The Large Hadron Collider: The Big Bang Machine

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CERN
The European Laboratory for Particle Physics

CERN is the European Organization for Nuclear Research, the world's largest Particle Physics Centre, near Geneva, Switzerland
It is now commonly referred to as European Laboratory for Particle Physics
It was founded in 1954 and has 20 member states + several observer states
CERN employes >3000 people + hosts 9000 visitors from >500 universities.
Annual budget ~ 1100 MCHF/year (2009)

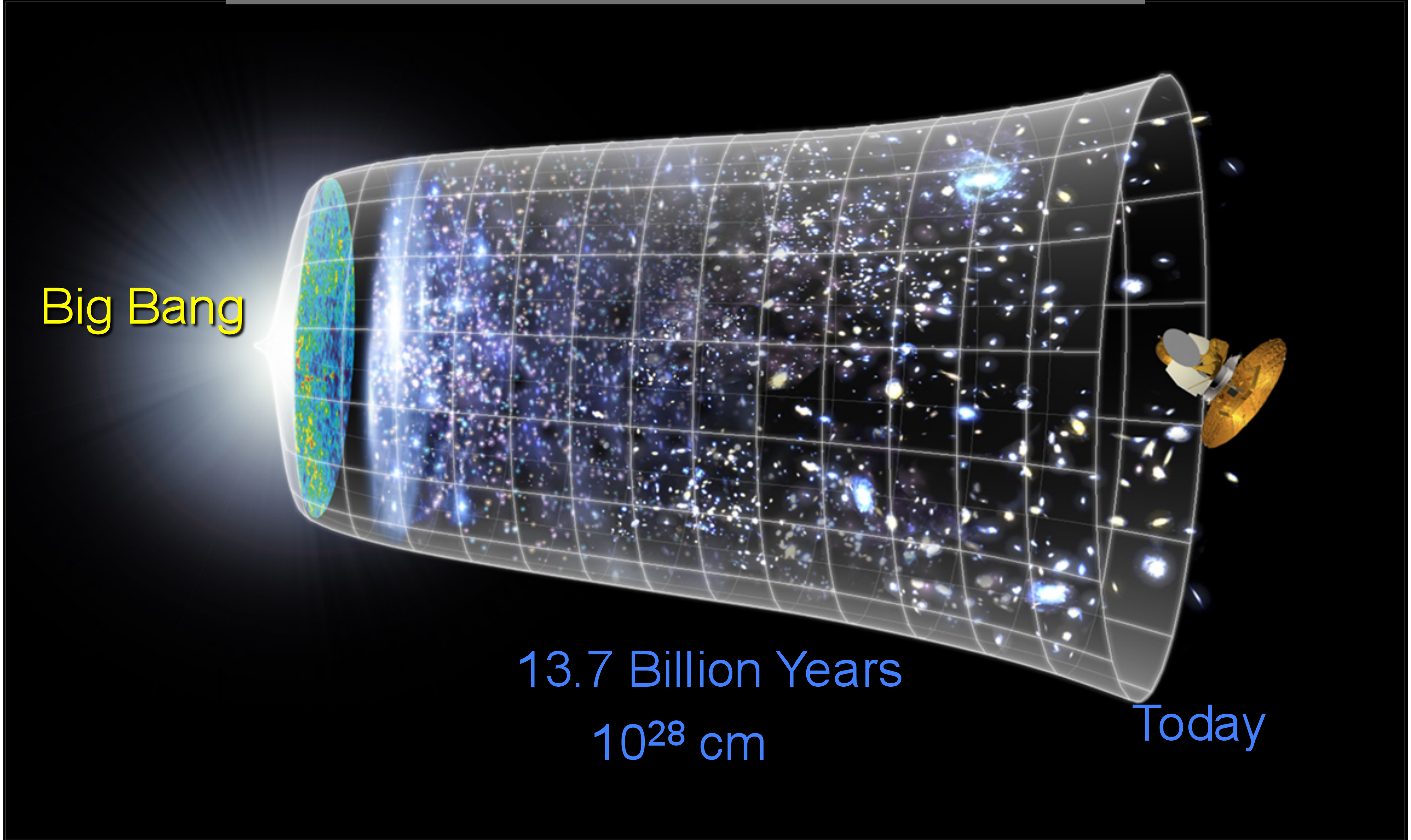
CERN: the place where the World Wide Web was born

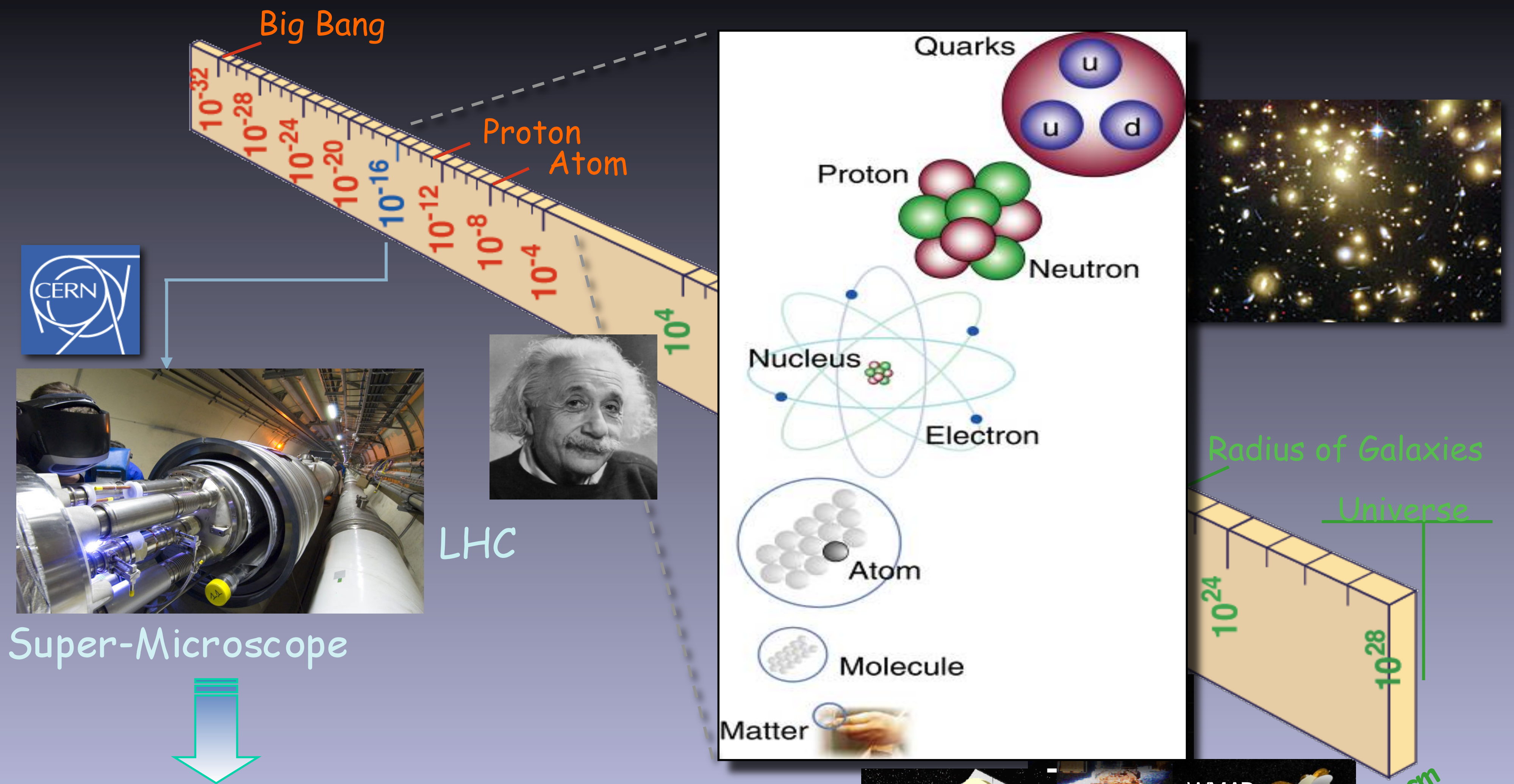
CERN
Provides
Particle Beams
&
Research Infrastructure

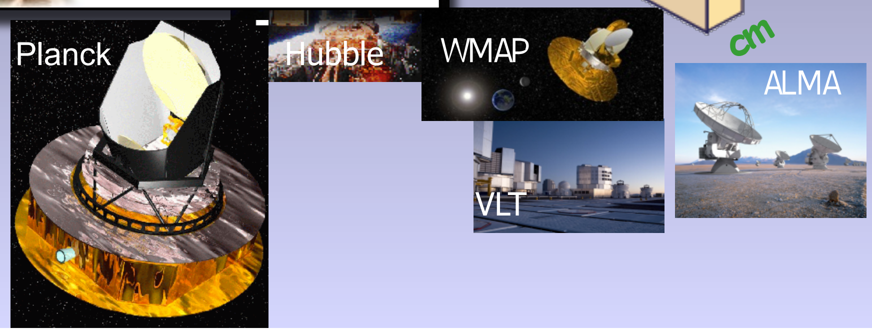
Why do we need particle accelerators?


What is the world made of?
What holds the world together?
Where did we come from?

Evolution of the Universe







Study physics laws of first moments after Big Bang

We can create particles from energy

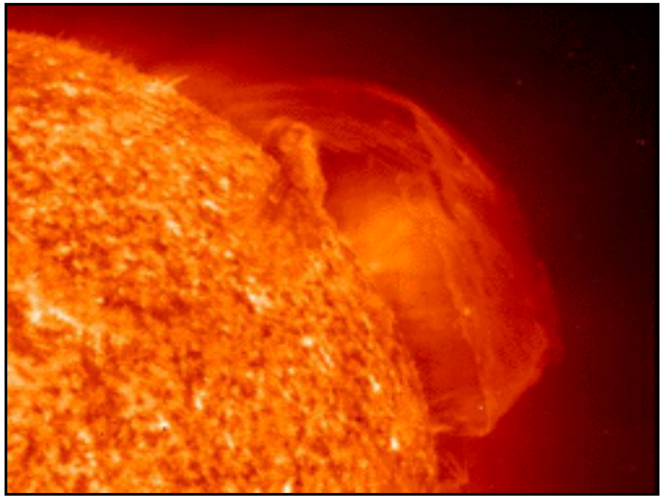
Two beams of protons collide and generate, in a very tiny space, temperatures over a billion times higher than those prevailing at the center of the Sun.

The Fundamental Forces of Nature

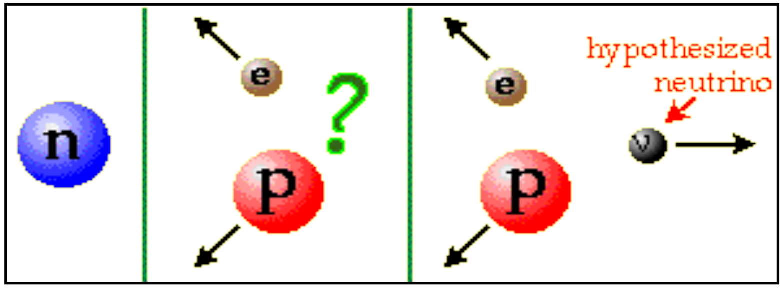
Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity

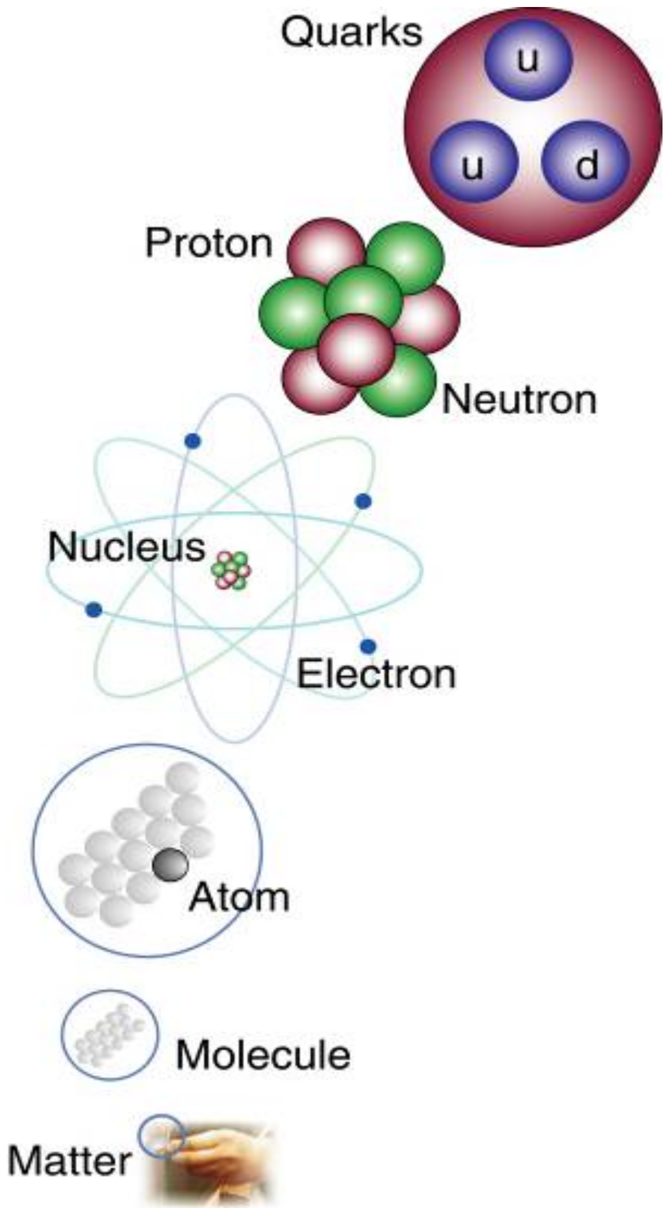


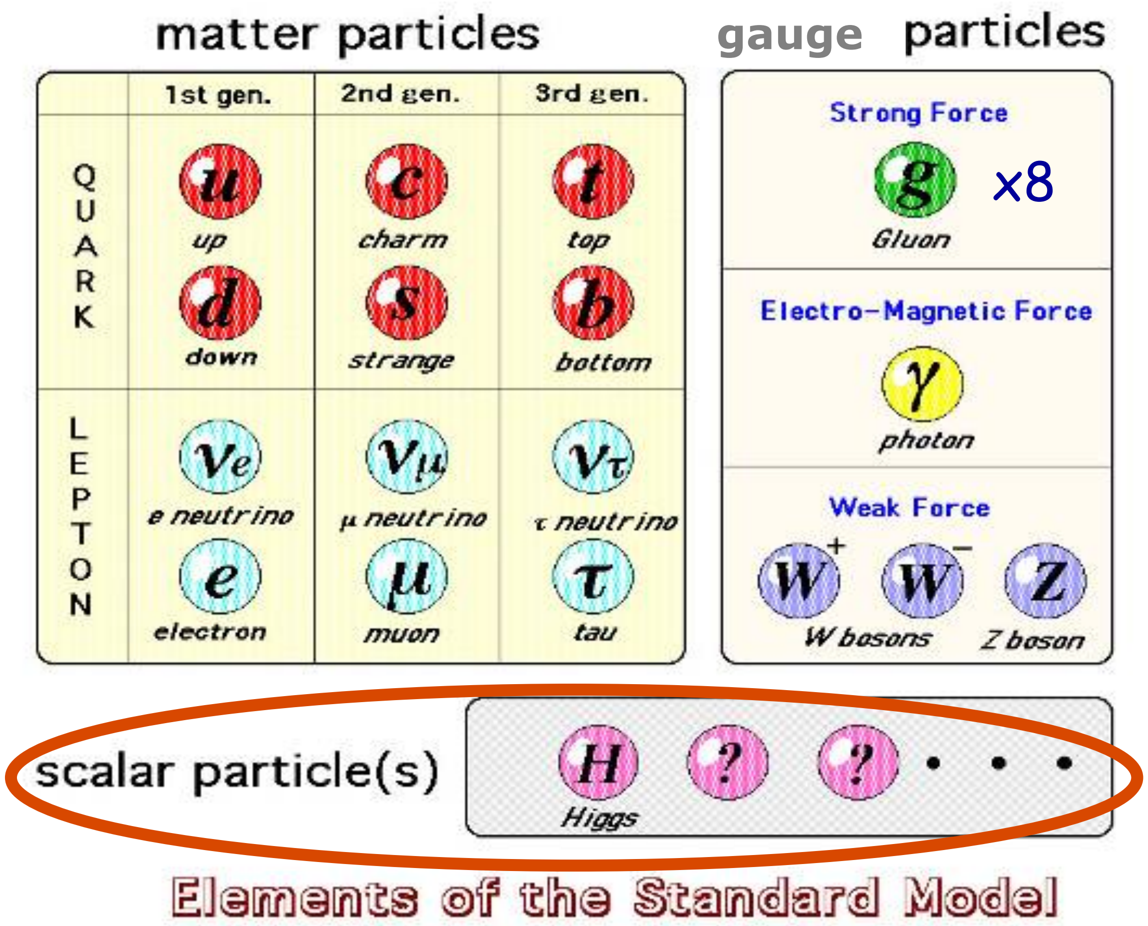
together they make the Sun shine



Gravity:
holds planets and stars together

The Study of Particles and their Interactions





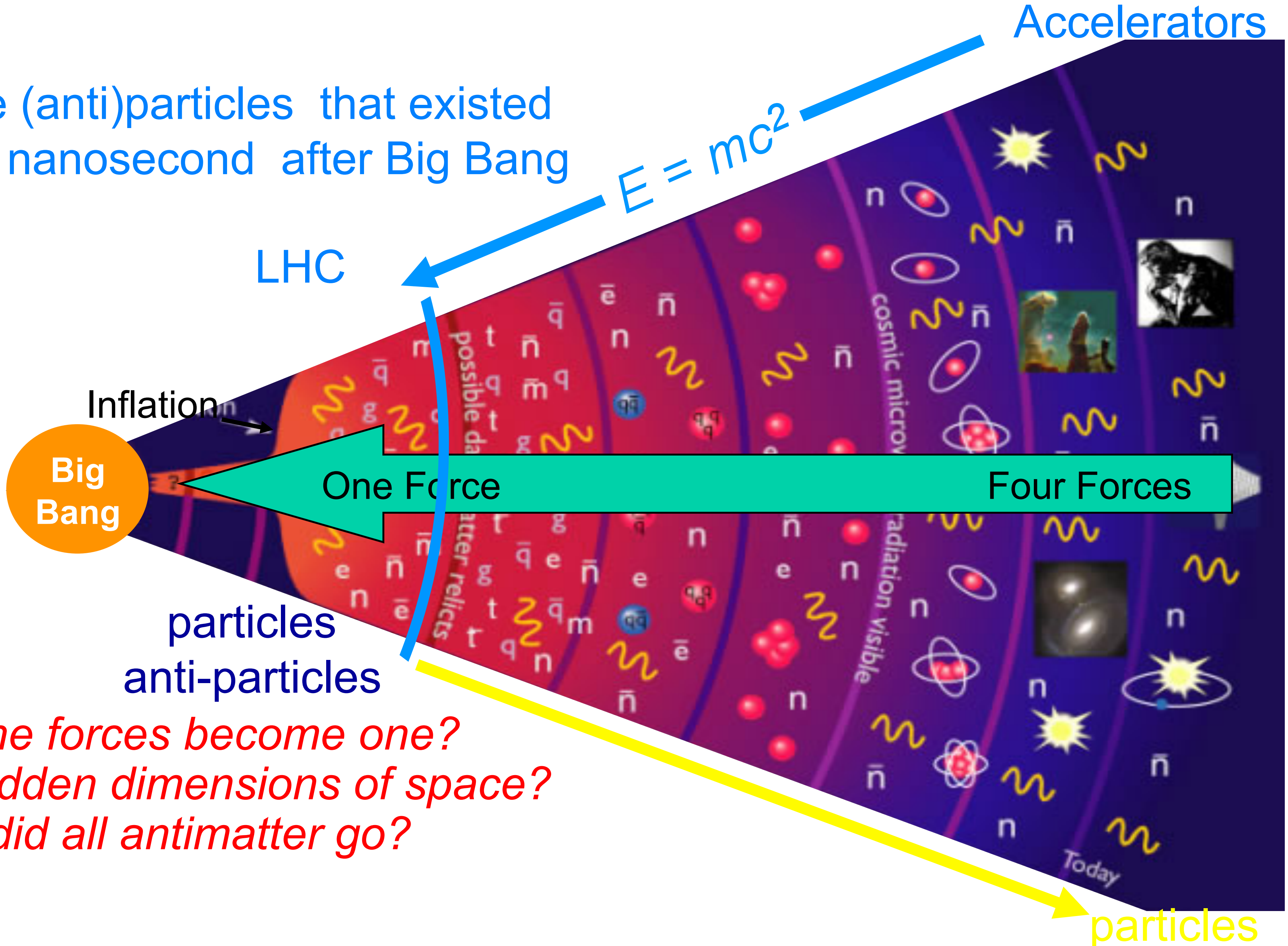
Important Questions in Particle Physics

- What is the origin of particle masses?
- Why are there so many types of matter particles?
- What is the cause of matter-antimatter asymmetry?
- What are the properties of the primordial plasma?
- What is the nature of the invisible dark matter?
- Can all fundamental particles be unified?
- Is there a quantum theory of gravity

"Quantum Universe" and
"Discovering the Quantum Universe"

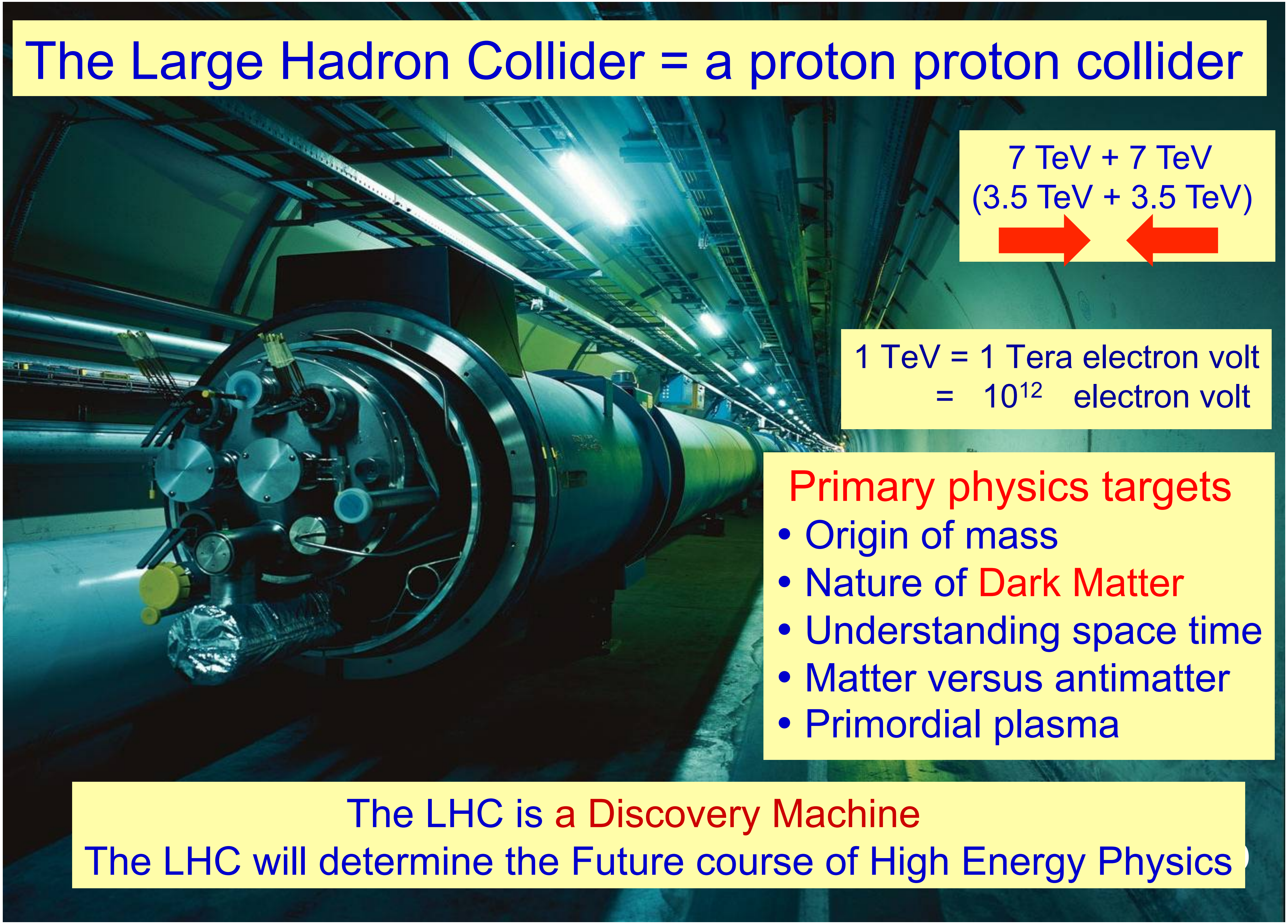
The physics programmes at CERN will address these questions and may well provide definite answers.

Create (anti)particles that existed
~0.001 nanosecond after Big Bang



Do all the forces become one?
Extra hidden dimensions of space?
Where did all antimatter go?

The Large Hadron Collider = a proton proton collider



7 TeV + 7 TeV
(3.5 TeV + 3.5 TeV)

1 TeV = 1 Tera electron volt
= 10^{12} electron volt

Primary physics targets

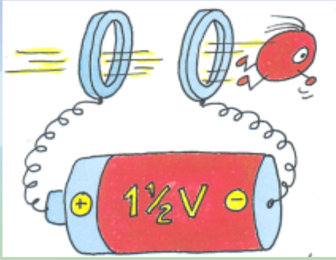
- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

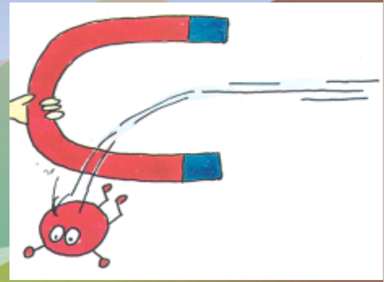
The LHC is a Discovery Machine

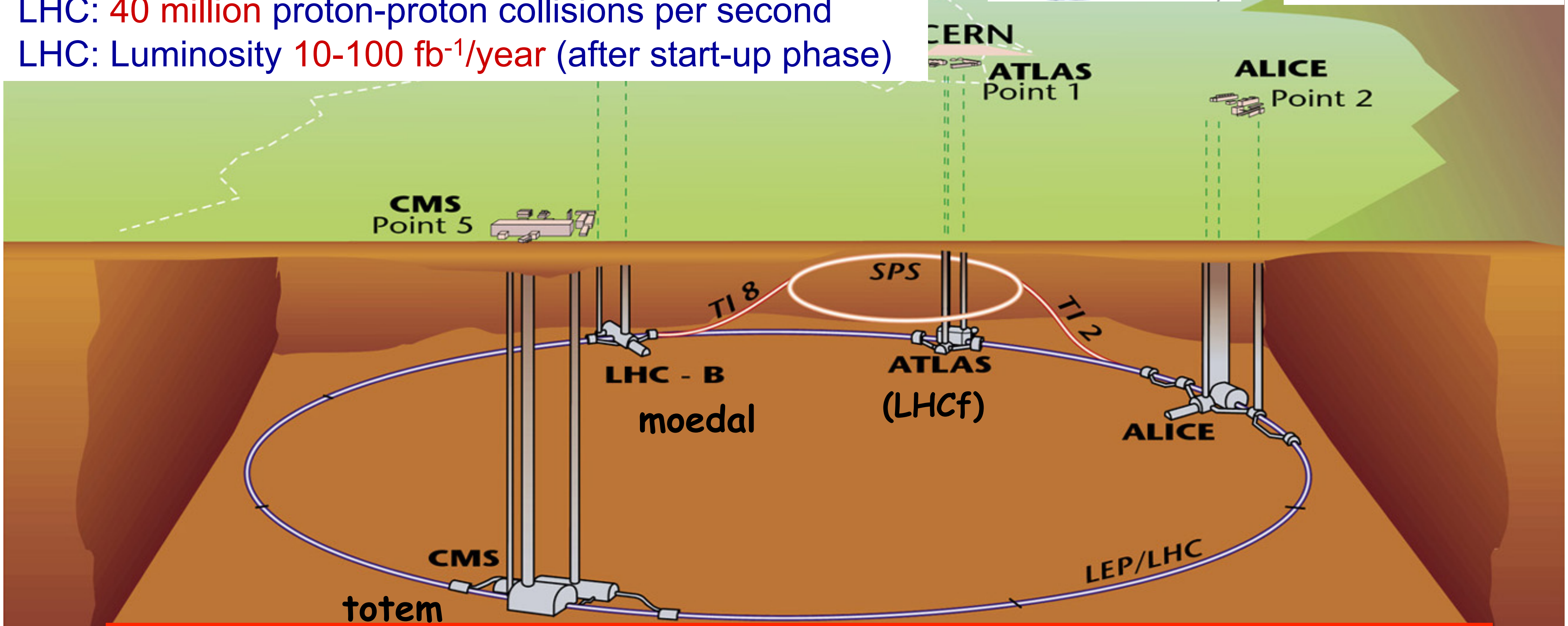
The LHC will determine the Future course of High Energy Physics

The LHC Machine and Experiments

LHC is 100m underground
LHC is 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second
LHC: Luminosity 10-100 fb^{-1}/year (after start-up phase)



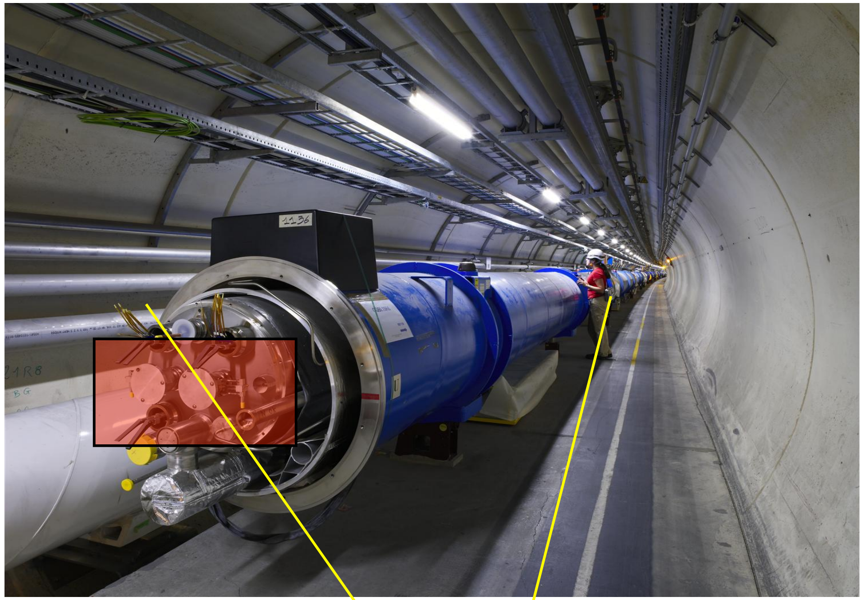




- High Energy ⇒ factor 7 increase w.r.t. present accelerators
- High Luminosity (# events/cross section/time) ⇒ factor 100 increase

LHC facts

The emptiest space in the solar system…



To accelerate protons to almost the speed of light, we need a vacuum similar to interplanetary space. The pressure in the beam-pipes of the LHC will be about ten times lower than on the moon.

LHC facts

One of the coldest places in the Universe…

the largest cryogenic system ever built

54 km fridge!

With a temperature of around -271 degrees Celsius, or 1.9 degrees above absolute zero, the LHC is colder than interstellar space.

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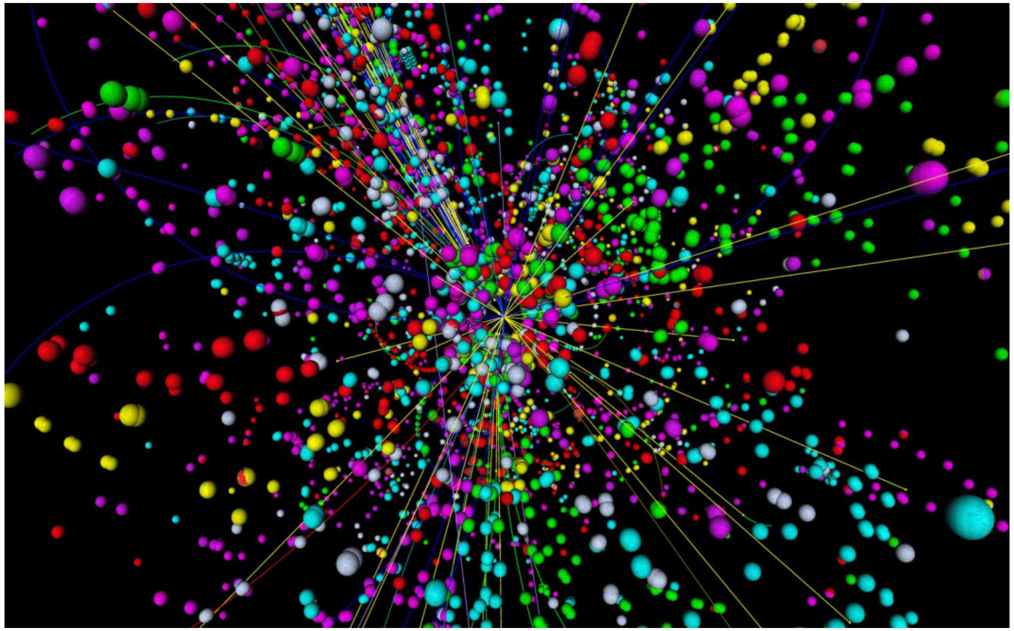
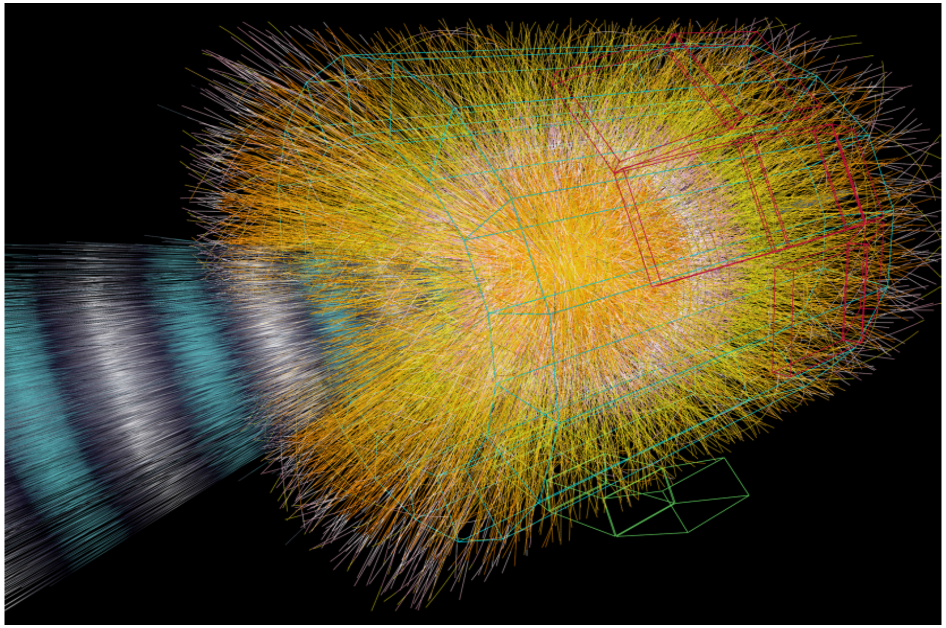
LHC facts

One of the hottest places in the Galaxy…



Simulation of a collision in the CMS experiment



Simulation of a collision in the ALICE experiment

When two beams of protons collide, they generate within a tiny volume, temperatures more than a billion times those in the very heart of the Sun.

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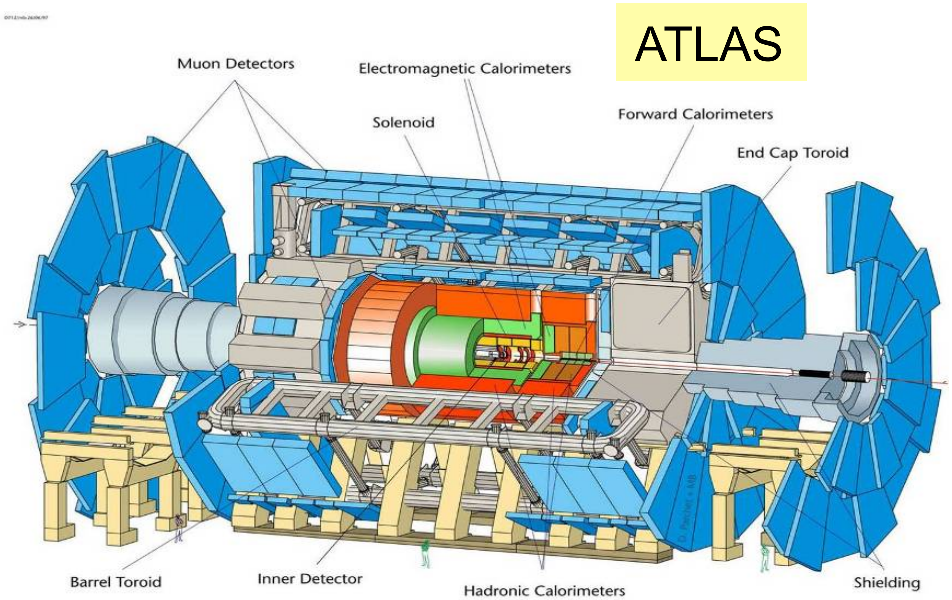
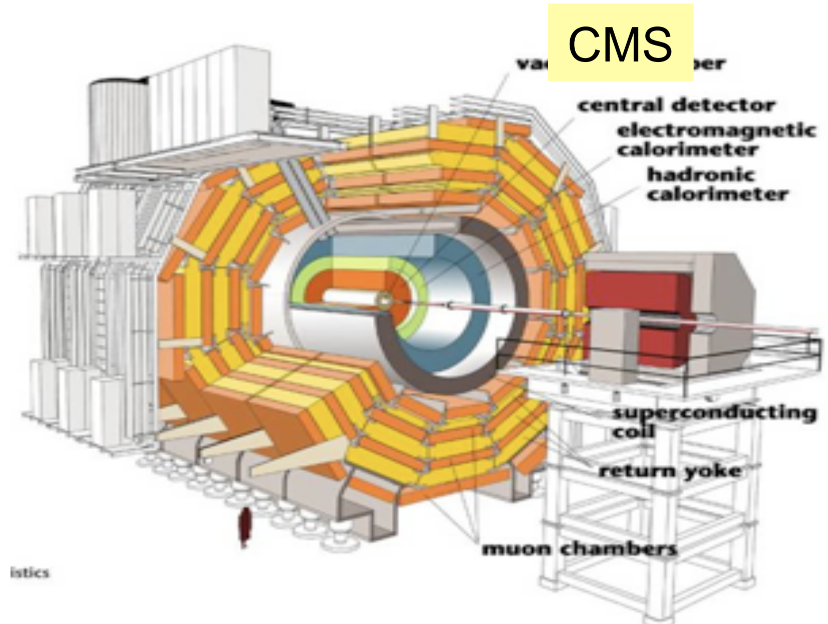
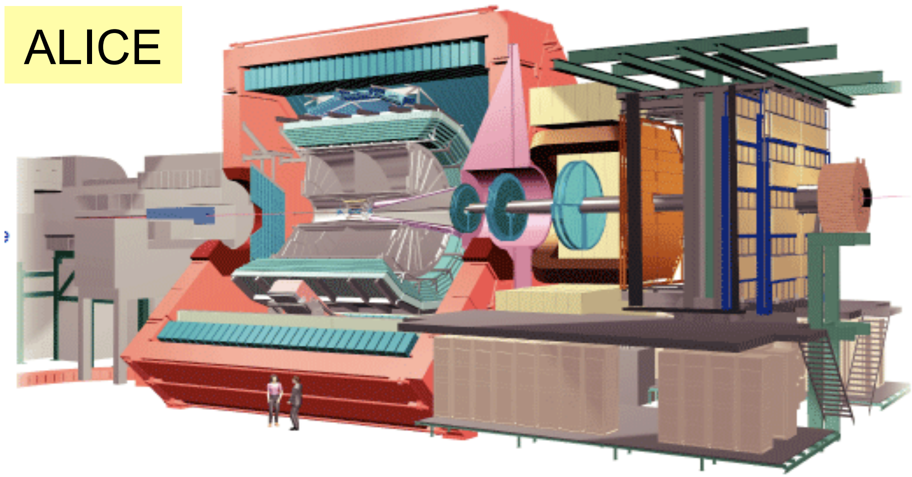
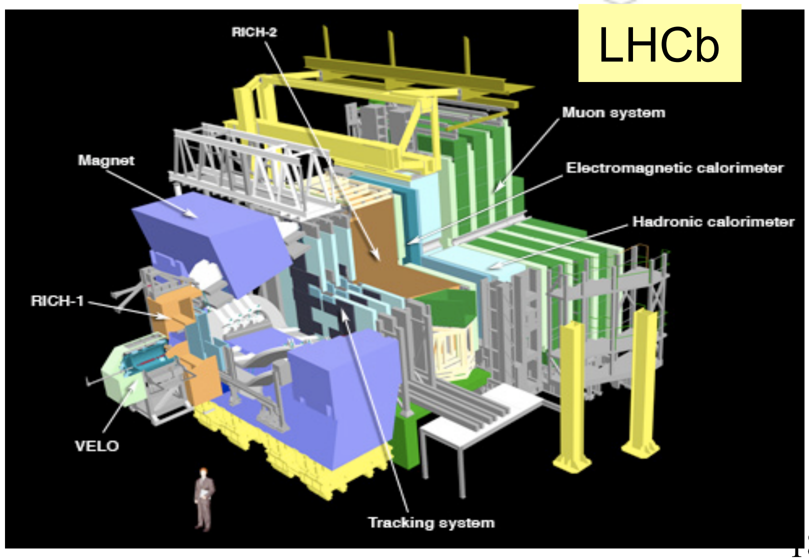
The Four Main LHC Experiments









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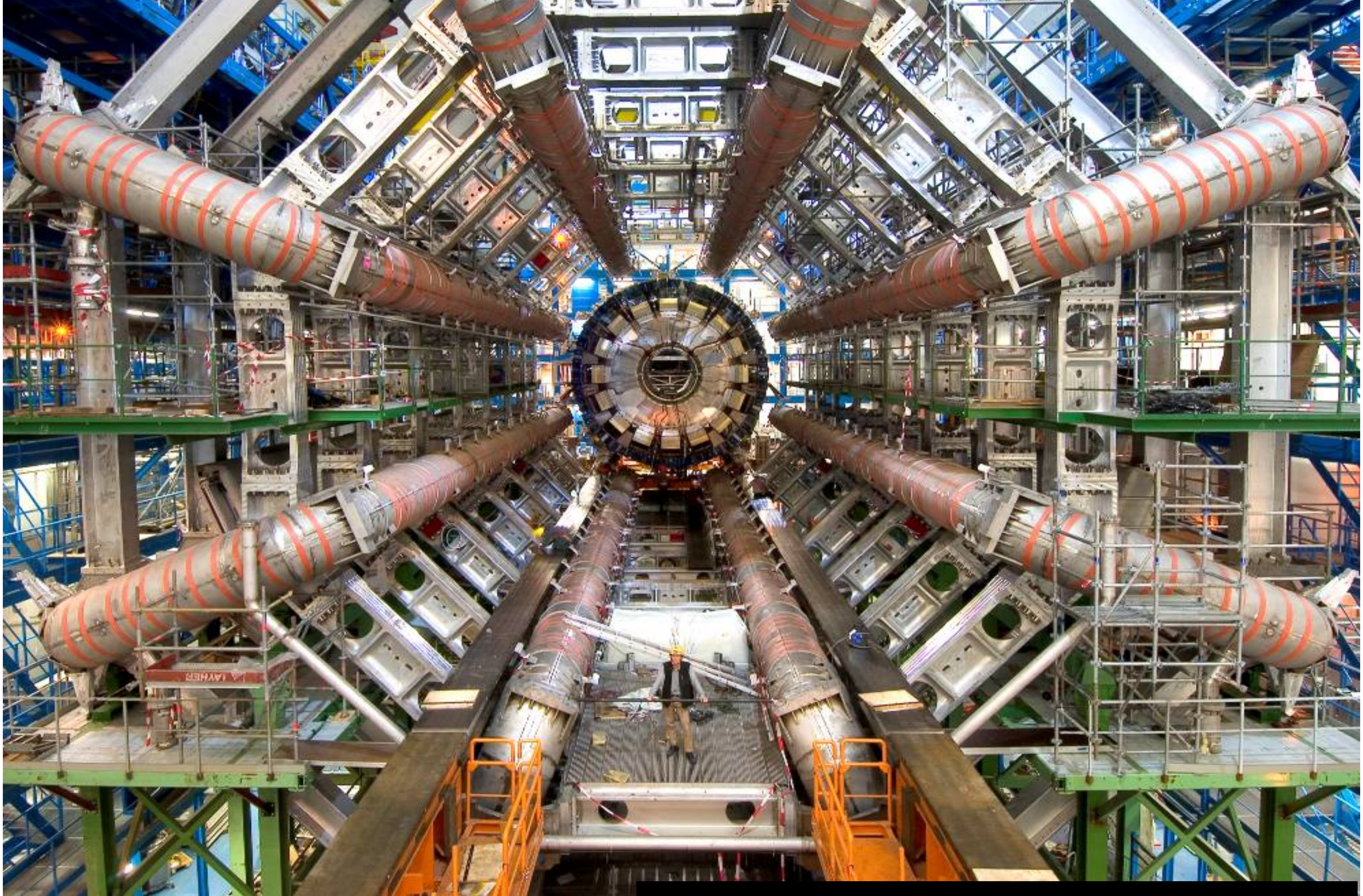
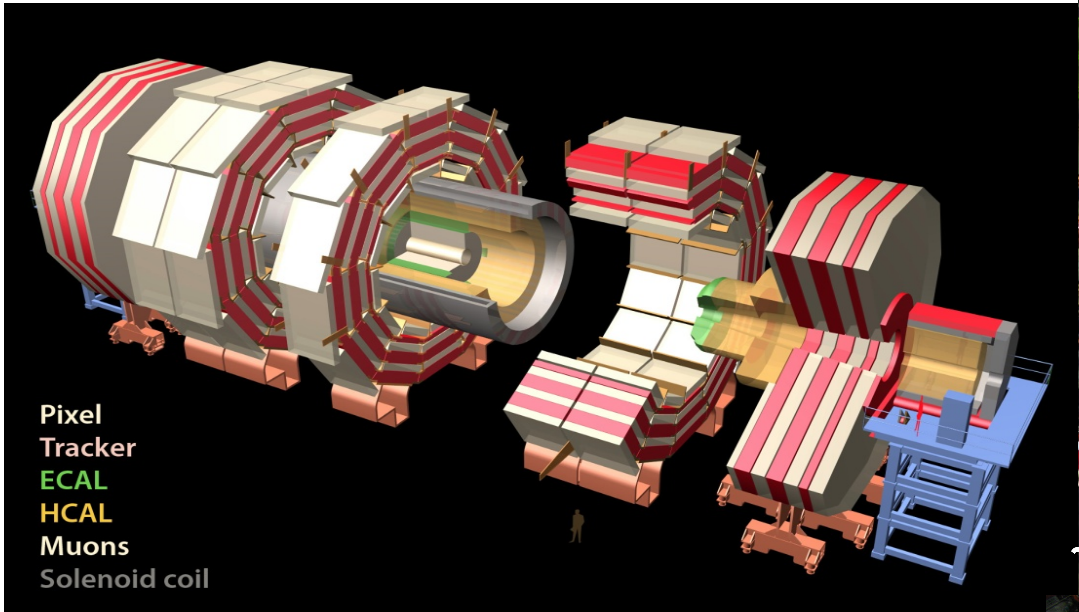
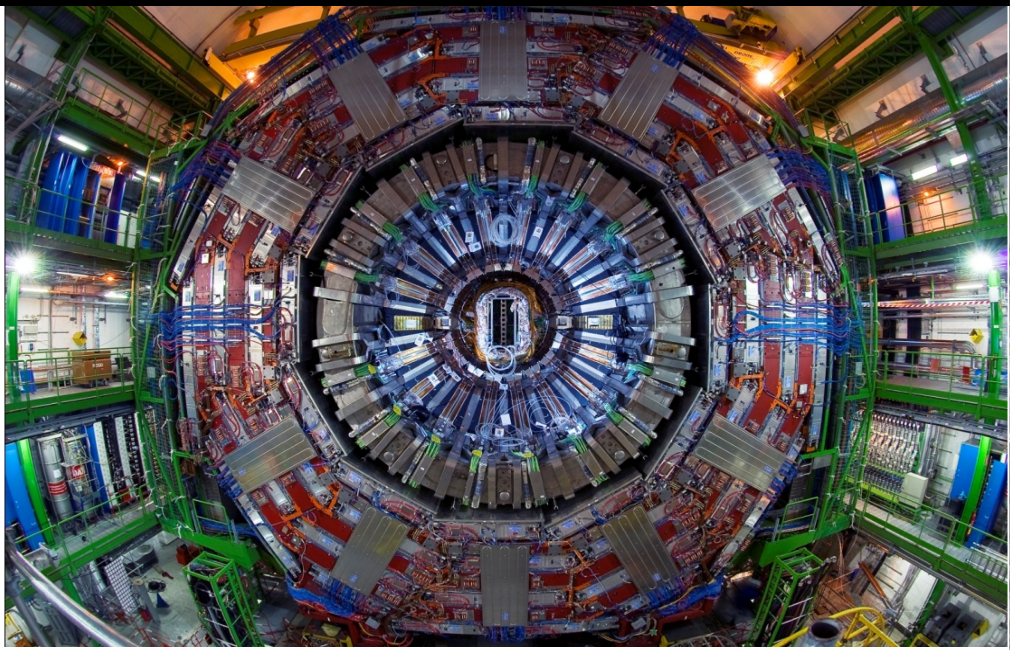
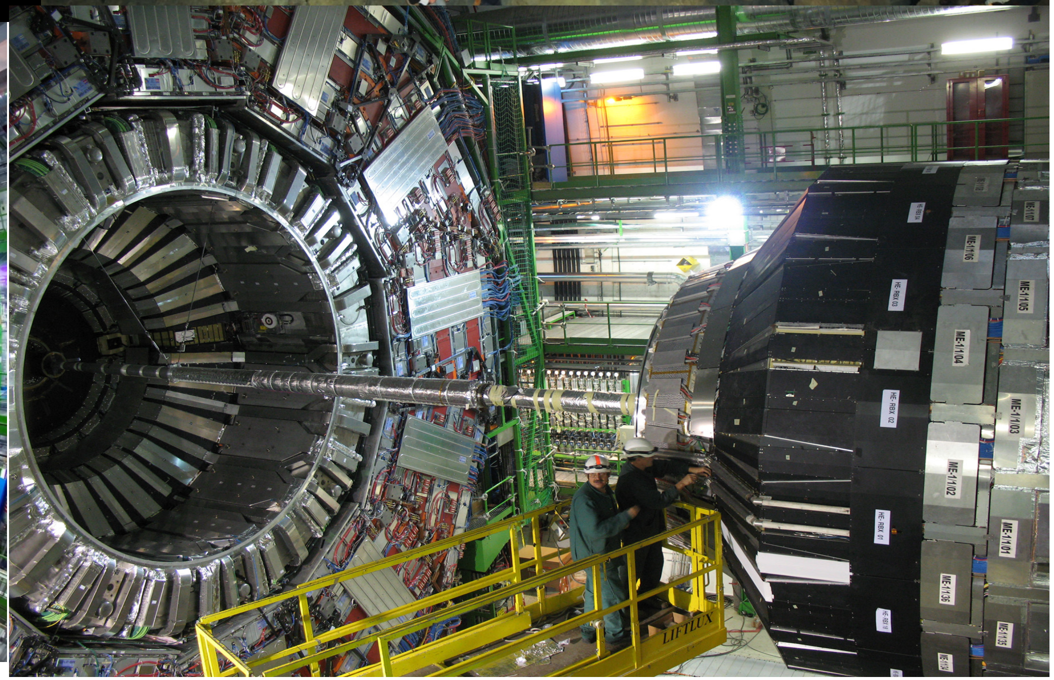


The ATLAS Experiment

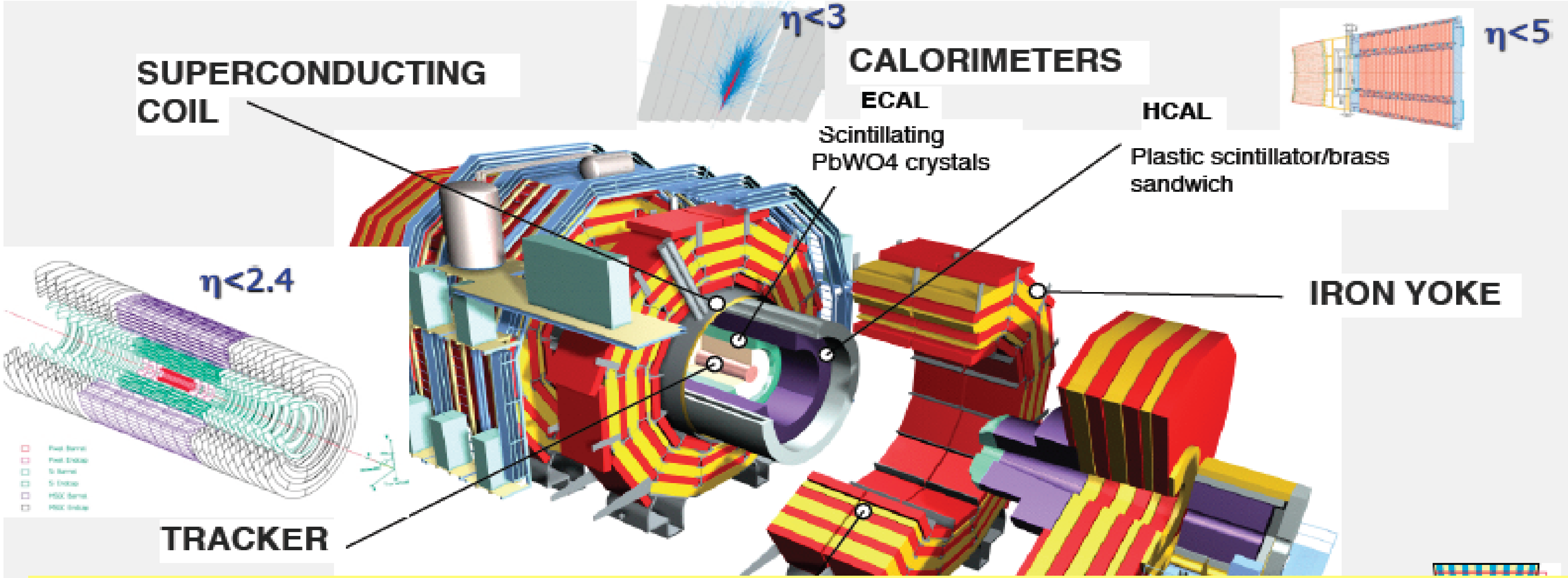
The CMS Collaboration: >3000 scientists and engineers, >700 students from 182 Institutions in 39 countries .







The Compact Muon Solenoid Experiment



In total about

~100 000 000 electronic channels

Each channel checked

40 000 000 times per second (collision rate is 40 MHz)

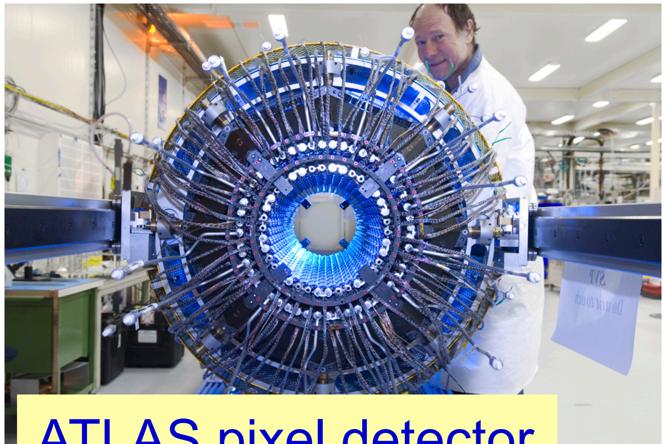
An on-line trigger selects events and reduces the rate from 40MHz to ~200 Hz

Amount of data of just one collisions

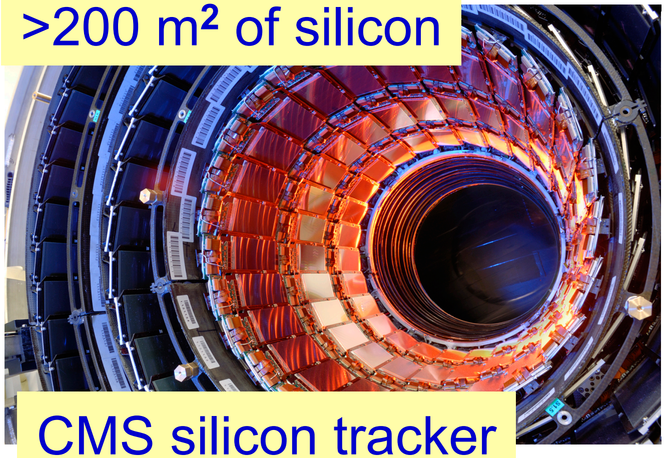
>1 500 000 Bytes

The LHC Detectors are Major Challenges

- CMS/ATLAS detectors have about 100 million read-out channels
- Collisions in the detectors happen every 25 nanoseconds
- ATLAS uses over 3000 km of cables in the experiment
- The data volume recorded at the front-end in CMS is 1 TB/second which is equivalent to the world wide communication network traffic
- Data recorded during the 10-20 years of LHC life will be about all the words spoken by mankind since its appearance on earth
- A worry for the detectors: the kinetic energy of the beam is that of a small aircraft carrier of 10^4 tons going 20 miles/ hour



ATLAS pixel detector

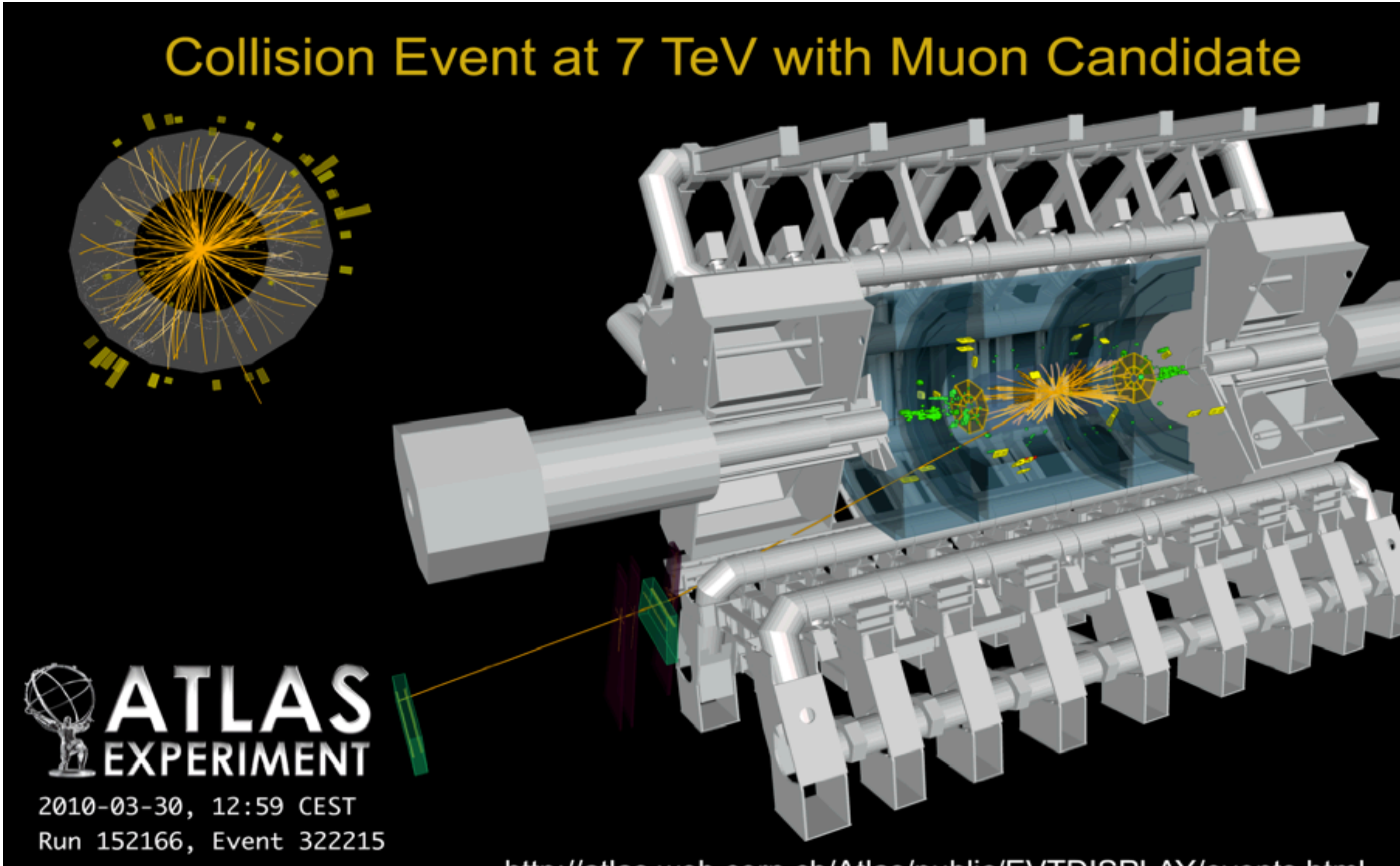


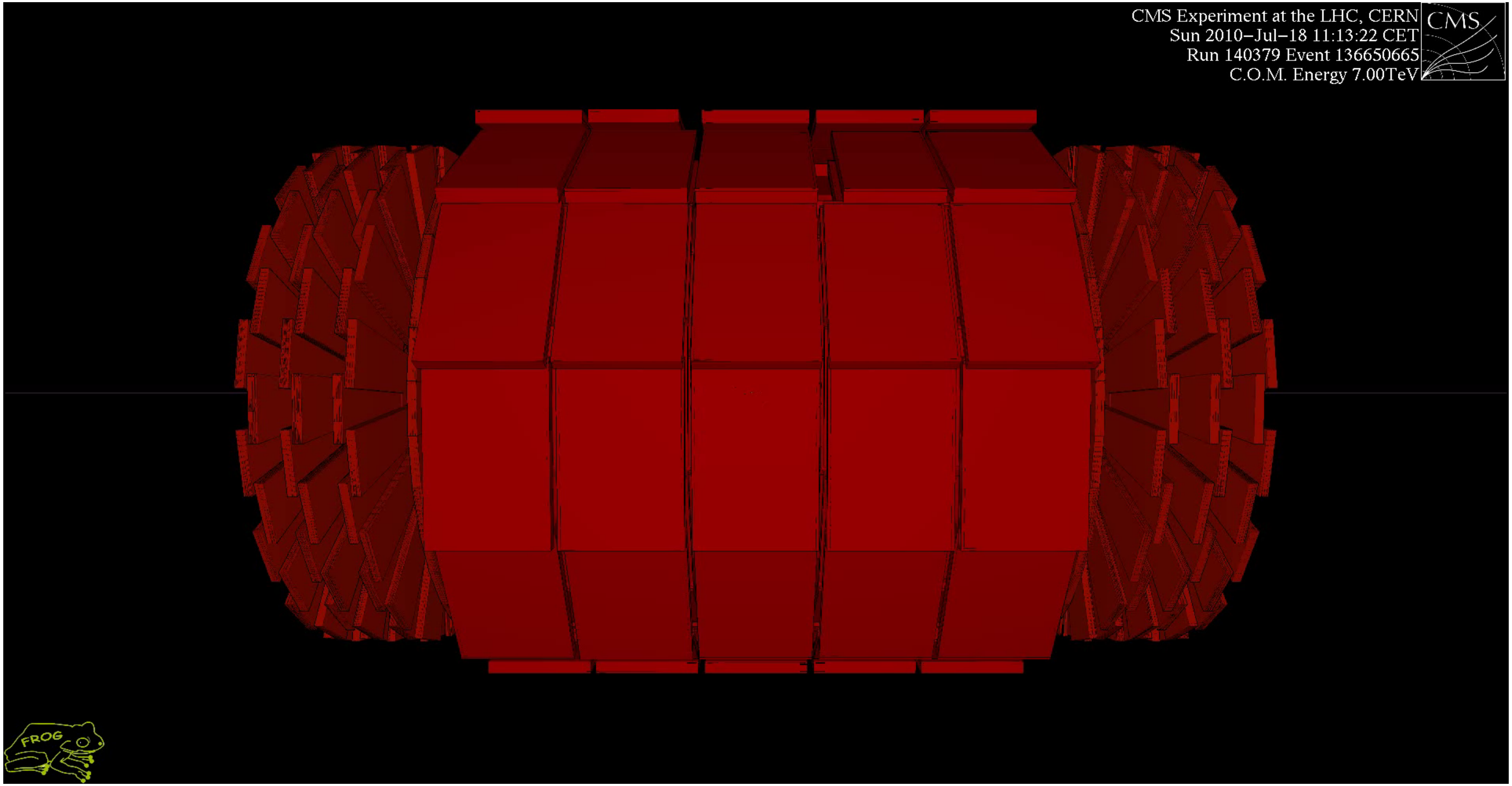
>200 m^2 of silicon

CMS silicon tracker

Object	Weight (tons)
Boeing 747 [fully loaded]	200
Endeavor space shuttle	368
ATLAS	7,000
Eiffel Tower	7,300
USS John McCain	8,300
CMS	12,500

First Collisions at 7 TeV




CMS Experiment at the LHC, CERN
Sun 2010–Jul–18 11:13:22 CET
Run 140379 Event 136650665
C.O.M. Energy 7.00TeV
CMS
FROG

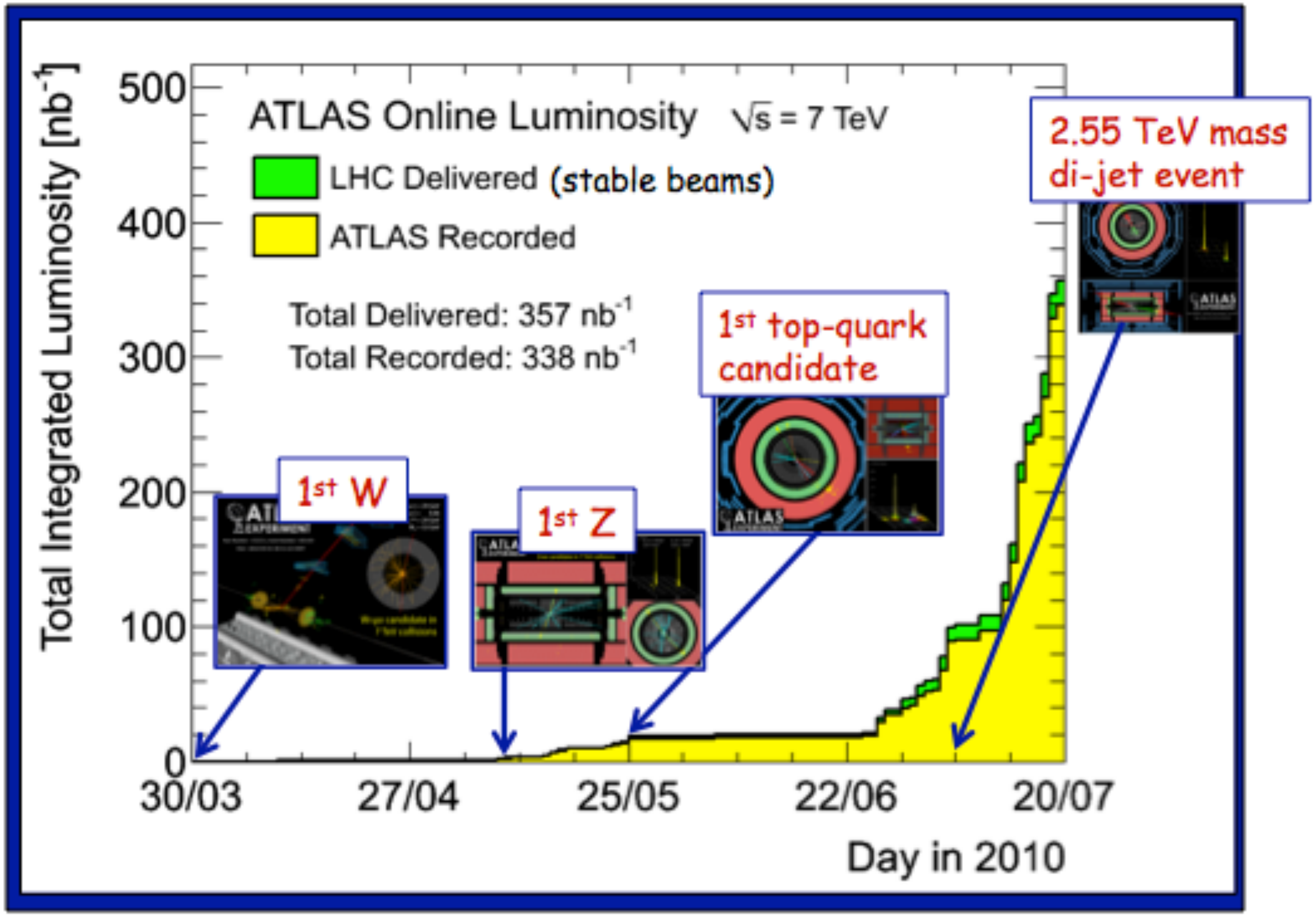
The Science of the LHC

$\Rightarrow$ Explore the new high energy regime: The Terascale

Collision Rates & Physics

The machine is still in the commissioning phase.

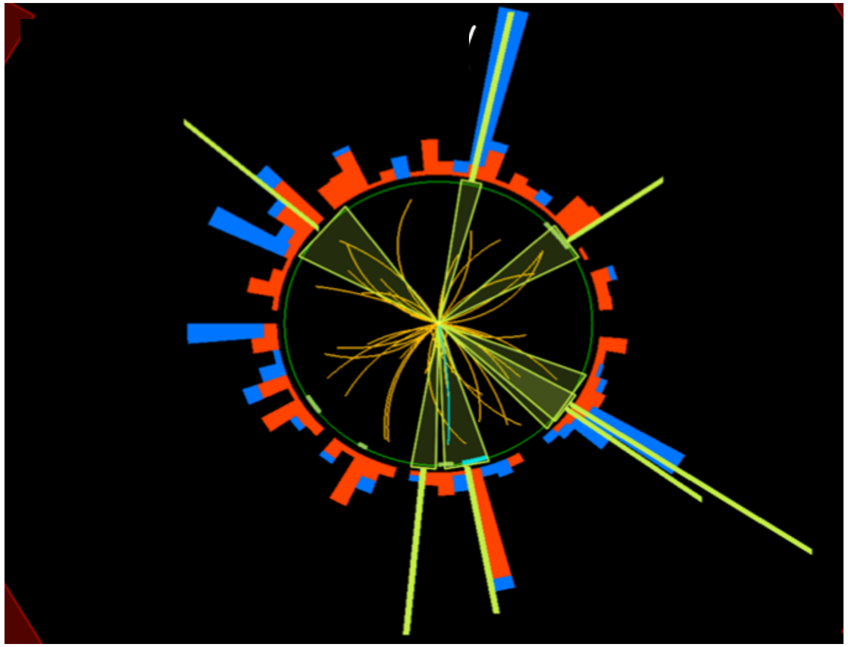
It's like driving a new car

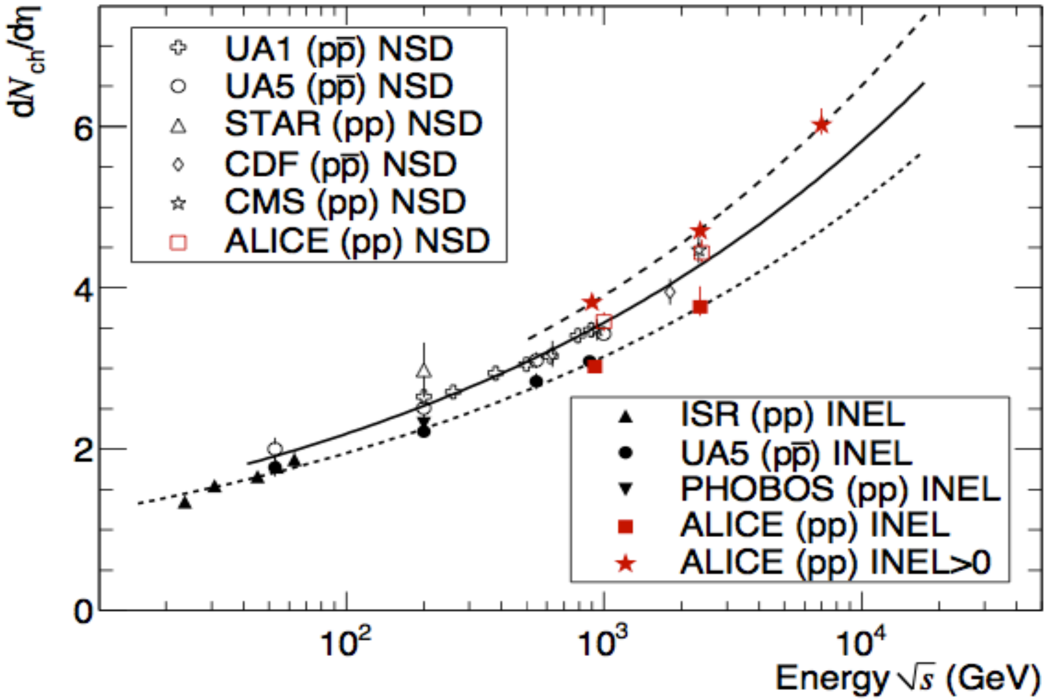


Right now we are re-discovering the know particles: W, Z, top…

7 TeV Early Analysis

We also learn a lot of particle production at the highest energies!!





Measurement of the charged particle density in proton proton collisions at 7 TeV

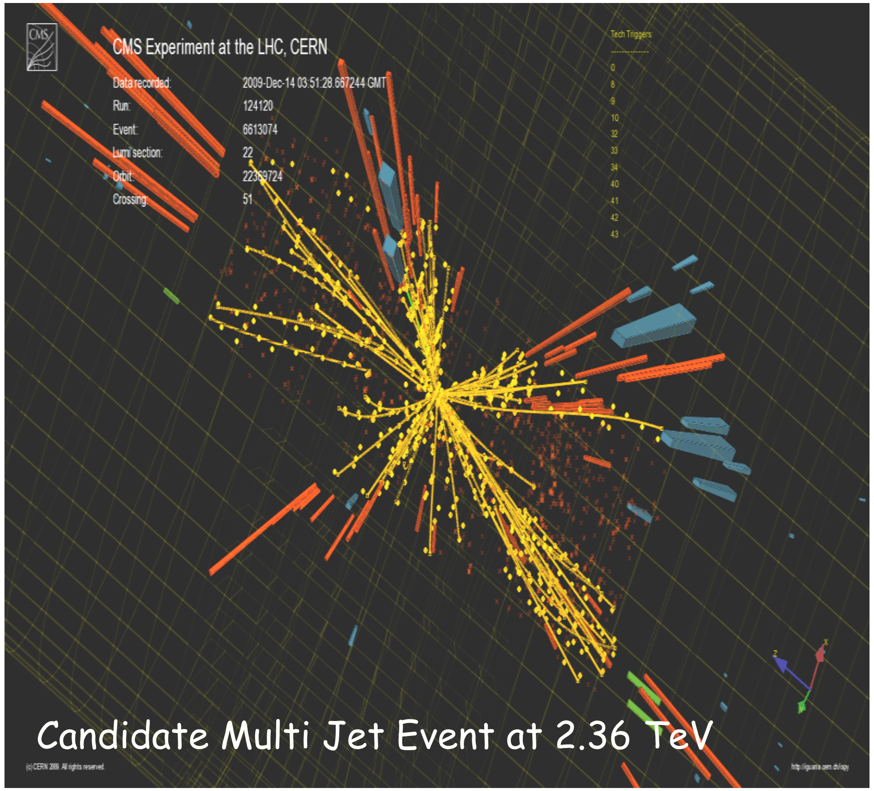
Strong rise of the central particle density with energy

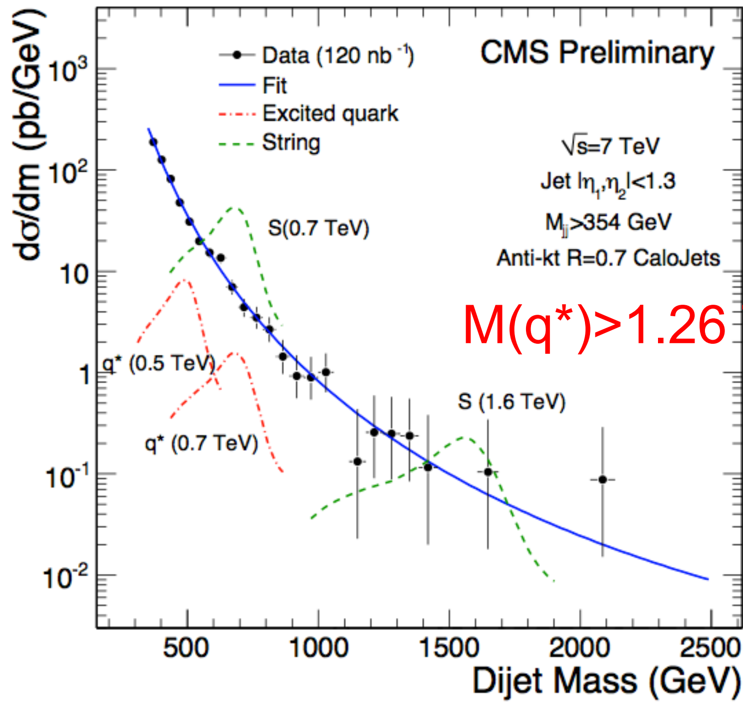
Events with Jets of Particles

Study of the strong force: QCD

Huge cross sections:

Eg for 100 pb^{-1} ~ 500 events with E_T> 1 TeV





M(q*)>1.26 TeV

Understanding QCD at the highest Energies is one of the first topics at the LHC

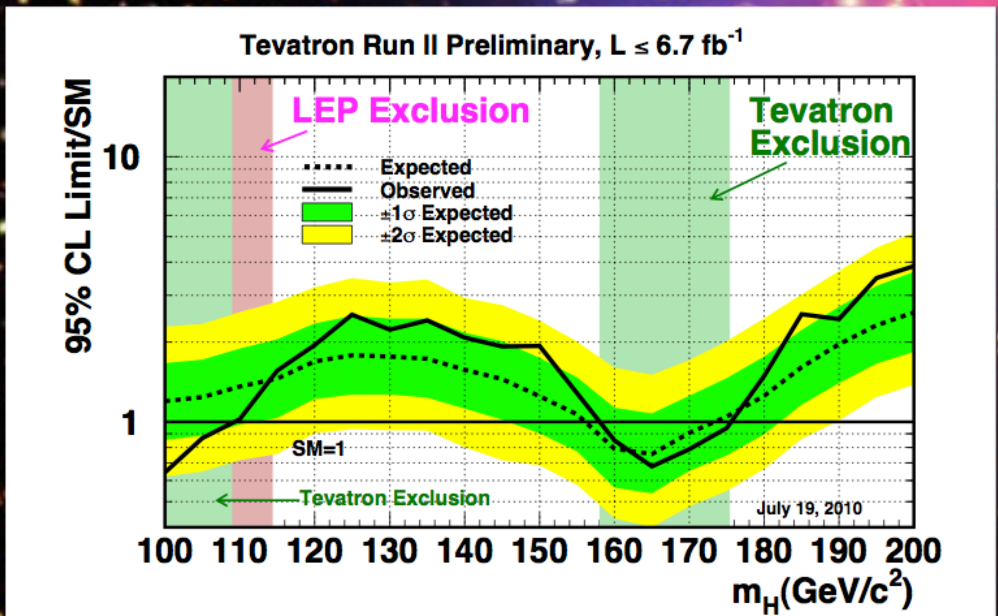
Can be used to test models for New Physics: eg excited quarks.
LHC has already best world limits

The Origin of Mass

Some particles have mass, some do not

Where do the masses come from ?

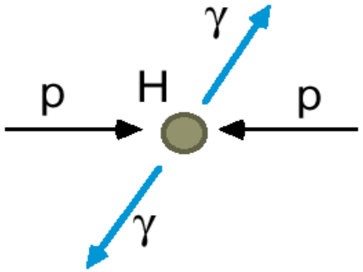
Explanation of Profs P. Higgs R. Brout en F. Englert
⇒ A new field and particle

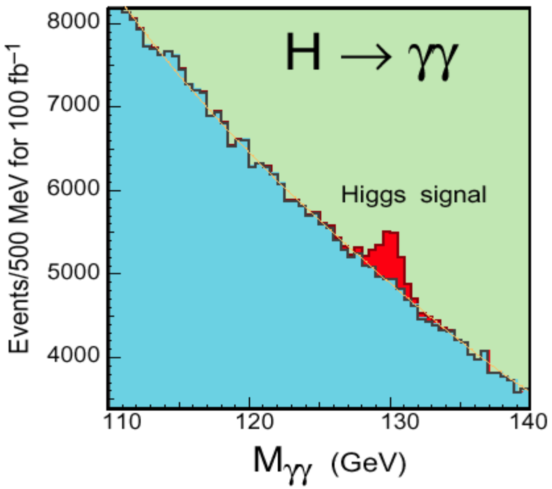


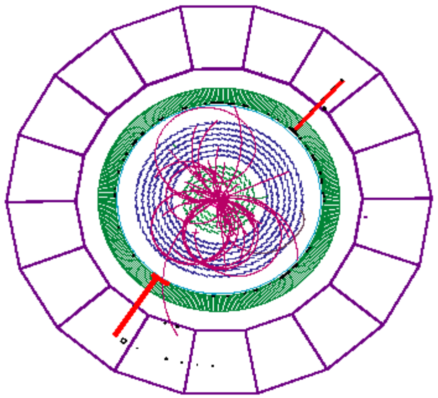
The key question:
Where is the Higgs?

Higgs Boson Searches

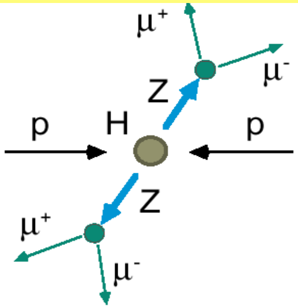
Low M_H < 140 GeV/c²

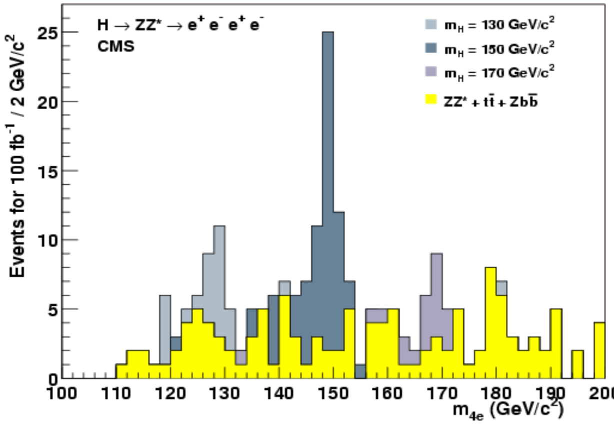


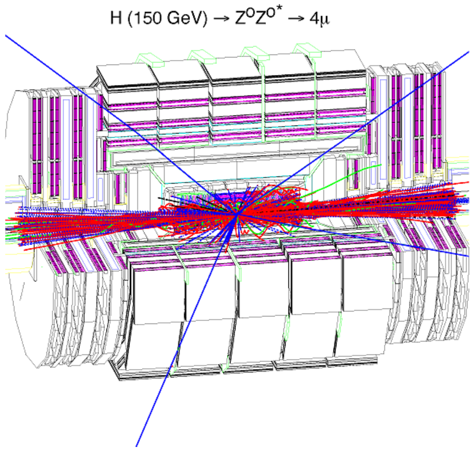




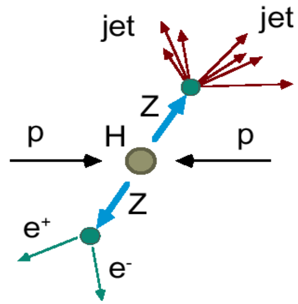
Medium 130<M_H<500 GeV/c²

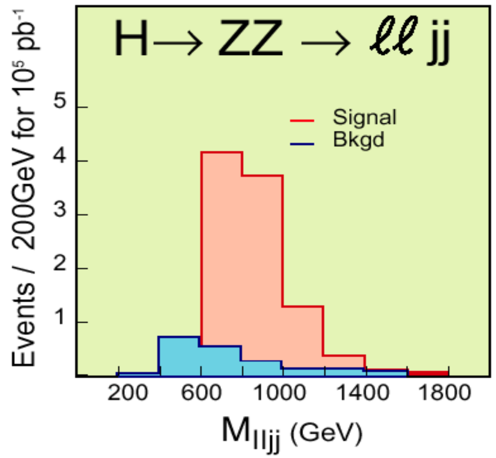


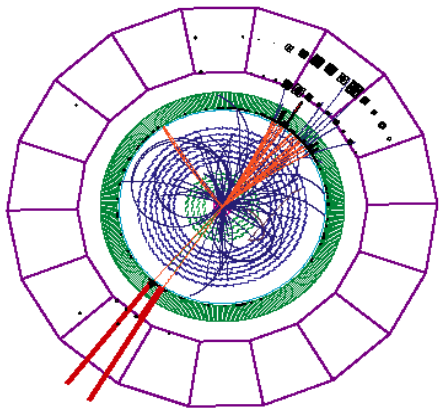




High M_H > ~500 GeV/c²



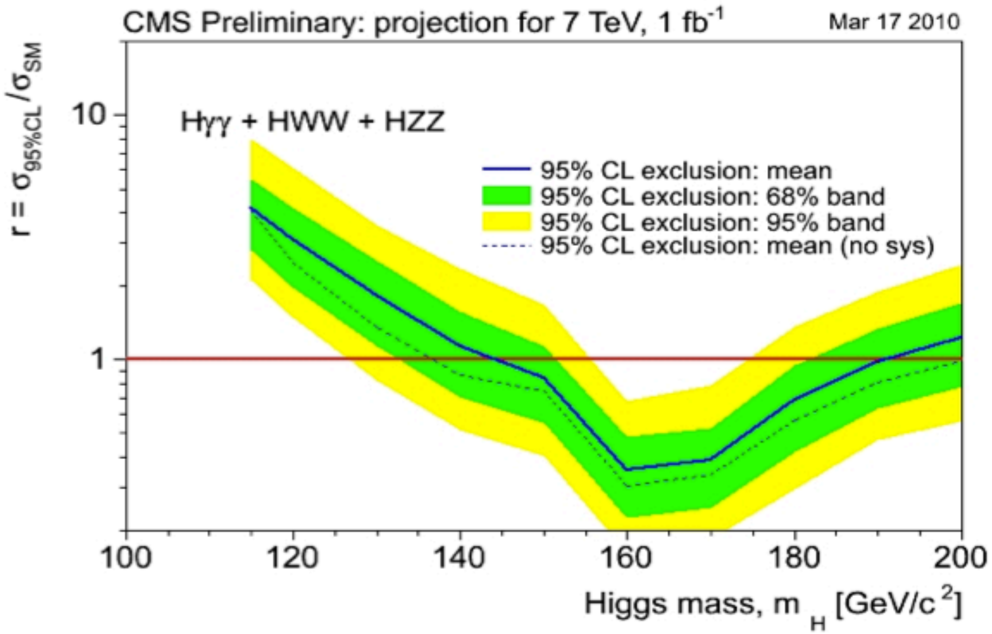




When can we discover the Higgs?

- Sizeable amount of collisions is needed before significant insights can be made in SM Higgs search. This will take many years
- However, by the end of 2011 we will start to probe the interesting region for some values of the Higgs mass

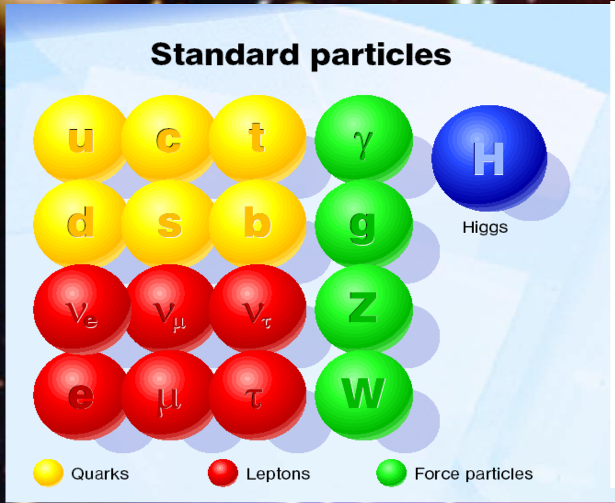
Example Reach by end of 2011

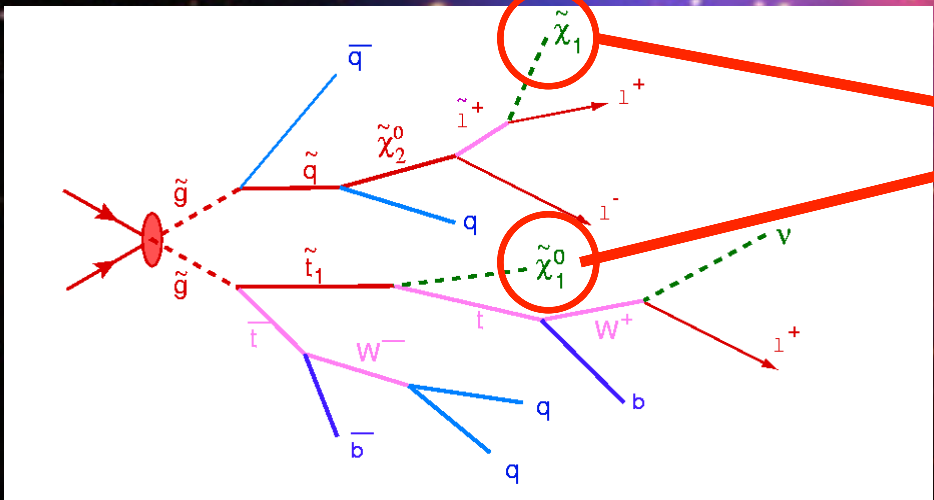


- If the Higgs exist: LHC will discover it after 3-4 years of operation
- If the Higgs does not exist: LHC should see other spectacular new effects

Beyond the Higgs Particle

Supersymmetry: a new symmetry in Nature

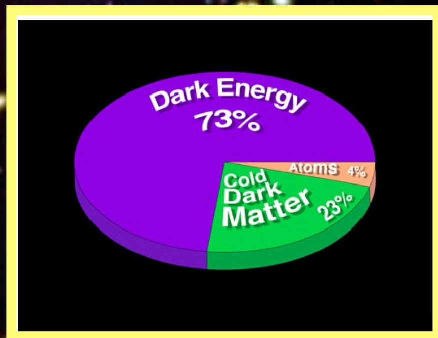




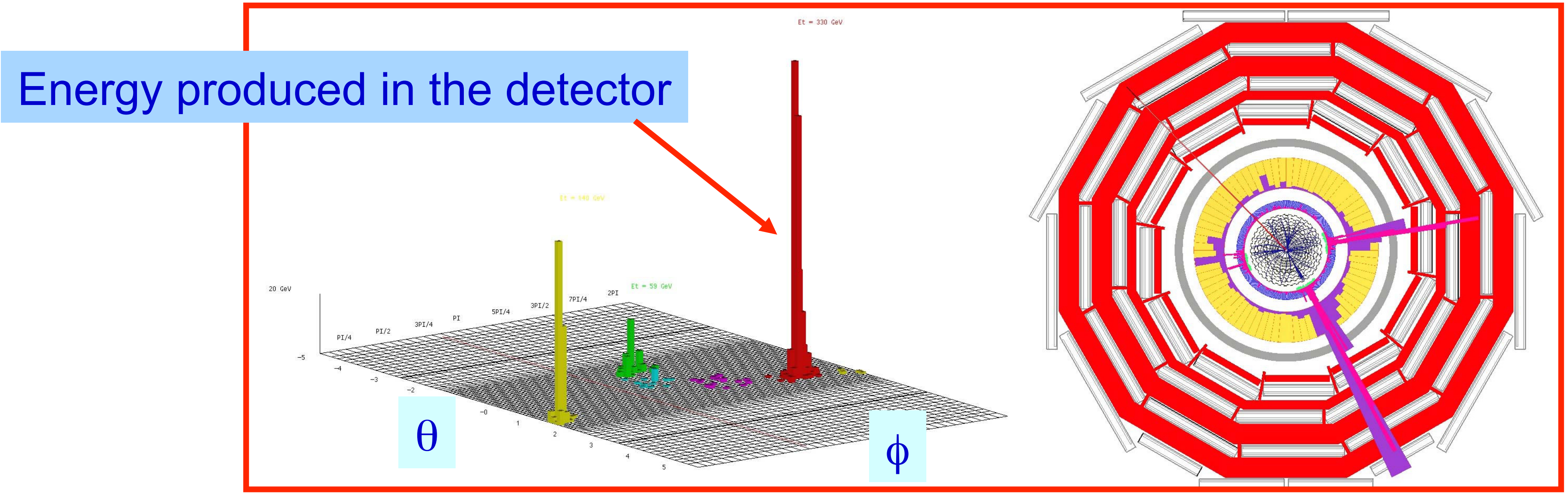
SUSY particle production at the LHC

+ 2 b-jets
+ 4 jets

Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab



Detecting Supersymmetric Particles



Supersymmetric particles decay and produce a cascade of jets, leptons and missing (transverse) energy due to escaping 'dark matter' particles

⇒ Very clear signatures in CMS and ATLAS

LHC can discover supersymmetric partners of the quarks and gluons as heavy as 2 to 3 TeV

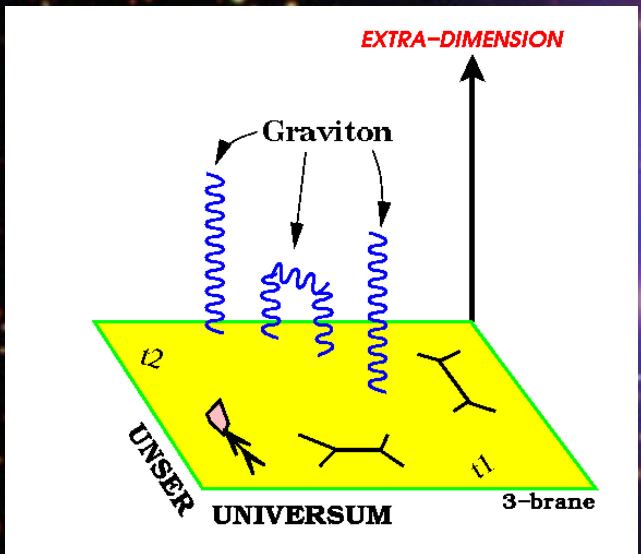
The expected cross sections are huge!! ⇒ 10,000 to 100,000 particles per year

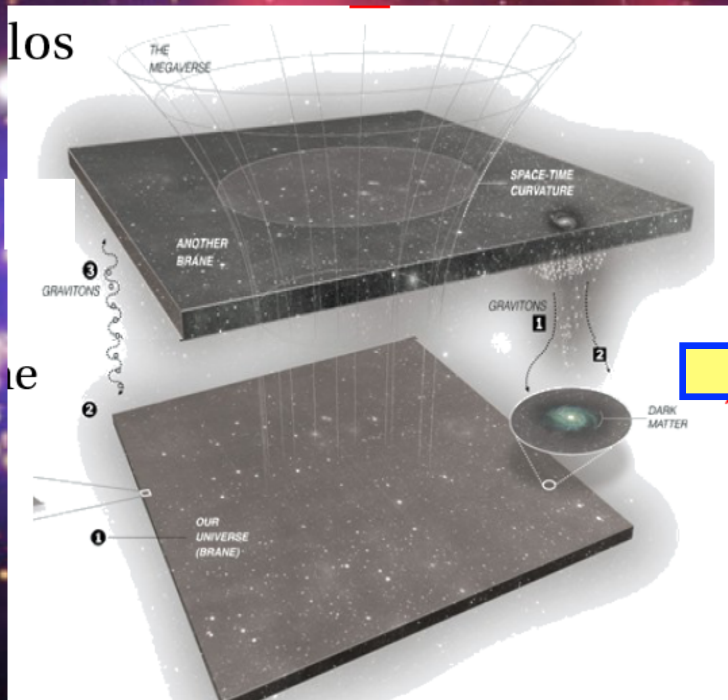
Extra Space Dimensions

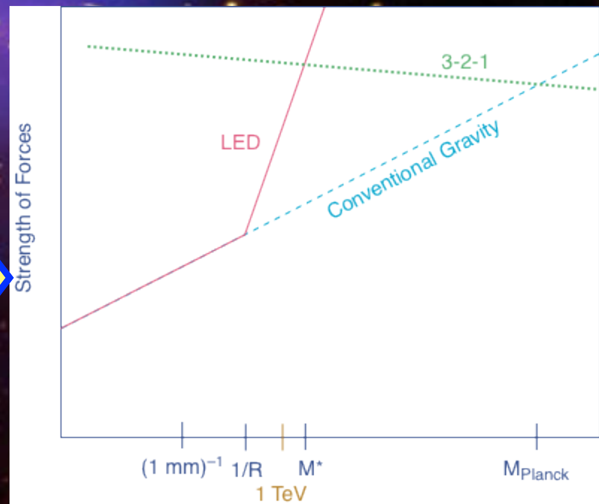
Problem:

$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246 \text{ GeV}$$

$$M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19} \text{ GeV}$$



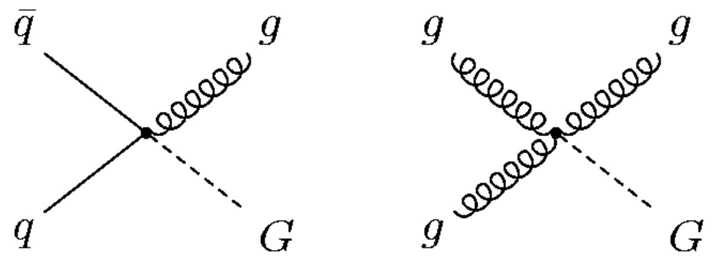


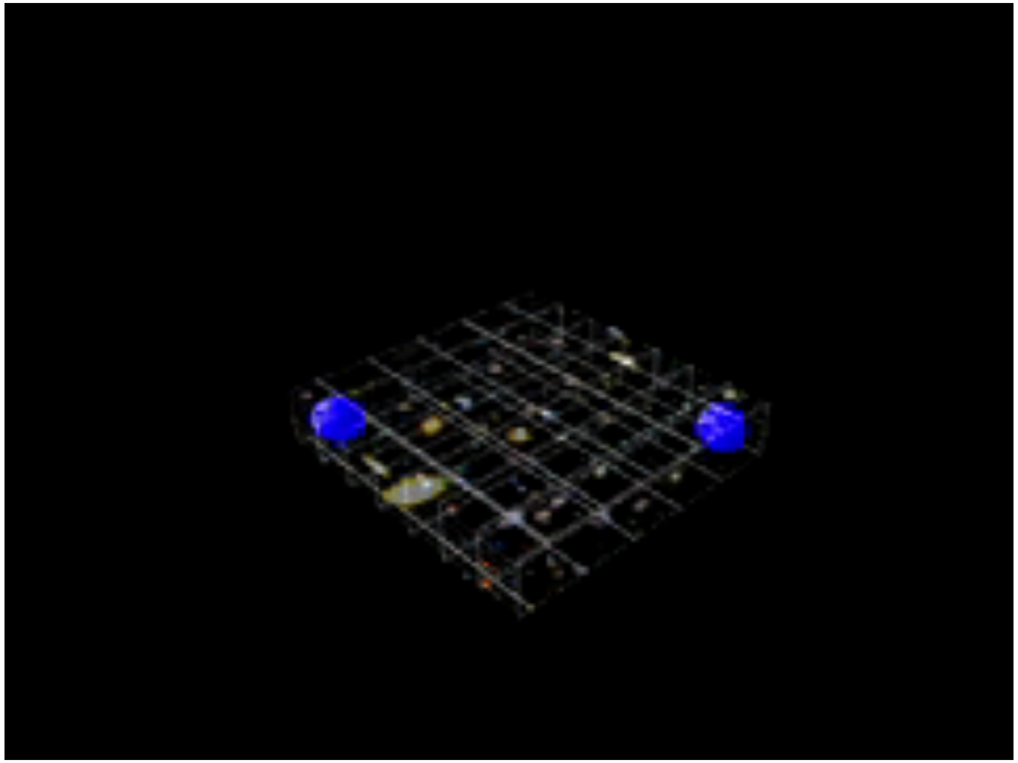


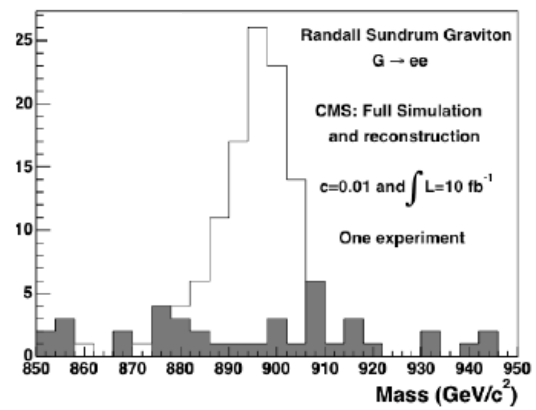
The Gravity force becomes strong!

Detecting Extra Dimensions at the LHC

Main detection modes at the experiments
- Large missing (transverse) energy
- Resonance production





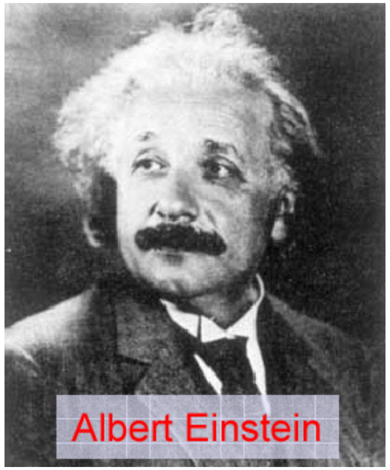


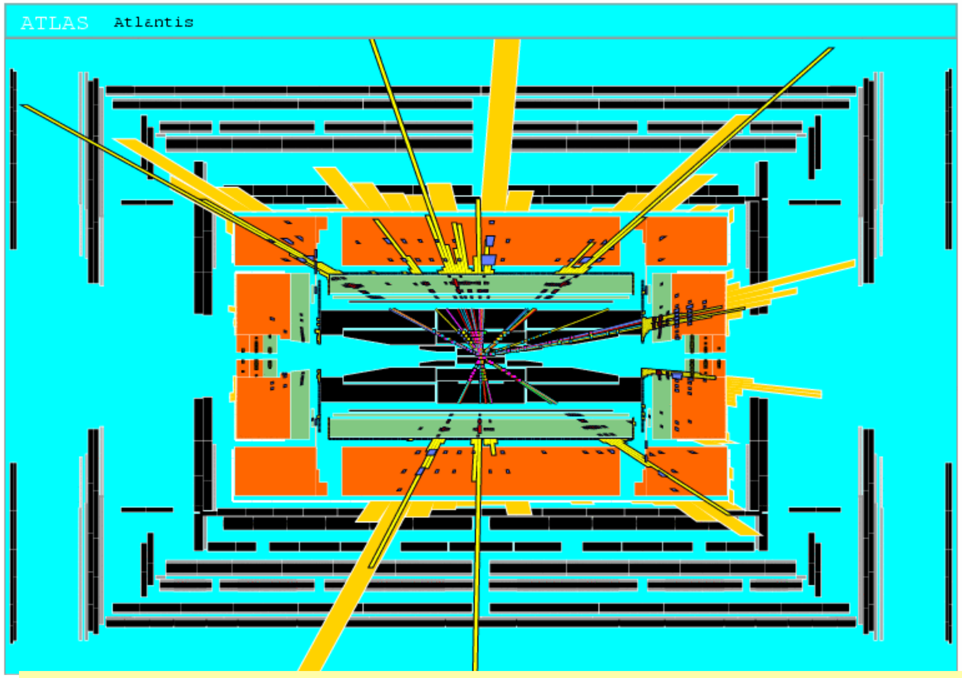
LHC can detect extra dimensions for scales up to 5 to 9 TeV

Quantum Black Holes at the LHC?

Black Holes are a direct prediction of Einstein's general theory on relativity

If the Planck scale is in ~TeV region:
can expect Quantum Black Hole production





Simulation of a Quantum Black Hole event

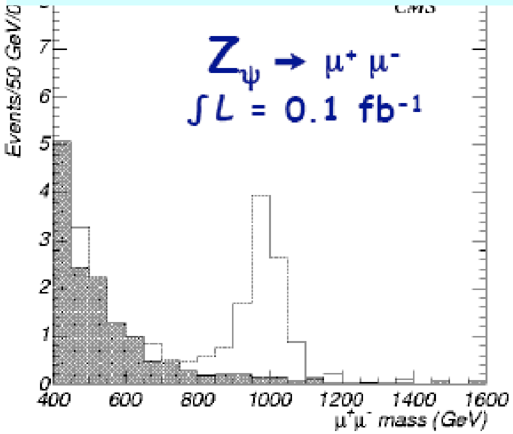
Quantum Black Holes are harmless for the environment: they will decay within less than 10^{-27} seconds ⇒ SAFE!

Quantum Black Holes open the exciting perspective to study Quantum Gravity in the lab!

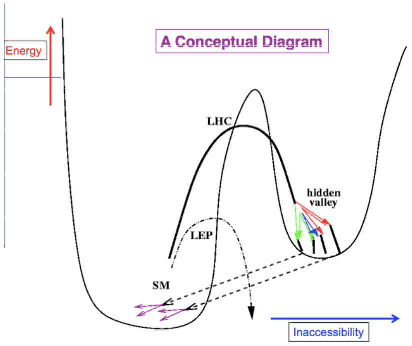
Black Holes Hunters at the LHC…

Other New Physics Scenarios at the LHC

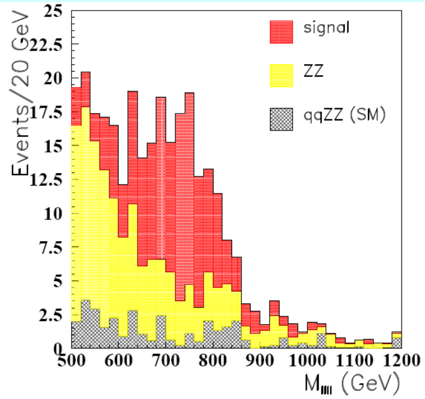
New Gauge Bosons?



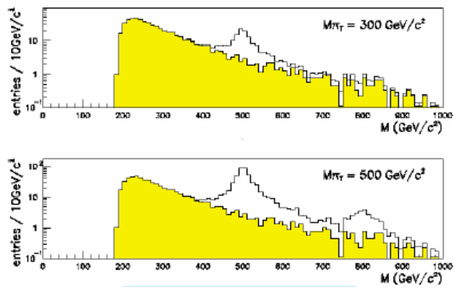
Hidden Valleys?



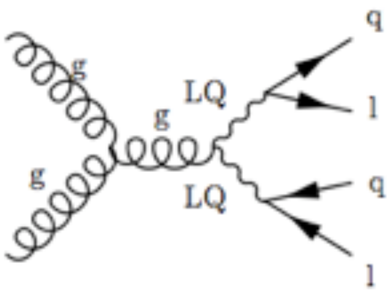
ZZ/WW resonances?



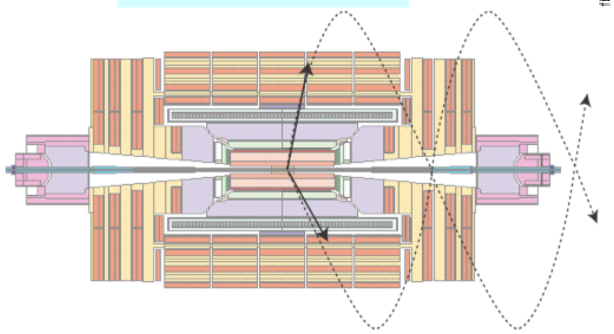
Technicolor?



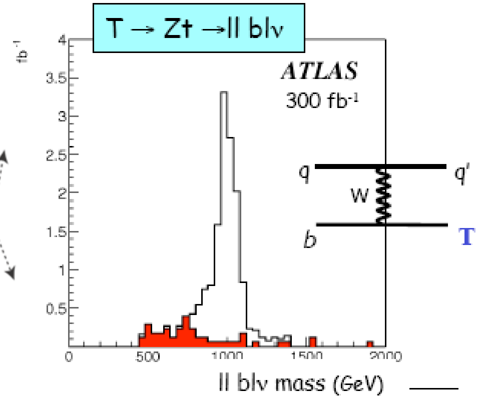
Leptoquarks?



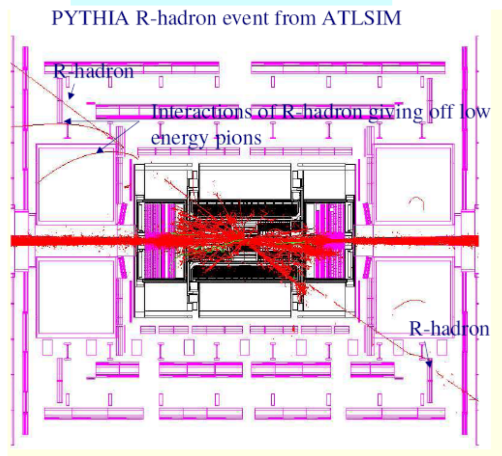
Quirks???



Little Higgs?



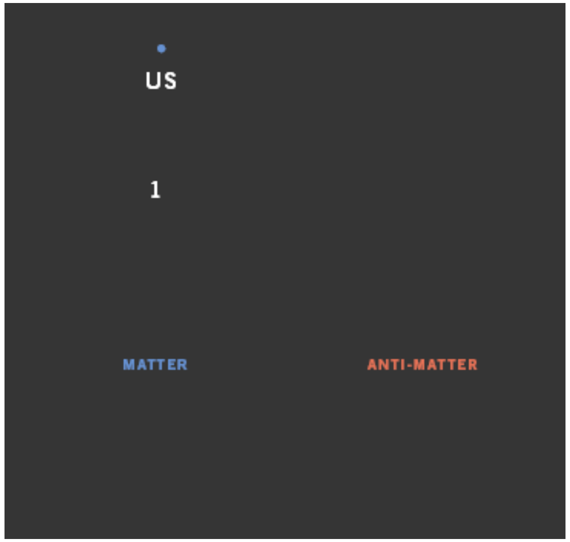
Split Susy?

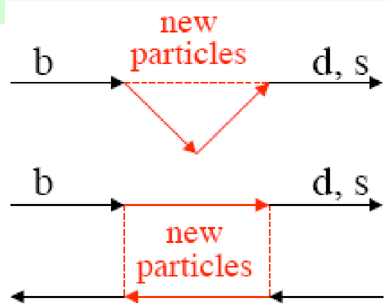


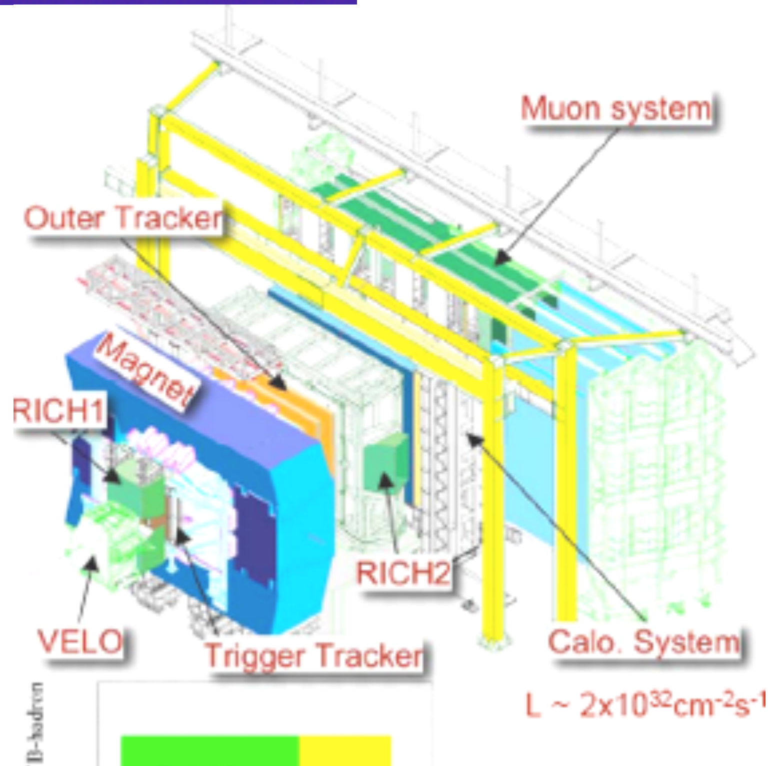
We do not know what is out there waiting for us…

Matter-Antimatter

The properties and subtle differences of matter and anti-matter using mesons containing the beauty quark, will be studied further in the LHCb experiment

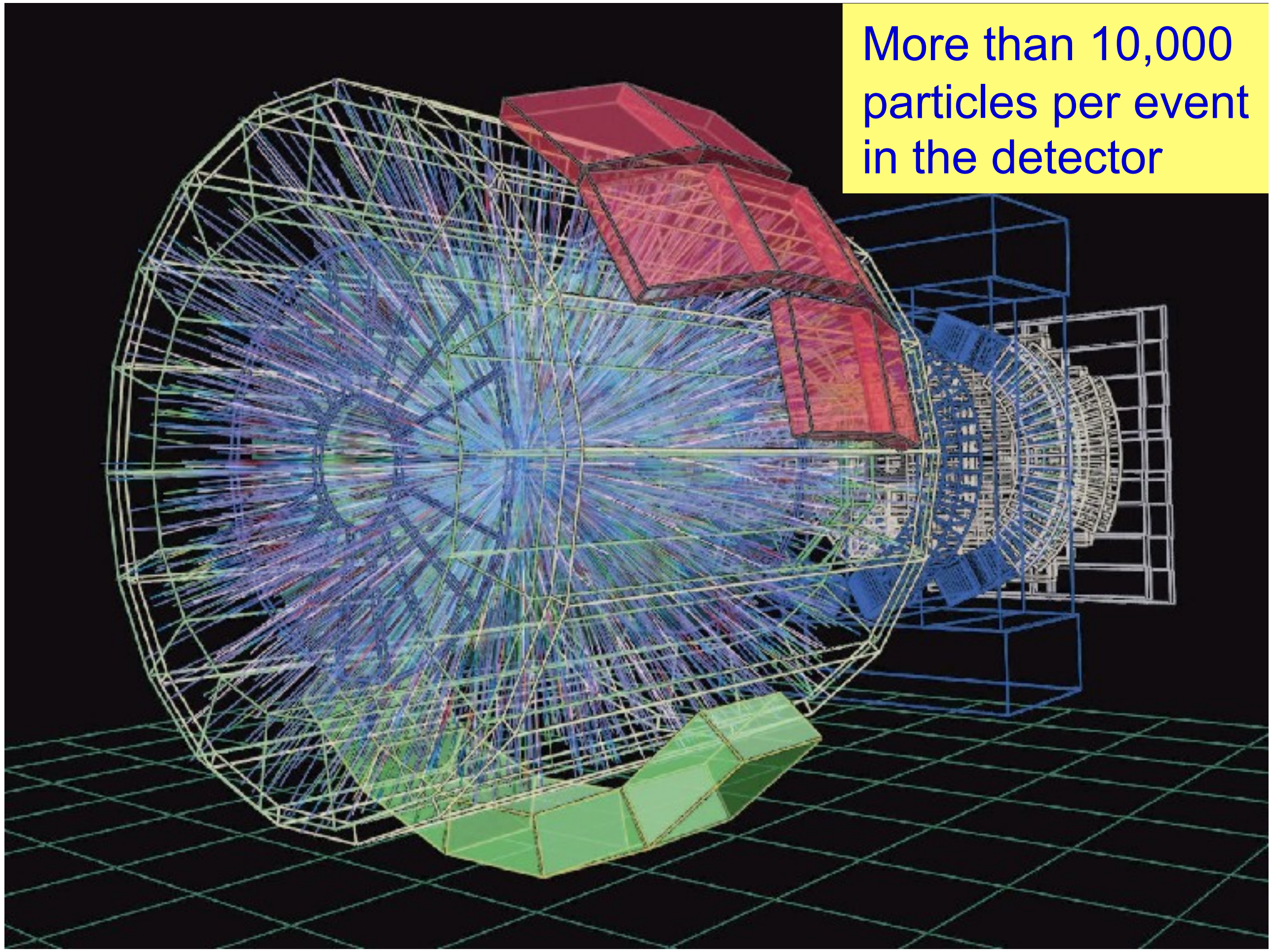






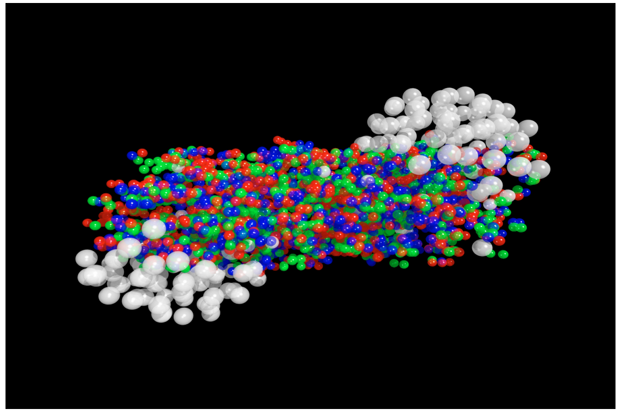
Primordial Plasma

Lead-lead collisions at the LHC to study the primordial plasma, a state of matter in the early moments of the Universe

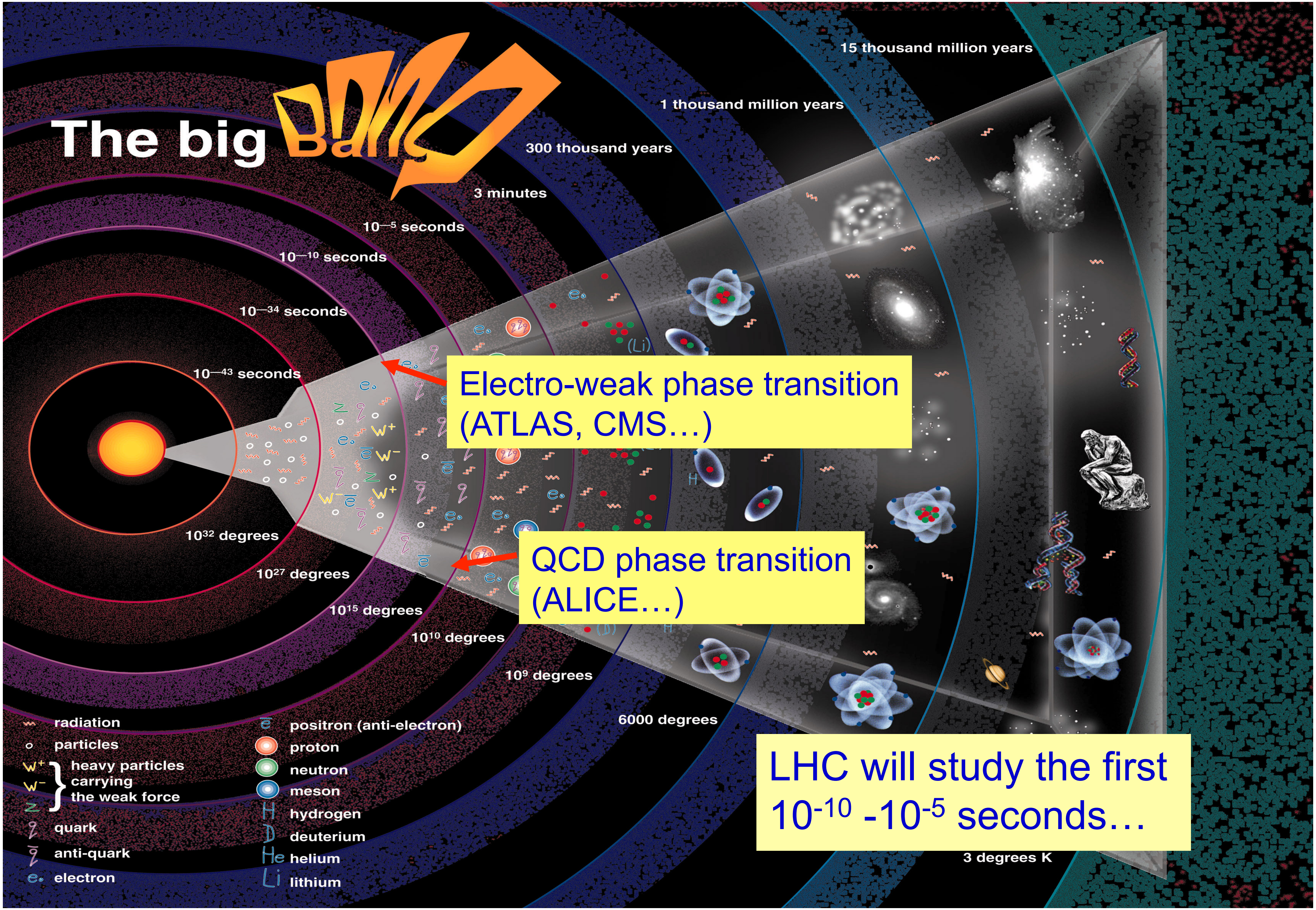


More than 10,000 particles per event in the detector

A lead lead collision simulated in the ALICE detector



Study the phase transition of a state of quark gluon plasma created at the time of the early Universe to the baryonic matter we observe today


The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10^{-5} seconds
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
3 degrees K
Electro-weak phase transition (ATLAS, CMS…)
QCD phase transition (ALICE…)
LHC will study the first 10^{-10} -10^{-5} seconds…
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

The LHC will reveal the origin of mass of particles

It will very likely reveal much more ….
There is mounting evidence, from neutrino mass to dark matter and dark energy observations, that there is something profound that we do not yet understand
Is it supersymmetry, extra dimensions, other…?

The LHC operates at an energy and precision that will take us far beyond our current understanding, into a new regime

Machine and detectors are of an unprecedented scale and complexity. The LHC has started for a first physics run in 2010 -2011.

We are on the verge of a revolution in our understanding of the Universe and our place within it

The End