

Course on Physics at the LHC

Lecture 1

Experimental program at the LHC

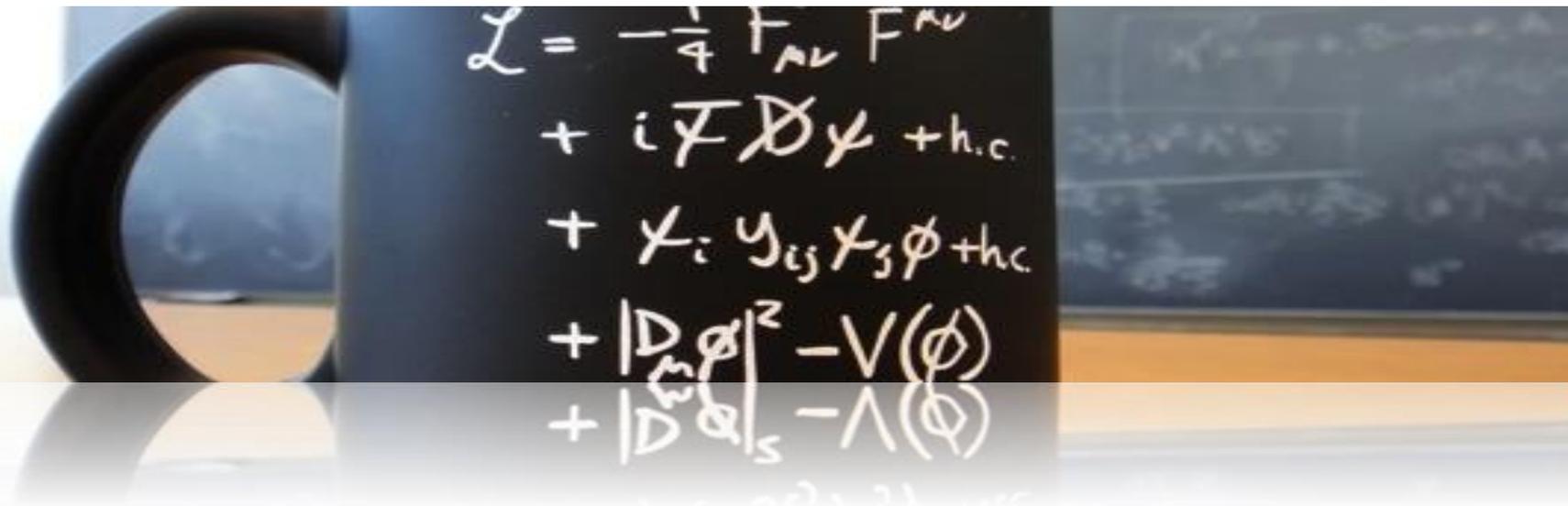
Joao Varela



LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

Lisbon, PORTUGAL
FEBRUARY – MAY 2026

The LHC physics case



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

Edward Witten

Aims to answer the two following questions:

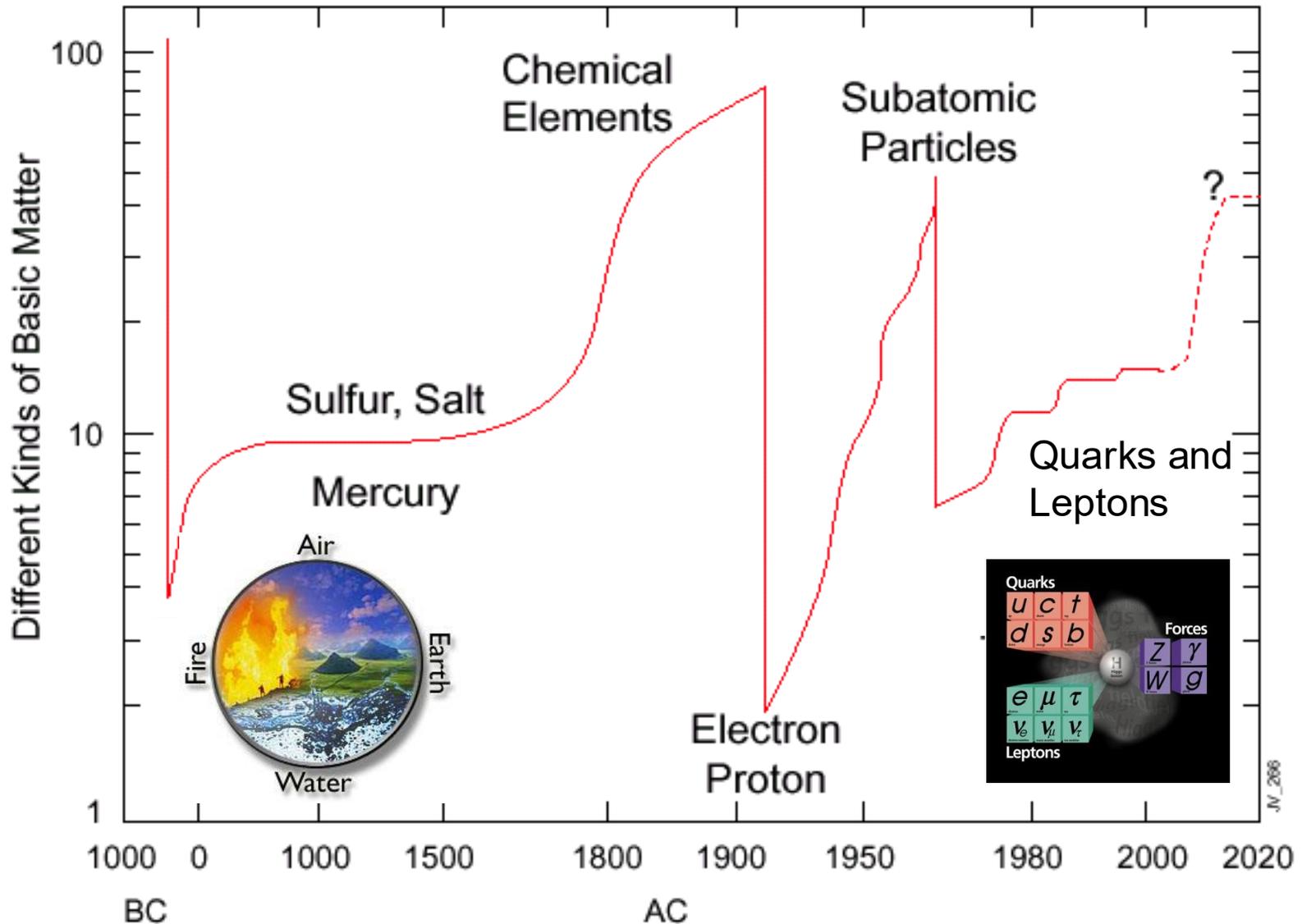
What are the elementary constituents of matter ?

What are the forces that determine their behavior?

Experimentally

Get particles to interact and study what happens

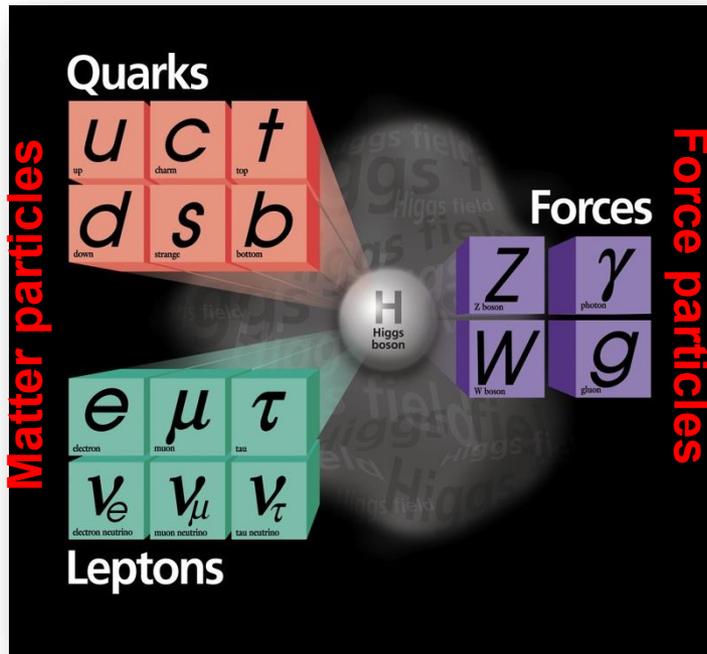
Constituents of matter along History



The Standard Model

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

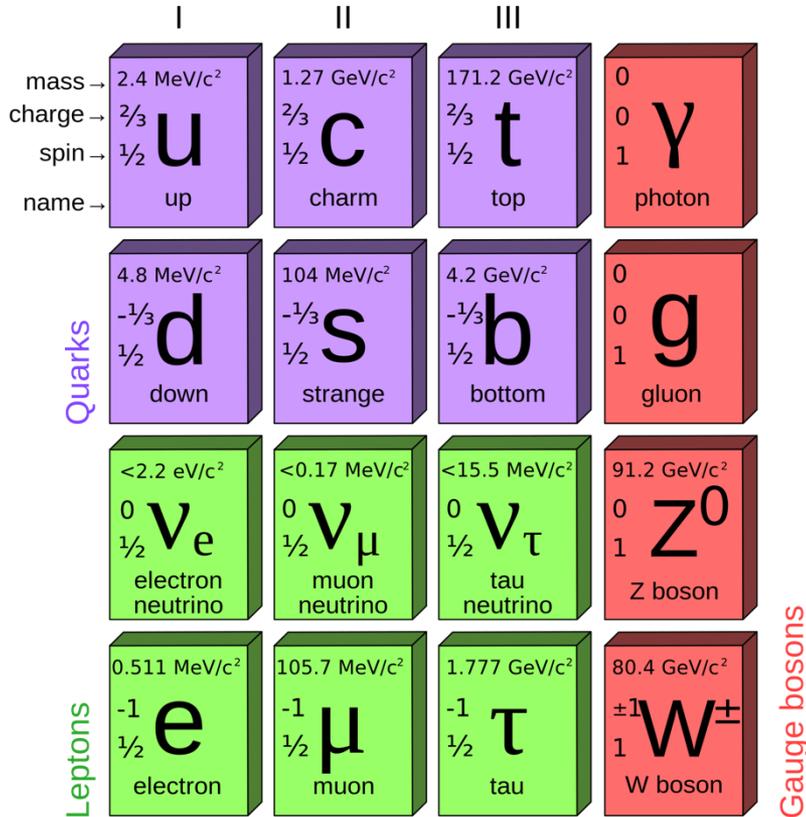
- **The Standard Model of Particle Physics**
 - With a new “Periodic Table” of fundamental elements



One of the greatest achievements of 20th Century Science

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

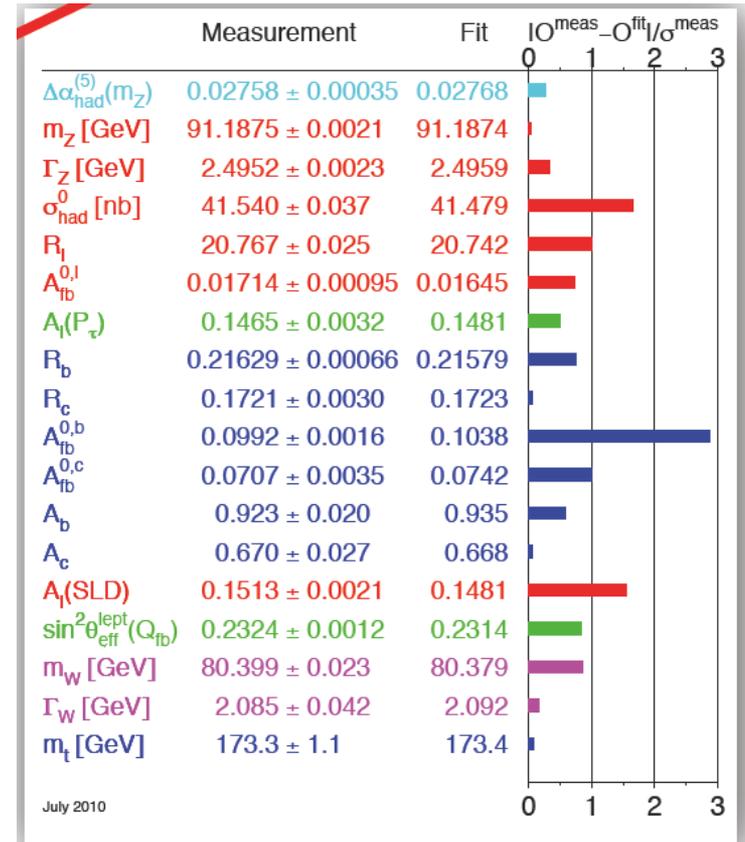
SM confirmed by data



Gauge bosons

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c.$$

STANDARD MODEL OF ELEMENTARY PARTICLES



Confirmed at sub 1% level!

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

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

- Photon do not have mass
- W, Z do have a mass $\sim 80\text{-}90$ GeV

Higgs mechanism:

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

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?

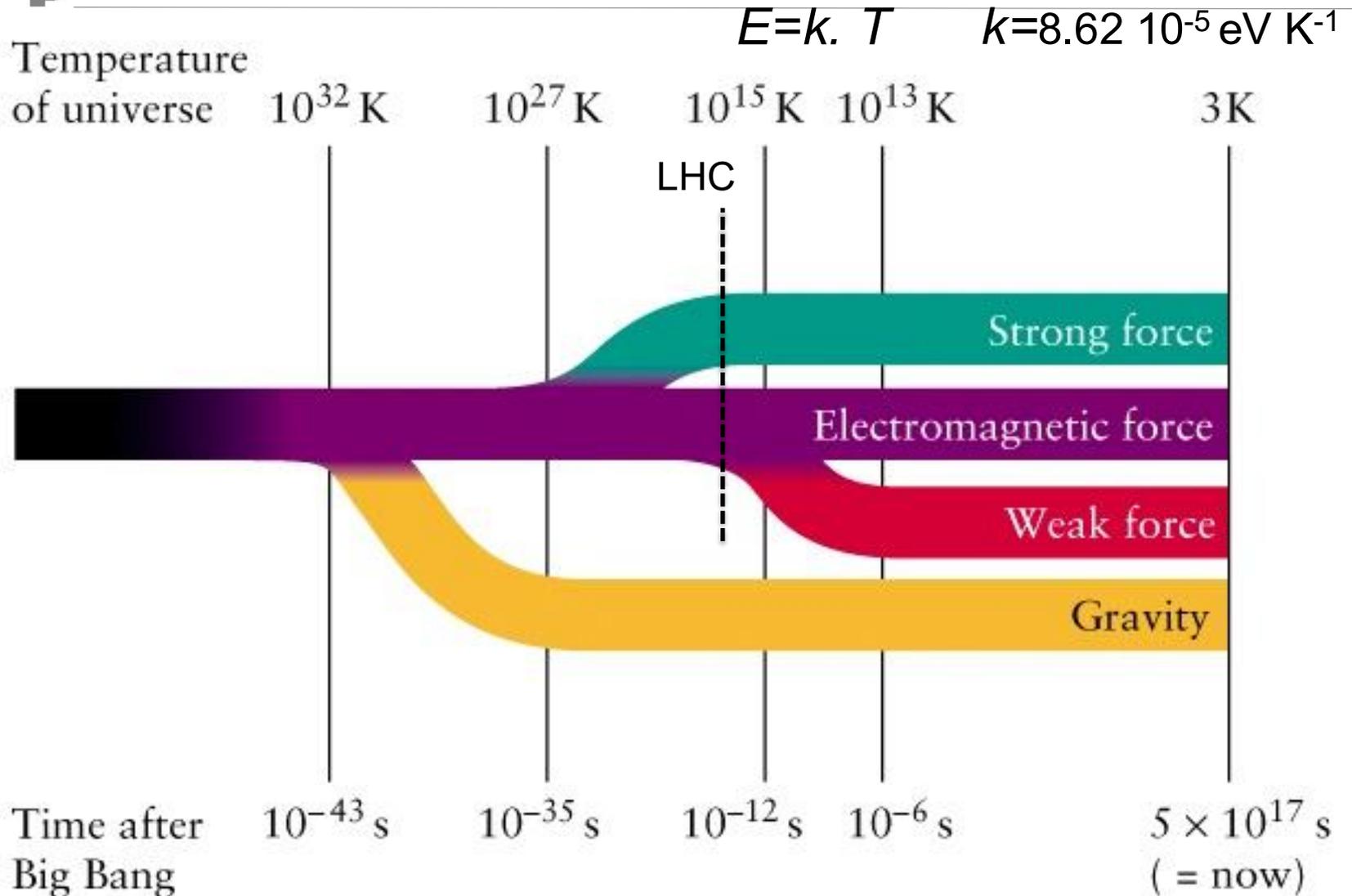
What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

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

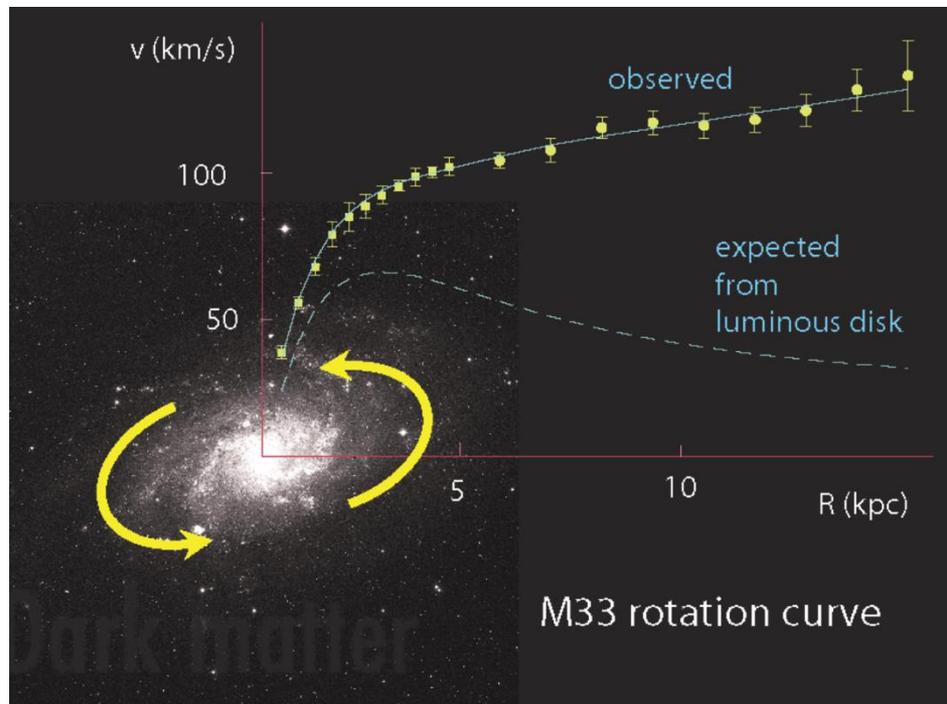


The dark side of the Universe

Long standing problem:

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

What is the remaining 96%?



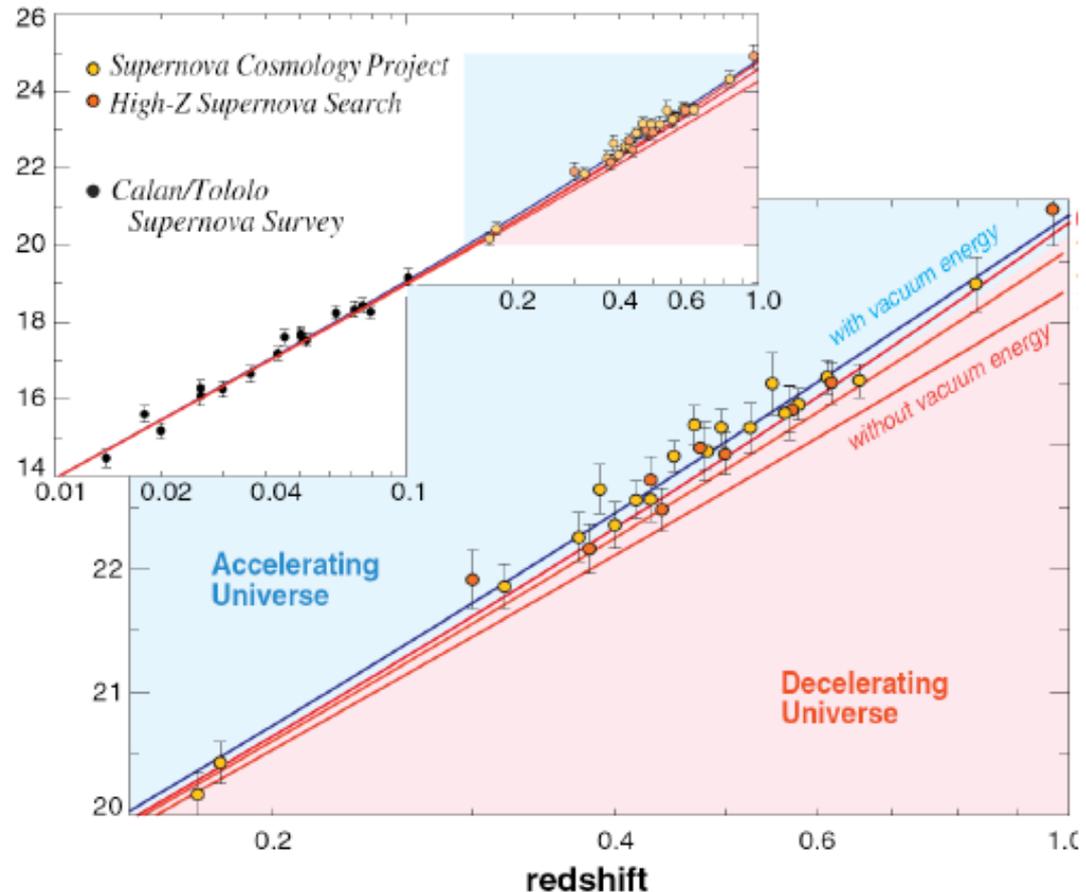
The LHC may help to solve this problem, discovering **dark matter**

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

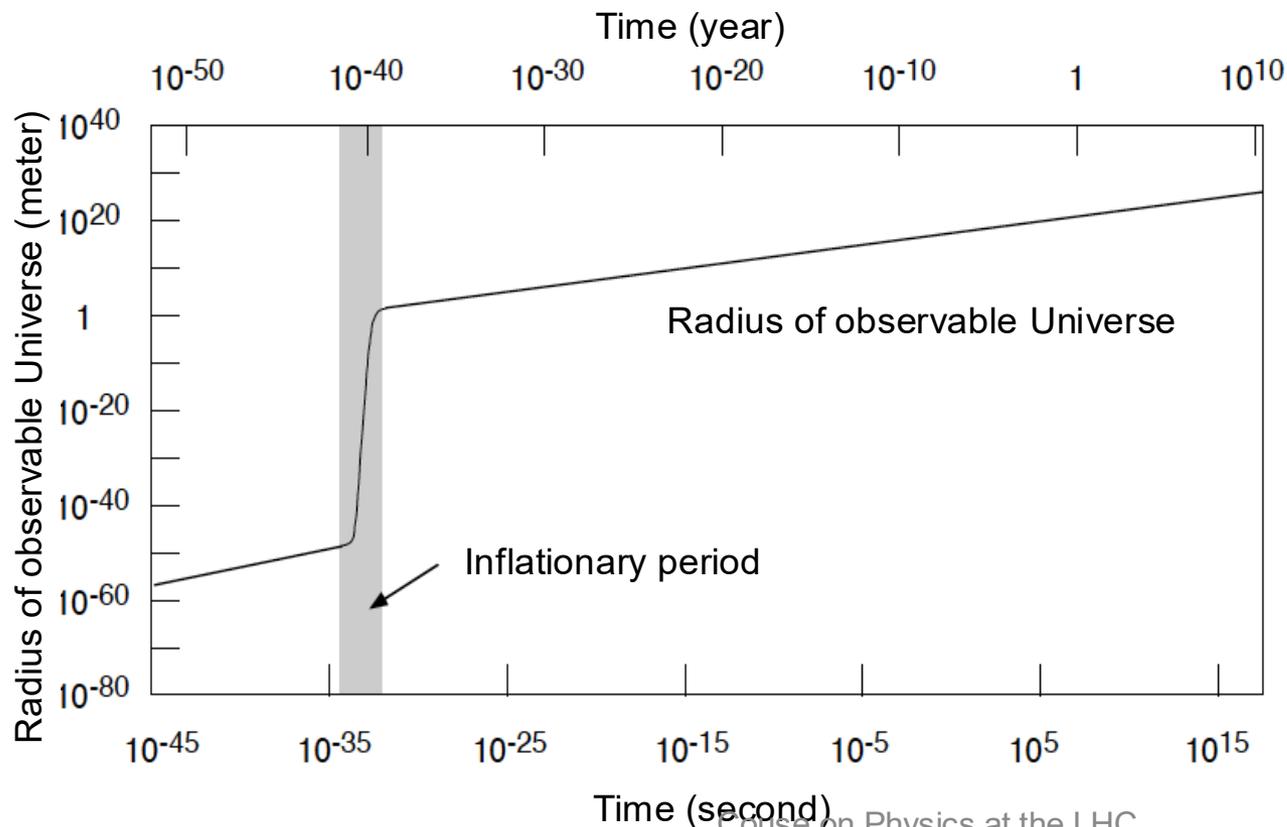
Some form of energy (dark energy) fills space



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

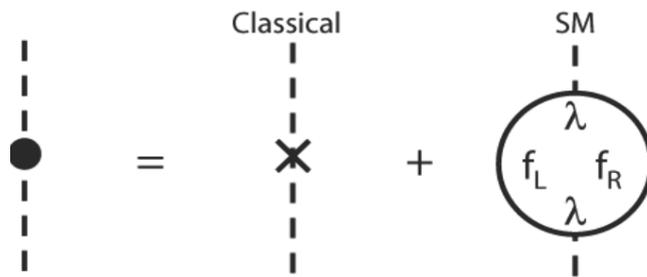


The inflation theory was developed independently in the late 1970's by Alan Guth, Alexey Starobinsky, and others

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



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

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:

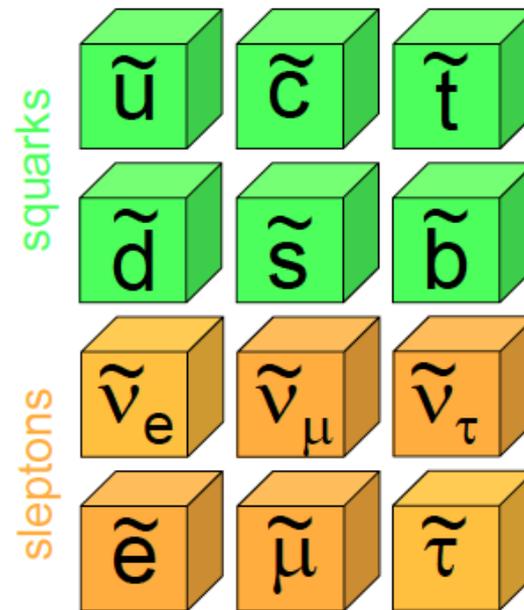
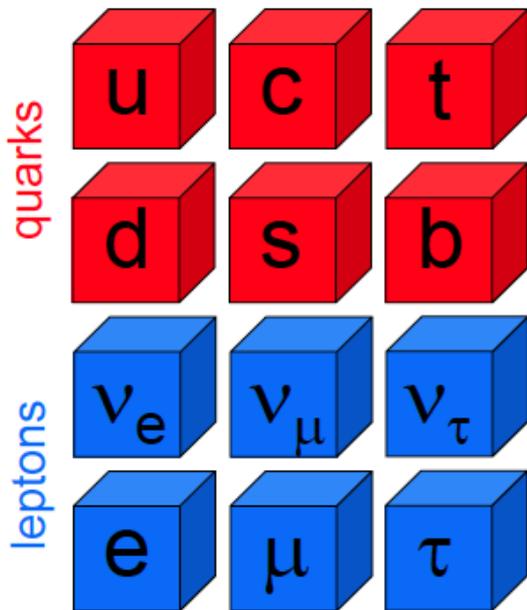
- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, ...)
- Leptoquarks
- New Heavy Gauge Bosons
- Compositeness

Any of this could still be found at the LHC

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

W, Z bosons

gluon

Higgs boson

photino

Wino, Zino

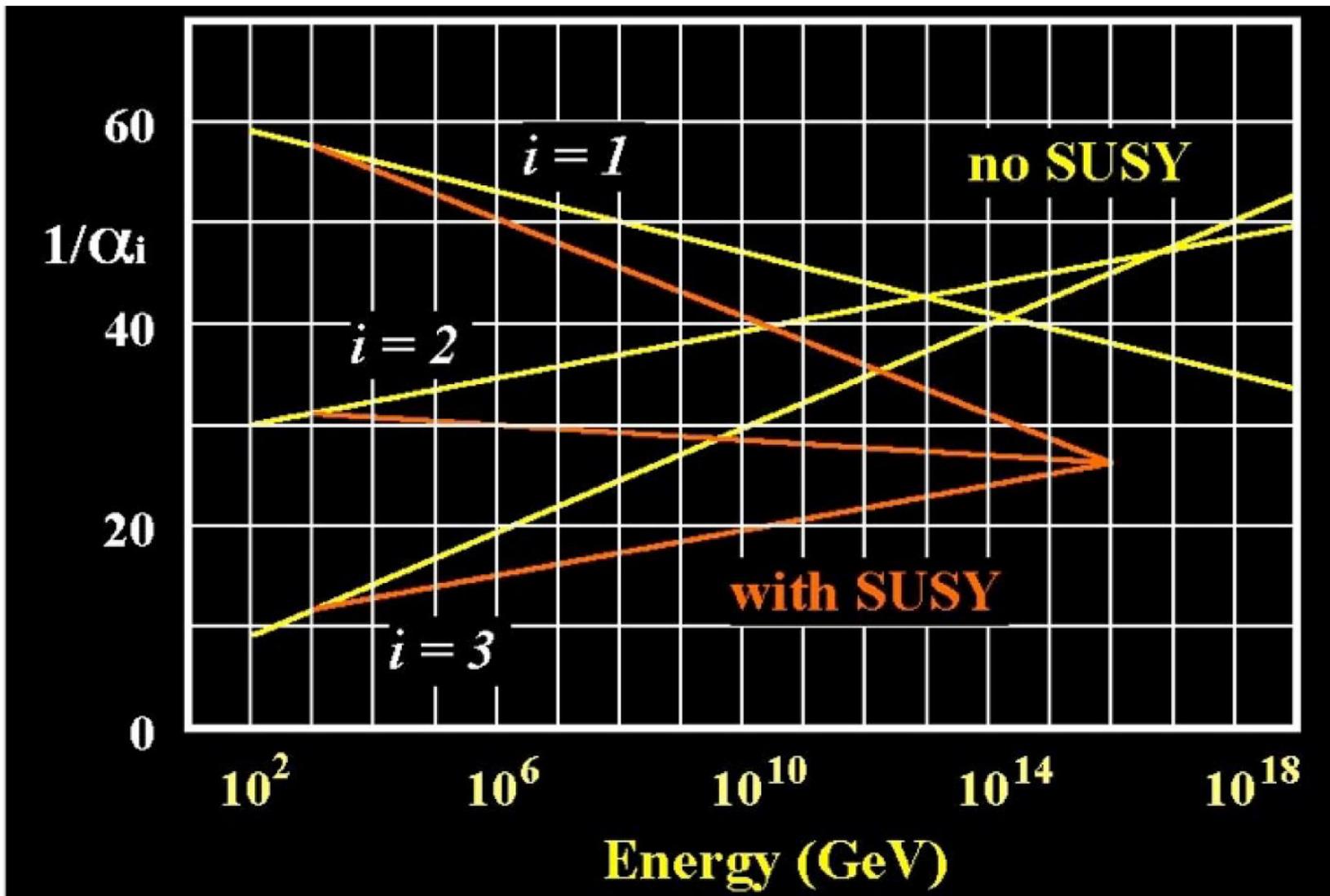
gluino

higgsino

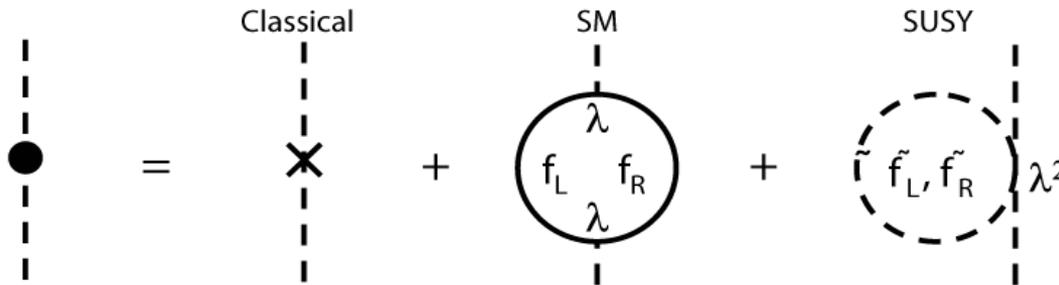
These “...inos” are prime suspects to be the galactic dark matter!

Relics from the Big Bang!

The temptation unification



SUSY and the Higgs mass



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

Higgs mass:

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

Superpartners fix this:

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

Cancellation

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

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

Extra dimensions

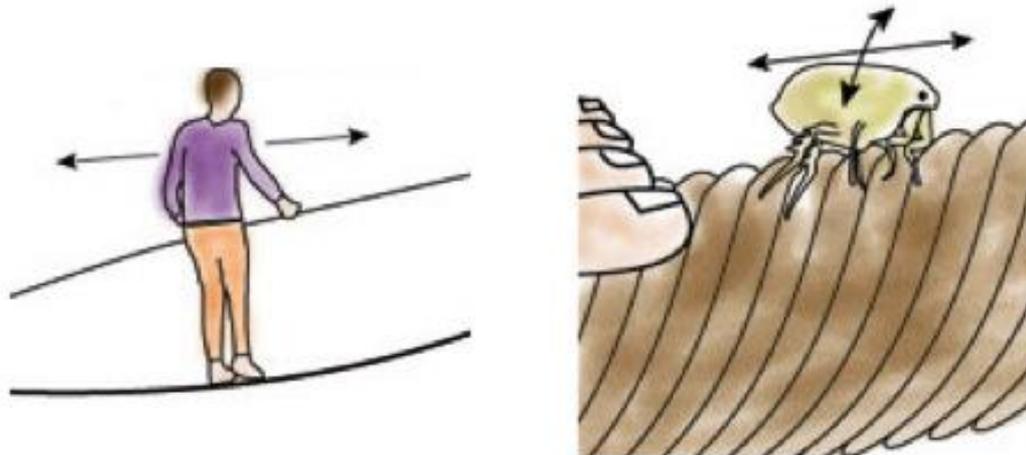
Space-time could have more than three space dimensions. The extra dimensions could be very small and undetected until now.

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.





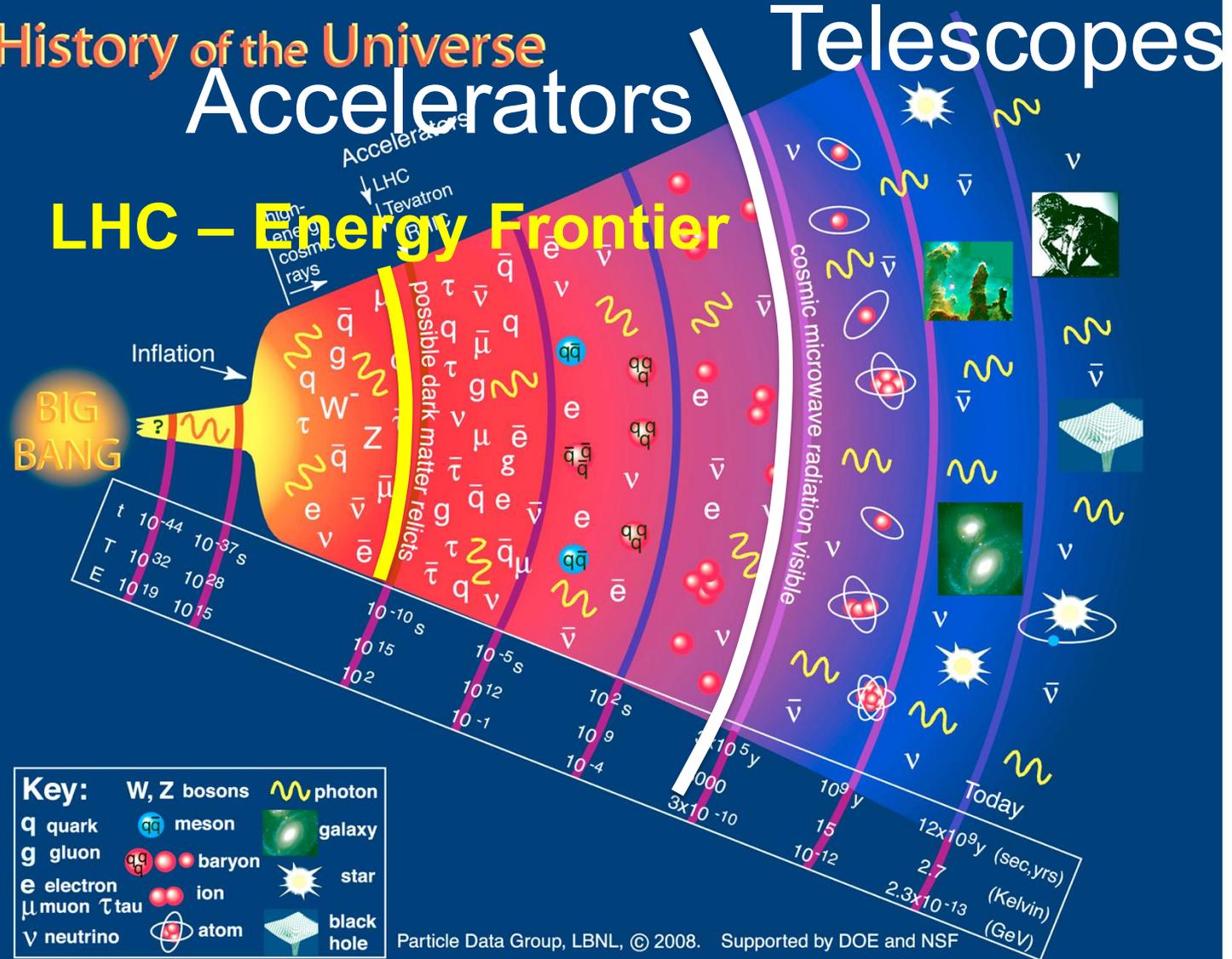
Understanding the Universe

History of the Universe

Accelerators

Telescopes

LHC – Energy Frontier

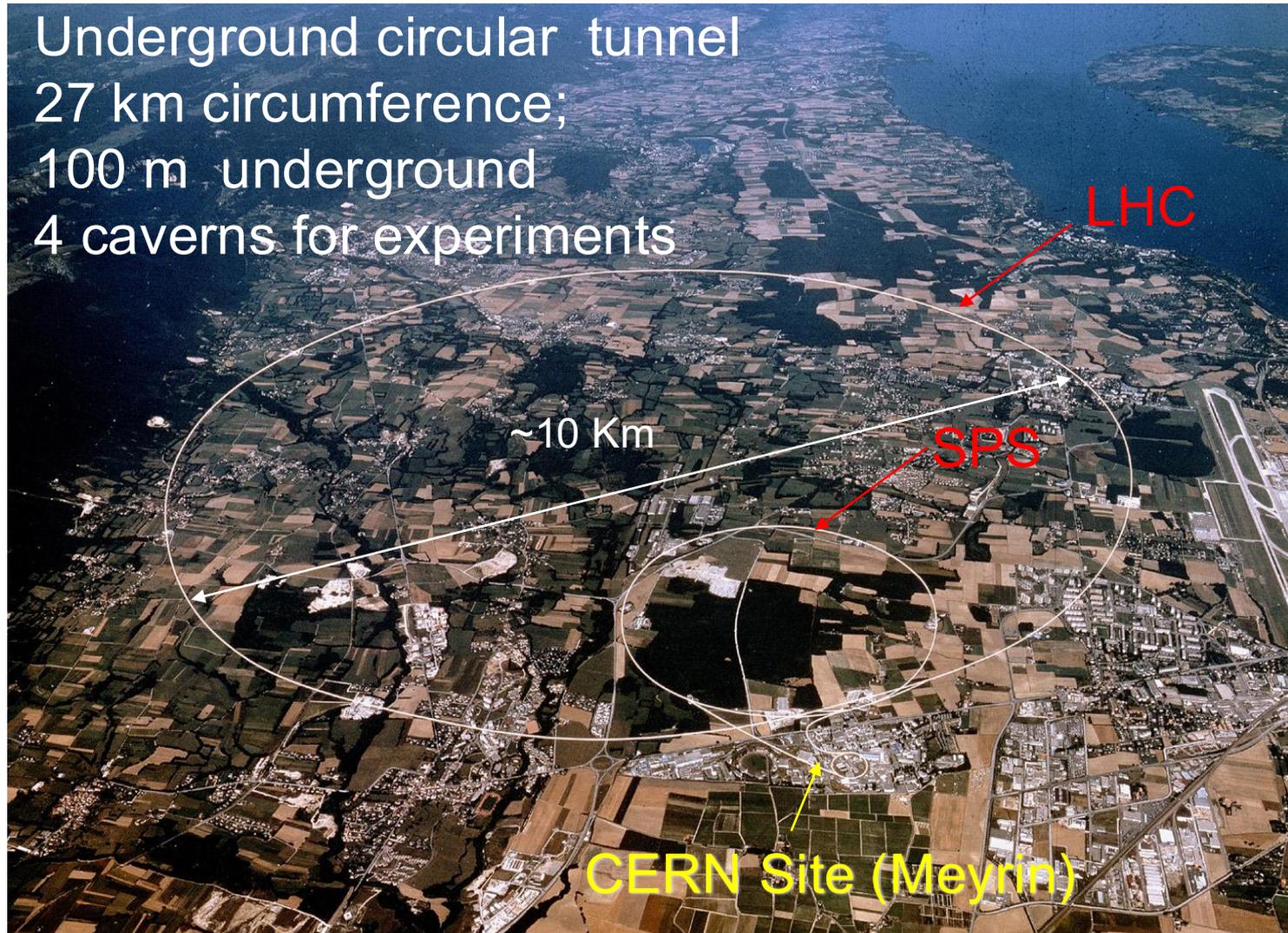


The LHC proton collider

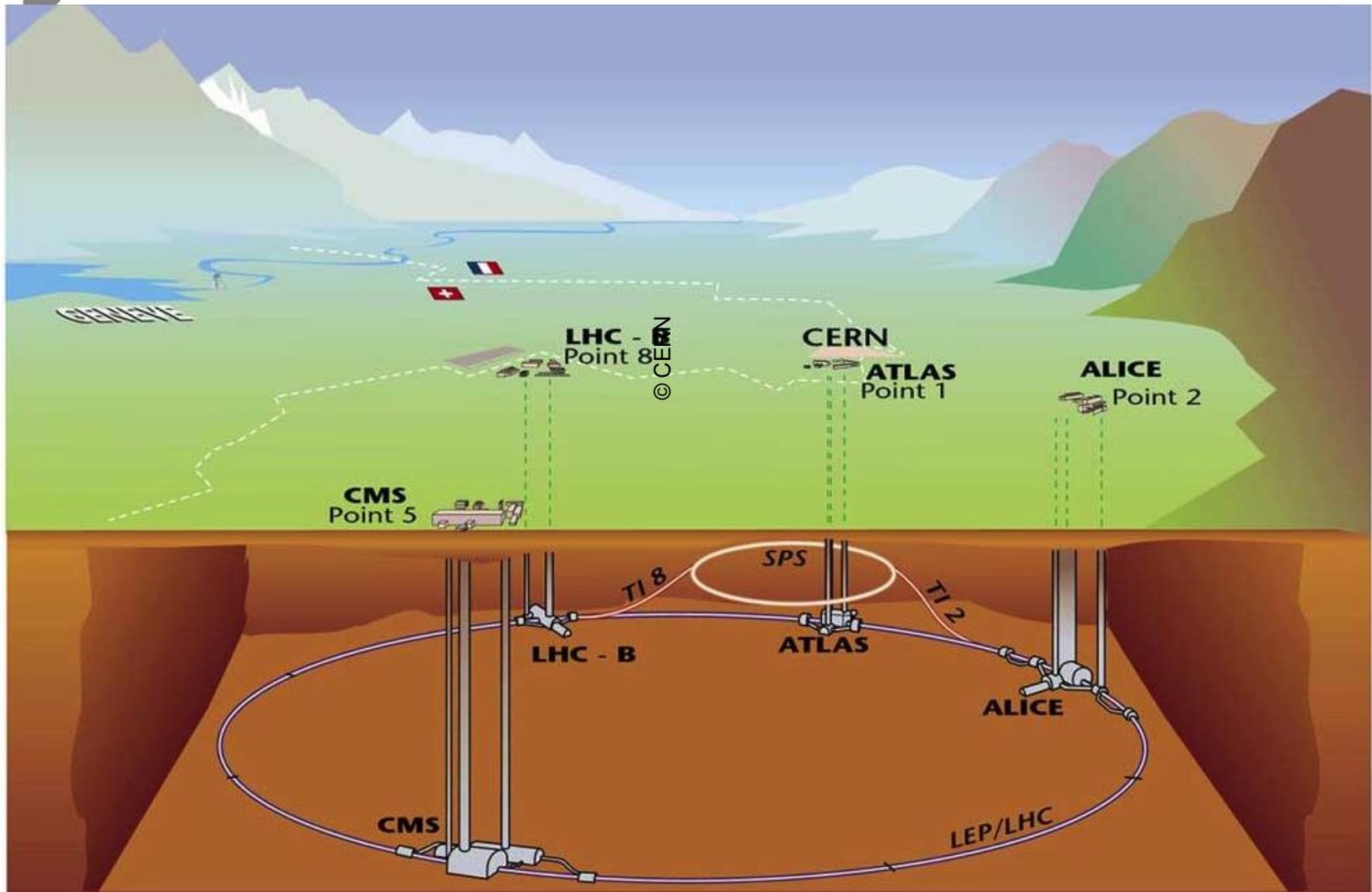


Accelerator and Experiments

Underground circular tunnel
 27 km circumference;
 100 m underground
 4 caverns for experiments



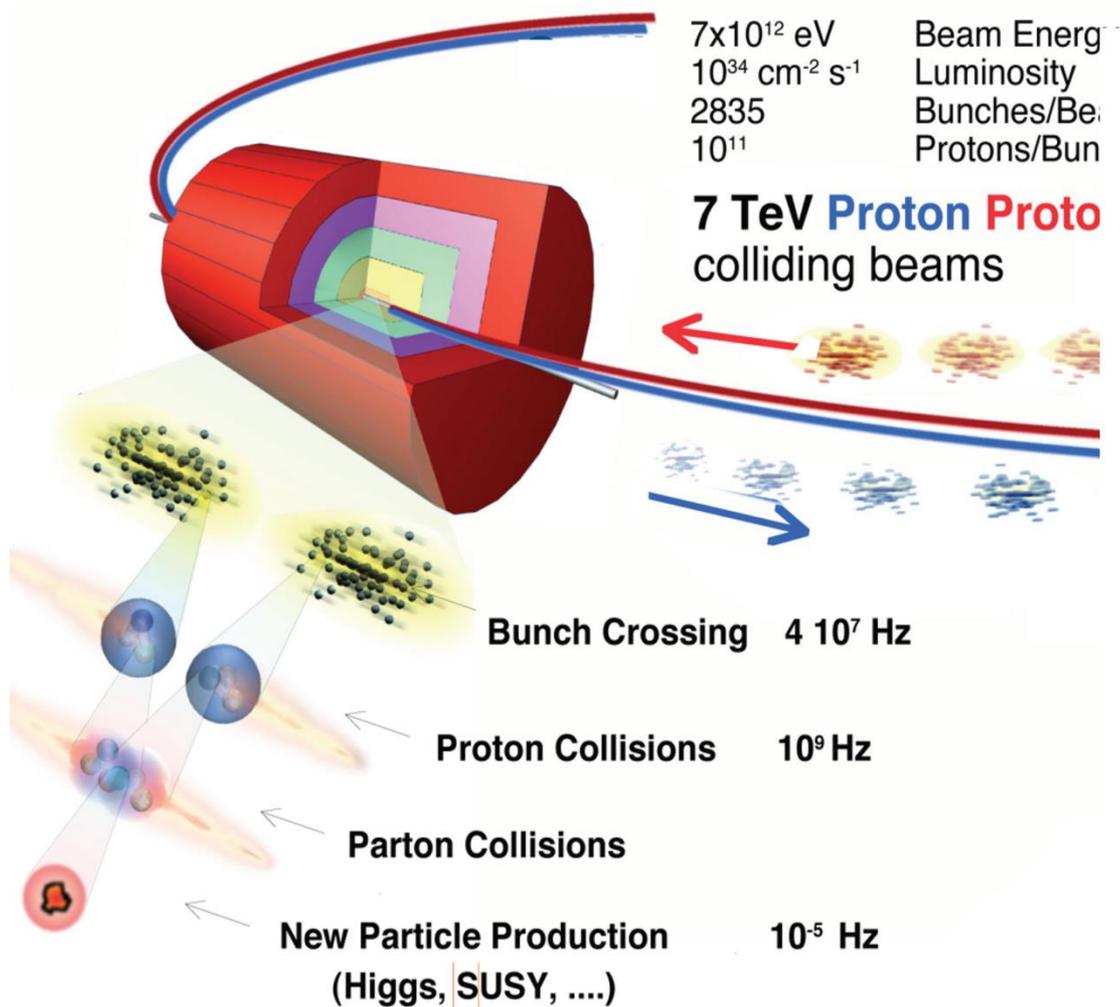
Accelerator and experiments layout



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

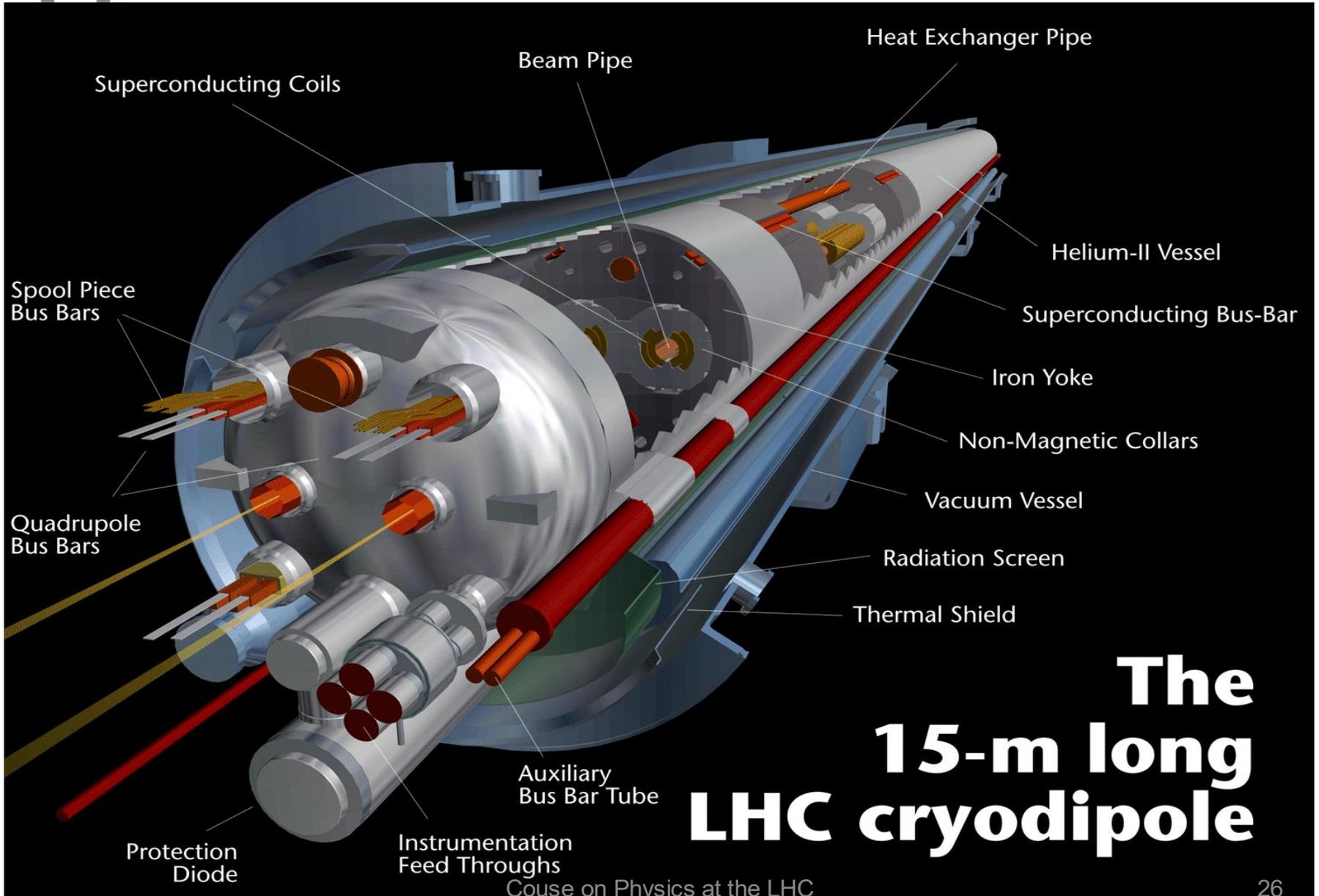
540 - V10/09/97

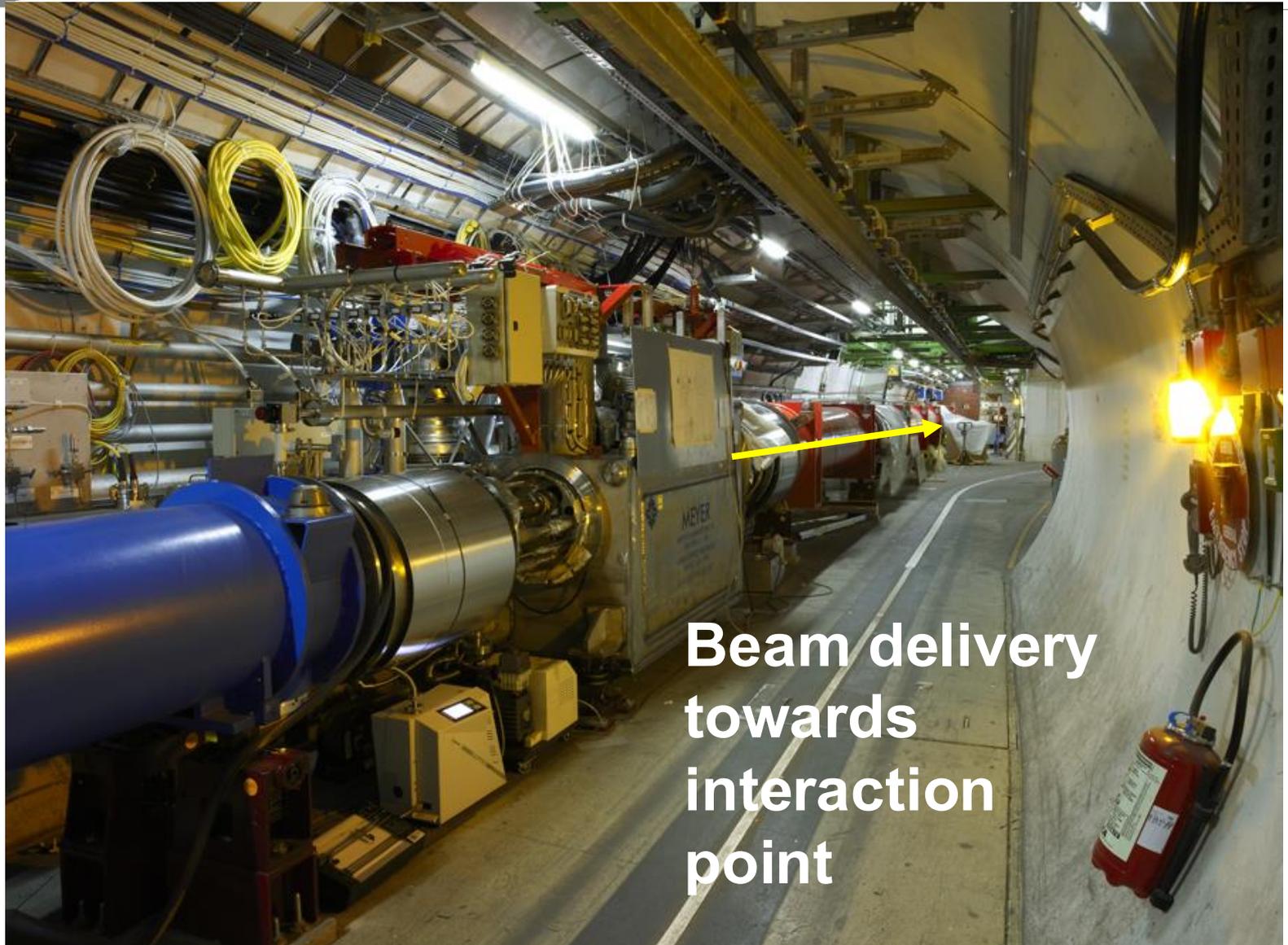
Collisions at LHC





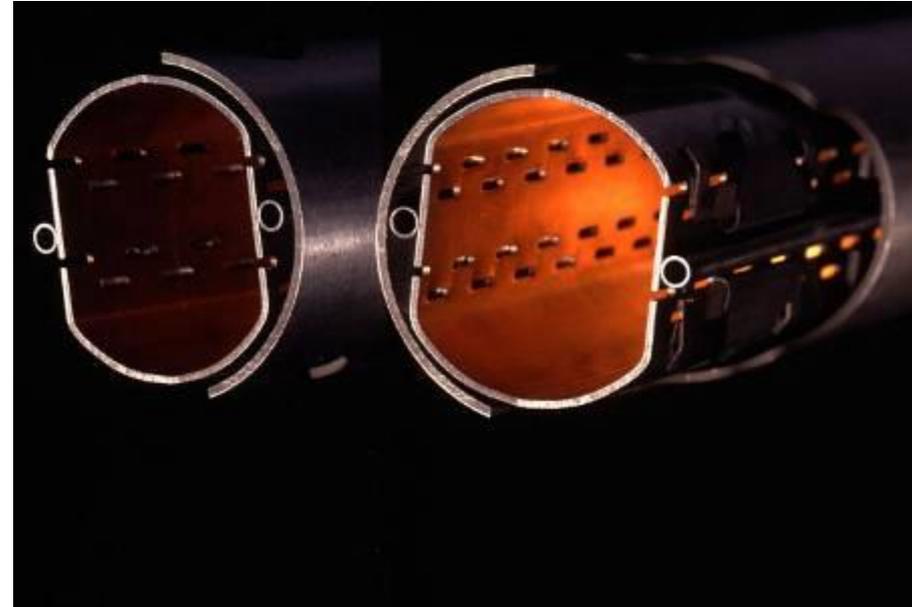
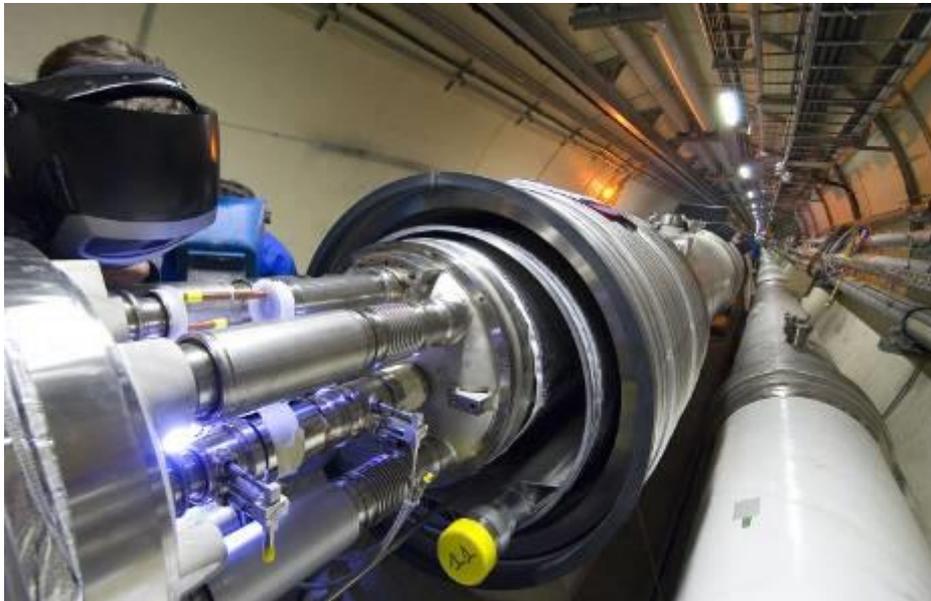
Superconducting magnetic dipole





It's empty!

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

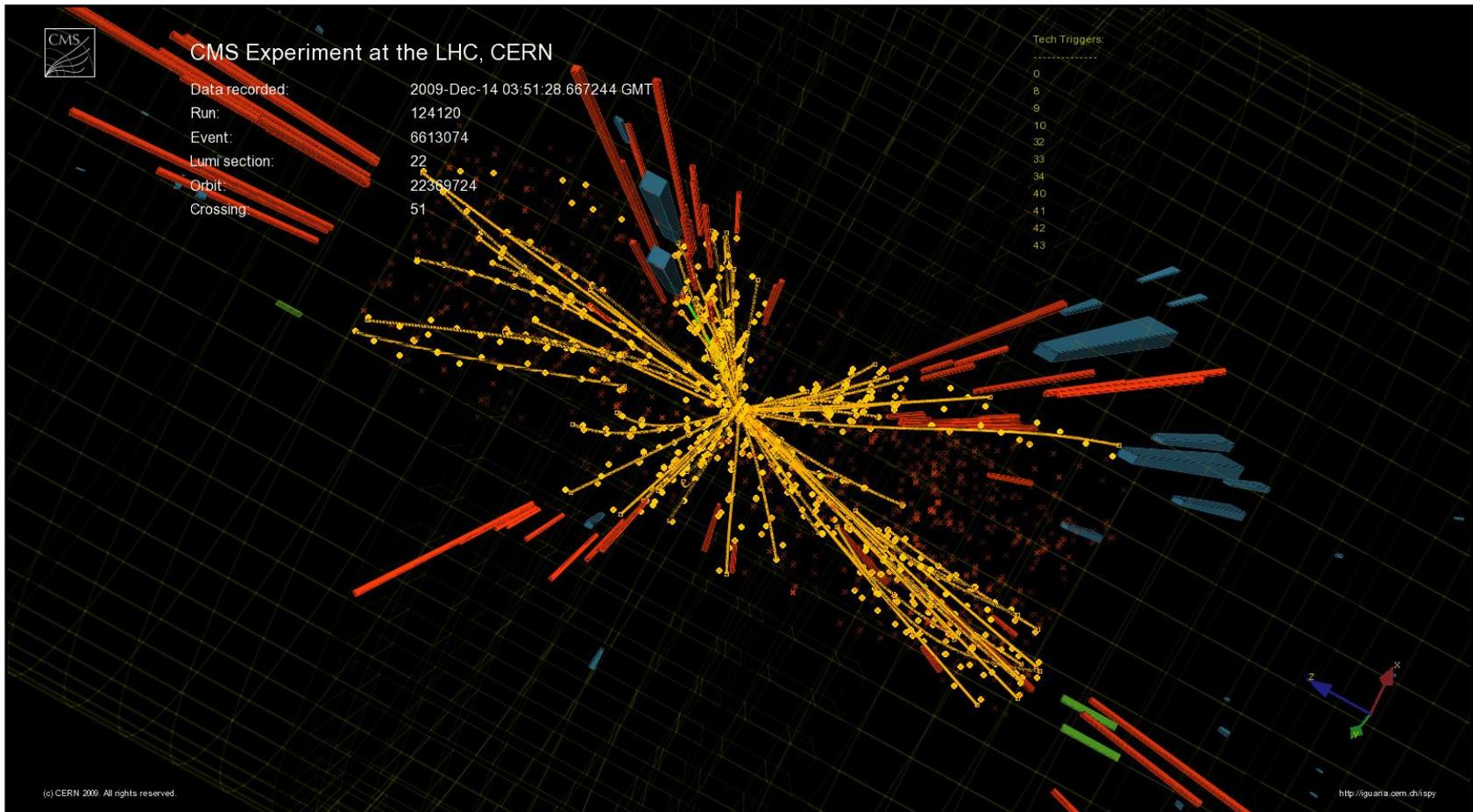


It's cold!

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



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

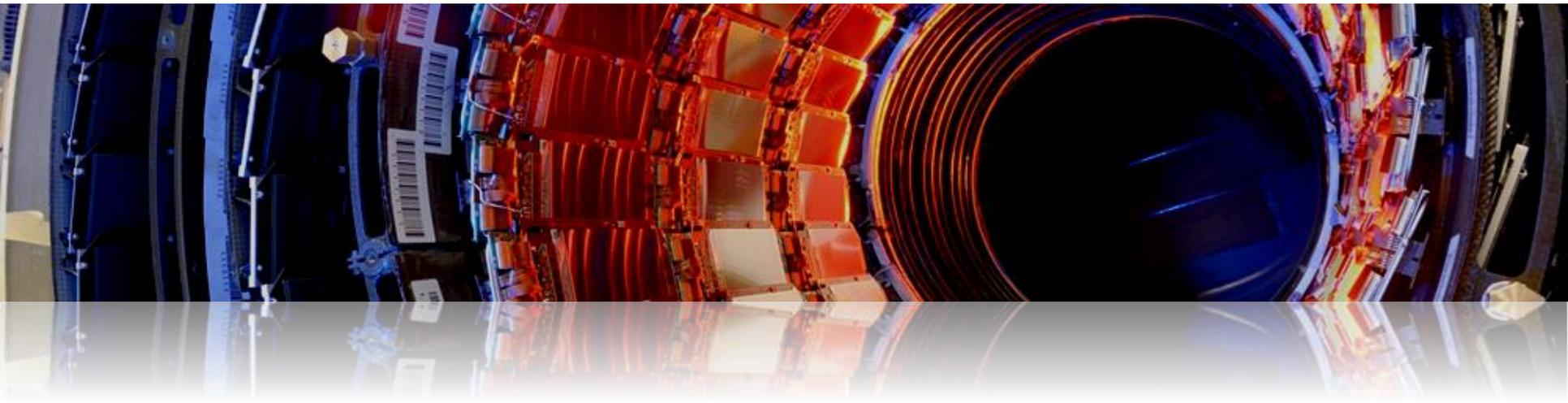


The LHC timeline



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

The Experiments

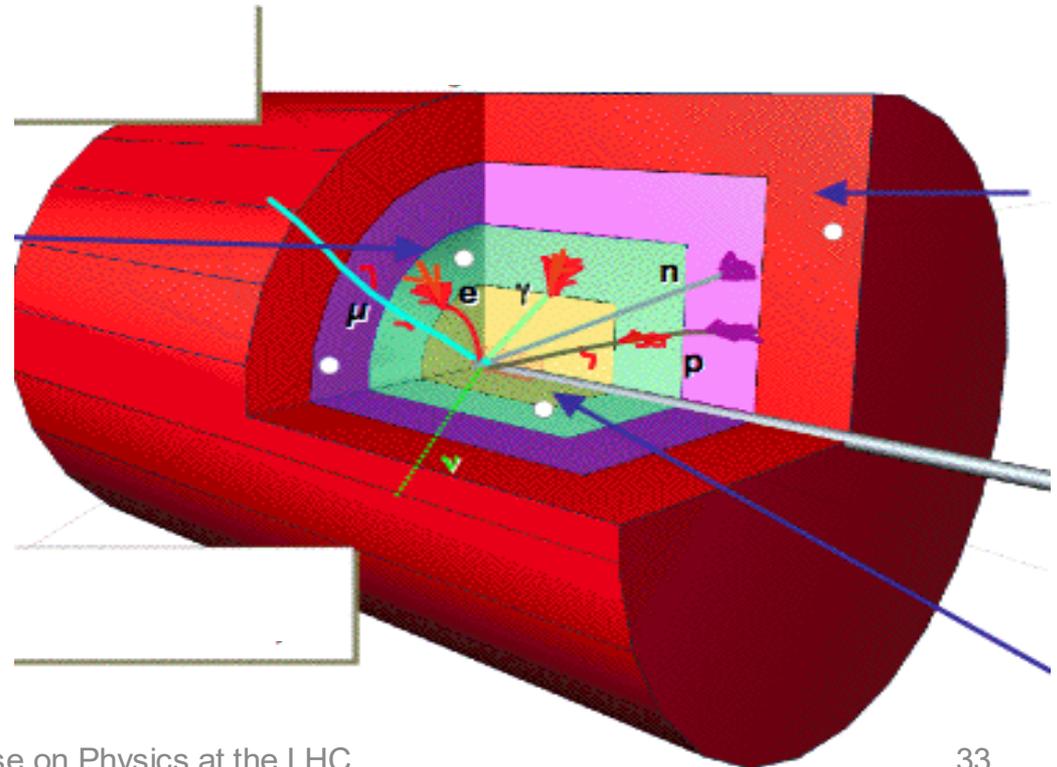


General purpose LHC experiments

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

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS

Pixel (100x150 μm) ~16m²~66M channels
Microstrips (80x180 μm) ~200m²~9.6M channels

CMS Detector

SUPERCONDUCTING SOLENOID

Niobium titanium coil carrying ~18,000A

MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER

Silicon strips ~16m²~137,000 channels

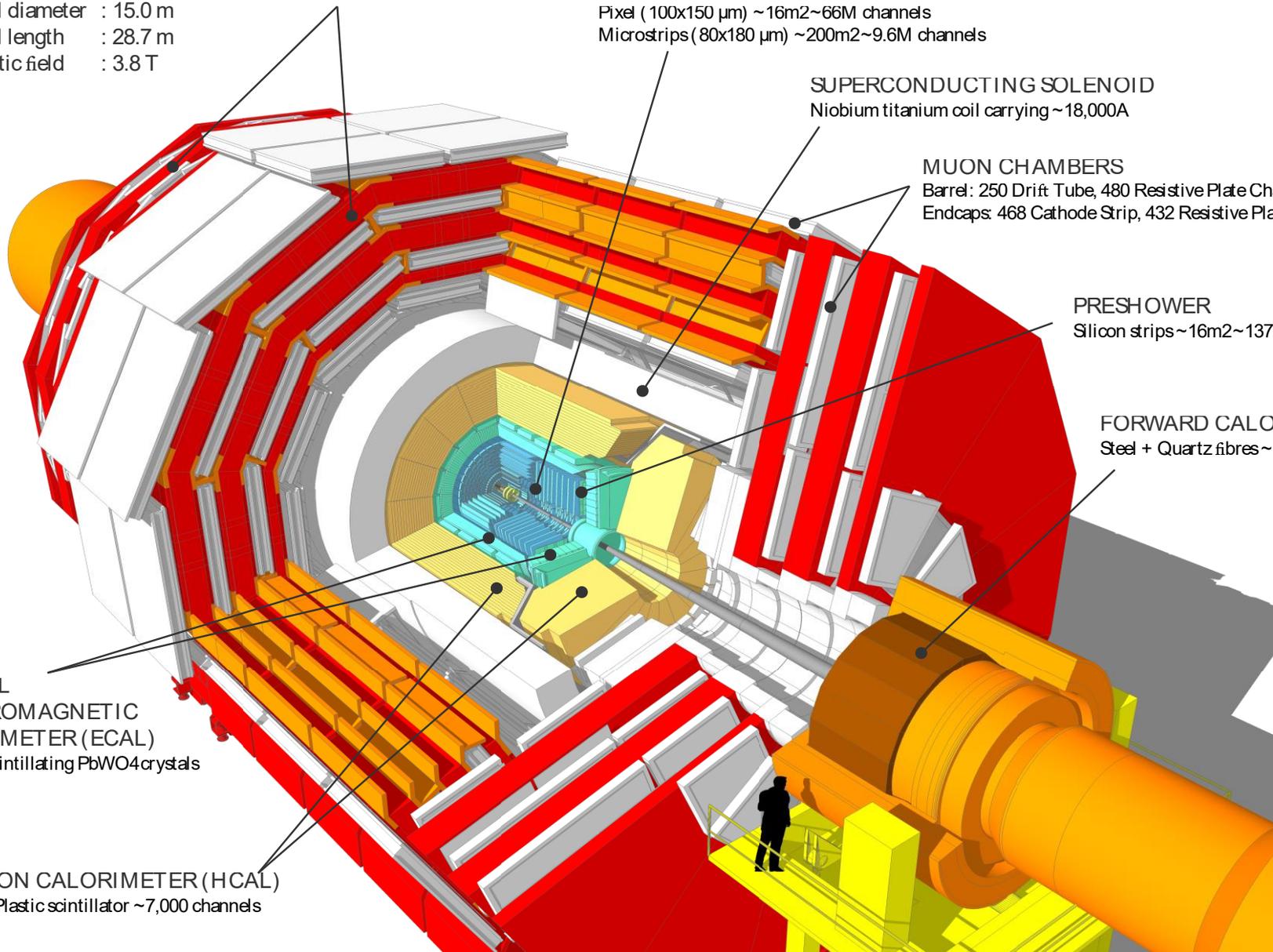
FORWARD CALORIMETER

Steel + Quartz fibres ~2,000 Channels

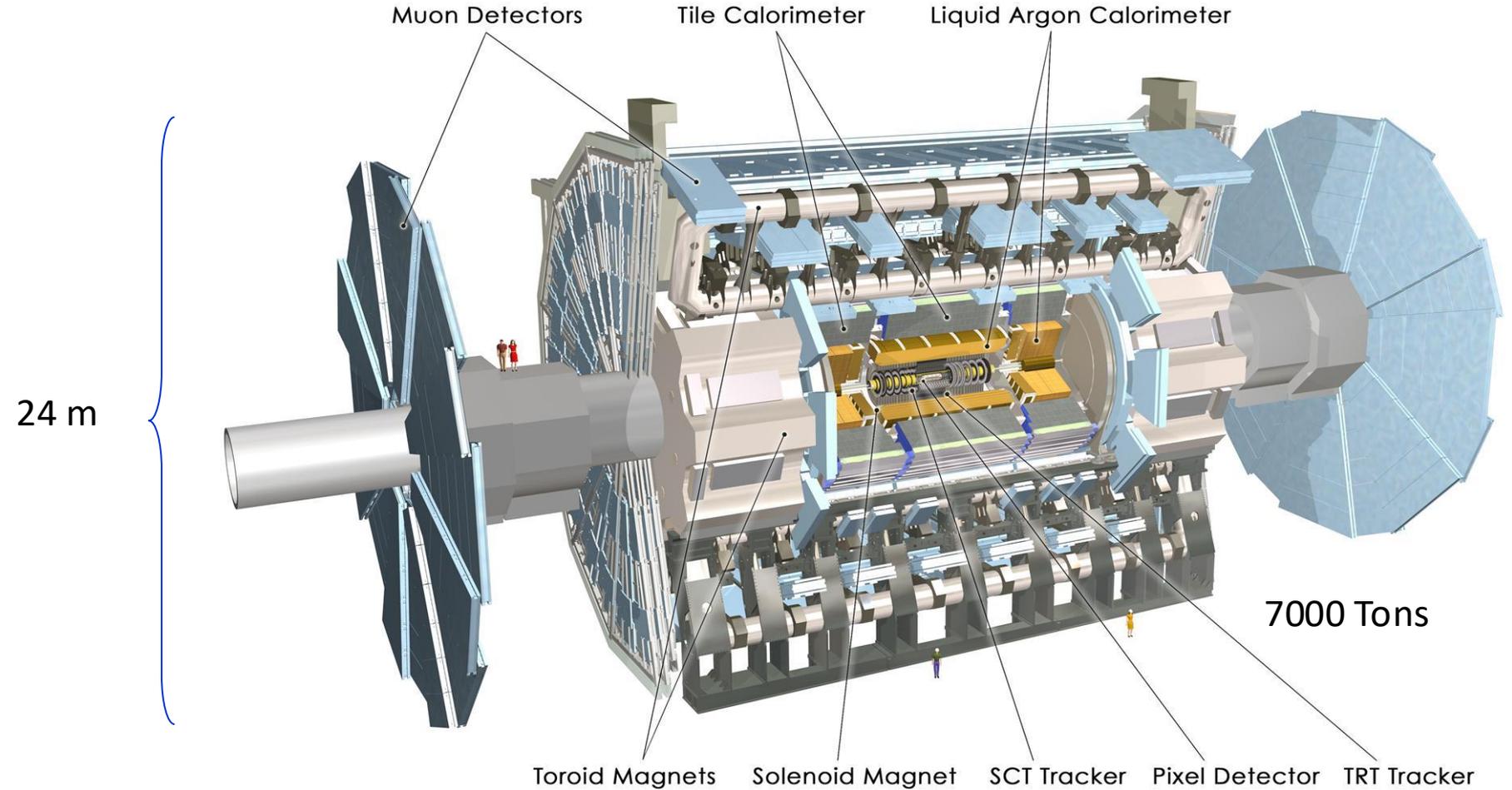
CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)

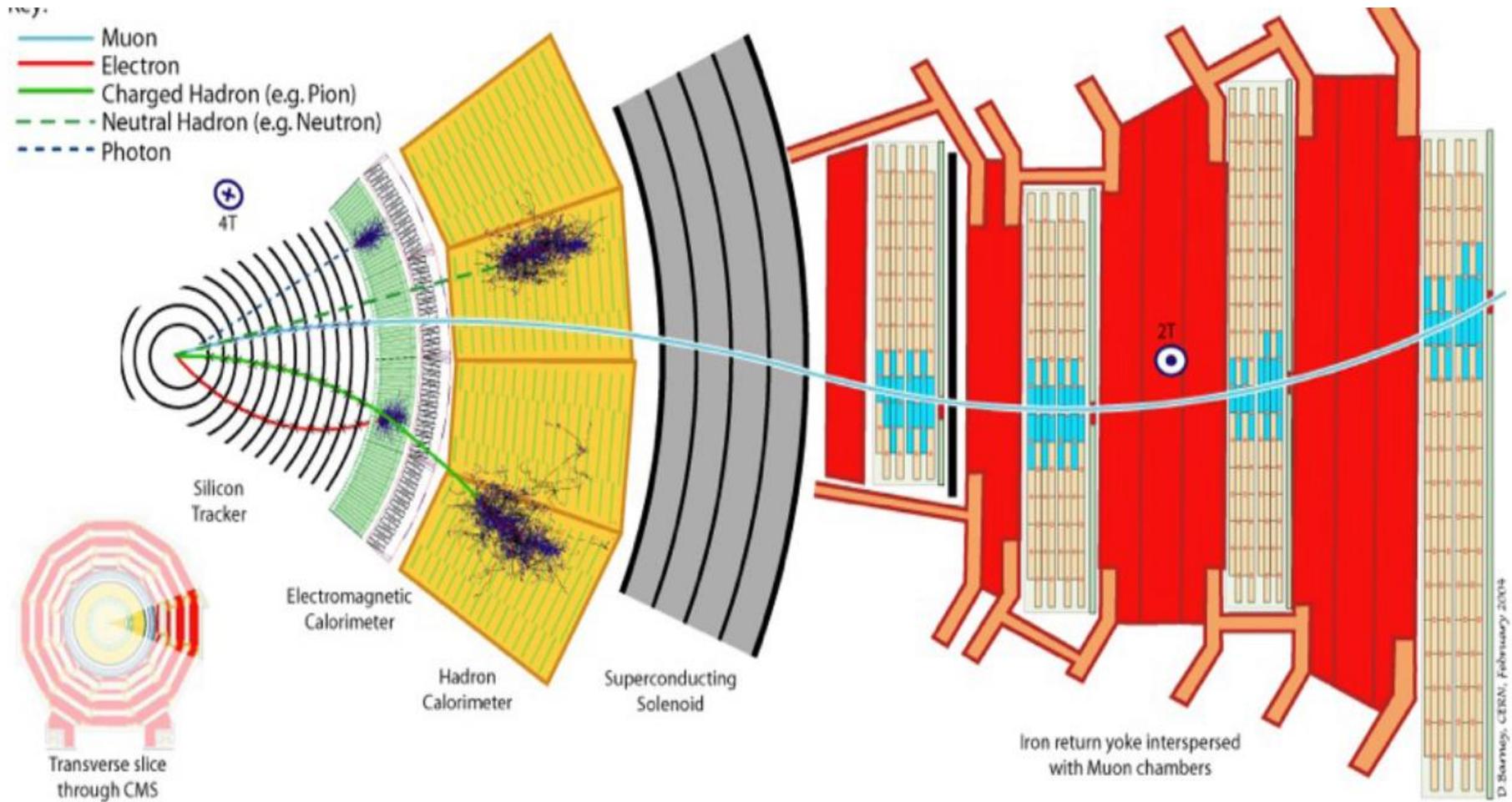
Brass + Plastic scintillator ~7,000 channels



ATLAS detectors



Detection of hadrons, e^\pm , γ and μ^\pm

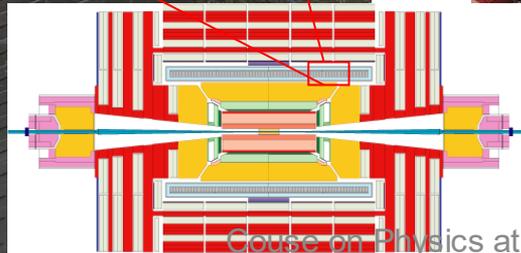
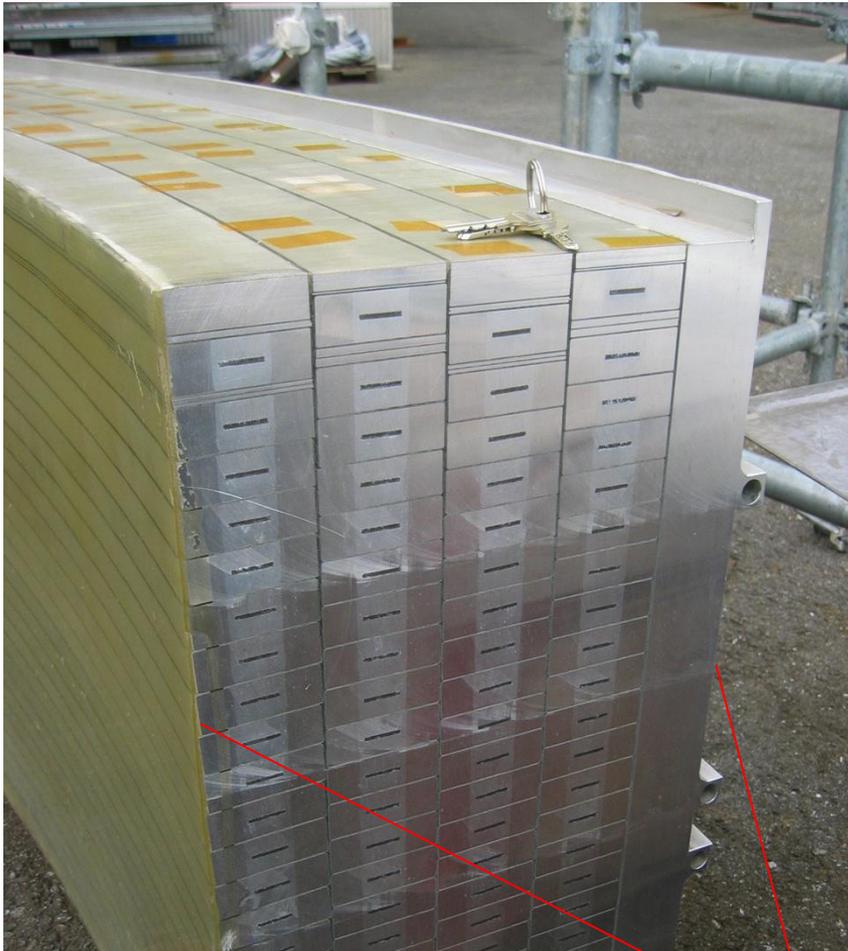


1993-2008: detector R&D and construction

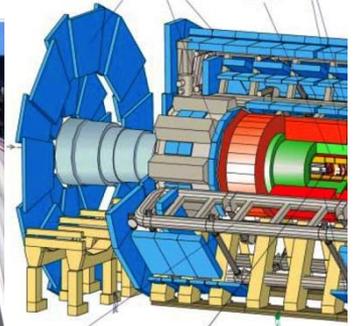
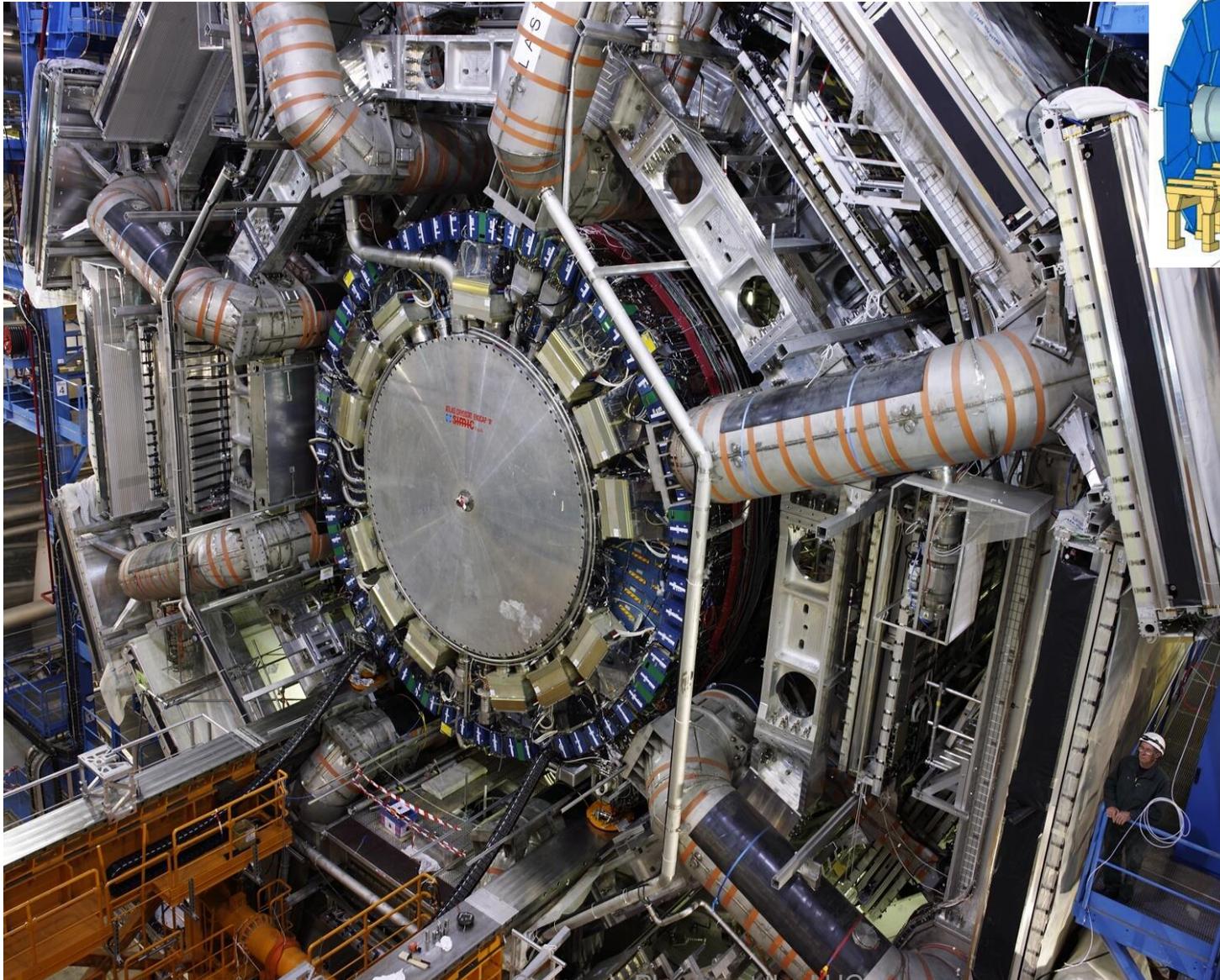
15 years !



Superconductor solenoid at 3.8 Tesla

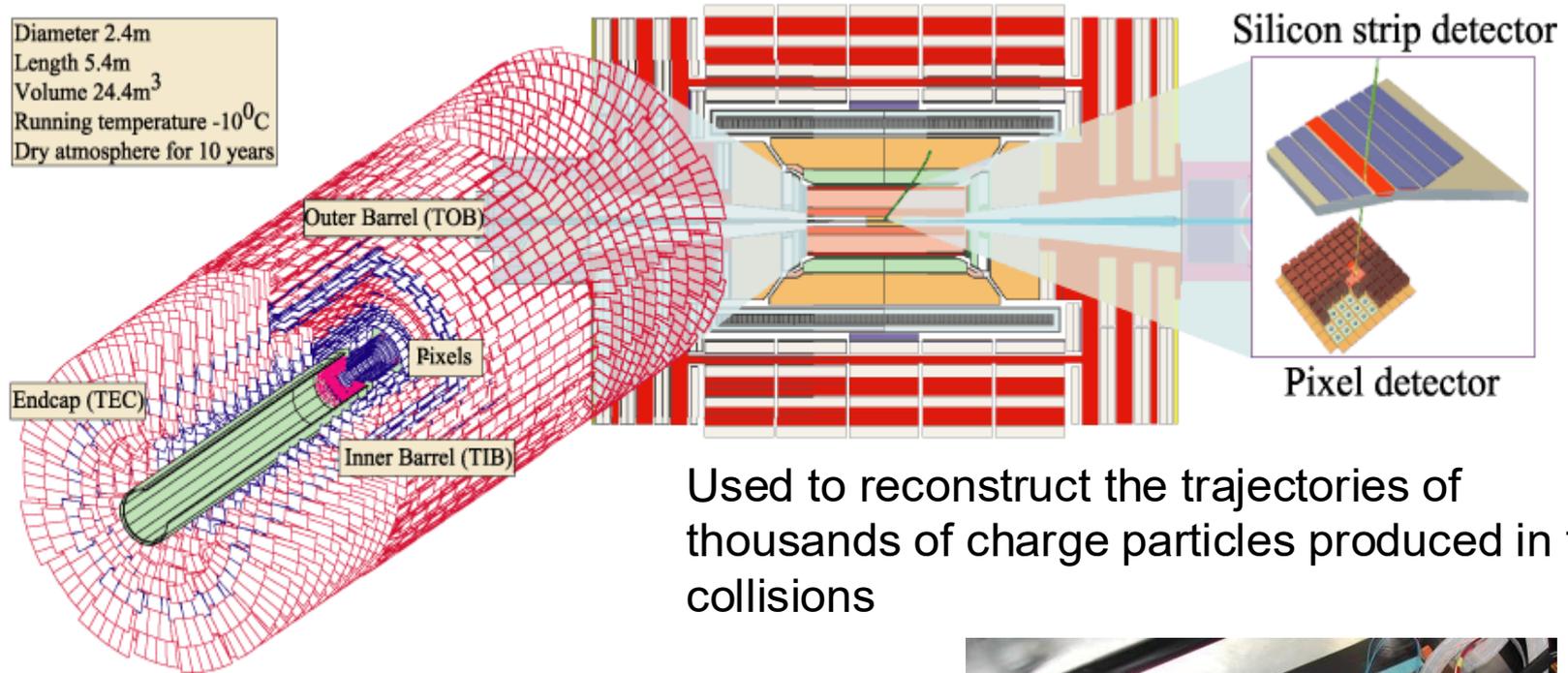


ATLAS Toroidal System



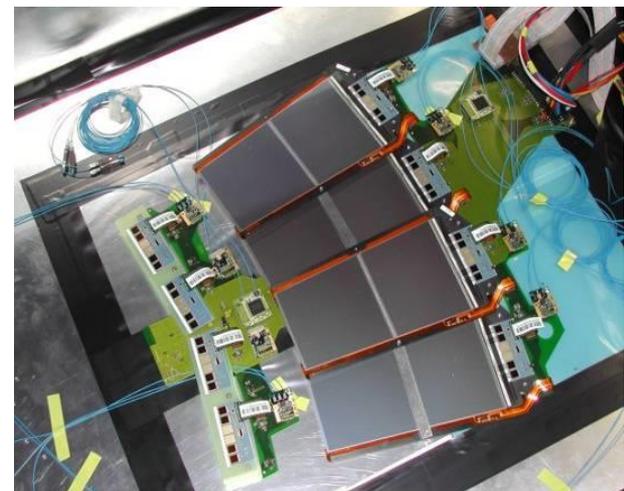
Silicon Tracker

Diameter 2.4m
 Length 5.4m
 Volume 24.4m³
 Running temperature -10⁰C
 Dry atmosphere for 10 years

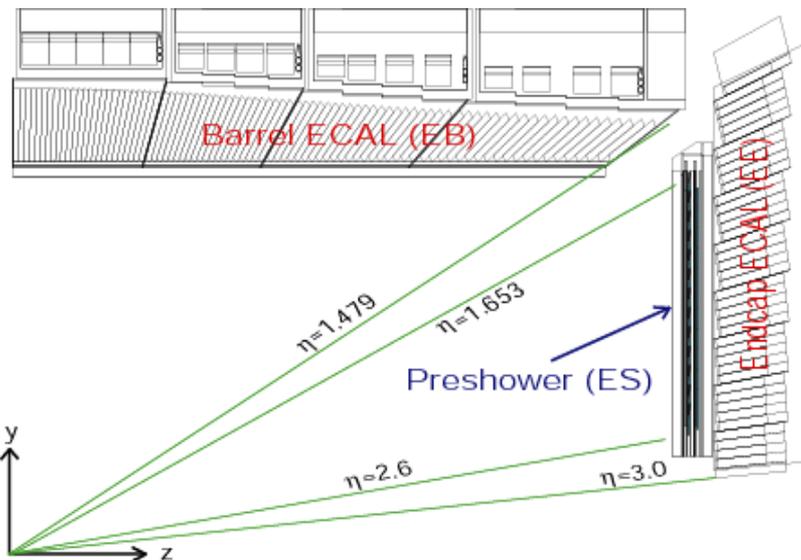
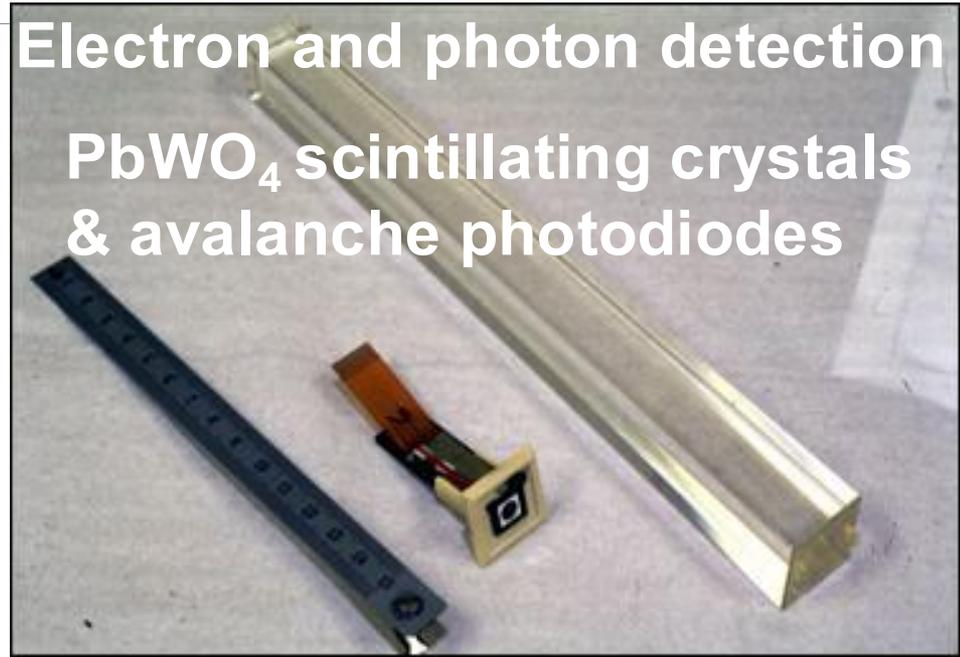
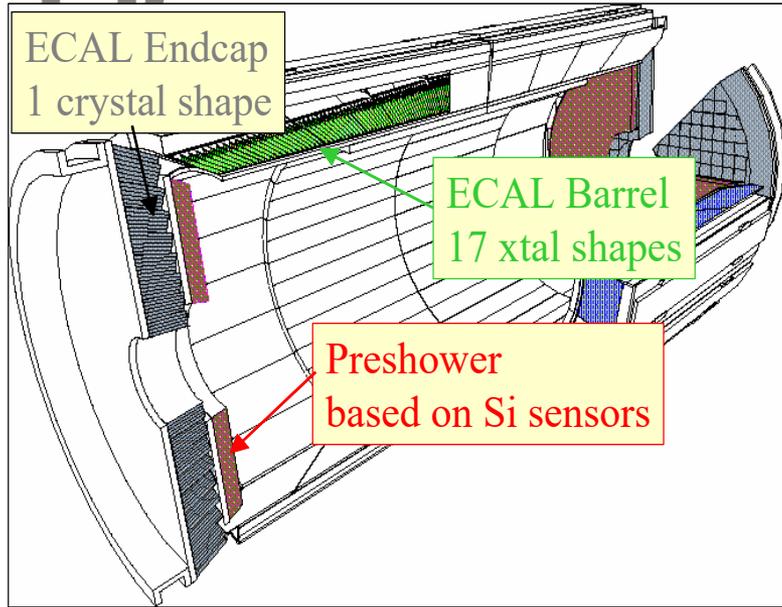


Used to reconstruct the trajectories of thousands of charge particles produced in the collisions

214m² 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 $\leq 0.5\%$

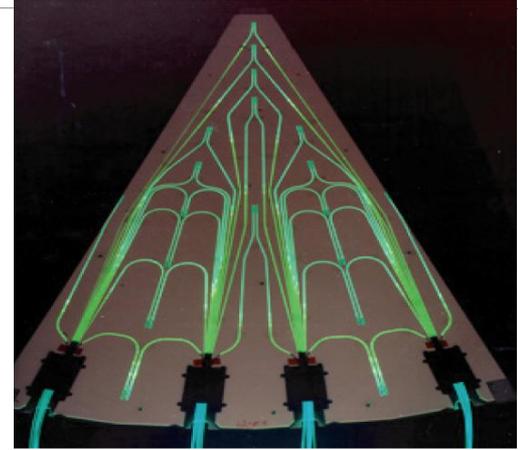
Parameter	Barrel	Endcaps
# of crystals	61200	14648
Volume	8.14m ³	2.7m ³
Xtal mass (t)	67.4	22.0

HCAL Hadronic Calorimeter

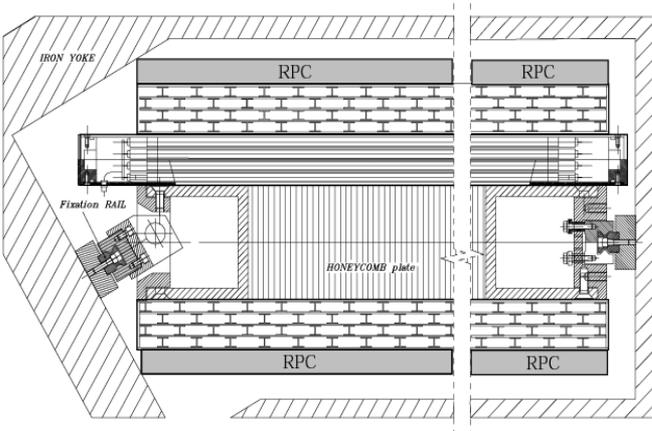
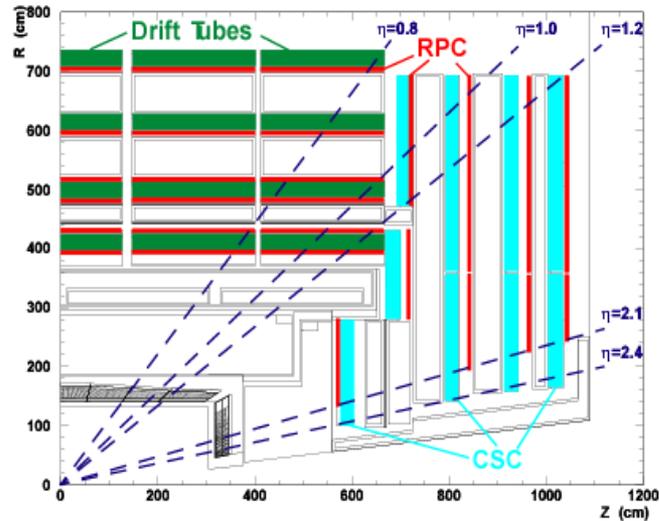
Detection of hadrons:

- protons, neutrons, pions, 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

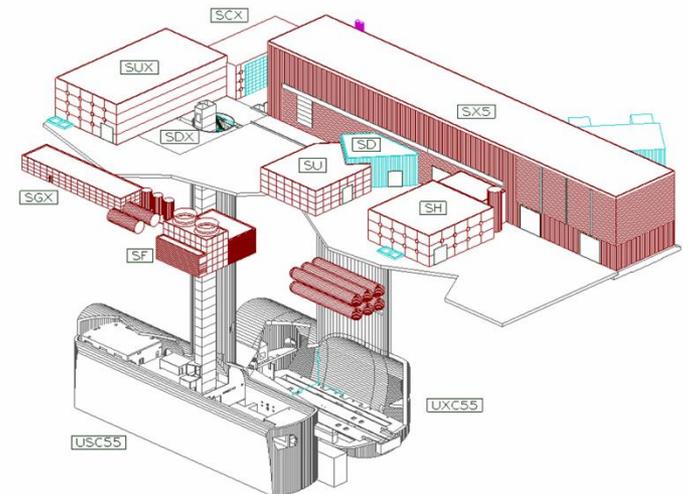
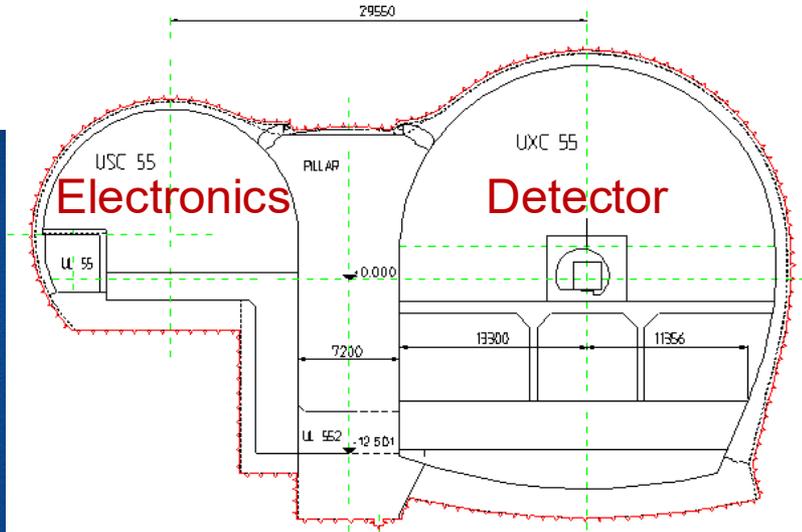
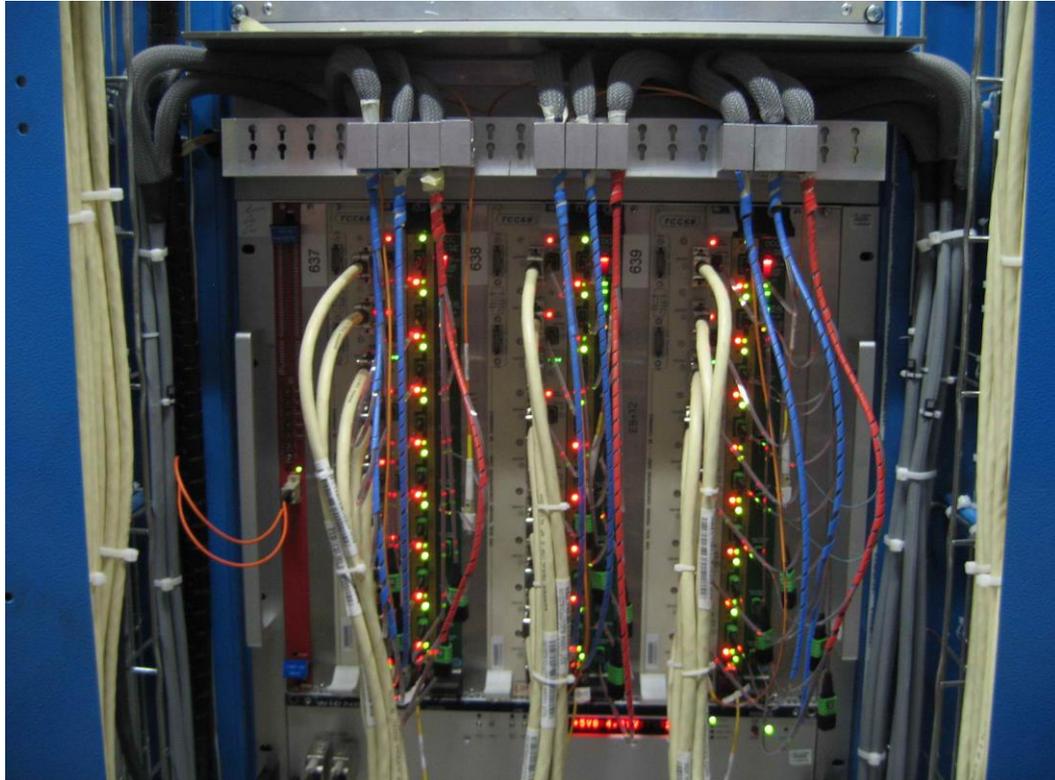


Drift Tubes (DT)
 Cathode Strip Chambers (CSC)
 Resistive Plate Chambers (RPC)



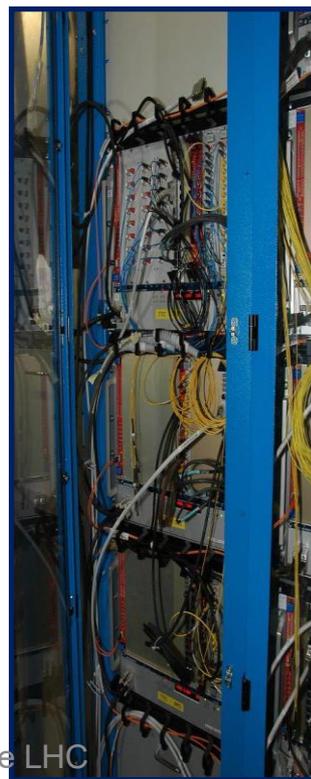
Trigger and readout electronics

Underground caverns



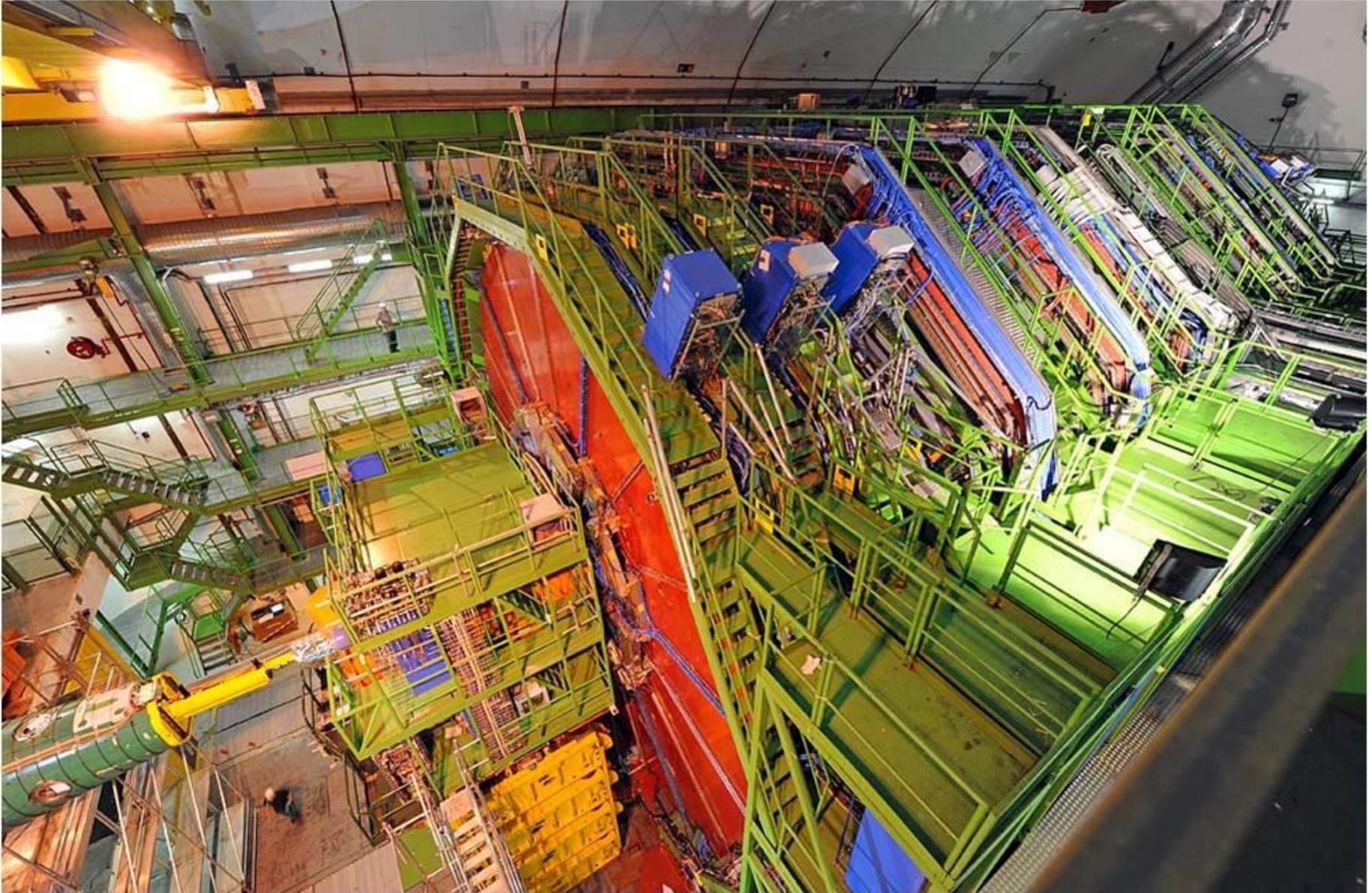
Electronics systems

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



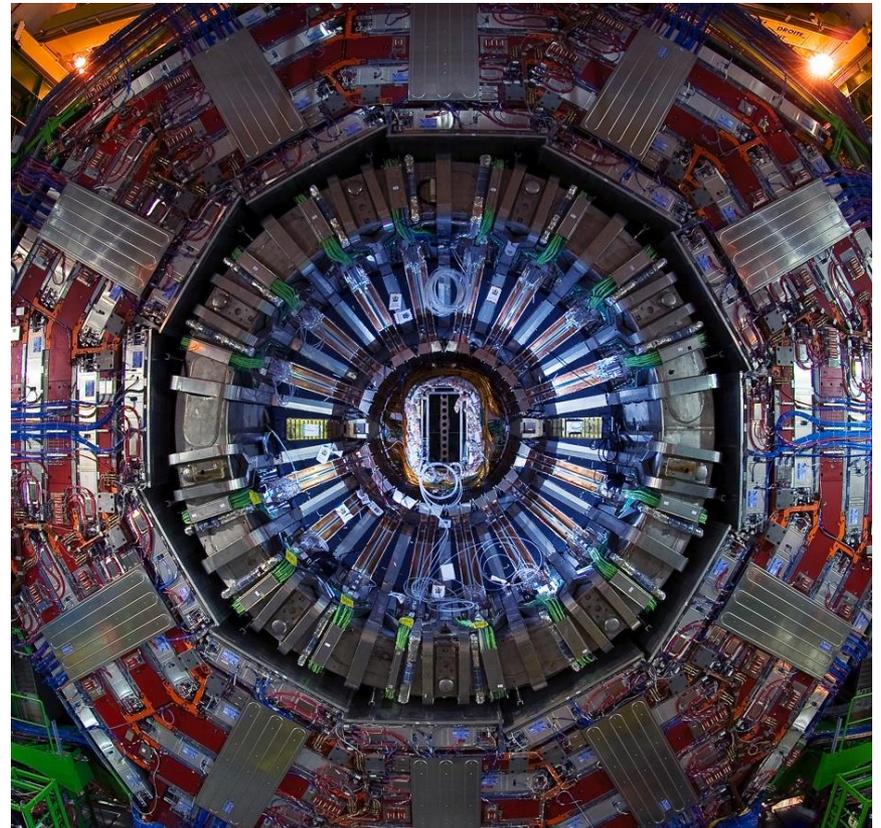
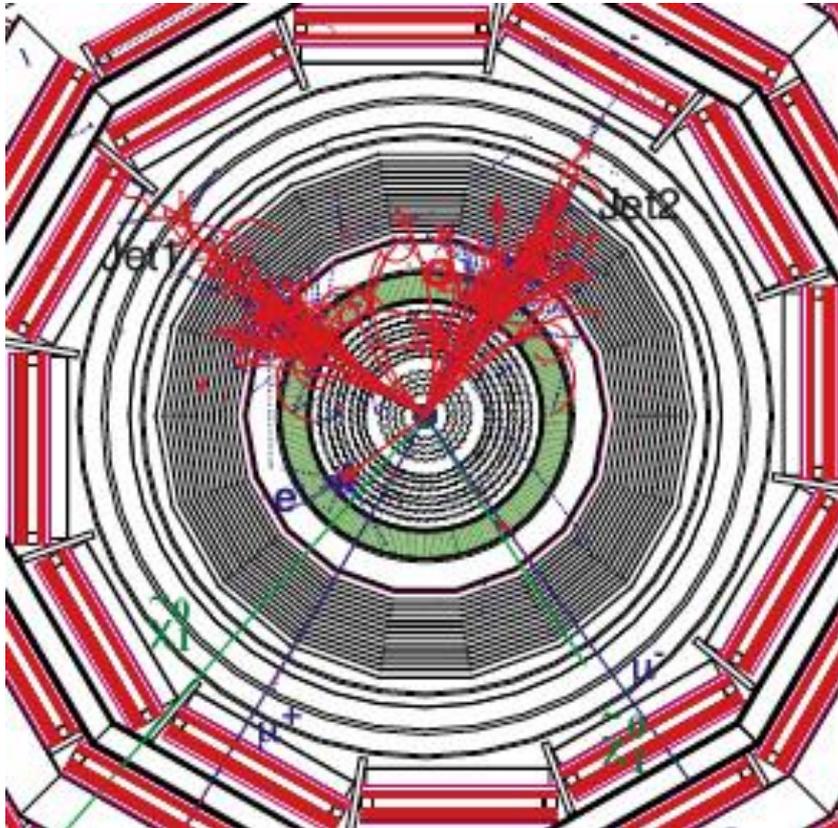


Sep 2008: CMS detector ready for beams



Detector simulation

Simulation of proton-proton collision
making two dark matter particles



The LHC Computing Grid

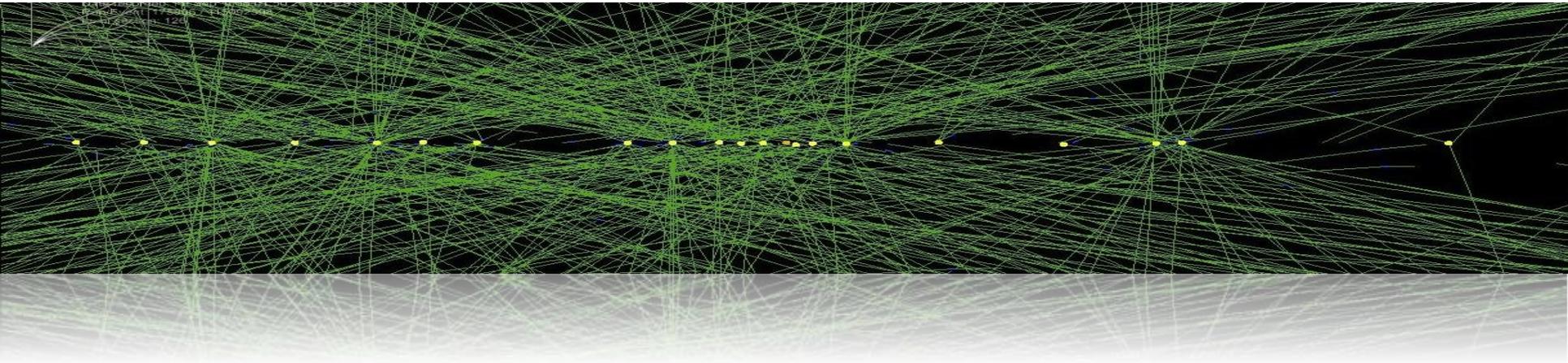
The Grid unites computing resources of particle physics institutions around the world

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:

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

$$= 10^7 \text{ Hz}/\text{mb}$$

Cross section:

$$\sigma \approx 100 \text{ mb}$$

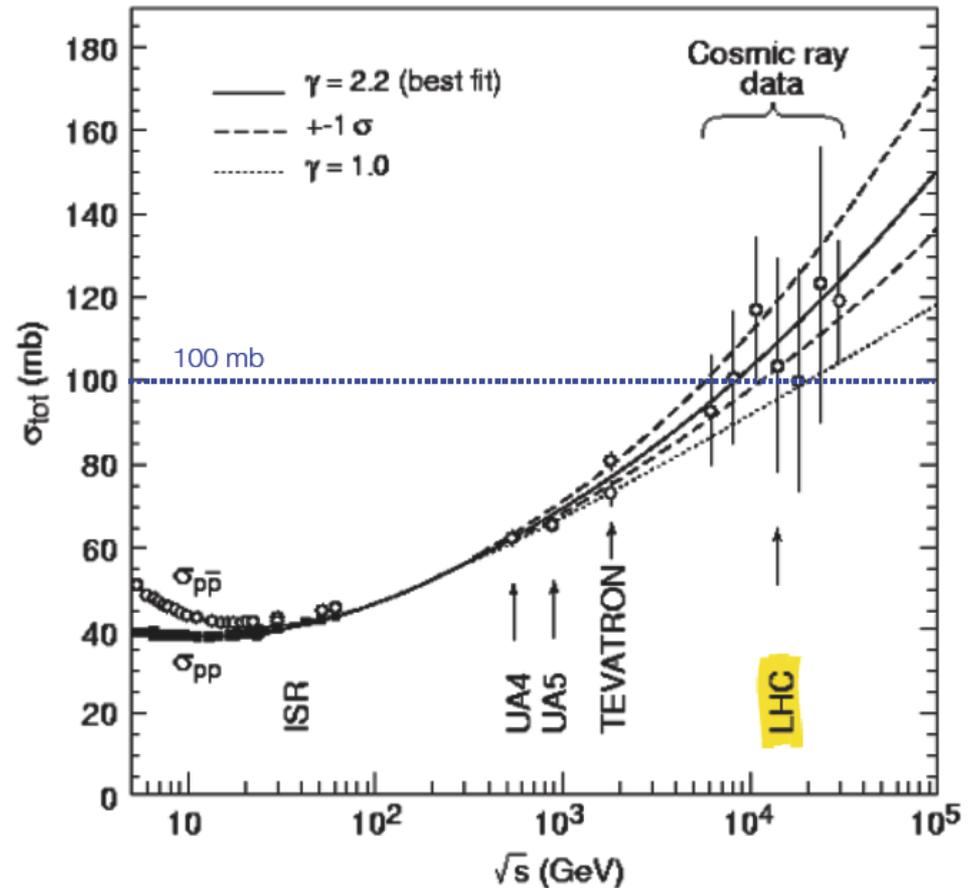
$$\rightarrow N = L\sigma \approx 1 \text{ GHz}$$

However:

Bunch crossing rate: 40 MHz

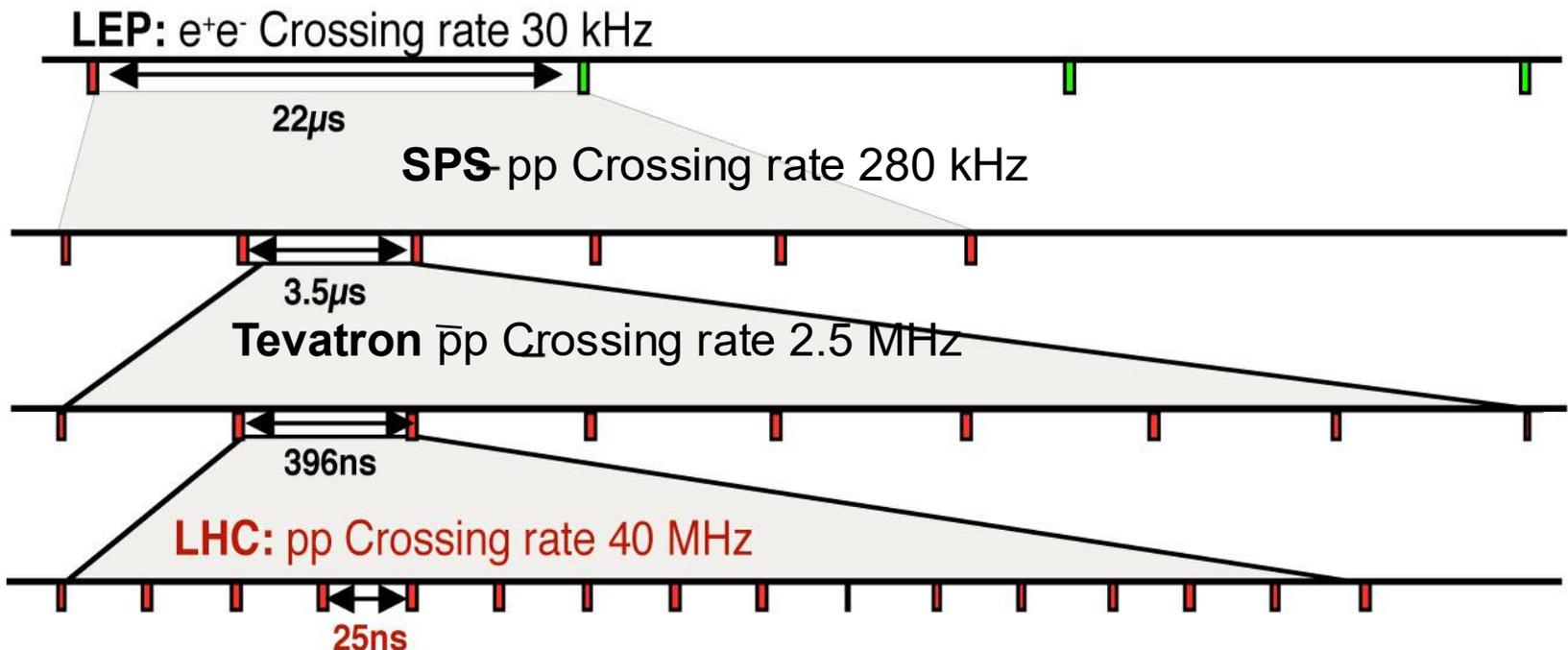
\therefore Interactions/crossing ~ 25

This is a
real challenge !

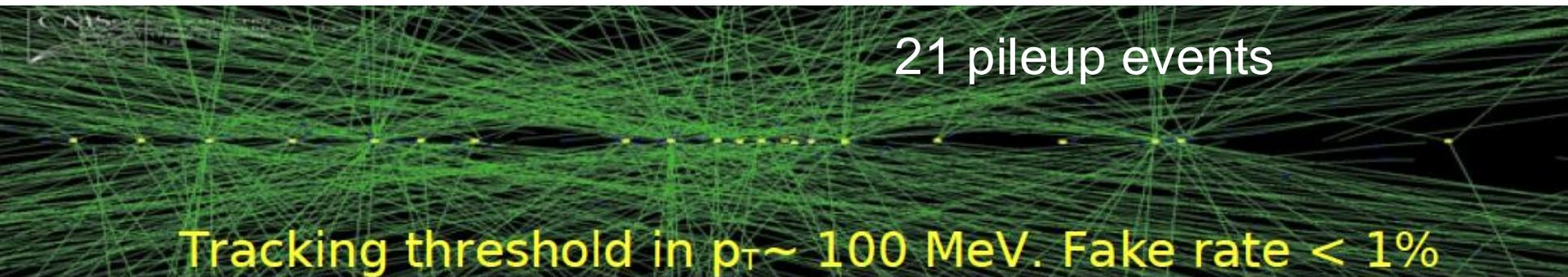


Bunch crossing frequency

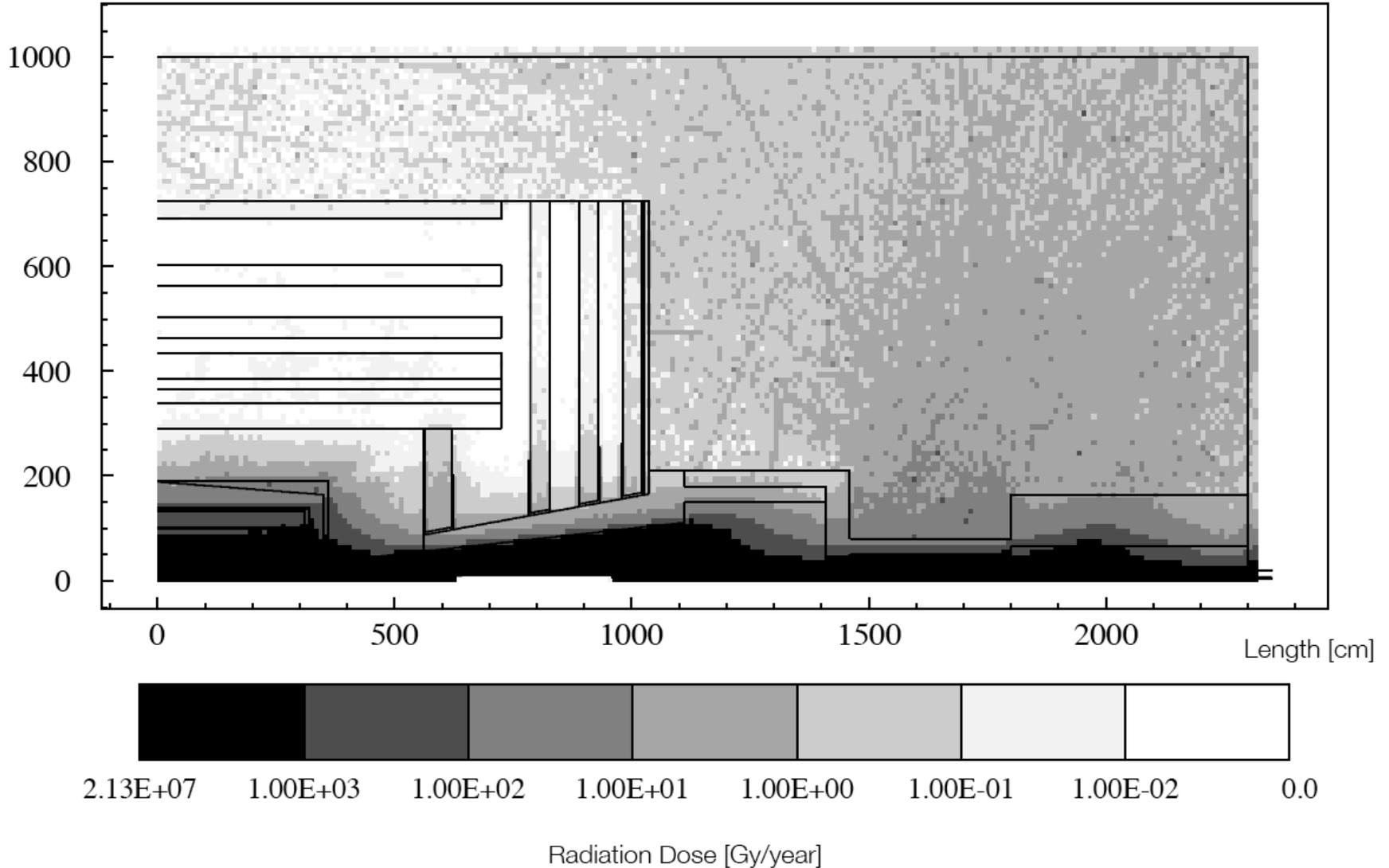
- LHC has 3564 bunches (2835 filled with protons)
- Crossing rate is 40 MHz
- Distance between bunches: $27\text{km} / 3600 = 7.5\text{m}$
- Distance between bunches in time: $7.5\text{m} / c = 25\text{ns}$
- Proton-proton collision per bunch crossing: ~ 25



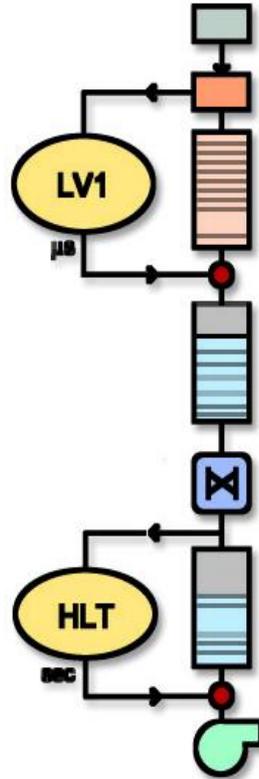
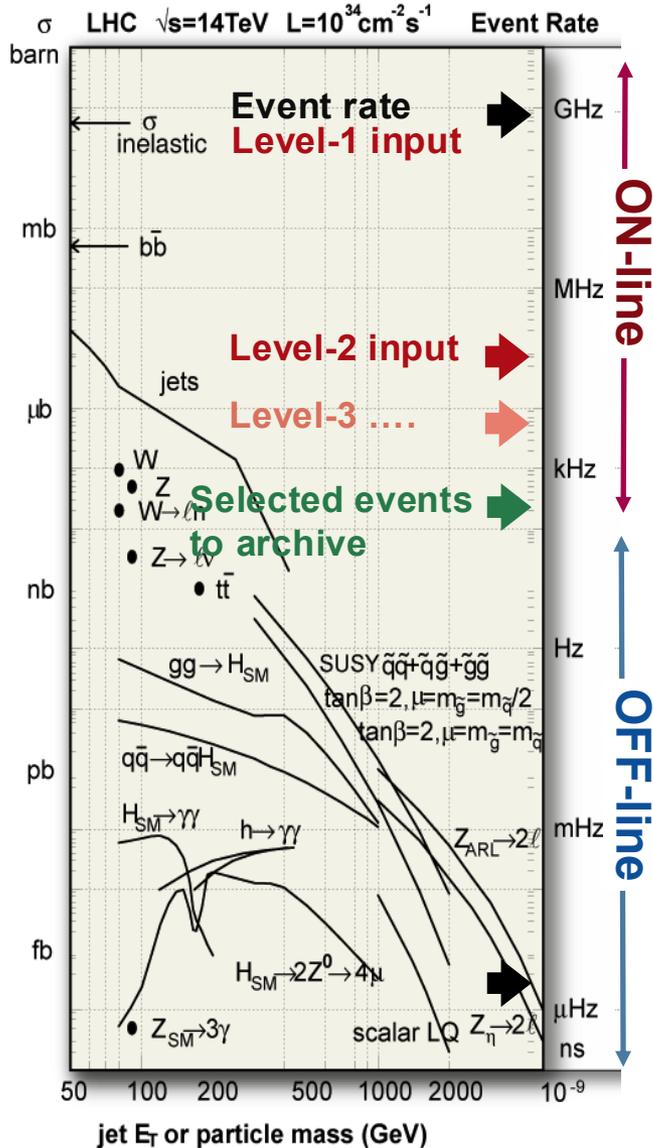
- Proton bunches have a cigar shape, about 5 cm long and 20 microns diameter
- Each bunch has $1.5 \cdot 10^{11}$ protons
- At each crossing of bunches, about 25 collisions occur
- The particles produced ($30 \times 25 = 750$ charged particles) are “seen” by the detector as a single image (event)



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

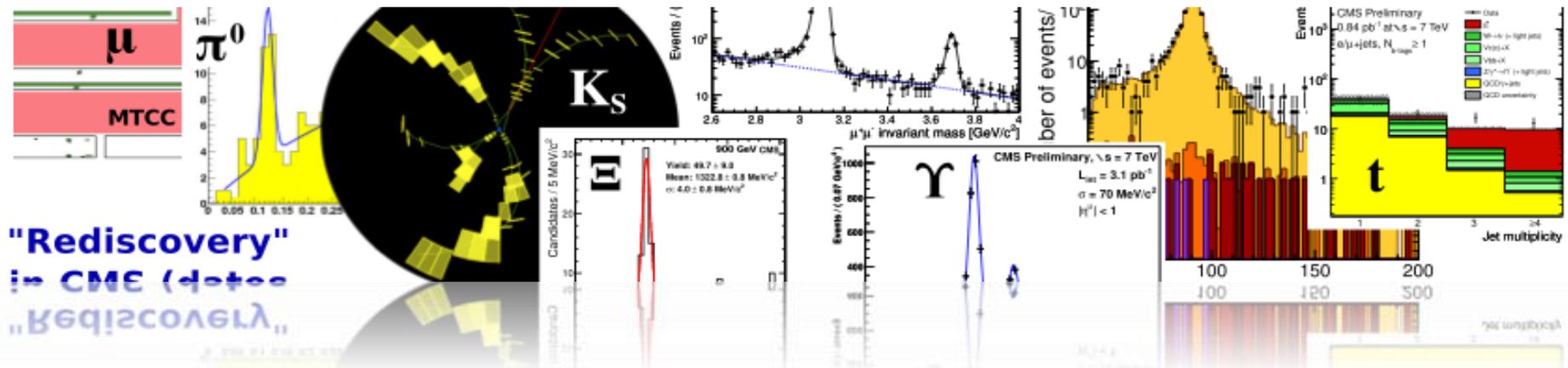
- **High level**: computer farm

Triggers and event selection

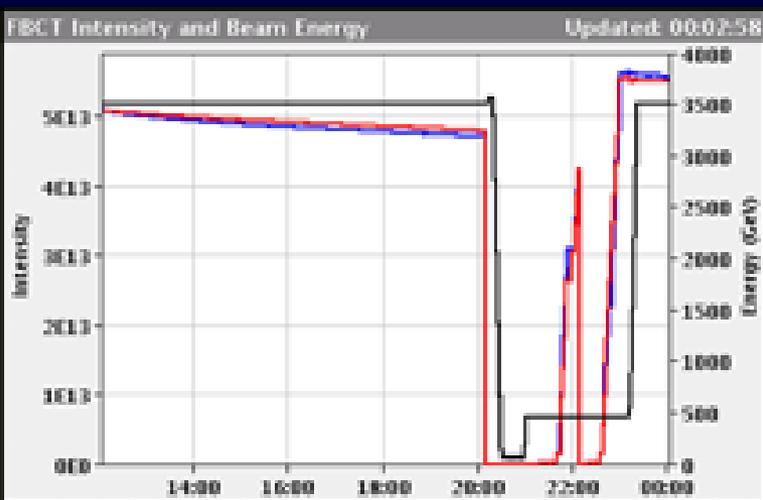
- Select processes that produce particles with high transverse energy
- Examples at $5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
 - Single lepton and photon triggers ($P_T \sim 30 \text{ GeV}$)
 - Multiple lepton and photon triggers ($P_T \sim 15 \text{ GeV}$)
 - Missing transverse energy ($P_T \sim 50\text{-}100 \text{ GeV}$)
 - Multiple jet triggers ($P_T \sim 50\text{-}100 \text{ GeV}$)
- About 100 trigger conditions in L1 trigger table
- About 400 trigger conditions in HLT trigger table

End of Lecture 1

Detector commissioning



LHC Page 1: stable beams

LHC Page1	Fill: 1729	E: 3500 GeV	22-04-2011 00:02:58																					
PROTON PHYSICS: STABLE BEAMS																								
Energy:	3500 GeV	I(B1):	5.50e+13	I(B2):	5.54e+13																			
FBCI Intensity and Beam Energy Updated: 00:02:58 		Instantaneous Luminosity Updated: 00:02:54 																						
Comments 22-04-2011 00:02:52 : <p style="text-align: center;">** Stable Beams **</p> <p style="text-align: center;">World record for luminosity for hadron machine</p> <p style="text-align: center;">Automatic LUMI LEVELING in IP8</p>		BIS status and SMP flags <table border="1"> <thead> <tr> <th></th> <th>B1</th> <th>B2</th> </tr> </thead> <tbody> <tr> <td>Link Status of Beam Permits</td> <td>true</td> <td>true</td> </tr> <tr> <td>Global Beam Permit</td> <td>true</td> <td>true</td> </tr> <tr> <td>Setup Beam</td> <td>false</td> <td>false</td> </tr> <tr> <td>Beam Presence</td> <td>true</td> <td>true</td> </tr> <tr> <td>Moveable Devices Allowed In</td> <td>true</td> <td>true</td> </tr> <tr> <td>Stable Beams</td> <td>true</td> <td>true</td> </tr> </tbody> </table>			B1	B2	Link Status of Beam Permits	true	true	Global Beam Permit	true	true	Setup Beam	false	false	Beam Presence	true	true	Moveable Devices Allowed In	true	true	Stable Beams	true	true
	B1	B2																						
Link Status of Beam Permits	true	true																						
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Setup Beam	false	false																						
Beam Presence	true	true																						
Moveable Devices Allowed In	true	true																						
Stable Beams	true	true																						
AFS: 50ns_480b+1small_424_12_468_36bpl15in]		PM Status B1 ENABLED PM Status B2 ENABLED																						

March 30, 2010: CMS Page 1

30/03/10 Session DAQ state Run Number Lv1 rate Ev. size DeadTime(AB) Acc. Hz(%) <HLT CPU>
 Tue 13:17:05 126284 Running 132440 1.044 kHz 495.9 kB 0.0% 1043.8(100.0) 1.47%

lhc1

LHC Page1 Fill: 1005 E: 3500 GeV 30-03-2010 13:17:01

BEAM SETUP: FLAT TOP

Energy: 3500 GeV I(B1): 1.88e+10 I(B2): 1.74e+10

Comments 30-03-2010 13:15:51:
 Preparing for stable beam!
 Preparing to move collimators IN

BIS status and SHIP flags
 Link Status of Beam Permits
 Global Beam Perms
 Setup Beam
 Beam Priorities
 Movable Devices Allowed In
 Stable Beams

LHC Operation in CCC : 77600, 70480
 PH Status B1: 126284 PH Status B2: 126284

Data to Surface

Sub-System	State	FRL	FED	IN
TRG	Running	3	3	3
CSC	Running	9	9	9
DAQ	Running	0	0	0
DQM	Running	0	0	0
DT	Running	11	11	11
ECAL	Running	54	54	54
ES	Running	40	40	40
HCAL	Running	32	32	32
PIXEL	Running	40	40	40
RPC	Running	3	3	3
SCAL	Running	1	1	1
TRACKER	Running	250	440	438
CASTOR	Running	3	3	3

SM streams

Stream	No.Events	Rate (Hz)	BnW (MB/s)
Calibration	379.676E+3	97.52	16.62
EcalCalibrati	379.676E+3	97.56	2.02
A	262.205E+3	112.70	20.95
Express	48.716E+3	37.87	7.55
ALCAPHYSYM	7.090E+3	5.53	0.02
HLTMON	3.303E+3	2.02	0.39
ALCAP0	684.000E+0	0.38	0.00
OnlineErrors	26.000E+0	0.03	0.01
RPCMON	15.000E+0	0.00	0.00
Error	0.000E+0	0.00	0.00

Data Flow

#LS 171

LHC_RAMPING false
 PHYSICS_DECLARED true
 PIX_HV_ON true
 TK_HV_ON true

CalibCyc ON

#Lv1(GT) 3909384
 Lv1 Rate 1.044 kHz

Pending Lv1 114131

#Frag. in RU Max 103 Min 42

FBI occ. % Max 0 Min 0
 FBO occ. % Max 0 Min 0

BnW (MB/s) 501
 EvSize (kB) 496.7

Events in BU 0
 <Ev.> 0

Pending Req. 15989
 <#P> 23.8

#Running FUs 4704 100.00%

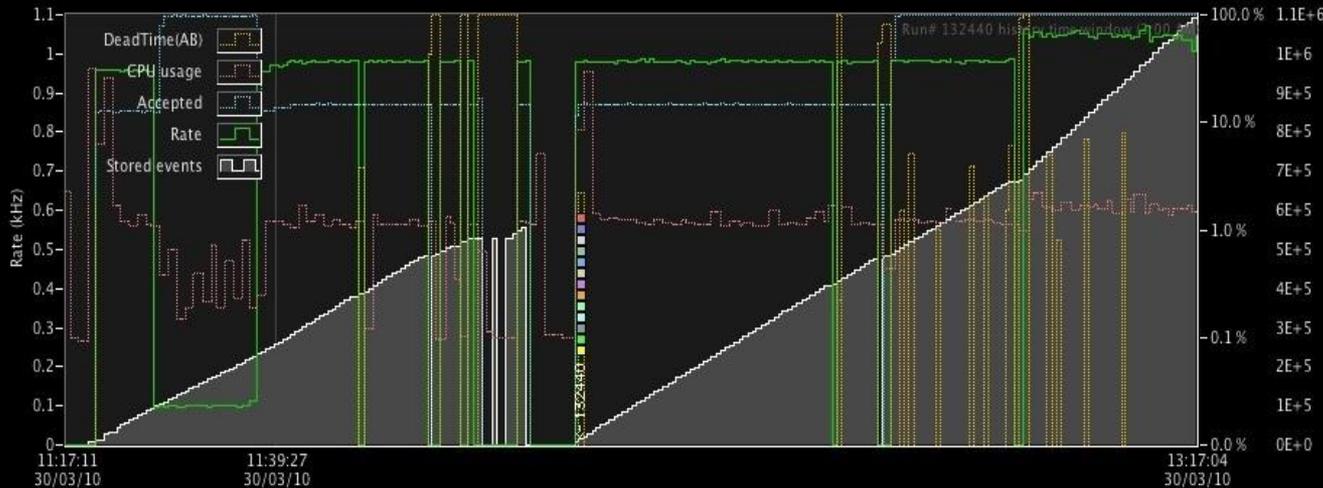
Acc.Rate 1043.792 Hz

BnW MB/s 47.4
 EventRate Hz 364.1

Disks usage % log scale
 <SM-CPU> 5.77 %
 Free space TB 229

Time to fill disk 2 of srv-c2c07-17 > week
 Stored 1092490

[Rate(kHz) | Stored | Accepted% | CPU%] / Time

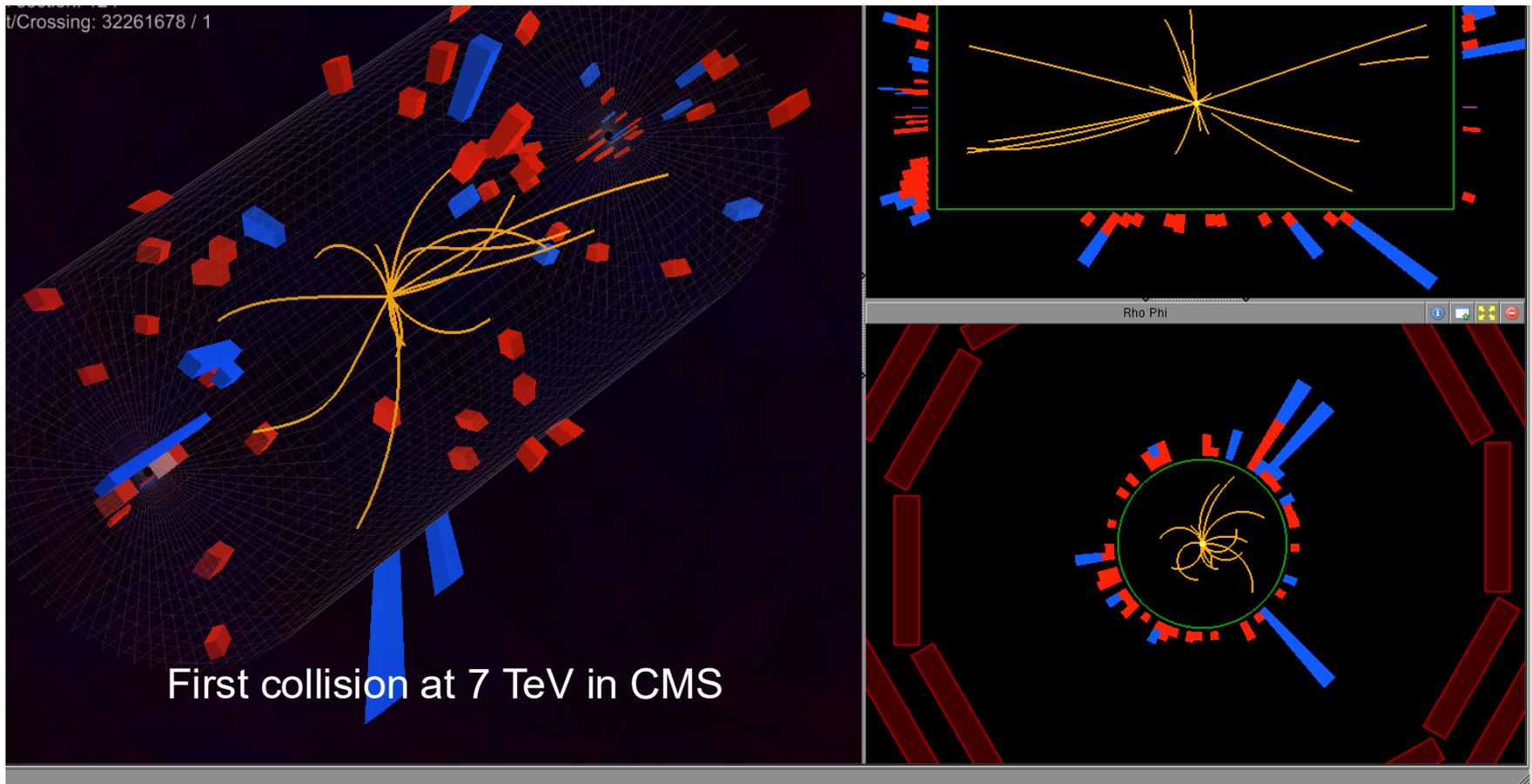


2009: First p-p collisions at LHC

November 23, 2009
First collisions at 900 GeV

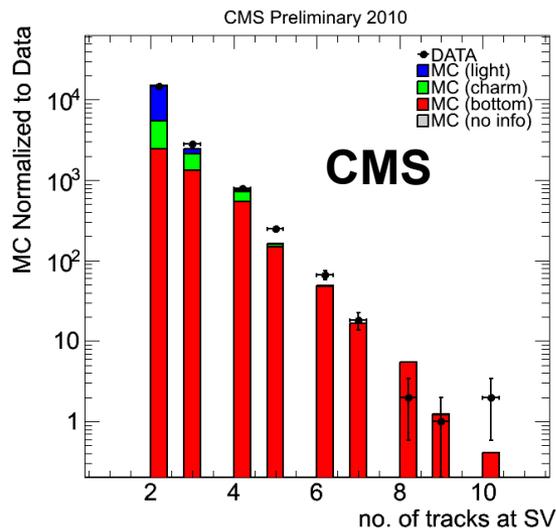
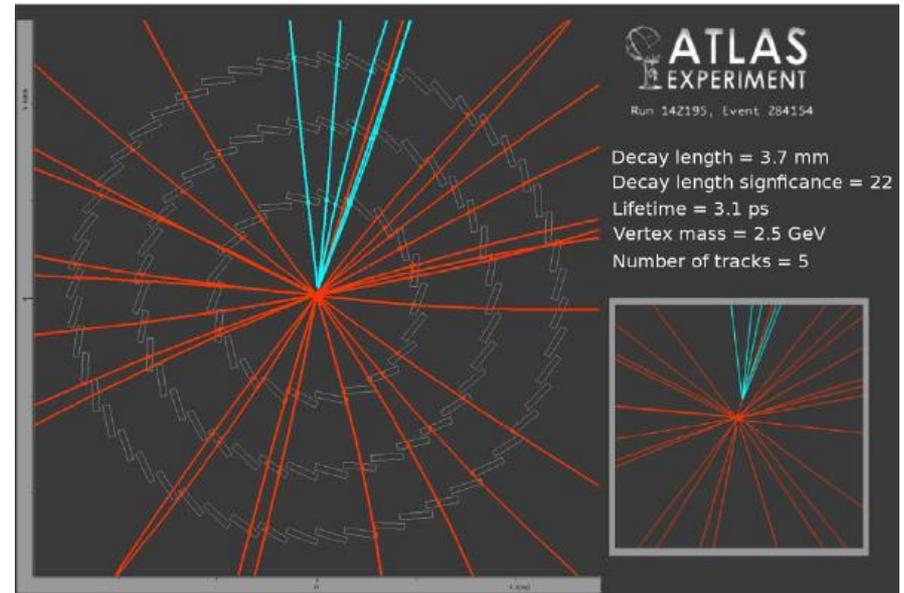
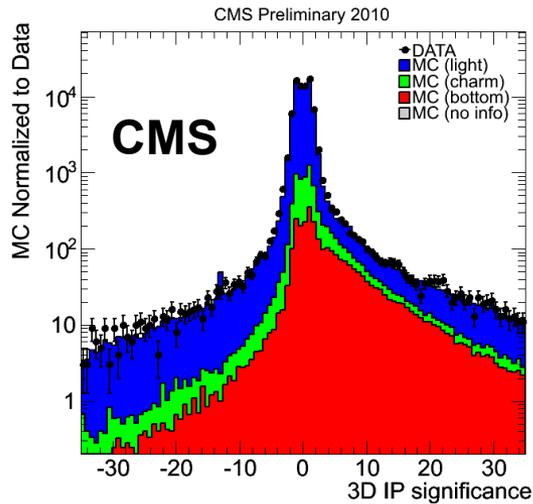
December 14, 2009
First collisions at 2.36 TeV

March 30, 2010
First collisions at 7 TeV



Tracking: secondary vertices

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

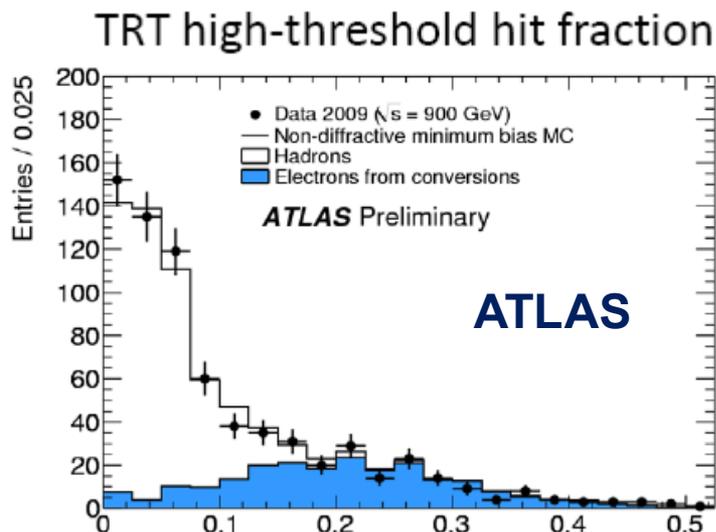
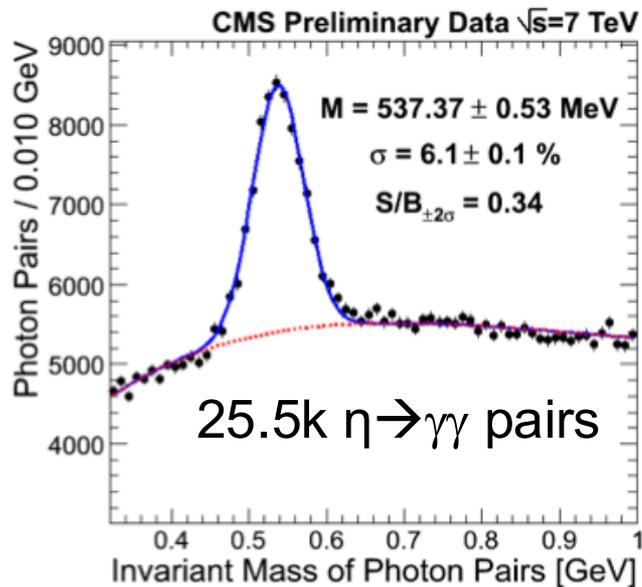
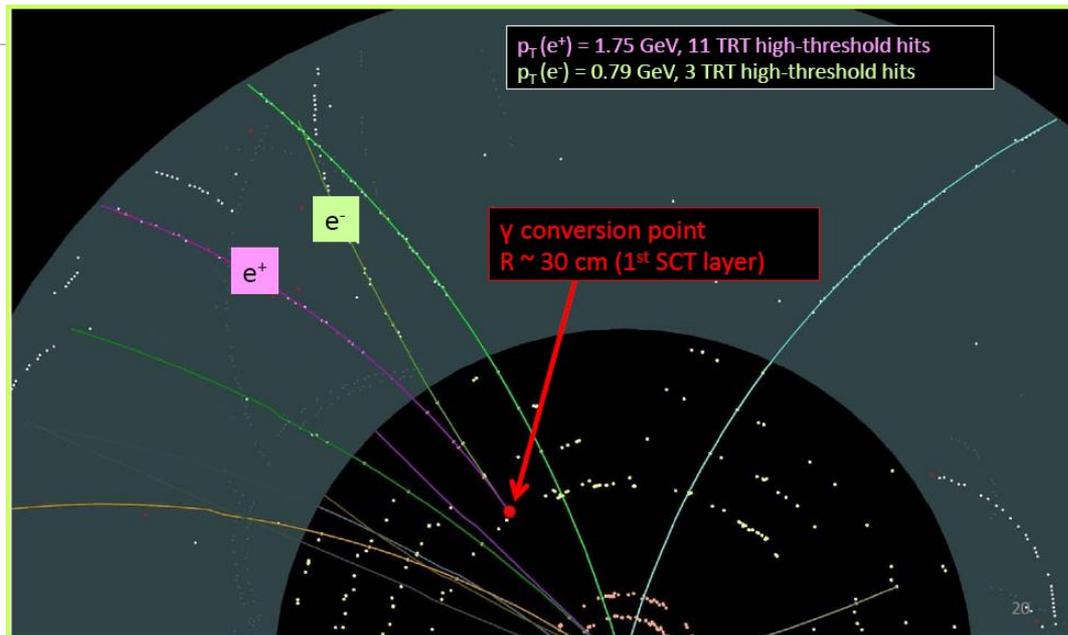
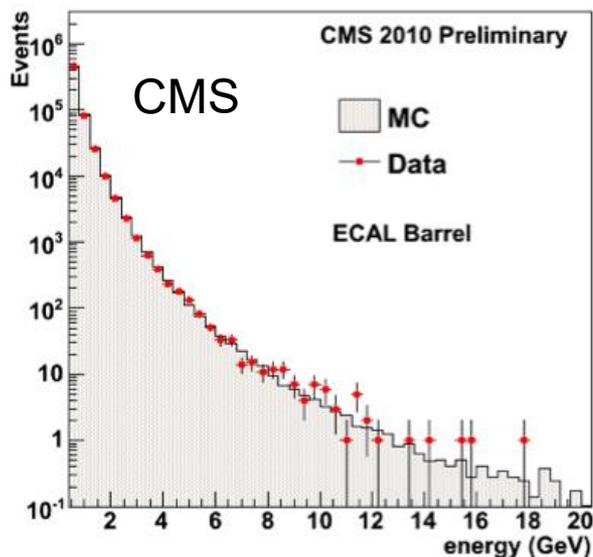


Secondary vertices compatible with heavy flavor production

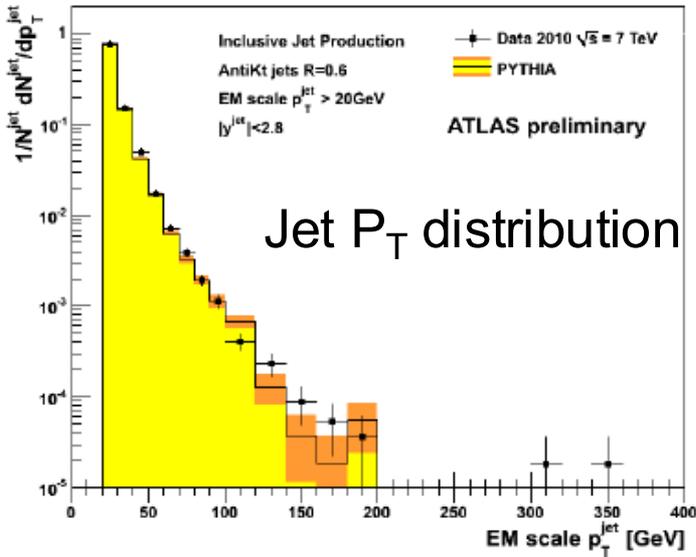
Photons and electrons



EM cluster energy

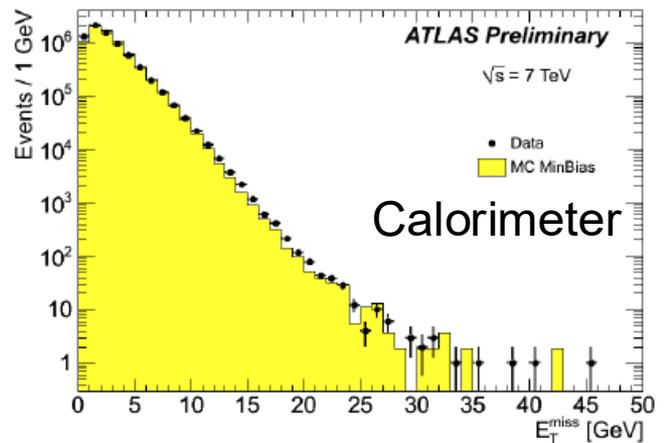


Jets and missing energy

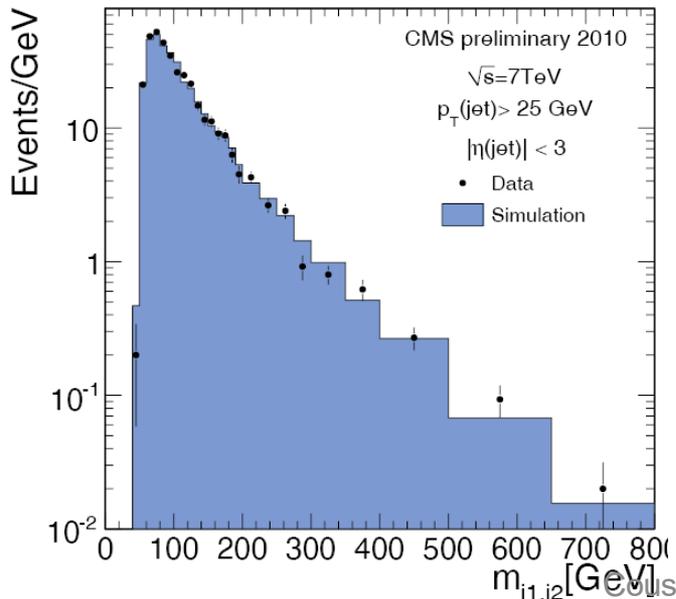


ATLAS

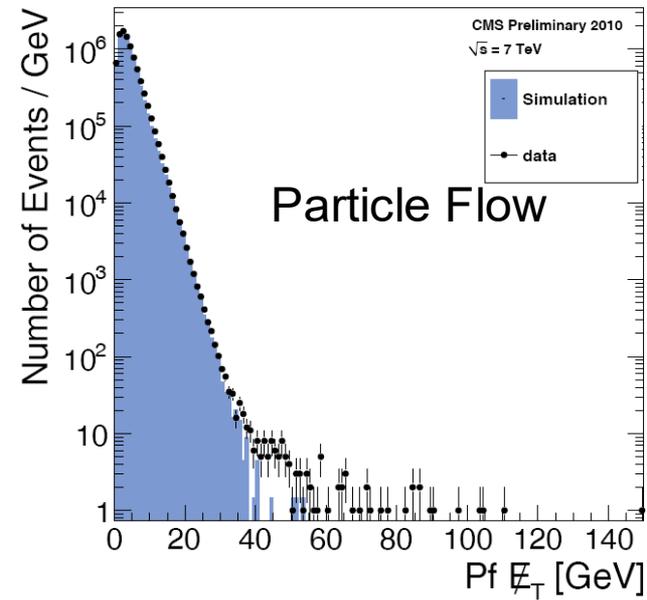
Missing Transverse Energy



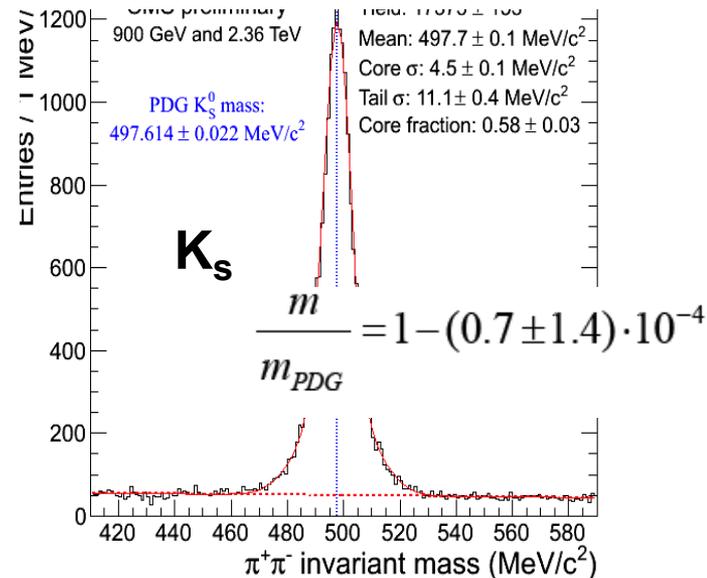
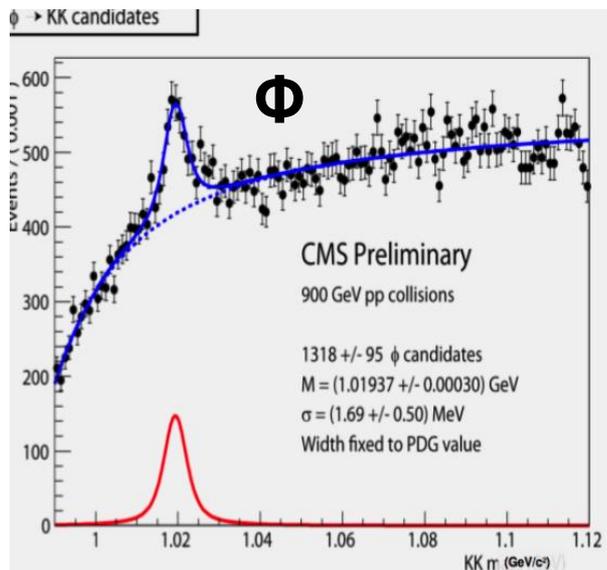
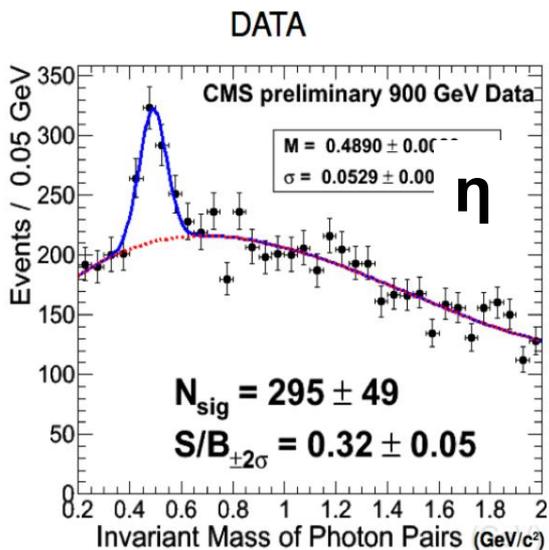
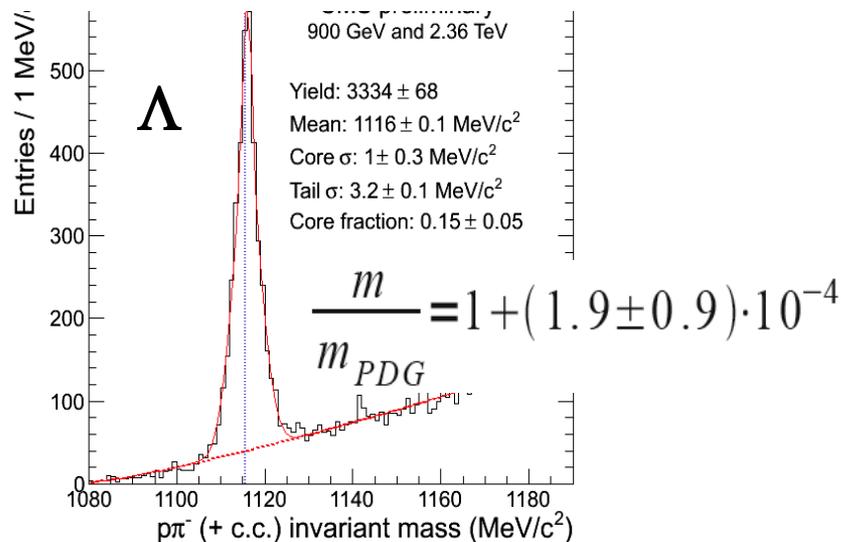
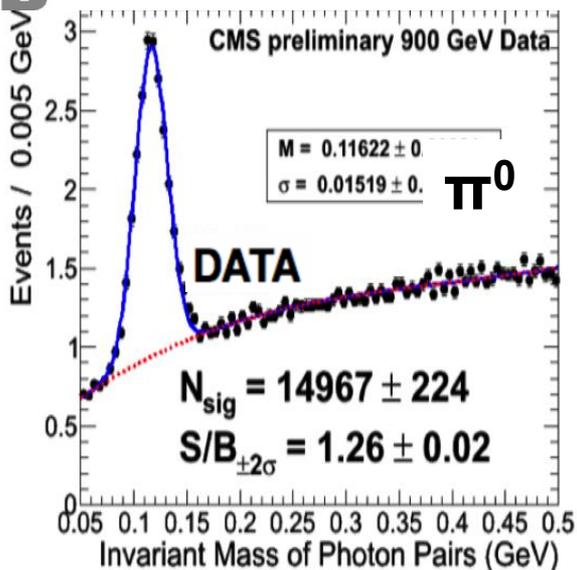
Di-jet mass



CMS



Rediscovery of resonances



Rediscovery of the Standard Model at LHC

