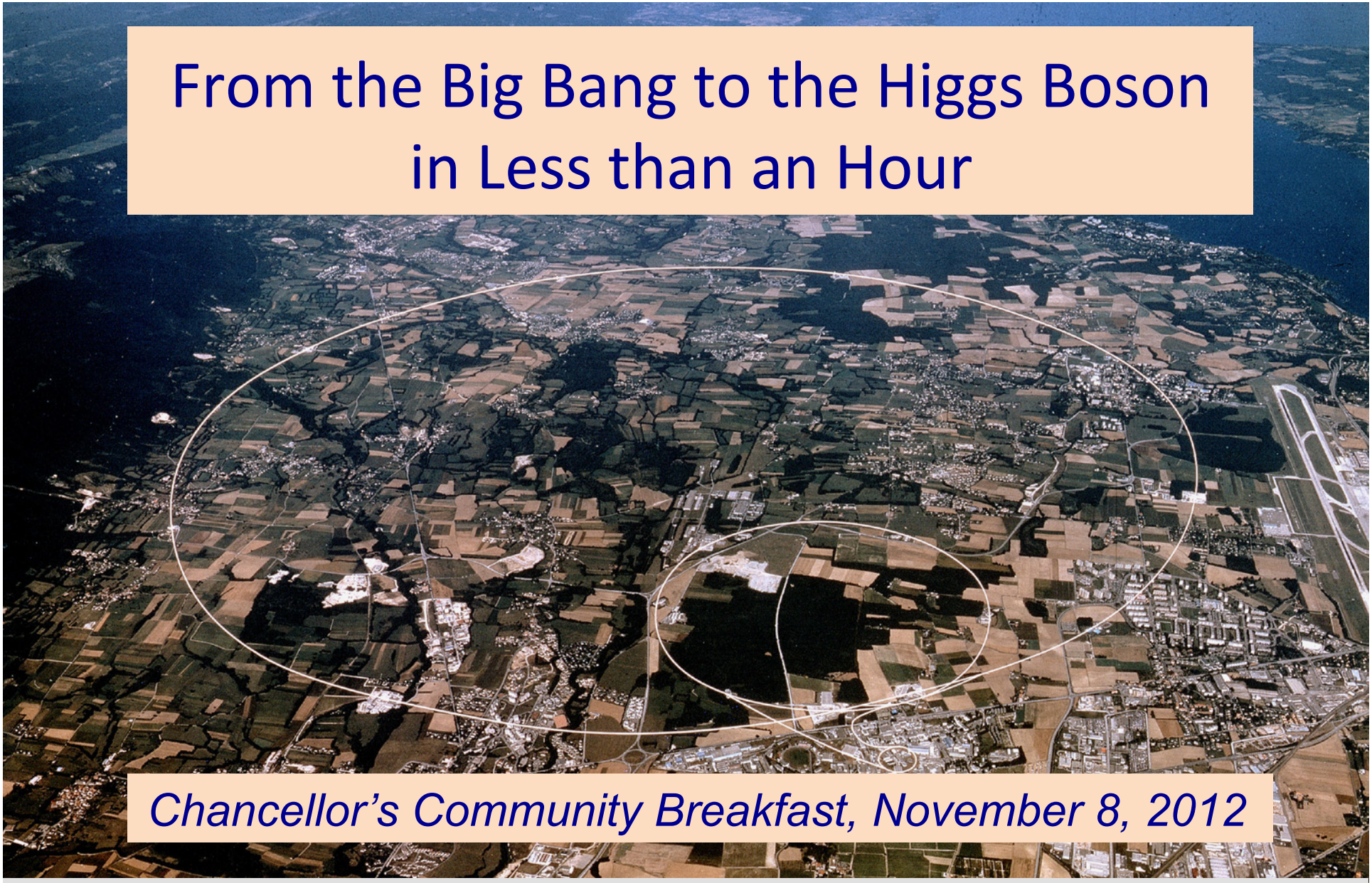
From the Big Bang to the Higgs Boson in Less than an Hour



Chancellor's Community Breakfast, November 8, 2012

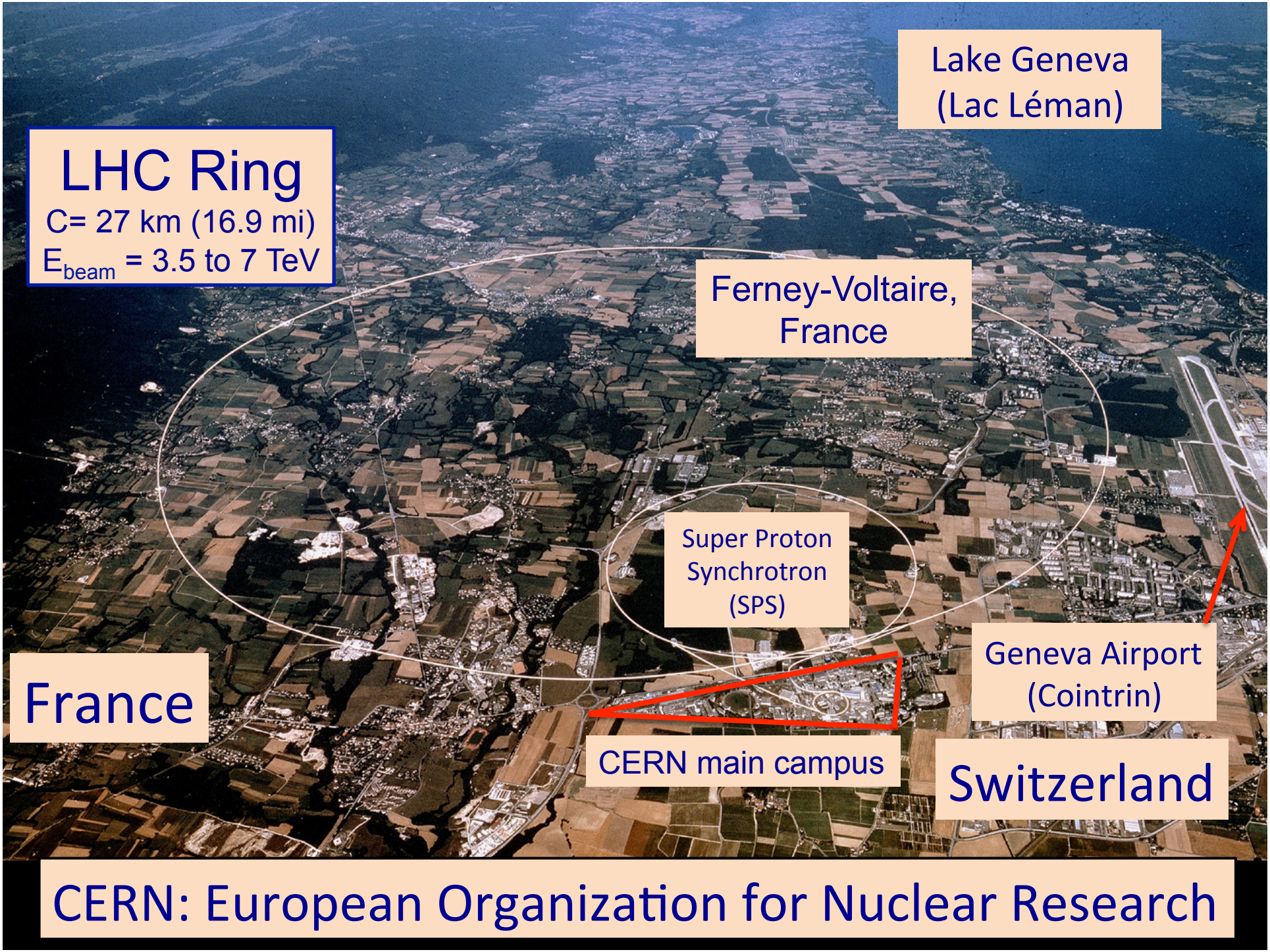
Jeffrey D. Richman
Department of Physics
University of California, Santa Barbara

European Organization for Nuclear Research
Geneva, Switzerland, July 4, 2012

photo courtesy CERN

Over Lac Léman (Lake Geneva)
View towards the east (Switzerland)

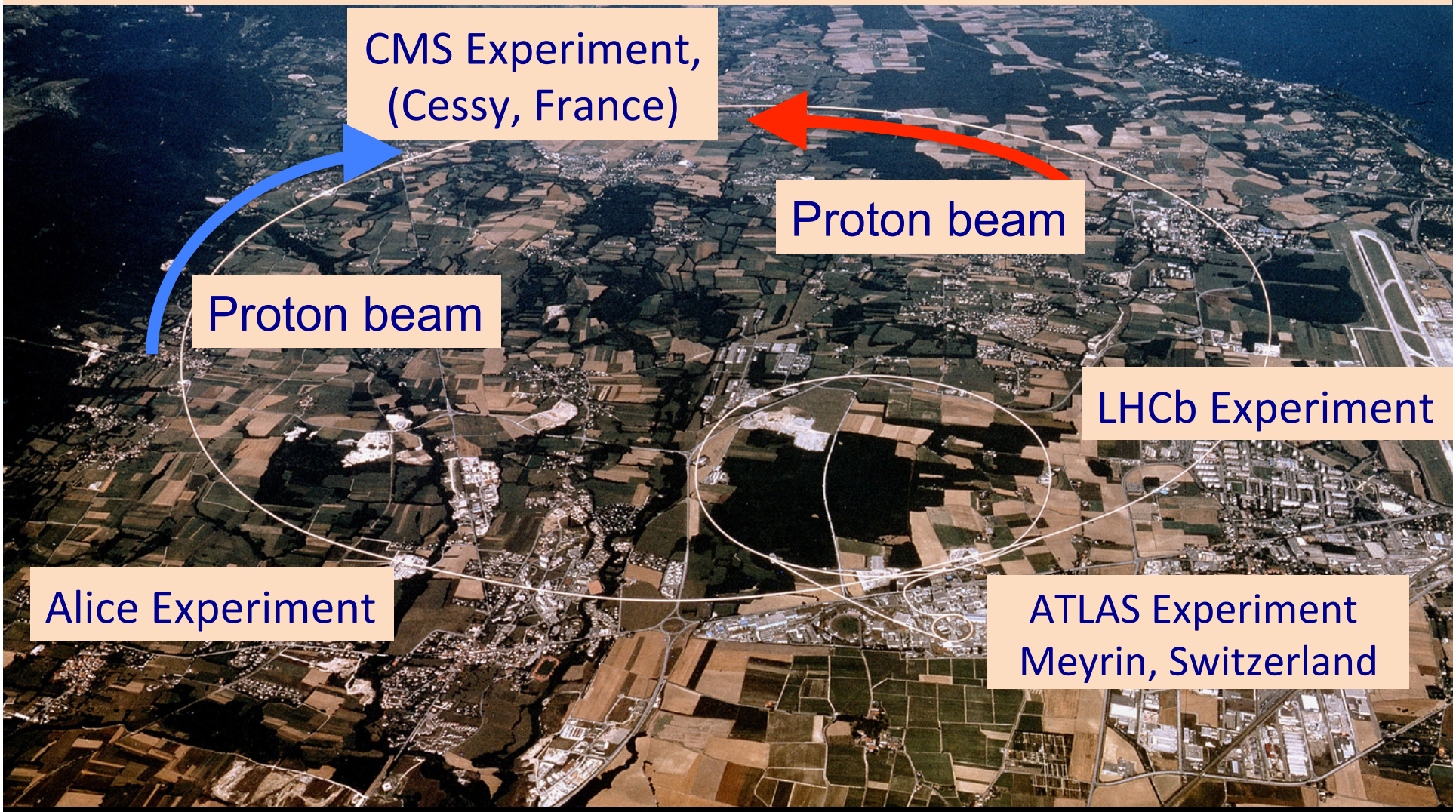
Over the Rhône River
View towards the west (France)



CERN: European Organization for Nuclear Research

LHC ring:

- 2 separate magnetic “highways”; 9300 magnets, incl. 1232 15-meter dipoles.
- Radio-frequency EM cavity devices to accelerate beams (8/beam; 40 MHz)



Beam: “bunch train” w/1374 bunches of protons (will increase to 2808 bunches). 1 bunch=10^{11} protons.

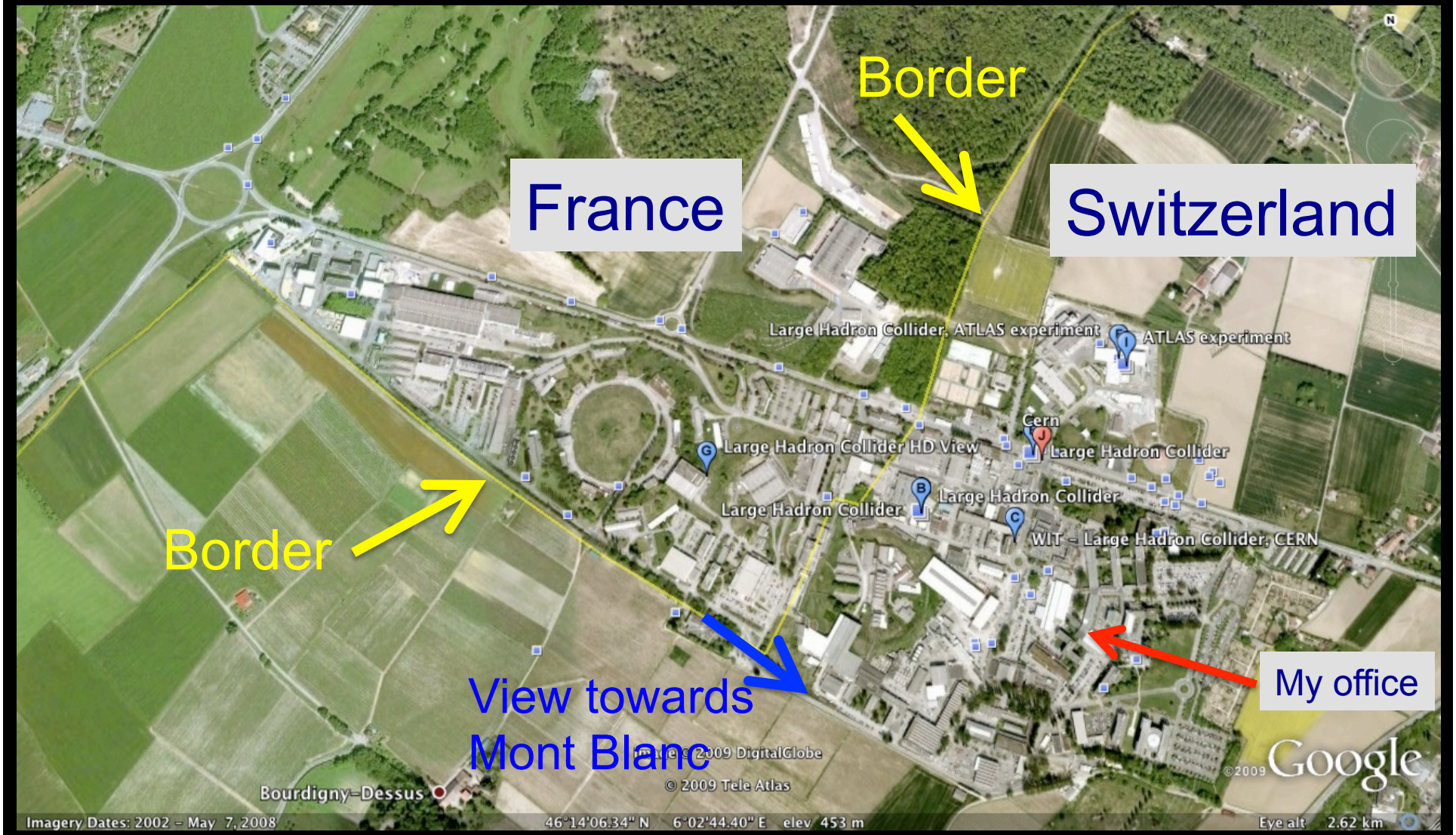
The beam bunches travel at nearly the speed of light (c−7 mph at 7 TeV)

- arrive at the collision points every 50 ns (25 ns in future)

- Beams make 11,245 turns/second
- Stored for 10 hrs (round trip to Neptune!)
- Designed for 600 M collisions/sec at each experiment.

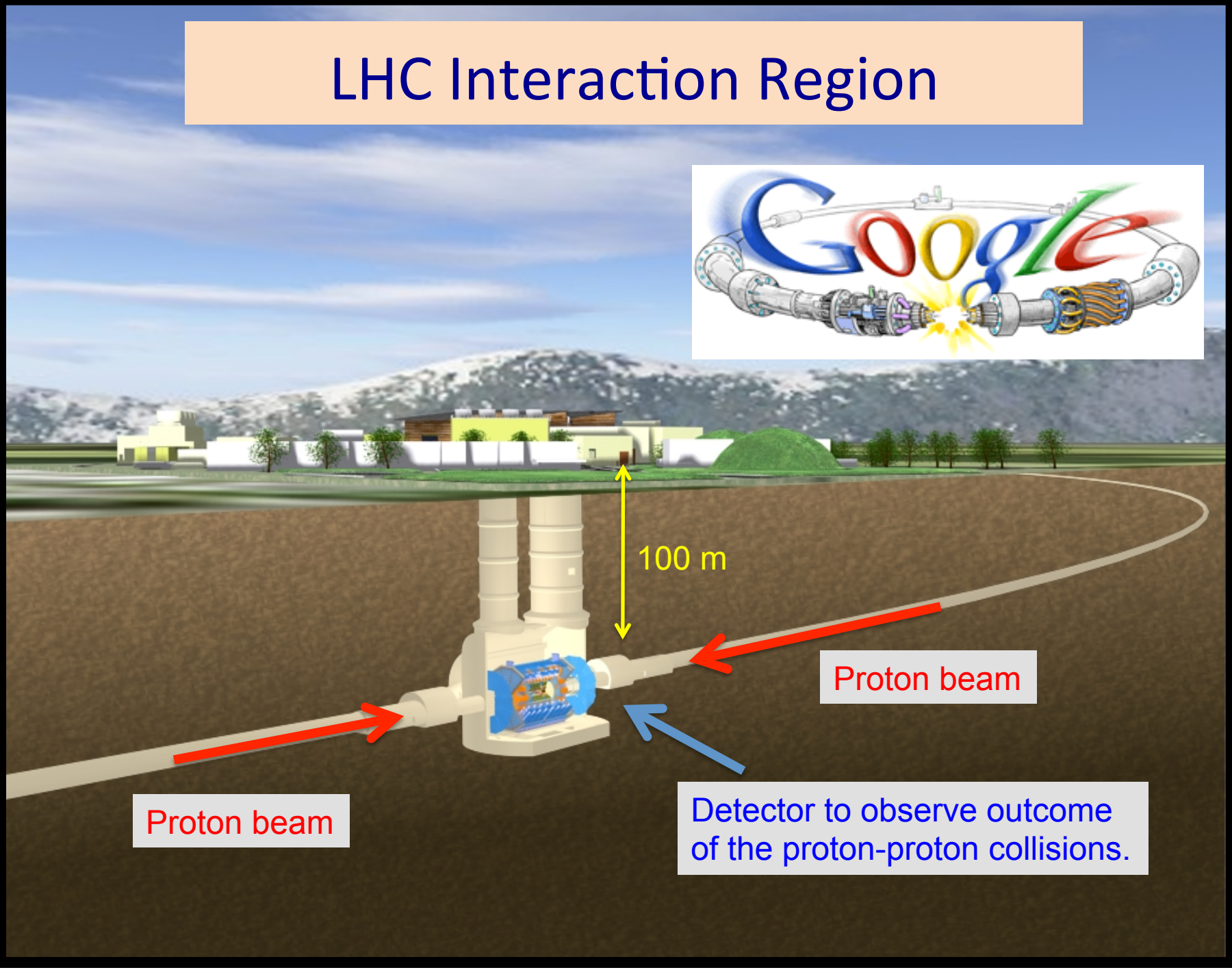
Stored energy per beam at design is 350 MJ, enough to melt 500 kg of Cu

CERN main laboratory site



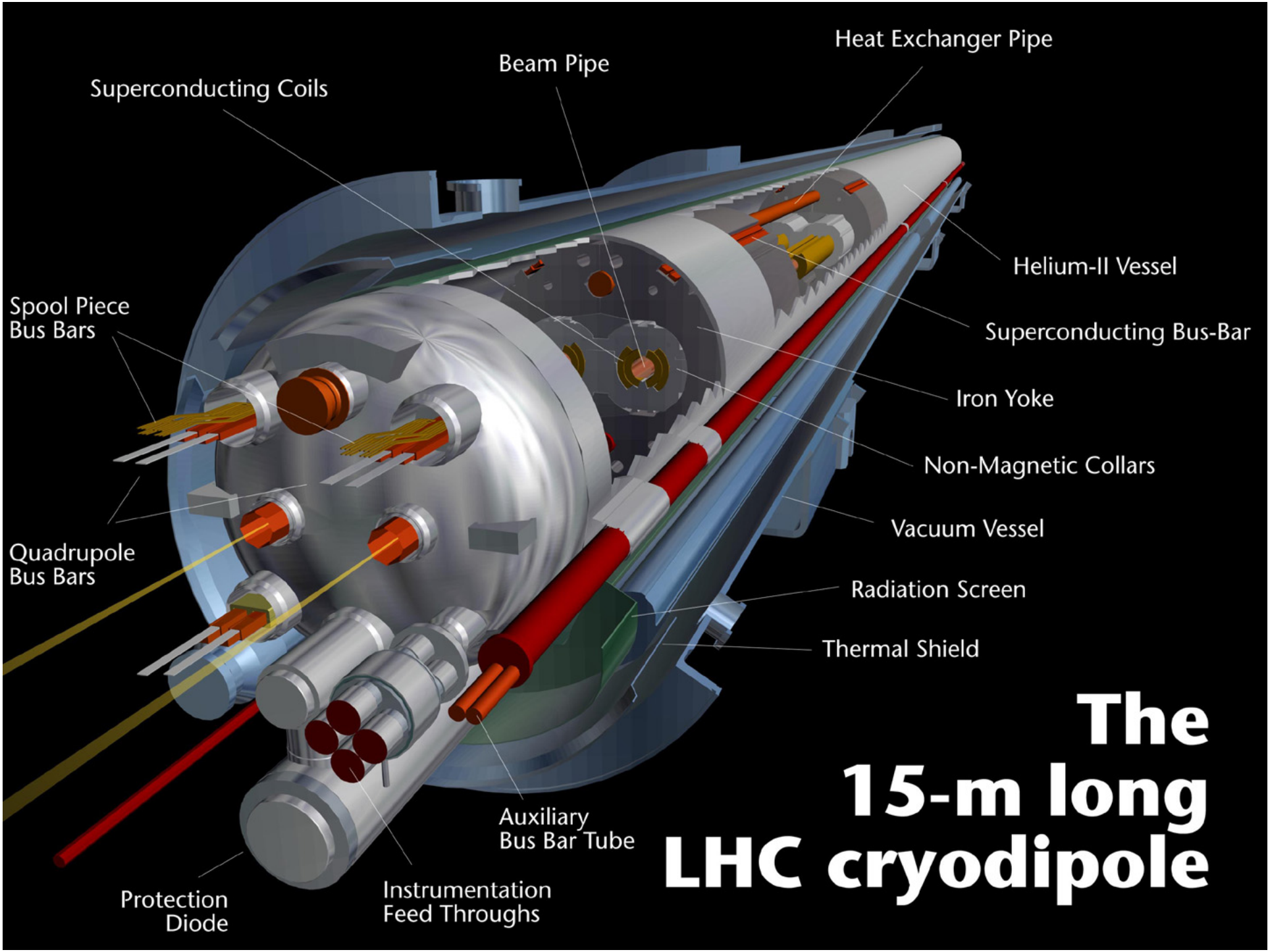
This place should look familiar!

LHC Interaction Region



Access shafts for the CMS Experiment under construction, Cessy, France

Inside the LHC Tunnel

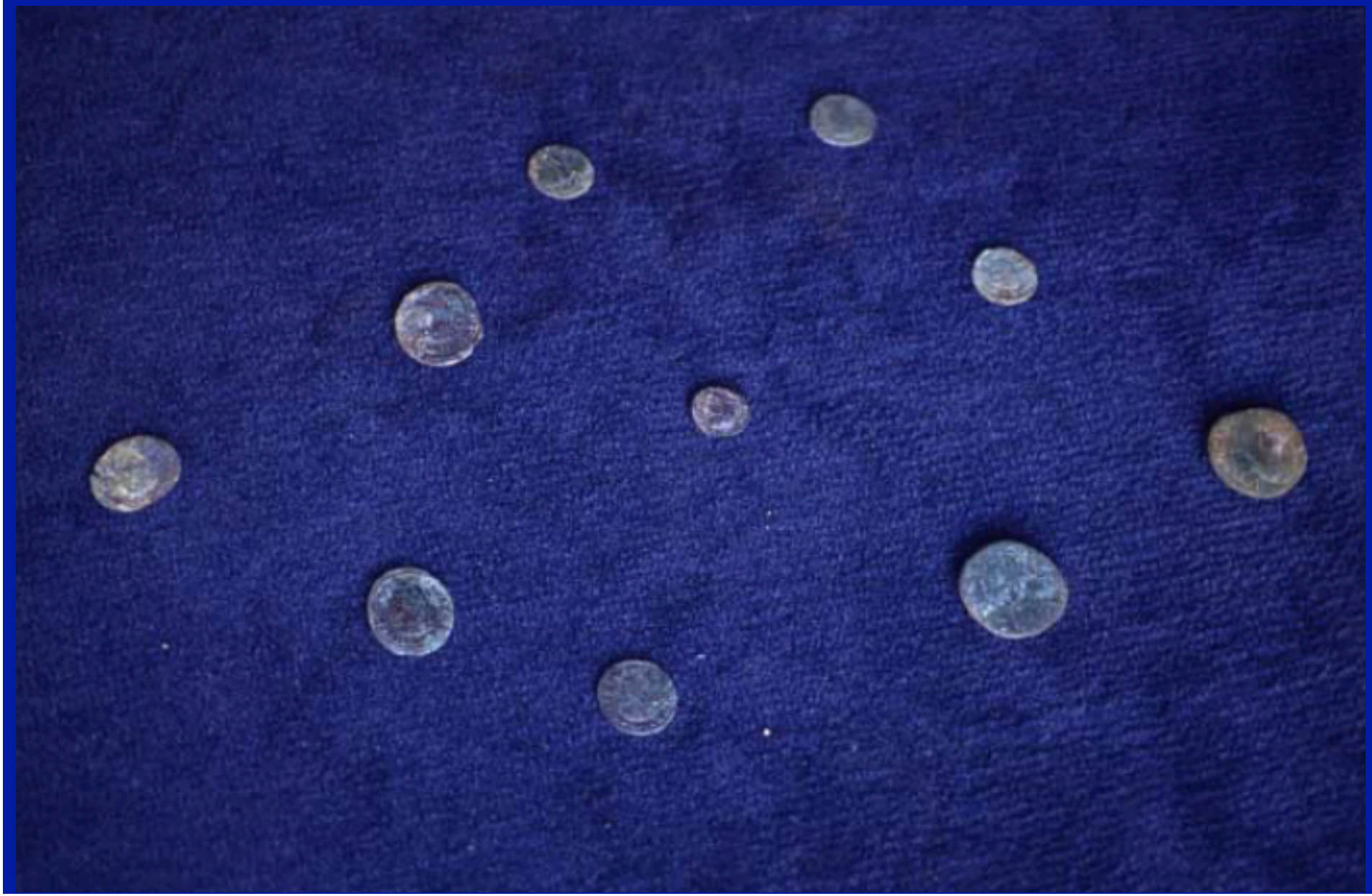


The 15-m long LHC cryodipole

LHC Radio-Frequency Cavities

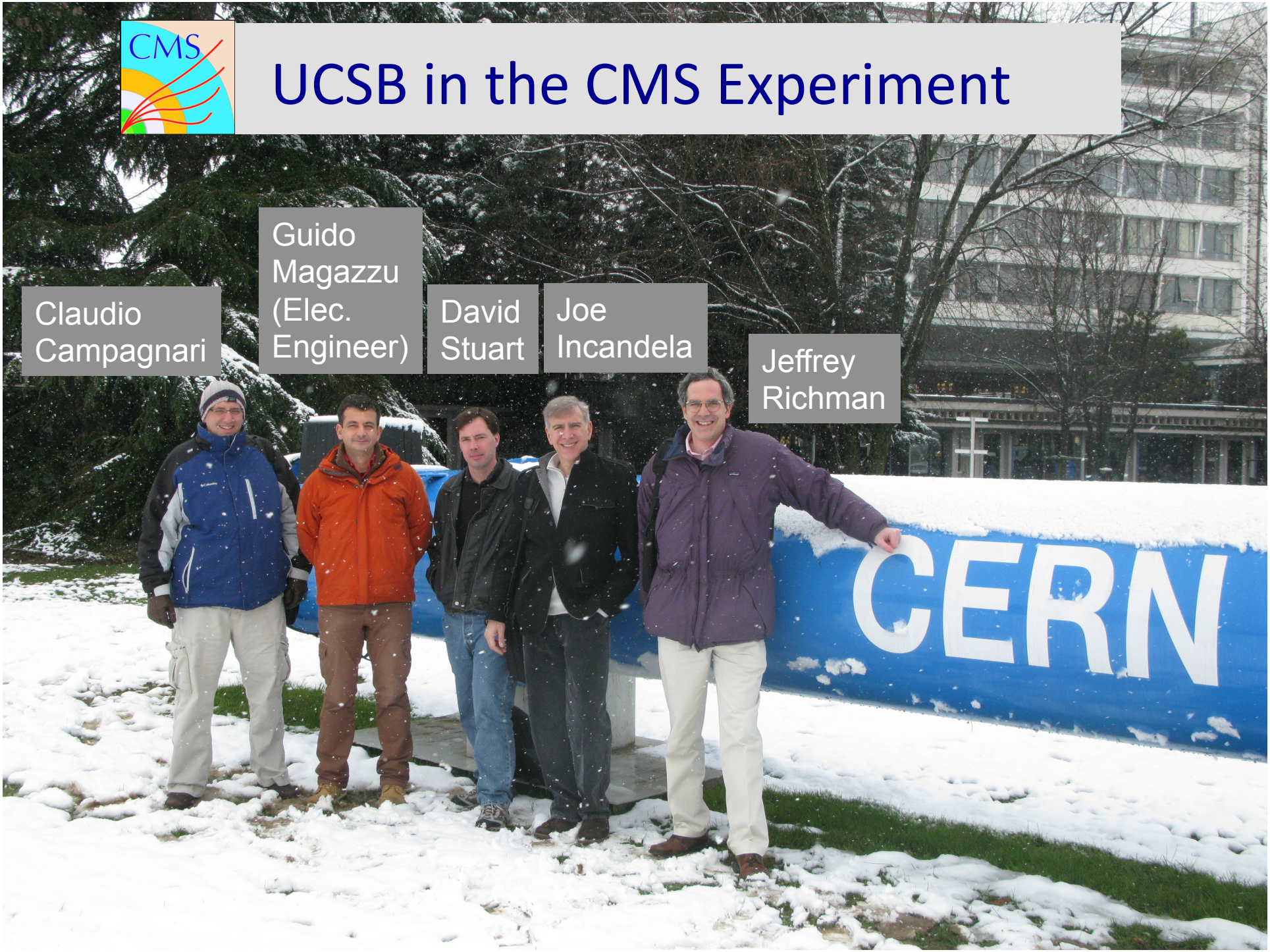
Practice run on putting out a fire

Archeology at the CMS site



UCSB in the CMS Experiment

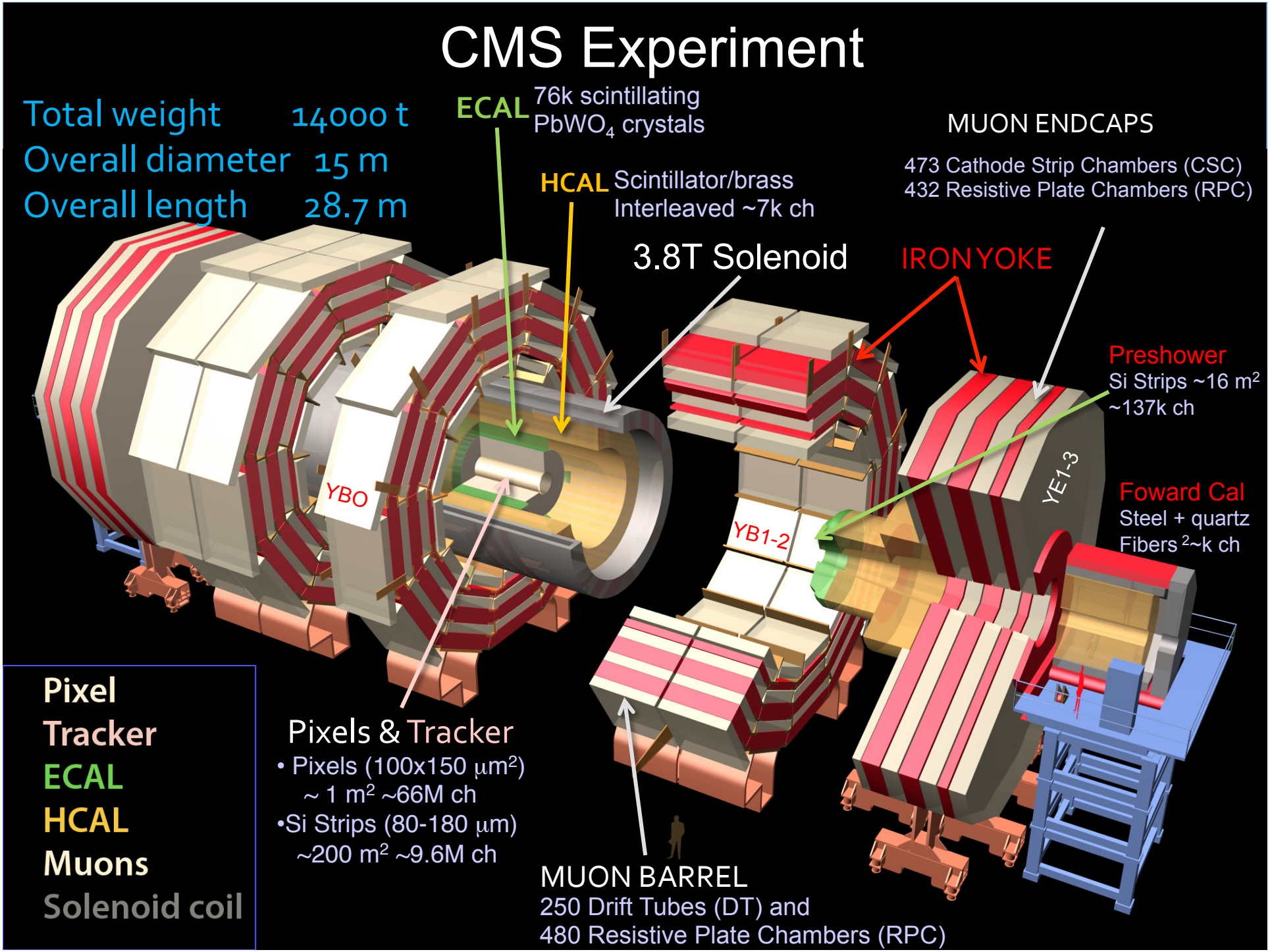
UCSB in the CMS Experiment



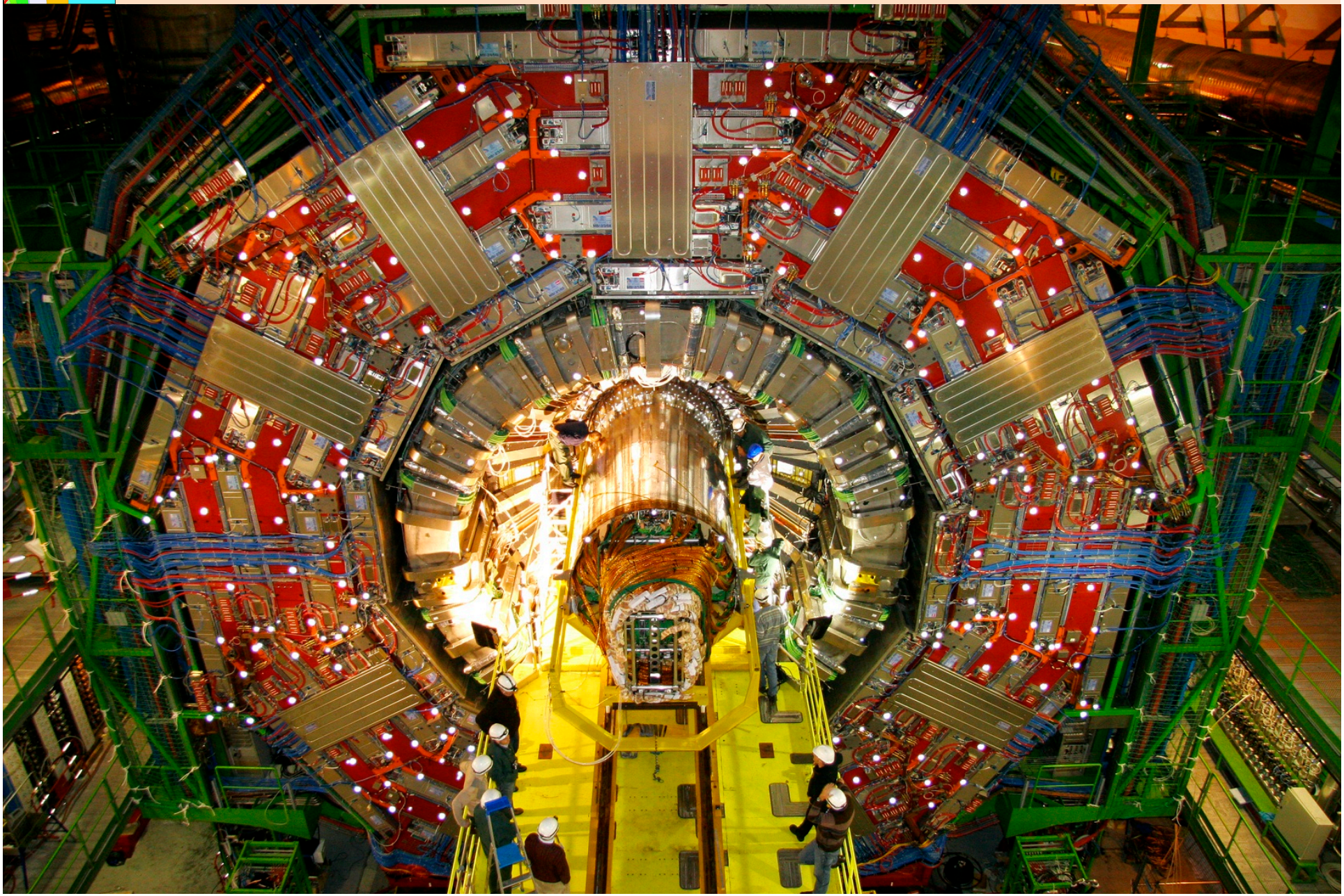
UCSB in CMS: research + education

- Faculty (4), engineers (4), technicians (4 –15)

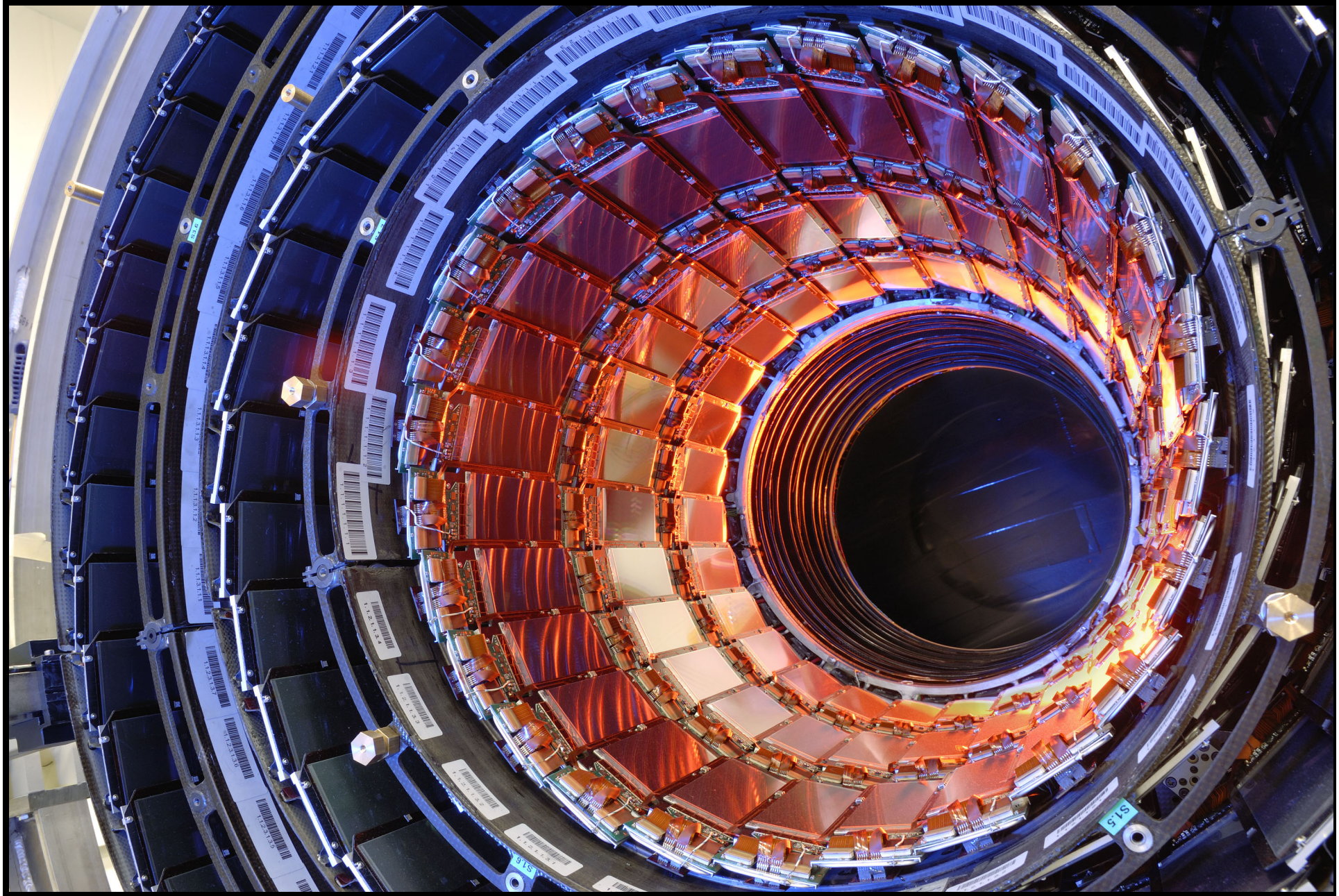
  Postdoctoral fellows (9), graduate students (10-12), undergraduates (3-5)
- Supported by the Department of Energy.
- Mission: Investigate the fundamental nature of matter and train the next generation of scientists.


CMS Experiment
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
ECAL 76k scintillating PbWO4 crystals
HCAL Scintillator/brass Interleaved ~7k ch
3.8T Solenoid
IRON YOKE
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Preshower
Si Strips ~16 m2
~137k ch
Foward Cal
Steel + quartz
Fibers 2~k ch
YBO
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm2)
~ 1 m2 ~66M ch
•Si Strips (80-180 μm)
~200 m2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

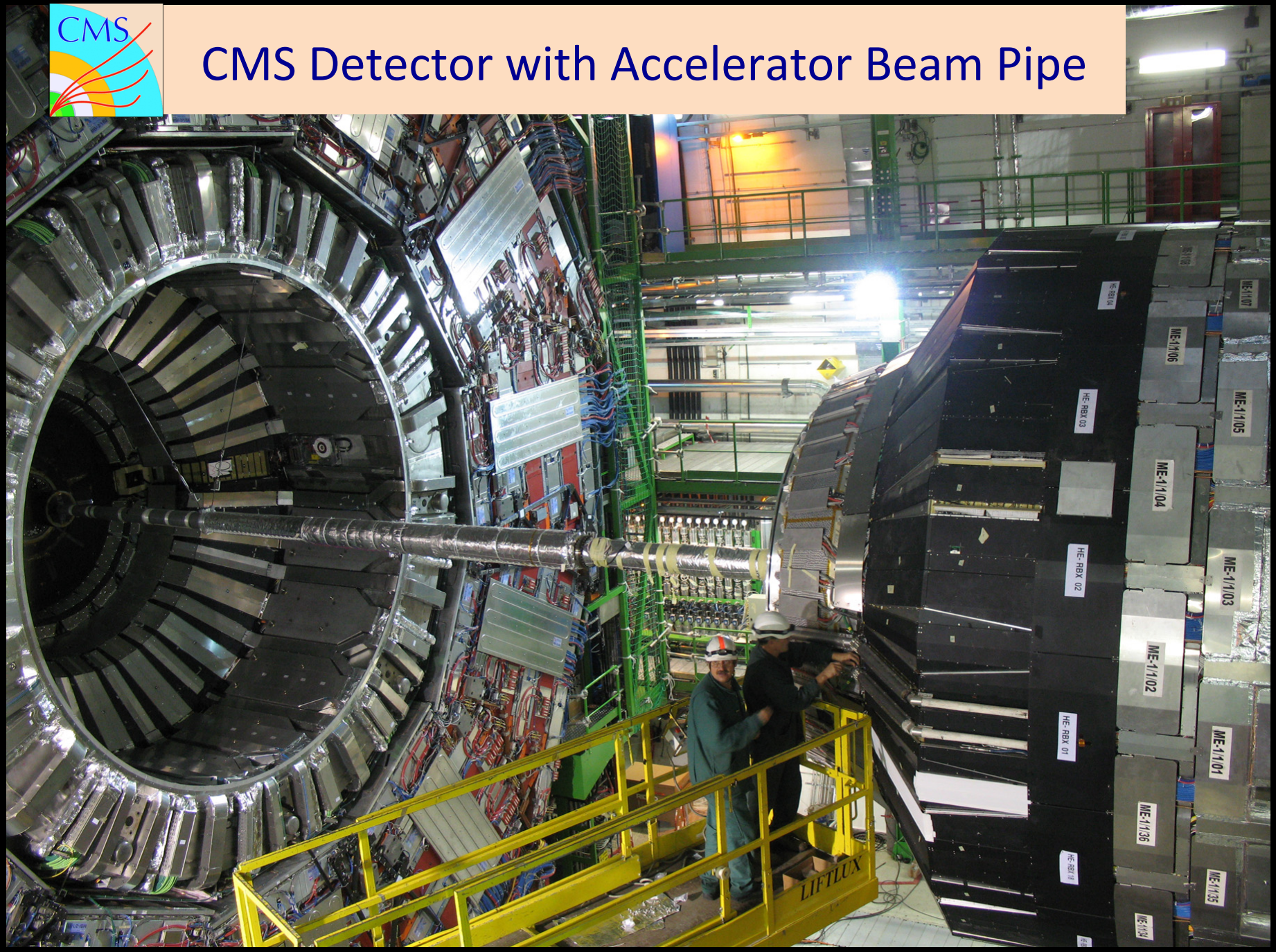
CMS Silicon Tracker Installation: Dec 2007



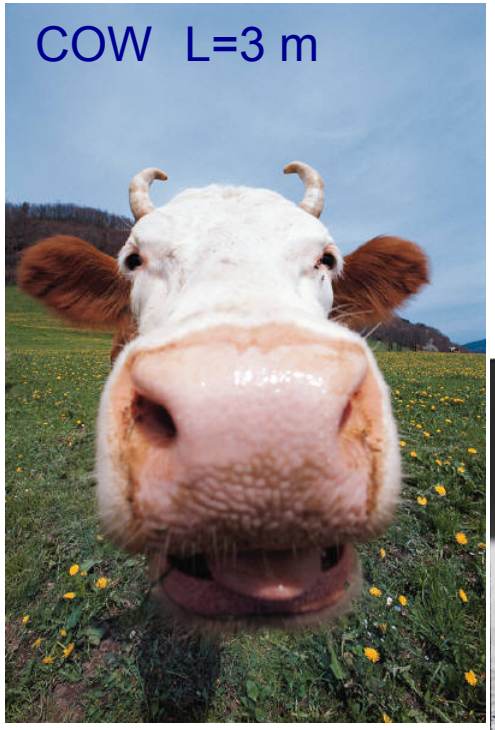
CMS Silicon-Strip Particle Tracking Detector



CMS Detector with Accelerator Beam Pipe

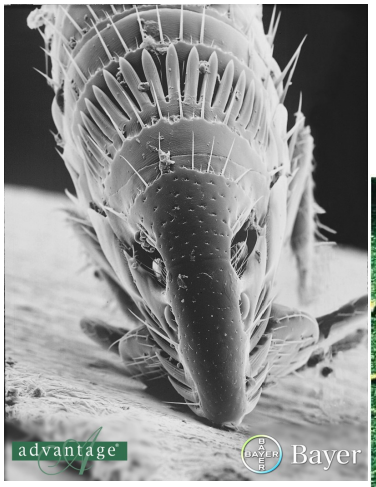


Shrinking down: cow → atom



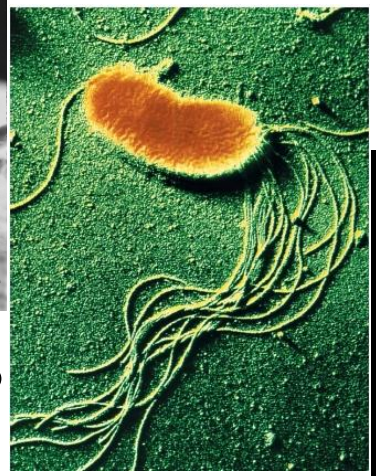
$\times 10^{-3}$

FLEA L = 0.0025 m = 2.5 mm



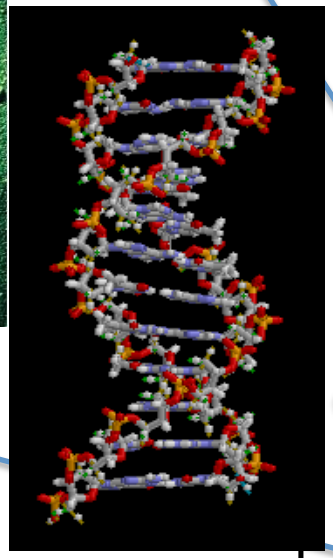
$\times 10^{-3}$

BACTERIUM
L=0.002 mm = 2 μm (large variation)



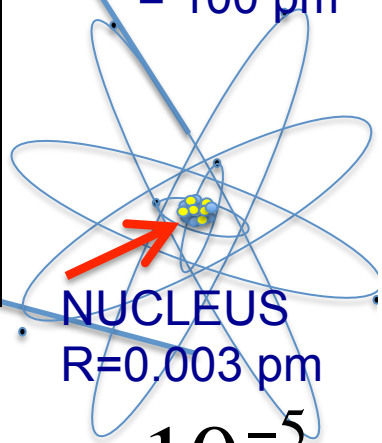
$\times 10^{-3}$

MOLECULE
W = 0.002 μm = 2 nm



$\times 10^{-1}$

ATOM
R = 0.1 nm
= 100 pm



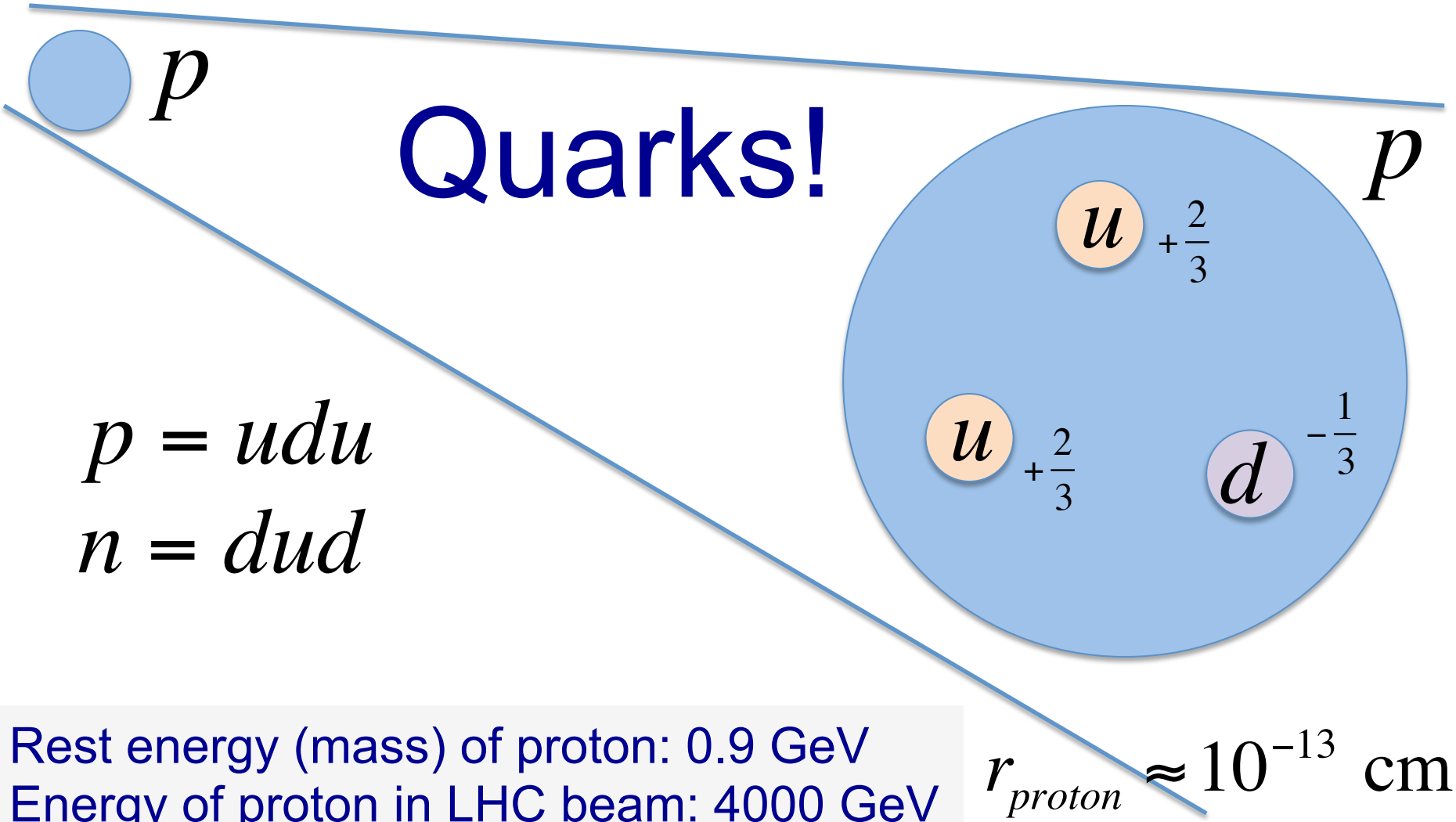
NUCLEUS
R=0.003 pm

$\times 10^{-5}$

COW ATOMIC NUCLEUS

$$1\ \text{m} \rightarrow 10^{-15}\ \text{m} = 0.000000000000000 1\ \text{m}$$

A first look inside of the proton



$$p = udu$$
$$n = dud$$

Rest energy (mass) of proton: 0.9 GeV
Energy of proton in LHC beam: 4000 GeV

$$r_{proton} \approx 10^{-13} \text{ cm}$$

Fundamental particles

Quarks

u up	c charm	t top
d down	s strange	b bottom

Leptons

e^- electron	μ^- muon	τ^- tau
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

Gauge bosons

Strong force	EM force	Weak force		
g	γ	Z^0	W^+	W^-
gluon (8)	photon	Z boson	W bosons	

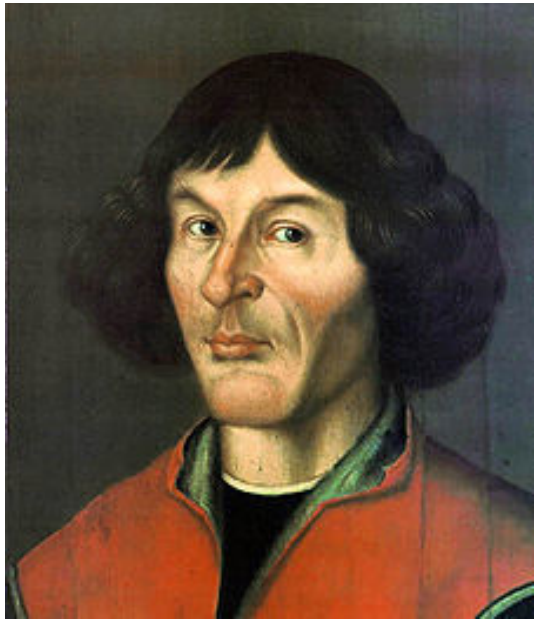
Higgs boson

and vacuum expectation value

H

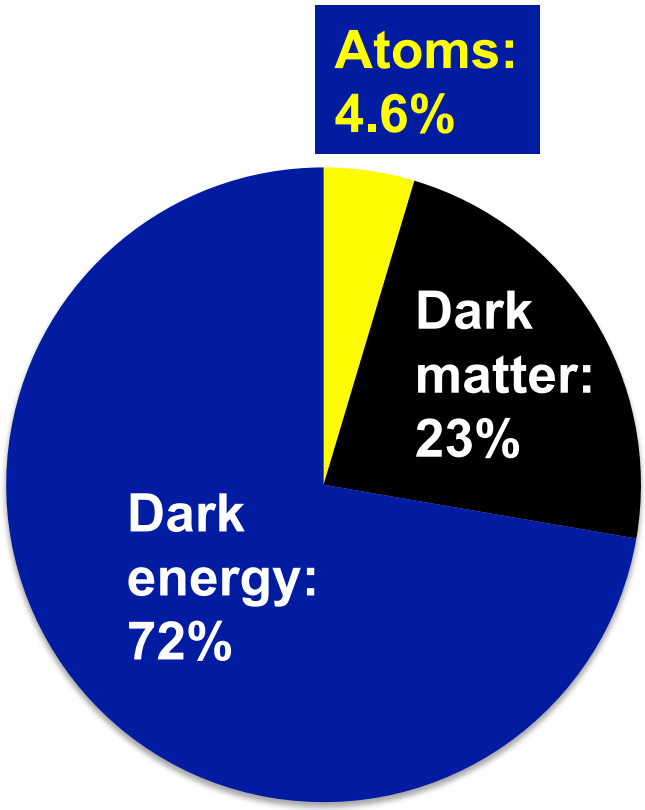
Higgs boson

The dark matter revolution



Nicolaus Copernicus (1473-1543): heliocentric model

Vera Rubin (1928-): dark matter in galaxies



WMAP

We aren't at the center of the solar system (or anything else), and we aren't made up of the dominant form of matter...

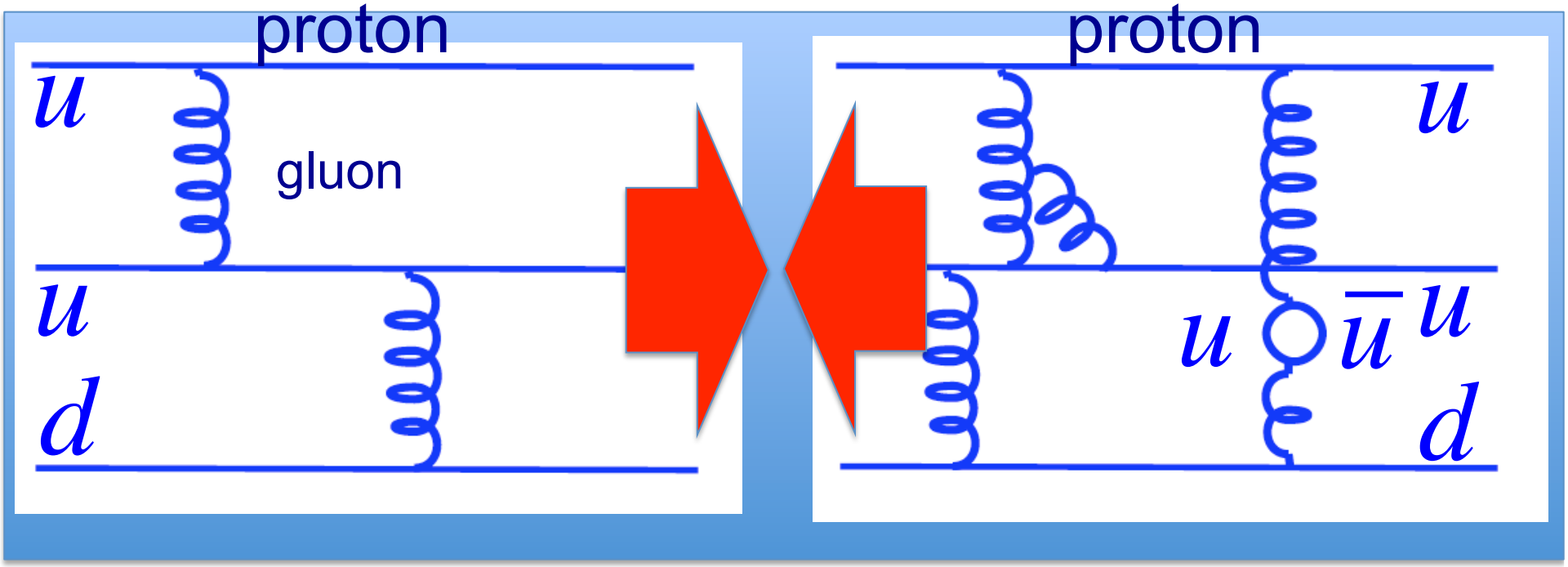
LHC Control Room: Hollywood Version

Angels and Demons, © Sony pictures.
(BTW, they also make computer displays).

LHC Control Room: the real thing

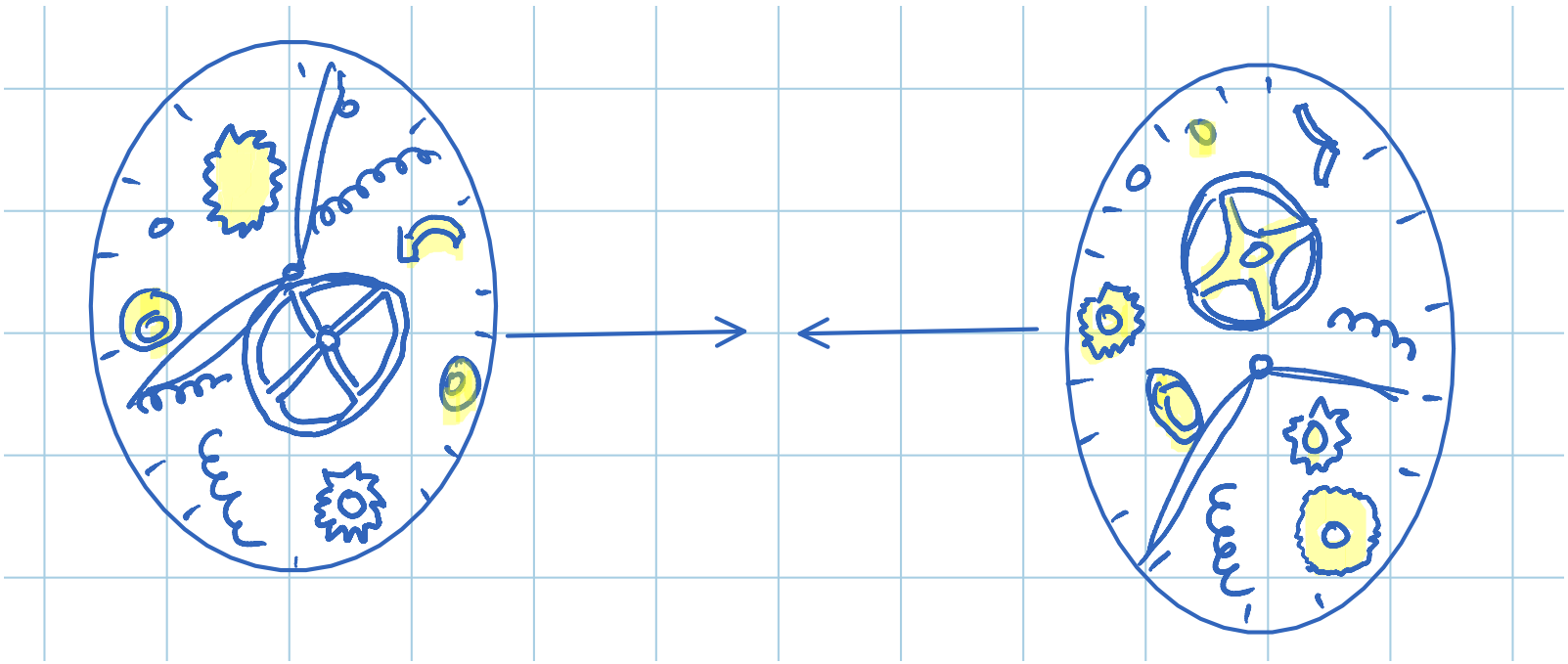
Feynman's Van: Particle Interactions

Two protons colliding



Just as photons are the quanta of the electromagnetic field, gluons are the quanta of the strong field. (Nobel Prize 2004: David Gross, David Politzer, Frank Wilczek.)

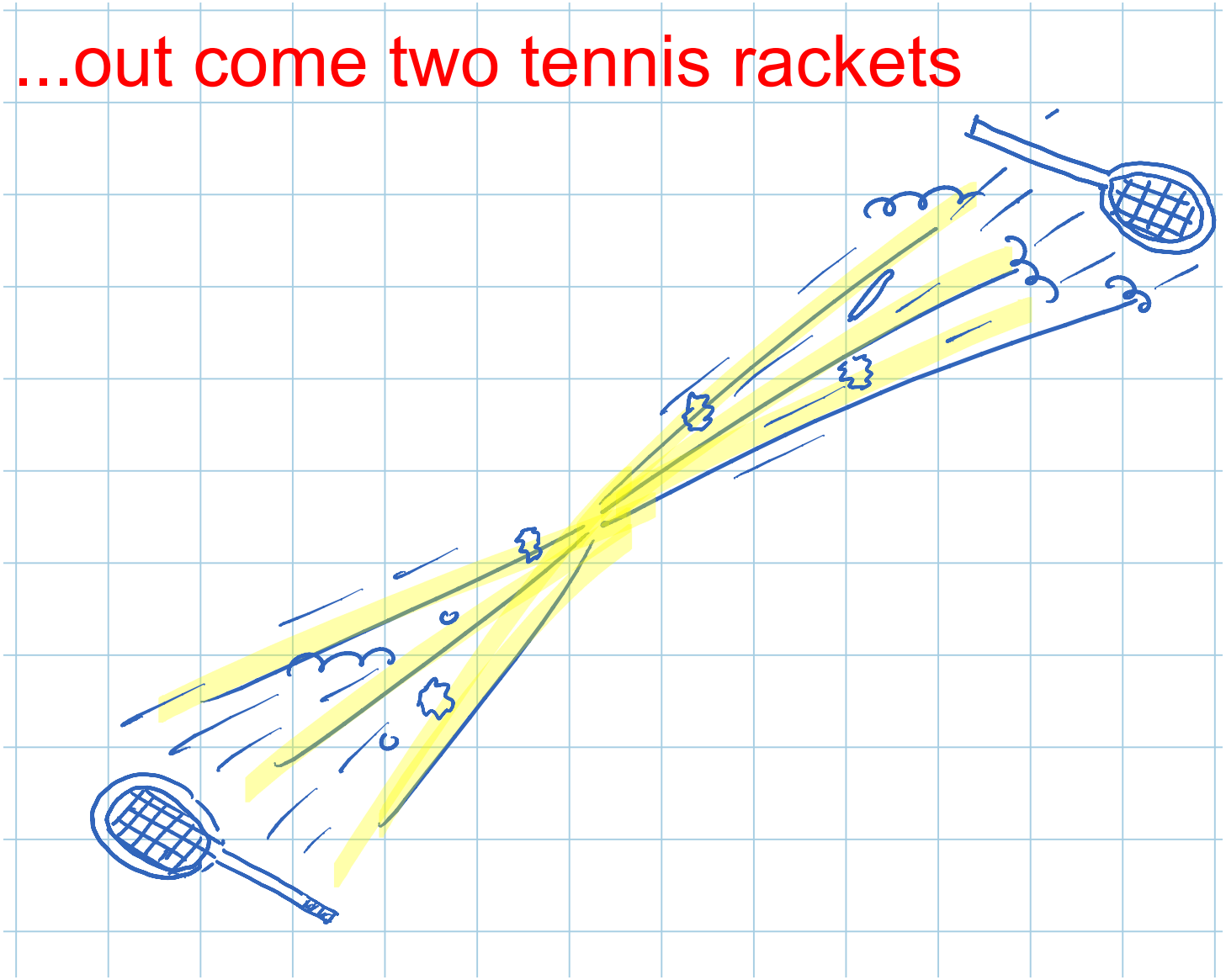
Smashing Swiss watches together



...after all, this is Geneva

Smashing Swiss watches together

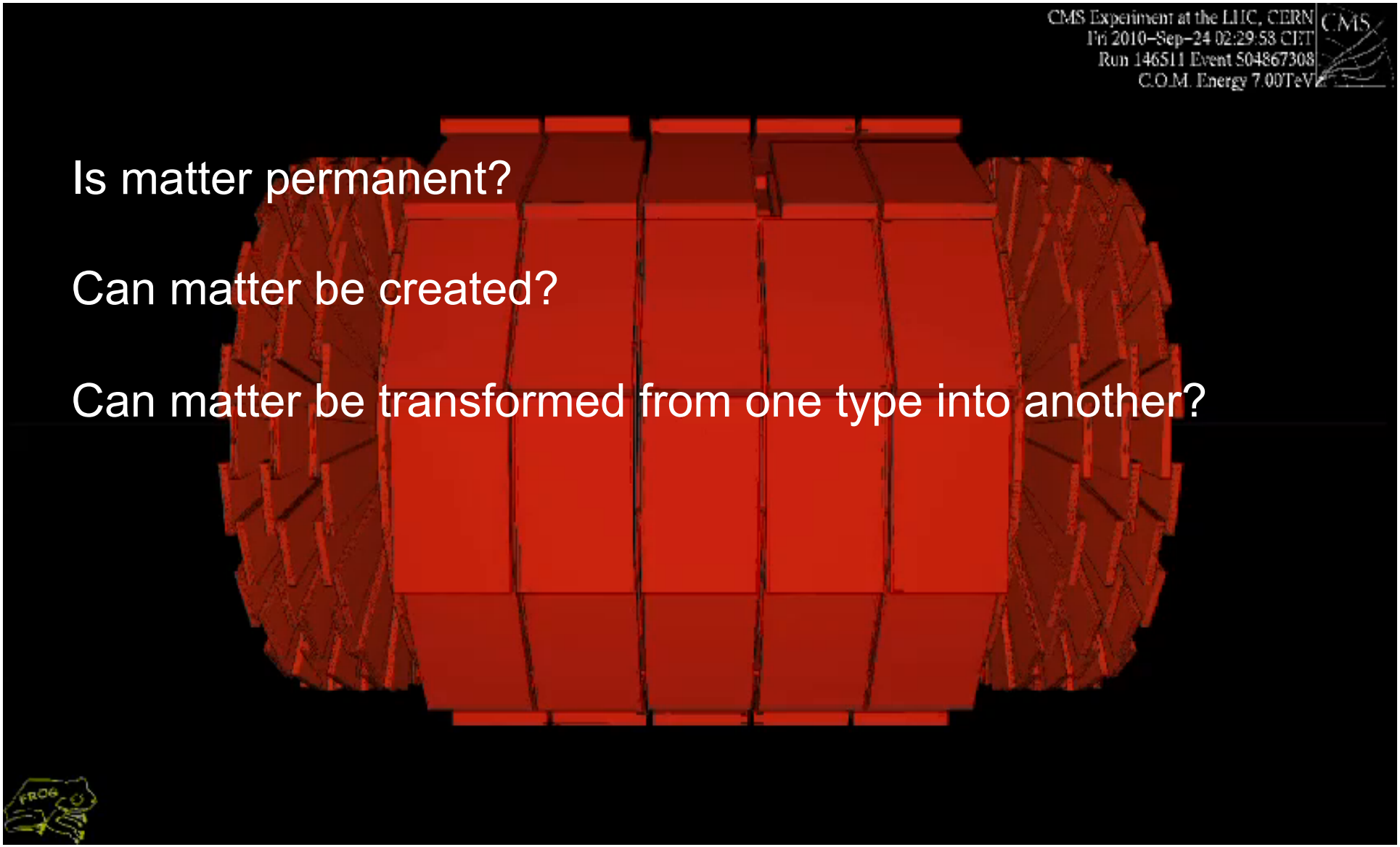
...out come two tennis rackets



From sunflowers to particles

- Macroscopic world: sunflowers are similar.
- Particle micro-world: particles of the same type are identical! (Everywhere, and at all times!)
- Particle properties & behavior follow mathematical laws of physics → everything has to "fit".
- "Particles aren't just lumps of clay – they're actors in a mathematical play."

Can Matter be Created?

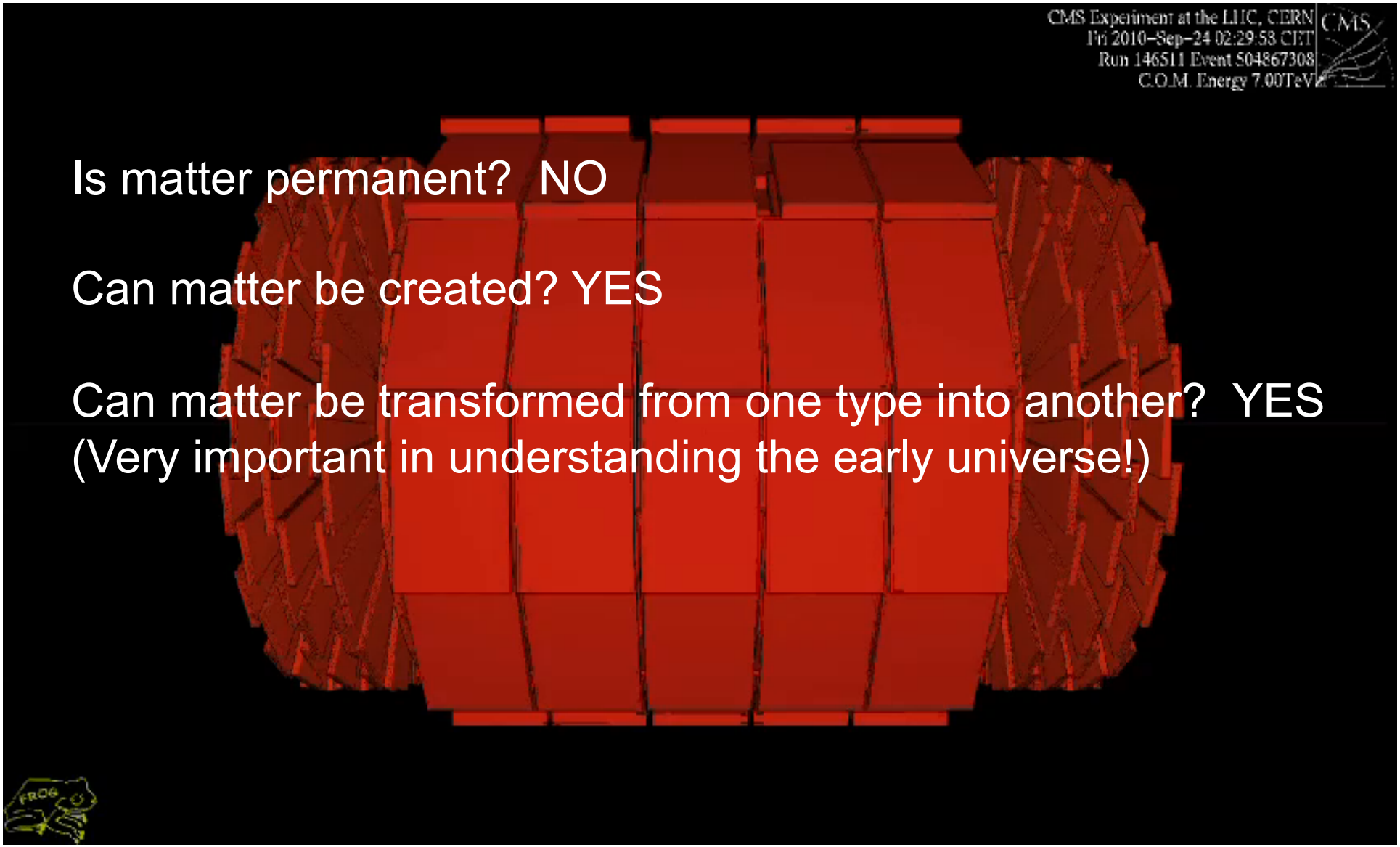


Is matter permanent?

Can matter be created?

Can matter be transformed from one type into another?

Can Matter be Created?

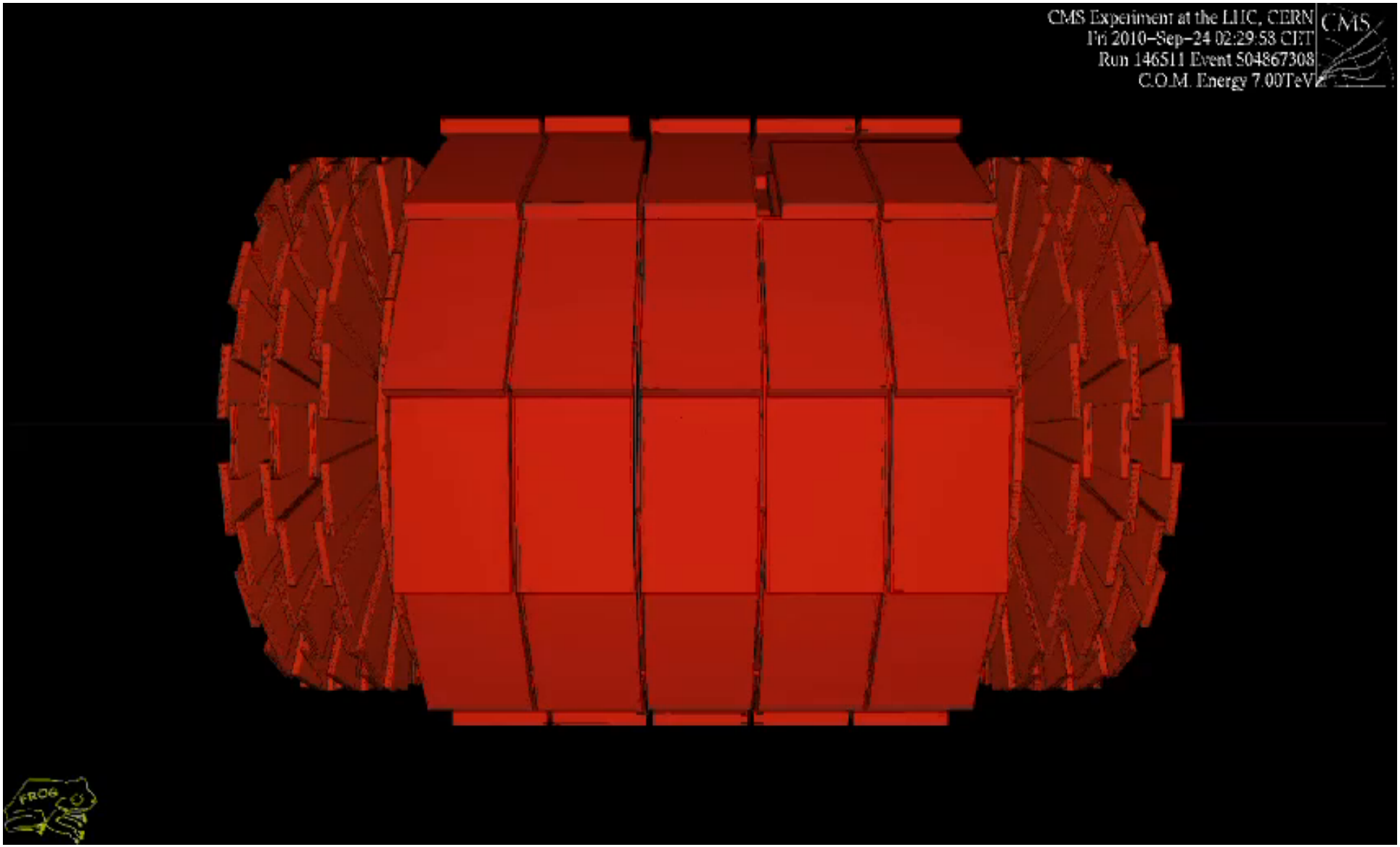


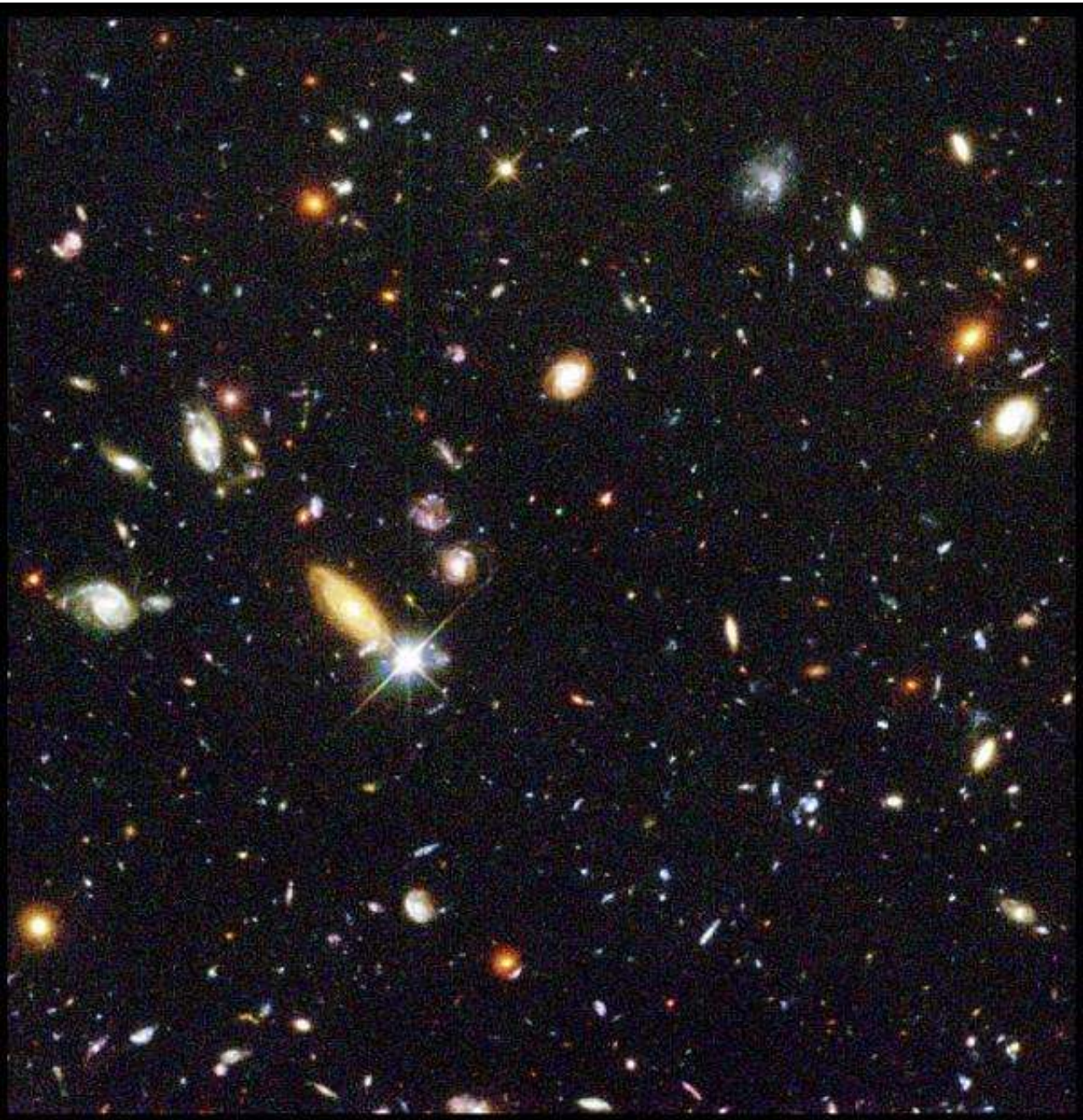
Is matter permanent? NO

Can matter be created? YES

Can matter be transformed from one type into another? YES
(Very important in understanding the early universe!)

Can Matter be Created?

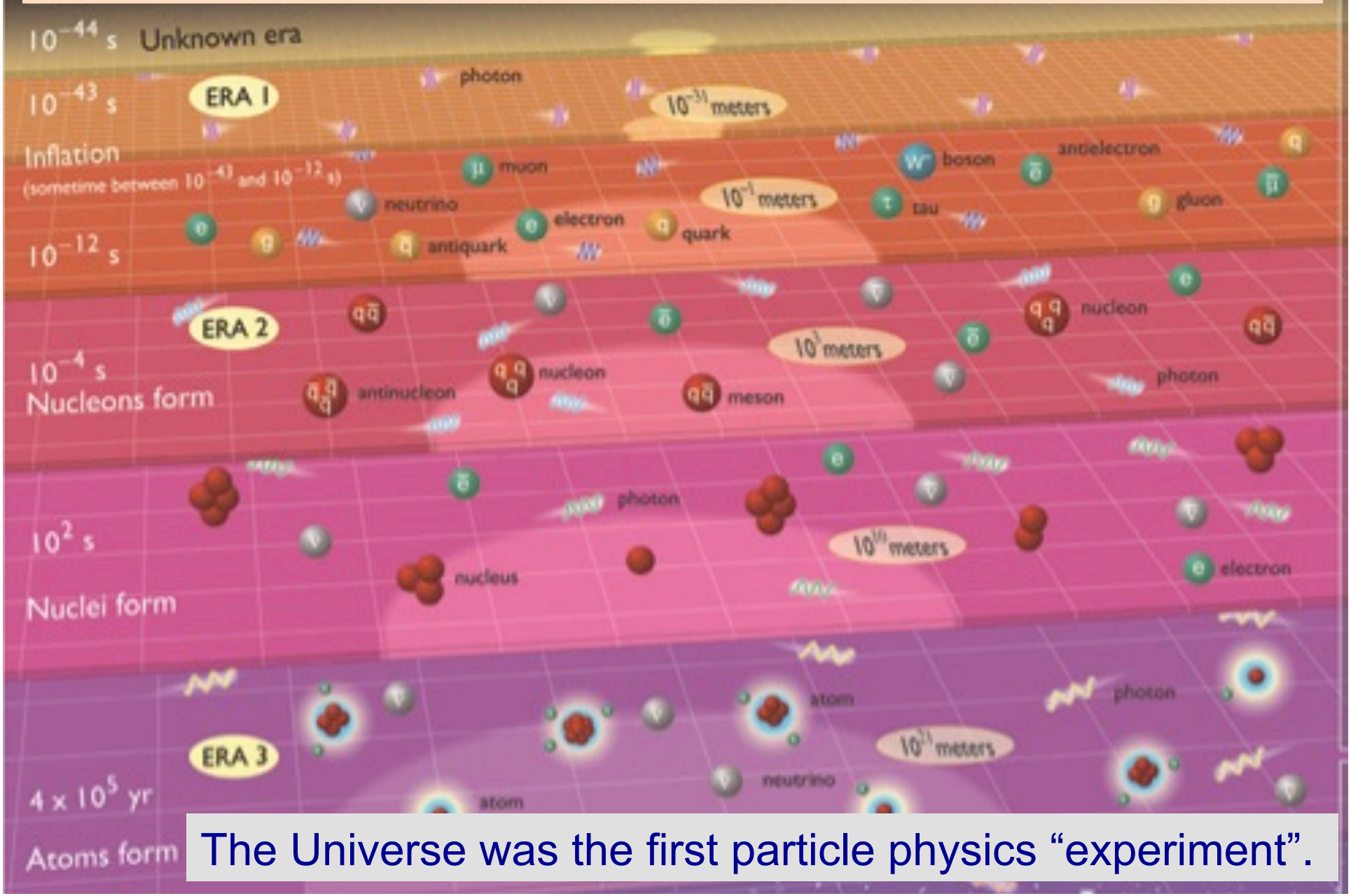




Hubble Deep Field HST • WFPC2

PRC96-01a • ST ScI OPO • January 15, 1996 • R. Williams (ST ScI), NASA

Big Bang and early eras of the universe



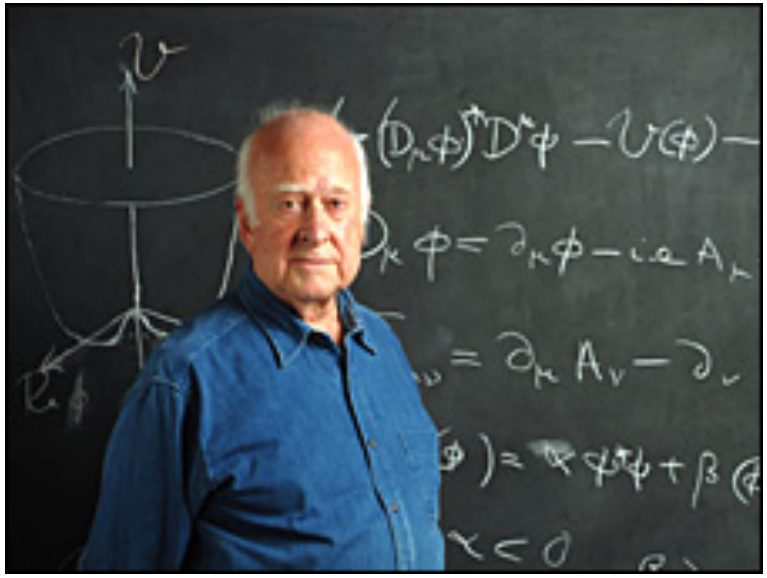
The Universe was the first particle physics “experiment”.

The Higgs Boson

My TV screen, summer 2010, Ferney-Voltaire, France

Satyendra Nath Bose, 1894-1974
Key contributions to early development of the theory of quantum mechanics. Some of his ideas play an important role in particle physics.

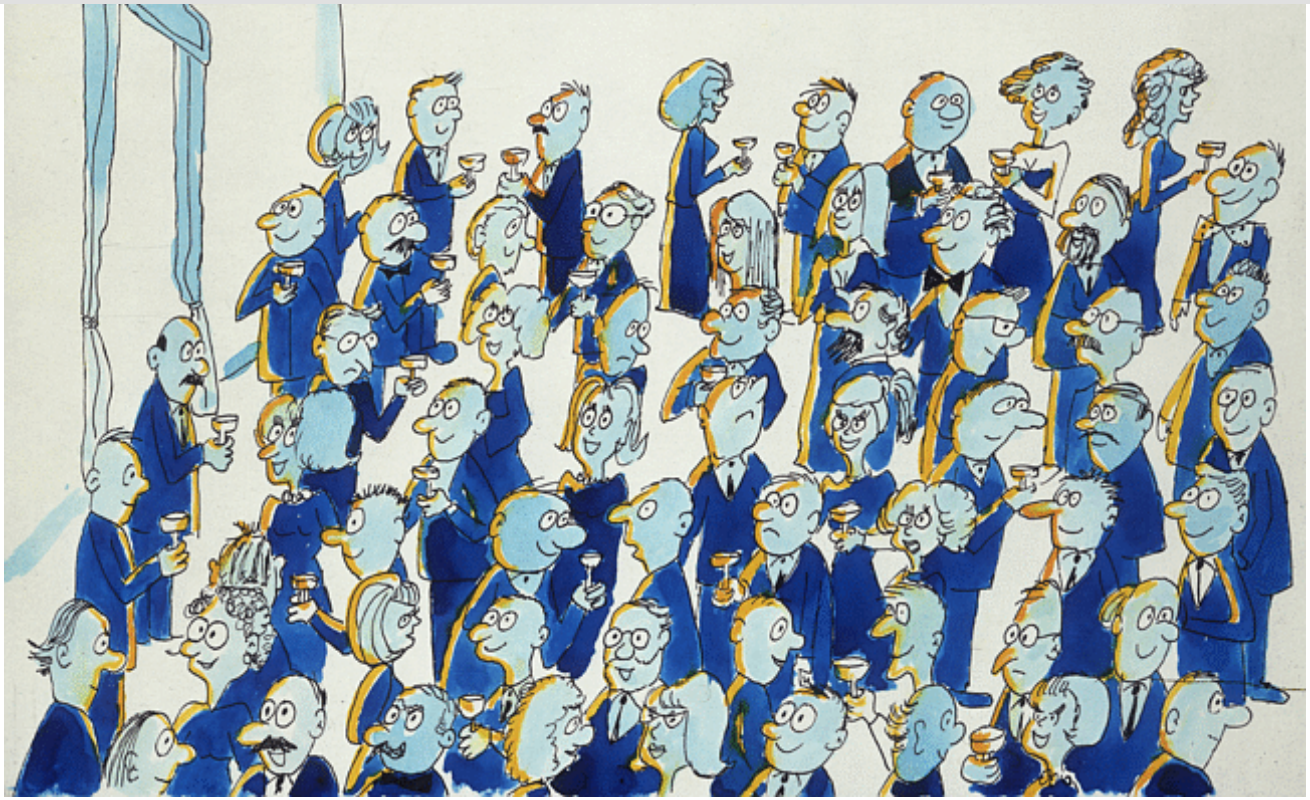
The Higgs mechanism: a high stakes game



- Existential paradox in particle physics: the mathematics describing the forces between particles was incompatible with particles having mass.
- Higgs: space itself has a special property (this Higgs field) that gives particles their masses.

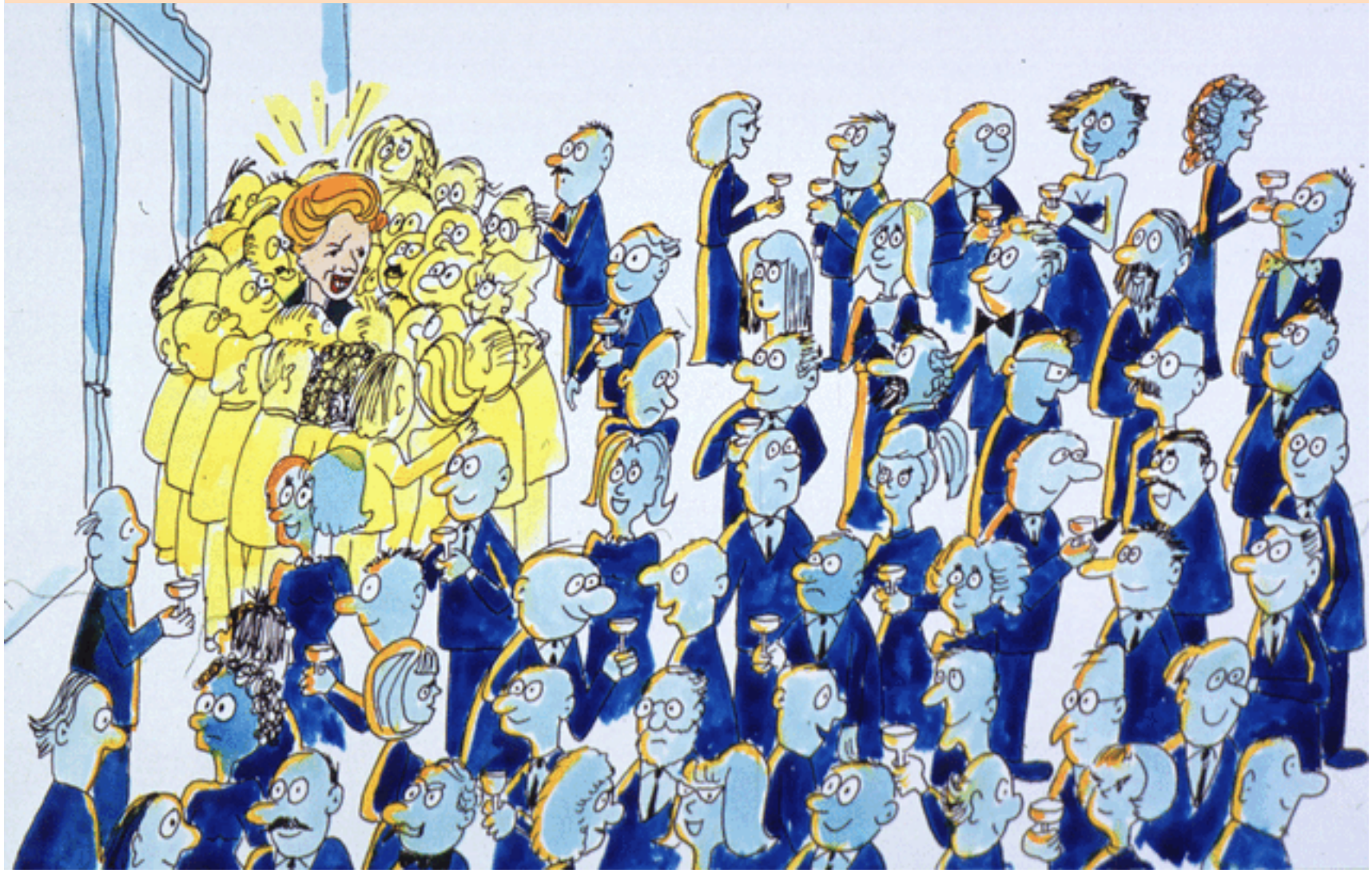
A quasi-political Explanation of the Higgs Boson; for Mr Waldegrave, UK Science Minister, 1993.

From David J. Miller, Physics and Astronomy, University College London
(cartoons courtesy CERN)

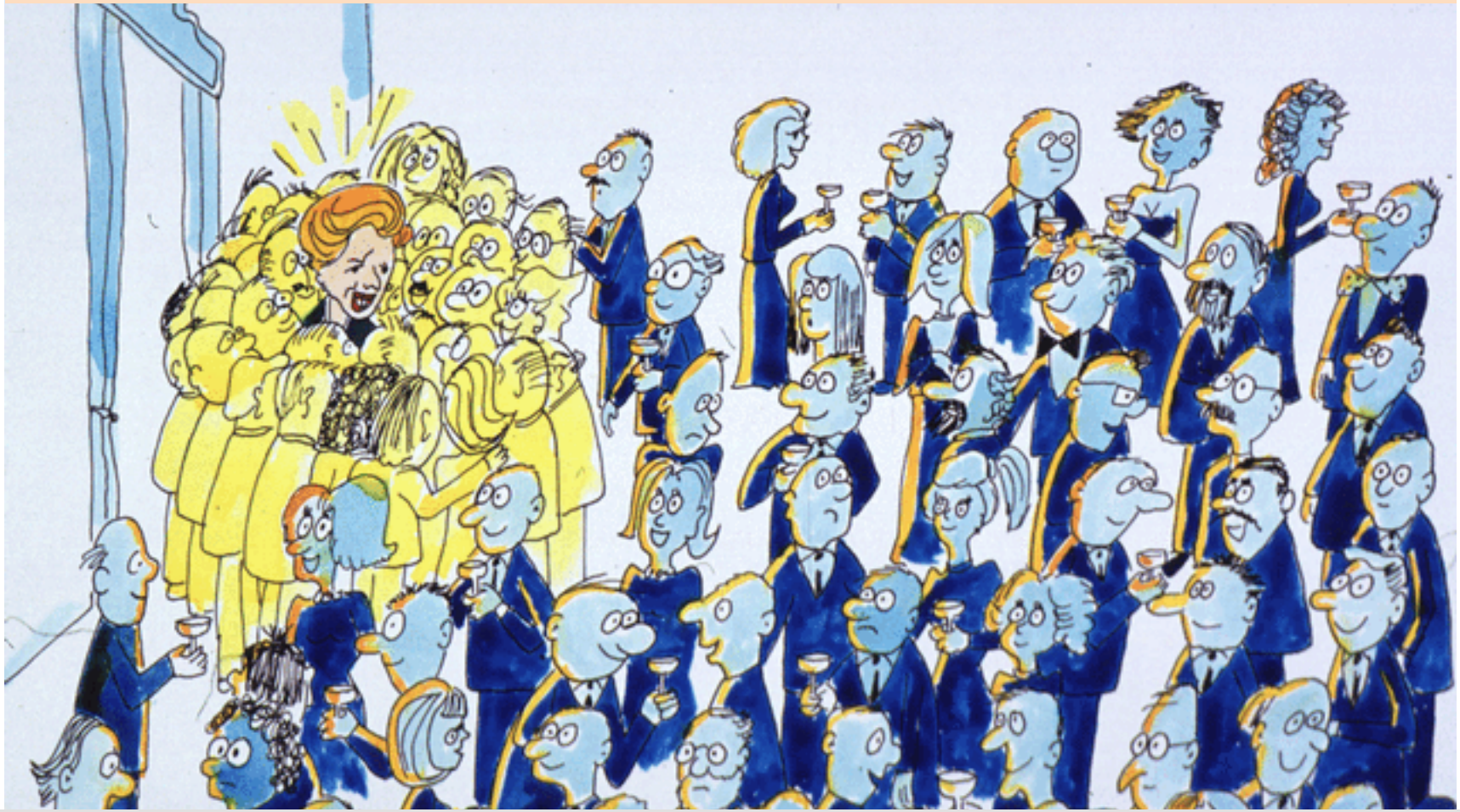


Imagine a cocktail party of political party workers who are uniformly distributed across the floor, all talking to their nearest neighbors.

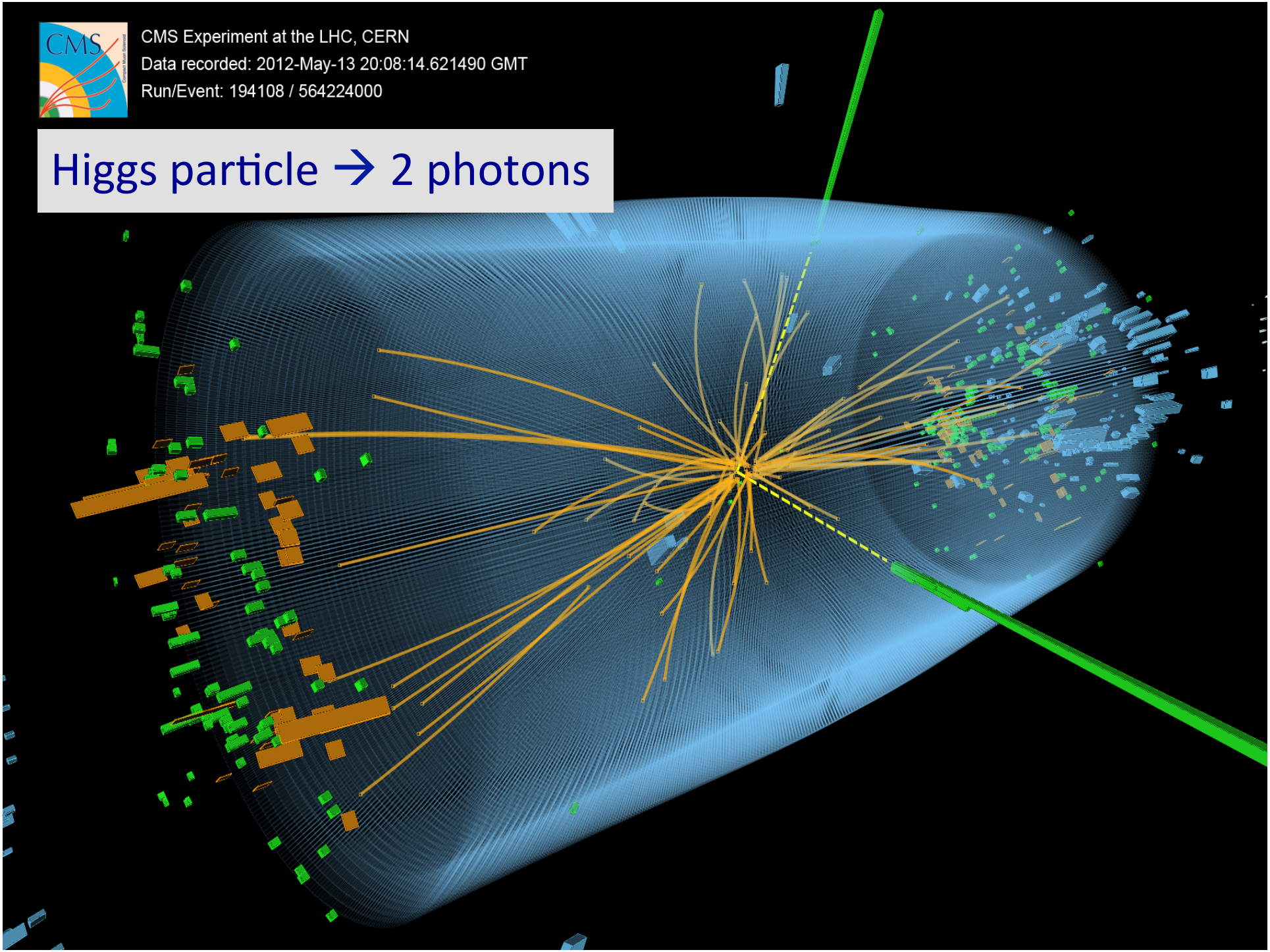
How the Higgs mechanism gives mass to massless particles



How the Higgs mechanism gives mass to massless particles

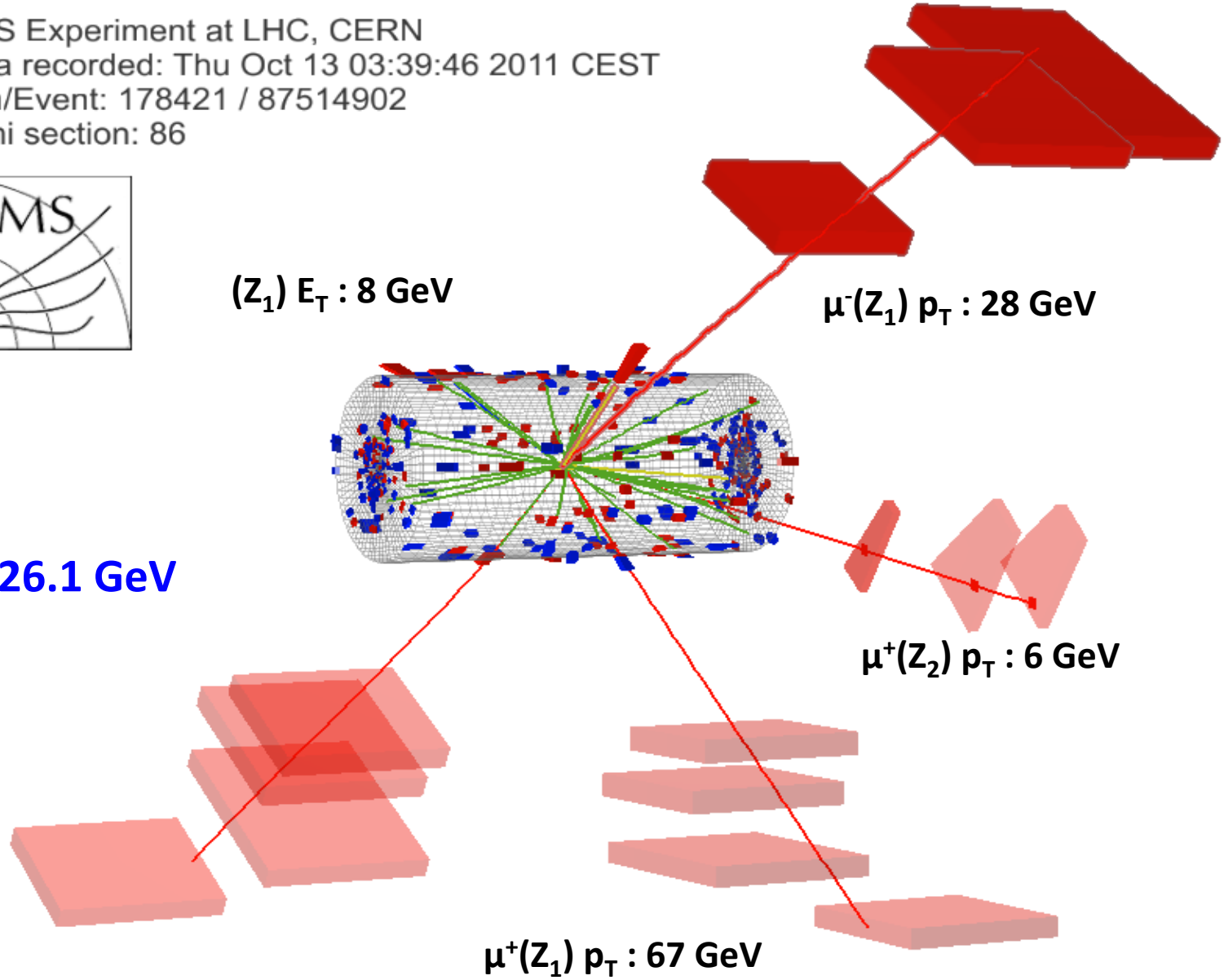


A particle that was originally massless (no inertia), acquires a mass through its interactions with the Higgs field, which permeates all of space.


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
Higgs particle → 2 photons

Higgs particle → two Z bosons → 4 muons

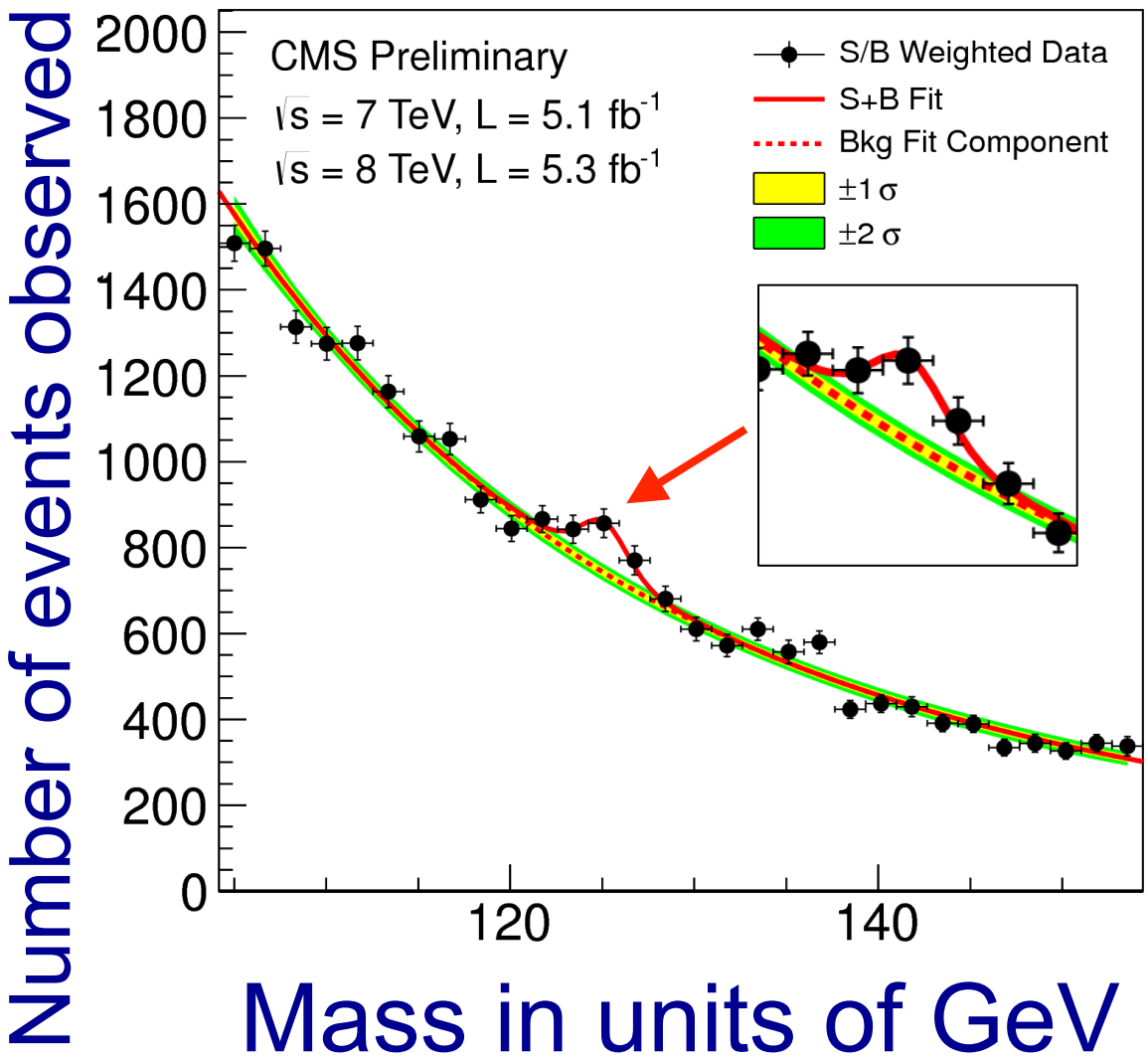
CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 03:39:46 2011 CEST
Run/Event: 178421 / 87514902
Lumi section: 86



7 TeV DATA

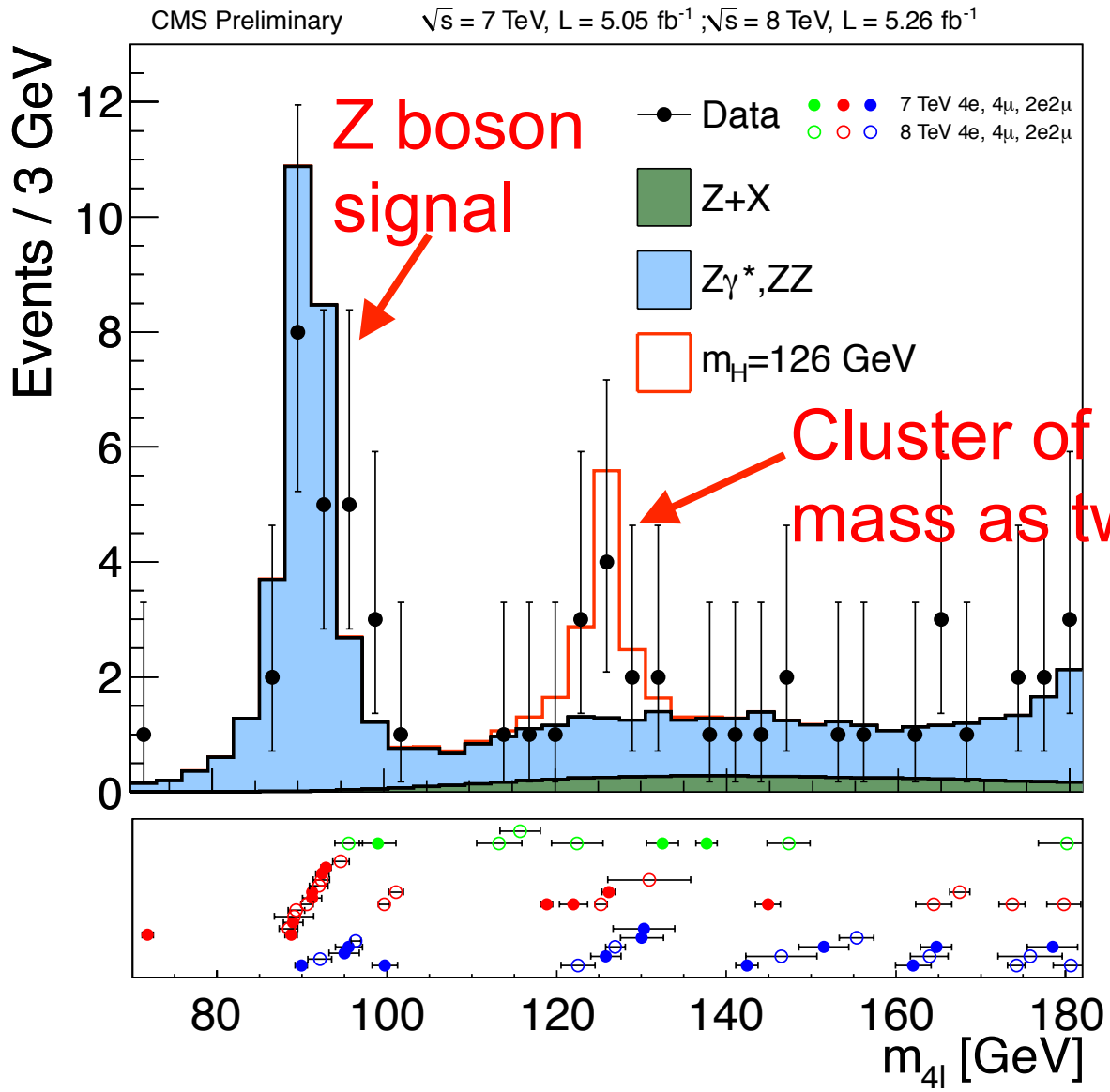
$4\mu+\gamma$ Mass : 126.1 GeV

Higgs particle → two photons



The mass of the Higgs particle can be inferred from the energies and directions the two photons that the Higgs particle decays into.

Higgs boson → two Z bosons → 4 leptons

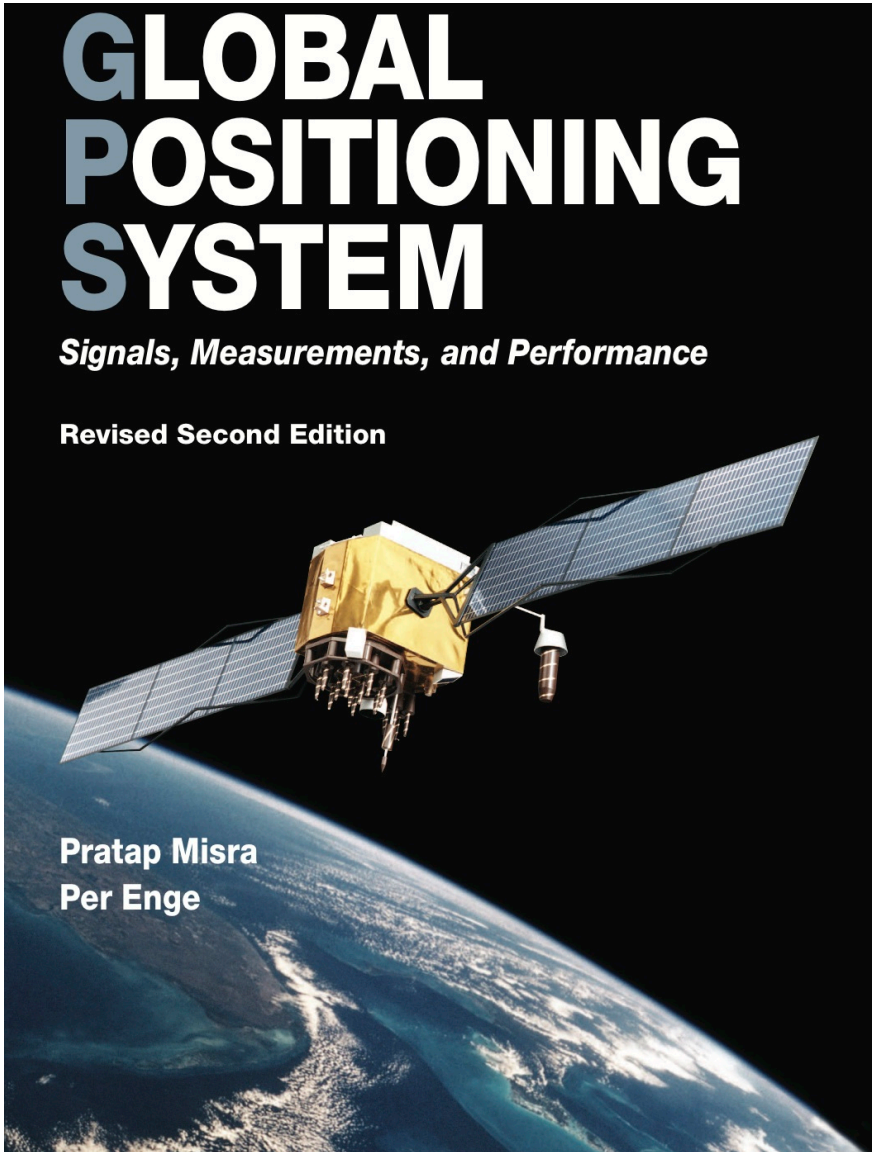


Cluster of events at same mass as two photon events!

Mass in units of GeV

Albert Einstein and the geometry of space-time

- Einstein taught us that matter causes the geometry of space-time to be curved.
- Clocks run at very slightly different speeds at different heights in a gravitational field.
- Tiny effect – who cares? We all do!



Information Management: A Proposal

Tim Berners-Lee, CERN
March 1989, May 1990

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 system.

Many of the discussions of the future at CERN and the LHC era end with the question - ªYes, but how will we ever keep track of such a large project?º This proposal provides an answer to such questions. Firstly, it discusses the problem of information access at CERN. Then, it introduces the idea of linked information systems, and compares them with less flexible ways of finding information.

(Sir) Tim Berners-Lee and early development of the World Wide Web

Berners-Lee proposed the WWW in March 1989 while working at CERN and developed the first web site.

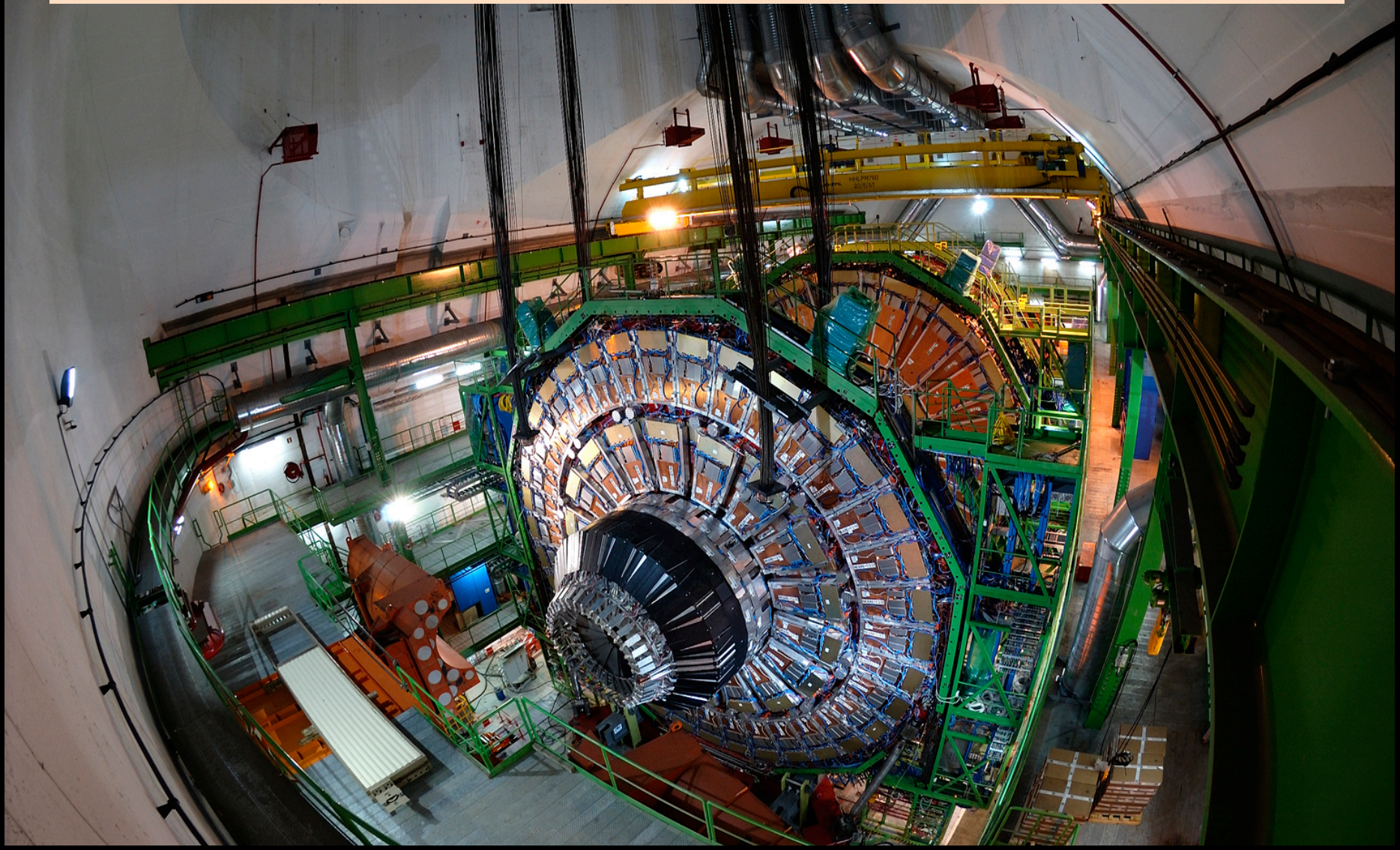
After 3 years of running...

- Over 100 physics papers published.
- Our first major discovery: a “Higgs-like particle”.
- Need to fully establish the properties of the new particle. There are scenarios with multiple Higgs bosons (e.g. five of them!).
- Intensity search for particles that can explain the dark matter (“supersymmetric particles”).
- Look for the unexpected.
- Train the next generation of scientists!

Extra Slides

Mont Blanc (4,810 m or 15,782 ft), as seen from CERN

Lowering one of the CMS endcap muon detectors into the cavern



Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

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Higgs

ABSTRACT

Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

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Collisions at 7 TeV

http://cdsweb.cern.ch/journal/CERNBulletin/2010/14/News%20Articles/1246424?ln=fr
http://press.web.cern.ch/press/PressReleases/Releases2010/PR07.10E.html

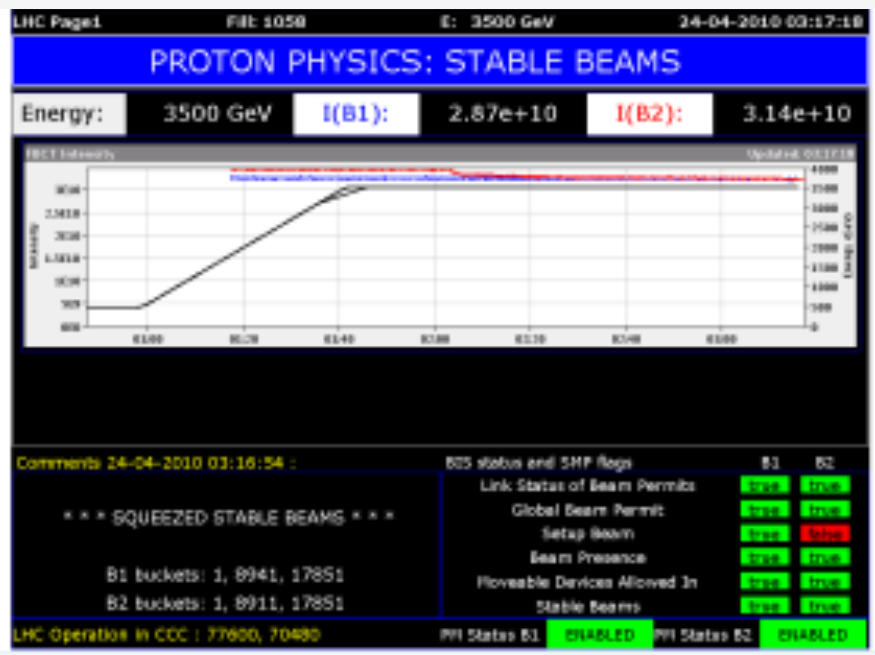
Nous avons réussi !

Presque 20 années de travail acharné accompli par des centaines de personnes ont permis au Grand collisionneur de hadrons (LHC) de passer du rêve à la réalité. Le LHC a livré aujourd'hui

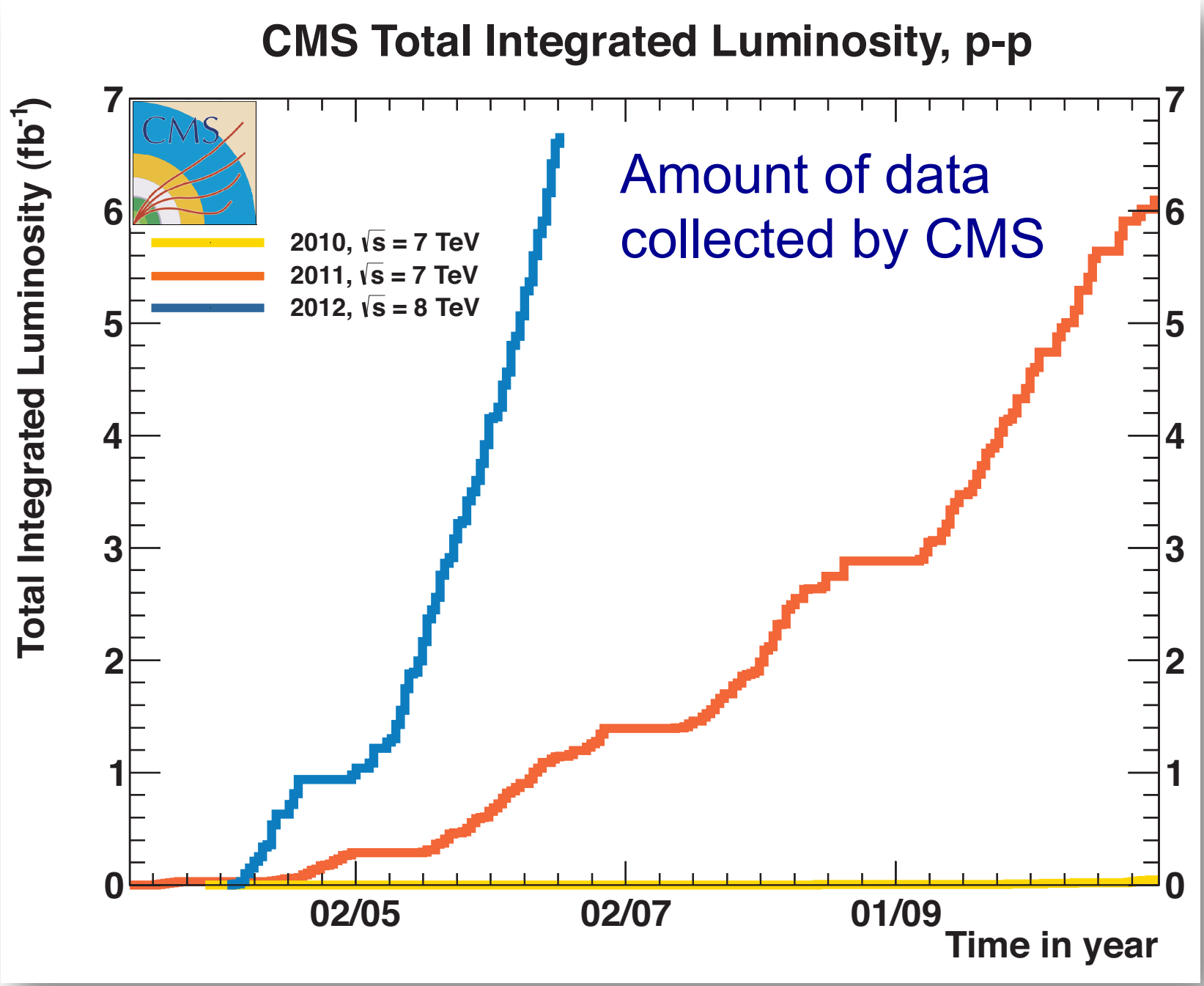
March 30, 2010: 1st 7 TeV Collisions

Il y a quelques instants à la CCC

May 1-2, 2010, squeezed, stable beams (30 hrs), L>1.1× 10^{28} $cm^{-2}s^{-1}$



http://cdsweb.cern.ch/journal/CERNBulletin/2010/18/News%20Articles/1262593?ln=en

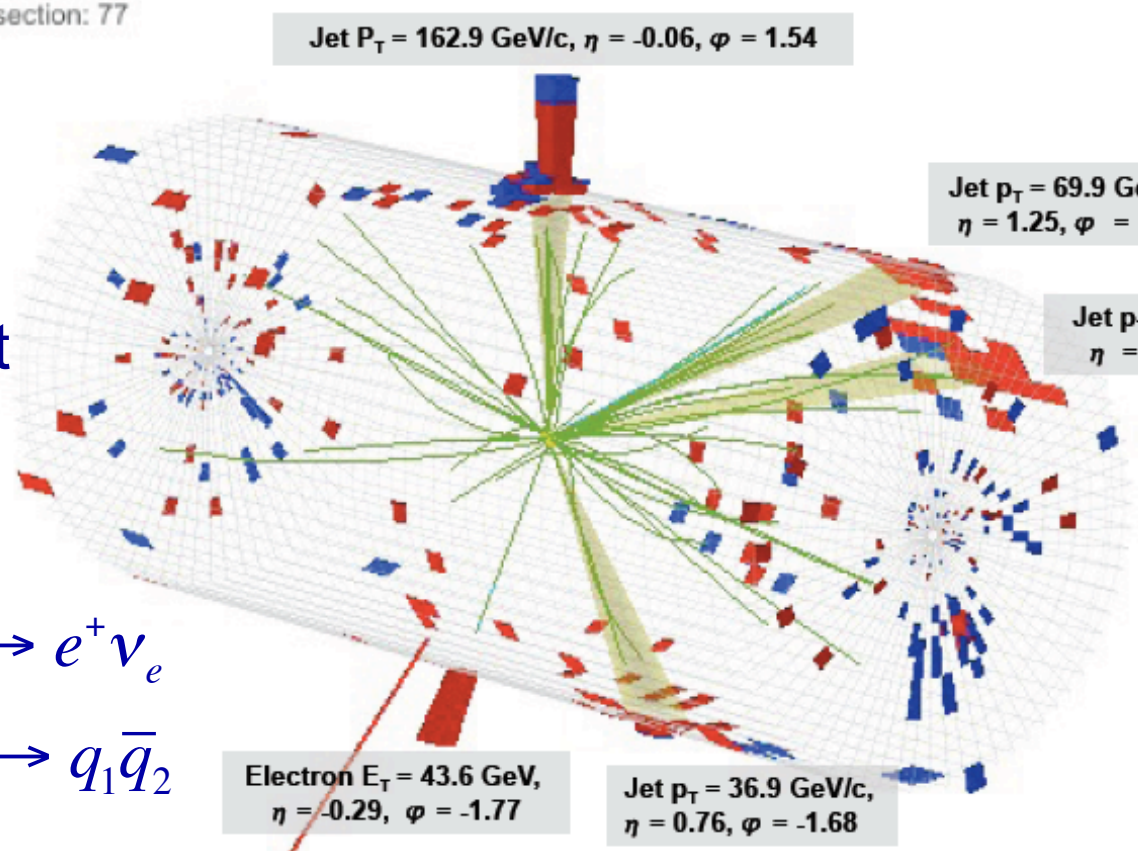

CMS Total Integrated Luminosity, p-p
Total Integrated Luminosity (fb^{-1})
2010, $\sqrt{s}$ = 7 TeV
2011, $\sqrt{s}$ = 7 TeV
2012, $\sqrt{s}$ = 8 TeV
Amount of data collected by CMS
0
1
2
3
4
5
6
7
02/05
02/07
01/09
Time in year

Inside the LHC Tunnel

Total magnets	9593
Num. main dipoles	1232 (L=15 m)
Num. main quads	392 (L= 5 to 7 m)
RF cavs/beam	8
Bunches/beam	2808
Protons/bunch	$1.1\ 10^{11}$
Collisions/sec	$600\ 10^{6}$
Bunch spacing (min.)	7 m (25 ns)
Dipole field	8.33 T
Dipole op. temp.	1.9 K
Dipole current	11,850 A
Design luminosity	10^{34} $cm^{-2}s^{-1}$

High Level Trigger Processing Farm

Observation of $pp \rightarrow t\bar{t}$



Candidate event for process

$$pp \rightarrow t\bar{t}$$

$$t \rightarrow bW^+; \quad W^+ \rightarrow e^+\nu_e$$

$$\bar{t} \rightarrow \bar{b}W^-; \quad W^- \rightarrow q_1\bar{q}_2$$

Missing momentum vector from neutrino

Some fancy physics: creating particles

Problems

1) According to the theory, Higgs particles should only be produced very rarely (less than one per billion proton-proton collisions).
2) The Higgs particle would then transform into other particles, with several different possibilities.

CERN: the first web site

http://info.cern.ch/hypertext/WWW/TheProject.html

World Wide Web

The WorldWideWeb (W3) is a wide-area hypermedia information retrieval initiative aiming to give universal access to a large universe of documents.

Everything there is online about W3 is linked directly or indirectly to this document, including an executive summary of the project, Mailing lists , Policy , November's W3 news , Frequently Asked Questions .

What's out there?
: Pointers to the world's online information, subjects , W3 servers, etc.

Help
: on the browser you are using

Software Products
: A list of W3 project components and their current state. (e.g. Line Mode ,X11 Viola , NeXTStep , Servers , Tools , Mail robot , Library)

Technical
: Details of protocols, formats, program internals etc

Bibliography
: Paper documentation on W3 and references.

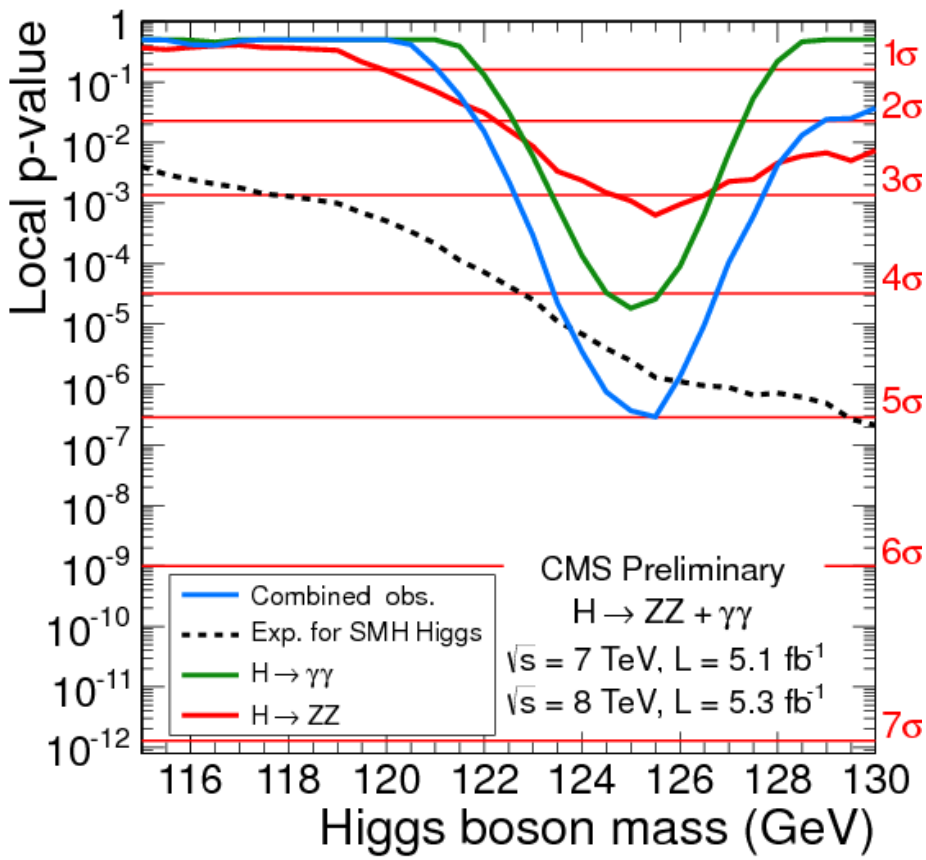
People
: A list of some people involved in the project.

History
: A summary of the history of the project.

How can I help ?
: If you would like to support the web..

Getting code
: Getting the code by anonymous FTP , etc.

Statistical significance of the observed signal

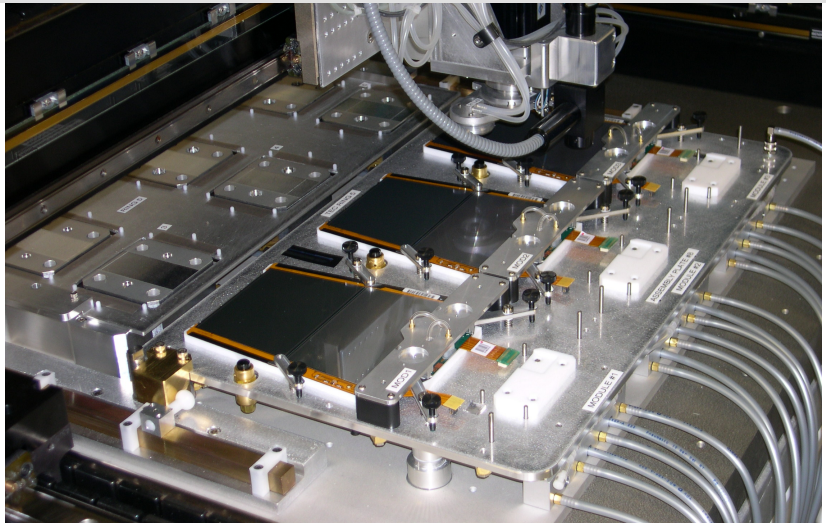


- **High sensitivity, high mass resolution channels: γγ+4l**
  - **γγ: 4.1 σ excess**
  - **4 leptons: 3.2 σ excess**
  - **near the <u>same mass</u> 125 GeV**
- **Comb. significance: 5.0 σ**
- **expected significance for SM Higgs: 4.7 σ**

Working on the CMS Silicon Strip Tracker

UCSB silicon-strip module assembly team

Module construction on gantry



Module installation at CERN

CMS: Major roles of UCSB group

Area	Examples
Leadership/management	Top-level management, physics & software convenorships
Silicon Tracker Construction	Module & rod construction at UCSB, detector testing and assembly at CERN, project management
Silicon Tracker Commissioning	Cooling systems; calibration & commissioning
Silicon Tracker Upgrade and SLHC Electronics Development	Endcap muon electronics, readout electronics development, tracker & trigger studies
General Physics Analysis Tools Development	Fireworks Event Display, Physics Datasets & Trigger Menu Development, Physics Analysis Toolkit (PAT) Development, Missing Transverse Momentum measurement, b-tagging studies, Conversion ID
Muon High Level Trigger	Development of Muon High Level Trigger Software
Tracking Software	Development of Tracker Reconstruction Software
Muon Reconstruction Software	Development of Muon Reconstruction methods
Physics Analysis	Broad range of analyses: Top, SUSY, Electroweak

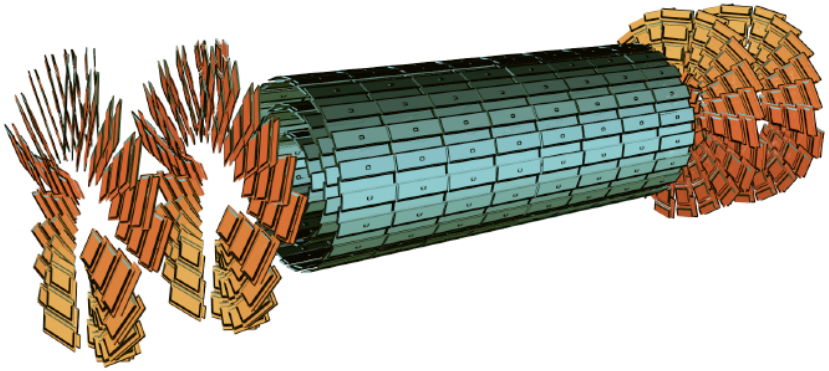
CMS Tracker Inner Region: Pixels

Inner part of all-silicon tracker

- Fast response to keep up with 25 ns beam xing interval (2 MHz)
- Pixels: 3 barrel layers, 2 pairs F/B

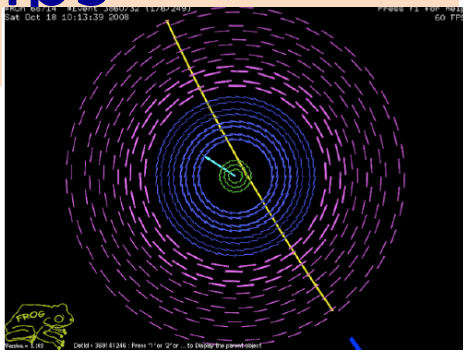
Pixel Detector Parameter	Value
Pixel Size	100 µm × 150 µm
Resolution	10 µm (rϕ)× 20 µm (z)
Number pixels	66 M
Sensor thickness	285 µm
Radii of barrel layers	4.3, 7.2, 11.0 cm
|z| of forward layers (disks)	34.5 cm, 46.5 cm (F and B)
Total sensor area	~1 m^2
Fraction operational	98.4%
Efficiency	97%

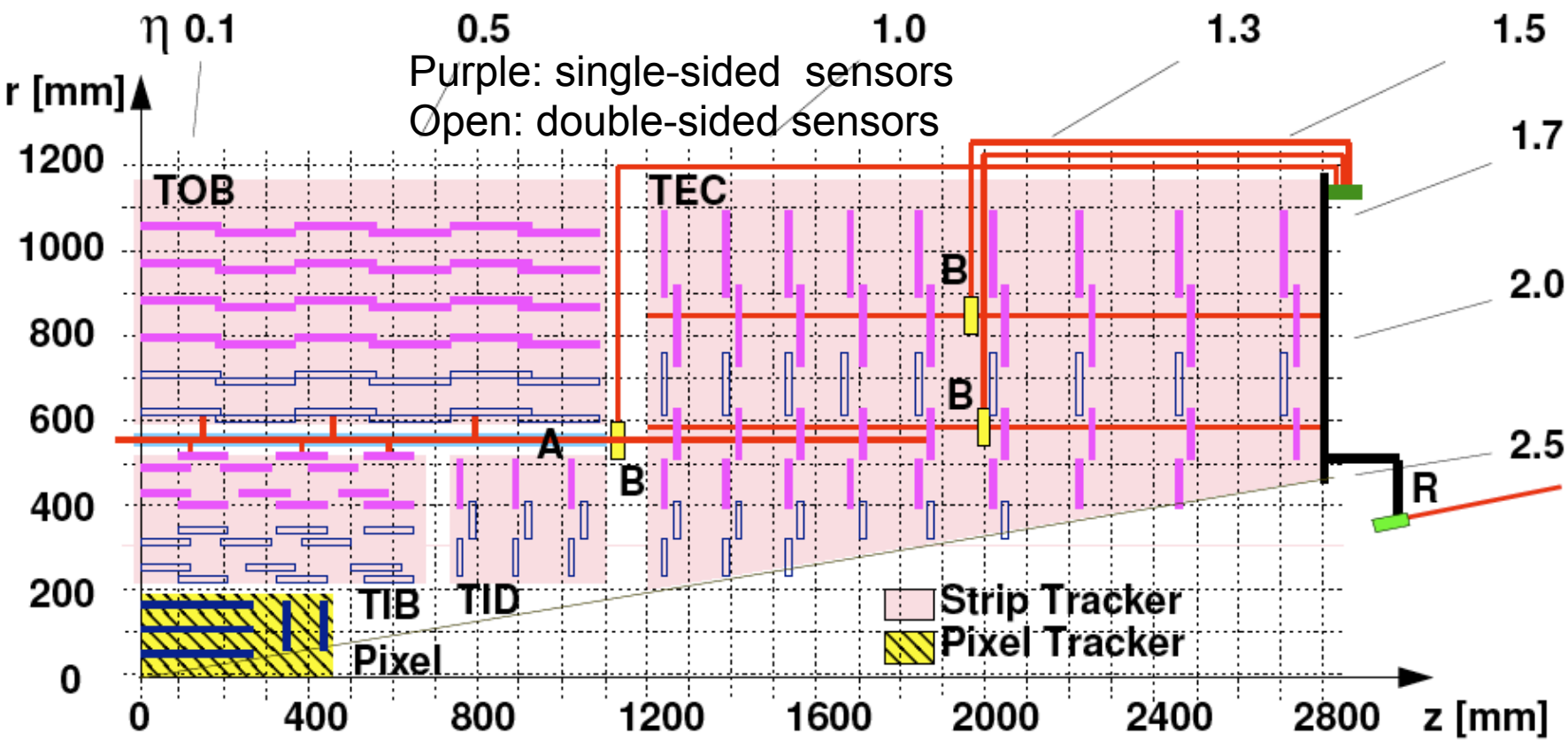
Pixel Detector Geometry



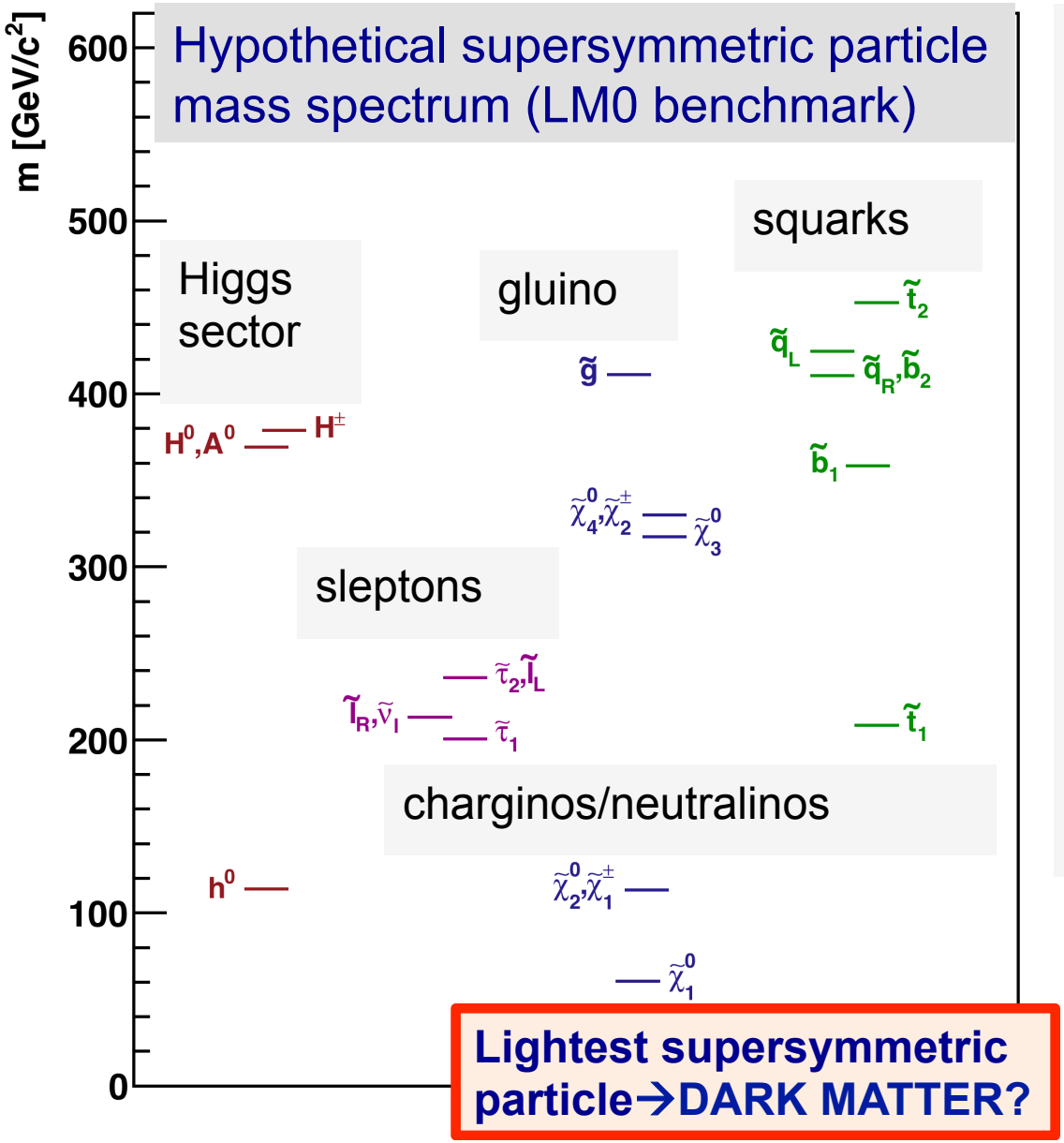
CMS Tracker: Silicon Strips

- Largest silicon tracker ever built: ~200 m^2
- Inner+outer barrel: 4+6 layers; 10-14 points
- 9.3 M strips, pitch 80-180 μm; 97.2% working
- Sensor thickness: 320 μm; 500 μm





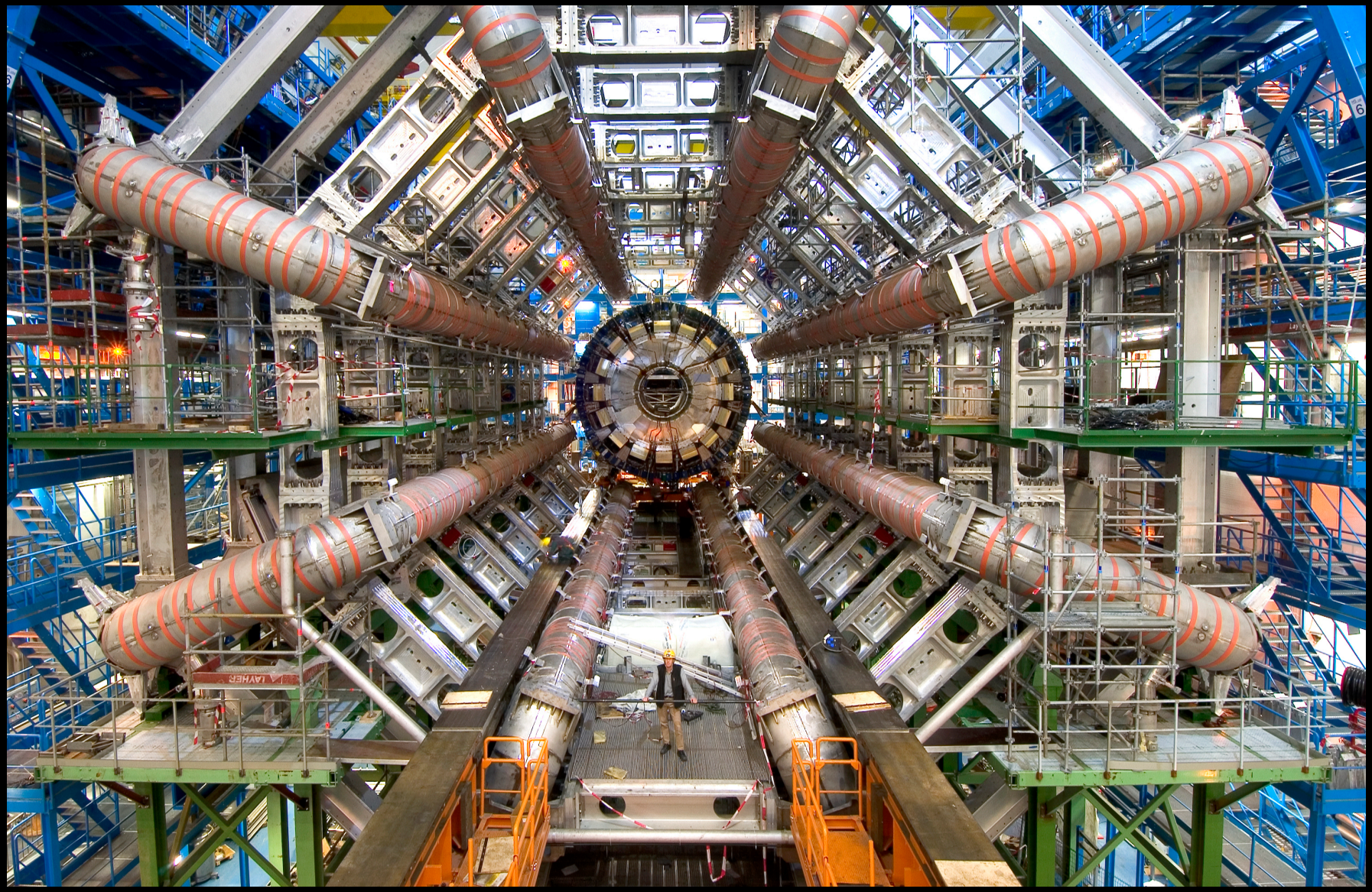
A new spectroscopy?



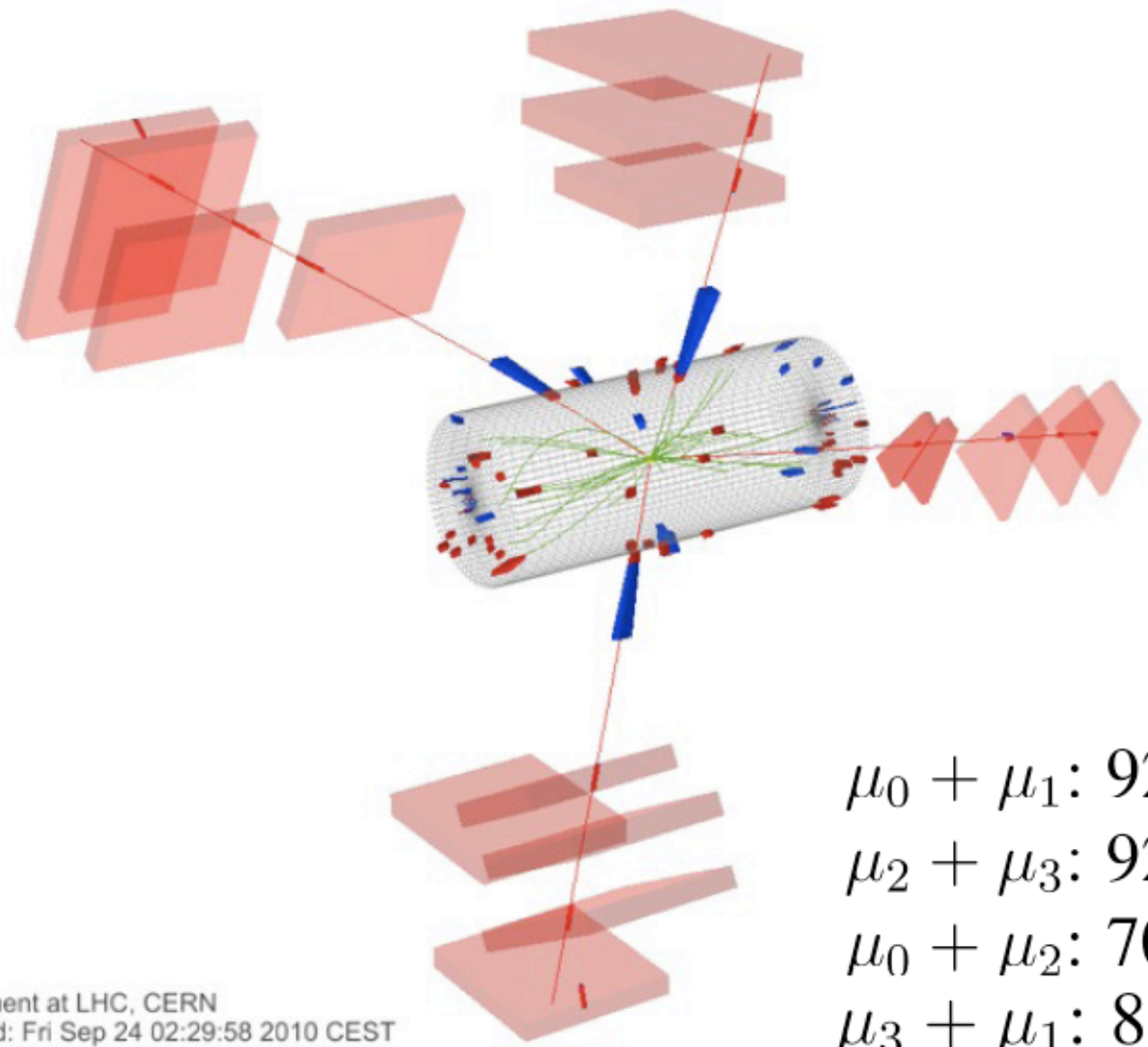
Lightest supersymmetric particle→DARK MATTER?

- Many SUSY signatures give very large (>200 GeV) missing momentum due to production of two LSPs.
- Broad range of signatures, with leptons, photons, b-quarks,...
- Currently carrying out full range of searches.

ATLAS experiment under construction: Toroidal Magnets



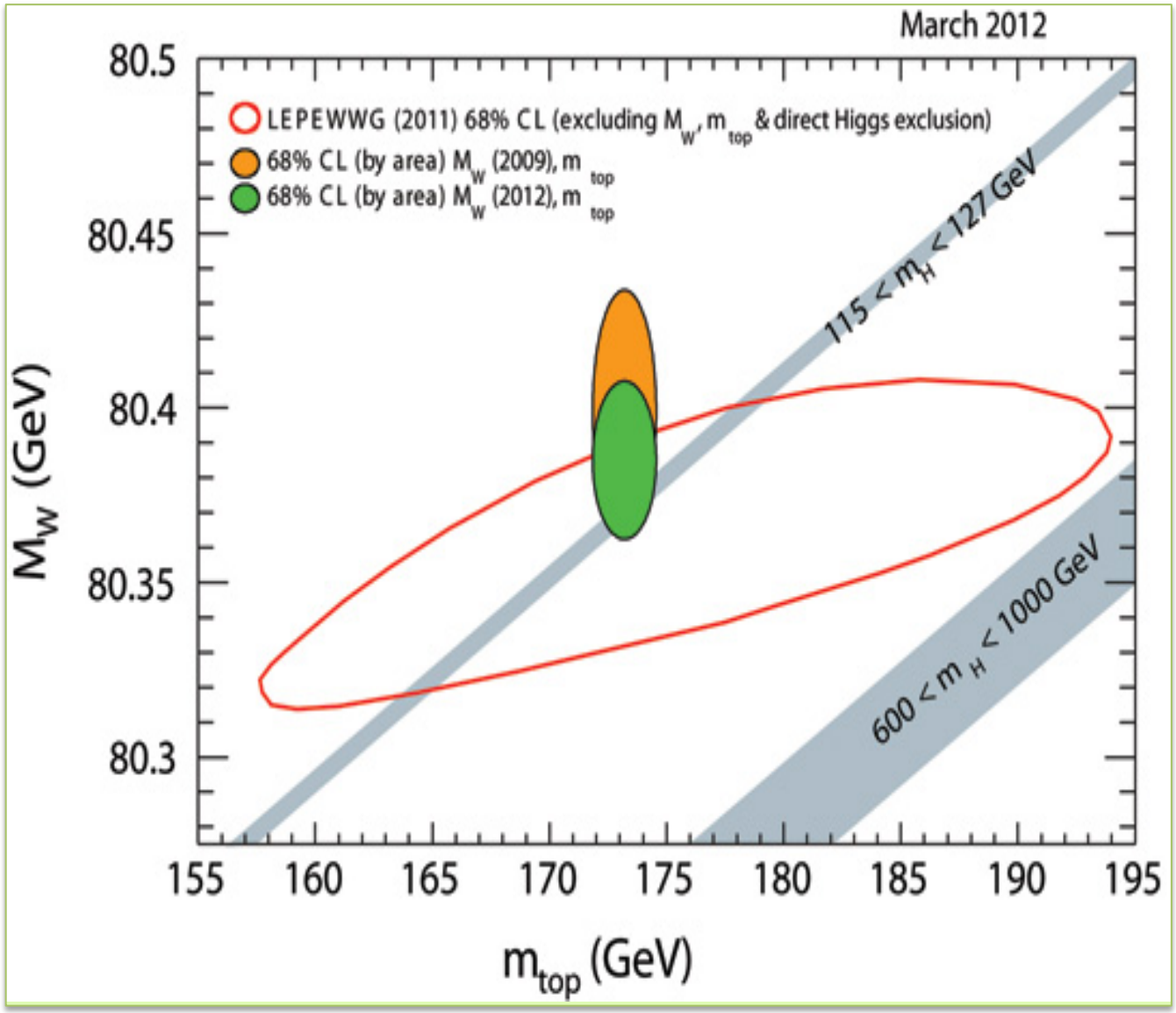
$pp \rightarrow Z(\rightarrow \mu^+\mu^-) + Z(\rightarrow \mu^+\mu^-)$



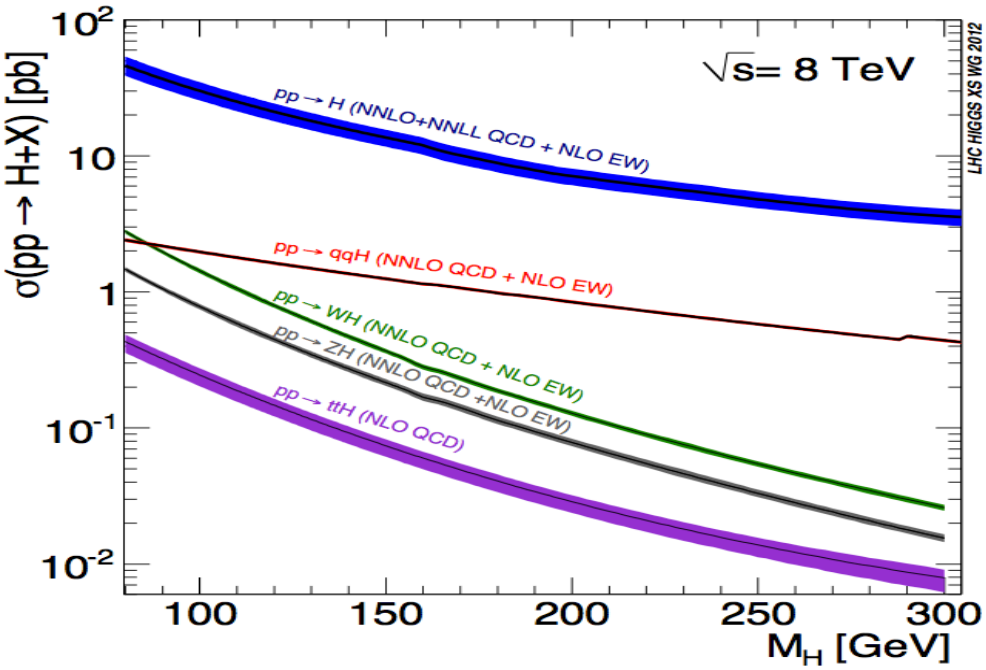
CMS Experiment at LHC, CERN
Data recorded: Fri Sep 24 02:29:58 2010 CEST
Run/Event: 146511 / 504867308

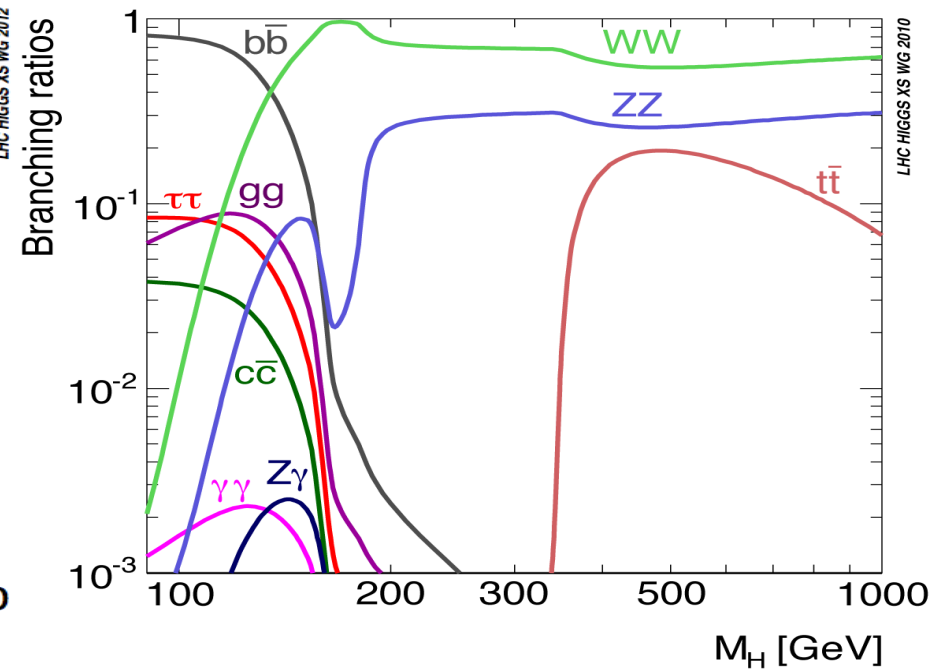
$\mu_0 + \mu_1$: 92.15 GeV
$\mu_2 + \mu_3$: 92.24 GeV
$\mu_0 + \mu_2$: 70.12 GeV
$\mu_3 + \mu_1$: 83.1 GeV

Standard Model constraints on m(Higgs)



Higgs boson production and decay





Antimatter

$\bar{u}$ anti-up	$\bar{c}$ anti-charm	$\bar{t}$ anti-top
$\bar{d}$ anti-down	$\bar{s}$ anti-strange	$\bar{b}$ anti-bottom

e^+ positron	μ^+ mu plus	τ^+ tau plus
$\bar{\nu}_e$ electron anti-neutrino	$\bar{\nu}_\mu$ muon anti-neutrino	$\bar{\nu}_\tau$ tau anti-neutrino

Antiparticles already included or particle is its own antiparticle.

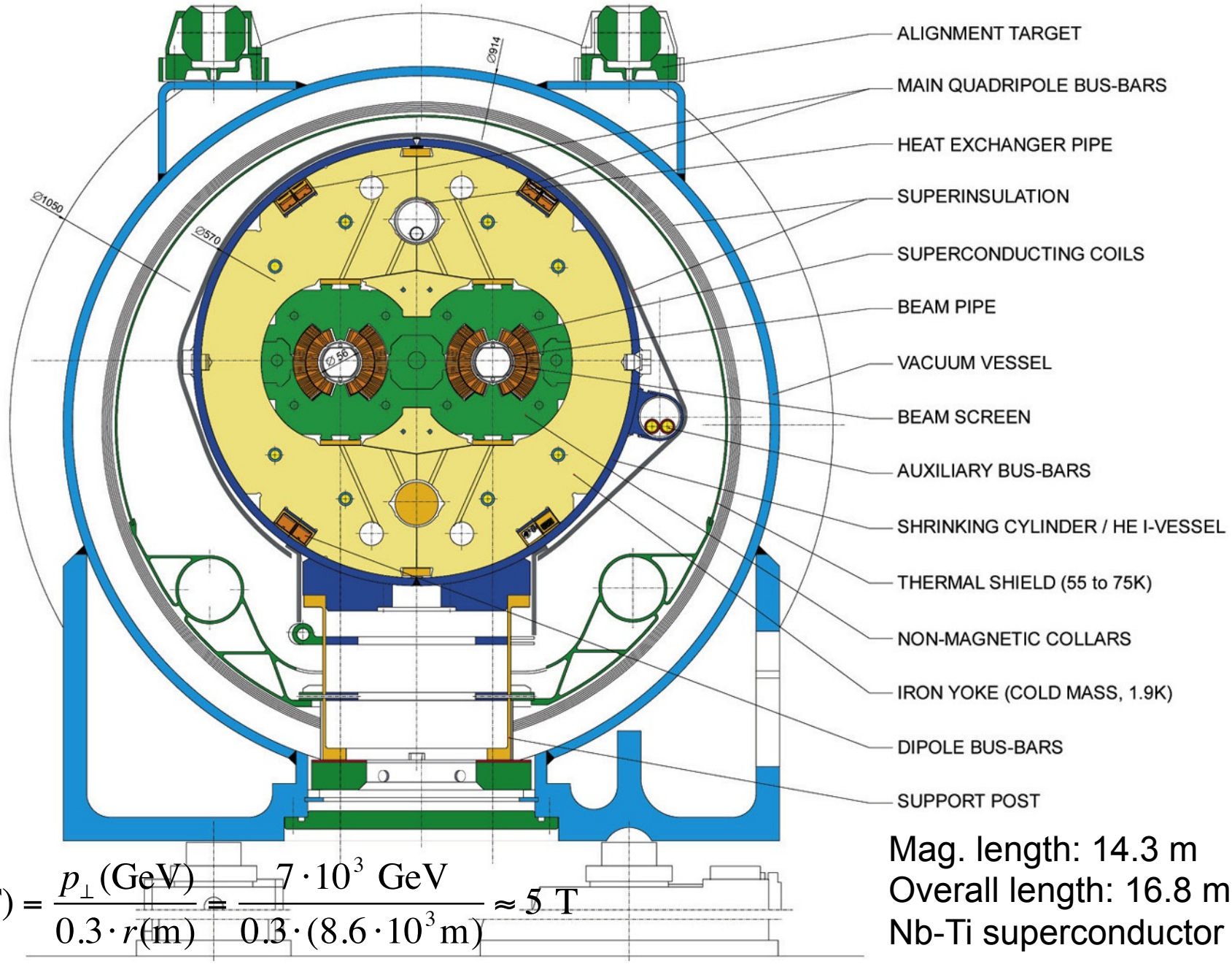
Strong Int.	EM Int.	Weak Interactions		
g	γ	Z^0	W^+	W^-
gluon (8)	photon	Z boson	W bosons	

H
Higgs boson

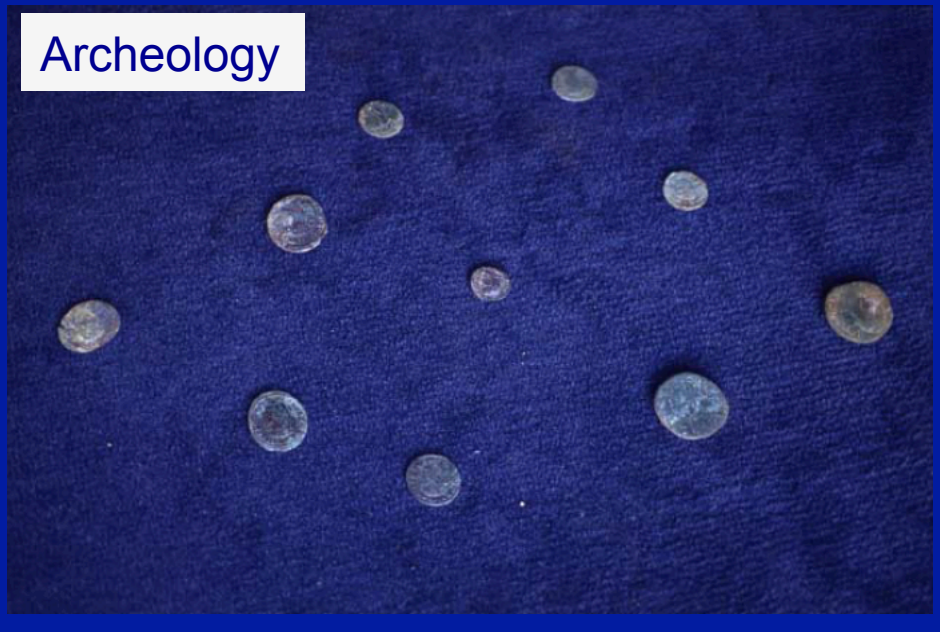
“Recent” history of the universe

LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DI/MM - HE107 - 30 04 1999



$$B(\mathrm{T}) = \frac{p_\perp(\mathrm{GeV})}{0.3 \cdot r(\mathrm{m})} = \frac{7 \cdot 10^3\ \mathrm{GeV}}{0.3 \cdot (8.6 \cdot 10^3\,\mathrm{m})} \approx 5\ \mathrm{T}$$

Mag. length: 14.3 m
Overall length: 16.8 m
Nb-Ti superconductor

Many different aspects to the LHC project