The Large Hadron Collider

At Discovery's Horizon

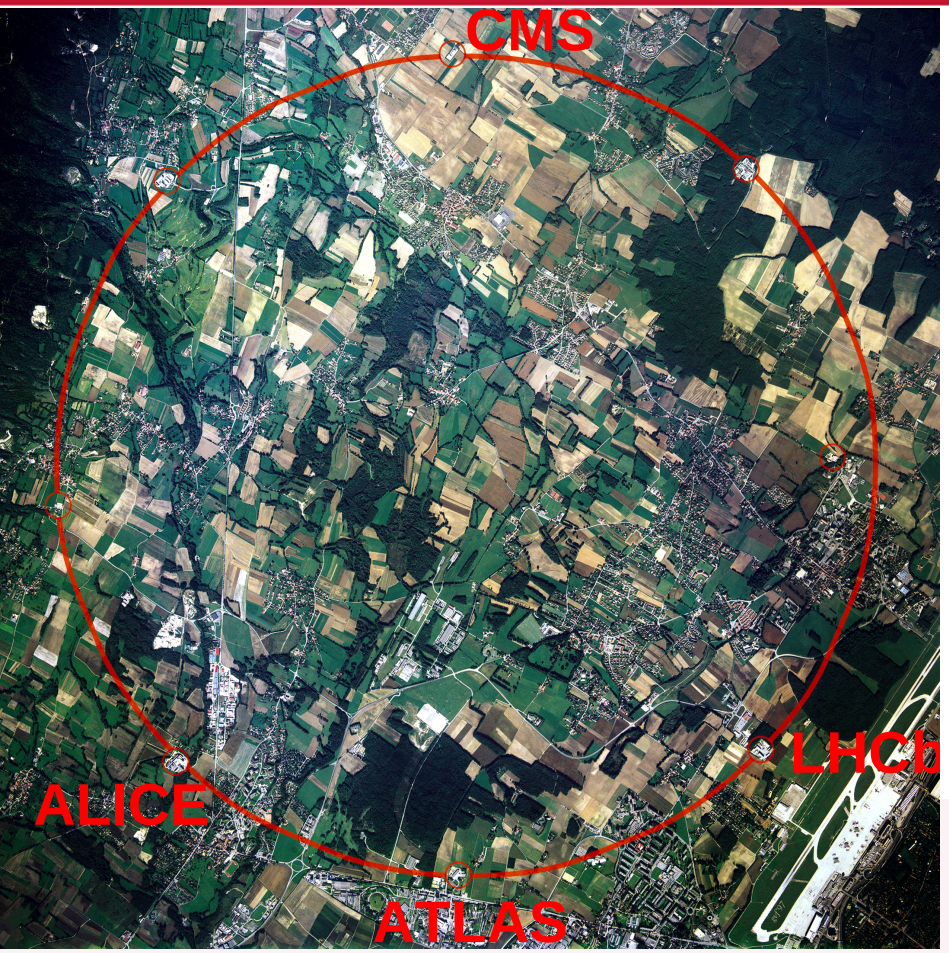
Aran Garcia-Bellido,
University of Rochester

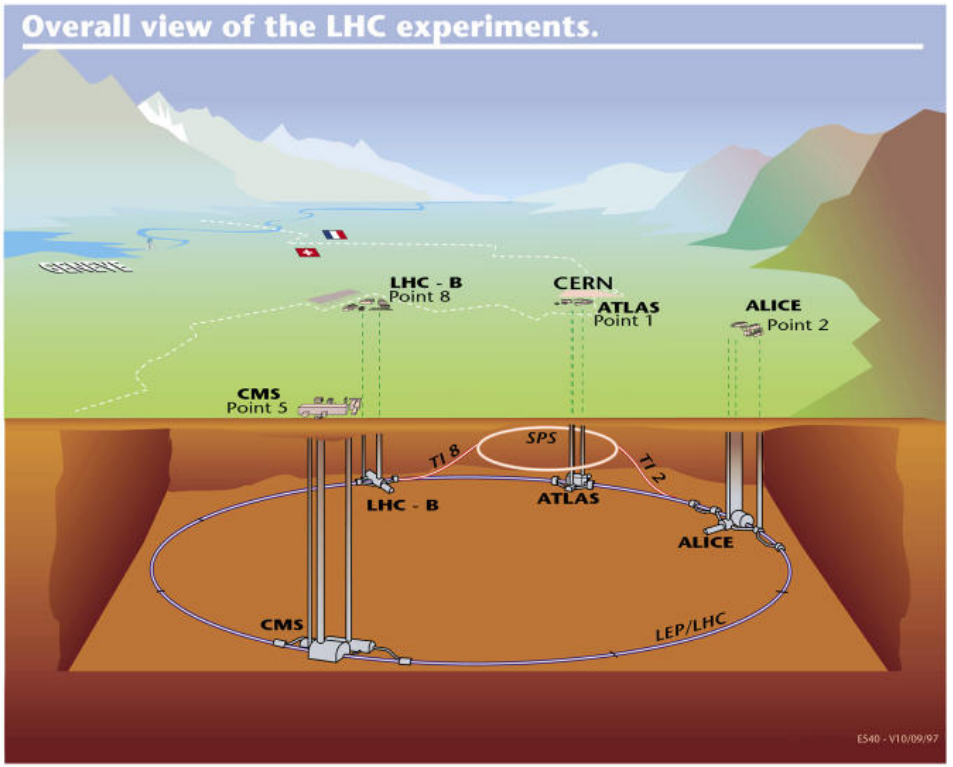
The Large Hadron Collider: A New Window into Matter, Spacetime and the Universe

University of Rochester · Fermilab · CERN · U.S. Department of Energy · National Science Foundation

The Large Hadron Collider
At Discovery's Horizon

Large Hadron Collider (LHC)
16.5 mi tunnel, 300 ft underground





- 4 detectors: CMS and ATLAS are general purpose

- 8000+ physicists & engineers
- 350 institutes
- 100+ countries

The Large Hadron Collider
At Discovery's Horizon

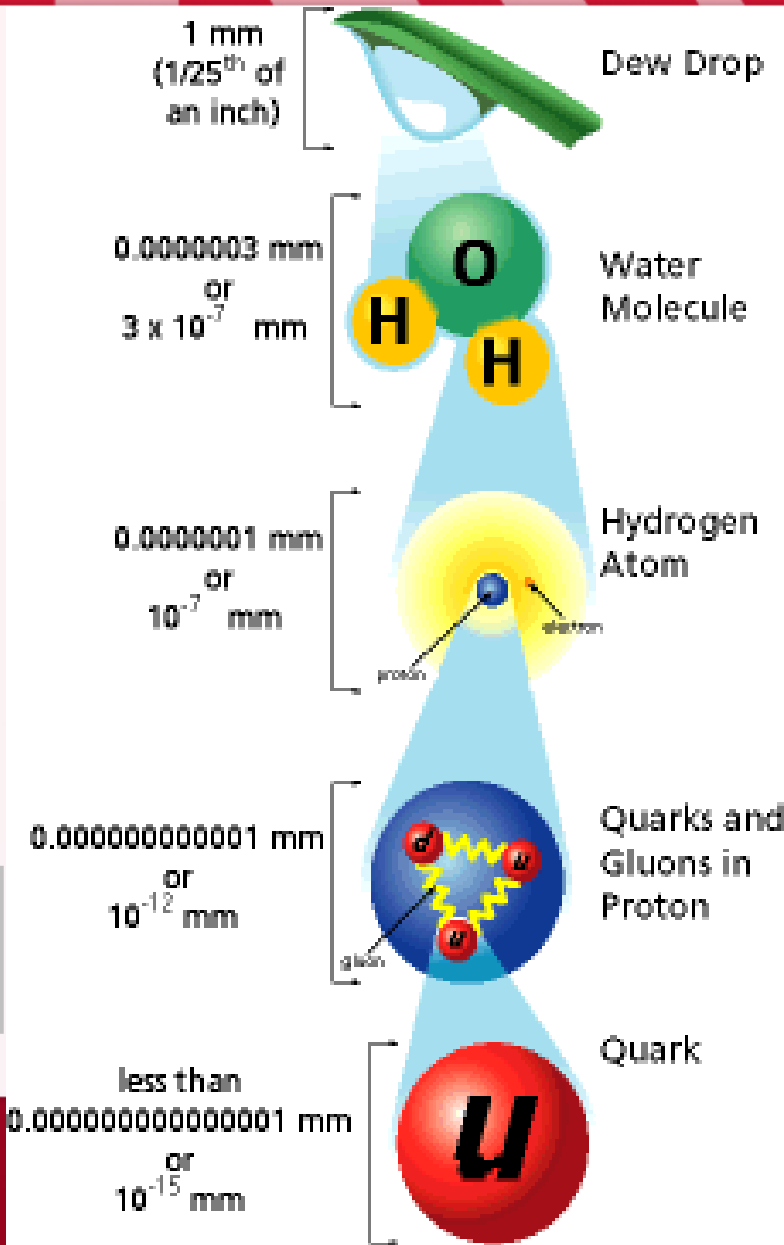
Particle Physics: Big Questions

Addresses the most fundamental questions:

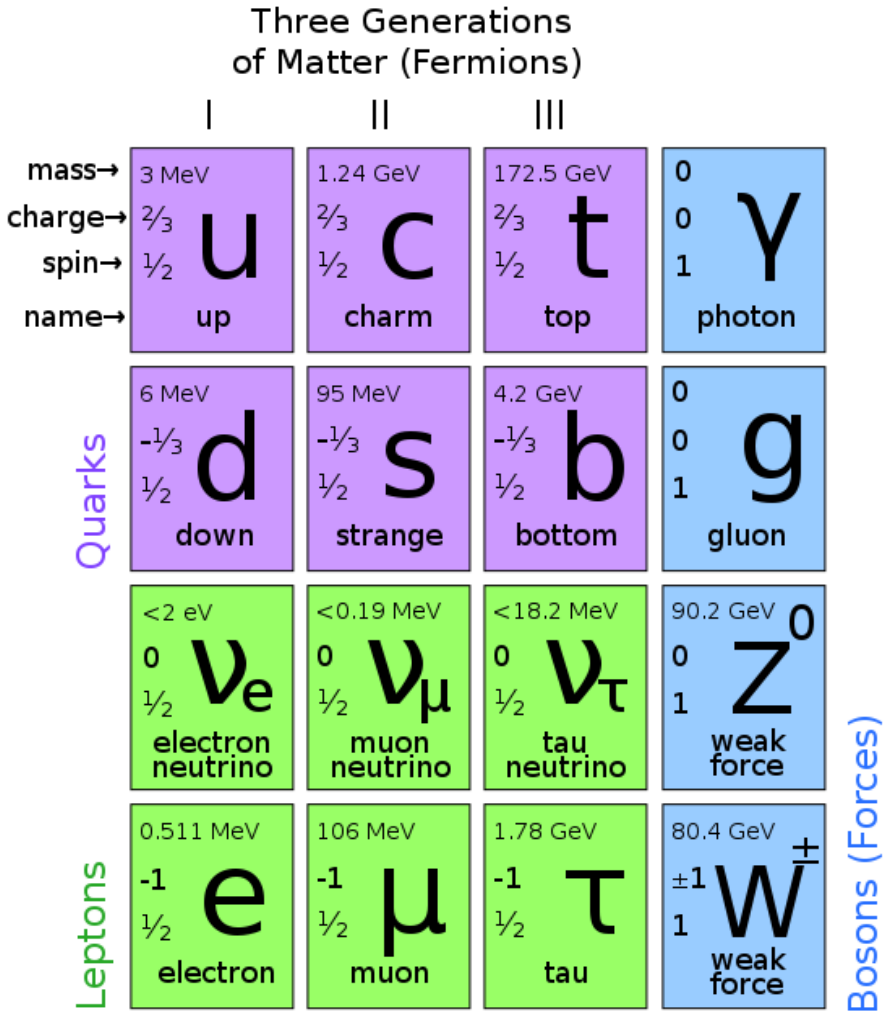
- Nature of matter and spacetime
  - What are the constituents of matter at the most basic level?
  - What are the forces involved?
- Evolution and composition of the Universe
  - What is the Universe made of?
  - How has it changed over time?
  - Were matter and forces as they are now?

A huge challenge!

Big questions need big science!



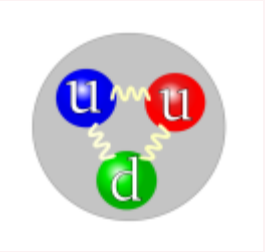
The Standard Model of Particle Physics: 3 families of matter and 4 forces



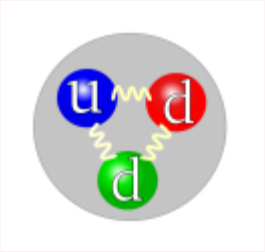
- A beautifully simple picture:
  - **12** particles make up **matter**
  - Come in three families
  - **4** particles describe **forces**
  - + the same number of **antiparticles**
- Describes all known matter and forces (except **gravity**!)
- Powerful predictions
- A triumph of 20th century physics
- But we still haven't found why particles have mass! **Higgs boson?**
- Many other questions...

Building a Universe

- We only need **up** and **down quarks**, together with **electrons** to build ALL the matter we see around us

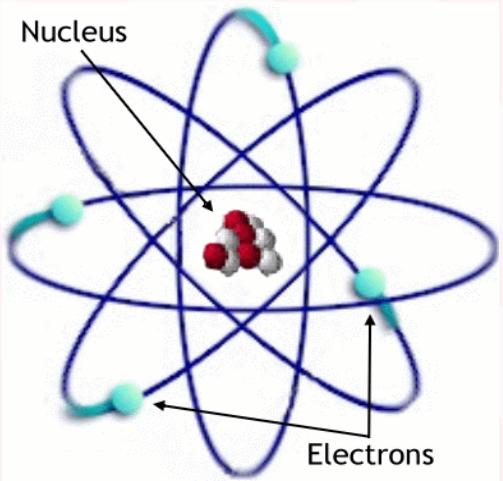


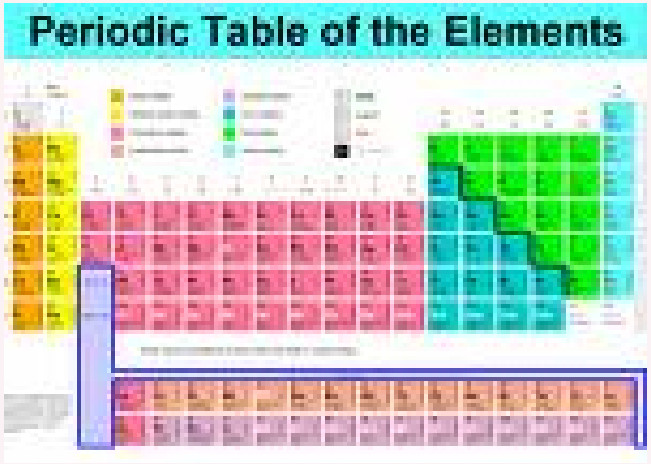
proton



neutron

electron

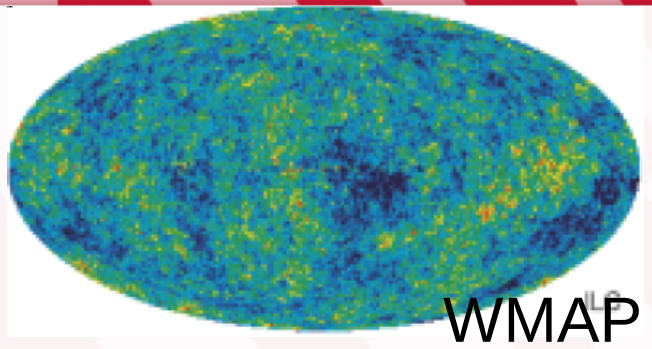


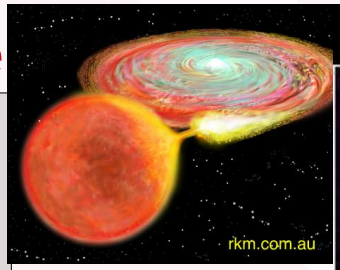


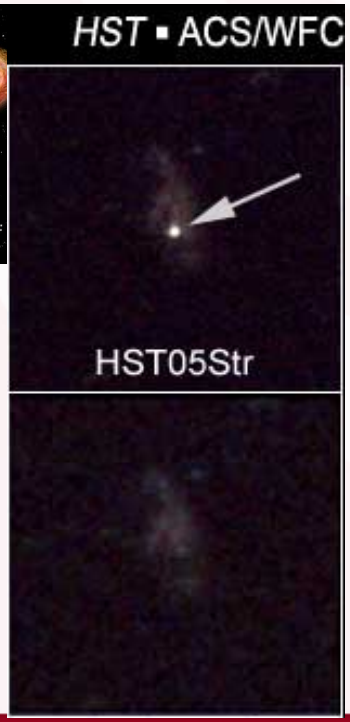
Enter cosmology

Cosmology has entered a **precision era** in the last 10 years

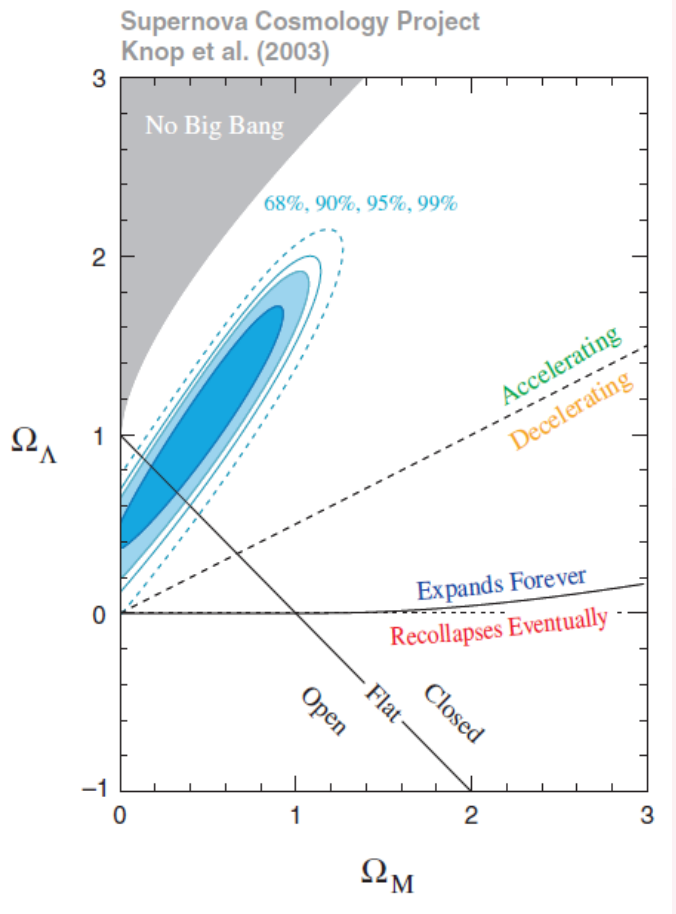
- From observations of the first light that scattered when the Universe was a hot soup of nuclei (400,000 years after Big Bang)
- And from observations of distant SuperNovae
- "**Standard Model**" of Cosmology:
  - Age: 13.7 billion years
  - Universe is expanding, at an accelerated rate
  - Universe is flat (Euclidean) geometry
  - Critical density
  - Mounting evidence for "**inflation**" in early stage: explains flatness, CMB homogeneity, large scale structure

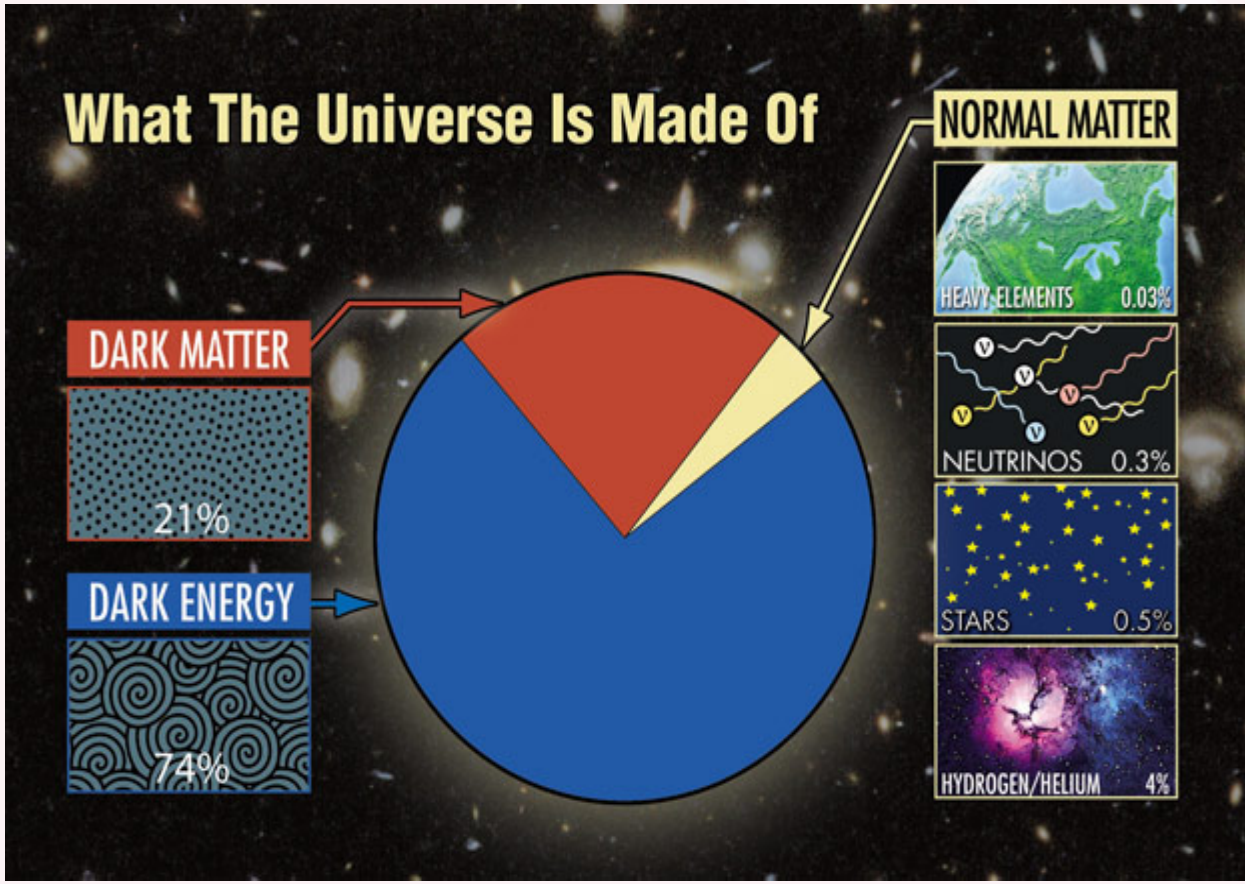






We now know what we don't know

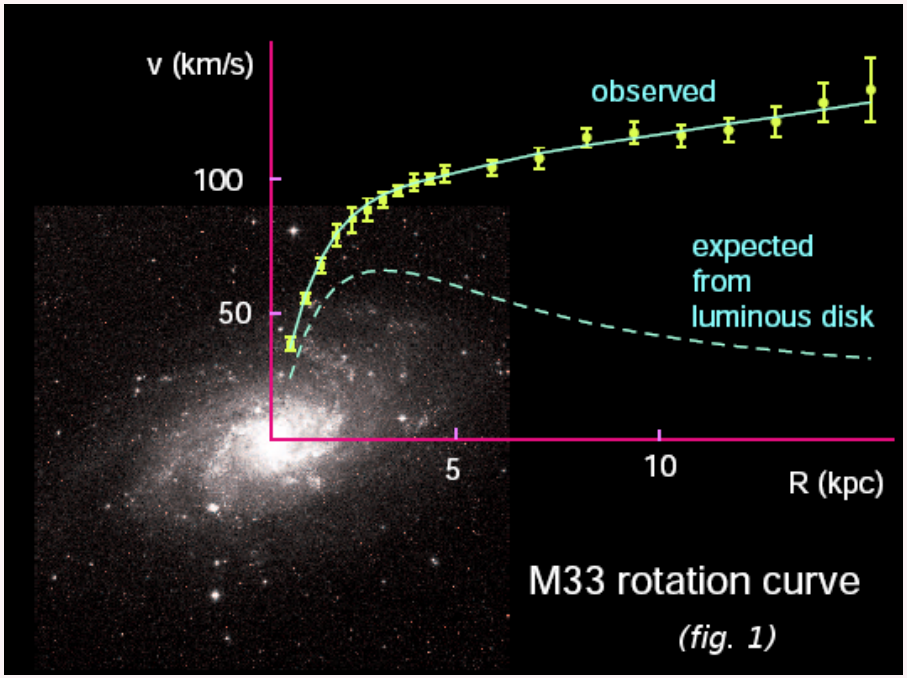




- We do not know what makes 95% of the Universe!
- What is this dark energy?

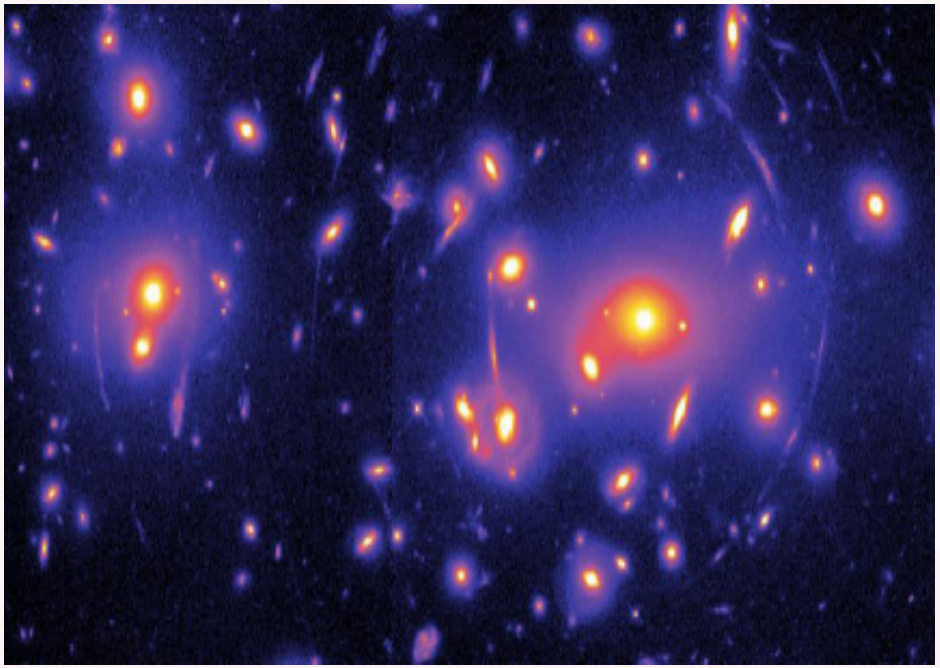
Evidence for dark matter

There is not enough visible mass in rotating spiral galaxies to hold them together



Gravitational lensing:

Light is bent by unseen mass, give distortions or multiple images



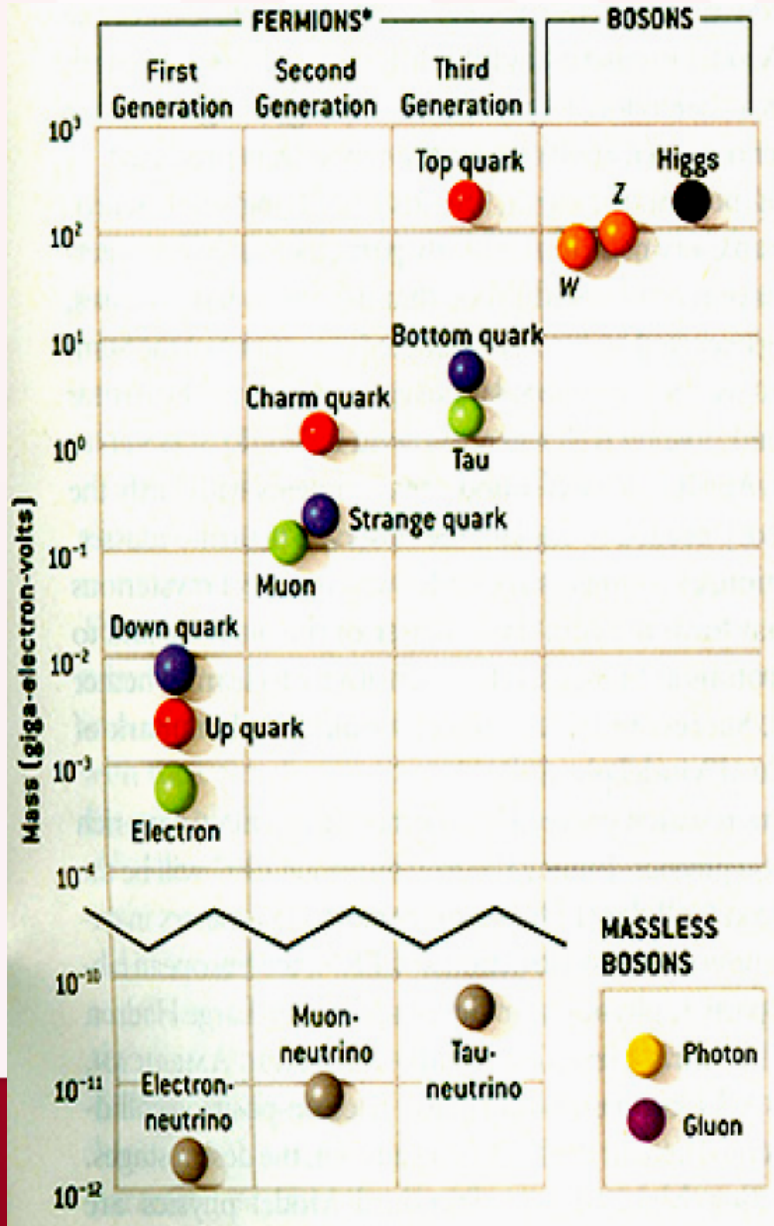
Also seen in galaxy clusters

The Large Hadron Collider
At Discovery's Horizon

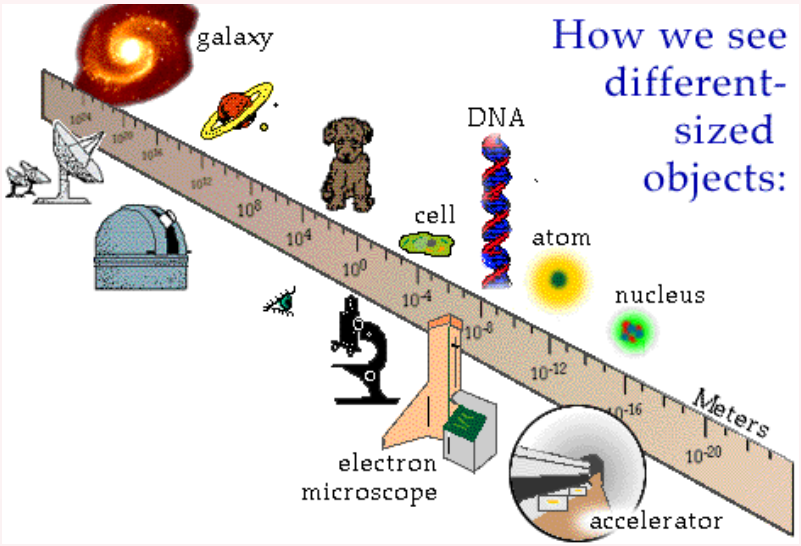
Great questions of Particle Physics & Cosmology

- Why three families?
- Why do particles have so vastly different masses: 10^{-11} - 100 GeV?
- Does the Higgs boson exist?
- Are forces unified at large energies?
- What is the nature of dark matter?
- Why is gravity so weak?
- Why is any matter left in the Universe?
- What is the dark energy?

FRANK & ERNEST reproduced by permission of NEA, Inc.

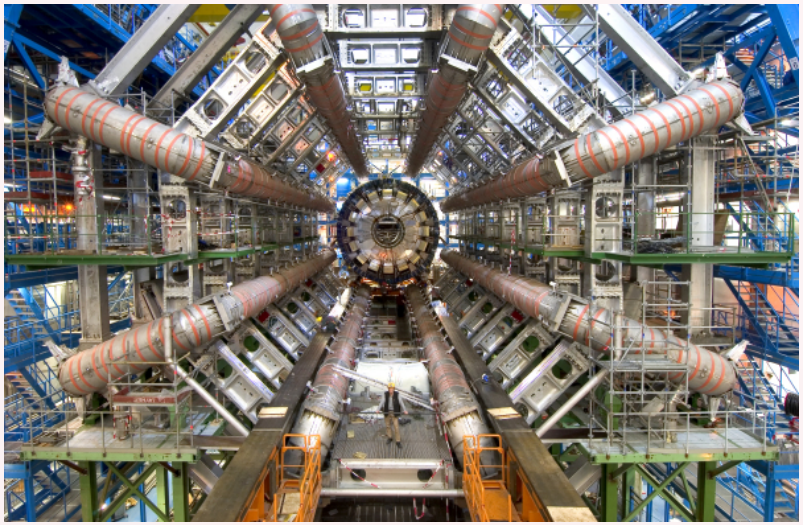


Particle Physics experiments require



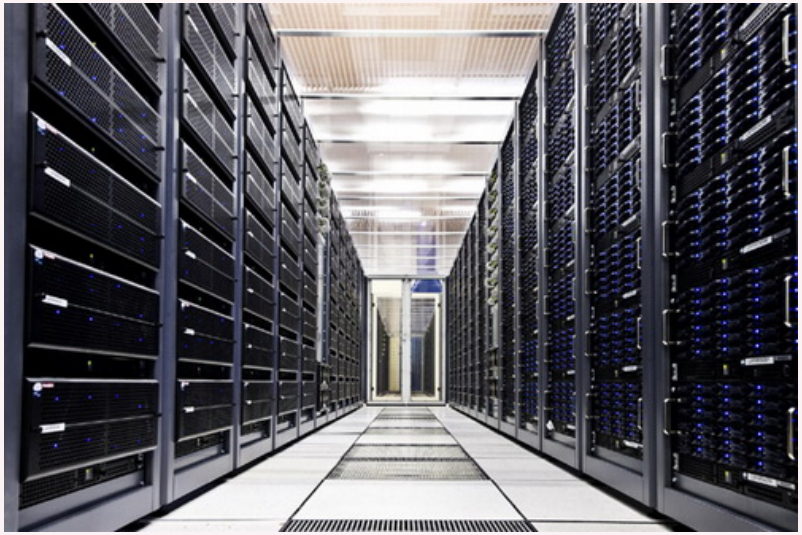
- **Accelerators**: powerful machines to accelerate particles to extremely high energies and bring them into collision

Particle Physics experiments require



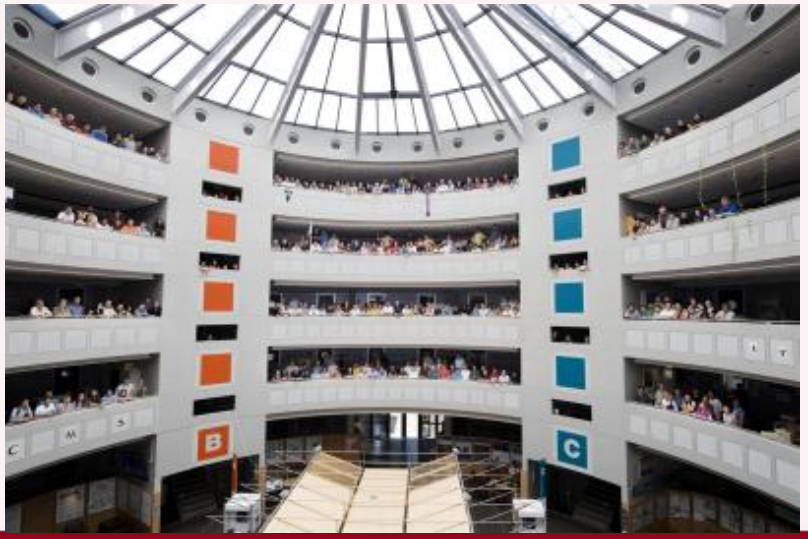
- **Accelerators**: powerful machines to accelerate particles to extremely high energies and bring them into collision
- **Detectors**: gigantic instruments that record the particles that come out of the collision

Particle Physics experiments require



- **Accelerators**: powerful machines to accelerate particles to extremely high energies and bring them into collision
- **Detectors**: gigantic instruments that record the particles that come out of the collision
- **Computing grids**: to collect, store, distribute and analyze the vast amount of data produced by the detectors

Particle Physics experiments require

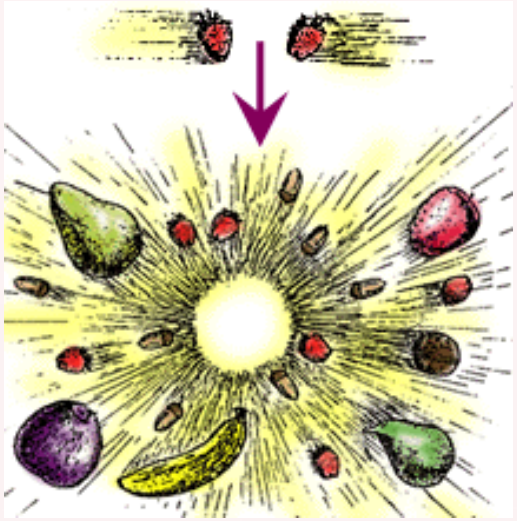


- **Accelerators**: powerful machines to accelerate particles to extremely high energies and bring them into collision
- **Detectors**: gigantic instruments that record the particles that come out of the collision
- **Computing grids**: to collect, store, distribute and analyze the vast amount of data produced by the detectors
- **People**: worldwide collaboration of scientists, engineers, technicians and support staff to design, build and operate such complex instruments

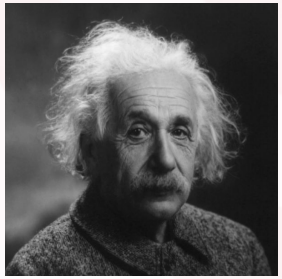
WELCOME TO THE LHC

PROTONS → ENERGY → NEW PARTICLES

- Convert the energy given to accelerated protons to create new, heavy particles



$E=mc^2$



Einstein

FASTEST

Trillions of protons travel the 16.5-mile-long tunnel

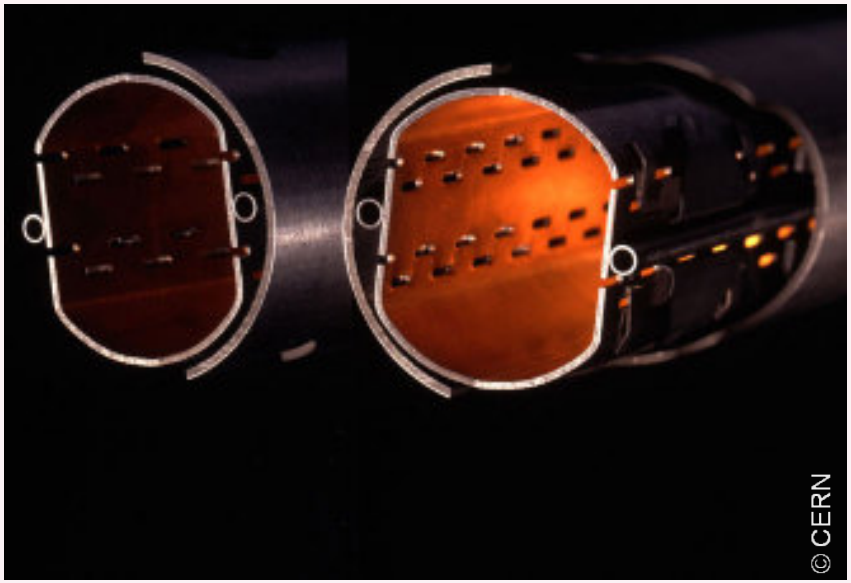
11,000 times a second (that's 670,626,025 mph)

- Only $2 \cdot 10^{-9}$ grams of Hydrogen consumed each day
- Protons are accelerated by powerful electric fields
- Using a chain of accelerators, protons go from 1 GeV at rest to 3500 GeV
- Like taking a 100 kg person and accelerating them until they weigh 350 ton

EMPTIEST

- The beampipes are evacuated to allow protons to travel freely

Particles travel in vacuum at 10^{-13} atm



More atmosphere on the moon than in the LHC

COLDEST

- Protons are guided around their circular orbits by powerful superconducting magnets

LHC's superconducting magnets operate at -456°F

Colder than the vacuum of outer space

LHC by the numbers

LHC	Everyday life
362 MJ Energy stored by all protons in LHC	361 MJ USS Ronald Reagan at 5.6 knots
43,000 tons LHC magnets combined weight	88,000 tons USS Ronald Reagan weight
$4.4bn cost of building the LHC	$4.5bn cost of the USS Ronald Reagan
8.3 T Magnetic field in one magnet	$5\ 10^{-5}$ T Earth's magnetic field
120 MW CERN's power consumption	1000 MW Typical breeder reactor power


USS Ronald Reagan


15 m long magnet being lowered into the tunnel

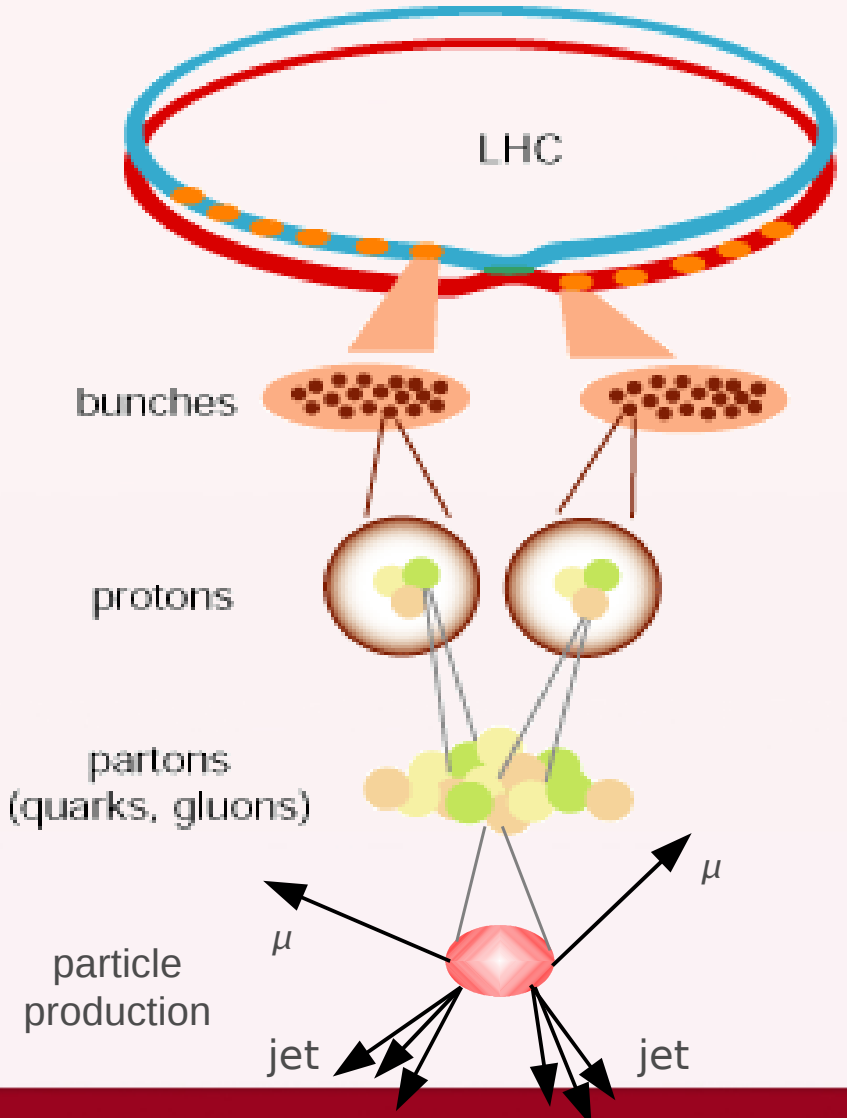
Dipole magnet with the two beampipes

Animations

Video showing LHC and ATLAS
http://www.atlas.ch/multimedia/html-nc/animation-intro.html

Video showing acceleration and collision in ATLAS
http://www.atlas.ch/multimedia/html-nc/animation-7TeV-event.html

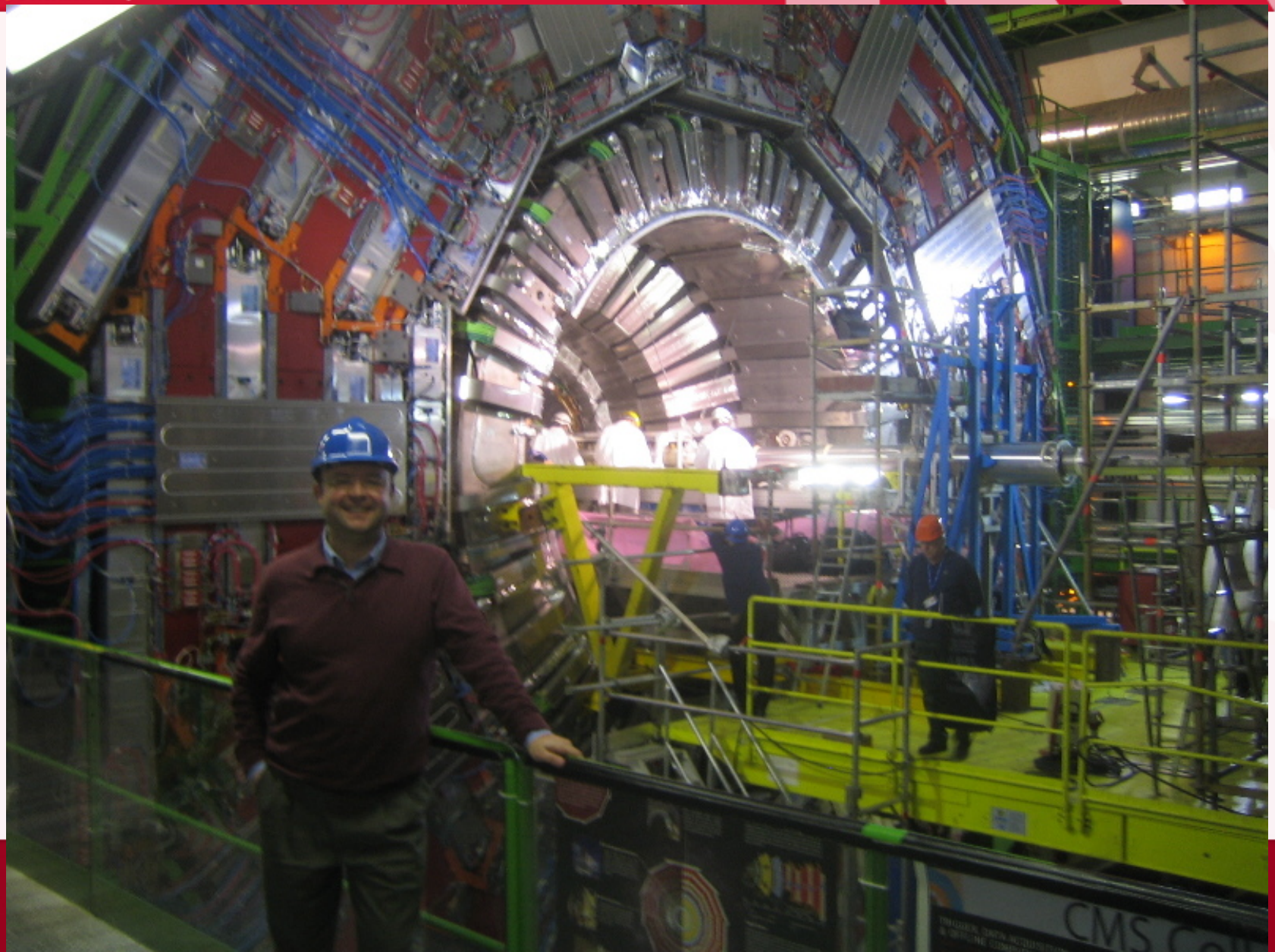
Collisions at the LHC



- Two beams: proton proton
- 2808 x 2808 bunches
- Crossing rate: 40 MHz
- Collision rate: ~10^9 Hz
- Stored data rate: ~100 Hz
- Rare processes: 1 in 10^{13}
- Like drinking from a firehose!

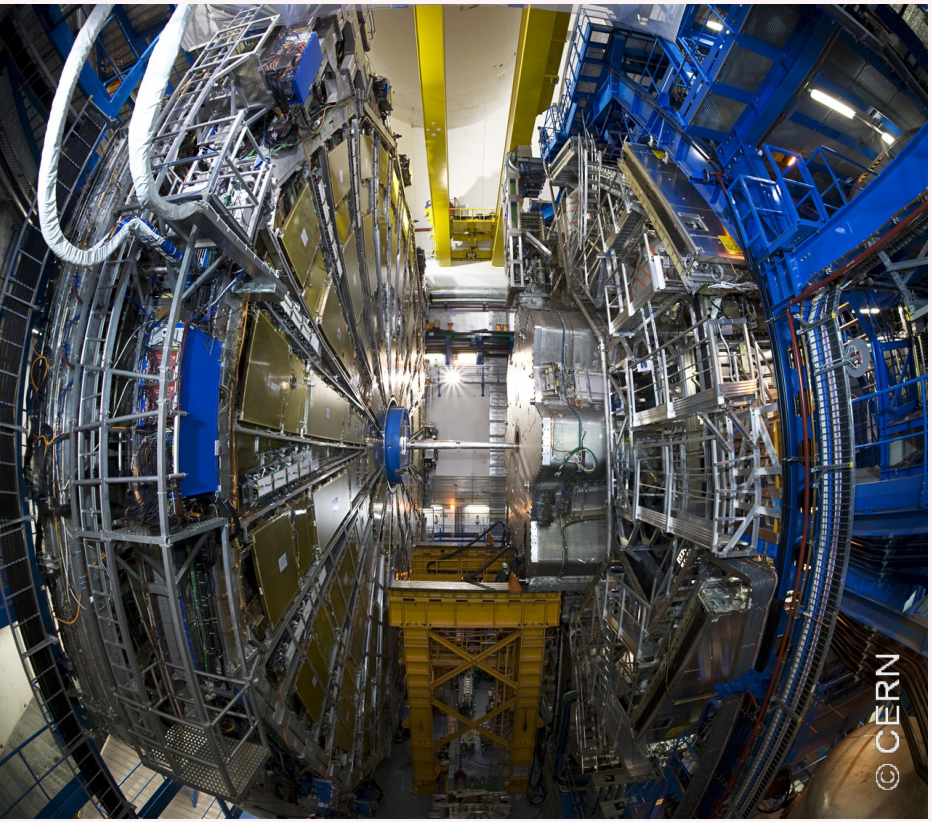
The Large Hadron Collider
At Discovery's Horizon

DETECTORS

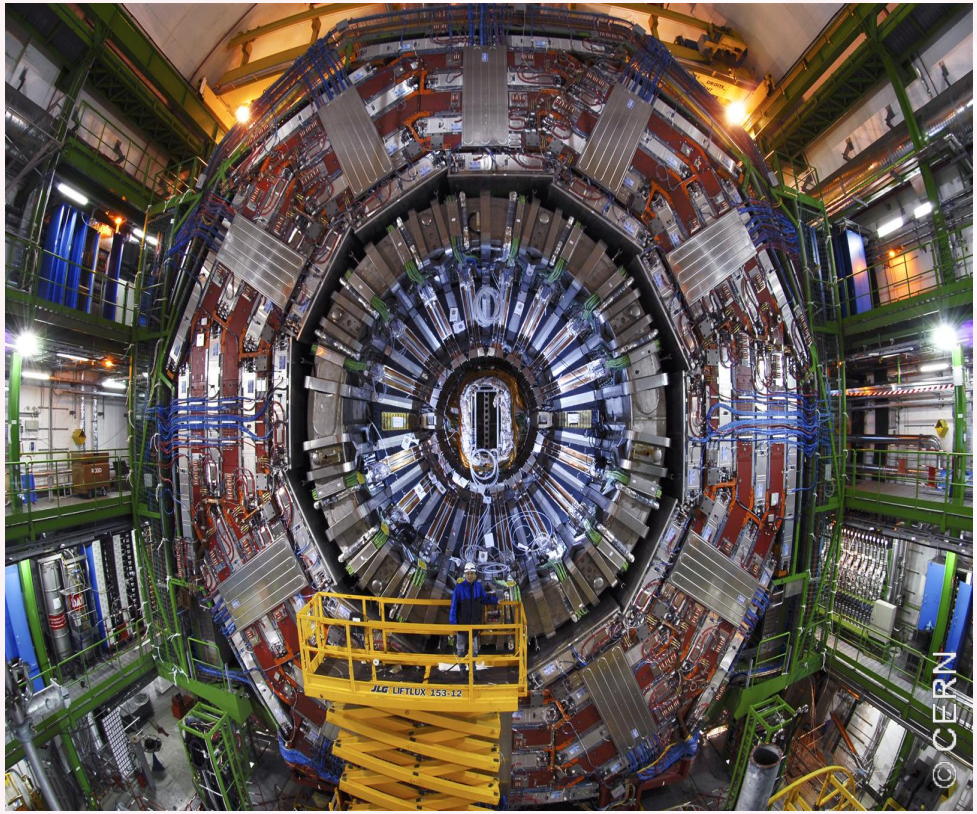


BIGGEST

Largest, most complex detectors ever built

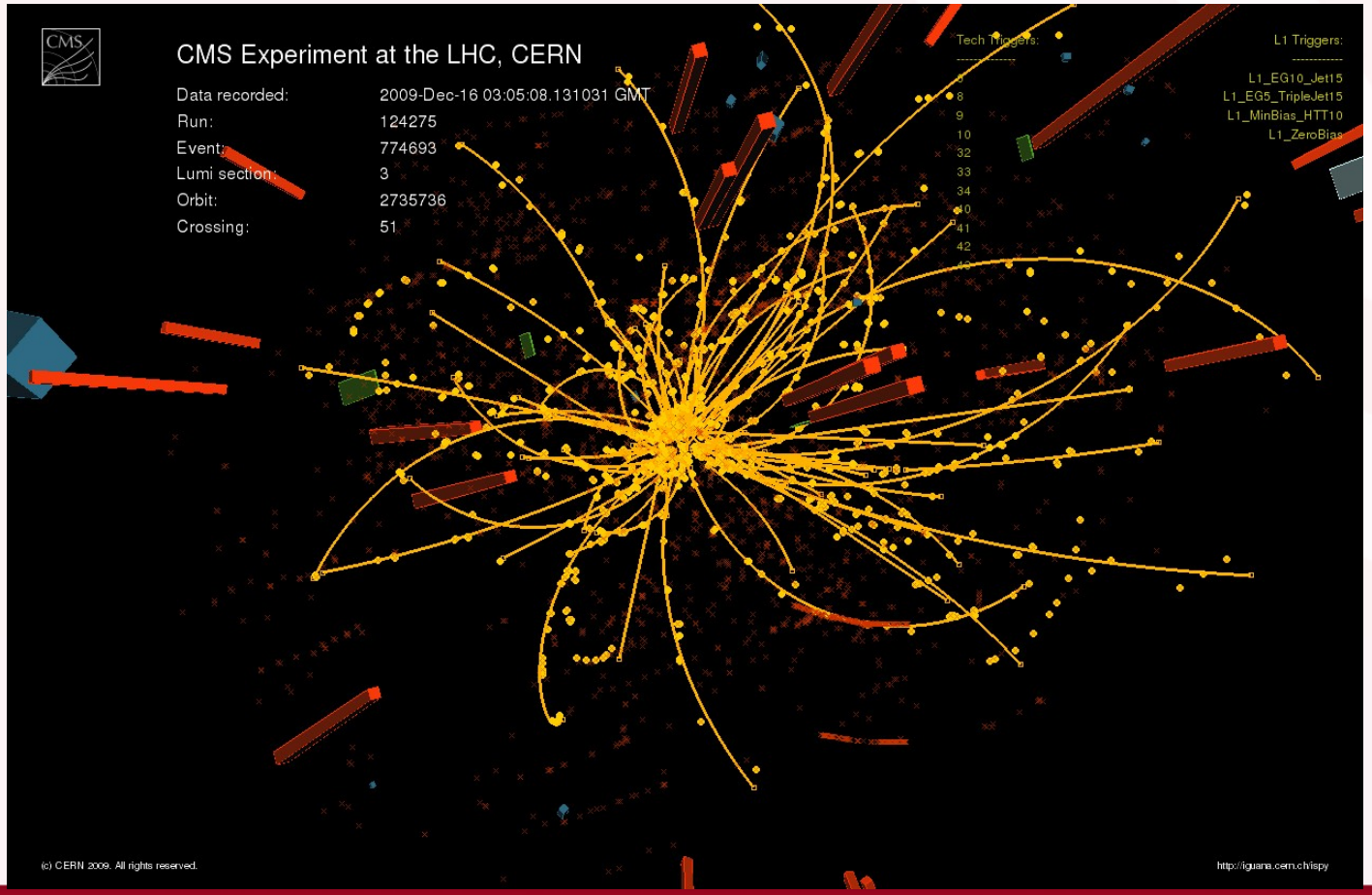


Study the tiniest particle with incredible precision



HOTTEST

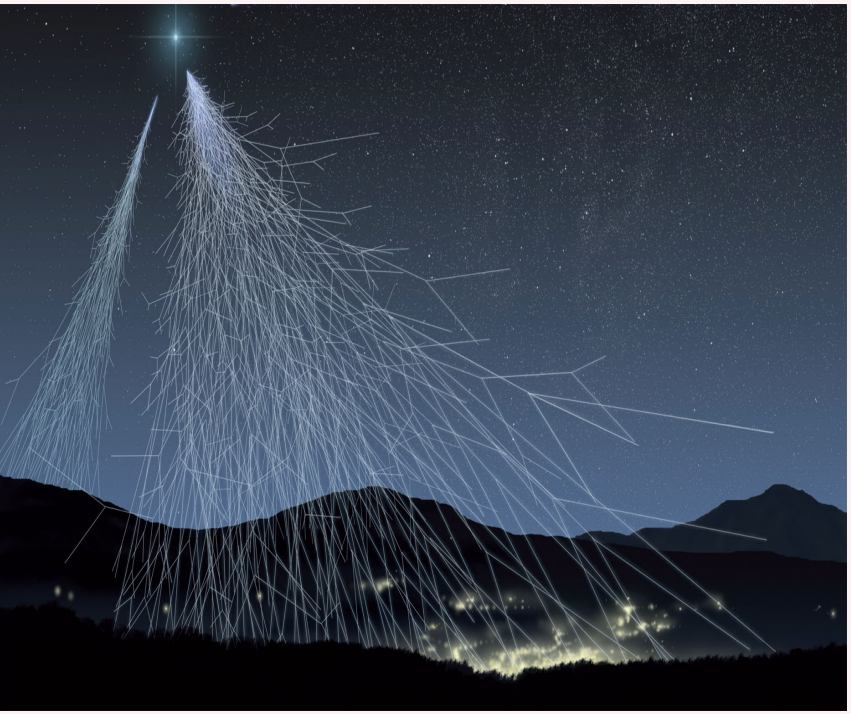
Colliding protons generate temperatures one billion times hotter than the center of the sun

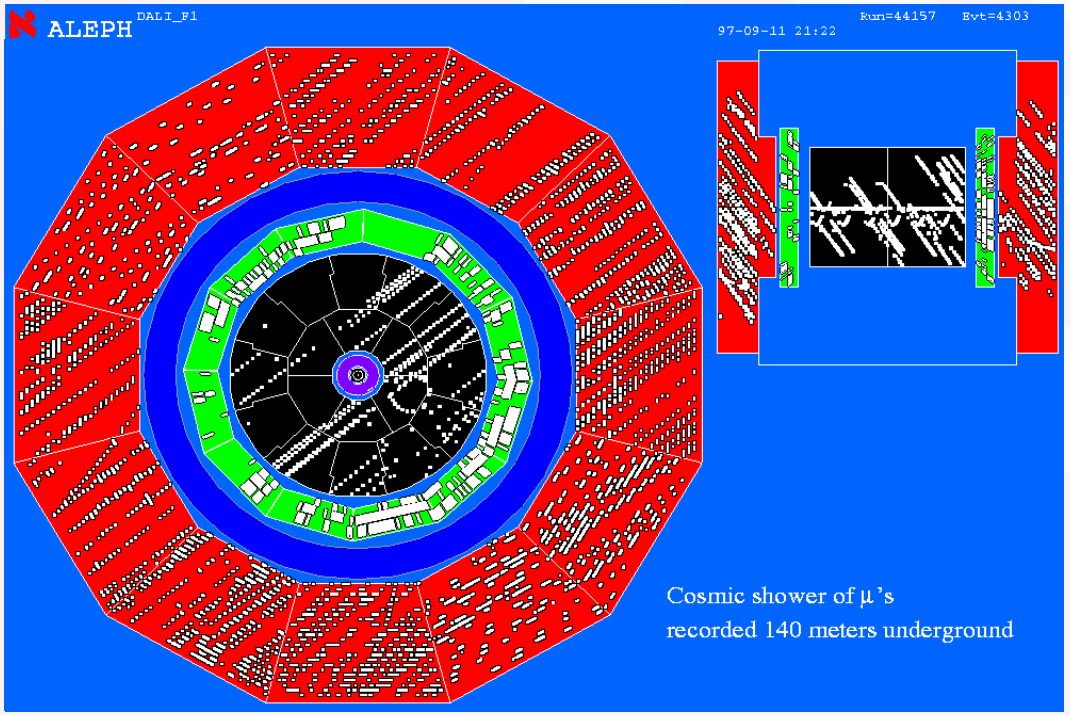


The Large Hadron Collider
At Discovery's Horizon

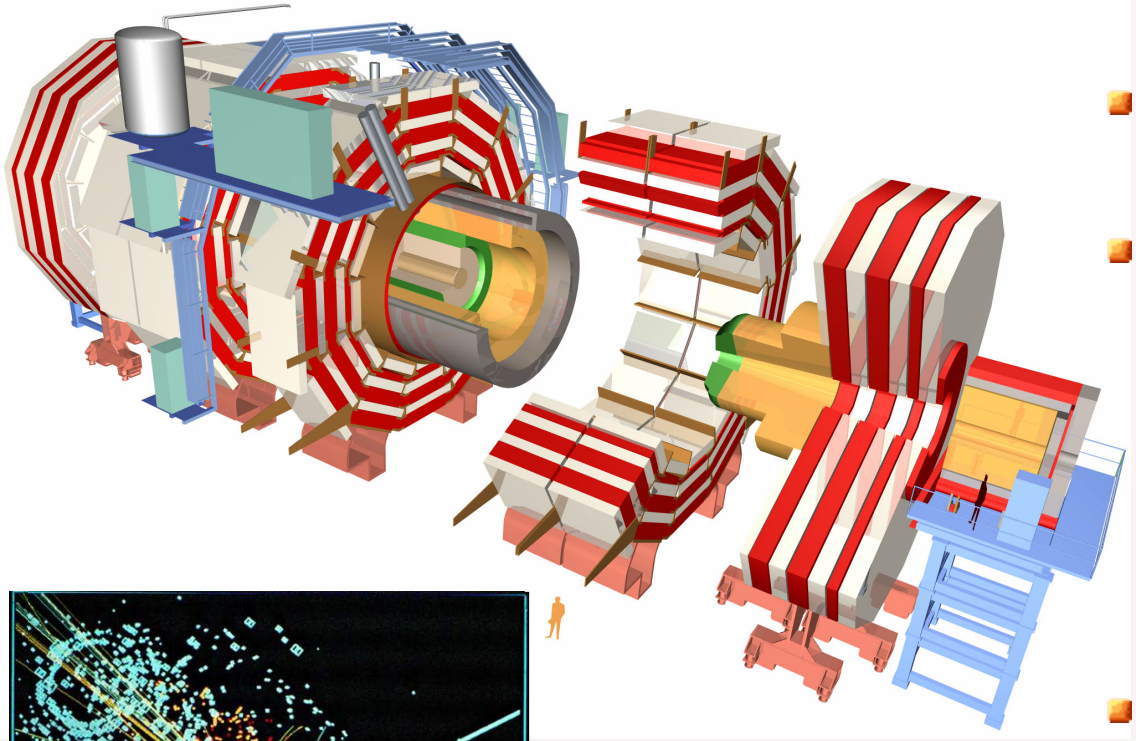
NOTHING THE EARTH HASN'T SEEN BEFORE

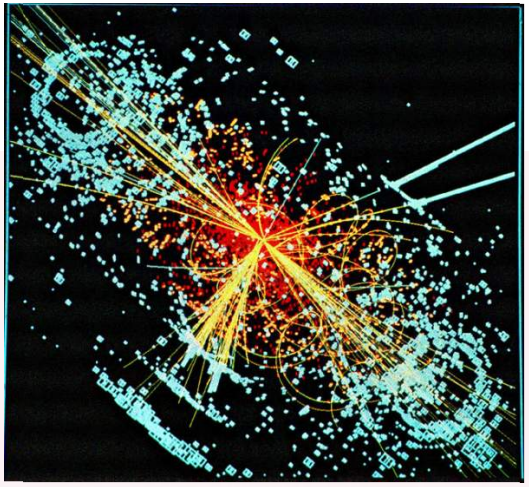
- LHC collisions aren't dangerous to the Earth
- Cosmic rays can far exceed LHC energies
- Nature has already performed 1 million LHC experiments on Earth
- The Universe performs 10 million LHC-like experiments every second





CMS schematic diagram



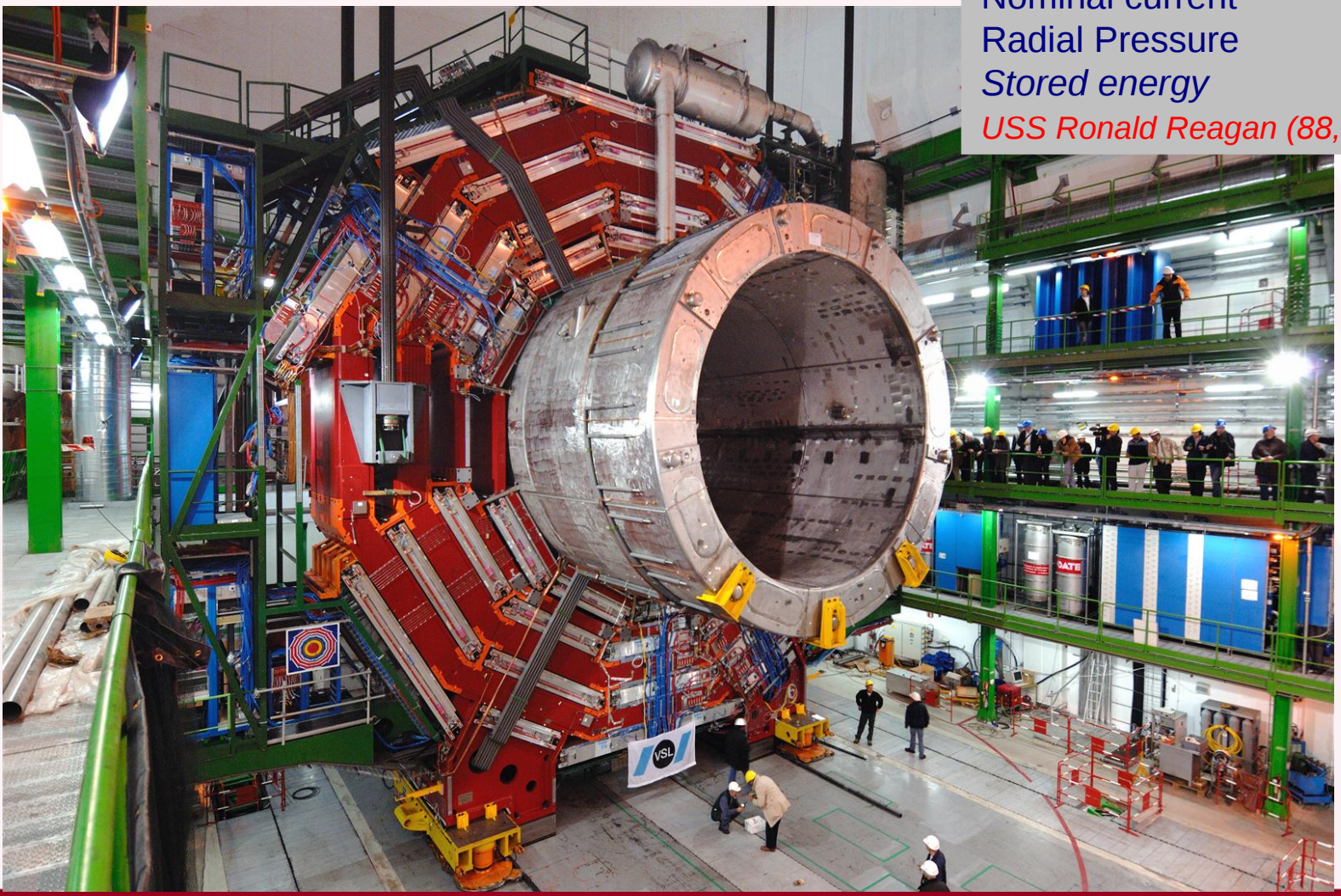


- General purpose detectors are composed of many layers
- Each layer designed to perform a specific task
  - Tracker
  - Calorimeter
  - Solenoid Magnet
  - Muons
- Together, these layers allow us to identify and precisely measure the energy and momentum of all the particles produced in the collisions

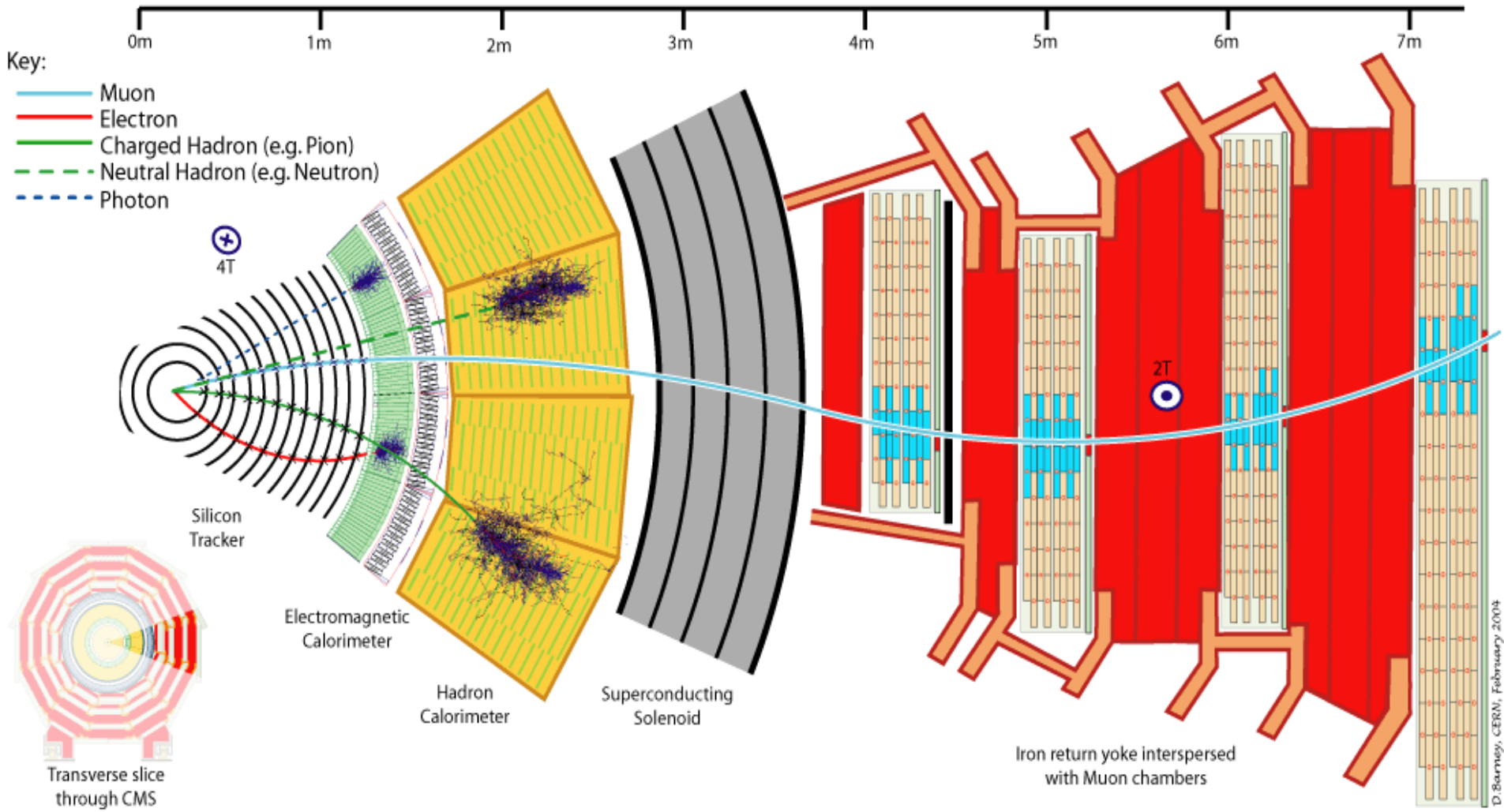
CMS solenoid magnet

Magnetic length	12.5 m
Free bore diameter	6 m
Central B Field	4 T
Temperature	4.2° K
Nominal current	20 kA
Radial Pressure	64 atm
Stored energy	*2.7 GJ*

USS Ronald Reagan (88,000 tons) at 20 mph

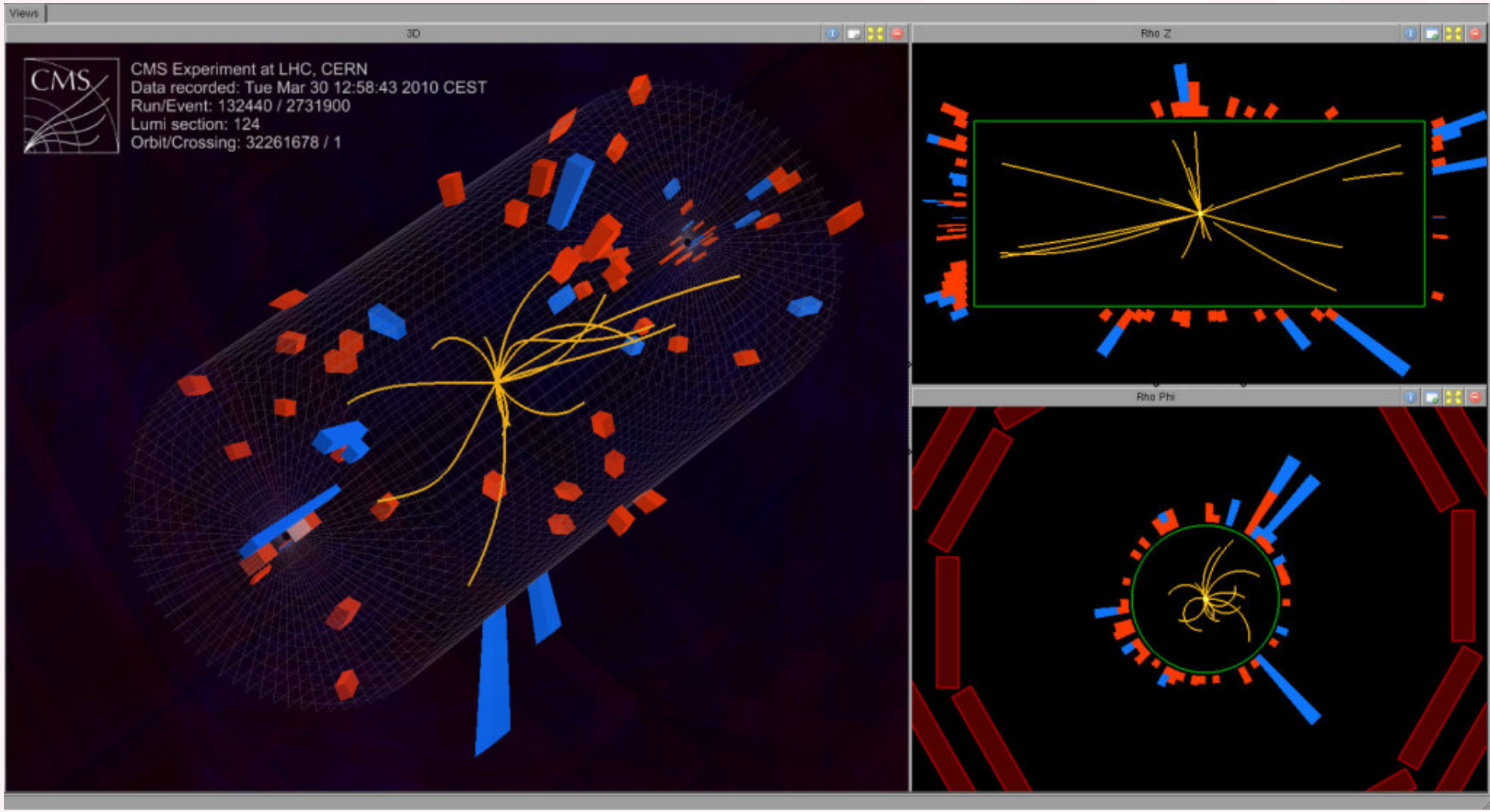


PARTICLE DETECTION IN CMS



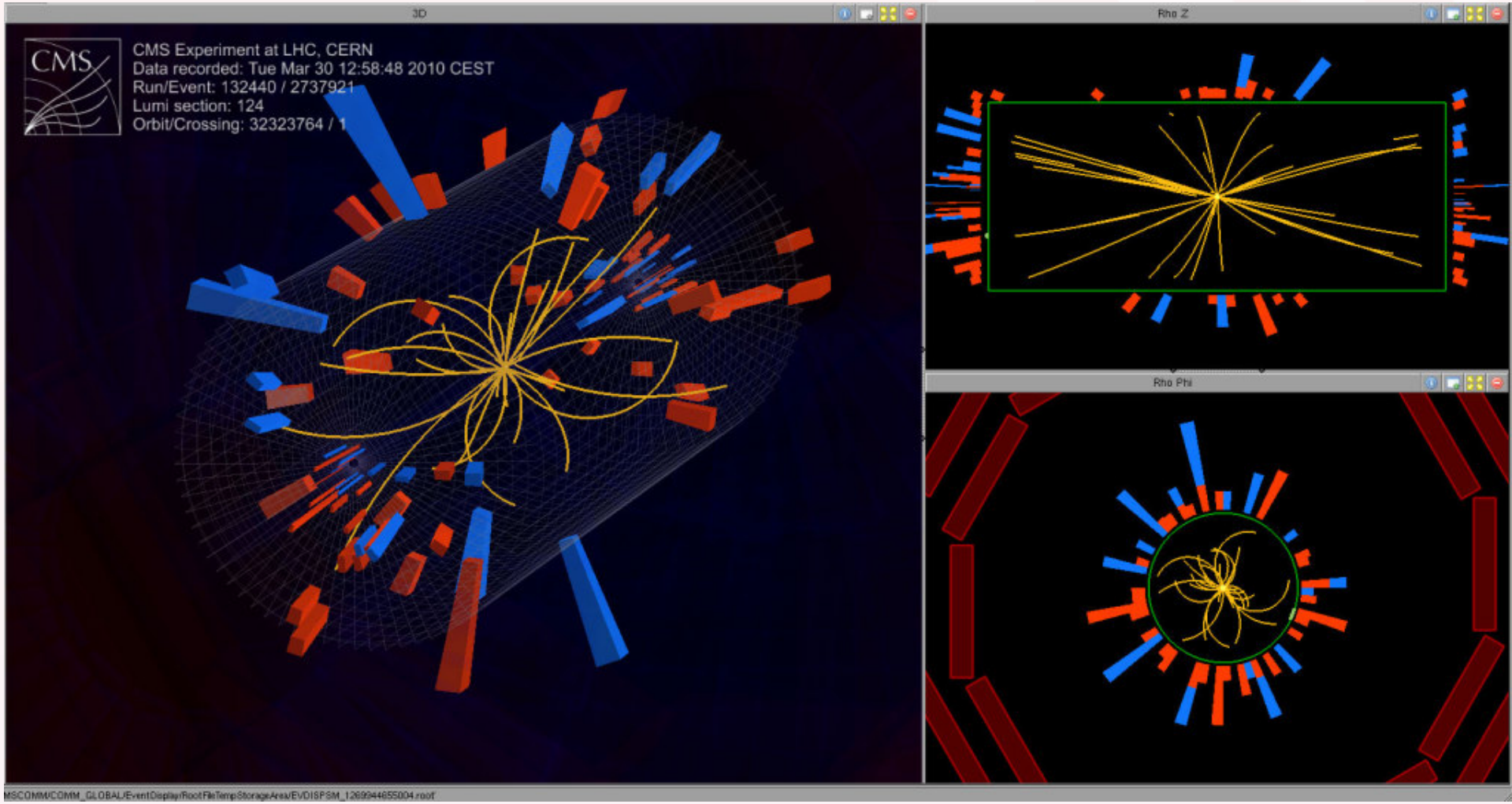
The Large Hadron Collider
At Discovery's Horizon

First data events at 7 TeV

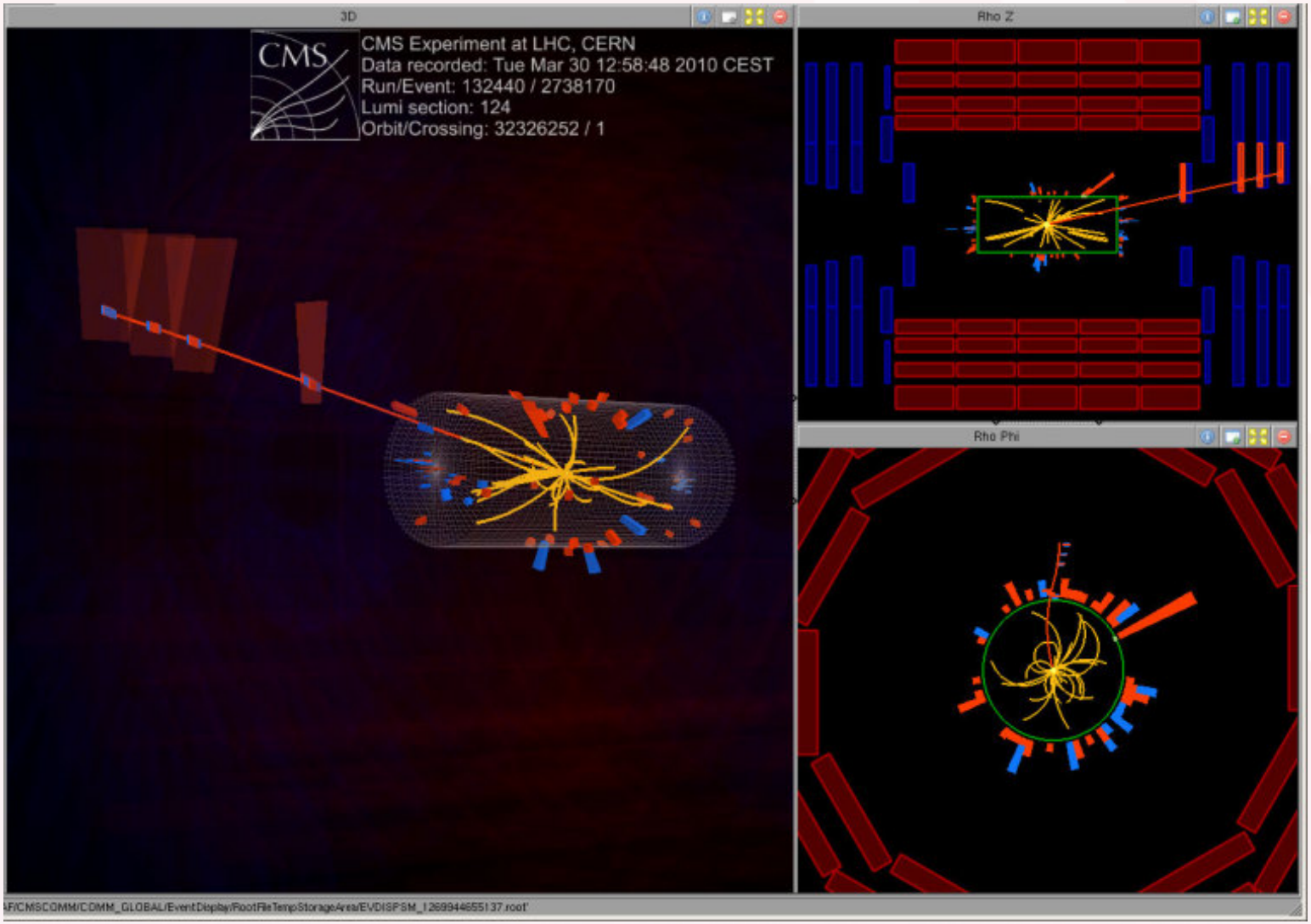


The Large Hadron Collider
At Discovery's Horizon

First data events at 7 TeV

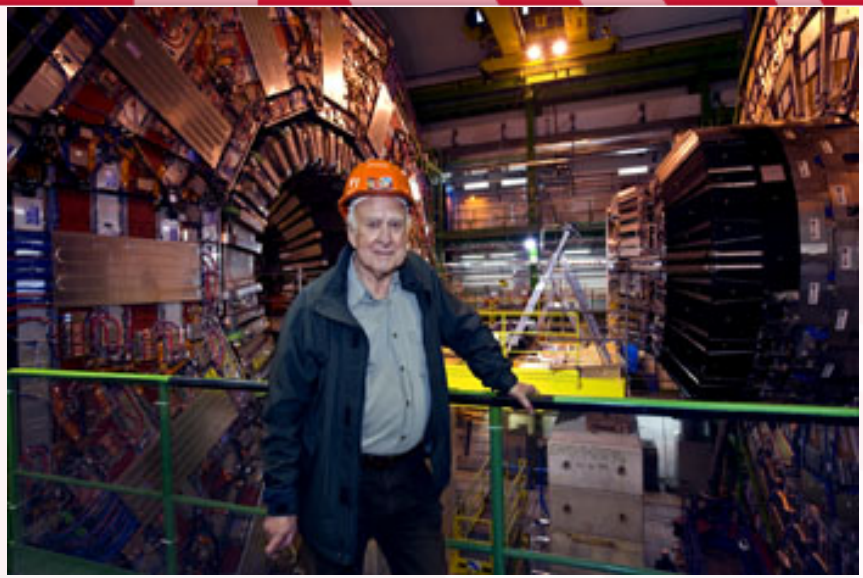


First data events at 7 TeV



Why do we have mass?

- **Still a mistery**
- One possibility: Higgs field
- Predicted in 1964, still unobserved
- Rochester connection:



2010 J.J. Sakurai Prize

"For elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses"

Peter W. Higgs
University of Edinburgh

Gerald S. Guralnik
Brown University

Robert Brout
Universite Libre de Bruxelles

Carl R. Hagen
University of Rochester

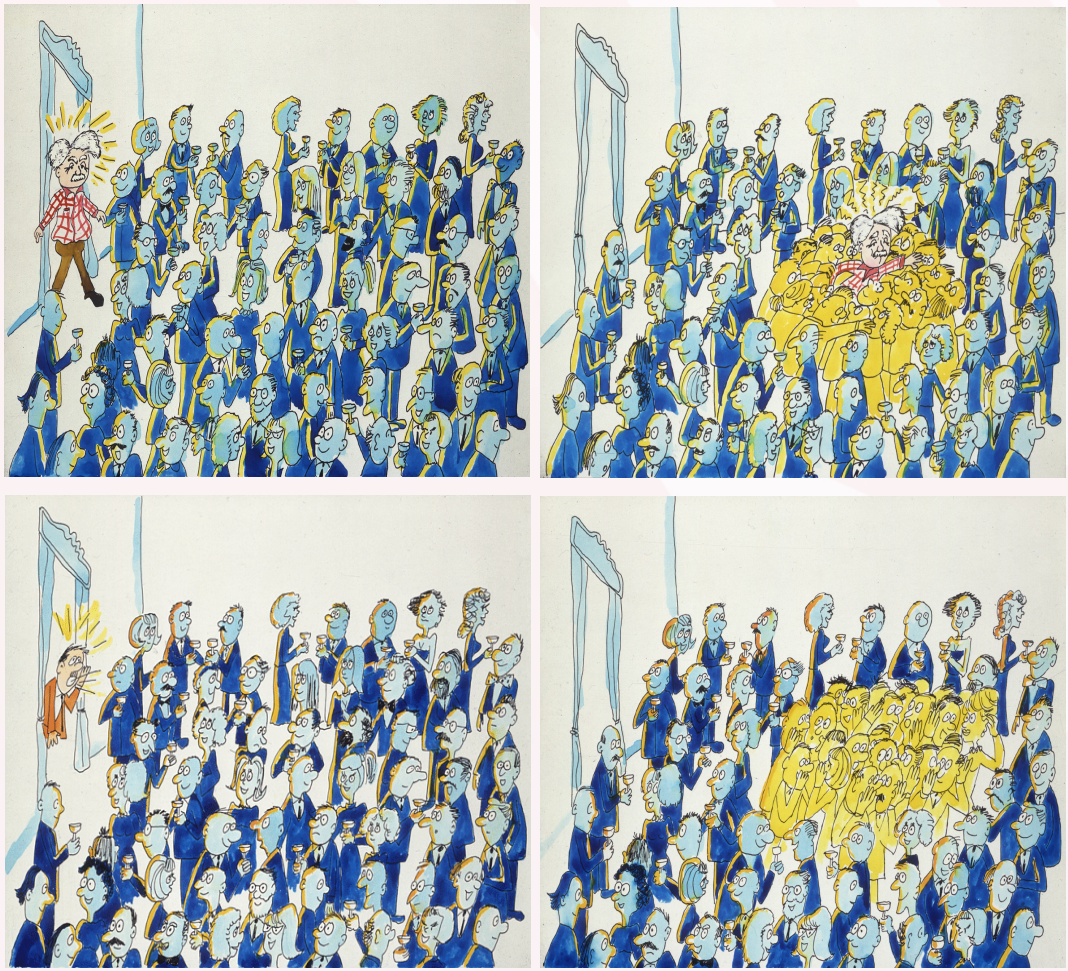
François Englert
Universite Libre de Bruxelles

T. W. B. Kibble
Imperial College

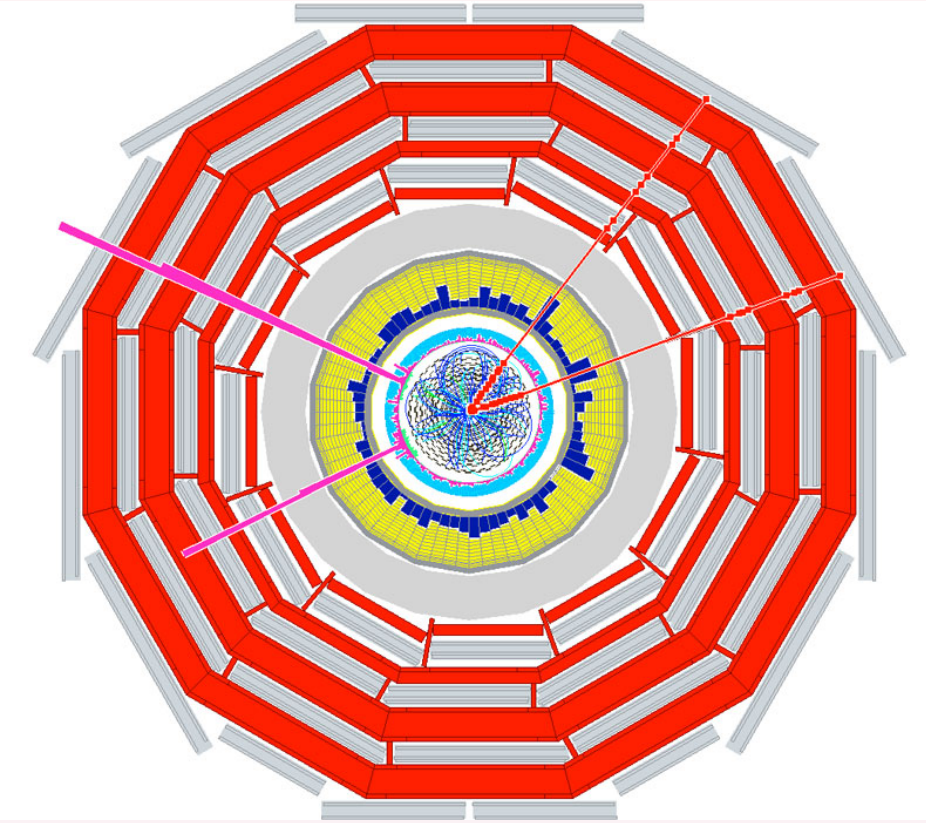
WHAT'S A HIGGS BOSON?

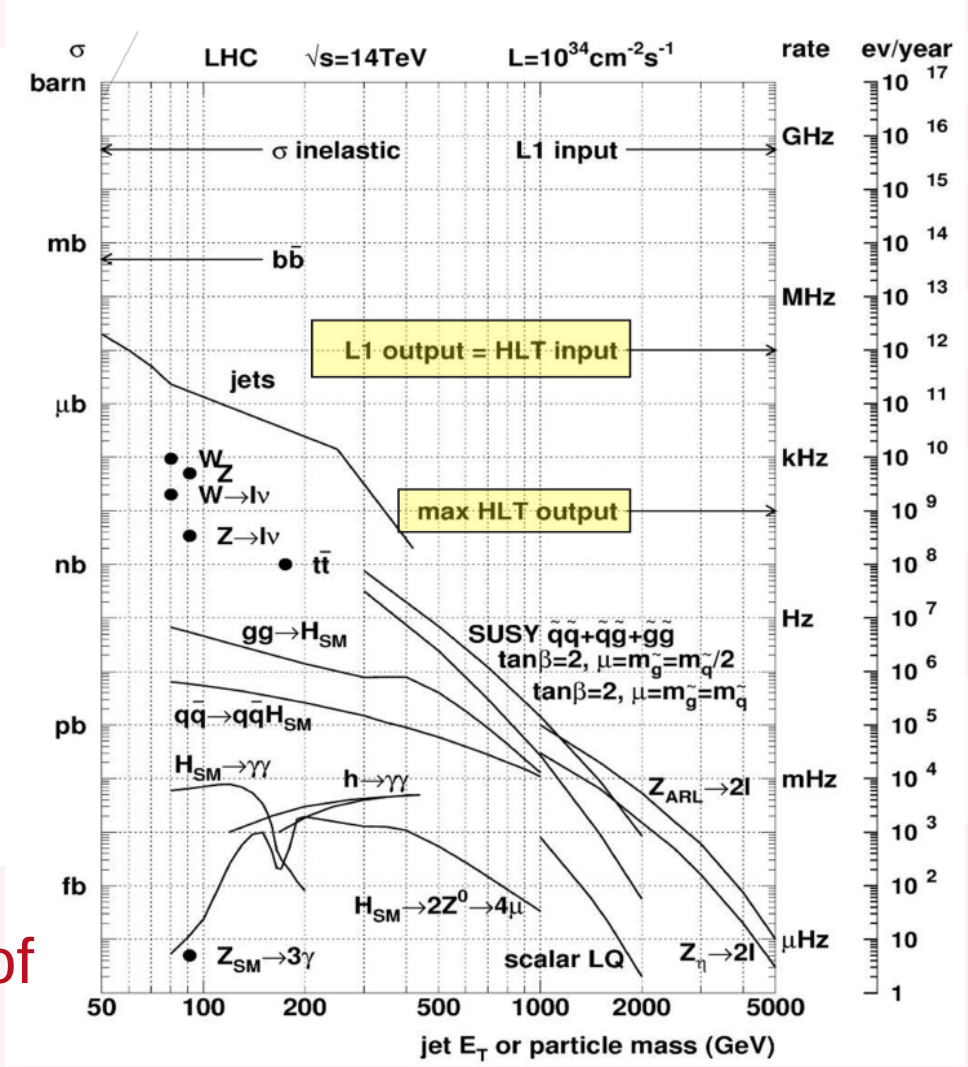
Imagine a room full of physicists chattering quietly is like space filled with the Higgs field

- A VIP enters the room
  - Creates a **disturbance** as he moves through: a cluster of people forms around him
  - His motion is more restricted: **more inertia** (mass)
  - Particles traveling through space also "feel" the pull/inertia from the medium (Higgs field)
- Imagine a rumor spreading
  - Causes people to **cluster**
  - This interaction is like **mass**
  - We can excite the medium to produce a **Higgs particle**



WHAT A HIGGS BOSON MIGHT LOOK LIKE





- Like finding a needle in a field of haystacks

Beyond the Standard Model

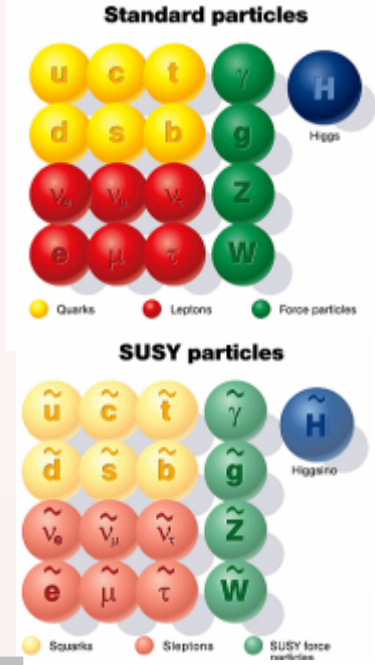
What do we hope to find at the LHC?

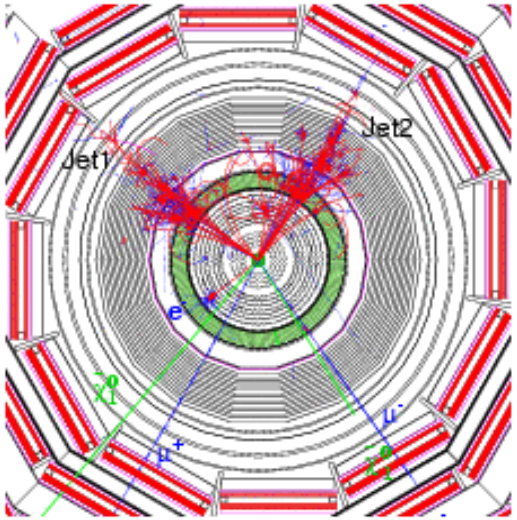
- New forces, new particles?
- Supersymmetry?
  - Matter and forces are the same!
- Dark matter?
- Higgsless resonances, technicolor?
- Extra dimensions?
- Mini black holes?

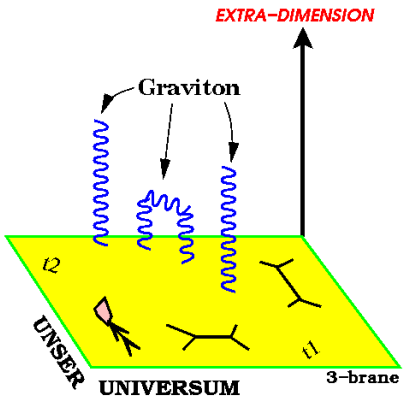
We do not know what is out there waiting for us

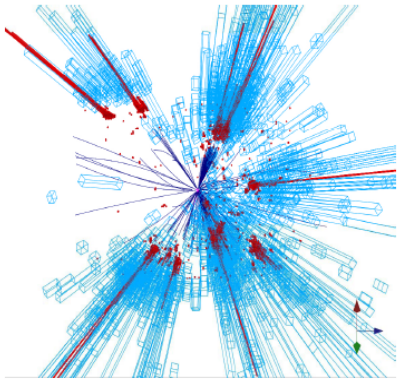
There are many possibilities... the best would be to find something unexpected, something we haven't thought of

We have to be ready!





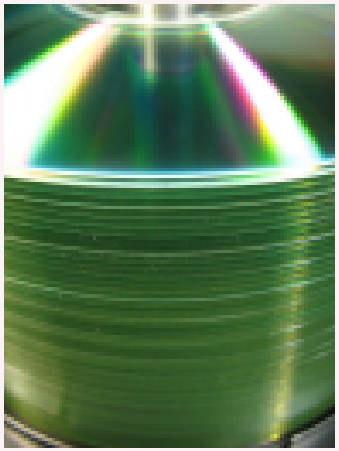


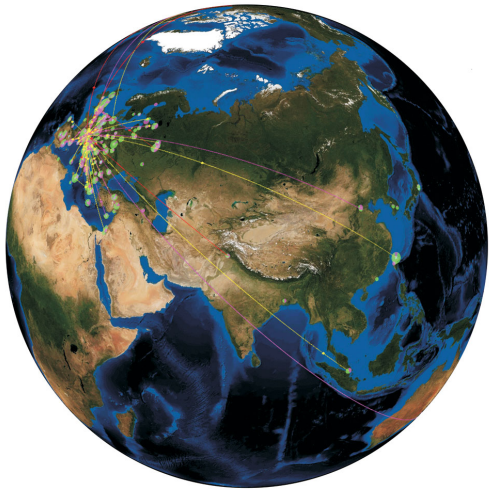


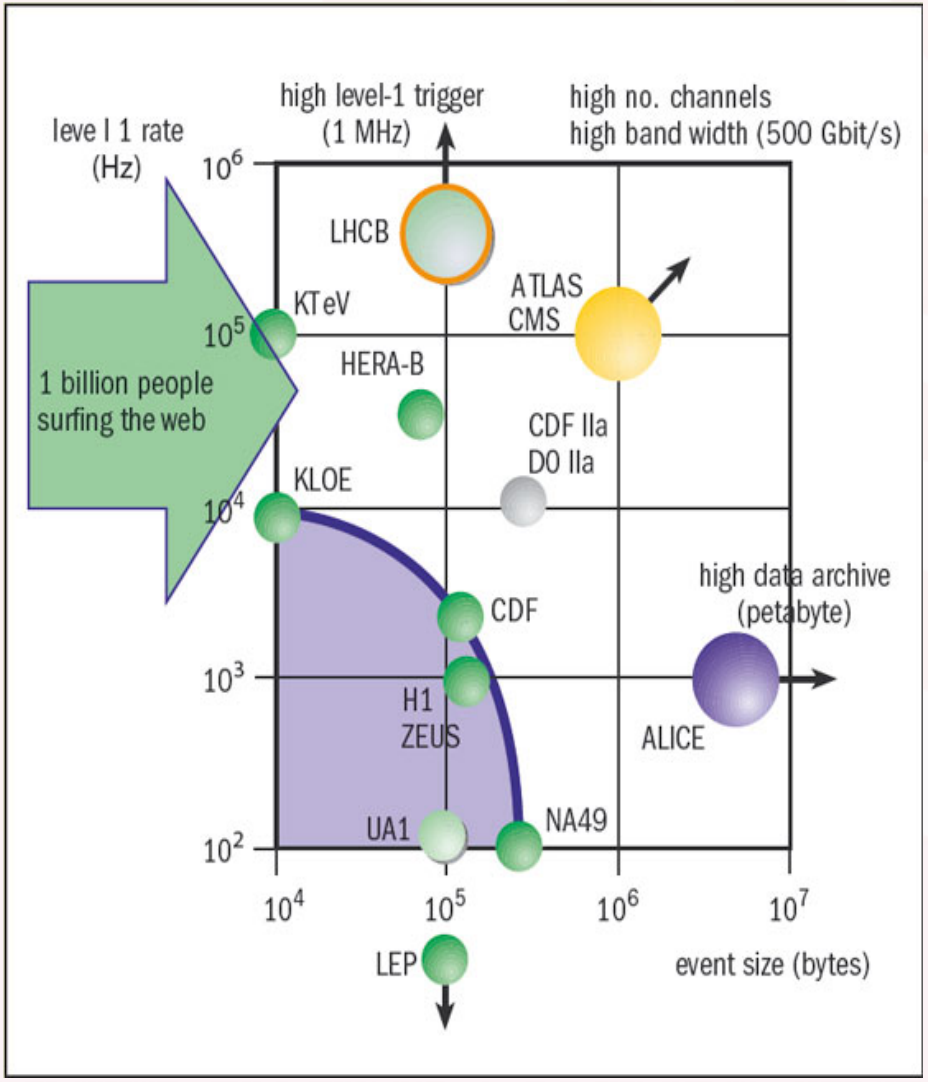
black hole

A GLOBAL DATA CHALLENGE

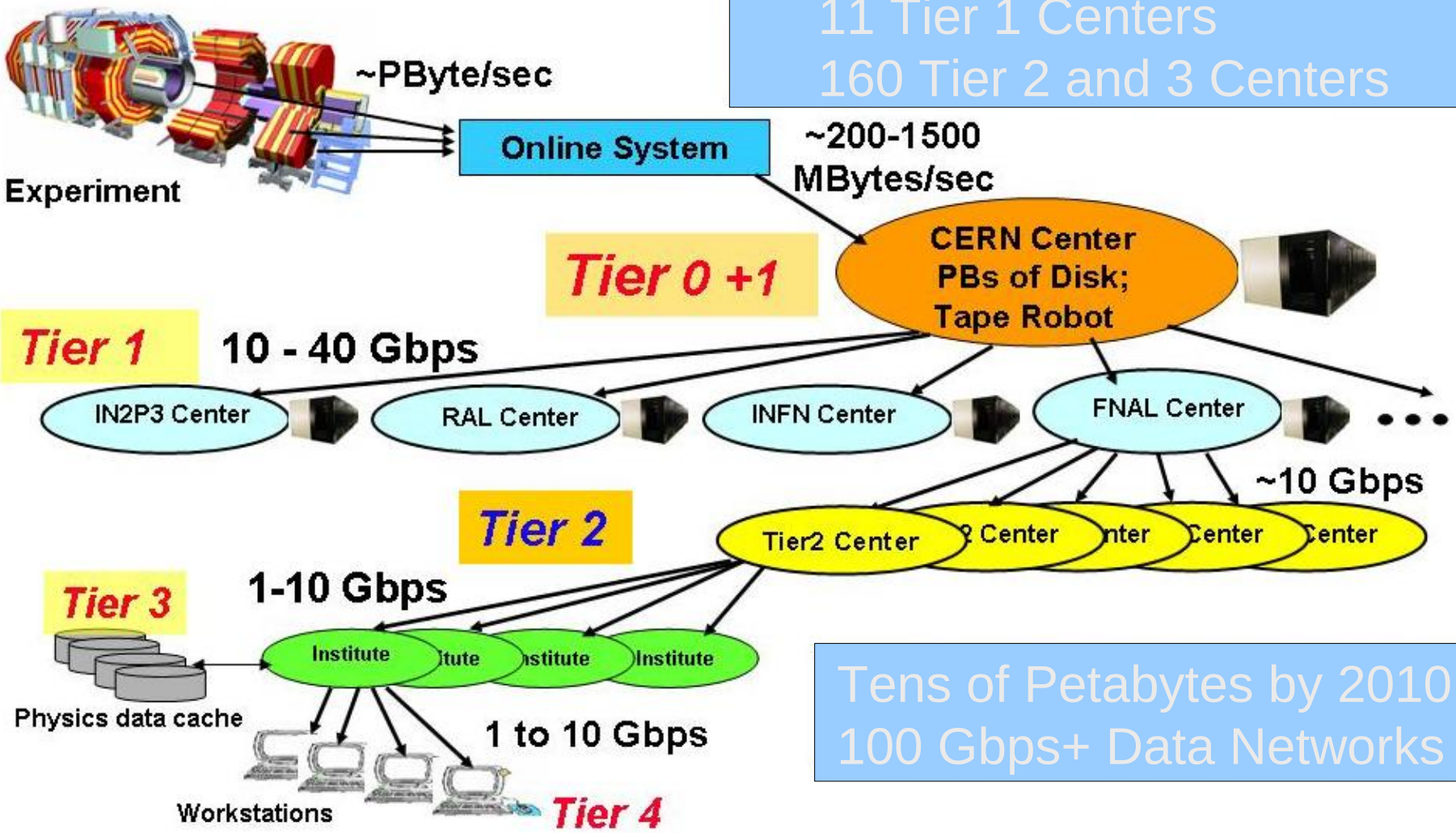
- 4 experiments
- 50 million sensors each
- 40 million collisions every second
- 15 petabytes of data every year (12-mile-high stack of CDs!)
- 8,000 scientists around the world





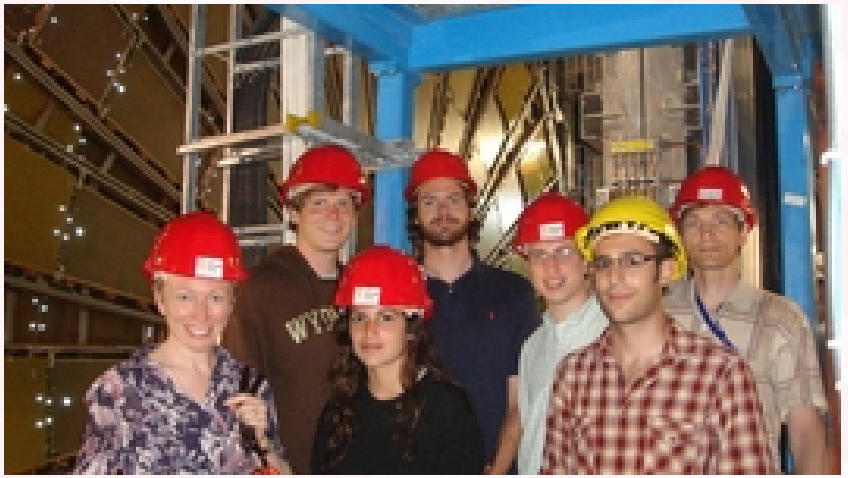


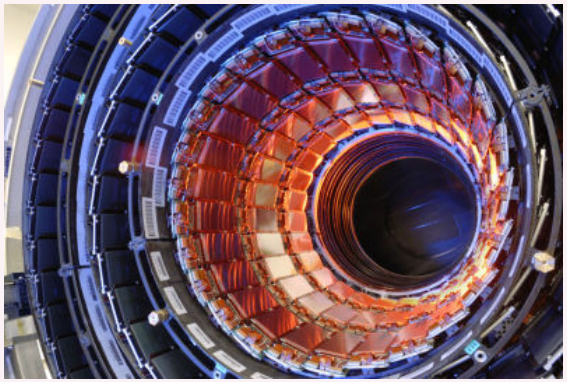
The LHC computing grid



University of Rochester contributions

- 5 faculty, 2 senior scientists, 2 engineers, 4 postdocs, 7 grad, 7 undergrad, and 4 REU students
- **Hadronic calorimeter**: design, construction, commissioning
  - 70,000 plastic scintillator tiles
- **Silicon detector**: prototyped, tested, and commissioned Si modules
  - 200 square meters of Si (100 kg)





The Large Hadron Collider

At Discovery's Horizon

THANK YOU

For more information, visit:
www.uslhc.us
www.cern.ch
www.fnal.gov
www.pas.rochester.edu

Check out the cloud chamber before you leave!

University of Rochester · Fermilab · CERN · U.S. Department of Energy · National Science Foundation

The Large Hadron Collider

At Discovery's Horizon

Nice video showing how the LHC works:

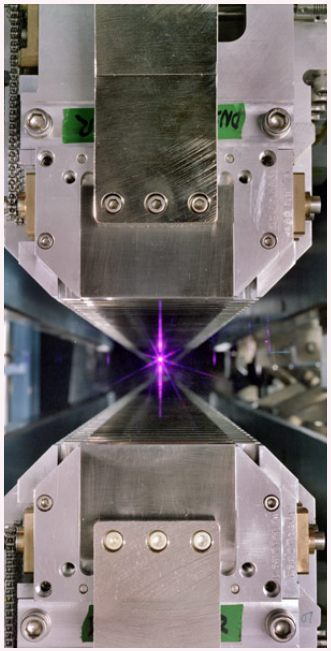
http://cdsweb.cern.ch/record/1125472

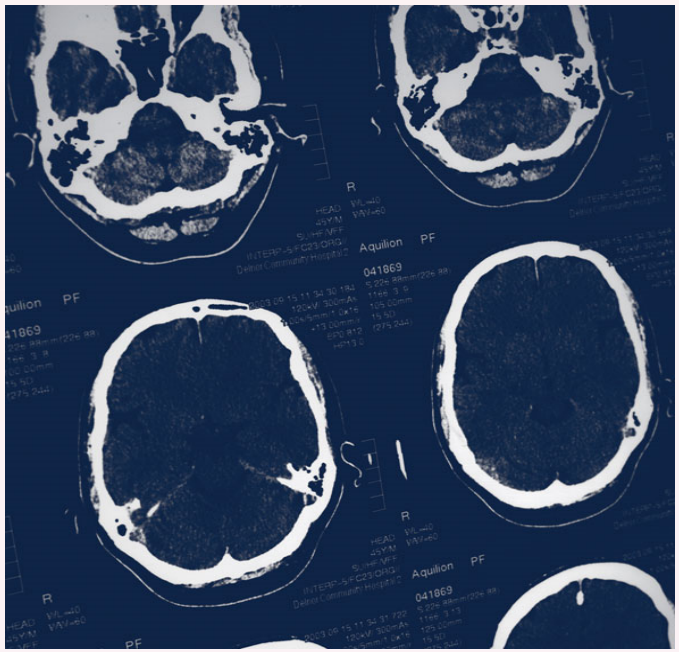
University of Rochester · Fermilab · CERN · U.S. Department of Energy · National Science Foundation

SPARE SLIDES

BENEFITS TO SOCIETY

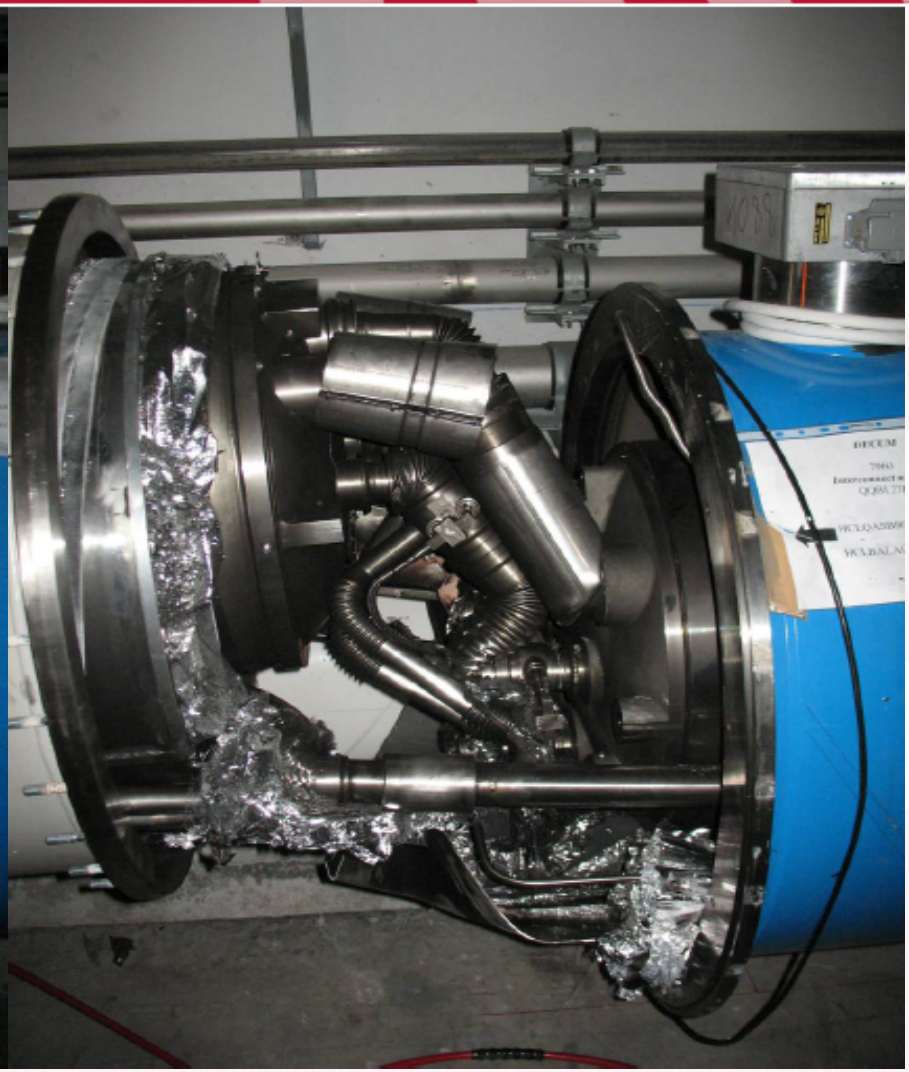
- More than 17,000 particle accelerators are in operation around the world today.
- Industry, hospitals and research institutions all use them to manufacture household products, treat cancer and make new scientific discoveries.





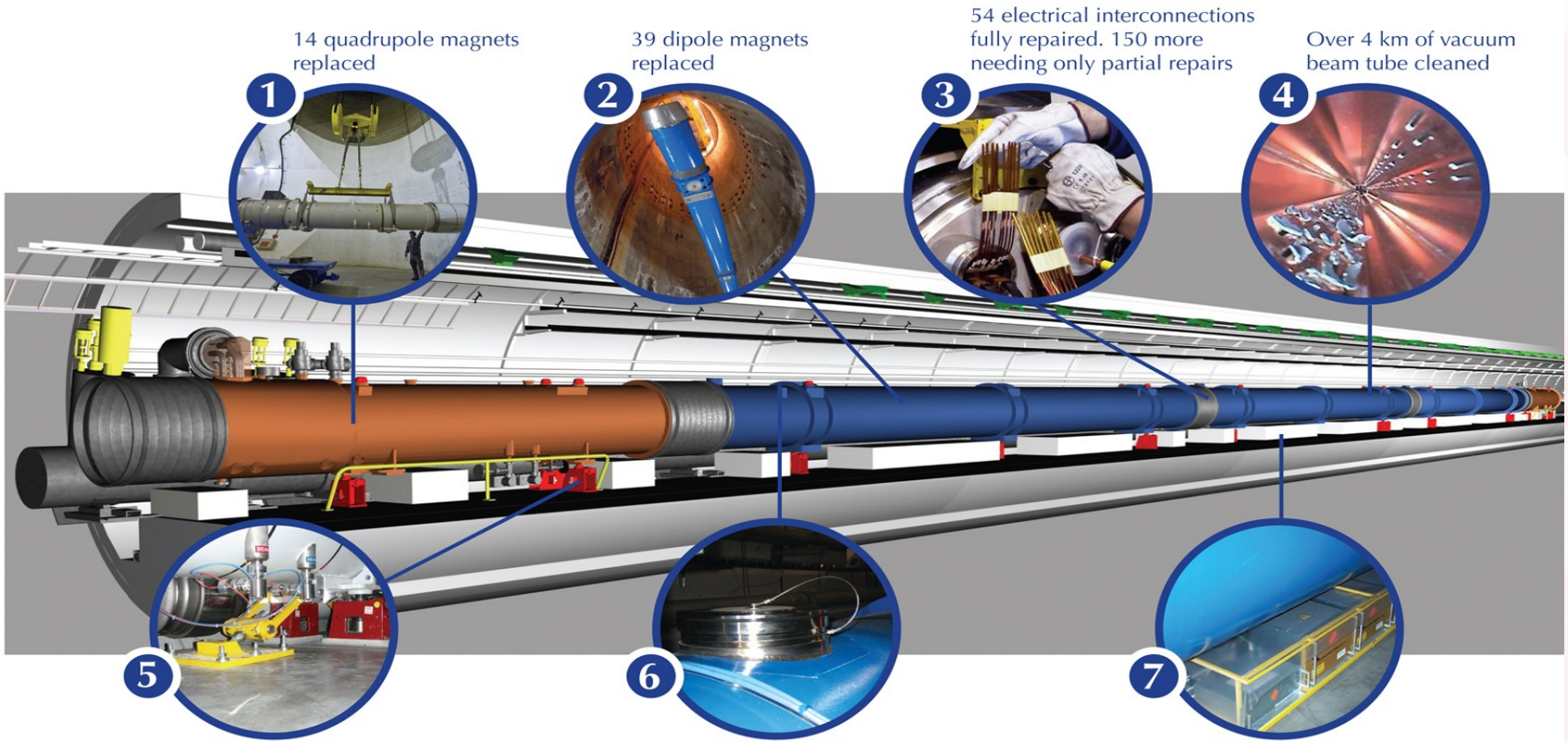
- Industry
  - Vacuum technology
  - Ultracold technology
  - Mining
- Medicine
  - Medical diagnostics
  - Cancer therapy
  - DNA research
- Silicon Valley
  - Semi-conductors
  - World Wide Web
  - Grid computing

Accident in September 2008



LHC REPAIRS IN 2009

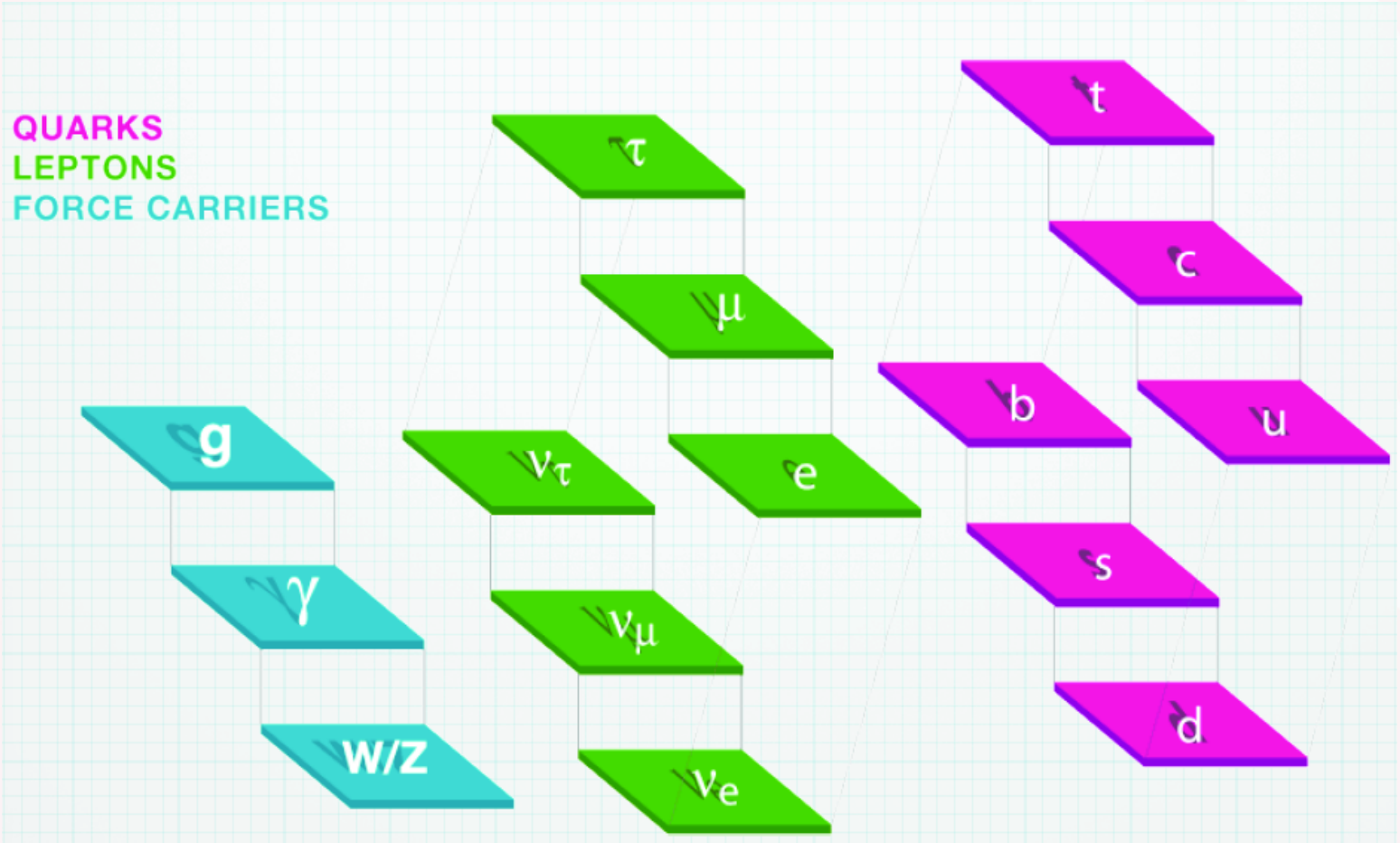
The LHC repairs in detail



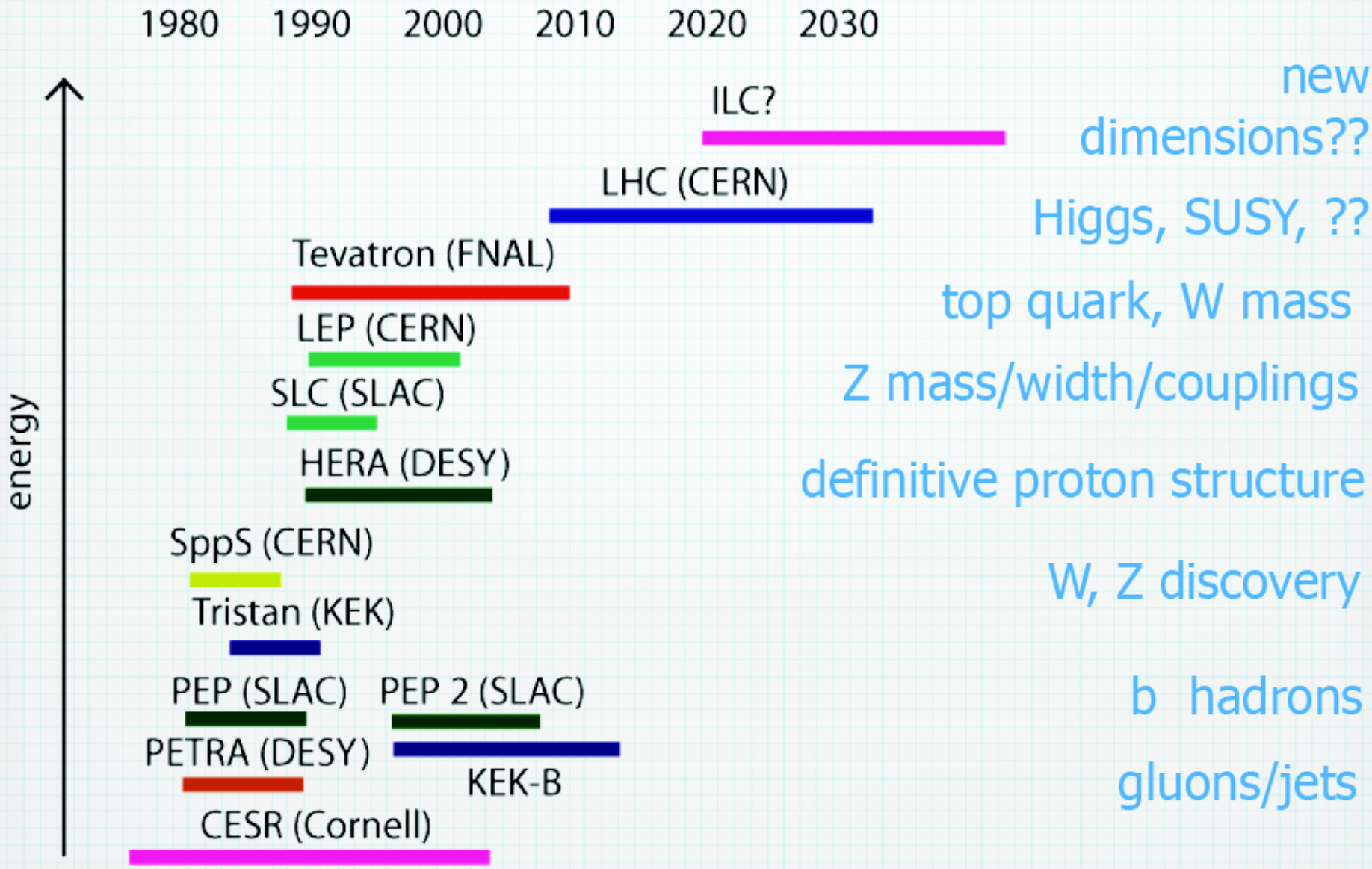
CERN

CERN

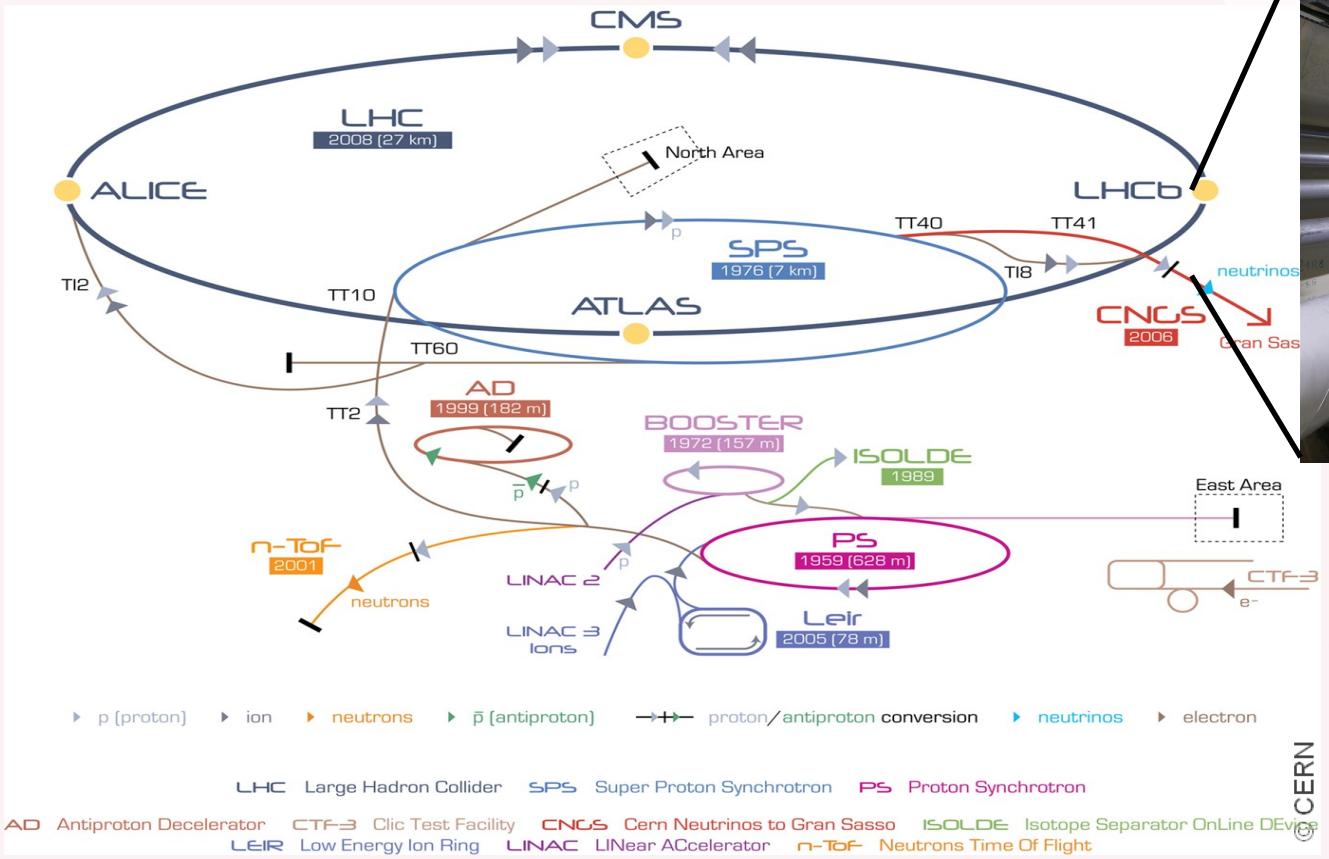
- European Laboratory for Particle Physics
- Founded in 1954
- 20 member countries
- More than 10,000 scientists
- More than 1,000 from U.S. universities and labs

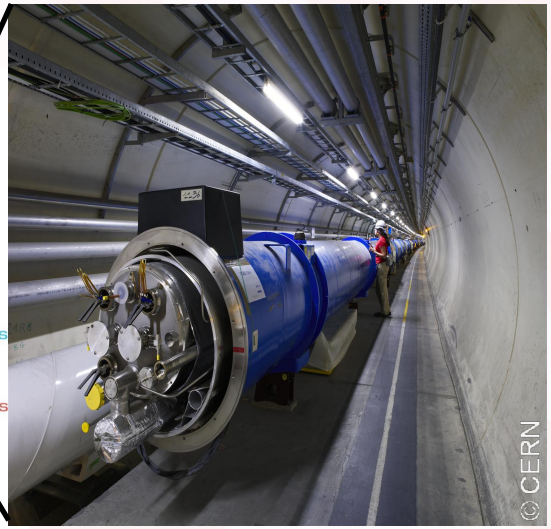

QUARKS
LEPTONS
FORCE CARRIERS
g
γ
W/Z
τ
μ
e
ντ
νμ
νe
t
c
u
b
s
d

Age of the Great Colliders

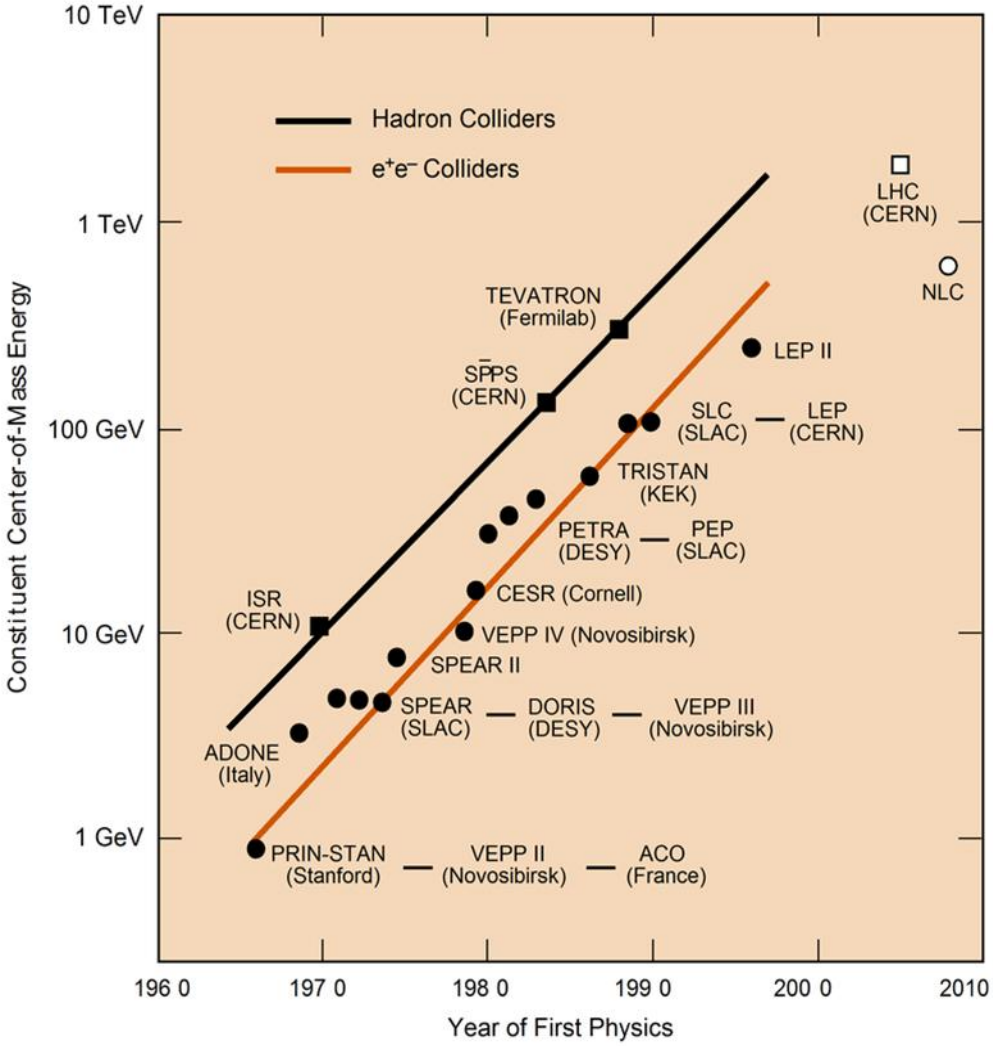


THE LHC ACCELERATOR CHAIN





History of accelerators



- We know that there is something particularly significant about the LHC energy scale (1 TeV or Terascale)
- SM is tremendously successful, but we know it is not a complete picture
- Possible solutions lie at 1 TeV

New dimensions?

Higgs, SUSY?

top, W mass

Z mass, width, couplings

Proton structure

W, Z discovery

B hadrons

Gluons, jets