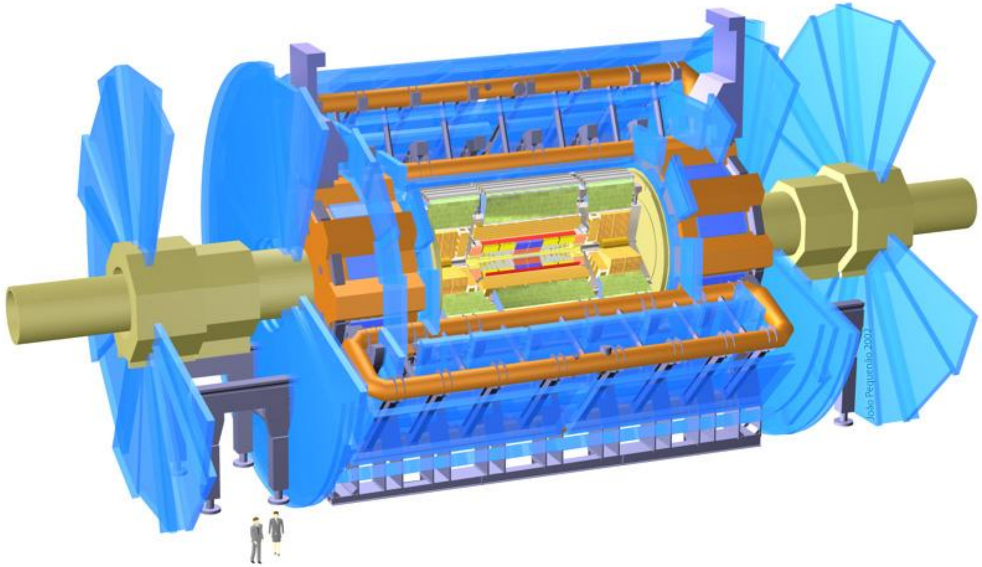
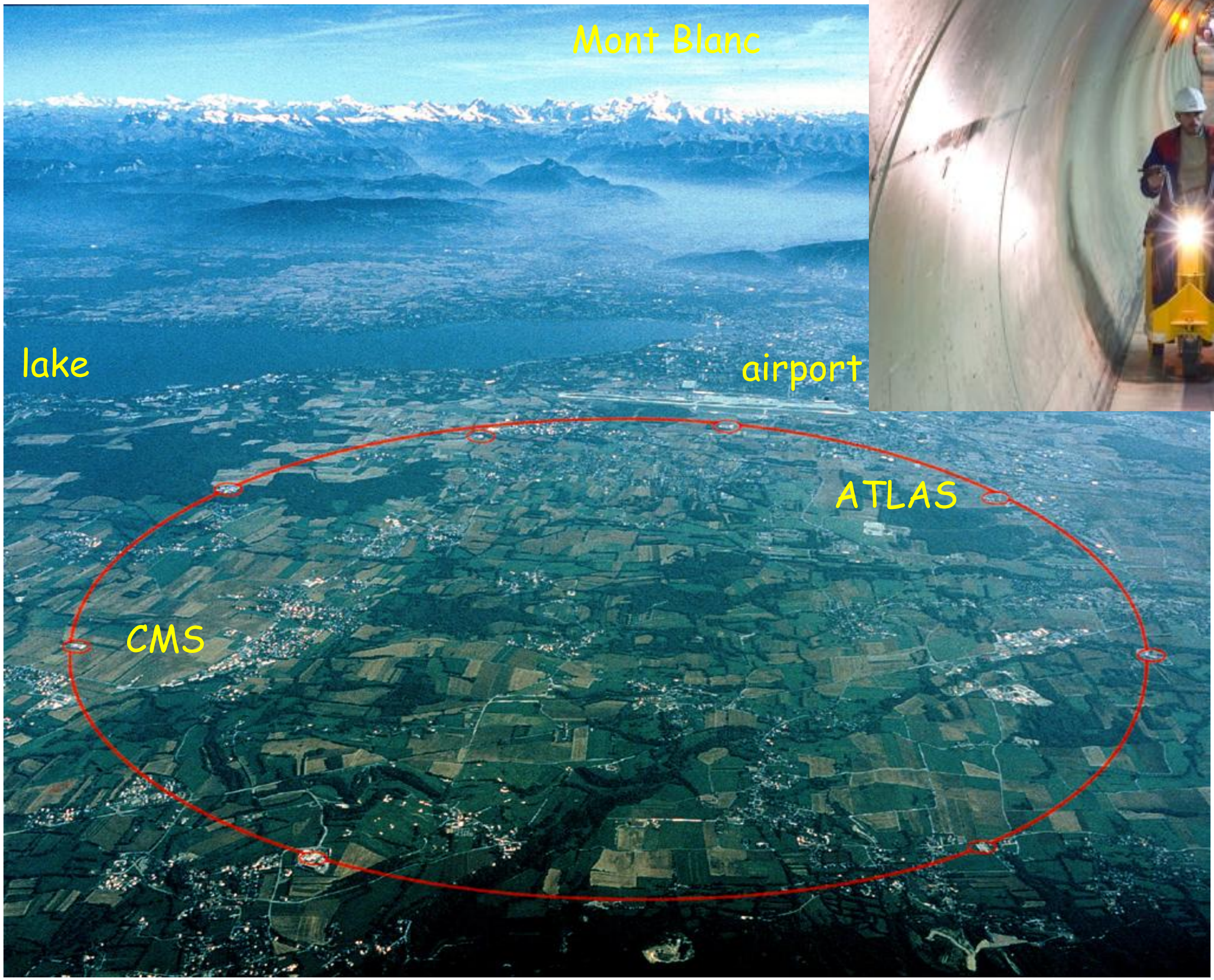


Design, construction and upgrade of the Tilecal sub-detector of ATLAS

Agostinho Gomes
(LIP and FCUL)

3 February 2016

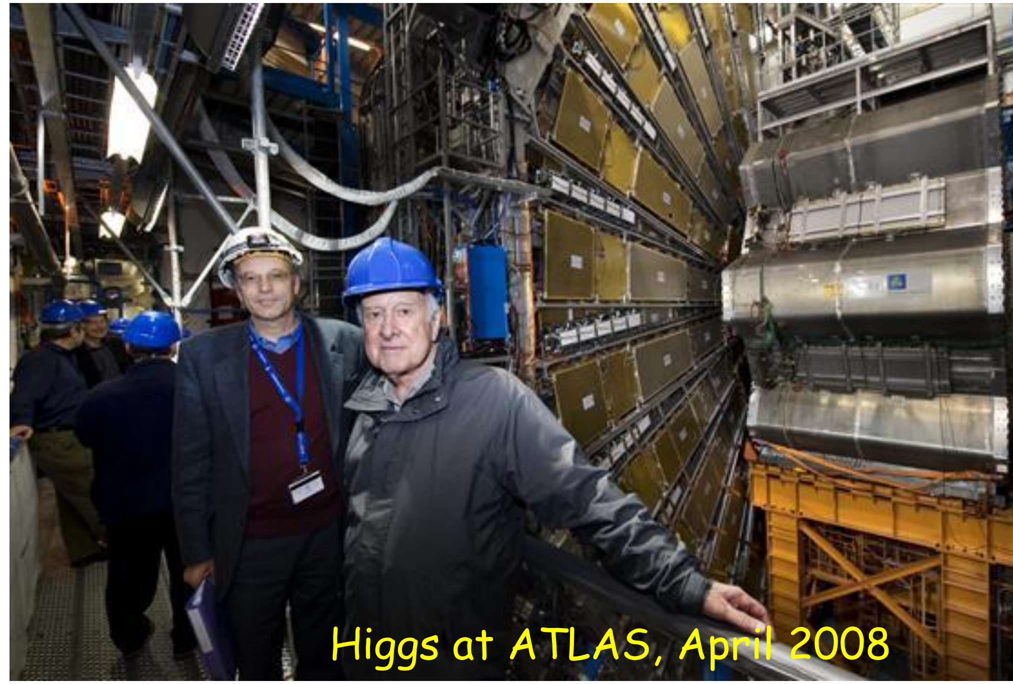
LHC – Looking for Higgs Collider



p-p collider
27 km perimeter
Designed for:
7 TeV/beam
Luminosity $10^{34} cm^{-2} s^{-1}$

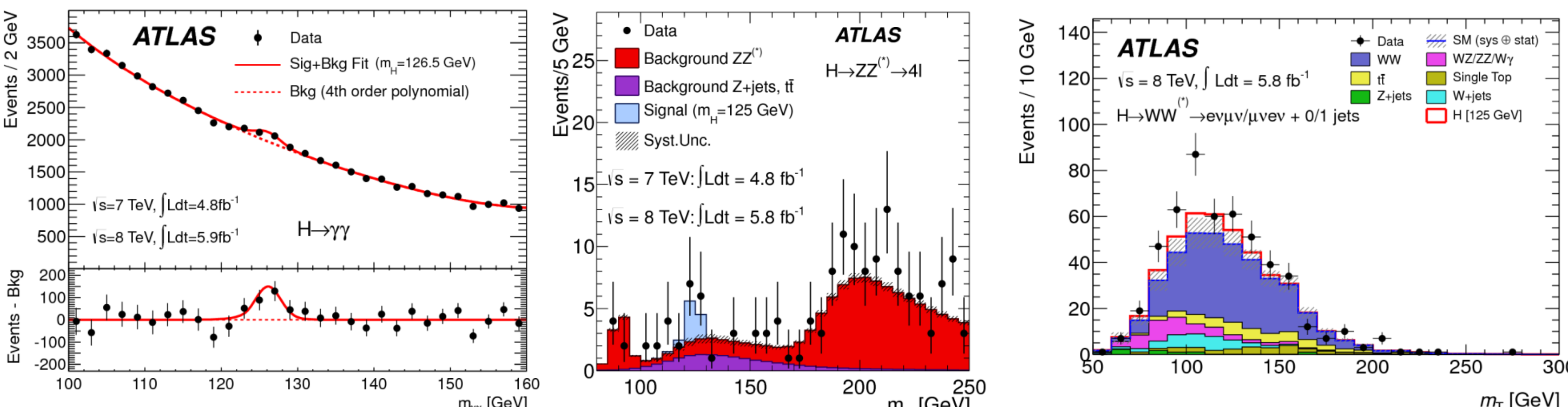
LHC – Looking for Higgs Collider

In the next slide we will see that it was not an easy task, but everybody knows the outcome, Higgs appeared himself at CERN



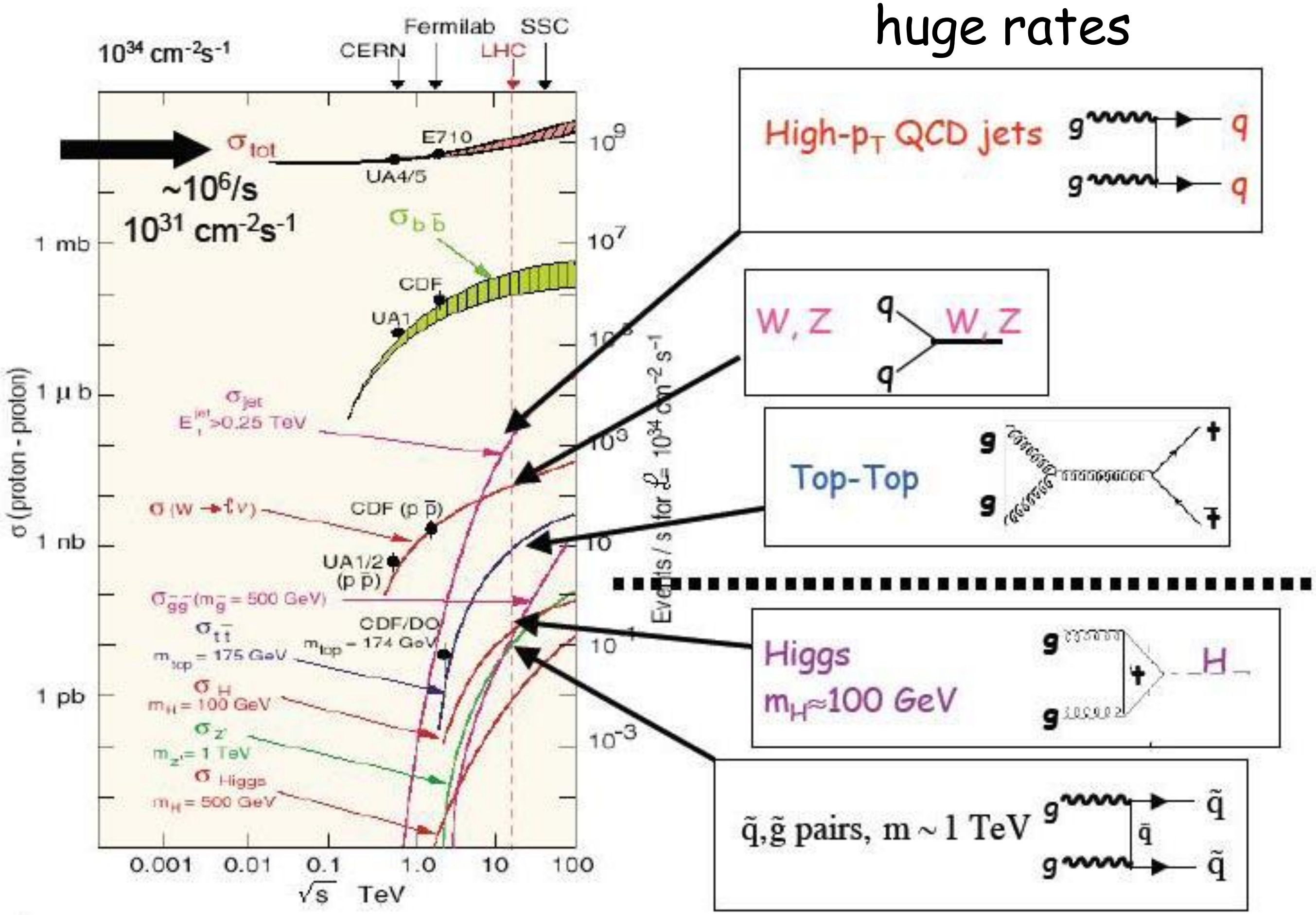
Higgs at ATLAS, April 2008

Higgs at ATLAS, July 2012



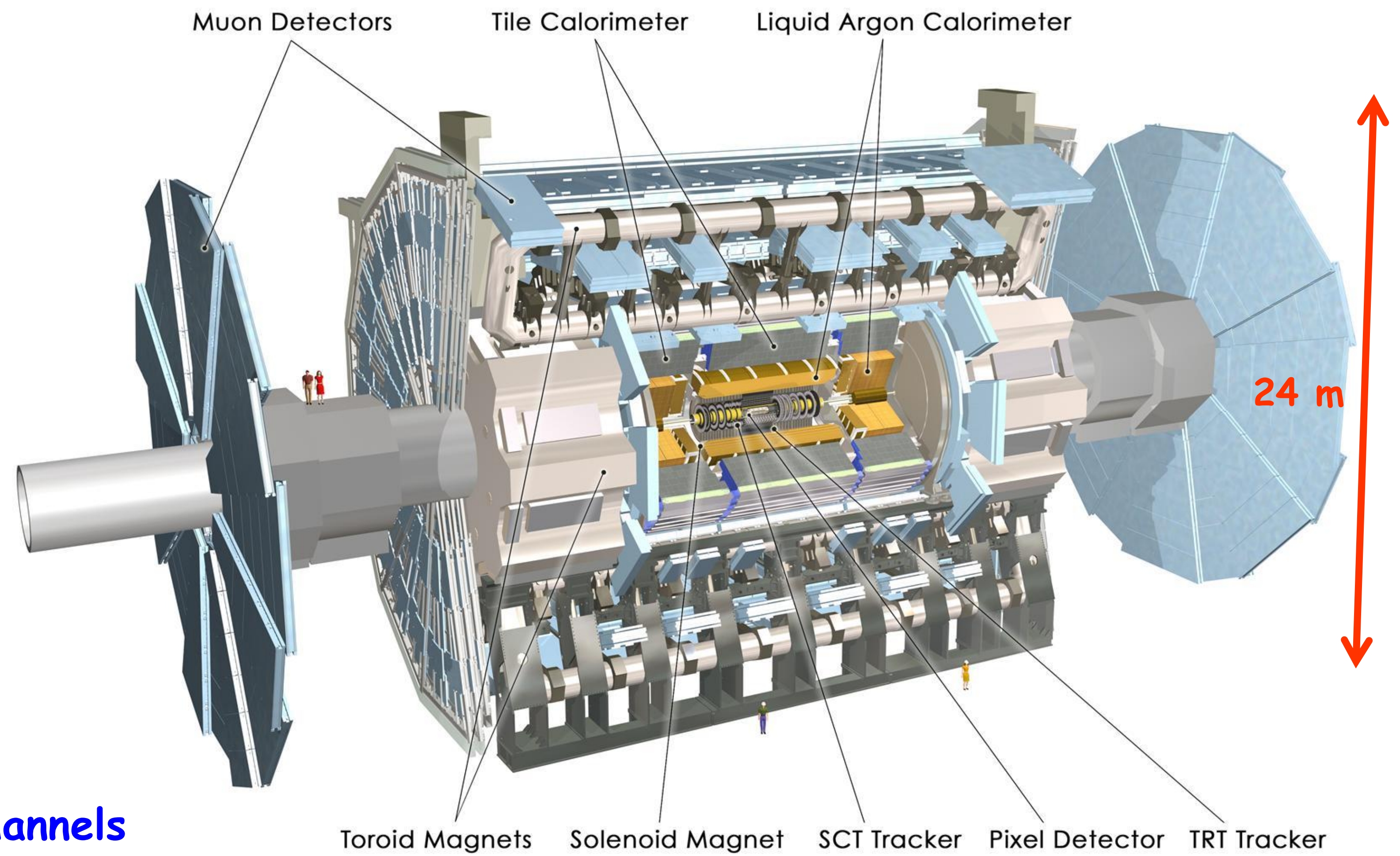
Signal and background in the LHC package

The uninteresting particles are produced at huge rates



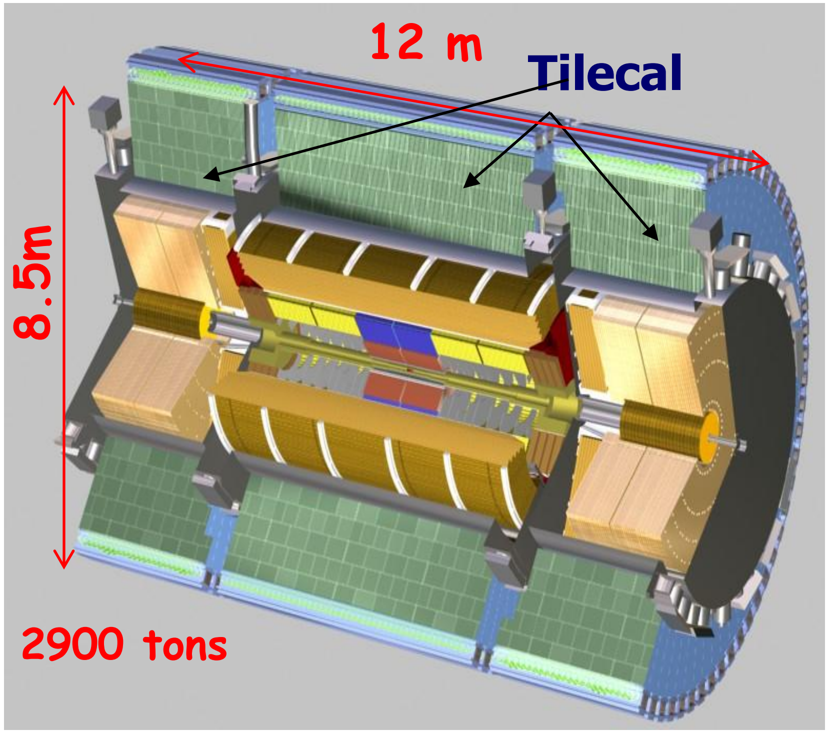
The particles we are looking for are here at the bottom

The ATLAS detector at LHC



7000 tons
88 Million channels
2T solenoid
Toroid (B ~ 0.5T in barrel;~1T end-cap)

ATLAS TileCal - motivation



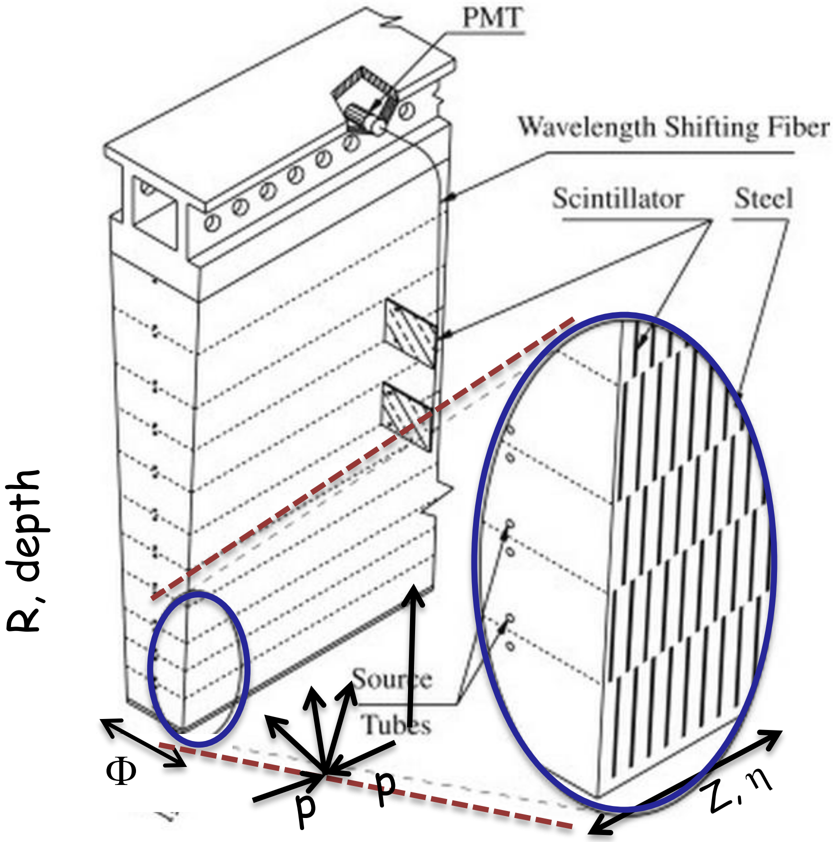
Hadron calorimeter with good performance at low cost

- Scintillating Tiles and WLS optical fibres
- Photomultiplier tubes (PMTs)
- Steel/Tiles, ratio 4.7 : 1 (λ = 20.7 cm)
- 10 k channels (5000 cells)
- Transversal granularity $\Delta\eta \times \Delta\phi$=0.1x0.1
- Longitudinal segmentation: 3 layers
- Containment ~ 98% TeV hadrons, jets
- ATLAS jet resolution: $\sigma_E/E \sim 50\text{-}60\%/\sqrt{E} \oplus 3\%$

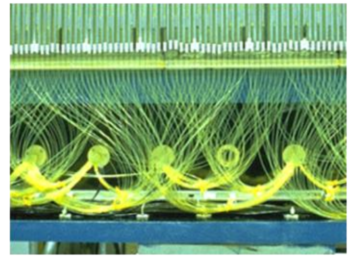
Robust technology for barrel region, but not suited for end-caps (radiation damage)

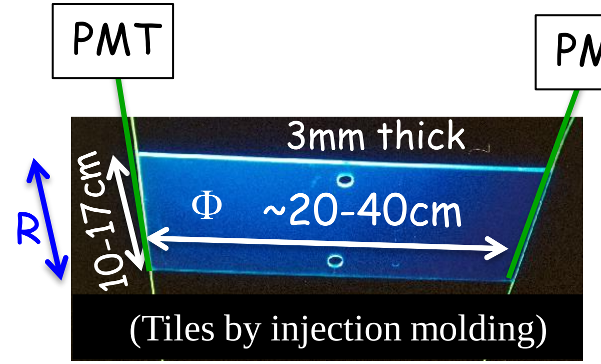
Tilecal MoU Core Cost (1998): 17 MCHF
(46% mechanics ;11% optics ;43% electronics)
~4% cost of the ATLAS detector

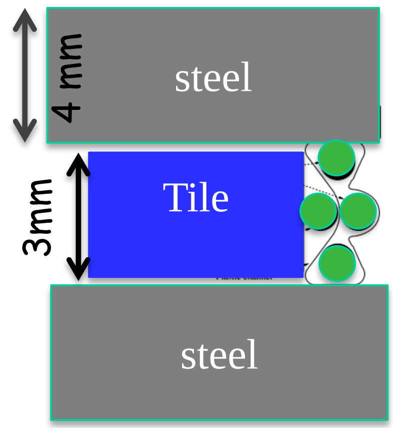
Tilecal layout



Fibre bundles
(at outer radius)

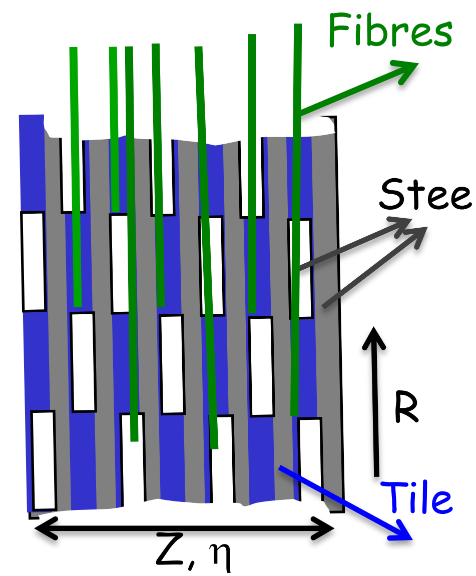






Fibres start at different R and go radially out =>

- No cracks in ϕ
- depth segmentation
- PMTs at outer Radius



ATLAS Tile cells $\Delta\eta \times \Delta\phi$=0.1x0.1 (0.2x0.1 in outer layer) and 3 layers driven by LHC requirements and electronics readout costs

But much better optics granularity (~ 620k fibres 400k tiles):

- $\Delta\eta$: 3mm tiles every 9-18mm in Z-> $\Delta\eta_{optics}$ < 0.004
- ΔR: 11 tiles and 8 fibres in R -> ΔR_{optics} < 1 λ
- $\Delta\Phi$: 20 cm tiles-> $\Delta\phi_{optics}$=0.1

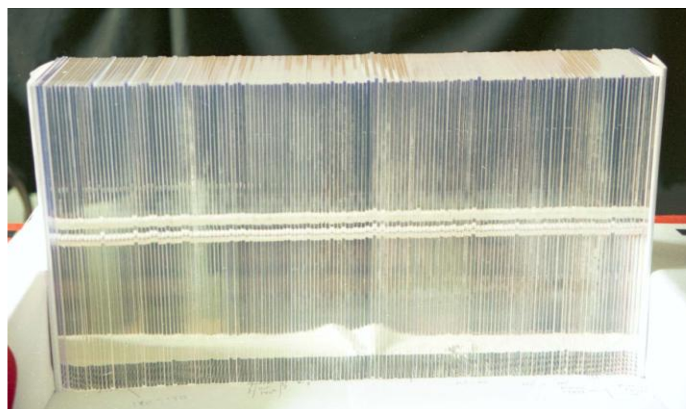
Tilecal main optics

Scintillating tiles
WLS optical fibers: responsibility Portuguese team led by Amélia Maio

Tilecal scintillating tiles

Number of scintillating tiles needed: ~400000, distributed by 11 sizes
Technique chosen: mould injection (cheap and fast)
Critical parameters: mould walls quality, polystirene, dopants, pressure, temperature

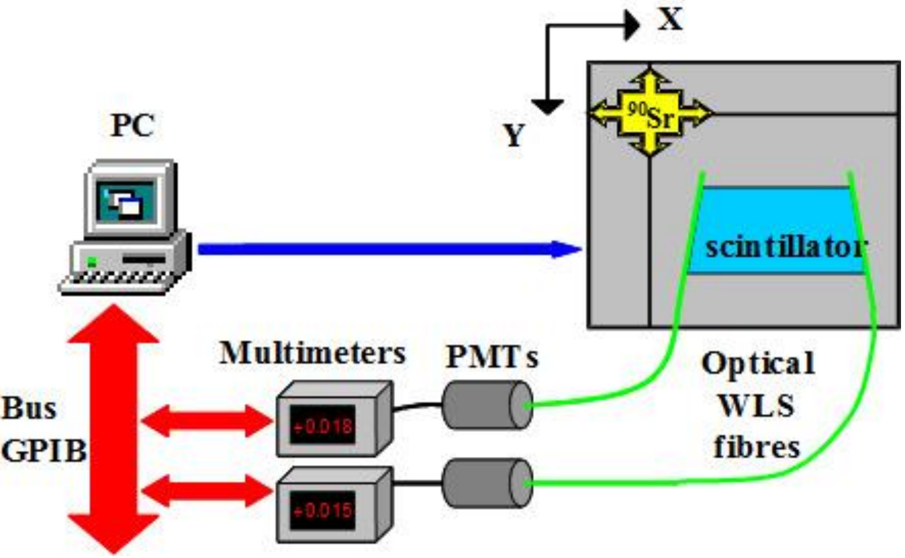
WaveLength Shifting (WLS) fibers
1 mm diameter, lengths 1 – 2.5 m



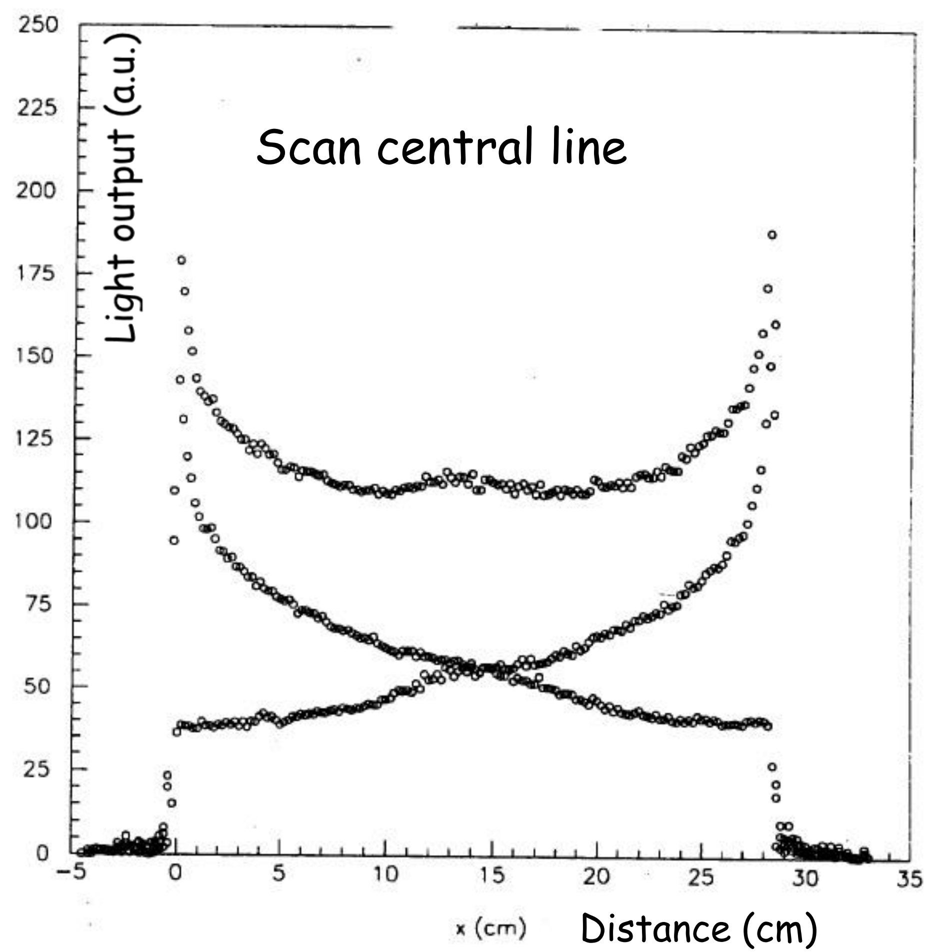
A set of scintillators

Setup to test scintillators

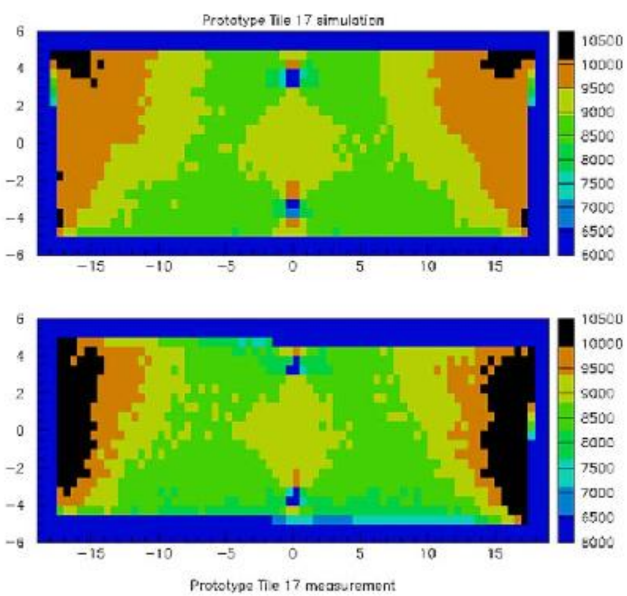
Tilecal layout, scintillating tiles



Setup to test scintillators



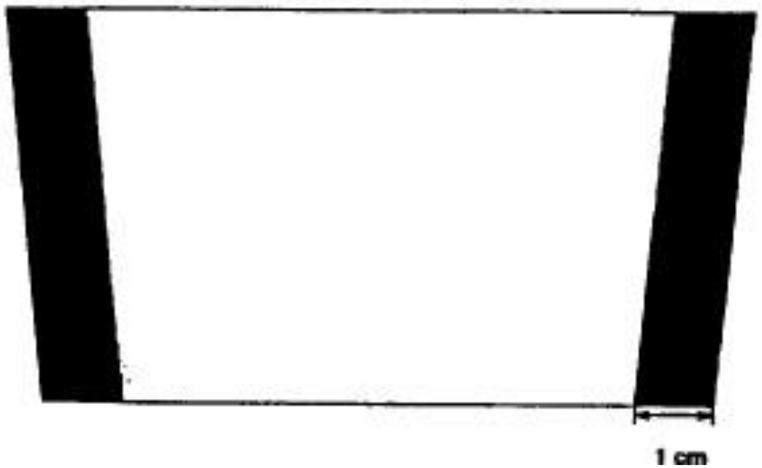
Non-uniformity excessive near edges

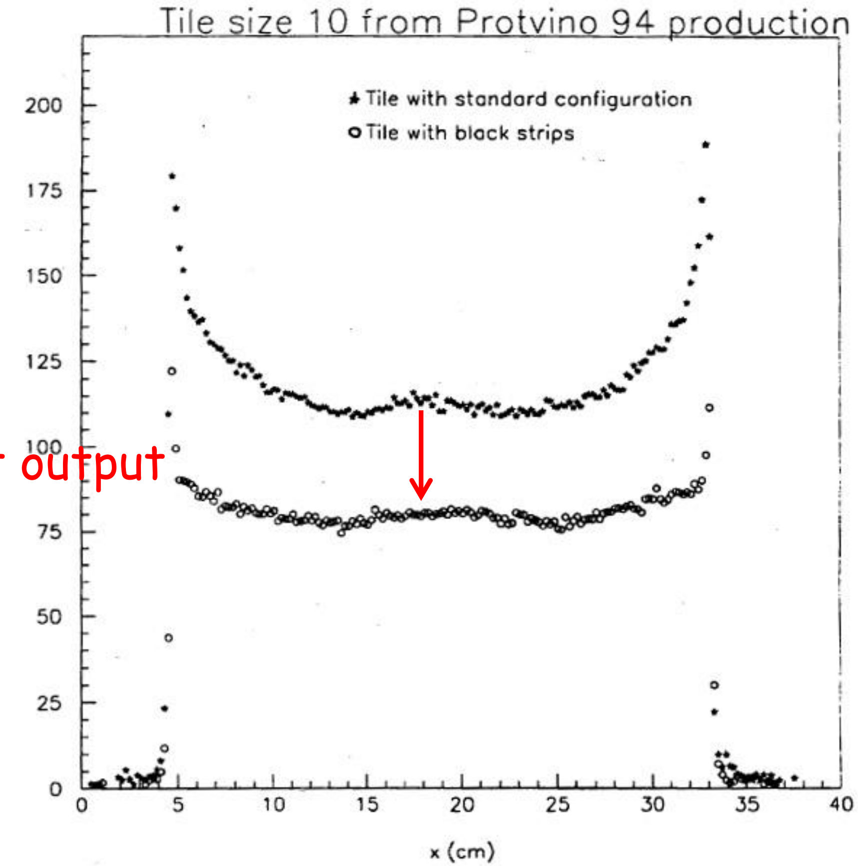


2D light collection scans

Tilecal layout, scintillating tiles

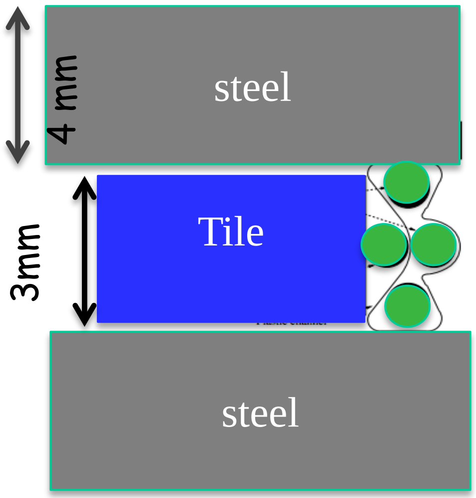
First trial with black strips to improve uniformity



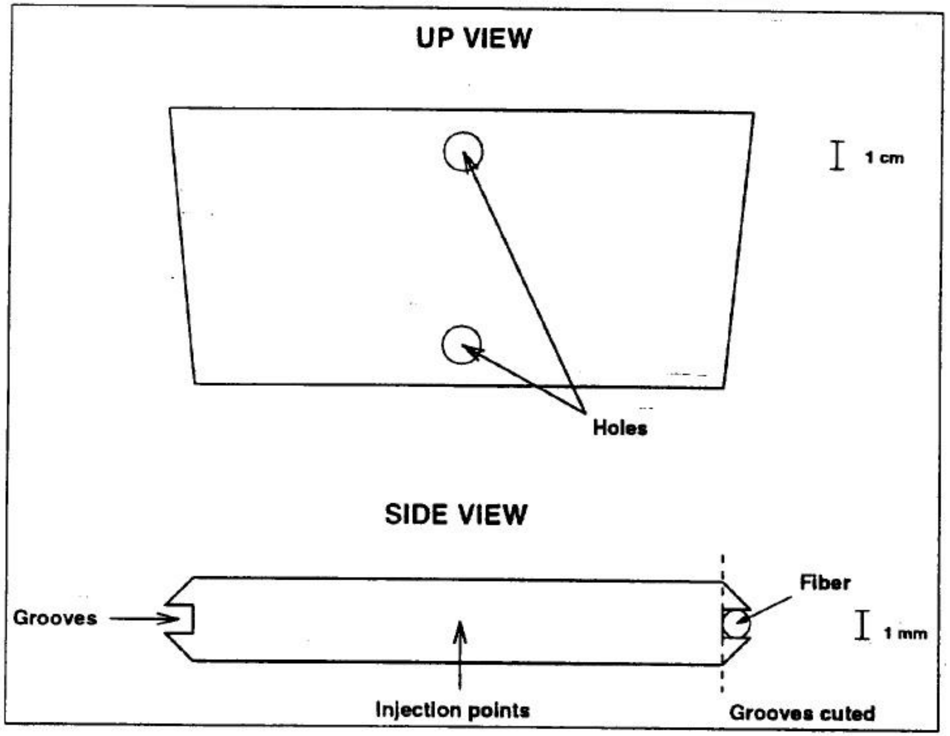


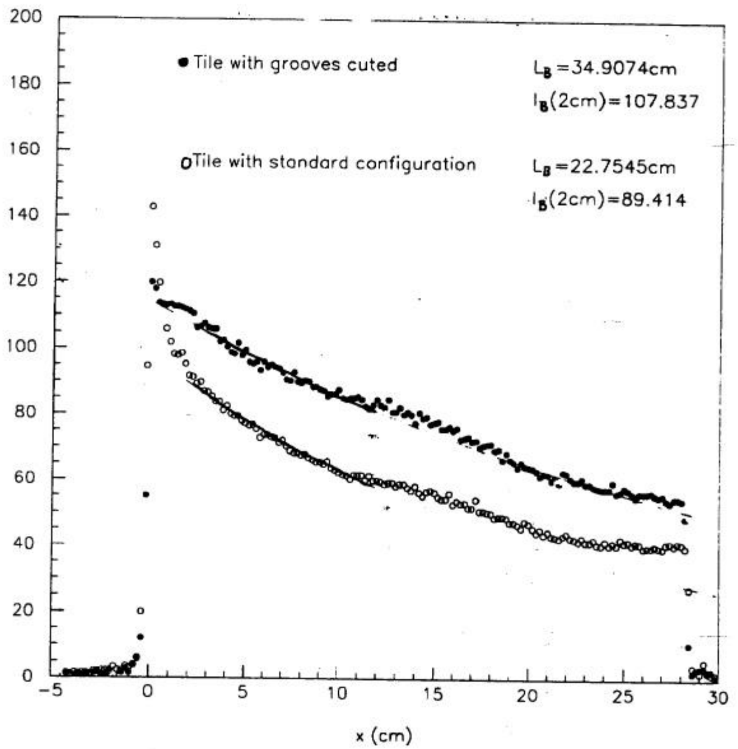
But also cut light output

Tilecal layout, scintillating tiles



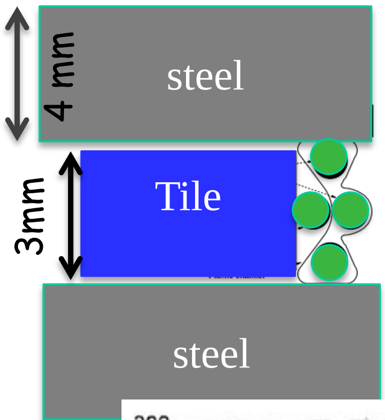
Geometry of the first tiles, with grooves for the fibers



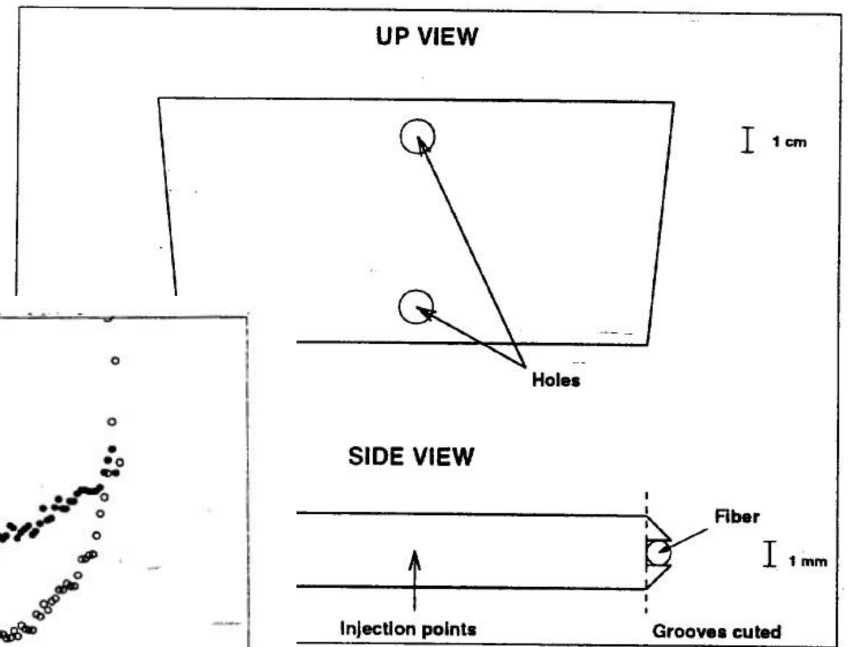


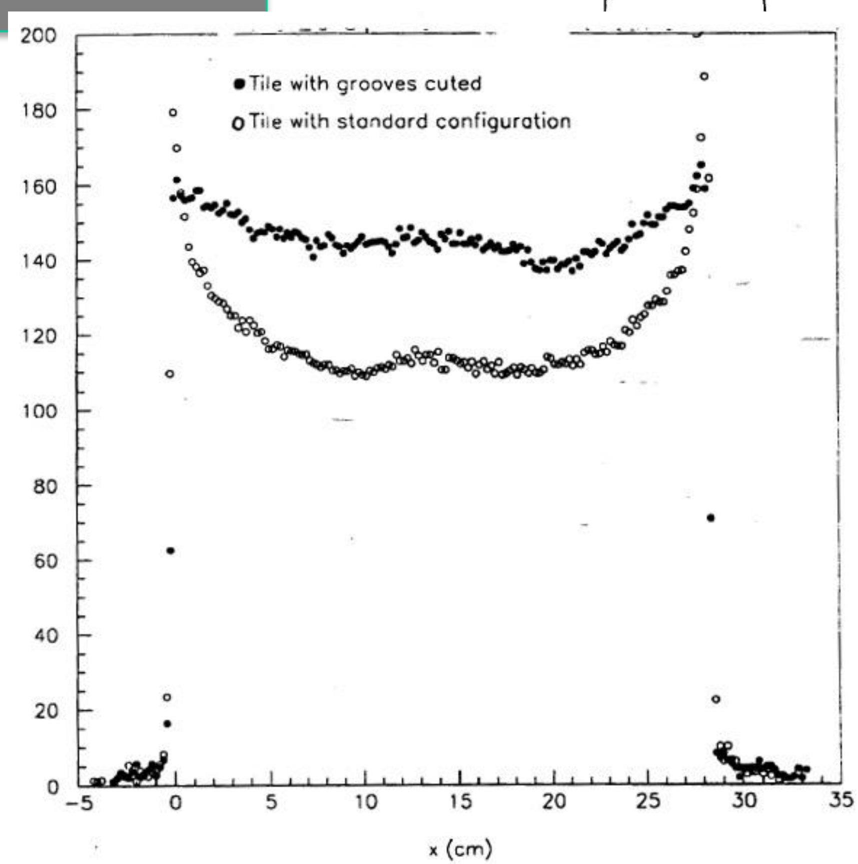
Grooves were cut and the uniformity improved

Tilecal layout, scintillating tiles



Geometry of the first tiles, with grooves for the fibers

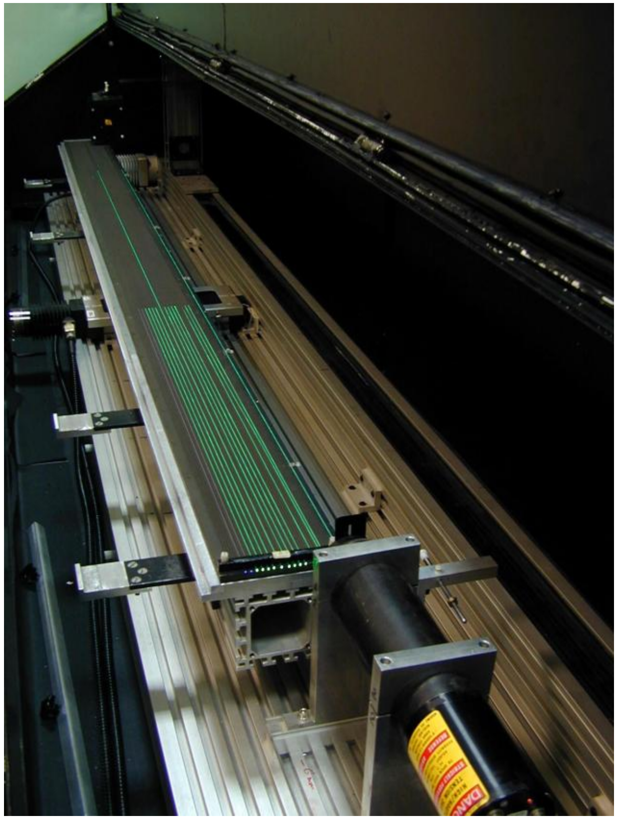




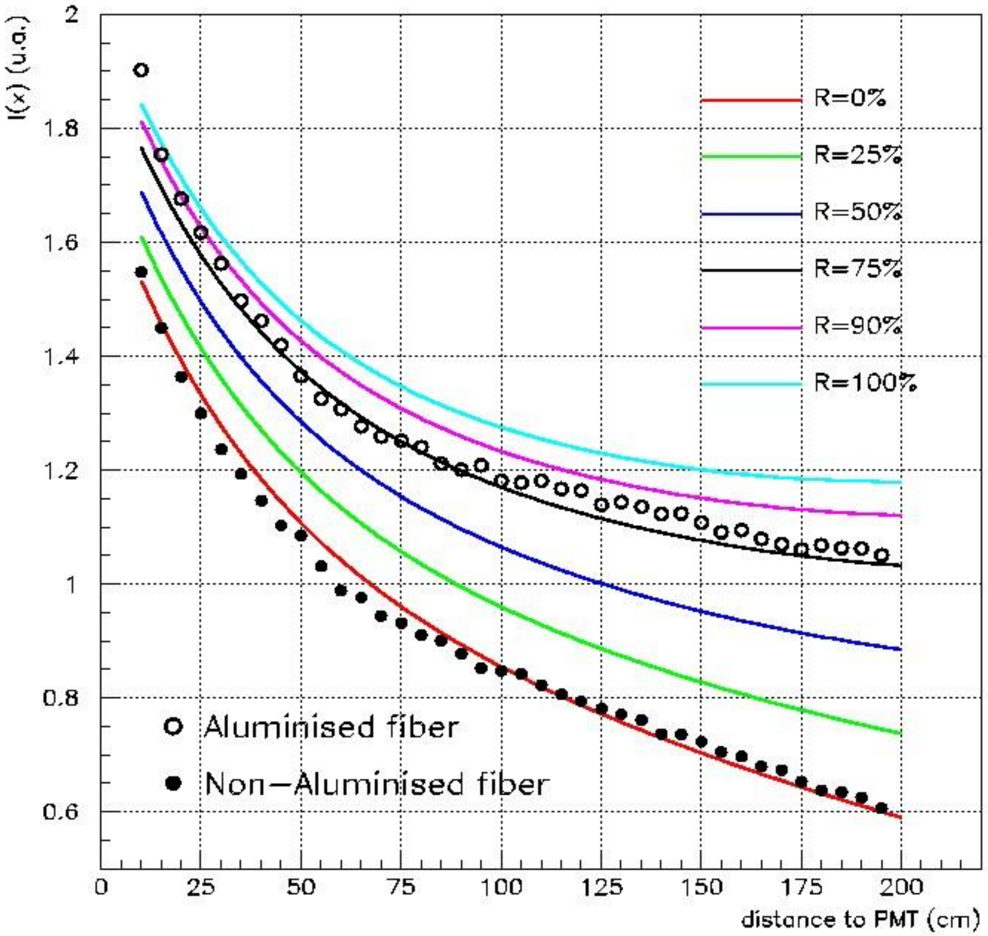
In the end both techniques used to improve uniformity:

- No grooves
- Black strips in longer tiles (masks)

WLS optical fibers



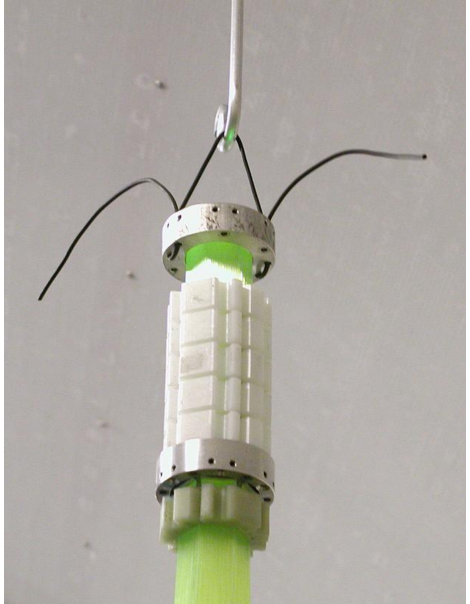
Light output vs distance

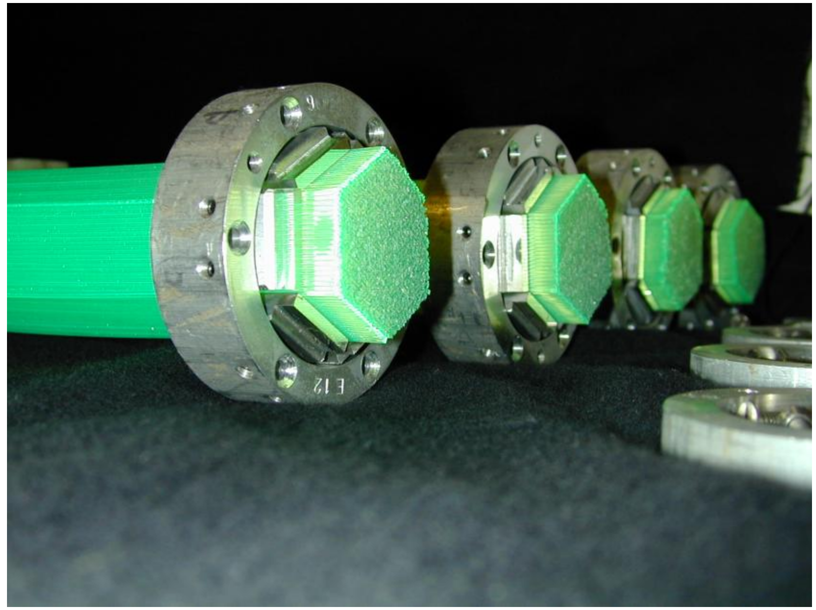


Aluminium mirror at the end allows:
- to improve light collection
- to improve uniformity of light collection in the fiber-scintillator contact area

WLS optical fibers (~620000)

(preparation for mirroring)

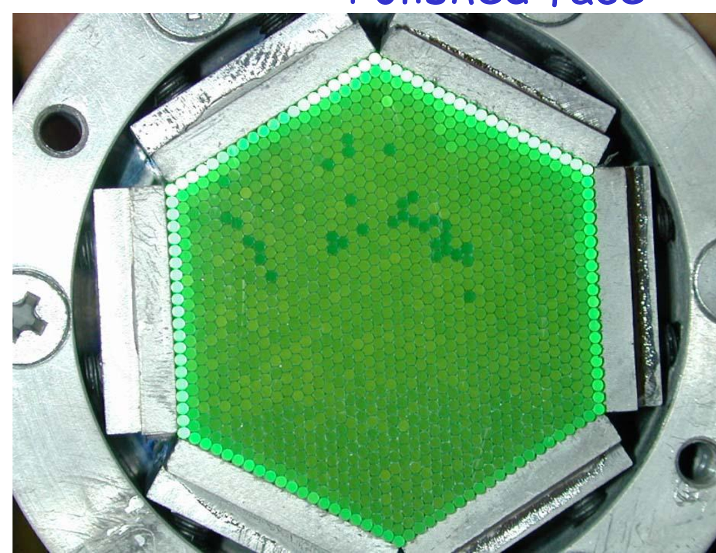




Rods with 1261 fibers each

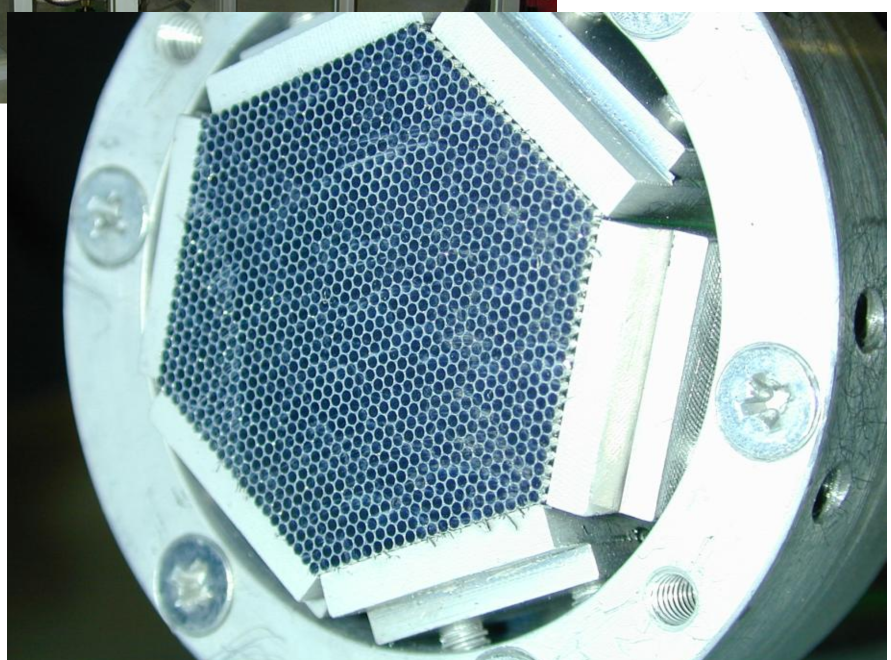
Milling machine to cut/polish

Polished face

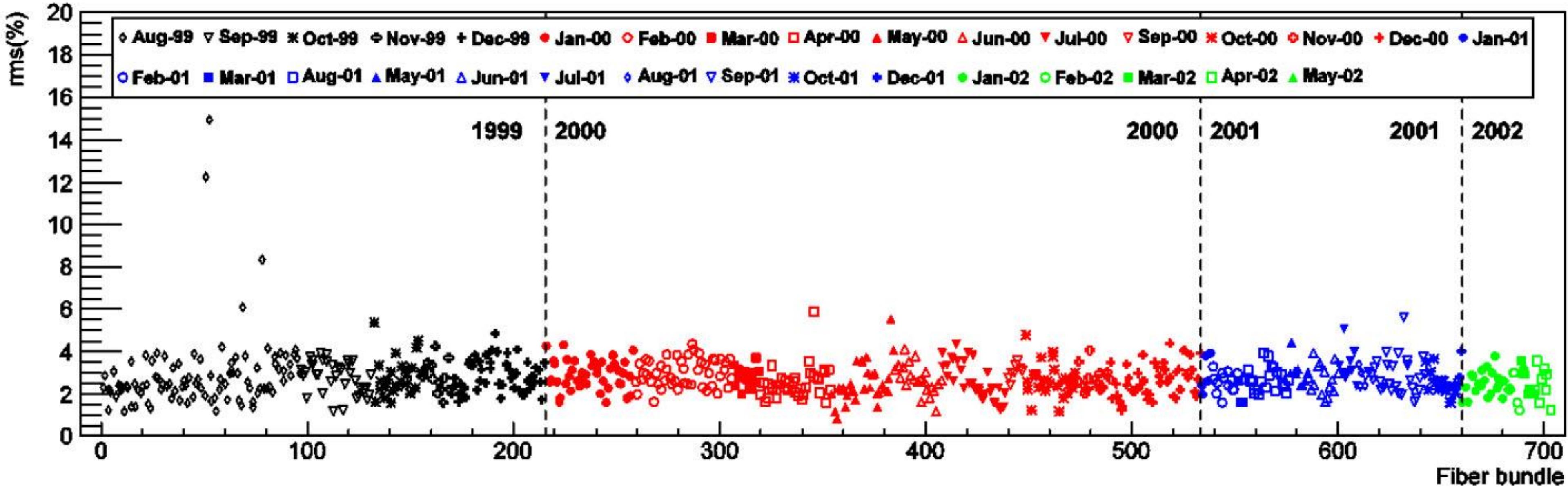


Mirroring the WLS optical fibers

Magnetron sputtering technique



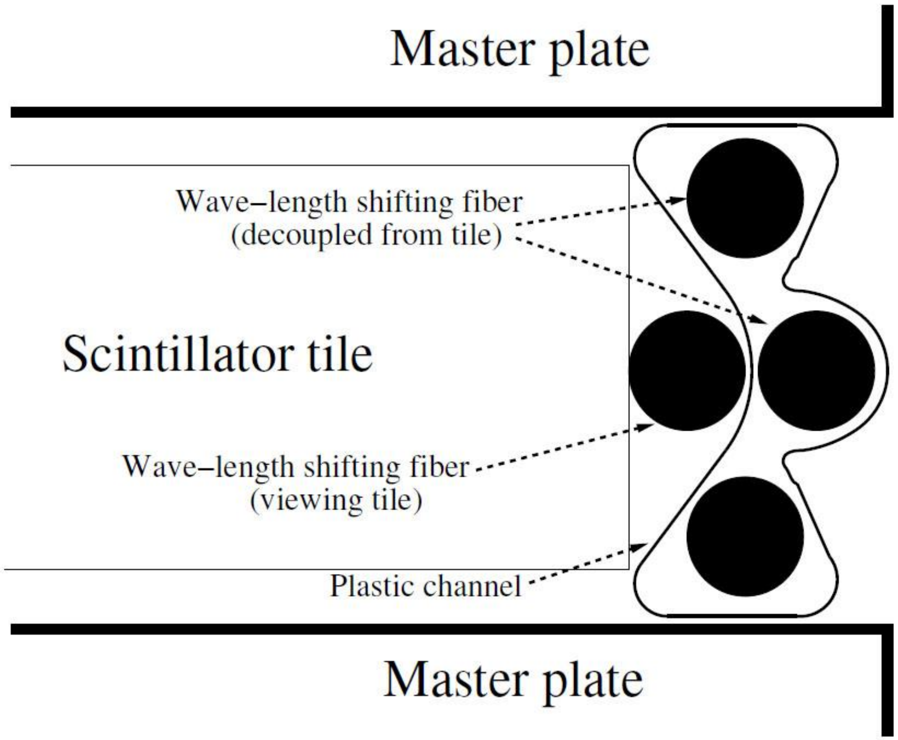
Quality control of the WLS optical fibers

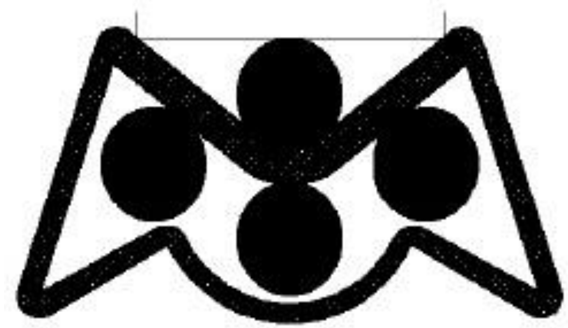


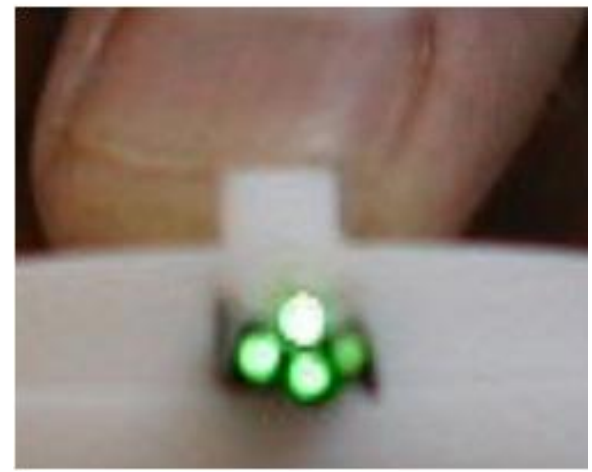
Dispersion of light output in each bundle (3 bundles above 7% redone)

Average reflection coefficient ~70%

How to insert the 620k WLS optical fibers?

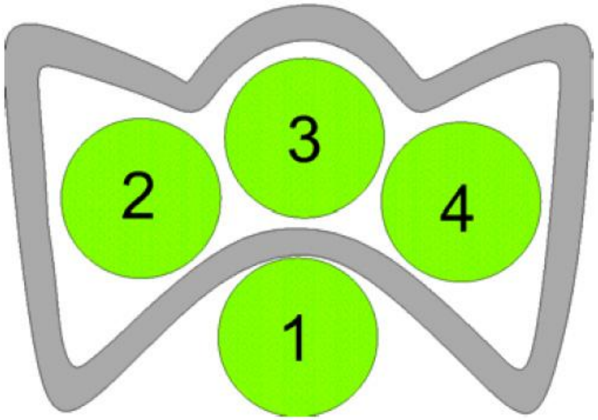






Invented long plastic profiles:
Length: 1.5 m
Width: 4 mm
Height: 2 mm
Thickness: 0.1 mm
Need to be opaque (black plastic)
Need to be excellent reflector: painted white with ink used in road signs
Need to hold in place mechanically

How to insert the 620k fibers in the 160k profiles?

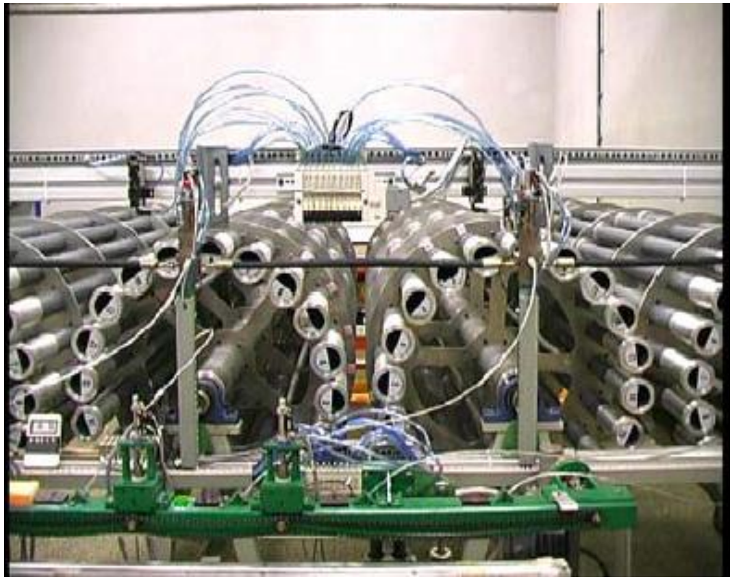


3 or 4 fibers in each profile

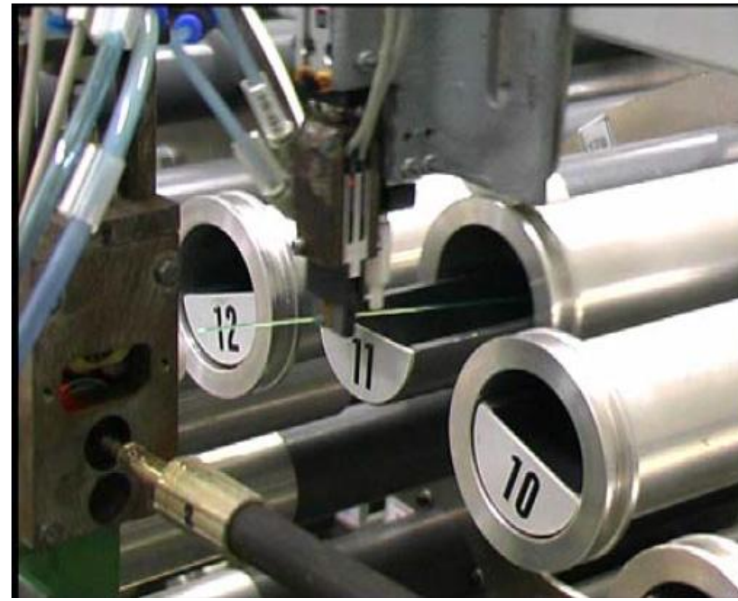
Manually it would take years, need several people, and probability of errors was high: Many combinations of 28 fiber lengths and 4 types of profiles

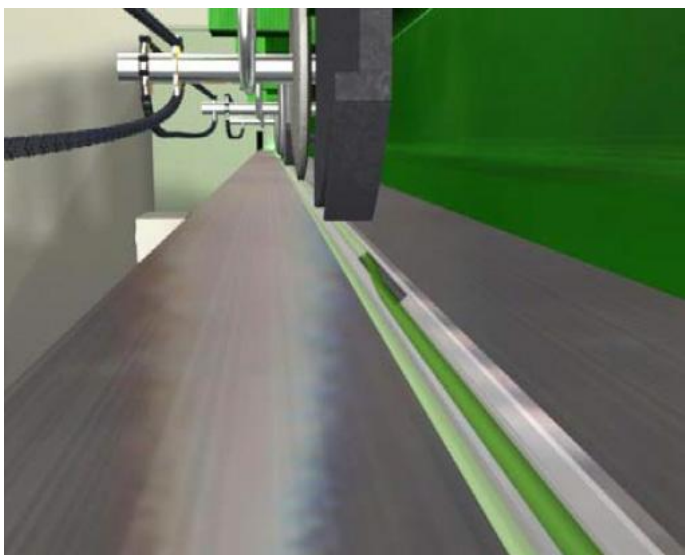
Solution: a robot

Inserting the fibers in the profiles

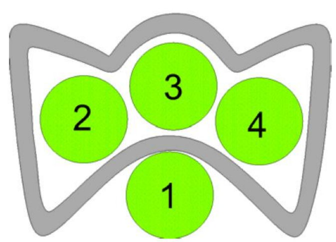


picking a fiber from the drums





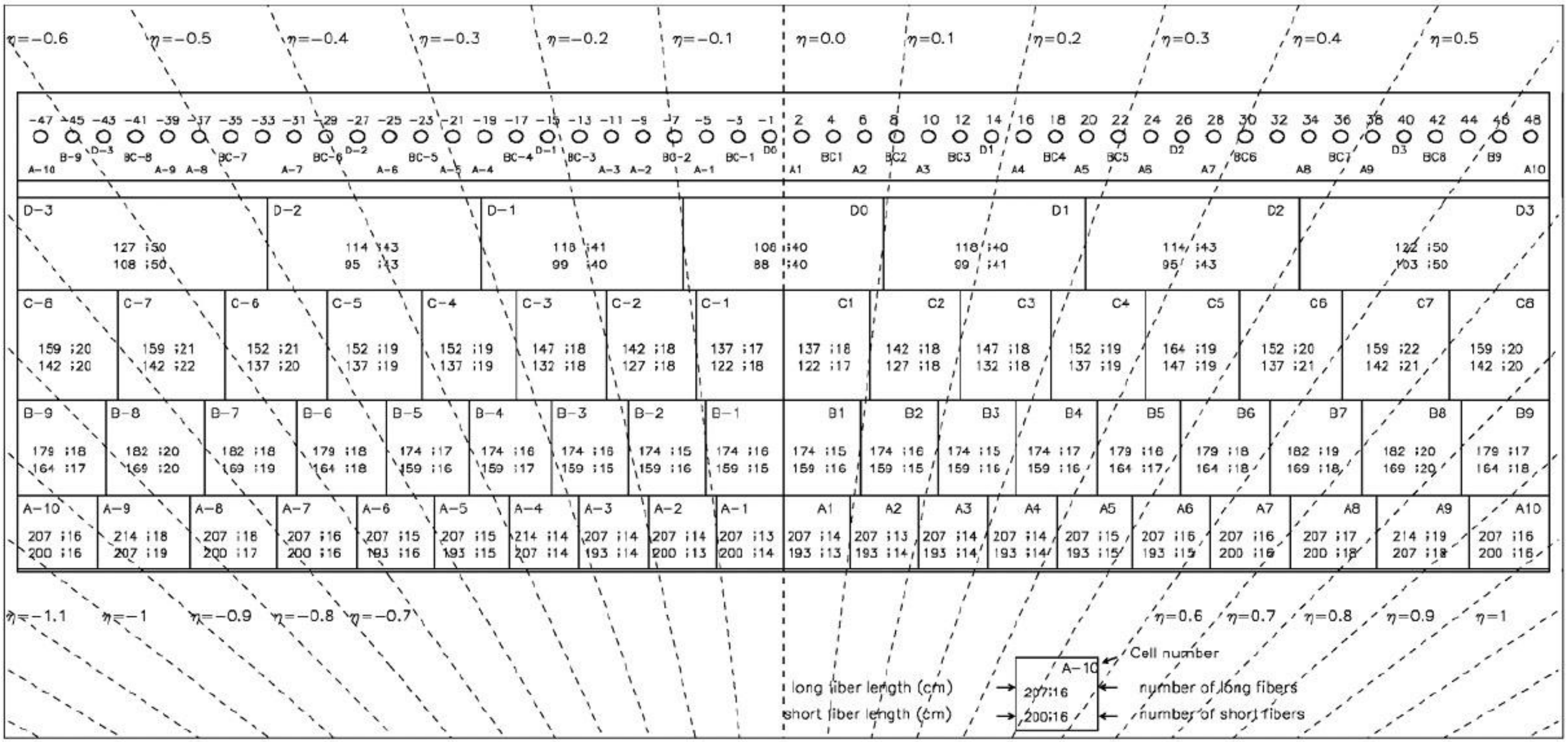
guiding a fiber inside the profile



gluing the fibers: not automatic

Tilecal cell structure – central barrel map

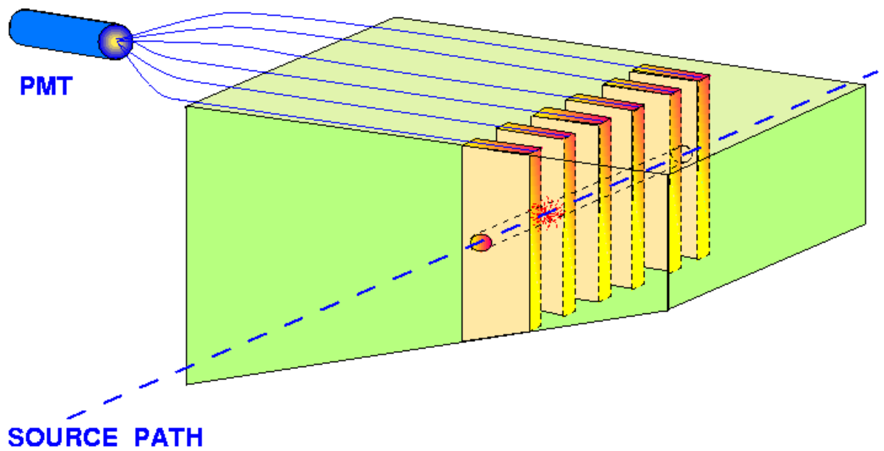
Cells obtained grouping many fibers in front of one PMT



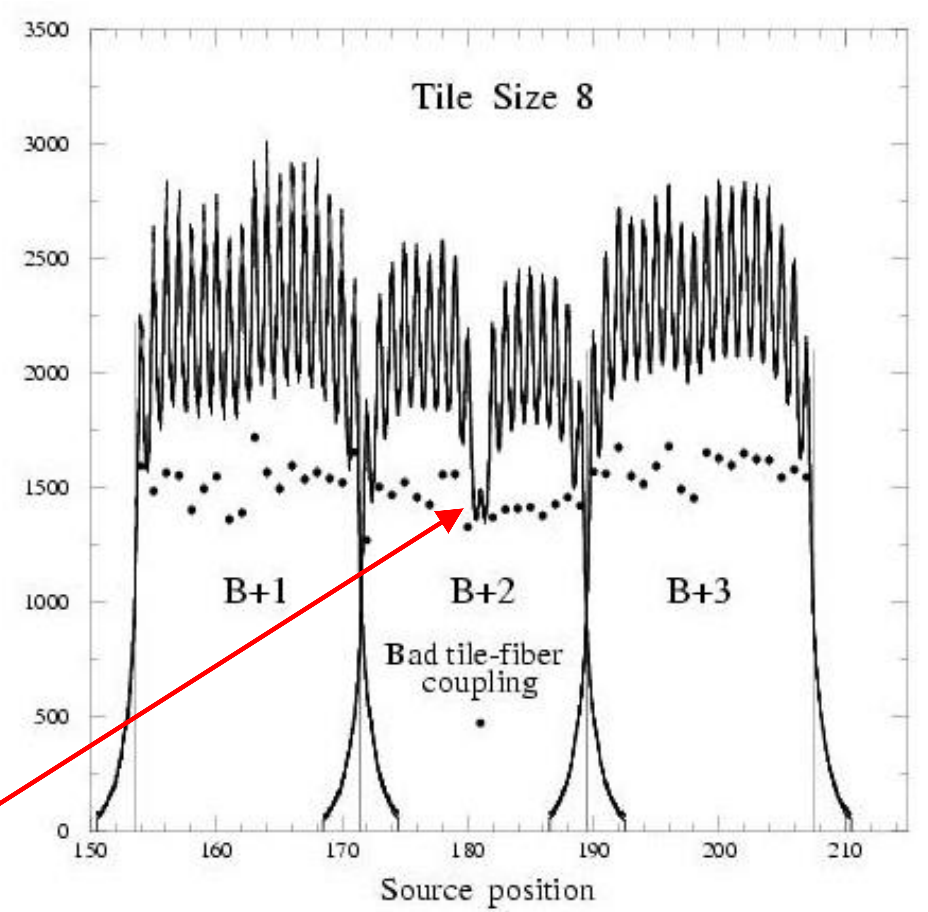
Cell structure - making the fiber bundles

A mock up needed to make the fiber bundles

Intercalibration using ^{137}Cs radiactive source



Moveable cesium source crosses each scintillator perpendicularly



Peaks – tile response

Dots – adjusted response from each individual tile (calculated taking into account the distribution of the cesium radiation through the several neighbour tiles)

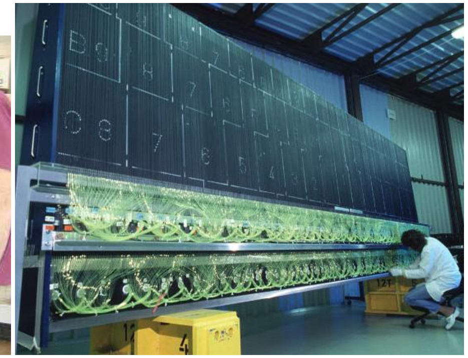
Calibration – equalization of the average response of each cell

Cesium source also used for quality control of the modules

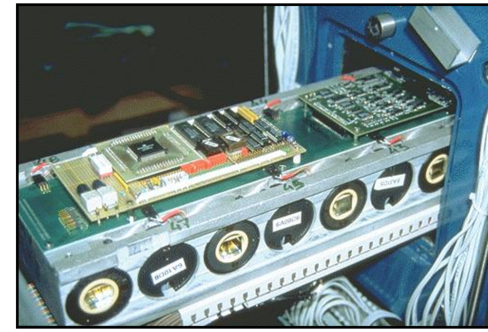
Tilecal from R&D->first collisions ~ 15 years (1993-2009)

1993-1995 R&D

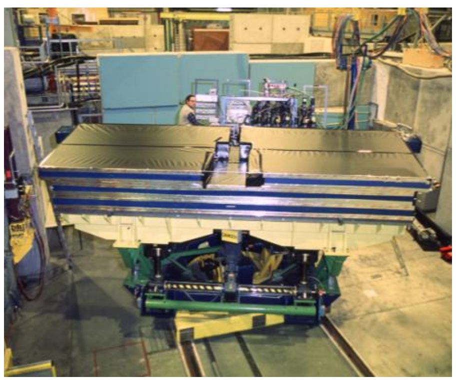
1996-2002:construction)



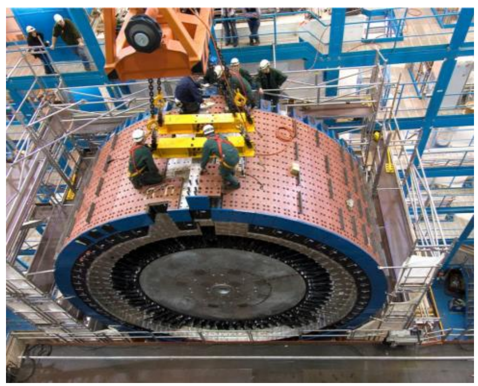
1999-2002 Instrumentation



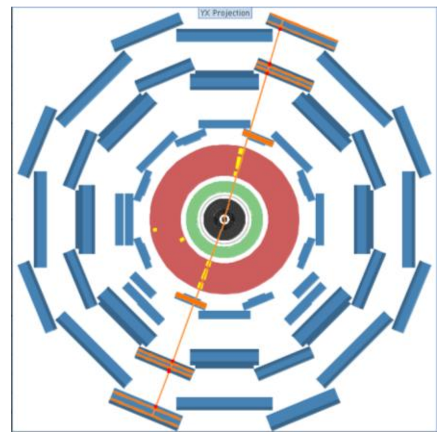
1999-2004: Electronics



2002-2004: calibrations

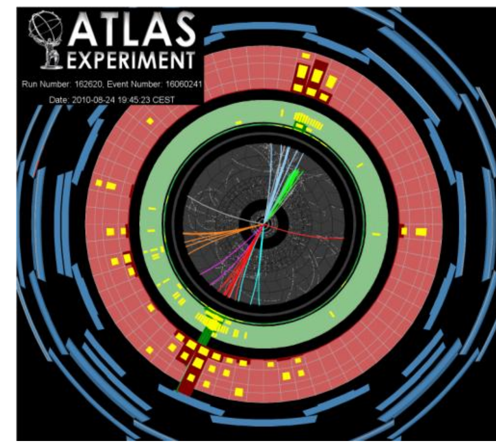


2004-2006 Installation



2007-2009 commissioning

(Mostly with cosmics)

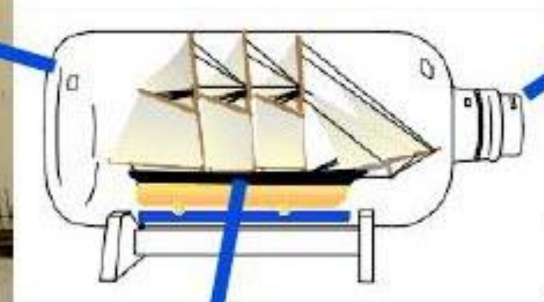


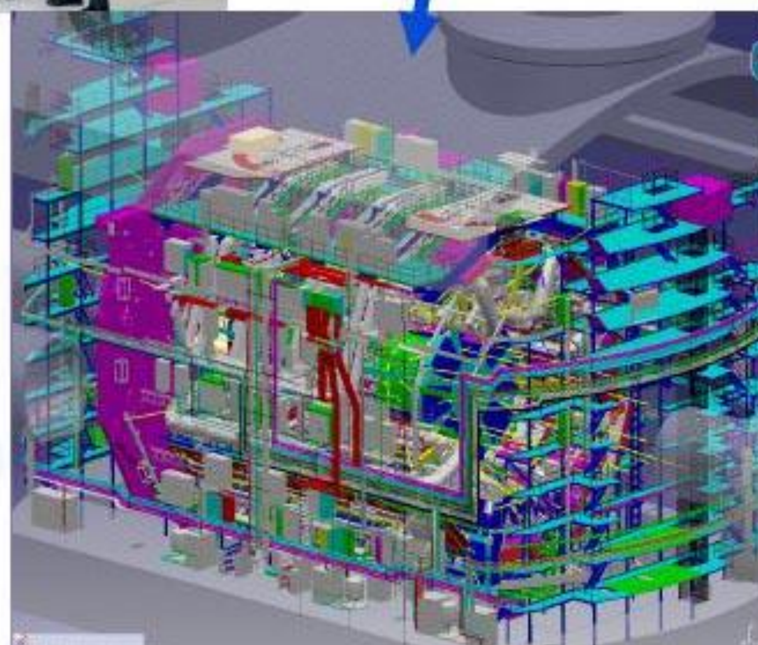
2009: first collisions

A long way to arrive to the excellent performance of Tilecal in ATLAS/LHC

Construct ATLAS = put the ship inside the bottle

June 2003

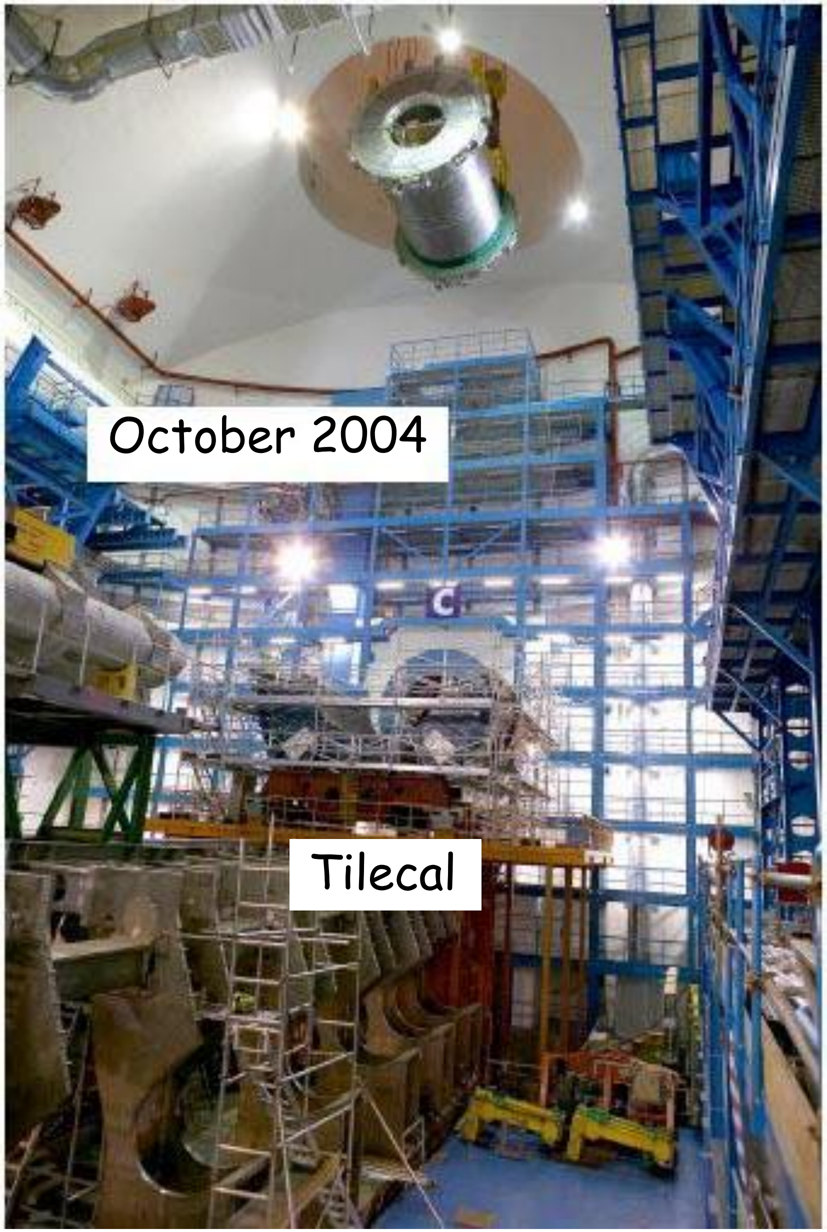




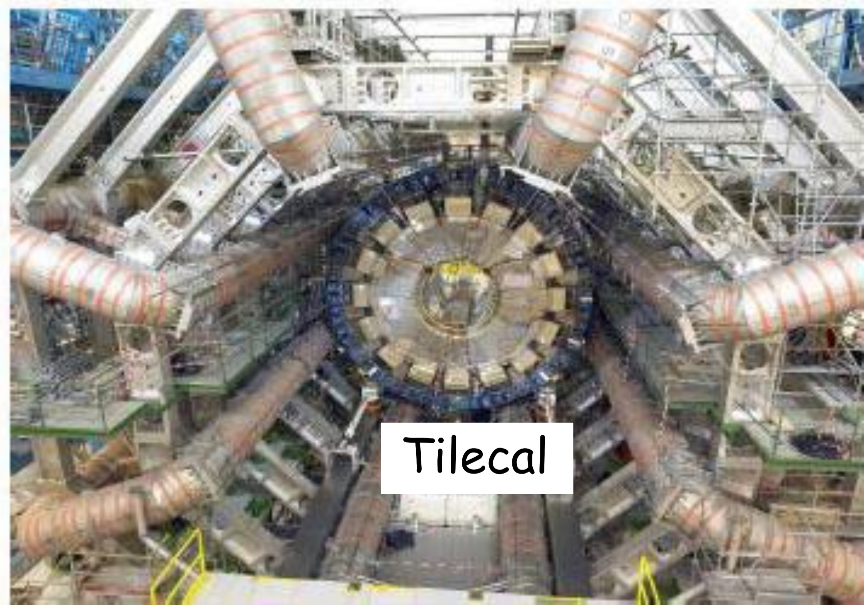
92 m deep cavern

Length: 55m
Width: 32m
Height: 35m

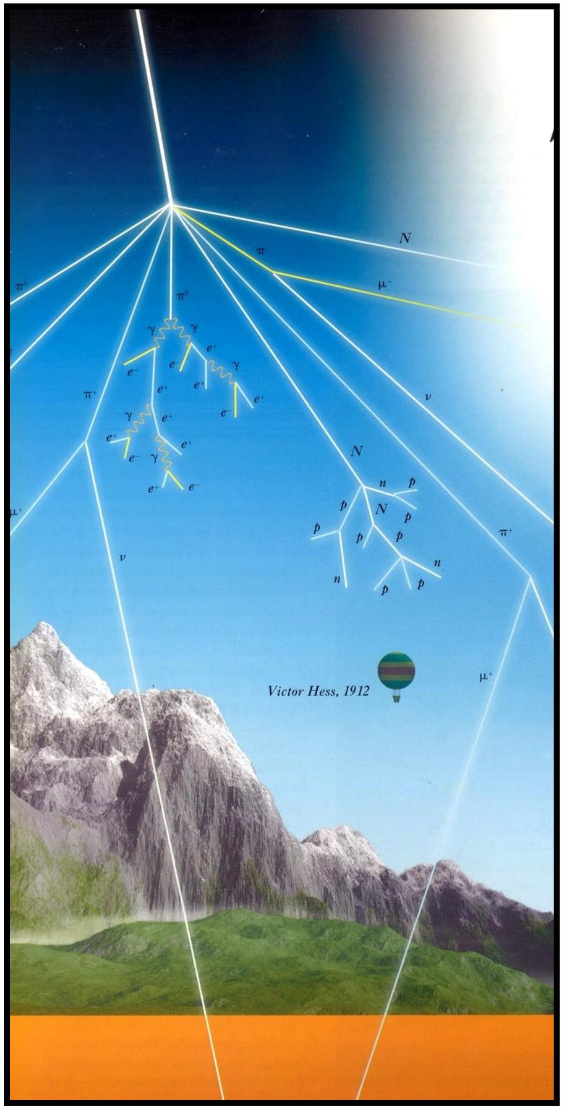
ATLAS construction



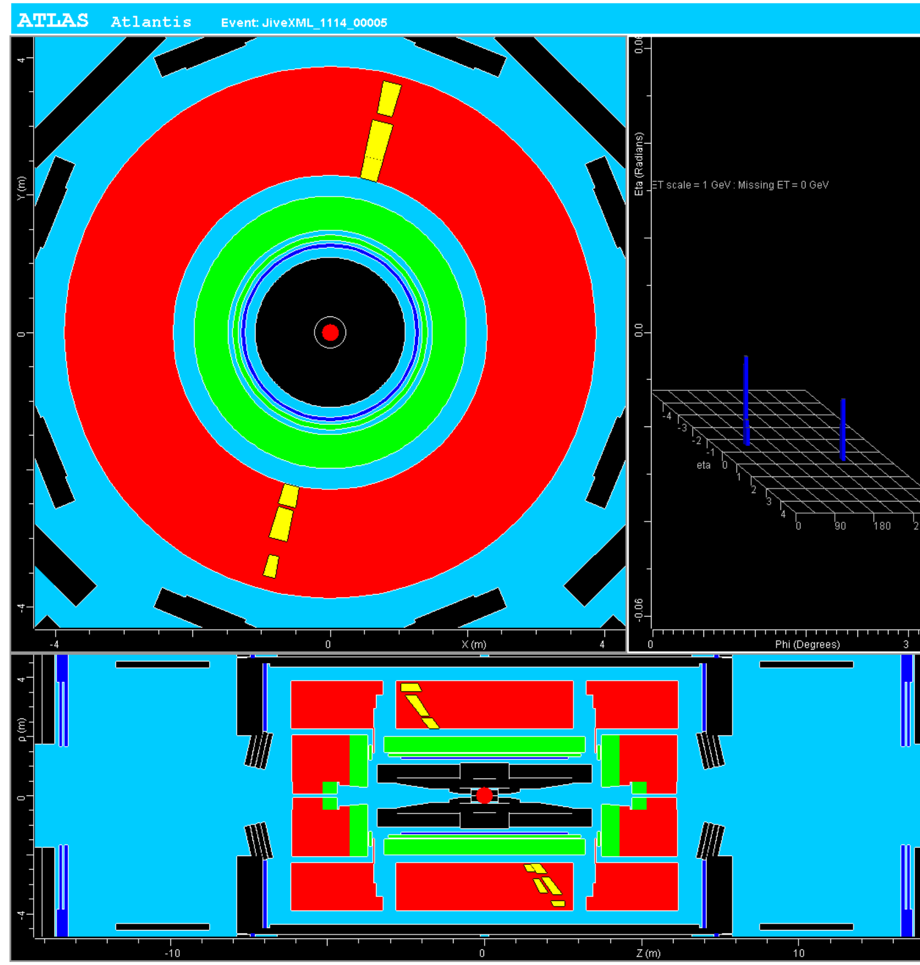
November 2005



Tilecal alone detects cosmic muons



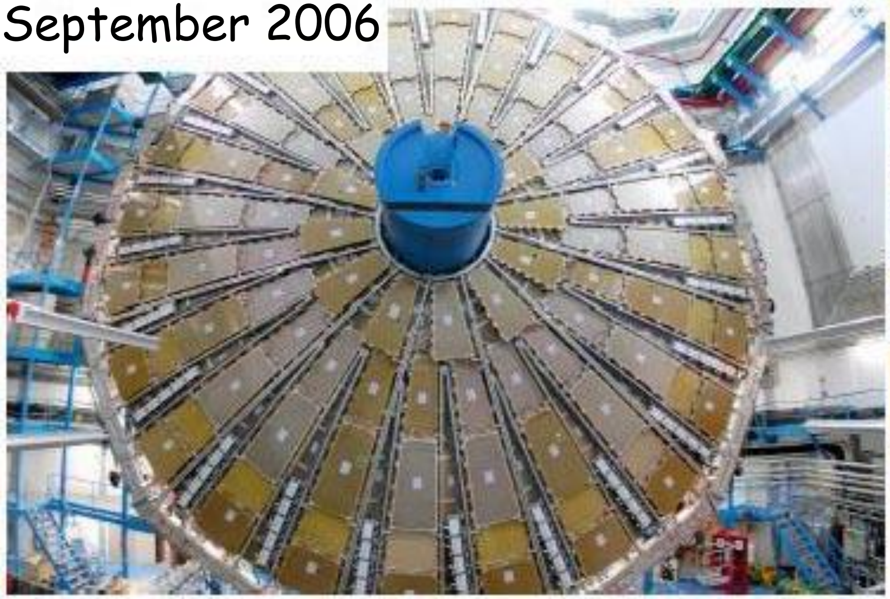
July 2005



Tilecal is the first sub-detector operational in the ATLAS cavern

ATLAS construction

September 2006

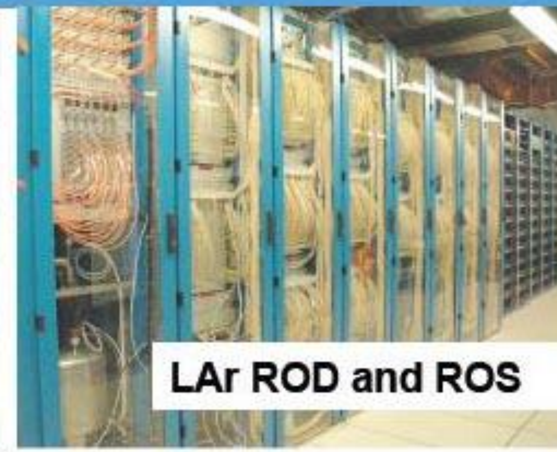


September 2007

February 2008

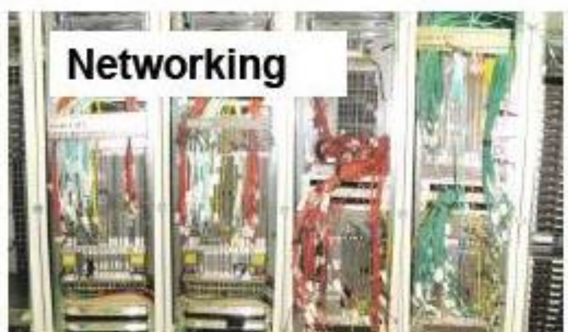
ATLAS construction (2008)

Trigger / DAQ / Control



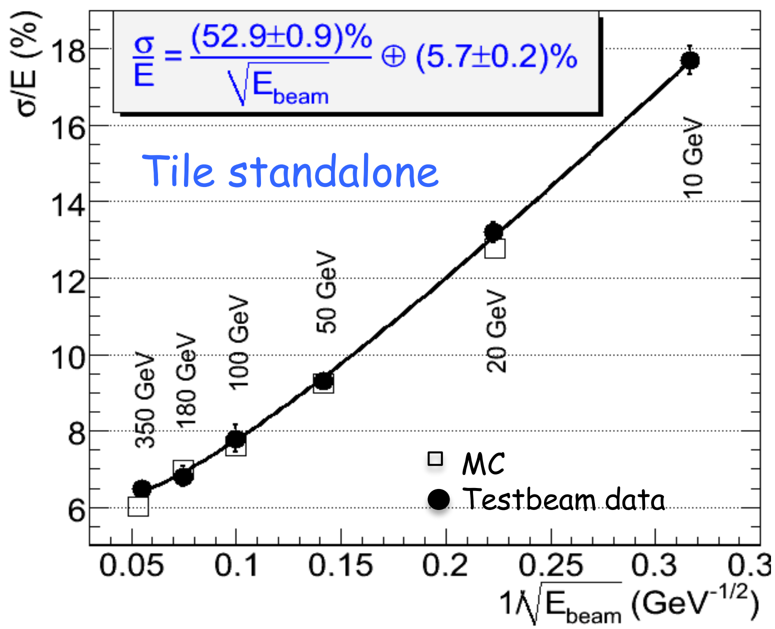
Full Online system being exercised since ~2 years

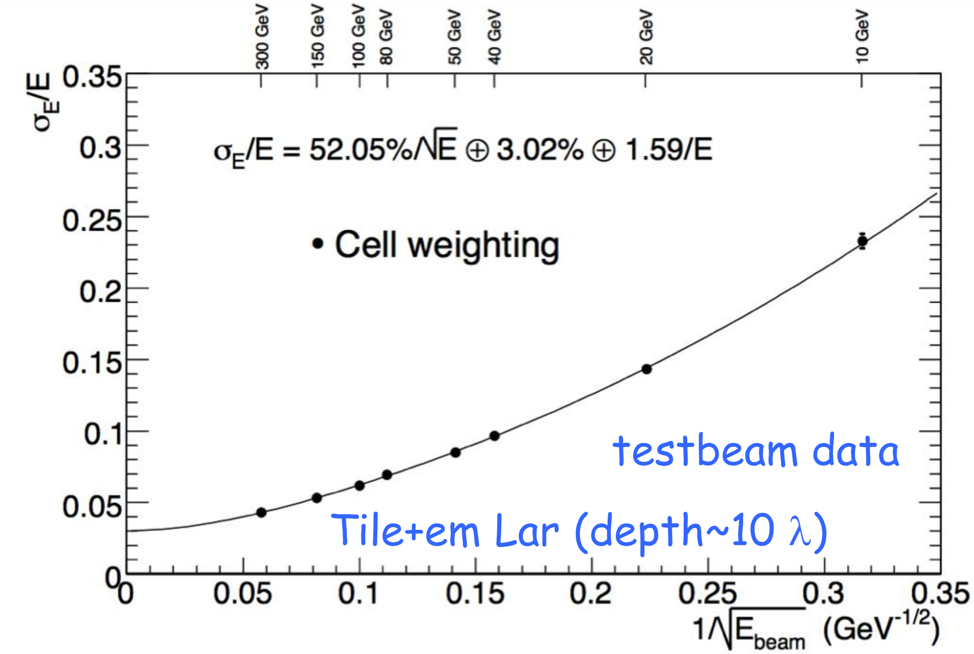
H/w now being completed - Ready for data-taking

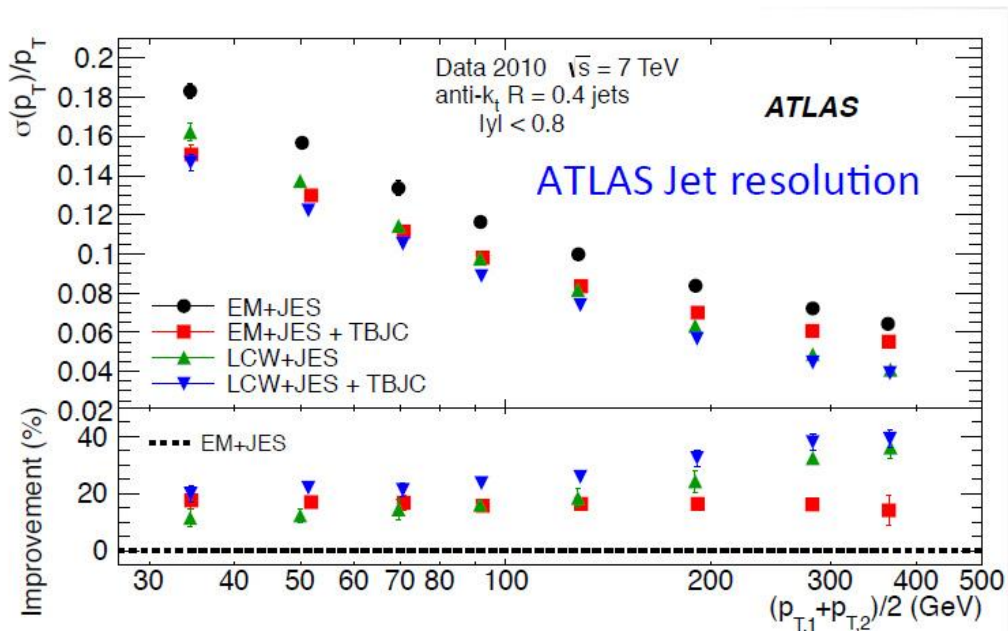


π resolution in testbeams->jet resolution in ATLAS

|η|=0.35 (depth=7.9λ)







Good performance thanks to >10 years R&D, test-beams, MC tuning, cosmics

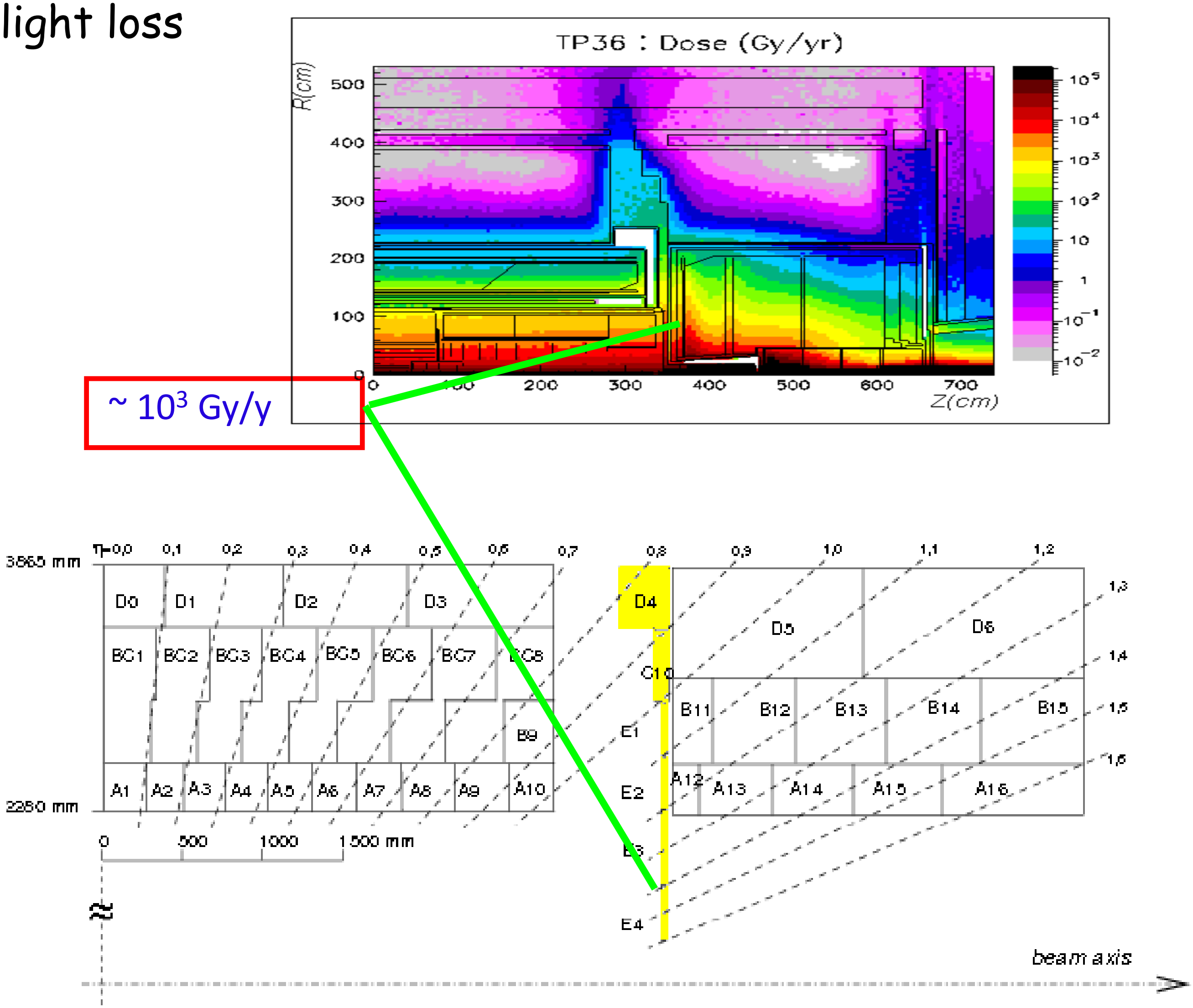
Jet resolution close to design:
- constant term ~3%
- Pile-up worsens low p_t resolution
- Improvements after pile-up corrections for in-time/out-time bunches/noise threshold tuning, etc.

Upgrades

Tilecal upgrades for Long shutdown 2019

Tilecal scintillators and WLS fibers do not need replacement.

Exception: long scintillators in the gap/crack region that suffer significative radiation damage causing light loss



Cryostat scintillators covering the rapidity range from 1.2 - 1.6 are in a high radiation environment, 1 kGy/year

Need to investigate radiation hard scintillators and WLS fibers and replace them

Tilecal upgrades for Long shutdown 2023-2024

Replace detector electronics (except PMTs, but studies ongoing – next slides)

Motivation:

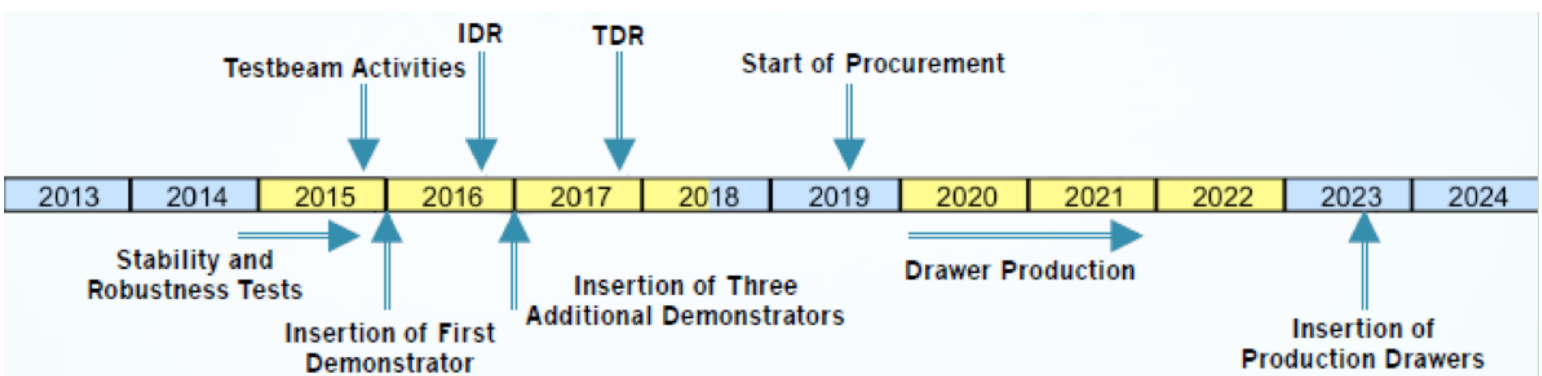
- Increasing Luminosity and pile-up require:
  - Better precision at trigger level
  - PMT signals digitized continuously at 40 MHz
- Electronics ageing (>10 years)
- Redundant power & readout → improve reliability

(in Lisbon: design of new High Voltage distribution boards for off detector option)

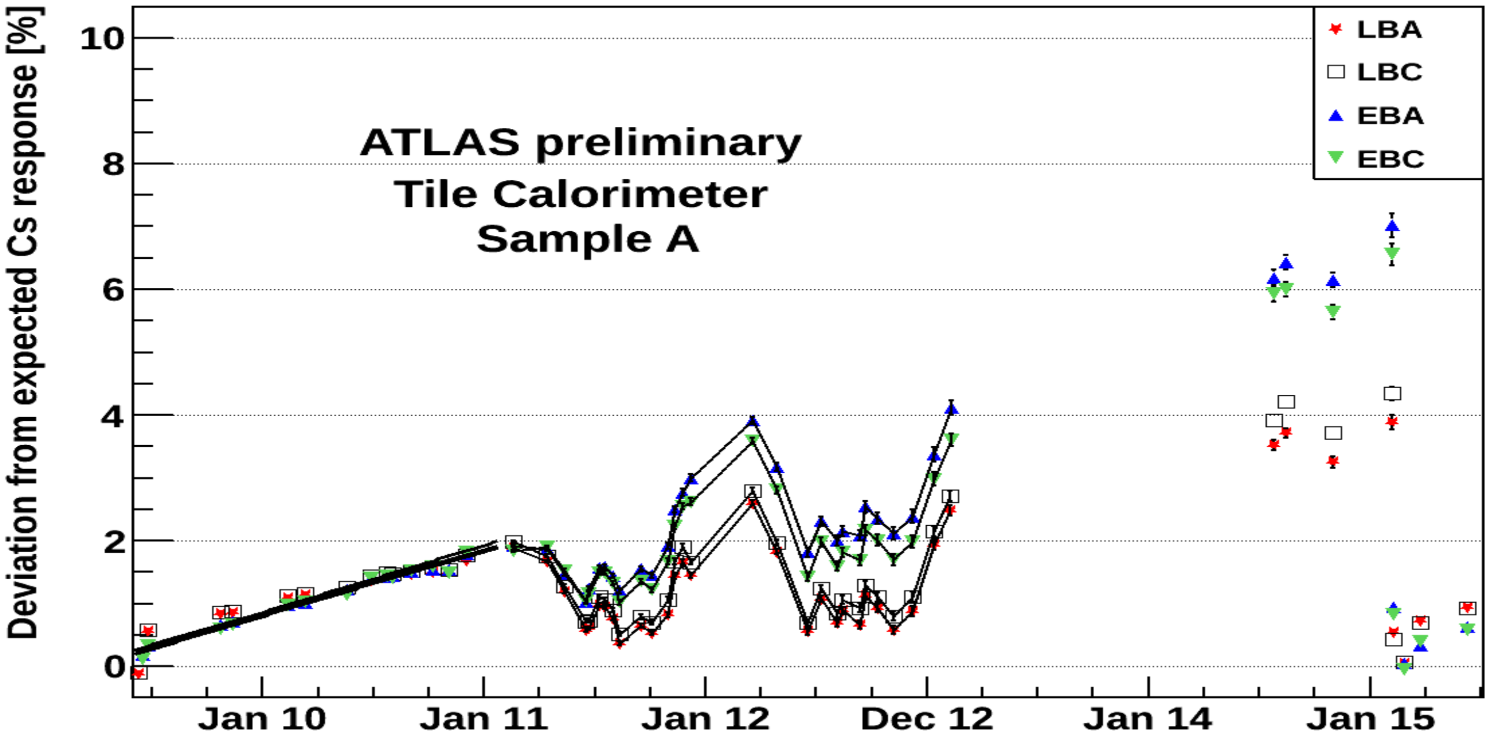
Ongoing validation/tests of a Demonstrator with 3 front-end electronics options:

Next steps:

- Tests/validation in test beams in 2016
- Insert the Demonstrator in ATLAS at the next possible detector opening



Tilecal PMTs response along the years



Triggered discussion on possible need to replace PMTs in the future

Take the oportunity to improve granularity using MAPMTs?

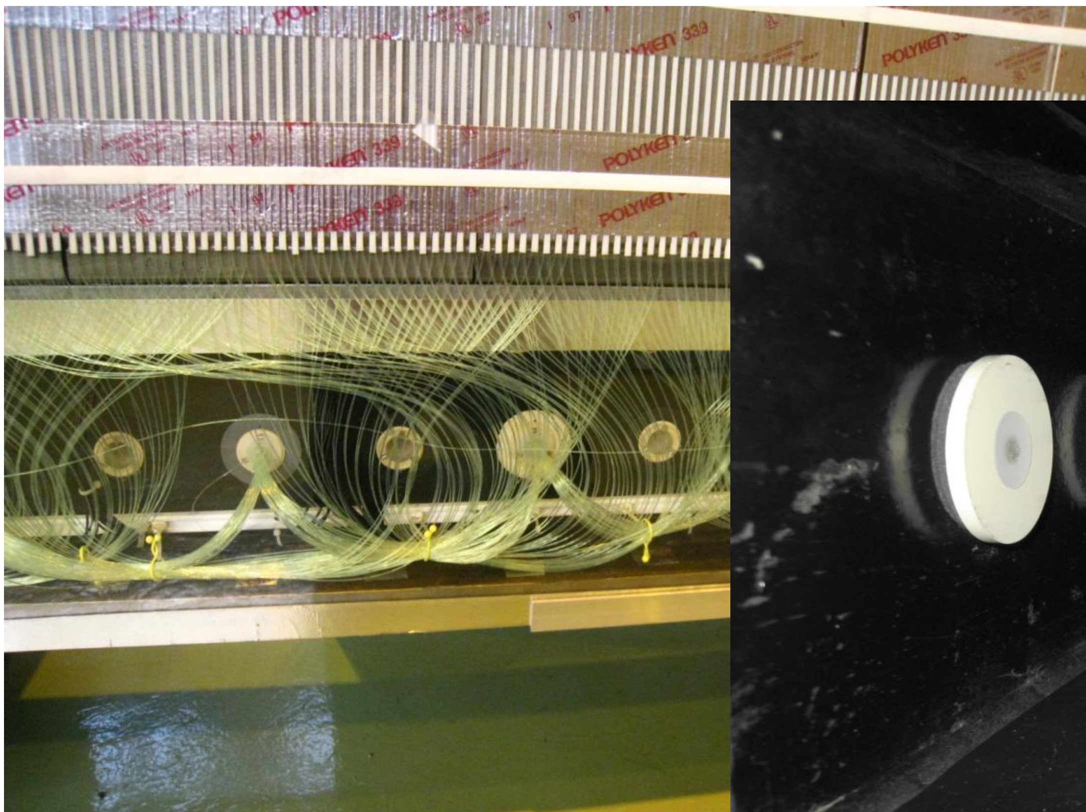
If replacement needed why not MultiAnode PMTs?

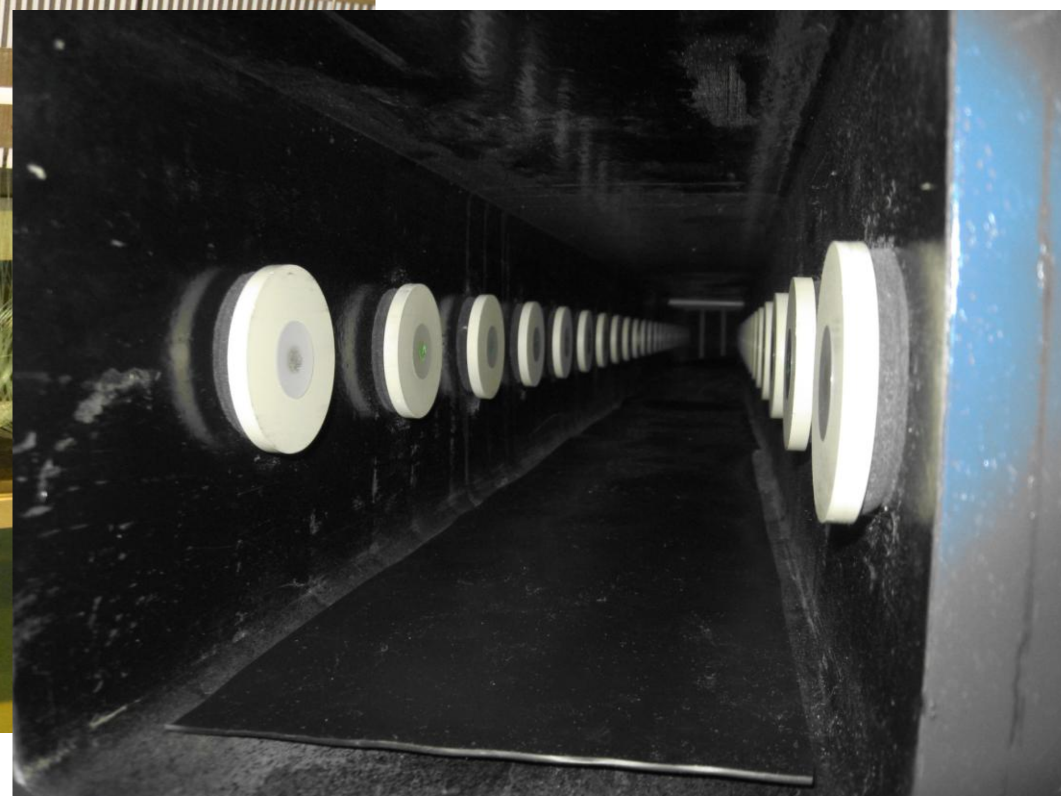
Would it allow better granularity?

How to play with the fibers to improve Tilecal granularity?

Redo fiber bundles? Not possible.

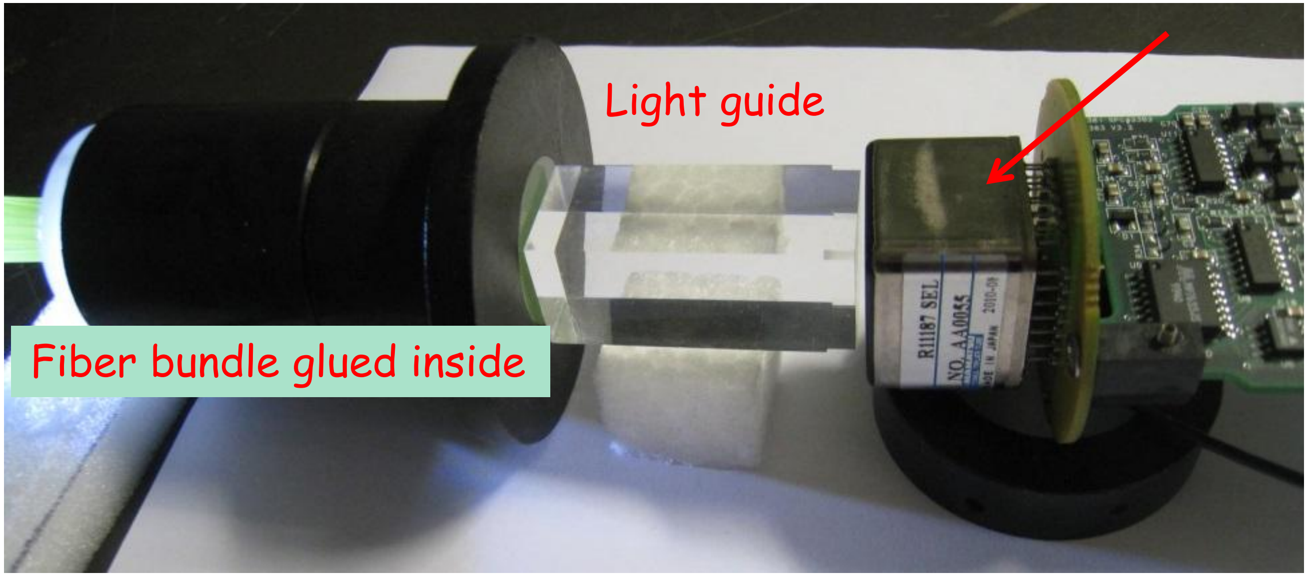
Single fiber output available inside girder in fiber bundles

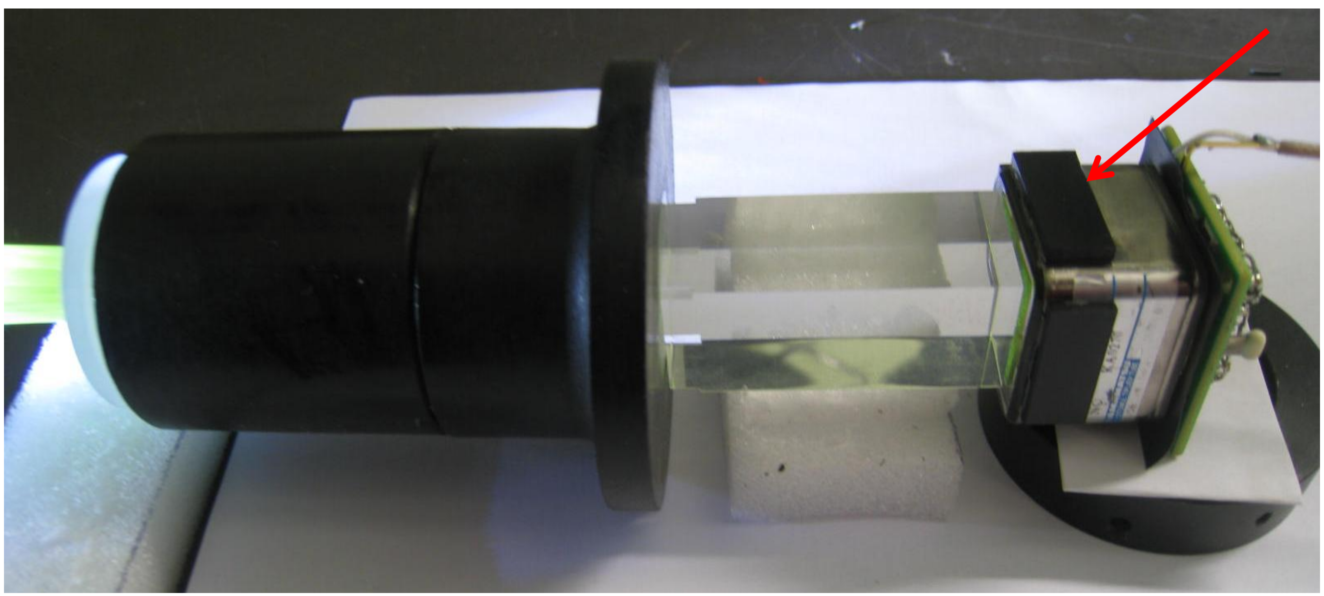




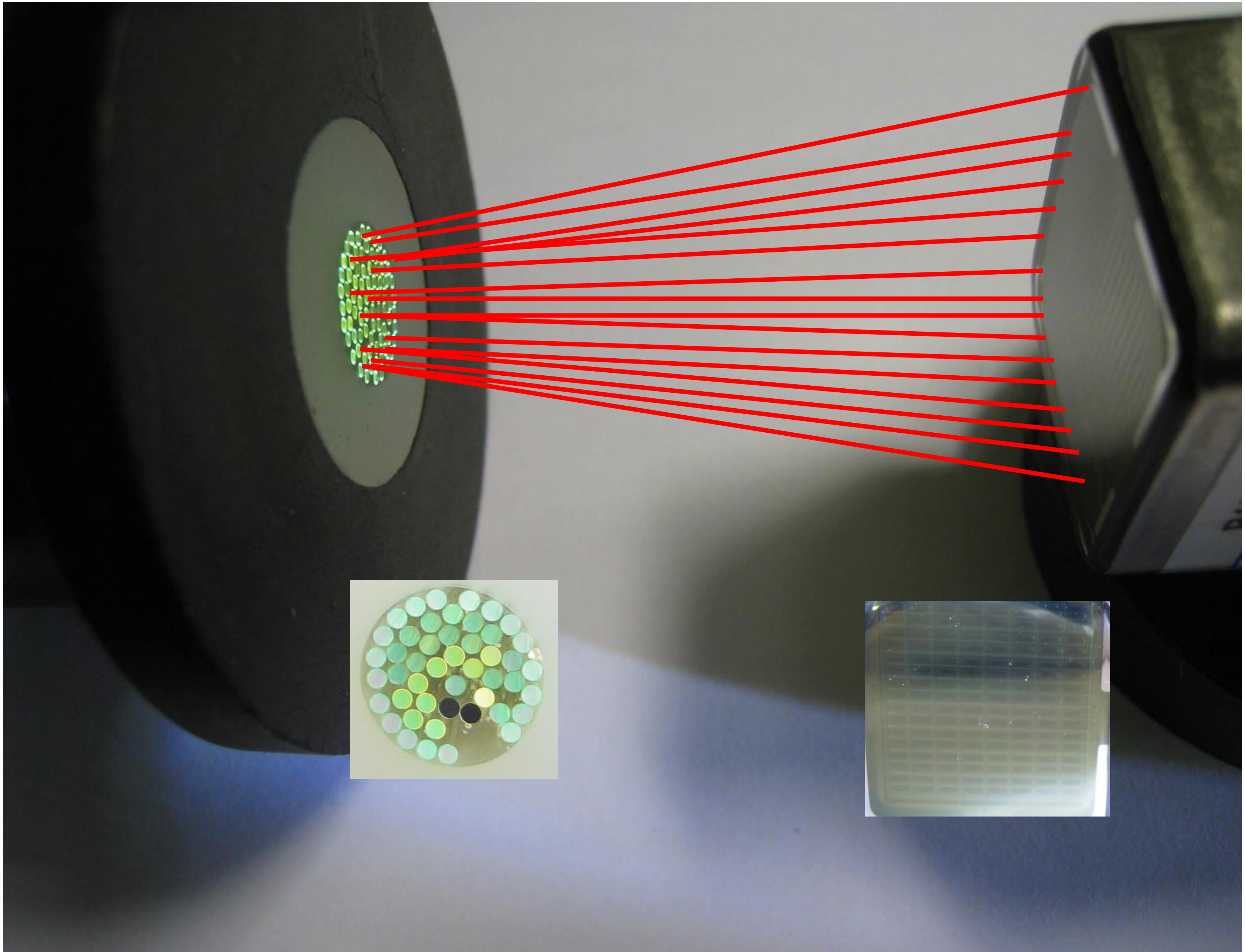
Fiber bundles

Each bundle is unique. The fibers are randomly positioned.


Tilecal PMT
Light guide
Fiber bundle glued inside


MAPMT

Special light guide to guide the light to the MAPMT?



A summary

- The ATLAS Tile calorimeter is essential for identification and precision measurements of ATLAS-LHC physics
- It performed very well during data taking, > 99% of good data for physics
- The performance is in agreement with design goals despite the big pile-up environment
- In long shutdown of 2013-2014 hardware consolidation cured main failures observed in run1
- For High Luminosity LHC Tilecal will upgrade the electronics only
- The construction was an adventure with many "crazy" ideas that resulted
- "Crazy" ideas still appearing to improve optics

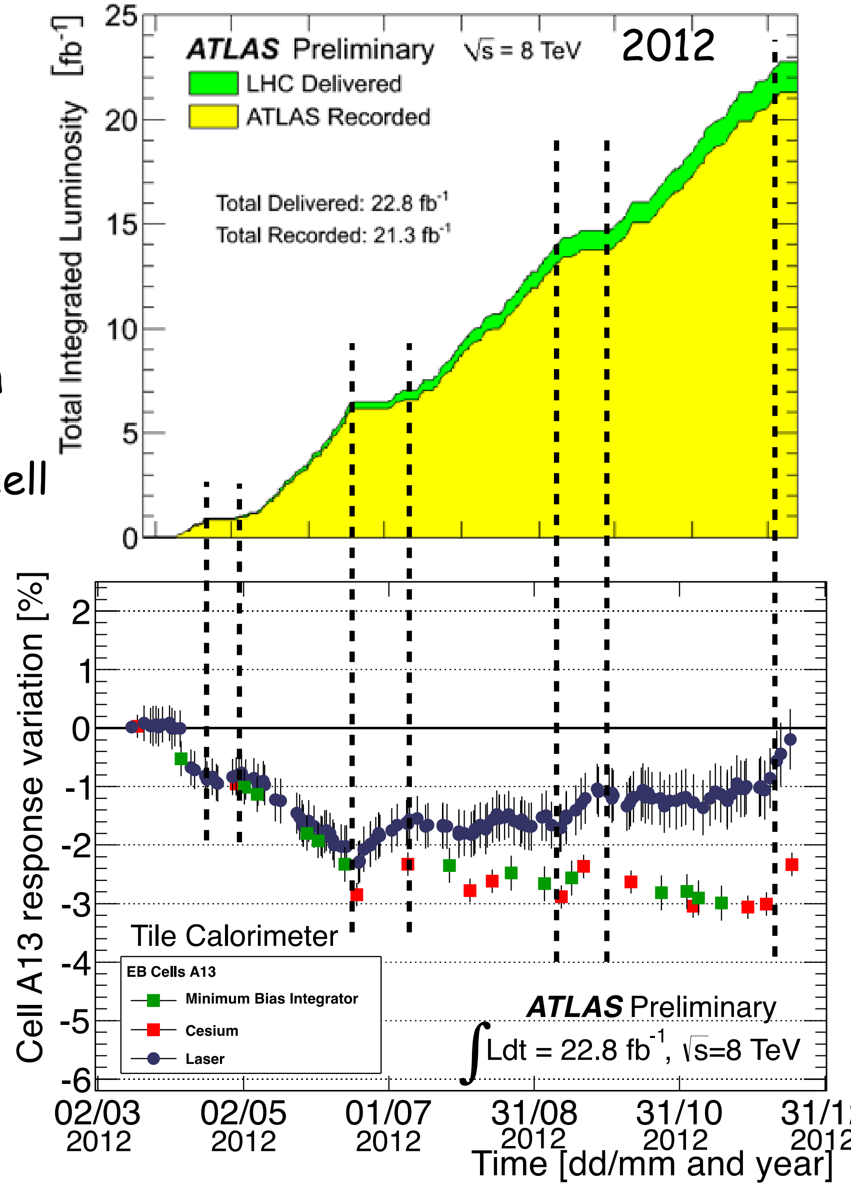
Backup

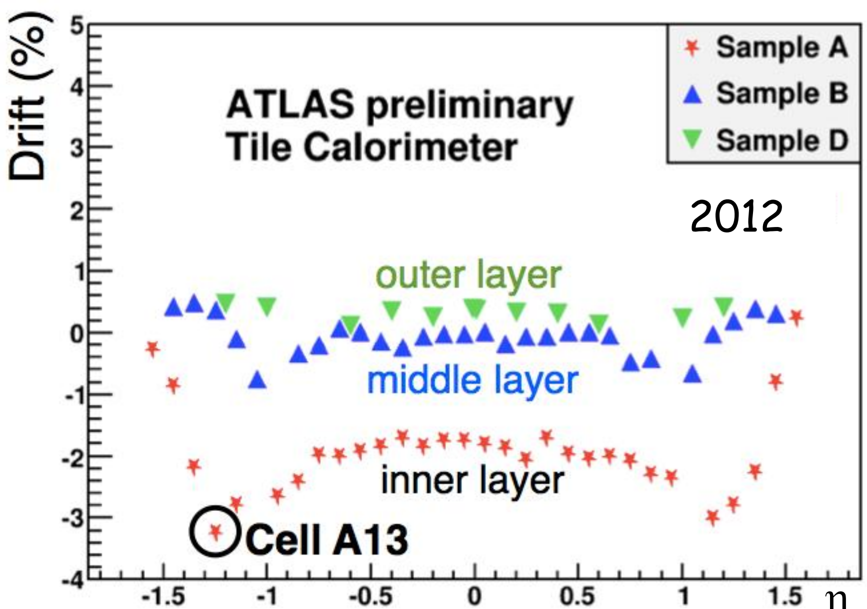
ATLAS Tilecal Calibrations

- ^{137}Cs:
- correct for optics +PMT+ electronics variations.
- Used in test beams to bring em scale to ATLAS + inter-calibrate all 10k channels.
- In run1 used ~1/month
- Laser: ~ 2/week monitor PMT gain + electronics
- Charge injection: ~ 2/week monitor electronics

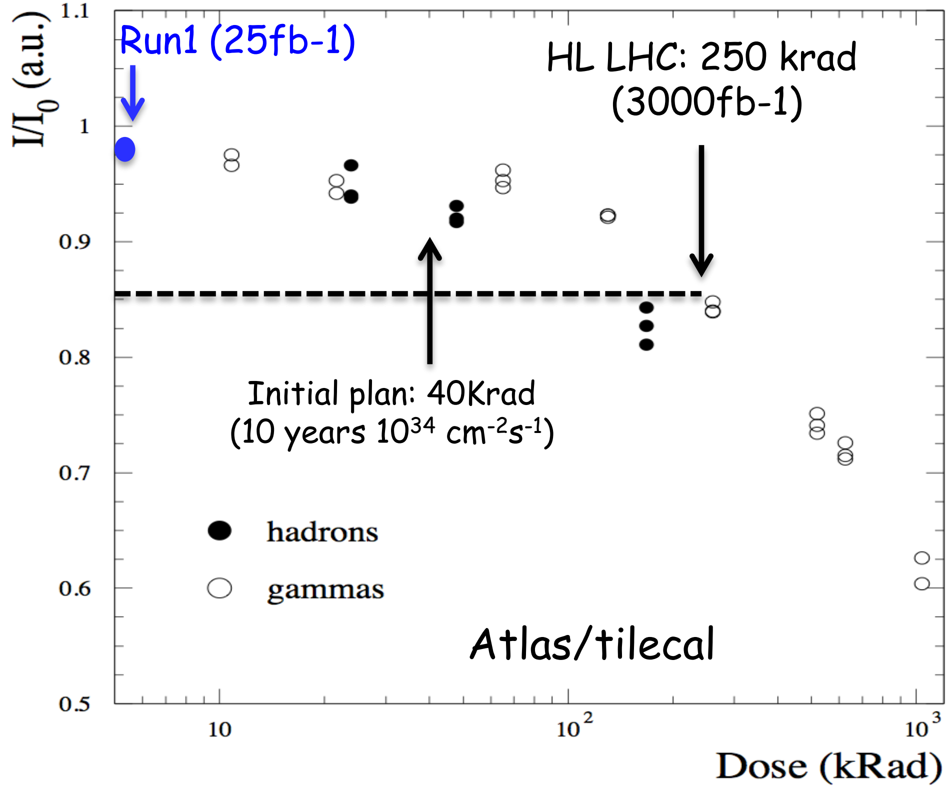
In run 1:

- Calibrations systems precision < 1%
- Short time scale drifts dominated by PMT ΔGain
- ~ -3.5% tot max. loss (~ half is optics irradiation; ~ half PMT down drift) in most irradiated inner cell (η~1.3), where em calorimeter in front is shorter



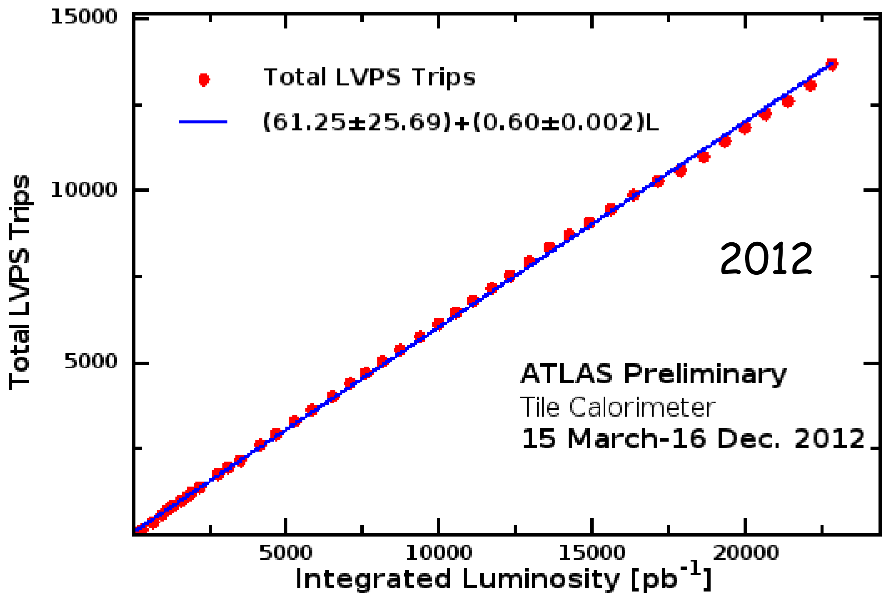


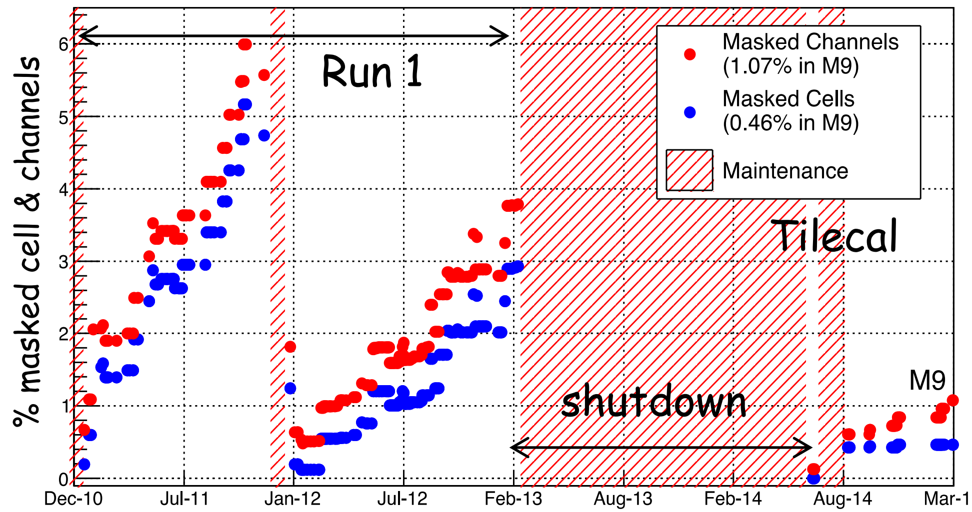
Expected Tilecal light losses in scintillator at HL-LHC (3000 fb^{-1})



- Run 1: -2% max (2.2Krad) in inner cells (η~1.3) w/ shorter em calo in front)
- At HL-LHC: -15% max (0.2-0.3 Mrad).
- Radiation levels and light losses in scintillator cells (tiles + fibres) as expected
- After cells recalibration impact in jet performance is negligible
- No upgrades in Tilecal for HL-LHC(2023), except in the electronics
- In Long shutdown 2 (2018) will only replace gap/crack scintillators sitting in the Barrel-Extended Barrel gap (as planned since the initial construction)

Hardware status in run1 -> after Consolidation in shutdown



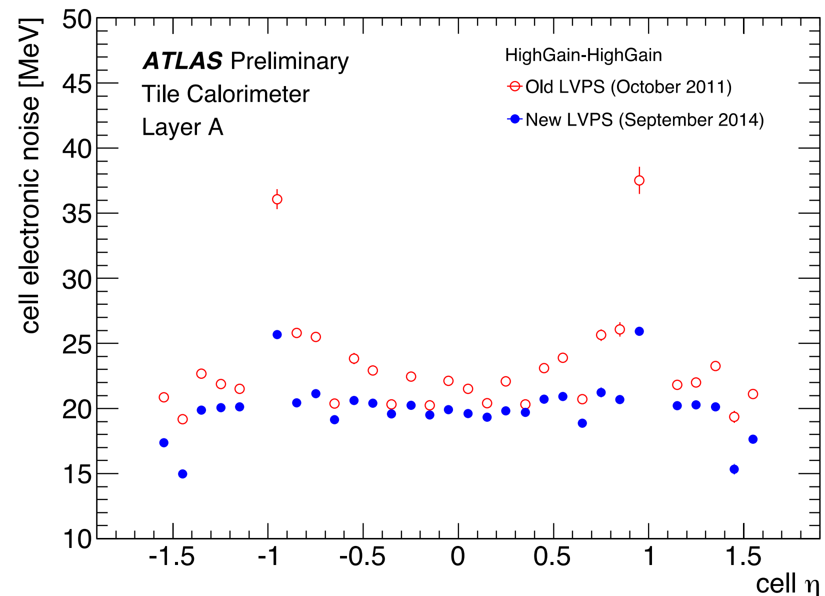


In Run1 the main source of Tilecal failures:

- Low voltage power supply OFF; frequent trips
- Power connectors reliability in FE electronics
- 3-6% masked cells in run 1
- Automatic LVPS recovery implemented
- Repaired main failures in 2011 short break
- Despite that Tile delivered good data for physics (~99 % in run1)

In the long shutdown (2013-2014):

- Replaced of all LVPS by new units
- Refurbished FE electronics (connectors)
- Consolidate Cs calib. against water leaks



ATLAS Tile calorimeter Performance

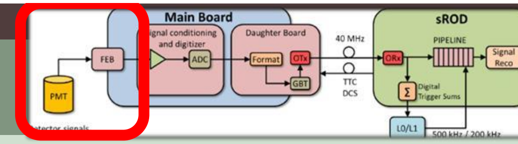
Characteristics	ATLAS $|\eta|<1.7$
Light yield	70 phe/GeV
σ_E/E (tbeam standalone)	52%/√E+ 5.7% (7.7 λ) 45%/√E+2 % (if 9.2 λ)
Jet resolution target	~50-60%/VE ⊕ 3%
e/h	1.33
em sampling fraction	3%
Max dose at HL LHC (3000 fb-1) Max light reduction due to irradiation in run1 Max. light reduction expected at HL LHC	0.2-0.3 Mard -2% -15%

ATLAS Tile calorimeter characteristics

Characteristics	ATLAS $\vert\eta\vert<1.7$
Absorber Absorber/scintillator ratio Geometry Tiles-Fe periodicity in Z	Steel 4.7:1 Tiles & fibres ⊥ to pp beam axis 18 mm (3mm Tiles+14mm Fe)
Tiles characteristics: - Tile dimensions (ηxϕxR): - Inner radius - Outer radius - WLS Fibres	Polystyrene+1.5%PTP+0.04%POPOP by injection molding, no grooves ; ~ 70 tons 11 trapezoidal sizes in depth/R ; ~ 40105 tiles 3 mm x ~22 cm x ~10 cm ; 3 mm x ~35 cm x ~19 cm Kurary Y11 ; 1mm diameter ; ~1062 Km ; ~620 000 fibres
3 cylinders (Barrel+2 Ext B): Length in Z Outer radius(w/supports+elect.) Outer active radius Inner active radius Active depth ΔR at η=0 Volume (inner-outer active R) Weight	 12m 4.2 m 3.9 m 2.3 m 1.6m; 7.7 λ 372m3 2900 T
Longitudinal Segmentation	3 layers
Transversal granularity ($\Delta\eta$x$\Delta\phi$)	0.1x0.1 inner and middle layers ; 0.2x0.1 outer layer
# channels/PMTs	10 000 channels
Gain-dynamic range	10^5 ; 2 gain 10 bits ADCs
Xo ; λ_p ; Moliere Radius	22.4 mm ; 20.7 cm ; 20.5 mm

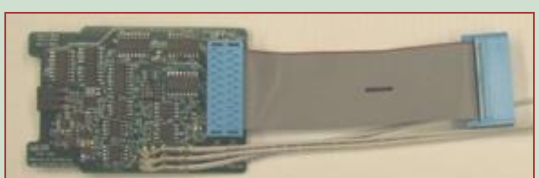
Phase 2 Tilecal Front-end electronics options

FRONT END BOARDS



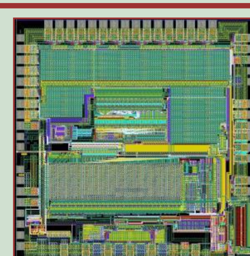
Modified 3-in-1

- Receive and shape
  - Provides analog outputs (2 gains)
  - Charge injection
  - Integrator
- Based on current 3-in-1 cards
  - Commercial off the shelf
- Improved
  - Radiation tolerance
  - Noise performance
  - Linearity performance



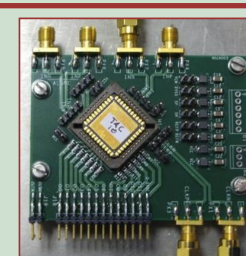
QIE ASIC

- Charge Integrator from Fermilab
- Different approach
  - Current splitter
  - Gated integrator
- Four different gains, but without shaping
  - No dead time
  - Useful for pile-up
- 17-bit dynamic range
- Clean measurement every 25 ns (40MHz)



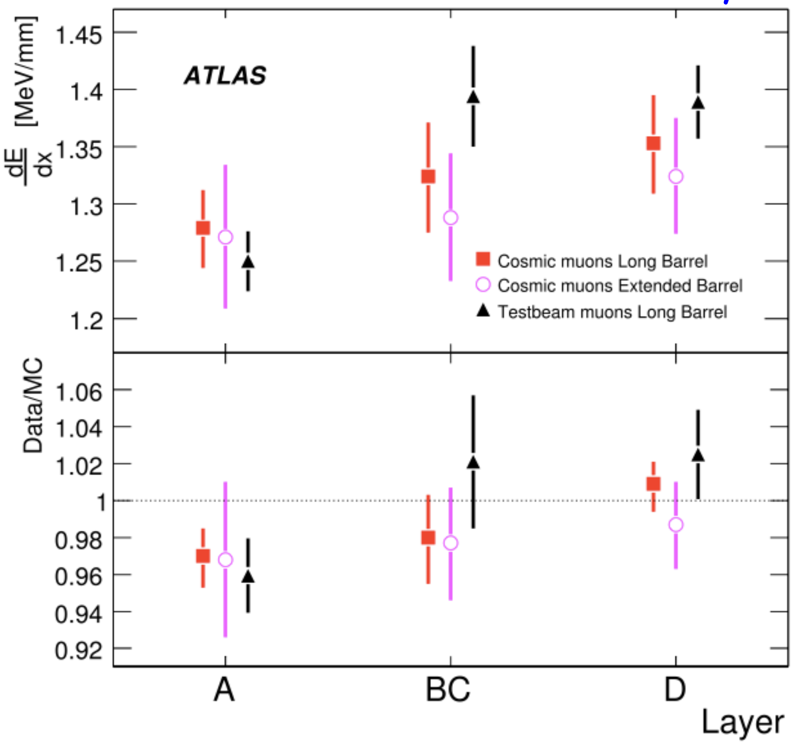
FATALIC

- Combines two ASIC solutions (TACTIC and FATALIC)
- FATALIC
  - Shaping stage with 3 gain ranges (1,8,64)
- TACTIC
  - 12-bit pipelined ADC
  - 40 MHz operations

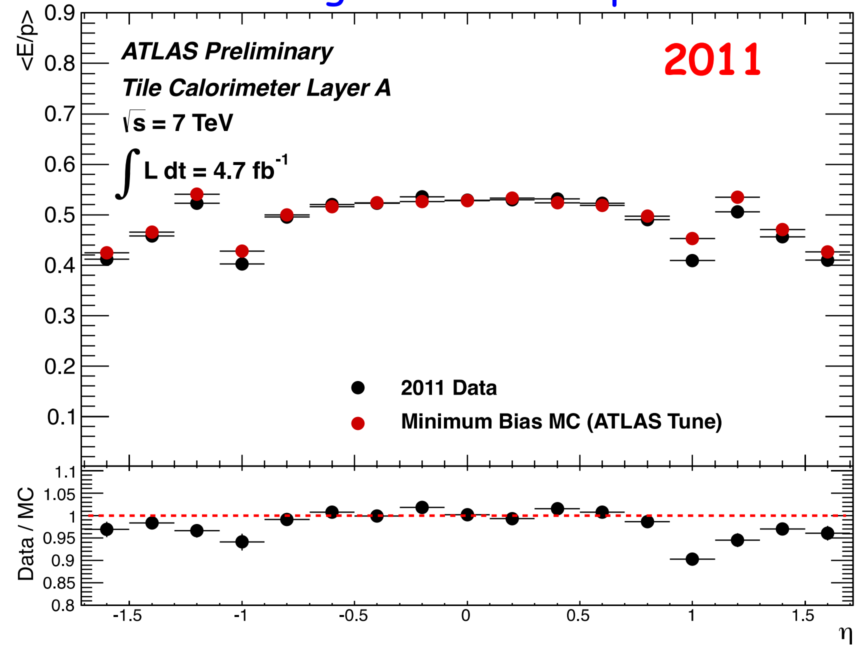


Jet energy scale precision (ΔJES) in run 1

Tilecal in test beam ; cosmic rays



Tilecal single hadron response in run1



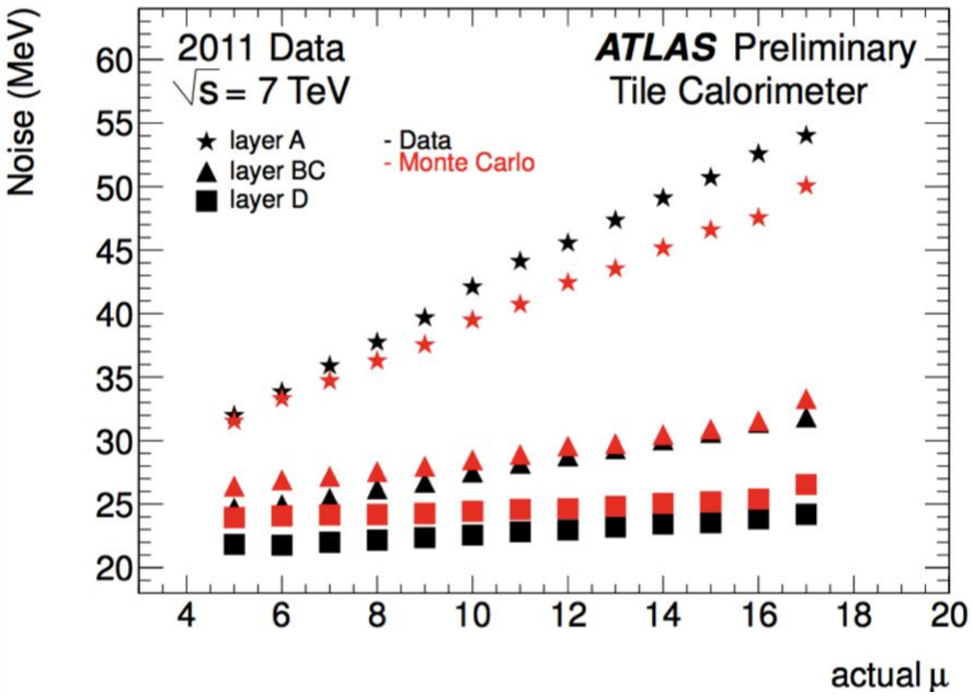
Tilecal electromagnetic scale:

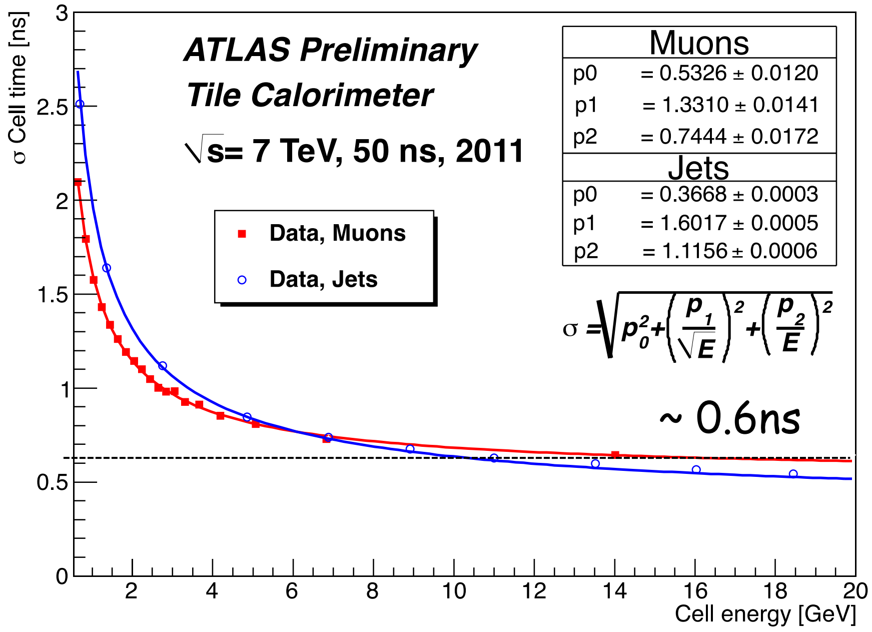
- from test beam (e, μ) in 11% of modules
- error ~3% (from test beam, cosmic rays)
- monitored after re-calibrations with μs from collisions, e/p, cosmic rays

ATLAS ΔJES is the main uncertainty in many physics channels. Achieved < 1% error in central region and medium p_t

η

Tile performance in run 1





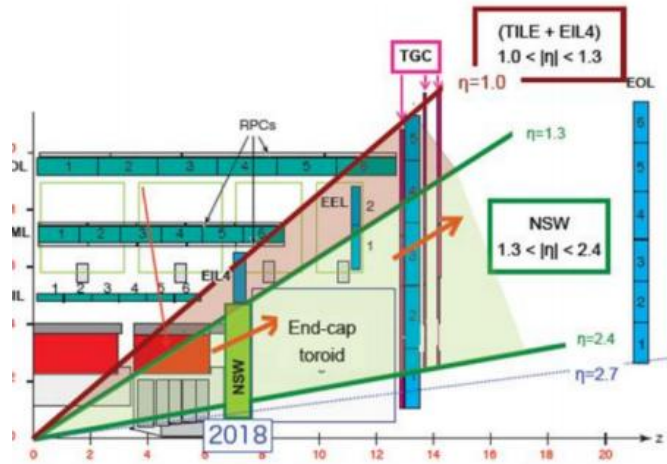
Tile cells noise has a moderate increase with pile-up (μ) and mostly in the inner layer (A)

Tilecal measure the time with very good precision (~ 0.6ns for Ecell>20 GeV)

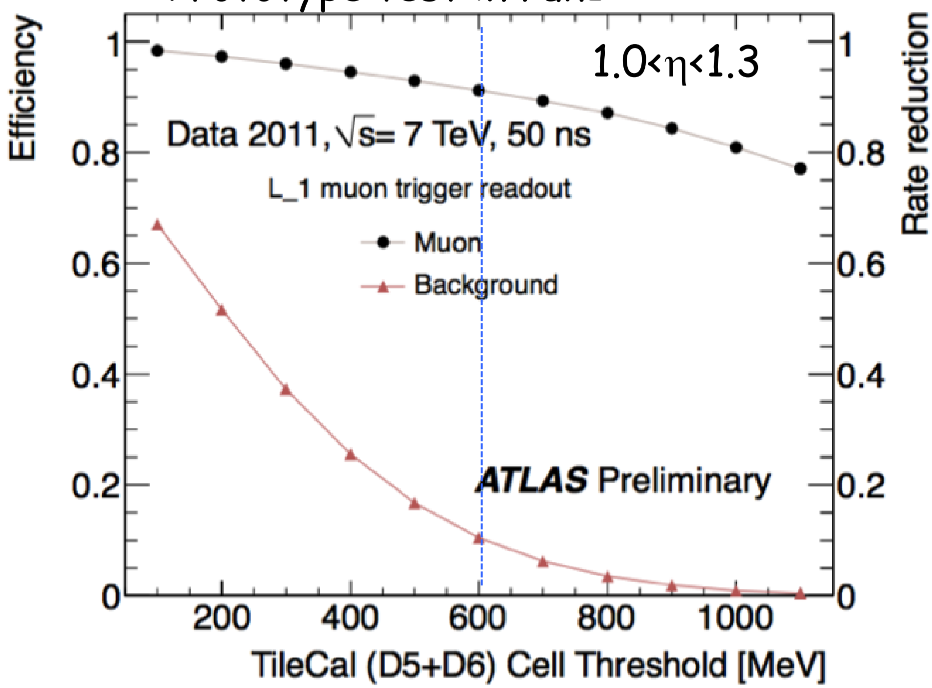
Tile D project - Tilecal Integration with Muon trigger

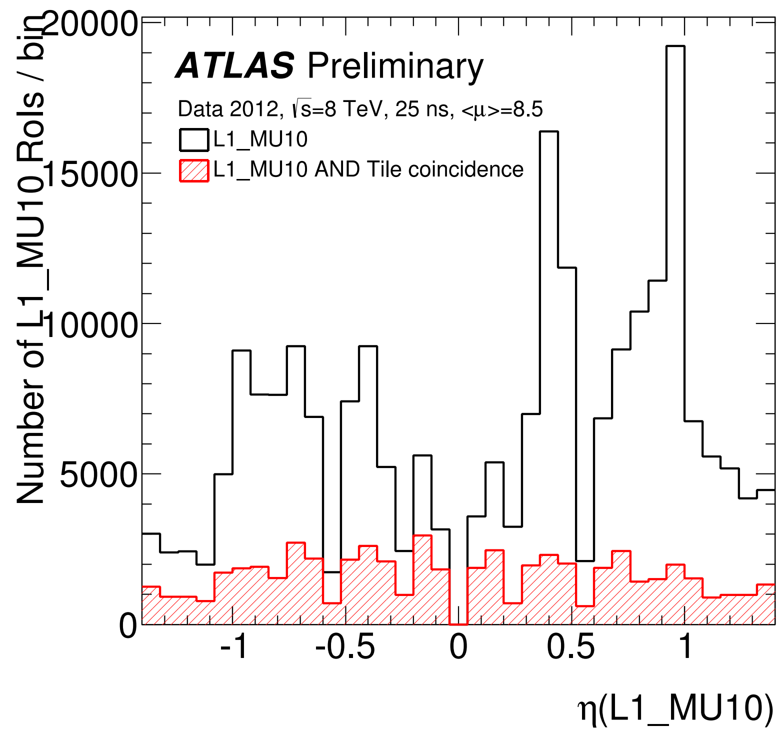
2015-2022: Integrate outermost Tilecal D layer of extended barrel ($1.0<\eta<1.3$) in level 1 muon trigger => remove ~ 85% muon fake rates, while keeping muon efficiency >90% (very effective to "clean" low muon P_T rates)

After 2023: Possible integration of all the Tilecal outer cells ($|\eta|<1.7$), after Tilecal electronics upgrades (lower cells noise levels)

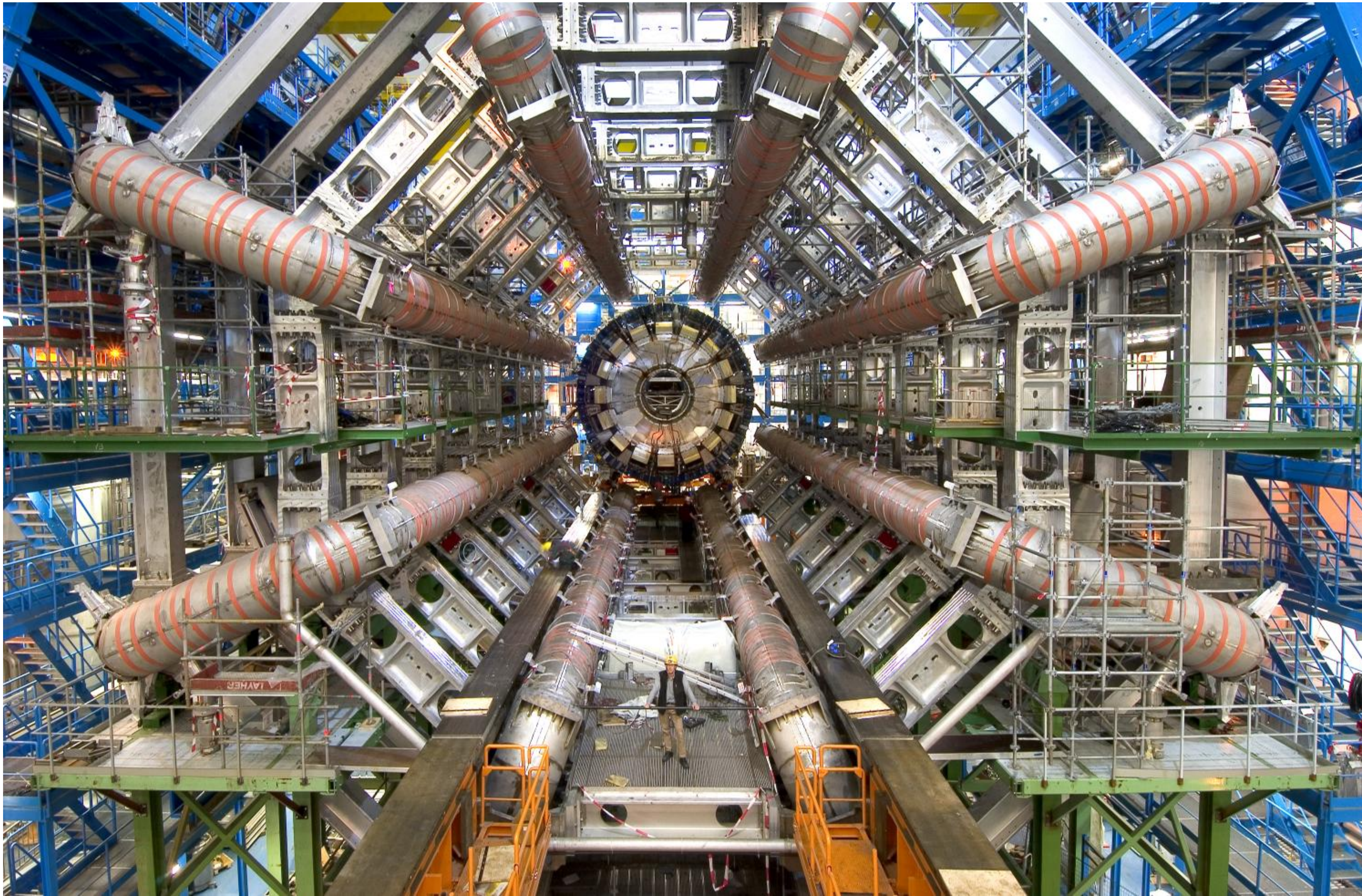


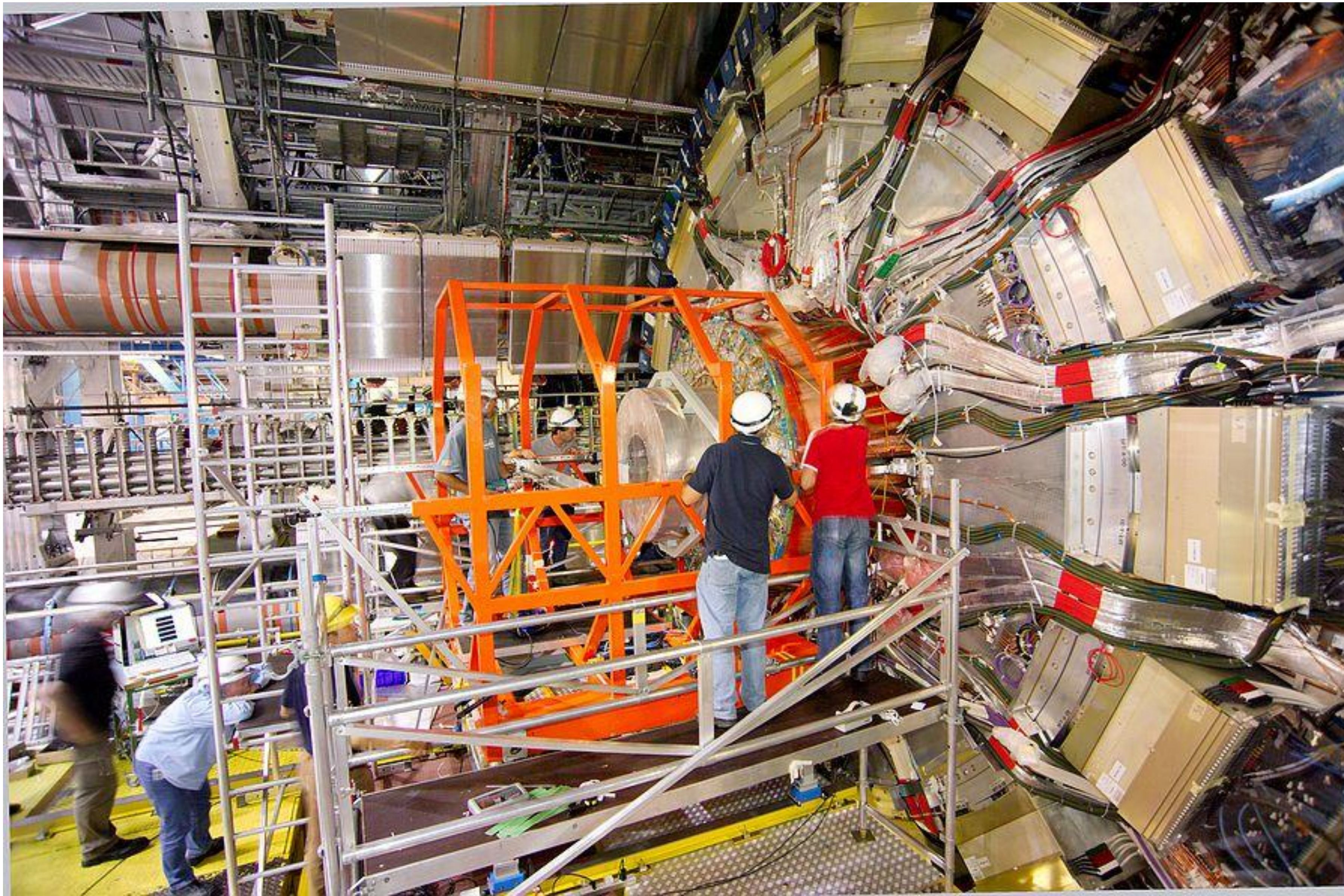
Prototype test in run1





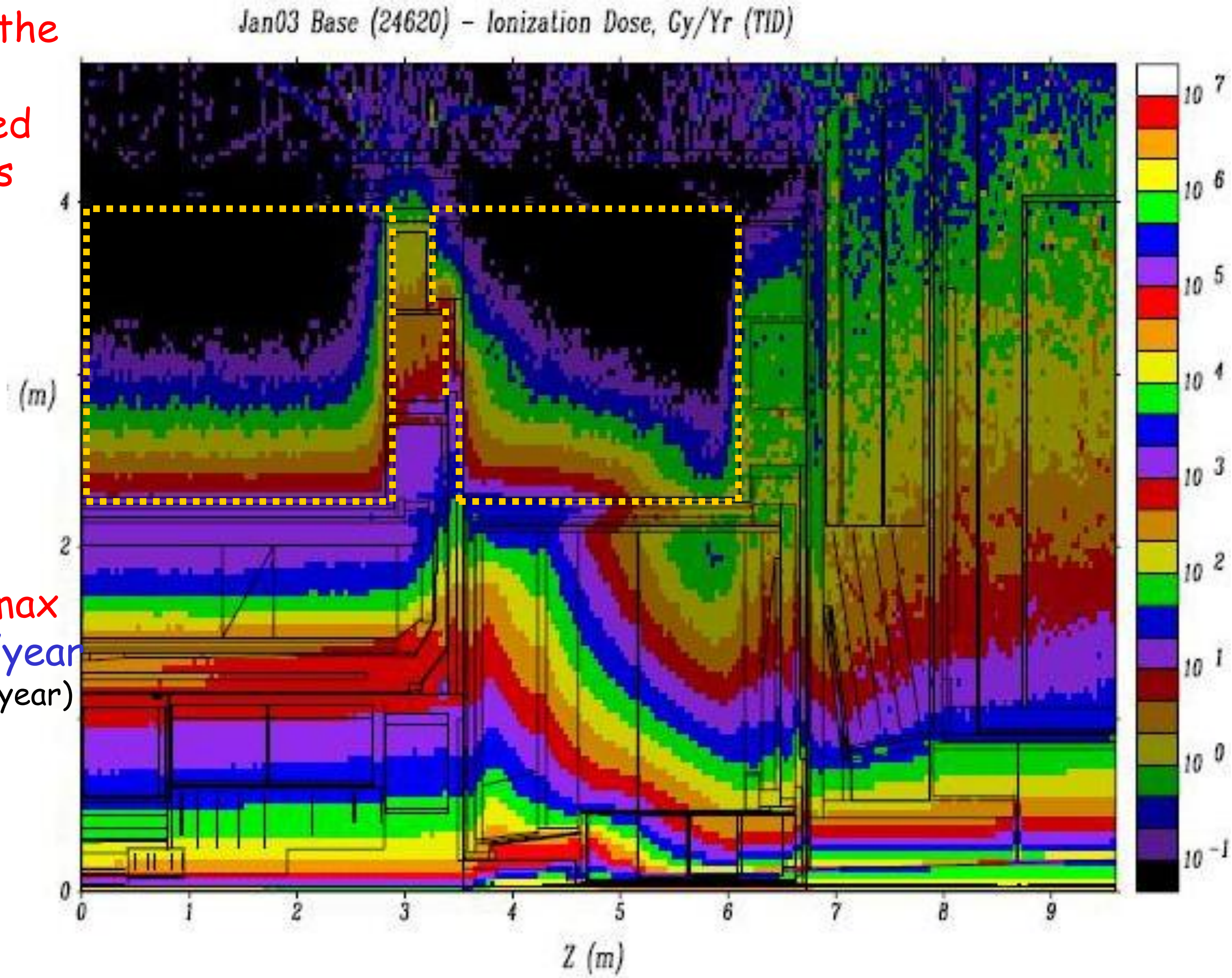

A





Radiation – dose deposited per year in ATLAS

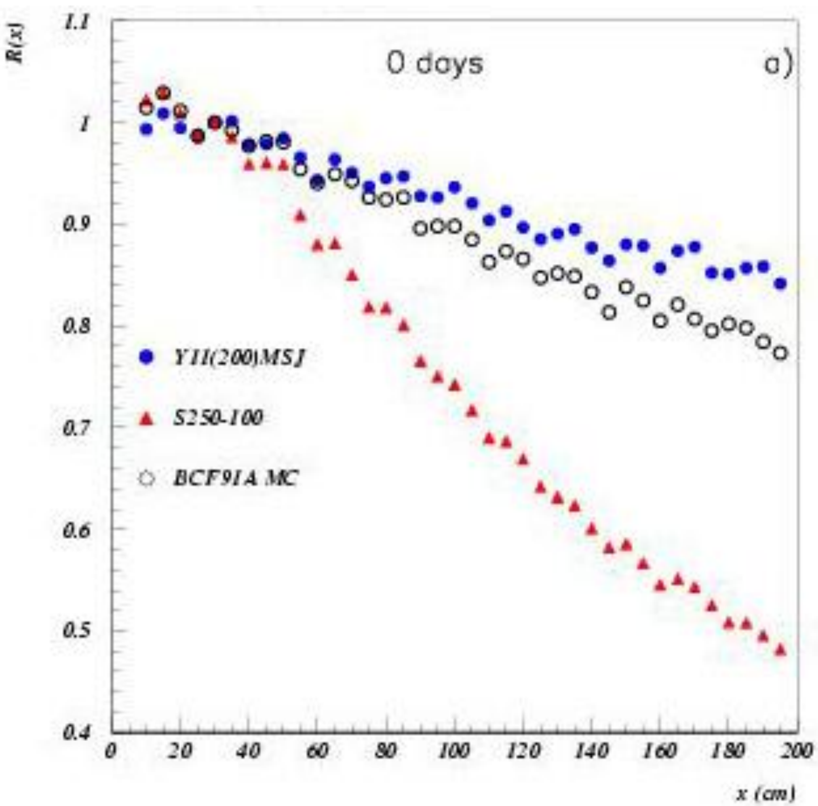
Dose is the energiy deposited per mass unit

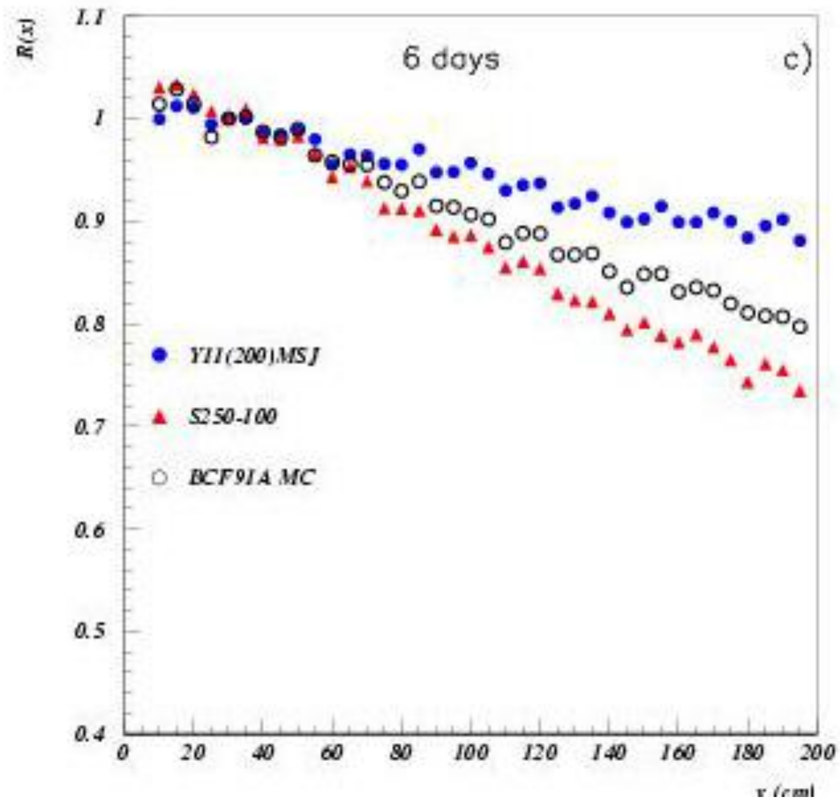


Tilecal max
~50 Gy/year
(0.5 krad/year)

Radiation damage of WLS optical fibers

Normalized light output after irradiation as a function of the distance to the photodetector





Used dose: 155 krad, source ^{60}Co
Max dose in Tilecal in 10 LHC years: 50 krad