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

UCSB Summer Research Mentorship Program
Groundbreaking Research/Innovative Technology Talk
July 1, 2013

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

CERN CMS

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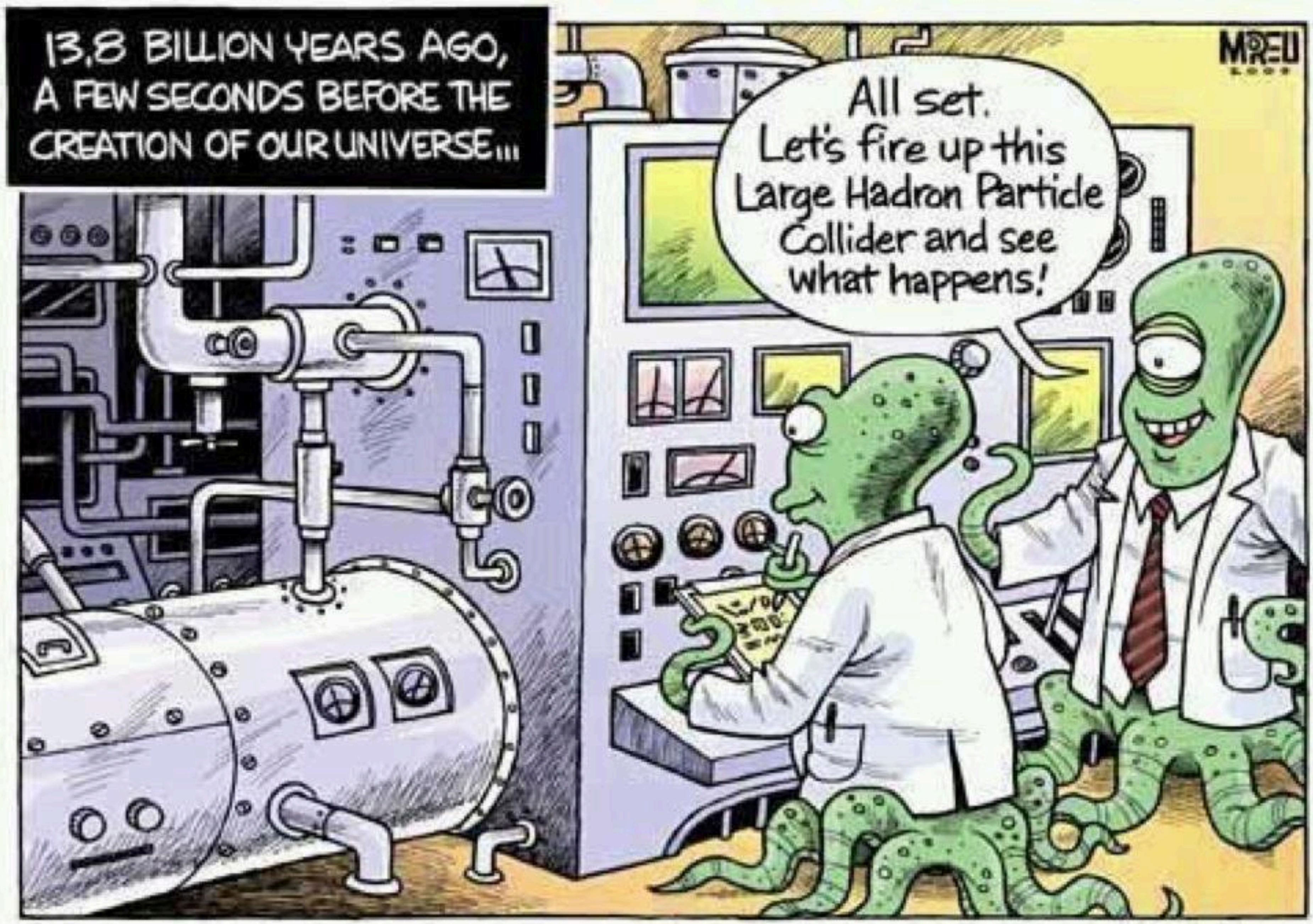
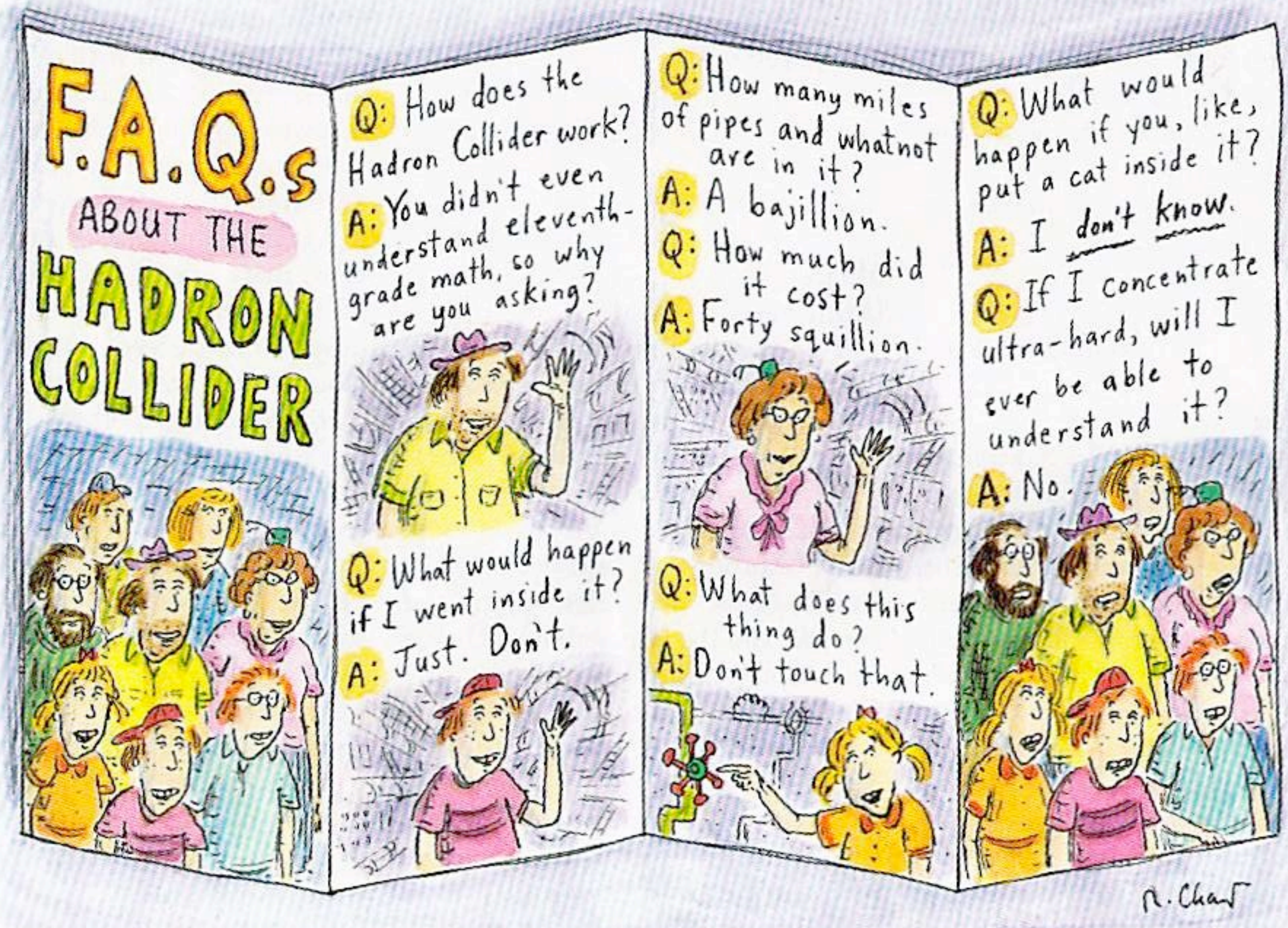

13.8 BILLION YEARS AGO, A FEW SECONDS BEFORE THE CREATION OF OUR UNIVERSE...
All set. Let's fire up this Large Hadron Particle Collider and see what happens!
MOREU


F.A.Q.s
ABOUT THE
HADRON
COLLIDER
Q: How does the Hadron Collider work?
A: You didn't even understand eleventh-grade math, so why are you asking?
Q: What would happen if I went inside it?
A: Just. Don't.
Q: How many miles of pipes and whatnot are in it?
A: A bajillion.
Q: How much did it cost?
A: Forty squillion.
Q: What does this thing do?
A: Don't touch that.
Q: What would happen if you, like, put a cat inside it?
A: I don't know.
Q: If I concentrate ultra-hard, will I ever be able to understand it?
A: No.
R. Chast

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


CERN main auditorium


Fabiola Gianotti, ATLAS
Peter Higgs

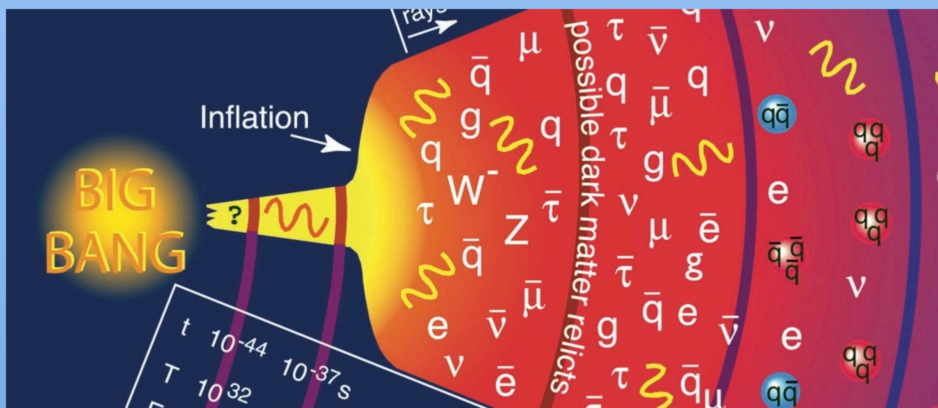
photo courtesy CERN


Peter Higgs

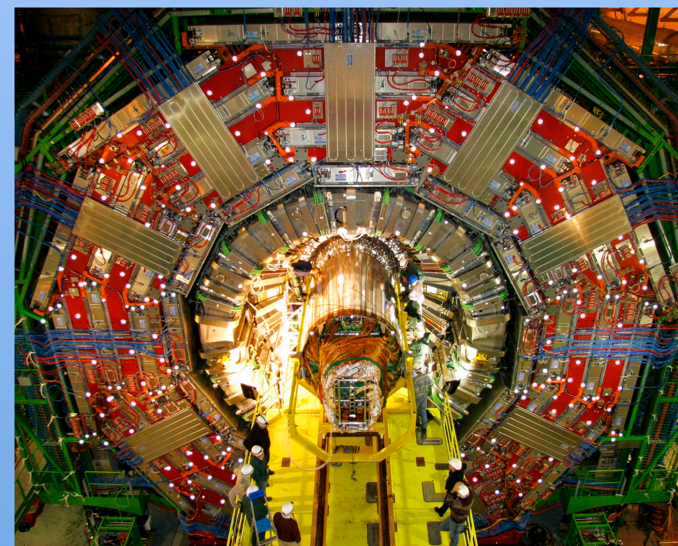

Joe Incandela. CMS, UCSB

Plan of my talk

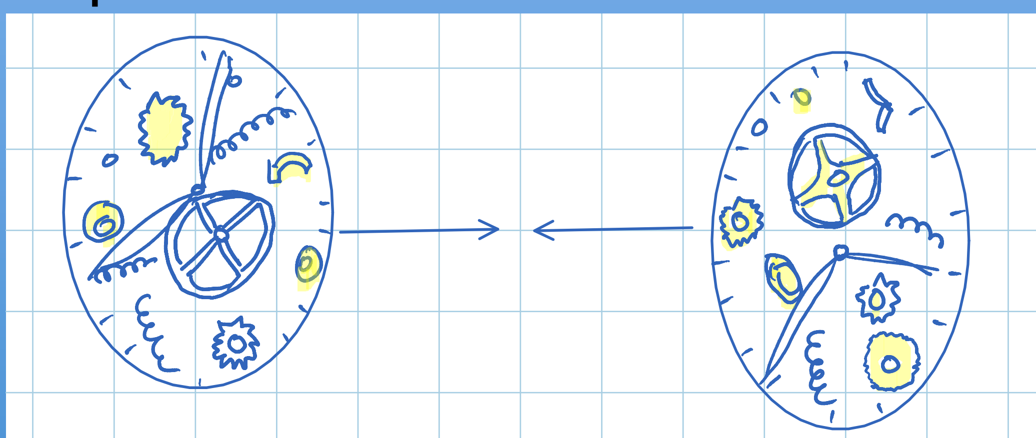
1. The universe, particles, and fields



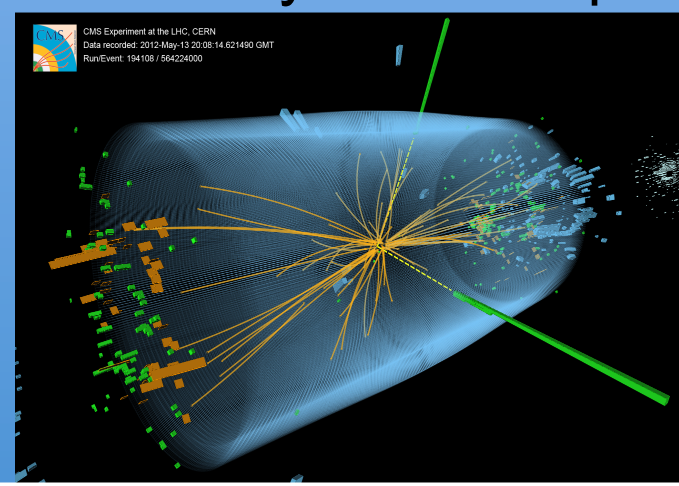
2. Accelerator and Detectors

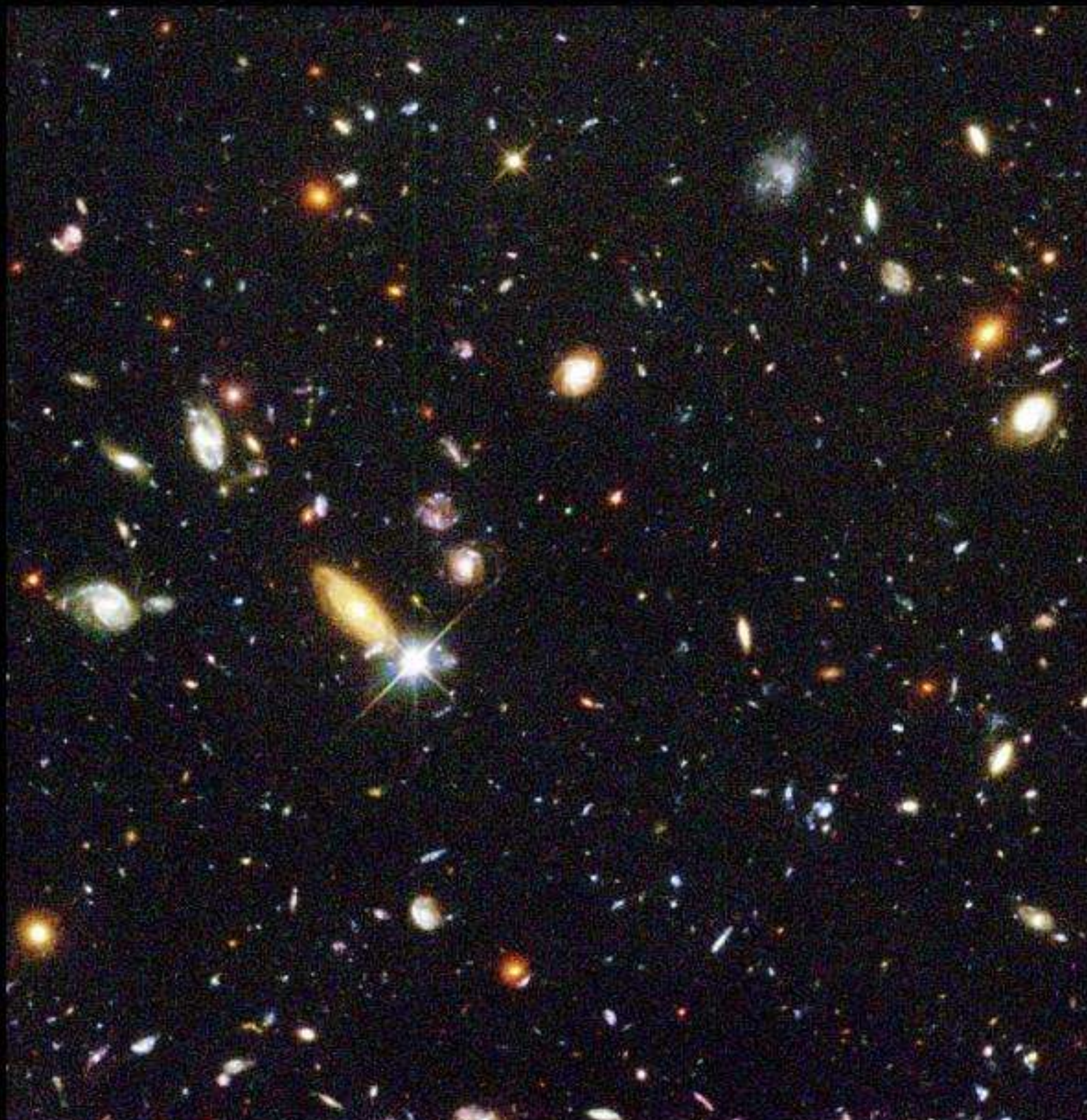


3. What happens when protons collide?



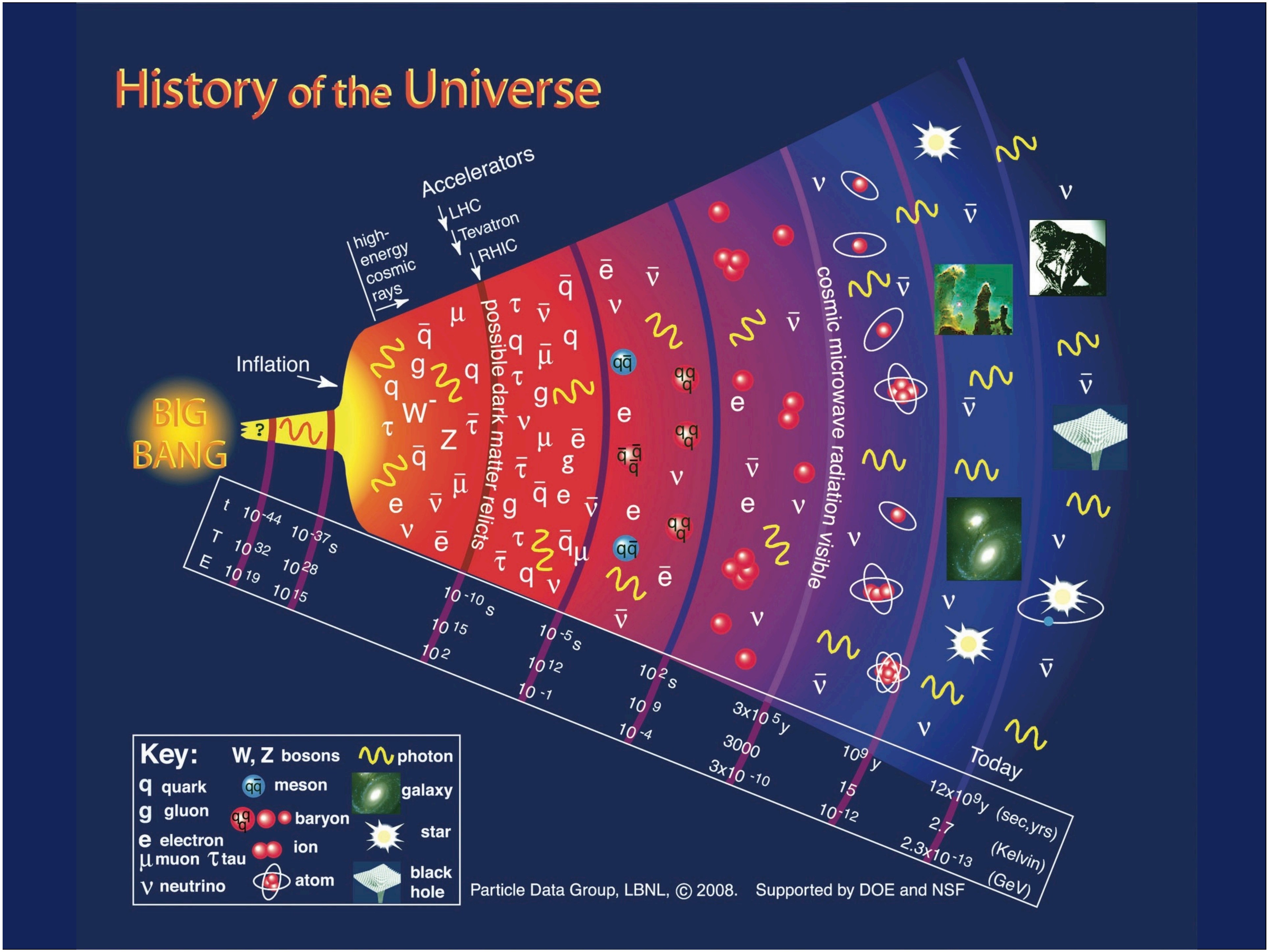
4. Discovery of a new particle



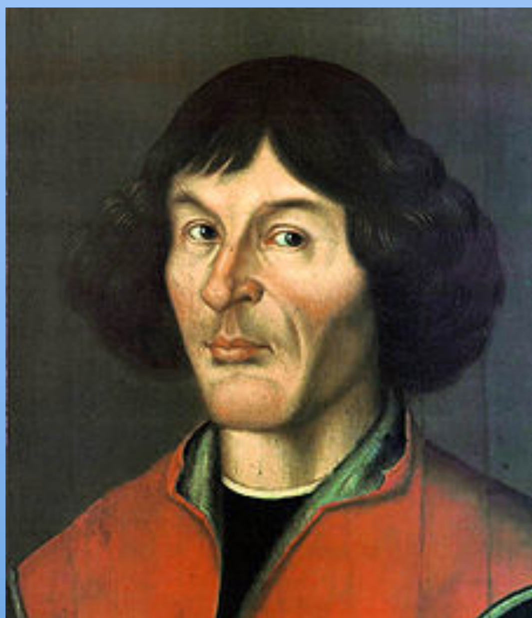


Hubble Deep Field HST • WFPC2

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

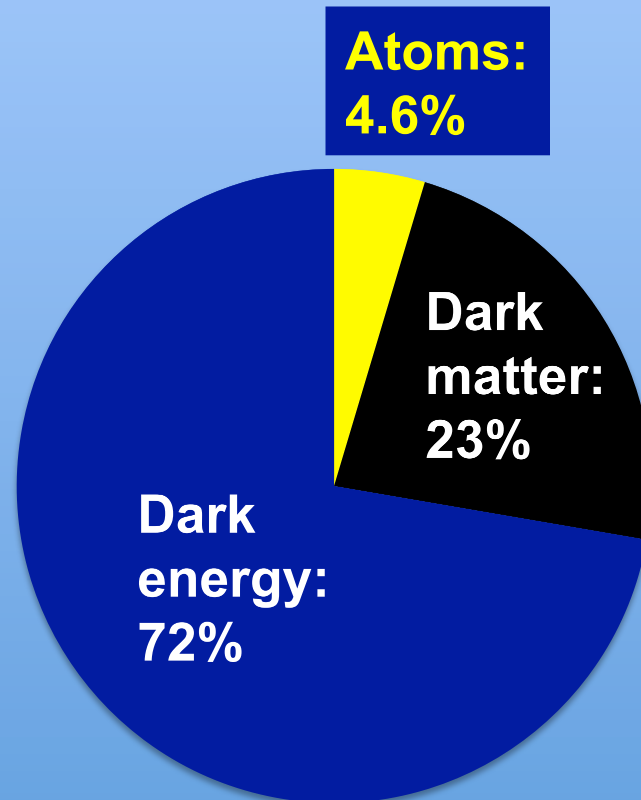

History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

The dark matter revolution/mystery



Nicolaus Copernicus (1473-1543): heliocentric model

Vera Rubin (1928-): dark matter in galaxies

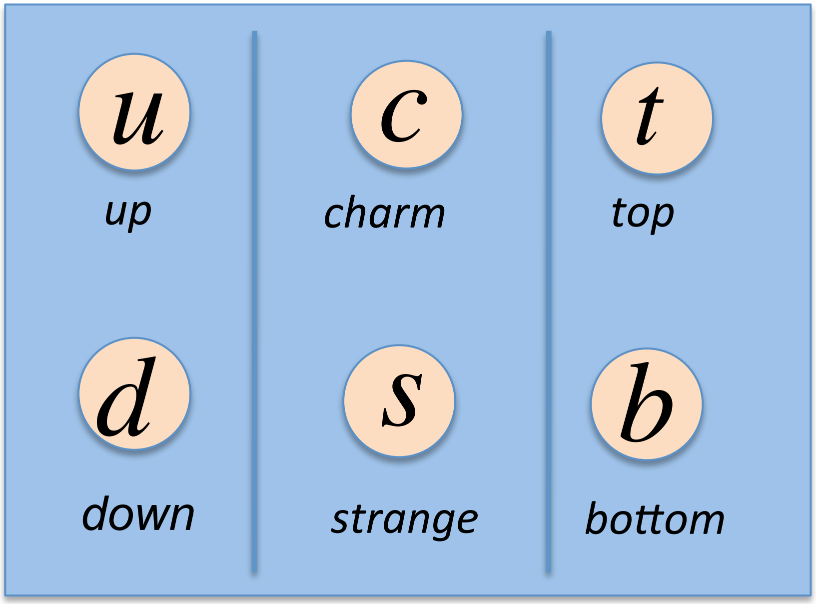


WMAP

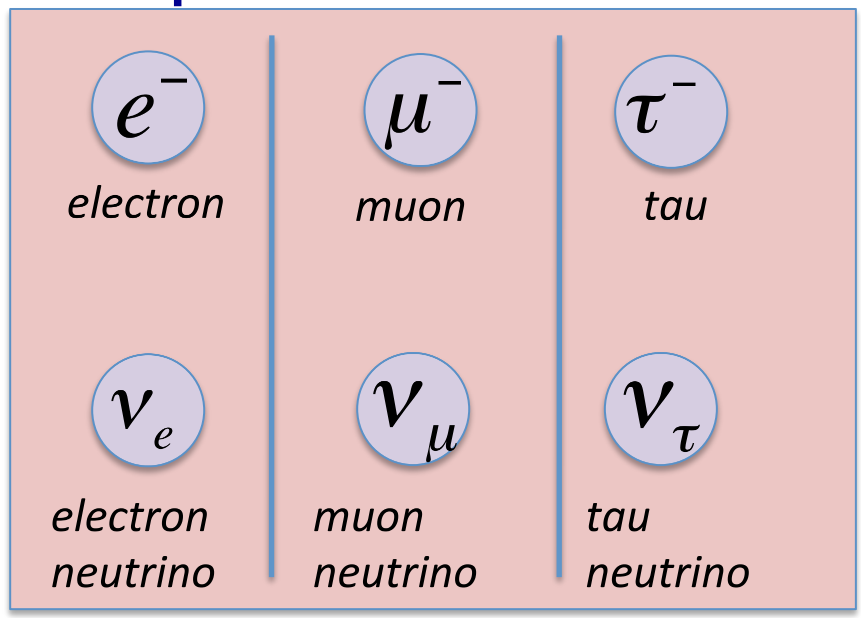
We aren't at the center of the solar system (or anything else), and we aren't made up of the dominant form of matter...

Who ordered that?

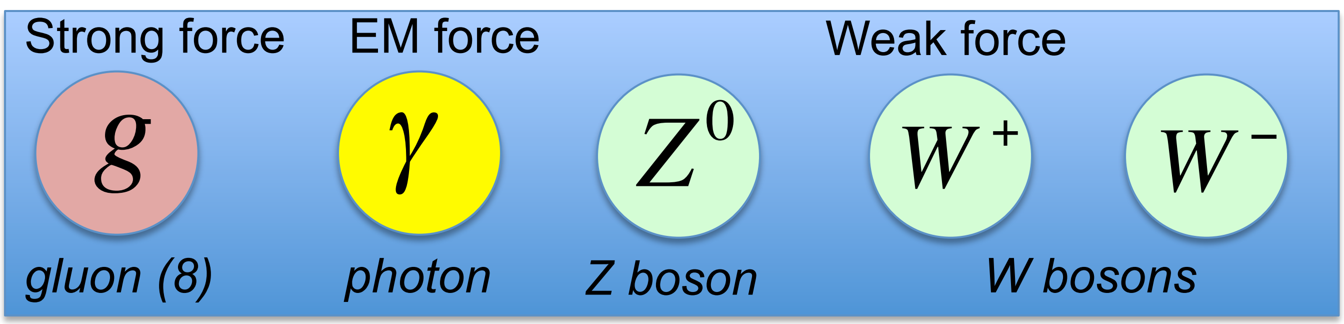
Quarks



Leptons

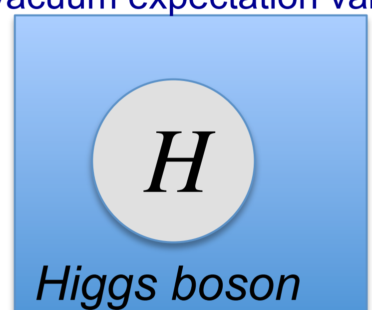


Gauge bosons (force field quanta)



Higgs boson

and vacuum expectation value



Particles all around: neutrinos and you

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!

Particles all around: neutrinos and you

How many neutrinos pass through your thumbnail every second?

(a) 0.1 (b) 1 (c) 10^6 (d) 10^{11} (e) 10^{23}
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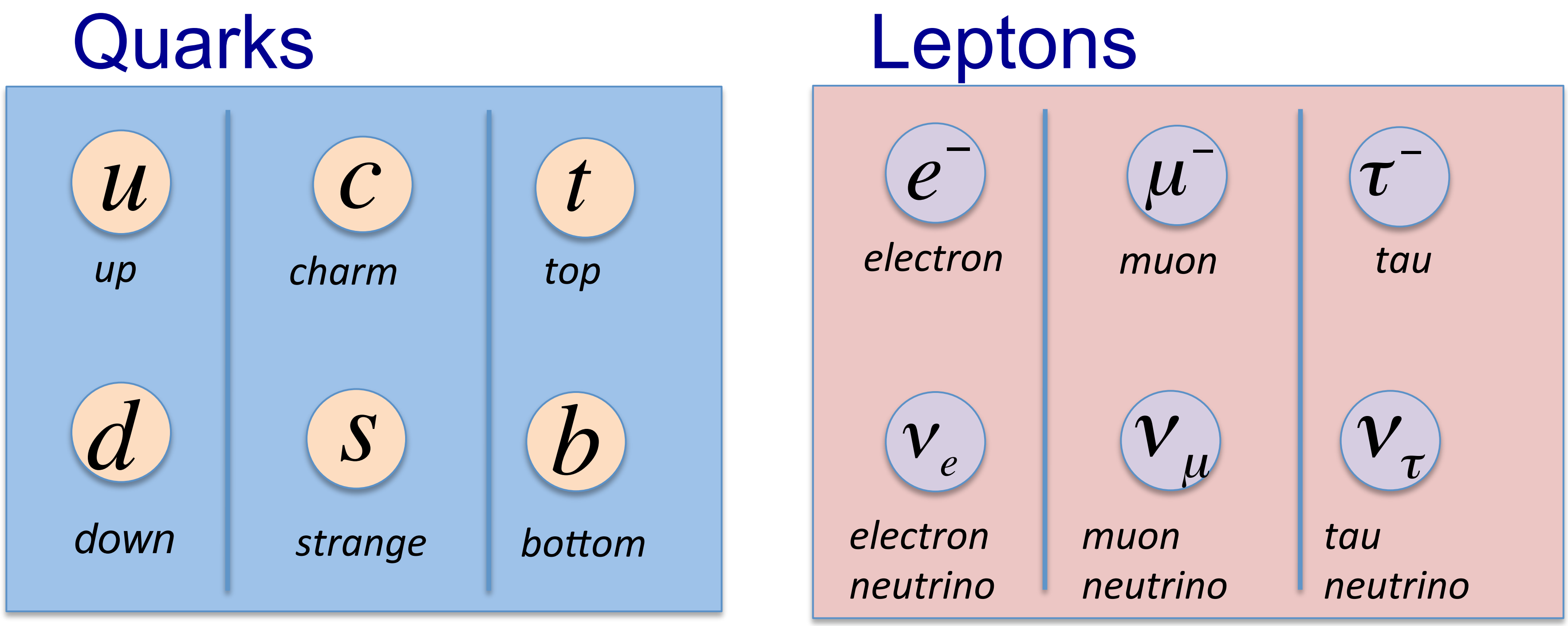
They are mostly from the sun!

Who ordered that? - Matter



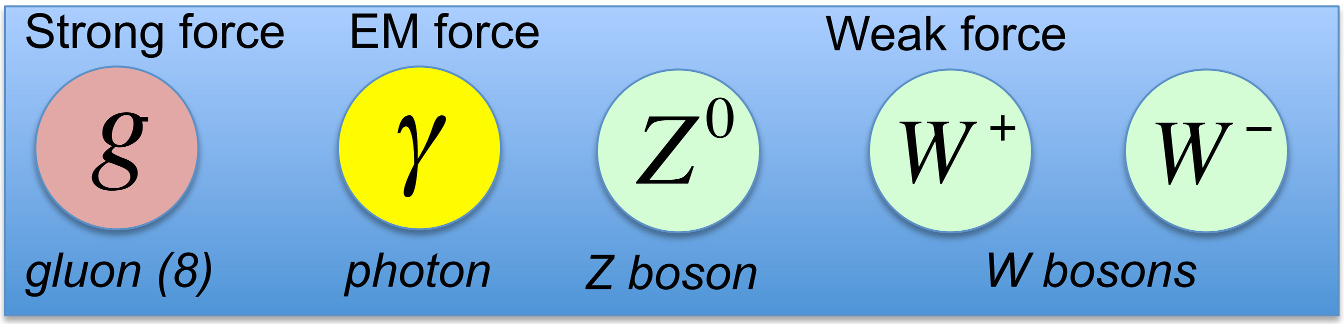
"Matter": made up of particles with spin (1/2)$\hbar$

$\hbar$ = Planck's constant

"Fermions" – obey Pauli exclusion principle!

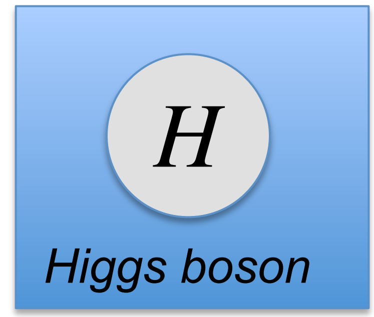
Who ordered that? - Fields

Gauge bosons (force field quanta)



Higgs boson

and vacuum expectation value



"Fundamental forces": transmitted by *fields*

Quantum excitations of fields are *particles* with
spin = $n\hbar$, n = integer $\hbar$ = Planck's constant

"bosons" – do not obey Pauli exclusion principle!

The four (known) fundamental forces of nature

Quantum field excitation	Fundamental forces/fields	Examples
γ	Electromagnetic	Light, electrical power, chemistry, civilization as we know it.
W^+ W^- Z^0	Weak	Many natural radioactive processes, operation of sun, supernova explosions, formation of elements.
g	Strong	Holds nuclear particles together.
G (graviton) [?]	Gravitational	Astrophysical systems, large scale dynamics of universe.

Electric and magnetic fields are unified!

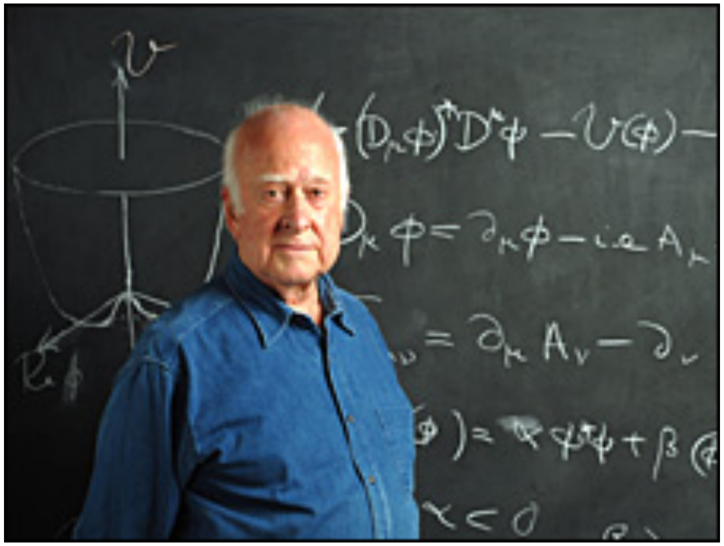
Demonstration of Faraday's Law, showing the connection between electric fields and magnetic fields.

Angels & Demons and Tom Hanks: What about antimatter?

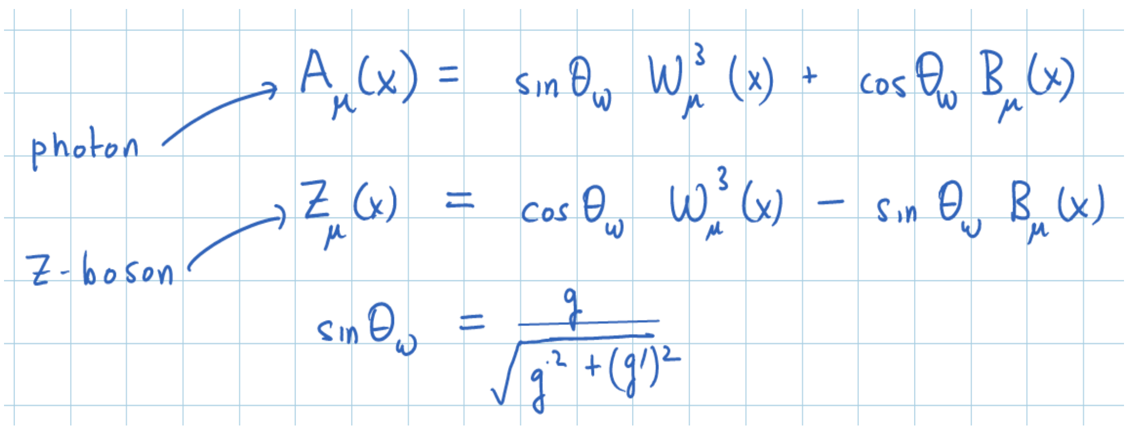
Angels and Demons, © Sony Pictures
(They also make computer displays.)

LHC Control Room: the real thing

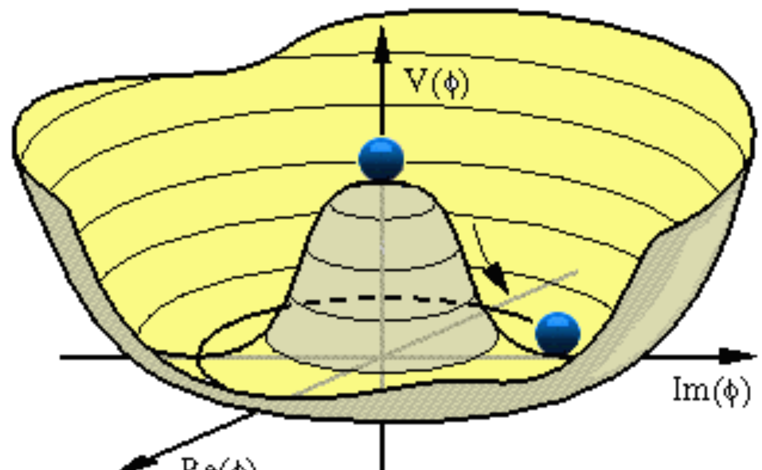
Peter Higgs and the origin of mass



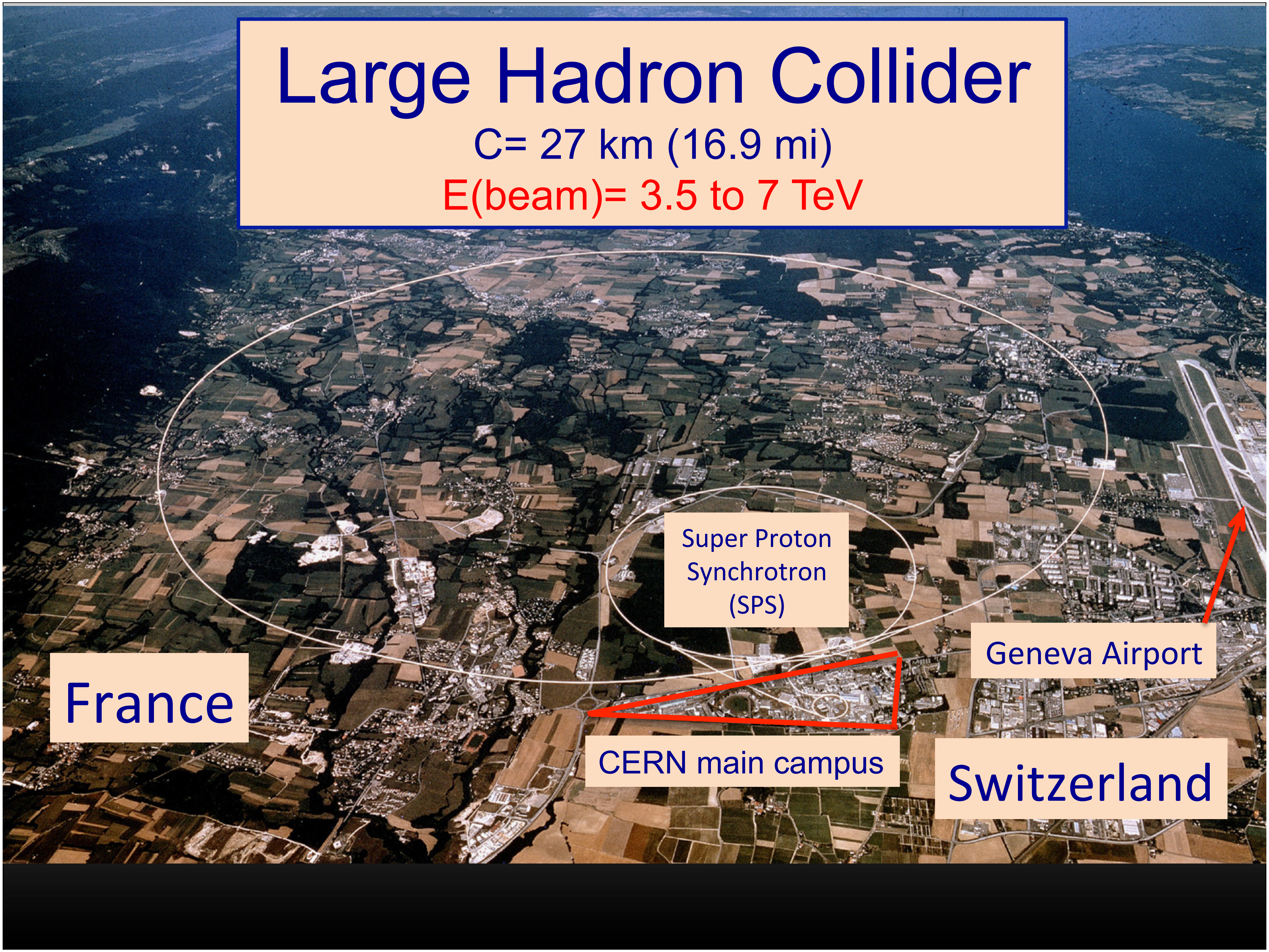
Fundamental particles interact with the Higgs field, which exists throughout all space. This gives mass to particles!



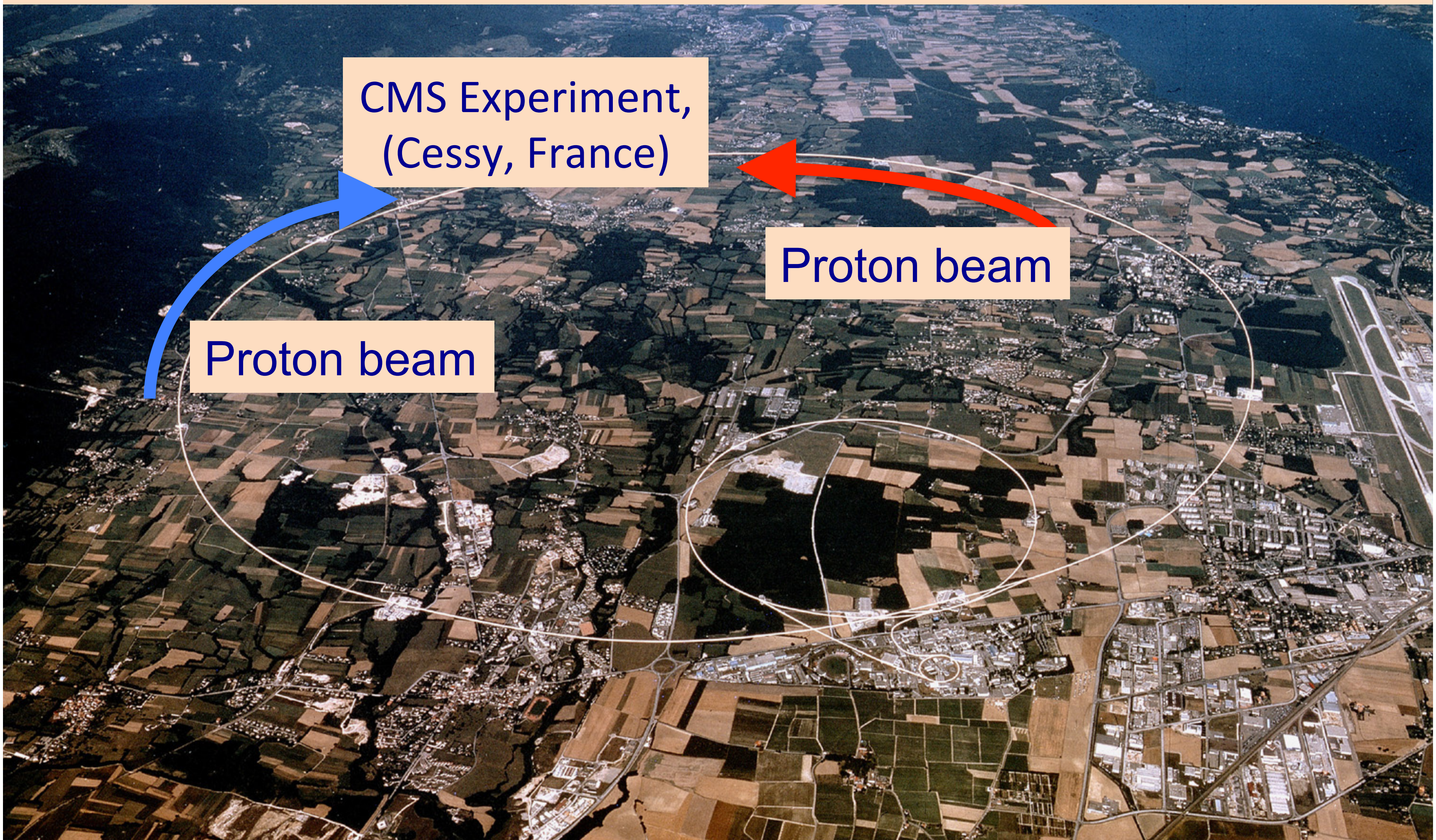
See J. Richman, Physics 225b, Lectures 7-17.



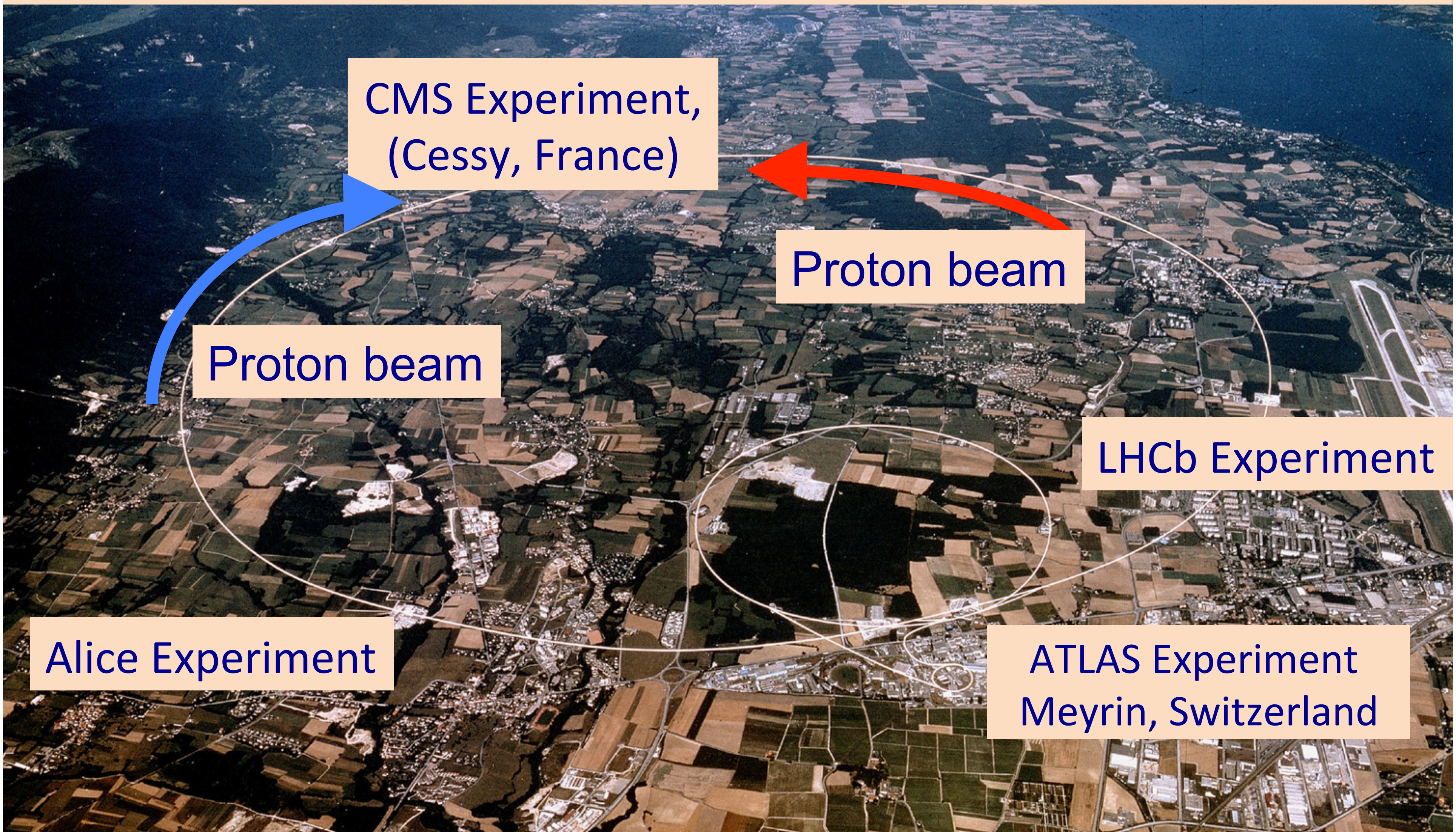
Higgs potential


Large Hadron Collider
C= 27 km (16.9 mi)
E(beam)= 3.5 to 7 TeV
Super Proton
Synchrotron
(SPS)
Geneva Airport
France
CERN main campus
Switzerland

LHC ring: 2 separate magnetic “highways”



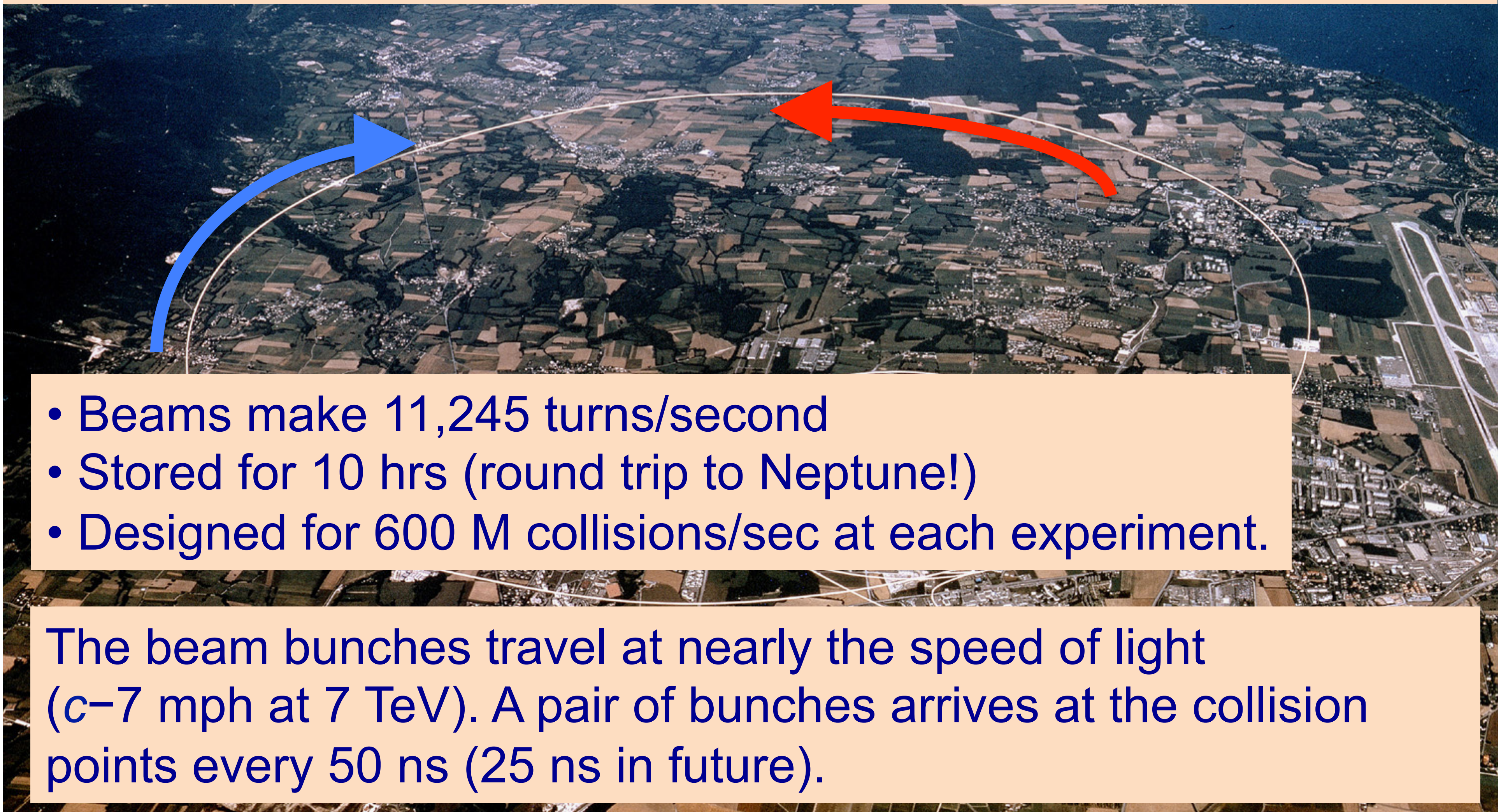
LHC ring: 2 separate magnetic "highways"



- 9300 magnets, including 1232 15-meter dipoles.
- Radio-frequency EM cavity devices to accelerate beams (8/beam; 40 MHz)

What is a proton "beam"?

"Bunch train" w/1374 bunches of protons; 1 bunch=10^{11} protons.



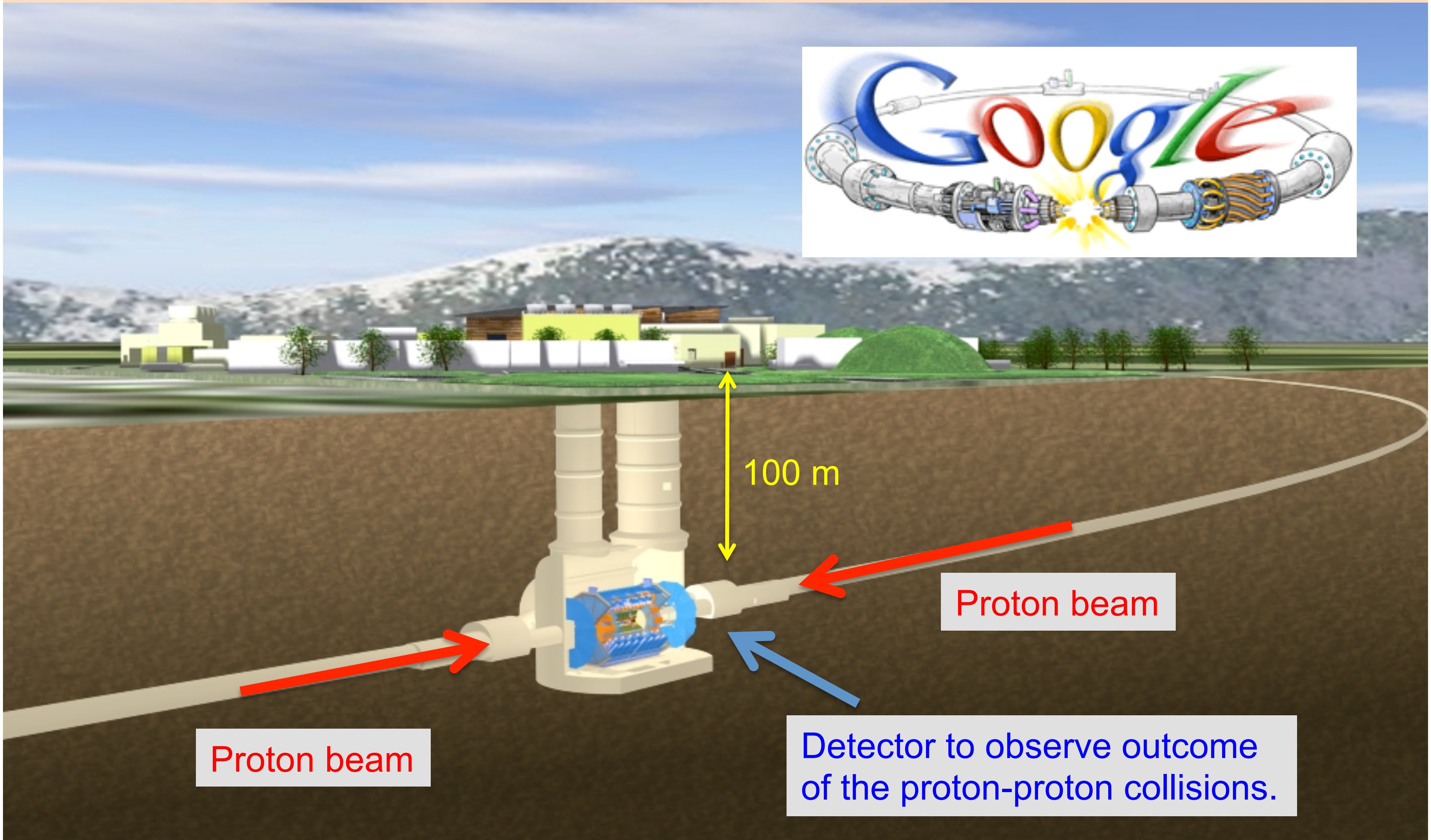
- Beams make 11,245 turns/second
- Stored for 10 hrs (round trip to Neptune!)
- Designed for 600 M collisions/sec at each experiment.

The beam bunches travel at nearly the speed of light (c−7 mph at 7 TeV). A pair of bunches arrives at the collision points every 50 ns (25 ns in future).

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

This place should look familiar!

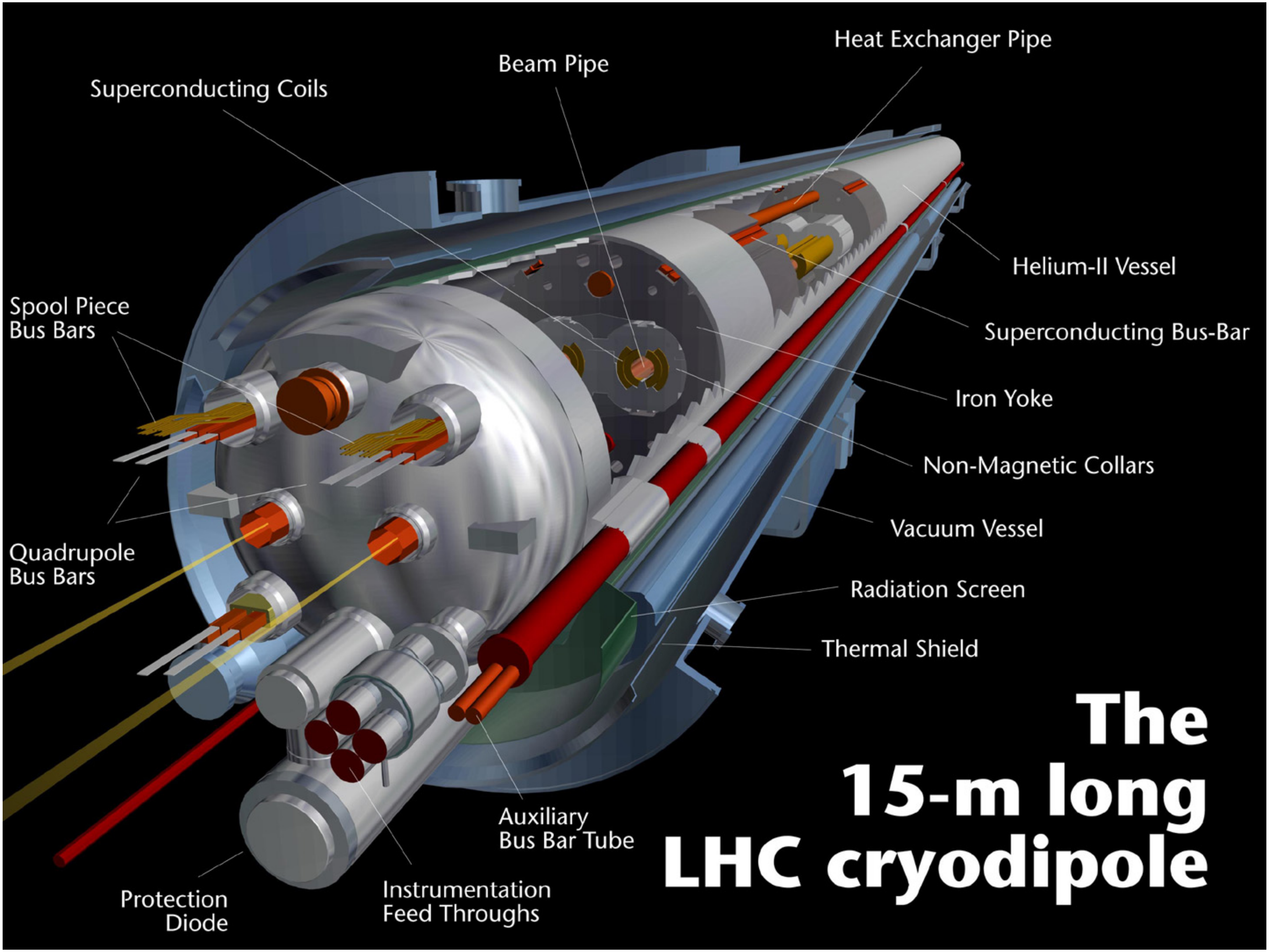
LHC Interaction Region



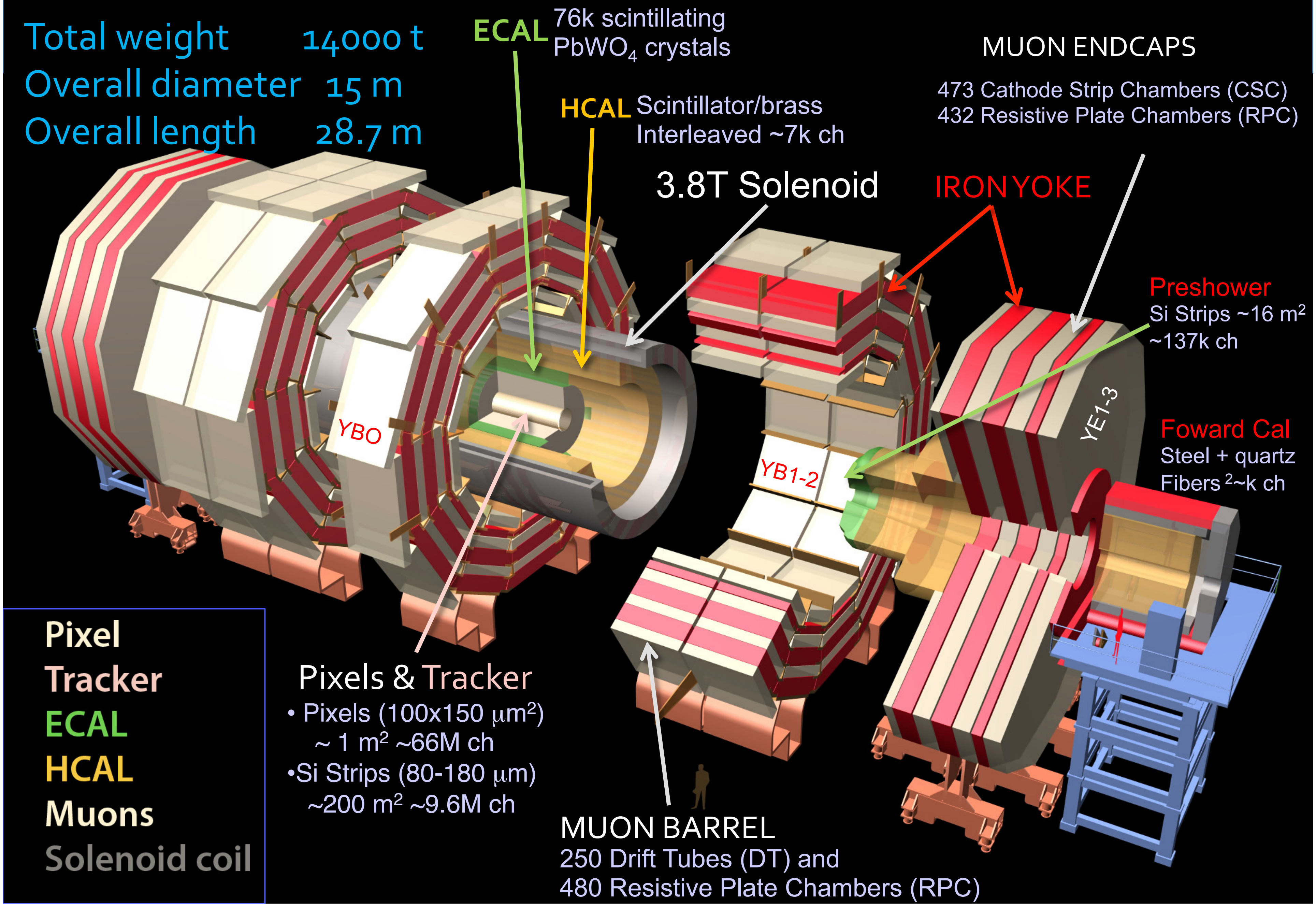
The detector is like a giant camera – or an observatory!

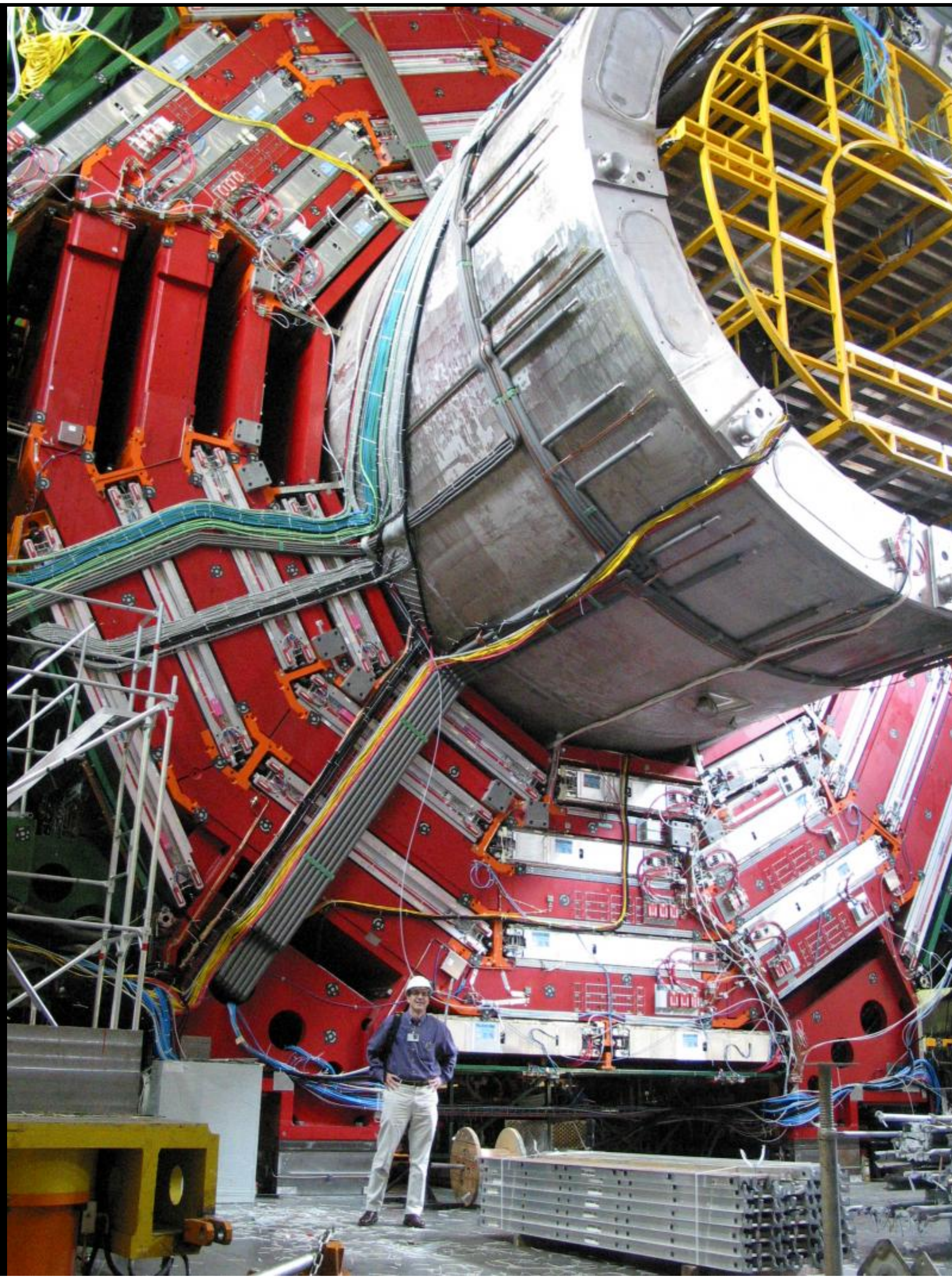
Inside the LHC Tunnel

Total magnets	9593
Num. main dipoles	1232 (L=15 m)
Num. main quadrupoles	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	7 m (25 ns)
Dipole field	8.33 T
Dipole op. temp.	1.9 K
Dipole current	11,850 A

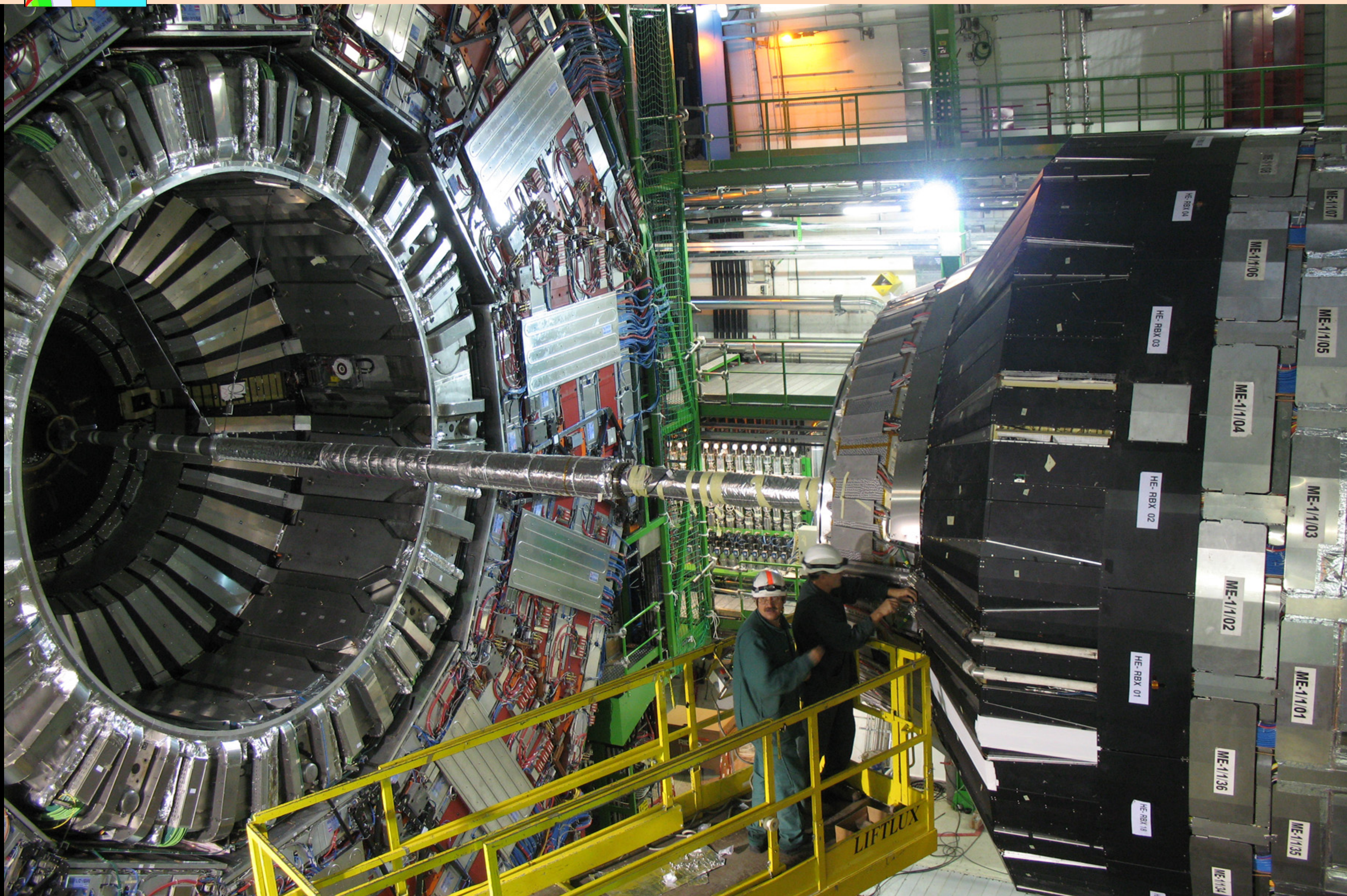

Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole
Bus Bars
Radiation Screen
Thermal Shield
Auxiliary
Bus Bar Tube
Protection
Diode
Instrumentation
Feed Throughs
The
15-m long
LHC cryodipole

CMS Experiment





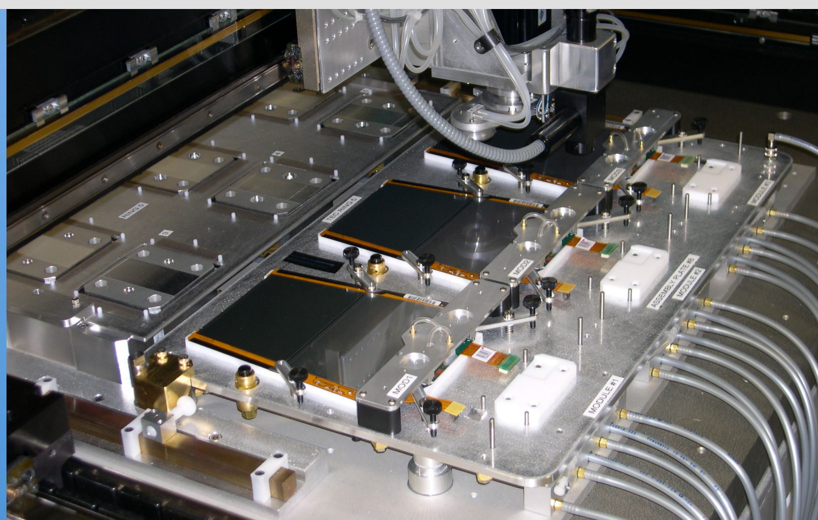
CMS Detector with Accelerator Beam Pipe



Working on the CMS Silicon Strip Tracker

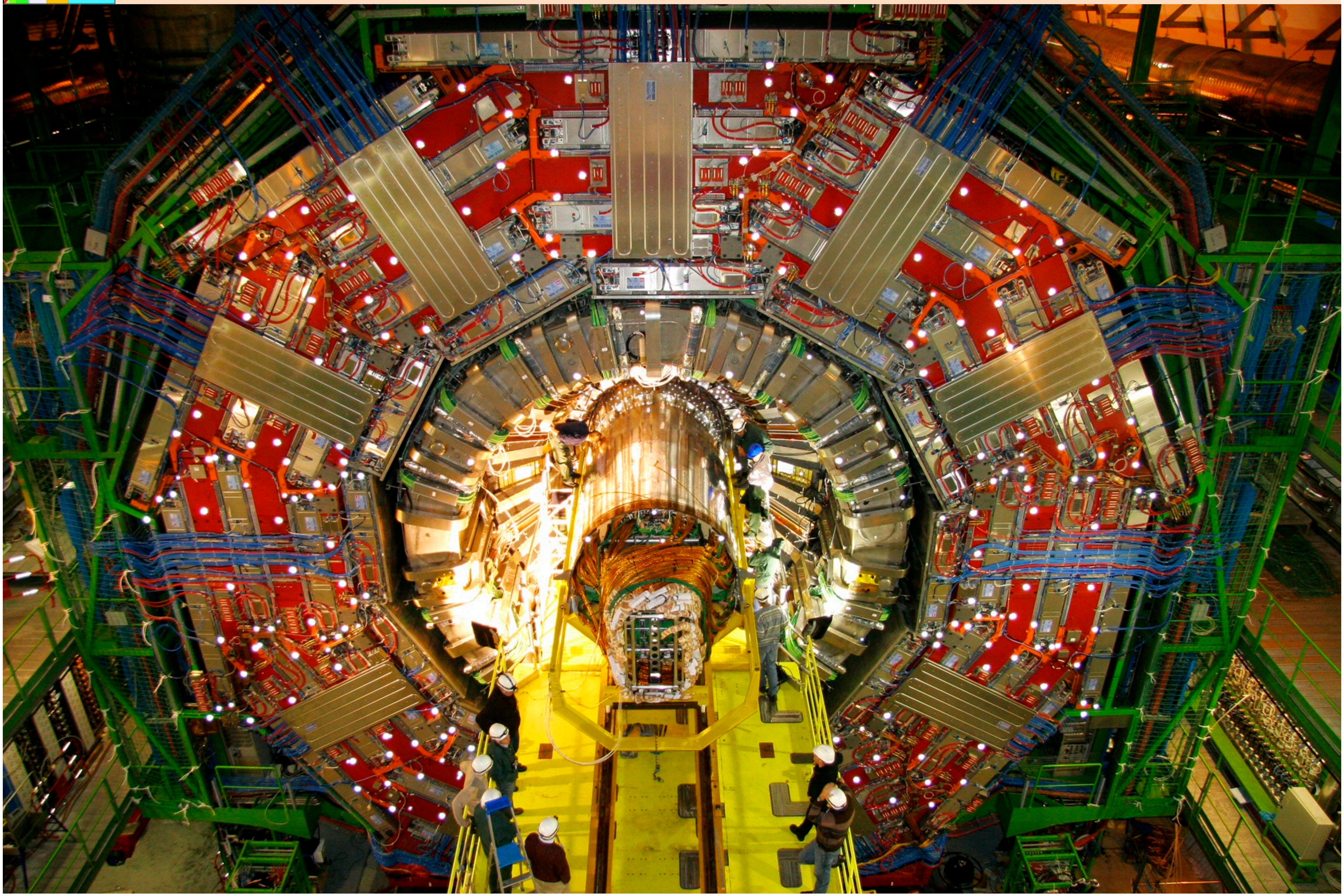
UCSB silicon-strip module assembly team

Module construction on ganty

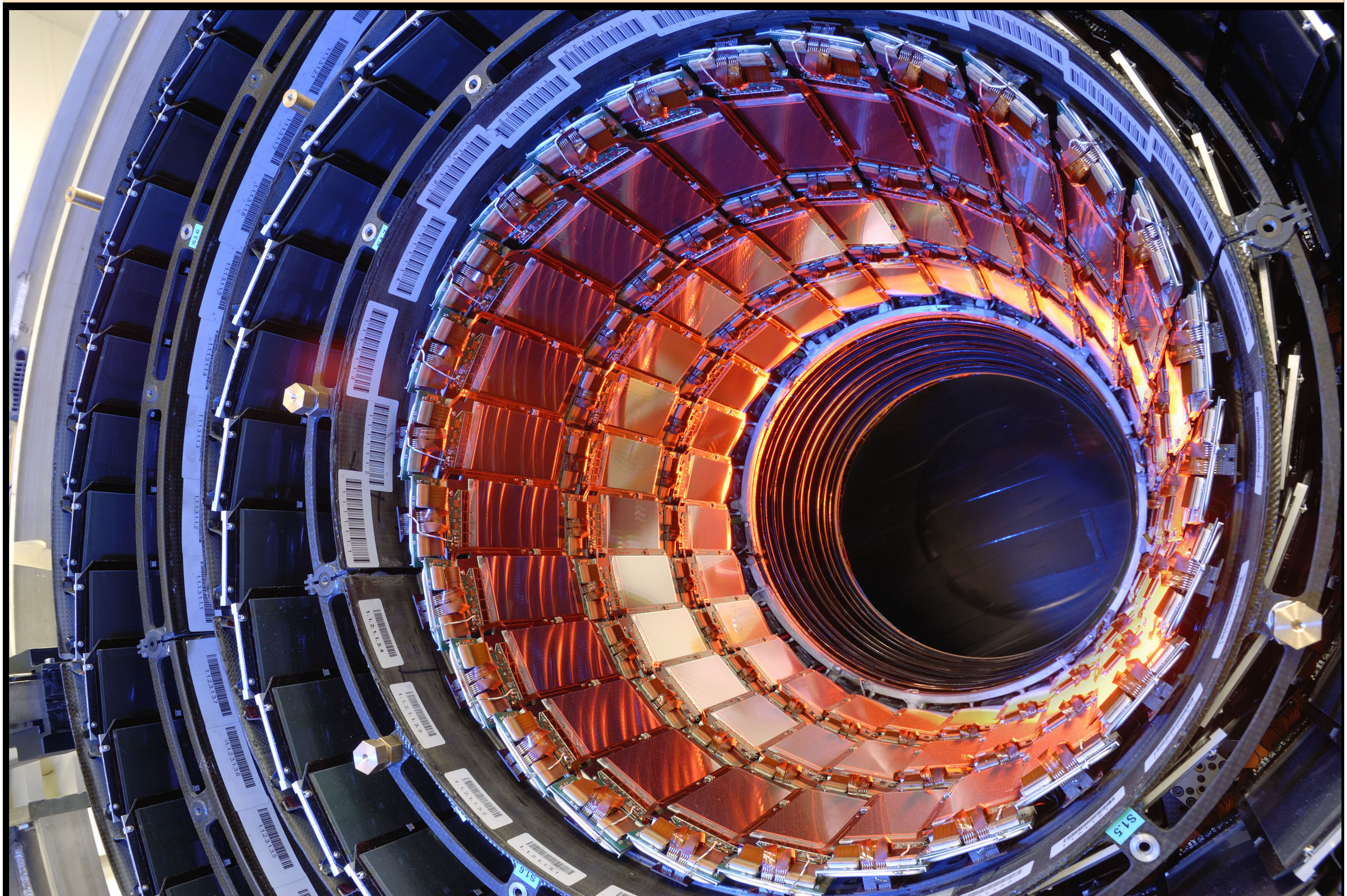


Module installation at CERN

CMS Silicon Tracker Installation: Dec 2007

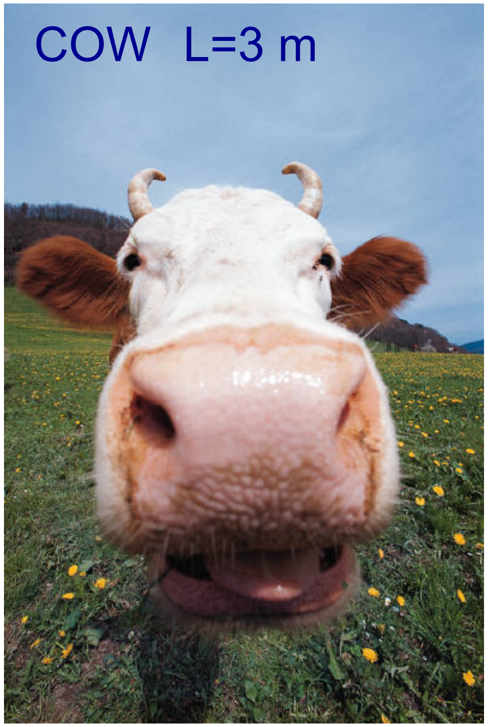


CMS Silicon-Strip Particle Tracking Detector



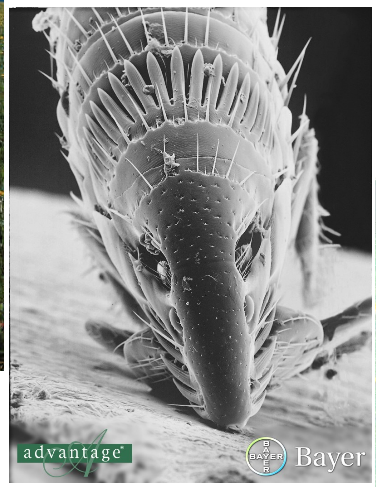
Shrinking down: cow → atom

COW L=3 m



$\times 10^{-3}$

FLEA L = 0.0025 m = 2.5 mm

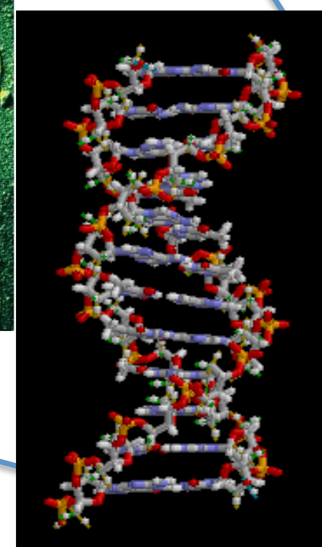


$\times 10^{-3}$

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

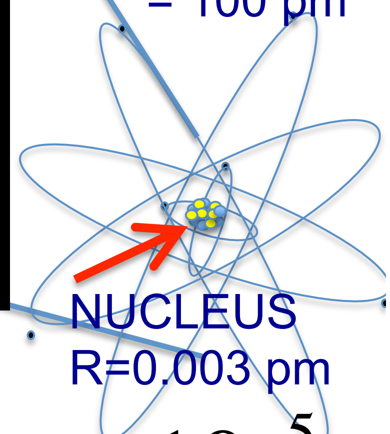
$\times 10^{-3}$

MOLECULE
W = 0.002 μm = 2 nm



$\times 10^{-1}$

ATOM
R = 0.1 nm
= 100 pm



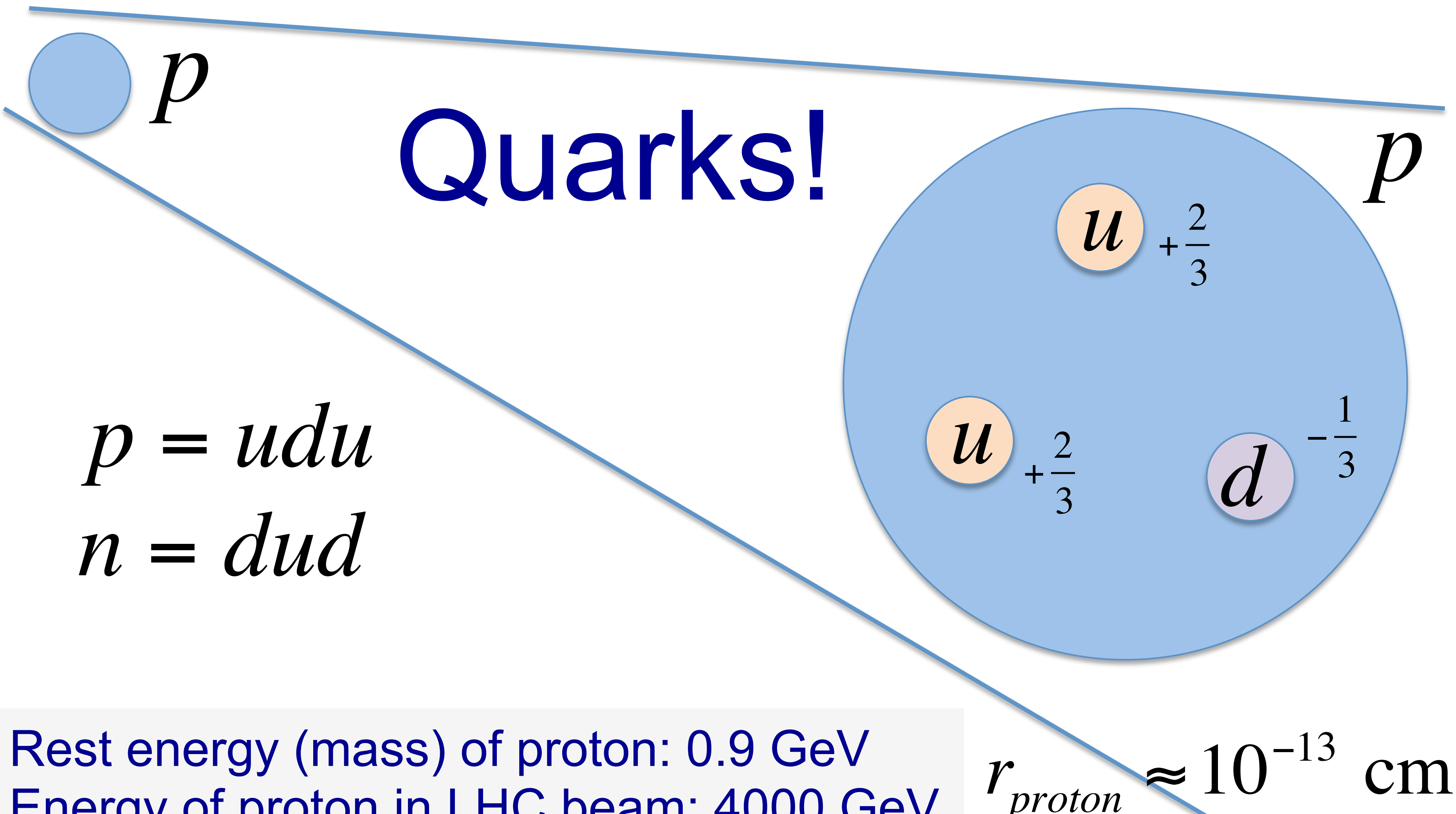
NUCLEUS
R=0.003 pm

$\times 10^{-5}$

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

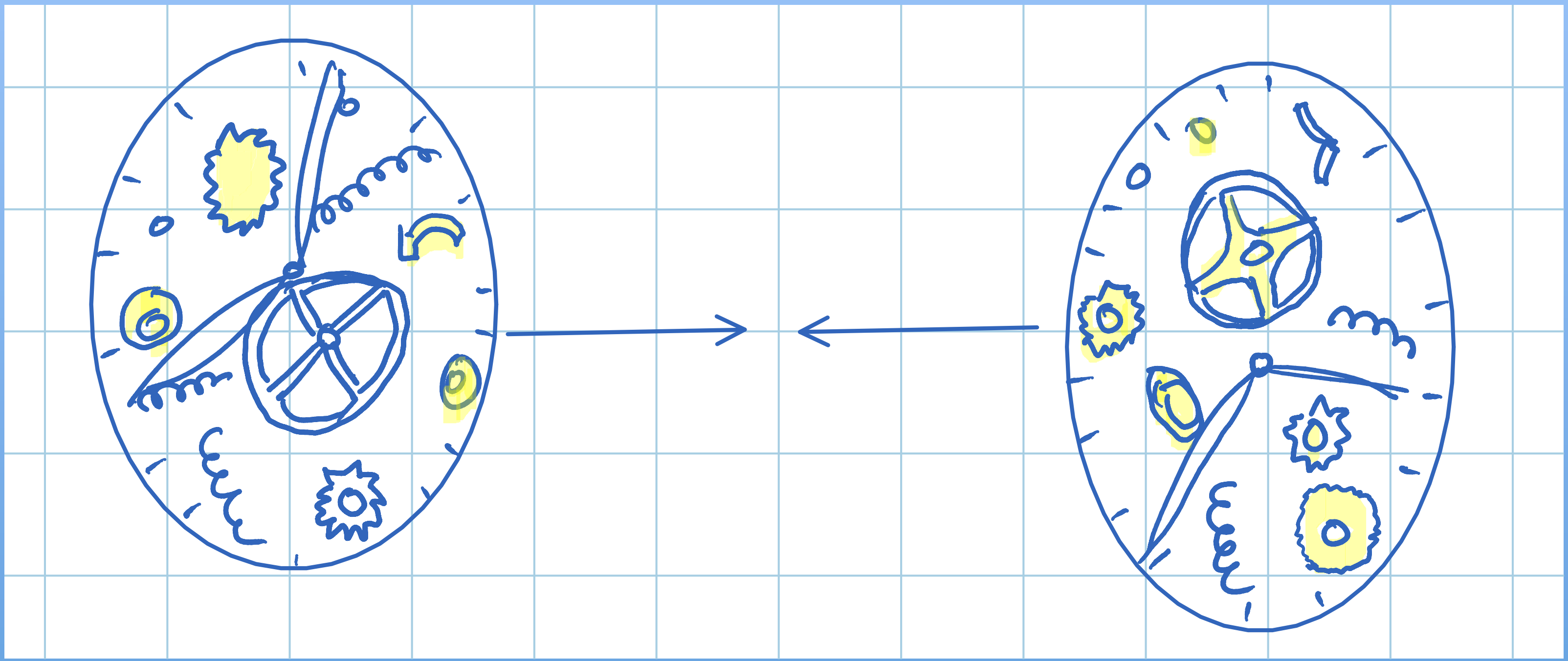
$$r_{proton} \approx 10^{-13}\ \text{cm}$$

Feynman's Van: Quantum Field Theory

Feynman’s Van: Quantum Field Theory

Fundamental forces don’t just produce “pushes” and “pulls”. Each type of force allows a well-defined set of **transformations of matter.**

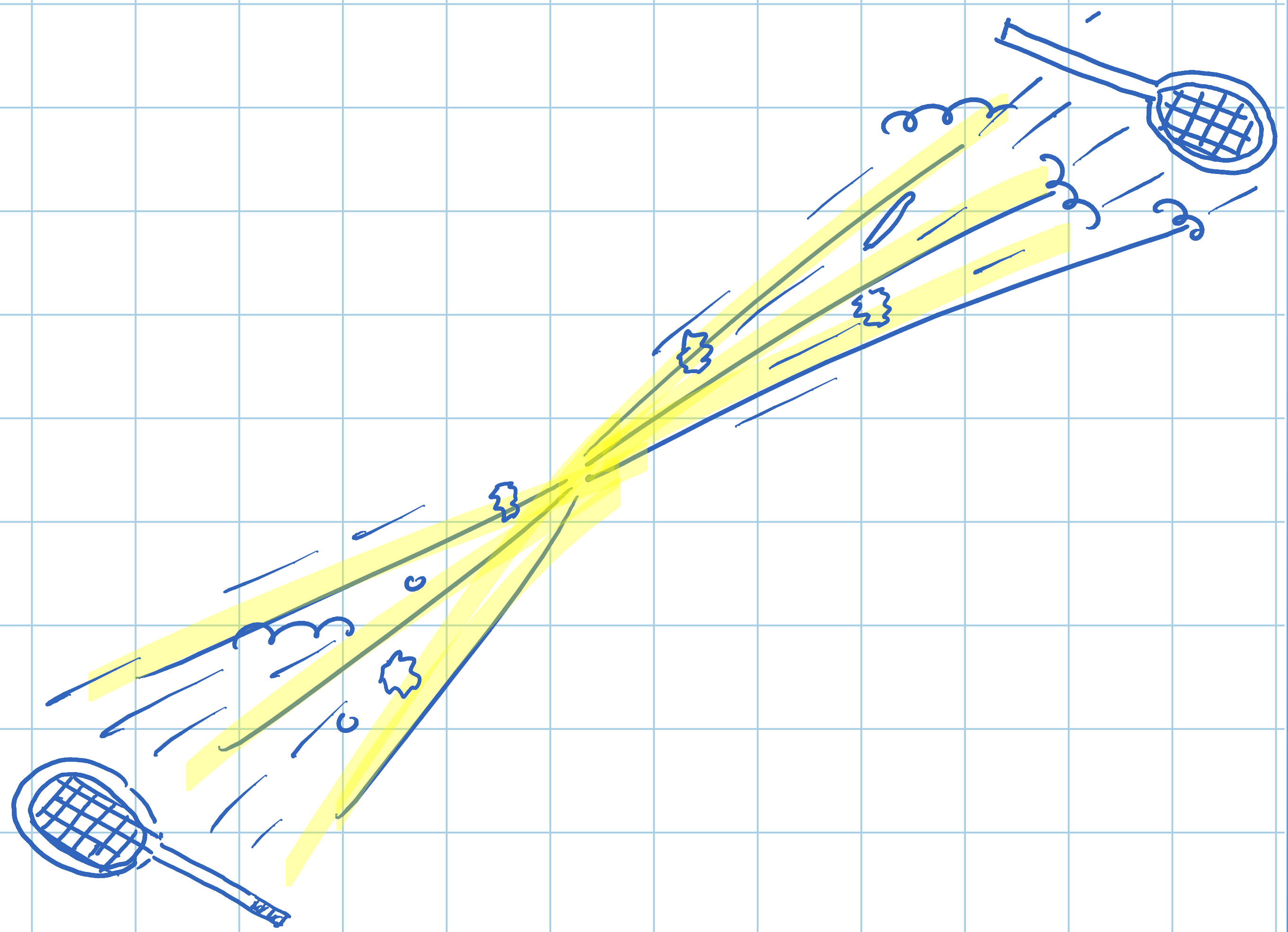
Smashing Swiss watches together



...after all, this is Geneva

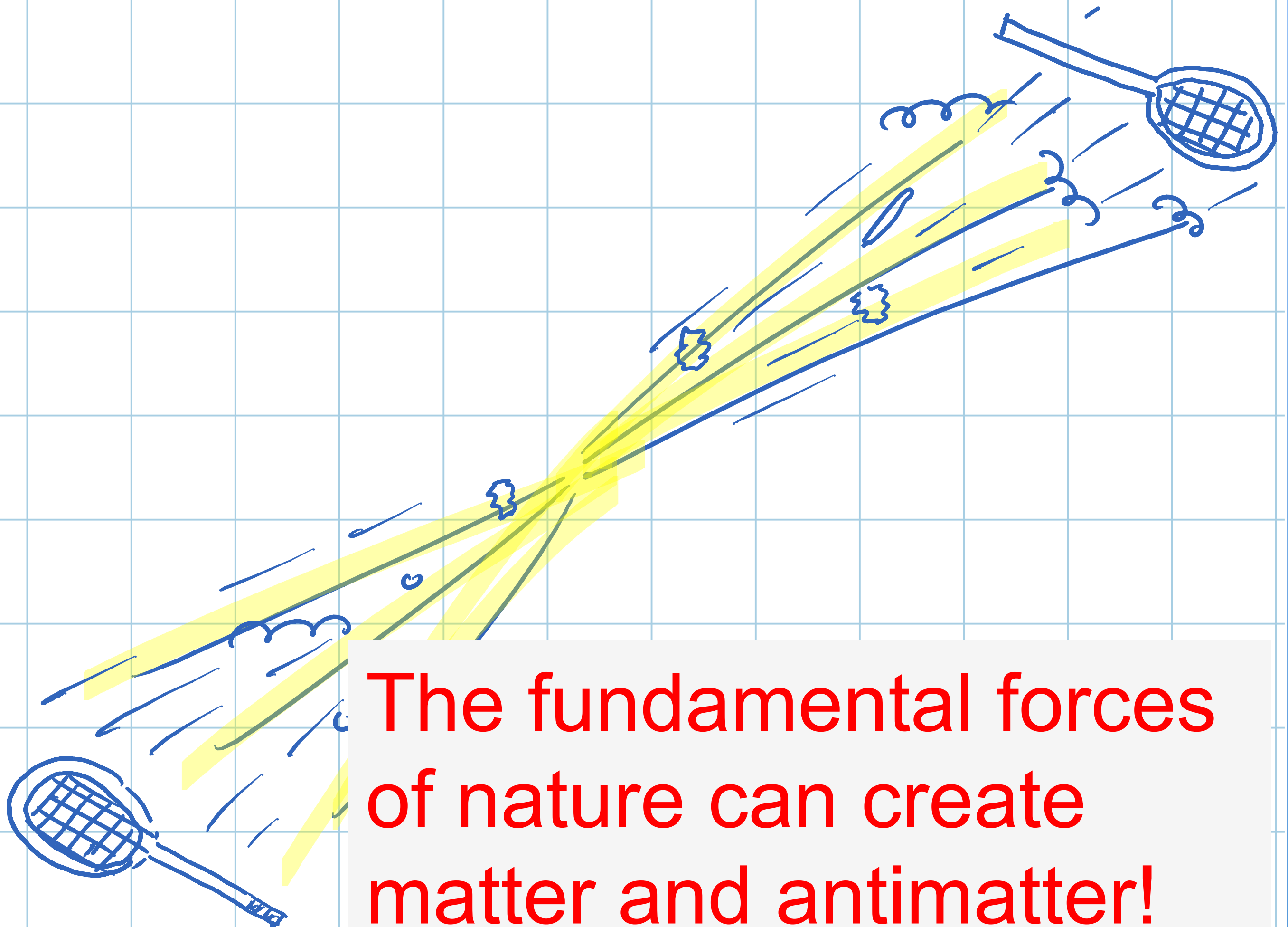
Smashing Swiss watches together

...out come two tennis rackets



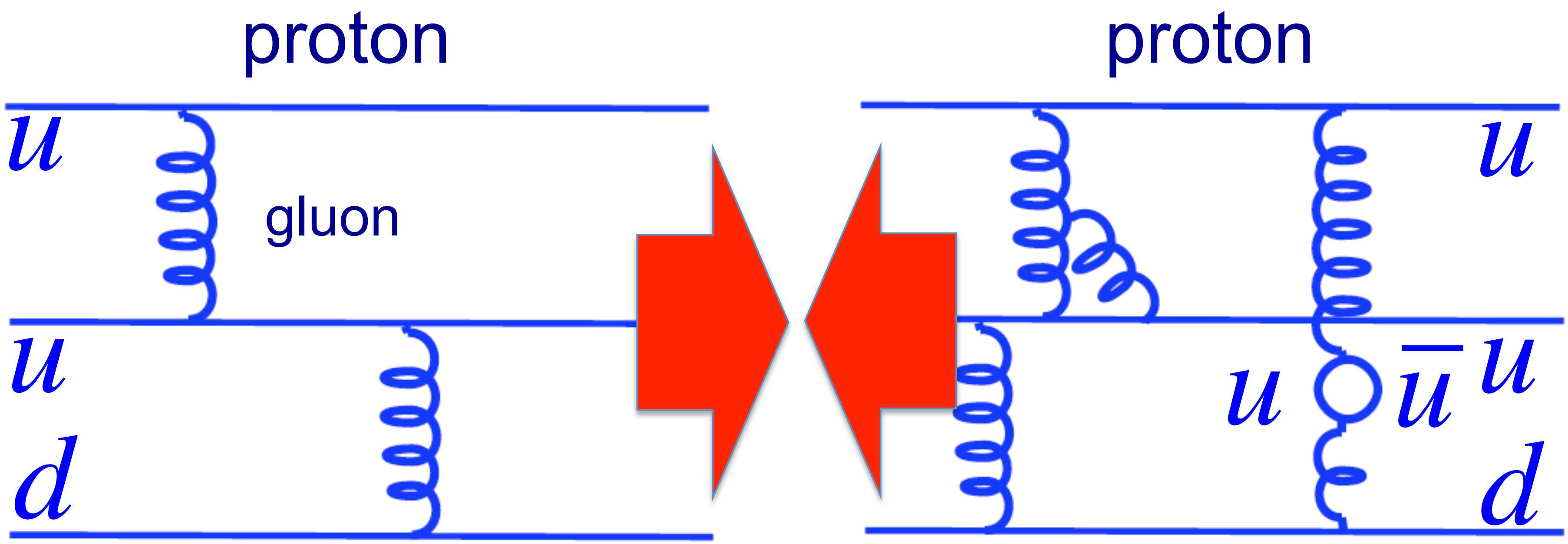
Smashing Swiss watches together

...out come two tennis rackets



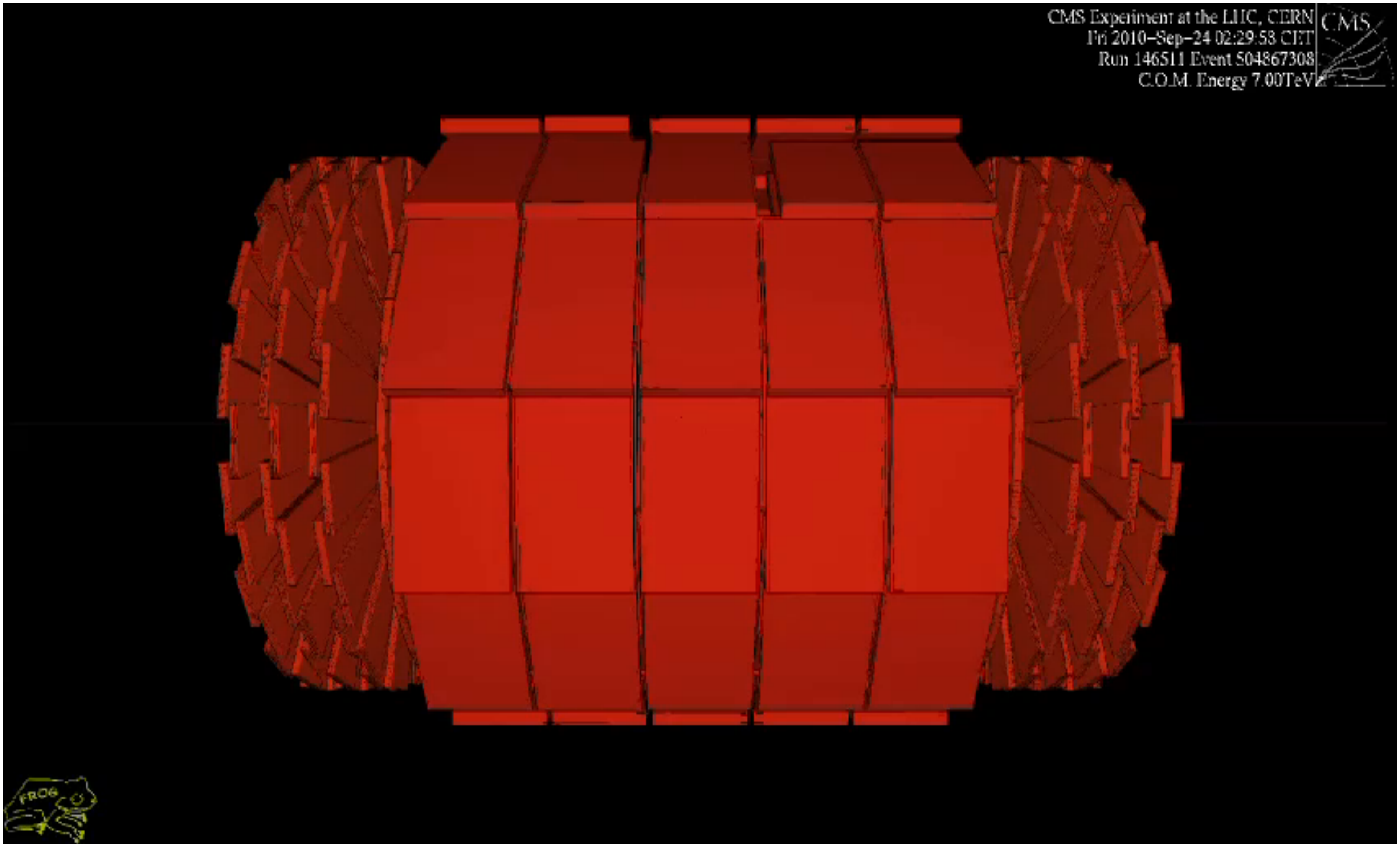
The fundamental forces of nature can create matter and antimatter!

Two protons colliding

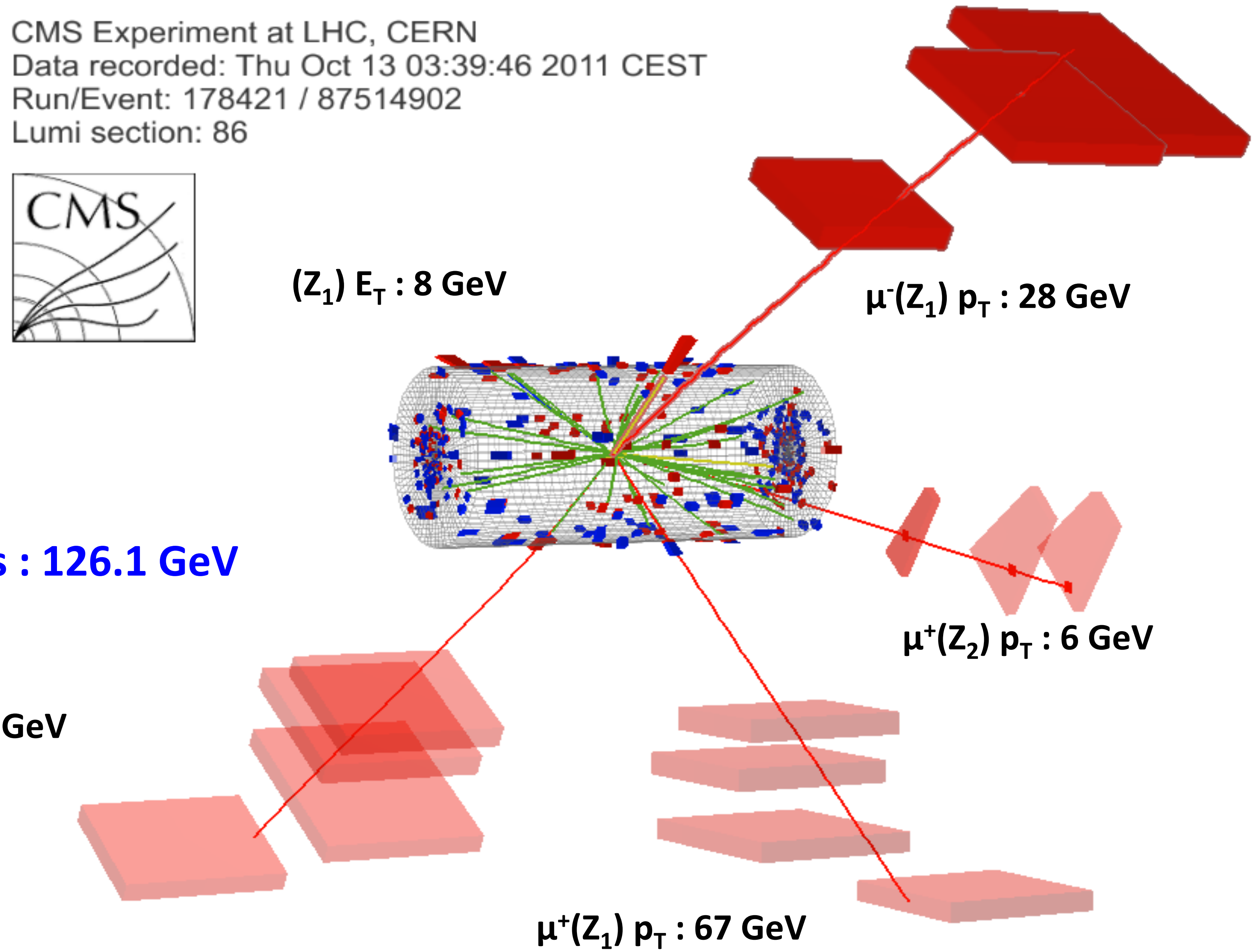


Gluons are the quanta of the strong field.
(Nobel Prize 2004: David Gross, David Politzer, Frank Wilczek.)

Can Matter be Created? (animation!)



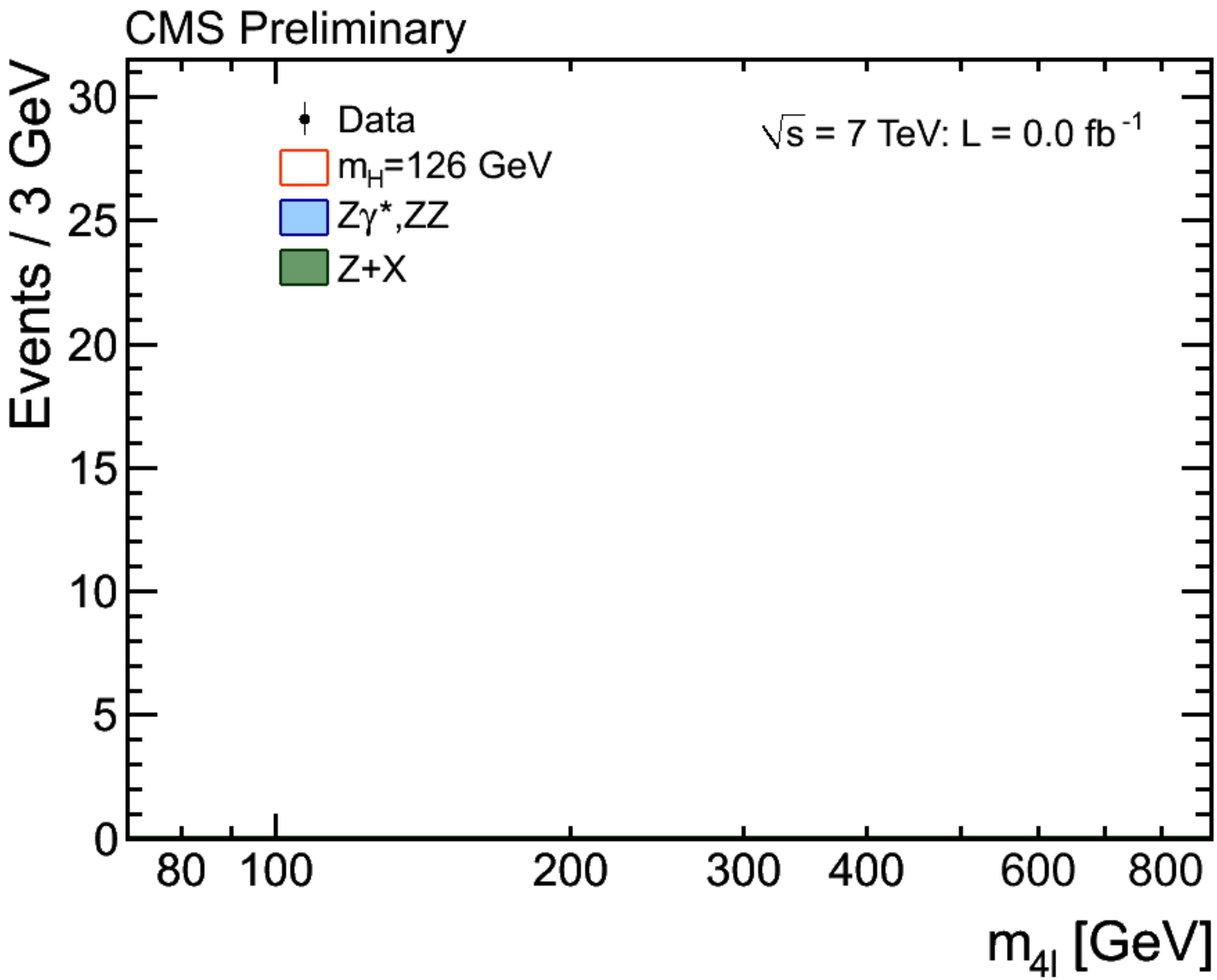
Higgs particle → two Z bosons → 4 muons



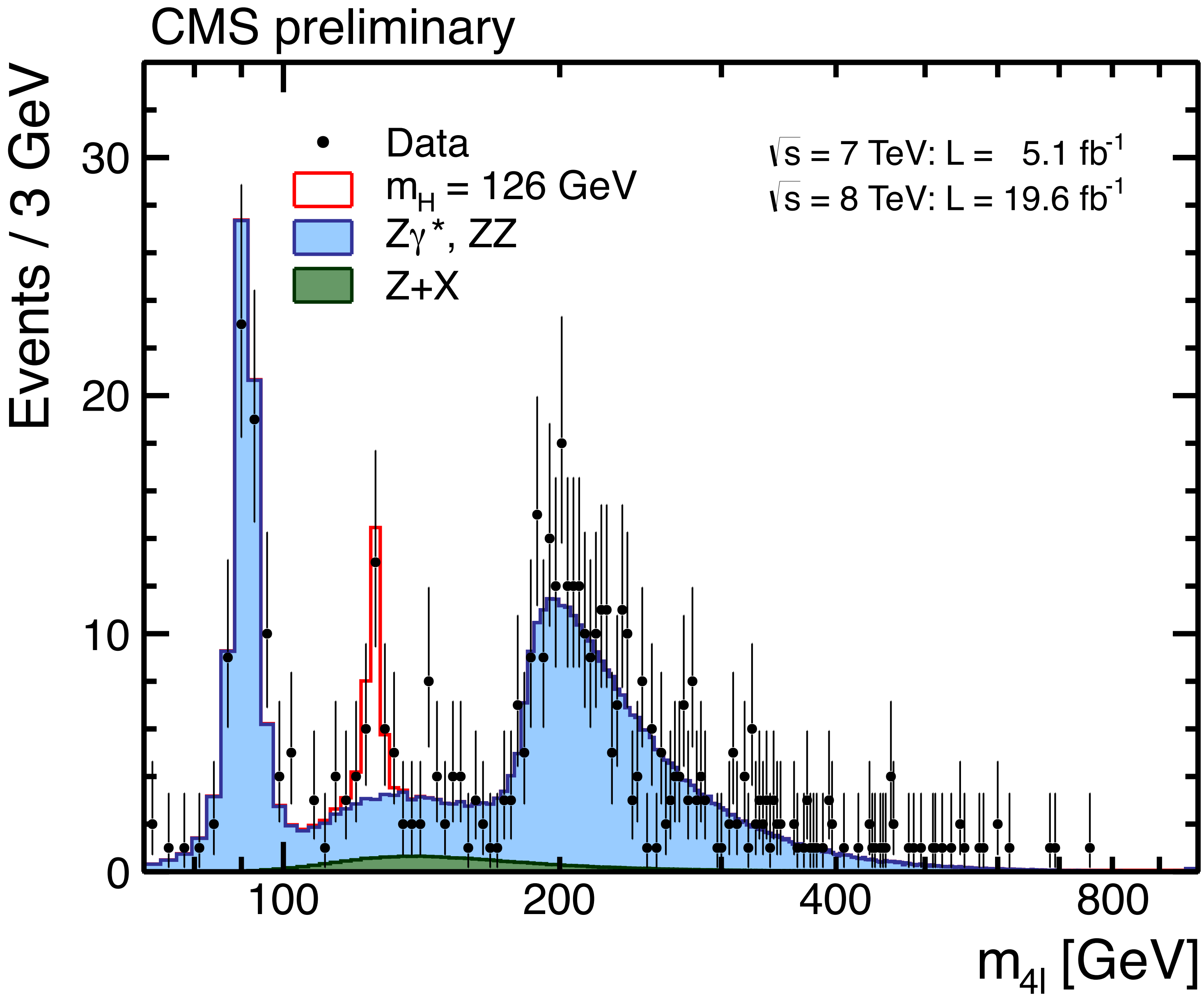
7 TeV DATA

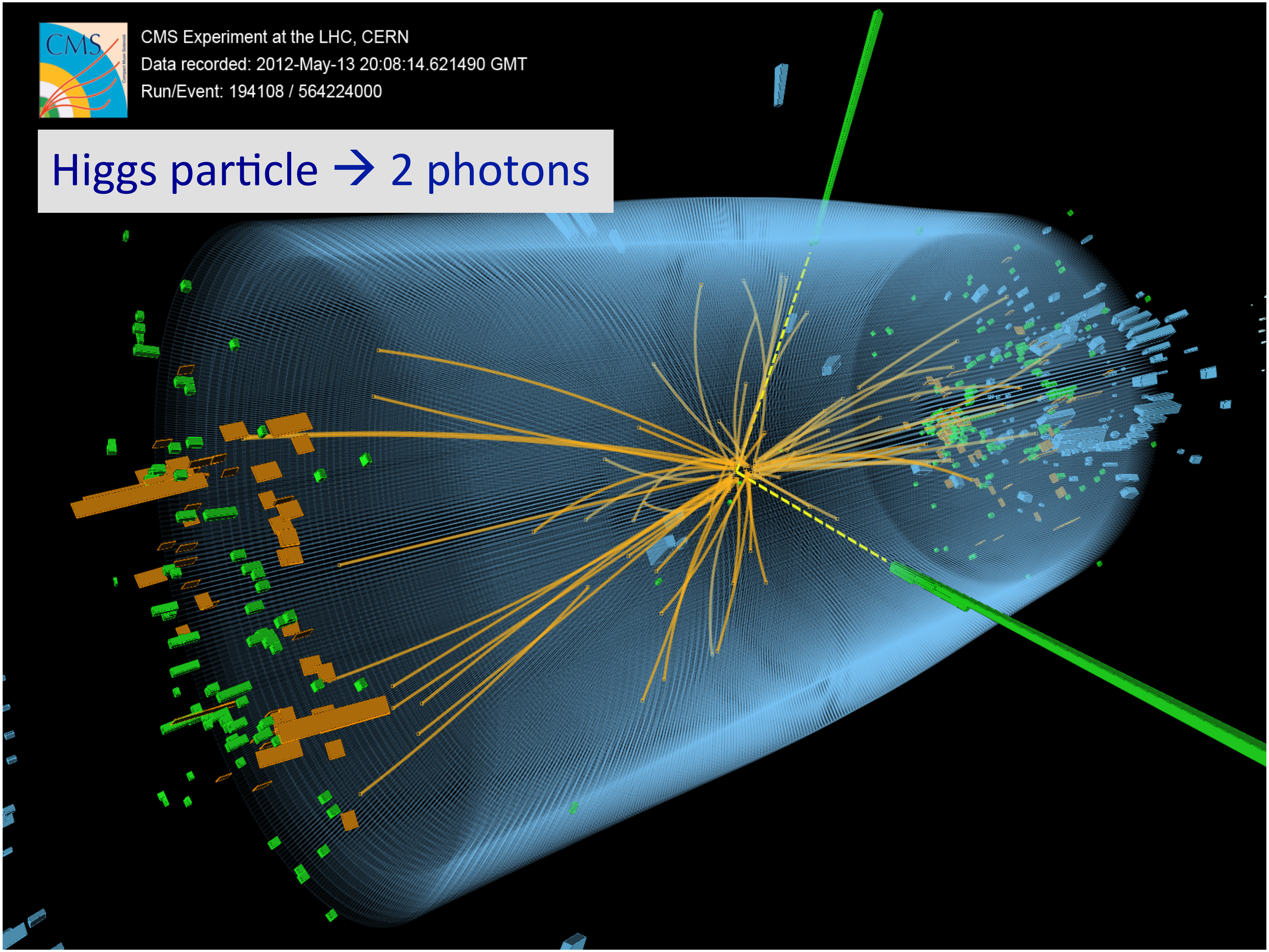
4μ+γ Mass : 126.1 GeV

Higgs boson → two Z bosons → 4 leptons



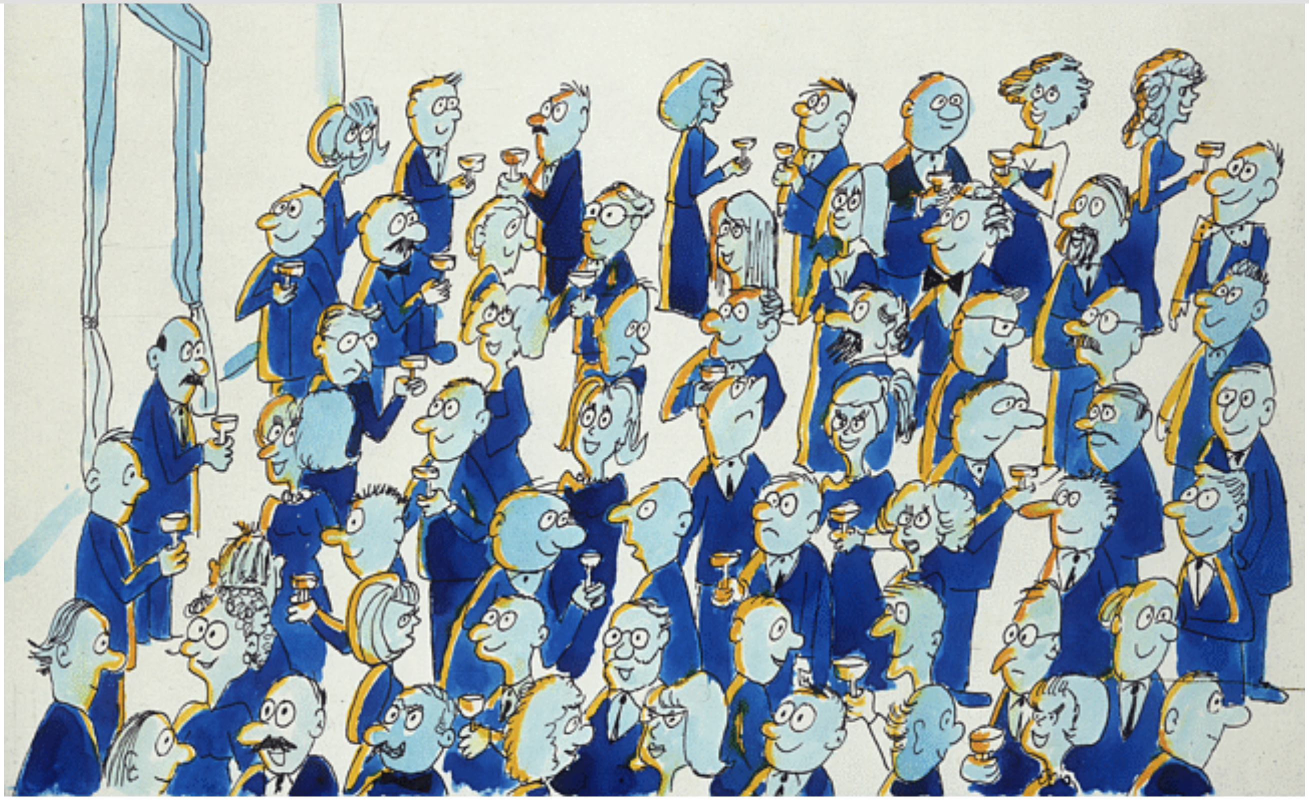
Higgs boson → two Z bosons → 4 leptons




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

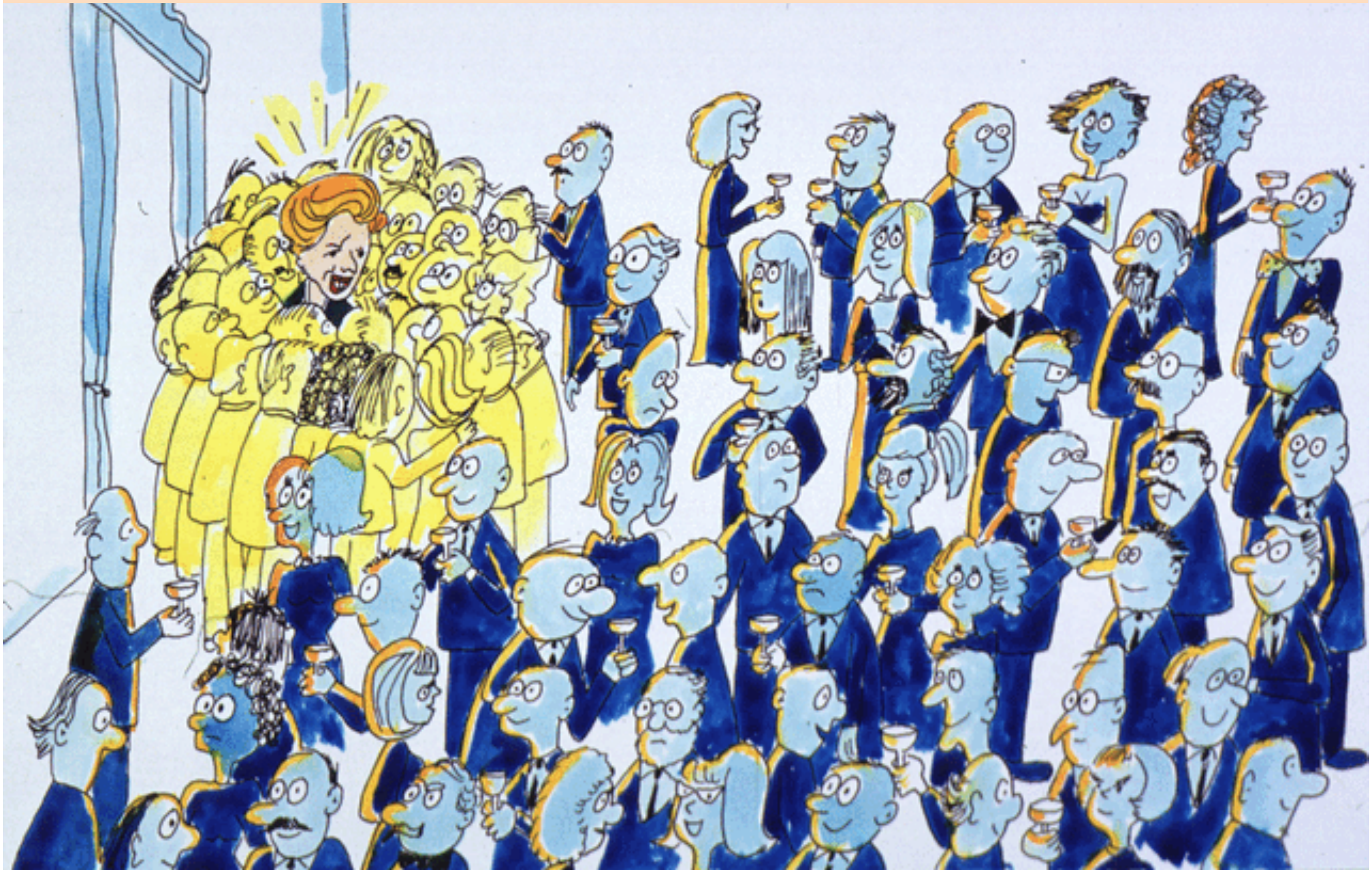
A quasi-political Explanation of the Higgs Boson; for Mr Waldegrave, UK Science Minister, 1993.

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.

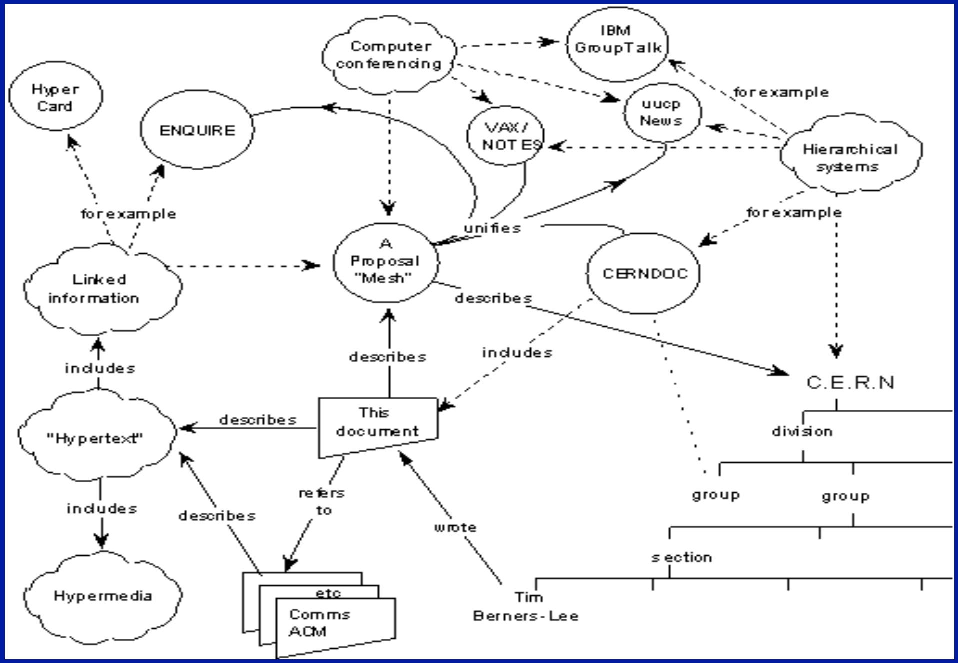
How the Higgs mechanism gives mass to massless particles



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.

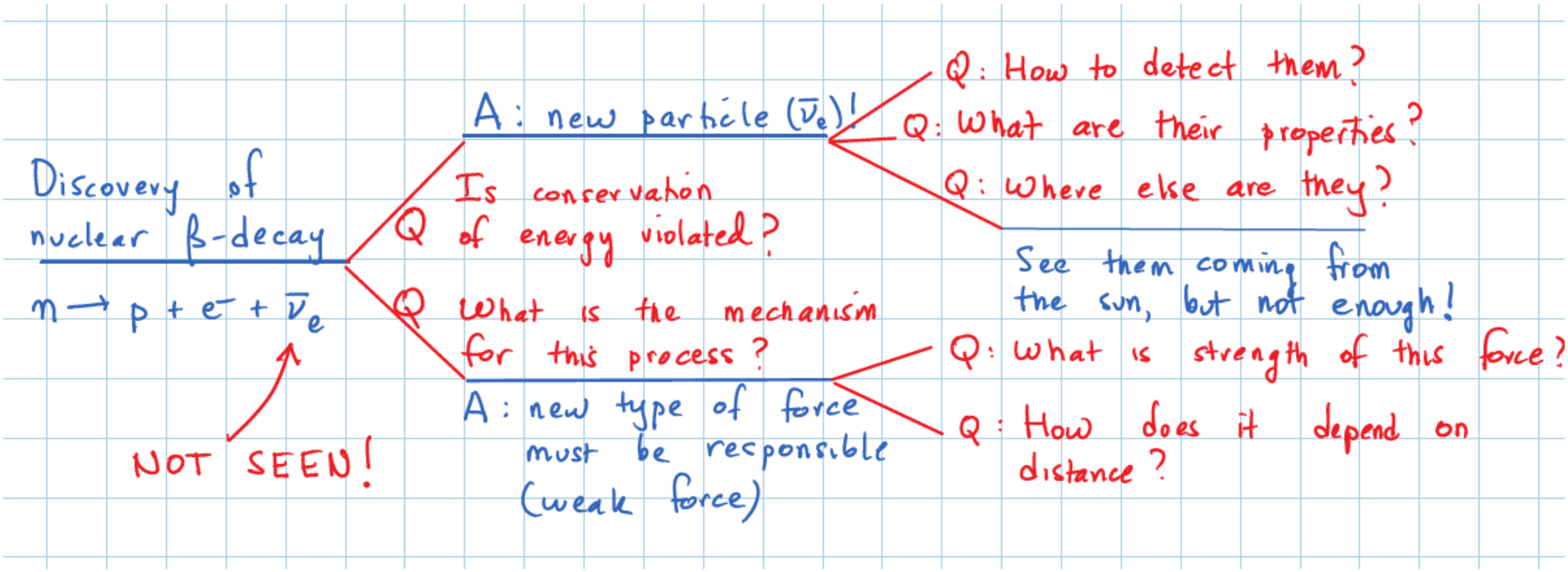


Many of the discussions of the future at CERN and the LHC era end with the question - ªYes, but how will we ever keep track of such a large project?º This proposal provides an answer to such questions. Firstly, it discusses the problem of information access at CERN. Then, it introduces the idea of linked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

Questions, Answers, Theories, Discoveries



Questions, questions!

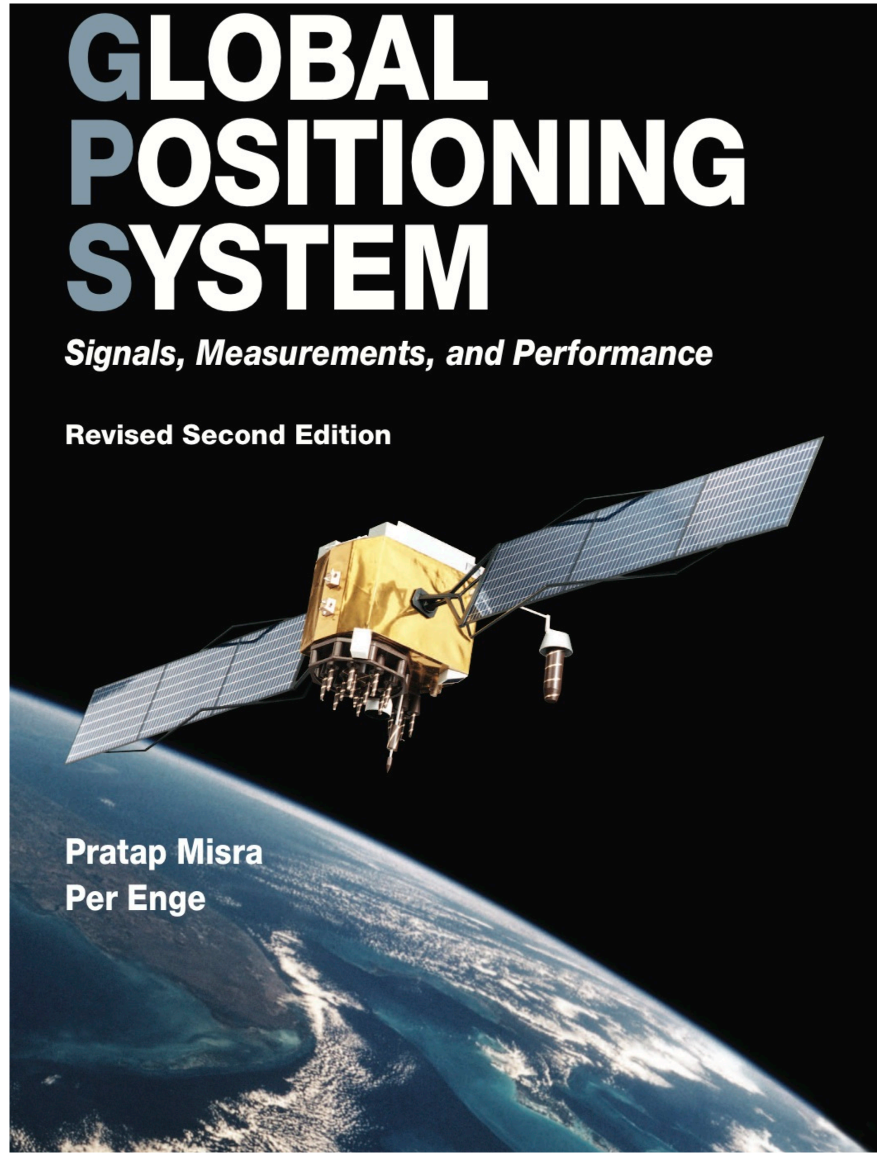
- Asking questions is what scientists do for a living.
- Usually, you can't answer a big question in one big leap.
- You have to break it down into little ones that you can make progress on.
- One of the "little questions" might turn out to be more important than your first question!
- How do you know if you got the right answer? (No answer book available!) Not simple! Lots of checking.
- Getting the right answer on just one little question is big accomplishment!

After 3 years of running...

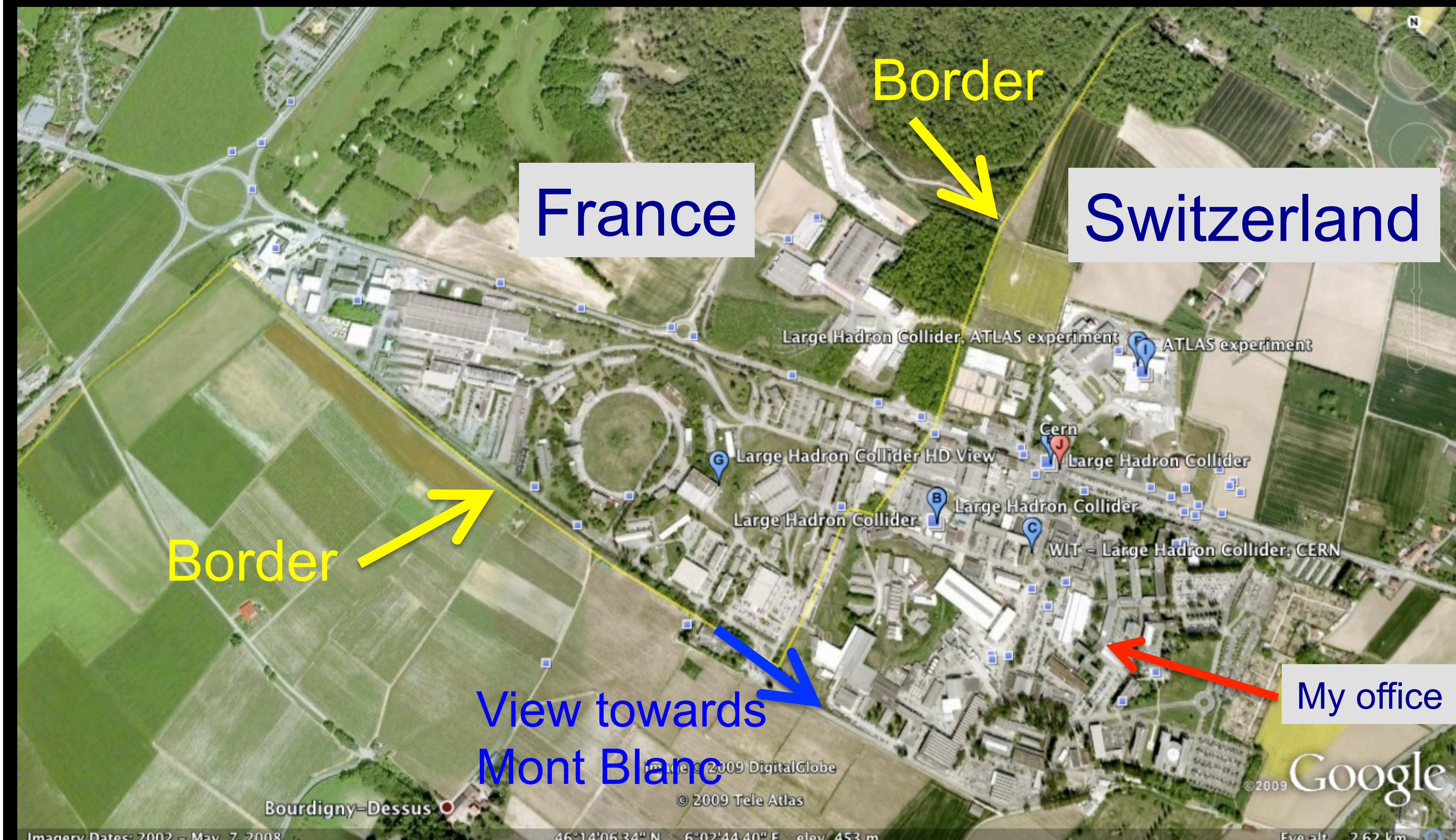
- Over 200 physics papers published.
- Our first major discovery: a “Higgs-like particle”.
- Need to fully establish the properties of the new particle. There are scenarios with multiple Higgs bosons (e.g. five of them!).
- Intensity search for particles that can explain the dark matter (“supersymmetric particles”).
- Train the next generation of scientists!
- The LHC project will continue for at least a decade.

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!



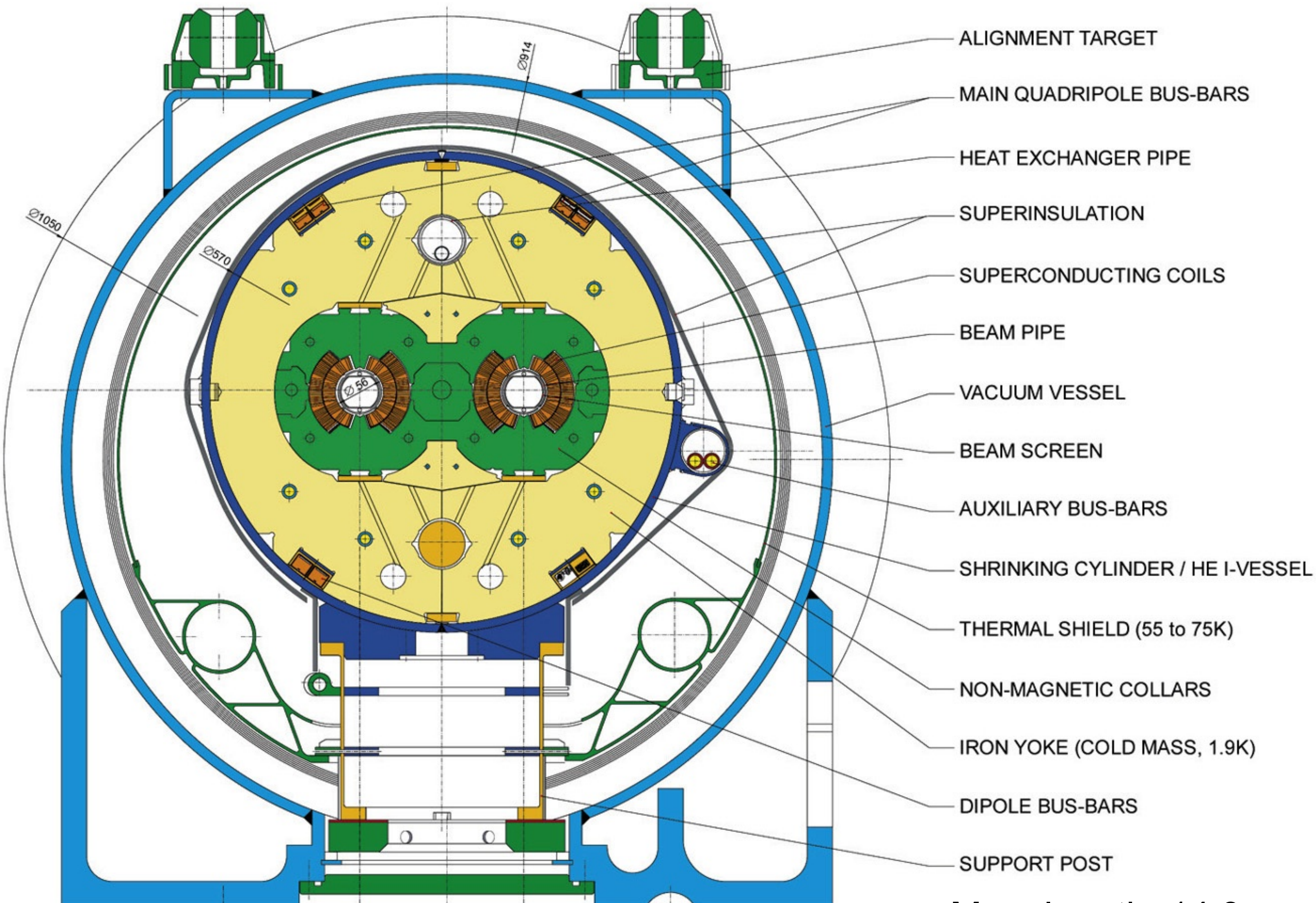
CERN main laboratory site



LHC Radio-Frequency Cavities

LHC DIPOLE : STANDARD CROSS-SECTION

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



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

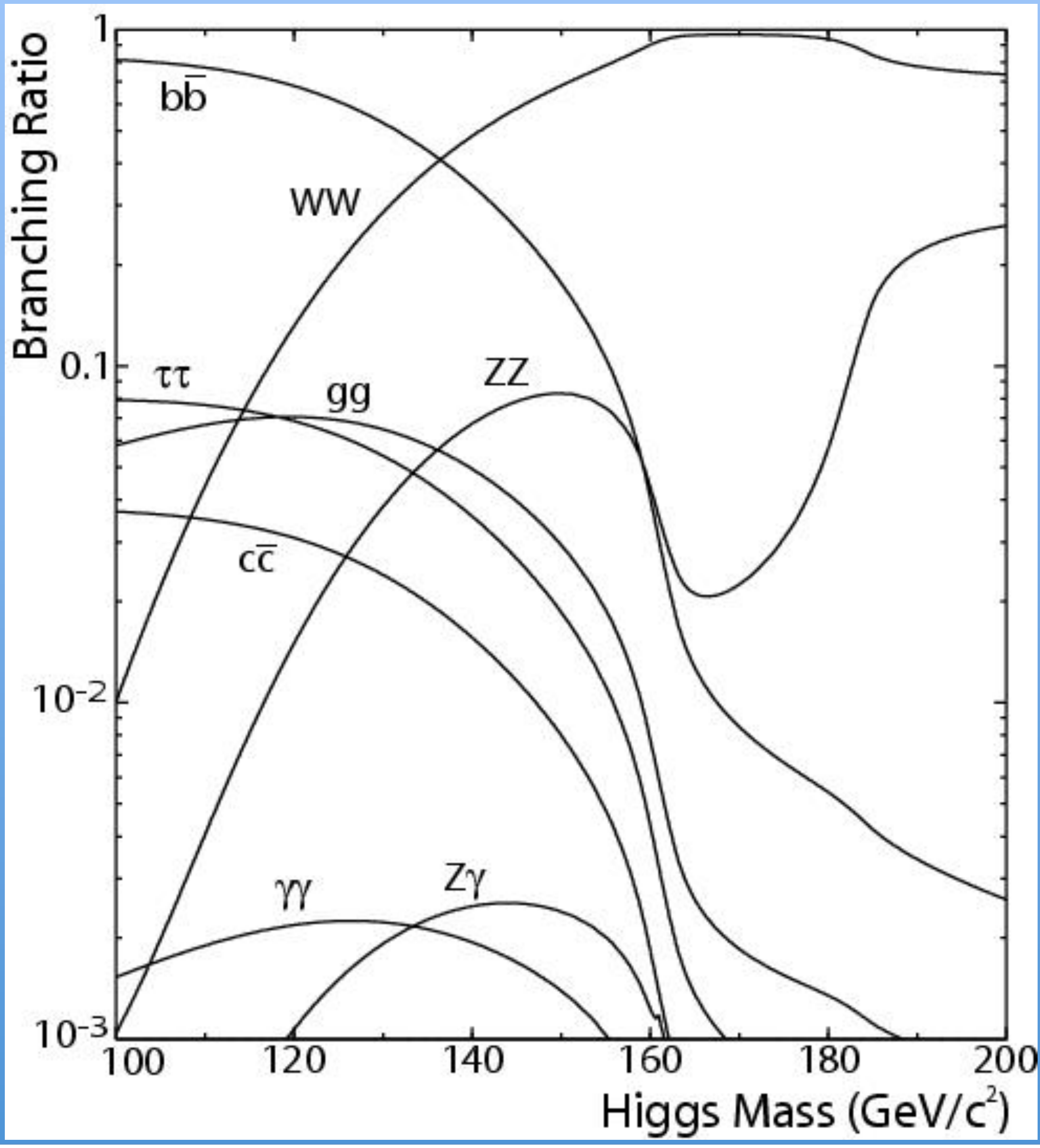
$$B(\mathrm{T}) = \frac{p_\perp(\mathrm{GeV})}{0.3 \cdot r(\mathrm{m})} = \frac{7 \cdot 10^3 \ \mathrm{GeV}}{0.3 \cdot (8.6 \cdot 10^3 \mathrm{m})} \approx 5 \ \mathrm{T}$$

Practice run on putting out a fire

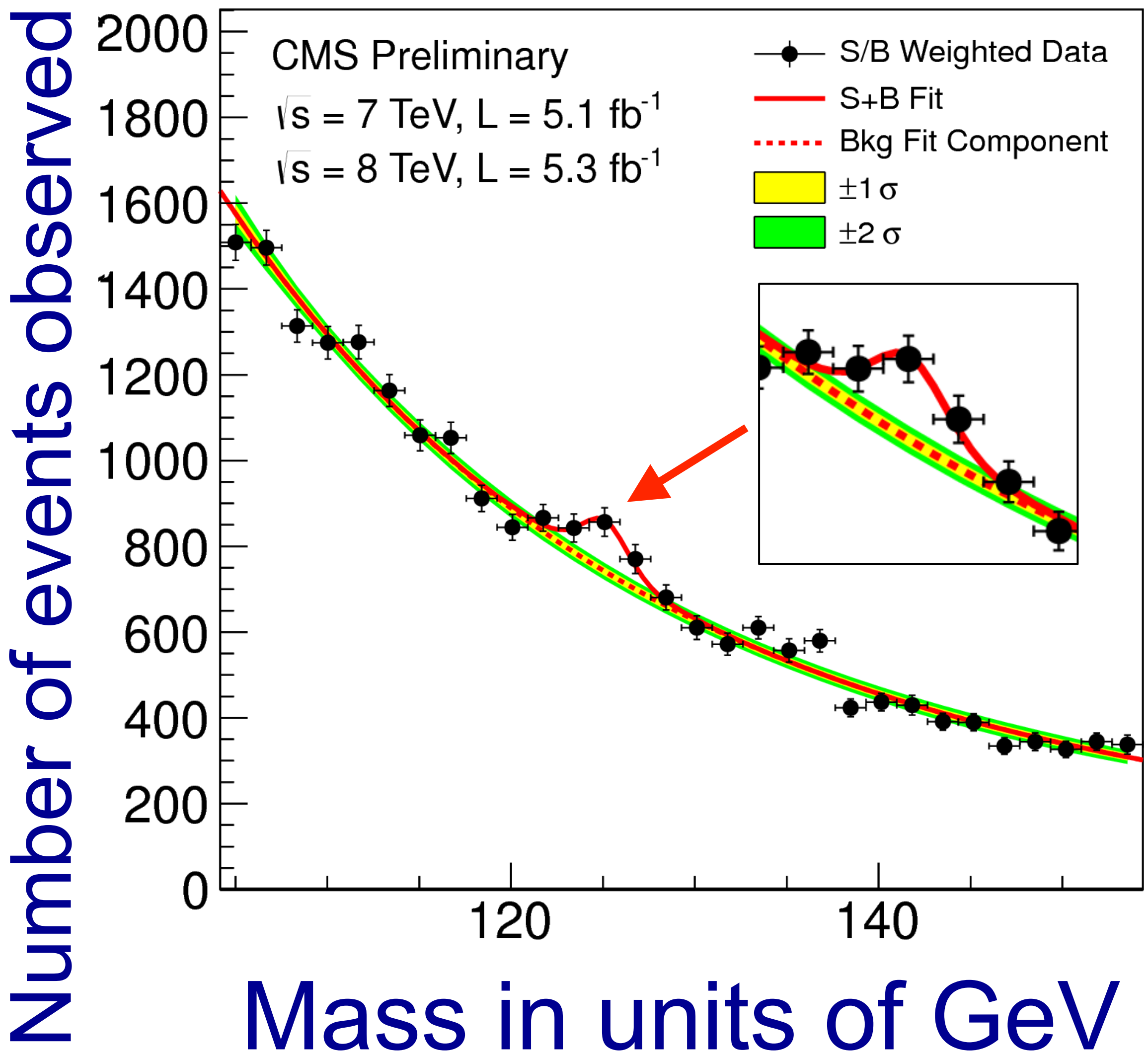
UCSB in the CMS Experiment

Lowering one of the CMS endcap muon detectors into the cavern

Higgs boson branching fractions



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.

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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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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.

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: Major roles of UCSB group

Area	Examples
Leadership/management	Top-level management, physics & software convenorships
Silicon Tracker Construction	Silicon detector module 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