Commissioning of the ATLAS Detector

Physics at the LHC Seminar

SoSe 2009

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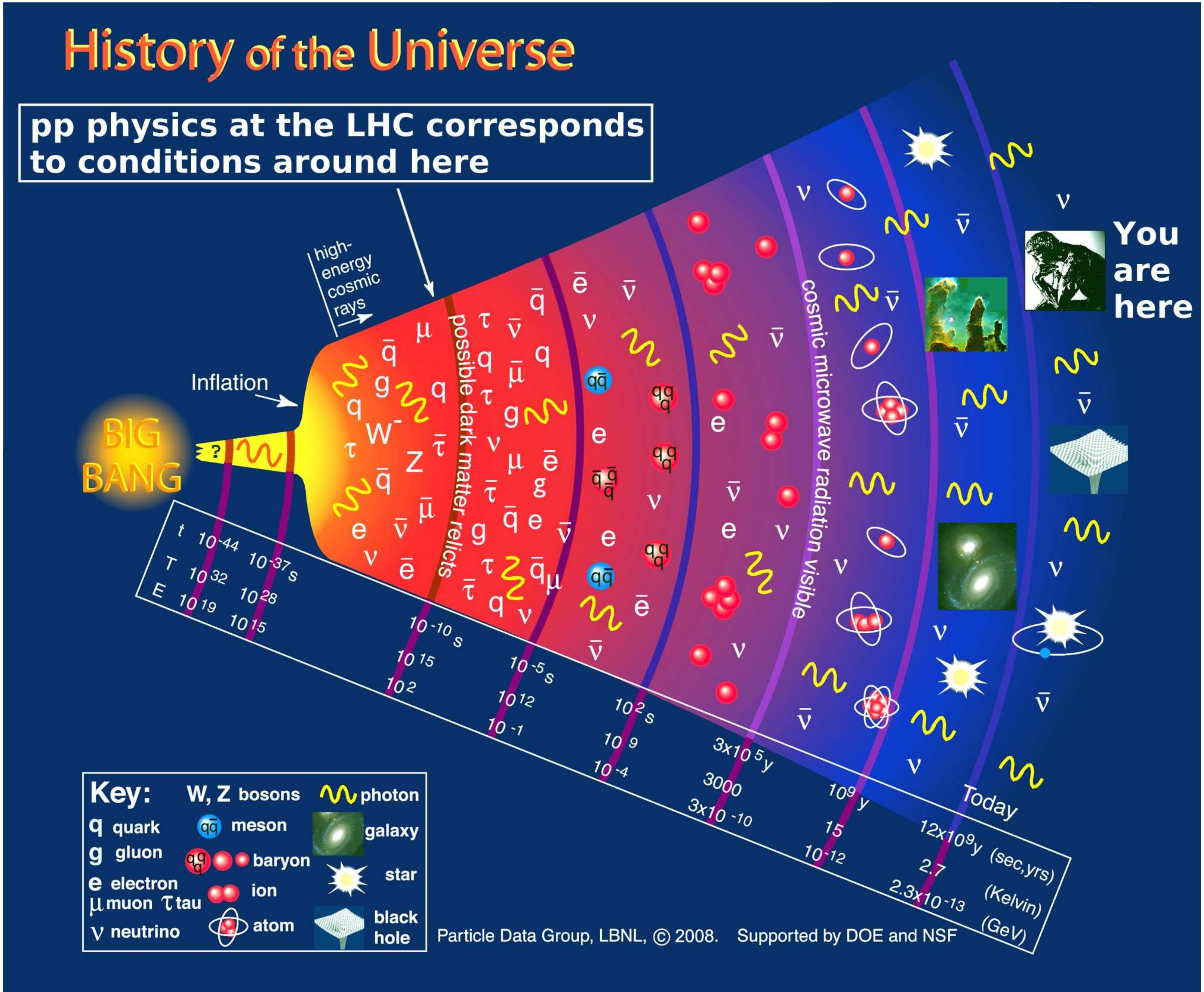
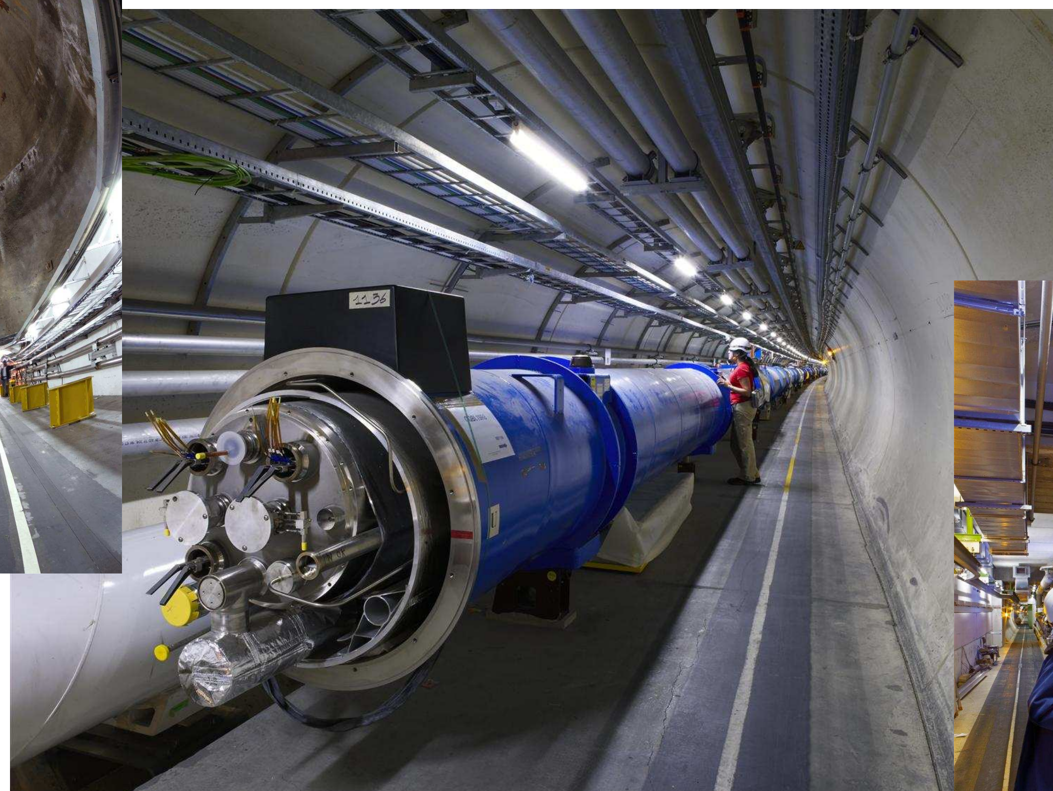
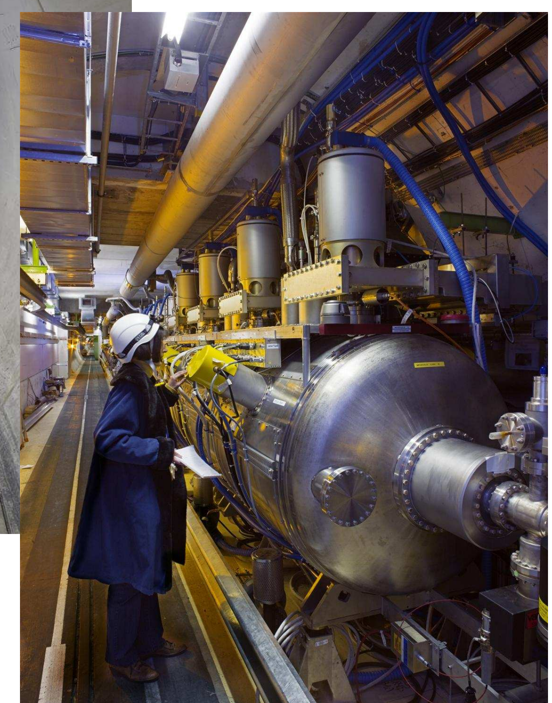
Introduction

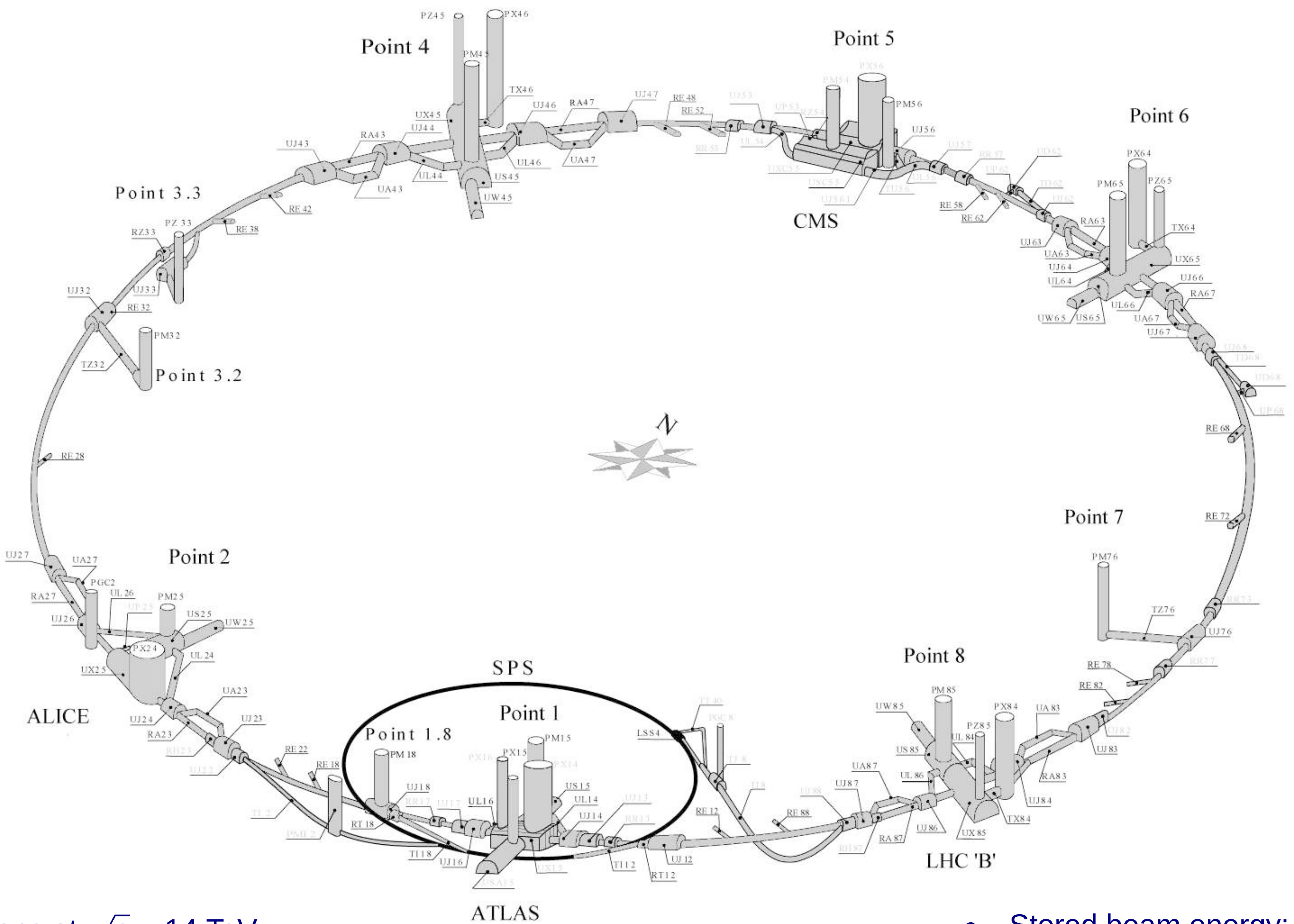

History of the Universe
pp physics at the LHC corresponds to conditions around here
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
You are here
t 10 -44 10 -37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
ion
star
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

The Large Hadron Collider





LARGE HADRON COLLIDER

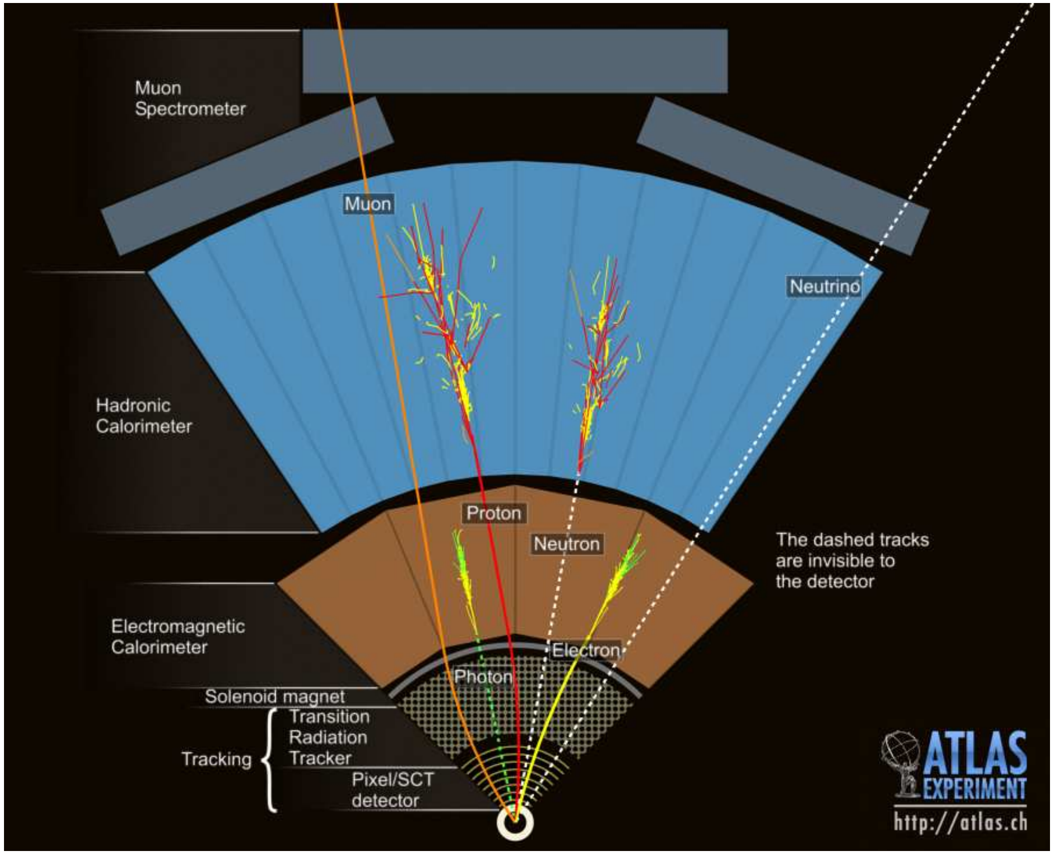


- pp collisions at $\sqrt{s}$ = 14 TeV
- Luminosity: 10^{34} cm^{-2} s^{-1}
- 40 MHz bunch crossing frequency
- 27 km circumference

- Stored beam energy: 362 MJ
- Stored magnet energy: 600 MJ
- 4 main experiments: ALICE, ATLAS, CMS, LHCb

Principle Design of Collider Detectors

Full coverage of solid angle and precise measurement of all particle momenta

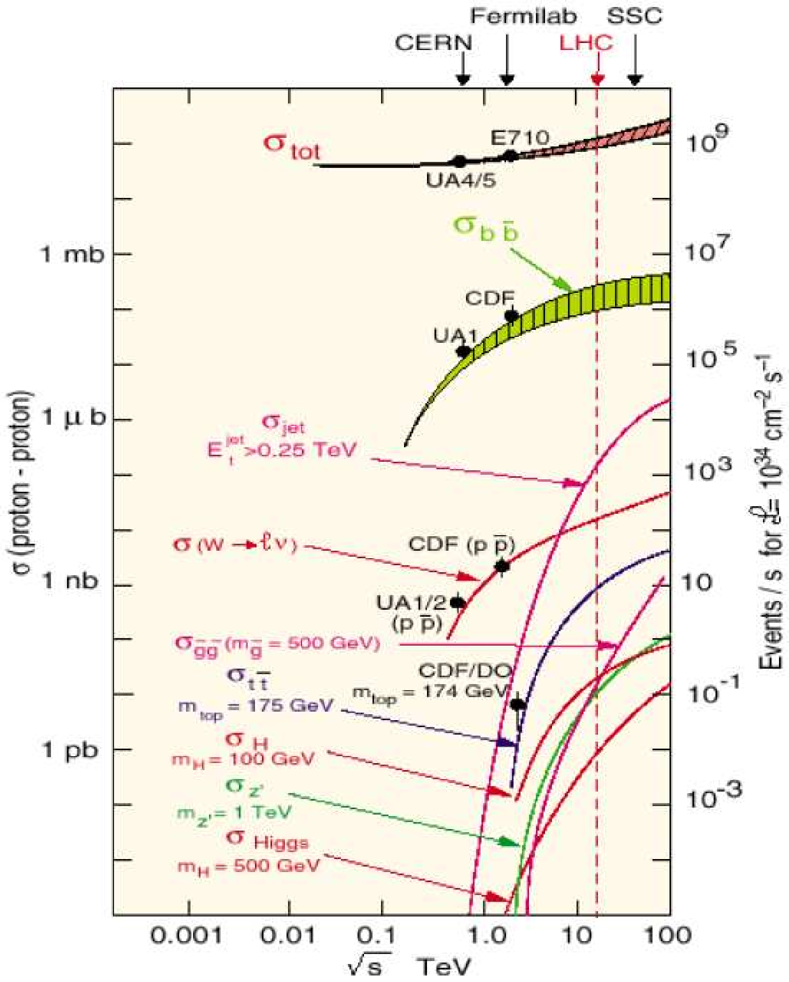


- Measurement of muon momentum
- Hadronic calorimeter for energy and direction measurement of charged and neutral strongly interacting particles
- Electromagnetic calorimeter for energy and direction measurement of electrons and photons
- Magnetic field for momentum measurement of charged particles
- Tracker for vertex reconstruction

Tracking systems with as little as possible material to minimize energy loss and multiple scattering

Calorimeters are total absorption detectors, completely stopping the measured particles. High-Z materials for electromagnetic calorimeters and dense (passive) materials for hadronic calorimeters

Cross Sections and Production Rates



Rates at L = 10^{34} cm^{-2} s^{-1}

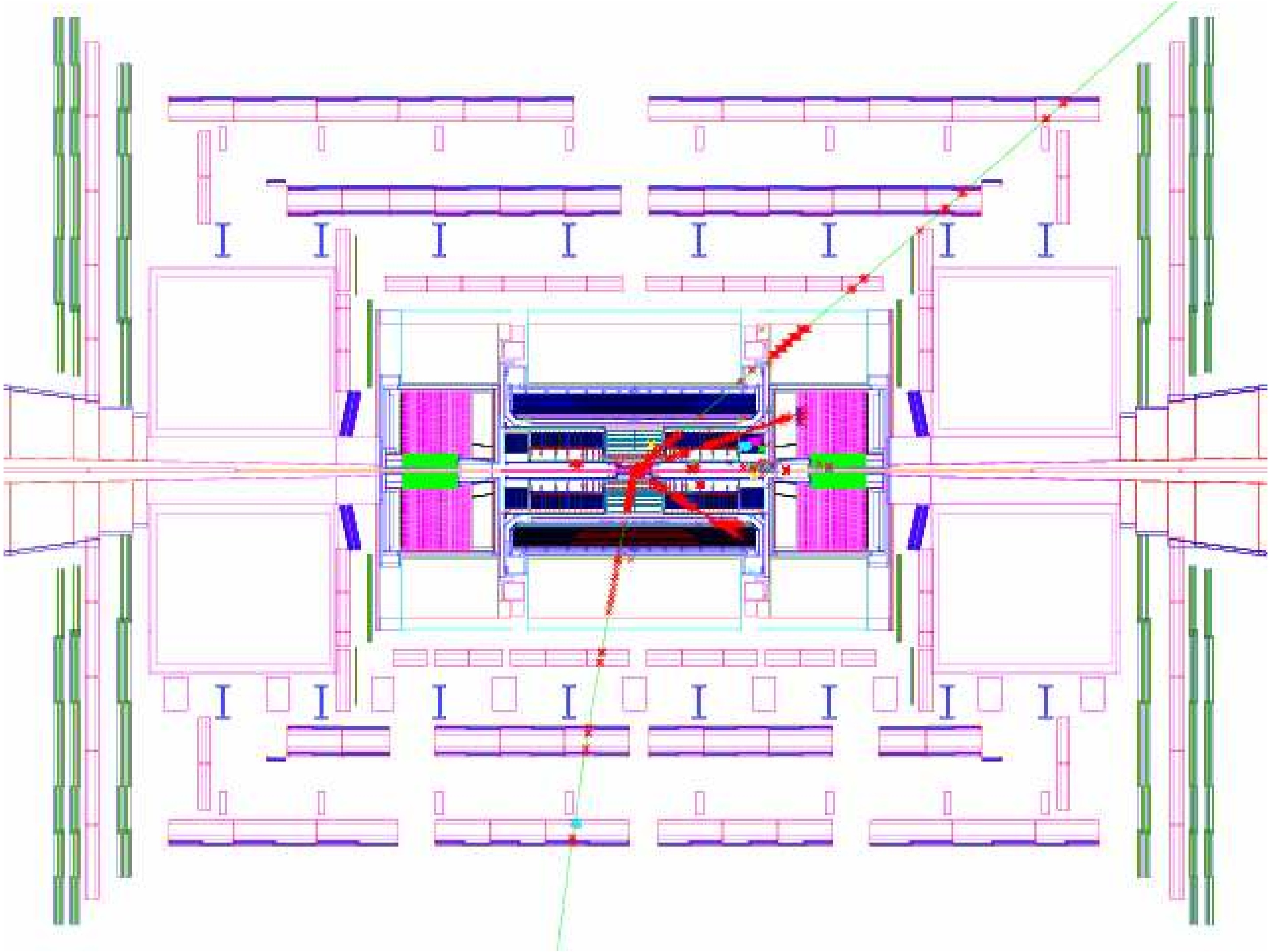
- Inel. pp reactions: 10^9 / s
- bb pairs: $5 \cdot 10^6$ / s
- tt pairs: 8 / s
- W $\longrightarrow \ell\nu$: 150 / s
- Z $\longrightarrow \ell\ell$: 15 / s
- Higgs (150 GeV): 0.2 / s
- Gluinos, Squarks (1 TeV): 0.03 / s

LHC is a factory for

b and top quarks, W, Z, . . . Higgs, . . .

but in an extremely challenging experimental environment

Simulated Decay H $\longrightarrow$ 2 e 2 μ at L = 10^{34} cm^{-2} s^{-1}



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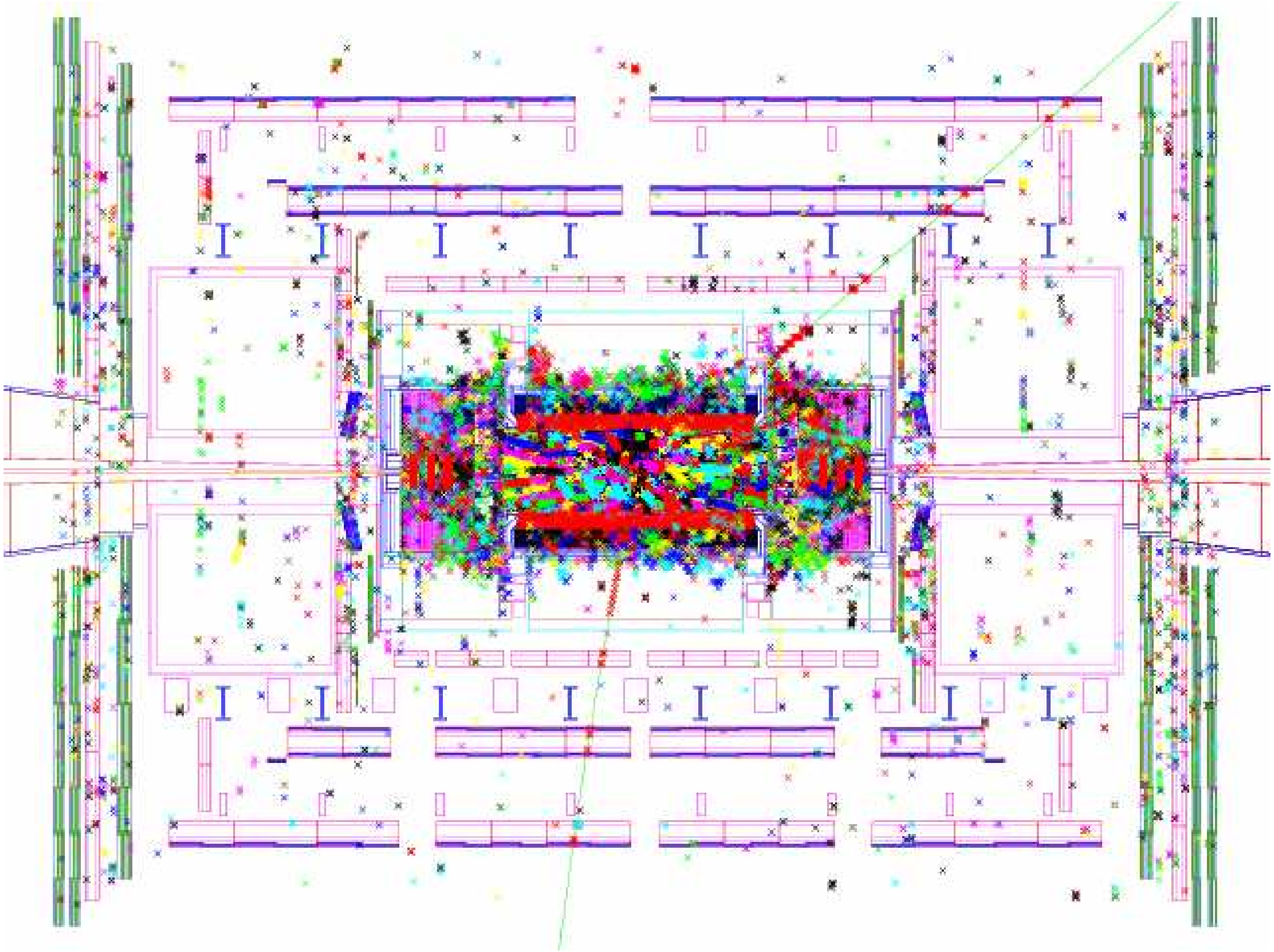
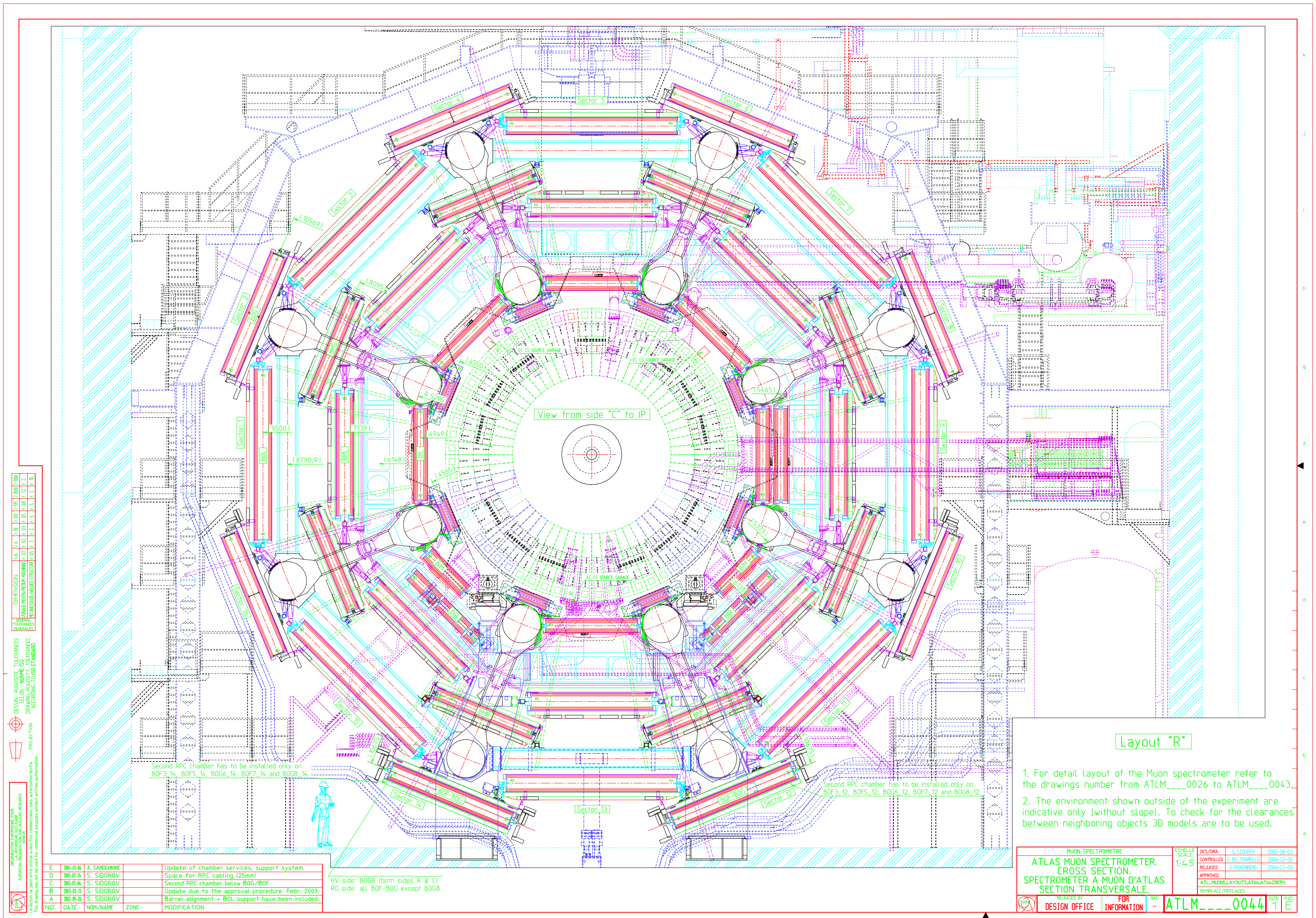


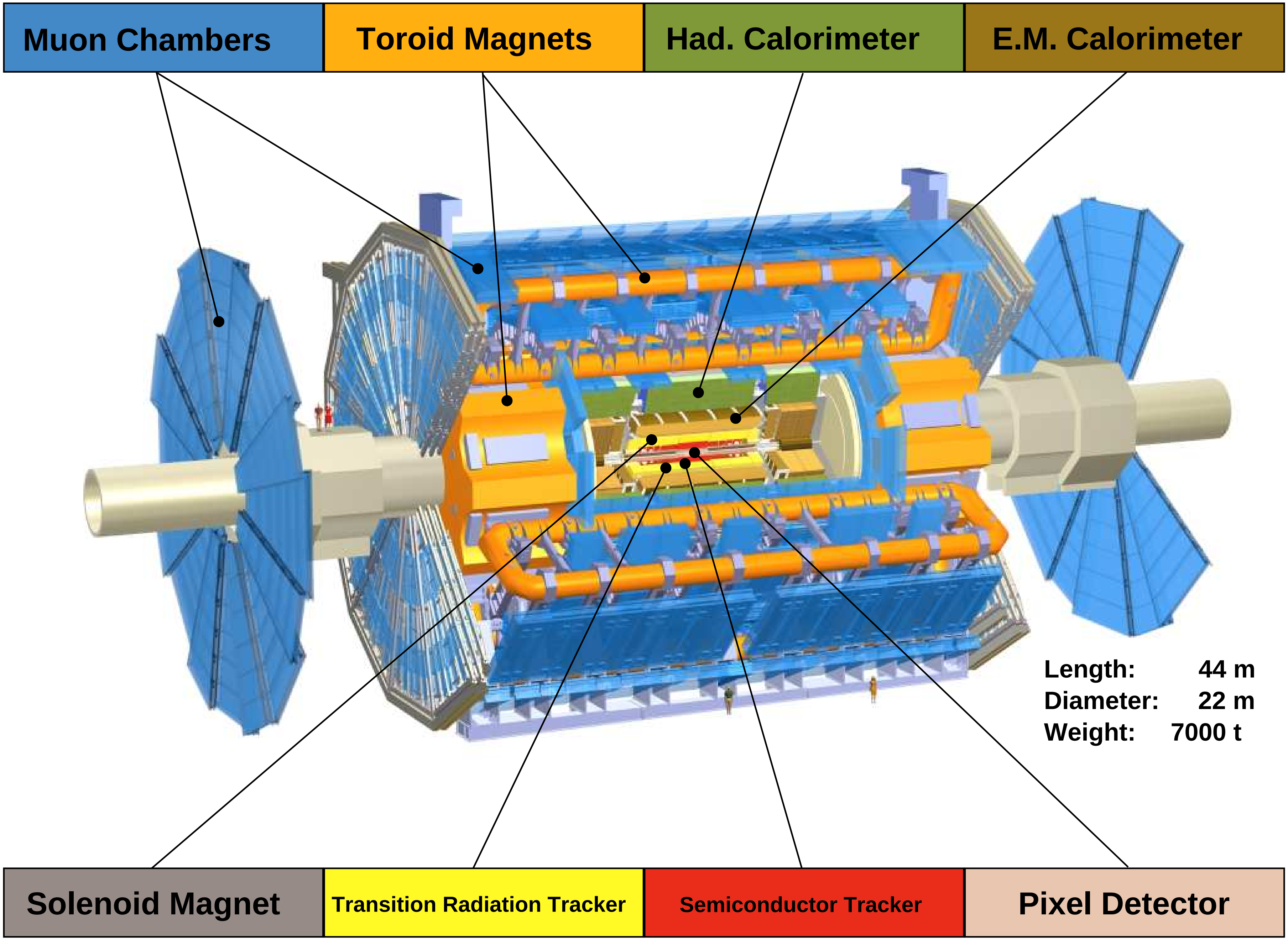
+ 23 min. bias events / bunch crossing $\longrightarrow$ 1750 additional particles

The ATLAS Detector



37 Countries — 169 Institutions — 2500 Scientific Authors

A Toroidal LHC ApparatuS



Commissioning

It's a Long Way Towards Physics Results...

Before 1st collisions

- Strict quality control during detector construction to meet physics requirements
- Test beams (15 year activity with combined test beam in 2004) to understand and calibrate (parts of) the detector and validate/tune simulation tools
- Detailed simulation of realistic detector as built and as installed (including misalignment, material non-uniformities, dead channels, etc.). Validation of calibration and alignment strategies
- **Commissioning of full detector with cosmic rays** in underground cavern

With 1st collision data

- Commission/calibrate detector and trigger in situ with physics (min. bias, $Z \longrightarrow \ell\ell, \ldots$)
- Rediscover Standard Model, measure at $\sqrt{s}$ = 10 TeV (min. bias, QCD jets, W, Z, tt)
- Validate and tune tools (MC generators)
- Measure and understand main background to New Physics

...then after careful analyses: first results (and discoveries?)

The impossible we do immediately, miracles take a little longer ;-)

Commissioning

Commissioning started in 2005 in parallel with the detector installation

- 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
- Obtain first calibration and alignment constants
- Develop and test monitoring tools
- Understand and improve detector performance

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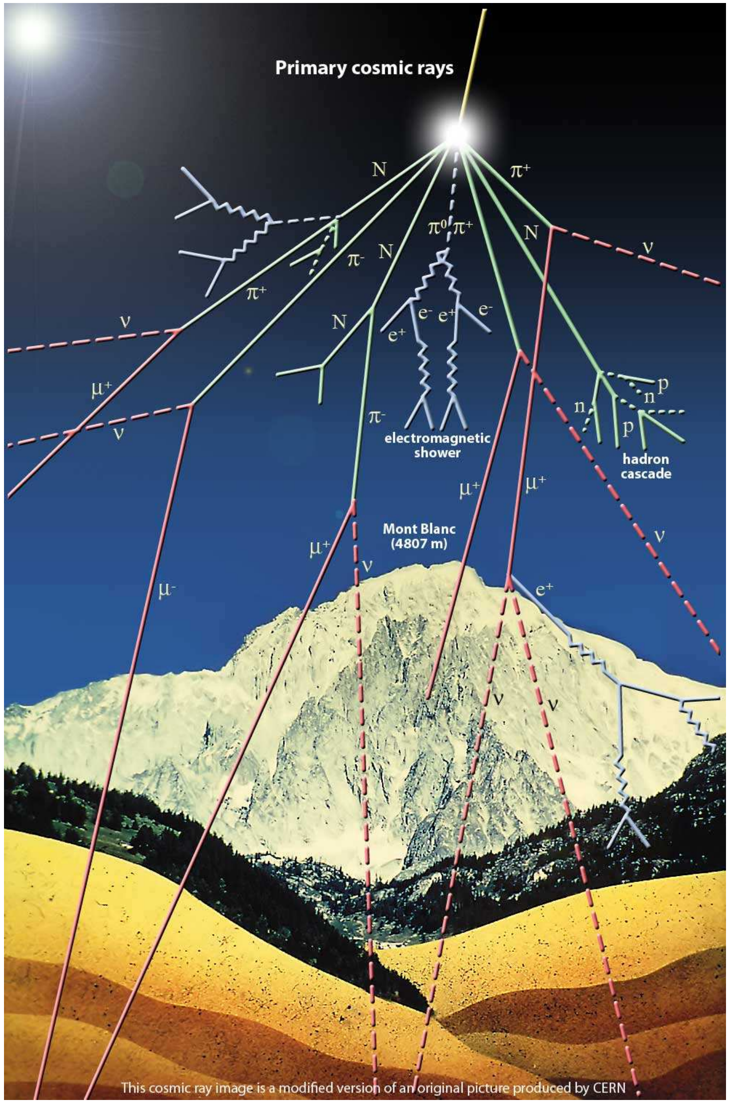
. . . but with LHC not yet operational, where do particles come from?

Using Nature's Particle Accelerator—Cosmic Rays

- **Cosmic radiation** incident on earth
  - **Primary particles** (p, He, e^-, C, O, Fe. . .) accelerated by **astrophysical sources** (including the sun)
  - **Secondary particles** (Li, Be, B, $\bar{p}$, e^+. . .) produced by **interaction of primaries with interstellar gas**

- **Interaction** with nuclei **in atmosphere creates** particle **cascades**
  - Electrons and hadrons stopped in upper atmosphere
  - **Main component at ground level: muons**
    - Flux ($p > 1$ GeV): 130 m^2 s^{-1}
    - Average energy: 4 GeV



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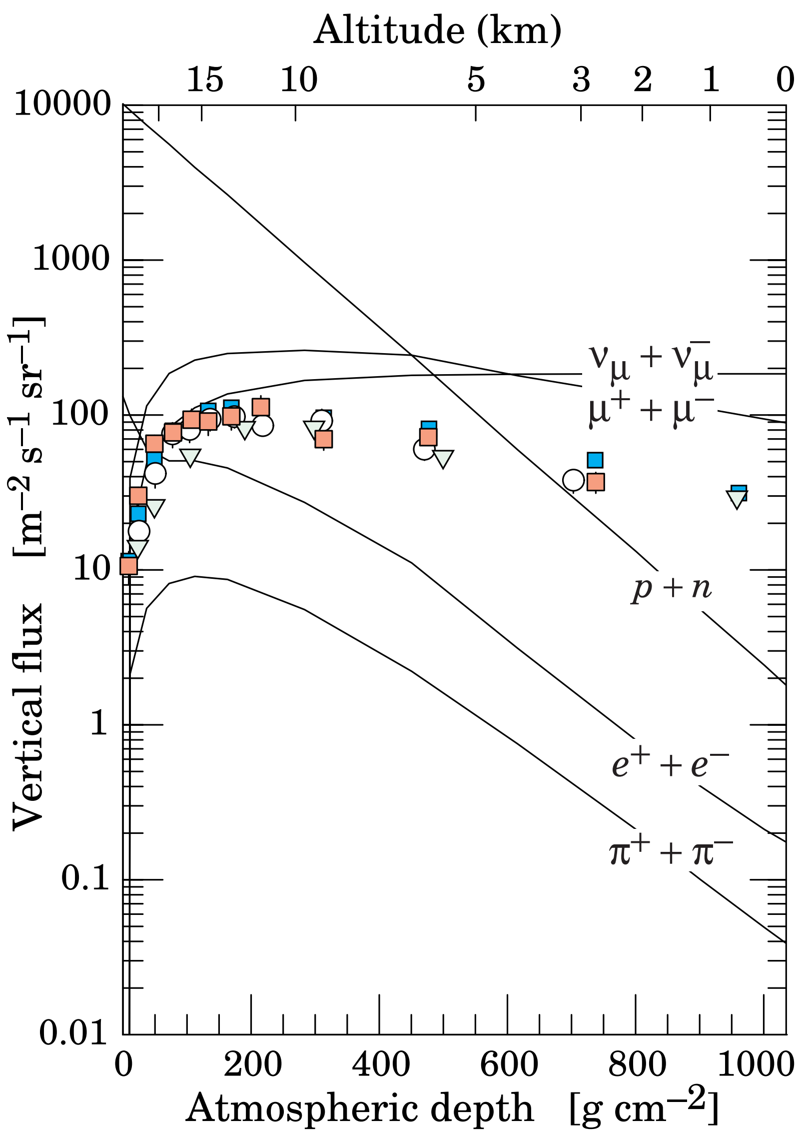

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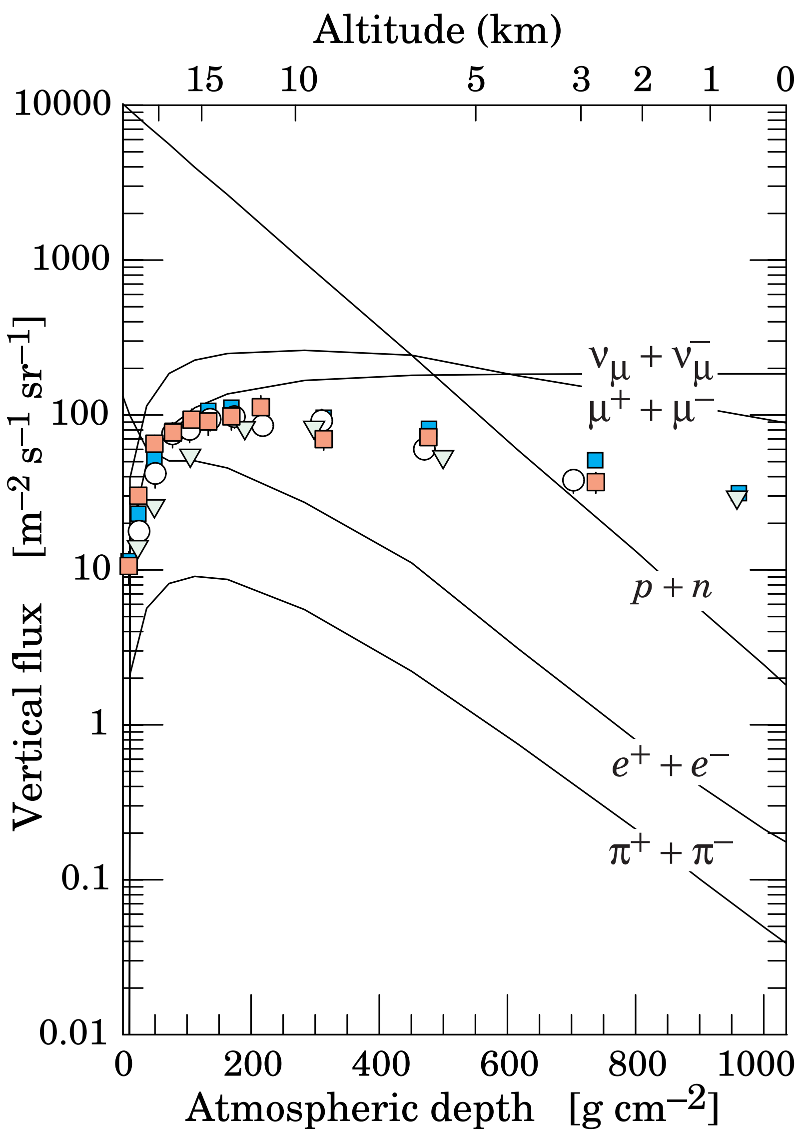
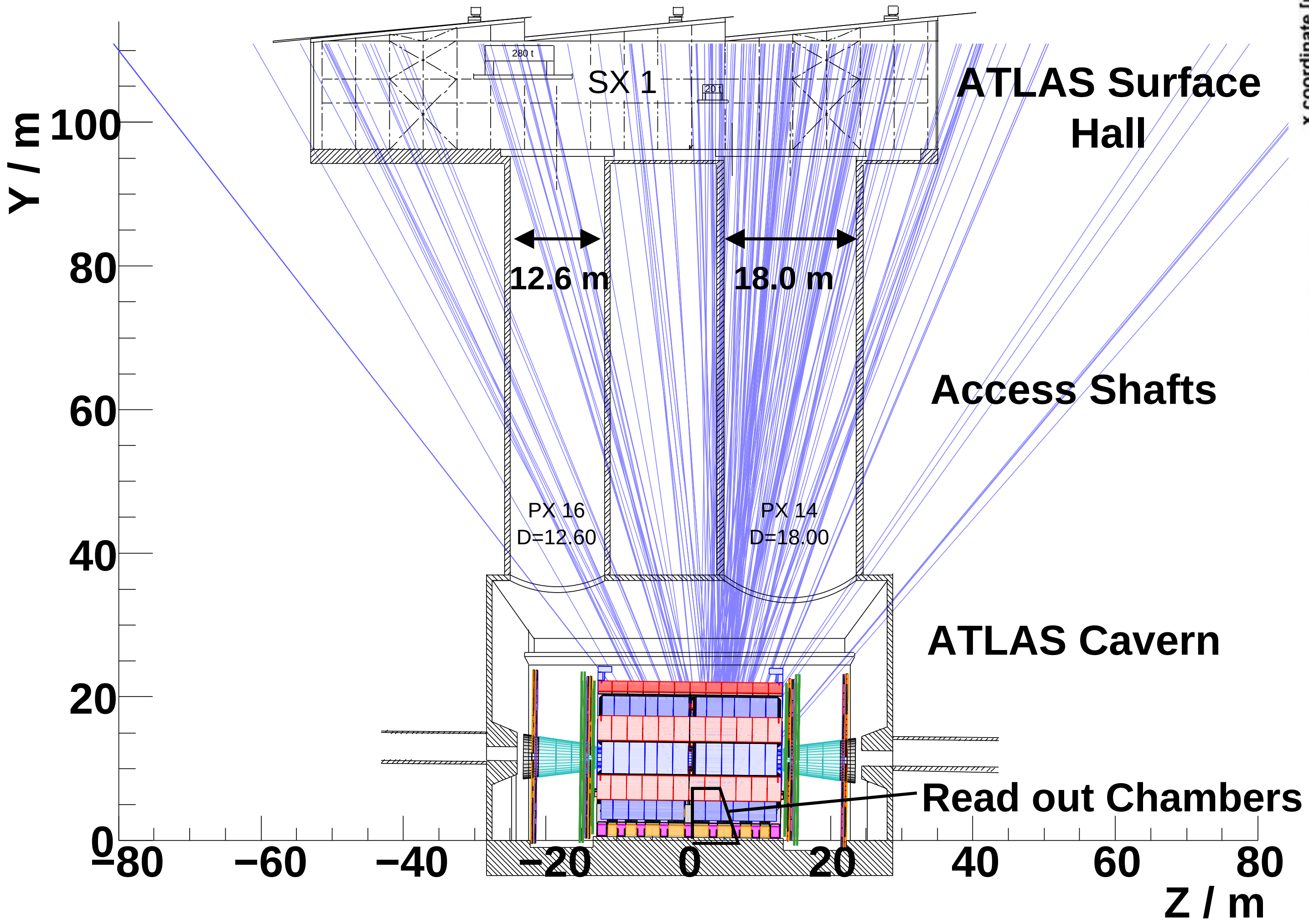
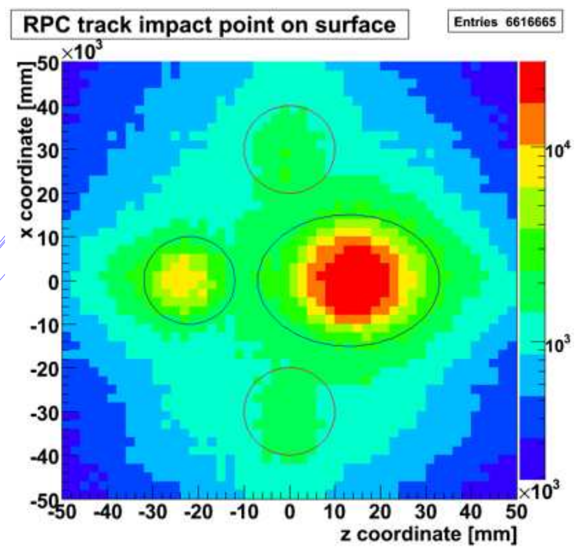


Flux in ATLAS: muon fiducial volume 4 kHz, in TRT 15 Hz, in Pixel 0.2 Hz

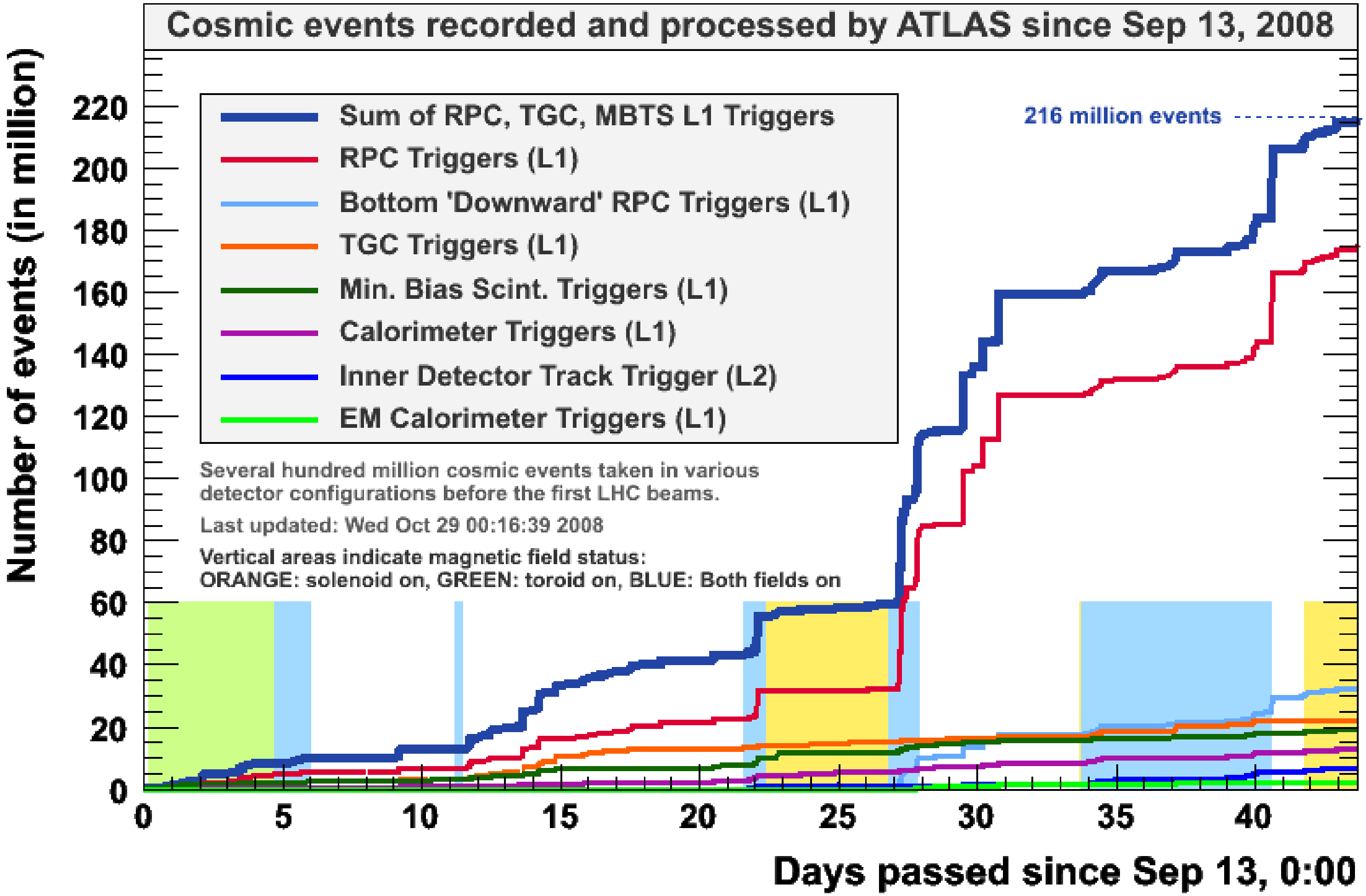
Origin of cosmic muons incident on the ATLAS detector



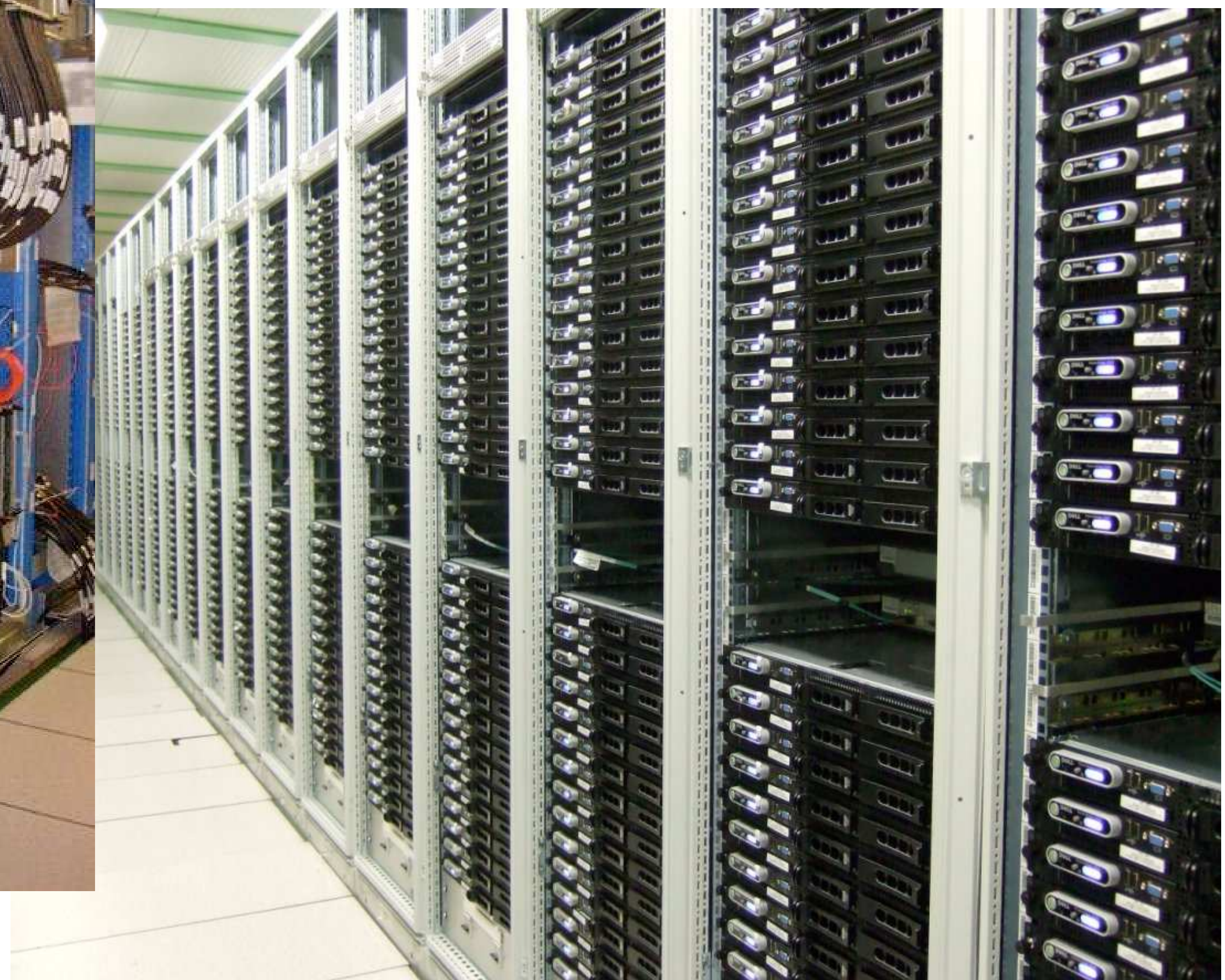


Commissioning started in 2005 in parallel with the detector installation

Most of cosmic data taken in Fall 2008 (and continuing now. . .)



Trigger and Data Acquisition



Trigger and Data Acquisition — Design

Level 1

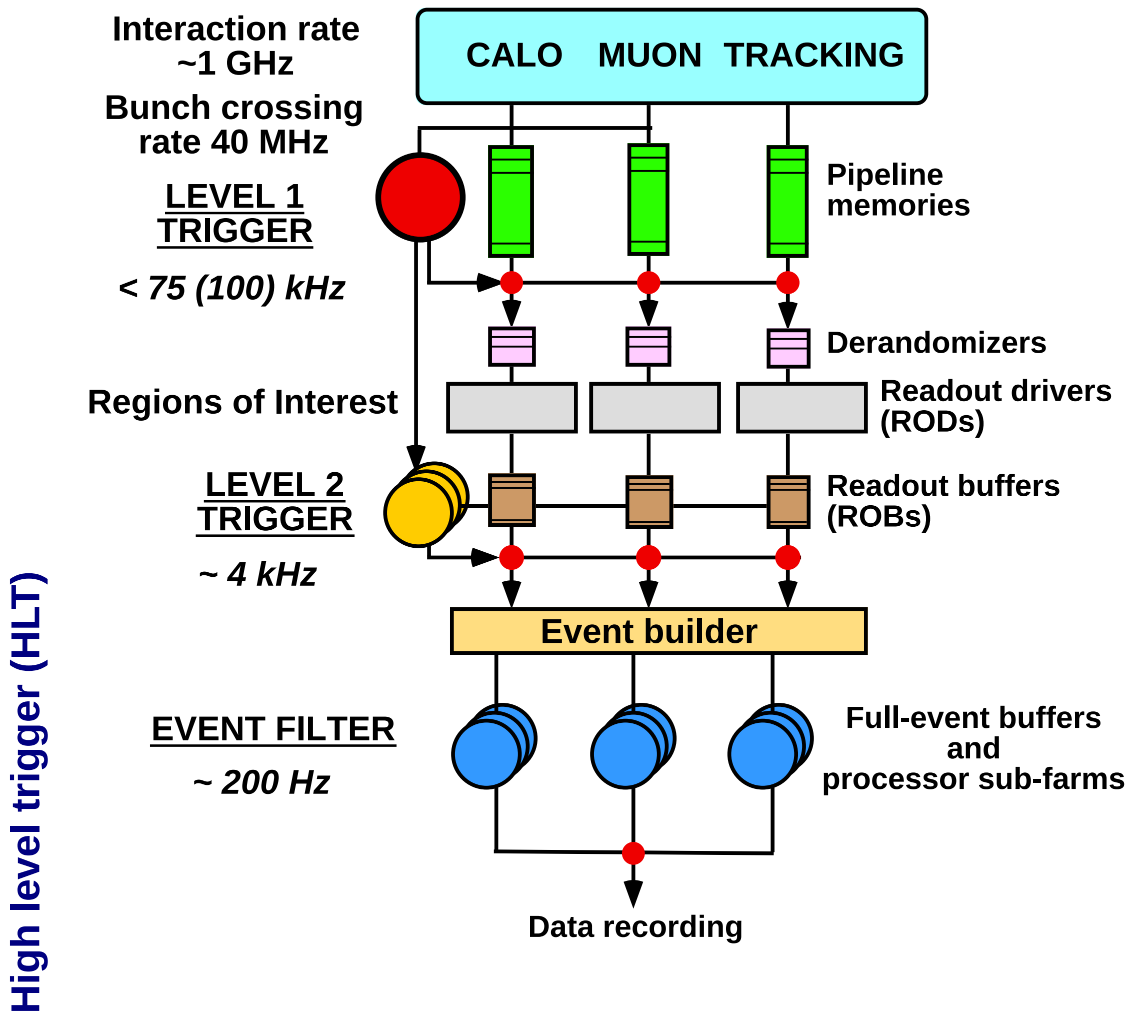
- Hardware implementation
  Synchronous at 40 MHz (LHC clock)
- Reduced granularity and detector information
- Selects Regions of Interest (ROI)
- Maximum output rate: 75KHz (upgradable to 100 KHz)
- 2.5 μs latency

Level 2

- Software implementation
- Full detector information only for ROI
- Source of high statistics calibration streams
- Maximum output rate: $\sim$4 KHz
- 40 ms latency

Event Filter

- Software implementation
- Full detector information
- Maximum output rate: $\sim$200 Hz
- 4 s latency



Event size: 1.5–2 MB

Trigger and Data Acquisition — Status

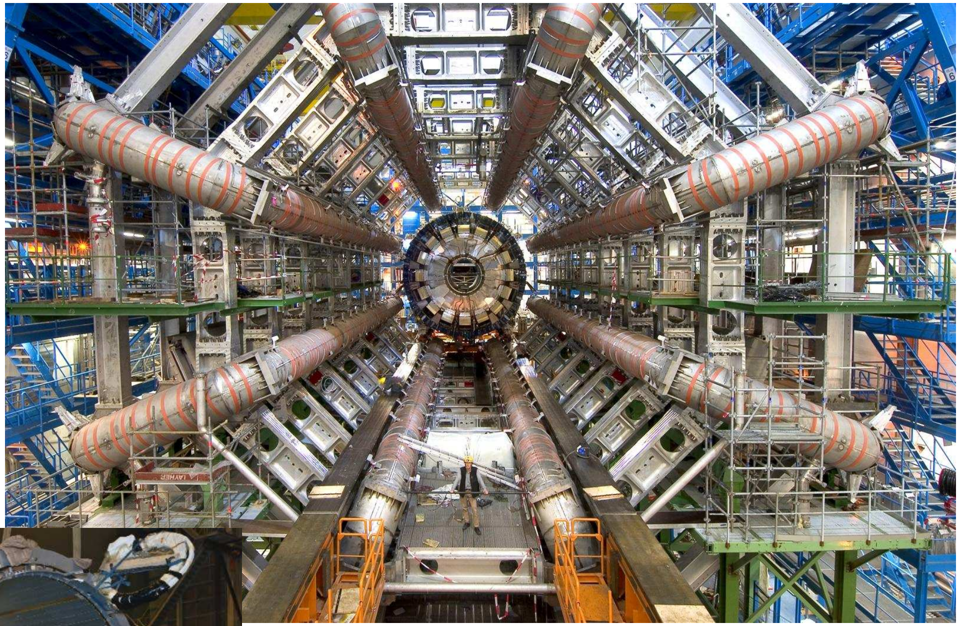
Level 1 Trigger

- System completely installed
- Rate test successful up to 40 KHz (random trigger) to be improved to nominal rate of 75 KHz in 2009
- Timing of all trigger work in progress

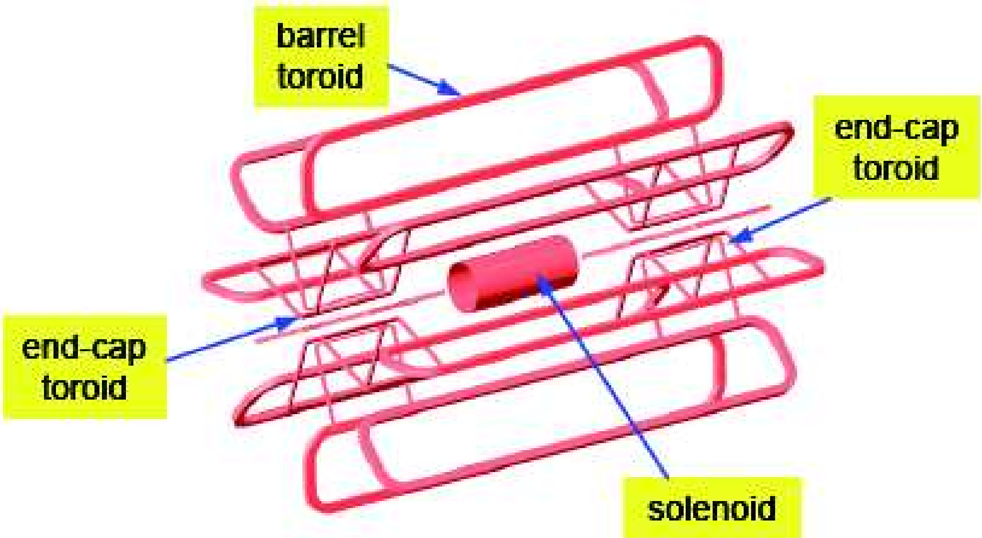
High Level Trigger (Level 2 + Event Filter)

- Current configuration
  - 850 PCs in 27 racks (can either be used by Level 2 or Event Filter)
  - Capable of 60 KHz sustained rate
- Final configuration
  - 500 PCs for LVL2, 1800 PCs for Event Filter (PC: 8 cores, 2.5 GHz with 2 GB / core RAM)
  - 17 Level 2 racks, 62 Event Filter racks (28 racks configurable)
  - Finalization of system will be luminosity driven
- Level 2 muon calibration stream working
  - Single muons
  - Nominal rate: $\sim$1 KHz
- HLT (tracking algorithms) used to enrich cosmic samples for inner detector studies

Magnet System



Magnet System — Design



Barrel Toroid

- Length: 25.3 m
- Outer diameter: 20.1 m
- 8 coils with individual cryostats
- Nominal current: 20.5 kA
- Field strength: 0.2–2.5 T
- Stored energy: 1100 MJ

Solenoid

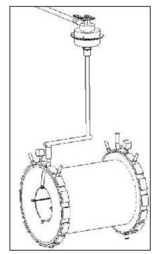
- Length: 5.3 m
- Outer diameter: 2.63 m
- 1 coil
- Nominal current: 7.73 kA
- Field strength: 2 T
- Stored energy: 39 MJ
- Thickness: 0.66 X_0

Two Endcap Toroids

- Length: 5 m
- Outer diameter: 10.7 m
- 2 $\times$ 8 coils with common cryostats
- Nominal current: 20.5 kA
- Field strength: 0.2–3.5 T
- Stored energy: 2 $\times$ 250 MJ

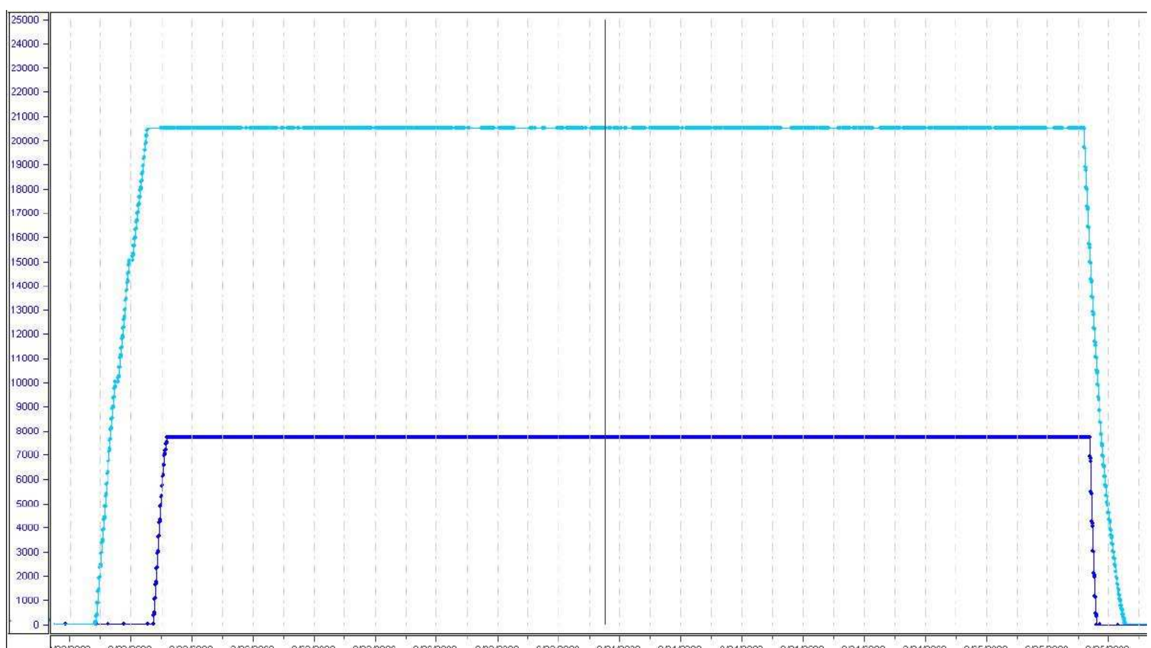
Stable continuous operation at nominal field

- Endcap toroid A required some training
  Nominal toroid current now at 20400 A
- Central solenoid works together with barrel toroid
  - Bus bars and instrumentation cables traverse toroid field



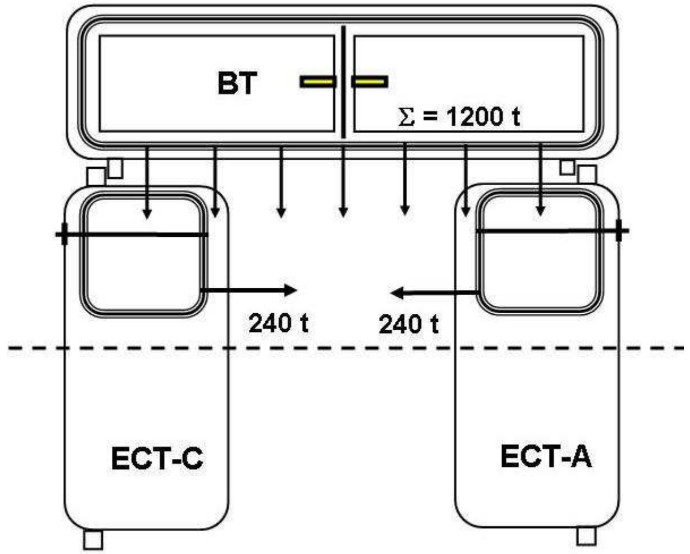
- Stress and heat distributions during fast quench (in case of loss of superconductivity) are safe
- Recovery of cryogenics after fast quench: 4 days

First test of complete magnet system in Aug. 2008

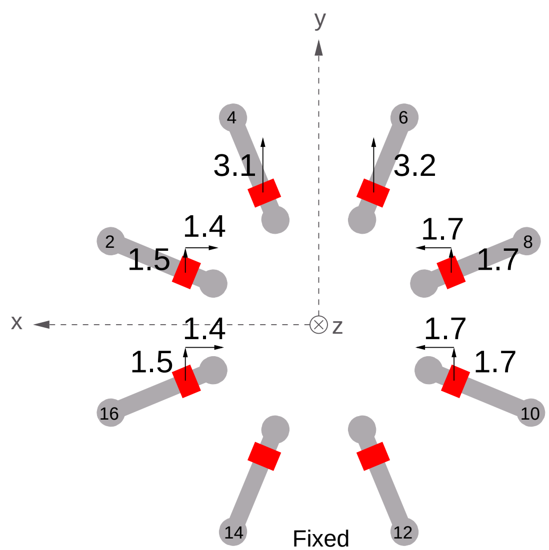


Magnet System — Status

- Load transfer endcap - barrel toroids OK

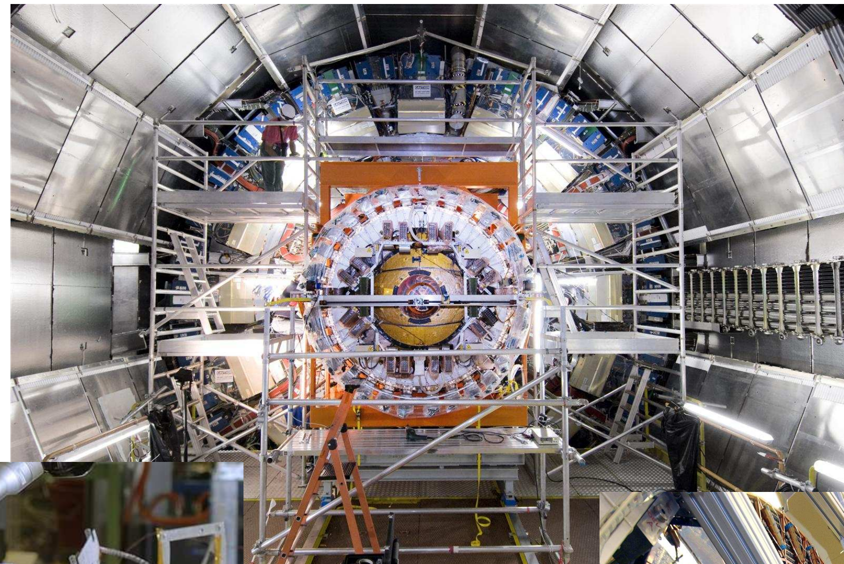


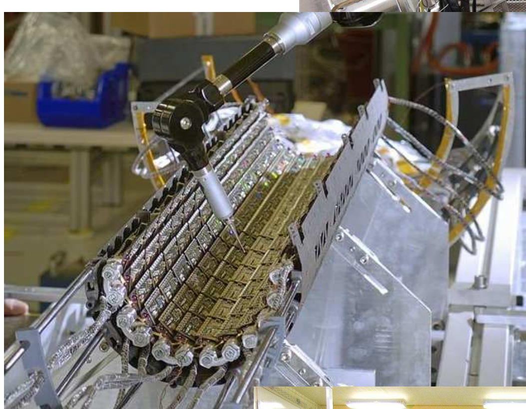
- Geometrical distortion of barrel toroid with field on as expected (light support structure)

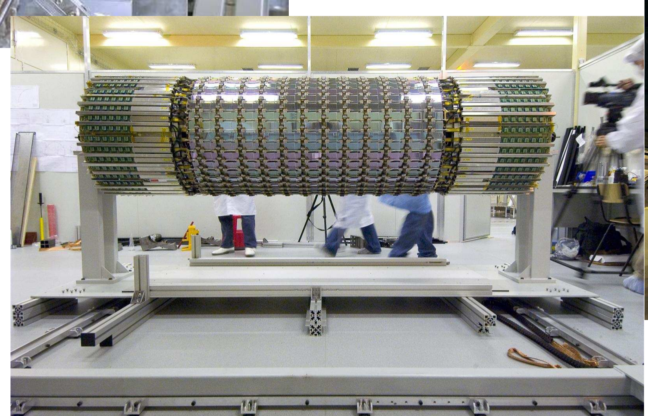


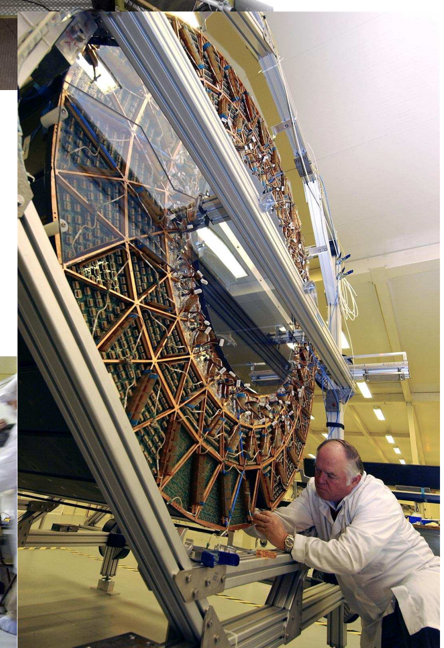
Magnet system worked without problems in June 2009 after 6 month shutdown

Inner Detector





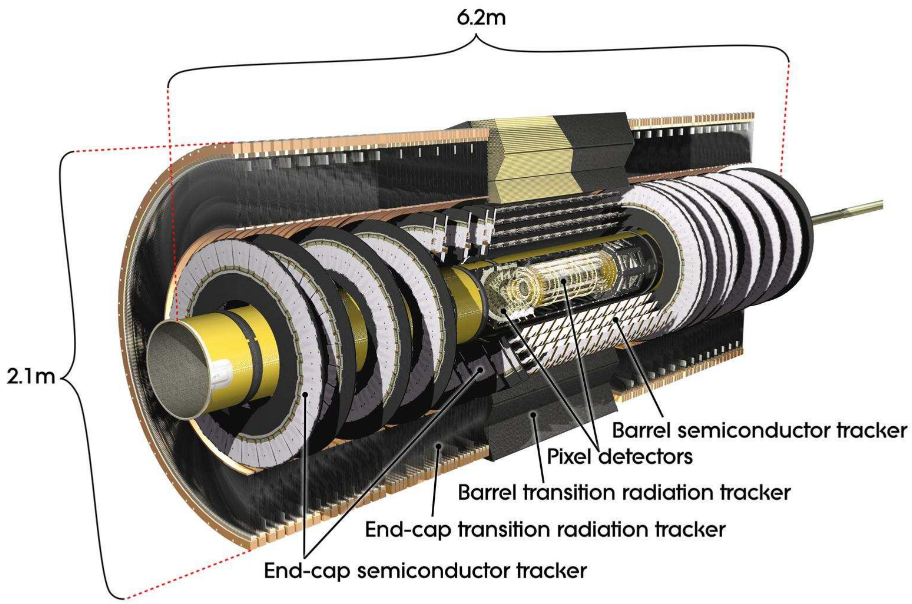




Inner Detector — Design

Operated inside 2 Tesla solenoidal field, coverage $\eta < 2.5$ (Transition Radiation Tracker $\eta < 2.0$)

$$\sigma / p_T = 0.05\% \; p_T \oplus 1\%$$



Pixel Detector

- 3 cylindrical layers with 5, 9, 12 cm radius in barrel region
- 2 $\times$ 3 disks in forward regions
- 1744 modules, each with 46860 pixel of 50 μm $\times$ 400 μm
- 80 M channel
- Resolution: 10 μm $\times$ 110 μm

Semiconductor Tracker (SCT)

- 4 cylindrical double layers with radius 30, 37, 44, 51 cm in barrel region
- 2 $\times$ 9 disks in forward regions
- 4088 modules with 80 μm strips
- 6 M channel
- Resolution: 17 μm $\times$ 580 μm

Transition Radiation Tracker (TRT)

- Polypropylen-polyethylene fibers (barrel) polypropylene foils (endcap) as radiator
- 4 mm diameter straw tubes with 35 μm anode wires
- 73 layers in barrel region with axial straws
- 2 $\times$ 160 (20 disks each) with radial straws in forward region
- 351 K channel
- e-π identification: 0.5 GeV $<$ E $<$ 150 GeV

Inner Detector — Status

Evaporative Cooling System

- Cooling system to operate silicon detectors at -7 ^{o}C
- Compressor damage with partial pollution delayed commissioning of Pixel and SCT (May – July 2008)
- Compressors modified to avoid cracks at piping

Pixel Detector

- $>$ 98% of modules operational
- Noise occupancy: $5 \cdot 10^{-9}$
- Hit efficiency: $>$ 98%
- 3 leaking cooling loops in endcaps (affect 3 of 24 modules) under investigation
- Problem with dying off-detector optical links (to be replaced until August)

SCT

- $>$ 99% of barrel and $>$ 97% of endcap modules operational
- Noise occupancy: $4.4 \cdot 10^{-5}$ (barrel), $5 \cdot 10^{-5}$ (endcap)
- Hit efficiency: $>$ 99%
- 2 cooling loops in endcaps not operated (to be repaired in shutdown)
- Problem with dying off-detector optical links (to be replaced until August)

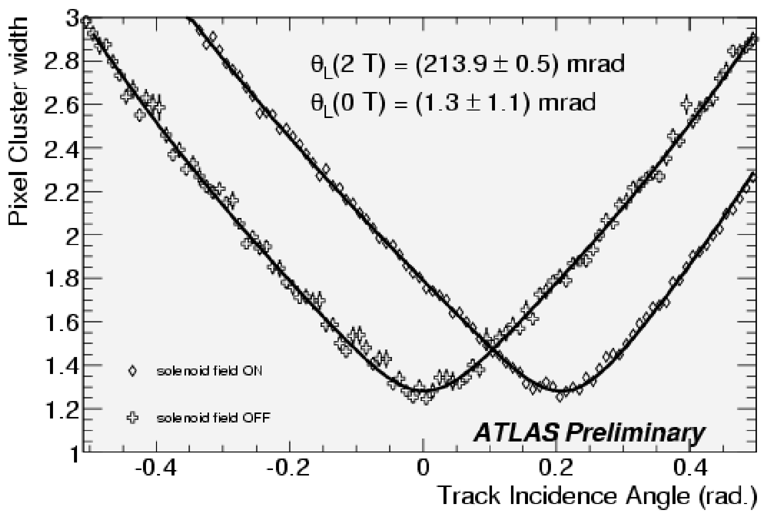
TRT

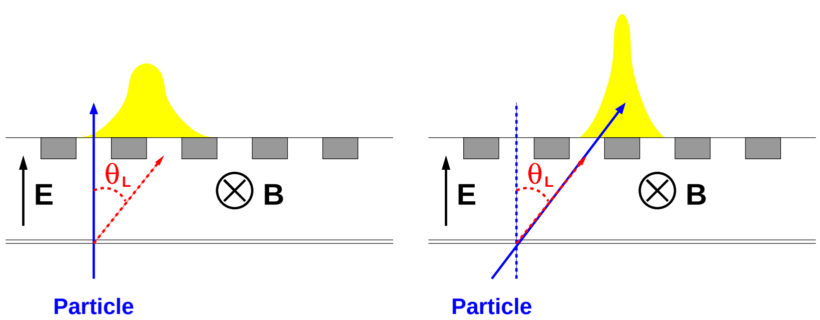
- 98% of channel operational (2% dead from assembly and installation)

Inner Detector — Results

Measurement of cluster width in pixels

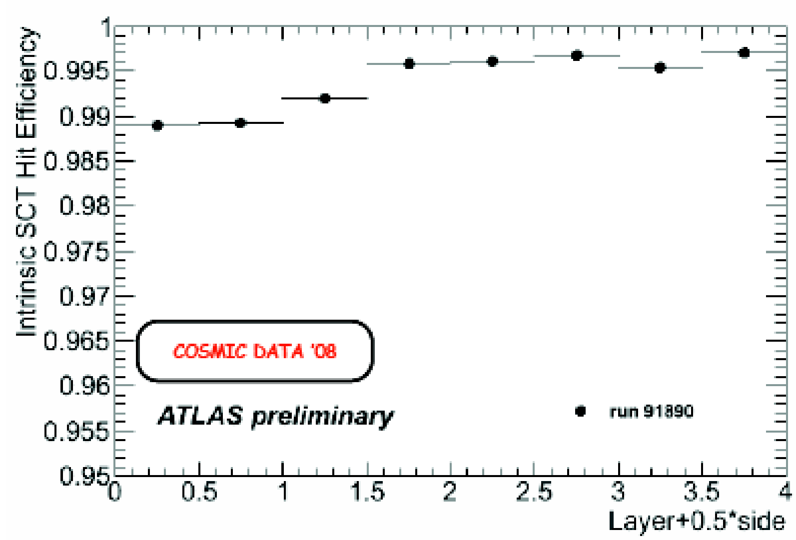
Determination of Lorentz angle, essential to understand final spatial precision (MC prediction: 224 mrad)





Measurement of barrel SCT efficiencies

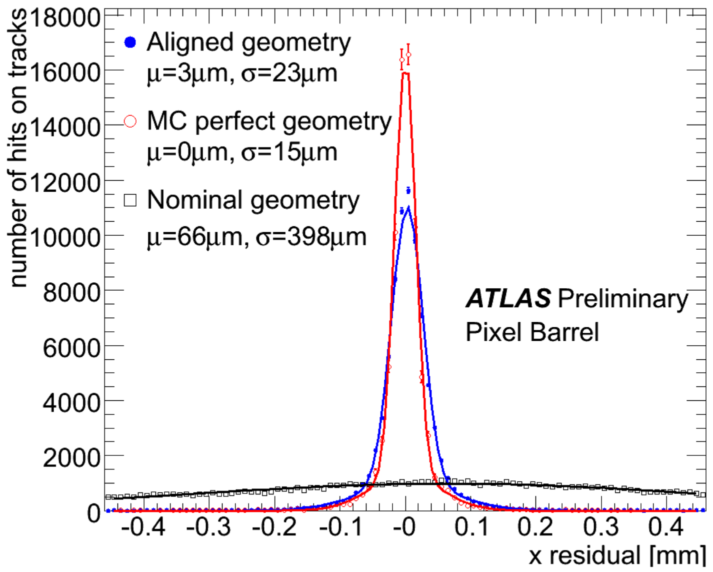
Systematic differences between layers due to preliminary alignment

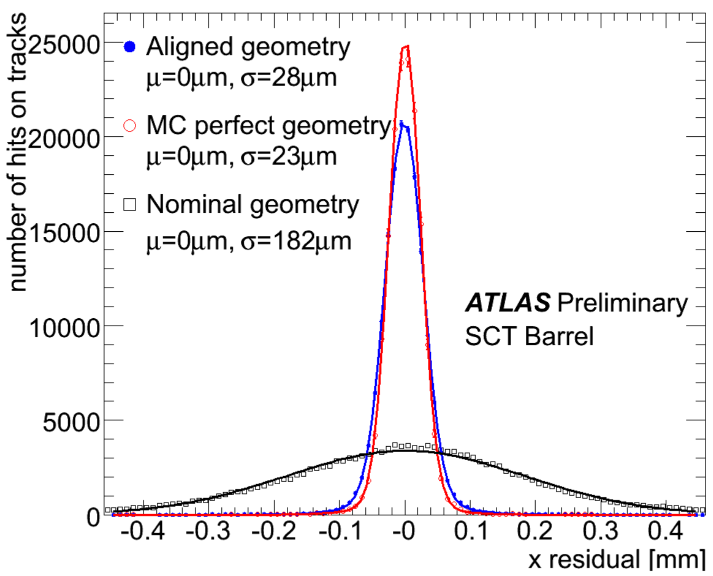


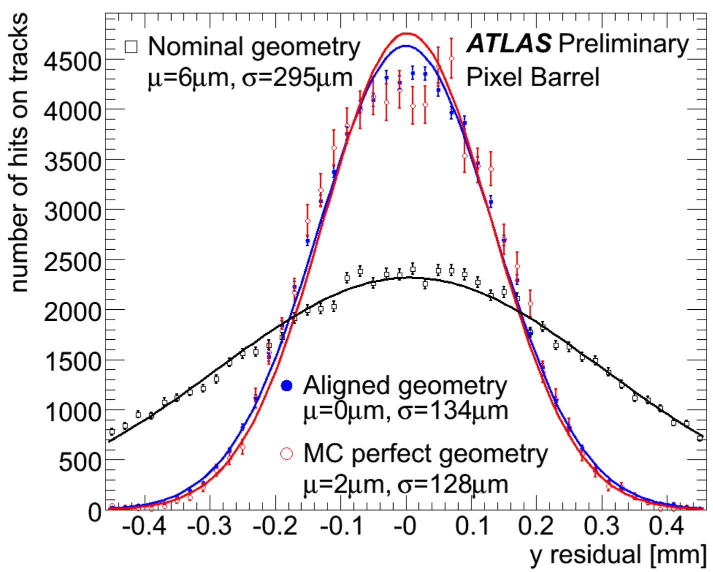
Inner Detector — Results

Alignment with tracks

- Alignment performed in steps of increasing number of DoF
  - O(1M) tracks needed for full alignment
- Track residuals close to perfect geometry for barrel region
- Limited statistics for endcaps

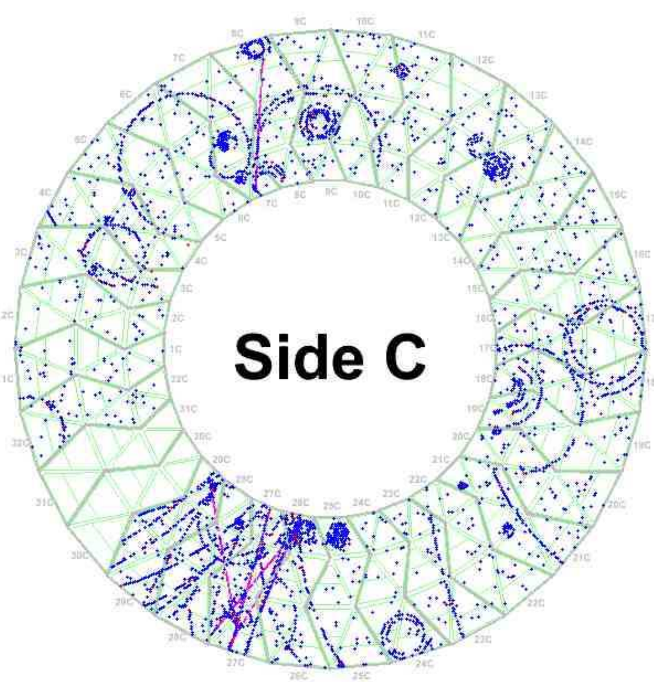






Transition Radiation Tracker

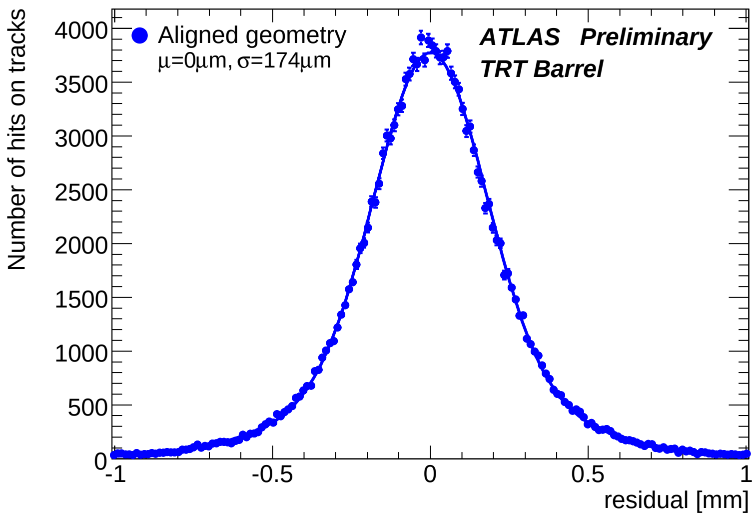
Bubble Chamber like events displays



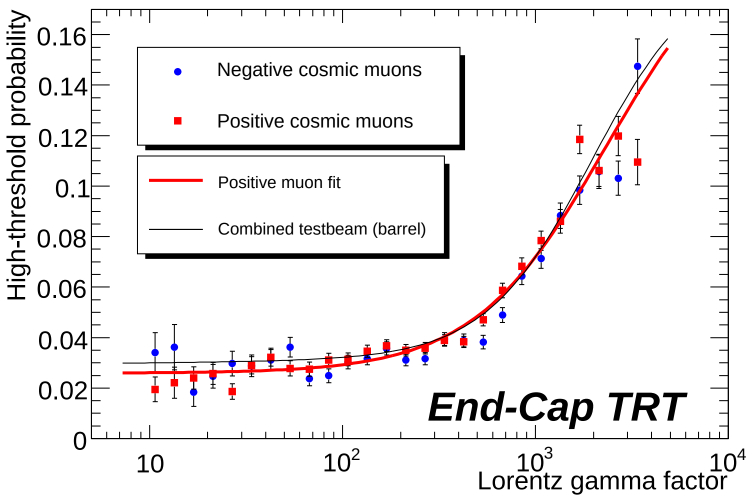
Right: Measurement of the probability of transition radiation

Good agreement with test beam data

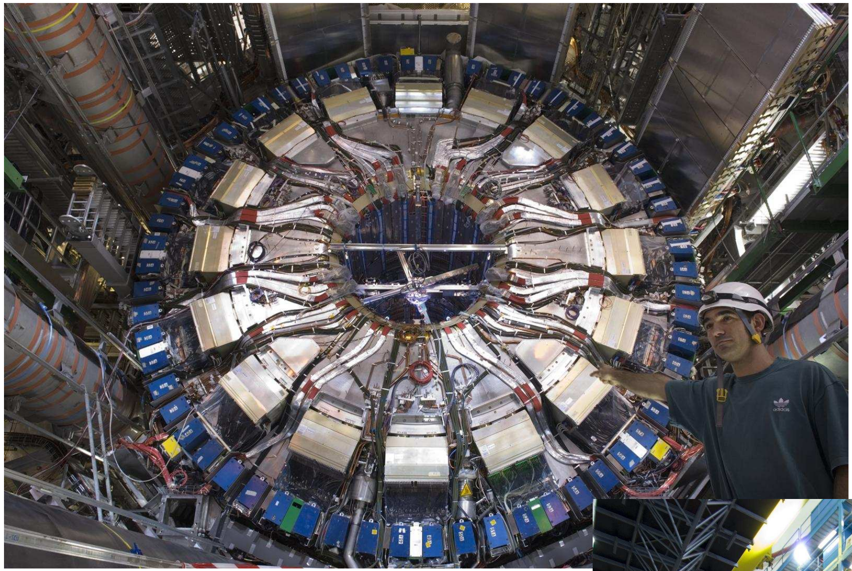
Track residuals

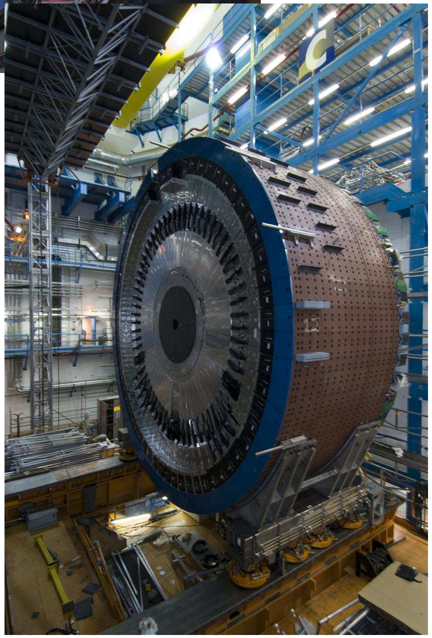


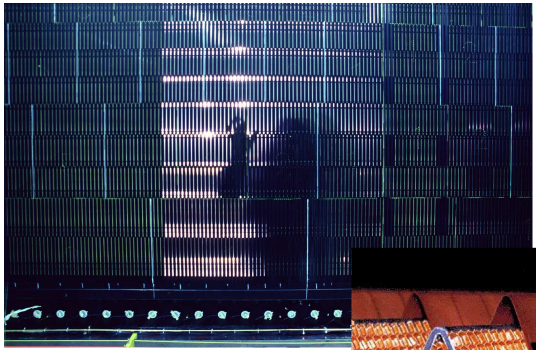
TRT design straw resolution: 130 μm

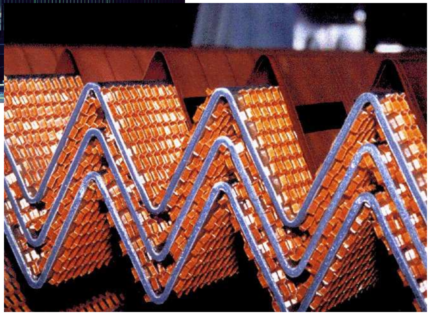


Calorimeters



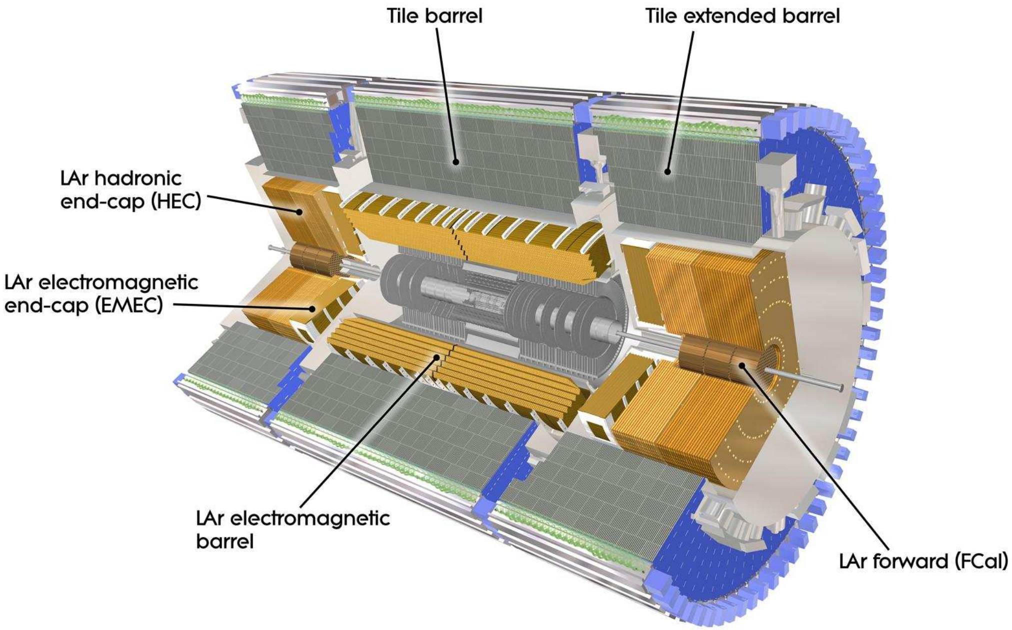






Calorimeters — Design

Complete azimuthal symmetry, coverage $\eta < 4.9$



Electromagnetic Calorimeter

- Pb-LAr accordion geometry
- 3 longitudinal samples $\eta < 2.5$
- Preshower detector $\eta < 1.8$
- 173 K channel
- σ(E)/E = 10%/$\sqrt{\text{E}}$ $\oplus$ 0.7%

Hadron Calorimeter

- Barrel: iron-scintillator tiles (3 longitudinal samples) Endcap/forward: Cu/W-LAr (4/3 longitudinal samples)
- 20 K channel
- σ(E)/E = 50%/$\sqrt{\text{E}}$ $\oplus$ 3% ($\eta < 3.2$) σ(E)/E = 100%/$\sqrt{\text{E}}$ $\oplus$ 10% ($\eta > 3.1$)

Calorimeters — Status

Liquid argon calorimeter (electromagnetic, hadron endcap, forward)

- Dead channel: 0.02% (+ 0.2% recoverable in next shutdown)
- Noisy channel: 0.1% ($>$ 5 sigma of ϕ-average), bad or no calibration: 0.32%
- Full detector operational with HV (6.1% of channel at reduced voltage)
- Electronic calibration procedure operational
  - Calibration constants used online
- Refurbishment of all LV power supplies finished (arching and problematic capacitors)

Tile calorimeter

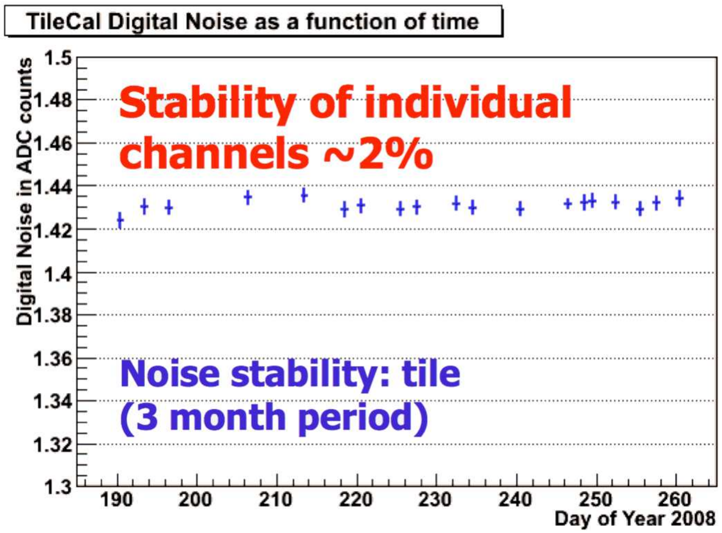
- Dead channel: 0.8% (front end electronics)
- Calibration system operational
  - Cs source (PMT gain and fiber attenuation)
  - Laser (PMT response and timing)
  - Charge injection (ADC-to-pC with 0.7% precision)

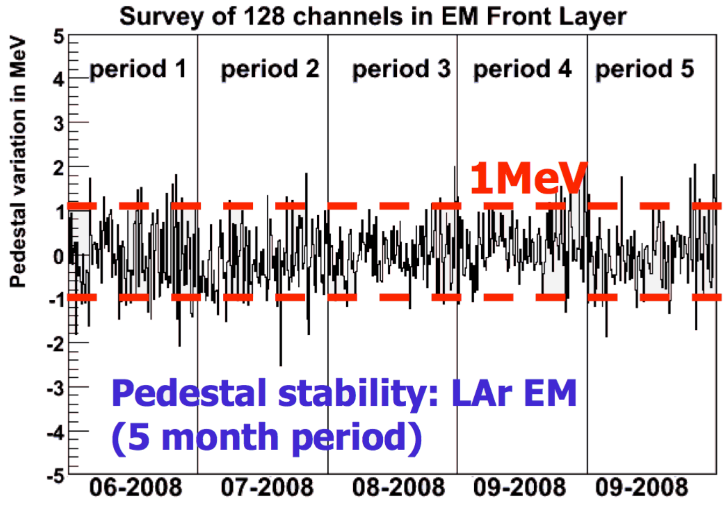
Level 1 Calorimeter Trigger (e/γ, jets, missing E_T...)

- Dead channel: $<$ 0.4% (+ 0.3% recoverable in shutdown) of 7200 analog channel
- Channel-to-channel noise suppression allows E_T = 1 GeV cut (aim: 0.5 GeV)

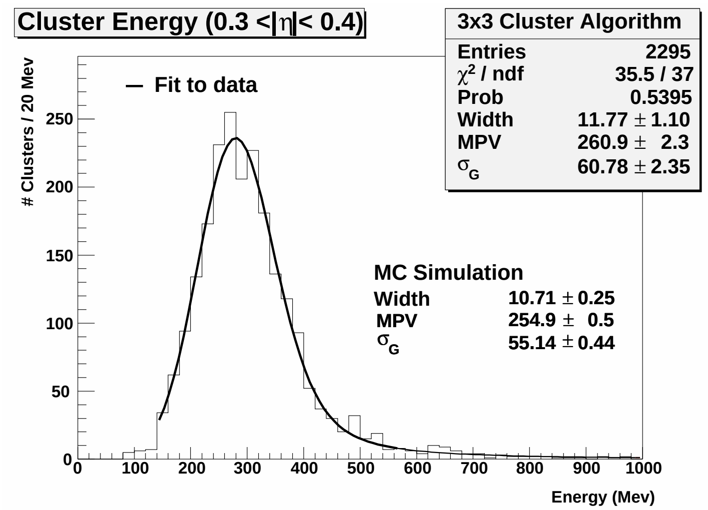
Calorimeters — Results

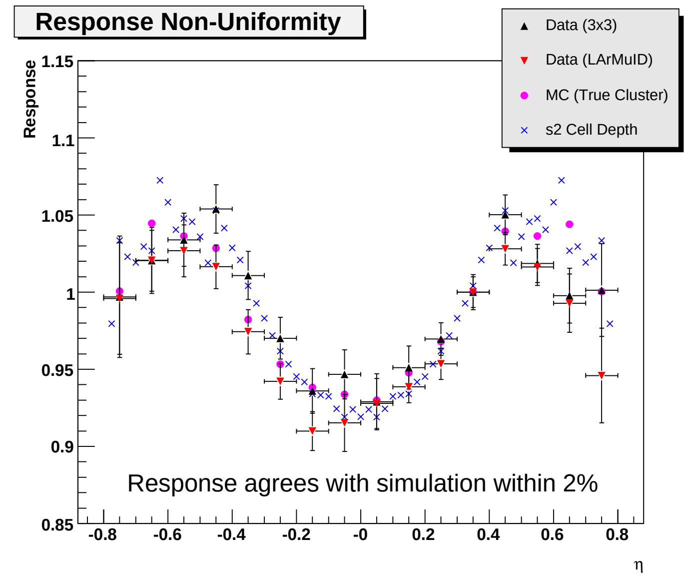
Stability of Tile and LAr calorimeters





Uniformity of LAr calorimeter

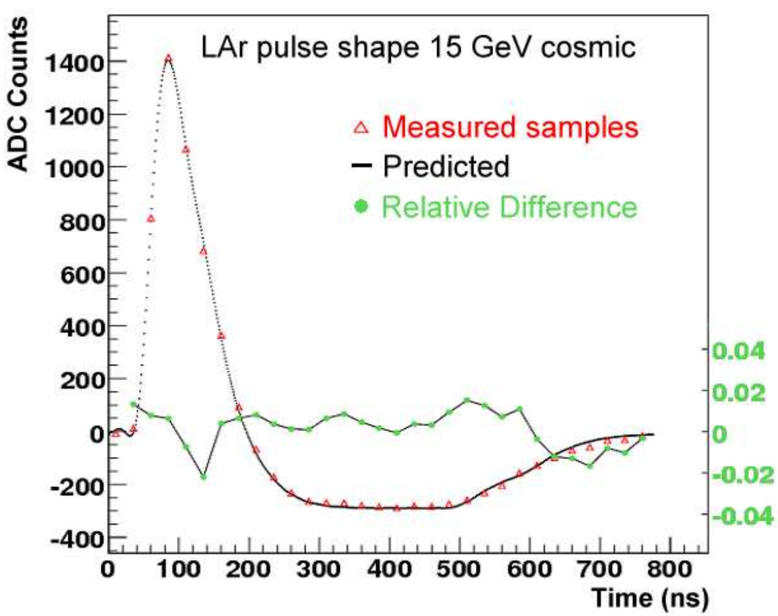


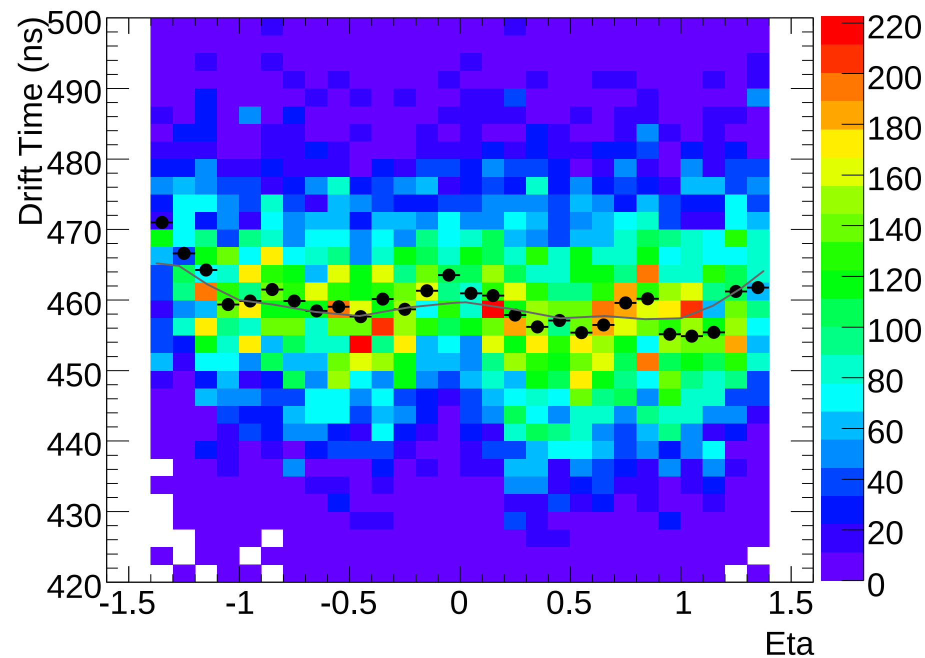


LAr calorimeter: pulse shape studies

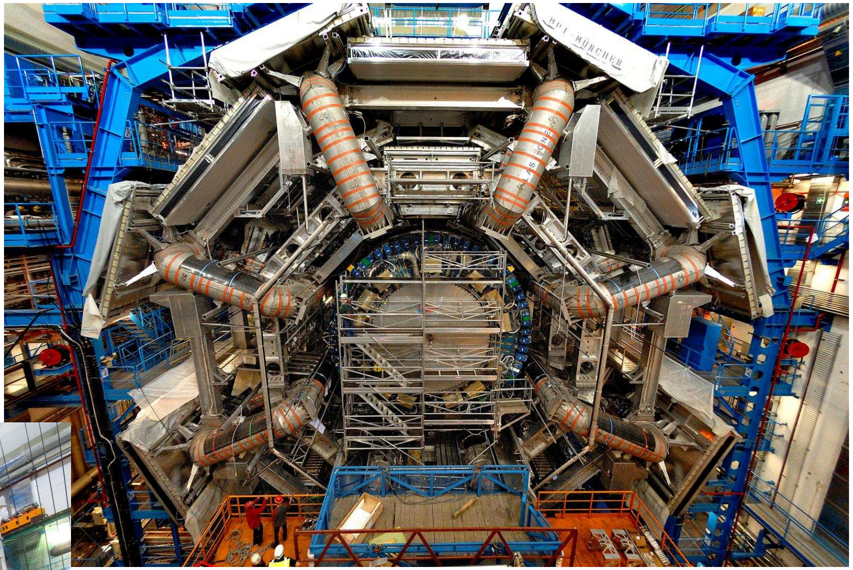
Detailed studies of pulse shape (32 samples instead of 5 sample during physics) allow very good understanding of electronic chain, drift properties and cell geometry

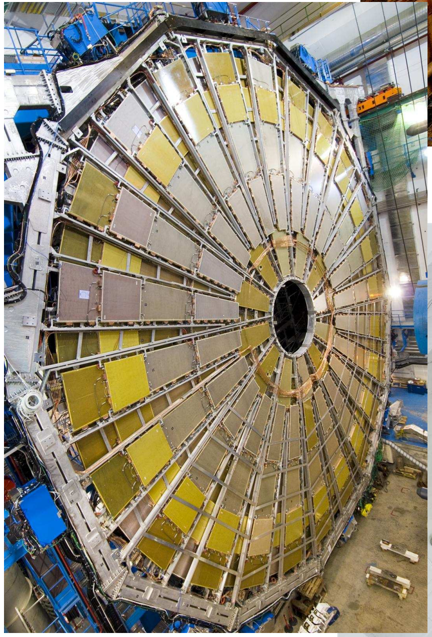
Example: Distribution of drift time derived from undershoot of pulse shape. Comparison with prediction from measurement of gap thickness during production

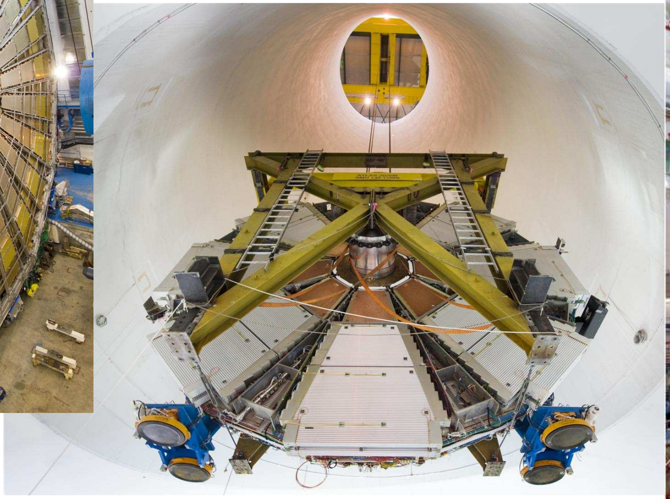


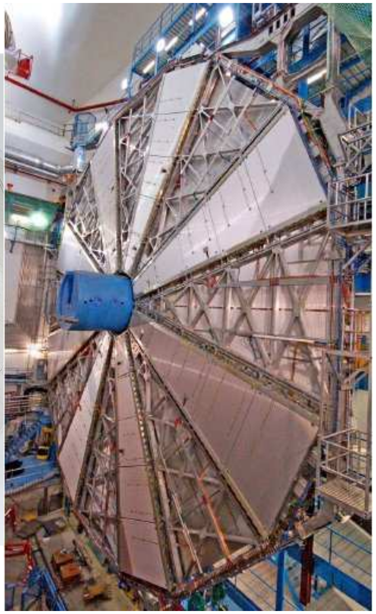


Muon Spectrometer



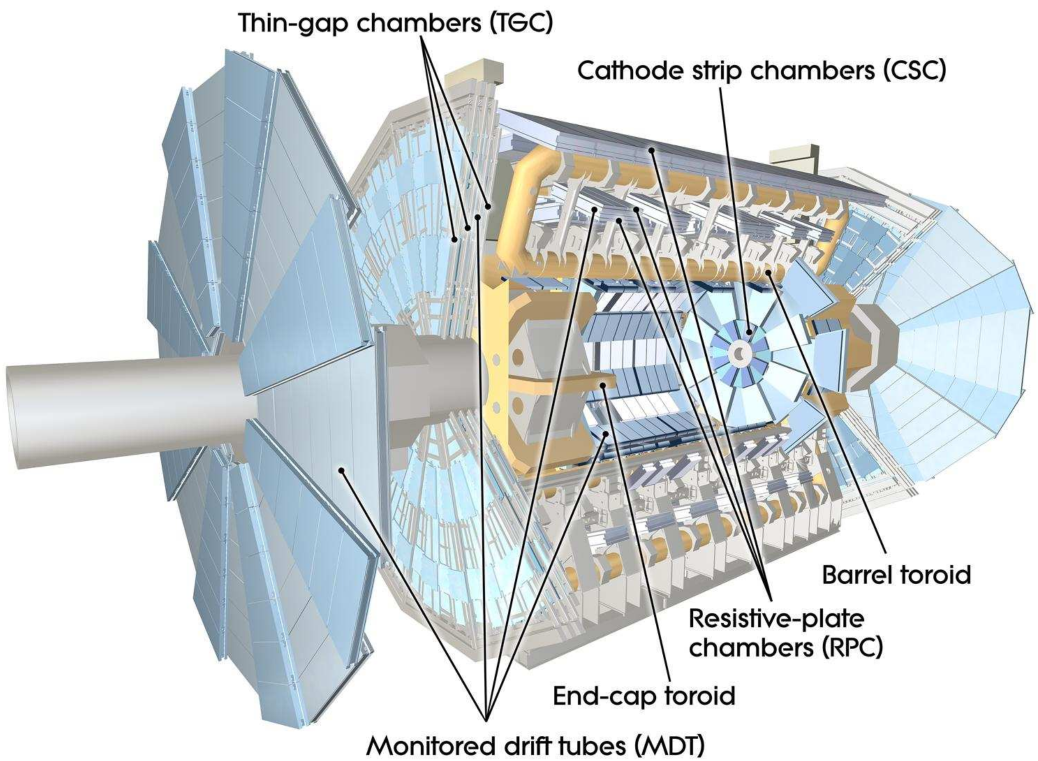






Muon Spectrometer — Design

Stand-alone momentum resolution: $\Delta p_T / p_T < 10\%$ up to 1 TeV (independent of η)



Dedicated fast trigger chambers

- RPC: 544 chambers with 359 K ch.
- TGC: 3588 chambers with 318 K ch.
- 2-dimensional readout
- Time resolution < 10 ns
- Spatial resolution 5–10 mm

High precision tracking chambers

- MDT: 1088 chambers with 339 K ch.
- CSC: 32 chambers with 31 K ch.
- Spatial resolution 35–40 μm
- Second coordinate meas. in forward chambers

Optical alignment system, 12232 sensors

Coverage: $\eta < 2.7$ (trigger $\eta < 2.4$)

Air-core toroid magnet system: 1.5–5.5 Tm ($\eta < 1.4$), 1–7.5 Tm ($1.6 < \eta < 2.7$)

Muon Spectrometer — Status

General worries of all systems: power system (improving) and rack turbines (refurbishment planned)

RPC

- 95.5% of chambers operational, trigger coverage currently 95.5%
- Dead strips: $< 2\%$
- Hot strips/spots: $< 1\%$
- Recirculating gas system working
- Commissioning on-going
- High-p_T trigger lost for one half of 2 projective towers (of 384) and 20 gas gaps disconnected (1 plane of doublet, no loss of coverage) due to gas leaks
- New cooling of upper sectors installed, to be tested this week

TGC

- 99.9% of chambers operational
- Dead channel: $< 0.01\%$
- Noisy channel: $< 0.02\%$ with $> 5\%$ occupancy
- 1 chambers lost in overpressure accident (used for 2nd coordinate measurement and background rejection)
- Full trigger coverage (4 chambers with HV problems, but 3/4 majority logic)
- n-pentane heater pressure vessel to be repaired — currently no operation possible

Muon Spectrometer — Status

MDT

- 99.9% of chambers operational
- Dead channel: 0.2% (+ 0.5% recoverable)
- Noisy channel: $< 0.2\%$ with $> 5\%$ occupancy
- Auto-calibration of space-drifttime-relation working
  - Single muon calibration stream from LVL2 trigger
  - Calibration constants and space-drift time relations regularly provided
- Cracked gas-jumper lead to leaks on EO-chambers, situation stable since water added to drift gas

CSC

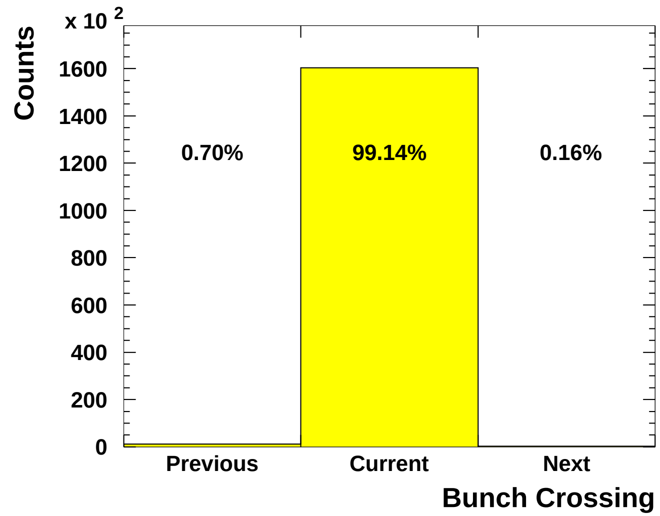
- 100% of chambers operational
- Dead channel $< 0.1\%$
- Two chambers with 1 dead plane (of 4)
- Calibration data collected
- Firmware problem limits stability and maximum read-out rate to O(1 KHz).
  Under investigation, CSC excluded from combined data taking

Optical alignment

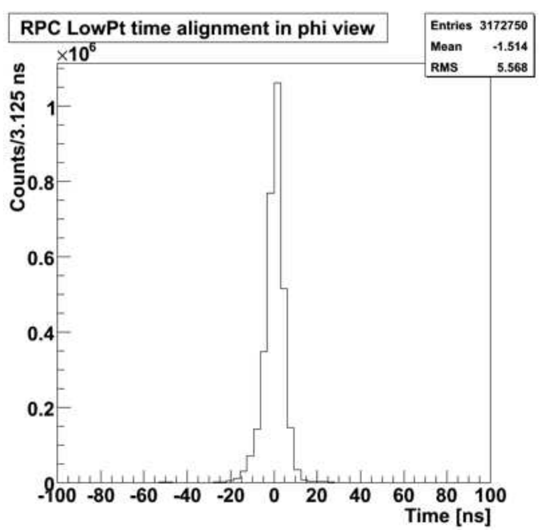
- 99.7% (barrel), 99% (endcap) operational

- Excellent TGC trigger timing (within 1 BC)
- Local RPC trigger timing approaching intrinsic resolution
- Global RPC trigger timing progressing well, improved from spread of 8 BC to 4 BC

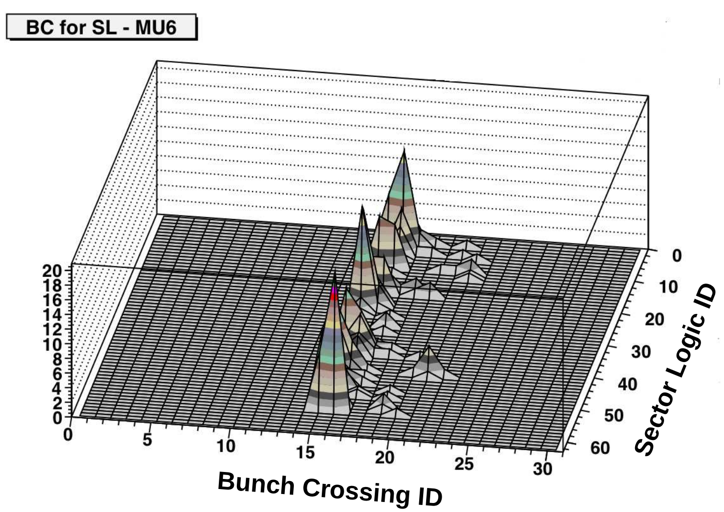
Timing of TGC



Time alignment of RPC low-p_T trigger



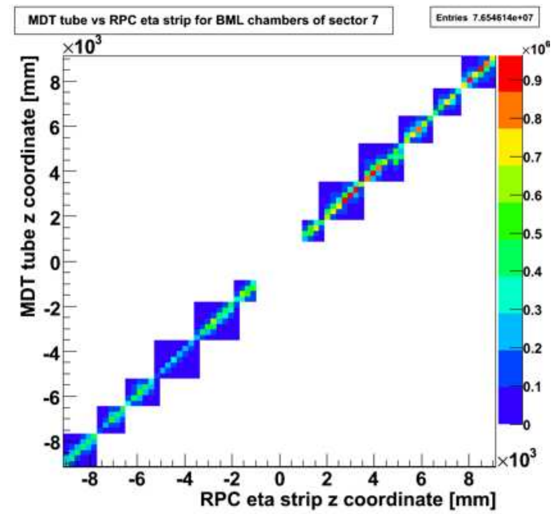
Time alignment of RPC sector logics



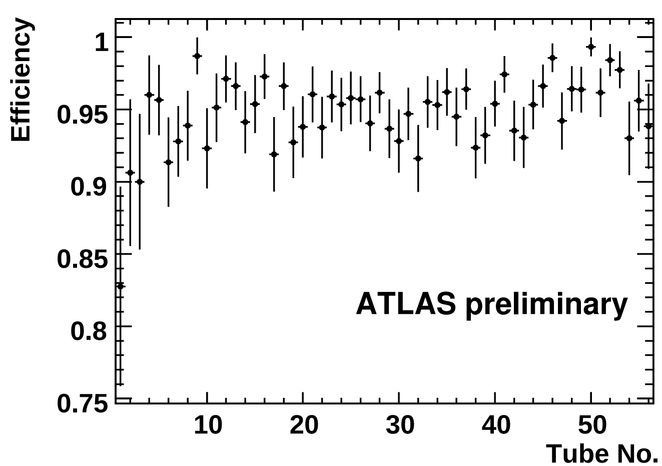
Muon Spectrometer — Results

- Very good correlation between hits in trigger and precision chambers
- Drift tube efficiency as expected (loss of efficiency caused by δ-electrons)
- Drift tube resolution approaching test beam measurements (deviation most likely caused by multiple scattering)

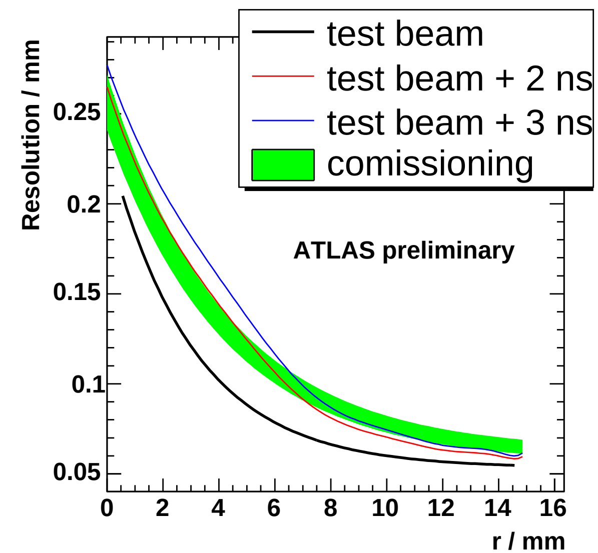
Correlation between RPC and MDT hit



Efficiency of drift tubes



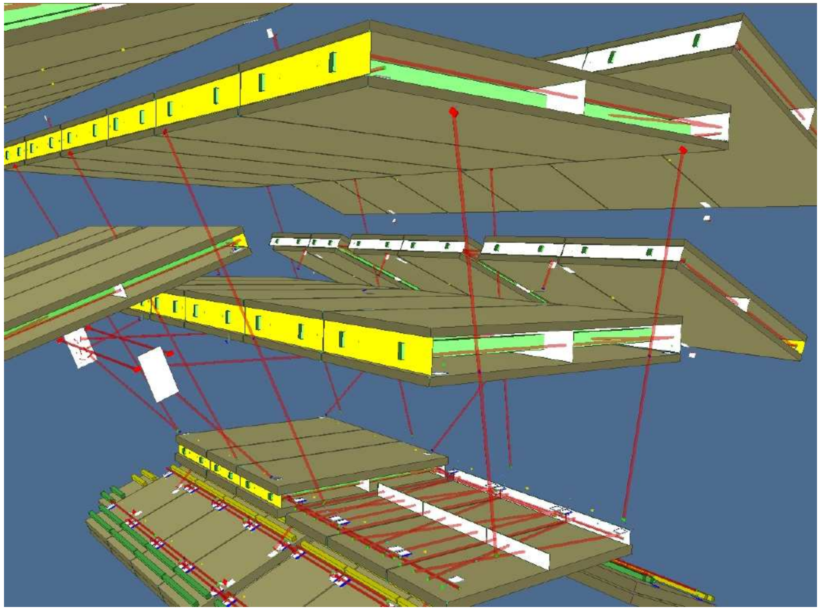
Drift tube resolution from auto-calibration



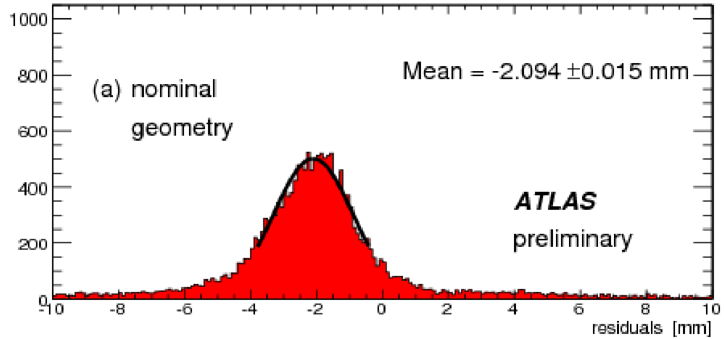
Muon Spectrometer — Results

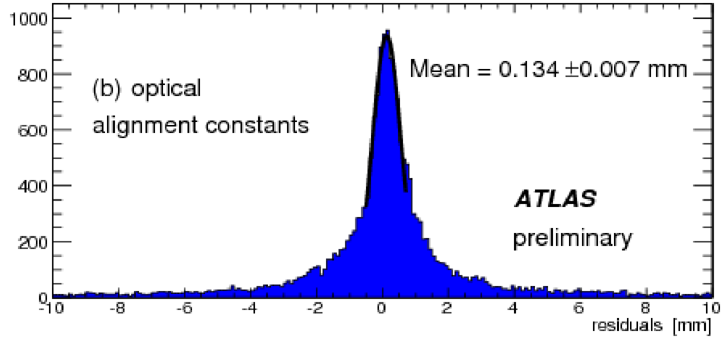
Optical alignment

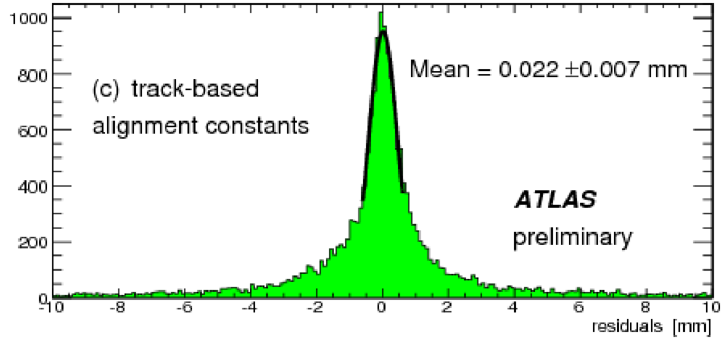
- Goal: precision of 30 μm
- Current precision
  - Endcap: 50–100 μm (absolute meas.)
  - Barrel: 100–200 μm
    up to 1000 μm in sectors with
    no projective alignment sensors
- Absolute barrel alignment with tracks

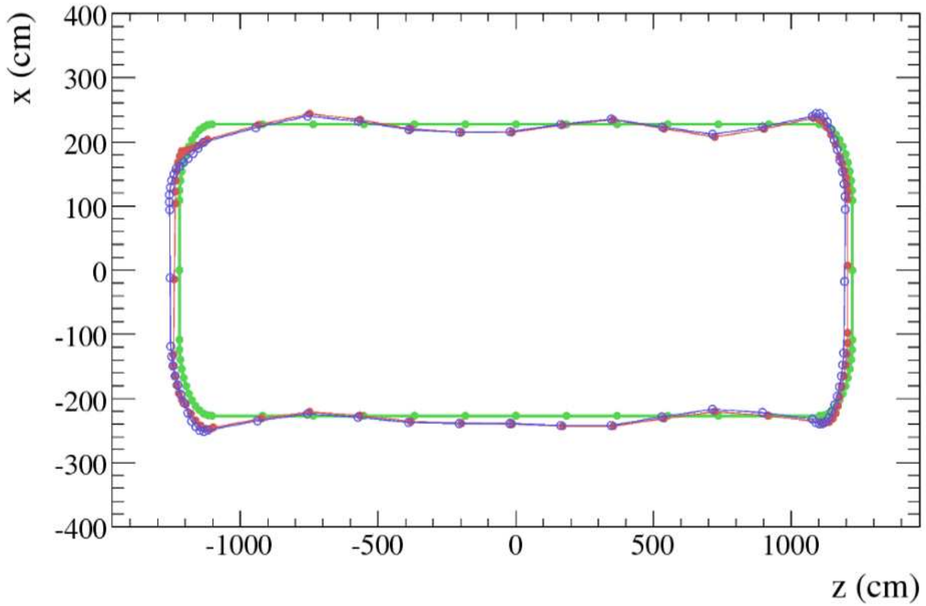


Track sagitta distribution without and with MDT chamber alignment (Barrel)









Nominal coil position

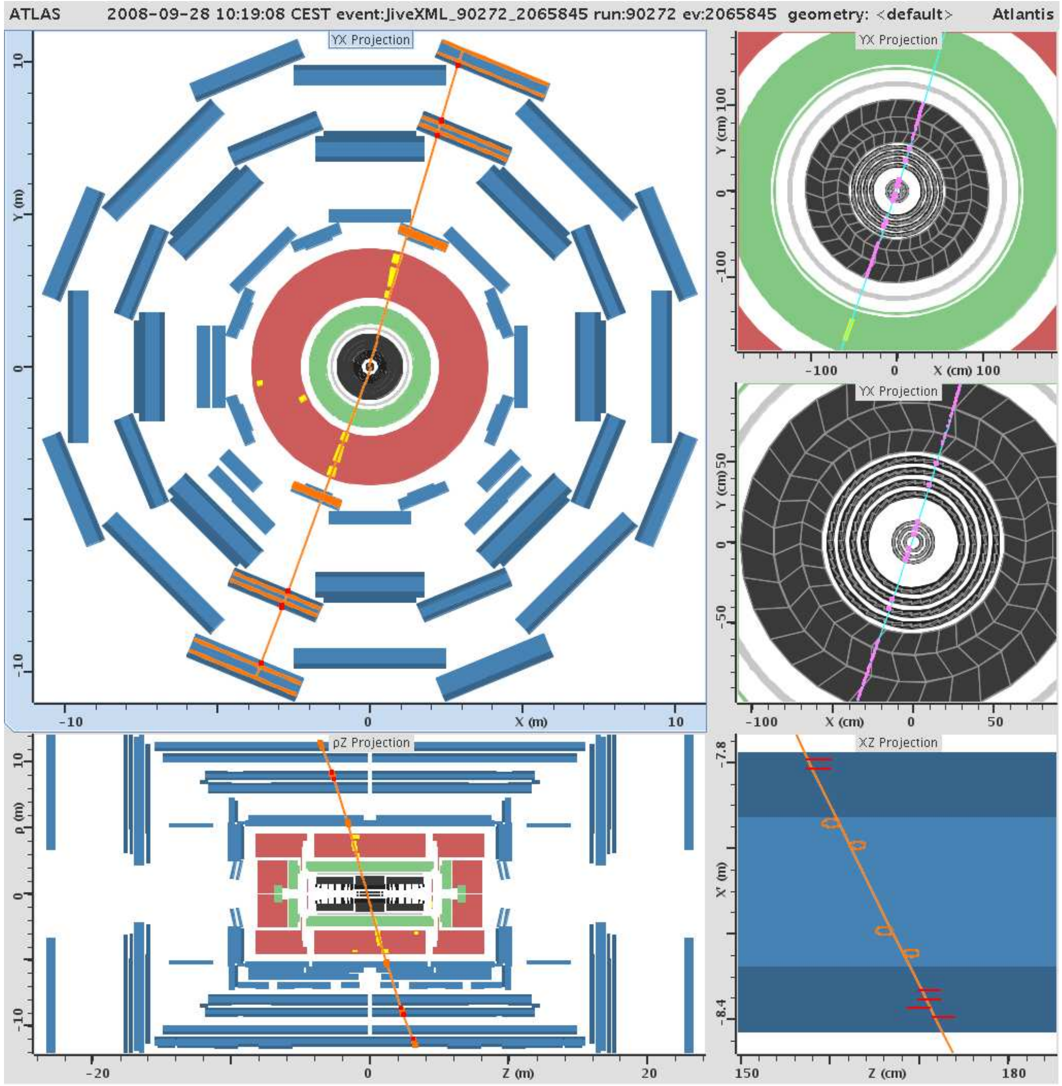
Simulated coil position, deviation × 20

Fitted coil position, deviation × 20

Magnetic field reconstruction

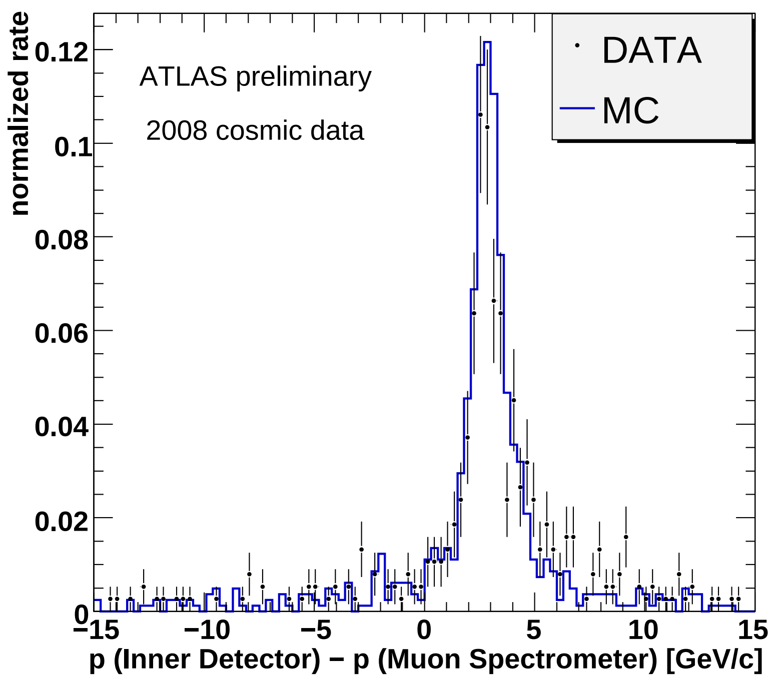
- Goal: 1–2 mT
- 99% of 1834 3d hall probes working
- Reconstruction of coil positions and deformation at the mm level
- Modeling of perturbations (TileCal, feet, access structure, shielding) progressing well
- New field measurements in June 2009
- Est. precision at 1st collisions: 2–10 mT

Combined Studies

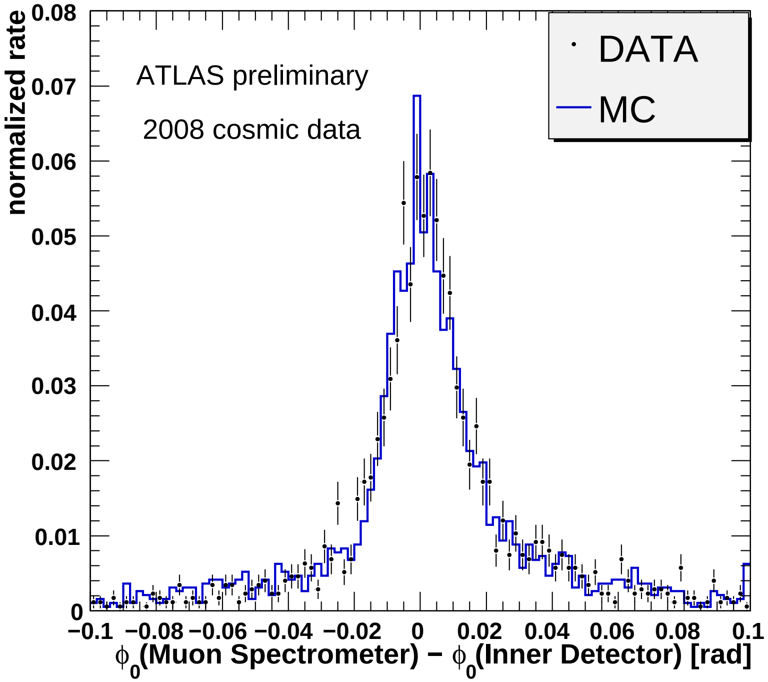


Tracking studies inner detector and muon spectrometer

Muon momentum



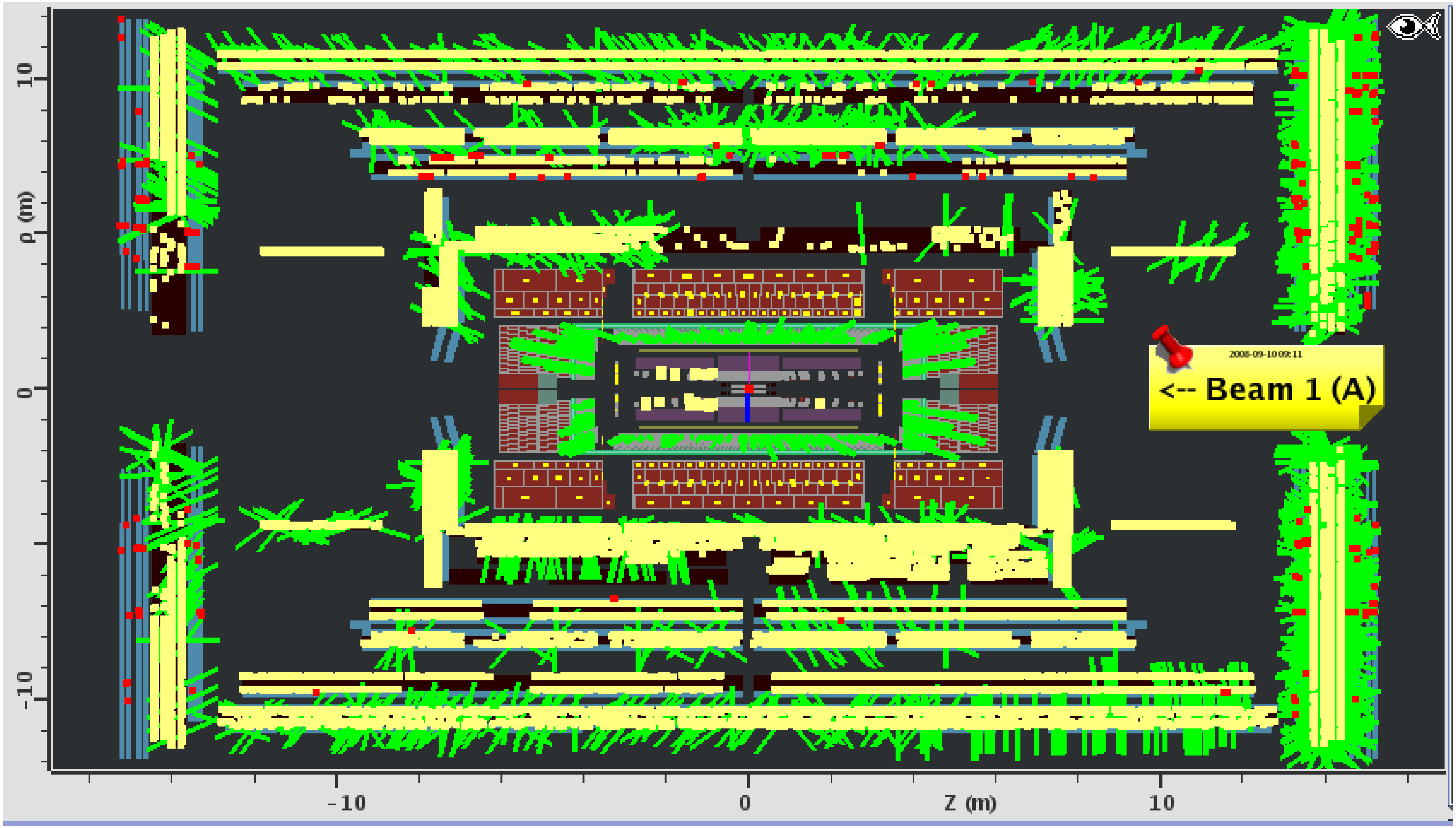
Track angle



Expected shift of 3 GeV from energy loss in calorimeter

Good agreement with Monte Carlo studies — but more work needed

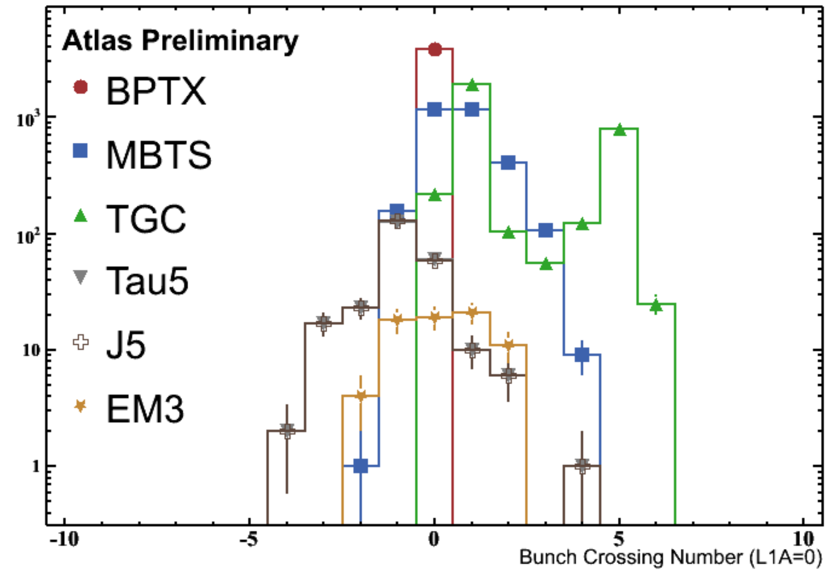
First Beam — September 2008

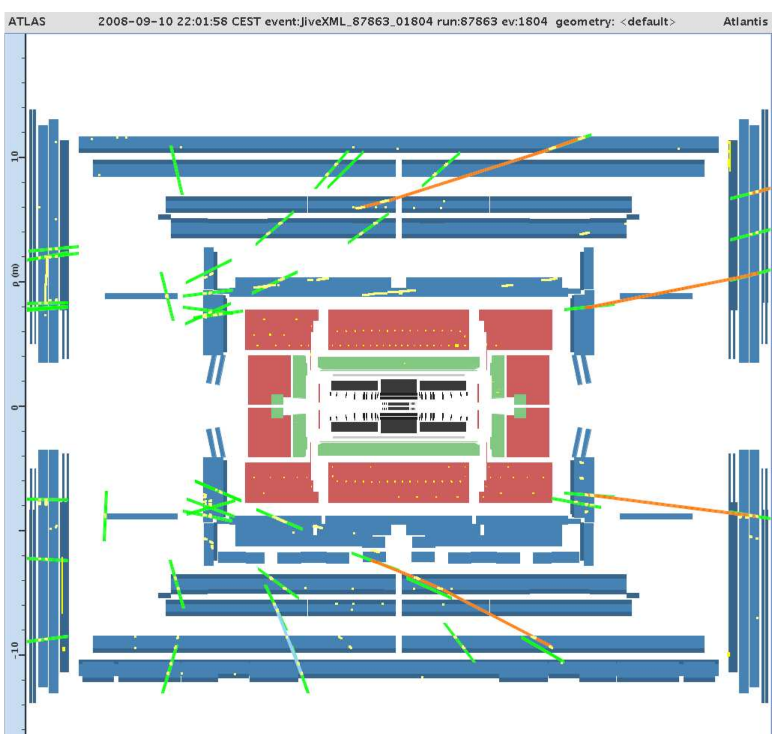


First Beam — September 2008

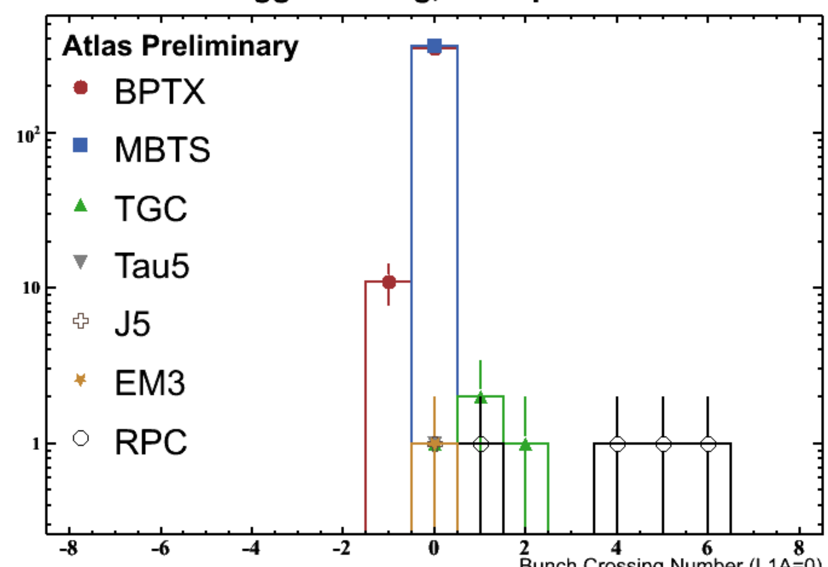
- **Splash events**
  - Beam stopped on closed collimator 140 m in front of ATLAS
  - Several millions of muons and hadrons traversing the detector
- **Beam halo events**
  - Low multiplicity events, interactions with residual gas in beam pipe
  - Used for timing of different L1 trigger sources

Relative Trigger Timing, 10 September





Relative Trigger Timing, 12 September



Conclusions

Conclusions

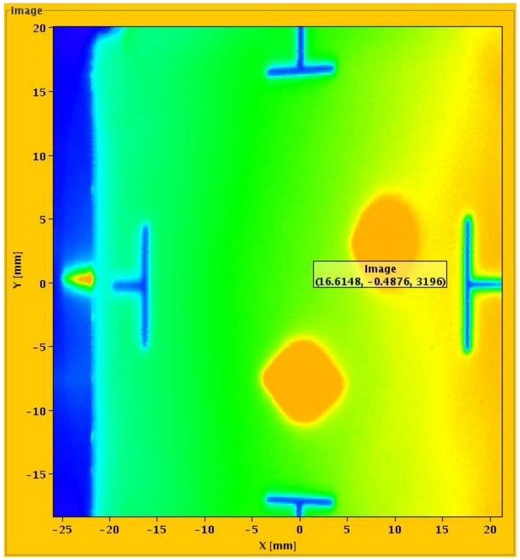
- Commissioning of the ATLAS detector started more than 3 years ago
- Understanding of the detector and its infrastructure is still improving steadily
- Large amount of cosmic data with all subsystems included taken in 2008
  Data taking resumed after winter shutdown and is ongoing
- ATLAS was ready for 1st beam on Sep. 10th
- During shutdown consolidation of the good detector status will allow us to arrive ready for physics with a better detector at LHC re-start

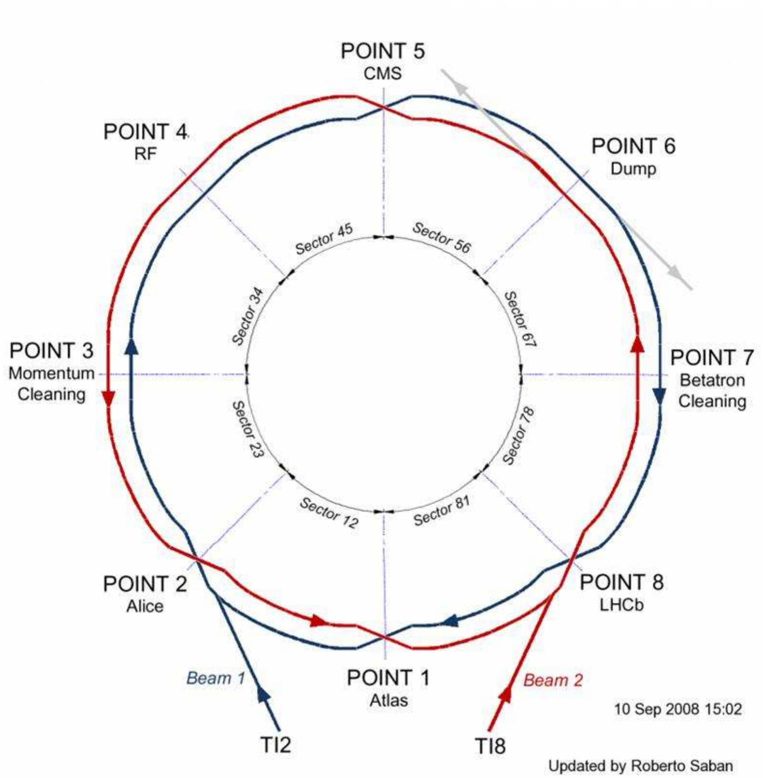
ATLAS is looking forward to 1st collisions in 2009

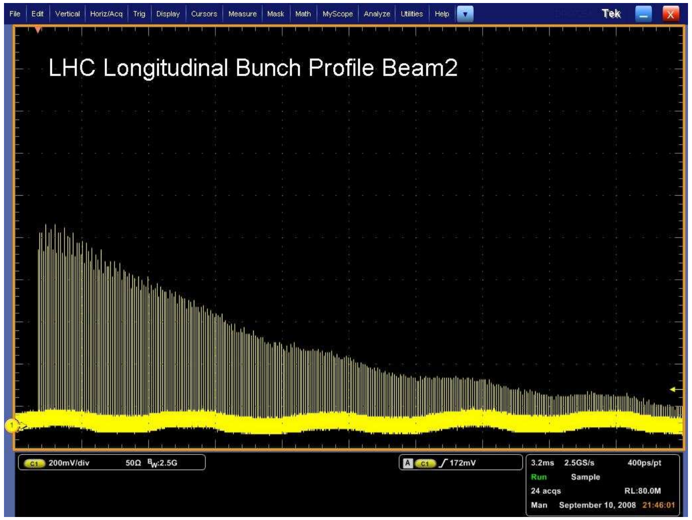
Additional Slides

First LHC operation on September 10th — Single Beams

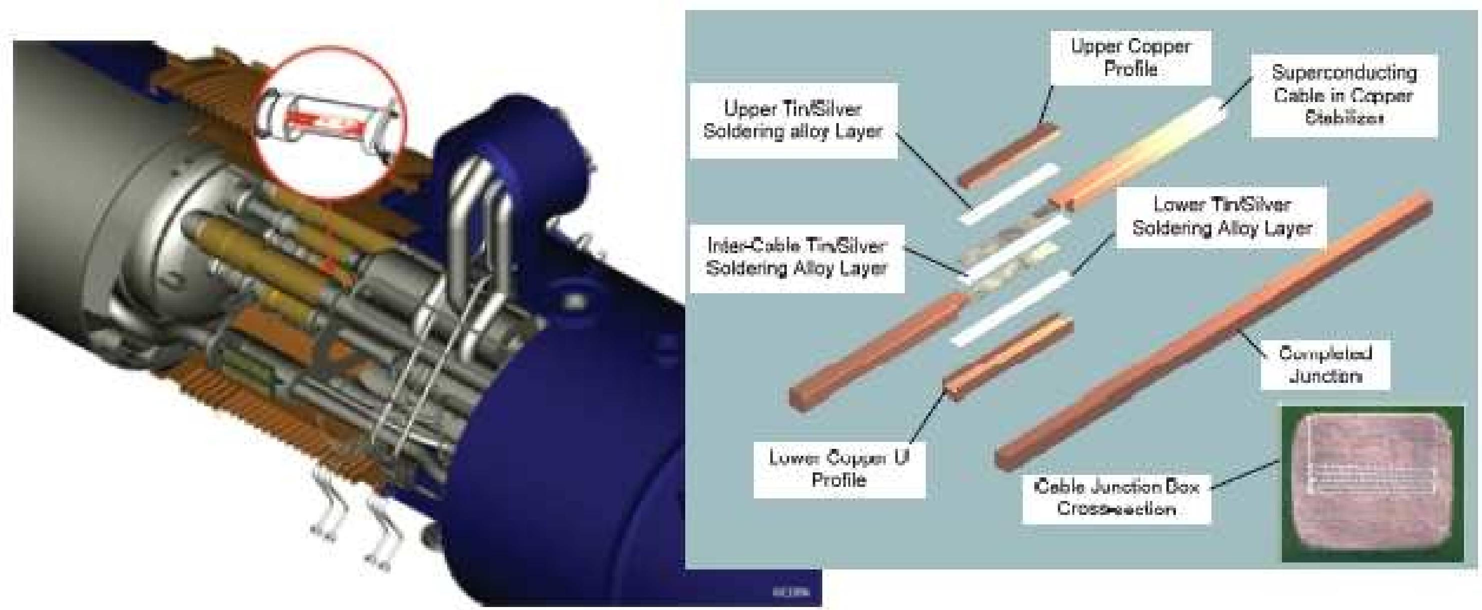
- 10:30: Beam 1 around the ring (in less than 1 h)
- 15:00: Beam 2 around the ring
- Beam 2 circulates hundreds of turns
  450 GeV, 2×10^9 protons (1 bunch)







- Routine power magnet tests in sector 3-4
- Resistive zone appeared at 8.7 kA (5.1 T) in splice between magnets
- Most likely caused an electric arc to punctured the helium enclosure
- Large amounts of helium released (6 t), safety valves could not control pressure
- Shock wave traveling along sector caused collateral damage
  - Displacement of magnets up to 50 cm
  - Superinsulation of magnets damaged
  - Beam pipe broken and contaminated
- 53 magnets to be replaced/repaired



Incident on Sep. 19th, 2008

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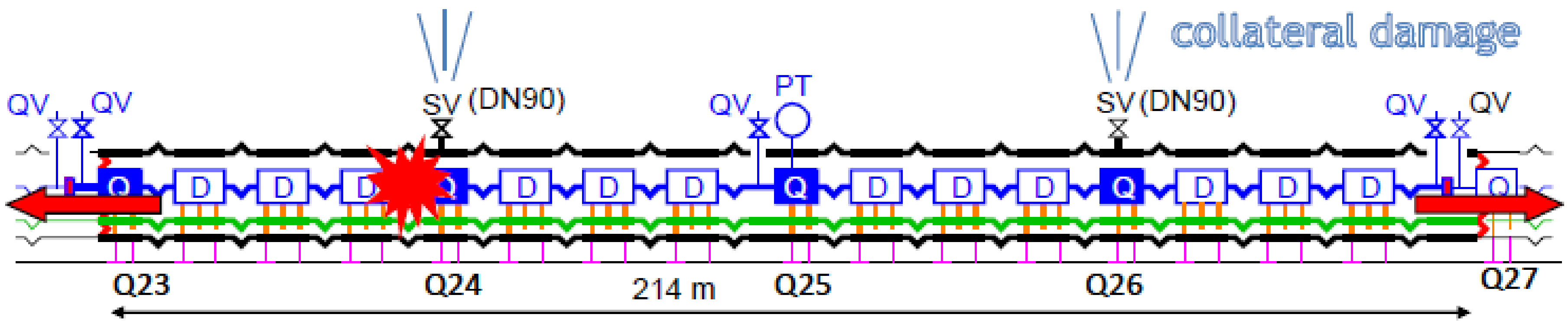

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Current LHC Status

- Last of 53 magnets lowered back into tunnel on April, 30th
- 4 (warm) sectors equipped with extra pressure relief valves
- 4 (cold) sectors equipped with extra pressure relief valves on short straight sections
- Quench protection system upgraded to cover all splices

Aim

- Machine **cold** by end of **August**
- **Ready for beam** injection in late **October**
- Safe beam energy **4–5 TeV**

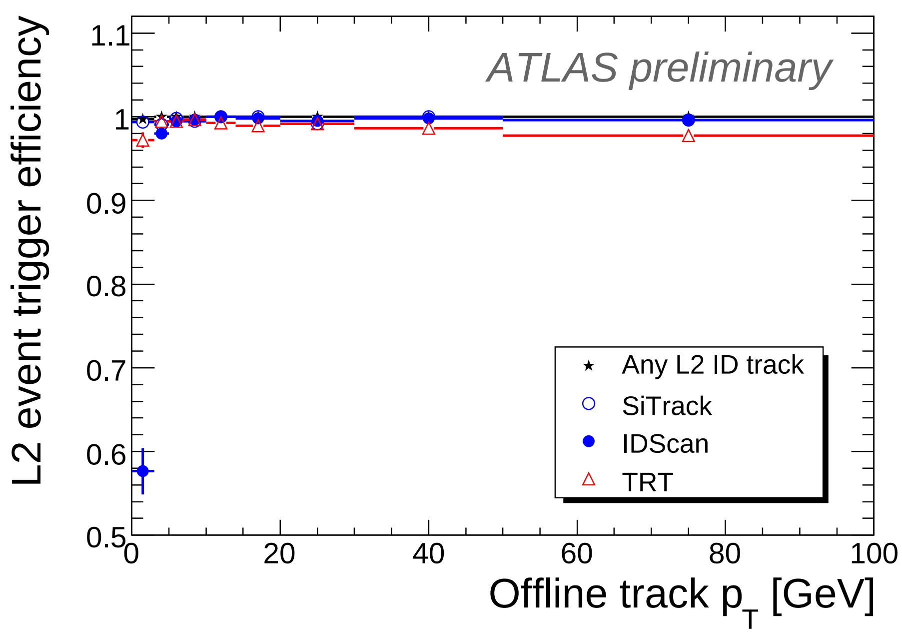
More news on LHC from S. Myers on July, 2nd

Impact on ATLAS schedule: Start of continuous operation beginning of September

High-Level-Trigger — Results

L2 track trigger efficiency

- Inner detector tracks
- Relative to offline reconstructed tracks using one arm of traversing muon track as reference



Muon trigger vs. muon reconstructed

- Event filter muon track parameters compared to offline reconstruction
- Tails due to slightly different configurations online and offline