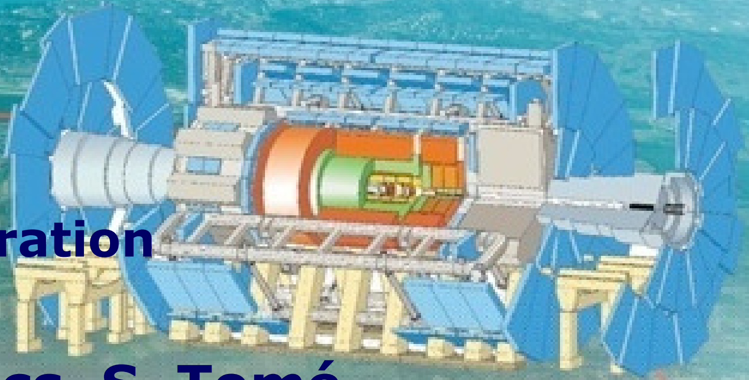
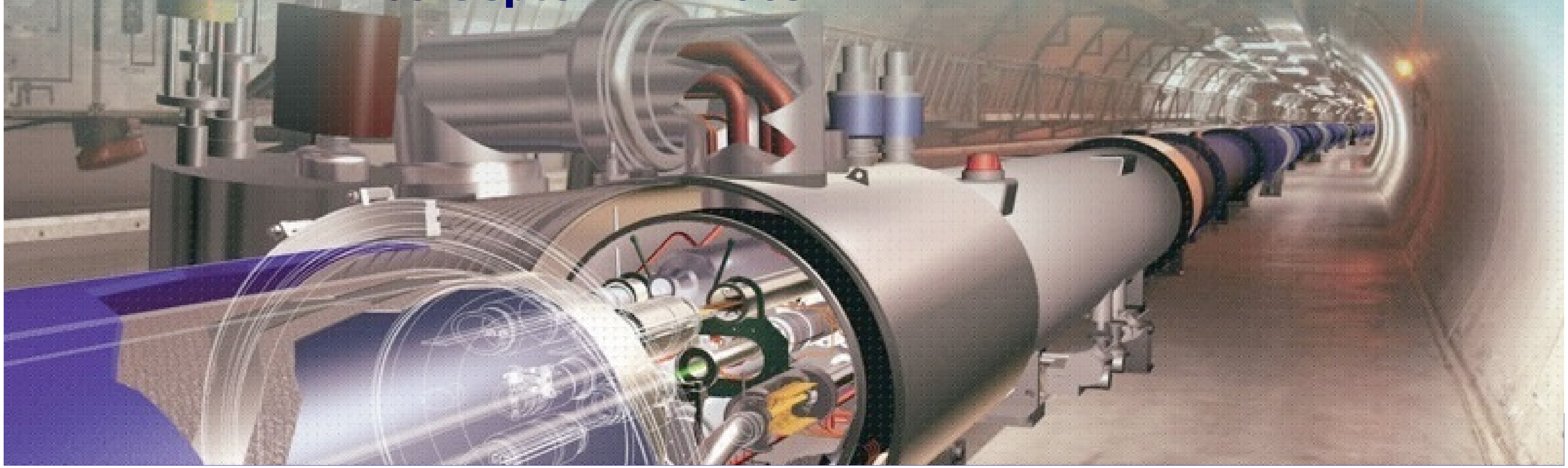
Performance of the ATLAS detector on cosmic rays data



J. Carvalho (LIP)
on behalf of the ATLAS Collaboration

New Worlds in Astroparticle Physics, S. Tomé
09 September 2009



Talk presented on behalf of the

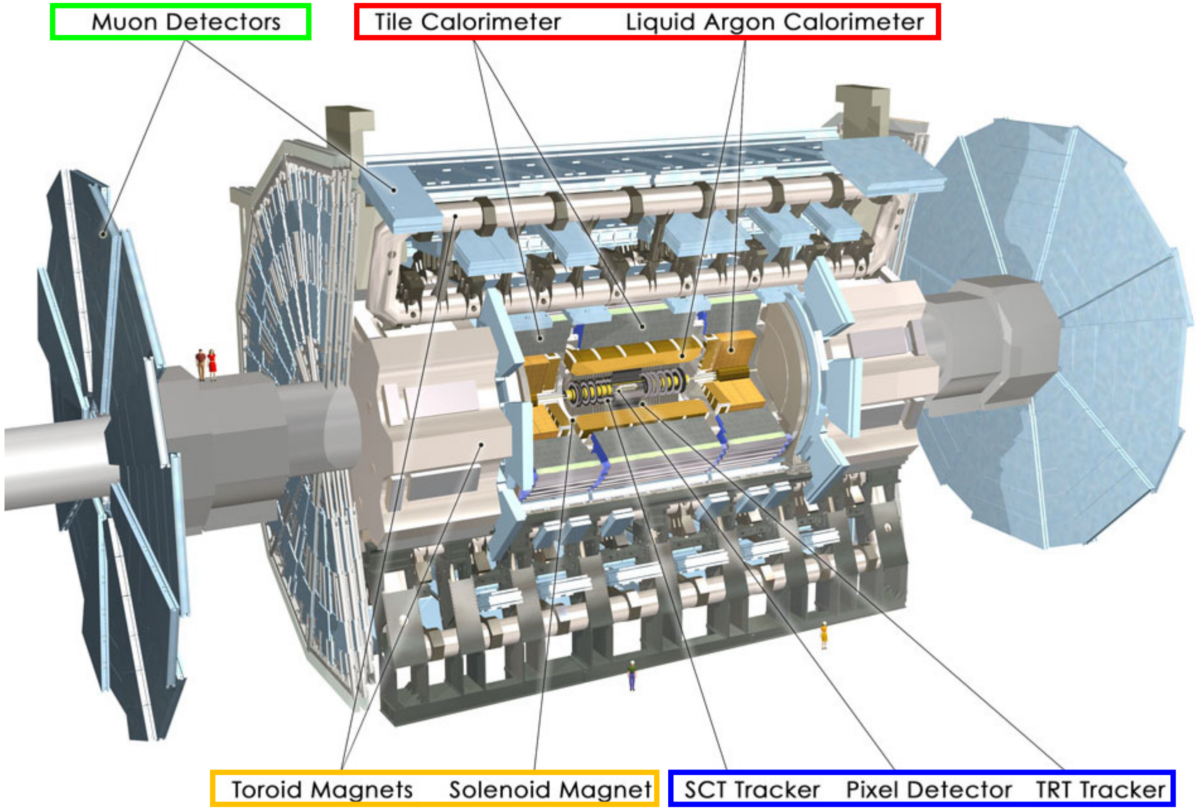
ATLAS Collaboration

37 Countries
169 Institutions
~2800 Scientific Authors
(~800 PhD students)

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, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, 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, 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, Olomouc, 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, 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/ICTP, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

Overview

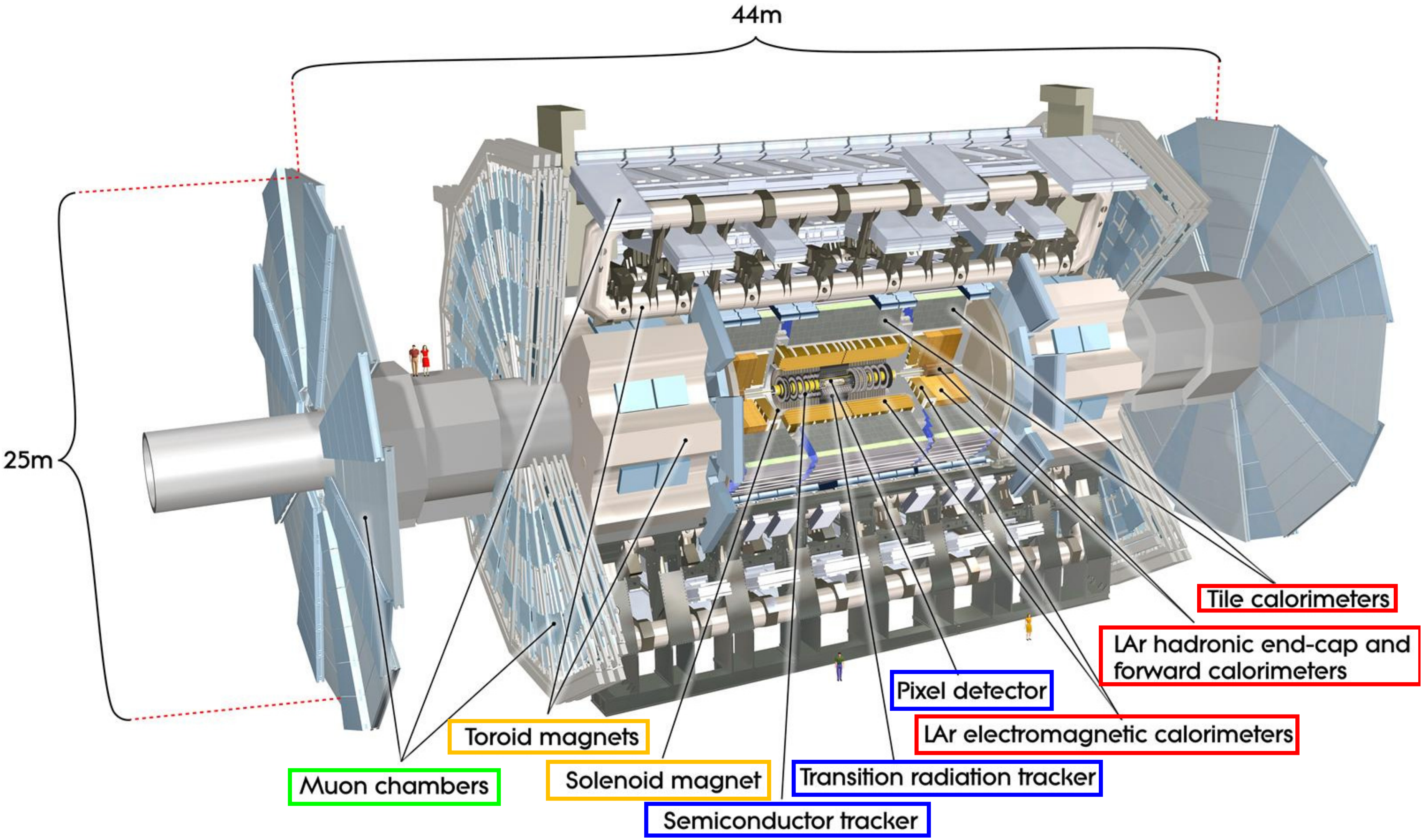
- The status of the ATLAS detector in a nutshell
  - Inner detector
  - Calorimeters
  - Muon system
- Commissioning with cosmic rays
  - What can be learned?
  - Results
- Conclusions



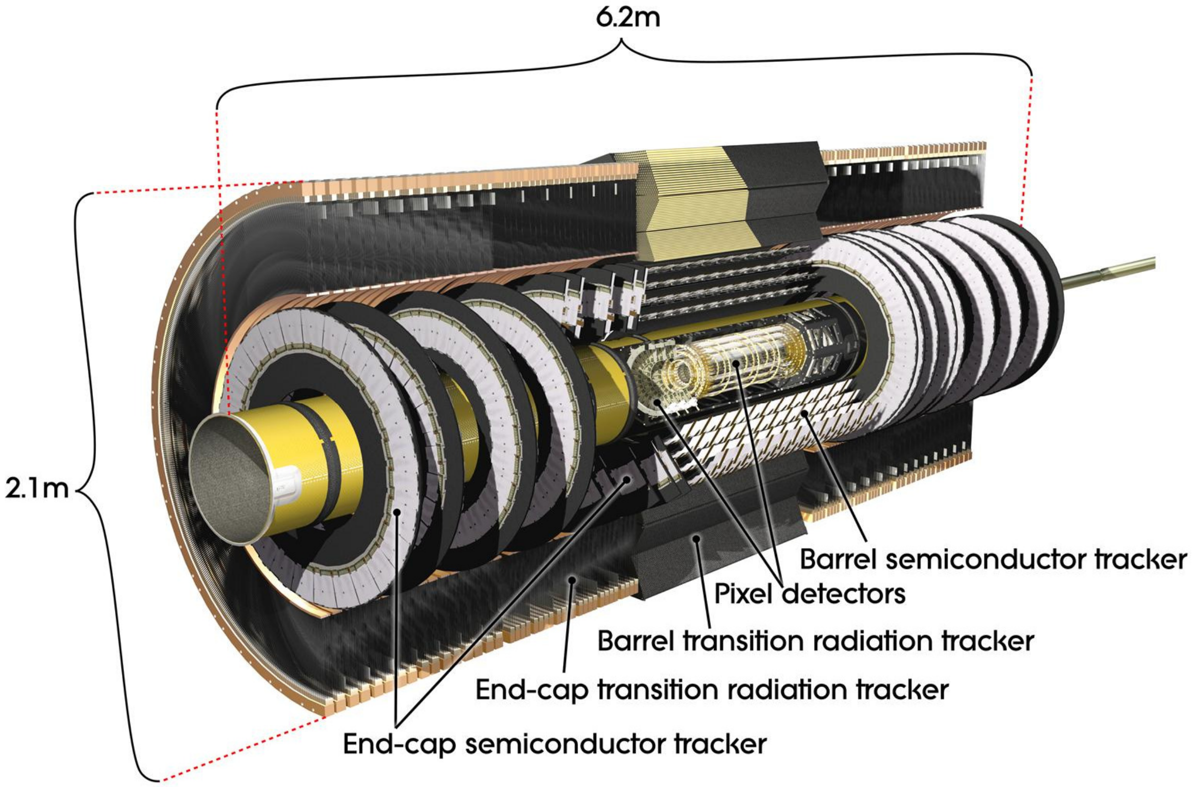
LHC

Proton collider with a design center of mass energy of 14 TeV, ~100 m underground

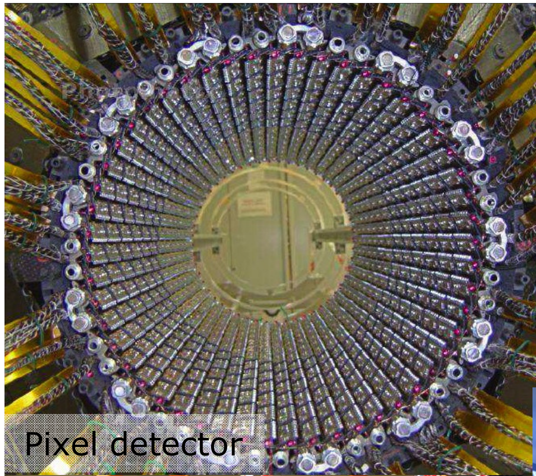
The ATLAS detector

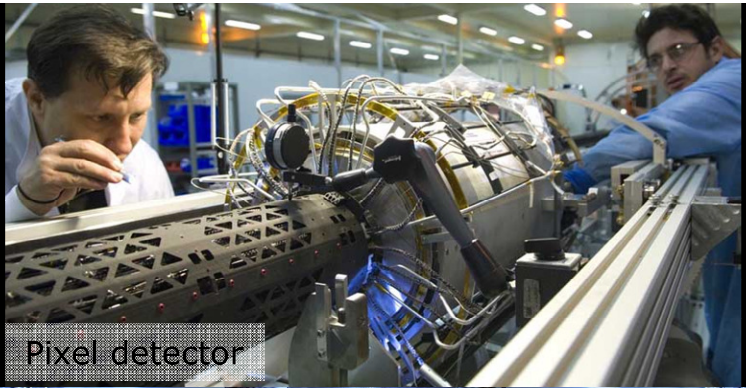


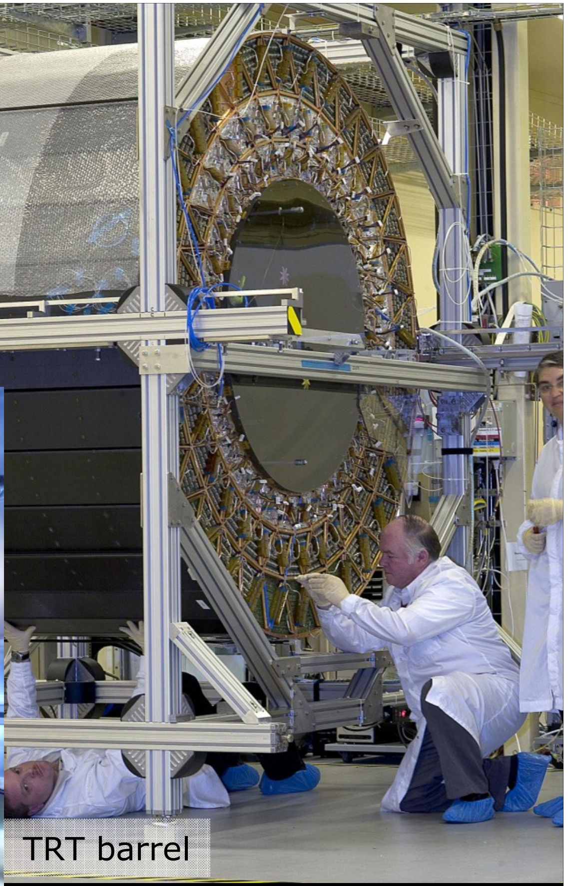
Inner Detector

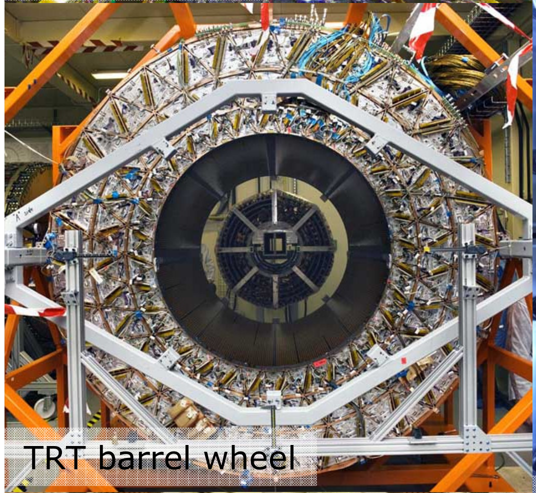


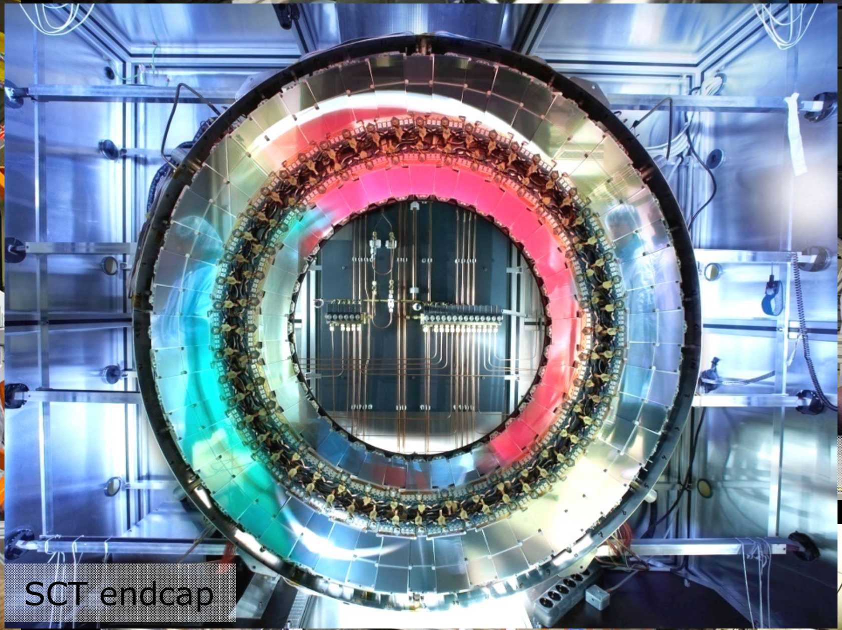
- Operates inside a 2 Tesla field, coverage $|\eta|<2.5$ (TRT $|\eta|<2.0$)
- $p_T \cdot \sigma(q/p_T) = 0.04\% \ p_T \oplus 1.5\%$ at $|\eta|=0$ (p_T in GeV)

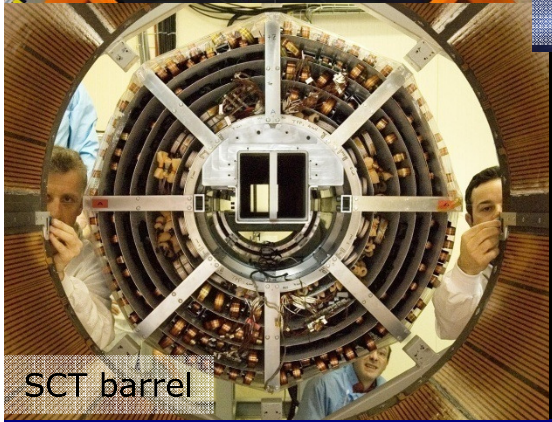

Pixel detector


Pixel detector


TRT barrel

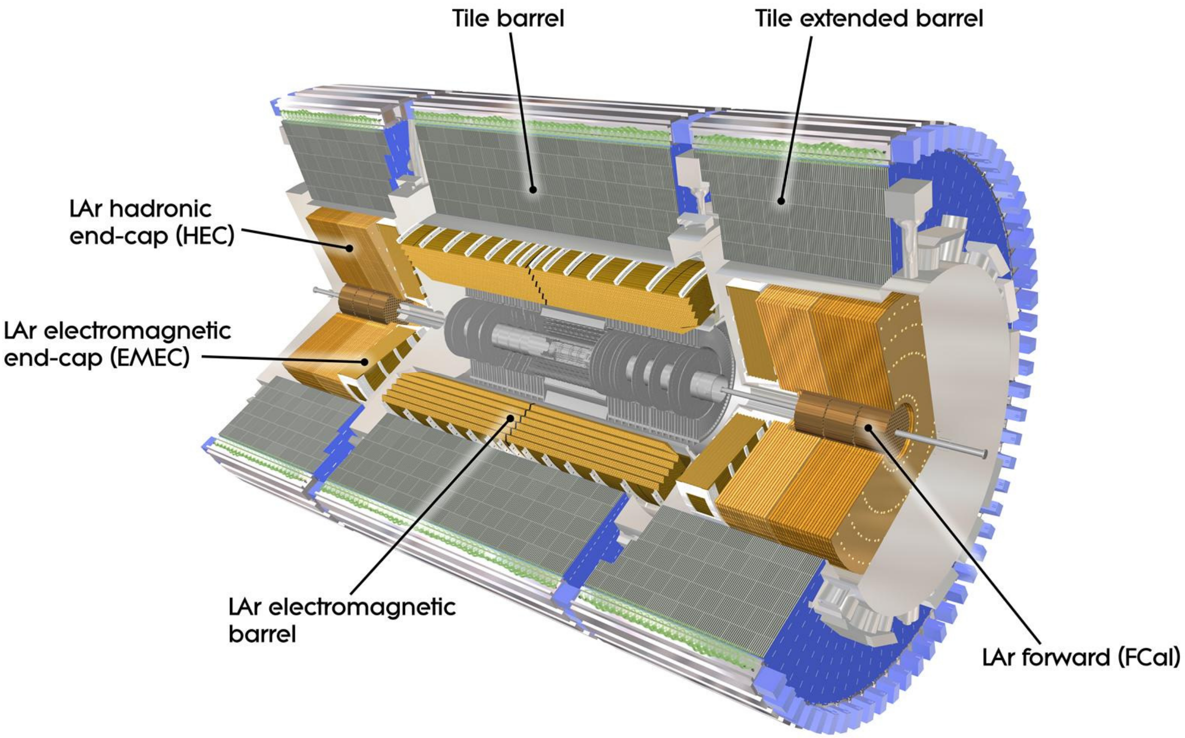

TRT barrel wheel


SCT endcap

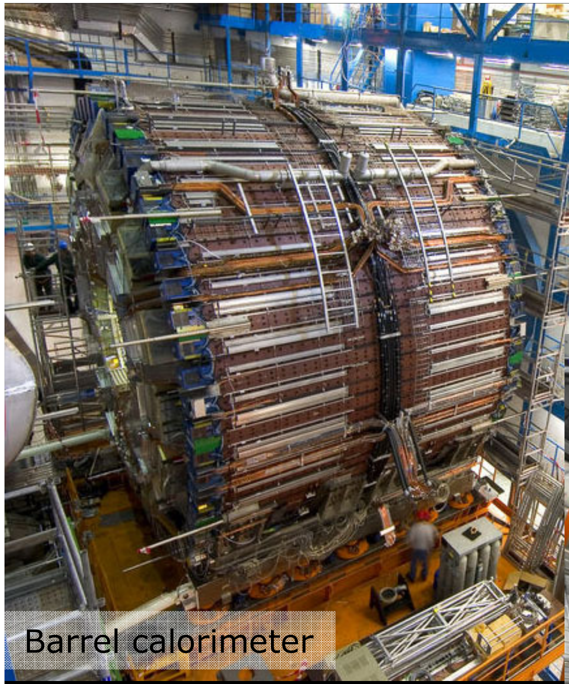

SCT barrel

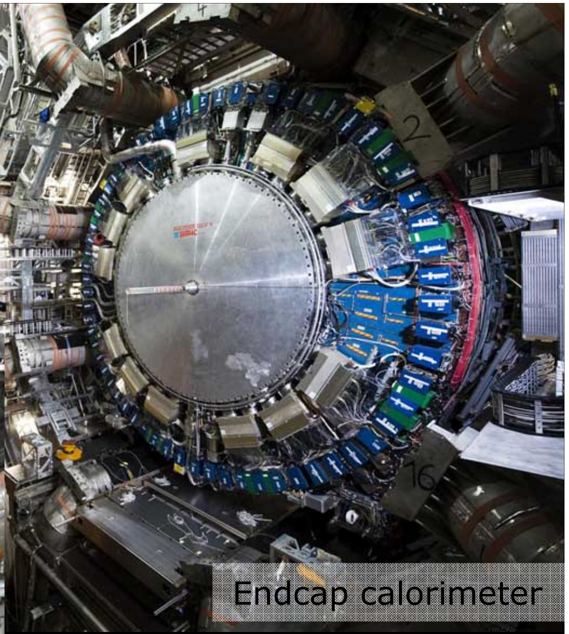

Pixel detector insertion

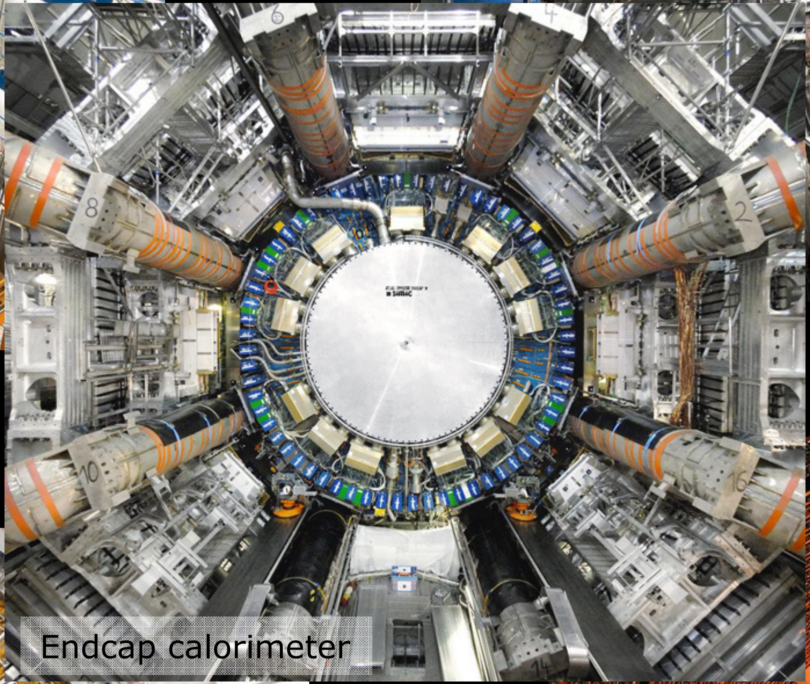
Calorimetry



- Electromagnetic energy resolution (noise subtracted):
  - $\sigma(E)/E = 10\%/\sqrt{E} \oplus 0.7\%$
- Hadronic energy resolution:
  - $\sigma(E)/E = 50\%/\sqrt{E} \oplus 3\%$ ($|\eta| < 3.2$)
  - $\sigma(E)/E = 100\%/\sqrt{E} \oplus 10\%$ ($|\eta| > 3.1$)


Barrel calorimeter


Endcap calorimeter

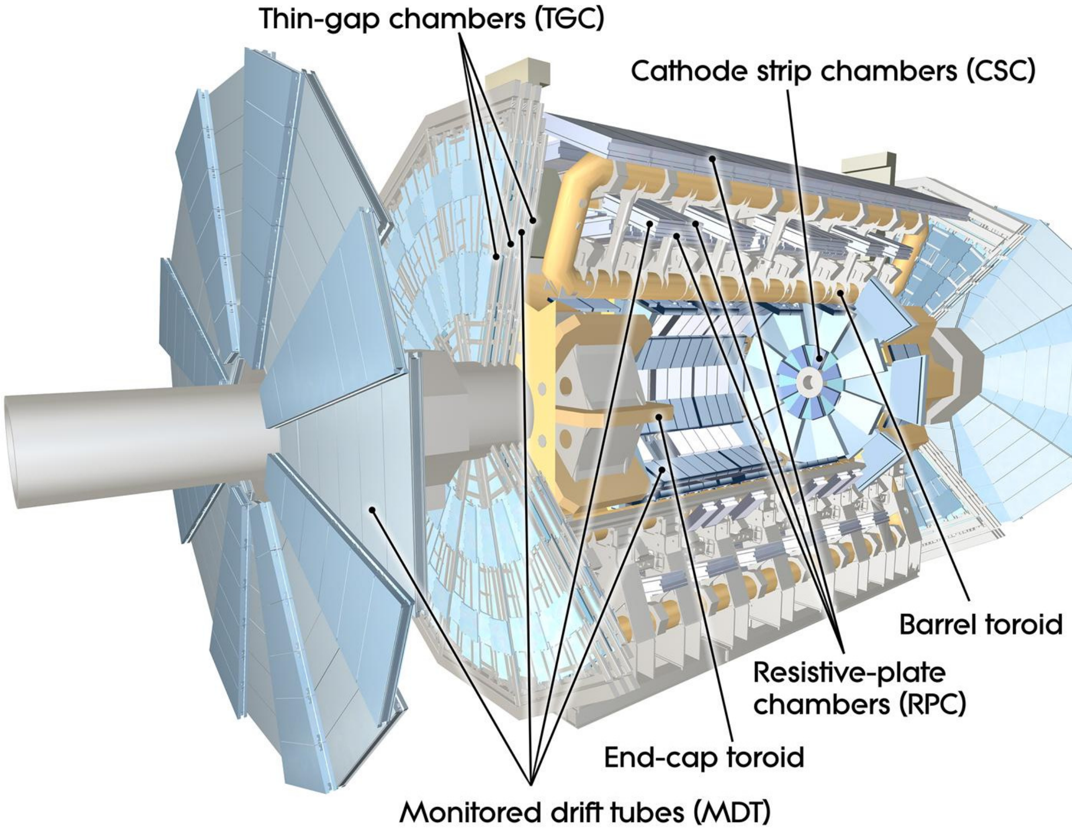

Endcap calorimeter


LAr barrel calorimeter wheel

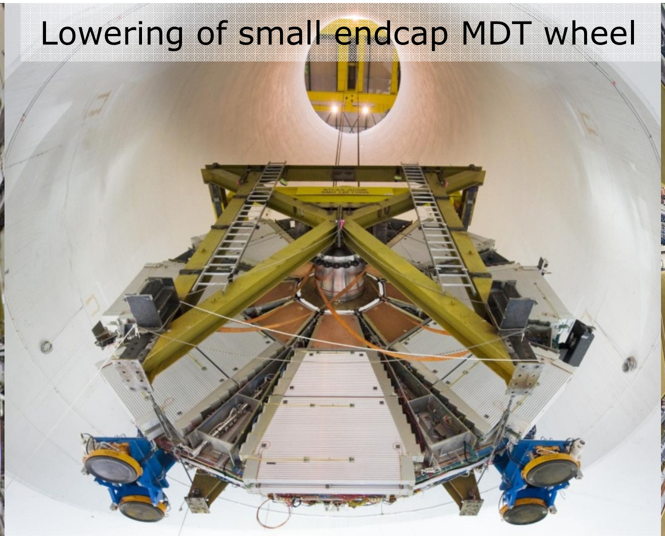

Hadronic endcap calorimeter wheels

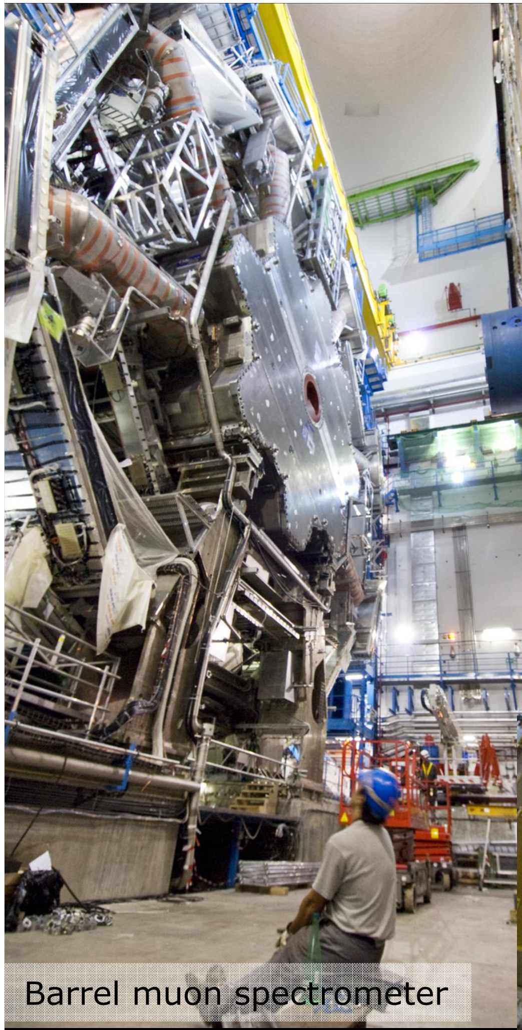
Barrel calorimeter in its final position

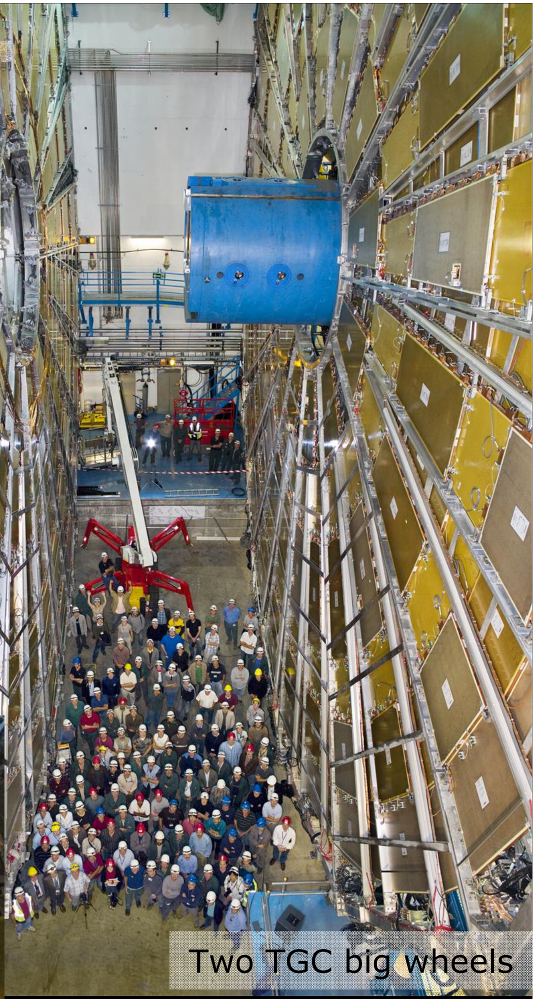
Muon system



- Air-core toroid magnet system
  - 1.5-5.5 Tm ($|\eta| < 1.4$) and 1-7.5 Tm ($|\eta| > 1.6$)
- Stand-alone momentum resolution:
  - $\Delta p_T/p_T$ = 10% at 1 TeV, $\Delta p_T/p_T$ = 3.5% to 4% at 100 GeV


Lowering of small endcap MDT wheel

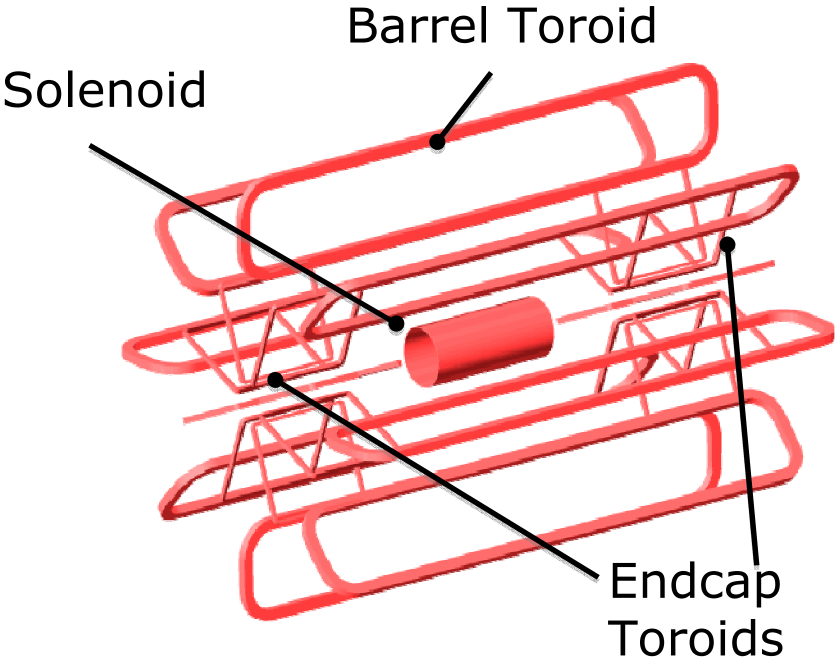

Barrel muon spectrometer

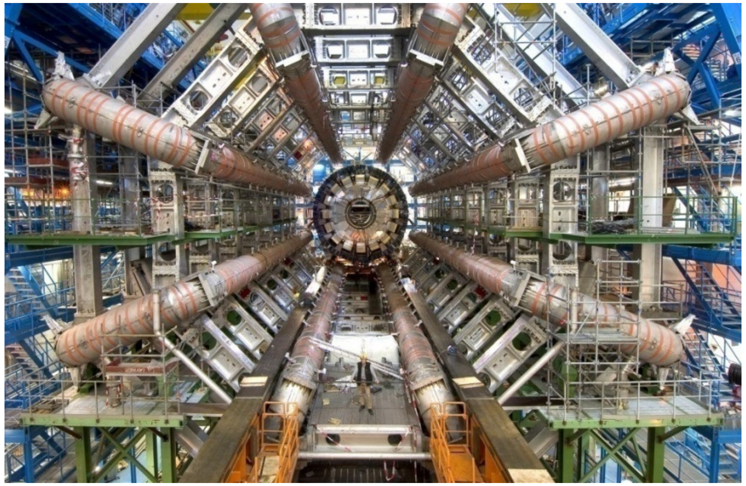

Two TGC big wheels


Part of end wall MDT wheel through TGC big wheel

Magnet system

- Solenoid (1 coil)
  - 2 T field (at 7.73 kA)
  - Located in radius between the inner detector and the electromagnetic calorimeter
- Barrel Toroid (8 coils)
  - 0.2-2.5 T field (at 20.5 kA)
- Two end-cap toroids (2 x 8 coils)
  - 0.2-3.5 T (at 20.5 kA)

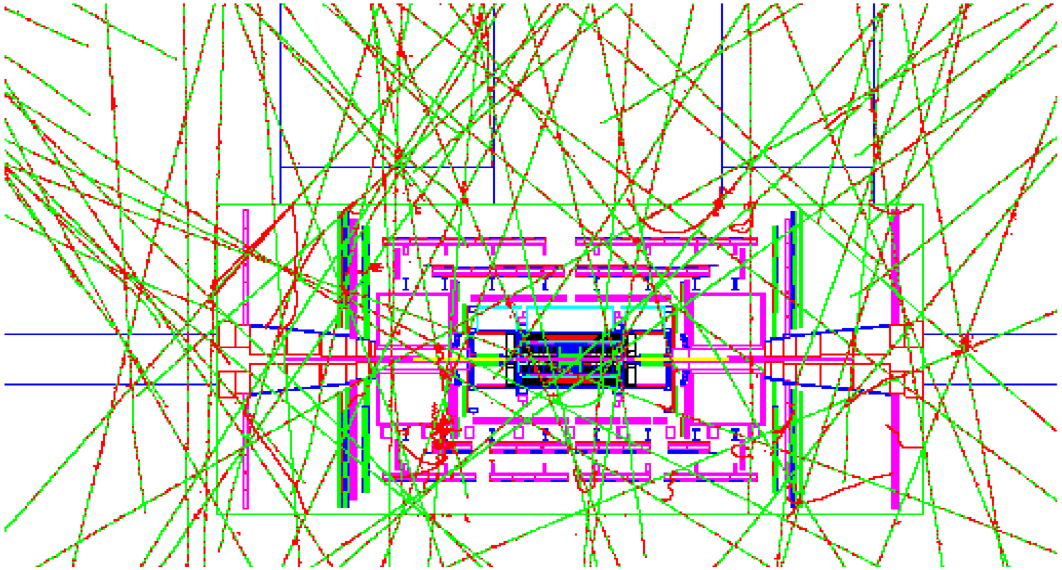




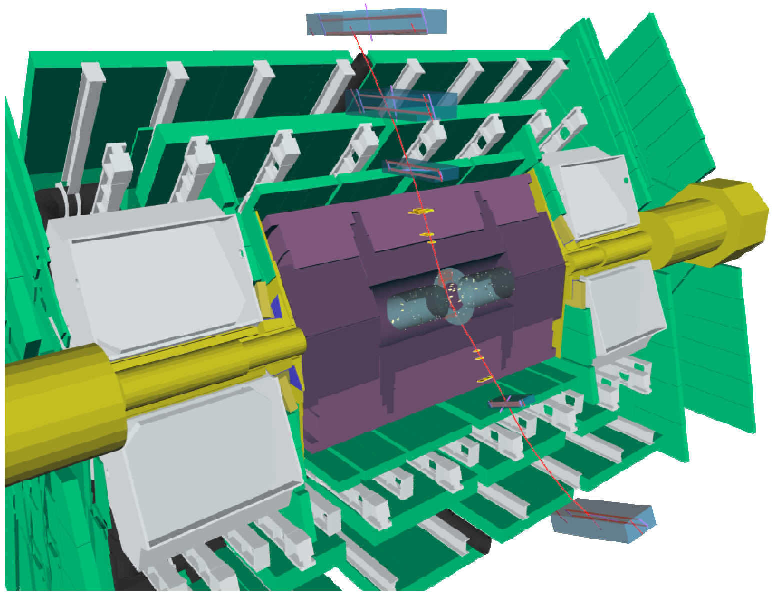
Using cosmic rays in ATLAS

In LHC cosmic rays are a very useful “beam”, always available for **commissioning**, **calibration** and **alignment** of complex and large detectors

Cosmic rays are a **tool** to study and improve the detector



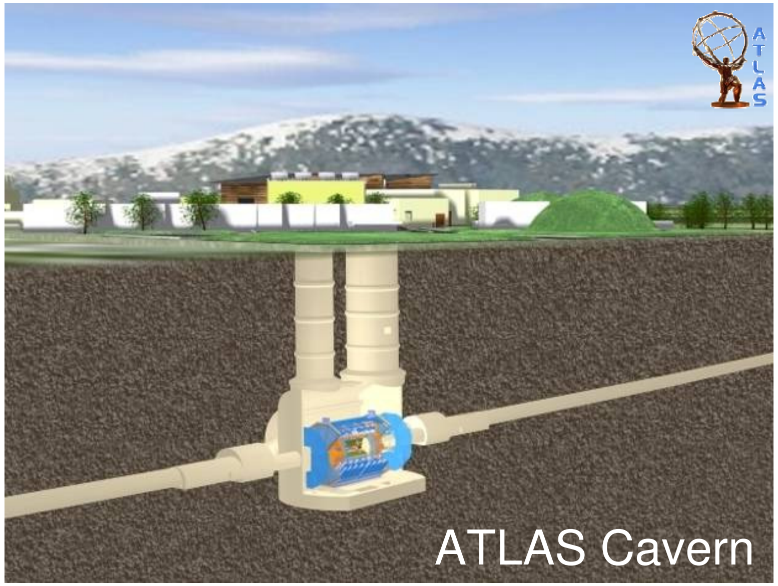
10 ms of cosmics

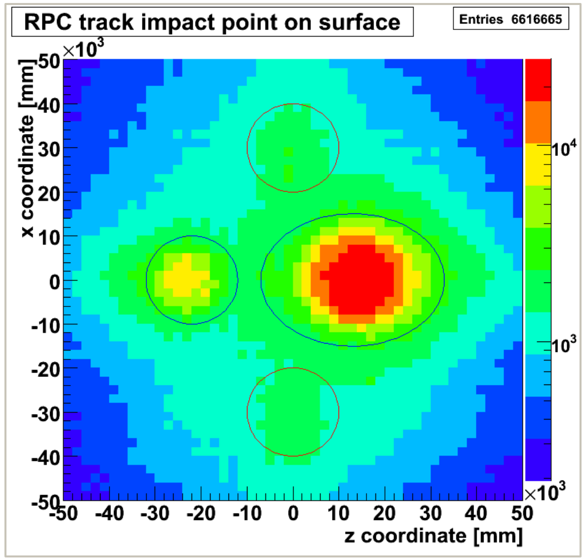


Commissioning using cosmic rays

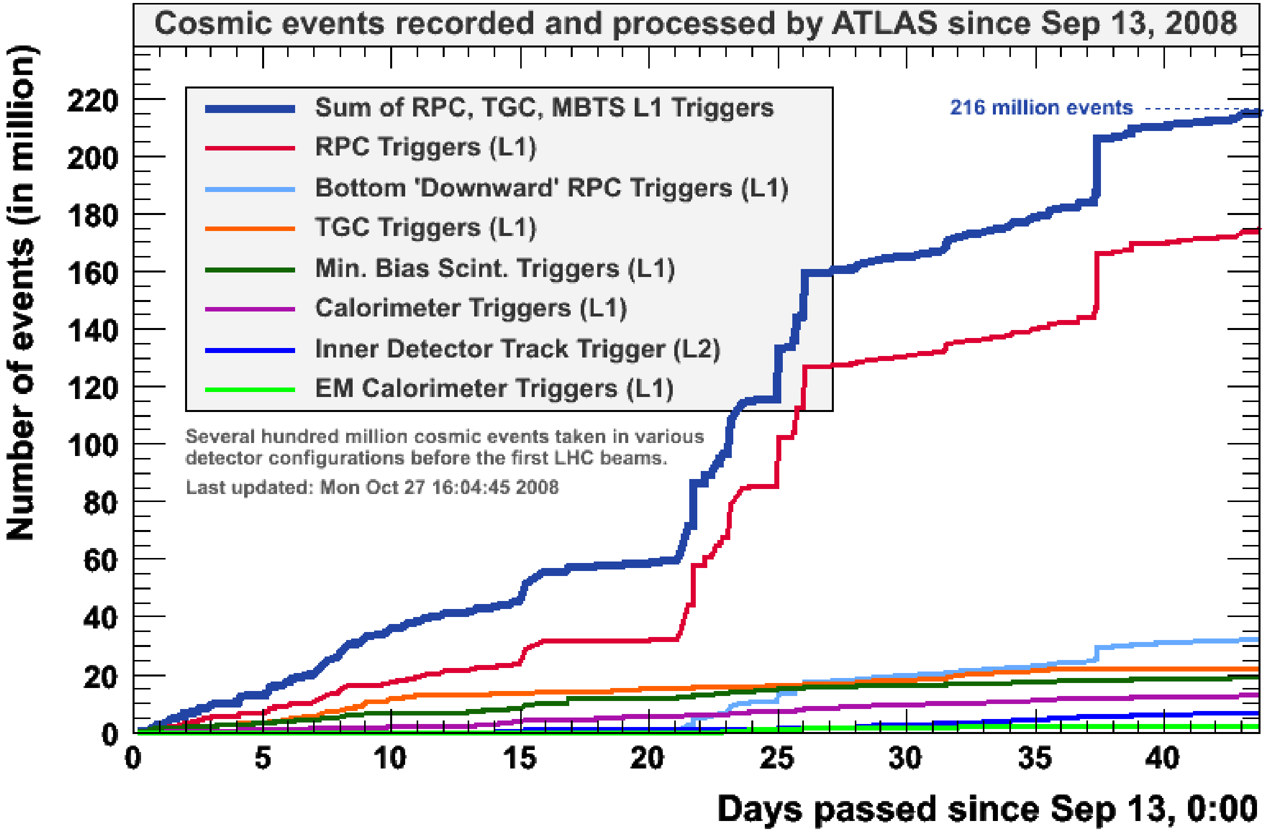
Started in 2005 in parallel with the detector installation

- –Muon flux at surface:
  - ~130 Hz/m^2 for $E_\mu > 1$ GeV
  - average energy ~4 GeV
- –Muon flux in ATLAS detector (simulation):
  - ~4 kHz in muon fiducial volume
  - ~15 Hz in TRT barrel





Cosmic muon data taking

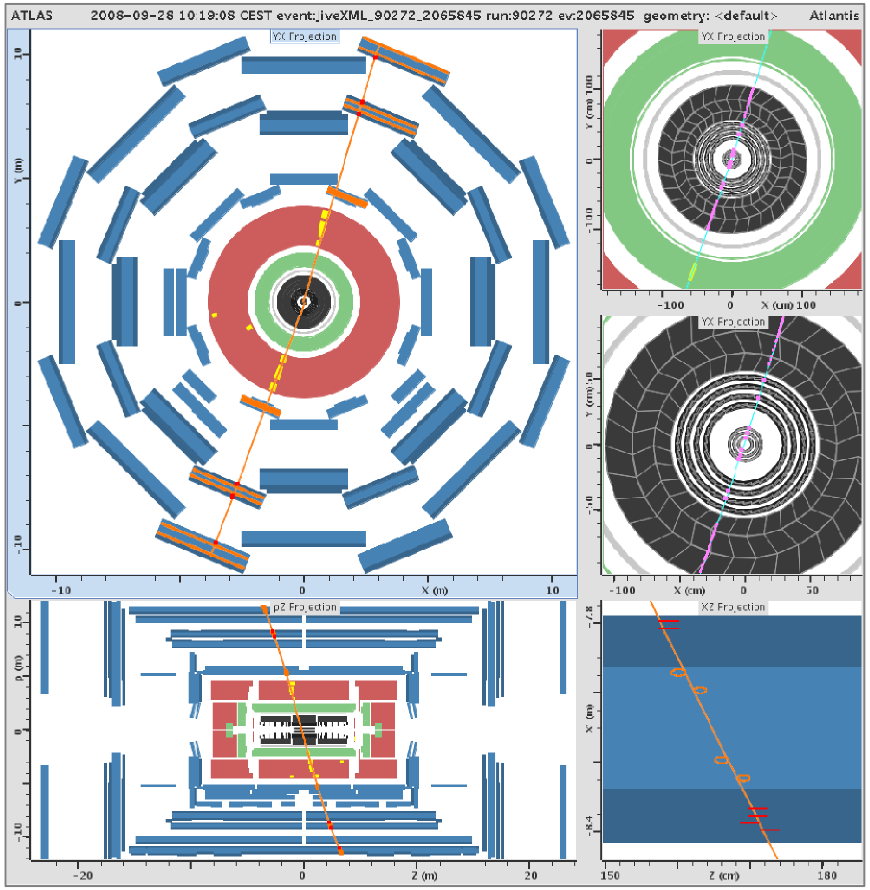


Several hundred million cosmic events taken in various detector configurations before the first LHC beams.

Last updated: Mon Oct 27 16:04:45 2008

Largest data sample of cosmic rays with the full ATLAS detector recorded in autumn 2008 (more than 200 million events!)

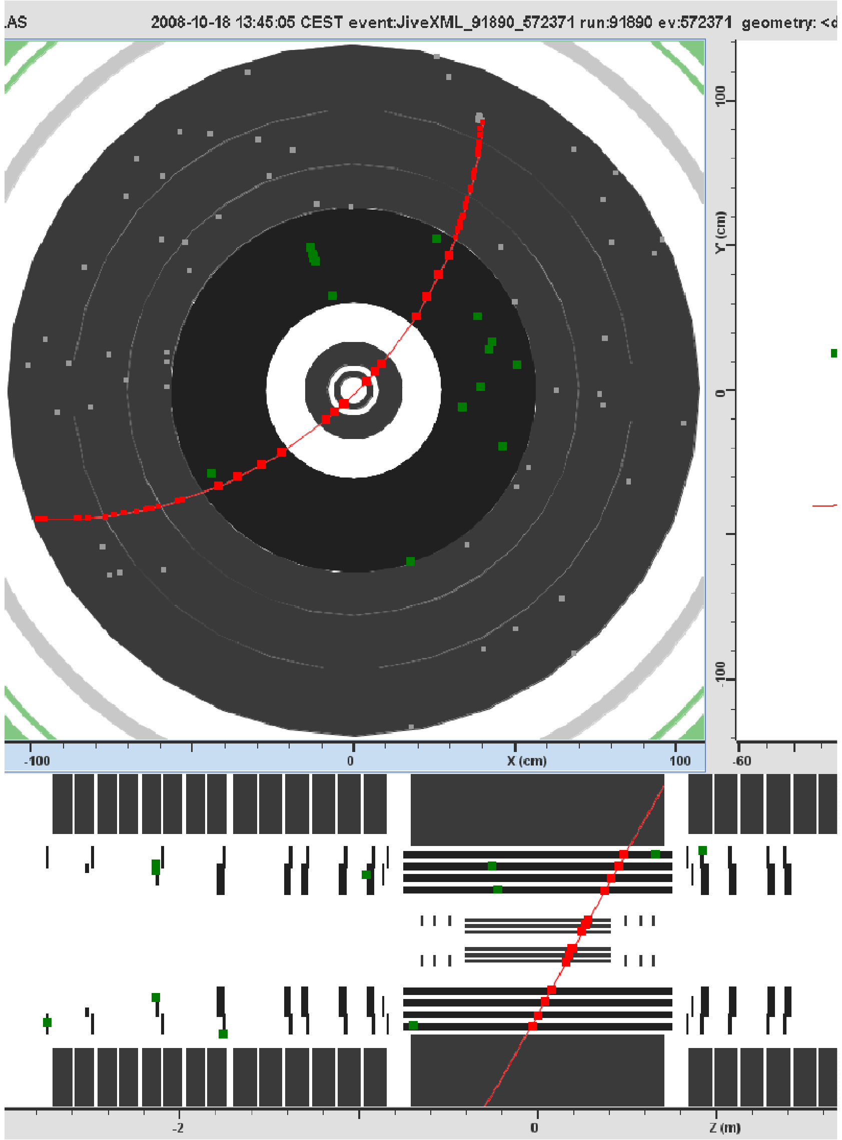
Cosmic muon data taking -goals



Cosmic muon event (ATLAS event display)

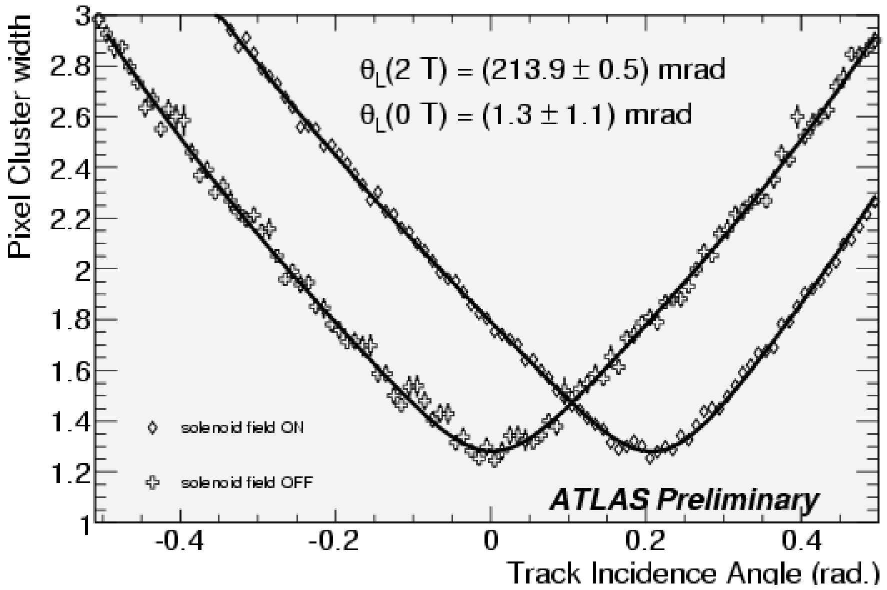
- Test channel mapping and timing
- Determine dead and noisy channels
- Verify stability of hardware components during operation
- Gain experience in detector operation and control, data acquisition and analysis chain
- Understand and improve detector performance
  - Detector alignment and calibration

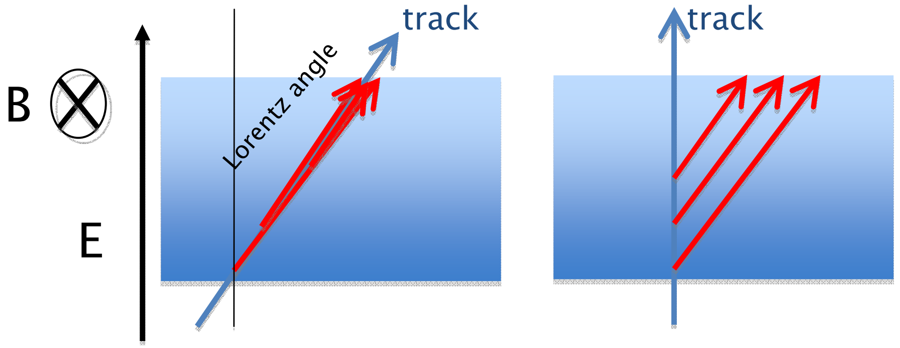
Cosmic muon results – Pixel detector



Cosmic muon track in the ID (event display)

Cosmic muon results – Pixel detector

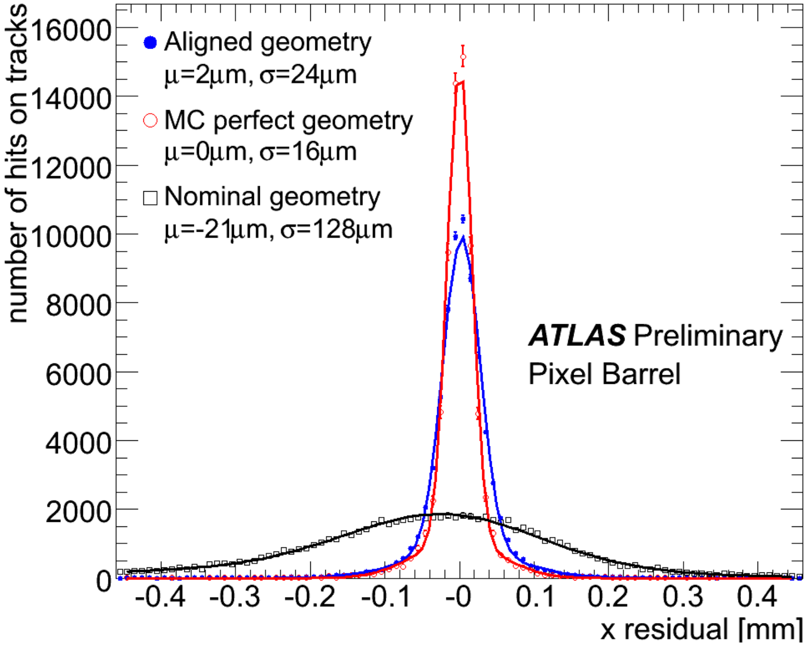


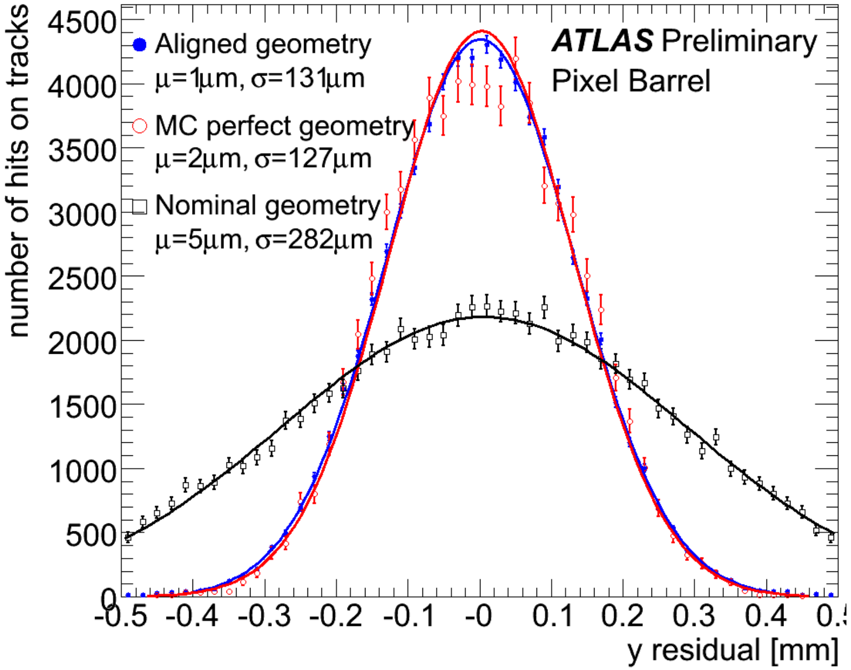


Measurement of Lorentz angle necessary to reach final spatial resolution

- Measurement of cluster width as a function of the incident angle of muon track
- Minimum of cluster width at incident angle = Lorentz angle
  - MC prediction at 2T: 224 mrad
  - Result at 2T: 213.9 ± 0.5 mrad

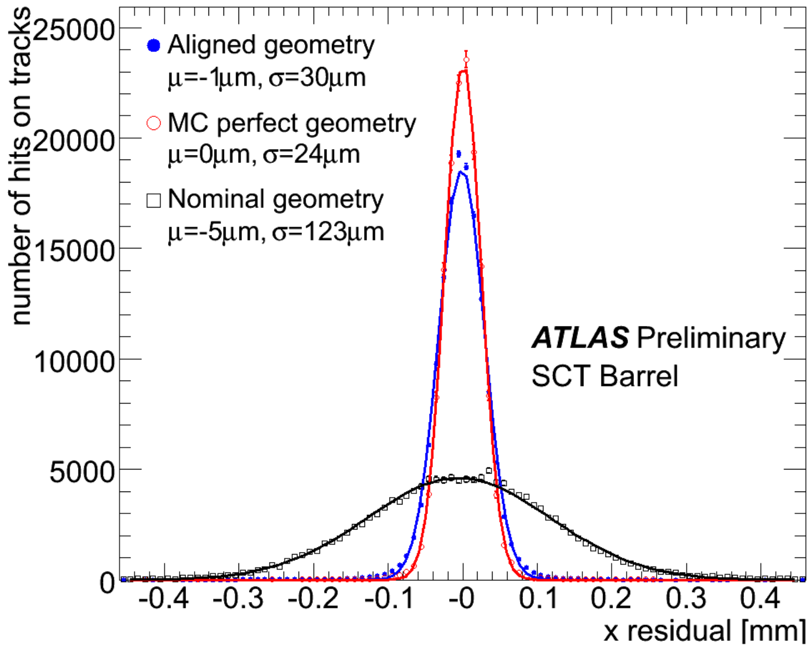
ID alignment with cosmic muons

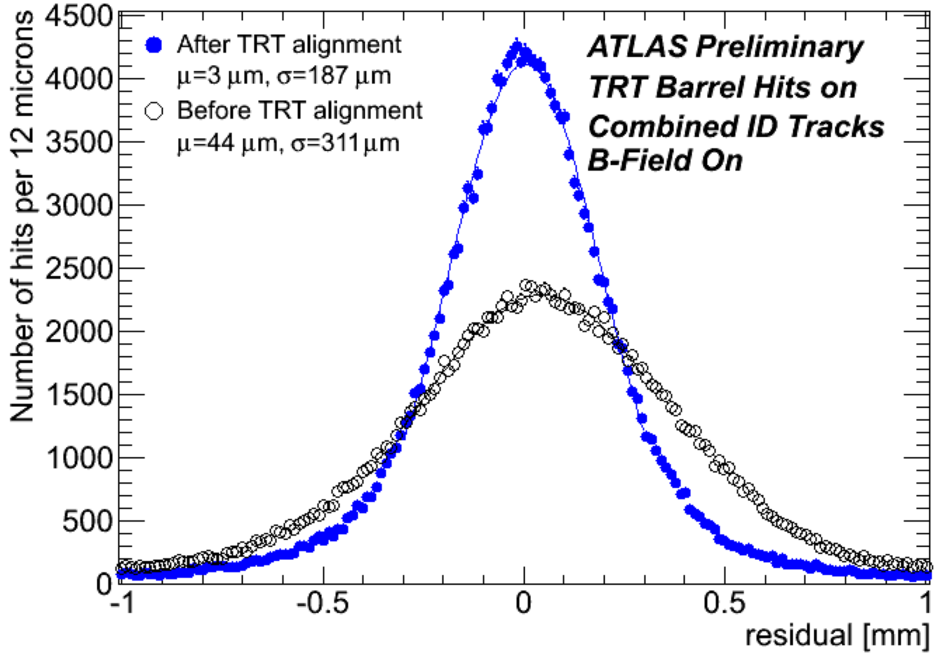




- Inner detector alignment done with cosmic muon tracks (solenoid on)
- Track residuals after alignment coming close to those expected for perfect geometry (barrel region)
- Limited by statistics in endcap region

ID alignment with cosmic muons

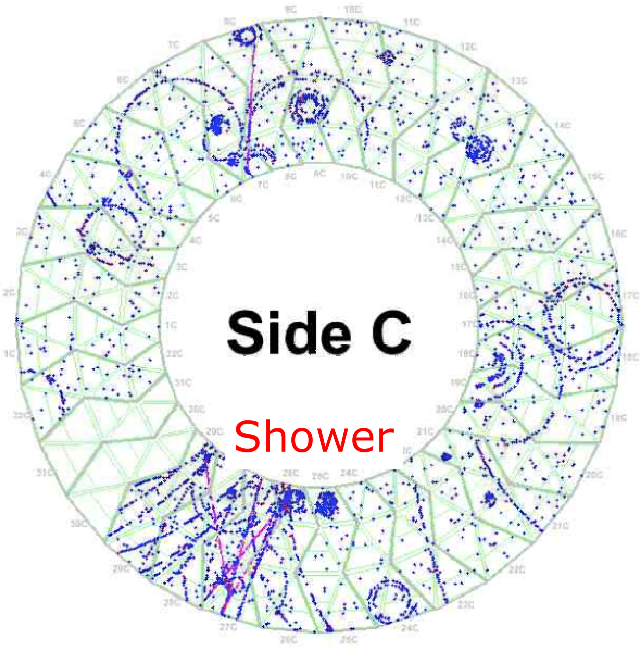




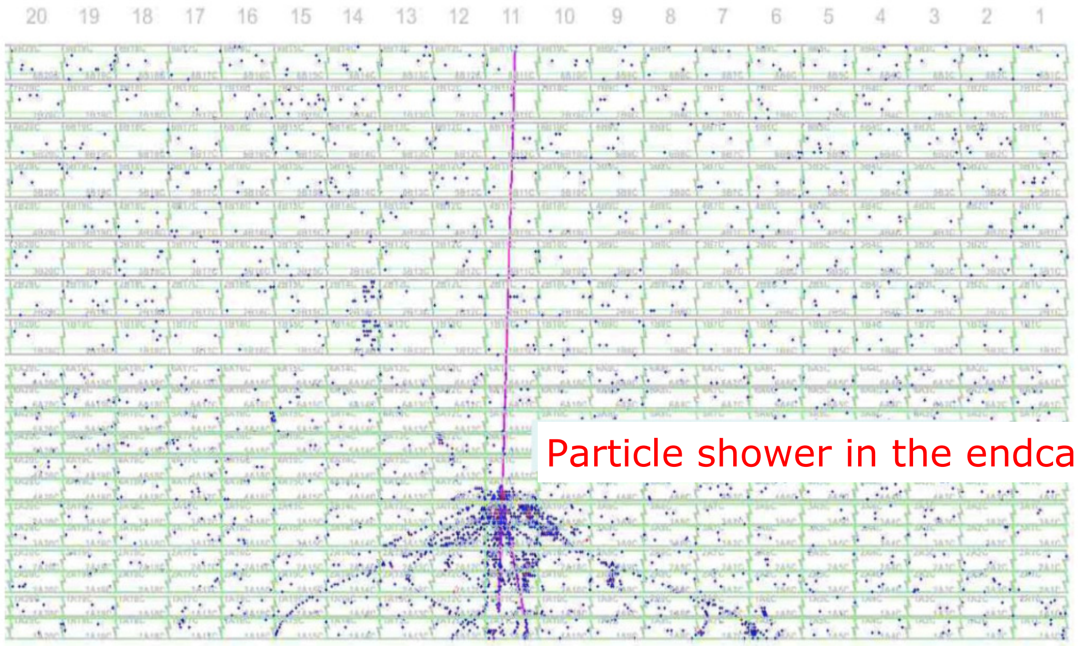
Magnetic field	OFF	ON
All Tracks	4.9 M	2.7 M
SCT Tracks	1.2 M	880 k
Pixel Tracks	230 k	190 k

ATLAS track statistics since Sep 2008

Cosmic muon results - TRT



Shower

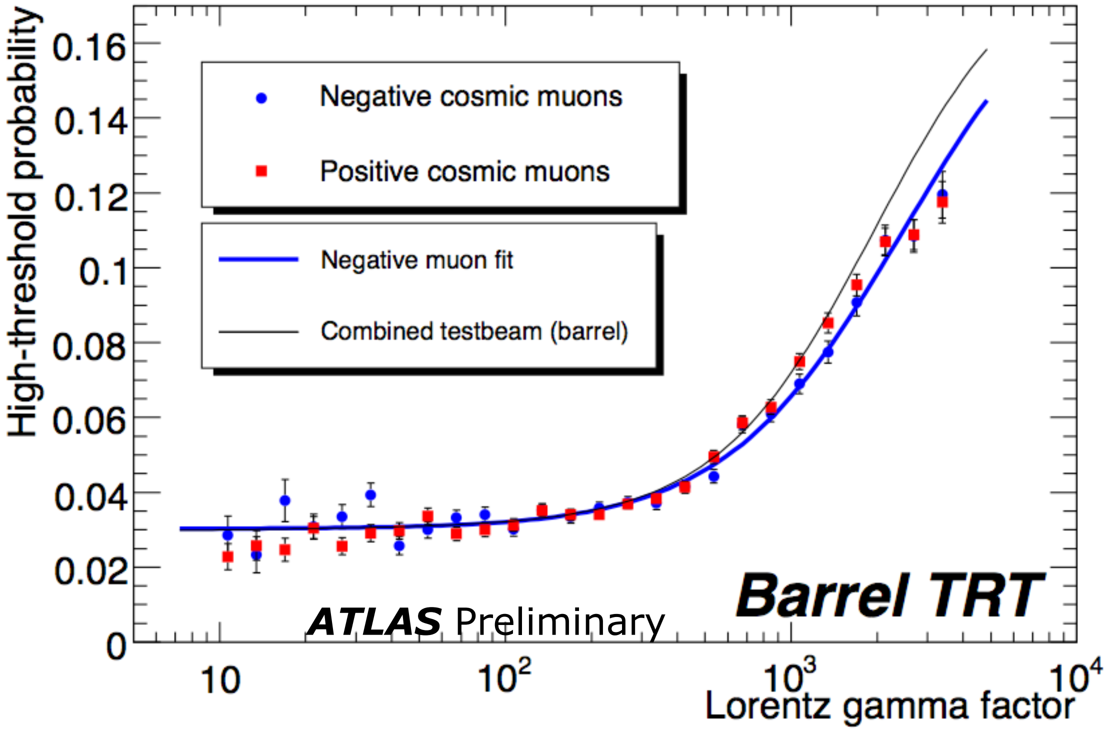


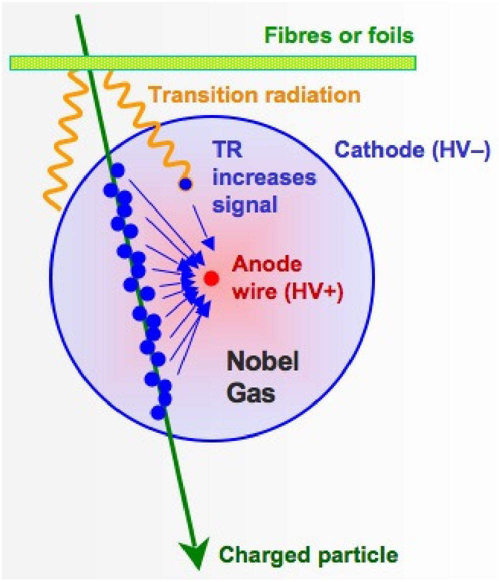
Particle shower in the endcap

Cosmic muon results - TRT

Measurement of transition radiation probability as a function of the Lorentz gamma factor

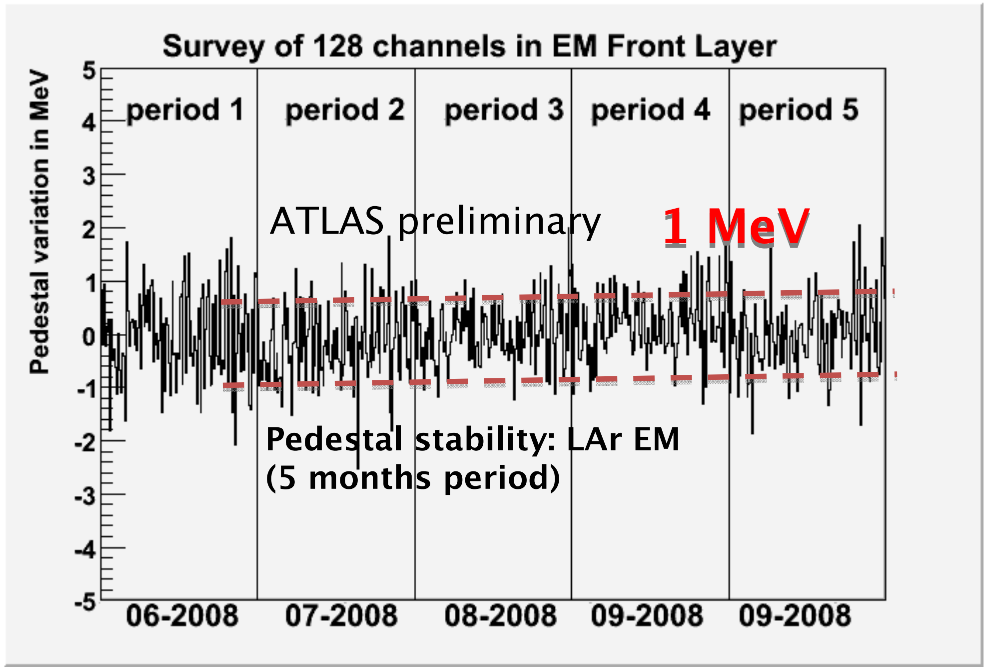
- Good agreement with curve measured in the testbeam
- Similar results for the endcap TRT





Calorimeter results

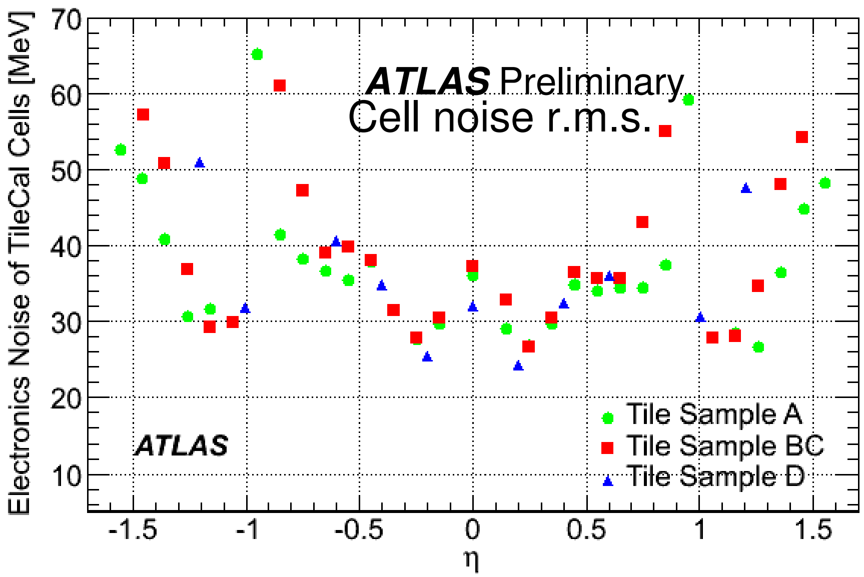
- Commissioning with calibration runs and during cosmic muon data taking
- Noise
  - Random triggers used to measure noise in calorimeters
  - High stability of read-out electronics and noise during months

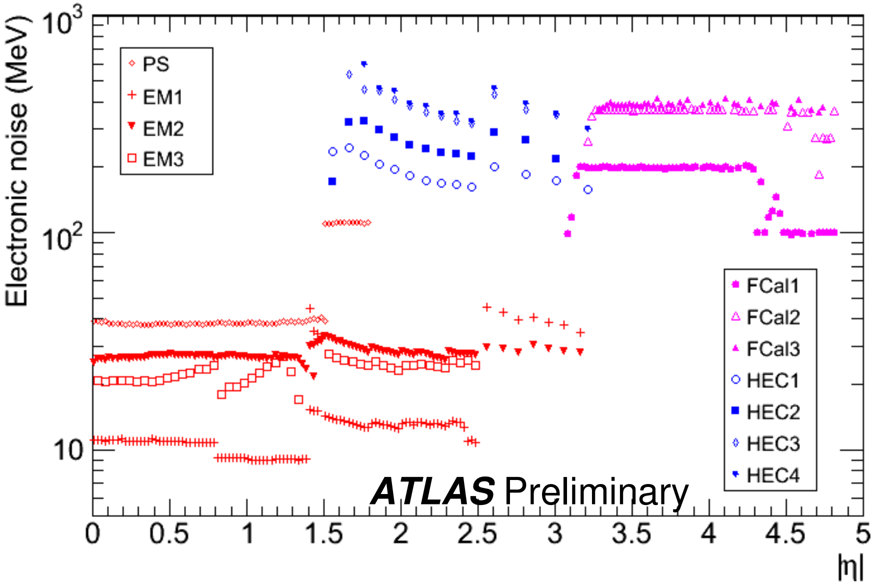


Calorimeter results

TileCal

Liq. Ar





Electronic noise in individual cells of the various longitudinal layers of the calorimeters as a function of pseudorapidity $\eta=-\ln[\tan(\theta/2)]$

In collision events, selected jets will have an energy greater than ~20 GeV

Missing E_T study (LAr)

Random triggered events used to estimate **missing E_T** variables (missing energy on the transverse plane)

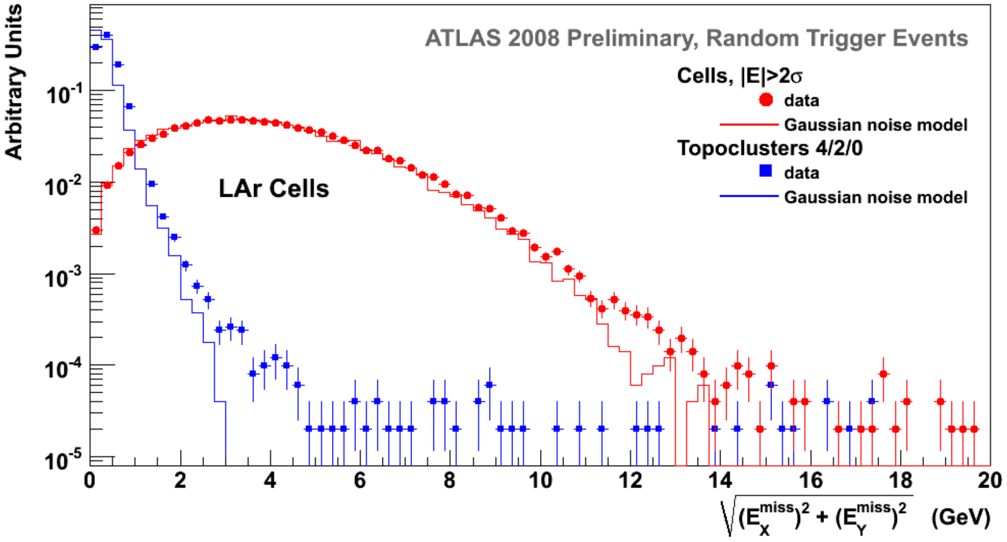
$E_X^{miss} = - \sum E \sin\theta \cos\varphi$

$E_Y^{miss} = - \sum E \sin\theta \sin\varphi$

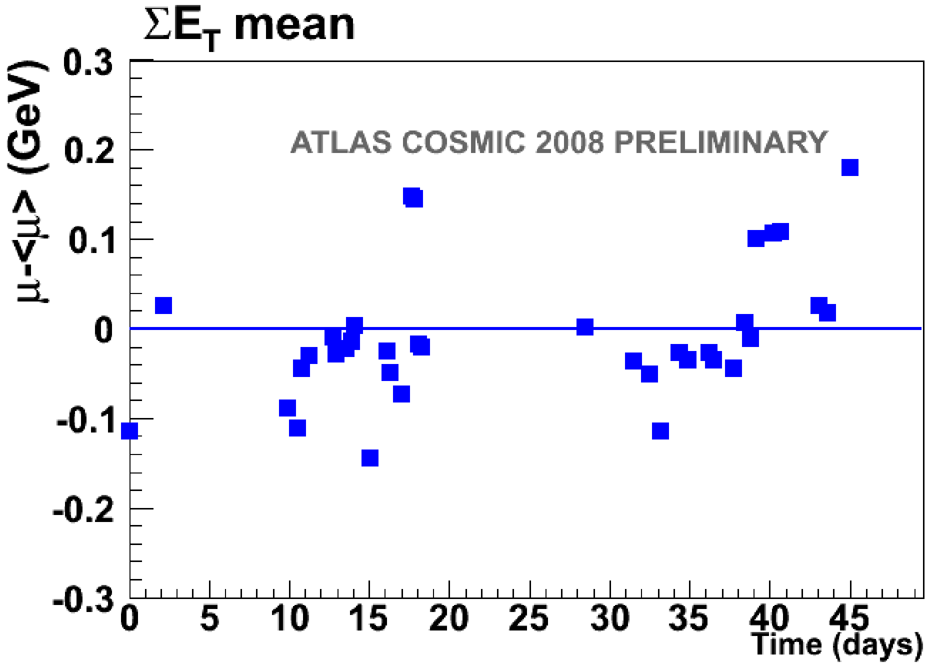
$(E_T^{miss})^2 = (E_X^{miss})^2 + (E_Y^{miss})^2$

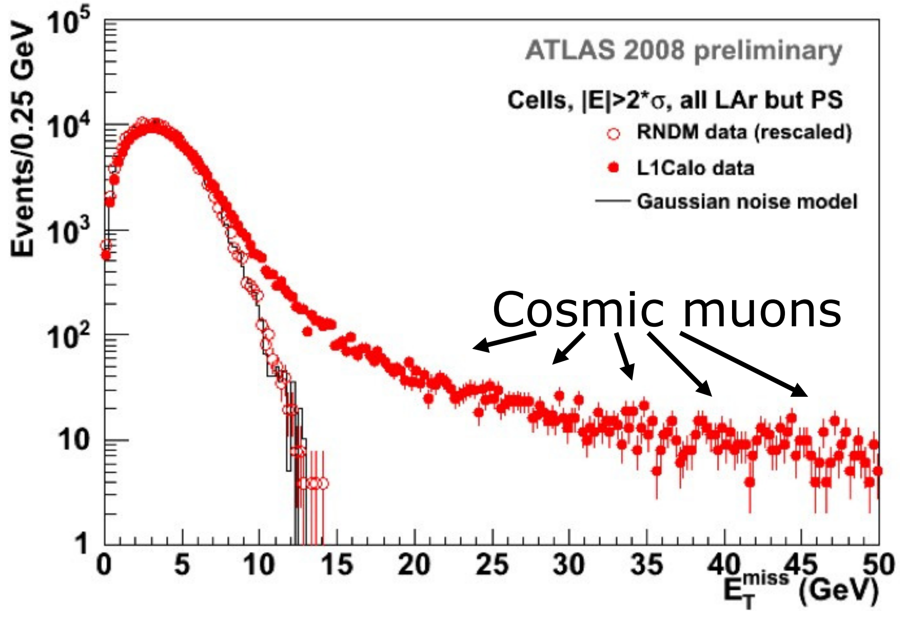
Better noise suppression using topo-cluster algorithm

- Width of distributions understood, very similar to the sum of uncorrelated Gaussian cell noise
- 0.04% of events coming from coherent noise problem in the LAr presampler (problem fixed during shutdown)



Missing E_T study (LAr)

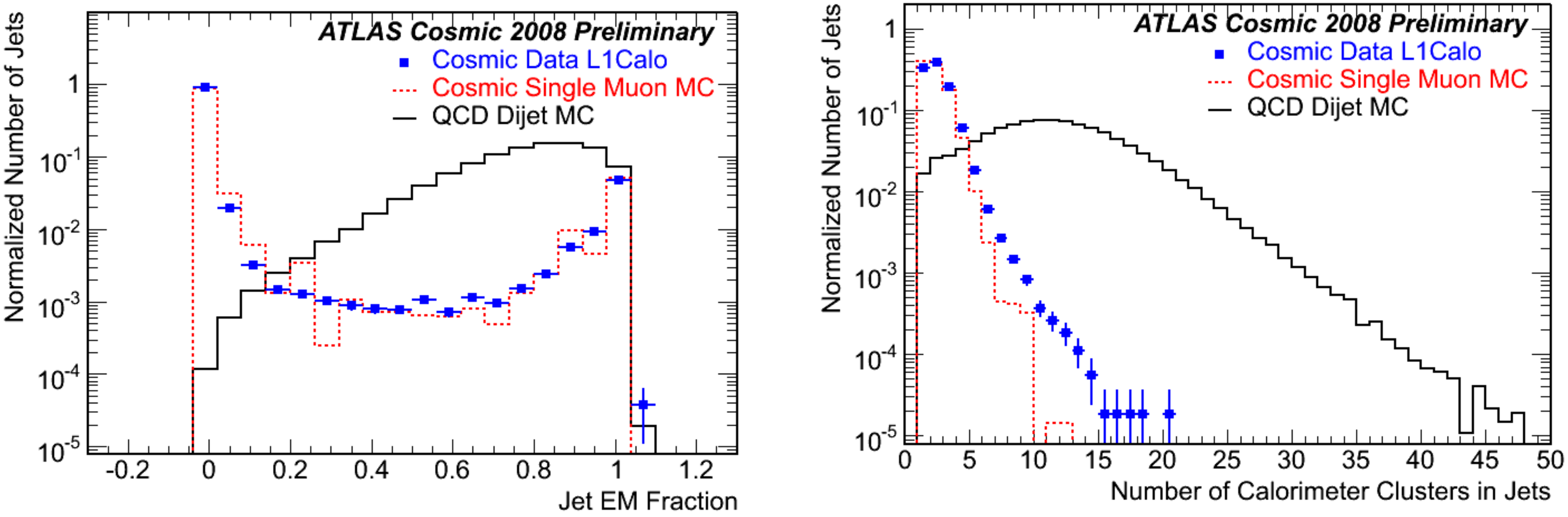




The relative missing E_T gaussian mean, computed with topo-clusters cells for random events, shows good time stability

Good description of the noise by the gaussian noise model

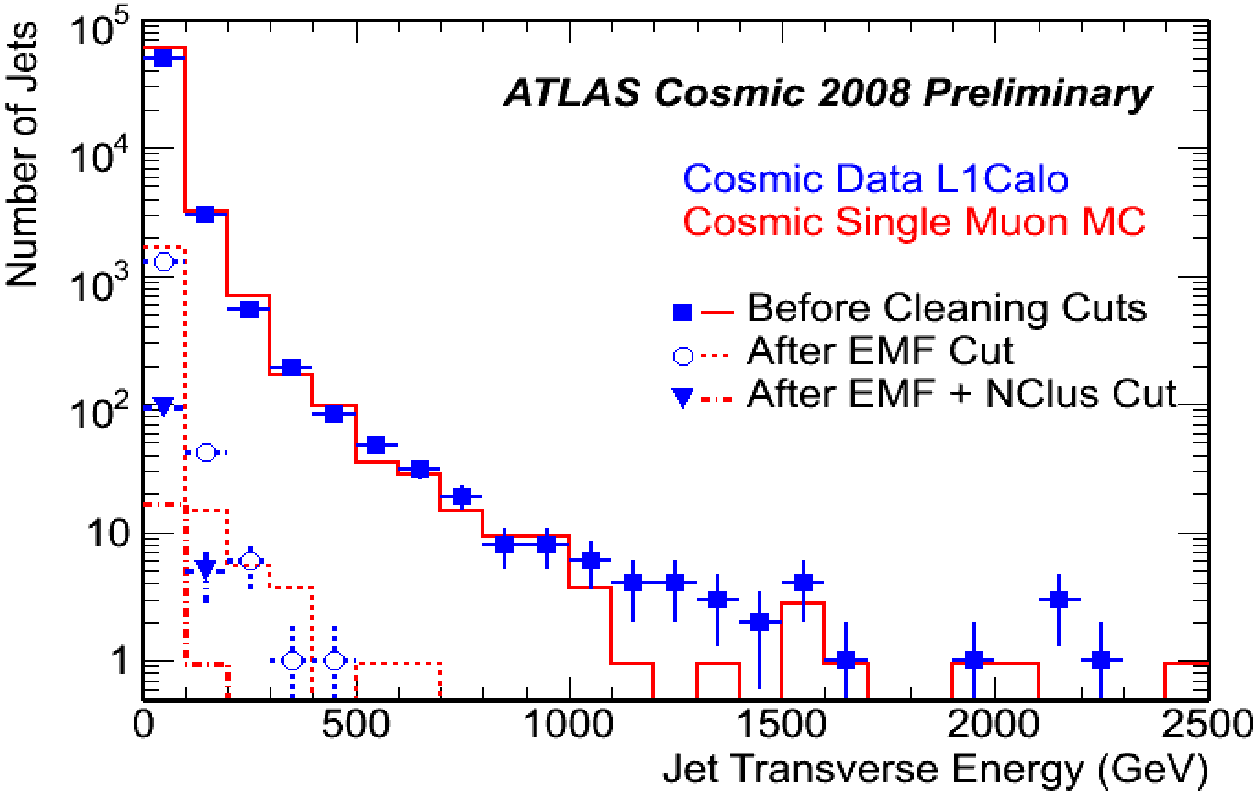
High energy events: jet cleaning cuts



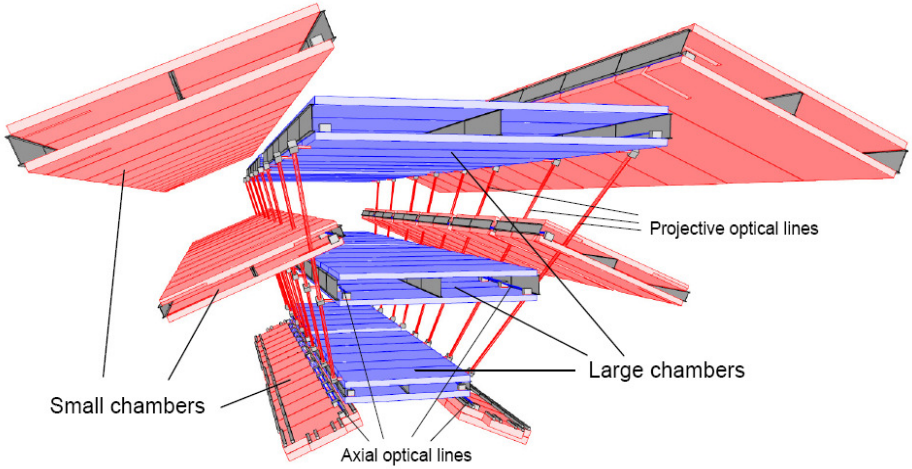
- Cosmic jets could fake QCD jets during normal (collision) data taking
  - Good agreement data – MC
- Cleaning cuts to suppress cosmic jets
  - Jet EM fraction
  - Jet Clusters multiplicity

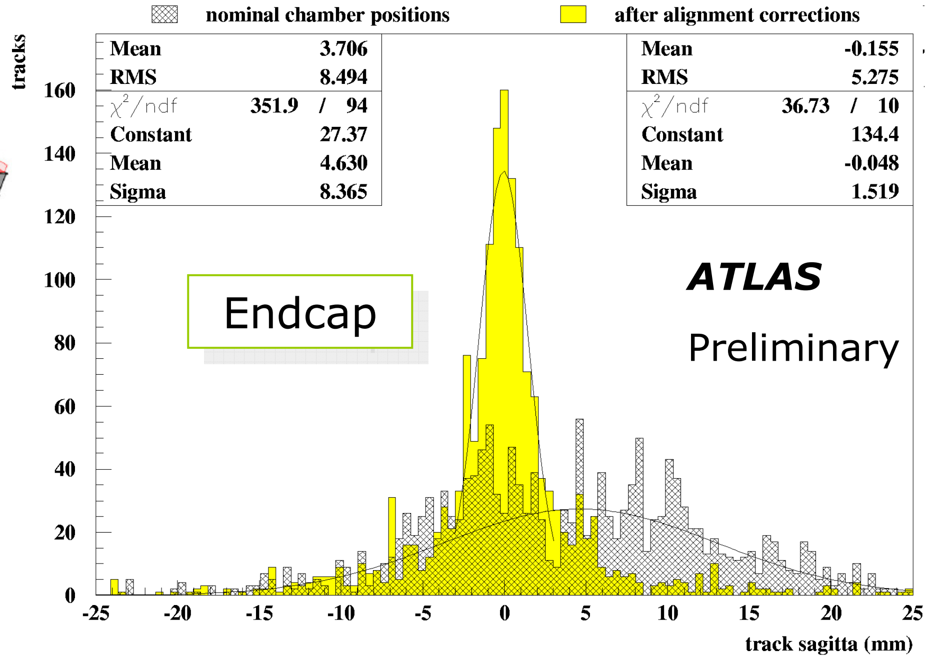
High energy events: jet cleaning cuts

- When applying both cuts
  - Very good cosmic jets rejection achieved
  - But performance can change when cosmic overlap with collision events



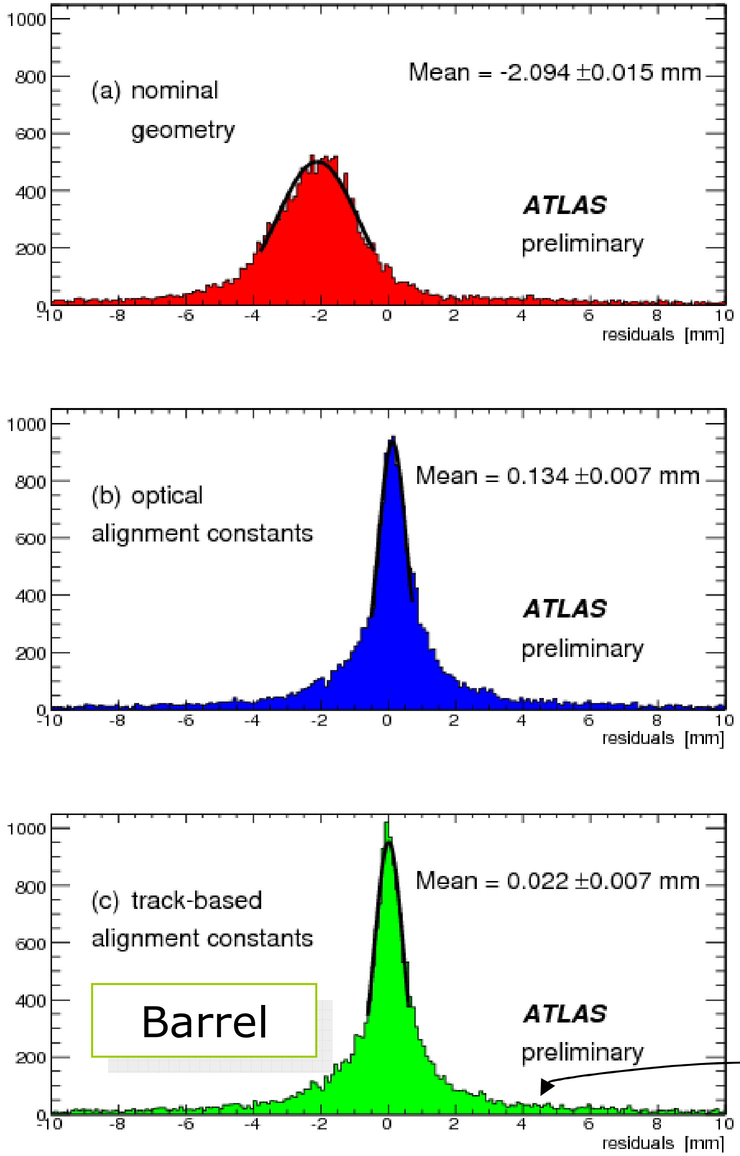
Muon system alignment





If the alignment (chamber position) shall not limit momentum (and charge!) measurement → it needs to be **better than 35 μm**

Muon system alignment



Alignment of muon system crucial to achieve required performance (10% at p_T=1TeV)

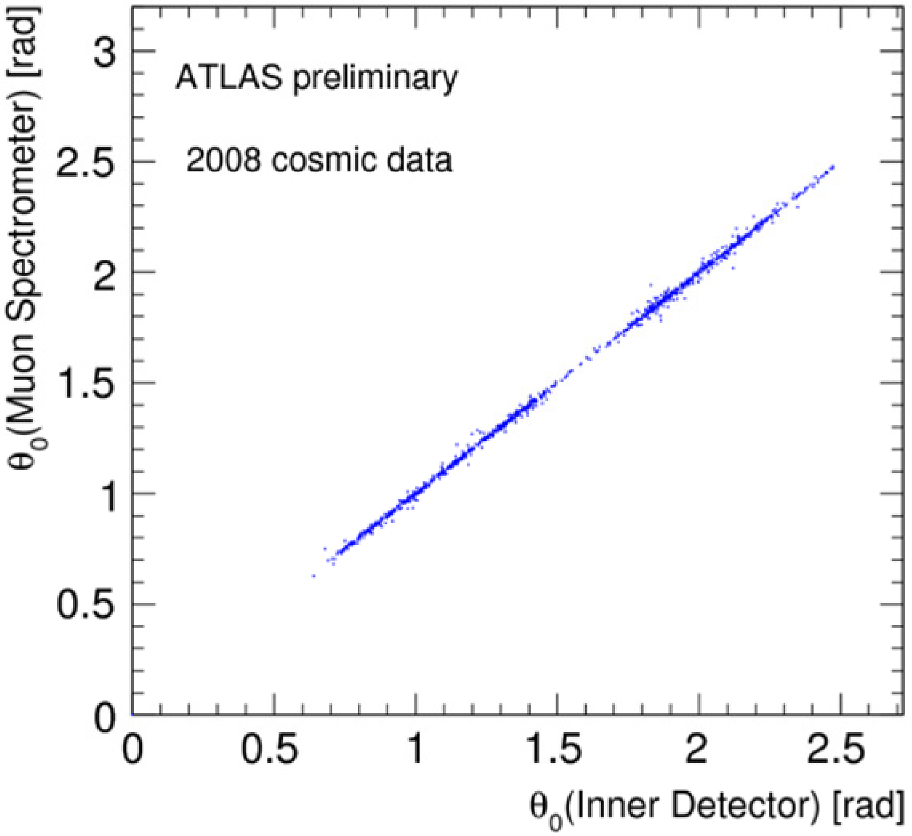
Large statistics of cosmic rays used to align muon precision chambers (data without magnetic field used)

Low-momentum muons, tails dominated by multiple scattering

Combined tracking results

Cosmic muon tracks measured in the ID and in the muon system

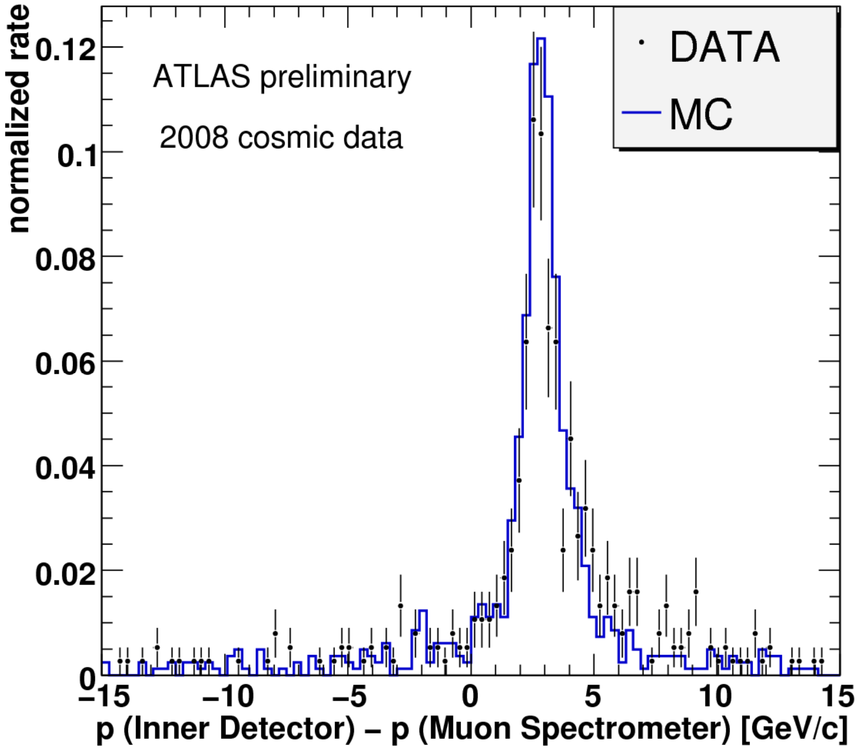
- – Very good correlation between ID and muon system measurement

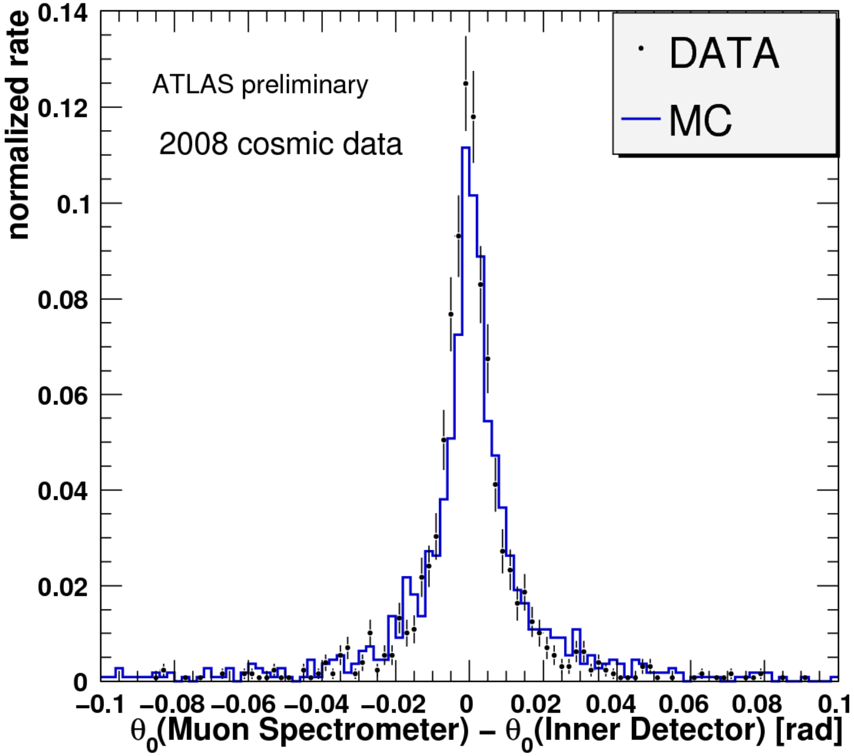


Combined tracking results

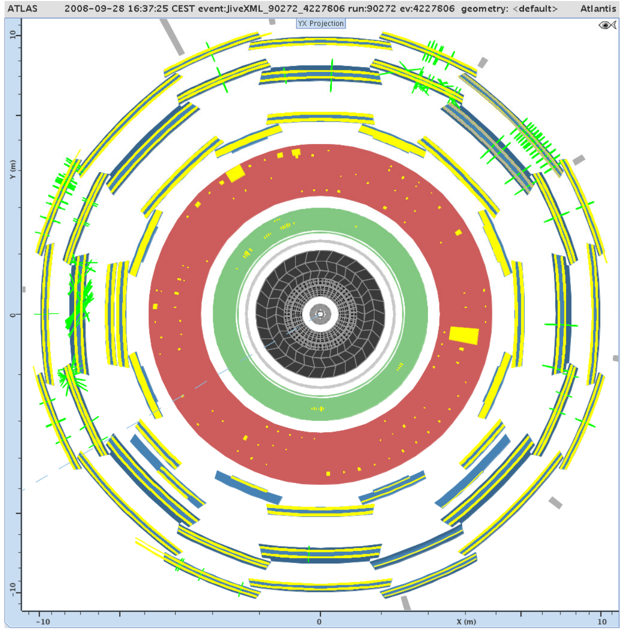
Cosmic muon tracks measured in the ID and in the muon system

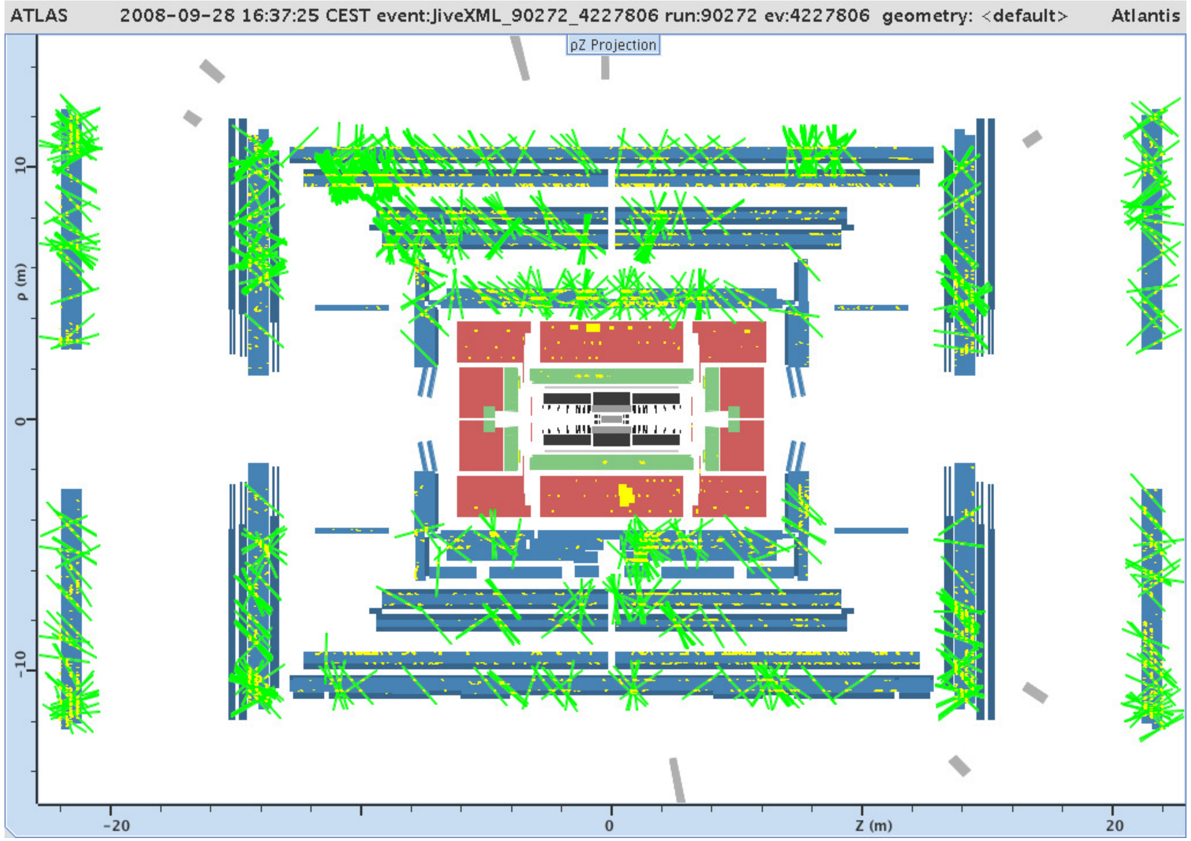
- Good agreement with MC studies!
- Momentum difference of ~3 GeV, which corresponds to the expected energy loss in the calorimeters





Air shower event



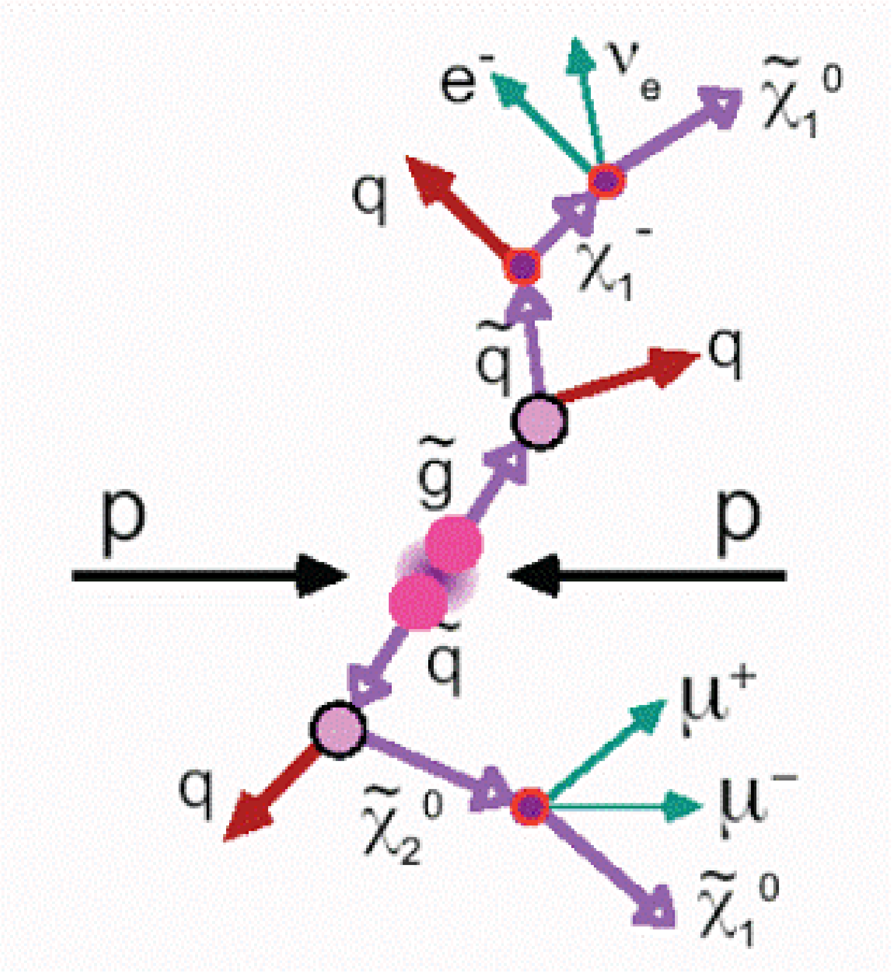


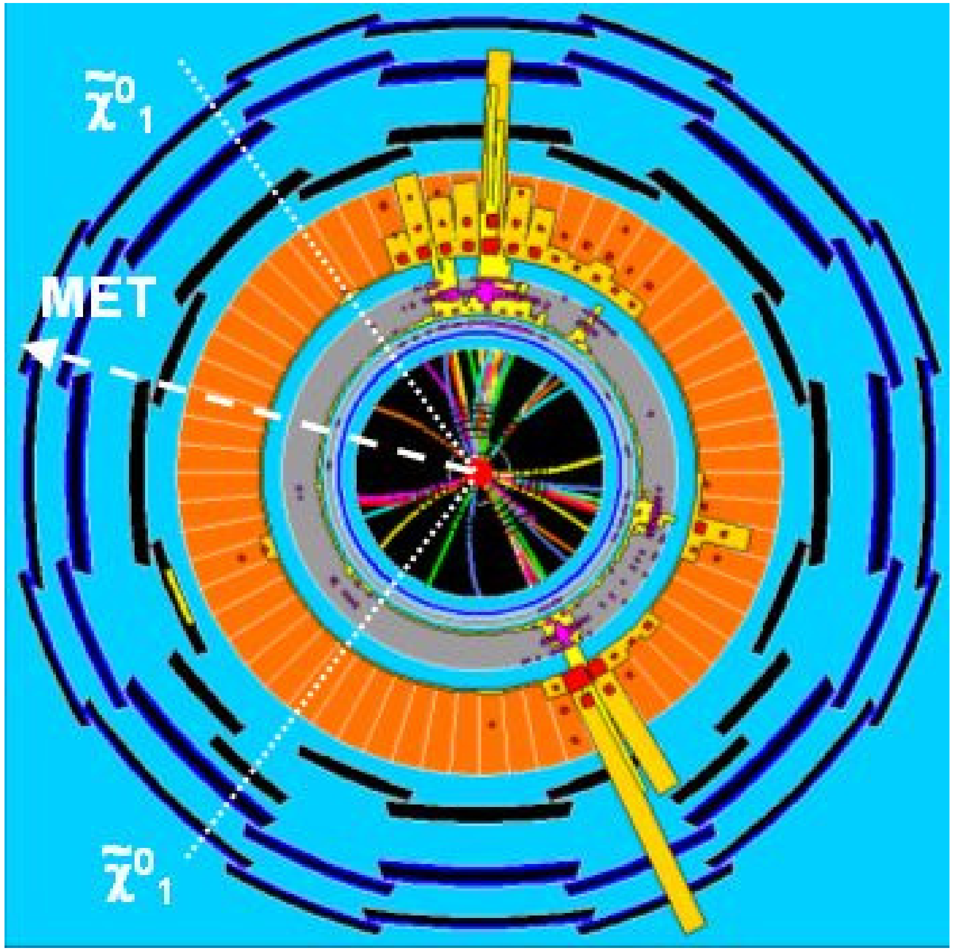
Physics

The major physics questions addressed by the ATLAS experiment are the origin of mass (Higgs boson?), supersymmetry (**Dark Matter candidates**?), differences matter-antimatter, extra dimensions, and precise studies of the particle physics Standard Model (QCD, W and Z bosons, bottom and top quarks, etc.)

New energy and luminosity frontier

Neutralino production and detection



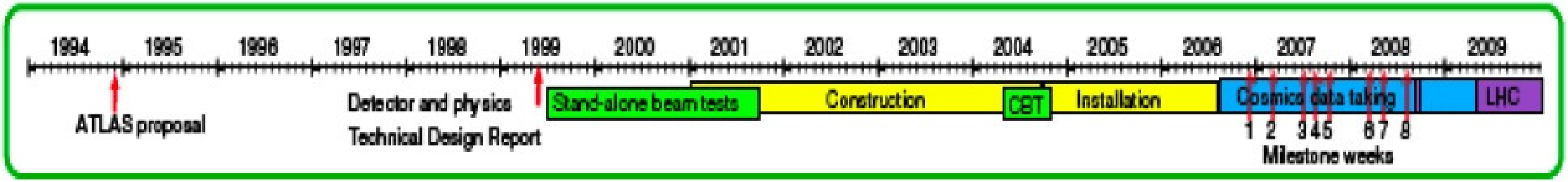


Physics

If the constituents of dark matter are new particles, with masses in the LHC energy range, the ATLAS experiment should discover them and measure their properties

Complementary to dedicated experiments and high energy cosmic rays searches

Conclusions



- Commissioning of the ATLAS detector in situ started three years ago
- Large amounts of cosmic muons recorded in 2008 with all sub-detectors active

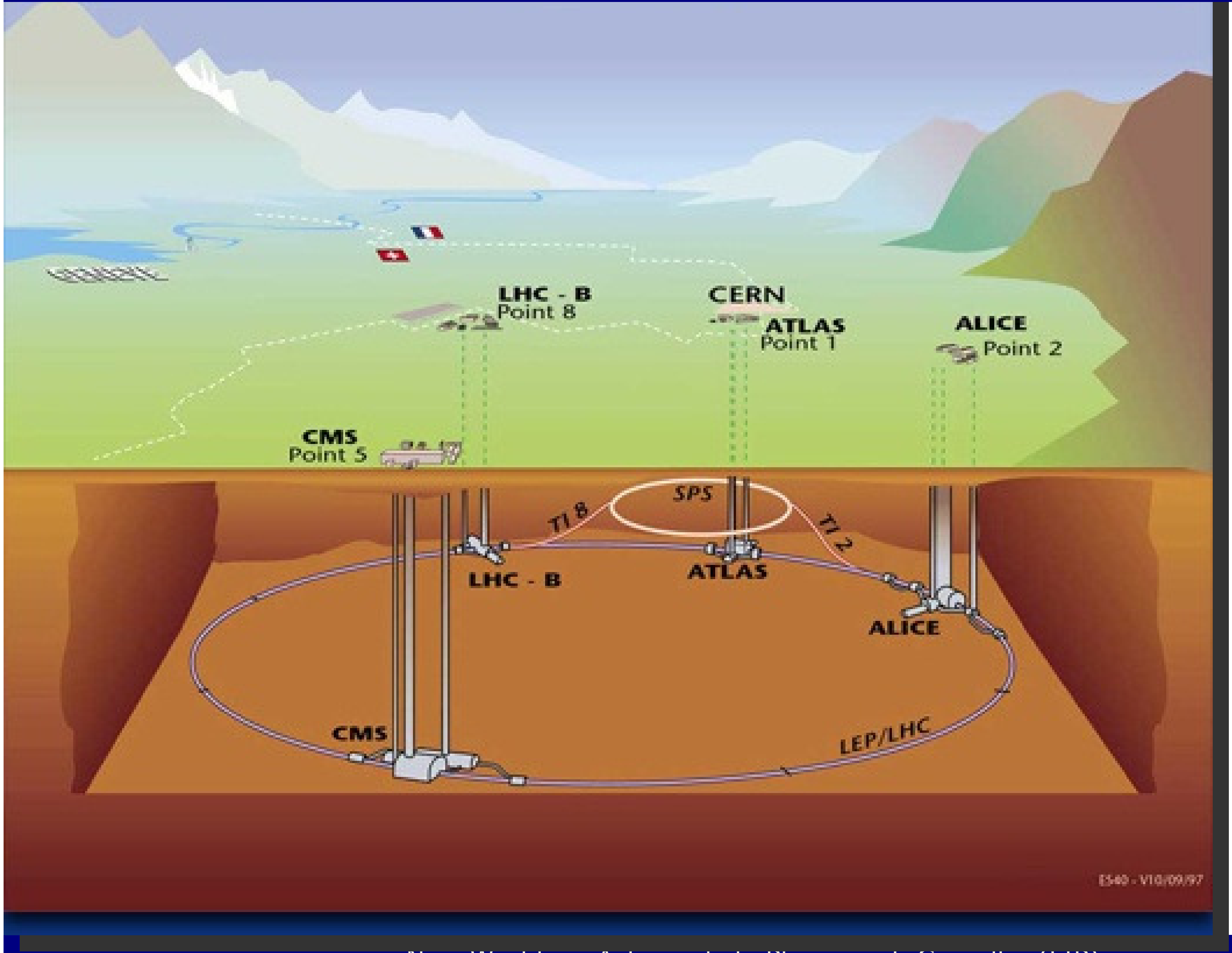
Conclusions

- ATLAS successfully took beam data in September 2008
- Cosmic muon and beam data are very useful for commissioning, detector calibration and alignment
- After current shutdown ATLAS will be in even better shape, ready again for beam

- Many thanks to ATLAS collaboration (in particular Martin Aleksa) for information and slides

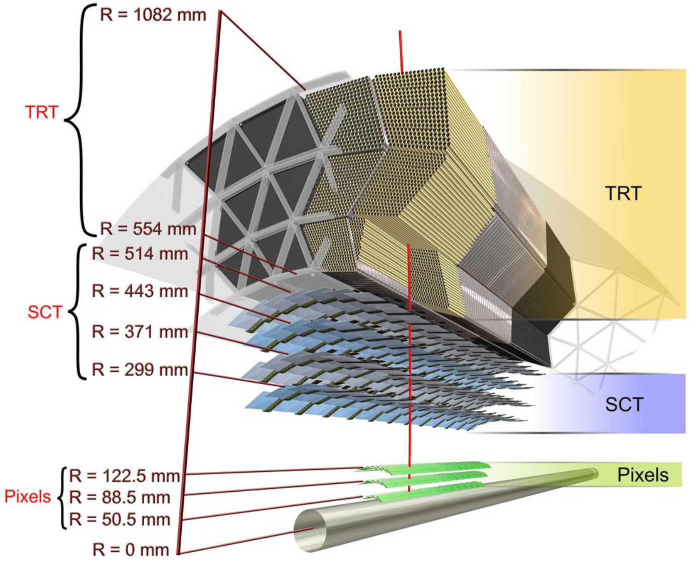
Back-Up Slides

LHC experiments



Proton collider with a design center of mass energy of 14 TeV, ~100 m underground

Inner Detector Status (May 2009)



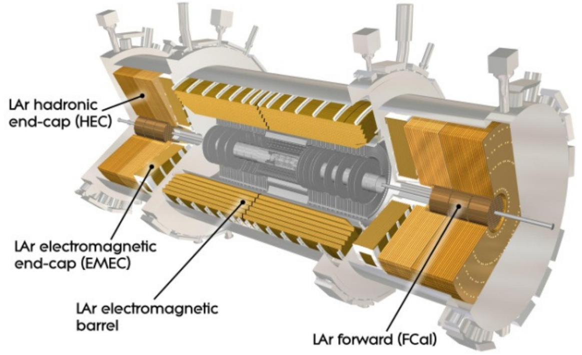
- Pixel Detector
  - 3 layers in barrel and end-cap
  - Resolution: 10µm x 110µm
  - Pixel size 50µm x 400µm
  - 80 million channels
  - >98% of modules operational
  - Noise occupancy: $5\text{x}10^{-9}$
  - Hit efficiency > 99.8%

- Transition Radiation Tracker (TRT)
  - combined straw tracker and transition radiation detector
  - 4mm diameter straw tubes with 31µm anode wires
    - Many layers, typically 36 straws per track
    - 2x160 layers (20 disks each) with radial straws in the end-cap region
  - Resolution: 130µm
  - e-π identification: 0.5 GeV < E < 150 GeV
  - 98% of channels operational

- Semiconductor Tracker (SCT)
  - 4 double layers of strips in barrel and 9 in end-caps
  - 4088 modules with 80µm strips
  - 6 million channels
  - Resolution: 17µm x 580µm per double layer
  - > 99% of barrel and end-cap modules operational
  - Noise occupancy: $4.4\text{x}10^{-5}$ (barrel), $5\text{x}10^{-5}$ (end-cap)
  - Hit efficiency > 99%

Calorimeter Status (May 2009)

- Liquid Argon Calorimeter
  - Housed in 3 cryostats, 182k channels
  - Electromagnetic (barrel+endcap)
    - Pb-LAr accordion geometry
    - 3 longitudinal compartments $\eta < 2.5$
    - Pre-shower detector $\eta < 1.8$
  - Hadronic endcap/forward calorimeter
    - Cu/W-LAr
    - 4/3 longitudinal samples
  - Dead channels: 0.02% (+0.2% recoverable in next shutdown)
  - Noisy channels: 0.003%, bad calibration: <0.2%
  - Electronic calibration procedure operational (calibration constants used online)



- Tile Calorimeter (barrel hadronic)
  - Iron scintillator tiles (3 longitudinal samples)
  - <1.4% dead cells in 2008 treated during shutdown, reduced to <<1%
  - Calibration system operational (Cs source, Laser, charge injection)
- Level-1 calorimeter trigger (e/γ, jets, τ, missing E_T, energy sums)
  - Dead channels: < 0.4% (+0.3% recoverable in shutdown) of a total of 7200 analogue channels
  - Channel-to-channel noise suppression allows E_T=1 GeV cut (aim: 0.5 GeV)

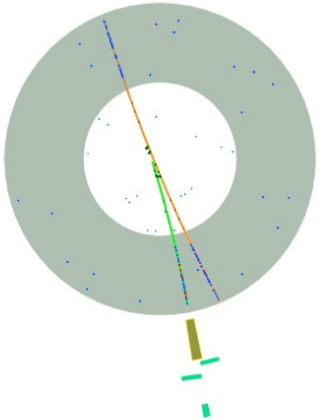
Muon System Status (May 2009)

- Barrel trigger: Resistive-Plate Chambers (RPC)
  - 544 chambers with 359k channels
  - 70% of chambers operational in 2008, now 95.5% (plan to be at 98.5% for first beam)
  - Dead strips < 2%
  - Hot strips/spots < 1%
- End-cap trigger: Thin-Gap Chambers (TGC)
  - 3588 chambers with 318k channels
  - 99.8% of chambers operational
  - Dead channels < 0.01%
  - Noisy channels <0.02% with >5% occupancy
  - 2-dimensional readout
  - Time resolution < 10ns
  - Spatial resolution: 5-10mm
- Precision chambers:
- Monitored Drift Tubes (MDT)
  - 1088 chambers with 339k channels
  - 98.7% of chambers operational in 2008, >99.5% for first beam
  - Dead channels: 0.5 %
  - Noisy channels: < 0.2 % with 5% occupancy
- Cathode-Strip Chambers (CSC)
  - 32 chambers with 31k channels
  - 98.5% of channels operational (1 plane out of four in two chambers not working)
  - 2-dimensional readout
  - Spatial resolution 35-40μm
- Optical alignment system: 12232 sensors
  - 99.7% (barrel), 99% (end-cap) operational

Cell and cluster reconstruction

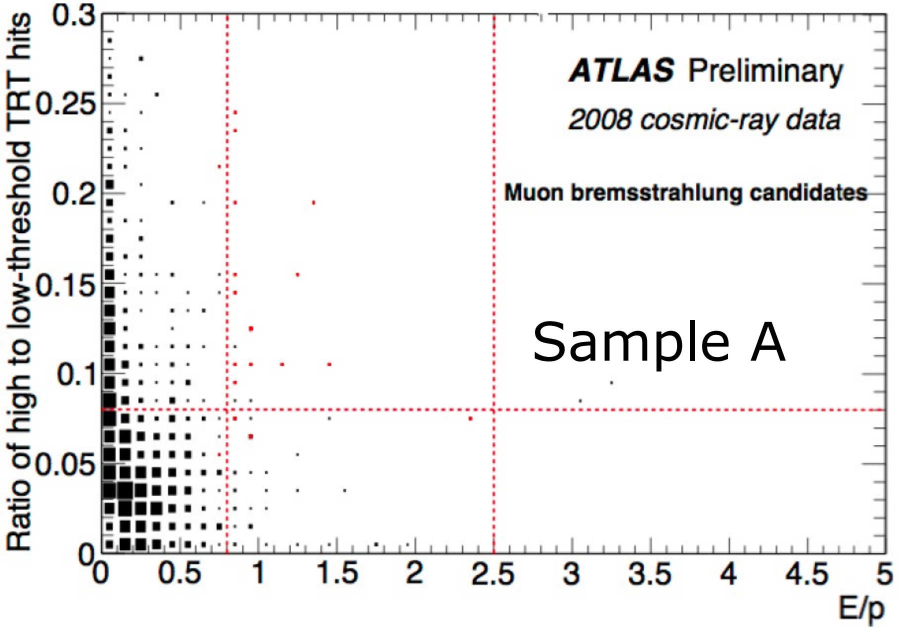
- Cells
  - All cells enter the computation of E_T missing if their energy is 2 times above the noise (simple method which characterizes the basic detector performance)
  - Cells are grouped in towers for jets, summing all cell energies in regions of size $\Delta\eta\times\Delta\varphi=0.1\times0.1$
- Topoclusters
  - Cells are grouped in topological clusters starting with a seed cell ($E>4*\sigma_{noise}$), and adding the energy in 3 dimensional neighboring cells (with $E>2*\sigma_{noise}$) until no cells in the neighborhood of the cluster are found

Electrons in cosmic ray events



Out of 3.5M cosmic muon events (tracks in the ID barrel)

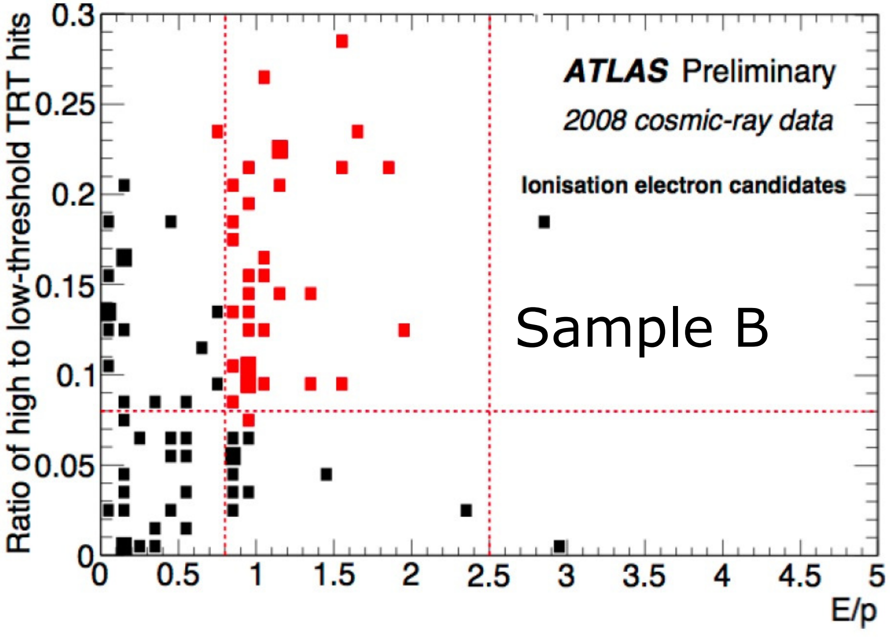
- Requiring 3 GeV E_T, loose track match in φ, medium electron cuts (25 TRT hits, track-cluster match, shower shapes)



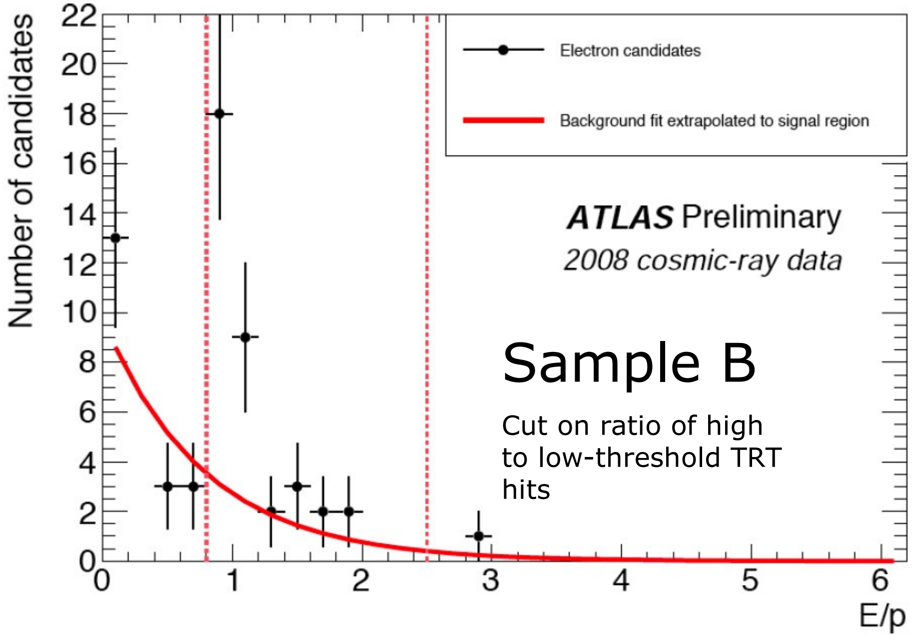
- **A**: Selected 1229 muon bremsstrahlung candidates (1 ID track)
  - Muons have low E/p, high level threshold hits only for $E_\mu > 100$ GeV
  - Only 19 events in signal region

Electrons in cosmic ray events

- **B**: Selected 85 ionization electron candidates (≥2 ID tracks)
  - 36 events in signal region



Sample B

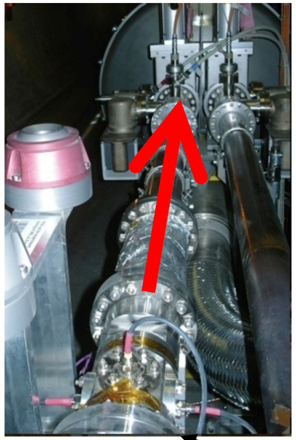


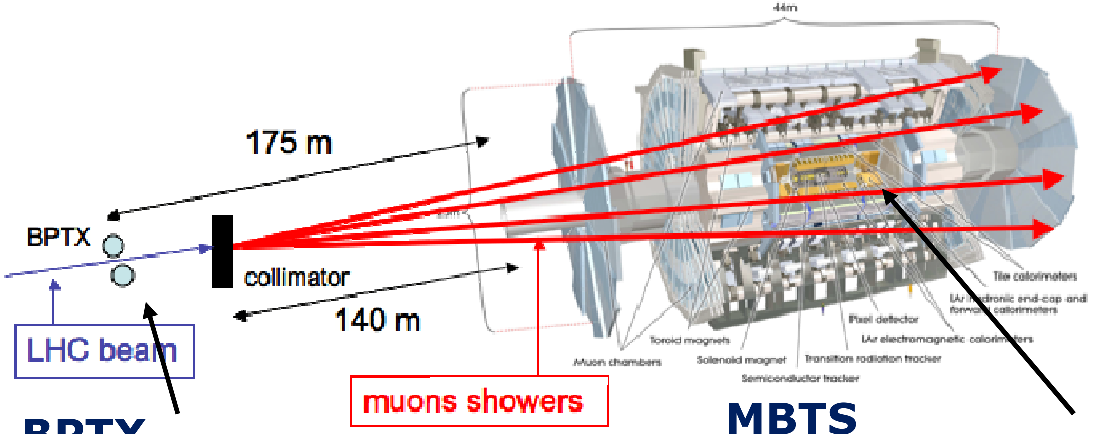
Sample B

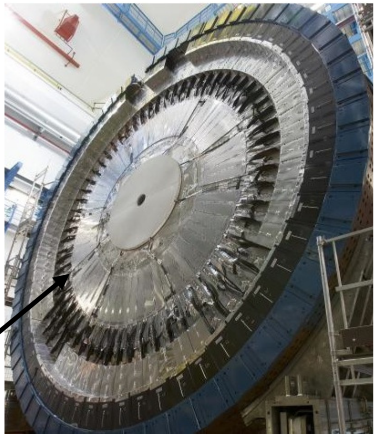
Cut on ratio of high to low-threshold TRT hits

Commissioning with beam

- First beam through ATLAS Sept. 10, 2008
- Beam "splash" events with closed collimators (on relevant side)
  - ATLAS recorded about 70 splash events (out of ~100)
    - Some parts of ATLAS at reduced HV or off for detector safety
      - Pixels and barrel SCT off
      - Endcap SCT, forward calorimeter and some parts of muon system at reduced HV







BPTX
Beam timing pick-ups

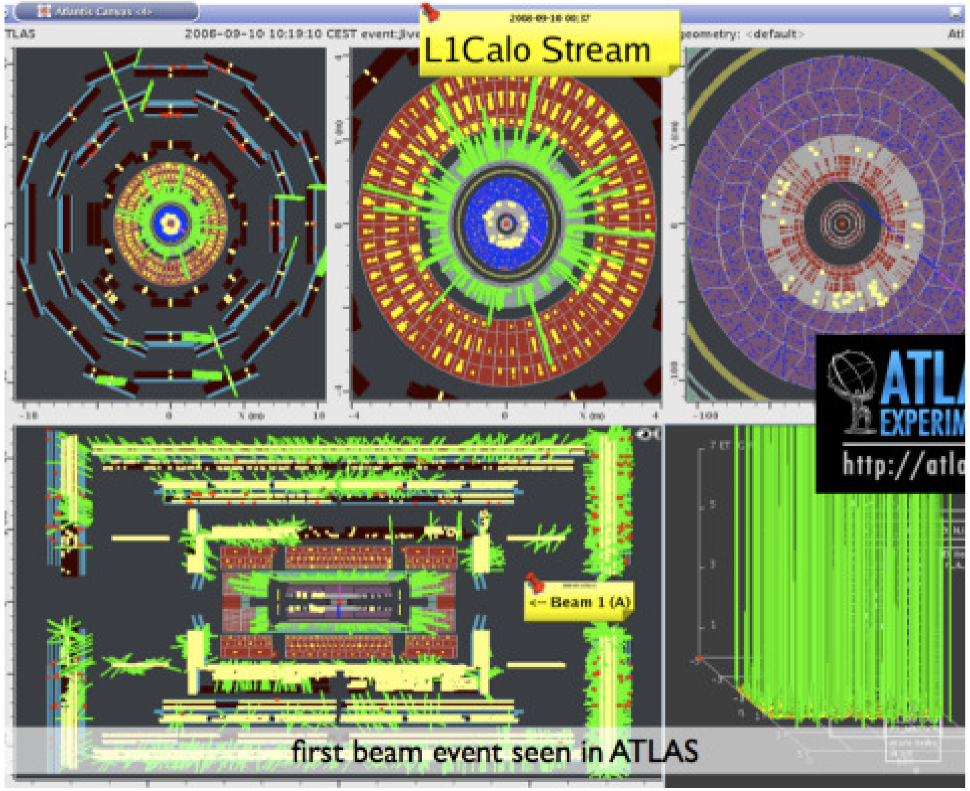
MBTS
Minimum bias trigger scintillator

Commissioning with beam

Calorimeter energy deposits of several TeV (up to ~1000 TeV), many tracks in tracking detectors

- –Used to time-in the detector components
- –Used to correlate position and energy response of various detector systems

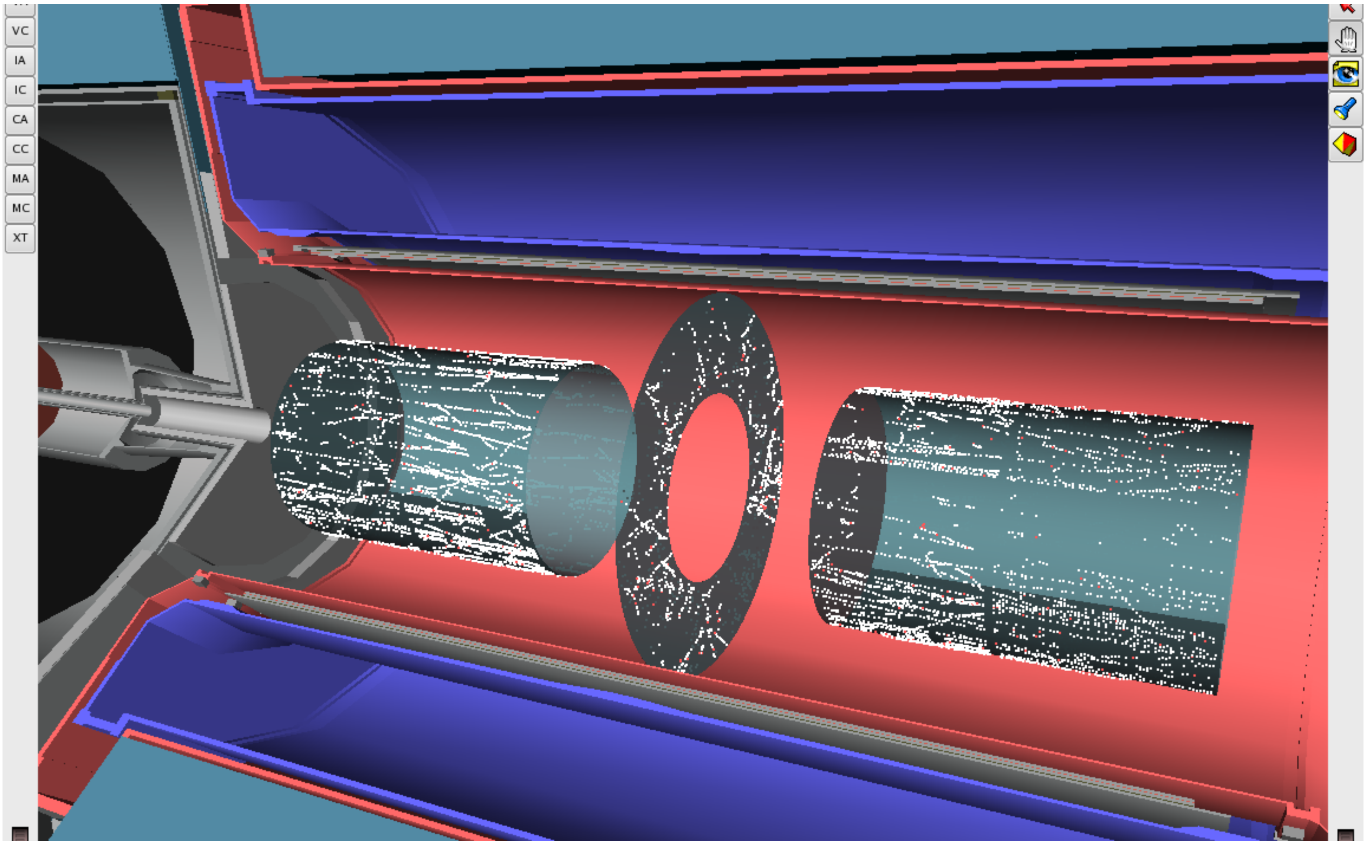
Circulating beams: typically lower energy deposits, depending on beam conditions



Beam splash and beam halo in the ID

Transition Radiation Tracker beam halo event

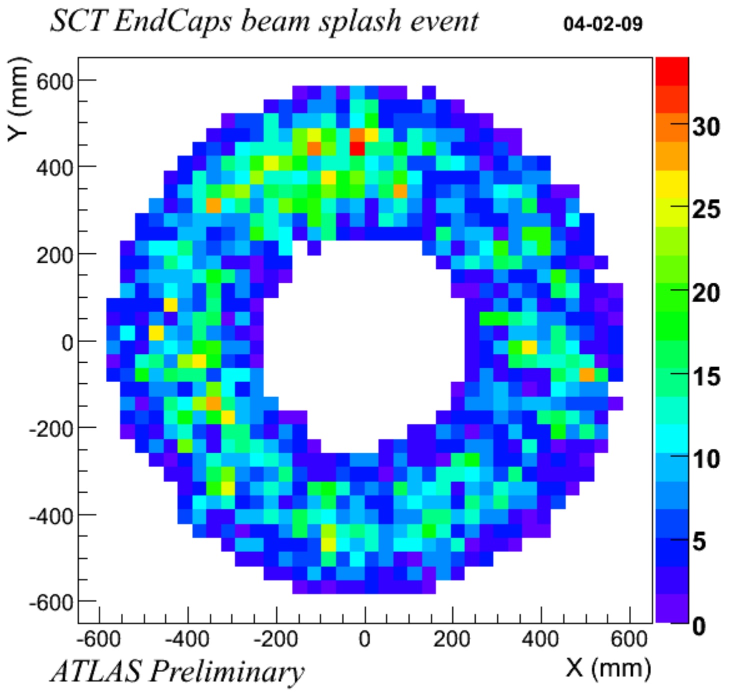
- TRT barrel hits collapsed into $r\phi$, endcap hits into $z\phi$

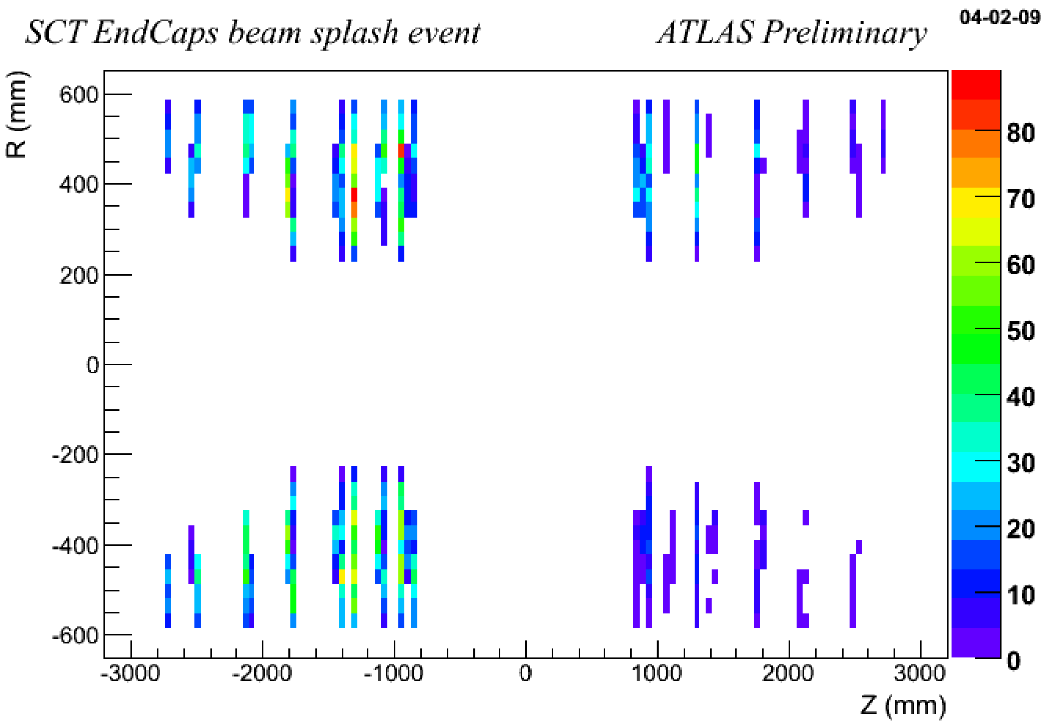


Beam splash and beam halo in the ID

SCT endcap occupancy during beam splash

- Operated at reduced voltage
- Number of hits displayed

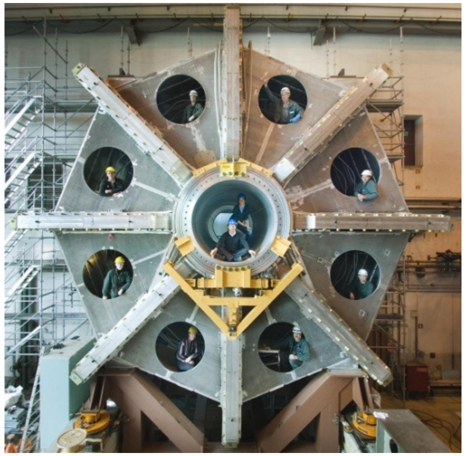


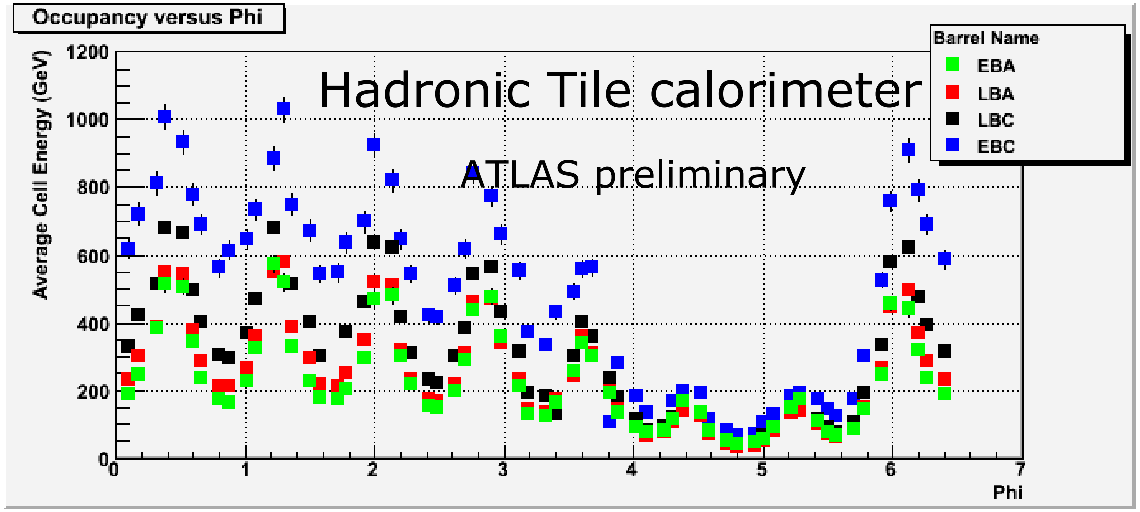


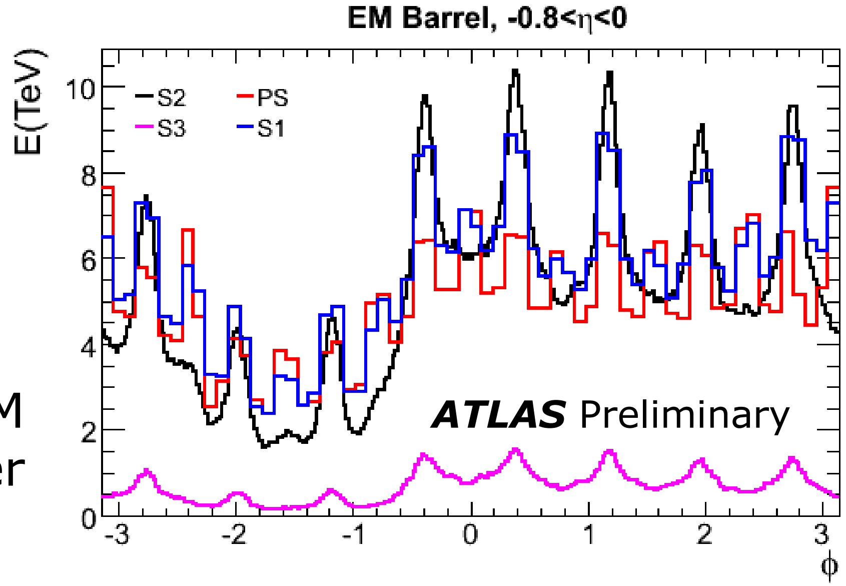
SCT end-cap event displays (barrel SCT off)

Beam splash in the calorimeters

Endcap toroid structure visible in the energy deposit plots





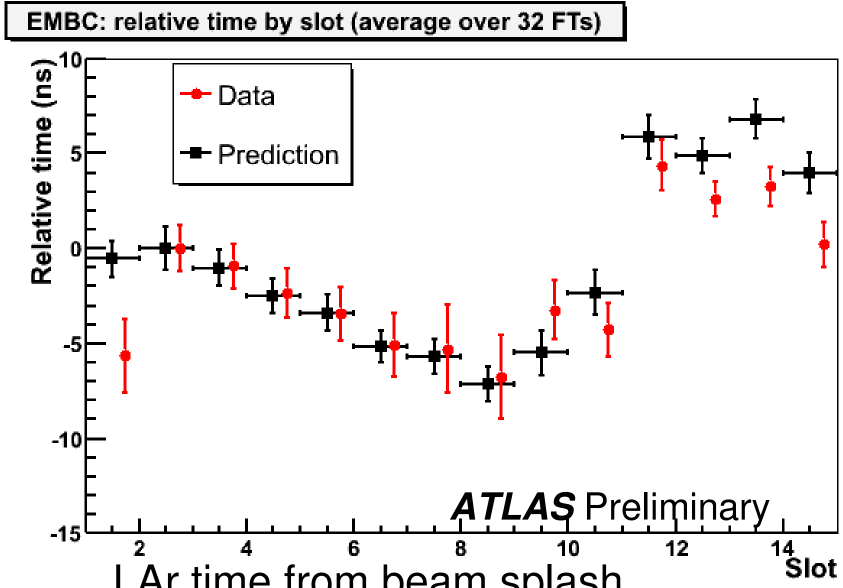


EM calorimeter

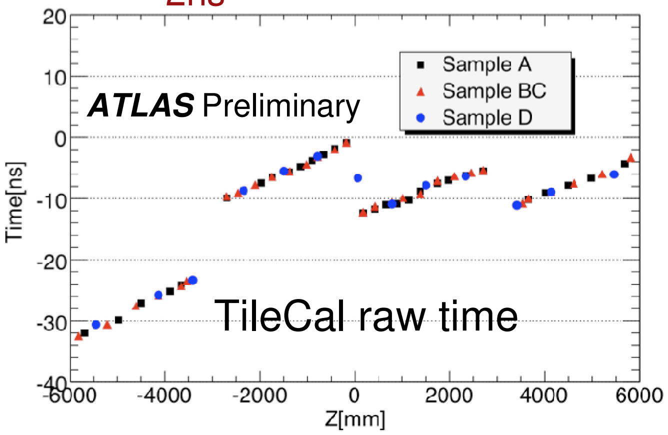
Timing with beam splash events

Beam-splash events yield almost horizontal muons that were exploited to check the timing

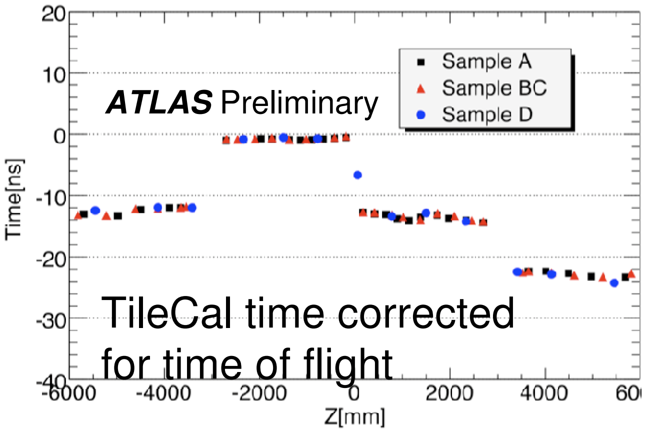
- Trigger timing: Quick progress during beam splash data taking to align different triggers within 1 bunch crossing (25ns)
- TRT: detector timed in to ~1ns event by event
- TileCal:
  - time dispersion in each partition ~2ns
  - Offsets between partitions well within 1 BC, these studies were used to align timing between partitions
- LAr electromagnetic calorimeter:
  - Agreement between prediction and time-of-flight corrected data from beam splash at the level of 2ns



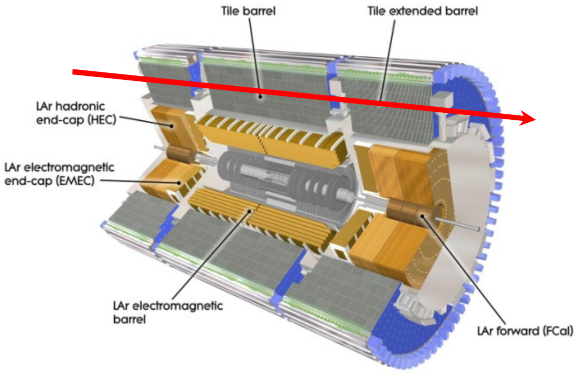
LAr time from beam splash compared to computations from calibration pulses and the read-out path



TileCal raw time

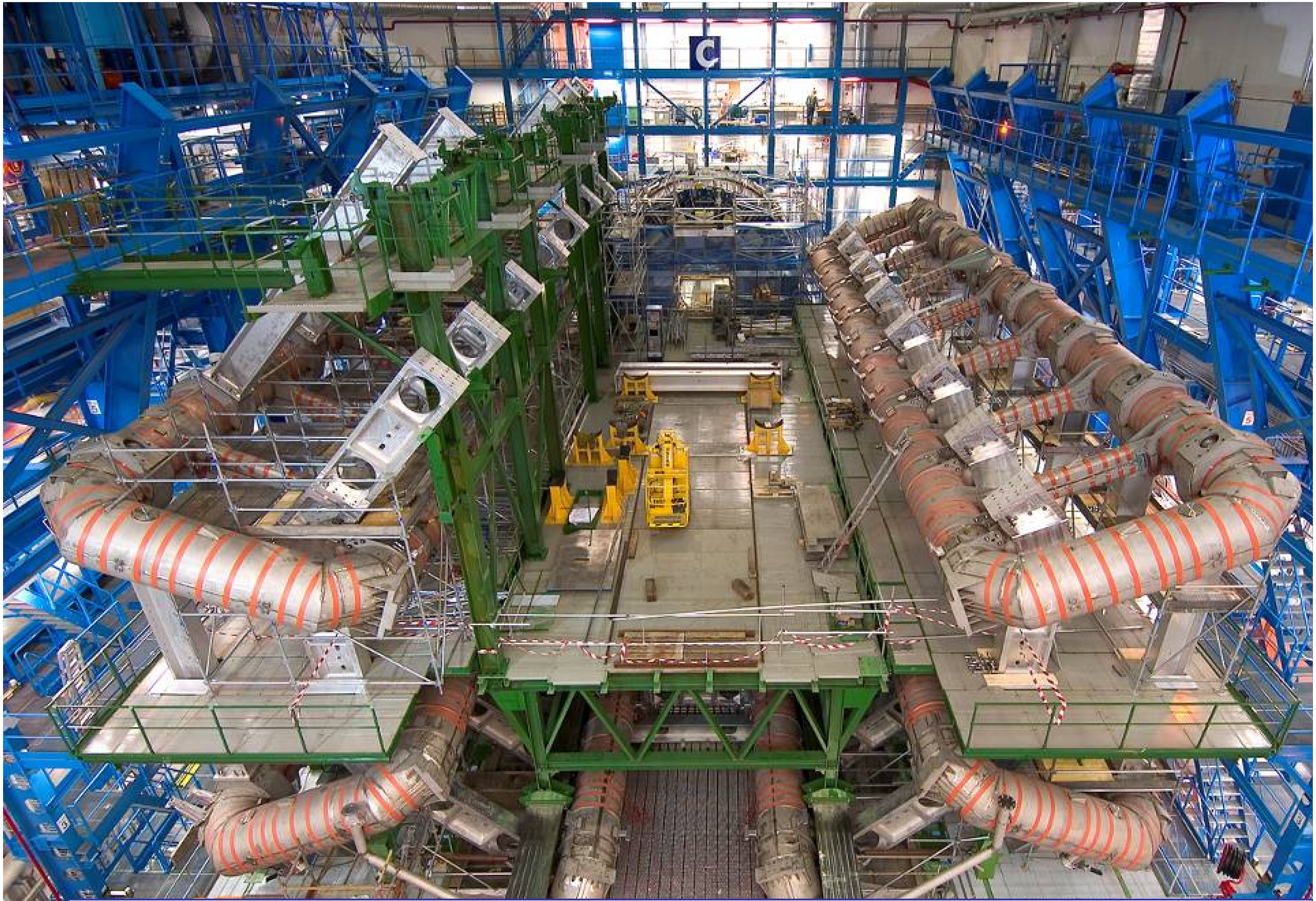


TileCal time corrected for time of flight



Comparison ATLAS-CMS detectors

- Using different and complementary technologies, the two large LHC experiments arrive at **similar overall performances**
- The **higher magnetic field** has advantages (better p resolution) and disadvantages (lower tracking eff.)
- The **crystal calorimeter** has advantages (superior energy resolution) and disadvantages (no longitudinal sampling and hard to keep constant term)
- The **muon acceptance**, although smaller in CMS, benefits from a simpler geometry and uniform magnetic field
- At the end, the two experiments will be very competitive and provide good Physics results



ATLAS cavern (-100 m) in June 2003

Oct. 2005: full barrel toroid is in place