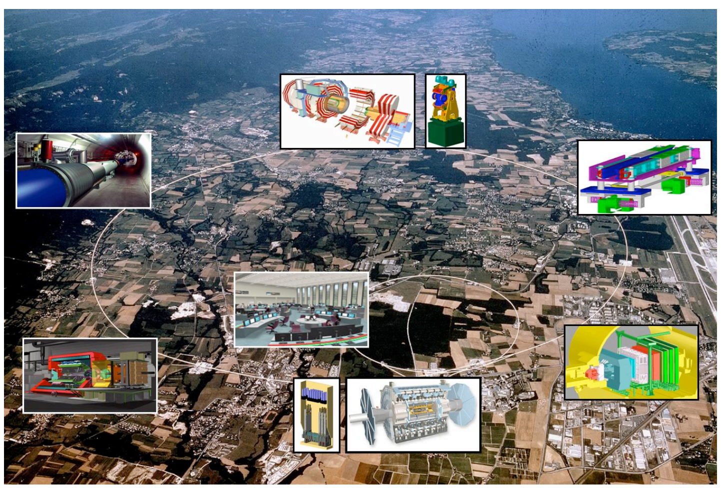
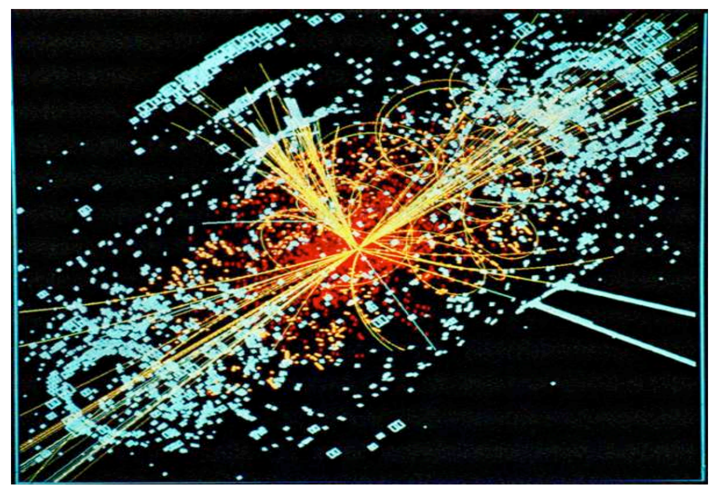
LHC Physics
GRS PY 898 B8

Introductory Lecture
1/14/2009

[Tulika Bose]





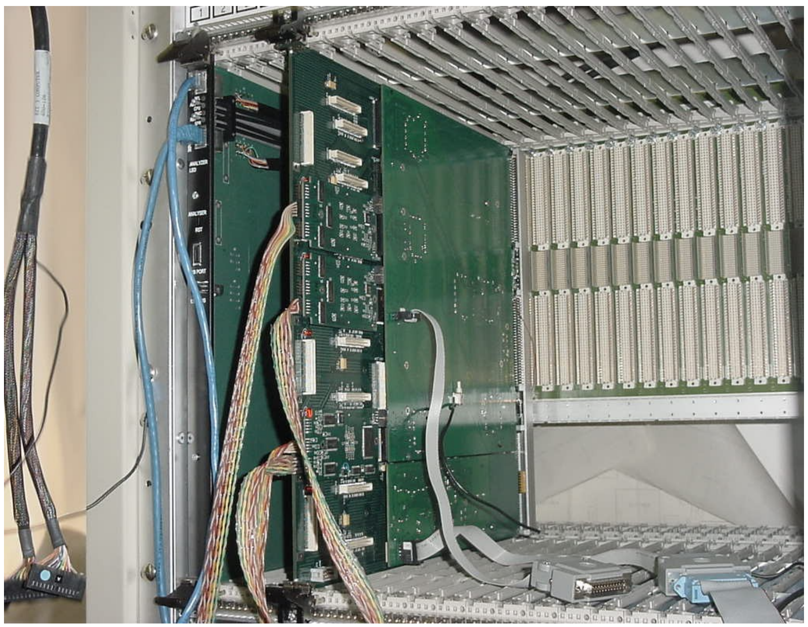
Lecturer

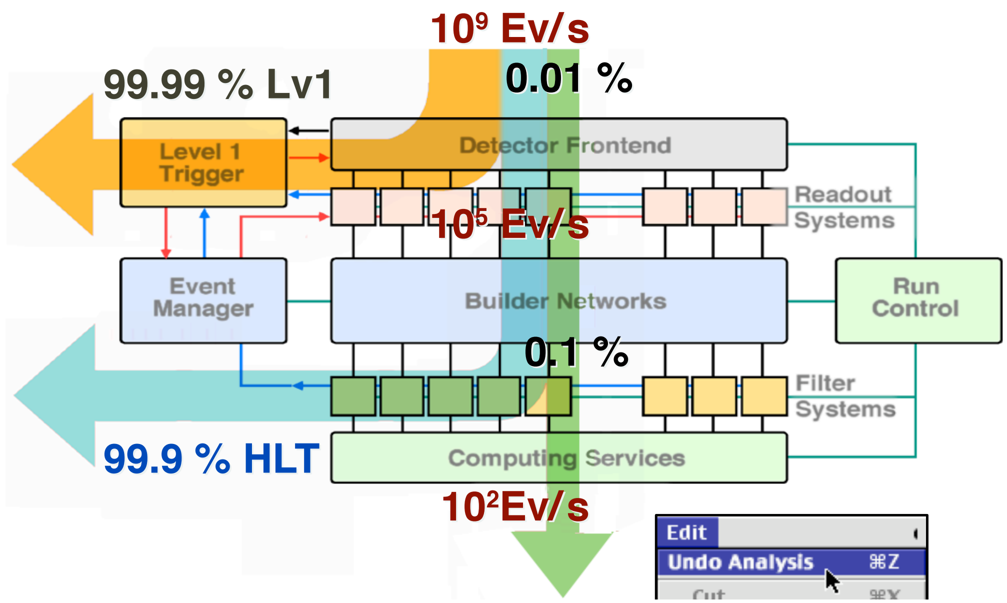
- Physics career
  - 1997-1998 Undergraduate project OPAL (LEP)
  - 1998-2000 Experimental plasma physics
  - 2000-2008 D0 (Fermilab)
  - 2006-present CMS (LHC)

- High Energy Physics measurements
  - Precision electroweak (W mass: OPAL)
  - B physics (Bs mixing)
  - Searches (W', long-lived particles, WZ resonances, heavy top quarks)

Lecturer

- Hardware/Software projects





L2 Silicon Track Trigger, L3 DAQ (D0)

HCAL L1 Trigger, High Level Trigger (CMS)

Course description

- Overview of the Large Hadron Collider (LHC) and its experiments
- Experimental methods/techniques for analysis of LHC data
- Discussion of some typical (sets of) analyses
  - Student reviews/seminars
- All the latest news from the LHC

You will learn how to do research as an experimentalist at the LHC or how experimentalists try to do research at the LHC

If you have specific requests for any topic please send me email

Course organization

- Course web-site: http://physics.bu.edu/~tulika/Teaching/Spring09/PY898.html
- Coordinates: Mon, Wed: 2:00-3:30pm ; PRB 261
  - Tentative schedule; to be finalized based on class size/ input
- Office hours: to be arranged (appointment via email)
- Lectures will be made available at the above web-site

Course requirements

- Participants will be given seminars/proceedings to review and asked to summarize/discuss in class
- Attend BU HEE seminars and submit a 1-page written summary of any ONE of them
  - Seminars start towards the end of January (Thursday afternoon)
- Plan to arrange a "mini-conference" at the end of the semester where participants will give a 15-30 minute talk on a LHC subject of their choice (that they learned during this course)

Course outline (tentative)

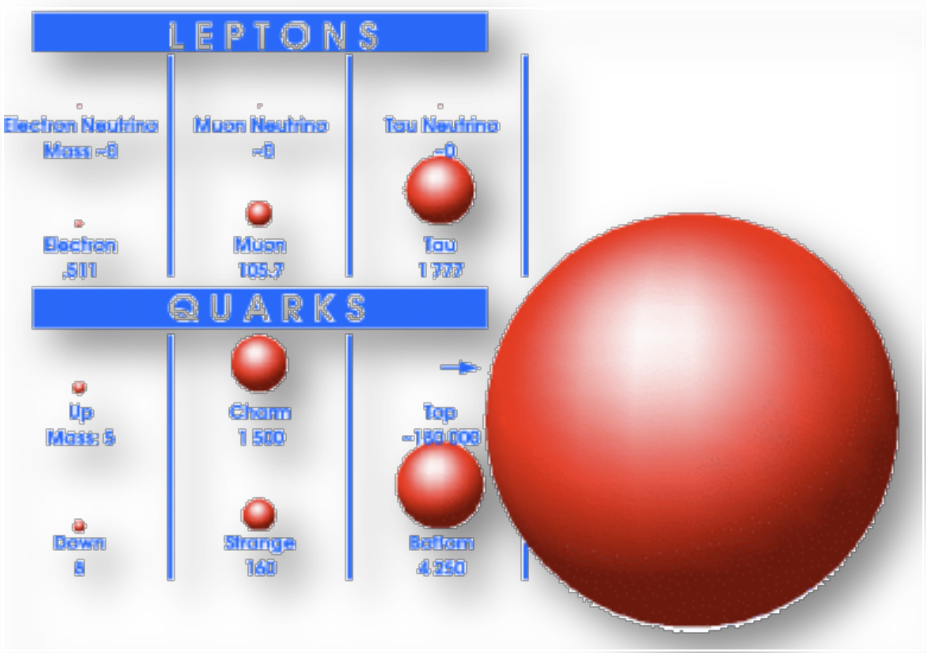
- Introduction to CERN/LHC
- The LHC experiments/detectors
- Overview of techniques/methods used for analysis of LHC data (including Tevatron experience)
  - Triggers
  - Lepton identification
  - Measurement of jets/MET
  - Tracking, b-tagging
  - Monte Carlo/simulation tools
  - Statistics
- Seminars on selected LHC analyses
  - Higgs, SUSY, Exotica, Top…

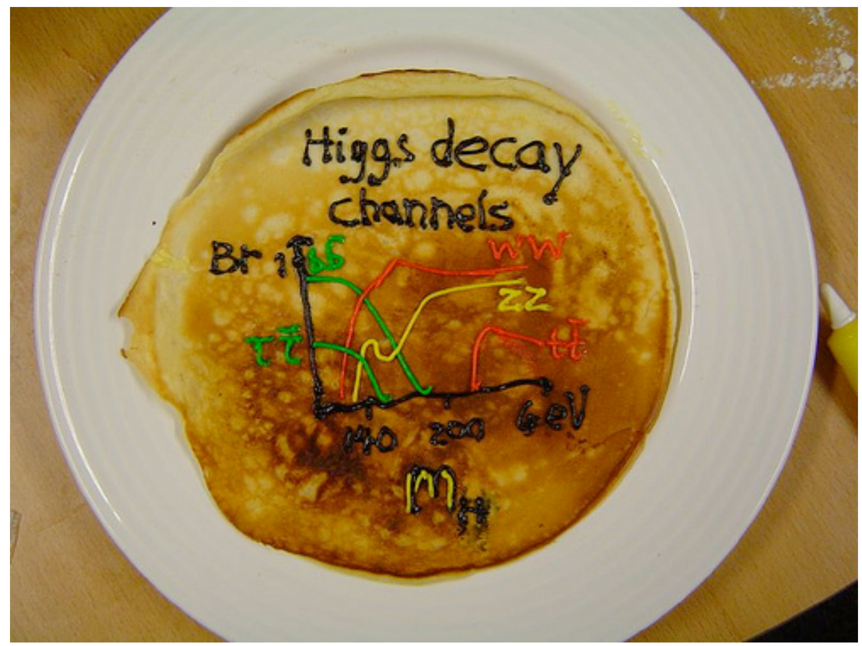
(Assuming that everybody has taken an introductory particle physics course; not essential though…)

The Standard Model: the fall ?

Some Unanswered Questions…

Why is there a large mass hierarchy
in the fermion sector ?

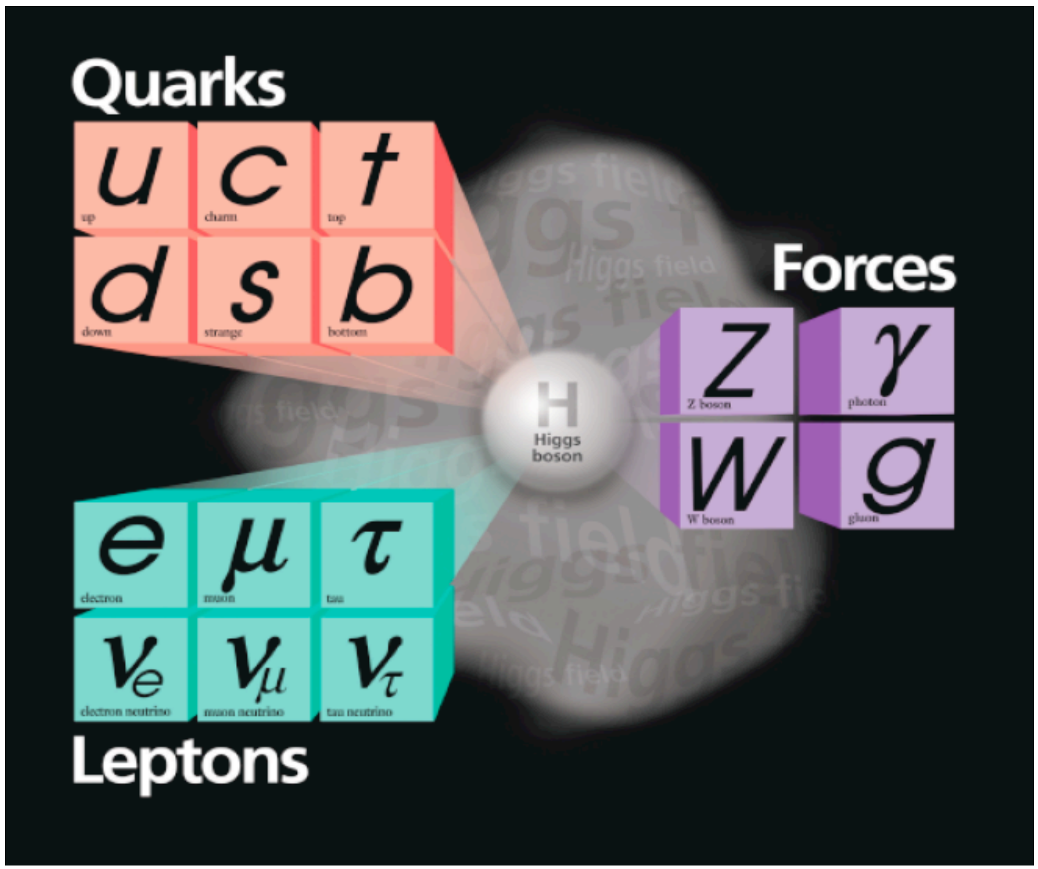




The Standard Model: the fall ?

Some Unanswered Questions…

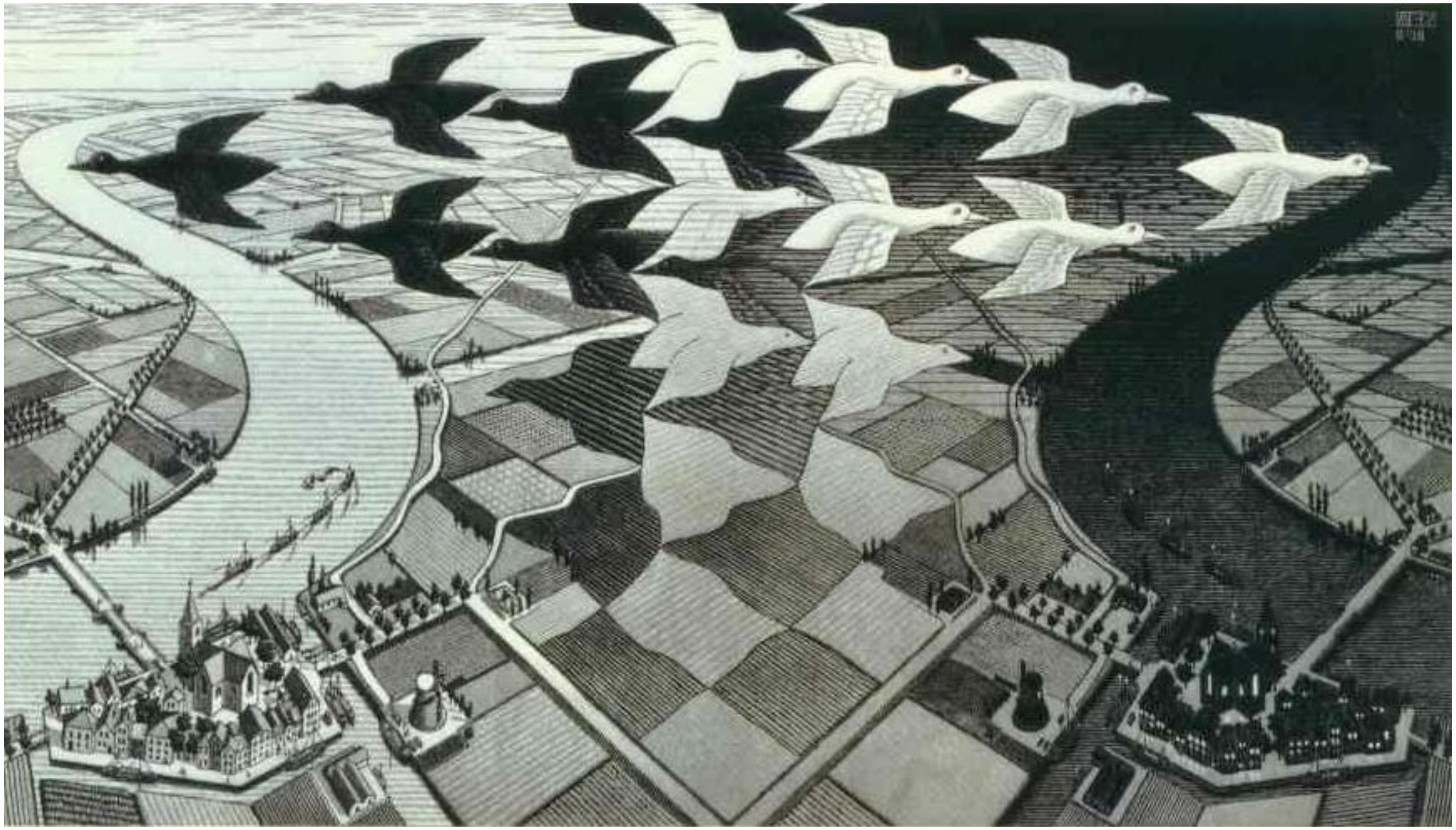
Why are there 3 generations ?



The Standard Model: the fall ?

Some Unanswered Questions…

How can we explain the matter anti-antimatter asymmetry ?



The Standard Model: the fall ?

Some Unanswered Questions…

What is dark matter ?

Are new particles the solution ?

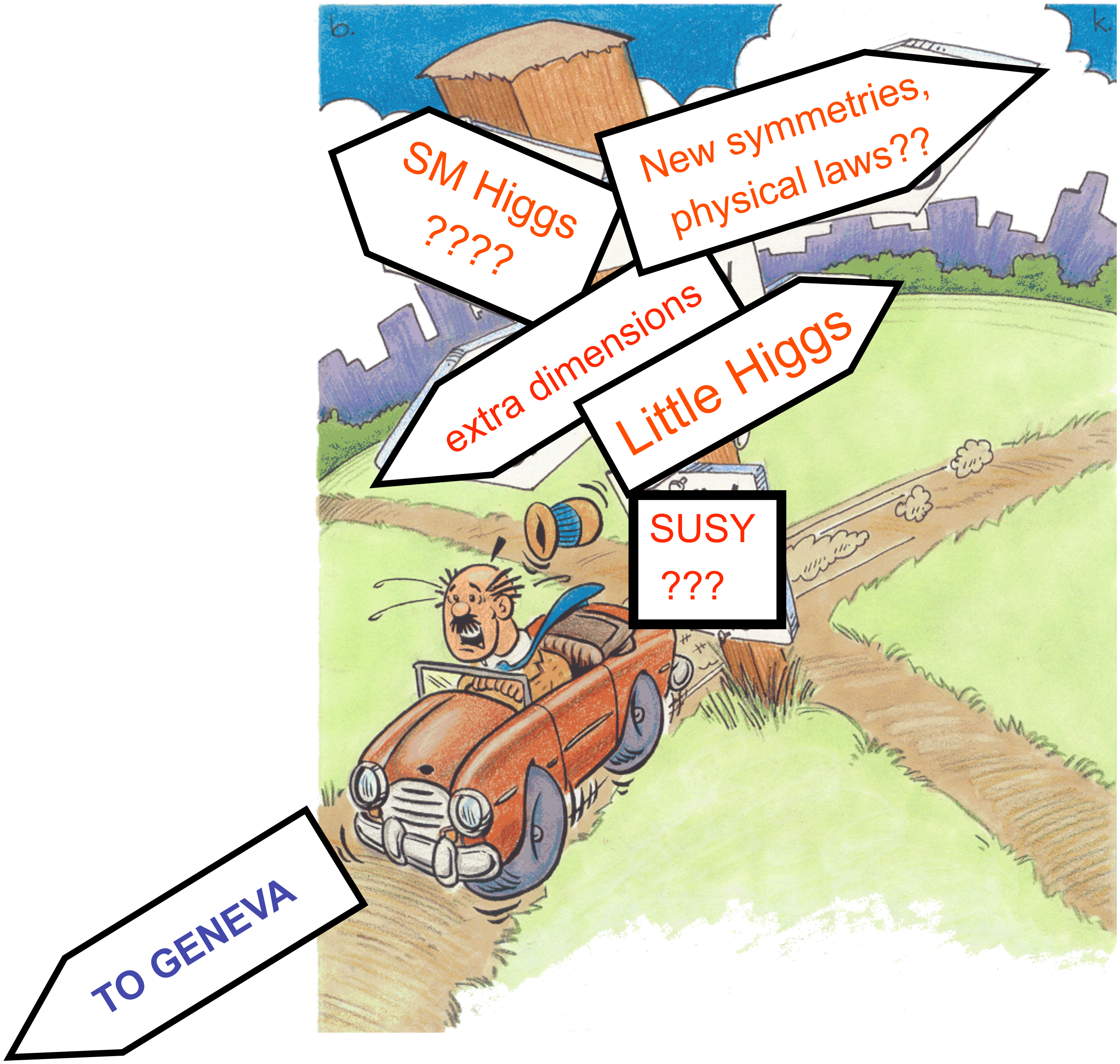
Hunting for the Exotic

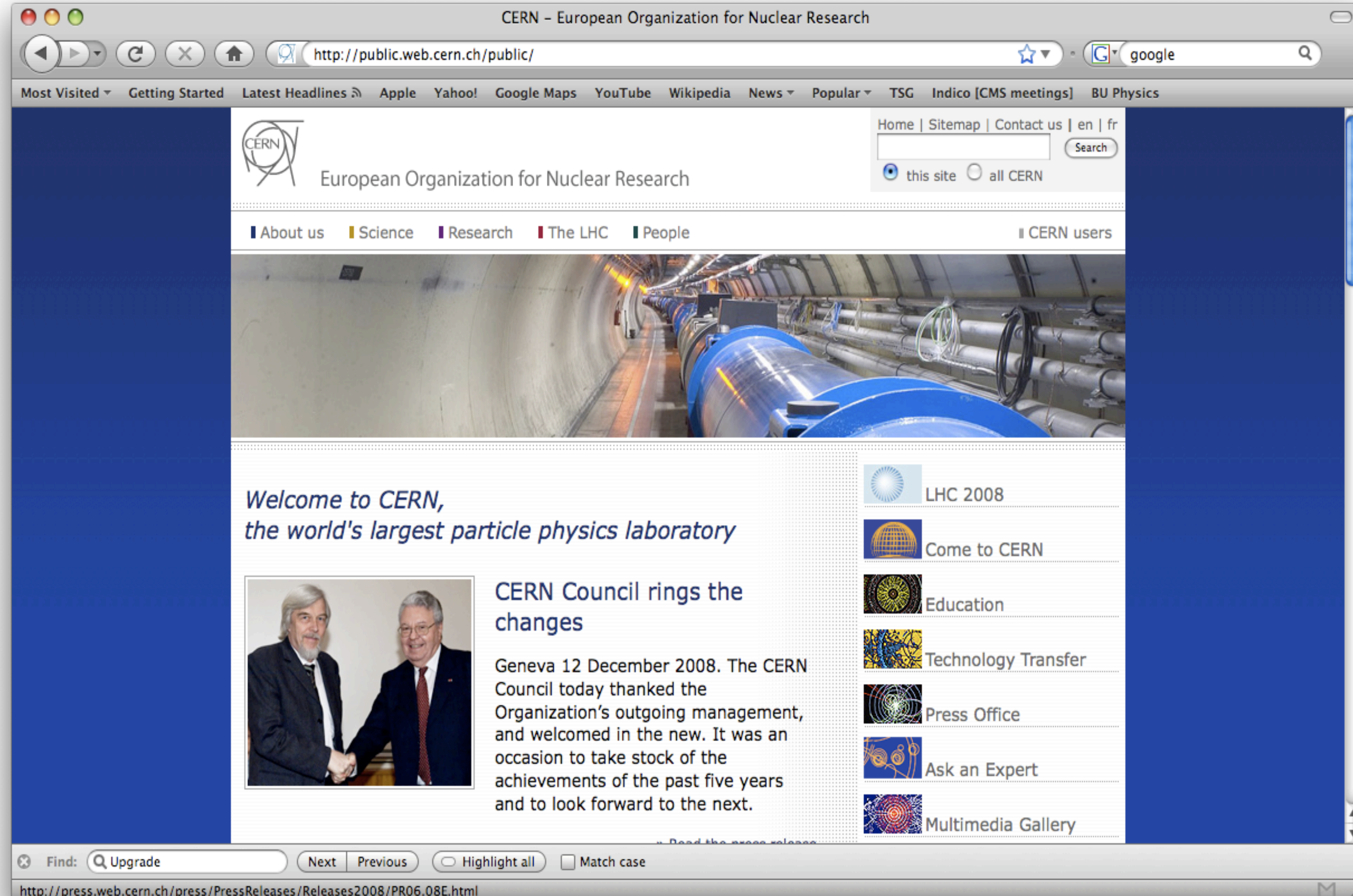
What new physics are we looking for ?

Start by asking these questions in the right way

Look more closely — More Precision, new techniques

Look in new places — Higher Energy, new measurements


SM Higgs
????
New symmetries,
physical laws??
extra dimensions
Little Higgs
SUSY
???
TO GENEVA



http://public.web.cern.ch/public/

The name CERN

CERN is the European Organization for Nuclear Research. The name is derived from the acronym for the French Conseil Européen pour la Recherche Nucléaire, or European Council for Nuclear Research, a provisional body founded in 1952 with the mandate of establishing a world-class fundamental physics research organization in Europe. At that time, pure physics research concentrated on understanding the inside of the atom, hence the word 'nuclear'.

When the Organization officially came into being in 1954, the Council was dissolved, and the new organization was given the title European Organization for Nuclear Research, although the name CERN was retained.

Today, our understanding of matter goes much deeper than the nucleus, and CERN's main area of research is particle physics — the study of the fundamental constituents of matter and the forces acting between them. Because of this, the laboratory operated by CERN is commonly referred to as the European Laboratory for Particle Physics.

Half of the world's particle physicists

- CERN employs around 2500 people
- Some 8000 visiting scientists, half of the world's particle physicists, come to CERN for their research. They represent 580 universities and 85 nationalities.

A brief history

1954 – first excavations at the site

2008 – all ready for beam

A brief history

- 29th September 1954 : the European Organization for Nuclear Research officially comes into being (acronym CERN)
- 1957: the first accelerator at CERN starts operating (600 MeV Synchrocyclotron or SC)
- 1959: Proton Synchrotron (PS) accelerates protons for the first time
- 1971: the world's first proton-proton collider – Intersecting Storage Rings (ISR)
- 1983: discovery of the W and Z at the Super Synchrotron (SPS)
- 1989: Large Electron Positron (LEP) collider commissioned
- 1994: CERN Council approves Large Hadron Collider (LHC)
- 2000: LEP shutdown; construction for the LHC starts
- 2008: The LHC sees first beam on Sep 10th
- 2009: first collisions expected at the LHC

Nobel dreams

Nobel dreams

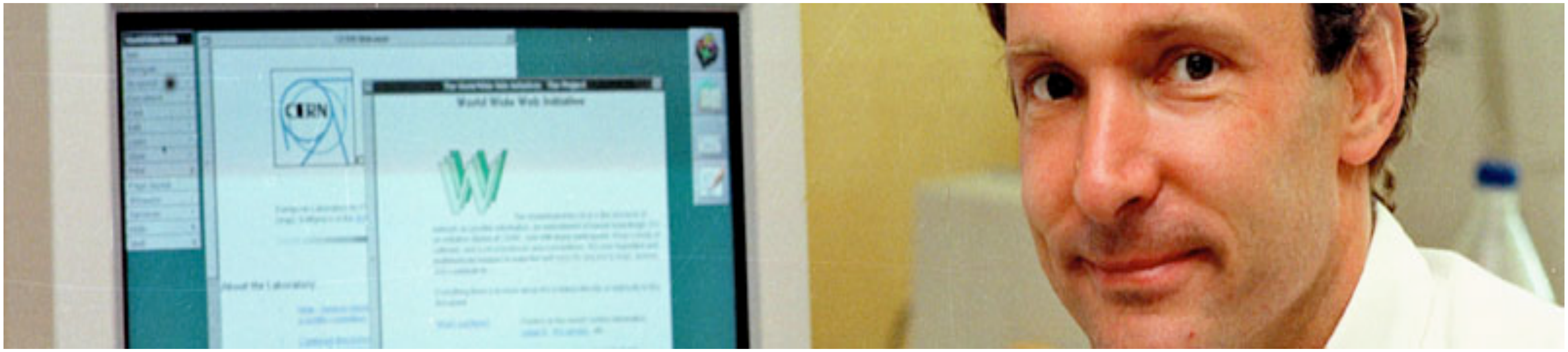
J. Steinberger, F. Bloch, S. Ting, G. Charpak, C. Rubbia, S. van deer Meer

Read more at

http://public.web.cern.ch/Public/en/About/Nobels-en.html

Something else happened at CERN in 1990 that changed the world forever….

The web was born



- Tim Berners-Lee (CERN) invented the World Wide Web (WWW) in 1990
- Main design aim: meet the demand for automatic information sharing between scientists working in different universities and institutes all over the world.

Some useful links

- CERN in 3 minutes (video link)
- CERN Bulletin
- CERN Courier

- Some fun links:
- http://www.youtube.com/watch?v=s9XotvwgnaY
- LHC rap

Some useful videos

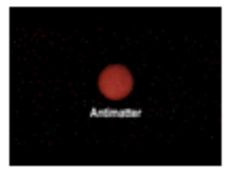
http://www.labreporter.com/

Featured Films: The Science behind the Large Hadron Collider

In Search of Giants

Hunting for Higgs

Sizing things up

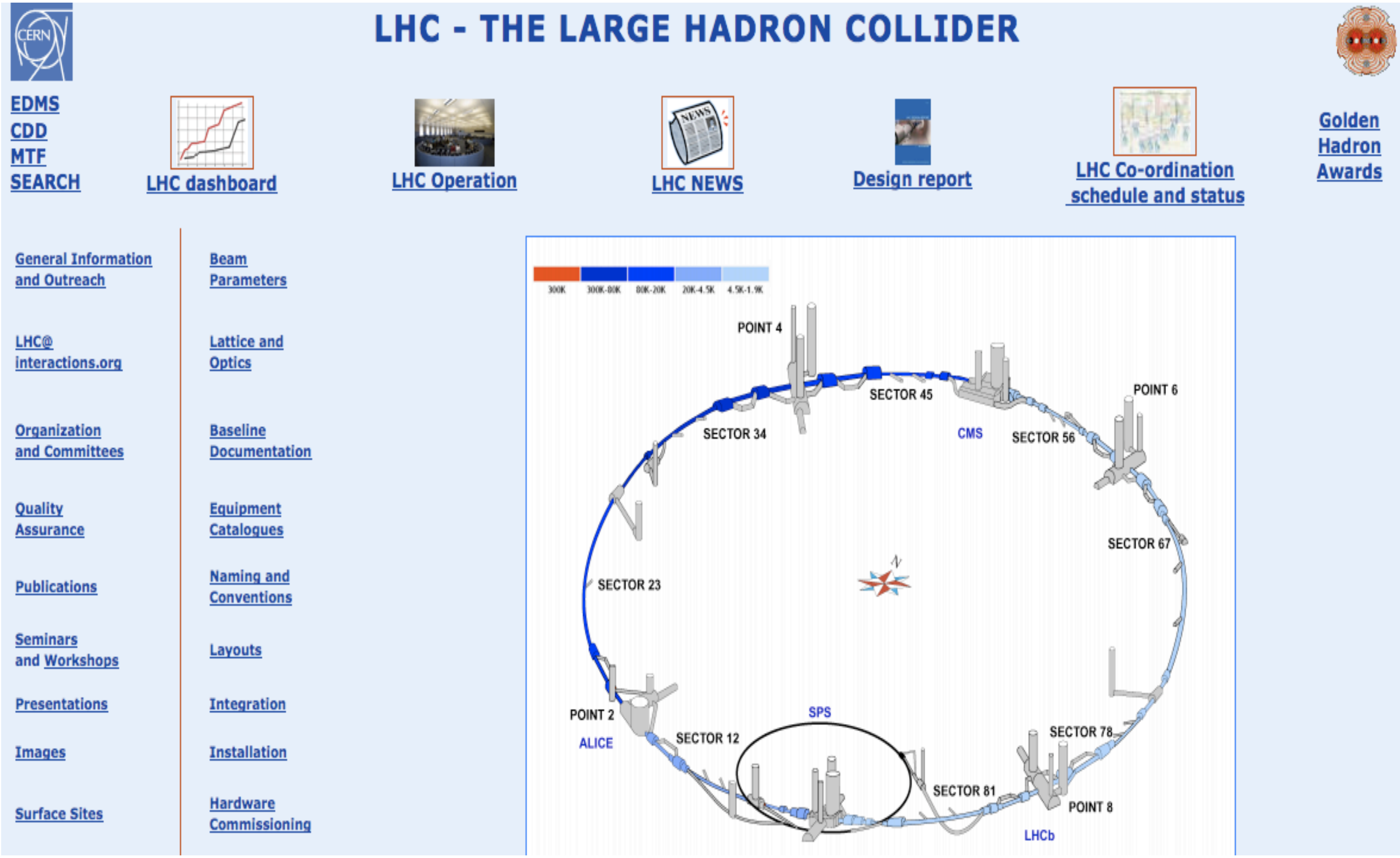


The Matter with Antimatter

The Mystery of the Missing Mass

B is for Beauty

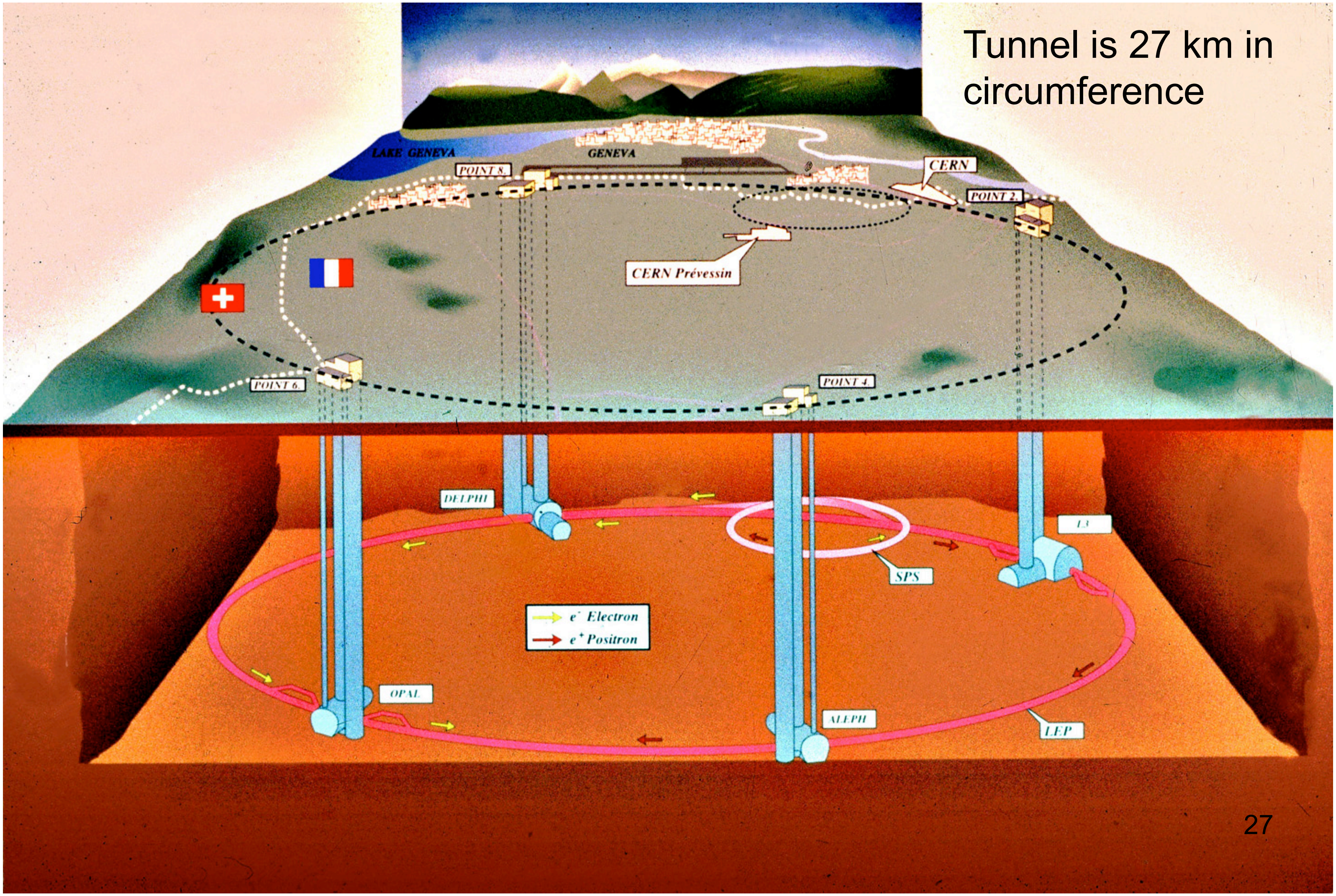
Deep beneath the ground in Geneva, thousands of scientists from all over the world are working together to build the biggest, most complicated machine in the world. It's part of the most ambitious scientific experiment of all time: The Large Hadron Collider (LHC) at CERN. These films reveal the scientific questions at the heart of the experiment and what scientists hope to achieve once the machine is switched on later this year.



http://lhc.web.cern.ch/lhc/

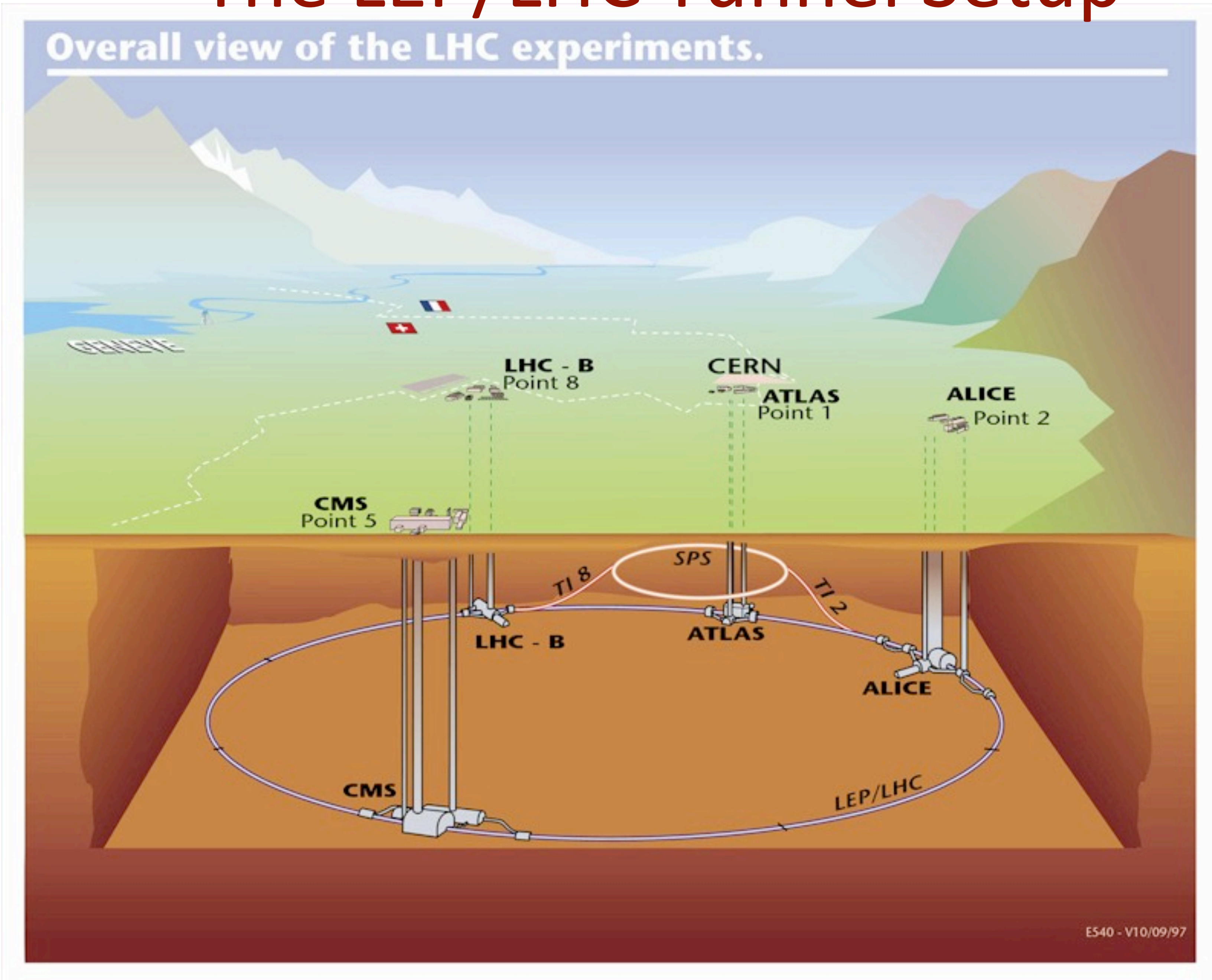
Lord of the Ring

The LHC re-uses the LEP tunnel



Tunnel is 27 km in circumference

The LEP/LHC Tunnel Setup



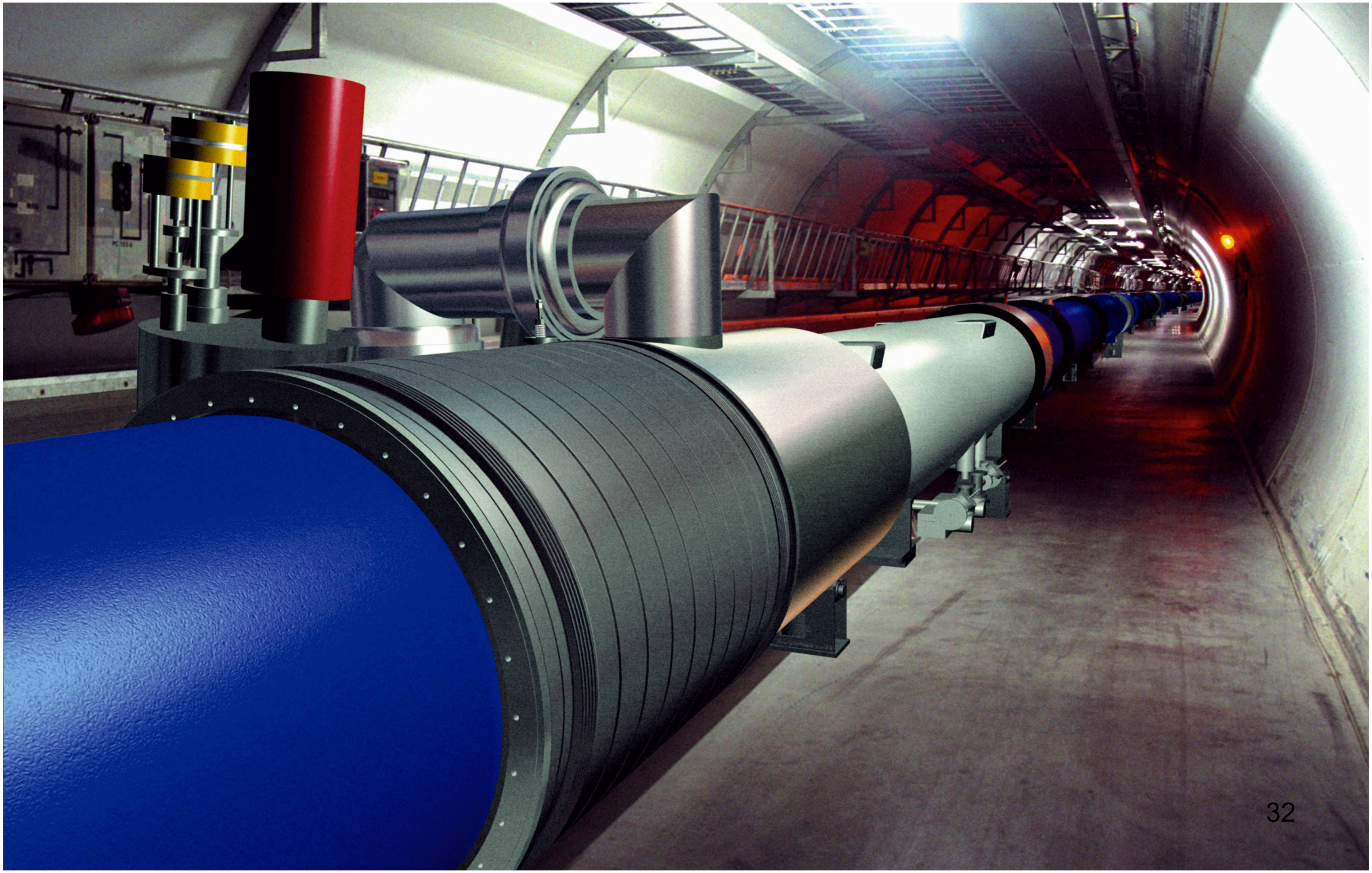
The LEP/LHC tunnel

- The 27 km circumference tunnel is built at a slight gradient of 1.4%
  - Due to geological constraints (translating into cost)
  - Reduce the depth of the costly vertical LEP access shafts
- The depth varies between 175m (under the Jura mountains) and 50 m (lake Geneva site)

LEP Tunnel before LHC

Empty Tunnel: LEP Disassembled

LHC : Simulation



May 2007: first LHC magnet being lowered into the tunnel

LHC : the real thing (2008)

Frontier Physics meets Frontier Technology

- It is the world's largest superconducting installation.
  - 27 km circumference
  - 30,000 tons of 8.4 Tesla dipole magnets (1232)

- It is colder than outer space (-271 ±C)
  - cooled to 1.9 degrees K by 90 tons of liquid helium

- It contains a vacuum more perfect than anywhere between the Earth and the space station.

- It will produce close to 40 million proton-proton collisions per second.

- All this makes it not only a machine for frontier physics, but also a machine for frontier technology.

Comparisons…

The energy of an A380 at 700 km/hour corresponds to the energy stored in the LHC magnet system :

Sufficient to heat up and melt 12 tons of Copper!!

The energy stored in one LHC beam corresponds approximately to…

- 90 kg of TNT

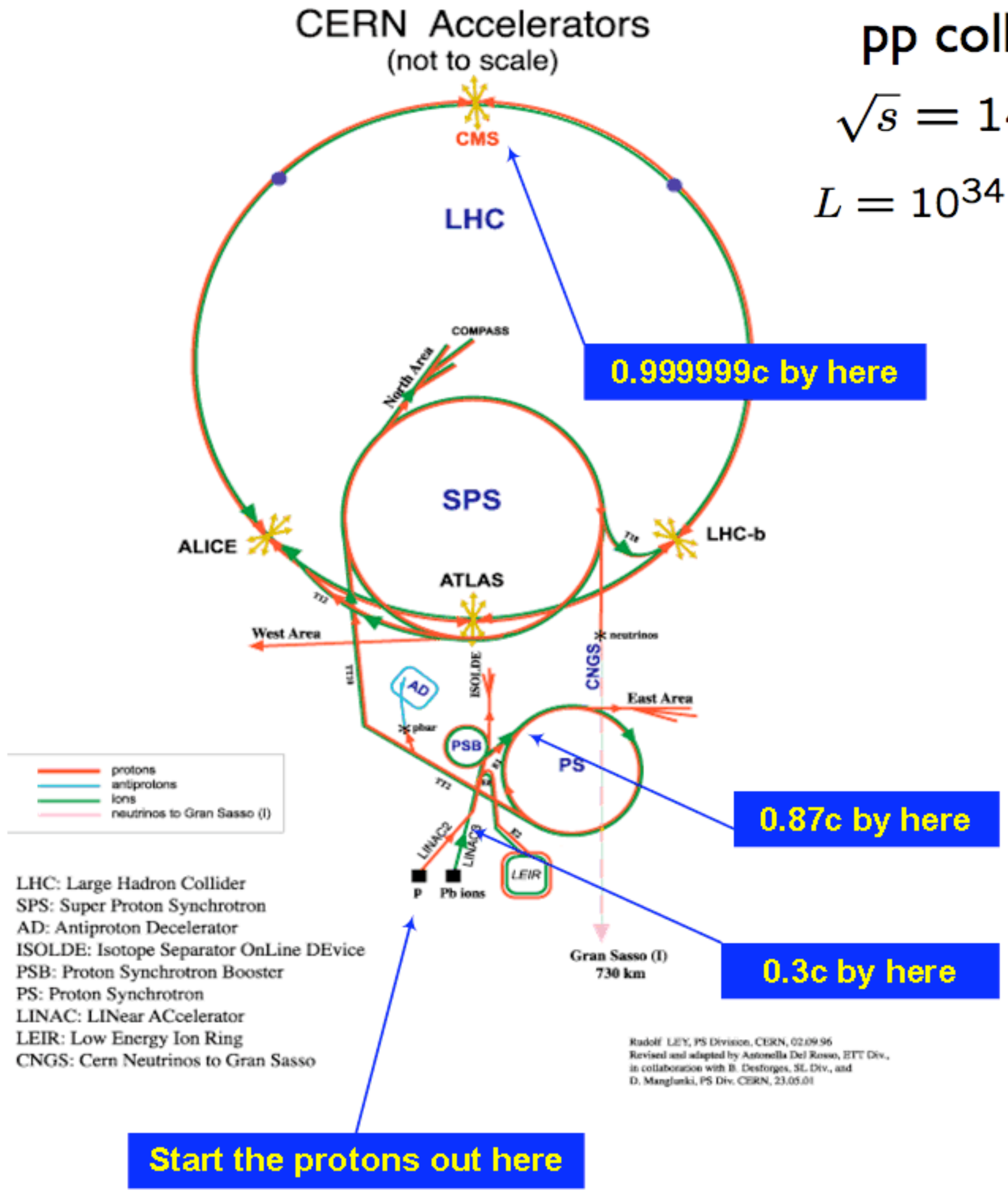
- 8 litres of gasoline

- 15 kg of chocolate

pp collisions:

$$\sqrt{s} = 14 \text{ TeV}$$

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



Brief story of a proton

- Hydrogen atoms taken from standard hydrogen bottle; electrons stripped off to yield protons
- Protons injected into the PS booster at an energy of 50 MeV from Linac2
- Booster accelerates protons to 1.4 GeV
- Proton beam sent to PS where it is accelerated to 25 GeV
- Protons sent to SPS; accelerated to 450 GeV
- Transferred to the LHC in bunches (clock-wise and anti-clockwise directions); accelerated for 20 minutes to their nominal 7 TeV

LHC parameters

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1×10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

(*) Energy per nucleon

LHC beam parameters @ 7 TeV

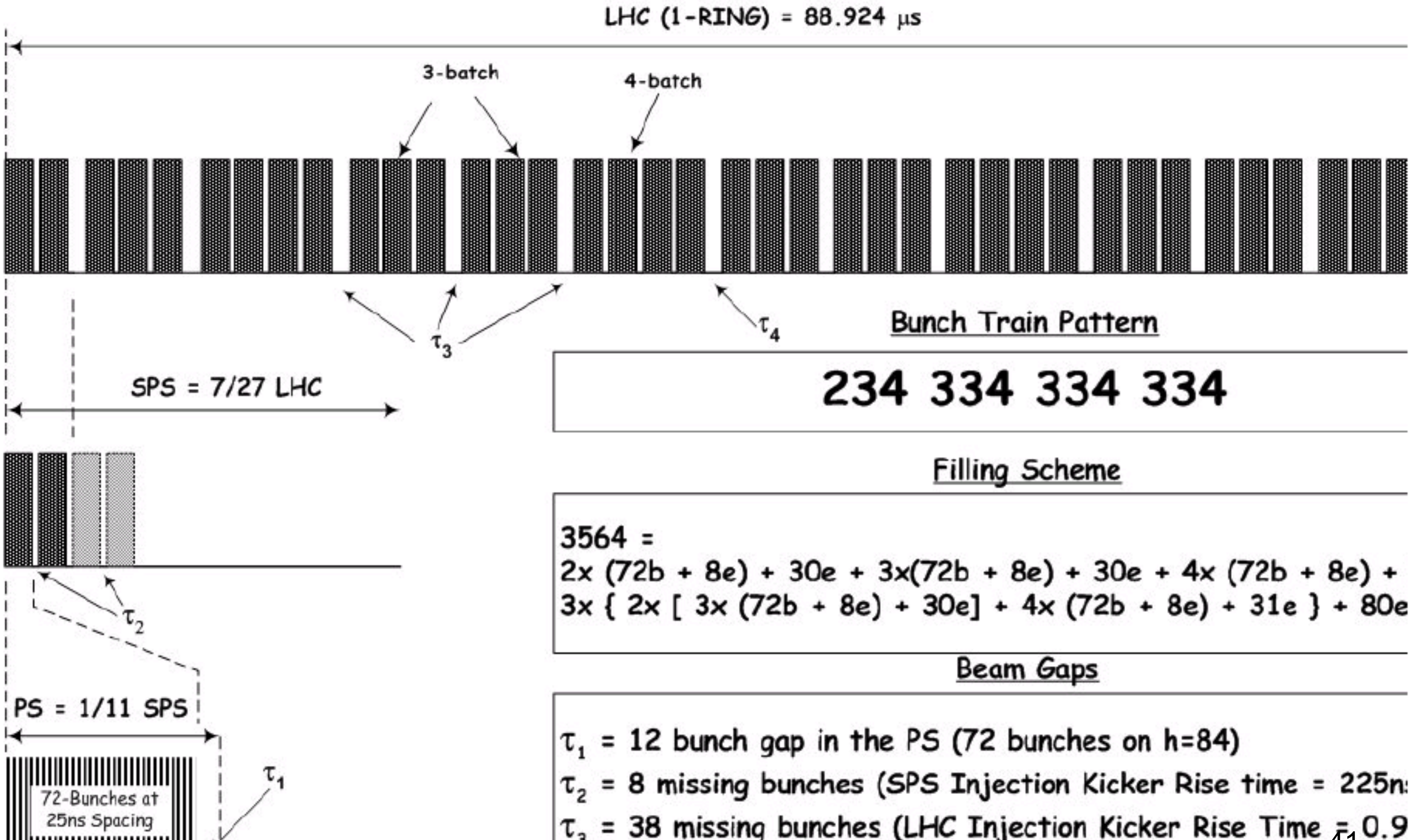
Bunch Intensity	1.1×10^{11}
Number of bunches	2808
emittance	5×10^{-10} m
β* fully squeezed	55 cm
beam size at IP	16 μm
Crossing angle	285 μrad
Bunch length	1.06 ns (7.5 cm)
Luminosity	10^{34} $cm^{-2}s^{-1}$
Total Beam energy	362 MJ per beam

Full list at:

http://cern.ch/ab-div/Publications/LHC-DesignReport.html

Chapter 2

Bunch Configuration



Buckets and bunches

- # of time slices or "buckets" = 3564
- 88924 ns/ 3564 = 24.95 ns (bucket size)

  = 40.079 MHz collision frequency
- A 25 ns. beam gives us a peak crossing rate of 40 MHz.

- Because of the gaps we get an average crossing rate = number of bunches * revolution frequency

  = 2808 * 11245 = 31.6 MHz.

Luminosity

Interaction rate $$\mathcal{R} = \mathcal{L} \cdot \Sigma$$

L = luminosity
Σ = cross section

$$\mathcal{L} = \frac{f_0 B N^2}{A}$$

f_0 = rev. frequency
B = # of bunches
N = # of particles in bunch
A = area

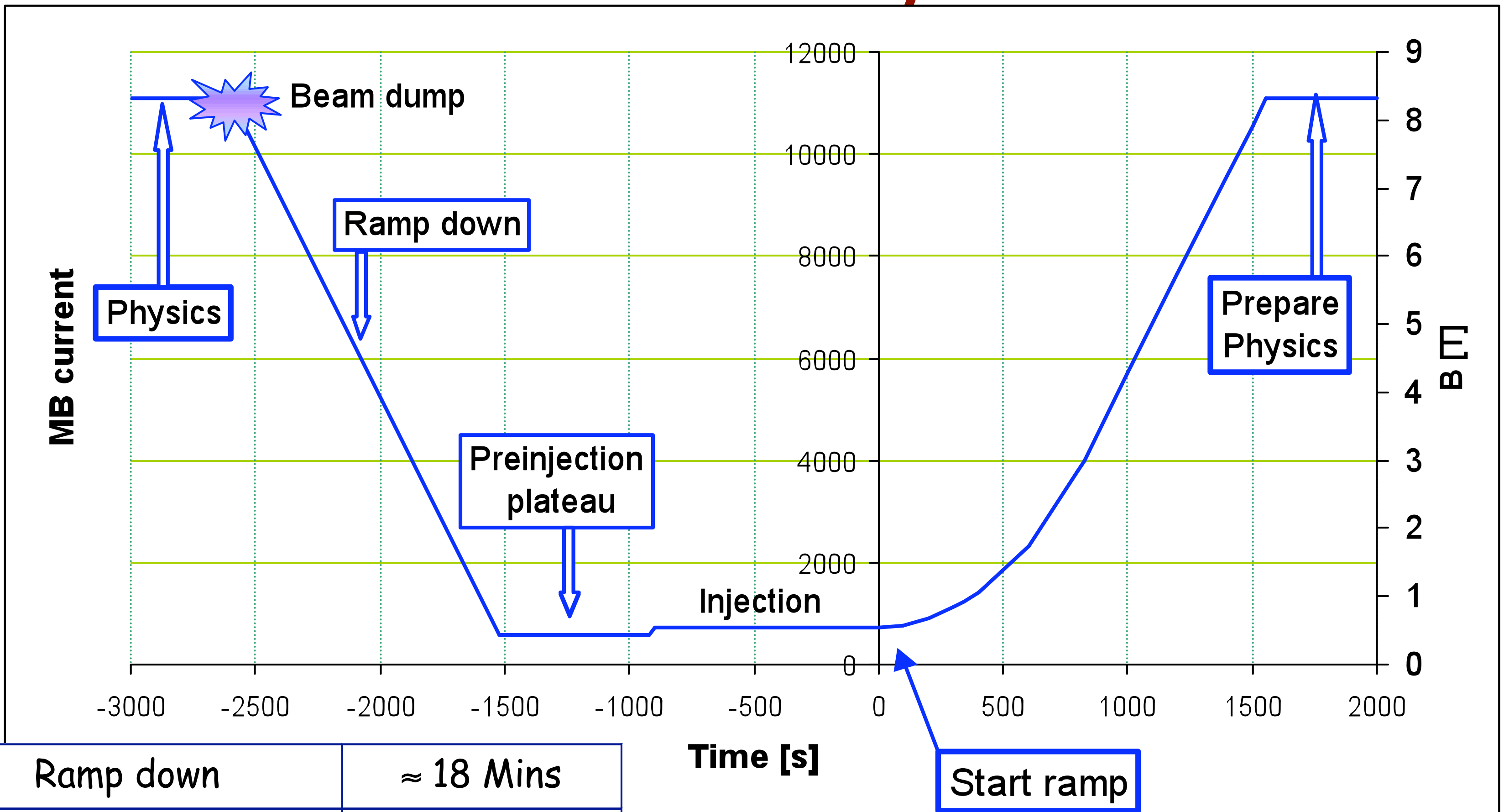
$(10^{34}\text{cm}^{-2}\text{sec}^{-1}$ for LHC)

$$\#\text{events} = \int \mathcal{L}(t)dt \cdot \Sigma$$

integrated luminosity

LHC Commissioning

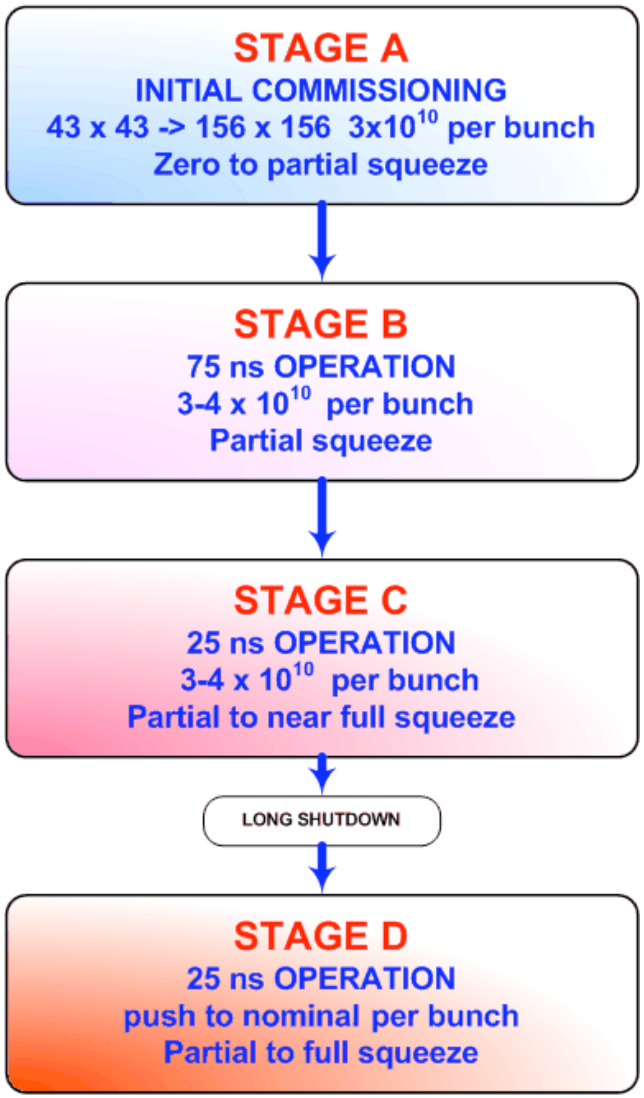
Baseline cycle



Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	≈ 20 Mins
Prepare Physics	≈ 10 Mins
Physics	0 - 20 Hrs

Injection from SPS:
- pilot, intermediate
- 12 x nominal per beam

Commissioning stages

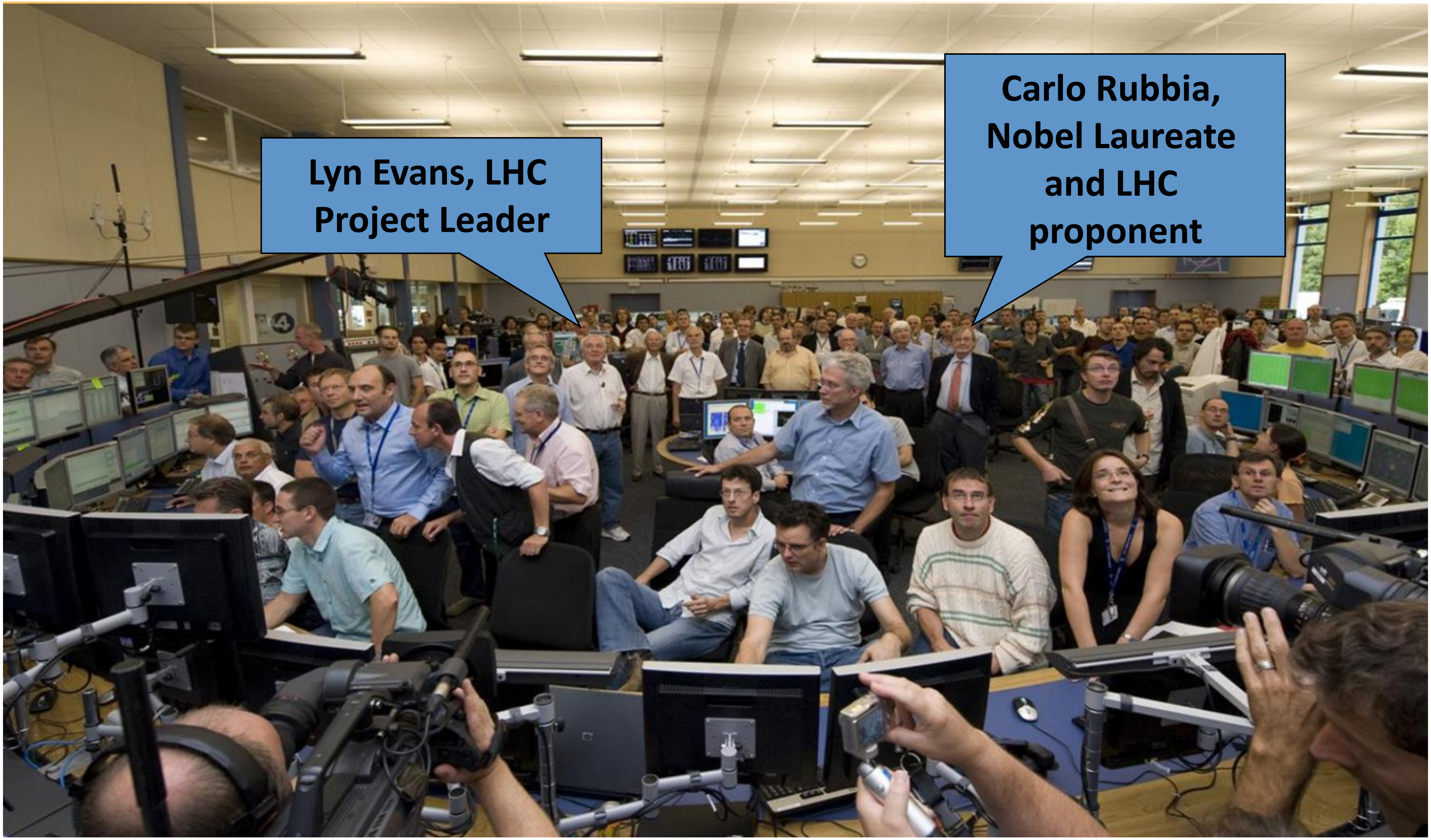


Safely establish colliding beams as quickly as possible

- 1 to N to 43 to 156 bunches per beam
- Pushing gradually one or all of:
  - ☐ Bunches per beam
  - ☐ Squeeze
  - ☐ Bunch intensity

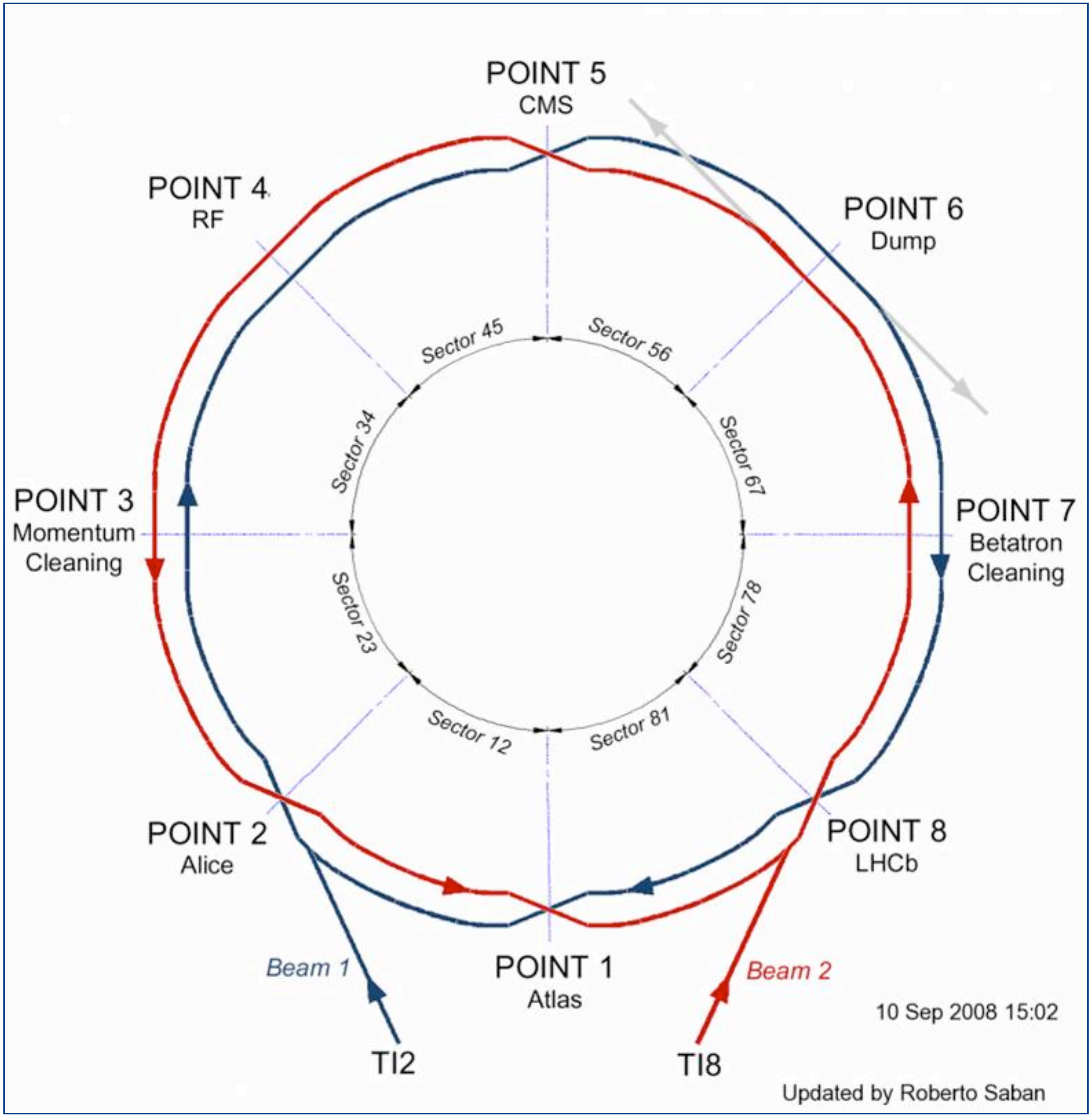
M. Lamont (HCP Summer School, 2008)

LHC Start-up


Lyn Evans, LHC Project Leader
Carlo Rubbia, Nobel Laureate and LHC proponent

A Brief Diary of LHC Events

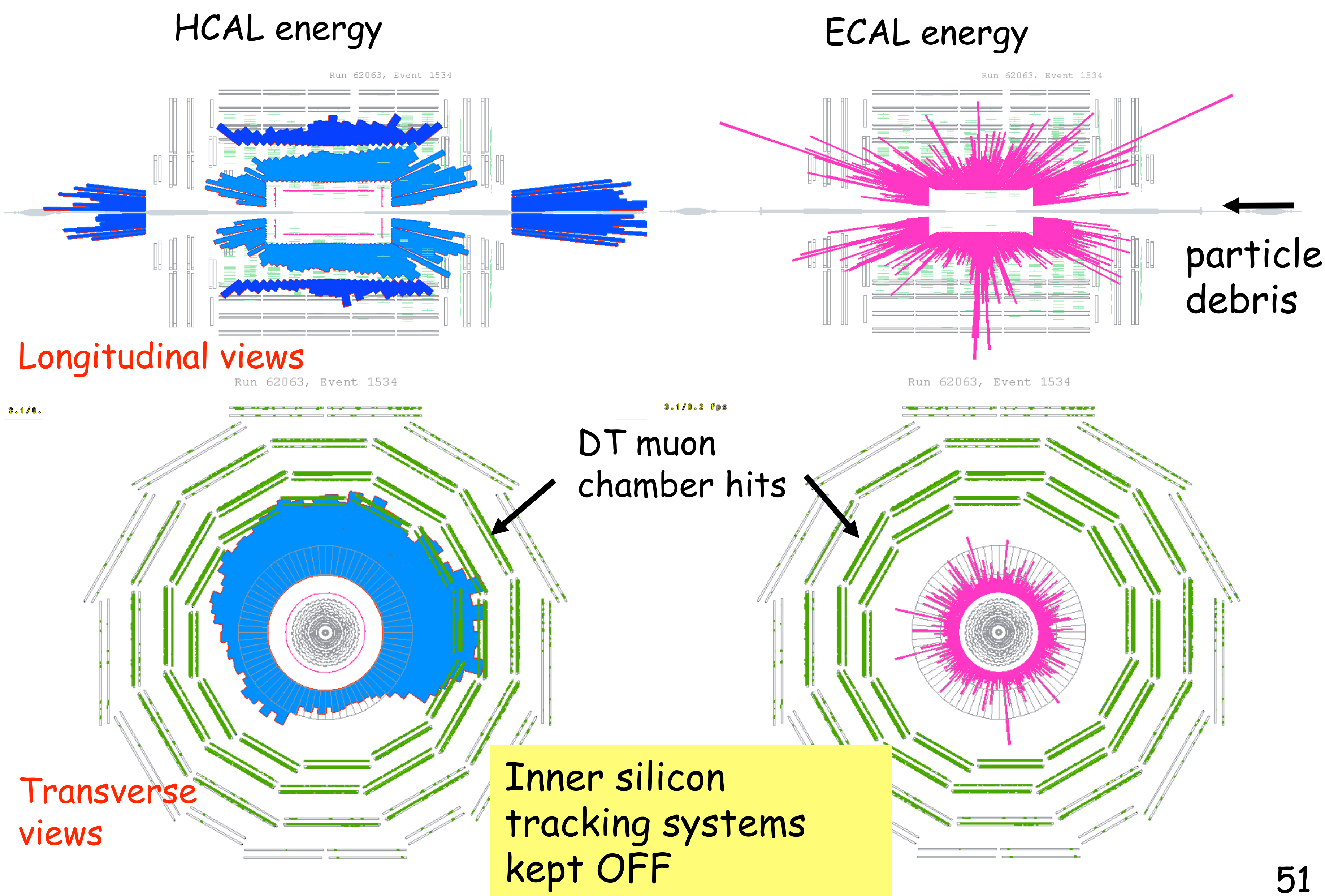
- Aug. 8 and Aug. 22 Weekends
  - "Synchronization tests" sent protons through the first arcs of the LHC in both directions, past ALICE and then LHCb experiments
  - By Aug.22, alternate injections of beam 1 and 2: *"…pretty blooming amazing…"*
- Sun/Mon, 7-8 Sept.
  - Single shots of beam 1 onto a collimator 150m upstream of CMS.
- Tues, 9-Sept
  - Additional single shots of beam 1 onto a collimator at CMS
- Wed., 10 Sept. (Media Day!)
  - Beam 1 circulated in the morning, 3 turns by 10:40am (1 hour!)
  - Beam 2 circulated by 3:00pm
  - 300 turns of beam 2 by 11:15pm


POINT 5
CMS
POINT 4
RF
POINT 6
Dump
POINT 3
Momentum
Cleaning
POINT 7
Betatron
Cleaning
POINT 2
Alice
POINT 8
LHCb
POINT 1
Atlas
Sector 45
Sector 56
Sector 34
Sector 67
Sector 23
Sector 78
Sector 12
Sector 81
Beam 1
Beam 2
TI2
TI8
10 Sep 2008 15:02
Updated by Roberto Saban

Beam Splash Events

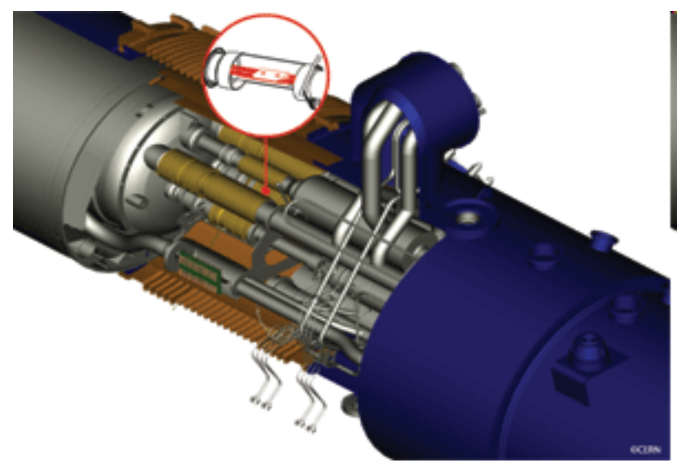
- Beam with $2x10^9$ protons dumped onto a target (collimator) 150m upstream of CMS
  - Sept. 7,9,10,18
- Leads to a "tsunami" wave of O(100K) muons coming down the tunnel!
  - A far cry from the single cosmic muon events…

First view of LHC Beam



Black Friday: September 19th

- An incident occurred during a powering test of one LHC sector for commissioning beam operation to 5 TeV
  - Massive helium loss in one arc of the tunnel (2 tons initially), cryogenics and vacuum lost
- The cause of the incident was determined to be a faulty electrical connection ("bus bar") between a dipole and a quadrupole
  - Mechanical damage occurred
  - Need to extract and repair dipole and quadrupole magnets in the region



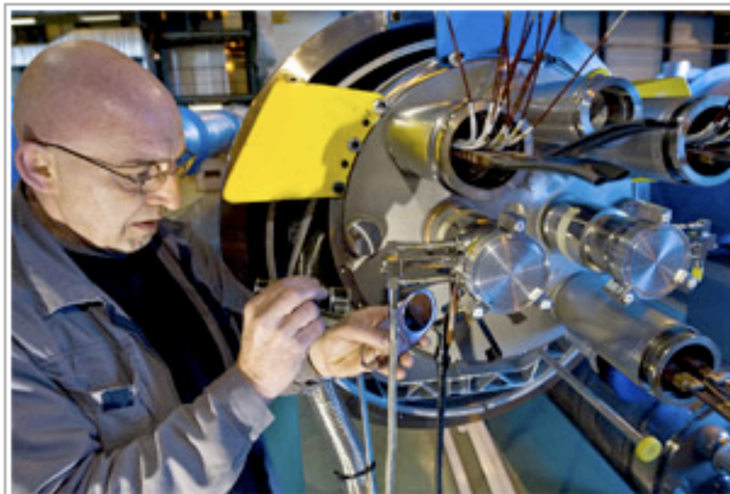
- Not enough time to make repairs before winter shutdown → Aim to restart LHC operations mid-2009

LHC to restart in 2009

PR17.08
05.12.2008

Geneva, 5 December 2008.

CERN[1] today confirmed that the Large Hadron Collider (LHC) will restart in 2009. This news forms part of an updated report, published today, on the status of the LHC following a malfunction on 19 September.



Final preparations on a replacement magnet ready to be lowered into sector 3-4

"The top priority for CERN today is to provide collision data for the experiments as soon as reasonably possible," said CERN Director General Robert Aymar. *"This will be in the summer of 2009."*

The initial malfunction was caused by a faulty electrical connection between two of the accelerator's magnets. This resulted in mechanical damage and release of helium from the magnet cold mass into the tunnel. Proper safety procedures were in force, the safety systems performed as expected, and no one was put at risk.

Detailed studies of the malfunction have allowed the LHC's engineers to identify means of preventing a similar incident from reoccurring in the future, and to design new protection systems for the machine. A total of 53 magnet units have to be removed from the tunnel for cleaning or repair, of these, 28 have already been brought to the surface and the first two replacement units

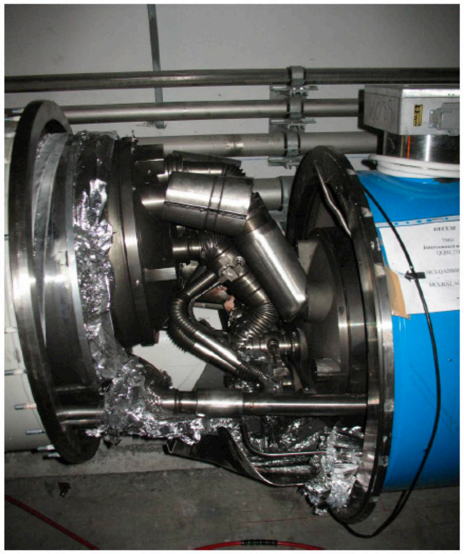
2009 Restart

CERN Press Release:

http://press.web.cern.ch/press/PressReleases/Releases2008/PR17.08E.html

Full Report of incident and plans for repair:

http://press.web.cern.ch/press/PressReleases/Releases2008/attachments/CERN_081205b_LHCrestart.pdf



Expect news about the LHC startup plans soon (1st week of Feb.)

Next Class : LHC Experiments

Particle Detectors allow us to "see" particles