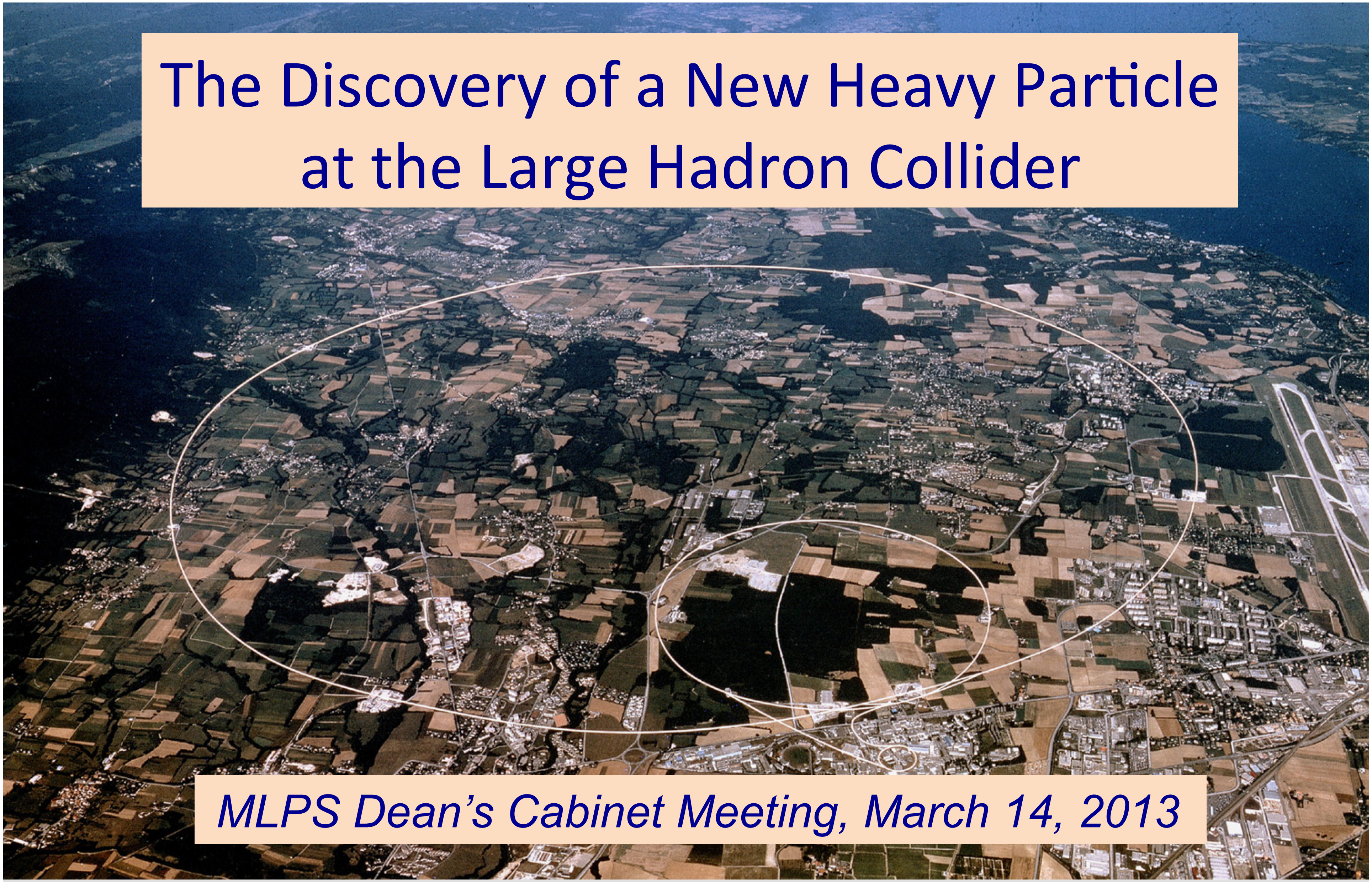
The Discovery of a New Heavy Particle at the Large Hadron Collider

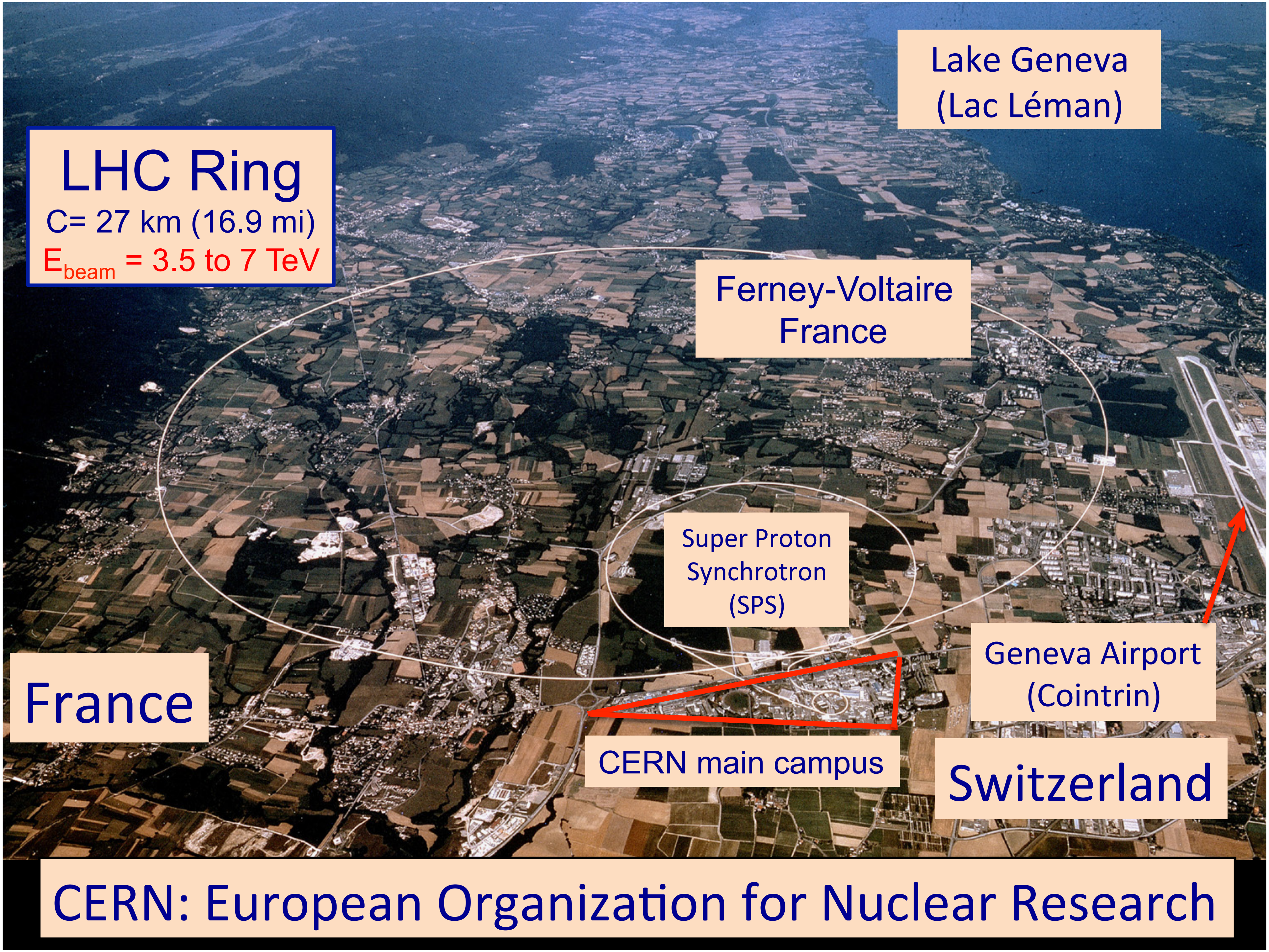


MLPS Dean's Cabinet Meeting, March 14, 2013

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

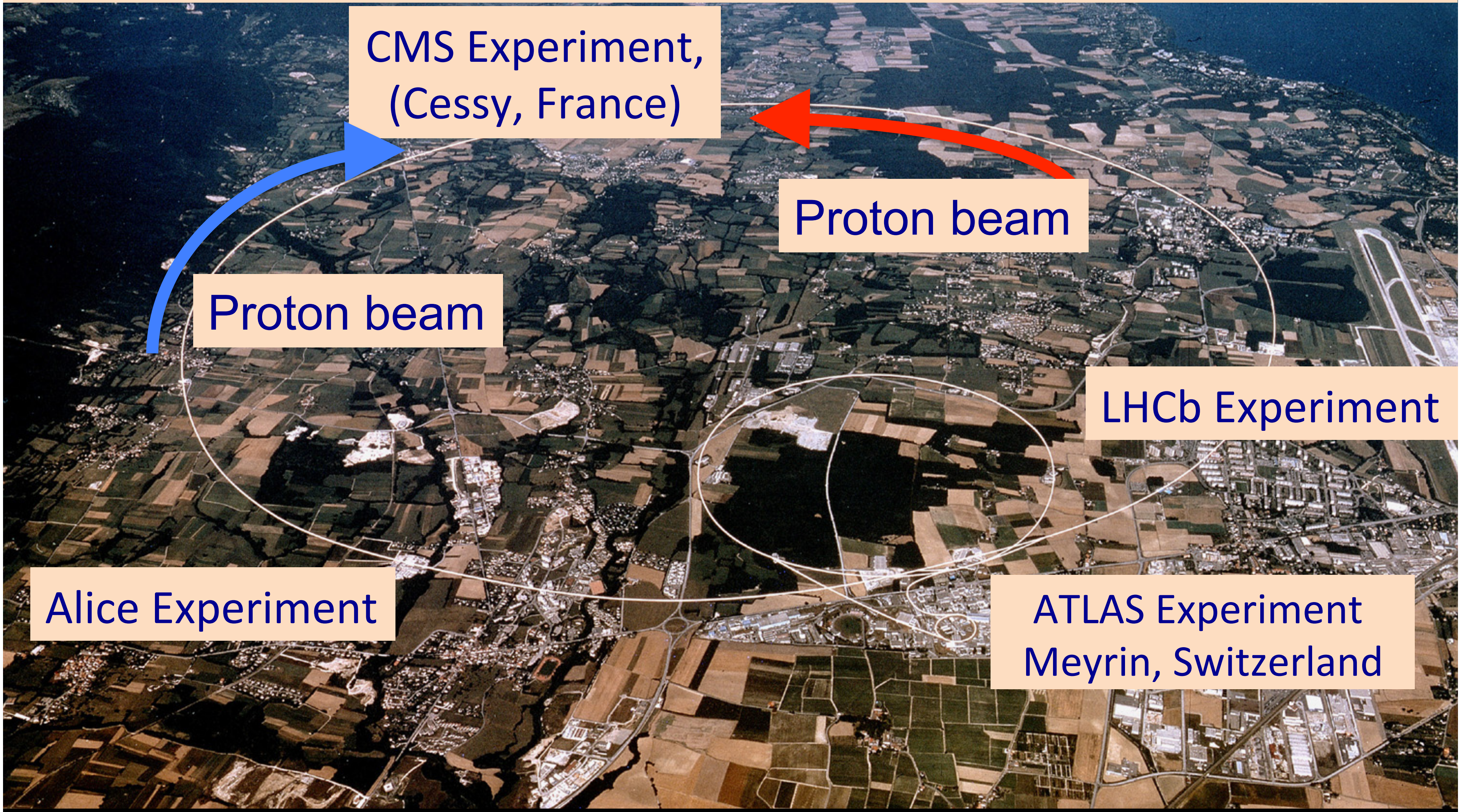
European Organization for Nuclear Research
Geneva, Switzerland, July 4, 2012

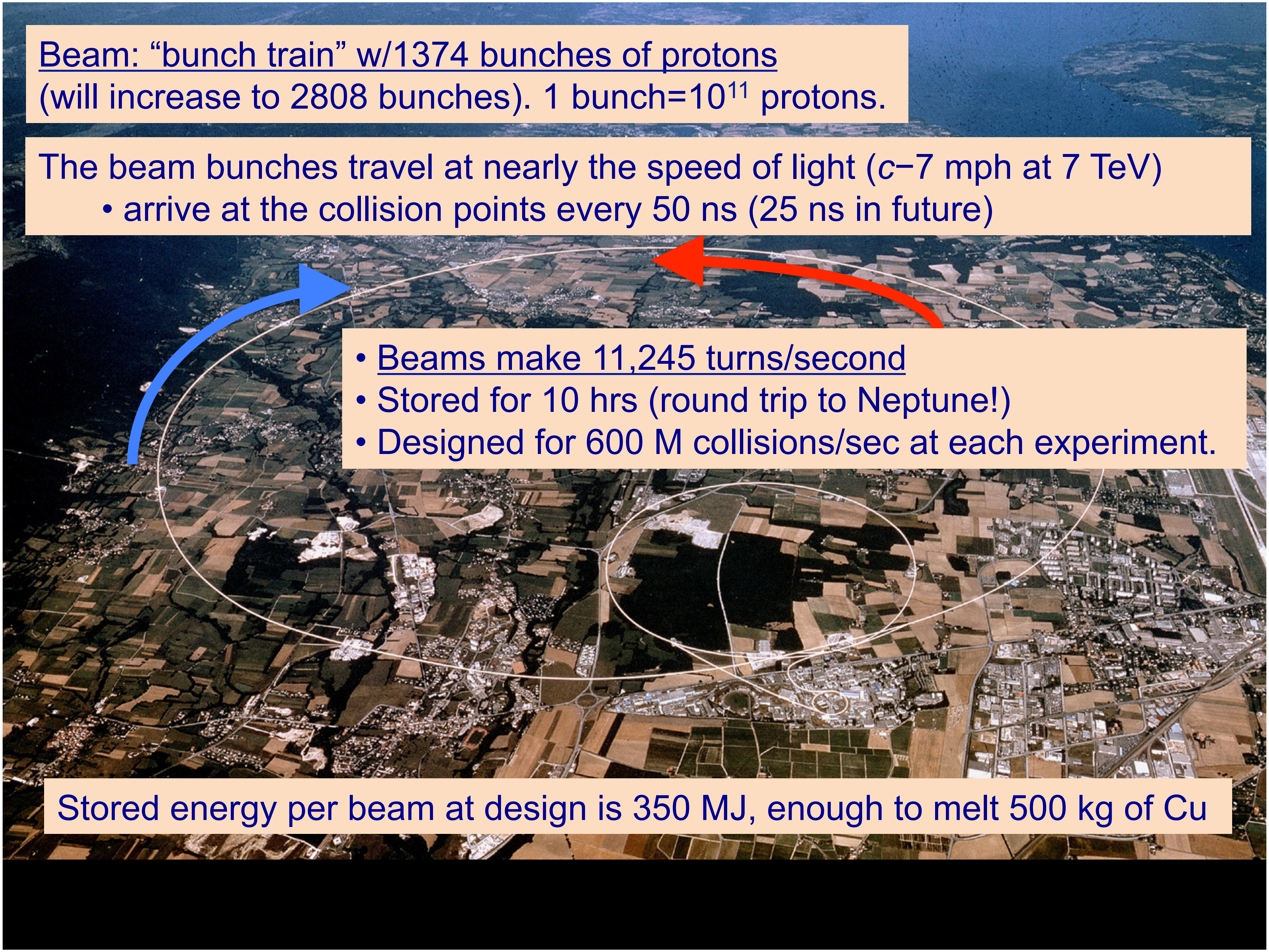
photo courtesy CERN


Lake Geneva
(Lac Léman)
LHC Ring
C= 27 km (16.9 mi)
E_beam = 3.5 to 7 TeV
Ferney-Voltaire
France
Super Proton
Synchrotron
(SPS)
Geneva Airport
(Cointrin)
France
CERN main campus
Switzerland
CERN: European Organization for Nuclear Research

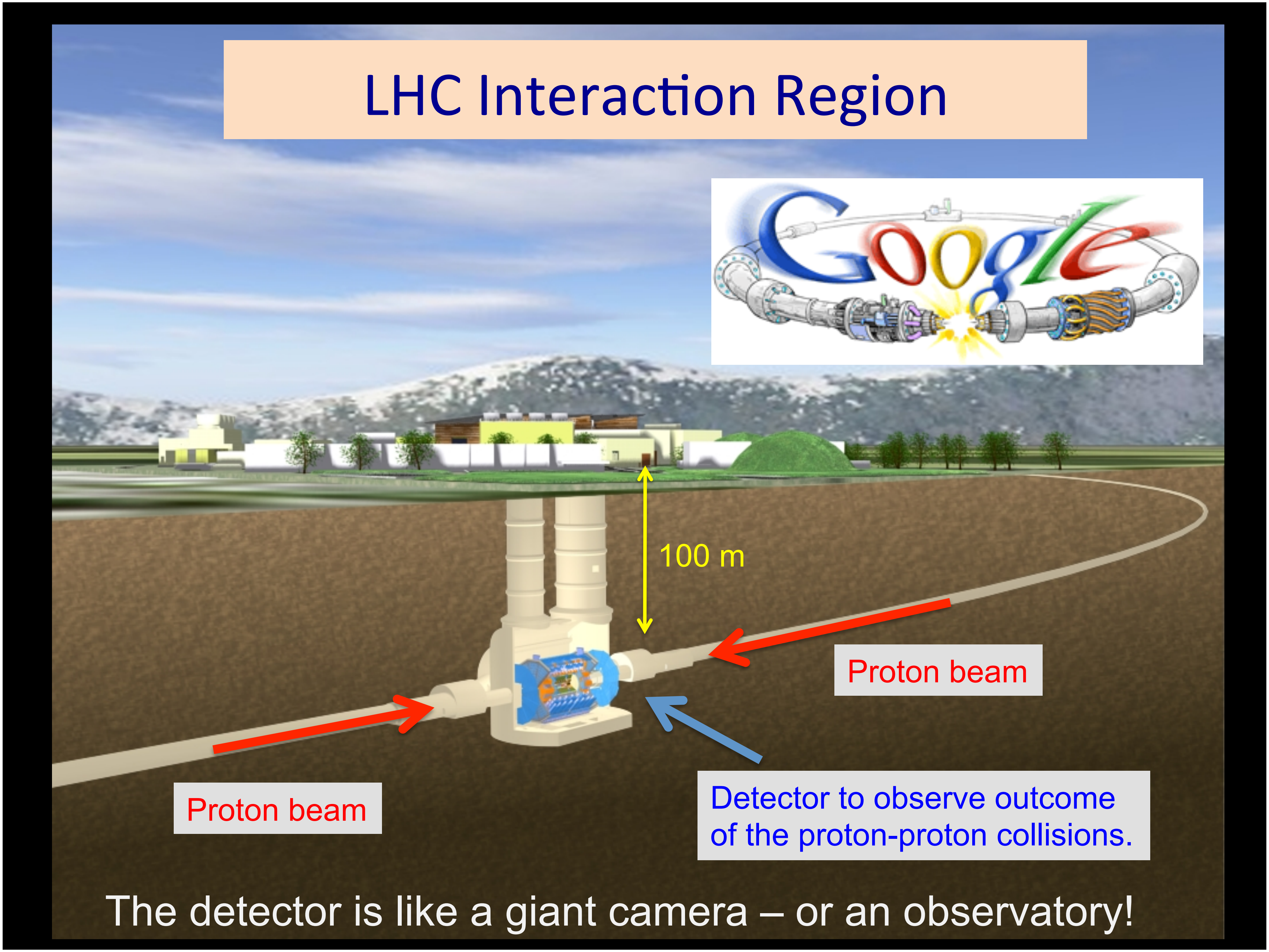
LHC ring:

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

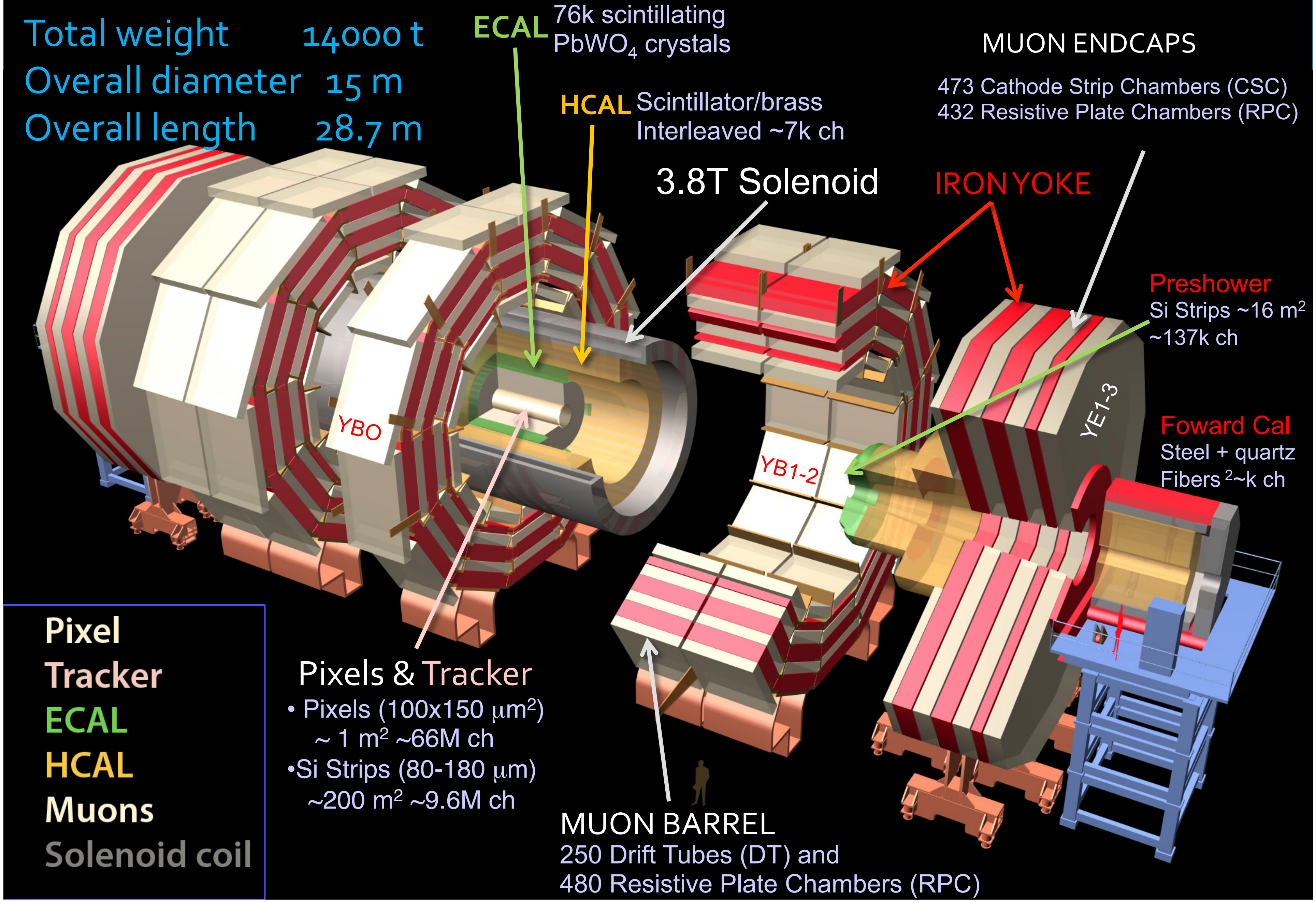



Beam: "bunch train" w/1374 bunches of protons
(will increase to 2808 bunches). 1 bunch=10^{11} protons.
The beam bunches travel at nearly the speed of light (c−7 mph at 7 TeV)
• arrive at the collision points every 50 ns (25 ns in future)
• Beams make 11,245 turns/second
• Stored for 10 hrs (round trip 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

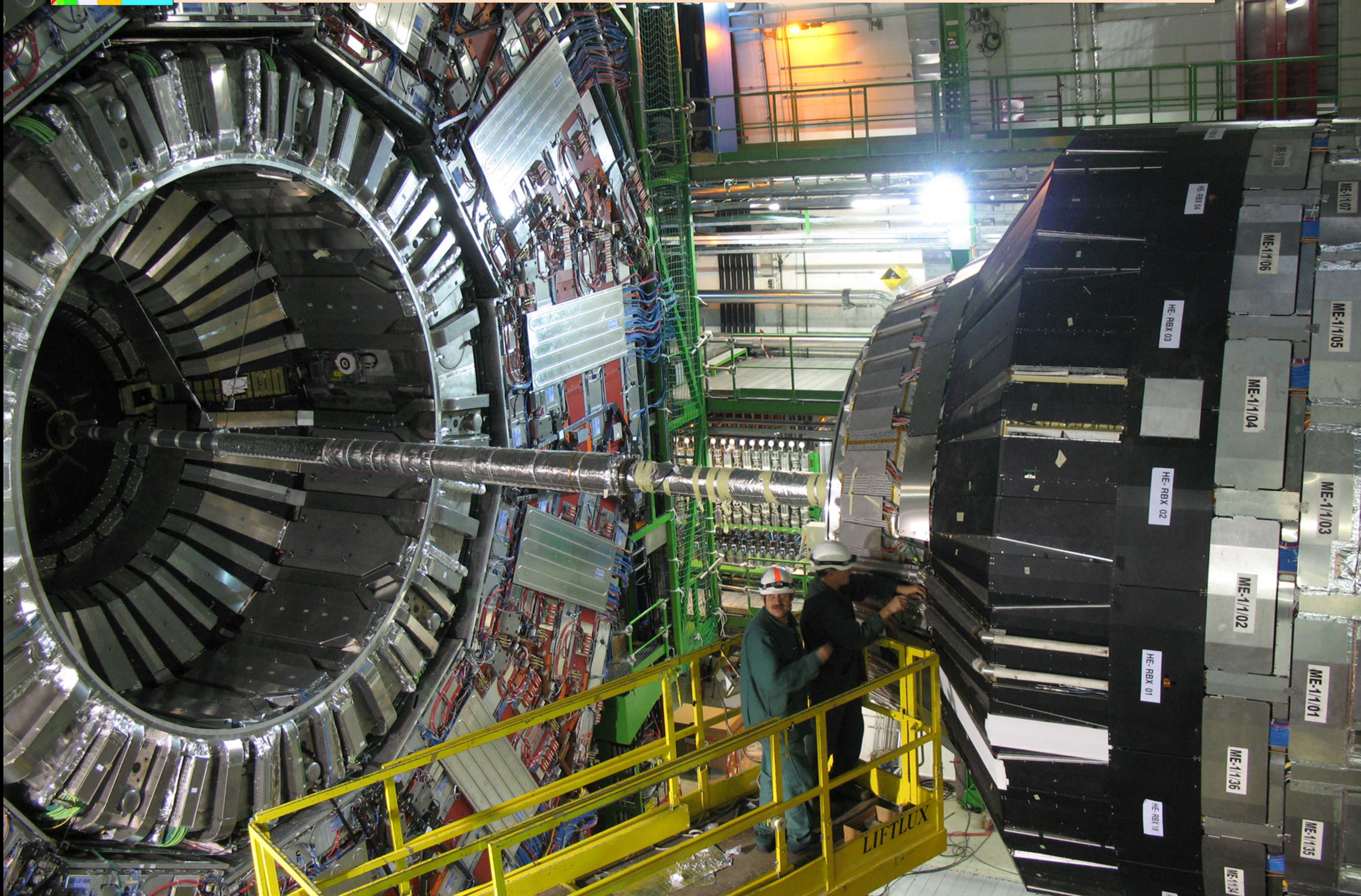
This place should look familiar!


LHC Interaction Region
Google
100 m
Proton beam
Proton beam
Detector to observe outcome of the proton-proton collisions.
The detector is like a giant camera – or an observatory!

CMS Experiment



CMS Detector with Accelerator Beam Pipe

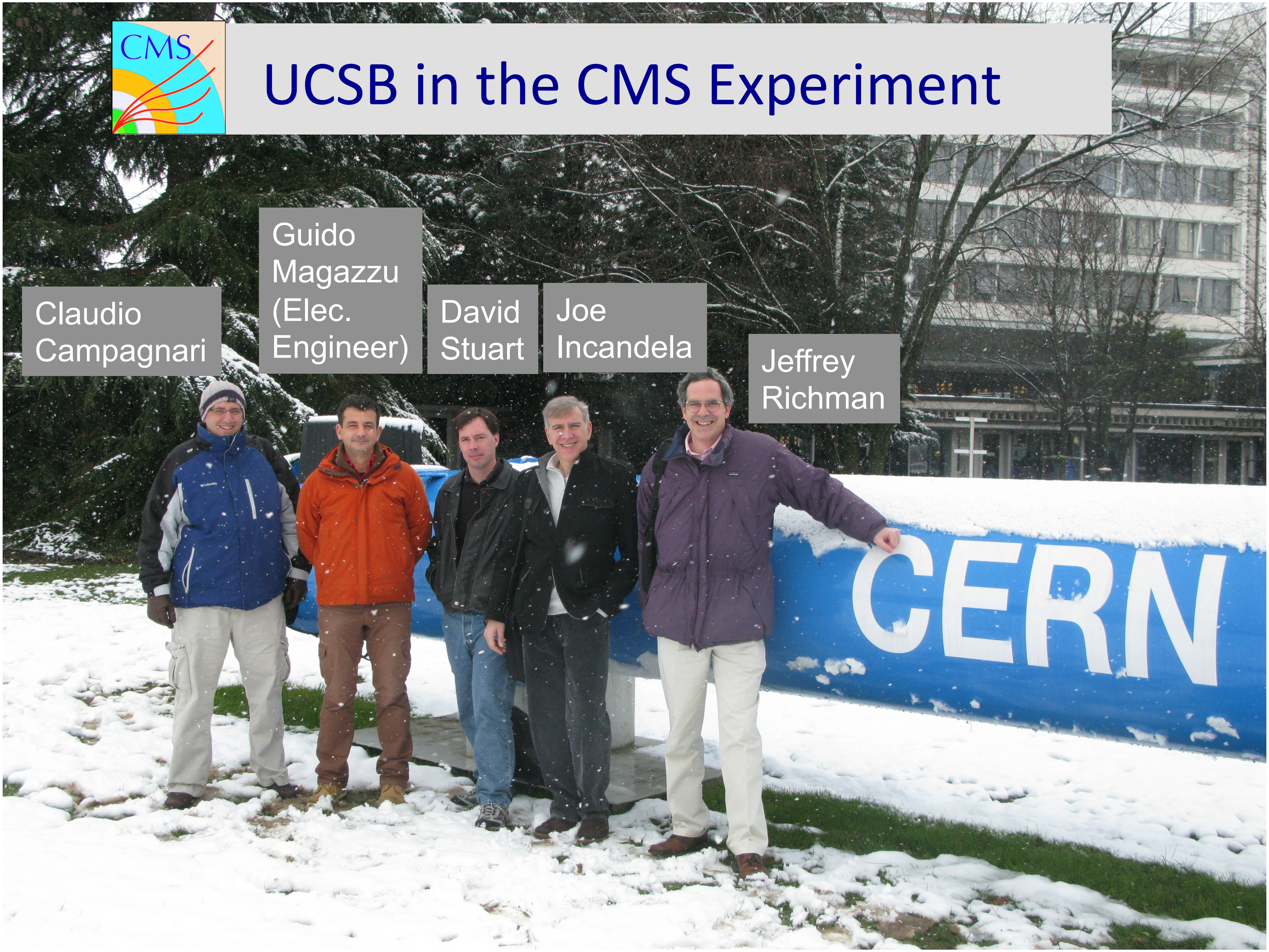


UCSB in HEP: research + education

- Faculty (7; 4 on CMS), engineers (4), technicians.

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

UCSB in the CMS Experiment



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

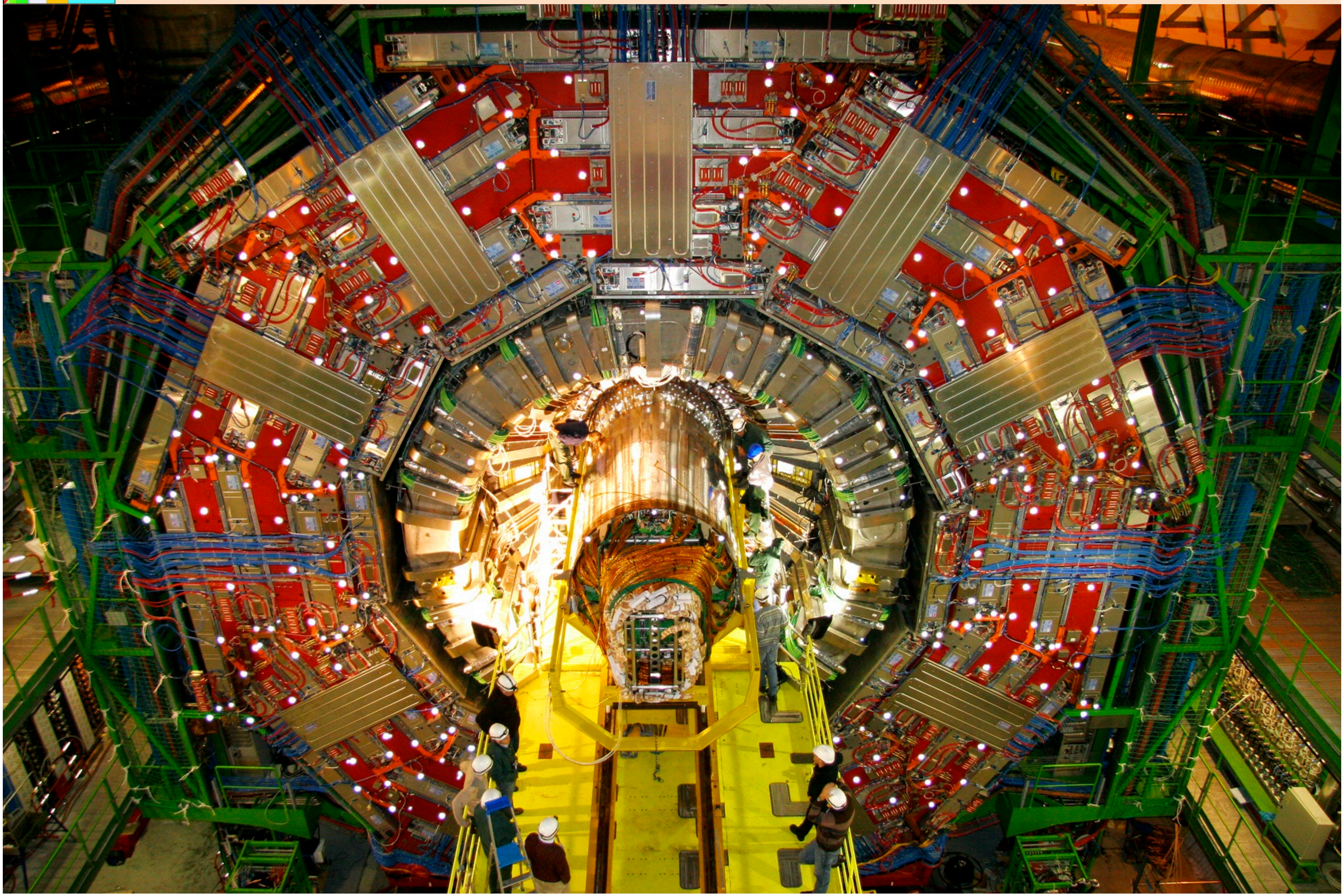
Leadership Roles in CMS: Faculty

Faculty member	Roles
Claudio Campagnari	Member of Physics Project Office (2011) Co-convenor of Top Physics Analysis Group (2008, 2009), Publications Board (2011), co-chair, Physics Dataset Working Group (2012)
Joe Incandela	Spokesperson (2012, 2013) Deputy Spokesperson (2010, 2011) -- previously Deputy Physics Coordinator) US CMS Tracker Project Leader
Jeffrey Richman	Collaboration Board Advisory Group (2013), Publications Steering Board (2012), Co-chair Exotica Pub Comm (2012), Co-convenor of Supersymmetry (SUSY) Physics Analysis Group (2009, 2010)
David Stuart	Co-convenor of Supersymmetry Physics Analysis Group (2011, 2012); previously co-convenor of leptonic SUSY subgroup.

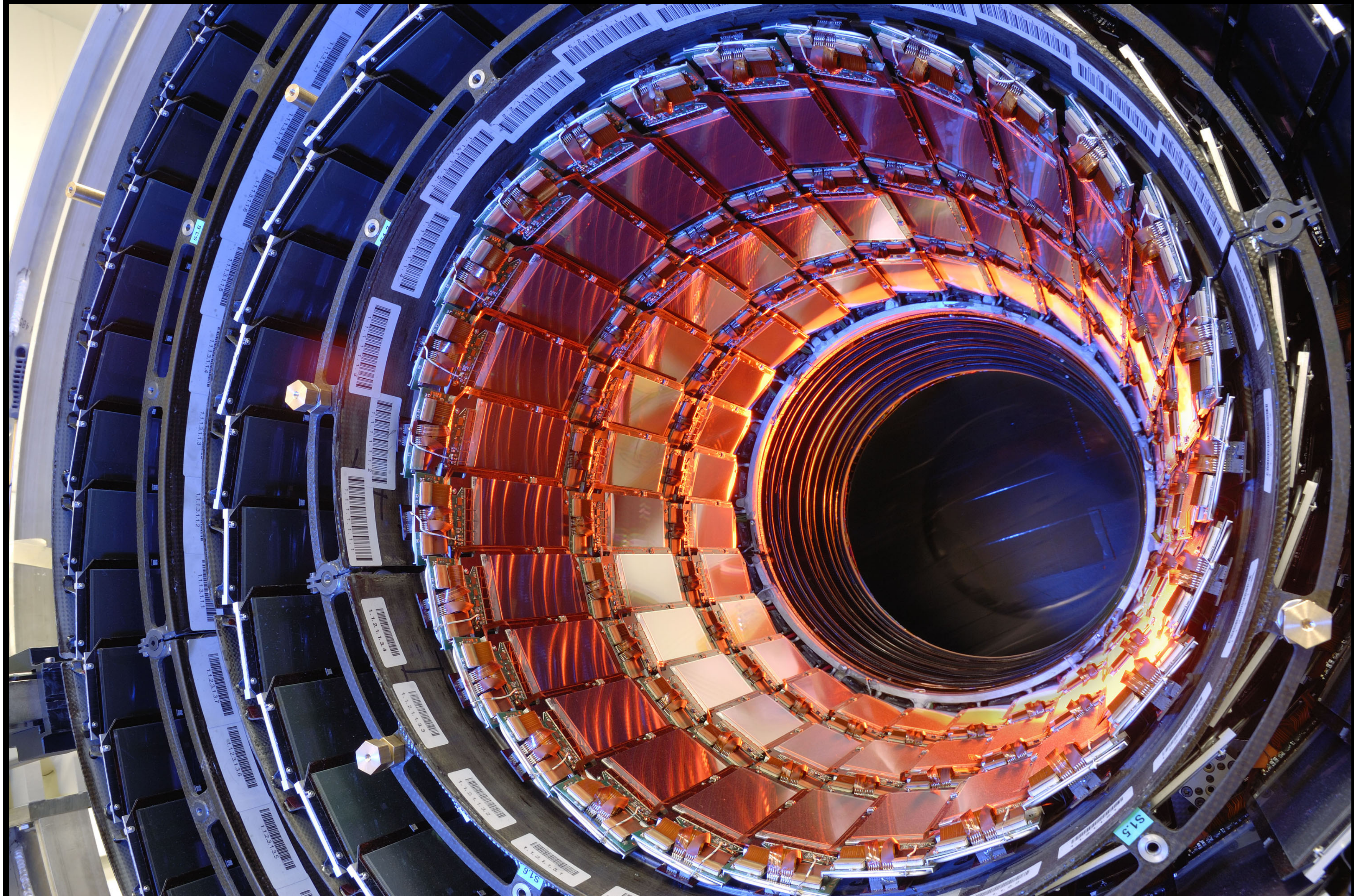
Leadership Roles in CMS: Faculty

Faculty member	Roles
Claudio Campagnari	Member of Physics Project Office (2011) Co-convenor of Top Physics Analysis Group (2008, 2009), Publications Board (2011), co-chair, Physics Dataset Working Group (2012)
Joe Incandela	Spokesperson (2012, 2013) Deputy Spokesperson (2010, 2011) -- previously Deputy Physics Coordinator) US CMS Tracker Project Leader
Jeffrey Richman	Collaboration Board Advisory Group (2013), Publications Steering Board (2012), Co-chair Exotica Pub Comm (2012), Co-convenor of Supersymmetry (SUSY) Physics Analysis Group (2009, 2010)
David Stuart	Co-convenor of Supersymmetry Physics Analysis Group (2011, 2012); previously co-convenor of leptonic SUSY subgroup.

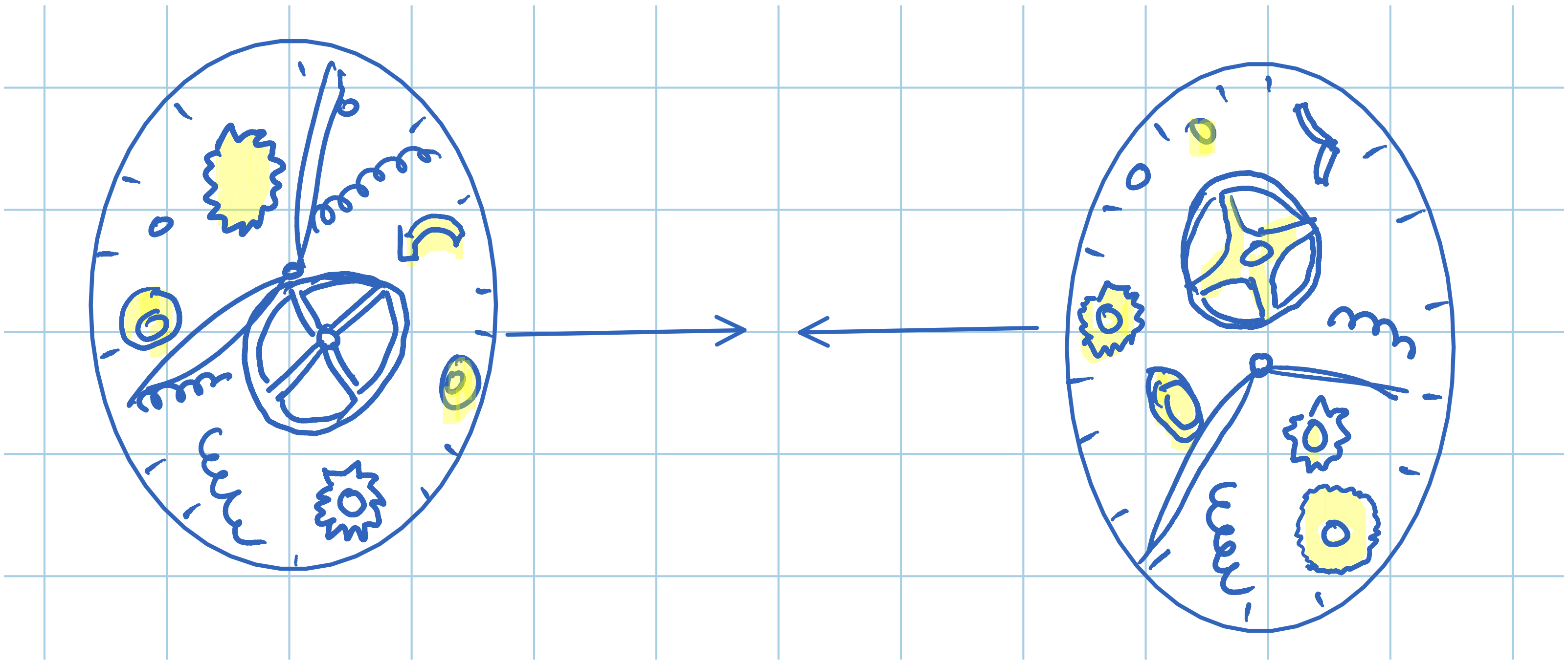
CMS Silicon Tracker Installation: Dec 2007



CMS Silicon-Strip Particle Tracking Detector



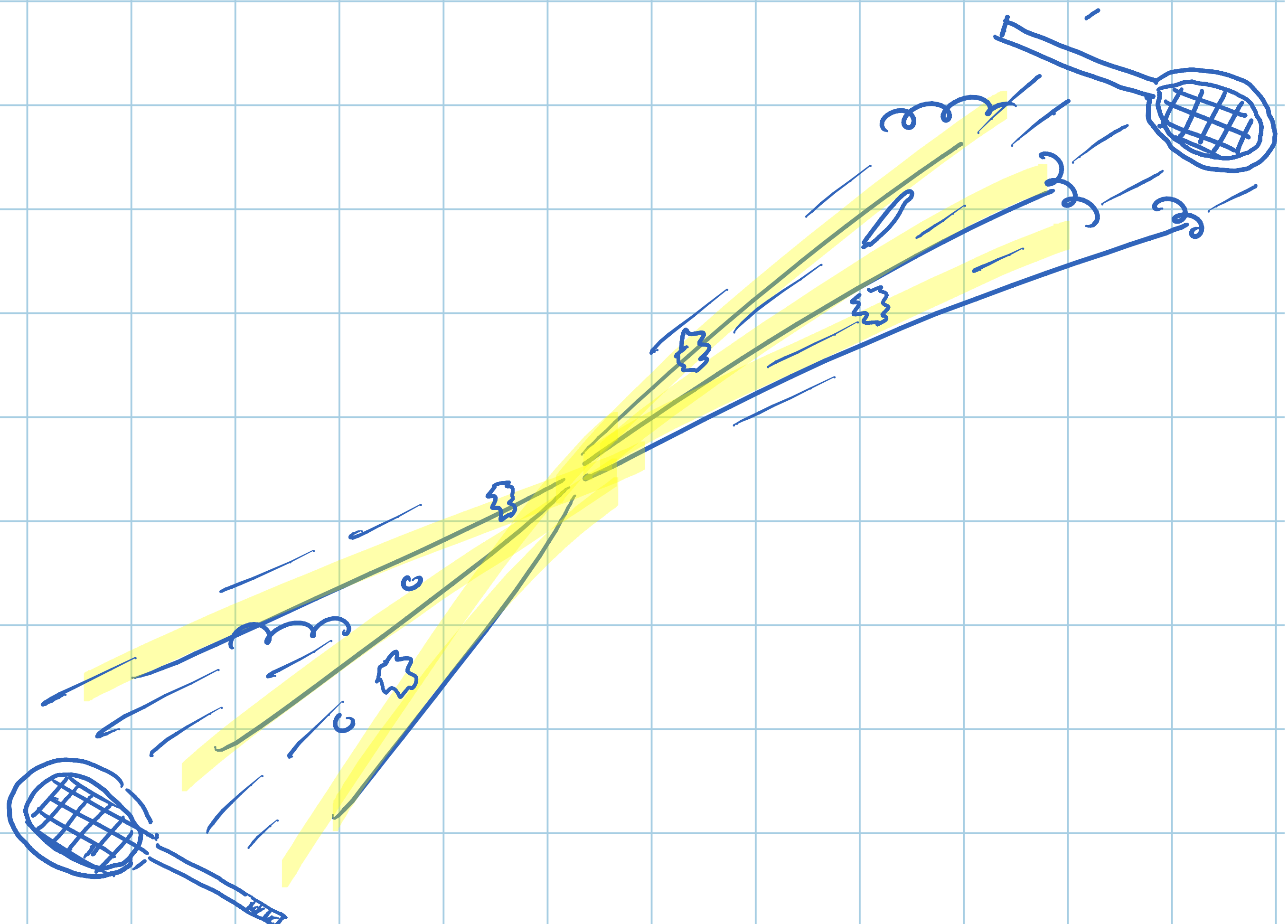
Smashing Swiss watches together



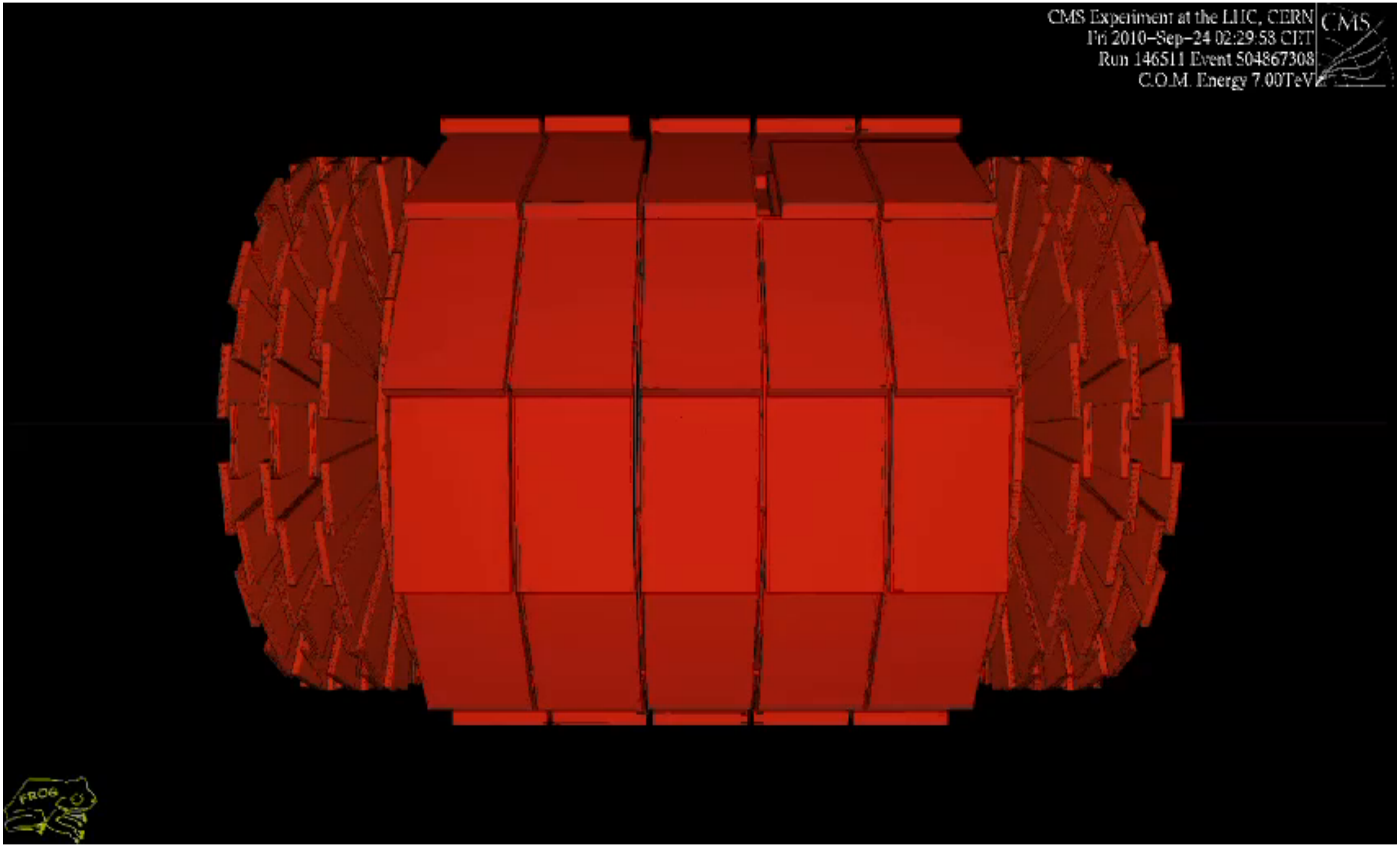
...after all, this is Geneva

Smashing Swiss watches together

...out come two tennis rackets



Can Matter be Created?



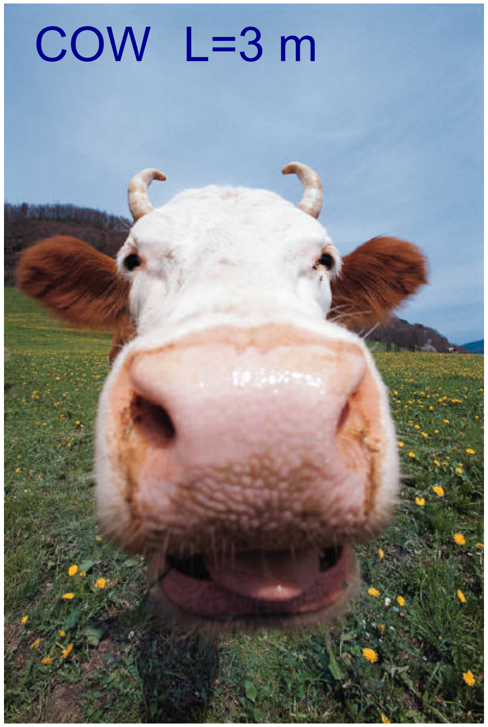
Feynman's Van: Quantum Field Theory

Quantum field theory in 1 slide

Fundamental forces/fields	Examples	Field excitation
Electromagnetic	Light, electrical power, chemistry, civilization as we know it.	Photon
Weak	Many natural radioactive processes, operation of sun, supernova explosions, formation of elements.	W^+, W^-, Z
Strong	Holds nuclear particles together.	g (8 gluons)
Gravitational	Astrophysical systems, large scale dynamics of universe.	G (graviton) [?]

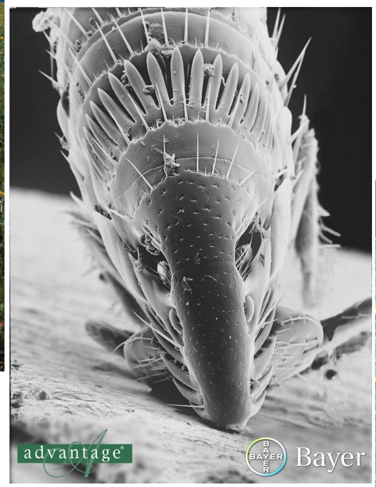
Shrinking down: cow → atom

COW L=3 m



$\times 10^{-3}$

FLEA L = 0.0025 m = 2.5 mm

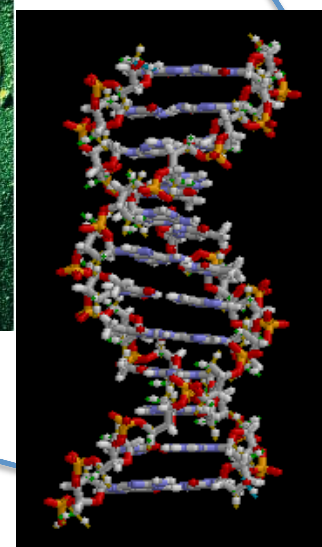


$\times 10^{-3}$

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

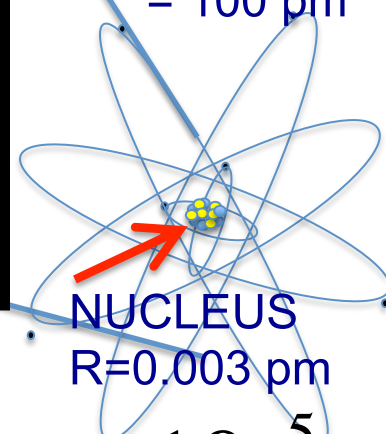
$\times 10^{-3}$

MOLECULE
W = 0.002 μm = 2 nm



$\times 10^{-1}$

ATOM
R = 0.1 nm
= 100 pm



NUCLEUS
R=0.003 pm

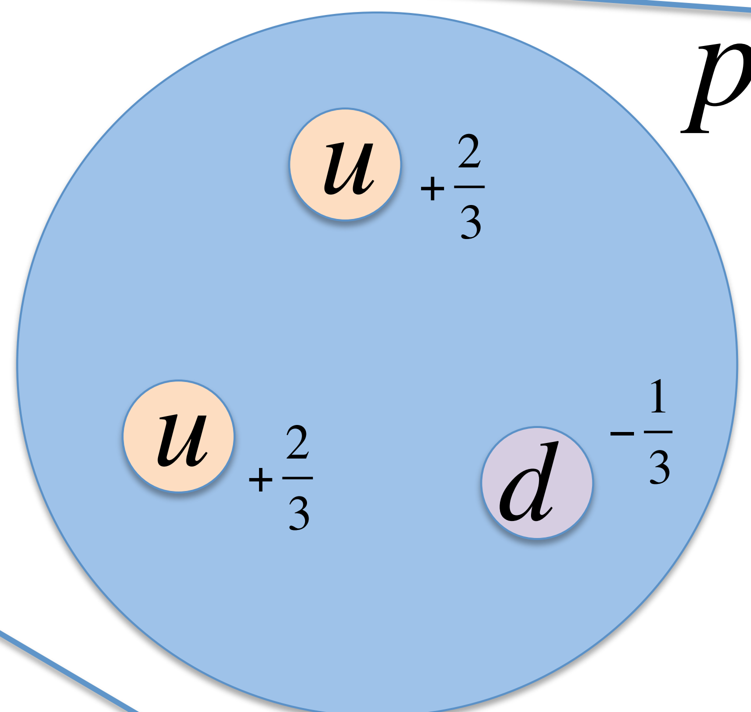
$\times 10^{-5}$

COW ATOMIC NUCLEUS

$1\ \text{m} \rightarrow 10^{-15}\ \text{m} = 0.000000000000001\ \text{m}$

A first look inside of the proton

Quarks!



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

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*	

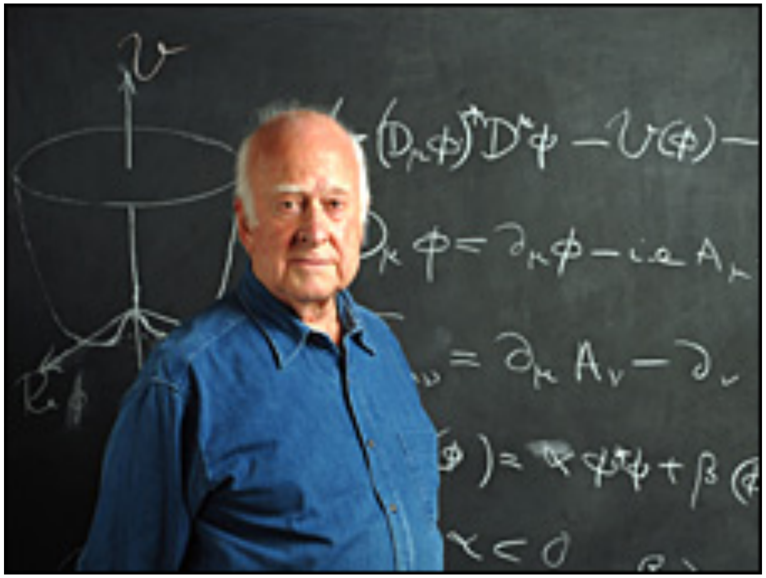
Higgs boson

and vacuum expectation value

H

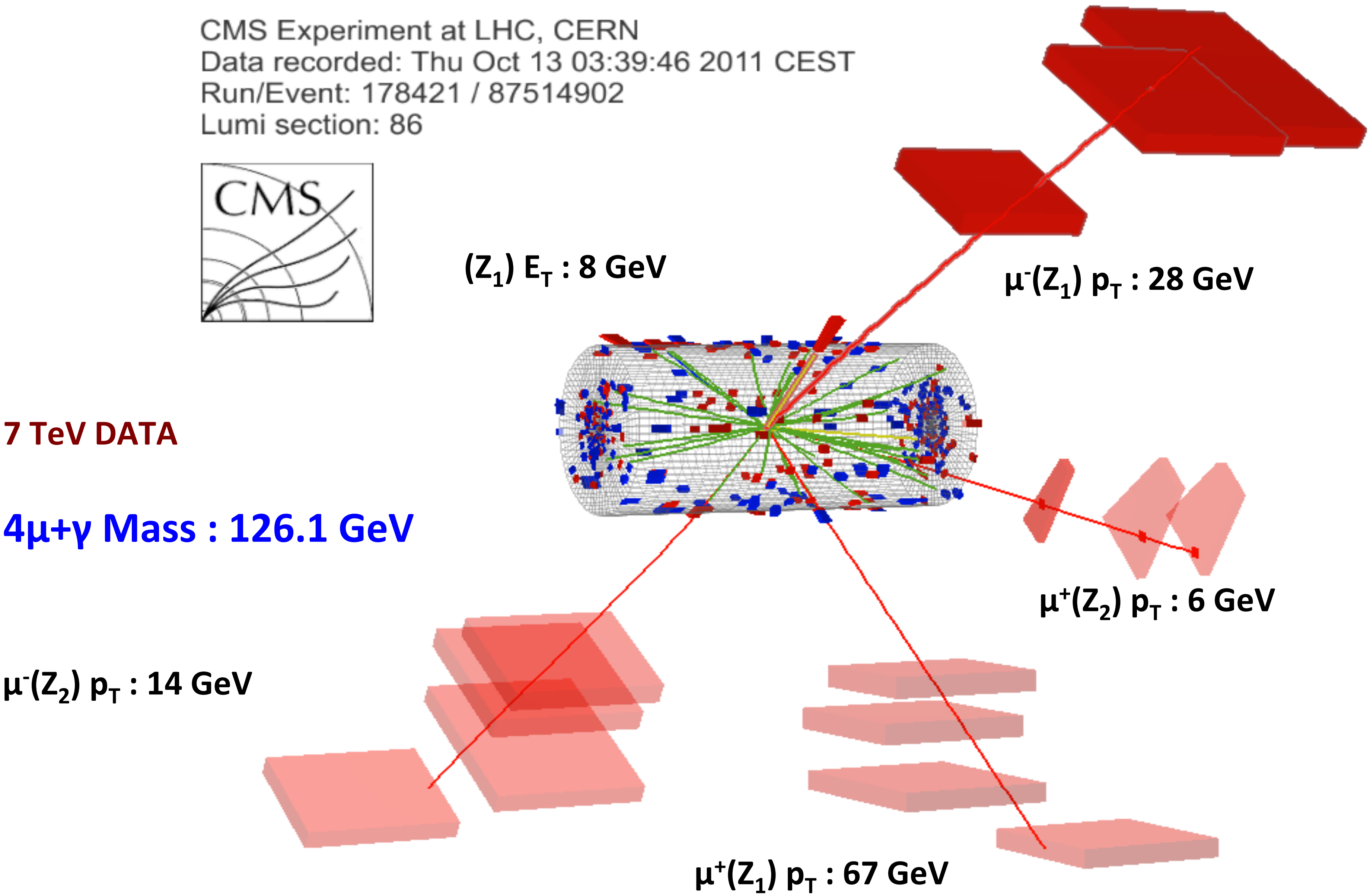
Higgs boson

The Higgs mechanism: a high stakes game

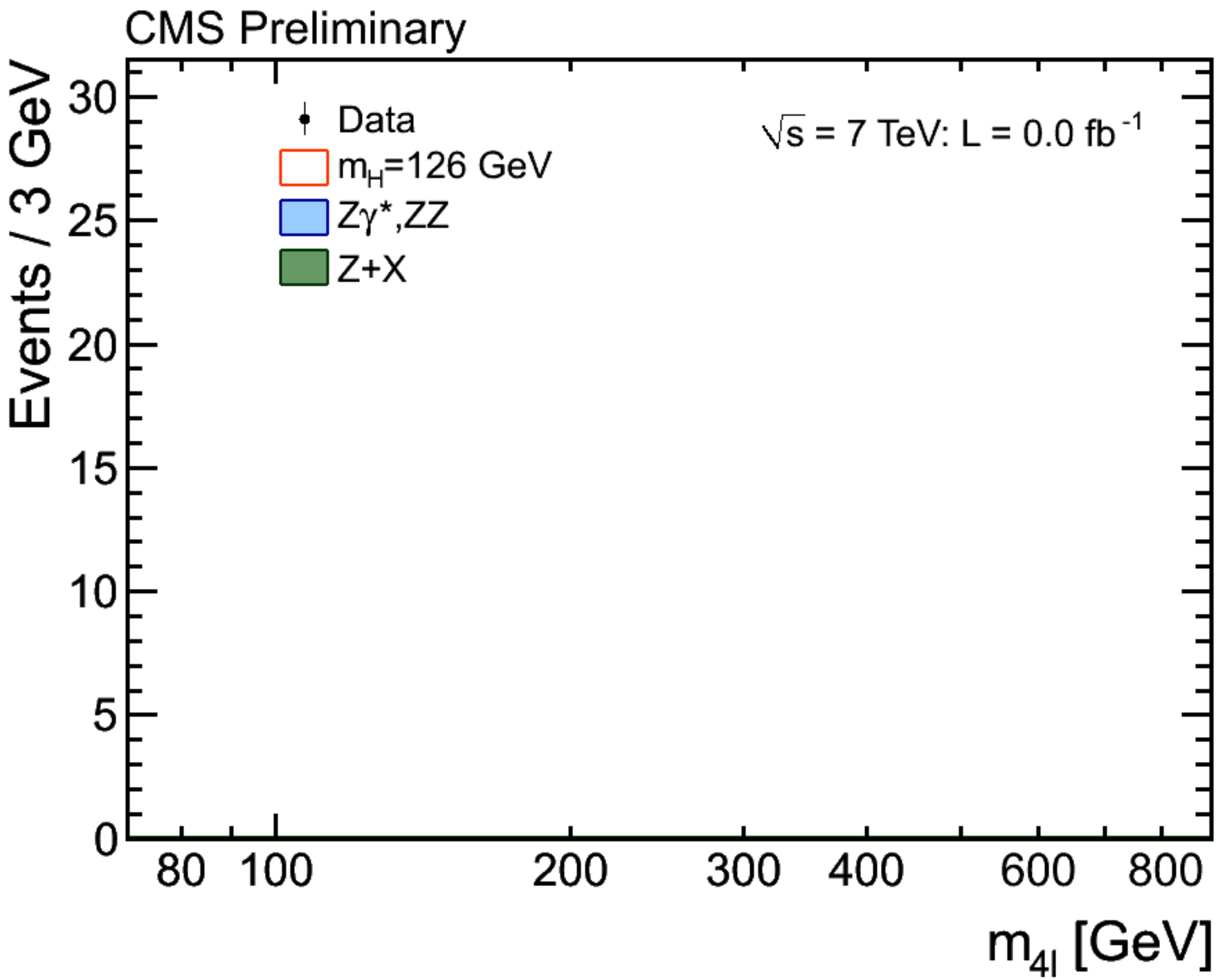


- The mathematical laws describing the *forces* between particles appeared to be incompatible with force carriers (W, Z) having *mass*.
- Higgs: Particles interact with a field that exists throughout all space; gives particles the appearance of having mass!

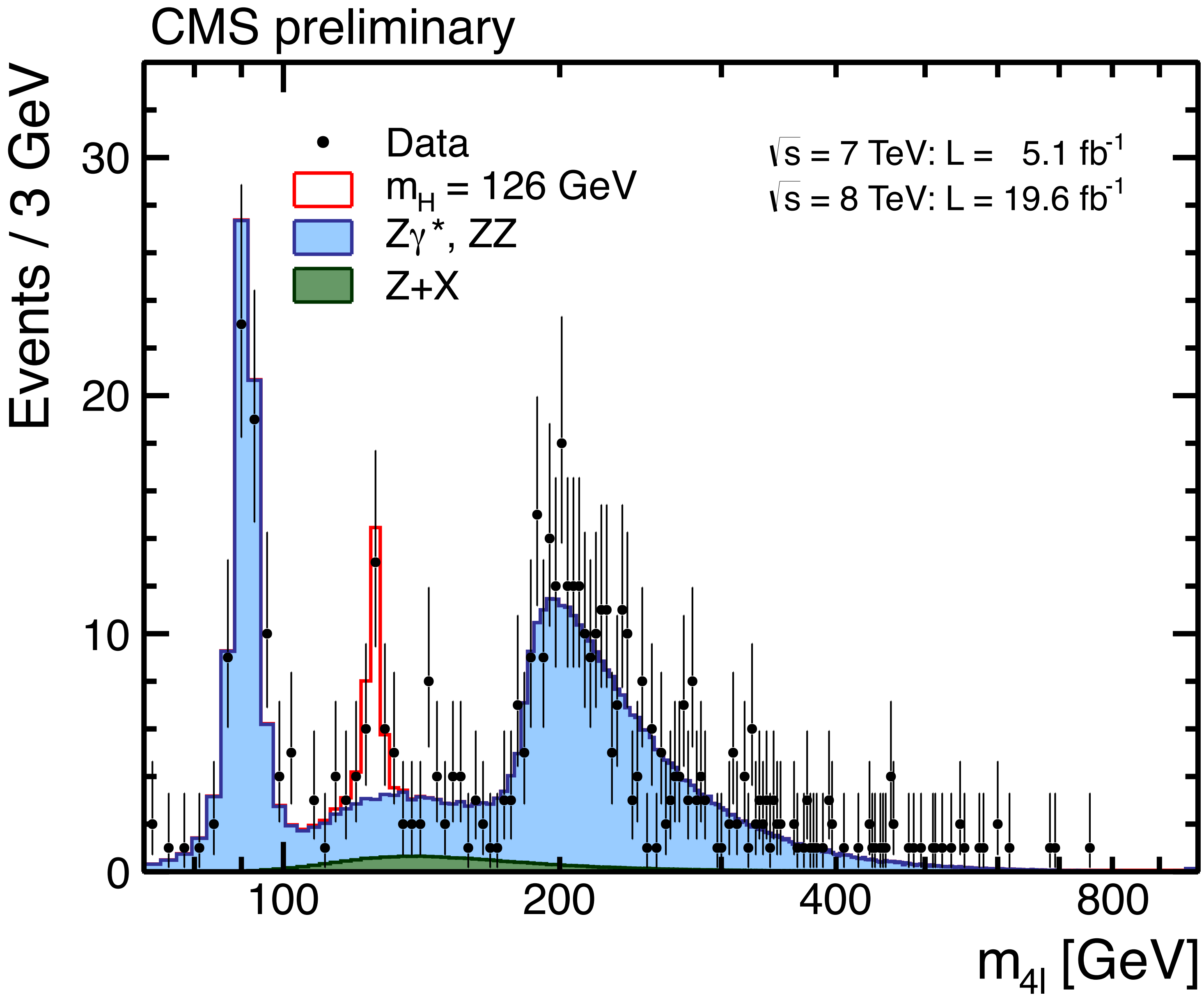
Higgs particle → two Z bosons → 4 muons

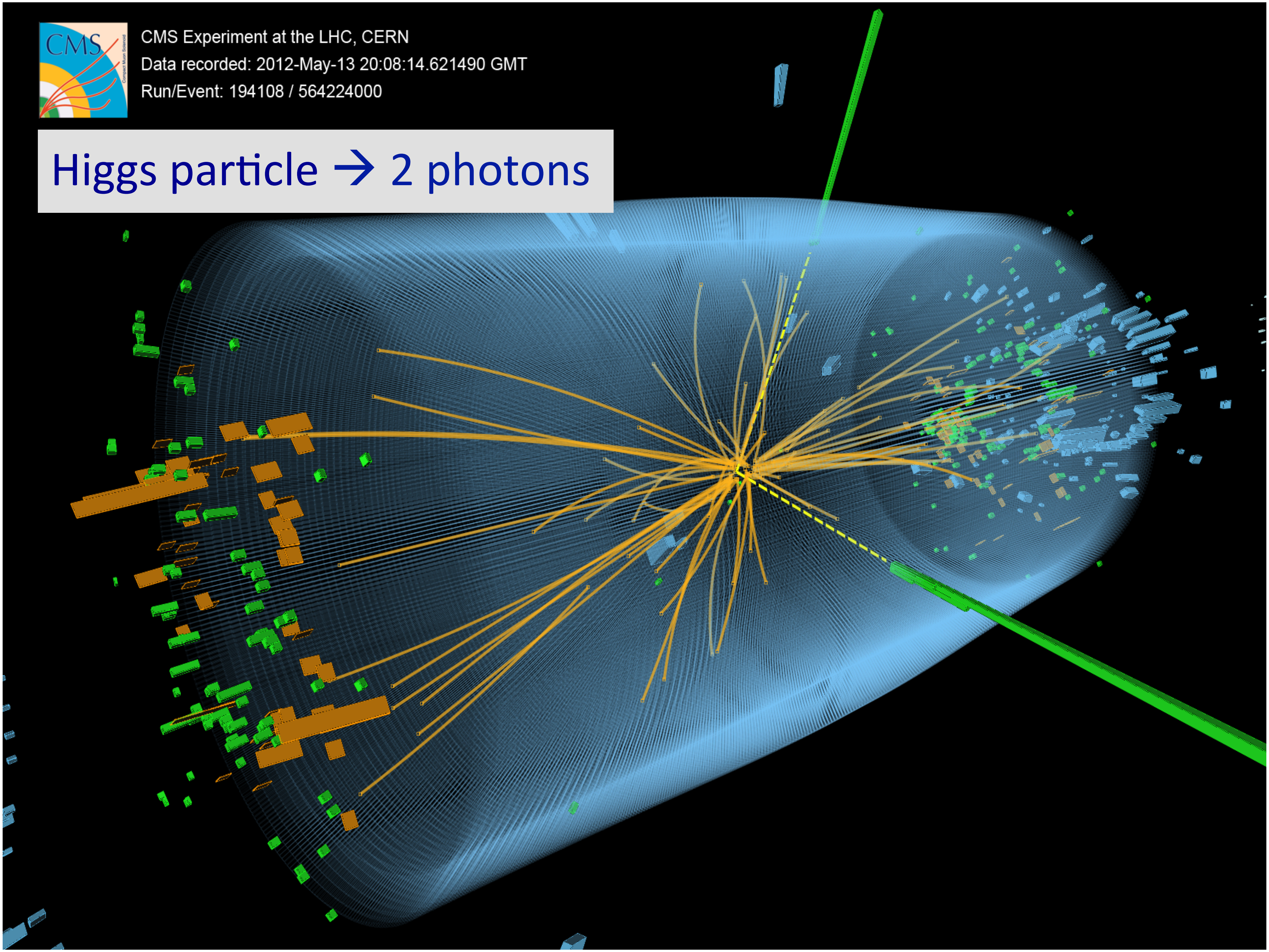


Higgs boson → two Z bosons → 4 leptons



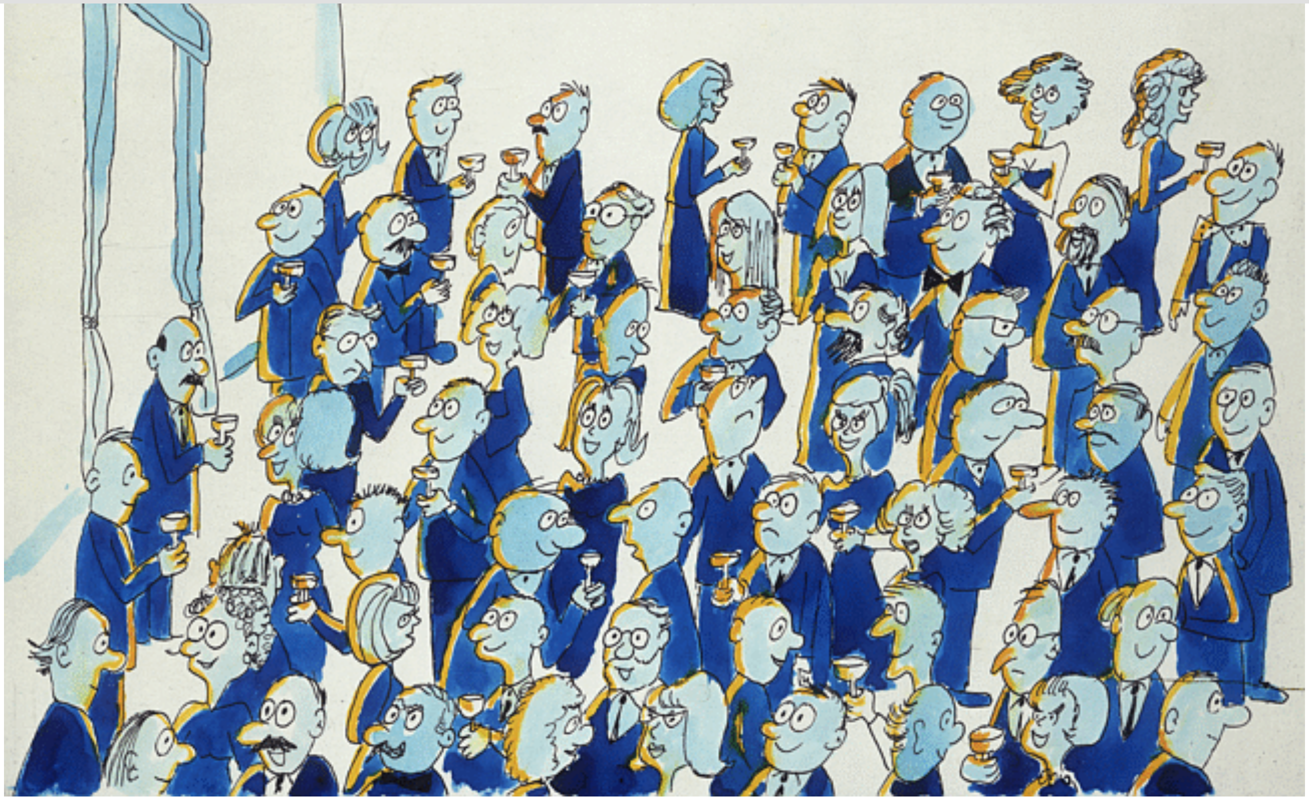
Higgs boson → two Z bosons → 4 leptons




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

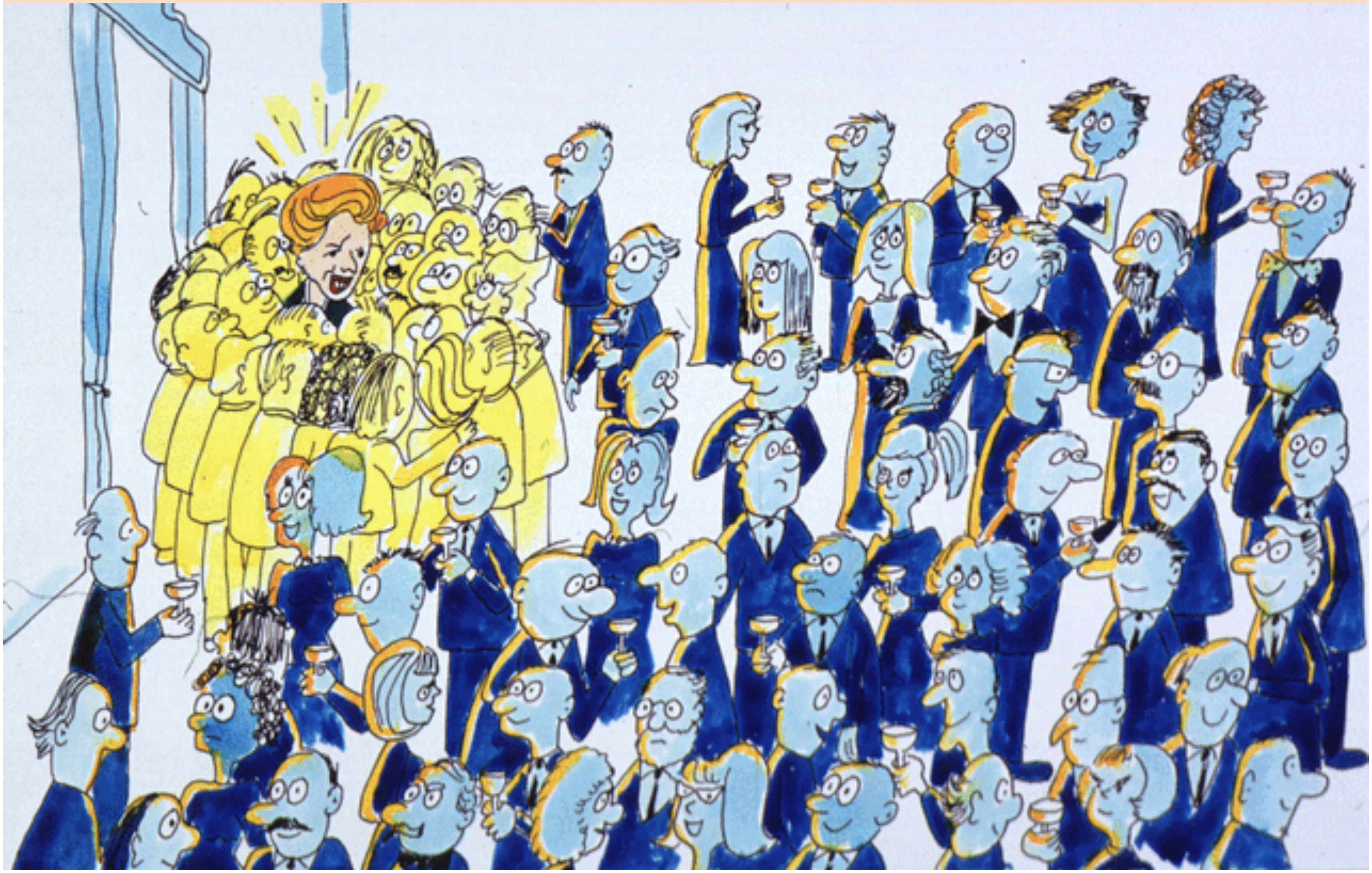
A quasi-political Explanation of the Higgs Boson; for Mr Waldegrave, UK Science Minister, 1993.

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



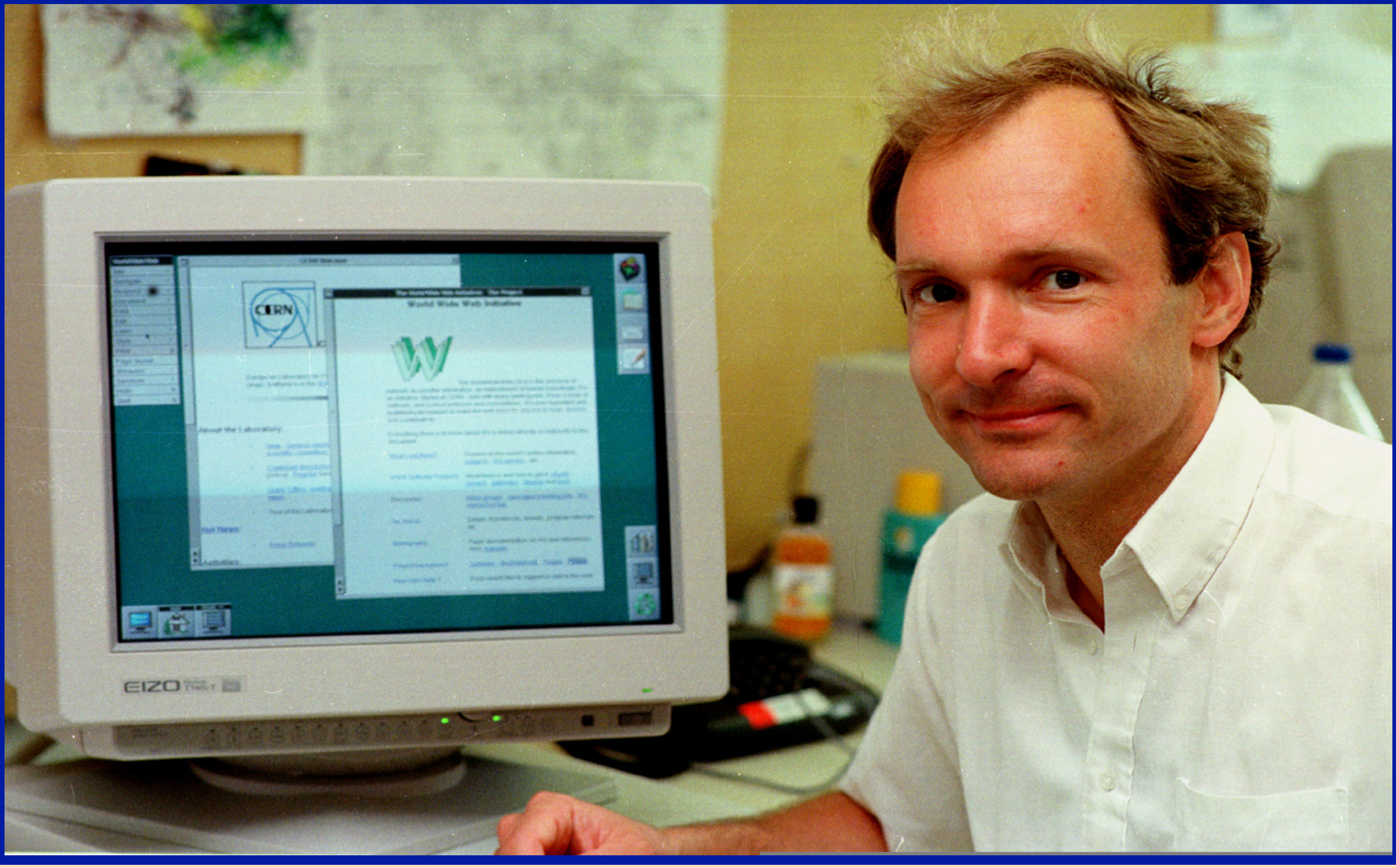
Information Management: A Proposal

Tim Berners-Lee, CERN
March 1989, May 1990

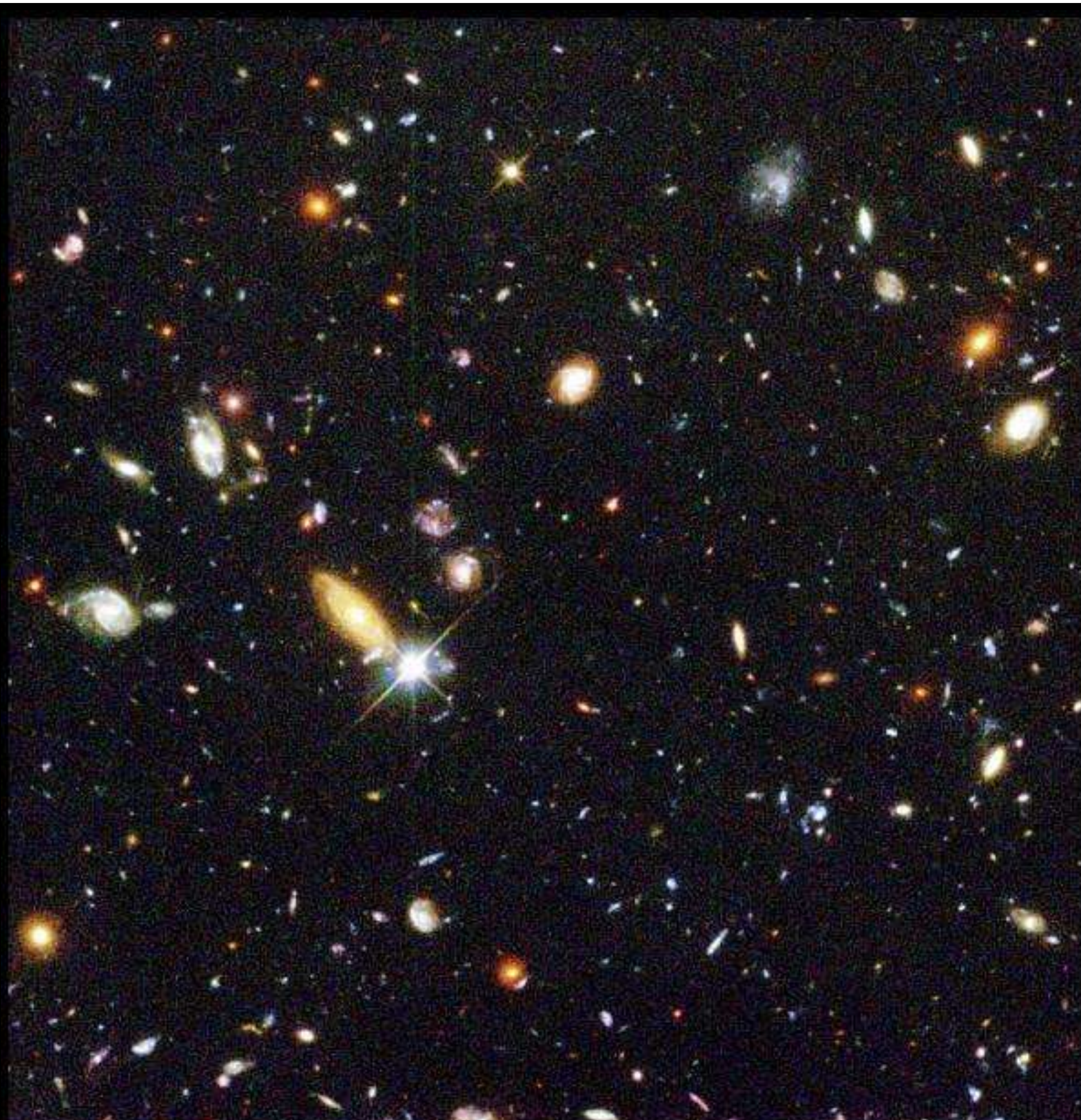
This proposal concerns the management of general information about accelerators and experiments at CERN. It discusses the problems of loss of information about complex evolving systems and derives a solution based on a distributed hypertext system.

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



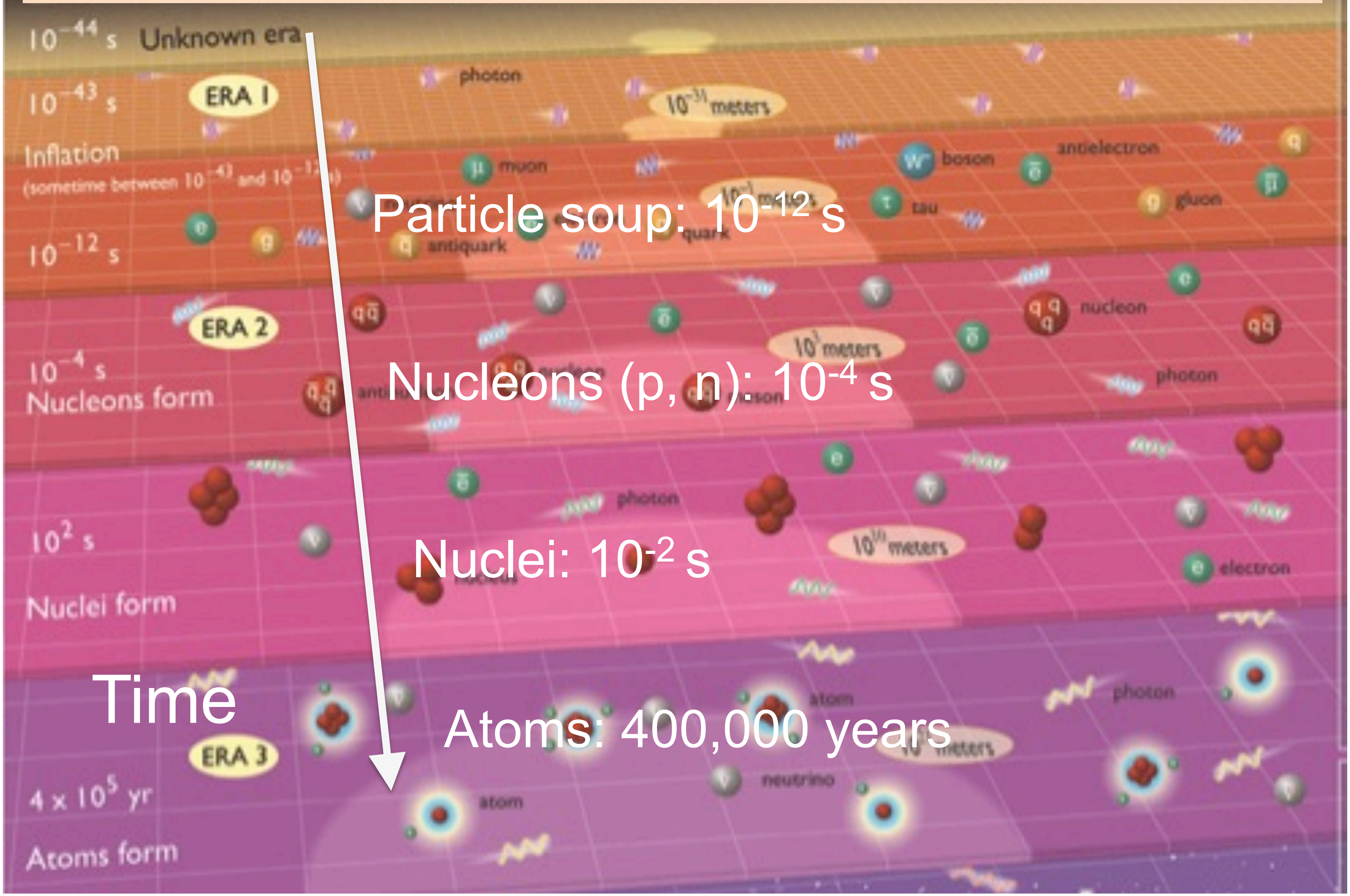
Berners-Lee proposed the WWW in March 1989 while working at CERN and developed the first web site.



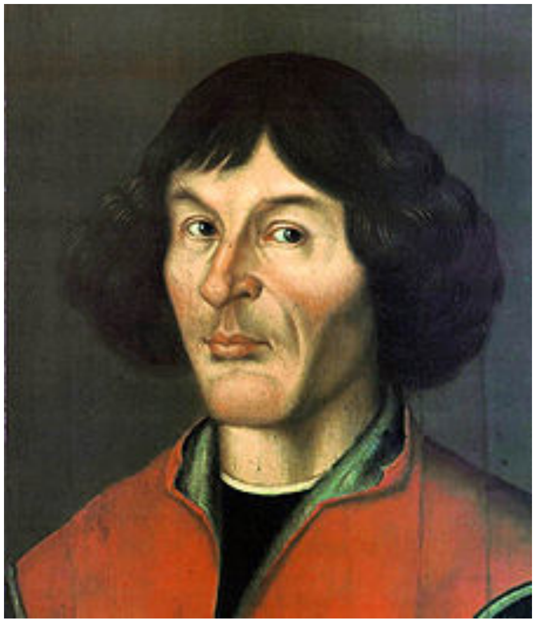
Hubble Deep Field HST • WFPC2

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

The Big Bang: the first particle experiment

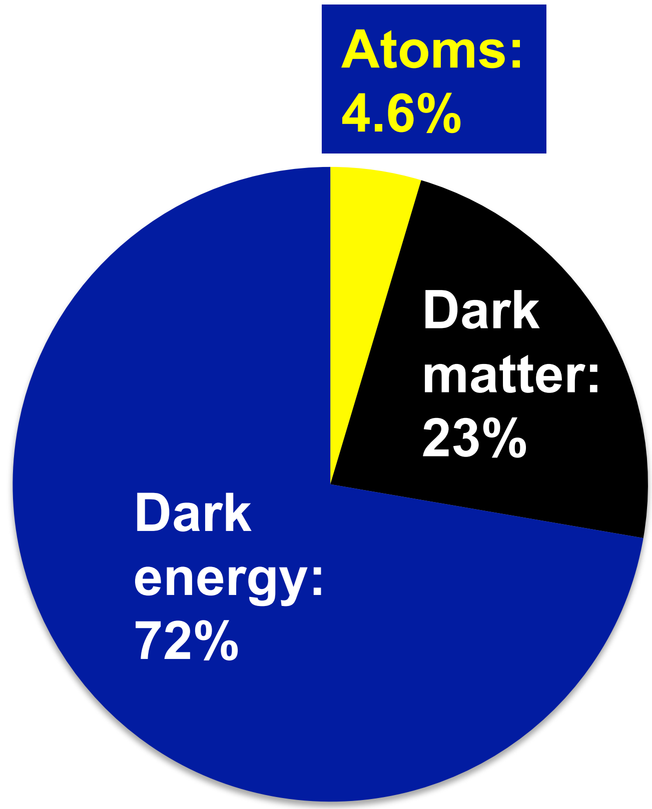


The dark matter revolution



Nicolaus Copernicus (1473-1543):
heliocentric model

Vera Rubin (1928-):
dark matter in galaxies



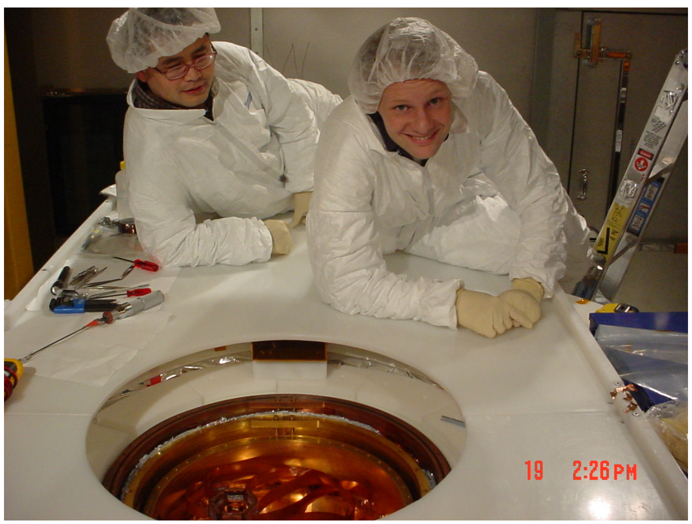
WMAP

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...

After 3 years of running...

- Over 200 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”).
- Train the next generation of scientists!
- The LHC project will continue for at least a decade.

Key goal: training scientists of the future



Current positions of recent postdoctoral fellows

Year left	Name	Current (or last known) position
2011	J. R. Vlimant	CERN Fellow, CMS experiment
2008	R. Mahapatra	Assistant Professor, Texas A&M University
2008	B. Brau	Assistant Professor, U. Mass., Amherst
2006	J. Berryhill	Wilson Fellow, Fermilab
2006	A. Affolder	Staff Physicist, U. Liverpool
2006	C. Hill	Associate Professor, Ohio State
2004	O. Long	Associate Professor (OJI recipient), UC Riverside
2004	W. Verkerke	Staff Scientist, NIKHEF, Amsterdam
2004	C. Issever	Lecturer, U. Oxford
2004	M. Spiropulu	Associate Professor, Caltech
2004	R. Taylor	Tessella (Scientific Software), Oxford
2002	P. Hart	Programmer/Analyst (GLAST), SLAC
2000	T. Hill	Staff Scientist, Los Alamos
1999	J. Gronberg	Staff Scientist, LLNL
1998	D. Roberts	Associate Professor, Univ. Maryland
1996	S. Menary	Associate Professor, York Univ., Toronto
1996	R. Kutschke	Research Physicist, FNAL
1995	H. Tajima	Research Physicist, SLAC
1992	A. Bean	Professor, Univ. Kansas

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

Examples of Improvements to Broida Hall

Physics Study Room

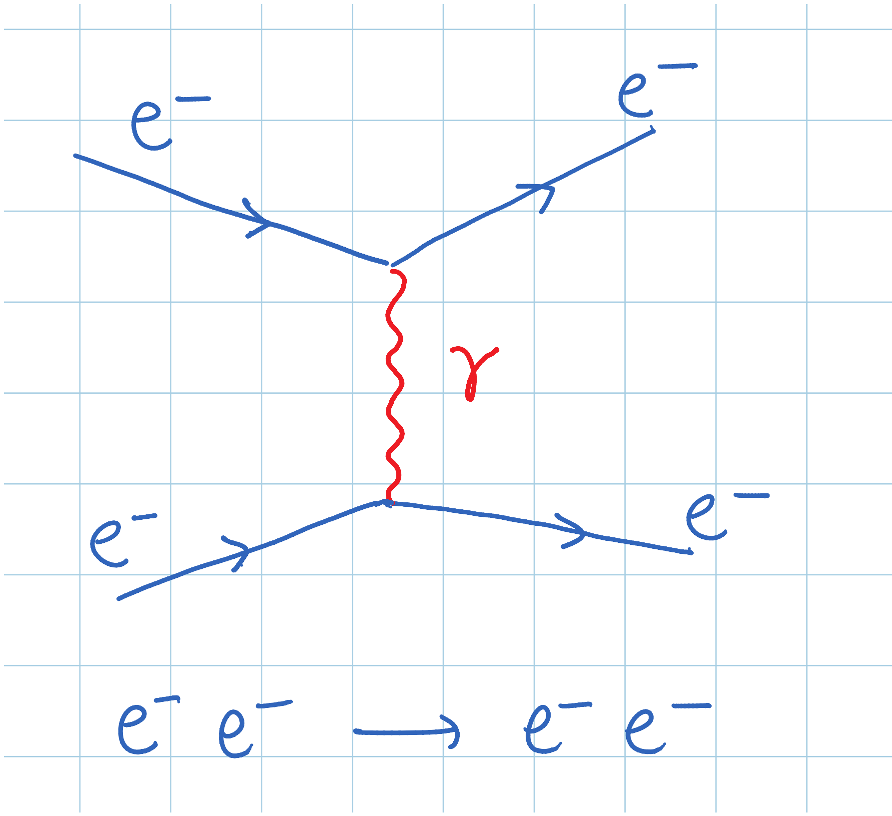
Broida Hall
5th floor displays

UCSB Physics Department Needs

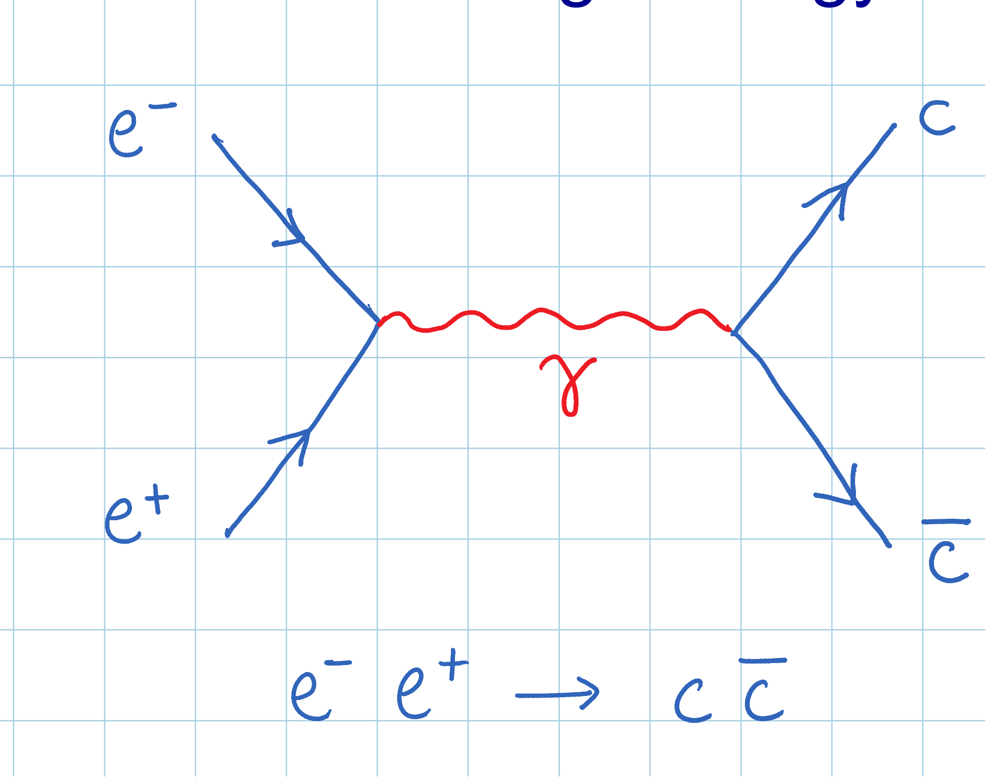
- HEP: support for Postdoctoral Fellows, graduate students, and travel to CERN.
- Graduate student fellowships
- Computing facilities for students
- Faculty support – endowed chairs
- Machine shop equipment
- Undergraduate labs, especially electronics
- Improvements to research laboratories
- Improve existing building & work towards new building.

Particle interactions can create matter

...if there is enough energy!

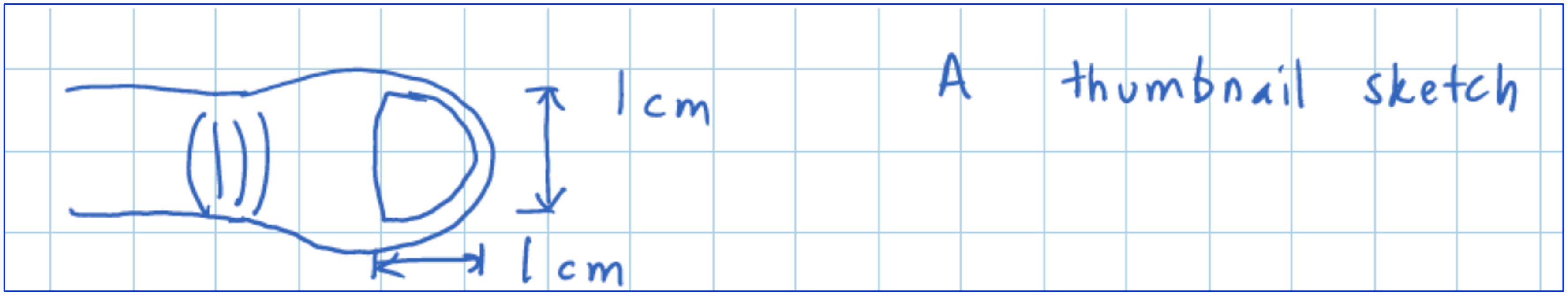


Repulsion of two electrons



Annihilation of an electron & positron into charm quark and an anti-charm quark.

Example: neutrinos and your thumb



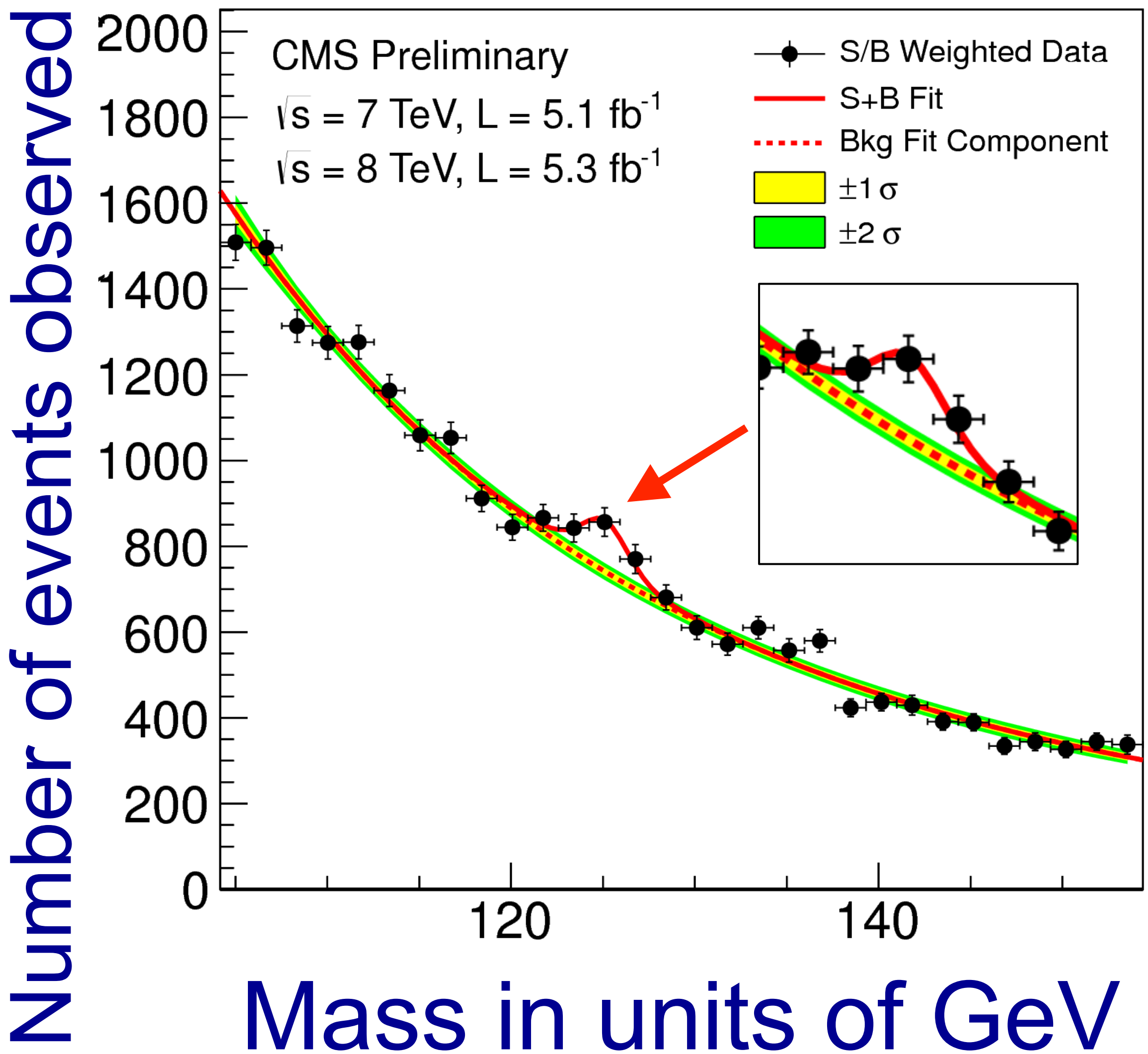
How many neutrinos pass through your thumbnail every second?

(a) 0.1 (b) 1 (c) 10^6 (d) 10^{11} (e) 10^{23}

(f) none of the above

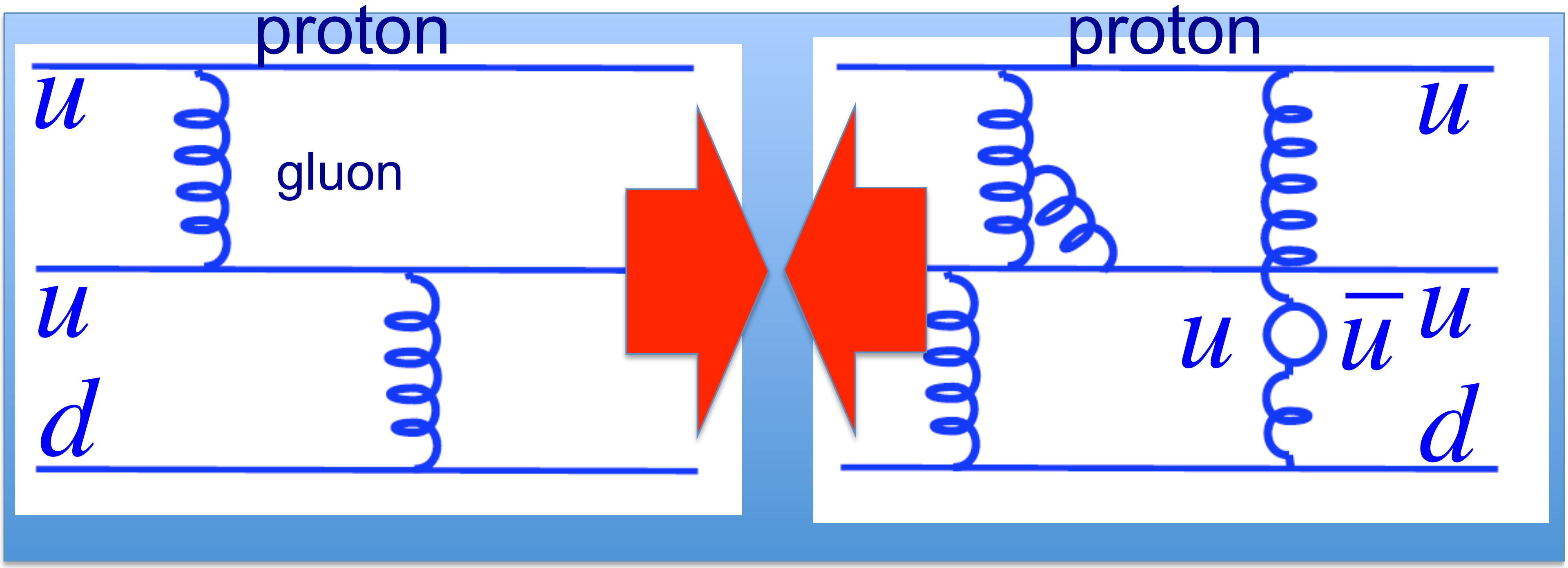
They are mostly from the sun!

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.

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.)

Physics Letters B 716 (2012) 30–61

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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.

ARTICLE INFO

Article history:
Received 31 July 2012
Received in revised form 9 August 2012
Accepted 11 August 2012
Available online 18 August 2012
Editor: W.-D. Schlatter

Keywords:
CMS
Physics
Higgs

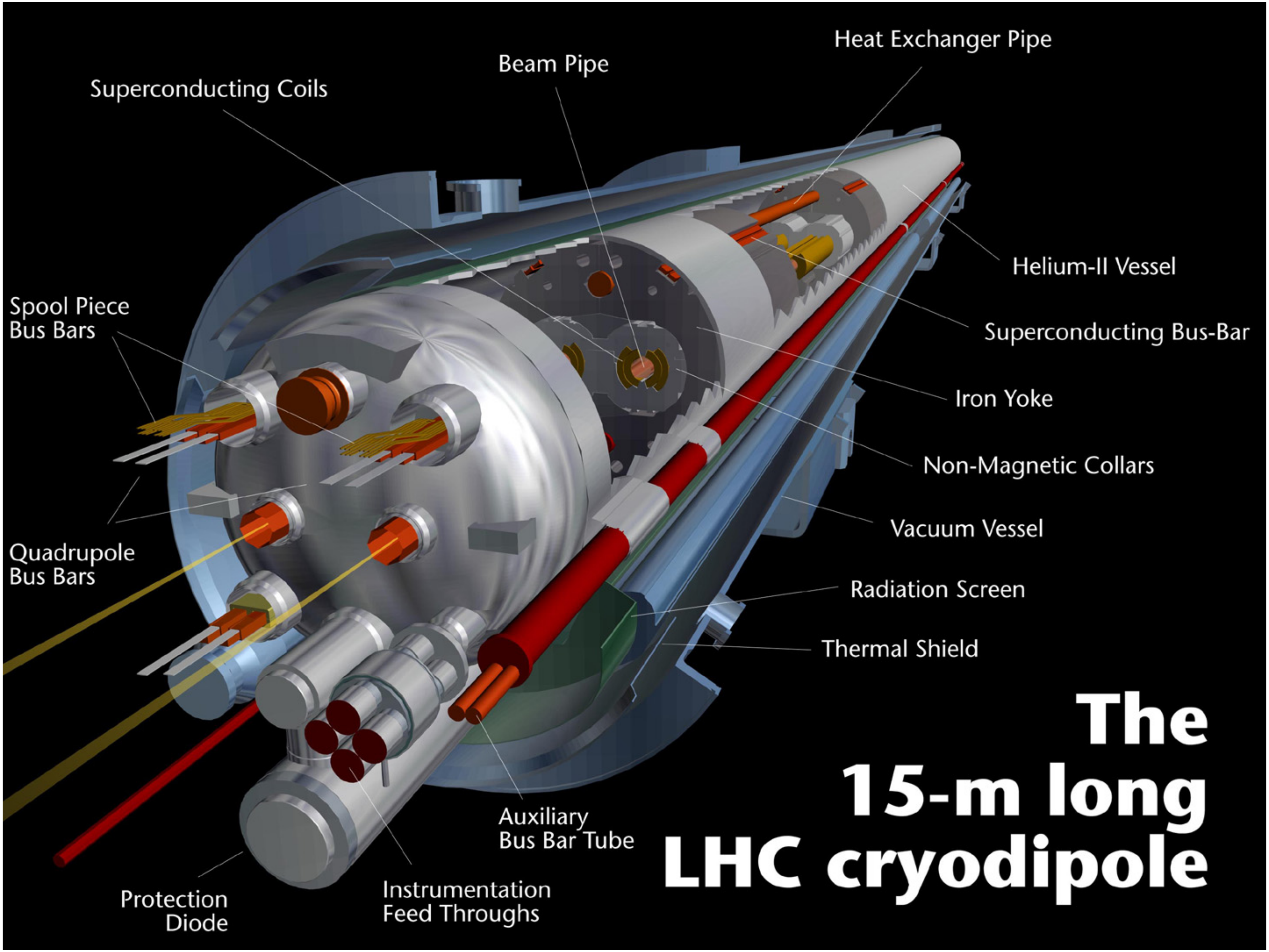
ABSTRACT

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, $\mathrm{W}^+\mathrm{W}^-$, $\tau^+\tau^-$, and $\mathrm{b\bar{b}}$. 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 $125.3 \pm 0.4(\mathrm{stat.}) \pm 0.5(\mathrm{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

Inside the LHC Tunnel

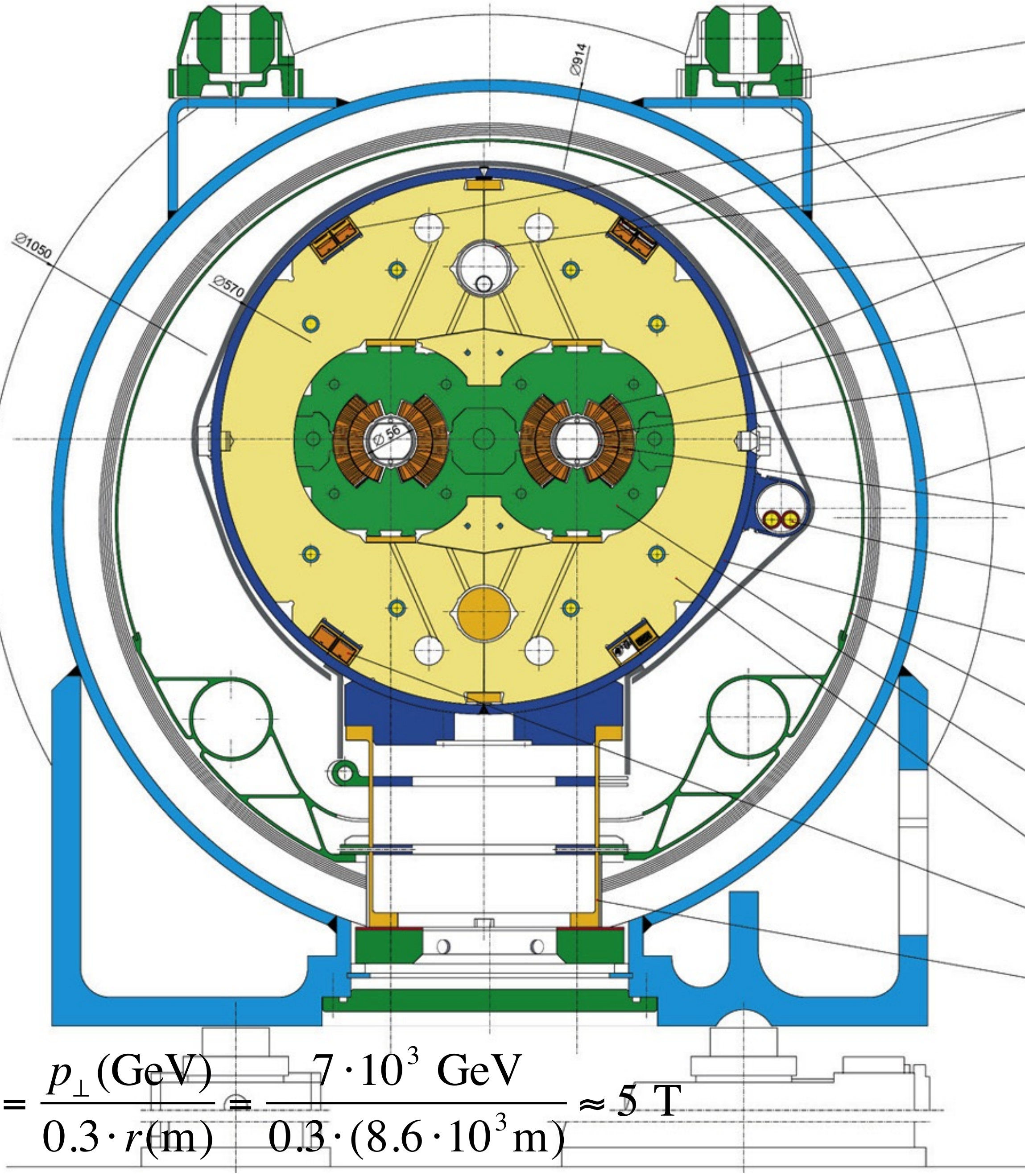
Inside the LHC Tunnel

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	$10^{34}\ cm^{-2}s^{-1}$


Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole
Bus Bars
Radiation Screen
Thermal Shield
The
15-m long
LHC cryodipole
Auxiliary
Bus Bar Tube
Protection
Diode
Instrumentation
Feed Throughs

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

LHC Radio-Frequency Cavities