The Large Hadron Collider: The Big Bang Machine

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Contents

In this talk I will present and discuss the most complex, most challenging and at the same time one of the most anticipated scientific instruments so far built by mankind:

The Large Hadron Collider (LHC), built at CERN, Switzerland

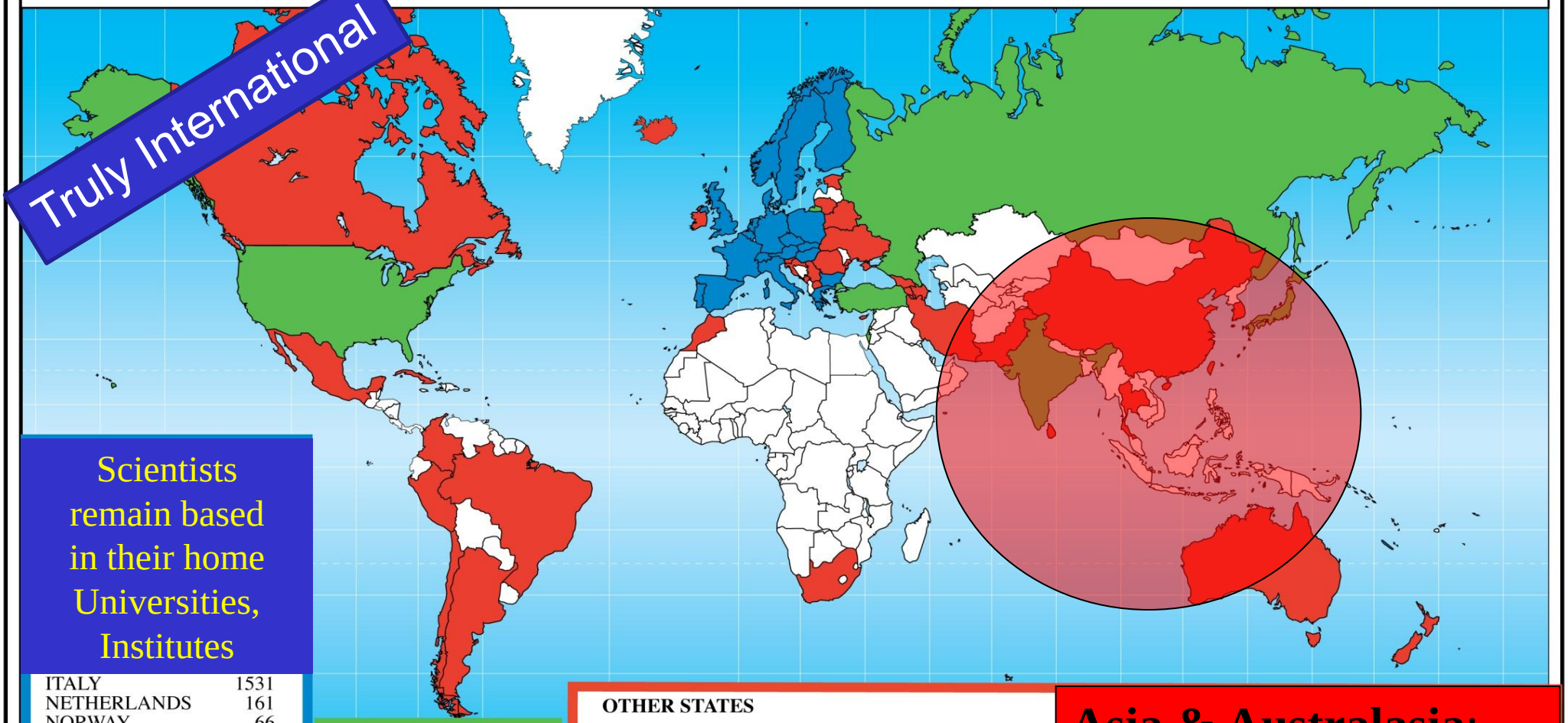
- What are the fundamental questions in particle physics?
- What is the Large Hadron Collider?
- What are the challenges of the collider and experiments?
- What is the science of the Large Hadron Collider?

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

Distribution of All CERN Users by Nation of Institute on 17 July 2007



Truly International

Scientists remain based in their home Universities, Institutes

ITALY	1531
NETHERLANDS	161
NORWAY	66
POLAND	179
PORTUGAL	100
SLOVAKIA	35
SPAIN	268
SWEDEN	69
SWITZERLAND	337
UNITED KINGDOM	602

5695

OBSERVER STATES

INDIA	87
ISRAEL	49
JAPAN	153
RUSSIA	959
TURKEY	38
USA	1269

2555

OTHER STATES

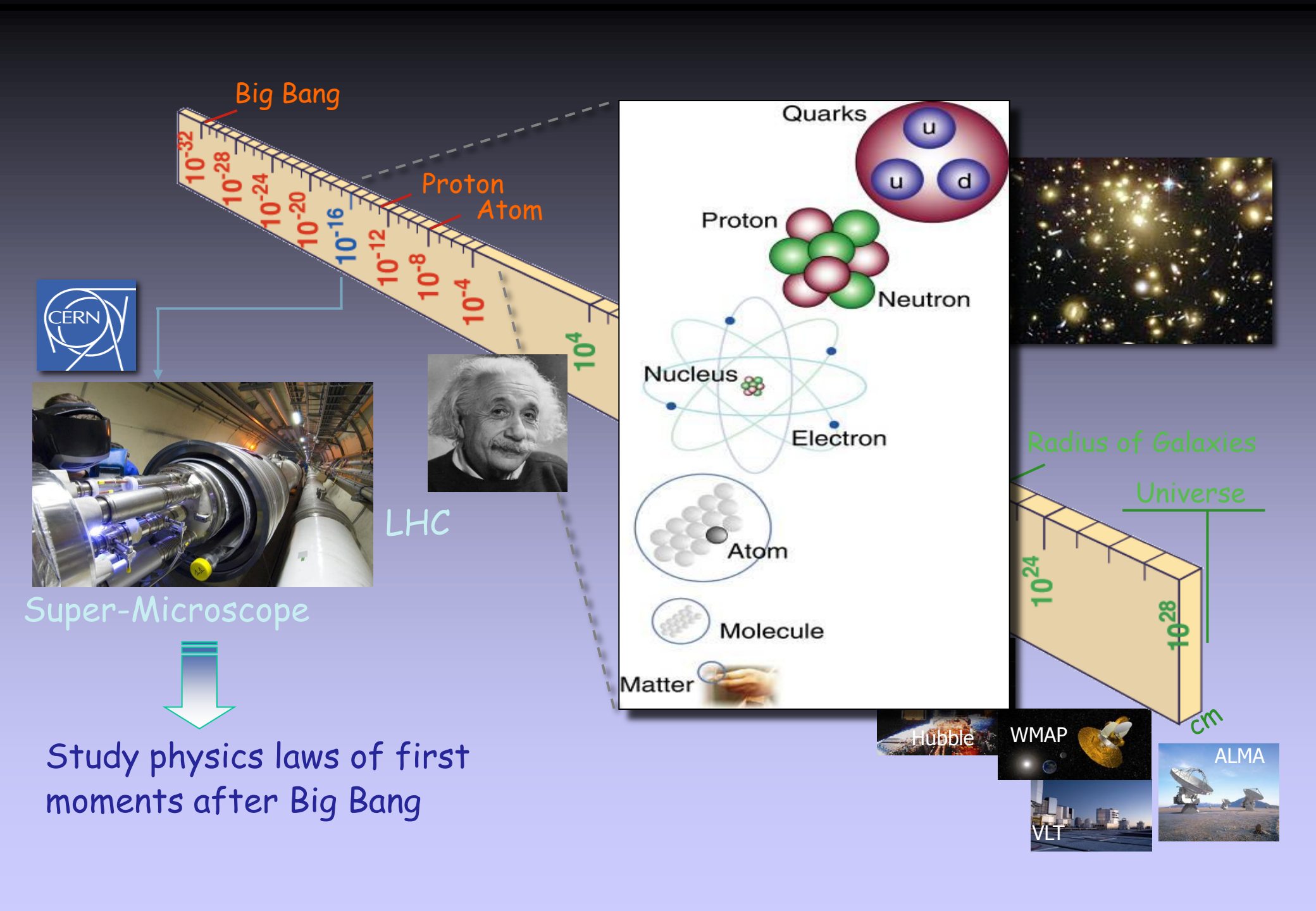
ARGENTINA	6	CROATIA	21
ARMENIA	17	CUBA	2
AUSTRALIA	13	CYPRUS	8
AZERBAIJAN	1	ESTONIA	14
BELARUS	19	GEORGIA	8
BRAZIL	55	ICELAND	4
CANADA	110	IRAN	6
CHILE	4	IRELAND	11
CHINA	62	KOREA	30
COLOMBIA	7	LITHUANIA	5

Asia & Australasia:
3 Observer States
Cooperation
Agreements
with 10 countries

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?

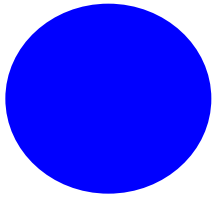


Study physics laws of first moments after Big Bang

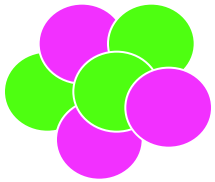
Accelerators are Powerful Microscopes.

They make high energy particle beams
that allow us to see small things.

$$\lambda = \frac{h}{p}$$

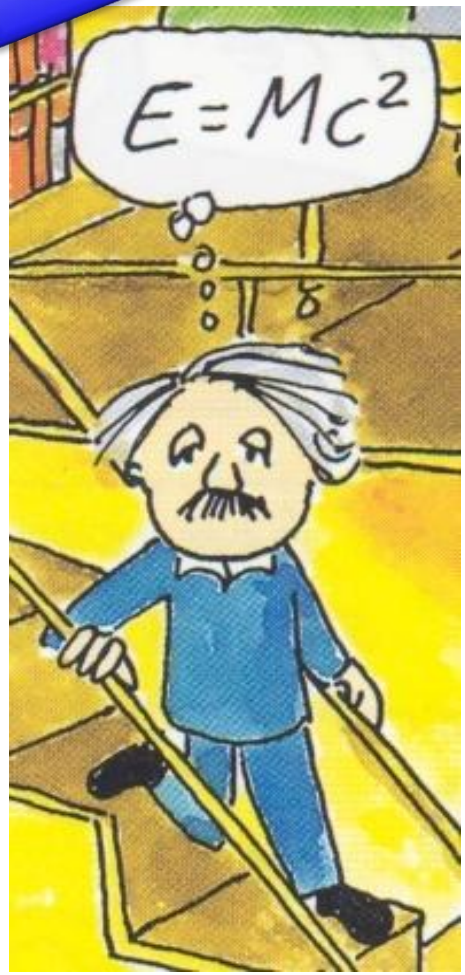


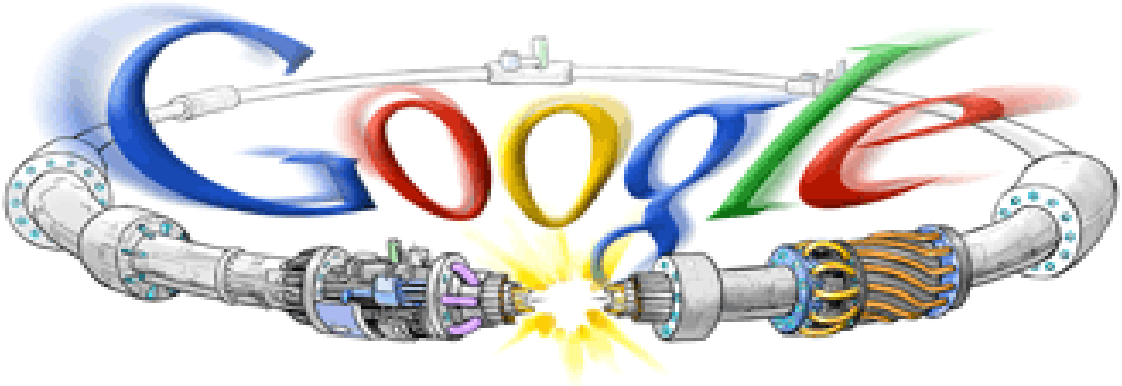
seen by
low energy beam
(poorer resolution)



seen by
high energy beam
(better resolution)

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.

Illustrating the experiment

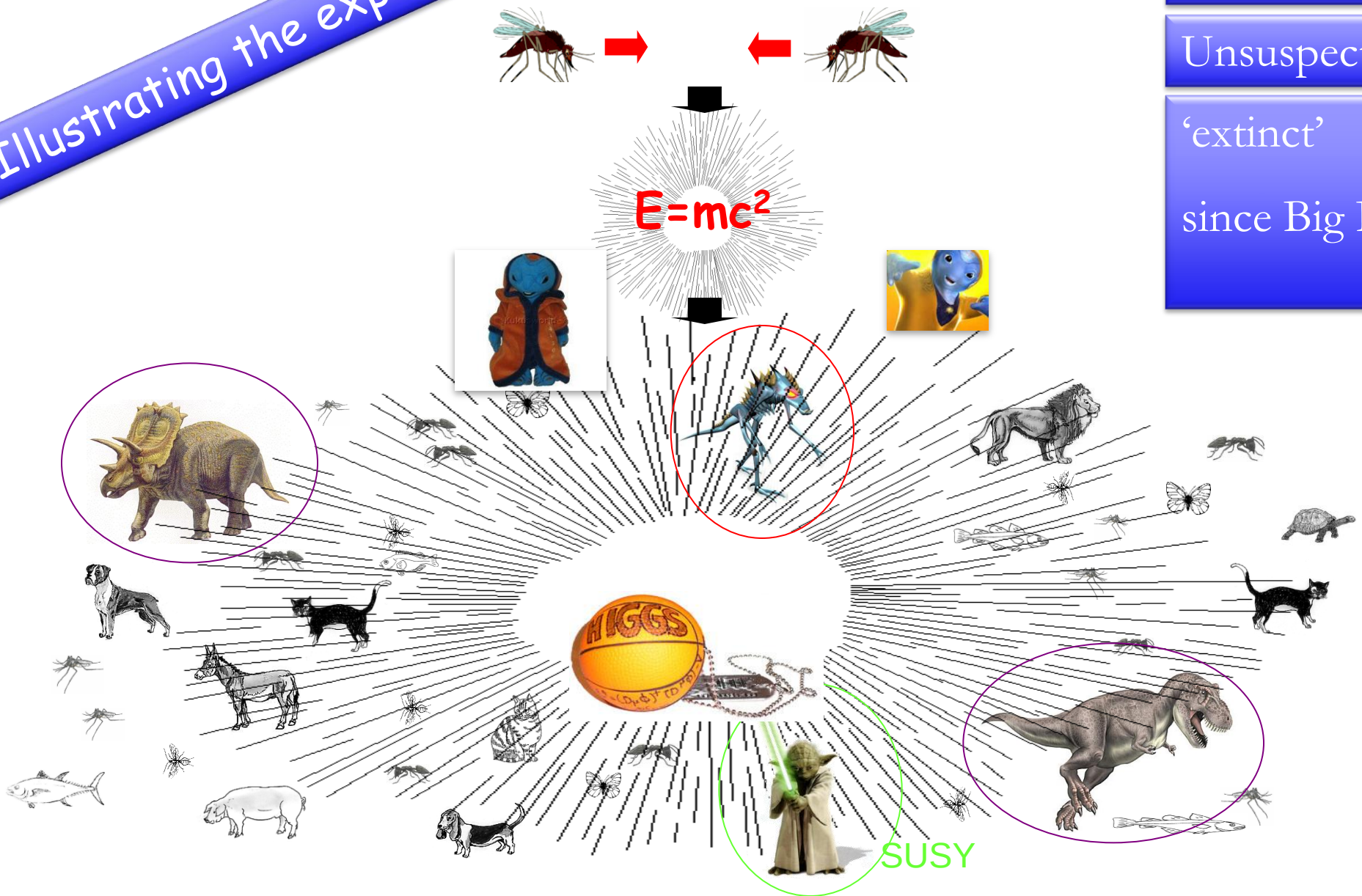
Highly Expected

Hypothetical

Unsuspected ?

'extinct'

since Big Bang

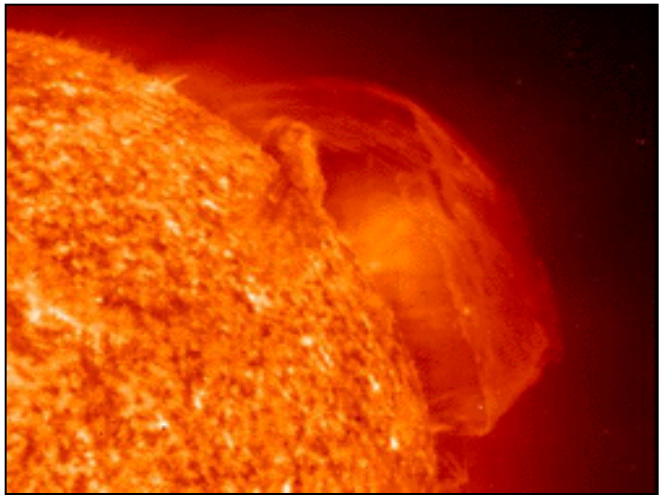


The Fundamental Forces of Nature

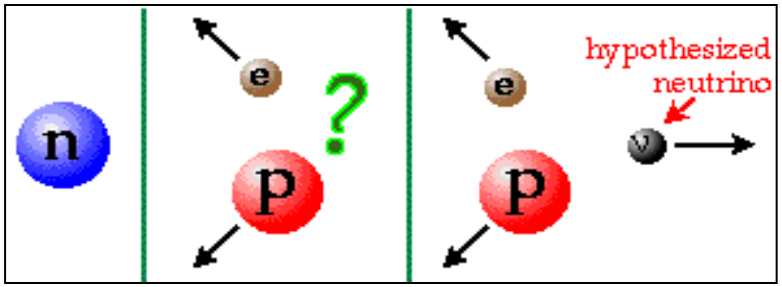
Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity



together they make the Sun shine



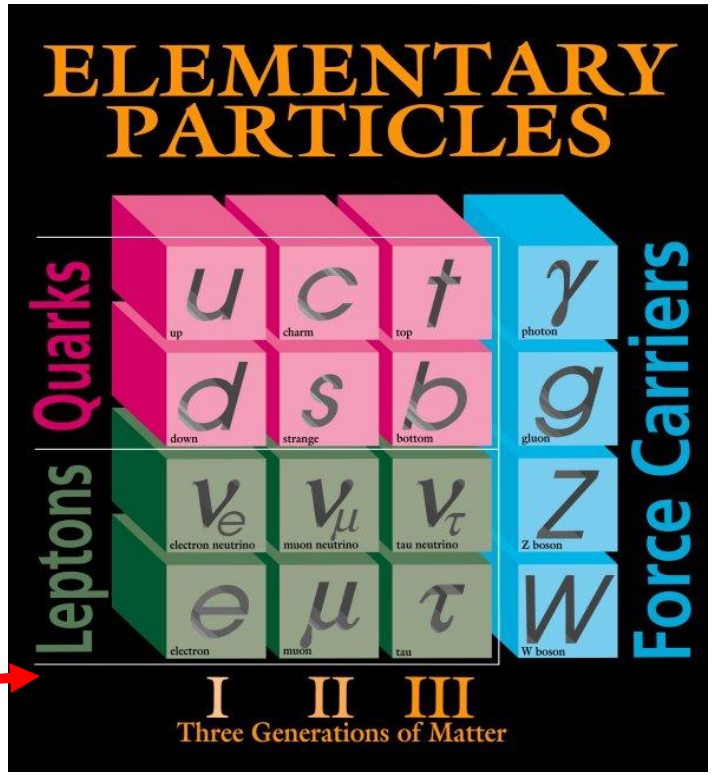
Gravity:
holds planets and stars together

The Standard Model in Particle Physics

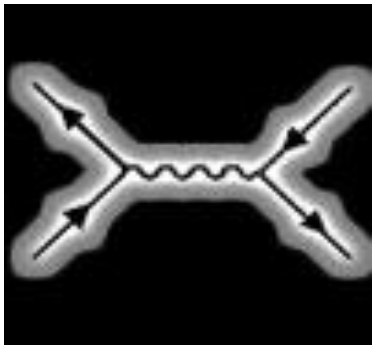
But not all questions solved:

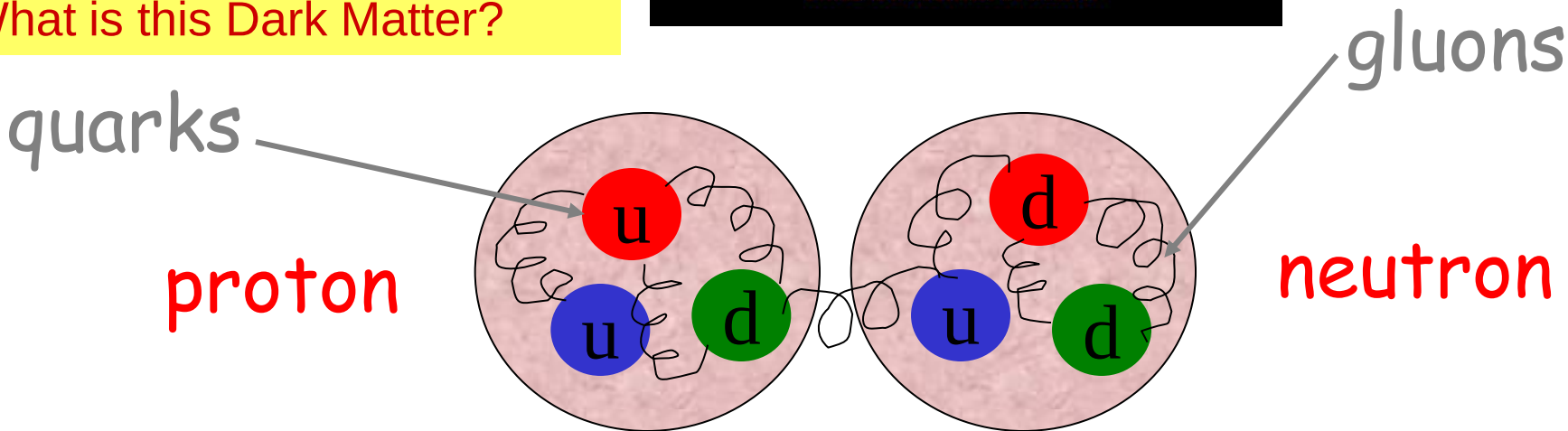
Why is the top quark much more heavy than the quarks
⇒Mass(top) = gold nucleus
What is the origin of mass?

Astrophysics/cosmological measurements show that most matter in the universe is NOT in this table
What is this Dark Matter?



Four known forces
- Gravity
- Electro-magnetisme
- Strong nuclear force
- Weak force





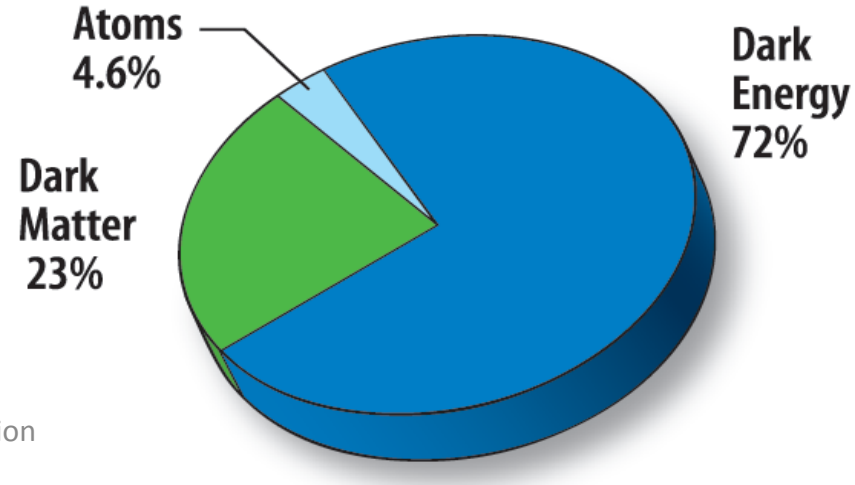
Dark Matter in the Universe

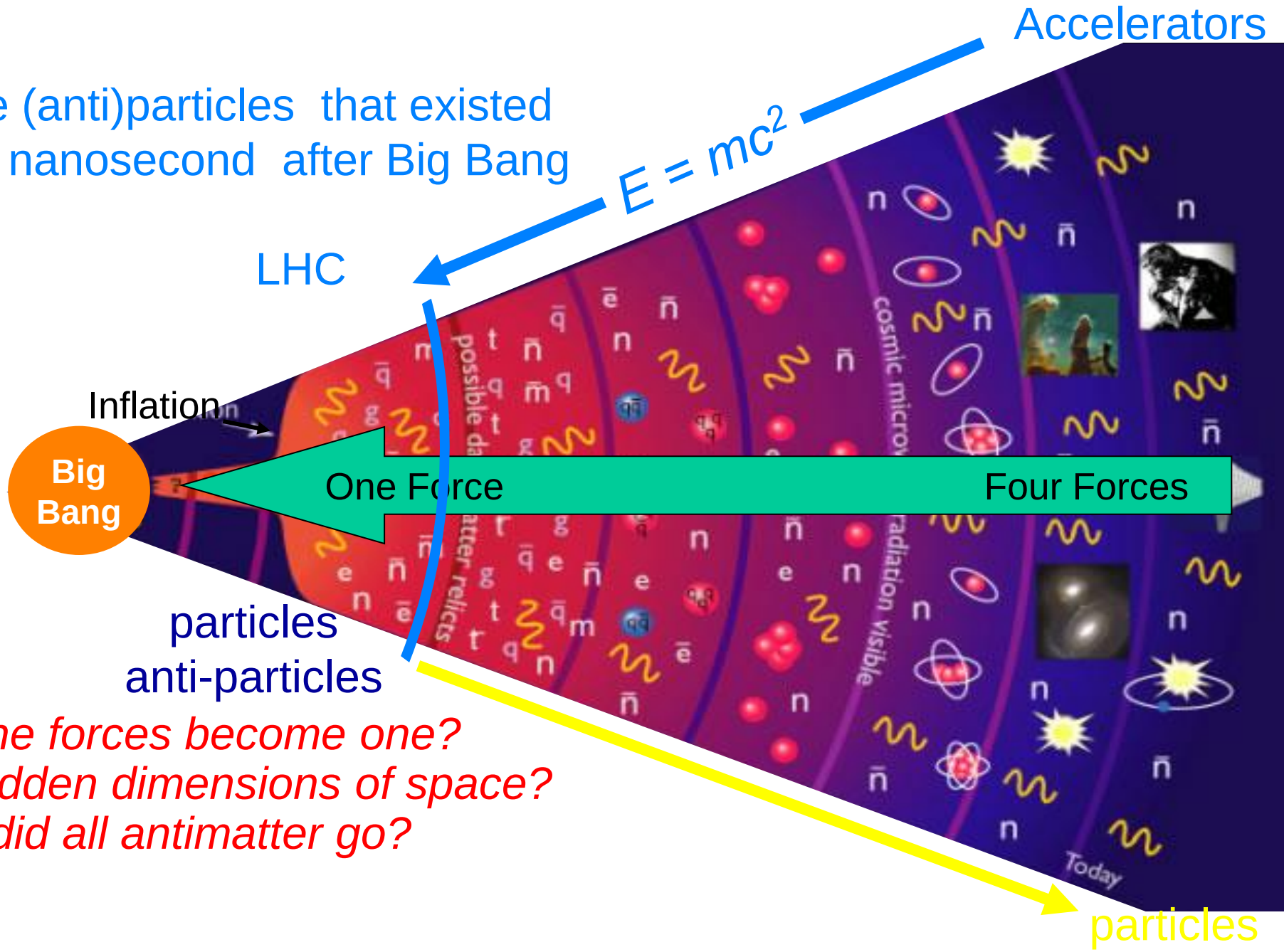
Astronomers say that most of the matter in the Universe is invisible Dark Matter

'Supersymmetric' particles ?

We shall look for them with the LHC

F. Zwicky 1898-1974




Accelerators
Create (anti)particles that existed
~0.001 nanosecond after Big Bang
E = mc2
LHC
Inflation
Big Bang
One Force
Four Forces
particles
anti-particles
Do all the forces become one?
Extra hidden dimensions of space?
Where did all antimatter go?
Today
particles

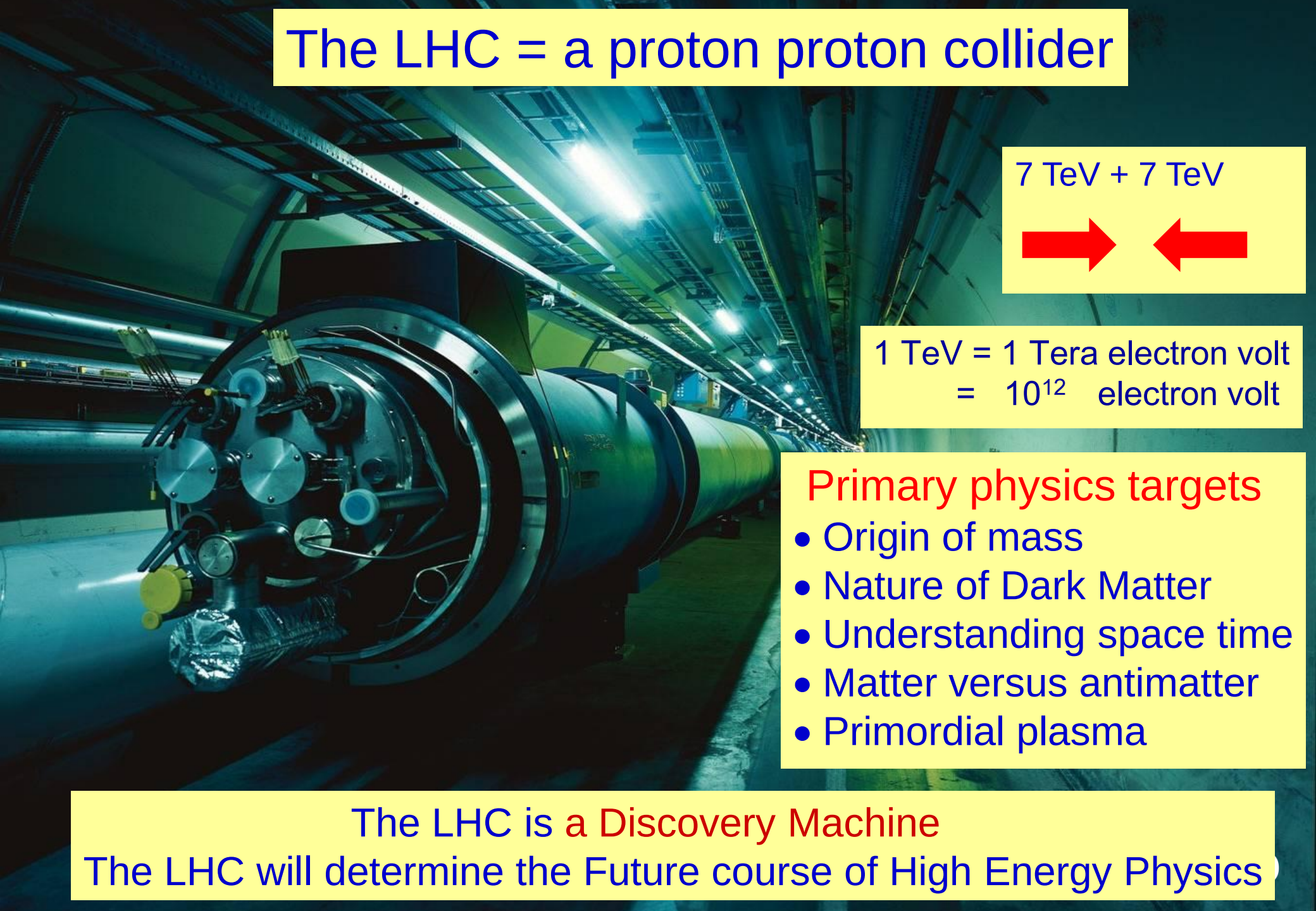
1. Are there undiscovered principles of nature:
   New symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter?
   How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?
10. What is mass?

"Quantum Universe" and
"Discovering the Quantum Universe"

Evolved Thinker

Discoveries and breakthroughs will likely come from Energy Frontier Accelerators at the Terascale.

The LHC = a proton proton collider



7 TeV + 7 TeV

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

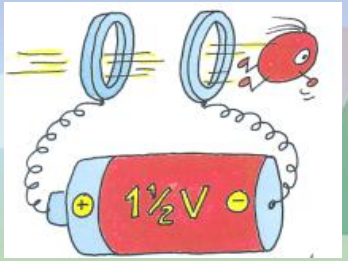
Primary physics targets

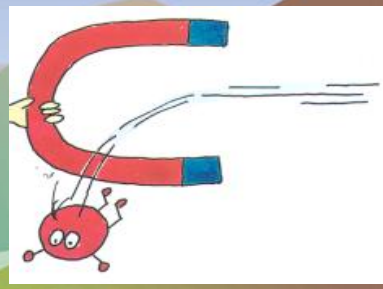
- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

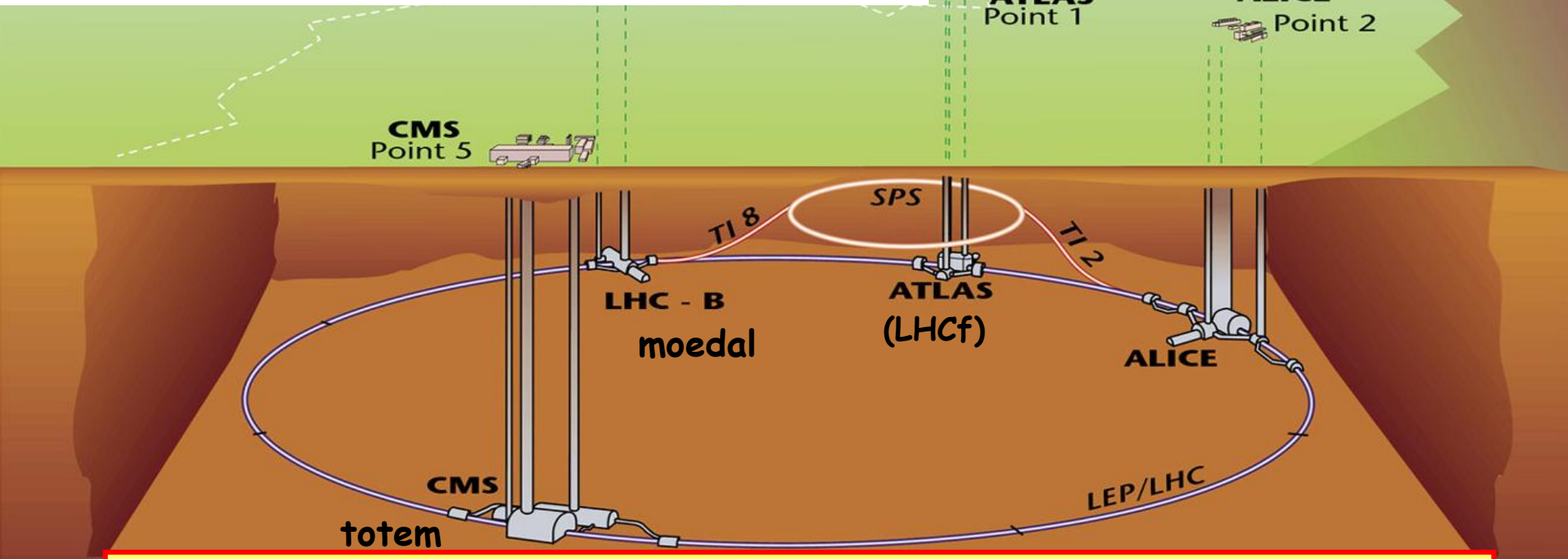
The LHC is a Discovery Machine
The LHC will determine the Future course of High Energy Physics

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)



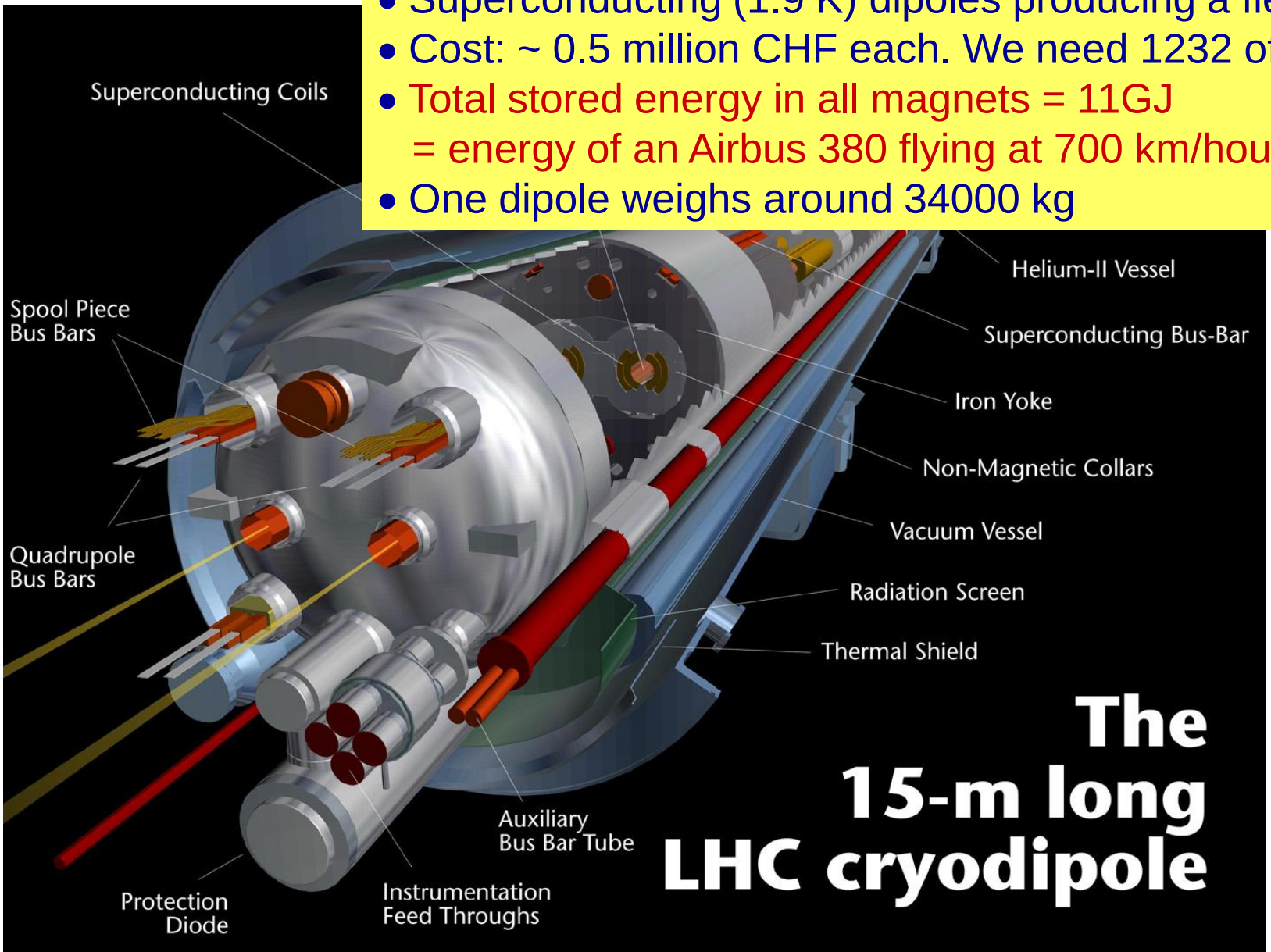




- High Energy ⇒ factor 7 increase w.r.t. present accelerators
- High Luminosity (# events/cross section/time) ⇒ factor 100 increase

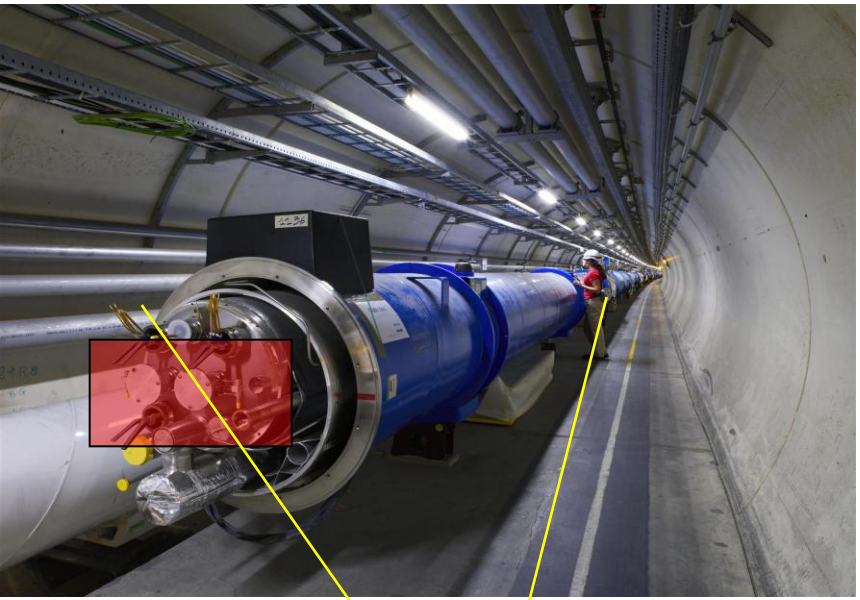
The Cryodipole Magnets

- Superconducting (1.9 K) dipoles producing a field of 8.4 T
- Cost: ~ 0.5 million CHF each. We need 1232 of them
- Total stored energy in all magnets = 11GJ
  = energy of an Airbus 380 flying at 700 km/hour
- One dipole weighs around 34000 kg



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…

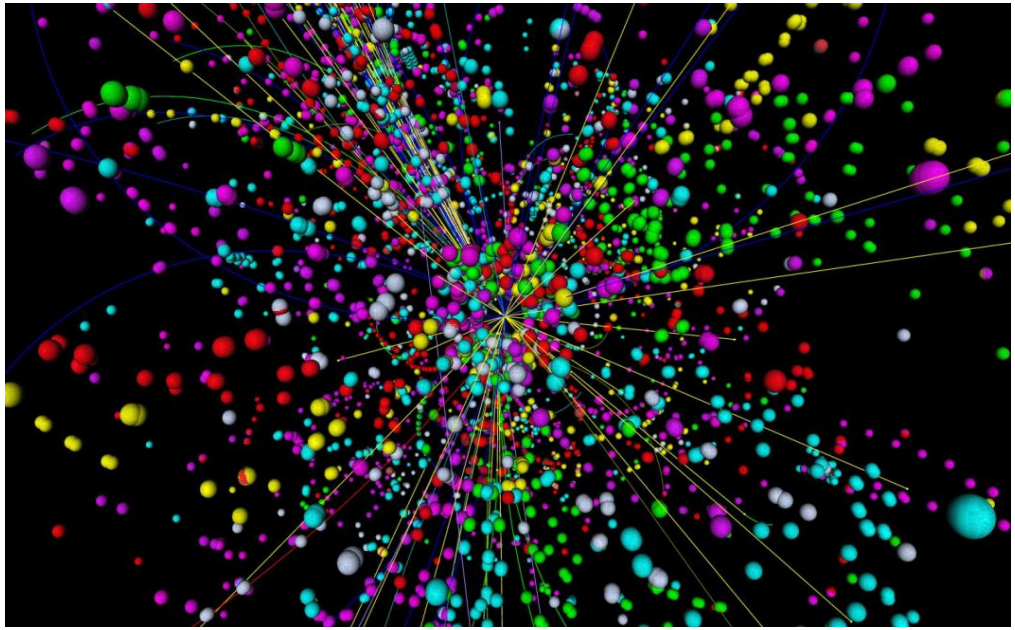
the largest cryogenic system ever built

54 km fridge!

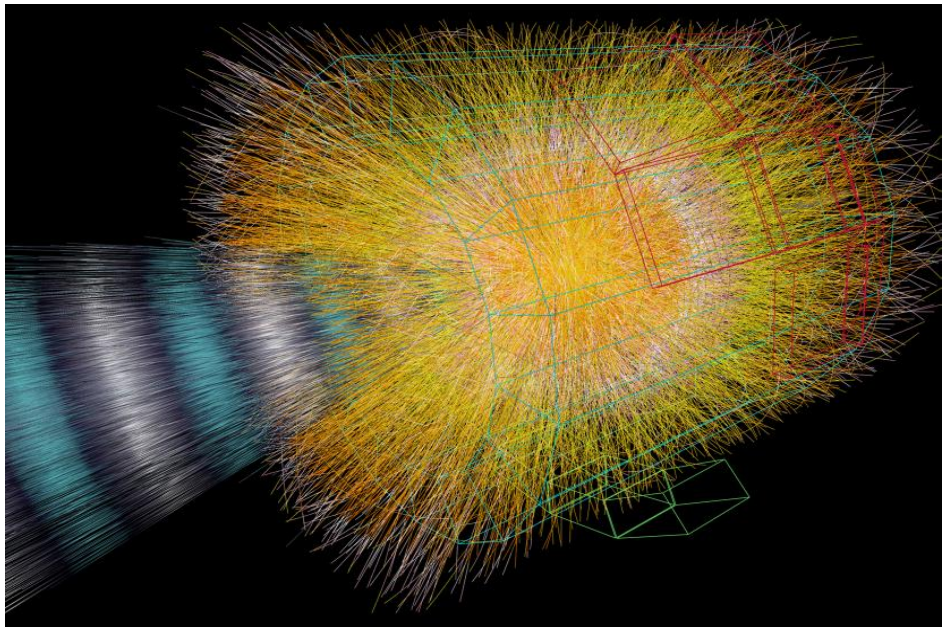
With a temperature of around -271 degrees Celsius, or 1.9 degrees above absolute zero, the LHC is colder than interstellar space.

LHC facts

One of the **hottest** places in the Galaxy…

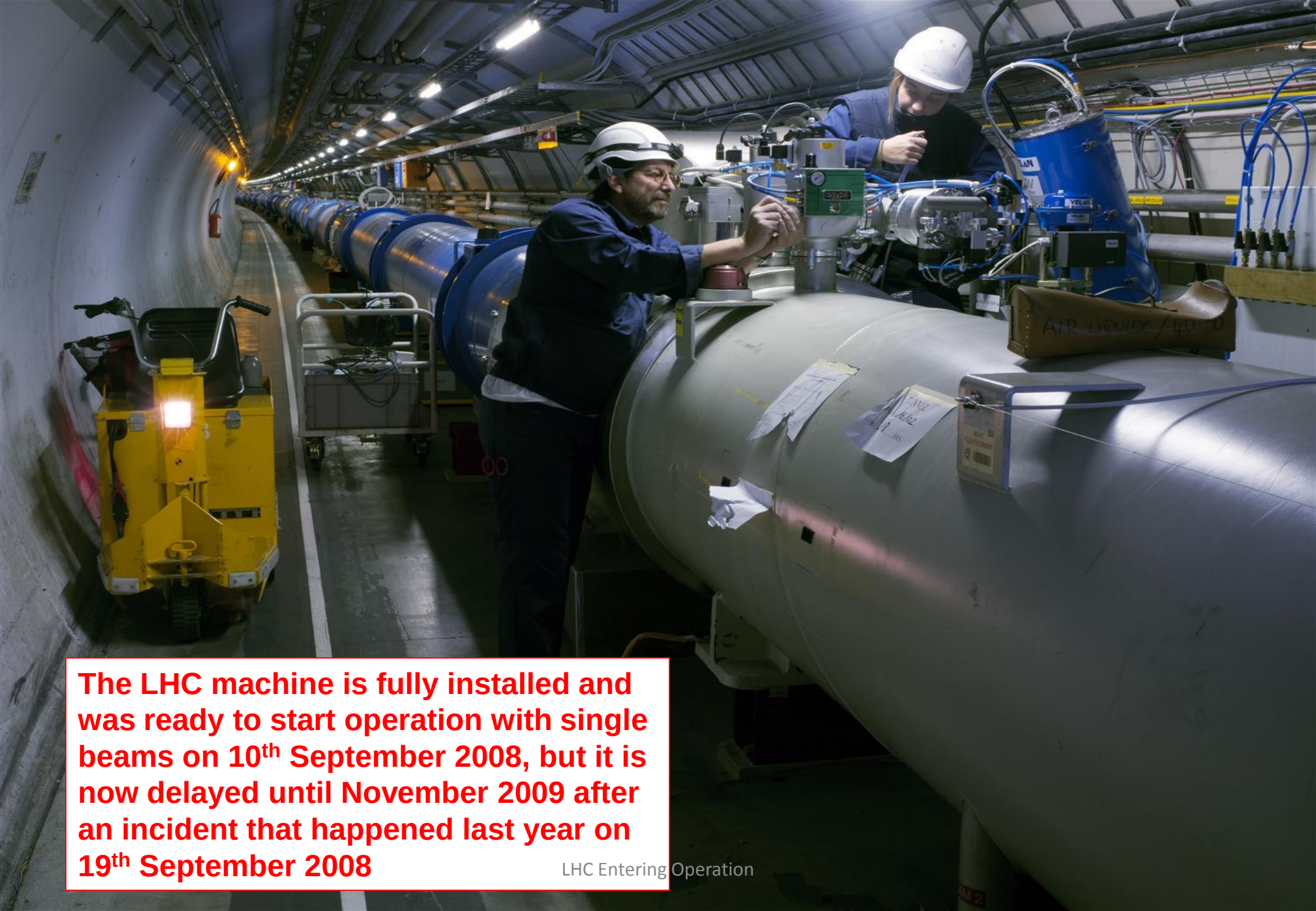


Simulation of a collision in the CMS experiment



Simulation of a collision in the ALICE experiment

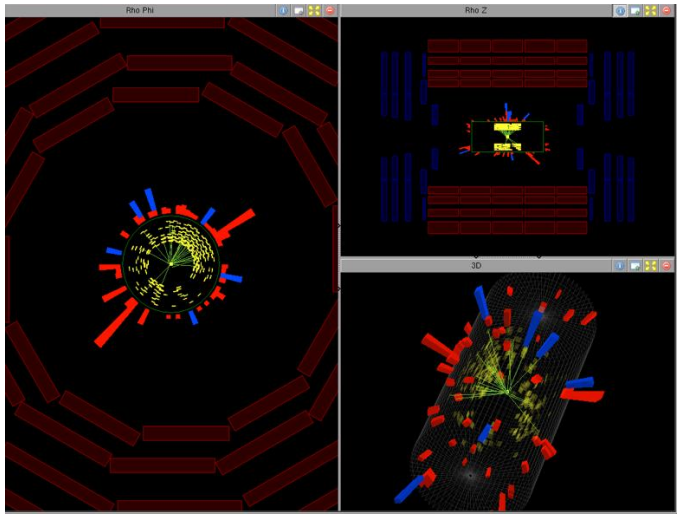
When two beams of protons collide, they generate within a tiny volume, temperatures more than a billion times those in the very heart of the Sun.

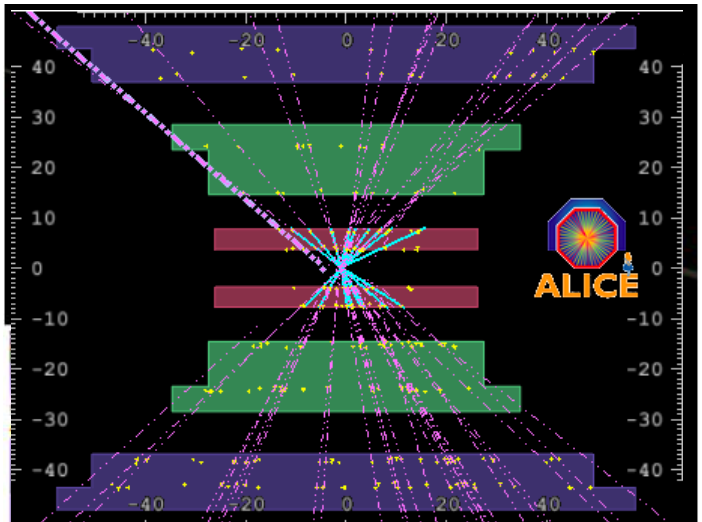


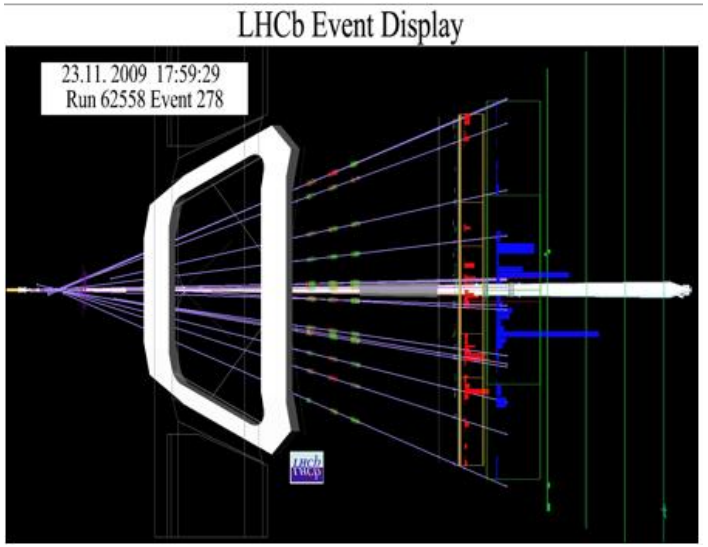
The LHC machine is fully installed and was ready to start operation with single beams on 10th September 2008, but it is now delayed until November 2009 after an incident that happened last year on 19th September 2008

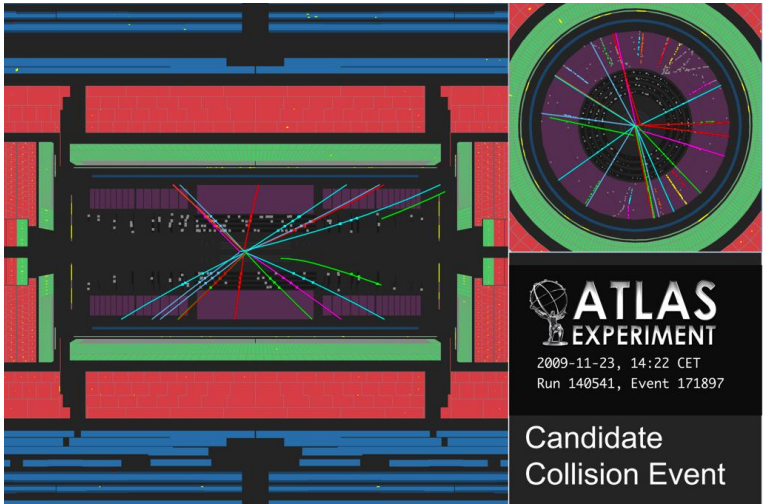
2009: First Collisions in the Experiments

23/11 First 'trial' collisions in the experiments at start up energy of 900 GeV



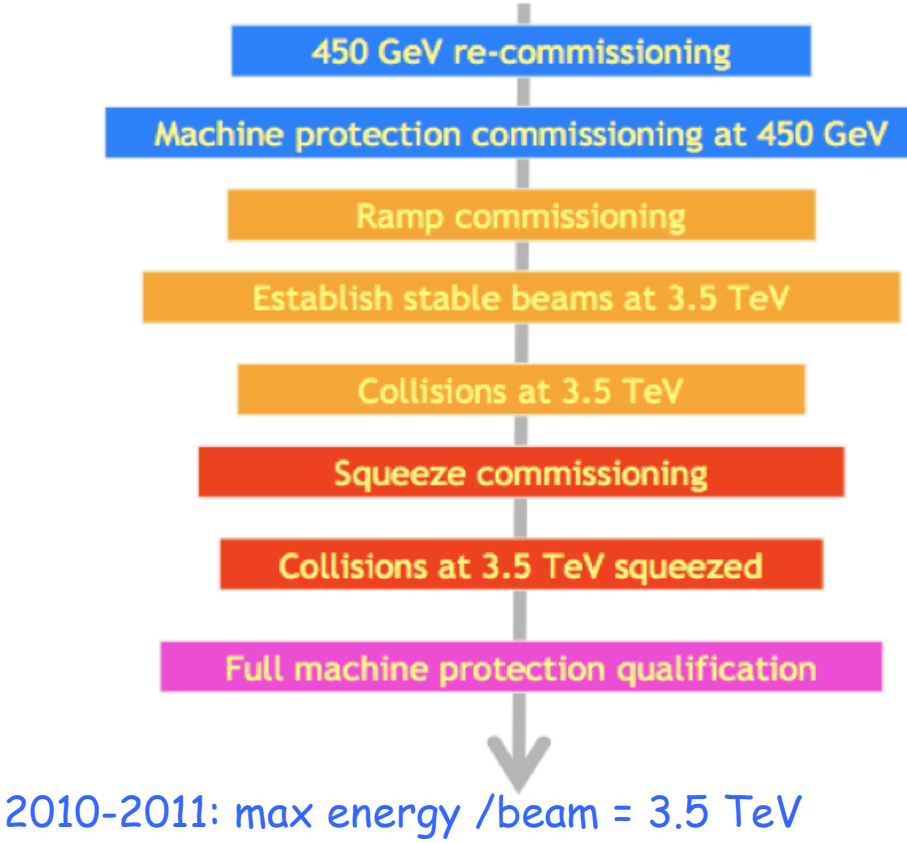






The LHC in 2010

Commissioning Strategy Last Weeks



Mike Lamont et al

30th of March

The LHC will run for two continuous years until 1 fb^{-1} of data is collected

We expect ~ 10-100 fb^{-1} per year in future

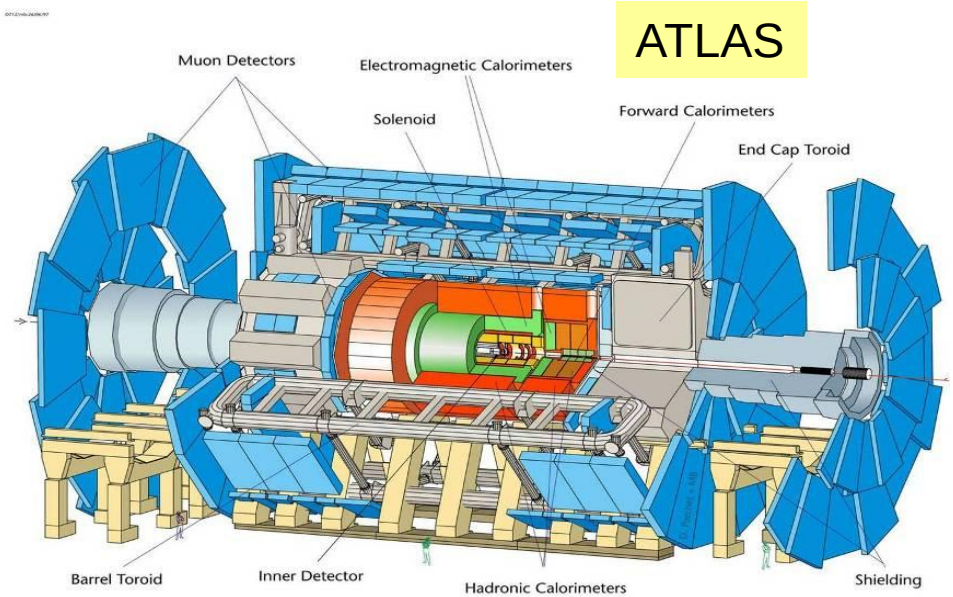
Integrated Luminosity= number of events/cross section/time

30/3: Experiments are waiting…

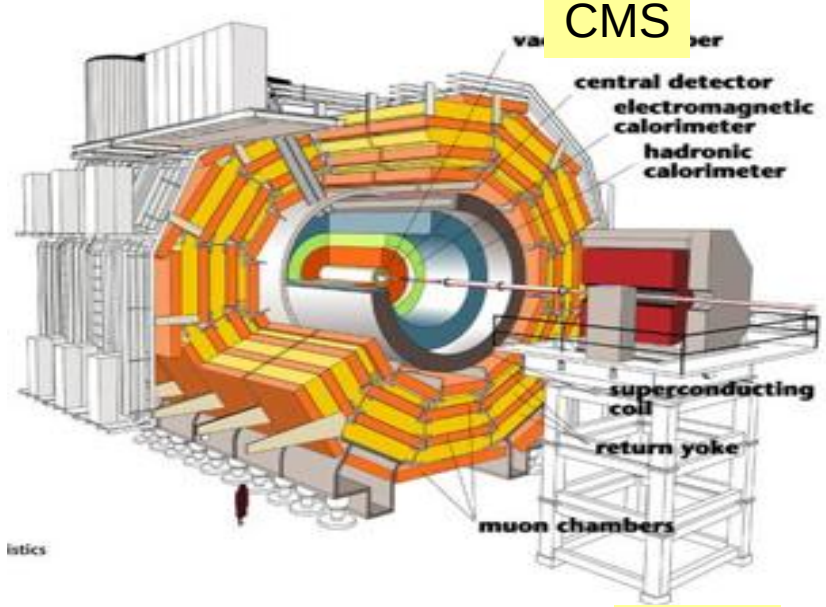
12:58
7 TeV collisions!!!

The Four Main LHC Experiments

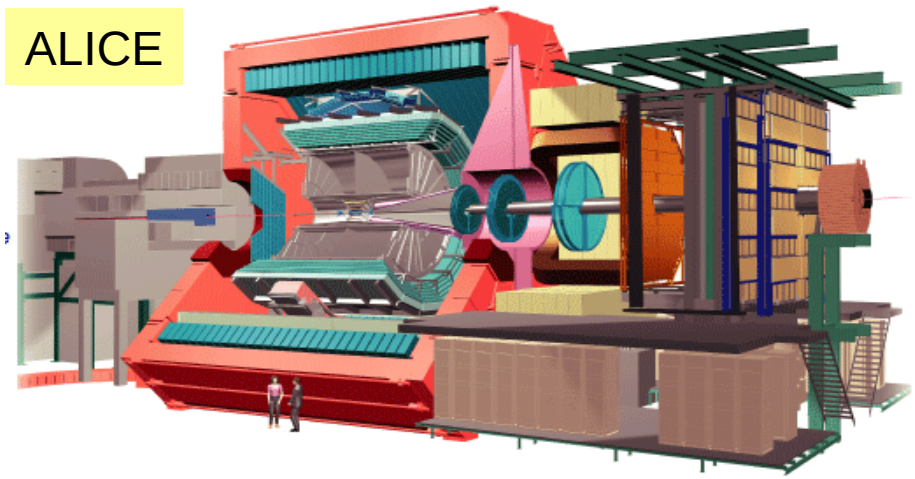
ATLAS



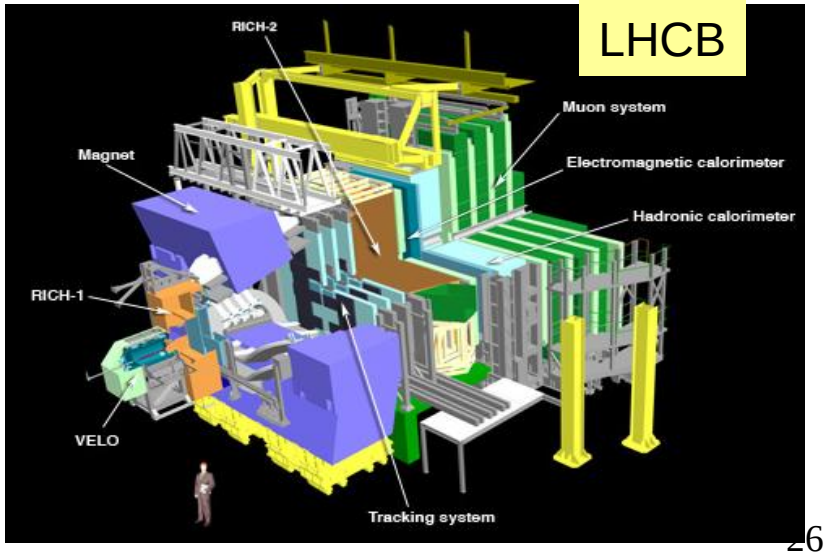
CMS



ALICE



LHCB



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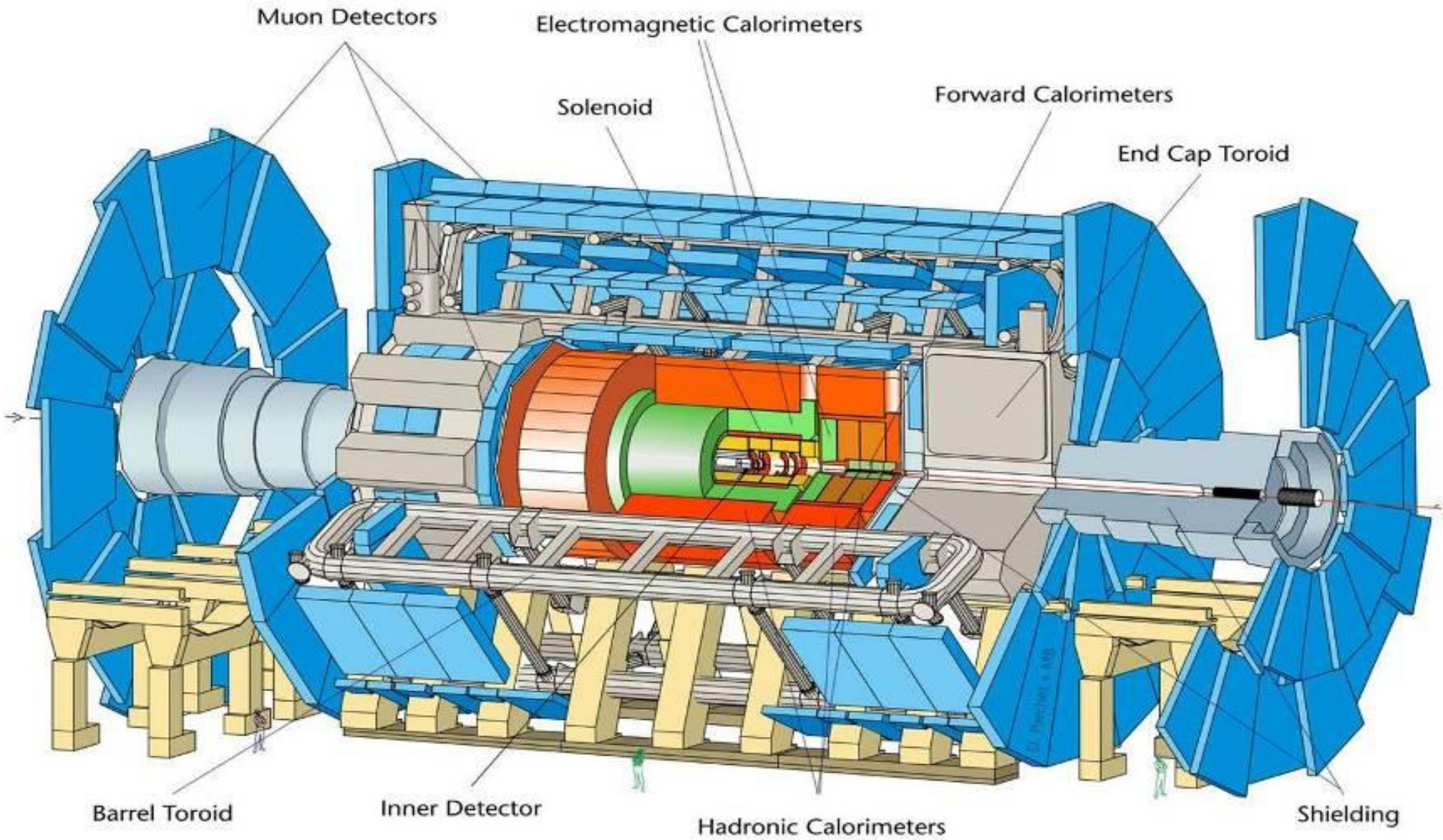
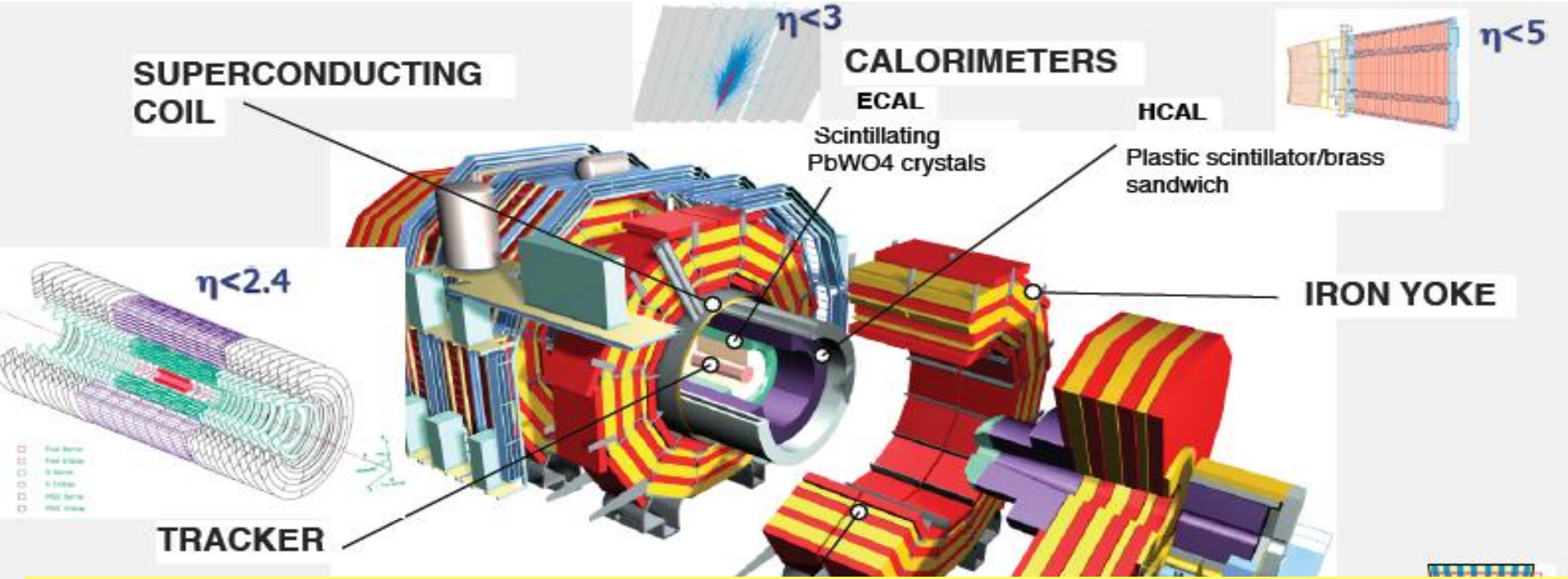


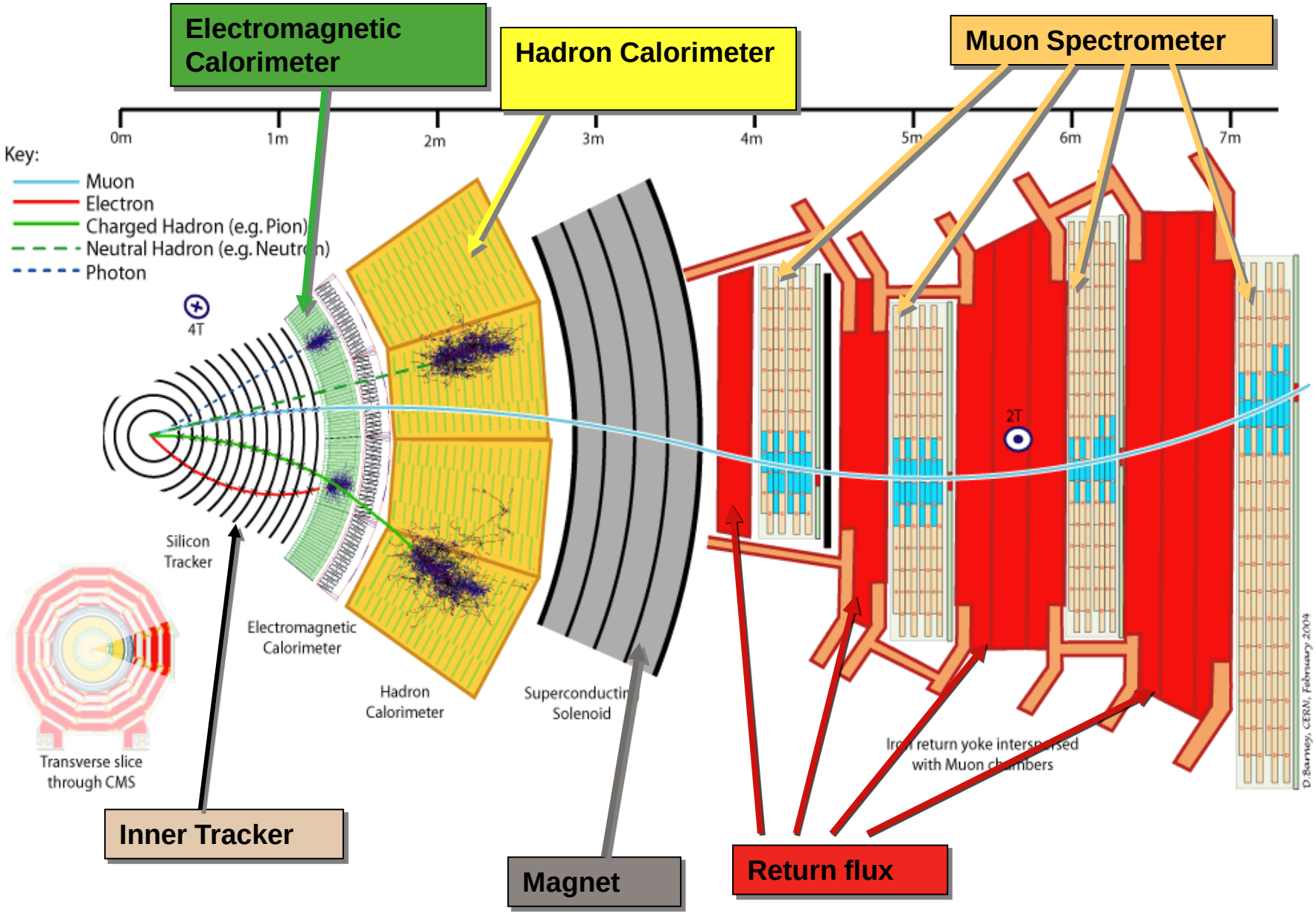
Length = 55 m Width = 32 m Height = 35 m but spatial precision ~ 100 μm

The Compact Muon Solenoid Experiment

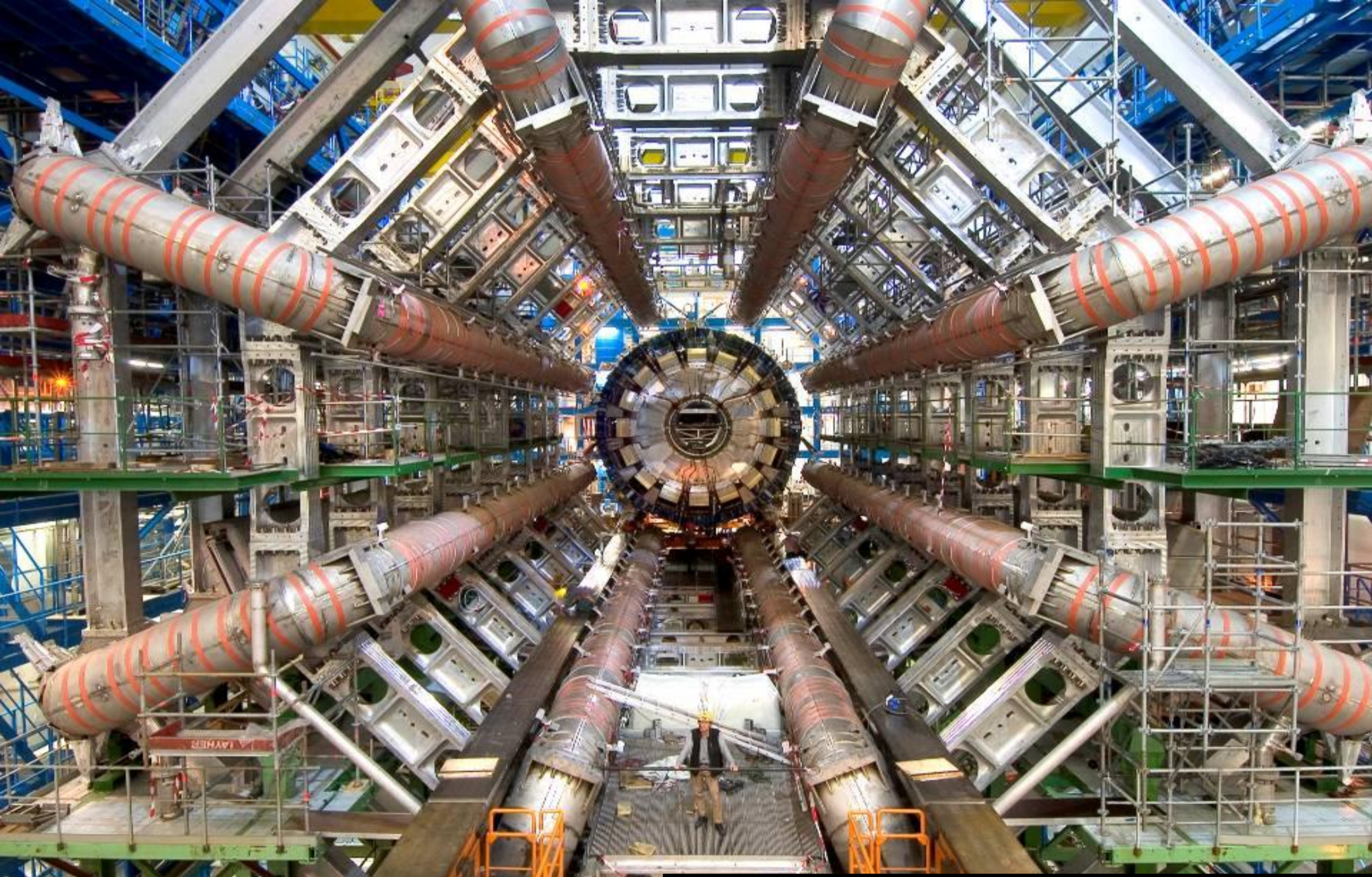


In total about
~100 000 000 electronic channels
Each channel checked
40 000 000 times per second (collision rate is 40 MHz)
An on-line trigger selects events and reduces the rate from 40MHz to 100 Hz
Amount of data of just one collisions
>1 500 000 Bytes

Particles in the detector



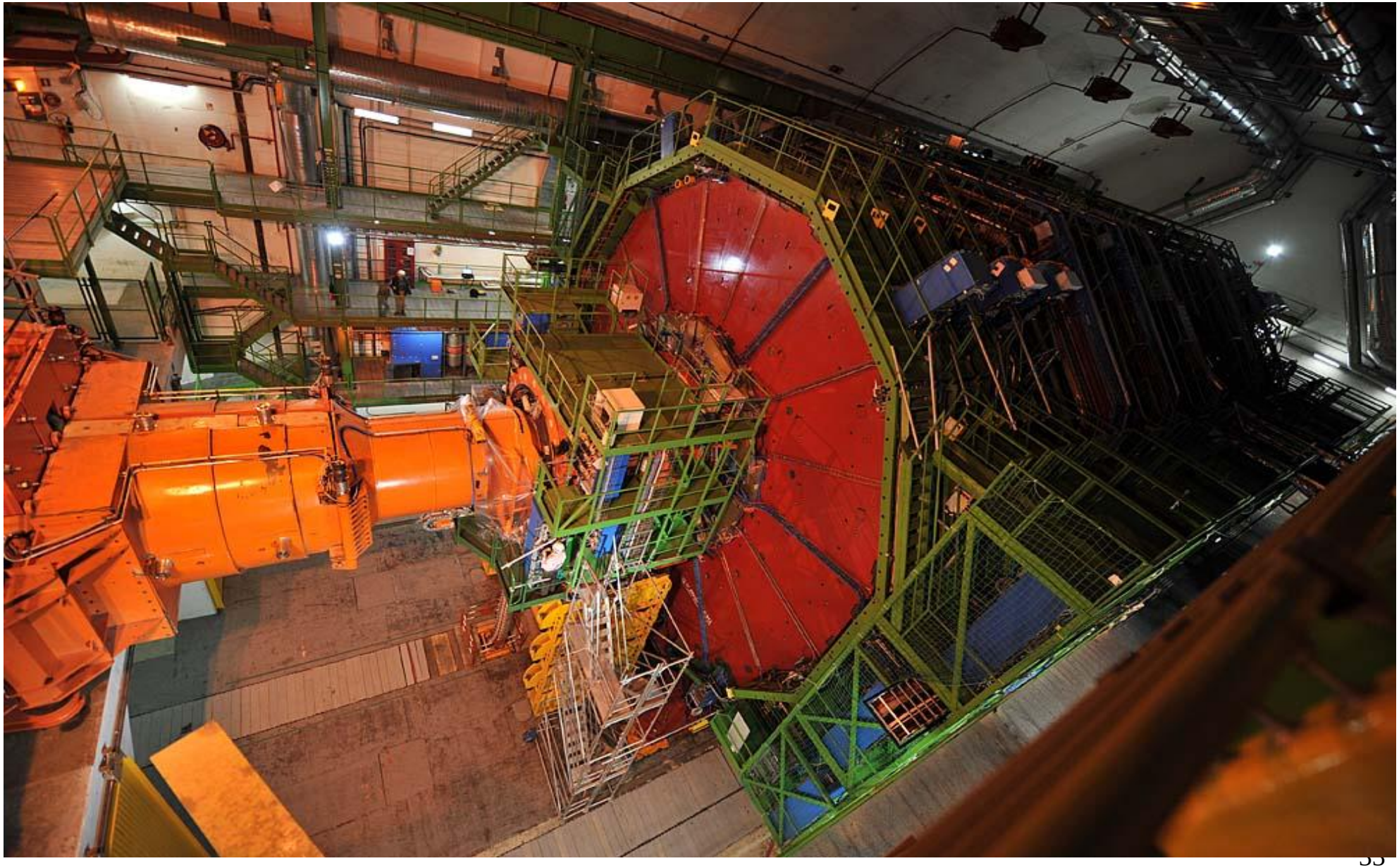
30



The ATLAS Experiment

CMS before closure

CMS: Ready for Collisions



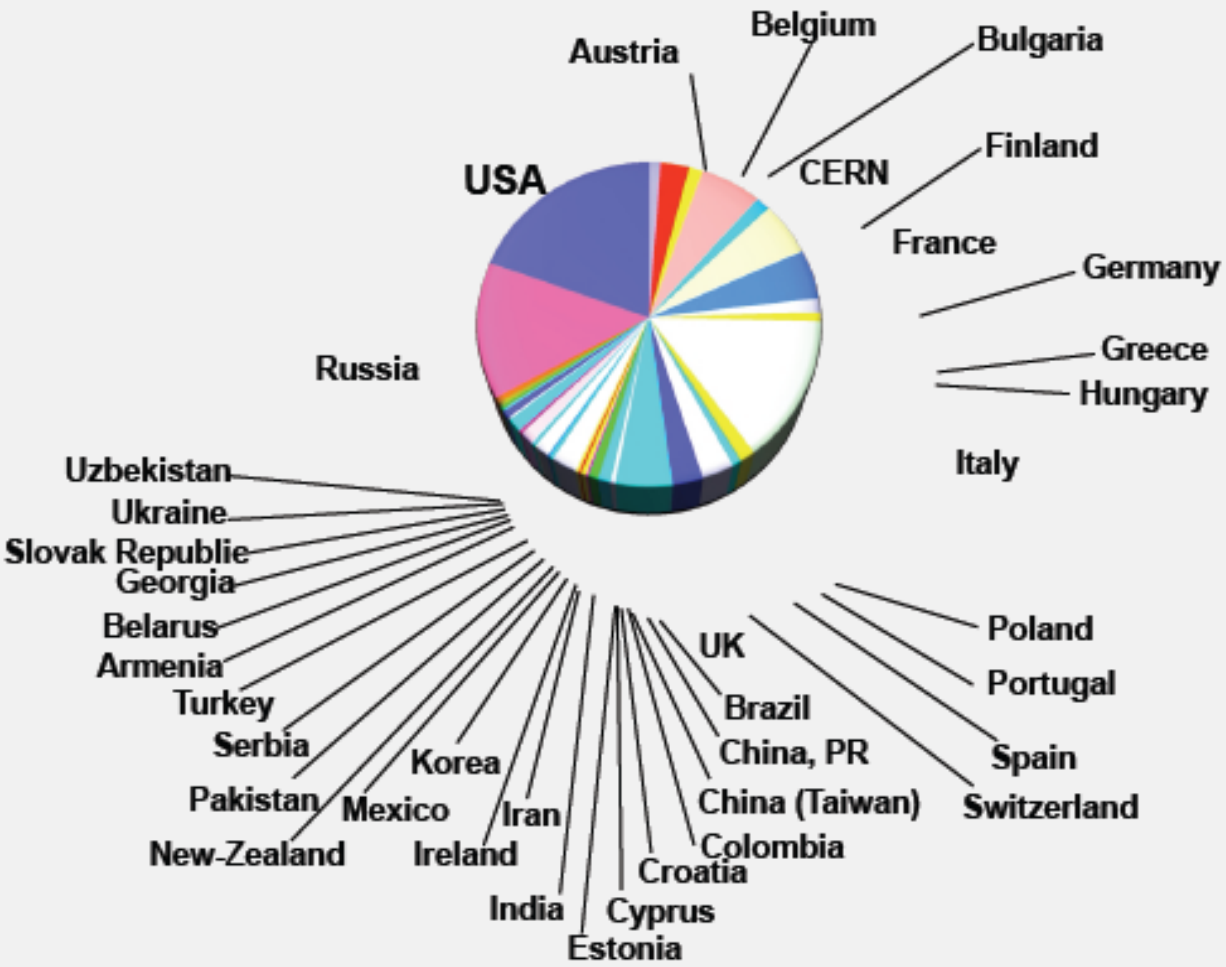
The CMS Collaboration

2006

	Institutions
Member States	61
Non-Mem. States	64
USA	49
Total	174

	Scientists
Member States	1055
Non-Mem. States	428
USA	547
Total	2030

Associated Institutes	
Number of Scientists	46
Number of Laboratories	8



Now: 2900 Physicists 184 Institutions 38 countries

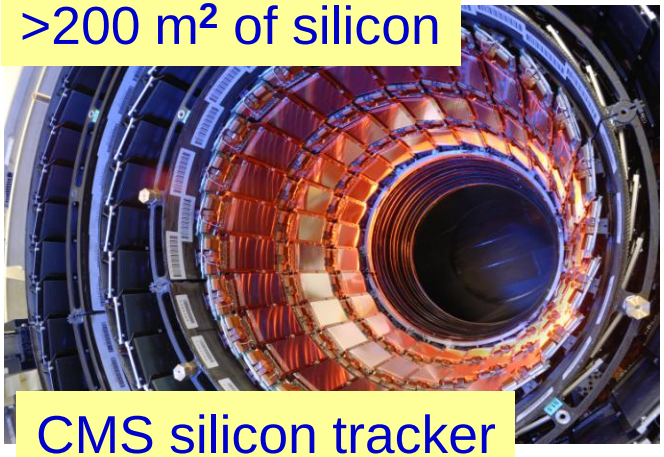
May, 04 2006/gm
http://cmsdoc.cern.ch/pictures/cmsorg/overview.html

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

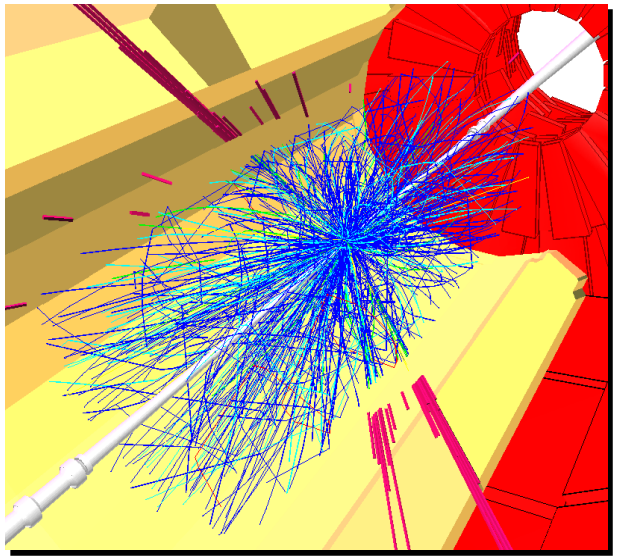
>200 m² of silicon



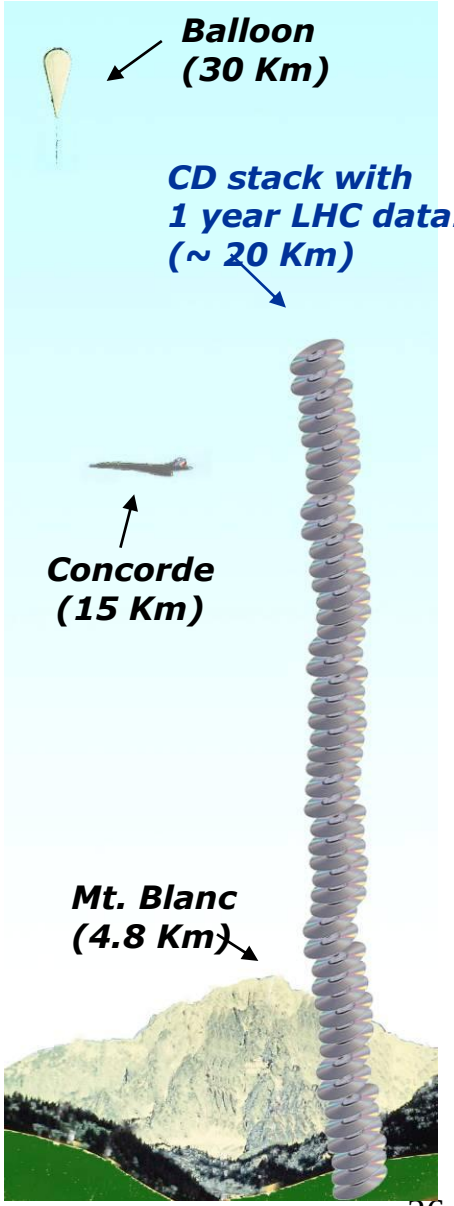
CMS silicon tracker

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

Worldwide LHC Computing Grid (wLCG)



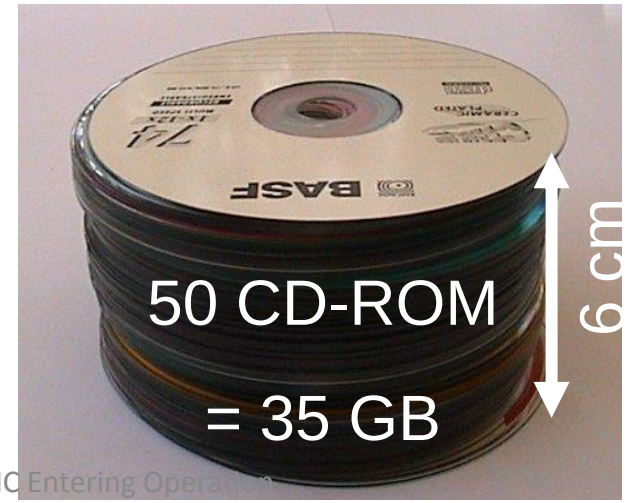
WLCG is a worldwide collaborative effort on an unprecedented scale in terms of storage and CPU requirements, as well as the software project's size



GRID computing developed to solve problem of data storage and analysis

LHC data volume per year: 10-15 Petabytes

One CD has ~ 600 Megabytes
1 Petabyte = 10^9 MB = 10^{15} Byte



(Note: the WWW is from CERN...)

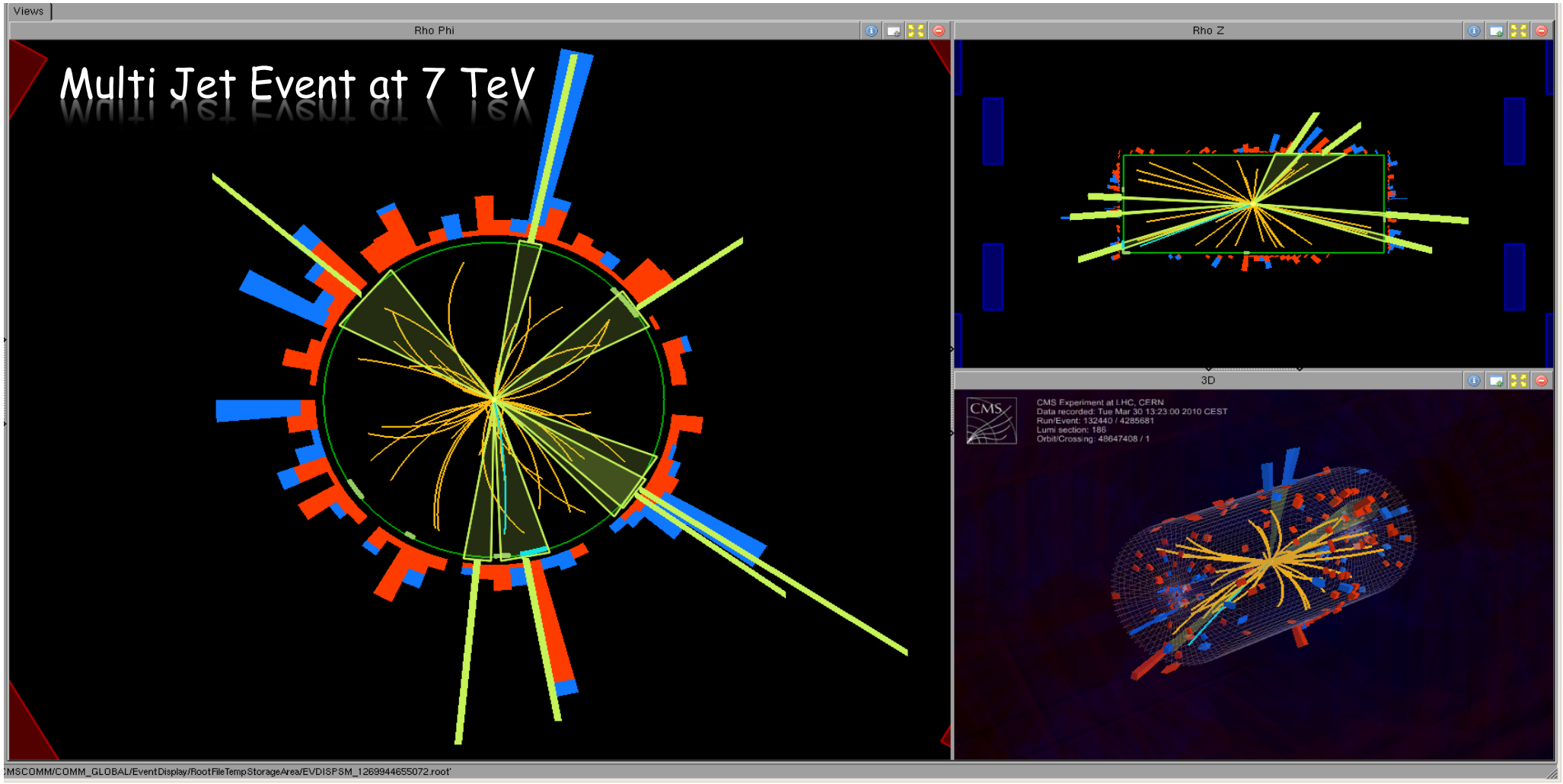
The Science of the LHC

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

LHC Physics Program

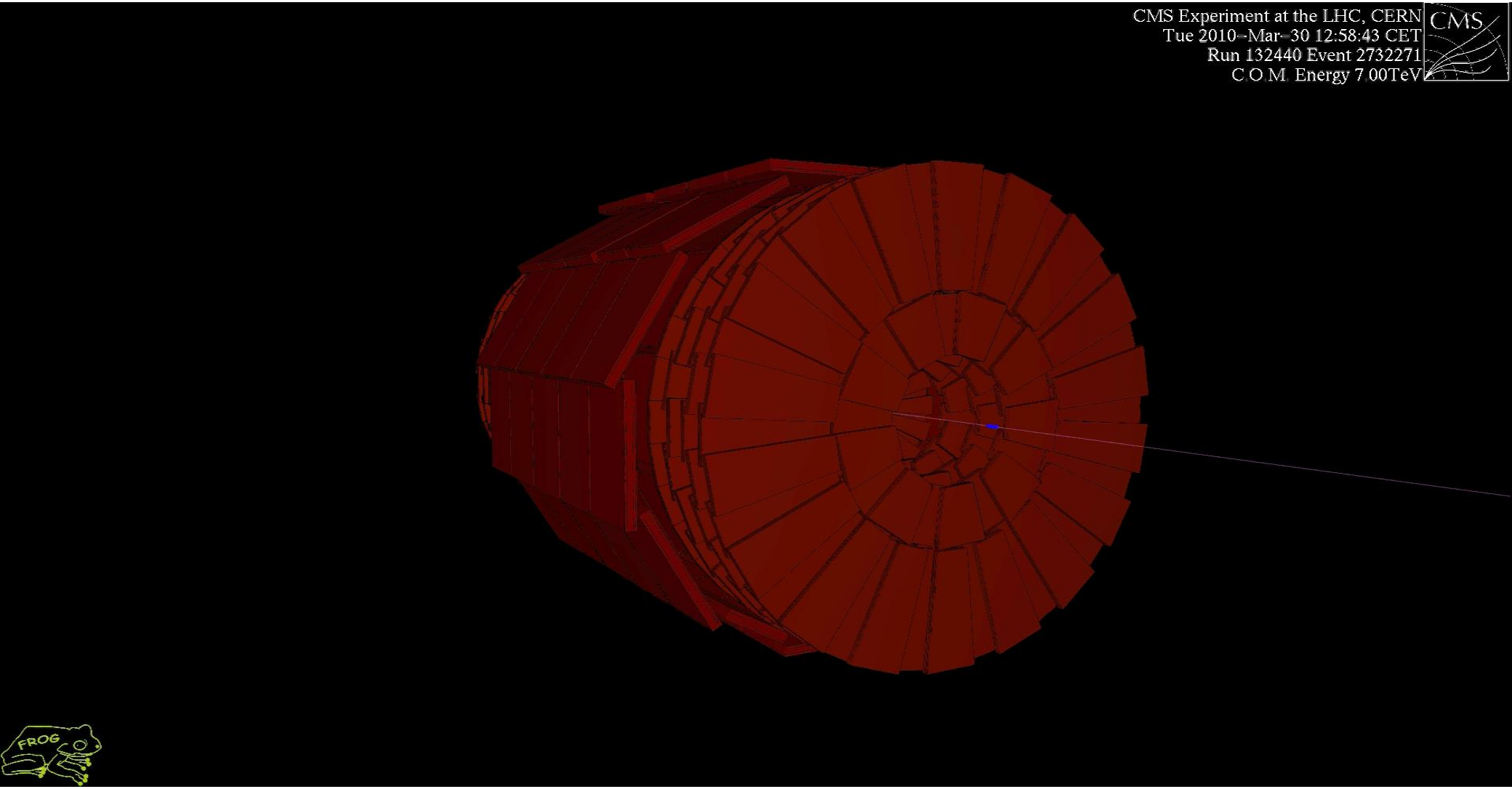
- Discover or exclude the Higgs in the mass region up to 1 TeV. Measure Higgs properties
- Discover Supersymmetric particles (if exist) up to 2-3 TeV
- Discover Extra Space Dimensions, if these are on the TeV scale, and black holes?
- Search other new phenomena (e.g. strong EWSB, new gauge bosons, Little Higgs model, Split Supersymmetry…)
- Study CP violation in the B sector,B physics, new physics in B-decays
- Precision measurements on top, W, anomalous couplings…
- Heavy ion collisions and search for quark gluon plasma
- QCD and diffractive (forward) physics in a new regime
- …

First Collisions at 7 TeV



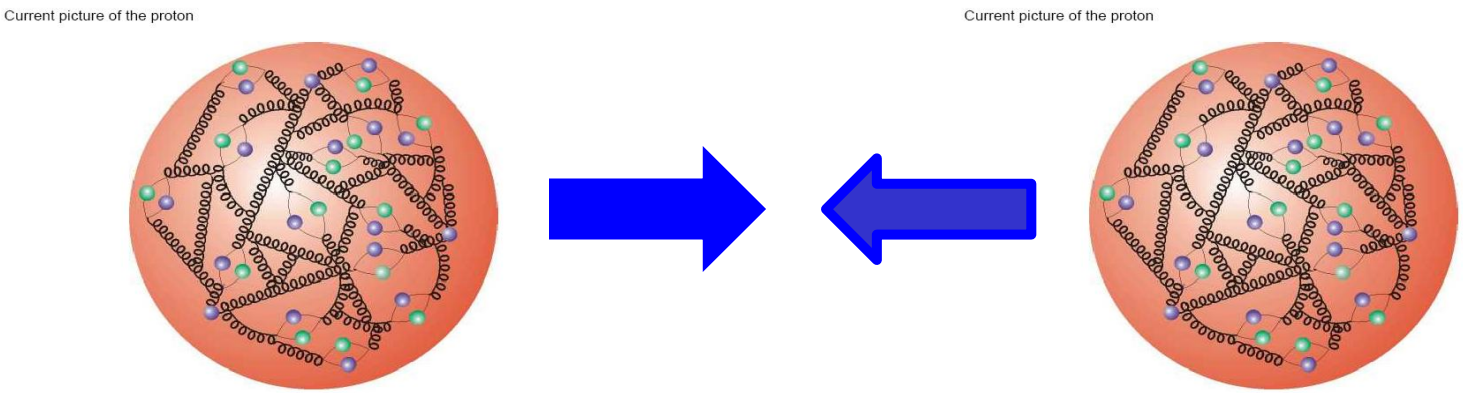
Very interesting events are coming!!

First Collisions at 7 TeV

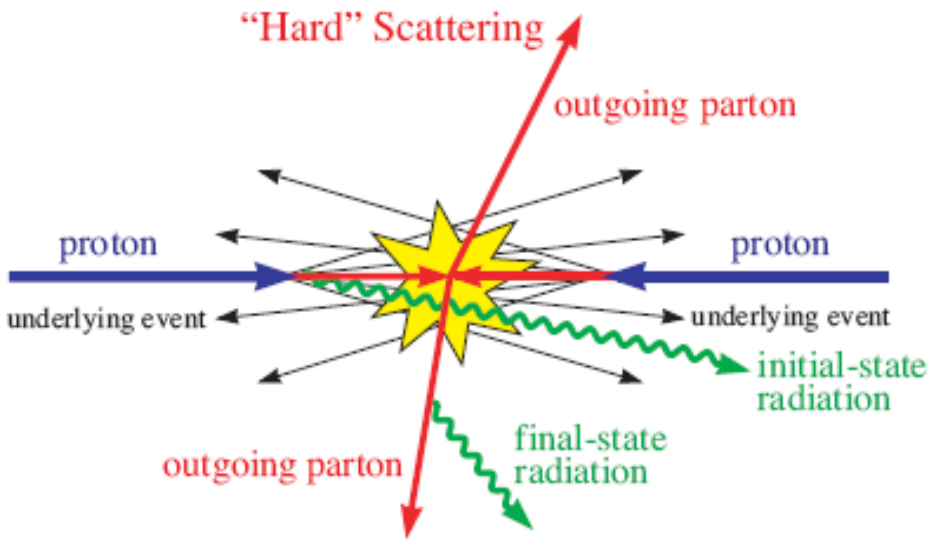

CMS Experiment at the LHC, CERN
Tue 2010-Mar-30 12:58:43 CET
Run 132440 Event 2732271
C.O.M. Energy 7.00TeV
CMS
FROG

pp collisons : complications…

Protons are composed objects

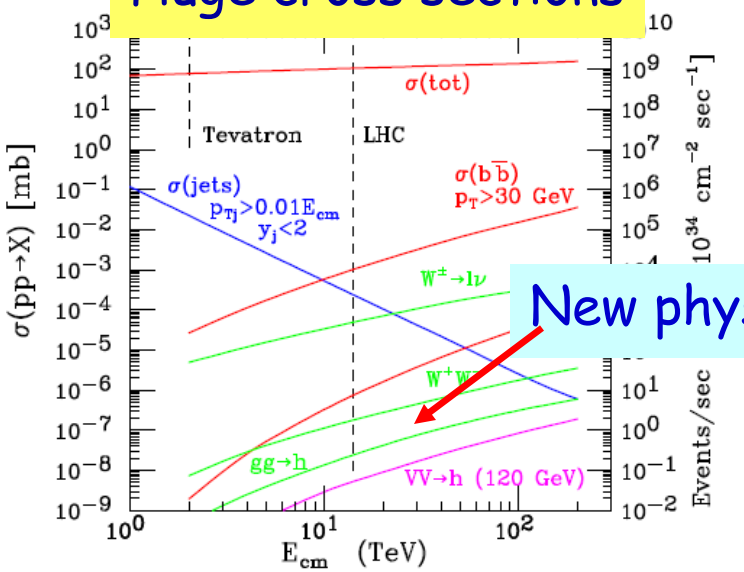


quark/gluon on quark/gluon scattering

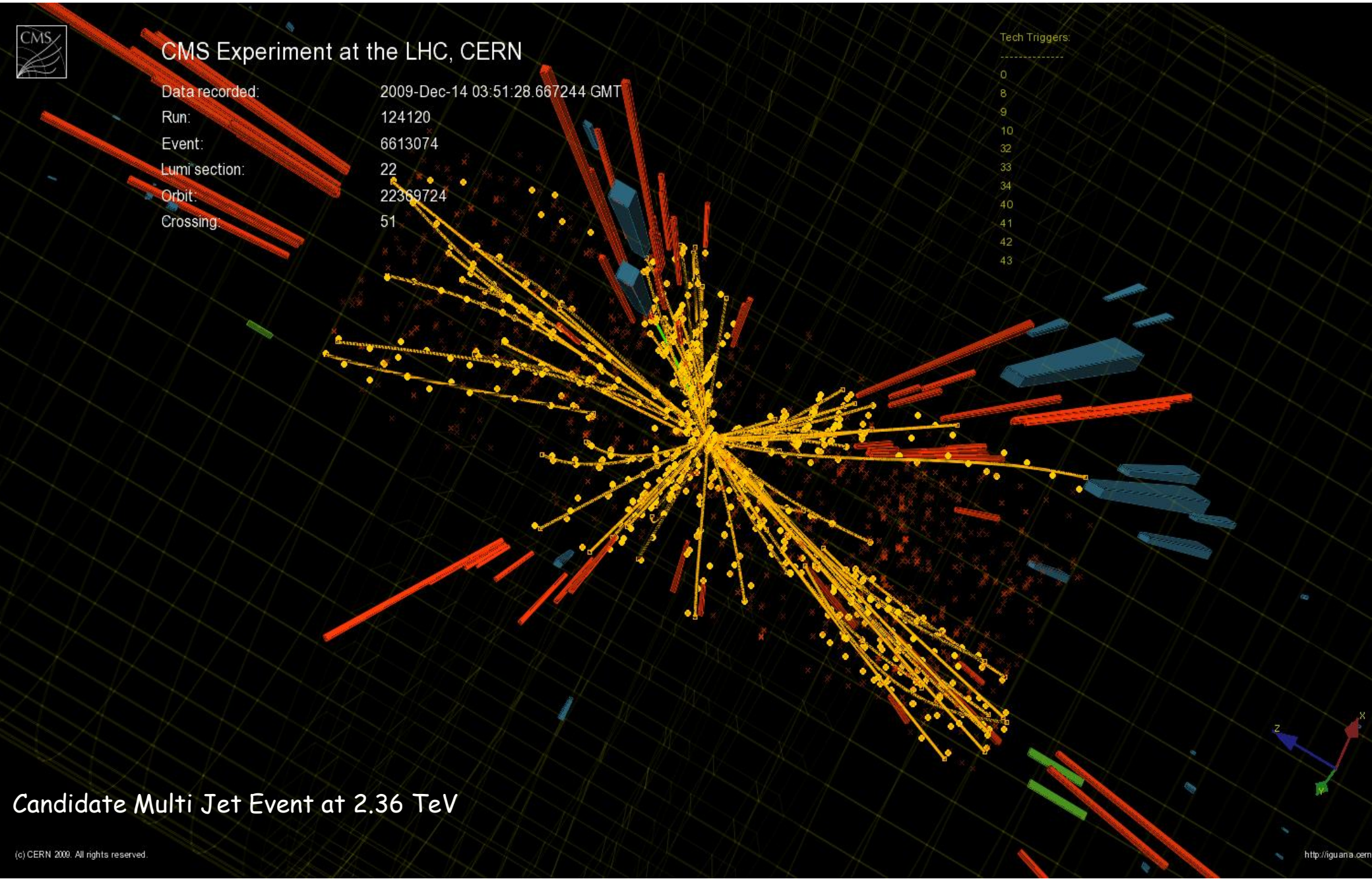


Scattering cross sections for various SM processes:

Huge cross sections



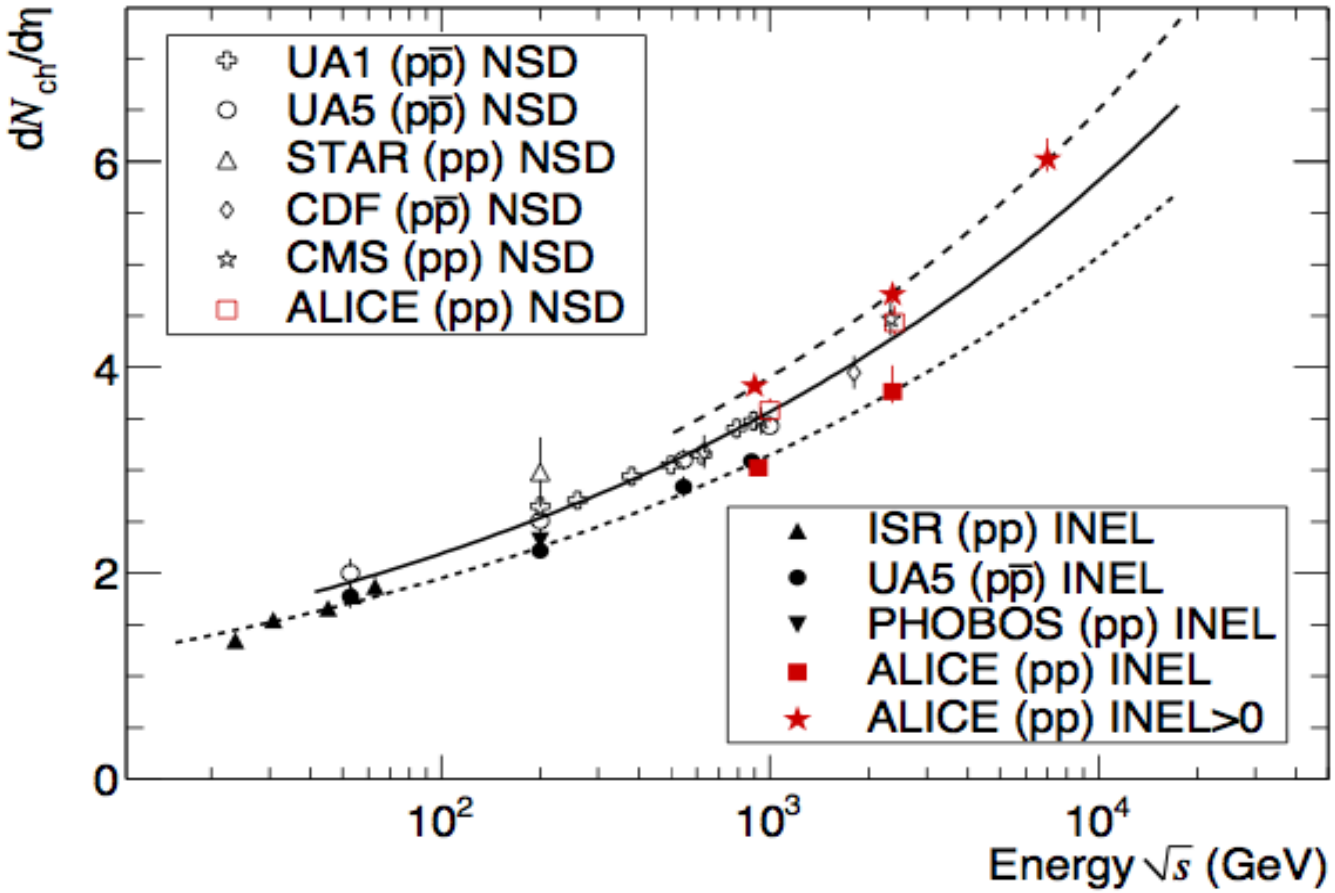
New physics ?



Candidate Multi Jet Event at 2.36 TeV

7 TeV Early Analysis

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



First physics papers of the experiments

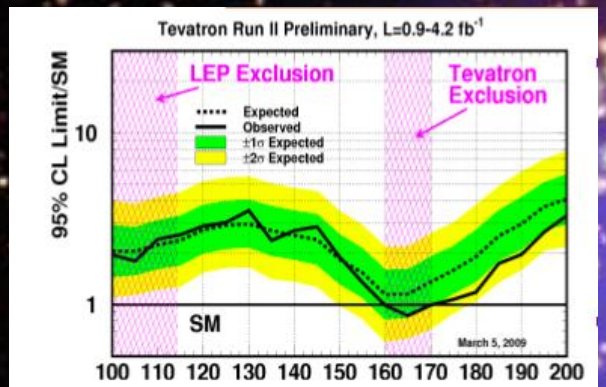
Strong rise of the central particle density with energy

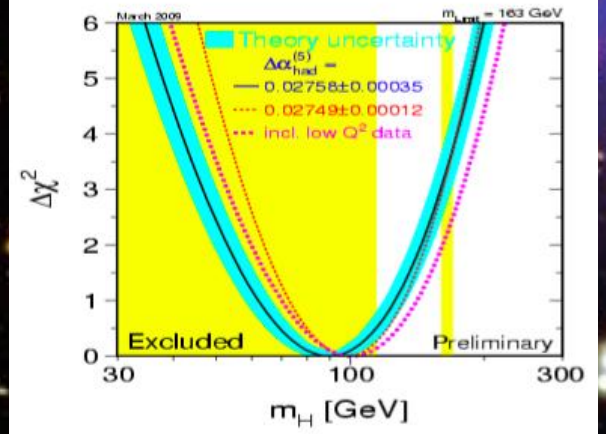
The Origin of Mass

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

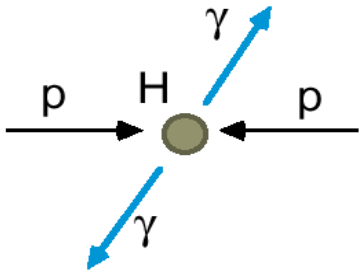


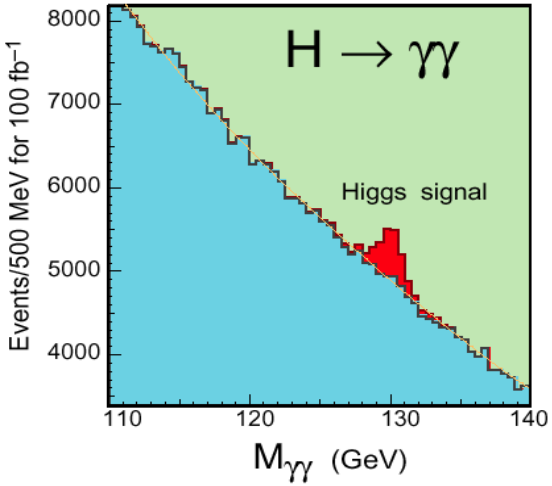


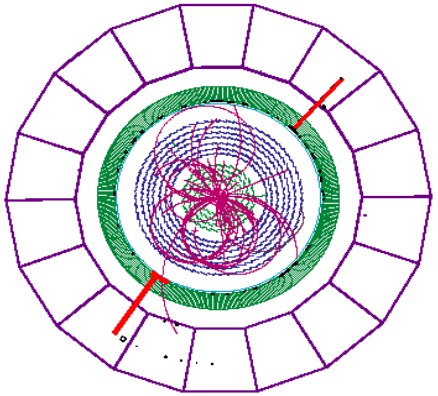
The key question:
Where is the Higgs?

Higgs Boson Searches

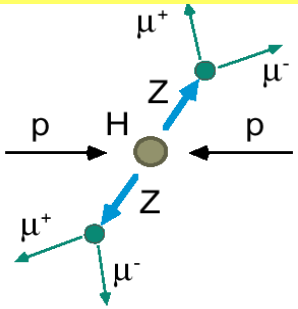
Low M_H < 140 GeV/c²

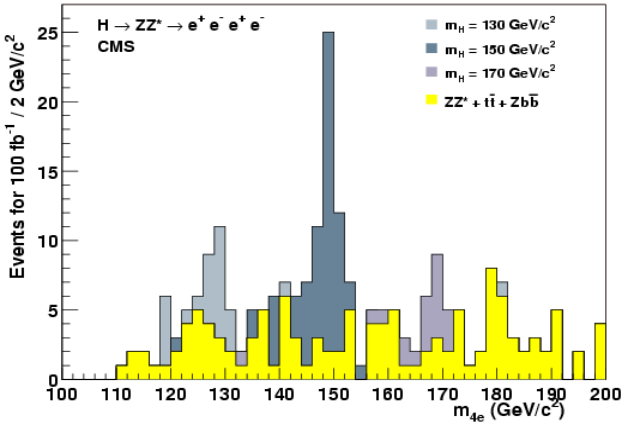


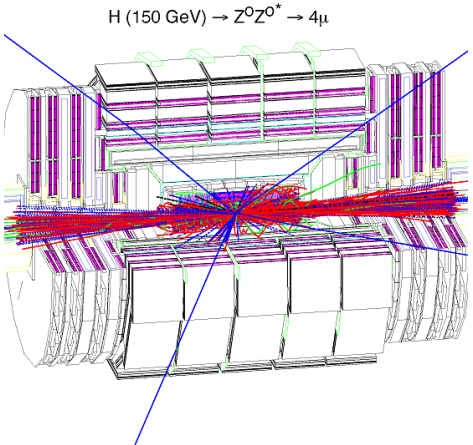




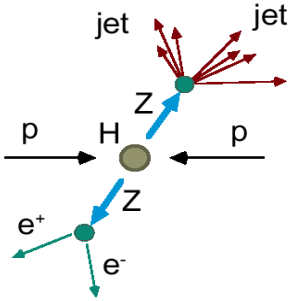
Medium 130<M_H<500 GeV/c²

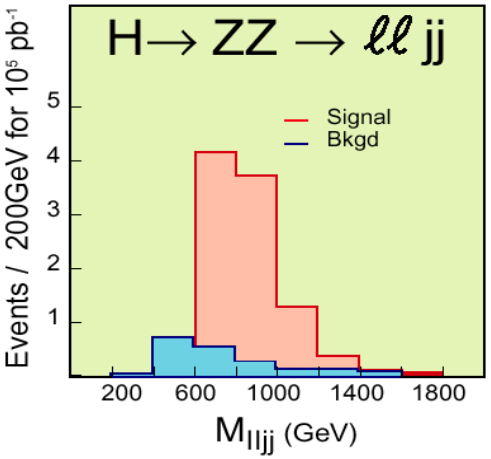


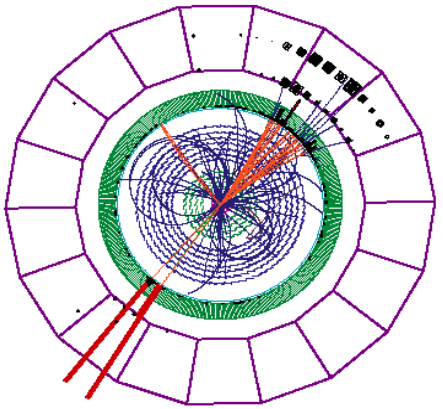




High M_H > ~500 GeV/c²



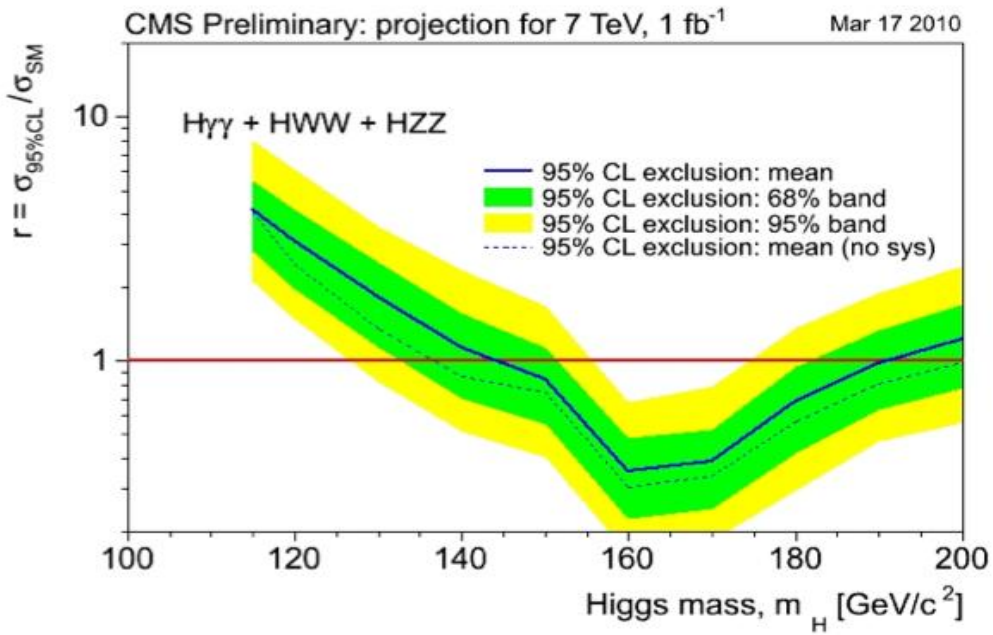




Search for Higgs (Simulation)

- Sizeable integrated luminosity is needed before significant insights can be made in SM Higgs search.
- However, even with moderate luminosity per experiment, Higgs boson discovery is possible in particular mass regions.

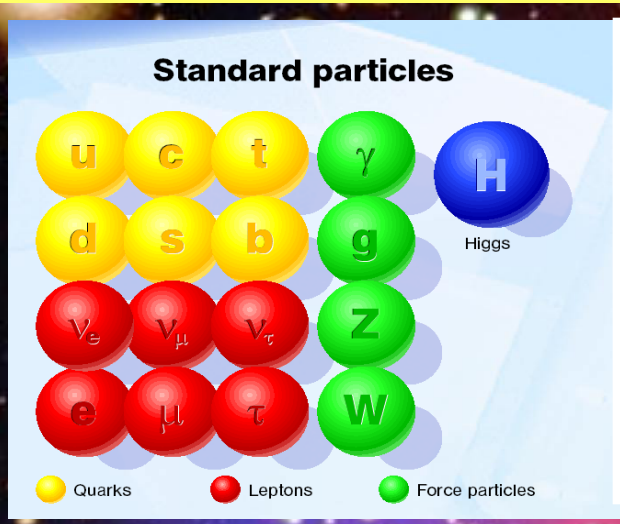
Example Reach by end of 2011

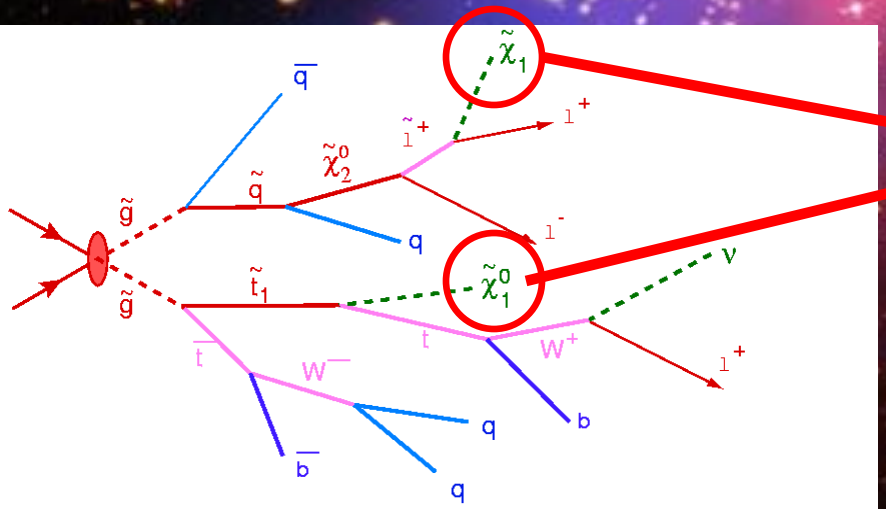


- If the Higgs exist: LHC will discover it after 3-4 years of operation
- If the Higgs does not exist: LHC should see other spectacular new effects

Beyond the Higgs Particle

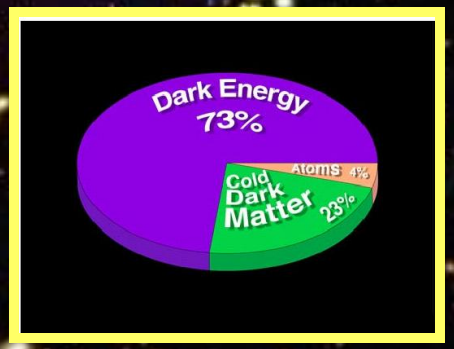
Supersymmetry: a new symmetry in Nature





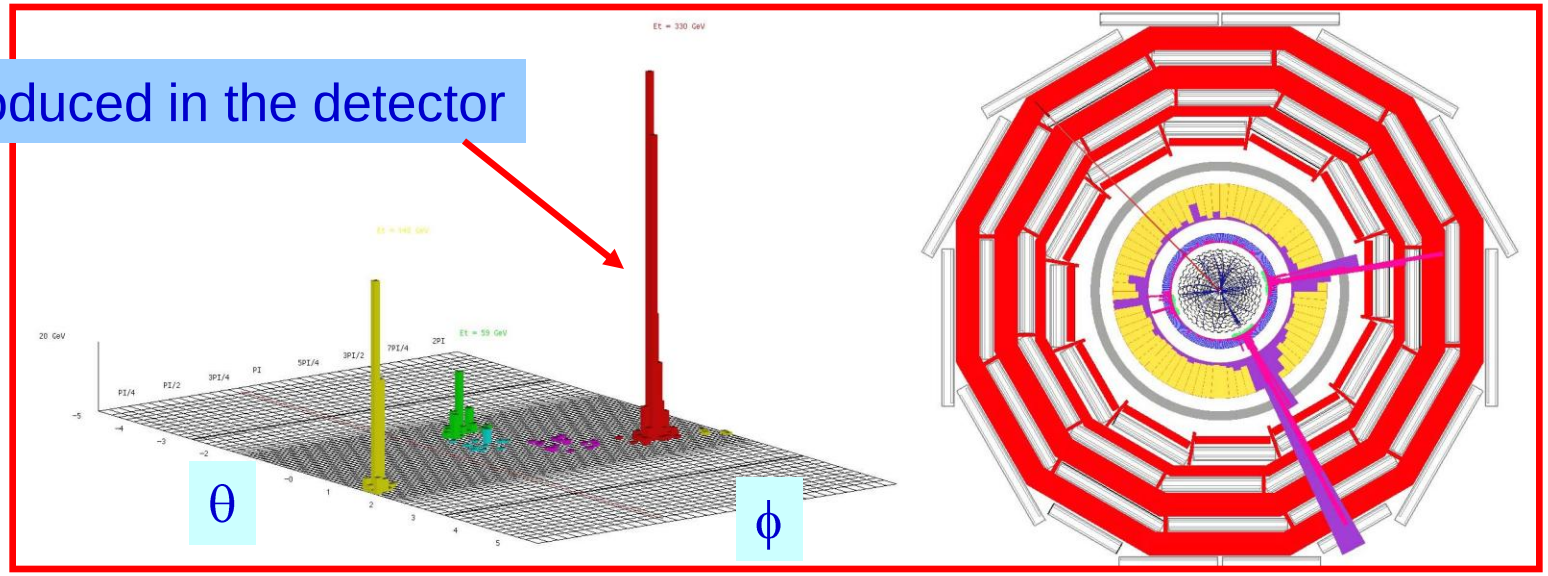
SUSY particle production at the LHC

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



Detecting Supersymmetric Particles

Energy produced in the detector



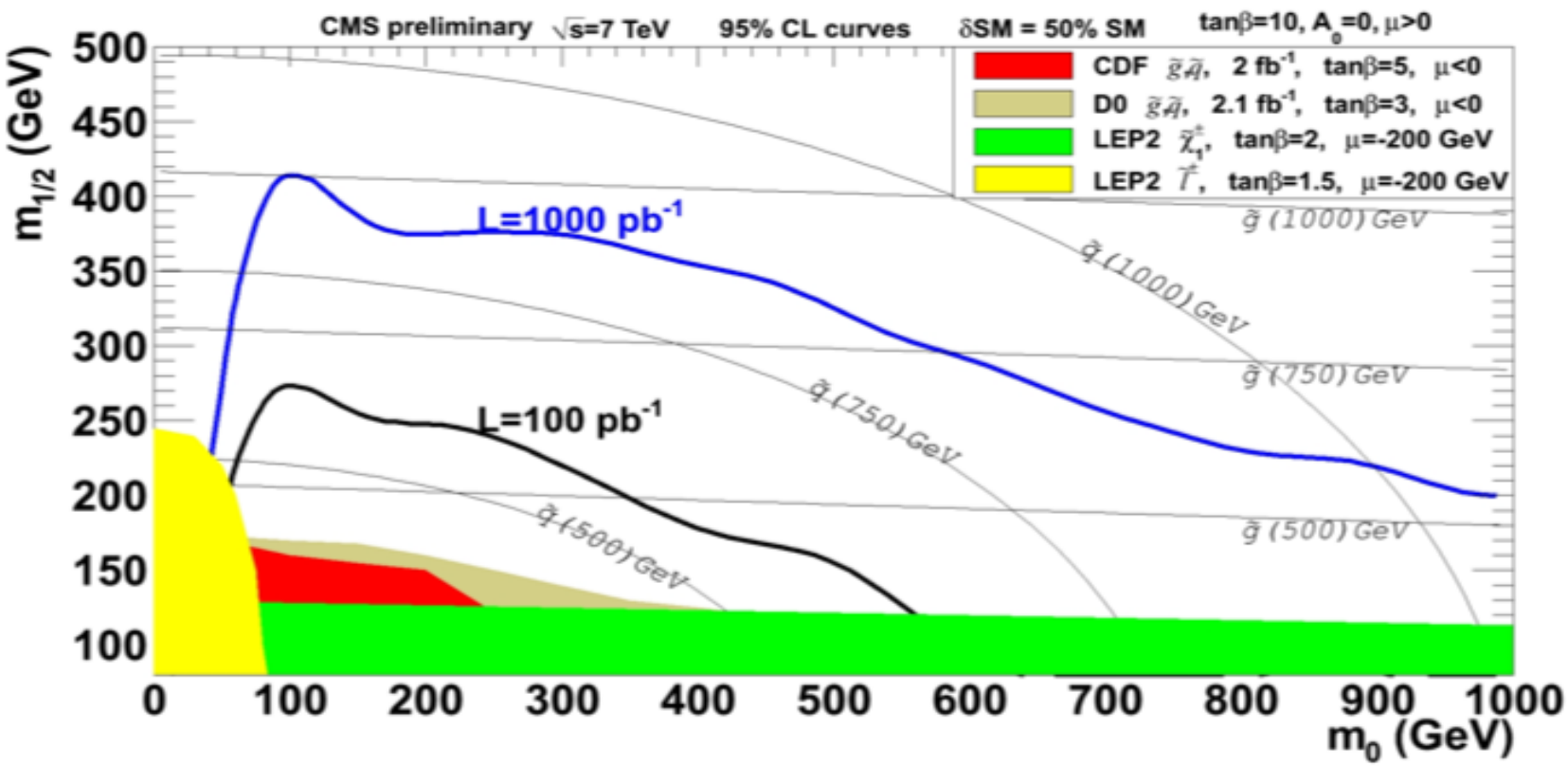
Supersymmetric particles decay and produce a cascade of jets, leptons and missing (transverse) energy due to escaping ‘dark matter’ particles

➡ 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

Example SUSY Particle Reach



100 pb^{-1} = end of 2010 1000 pb^{-1} = end of 2011

m_0, $m_{1/2}$ universal scalar and gaugino masses at the GUT scale

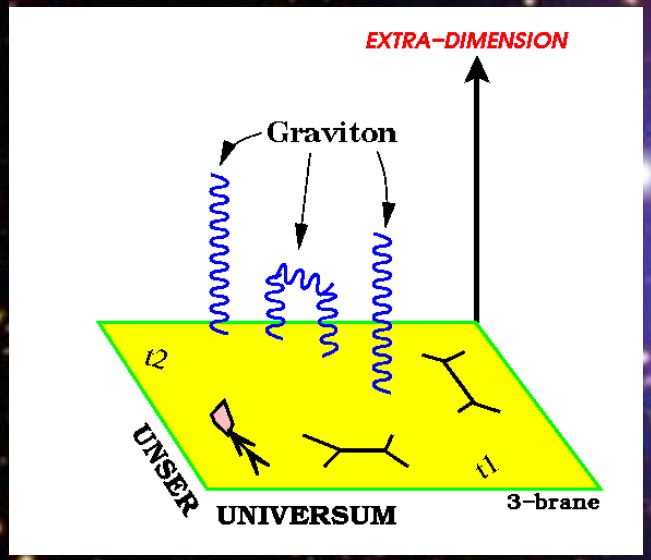
Beyond the Higgs Particle

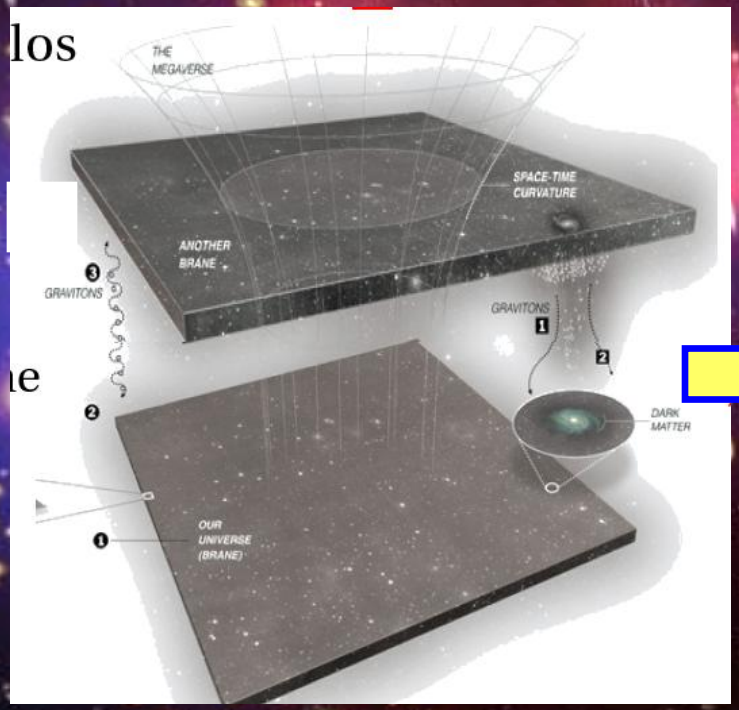
Extra Space Dimensions

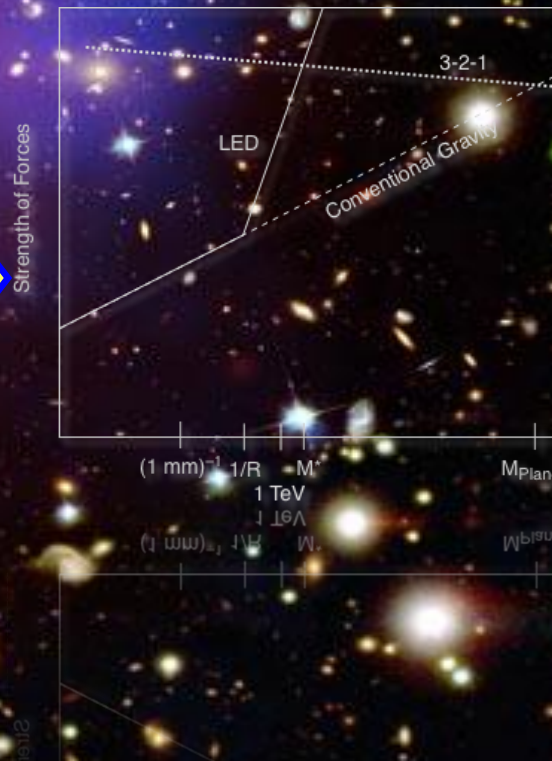
Problem:

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

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



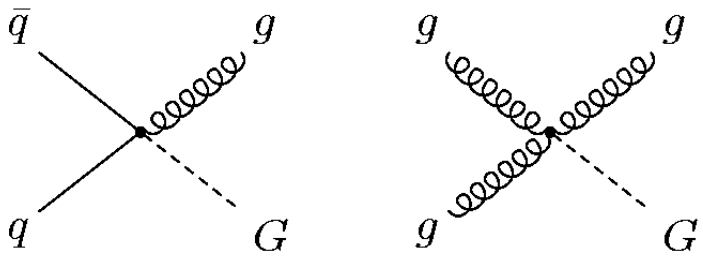


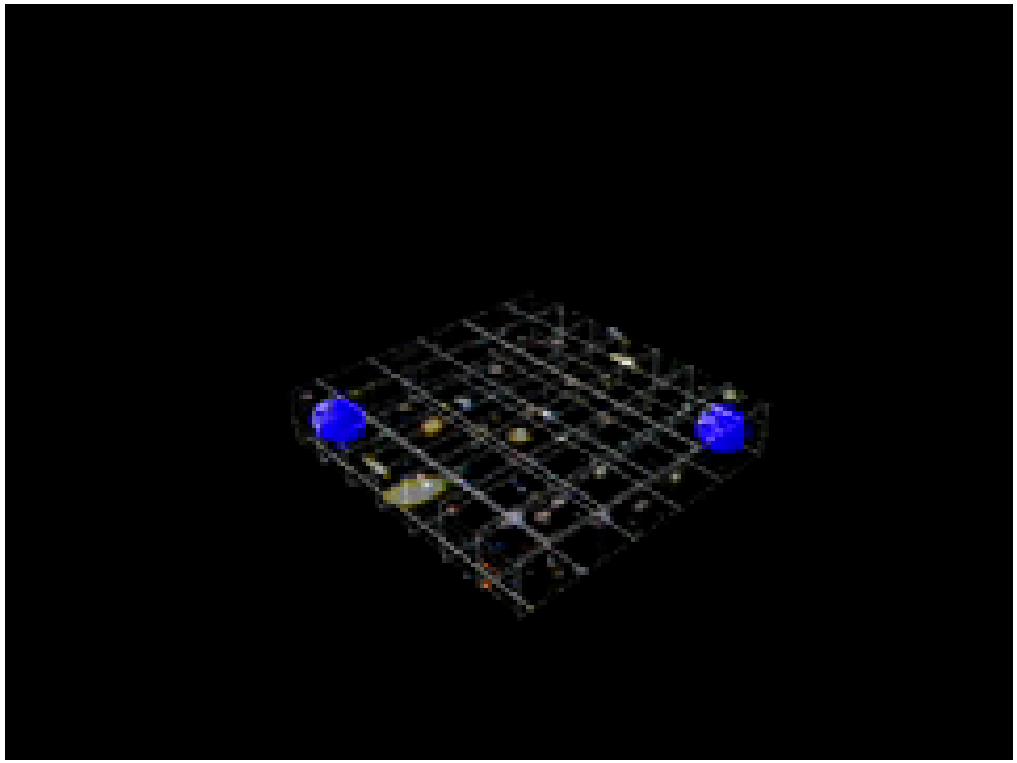


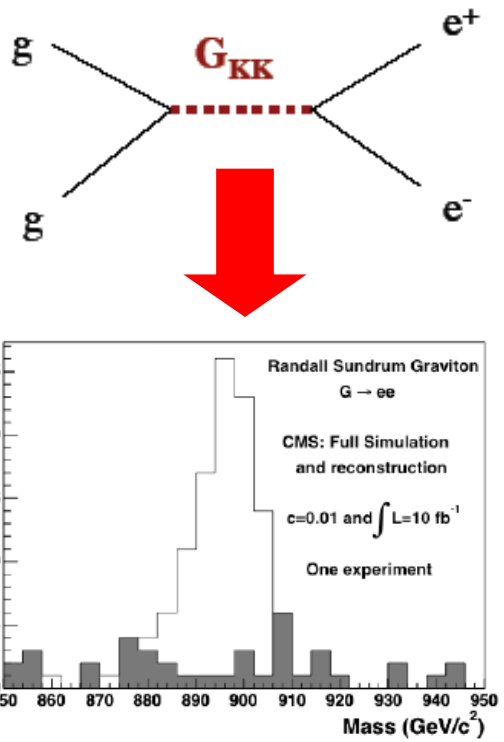
The Gravity force becomes strong!

Detecting Extra Dimensions at the LHC

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





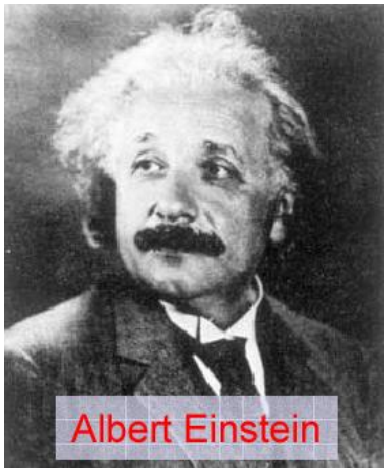


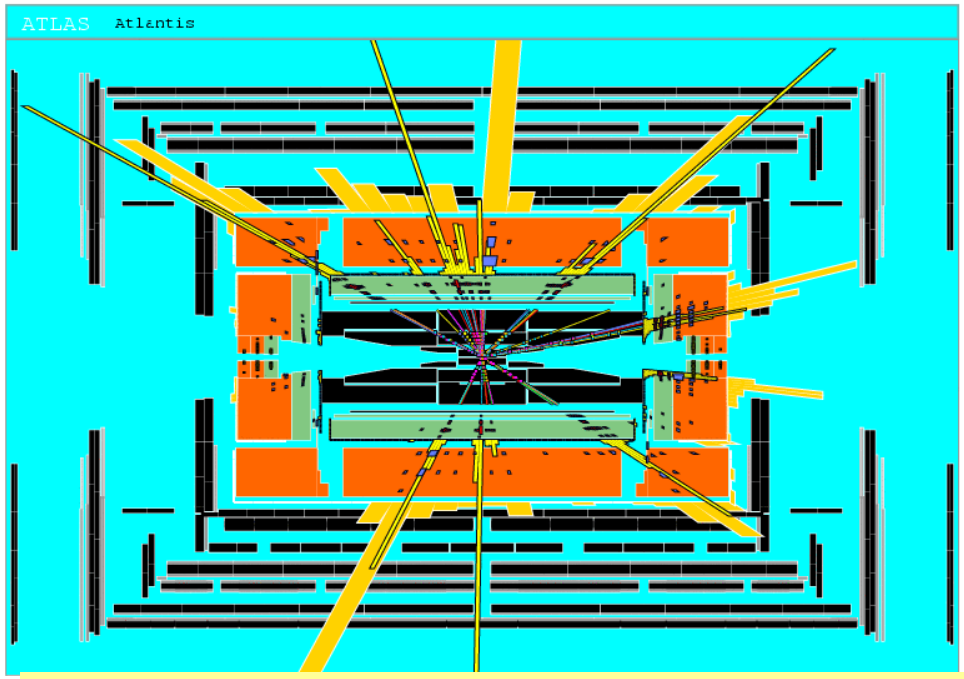
LHC can detect extra dimensions for scales up to 5 to 9 TeV

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

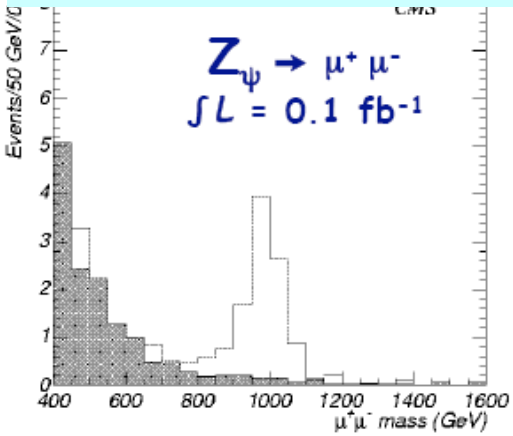
Quantum Black Holes are harmless for the environment: they will decay within less than 10^{-27} seconds $\Rightarrow$ SAFE!

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

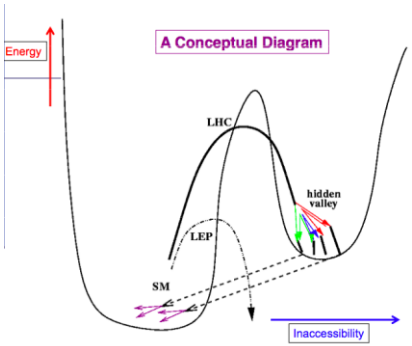
Black Holes Hunters at the LHC…

Other New Physics Scenarios at the LHC

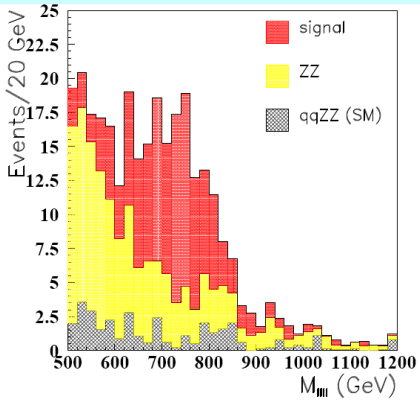
New Gauge Bosons?



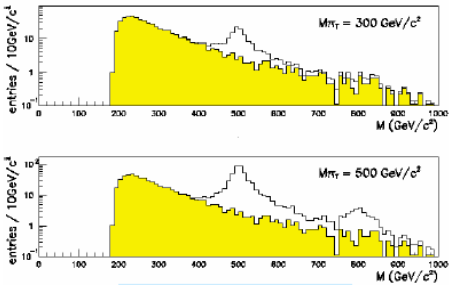
Hidden Valleys?



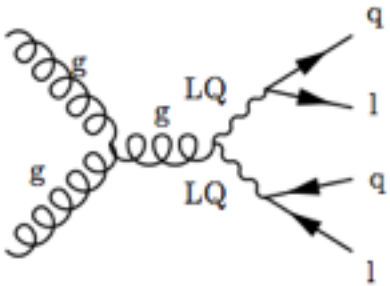
ZZ/WW resonances?



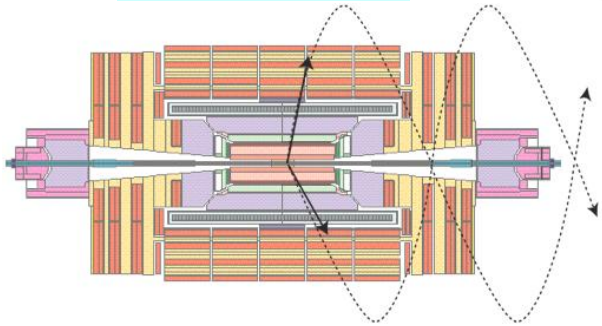
Technicolor?



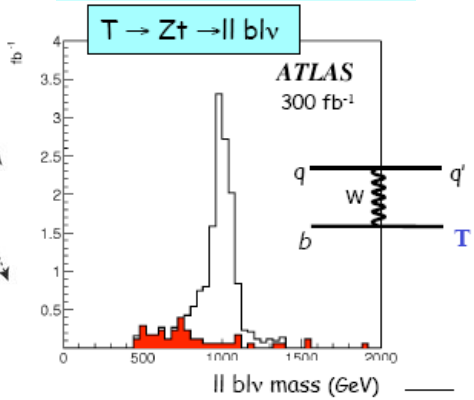
Leptoquarks?



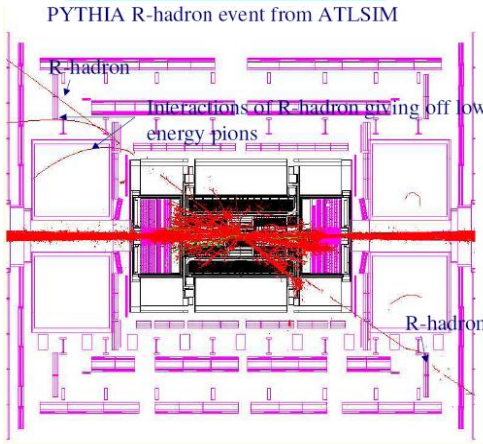
Quirks???



Little Higgs?



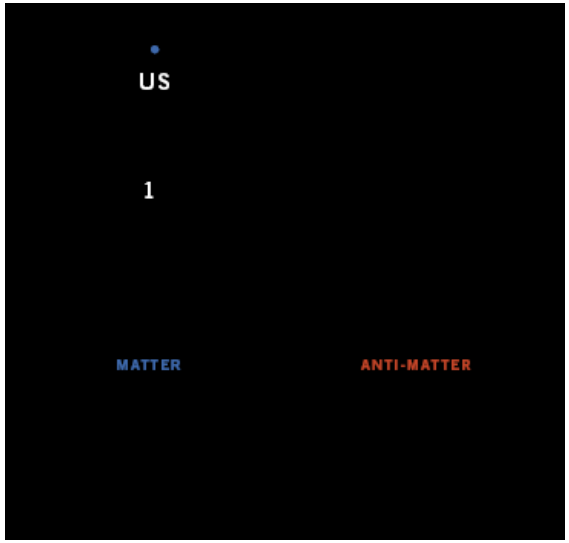
Split Susy?

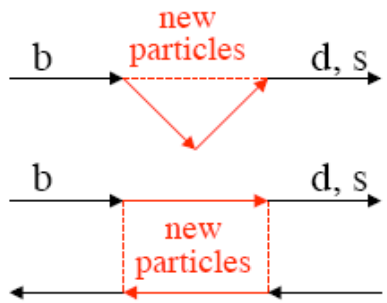


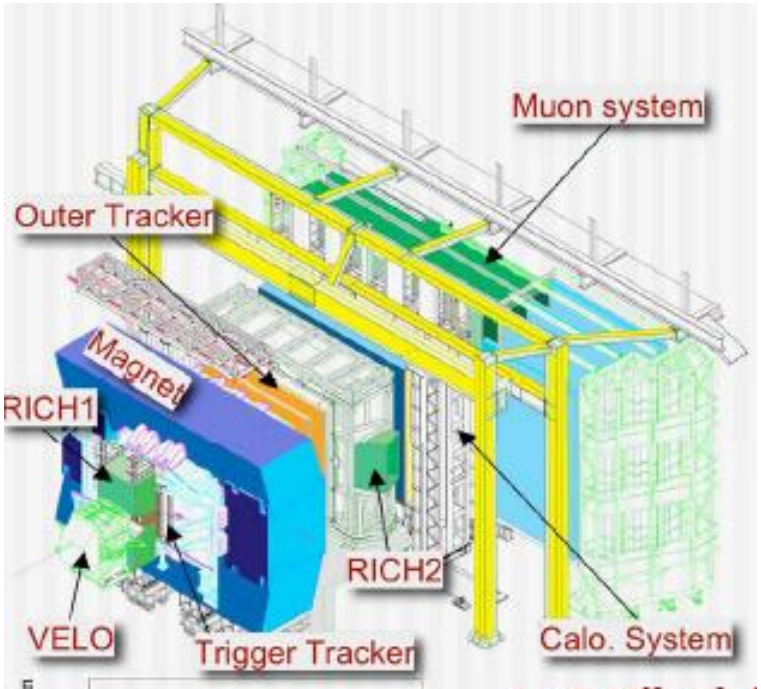
We do not know what is out there waiting for us…

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

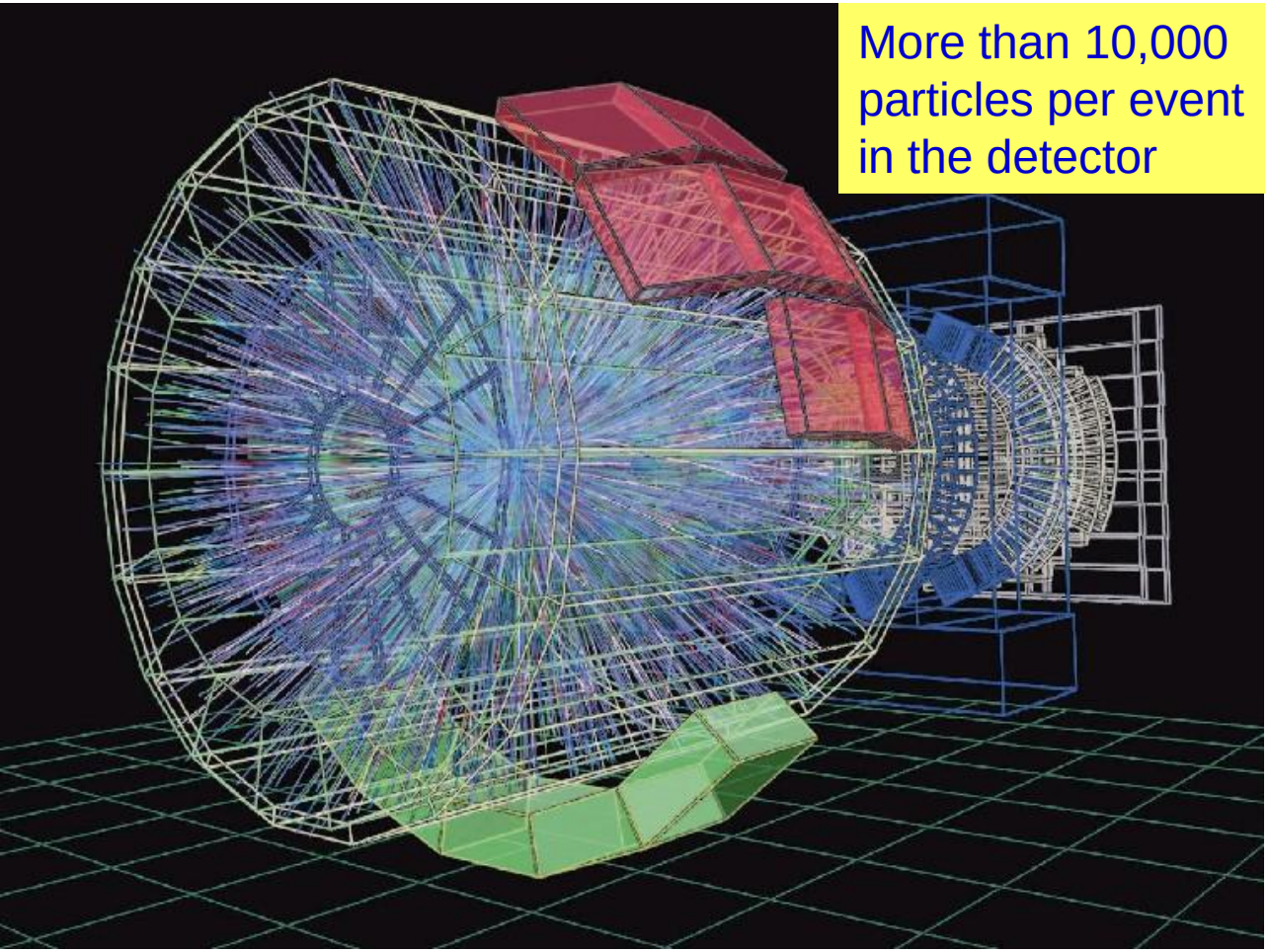




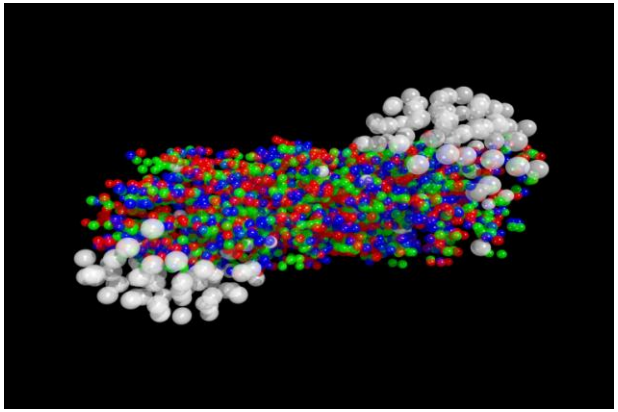


Primordial Plasma

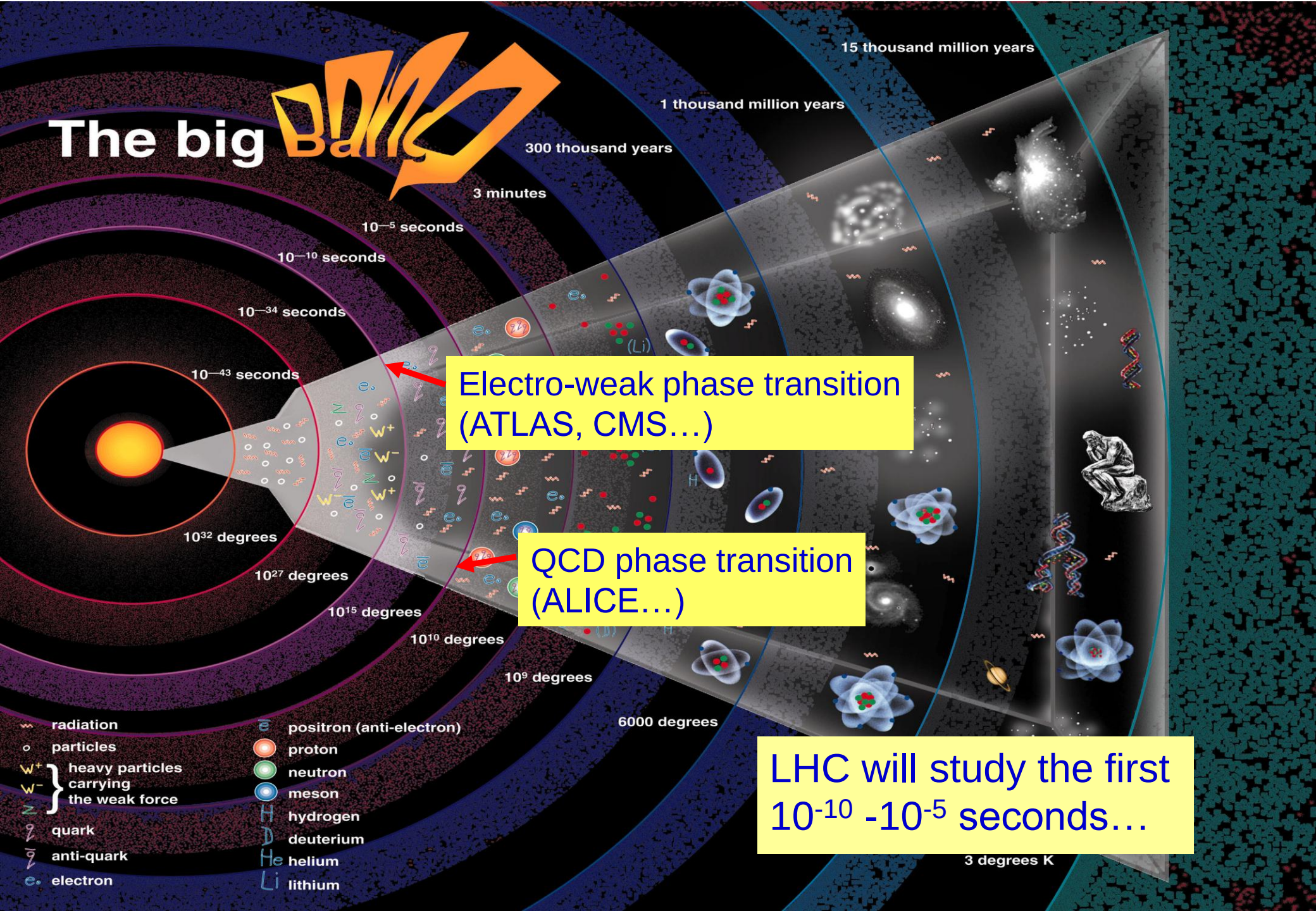
Lead-lead collisions at the LHC to study the primordial plasma, a state of matter in the early moments of the Universe



A lead lead collision simulated in the ALICE detector



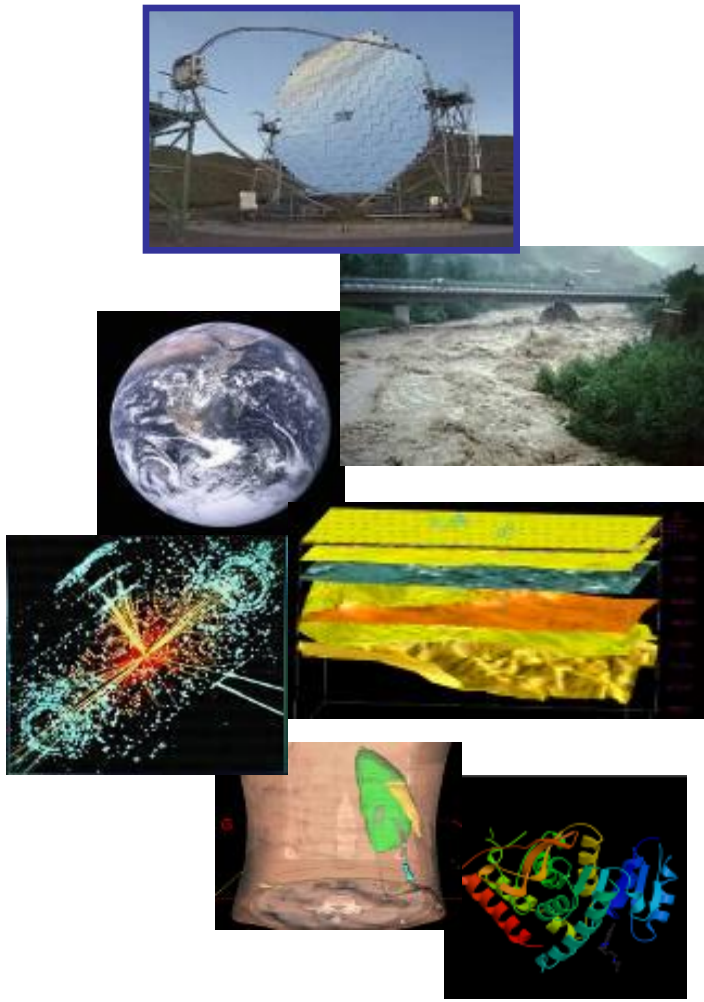
Study the phase transition of a state of quark gluon plasma created at the time of the early Universe to the baryonic matter we observe today


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
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium
Electro-weak phase transition (ATLAS, CMS…)
QCD phase transition (ALICE…)
LHC will study the first 10^{-10} -10^{-5} seconds…

Applications of Grid Computing

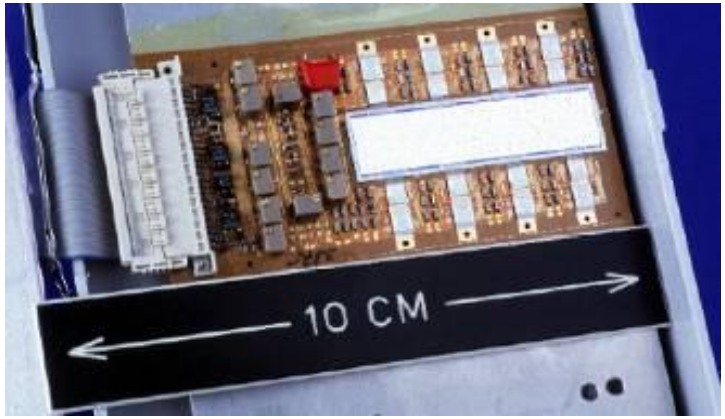
Multitude of applications from a growing number of domains

- Archeology
- Astronomy & Astrophysics
- Civil Protection
- Computational Chemistry
- Earth Sciences
- Financial Simulation
- Fusion
- Geophysics
- High Energy Physics
- Life Sciences
- Multimedia
- Material Sciences
- …

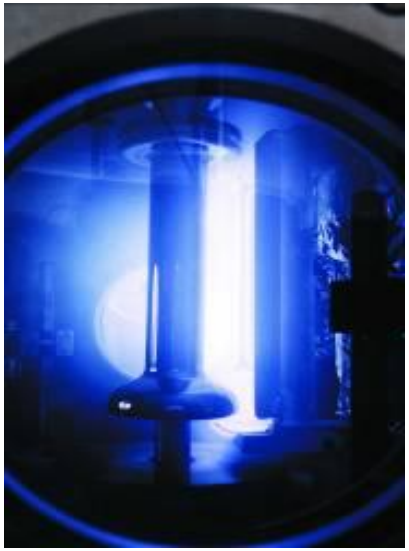


Infrastructure used by >5000 researchers
- submitted ~20 millions jobs in 2006

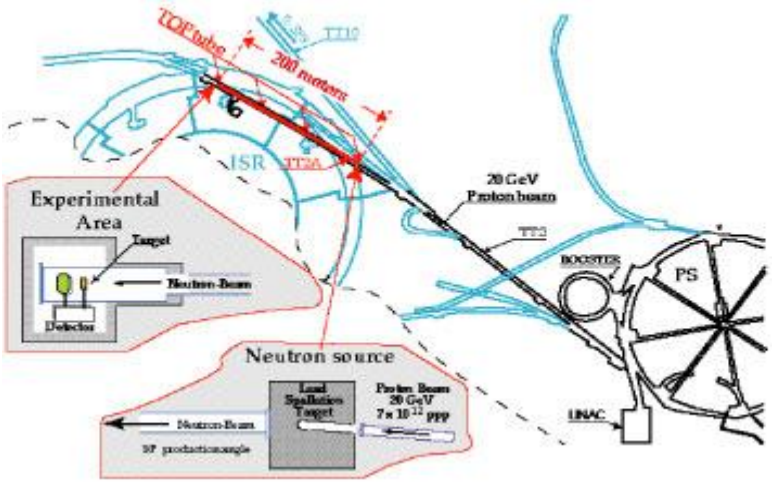
Technology Transfer Projects



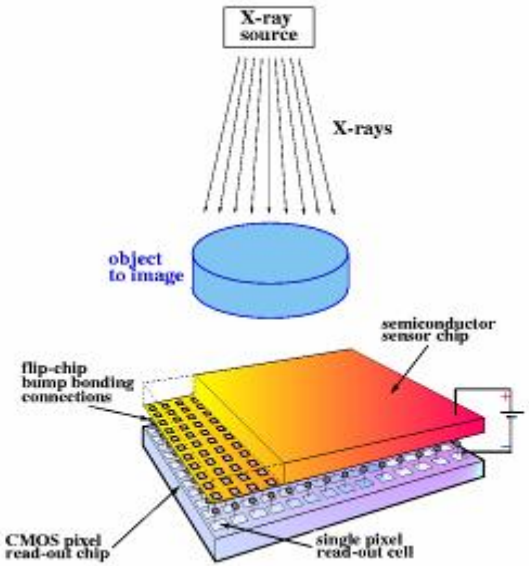
Silicon detector for a Compton camera in nuclear medical imaging



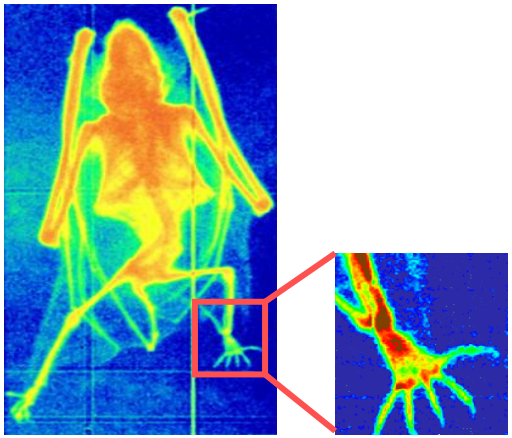
Thin films by sputtering or evaporation



Radio-isotope production for medical applications



Medipix: Medical X-ray diagnosis with contrast enhancement and dose reduction



Radiography of a bat, recorded with a GEM detector

[redacted]

CERN as an Educator

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