Large Hadron Collider

Lecture 3

The Detectors, performance and operation

Juan A. Fuster Verdú IFIC-València
Taller de Altas Energías
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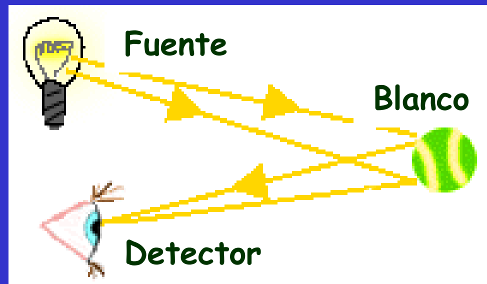
Detectores (principio general)

Principio de detección del paso de una partícula:

interacción con el medio + conversión en señal eléctrica + digitalización + procesado ....

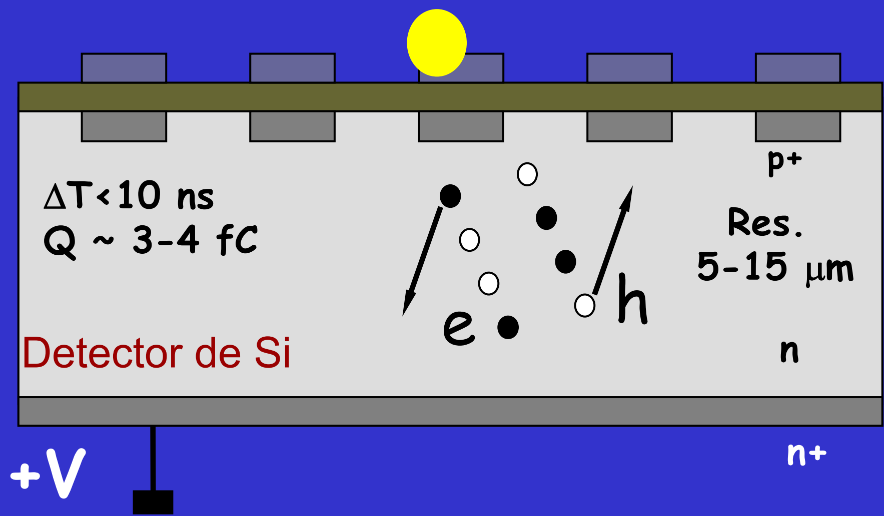
Principio General



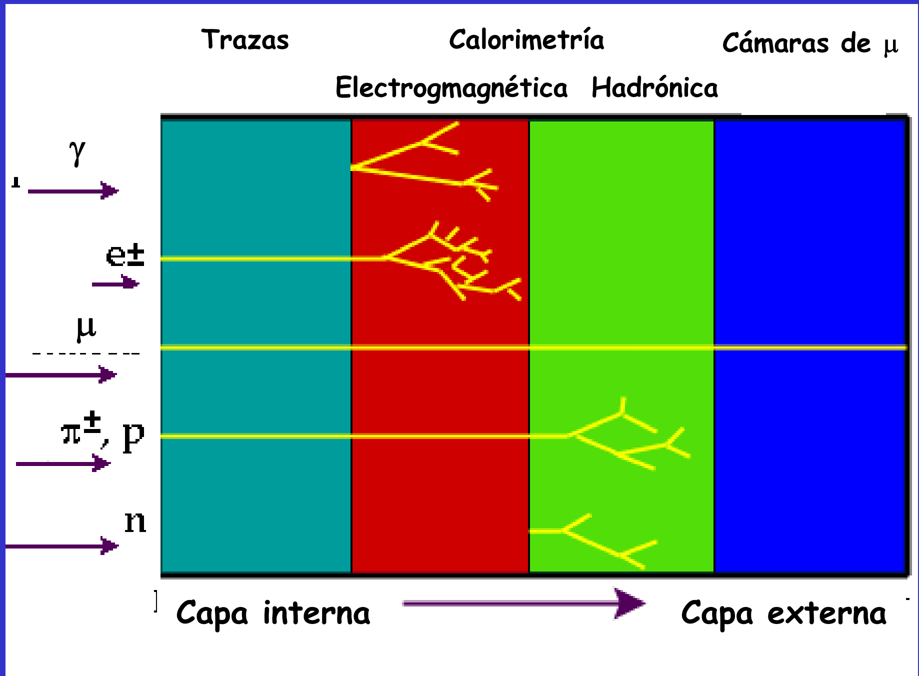
Ejemplo práctico

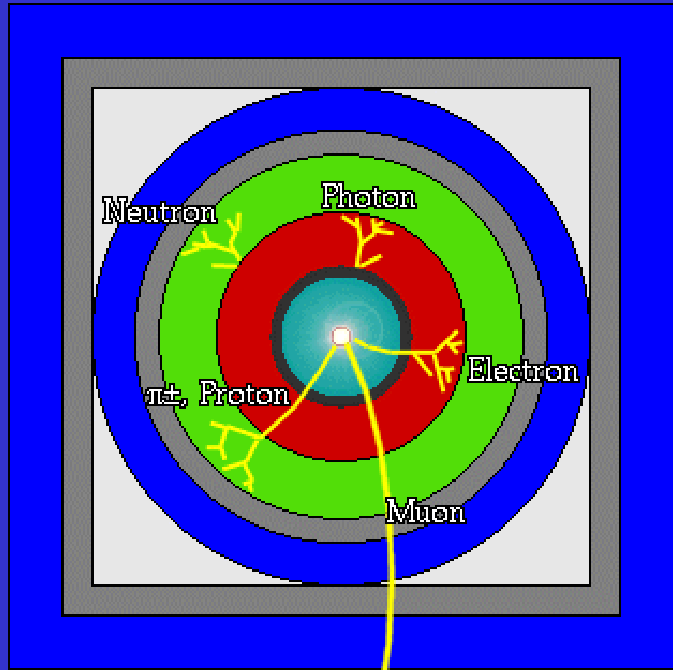
Lectura de la señal

(amplificación, digitalización...)



Los detectores de los Grandes Aceleradores
Principios Básicos





Ejemplo DELPHI en LEP

Concepción + proyecto:	3 años
Construcción:	4 años
Explotación y toma de datos:	10 años
Colaboración internacional:	~ 50 institutos
Número de físicos:	400-500
Coste de un experimento:	50 Meuros

Organización y especialización

Ejemplo ATLAS en LHC

Concepción + proyecto:	10-15 años
Construcción:	6 años
Explotación y toma de datos:	10 años
Colaboración internacional:	130 institutos
Número de físicos:	~1500
Coste de un experimento:	300 Meuros

Mayor organización y especialización !!

Historical introduction

1984: First discussions on LHC and SSC

1987: First studies on the physics potential of hadron colliders (LHC/SSC)

1989: R&D for LHC detectors begins

1993: Demise of the SSC

1994: LHC machine is approved (start in 2005)

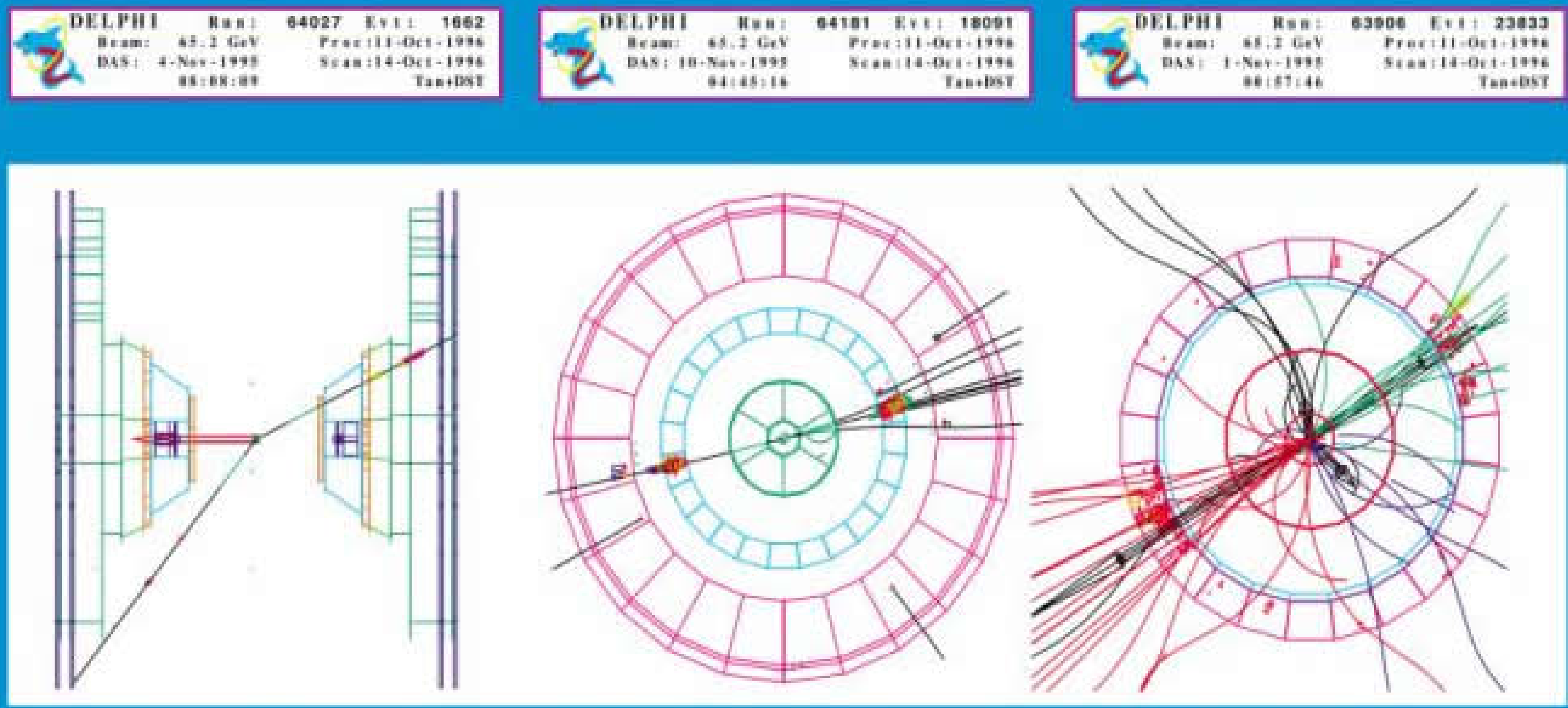
1995: Approval of ATLAS and CMS

2001: LHC schedule delayed by two more years (start in 2007 ?)

During the last 12 years, three parallel activities have been ongoing at CERN:

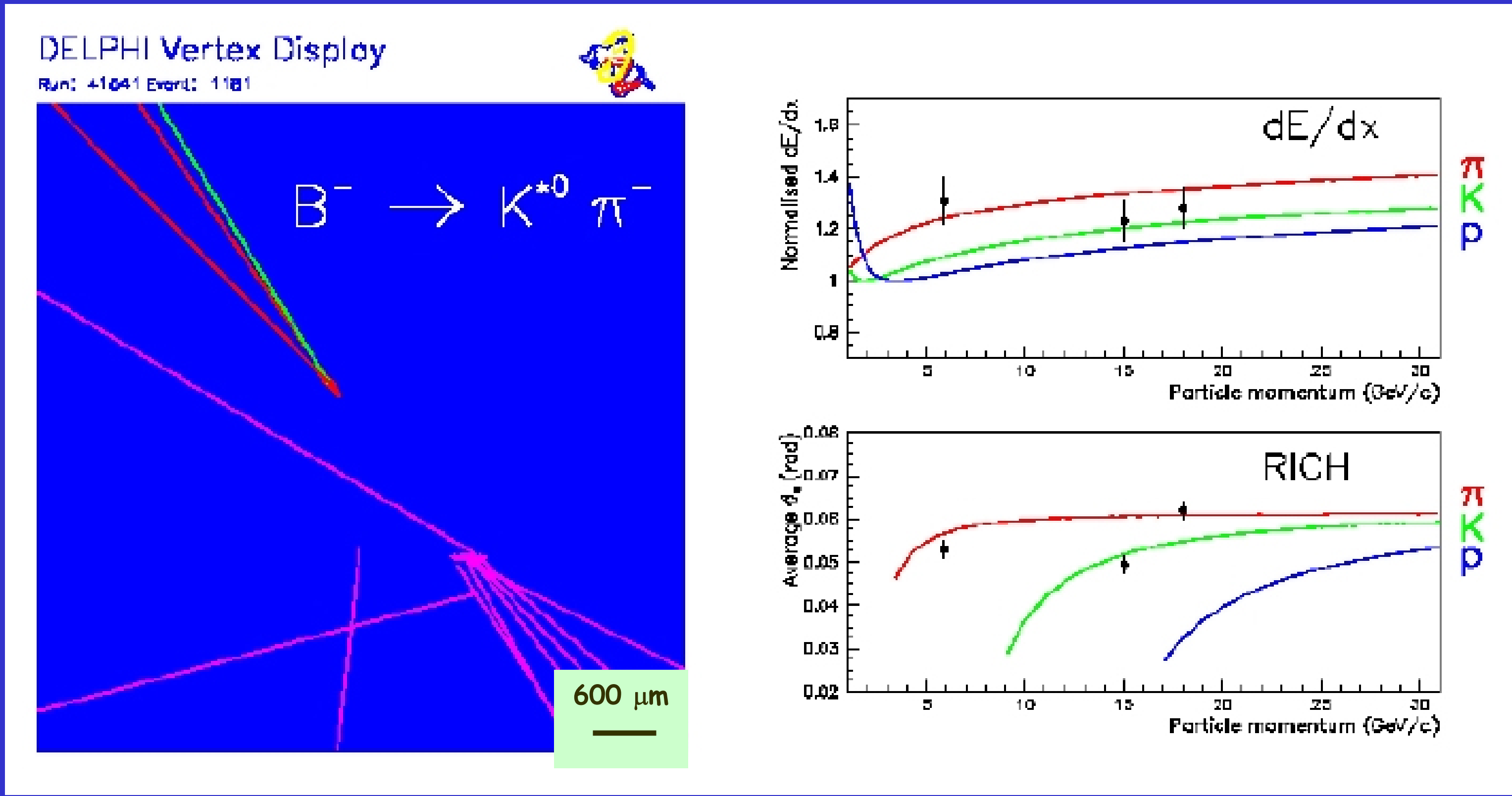
1) Physics at LEP with many physics results
2) Construction of the LHC machine
3) Construction of the LHC detectors after an initial very long R&D period

Qué se observa en los detectores ?
(procesos distintos)



$e^+ + e^- \rightarrow \mu^+ + \mu^- + \gamma$ $\quad$ $e^+ + e^- \rightarrow \tau^+ + \tau^-$ $\quad$ $e^+ + e^- \rightarrow q\bar{q} + 2g$

Qué se observa en los detectores ?



Identificación de producción de una partícula de la tercera generación: B^-

Vida media de B^- : 0.000000000001674 (18) seg

Merced a su alta velocidad ~c y la dilatación relativista del tiempo estas partículas recorren unos pocos milímetros antes de desintegrarse.

Suficiente para que detectores muy precisos detecten su "efímera" existencia.

Cómo construir un detector del LHC ?

Generic features required of ATLAS and CMS

- Detectors must survive for at least 10 years of operation
  - Unprecedented radiation damage to detector components: NEW!
- Detectors must provide precise timing and be as fast as feasible
  - Bunch crossing of 25 ns : NEW!
- Detectors must have excellent spatial granularity
  - Need to minimise pile-up effects: NEW!
- Detectors must identify extremely rare events, mostly in real time
  - Lepton identification above huge QCD backgrounds: NEW!
  - Online rejection to be achieved is ~ 10^7: NEW!
  - Store huge data volumes (~ 10^9 evts/year of 1 Mbyte) : NEW!

How huge are ATLAS and CMS?

- Size of detectors

    - Volume: 20 000 m^3 for ATLAS
    - Weight: 12 500 tons for CMS
    - 66 to 80 million pixel readout channels near vertex
    - 200 m^2 of active Silicon for CMS tracker
    - 175 000 readout channels for ATLAS LAr EM calorimeter
    - 1 million channels and 10 000 m^2 area of muon chambers
    - Large-scale offline software and computing (GRID)

- Time-scale

    about 25 years from first conceptual studies (Lausanne 1984) to first significant data (early 2009?)

- Size of collaboration

ATLAS Collaboration

As of July 2006:

35 Countries
162 Institutions
1650 Scientific Authors
(1300 with a PhD)

Main specific design choices of ATLAS/CMS

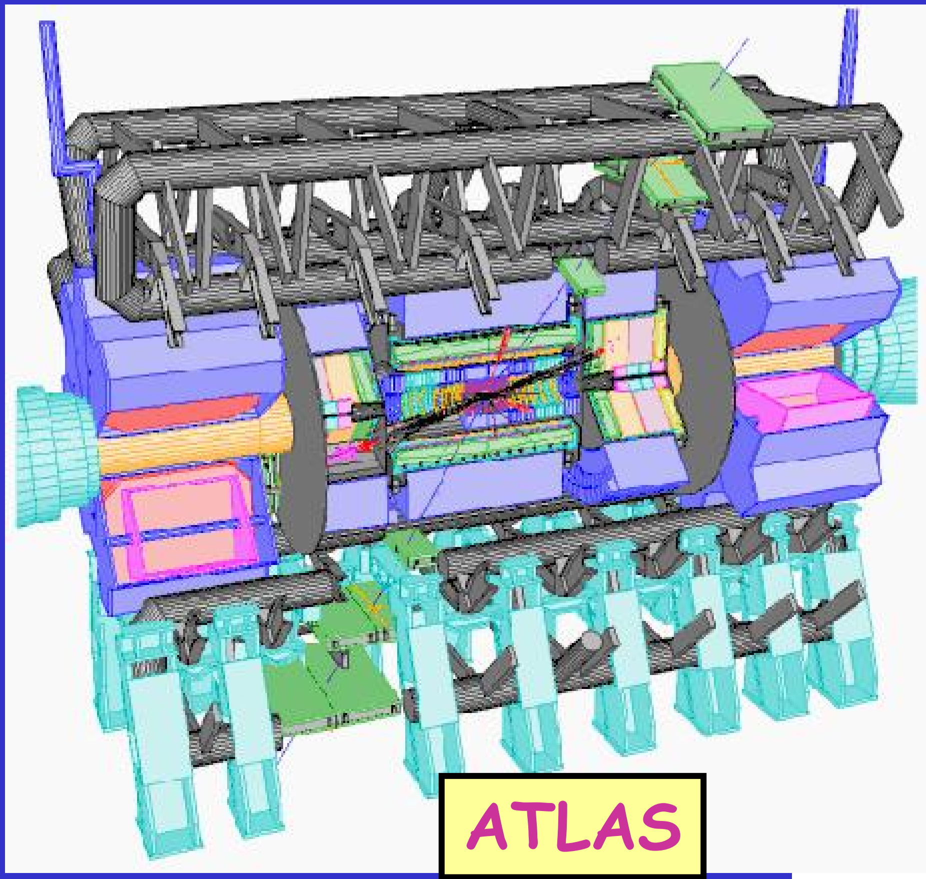
Choice of magnet system has shaped the experiments in a major way

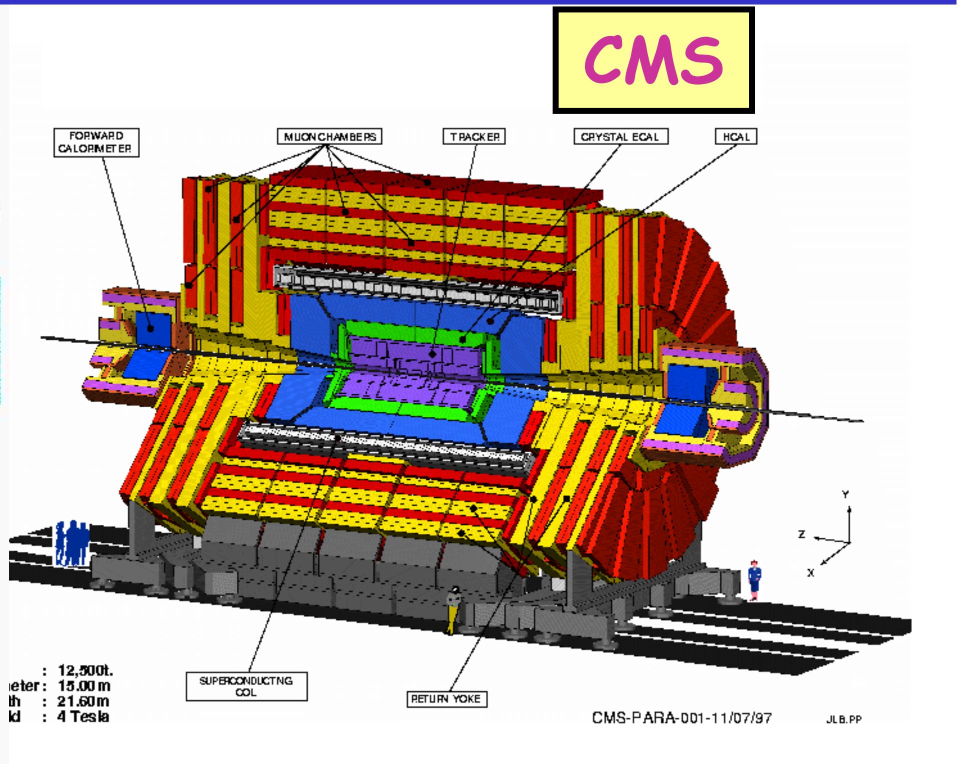
- ATLAS choice: two separate magnet systems (small 2 T solenoid for tracker and huge toroids for muon spectrometer)
  Pros: large acceptance for muons and excellent muon momentum resolution
  Cons: very expensive and large-scale toroid magnet system
- CMS choice: one large 4 T solenoid with instrumented return yoke
  Pros: excellent momentum resolution for inner tracker and more compact experiment
  Cons: limited performance for muons and limited space for calorimeters inside coil

EM calorimetry of ATLAS and CMS is based on very different technologies

- ATLAS LAr sampling calorimeter with good energy resolution and excellent lateral and longitudinal segmentation (e/γ identification)
- CMS PbWO4 scintillating crystals with excellent energy resolution and lateral segmentation but no longitudinal segmentation

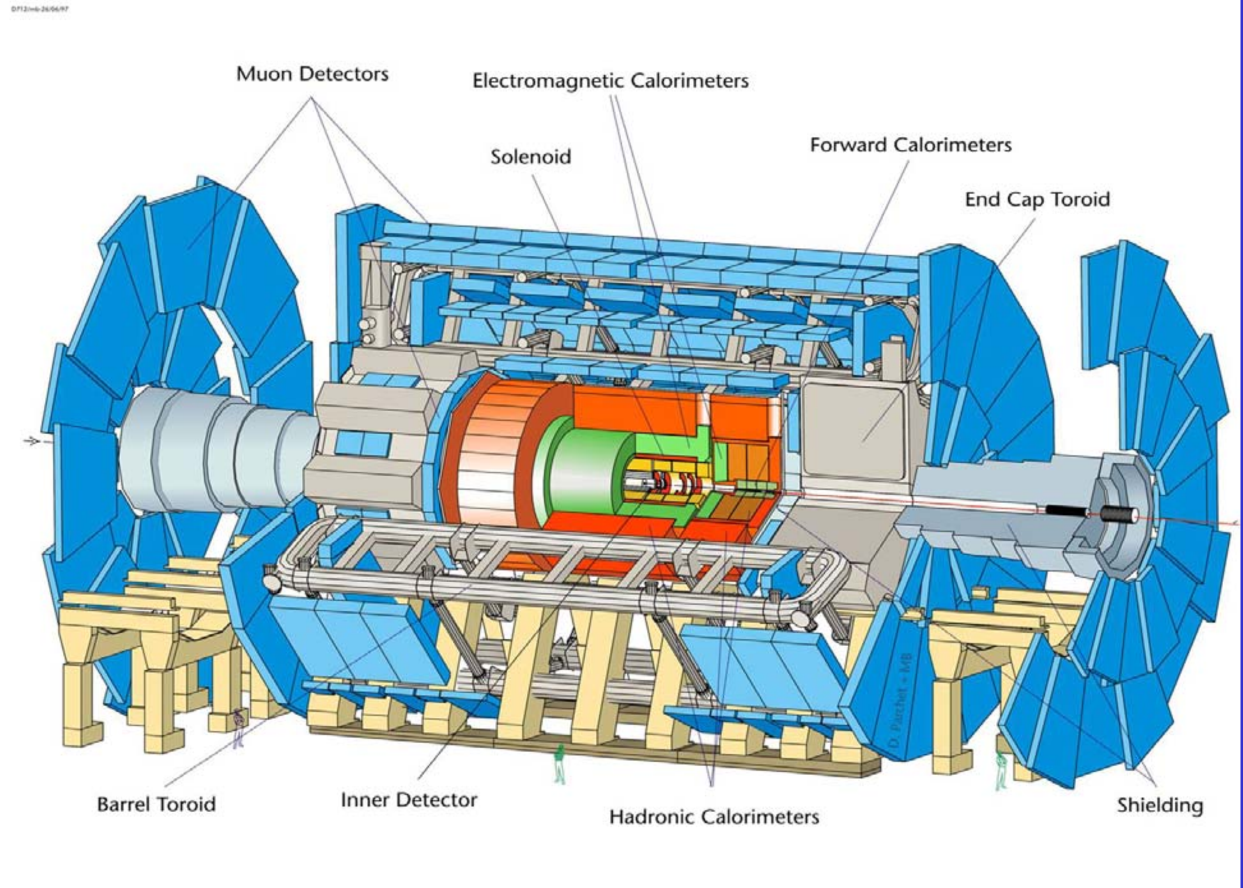
Overall detector parameters





	ATLAS	CMS
Overall weight (tons)	7000	12500
Diameter	25 m	15 m
Length	44 m	22 m
Solenoid field	2 T	4 T

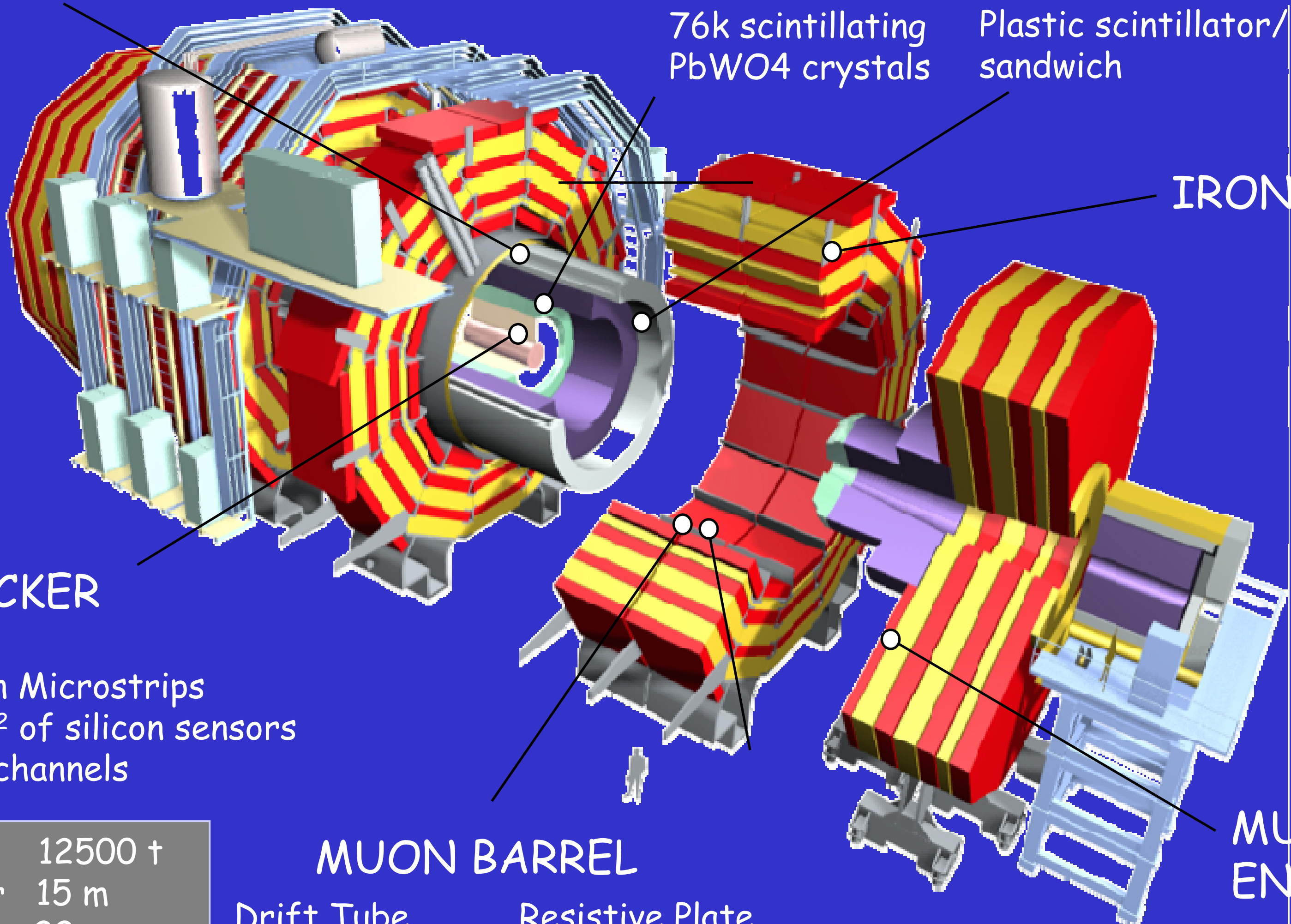
The ATLAS experiment



- Solenoidal magnetic field (2T) in the central region (momentum measurement)
- High resolution silicon detectors space resolution: ~ 15 mm
- Energy measurement down to 1° to the beam line
- Muon spectrometer (supercond. toroid system)

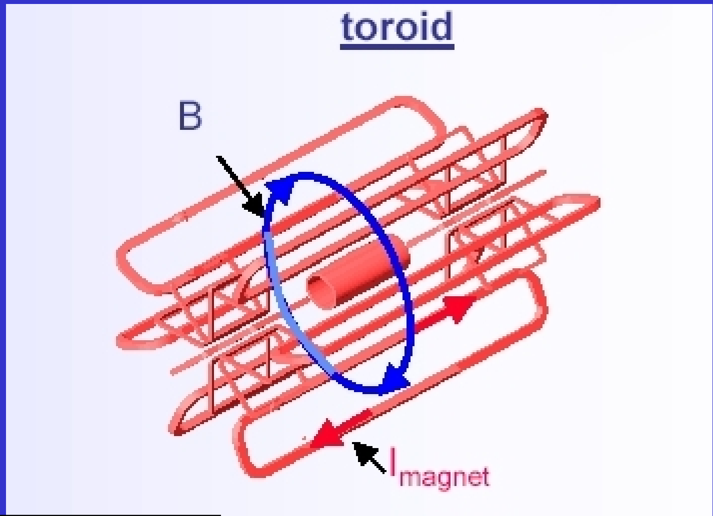
Overall diameter	25 m
Overall length	44 m
Overall weight	7000 Tons

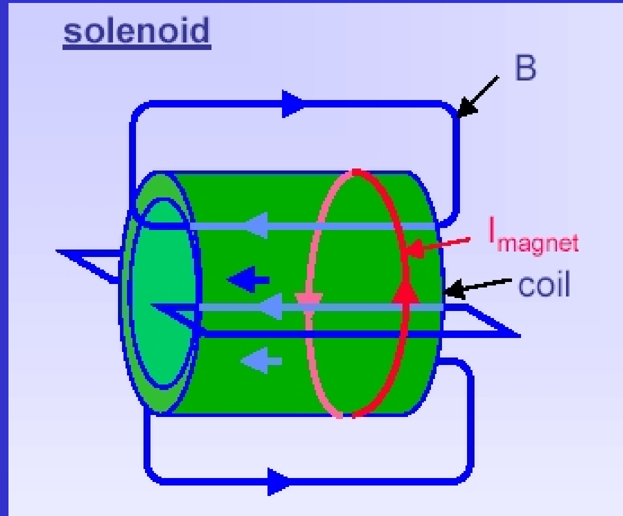
CMS



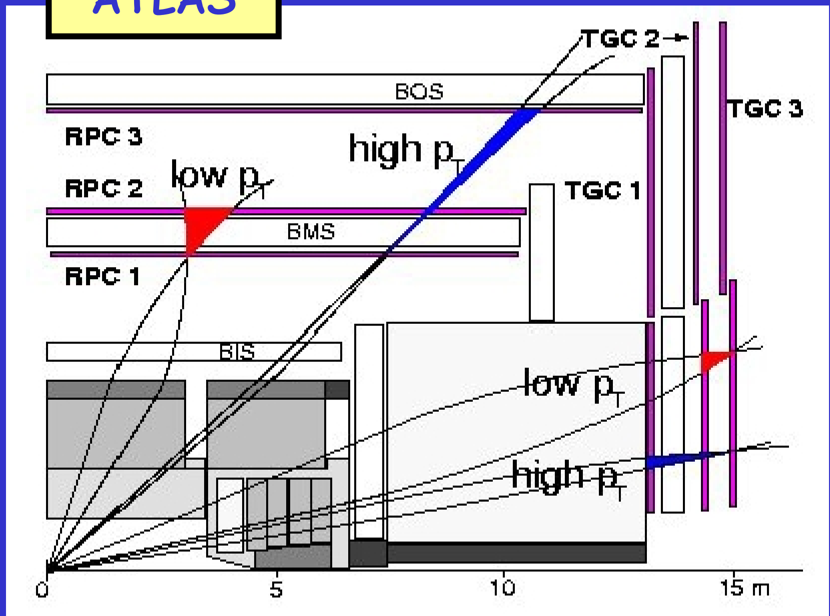
Total weight	12500 t
Overall diameter	15 m
Overall length	22 m

Main specific design choices: magnet system

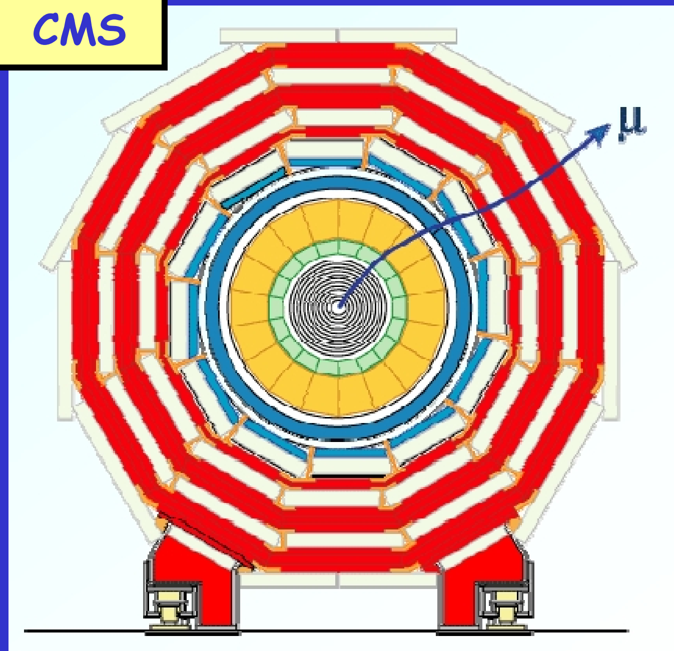




ATLAS

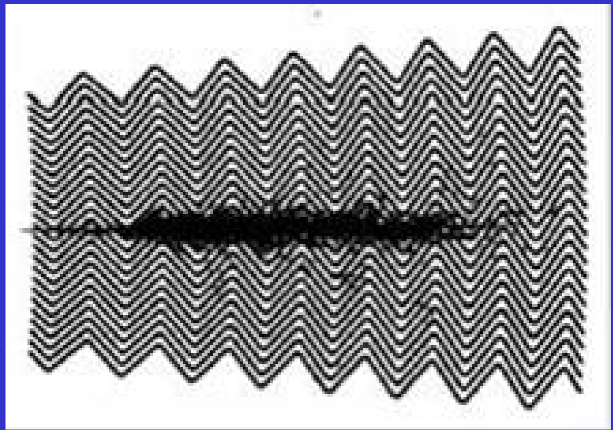


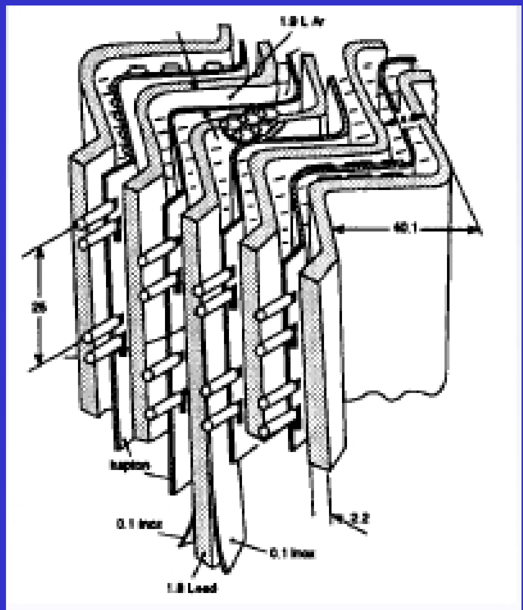
CMS



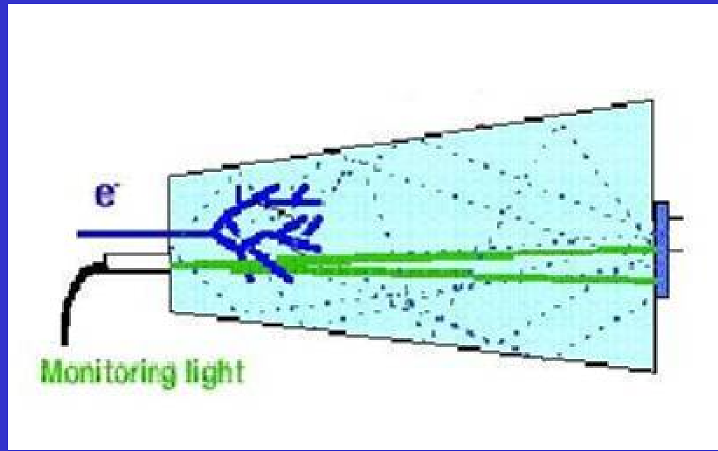
Main specific design choices: EM calorimetry

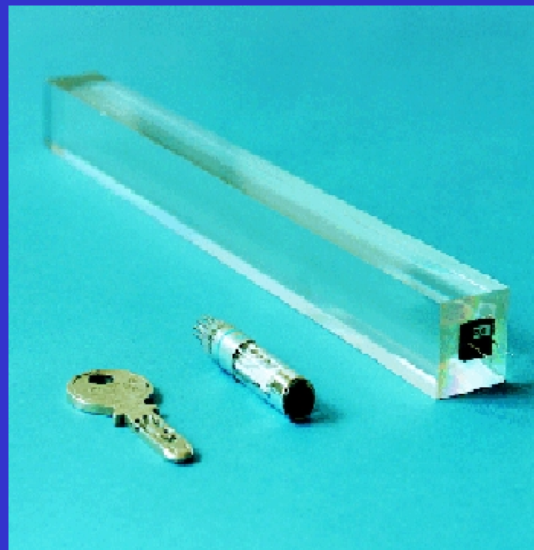
ATLAS: LAr accordion



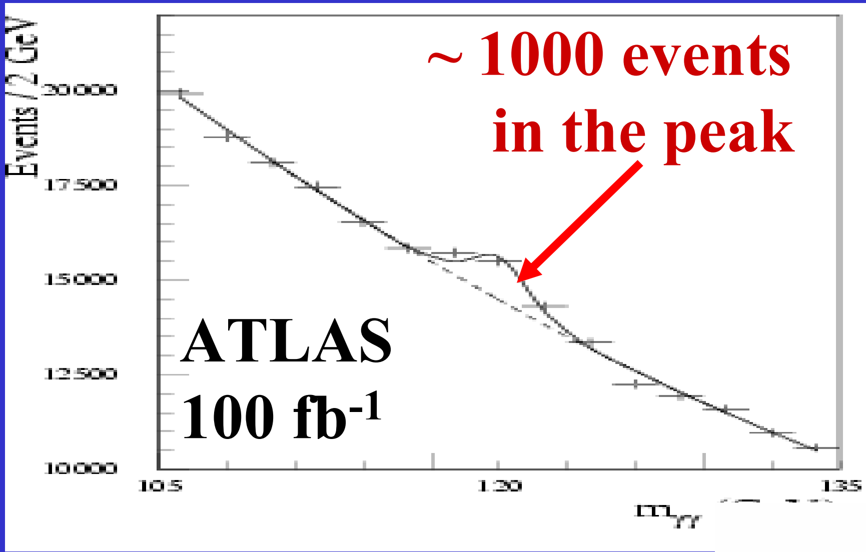


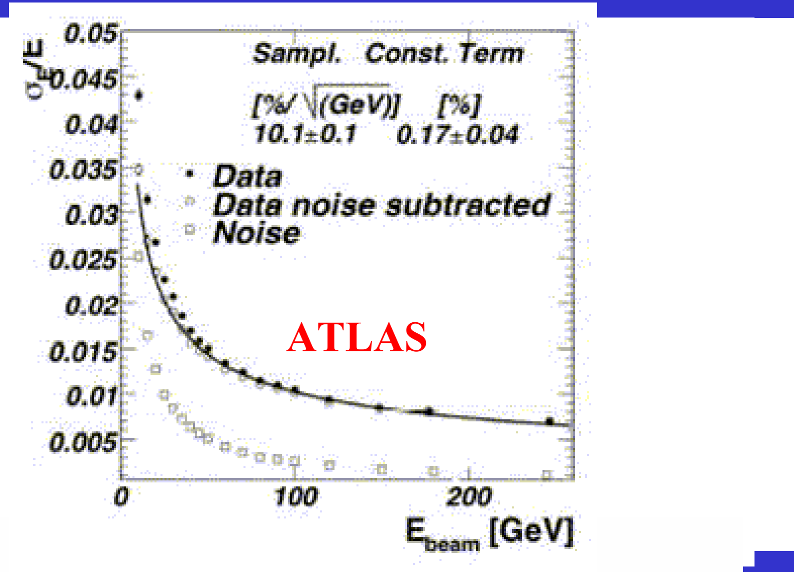
CMS: $PbWO_4$ crystals

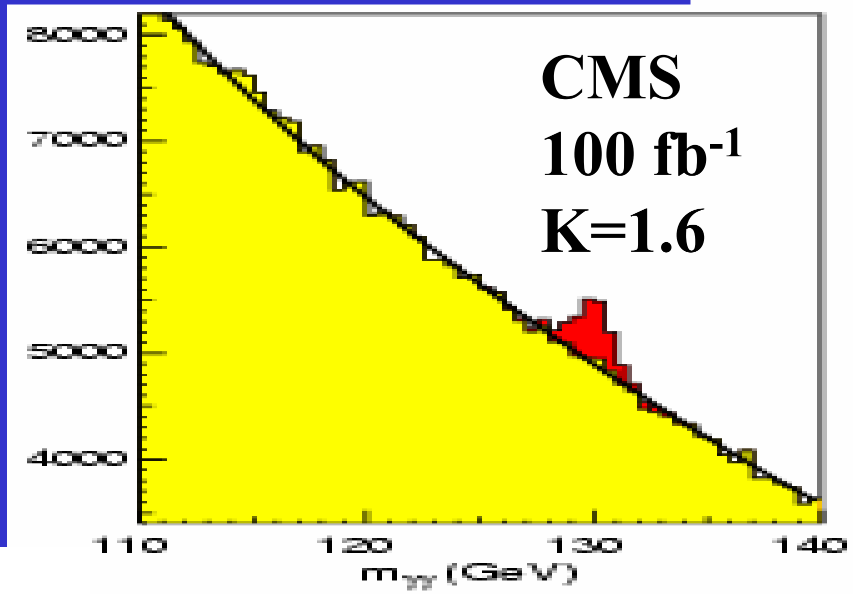


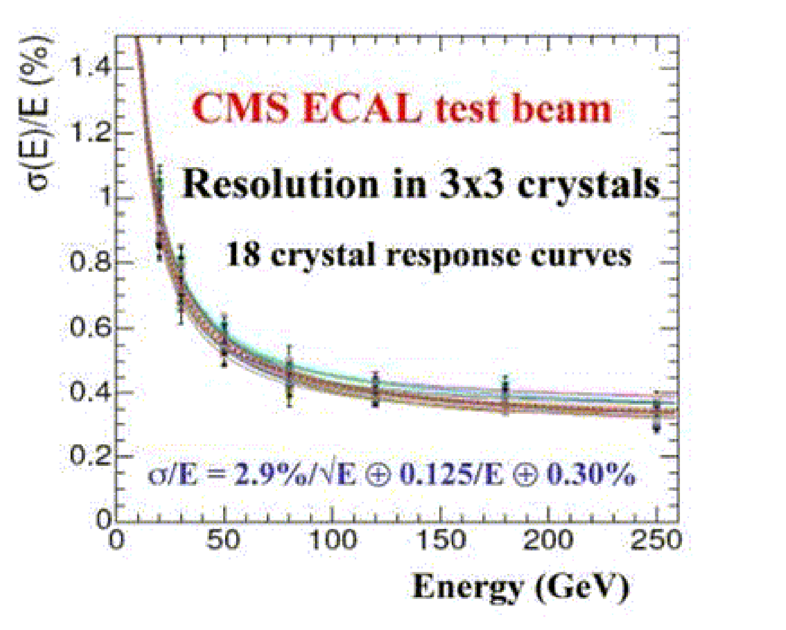


Detector optimisation example: $H \rightarrow gg$





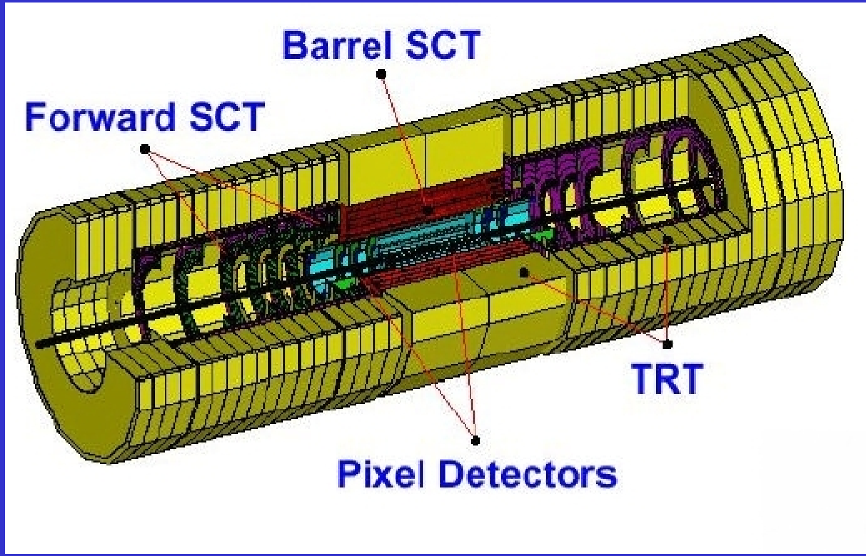




Main specific design choices: Inner Tracker

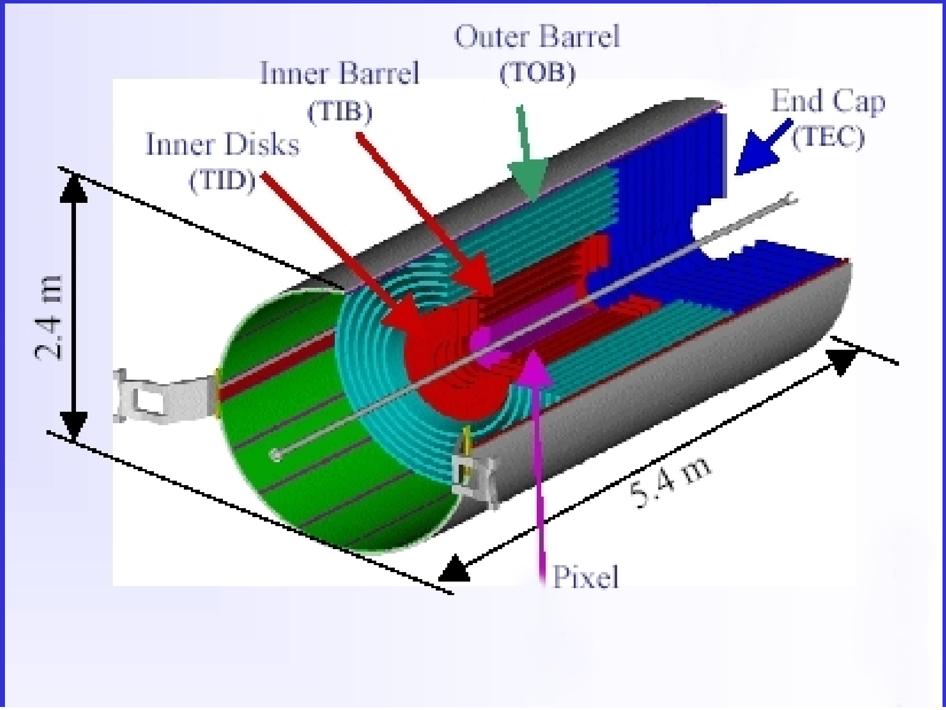
ATLAS

7.0 X 2.3 m cylinder
63 m^2 of Si sensors
6 M silicon strips
80 M pixels
TR detector



CMS

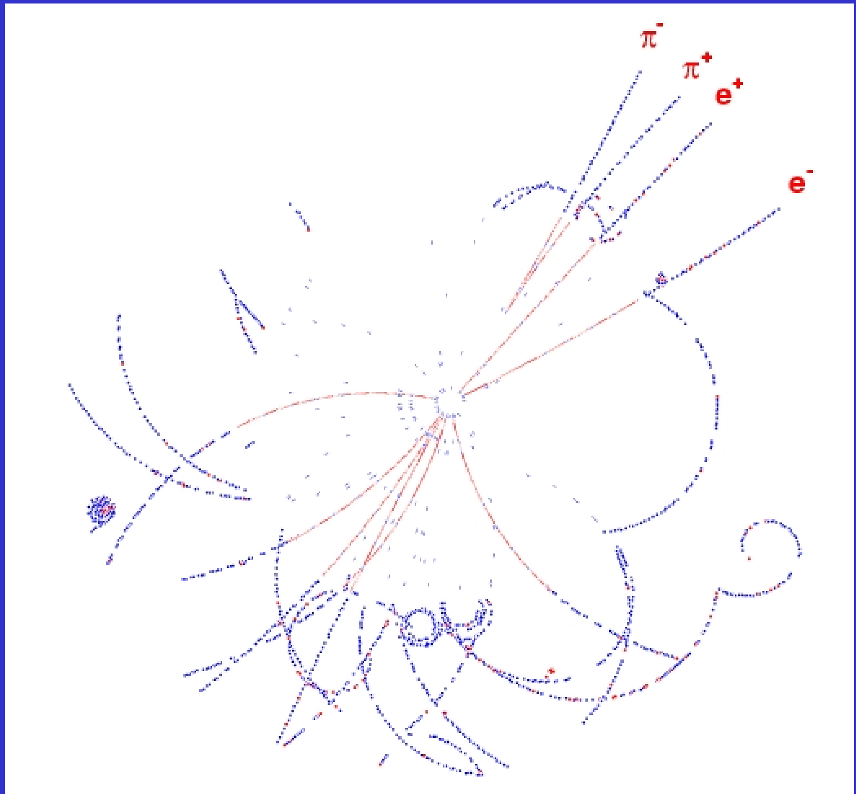
5.4 X 2.4 m cylinder
210 m^2 of Si sensors
10 M silicon strips
67 M pixel

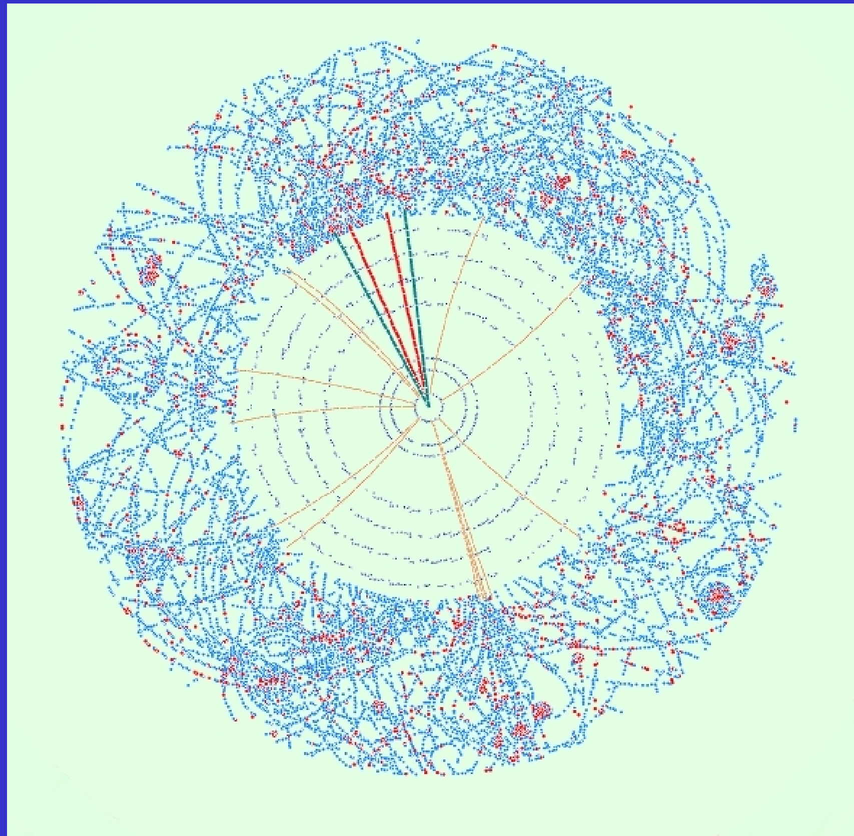


Inner Tracker: low and high luminosity

ATLAS
$B_0 \to J/\psi K_S \to eepp$
low lumi

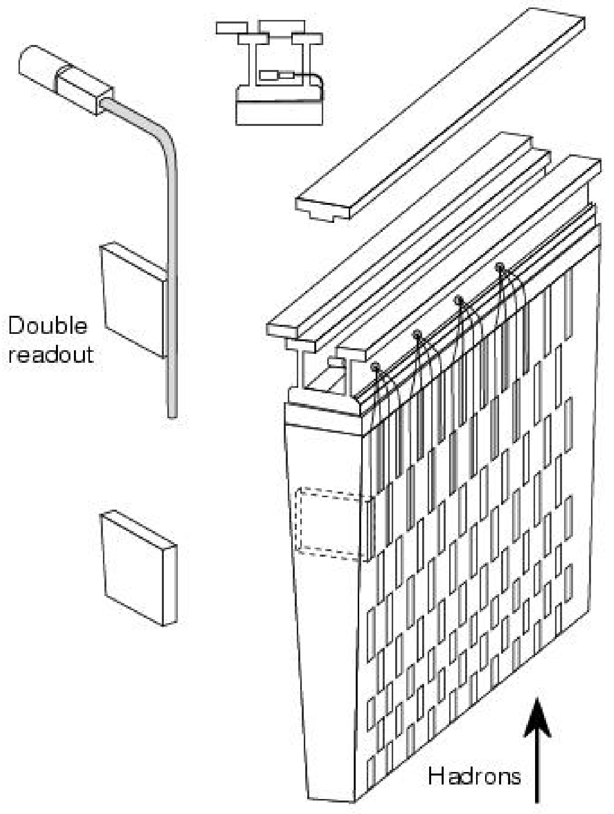
ATLAS
$H \to ZZ^* \to ee\mu\mu$
high lumi





Main specific design choices: HAD calorimetry

ATLAS: Iron/scintillator



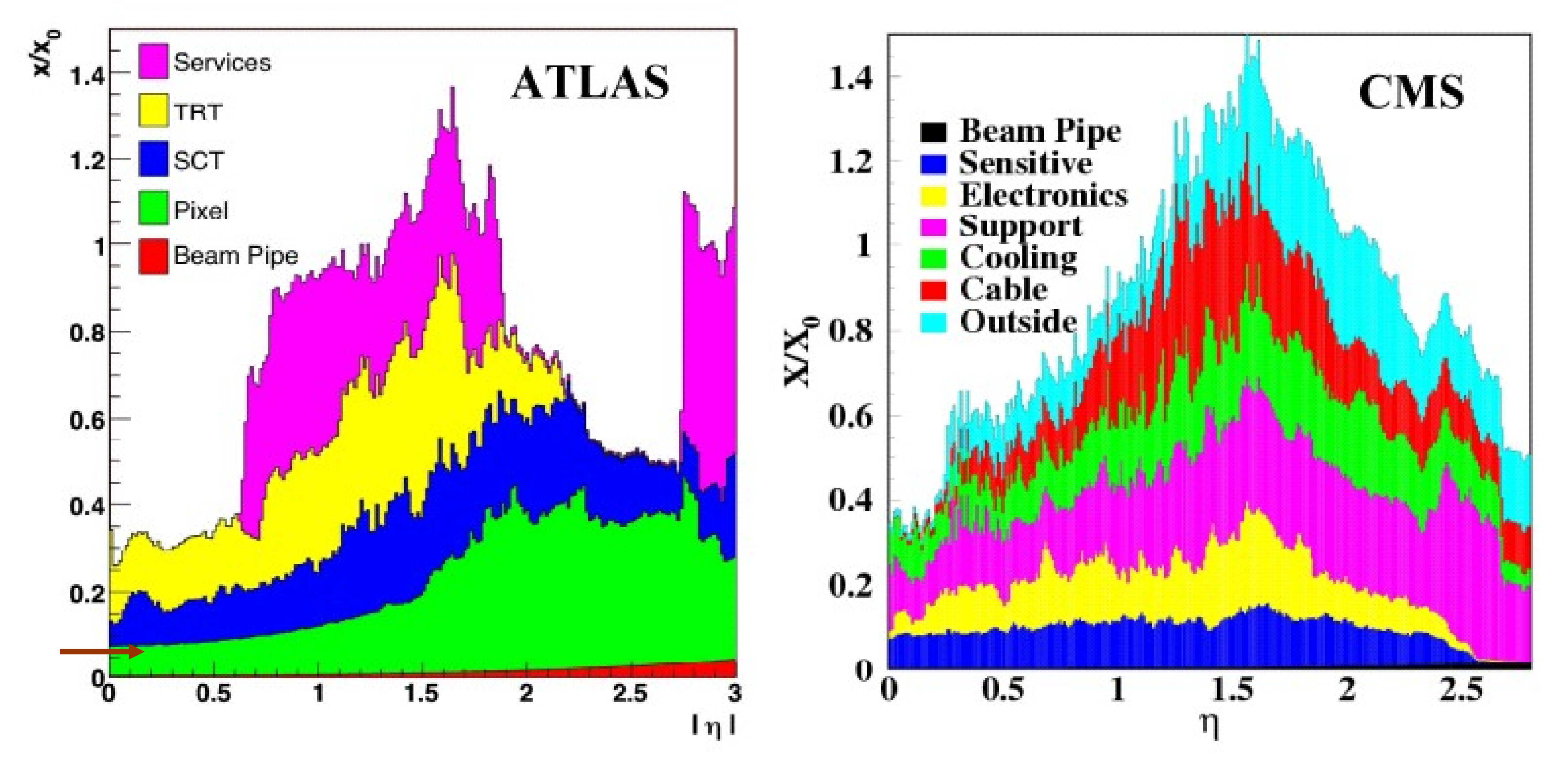
$$\frac{\Delta E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%$$

CMS: Brass/scintillator

Test beam resolution for single hadrons $\frac{\sigma_E}{E} = \frac{65\%}{\sqrt{E}} \oplus 5\%$

ATLAS/CMS: from design to reality

Amount of material in ATLAS and CMS inner trackers



- Material increased by ~ factor 2 from 1994 (approval) to now (end constr.)
- Electrons lose between 25% and 70% of their energy before reaching EM calo
- Between 20% and 65% of photons convert into e^+e^- pair before EM calo
- Need to bring 70 kW power into tracker and to remove similar amount of heat

Physics at the LHC: the environment

Damage caused by ionising radiation

caused by the energy deposited by particles in the material: ≈ 2 MeV g^{-1} cm^{-2} for a min. ion. particle also caused by photons created in electromagnetic Showers_the damage is proportional to the deposited energy or dose

Expected dose at the LHC

- Bunch crossing = 25 ns
- Pile-up at high luminosity ($L = 10^{34}$ cm^{-2}s^{-1})

Each event contains $\approx$ 700 charged tracks

Expected track density $\approx 10^{-2}$ tracks/cm^2/event at R=60 cm from I.P.

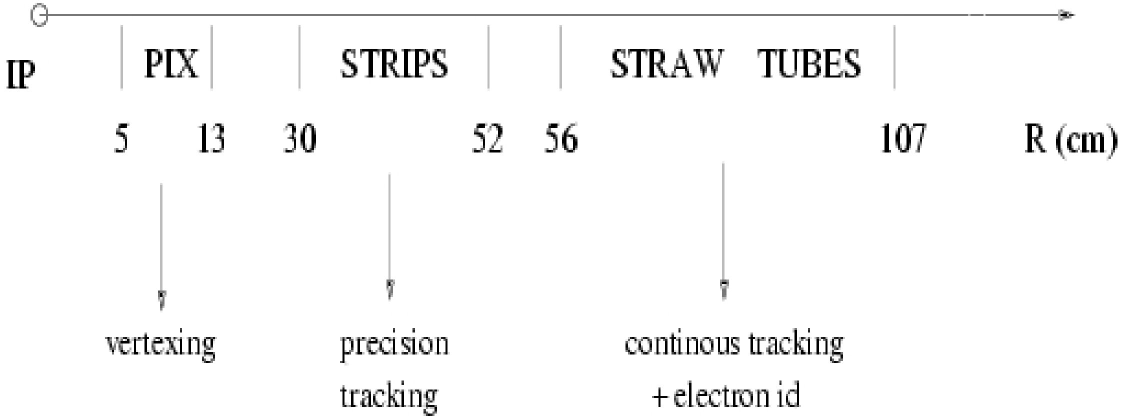
Expected total particle fluence $\approx 10^{13}$ tracks/cm^2 after 10 years.

Physics at the LHC: the environment

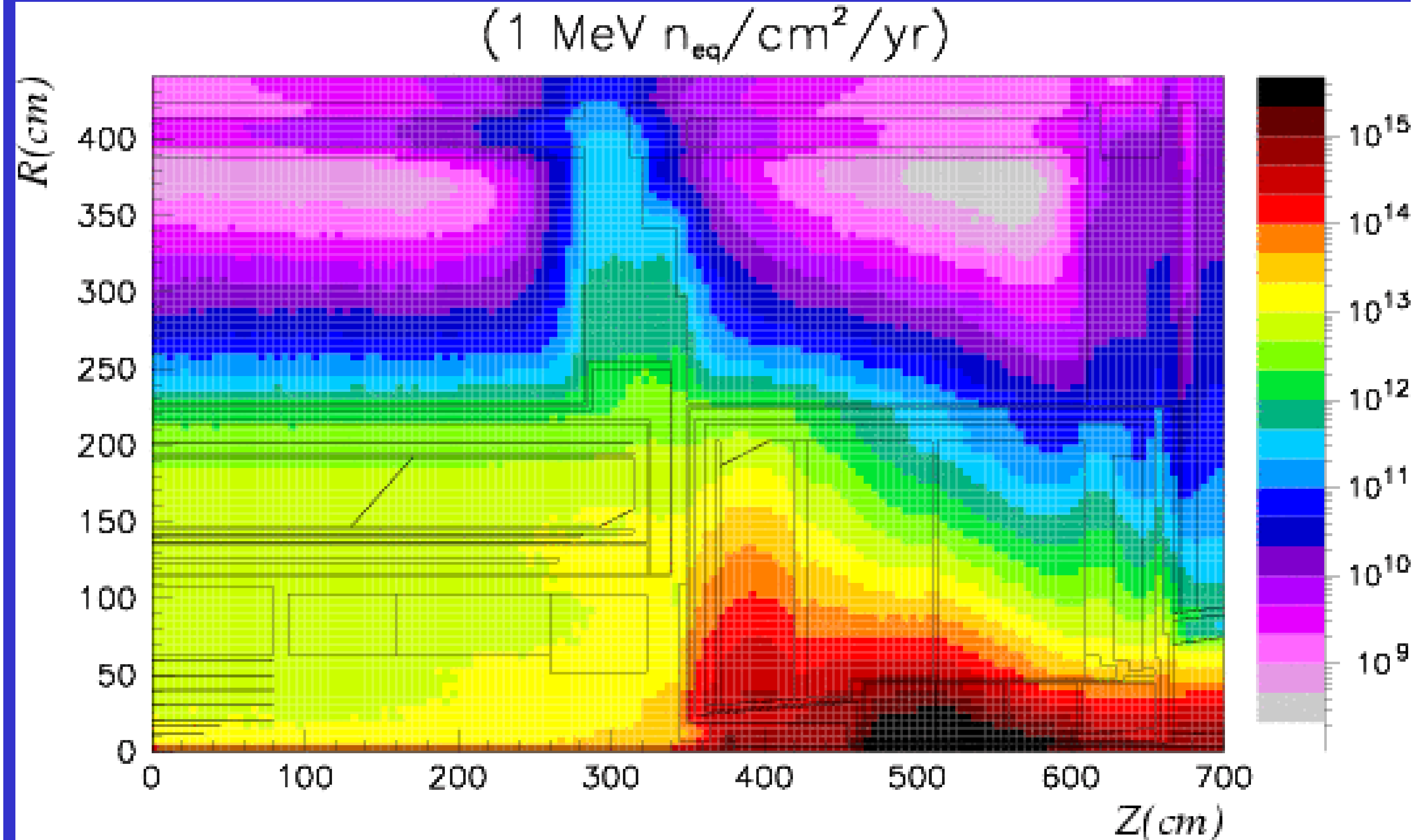
Problem of occupancy/survival

R (cm)	track density (mips/cm^2/ev)	total fluence (mips/cm^2)	comments
60	10^{-2}	10^{13}	max. level for conventional gas detector
20	10^{-1}	10^{14}	max. level for strip detector (10^{-1}cm^2)
2	10	10^{16}	max. level for pixel detector (10^{-4}cm^2)

ATLAS strategy



ATLAS neutron fluences



Physics at the LHC: the environment

Damage caused by neutrons

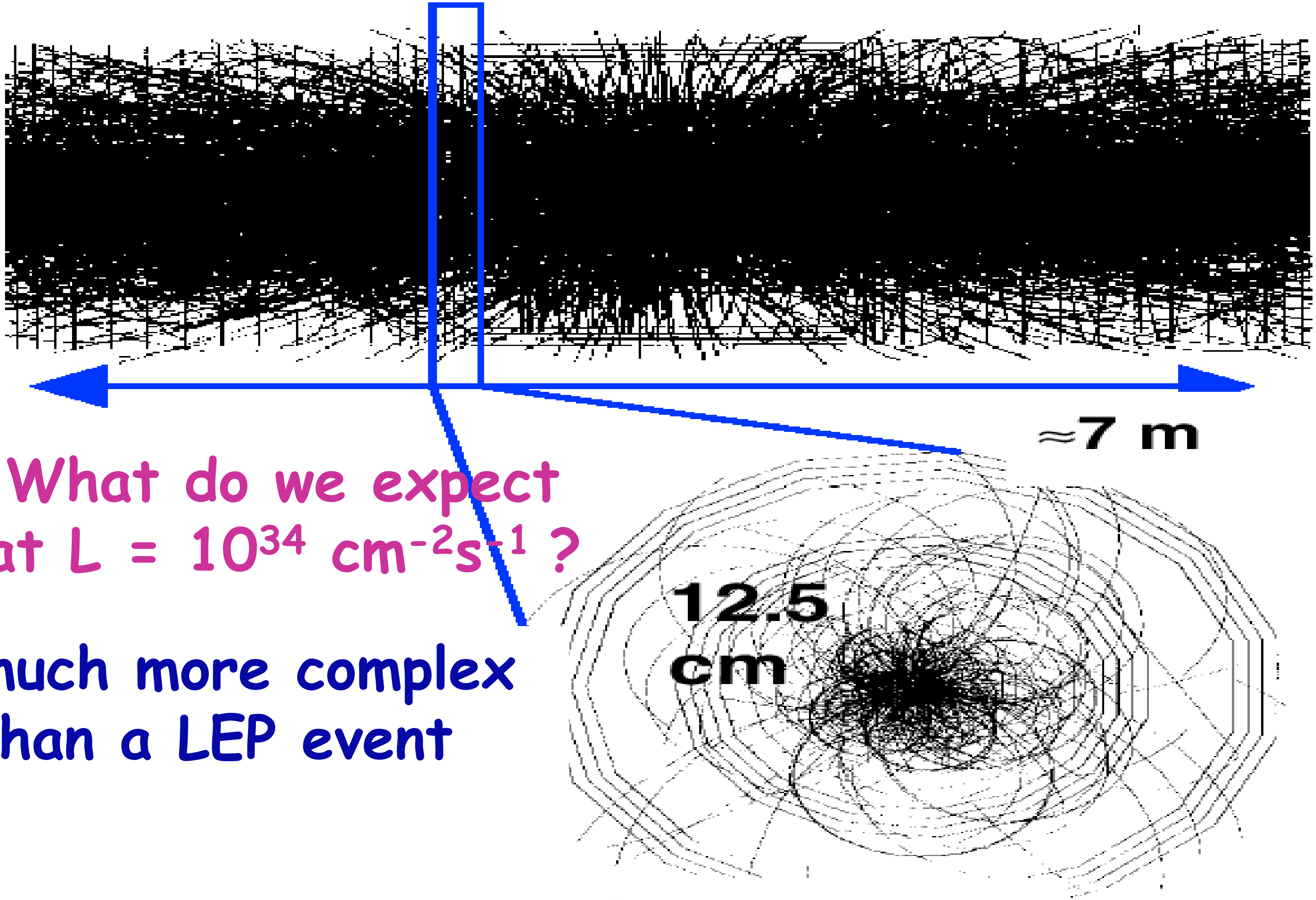
- the neutrons are created in hadronic showers
- these neutrons (with energies in the 0.1 to 20 MeV range) bounce back and forth and fill up the whole detector
- expected neutron fluence is about 3 10^{13} /cm^2/year in the innermost part of the detectors (inner tracking systems)

- the neutrons modify the cristalline structure of semiconductors

$\rightarrow$ need radiation-hard electronics

- usual electronics dies out for fluences above 10^{13} neutrons/cm^2
- rad-hard electronics can survive up to 10^{15} neutrons/cm^2

Physics at the LHC: the environment



What do we expect at $L = 10^{34}\ cm^{-2}s^{-1}$?

much more complex than a LEP event

Physics at the LHC: the environment

<u>Pile-up effects at high luminosity</u>

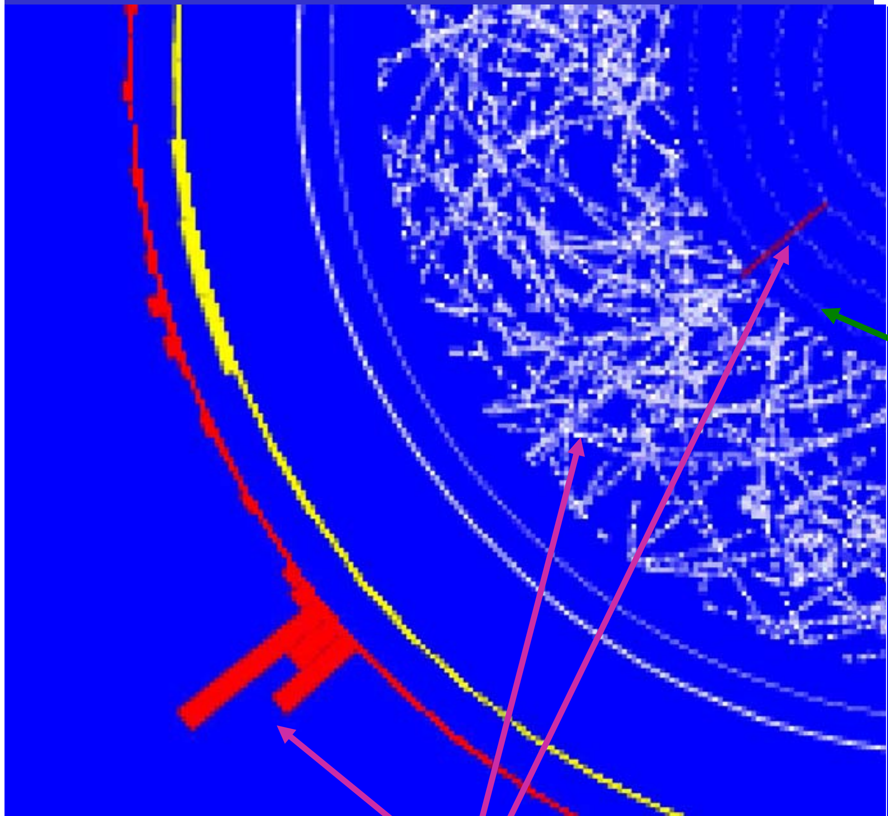
Pile-up is the name given to the impact of the 23 uninteresting (usually) interactions occurring in the same bunch crossing as the hard-scattering process which generally triggers the apparatus

Minimising the impact of pile-up on the detector performance has been one of the driving requirements on the initial detector design:

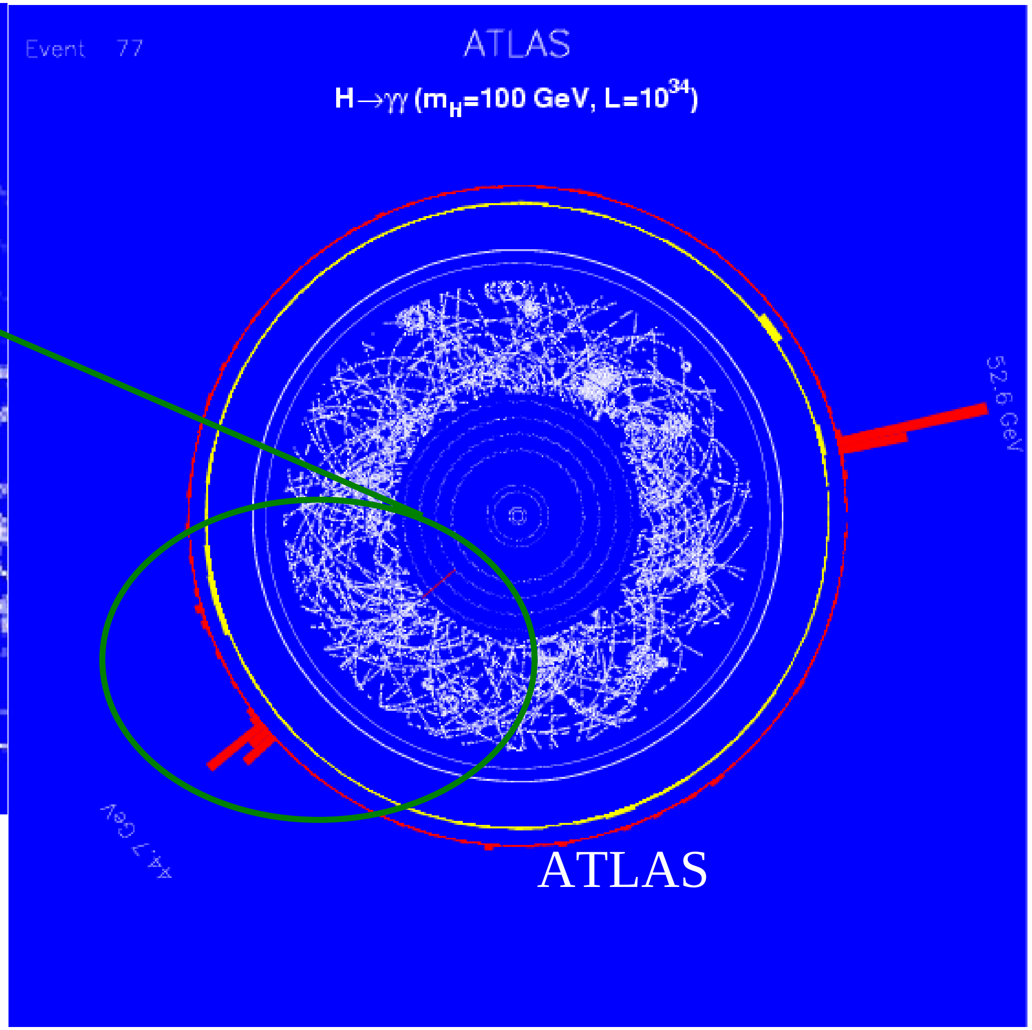
- a precise detector response minimises pile-up in time
  - $\rightarrow$ very challenging for the electronics in particular
  - $\rightarrow$ typical response times achieved are 20-50 ns
- a highly granular detector minimises pile-up in space
  - $\rightarrow$ large number of channels (100 million pixels, 200,000 cells in electromagnetic calorimeter)

Physics at the LHC: the environment

Pile-up effects at high luminosity



Photon converts at R = 40 cm and electron pair is visible in ATLAS TRT and EM calo

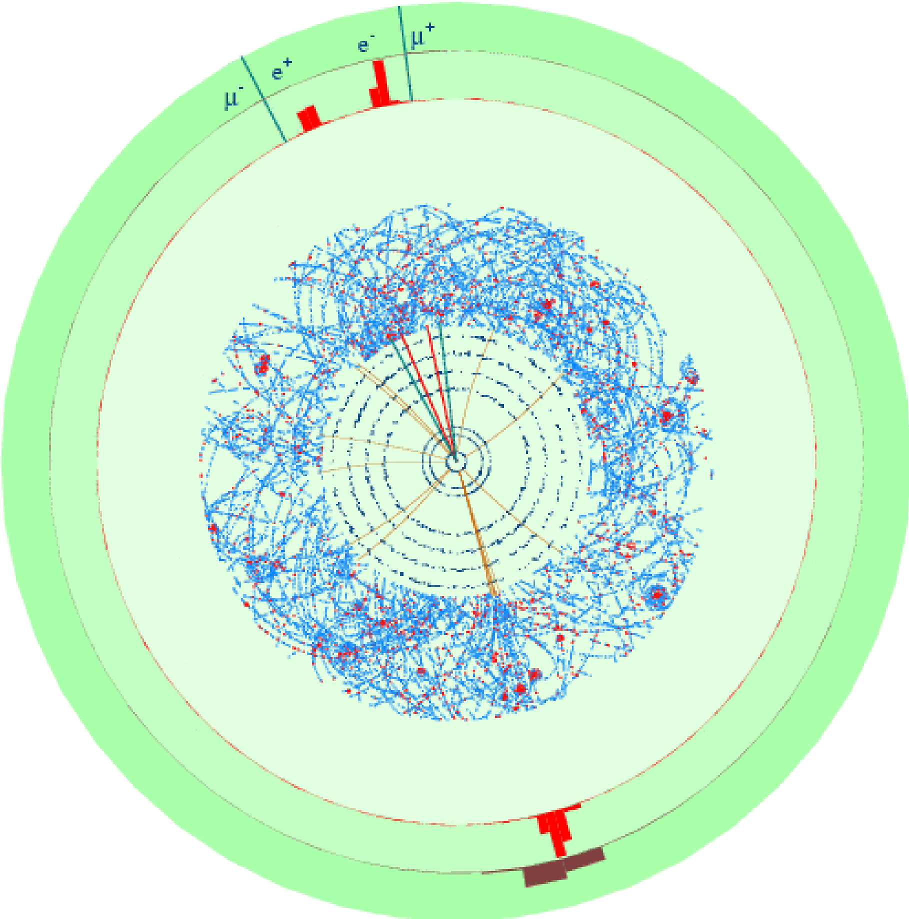


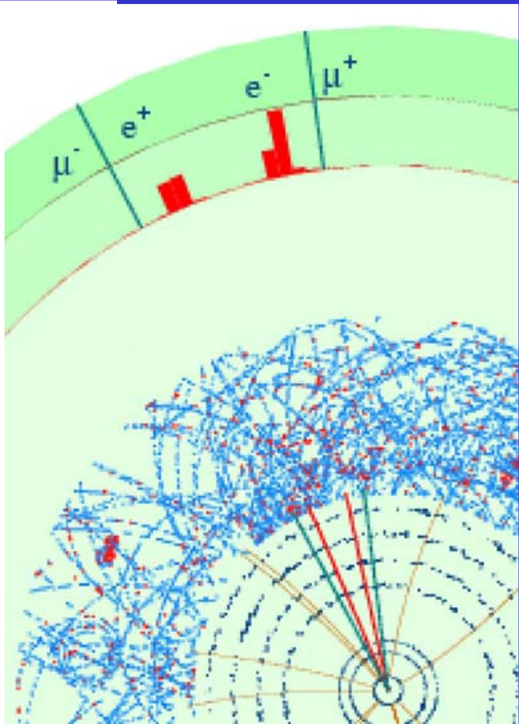
Physics at the LHC: the environment

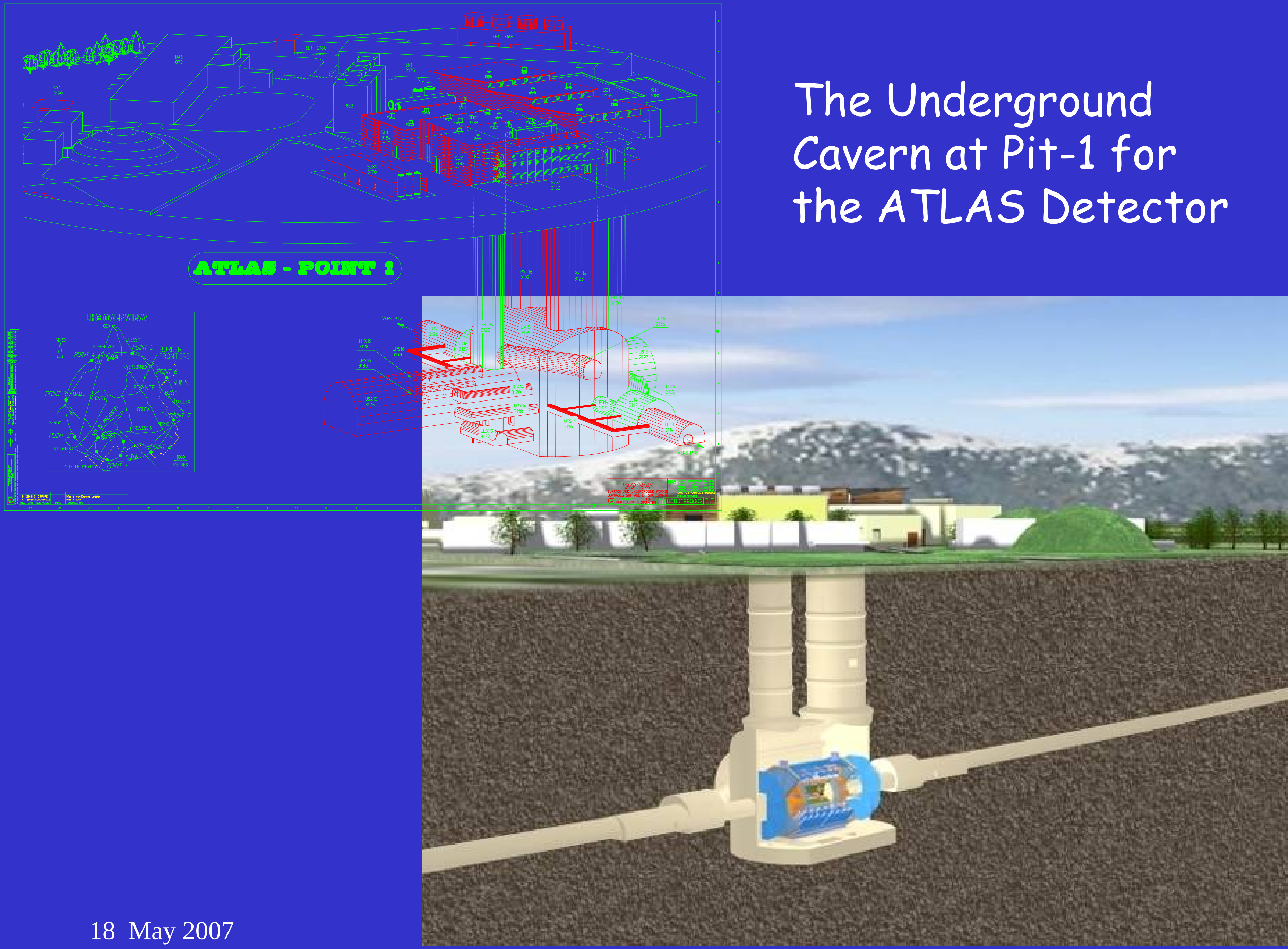
Pile-up effects at high luminosity

ATLAS barrel

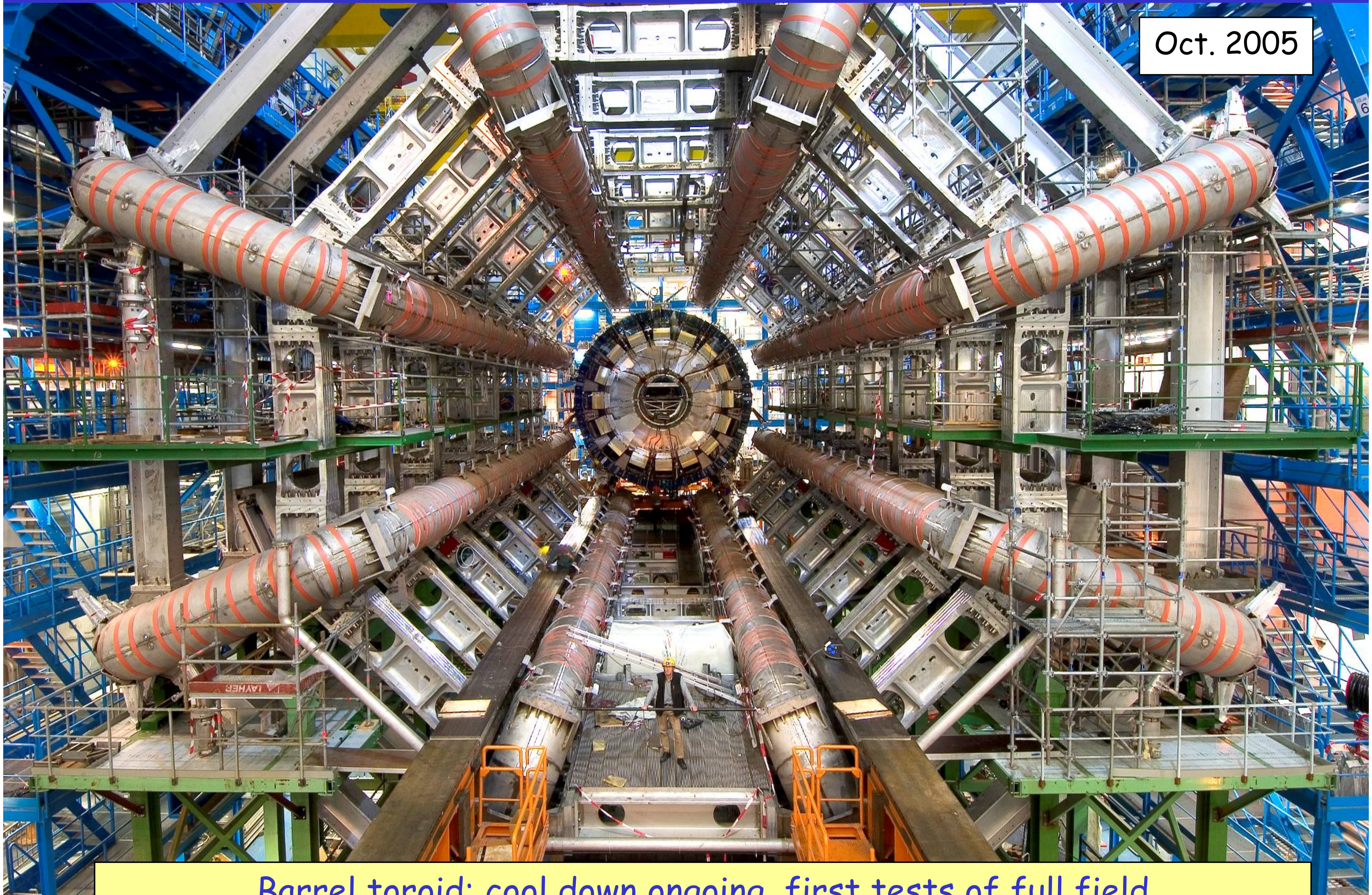
$H \rightarrow ZZ^{*} \rightarrow ee\mu\mu$ ($m_H = 130$ GeV)





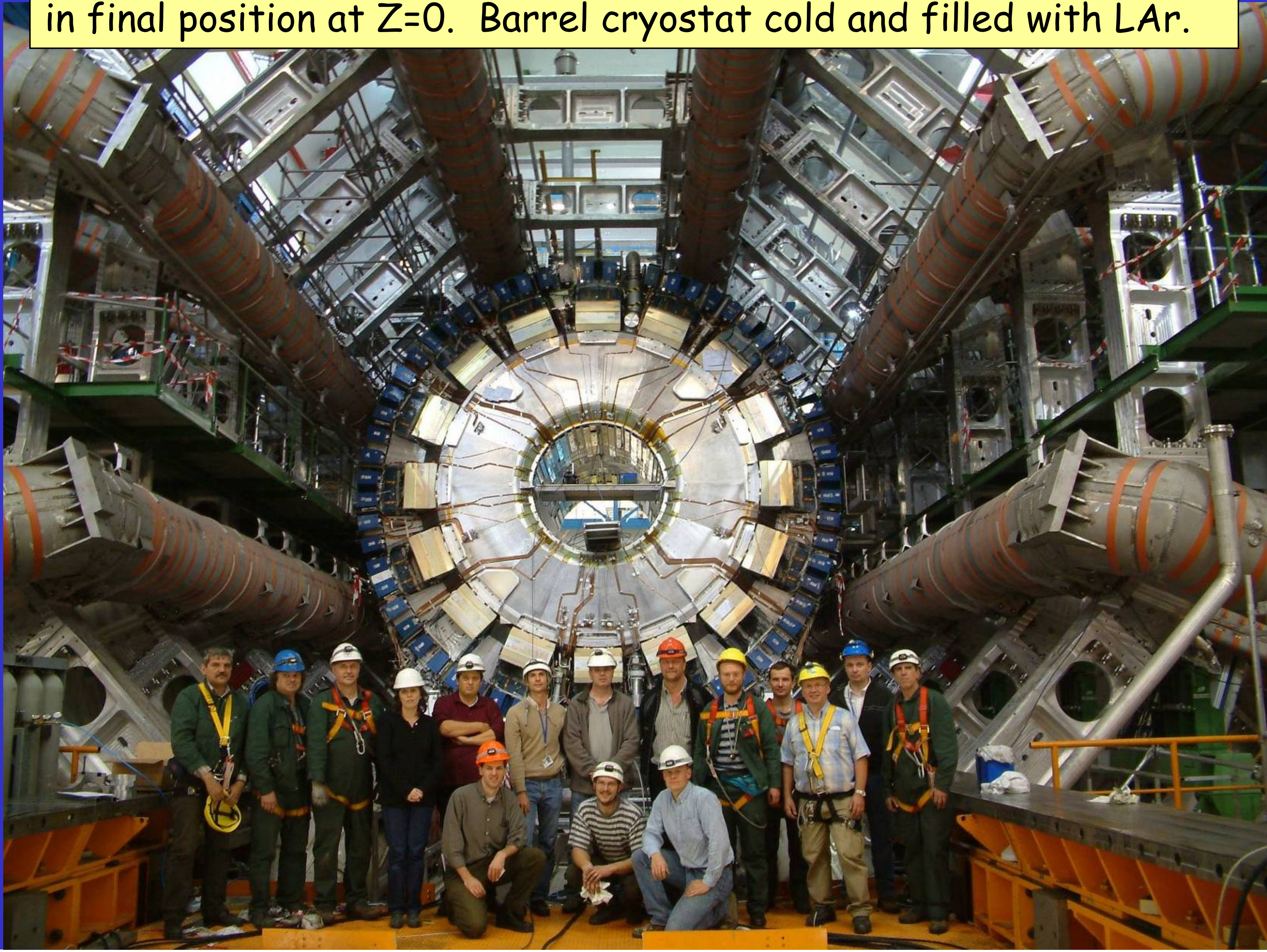


The Underground Cavern at Pit-1 for the ATLAS Detector

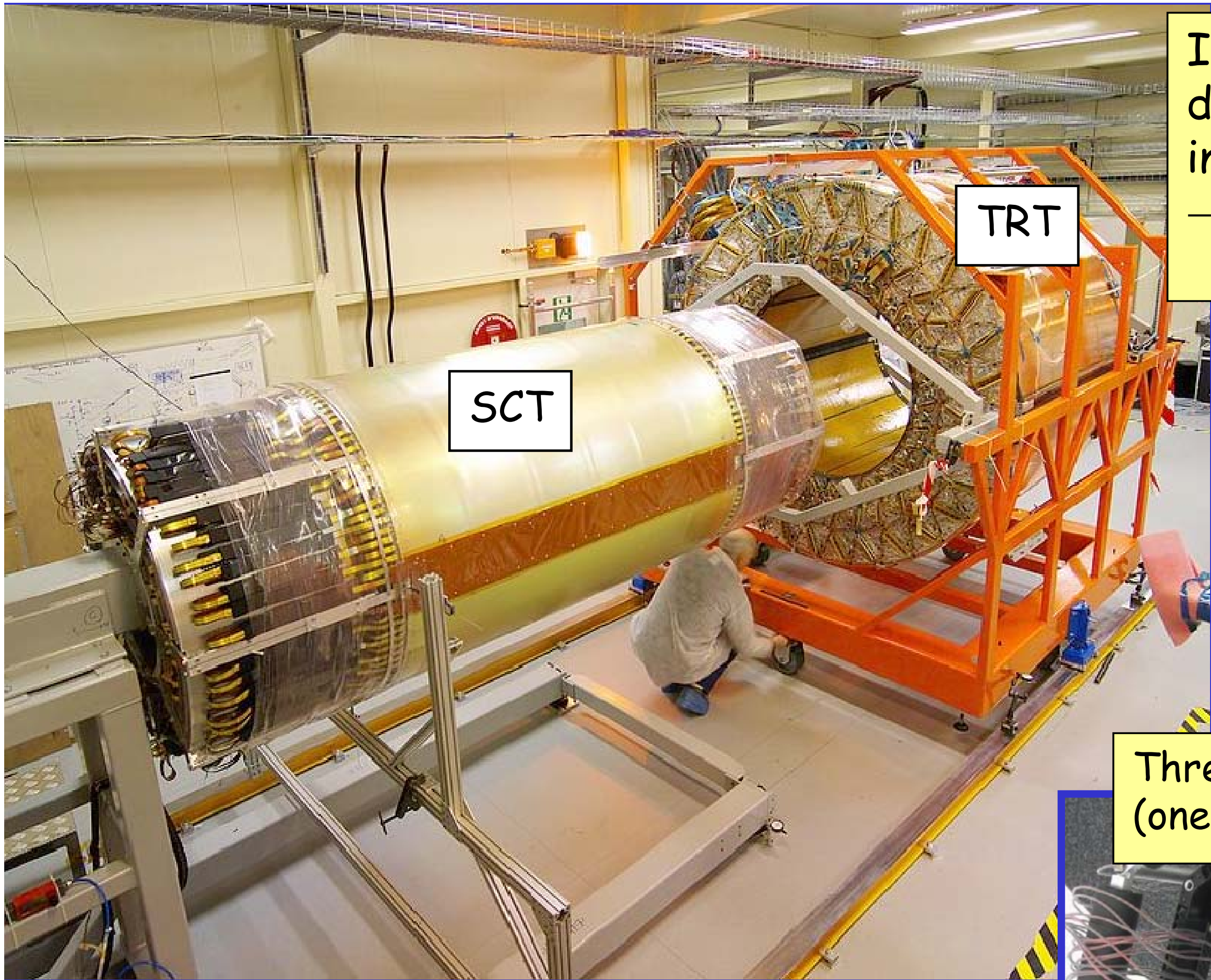


Barrel toroid: cool down ongoing, first tests of full field
End-cap toroids: installed in the pit end 2006-beg 2007

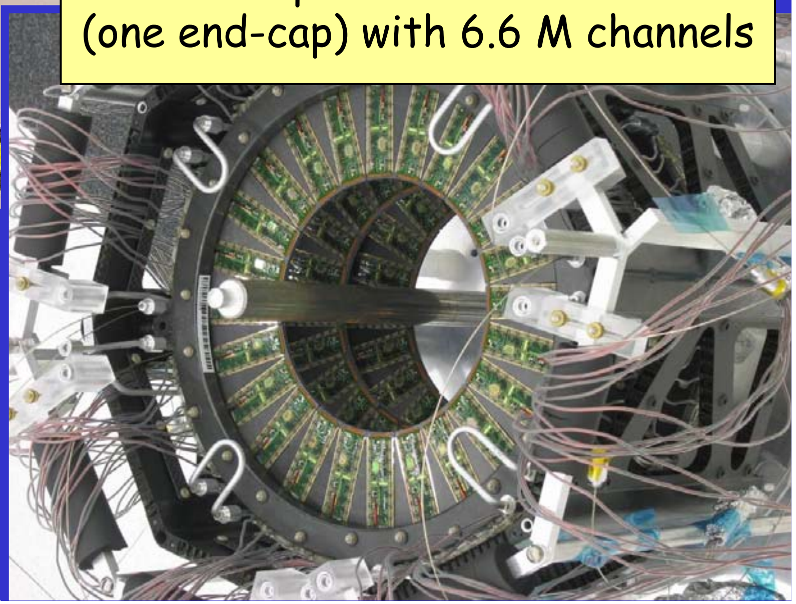
Barrel calorimeter (EM liquid-argon + HAD Fe/scintillator Tilecal) in final position at Z=0. Barrel cryostat cold and filled with LAr.



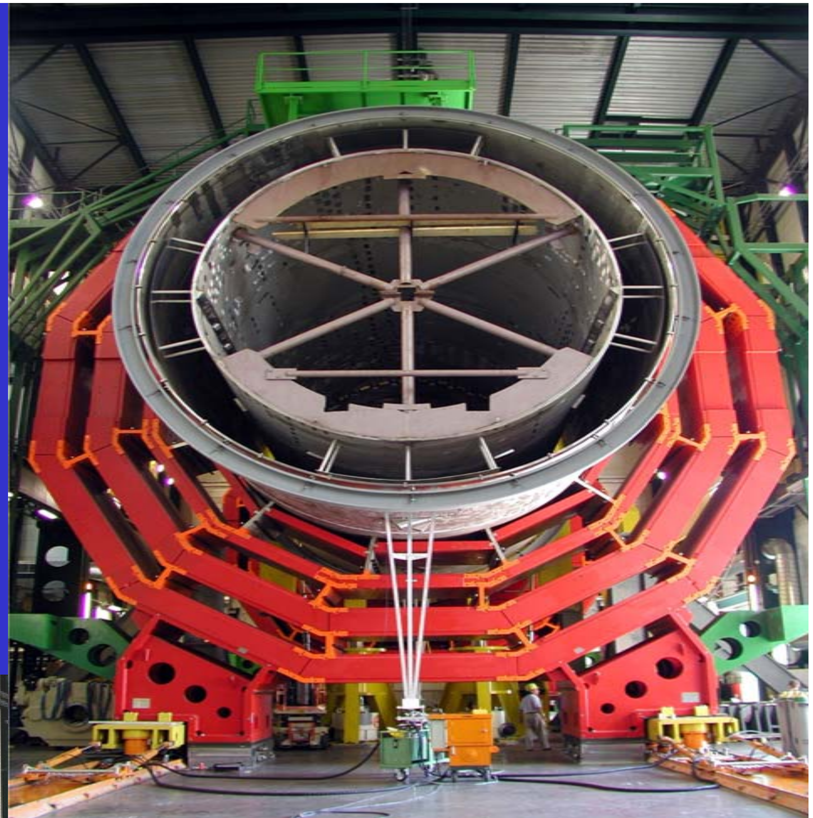
In Feb. 2006 barrel Si detector (SCT) was inserted into barrel TRT → ready for installation in the pit in August 2006

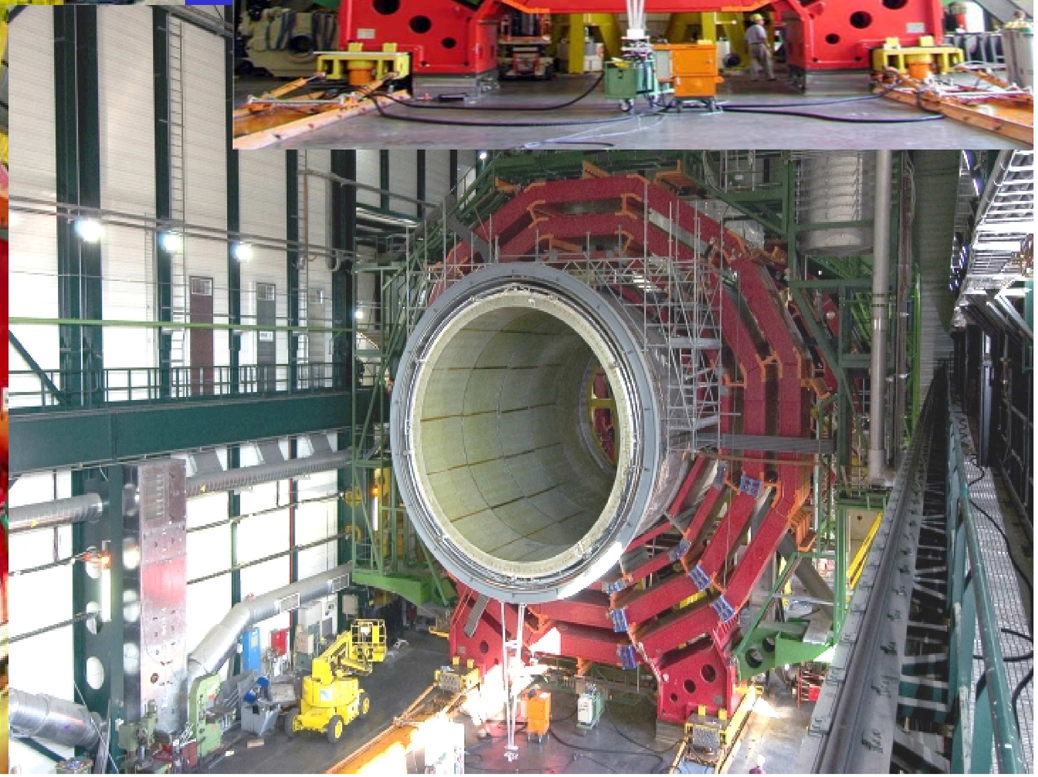


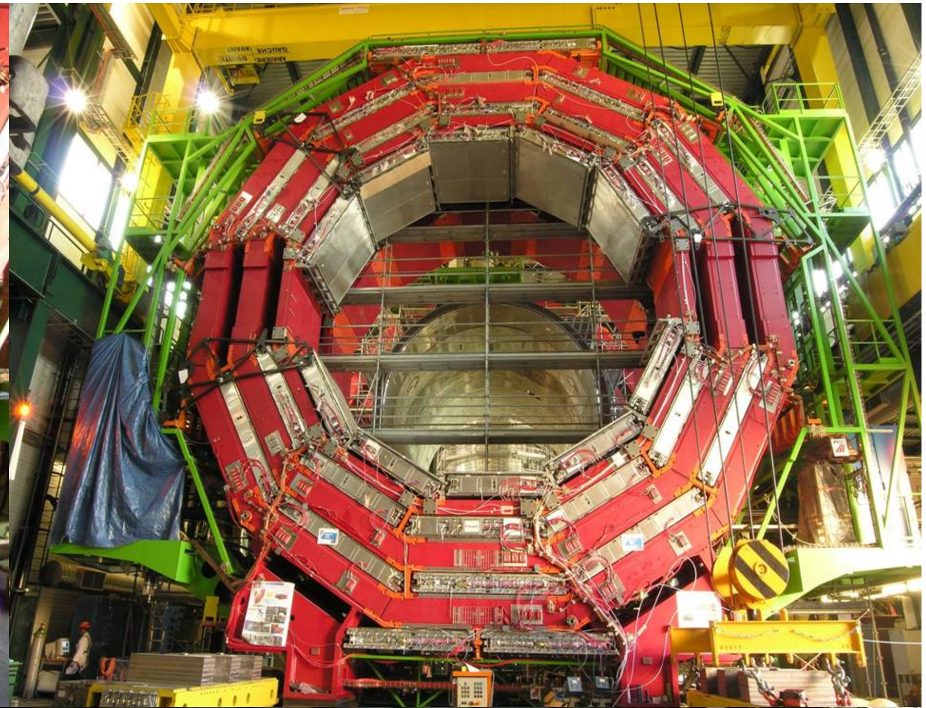
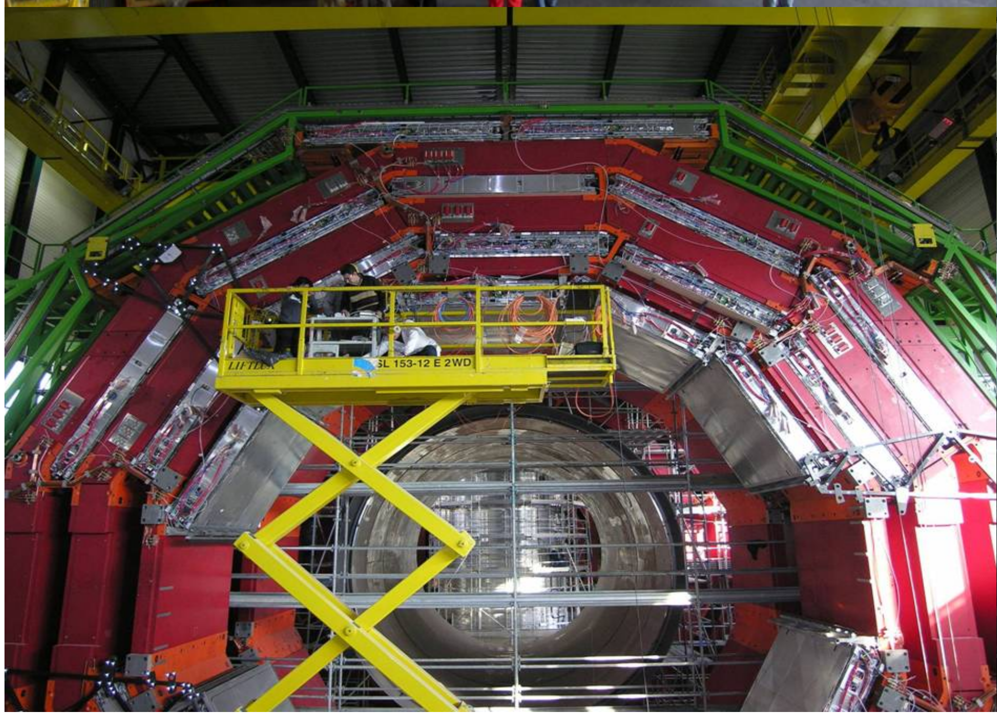
Three completed Pixel disks (one end-cap) with 6.6 M channels

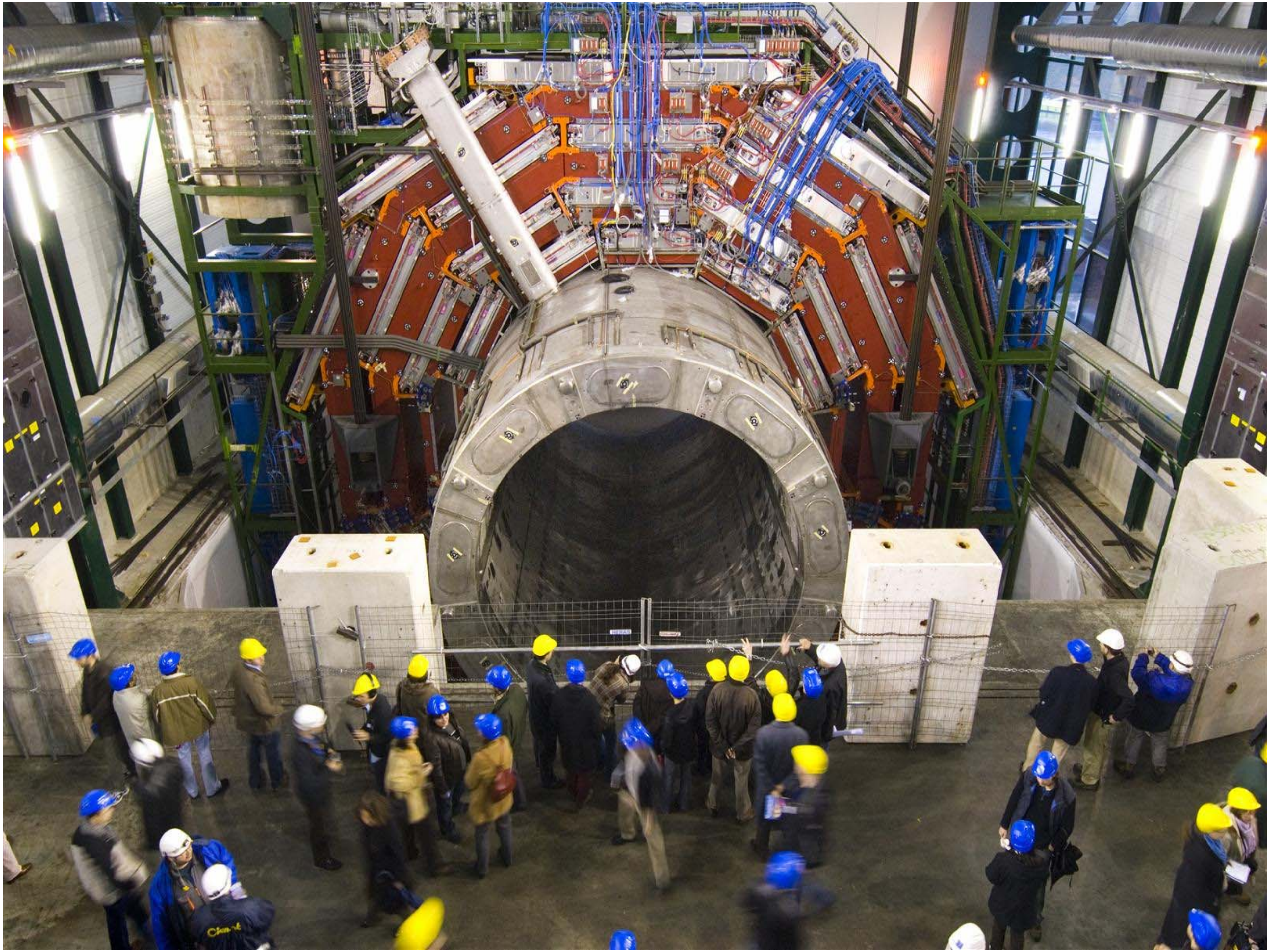


Barrel pixel detector on critical path (problems with low-mass cables), but still scheduled for installation in the pit in April 2007

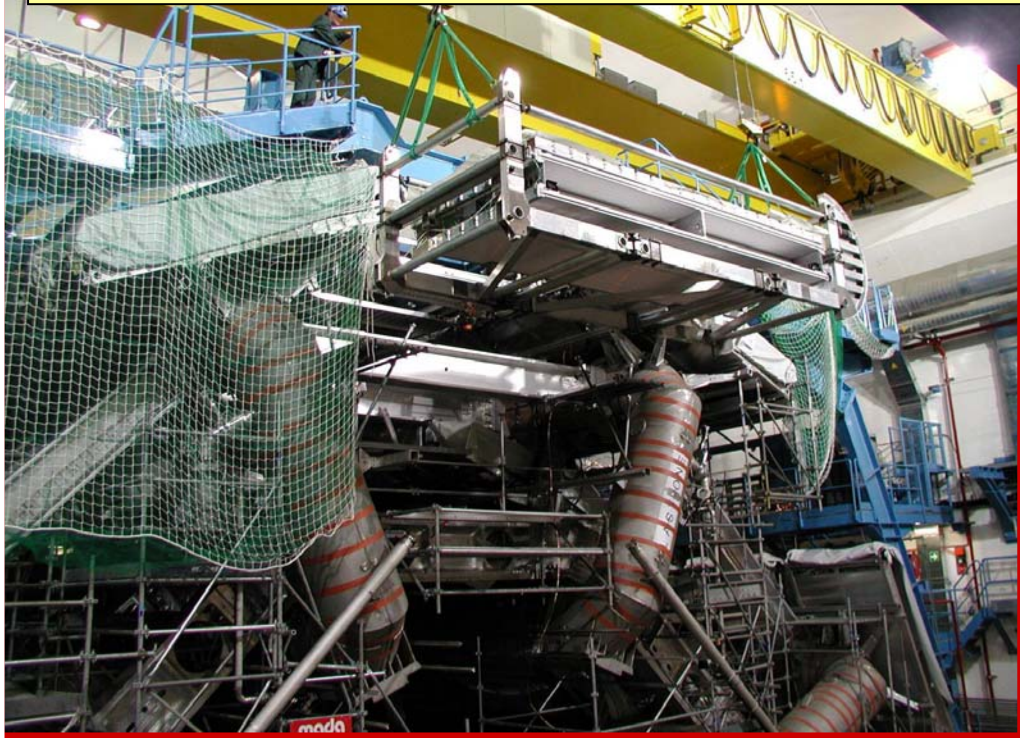



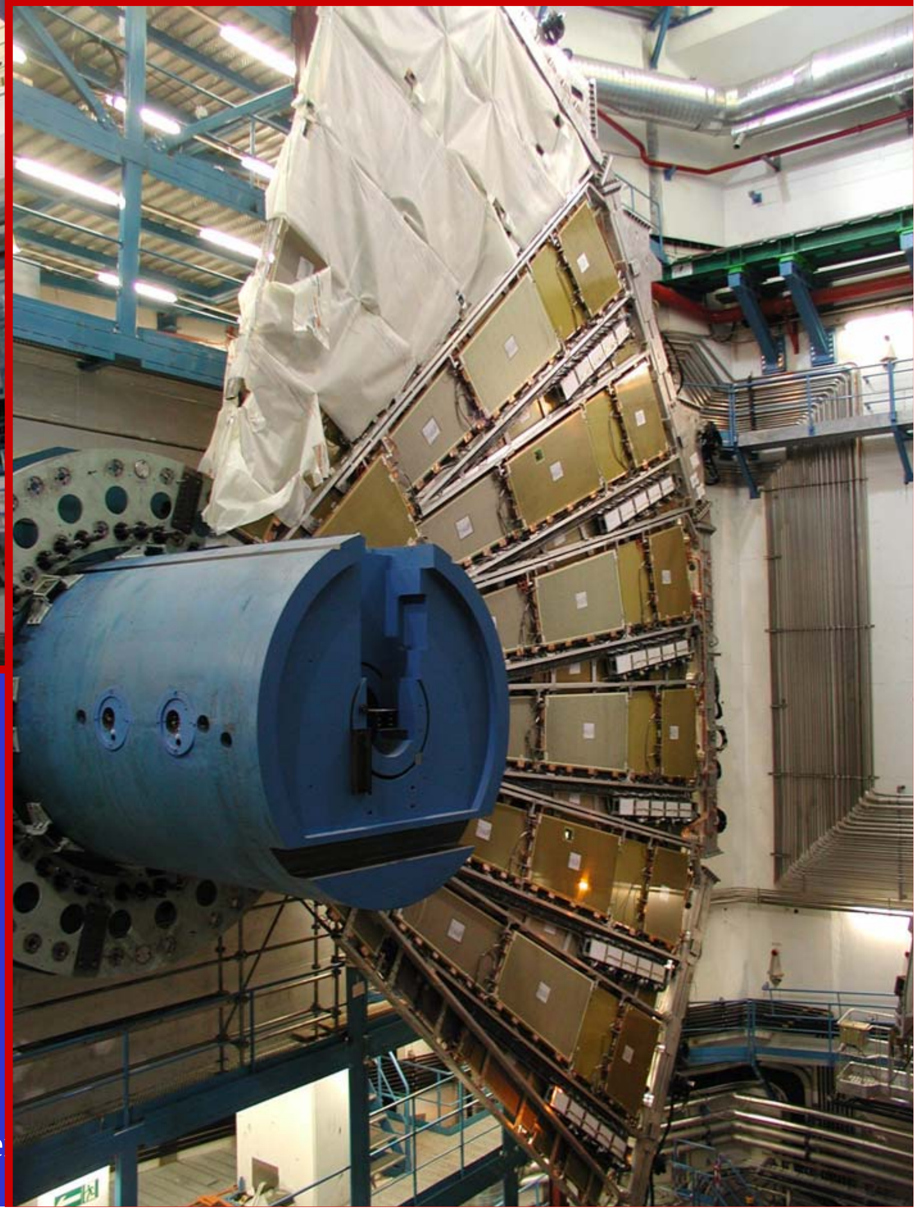





SL 153-12 E 2WD

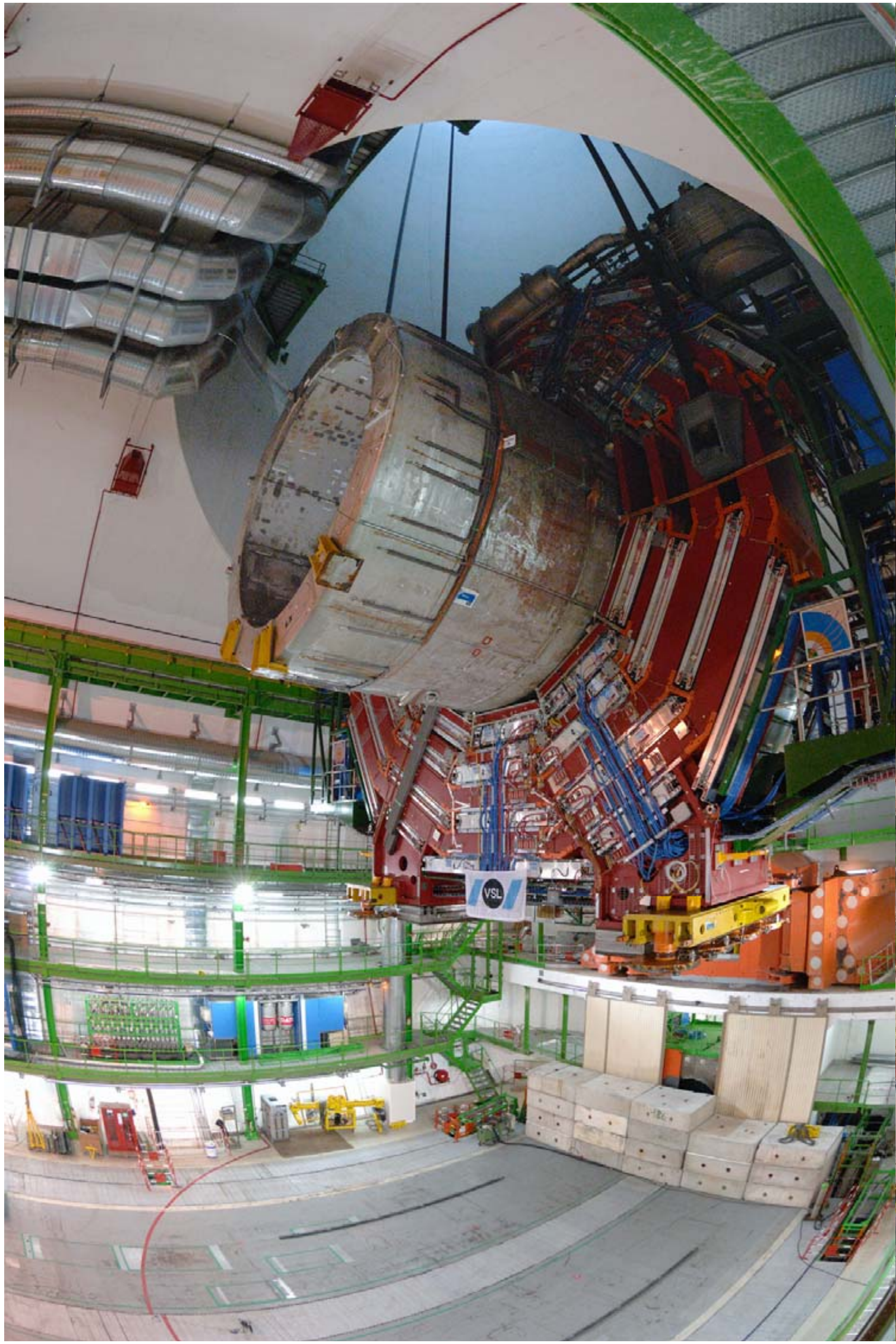
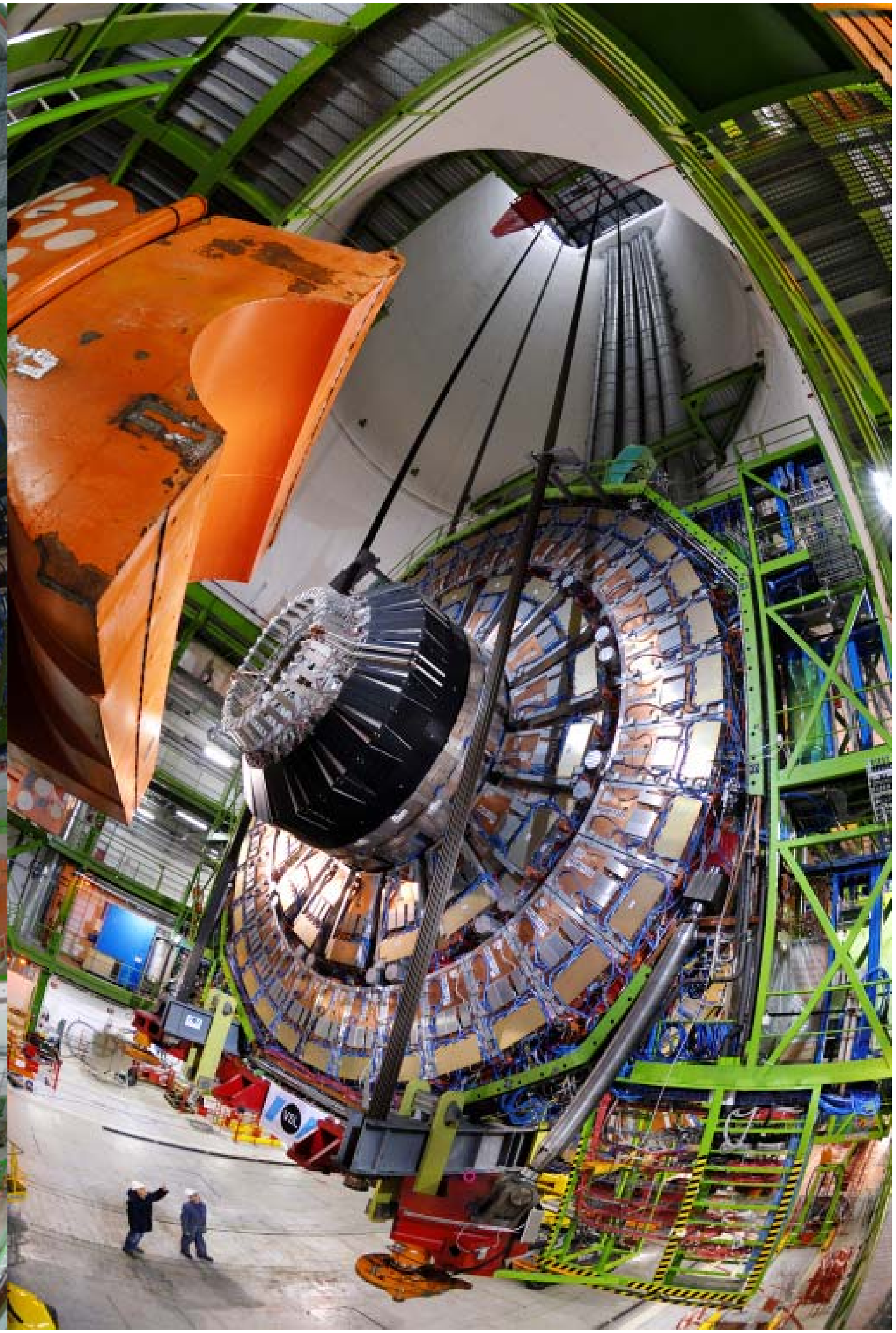



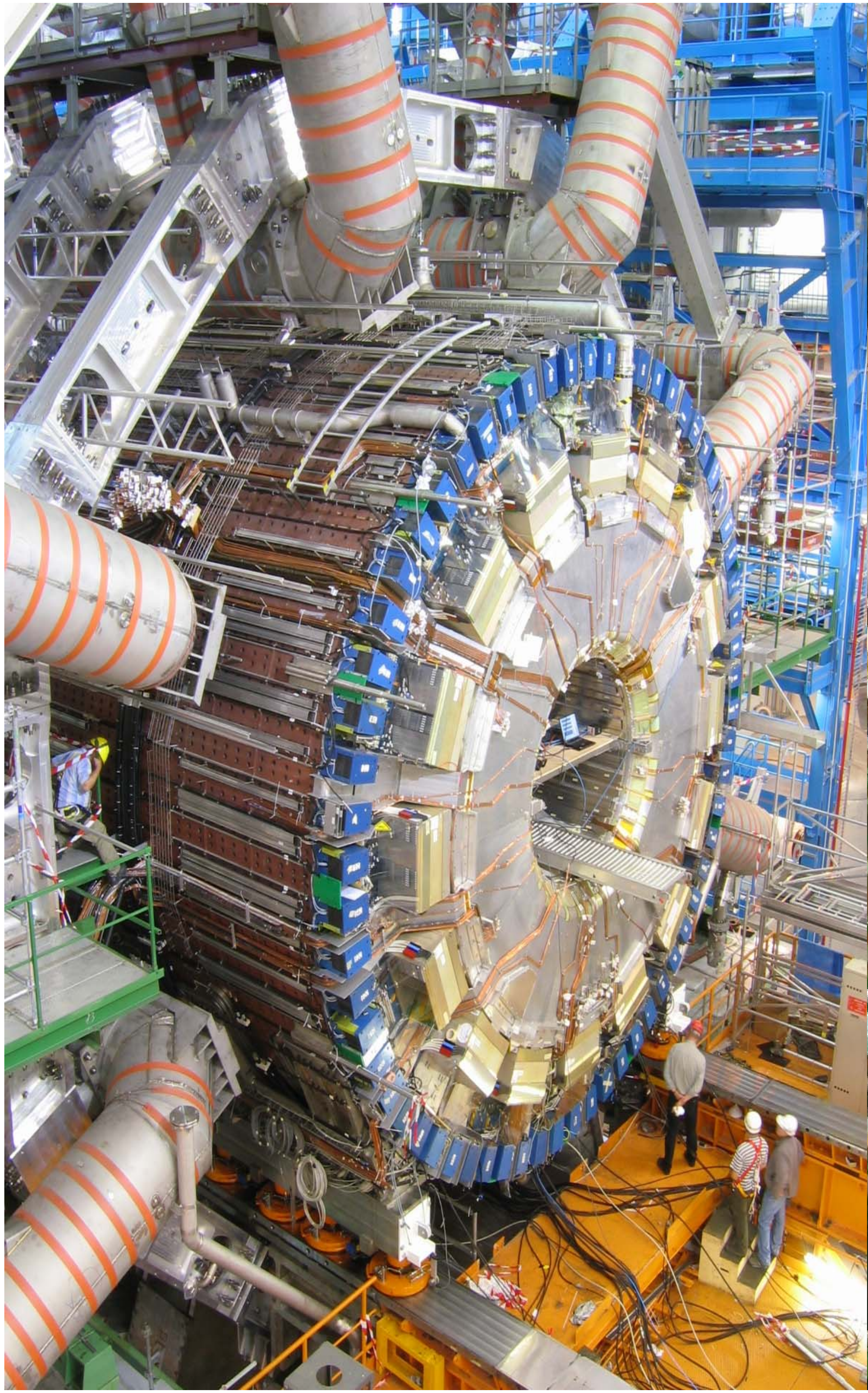
Muon Spectrometer : measurement chambers MDT, CSC (innermost forward)
trigger chambers RPC (barrel), TGC (end-caps)

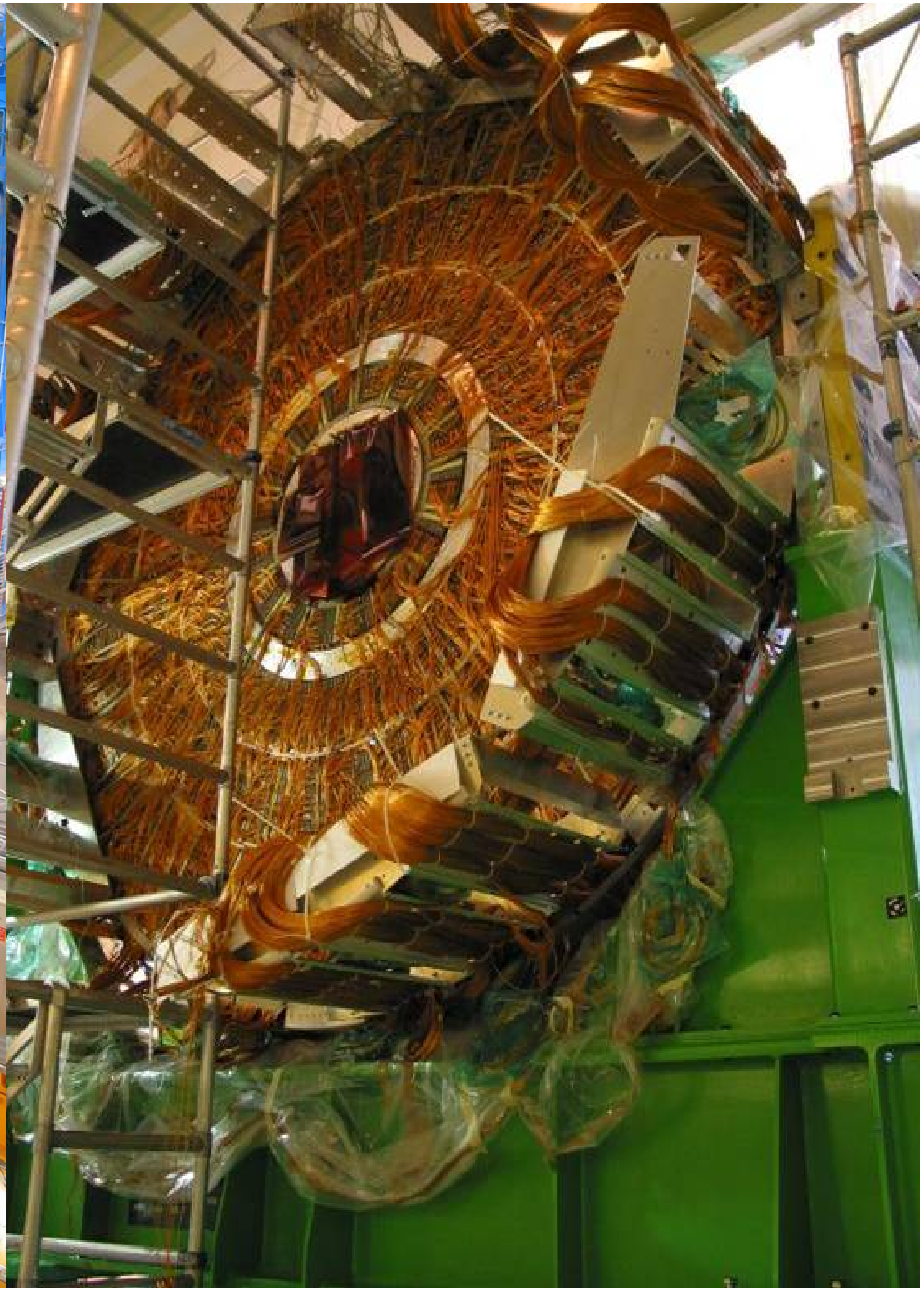


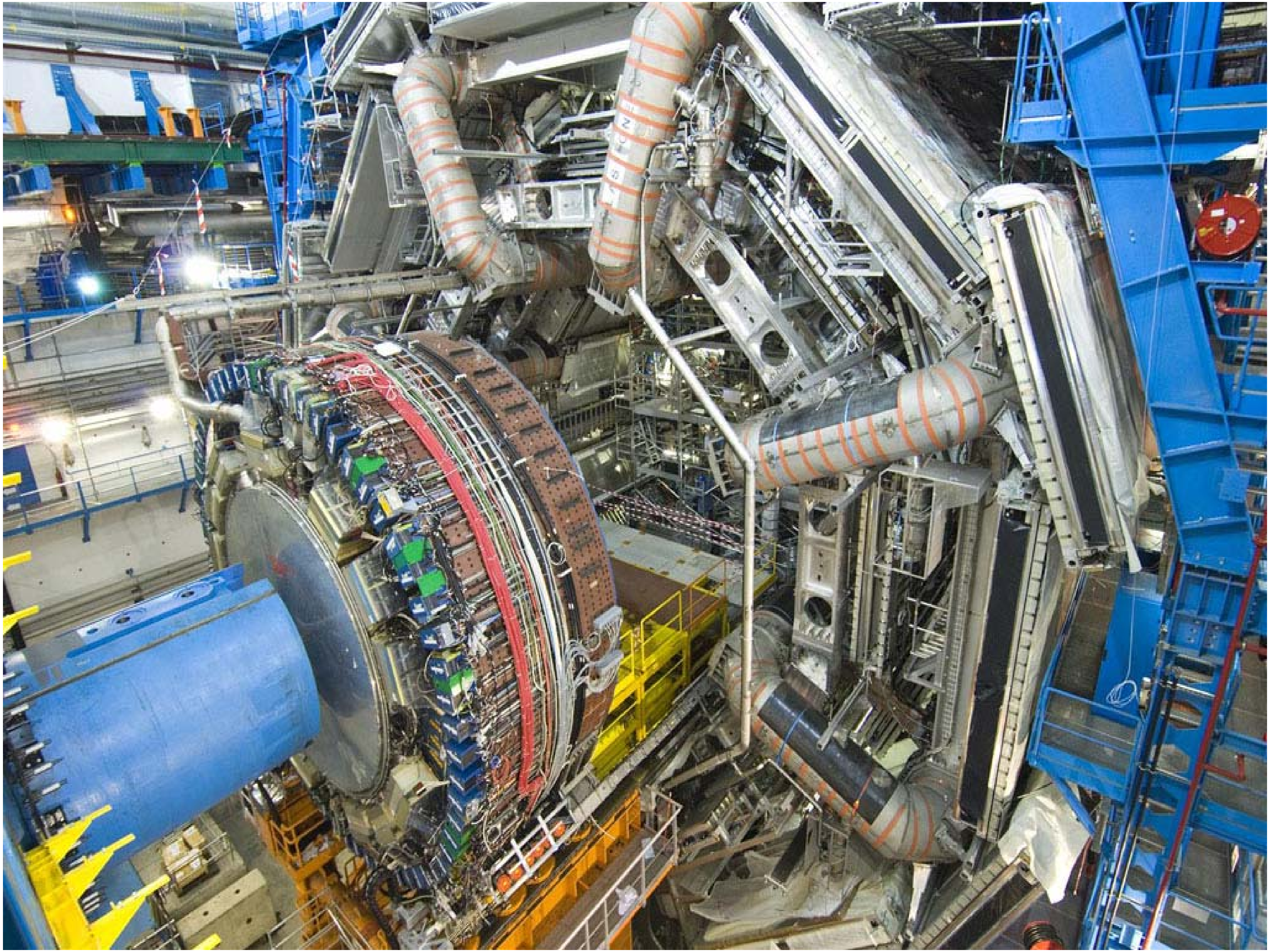


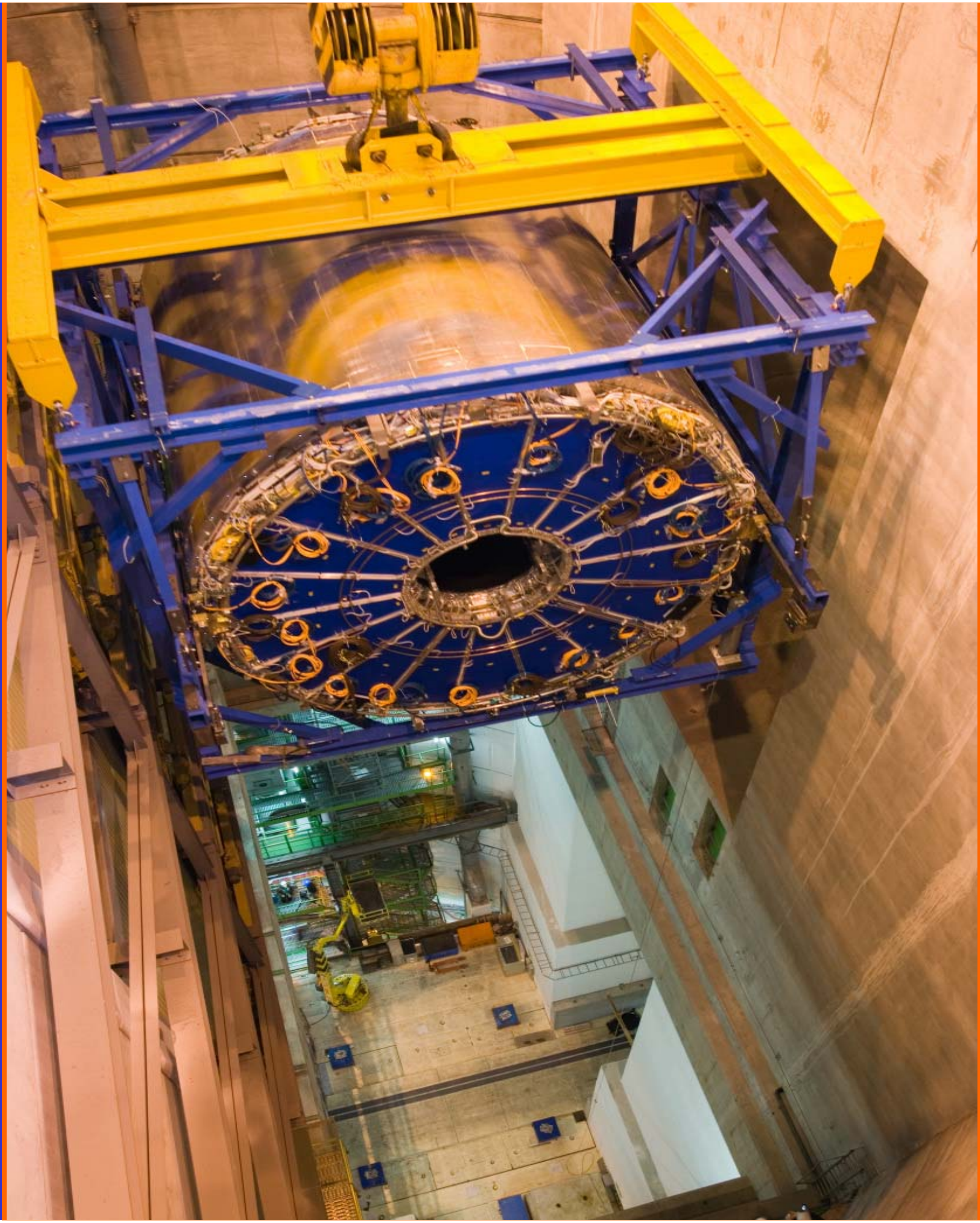
First sectors of TGC end-cap
"big-wheels" installed


VSL

VSL





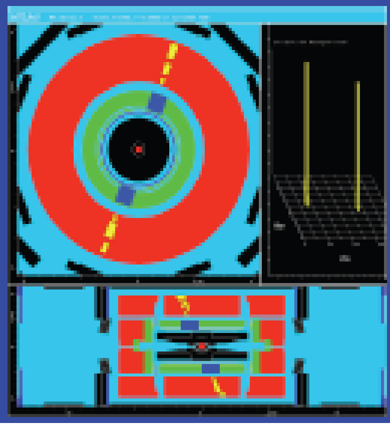




Tentative Agenda

1: Test beams

2: Instalación sub-detectores,
Puesta a punto con rayos cósmicos



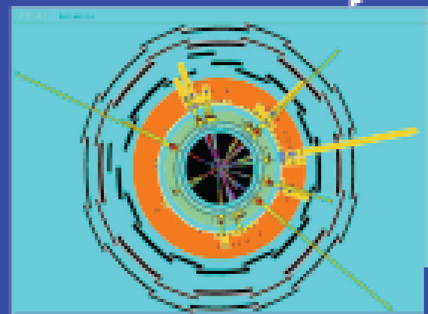
2.5: Primavera '07: Run global de cósmicos

3: 1 haz en LHC

4: Primeras colisiones LHC

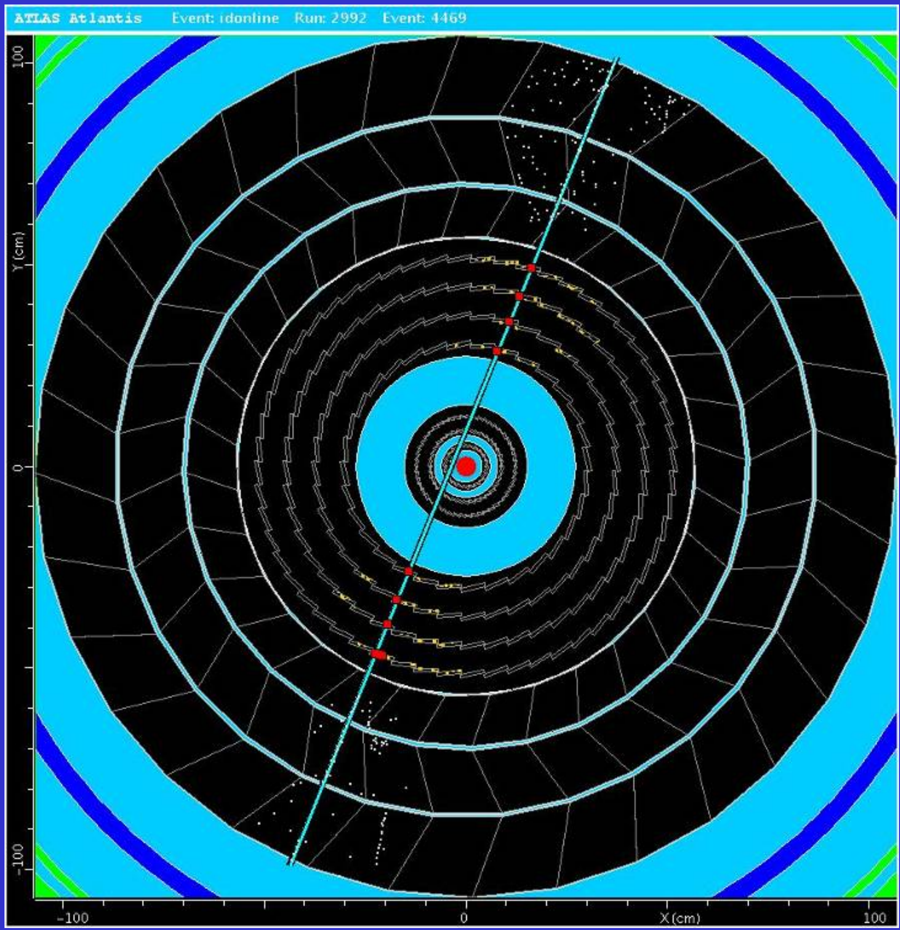
5: Primera física

2005 2006 2007 2008

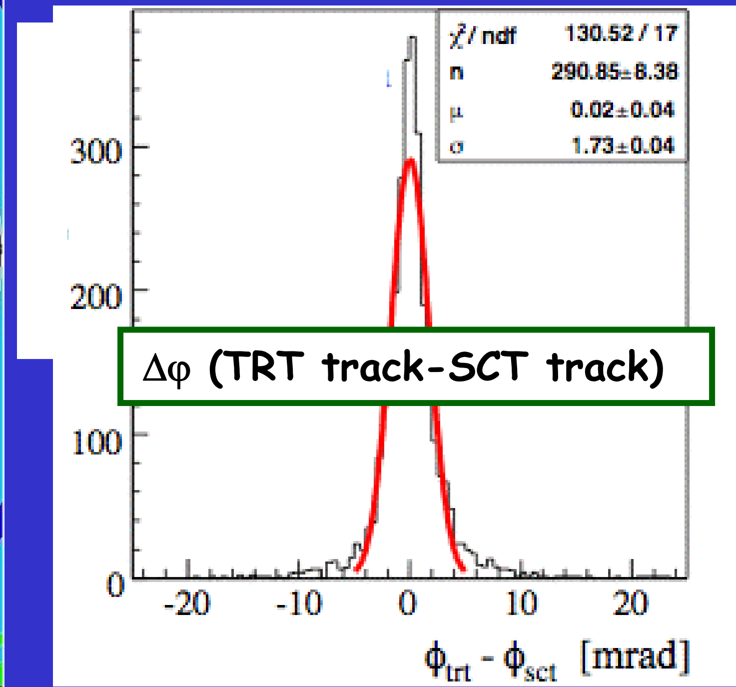


Qué podemos y debemos aprender de cada una de estas fases para poder hacer física con los primeros datos de ATLAS?

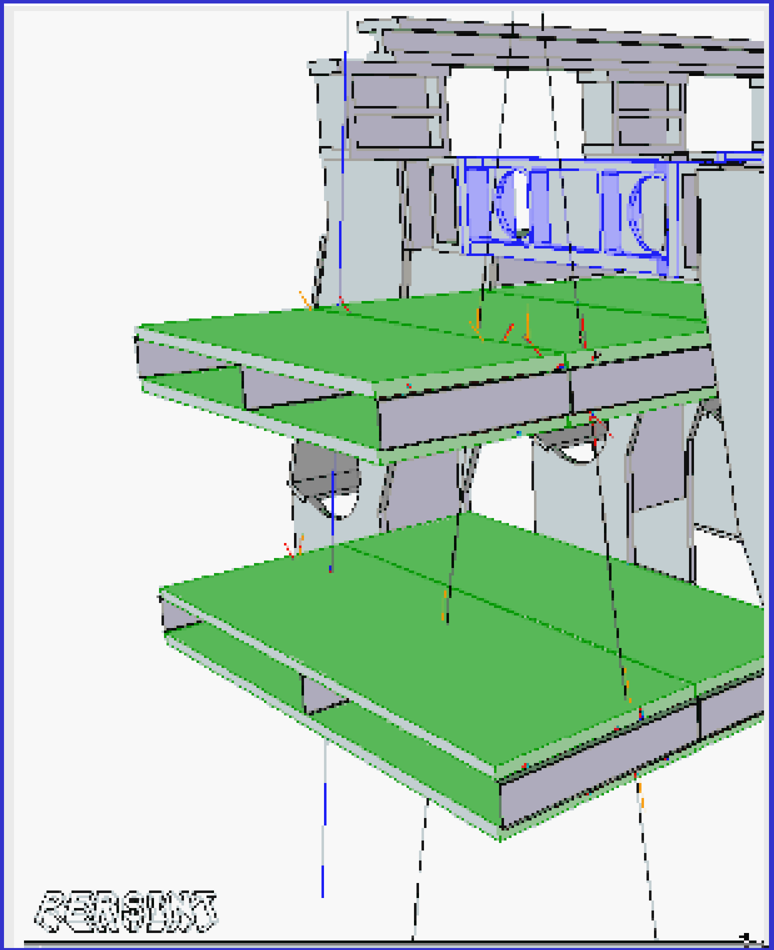
Cosmics DATA taken in barrel SCT+TRT

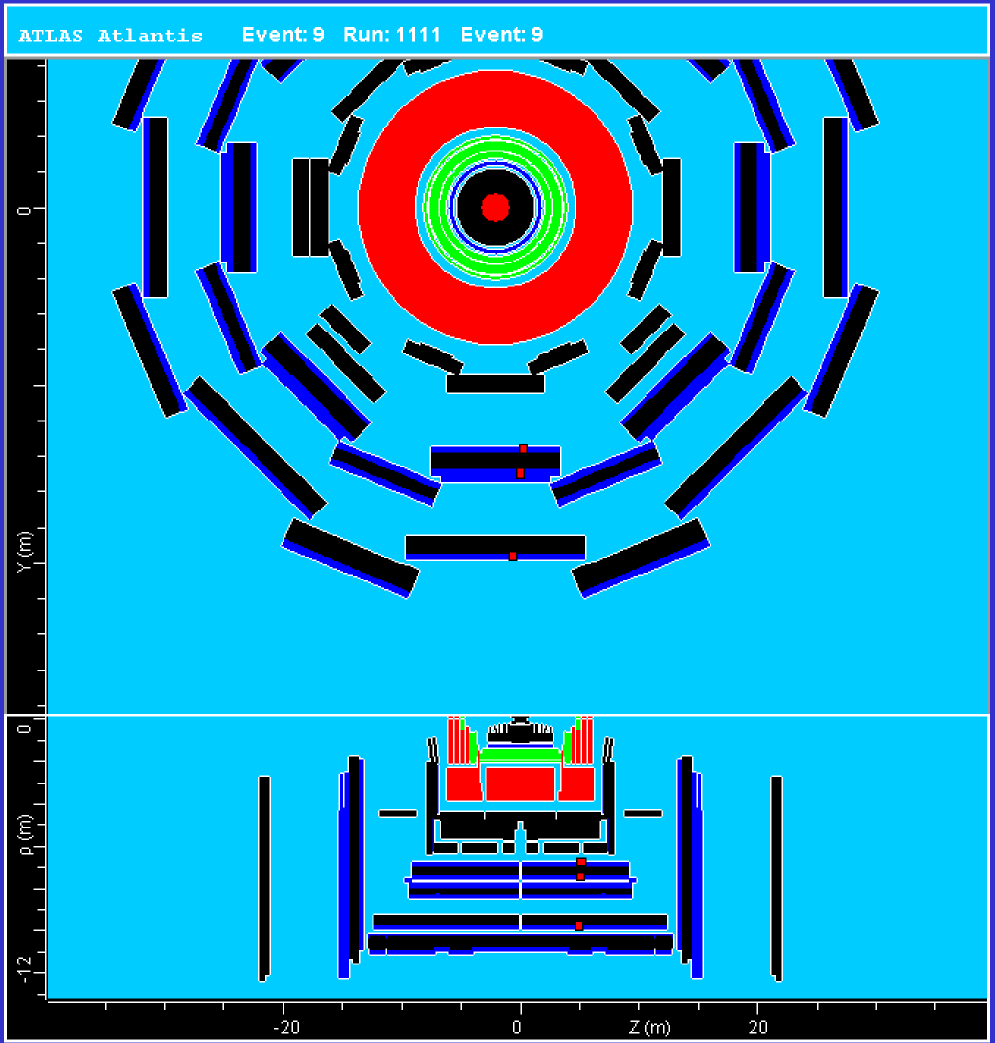


ATLAS preliminary

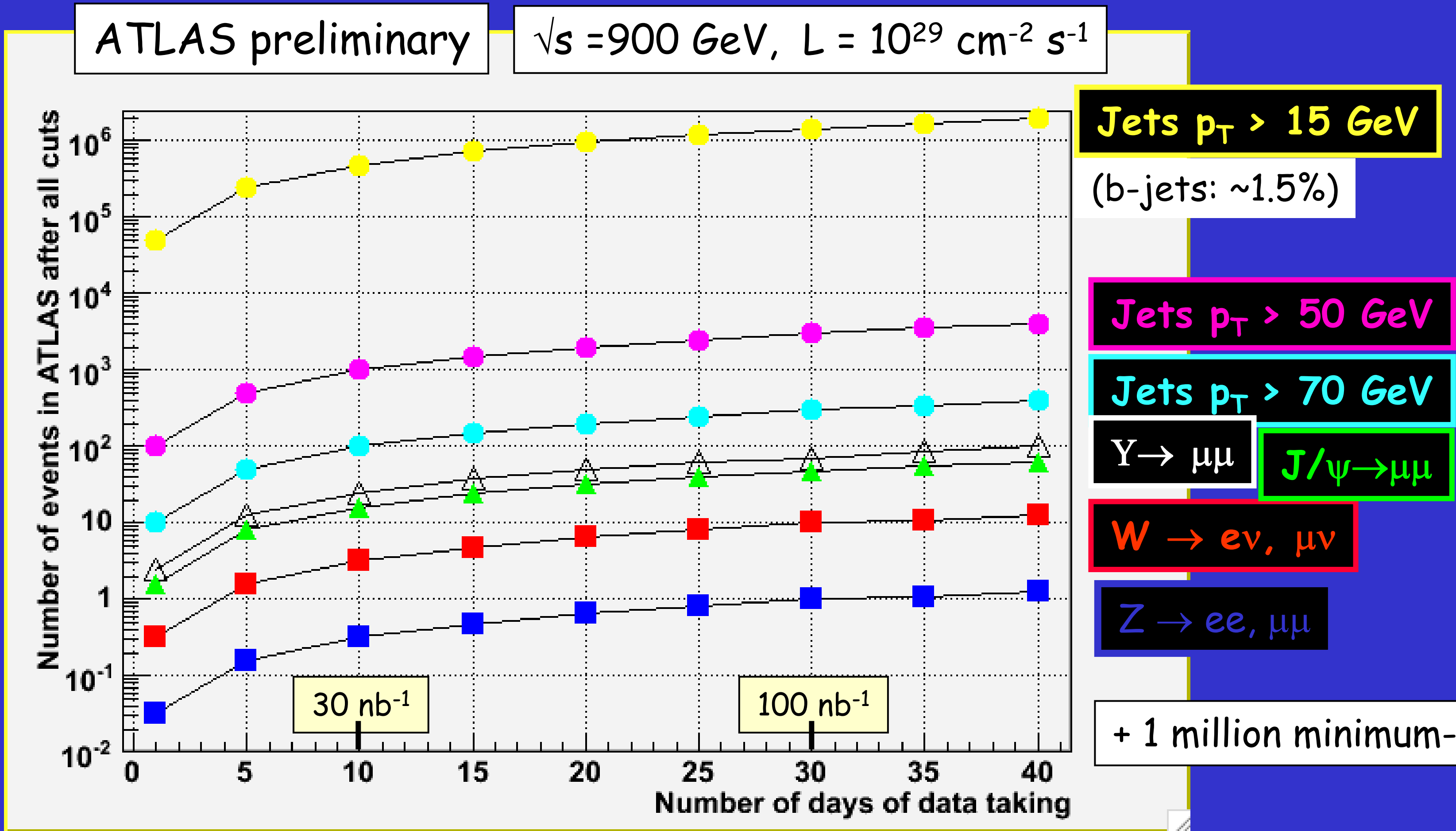


First cosmics have been registered in the underground cavern with barrel Muon chambers (MDT and RPC) and Level-1 μ trigger





Which analyses with early data



+ 1 million minimum-bias/day

Example of initial measurement: physics with top events

Can we observe an early top signal with limited detector performance ?

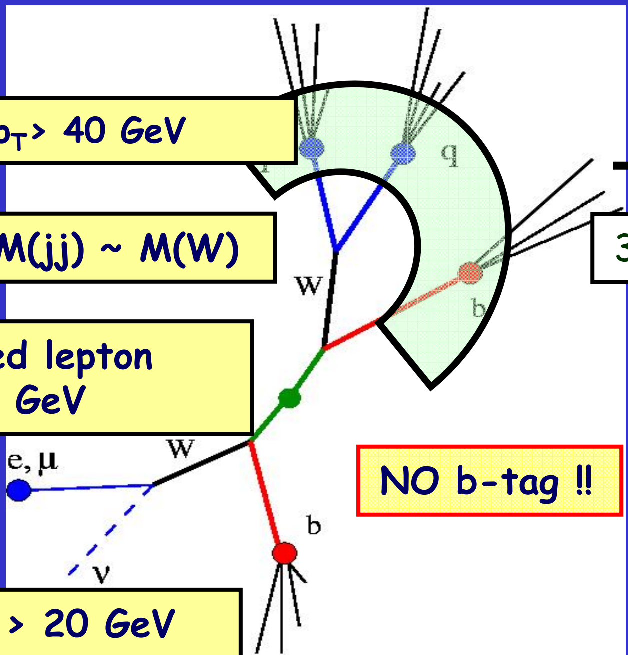
$\sigma_{tt} \approx 250$ pb for $tt \rightarrow bW\,bW \rightarrow bl\nu\,bjj$

4 jets $p_T >$ 40 GeV

2 jets M(jj) ~ M(W)

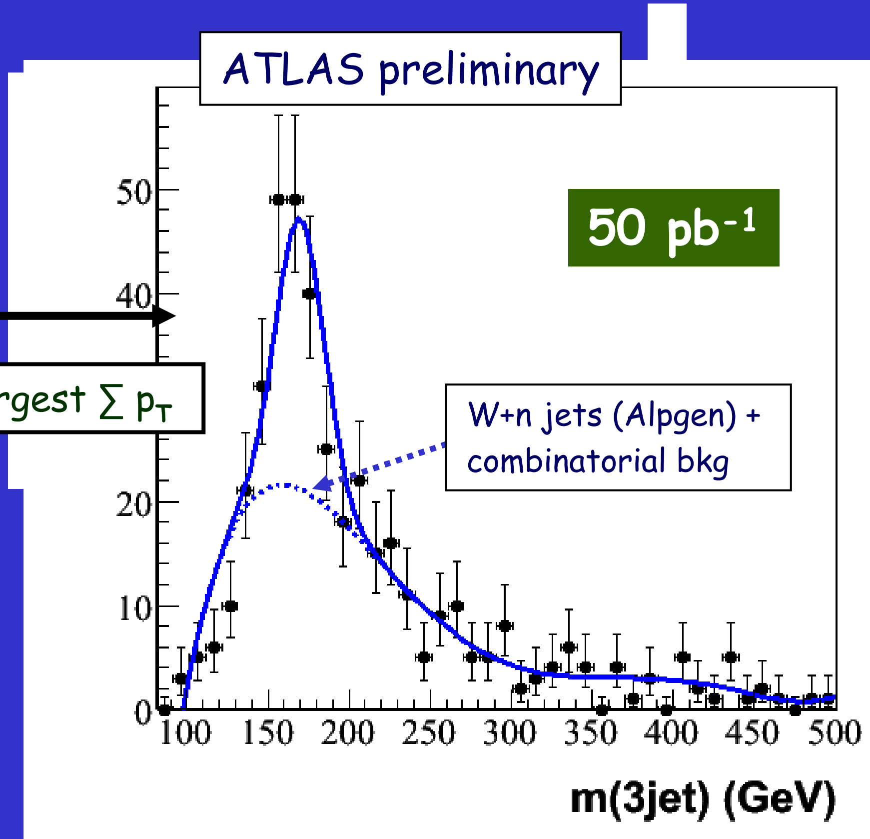
Isolated lepton $p_T >$ 20 GeV

$E_T^{miss} >$ 20 GeV



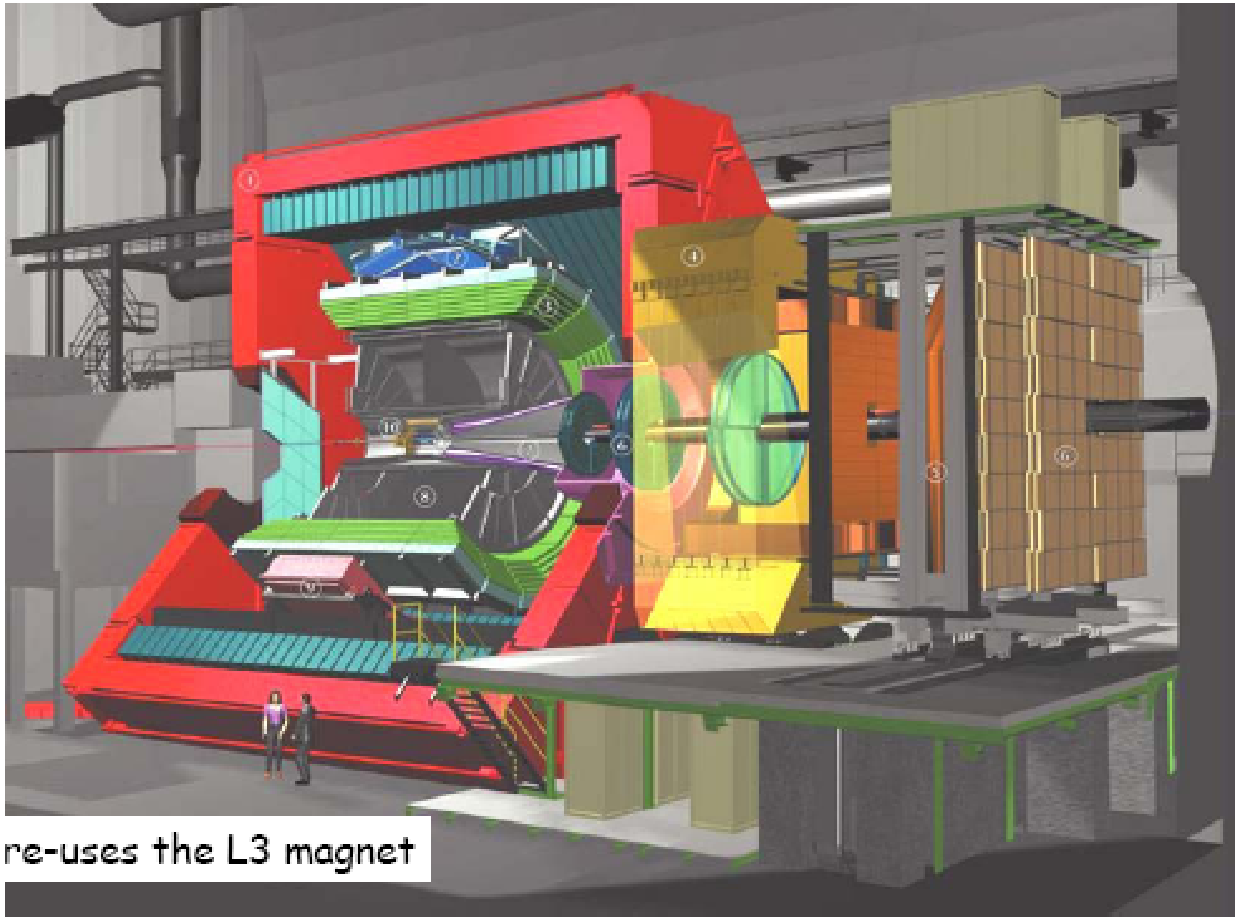
NO b-tag !!

3 jets with largest $\sum p_T$



Top signal observable in early days with no b-tagging and simple analysis (100 ± 20 evts for 50 pb^{-1}) → measure σ_{tt} to 20%, m to 10 GeV with ~100 pb^{-1} ?
In addition, excellent sample to:
understand detector performance for e, μ, jets, b-jets, missing E_T, …

ALICE Detector



Alice re-uses the L3 magnet

Pb-Pb total Xsection= 8barns $\rightarrow$ at $L=10^{27}\ cm^{-2}s^{-1}$ the rate is only 8 kHz
Multiplicity is the problem....

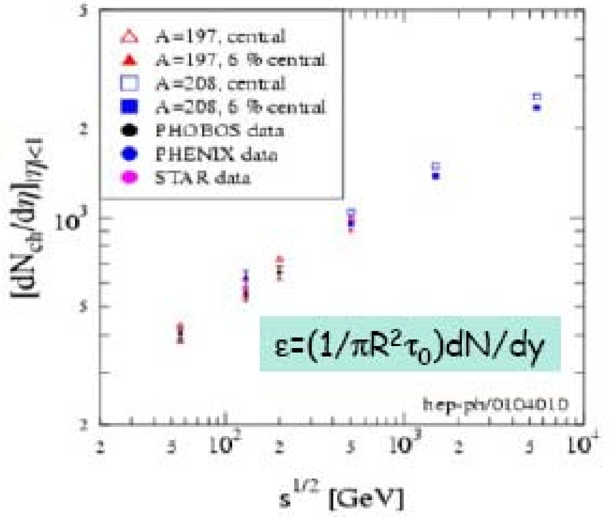
Soft particles in lead-lead collisions

At small impact parameter and high energy, the head on collisions of nuclei generate a large number of soft gluons, which in turn materialise into hadrons.

Expected density of gluons per pseudo-rapidity interval is ~3000 at LHC

There is interest in understanding:

- In which conditions (energy density ε) this evolves through an intermediate quark-gluon plasma (new state of matter, possibly already observed)
- How hard probes (ψ, Y) behave when traversing such a medium
- How this medium "cools-down" to ordinary hadrons.

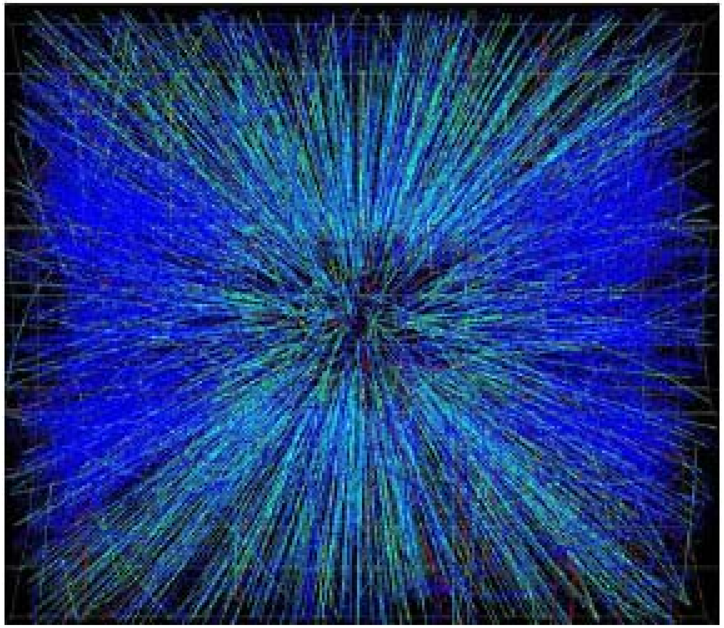


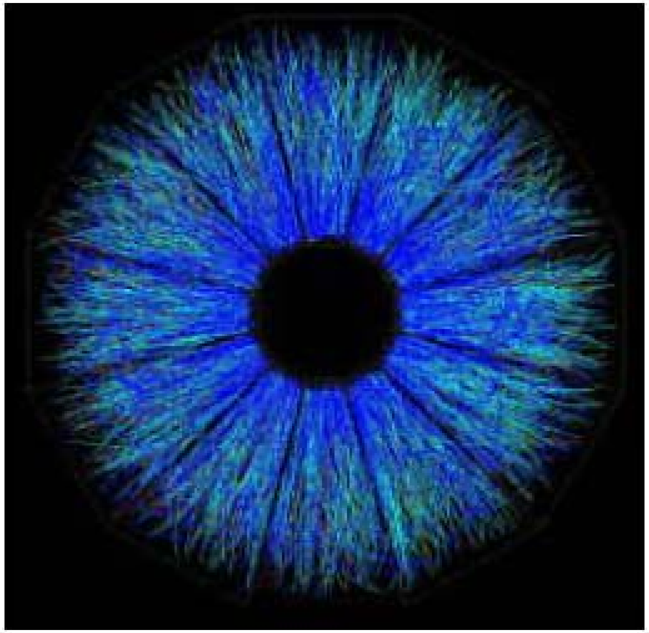
This last part is best studied with soft particles . Important observables are:

- **Nature of produced hadrons (fraction of strange part,..)**
- **Transverse momentum spectrum**
- **Intermediate states (resonances like $\phi\rightarrow KK$),....**

$\rightarrow$ALICE is aiming at 3σ $\pi/K/p$ ID in the 0.1 GeV to "few GeV" range

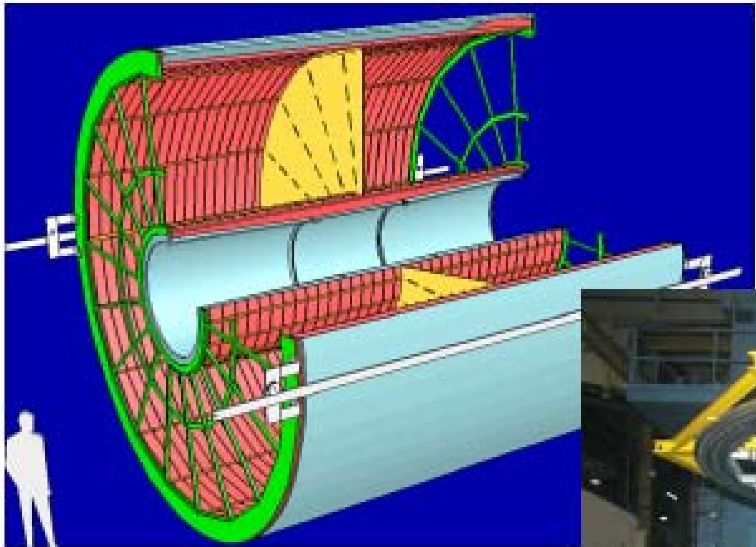
An event in STAR at RHIC





The centrality of the collision (impact parameter between the two line of flights)
is measured from several observables, in particular :
-the energy in ZDC which allows to count the number of "non-interacting nucleons"
-the multiplicity of charged particles at the vertex.
Central events have the highest probability to contain high energy density areas

The Alice TPC (2)

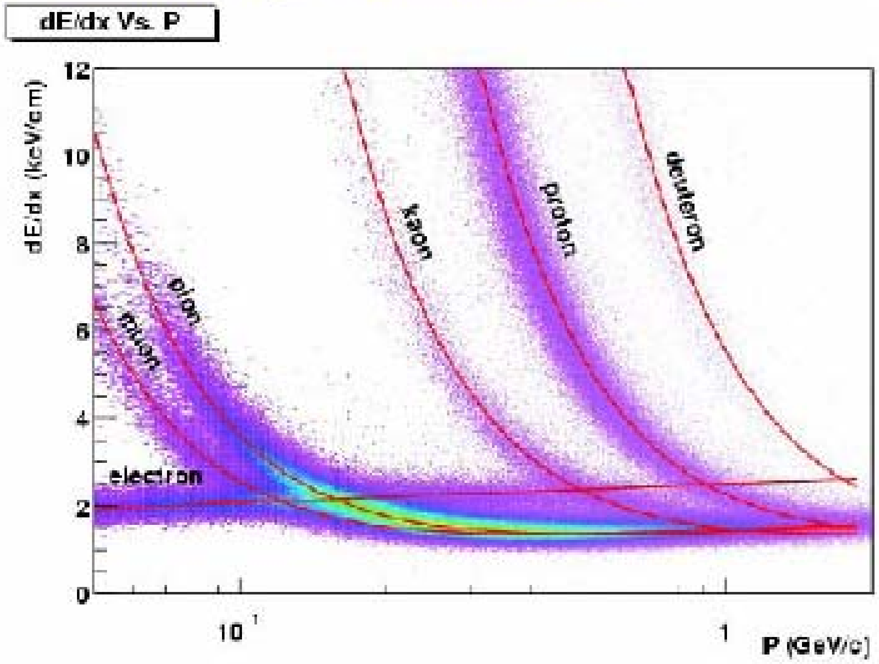


The Alice TPC (3)

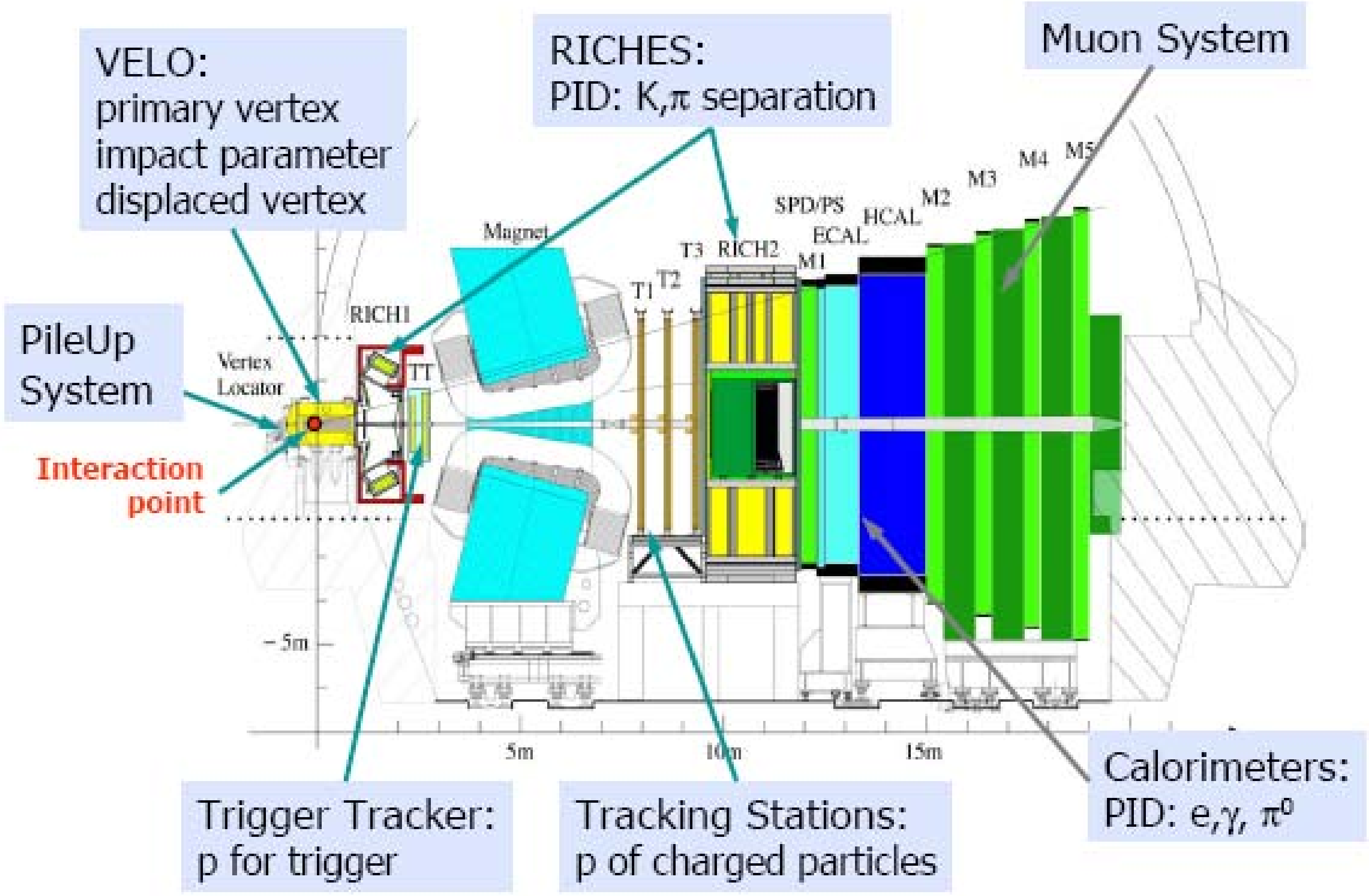
- dE/dx resolution goes like $N^{-0.43} \times (Pl)^{-0.32}$

  (N nb of samples , P pressure, l length of sample)
- Best dE/dx precision (~2%) was achieved by PEP4 (8 bars)
- *Alice expects 5.5% for isolated tracks and 7% with dN/dy ~ 8000*
- STAR (at RHIC)obtains the performance below:

Muon and pions Resolved below 100 MeV/c



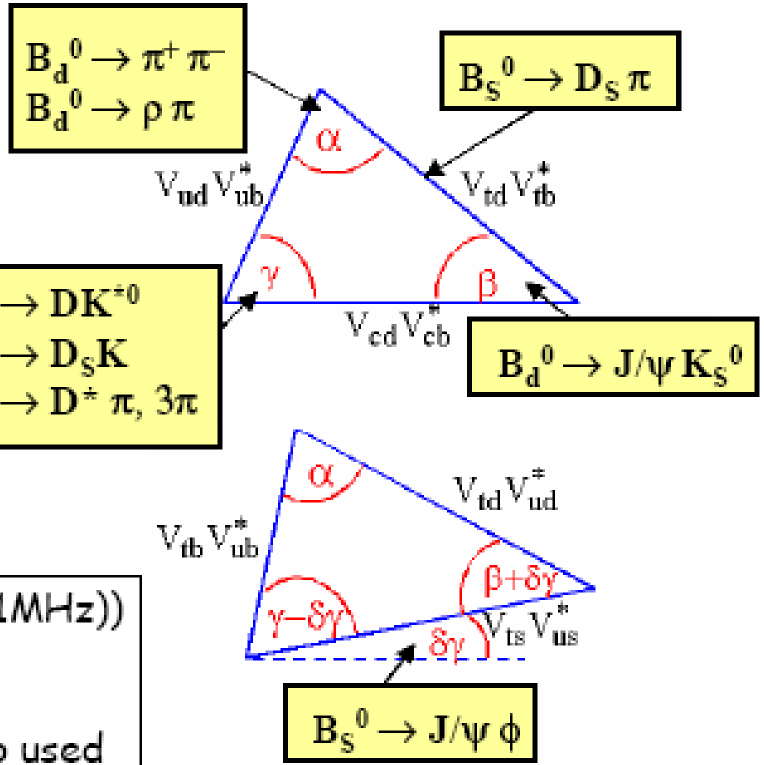
LHCb: single arm spectrometer



CP violation with LHCb

Among the main goals:
measure α and γ

2 CKM Unitary triangle relations most useful:



- Need precise measurements of exclusive modes, with K/π id
- Need trigger on hadronic modes

Hadronic calorimeter trigger(~2GeV E_T,1MHz))
Track trigger
Displaced vertex trigger
Leptonic decay of companion B(tag) also used

LHCb performances in perspective (1 year)

Measurement	Channel	LHCb	ATLAS	CMS
β [sin(2β)]	$B^0 \to J/\psi\ K_s^0$	0.3^O to 0.5^O	0.5^O	0.7^O
α [sin(2α)]	$B^0 \to \pi^+ \pi^-$ (assuming no penguin)	2^O to 10^O	down to 5^O	down to 5^O
α [sin(2α) and cos(2α)]	$B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$	5^O to 15^O	--	--
$2\beta + \gamma$	$B^0 \to D^{*+} \pi^-$	down to 7^O	--	--
$\gamma - 2\delta\gamma$	$B_s^0 \to D_s^- K^+$	3^O to 16^O	--	--
γ	$B_d^0 \to D^0 K^*$	4^O to 18^O	--	--
$\delta\gamma$	$B_s^0 \to J/\psi\ \Phi$	0.6^O	0.9^O	
X_s	$B_s^0 \to D_s^- \pi^+$	< 90	< 36	< 48
Rare decays	$B_s^0 \to \mu^+\mu^-$ (SM. BR. ~$3.5\text{x}10^{-9}$)	4.4σ SM signal	4.7σ SM signal	10σ SM signal
	$B_d^0 \to K^* \gamma$	26k evts.	--	--

The LHC computing

40 MHz (1000 TB/sec)

Level 1 - Special Hardware

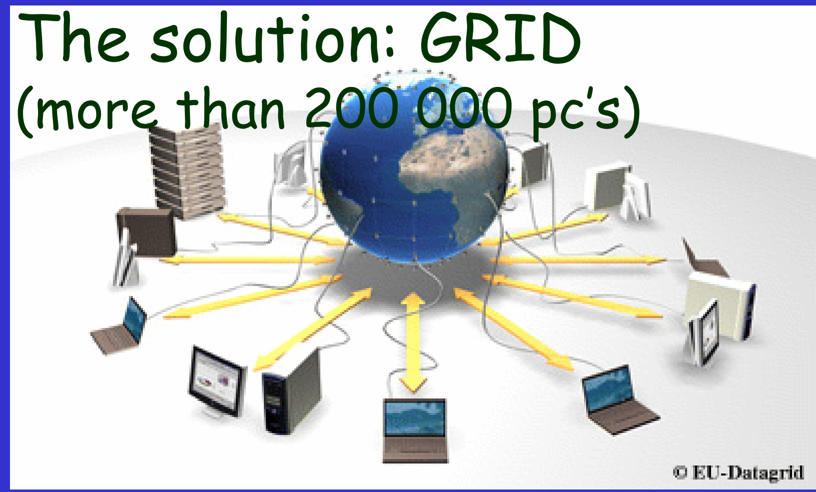
75 KHz (75 GB/sec)

Level 2 - Embedded Processors

5 KHz (5 GB/sec)

Level 3 - Farm of CPUs

100 Hz (100 MB/sec)



100 MB/sec ~ 2 Petabytes/year

(1 PB = 10^3 TB = 10^6 GB)

Data Recording,
Reconstruction,
&
Offline Analysis

Summary

LHC is really a difficult machine (we saw yestterday). The detectors as well !!

LHC detector in good shape prepared to collect data soon..