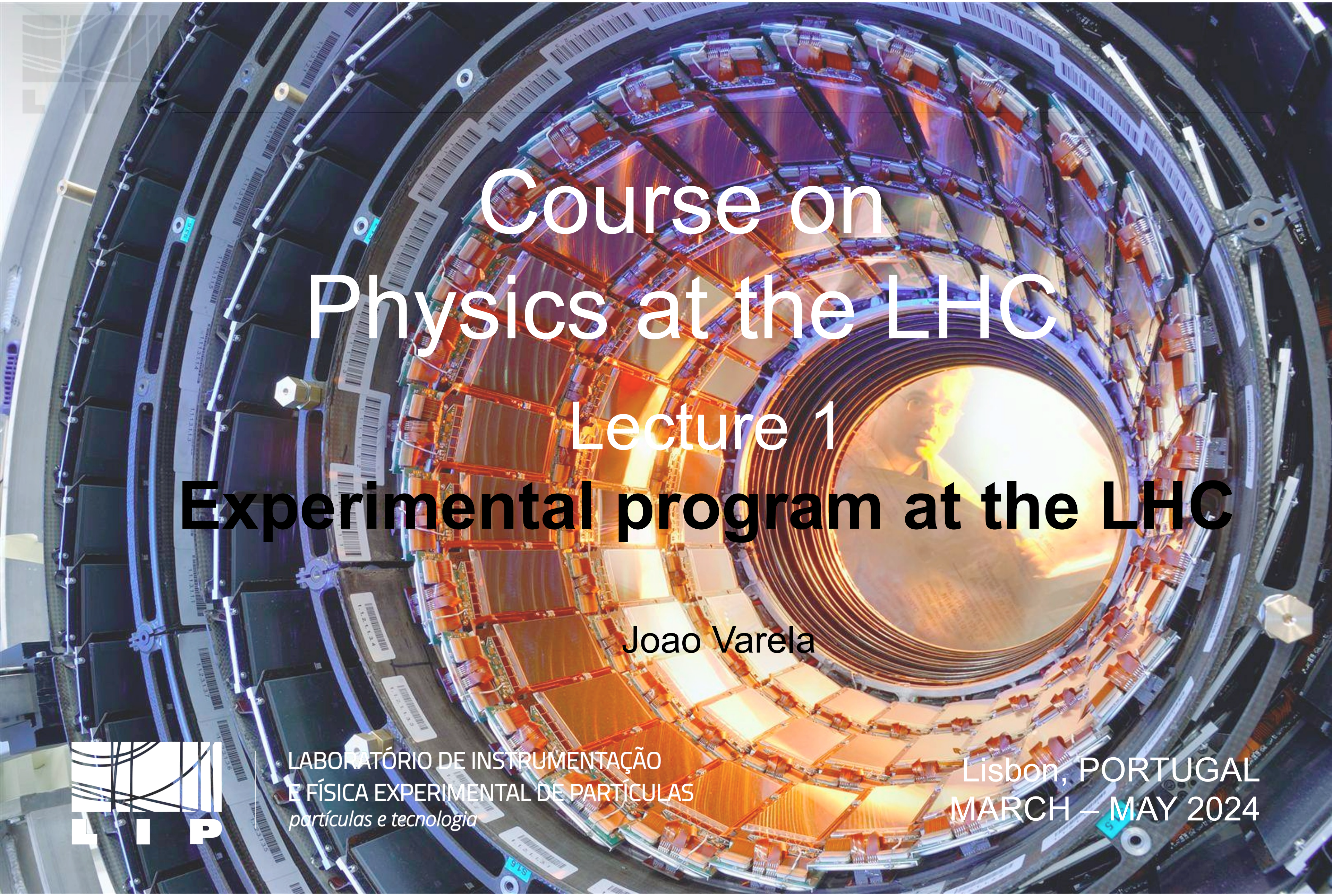


Course on Physics at the LHC

Lecture 1

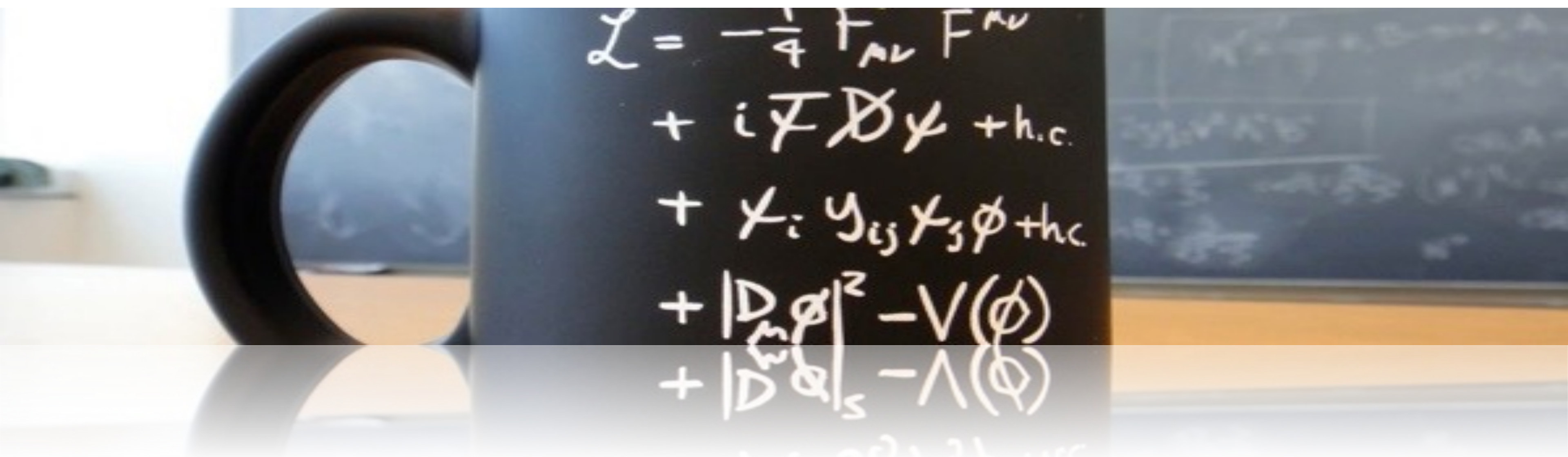
Experimental program at the LHC

Joao Varela

LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

Lisbon, PORTUGAL
MARCH – MAY 2024

The LHC physics case



Particle Physics

Particle physics is a modern name for the centuries old effort to understand the basics laws of physics.

Edward Witten

Aims to answer the two following questions:

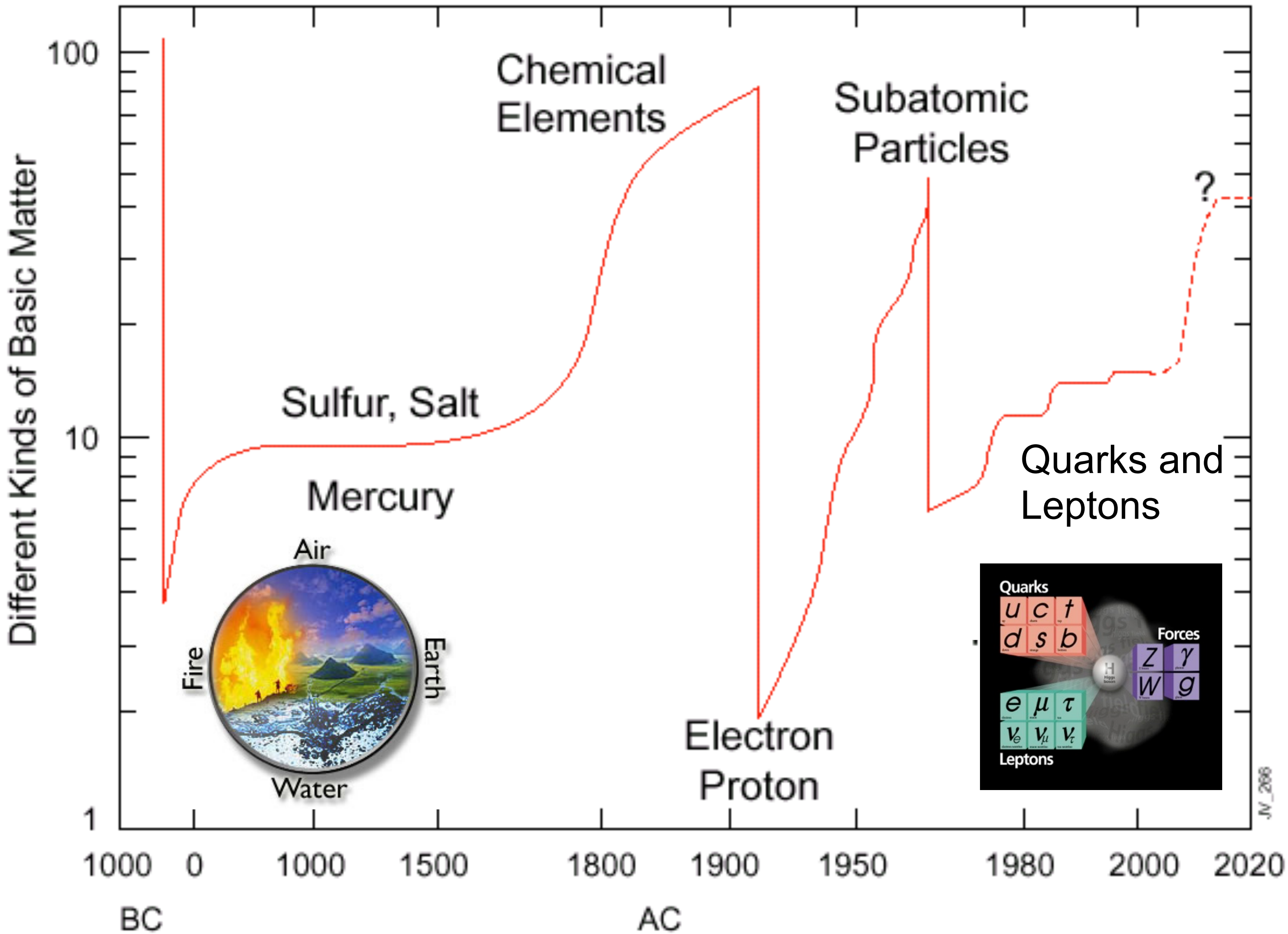
What are the elementary constituents of matter ?

What are the forces that determine their behavior?

Experimentally

Get particles to interact and study what happens

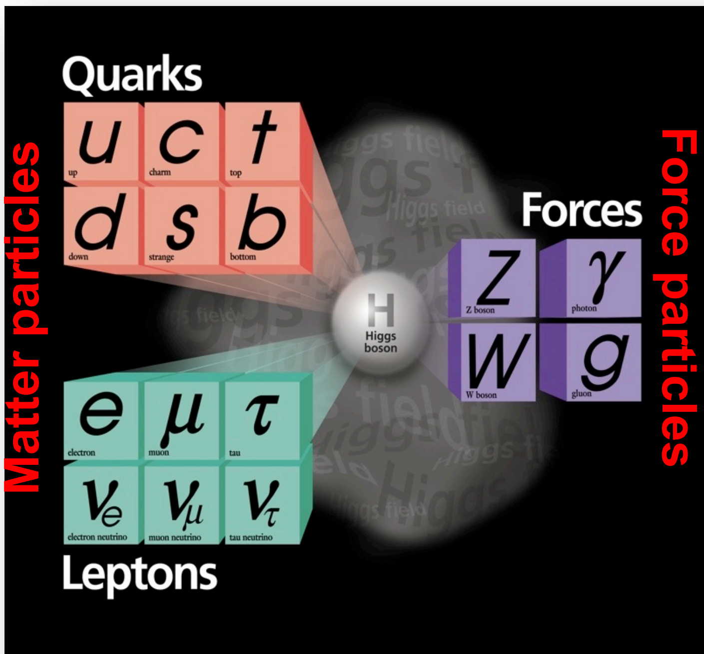
Constituents of matter along History



The Standard Model

Over the last ~100 years: The combination of Quantum Field Theory and discovery of many particles has led to

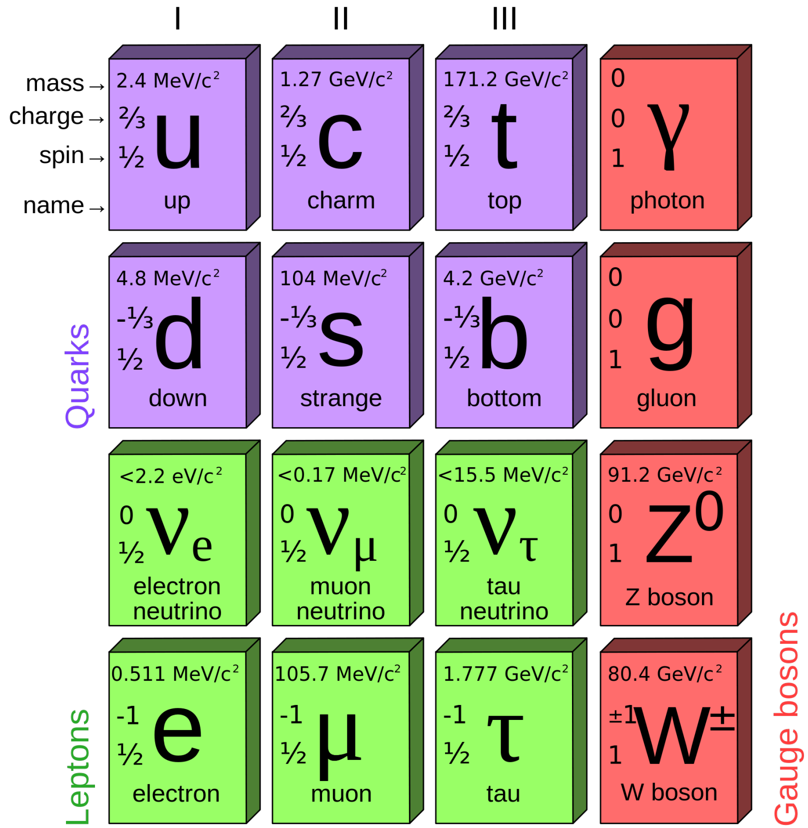
- The Standard Model of Particle Physics
  - With a new “Periodic Table” of fundamental elements

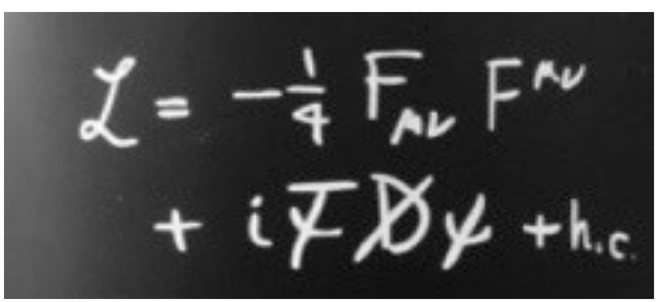


One of the greatest achievements of 20th Century Science

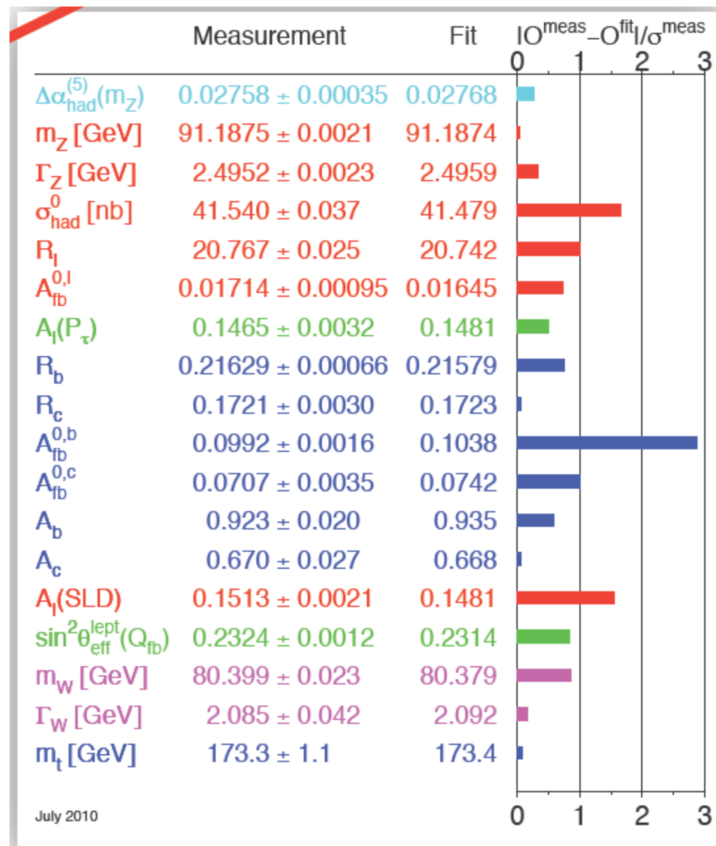
$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4}H^4 + \frac{g^2}{4}(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu)(\lambda^2 + 2\lambda H + H^2) + \sum_{l,q,q'}(\frac{m_l}{\lambda}\bar{l}l + \frac{m_q}{\lambda}\bar{q}q + \frac{m_{q'}}{\lambda}\bar{q}'q')H$$

SM confirmed by data





STANDARD MODEL OF ELEMENTARY PARTICLES



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4

Confirmed at sub 1% level!

The Higgs

In the simplest model the interactions are symmetrical and particles do not have mass

The symmetry between the electromagnetic and the week interactions is broken:

- Photon do not have mass
- W, Z do have a mass ~ 80-90 GeV

Higgs mechanism:

mass of W and Z results from the interactions with the Higgs field

The Terascale

The Standard Model would fail at high energy without the Higgs particle or other ‘new physics’

Based on the available data and on quite general theoretical insights it was expected that the **‘new physics’** would manifest at an energy around

1 Tera-electronVolt = 10^{12} electronVolt

accessible at the LHC for the first time

Beyond the standard model

The Standard Model answers many of the questions about the structure of matter. But the Standard Model is not complete; there are still many unanswered questions.

Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

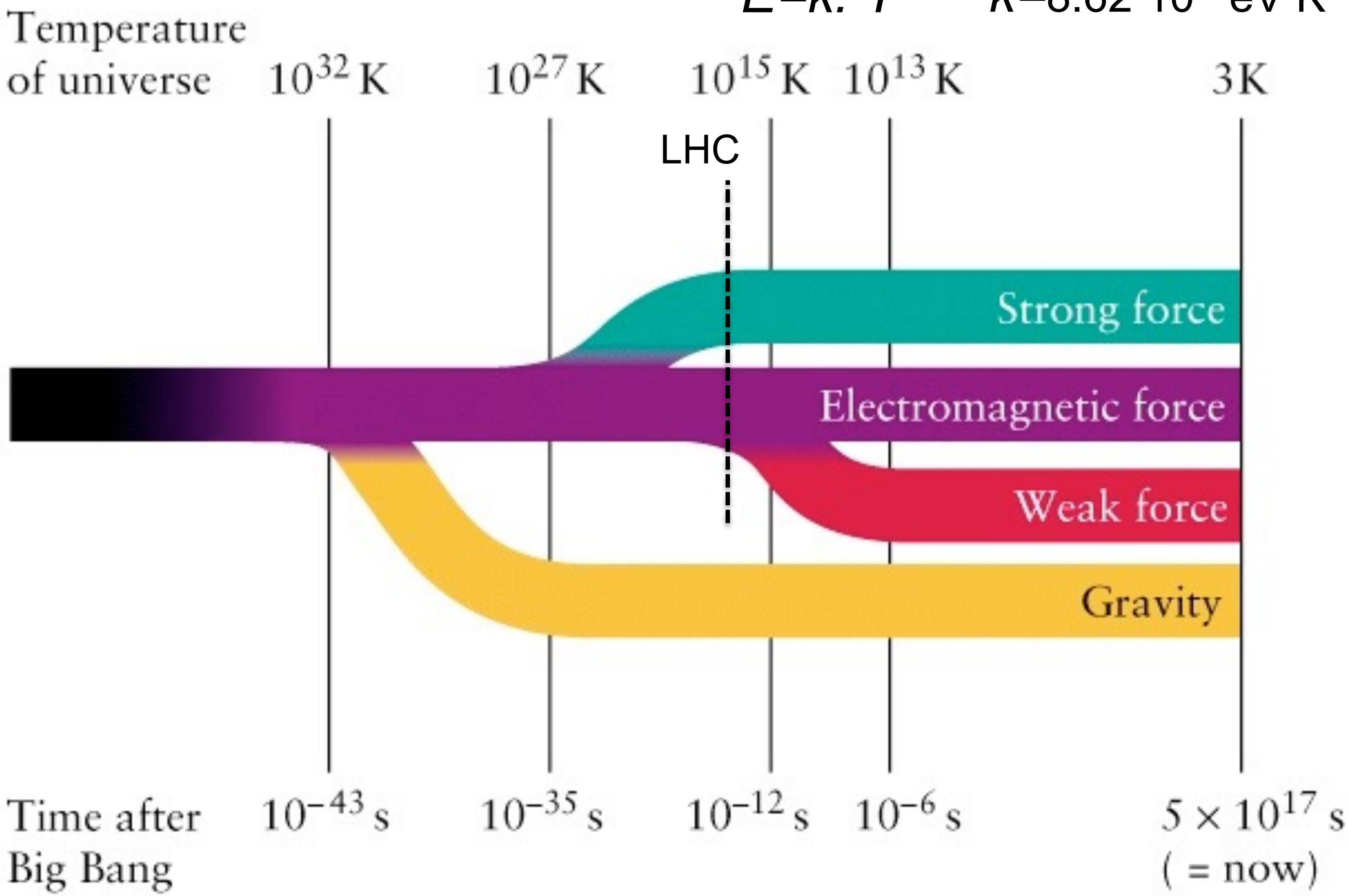
Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

How does gravity fit into all of this?

Forces and expansion of the Universe

$E = k.\ T \qquad k = 8.62\ 10^{-5}$ eV K^{-1}

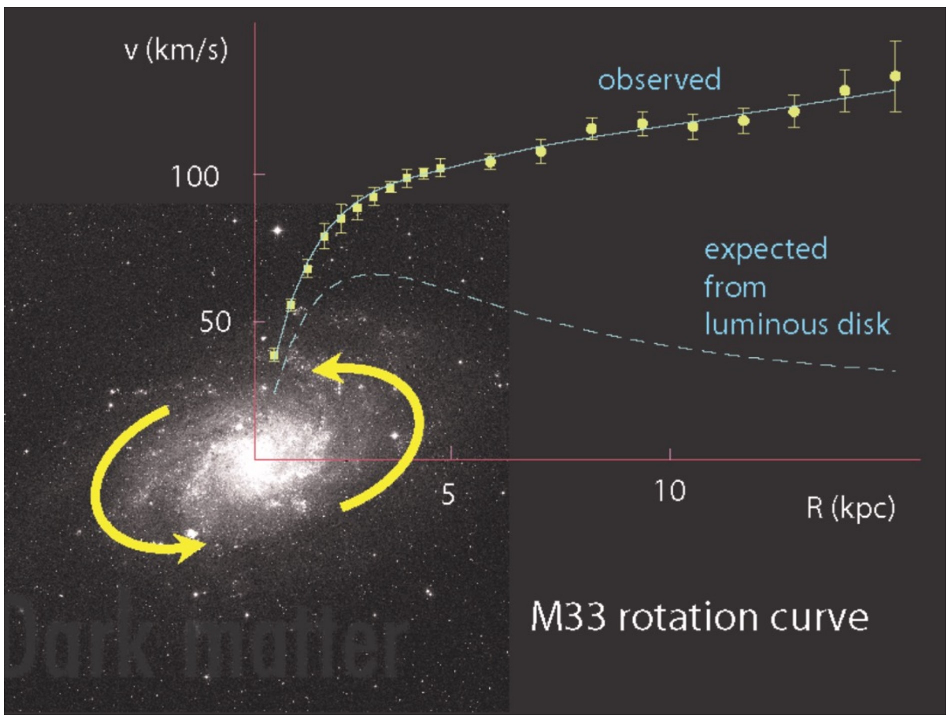


The dark side of the Universe

Long standing problem:

We know that ordinary matter is only ~4% of the matter-energy in the Universe.

What is the remaining 96%?



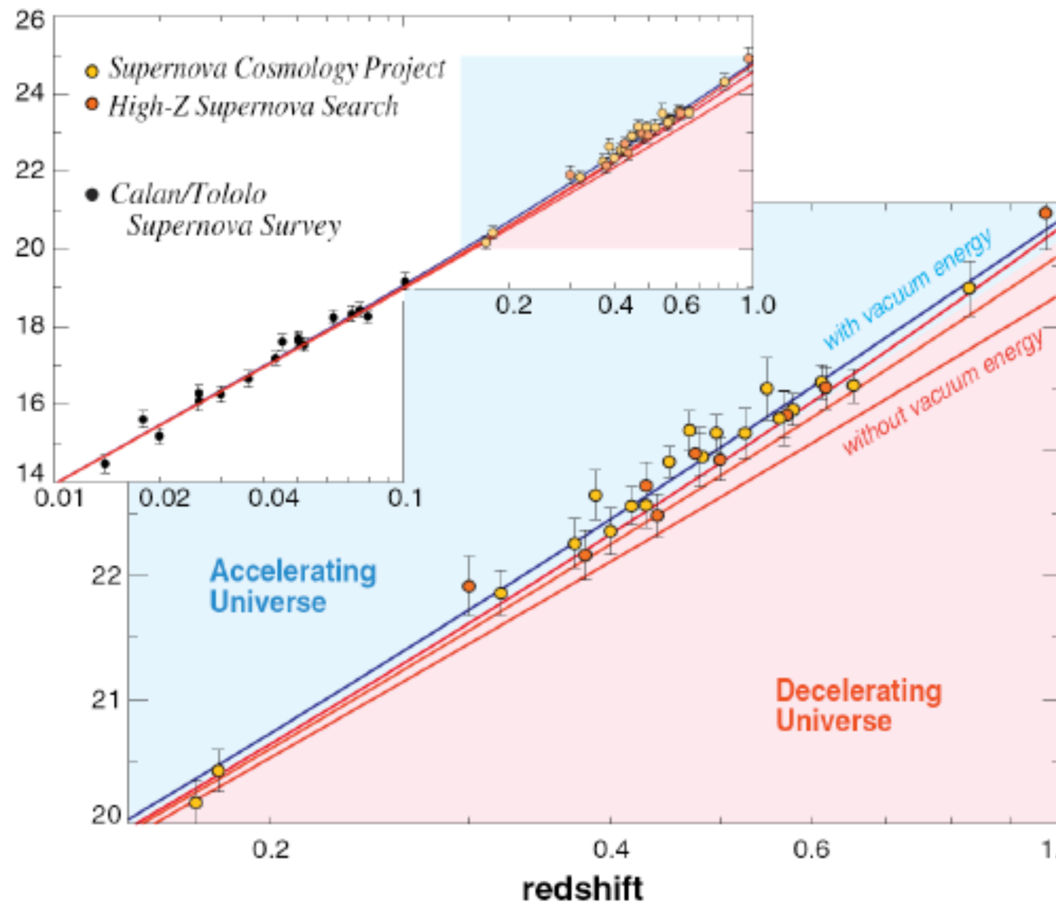
The LHC may help to solve this problem, discovering **dark matter**

The Universe expansion is accelerating

In 1998, two groups used distant **Supernovae** to measure the expansion rate of the universe: Perlmutter et al. (Supernova Cosmology Project), and Schmidt et al. (High-z Supernova Team)

They got the same result:
The Universe expansion is accelerating

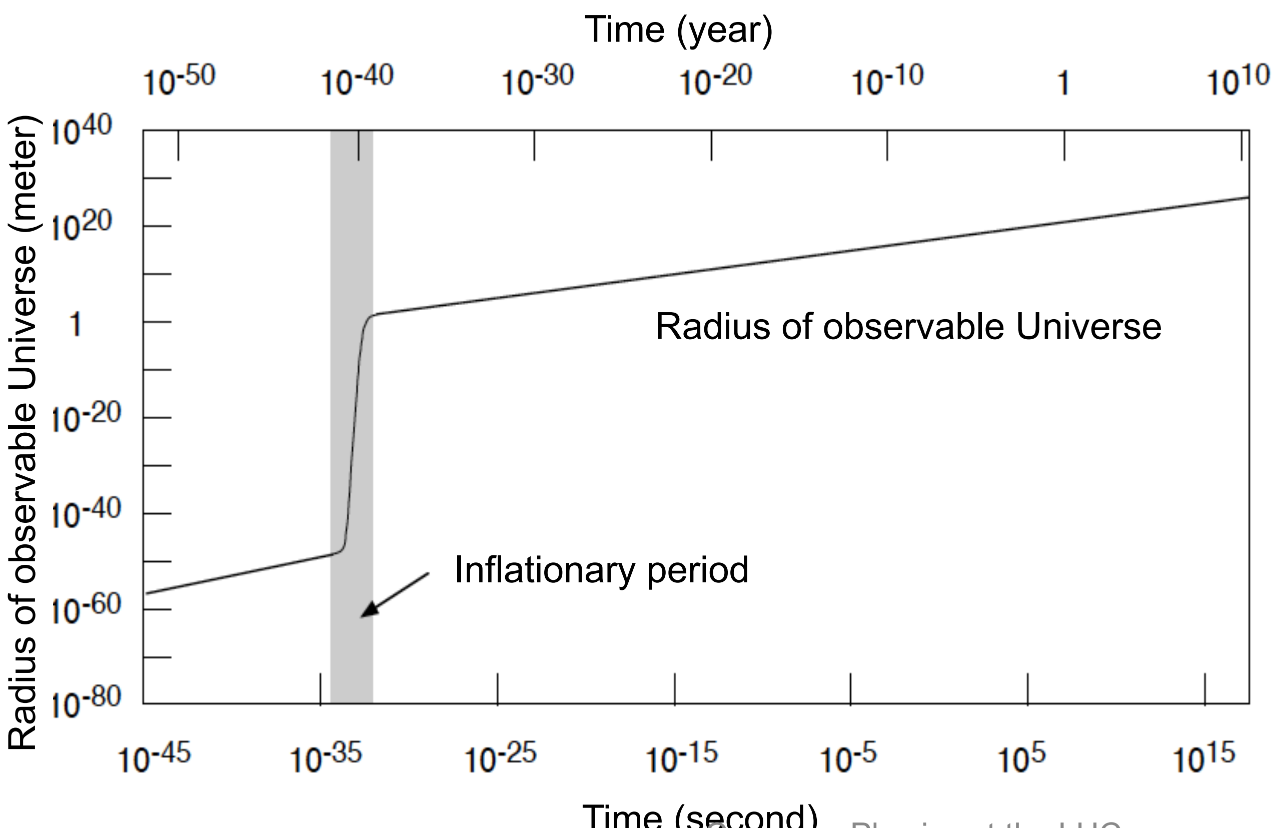
Some form of energy (dark energy) fills space



Cosmological inflation

In the very early universe space undergoes a dramatic exponential expansion.

Explains why the Universe has a uniform Temperature (3 K) and why space-time has a flat geometry

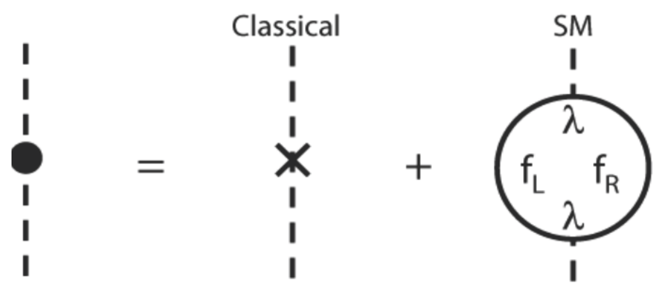


The inflation theory was developed independently in the late 1970's by Alan Guth, Alexey Starobinsky, and others

Higgs and hierarchy problem

In the SM the Higgs mass is a huge problem:

- Virtual particles in quantum loops contribute to the Higgs mass
- Contributions grow with Λ (upper scale of validity of the SM)
- Λ could be huge – e.g. the Plank scale (10^{19} GeV)
- Miraculous cancelations are needed to keep the Higgs mass < 1 TeV



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

This is known as the hierarchy problem

Many possible theories

There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, …)
- Leptoquarks
- New Heavy Gauge Bosons
- Compositeness

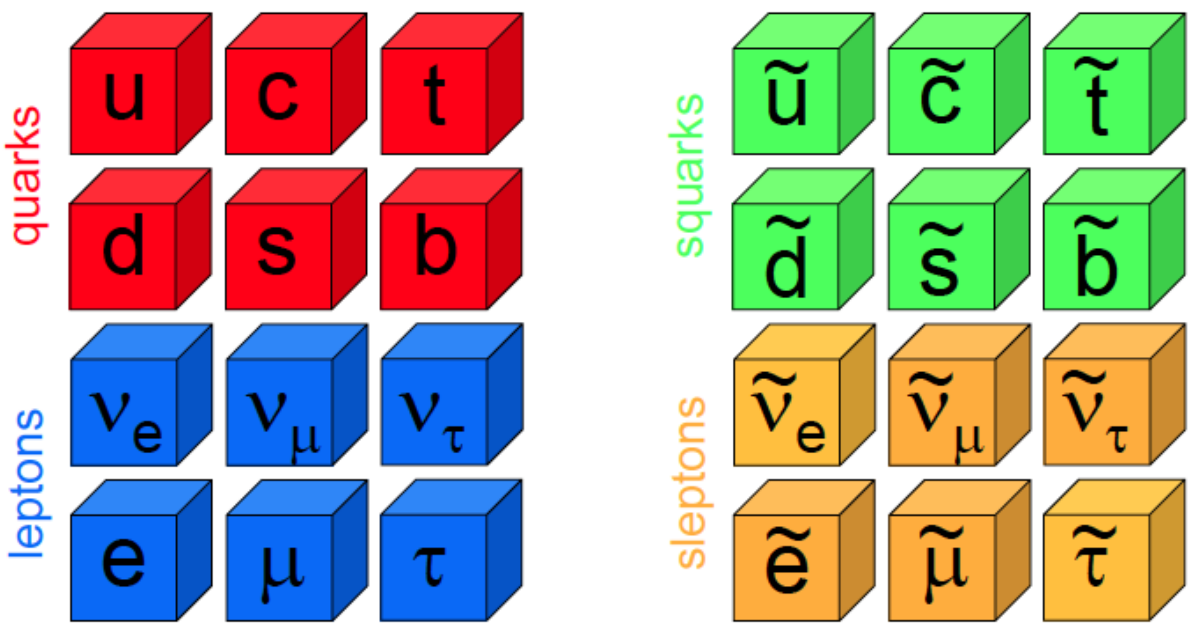
Any of this could still be found at the LHC

Supersymmetry

New fundamental symmetry:

- Every fermion should have a massive "shadow" boson
- Every boson should have a massive "shadow" fermion.
-

This relationship between fermions and bosons is called supersymmetry (SUSY)



Heavy versions of every quark and lepton

Supersymmetry is broken

Could DM be SUSY particles?

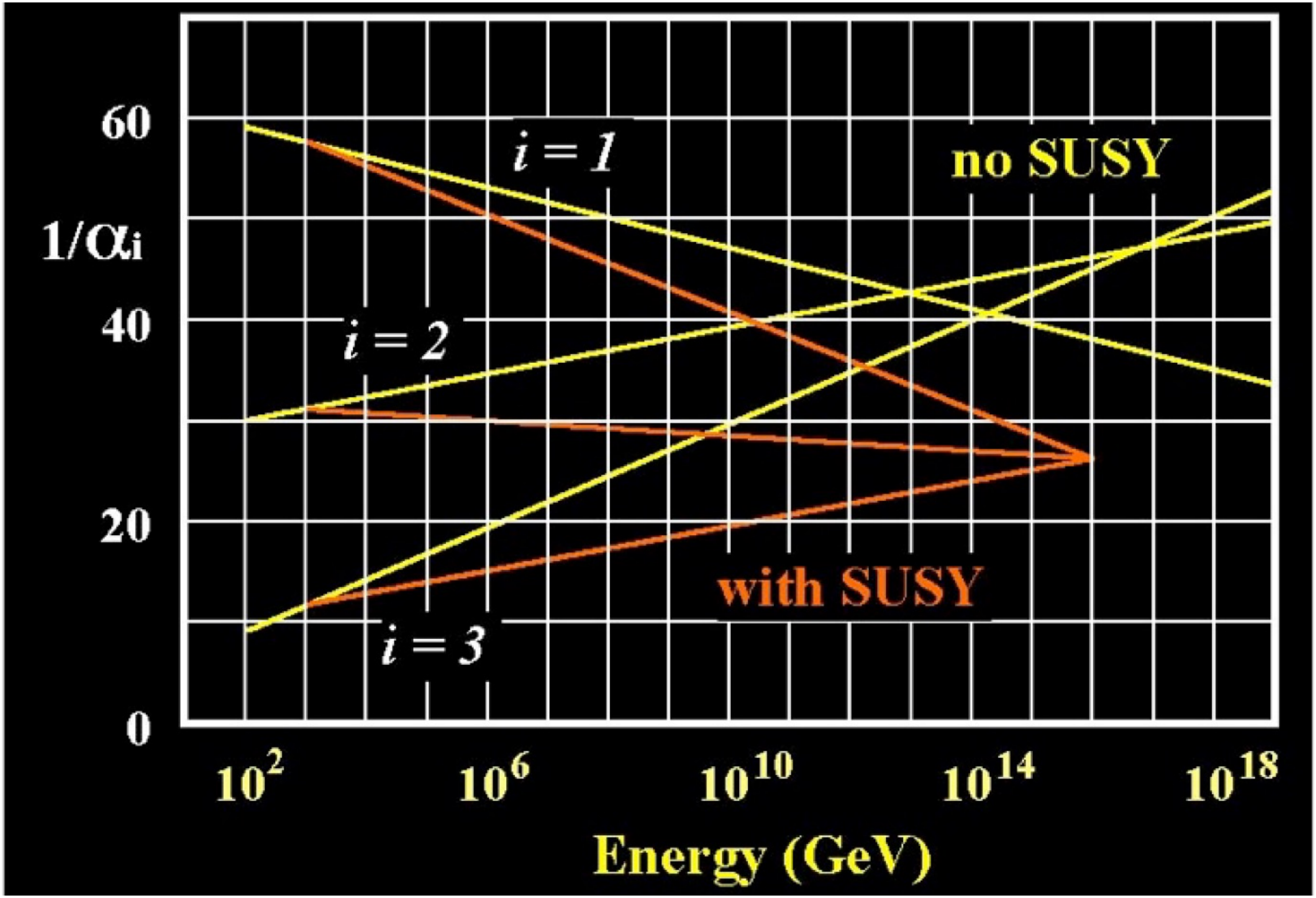
For every "normal" force quanta (boson), there are supersymmetric partners:

photon	photino
W, Z bosons	Wino, Zino
gluon	gluino
Higgs boson	higgsino

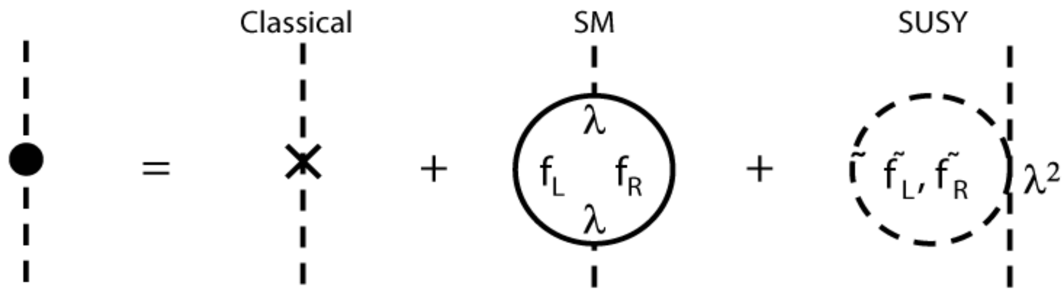
These "…inos" are prime suspects to be the galactic dark matter!

Relics from the Big Bang!

The temptation unification



SUSY and the Higgs mass



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

Higgs mass:

- correction has quadratic divergence!
  - Λ a cut-off scale – e.g. Planck scale

Cancellation

$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots$$

$$\approx (m_h^2)_0 + \frac{1}{16\pi^2}(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_{\tilde{f}}),$$

Superpartners fix this:

- Need superpartners at mass ~1-2 TeV
  - Otherwise the logarithmic term becomes too large, which would require more fine-tuning.

Extra dimensions

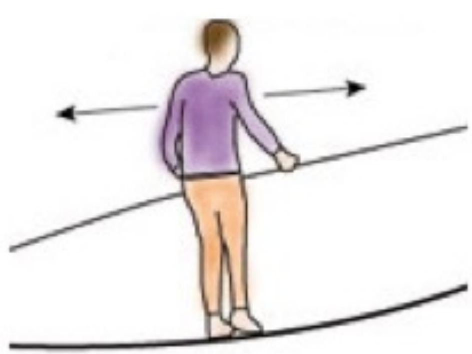
Space-time could have more than three space dimensions. The extra dimensions could be very small and undetected until now.

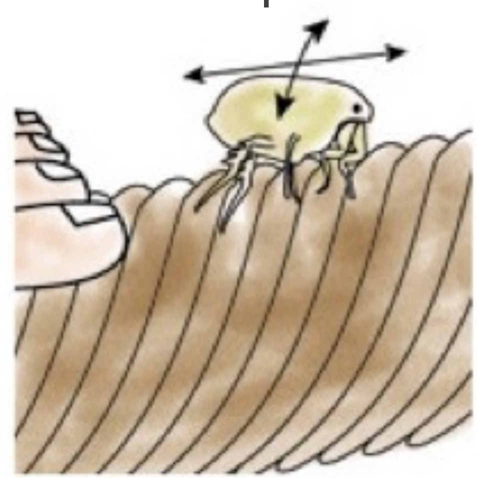
How can there be extra, smaller dimensions?

The acrobat can move forward and backward along the rope: **one dimension**

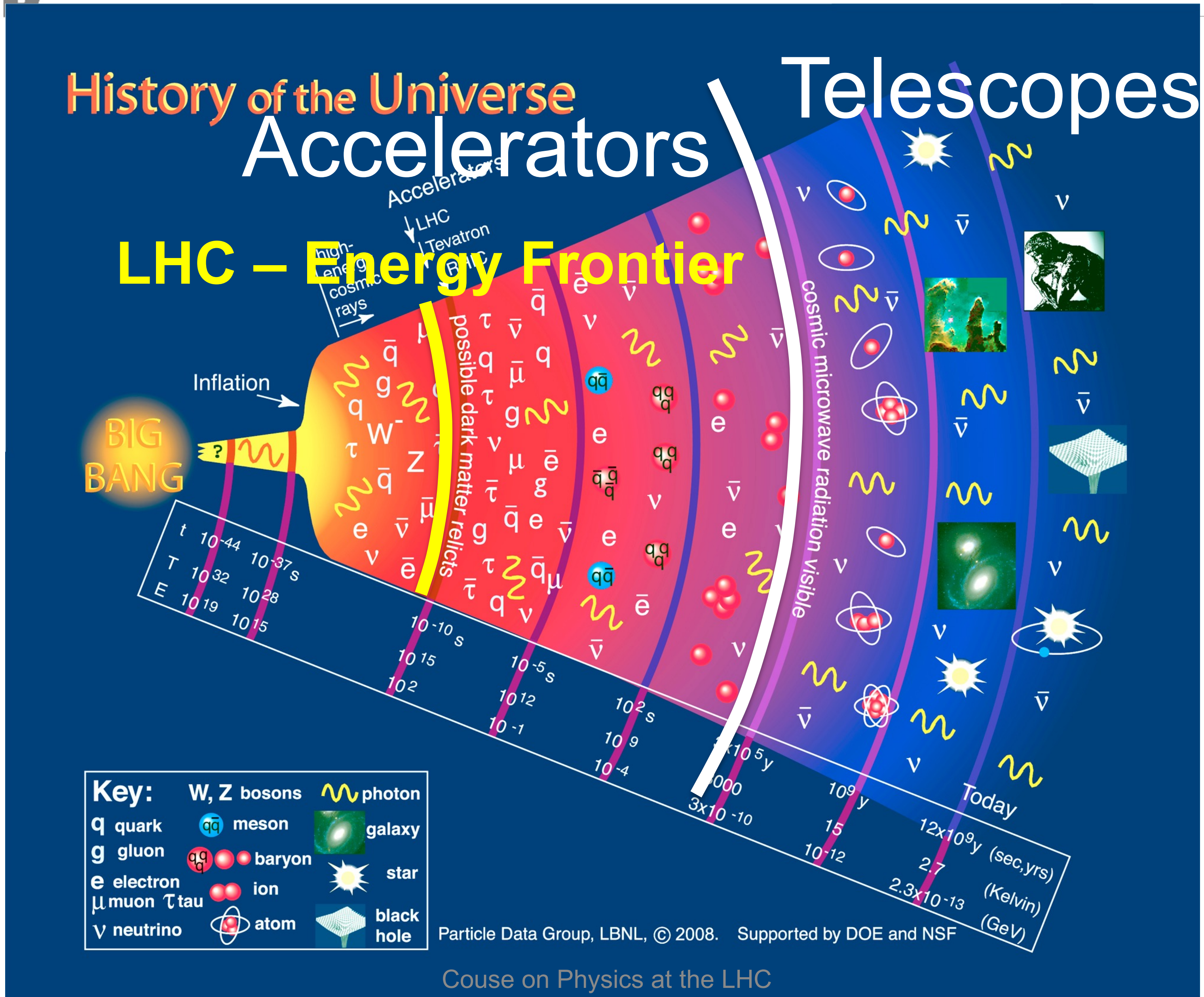
The flea can move forward and backward as well as side to side: **two dimensions**

But one of these dimensions is a small closed loop.





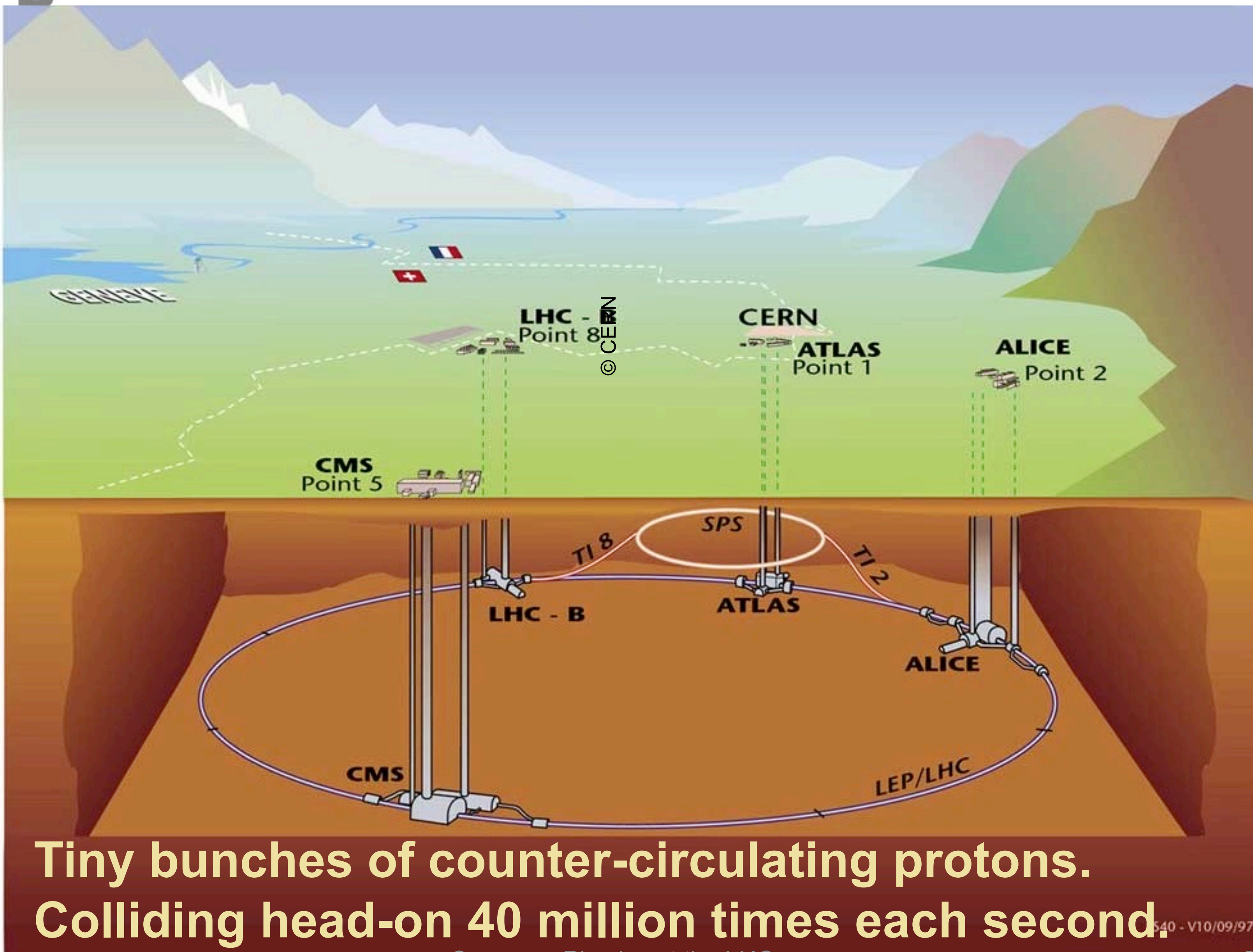
Understanding the Universe



The LHC proton collider

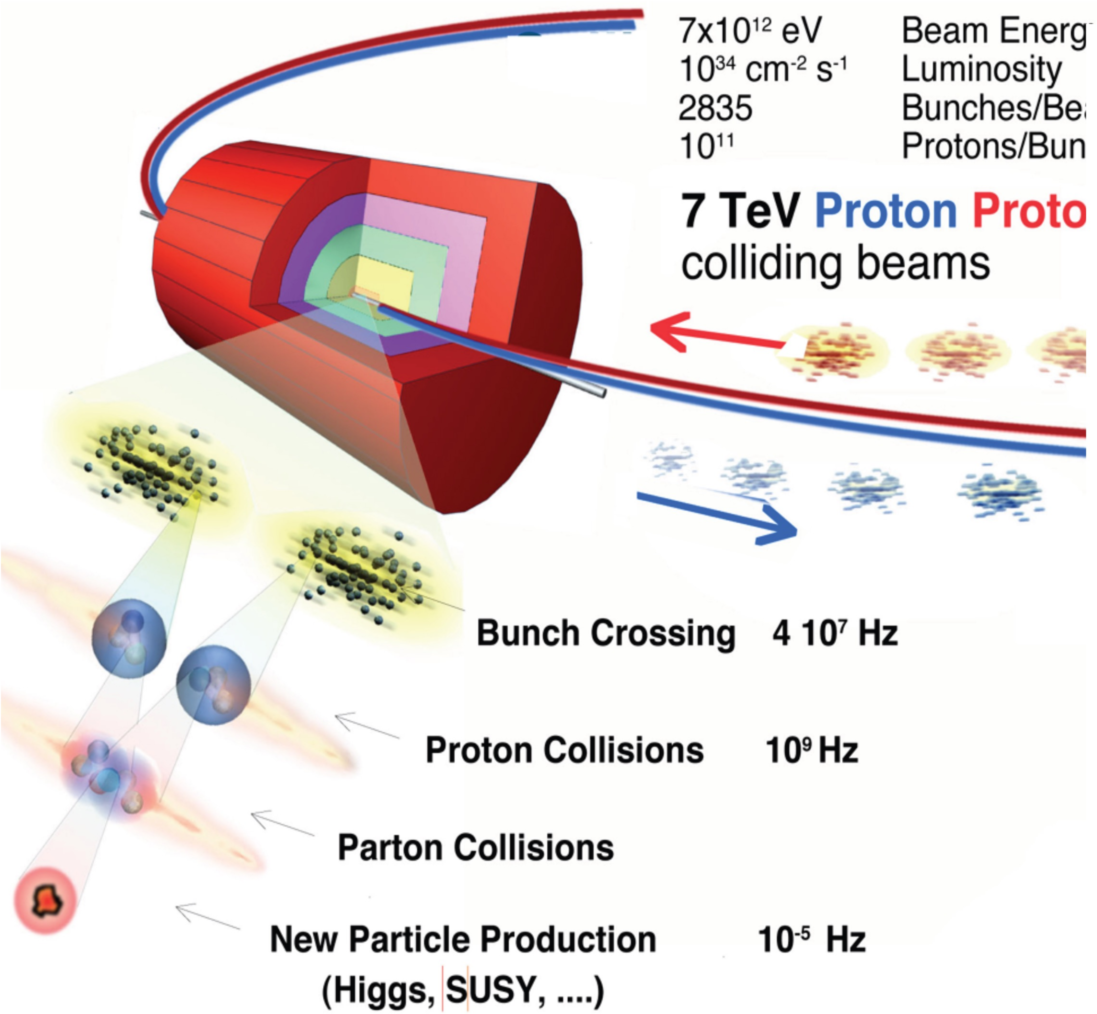
Accelerator and Experiments

Accelerator and experiments layout

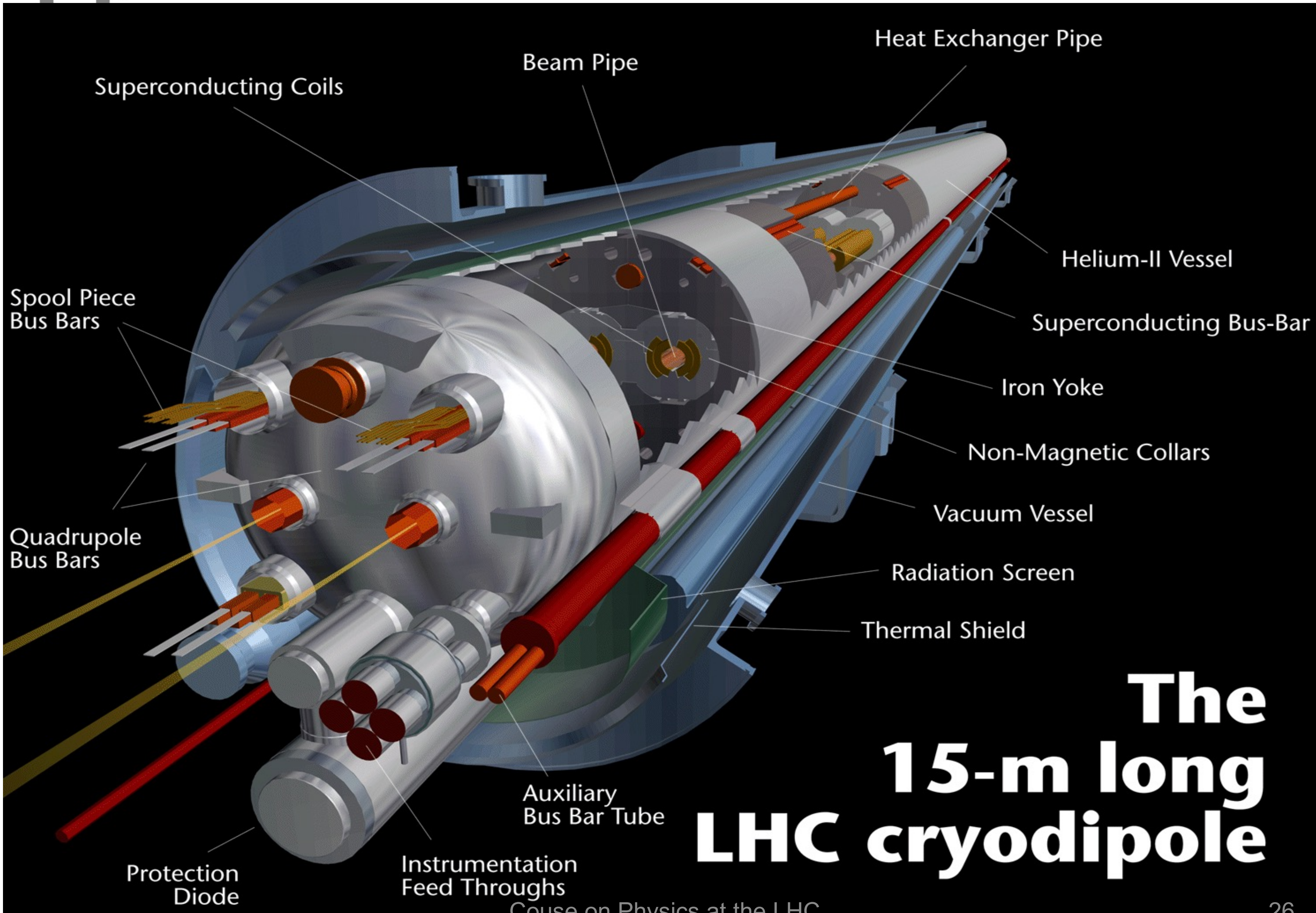


Tiny bunches of counter-circulating protons.
Colliding head-on 40 million times each second.

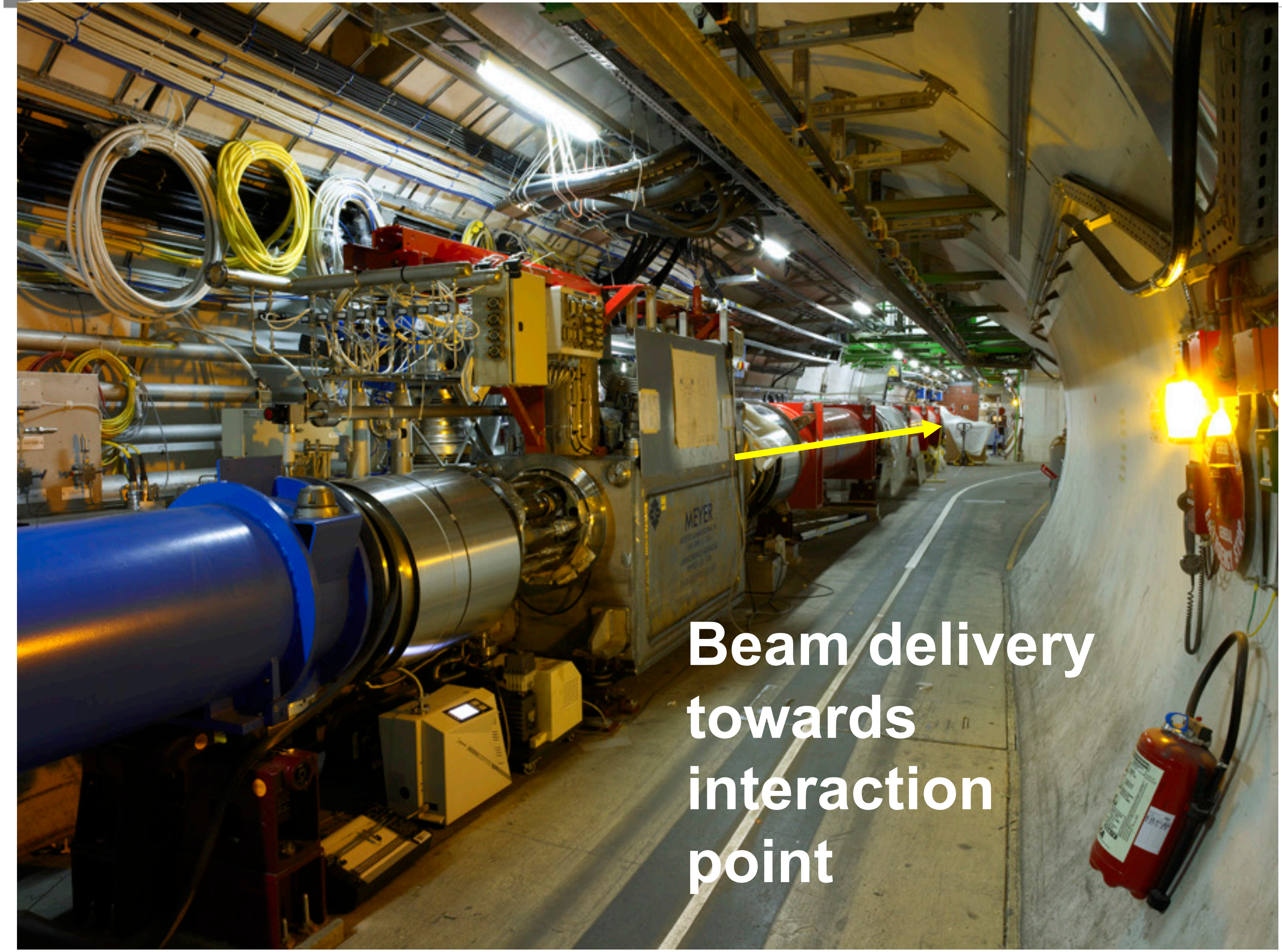
Collisions at LHC



Superconducting magnetic dipole

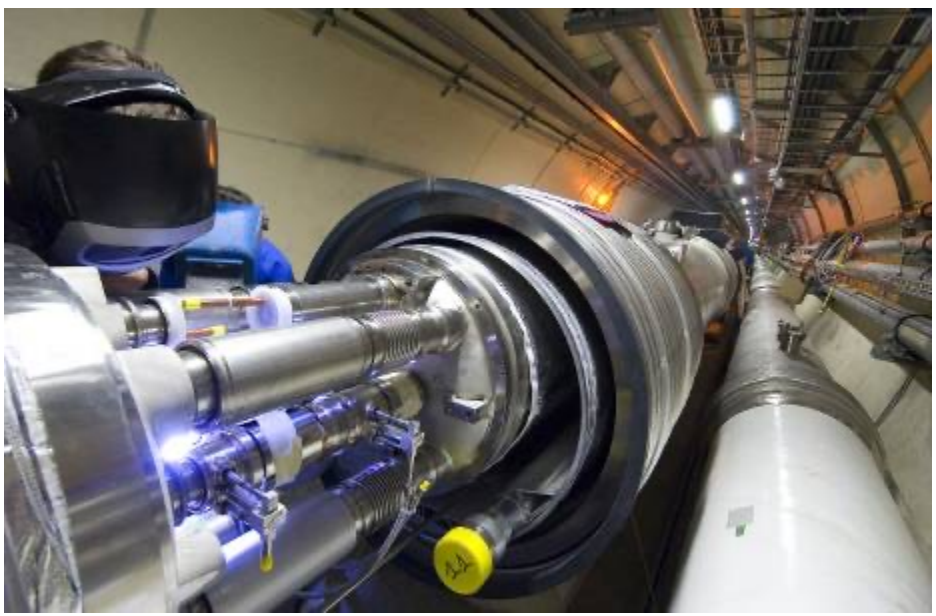


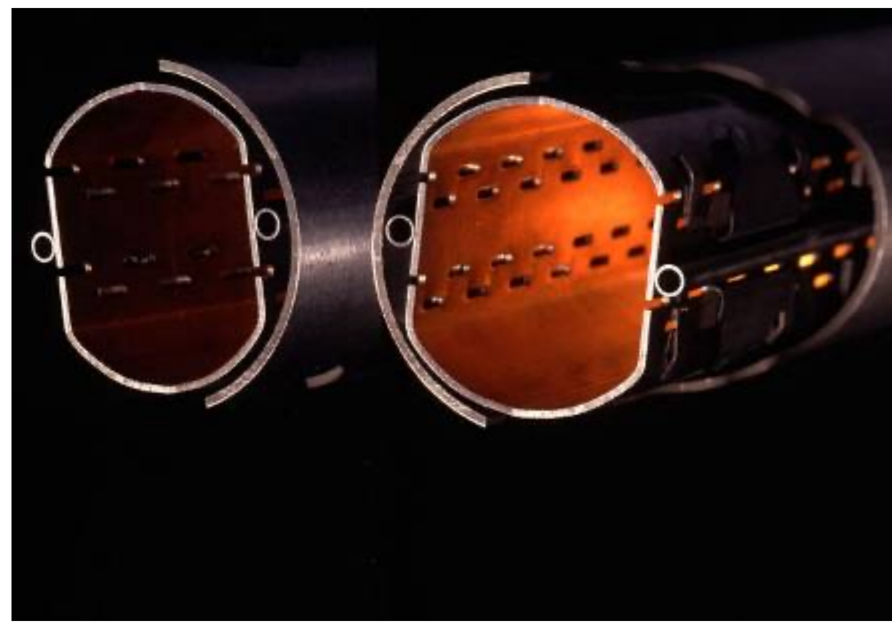
In the tunnel



It's empty!

Air pressure inside the two 27Km-long vacuum pipes (10^{-13} atm) is lower than on the moon.



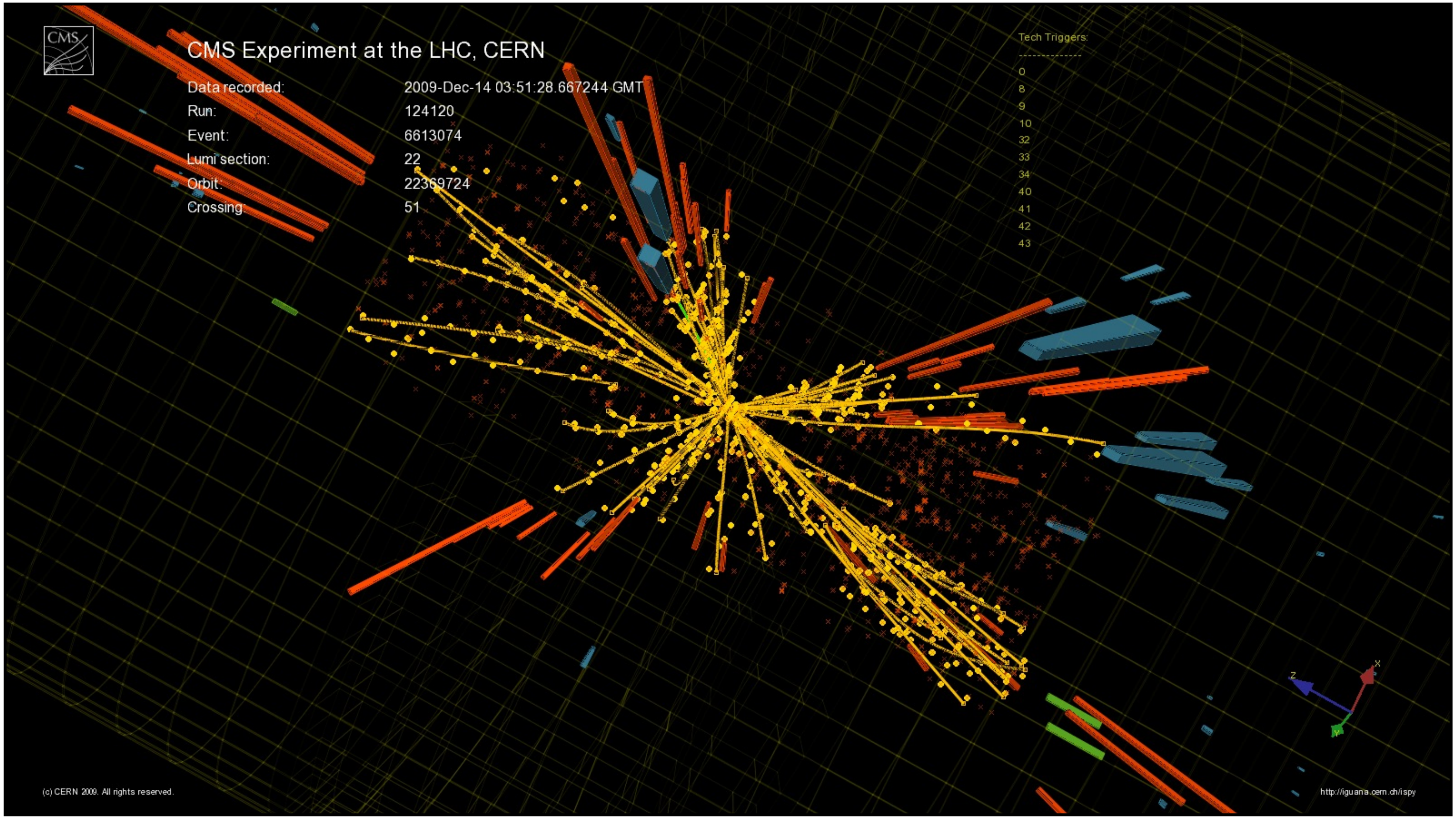


It's cold!

27 Km of magnets are kept at 1.9 ^{o}K, colder than outer space, using over 100 tons of liquid helium.

It's Hot!

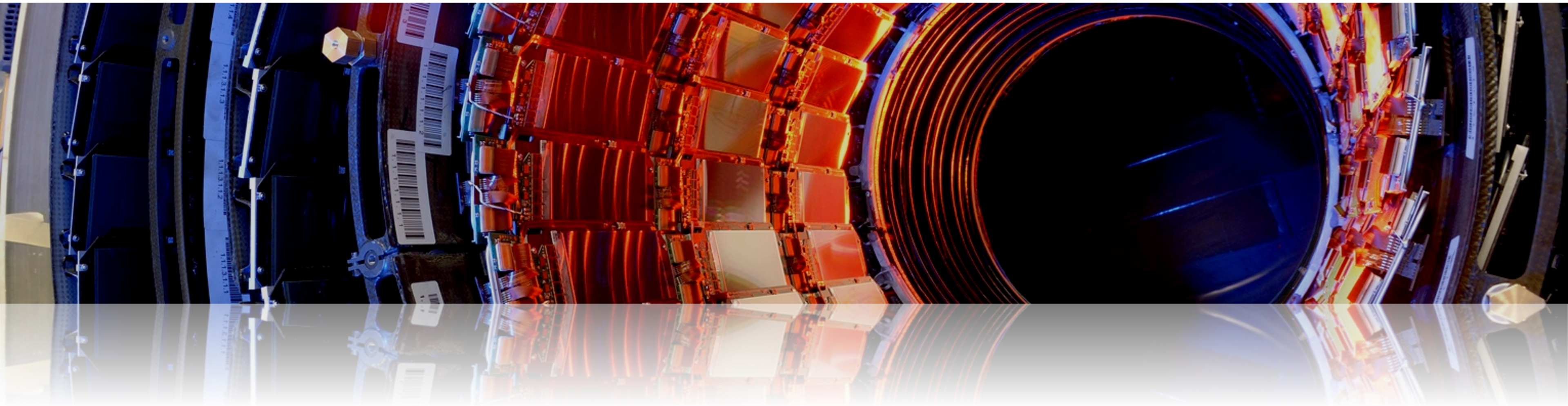
In a *tiny* volume, temperatures one billion times hotter than the center of the sun.



The LHC timeline

Bound to be one of the greatest endeavors of science in the 21st century

The Experiments

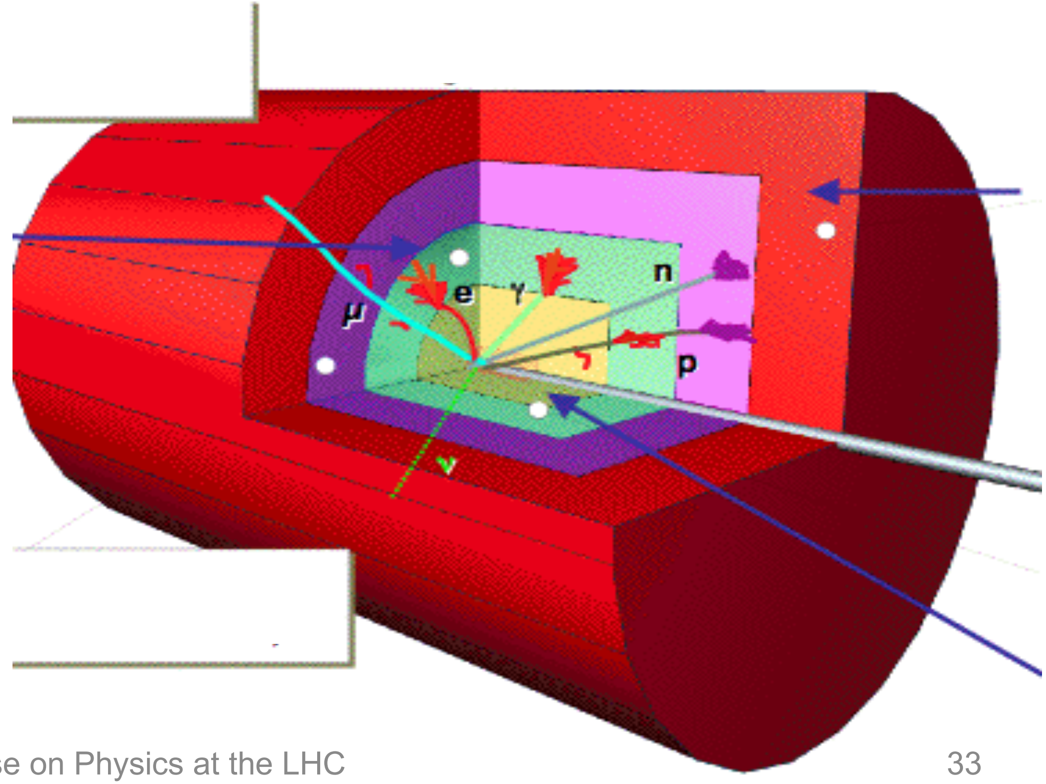


General purpose LHC experiments

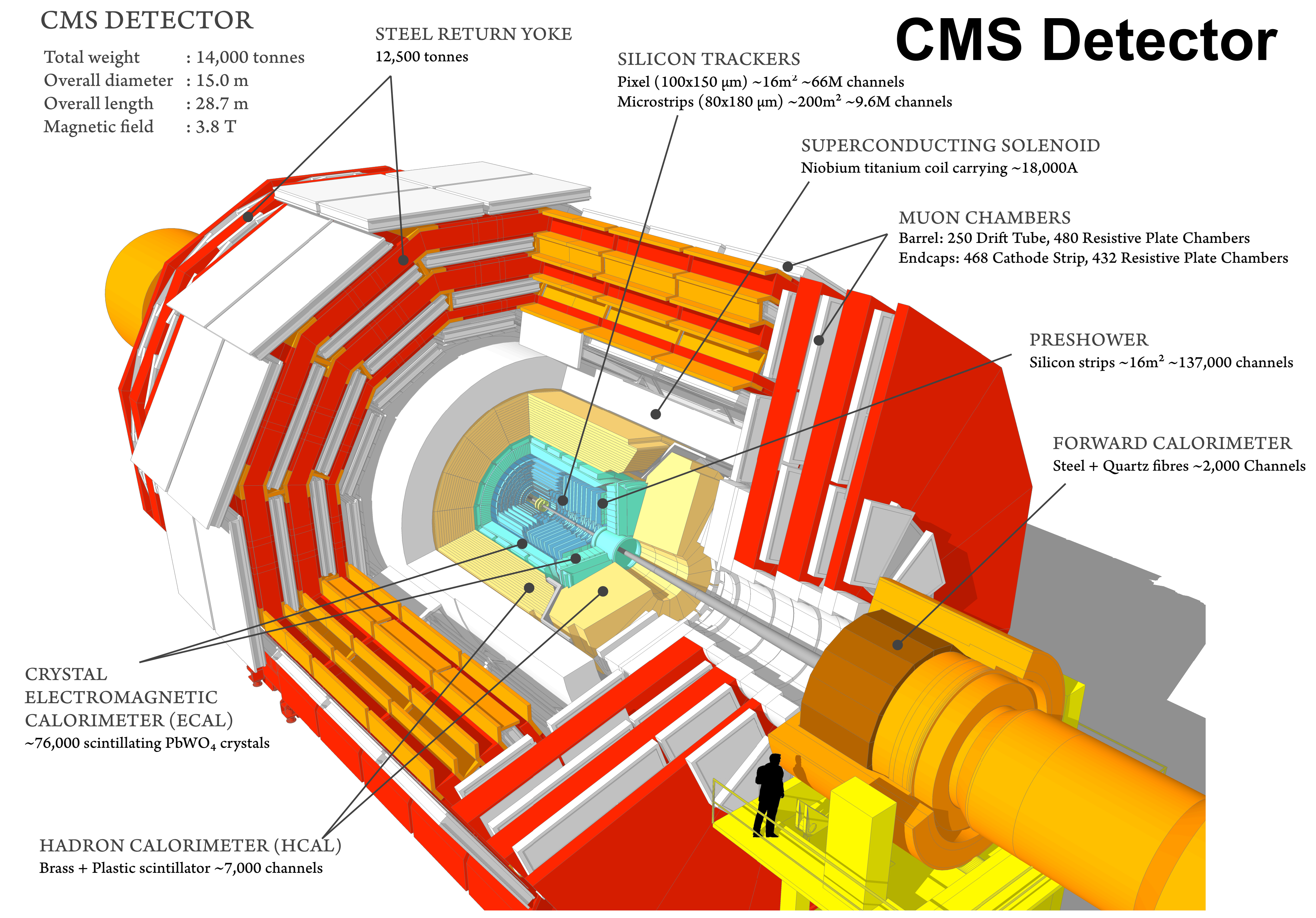
Advanced detectors comprising many layers, each designed to perform a specific task.

Together these layers allow to identify and precisely measure the energies of all stable particles produced in collisions.

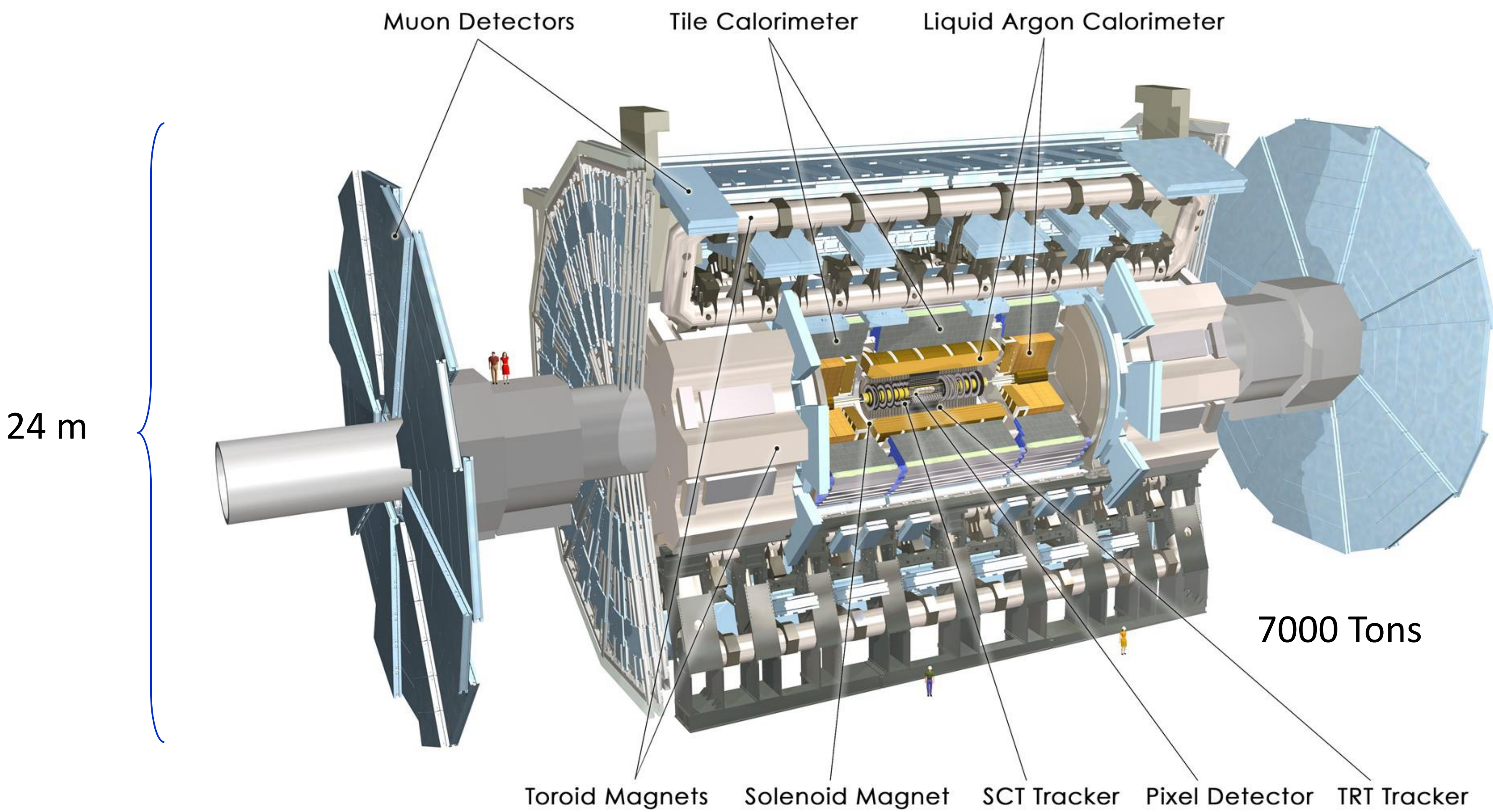
Photons,
Electrons,
Muons,
Quarks
(as jets of particles)
Neutrinos
(as missing energy)



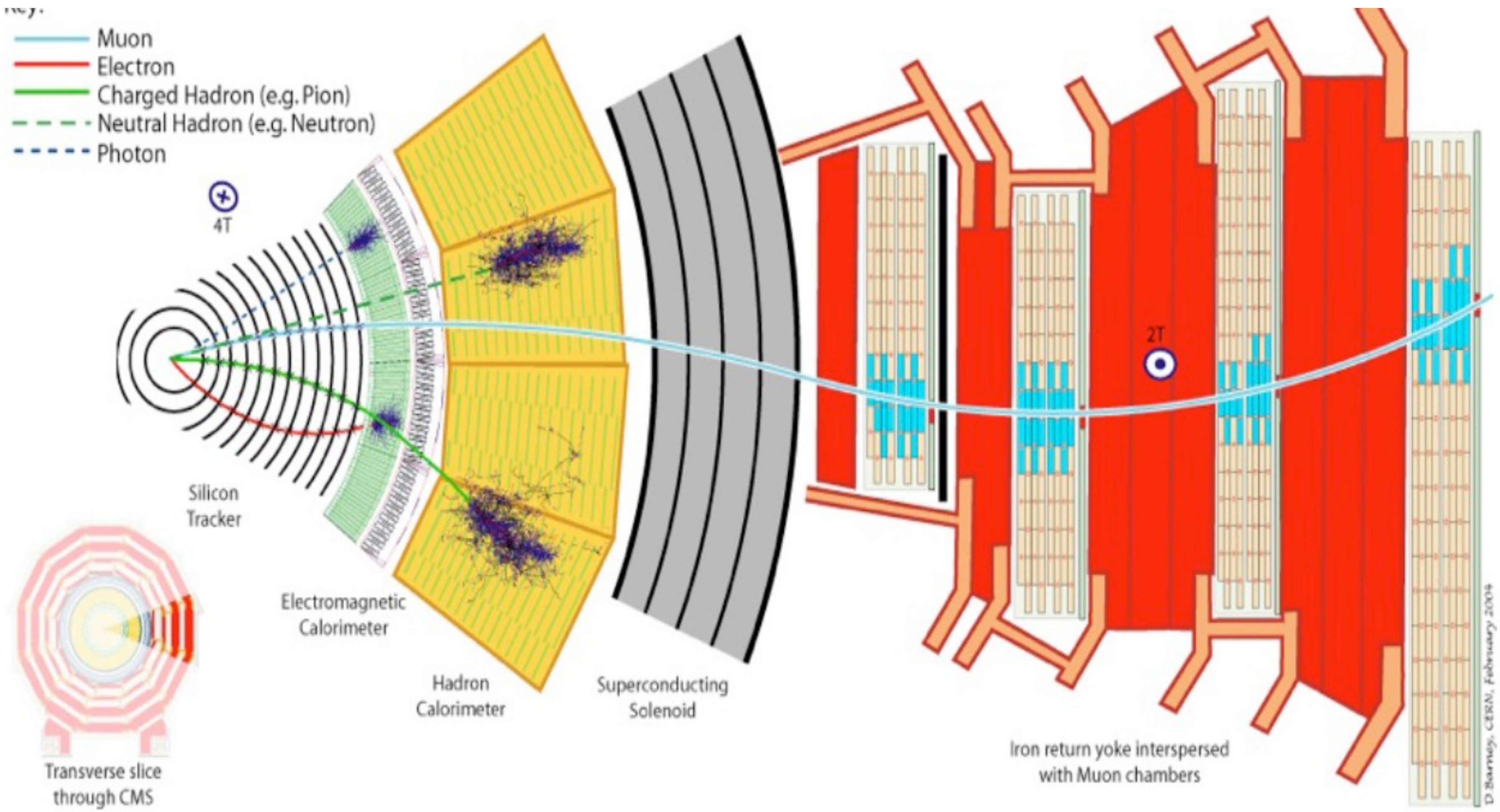
CMS Detector



ATLAS detectors



Detection of hadrons, e$^{\pm}$, γ and $\mu^{\pm}$

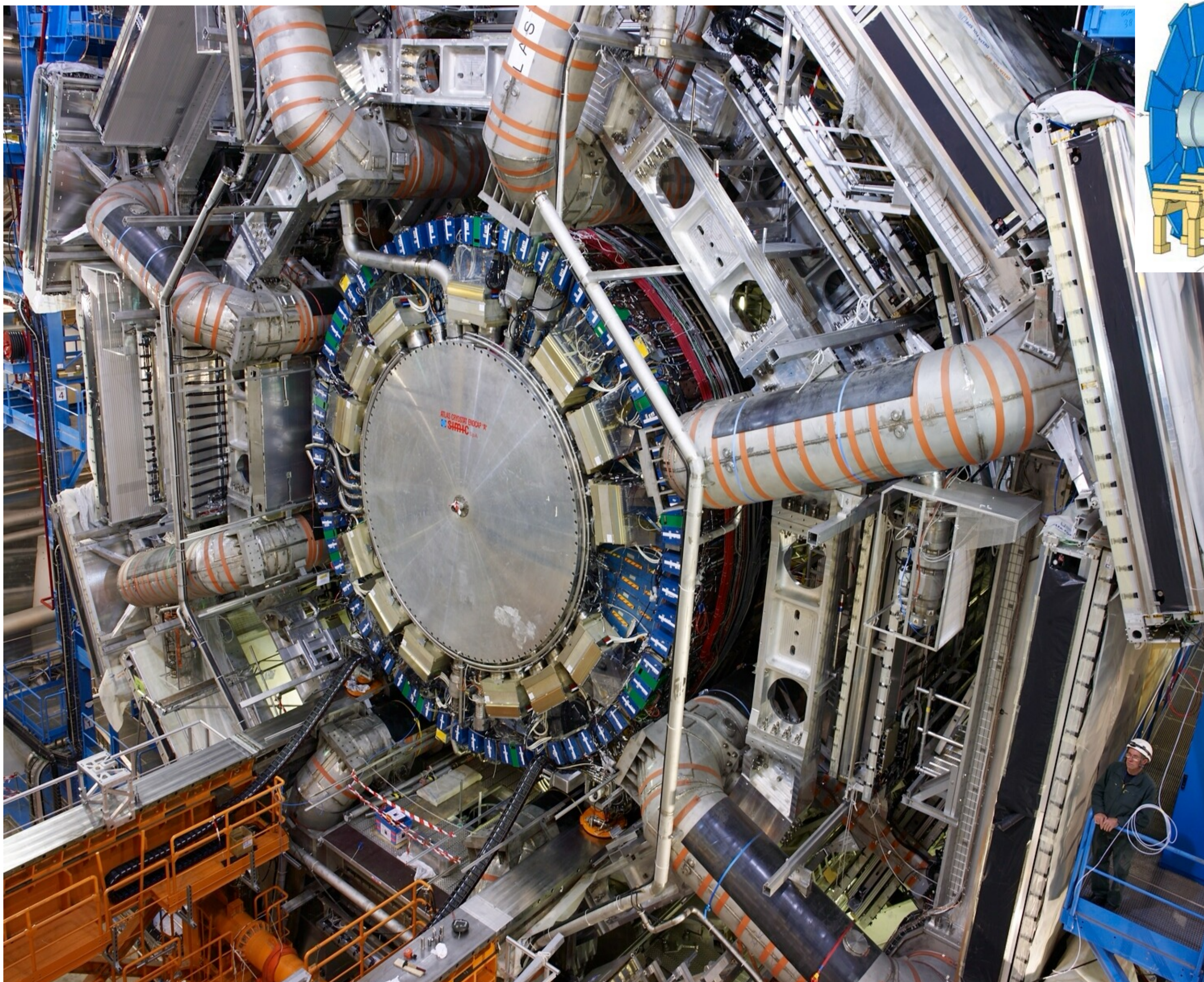


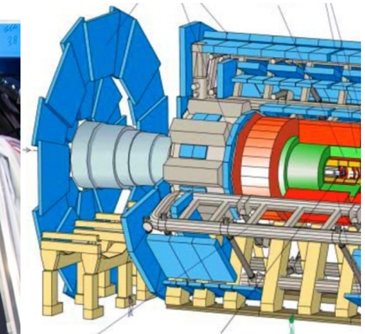
1993-2008: detector R&D and construction

15 years !

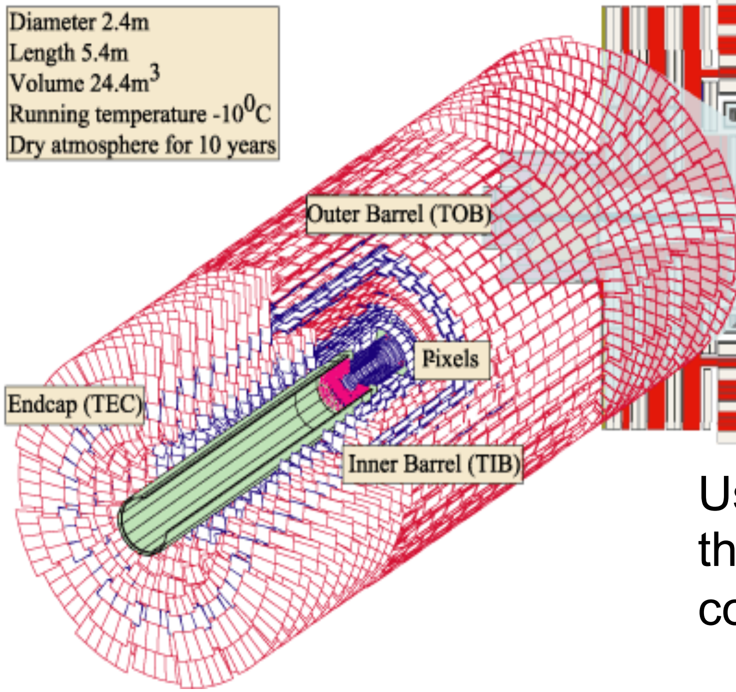
Superconductor solenoid at 3.8 Tesla

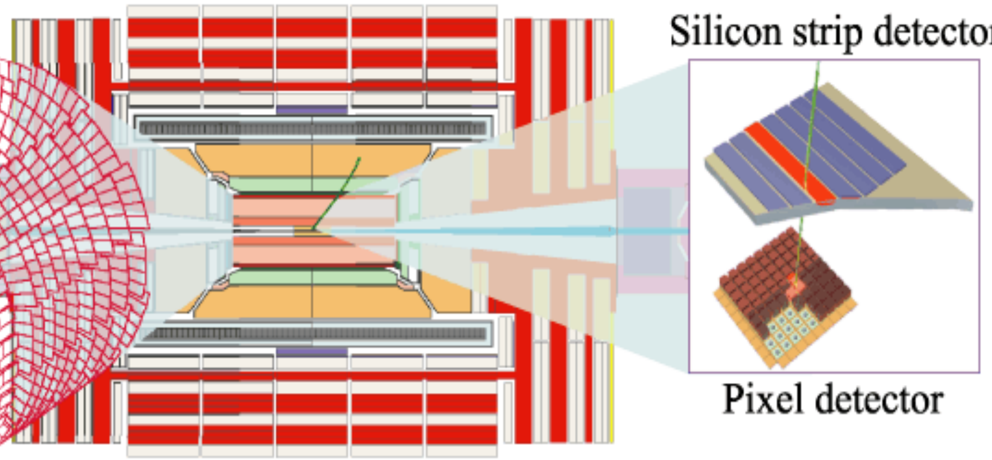
ATLAS Toroidal System





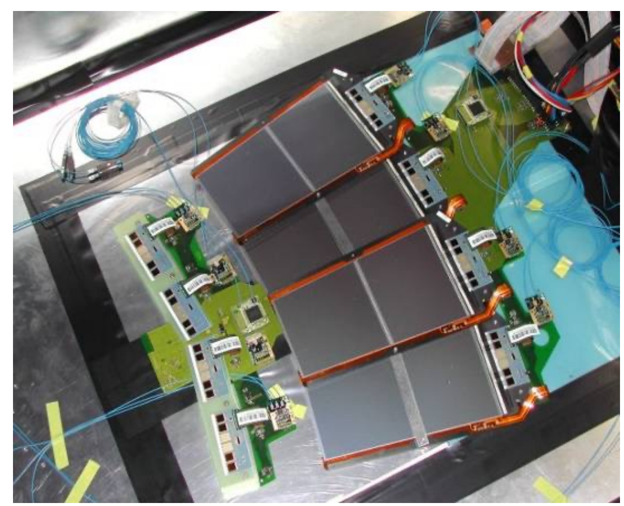
Silicon Tracker



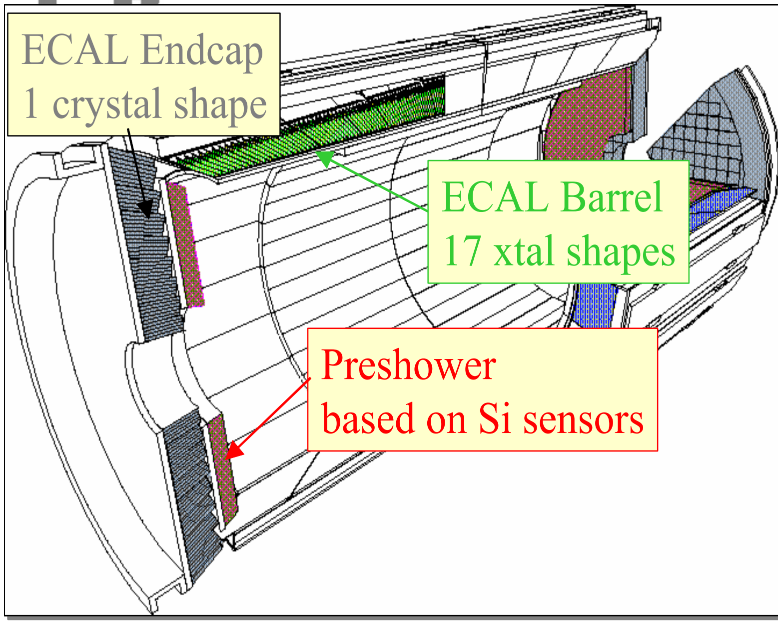


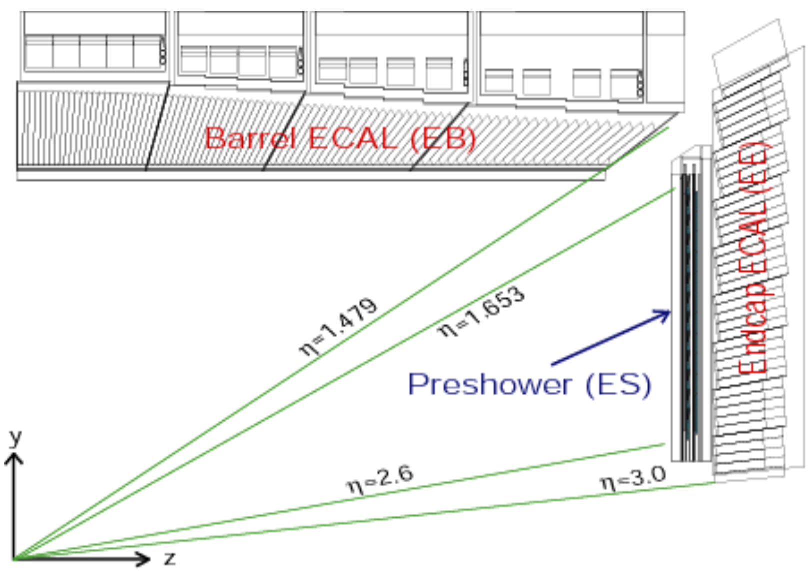
Used to reconstruct the trajectories of thousands of charge particles produced in the collisions

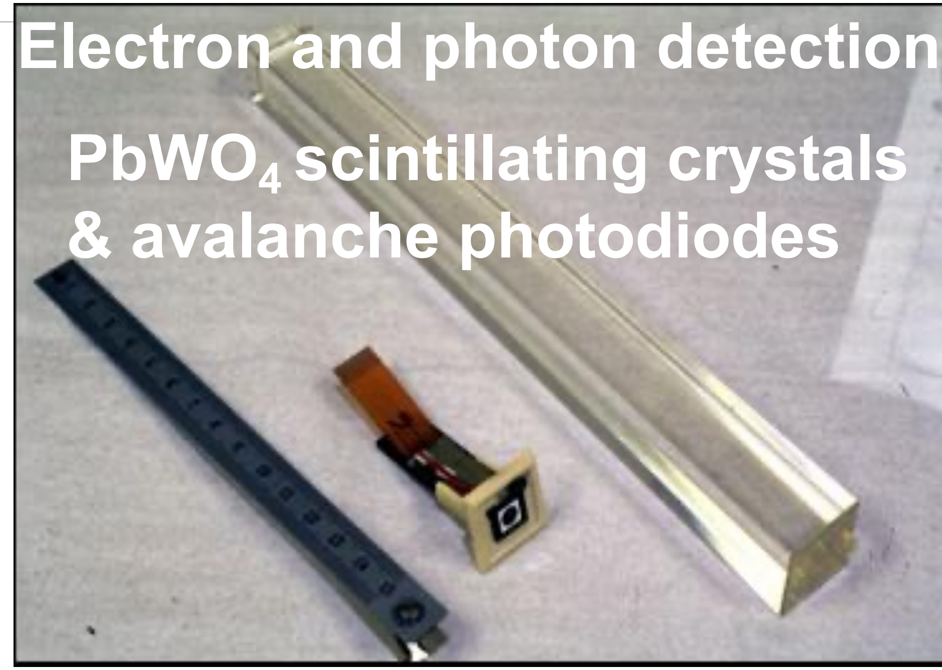
$214m^2$ silicon sensors
11.4 million silicon strips
65.9 million silicon pixels



ECAL Electromagnetic Calorimeter



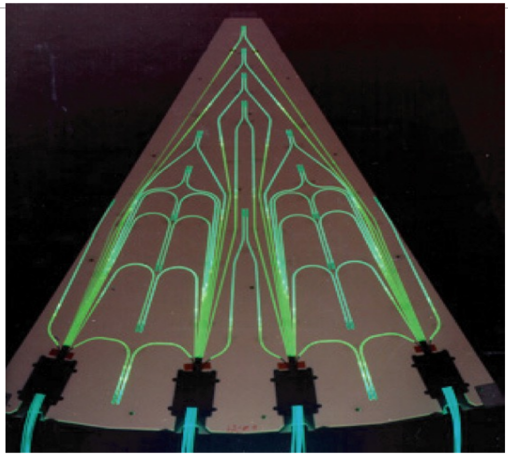




Design Goal: Measure the energies of photons from a decay of the Higgs boson **to precision of ≤ 0.5%**

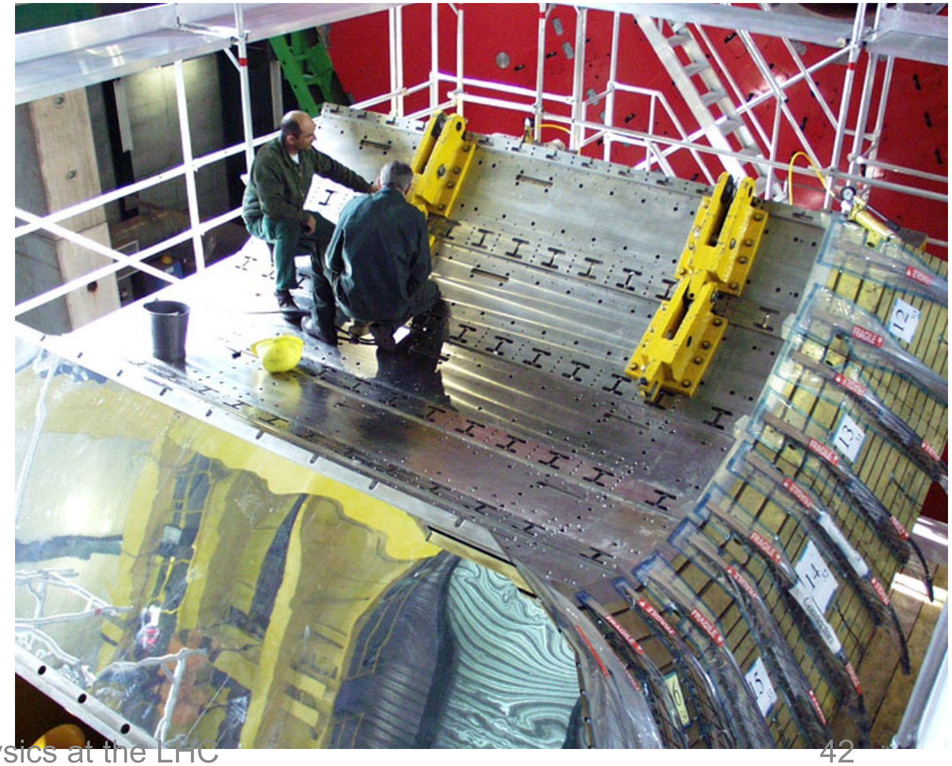
Parameter	Barrel	Endcaps
# of crystals	**61200**	**14648**
Volume	**8.14m³**	**2.7m³**
Xtal mass (t)	**67.4**	**22.0**

HCAL Hadronic Calorimeter

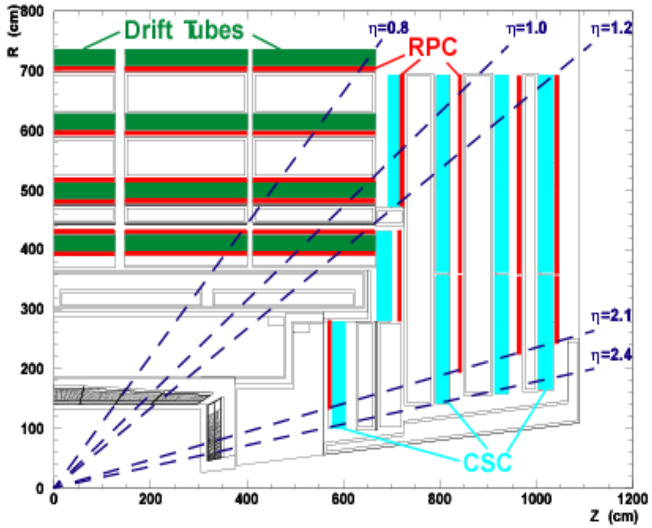


Detection of hadrons:
- protons, neutrons, peons, etc.

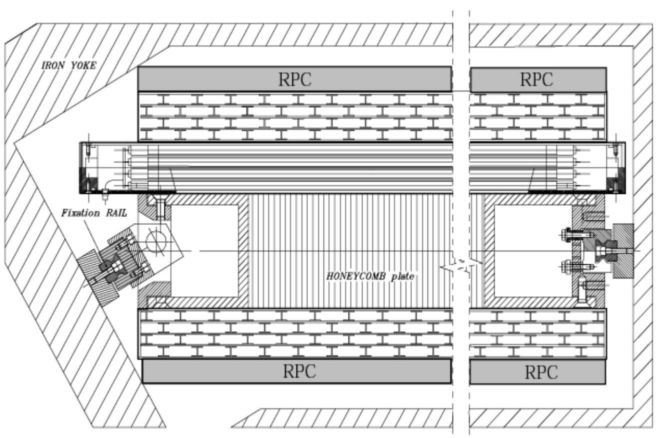
- CMS HCAL has three components:
  - Barrel HCAL (HB)
  - Endcap HCAL (HE)
  - Forward HCAL (HF)
- Plastic scintillator and brass
- Quartz fibers and steel



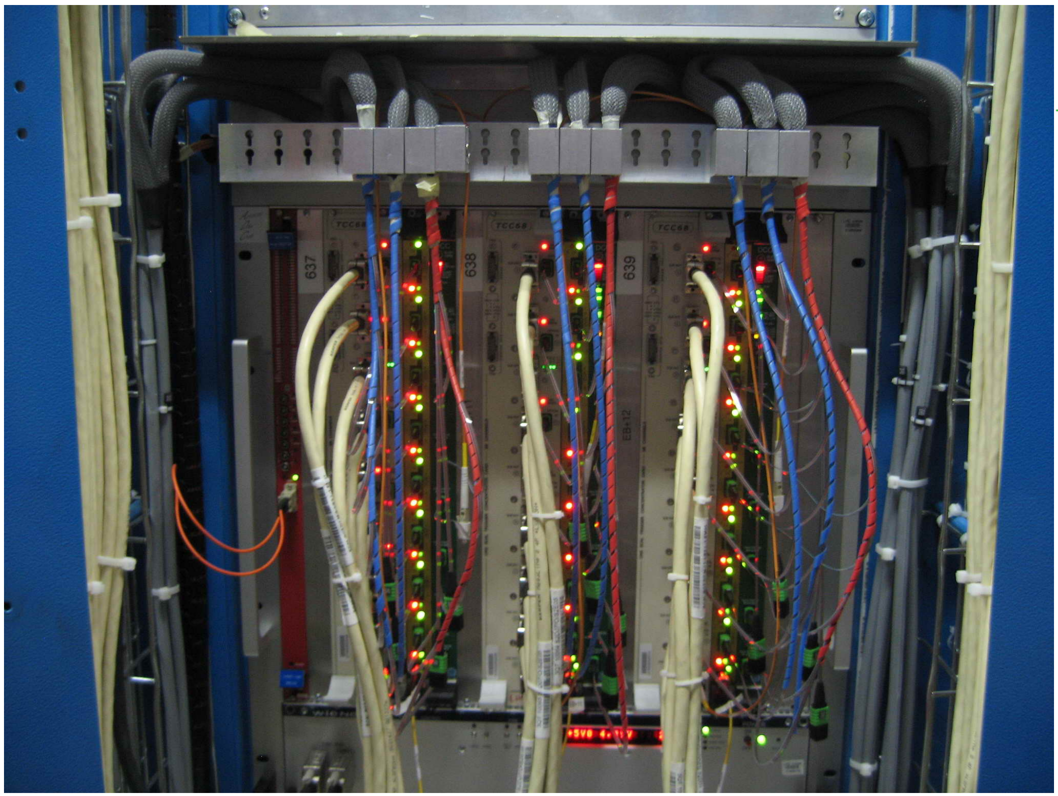
Muon detectors



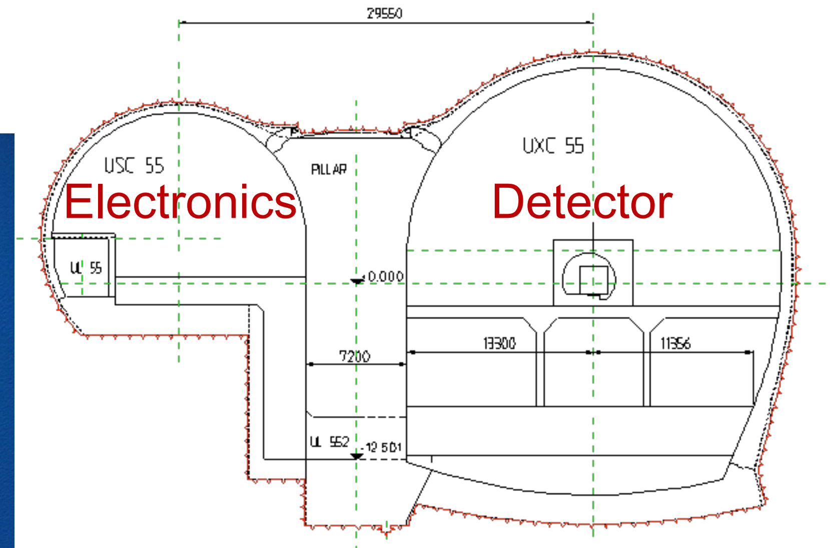
Drift Tubes (DT)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

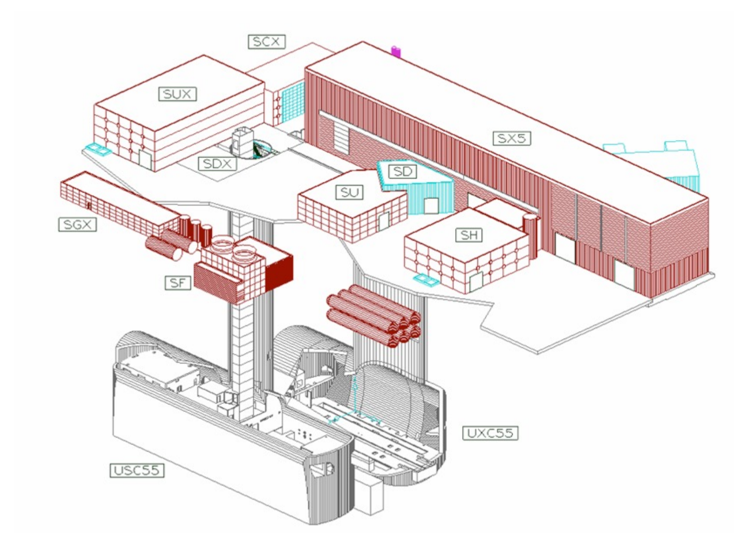


Trigger and readout electronics



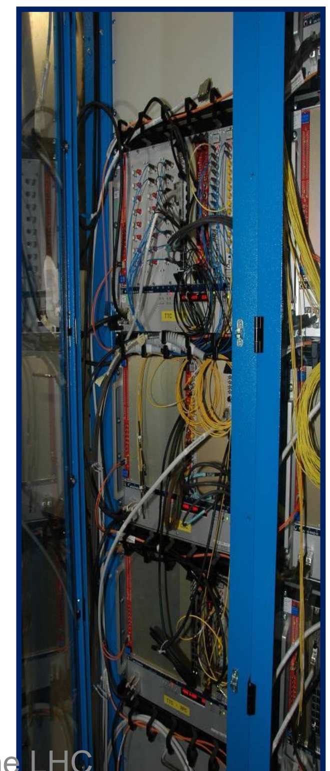
Underground caverns



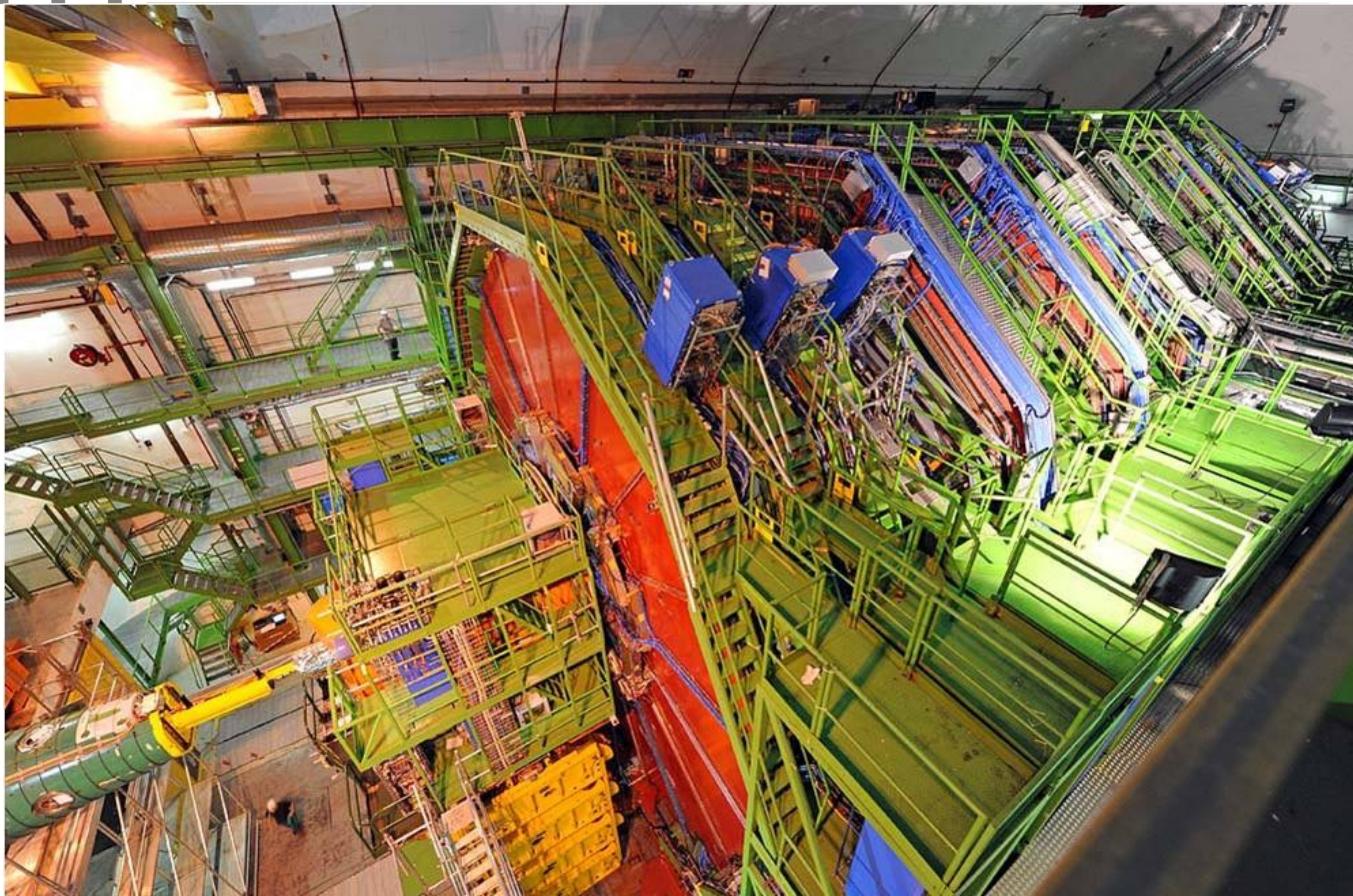


Electronics systems

Electronics systems in the Service Cavern.
About 150 racks occupy two floors.
Most electronics was designed and built specifically for the experiment

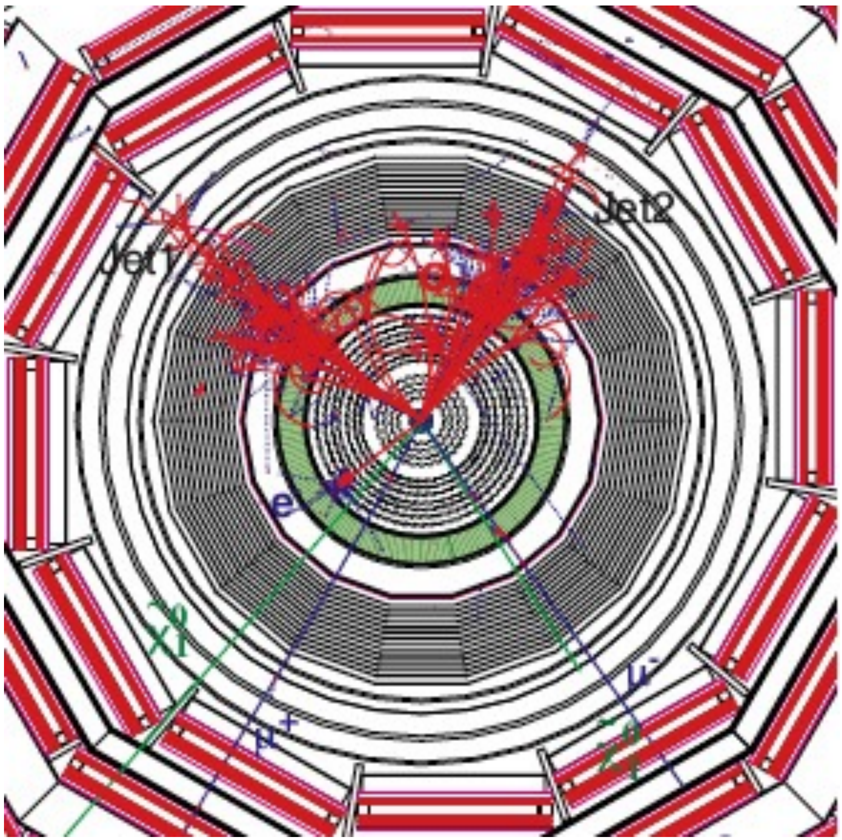


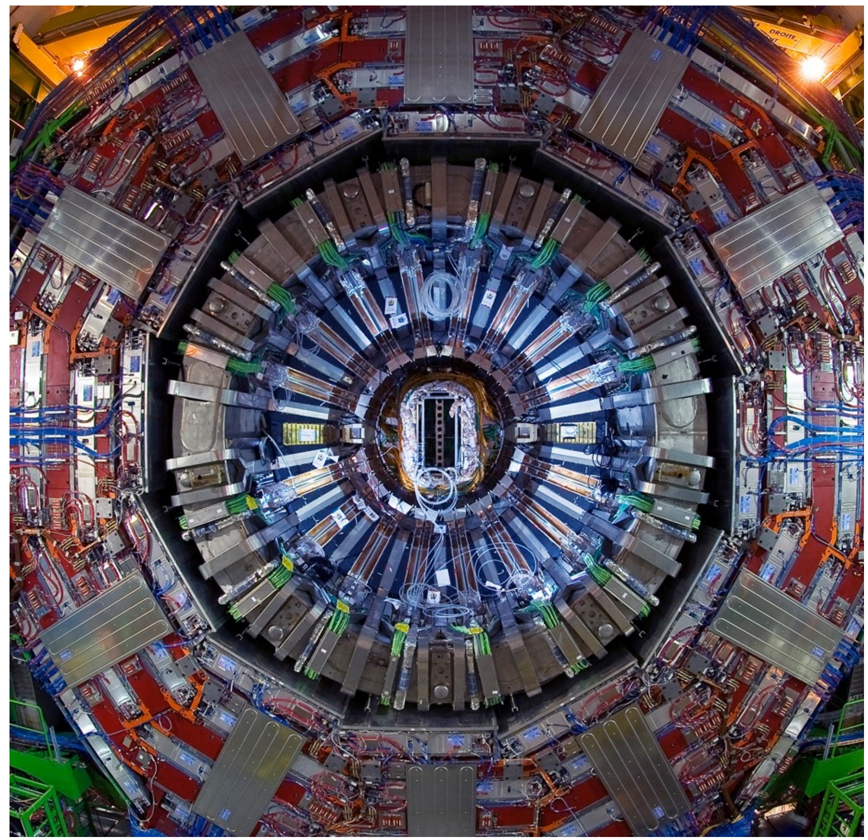
Sep 2008: CMS detector ready for beams



Detector simulation

Simulation of proton-proton collision making two dark matter particles





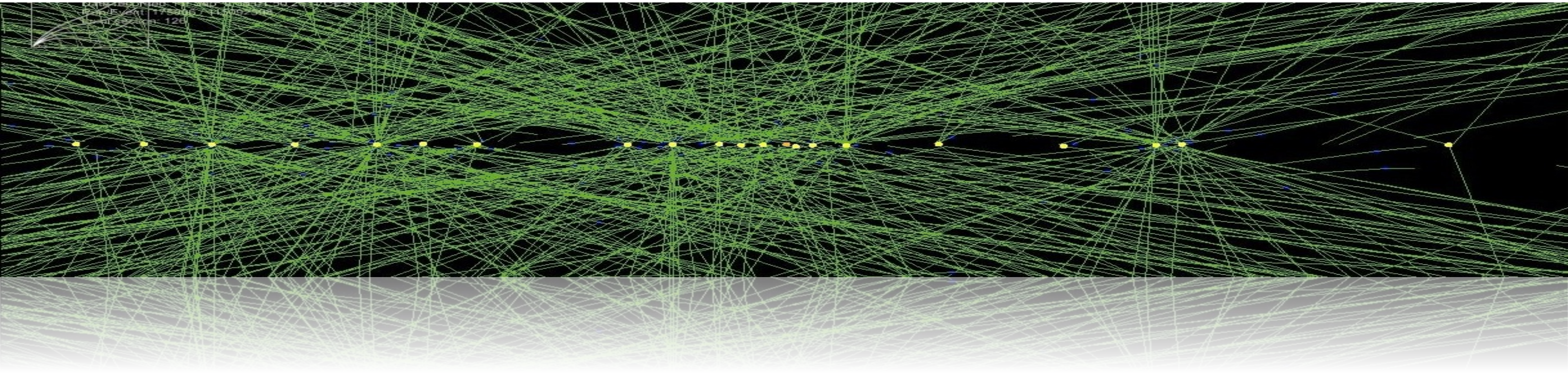
The LHC Computing Grid

The Grid unites computing resources of particle physics institutions around the world

The **World Wide Web** (invented at CERN) provides seamless access to information that is stored in many millions of different geographical locations

The **Grid** is an infrastructure that provides seamless access to computing power and data storage capacity distributed over the globe

Experimental challenges



High collision rate

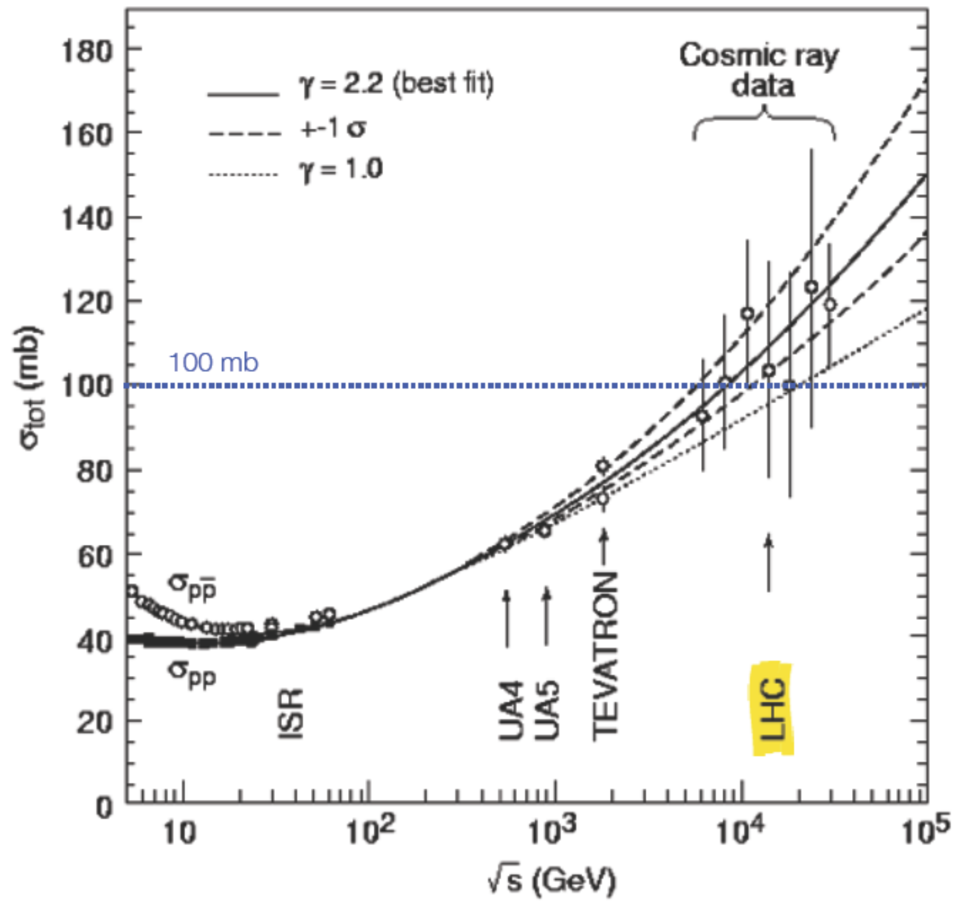
Luminosity:

$L = 10^{34}\ cm^{-2}s^{-1}$
$= 10^{7}$ Hz/mb

Cross section:

$\sigma \approx 100$ mb

➡ $N = L\sigma \approx 1$ GHz



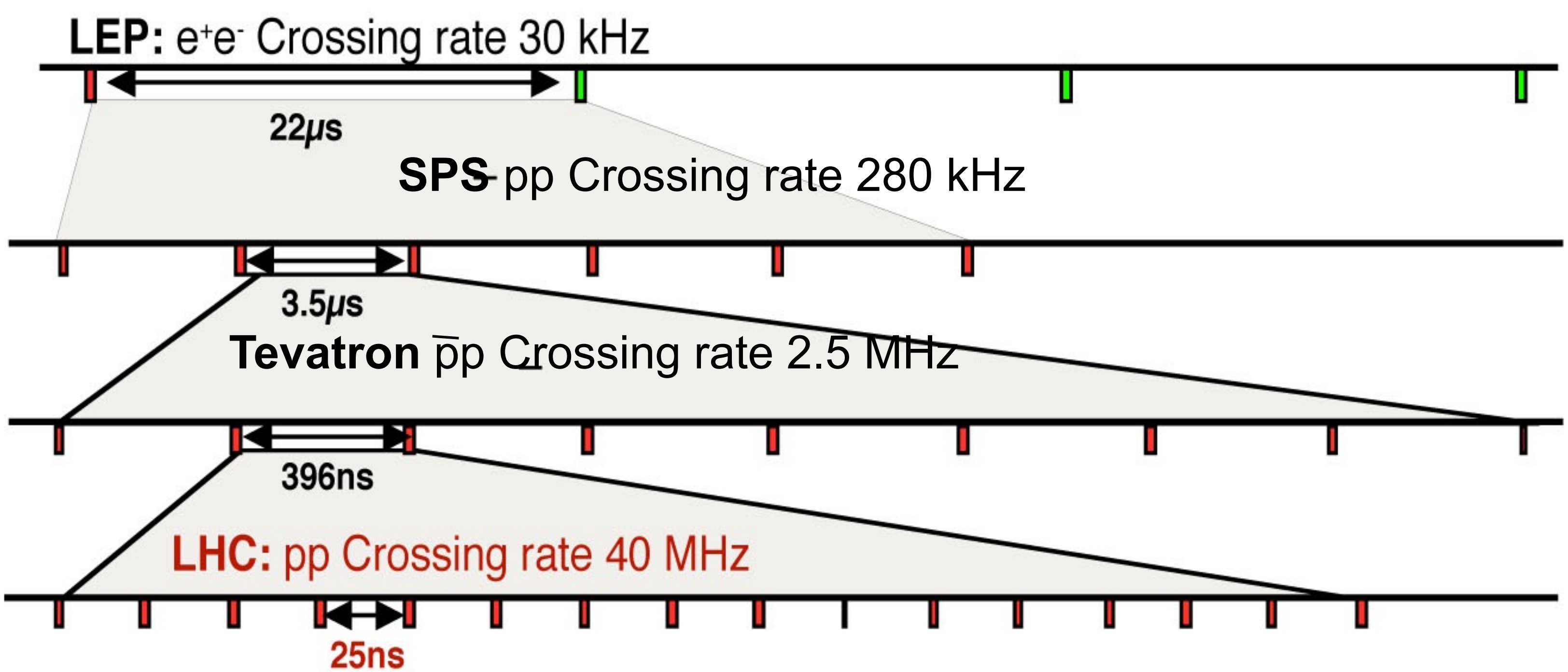
However:

Bunch crossing rate: 40 MHz
∴ Interactions/crossing ~ 25

This is a real challenge !

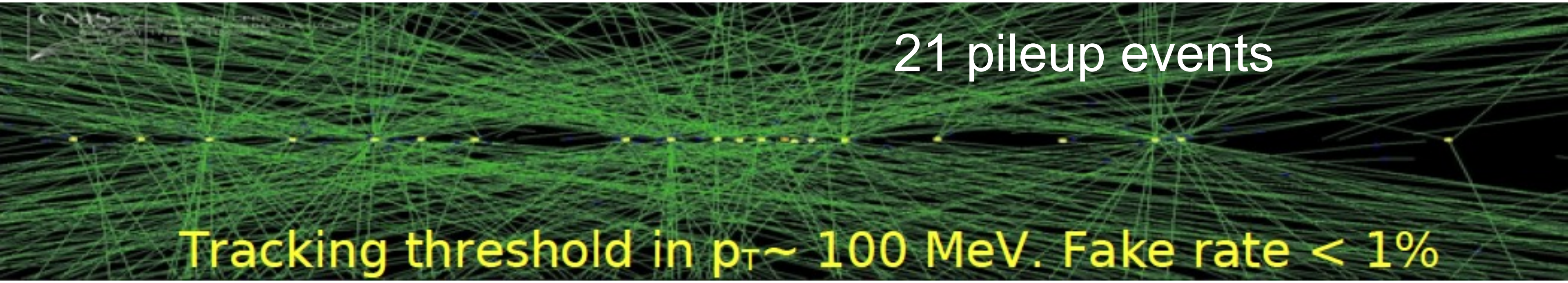
Bunch crossing frequency

- LHC has 3564 bunches (2835 filled with protons)
- Crossing rate is 40 MHz
- Distance between bunches: 27km / 3600 = 7.5m
- Distance between bunches in time: 7.5m / c = 25ns
- Proton-proton collision per bunch crossing: ~ 25

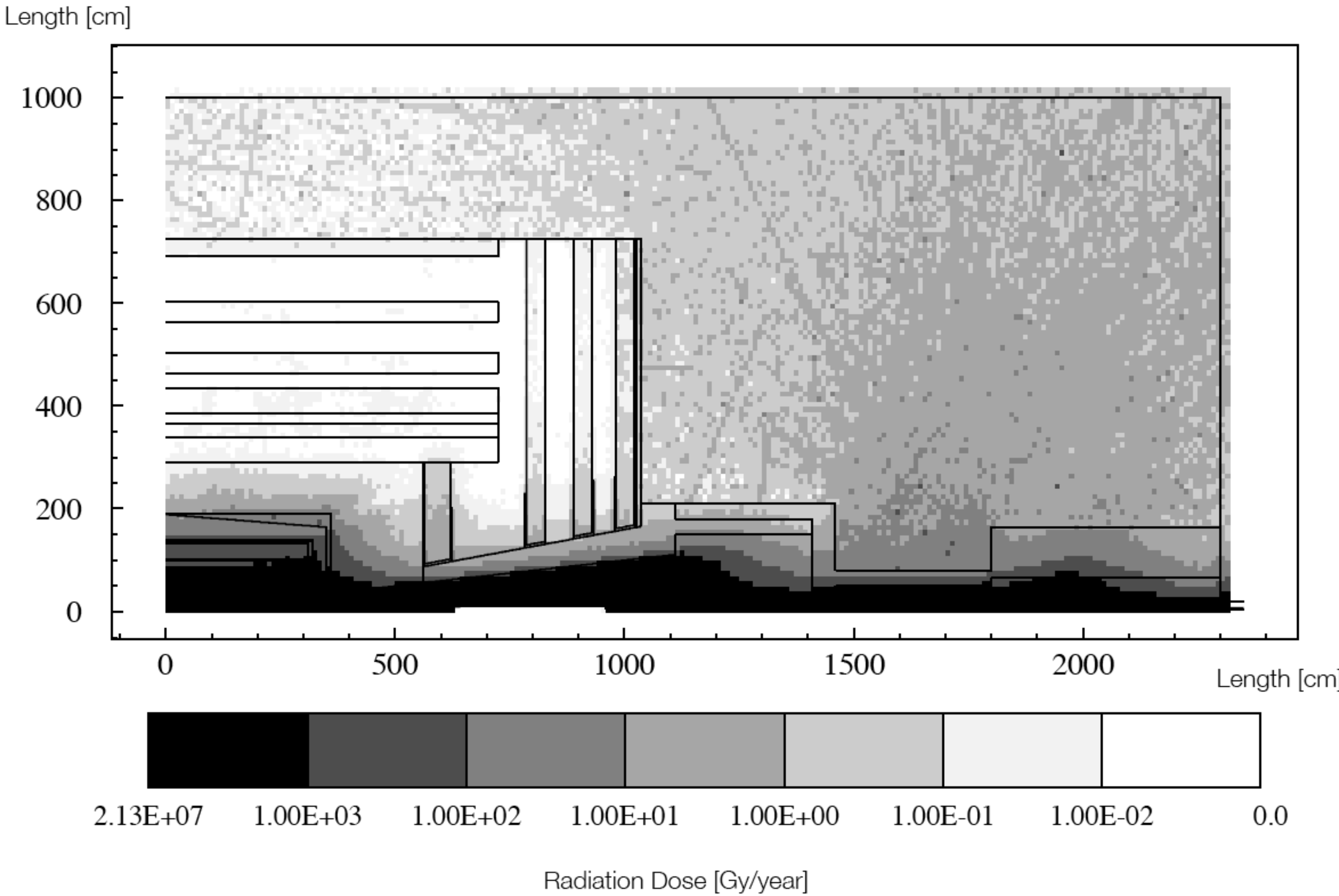


Event pileup

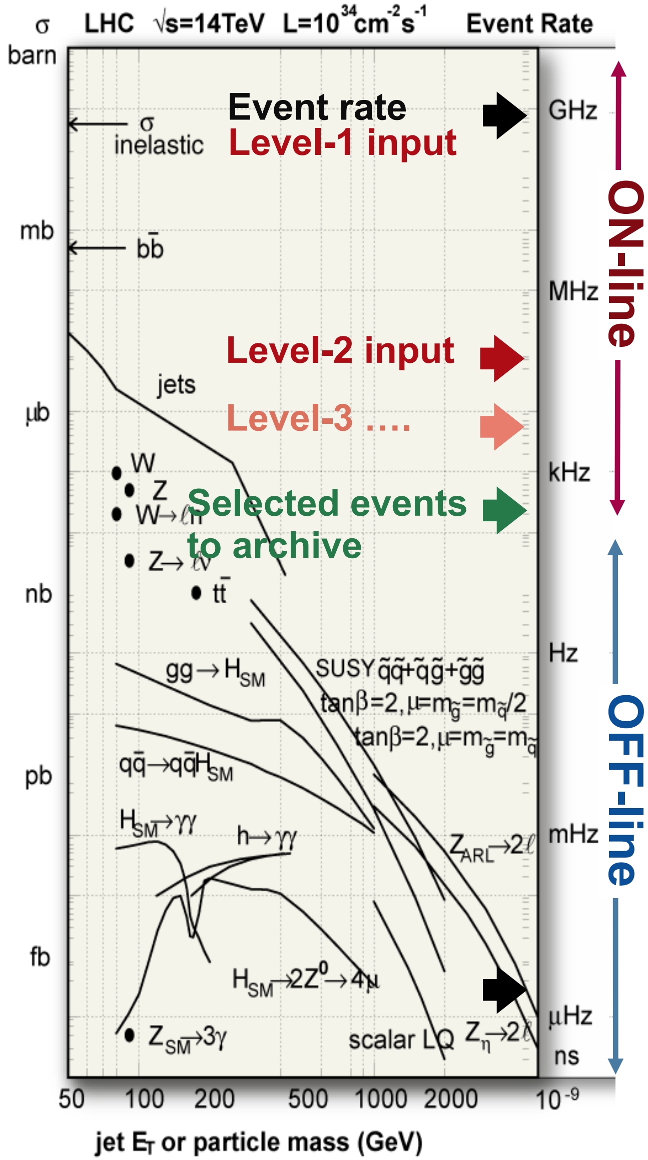
- Proton bunches have a cigar shape, about 5 cm long and 20 microns diameter
- Each bunch has 1.5 10^{11} protons
- At each crossing of bunches, about 25 collision occur
- The particles produced (30x25 = 750 charged particles) are “seen” by the detector as a single image (event)

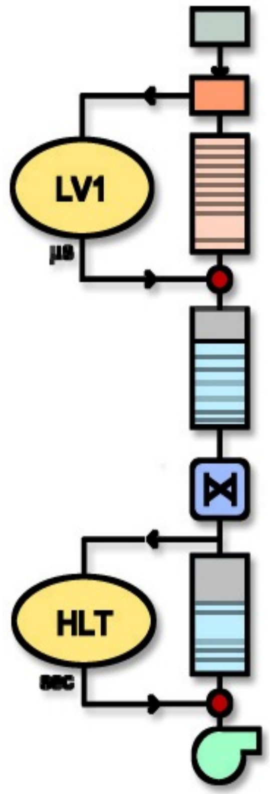


High radiation levels



Two-level trigger





Trigger system decide if the event is interesting to be recorded

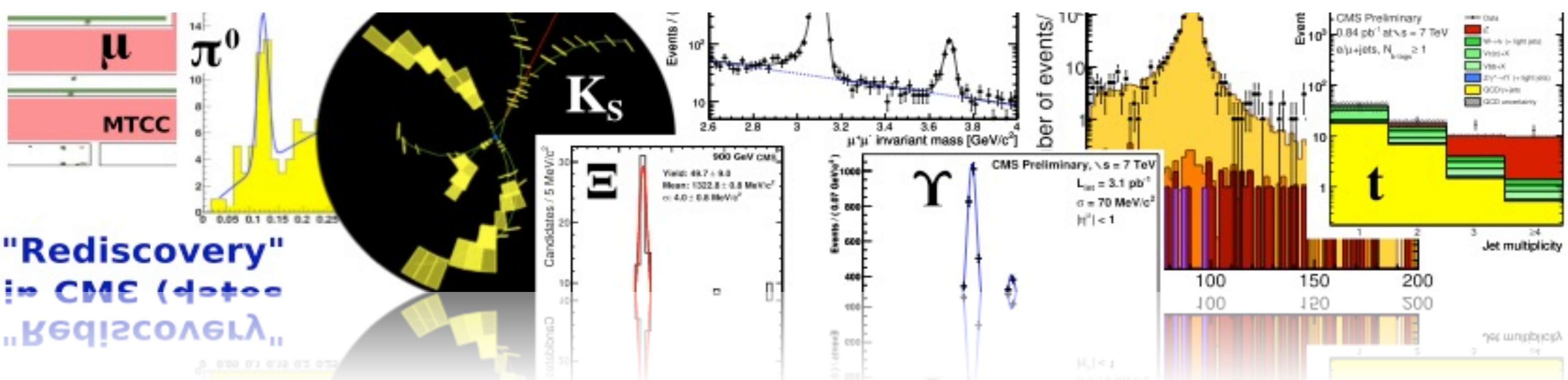
Two-step process:
- Level 1: dedicated hardware processors

- High level: computer farm

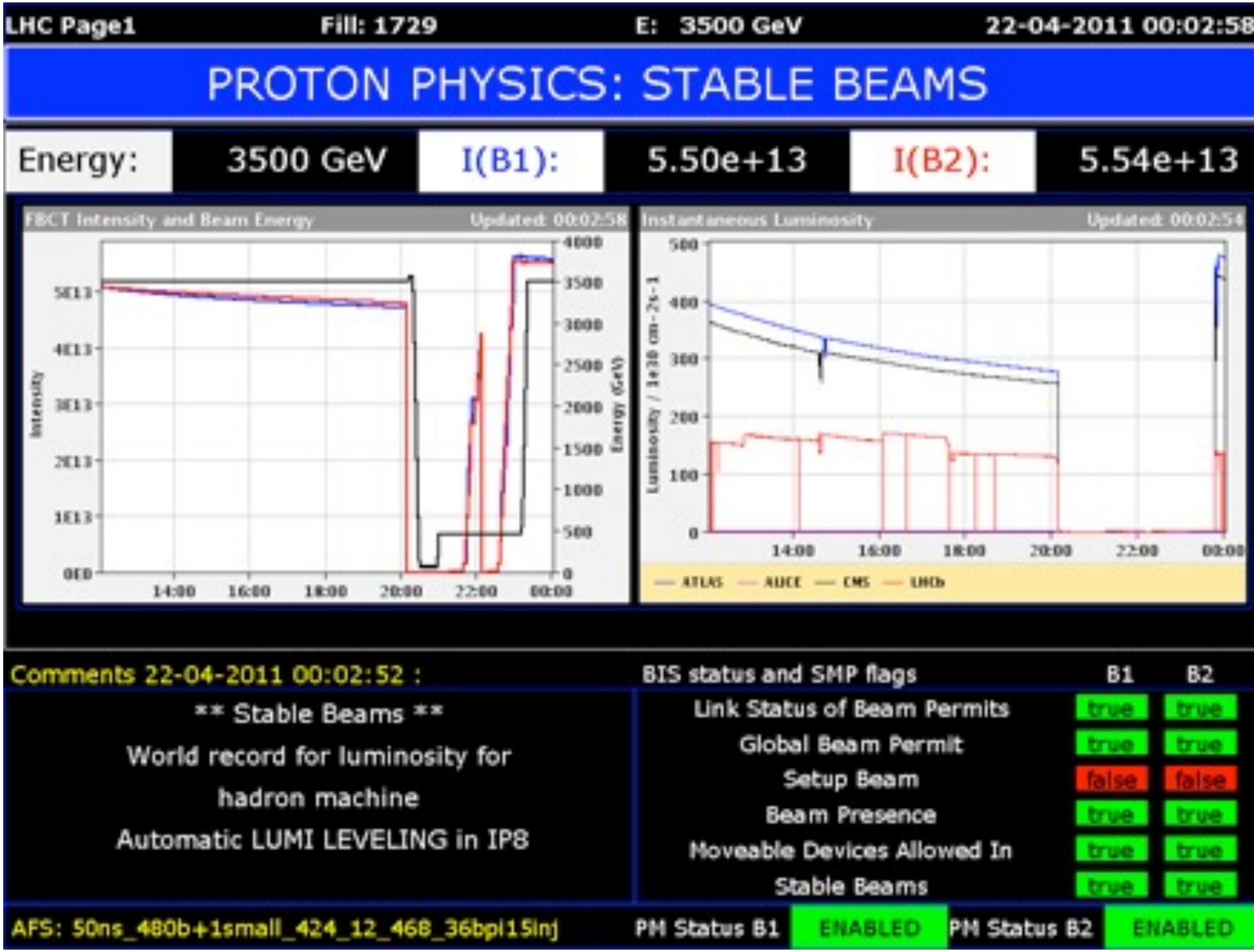
Triggers and event selection

- Select processes that produce particles with high transverse energy
- Examples at $5.x10^{33}$ $cm^{-2}s^{-1}$
  - Single lepton and photon triggers (P_T ~ 30 GeV)
  - Multiple lepton and photon triggers (P_T ~ 15 GeV)
  - Missing transverse energy (P_T ~ 50-100 GeV)
  - Multiple jet triggers (P_T ~ 50-100 GeV)
- About 100 trigger conditions in L1 trigger table
- About 400 trigger conditions in HLT trigger table

Detector commissioning



LHC Page 1: stable beams



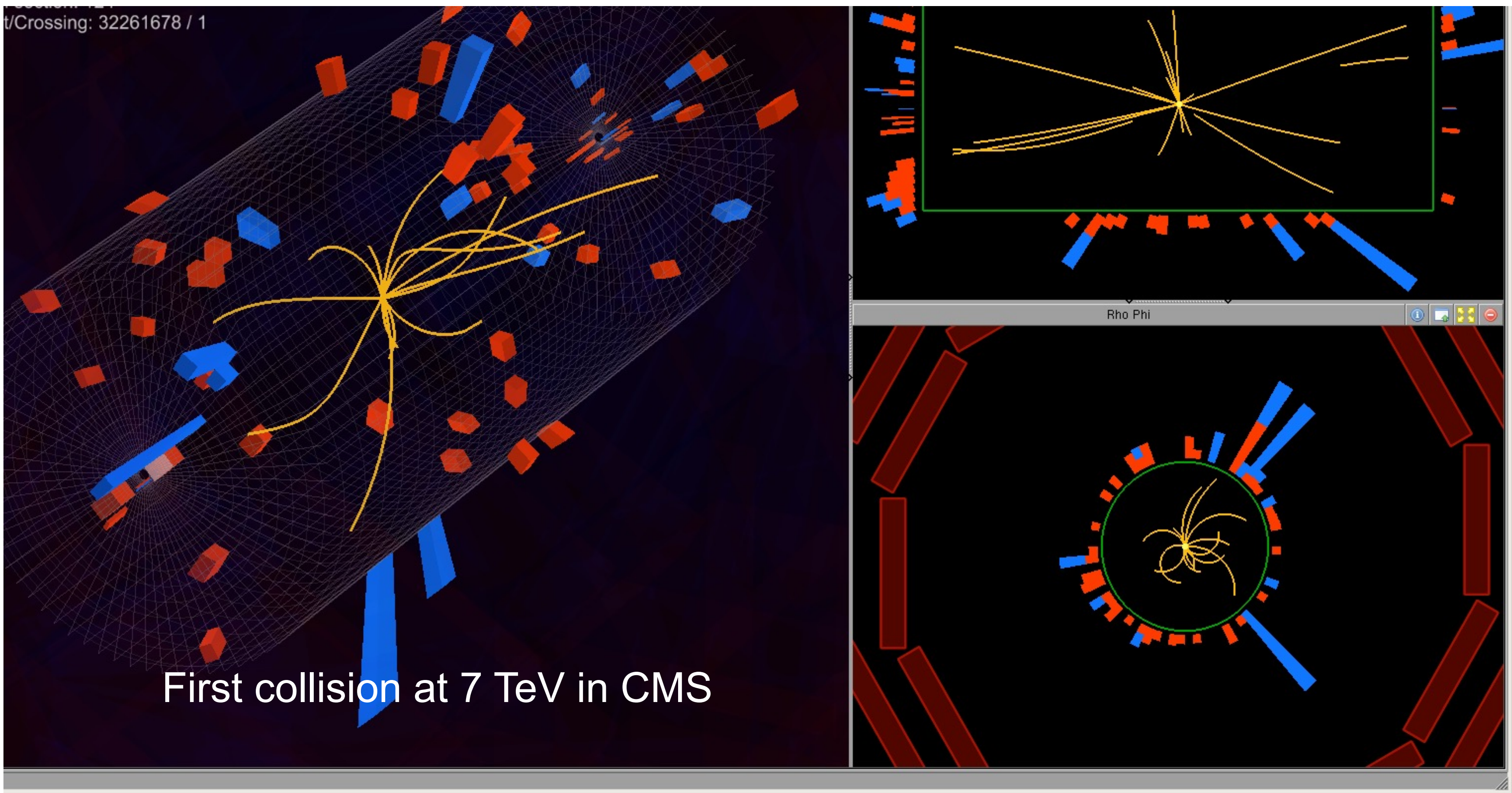
March 30, 2010: CMS Page 1

2009: First p-p collisions at LHC

November 23, 2009
First collisions at 900 GeV

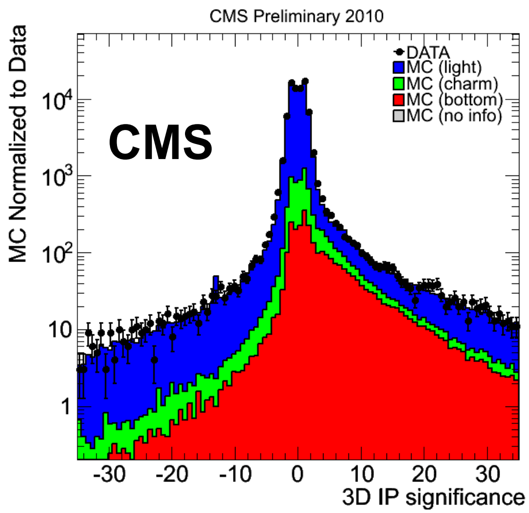
December 14, 2009
First collisions at 2.36 TeV

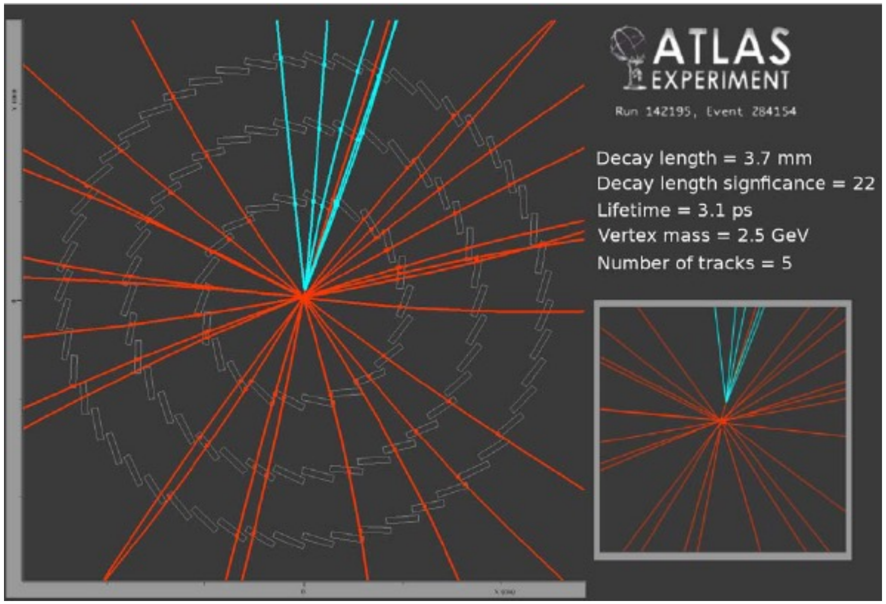
March 30, 2010
First collisions at 7 TeV

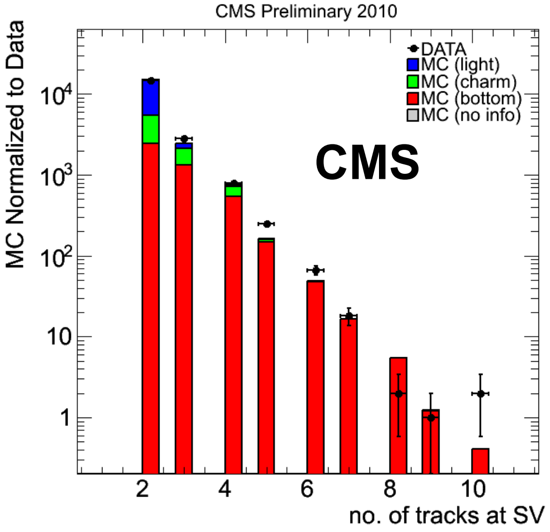


Tracking: secondary vertices

Basic variables relevant for B-tagging are well described by the simulation



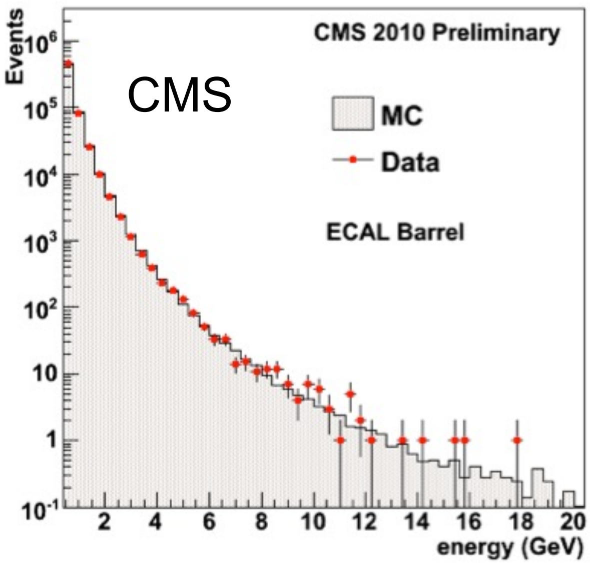


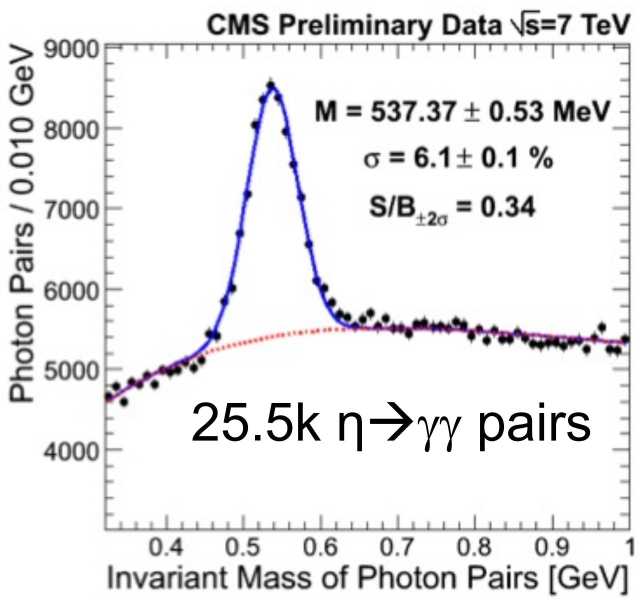


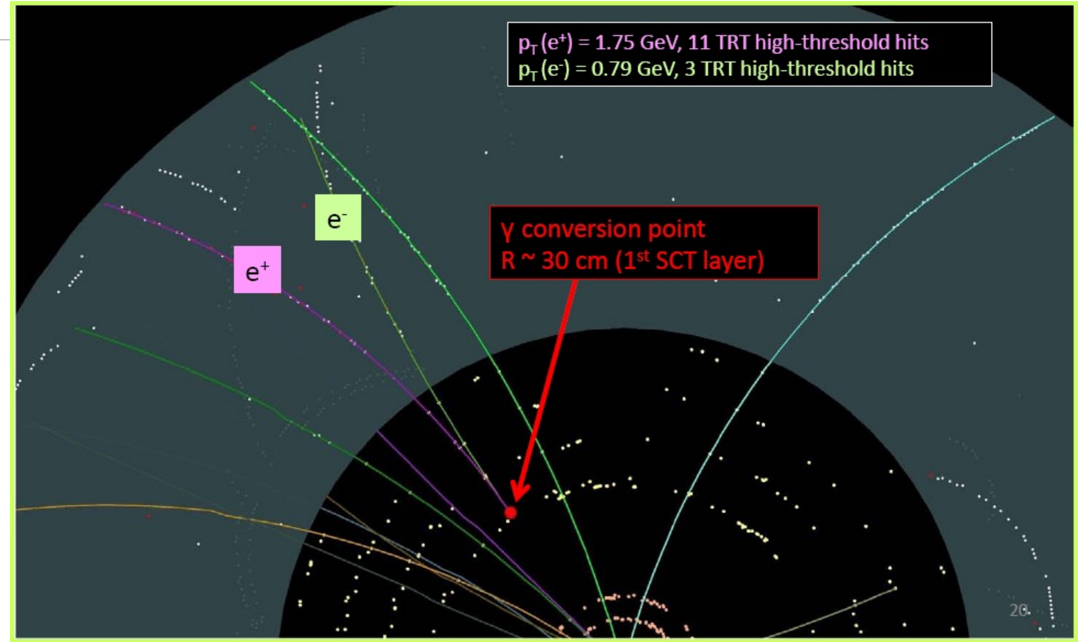
Secondary vertices compatible with heavy flavor production

Photons and electrons

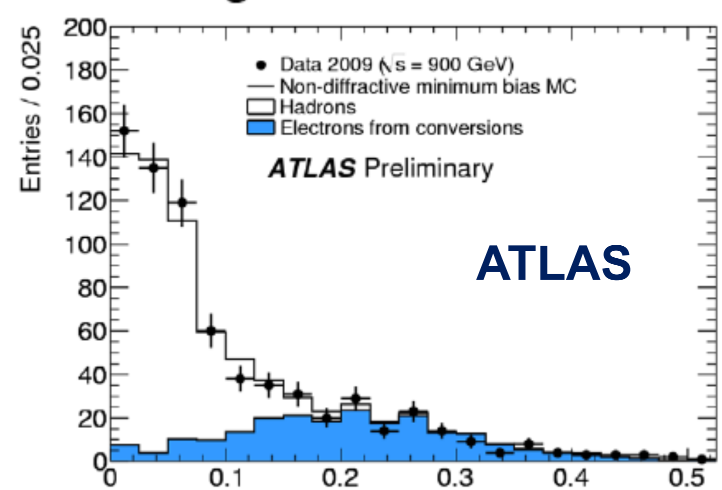
EM cluster energy







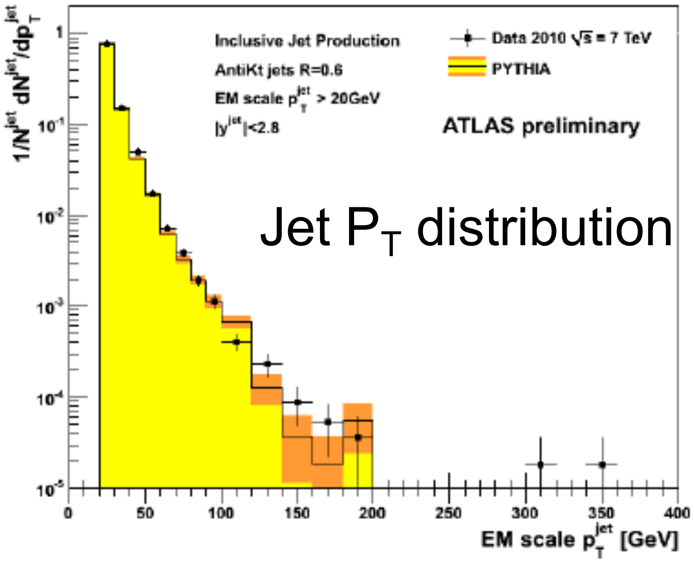
TRT high-threshold hit fraction



Jets and missing energy

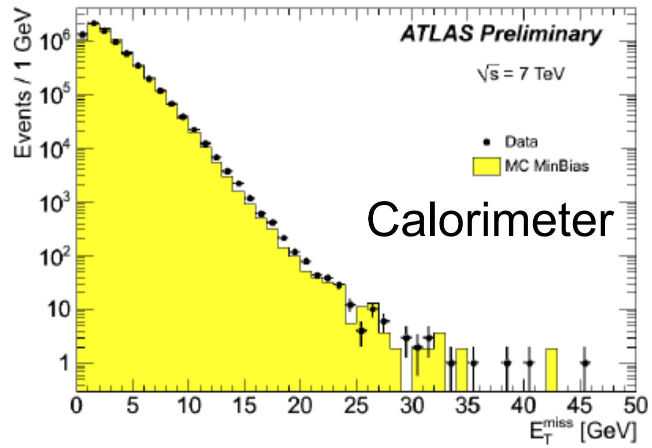
ATLAS

Jet P_T distribution



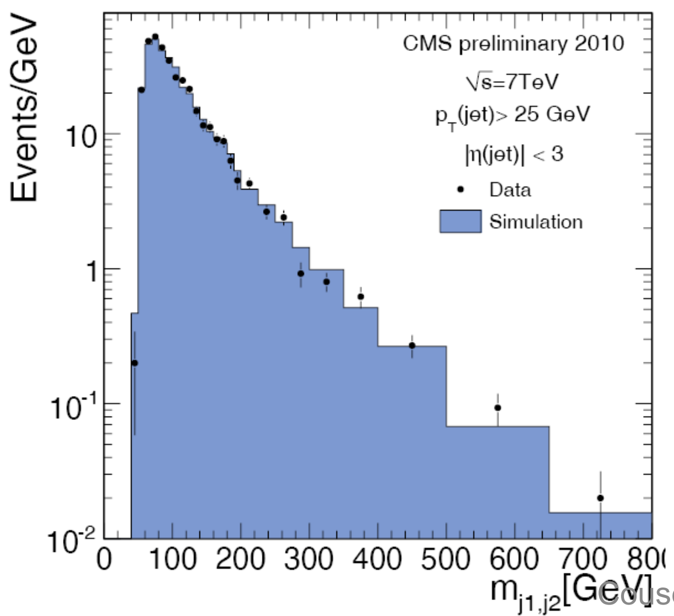
Missing Transverse Energy

Calorimeter

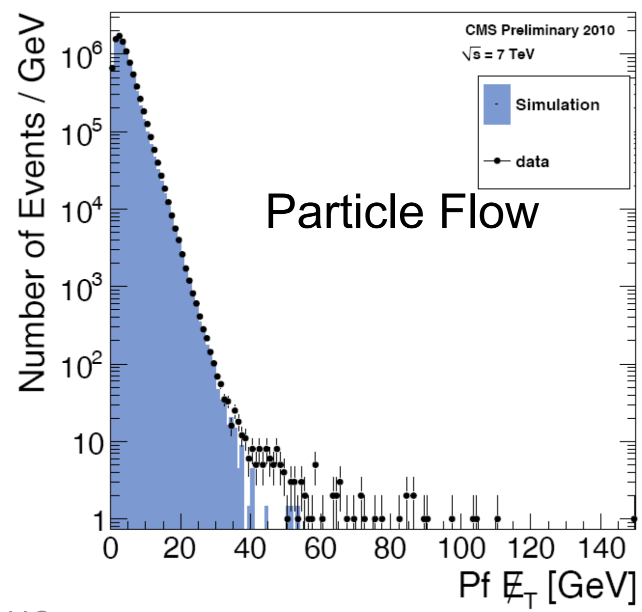


CMS

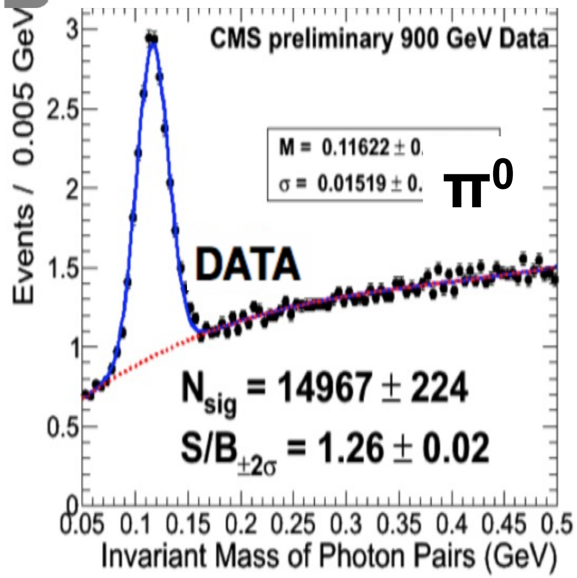
Di-jet mass

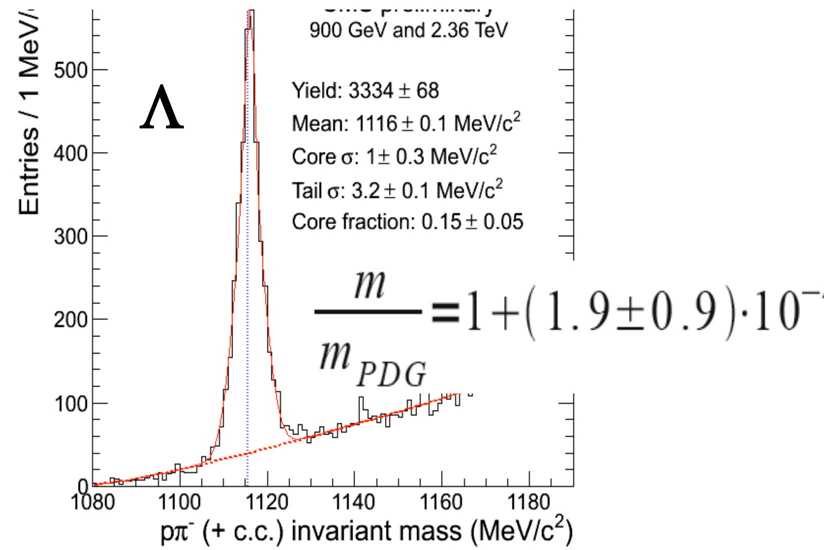


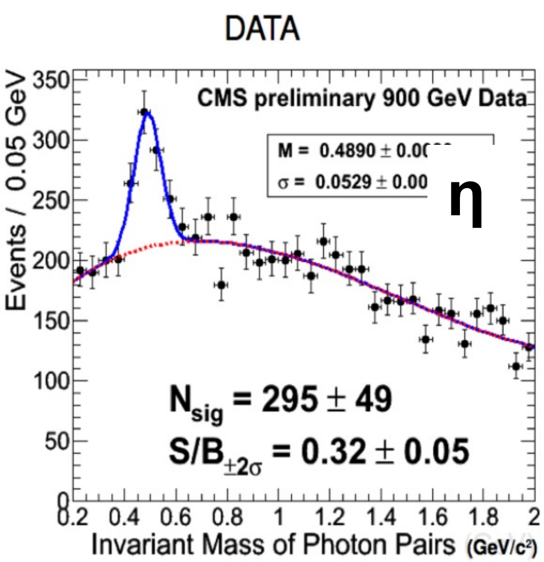
Particle Flow

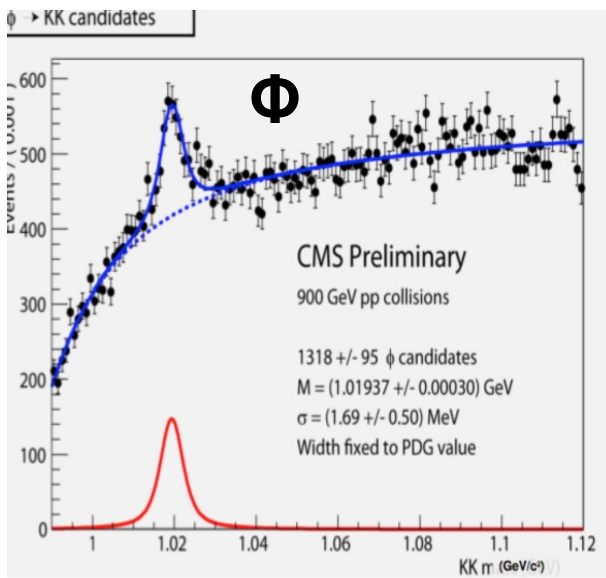


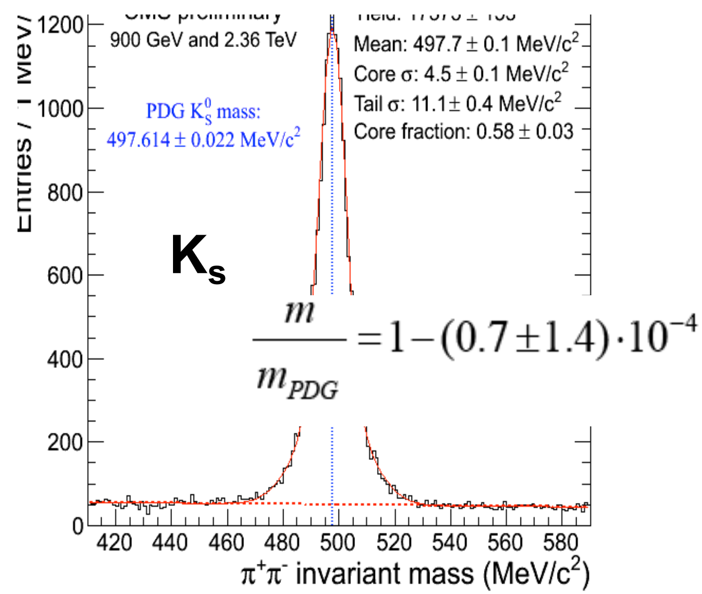
Rediscovery of resonances



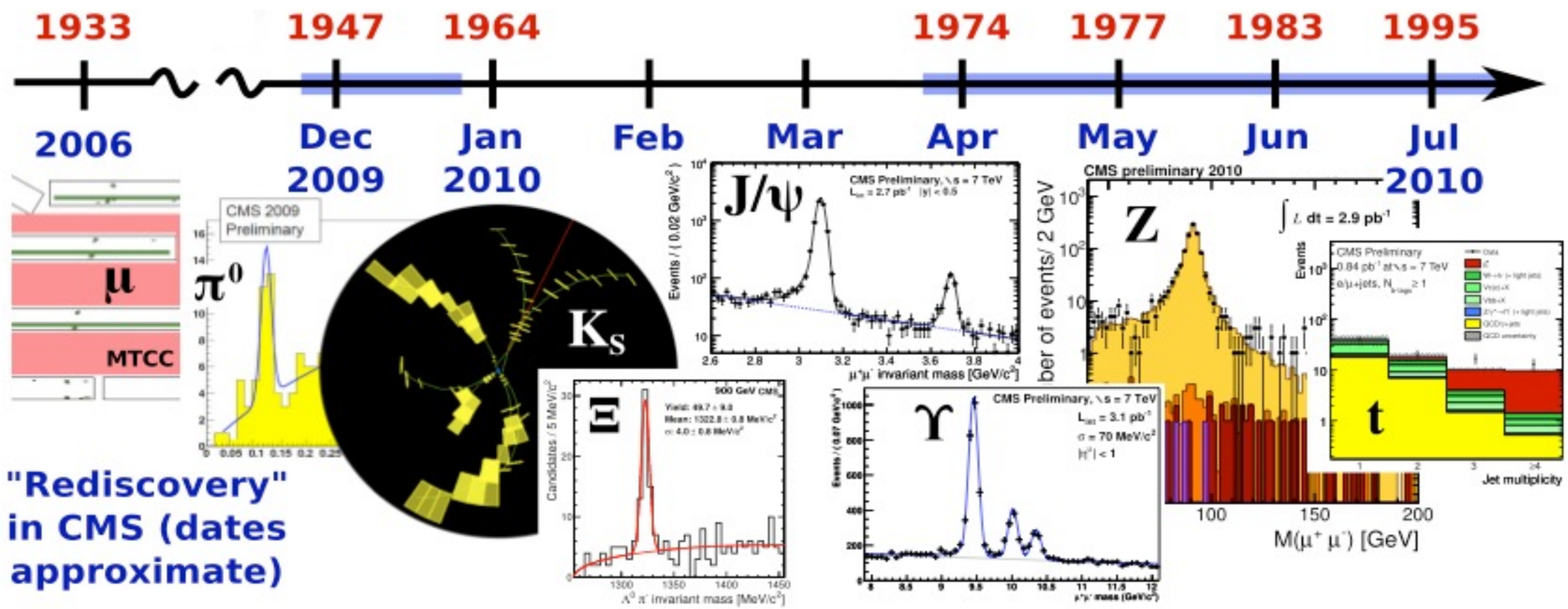








Rediscovery of the Standard Model at LHC



End of Lecture 1