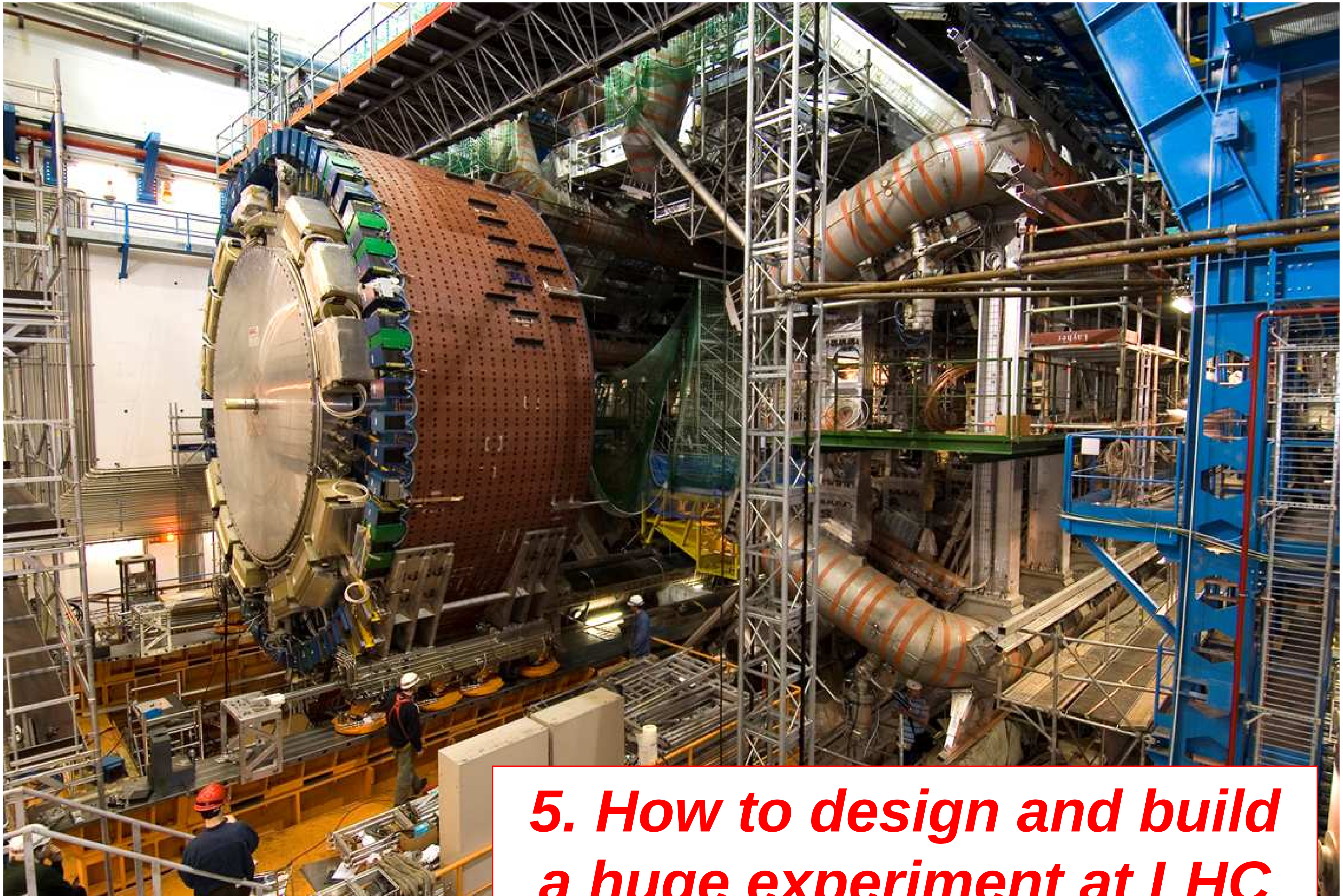


5. How to design and build a huge experiment at LHC

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)

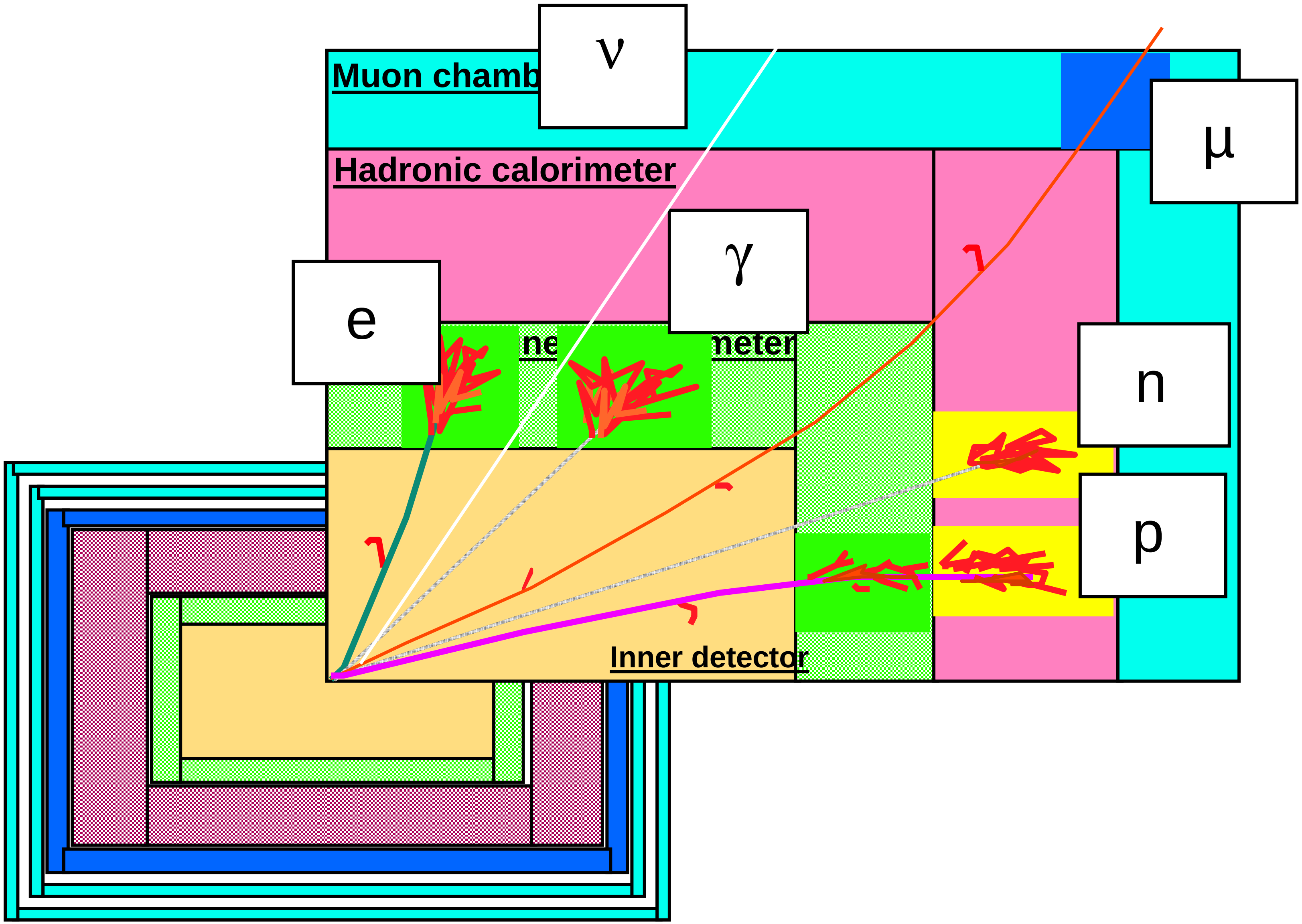
1995: Approval of ATLAS and CMS

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

Overall detector structure



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

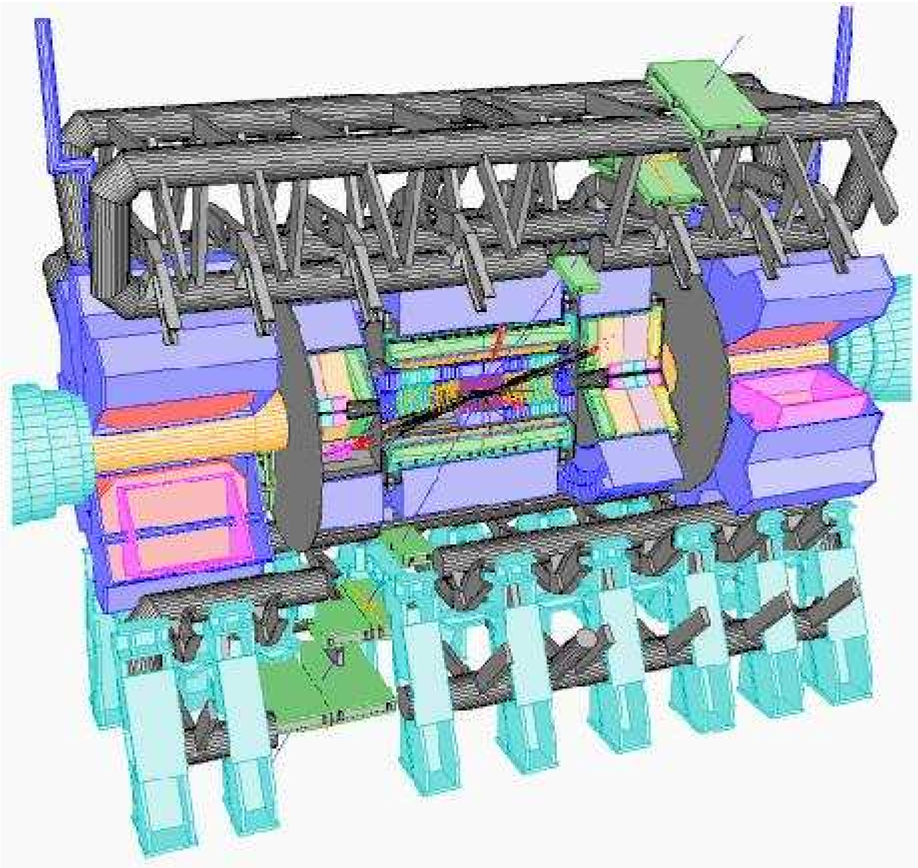
Choice of magnet system has shaped the experiments in a major way

- 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

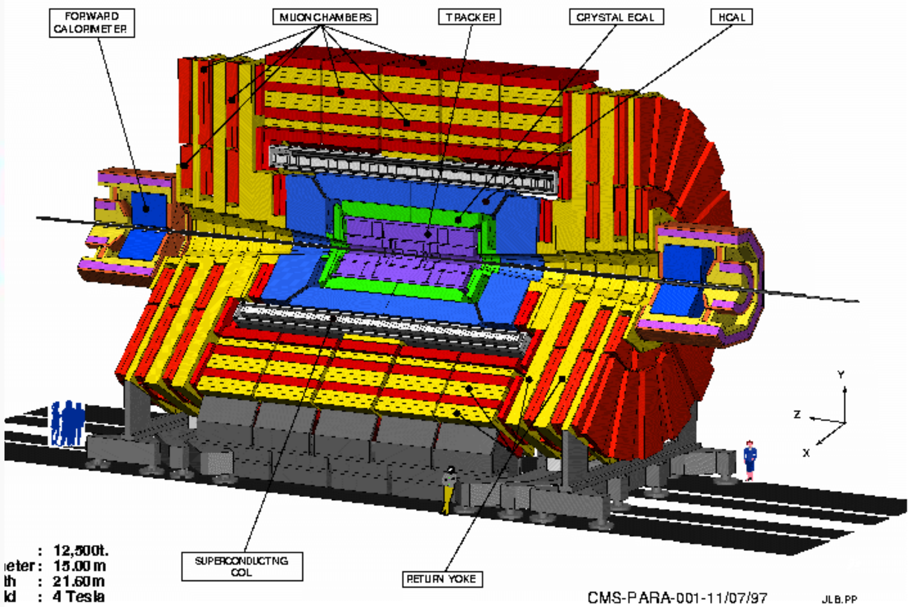
EM calorimetry of ATLAS and CMS is based on very different technologies

- 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



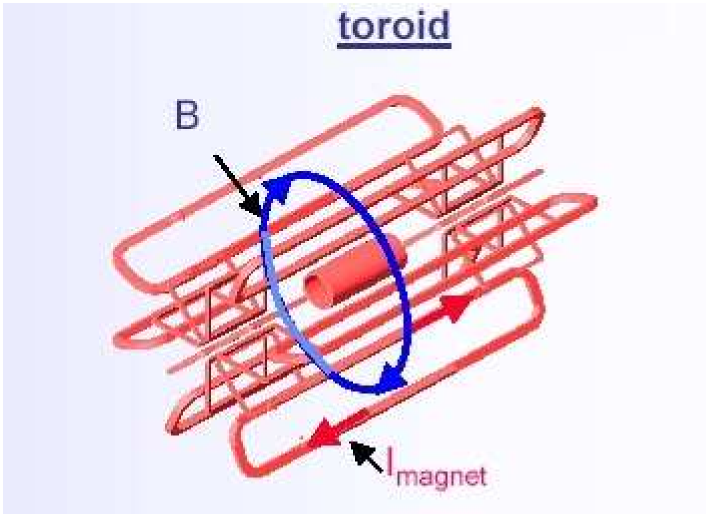
CMS

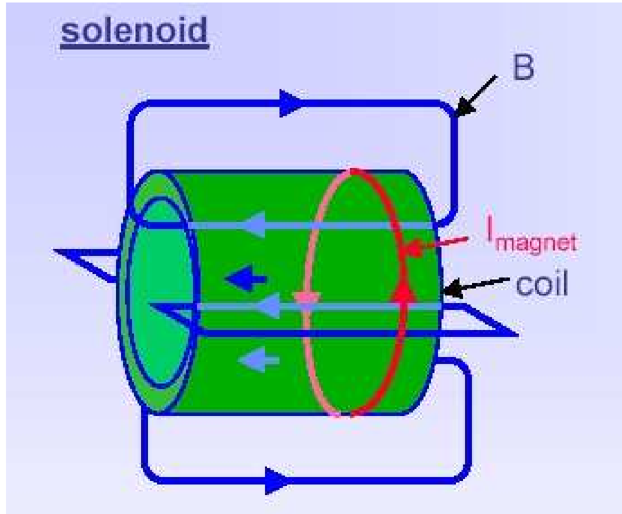


ATLAS

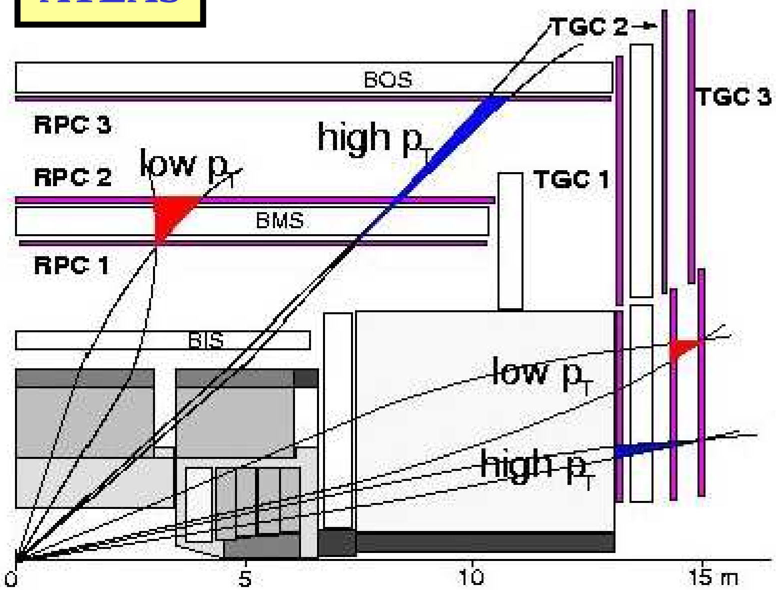
	ATLAS	CMS
Overall weight (tons)	7000	12500
Diameter	22 m	15 m
Length	46 m	22 m
Solenoid field	2 T	4 T

Main specific design choices: magnet system

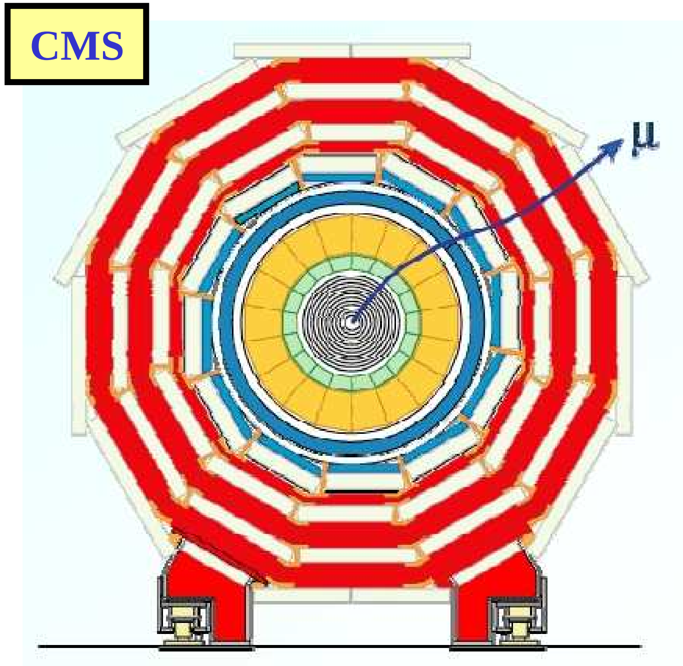




ATLAS



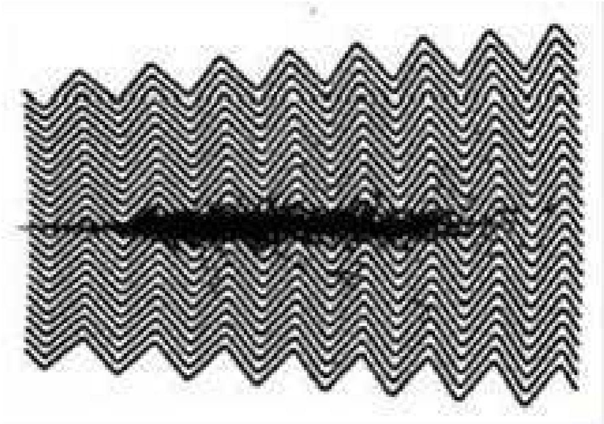
CMS

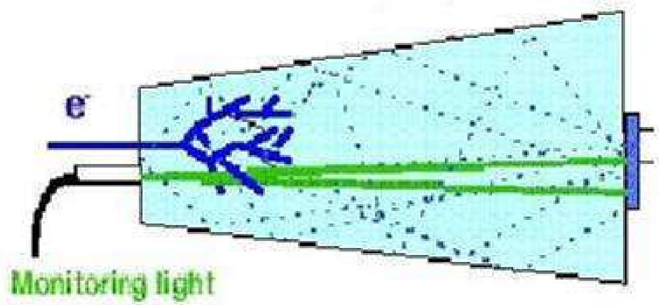


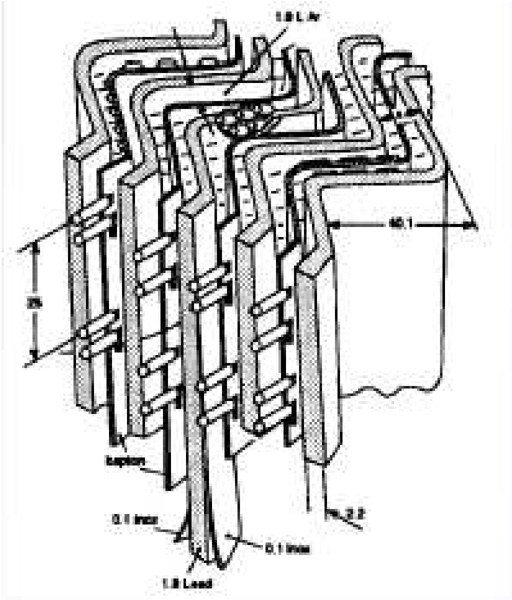
Main specific design choices: EM calorimetry

ATLAS: LAr accordion

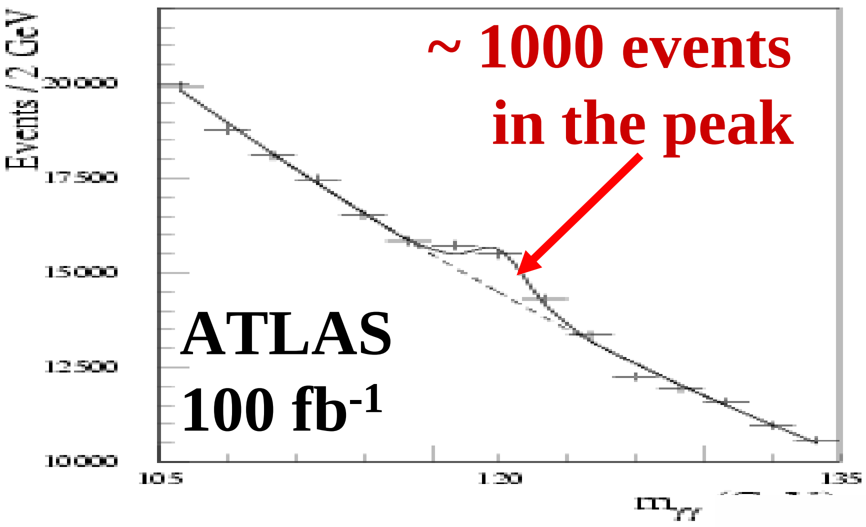
CMS: $PbWO_4$ crystals

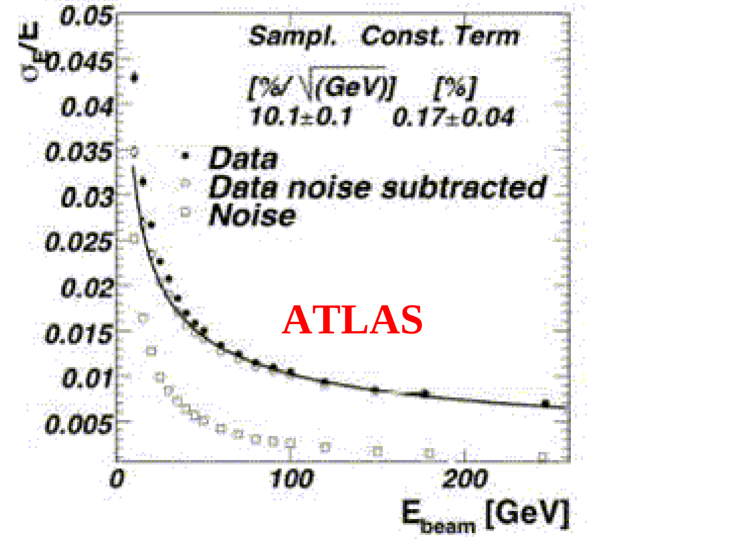


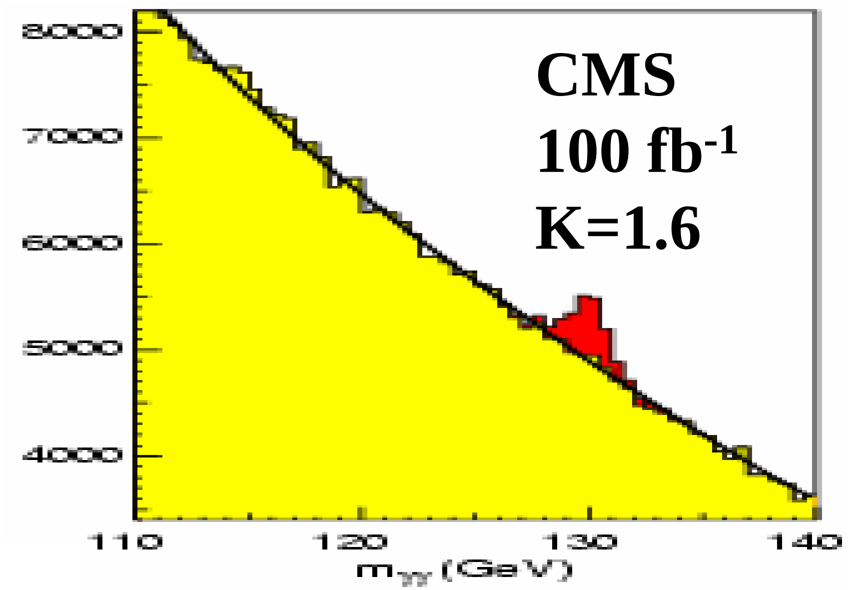


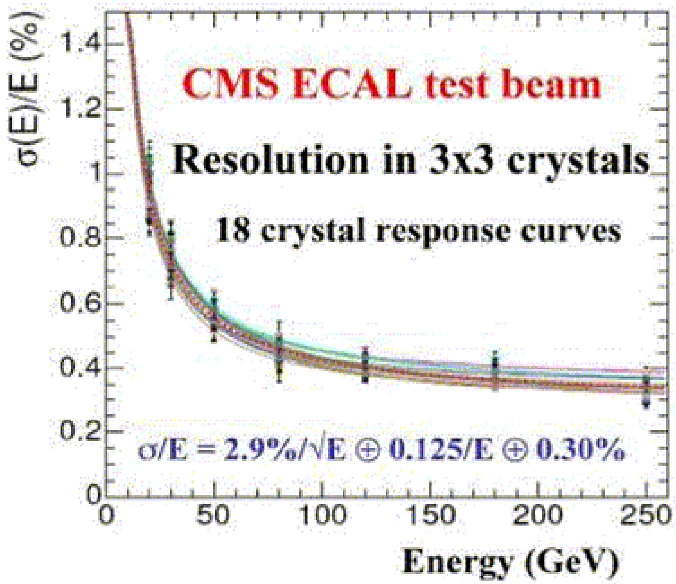


Detector optimisation example: H→ γγ





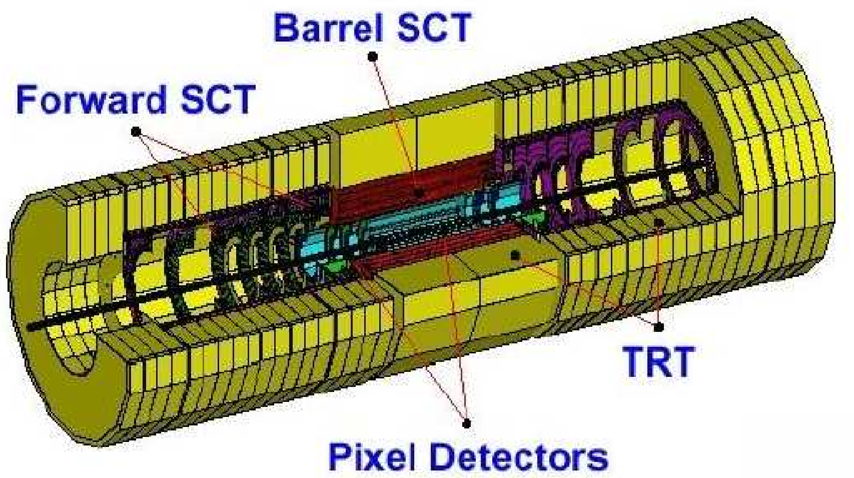




Main specific design choices: Inner Tracker

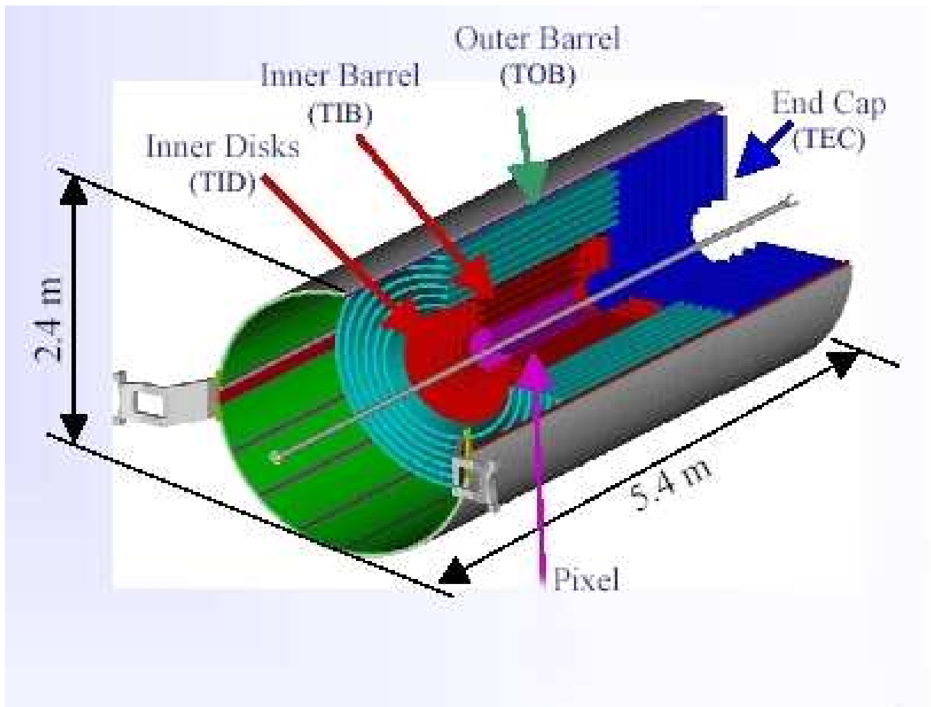
ATLAS

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



CMS

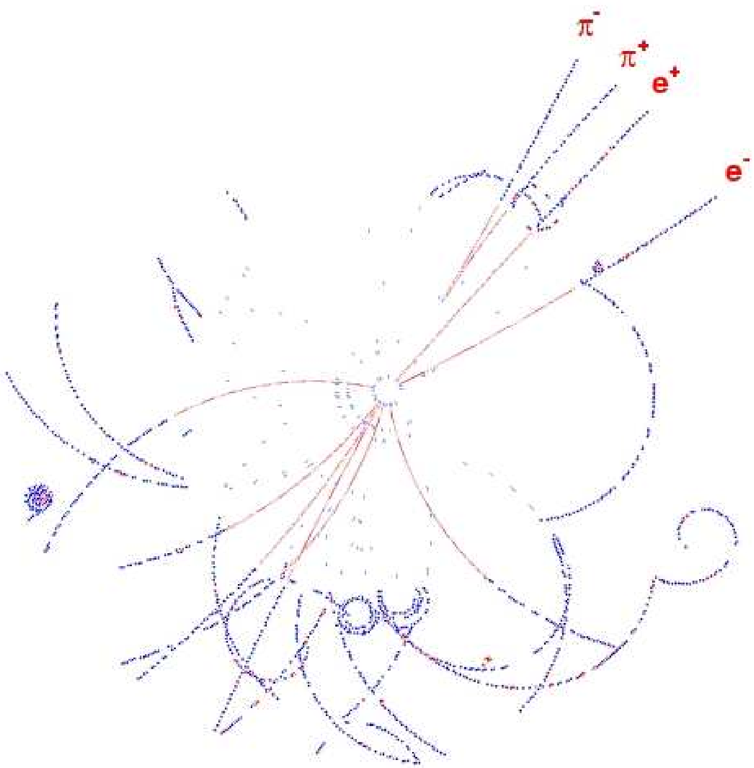
5.4 X 2.4 m cylinder
210 m^2 of Si sensors
10 M silicon strips
67 M pixel

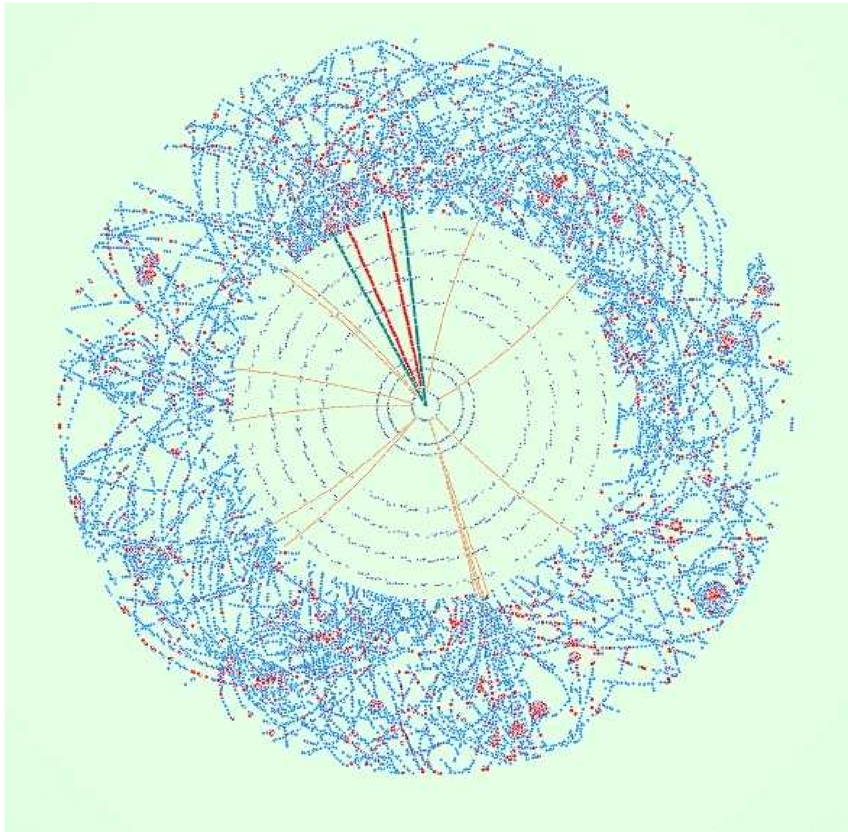


Inner Tracker: low and high luminosity

ATLAS
$B_0 \to J/\psi K_S \to ee\pi\pi$
low lumi

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

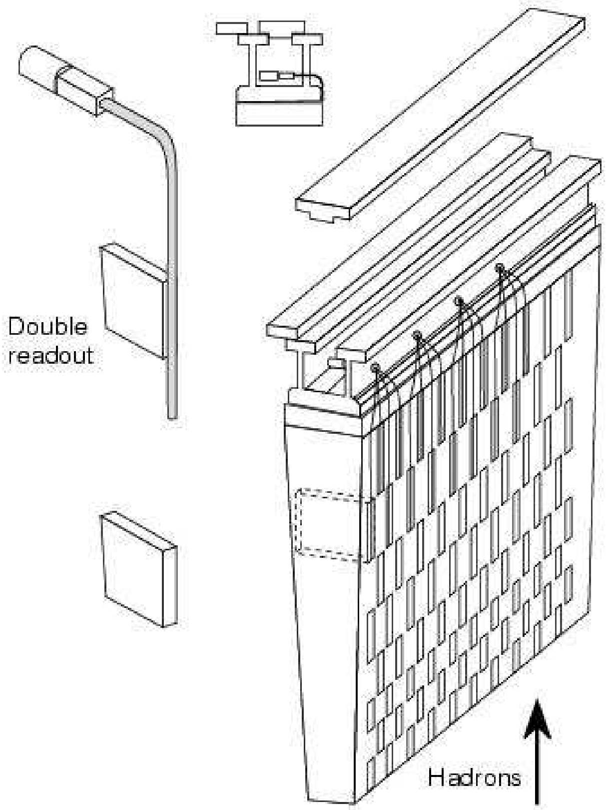




Main specific design choices: HAD calorimetry

ATLAS: Iron/scintillator

CMS: Brass/scintillator



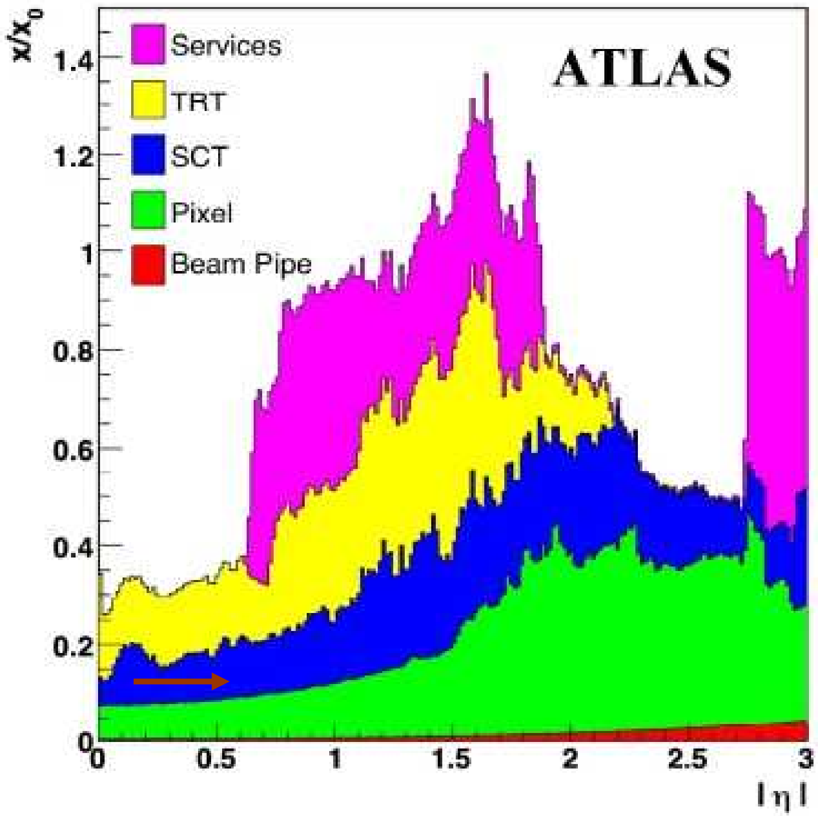
$$\frac{\Delta E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%$$

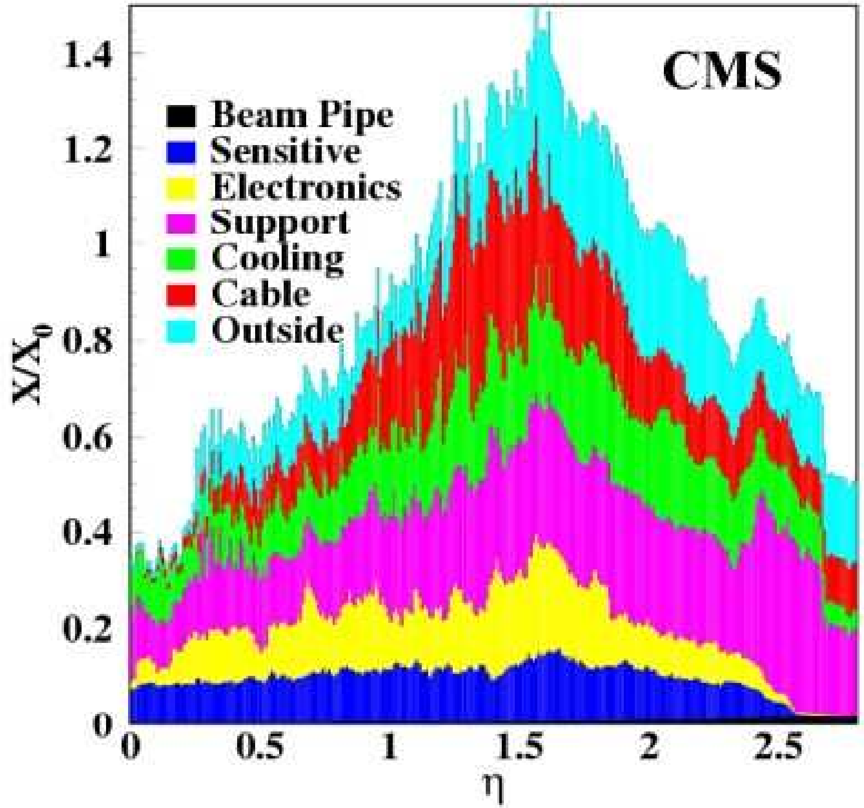
Test beam resolution for single hadrons

$$\frac{\sigma_E}{E} = \frac{65\%}{\sqrt{E}} \oplus 5\%$$

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:

$\approx$ 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.

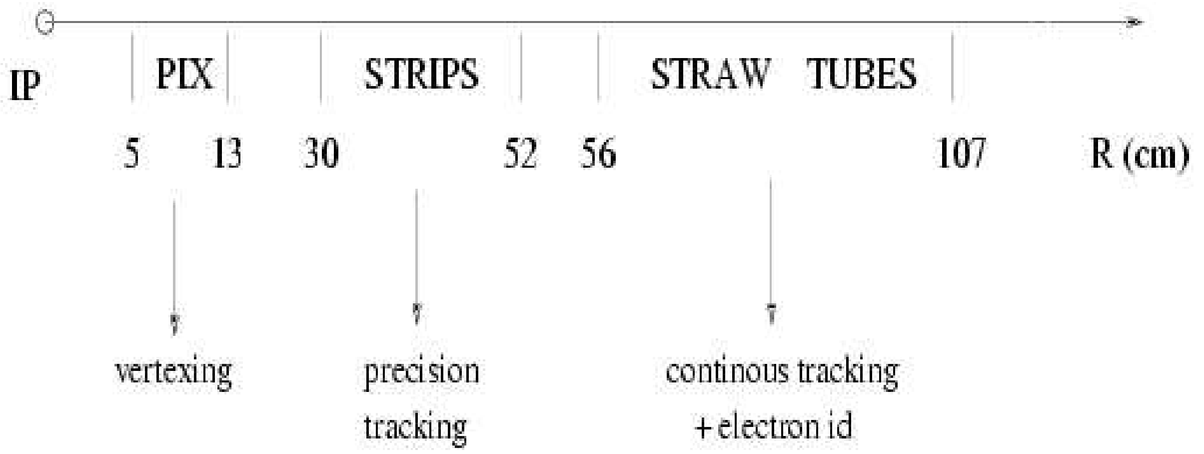
Expected total particle fluence $\approx 10^{13}$ tracks/cm^2 after 10 years.

Physics at the LHC: the environment

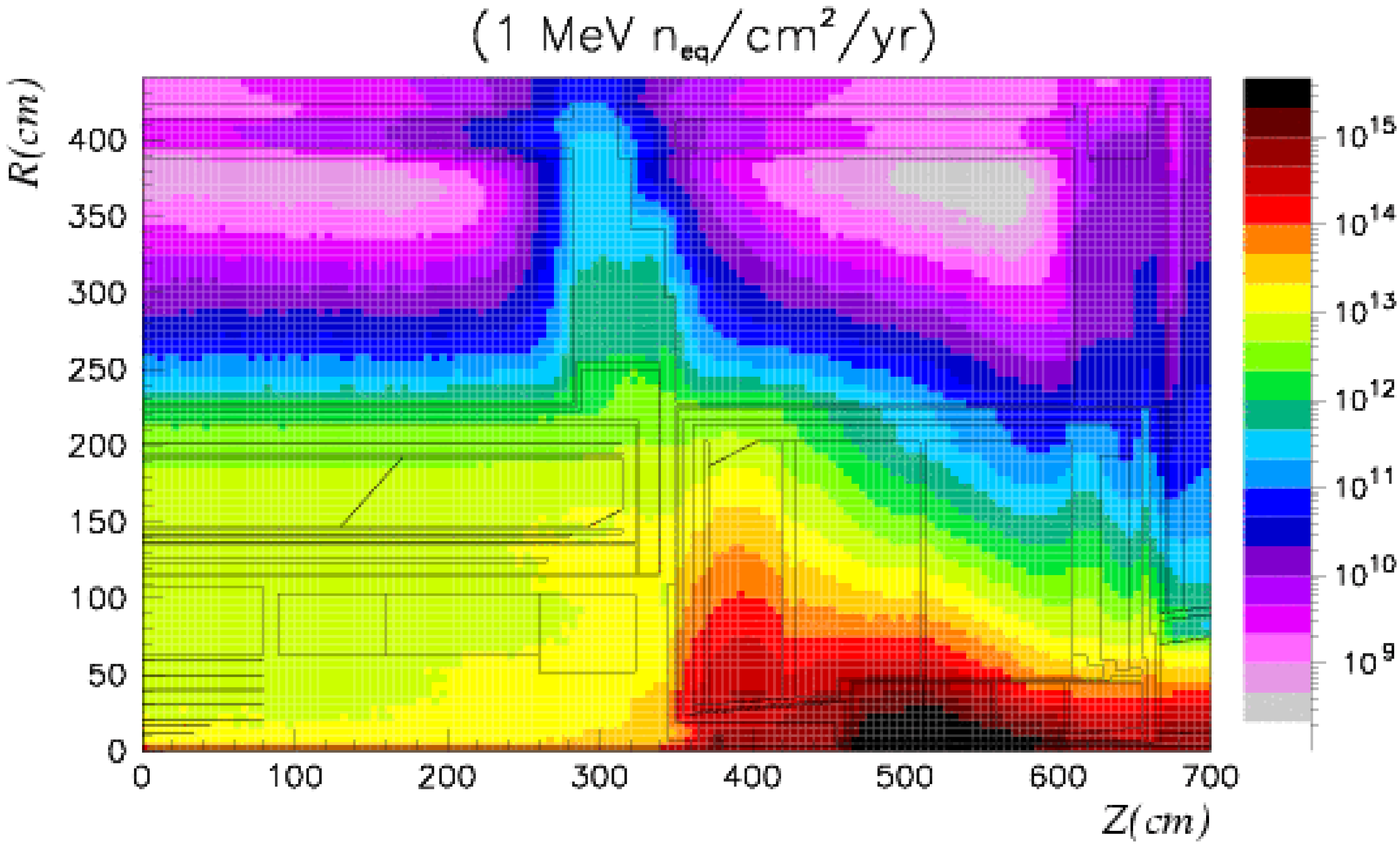
Problem of occupancy/survival

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

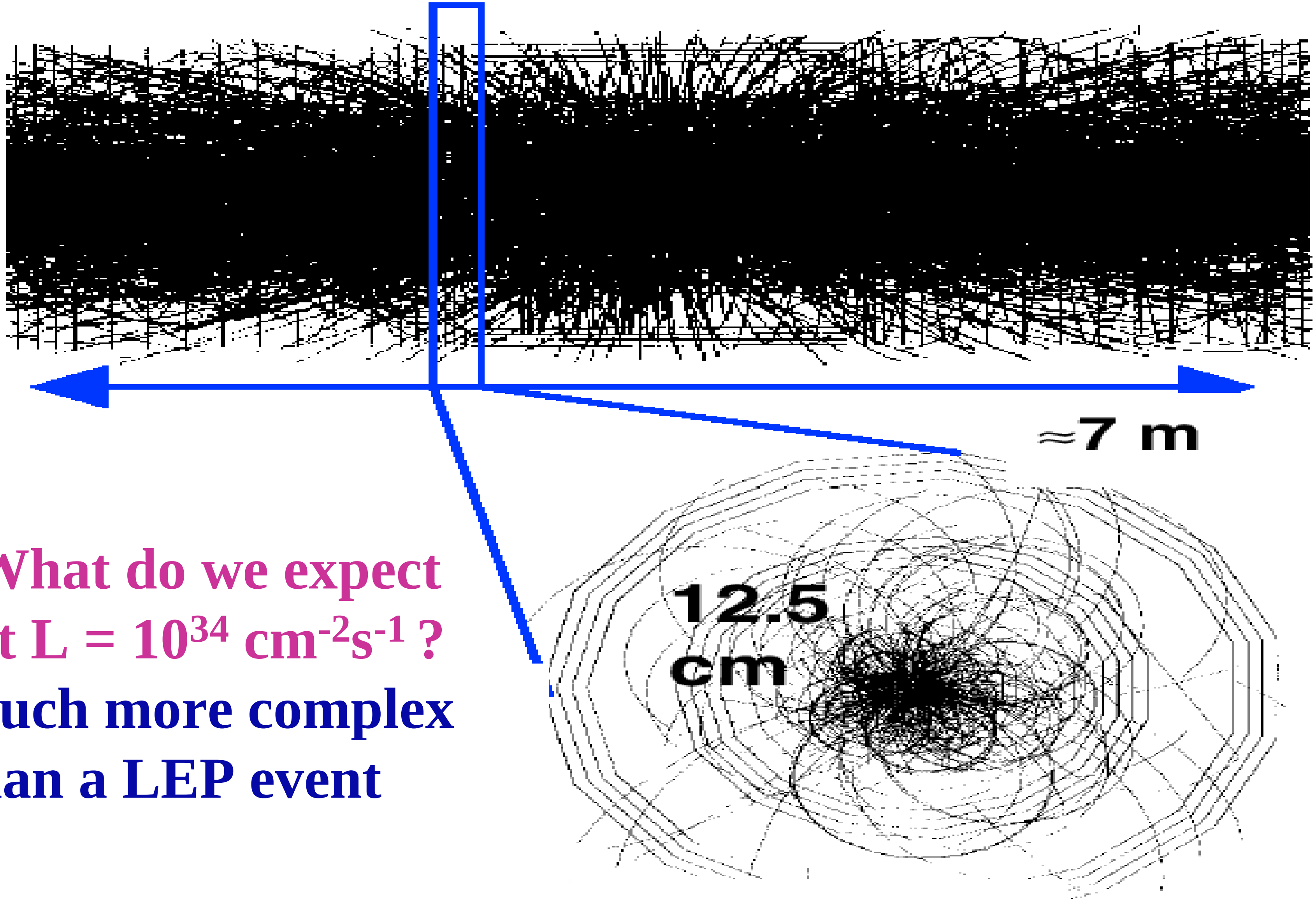
- the neutrons are created in hadronic showers
- these neutrons (with energies in the 0.1 to 20 MeV range) bounce back and forth and fill up the whole detector
- expected neutron fluence is about 3 10^{13} /cm^2/year in the innermost part of the detectors (inner tracking systems)

- the neutrons modify the cristalline structure of semiconductors

→ 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

Pile-up effects at high luminosity

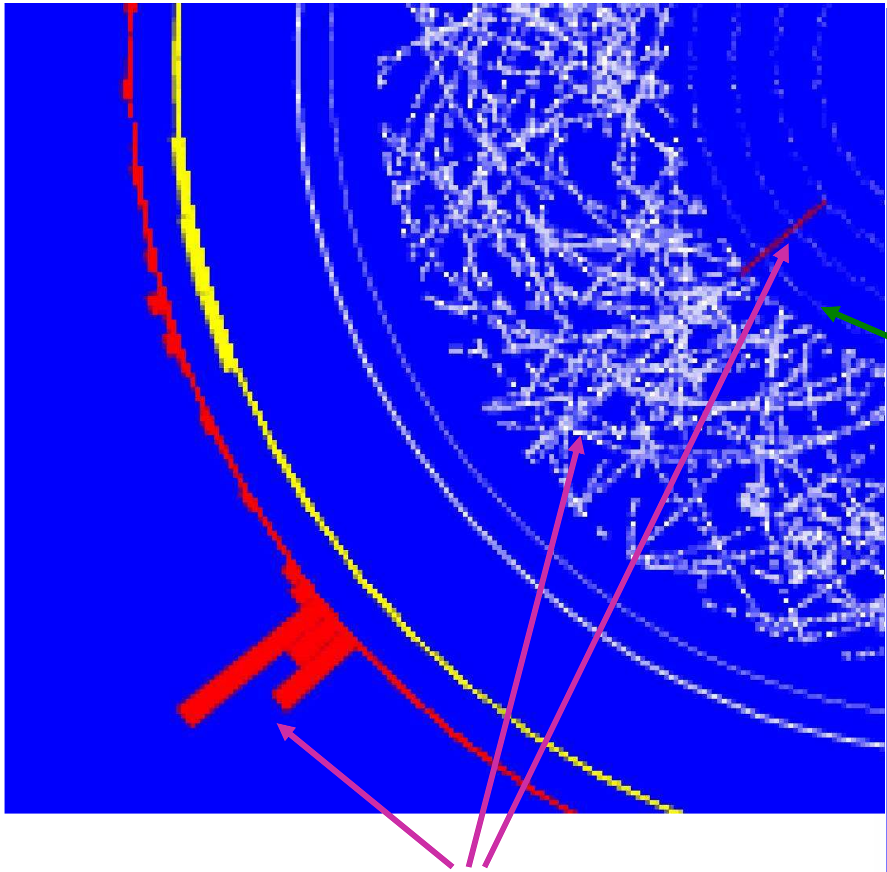
Pile-up is the name given to the impact of the 23 uninteresting (usually) interactions occurring in the same bunch crossing as the hard-scattering process which generally triggers the apparatus

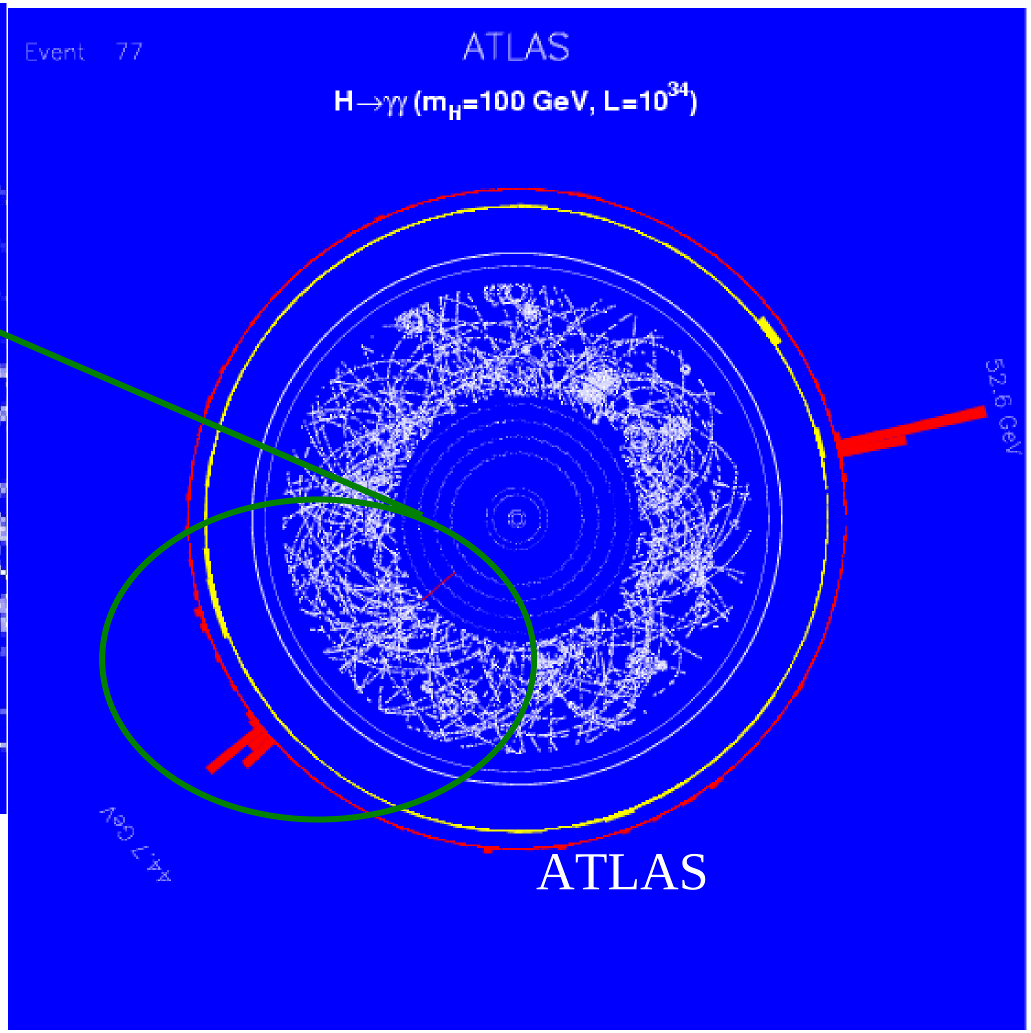
Minimising the impact of pile-up on the detector performance has been one of the driving requirements on the initial detector design:

- **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





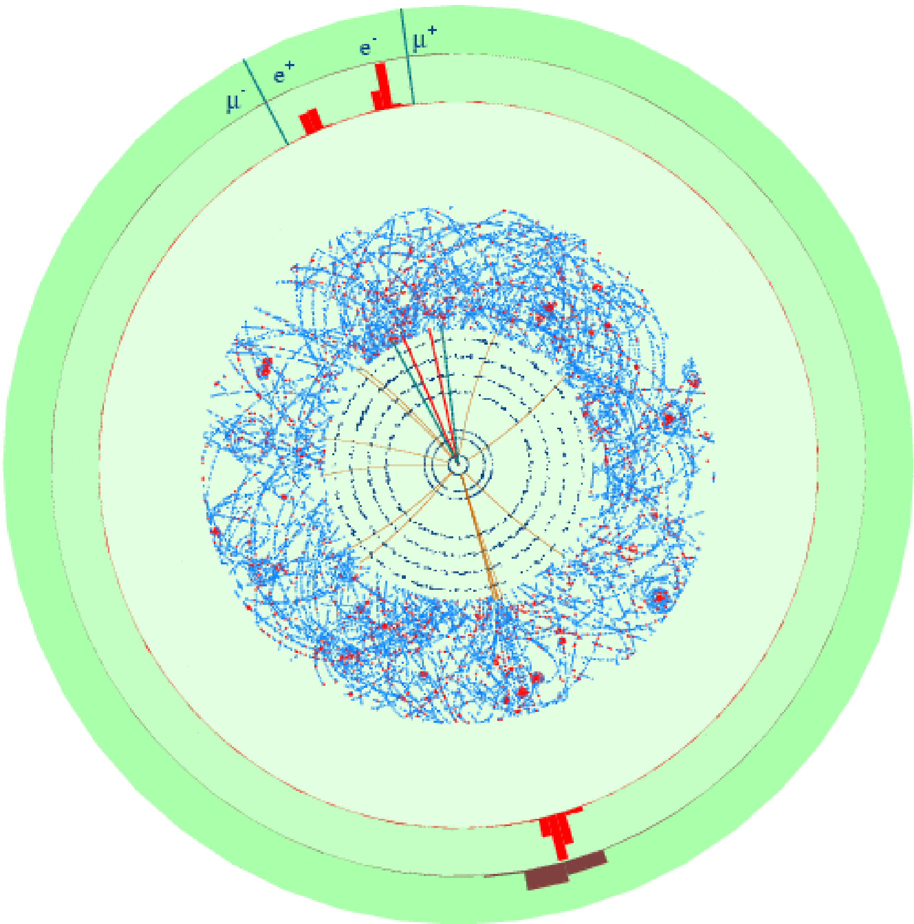
Photon converts at R = 40 cm and electron pair is visible in ATLAS TRT and EM calo

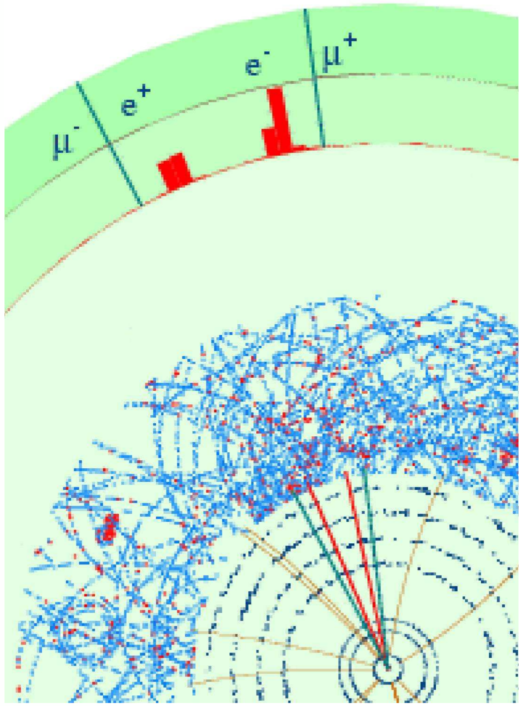
Physics at the LHC: the environment

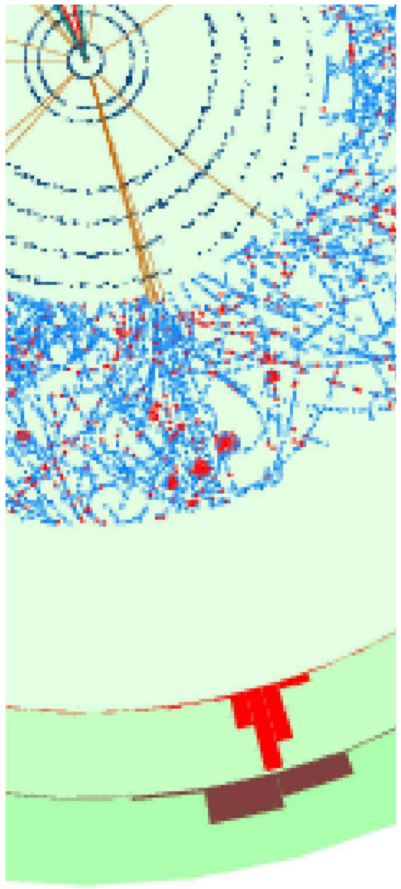
Pile-up effects at high luminosity

ATLAS barrel

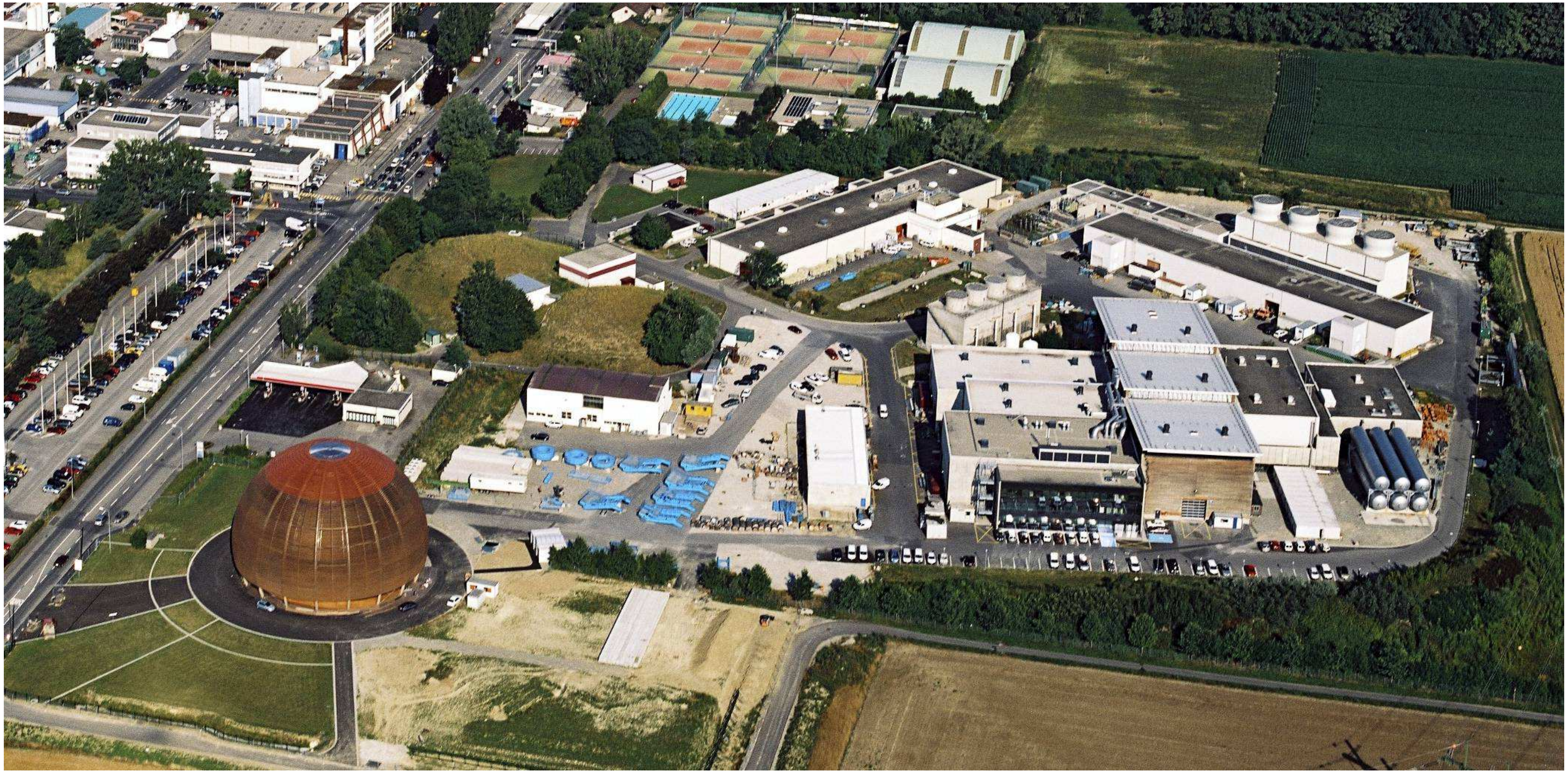
$H \rightarrow ZZ^{*} \rightarrow ee\mu\mu$ (m_H = 130 GeV)

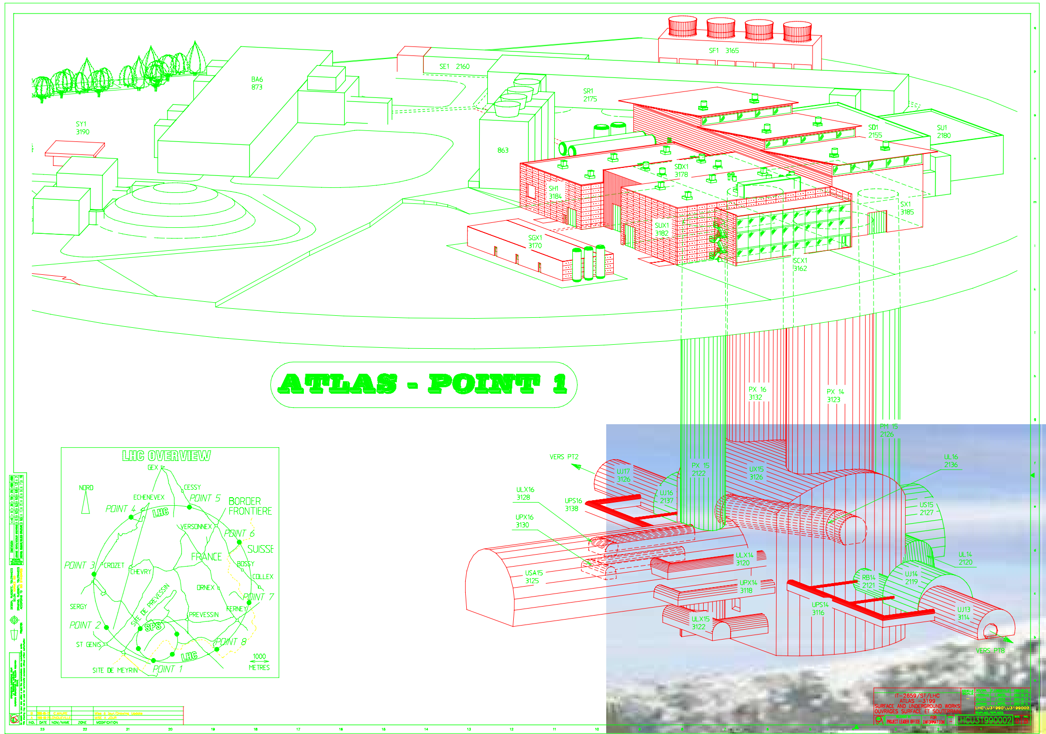




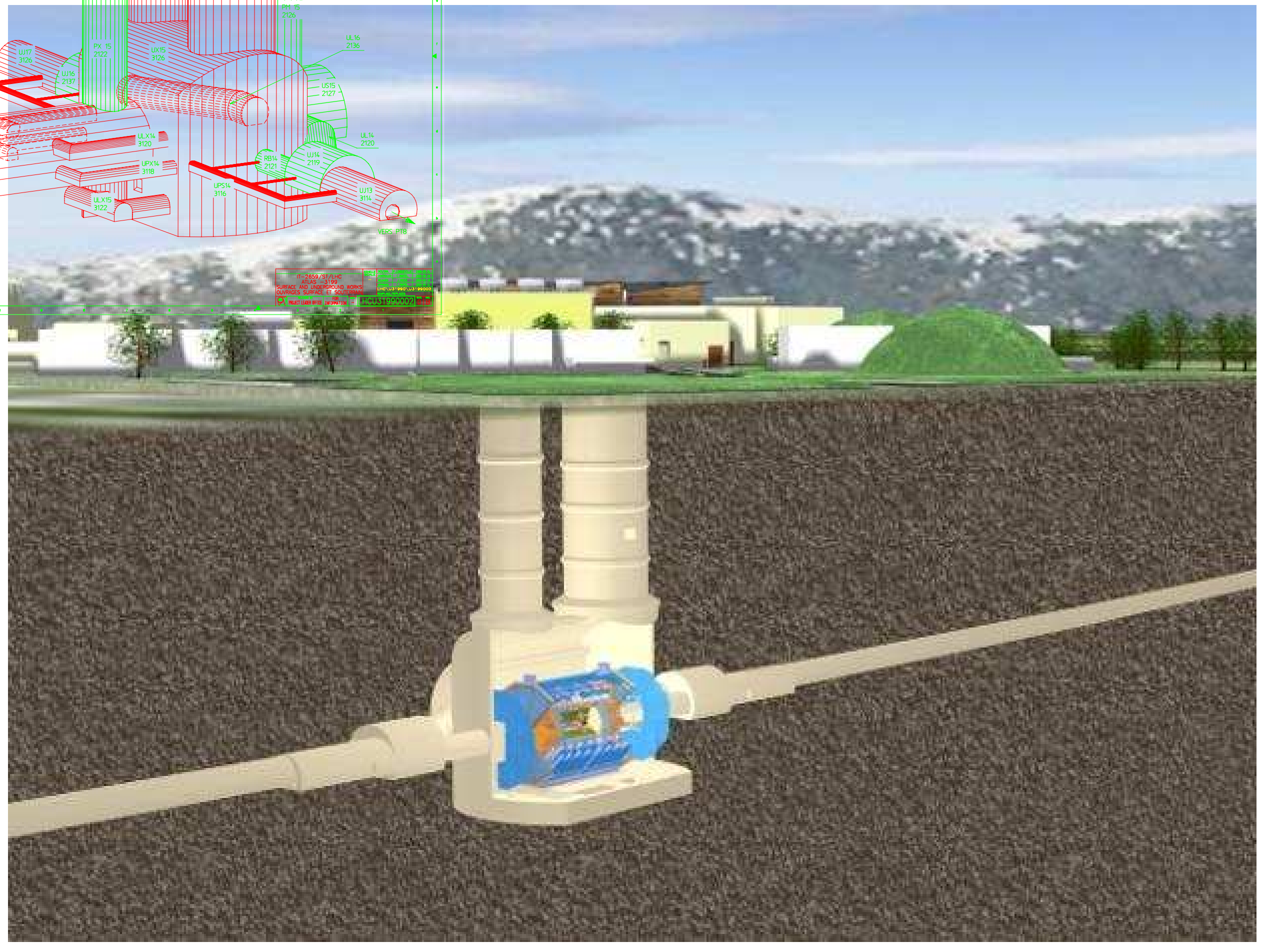


An Aerial View of Point-1

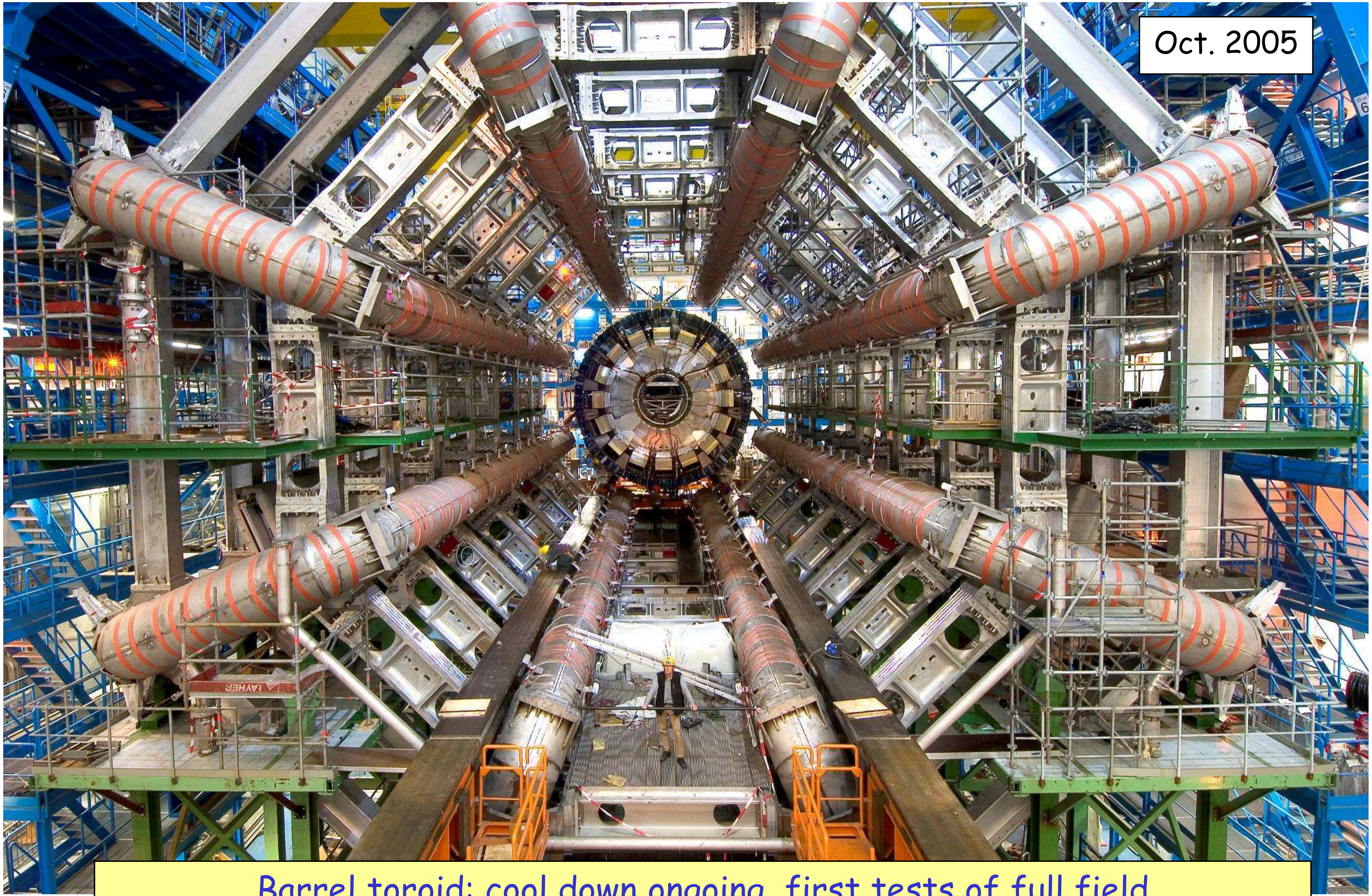




The Underground Cavern at Pit-1 for the ATLAS Detector

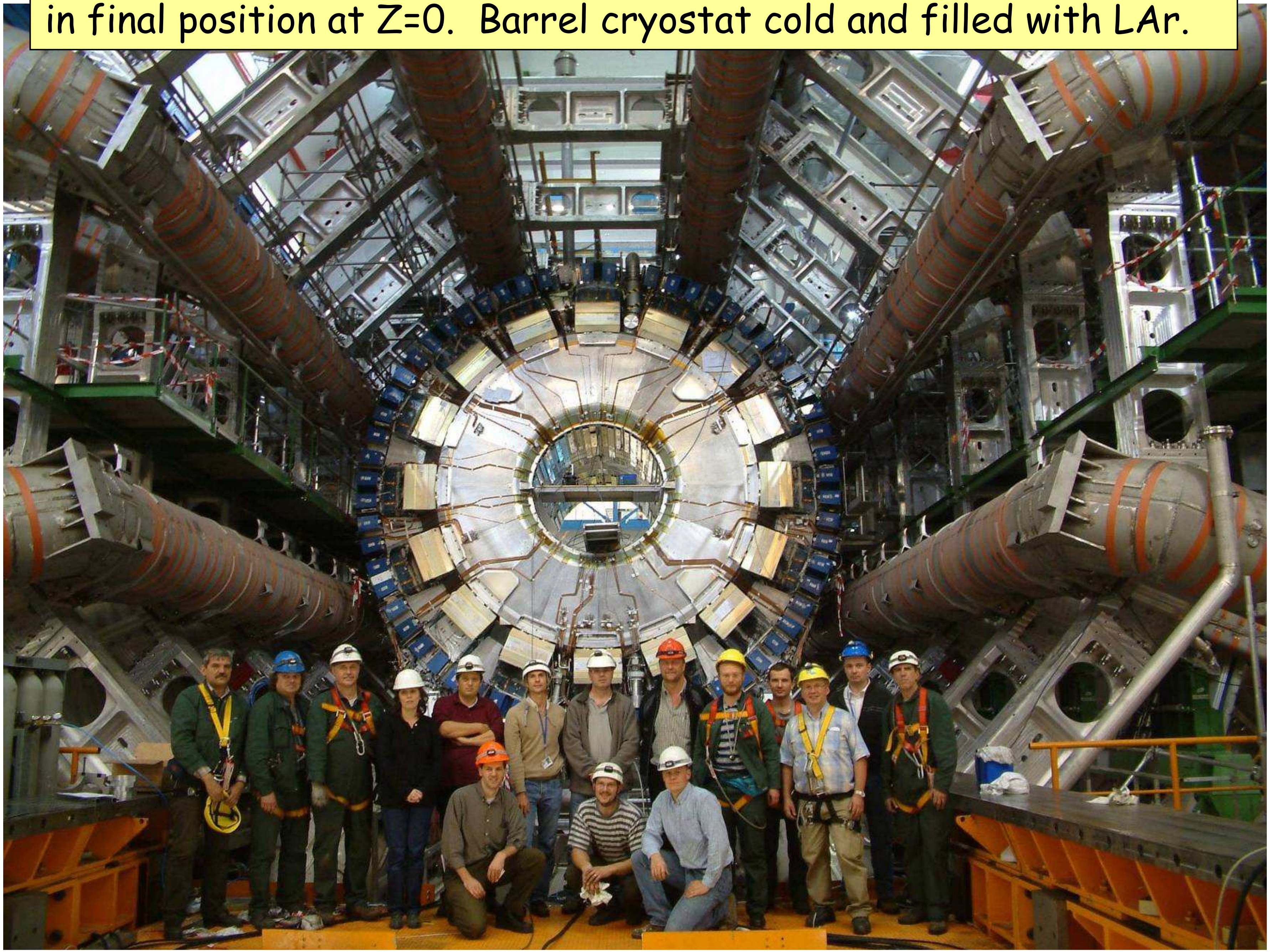


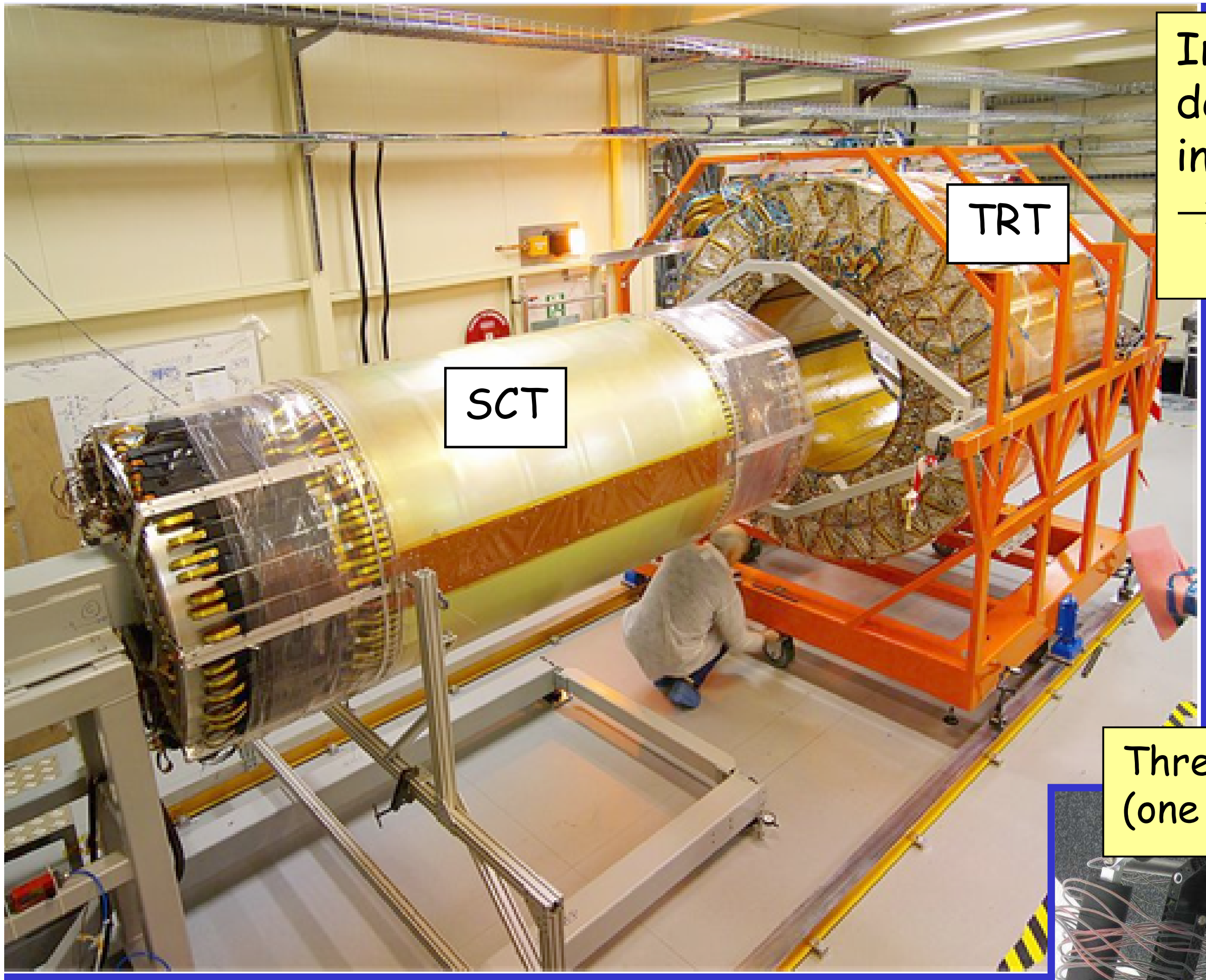
Length = 55 m
Width = 32 m
Height = 35 m



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

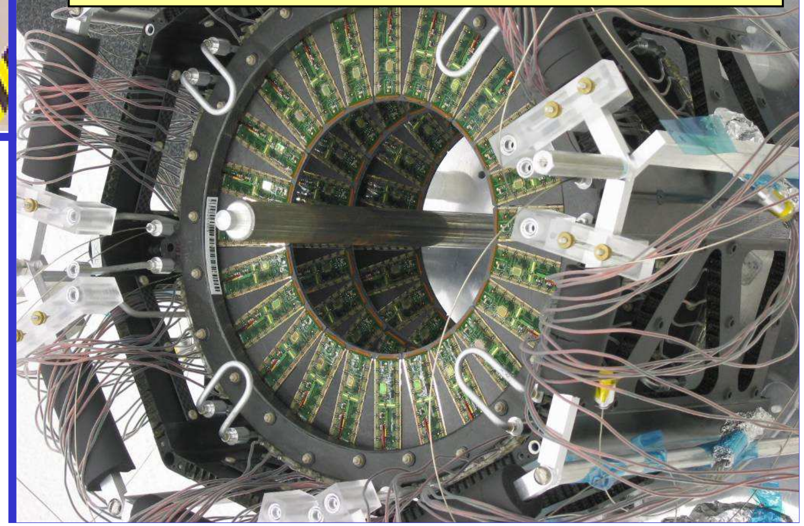
Barrel calorimeter (EM liquid-argon + HAD Fe/scintillator Tilecal) in final position at Z=0. Barrel cryostat cold and filled with LAr.





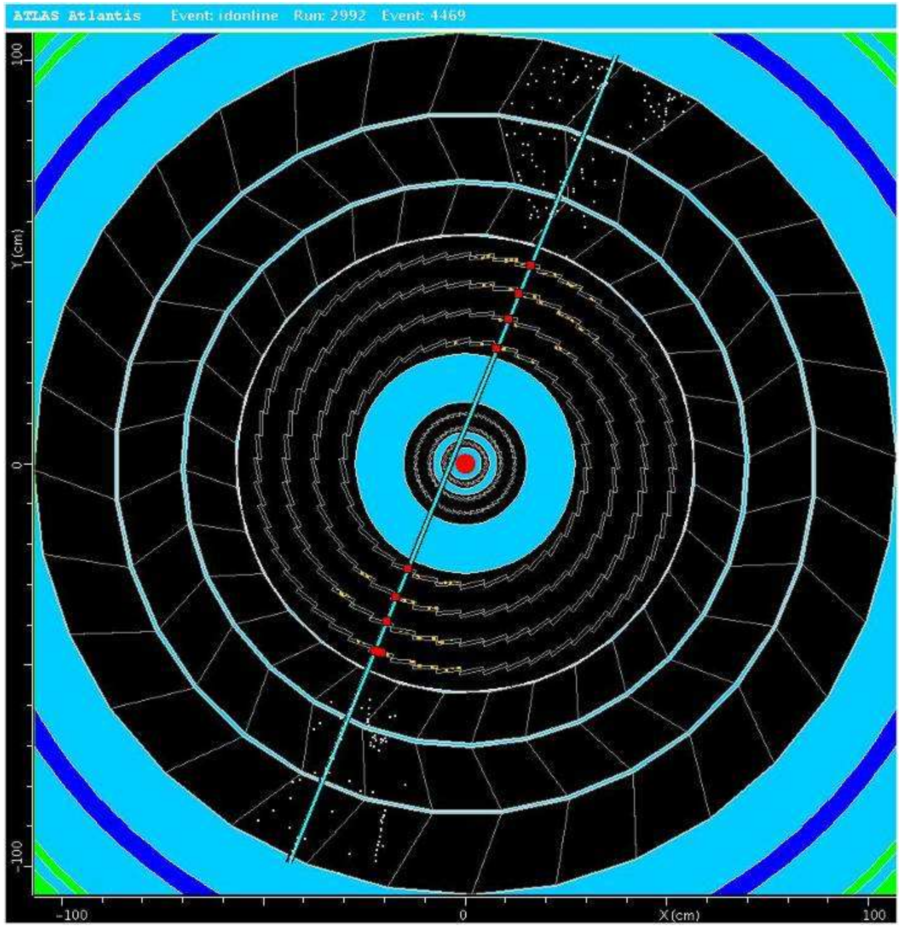
In Feb. 2006 barrel Si detector (SCT) was inserted into barrel TRT
→ ready for installation in the pit in August 2006

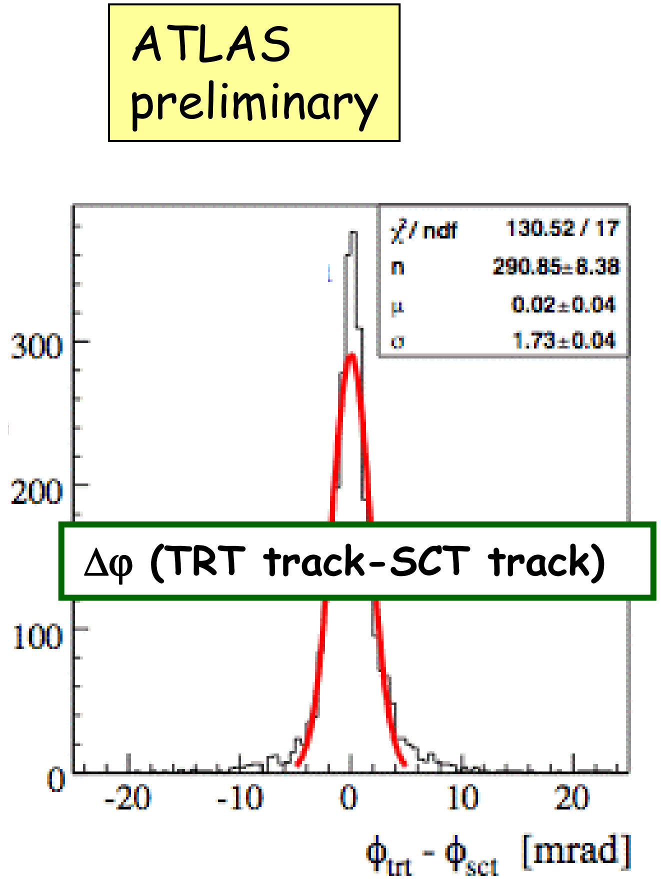
Three completed Pixel disks (one end-cap) with 6.6 M channels



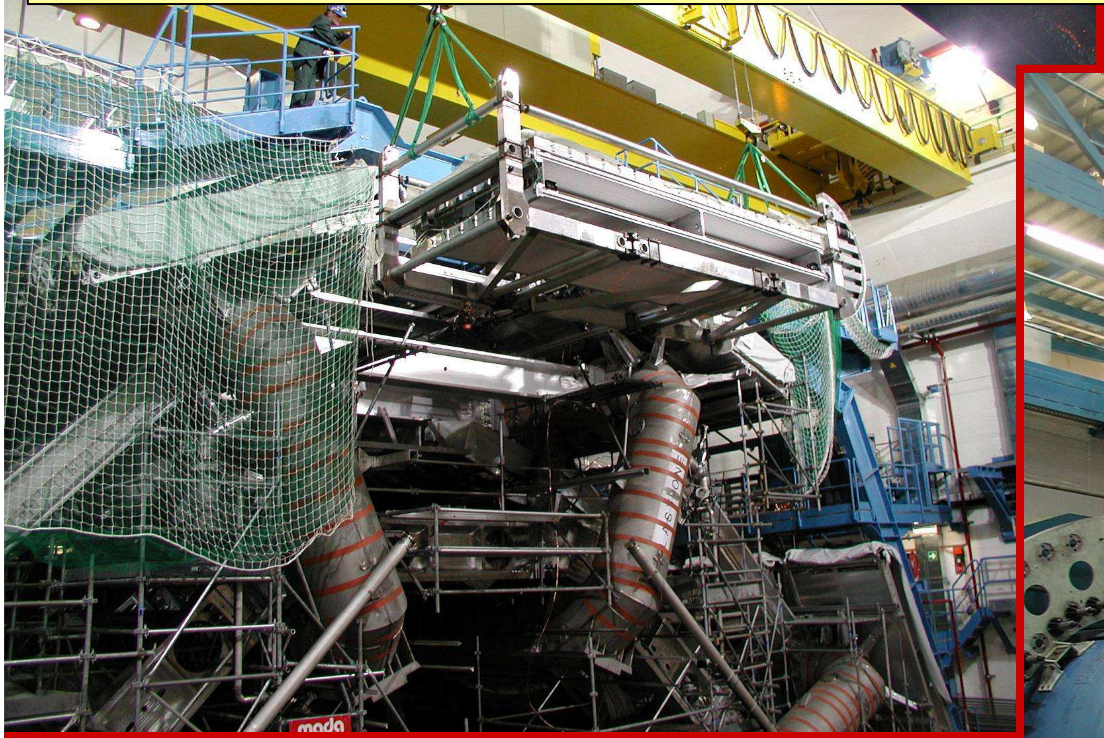
Barrel pixel detector on critical path (problems with low-mass cables), but still scheduled for installation in the pit in April 2007

Cosmics DATA taken in barrel SCT+TRT

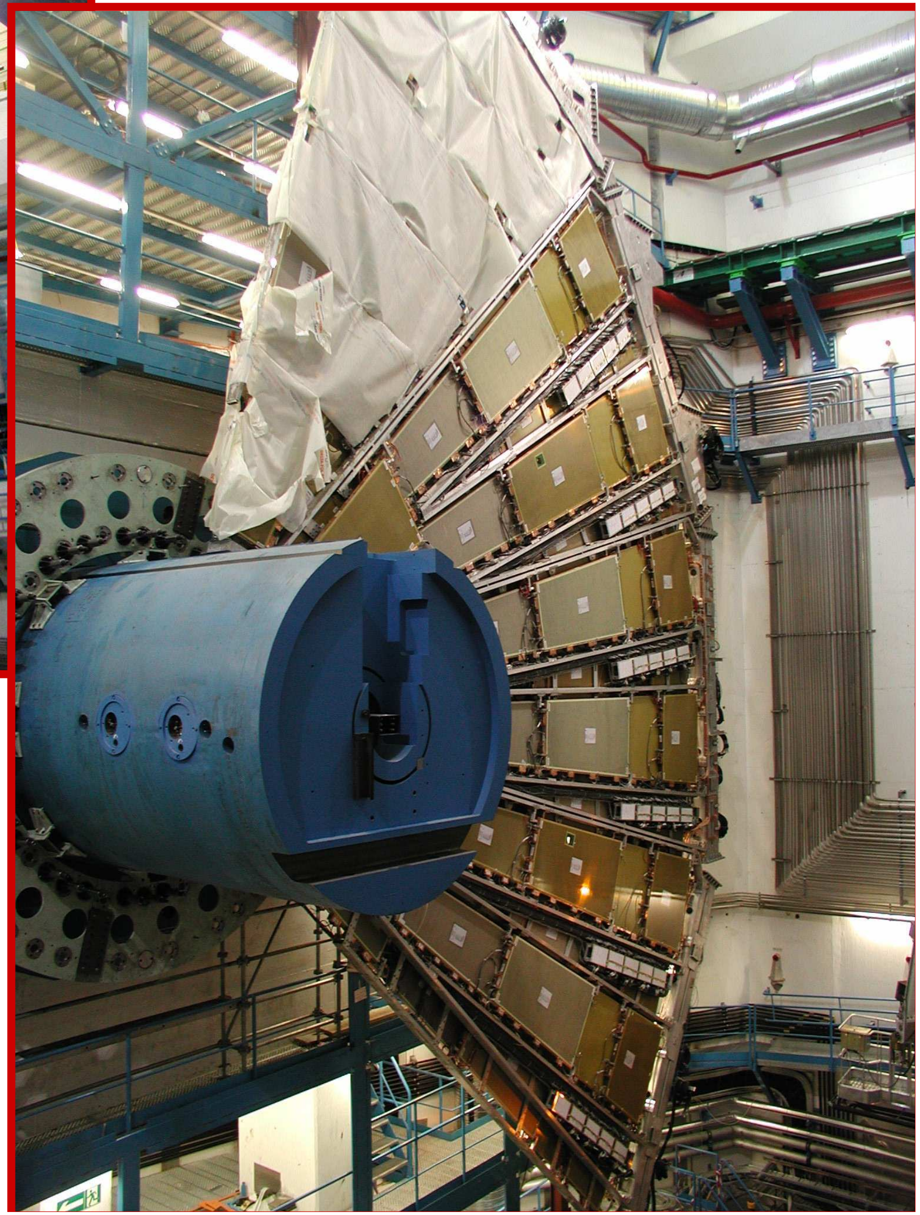




Muon Spectrometer : measurement chambers MDT, CSC (innermost forward)
trigger chambers RPC (barrel), TGC (end-caps)

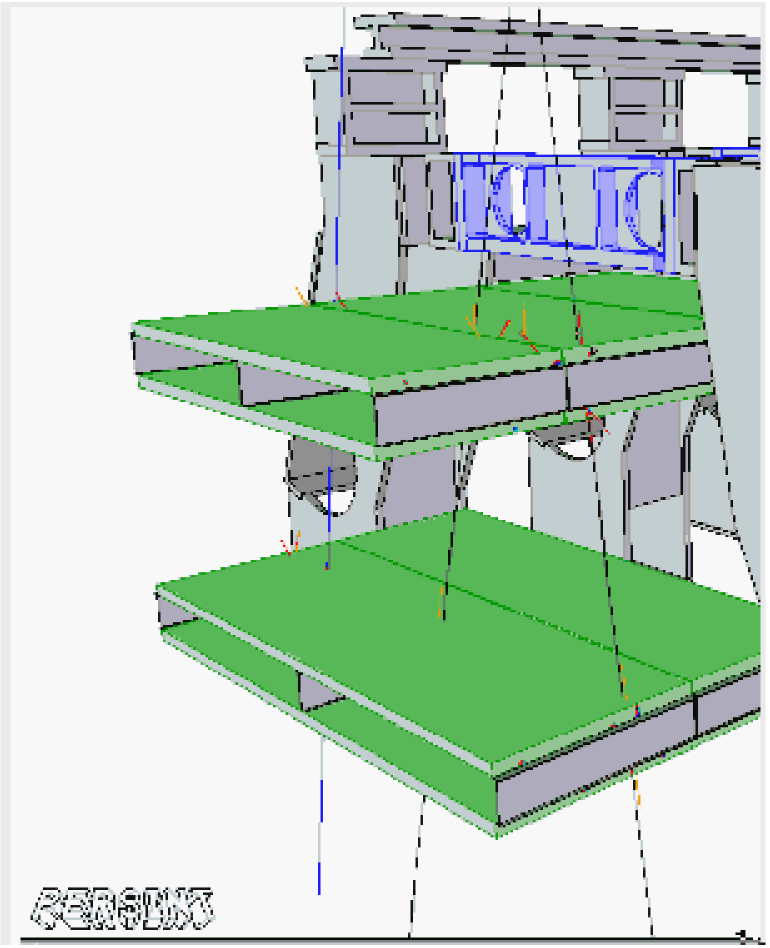


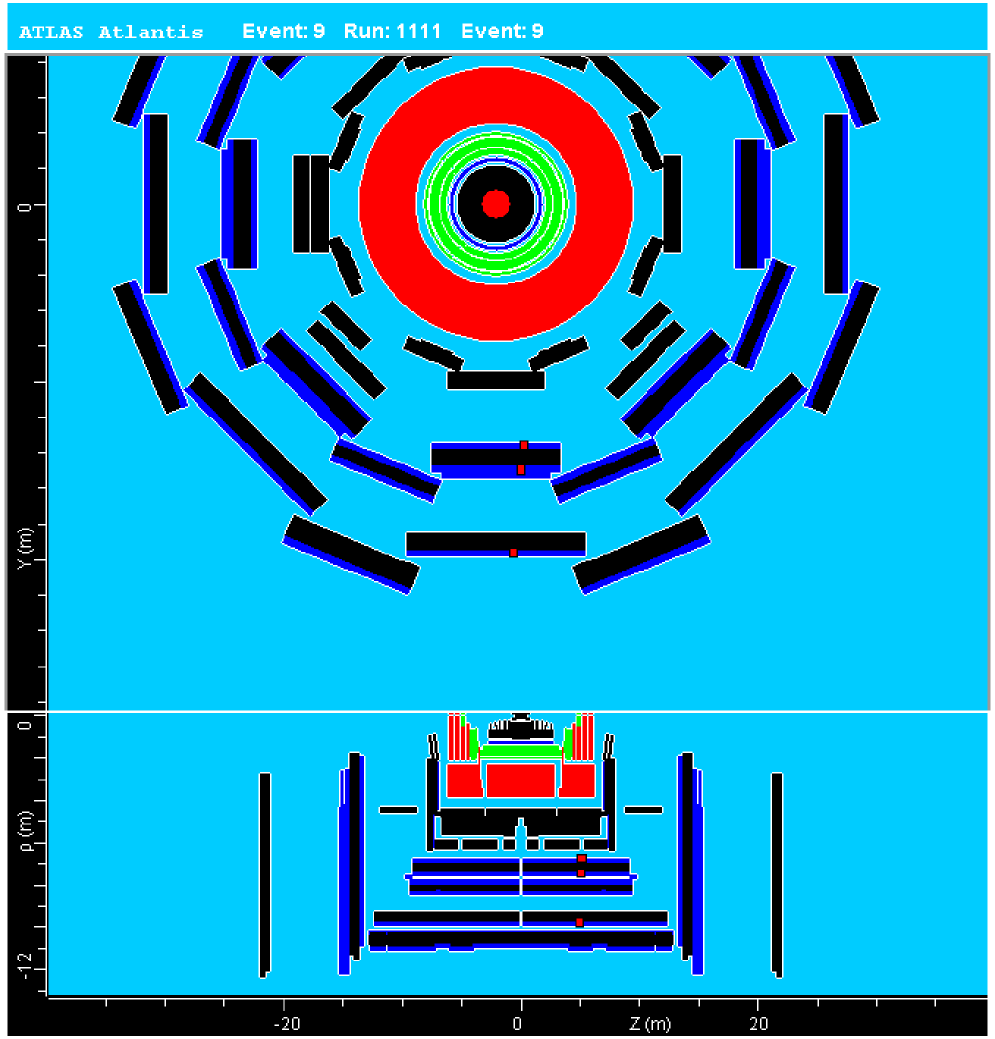
~50% of barrel stations installed
(mostly complete end of Summer ‘06)



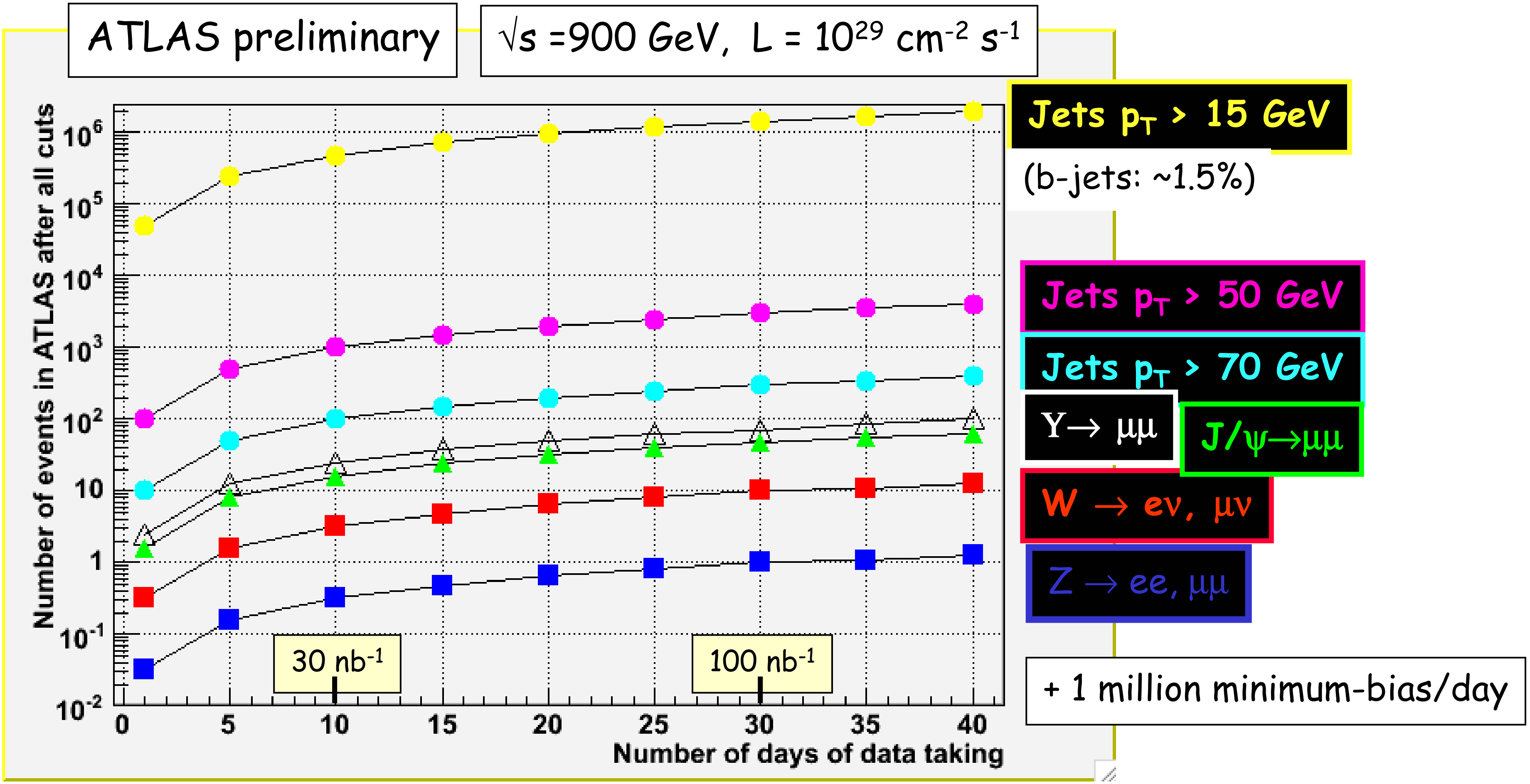
First sectors of TGC end-cap
“big-wheels” installed

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





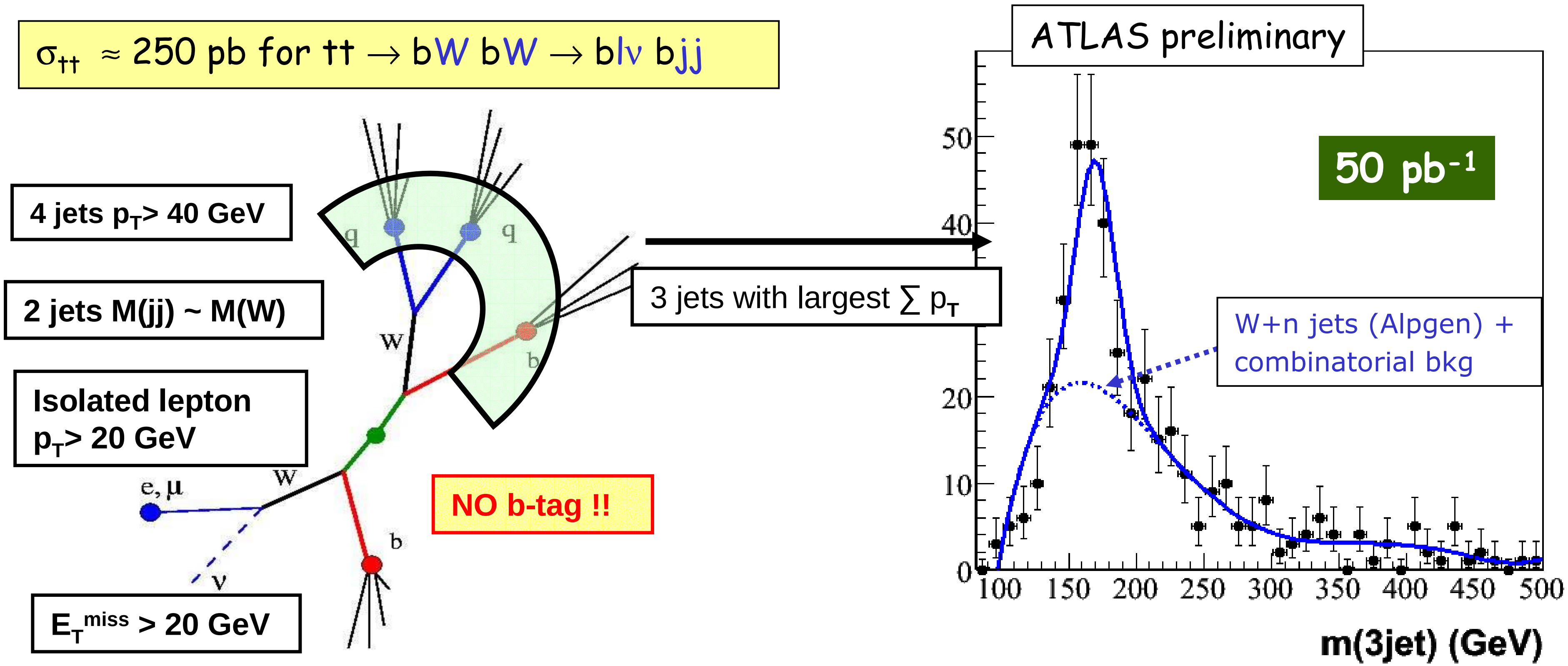
What data samples in 2007 ?



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 $tt \to bW\ bW \to bl\nu\ bjj$



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, ...