Commissioning of the ATLAS experiment towards first LHC physics
(Lecture 3)

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Contents and lectures

- What is ATLAS?
- The complete operation chain
- Reconstruction: from raw data to physics input objects

Lecture 1: M.J.Costa

- Track reconstruction and alignment

Lecture 2: S. Martí

- How the full operation chain is being commissioned?
- Results from cosmic rays and LHC single beam analysis
- Strategy towards first LHC physics results

Lecture 3: M.J.Costa

Commissioning of the ATLAS experiment

Commissioning Strategy

- 2 complementary strategies are being followed in parallel in order to put in place different aspects of the chain:

Real data:

Operate the ATLAS detector to collect data from:

- Cosmic rays (since 2005)
- LHC single beam operations (3 days Sep 2008)

Real data → Useful to:

- Commission the full operation chain (TAQ, monitoring, alignment & calibration, reconstruction, computing, analysis)
- Gain experience in operating the detector (from TDAQ up to analysis in the GRID)
- Get to know the detector
- Provide first alignment and calibration constants
- Measure the detector performance from data
- First tuning of simulation to reproduce data

Simulation:

Several data challenges of increasing functionalities, size and realism. Examples:

- Computing System Commissioning CSC 2007 @ 14 TeV
- Calibration Data Challenge CDC 2007 @ 14 TeV
- Full Dress Rehearsal 2008 @ 14 TeV
- MC08 @ 10 TeV
- MC09 @ 10 TeV
- TDAQ Technical Runs

LHC like collisions data → Useful to:

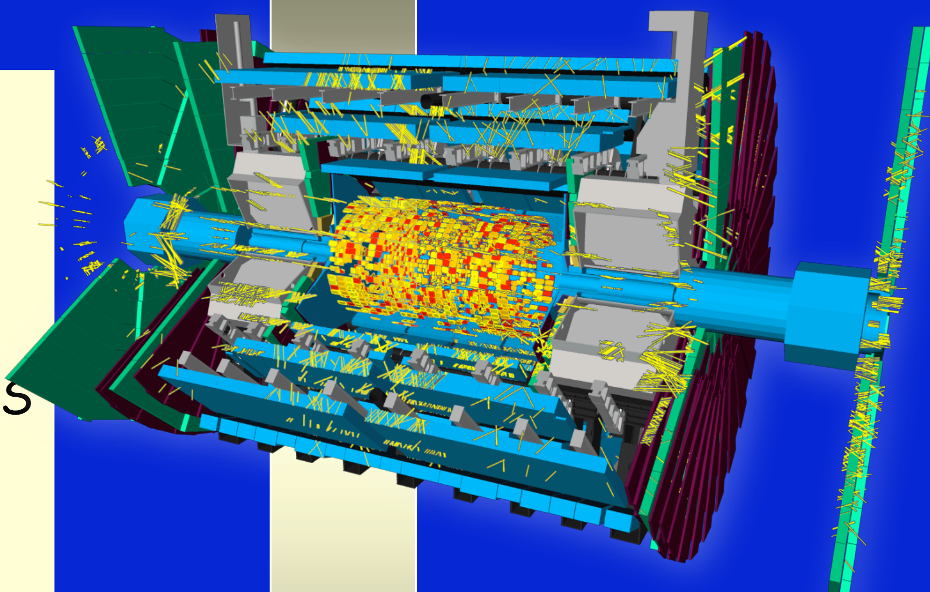
- test the complete analysis model
- test the computing model
- study expected detector performance and physics potential
- test reconstruction, calibrations & alignment
- develop methods to measure performance from data
- improve physics analysis

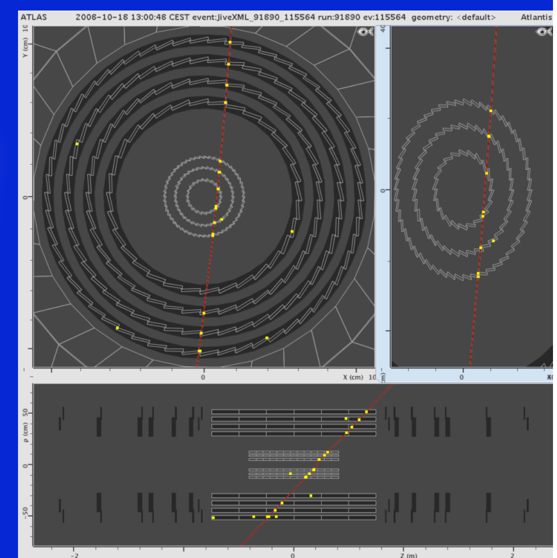
Data taking from 2005 to 2008

Cosmic rays

LHC single beam 10-12 Sept

Cosmic rays





• Cosmic rays were taken with different detector and magnet configurations as systems were ready.
• In July 2008 ATLAS entered in a semi-continuous operation mode.

Data from the 2008 combined run and LHC single beam have been re-processed @ Tier1s and analised in detailed (second part of this lecture)

Global Combined Cosmic run

July August September October November December

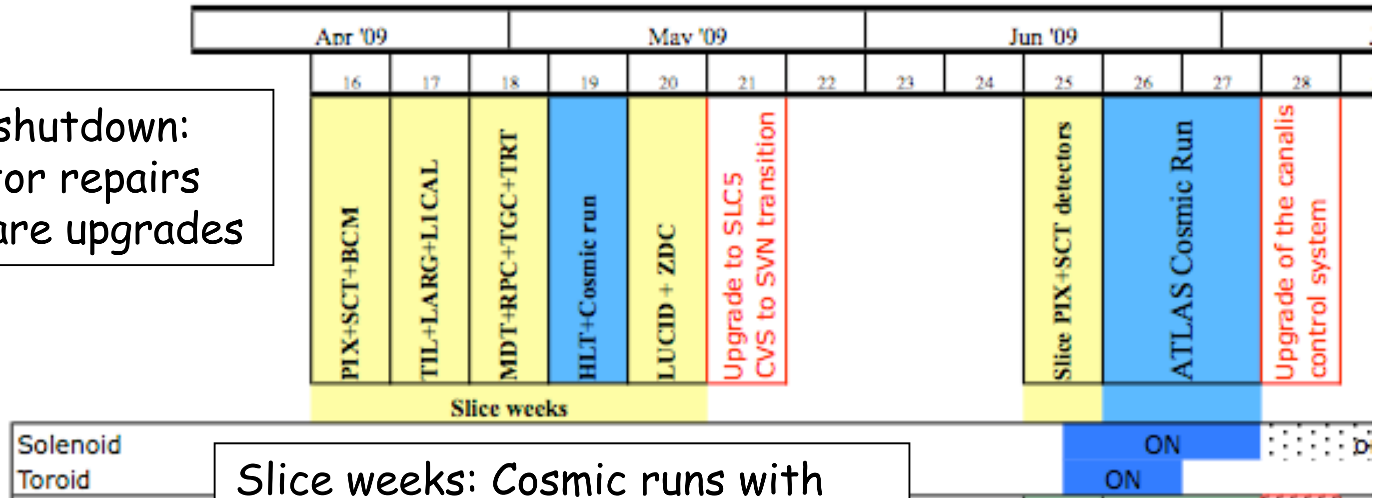
Shutdown winter 2008-2009

- The winter shutdown was well profited to repair problems detected during 2008

Present status of the ATLAS detector

Sub-detector	N. of channels	Fraction of working detector (%)
Pixels	80×10^6	98.5
Silicon strip detector (SCT)	6×10^6	~99.5
Transition Radiation Tracker (TRT)	3.5×10^5	98.2
LAr electromagnetic calorimeter	1.7×10^5	99.5
Fe/scintillator (Tilecal) calorimeter	9800	~99.5
Hadronic end-cap LAr calorimeter	5600	99.9
Forward LAr calorimeter	3500	100
Muon Drift Tube chambers (MDT)	3.5×10^5	99.3
Barrel muon trigger chambers (RPC)	3.7×10^5	~ 95.5 (aim: > 98.5 by first beams)
End-cap muon trigger chambers (TGC)	3.2×10^5	> 99.5

Data taking in 2009

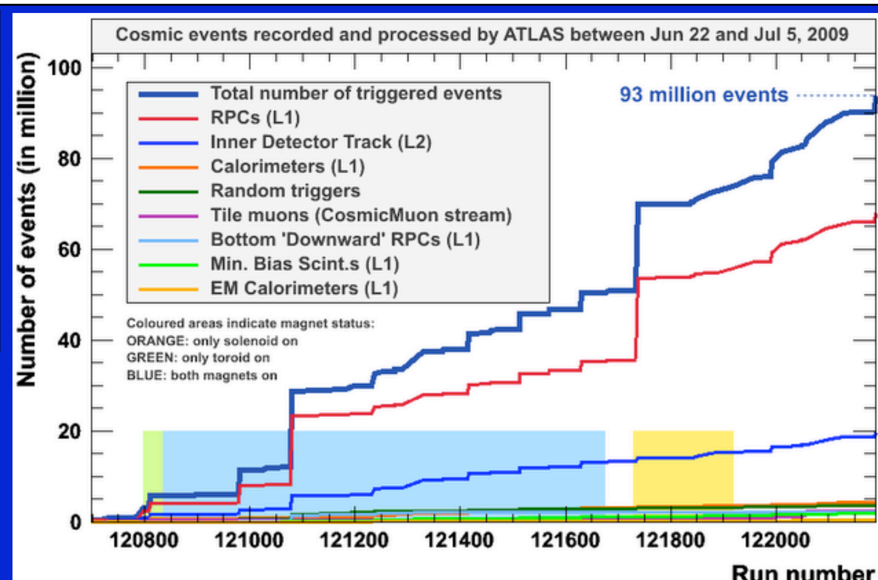


ATLAS shutdown:
- Detector repairs
- Software upgrades

Slice weeks: Cosmic runs with different sub-systems

ATLAS Combined Cosmic Run

Overall data taking efficiency: already ~ 83% during the 2008 Combined Cosmic Run (1-6 July 2009).
Calculated over 6-14 hour long simulated LHC stores



A detailed schedule of cosmic rays data taking from now to mid November (LHC)
ATLAS will enter in a continuous operation mode well in advance the first LHC beams

Data challenges with simulation

- Simulated data always comes before real data, so these challenges have been done for a longer time.
- The most recent ones are:
  - Computing System Commissioning CSC, @ 14 TeV (2007)
  - Calibration Data Challenge CDC, @ 14 TeV (2007)
  - Full Dress Rehearsal FDR, @ 14 TeV (2008)
  - MC08 @ 10 TeV (2008-2009)
  - MC09 @ 10 TeV (2009)
  - Scale Testing for Experiments Program STEP09

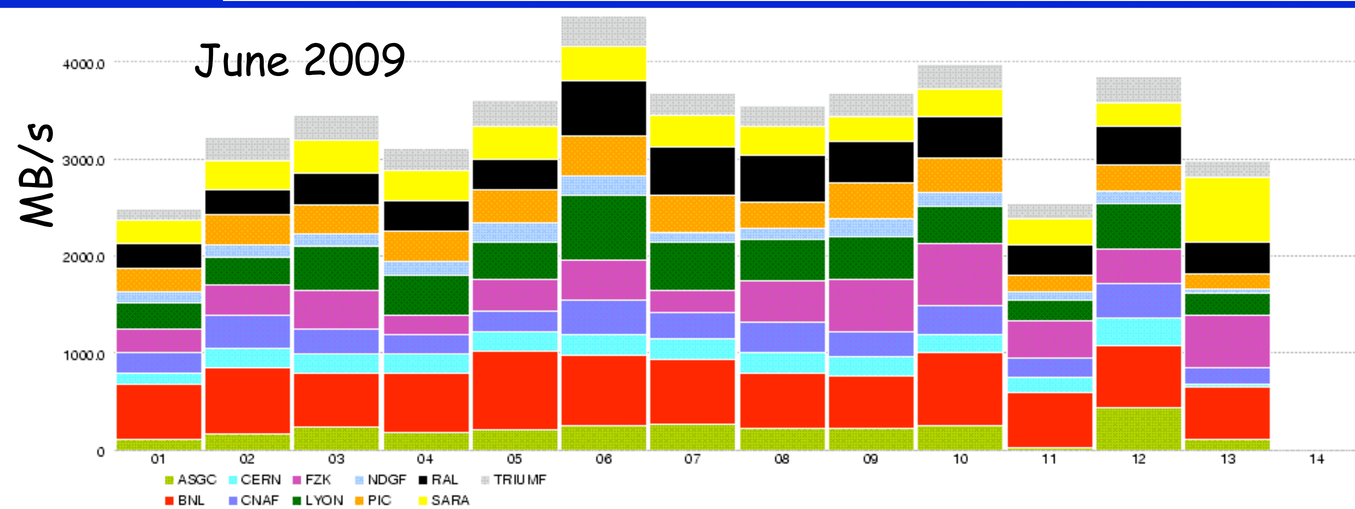
• Obviously, no time to cover all of them
• The last part of this Lecture (Strategy towards first LHC physics results) will cover part of the performance and physics studies done with these data.
→ So just a few words about STEP09 and FDR

Scale testing for experiment program 2009

An offline commissioning computing test done with other LHC experiments:

- Monte Carlo Production: 12 M events
- Full chain data distribution: 4PB
- Re-processing @ Tier1's centers
- User analysis challenge: ~1M analysis jobs

Data transfer Tier0→ Tier-1s and Tier-1s → Tier-2s
Higher peak rate than nominal (1-2 GB/s at LHC) sustained over 2 weeks

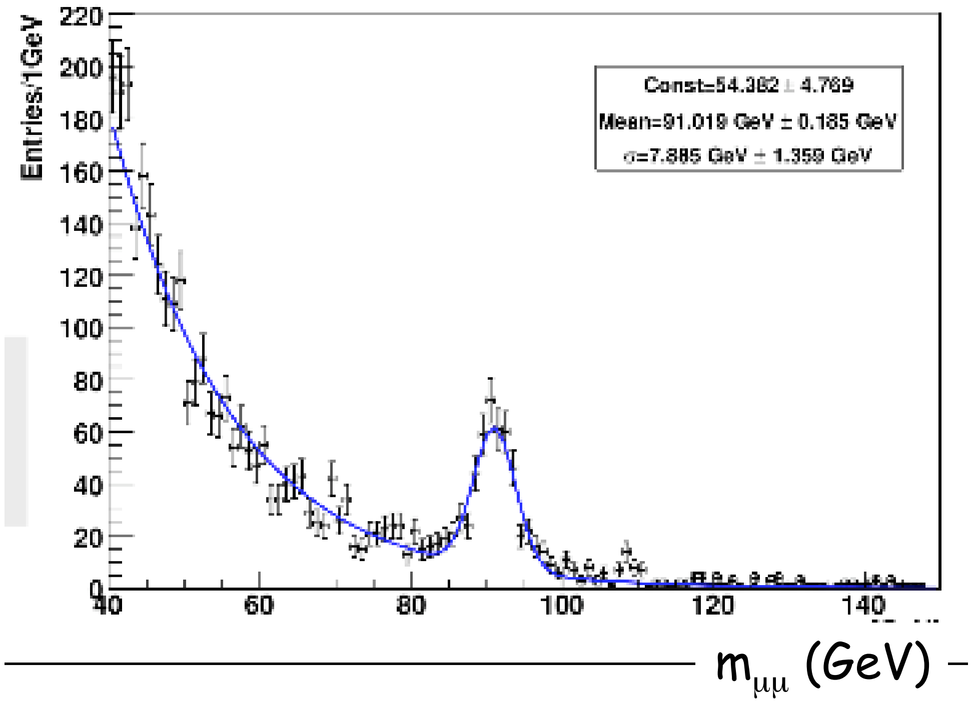


Full Dress Rehearsal

Realistic test of the processing chain from online to physics analysis including all major steps:

- exercise full software infrastructure
- perform calibration and alignment in 24 hours and provide data monitoring
- provide sample for emulation of early physics data

Example of di-muon mass plot after 5 days of "data taking"

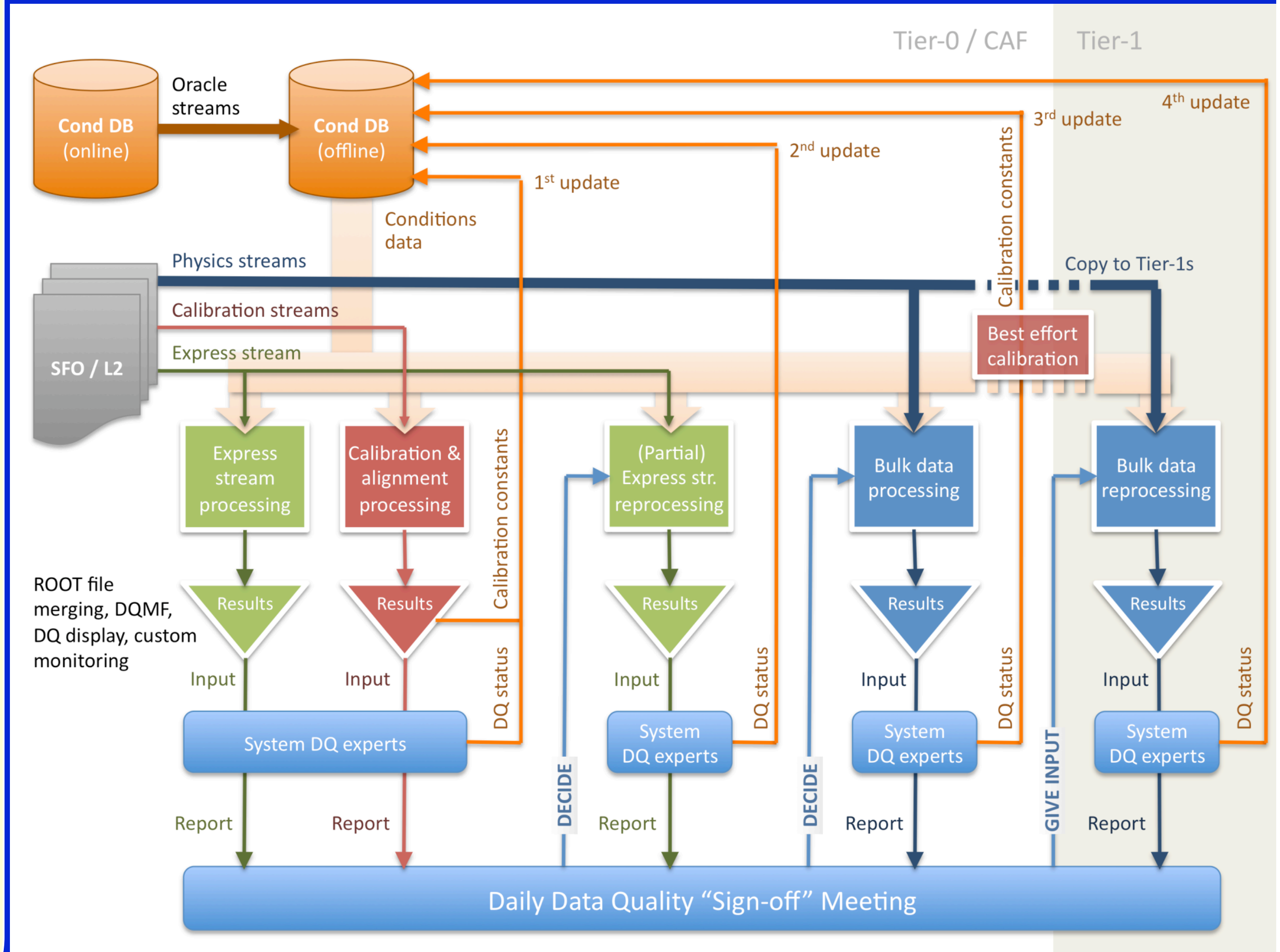


Full Dress Rehearsal

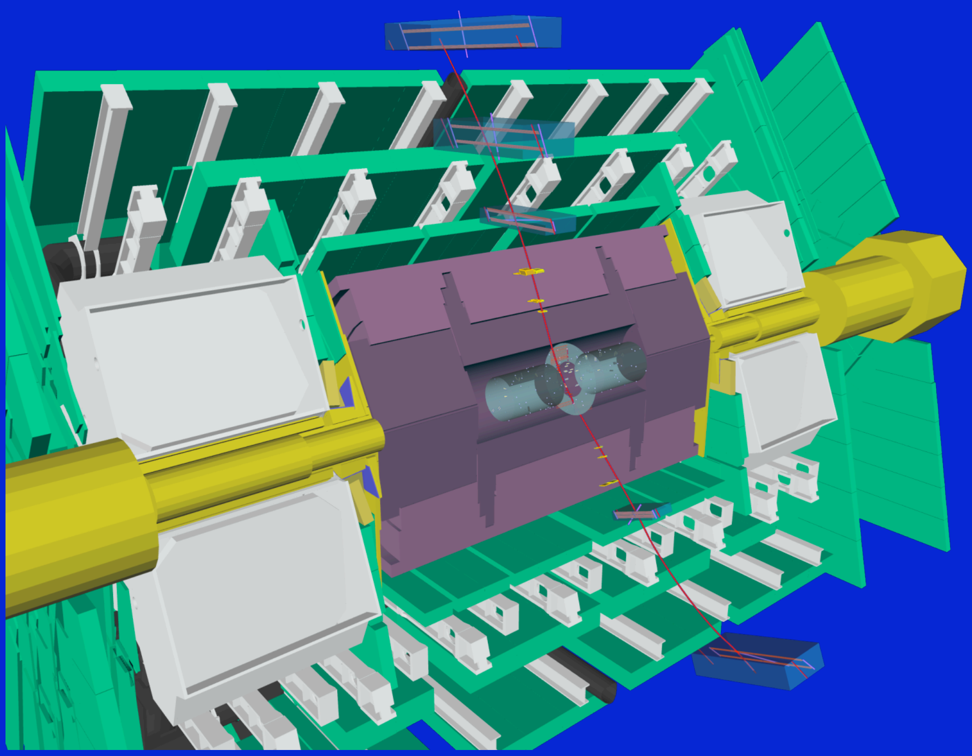
STEPS FOLLOWED

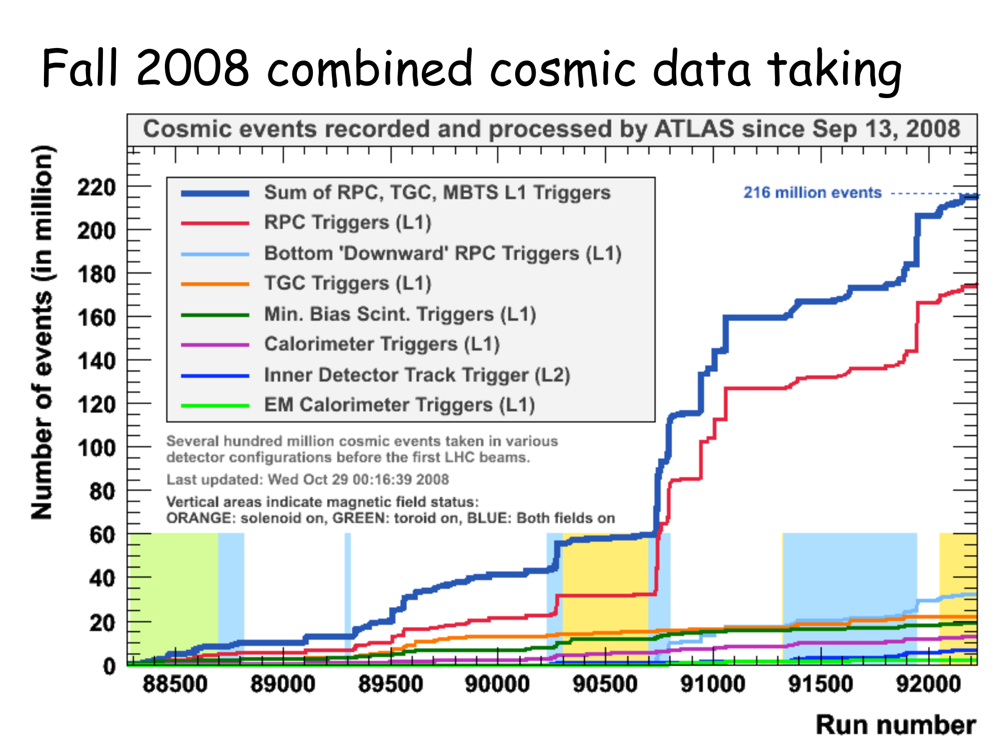
- Mix simulated event samples quasi-realistic compositions intro raw data streams
- Pre-load output buffers of online farm (SFO), copy to Tier0 (300MB/s)
- Process express stream @ Tier0 as data comes in and apply data quality monitoring
- Run calibration & alignment tasks @ calibration centers
- Sign-off and run bulk data reconstruction @ Tier0
- Distribute output to Tier1s and Tier2s
- Re-process data @ Tier1s
- Perform user analyses @ Tier2s or Tier3s

How a few hours of ATLAS typical running @ LHC L= 10^{31-32} $cm^{-2}s^{-1}$ were emulated?

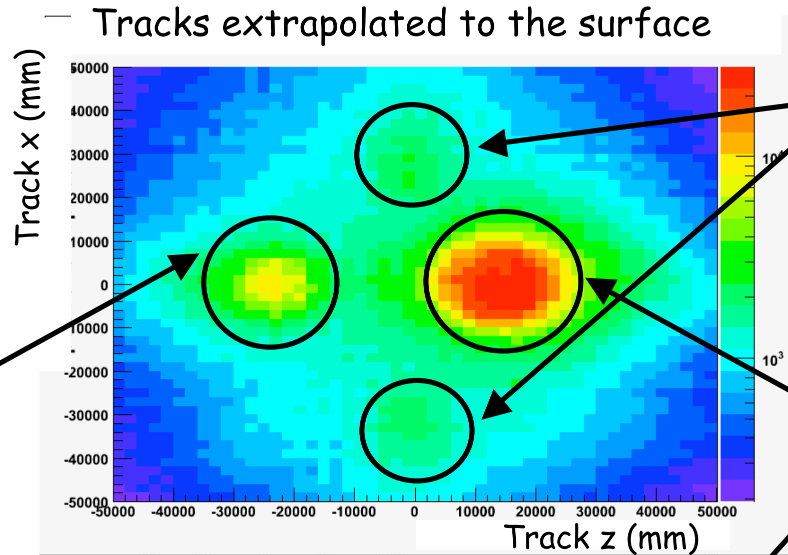


Results of cosmic rays analysis
(based on data from the 2008 combined run)





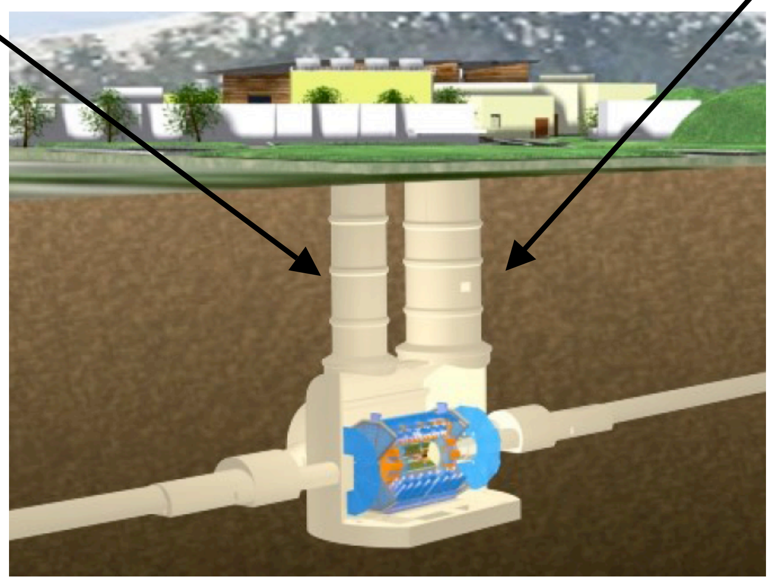
Where do most events come from?



Elevators

Small shaft

Big shaft



As expected, most of the comic muons seen by ATLAS are entering through the cavern access shafts and elevators
→A simple and nice cross check that the full operation chain is working!!!!
What can we learn from them useful towards LHC physics?

What we can learn towards LHC physics

- Are the detectors OK? i.e. within the required (imposed by physics) specifications?
  - Efficiencies
  - Noise
  - Number of operating channels

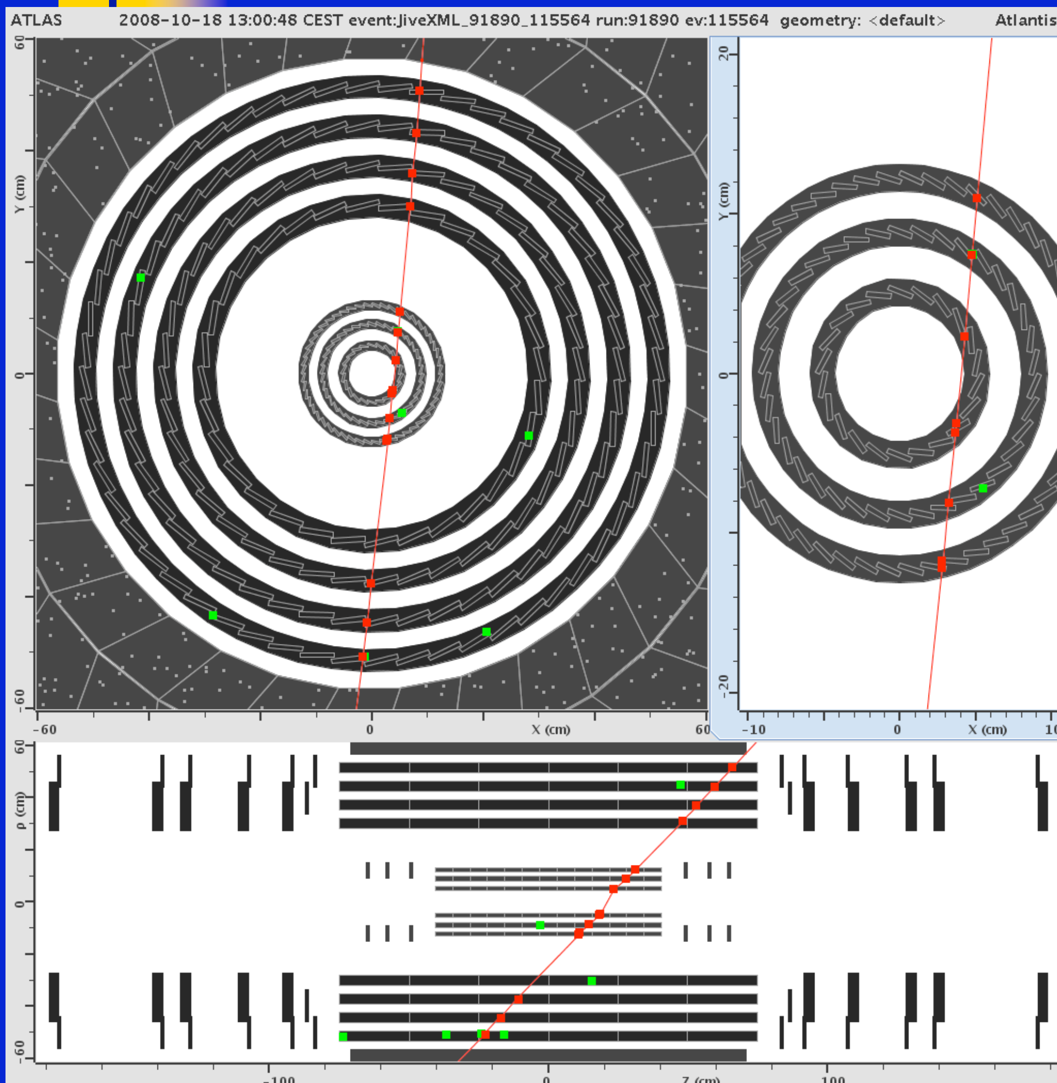
Keep in mind that all this was tested during construction and in test beams, but is it still the case after installation in the cavern?

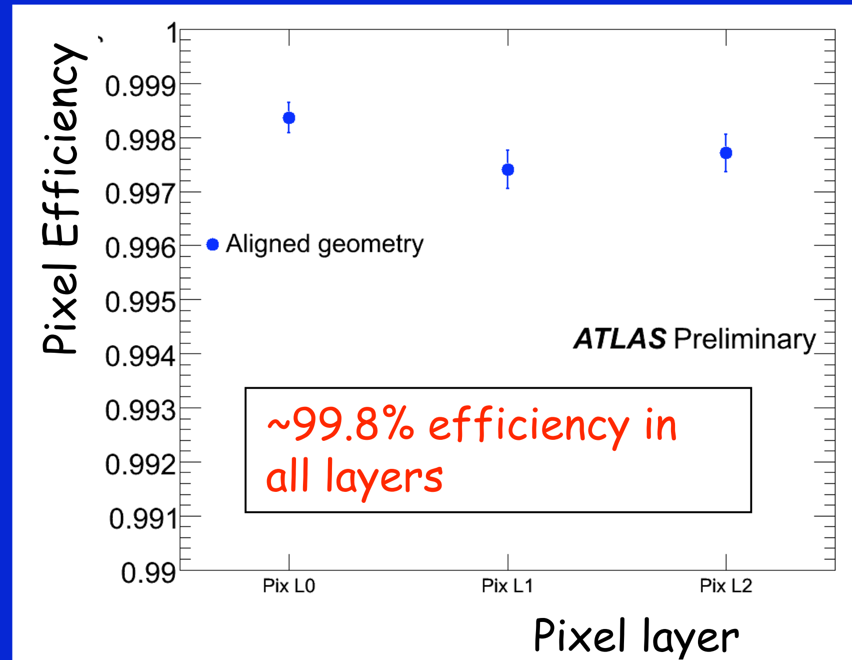
- Is the reconstruction OK?
  - Tracking, energy reconstruction, muon identification & reconstruction, etc
  - Measure its performance from data
- Can we try to align and calibrate the detectors with these kind of events?
  - The physics we want to do imposes very challenging requirements in terms of knowing well the position of the detector and their calibrations
  - To reach the required precision we will have to wait for collisions data, but what can already be done?
- Tune the Monte Carlo to reproduce well the data
- Cosmic rays are now our signal but once LHC starts operation it will be the background → Get to know the background and how to reject it!

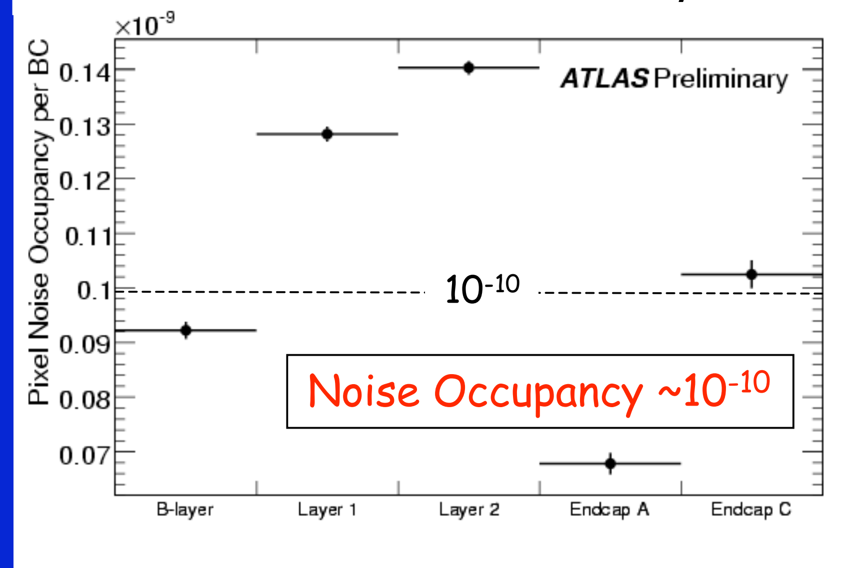
ATLAS is seriously focusing on the understanding of the detector performance making use of the collected cosmic rays data
I can only show here a few examples of each of these 5 mentioned essential topics

Are the detectors ok?

Ex: Pixel detector







The detector is well within specifications

Is the reconstruction ok?

Ex: Tracking

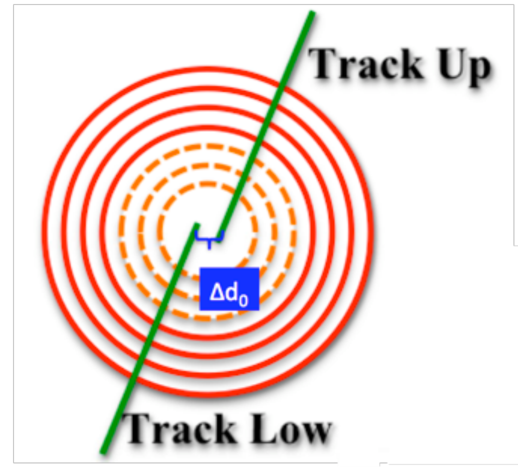
ESTIMATION OF TRACKING PERFORMANCE FROM DATA

Cosmic tracks cross both the upper and bottom hemispheres of the detector →

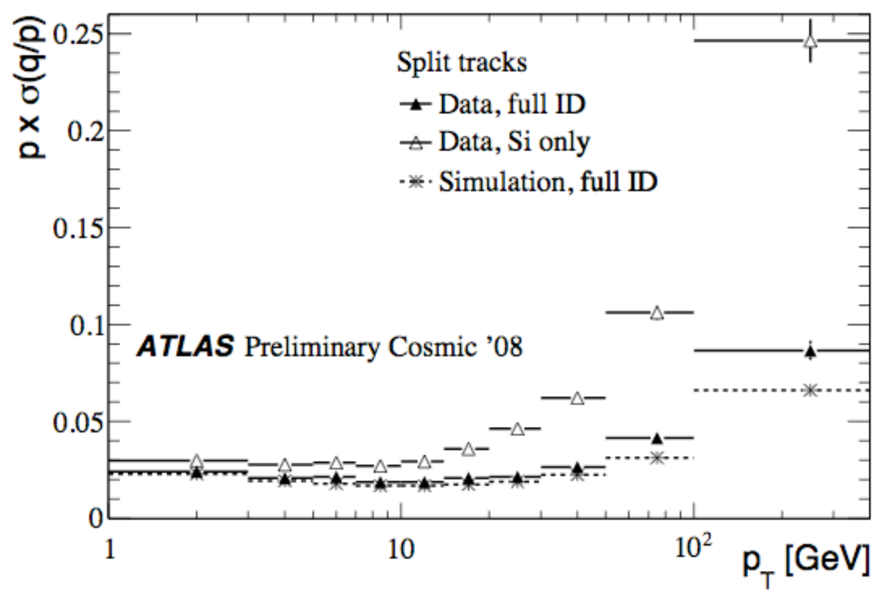
<u>Method:</u>

• Split tracks in the center and re-fit each individually
• Look at the difference of the track parameters of both track (μ,σ)

→ Obtain biases and resolutions



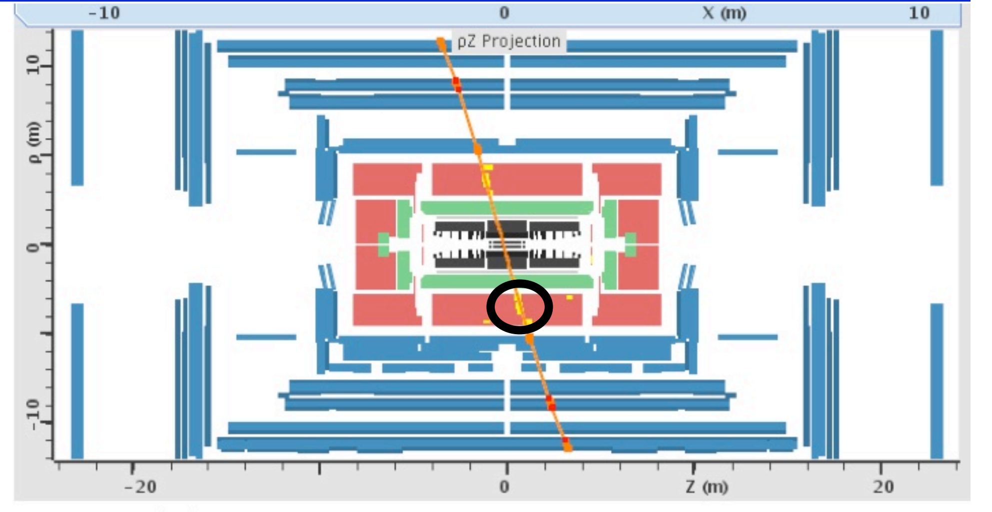
Momentum resolution

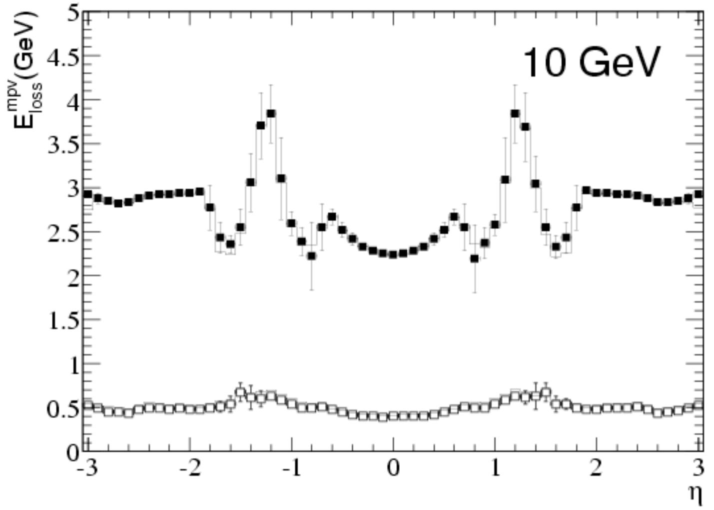


Is the reconstruction ok?

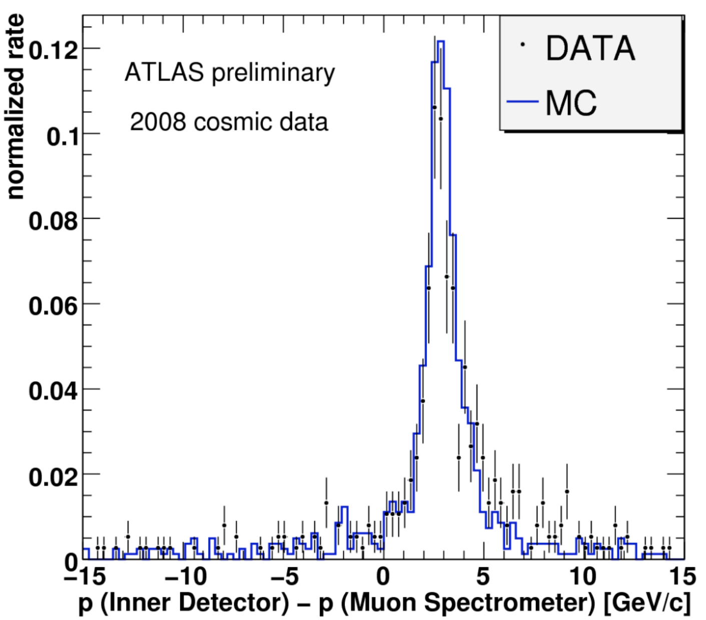
Ex: Tracking in the Inner Detector and Muon Spectrometer

The difference between the momentum measured by the Inner Detector and the one measured by the Muon Spectrometer should correspond to the energy deposited in the material in between (mostly calorimeters) → a peak ~3 GeV is obtained as expected!





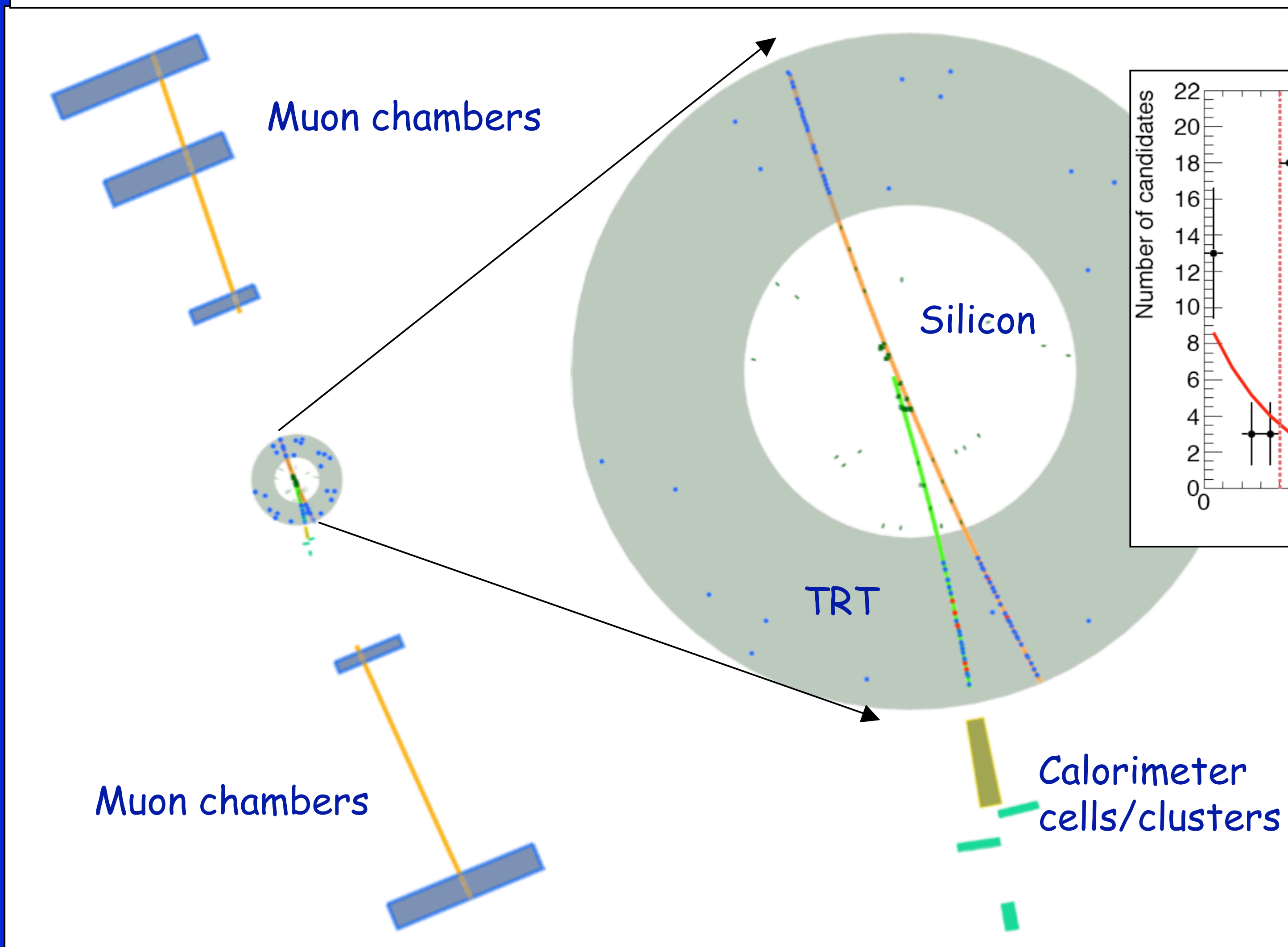
MPV of E loss by a 10 GeV muon from the beam pipe to the exit of the calorimeter given by GEANT4

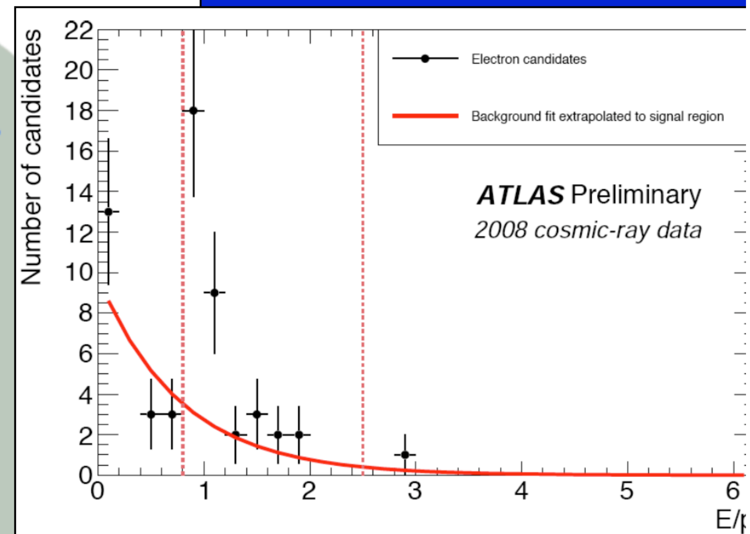


Is the reconstruction ok?

Ex: electron

Event display of one of the electron candidates, recorded on 28/9/2008



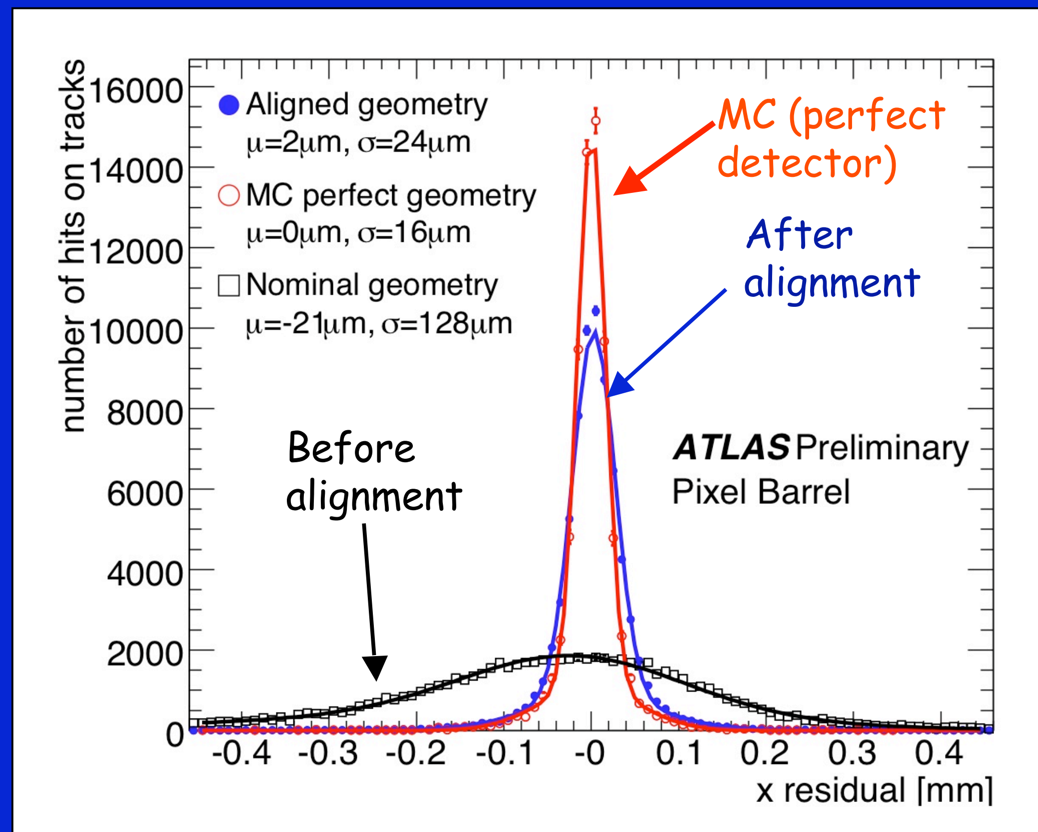


First electrons observed in ATLAS: from ionization of cosmics muons

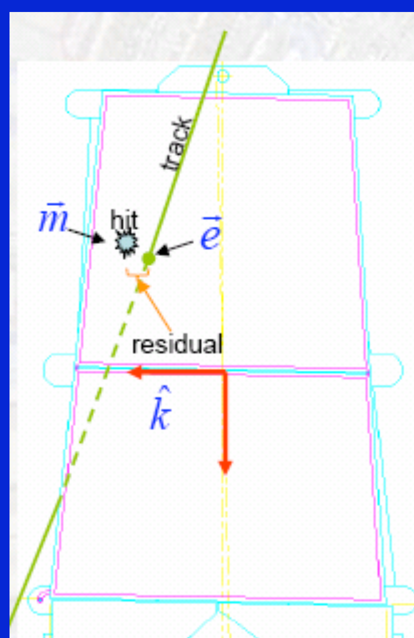
Can we try to align and calibrate?

Ex: Inner Detector Alignment

- The position of the modules has to be known extremely well for physics @ LHC (e.g. a precise measurement of the W mass)
- Cosmic tracks have been used to obtain a first alignment of the inner detector



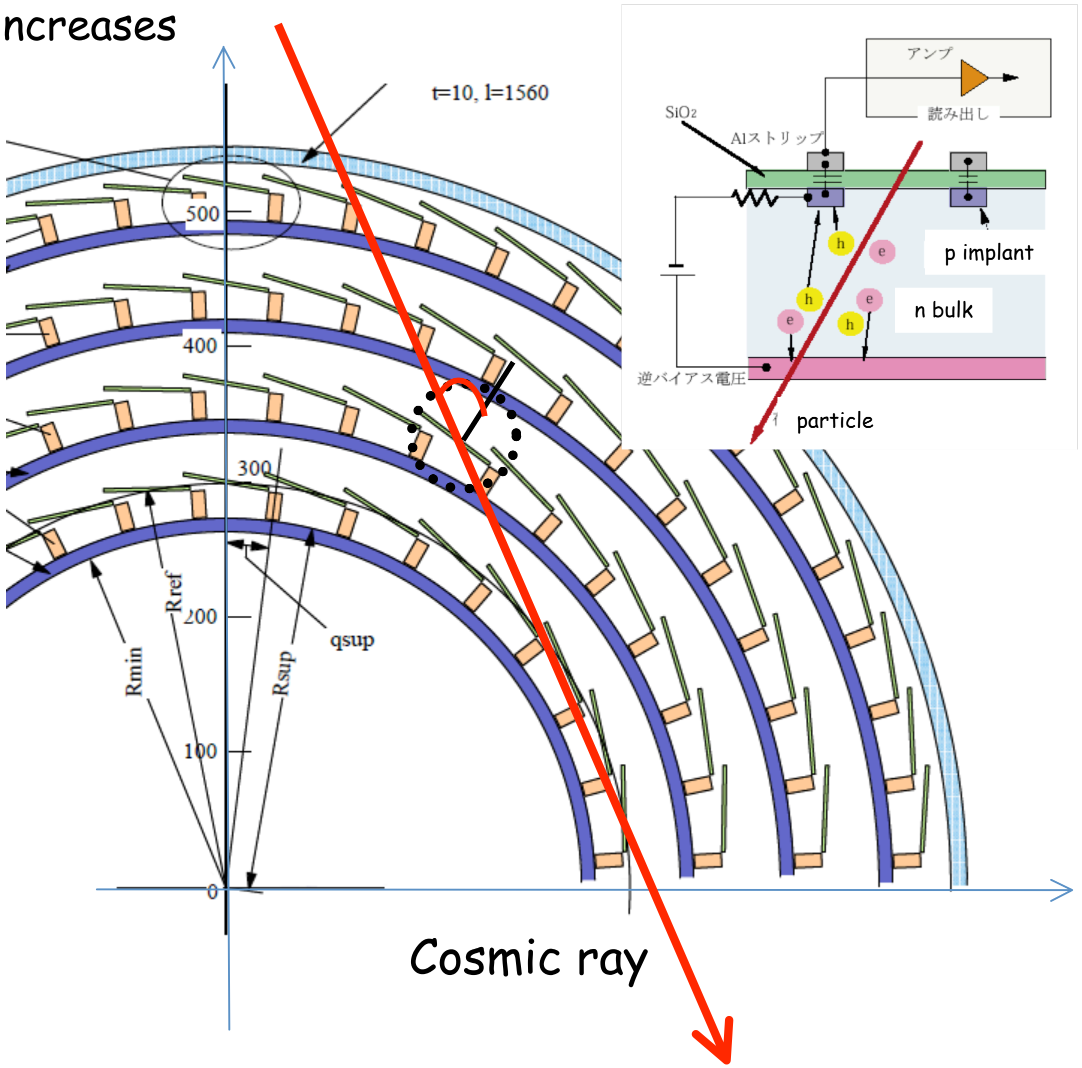
A precision ~ 20 μm has been reached for the Silicon detectors (ultimate goal 5-10 μm)

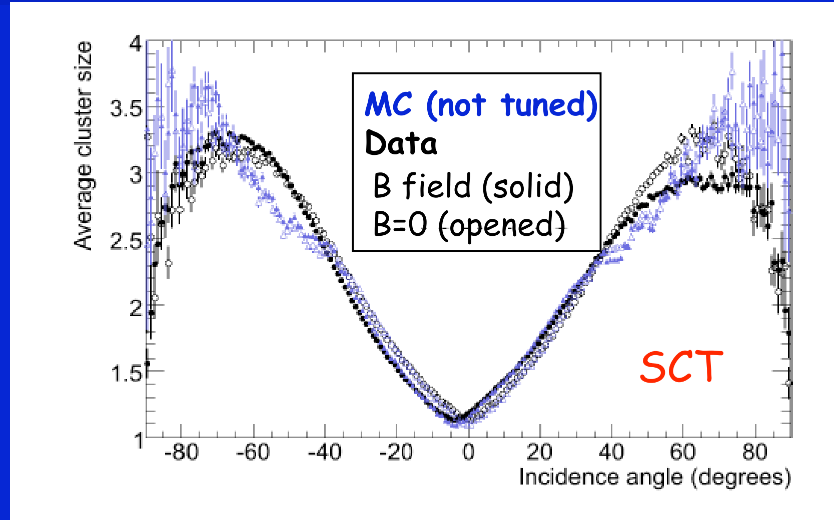


Tuning the Monte Carlo

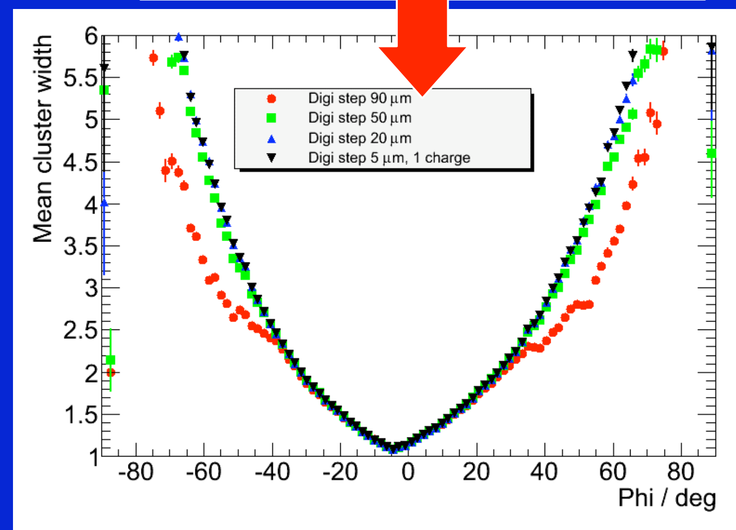
Ex: SCT cluster width

Cosmic rays can traverse the SCT modules with large incident angles → cluster width (#strips with signal) increases





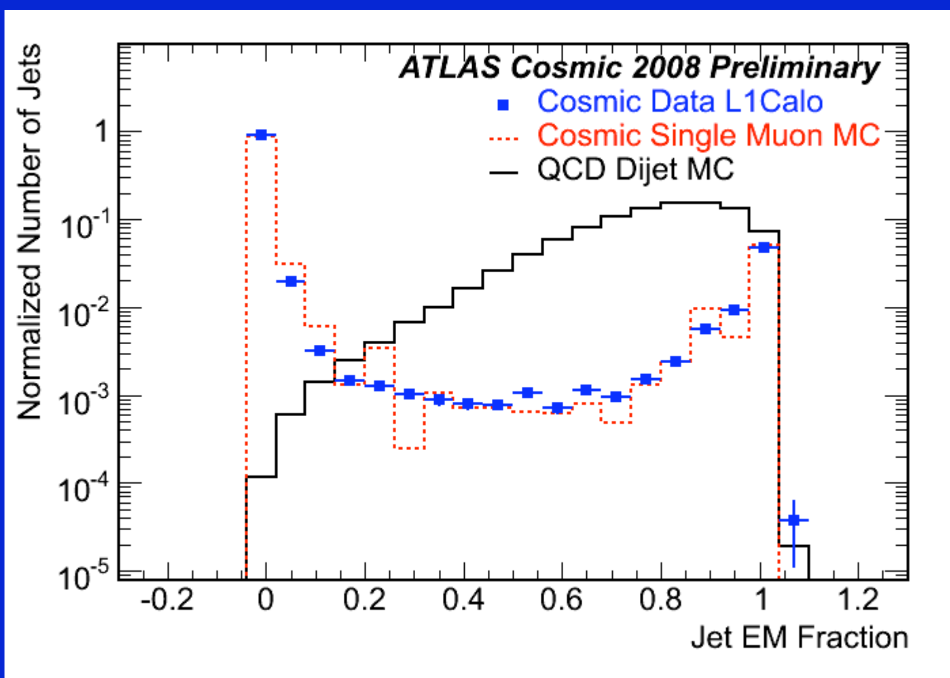
Data/MC discrepancies can be cured by tuning the model that emulates the electronics



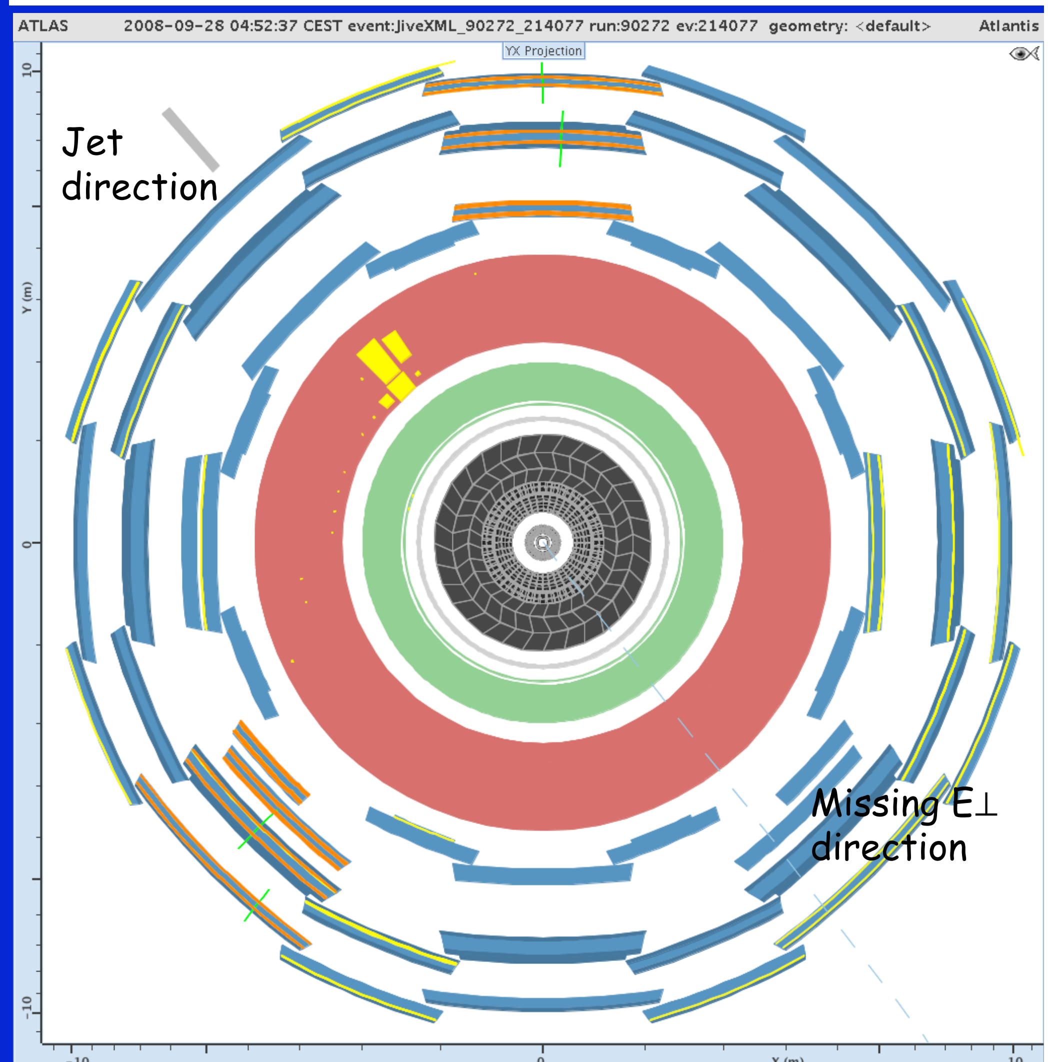
Get to know physics background

- Jets and high missing $E_\perp$ can originate from high energy cosmic muons passing through the calorimeters →

Cleaning cuts have been found to reject cosmic events, checking that MC reproduces well the data

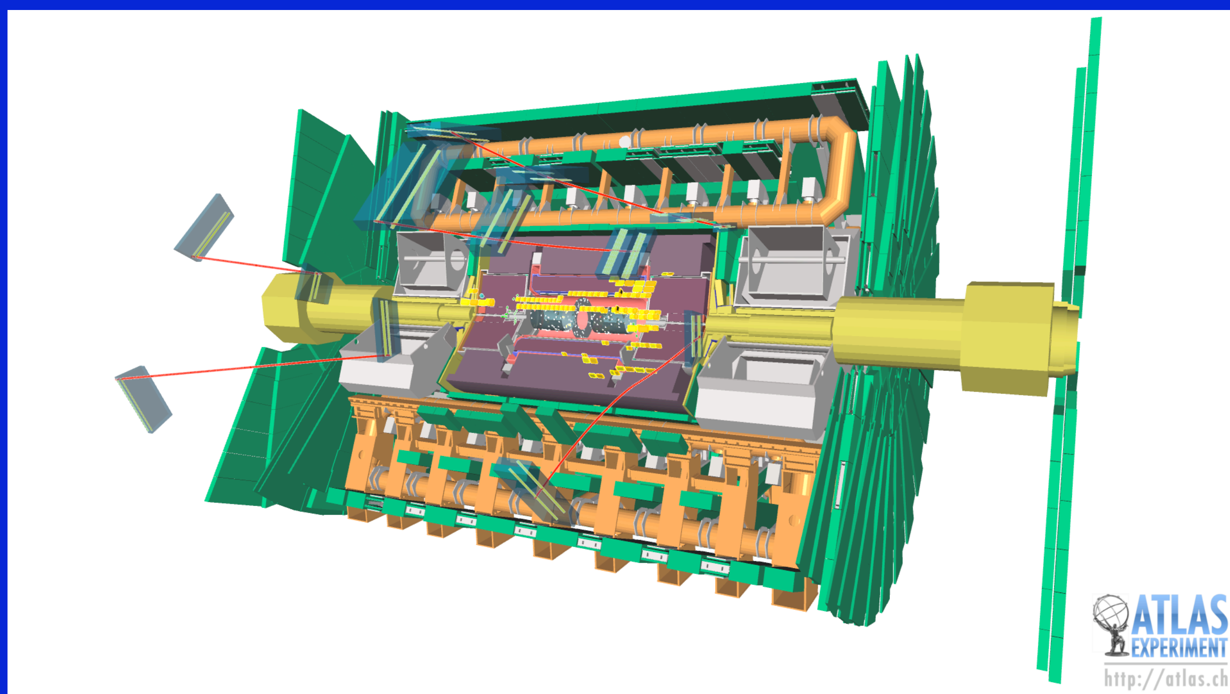


Event in which a cosmic muon deposited > 1 TeV in the Hadronic Calorimeter

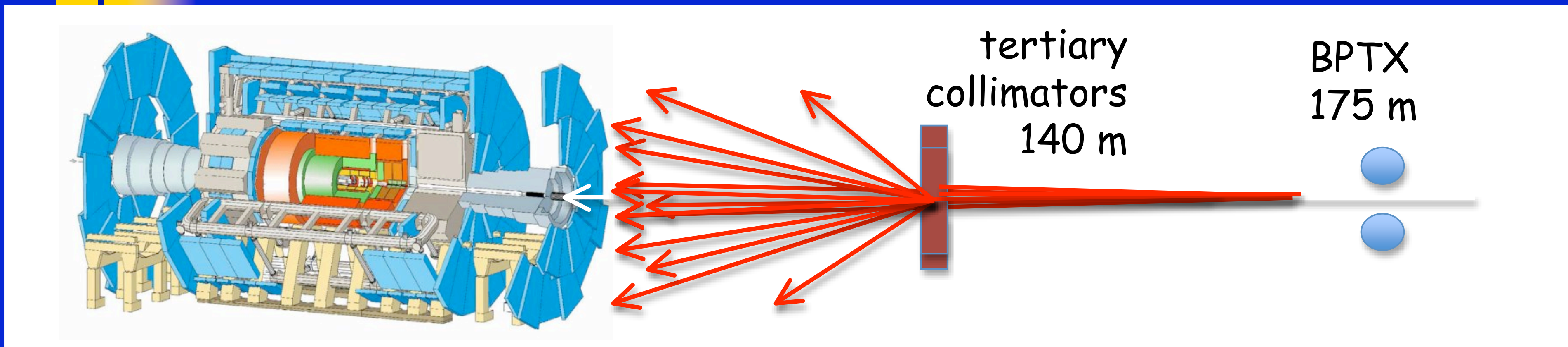


LHC single beam

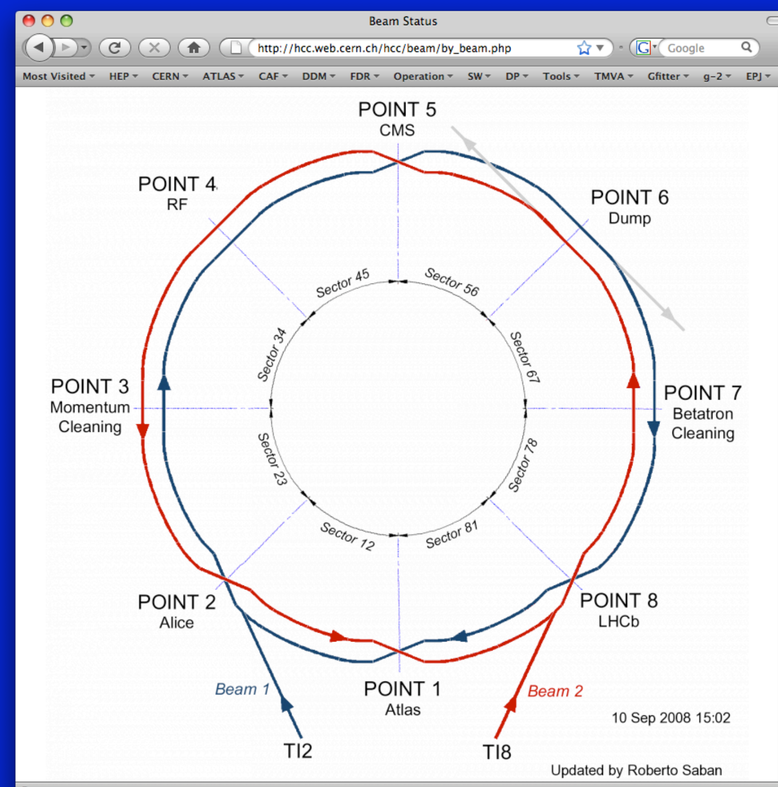
- Data collected
- What have we learnt from it? (some analysis results)



LHC start-up conditions



- LHC data in ATLAS (Sep 10th-12th):
  - 1 bunch of $2 \cdot 10^9$ p at 450 GeV
  - Start stopping beam on collimators, re-align with center, open collimators, keep going → expected:
    - Splash events when collimators closed
    - Beam halo and beam-gas events
- ATLAS was ready for first beam:
  - SCT, muon chambers and forward calorimeter at reduced HV and Pixels OFF for safety reasons.
  - LVL1 processor and DAQ up and running, HLT available (but only used for streaming)

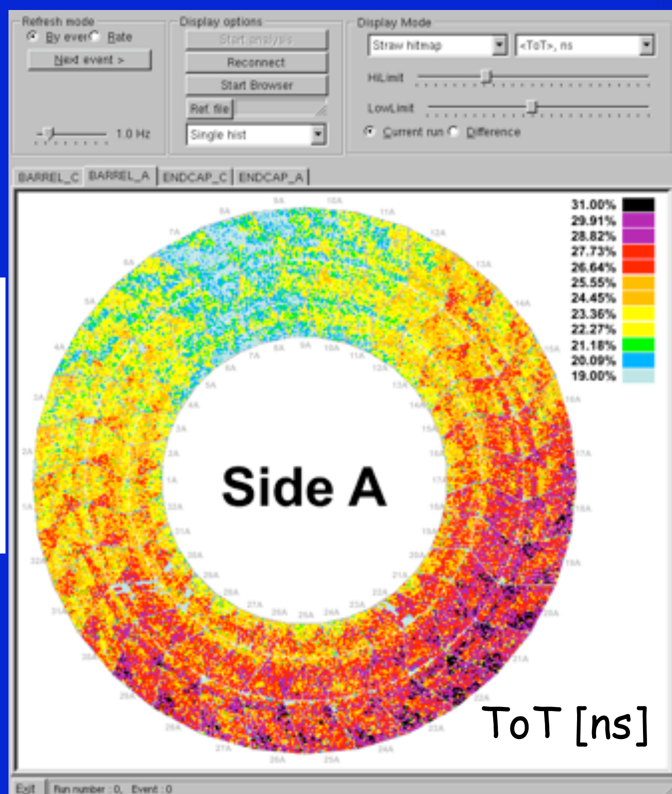


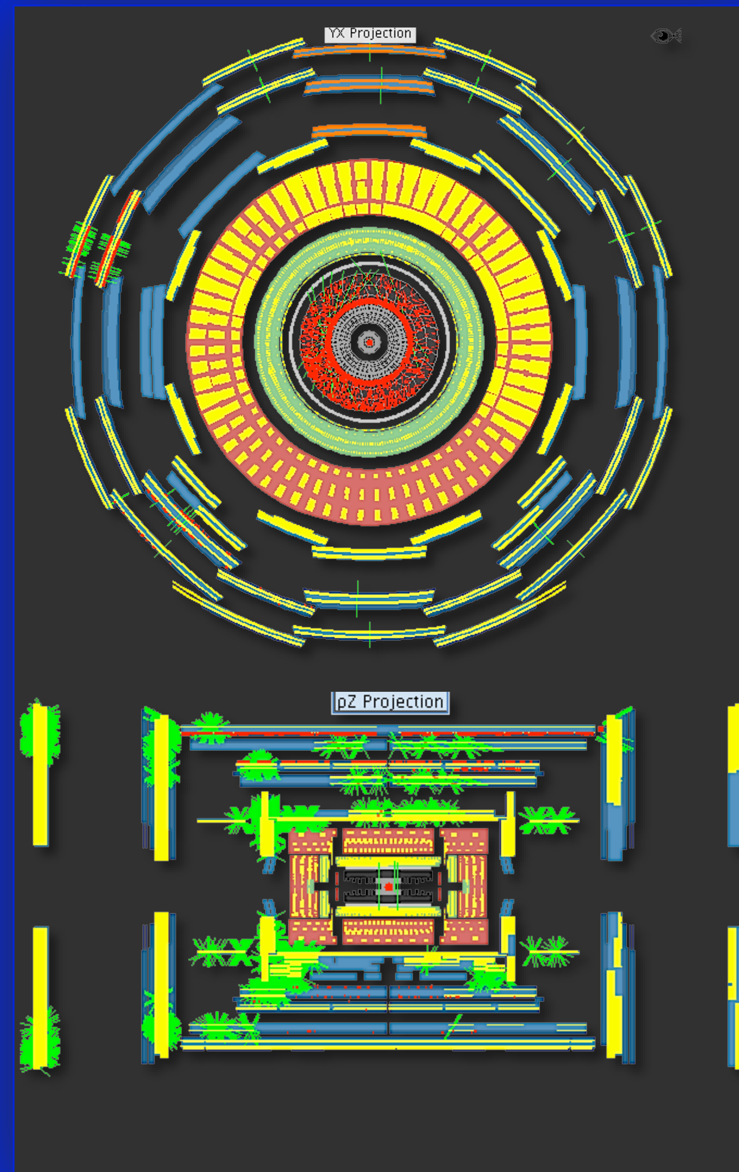
First splash event seen by ATLAS

Splash events

- Events characterized by:
  - Huge number of signals in the detector
  - Huge energy deposited (HAD cal > 1000 TeV, EM Cal ~ several TeV)
- Excellent for timing studies and to find dead channels.

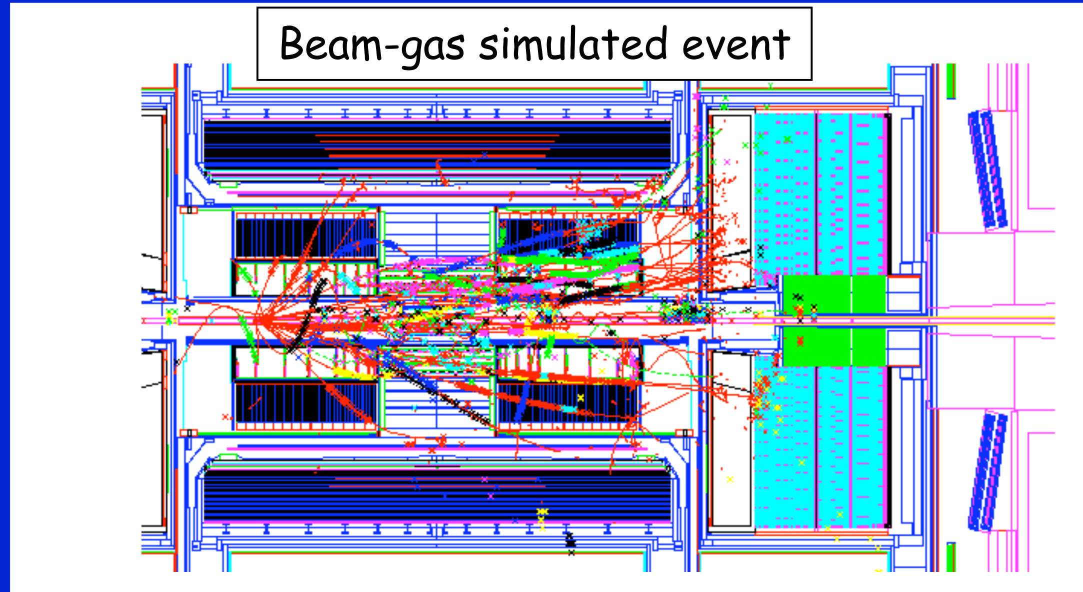
Beam splashed event in the TRT: These events were used to time in the detector at the ~ 1ns level.

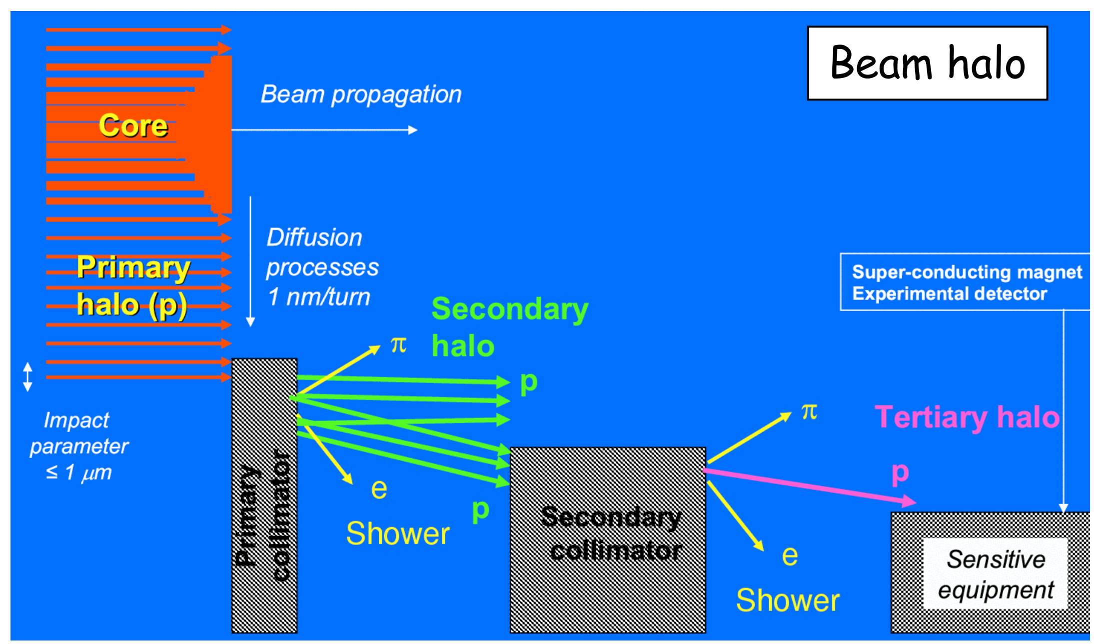




Expected events during circulation of a single beam

- beam – gas interactions (this is fixed target physics)
  - E_{cm} = 28 GeV (p – p, 450 GeV) or E_{cm} = 113 GeV (p – p, 7 TeV)
  - low p_T tracks, very forward
  - rate depends on vacuum conditions + rest gas composition
- beam halo (hadrons, muons)
  - mainly from secondary/tertiary interactions of protons with collimators
  - Traverse the detector horizontally

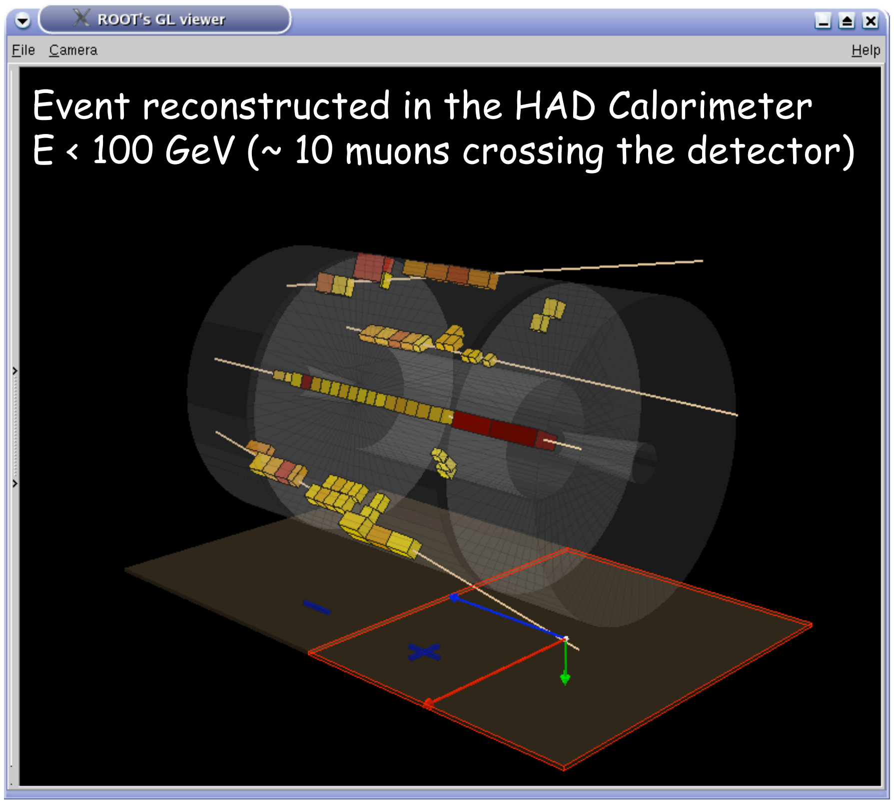


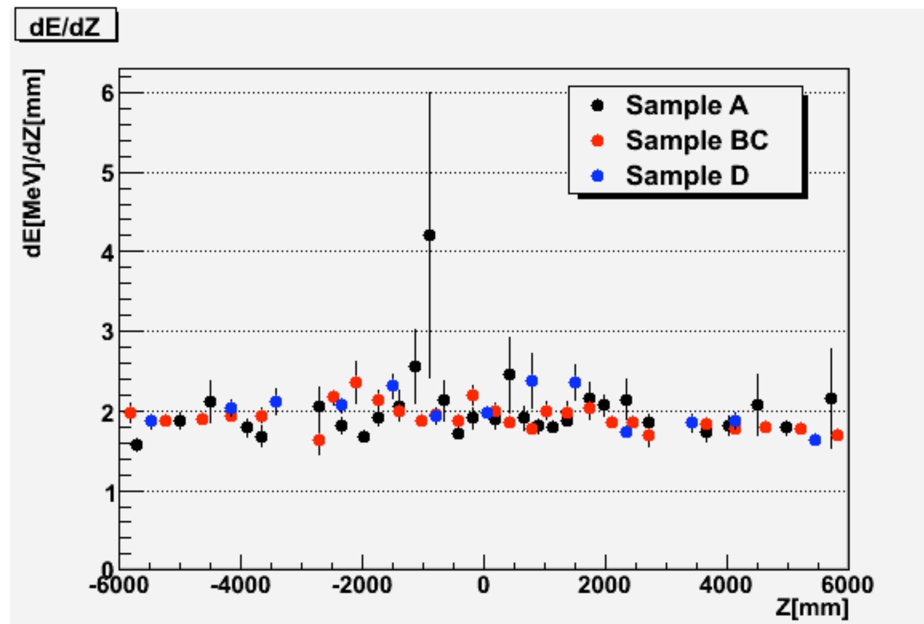


Beam halo events

- Single LHC proton beam circulating.
- At the beginning, the beam was not well focused → quite a few particles (muons) crossing horizontally the detector.

Ex: Validation of the energy calibration in the HAD calorimeter





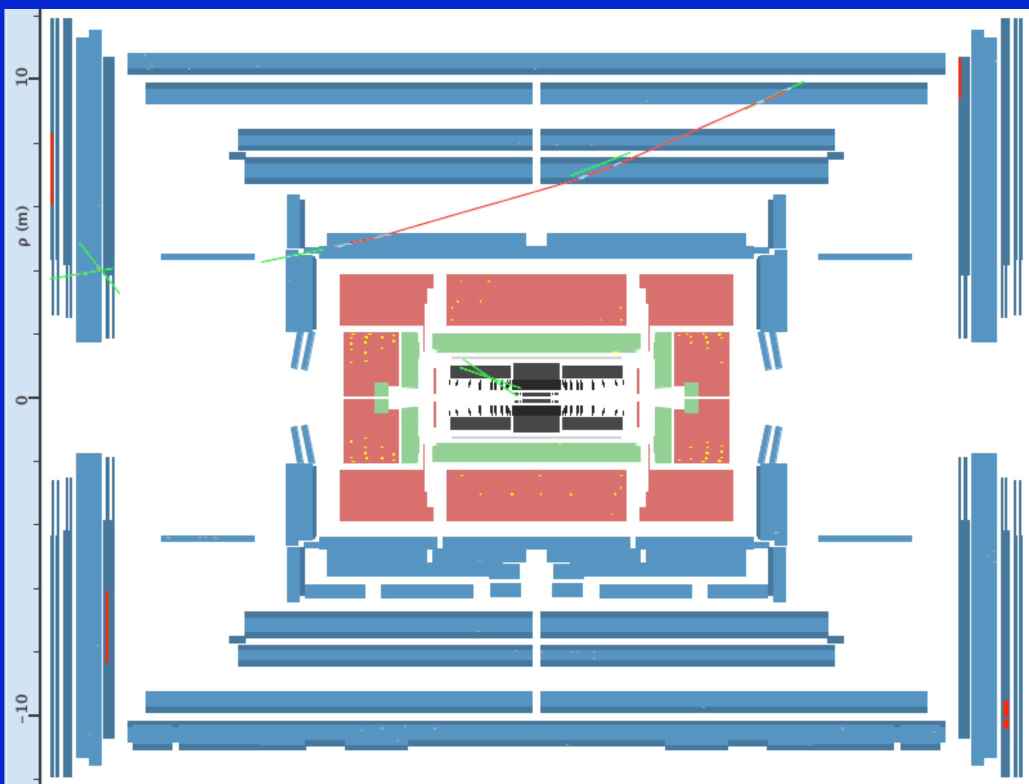
- Beam data: dE/dz = 1.9±0.2 MeV/mm
- Cosmic data: dE/dz = 1.7±0.3 MeV/mm

⇒ Good agreement of the detector response between cosmic and beam data.

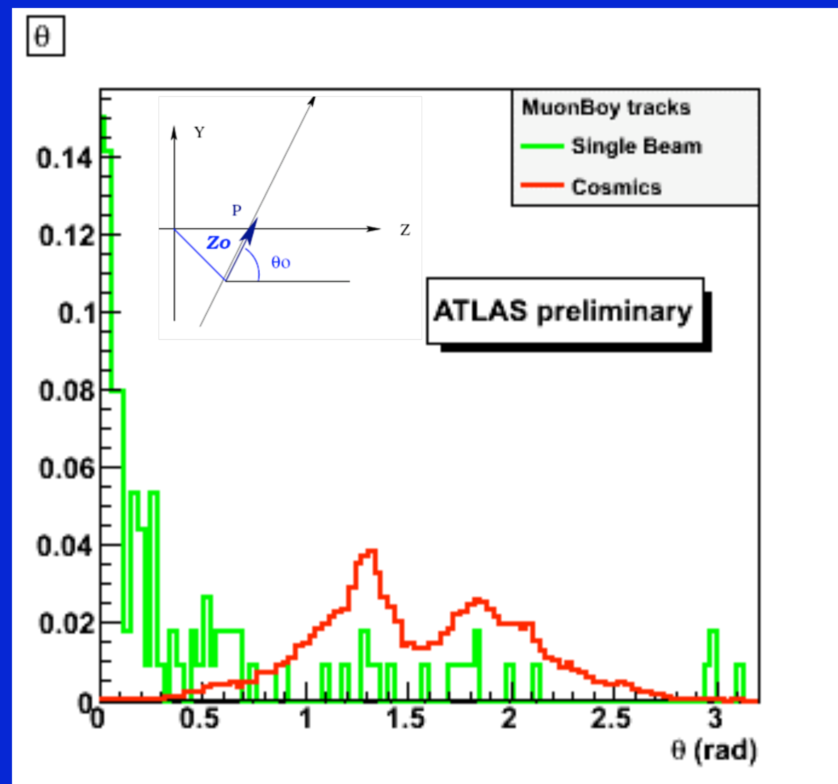
⇒ Uniform response (within 6%)

Beam halo events

- The beam was then very clean (good for physics, harder to time in the detector).

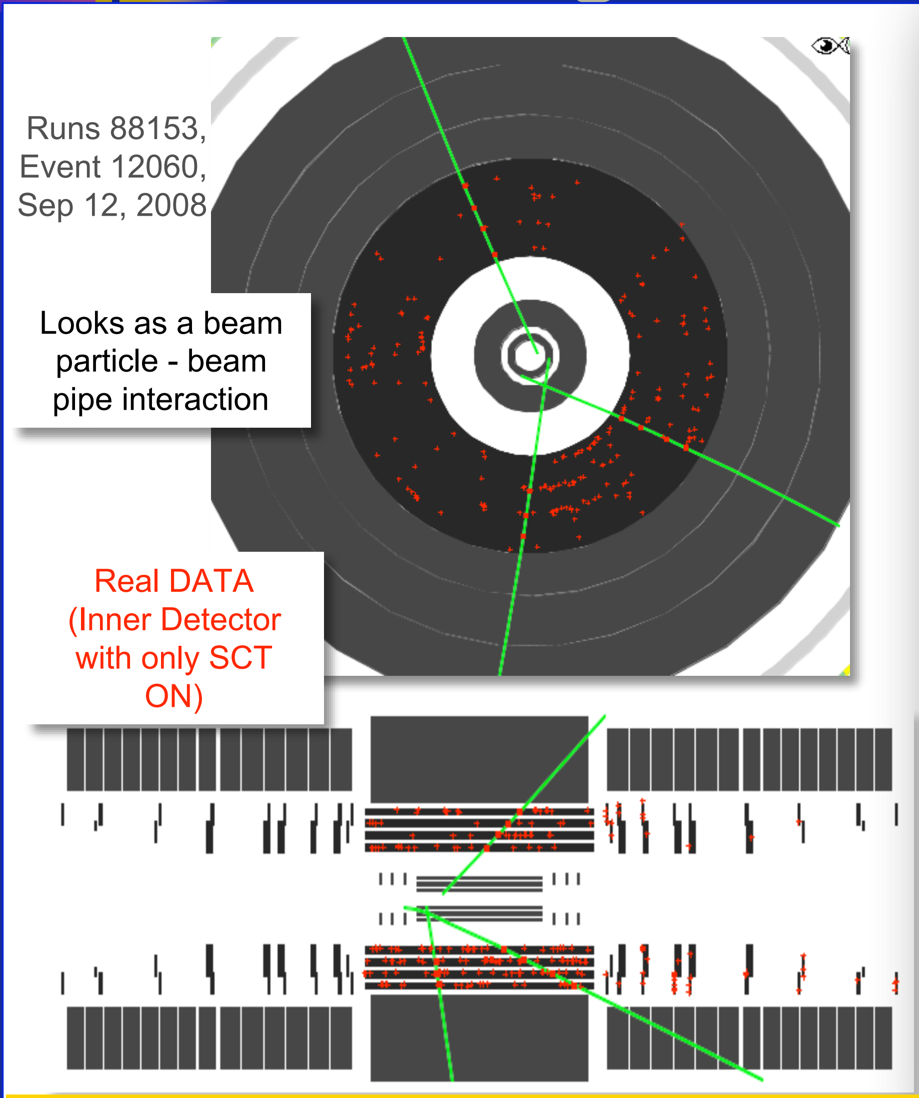


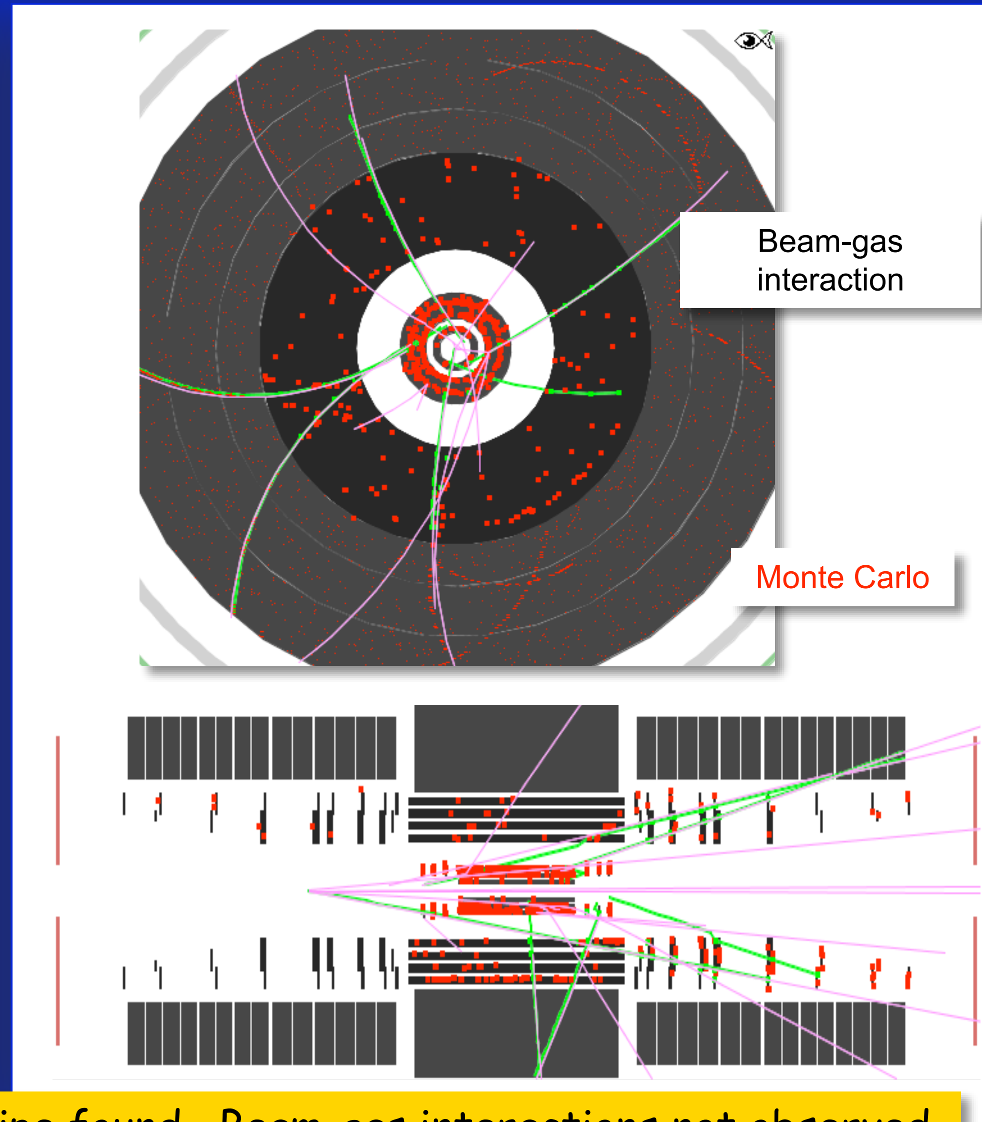
LHC single beam data event display



Distribution of the muon spectrometer θ track parameters for single beam and cosmic data.

Beam-gas events?





Some candidates for beam hitting the beam pipe found. Beam-gas interactions not observed, probably because of the excellent vacuum in beam pipe but also the Inner detector was not fully ON during this period.

Strategy towards first LHC physics results

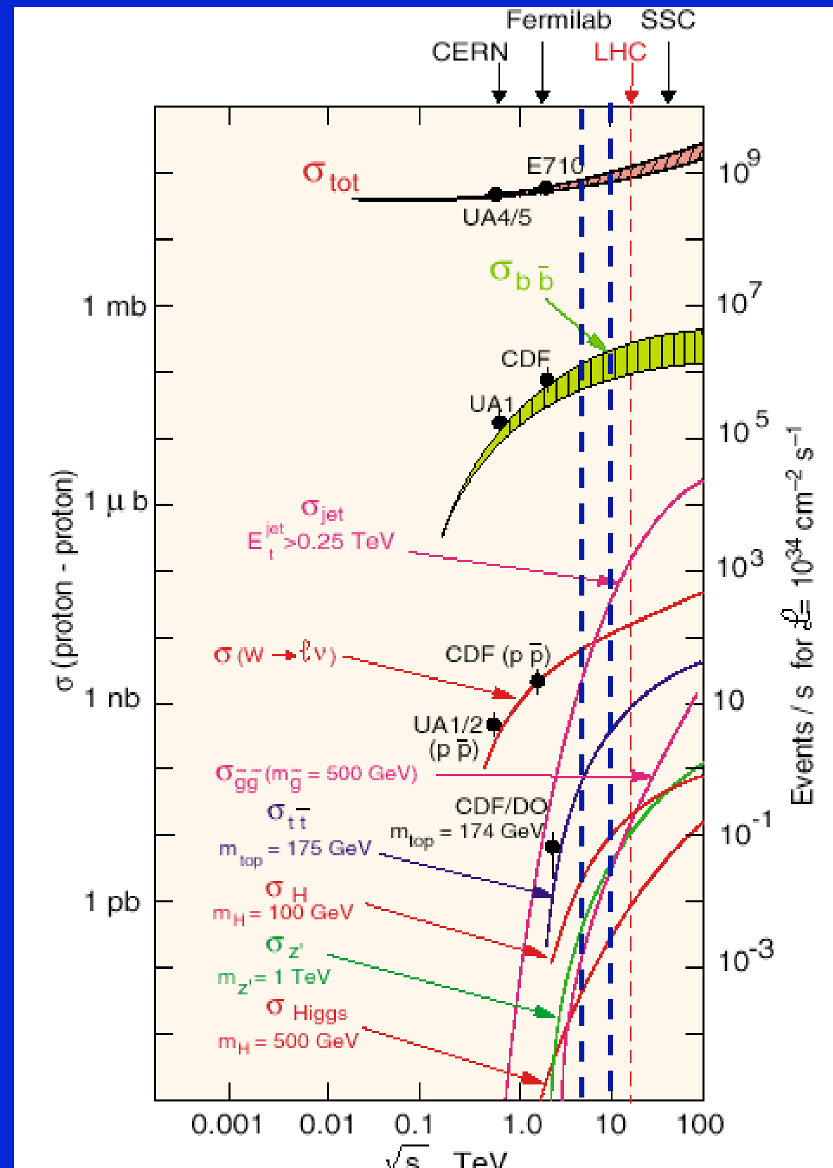
First expected LHC data

- LHC plan for 2009-2010:
  - run at $\sqrt{s}$ = 7 TeV until a significant data sample has been collected.
  - And then go up to $\sqrt{s}$ = 10 TeV
- Let's focus mainly on $\sqrt{s}$ = 10 TeV where more studies have been done

Amount of events in some channels with 100 pb^{-1}

Channels (examples ...)	Expected events in ATLAS after cuts $\sqrt{s}$= 10 TeV, 100 pb^{-1}
$J/\psi \to \mu\mu$	~ 10^6
$\Upsilon \to \mu\mu$	~ 5 10^4
$W \to \mu\nu$	~ 3 10^5
$Z \to \mu\mu$	~ 3 10^4
$tt \to W b W b \to \mu\nu + X$	~ 350
QCD jets p_T > 1 TeV	~ 500
$\tilde{g},\tilde{q}$ m ~ 1 TeV	~ 5

In addition, > 1M minimum bias (MB) events with 10pb^{-1}



The road towards physics

Will only show some examples in each step

The strategy towards physics

- Commission and calibrate the detector using well known physics samples
  - Using MB, J/ψ, Υ, W, Z, etc)
- "Re-discover" and measure Standard Model at $\sqrt{s}$ = 10 TeV
  - Particle multiplicity in MB
  - QCD jet cross section
  - W, Z cross section
  - Observe top signal, measure tt cross section
- First tuning of Monte Carlo
  - MB, underlying event, tt, W/Z+jets, etc
- Measure main backgrounds to new physics
  - W/Z+jets, tt+jets, QCD jets, etc
- Early discoveries
  - Potentially accessible: Z', SUSY, … surprises?

Obtain muon efficiencies from data

Observe top signal and measure σ_{tt}, M_t

Tuning Minimum bias

A lot of work to be done before claiming discoveries, will take time but it is

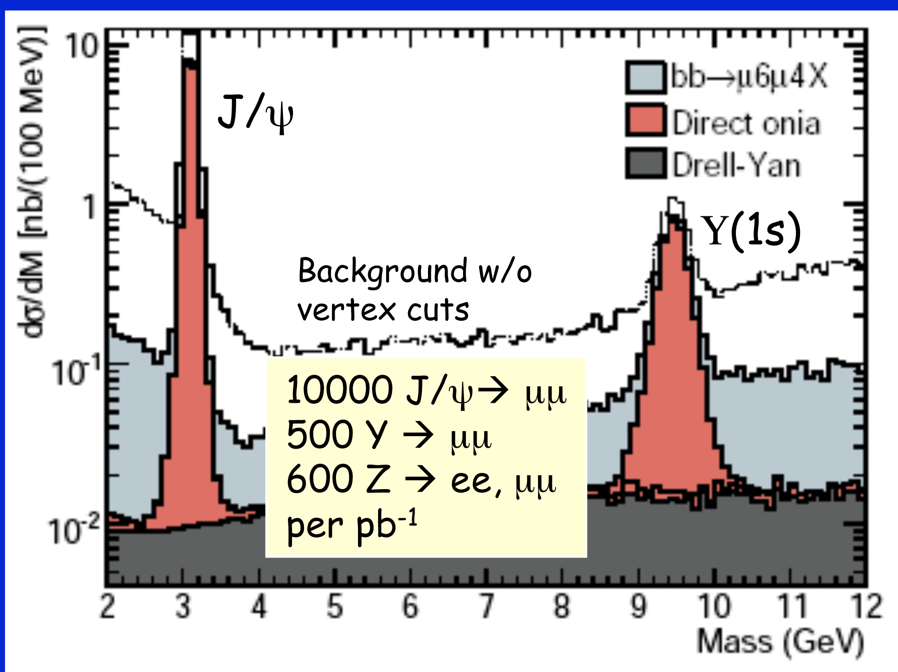
Z' potential discovery

Commission and calibrate detector

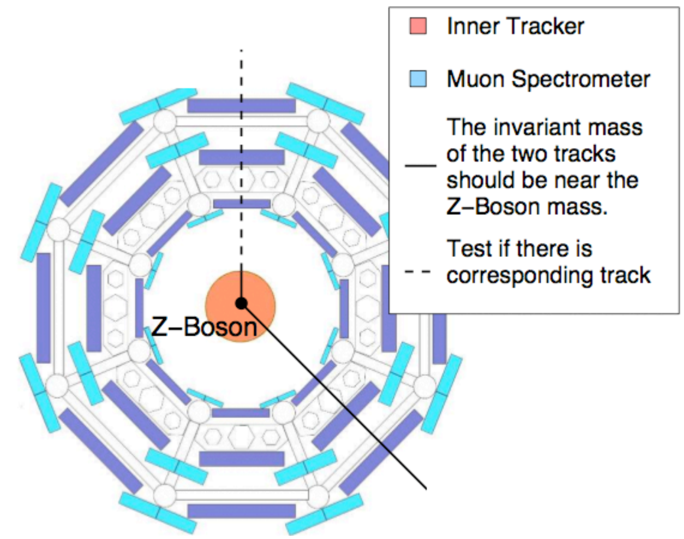
Example: Muon Performance In-Situ determination

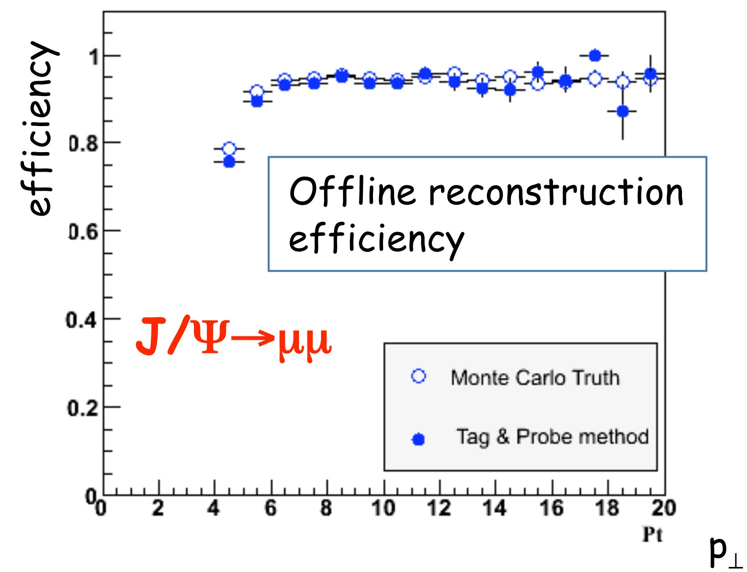
Muon Spectrometer muon efficiency can be determined using e.g. $J/\psi / Z \rightarrow \mu\mu$ via tag &probe:

- tag muon: combined muon track reconstructed in both ID and MS
- probe muon: ID track
- $M_{inv}(\mu_{tag}, \mu_{probe}) \sim M_{J/\psi}$
- Cuts to reject background



Tag & probe methods to determine muon efficiency

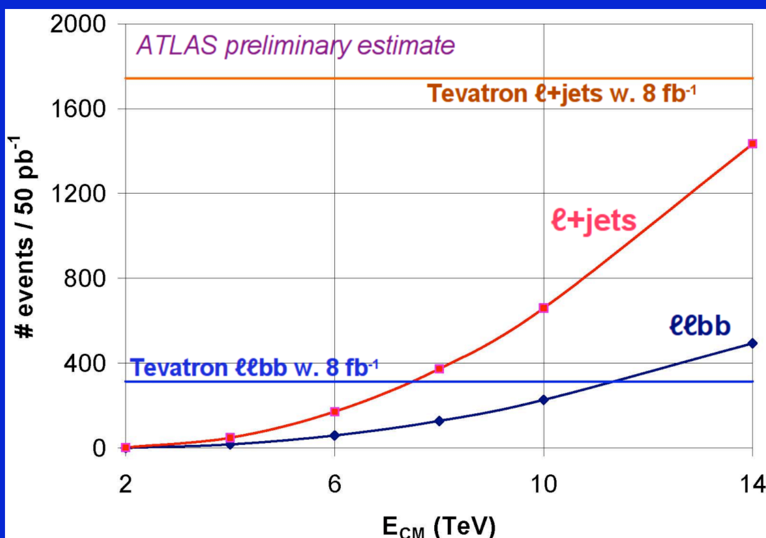




Re-discover and measure Standard Model

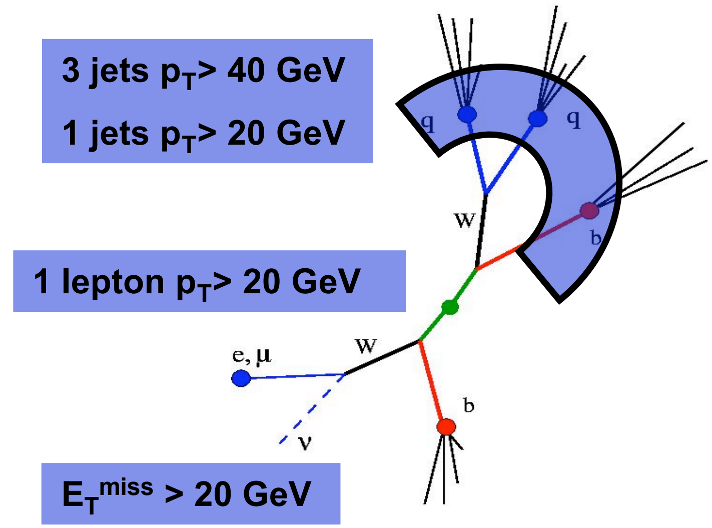
Observe top signal and measurements

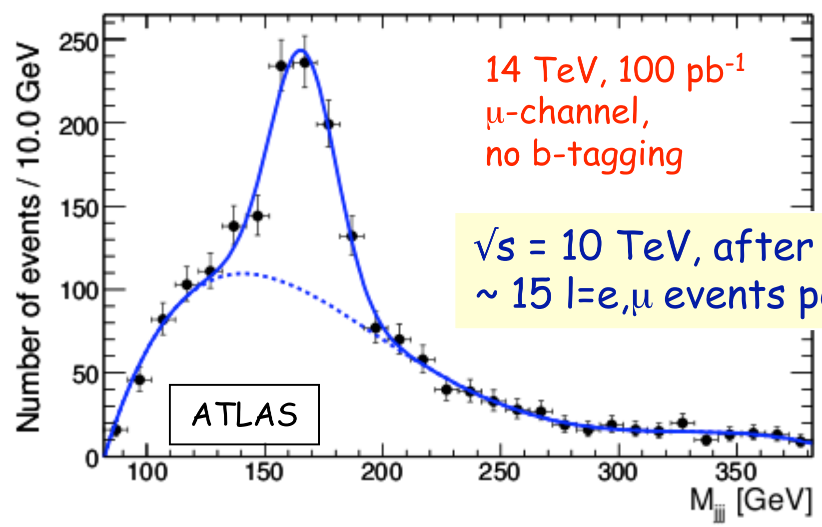
- Top signal observable in early days with no b-tagging and simple analysis
- Measure σ_{tt} to 10-20% and M_{top} to 10 GeV with ~100 pb^{-1}



■ contain most physics objects: leptons, jets, E_T^{miss} , b-jets
■ background to ~ all searches
→ when top measured, experiment is ready for discovery phase

Semi-leptonic tt channel (golden channel):
$tt \rightarrow bW\ bW \rightarrow bl\nu\ bjj$



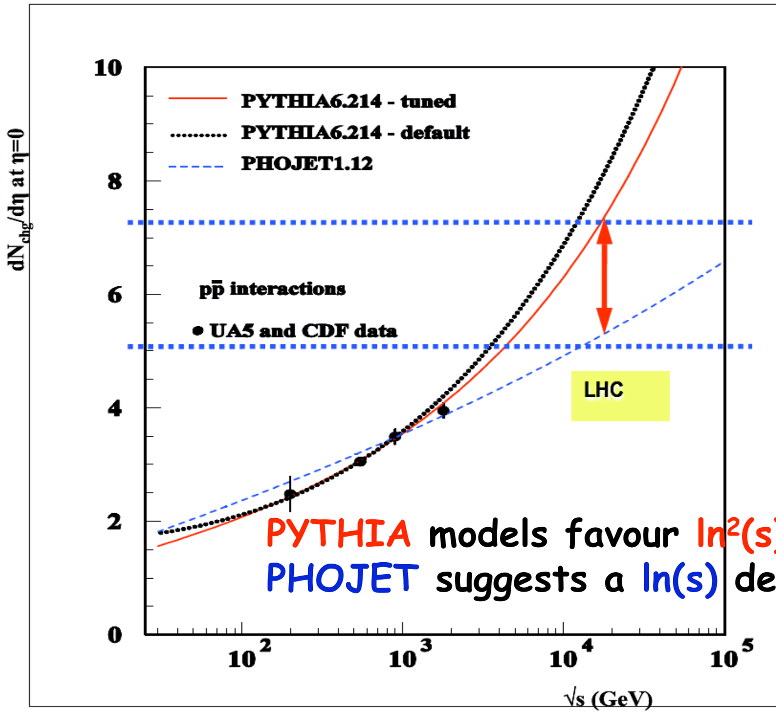


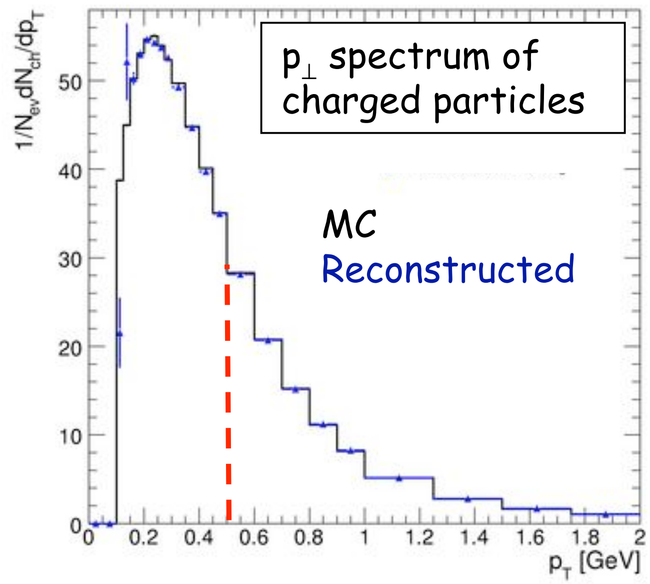
√s = 10 TeV, after cuts:
~ 15 l=e,μ events per pb-1

First tuning of Monte Carlo

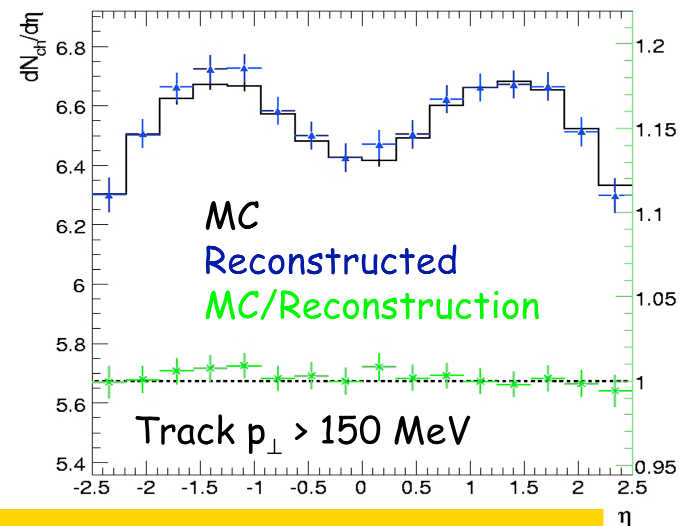
Minimum bias, dominant process at the LHC →
• its modeling is a necessary tool for high $p_\perp$ physics
• early measurement ~1 pb^{-1} ≠ easy measurement (Challenge to extend tracking to low $p_\perp$)

Charged particle density large discrepancies at LHC energies → essential measure it and tune MC!





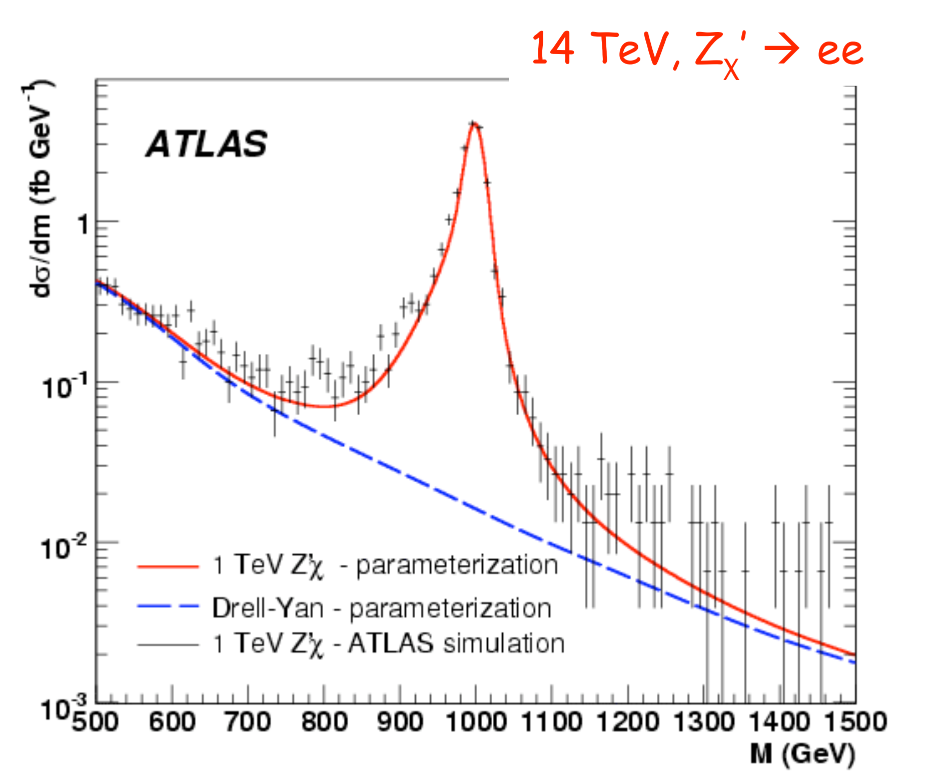
Charged particle density vs η

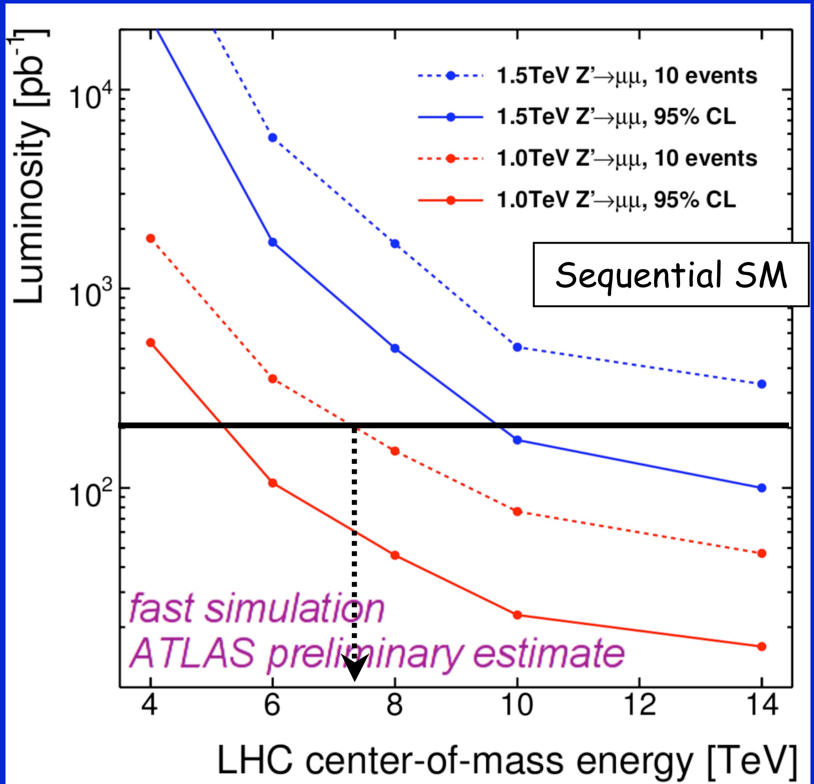


Requires a well understood ID performance

Early discoveries

Heavy resonance decaying into leptons Z′ → ll, mass ~ 1 TeV





- Signal is (narrow) mass peak above small and smooth SM background
- Does not require ultimate EM calorimeter performance (however, for Z′→μμ Muon Spectrometer alignment is very important)
- Discovery beyond Tevatron exclusion reach (m ~ 1 TeV) possible with 200 pb^{-1} and $\sqrt{s} \geq 7$ TeV (100 pb^{-1} at 10 TeV)

→ perhaps sometime in 2010 ?

Summary

- The ATLAS experiment (detector, trigger and data acquisition, data quality, calibration and alignment, data processing and world-wide distribution) is in good shape for the LHC start-up, thanks to:
  - Commissioning with real data: collect cosmic rays & 2008 LHC single beam
  - Commissioning with simulated data: data challenges of increasing functionalities, size and realism

- Detailed analysis of cosmic rays data have allowed to obtain a good understanding of the detector performance and calibration and alignment accuracies good enough for first physics.

- With the first LHC collisions data, the first goal will be to improve further our understanding of the detector performance in order to reach the very challenging physics requirements

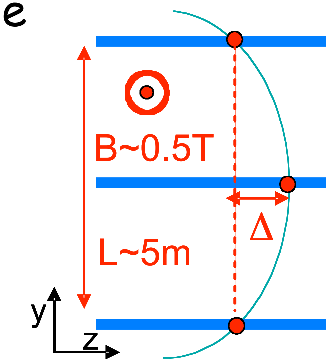
- As detector understanding improves, a rich program of early physics will be available with even possible discoveries.

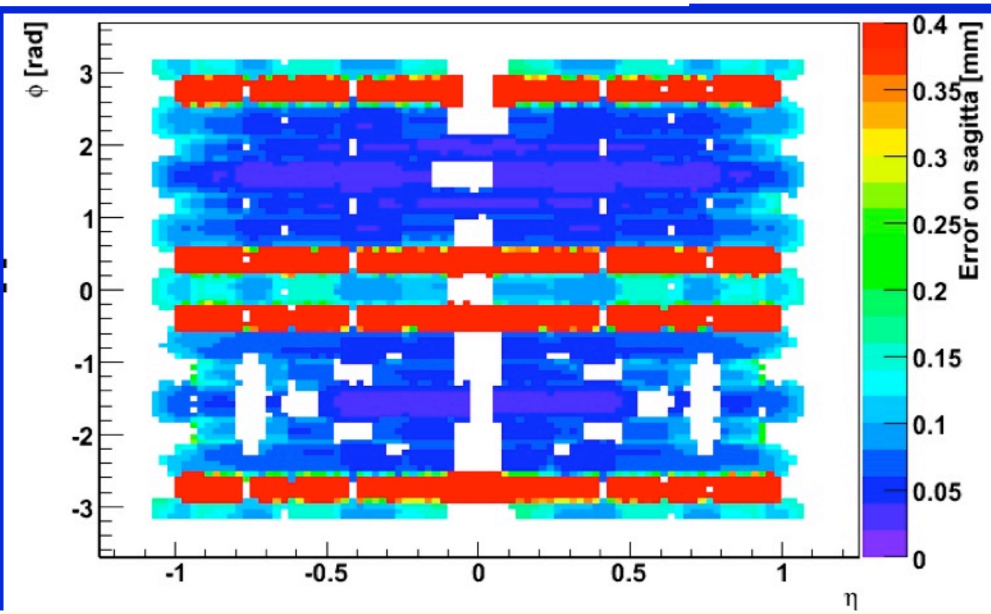
Backup slides

Can we try to align and calibrate?

To observe new heavy resonance $X \to \mu\mu$ as "narrow" peak →
$\sigma/p < 10\%$ for $E_\mu \sim 1$ TeV
$E_\mu \sim 1$ TeV ⇒ sagitta $\Delta \sim 500$ μm

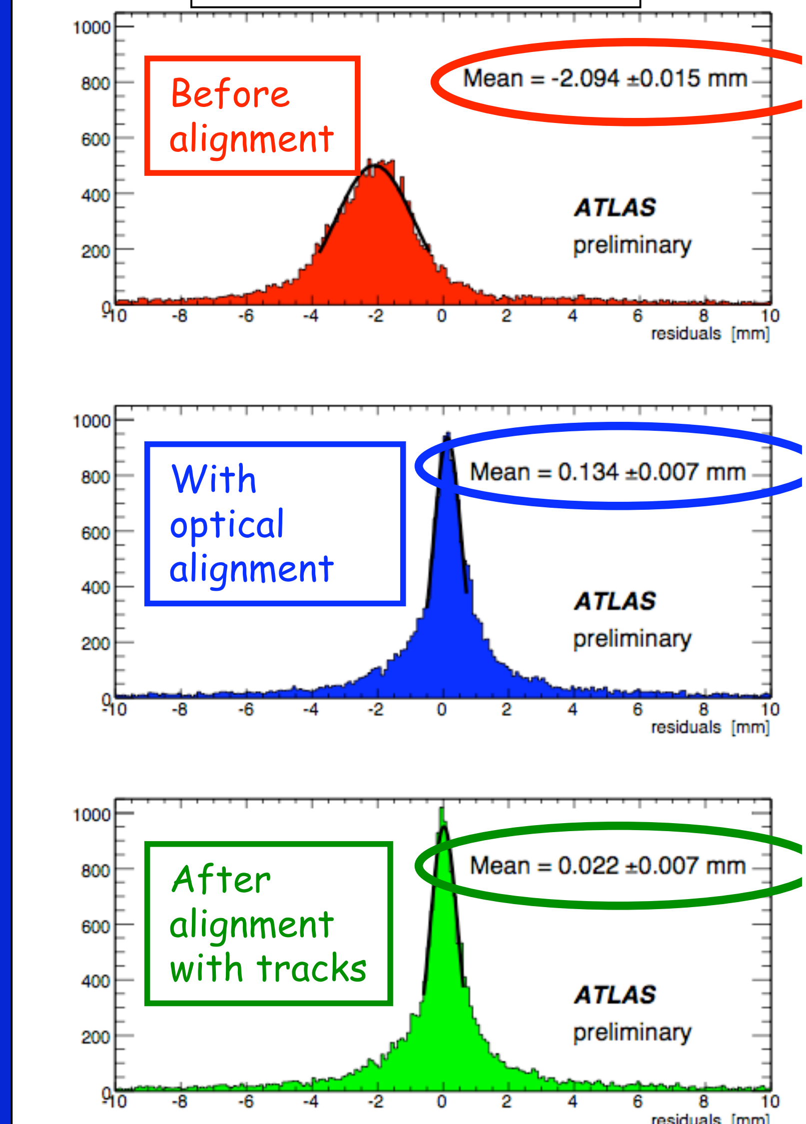
- $\sigma/p \sim 10\%$ ⇒ $\delta\Delta \sim 50$ μm
- alignment accuracy to ~40 μm



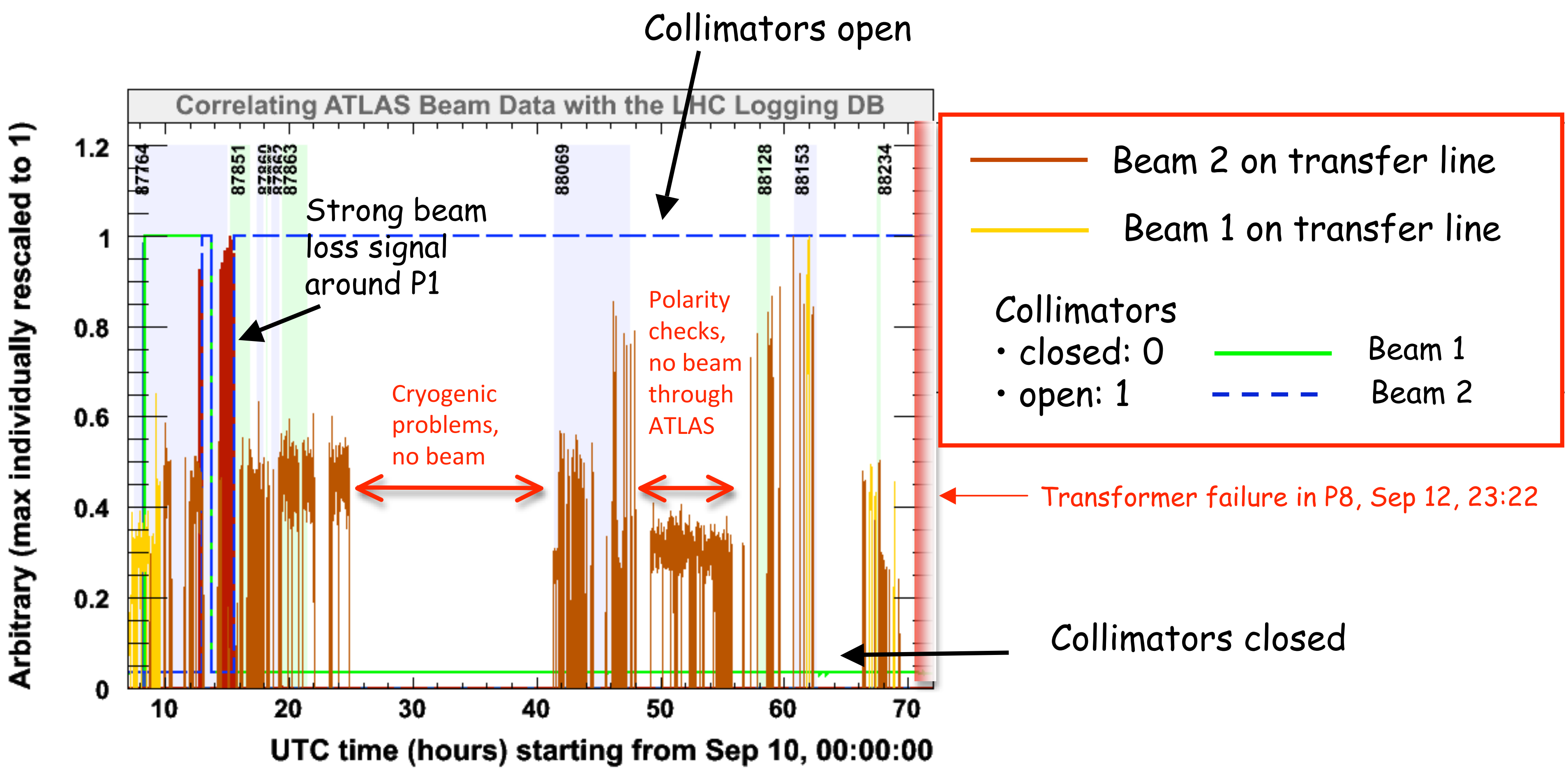


Expected alignment accuracy on "Day-1" (first collisions) combining cosmics and optical alignment (red regions are sectors on horizontal plane w/o optical alignment)

MDT track residuals



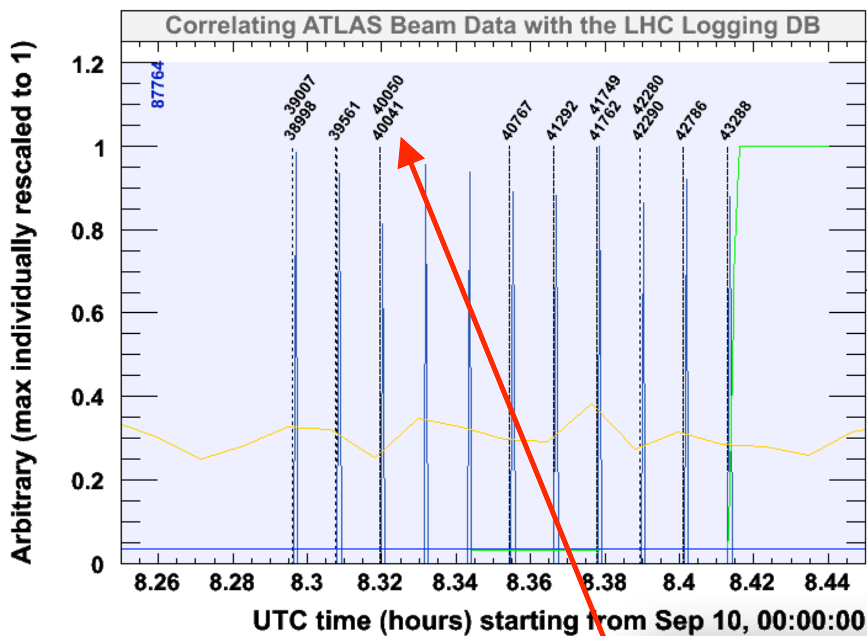
Overview of beam injections and ATLAS runs



- ATLAS saw the LHC beam during 3 days.
- Both beams went through ATLAS but mostly beam 2

Collimator splash events

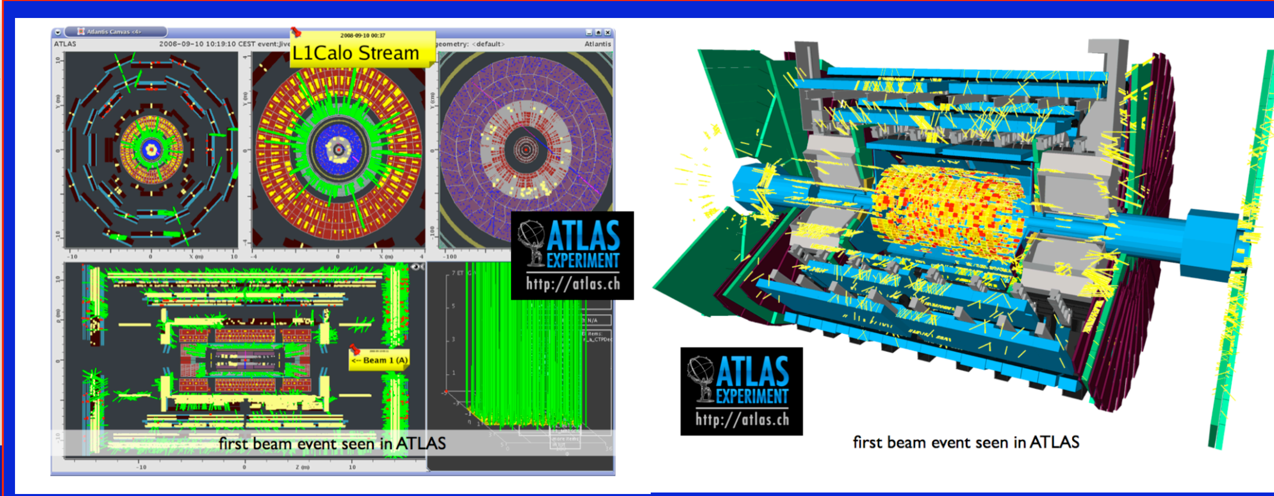
Zoom into first period of beam splashed activity



- - - - ATLAS observed splash event (#hits MDT>100K)

——— Beam 1 injections

First event seen in ATLAS!!



Good correlation between the LHC beam injections and the splash events recorded by ATLAS