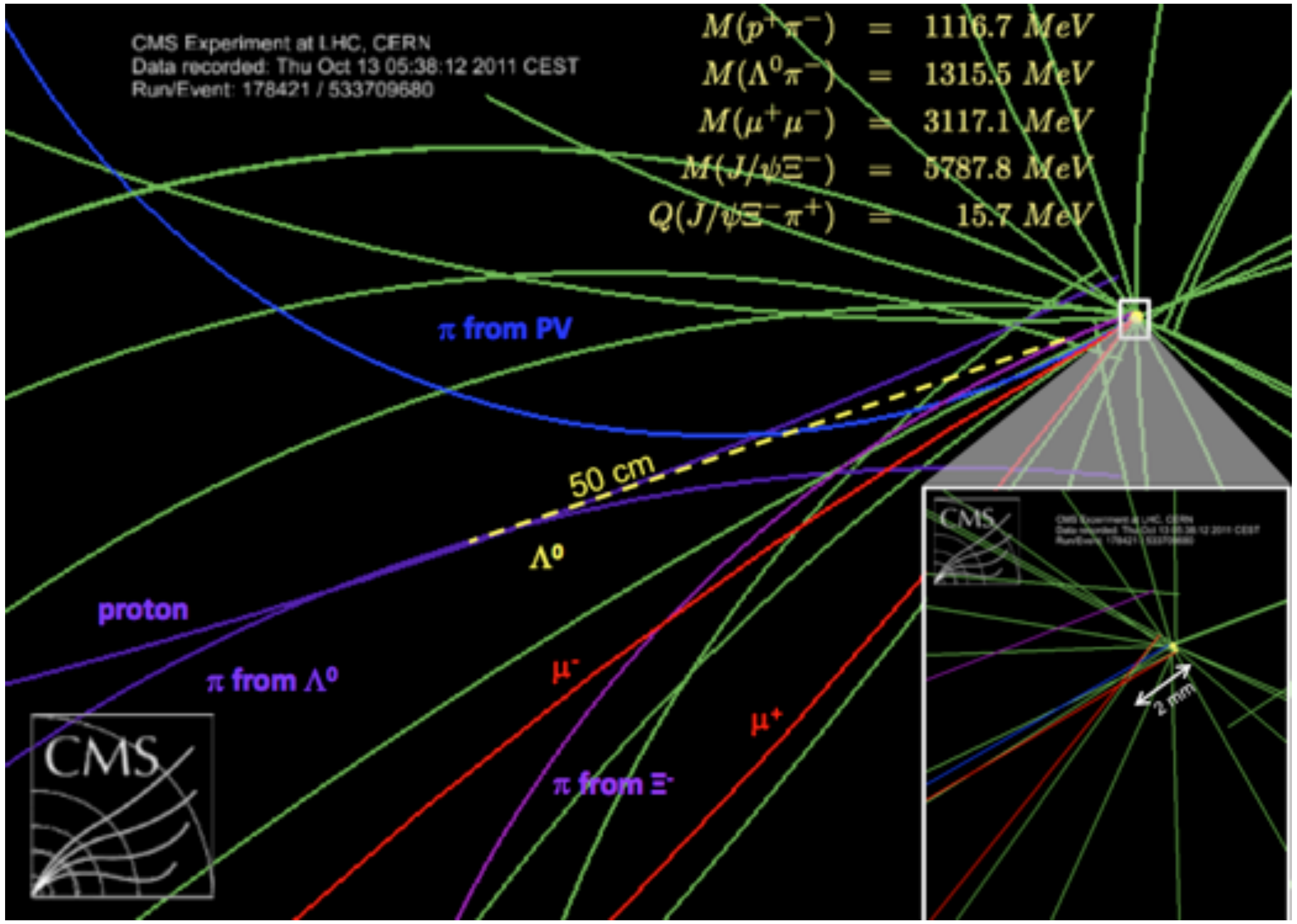
$\chi_b(1P)$ m=9.9GeV

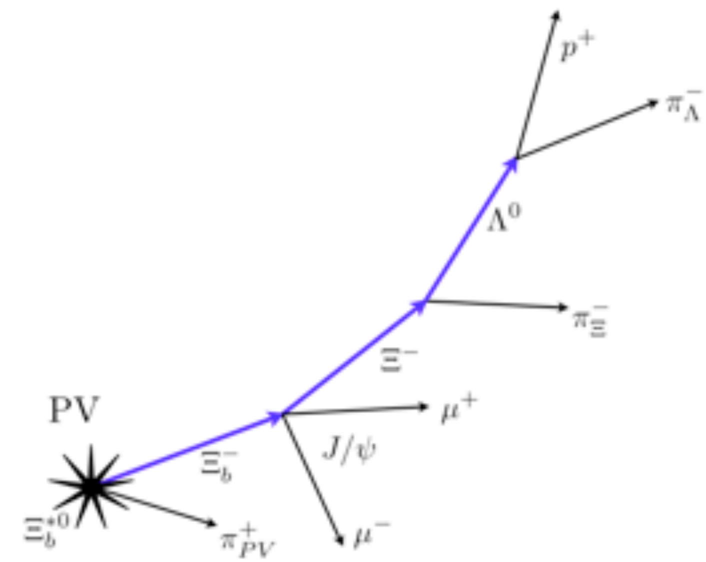
$\chi_b(2P)$ m=10.2GeV

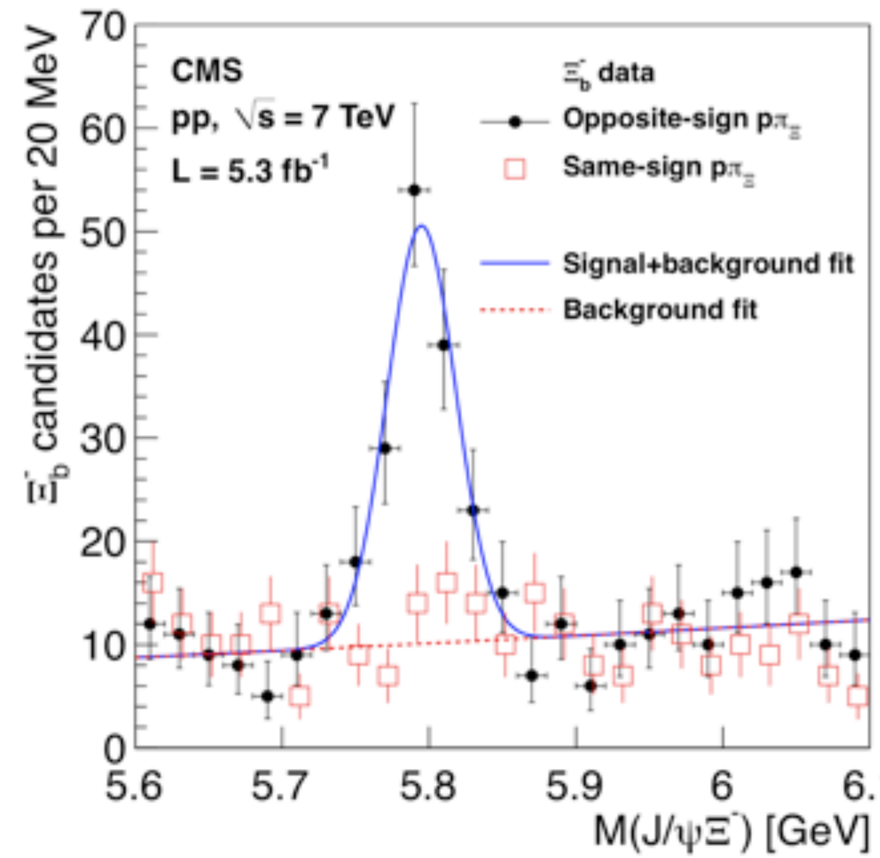
Observed peak at m=10.5GeV

$\chi_b(3P)$

May 2012: observation of a new barion $\Xi^{*}{}_{b}{}^{0}$







$\Xi^{*}{}_{b}{}^{0} \rightarrow \Xi^{-}{}_{b}\, \pi^{+}$

$\Xi^{-}{}_{b} \rightarrow J/\Psi\ \Xi^{-}$

A long wait: the existence of a "Higgs boson" was predicted in 1964.

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

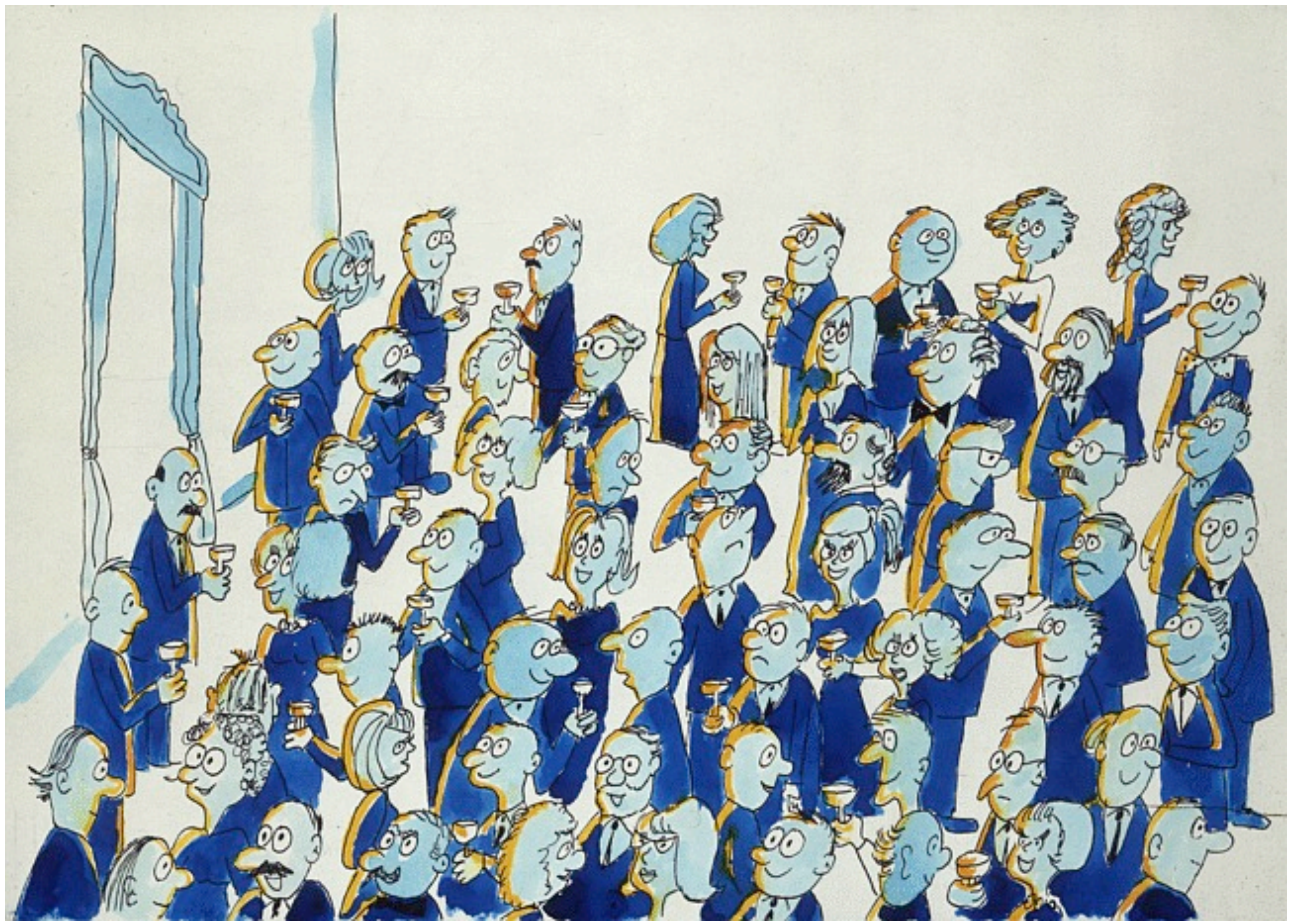
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

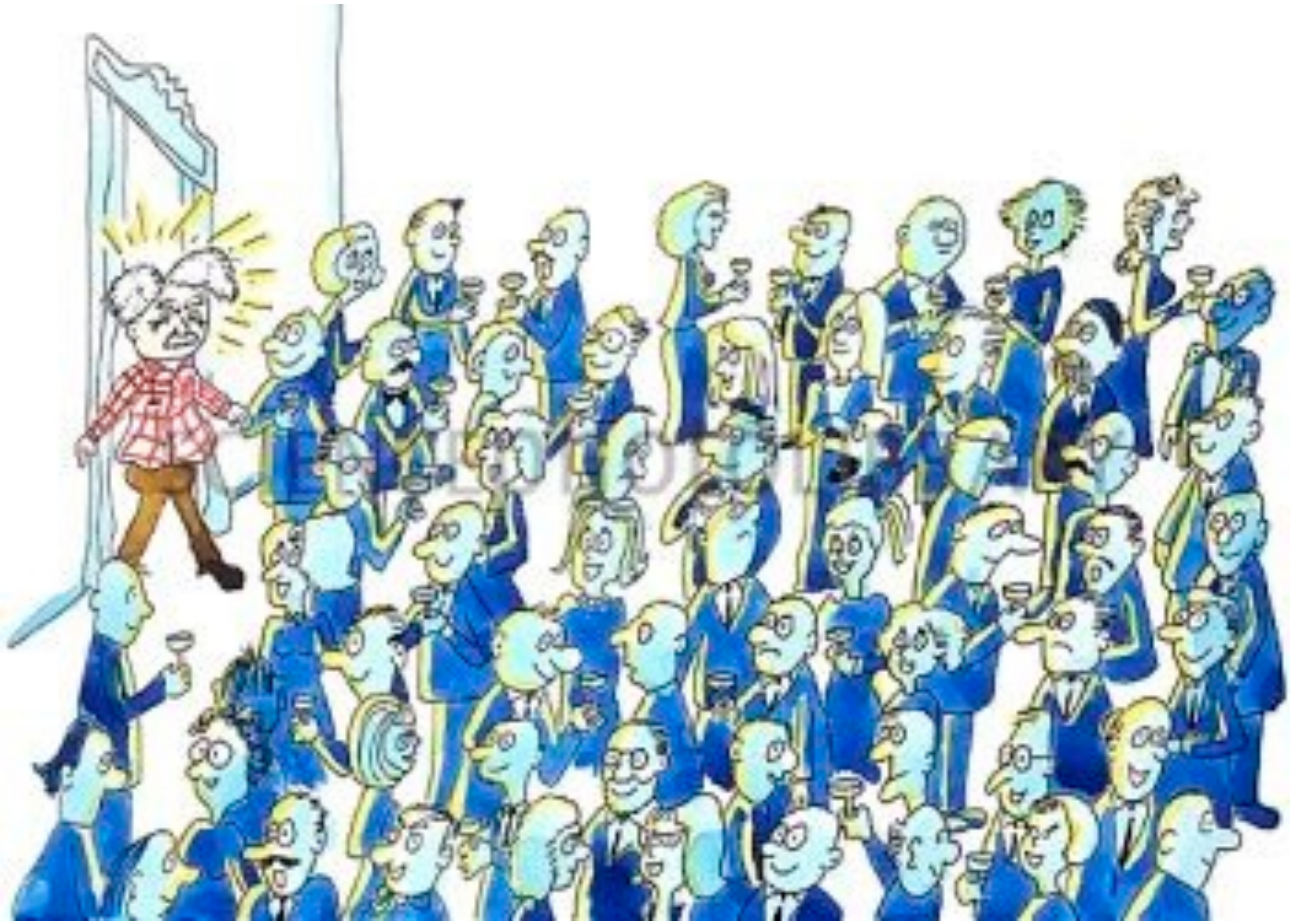
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Peter Higgs visiting the LHC tunnel

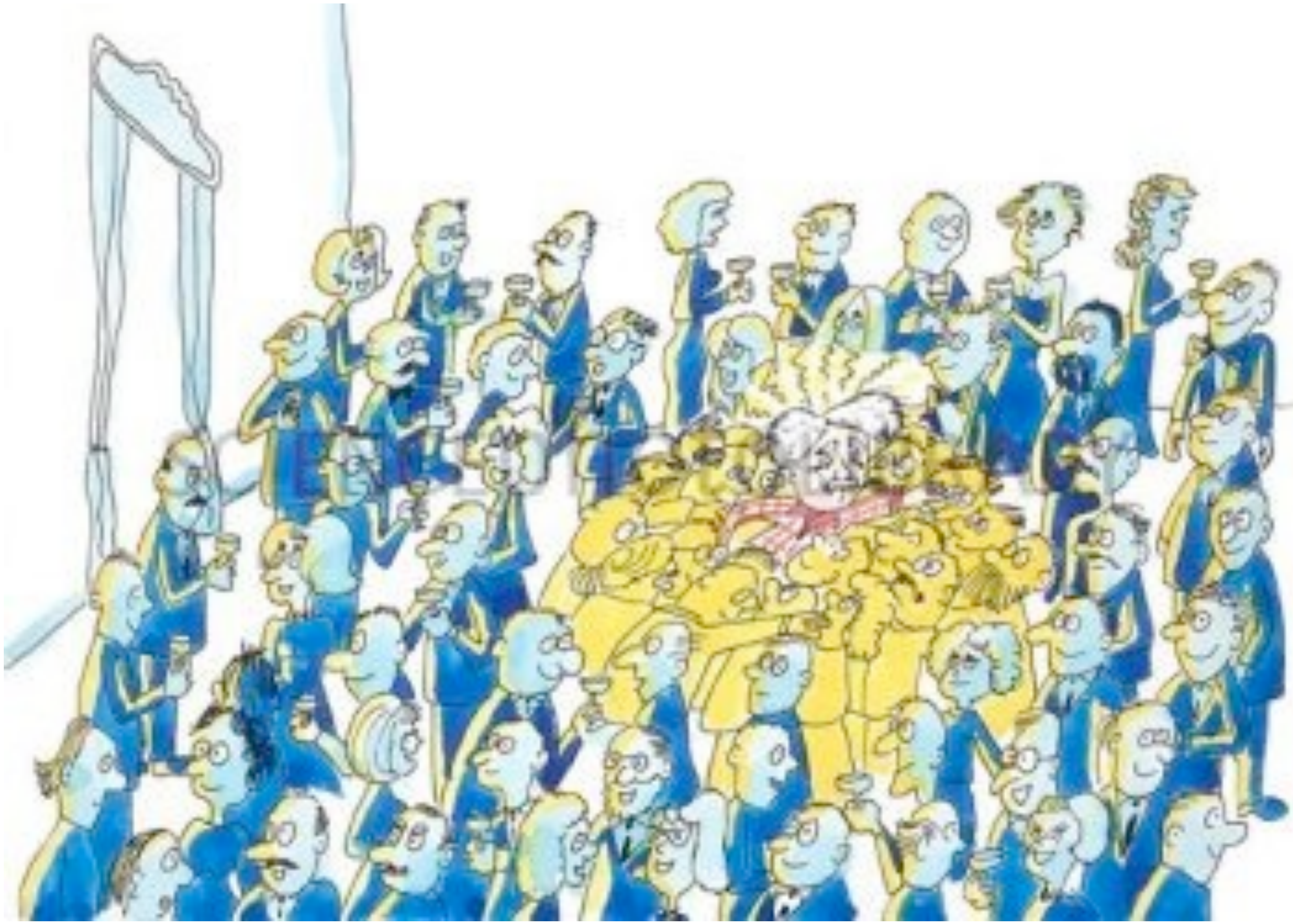
Imagine a ballroom filled with physicists calmly chatting and fraternising...that would be equivalent to the space filled with the Higgs potential



...then, a famous scientist walks into the room causing a "disturbance" as he walks through the room, attracting a group of admirers as he moves around.



…the "fan frenzy" directed at the celebrity increases the resistance of movement, in other words he acquires mass as a particle does when interacting with the Higgs field.

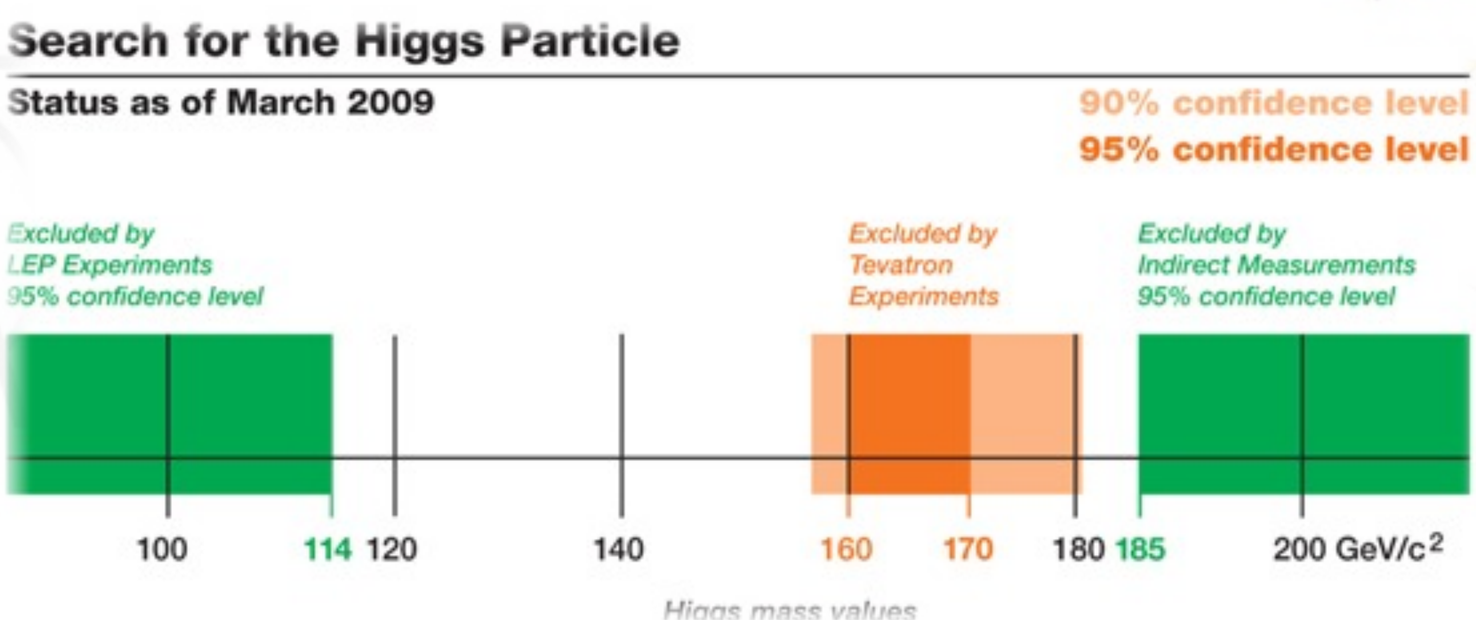


The hunt for the Higgs boson...

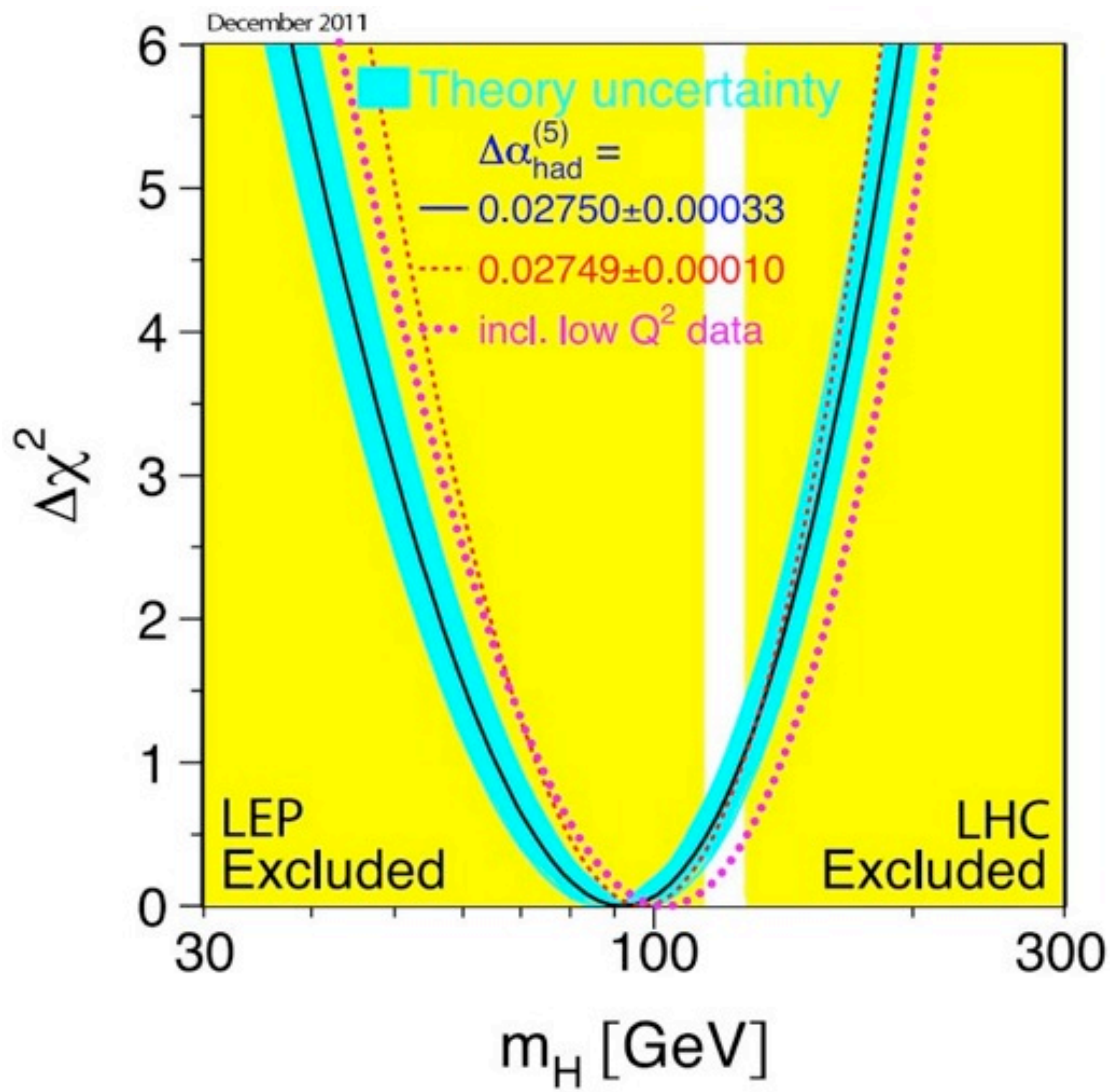
Over 30 years of experimental searches!

LEP/CERN: e+e- collisions

Tevatron/Fermilab: p+p- collisions

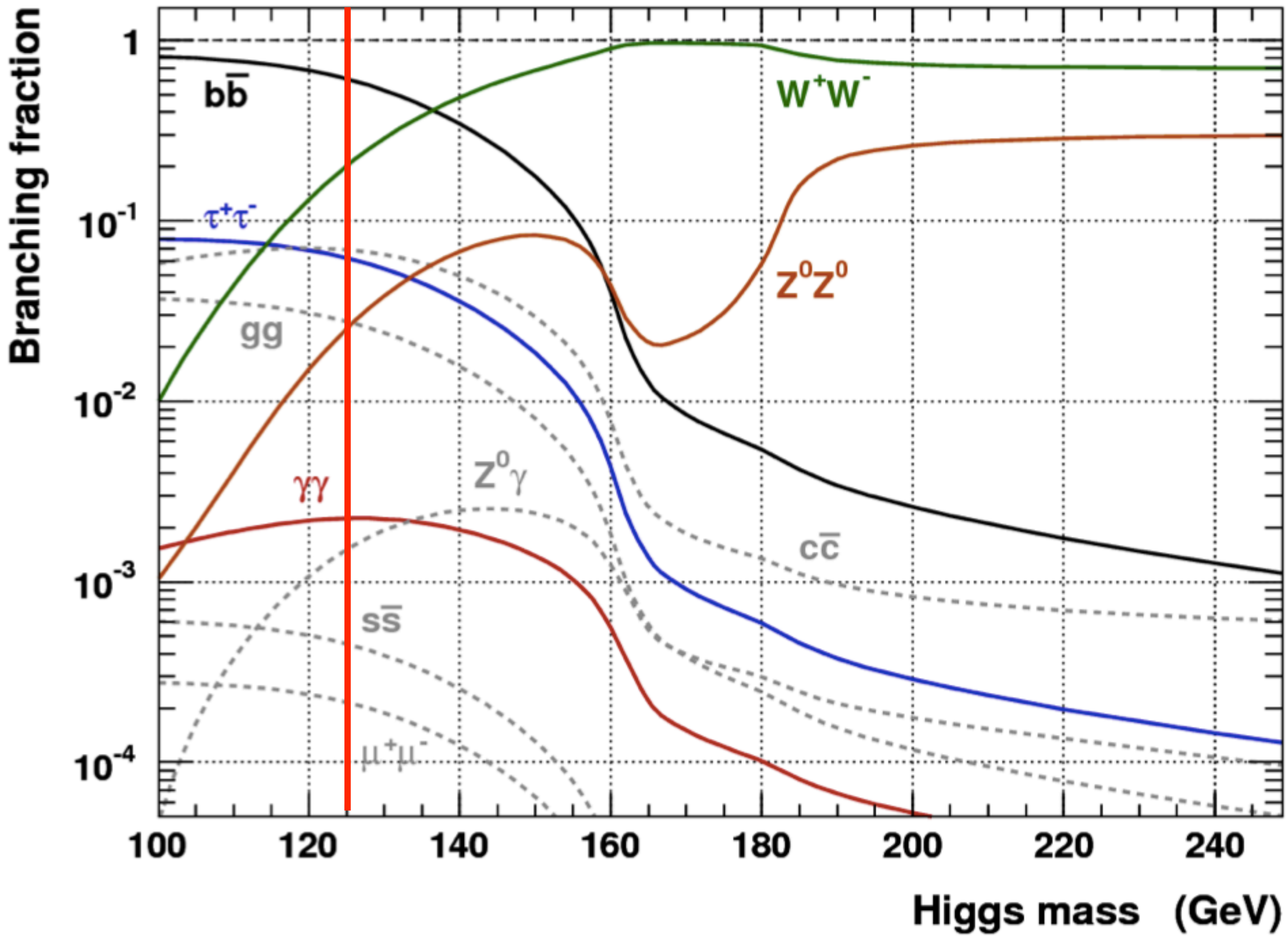


- There was a fundamental prediction from the Standard Model which lacked experimental evidence: no sign of a particle corresponding to the Higgs boson had been observed!



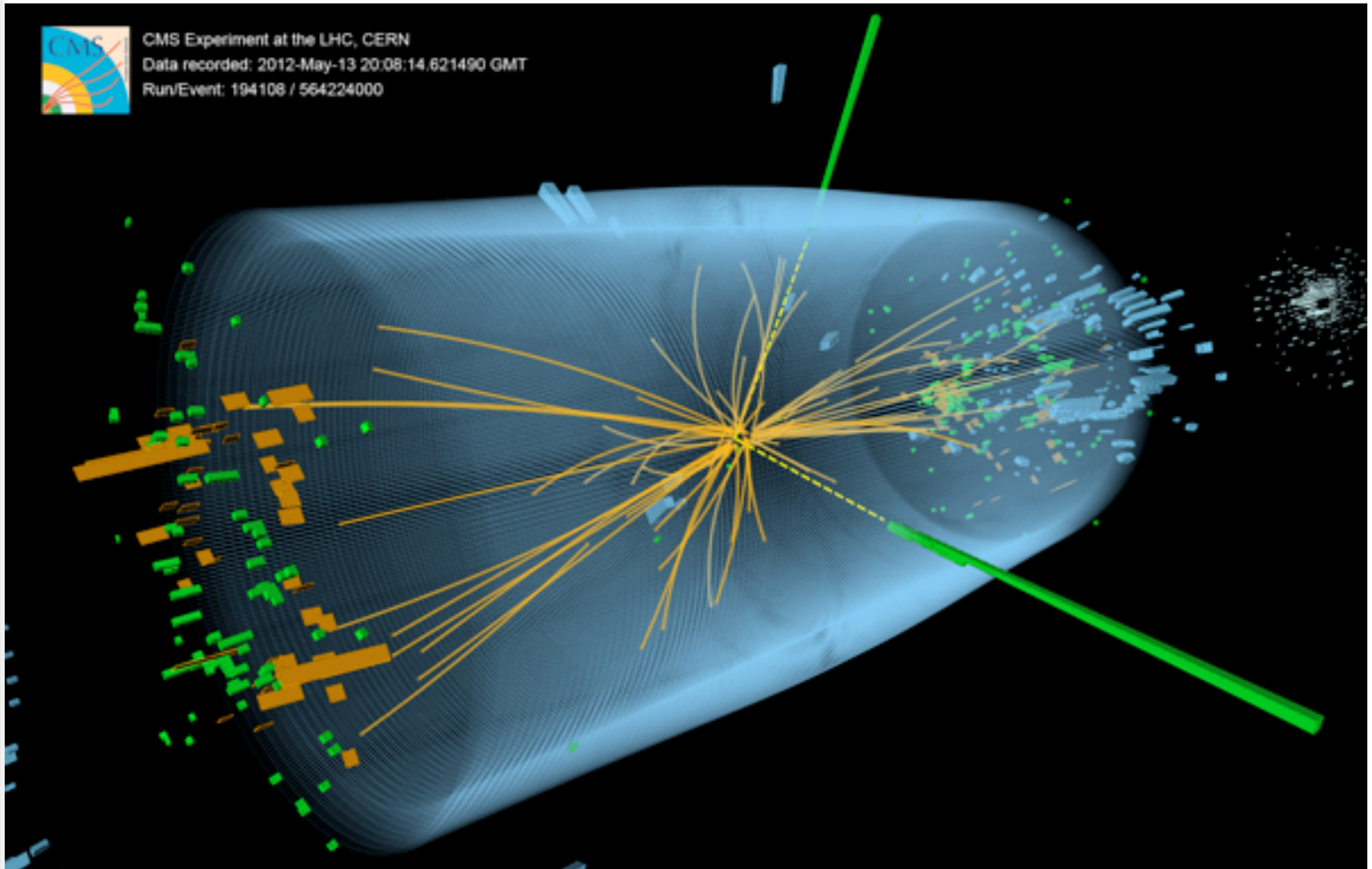

Where is
WALLY?
Higgs?

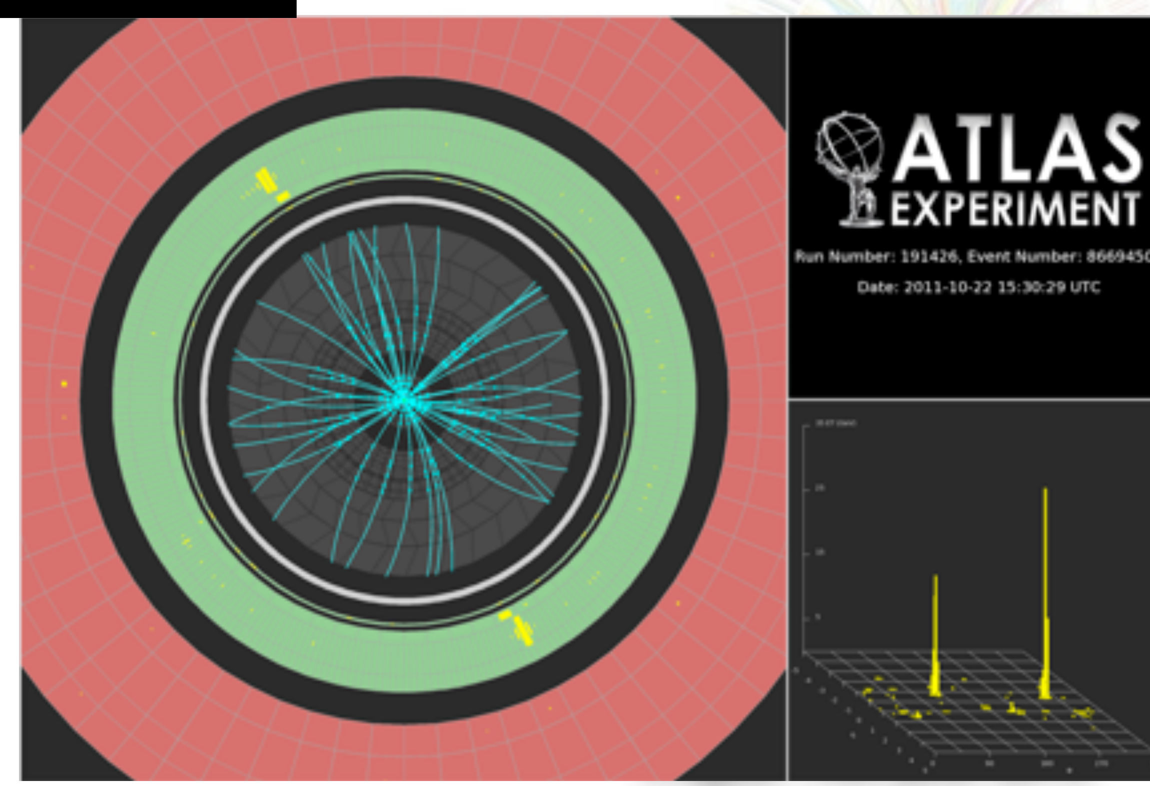
Higgs boson decay modes

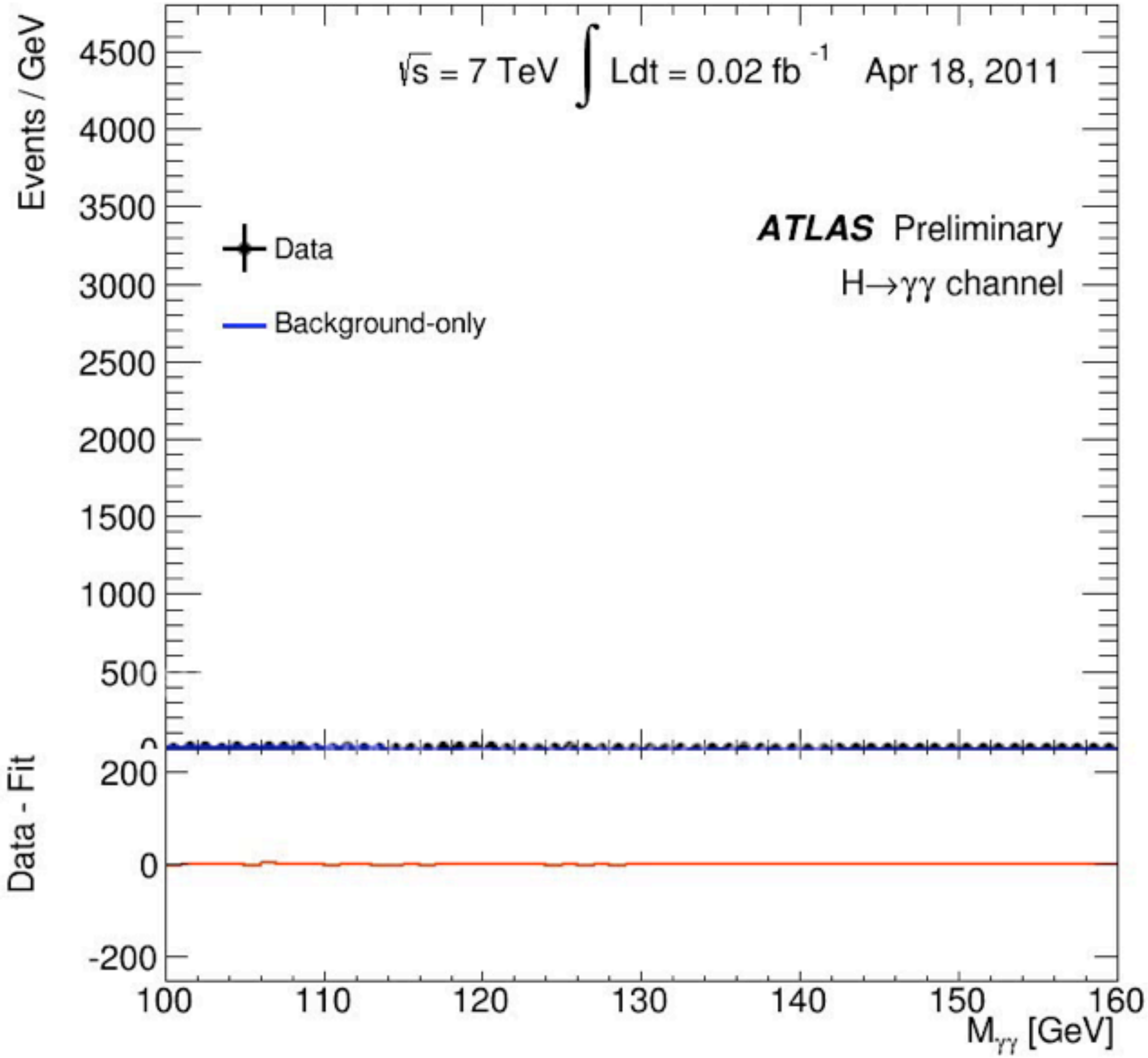


The Higgs boson typically decays in ~10^{-22} s.

H→γγ

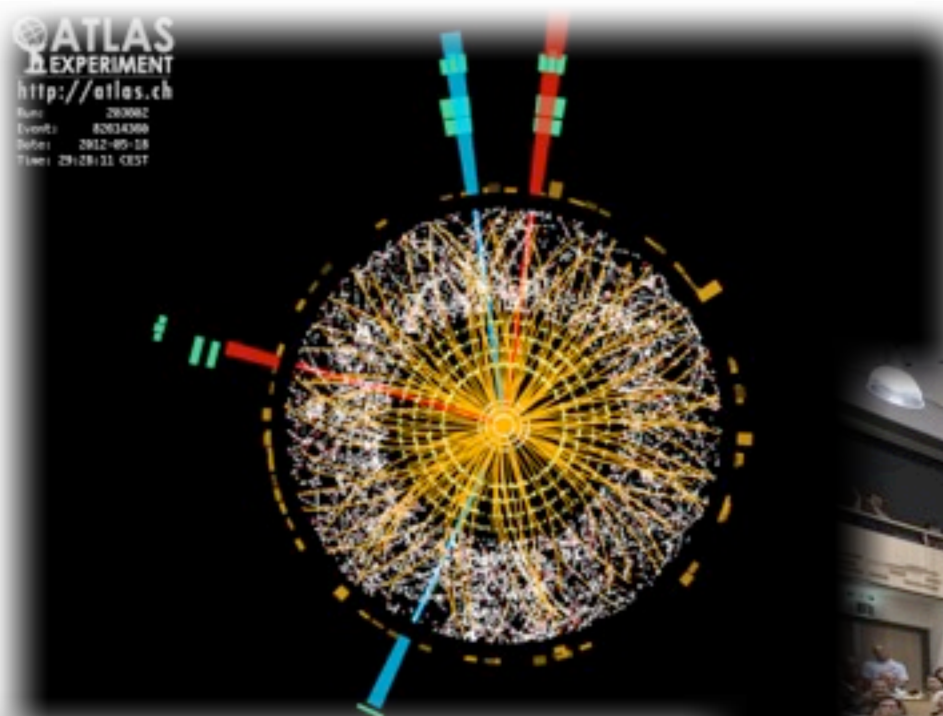

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

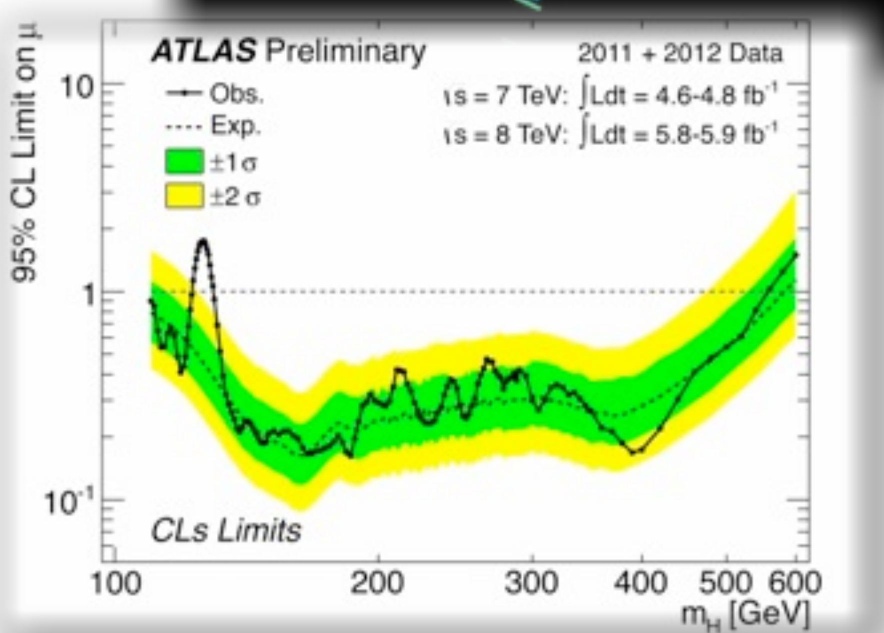

ATLAS
EXPERIMENT
Run Number: 191426, Event Number: 86694500
Date: 2011-10-22 15:30:29 UTC



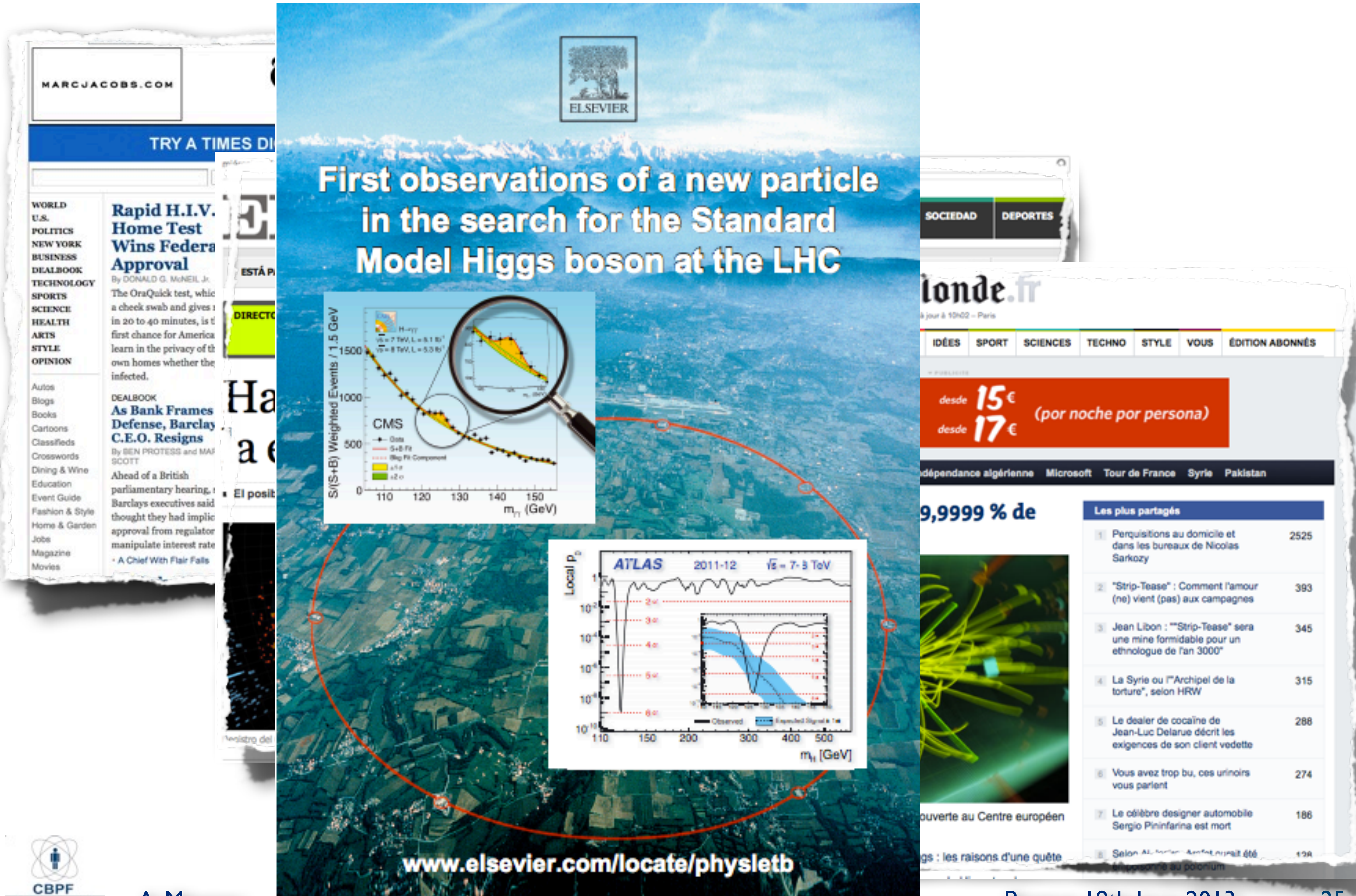
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
√s = 7 TeV ∫ Ldt = 0.02 fb -1 Apr 18, 2011
Data
Background-only
ATLAS Preliminary
H→γγ channel
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]

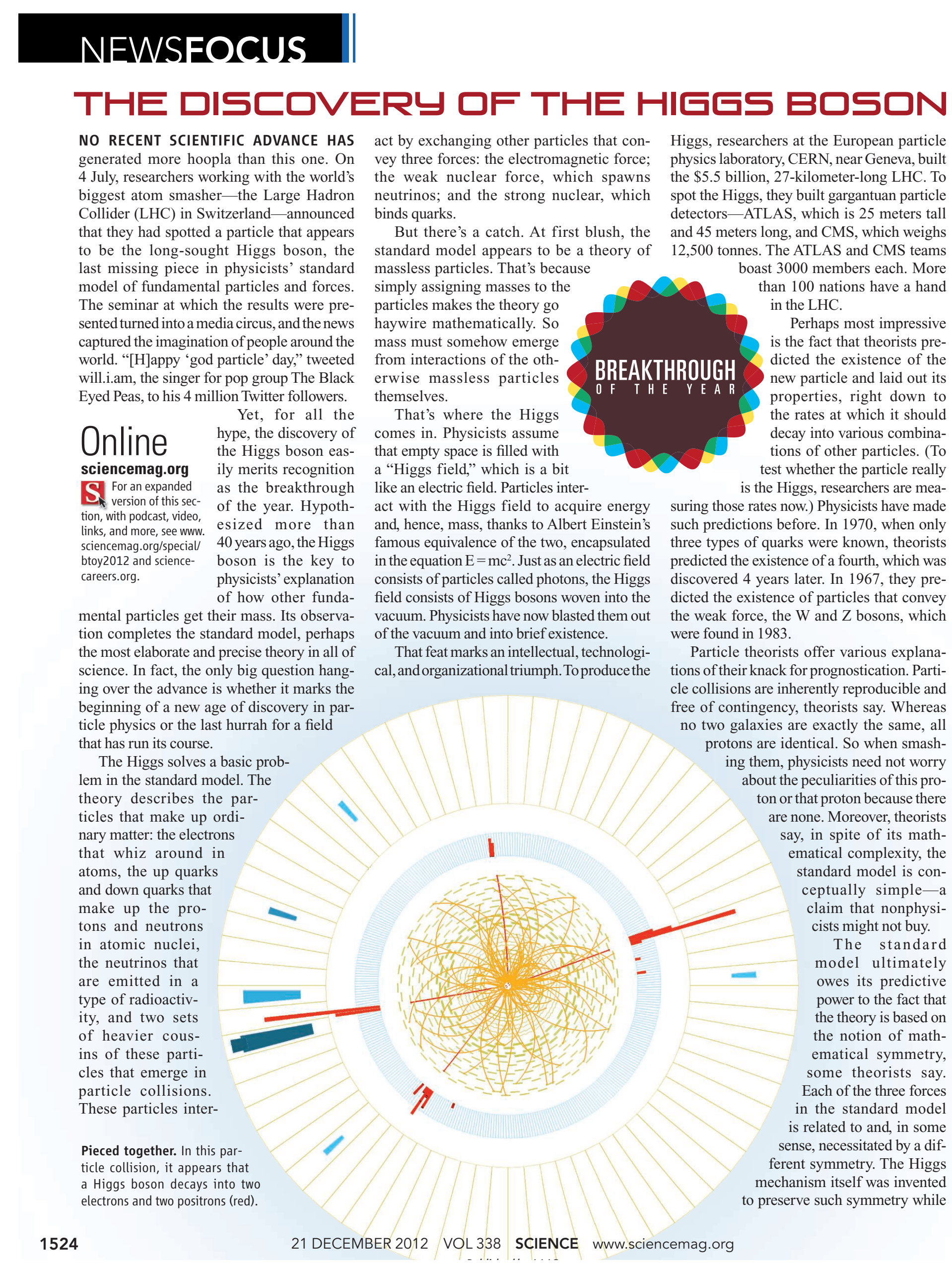
4th of July 2012: CERN announces the observation of a “new particle”





4th of July 2012: witnessing history being made!





THE DISCOVERY OF THE HIGGS BOSON

NO RECENT SCIENTIFIC ADVANCE HAS generated more hoopla than this one. On 4 July, researchers working with the world's biggest atom smasher—the Large Hadron Collider (LHC) in Switzerland—announced that they had spotted a particle that appears to be the long-sought Higgs boson, the last missing piece in physicists' standard model of fundamental particles and forces. The seminar at which the results were presented turned into a media circus, and the news captured the imagination of people around the world. "[H]appy 'god particle' day," tweeted will.i.am, the singer for pop group The Black Eyed Peas, to his 4 million Twitter followers.

Online
sciencemag.org
For an expanded version of this section, with podcast, video, links, and more, see www.sciencemag.org/special/btoy2012 and sciencecareers.org.

Yet, for all the hype, the discovery of the Higgs boson easily merits recognition as the breakthrough of the year. Hypothesized more than 40 years ago, the Higgs boson is the key to physicists' explanation of how other fundamental particles get their mass. Its observation completes the standard model, perhaps the most elaborate and precise theory in all of science. In fact, the only big question hanging over the advance is whether it marks the beginning of a new age of discovery in particle physics or the last hurrah for a field that has run its course.

The Higgs solves a basic problem in the standard model. The theory describes the particles that make up ordinary matter: the electrons that whiz around in atoms, the up quarks and down quarks that make up the protons and neutrons in atomic nuclei, the neutrinos that are emitted in a type of radioactivity, and two sets of heavier cousins of these particles that emerge in particle collisions. These particles interact by exchanging other particles that convey three forces: the electromagnetic force; the weak nuclear force, which spawns neutrinos; and the strong nuclear, which binds quarks.

But there's a catch. At first blush, the standard model appears to be a theory of massless particles. That's because simply assigning masses to the particles makes the theory go haywire mathematically. So mass must somehow emerge from interactions of the otherwise massless particles themselves.

BREAKTHROUGH OF THE YEAR

That's where the Higgs comes in. Physicists assume that empty space is filled with a "Higgs field," which is a bit like an electric field. Particles interact with the Higgs field to acquire energy and, hence, mass, thanks to Albert Einstein's famous equivalence of the two, encapsulated in the equation $E = mc^2$. Just as an electric field consists of particles called photons, the Higgs field consists of Higgs bosons woven into the vacuum. Physicists have now blasted them out of the vacuum and into brief existence.

That feat marks an intellectual, technological, and organizational triumph. To produce the Higgs, researchers at the European particle physics laboratory, CERN, near Geneva, built the $5.5 billion, 27-kilometer-long LHC. To spot the Higgs, they built gargantuan particle detectors—ATLAS, which is 25 meters tall and 45 meters long, and CMS, which weighs 12,500 tonnes. The ATLAS and CMS teams boast 3000 members each. More than 100 nations have a hand in the LHC.

Perhaps most impressive is the fact that theorists predicted the existence of the new particle and laid out its properties, right down to the rates at which it should decay into various combinations of other particles. (To test whether the particle really is the Higgs, researchers are measuring those rates now.) Physicists have made such predictions before. In 1970, when only three types of quarks were known, theorists predicted the existence of a fourth, which was discovered 4 years later. In 1967, they predicted the existence of particles that convey the weak force, the W and Z bosons, which were found in 1983.

Particle theorists offer various explanations of their knack for prognostication. Particle collisions are inherently reproducible and free of contingency, theorists say. Whereas no two galaxies are exactly the same, all protons are identical. So when smashing them, physicists need not worry about the peculiarities of this proton or that proton because there are none. Moreover, theorists say, in spite of its mathematical complexity, the standard model is conceptually simple—a claim that nonphysicists might not buy.

The standard model ultimately owes its predictive power to the fact that the theory is based on the notion of mathematical symmetry, some theorists say. Each of the three forces in the standard model is related to and, in some sense, necessitated by a different symmetry. The Higgs mechanism itself was invented to preserve such symmetry while

Pieced together. In this particle collision, it appears that a Higgs boson decays into two electrons and two positrons (red).

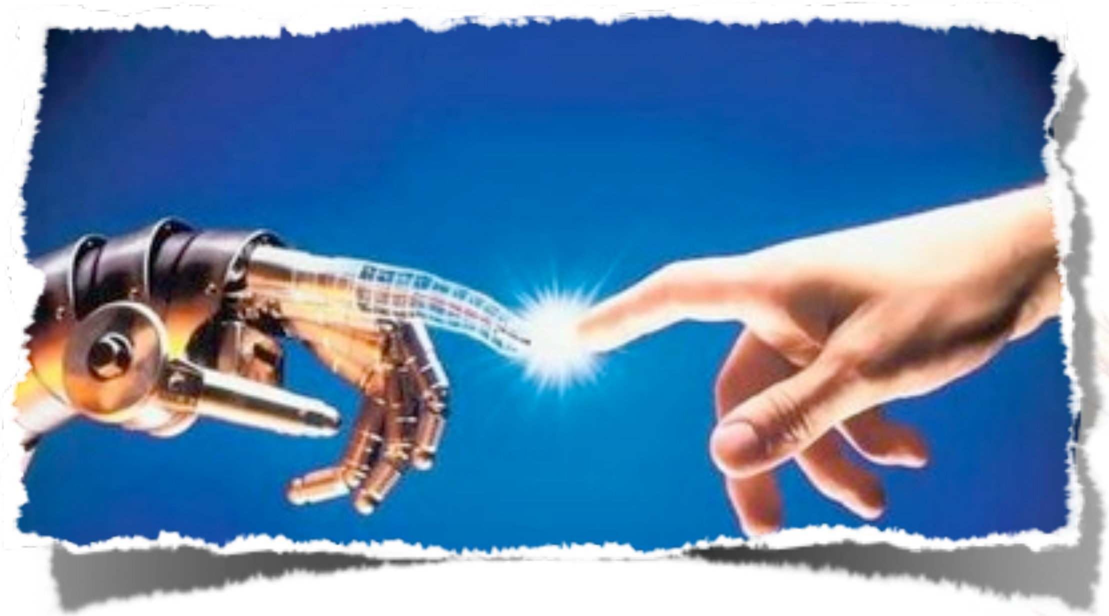
CREDIT: CERN/L. TAYLOR/T. MCCAULEY

CBPF Centro Brasileiro de Pesquisas Físicas

A. Moraes

Wednesday, 19 June 13

Technologies for particle hunting and for humankind



1- Computing

2- Particle accelerators

3- Particle detectors

Computing

From the "World Wide Web" to the "GRID" system

sharing of information

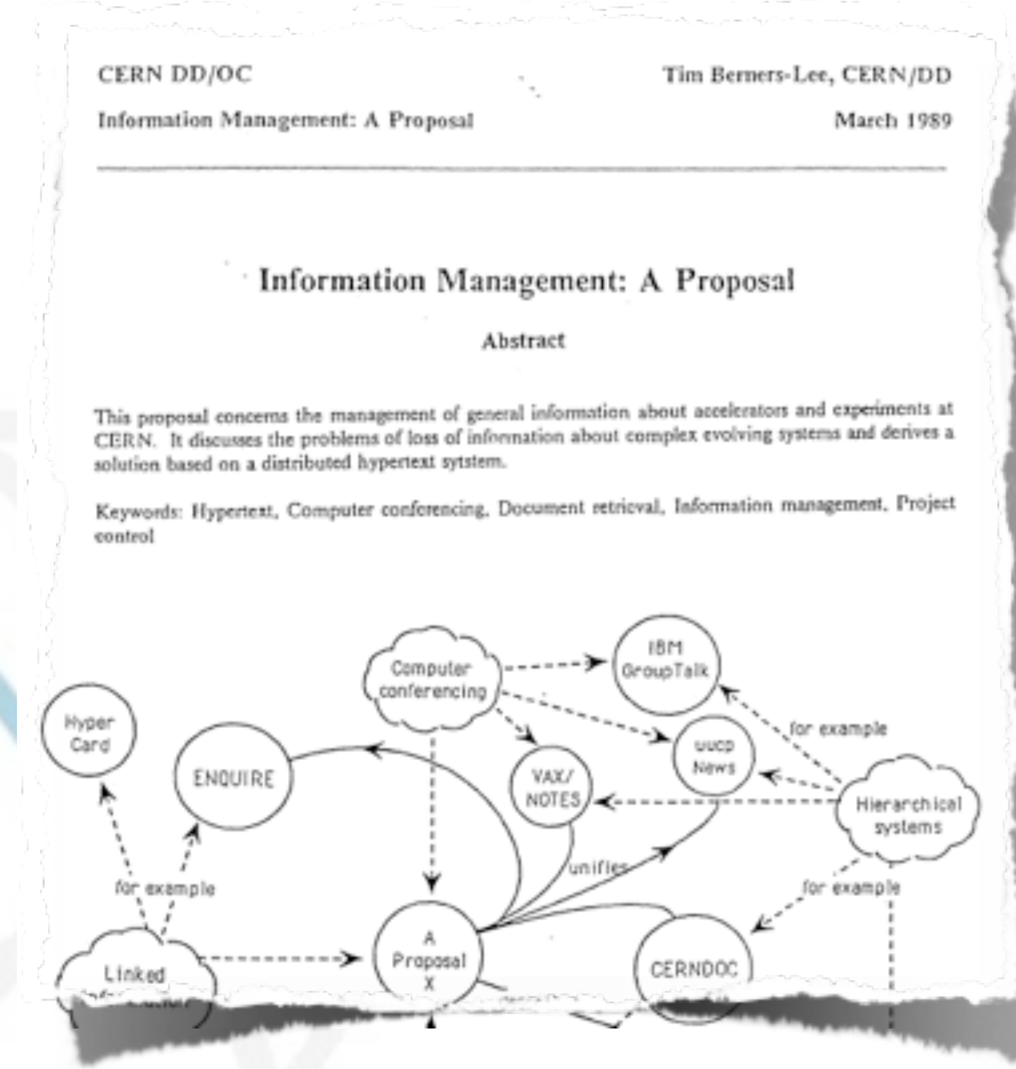
information sharing, data storage and processing capacity

(parallel processing)

“The World Wide Web”

The WWW was created by CERN’s scientist Tim Berners-Lee, as a tool to allow communication and information sharing between institutes spread around the world and CERN.

Few technological advances have revolutionised society as the internet has.


CERN DD/OC — Tim Berners-Lee, CERN/DD

Information Management: A Proposal — March 1989

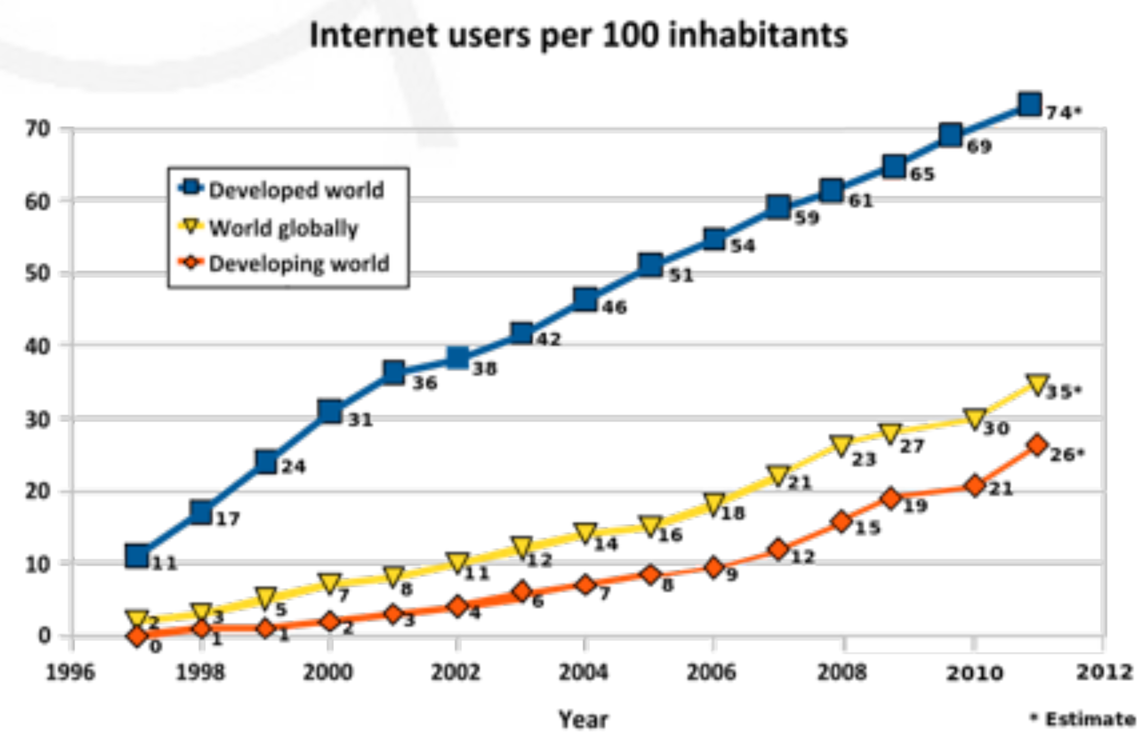
Information Management: A Proposal

Abstract

This proposal concerns the management of general information about accelerators and experiments at CERN. It discusses the problems of loss of information about complex evolving systems and derives a solution based on a distributed hypertext sytstem.

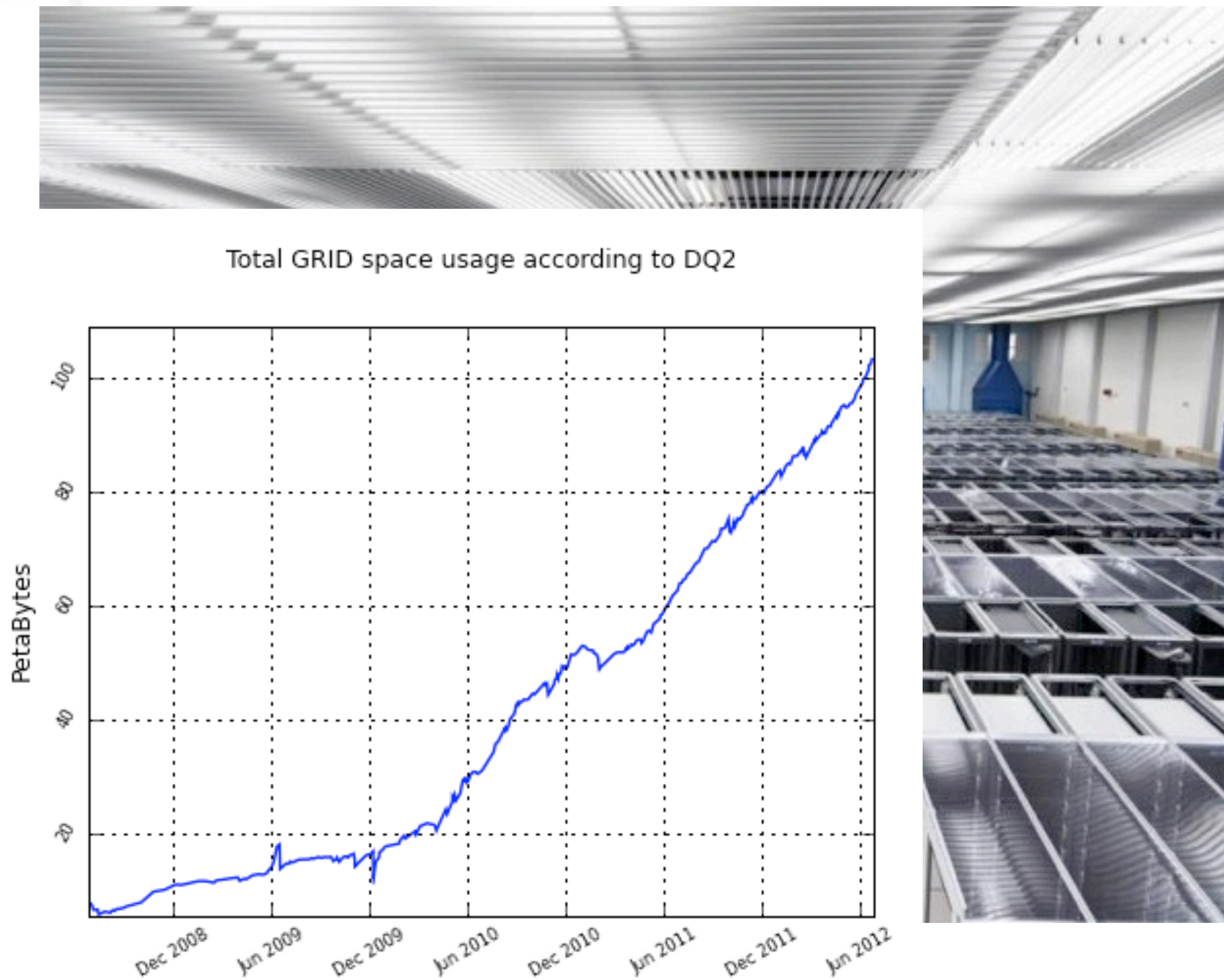
Keywords: Hypertext, Computer conferencing, Document retrieval, Information management, Project control

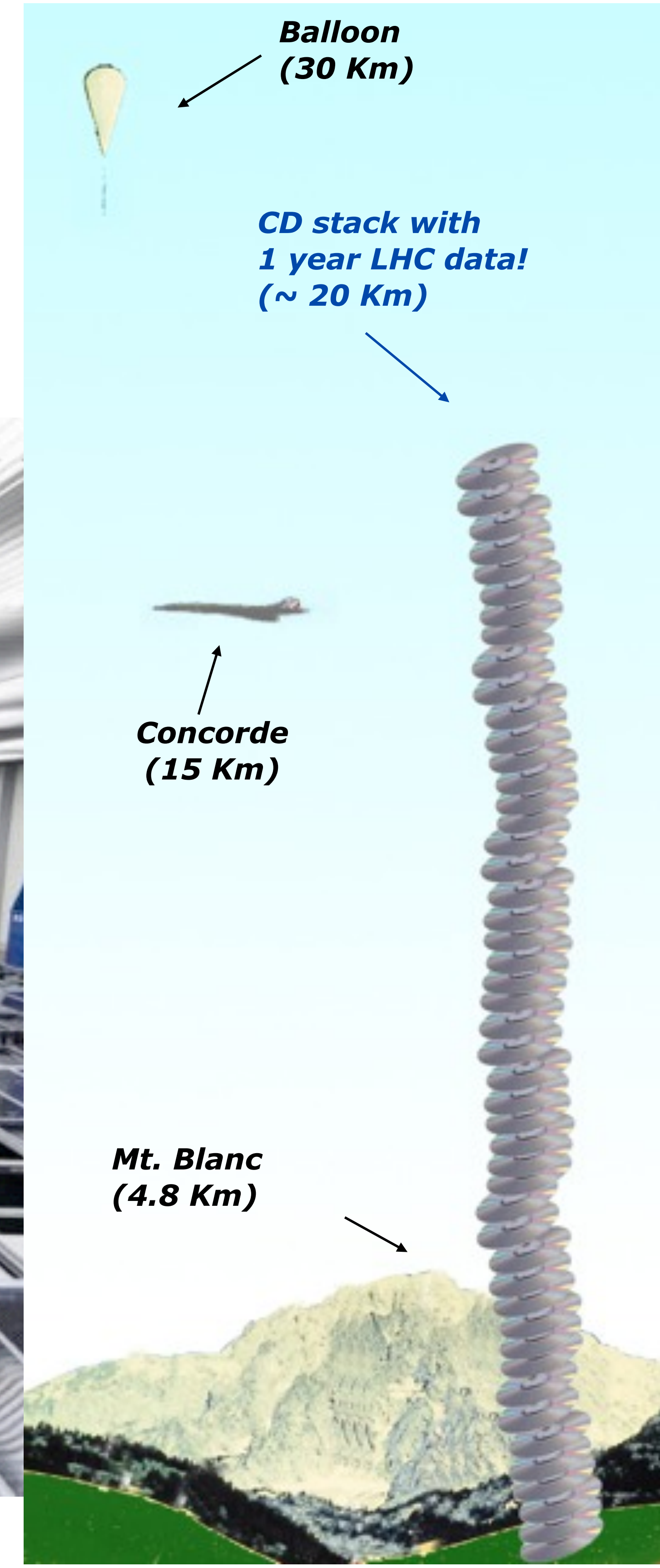
Sir Tim Berners-Lee, 1989



The GRID and the LHC

- Each LHC experiment generates ~15 PB of data per year.
  - $1PB = 10^6$ GB
  - This amount of data is equivalent to ~20 million DVDs

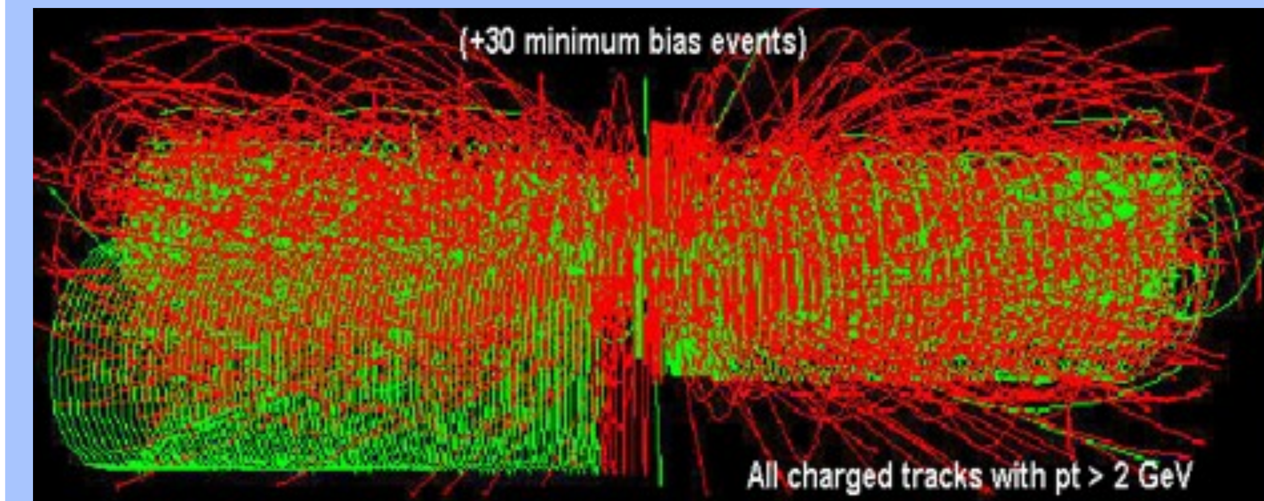


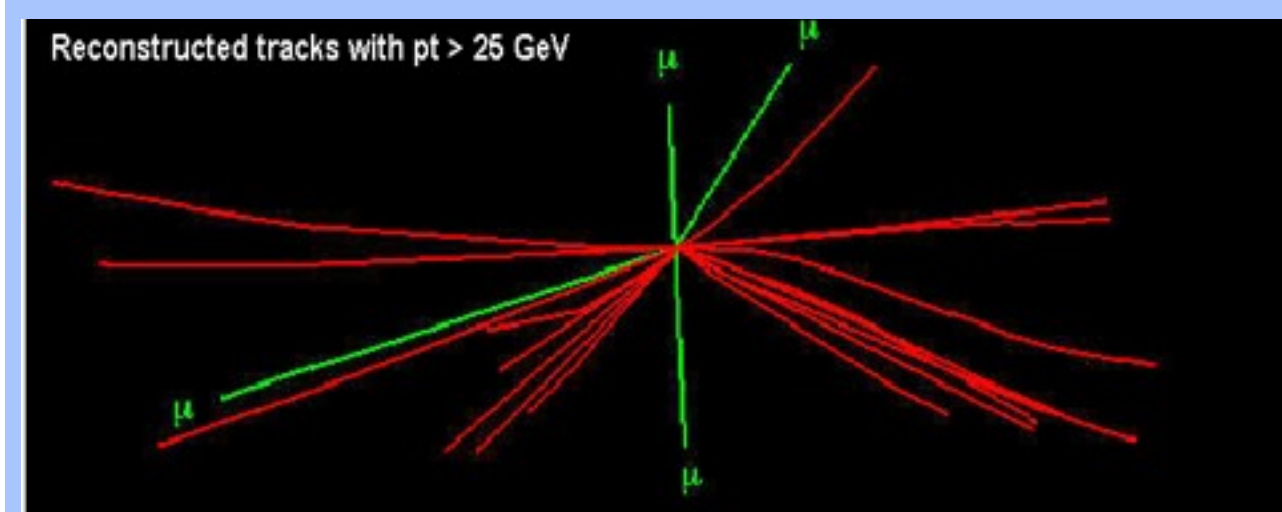


The GRID and the LHC

<u>Analysis</u>: GRID is indispensable for separating signal from background, reconstructing collisions from electronic signals, simulating new phenomena, etc...

- ~200.000 computers (modern and “fast”) are currently being used in LHC data analyses.



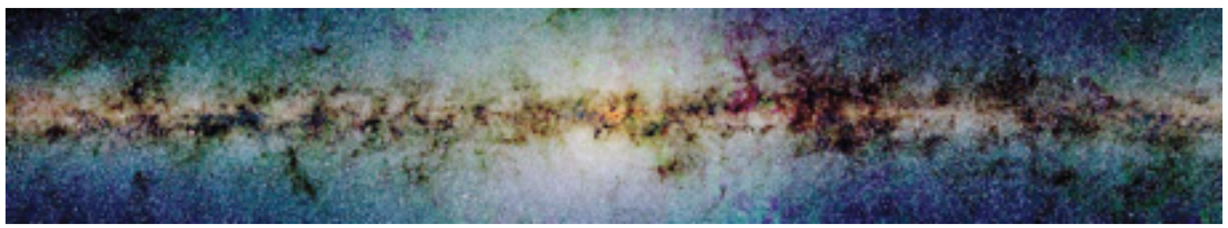


Other GRID applications

Astronomy

(GRID users since 2003)

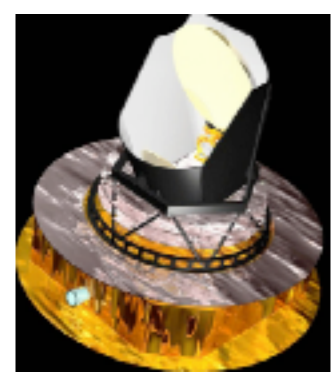
Processing and data storage / astronomical images: "mining" for discoveries!

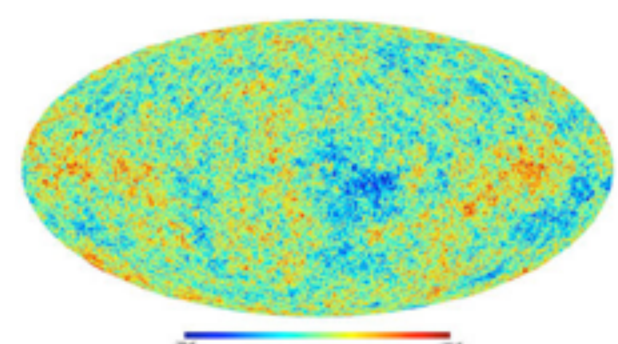


Galactic Plane: processing of angular regions
Typically: tens of GB per angular band & 4h processsing in isolated clusters (~10 processors)

With the GRID: processing time reduced from days to minutes

Computing simulations / preparing for satellite launch and operation

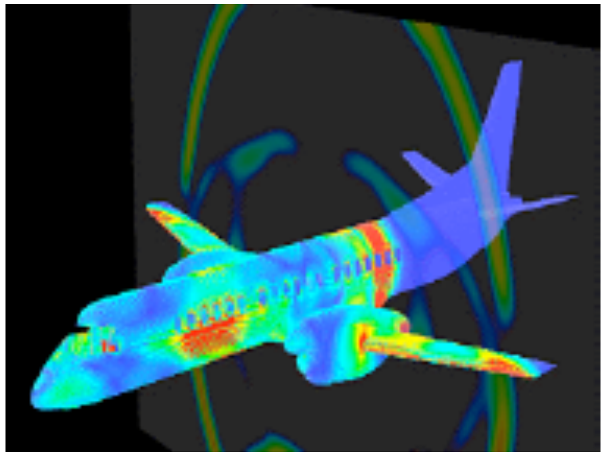


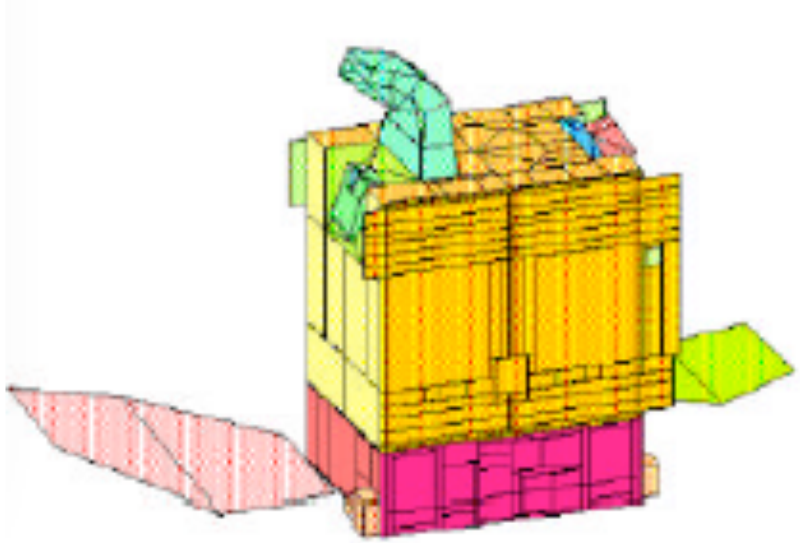


Planck Satellite

Aerospace Industry

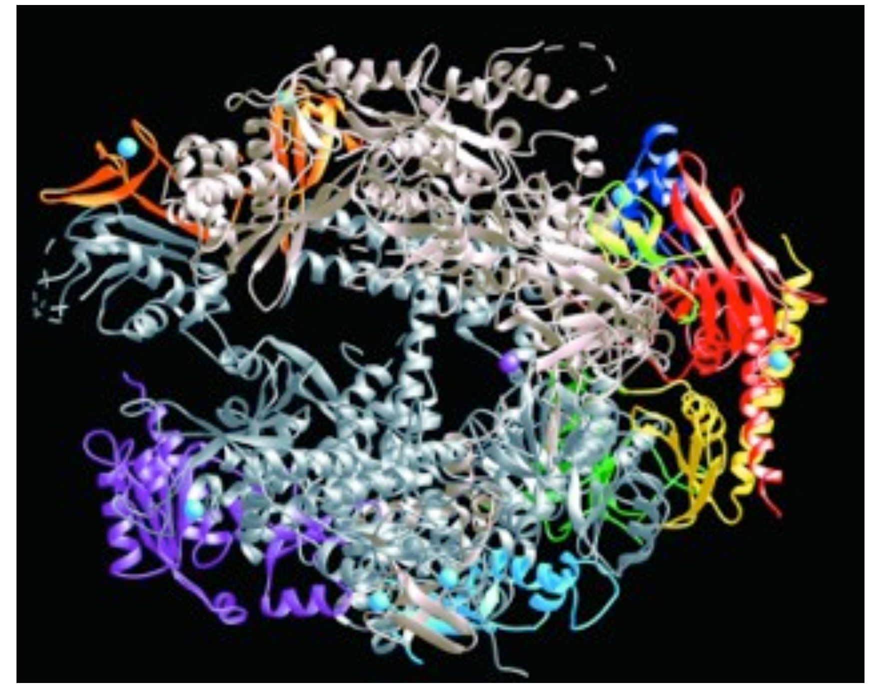
Structural mechanics: dynamical structure, thermal effect, electrostatic, optics, mechanical vibration, ...





Projecting new satellites

Bioinformatics



Protein structures:
file size ~ 10GB

Monte Carlo simulations

Calculating the Molecular Dynamics (it can take ~ 3 months in single core computers)

Development of new drugs for treatment of ilnesses such as Alzheimer, Parkinson, Malaria, etc.

and (many) other projects...

Commerce and financial markets

Computational chemistry

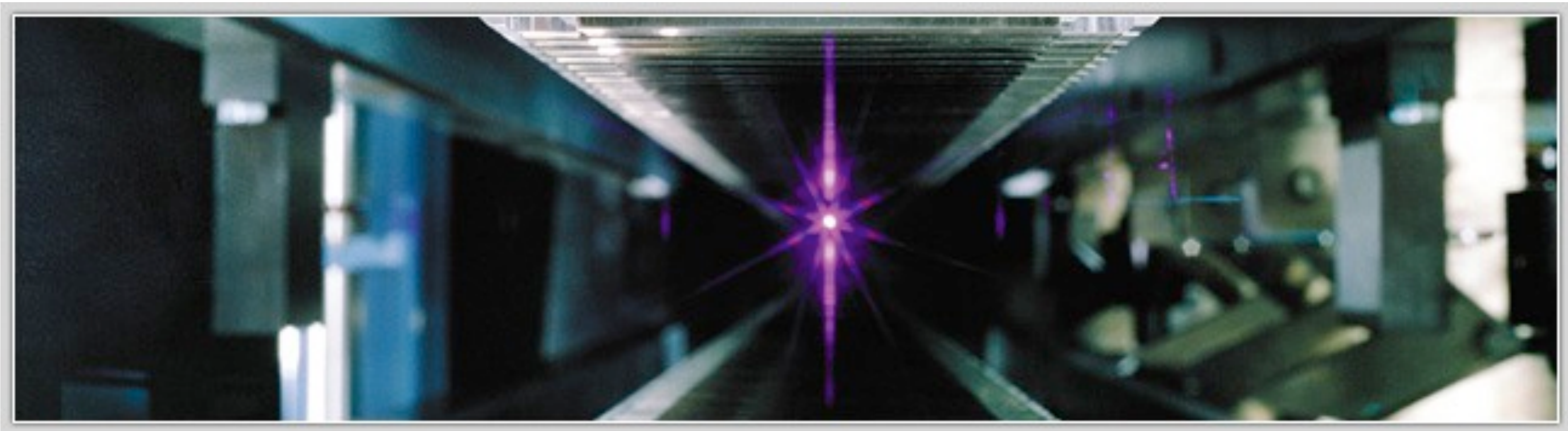
SETI INSTITUTE

SETI

Protein Folding (~30% human proteins aren't known...)

Video-game industry

Particle accelerator applications



There is more than 30.000 particle accelerators currently in operation serving several areas such as medicine, energy industry, environment, security and basic science.

Medicine Applications

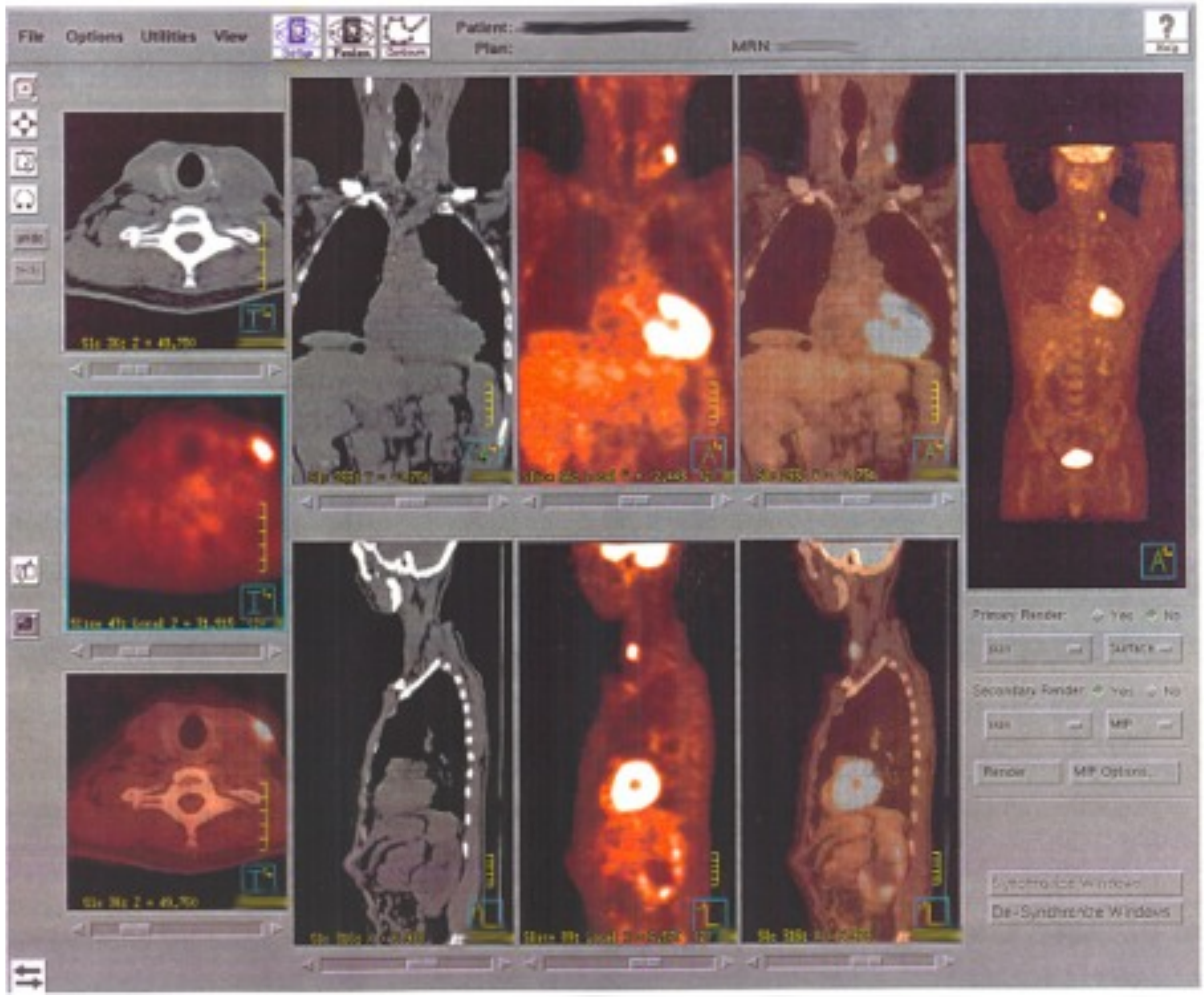
Medical diagnosis: particle accelerators are used in the preparation of radioisotopes for diagnosis and treatment of patients in many countries.

~ 10.000 hospitals

~ 30 million patients/year

CERN is developing a new generation of proton accelerators aimed at "cleaner" production of radioisotopes for hospitals.

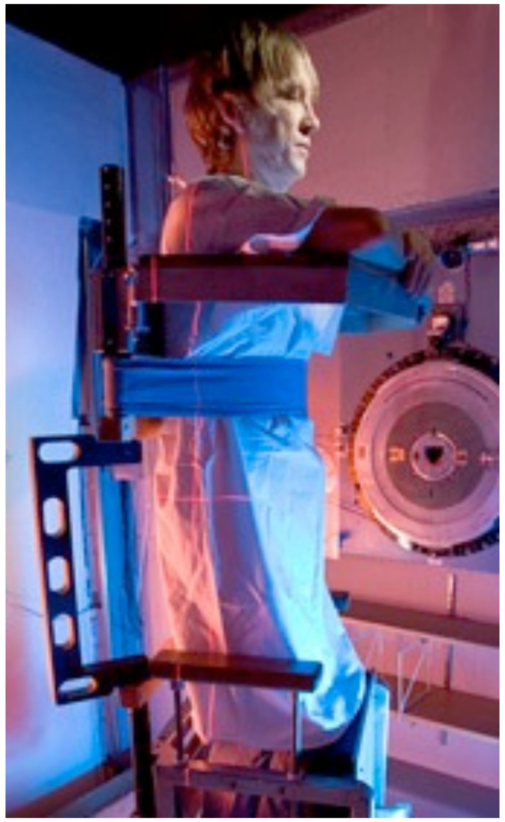
Positron Emission Tomography (PET):



Magnetic resonance

makes use of powerful magnets, originally developed for particle accelerators.

Medicine Applications



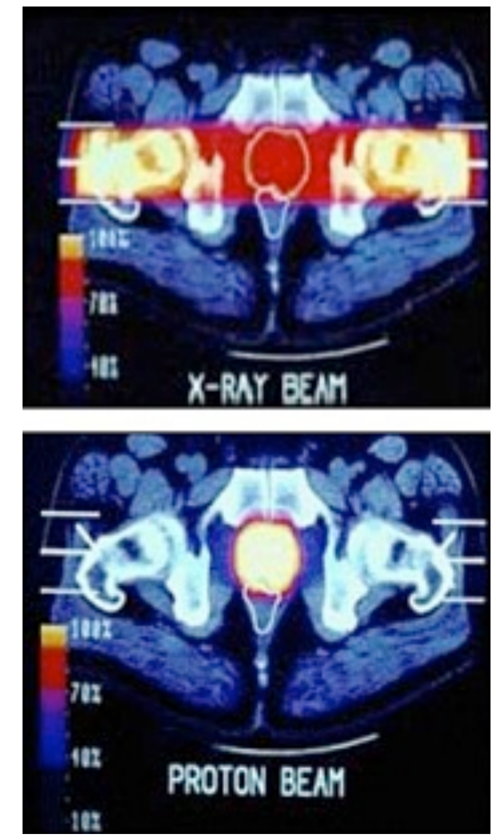
Cancer treatment therapy

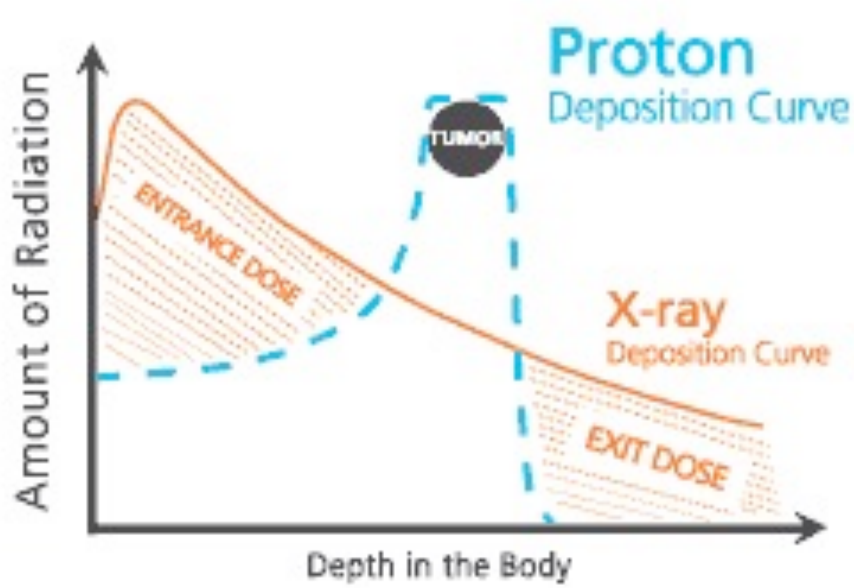
Proton beams are being used in cancer treatment.

Thousands of patients have already benefited from these treatments (since 1990).

~ 39 hospitals have been using these techniques.

Technologies developed for the LHC are contributing to the design of smaller and cheaper accelerators.

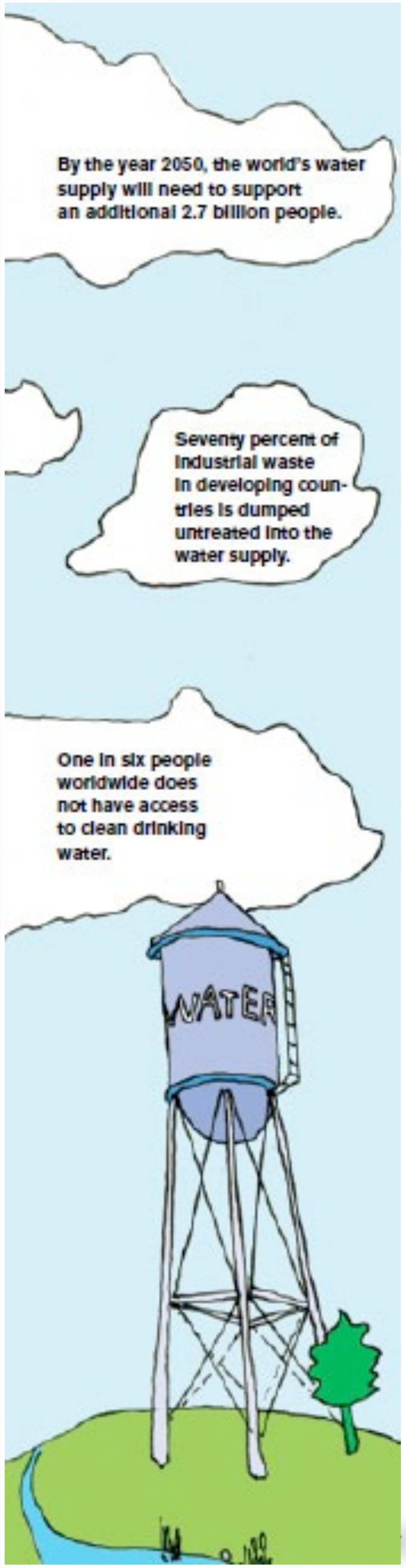




Proton beams allow greater energy deposition on tumours in deeper regions with less side effects on the healthy tissues surrounding the tumour.

CBPF
Centro Brasileiro de Pesquisas Físicas

Particle accelerators and other applications...



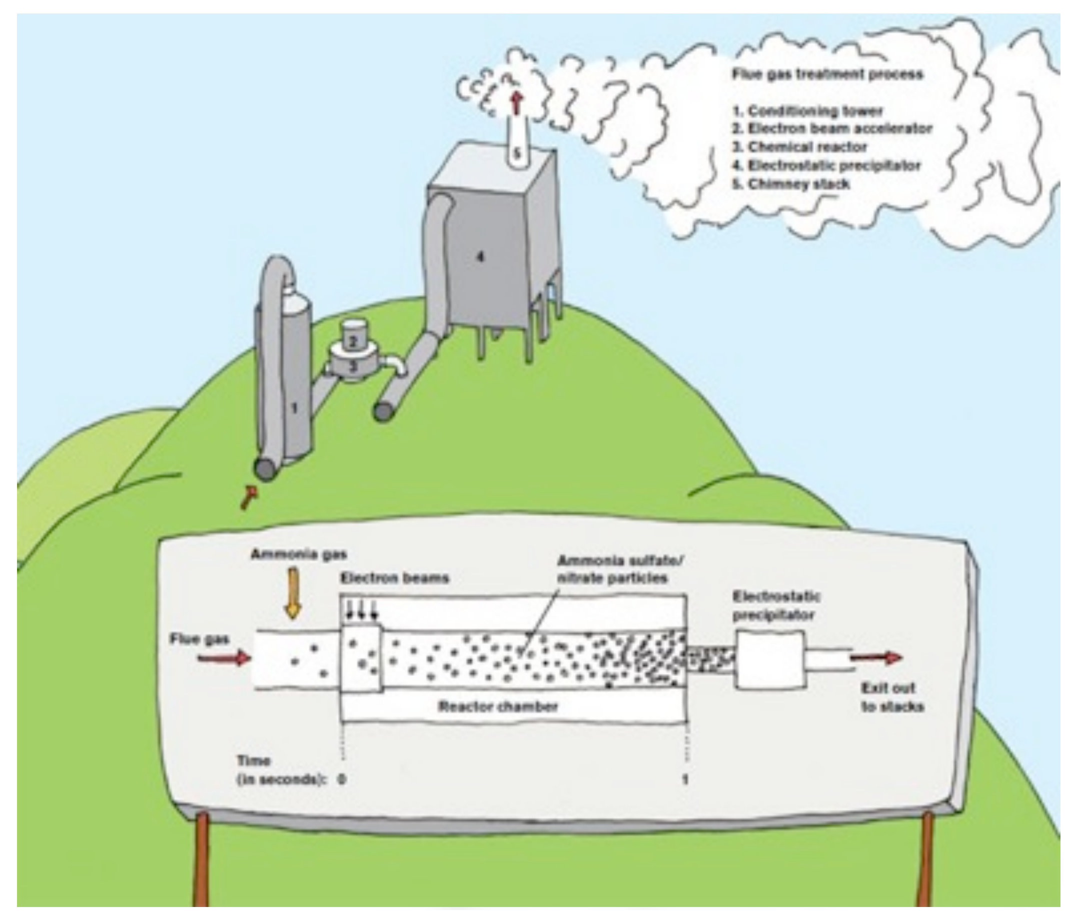
Electron beams in depollution of water and air:

Traditionally, water treatment is done in three stages: micro-organisms elimination, filtering and treatment for chemical residues.

Electron irradiation simplifies this process with a single application.

Treatment of polluting gases: the use of electron beams is more efficient than traditional chemical treatment.

These techniques are already being employed in countries like the USA, South Korea, Poland, China, Saudi Arabia and others.



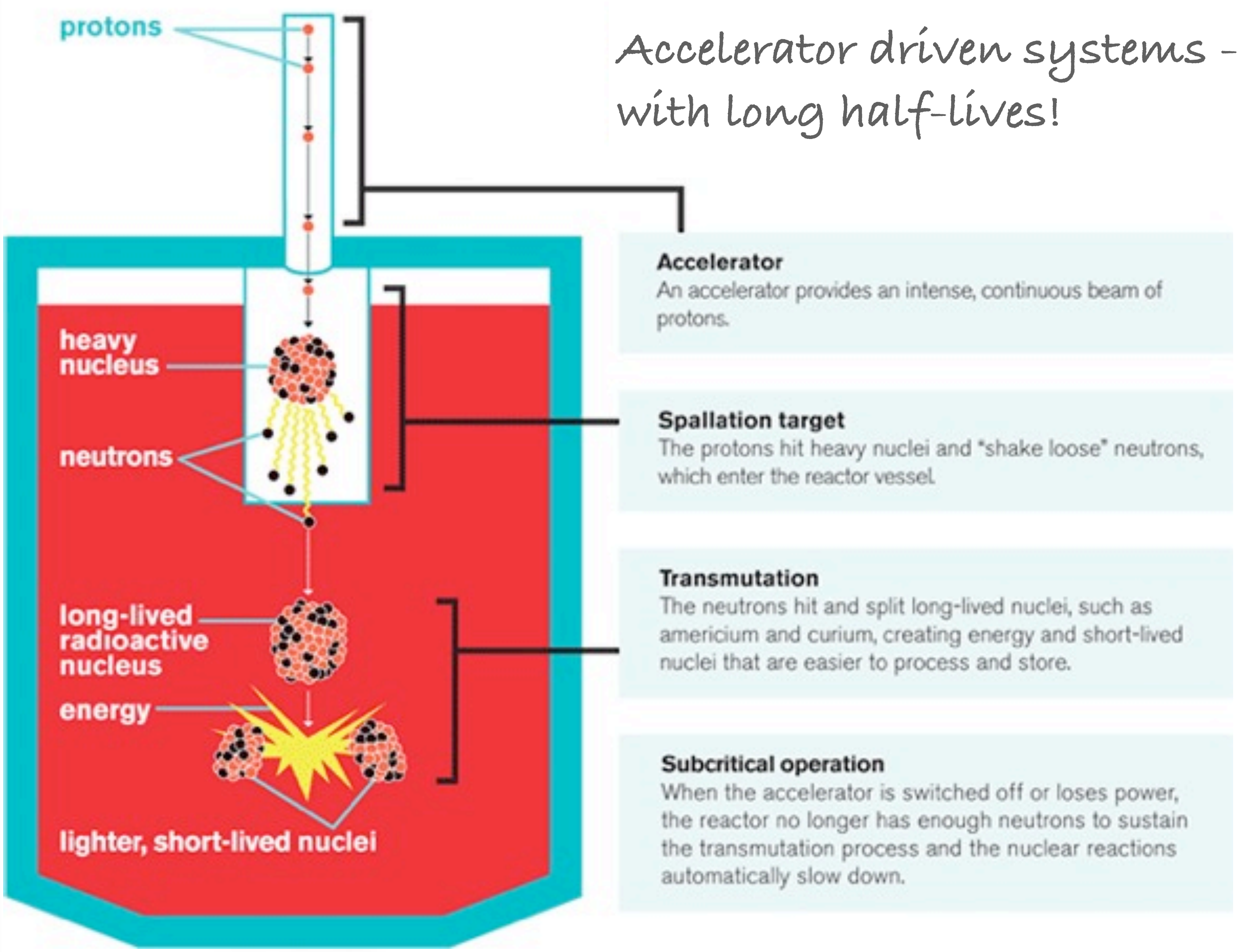
Particle accelerators and other applications...

Treatment of nuclear waste

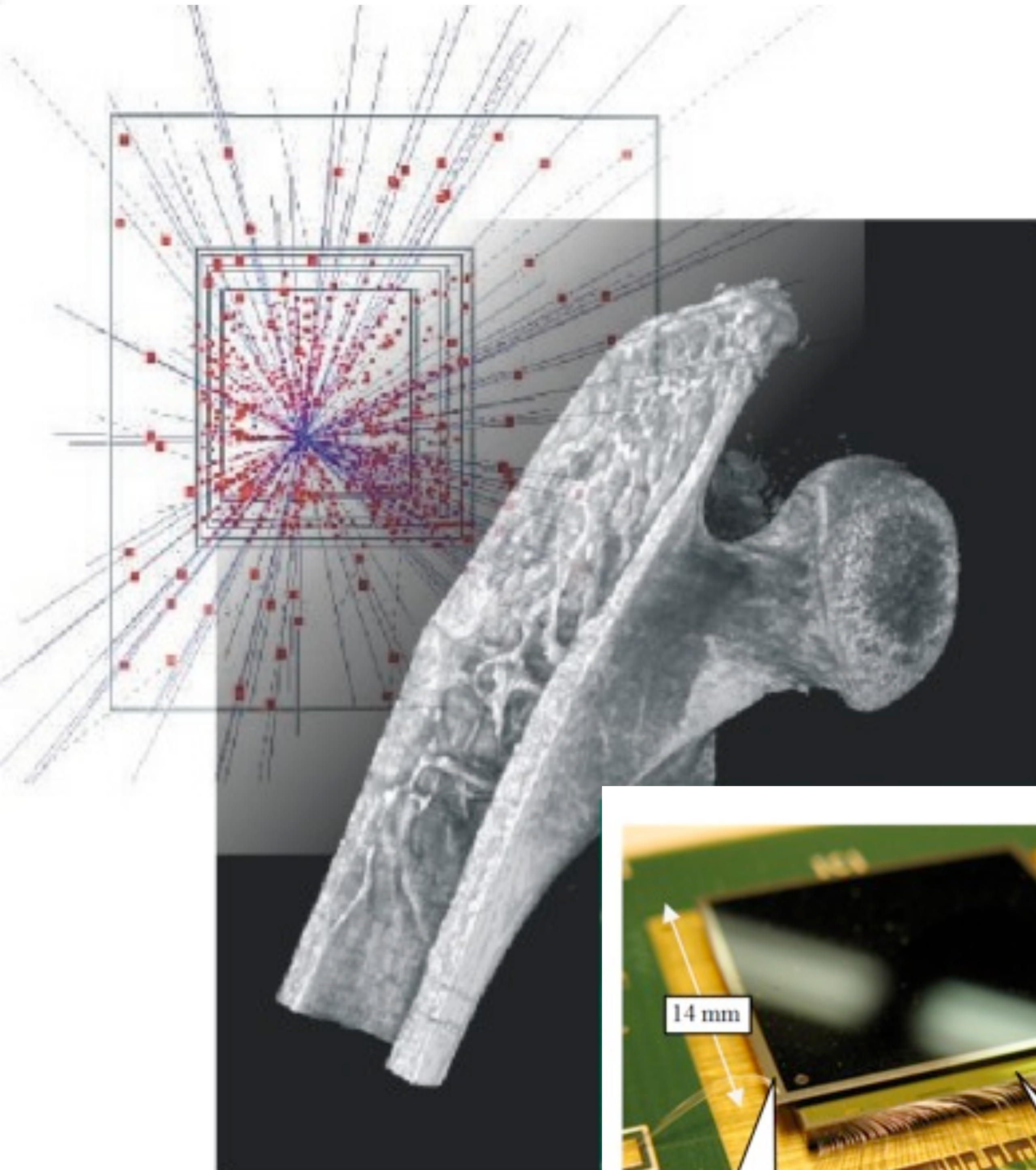
Particle accelerators are being used to re-process nuclear material.

This allows the nuclear waste's geological storage time to drop from ~300.000 years to 500 years.

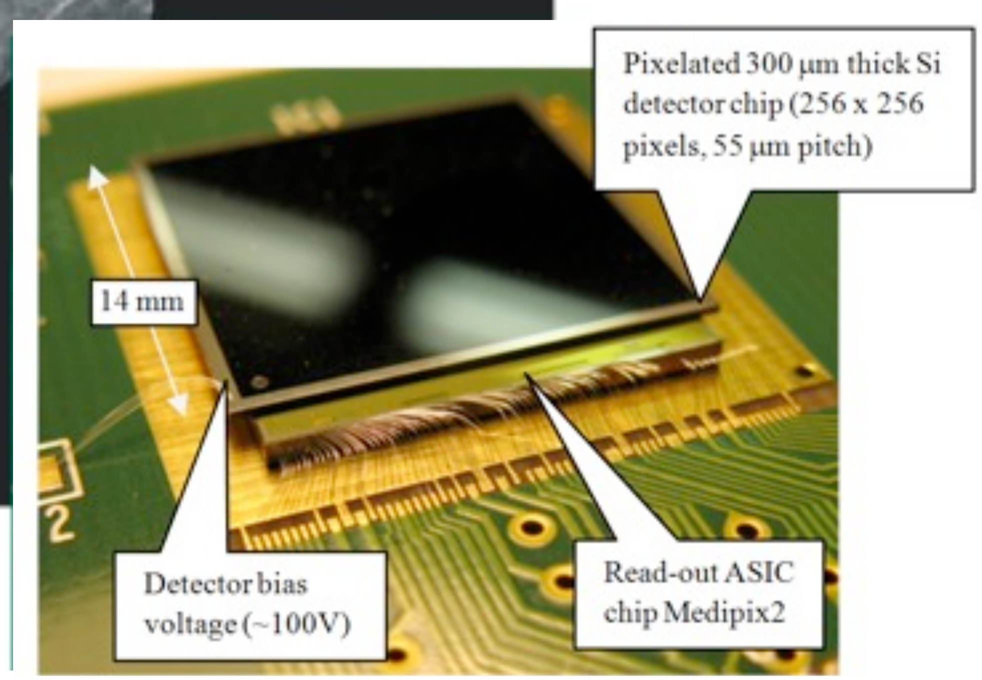
Accelerator driven systems - ADS: transmutation of isotopes with long half-lives!



Technology applications developed for particle detectors



MediPix



Si detectors for the LHC:

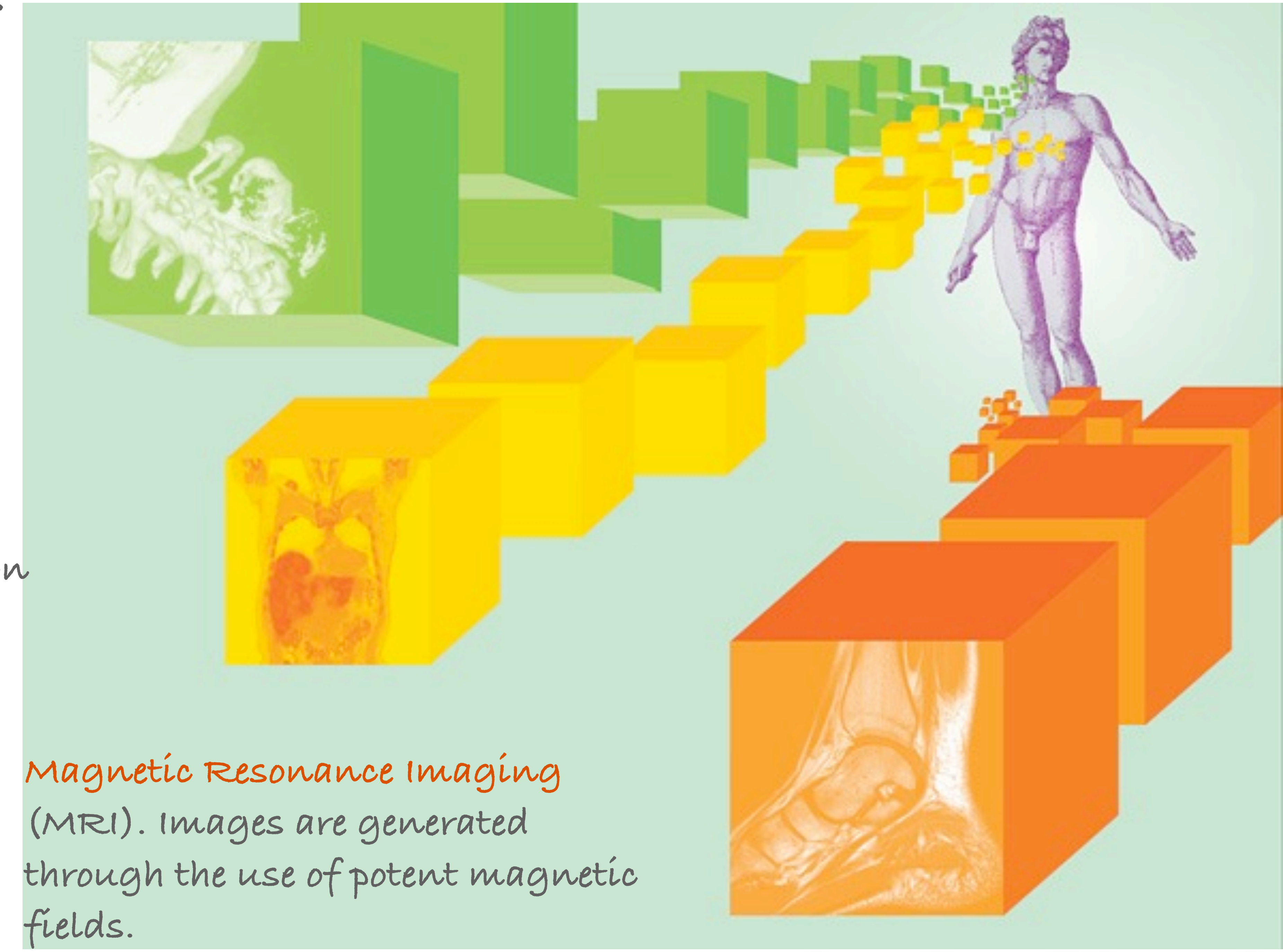
Essential components for track measurements.

Fast response, high performance and resilience even in the highly radioactive environment generated at the LHC!

The amount of Si detectors required to build the LHC detectors is extremely high and has no precedent in HEP.

Detectors in Medicine: lowering costs and reducing exposure to radiation

Computerised Tomography (CT scan). The passage of X-rays through the patient's body is mapped out. This allows the build up of 3D images.



PET scans (Positron emission tomography). γ rays produced via positron annihilation are mapped out.

Magnetic Resonance Imaging (MRI). Images are generated through the use of potent magnetic fields.

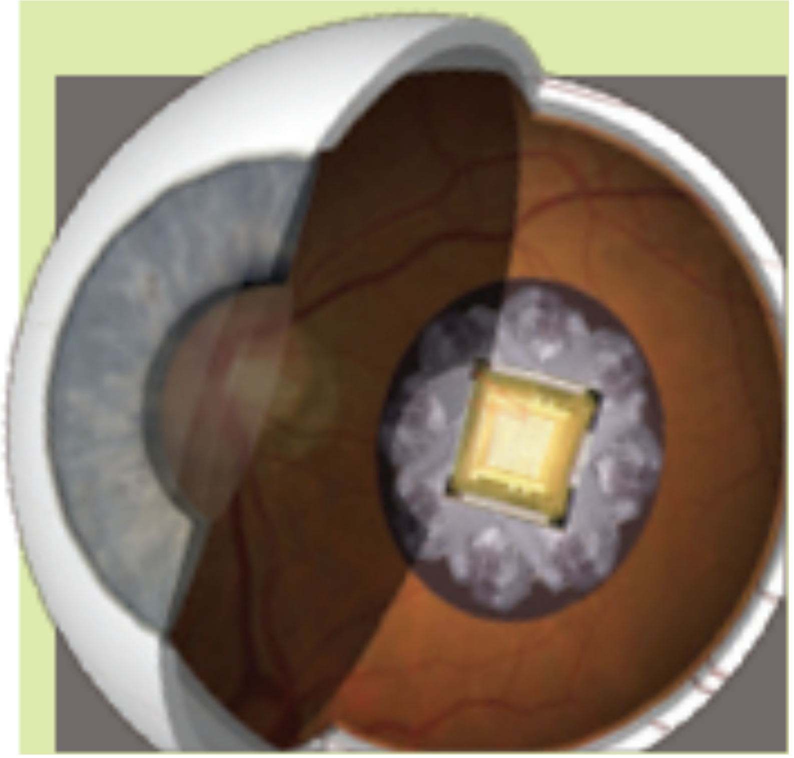
Artificial retina implants

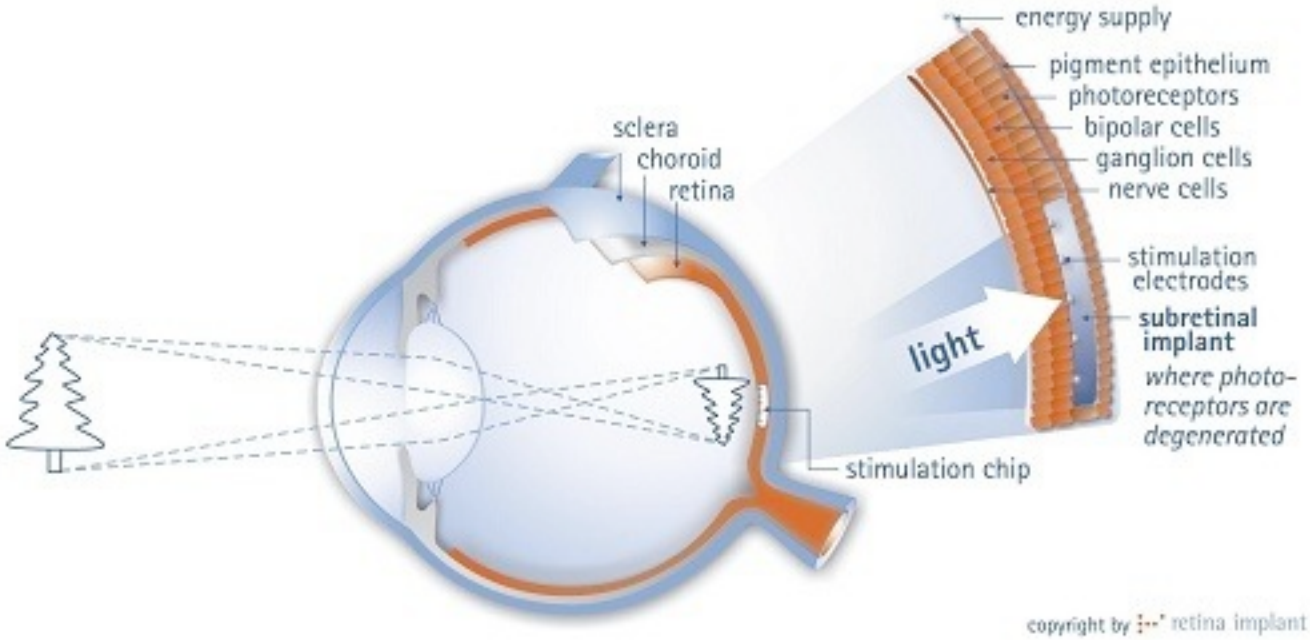
"The bionic eye implant"

One of the pixel sensors developed for the LHC is being used as an artificial retina implant.

Recent studies are focused on establishing partial vision to the blind.

Results are extremely exciting!





Other industrial sectors

Energy transmission

Superconducting technology used in particle accelerators are being applied to the manufacturing of transmission cables.

Transport

Superconducting technology applied to magnets is also being used in the design of trains with magnetic levitation (Mag-Lev).

Biomedicine and new drug developments

Synchrotron Light Laboratories are being widely used in the study of complex proteins helping the development of new, more effective drugs.

Human Resources

"Developing a highly specialised work force"

In modern particle physics, approximately one in six scientists who graduate to obtain a PhD continues the research career in basic research.

The other graduates migrate to the most diverse sectors of the economy:
- technology industry
- electronics
- communication
- biophysics
- financial sector

a growing list...

- food sterilisation
- production of isotopes for medical use
- computer simulation for cancer treatment
- “scanning” of transport containers
- parallel processing
- international relations
- operating remote facilities

LHC: the biggest, most complex scientific endeavour currently in activity. We're only on the 4th year of a programme that will be active for (at least...) 2 decades.

Expanding the frontier of our knowledge: results (including the discoveries) confirm predictions from the Standard Model!

Technologies that serve not only the particle hunt but also benefit humankind: accelerators, detectors e computing.