The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

SMR/1847-3

Summer School on Particle Physics

11 - 22 June 2007

LHC Accelerators and Experiments (part II)

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CERN, Switzerland

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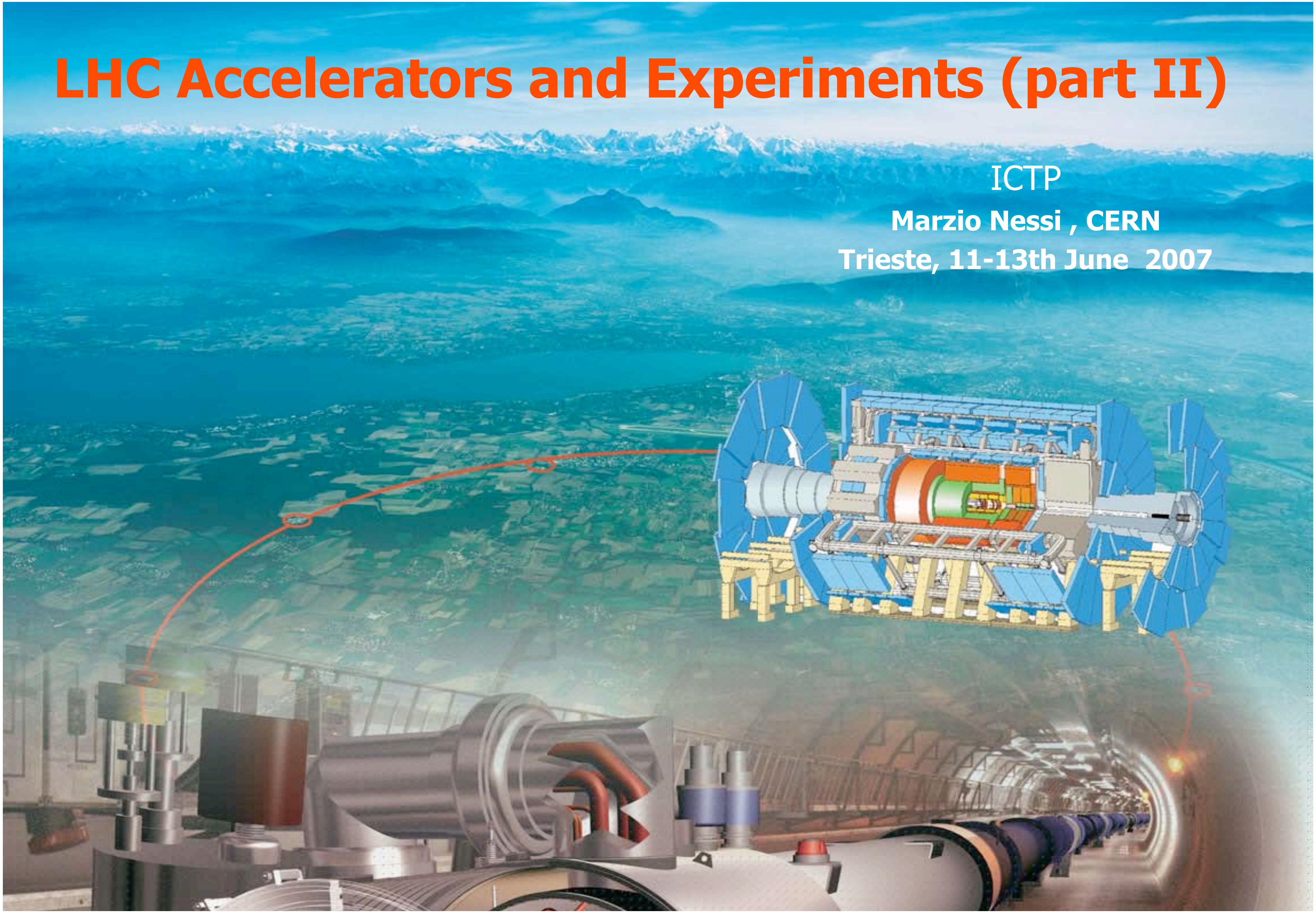
ICTP

Marzio Nessi , CERN

Trieste, 11-13th June 2007



ICTP-2007 The LHC project

Part I : motivation, the LHC accelerator

Part II : experimental goals, ATLAS and CMS detectors

Part III : LHCb and Alice experiments,
luminosity measurements,
early discovery potential

- This will be a set of experimental lectures, with the goal of giving you an impression of the complexity and challenges of this project

- My deep involvement in the design and construction of the ATLAS detector will bias me towards it as a showcase … sorry!

Table of Content (Part II)

- ✓ The LHC environment
- ✓ Detectors design
- ✓ How detectors work

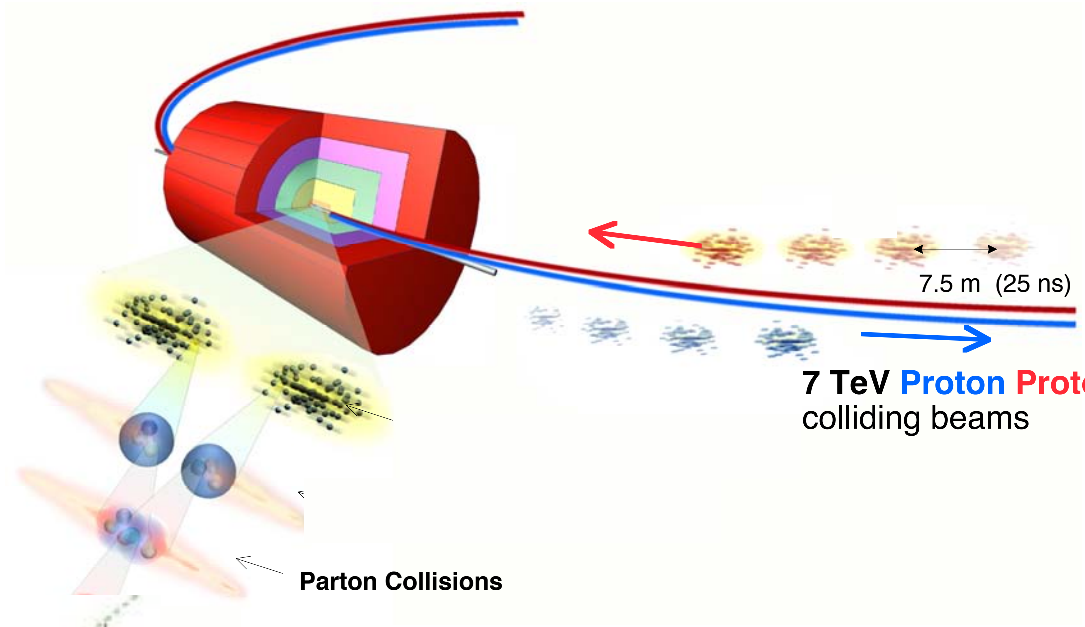
- ✓ The ATLAS detector
- ✓ The CMS detector
- ✓ Main differences/strategies

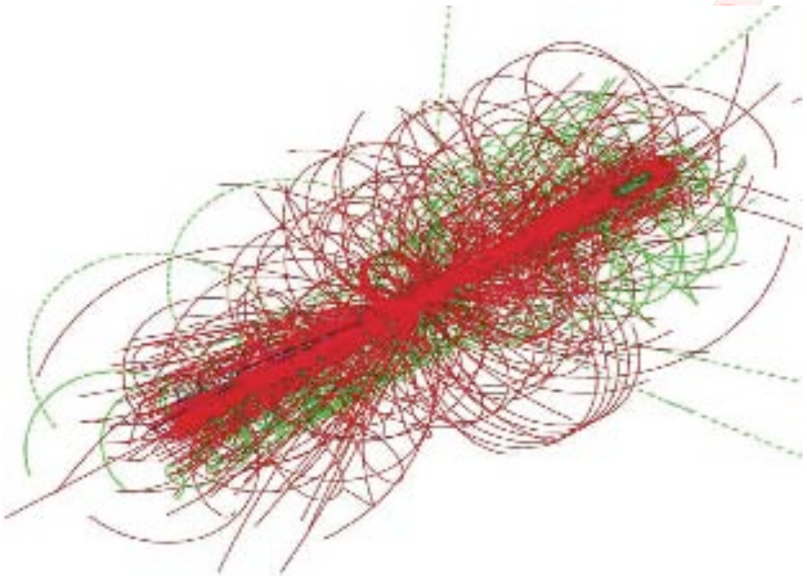
- ✓ Beam readiness

The LHC environment

Protons on protons
2808 x 2808 bunches
spaced: 7.5 m (25 ns)

10^{11} protons/bunch
bunch collisions 40 million/s
Luminosity L = 10^{34} cm^{-2} s^{-1}





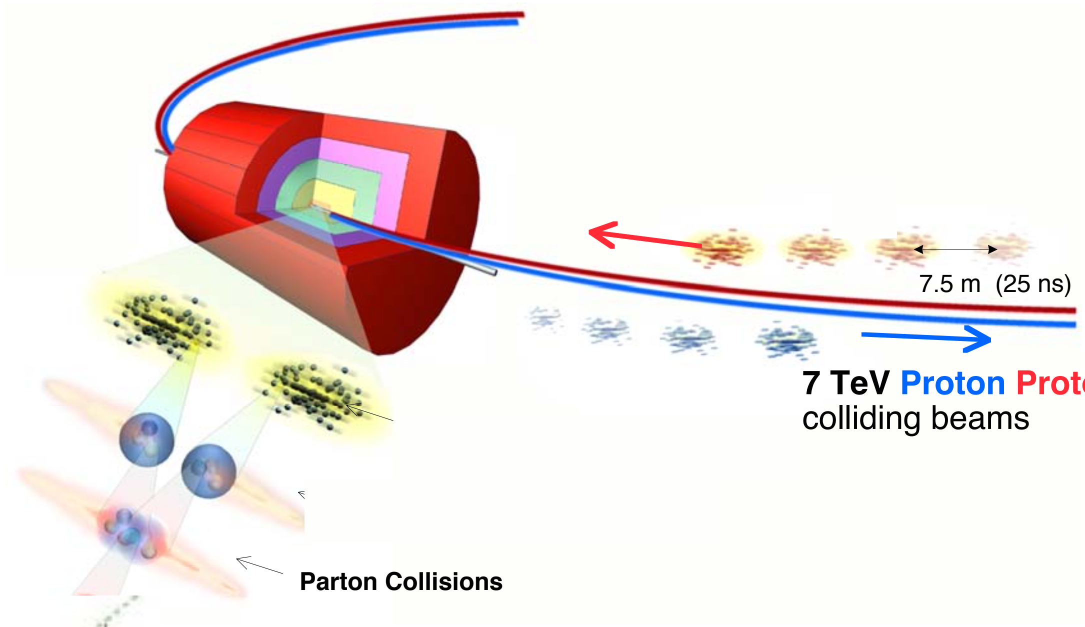
σ (pp) » 0.1 b -> ~ 10^9 pp Collisions / s

23 pp Interactions per bunch crossing
overlapping in time and space

> 1000 particle signals in the detector at
40MHz rate

Some more numbers

Protons on protons
2808 x 2808 bunches
spaced: 7.5 m (25 ns)



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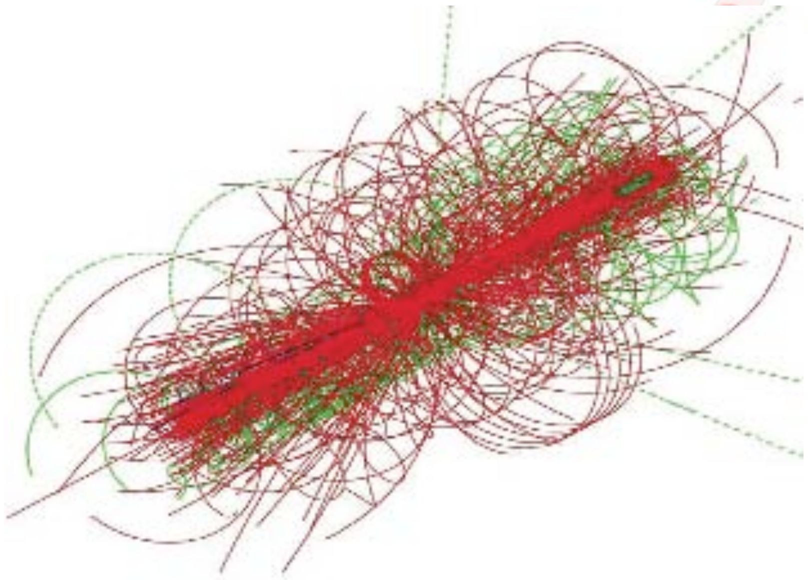


σ (pp) » 0.1 b -> ~ 4 10^{10} tracks / s

σ (new physics) < pb ~ 0.01 Hz

If you add the BR (Branching Ratio) typically ~ few%

-> you look for 1 interesting collision in ~10^{13}

…. Challenges ….

- New particles are produced in collisions between ***partons.*** We do not know a priori the centre-of-mass energy nor rest frame of the parton-parton collision
- The other partons in the colliding protons also produce particles that are visible in the detector
- The incoming quarks or gluons couple strongly, and they may give high-p_T gluon radiation (seen as jets in the detector)
- The incoming partons generally have different *x* values, so any particle produced is not at rest in the laboratory frame
- Pileup of additional proton-proton collisions further complicates the situation

- *The most important production mechanism at high-p_T involves production of di-jets. Their fragmentation mode might lead to confuse direct lepton production with leading π_0 jet fragmentation. Lepton identification is a great challenge*

- Collisions every 25 ns means that the detector has to react quickly
- 25 ns = ~8m at speed of light. So if the detector is large (>10m), the electronics might register at the same time particles coming from different bunches, collisions …. perfect synchronization is needed !

- *The high flux of particles originating from proton-proton collisions creates a challenging radiation environment for detectors and electronics: radiation-resistant detectors, radiation-hard (or tolerant) electronics, the need to consider "noise" signals induced in detectors by the radiation as well as conventional noise signals*

What do we actually measure ?

The detectors give information on comparatively long-lived particles that are generally the decay products of the fundamental objects that we wish to study

- We do not directly "see":

  - ✓ *Up, down, charm, strange and beauty quarks, gluons (that manifest themselves as jets of hadrons)*
  - ✓ *Top quarks, since they decay rapidly (e.g. $t \rightarrow bW$)*
  - ✓ *W and Z bosons, since they decay rapidly to quarks or leptons*
  - ✓ *Higgs bosons*
  - ✓ *Etc*

- We do "see" somewhat more directly:

  - ✓ *Electrons*
  - ✓ *Muons*
  - ✓ *Photons*
  - ✓ *Long-lived charged and neutral hadrons (which may form jets)*
  - ✓ *Missing transverse momentum (e.g. due to high transverse momentum neutrinos)*

Generic concept of a detector

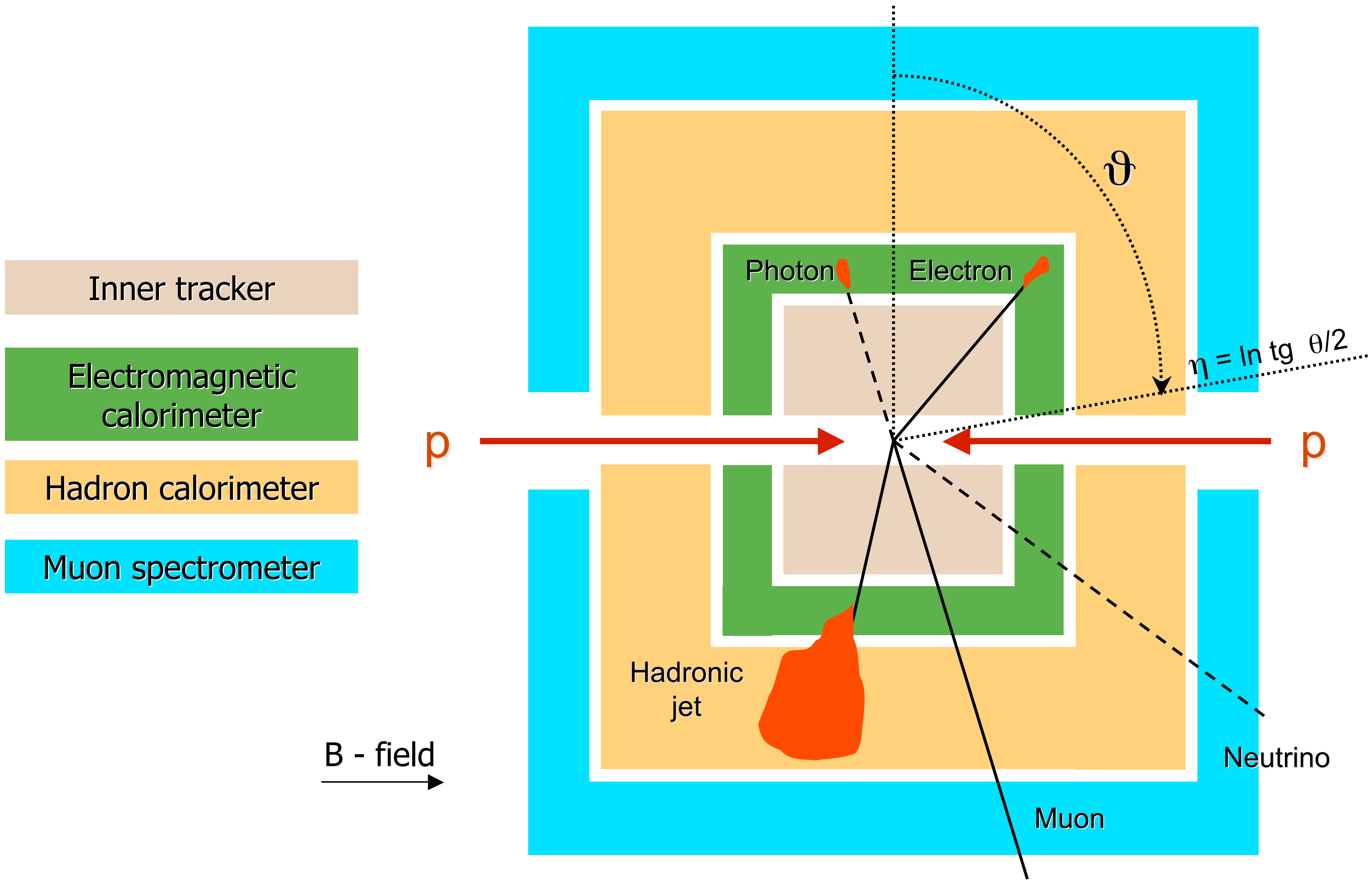
- Collisions take place in the centre of the detector
  - → *Collision products move outwards from the centre*

- Trajectories of charged particles are measured in precision trackers
  - → *Solenoidal magnetic field, so particles follow helical paths*
    - *$p = 0.3 \times B \times r \times Q$ used to determine momentum from radius of curvature (assuming charge $Q = \pm 1$)*

- Calorimeters measure energy deposited by electrons, photons and hadrons
  - → *Calorimeters are sufficiently thick that almost all energy is absorbed, apart for muons (only minimally ionising) and neutrinos (and possibly other particles beyond those of the Standard Model)*

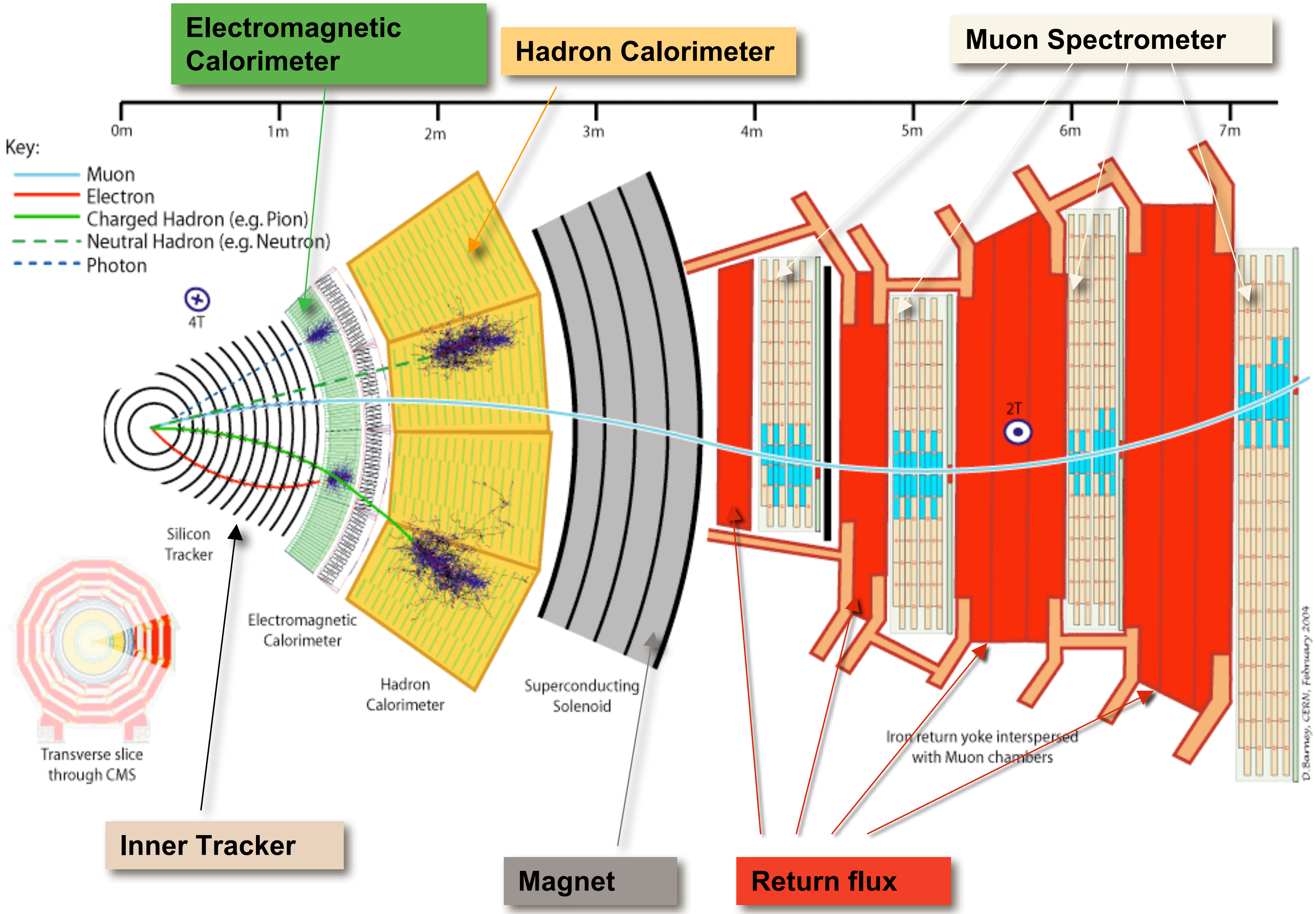
- Trajectories of remaining charged particles (= muons) are measured
  - → *Providing muon identification and additional information on momentum*

Detector generic layout



* ϑ_{max} as close a possible to $\pi/2 \longrightarrow$ hermeticity

With some more details (CMS case)



How to reconstruct an event (collision) ?

- ✓ Associate to each signal seen a bunch identifier and regroup signals according to it

- ✓ Start with signals seen in the detectors
  - → *Points in space along charged particle trajectories*
  - → *Energies measured in calorimeter cells*
  - → *Signals from particle-identification detectors (preshowers, transition radiation,…)*

- ✓ Reconstruct quantities more closely related to particles

  - → *Parametrize trajectory of charged-particle "tracks" in the inner tracking detectors and in the external muon detectors*
    - Position and direction at some "start point"; radius of curvature
      - Infer charge sign and momentum (assuming $|Q| = 1$)
  - → *Parametrize energy depositions in the calorimeters in terms of "clusters"*
    - Energy
    - Longitudinal and lateral shape
      - Can (e.g.) test consistency with shower from isolated electron or photon
    - Direction of energy flow

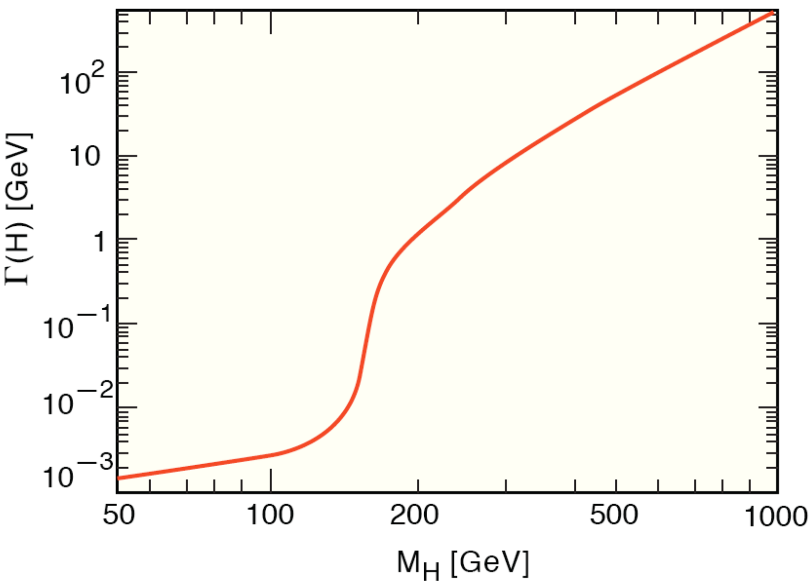
How to reconstruct an event (collision) ?

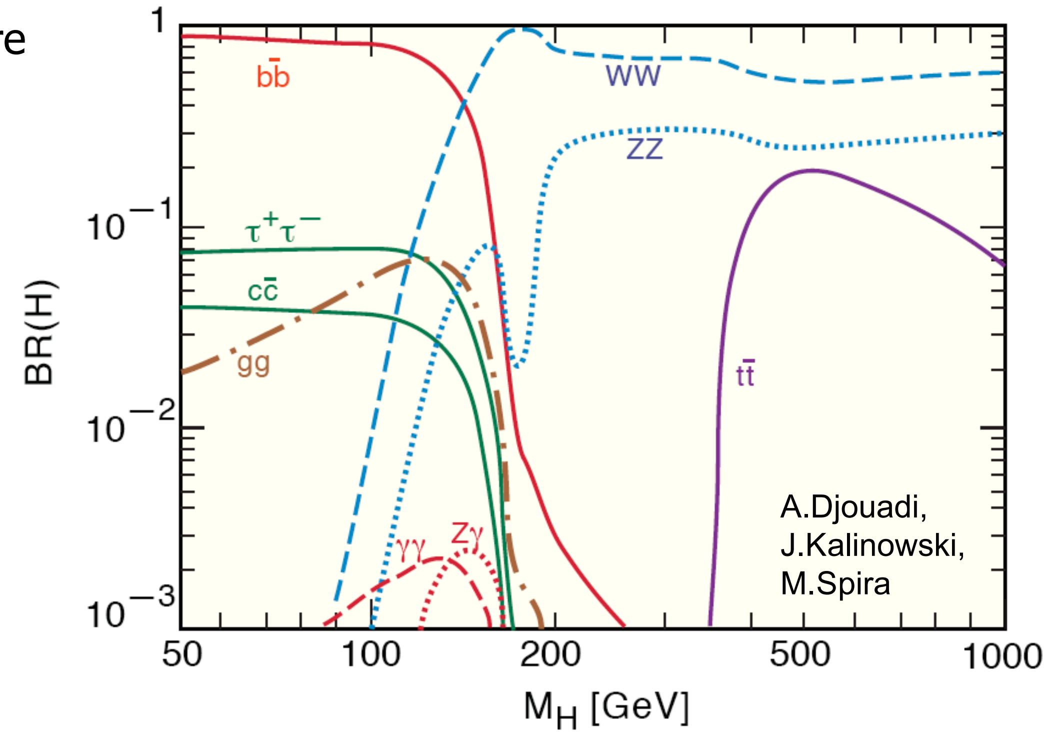
- ✓ Associate each track/energy deposition to a known particle (particle ID)
- ✓ Correlate all particles properties, reconstruct decay mechanisms, reconstruct effective masses, ….
- ✓ Reconstruct quantities more closely related to the collision
  - → *Final products database*
  - → *Decay products database*
  - → *Not visible transverse energy*
  - → *Energy distribution in space*
  - → *…..*

Look for new physics

CMS and ATLAS have been benchmarked on the Higgs

For fixed m_H, branching rations (BR) and widths (Γ) for all possible Higgs decays are determined





For small m_H :

b-quark → jets, difficult (huge background)

H → γγ (M_H < 140 GeV) , small cross section, but „clean" signature

Small width: Detector energy resolution and particle ID are crucial

For large m_H :

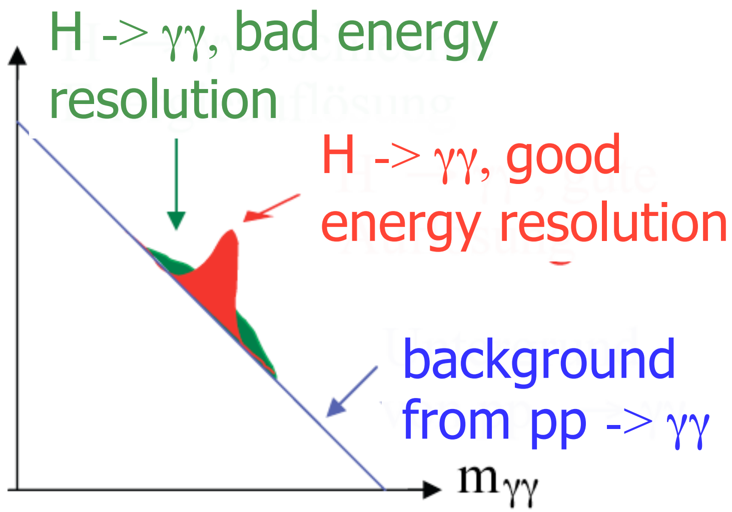
H → ZZ → 4ℓ, H → WW → jets or $\ell\nu\ell\nu$

and more specifically .... on the Higgs to $\gamma\gamma$

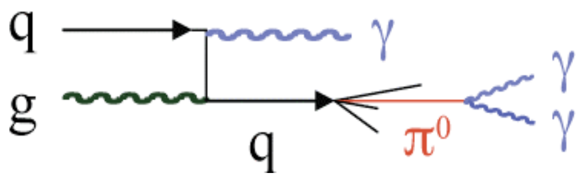
$$m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{\gamma\gamma})}$$

where

$$\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2}\left[\frac{\Delta E_{\gamma_1}}{E_{\gamma_1}} \oplus \frac{\Delta E_{\gamma_2}}{E_{\gamma_2}} \oplus \frac{\Delta\theta_{\gamma\gamma}}{\tan(\theta_{\gamma\gamma}/2)}\right]$$



"reducible" background: pp → γ jet and pp → jet jet



"irreducible" background: pp → γγ

which requires in first place an excellent EM Calorimeter

- ✓ With good energy resolution : longitudinal energy containment, small amount of dead material, easy cells inter-calibration
  - ➙ to ensure good energy calibration

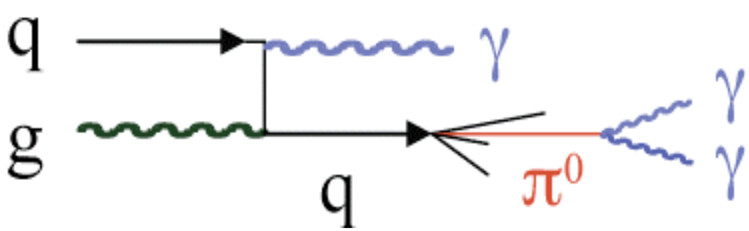
- ✓ With good angular resolution : high granularity and longitudinal segmentation

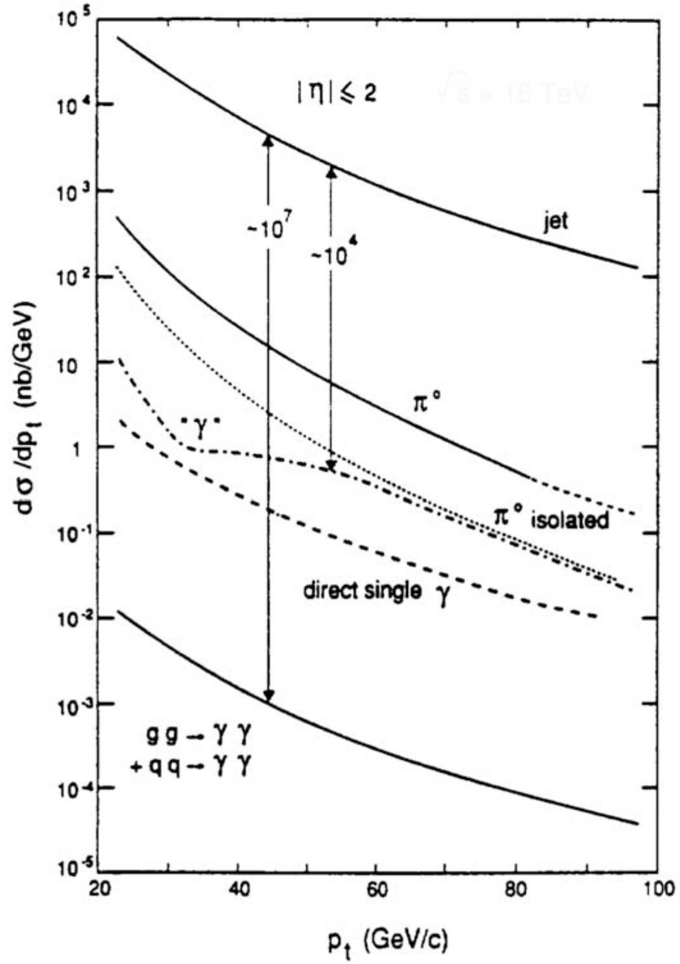
To keep a favorable Signal to Background ratio, we need a Higgs mass resolution at the level of few %, therefore we will need each of the 3 components to contribute at the 1-2 % level

This mean for photons and electrons in an energy range of 20-70 GeV to be measured with an uncertainty in the calorimeters at the level of 1.0-2.0 GeV

Need to be sure to identify the electrons and the photons

- Most channels require to identify electrons and photons in their final states
- At LHC the di-jets background dominates all high-p_T channels
- Jet fragmentation into leading π_0s (probability 10^{-4}) represents the main source of identification errors





Need to be sure to identify the electrons and the photons

Combine information from the calorimeters and the inner tracking detectors

- ✓ *Electrons and photons identified as narrow clusters in electromagnetic calorimeters*
- ✓ *Electrons have an associated track; can check consistency of parameters between cluster and track (p / E, impact point / cluster centre, etc.)*
- ✓ *Photons have no associated track*

For many interesting processes, the electrons and photons are "isolated", whereas the candidates are often in jets for background processes

- ✓ *Genuine electrons from charm and beauty decays*
- ✓ *Photons from π^0 decays (which may "convert" to given electrons)*
- ✓ *Misidentified hadrons in their final states*

Requirements summary

Lepton measurement:

$p_T \approx$ GeV → 5 TeV
(b → ℓX, W'/Z')

Mass resolution (m ~ 100 GeV) :

≈ 1 % **(H → $\gamma\gamma$, 4ℓ)**

≈ 10 % **(W → jj, H → bb)**

Particle identification :

e_b	≈ 60 %	$R_j \approx 100$	(H → bb,SUSY)
e_τ	≈ 50 %	$R_j \approx 100$	(A/H → tt)
e_γ	≈ 80 %	$R_j > 10^3$	(H → gg)
e_e	> 50 %	$R_j > 10^5$	

e/jet ~ 10^{-5}
$\sqrt{s}$ = 14 TeV

Calorimeter coverage :

$|\eta| < 5$

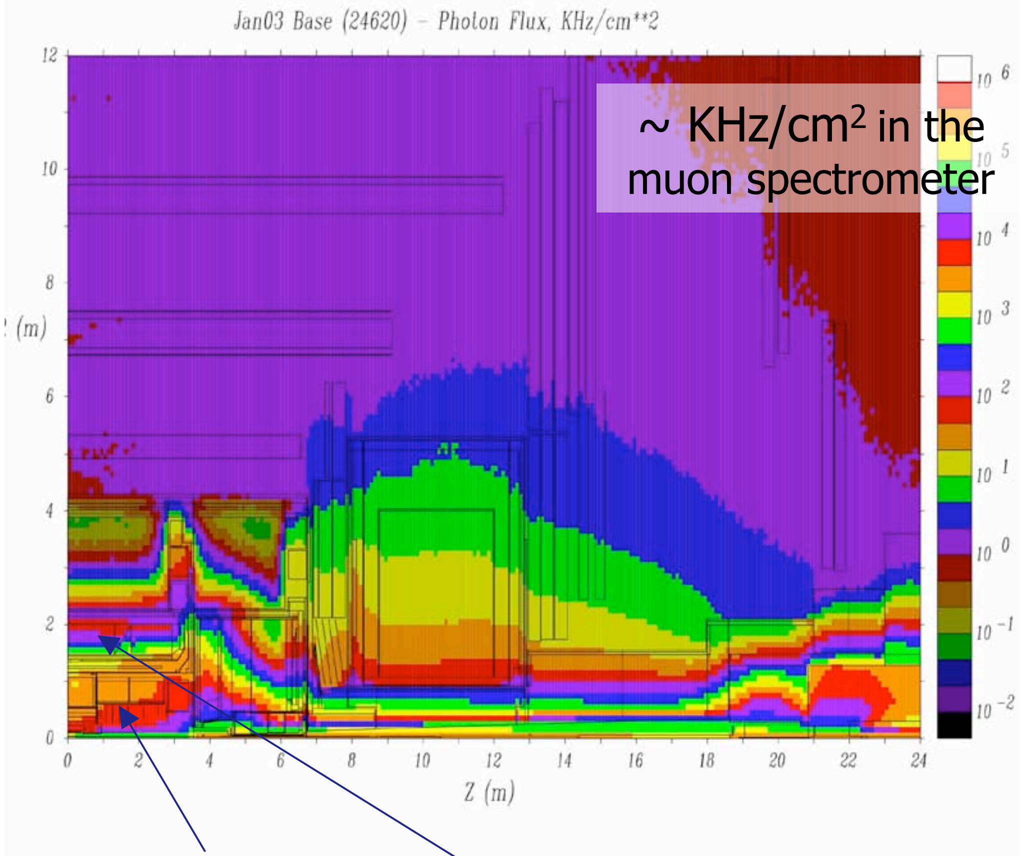
(E_T^{miss}, forward jet tag for heavy Higgs)

Trigger : 40 MHz → 100 Hz reduction

Bunch crossing identification

High background radiation

Photon flux in KHz/cm²



~1 MHz/cm² in ID

~50 kHz/cm² in the EM Barrel Calorimeter

Radiation mostly coming from the interaction point and proportional to the luminosity …. Mostly dominated by shower production in the beam pipe material

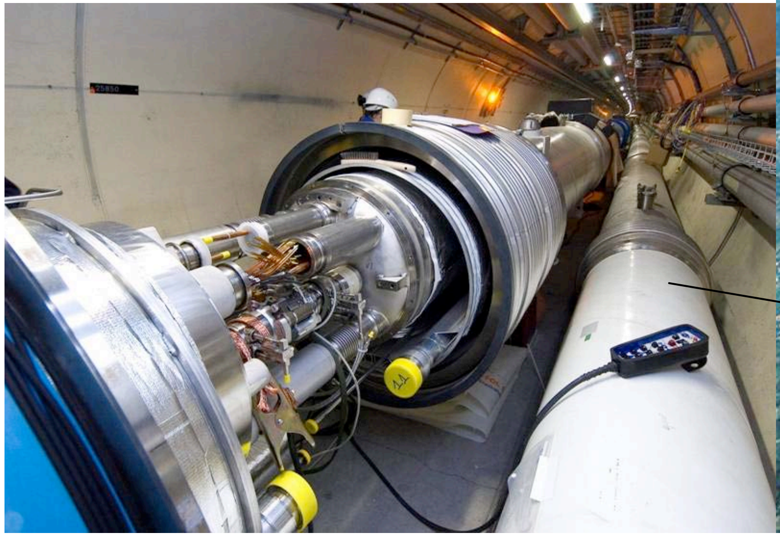
Radiation effects:

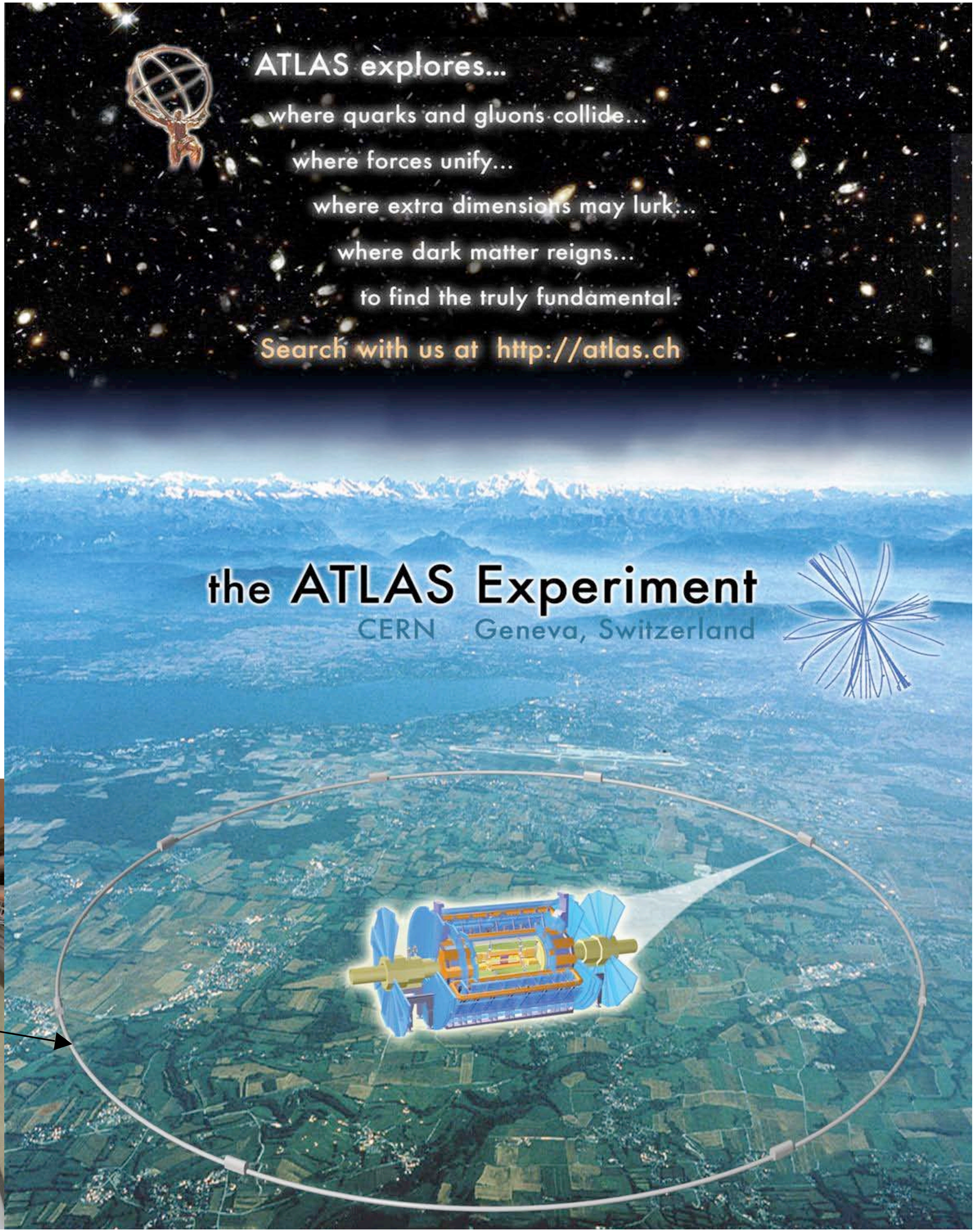
- ✓ *life time of the electronics components on the detector*
- ✓ *Increases noise occupancy in the various active cells*
- ✓ *Changes the mechanical properties of certain materials*
- ✓ *Initiate an aggressive chemical behavior of various material, gases …*

The LHC project

- ✓ the p + p accelerator (LHC)
- ✓ 2 multipurpose pp detectors (ATLAS and CMS)
- ✓ 2 smaller experiments dedicated to B-physics (LHCb) and to heavy ion collisions (ALICE)

The LHC accelerator
(p+p, 7 TeV + 7 TeV)





How to get to a real experiments ?

Ingredients :

- a firm determination by the IHEP community
- a healthy R&D program to access the necessary technology
- a large international Collaboration which functions over 2-3 decades
- the necessary financial plan to cover all costs (design, construction, operation), backed up by all funding agencies associates
- an experimental zone, capable of hosting the detector and all its infrastructure

…… and a lot of good will by everybody !!!

The ATLAS Collaboration

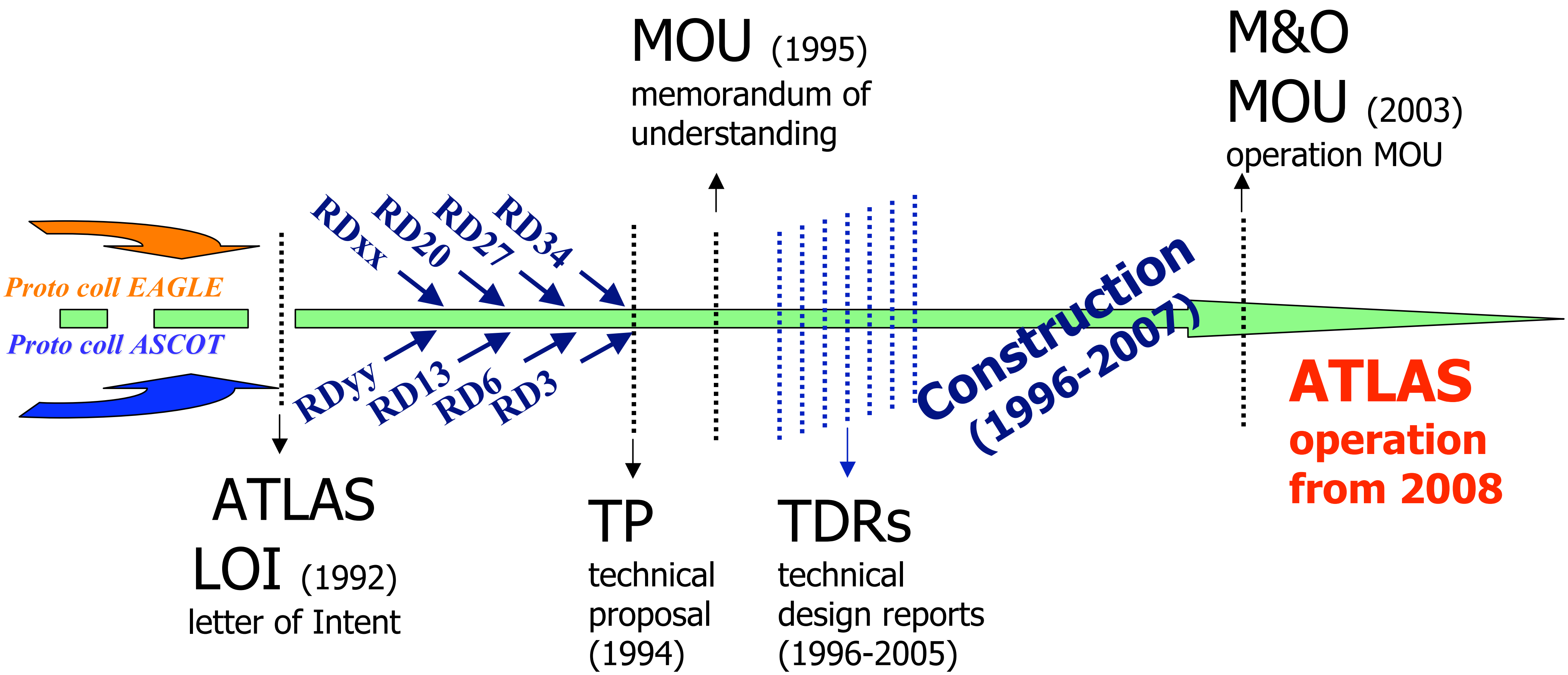
(As of the April 2007)

35 Countries
164 Institutions
1900 Scientific Authors
(1500 with a PhD)

--> It has become a global project

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Irvine UC, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Regina, Ritsumeikan, UFRJ Rio de Janeiro, Rochester, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, Southern Methodist Dallas, NPI Petersburg, Stockholm, KTH Stockholm, Stony Brook, Sydney, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Toronto, TRIUMF, Tsukuba, Tufts, Udine, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Yale, Yerevan

The ATLAS road map



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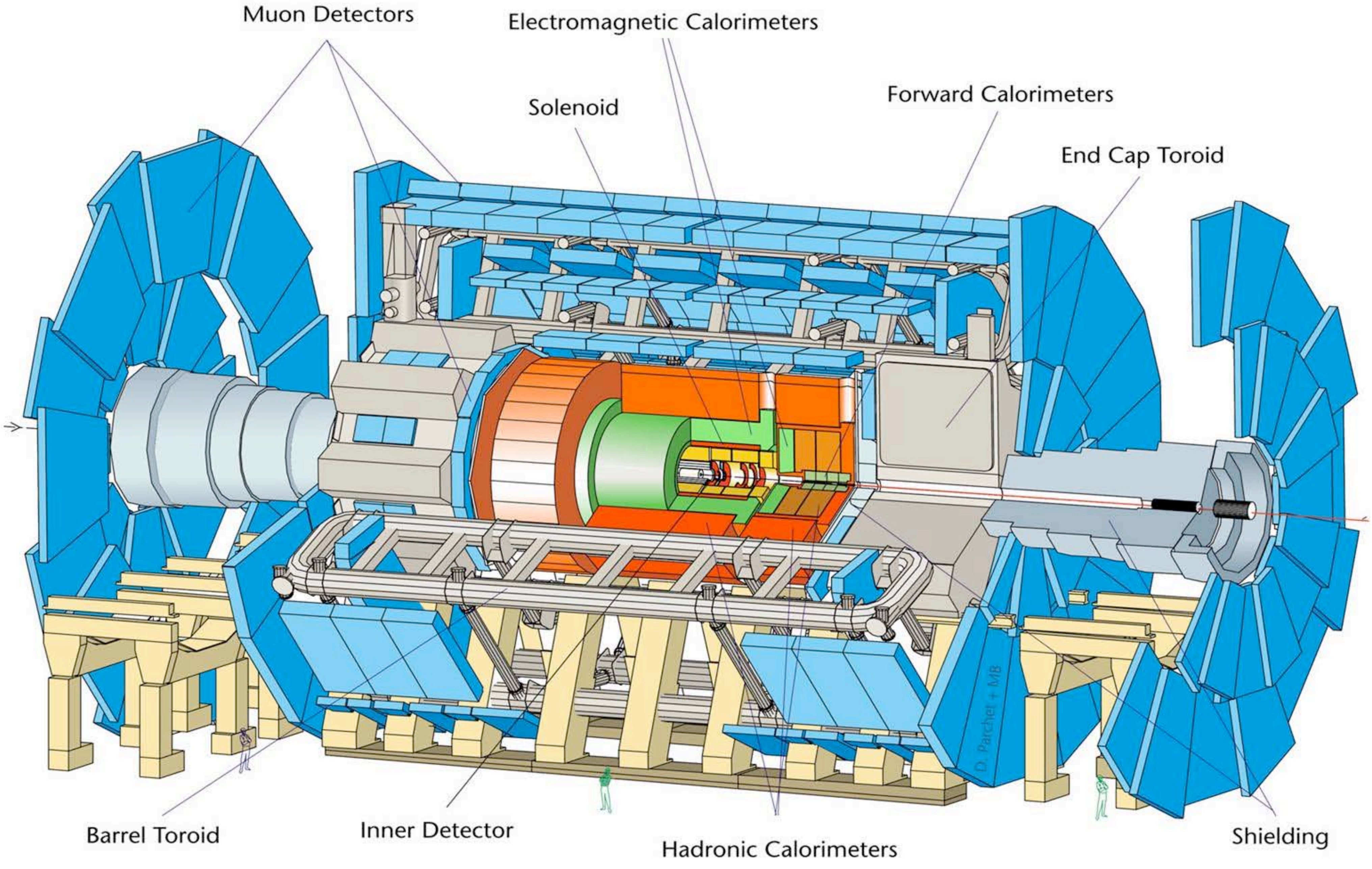
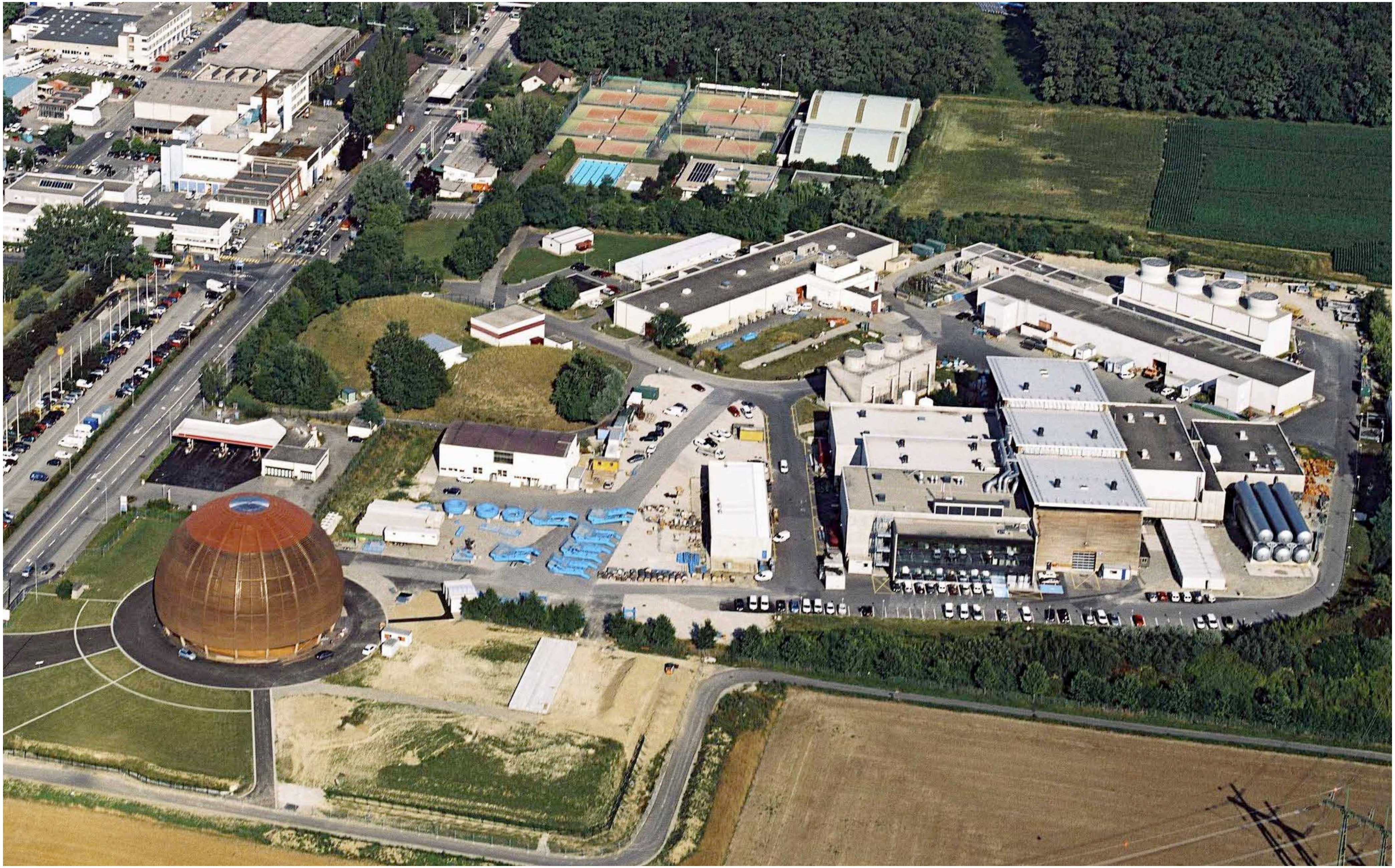
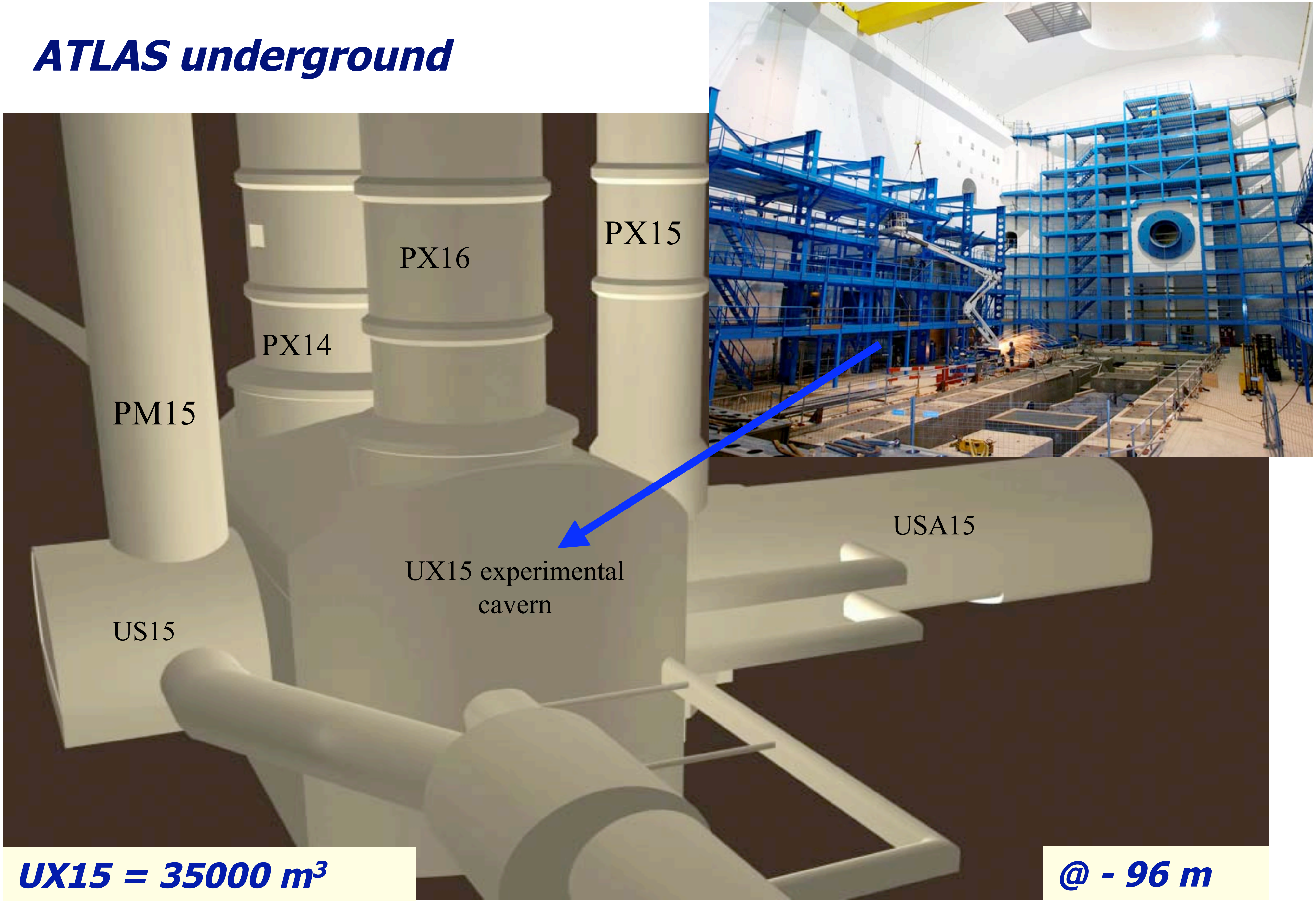
The ATLAS Detector



ATLAS experimental area (CERN Point 1)



ATLAS underground



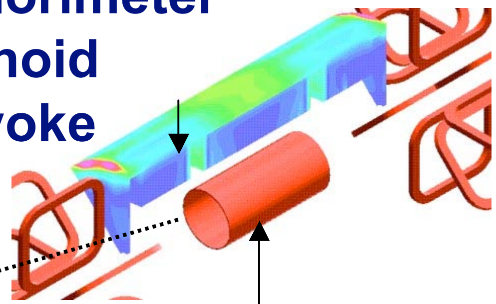
UX15 = 35000 m³

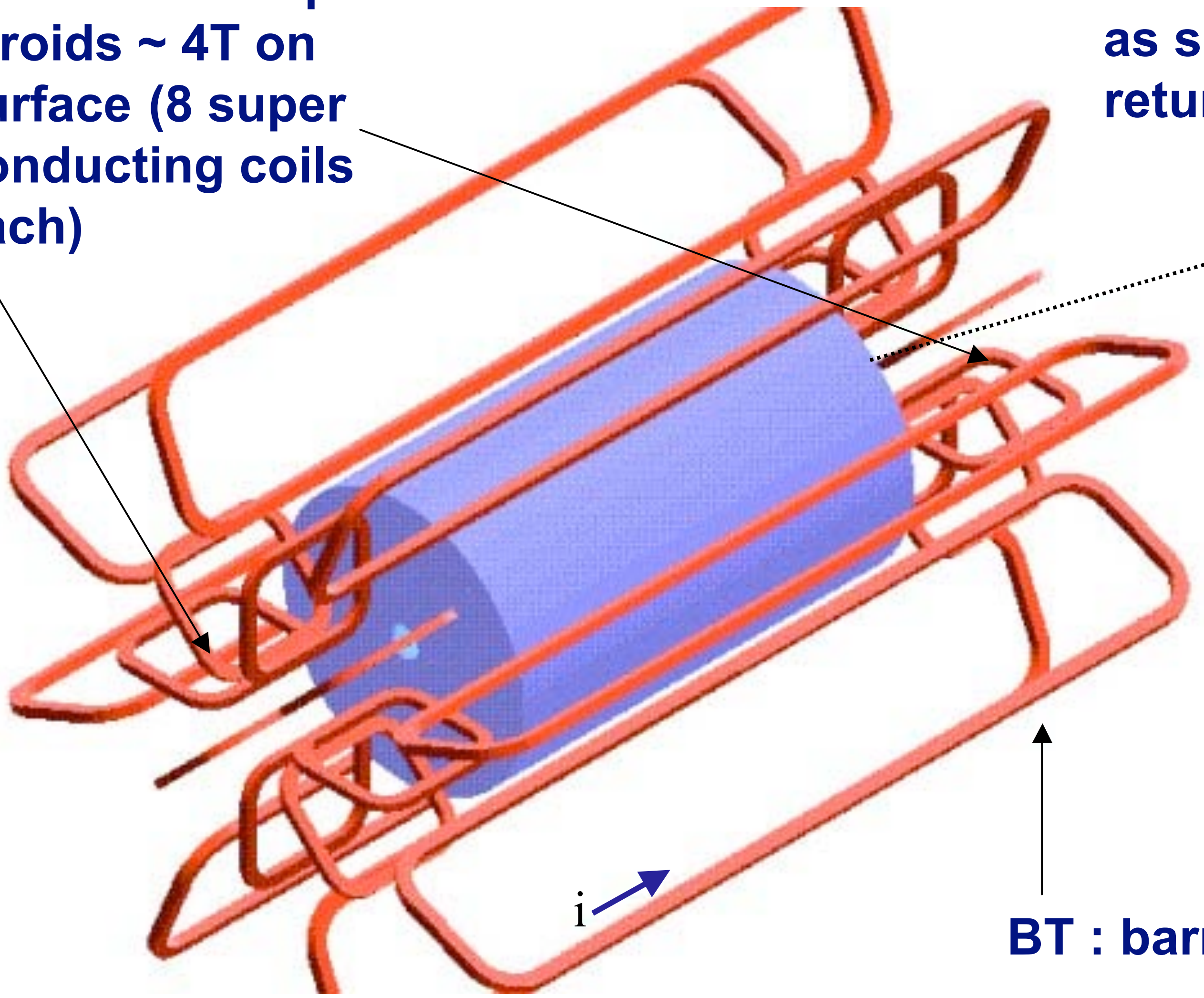
@ - 96 m

The magnet systems (4 magnets)

ECT : 2 end-cap toroids ~ 4T on surface (8 super conducting coils each)

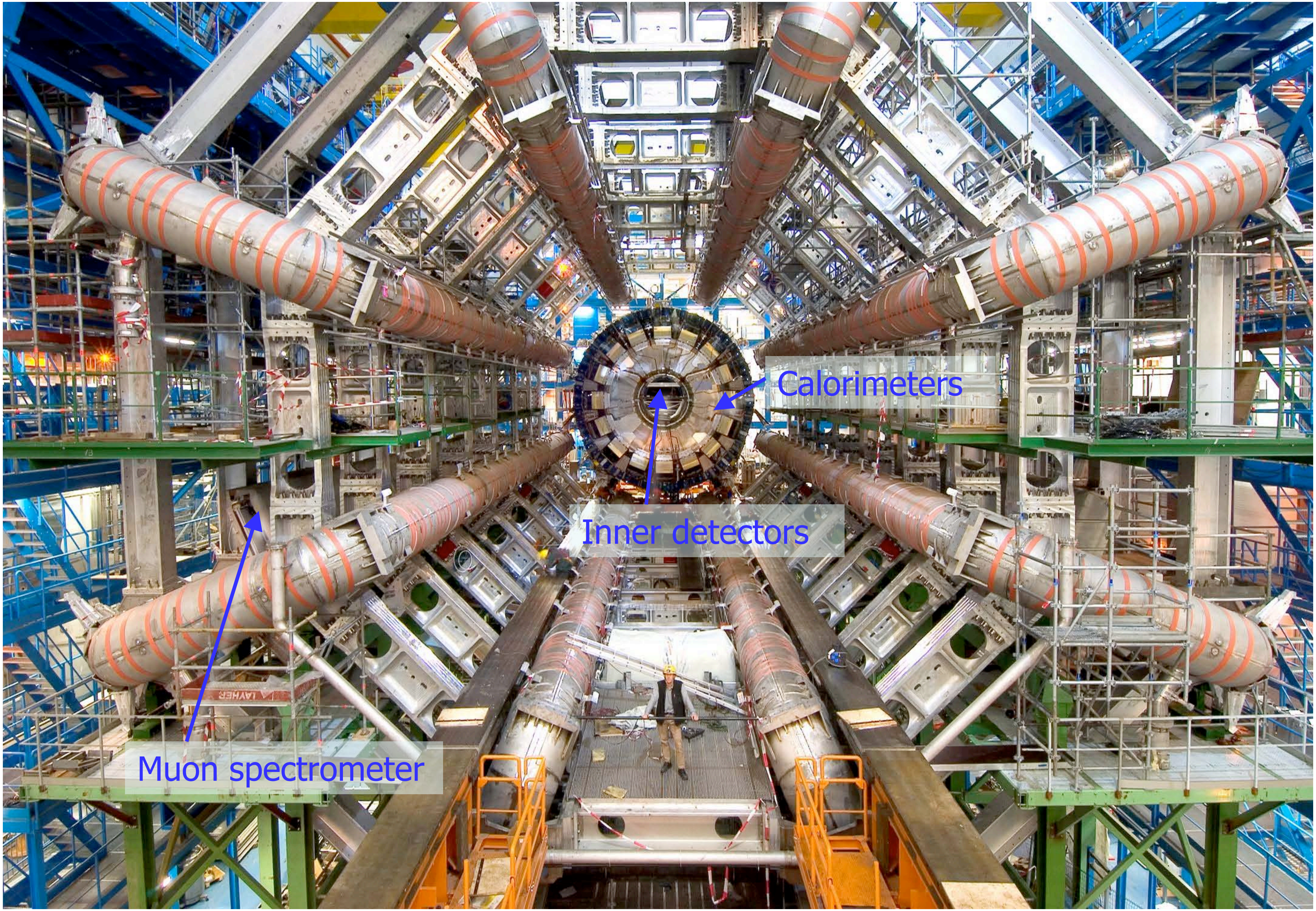
Had Calorimeter as solenoid return yoke





Inner solenoid (2 T, superconducting)

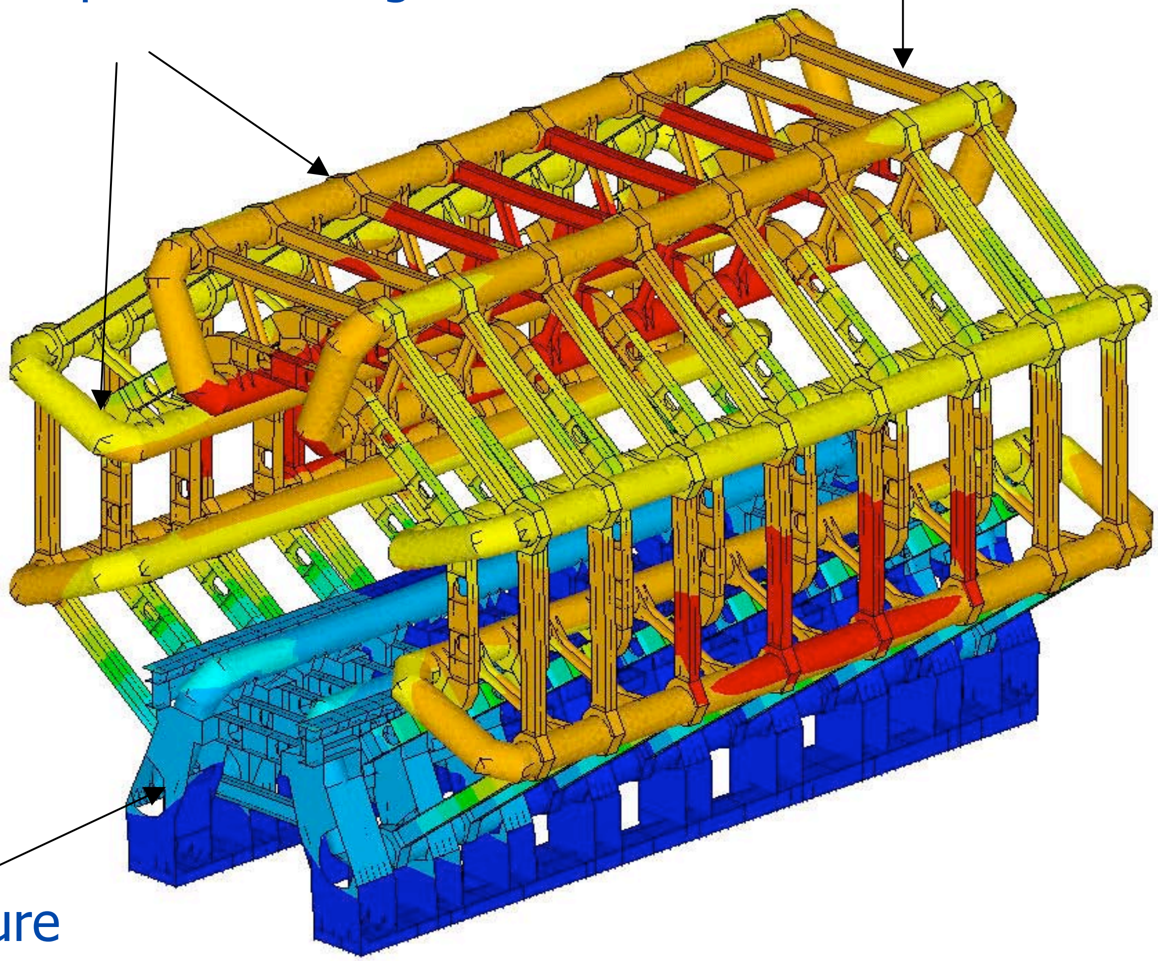
BT : barrel toroid ~ 4T on surface (8 superconducting coils)


Calorimeters
Inner detectors
Muon spectrometer

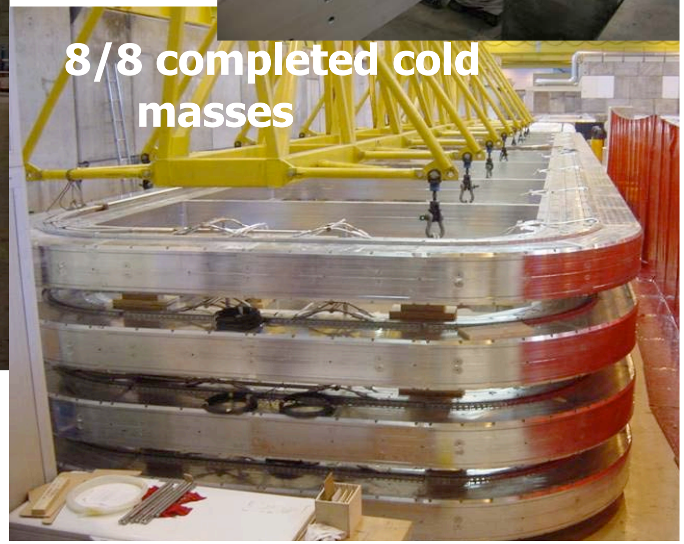
ATLAS Barrel Toroid (BT)

BT Parameters:

- 25.3 m length
- 20.1 m outer diameter
- 8 coils
- 1.08 GJ stored energy
- 370 tons cold mass
- 830 tons weight
- 118 tons superconductor
- 56 km Al/NbTi conductor
- 20.5 kA @ 4 T nominal current
- 4.5 K working point



ATLAS BT: 8 years of manufacturing

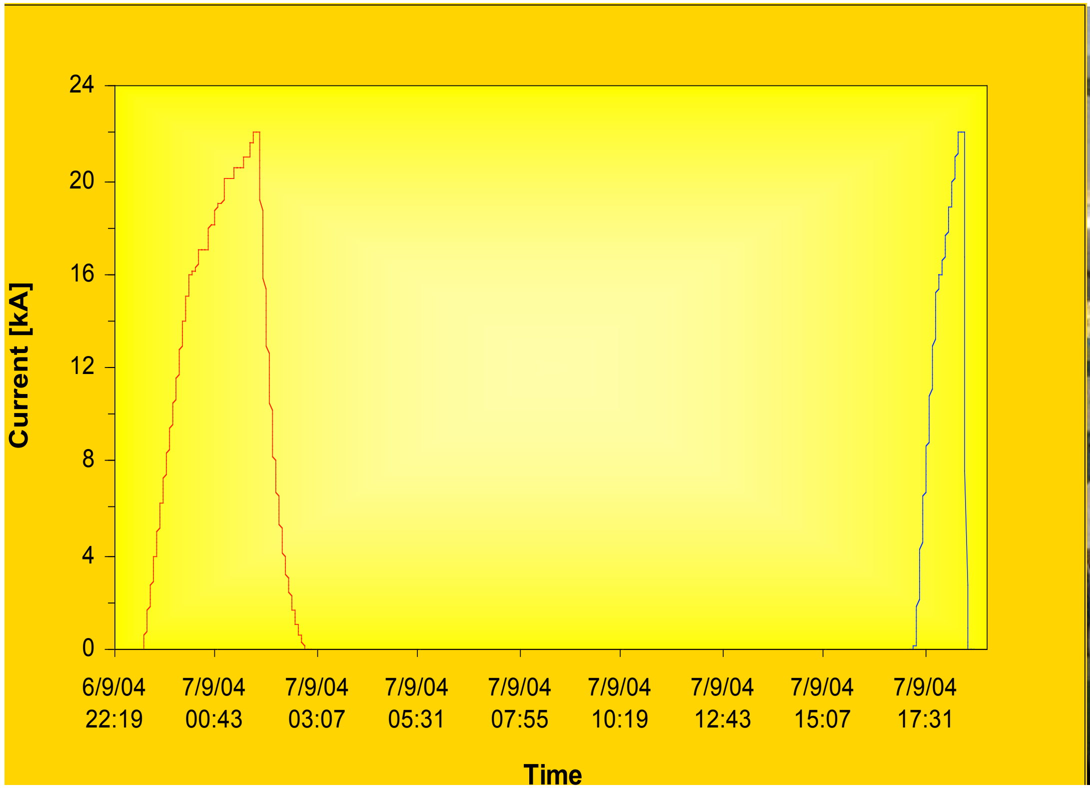


Cold mass insertion in its vacuum vessel

BT1 and BT2 coils tested

BT 1 & 2 Coil Test : Slow & Fast dumps

- *On 7 Sep '04 we charged the coil#1 twice up to 22 kA*
- *Slow dump (1hr normal ramp down without quench)*
- *Fast dump (2 minutes emergency ramp down with quench)*
- *Tested up to 22 kA (nominal 20.5 kA)*
- *Stability test of 8 hrs, all fine*
- *All coils have then been tested with the same procedure, all are fine*

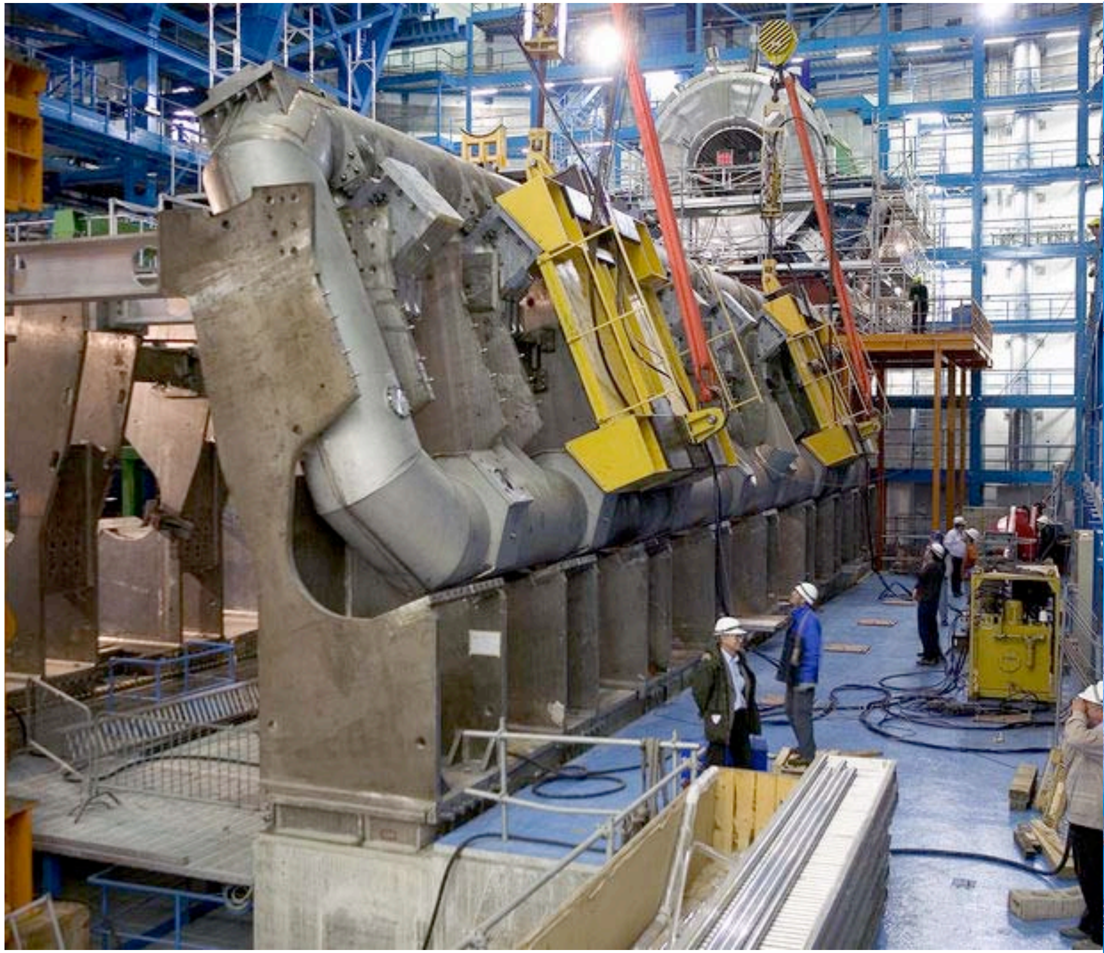


Preparing for installation

BT Mechanical Assembly

- ✓Difficult but safe manipulations (coil 25m, shaft 19m)
- ✓Use of 2 lifting frames
- ✓Hydraulic winch with load capacity 190T (subcontracted)

BT Mechanical Assembly (2)



- First the lower 4 coils
- …. and a lot of temporary support structures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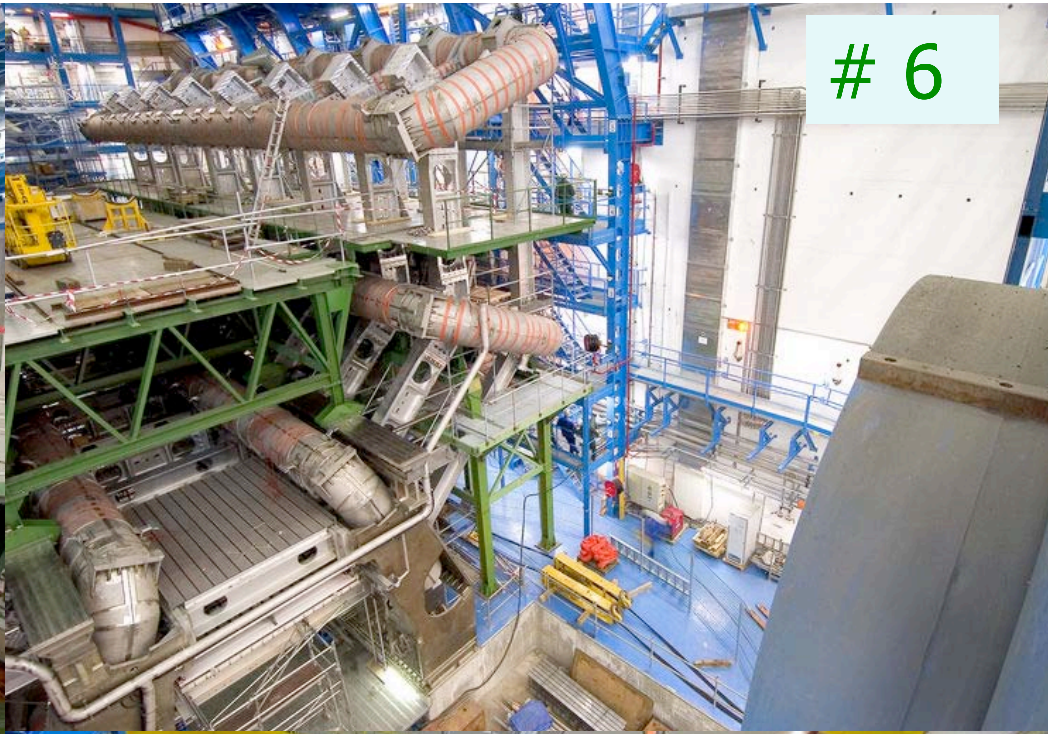
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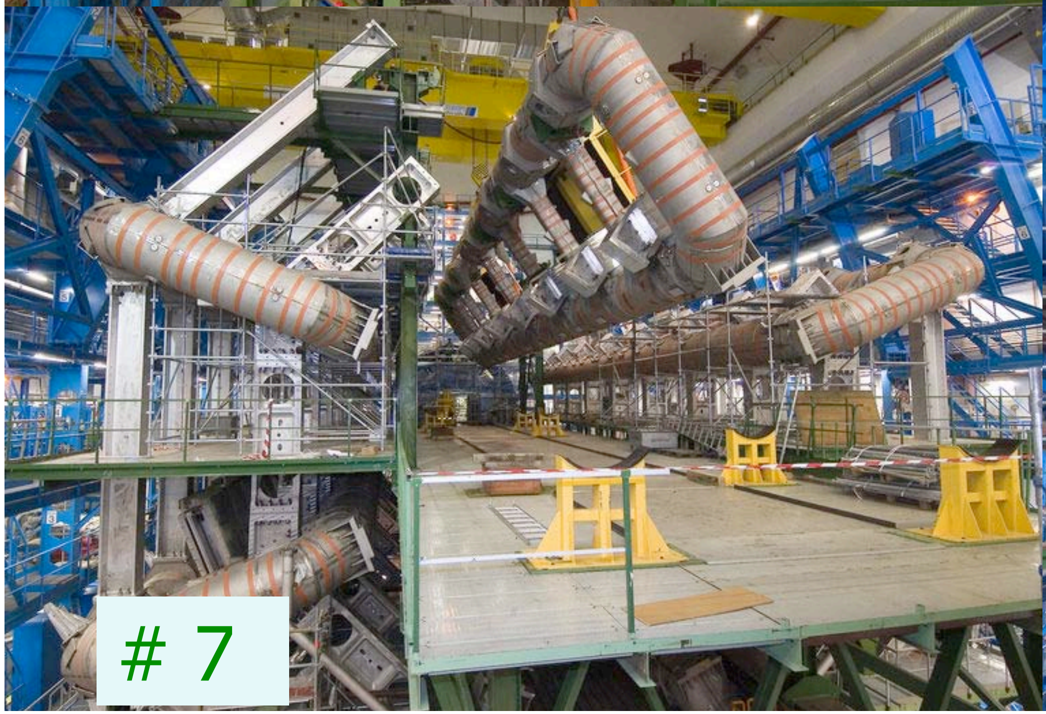
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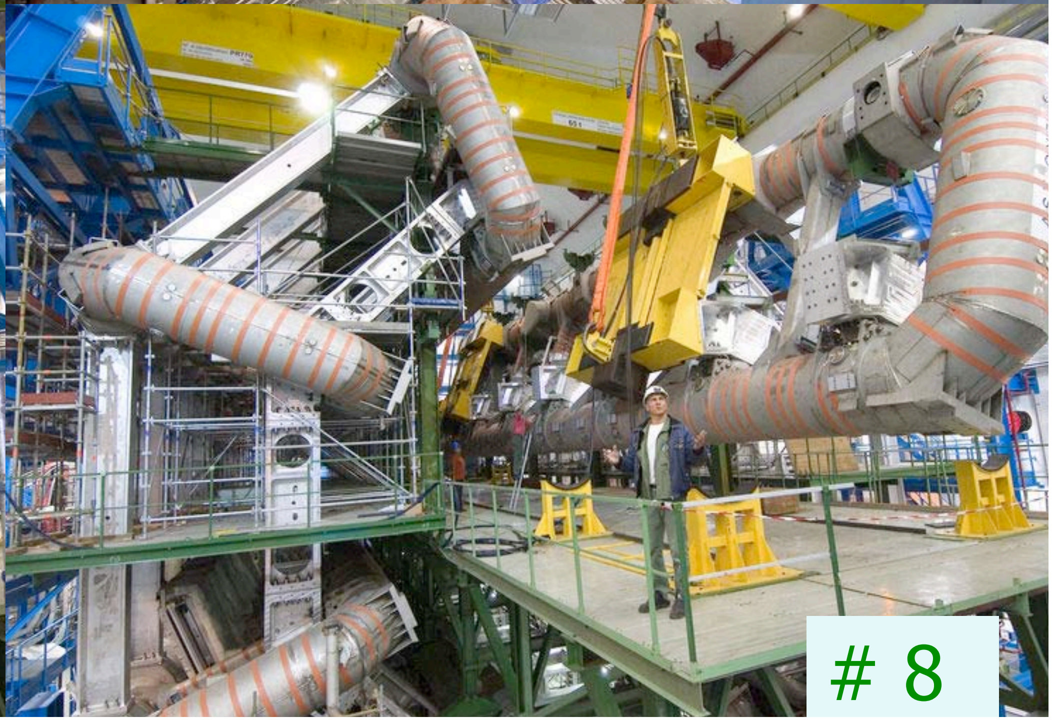
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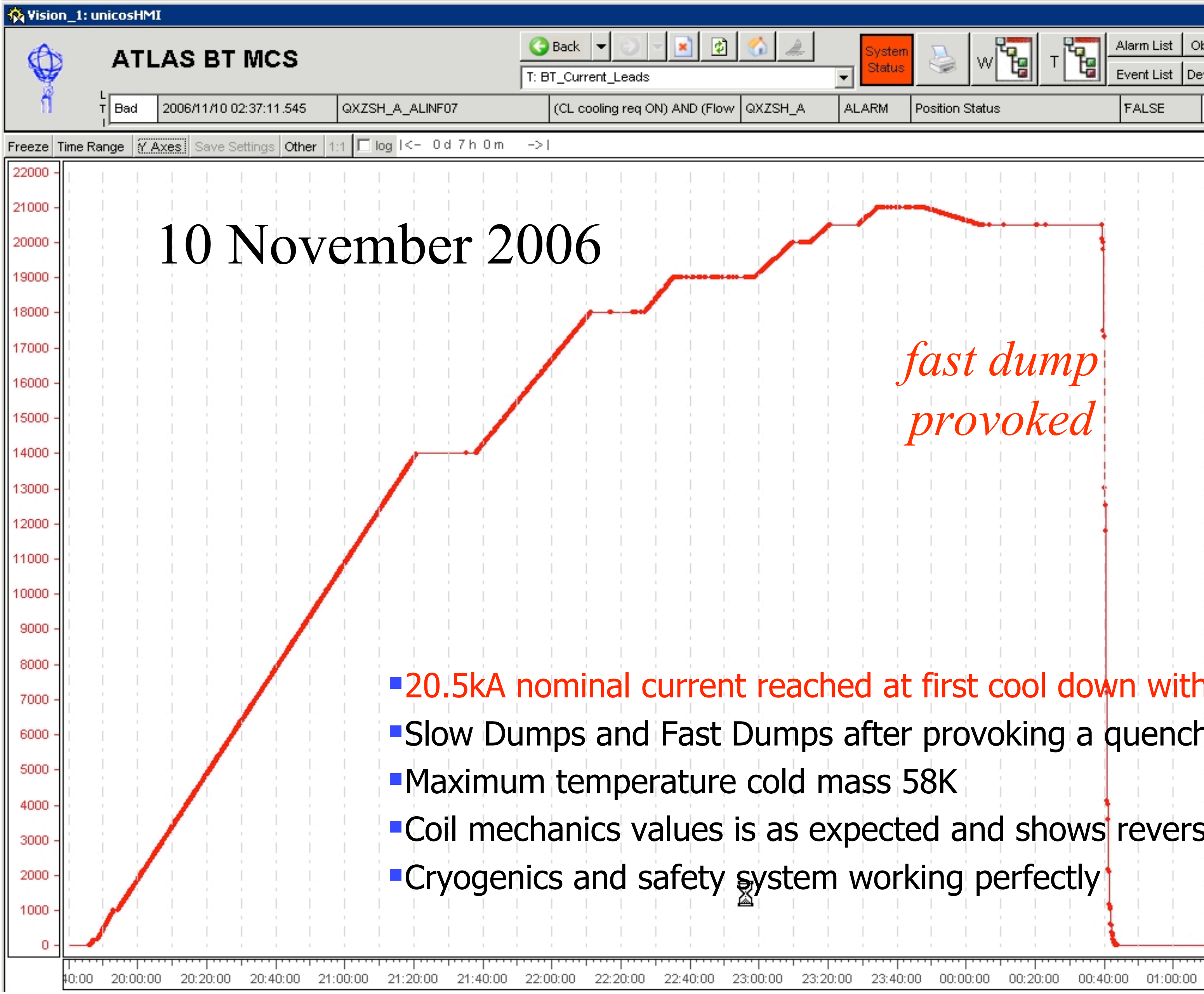
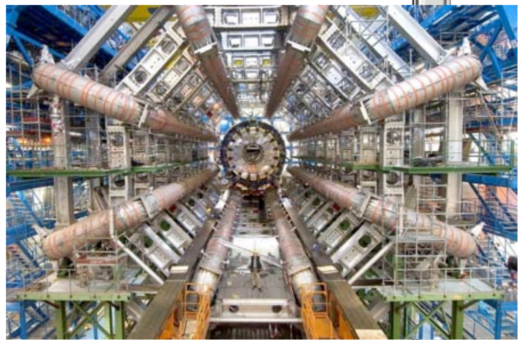
Barrel Toroid full current tests

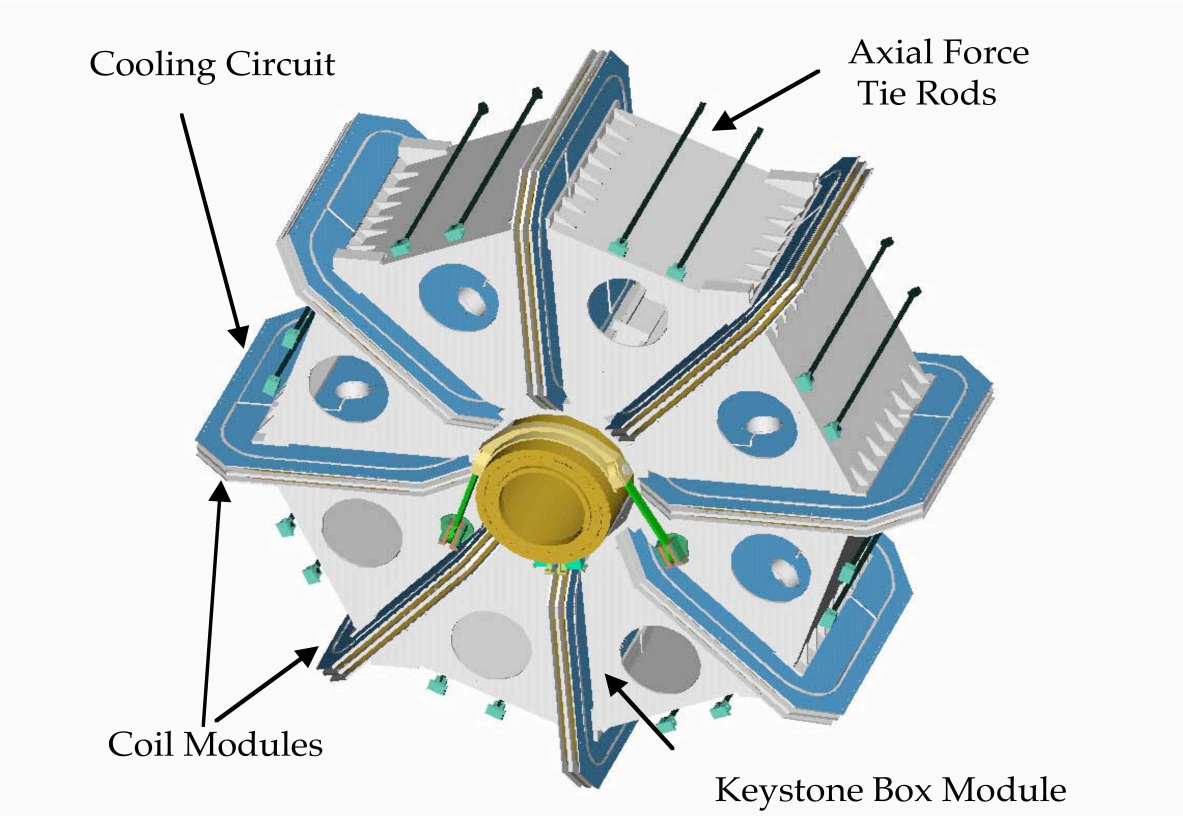




- 20.5kA nominal current reached at first cool down with NO training
- Slow Dumps and Fast Dumps after provoking a quench are safe
- Maximum temperature cold mass 58K
- Coil mechanics values is as expected and shows reversibility, safe as well
- Cryogenics and safety system working perfectly

The End Cap Toroids

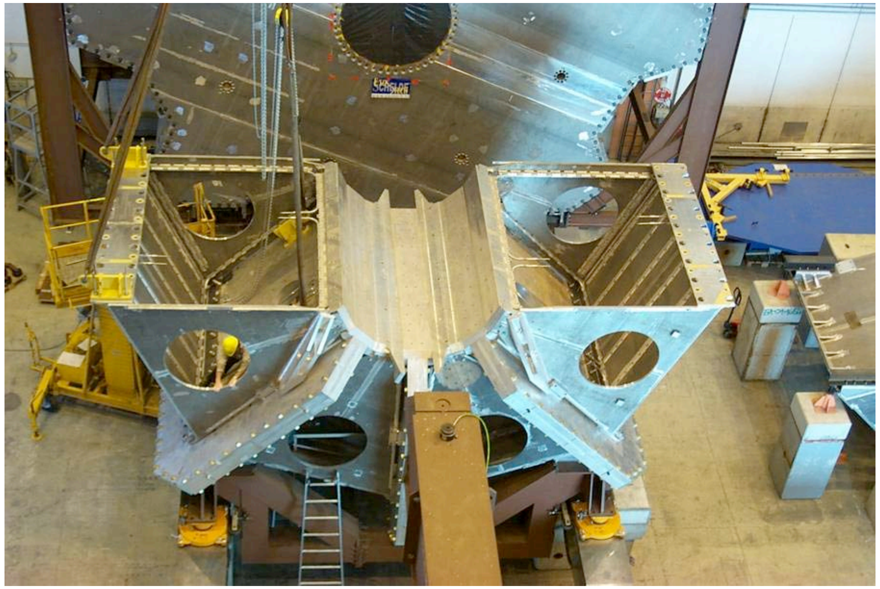
ECT cryostats

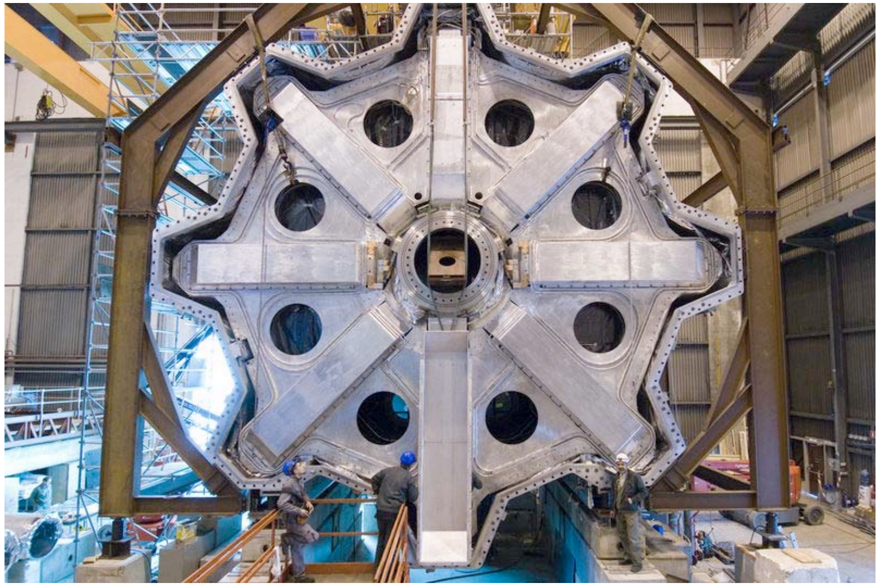


Integration work

8 coils + 8 keystone boxes / cold mass

Final assembly and installation



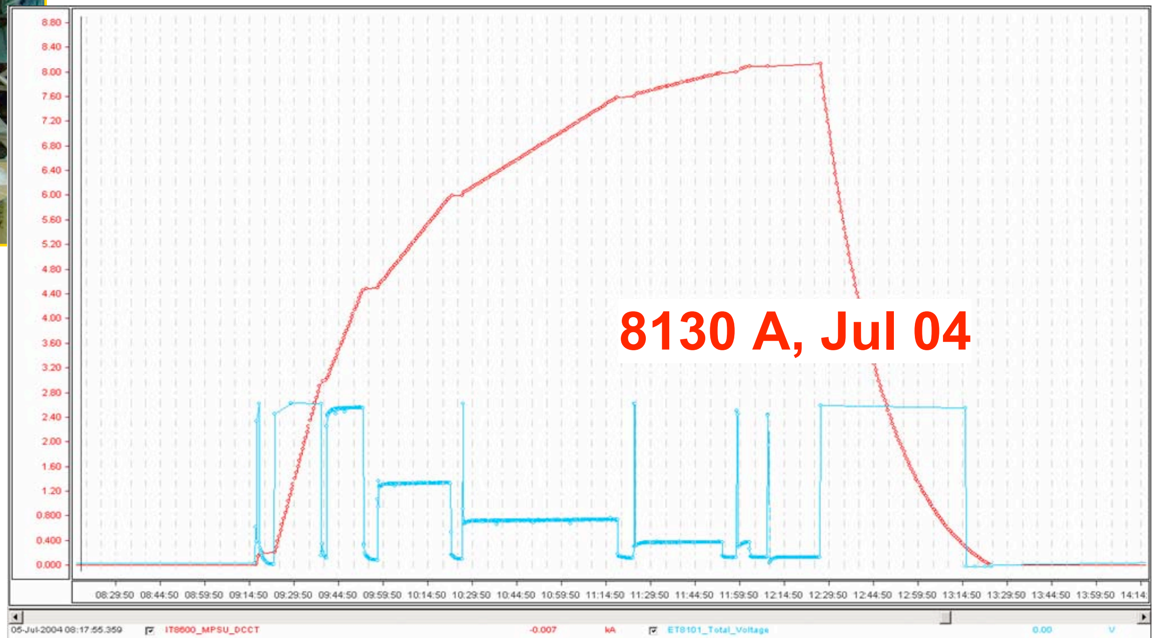


Installation in the cavern

scheduled for 13/6/07

Central Solenoid integration and test

During on-surface test at CERN in Jul 04 it achieved after 2 training quenches at 7950 and 8110 A (both beyond the nominal current 7600 A) the test maximum of 8130 A (6% safety margin)



- Cooled down in May ‘04
- Surface test in June ‘04
- Test completed in July ‘04
- Installed into the cavern
  28th Oct ‘04

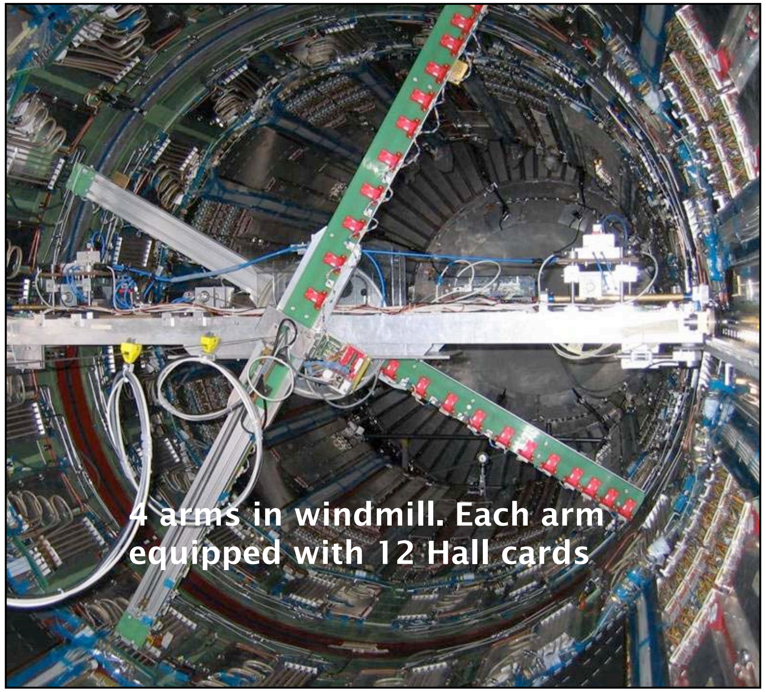
Coil is healthy and accepted for installation

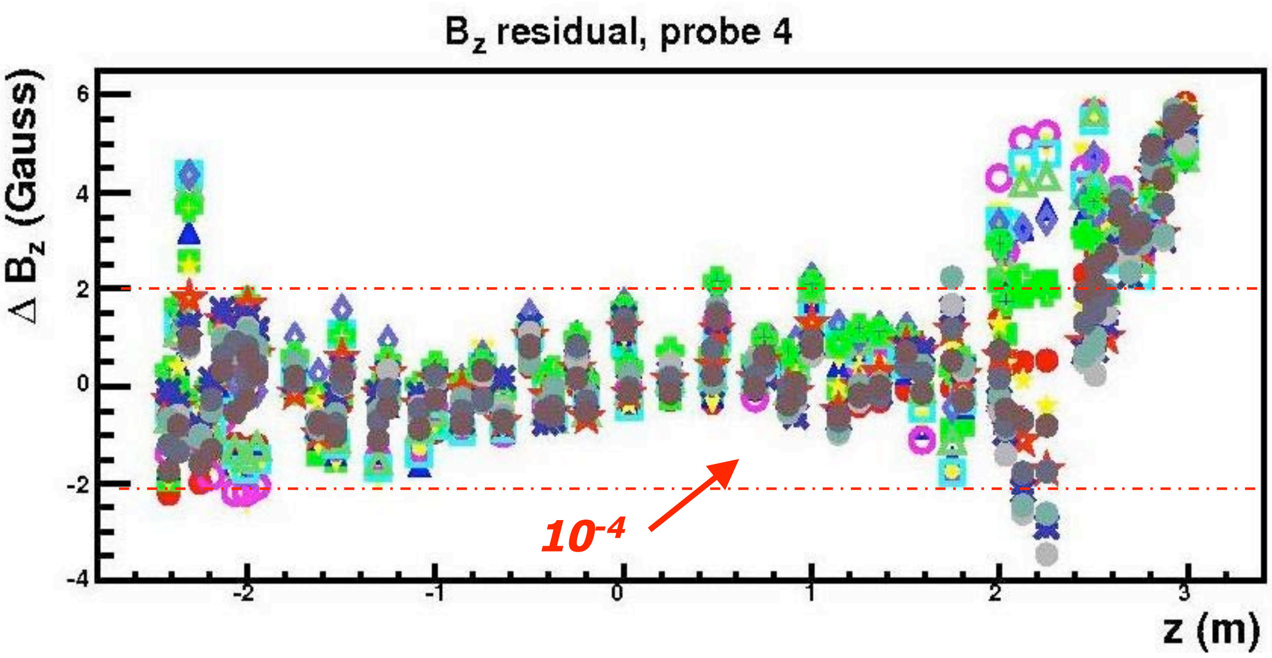
Central Solenoid tested in situ (Dec '06)

Full maps made at 7730 A (nominal 2 T at centre) + various lower A. Typical map contains 300 x 12 x 16 = 57600 data points. Three field components measured at each data point.

Data quality. Difference between fields re-measured by one probe at the same point after 1 turn of the windmill has r.m.s. < 1 Gauss.

Data corrections. Probe calibration accuracy 5G at 2T(2G up to 1.4T) Probe position accuracy 0.5 mm. Maxwell constraints allow correction of individual probe alignment (to ±0.2 mrad.)





Example of fit to first 7730 A map

Data fits model well: χ^2/dof = 116620/(89088-11)

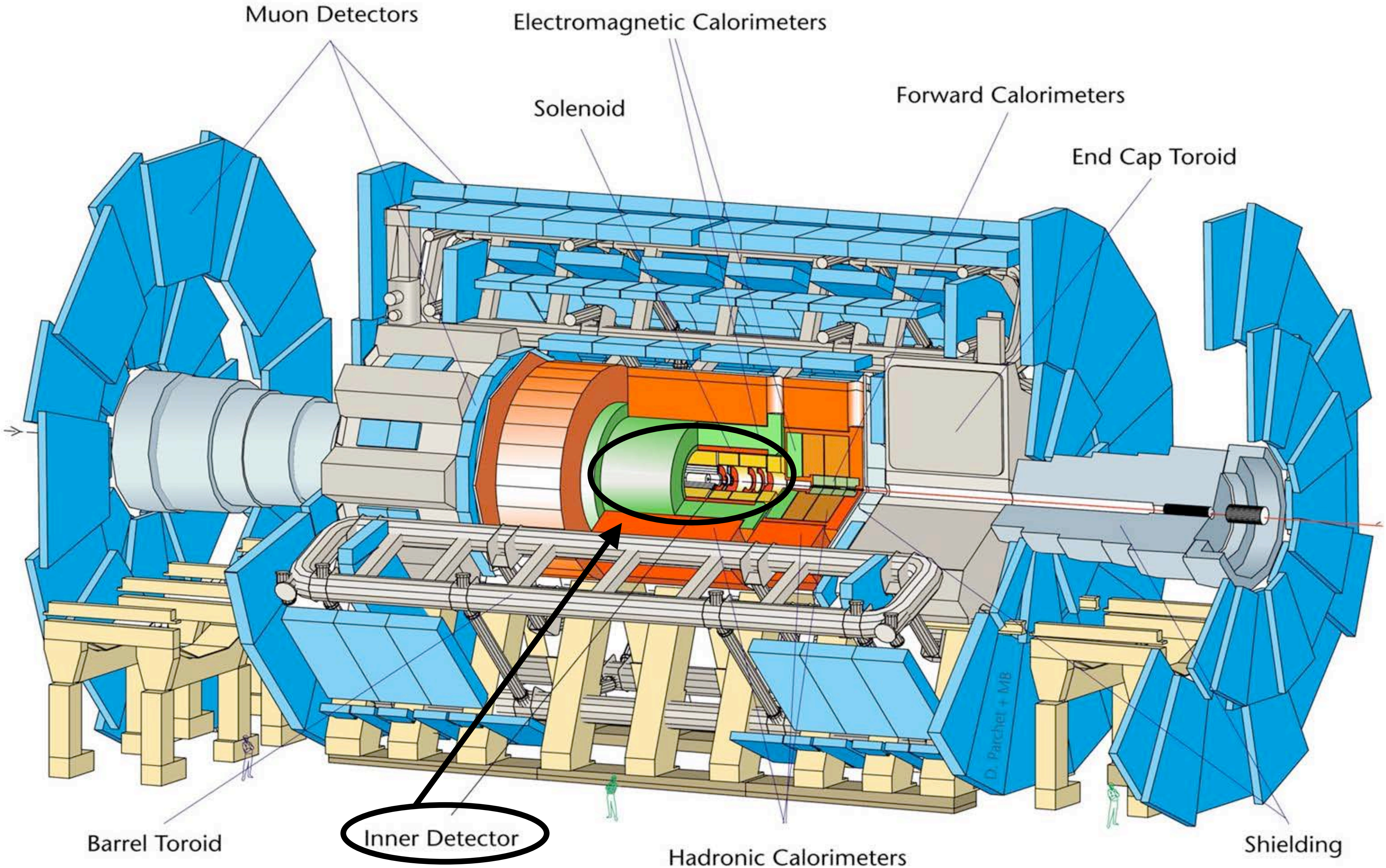
r.m.s. residuals are

Bz=4.4, Br=4.9, Bφ=3.3 Gauss.

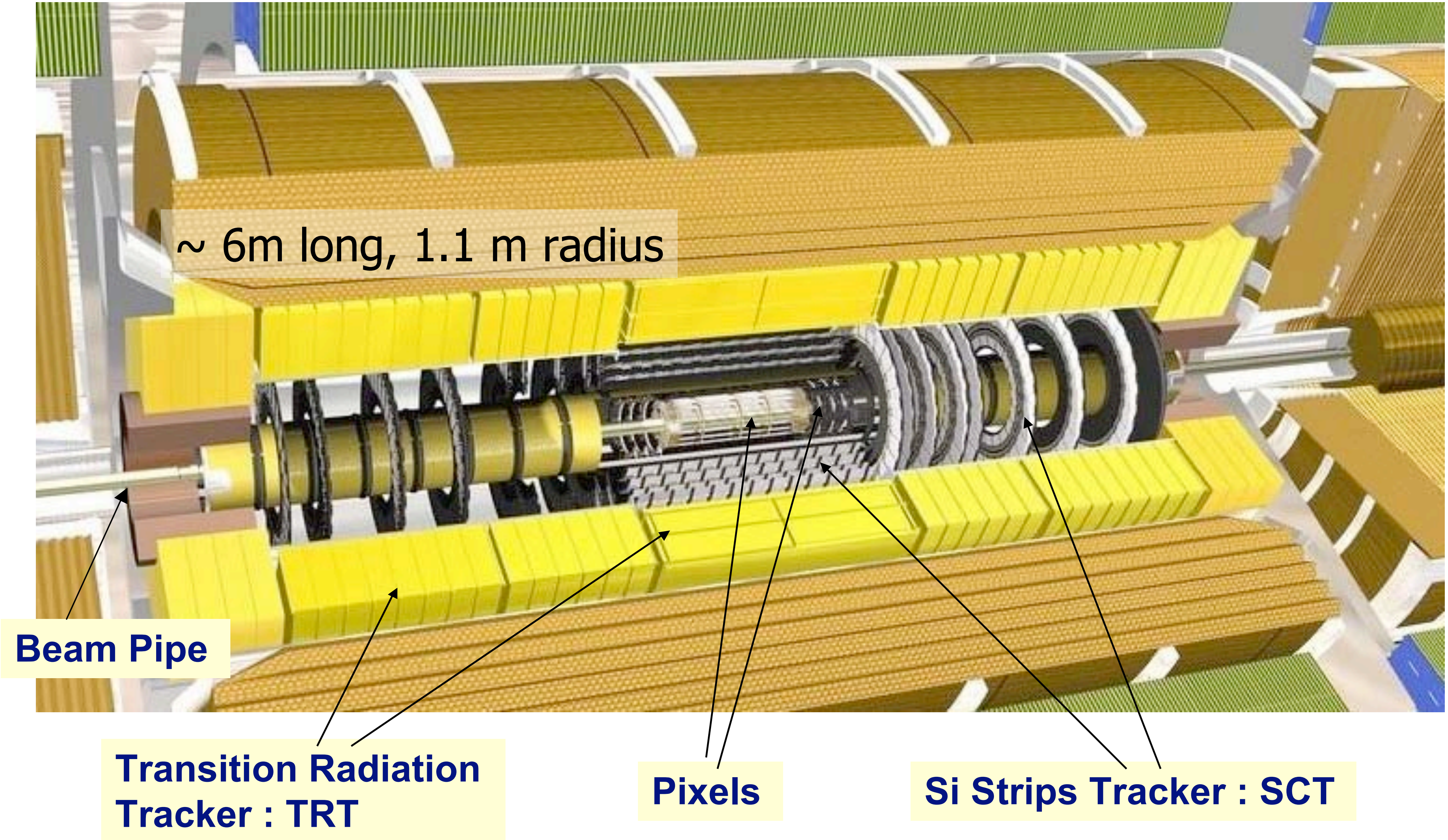
Still possible to improve fit quality at coil extremes!

D712/mb-26/06/97

The ATLAS Detector

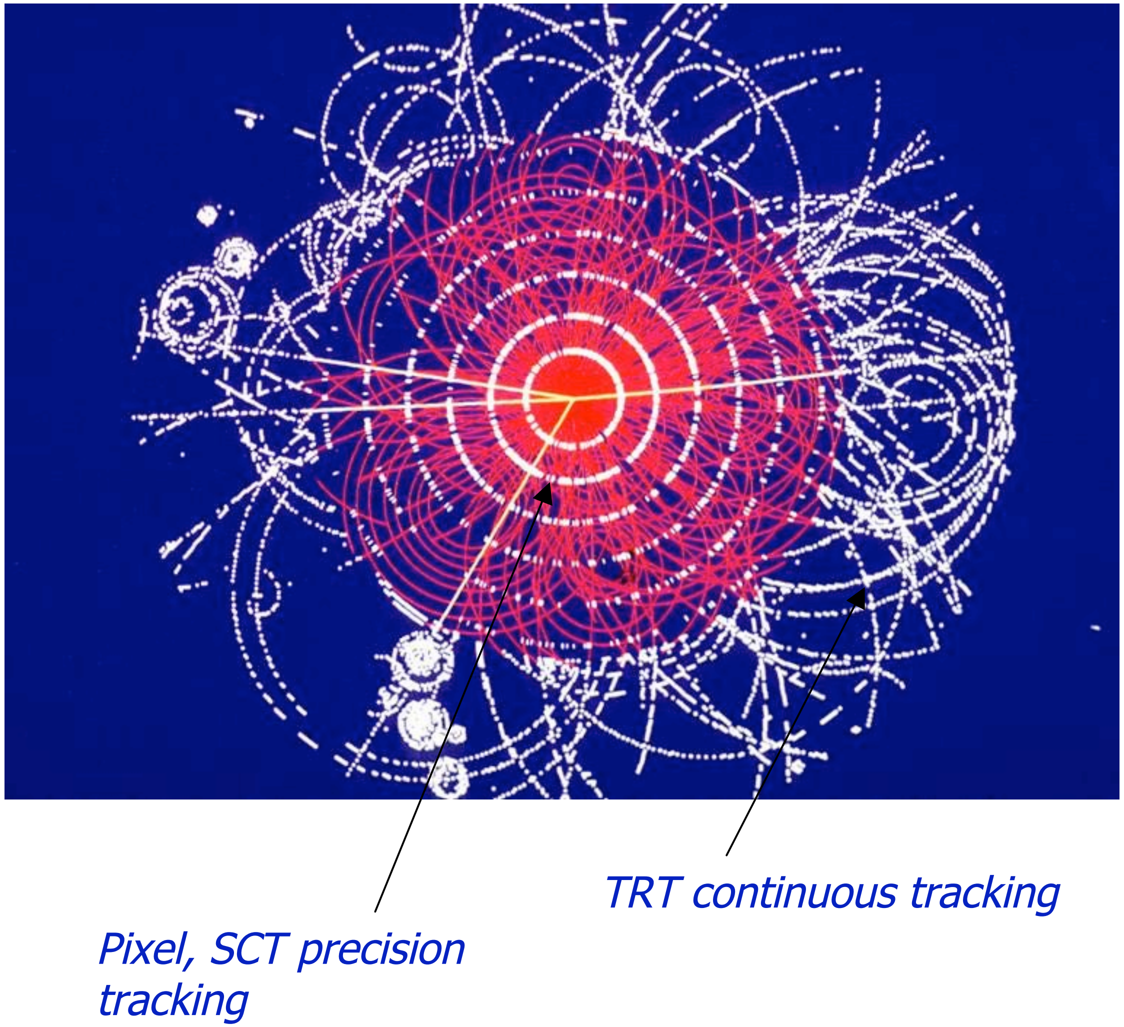


The Tracking Detectors



The Tracking Detectors

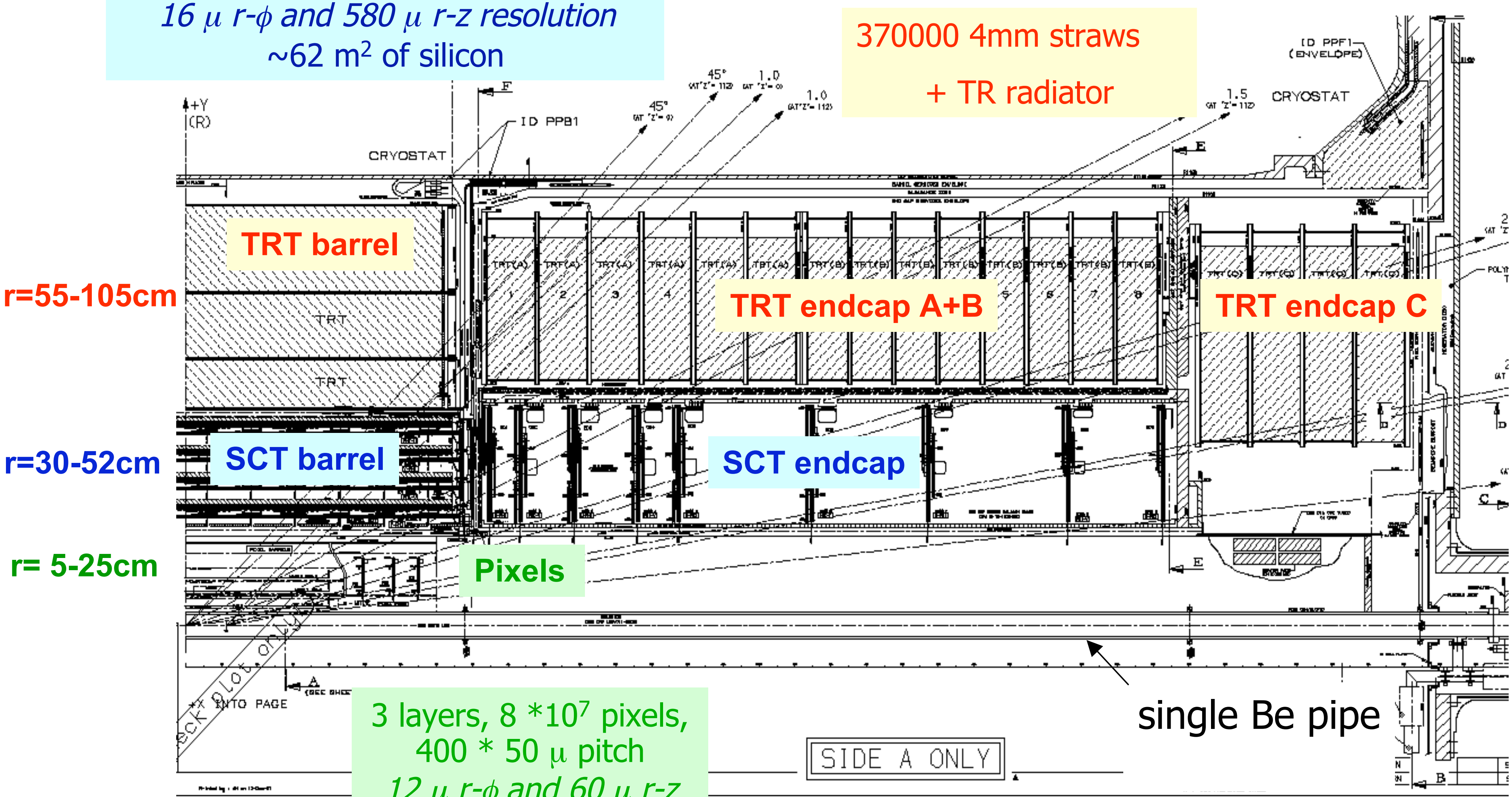
- Patter recognition:
  Challenging: high track density
  - ✓7 precision points/track (3 pixel+4 SCT)
  - ✓Each r-ϕ and z (40 mrad stereo in SCT)
  - ✓Up to 36 TRT straw hits
  - ✓Continuous tracking… optimised for tracking performance, not TR e-
  - ✓π rejection up to 100 for 80% e- efficiency
- Needs to operate up to an integrated dose between 10 and 60 Mrad
- ID located inside a barrel cryostat including solenoid
  - ✓2T field, non-uniform at high z -> Reduces to 1T at z=2.7m
  - ✓Hermetic coverage up to $|\eta|$=2.5



The Tracking Detectors

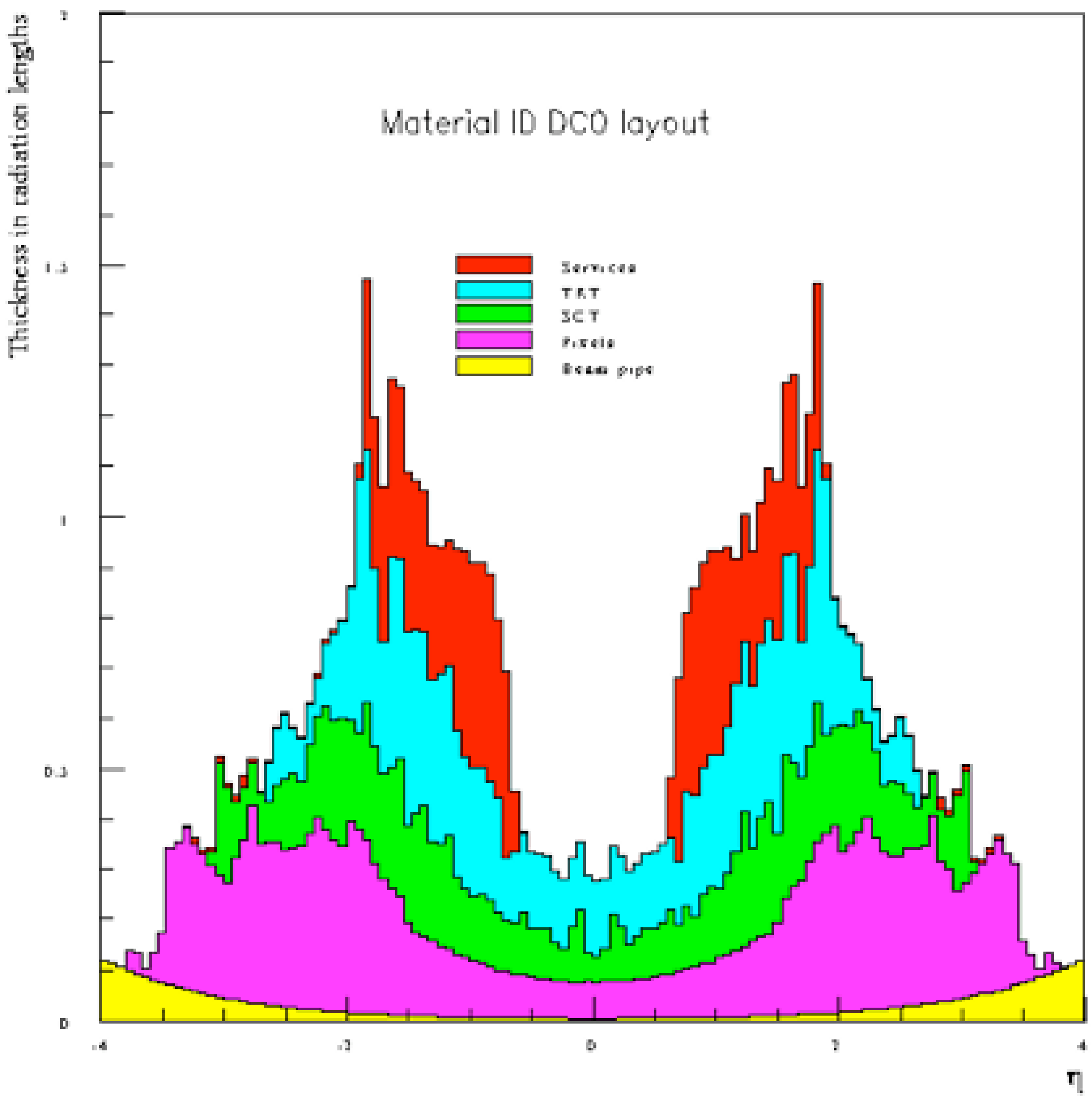
SCT : 4088 modules, 80 μ pitch
16 μ r-φ and 580 μ r-z resolution
~62 m^2 of silicon

370000 4mm straws
+ TR radiator



3 layers, 8 *10^7 pixels,
400 * 50 μ pitch
12 μ r-φ and 60 μ r-z resolution

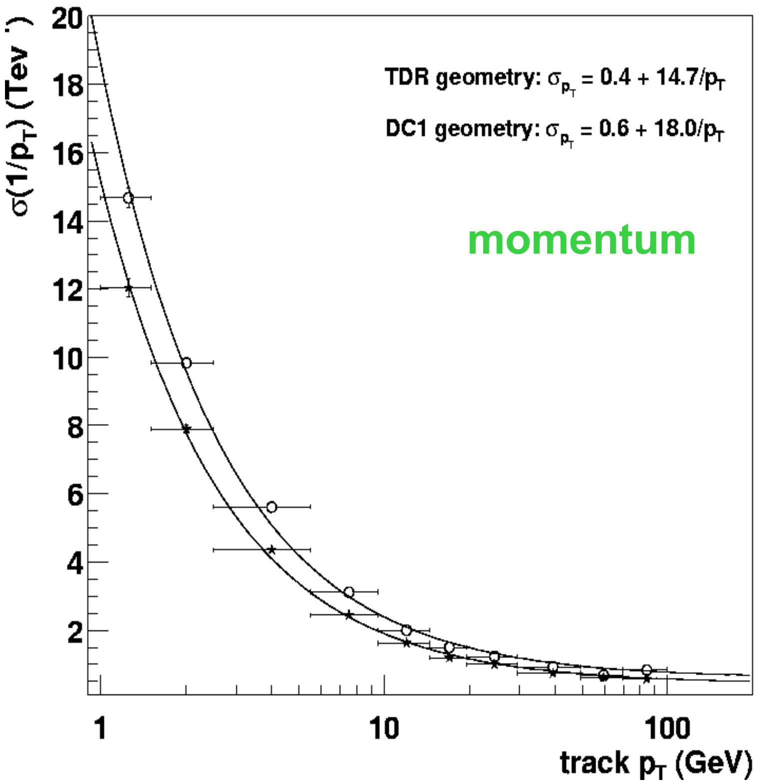
The Tracking Detectors



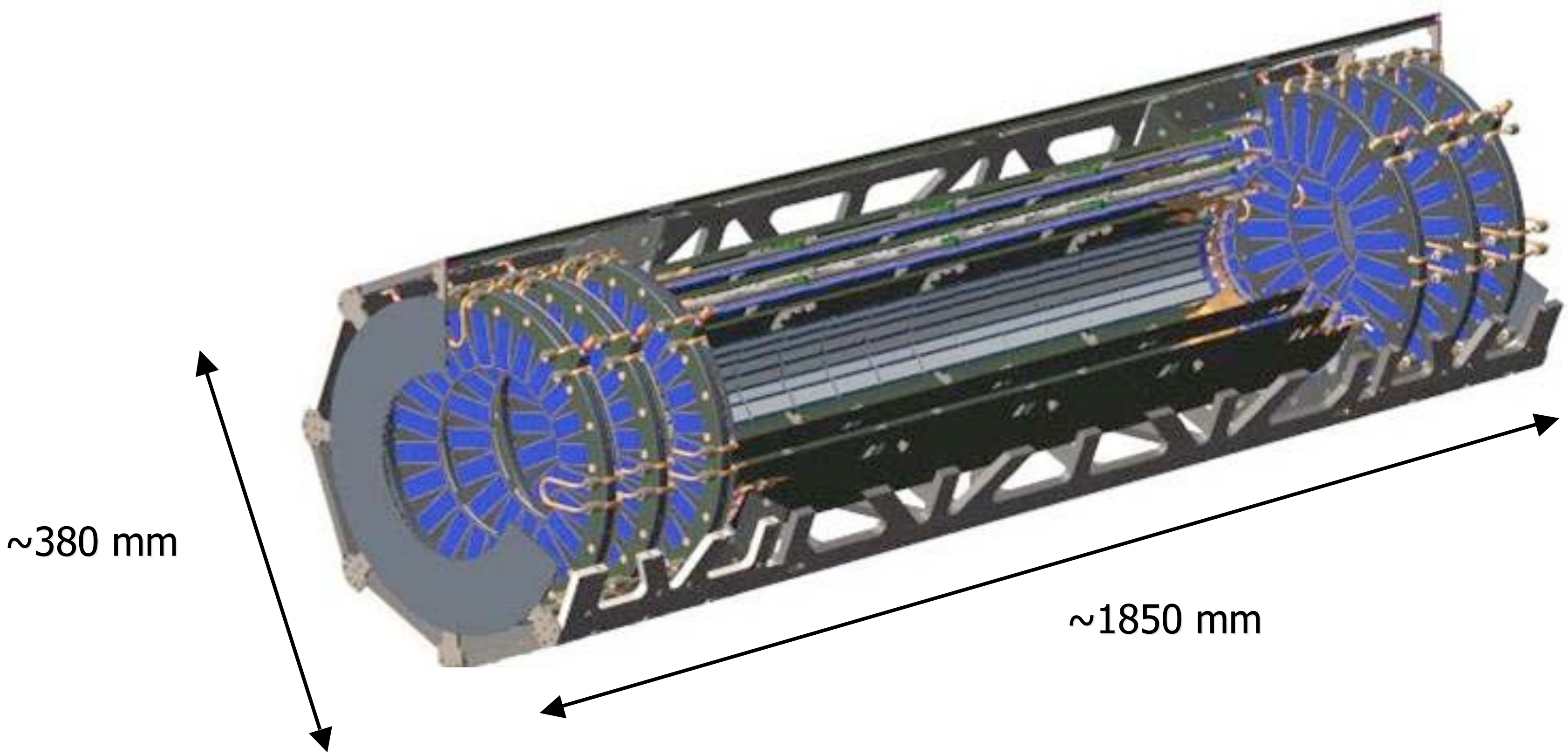
At η=0, have 0.3 X_0, rising to around 1 X_0 in detectors at |η|=2

Continuous effort to reduce the amount of material in order to :

- reduce γ conversions
- minimize multiple scattering
- minimize early preshowering



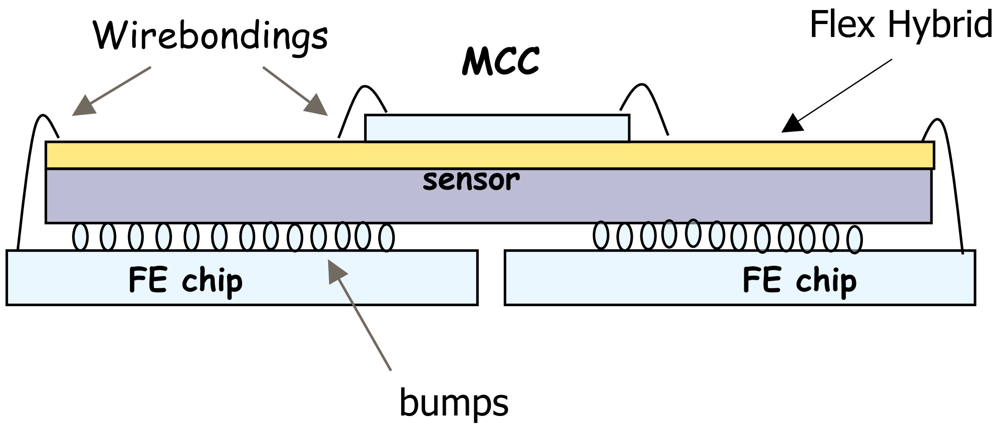
ATLAS pixels

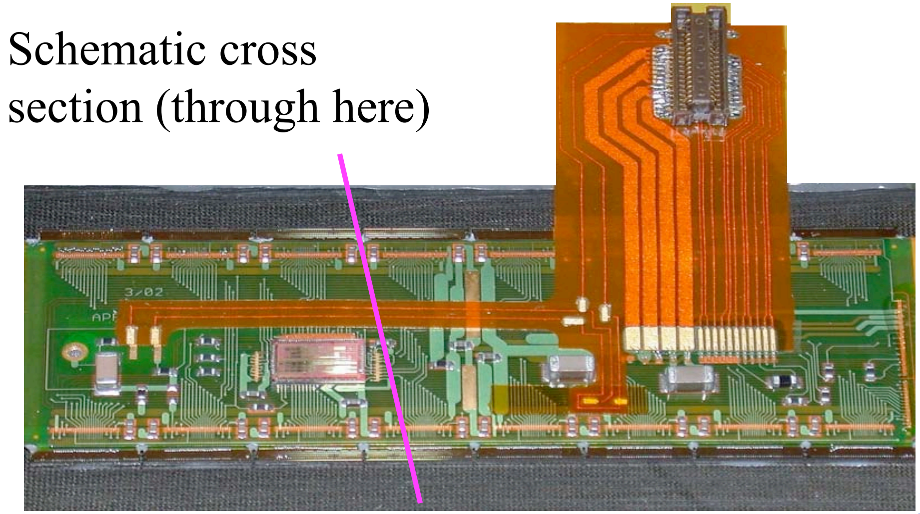


- ~1.7 m^2 of sensitive area with 67M (barrel) + 13M (disks) channels.
- n+ on n oxygenated sensors, 400μm x 50μm pixels.
- Total dose 50 Mrad on the middle layer in 10 years of LHC.

ATLAS pixels

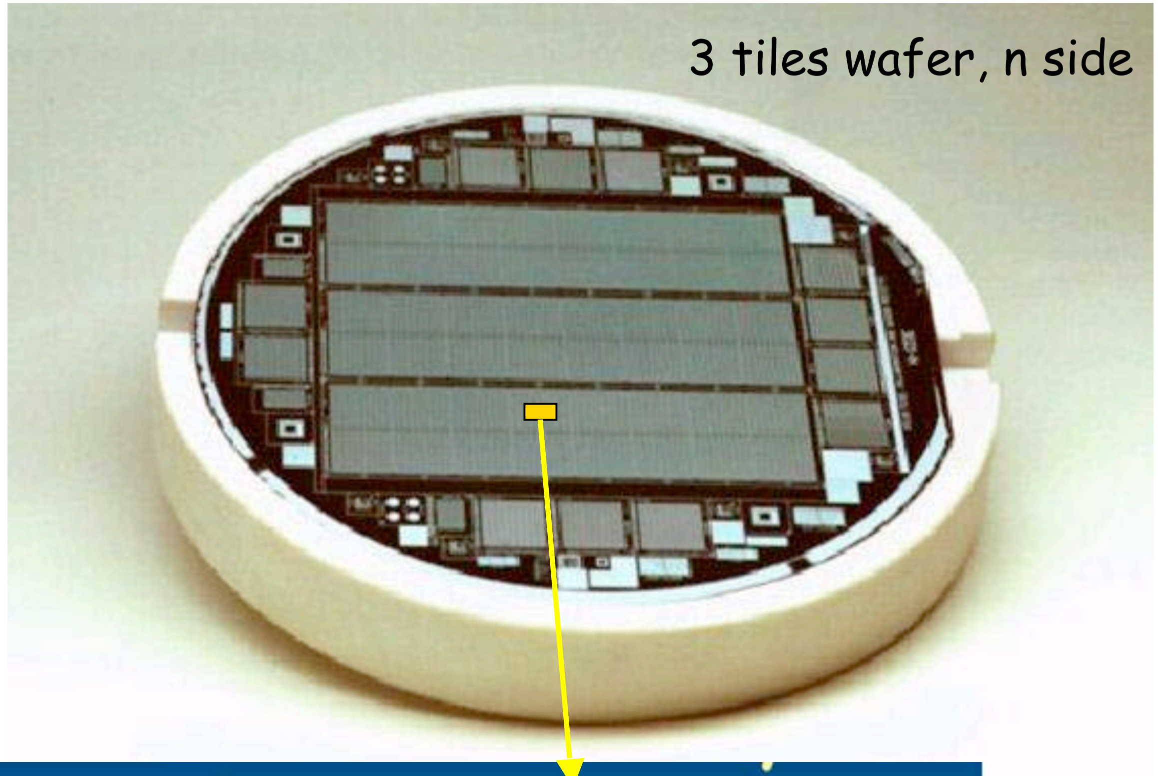
- ✓ Modules are the basic building elements of the detector (1456 in the barrel, 288 in the end-caps).
- ✓ The sensitive area is read out by 16 FE chips which are controlled by a Module Controller Chip (MCC).
- ✓ A Flex-Hybrid circuit glued on the sensor backside provides the signal/power routing.
- ✓ A pigtail (barrel) + Al/Cu wire bundle connect flex hybrid to patch panels at either end of pixel detector. Pigtail is the only difference between barrel and disks modules.

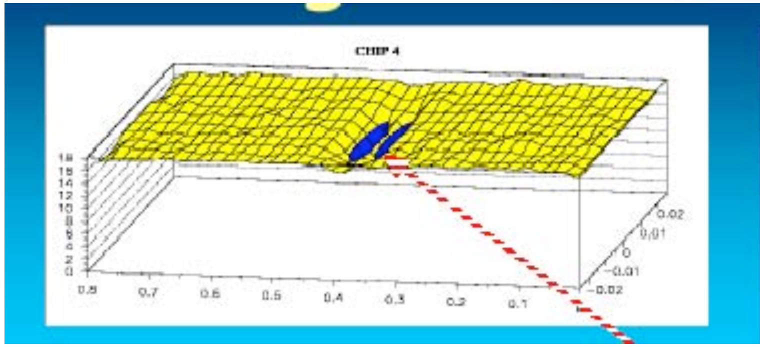




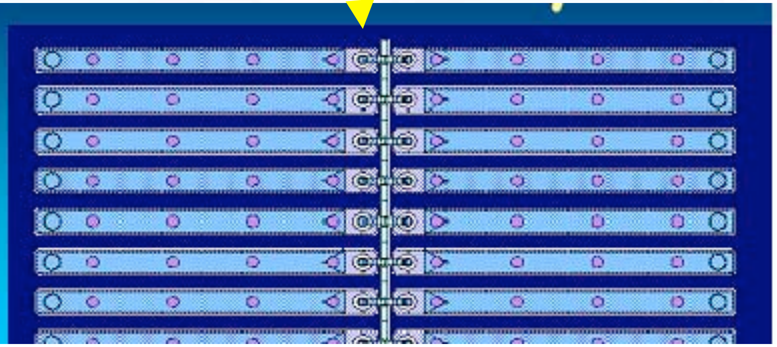
ATLAS pixels

- Baseline design:
  - ✓ *n+ pixel in n-bulk material:*
  - ✓ *Moderated p-spray isolation.*
  - ✓ *Bias grid to allow testing before module assembly.*
  - ✓ *Oxygenated silicon to improve radiation resistance and increase allowable time to room temperature (for repair/upgrades).*
- Two vendors: Cis and Tesla





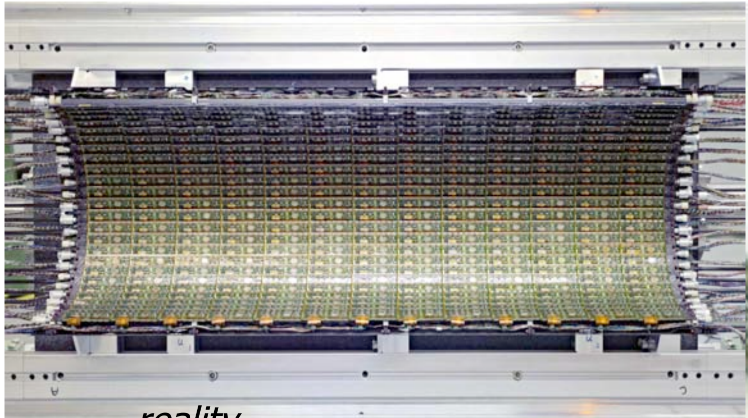
Charge collection efficiency (meas)



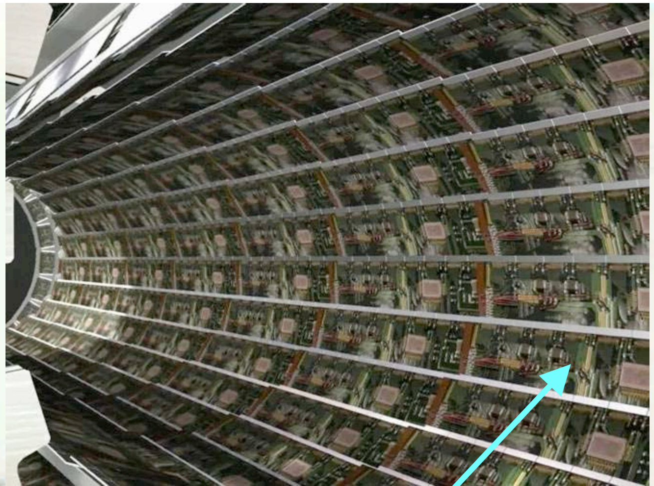
n+ implants and bias grid

ATLAS pixels staves

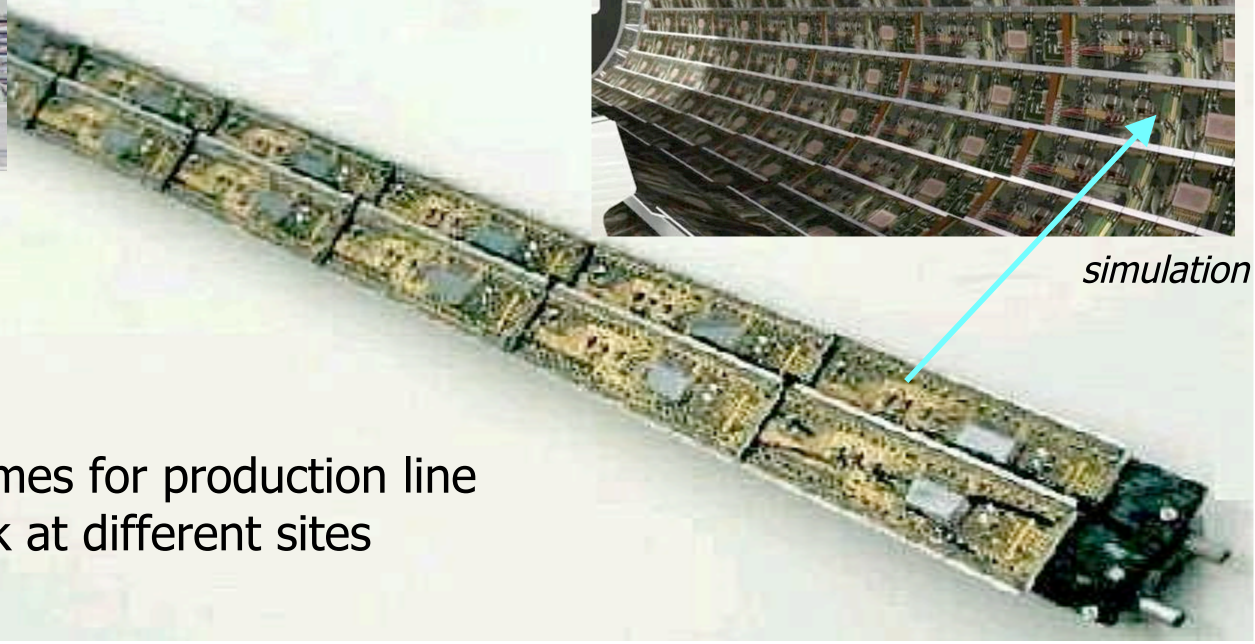
- ✓ Barrel staves and disk sectors are the local supports that hold and cool pixel modules (T sensors <0^{o}C).
- ✓ They are carbon-carbon structures to minimize material.
- ✓ The cooling fluid (C_3F_8) flows in thin Al tubes (0.2mm) both for staves and disks.



reality

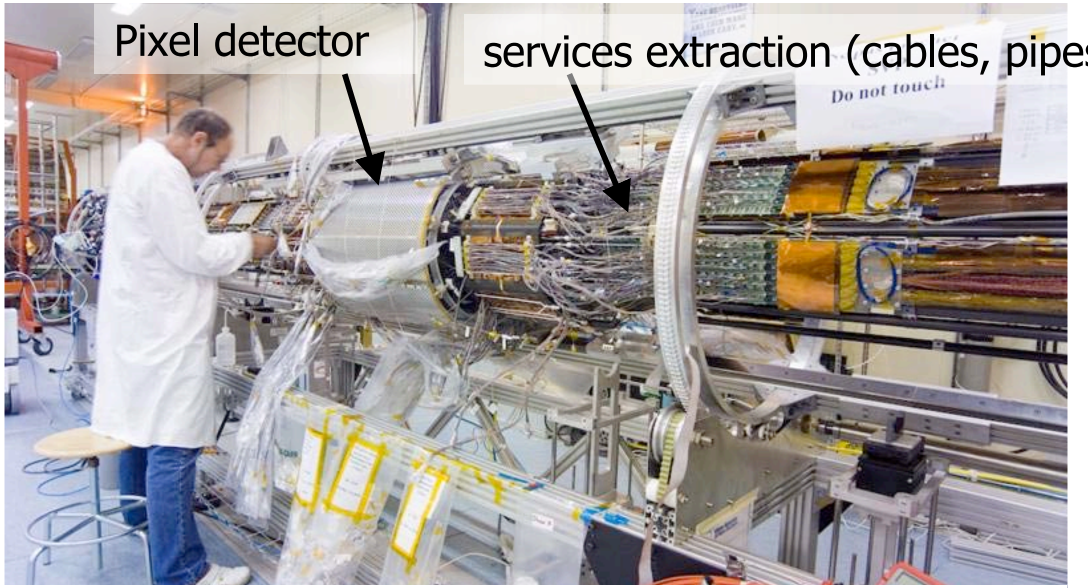


simulation

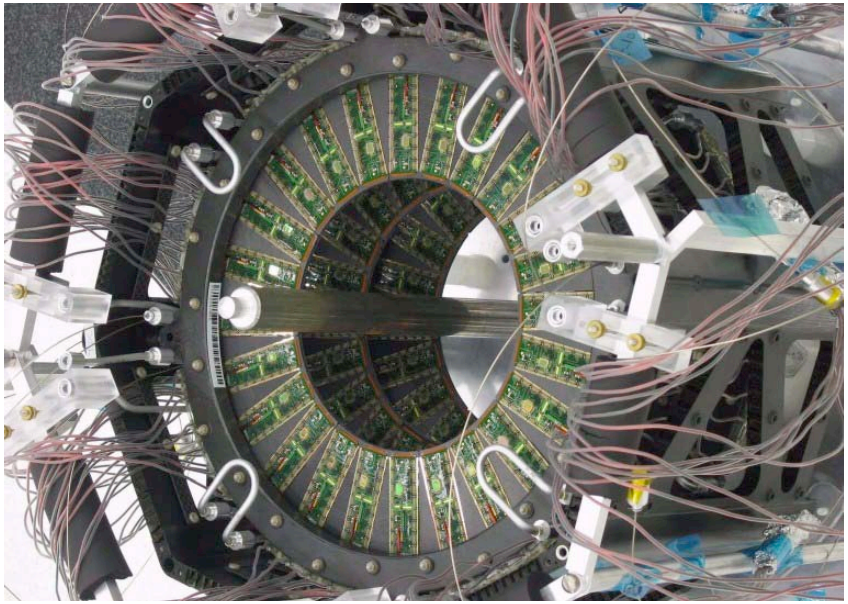


Bi-stave assembly
is replicated to form
Barrel layers. 2x13 modules.
Same unit repeated many times for production line assembly, uniformity of work at different sites

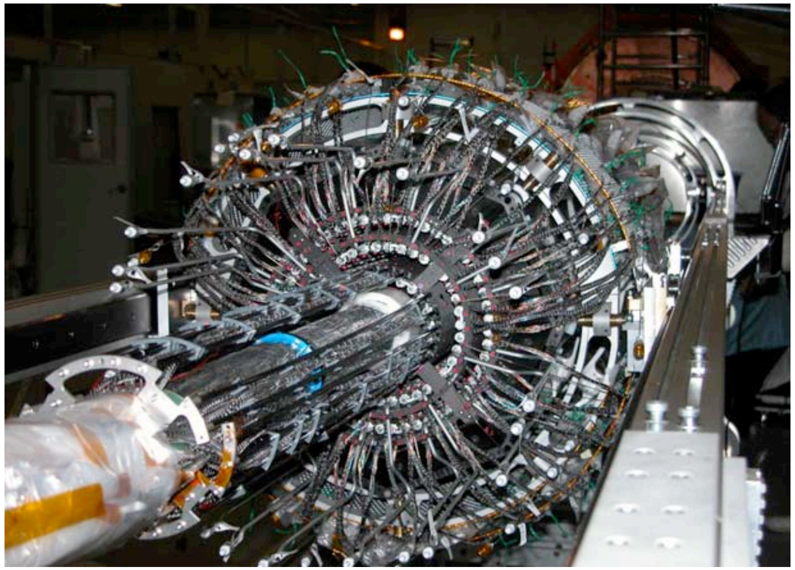
ATLAS pixels assembly



Full pixel detector, including services and beam pipe.
It will be installed inside ATLAS in July 2007



First 3 disks being integrated in their support structure (>0.07% dead channels out of 6.6M)



Staves integration in the barrel cylinders

The SCT (SemiConductor Tracker)

4-Layer Barrel

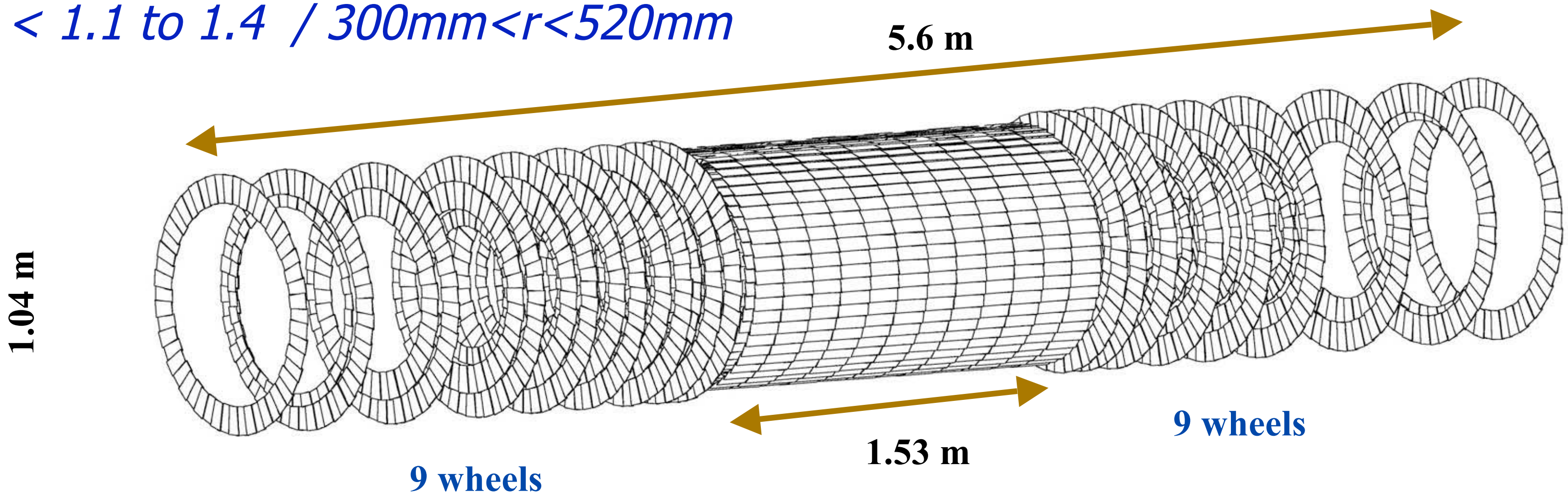
~34.4 m^2 of silicon
~3.2 x 10^6 channels
2112 barrel modules (1 type)

Space point resolution:
$r\phi \sim 16\mu m$ / $Z \sim 580\ \mu m$
Coverage:
$|\eta| < 1.1$ to 1.4 / $300mm<r<520mm$

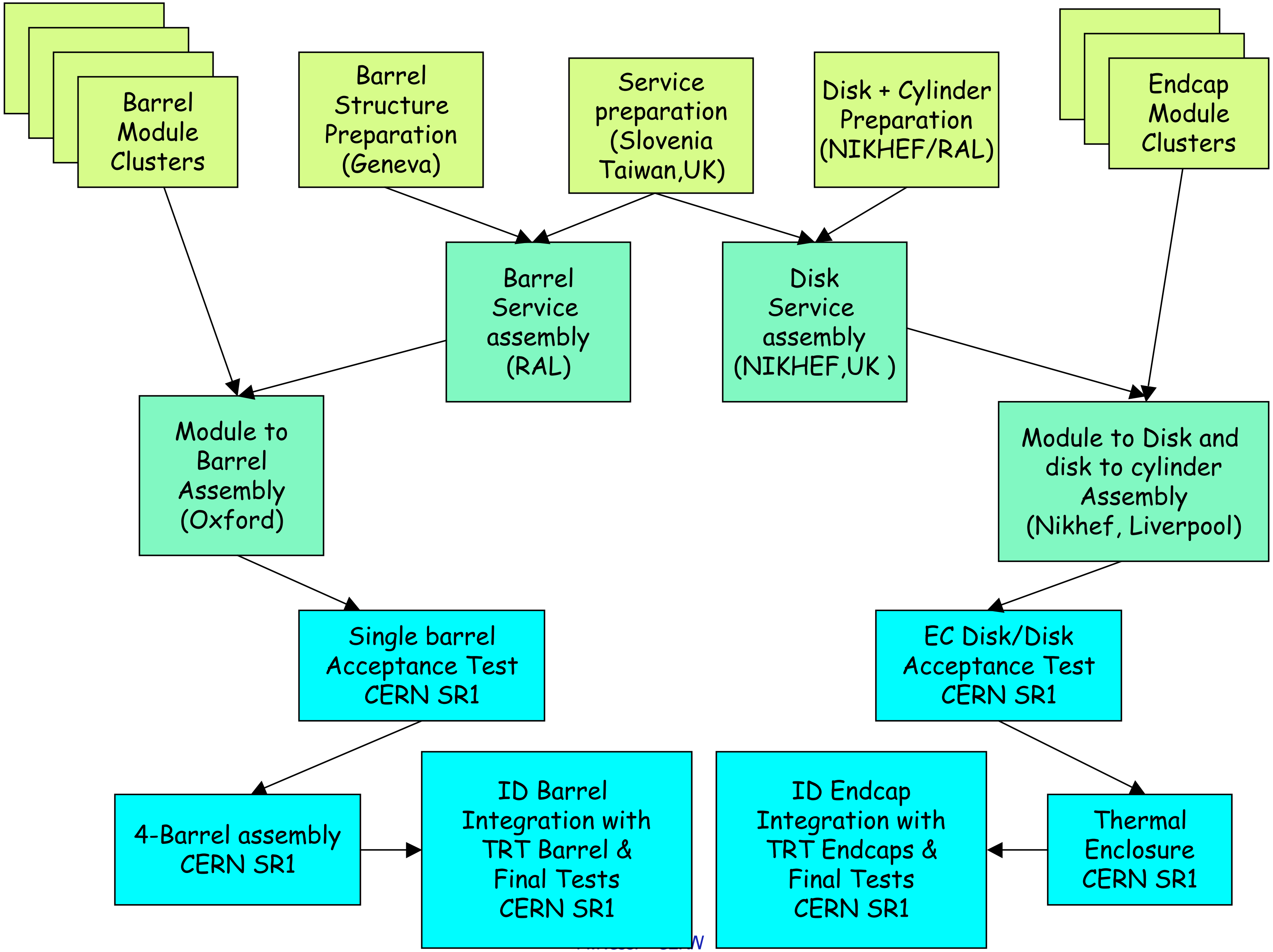
Two Endcaps

~26.7 m^2 of silicon
~3.0 x 10^6 channels
1976 endcap modules (4 types)

Space point resolution:
$r\phi \sim 16\mu m$ / $R \sim 580\ \mu m$
Coverage:
1.1 to $1.4 < |\eta| < 2.5$



Production flow chart



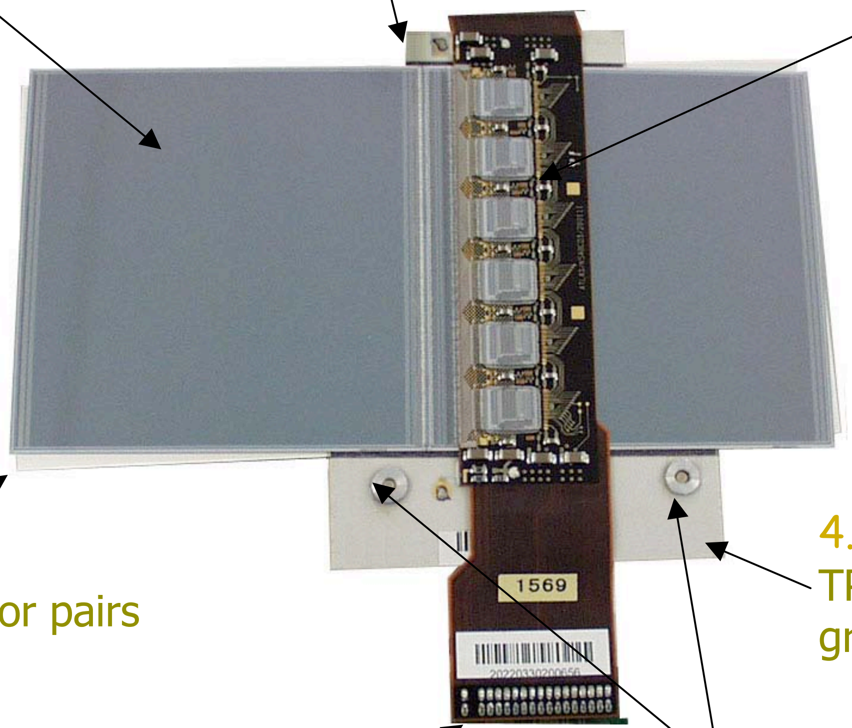
The barrel module

1. 4 Sensors
280 microns thick p-n
Strip length 12cm
Pitch 80μm

2. 3rd Mounting point

3. Hybrid & Binary Readout chips
Flex circuit with 12 x ABCD chips.

7. Overlaps
Overlap in r ϕ and Z to adjacent modules



4. Be Facing & Central TPG
TPG (thermal pyrolythic graphite) plate for sensor cooling

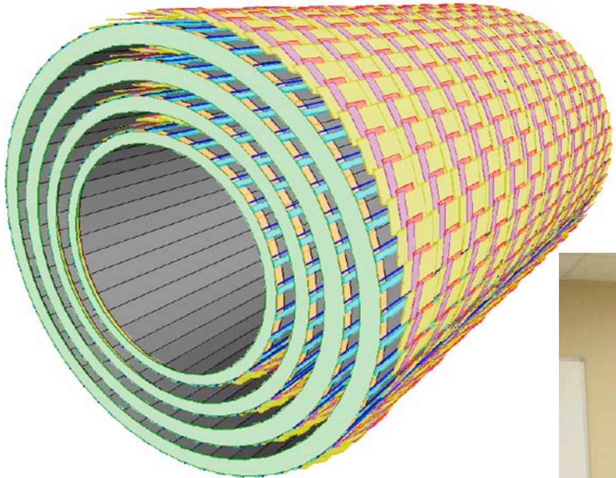
8. Stereo angle
Upper or lower detector pairs rotated by 40 mRad

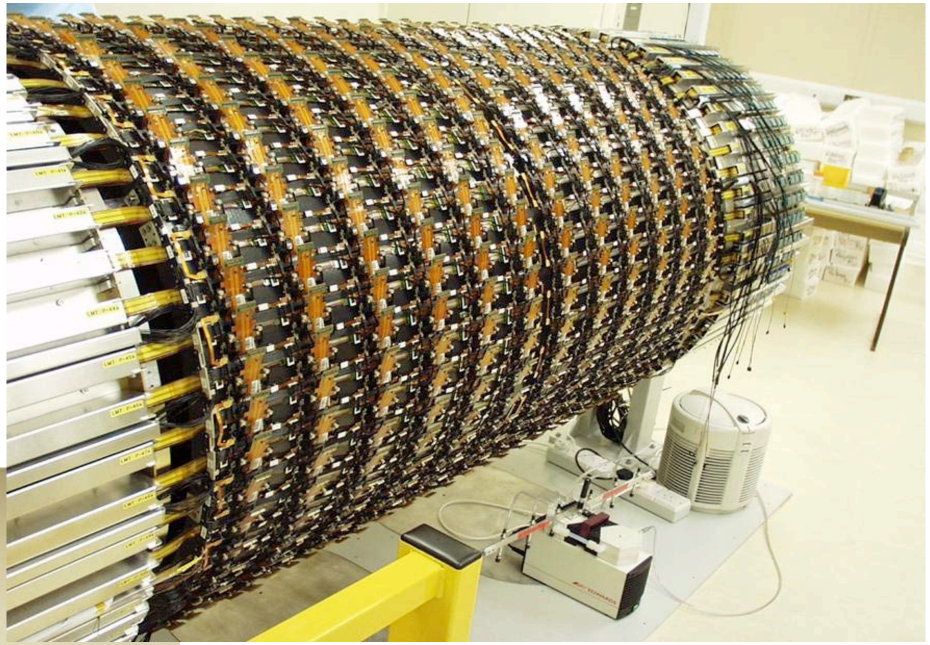
6. Connector
Power & Data

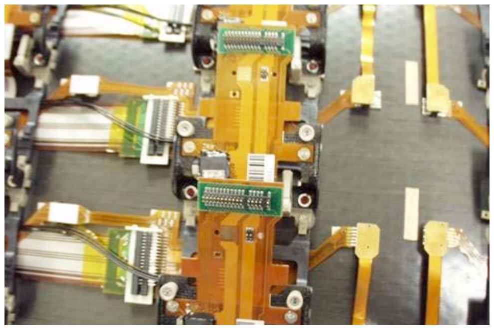
5. Module support & Location Holes
fix to brackets, one hole & one slot

ATLAS barrel SCT

4 cylinders mechanically constructed and being assembled with services

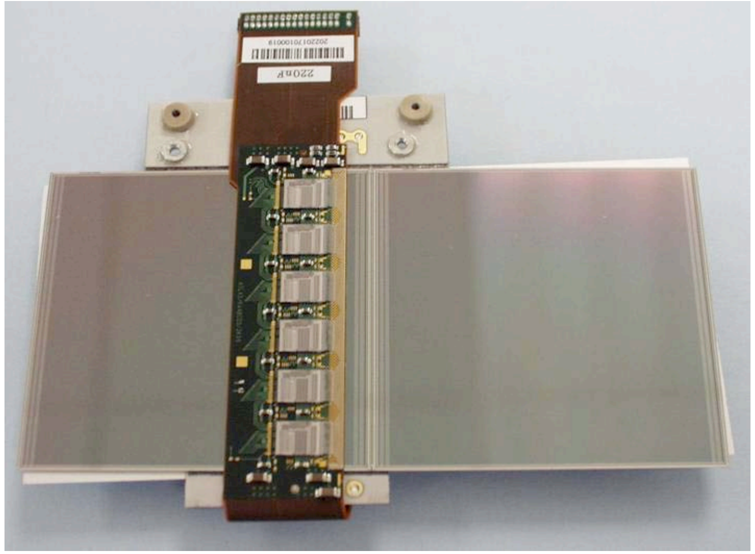




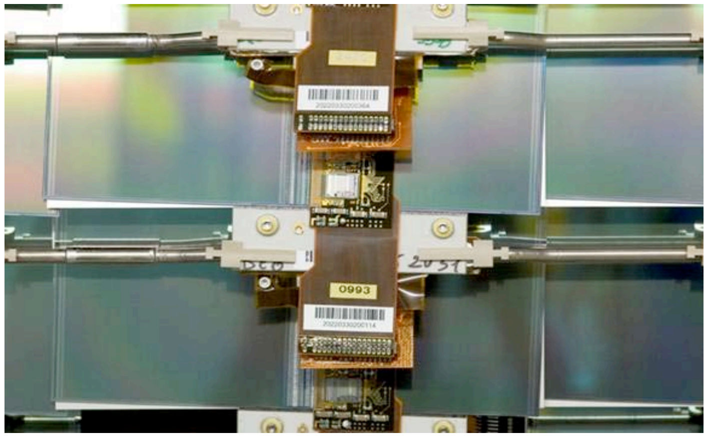


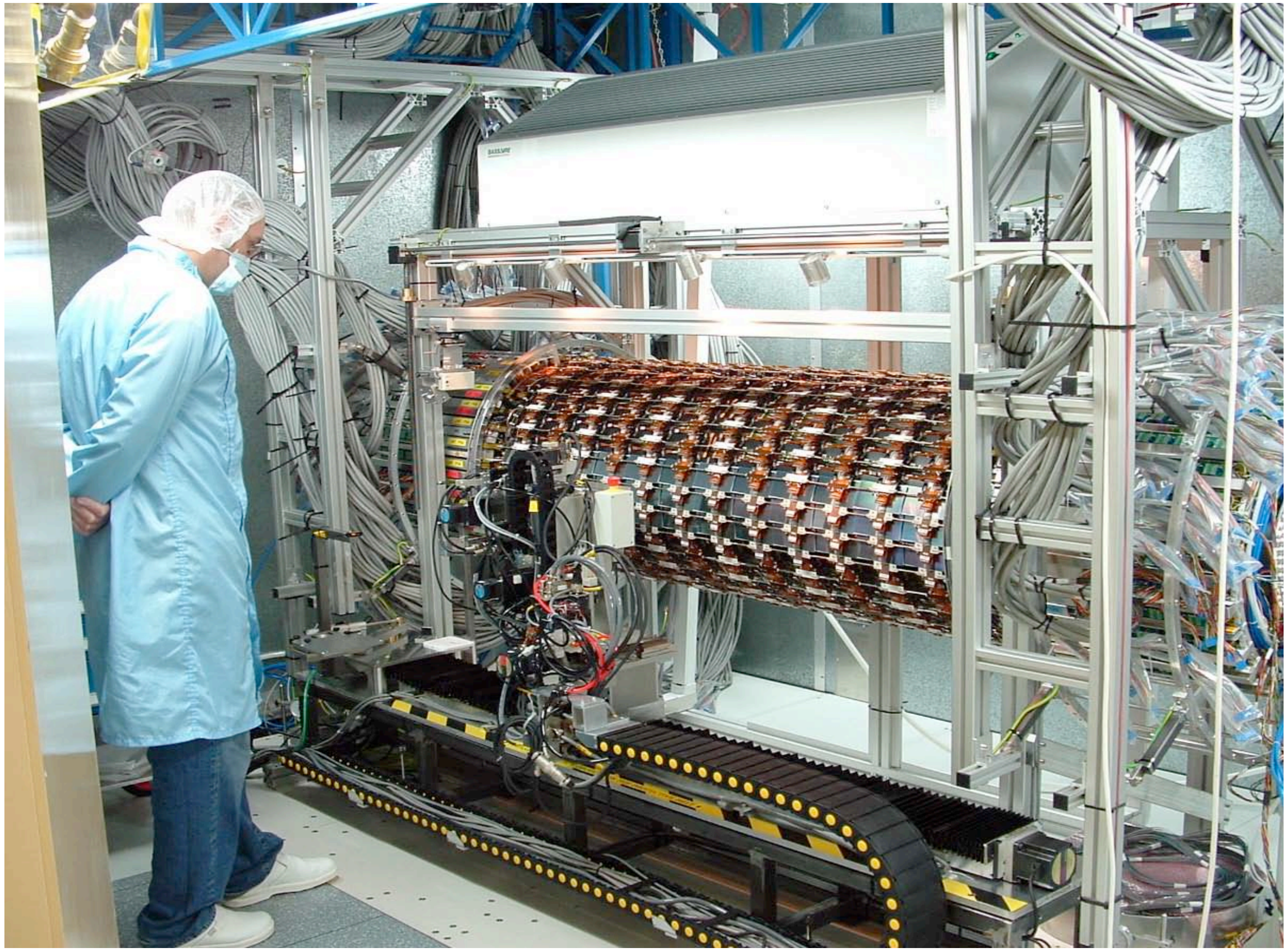
cylinders ready with all services mounted on it

ATLAS barrel SCT



Sensors procurement and assembly final yield > 90%. Sensor alignment and position tolerance typically +/-5 μm





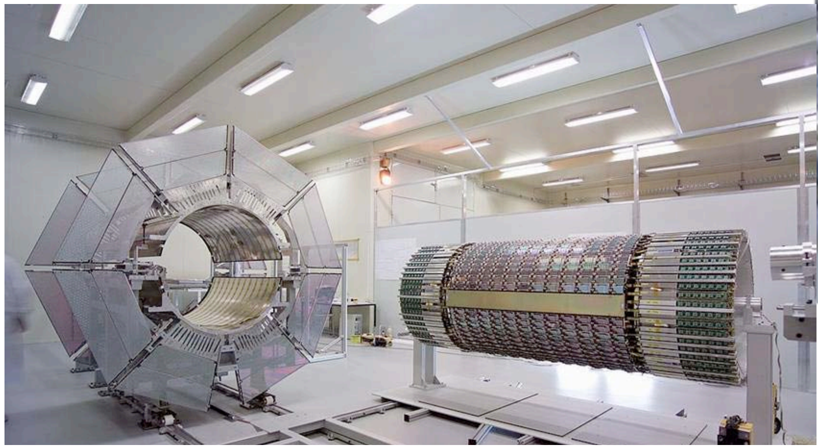
Macro-assembly of the modules on the support cylinder using a dedicated robot.

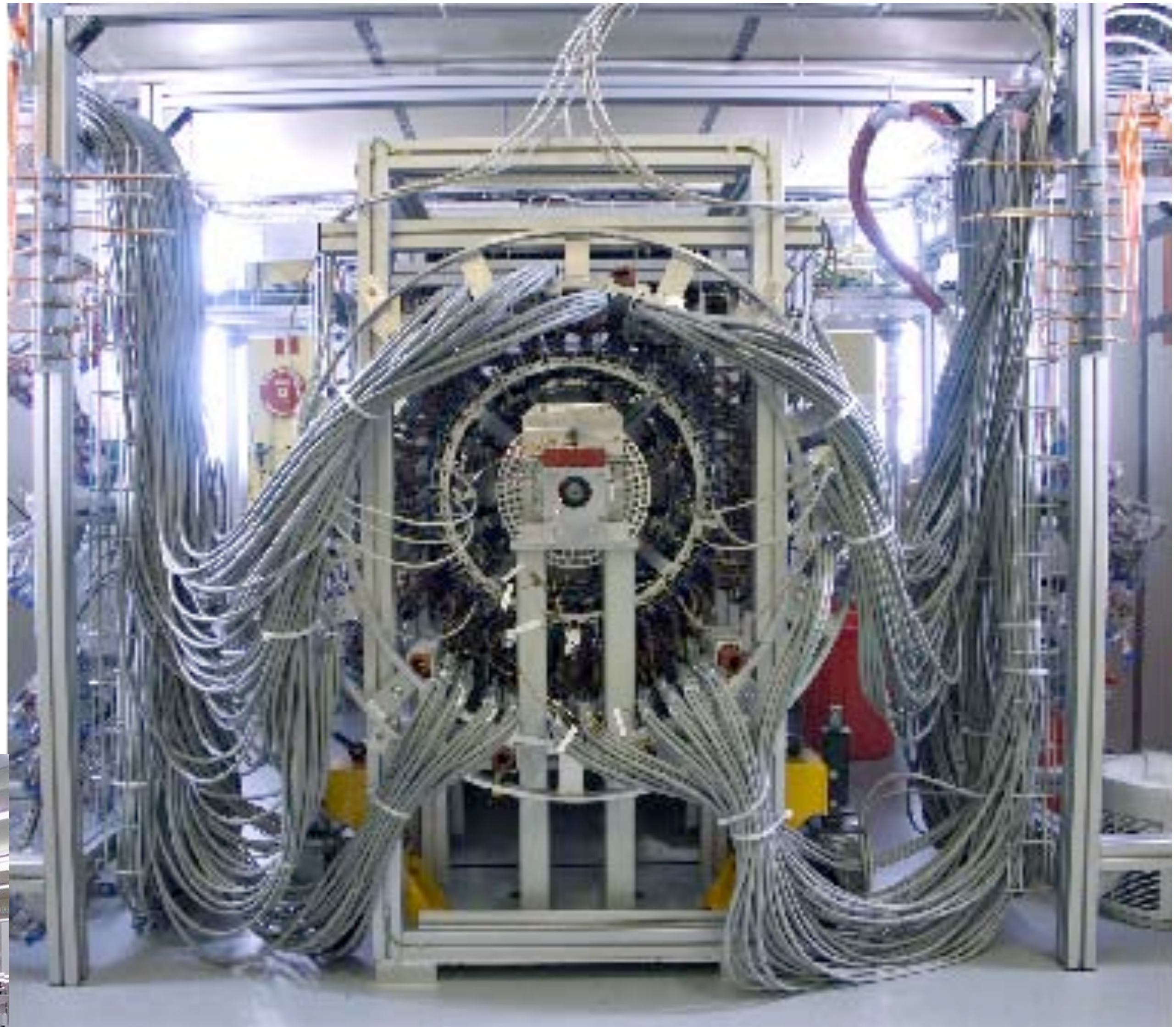
SCT barrel acceptance tests

SCT acceptance tests
(each barrel was fully tested)

Barrel	Total Channels	Total Defects
3	589824	1483
4	737280	841
5	884736	1818
6	1032192	5720
Total	**3244032**	**9862**

Total of 99.7% of all channels fully functional

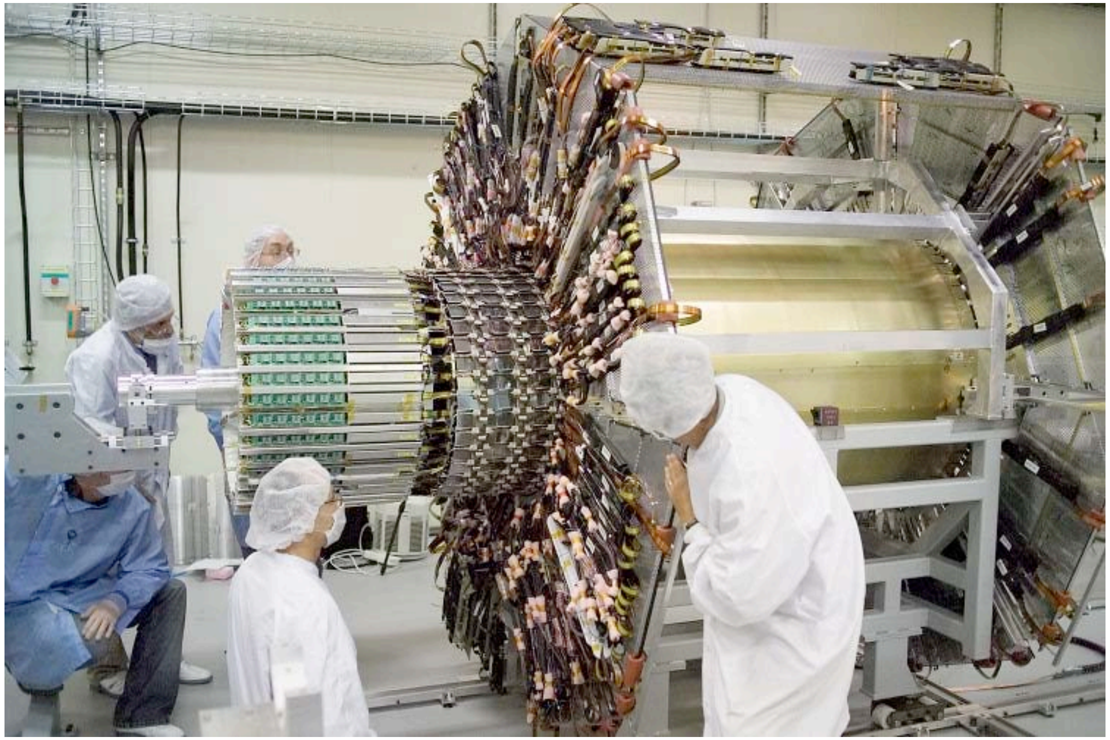


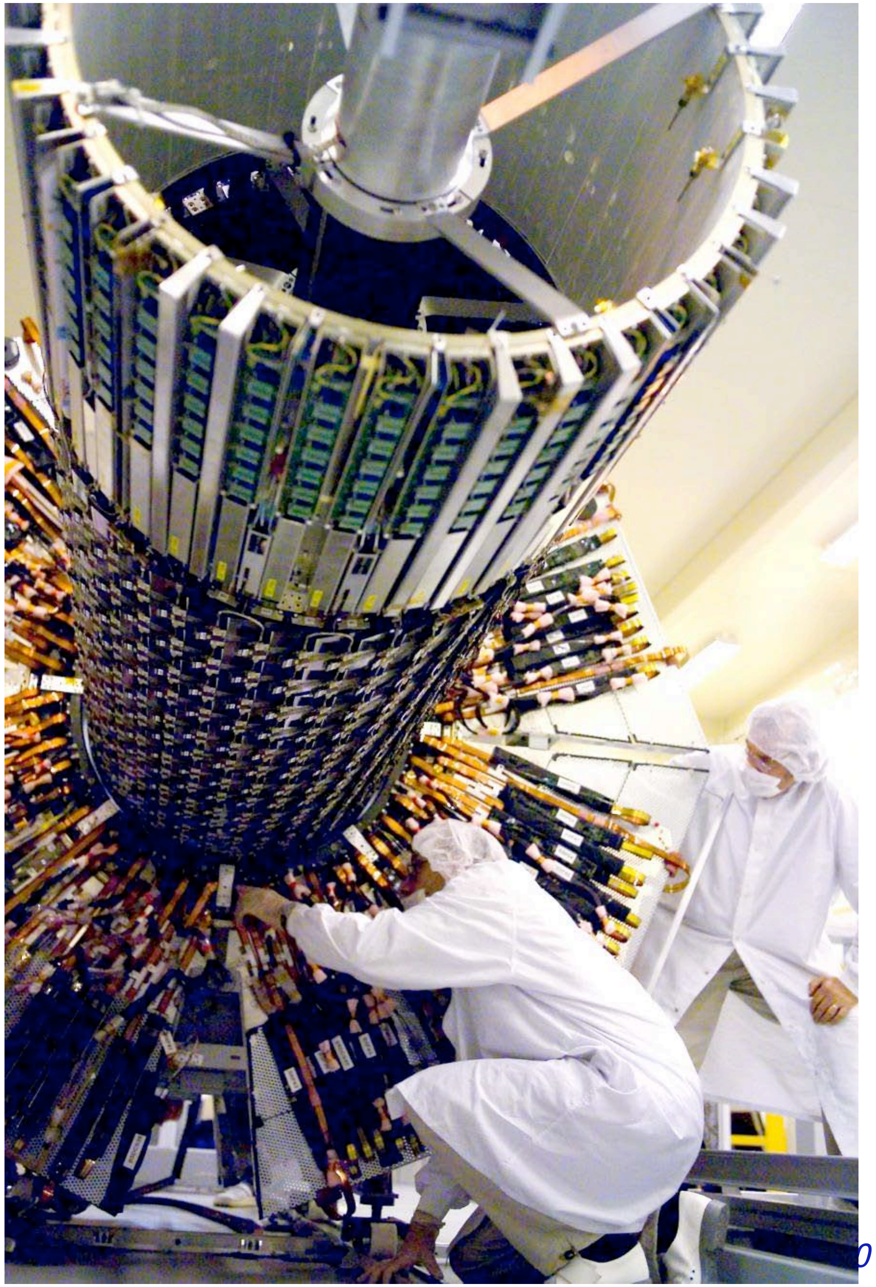


SCT barrel during acceptance test

SCT barrel assembly

Insertion of the 3rd cylinder (out of the four) into the barrel SCT

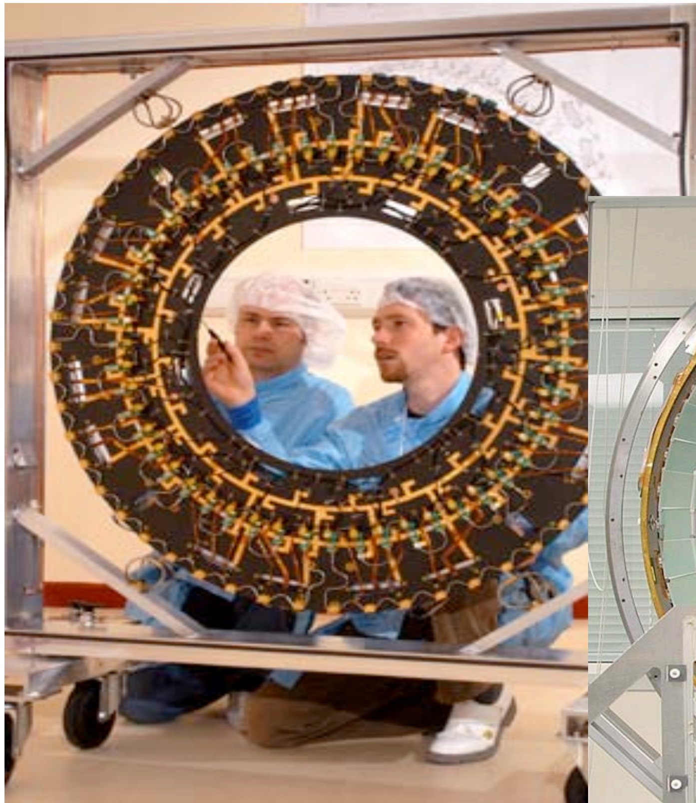




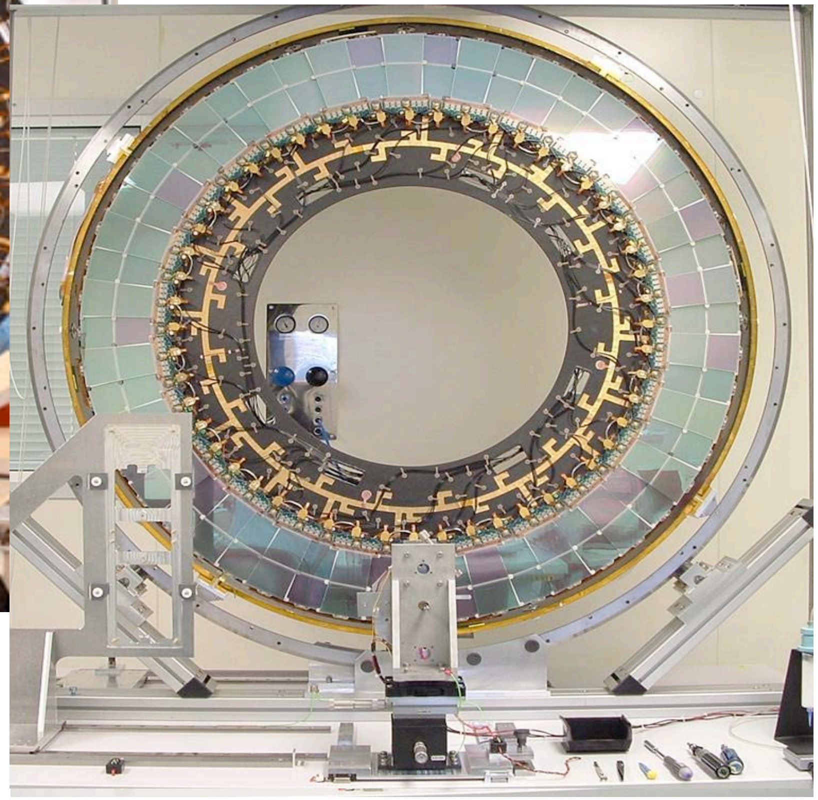
ATLAS SCT disks assembly

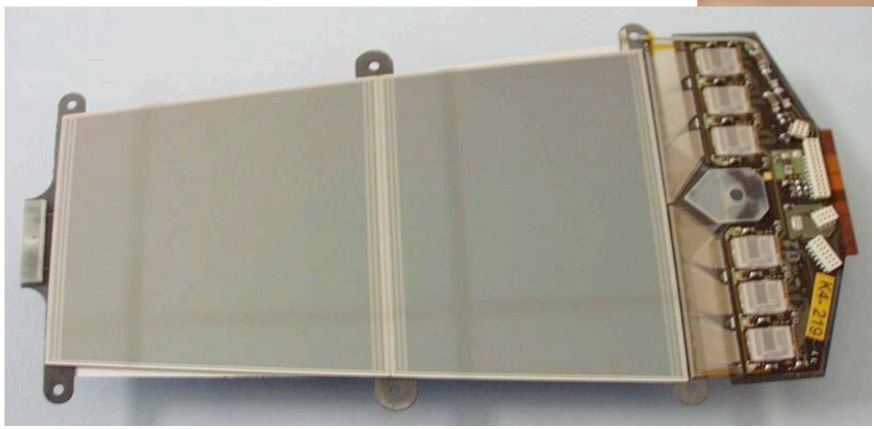
All sensors procured using two producers.

Major effort to instrument with high precision the disks with services and module support



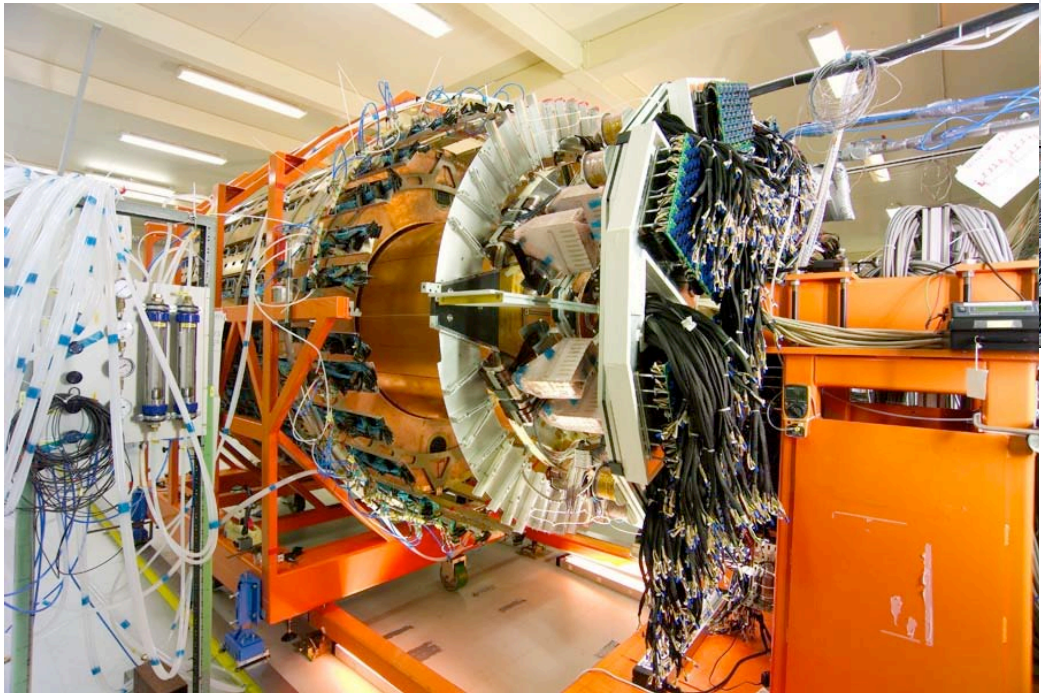
The support disks preparation and then the mounting of the active sensors

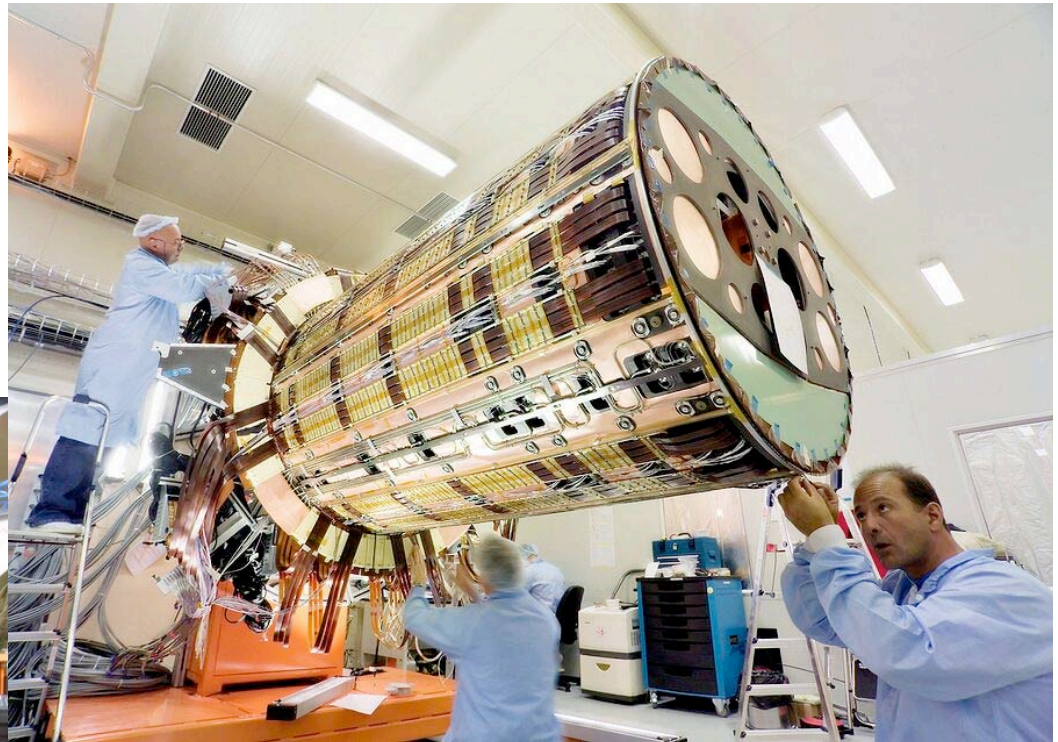




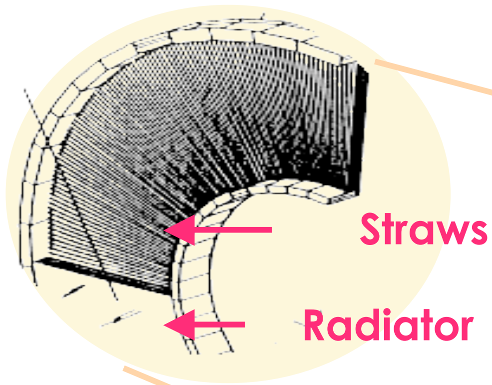
Some hybrid production problems (delamination) have slowed down the final production, but solved.

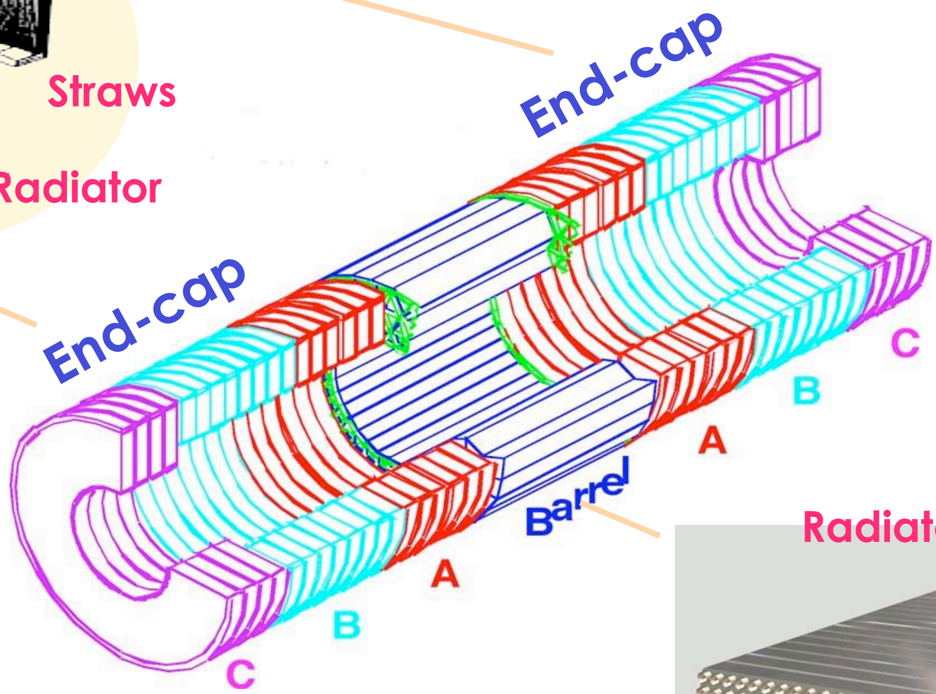
SCT disks integration



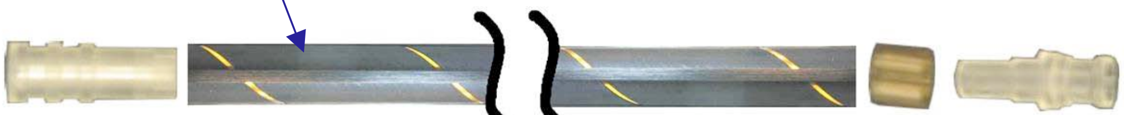


The TRT (Transition Radiation Tracker at the outer radius)

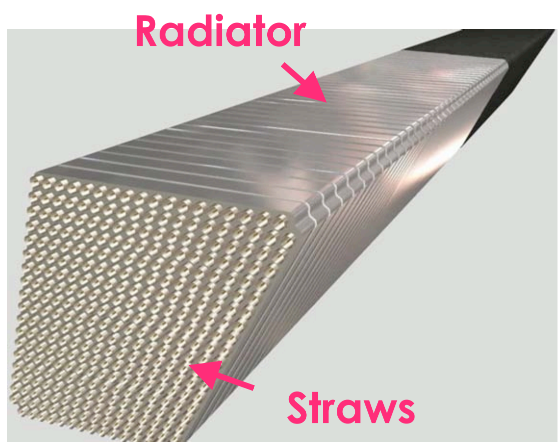




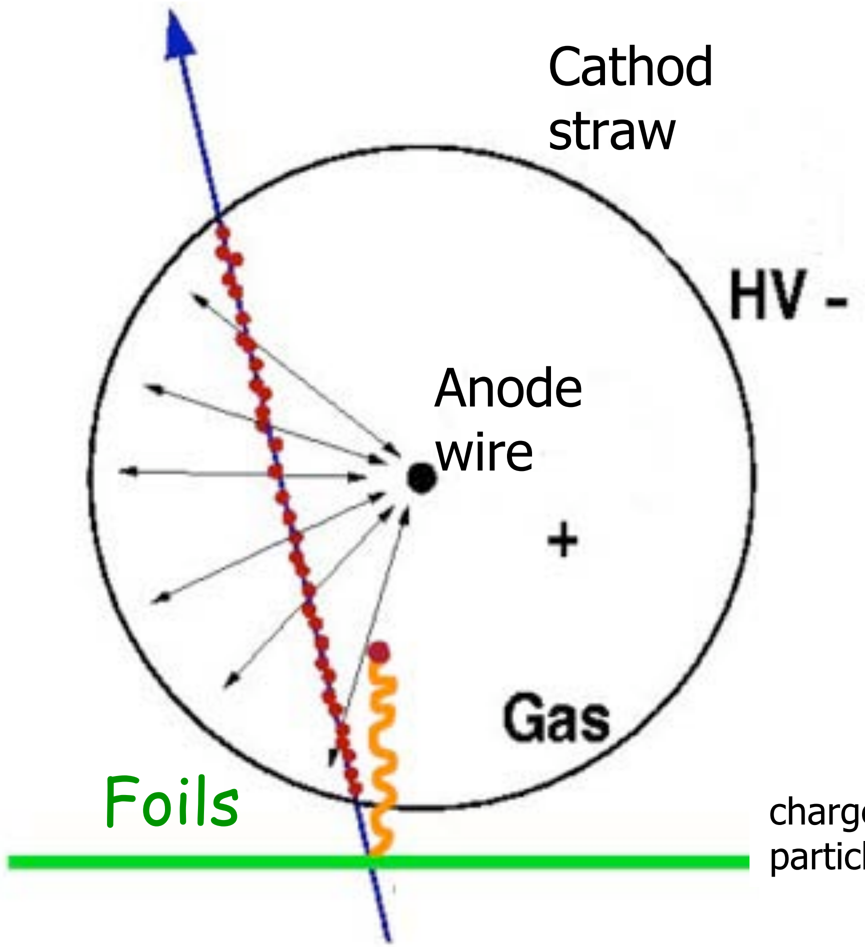
The gas mixture is *Xe/CO2/O2 in a 70/27/3*



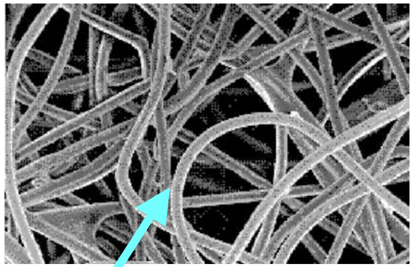
4 mm diameter kapton straws



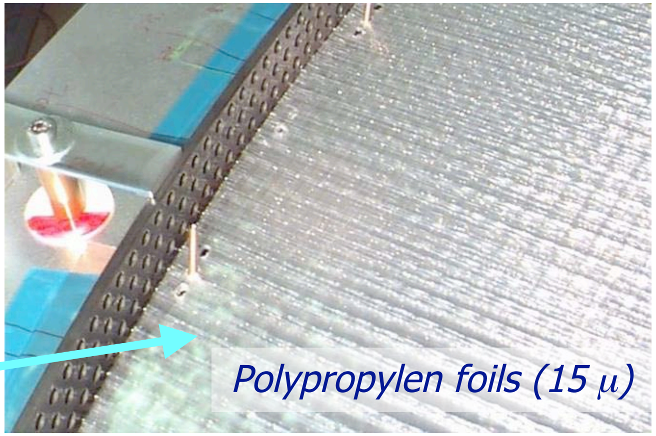
The TRT (Transition Radiation Tracker)

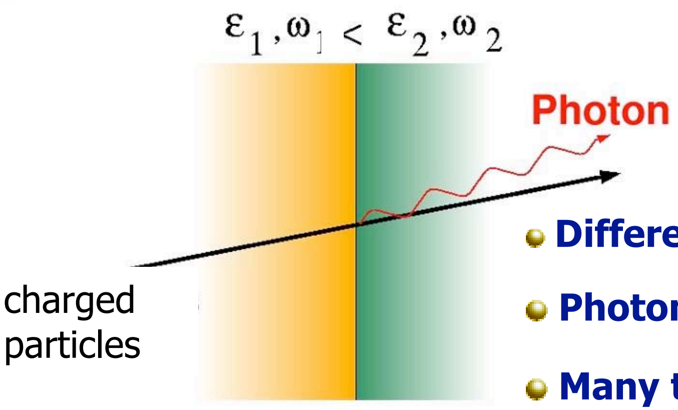


radiator



Barrel end-cap

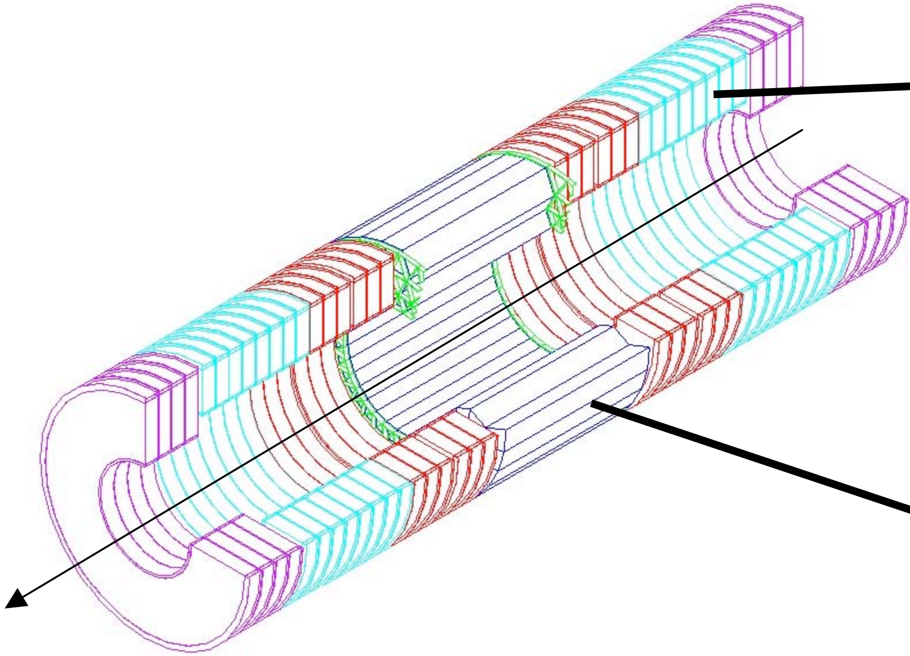


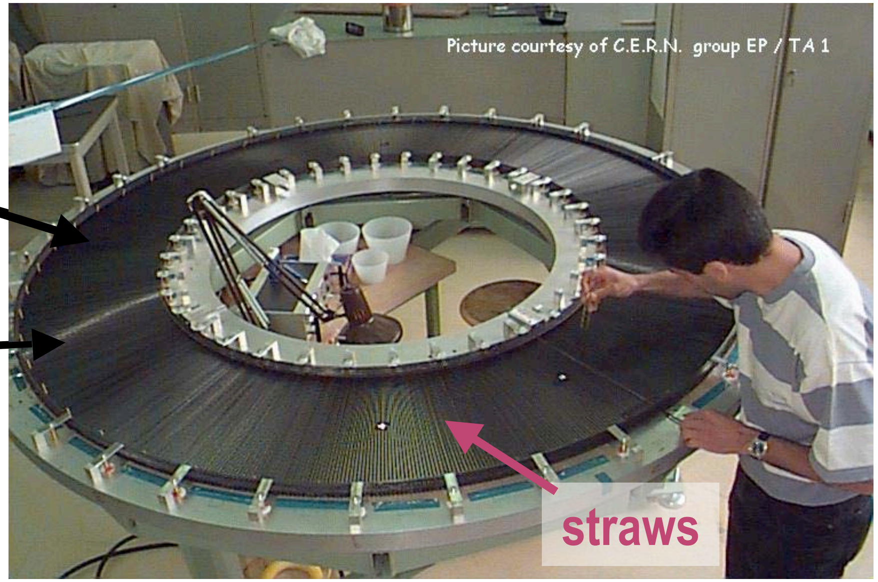


- **Different dielectric constants**
- **Photon energy ~ ($\varepsilon_1 - \varepsilon_2$)**
- **Many transition to enhance probabilty**
- **Photon energy (x-rays): 10-30keV**
- **Xe gas as good X-rays absorber**

The TRT (Transition Radiation Tracker)

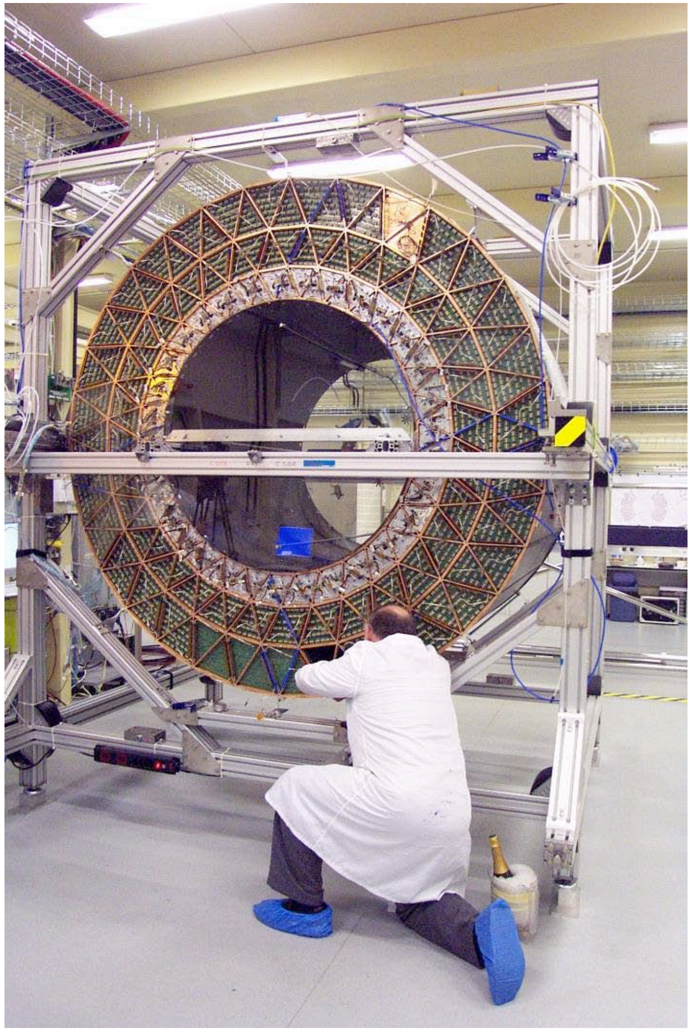
Endcap (~320000 straws)
radial from beam axis





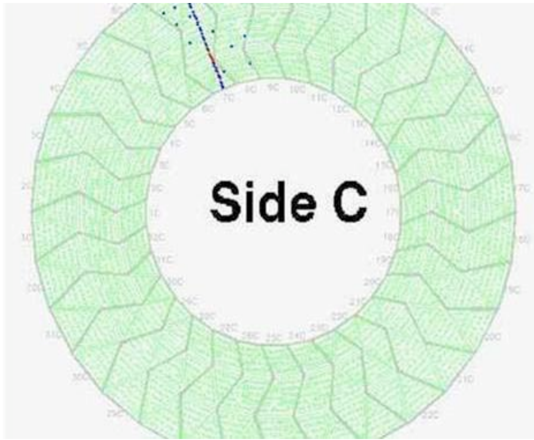
Barrel (~100000 straws)
parallel to beam axis

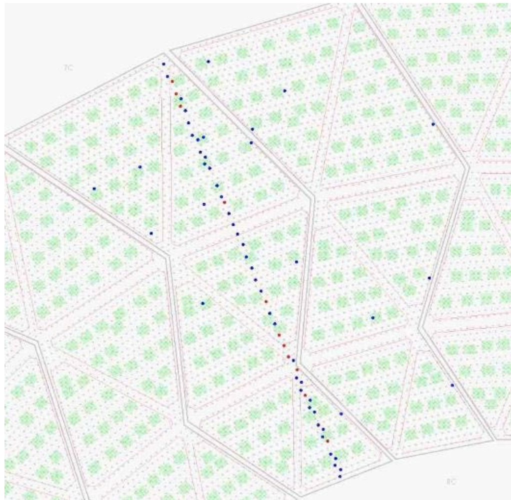
Two examples of cosmic rays registered in the barrel TRT



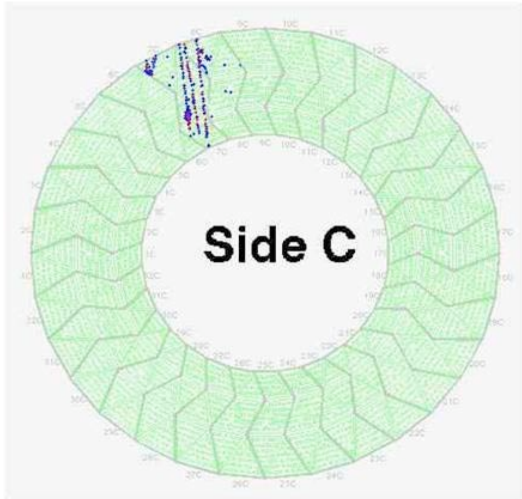
Barrel TRT during insertion of the last modules

Example 1

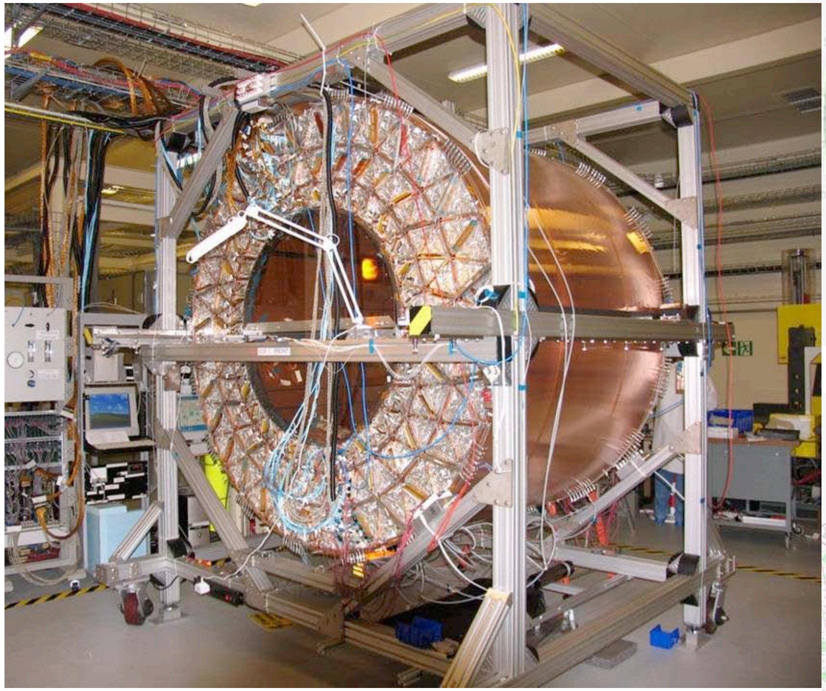




Example 2

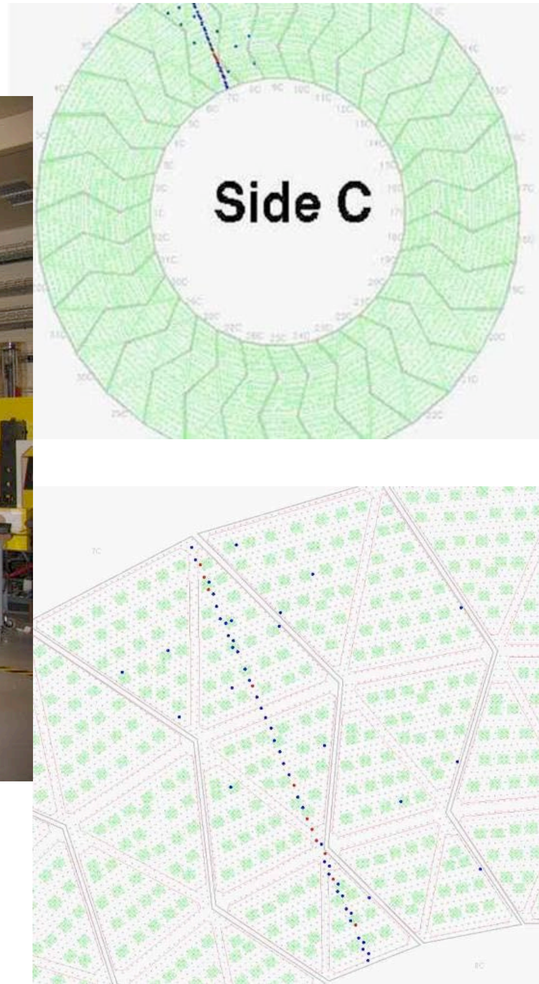


Two examples of cosmic rays registered in the barrel TRT

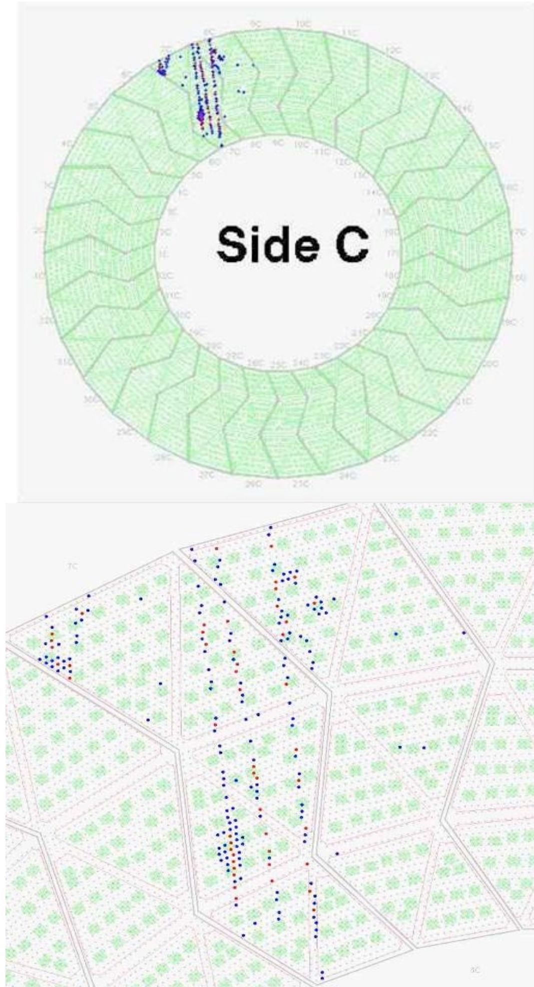


Barrel TRT completed

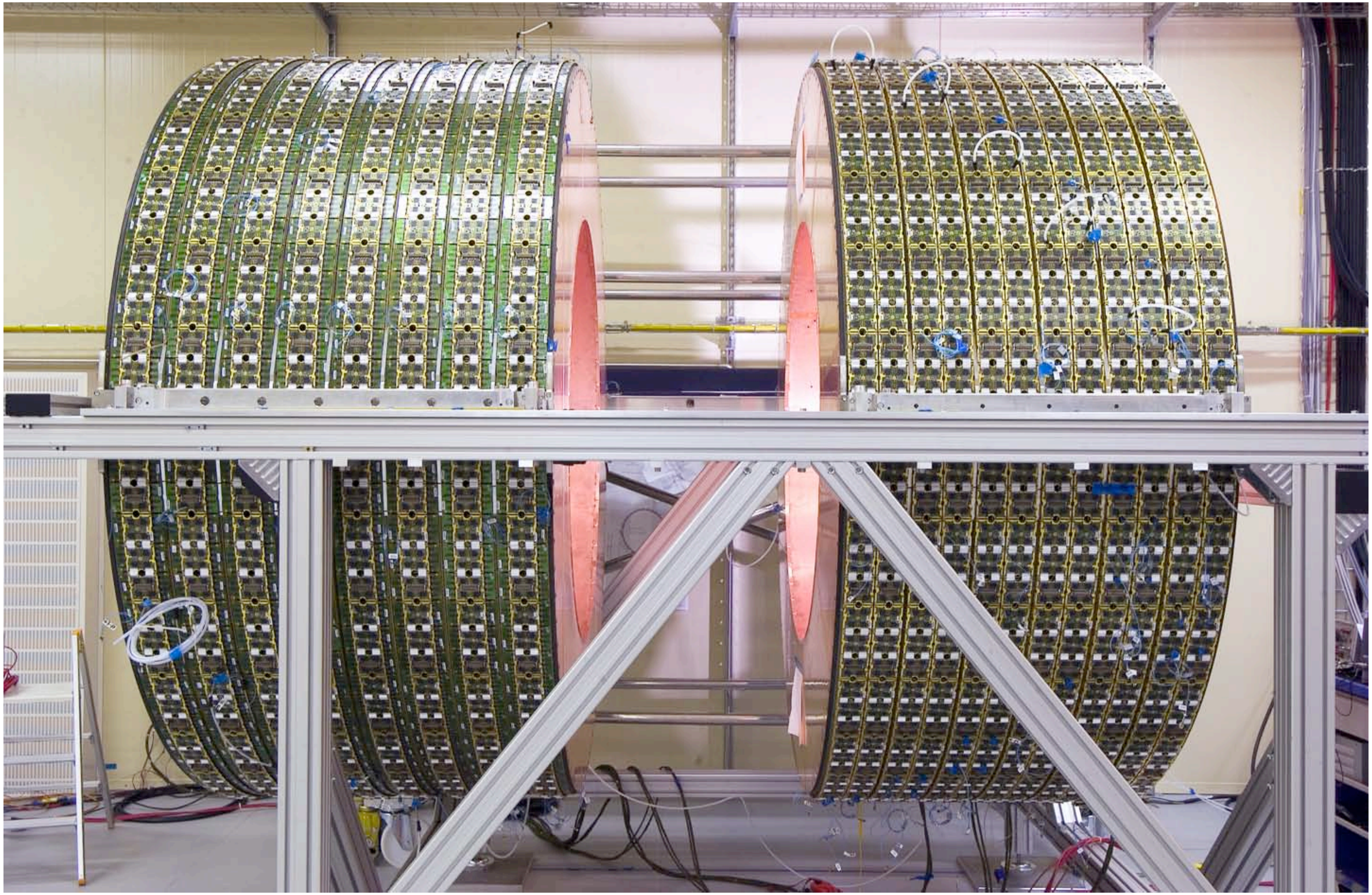
Example 1



Example 2

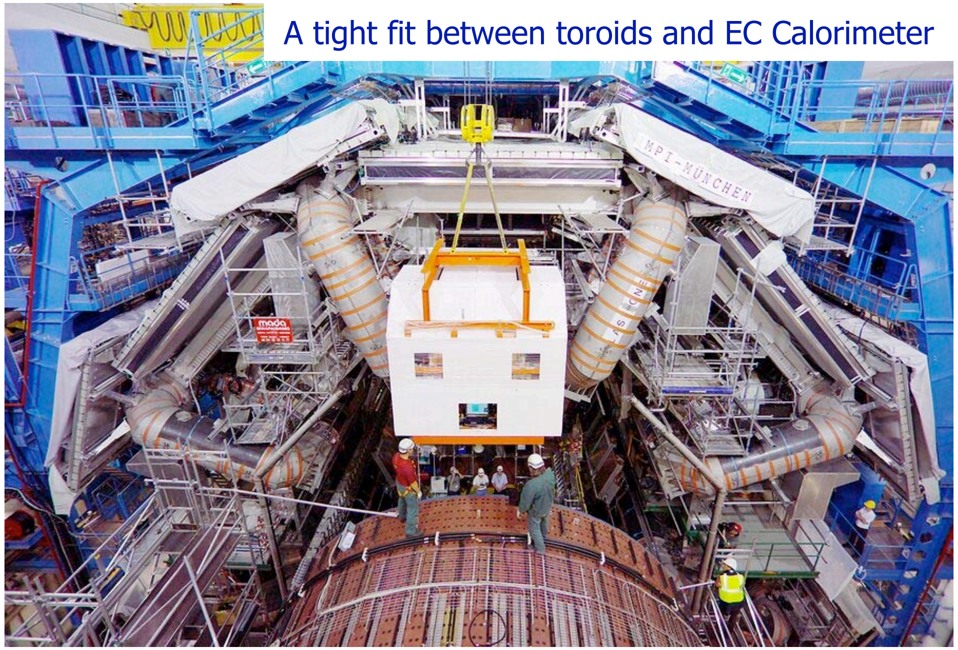


First end-cap wheel assembled



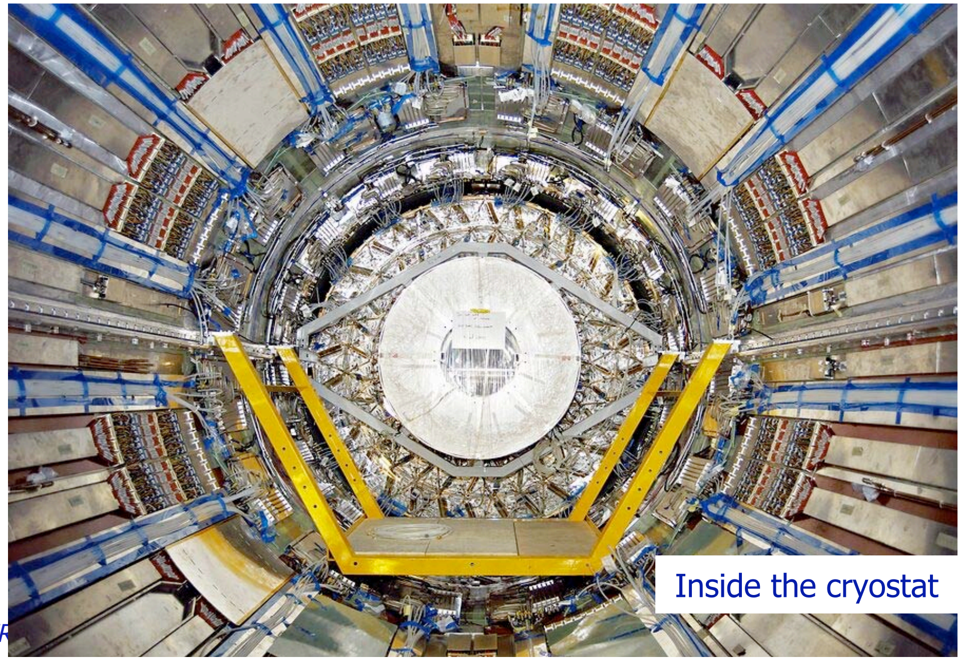
Barrel ID installation

24 & 25 Aug `06



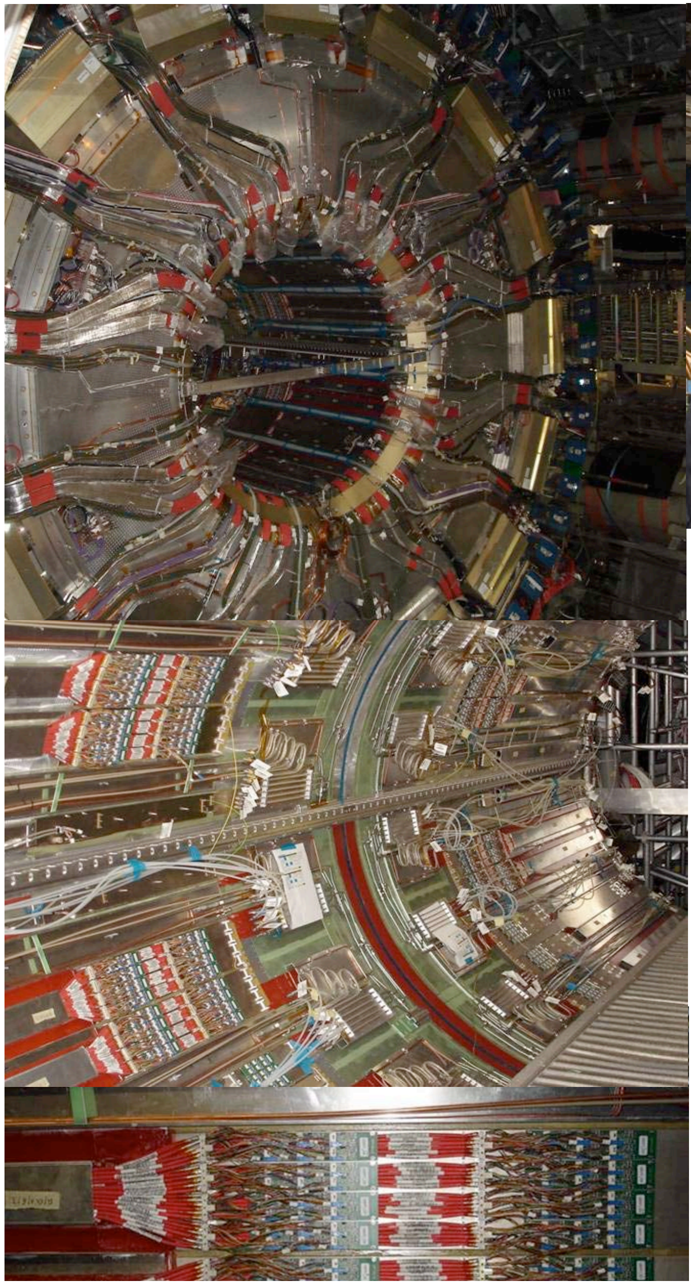
A tight fit between toroids and EC Calorimeter

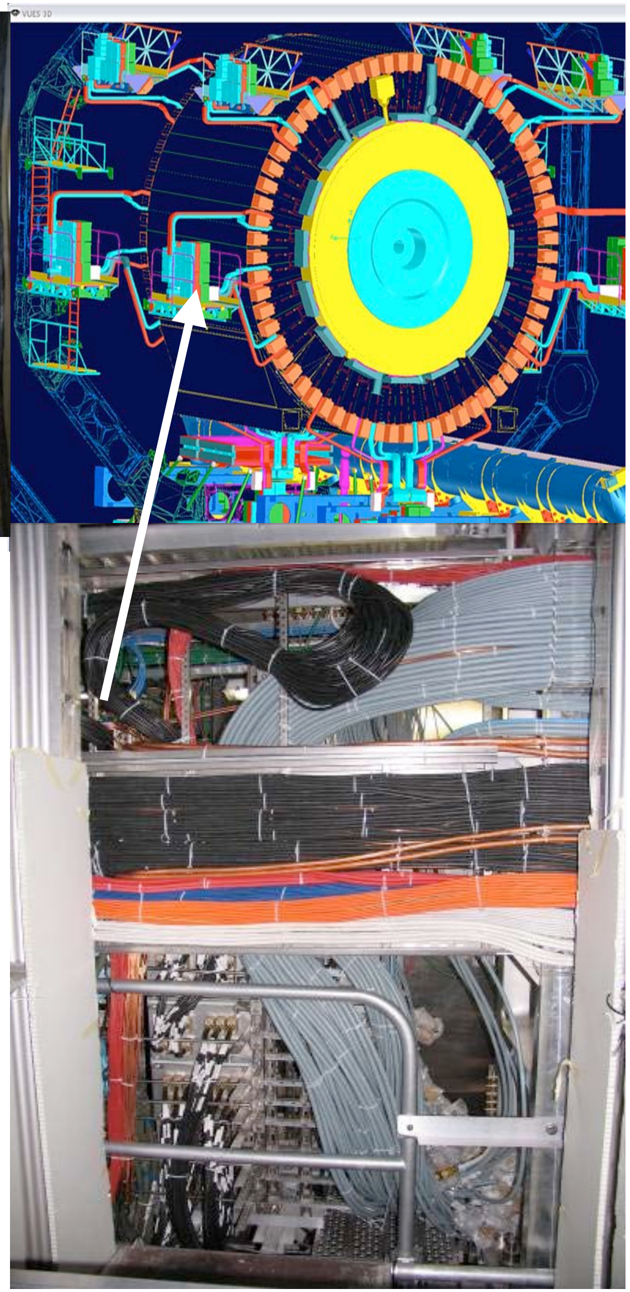
From the trolley to the support rails



Inside the cryostat

Inner detector services all installed

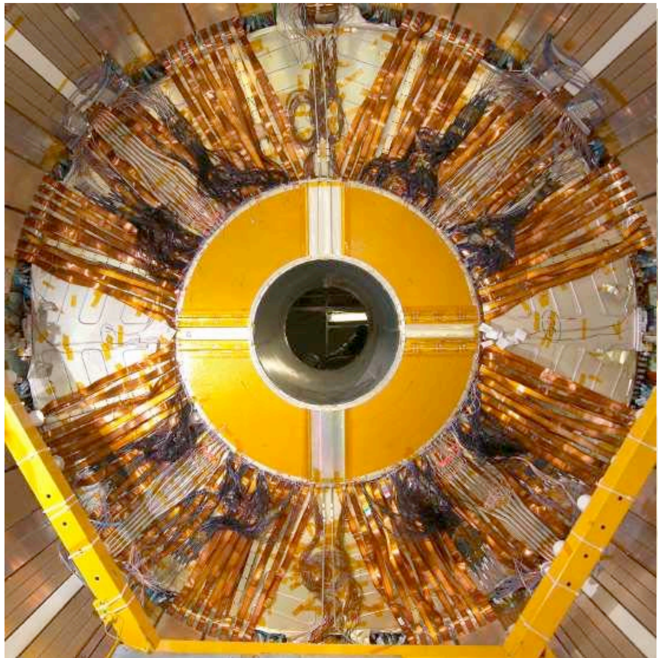


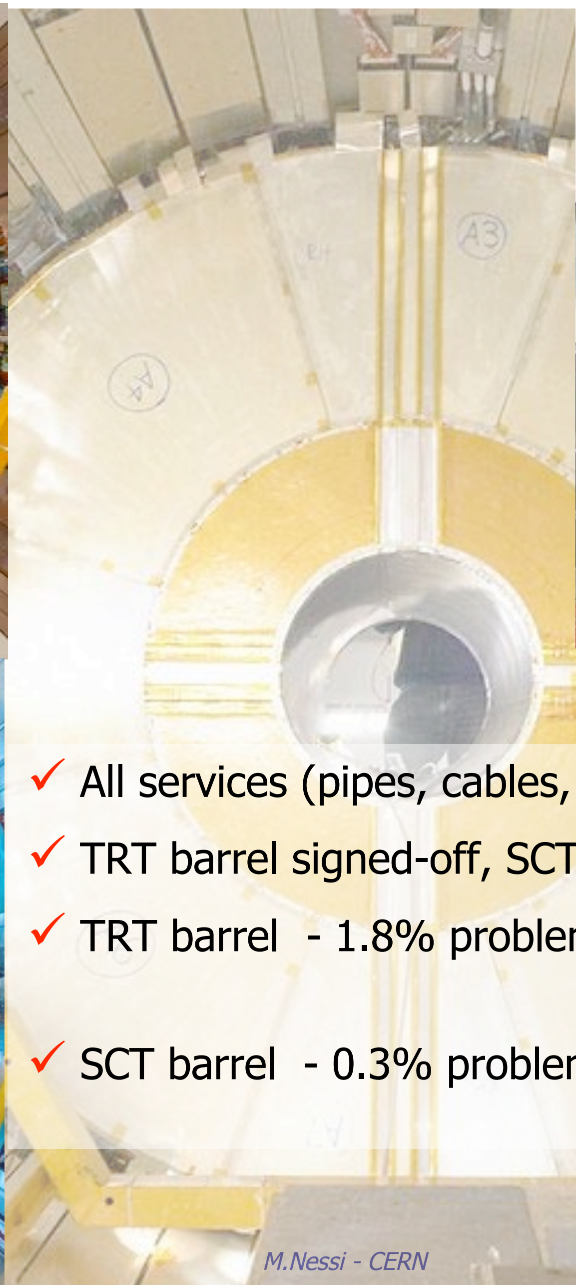


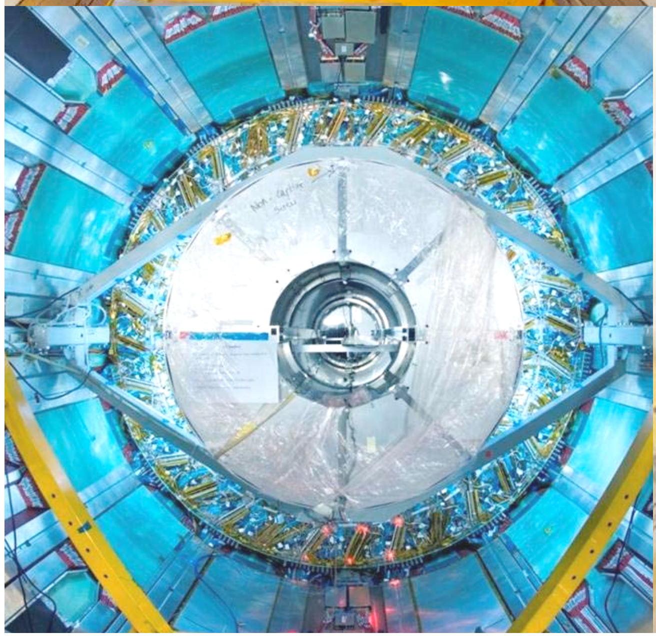
~ 800 man-months of installation work over ~18 months, ~ 45 people involved/day

- ✓ ~ 9300 SCT cable-bundles
- ✓ ~ 3600 pixel cable-bundles
- ✓ ~ 30100 TRT cables
- ✓ ~ 2800 cooling & gas pipes

Barrel Inner detector connection and commissioning

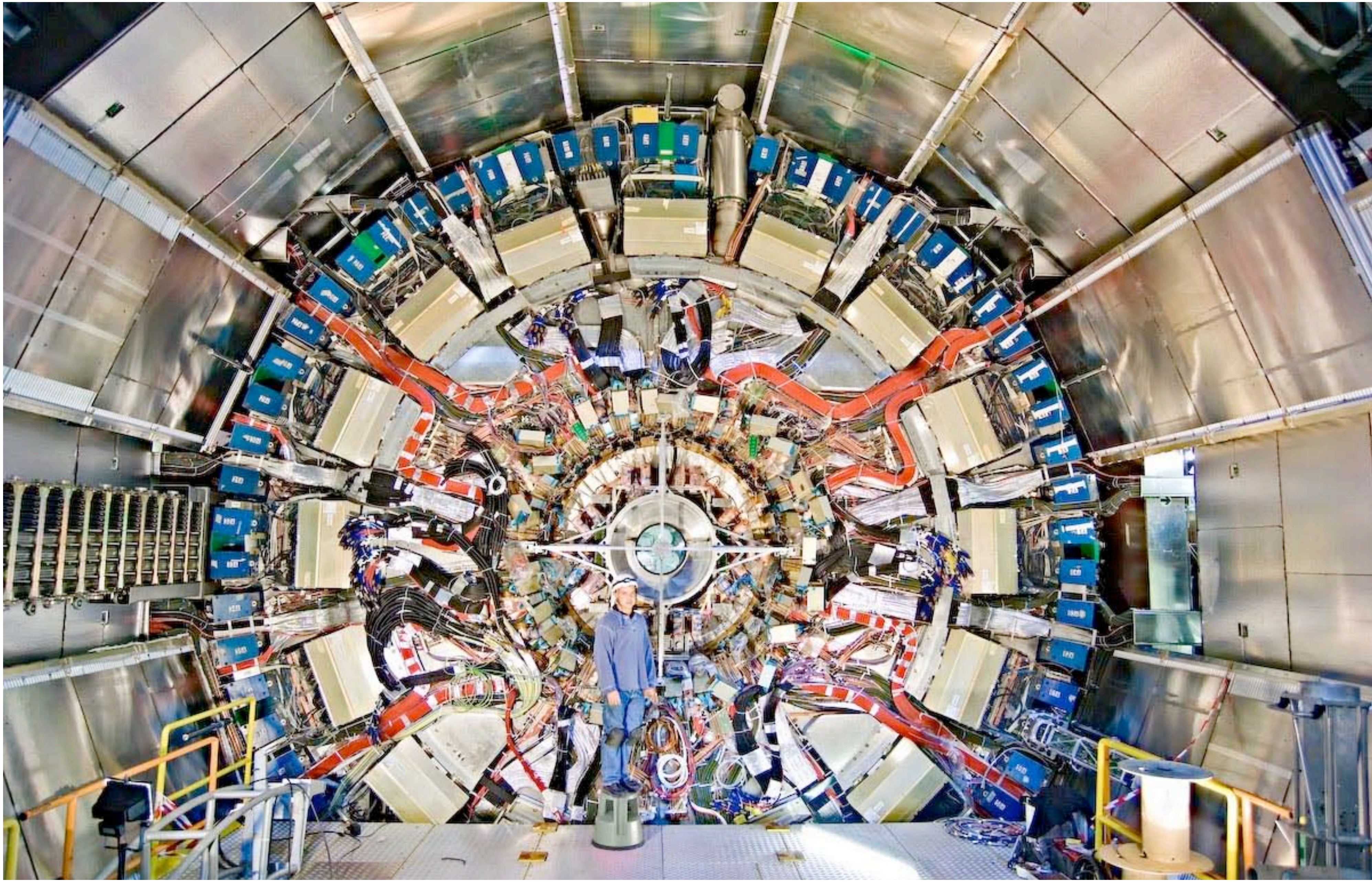




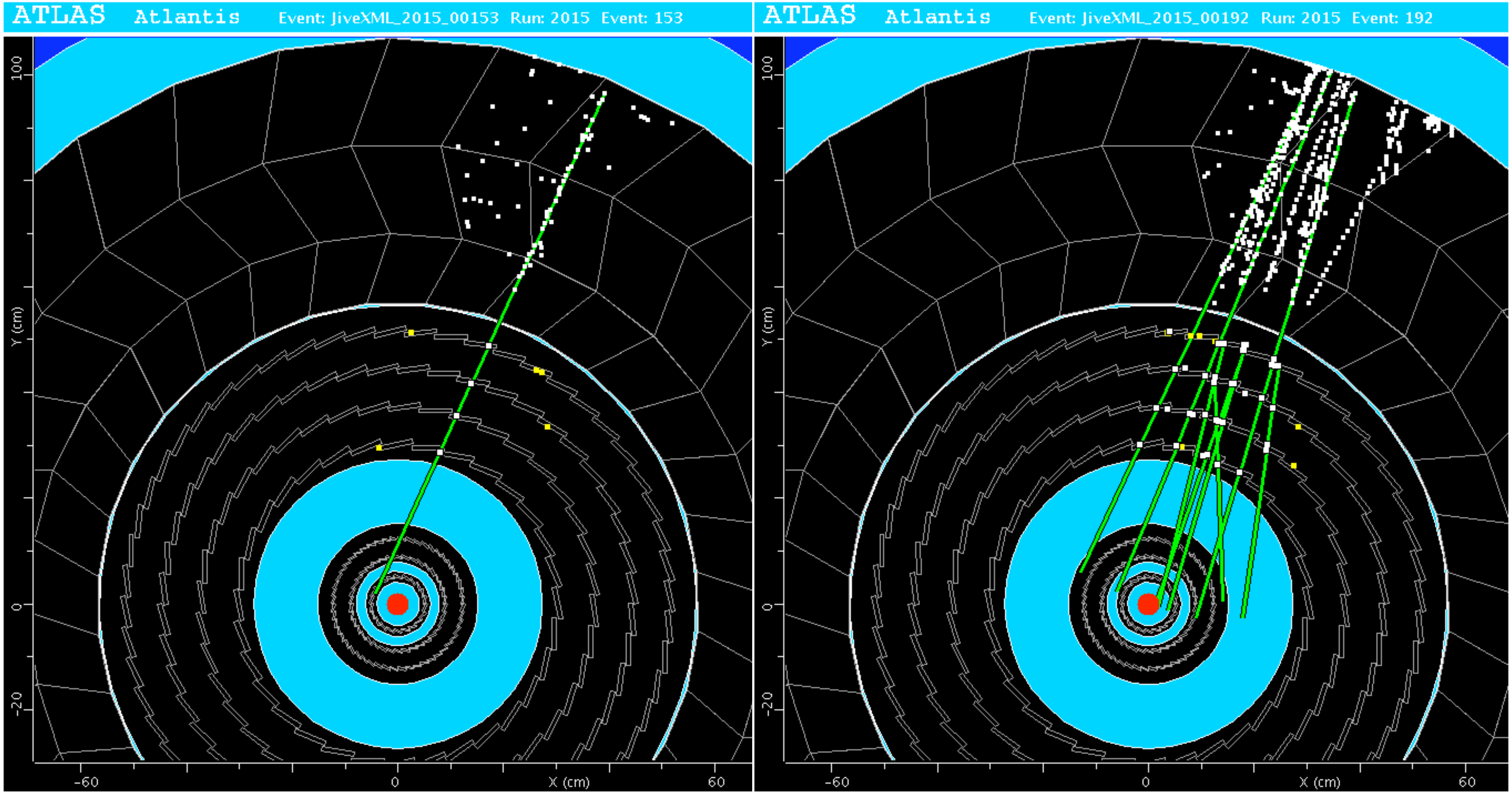


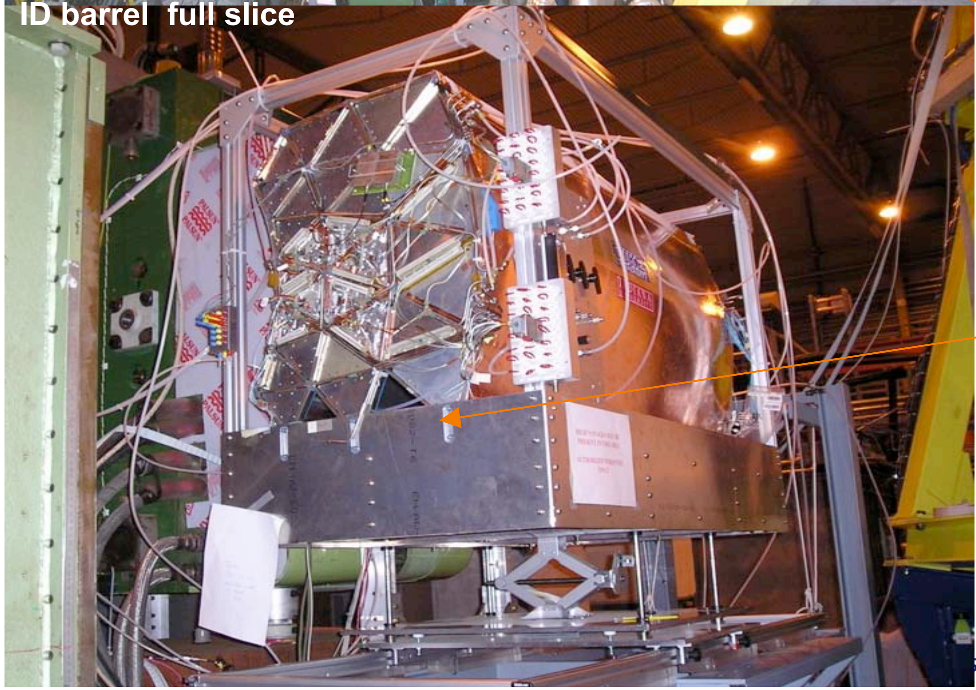
- ✓ All services (pipes, cables, fibers,..) connected
- ✓ TRT barrel signed-off, SCT barrel ready and sign-off
- ✓ TRT barrel - 1.8% problematic channels out of 105K, noise figure as on surface
- ✓ SCT barrel - 0.3% problematic channels out of 3.244M, >99% efficiency on cosmics

ID installation status



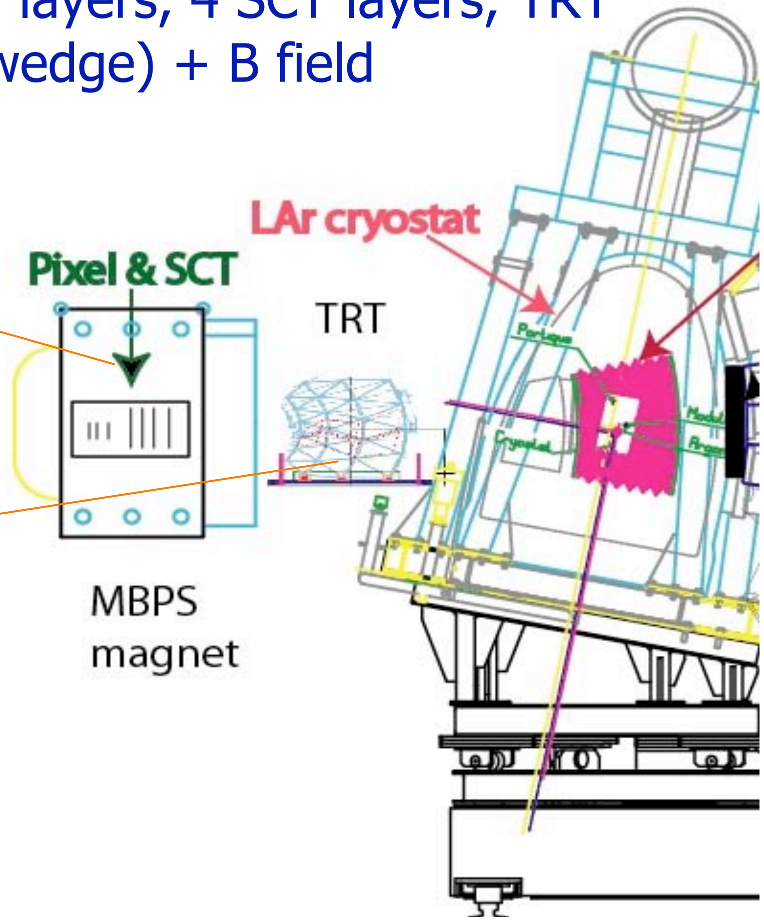
First cosmic rays through the barrel ID





ATLAS ID combined test beam

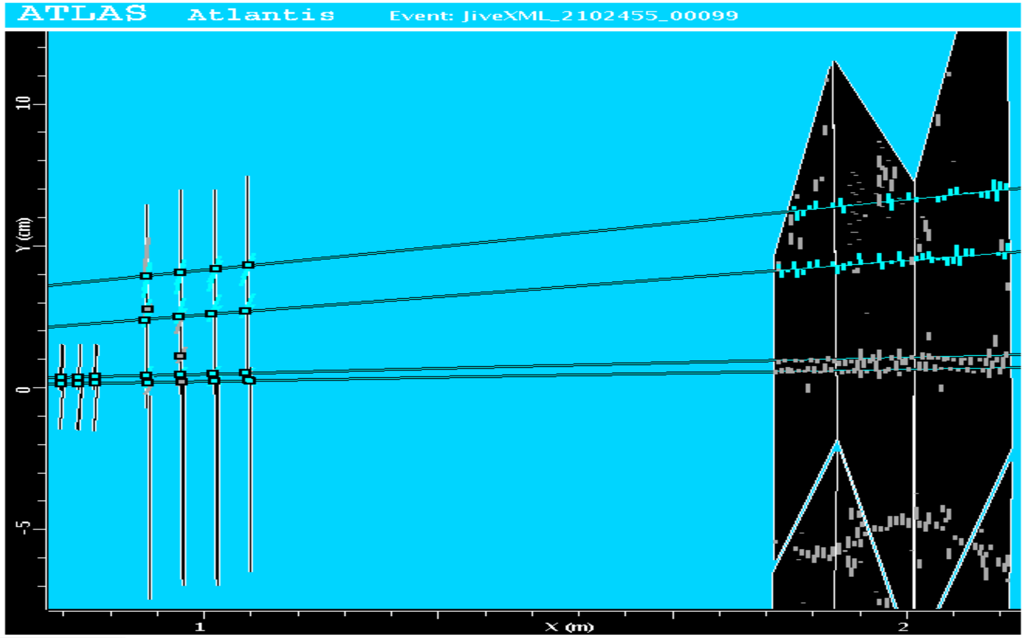
Full barrel slice using prototypes the H8 SPS beam line (3 pixel layers, 4 SCT layers, TRT barrel wedge) + B field

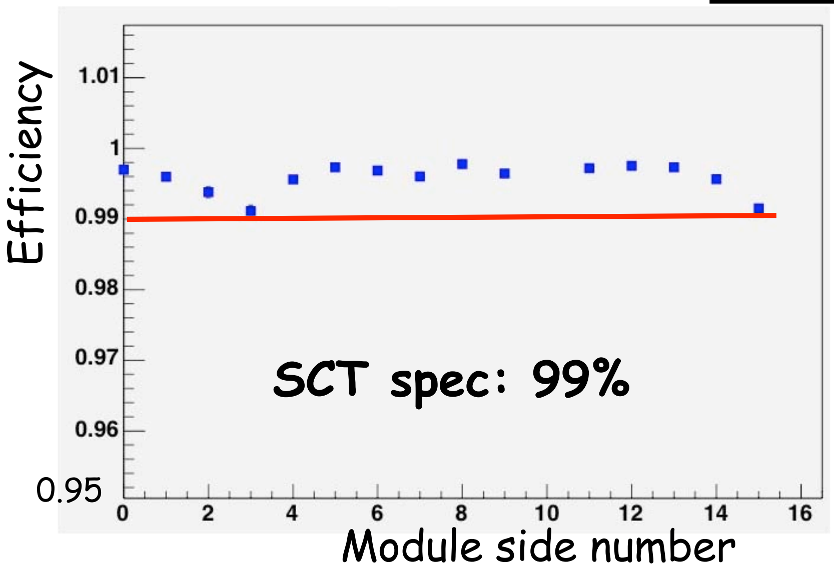


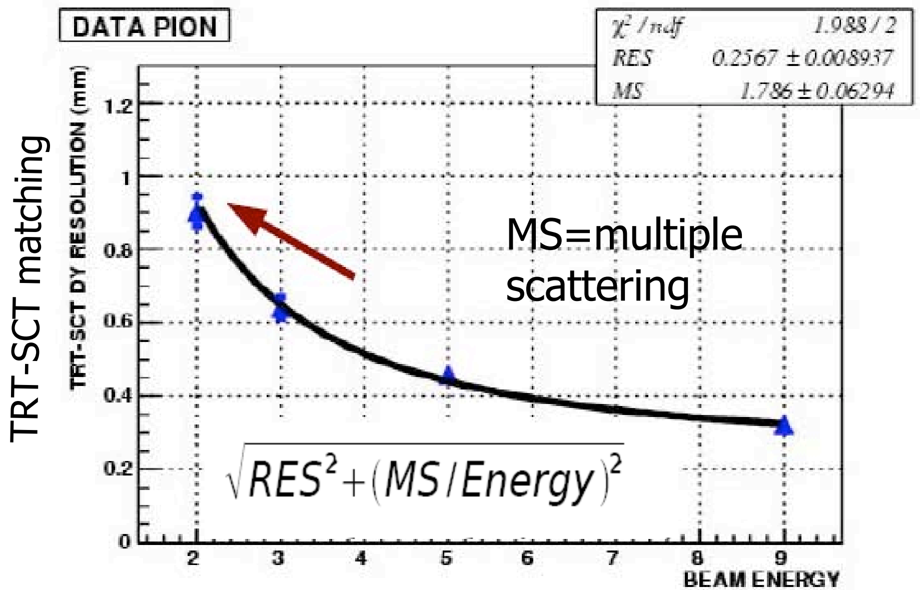
ID combined test beam

The (ID-part) setup

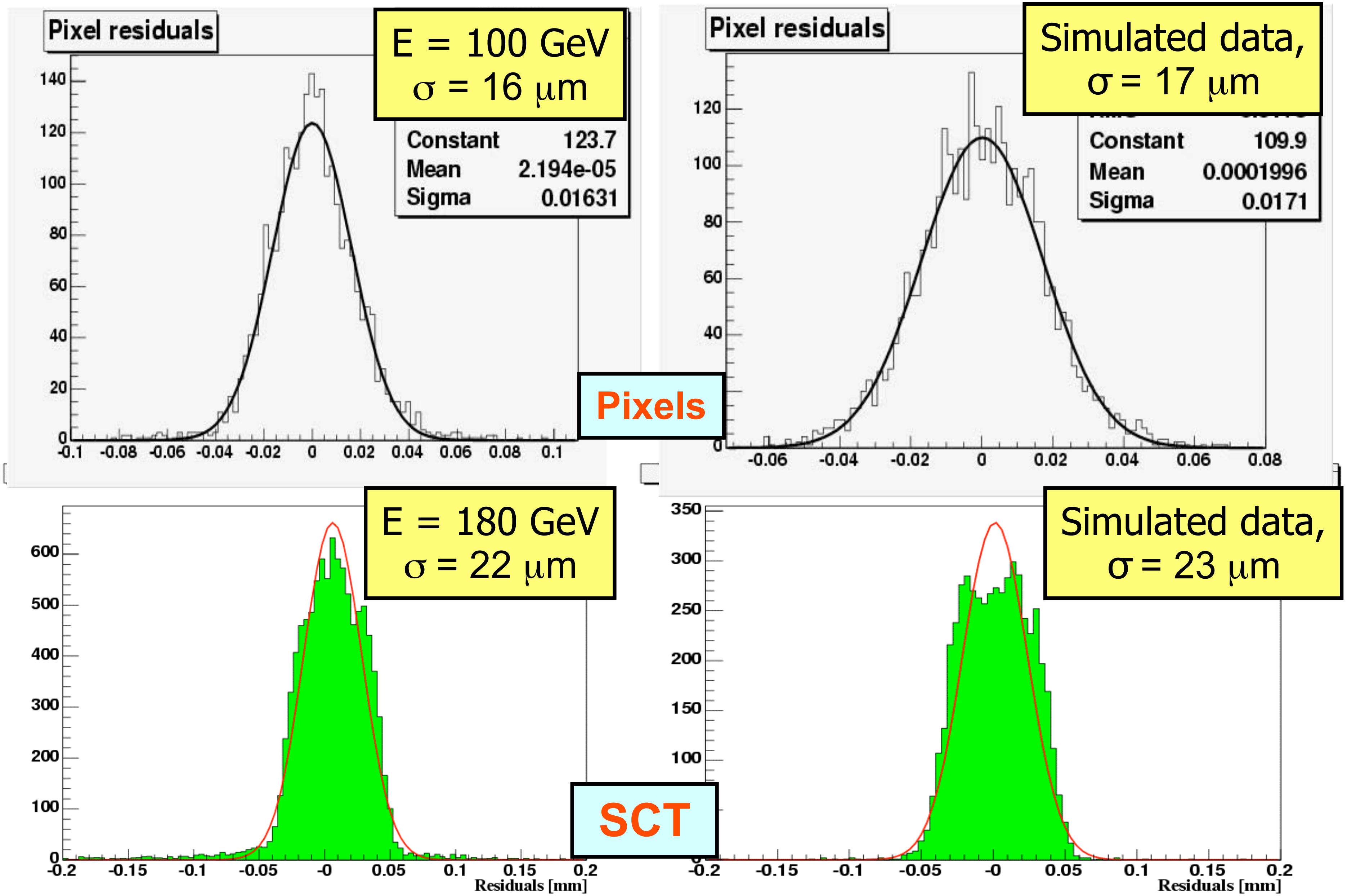
- ✓ 3 pixel layer
- ✓ 4 SCT layer
- ✓ TRT barrel stack



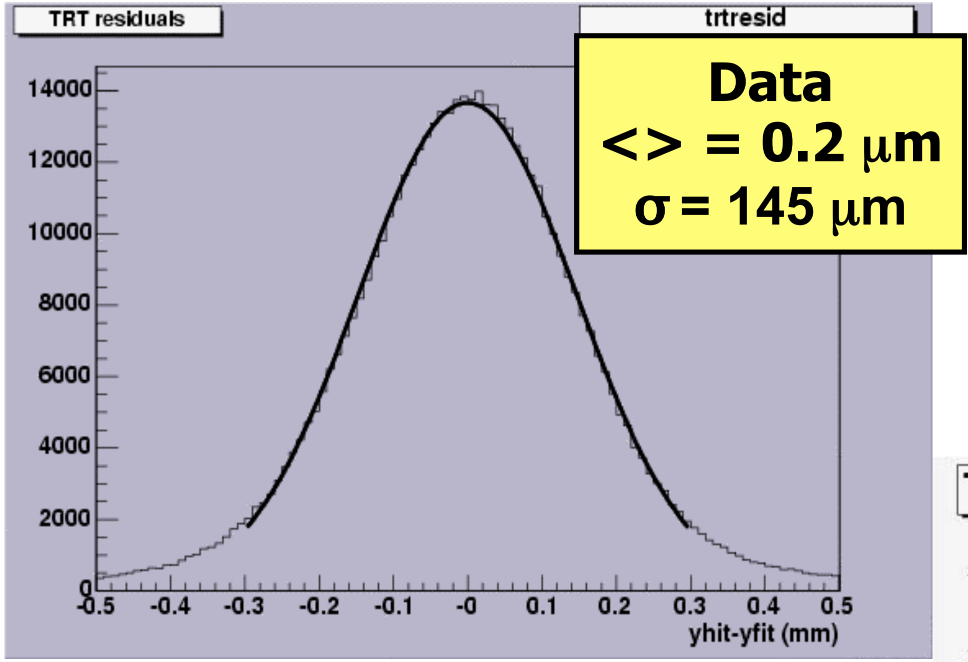




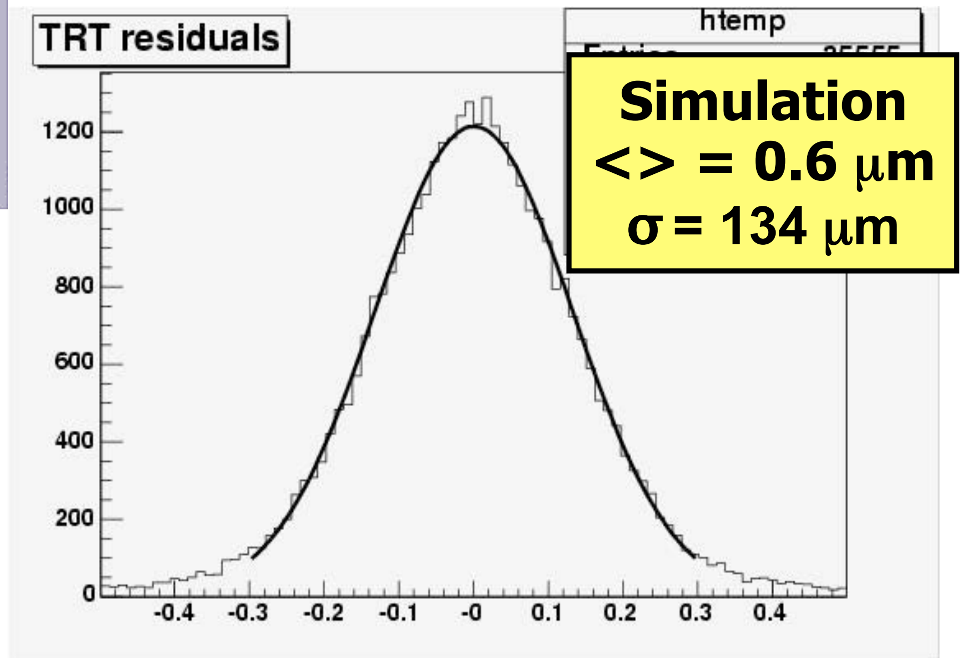
Pixel + SCT tracking resolution



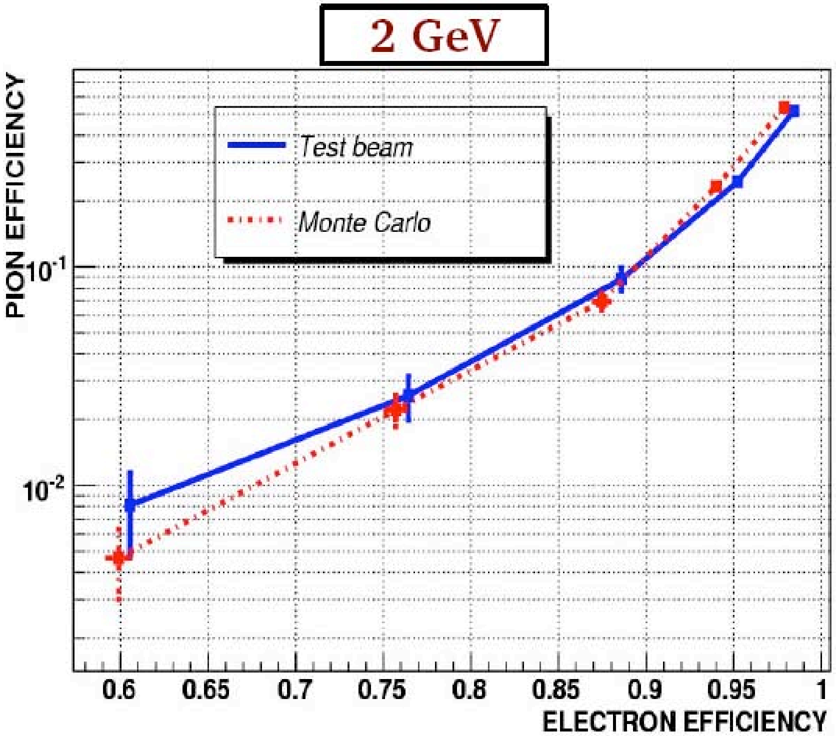
TRT tracking resolution

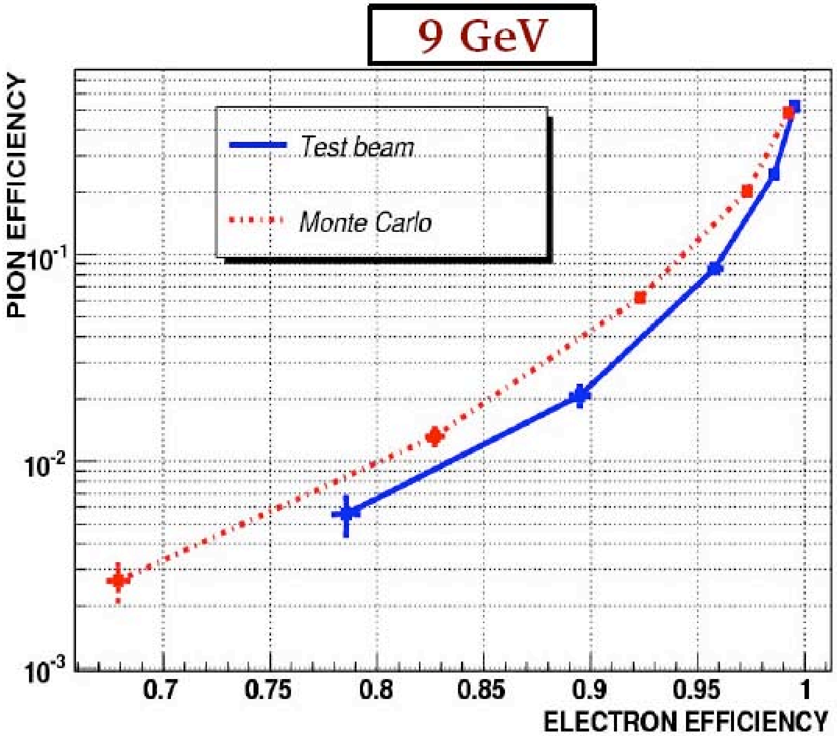


Eπ = 100 GeV



TRT e/π separation

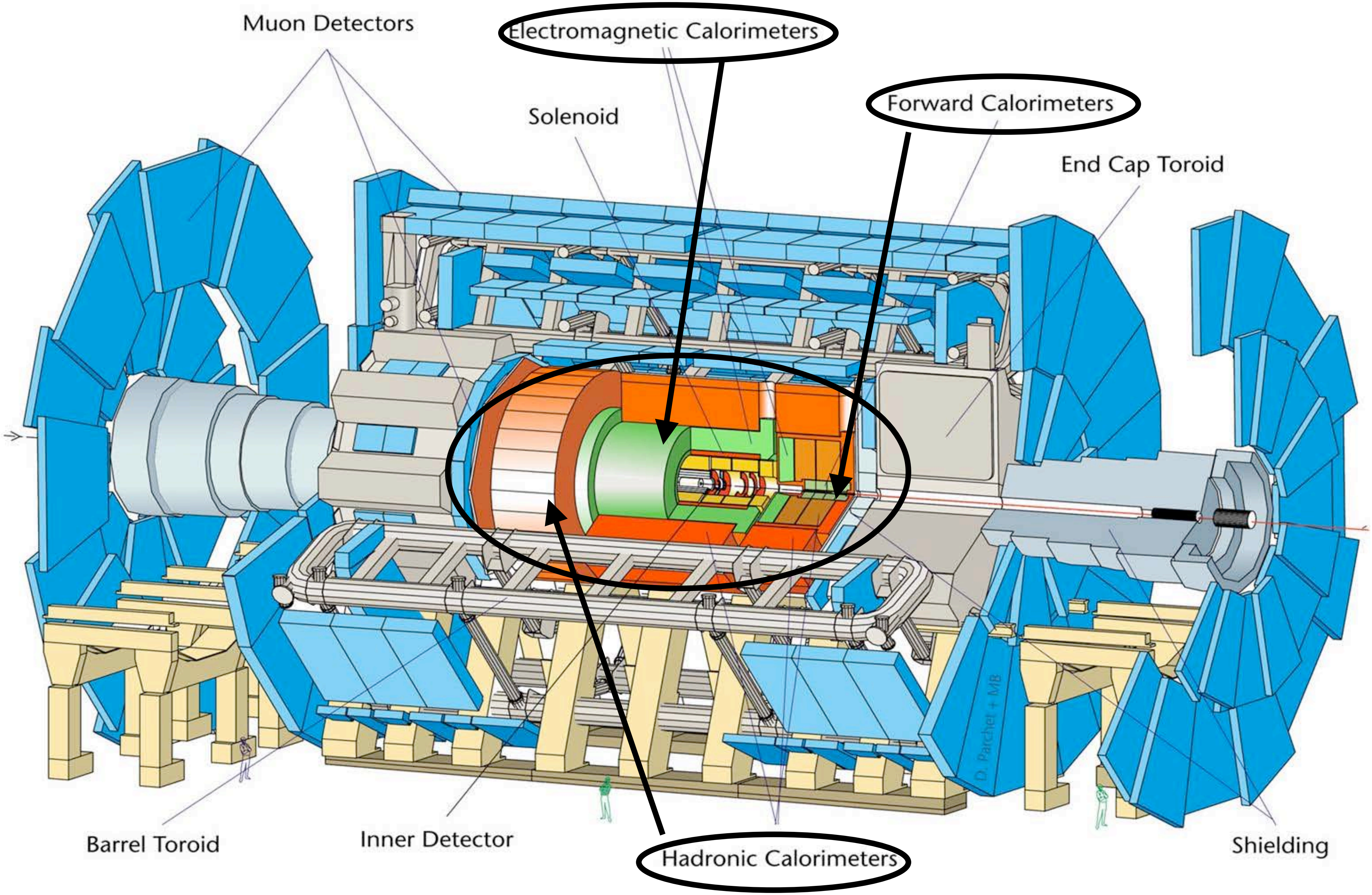




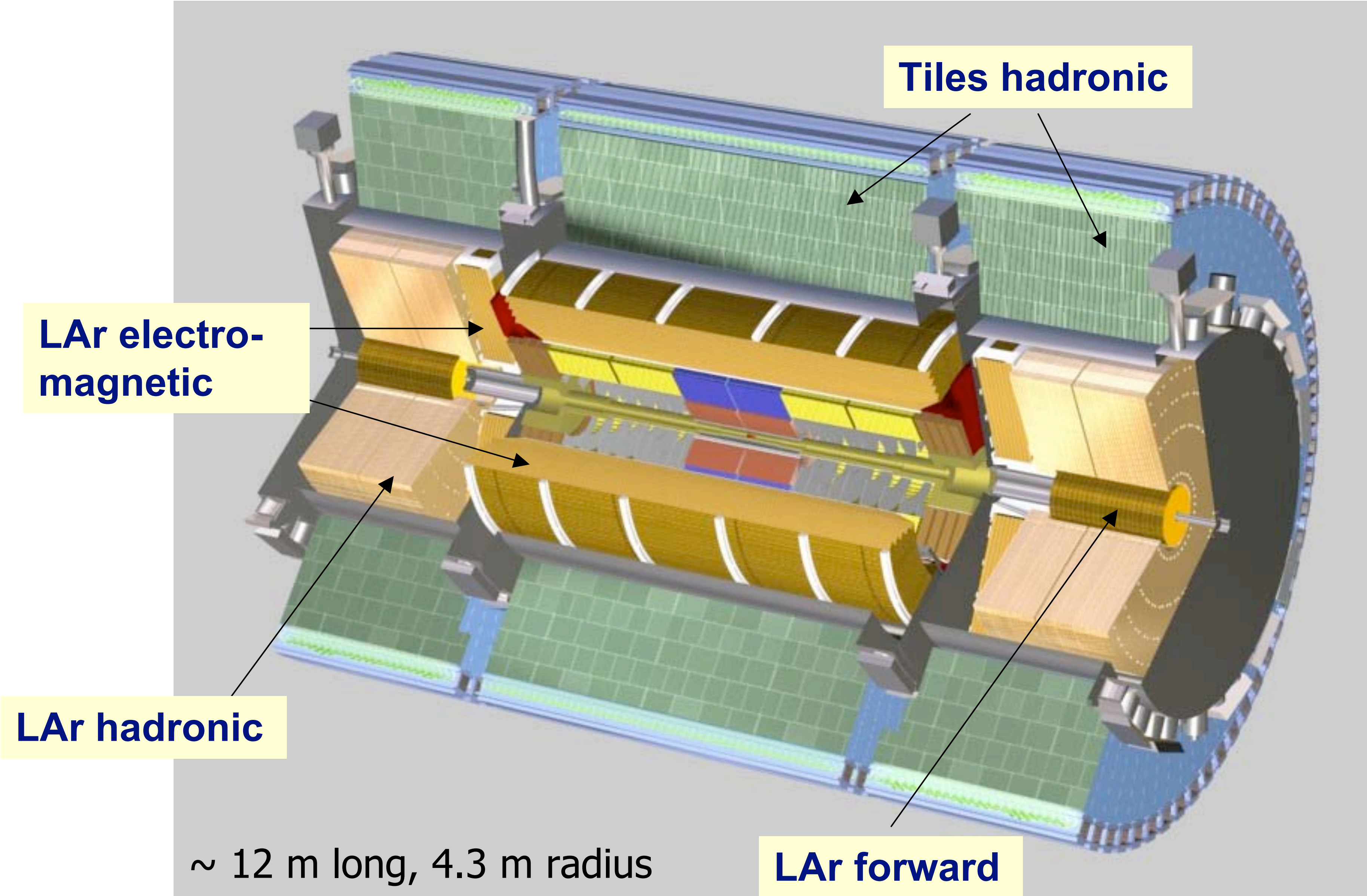
- ✓ e/π samples selected with Cherenkov + LAr
- ✓ Good agreement data/simulation at 2 GeV
- ✓ At 9 GeV rejection better in data than in simulation

D712/mb-26/06/97

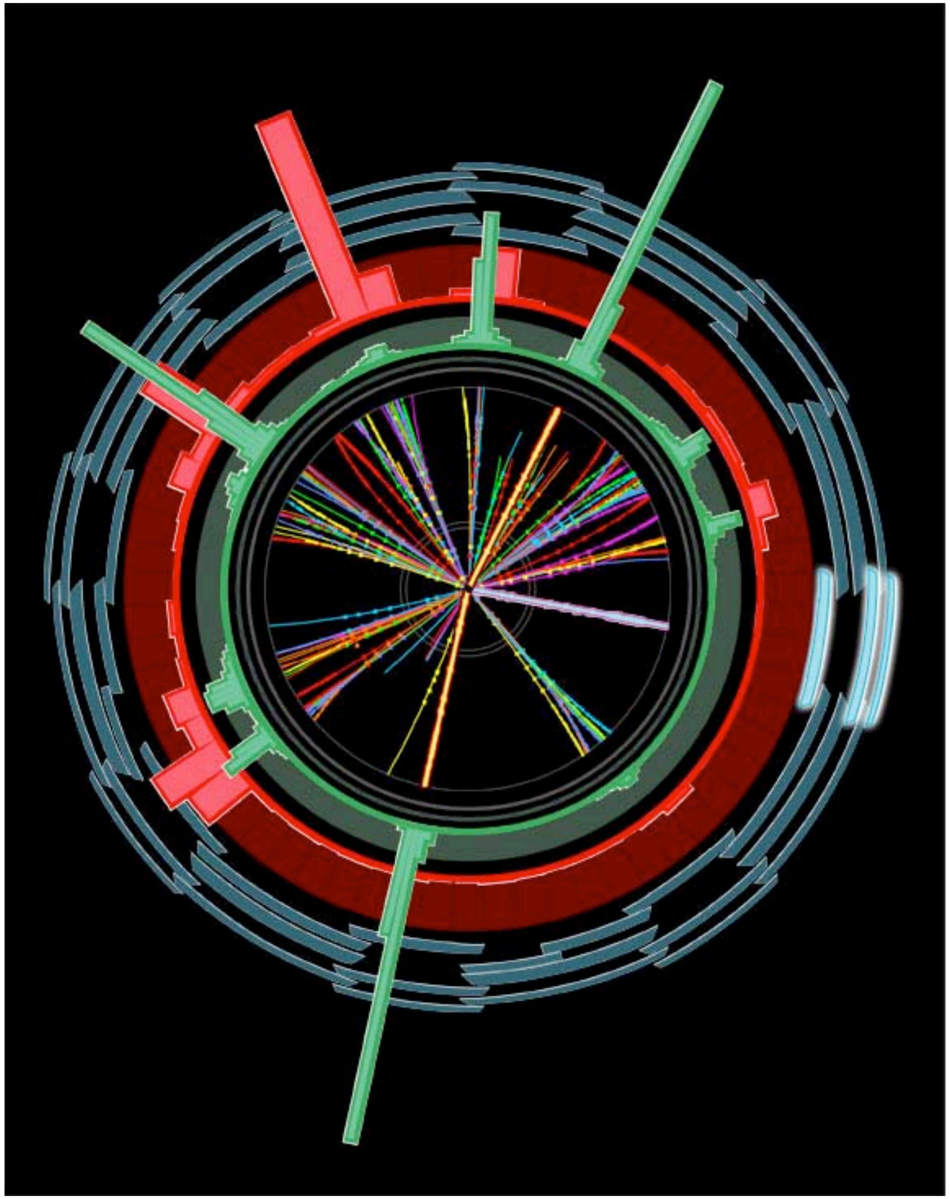
The ATLAS Calorimeters



The Calorimeters



The Calorimeters

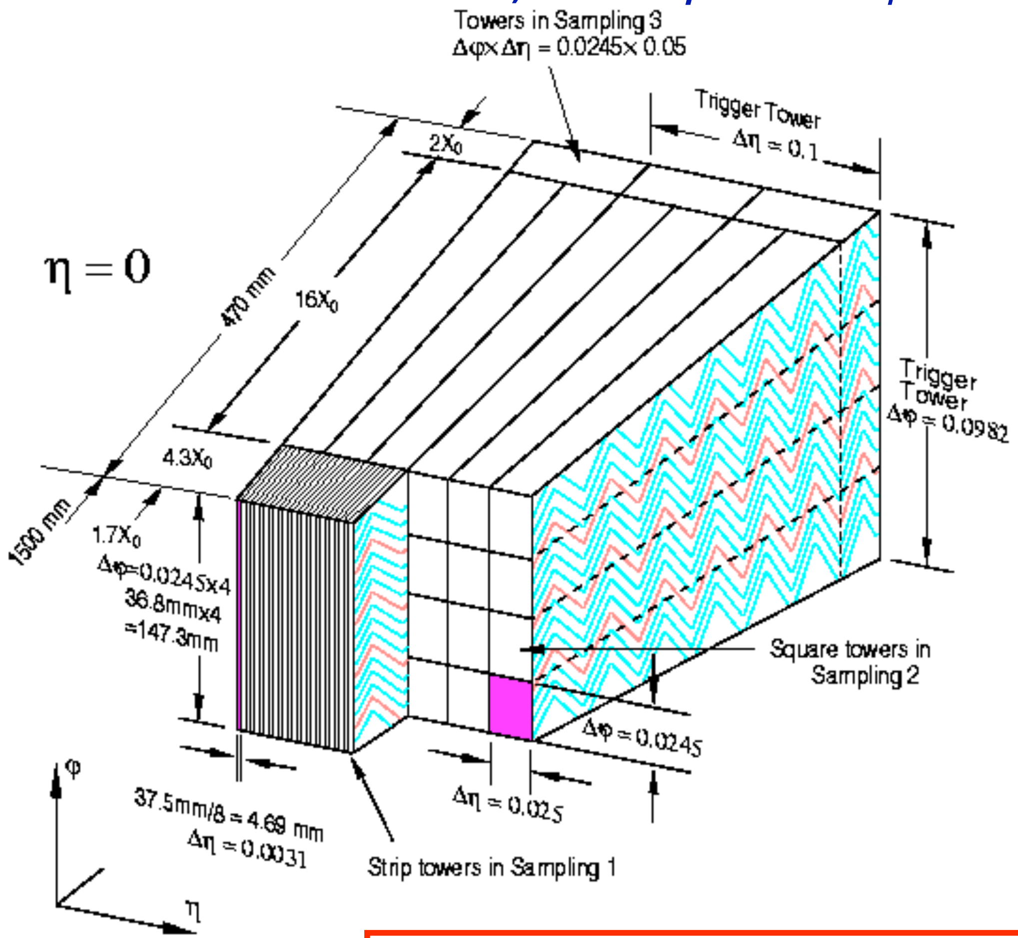


- Need to trigger and measure γ,e and hadron energies by total absorption in sampling mode.
- Need to operate in a integrated dose of γ and n, ranging up to a few Mrad.
- Need to maintain the energy scale precision at the 1% level.
- Need to allow particle identification (γ vrs. e, jets, γ conversion,..) --> longitudinal and transverse segmentation, preshower in the first radiation lengths.

The Calorimeters

Barrel EM accordion, 0.025 η x 0.025 ϕ

Barrel HAD tiles, 0.10 η x 0.10 ϕ

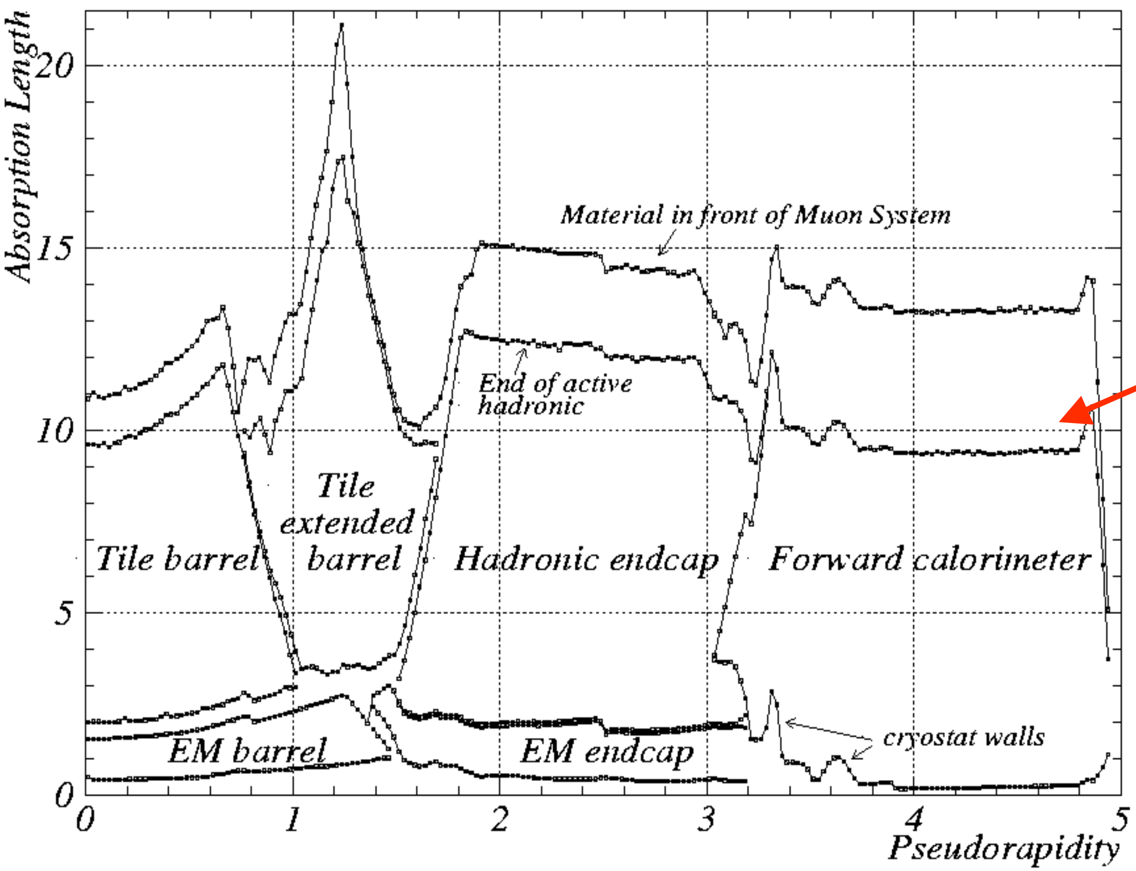


- Need to trigger and measure the γ,e and hadron energies by total absorption in sampling mode.
- Need to operate in a integrated dose of γ and n, ranging up to few Mrad.
- Need to maintain the energy scale precision at the 1% level.
- Need to allow particle identification (γ vrs. e, jets, γ conversion,..) --> longitudinal and transverse segmentation, preshower in the first X_0s.

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E(GeV)}} + b + \frac{c}{E},$$

$a = 10\%$, $b = 0.5\%$, $c \sim$ 0.2 GeV

The Calorimeters



- Need to trigger and measure the γ,e and hadrons energy by total absorption in sampling mode.
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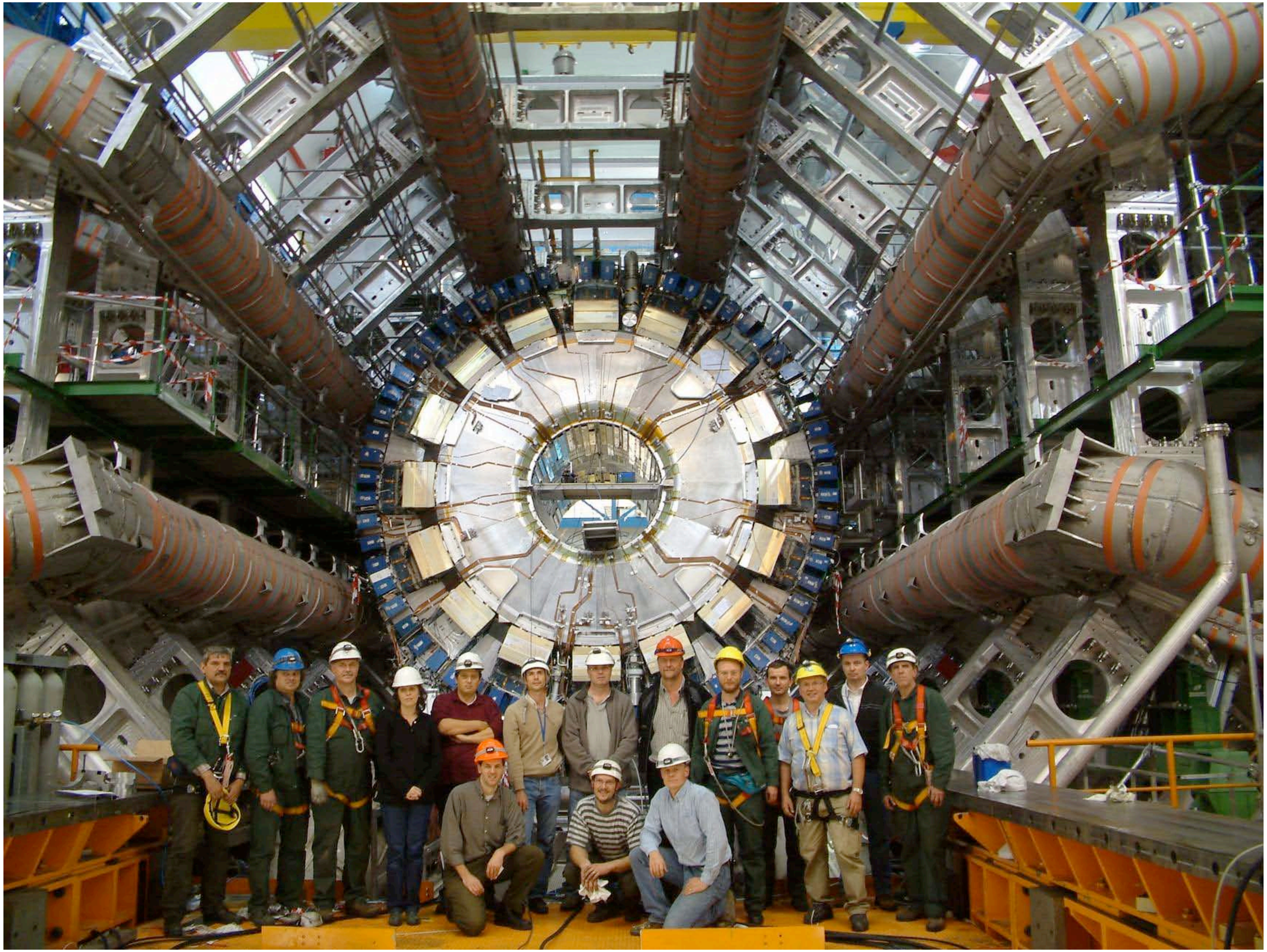
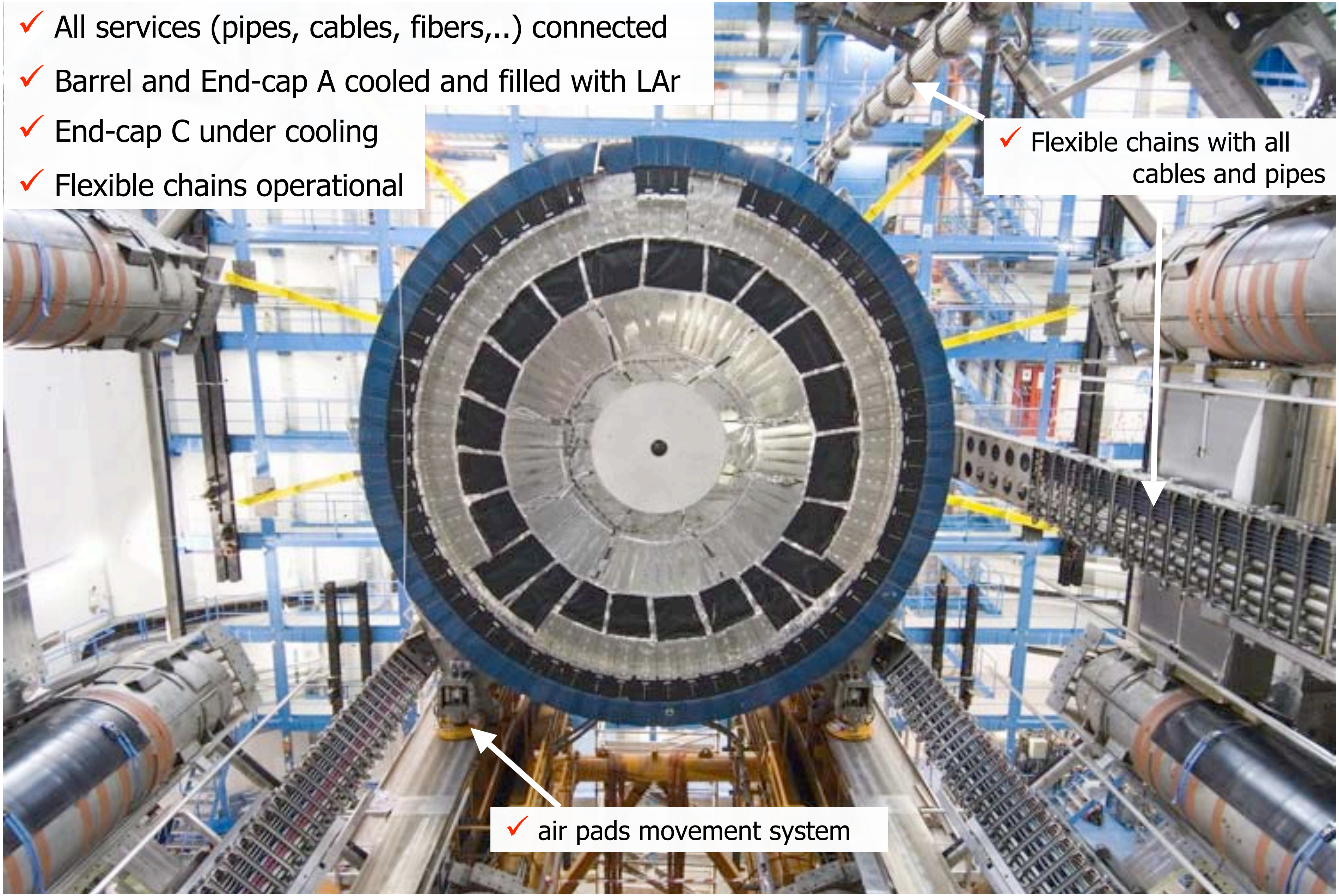
- Need to maintain the energy scale precision at the 1% level.
- Need to allow particle identification (γ vrs. e, jets, γ conversion,..) --> longitudinal and transverse segmentation, preshower in the first X_0s.

The calorimeters

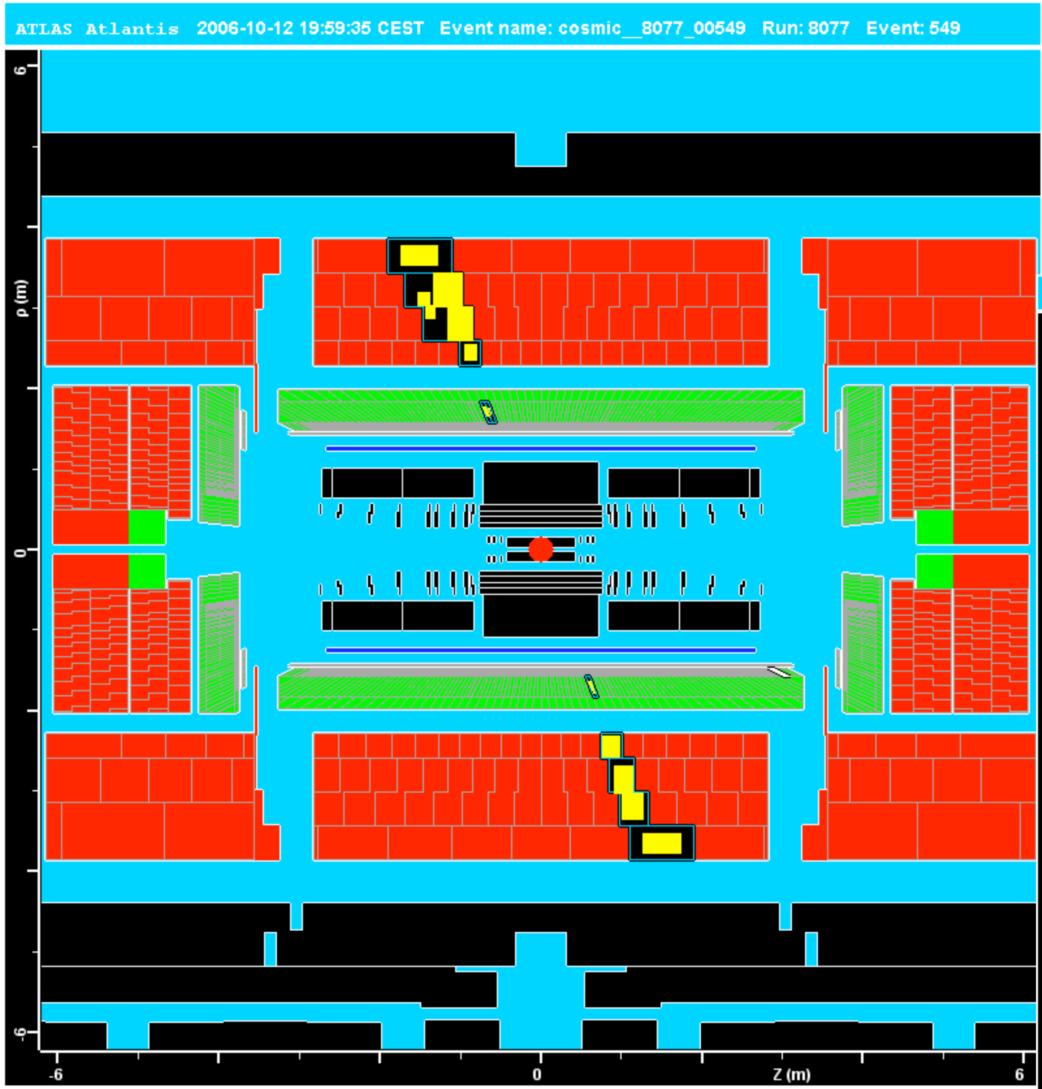


Calorimeters fully connected and cooled

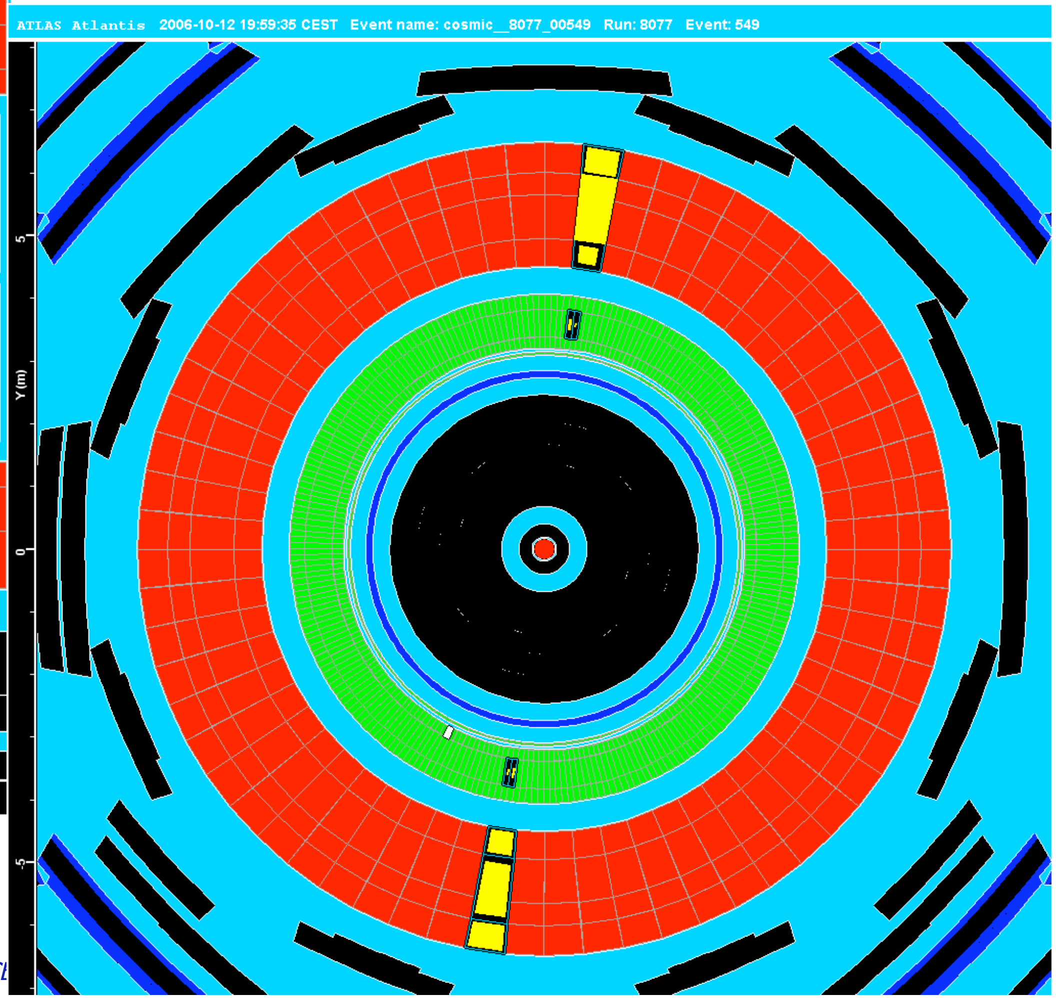
- ✓ All services (pipes, cables, fibers,..) connected
- ✓ Barrel and End-cap A cooled and filled with LAr
- ✓ End-cap C under cooling
- ✓ Flexible chains operational



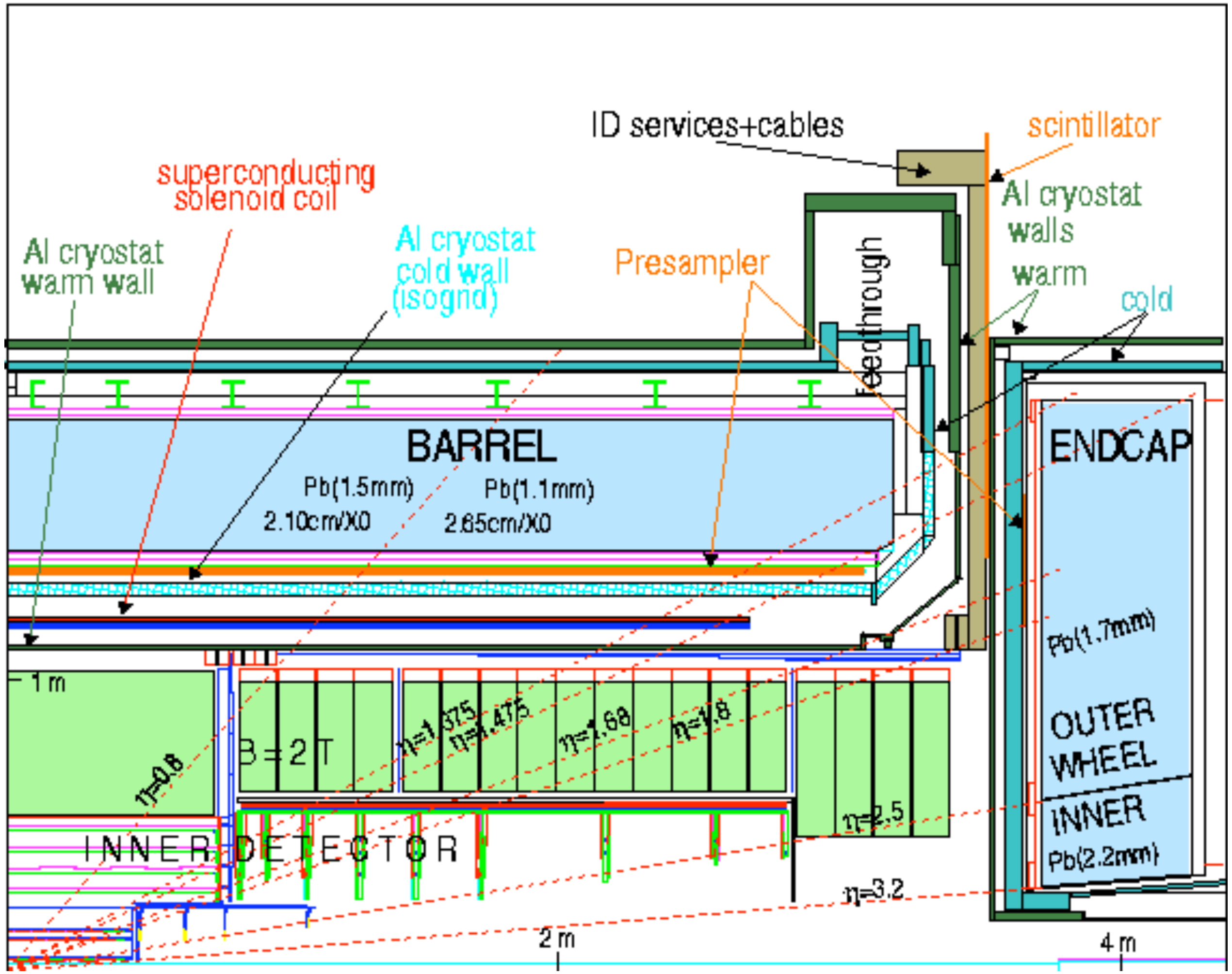
Cosmics in situ



First cosmic muon events registered in ATLAS using the Barrel Calorimeters



ATLAS LAr EM Calorimetry



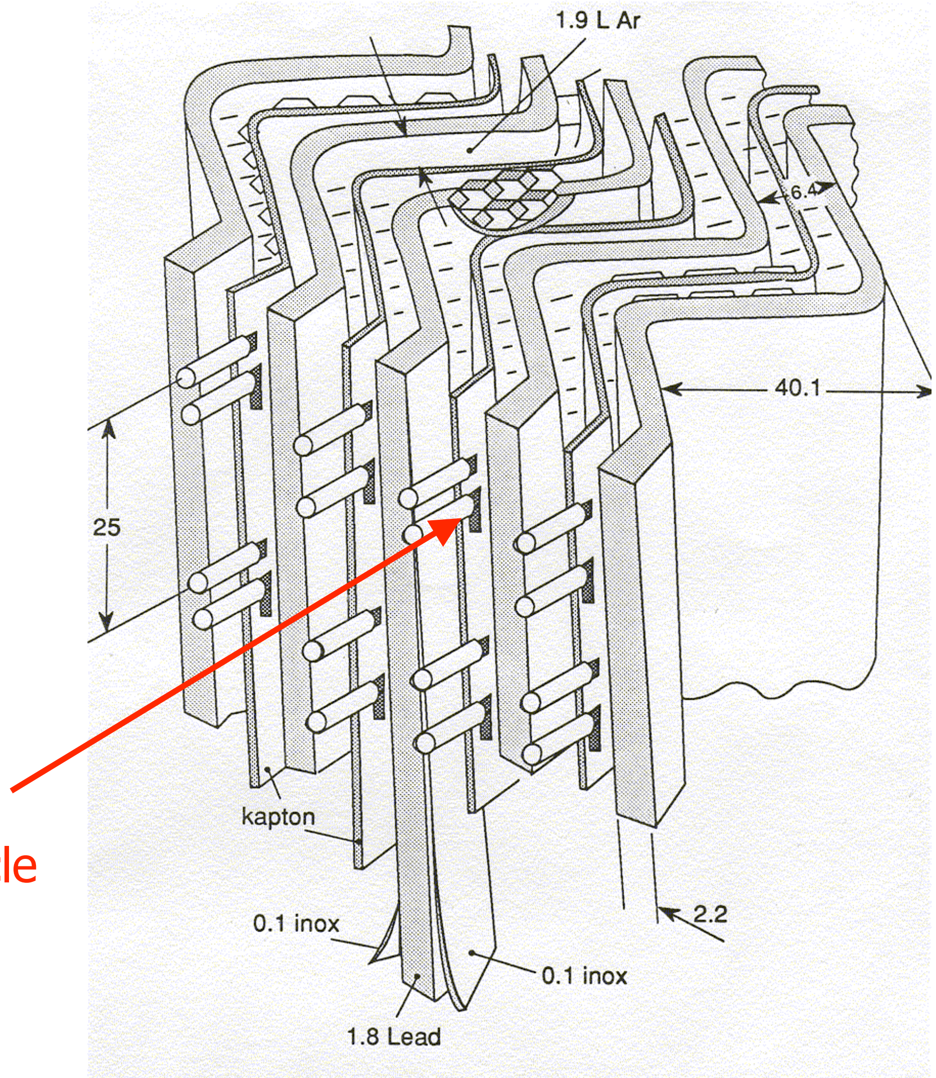
$\sigma/E \sim 10\% / \sqrt{E}$

$b \sim 0.5\ \%$

- ✓ *LAr ionization chamber, with fast signal shaping*
- ✓ *Pb as absorber* X_o *eff = 2.2 cm*
- ✓ *Sampling fraction* ~ 0.25 @ $\eta < 0.8$
- ✓ *3 longitudinal samples + preshower*

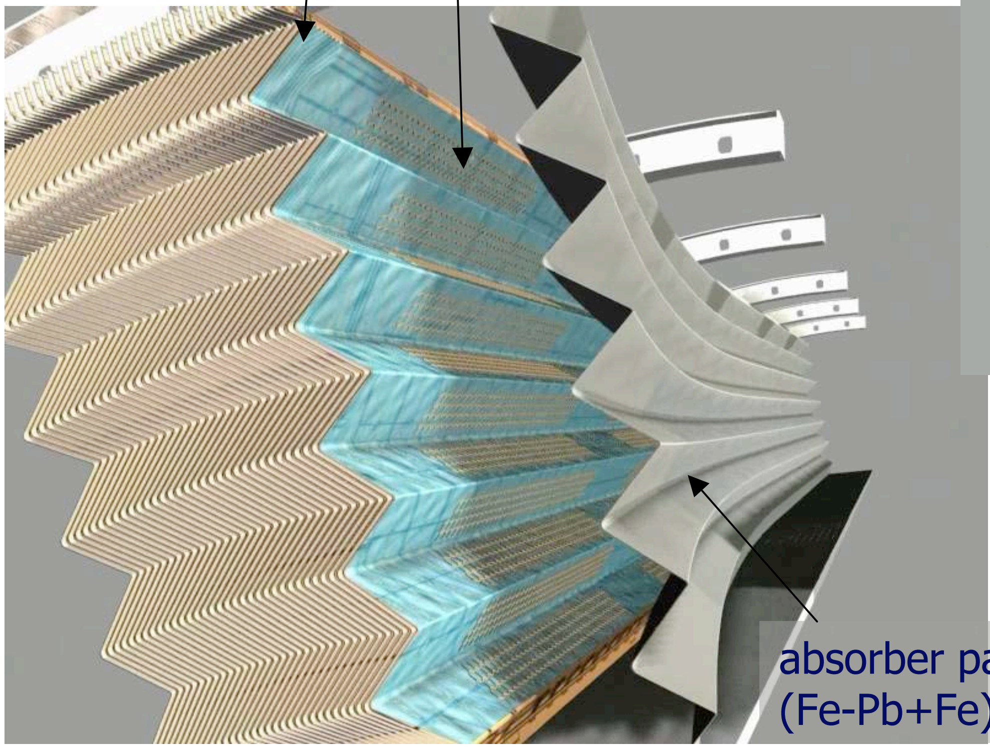
ATLAS LAr EM Calorimetry

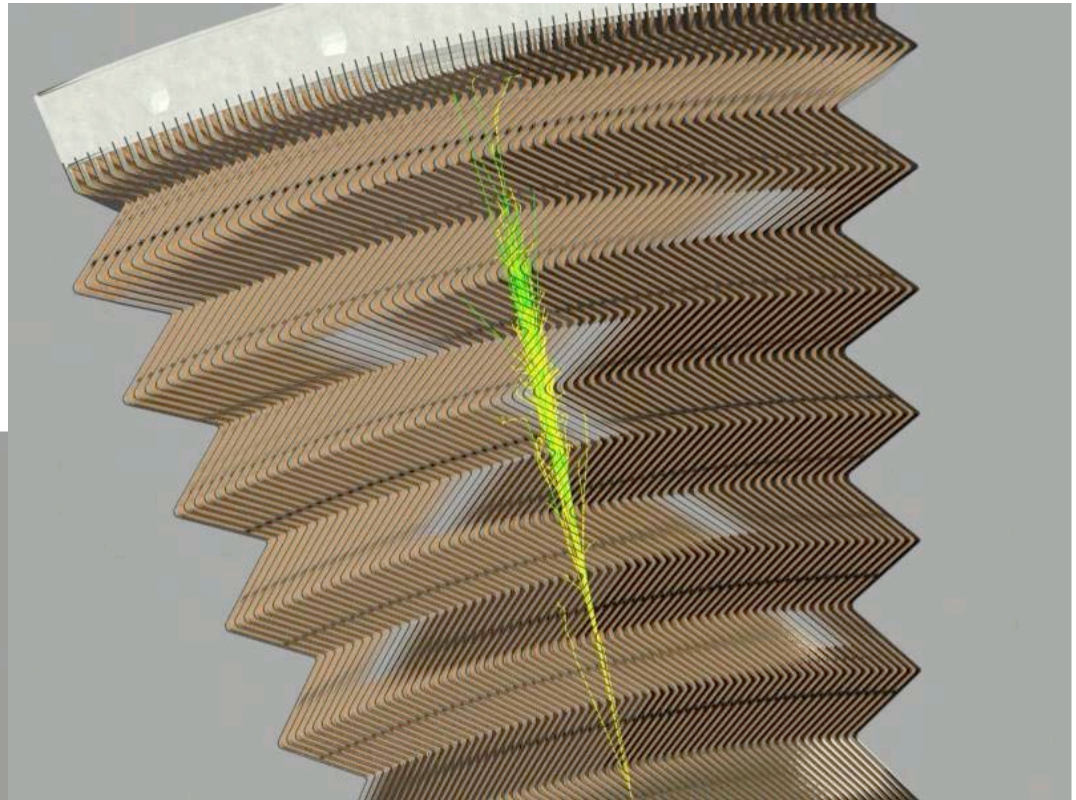
45º sampling



particle

ATLAS LAr EM Calorimetry





accordion geometry

ATLAS LAr EM Calorimetry

- 1024 accordion absorber plates
- 16 identical modules
- $\eta < 1.7$

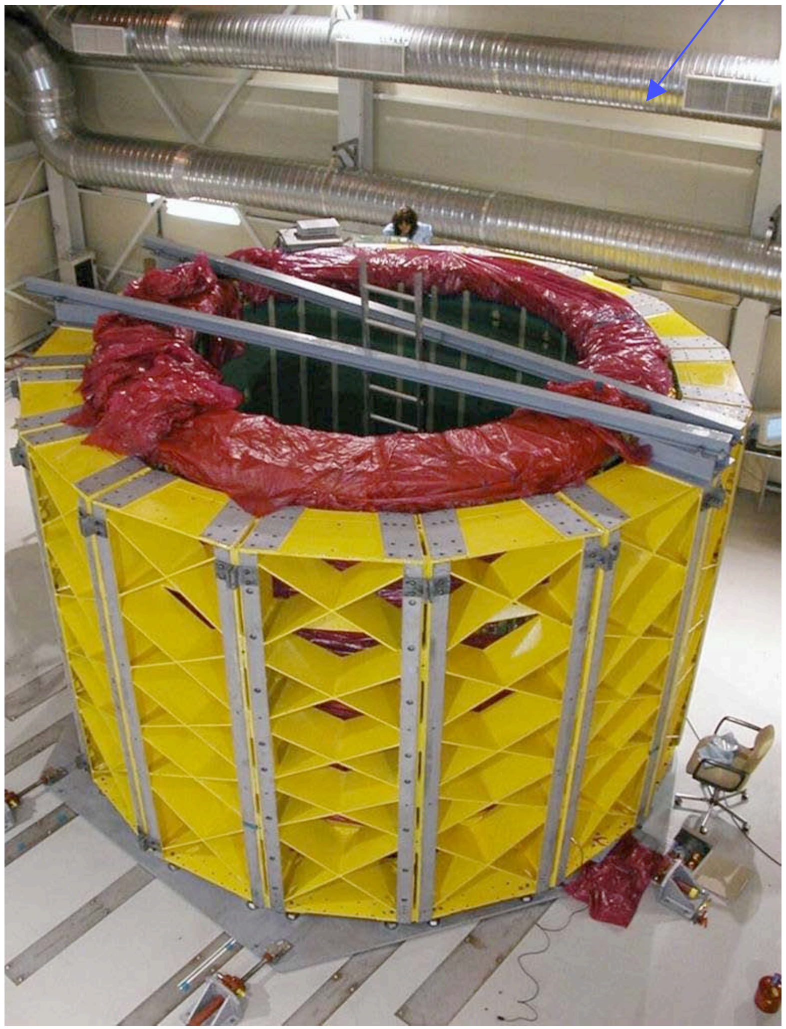
Completely stacked series LAr EM barrel module at Saclay

- Inner +Outer wheel
- 768 (256) accordion absorbers/wheel
- 8 identical modules/wheel
- $1.375 < \eta < 3.2$

Series LAr EM end-cap module during stacking at CPPM Marseille

ATLAS LAr EM Calorimetry

LAr EM barrel assembly in the vertical position



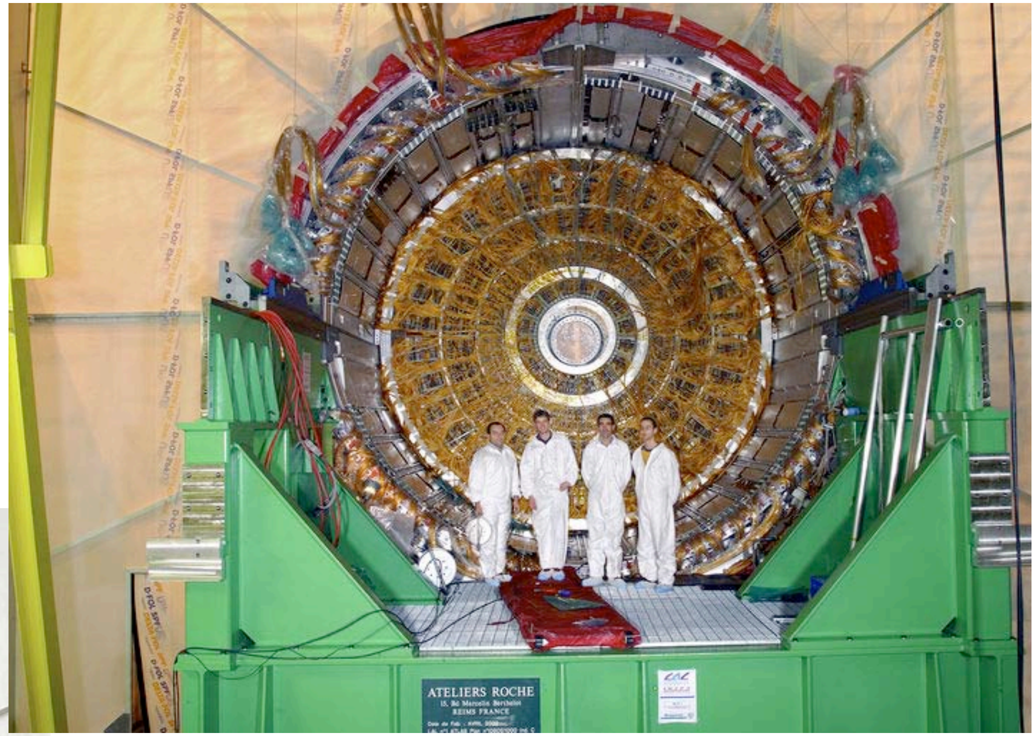
LAr EM end-cap wheel during assembly

ATLAS LAr EM Calorimetry

The barrel EM calorimeter is installed in the cryostat, and after insertion of the solenoid, the cold vessel has been closed and welded

The warm vessel has been closed as well, the detector has been cooled down

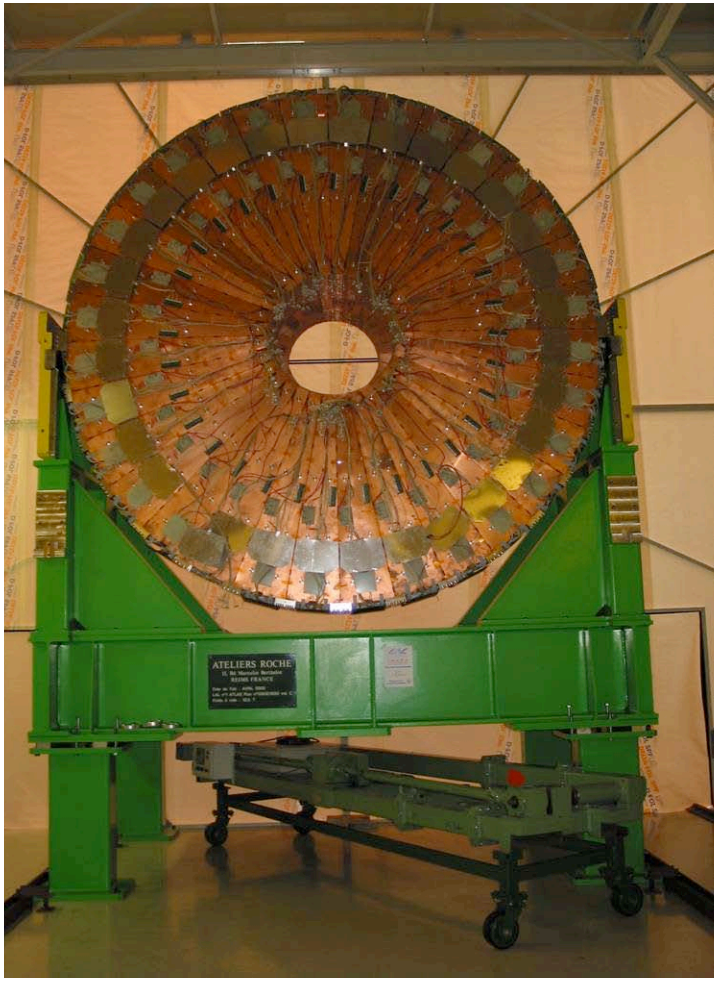
The final cold tests of the barrel EM have been done over summer 2004 with excellent results!



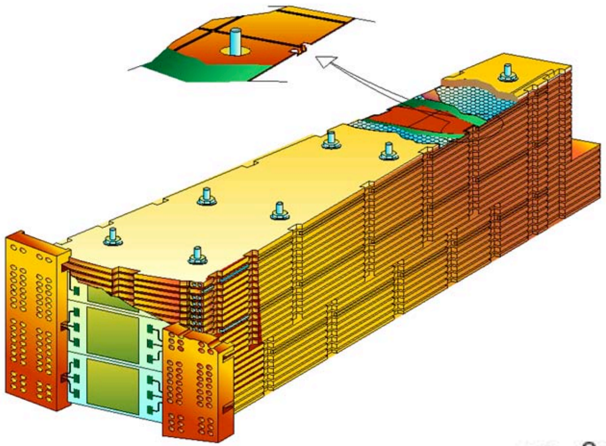
The first of the two LAr end-cap EM calorimeter wheels inserted in the cryostat (for side C)

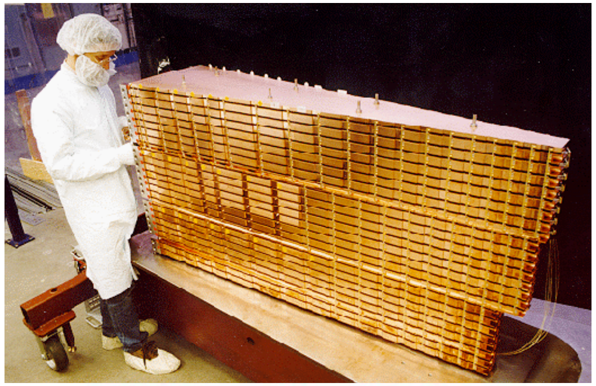
The second wheel has been completed as well and inserted into the side-A cryostat

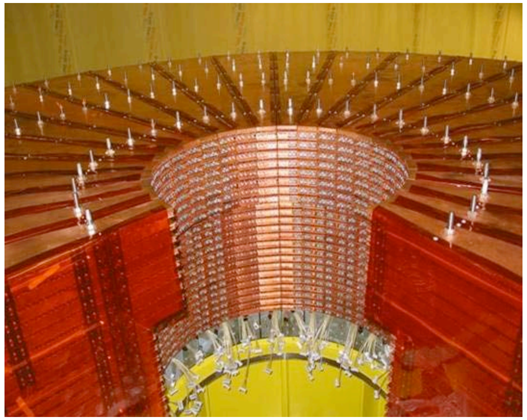
LAr Hadronic

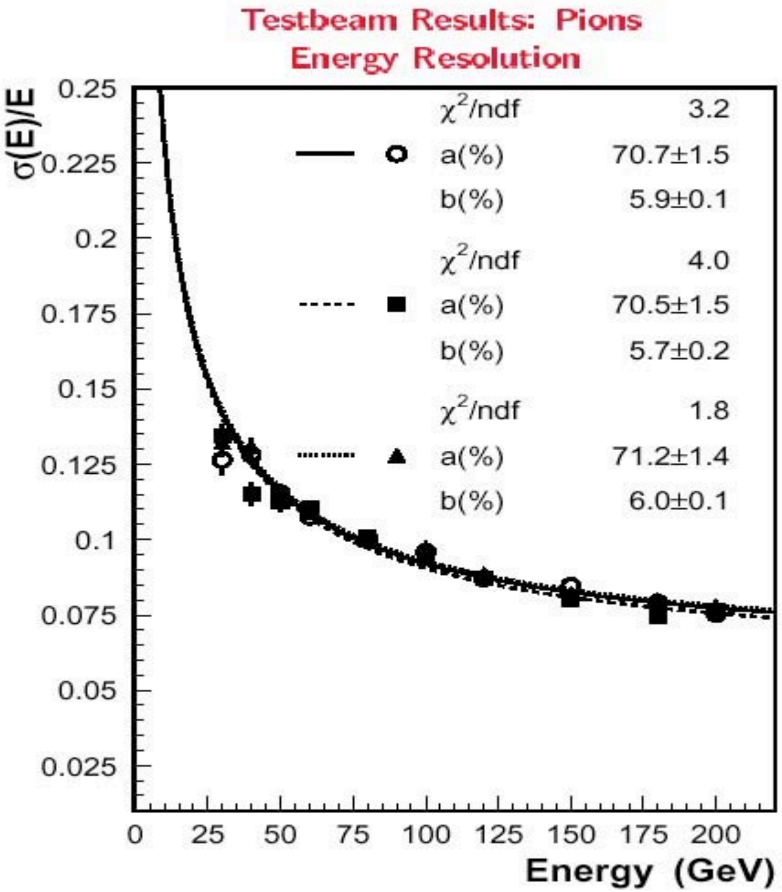


4 wheels fully assembled @ CERN

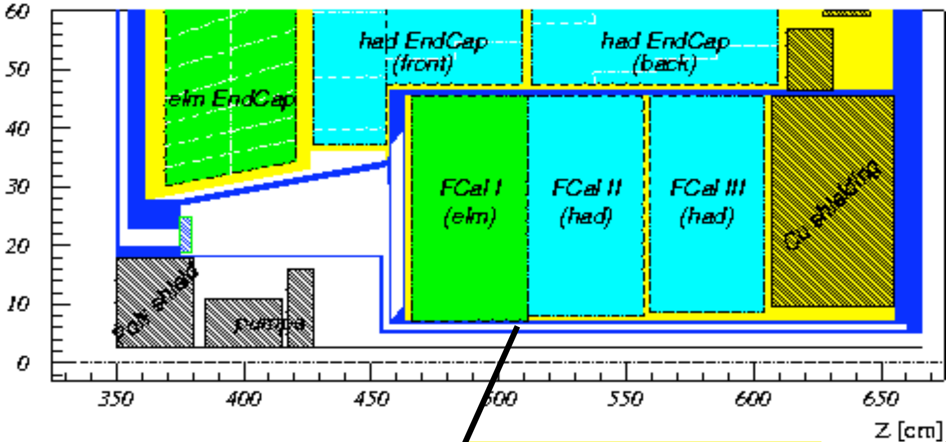


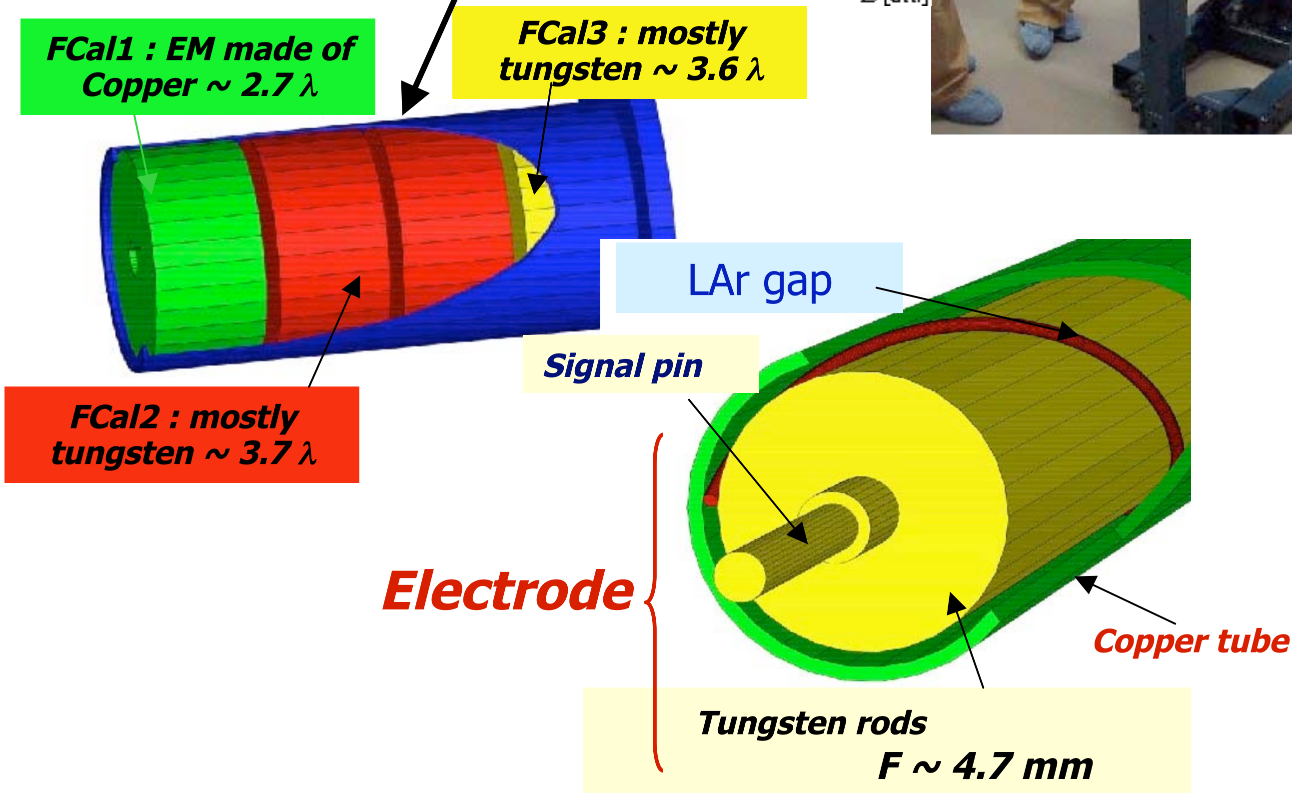






Forward Calorimetry

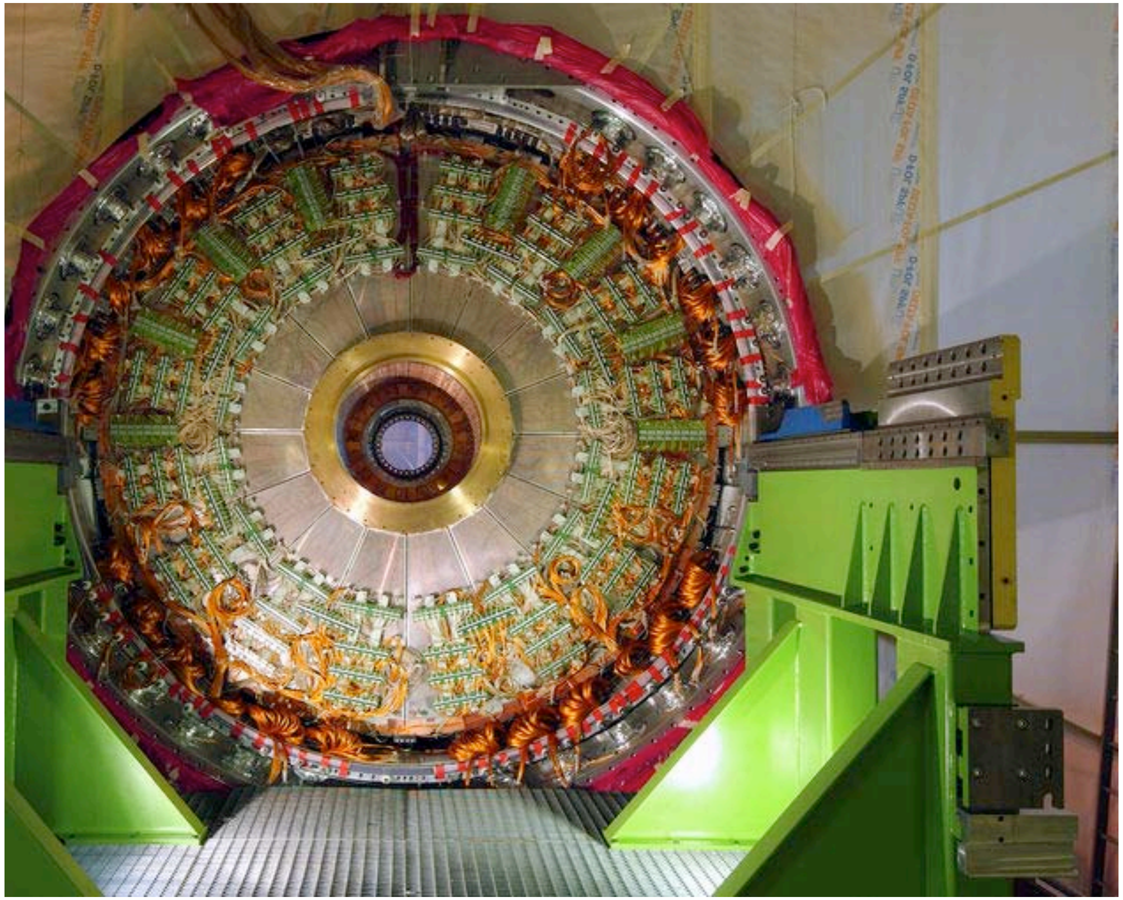




FCal2 and 3 assembly; insertion of tungsten slugs

FCal1 copper matrix stacking

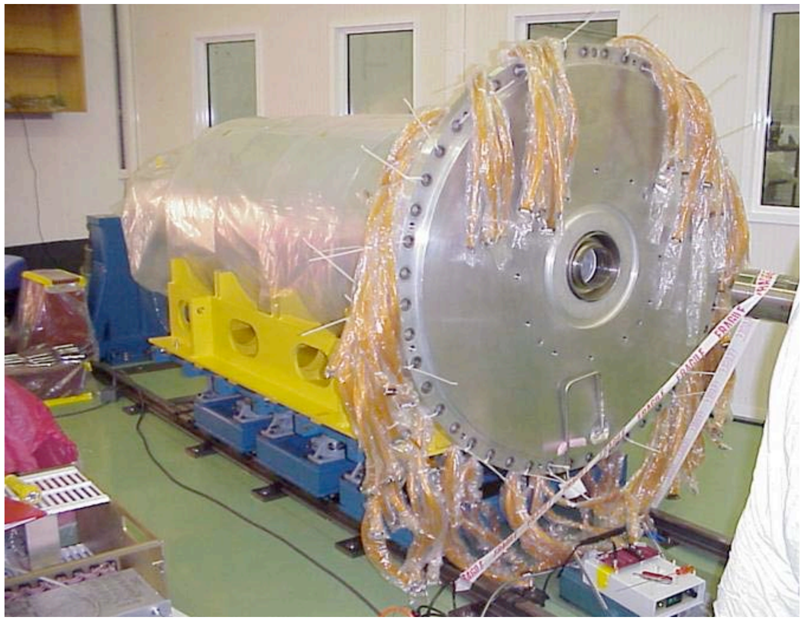
LAr Hadronic & Forward Calorimetry



Back view of the HEC wheels in cryostat side-C

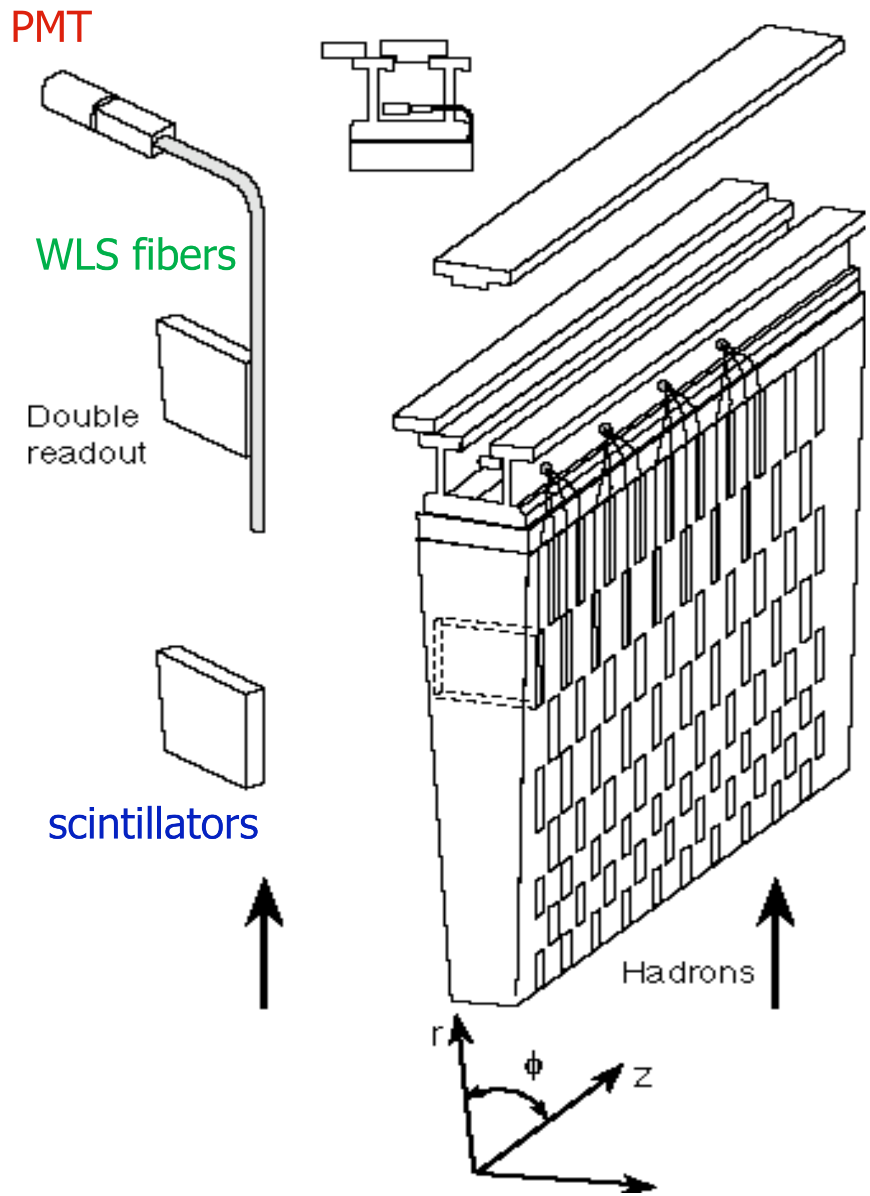
The LAr hadronic end-cap (HEC) wheels are all assembled, and were inserted in the cryostat (side A & C) and tested with very good results

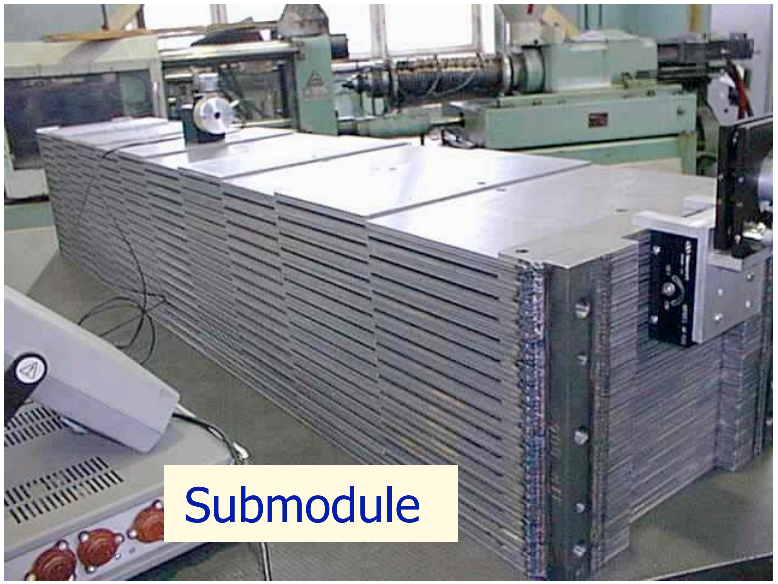
The LAr forward calorimeters (FCAL) are integrated and cold-tested as well.



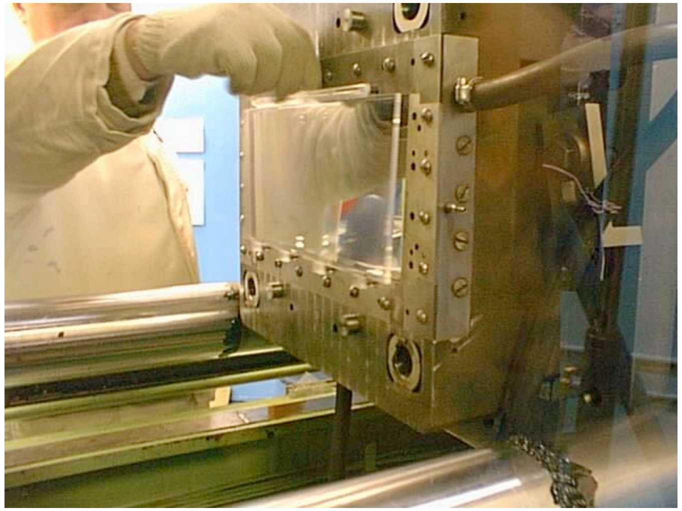
Integrated FCAL ready for insertion

ATLAS Tile Calorimeter

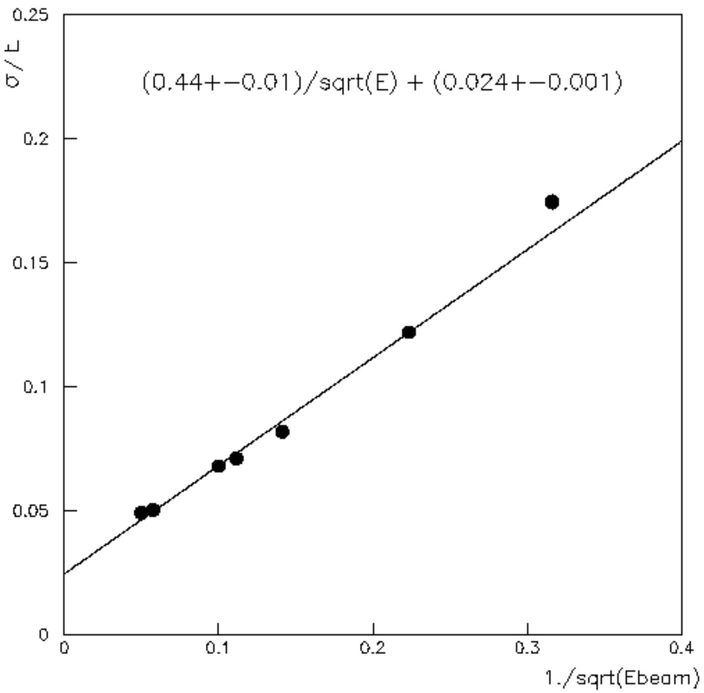




ATLAS Tile Calorimeter

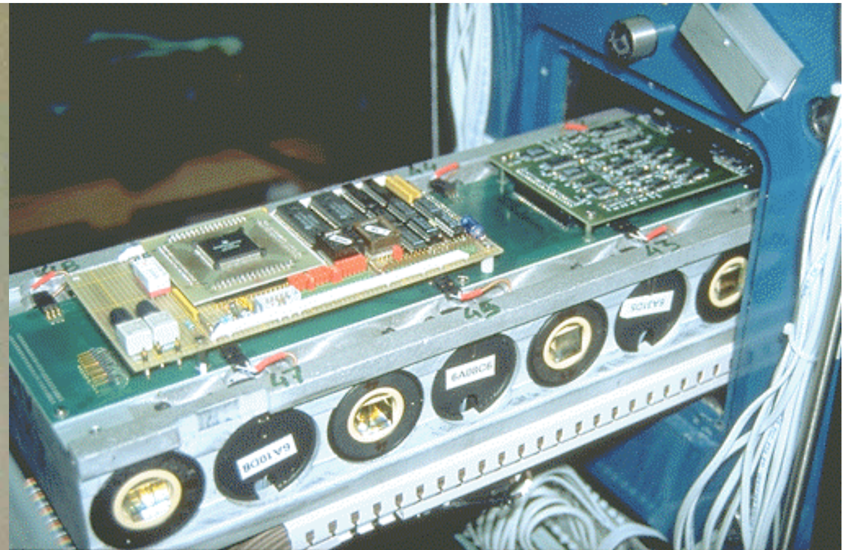


~ 3000 tons of hadronic calorimeter: iron absorber, active material scintillator (60 tons) read-out by WLS green fibers (1100 Km). Acts also as return yoke for inner solenoid



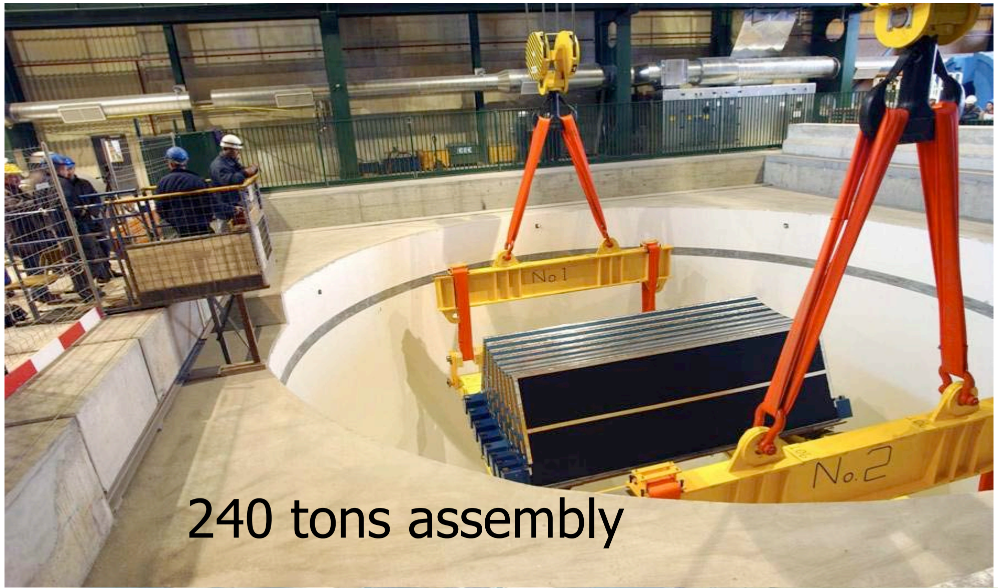
ATLAS Tile Calorimeter

Modules construction and optical instrumentation has been completed since a few years, and in the meantime the pre-assembly and disassembly on the surface of the first extended barrel (EB) cylinder as well as of the barrel have been completed, the second EB has gone through the same procedure. By now all 3 cylinders are installed in ATLAS



The electronics components are fabricated, and a ‘drawer’ system with all on-detector circuits has been installed in all modules underground.

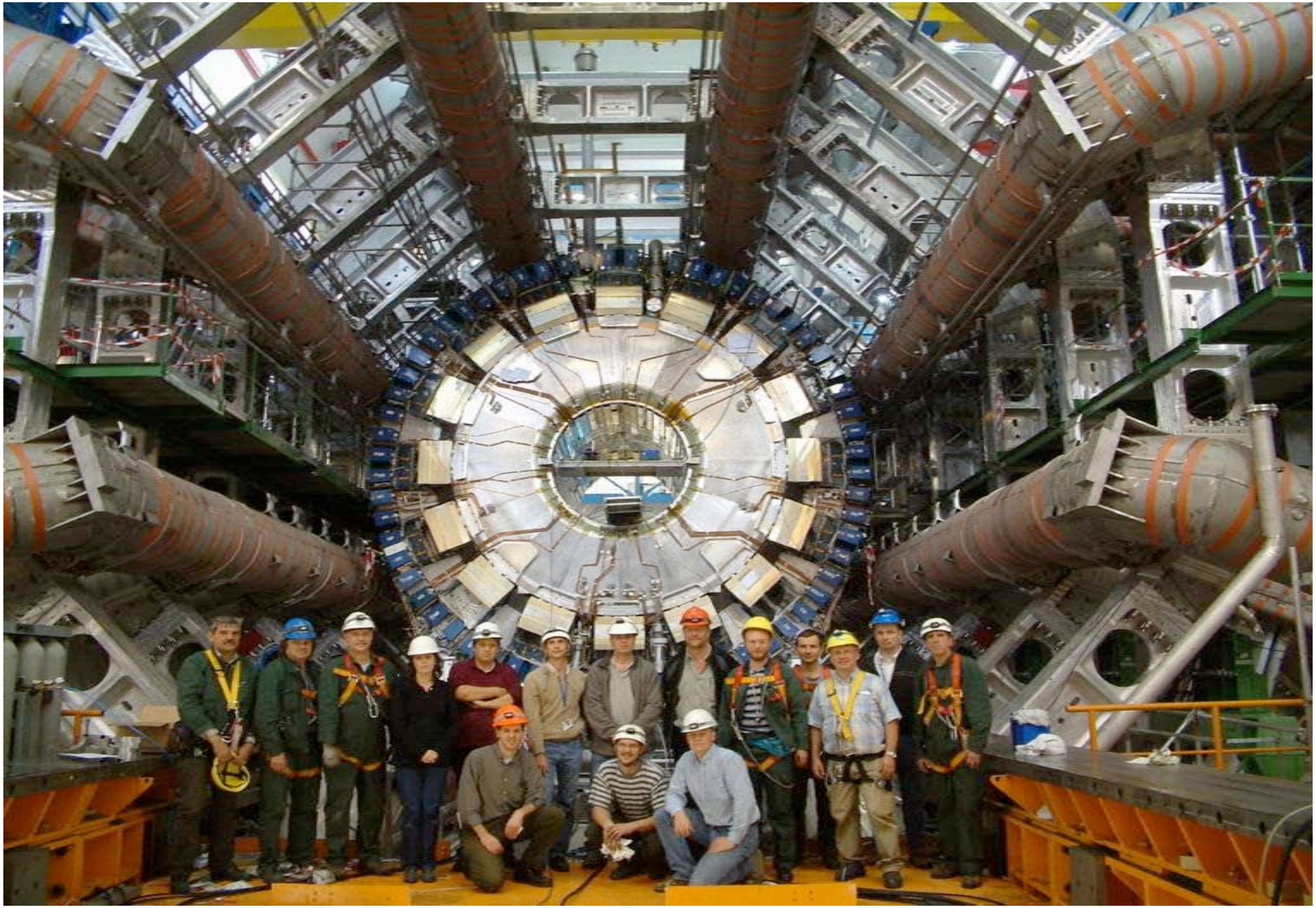
Barrel Tile Calorimeter lowering

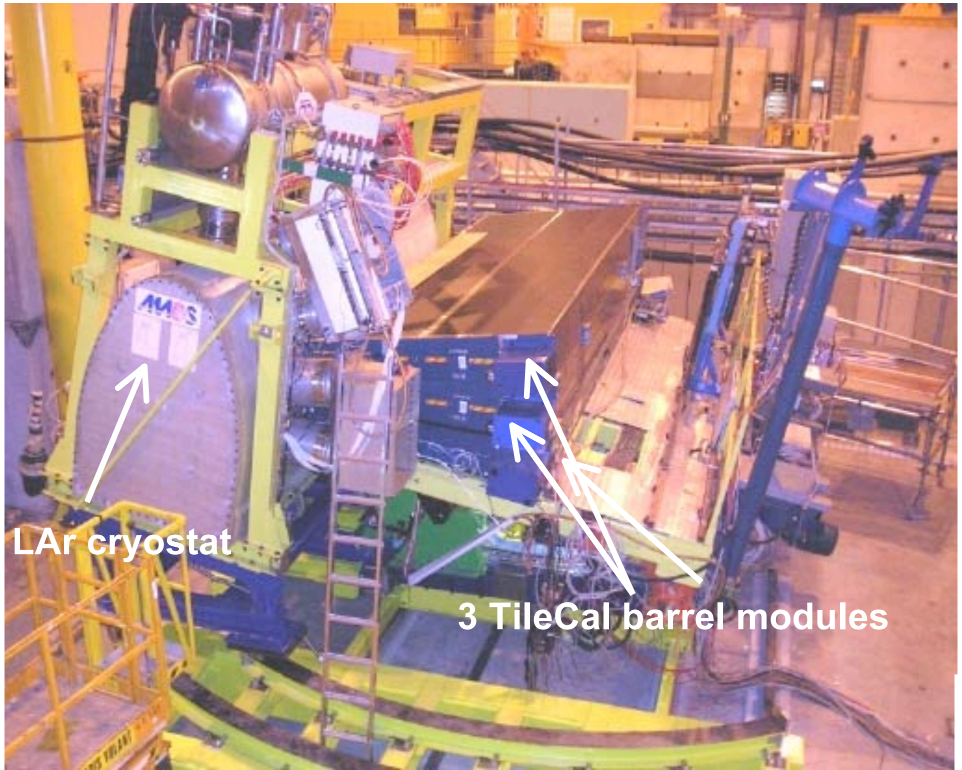


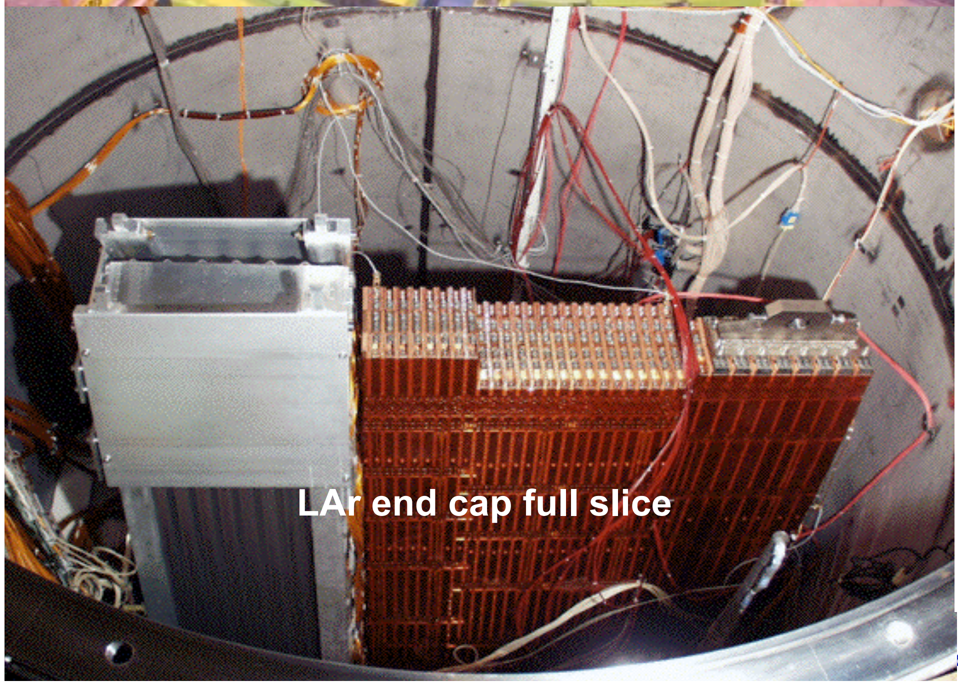
Barrel LAr Calorimeter lowering

170 tons assembly

Barrel Calorimeter positioning at z=0

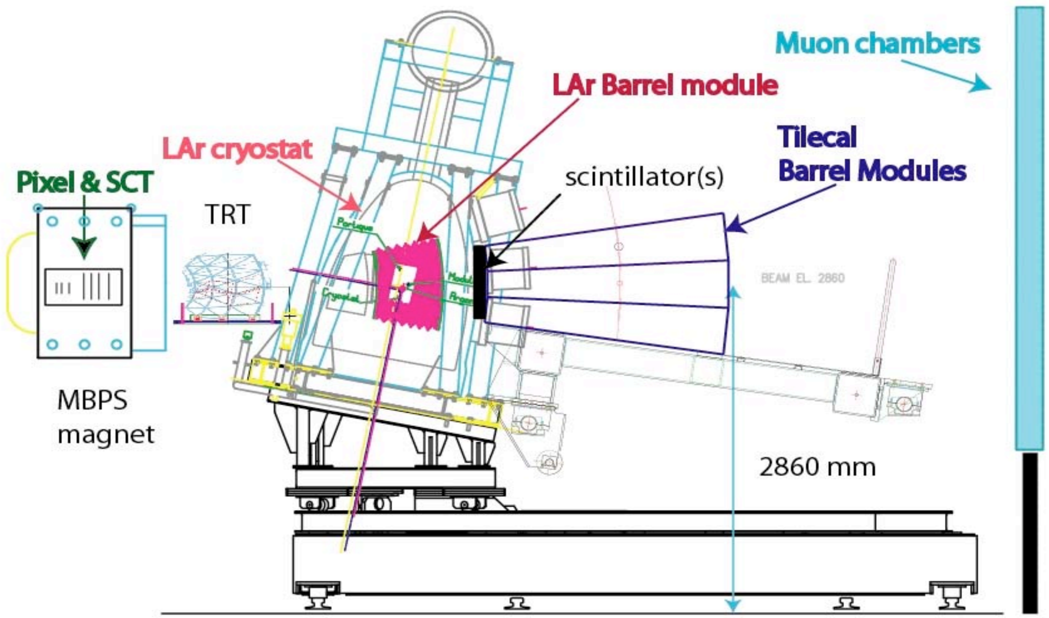






Combined test beam

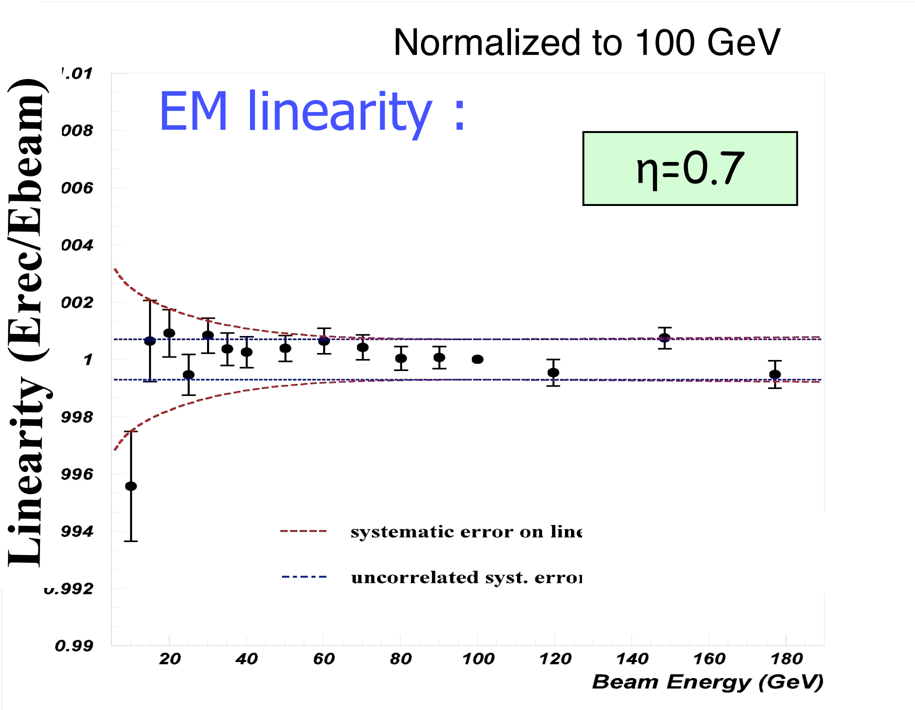
The combined test beam runs 2004 in the CERN SPS H8 and H6 beam lines are just finished (1 to 300 GeV/c).



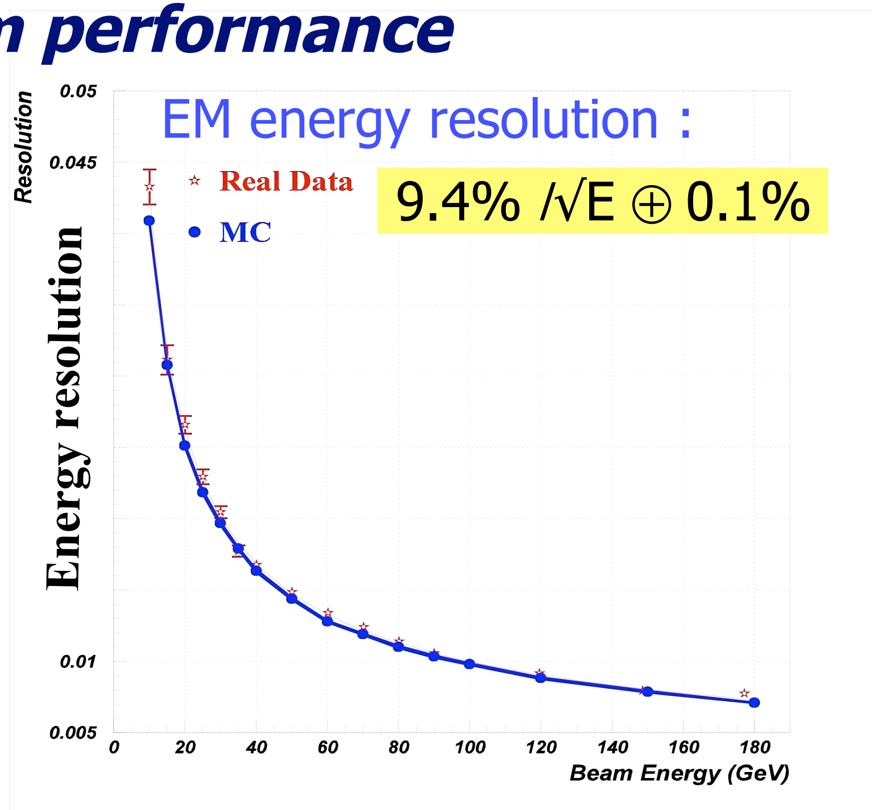
LAr Calorimetry test beam performance

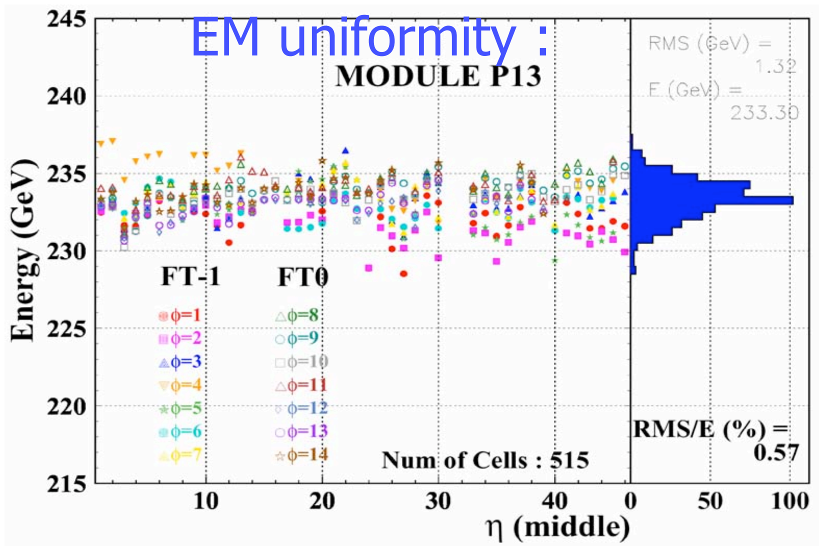
Test beam runs of series modules:

- ✓ EMB finished in 2002. 4 / 32 modules tested.
- ✓ EMEC finished in 2002. 3 / 16 modules tested.
- ✓ HEC finished in 2001. 24 / 128 modules tested.
- ✓ FCAL beam calibration in 2003. 3 / 6 modules.



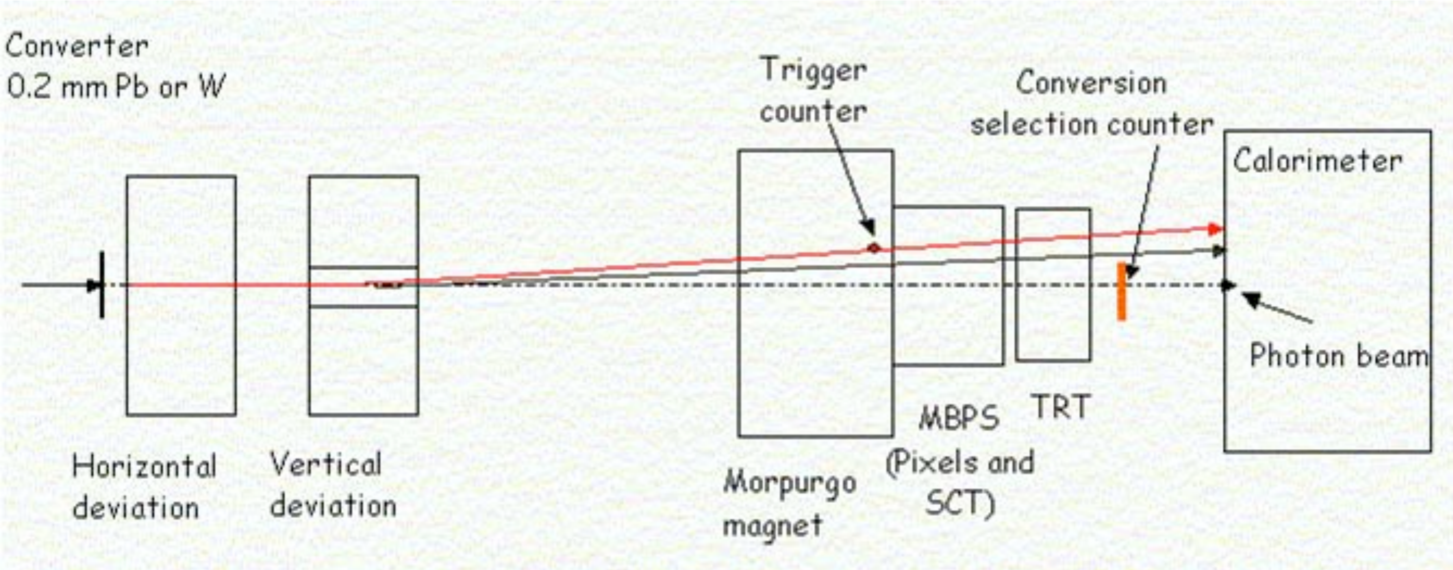
Detector linear within ±0.25% (± 0.1%) for E>10 (40) GeV



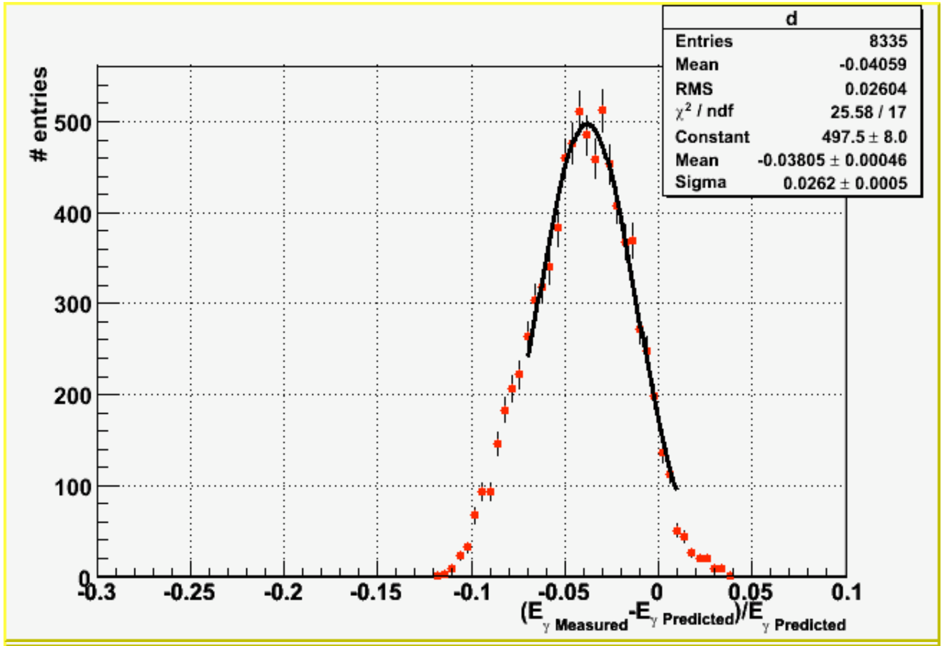


LAr: Photon runs

180 GeV e



- ✓ *Primary electron bent away from beam line in both directions*
- ✓ *Trigger counter selects e^- angle, hence γ energy*
- ✓ *Conversion electrons in the Si part separated by MBPS-ID magnet*



Impact on Higgs mass resolution

Simulations, m_H=130 GeV

✓ $H \rightarrow \gamma\gamma$

Resolution: 1% (low luminosity)

1.2% (high luminosity)

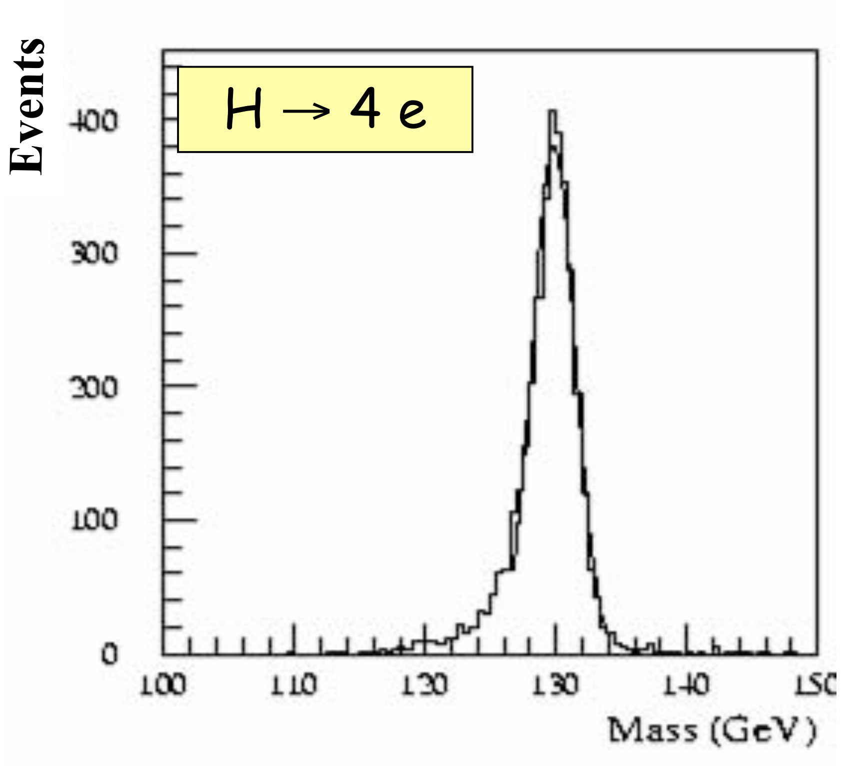
Acceptance: 80% within $\pm 1.4\ \sigma$

✓ $H \rightarrow 4e$

Resolution: 1.2% (low luminosity)

1.4% (high luminosity)

Acceptance: 84% within $\pm 2\ \sigma$



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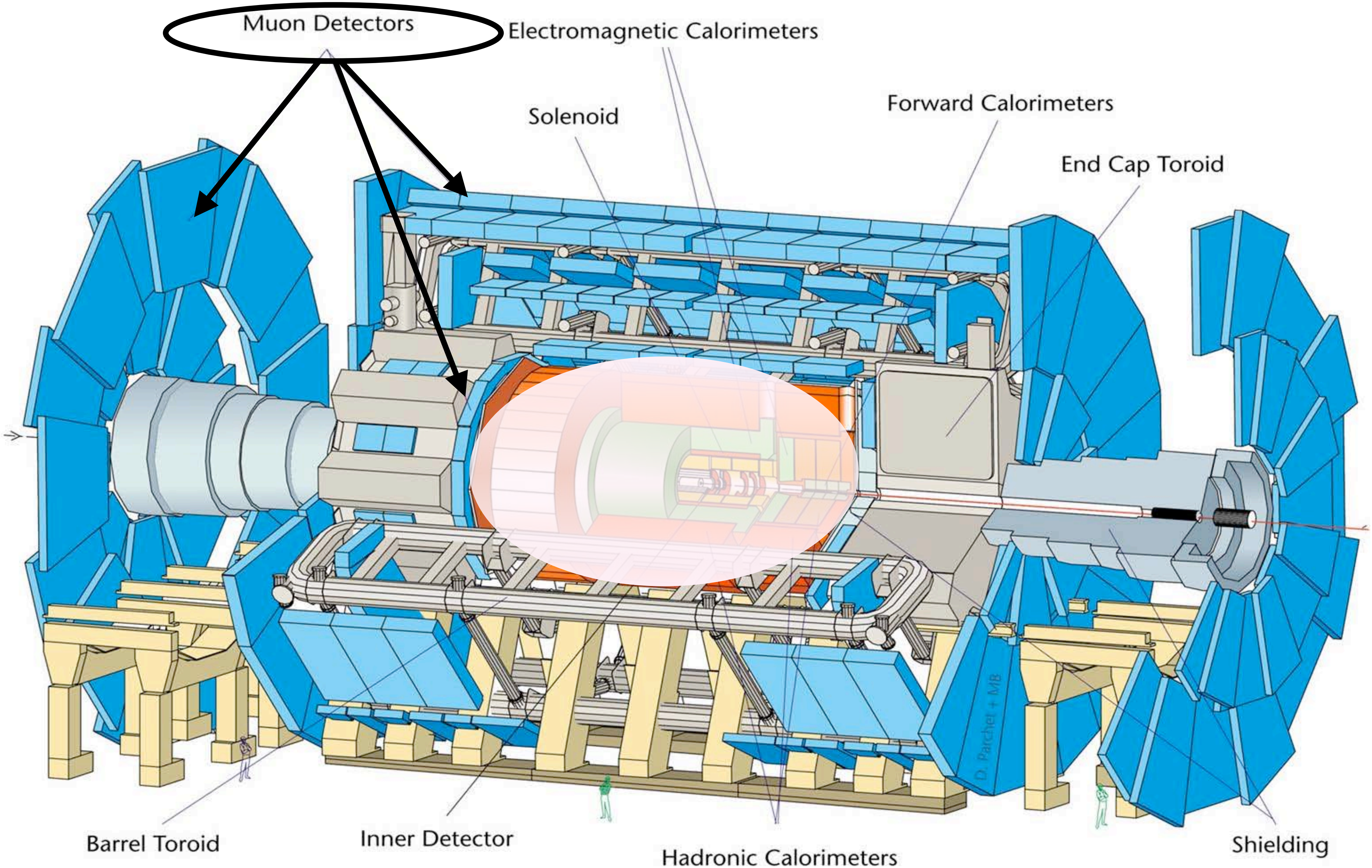
The ATLAS Muon Spectrometer

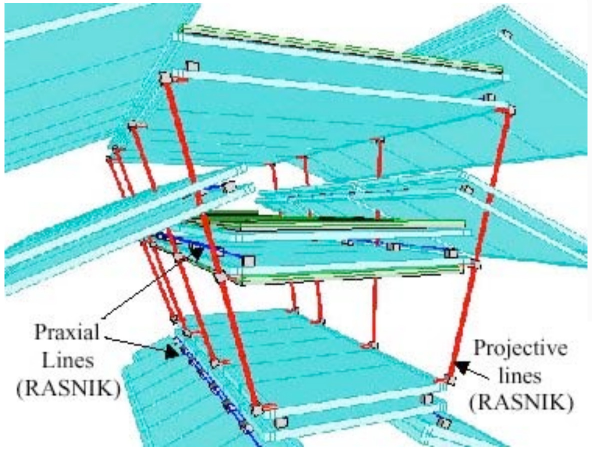


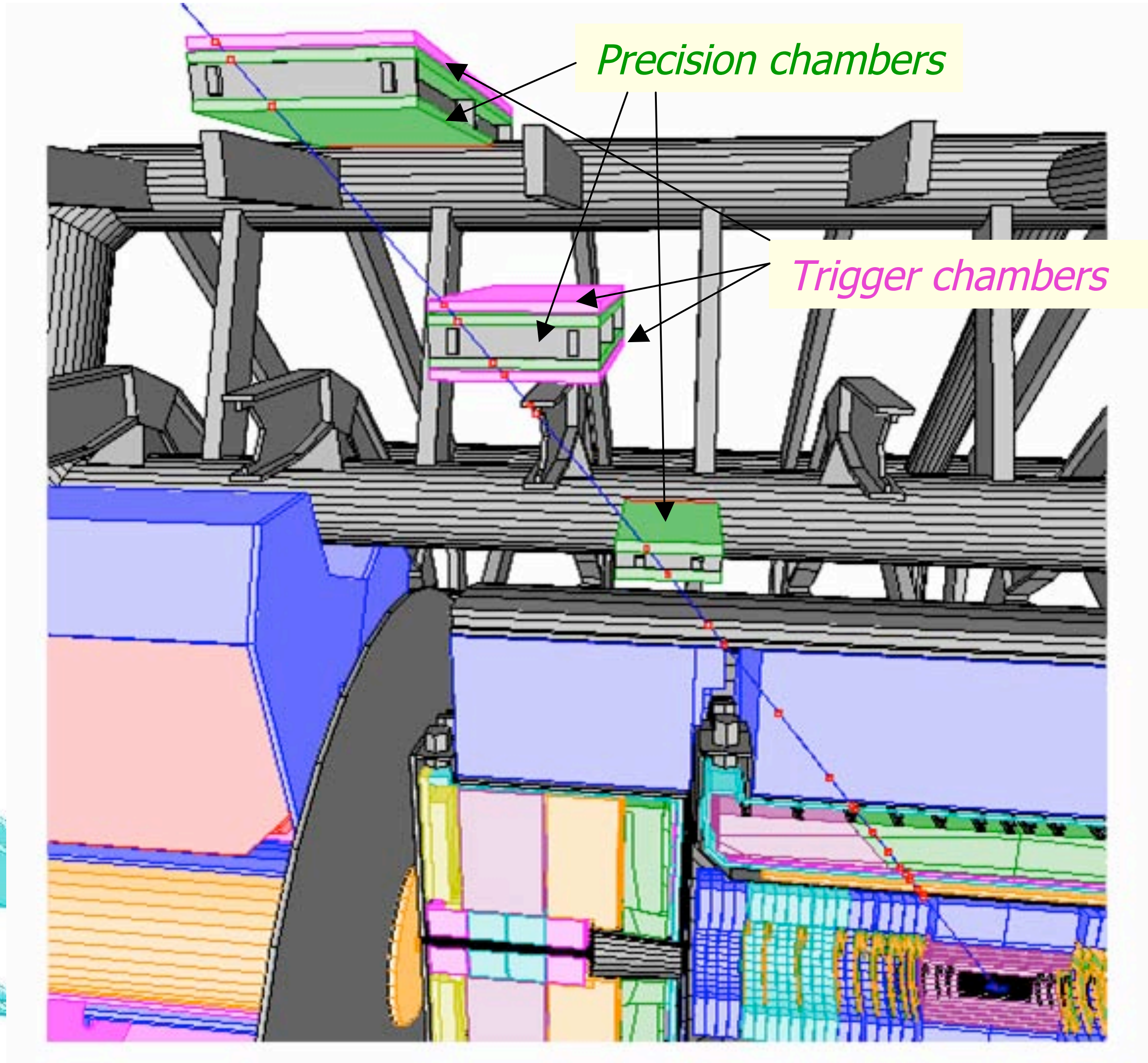
The Muon Spectrometer

- Needs to trigger and measure the μ trajectory in **6** points with a precision of **50**μ at each point, for particles going through a Toroidal field of max. 4Tesla.

- Needs to operate in a background of γ and n, ranging from **few** Hz to **500Hz/cm^2**.

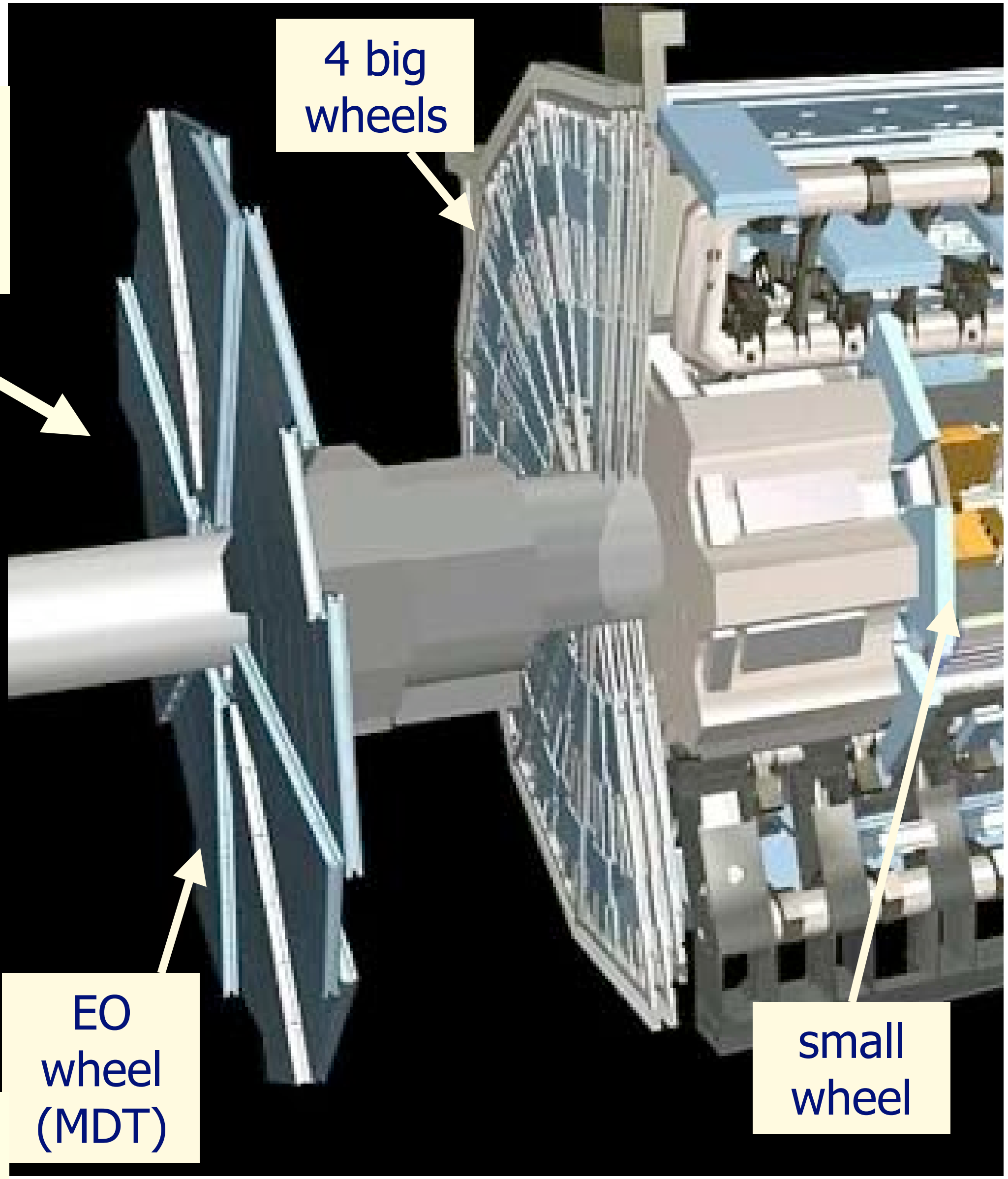
- Needs to follow the position of every measuring element with a precision of **30μ.**

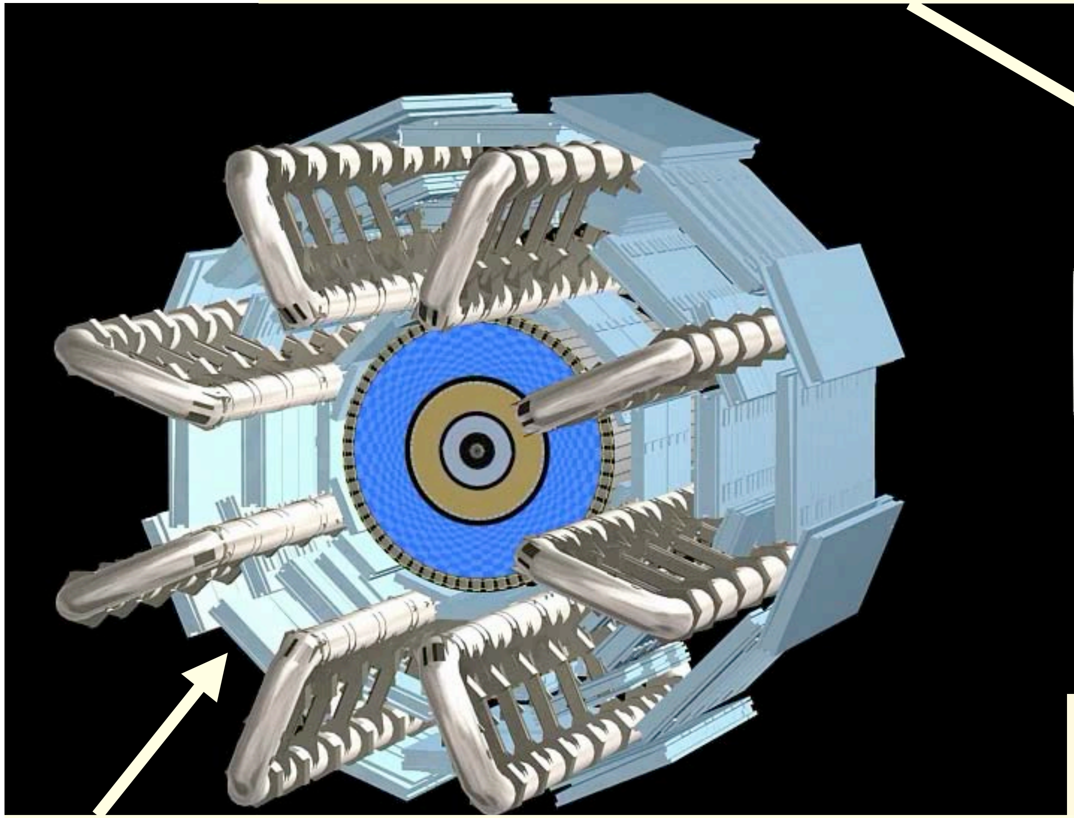




The Muon Spectrometer

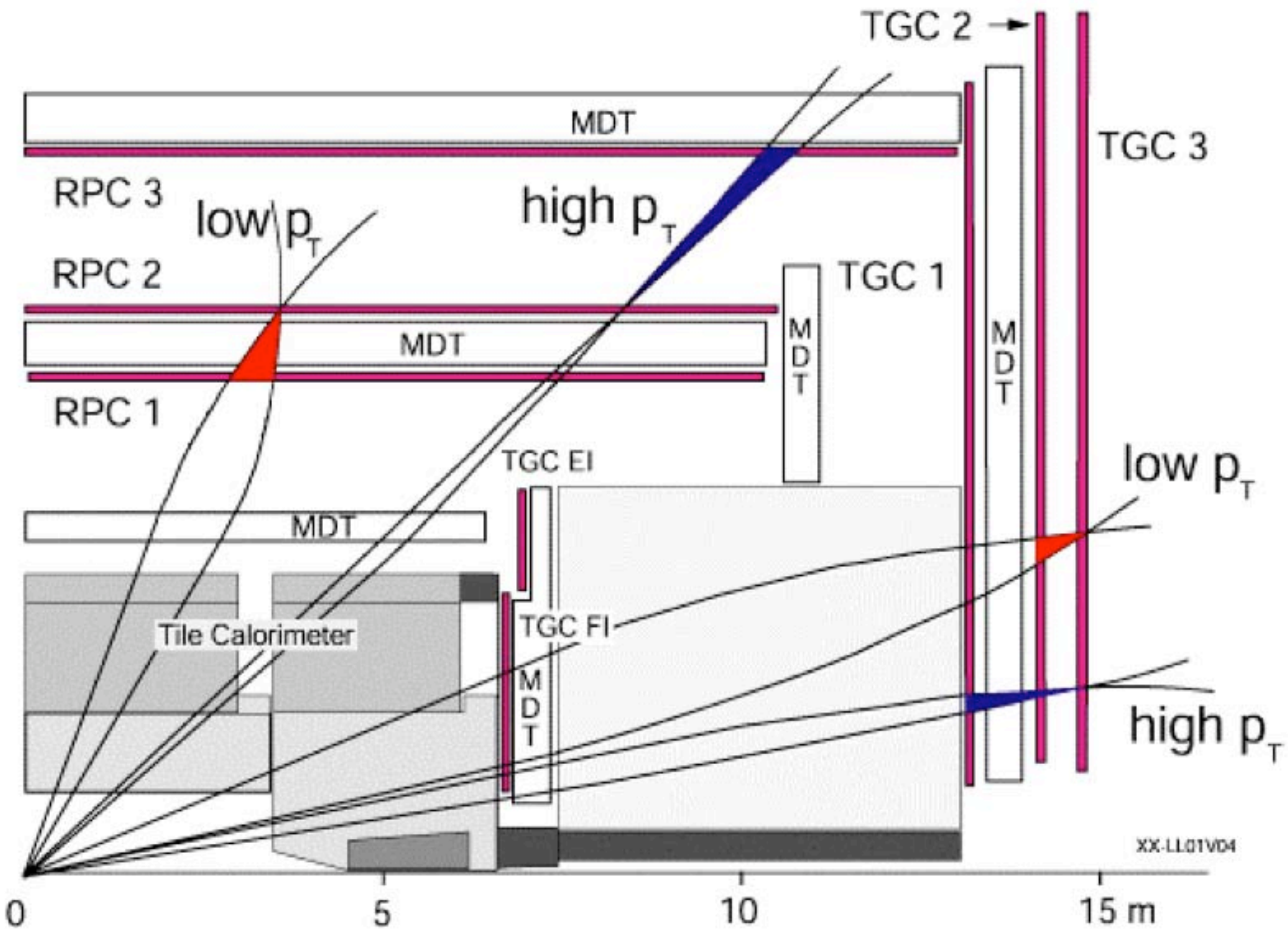
Forward: precision and trigger chambers in 5 wheels:
small - big - EO





Barrel: precision and trigger chambers in 3 layers: *I (inner) - M (middle) - O(outer)*

The Muon Spectrometer (LVL1 trigger)



Precision chambers :

MDT : monitored drift tubes

1091 chambers, 370 k channels

CSC : cathode strip chambers

32 chambers, 31 k channels

Trigger chambers :

RPC : resistive plate chambers

1136 chambers, 385 k channels

TGC : thin gap chambers

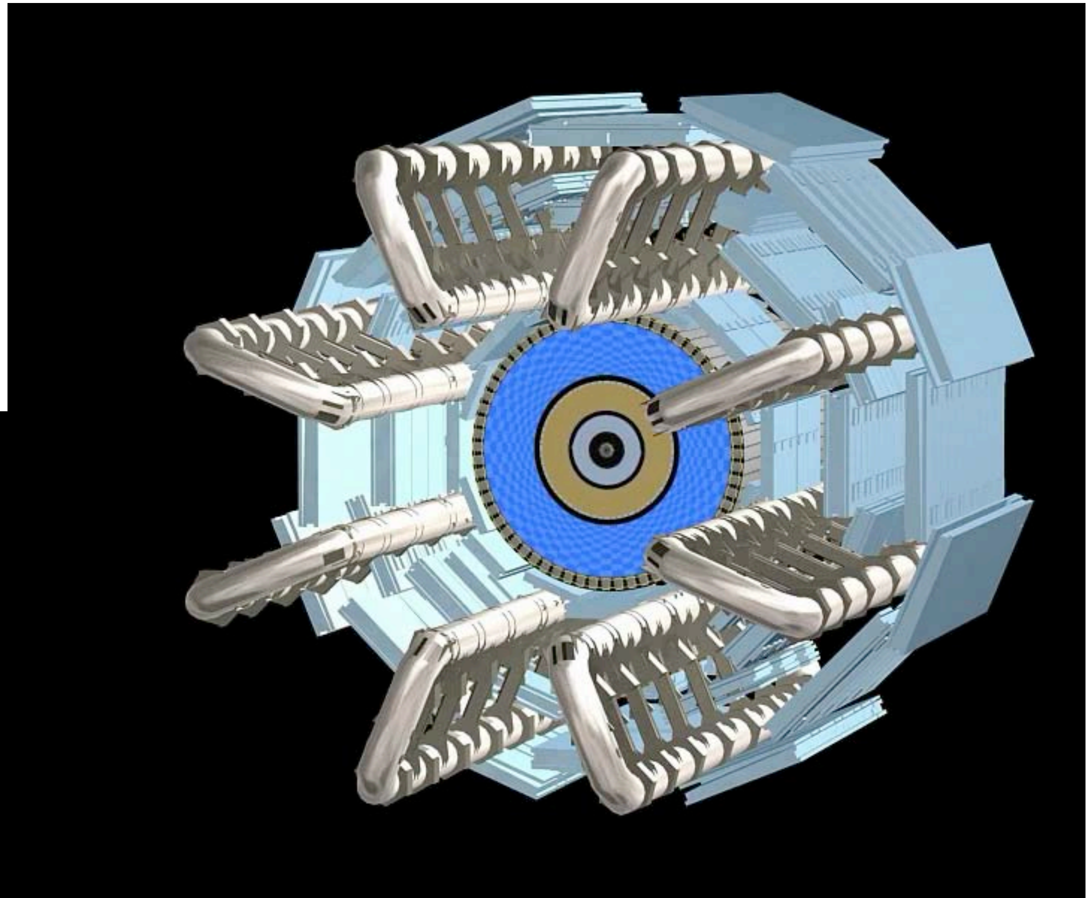
1584 chambers, 322 k channels

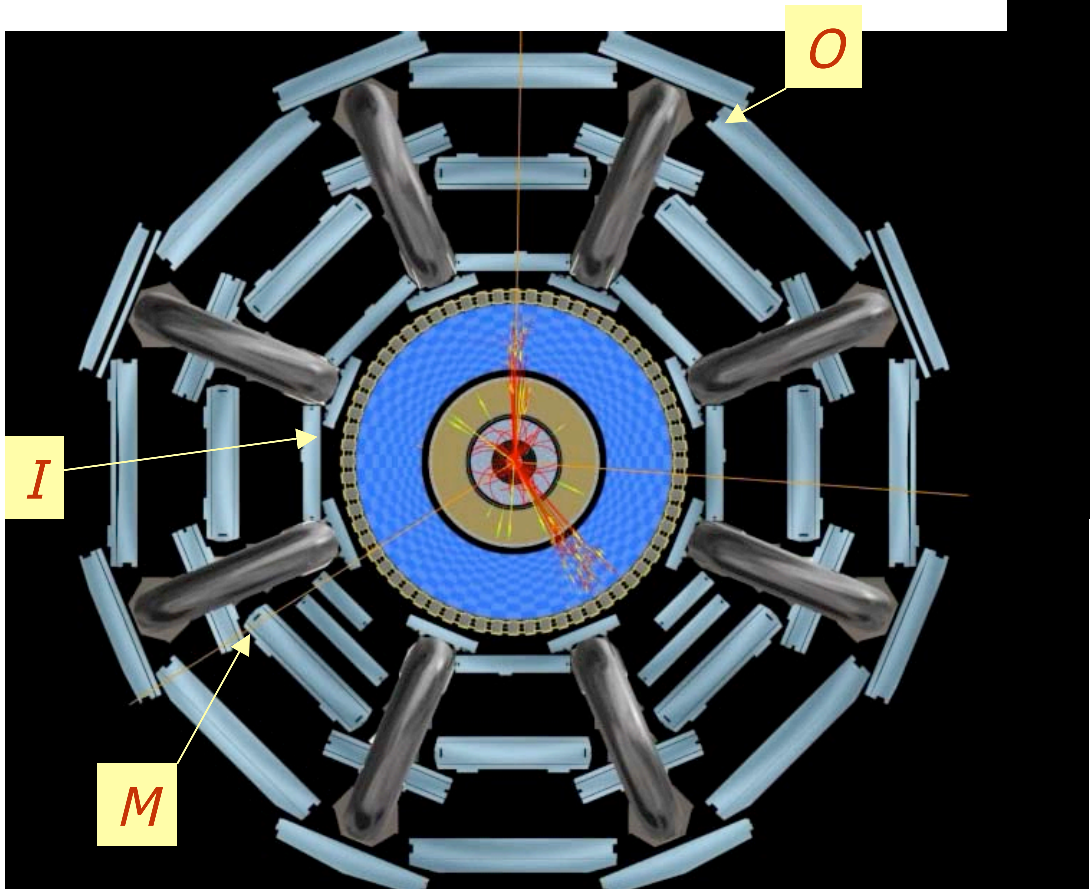
$\Delta p_T / p_T$ ~ 2% for p_T = 10–100 GeV in standalone mode

Total : ~12’000 m^2, ~ 1.1 M channels

The muon spectrometer (barrel)

Barrel: precision and trigger chambers in 3 layers:
I (inner) - M (middle) O(outer)





2 technologies:

MDT - *Monitored Drift Tubes (layers: I,O,M)*

RPC - *Resistive Plate Chambers (trigger) (layers M+M,O)*

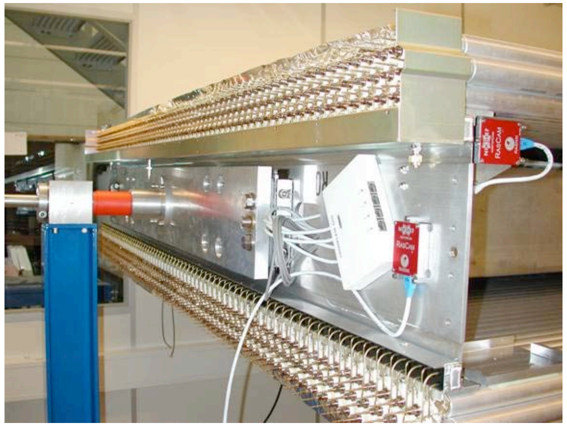
The muon spectrometer

Barrel station:

Two MDT layers (2 x 3 planes)

Two (M-layer), One (O-layer) RPC chambers

The muon spectrometer (MDT)

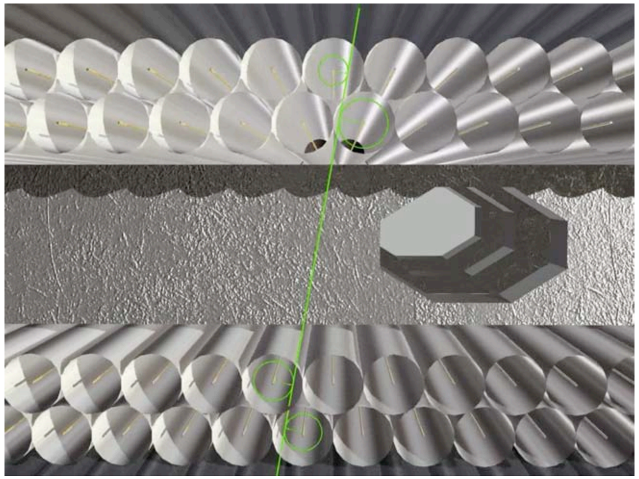


30 mm ϕ high precision Al tubes

Wire ϕ 50 μm

Operating pressure 3 bar

Gas : Ar/CO_2; HV : 3270 V



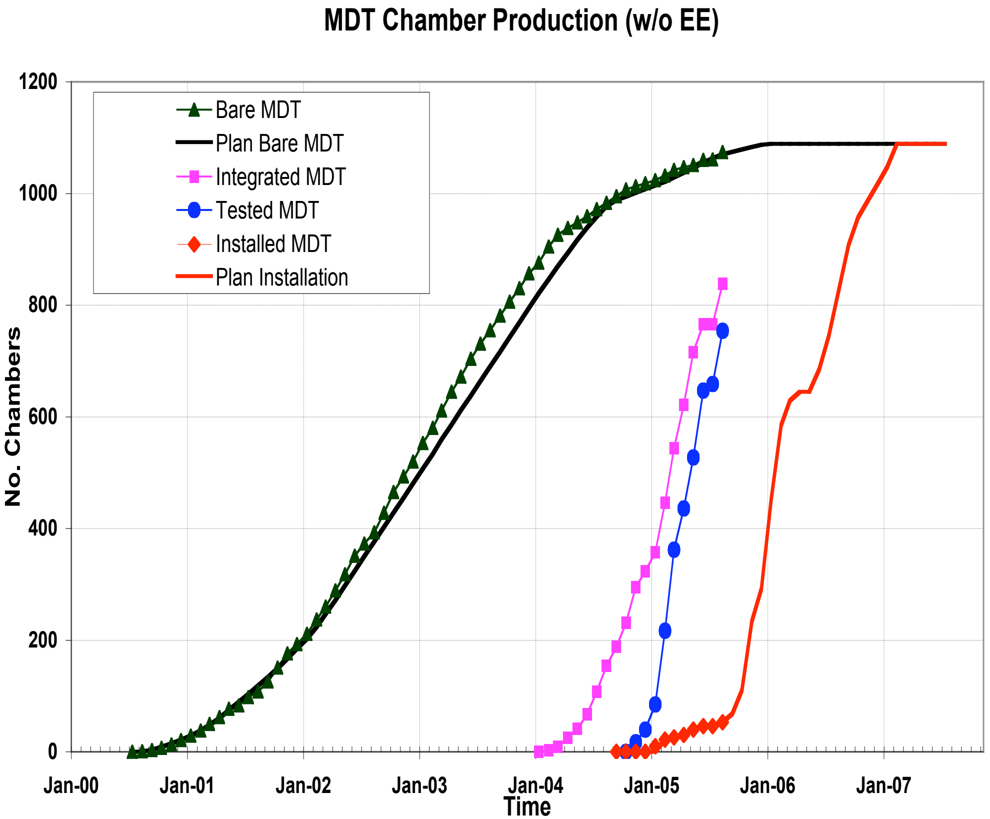
3 layers of tubes
(4 layers inner ch.)

3(4) layers of tubes
(wire position 20μm)

Single wire resolution 80 μm

1091 MDT chambers needed, ~ 5500 m^2, construction in 18 ATLAS Labs.

The muon spectrometer (MDT)



Production status as of October 2005, by Feb '07 all was installed

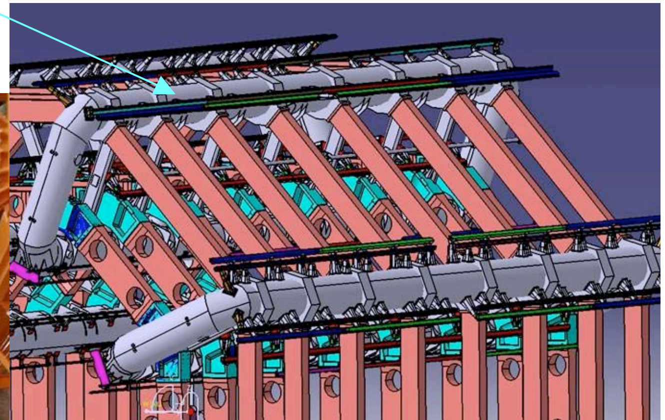
All chambers tested with cosmics. All production plants monitored with a X-rays Tomograph (chambers sampling). All stations tested on cosmics, just before installation

The muon spectrometer (barrel assembly)

~ 85 stations installed during magnet assembly (most difficult and inaccessible locations)

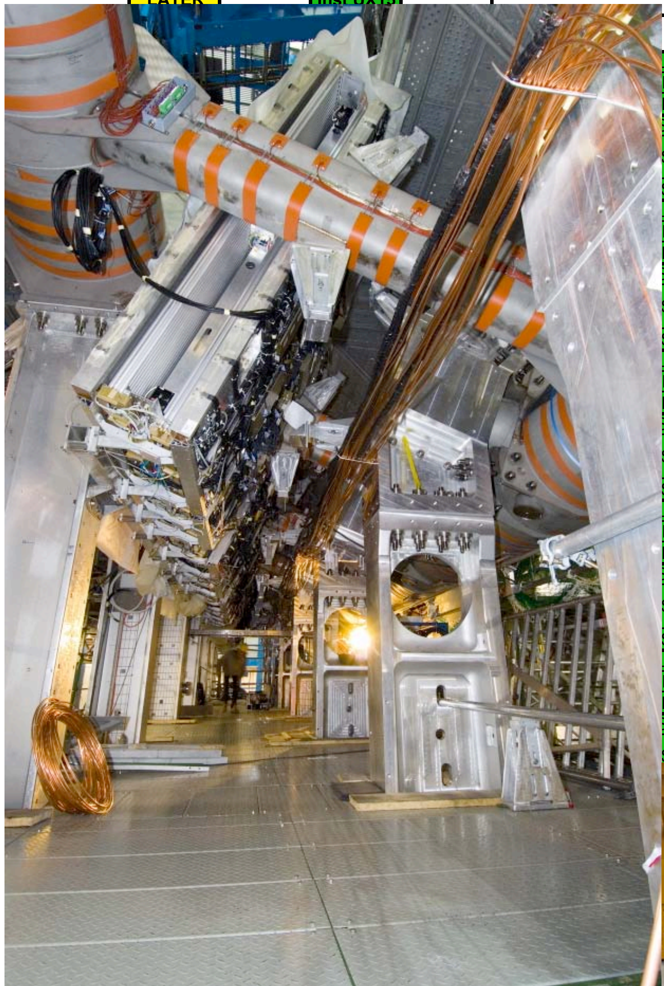
Main installation campaign between December 2005 and February2007

Stations sliding on pre-assembled rails from the extremities



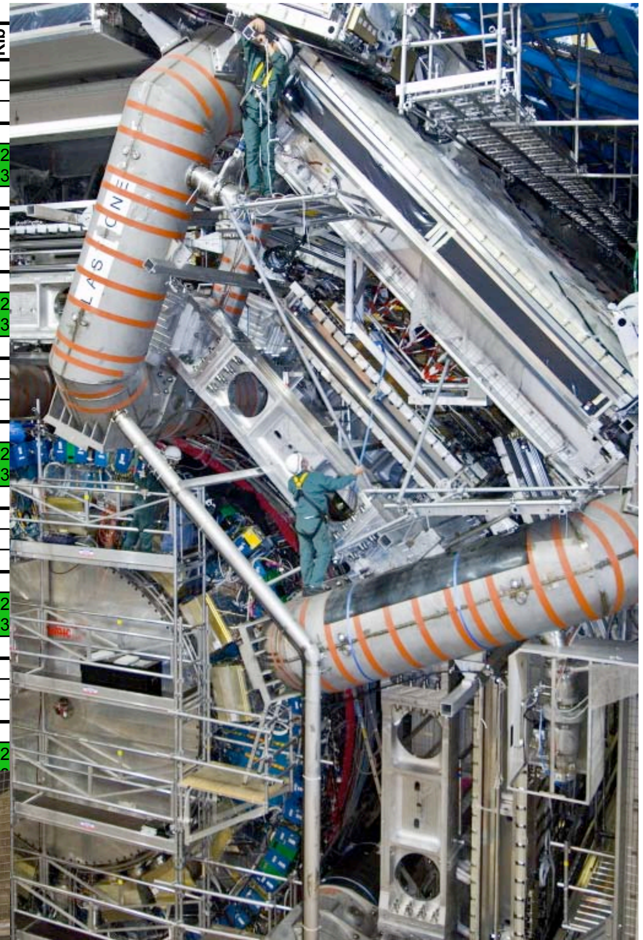
99% of all barrel muon chambers installed

LATER		Inst UX15	



Rib			Side B			Rib	Side C		Rib
	BIL.2	BIL.1		BIL.1	BIL.2		BIL.3	BIL.4	
	BIS.2	BIS.1		BIS.1	BIS.2		BIS.3	BIS.4	
S2 S2	BMS.2	BMS.1		BMS.1	BMS.2	S2 S2	BMS.3	BMS.4	S2 S3
	BOS.2	BOS.1		BOS.1	BOS.2		BOS.3	BOS.4	
	BIL.2	BIL.1		BIL.1	BIL.2		BIL.3	BIL.4	
	BML.2	BML.1		BML.1	BML.2		BML.3	BML.4	
	BOL.2	BOL.1		BOL.1	BOL.2		BOL.3	BOL.4	
	BIS.2	BIS.1		BIS.1	BIS.2		BIS.3	BIS.4	
S2	BMS.2	BMS.1		BMS.1	BMS.2	S2	BMS.3	BMS.4	S2

- ✓ 695/704 stations installed
- ✓ ~75% precisely positioned
- ✓ very acrobatic enterprise, no accidents, no damages
- ✓ all gas pipes and distribution installed
- ✓ ~95% of all cables installed



Bottom			BOL.6	BOL.5		BOL.4	BO
Sector 14	BIS.8	BIS.7	BIS.6	BIS.5		BIS.4	BIS
				BMF.3			BM
US	BOG.8	BOF.7	BOG.6	BOF.5		BOG.4	BO
Sector 15				BIM.5		BIM.4	BIM
		EIL4	BIR.6	BIR.5		BIR.4	BIF
		BML.7	BML.6	BML.5		BML.4	BM
US			BOL.6	BOL.5		BOL.4	BO
Sector 16	BIS.8	BIS.7	BIS.6	BIS.5		BIS.4	BIS
			BMS.6	BMS.5	S2 S3	BMS.4	BM
US			BOS.6	BOS.5		BOS.4	BO

BOF.5	BOG.6	BOF.7	BOG.8	15	17	88%
BIL.5	BIL.6	EIL4		11	14	79%
BML.5	BML.6	BML.7		12	12	100%
BOL.5	BOL.6			10	12	83%
BIS.5	BIS.6	BIS.7	BIS.8	16	16	100%
BMF.3				6	6	100%
BOF.5	BOG.6	BOF.7	BOG.8	15	17	88%
BIM.5				10	10	100%
BIR.5	BIR.6	EIL4	0	14	14	100%
BML.5	BML.6	BML.7		14	14	100%
BOL.5	BOL.6			12	12	100%
BIS.5	BIS.6	BIS.7	BIS.8	16	16	100%
BMS.5	BMS.6			20	20	100%
BOS.5	BOS.6			12	12	100%
			All	695	704	99%

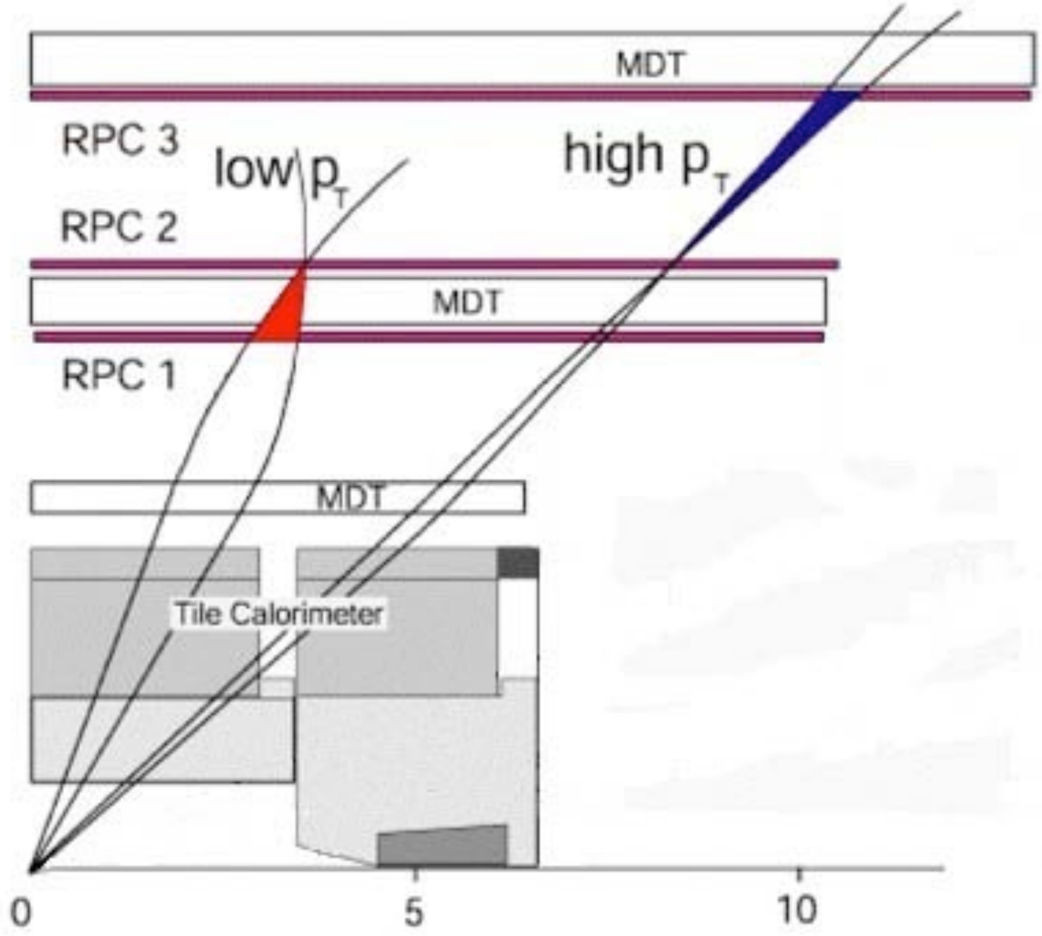
The muon spectrometer (trigger)

Low p_T trigger:

- at least 3 out 4 track hits in RPC1 and RPC2
- p_T > 6 GeV
- progr. coincidence matrix + pipeline

High p_T trigger:

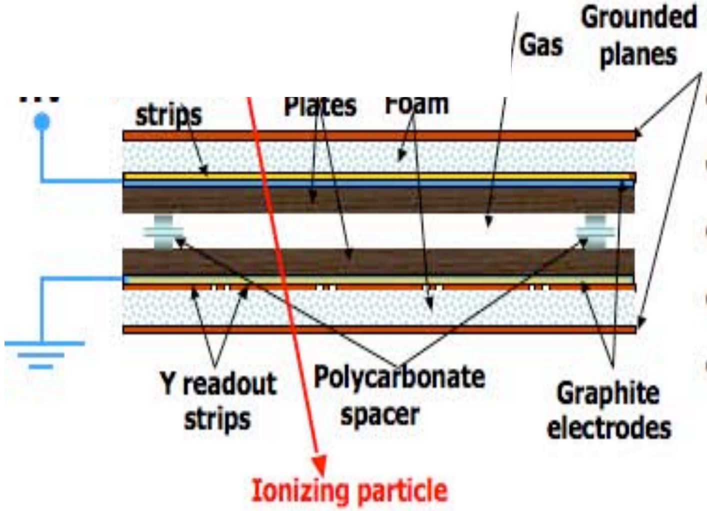
- low p_T and at least 1 track hit in RPC3
- p_T > 20 GeV
- progr. coincidence matrix + pipeline



Trigger chambers (RPC) rate capability required ~ 1 kHz/cm^2

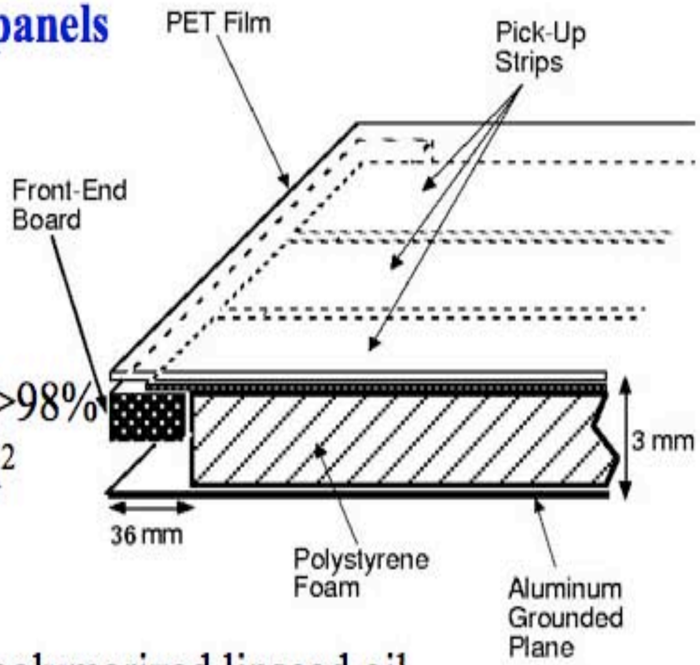
The muon spectrometer (RPC)

ATLAS RPC



- Saturated avalanche regime.
- Bunch crossing ID (TW ~ ns).
- XY measurement (~ 1 cm).
- Rate Capability ~1 kHz/cm^2@Eff.>98%
- Gap volume size from 1.72×0.75m^2 up to 2.96x1.2m^2.

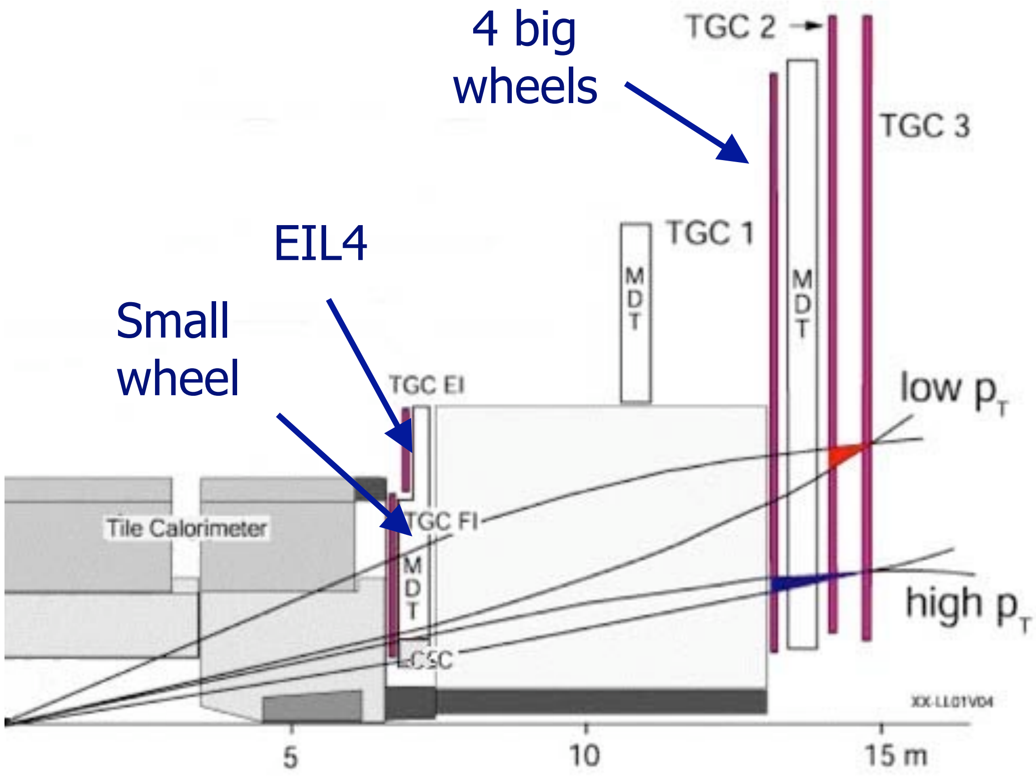
Readout panels layout

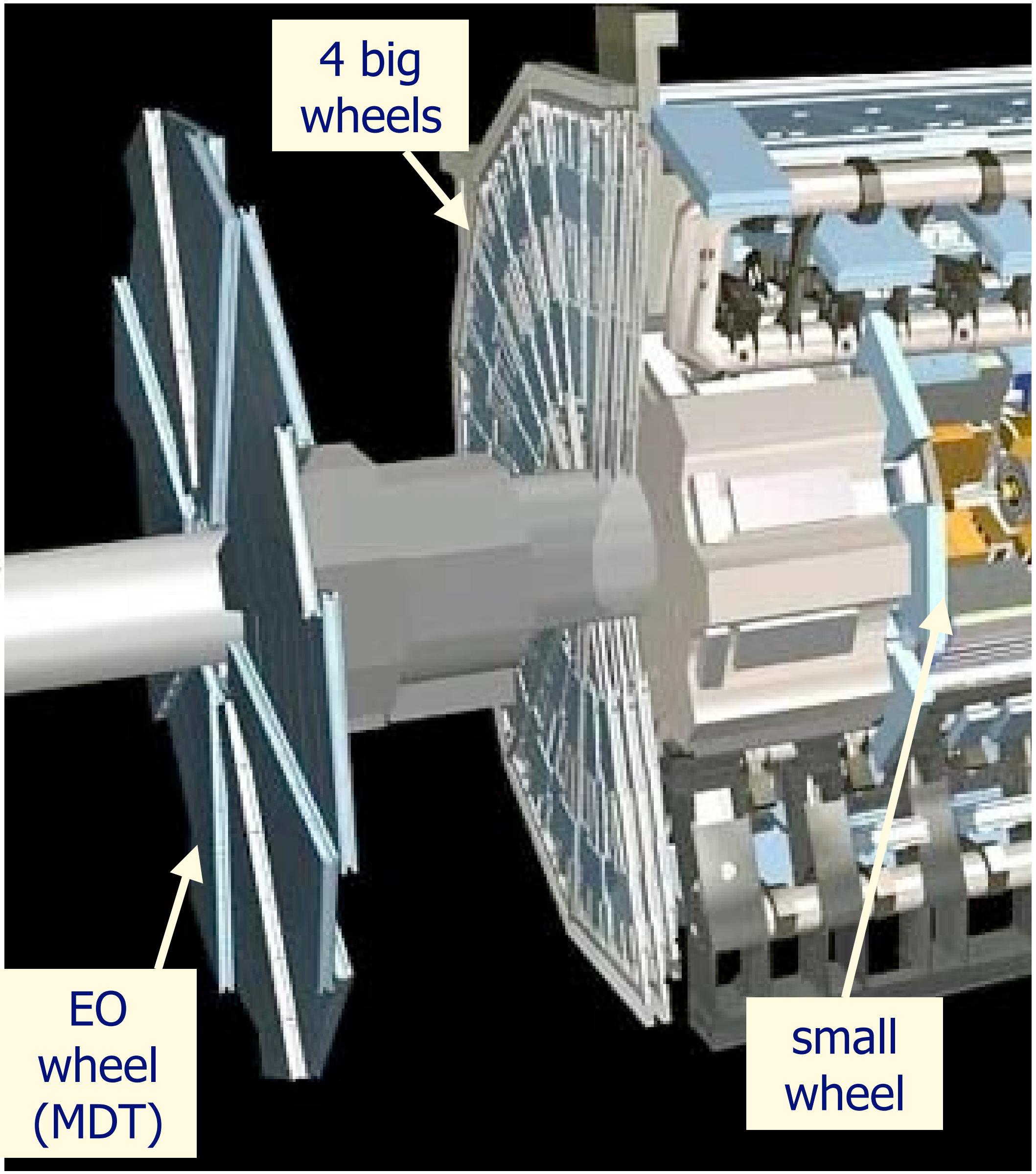


- Electrodes: graphite layer+ 2 mm thick bakelite (ρ~ 1÷4x10^{10} Ωcm) + polymerized linseed oil.
- Gap gas: d = 2 mm, $C_2H_2F_4$(94.7%)C_4H_{10}(5%)SF_6(0.3%), HV~10 KV (E_{gas} ~ 5KV/mm)
- Readout panels: X and Y copper strip (pitch ~3 cm).

1136 RPC chambers needed, ~ 3650 m^2, construction in 5 ATLAS Labs.

The muon spectrometer (forward)





3 technologies:

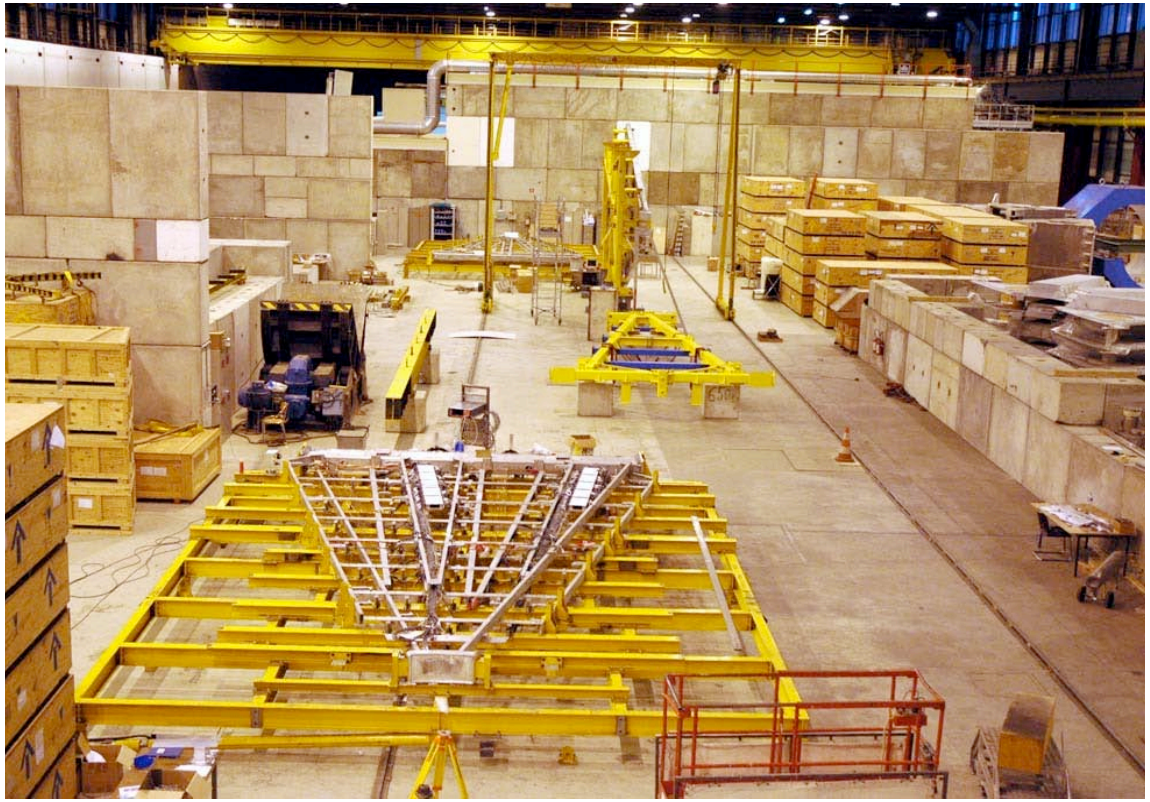
MDT - *Monitored Drift Tubes*

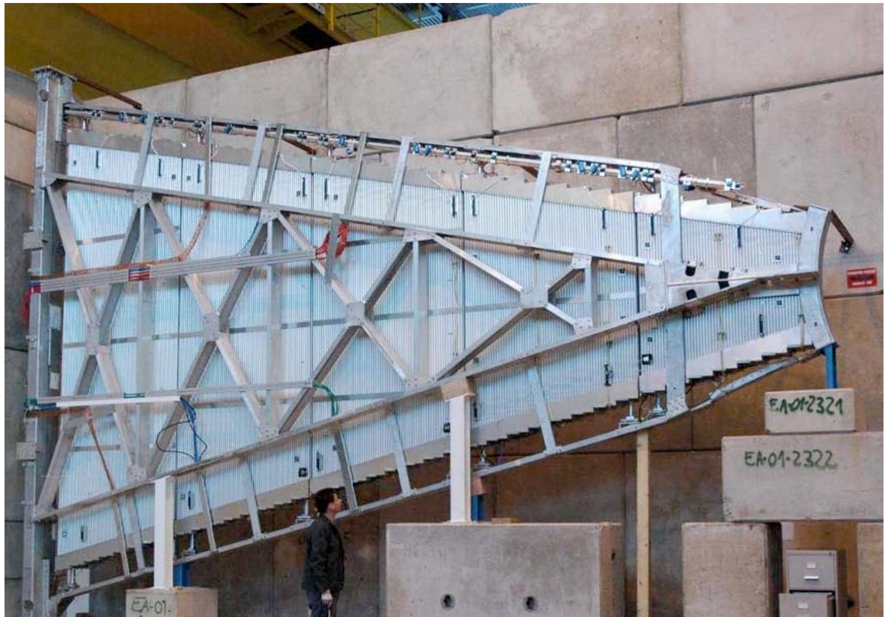
CSC - *Cathod Strip Chambers* *($|\eta| > 2$, sm. Wheel)*

TGC - *Thin Gap Chambers (trigger)*

The Muon Spectrometer (wheels)

Big wheels sectors integration at CERN

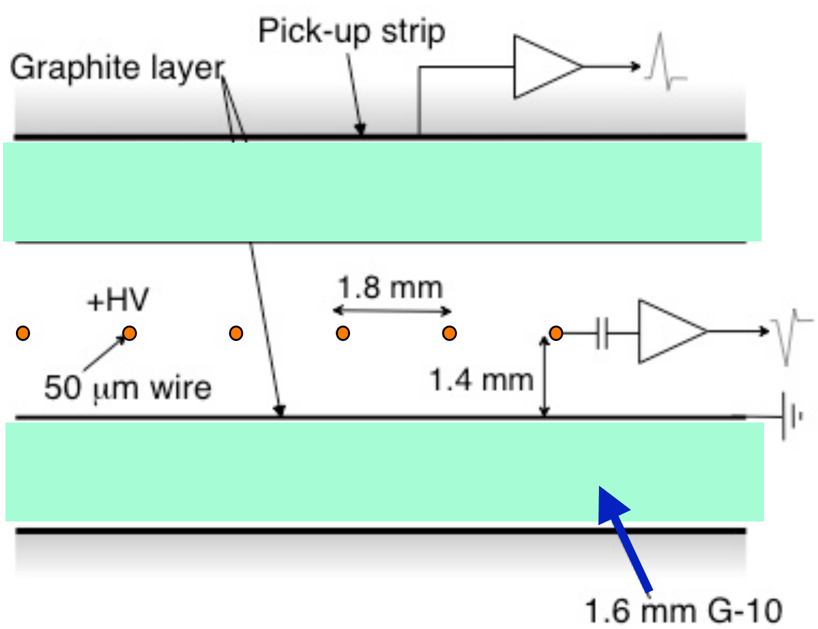


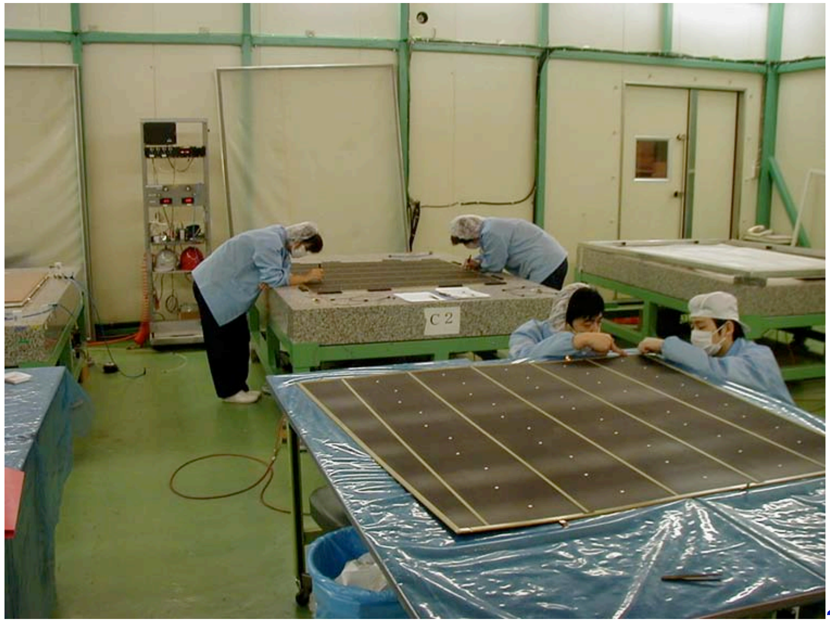


The muon spectrometer (Big Wheels)

The muon spectrometer (TGC)

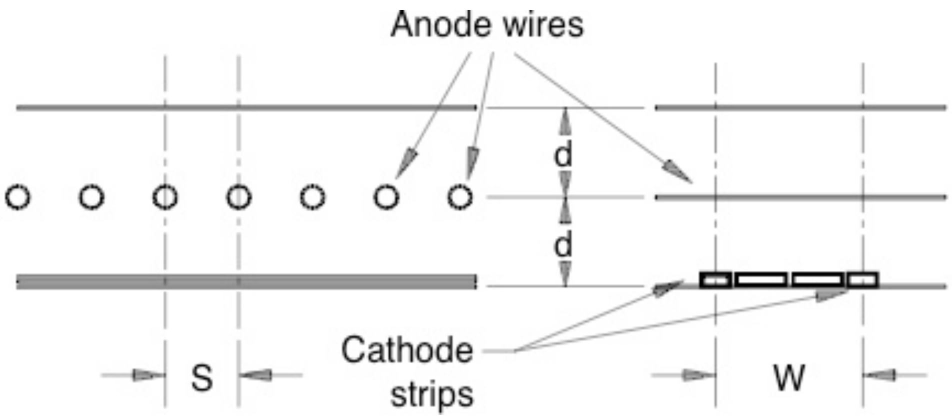
- Proportional chambers operating with a very thin gap, small drift time
- Wire signal for trigger, cathode signal for trigger and second coordinate (high rate, < 25 ns)
- Gas CO_2 + n-pentane, 3.1 KV

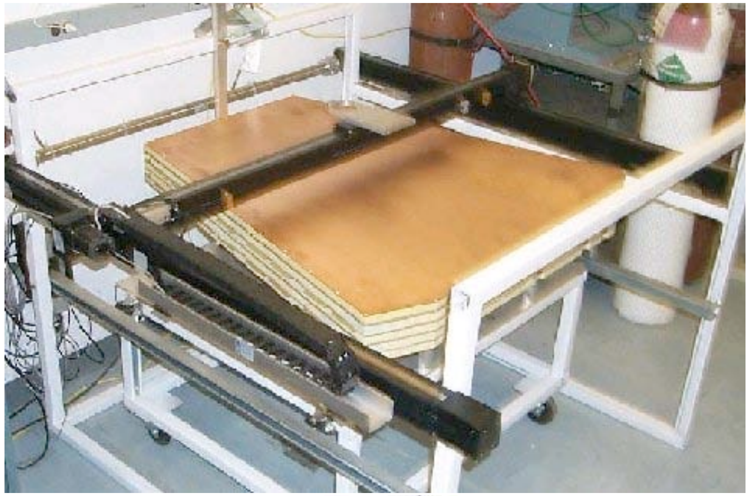




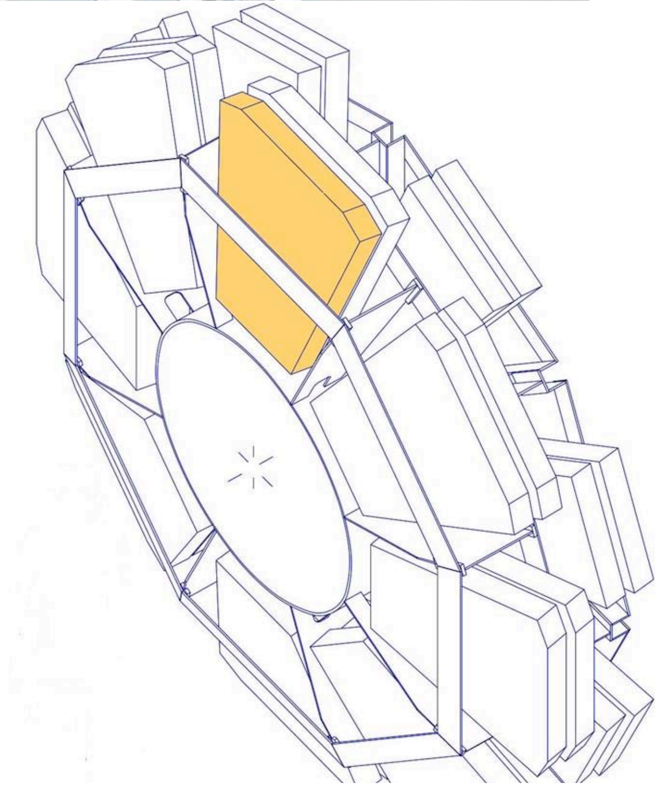
1584*2 TGC chambers needed, ~ 2900 m^2, construction in 5 ATLAS Labs.

The muon spectrometer (CSC)



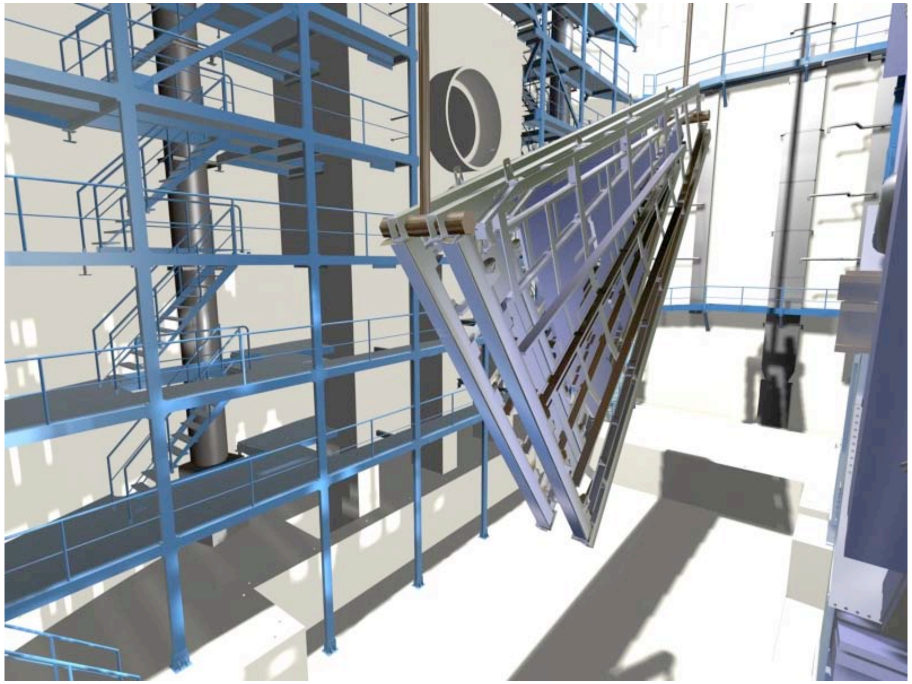


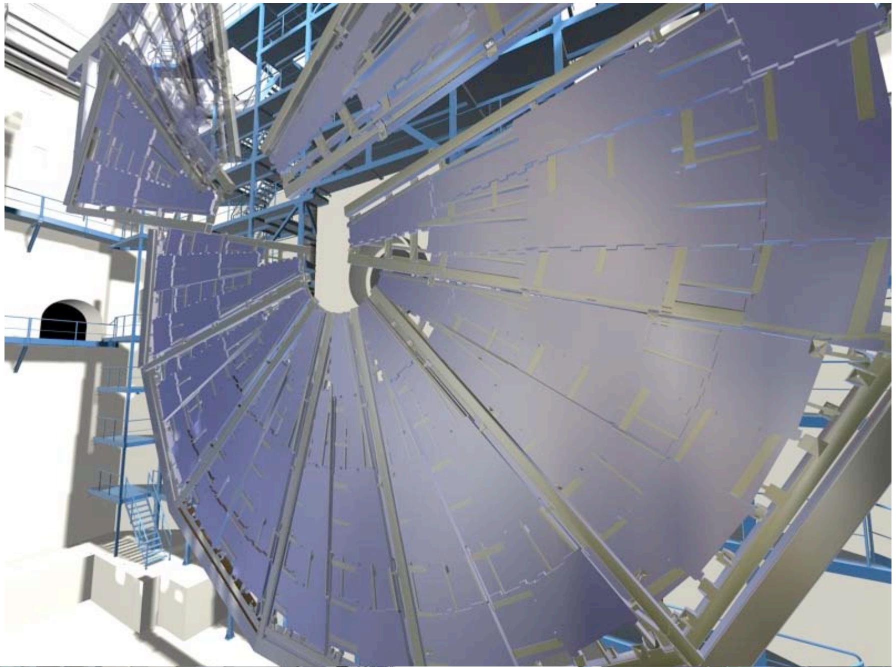
- Multiwire Proportional Chambers operating with
  d=s=2.54 mm , wire=0.015 mm
- Time resolution <7 ns, W ~ 5mm, hit resolution~ 60 μ
- Gas $Ar/CO_2/CF_4$, 2.6 KV
- All chambers constructed

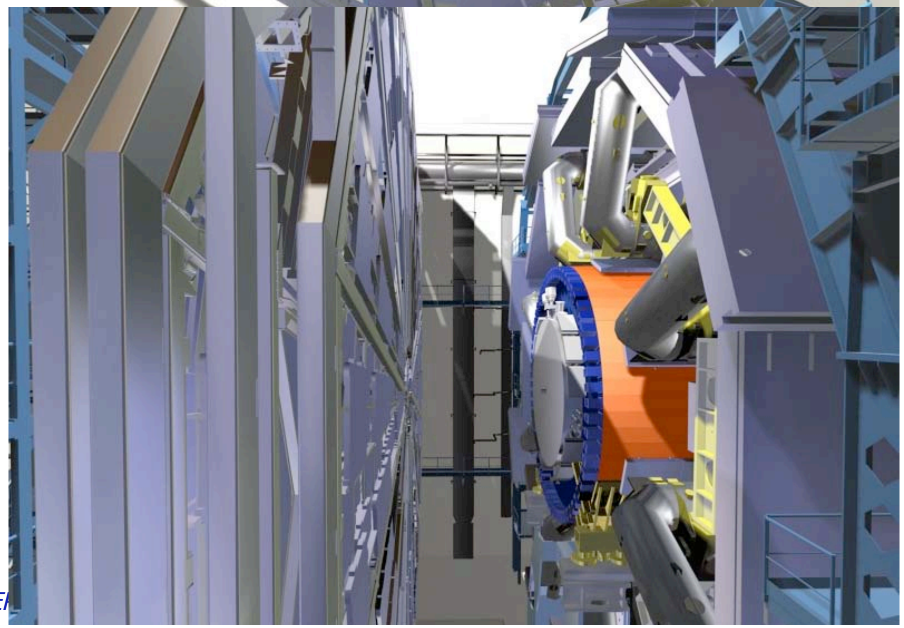


32 CSC chambers needed, ~ 27 m^2,
construction in 2 ATLAS Labs.

The muon spectrometer (wheels installation)







4 wheels on each side, 24 m diameter

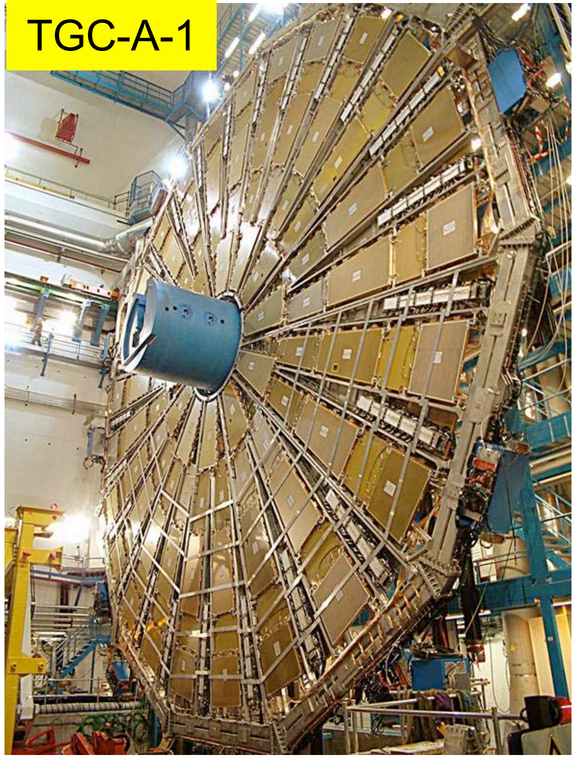
- ✓ installation in octants
- ✓ each octant is instrumented and tested on the surface
- ✓ the production of the mechanical wheels has started, installation in the ATLAS cavern in summer '06, by now 75% installed

>75% of all big wheels installed

- 1 sector / day
- 4 wheels fully assembled
- MDT side-A ongoing

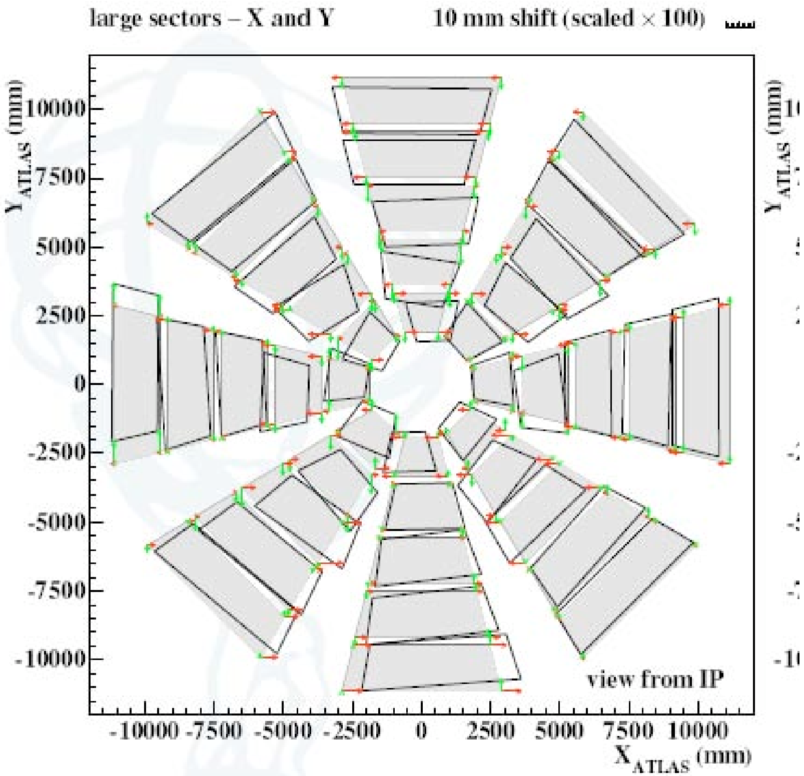
- services immediately connected
- gas, HV and alignment tests almost online
- excellent results

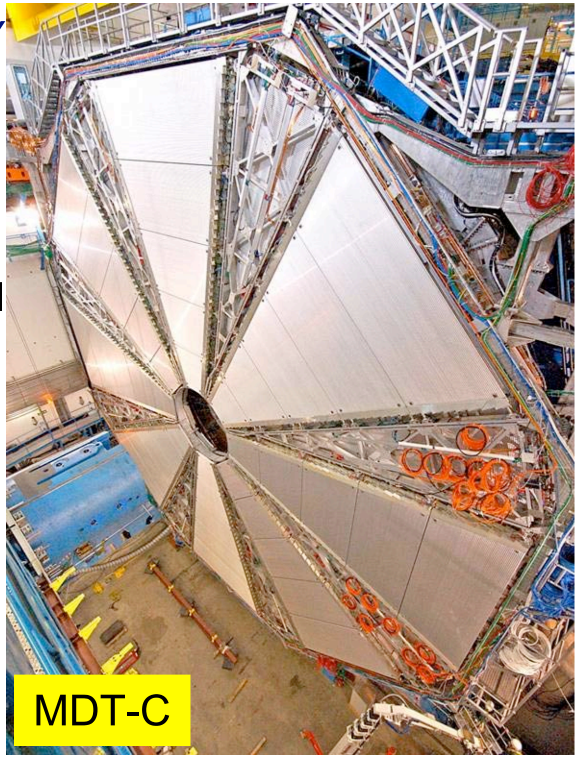
Big Wheels assembly



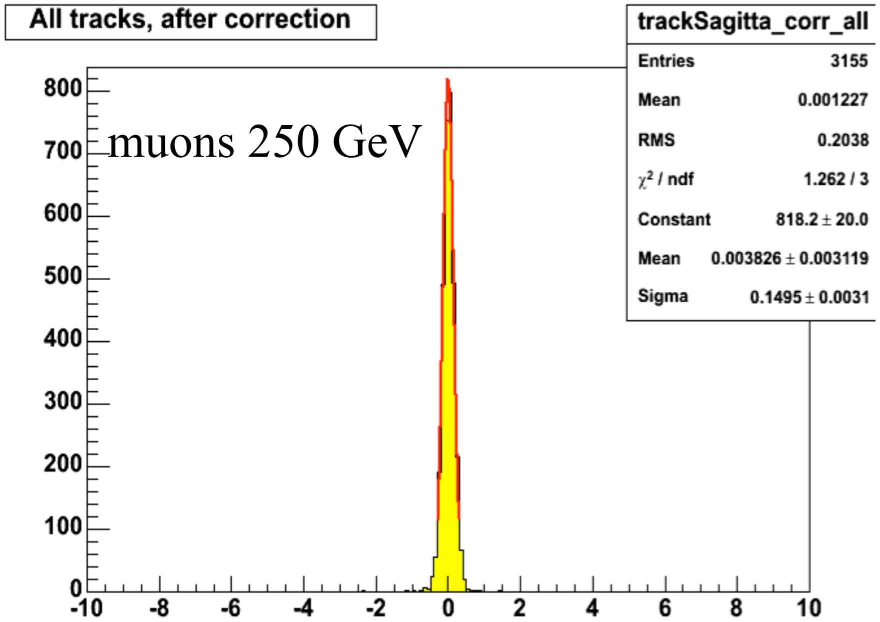
BW geometry and orientation checked by survey and alignment system. Accuracy for MDT-C:

- *x-y:* ~3 mm rms
- *z:* ~5 mm rms (mild wheel deformation)
- 24 chambers repositioned in situ to achieve satisfactory orientation of chambers and full functionality of alignment system
- Structure mechanical deformation well within predictions
- Translation system operational





Test beam :Alignment with straight tracks

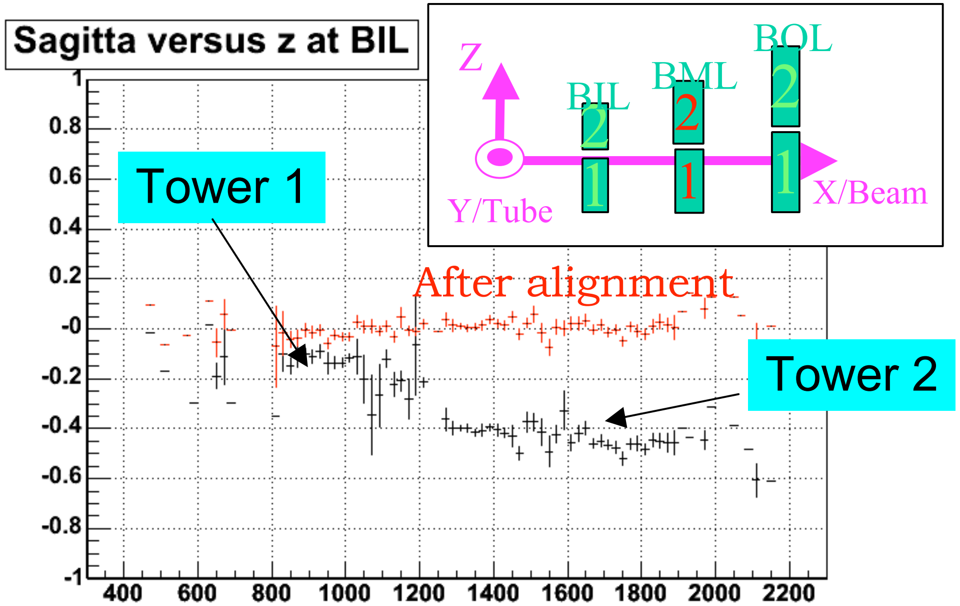


After alignment:

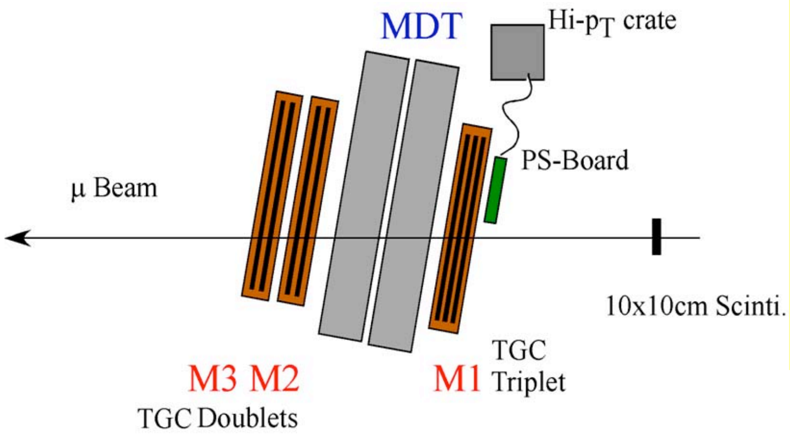
Sagitta mean value: 4 μm

Statistical error on alignment: 3μm

Relative alignment of two towers using tracks in the overlap region achieved



Test beam : TGC muon LVL1 efficiency

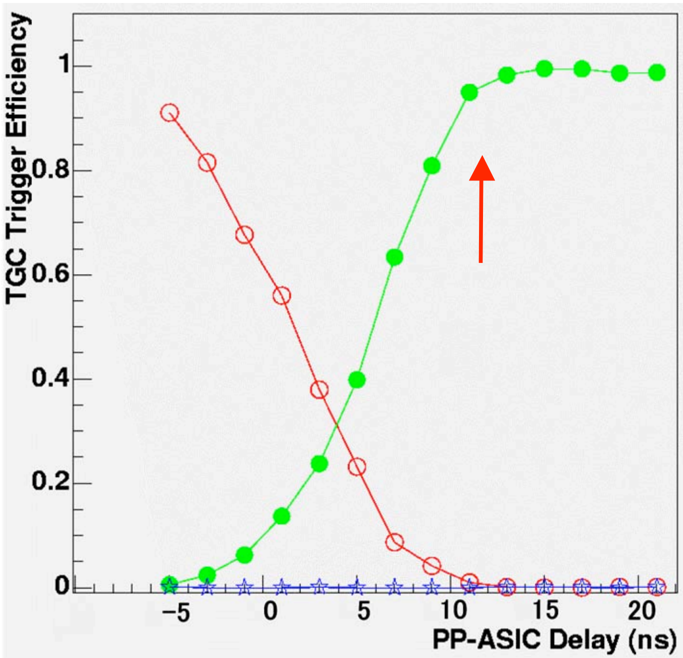


7 layers of TGC in 3 stations
Full chain of trigger/readout electronics for a part of "forward region"

- ✓ All on-board ASICs have full functionality
- ✓ DAQ including DCS in RCD framework
- ✓ 25ns bunched Muons triggered with 10x10 scintillators to measure High-Pt trigger efficiency

Adjust Delay/Gate Width parameters

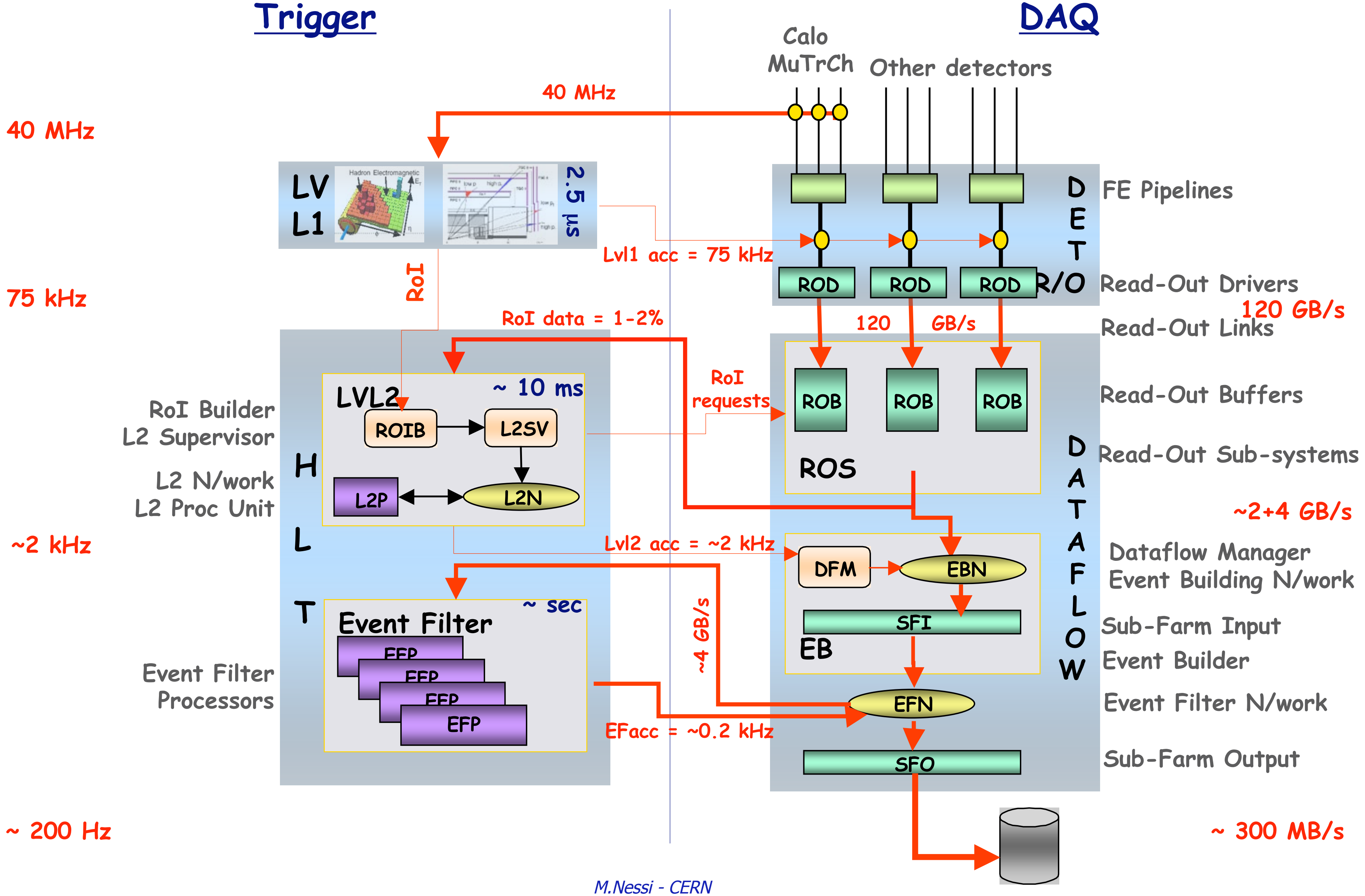
maximize Trigger efficiency and BCID performance



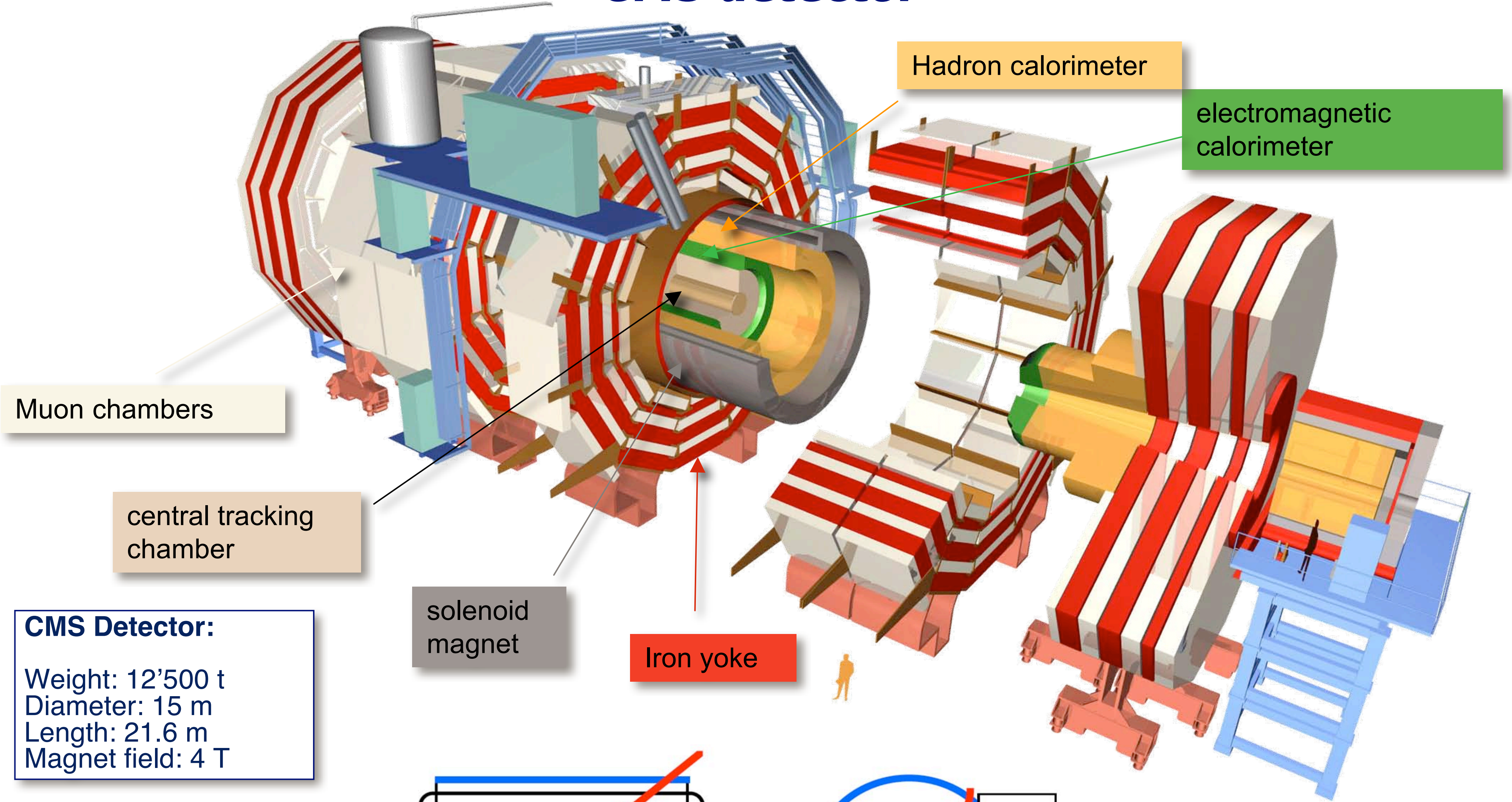
98% trigger efficiency
~1% spurious 10x10
~1% tracks out of phase

Triggered Bunch
Next Bunch
Previous Bunch

Trigger and Data Acquisition

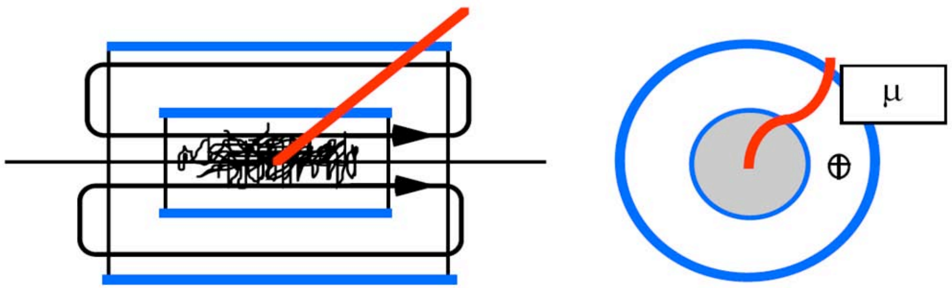


CMS detector



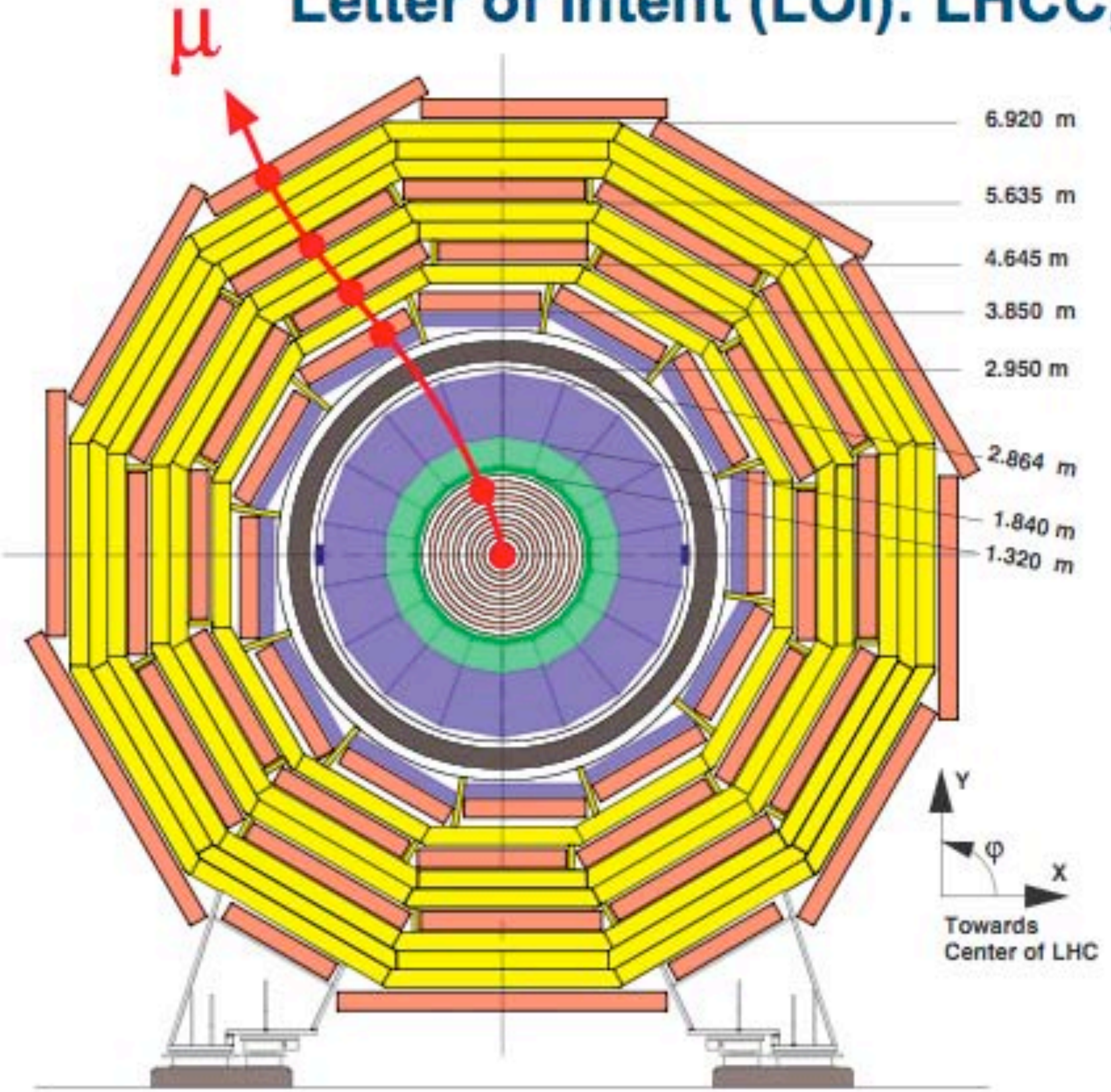
CMS Detector:

Weight: 12’500 t
Diameter: 15 m
Length: 21.6 m
Magnet field: 4 T



CMS detector

Letter of Intent (LOI): LHCC, TDR in 1994



Strong Field 4T

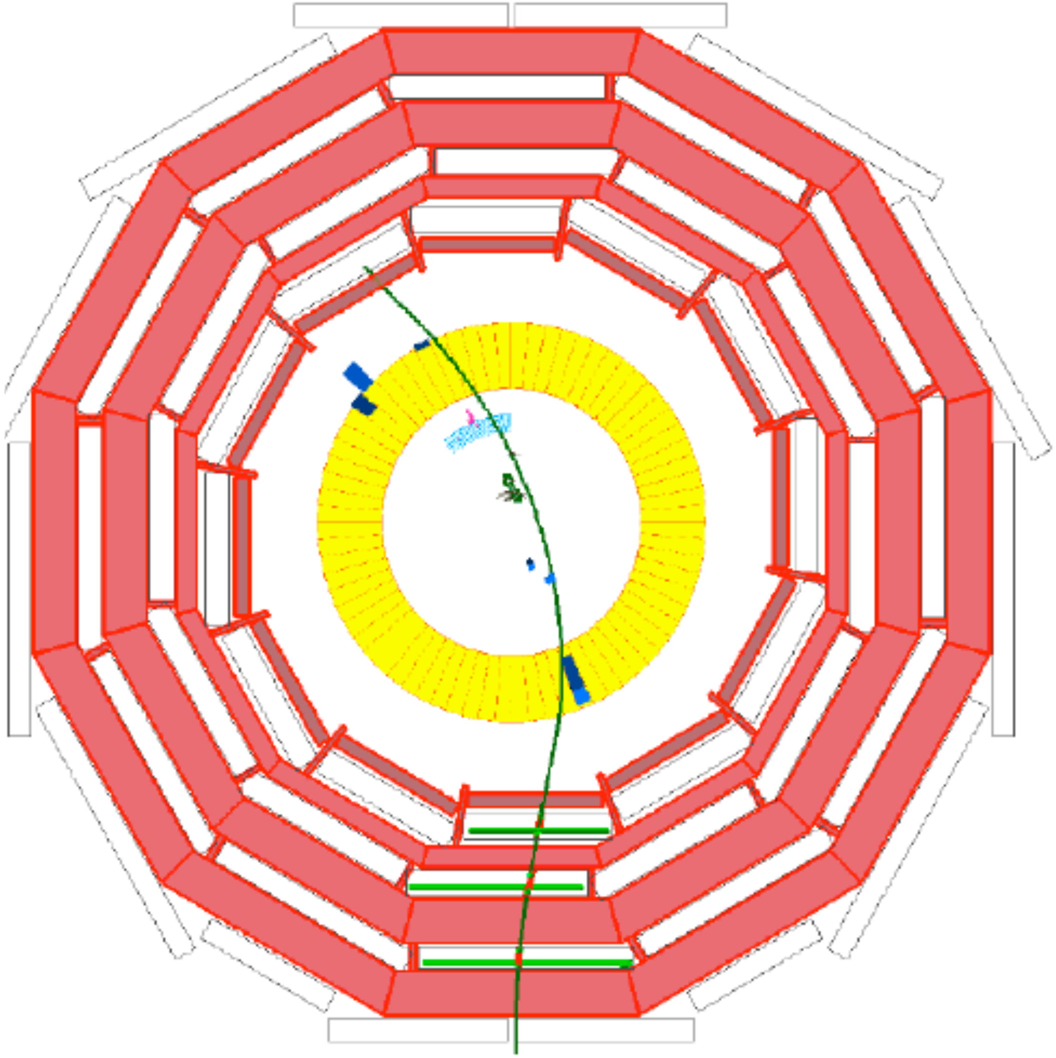
Compact design

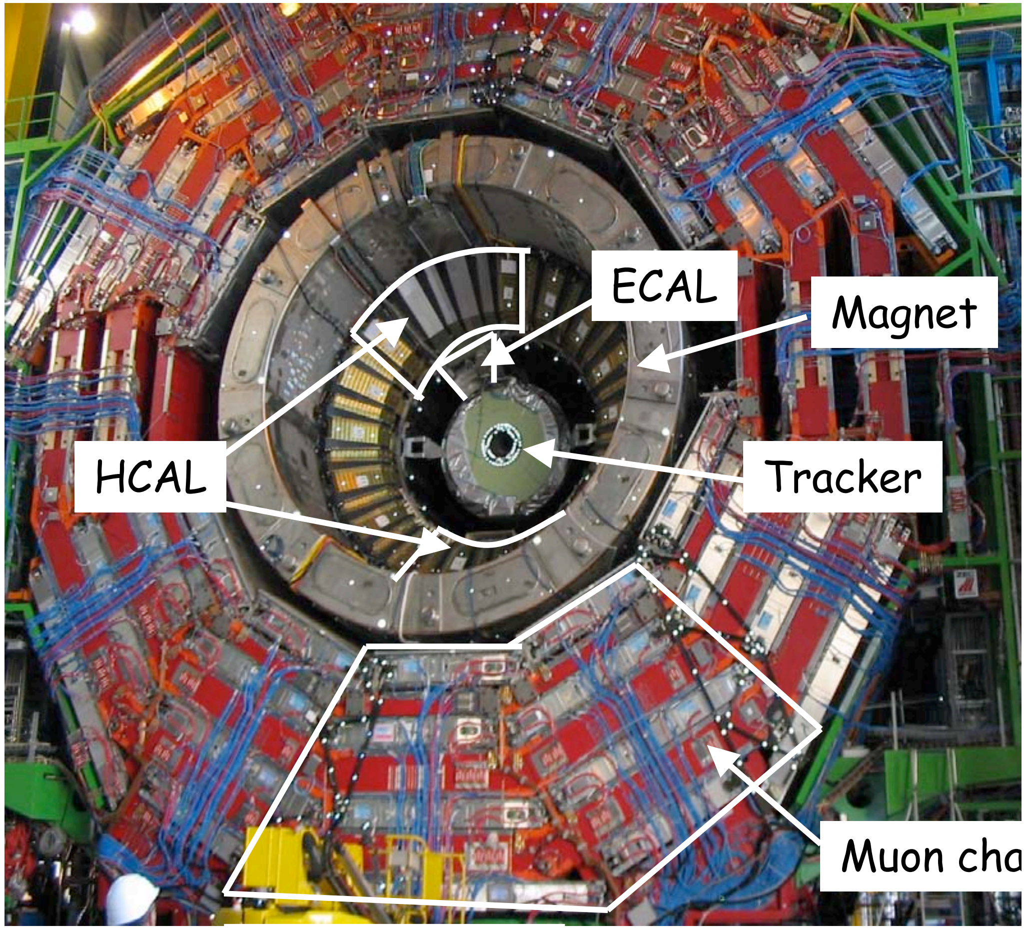
Solenoid for Muon P_t trigger in transverse plane

Redundancy: 4 muon stations with 32 r-phi measurements

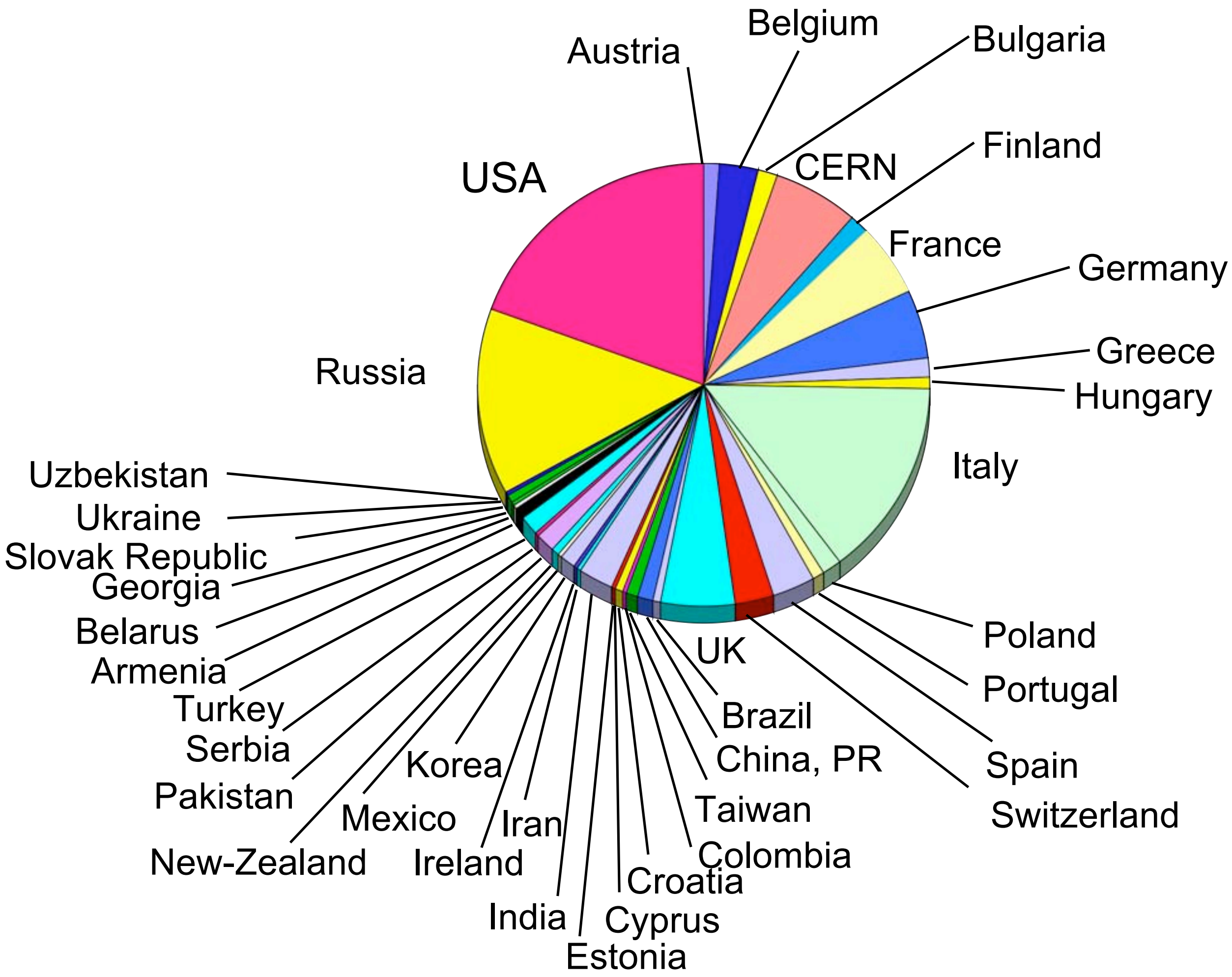
$\Delta P_t/P_t \sim 5\%$ @1TeV for reasonable space resolution of muon chambers (200μm)

First cosmics results in 2006



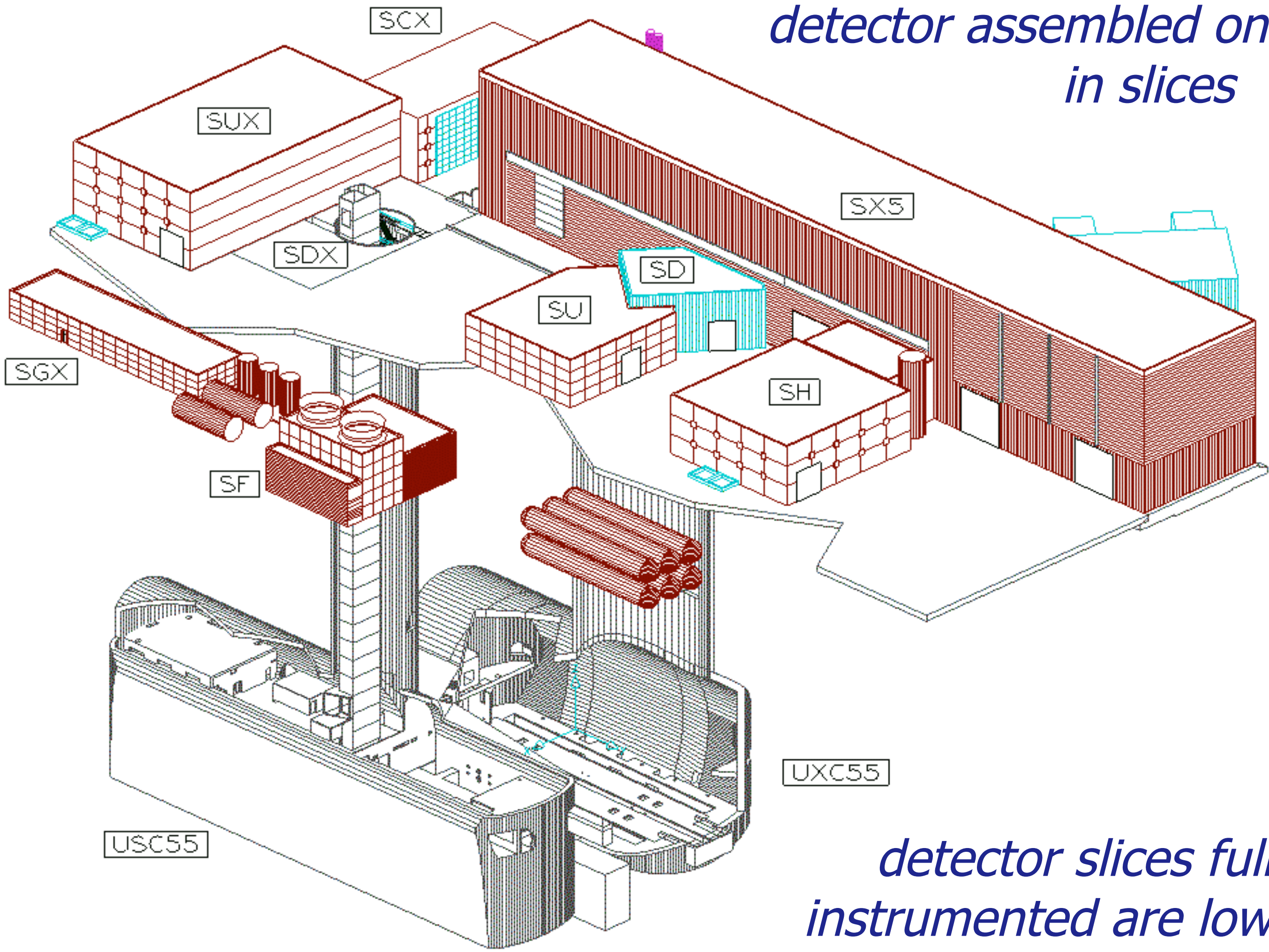


CMS collaboration (October 2006)



2524 Physicists and engineers
39 Countries
181 Institutes

CMS experimental area (Point 5)



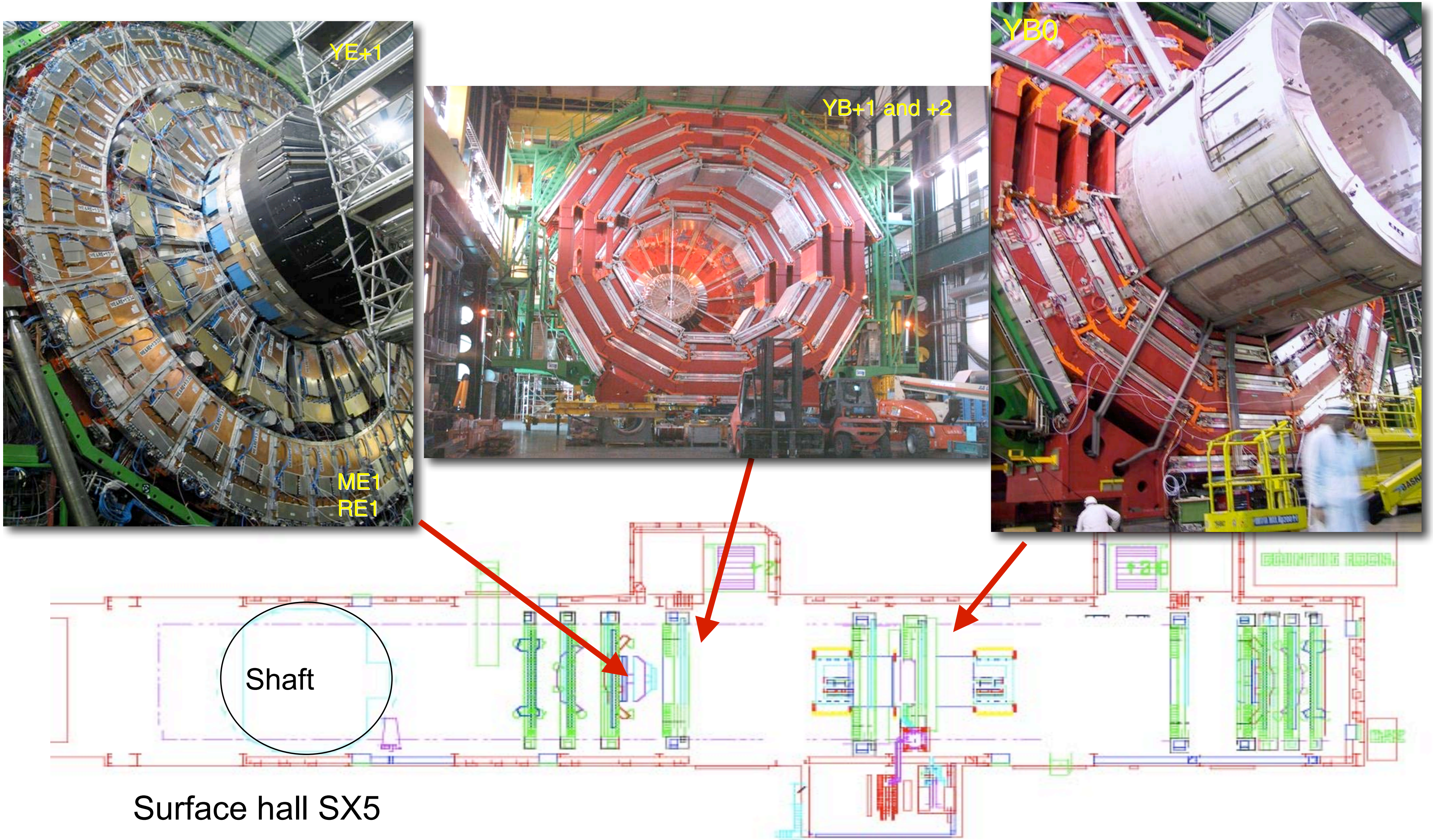
detector assembled on the surface in slices

detector slices fully instrumented are lowered down with a "gantry crane"

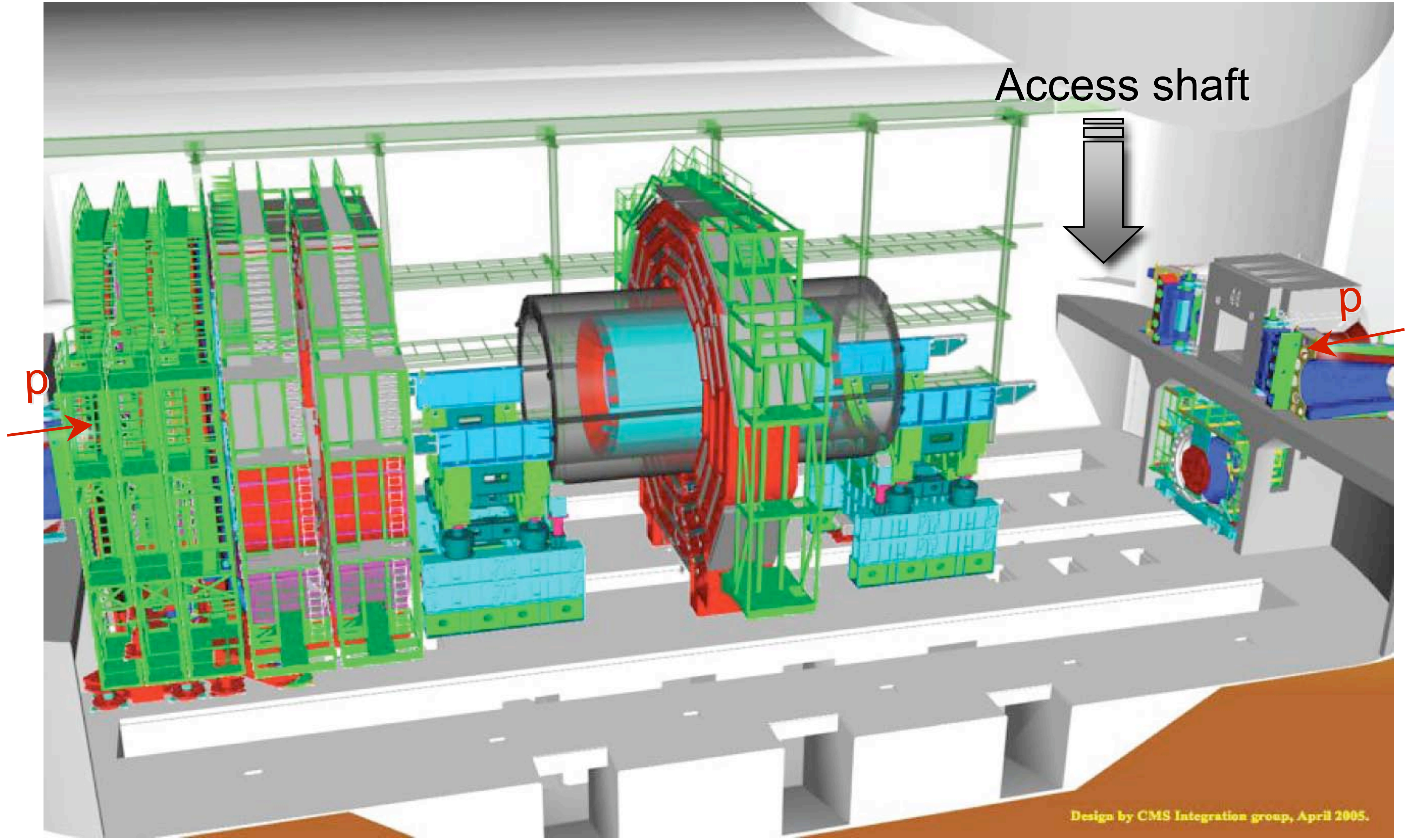
The CMS experimental cavern

The cavern is excavated in the molassa ground

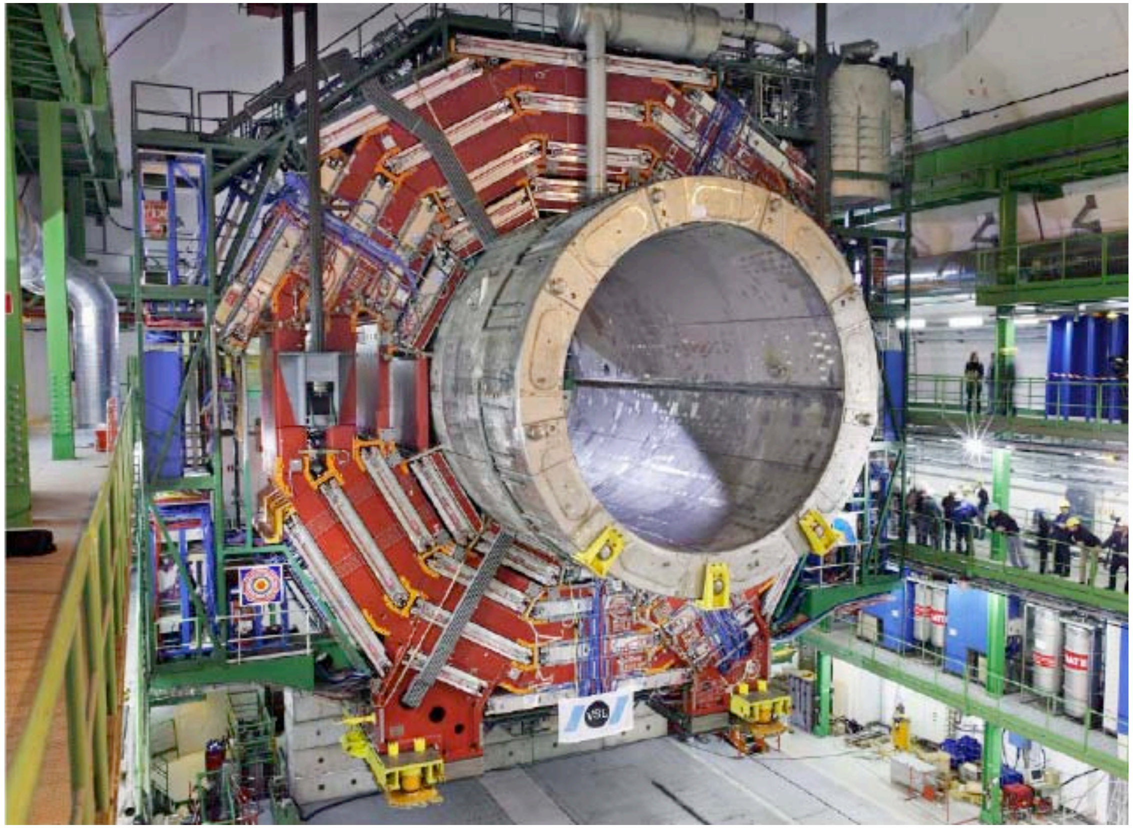
CMS Surface assembly

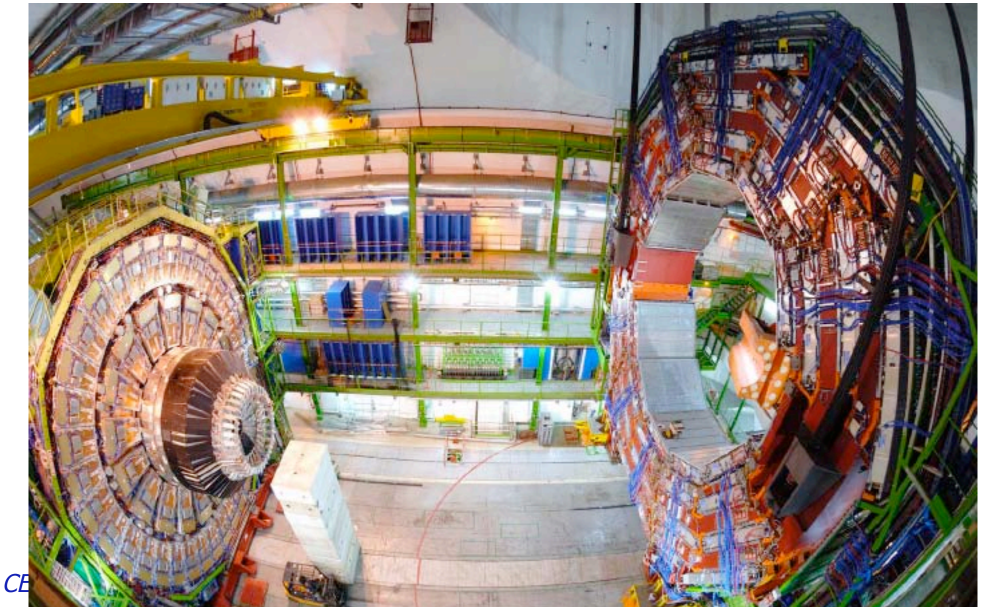


Detector assembly in the experimental cavern



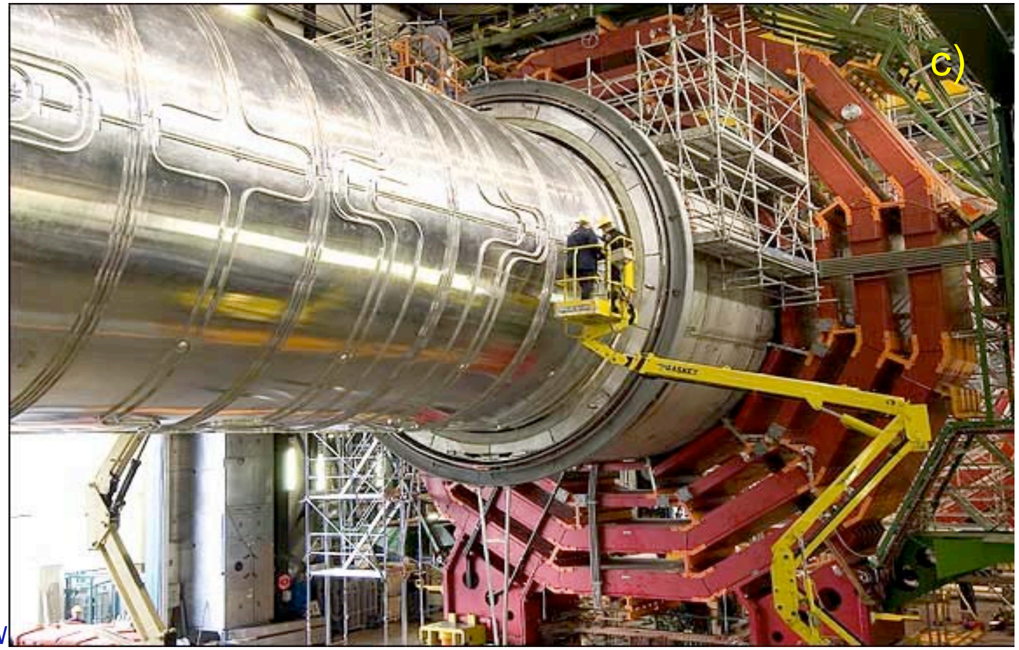
Slices lowering (2006/2007)





The Large Solenoid

The solenoidal coil (a) is introducted into the outer vacuum tank (b). The inner vacuum tank is introduced (c)



Parameters:

Coil: 230 tons

Nb-Ti Superconductor, 4 layers of winding

Outer vacuum tank: 13 m long, 7.6 m diameter

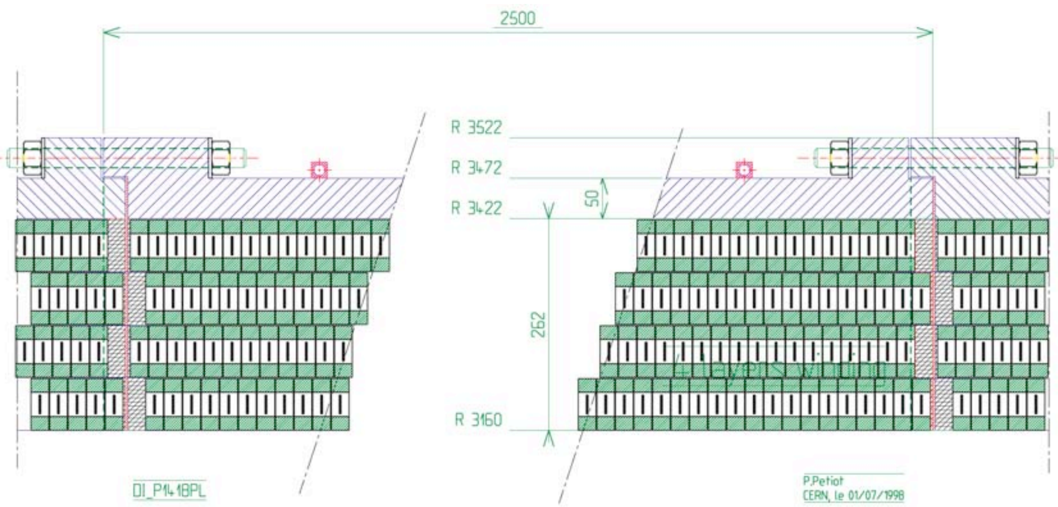
Magnet field on Axis: 4 T

Current: 20 kA

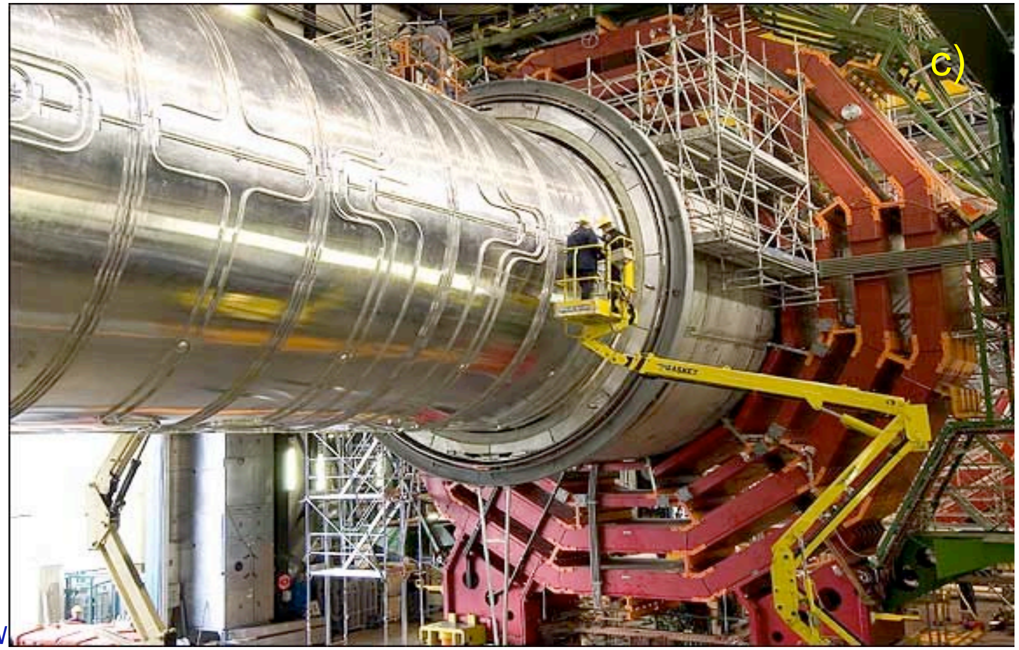
Stored Energy: 2.7 GJ

Magnetic radial pressure 64 atmospheres

The Large Solenoid



The solenoidal coil (a) is introducted into the outer vacuum tank (b) .The inner vacuum tank is introduced (c)



Parameters:

Coil: 230 tons

Nb-Ti Superconductor, 4 layers of winding

Outer vacuum tank: 13 m long, 7.6 m diameter

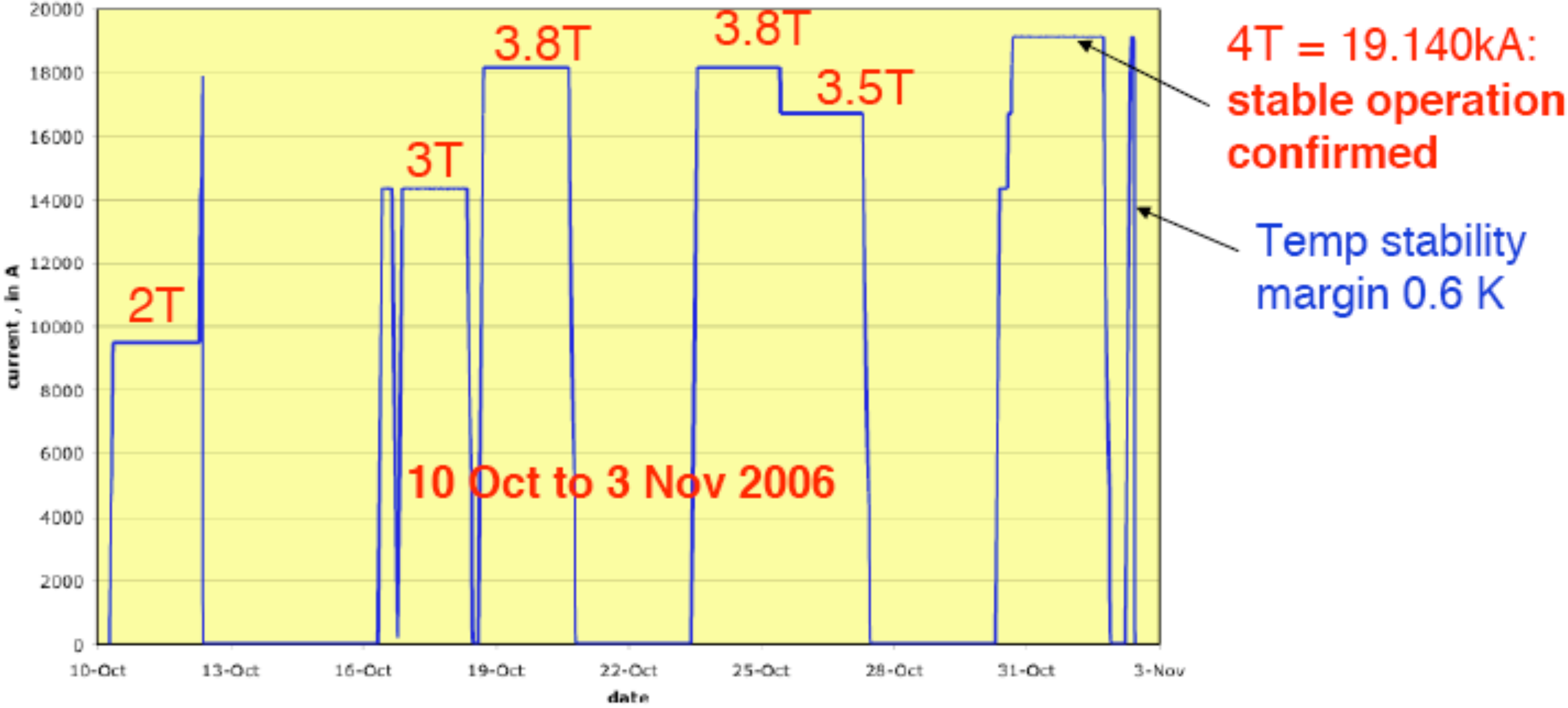
Magnet field on Axis: 4 T

Current: 20 kA

Stored Energy: 2.7 GJ

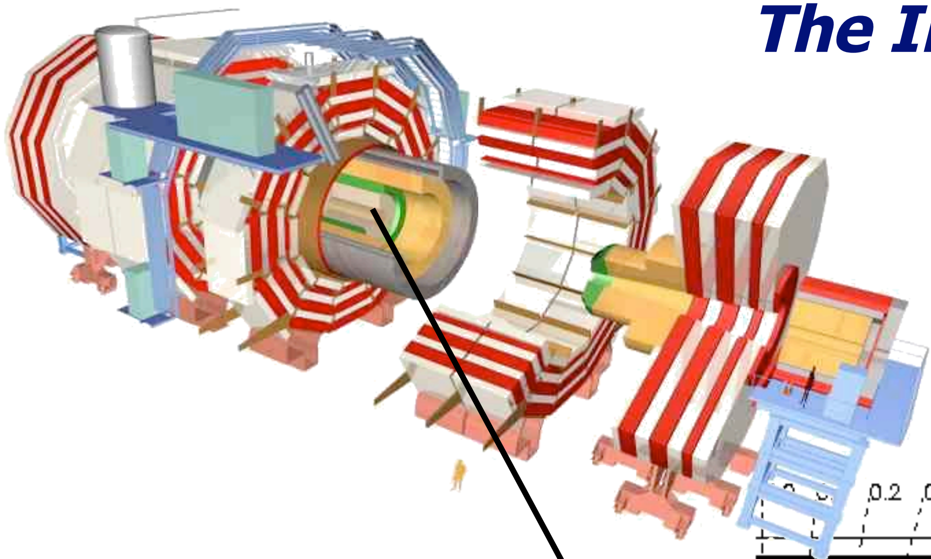
Magnetic radial pressure 64 atmospheres

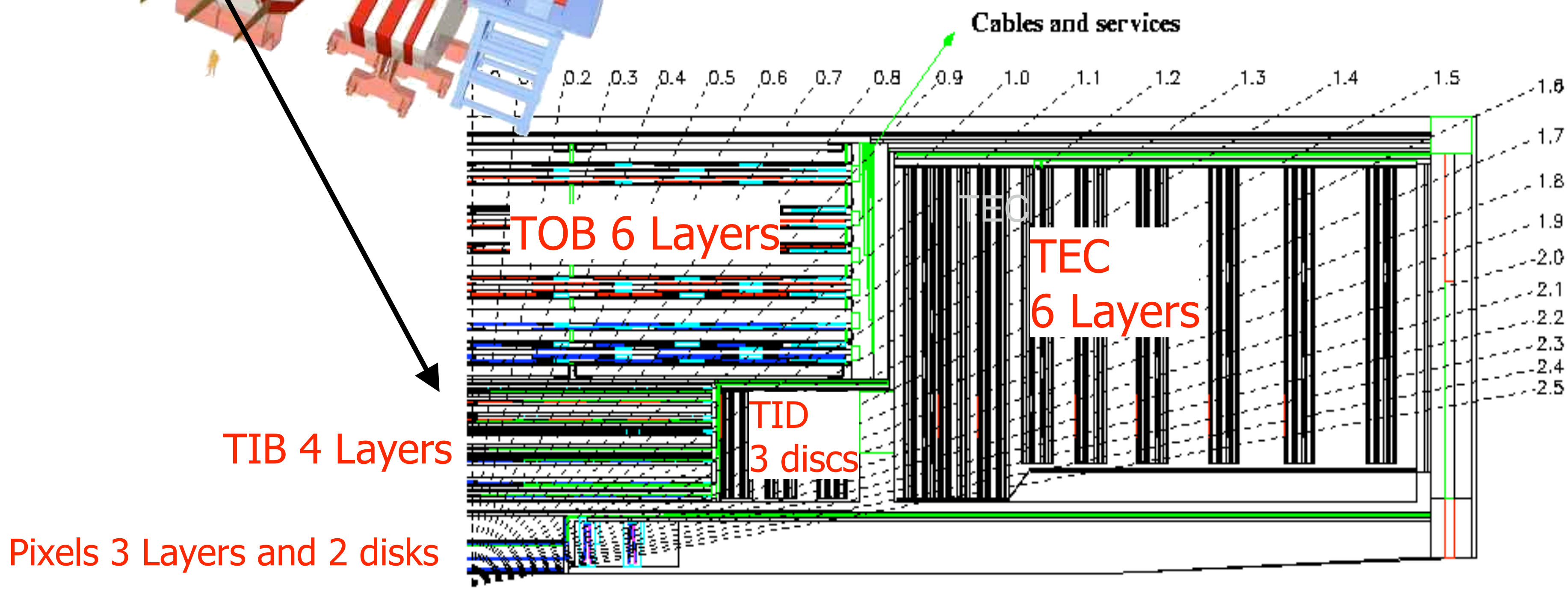
Solenoid test on surface



Field mapped at: 2.0, 3.0, 3.5, 3.8(twice) & 4.0 T with 0T references.
Target precision of 10^{-4} achieved

The Inner Tracker





Pixels:

100 μm x 150μm

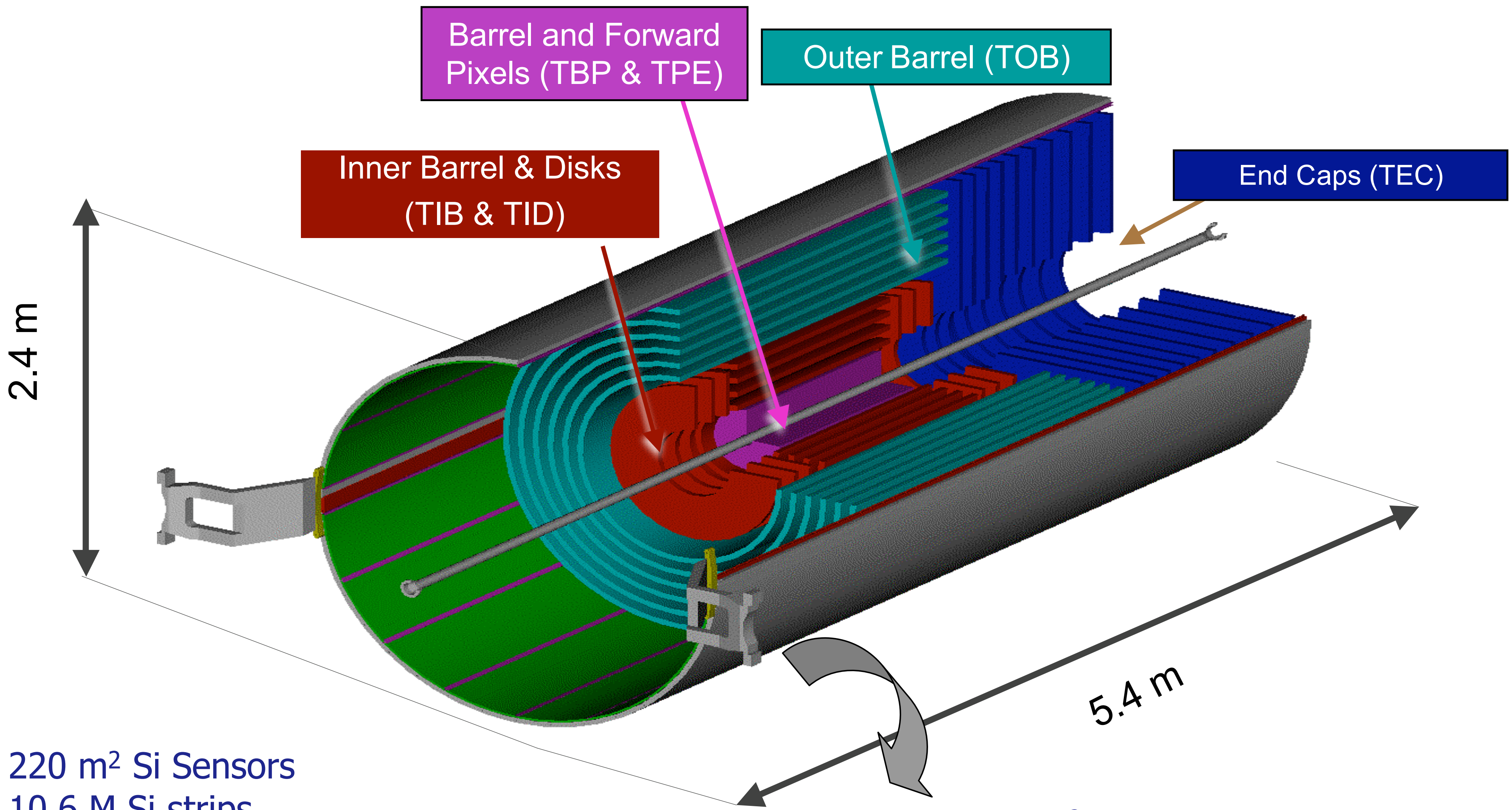
rφ and z resolution: 15-20 μm

Strips:

Pitch: 80 μm to 180μm

resolution: 20 μm to 50μm

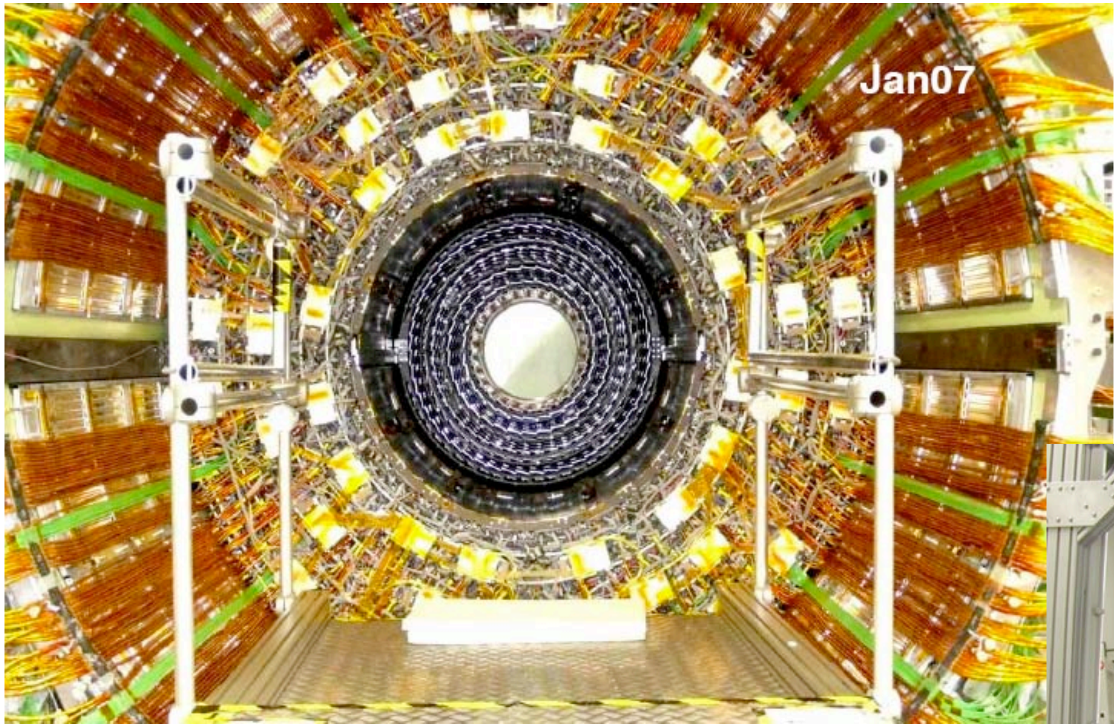
The Inner Tracker (all Si)



220 m² Si Sensors
10.6 M Si strips
65.9 M Pixels ~ 1.1 m²

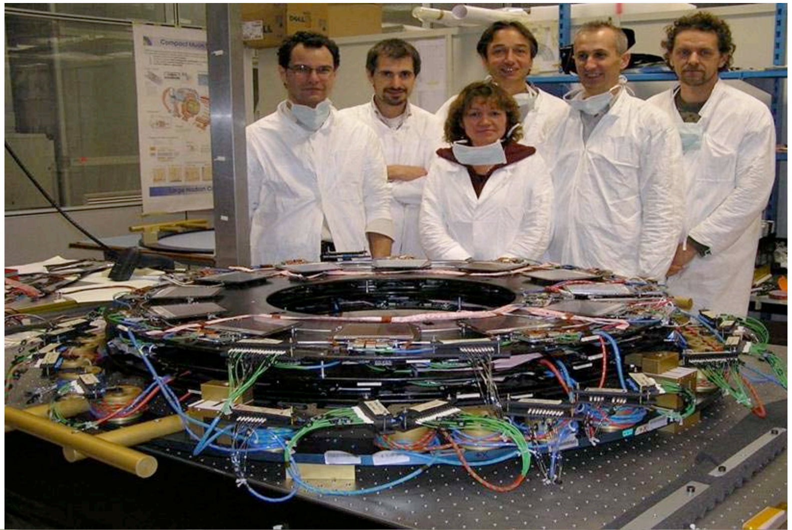
Volume 24.4 m³
Operating temperature – 20 ⁰C

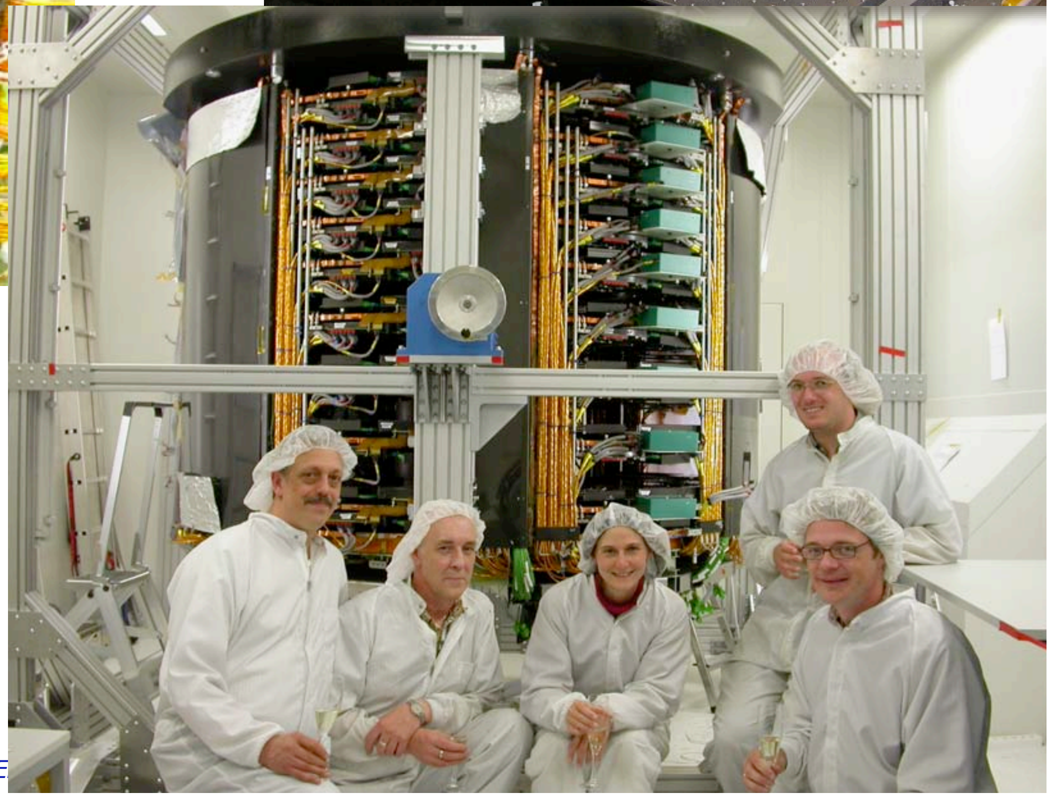
dead or noisy strips < 3/1000



TIB inserted into the TOB

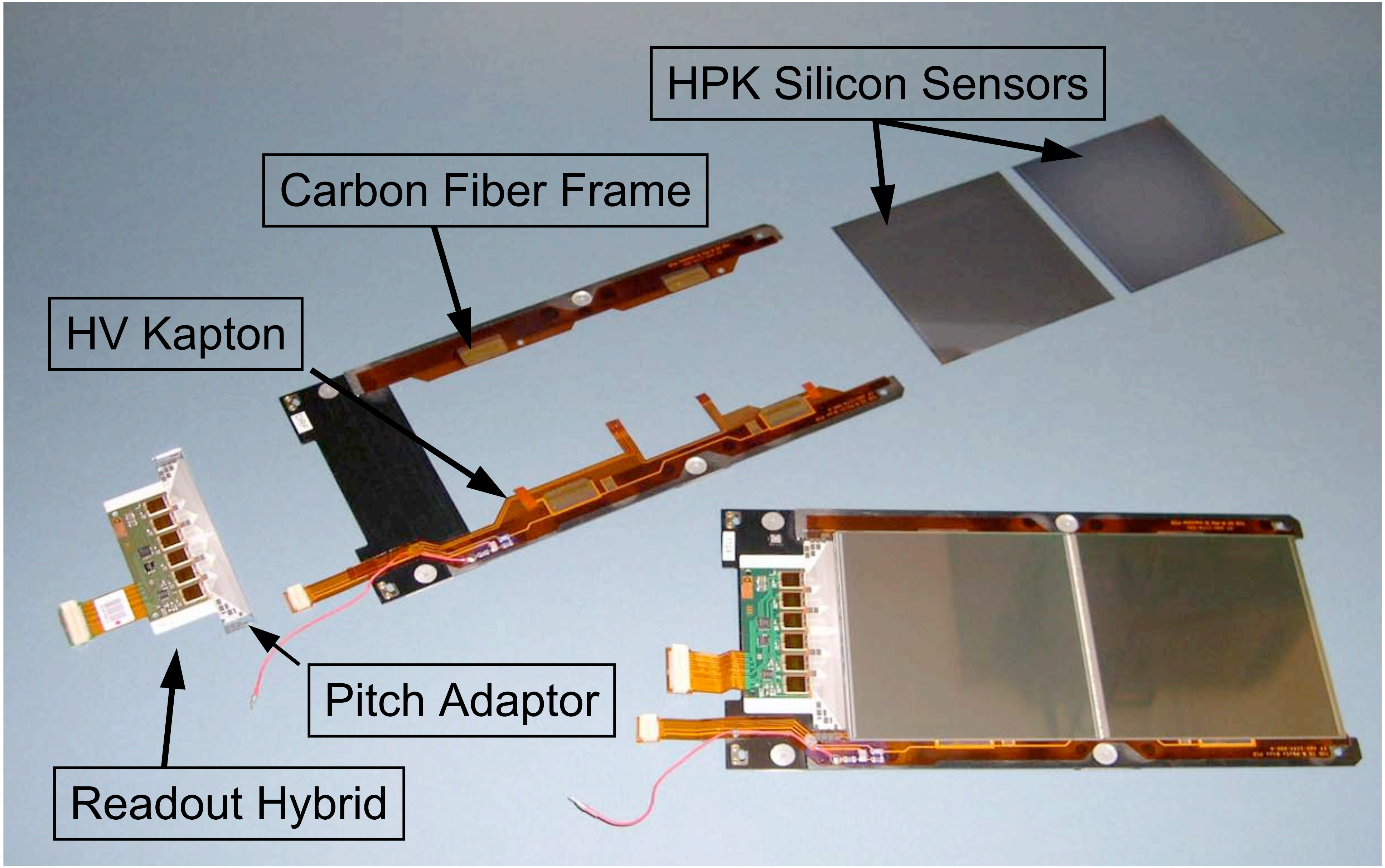
TID assembled



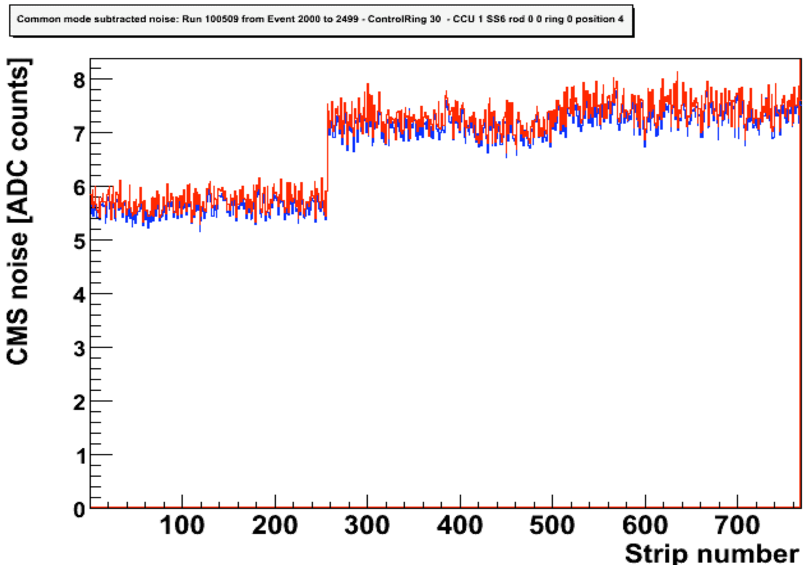


TEC fully assembled

Si Strip Module



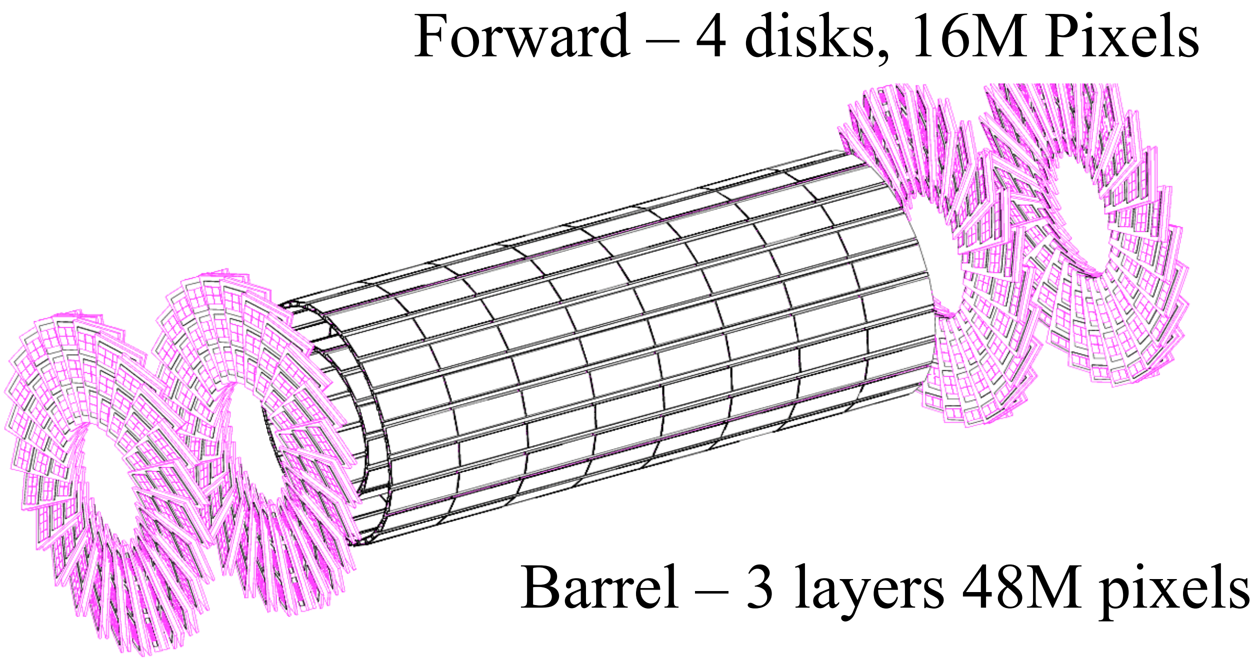
Tracker Petals



Signal (1 MIP) ~ 180 counts

(500 mm thick Si)

The Pixel Detector



LAYERS: R = 4.3cm 7.2cm 11.0 cm → Area Barrel = $0.78\ m^2$

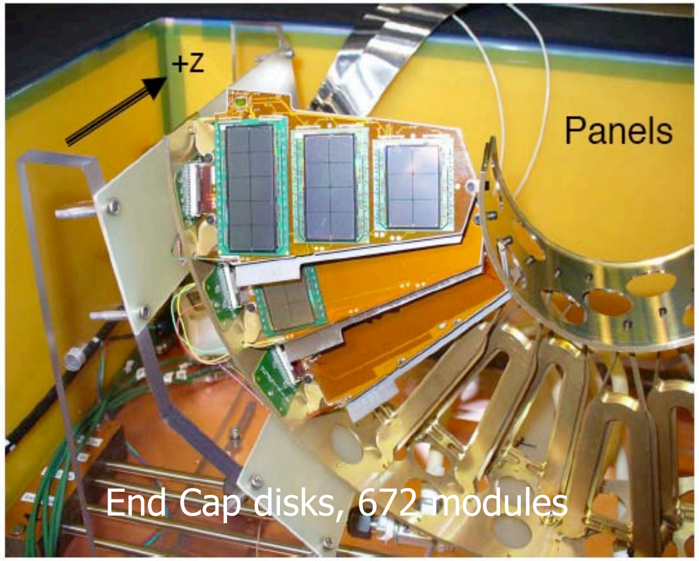
Disk = $0.28\ m^2$

Total ~ $1.1\ m^2$

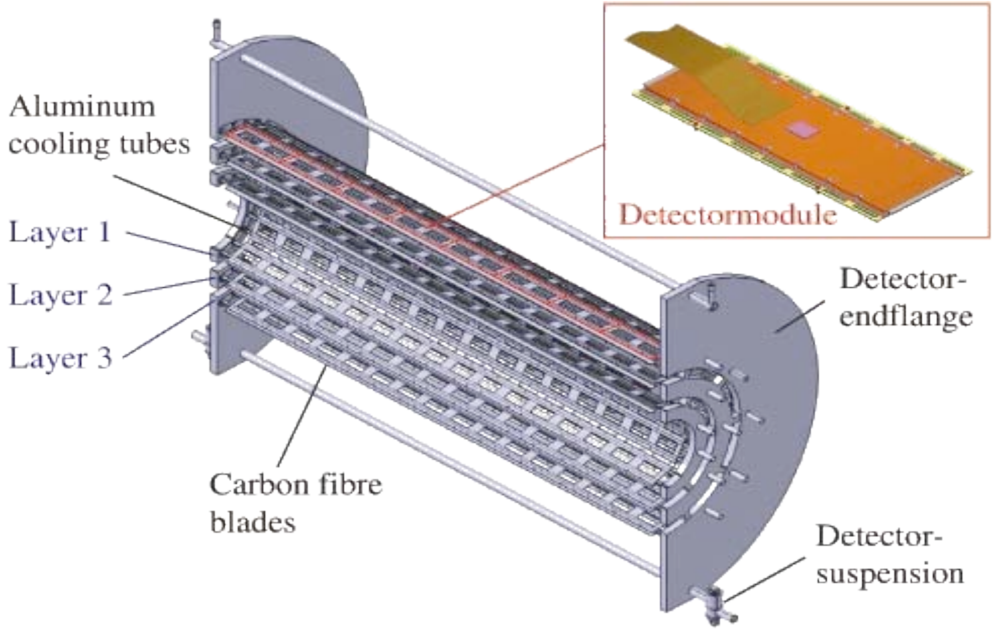
↑ Installation + Fluence limited → ΔT_{max}~ 2 years

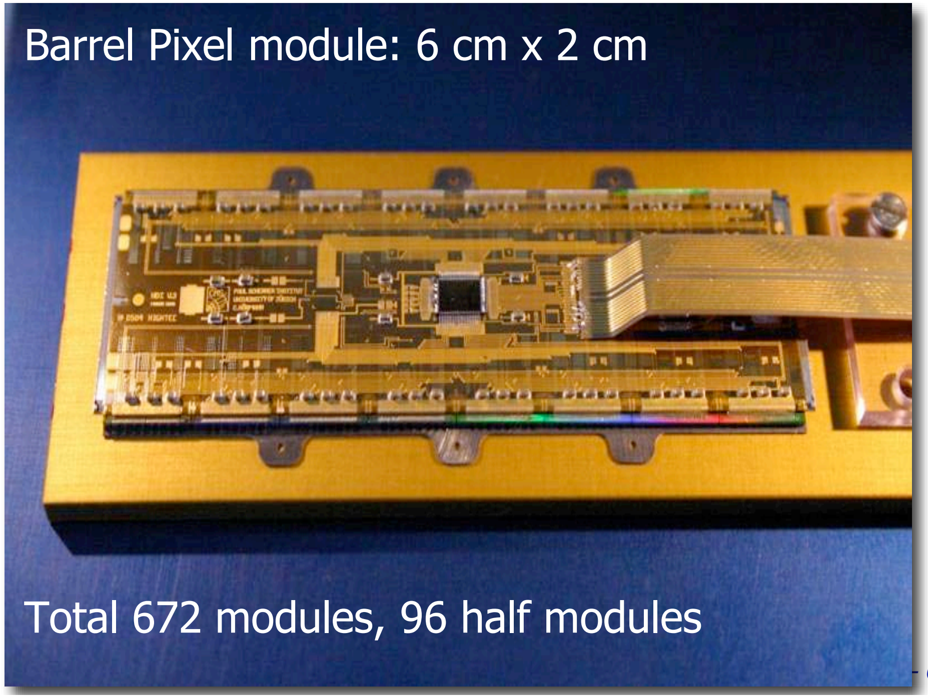
↑ Cost limited !! → R_{max}

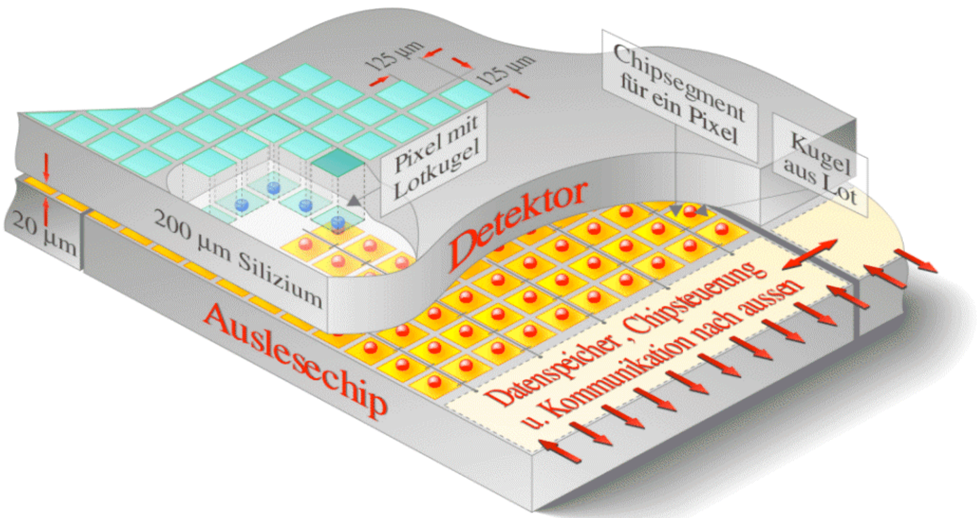
The Pixel detector



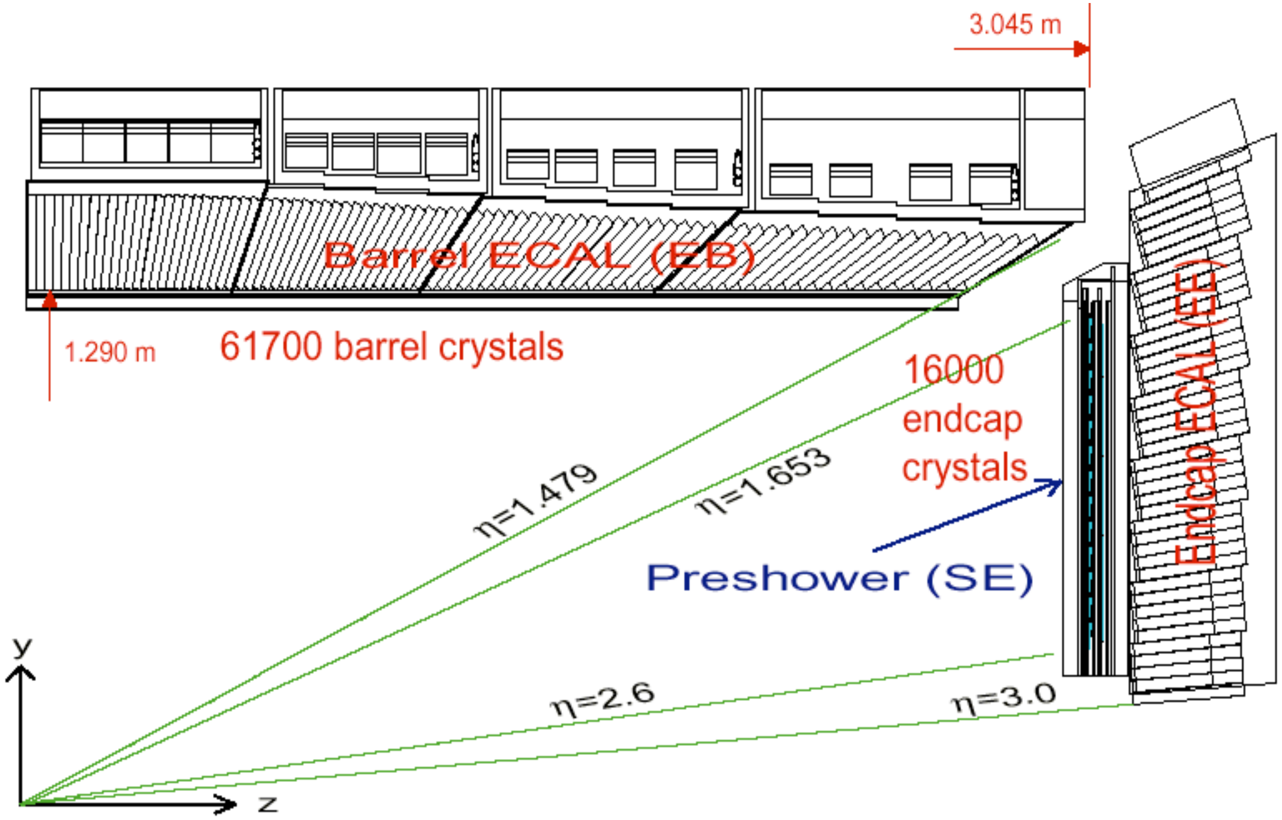
Radius
4.4 cm
7.3 cm
10.2 cm

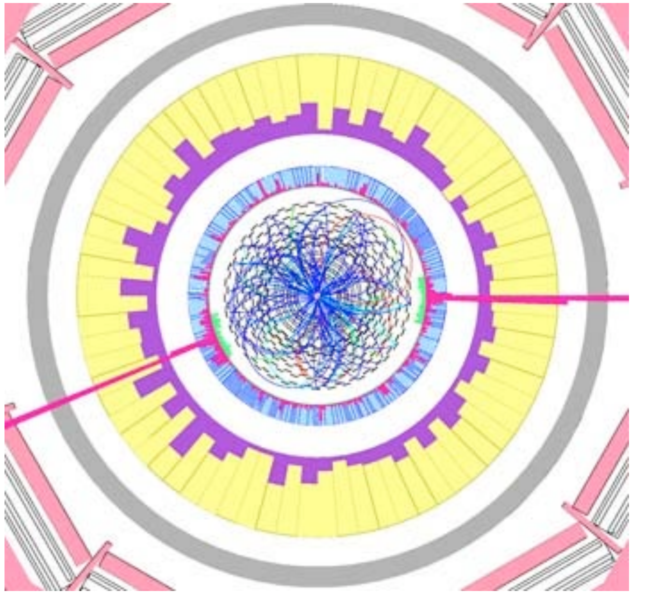


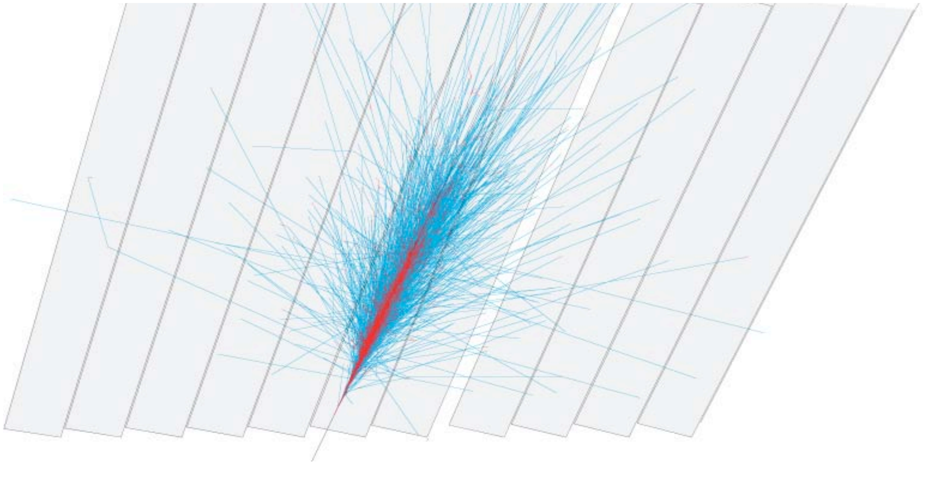


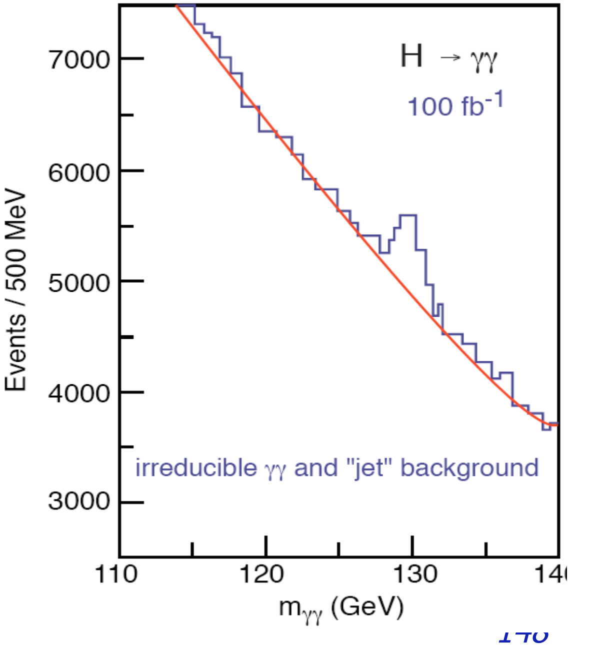


ECAL Lead Tungstate Calorimeter

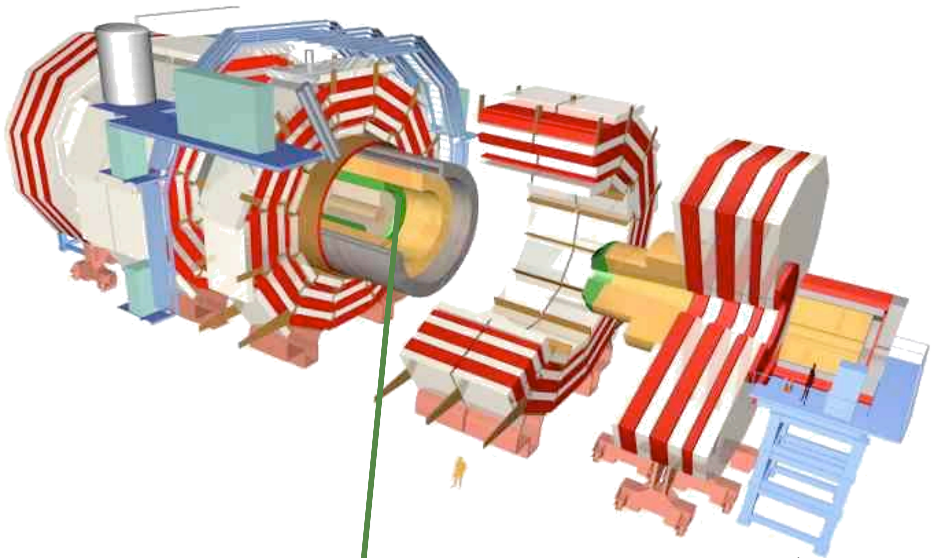


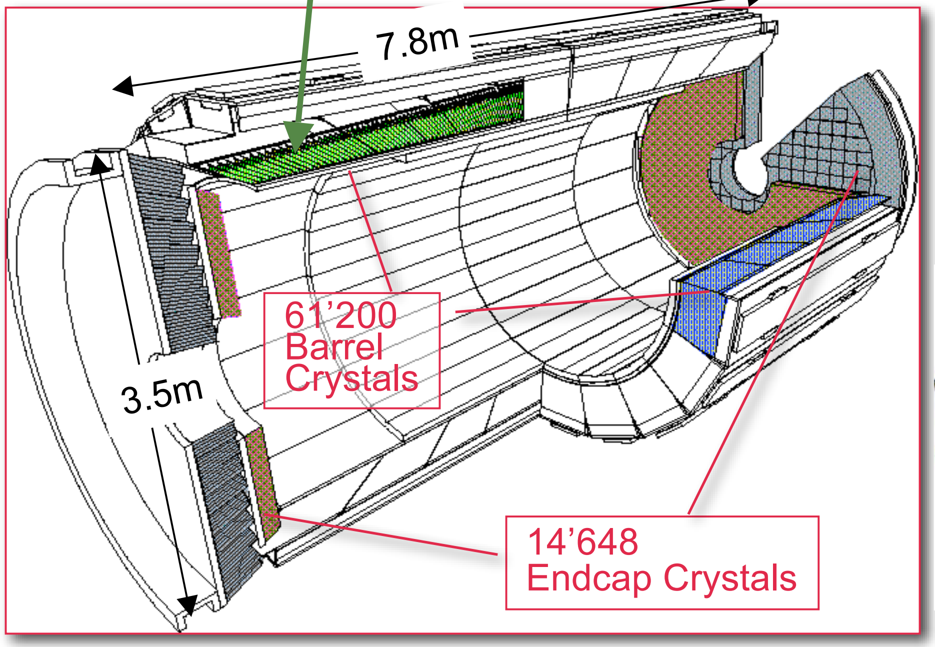


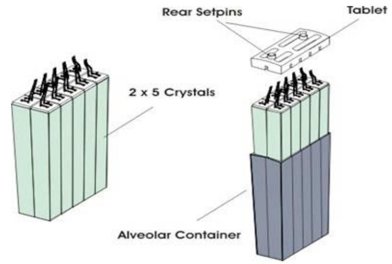




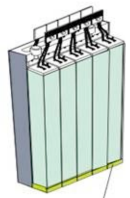
ECAL Assembly

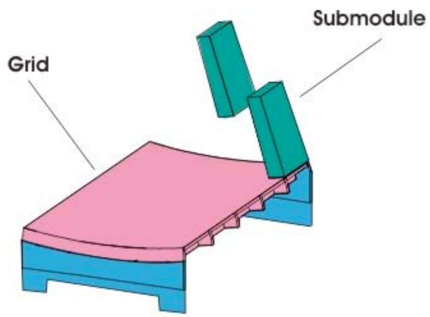




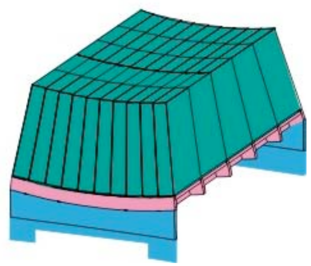


Submodule
10 Crystals

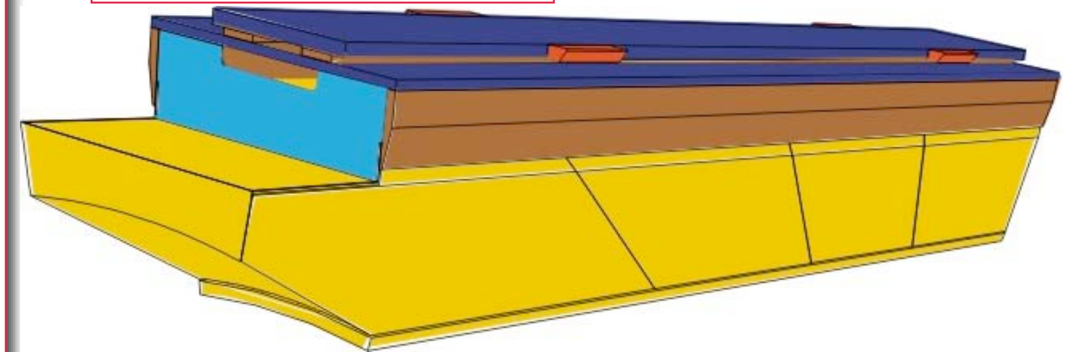




Module
400/500 Crystals



SuperModule
4 Modules, 1700 Crystals



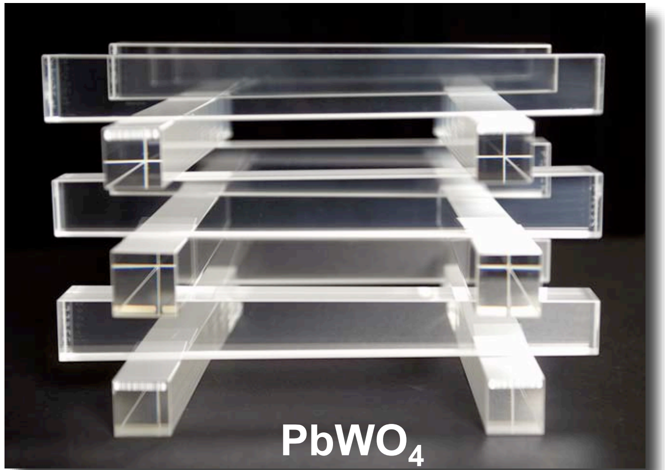
ECAL Technology

Parameter:	ρ	M.P.	X_0	R_M	dE/dx	λ_I	τ_{decay}	λ_{max}	n^*	Relative output†	Hygro-scopic?	$d(LY)/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%°C‡
NaI($T\ell$)	3.67	651	2.59	4.8	4.8	41.4	230	410	1.85	100	yes	$\sim$0
BGO	7.13	1050	1.12	2.3	9.0	21.8	300	480	2.15	9	no	-1.6
BaF_2	4.89	1280	2.06	3.4	6.6	29.9	630^s	300^s	1.50	21^s	no	-2^s
							0.9^f	220^f		2.7^f		$\sim 0^f$
CsI($T\ell$)	4.51	621	1.85	3.5	5.6	37.0	1300	560	1.79	45	slight	0.3
CsI(pure)	4.51	621	1.85	3.5	5.6	37.0	35^s	420^s	1.95	5.6^s	slight	-0.6
							6^f	310^f		2.3^f		
$PbWO_4$	8.3	1123	0.9	2.0	10.2	18	50^s	560^s	2.20	0.1^s	no	-1.9
							10^f	420^f		0.6^f		
LSO(Ce)	740	2070	1.14	2.3	9.6	21	40	420	1.82	75	no	-0.3
GSO(Ce)	6.71	1950	1.37	2.4	8.9	22	600^s	430	1.85	3^s	no	-0.1
							56^f			30^f		
CeF_3	6.16	1460	1.68	2.6	7.9	25.9	30	310 - 340	1.62	6.6	no	0.14

* Refractive index at the wavelength of the emission maximum.
† Relative light yield measured with a bi-alkali cathode PMT.
‡ Variation of light yield with temperature evalutated at room temperature.
f = fast component, s = slow component

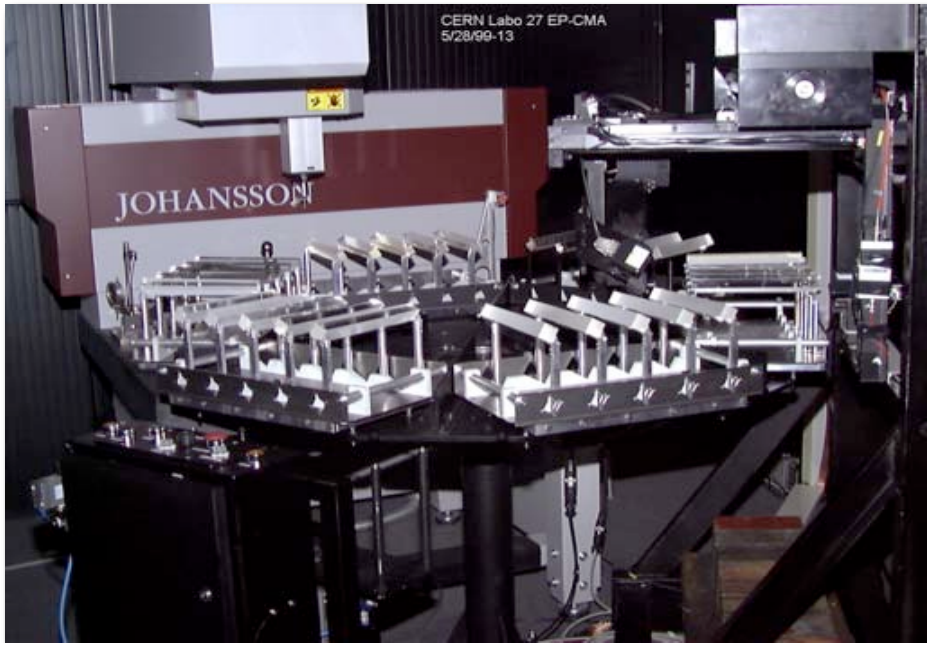
Lead Tungstate Crystals (~90 tons, ~ 76K units)

Front face ~ 22x22cm^2 , Length 23 cm



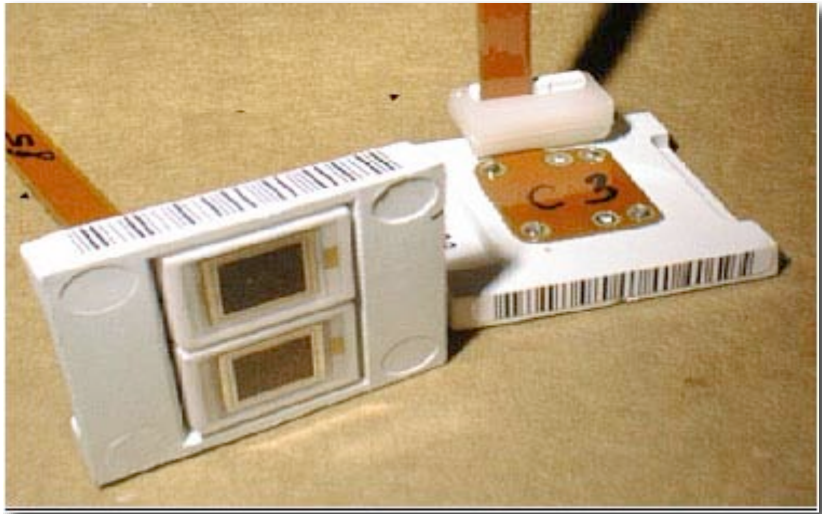
Production in Russia and in China

Parameter	Barrel	Endcaps
Range	$\|\eta\|<1.48$	$1.48<\|\eta\|<3.0$
$\Delta\phi$ x $\Delta\eta$	0.0175 x 0.0175	0.0175 x 0.0175 to 0.05 x 0.05
Thickness in X_0	25.8	24.7
# Crystals	61200	14648
Volume	8.14m^3	2.7m^3
Mass (t)	67.4	22.0



Light Detectors

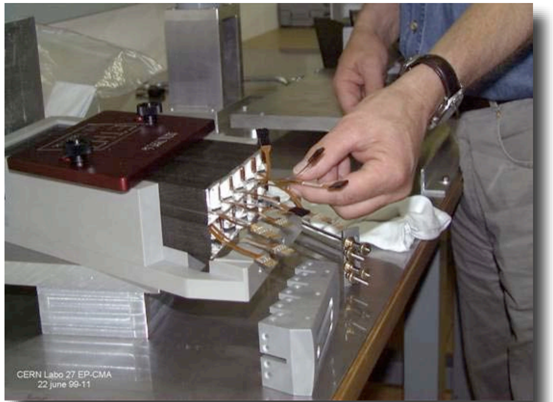
Operate in 4T field

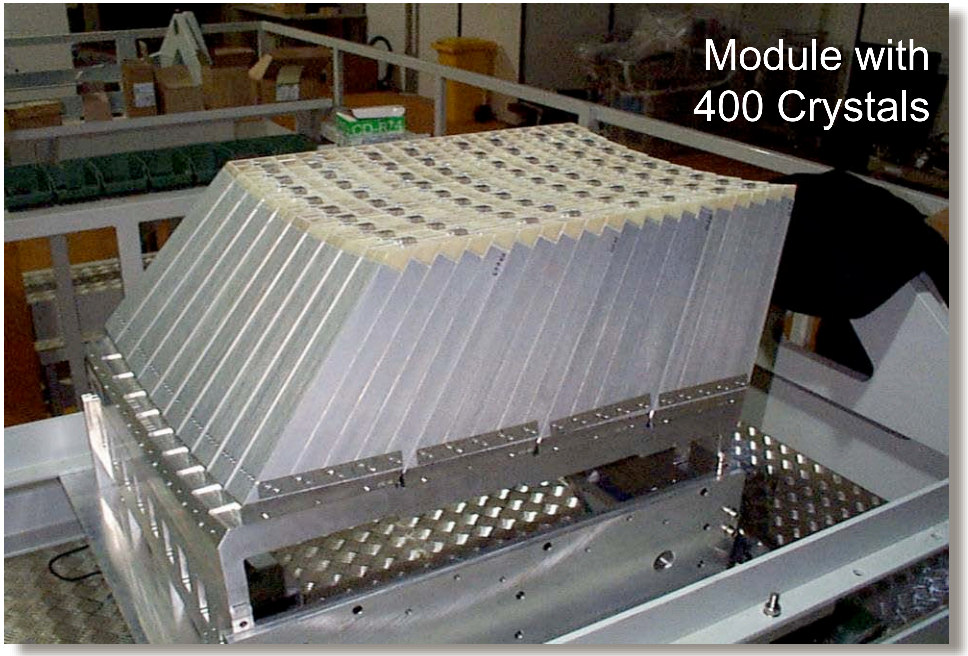


Silicon Avalanche Photo Diode (APD, Hamamatsu)
in ECAL Barrel
2 APDs in parallel / Crystal
(gain = 50, QE 70-80%, Active Surface 5 x 5 mm2)

Vacuum Photo Triode (VPT, Russland)
in ECAL Endcaps
1-stage photon amplification, below < 26^0 to the field lines
(gain = 10, QE ~20%, very radiation hard)

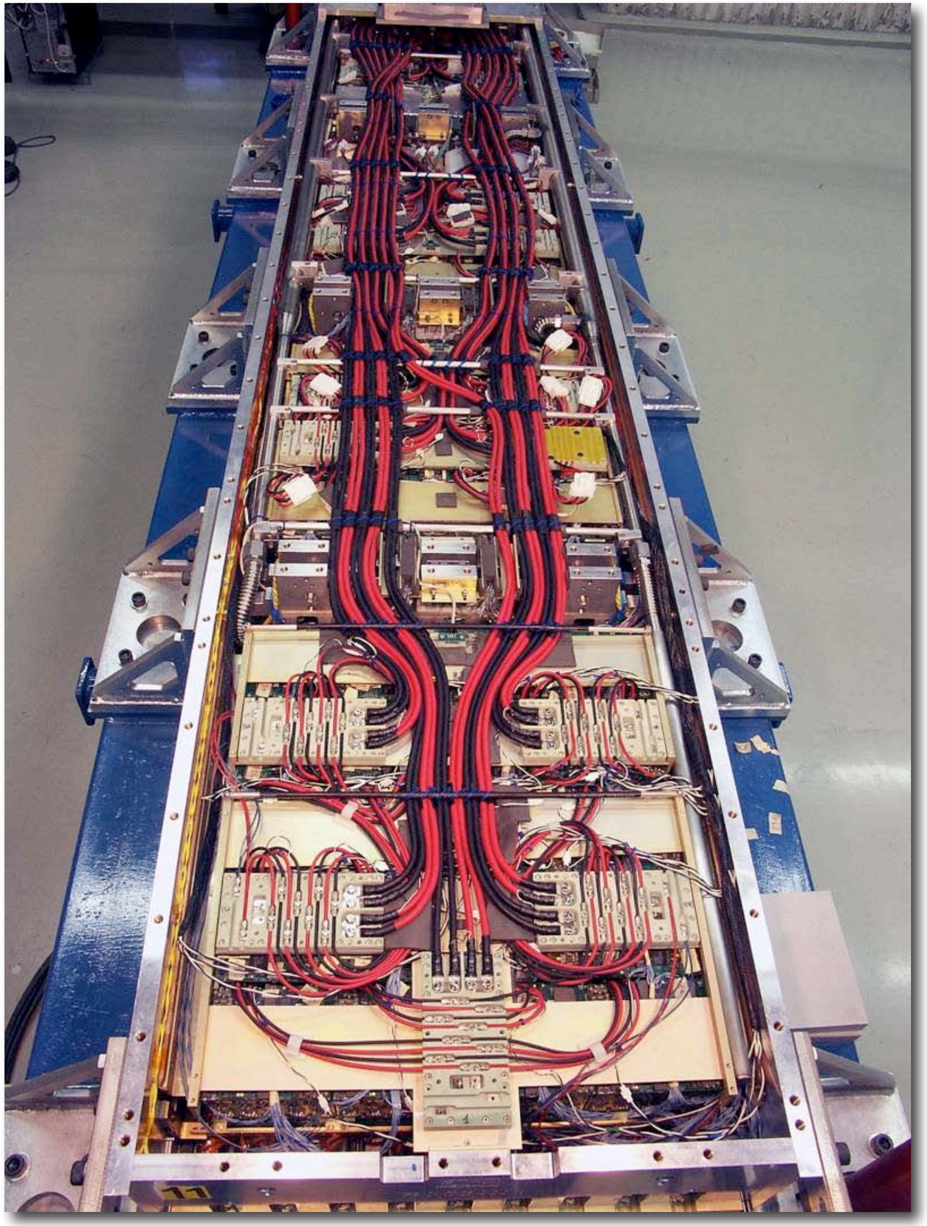
Modular Assembly

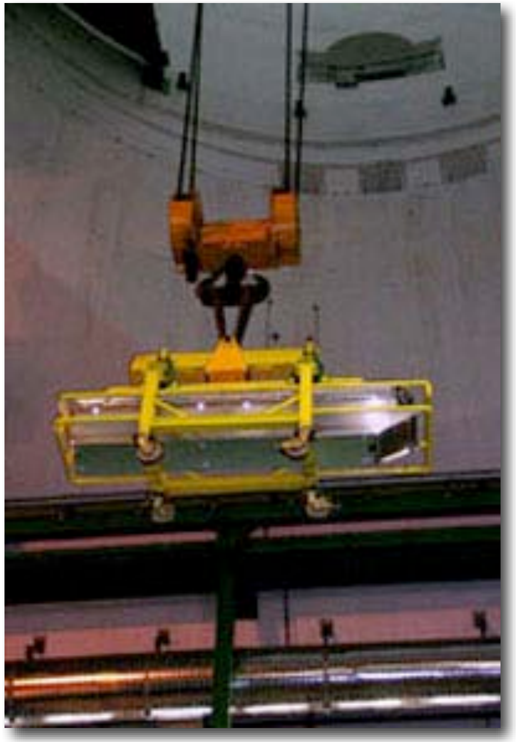




36 SuperModules in total

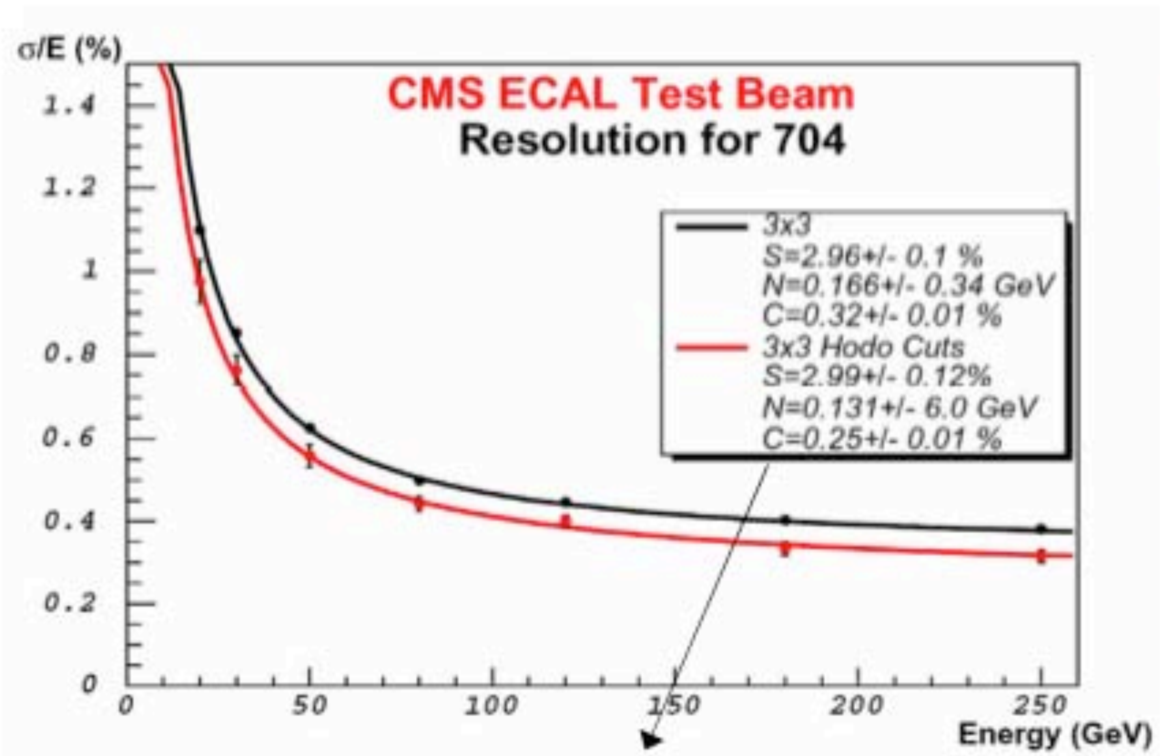
SuperModules integration



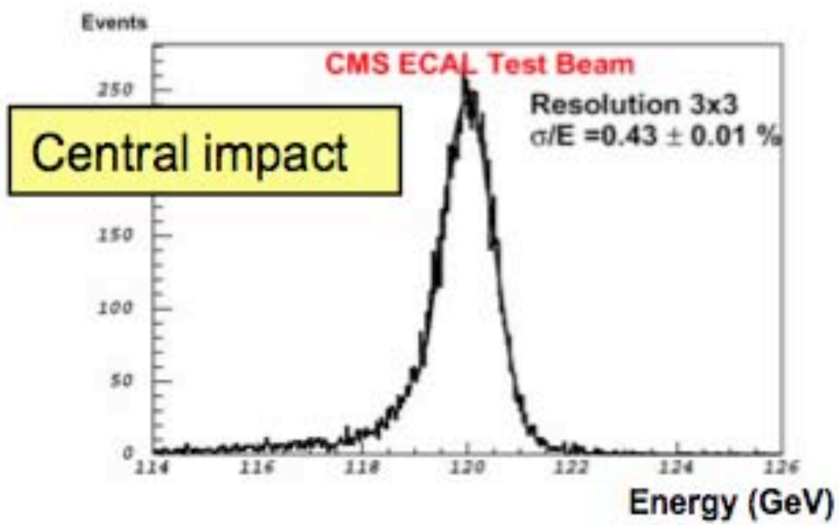


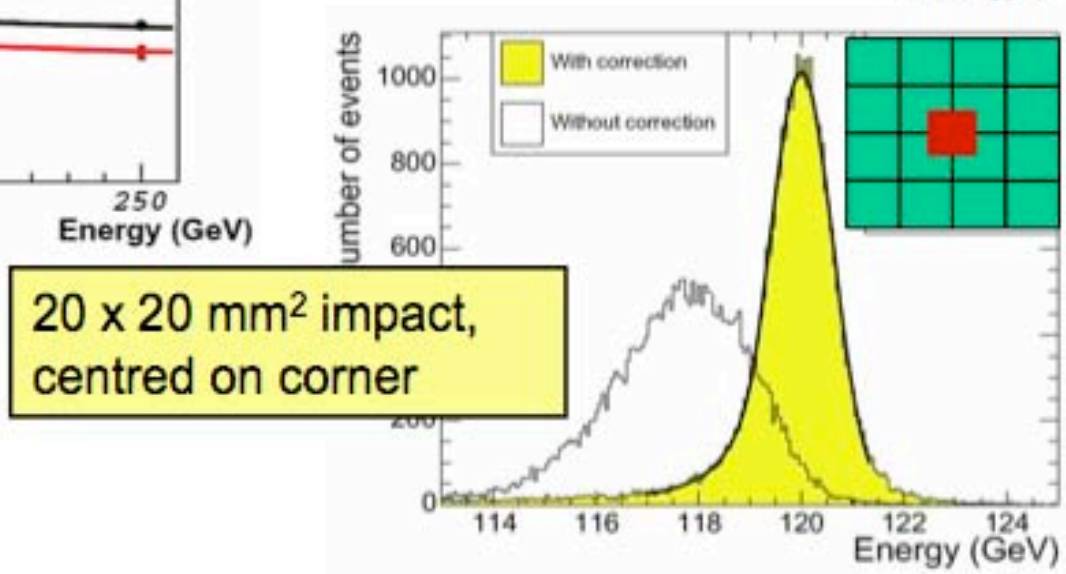
18 SuperModules installed in CMS as of 22-MAY-07

ECAL Performance

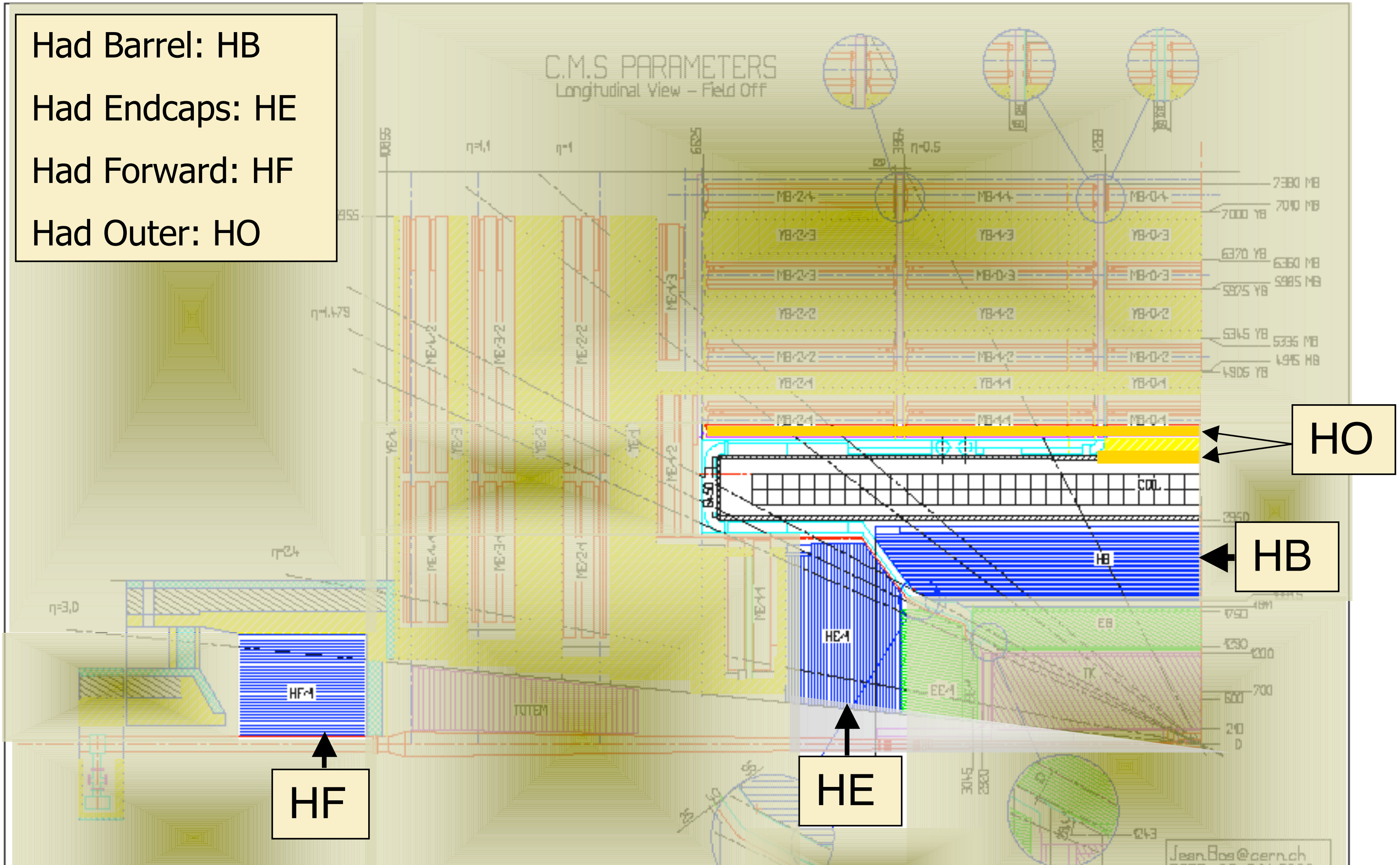


$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2,$$



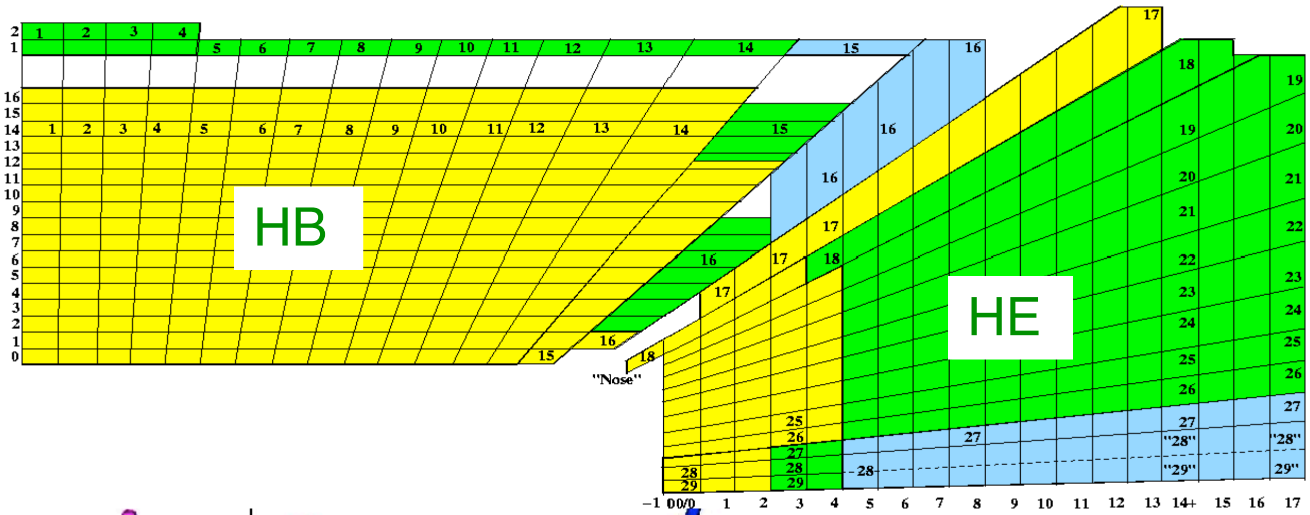


The Hadron Calorimeter

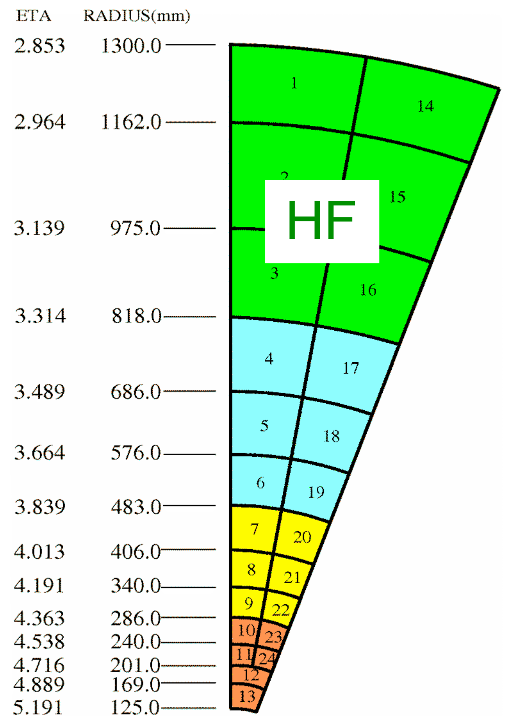


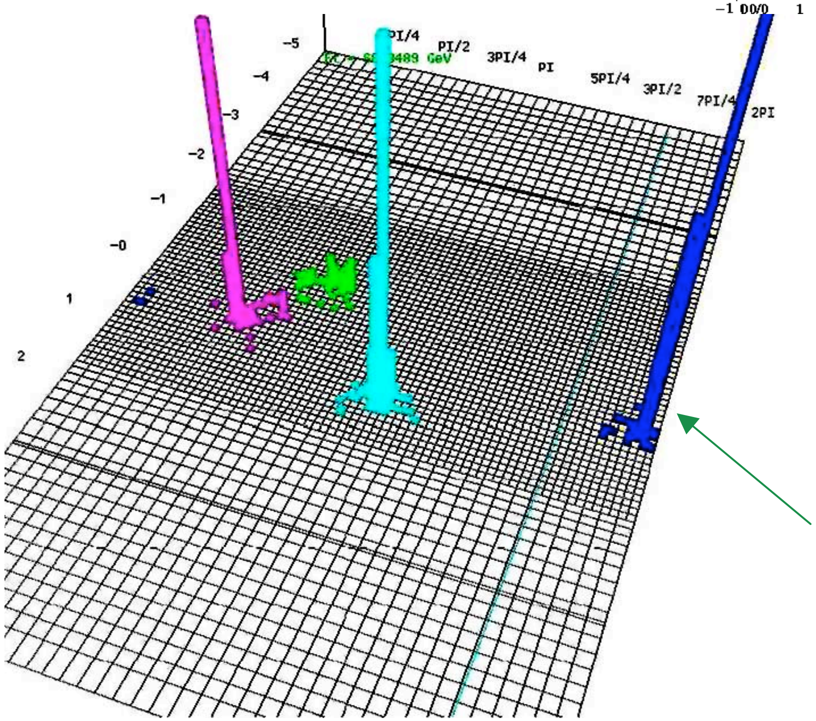
HB & HF: Brass Absorber and Scintillating tiles.
HO: Scintillator "catcher". HF: Iron and Quartz fibers

The Hadron Calorimeter



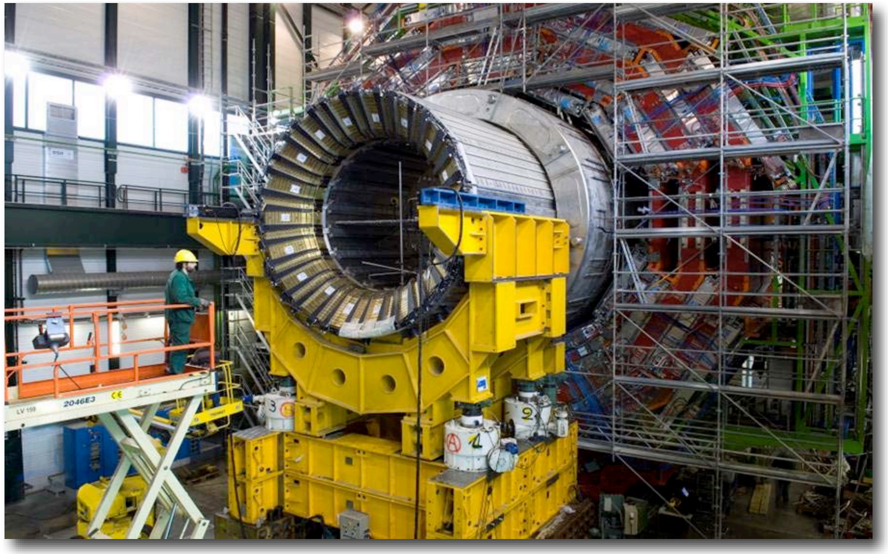
HF: 3<|η|<5
Δφ x Δη =10º x 13 η towers

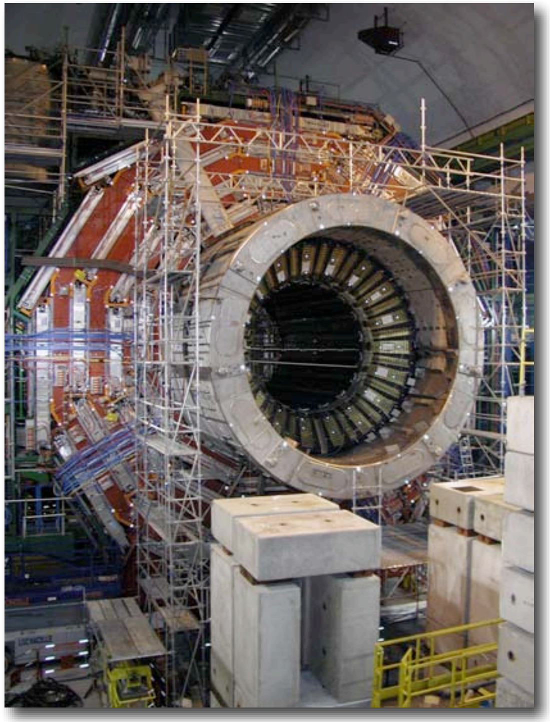




HB: |η|<1.3
HE: 1.3<|η|<3
HF: 3<|η|<5
Very Fine Granularity:
Δφ x Δη = 0.087x0.087 for |η|<1.7

HCAL Assembly





The full HB- inside the Solenoid of CMS in the underground cavern

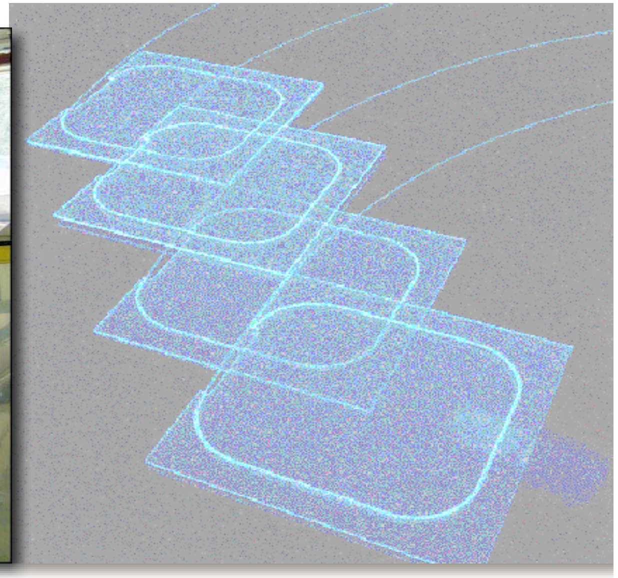
The HCAL calorimeter

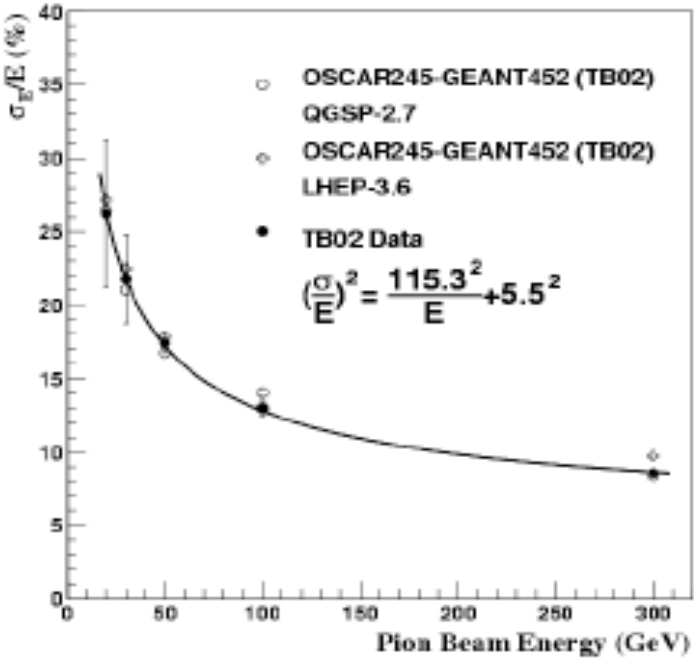
Barrel (HB) and End Cap (HE) Calorimeter:

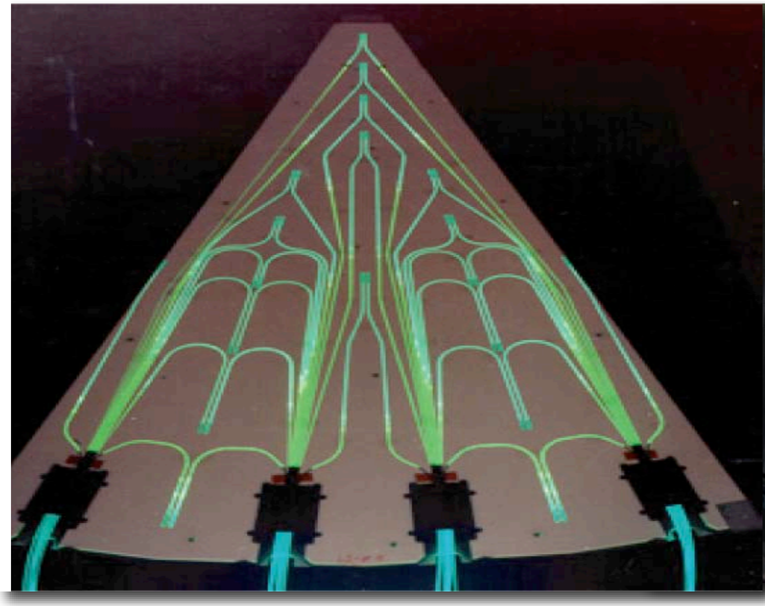
Brass plates alterating with scintillator tiles. The light is extracted via optical fibres

Forward HCAL (HF)

Steel plates, quartz fibers inserted (right)

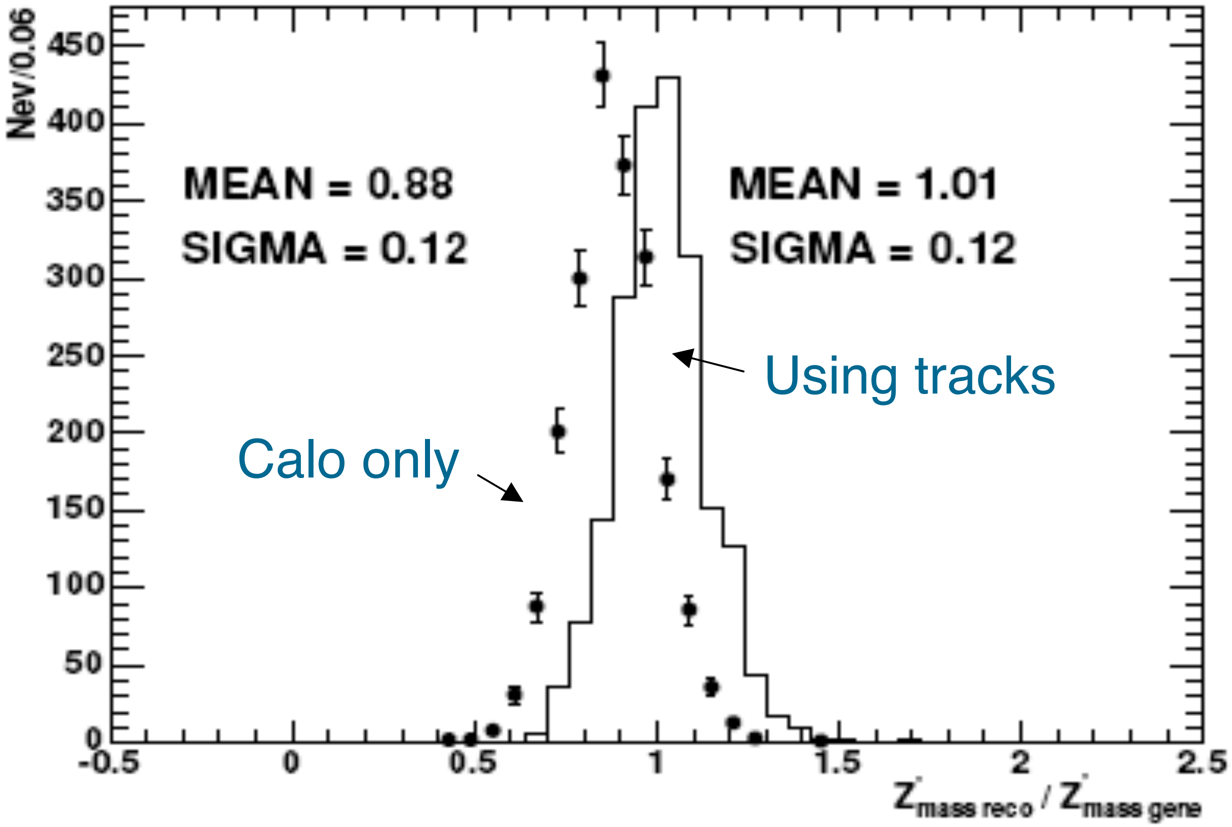






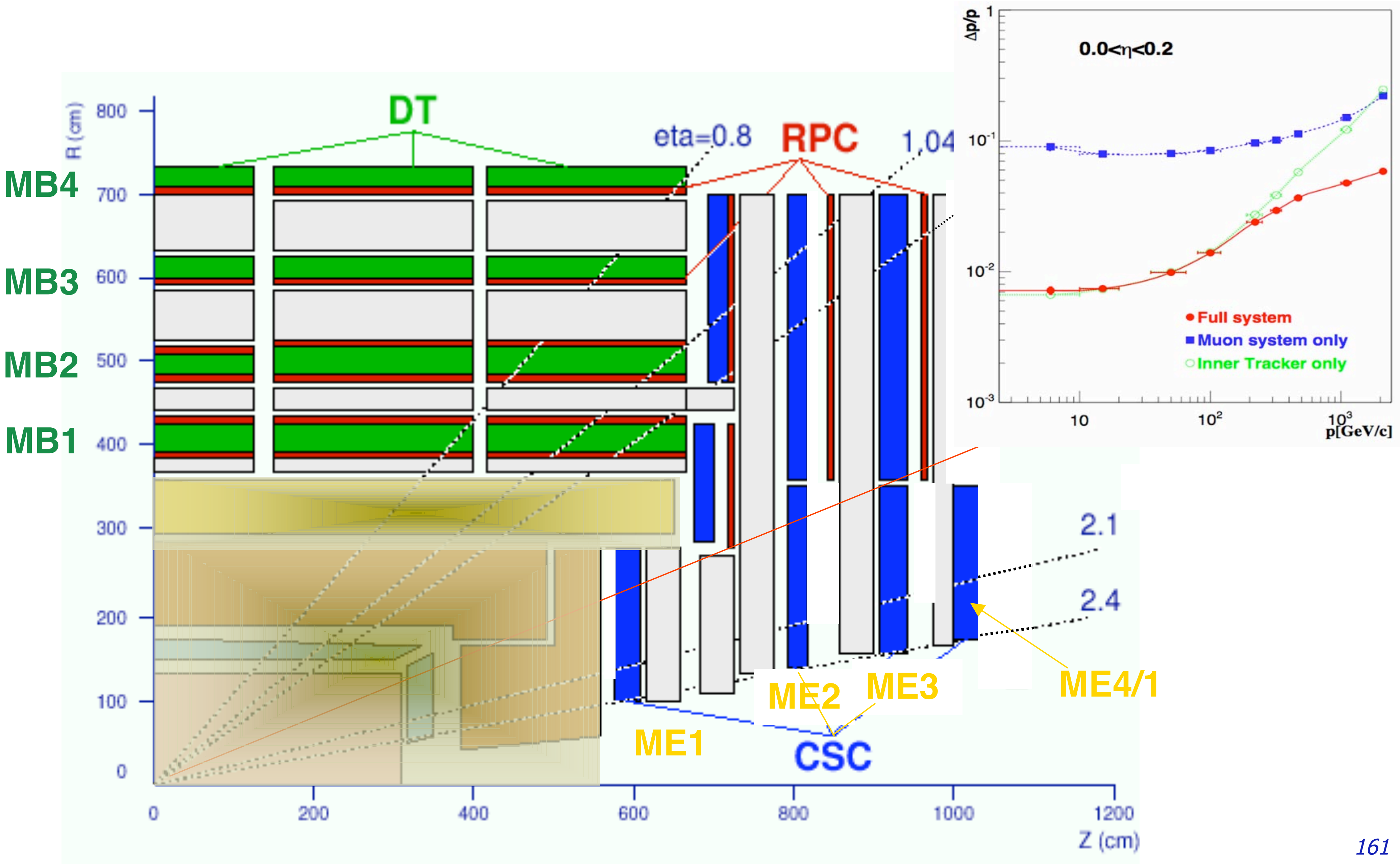
The HCAL performance

M_{jj} resolution at 120 GeV



M_{jj} resolution ≤ 15%

Muon Detectors

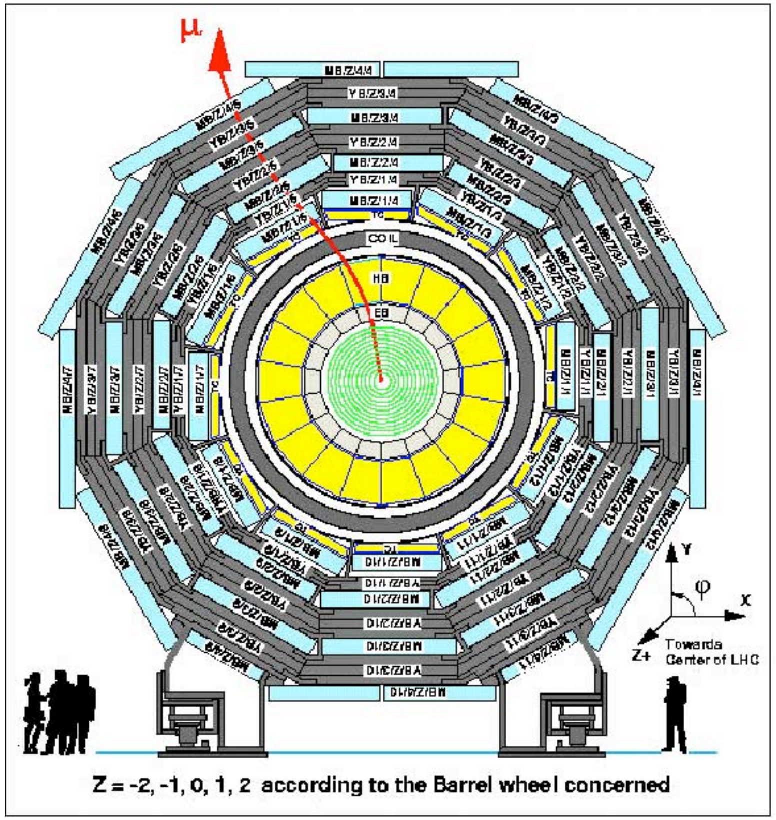


Muon system

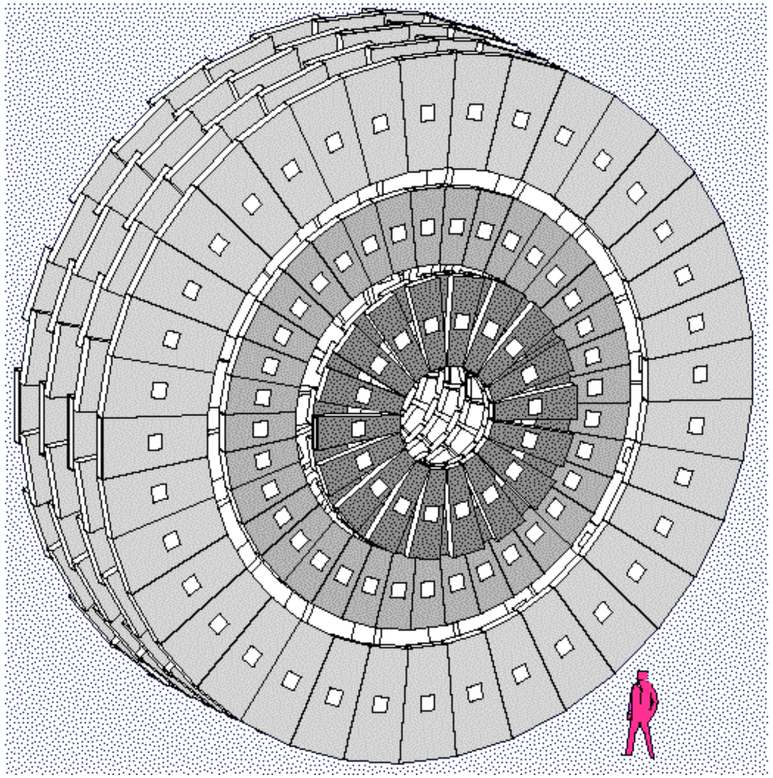
250 stations (in the iron magnet return yoke)
5 wheels
4 Layers: MB1,MB2,MB3,MB4
a station: 1 DT and 2 RPCs on MB1,MB2
1 DT and 1 RPC on MB3,MB4

Each endcap:
4 planes, 2-3 rings/plane
Proposed initial System:
CSCs: NO ME4/2
➔ 468 Chambers
RPCs:3 planes up to η = 1.6
➔ 432 Chambers

BARREL



ENDCAP



Muon system

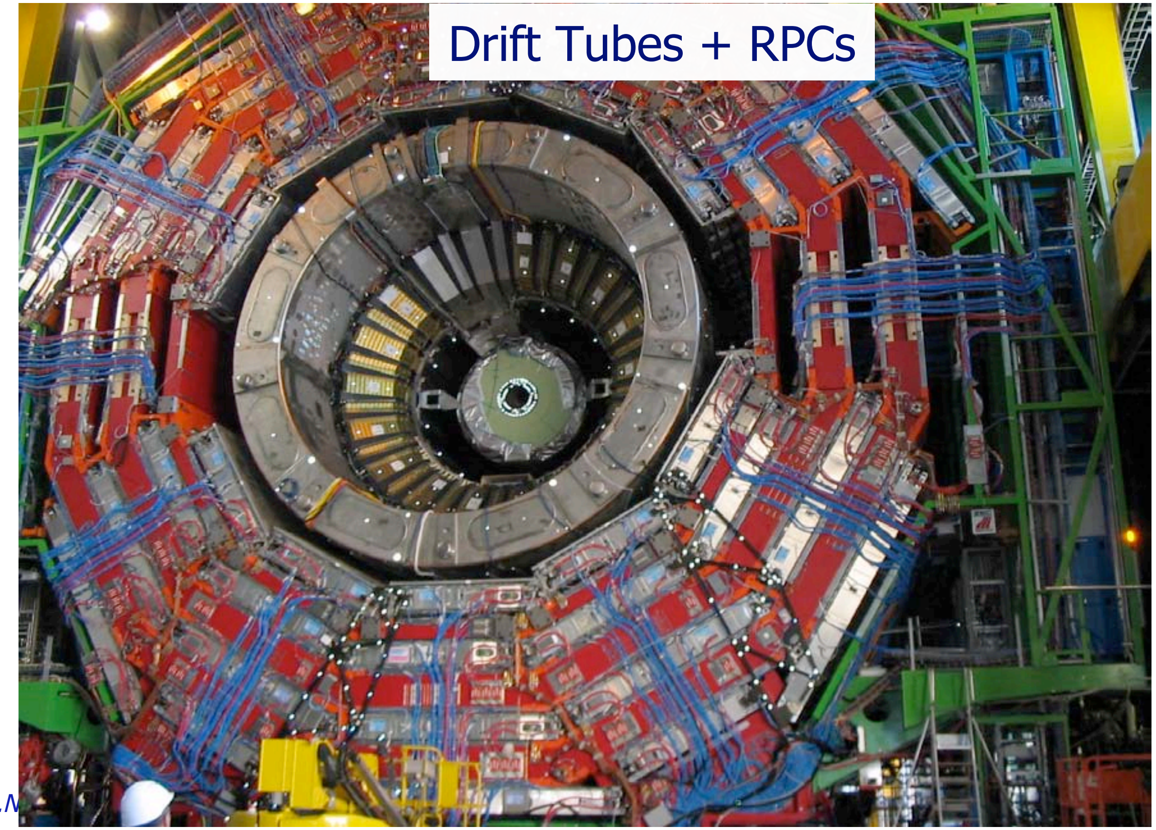
–Good position resolution ~150-200 μm

✓*Drift Tubes (DT) central (low field, low radiation and background)*

✓*Cathode Strip Chambers (CSC) Forward (high field, radiation and backgrounds)*

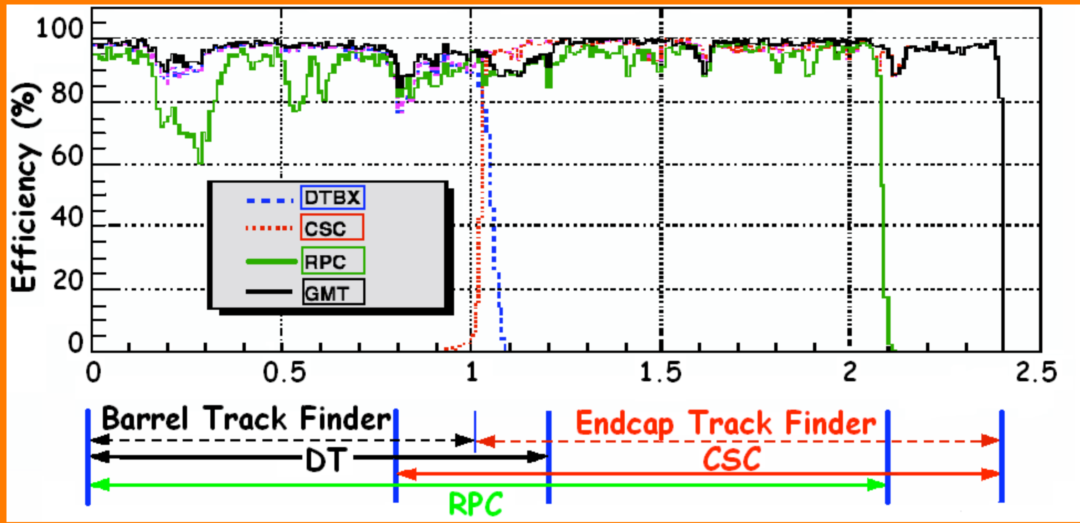
–Speed for triggering and redundancy

✓*Resistive Plate Chambers (RPC)*

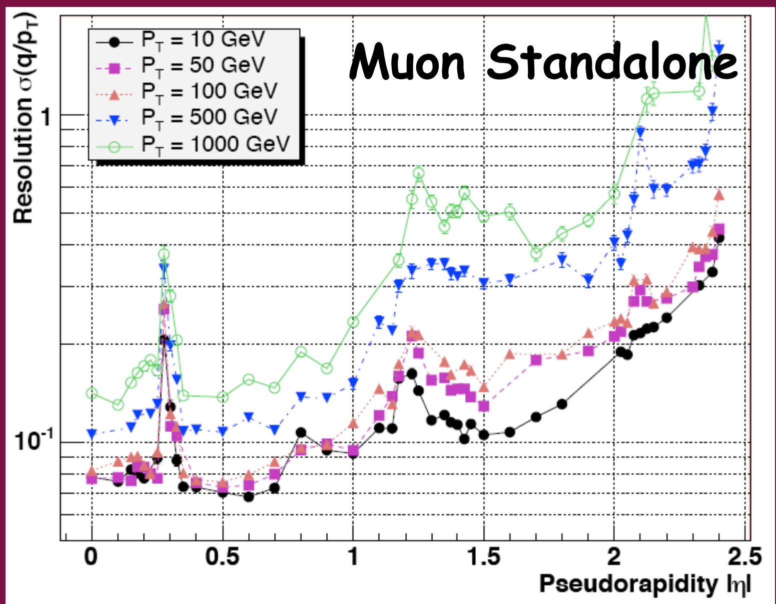


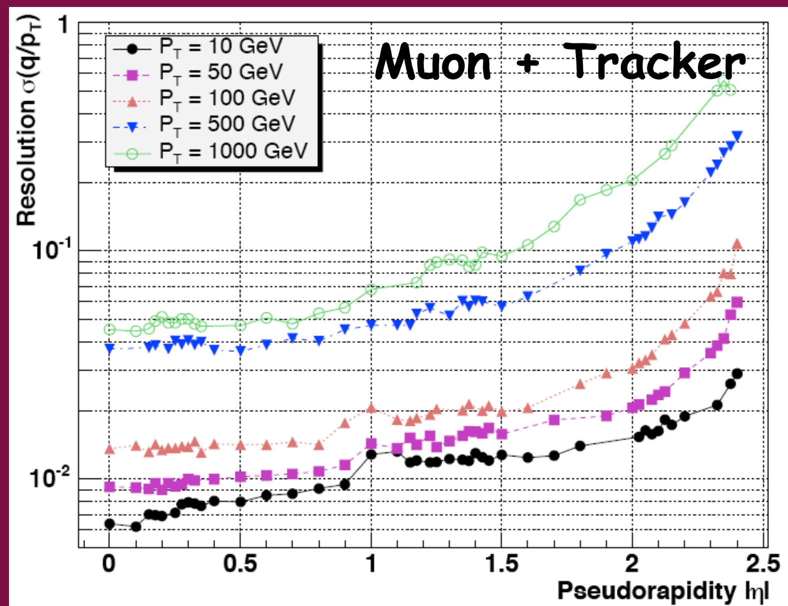
Expected muon system performance

Trigger Efficiency



$1/P_T$





ATLAS & CMS experimental facilities

Big HEP "experiments" such as those at LHC are really experimental facilities

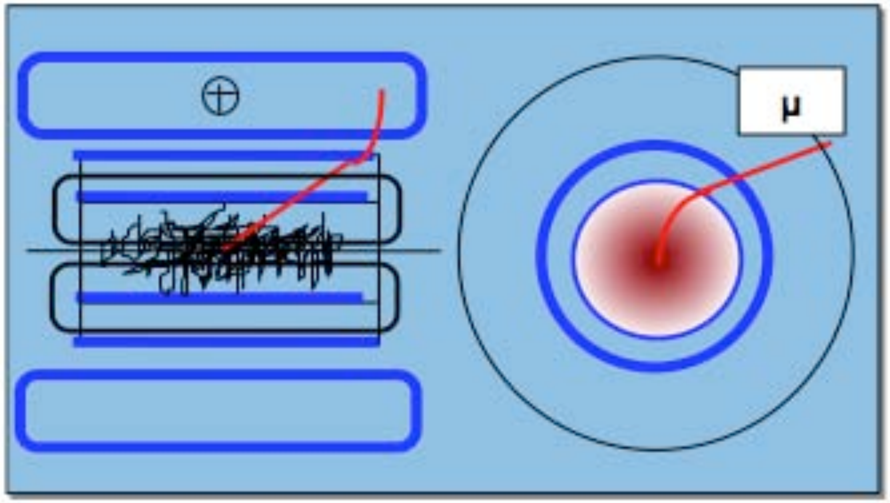
- *The very large international collaborations work together to prepare, maintain and operate the detectors*
- *Detailed analyses for specific physics areas are performed in working groups of much smaller size*

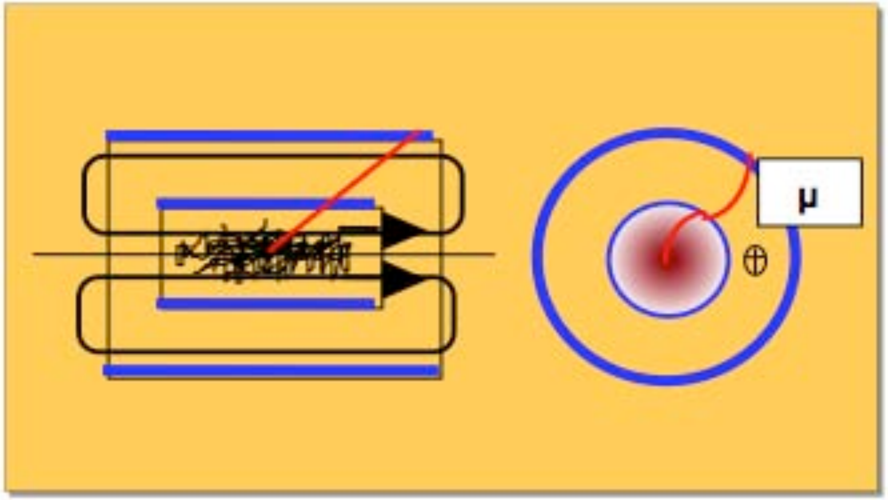
In contrast to some other fields of study, HEP is doing many measurements concurrently using the same detector system

- *Most efficient way to exploit the hugely expensive LHC complex (machine and detector systems)*

ATLAS & CMS main differences

- ✓ CMS high field solenoid has intrinsically higher bending power, homogeneous field ….
  But space is confined and forces Calorimetry in the high-field region and does not
  do so great in the forward region
- ✓ ATLAS Toroids allow a independent muon high-performance spectrometer, no need to have the ID fully operational, but it is a very complex machine to construct (4 magnets system)
- ✓ ATLAS air-core toroid is big and requires to increase the detector volume by a factor 6. This adds integration complexity and costs
- ✓ CMS can be built in slices and preassembled on the surface. Very elegant integration design



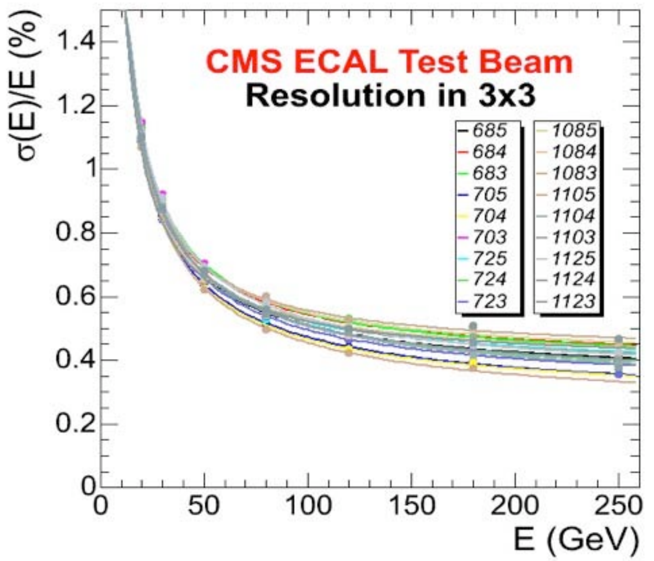


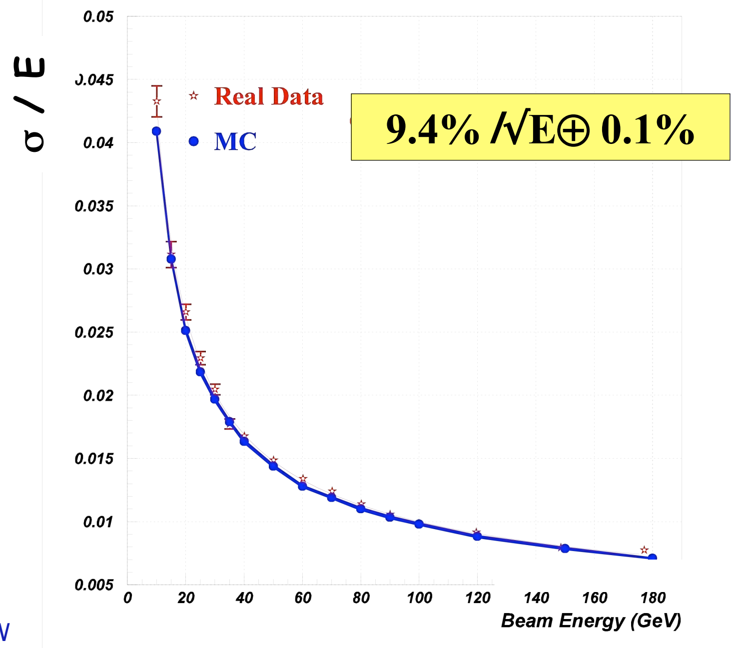
ATLAS & CMS main differences

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV only combining with tracker

ATLAS & CMS main differences (EM calorimeter)

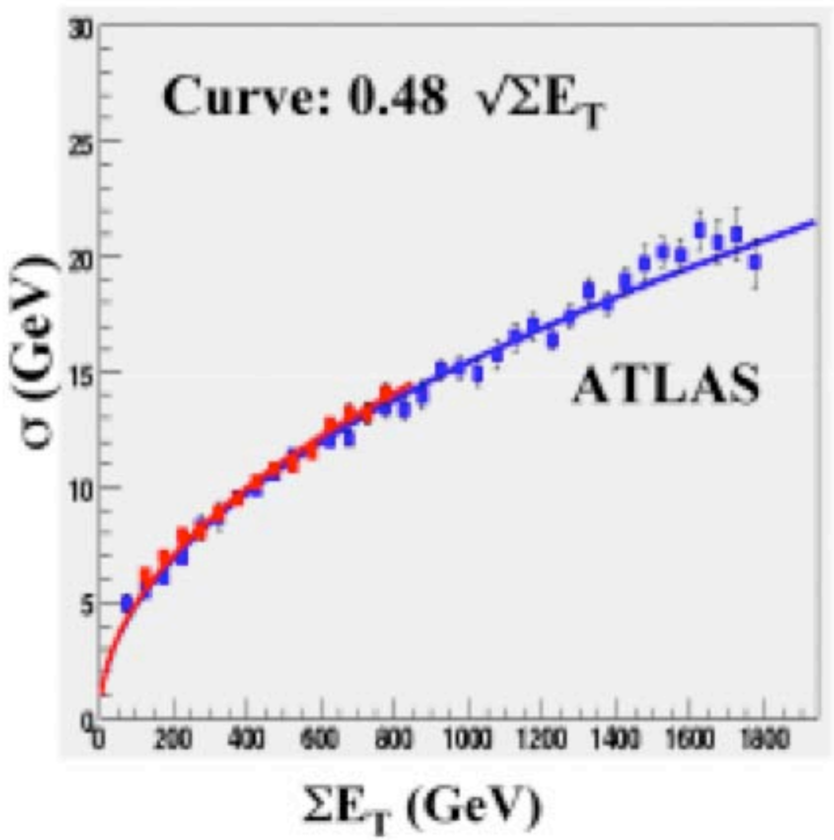
- ✓ PbWO4 crystals provide an excellent energy resolution (stochastic term 2 times better than ATLAS)
- ✓ The problem is to keep the constant term low (ATLAS c=0.25, CMS c=0.5), which dominates at high energies
- ✓ CMS will do a better job on Higgs to γγ, to narrow the mass signal … but will have more difficulties with e/γ identification, missing in the barrel a preshower detector and having no longitudinal segmentation
- ✓ ATLAS LAr Calorimeter is intrinsically radiation hard and can be calibrated electronically, CMS crystals are difficult to be kept intercalibrated … more work needed

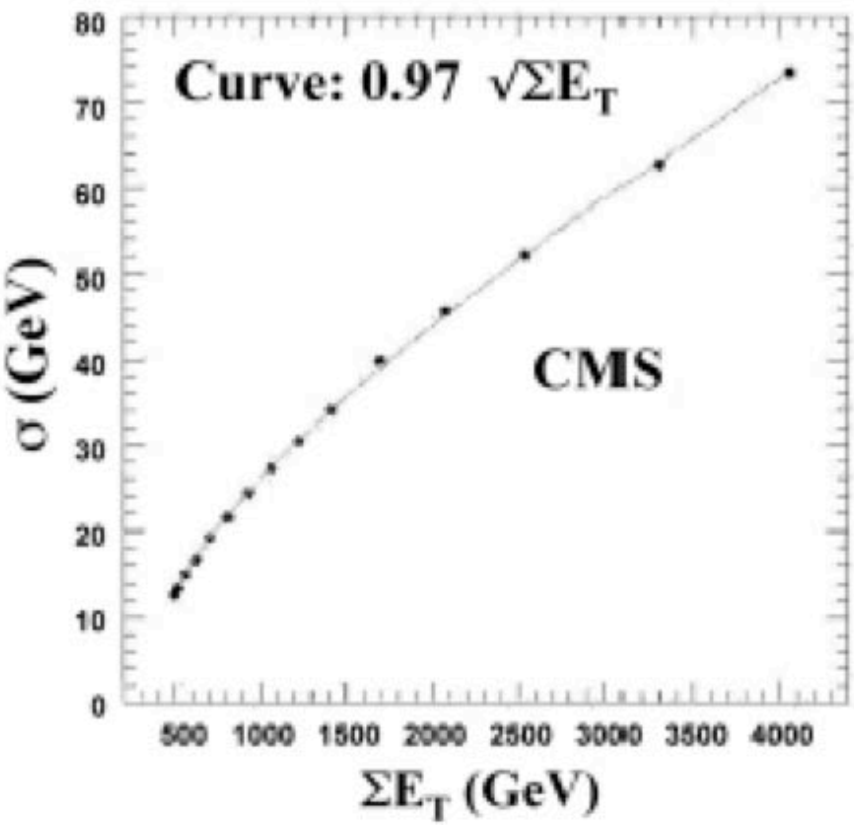




ATLAS & CMS main differences (E_T miss)

ATLAS Hadron Calorimetry is superior (more interaction lengths, better e/h compensation, less dead material, less B-Field, …) … this is very visible in the E_T miss and jets resolution ….





ATLAS & CMS main differences (Muon Spectrometer)

Parameter	ATLAS	CMS
Pseudorapidity coverage:		
- Muon measurement	$\|\eta\| < 2.7$	$\|\eta\| < 2.4$
- Triggering	$\|\eta\| < 2.4$	$\|\eta\| < 2.1$
Dimensions (m):		
- Innermost (outermost) radius	5.0 (10.0)	3.9 (7.0)
- Innermost (outermost) disk (z-point)	7.0 (21-23)	6.0-7.0 (9-10)
Segments/super-points per track for barrel (end-caps)	3 (4)	4 (3-4)
Magnetic field B (T)	0.5	2
- Bending power (BL, in T·m) at $\|\eta\| \approx 0$	3	16
- Bending power (BL, in T·m) at $\|\eta\| \approx 2.5$	8	6
Combined (stand-alone) momentum resolution at:		
- $p = 10$ GeV and $\eta \approx 0$	1.4% (3.9%)	0.8% (8%)
- $p = 10$ GeV and $\eta \approx 2$	2.4% (6.4%)	2.0% (11%)
- $p = 100$ GeV and $\eta \approx 0$	2.6% (3.1%)	1.2% (9%)
- $p = 100$ GeV and $\eta \approx 2$	2.1% (3.1%)	1.7% (18%)
- $p = 1000$ GeV and $\eta \approx 0$	10.4% (10.5%)	4.5% (13%)
- $p = 1000$ GeV and $\eta \approx 2$	4.4% (4.6%)	7.0% (35%)

ATLAS toroidal spectrometer provides a high performance independent muon spectrometer, no need for the inner tracker for major discoveries

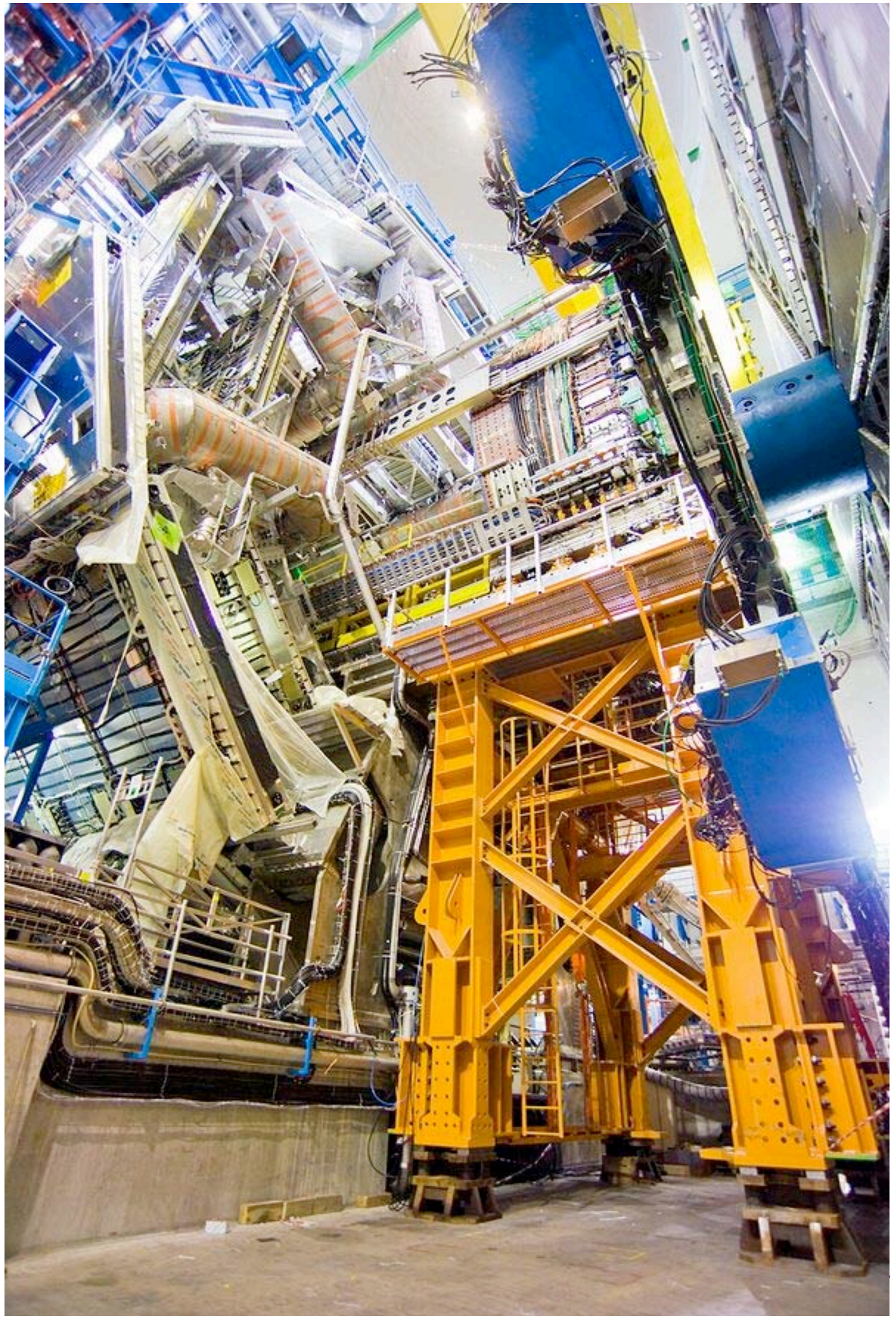
CMS : higher bending power in the z=0 region, better resolution at low η

ATLAS : higher bending power in the forward, better resolution at high η

ATLAS : higher rapidity coverage

ATLAS & CMS readiness

- ✓ Both detectors are in their final installation phase. All major components are installed or are in the final phase of installation
- ✓ For cost reasons some of the redundancy necessary when going to high luminosity was staged (this is mostly computing power in the high-level triggers and data acquisition). It will be restored in 2009/2010.
- ✓ CMS has a problem with getting the EM calorimeter end-caps fully ready in time. The last one is foreseen in spring 2008… but a scenario to install it after the detector is completed exists.
- ✓ Both detectors are commissioning their readout, are taking cosmic events and are preparing the data processing chain



Example ATLAS final schedule