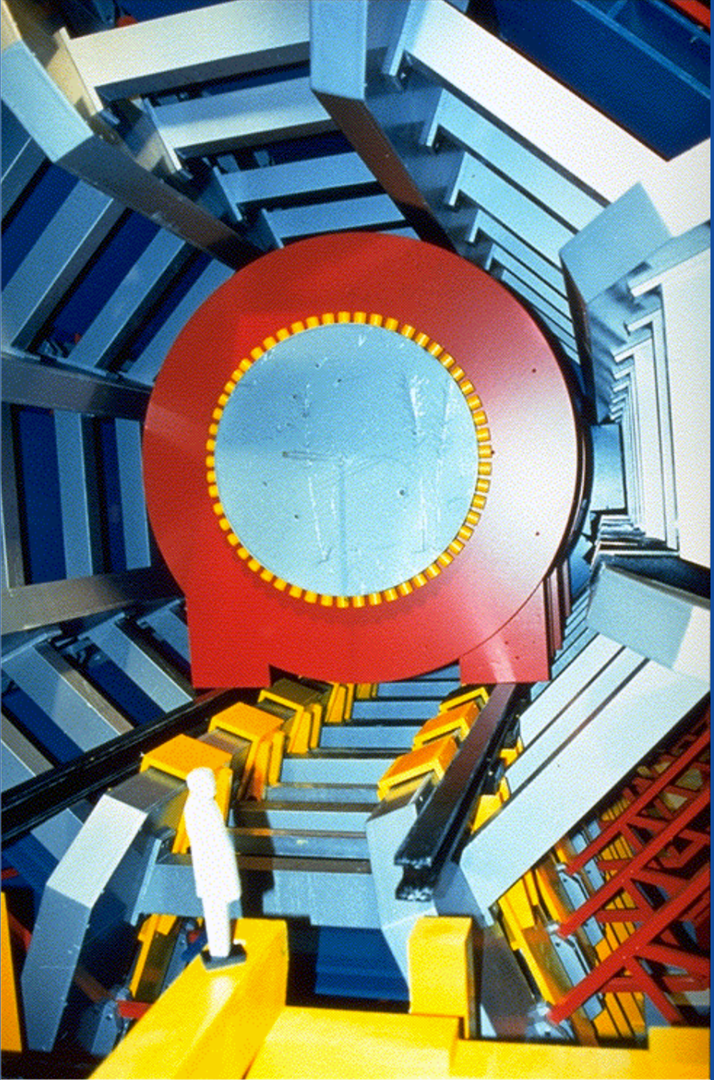


LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

ATLAS EXPERIMENT

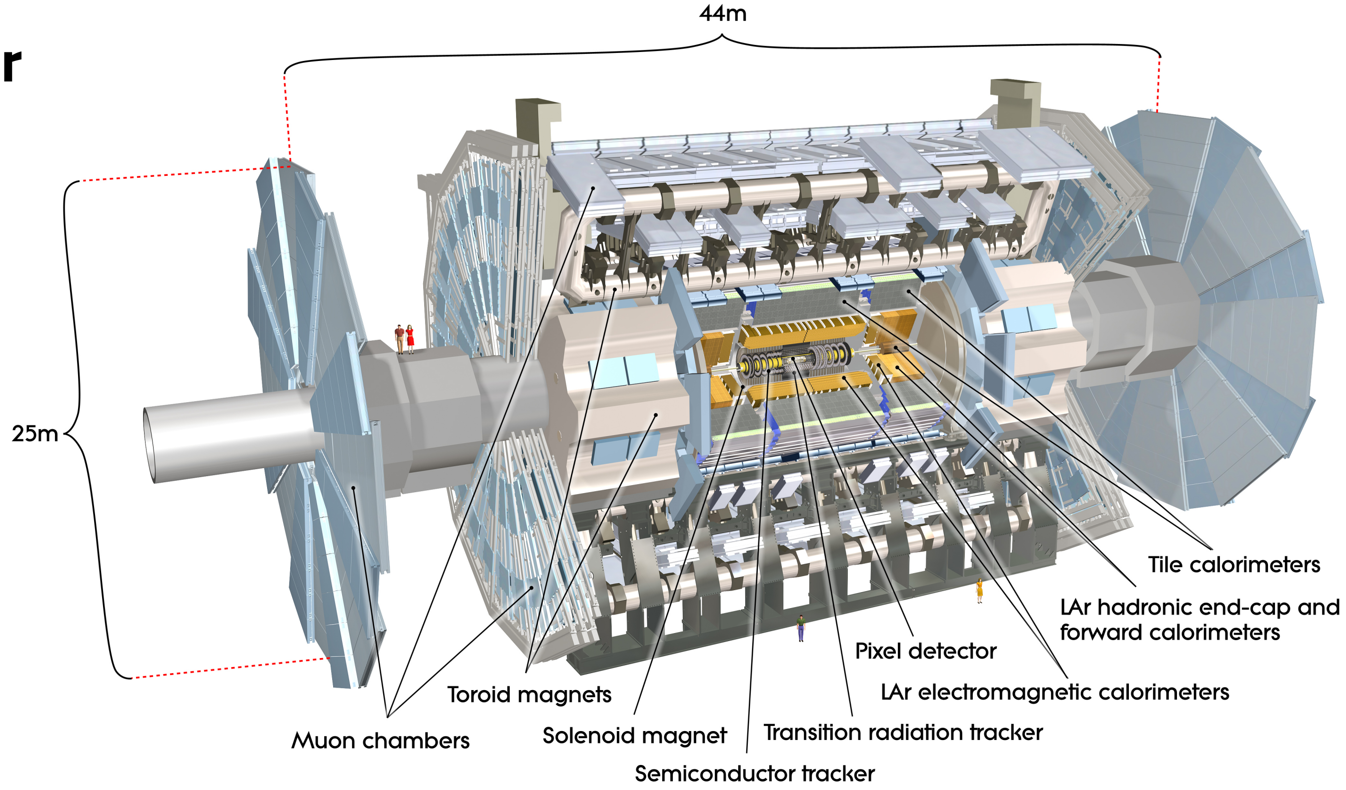
Tile Calorimeter

Past, Present and Bridges to Future

Rute Pedro

LIP Seminar | 24 June 2021

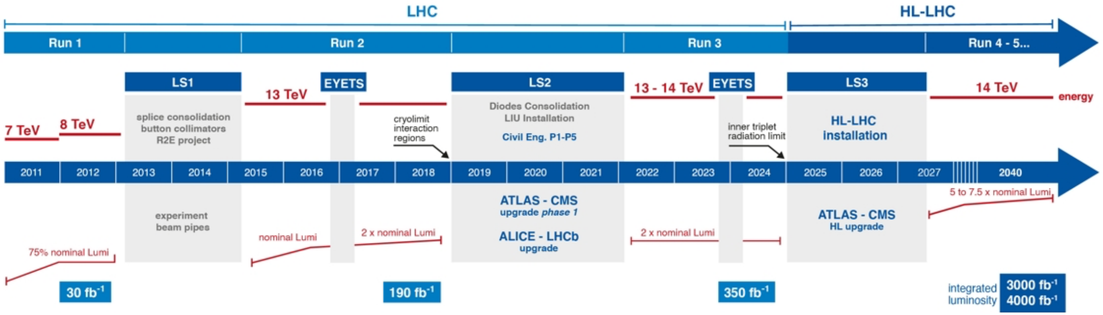
Tile Calorimeter



- Central hadronic calorimeter of ATLAS, covering $|\eta|<1.7$
- Measures hadrons, jets, taus, missing transverse energy, assists in the muon reconstruction and electron ID
- Provides input to the Level 1 Calorimeter trigger

Past, Present, Future

1992



>2040

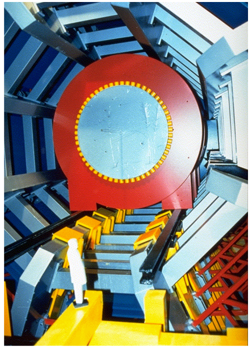
>>2050

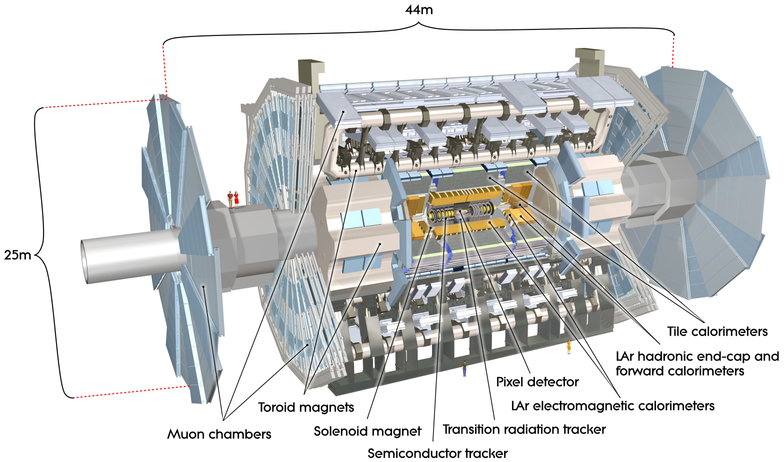
FCCee

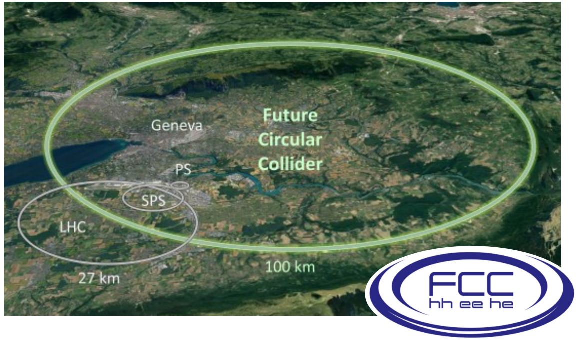
FCChh

ATLAS

Letter of Intent
for a
General-Purpose pp Experiment
at the
Large Hadron Collider at CERN

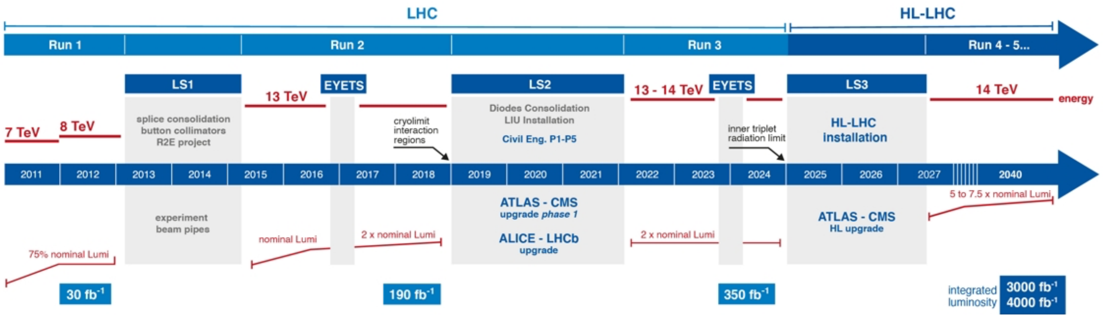






Outline

1992



>2040

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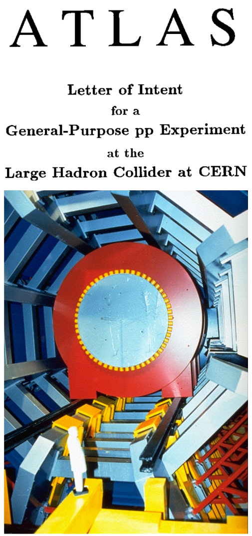
FCCee

FCChh

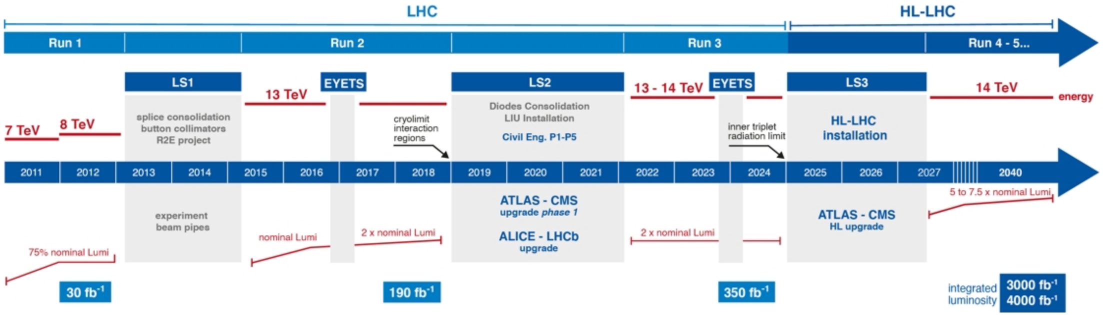


Detector design features

LIP contributions

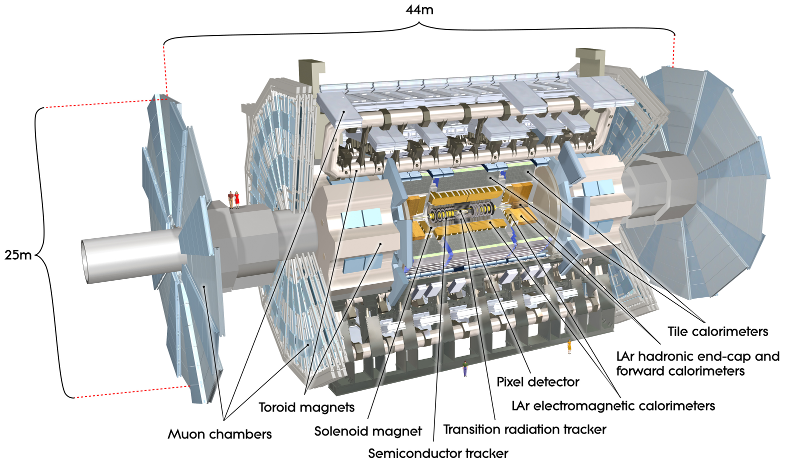
Outline

1992



>2040 >>2050

FCCee FCChh

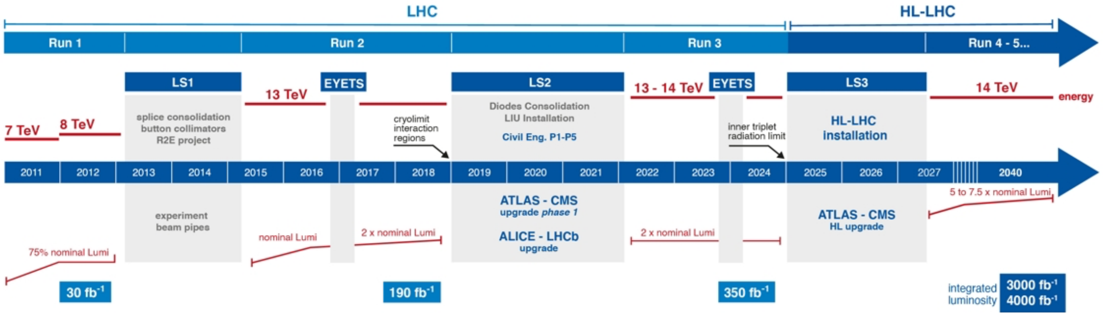


Detector Operation and Performance

How to face the HL-LHC challenges

Outline

1992

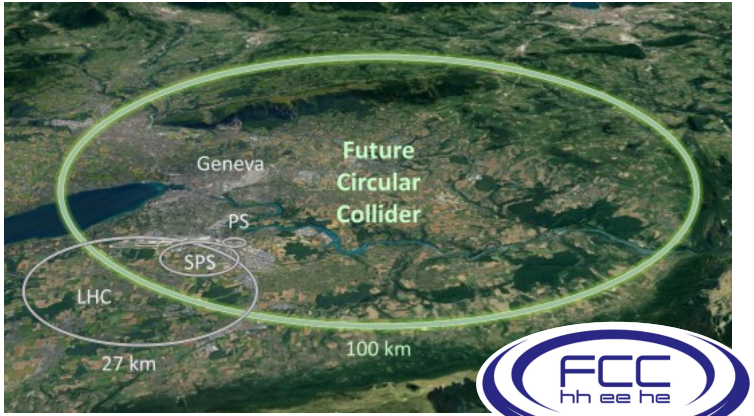


>2040 >>2050

FCCee FCChh

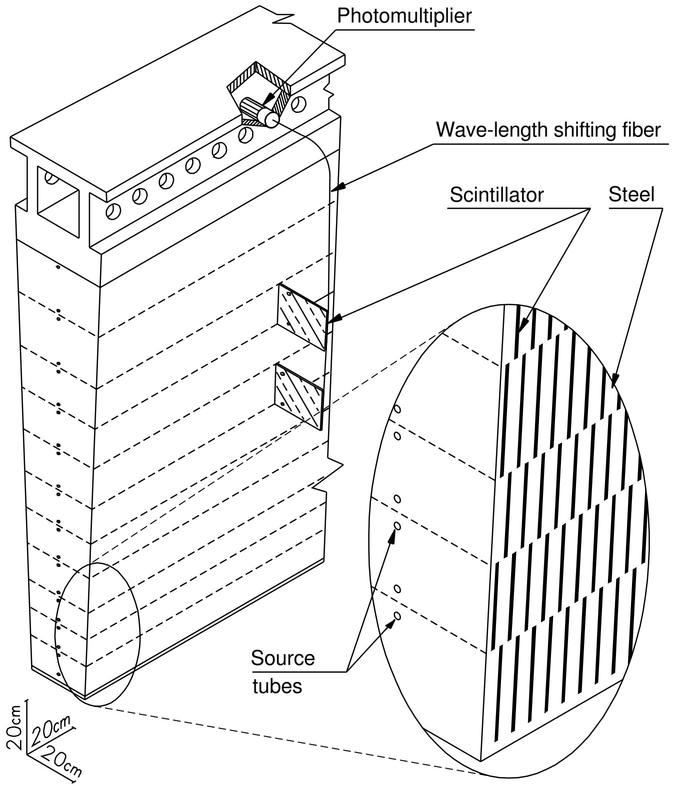
Lessons to future detector design

Detector R&D plans

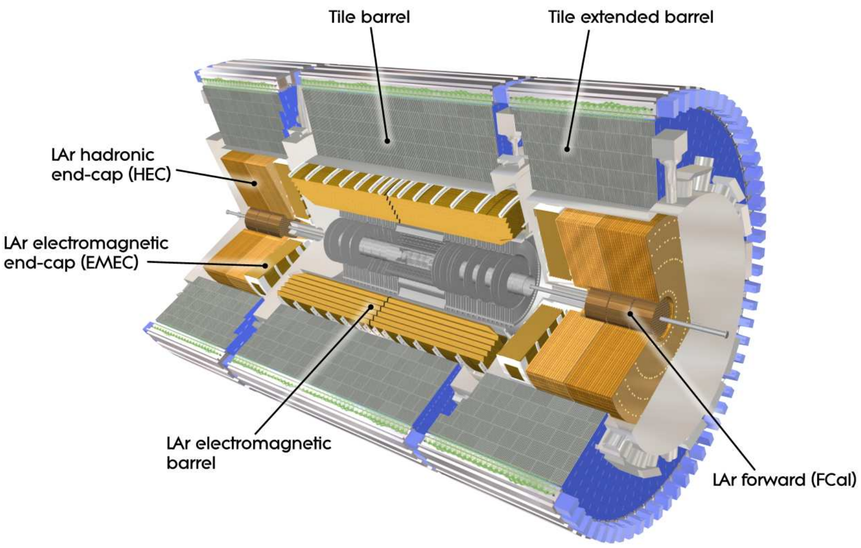


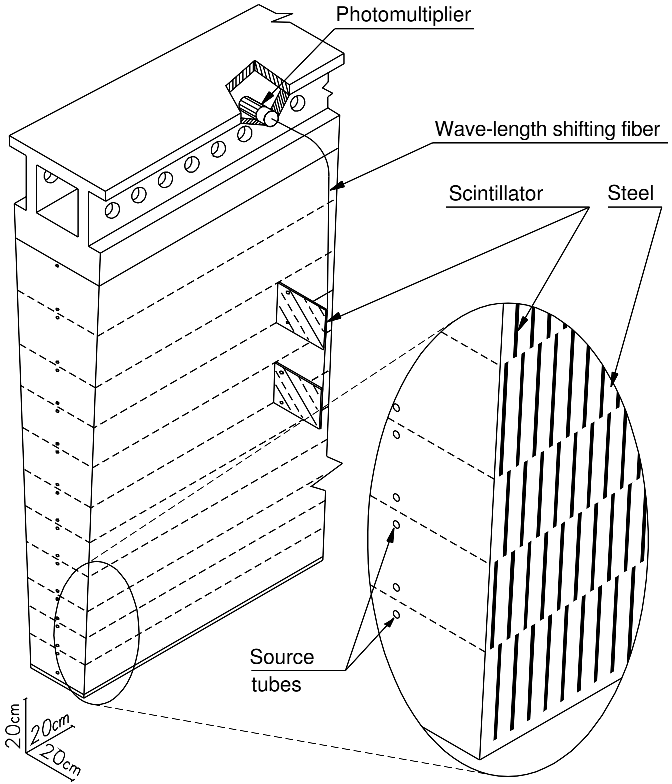
Detector design features

LIP contributions



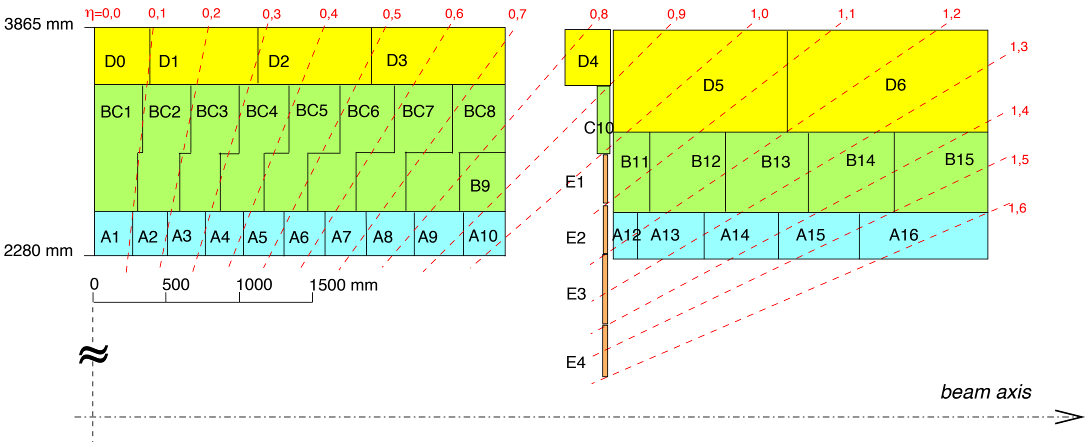
Overview of the Tile Calorimeter





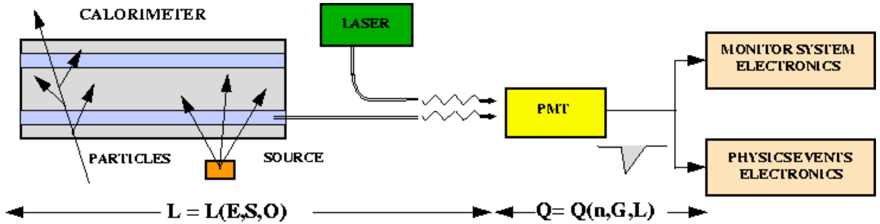
- Designed for jet energy resolution $\frac{\Delta E}{E} \sim \frac{50\,\%}{\sqrt{E}} \oplus 3\,\%$
- Steel plates (absorber) interleaved with plastic scintillator tiles (active medium) (4.7:1)
- Sampling period 18 mm, 64 wedged modules
- Plastic scintillators made of Polystyrene PS doped with PTP (1.5%) + POPOP (0.04%)

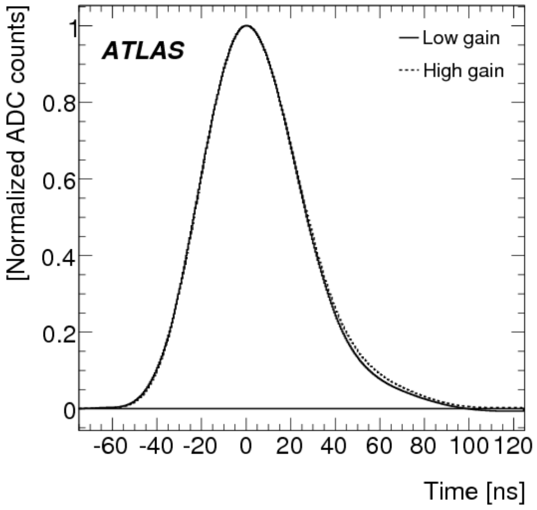
Detector Readout and Granularity



- Tile read out by wavelength shifting (WLS) optical fibres
- Fibres bundled and read by a Photomultipliers (PMTs) to define the unit cell
- Radially segmented: A, B(C) and D layers
- 5182 cells, (η, ϕ) granularity: cells in the A, B(C) layer 0.1 X 0.1, cells in the D layer 0.2 X 0.1
- Double PMT readout: 9852 readout channels

Signal Readout and Reconstruction





- PMT signals are shaped and amplified in two gains (low/high ratio 1:64) for high/low signal
- Amplified signal is digitised every 25 ns by a 10-bit ADC
- Signal amplitude A and time τ determined from a 7 signal samples S_i: $A = \sum_i^7 a_i S_i \qquad \tau = \frac{1}{A}\sum_i^7 b_i S_i$
- Energy is reconstructed from signal amplitudes using calibration factors:

$$E[GeV] = A[ADC] \times f_{ADC \to pC} \times f_{pC \to GeV} \times f_{Cs} \times f_{Laser}$$

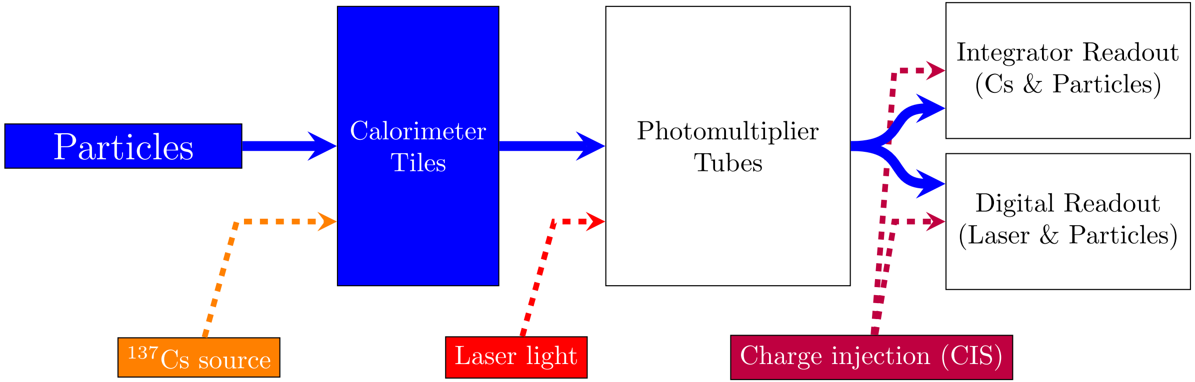
- $f_{pC \to GeV}$ is the EM energy scale constant measured during test beam (2001-2003)

TileCal Calibration Systems

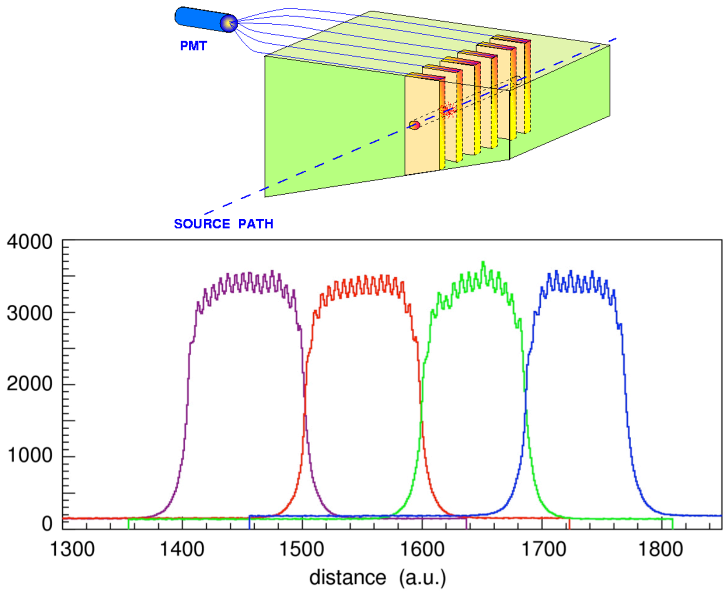
$$E[GeV] = A[ADC] \times f_{ADC\to pC} \times f_{pC\to GeV} \times f_{Cs} \times f_{Laser}$$

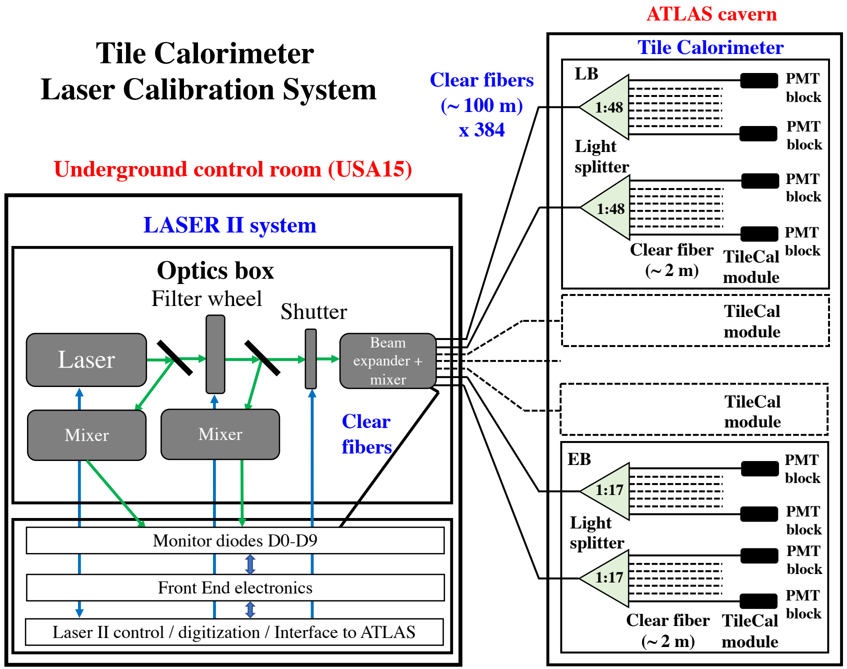
- Cesium source calibrates optical components and PMTs responses: f_{Cs}
- Laser light system calibrates the response of PMTs and readout electronics: f_{Laser}
- Charge Injection System (CIS) calibrates the response of ADCs: $f_{ADC\to pC}$
- Integrator readout of Physics events to monitor the full detector response

- Cell response fluctuates due to PMT and scintillators performance variation, correlated to LHC operation



TileCal Calibration Systems





- 3 ^{137}Cs $\gamma-$sources (662 keV) to scan the calorimeter cells
- Hydraulic drive at 35 cm/s, few hours/scan
- Cell signal measured by the integrator readout (10 ms)

- Laser light source (532 nm)
- Attenuation filters wheel to adjust light intensity
- Beam expander and mixer into 400 dispatching fibres
- Monitoring photodiodes along the light path
- Pulses sent to each PMT
- Upgraded in LS1

arxiv:2002.12800

LIP responsibilities in TileCal construction

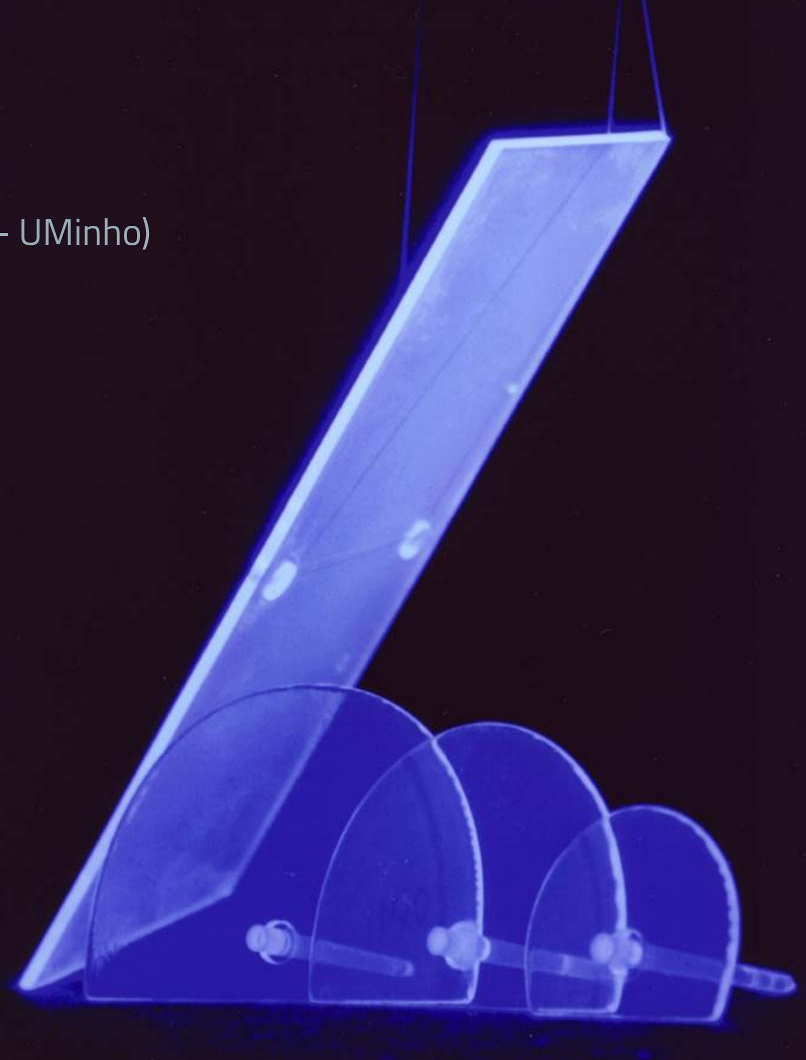
Activity	Institution
Optics:	
Scintillator material procurement, including moulds	CERN, IHEP-Protvino, Lisbon
Scintillator construction	IHEP-Protvino
Wrapping material and tooling	Michigan
Scintillator for the gap region	U.T. Arlington
Fibres procurement, preparation, aluminization	Lisbon/Coimbra, Pisa
Fibres profiles and insertion tooling	CERN, Lisbon/Coimbra
Girder rings and installation tooling	Clermont
Fibre bundle tools	Lisbon/Coimbra
Fibre bundle polishing tools	Yerevan
Instrumentation and testing of the barrel modules	CERN, Lisbon/Coimbra, Pisa, Prague, JINR, IHEP, Rio
Instrumentation and testing of ext. barrel A modules	Argonne, Illinois, Michigan, U.T. Arlinton, Chicago
Instrumentation and testing of ext. barrel C modules	Barcelona IFAE

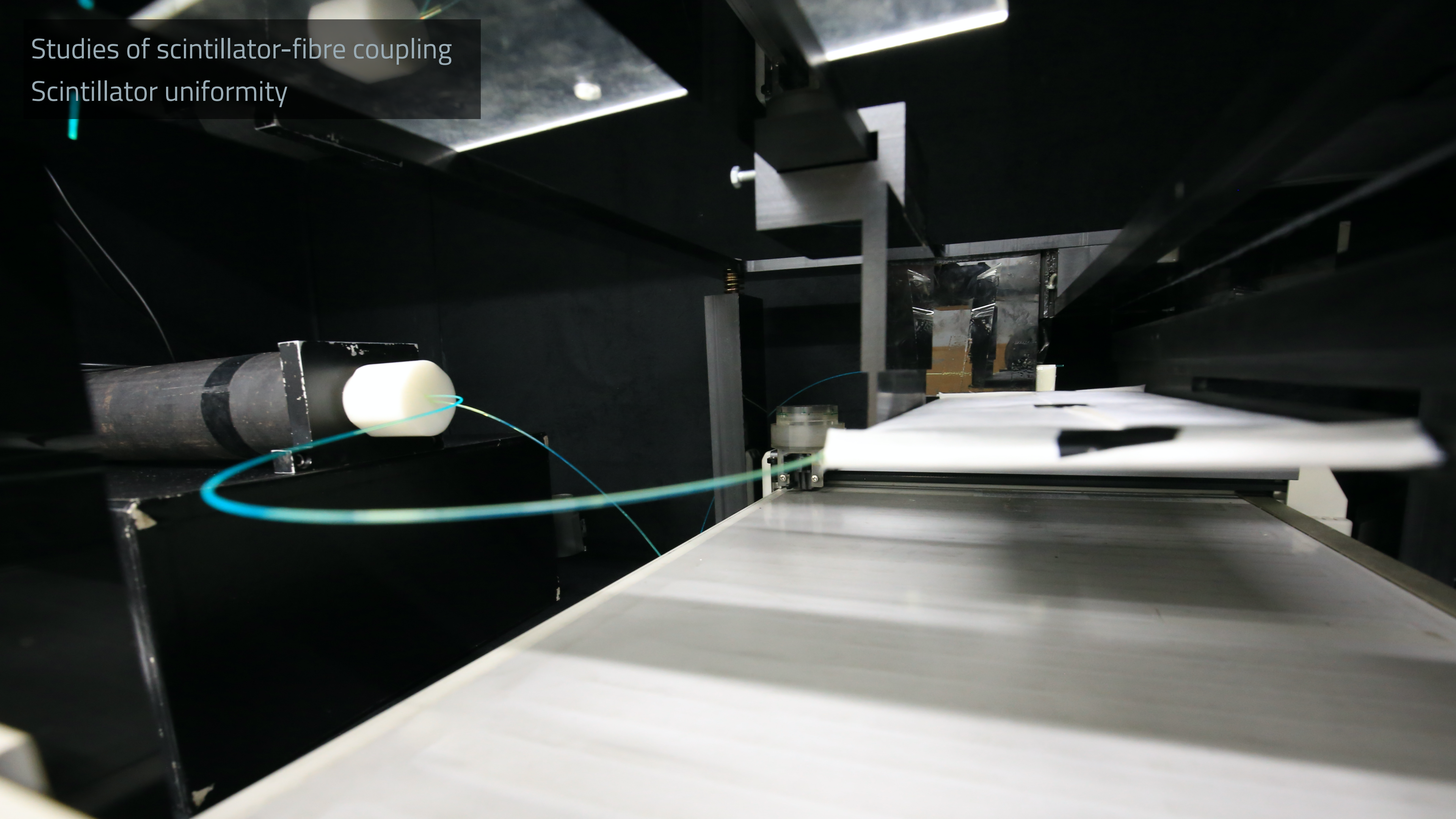
Activity	Institution
Electronics:	
PMT blocks:	
• PMT procurement	CERN, Clermont, Illinois, Lisbon/Coimbra, Pisa, Valencia
• PMT magnetic shielding	Yerevan, CERN
• HV dividers	Clermont
• 3-in-1 cards	Barcelona, Chicago, Stockholm
• light mixers	Lisbon/Coimbra, Prague
• mechanical parts of PMT blocks	Clermont, Lisbon/Coimbra
• PMT tests and PMT block assembly	Clermont, Illinois, JINR-Dubna, Pisa, Lisbon/Coimbra, Valencia
Calibration systems:	
• Laser system	Clermont, Lisbon/Coimbra
• Source mechanics, including sensors and sources	Barcelona, CERN, IHEP-Protvino, JINR-Dubna

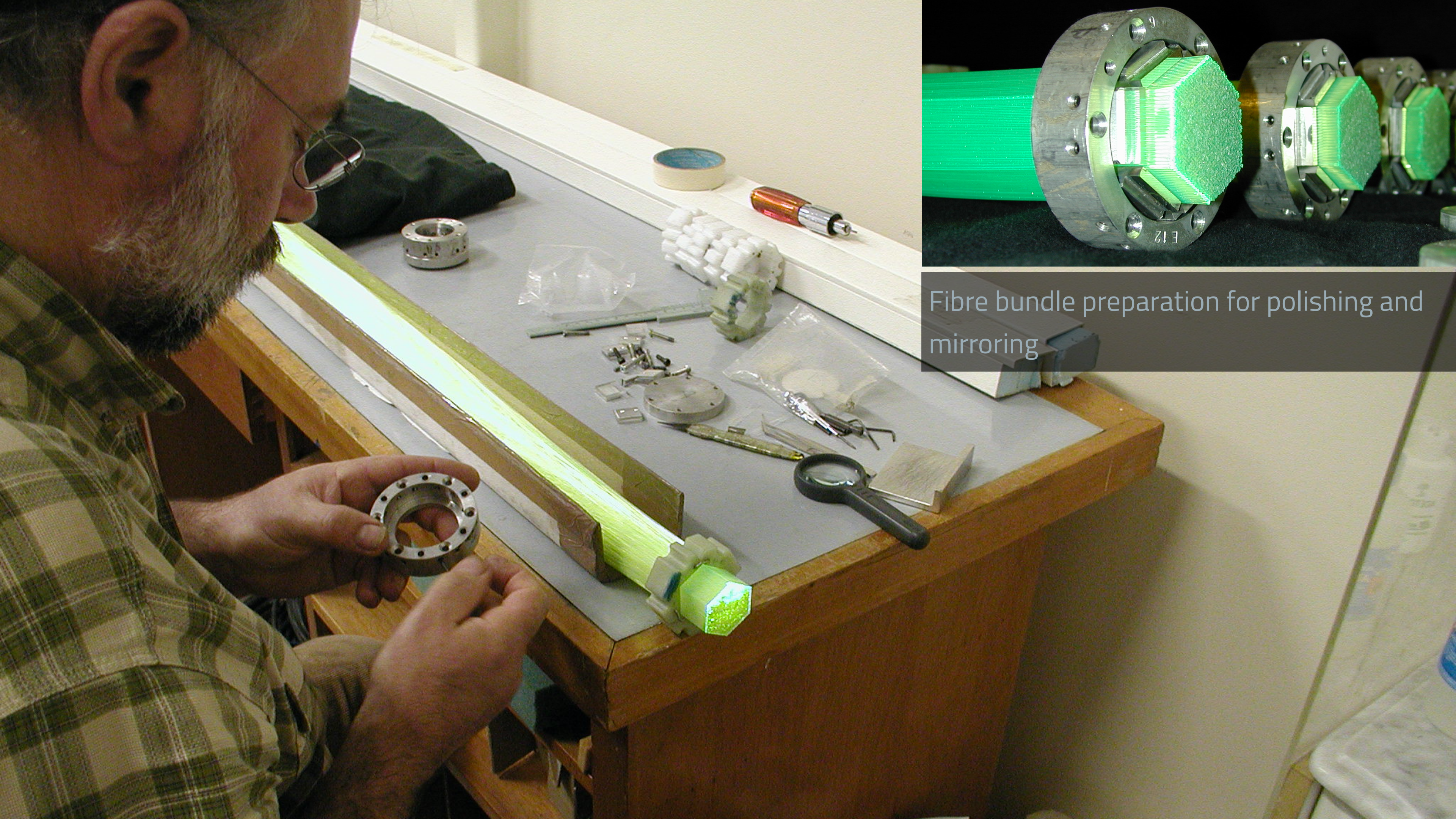
Scintillator procurement

R&D on scintillator production

(in collaboration with the Institute for Polymers and Composites - UMinho)



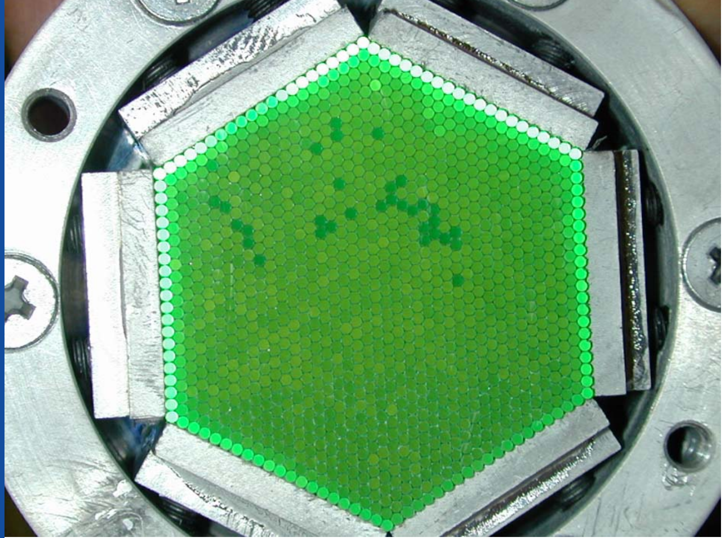

Studies of scintillator-fibre coupling
Scintillator uniformity

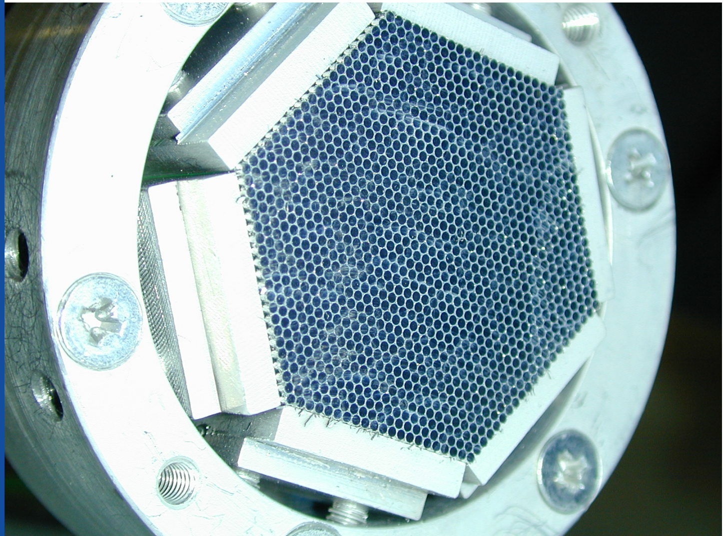


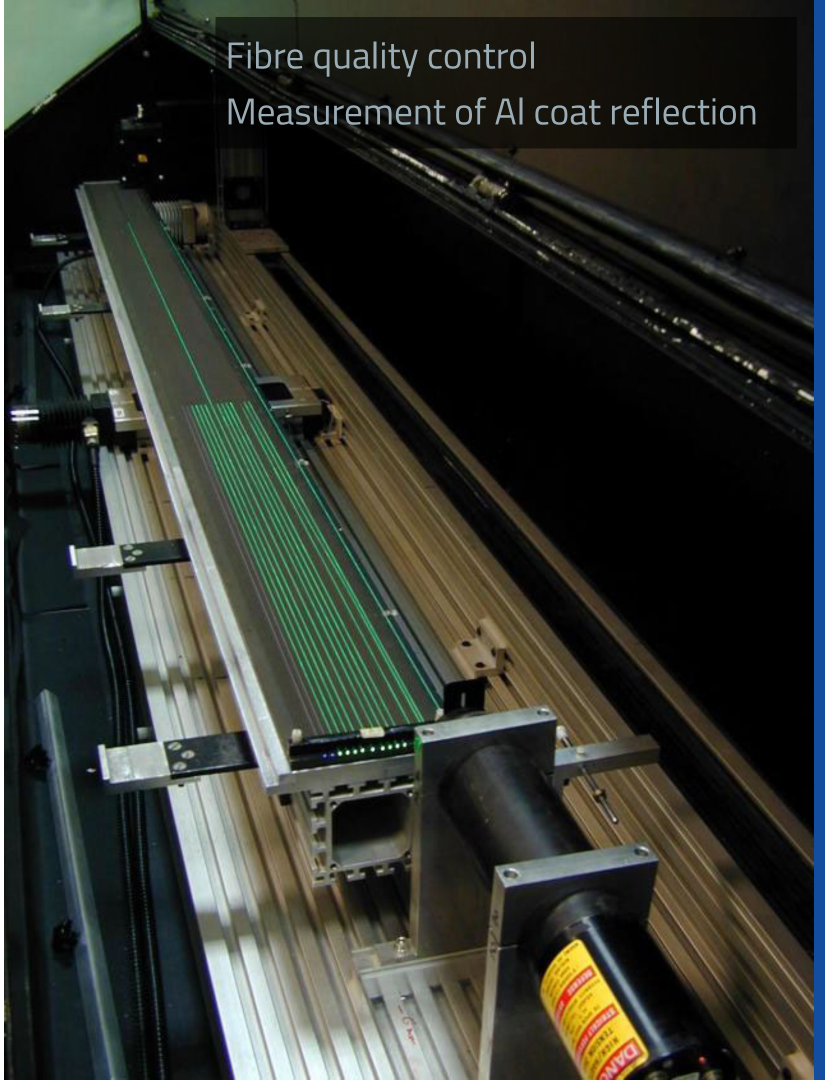
Fibre bundle preparation for polishing and mirroring


Fibre polishing

Fibre mirroring by Al deposit by magnetron sputtering



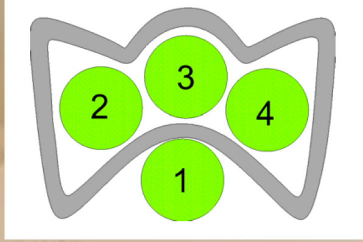




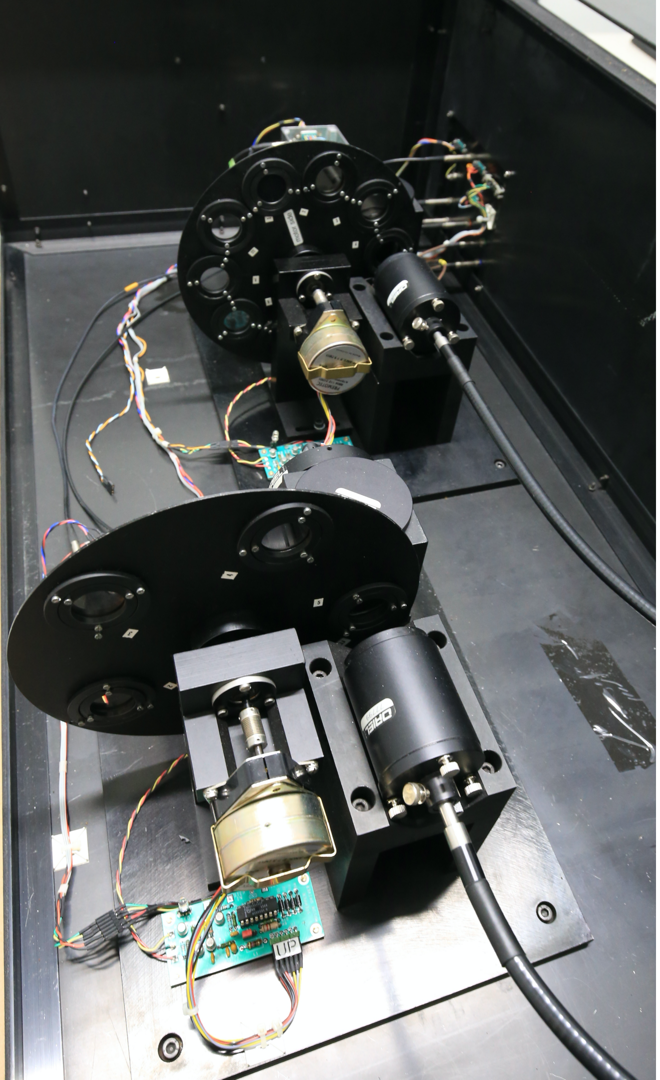
Fibre quality control

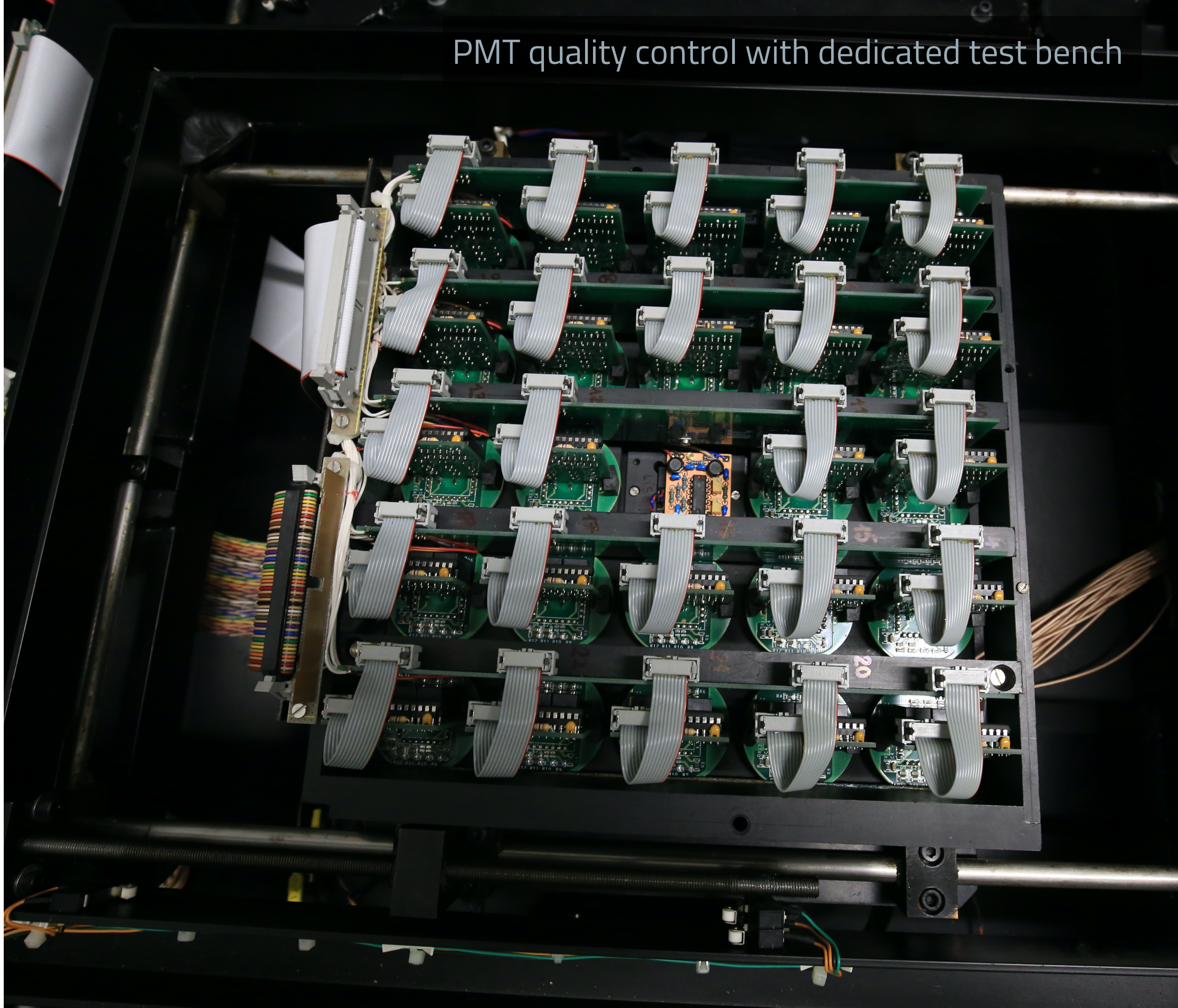
Measurement of Al coat reflection

Development of a robot for automatic fibre insertion in mechanical profiles (in collaboration with IST robotics)



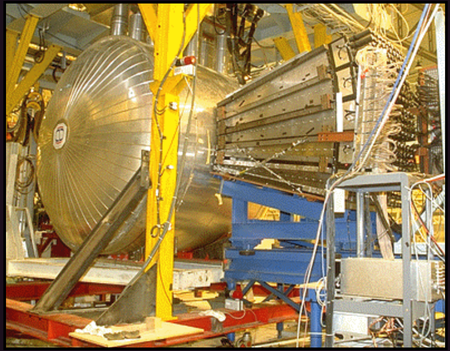
PMT quality control with dedicated test bench





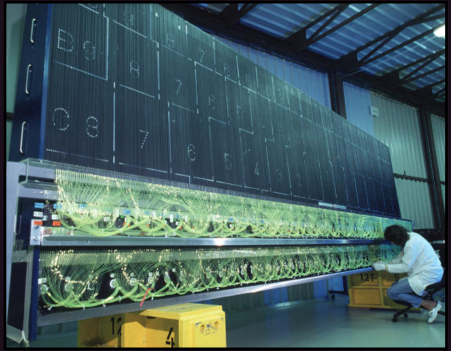
TileCal, from R&D to first collisions ~ 15 years (1993-2009)

Slide from A. Henriques

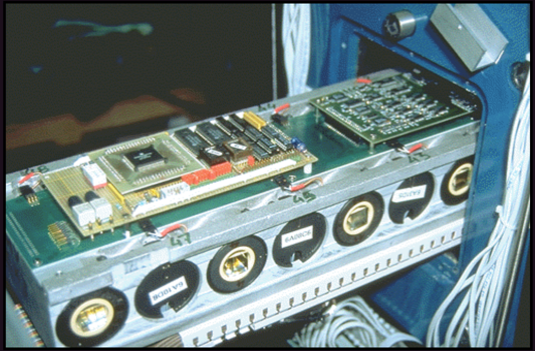


1993-1995 R&D

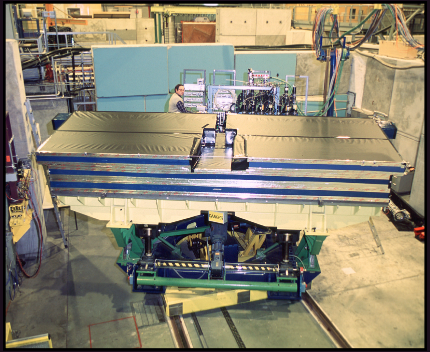
1996-2002 Construction



1999-2002 Instrumentation

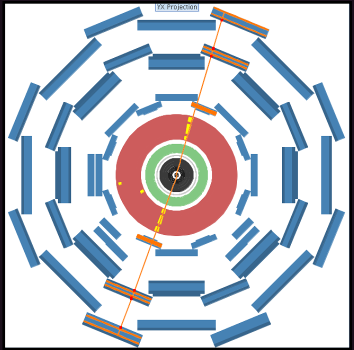


1999-2004 Electronics



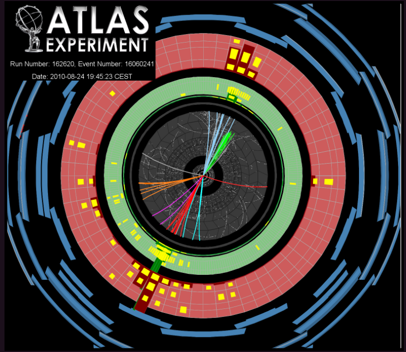
2002-2004 Calibrations

2004-2006 Installation



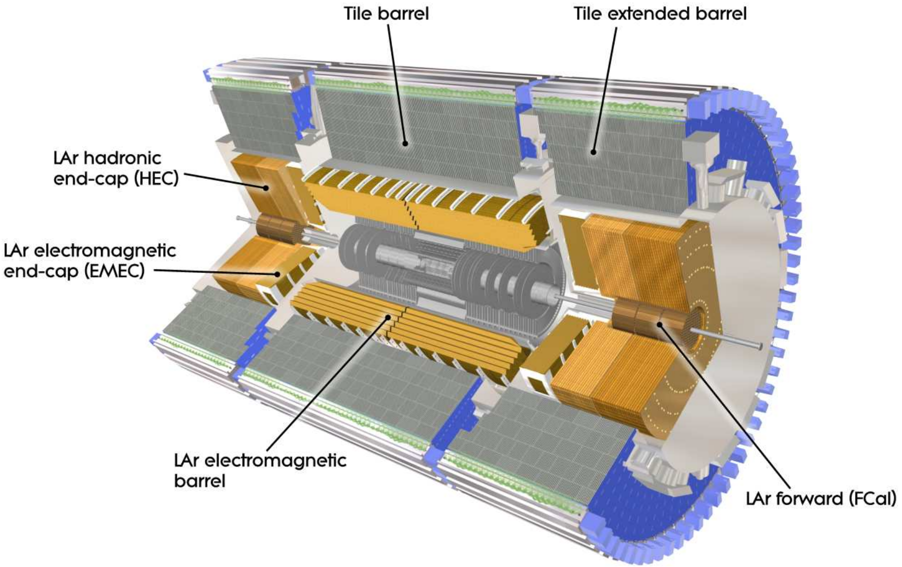
2007-2009 Commissioning

(Mostly with cosmic muons)

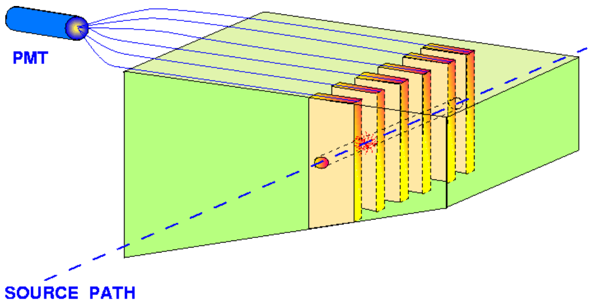


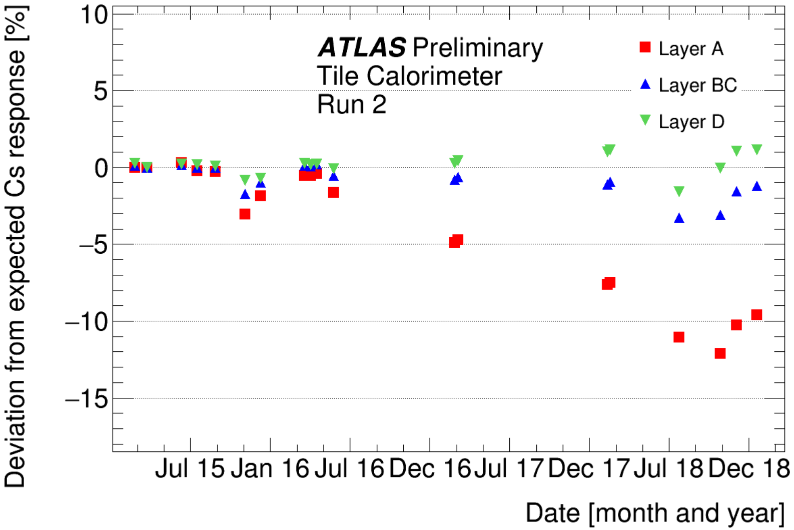
2009: First collisions

Detector Operation and Performance
How to face the HL-LHC challenges

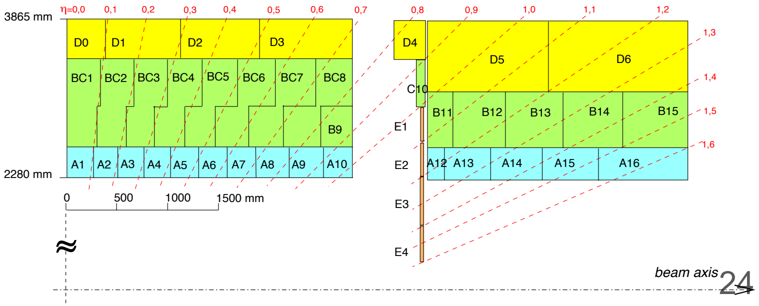


Calibration with the Cs system





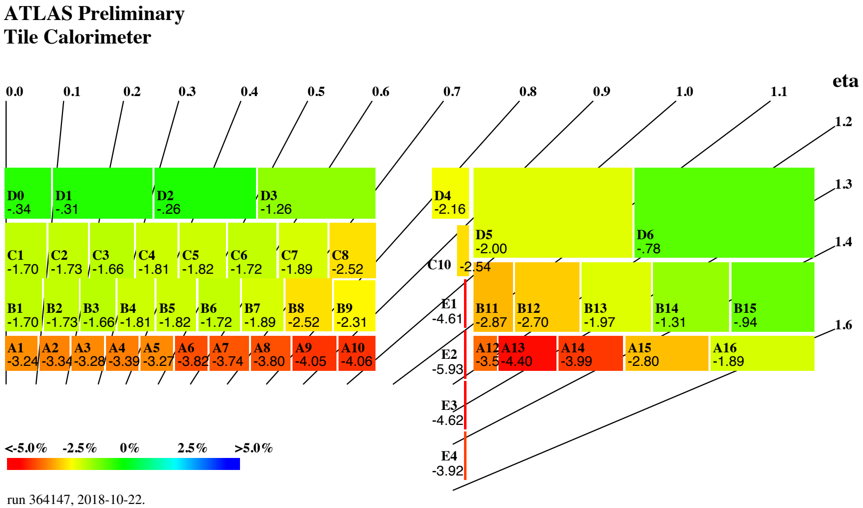
- $^{137}Cs\ \ \gamma-$source scans 2-3 times/year in Run 2
- Cell response drifts due to scintillator degradation with exposure to radiation and PMT response loss with accumulated anode current
- Precision of the system for a typical cell is around 0.3%
- Maximal down-drifts for the innermost A layer

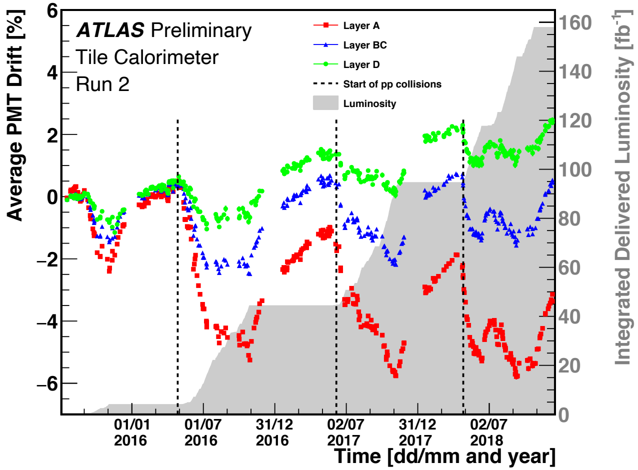


arxiv:2002.12800

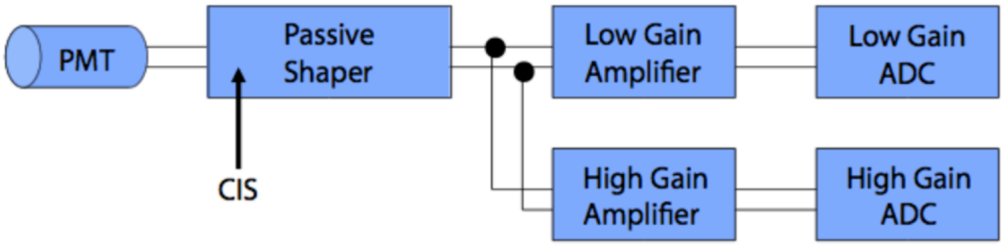
Calibration with the Laser system

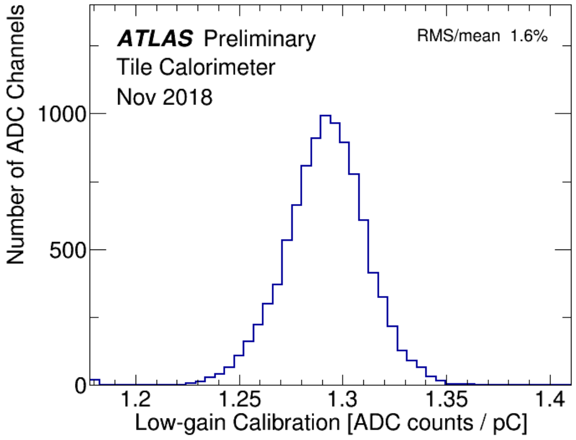
- Dedicated laser runs taken weekly
- Pulses also sent during collisions (in empty bunches) to calibrate timing
- PMT response variation evaluated w.r.t. last Cs scan, with calibration factors updated weekly (precision around 0.5%)
- Larger drifts in PMTs reading the A layer and E cells, with highest energy deposits



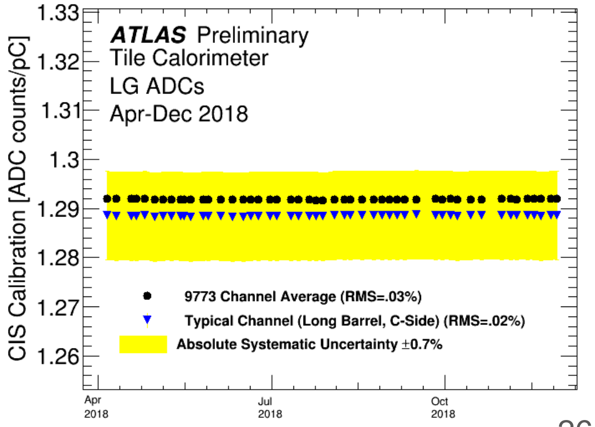


Charge Injection system



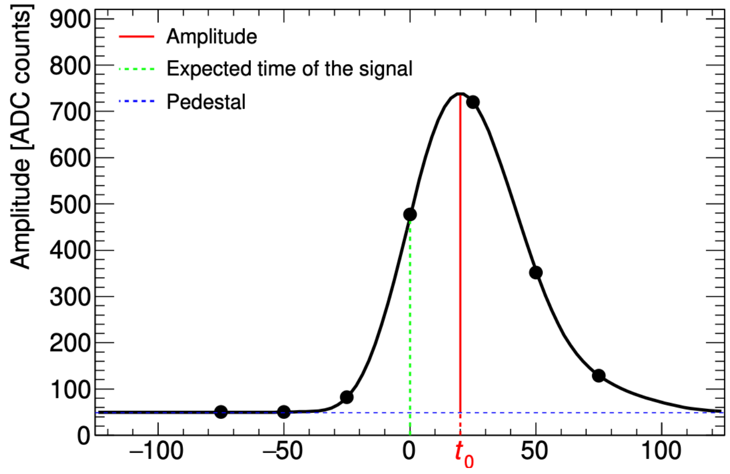


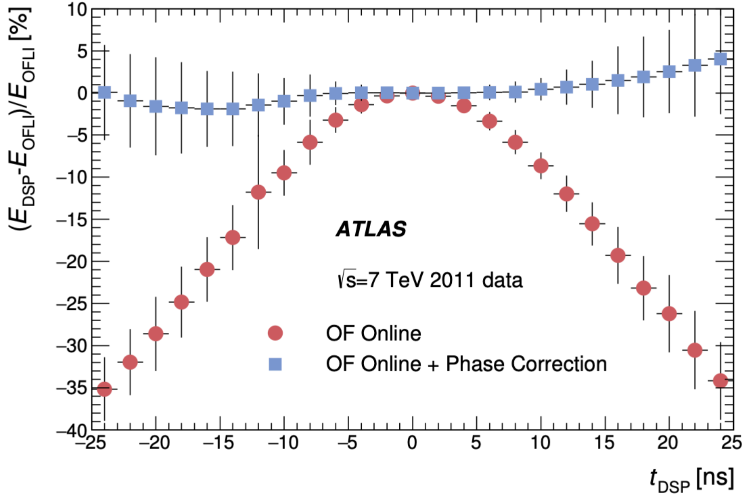
- Calibrates the response of analog amplifiers and ADCs
- Injection of known charge signal (0 to 800 pC), shaped to match PMT signal
- Dedicated runs taken weekly to extract the pC to ADC conversion factor
- Precision of 0.7% and stability over time is ~0.03%



Time Calibration

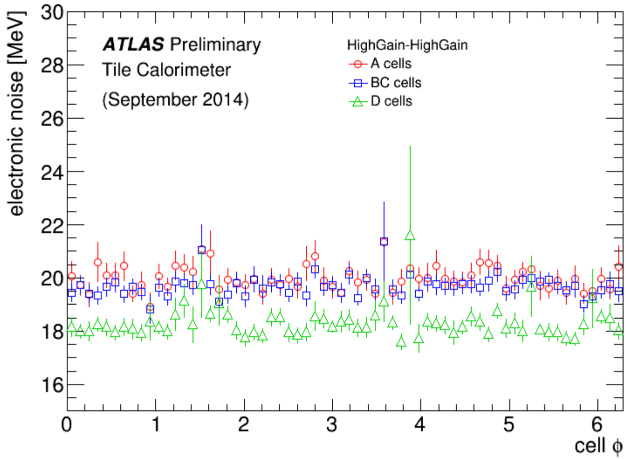
- Adjust the digitiser sampling clock to the peak of the signal
- Bad time calibration can underestimate signal amplitude
- Time calibrations derived from time distribution in cells associated to jets, additional monitoring from laser signals
- Average cell time ~0.4 ns for $E_{cell} > 20$ GeV
- Resolution better than 1 ns for $E_{cell} > 4$ GeV

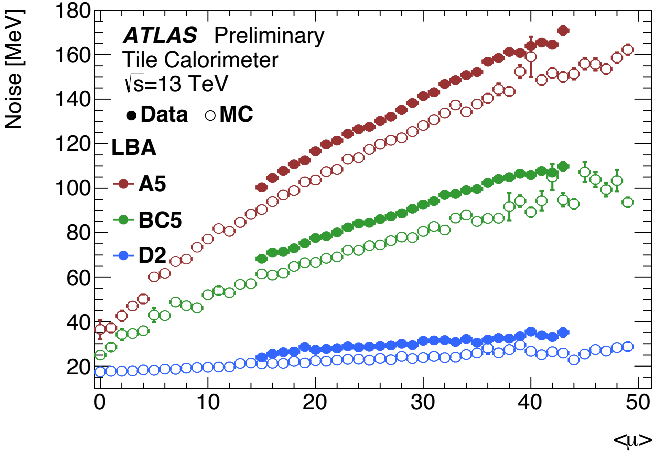




Noise measurement

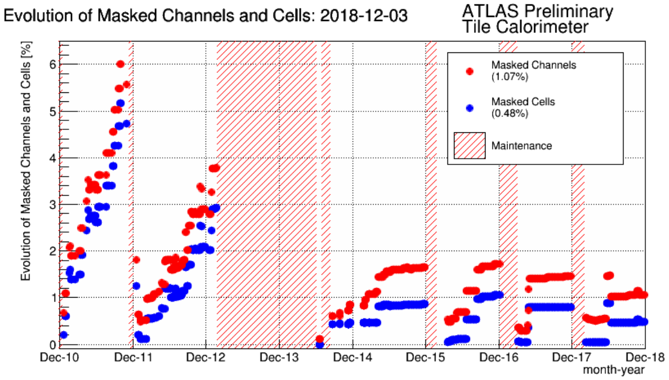
- Total noise per cell in the calorimeter comes from:
  - Electronics
  - Pile-up
- Electronics noise ~20 MeV for all cells, measured regularly in dedicated runs without signal in the detector
- Pile-up noise dependent of the average number of interactions per bunch crossing
- Innermost cells in the A layer with larger energy deposits are more affected by pile-up noise



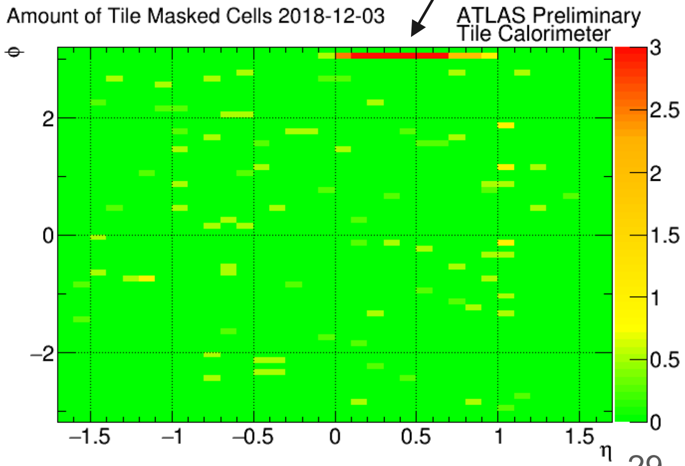


Detector Operation and Data Quality

- **Detector Control System** (a SCADA infrastructure) to Control and Monitor the TileCal operation and the detector parameters
- Run coordination, maintenance and data quality teams ensure the smooth operation of the detector
- Continuum monitoring to **identify and mask problematic channels**, correct mis-calibrations, detect data corruption and hardware issues
- Redundancy in the cell readout reduces the impact of masked channels
- Maintenance campaigns fix all issues to fully recover the system
- TileCal had **99.7% DQ efficiency in Run 2**

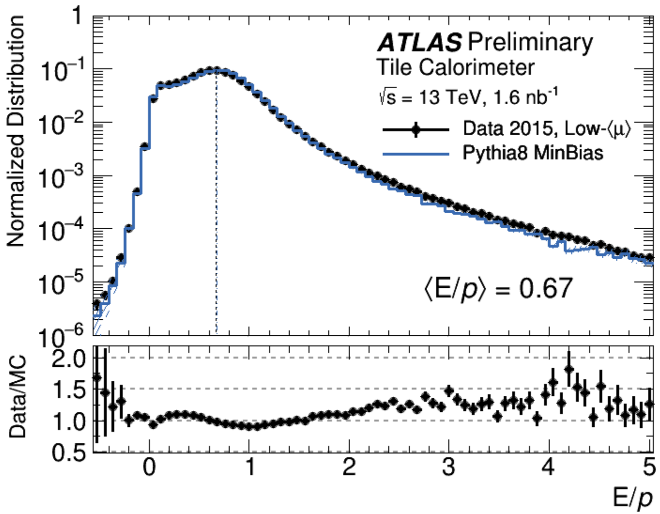


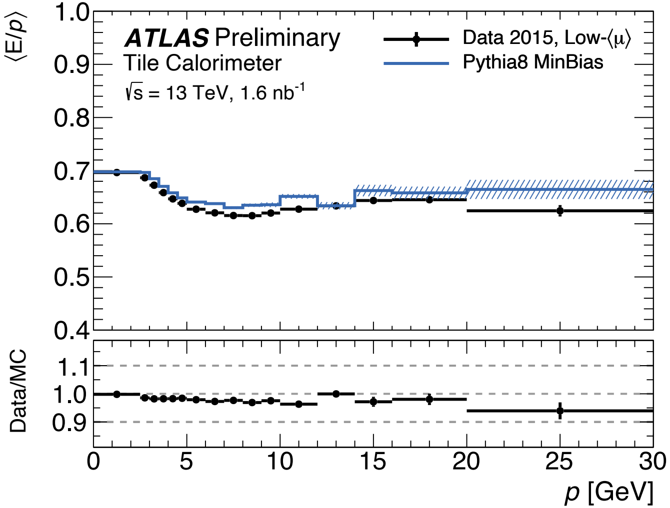
Masked module, also modelled in data simulation



Performance:
Response to isolated hadrons

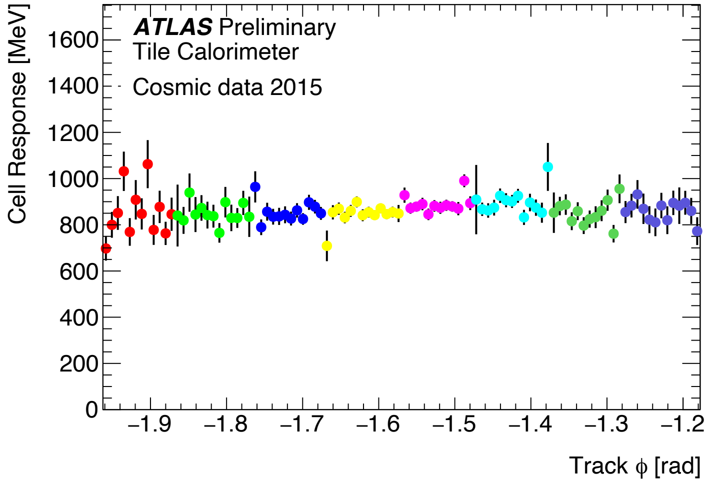
- The ratio of the calorimeter energy response to isolated charged hadrons (EM scale) to the track momenta $< E/p >$ is used to evaluate uniformity and linearity during data taking
- Measured in Minimum Bias events
- Expected $< E/p > < 1$ due to the non-compensating nature of the TileCal (sampling calorimeter: $e/h = 1.36$)
- Data/MC agreement within 5%
- Jets are further calibrated to the jet energy scale

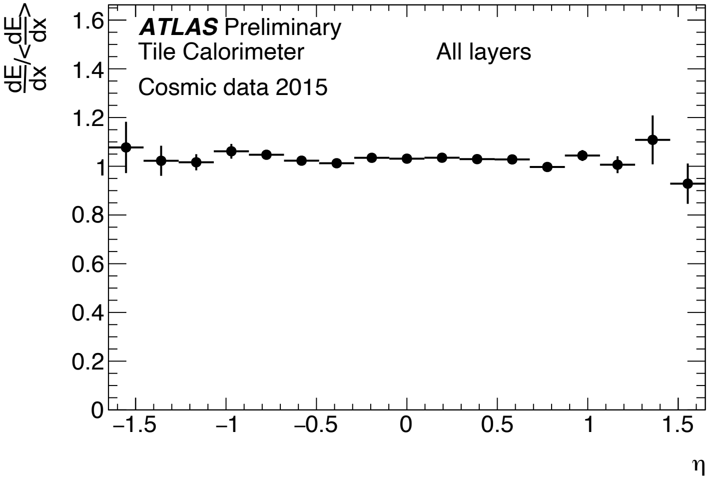




Performance:
Response to cosmic muons

- Isolated muons from cosmic rays are used to study in situ the EM scale and the cells inter-calibration
- Cell response is evaluated as the energy deposited by the muon path length dE/dx
- Good energy response uniformity over ϕ
- < 5% non-uniformity in the η response to cosmic muons

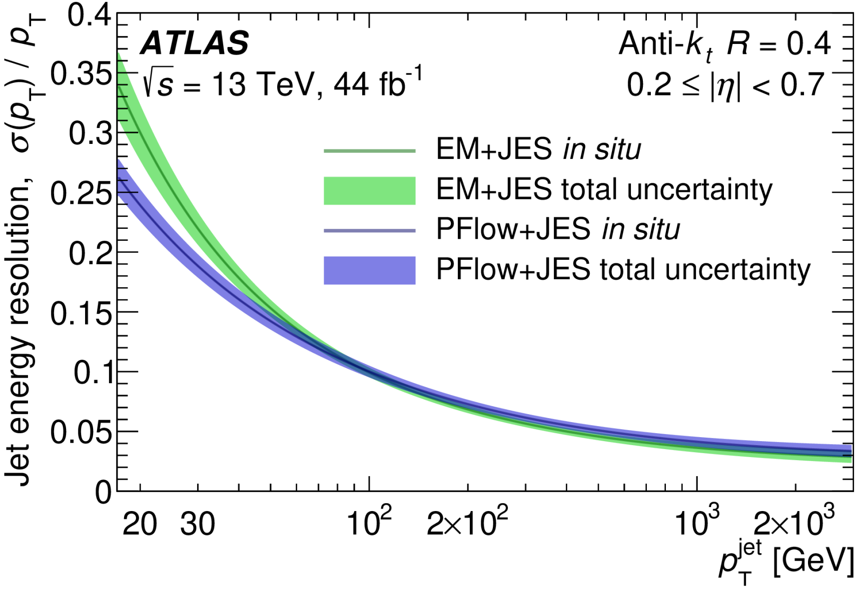




Performance:

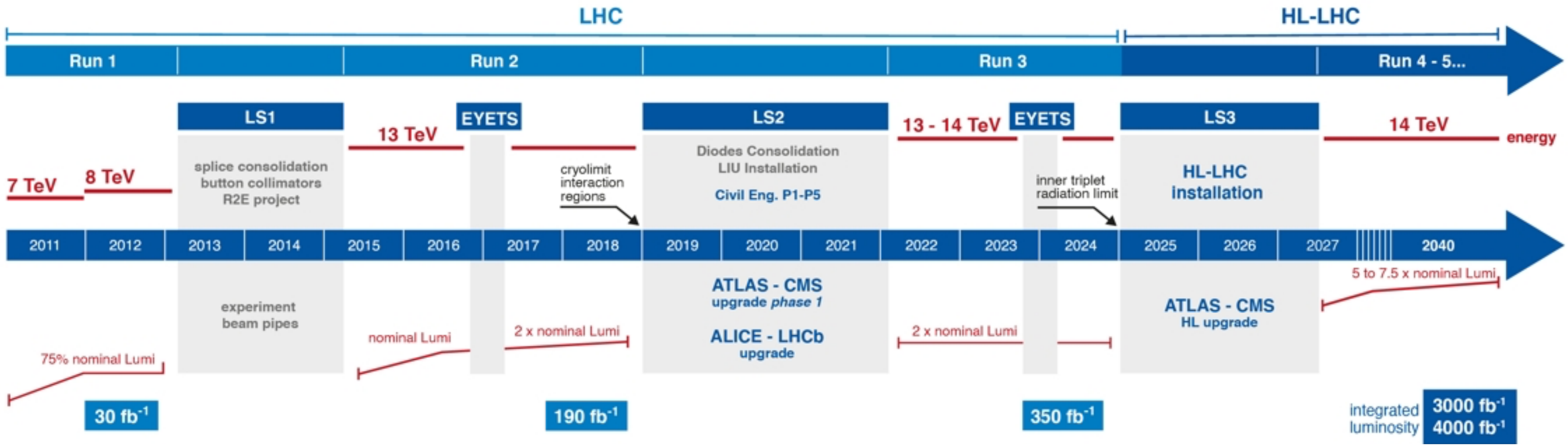
Jet energy resolution

- Jet energy resolution better 10% for $p_T^{jet} > 100$ GeV
- TileCal designed for $\frac{\Delta E}{E} \sim \frac{50\,\%}{\sqrt{E}} \oplus 3\,\%$
- Constant term within the expected 3%



How to face the HL-LHC challenges

cds.record/2285583



- Detector upgrade
  - Electronics: PMT signals will be digitised and sent directly to the back-end to cope with new fully digital Trigger/DAQ
  - New HV remote system

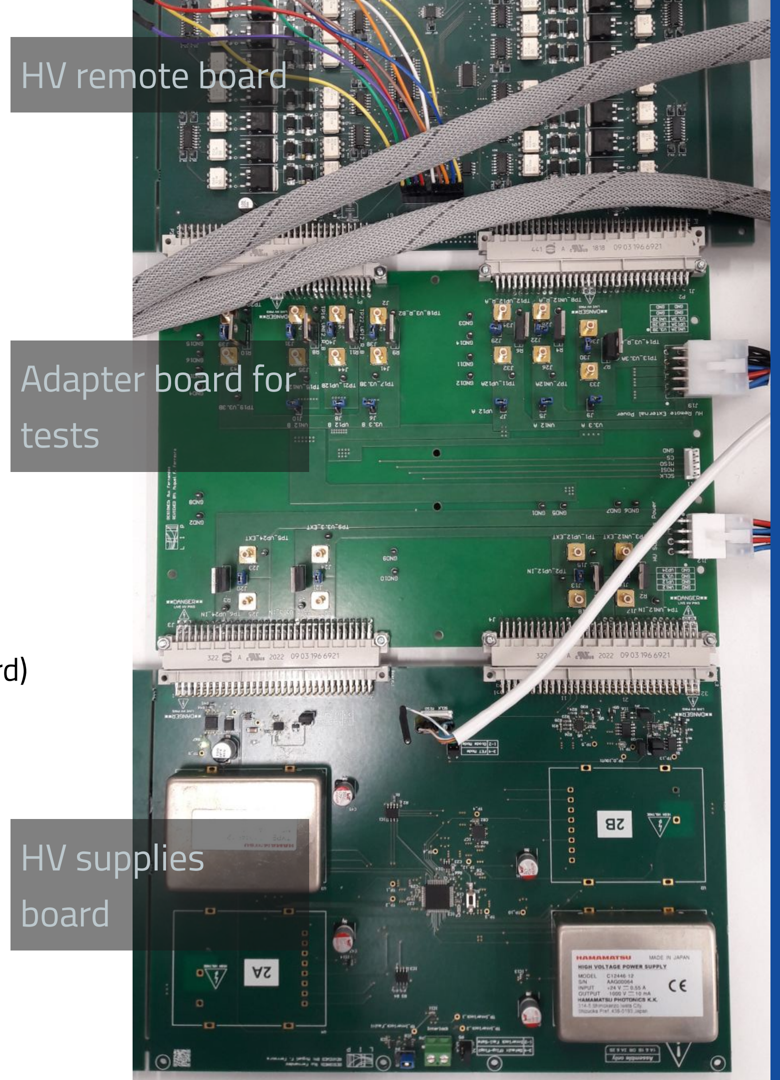
- TileCal was designed for a 10 year operation at LHC nominal conditions
  - Understand detector ageing
  - Radiation damage in active components
  - Expected performance at the HL-LHC phase

High Voltage Upgrade

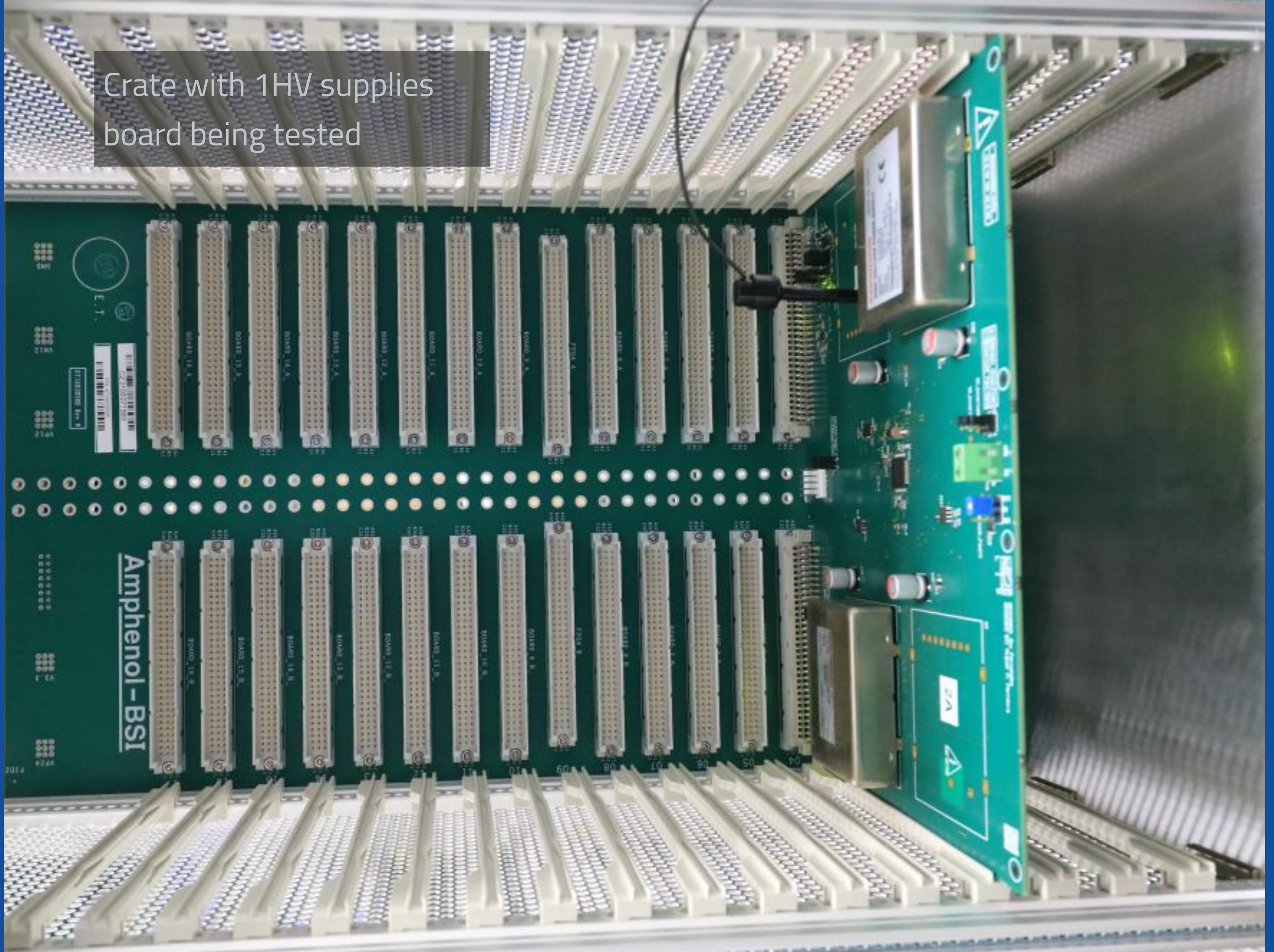
- High voltage regulation will be moved away from the detector
  - To ease access/maintenance and avoid radiation
- New crate, control and monitoring
- 100 m long cables needed to bring the HV to the detector

- Several boards being designed in collaboration with eCRLab
  - HV remote – for the regulation of individual high voltages (48 ch / board)
  - HV supplies – low voltage and primary high voltage (max -950 V)
  - FPGA adapter board for Zybo Z7 Zynq - for control and monitoring

- Cables – General Cable (Portuguese) developing new version



Thanks for the slide, Agostinho!

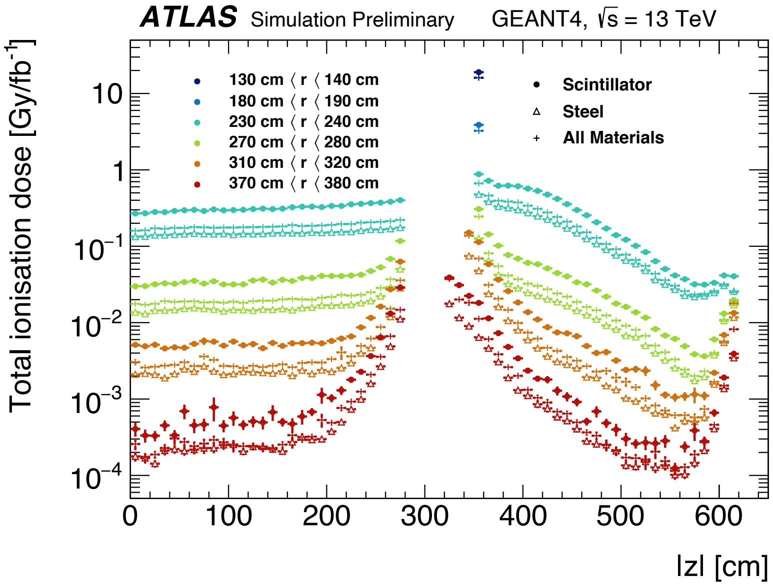


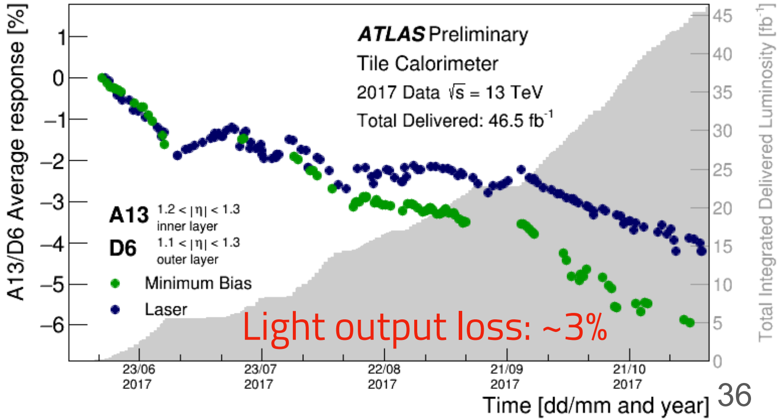
Crate with 1HV supplies board being tested

Optics Robustness

- Long plan ahead for the TileCal operation: study the radiation hardness of the TileCal optics
  - Bulk active elements can't be upgraded
  - Radiation degrades scintillator light output and WLS fibre's transparency

- Optics response obtained from comparison between
  - Cell response to Cs (or Minimum Bias events): ΔCs
  - PMT response to Laser pulses: ΔLas

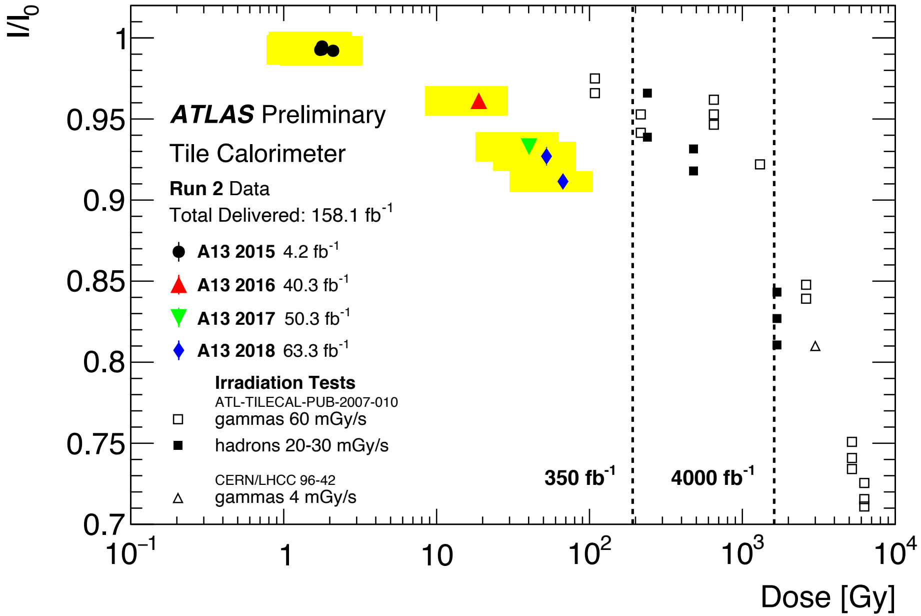




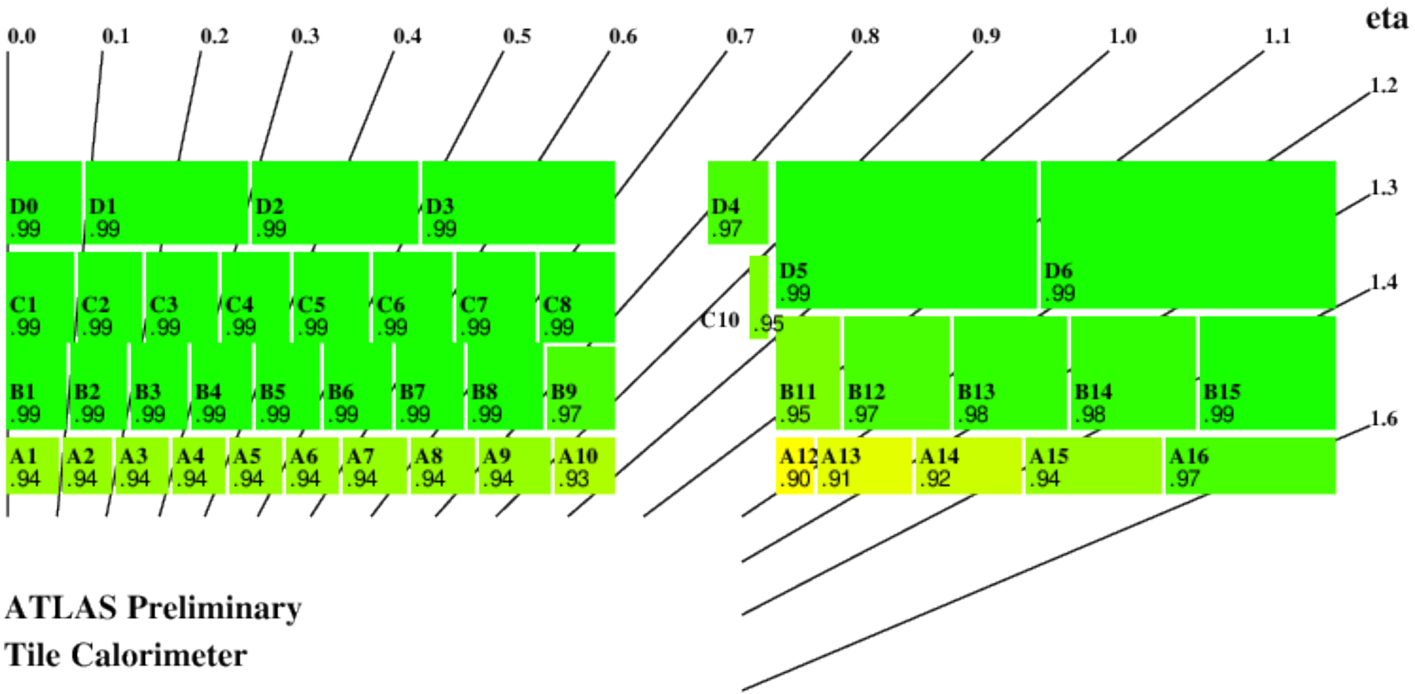
Optics Robustness

$$I/I_0 = 1 + \frac{\Delta R_{Cs} - \Delta R_{Las}}{100\%}$$

- Multi-year cumulative I/I_0 assumes no light yield evolution in between collision years
- Spread of the dose estimate within the large cell volume
- Uncertainty on I/I_o assumes no correlation
  - Cesium systematics: ~0.5% (referenceCSsysts)
  - Laser uncertainties derived (referenceLasUnc)



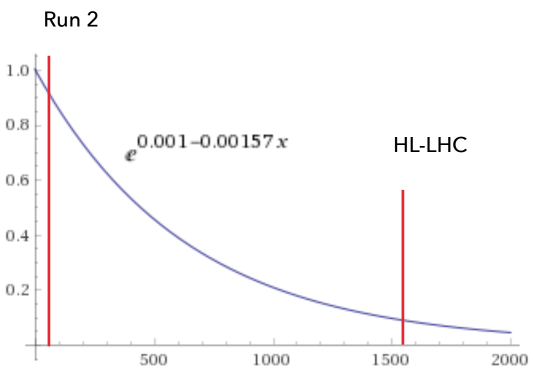
Measured Relative Light Yield at the end of the Run2

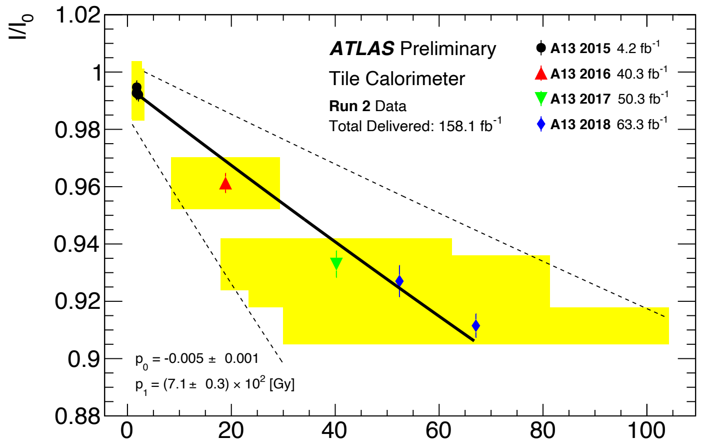


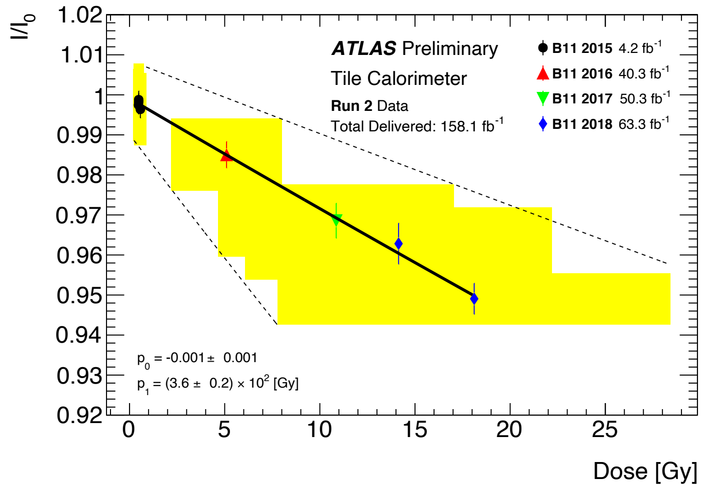
- Great majority of the cells did not degrade (B and D layer), relative uncertainty is ~1%
- 6% light output loss in average for the A layer
- At the most, 10% light loss for A12, the most exposed barrel cell

Optics Robustness: Extrapolation to future runs

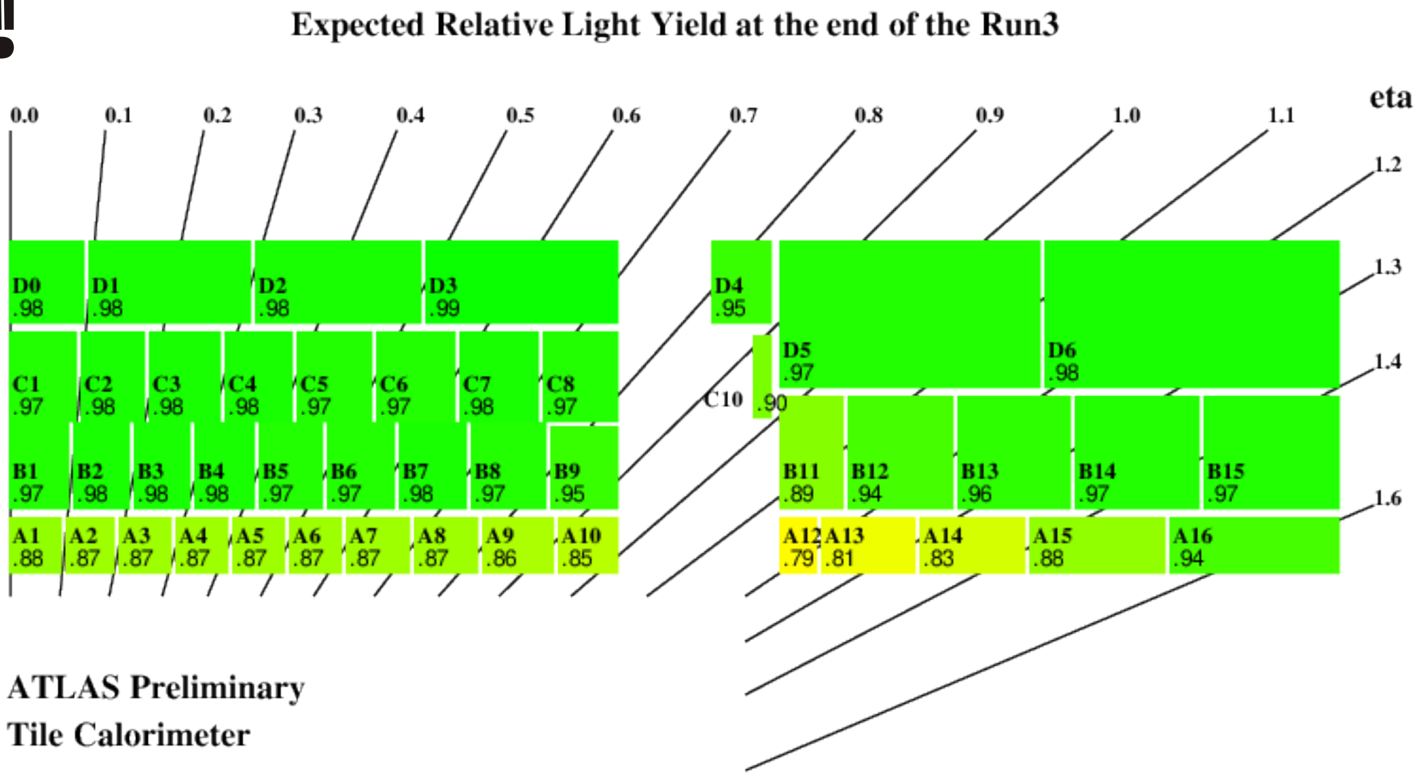
- Typically, the light output decreases exponentially with the dose, fitting exponential function
  - $$I/I_0 = e^{p_o - dose/p_1}$$
- Up and down systematics variations fitted to determine uncertainty on the fit parameters
- Large extrapolation, data only in the beginning of the curve





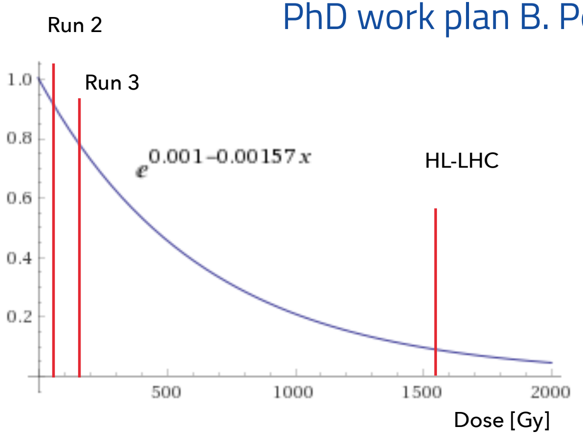


350 fb^{-1} @ Run 3



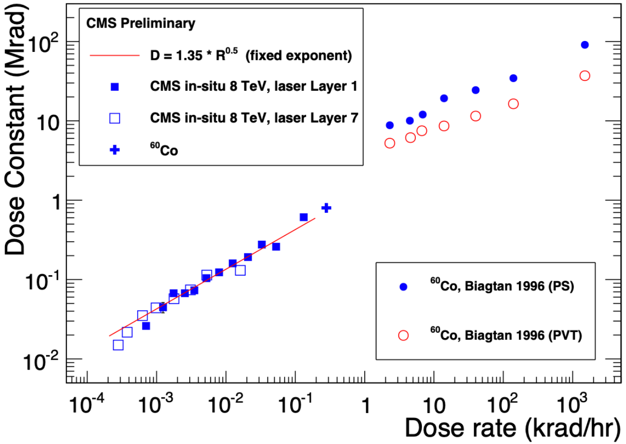
- Relative uncertainty 8 to 16% for the A layer and B cells (EB) and 5% for the remaining
- Expected about the same amount of light loss in Run 3 than we had in Run 2
- 6% light output loss in average for the A layer

Optics Robustness: What's next?



- Run 3 data will hep constrain the degradation model
  - More precise extrapolations
  - Measure eventual scintillator recovery (annealing)
- Dose rate effects?
  - CMS observed larger degradation for lower dose rates in the Endcap HCAL, 1608.07267
    - Bicron-408, Polyvyniltoluene (PVT)-based, Saint-Gobain
    - SCSN-81, Polystyrene (PS)-based from Kuraray
  - Our preliminary results agree… (can play in our favor in the HL-LHC)

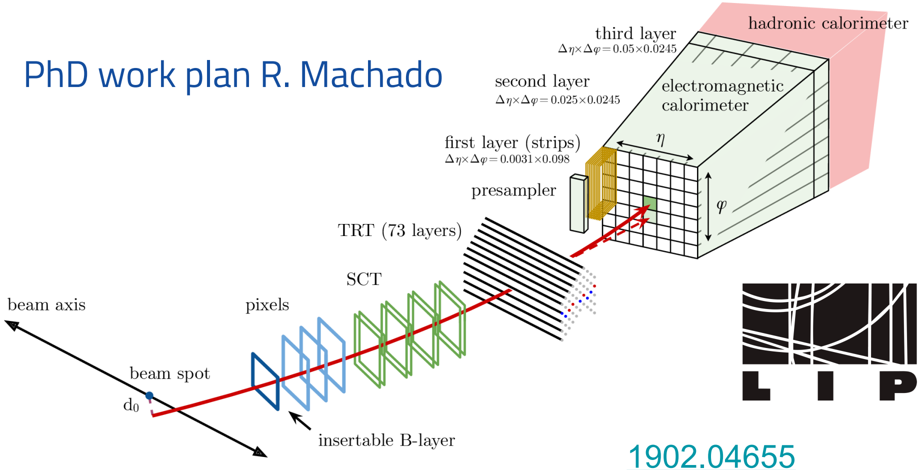
$$L(d) = L_0 \exp(-d/D)$$



Optics Robustness: What's next?

PhD work plan R. Machado

- Study the effect of light loss on the detector performance at the HL-LHC
  - Define a few HL-LHC benchmark scenarios based on extrapolations
  - Simulate the degraded TileCal response on Geant4
  - Evaluate the impact on the detector measurements
    - Sensitivity to hadronic leakage (electron ID)
    - Jet energy resolution
- Mitigation strategy
  - Compensate light output loss with higher efficiency photodetectors
  - PMTs reading the A-layer will be replaced in the Phase-II upgrade



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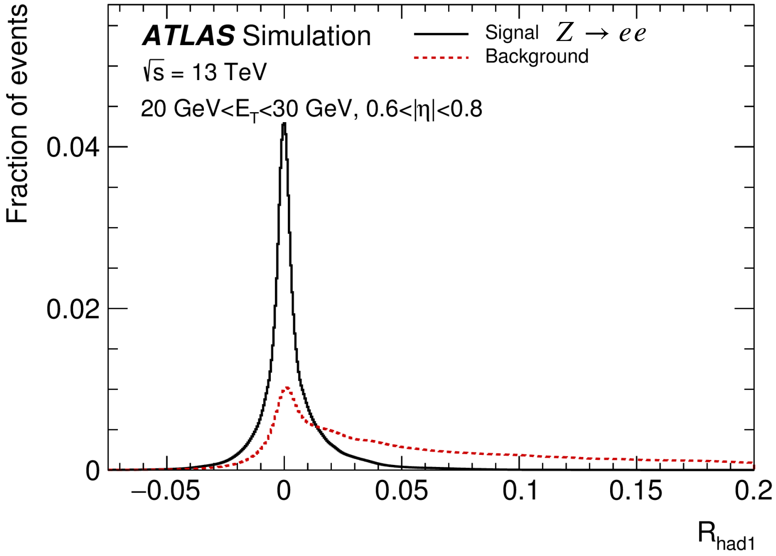
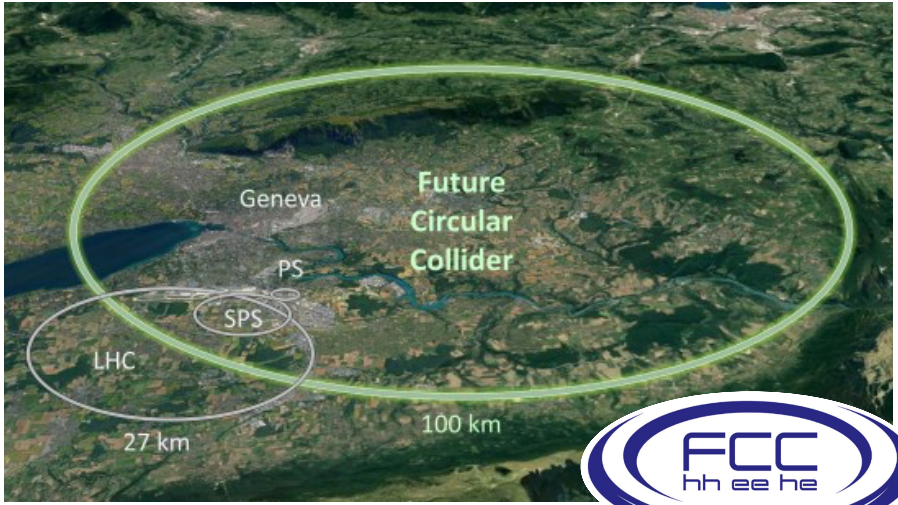


Lessons to future detector design

Detector R&D plans

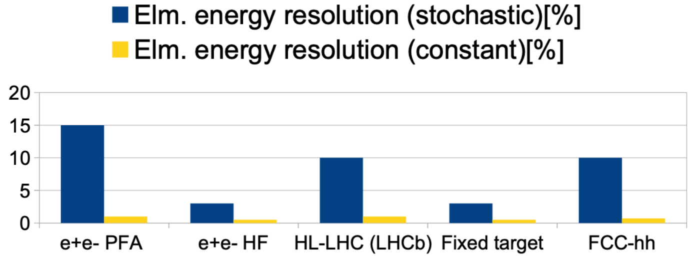


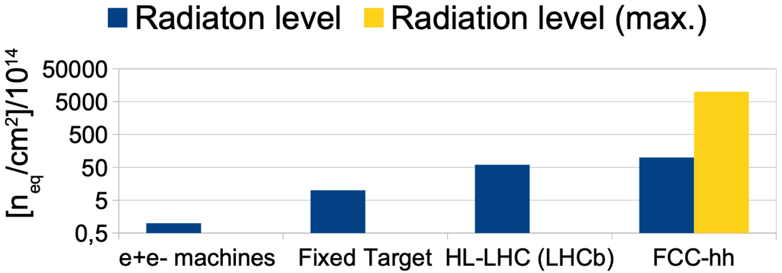
Future colliders: requirements for calorimeters

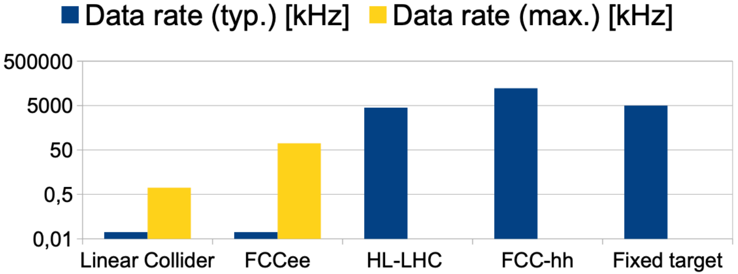
- FCC-ee: $\sqrt{s} = [90{,}350]\ GeV$
- FCC-hh: $\sqrt{s} = 100\ TeV,\ \mathscr{L} < 3 \times 10^{35} cm^{-2} s^{-1}$

- Requirements for calorimetry
  - Excellent energy resolution and linearity
  - Time resolution $\mathcal{O}(20)\,ps$ to fight pile-up
  - Technology to stand radiation environment

- Open directions
  - Particle flow (combined calorimeter and tracker information)
  - Dual readout (event by event compensation, e/h =1)
  - High-granularity segmentation (E, position (x,y,z))
  - Precise timing







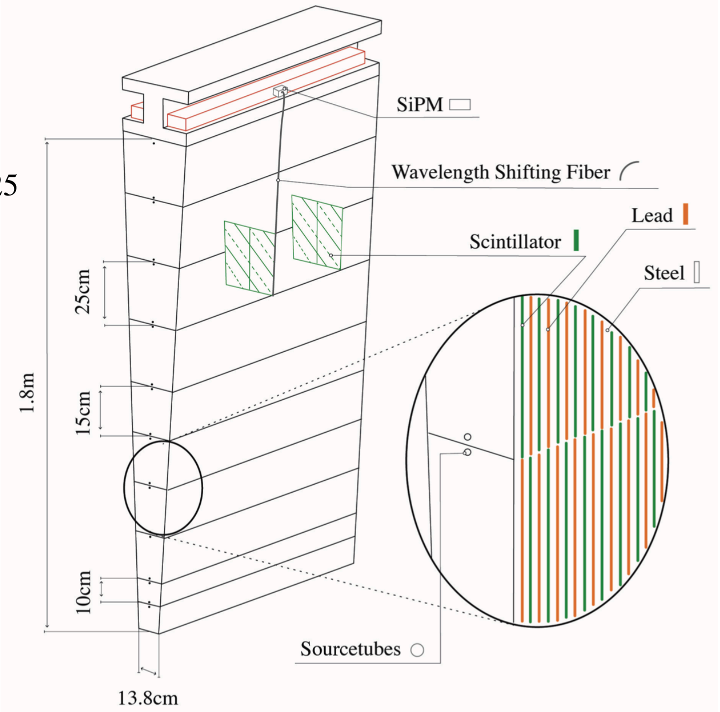
ECFA Detector R&D Roadmap - Calorimetry

Future calorimeters

[1912.09962](https://arxiv.org/abs/1912.09962)
[ECFA Detector R&D Roadmap - Calorimetry]()

$$\frac{\sigma_{p_T}}{p_T} = \frac{50-60\,\%\sqrt{\mathrm{GeV}}}{\sqrt{p_T}} \oplus 3\,\% \quad \text{for} \quad |\eta| \leq 4$$

- Proposal of TileCal-like design as central hadronic calorimeter - HCAL
  - Steel:lead:scintillating plastic tiles = 3.3:1.3:1
  - 128 modules in ϕ, tiles separated by reflector material: $\Delta\phi = 0.025$
  - Tile individual readout with WLS fibre into SiPM, signals merged into $\Delta\eta = 0.025$
  - Also a valid option for FCC-ee (?)



- Other concepts available (e.g.)
  - Integrated readout of scintillators with SiPMs (CALICE, CMS HGCAL)
  - Dual-readout (eg. compact high-granular w/ ADRIANO2 tiles: 10% stochastic term)
  - Silicon-based High granular calorimeters (CALICE, CMS HGCAL)

What can we learn with the TileCal operation history?

- Detector design must optimise calorimeter response throughout the experiment lifetime
  - Light yield and detection efficiency
  - Response depends on design factors: scintillator properties, tile size, fibre coupling, fibre length, photodetector type, cell granularity…

$$R_{cell} = \Big(\sum^{tiles} f(\varepsilon_{scint}, \varepsilon_t(\lambda_{att}, \ell_{scint})) \otimes f(\varepsilon_{coupling}, \varepsilon_{WLS}(\lambda), \varepsilon_r, \varepsilon_t(\lambda_{att}, \ell_{fibre}))\Big) \otimes f(\varepsilon_Q, G)$$

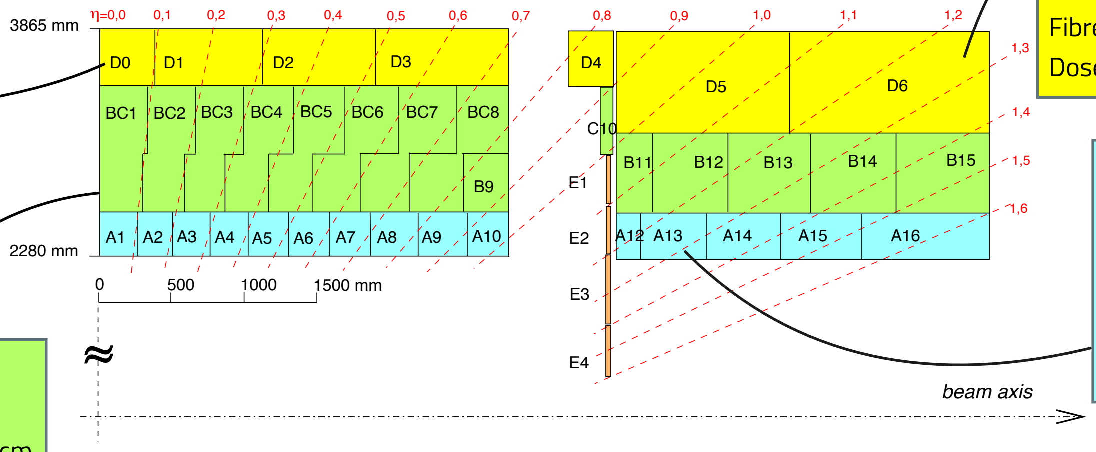
Scintillators — WLS fibres — Photodetector

  - Natural ageing: $\varepsilon \rightarrow \varepsilon(t)$
  - Radiation damage: $\varepsilon \rightarrow \varepsilon(d, \dot{d})$

Unique data set from TileCal

~80 tiles
2 rows
Tiles size: 19x[33,35]x[35,37] cm
40+40 fibres
Fibres length: 88,108 cm
Dose rate: 0.02 mGy/h

~300 tiles
4 rows
Tiles size: {19,15}x[30,35]x[32,37] cm
75+75 fibres
Fibres length: 122,137,159,174 cm
Dose rate: 0.06 mGy/h



~75 tiles
3 rows
Tiles size: 97x[22,24]x[23,25] cm
25+25 fibres
Fibres length: 207,214 cm
Dose rate: 14.9 mGy/h

~120 tiles
6 rows
Tiles size: {13,15}x[25,32]x[26,33] cm
18+17+15+16 fibres
Fibres length: 122,137,159,174 cm
Dose rate: 0.6 mGy/h

- Unique data set from TileCal, several advantages
  - In-situ conditions
  - Low dose rates (very difficult to assess with laboratory irradiations)

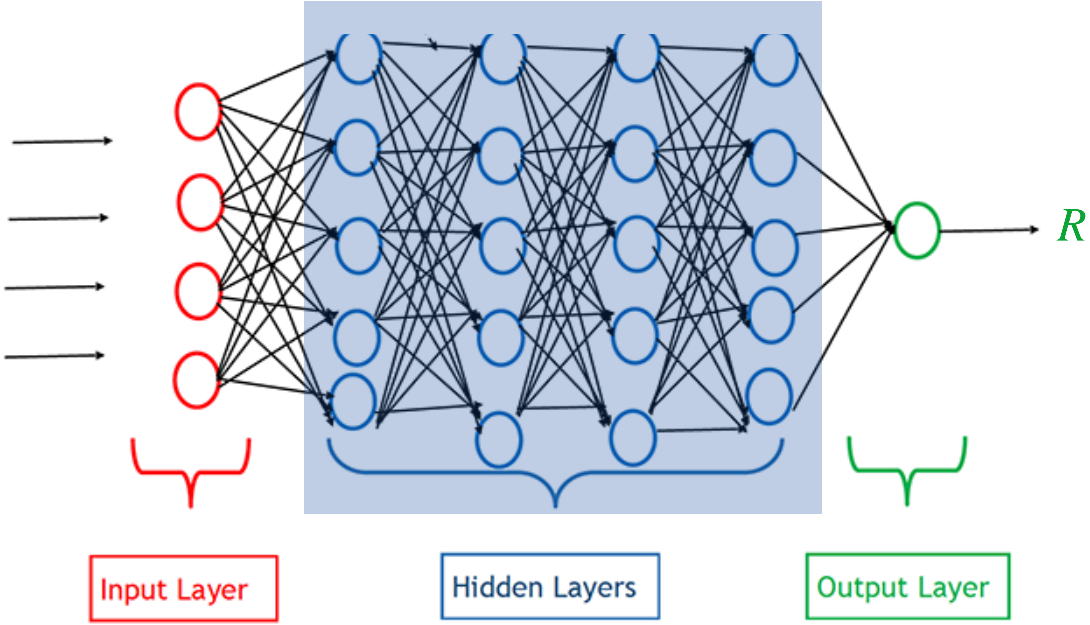
inspirehep/1197250
inspirehep/811858
Approximate numbers

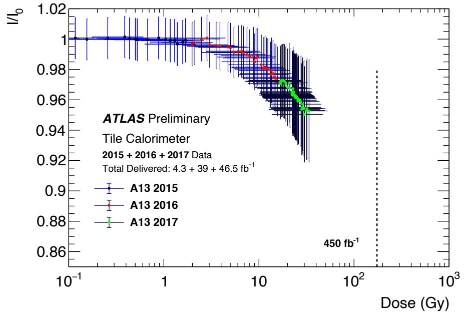
Can Machine Learning teach us something?

PhD work plan B. Pereira

$$\sum^{tiles} f(\varepsilon_{scint}, \varepsilon_t(\lambda_{att}, \ell_{scint})) \otimes f(\varepsilon_{coupling}, \varepsilon_{WLS}(\lambda), \varepsilon_r, \varepsilon_t(\lambda_{att}, \ell_{fibre}))$$

- N tiles
- N rows
- Tiles size
- N fibres
- Fibres length
- Dose rate
- Dose points
- Time points





- Combined fit to the TileCal geometry and optics response data with DNN regression
- Investigate the dependence of the obtained model on the different detector parameters and dose conditions

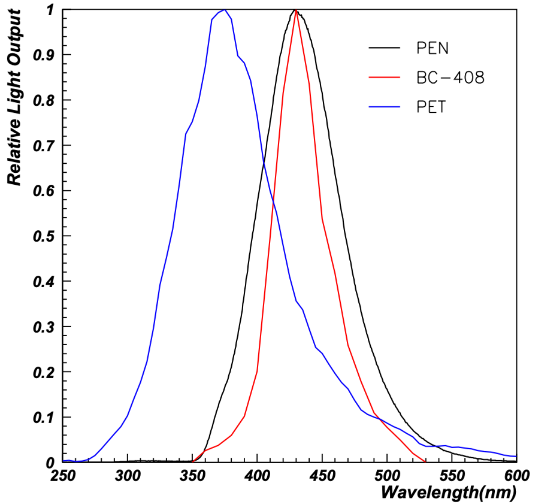
R&D on brighter and radiation-harder scintillators

- Independently of geometry optimisation and technology choices, active material must improve
  - Initial light yield is an overhead to maximise
  - More radiation hardness
  - More detectable light, i.e., best possible matching between emitted light wavelength and photodetector efficiency peak

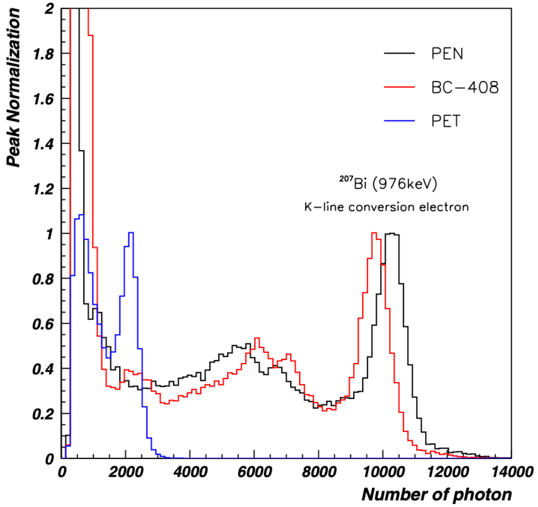
- Novel materials look promising
  - PEN - Polyethylene Naphtalate
  - PET - Polyethylene Terephtalate

PET and PEN, scintillation properties

Material	Polyethylene naphthalate	Organic scintillator (ref. [14])	Plastic bottle (ref. [13])
Supplier	Teijin Chemicals	Saint-Gobain	Teijin Chemicals
Base	$(C_{14}H_{10}O_4)_n$	$(C_9H_{10})_n$	$(C_{10}H_8O_4)_n$
Density	$1.33\,g/cm^3$	$1.03\,g/cm^3$	$1.33\,g/cm^3$
Refractive index	1.65	1.58	1.64
Light output	~10500 photon/MeV	10000 photon/MeV	~2200 photon/MeV
Wavelength max. emission	425 nm	425 nm	380 nm



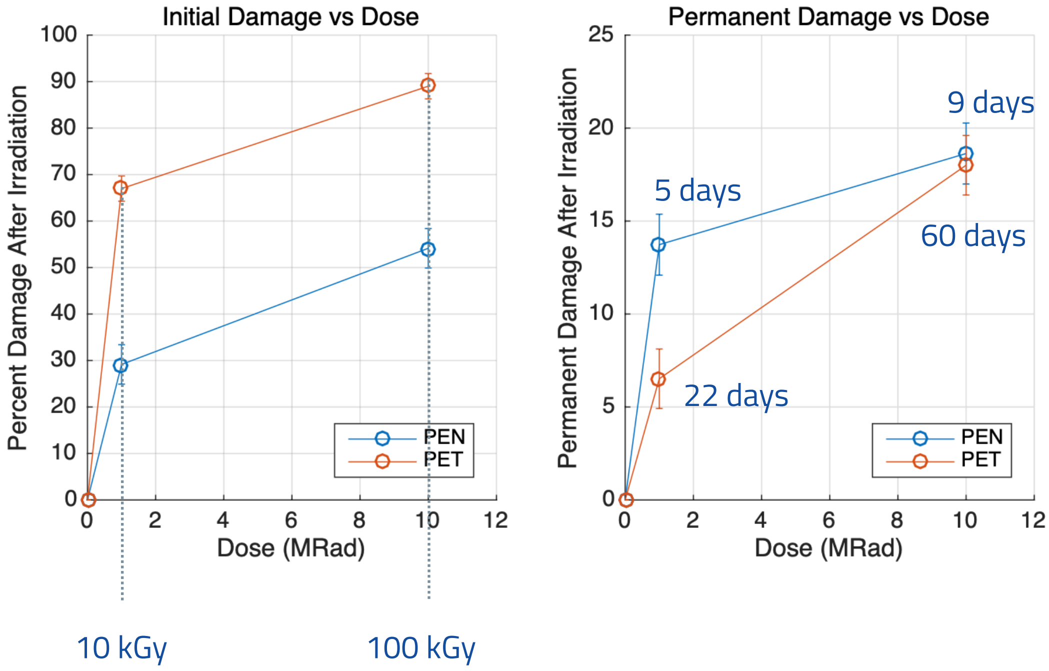
- Scintillate without addition dopants
- Emission spectrum well matched to typical photodetector efficiency
- PEN has larger light yield than expensive commercial BC-408
- PEN has large radiopurity and good mechanical properties
  - proposed as active vetoing structure in low-background experiments
- PEN affords an energy resolution of ~10% at 1 MeV, better than BC-408



iopscience/10.1209
arxiv:1806.04020

PET and PEN, radiation hardness

- Irradiation of PET and PEN sheets Goodfellow
- Cs-137 gamma source
- 10 and 100 kGy in 67 h
- Dose rates 150Gy/h and 1.5 kGy/h



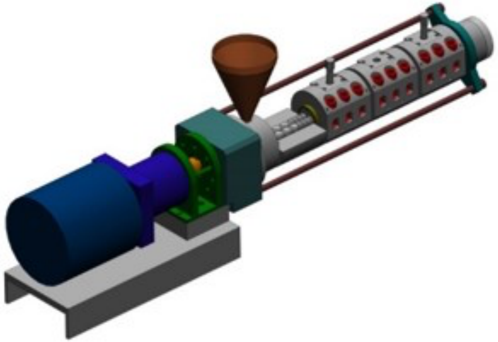
- PEN degrades less and recovers faster
- PET degrades faster, recovers slower but shows larger recovery
  - (For doses and dose rates closer to real detector in-situ conditions)

arxiv:1605.00700

R&D on brighter and radiation-harder scintillators

- Re-initiated the collaboration with the Institute for Composites and Polymers - UMinho
- Original initiative of Prof. A. Maio
- Goal of the project is to develop and investigate samples of PET and PEN blends
  - Do PEN and PET blend synergistically? What is the best material formula?
  - Is it advantageous to add dopants at all?

- Characterise the optical and scintillation properties of the samples at LOMaC/LIP
- Optimise and set up a scalable manufacturing technique
- Irradiate the best samples at laboratory to characterise the radiation resistance
  - Important to study dose rate effects



Extrusion machine

1 - volumetric feeder

2 - twin screw extruder

3 - mini-gear pump

4 - rheo-optical die

5 - laser He-Ne

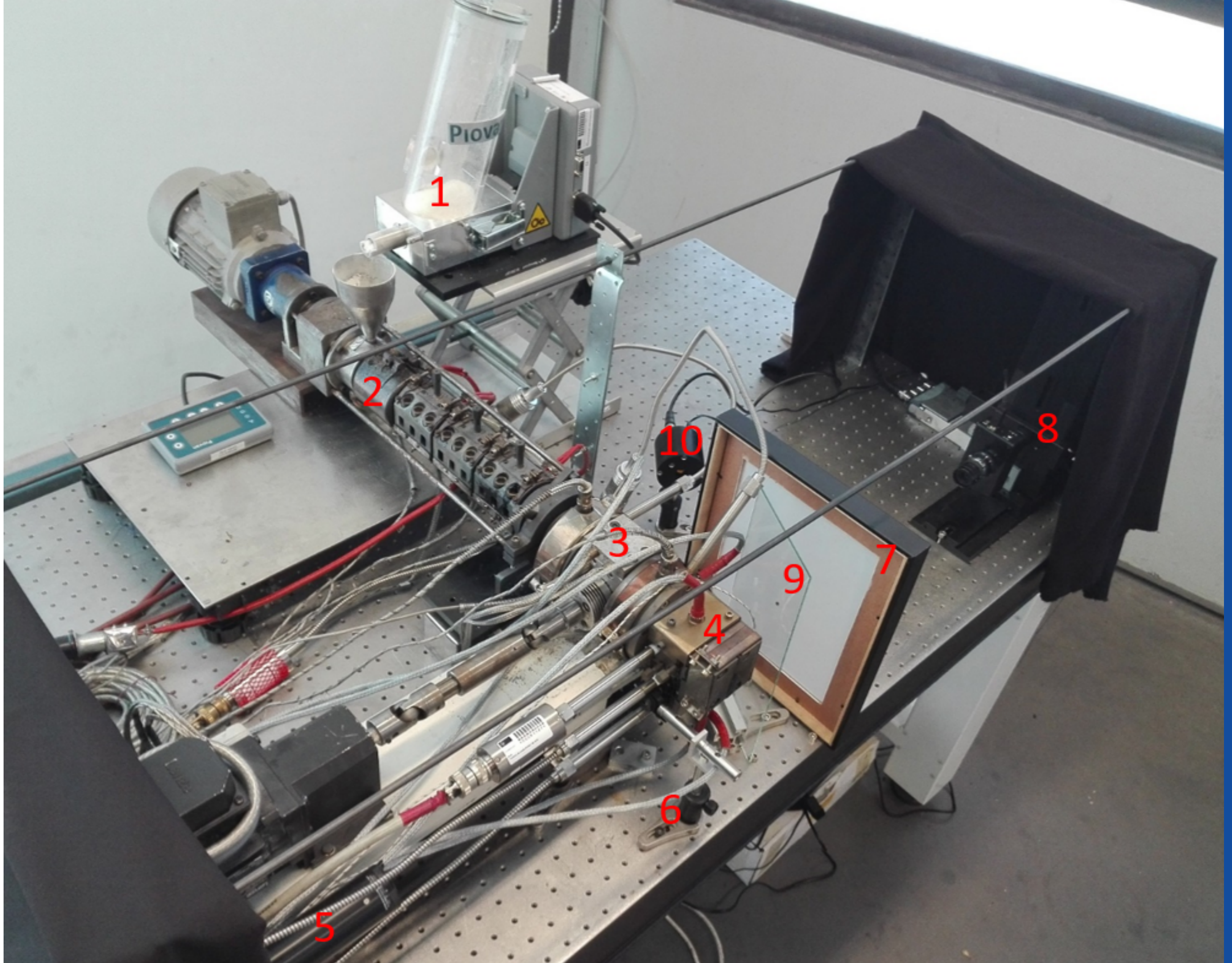
6 – pinhole

7 – screen

8 - CCD camera

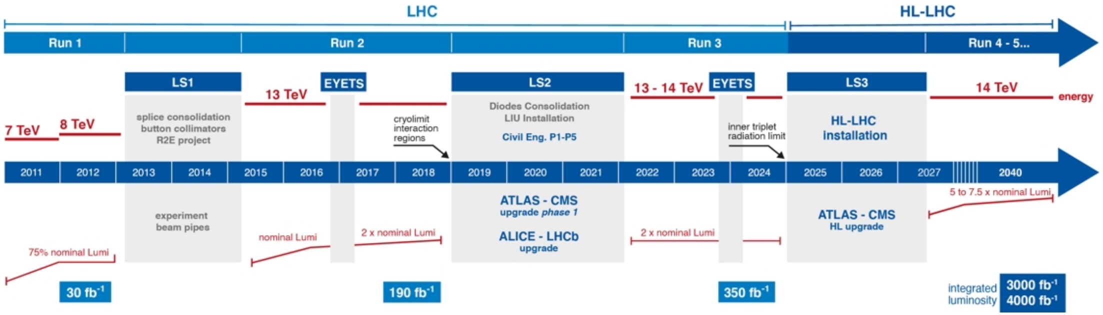
9 – glass

10 - photo detector



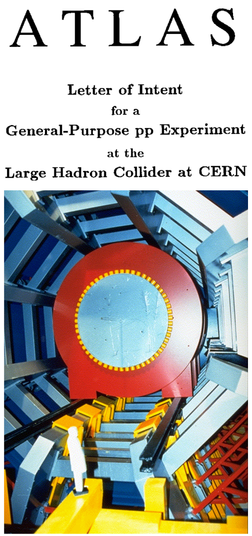
Summary

1992



>2040 >>2050

FCCee FCChh

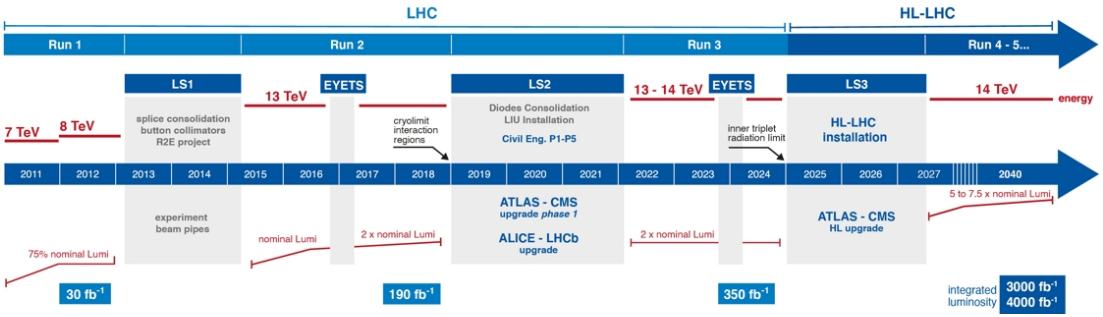

ATLAS

Letter of Intent
for a
General-Purpose pp Experiment
at the
Large Hadron Collider at CERN

In-house expertise and experience gained from LIP contribution to TileCal construction

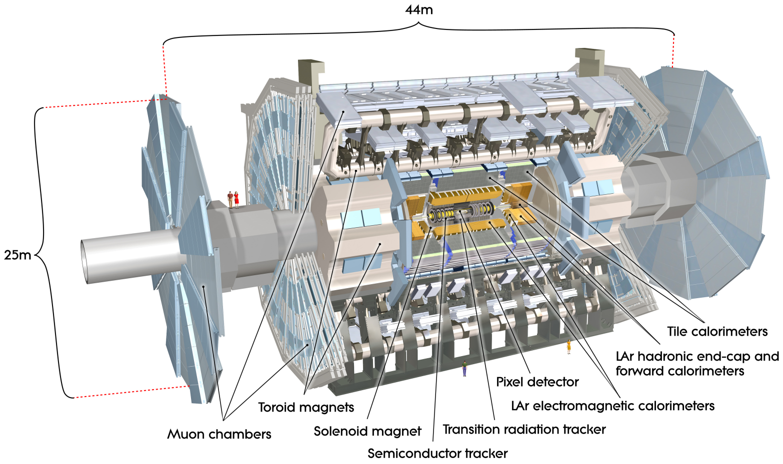
Summary

1992



>2040 >>2050

FCCee FCChh

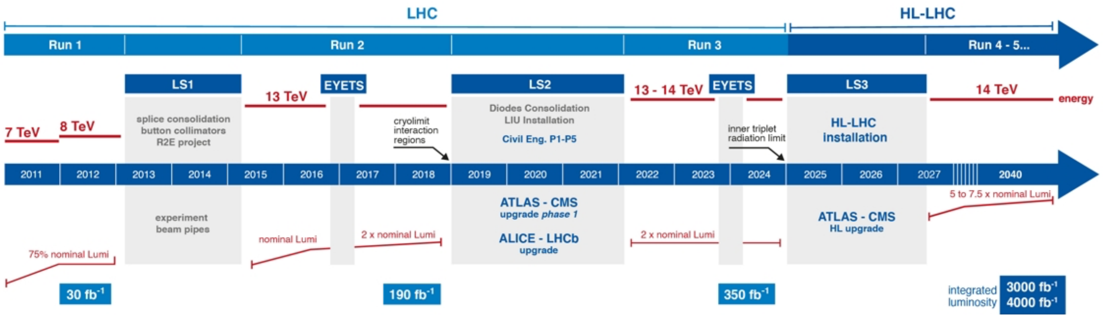


Detector Operating and Performing very well

Phase-II upgrade projects ongoing

Study the expected detector performance at the HL-LHC

Summary



1992

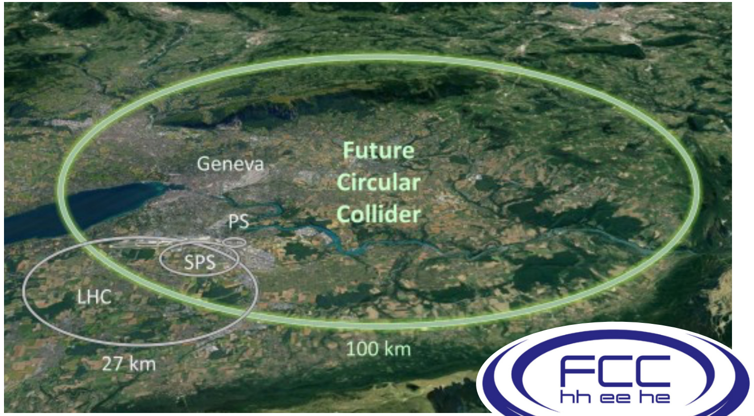
>2040 >>2050

FCCee FCChh

Radiation hardness is a critical aspect of plastic scintillator-based calorimetry

Investing in R&D on potential radiation-harder scintillators

ECFA Roadmap for the R&D on future detectors will help lightening the way




THANK you

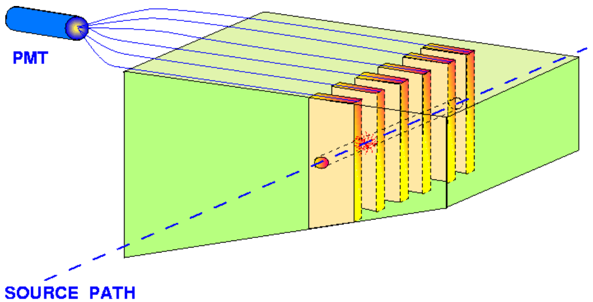
ACKNOWLEDGEMENTS

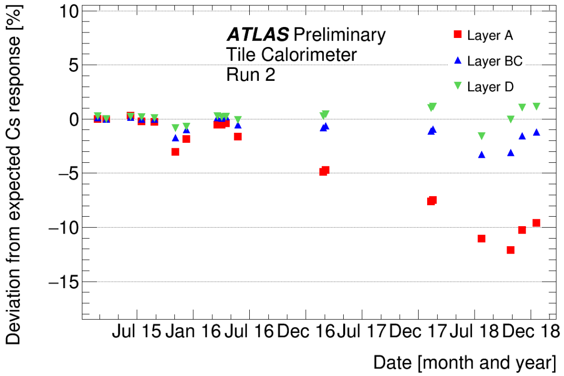
FCT Fundação para a Ciência e a Tecnologia

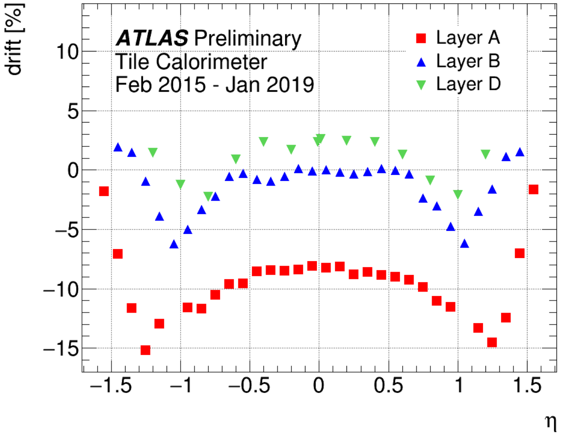
REPÚBLICA PORTUGUESA

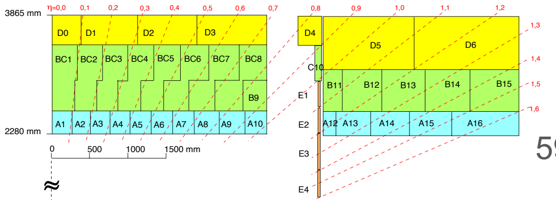
CERN/FIS-PAR/0002/2019

Calibration with the Cesium system





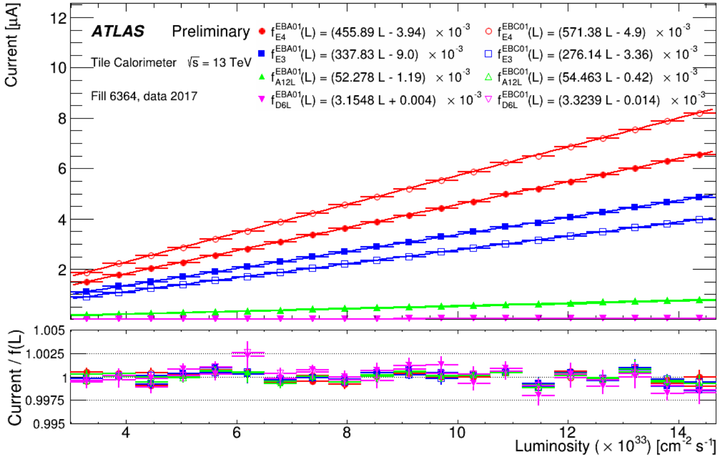


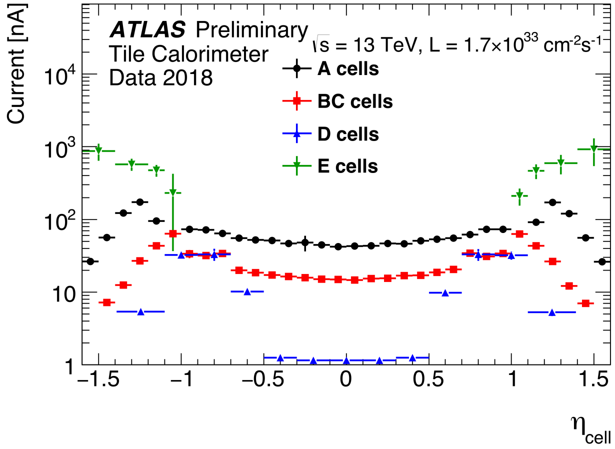


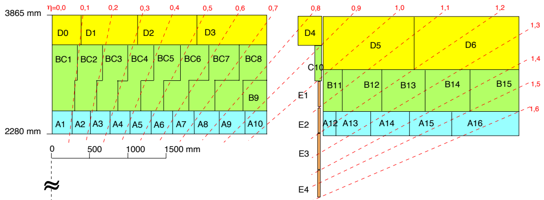
- ^{137}Cs $\gamma-$source scans 2-3 times/year in Run 2
- Cell response drifts due to scintillator degradation with exposure to radiation and PMT response loss with accumulated anode current
- Precision of the system for a typical cell is around 0.3%
- Maximal down-drifts for the innermost A layer

Integrator readout of Minimum Bias events

- Soft inelastic interactions (minimum bias events) are the most frequent in high energy proton collisions
- The total energy deposit in the calorimeter over a large time is proportional to the instantaneous luminosity
- Integrator readout of the PMT signals (10 ms) provides an independent measurement of the instantaneous luminosity (given an initial calibration)
- The system also monitors the full detector chain and allows finer grained calibration of more drifting cells in between Cs runs (specially relevant for E-cells not scanned with the Cs-source)







Performance:
Response to jets

- Good description of the cell energy and noise distributions are crucial for building topoclusters and to reconstruct the missing transverse energy
- Good data/MC agreement in the tile cell energy distribution
- Jet energy resolution better 10% for $p_T^{jet} > 100$ GeV
- TileCal designed for $\frac{\Delta E}{E} \sim \frac{50\,\%}{\sqrt{E}} \oplus 3\,\%$
- Constant term within the expected 3%