The Phase-II Upgrade of the ATLAS Tile Calorimeter

Tigran Mkrtchyan (KIP, Heidelberg)

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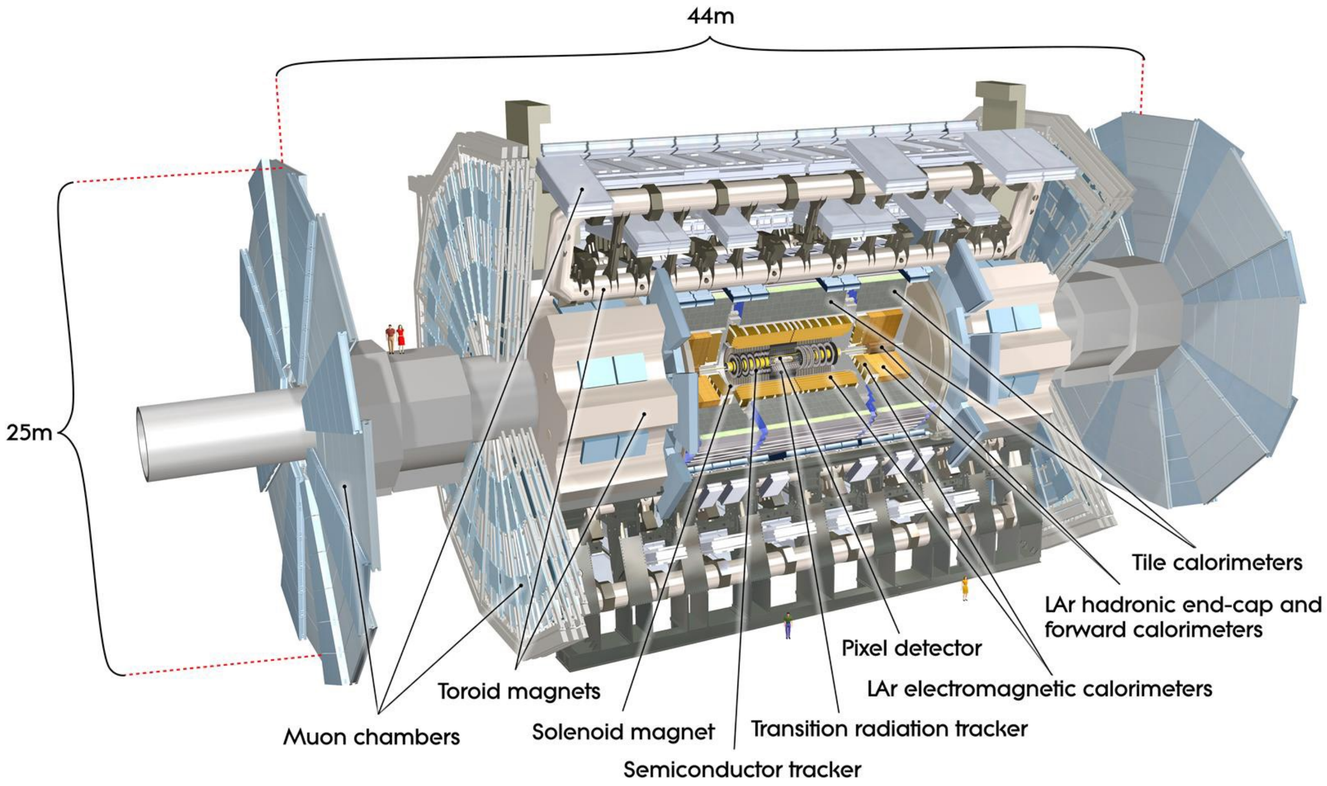
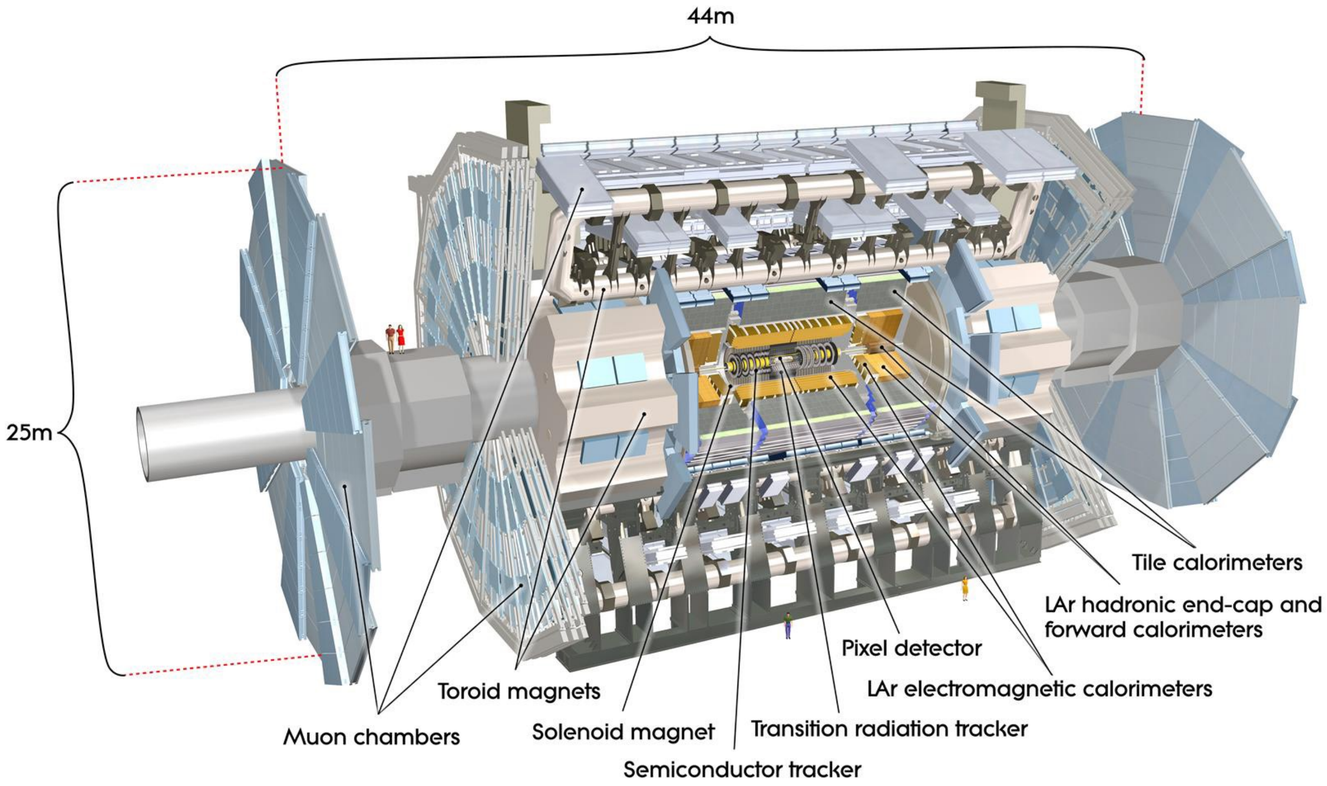
The ATLAS Detector



The ATLAS Detector

The ATLAS Detector

- Largest detector at the LHC
- pp collisions at $\sqrt{s} = 13$ TeV
- Multi-purpose detector
  - Precision Measurements
  - Searches for BSM signatures
  - Flavour Physics & Heavy-Ion Physics



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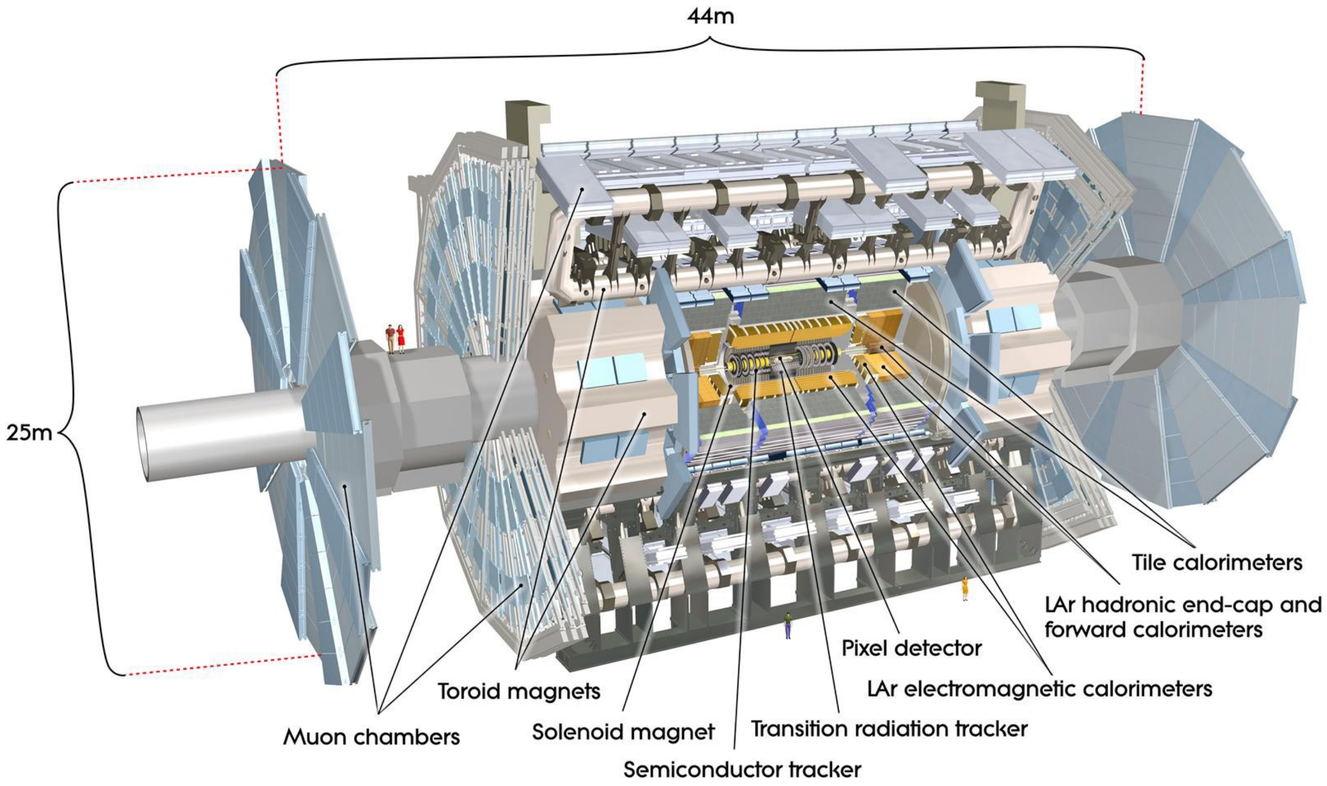
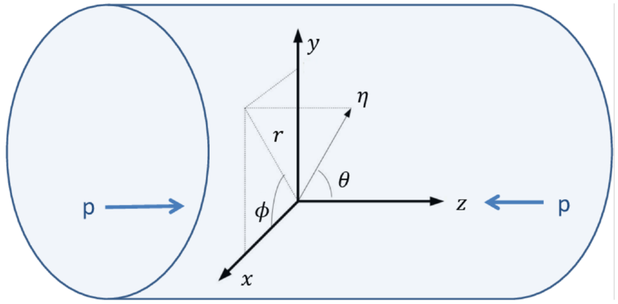


The ATLAS Detector

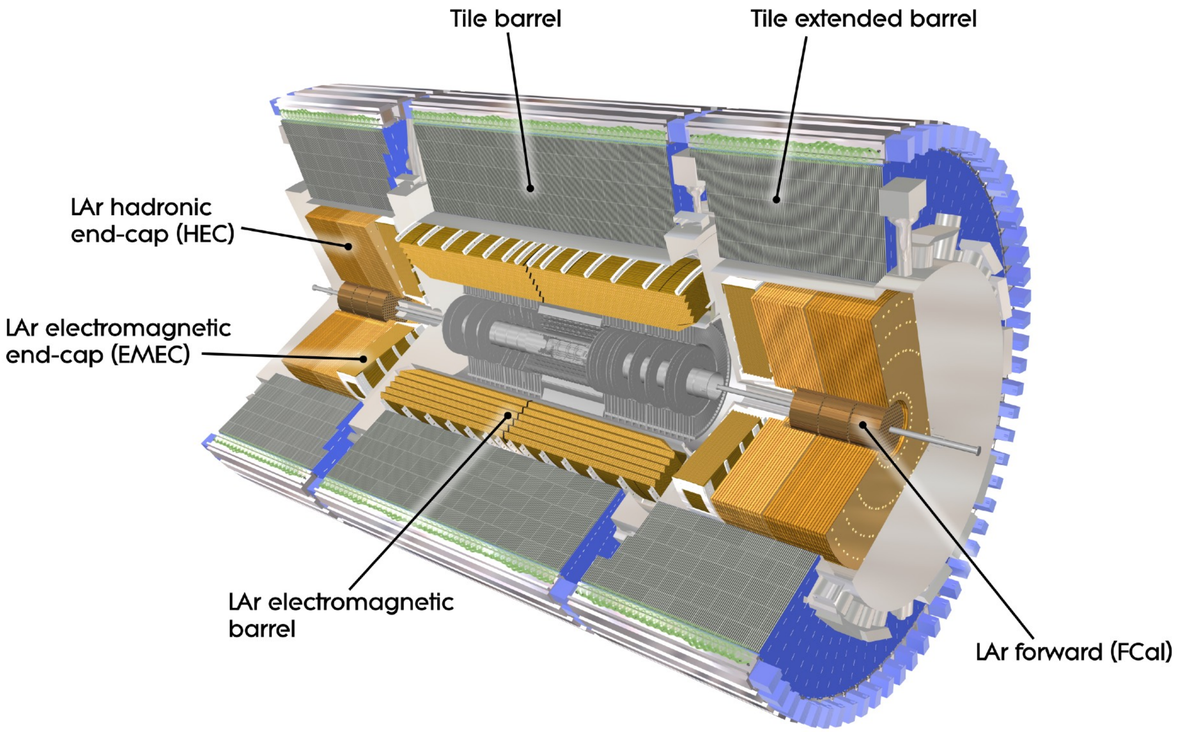
The coordinate system used in ATLAS



Pseudorapidity:

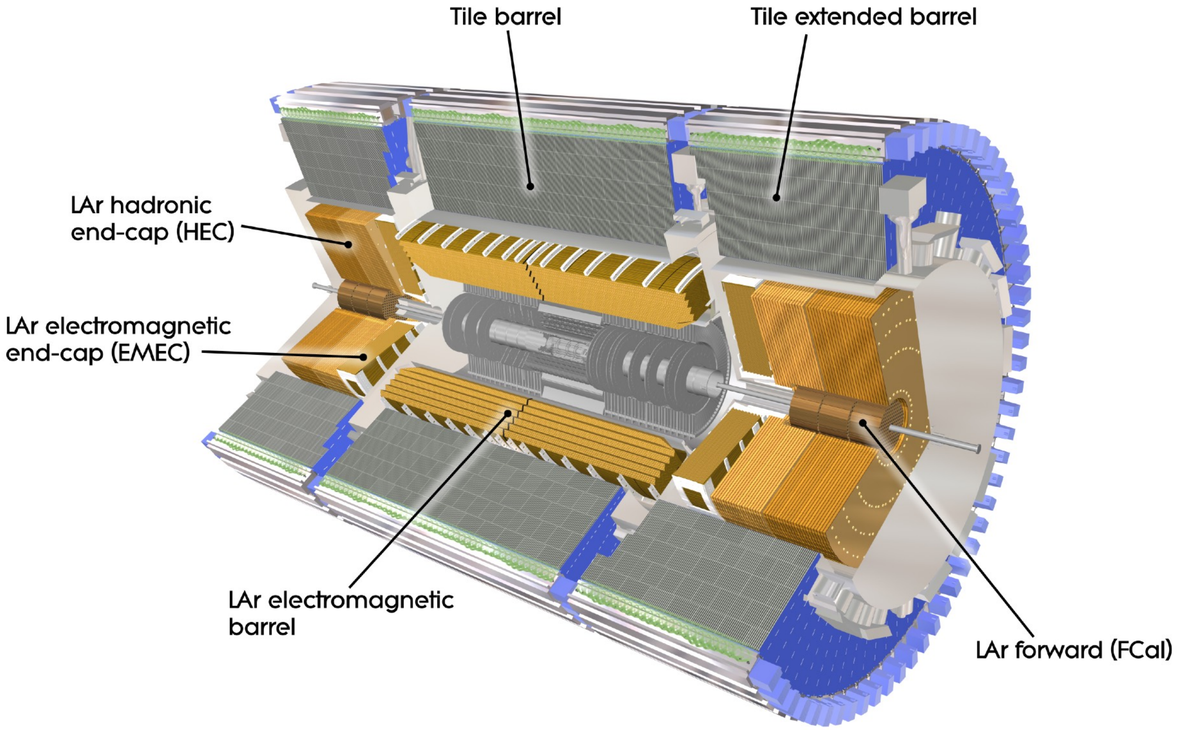
$$\eta = -\ln[\tan(\frac{\theta}{2})]$$

ATLAS & the Tile Calorimeter



ATLAS & the Tile Calorimeter

- Central hadronic calorimeter $\eta = 1.7$
- Sampling calorimeter with steel absorbers
- Plastic scintillators as active medium



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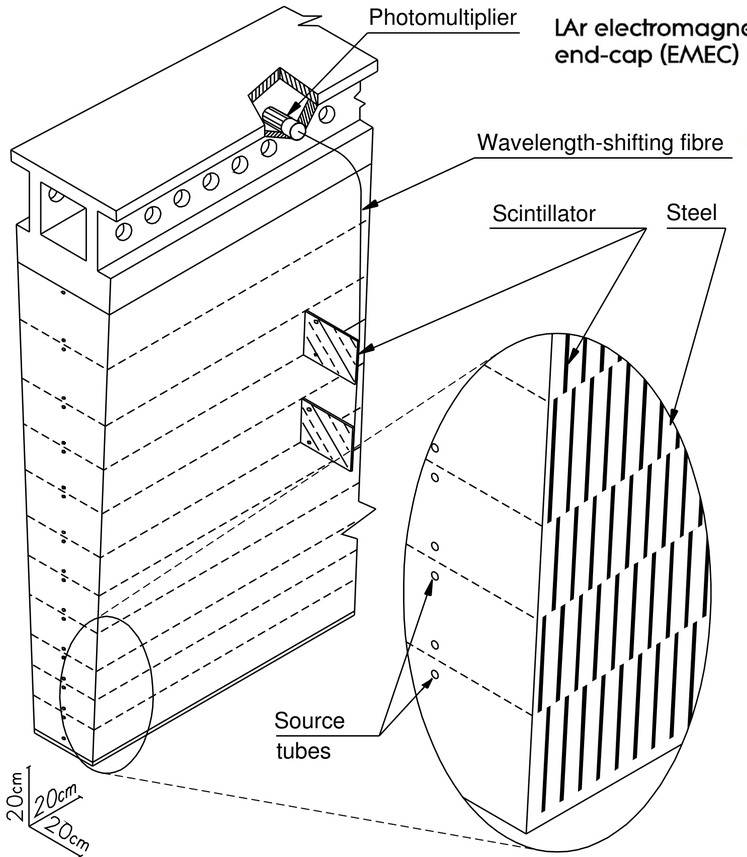

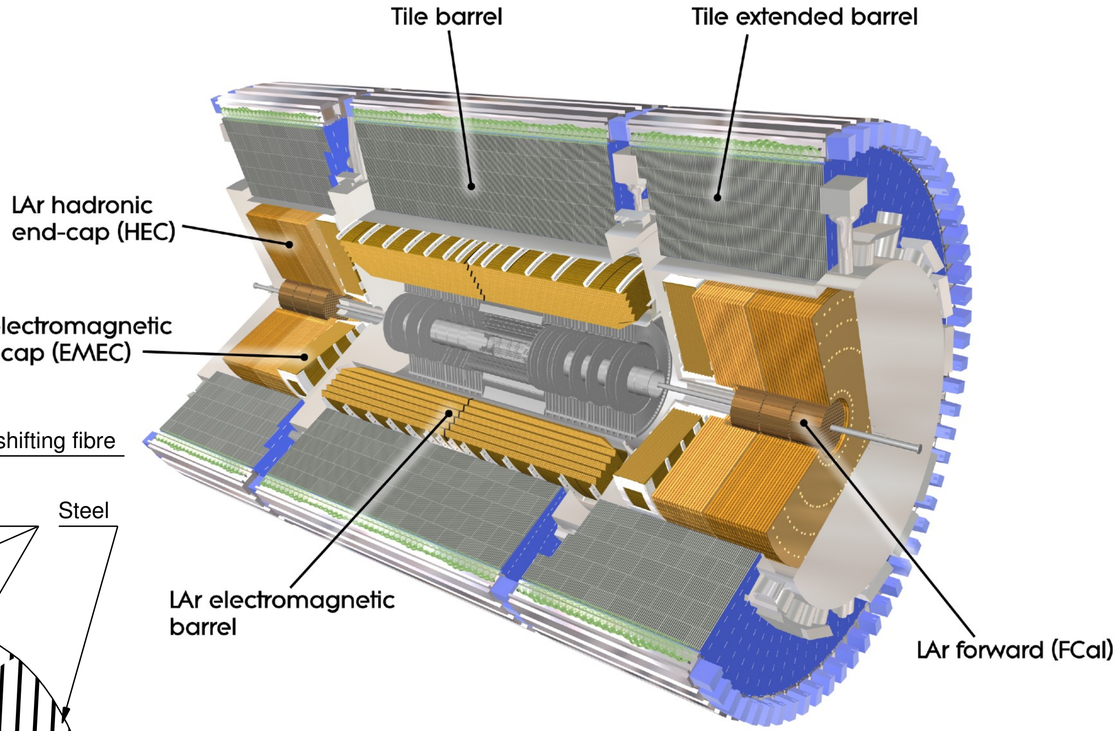

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- Central hadronic calorimeter $\eta = 1.7$
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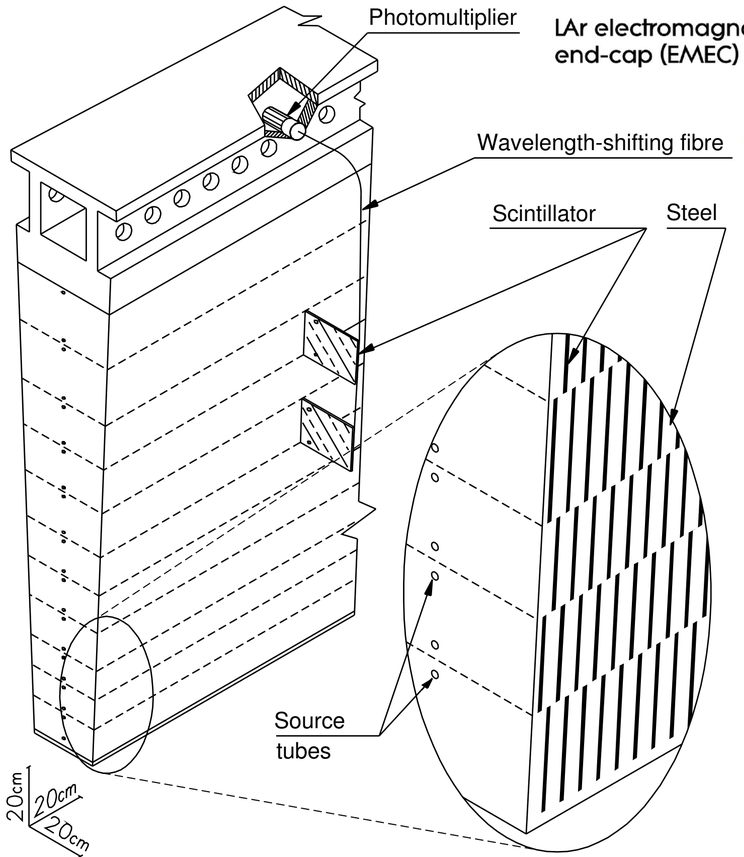
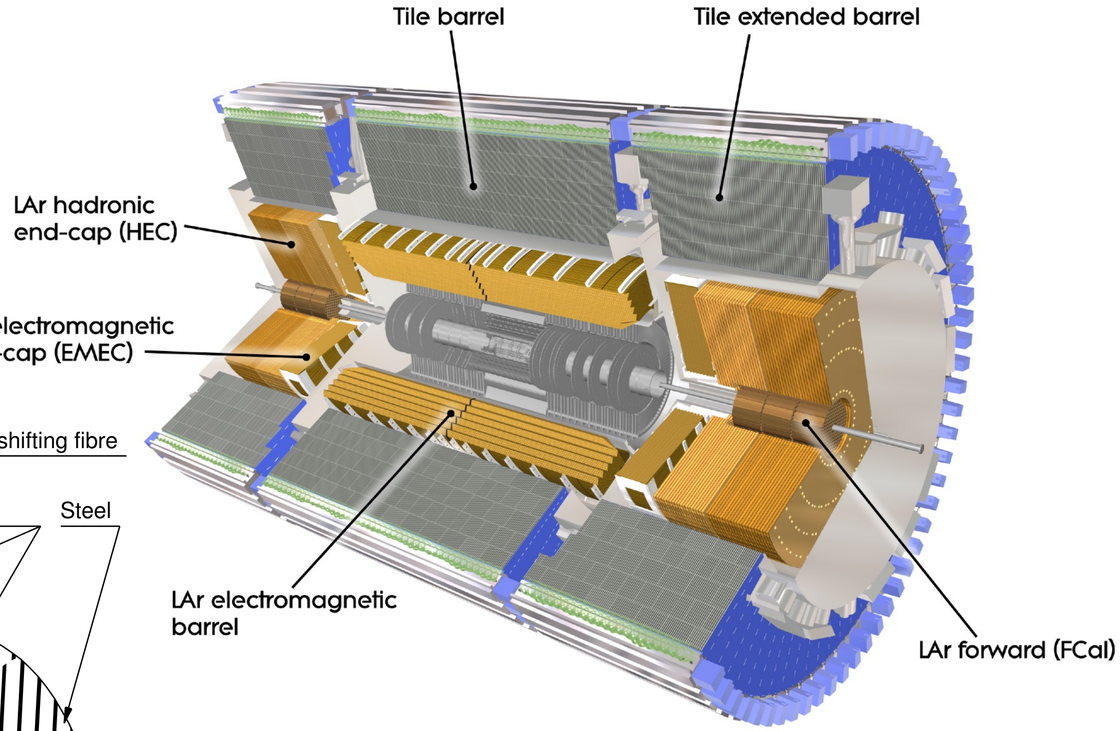
- ~ 5000 cells
- ~10000 Photomultipliers (PMT)
- Each cell is read out by 2 PMTs using wavelength shifting (WLS) fibers





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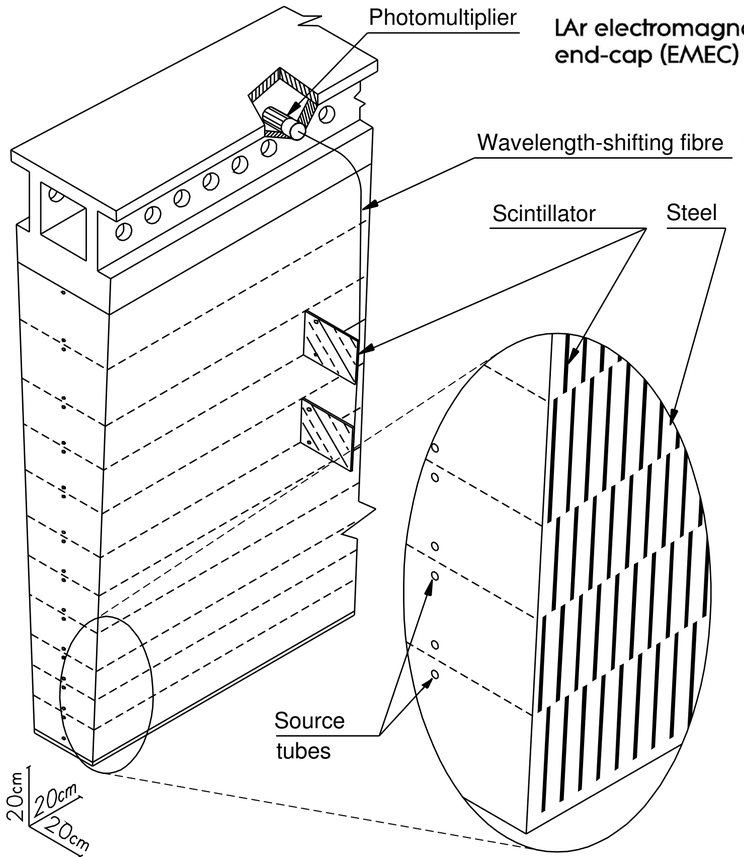

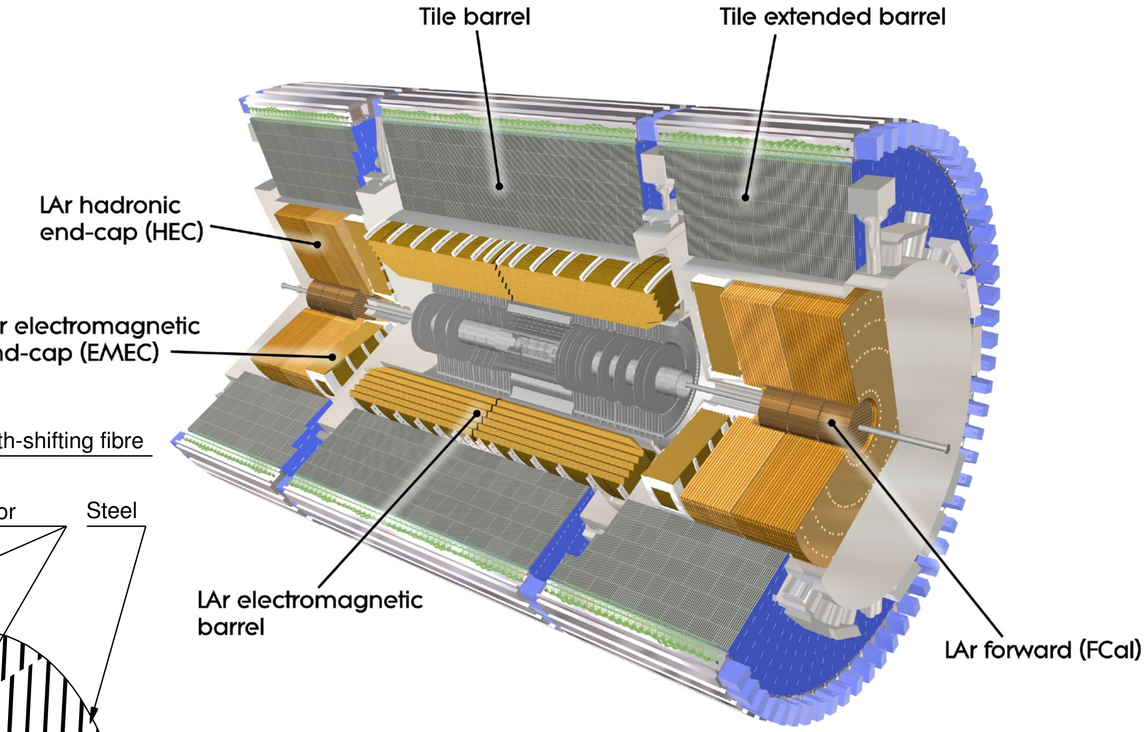

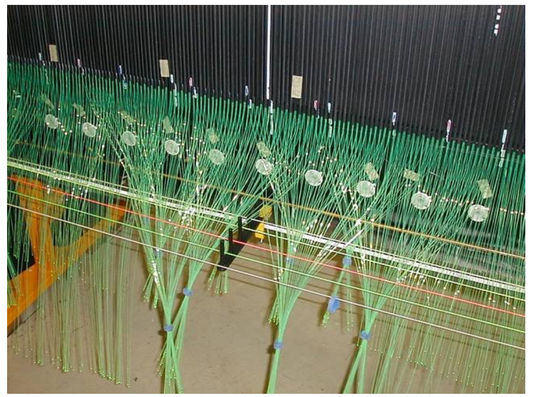

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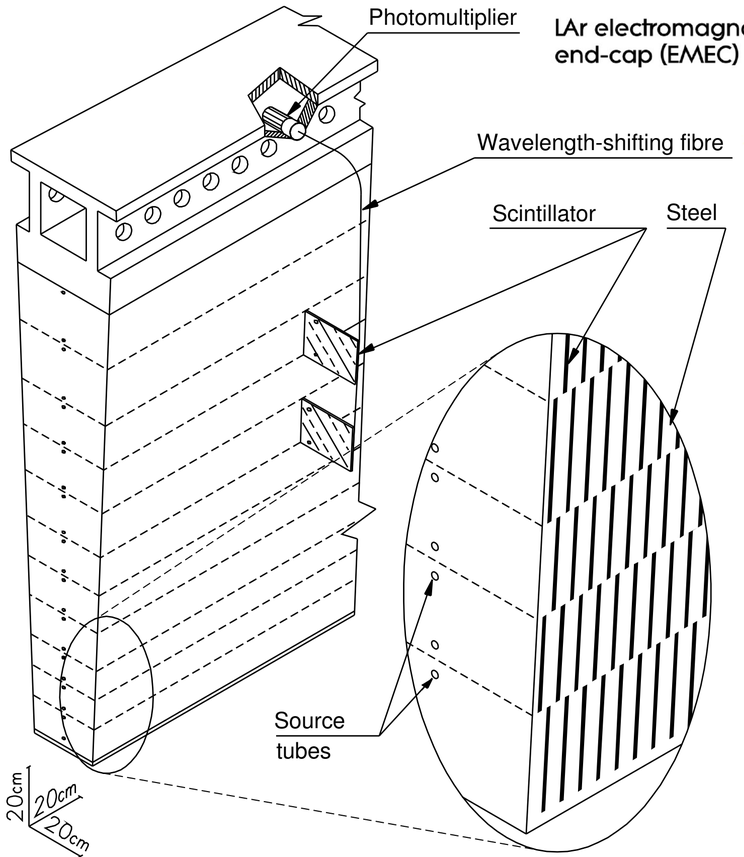
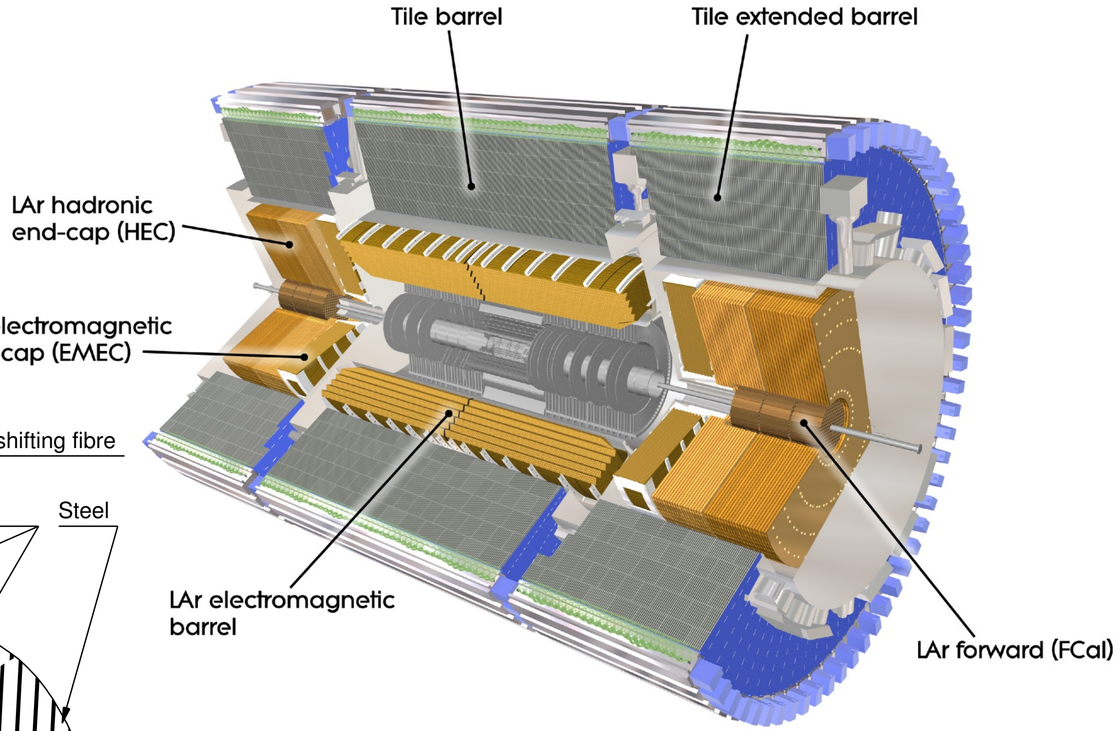
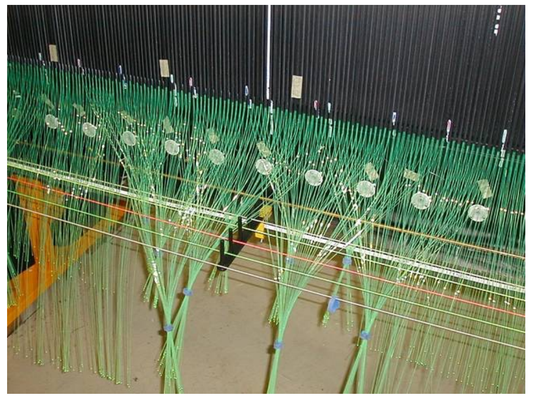
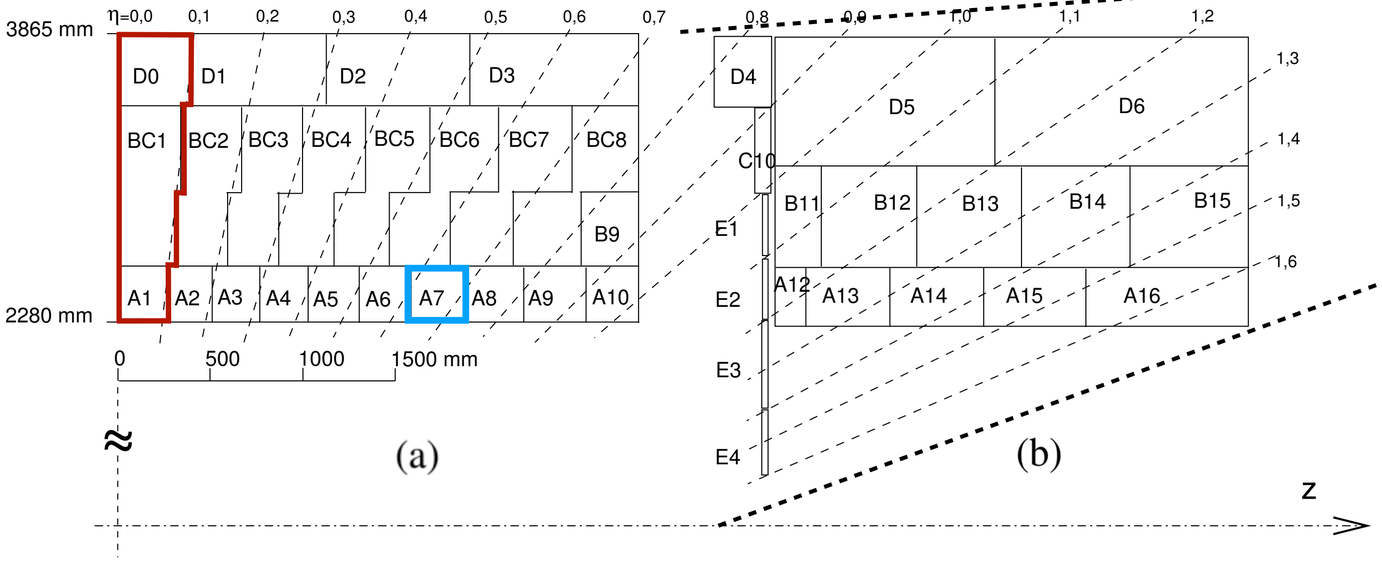
- Critical for physics signatures:
  - Jets, Missing p_T
  - Muons & Electrons/photons

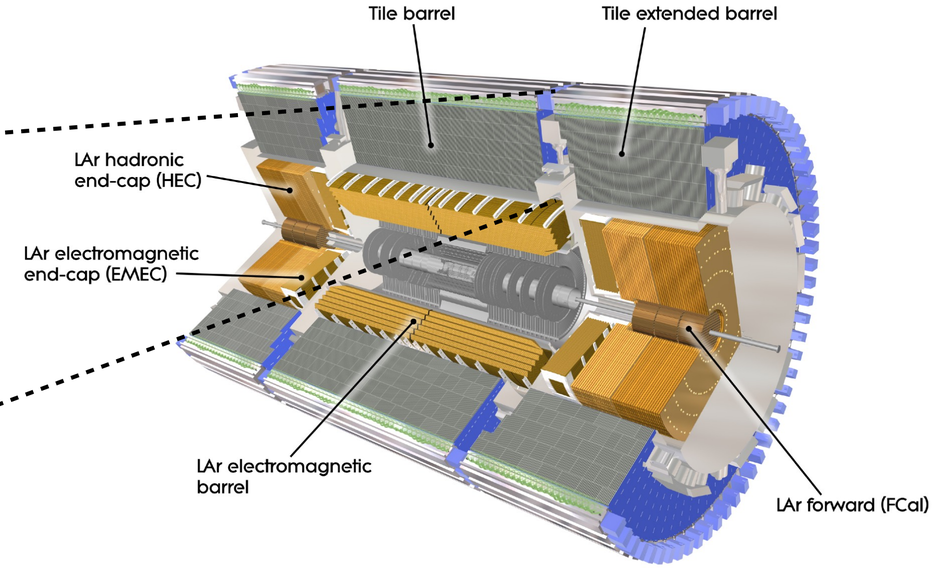






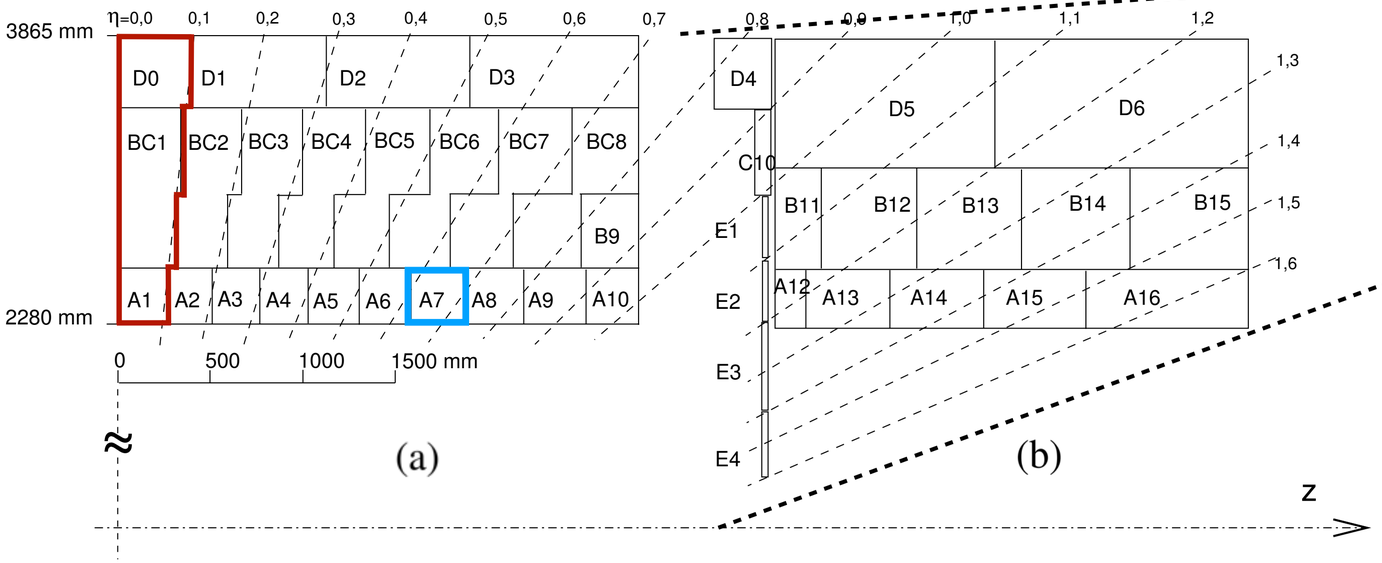
TileCal cell segmentation

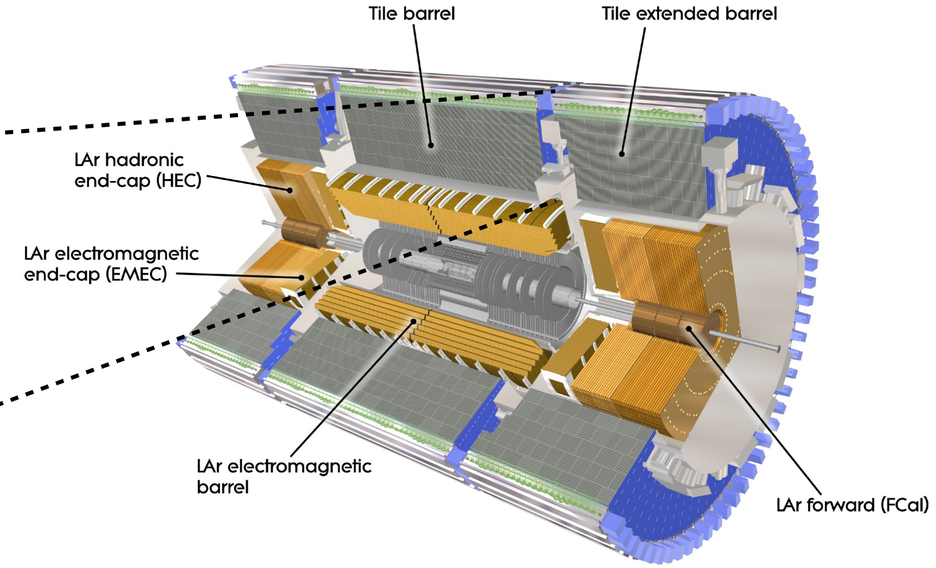




- **Cells**
- **Trigger Tower**

TileCal cell segmentation





- **Cells**
- **Trigger Tower**

- 3 Radial layers:
- A-layers: $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
- BC-layers: $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
- D-layers: $\Delta\eta \times \Delta\phi = 0.2 \times 0.1$

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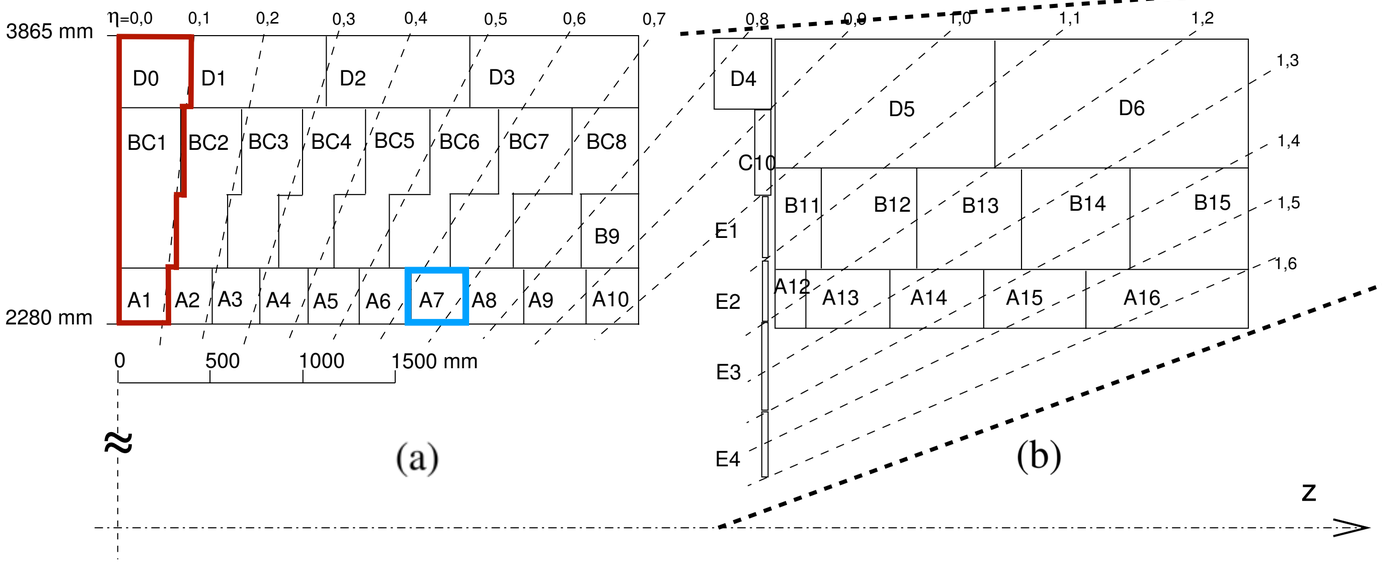

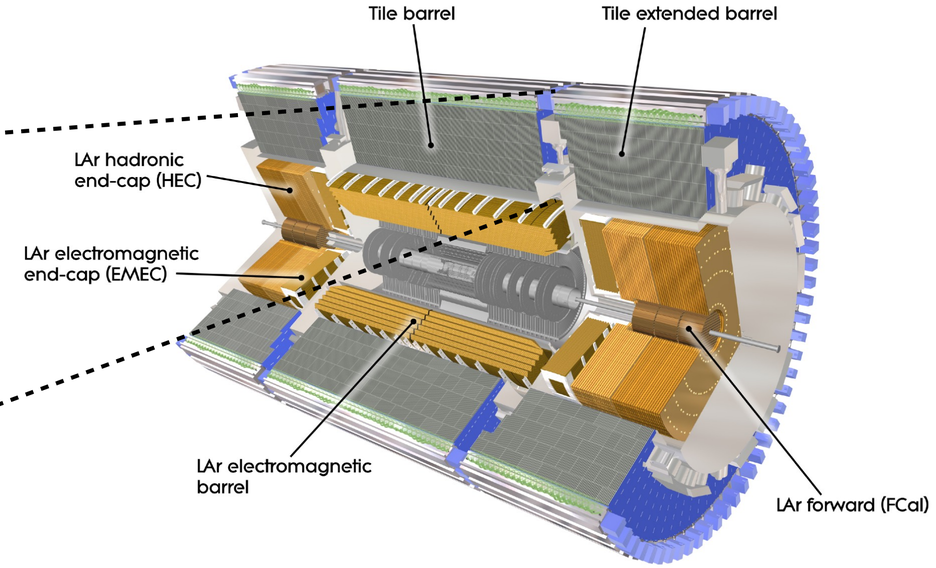

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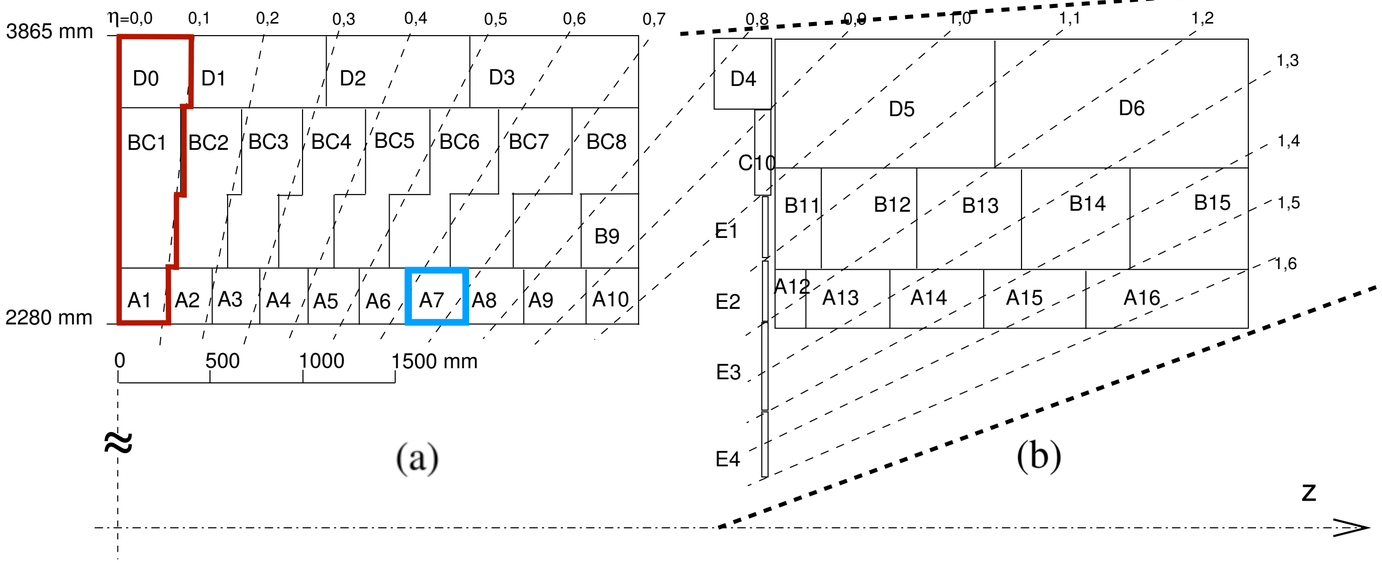
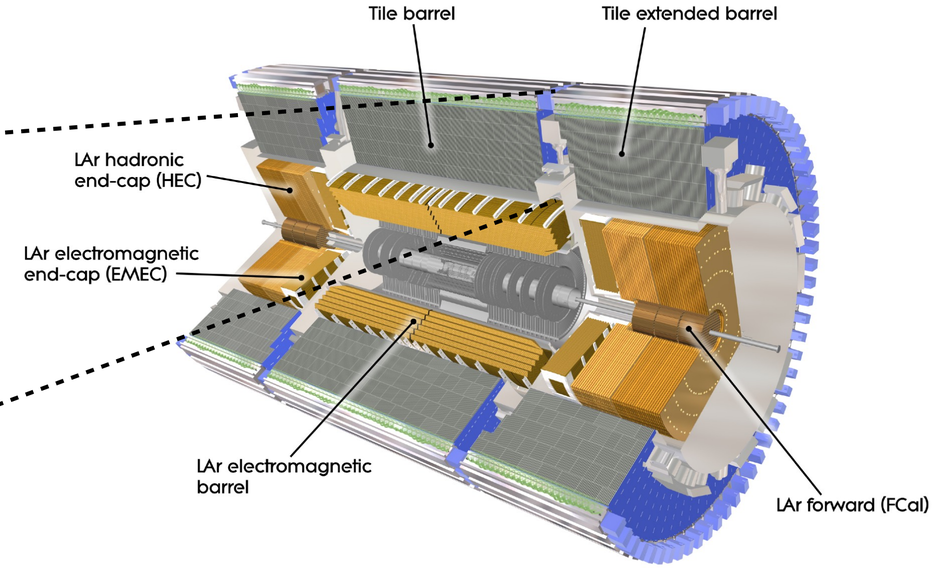
- 2x Long Barrels & 2 Extended Barrels
- 256 wedge-shaped modules with $\Delta\phi = 0.1$

TileCal cell segmentation





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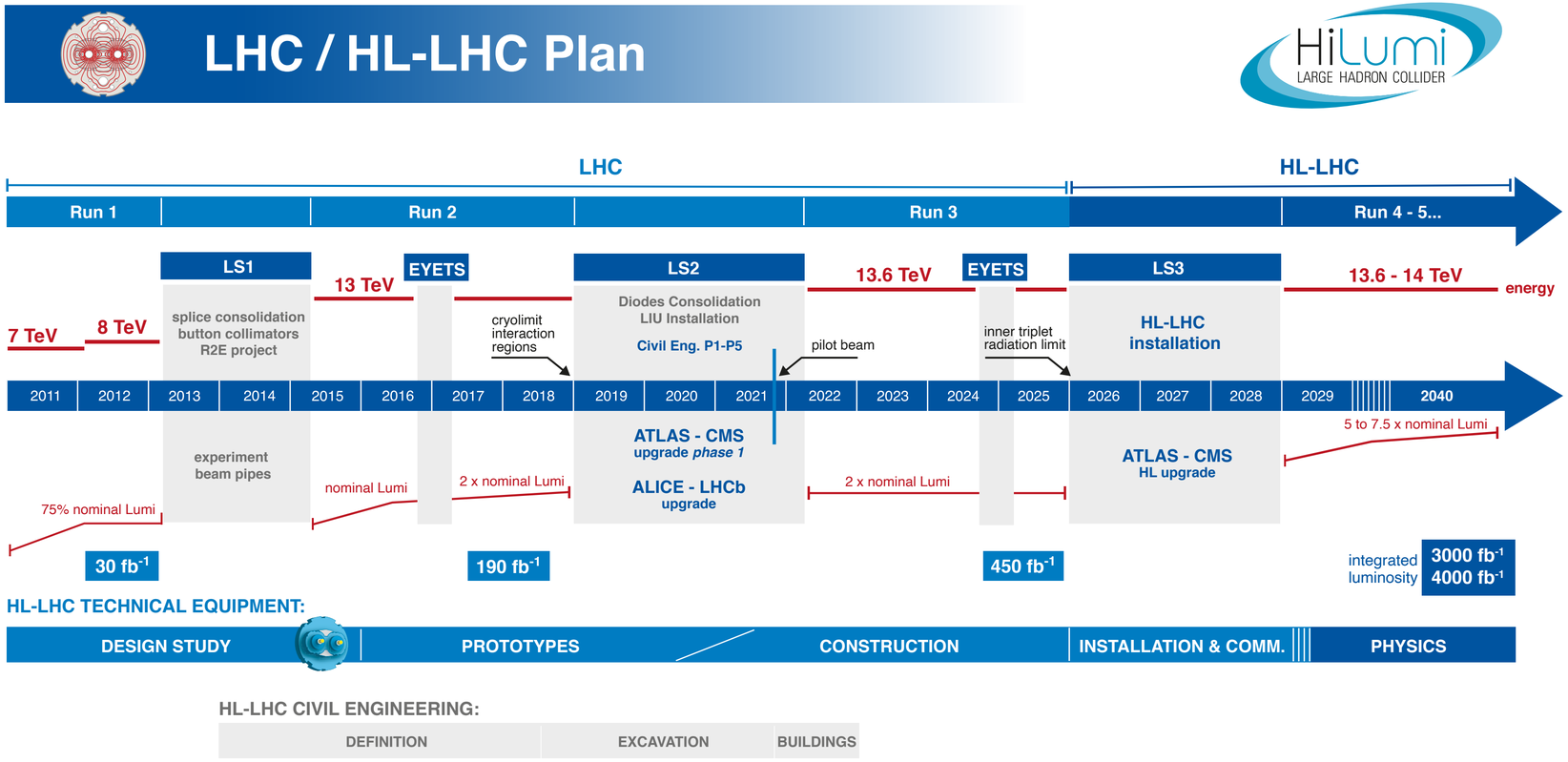
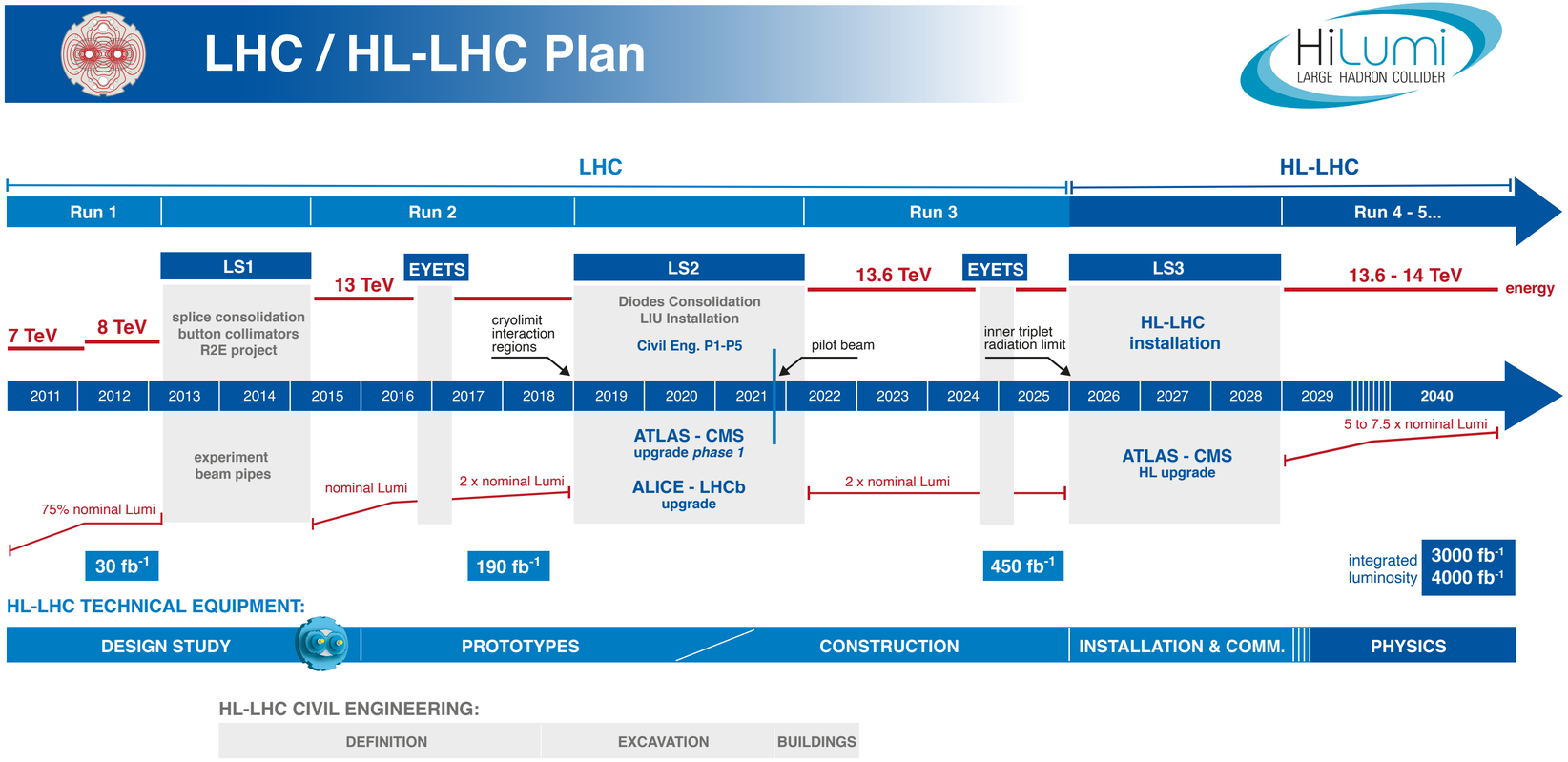
- 2x Long Barrels & 2 Extended Barrels
- 256 wedge-shaped modules with $\Delta\phi = 0.1$
- Current energy resolution: $\sigma/E \sim 50\,\%/E \oplus 3\,\%$

The HL-LHC

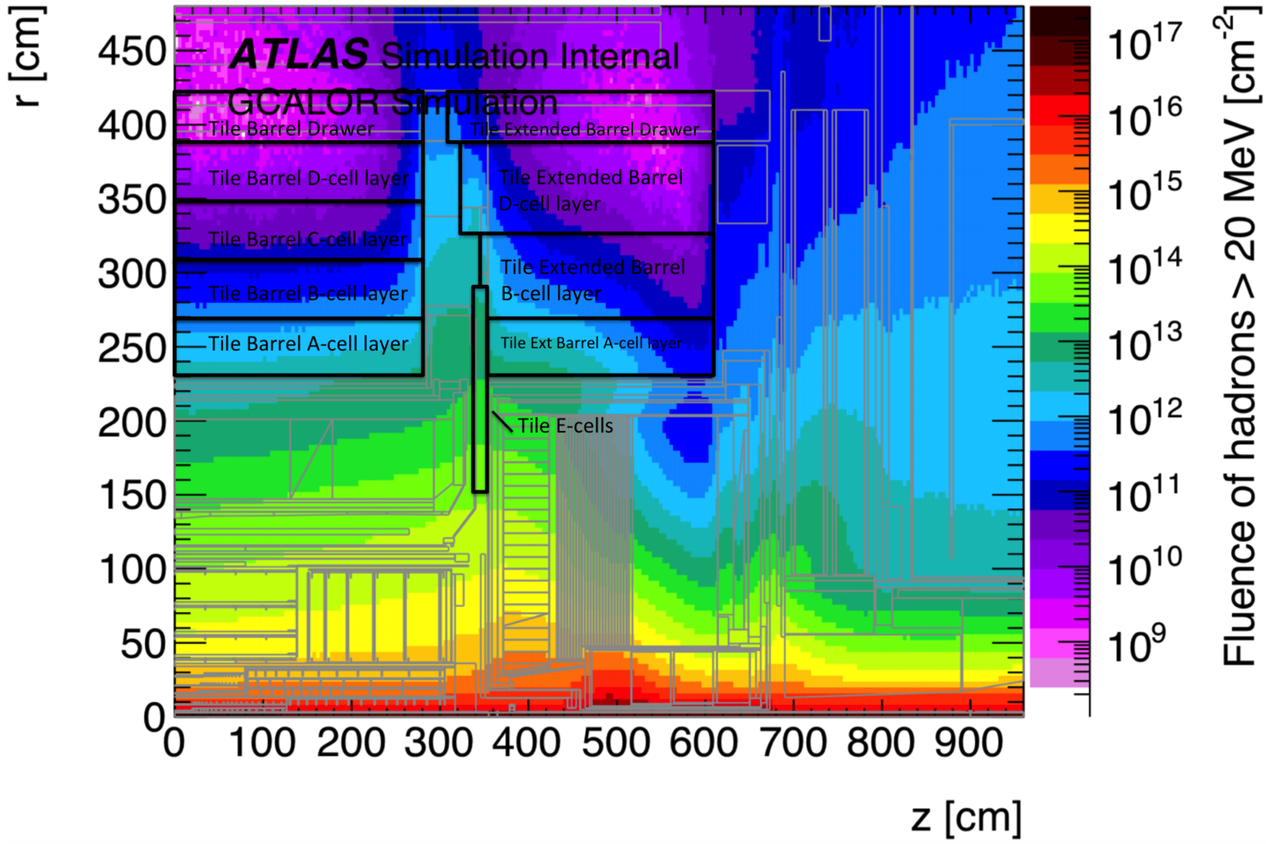

LHC / HL-LHC Plan
HiLumi
LARGE HADRON COLLIDER
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
EYETS
LS3
7 TeV
8 TeV
13 TeV
13.6 TeV
13.6 - 14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
Civil Eng. P1-P5
pilot beam
inner triplet
radiation limit
HL-LHC
installation
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2040
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
ATLAS - CMS
HL upgrade
5 to 7.5 x nominal Lumi
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
30 fb-1
190 fb-1
450 fb-1
integrated
luminosity
3000 fb-1
4000 fb-1
HL-LHC TECHNICAL EQUIPMENT:
DESIGN STUDY
PROTOTYPES
CONSTRUCTION
INSTALLATION & COMM.
PHYSICS
HL-LHC CIVIL ENGINEERING:
DEFINITION
EXCAVATION
BUILDINGS

The HL-LHC



- The instantaneous luminosity will increase by a factor of ~ 7
- 200 proton-proton collisions per bunch crossing
- Increased particle flux through TileCal - 2 to 24 Gy for 4000 fb^{-1}

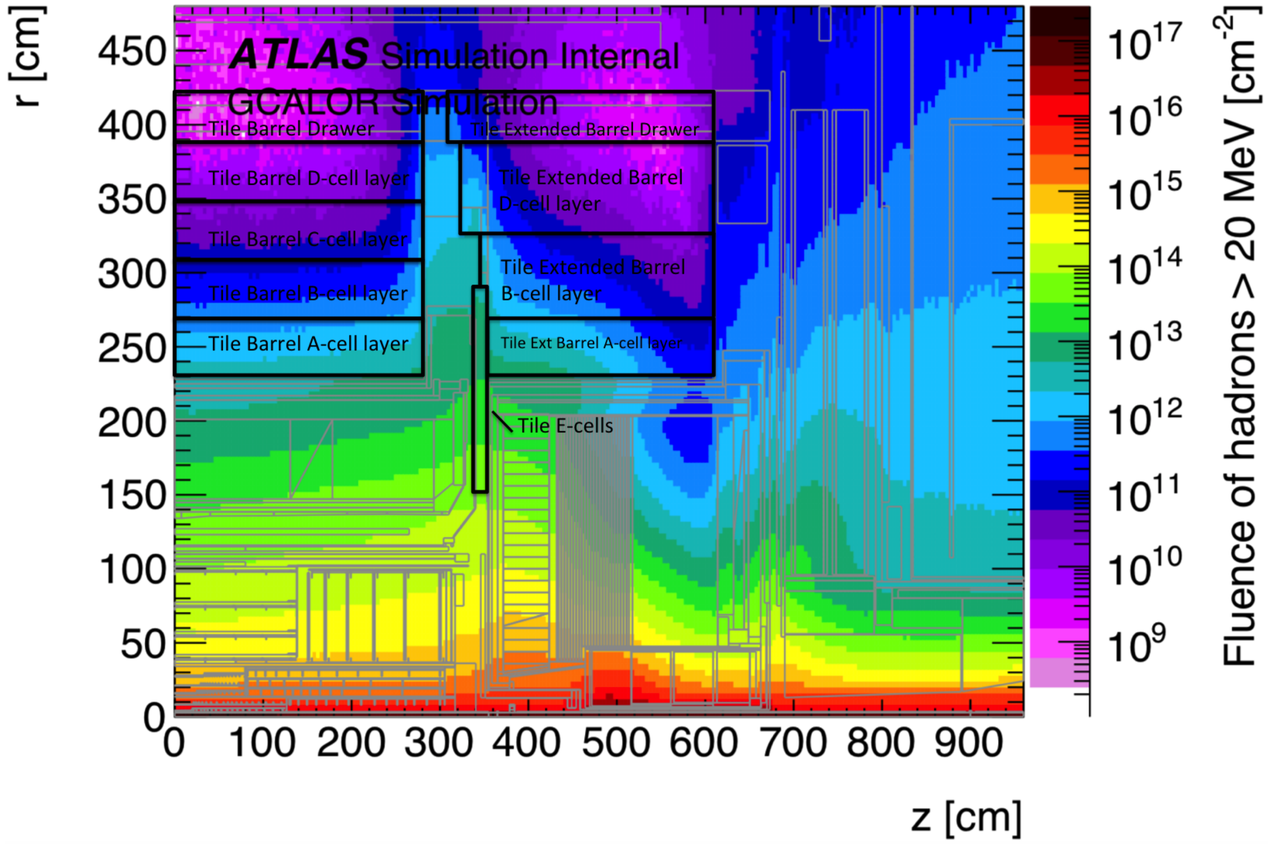
The TileCal Upgrade Strategy



Simulated radiation levels

The TileCal Upgrade Strategy

- Employ electronics components with higher radiation tolerance



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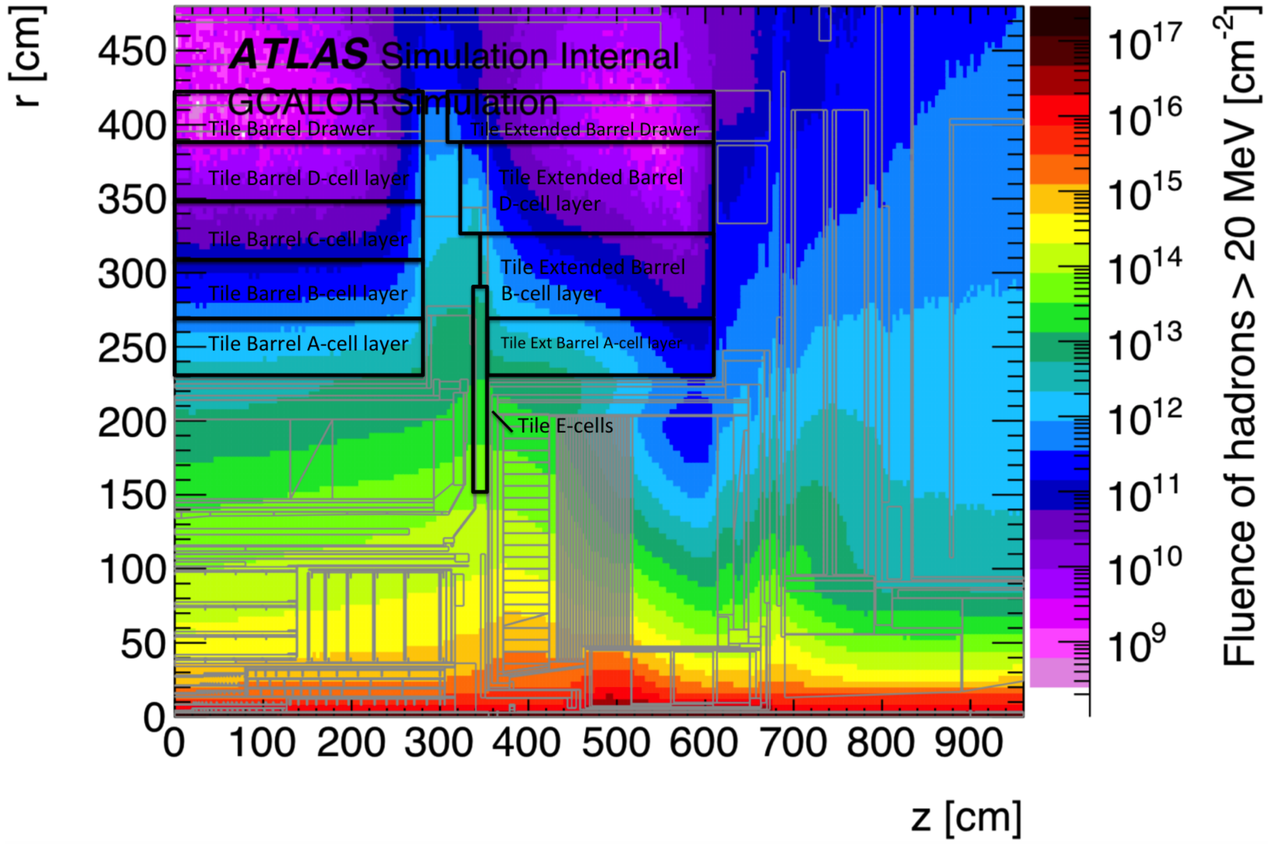
- Add reliability by means of redundancy
  - Minimise single point of failures



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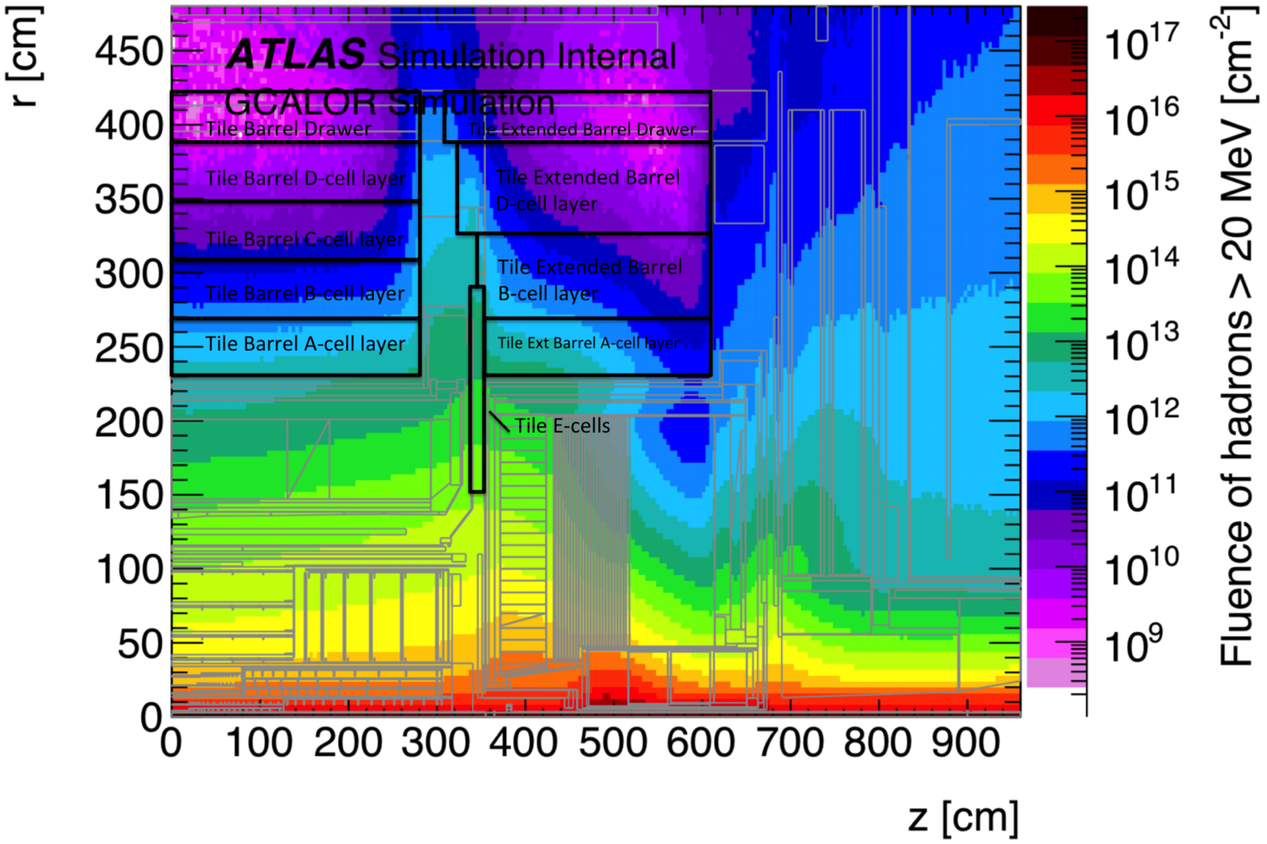
- New readout architecture
  - Digital Trigger at 40 MHz
  - Higher trigger rates ~ 1MHz
  - Larger data buffering - all done off-detector
  - High-speed optical transmission



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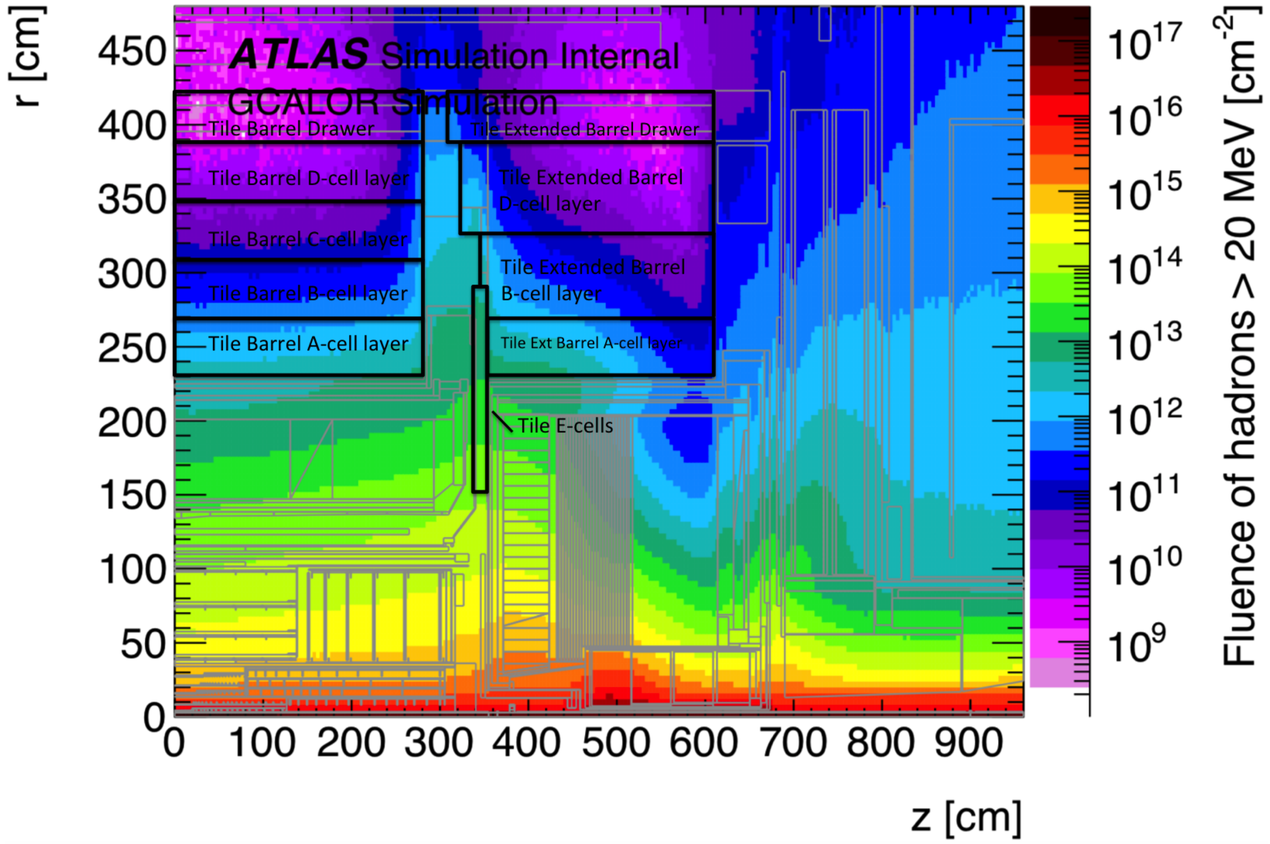

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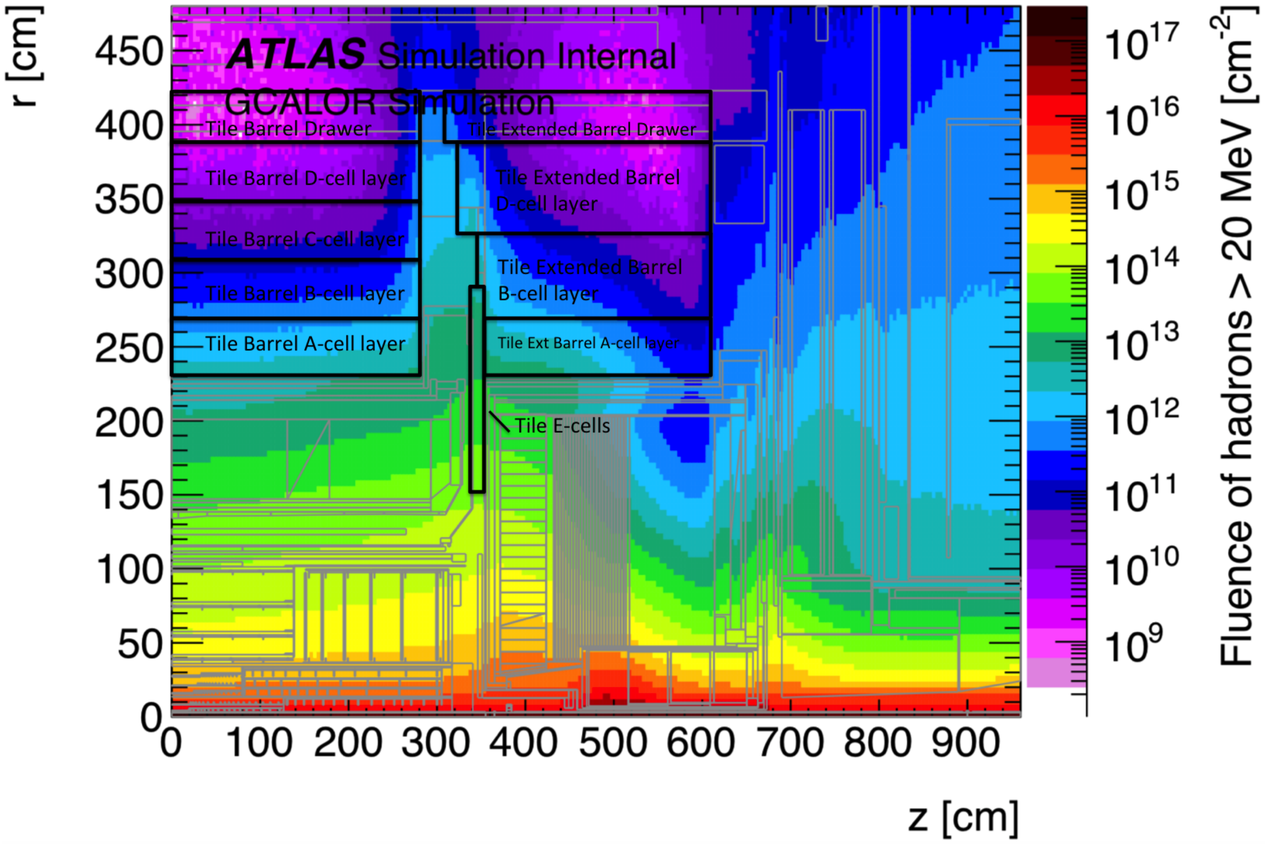
- Detector components (absorbers, scintillators, most PMTs) will not be replaced



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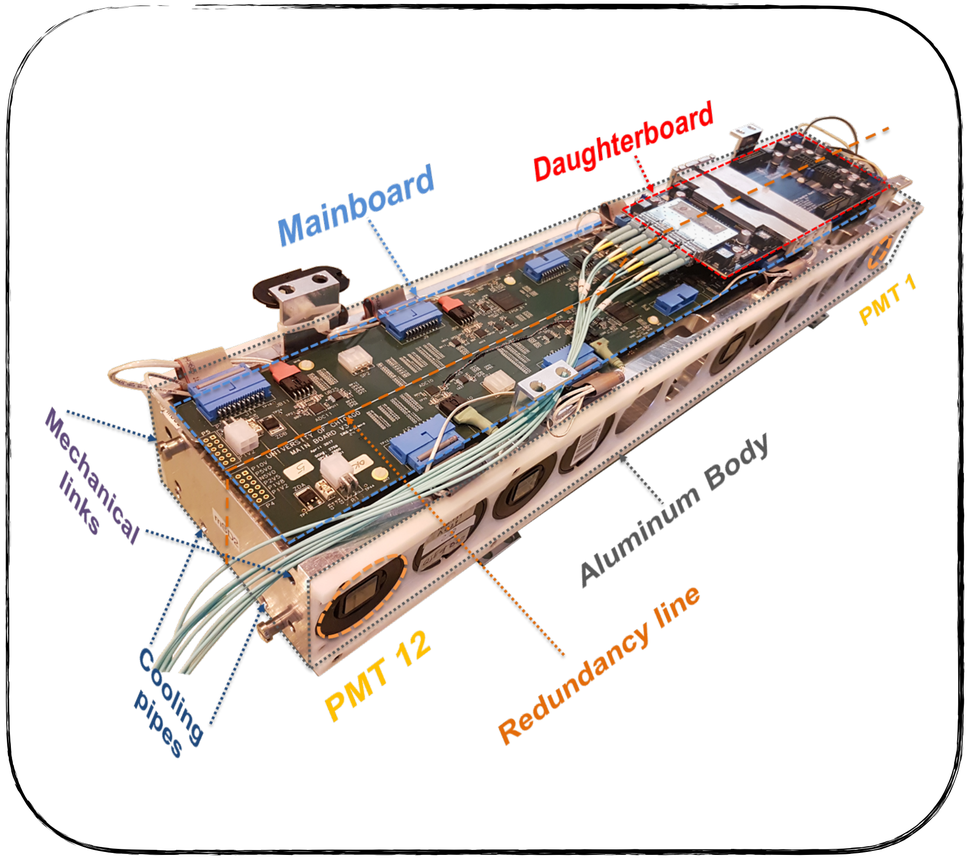
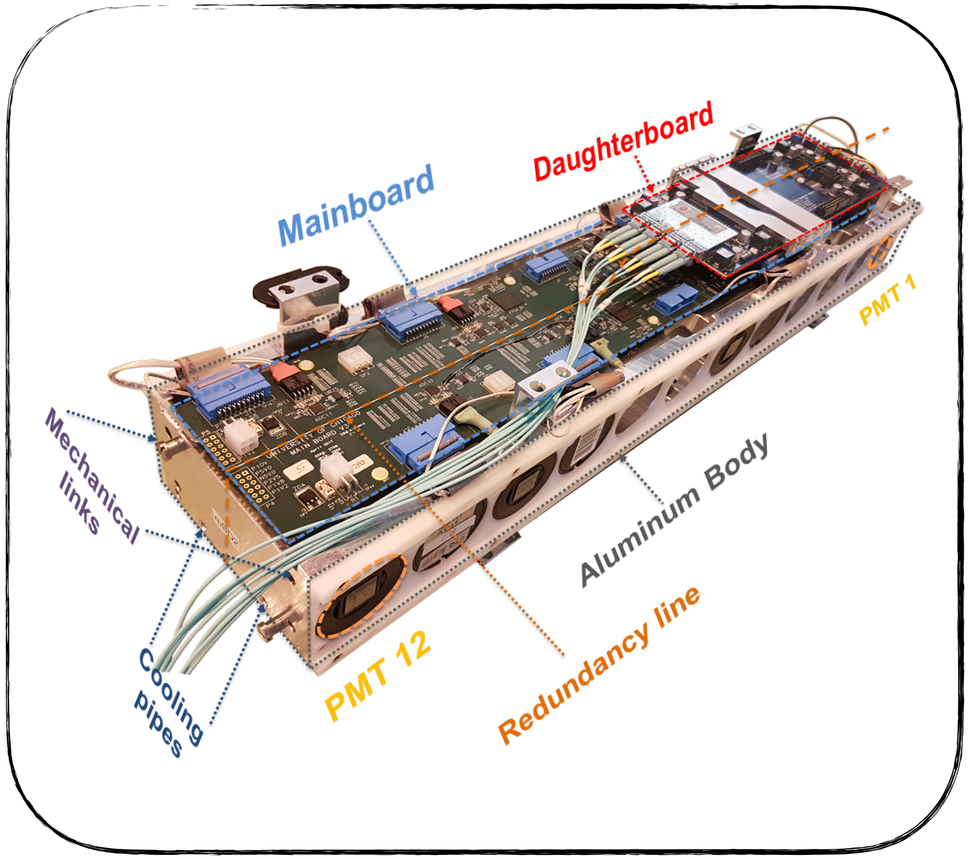


The new Mini-Drawer

The TileCal Phase-II Upgrade

- **Replacement** of the entire Front- and Back-End Electronics



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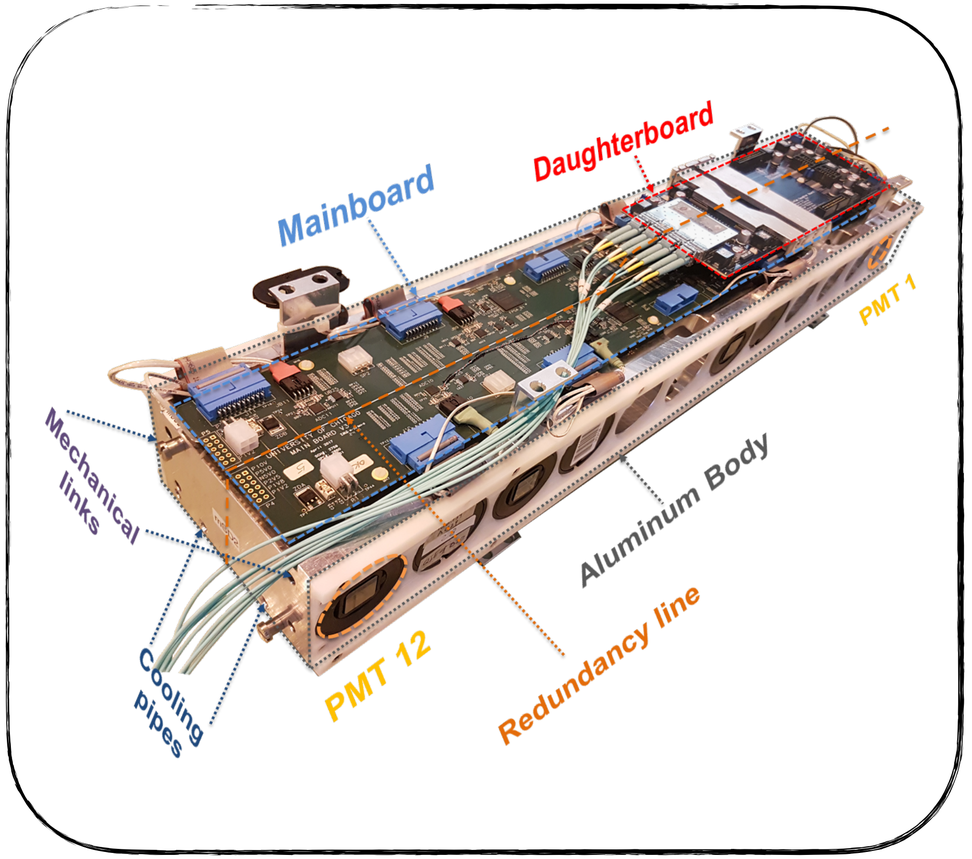

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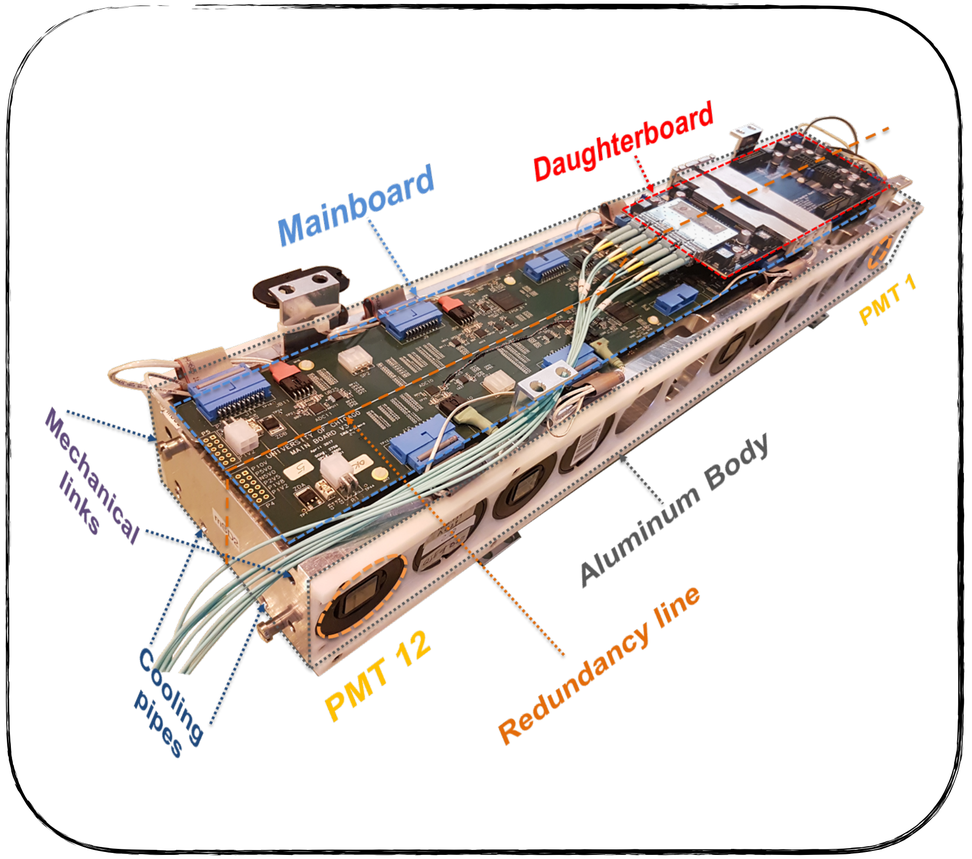

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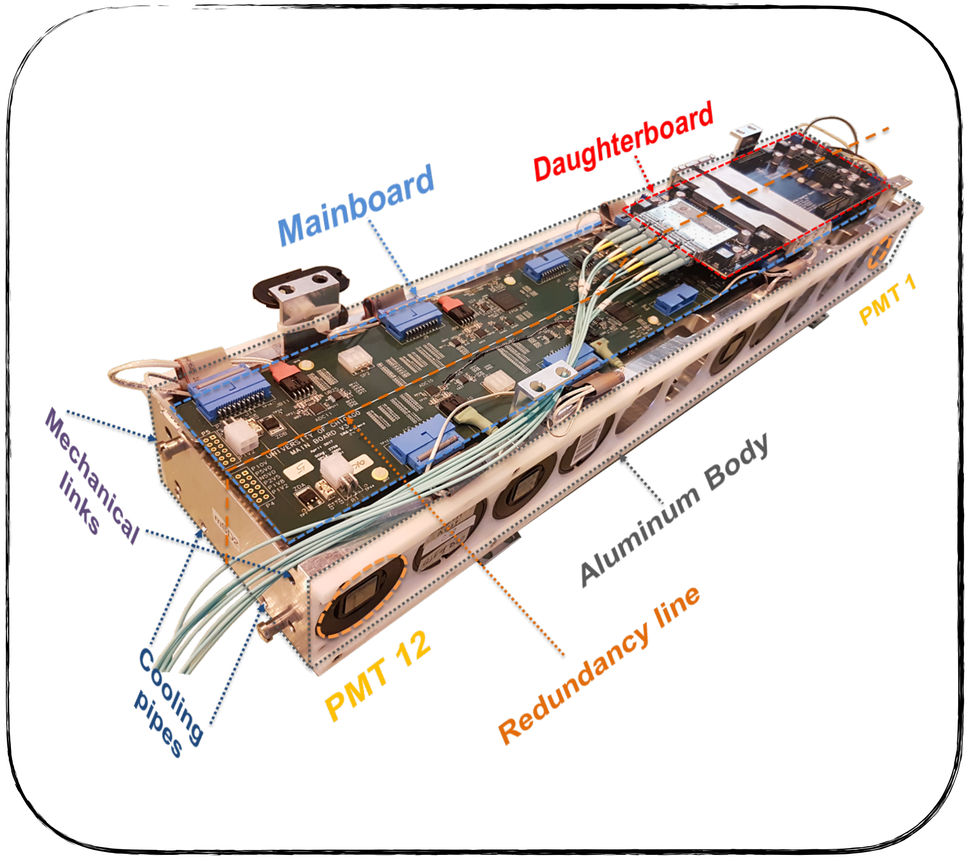

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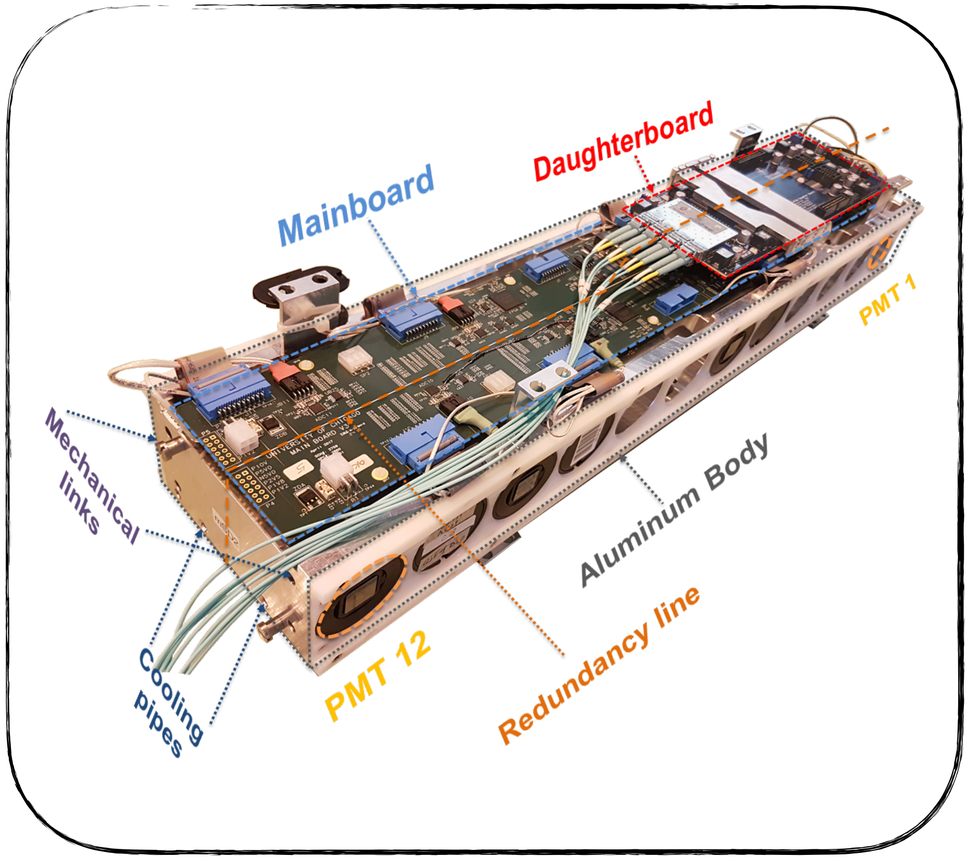

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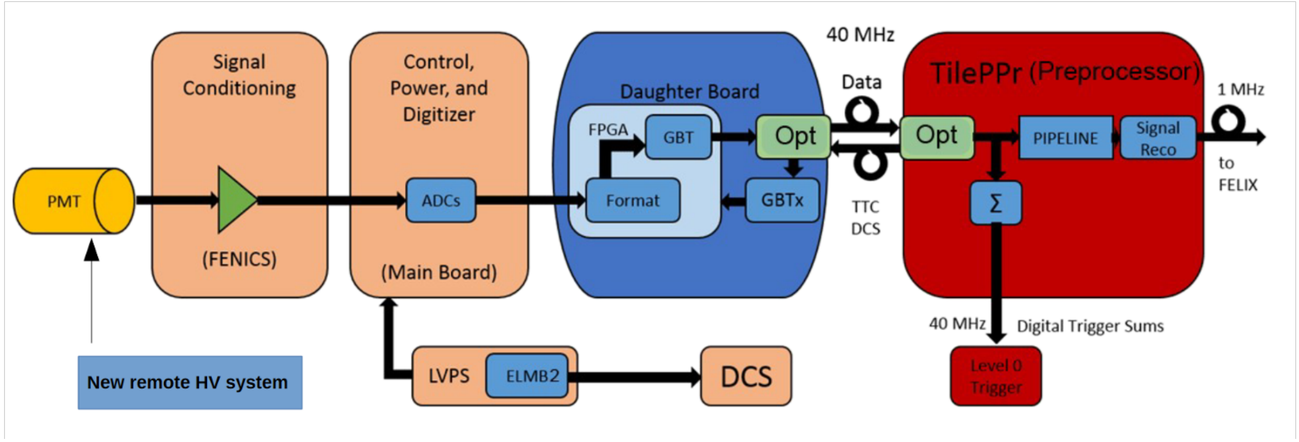
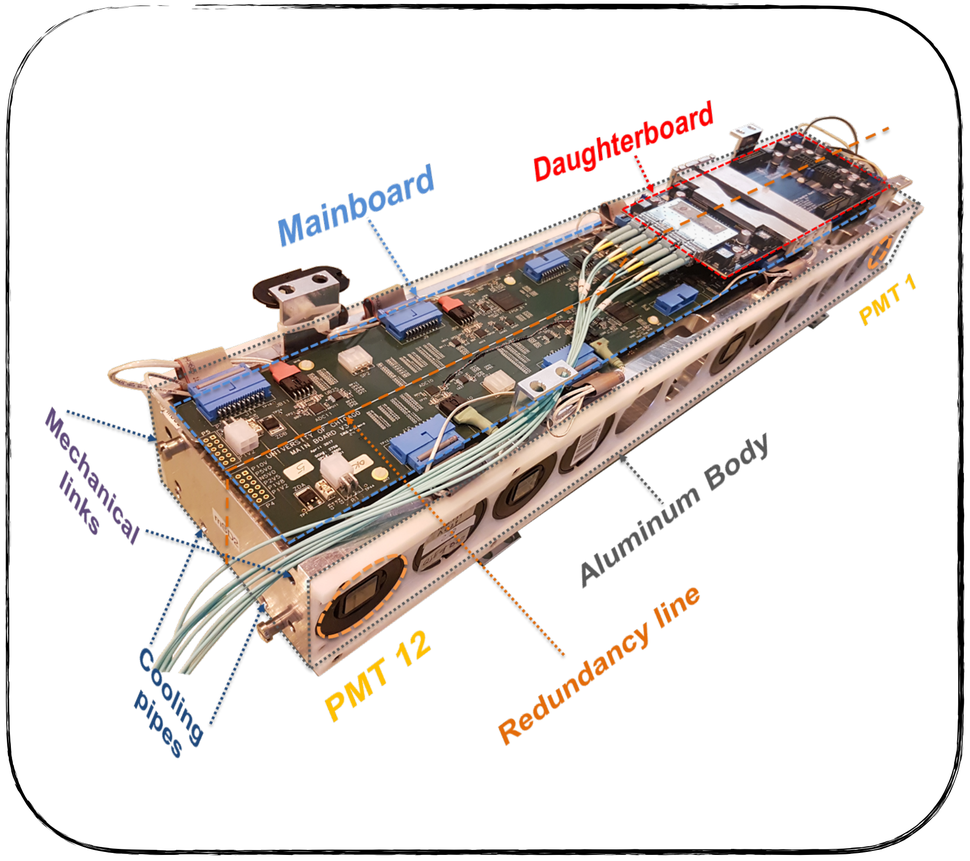
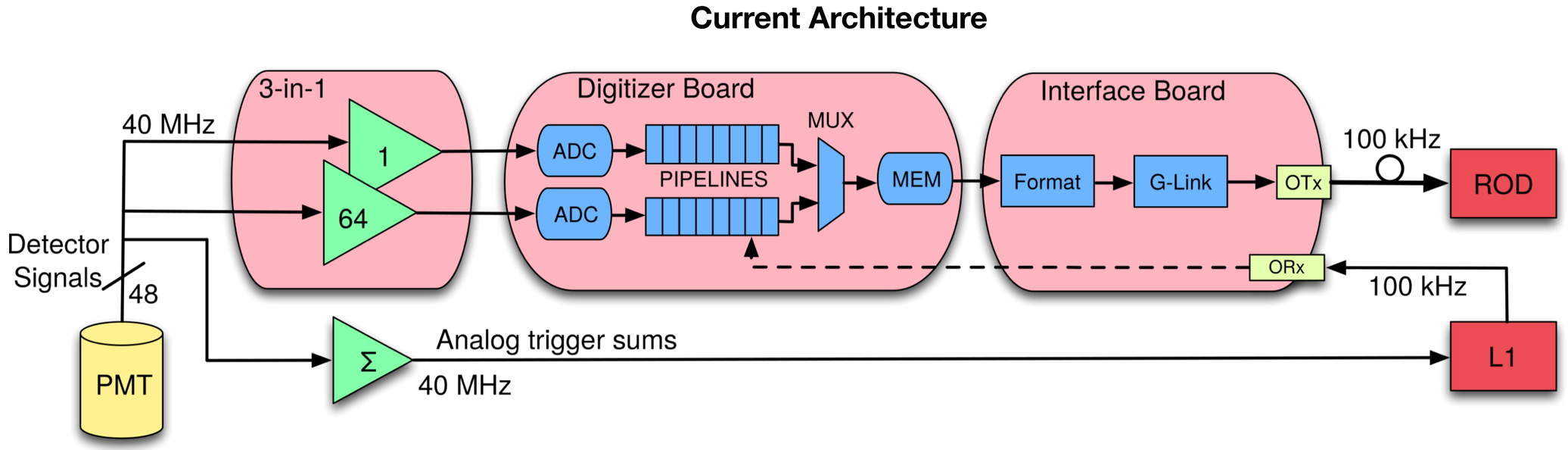


Overview of the Upgrade Electronics



The new Mini-Drawer

The TileCal Readout and Trigger chain



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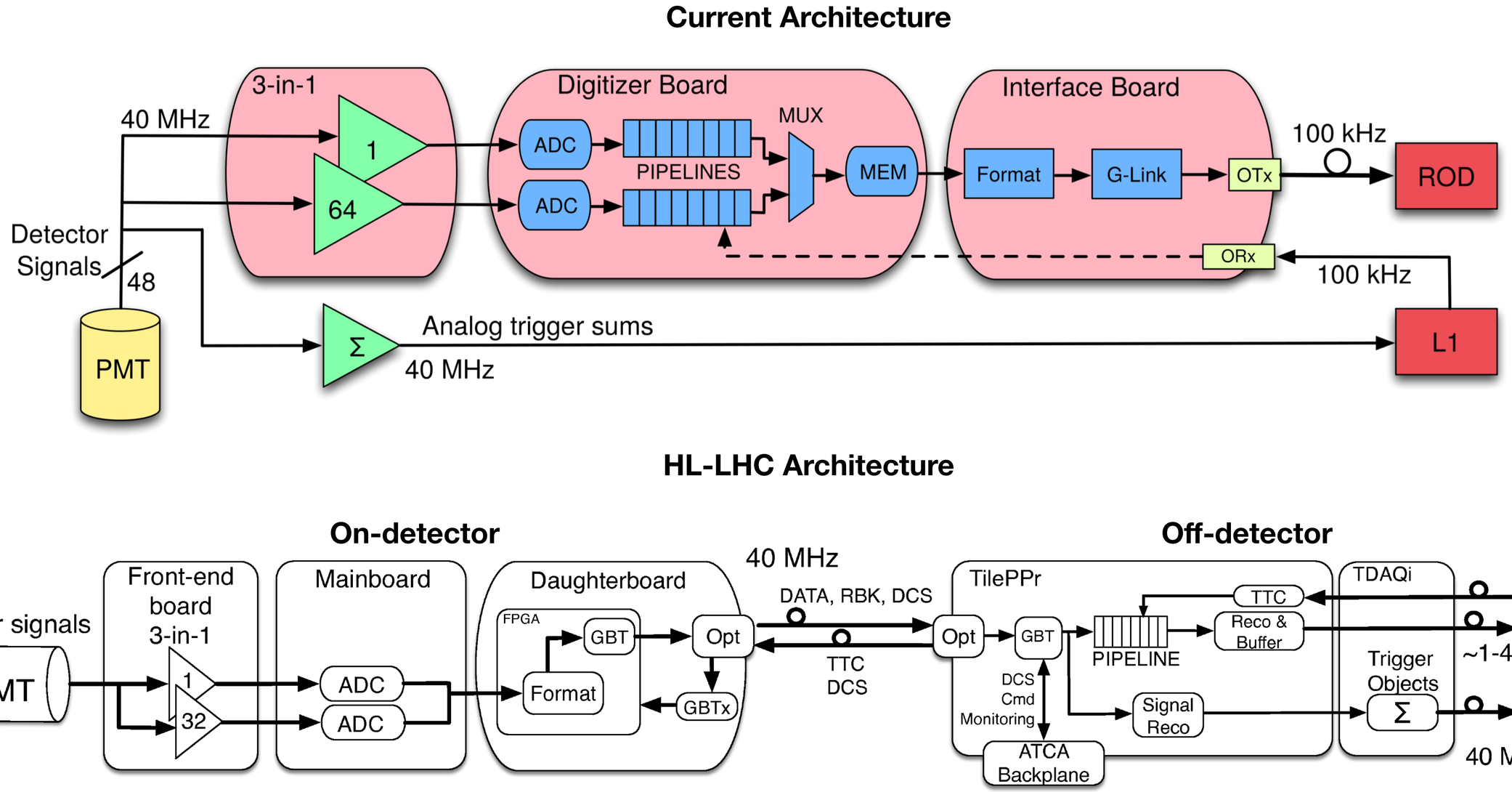
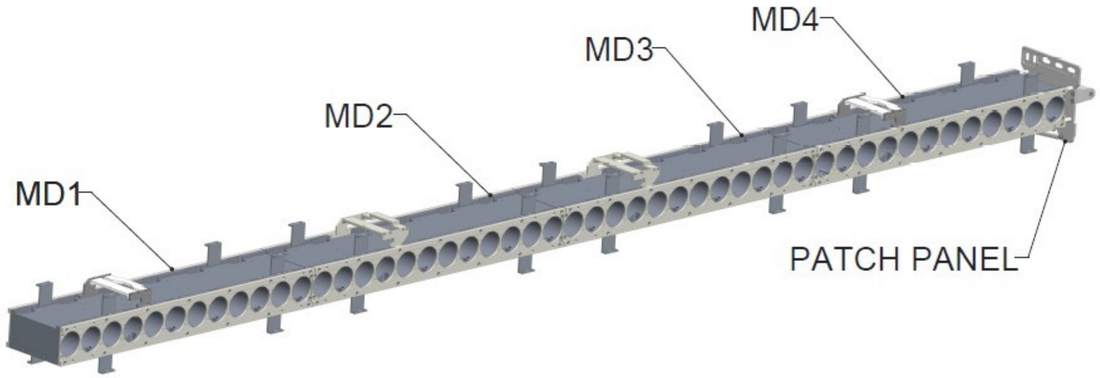
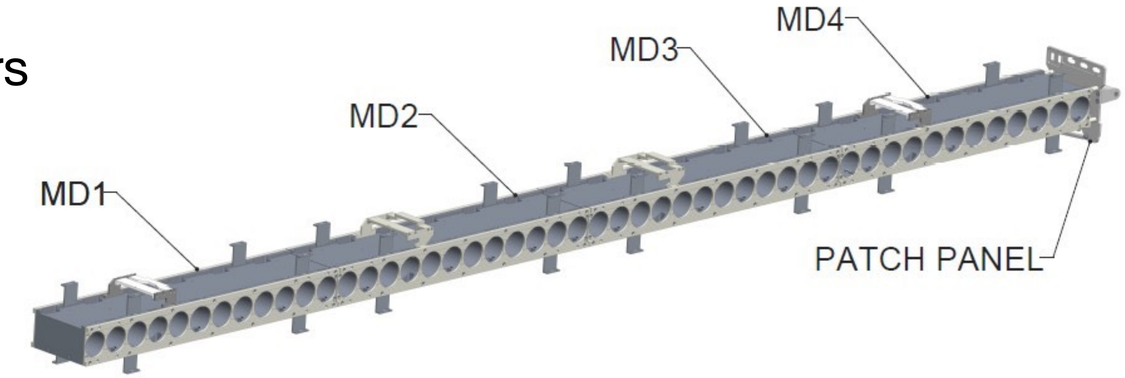


The Upgrade Mechanics



The Upgrade Mechanics

- Each TileCal drawer is made-up of four new Mini-Drawers (MD)
  - Each MD equipped with 12 PMTs
  - Highly modular - ease of maintenance
  - Independent low- and high-voltage distribution
  - Independent readout electronics
  - Minimisation of single point of failure



The Upgrade Mechanics

- Each TileCal drawer is made-up of four new Mini-Drawers (MD)
  - Each MD equipped with 12 PMTs
  - Highly modular - ease of maintenance
  - Independent low- and high-voltage distribution
  - Independent readout electronics
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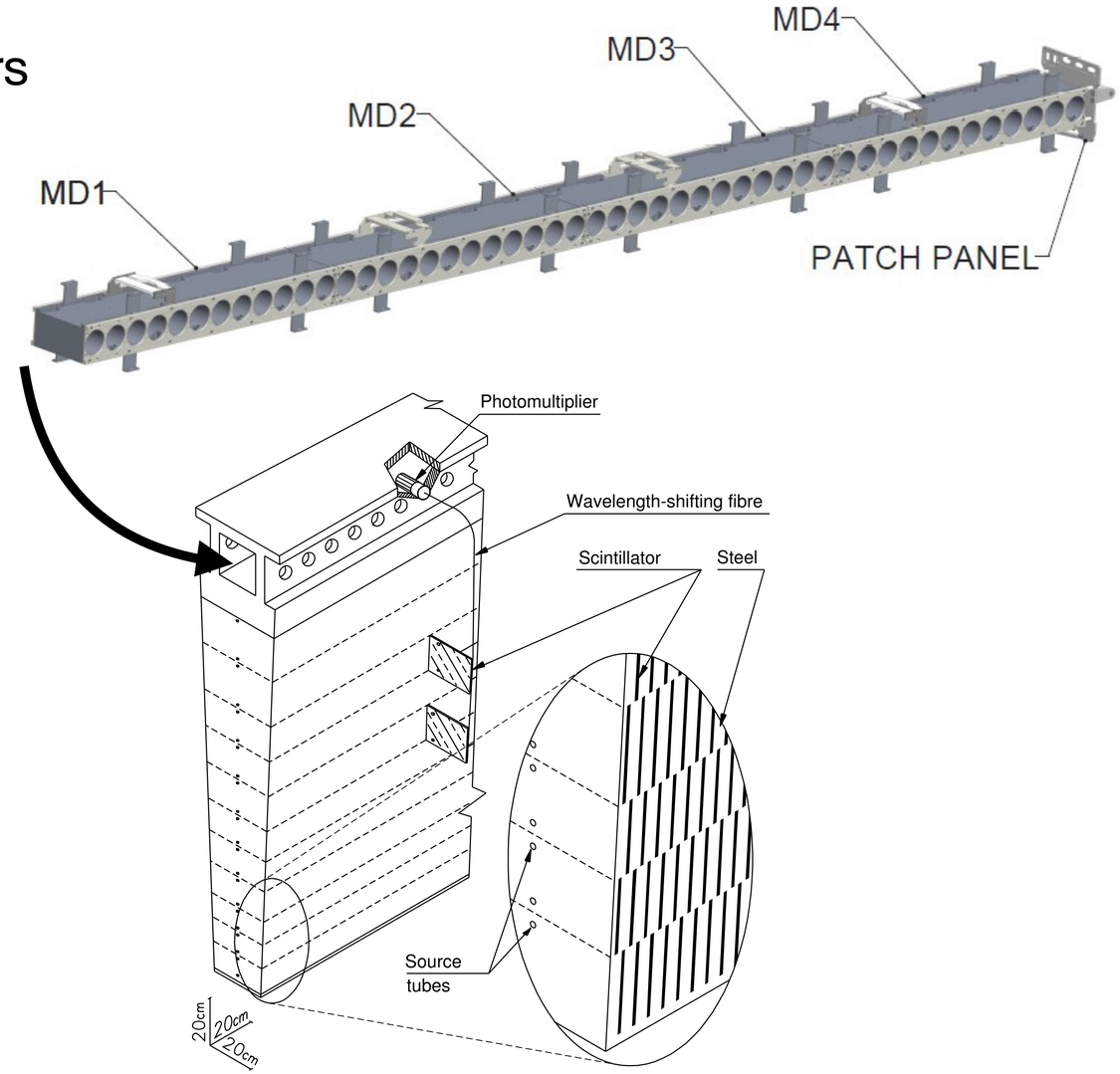

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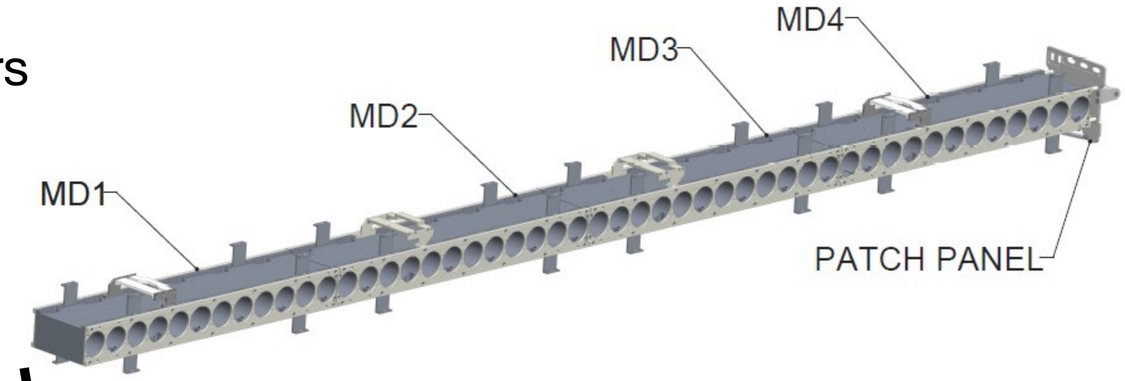
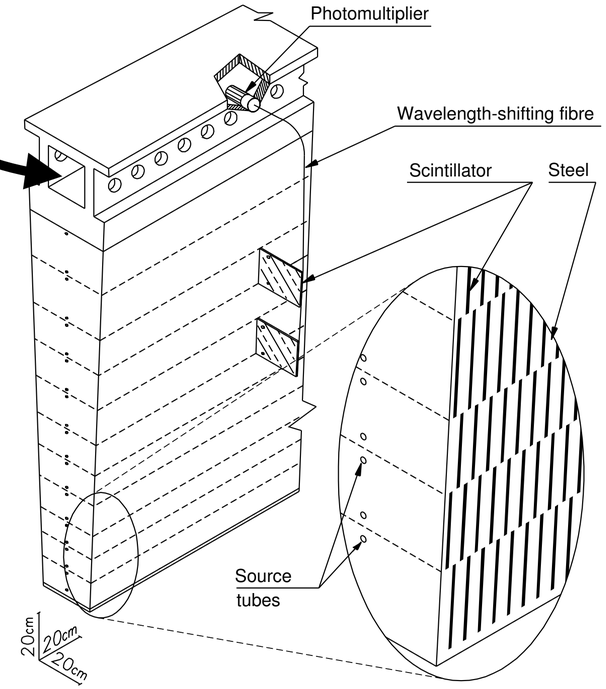
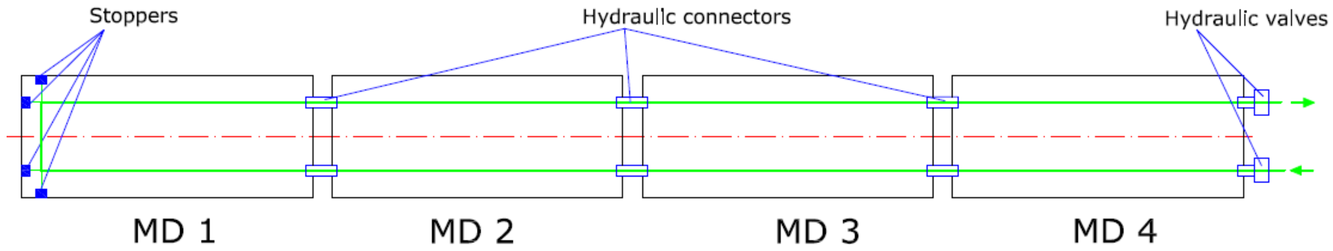
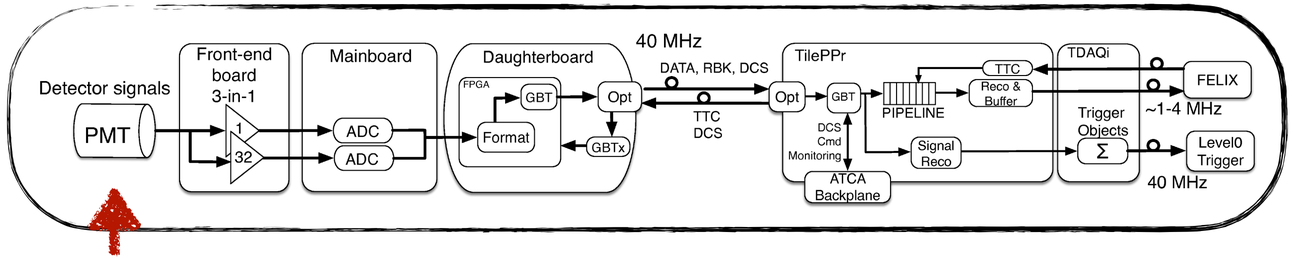






Photomultipliers



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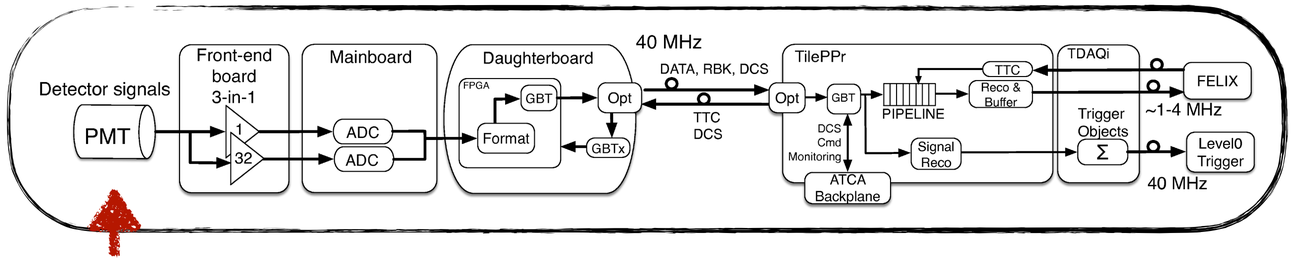
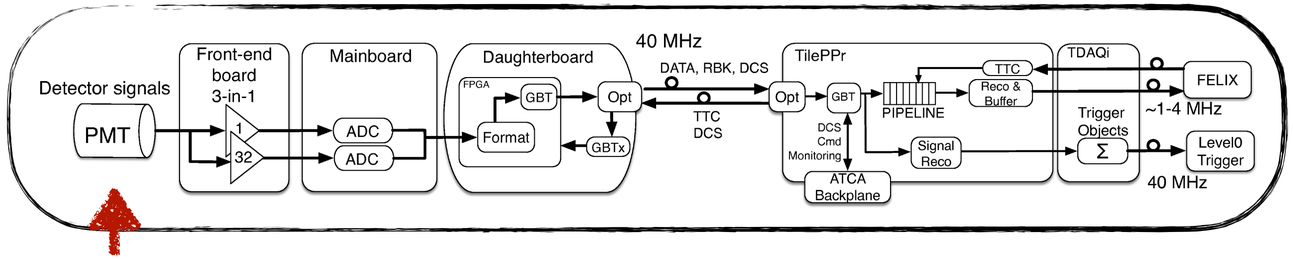


Hamamatsu PMTs used in TileCal

Photomultipliers

- Photomultiplier Tubes (PMTs) from Hamamatsu
- 9582 PMTs currently in use
- 1024 PMTs to be replaced due to ageing and response degradation
- Replacement with newer R11187 models
- PMT qualification & characterization test-benches prepared - all 10k PMTs will be re-qualified



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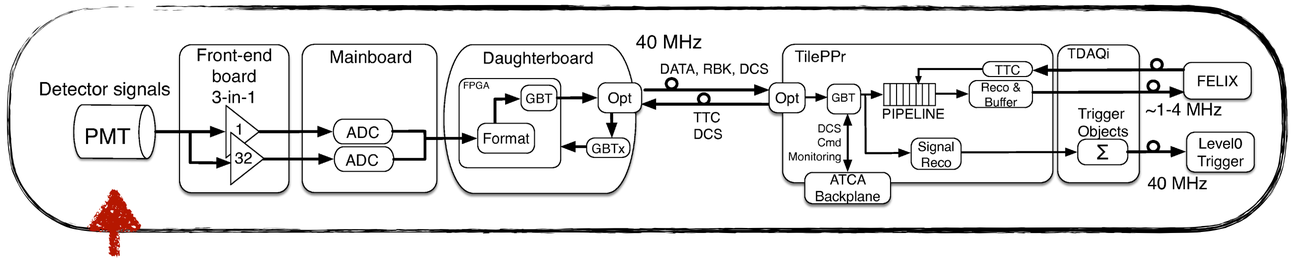
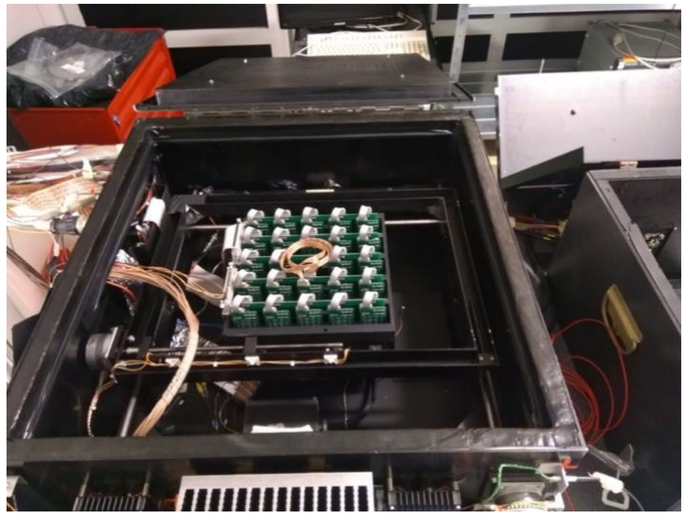
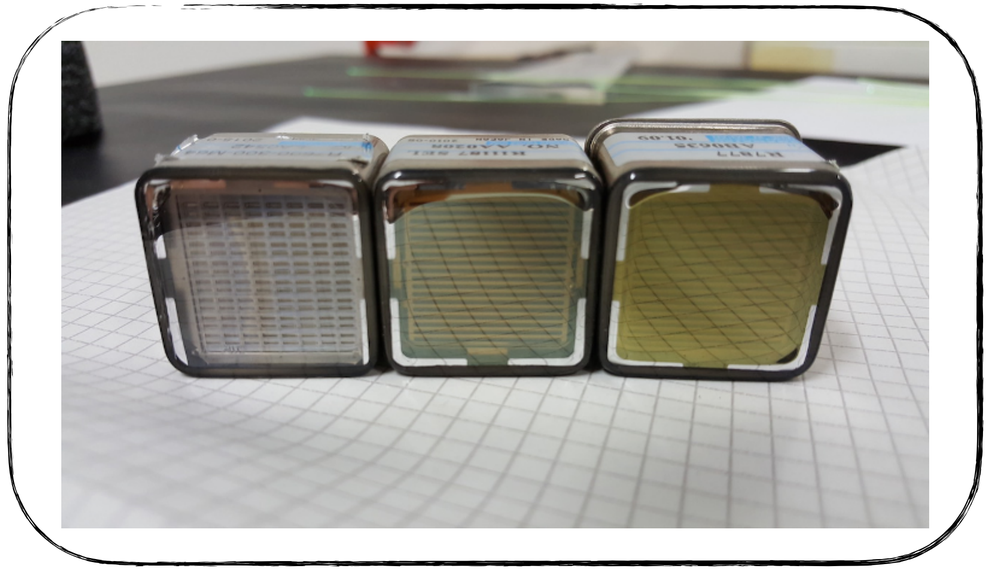


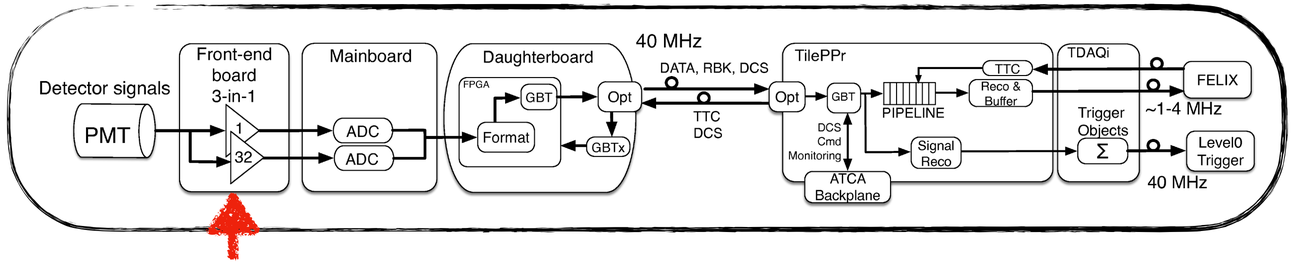


Light-tight box for testing new PMTs

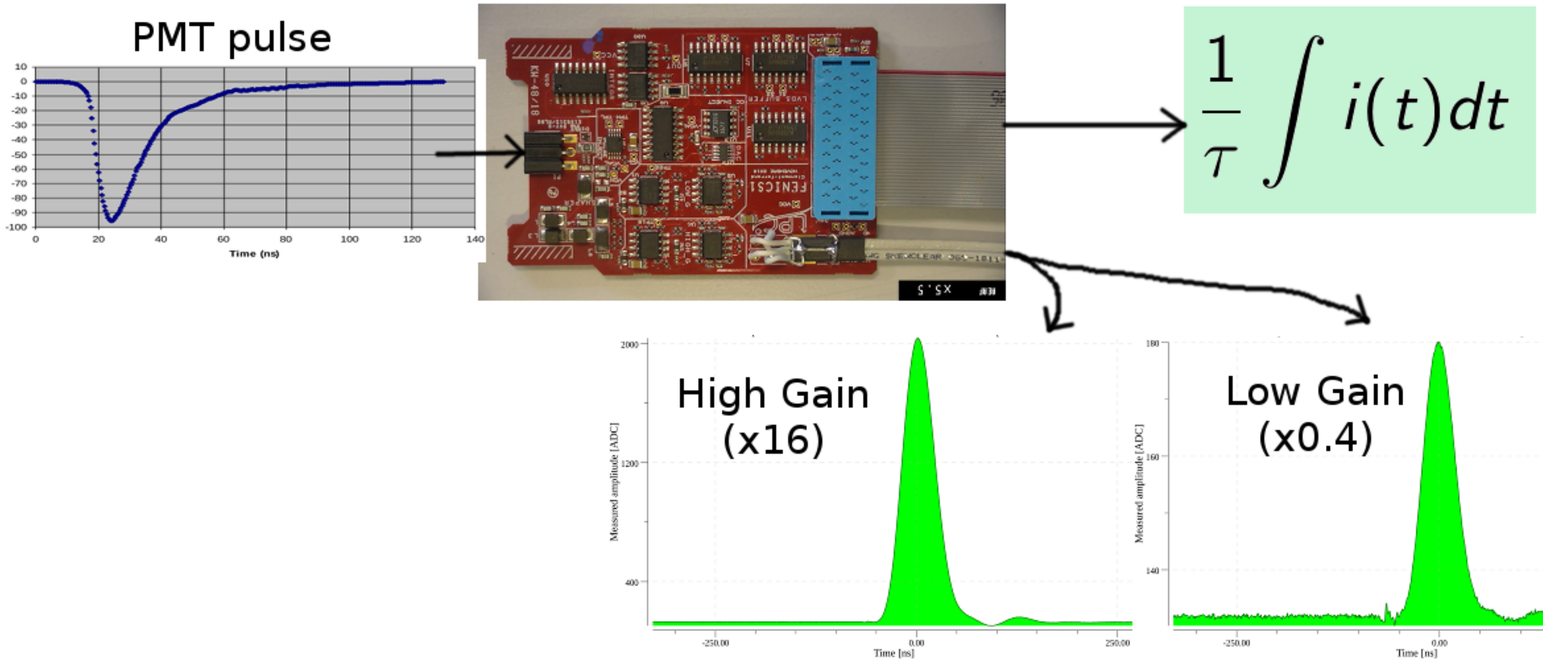


Hamamatsu PMTs used in TileCal

The Very Front-End

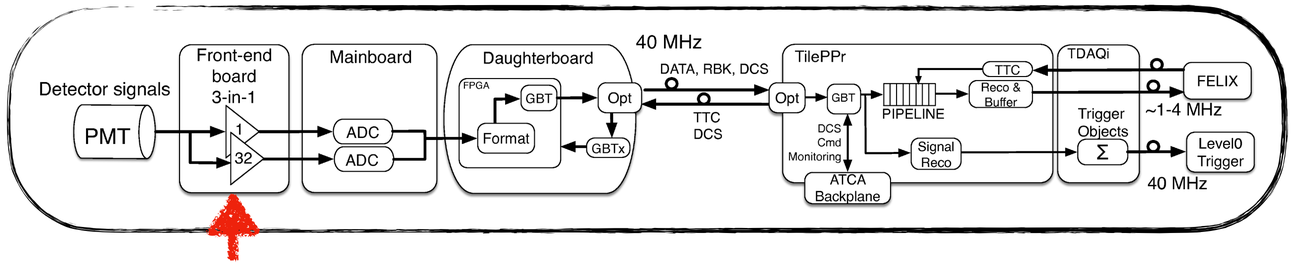


Functionality of the front-end card



The Very Front-End

- 1st processing stage of the PMT signal
- Preparing PMT signal for fast and slow readout
- Shaping & amplification
- Fast readout:
  - Two gains:
    - x16 - High Gain
    - x0.4 - Low Gain
- Slow readout:
  - PMT current integration for calibrations
  - 6 Programmable Gains
- 11 000 cards to be produced



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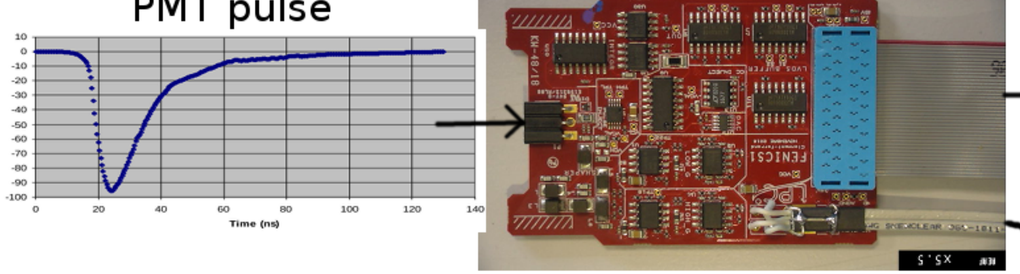
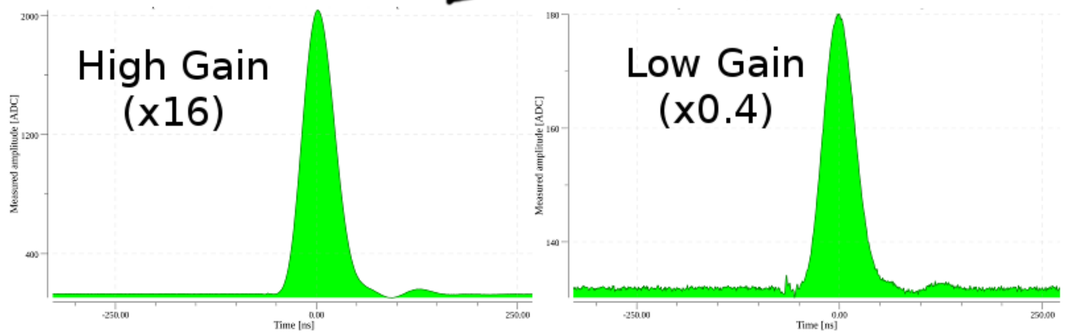
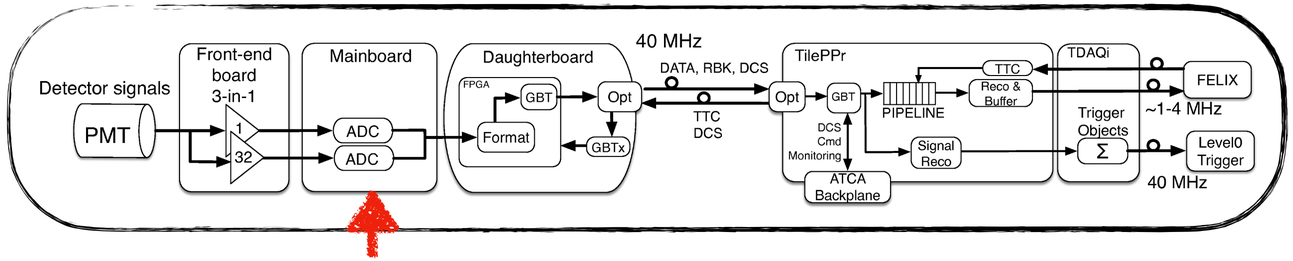
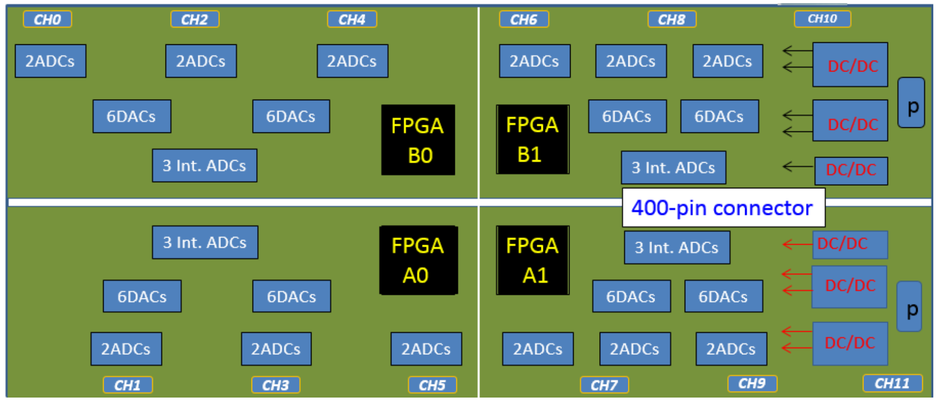


$$\frac{1}{\tau}\int i(t)dt$$



The Front-End: Mainboard



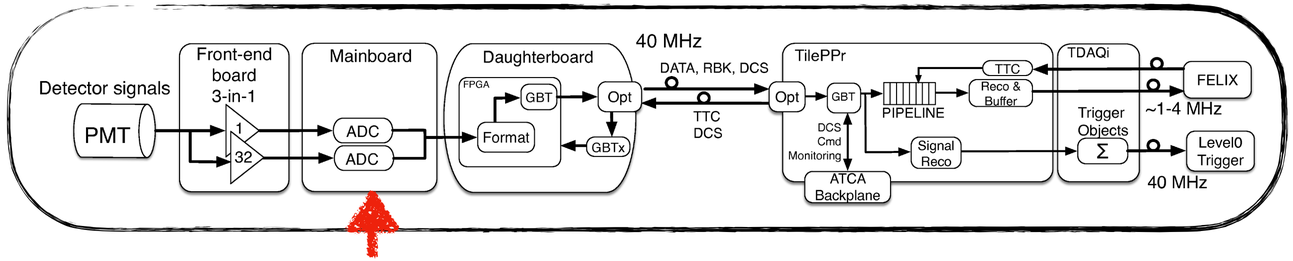


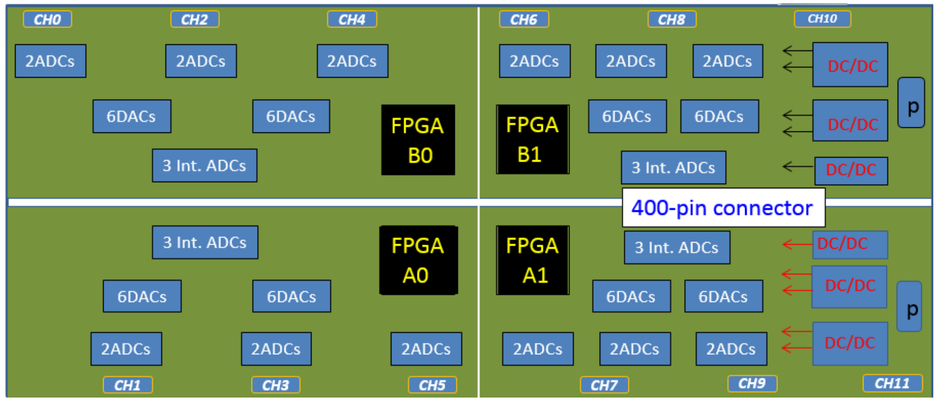
Overview of the Mainboard

Production Mainboard

The Front-End: Mainboard

- 16-layer board - 69 cm long
- Divided into two independent halves
- 6 PMT signals per side
- Hosts the ADCs (12-bit/ 40 Msps)
  - Digitization of the analog PMT signals
- Control of the front-end cards
  - Gains and Charge Injection calibration
- Distribution of low voltage power on-detector
- 896 boards to be installed in ATLAS

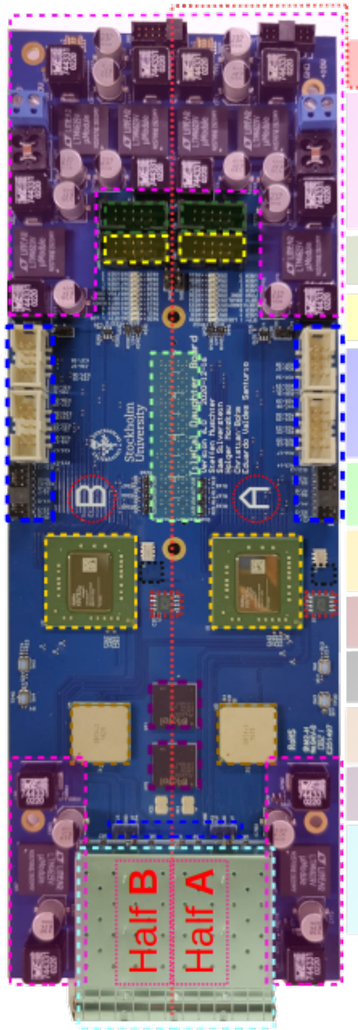




Overview of the Mainboard

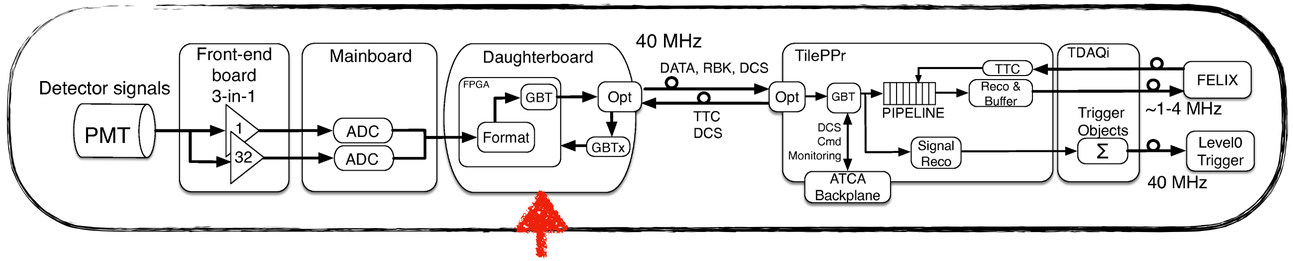
Production Mainboard

The Front-End: Daughterboard



- **Redundancy** Line
- **Power circuitry**
  - Chained Power-up and Fast triggered power-cycle sequence
  - Current monitoring
- **Cesium** interfaces (5V)
- **xADC** interface
- **GBTx I2C/configuration**
- **ProASIC JTAG**
- **Kintex Ultrascale JTAG**
- **400 pin FMC** connector to MB
- **Kintex Ultrascale** FPGAs
- **128-Mbit** PROM chips
- **48-bit ID** chips
- CERN radiation tolerant **GBTxs**
- **ProASIC** FPGAs
- **4x SFPs+**
  - **2x Downlink RX** @4.8Gbps
  - **4x Uplink TX** @9.6 Gbps

Current Architecture



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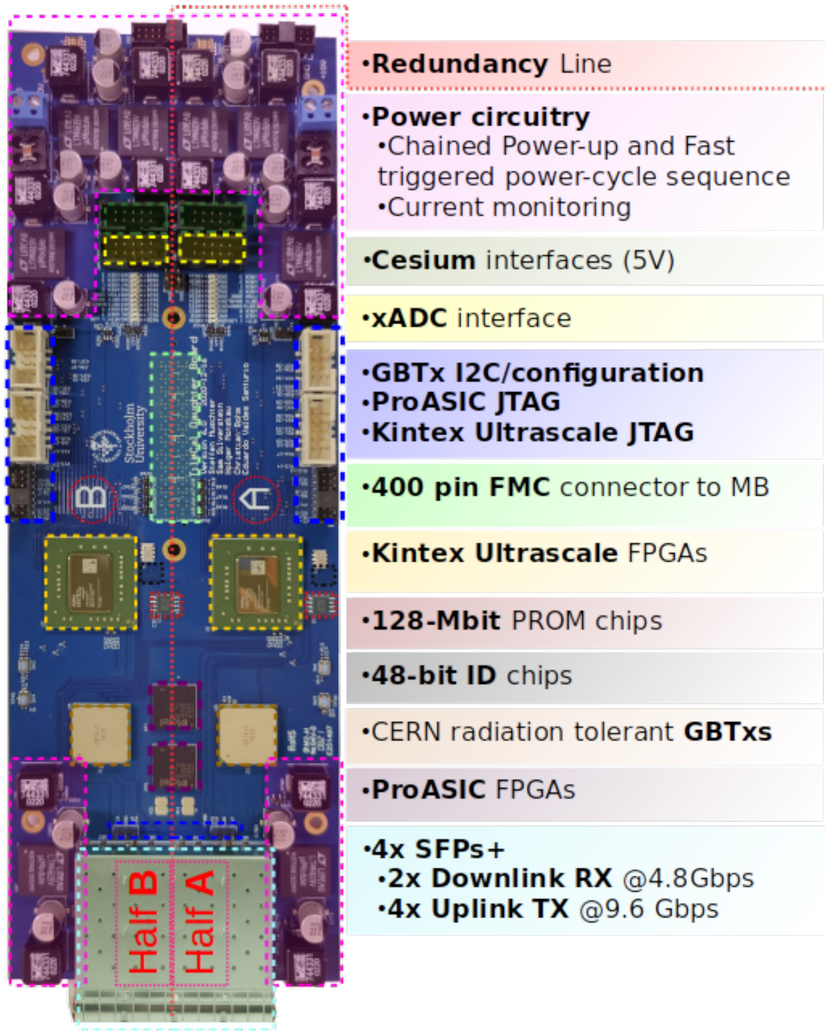

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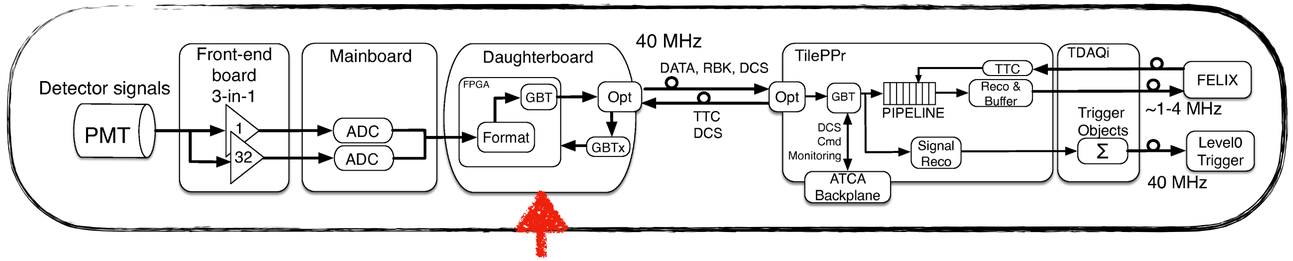
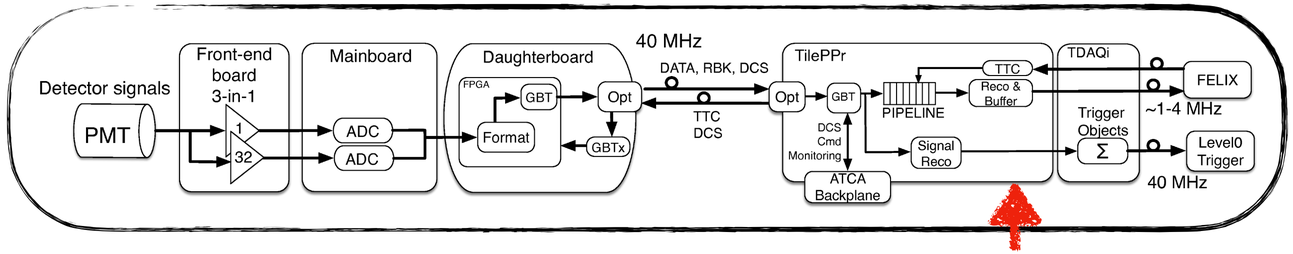
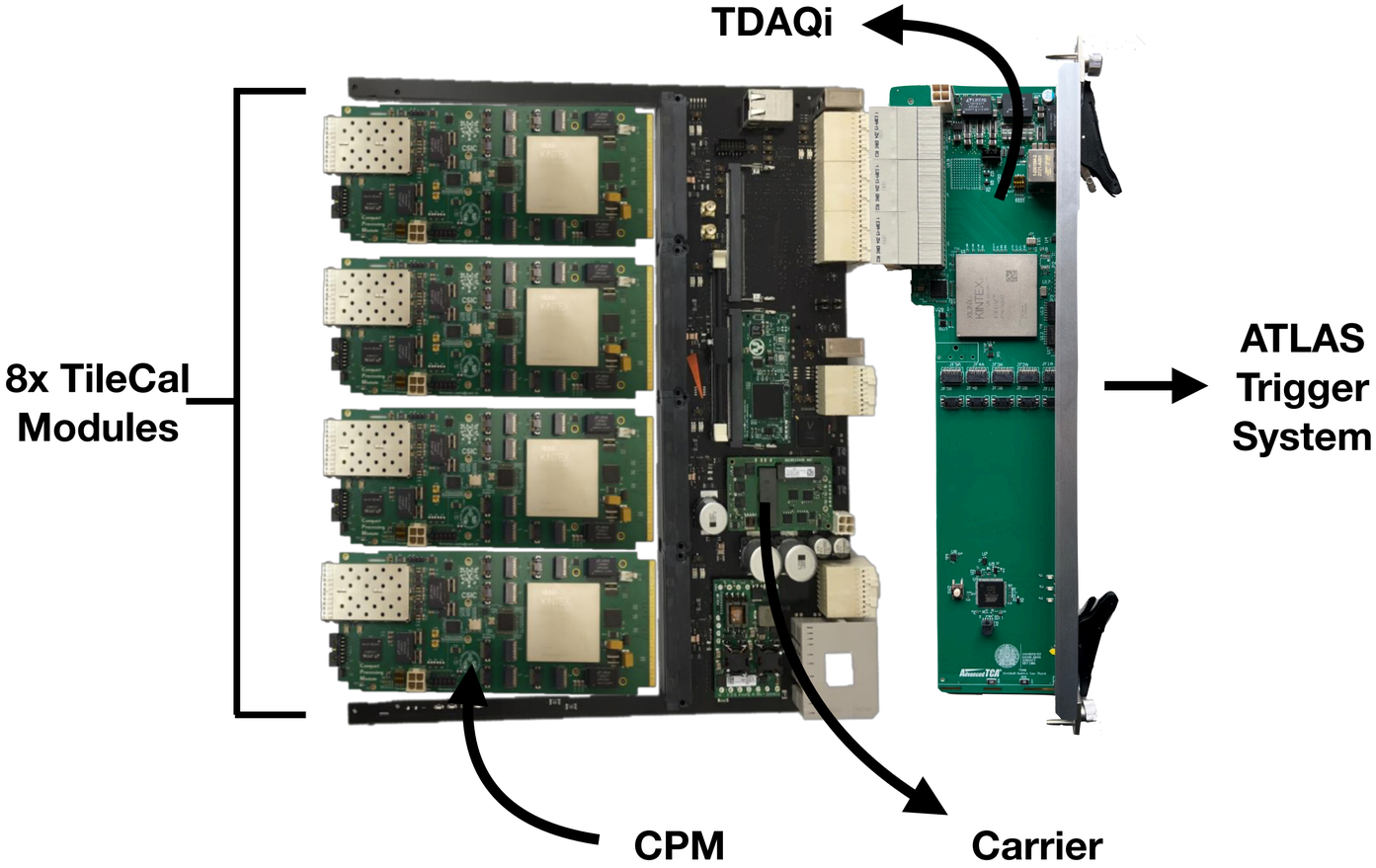


- Interface between on-detector and off-detector
- Communication via radiation-tolerant, high speed links (GBT)
  - 2x 4.6 Gbps downlinks & 2x 9.6 Gbps uplinks
- Downlink:
  Control and configuration commands for the front-end, clock and timing information
- Uplink:
  Continuous high-speed transmission of PMT signal data
- High redundancy:
  Independent halves with equal functionality
- 896 boards to be used in ATLAS

Off-detector: The PreProcessor





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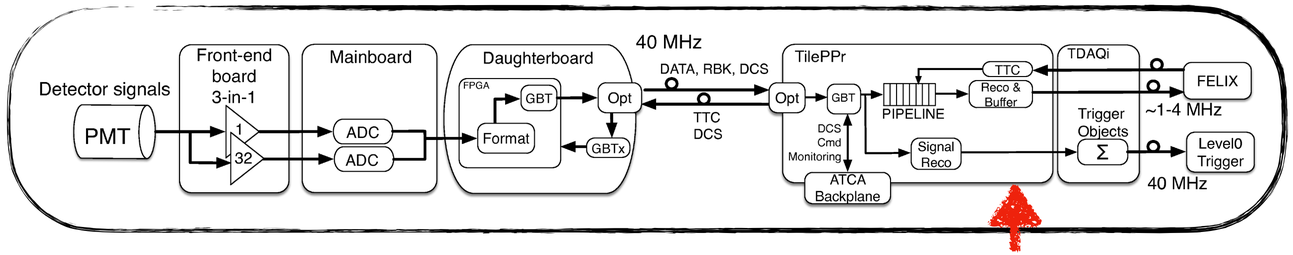
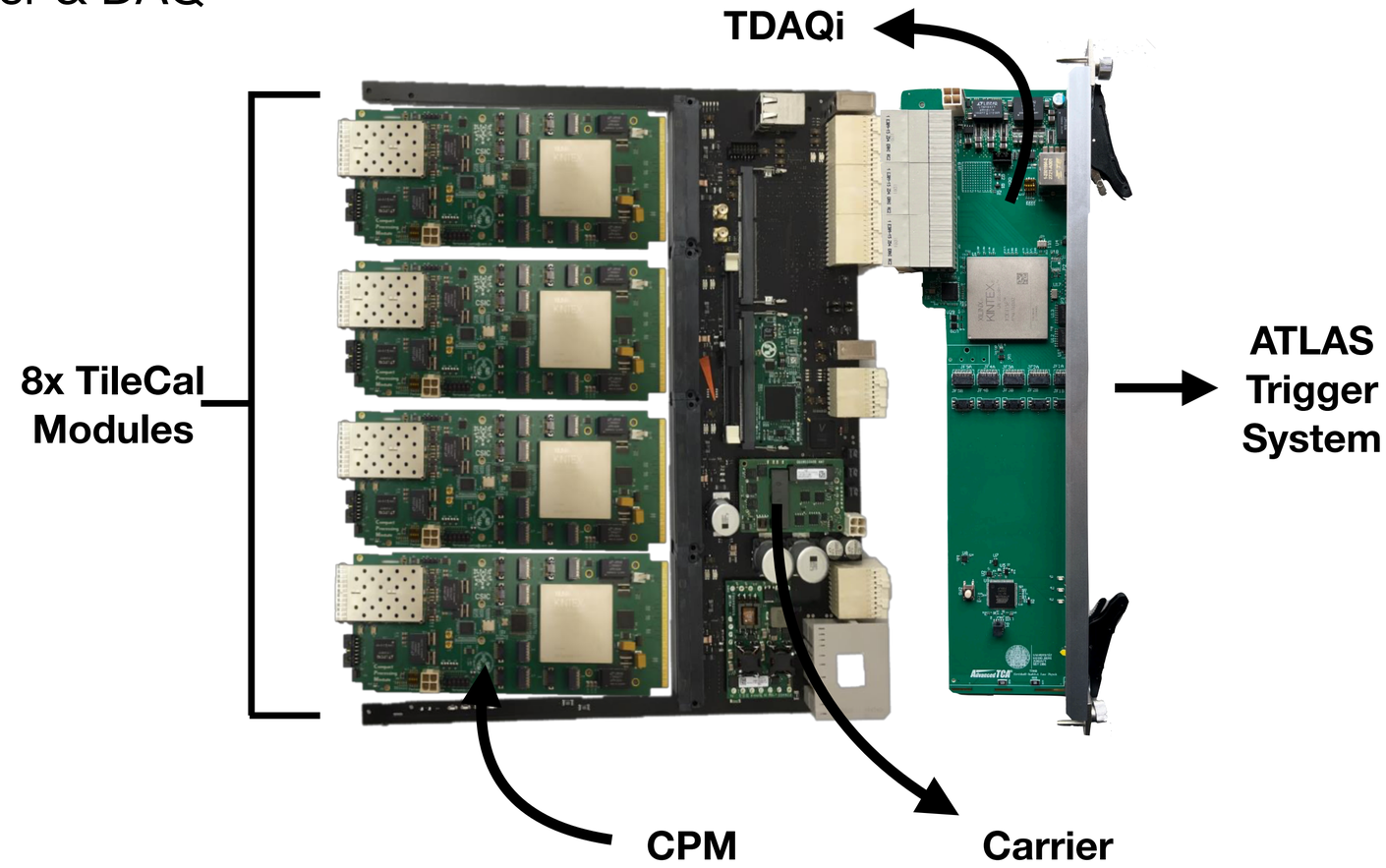
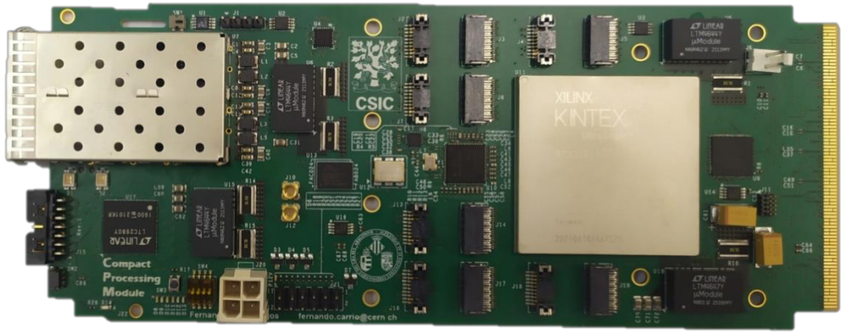


- AdvancedTCA-based blades
- Hub between the on-detector and ATLAS Trigger & DAQ
- One PPr board includes:
  - 4x Compact Processing Modules (CPM)
  - 1x Carrier Board
  - 1x Trigger & DAQ interface (TDAQi)
- 8 TileCal module are read out by one PPr

- The total system is made up of 32 PPr boards
  - 128x CPMs
  - 32x Carrier boards
  - 32x TDAQis



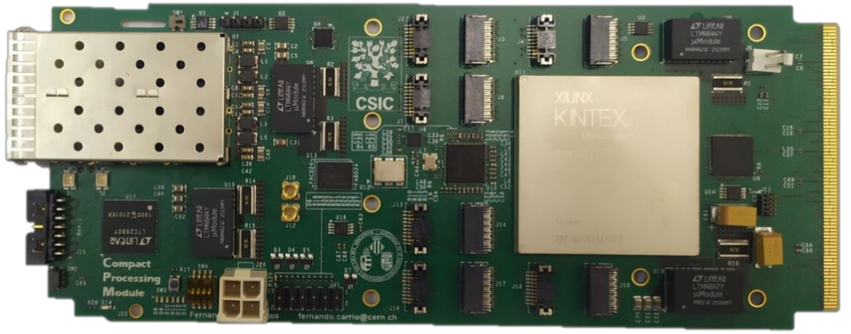
The Compact Processing Module



CPM v2

The Compact Processing Module

- Configuration & Control of the On-detector electronics
- LHC Clock recovery & distribution
- Reception of signals from the Daughterboard
- Data calibration, processing (cell energy calculation) for every bunch crossing @ 40 MHz
- Data pipelining & awaiting Trigger decision
- Passes reconstructed cell energies to the TDAQi for triggering @ 40 MHz



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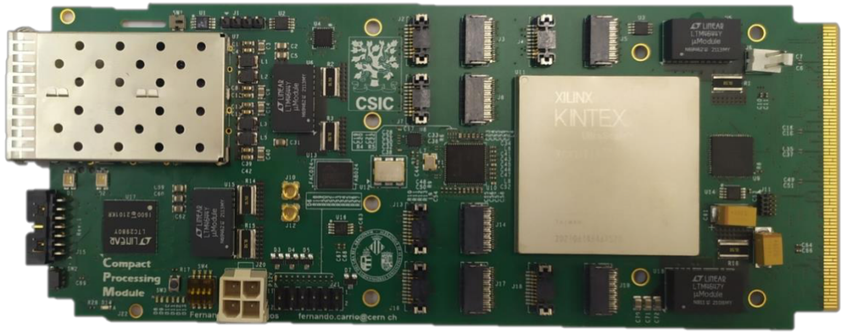

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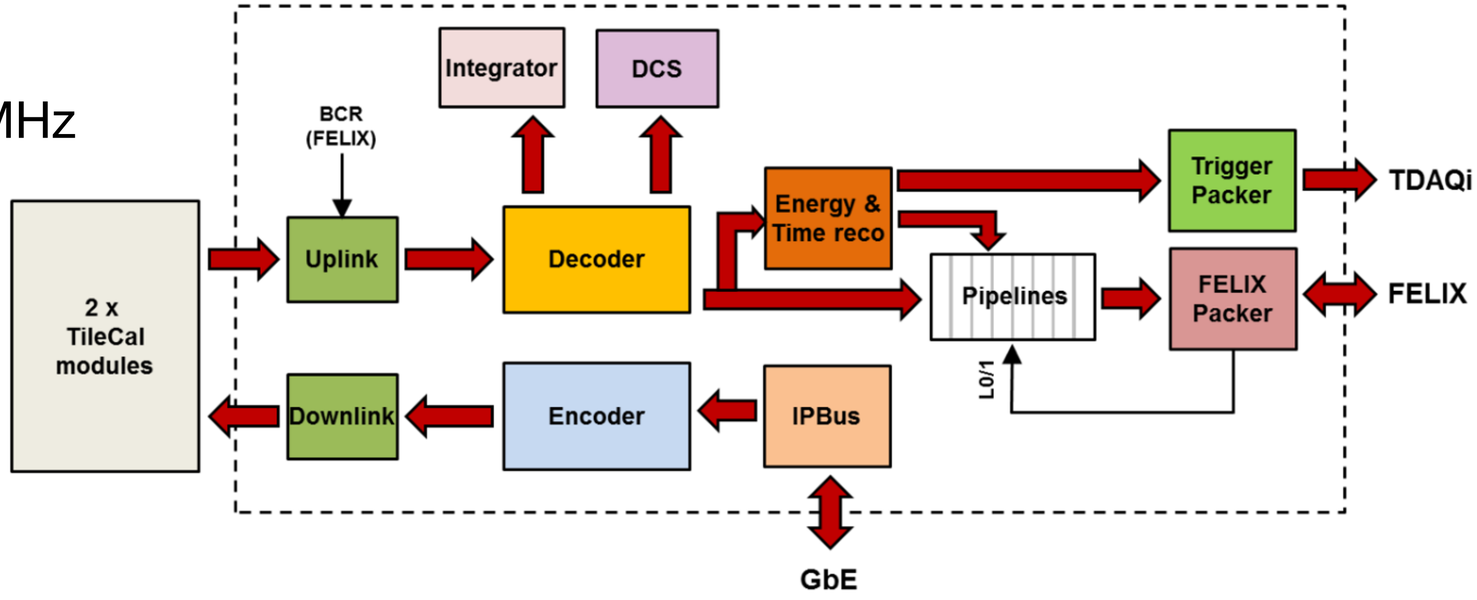

Overview of the CPM Firmware

The Trigger & DAQ Interface

TDAQi v2

The Trigger & DAQ Interface

- Reception of cell energies from the CPMs
- Calculation of trigger primitives:
  - Summed Cells (Trigger-Towers)
  - Energy Flags
  - Sorted cell energies
- Transmission to Trigger subsystems identifying e/gamma, jet and muon signatures
- Data Buffering and transmission to the ATLAS DAQ system
- 70 high-speed links ranging from 9.6 Gbps to 11.2 Gbps

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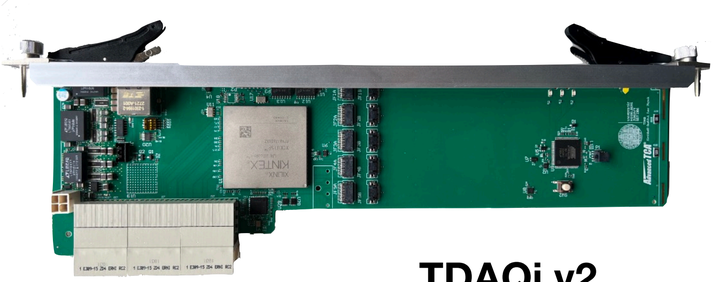
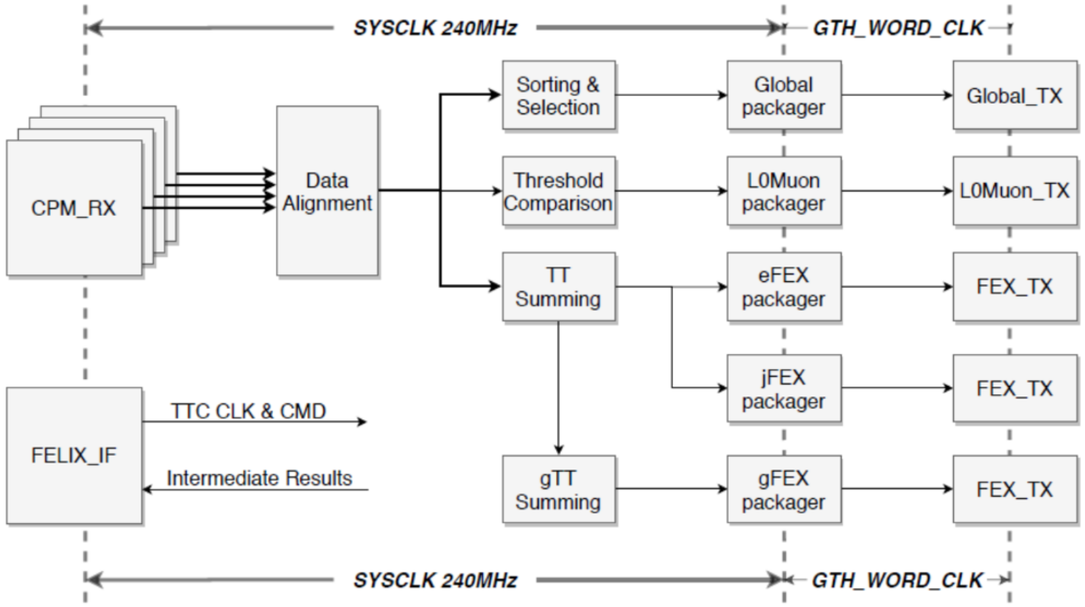


TDAQi v2



Overview of the TDAQi Firmware

Testbeam Campaigns

Testbeam Campaigns

Testbeam Area

Testbeam Campaigns

- At the SPS H8 beamline
- An environment to validate hardware with real beam data and perform physics studies in parallel
- 3 modules from the calorimeter
  - 2 Long-Barrel and 1 Extended-Barrel modules
- Exposed to electron, muon and hadron beams at various energy ranges
- Today's focus are the hadron response studies:
  - Paper published in EPJC
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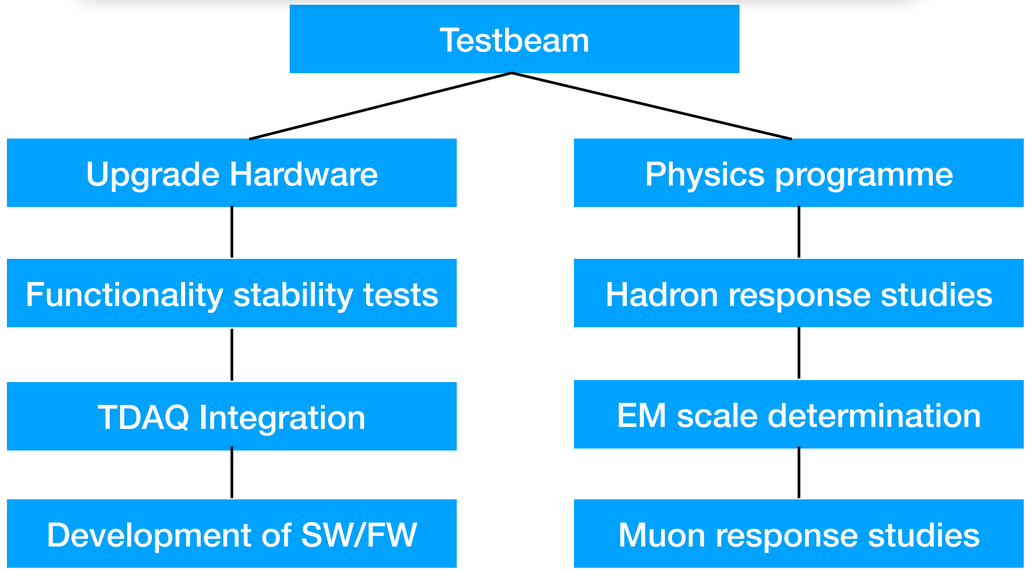
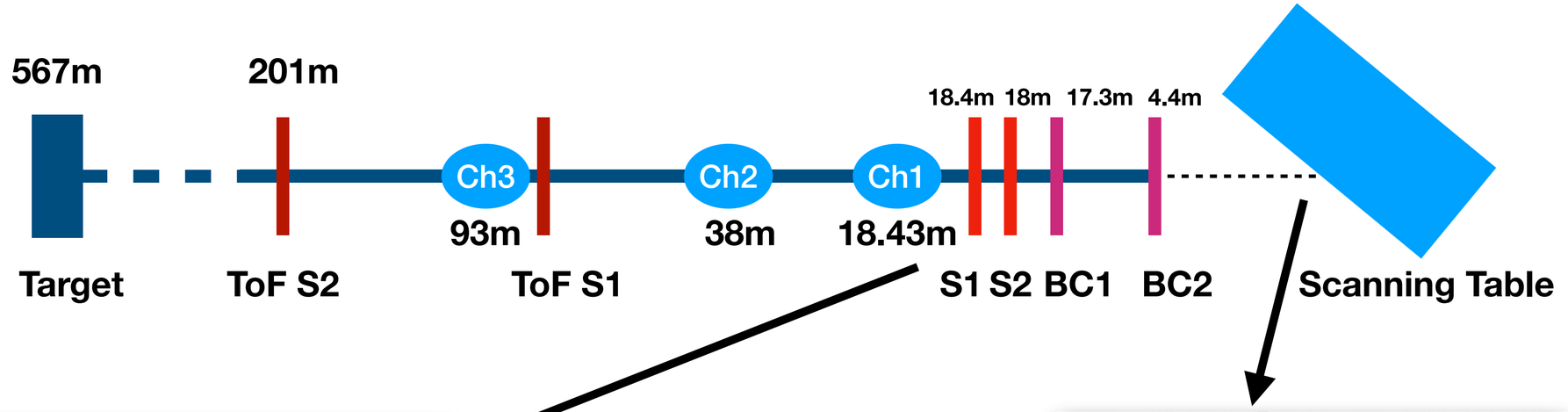


The TileCal Testbeam

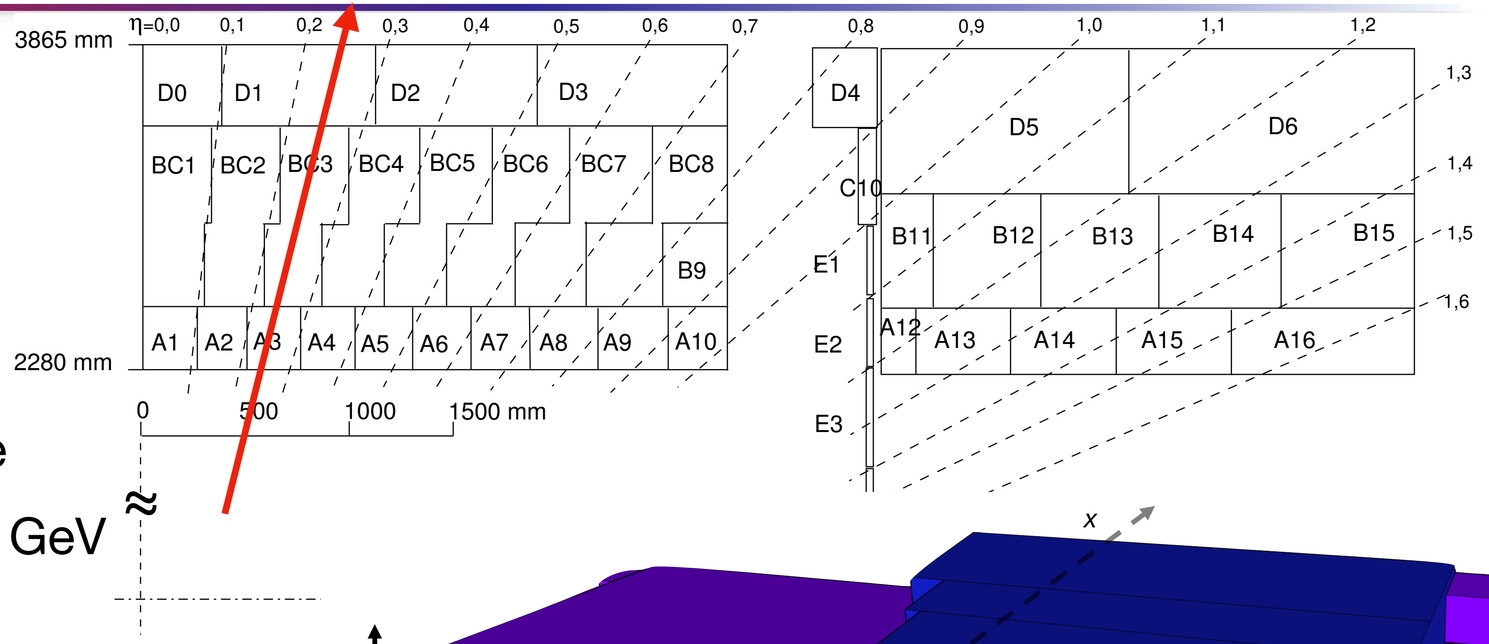


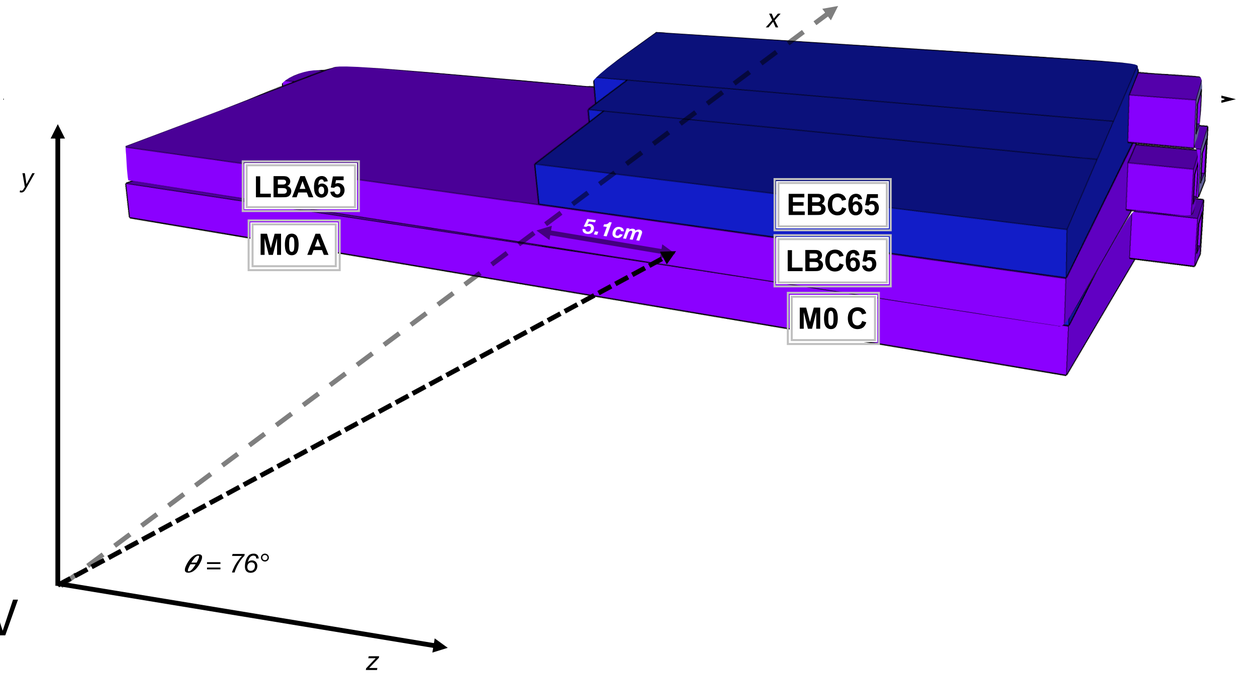
Beamline elements

Experimental area

Testbeam Setup

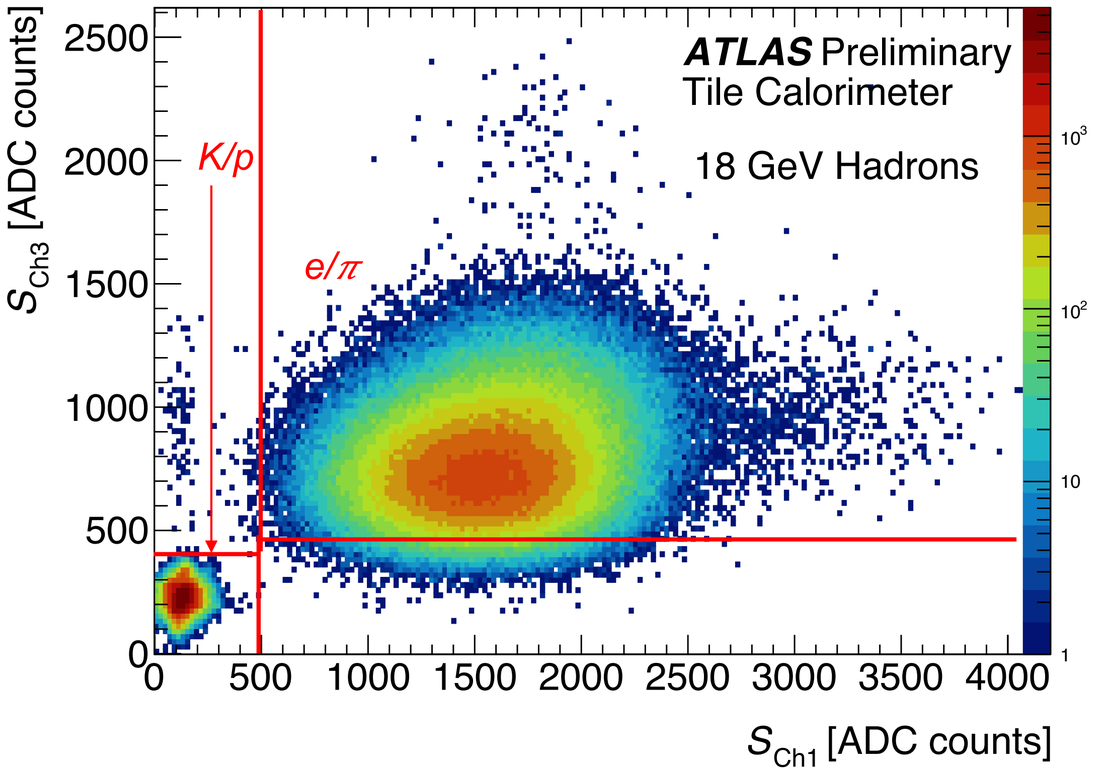
- Configuration used in the study:
  - Projective $\eta = 0.25$
  - Beam pointed to the middle module
  - Hadron beams at 16, 18, 20 and 30 GeV

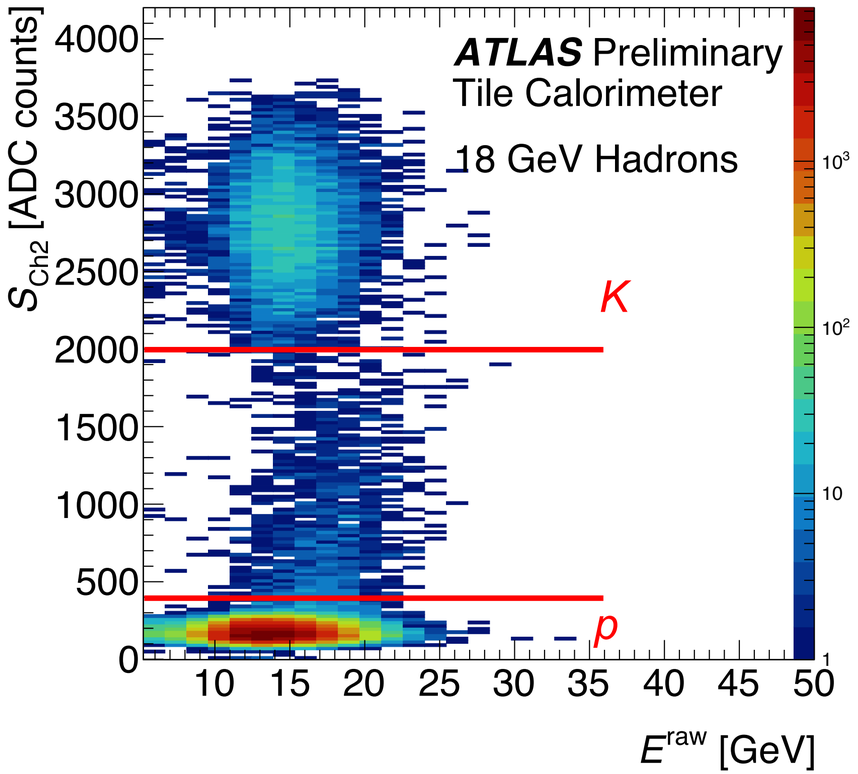




- Mix of muons, electrons, pions, kaons and protons
- Muons have low energy deposits
- Spurious particles rejected by using a wire chamber
- Taken into account only cells with energies > 60 MeV

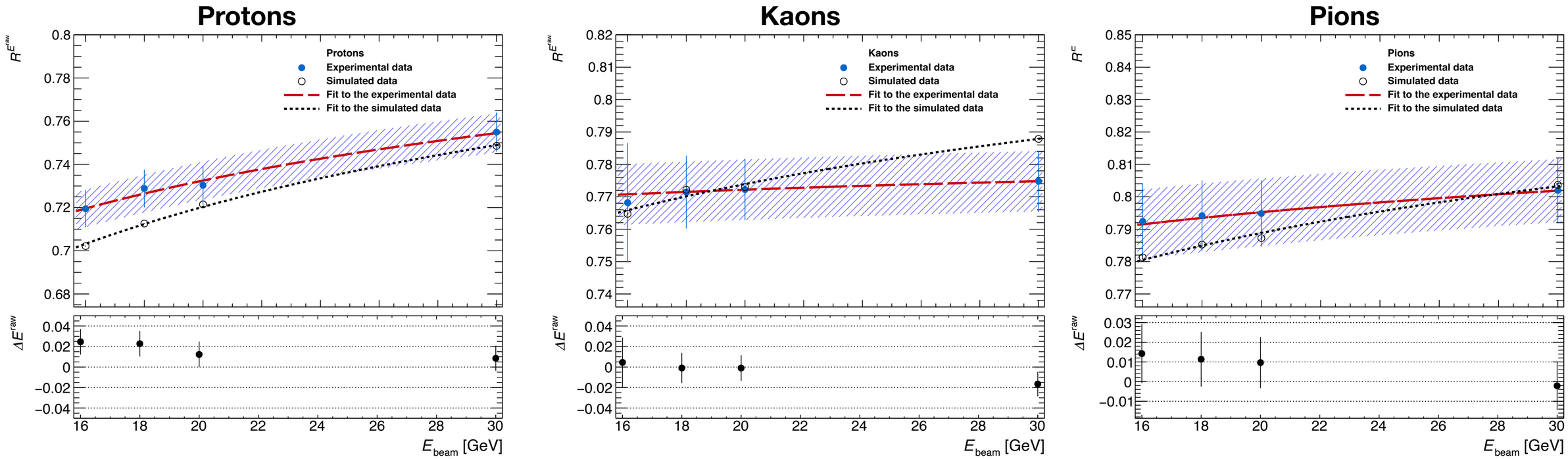
Particle ID





- **2 CO2 and 1 He filled Cherenkov detectors**
- Adjustable gas pressure for changing the refractive index
- Allows to separate particles up to 50 GeV max
- Inefficient at energies below 15 GeV

Energy Response



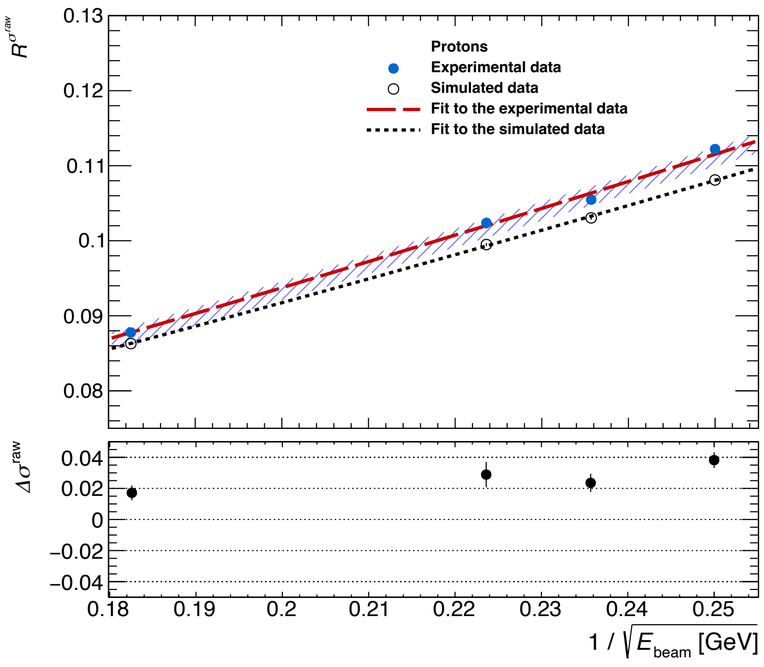
- **The response can be parametrized:**
- Kaon content is smaller in the beam - dominated by statistical errors
- Protons have high statistics - low systematic and statistical uncertainties

$$R^{<E^{raw}>} = (1 - F_h) + F_h(\frac{e}{h})^{-1}$$

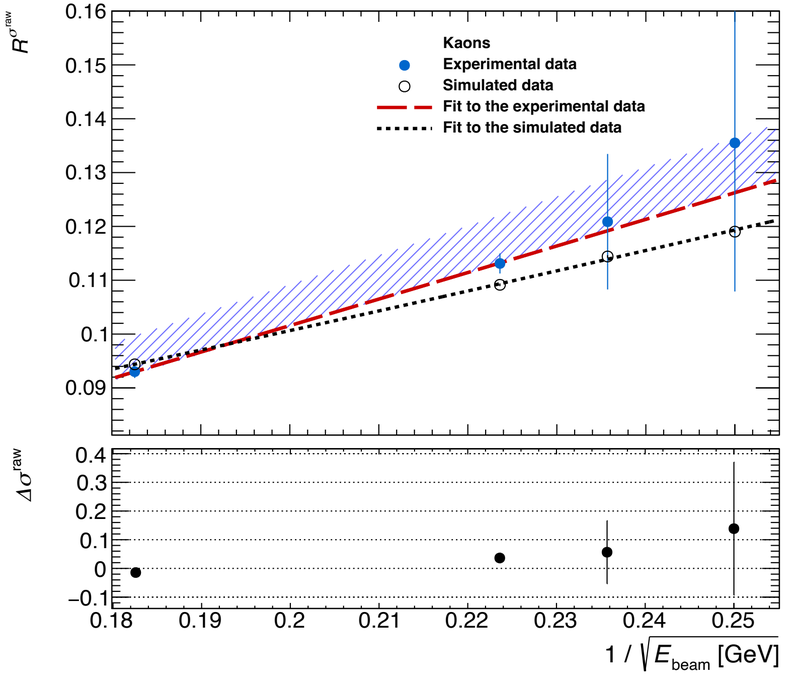
- $(\frac{e}{h})$ - ratio between the responses to the purely EM and hadronic components of showers
- F_h - non-electromagnetic energy component of showers

Energy Resolution

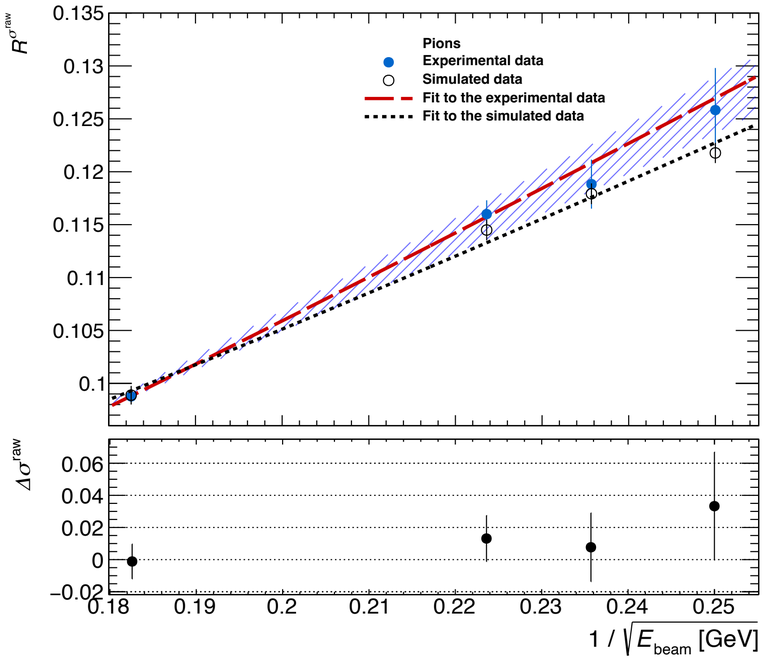
Protons



Kaons



Pions



- **Energy resolution can be parametrized:**
- **a** is consistent for kaon and pion data within large uncertainties
- **b** is ~5% and consistent for all particles

$$R^{<\sigma^{raw}>} = \frac{a}{\sqrt{E_{beam}}} \oplus b$$

Comparisons to model predictions

E_{beam} [GeV]	Experimental Data	Simulated Data
	$F_{\text{h}}(K)/F_{\text{h}}(\pi)$	
16	$1.1165 \pm 0.0761 \pm 0.0354$	1.0756 ± 0.0028
18	$1.1102 \pm 0.0309 \pm 0.0276$	1.0608 ± 0.0028
20	$1.1101 \pm 0.0083 \pm 0.0186$	1.0669 ± 0.0028
30	$1.1371 \pm 0.0059 \pm 0.0098$	1.0805 ± 0.0027
	$F_{\text{h}}(p)/F_{\text{h}}(\pi)$	
16	$1.3512 \pm 0.0039 \pm 0.0418$	1.3617 ± 0.0034
18	$1.3173 \pm 0.0030 \pm 0.0326$	1.3382 ± 0.0033
20	$1.3144 \pm 0.0019 \pm 0.0217$	1.3091 ± 0.0033
30	$1.2373 \pm 0.0018 \pm 0.0107$	1.2807 ± 0.0031

	a (% GeV$^{-1/2}$)	b (%)
Experimental data		
π	$46.68 \pm 0.30 \pm 2.22$	$4.99 \pm 0.11 \pm 0.58$
K	$49.9 \pm 2.60 \pm 2.46$	$1.78 \pm 2.78 \pm 1.03$
p	$40.28 \pm 0.38 \pm 0.08$	$4.79 \pm 0.15 \pm 1.44$
π [12]	52.9 ± 0.9	5.7 ± 0.2
Simulated data		
Pions	42.25 ± 1	6.2 ± 0.4
Kaons	42.8 ± 0.3	5.3 ± 0.1
Protons	38.05 ± 0.23	5.12 ± 0.08

- Results used to validate & improve Geant4 simulation showering models
- https://geant-val.cern.ch/

- Extracted ratio of purely EM and hadronic components of showers:

New Study

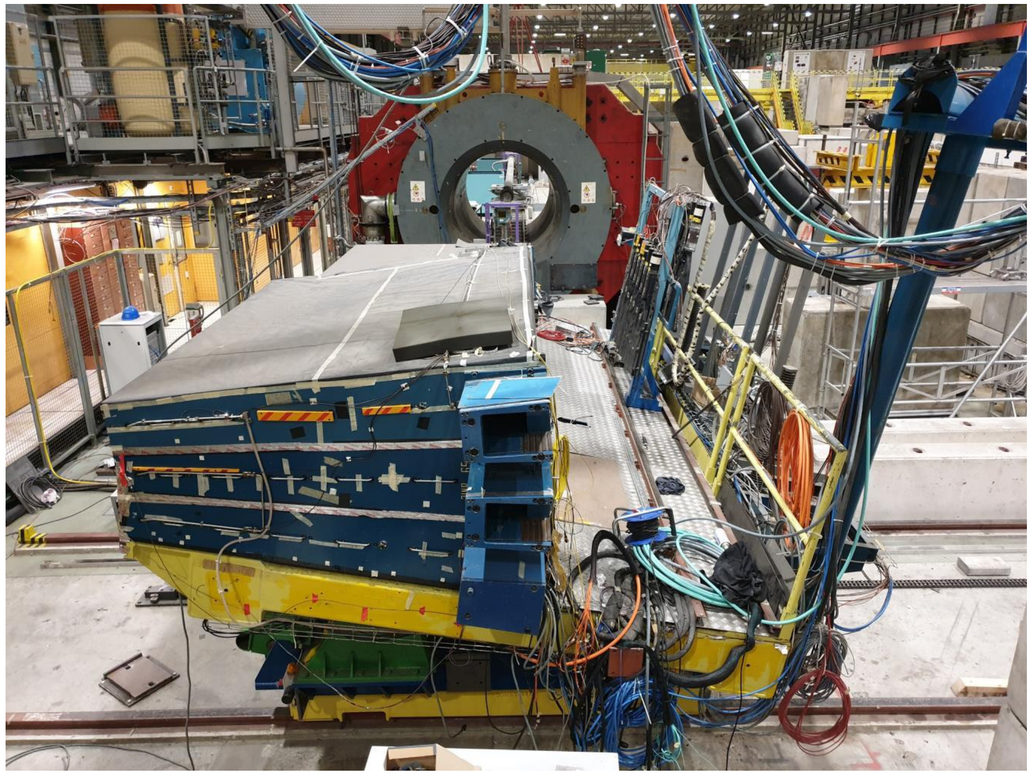
$$e/h = 1.3535 \pm 0.0304$$

Past Study

$$e/h = 1.33 \pm 0.02$$

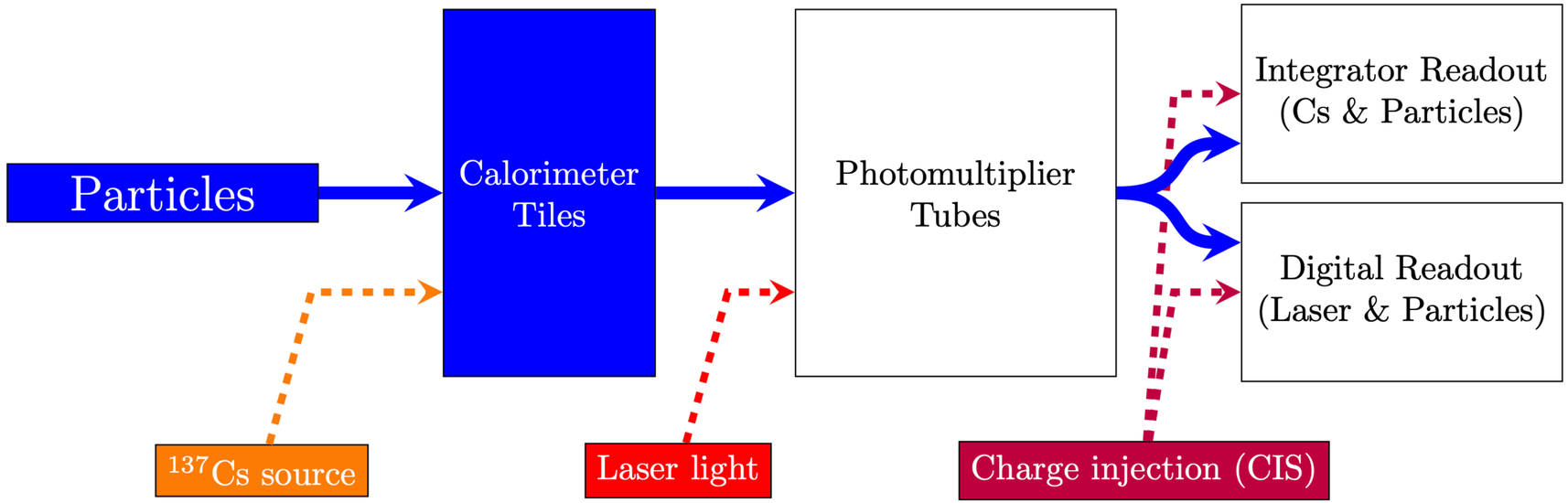
Summary

- The TileCal will play a vital role in HL-LHC
- Entire detector readout electronics is being replaced & upgraded
  - Conform with new readout architecture requirements (transmission, latency)
  - HL-LHC has higher radiation levels
- The Upgrade R&D is finished - moving to pre-production phase
- Testbeam campaigns are used to validate the new upgrade hardware & perform unique physics studies



Backup

Calibration scheme



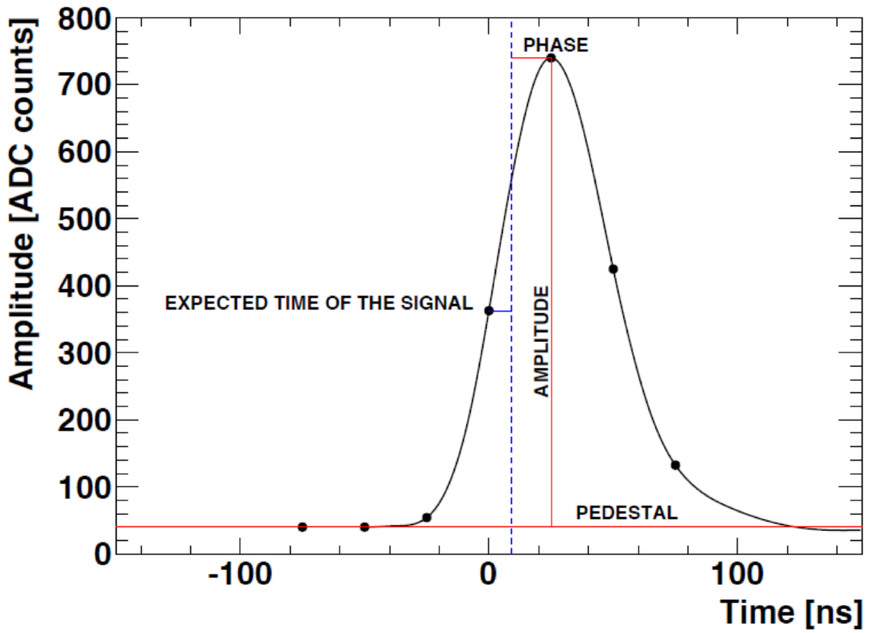
Energy Reconstruction

- Considered signal model for Optimal Filter:

$$y(n) = Ah(n) + A\tau\dot{h}(n) + ped + w(n)$$

- A - The pulse amplitude
- τ - Phase deviation
- $h(n)$ - normalized reference pulse shape
- $\dot{h}(n)$ - time derivative of the reference pulse
- ped - baseline added to the signal
- $w(n)$ - electronic noise

- Calculation of the weights:

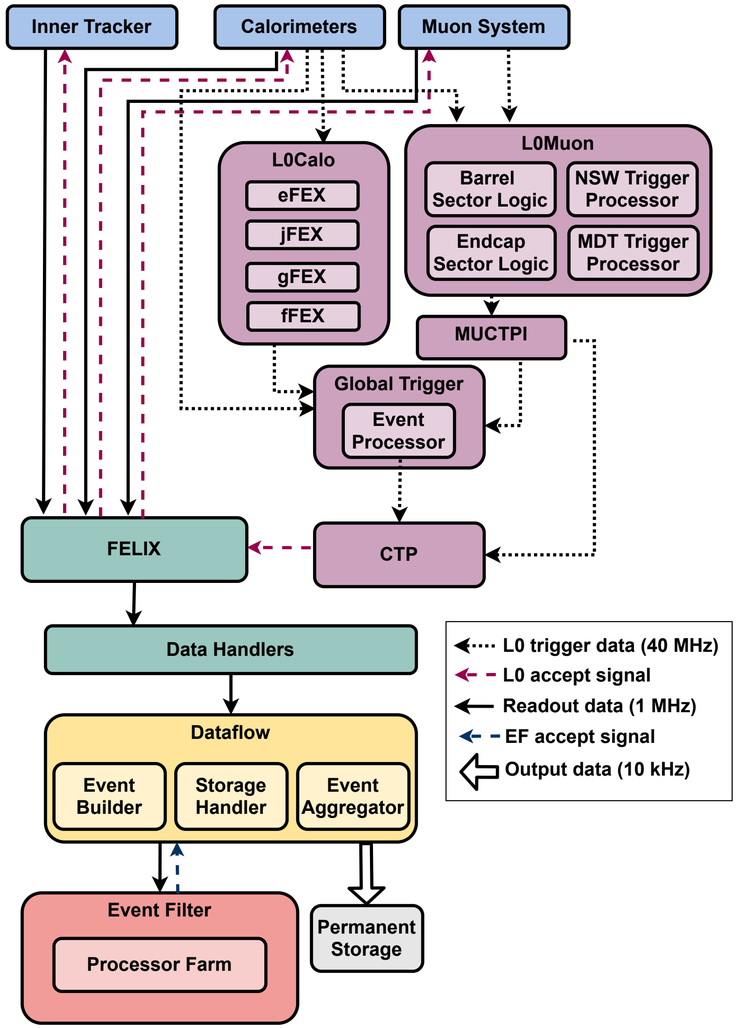


Optimal Filtering based on weighted sums of the samples

$$E = \sum_{i=1}^{n} a(i)y(i) \qquad E\tau = \sum_{i=1}^{n} b(i)y(i)$$

The Trigger & DAQ Interface

- Fully digital Trigger system
- Only optical inputs from the detector
- Summed **Trigger-Towers**:
  - L0Calo - Calorimeter Trigger
- **Cell Energy Flags**:
  - L0Muon - Muon Trigger System
- **Cell energies**
  - Global Trigger
- Estimated allowed latency of ~**10 µs**



ATLAS Trigger System