The current status and plans of the ALICE and ATLAS calorimeters

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Outline

- Performance of the ALICE electromagnetic calorimeter (EMCal/DCal) during Run 1 and 2 (2010–2018)
- The ALICE calorimeters upgrade projects commissioned at Run 3
- Commissioning of ATLAS electromagnetic calorimeter (LAr) for LHC Run 3
- Commissioning of ATLAS hadron calorimeter (TileCal) for LHC Run 3

ALICE Calorimeters – physics goal

- The primary goal of ALICE is to investigate the properties of hot quark-gluon matter created in ultrarelativistic heavy-ion collisions
- In the central region, ALICE includes two electromagnetic calorimeter systems:
  - the PHOton Spectrometer (PHOS), designed to measure spectra and correlations of thermal and direct photons, and of neutral mesons via their decay into photon pairs: requires high granularity as well as excellent energy and position resolution
  - the Electro Magnetic Calorimeter (EMCal), designed for the measurements of electrons from heavy-flavor hadron decays, the electromagnetic component of jets, and spectra of direct photons and neutral mesons: requires a larger acceptance but less stringent requirements on the energy and position resolution

ALICE Calorimeters – basic geometry

- In the central region, ALICE includes two electromagnetic calorimeter systems:
  - PHOton Spectrometer (PHOS)
  - Electro Magnetic Calorimeter (EMCal),

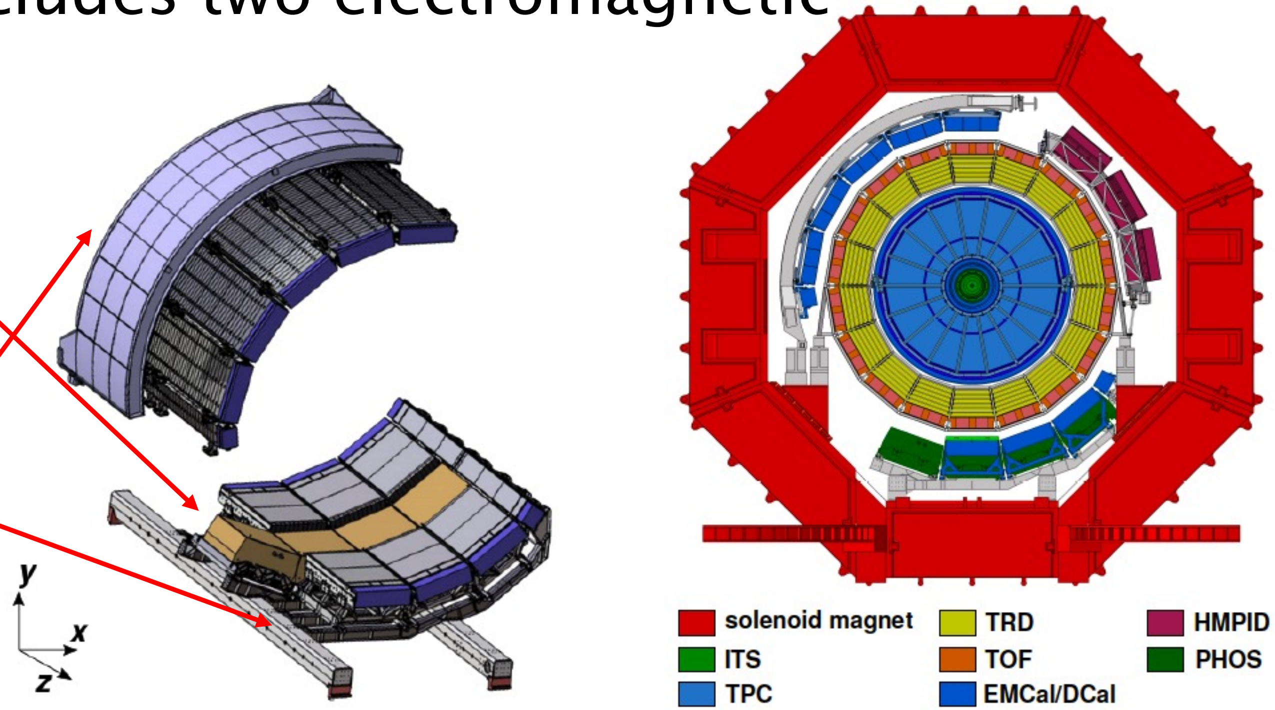

Figure 1: Schematic view of the EMCal (left) illustrating the module position on two approximately opposite locations in azimuth. The PHOS calorimeter inside the DCal is indicated in brown. The right figure shows a cross section of the ALICE barrel detectors.

arXiv:2209.04216

ALICE Calorimeters – data collection

- A brief list of data collected by ALICE calorimeters in 2010-2018

Table 1: Data collected in pp collisions for different center-of-mass energies ($\sqrt{s}$) with minimum-bias and EMCal triggers.

$\sqrt{s}$	Year	MB events (x10^6)	L_{int} MB	L_{int} EMCal
0.9 TeV	2010	5.8	0.12 nb^{-1}	-
2.76 TeV	2011	26.4	0.55 nb^{-1}	1.2 nb^{-1}
	2013	15.6	0.33 nb^{-1}	47.1 nb^{-1}
5.02 TeV	2015	100	1.95 nb^{-1}	0.075 pb^{-1}
	2017	1129	22.05 nb^{-1}	0.435 pb^{-1}
7 TeV	2010	358	5.74 nb^{-1}	-
	2011	1.8	0.03 nb^{-1}	0.47 pb^{-1}
8 TeV	2012	108	1.93 nb^{-1}	0.62 pb^{-1}
13 TeV	2016	382	6.61 nb^{-1}	2.44 pb^{-1}
	2017	519	8.97 nb^{-1}	3.74 pb^{-1}
	2018	615	10.64 nb^{-1}	3.23 pb^{-1}

Table 2: Data collected in p–Pb collisions for different nucleon–nucleon center-of-mass energies ($\sqrt{s_{NN}}$) with minimum bias and EMCal triggers. The numbers in parentheses denote the corresponding data set with only the triggering and vertexing detectors in the readout.

$\sqrt{s_{NN}}$	year	MB events (x10^6)	L_{int} MB	L_{int} EMCal
5.02 TeV	2013	94	0.045 nb^{-1}	7.38 nb^{-1}
	2016	490	0.235 nb^{-1}	-
8.16 TeV	2016	38(83)	0.018 (0.041) nb^{-1}	1.42 (5.67) nb^{-1}

Table 3: Data collected in heavy-ion collisions at different nucleon–nucleon collision center-of-mass energies ($\sqrt{s_{NN}}$) using minimum bias, centrality [14] or EMCal triggers. Centrality triggers are defined as minimum bias (0-100%), central (0-10%), and mid-central (0-50% for 2011 and 30-50% for 2018). The corresponding cross sections are given in μb^{-1} in the brackets.

		centrality triggered events (x10^6)			L_{int} EMCal
System	Year	minimum bias	central	mid-central	
Xe, 5.44 TeV	2017	1.7 (0.3)	-	-	-
Pb, 2.76 TeV	2010	14.8 (2.0)	-	-	-
	2011	1.6 (0.2)	11.5 (15.3)	10.6 (4.7)	25.3 μb^{-1}
Pb, 5.02 TeV	2015	74 (9.7)	-	-	51.2 μb^{-1}
	2018	159 (20.9)	133 (174.5)	73 (48.1)	116.9 μb^{-1}

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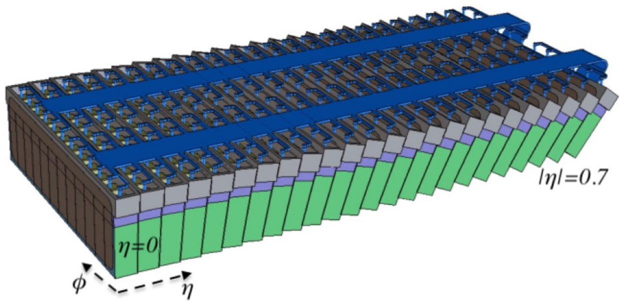
ALICE Calorimeters – module design

- EMCal module contains 2×2 optically isolated towers
- each tower is read out individually and spans a region of $\Delta\eta \times \Delta\phi \sim 0.0143 \times 0.0143$
- Each full-size SM is assembled from $12 \times 24 = 288$ modules



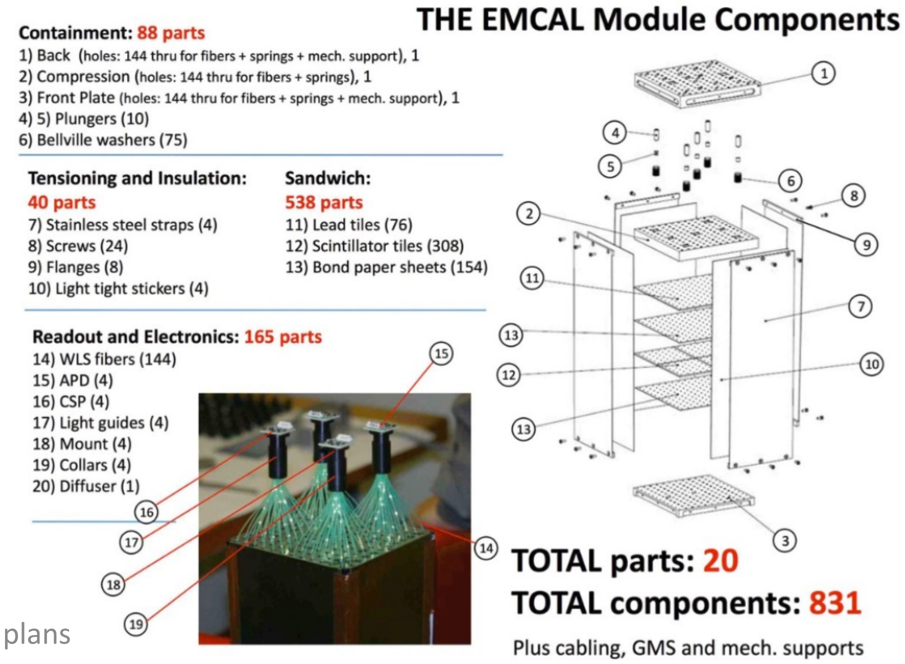


Figure 2: Photo and drawing of EMCal module showing all components.

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ALICE Calorimeters – module design

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- each tower is read out individually and spans a region of $\Delta\eta \times \Delta\phi \sim 0.0143 \times 0.0143$
- Each full-size SM is assembled from $12 \times 24 = 288$ modules
- Each FEE card readout of 32 towers
- Scintillation photons collected by Avalanche Photo Diodes (APD) of 5×5 mm^2 size in the 0.5 T magnetic field
- Both EMCal and DCal provide L0 and L1 trigger

Table 4: EMCal module physical parameters.

Parameter	Value
Tower Size (on front face)	$6.0 \times 6.0 \times 24.6$ cm^3
Tower Size (at η=0)	$\Delta\eta \times \Delta\varphi \simeq 0.0143 \times 0.0143$
Sampling Ratio	1.44 mm Pb / 1.76 mm Scint.
Layers	77
Scintillator	Polystyrene (BASF143E + 1.5%pTP + 0.04%POPOP)
Absorber	natural lead
Effective radiation length X_0	12.3 mm
Effective Molière radius R_M	3.20 cm
Effective Density	5.68 g/cm^3
Sampling Fraction	1/10.5
No. of radiation lengths	20.1

arXiv:2209.04216

ALICE Calorimeters – photon reconstruction

- EMCal reconstructs photons by cluster shape, plus:
- isolated photons: isolation momentum
- decayed photon (pairs): invariant mass
  - (2nd photon can also made by conversion pairs)

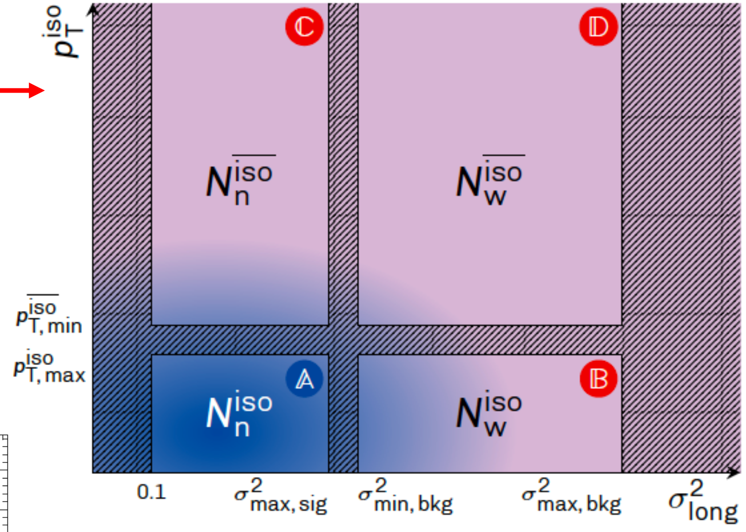

Figure 73: (Color online) Illustration of the parameter-space of the photon p_T^{iso} and σ^2_{long}, used to estimate the background yield in the signal region (𝔸) from the observed yields in the three control regions (𝔹, ℂ, 𝔻). The red regions indicate areas dominated by background and the blue regions by the photon signal. The color gradient indicates mixture of signal and background.

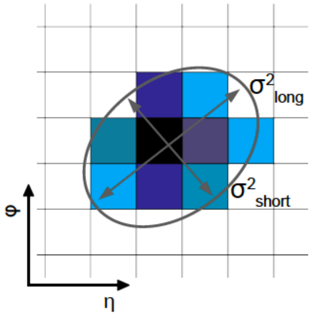

Figure 13: (Color online) Schematic representation of the shower shape and the ellipse axes. The different colors indicate the amount of energy deposited in each cell, the darker the more energy.

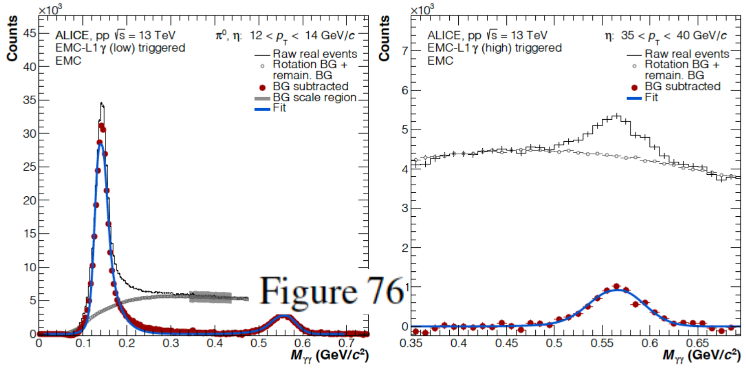

Figure 76

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ALICE Calorimeters – physics performance

- Isolated photon:

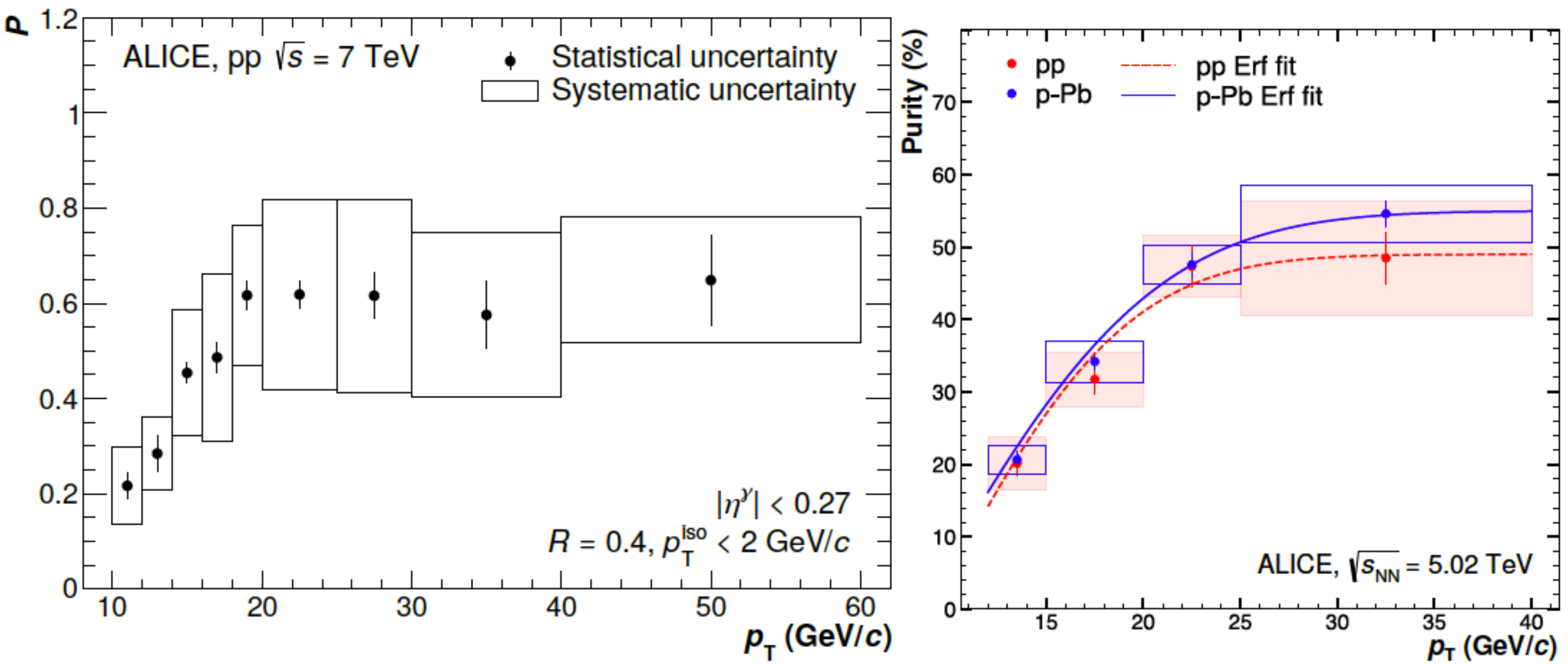

Figure 75: (Color online) Isolated photon corrected purity in pp collisions at $\sqrt{s} = 7$ TeV with $p_T^{iso} < 2$ GeV/c and $|\eta^\gamma| < 0.27$ calculated using Eq. 35, taken from [50] (left) and for pp and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with $|\eta^\gamma| < 0.67$ using the template fit technique taken from [51] (right). The boxes indicate the systematic uncertainty, while the error bars reflect the statistical uncertainty. Figures are taken from the mentioned references.

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ALICE Calorimeters – physics performance

- Neutral mesons:

(note: the pairs of decay photons may hit the same tower(s) and requires cluster splitting)

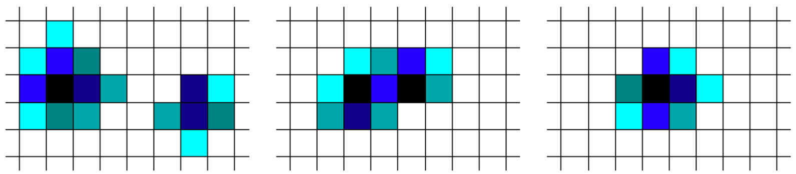

Figure 82: (Color online) Schematic view of cluster shower overlaps from π^0 meson decays with $E_{\pi^0} = 4$, 10 and 20 GeV from left to right. The cell color indicates the deposited energy; the darker, the more energy.

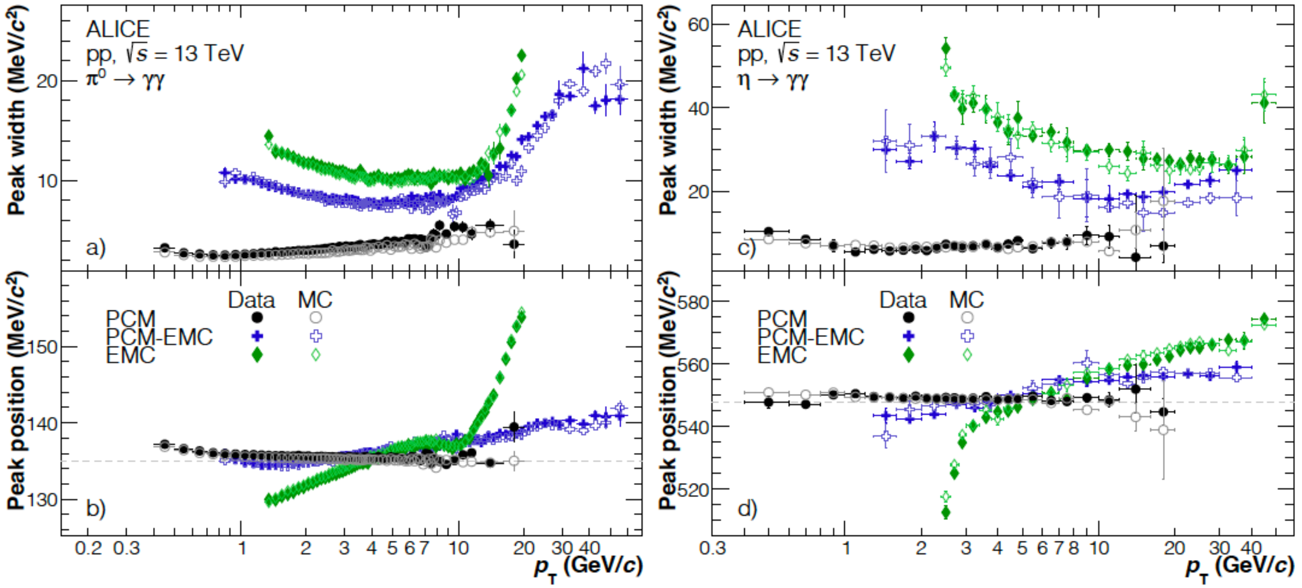

Figure 78: (Color online) π^0 (left) and η (right) meson peak position (b,d) and width (a,c) as a function of the meson momentum measured in pp collisions at $\sqrt{s} = 13$ TeV combining two photons reconstructed with EMCal or PCM.

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ALICE Calorimeters – physics performance

- Identify electrons

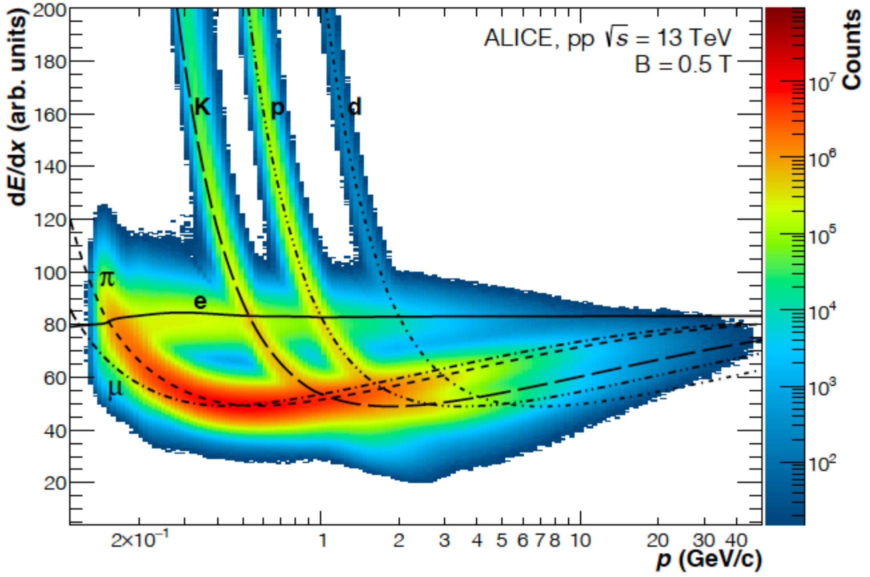

Figure 89: (Color online) dE/dx distribution of tracks measured in the TPC

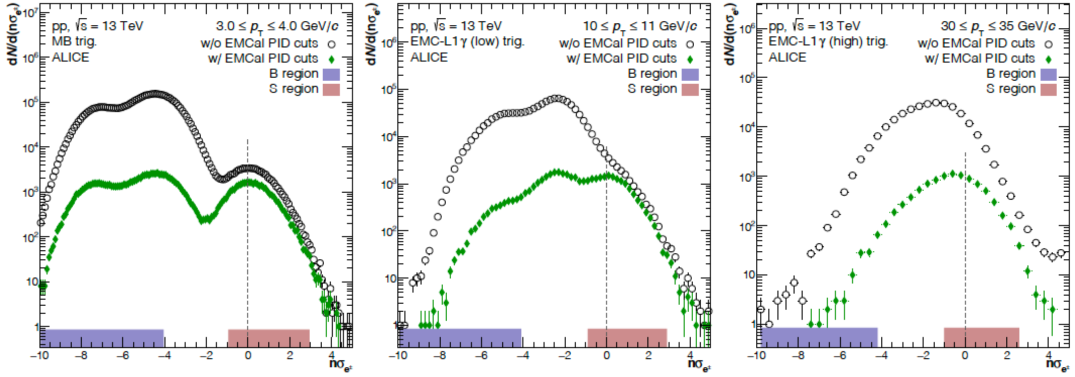

Figure 90: $n\sigma_{e^{\pm}}^{\mathrm{TPC}}$ distribution without (black) and with (green) EMCal electron identification cuts of E/p and σ^2_{long}. Electrons form a Gaussian distribution centered around zero, indicated by the gray dashed line. The signal and background selection windows considered for the following E/p plots are indicated by the red and blue shaded area, respectively. The distributions are shown for various event triggers in pp collisions at $\sqrt{s} = 13$ TeV in different p_{T} intervals.

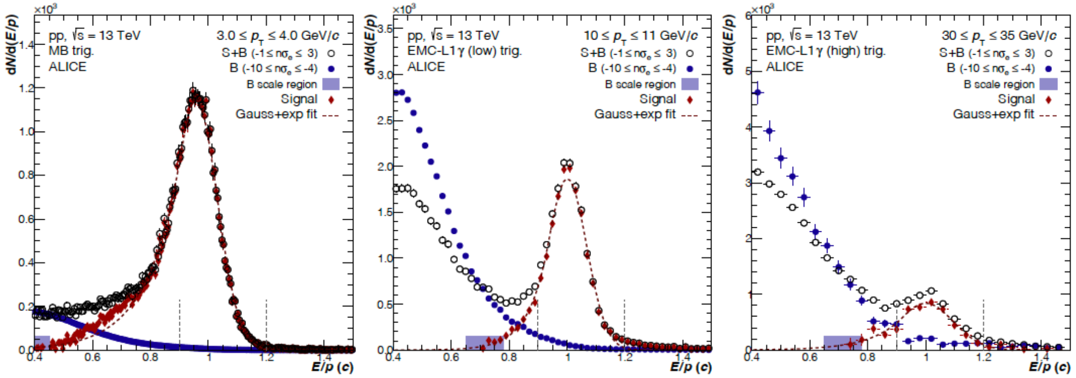

Figure 91: (Color online) E/p distribution for electron candidates selected by applying $-1 \leq n\sigma_{e^{\pm}}^{\mathrm{TPC}} \leq 3$ (black open circles), and for hadrons with $-10 \leq n\sigma_{e^{\pm}}^{\mathrm{TPC}} \leq -4$ (blue dots) scaled to

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ALICE Calorimeters – physics performance

- Identify electrons
- And the data samples with the EMCal photon/electron trigger can also be used to enrich the sample of events containing heavy flavor (charm and beauty) hadrons

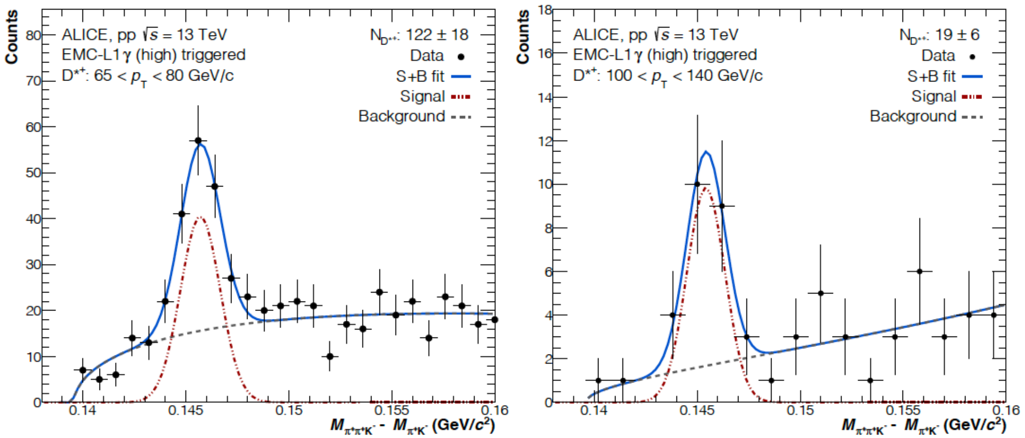

Figure 94: (Color online) Invariant mass distribution of D^{*+} candidates in pp collisions at $\sqrt{s}$ = 13 TeV for $65 < p_T < 80$ GeV/c (left) and $100 < p_T < 140$ GeV/c (right) using the

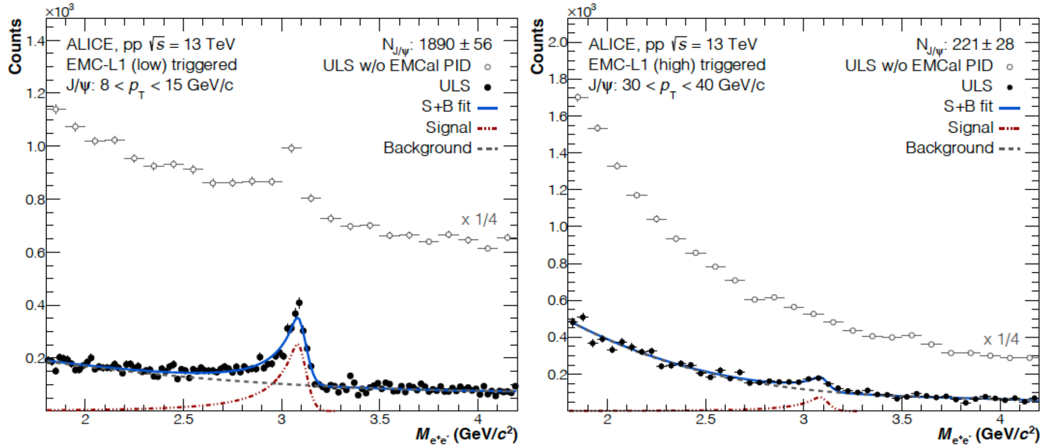

Figure 95: (Color online) Invariant mass distribution of J/ψ candidates in pp collisions at $\sqrt{s}$ = 13 TeV for $8 < p_T < 15$ GeV/c (left) and $30 < p_T < 40$ GeV/c (right). The gray open markers depict the distribution for e^+e^- pairs where at least one track could be matched to an EMCal cluster. It is scaled by 1/2 and 1/4, respectively, for the different p_T intervals, to

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ALICE Calorimeters – physics performance

- And jet reconstruction

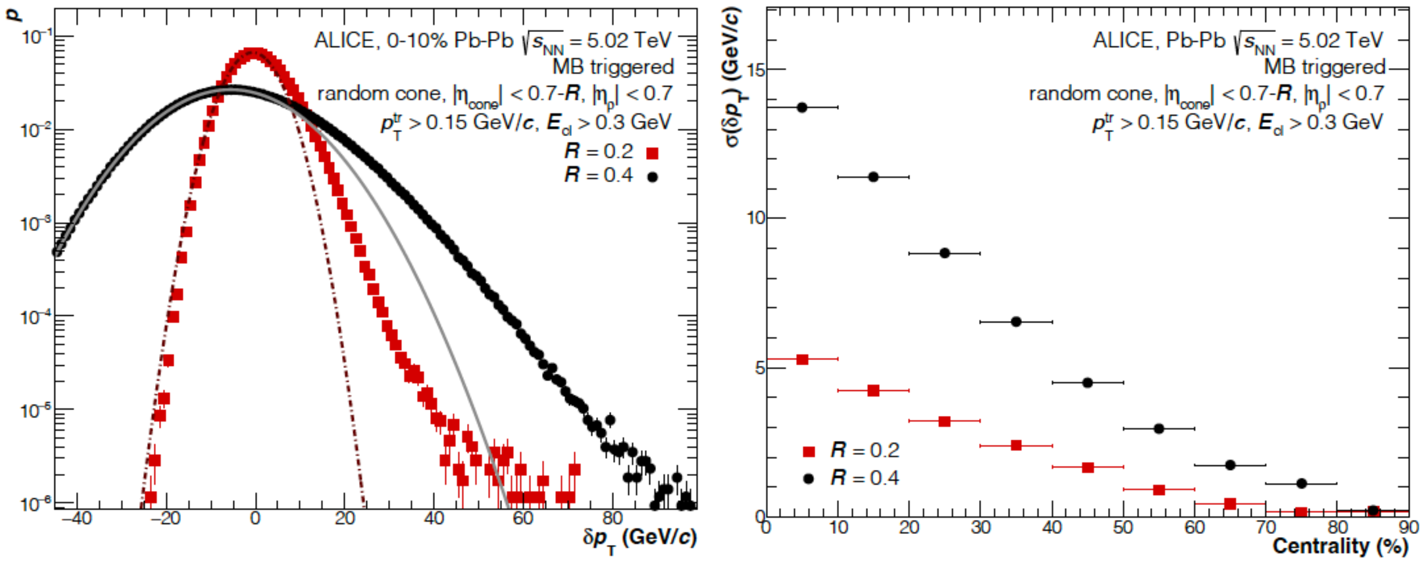

Figure 102: (Color online) Left: Probability distribution of the δp_T distribution for random cones with radii of $R = 0.2$ and $R = 0.4$ excluding the 2 leading jets in the EMCal for the 10% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. On top of the distributions, the corresponding Gaussian fits for $\delta p_T < 0$ are displayed as dashed and dotted lines. Right: Comparison of the Gaussian width of the δp_T distribution as a function of centrality for $R = 0.2$ and $R = 0.4$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

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ALICE Calorimeters – FoCal upgrade

Upgrade projects

2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
LHC Run 2		LHC LS2			LHC Run 3				LHC LS3			LHC Run 4				LHC LS4		LHC Run 5

FoCal

- Preparations for test beams with full prototypes
- Work towards TDR

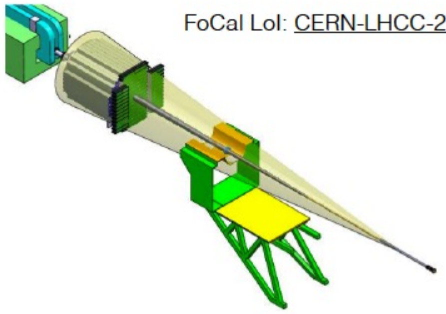
ITS3

- MLR1 sensor characterisation
- Engineering models
- Preparation of ER1

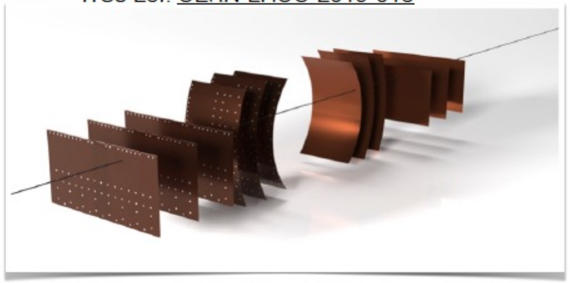
ALICE 3

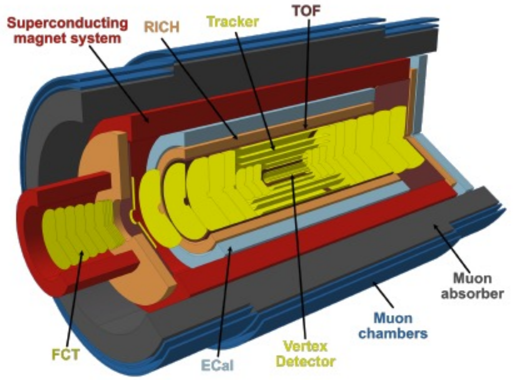
- LHCC review concluded
- Additional physics studies
- **R&D programme**

FoCal LoI: CERN-LHCC-2020-009



ITS3 LoI: CERN-LHCC-2019-018

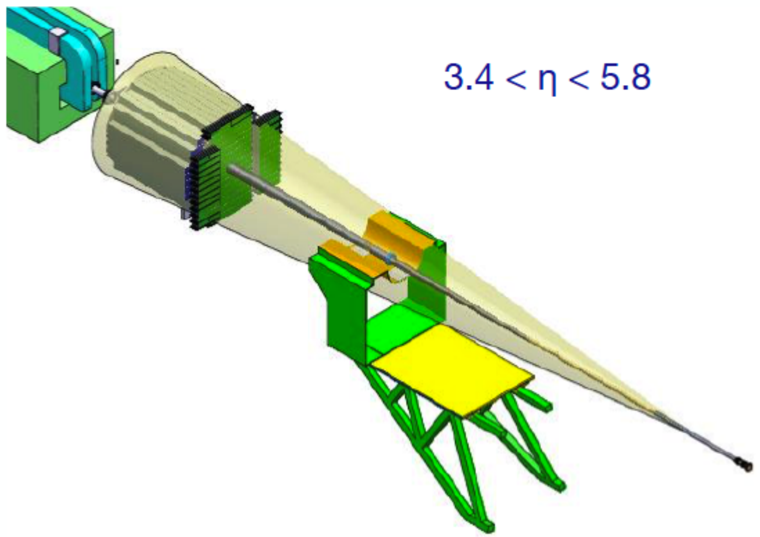




ALICE 3 LoI: CERN-LHCC-2022-009

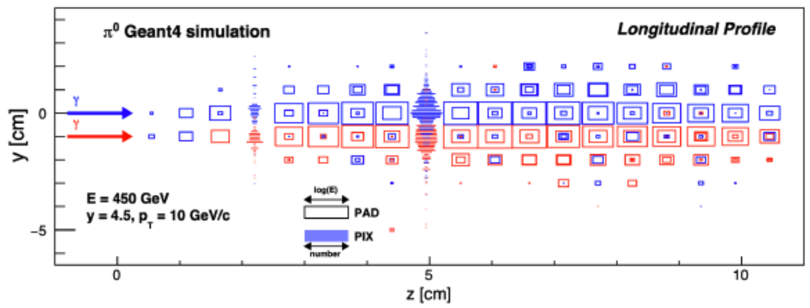
In addition:
Studies on Fixed Target programme at IP2

ALICE Calorimeters – FoCal upgrade

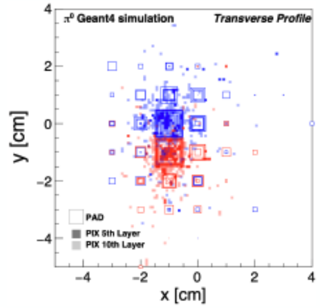


EMCal: Si-W for photon detection
HCal: Cu-scintillator: direct photon isolation and jets

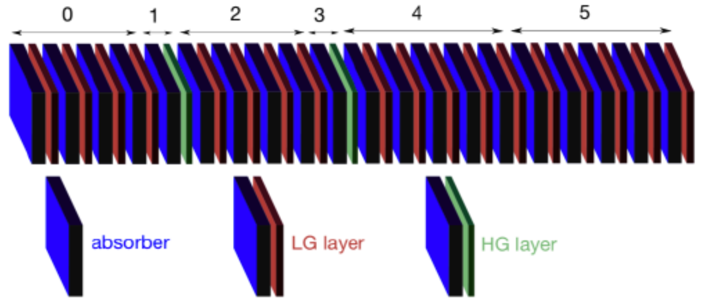
Longitudinal profile (2γ showers)



Trans. profile



Longitudinal segmentation

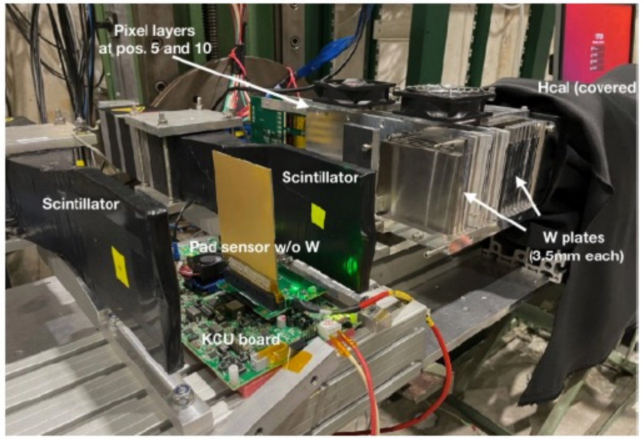


Letter-of-Intent: CERN-LHCC-2020-009

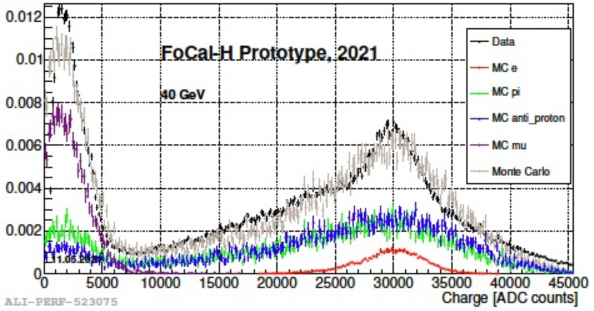
- Goals: direct photon detection to probe gluon density at small x, forward π^0 in pp, pPb, PbPb
- Current focus: prototype development and beam tests

ALICE Calorimeters – FoCal upgrade

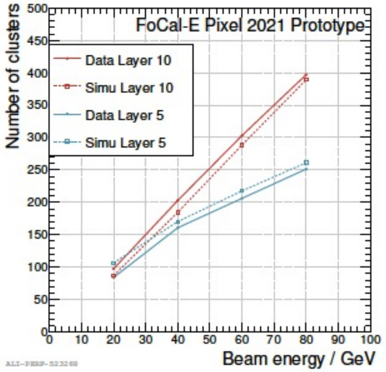
FoCal: 2021 test beam results



HCAL: beam composition

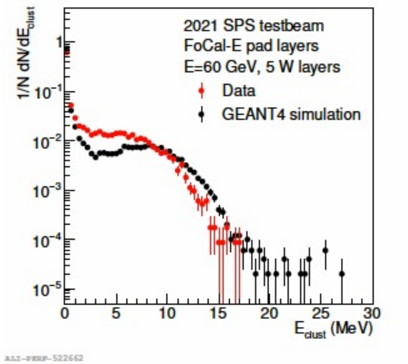


Pixel layers: # clusters vs energy

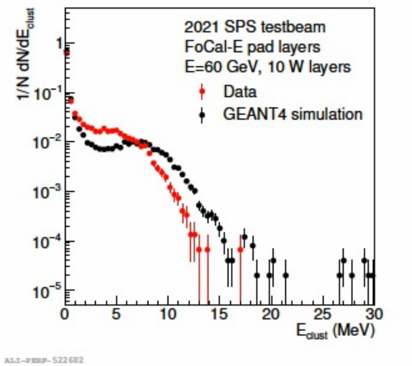


- 2021 setup:
  - 1 pad layer
  - 2 pixel layers
  - HCAL: short module, commercial readout (limited dynamic range)

Pad response (5 W layers)



Pad response (10 W layers)



Important commissioning steps for new systems: several **improvements implemented for 2022 test beam**

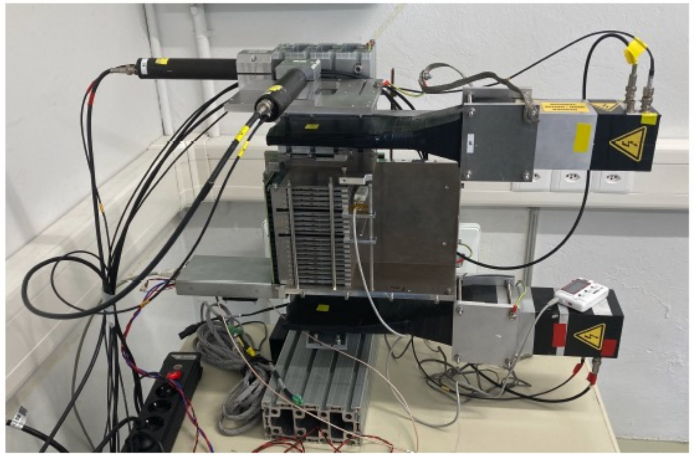
ALICE Calorimeters – FoCal upgrade

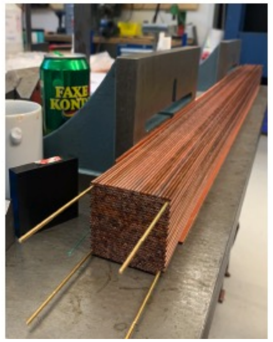
FoCal: full module prototype test

- 3 test beam sessions planned for 2022
  - PS (start this week): test full pad setup + new HCAL
    - Pads: improved grounding - read out multiple layers
    - HCAL: longer modules, new CAEN (VMM) readout
  - SPS (Sept+Nov): test full prototype
    - Pixel layer repairs ongoing
    - HGCROC/VMM readout for HCAL — if available

Further schedule:
2023: TDR
2023/2024: final design for production
2024-2027: production and calibration in beam
2027: installation

Pad layer prototype for test beam





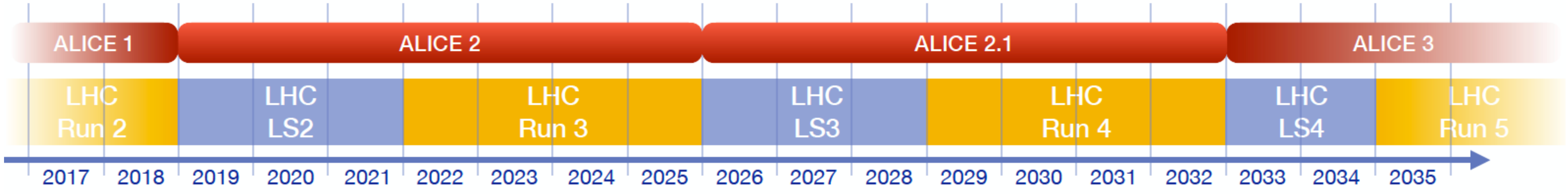
New (longer) HCAL prototype module

ALICE Calorimeters – Future plan

ALICE 3 time line

- **2023-25**: selection of technologies, small-scale proof of concept prototypes
- **2026-27**: large-scale engineered prototypes
  → Technical Design Reports
- **2028-31**: construction and testing
- **2032**: contingency
- **2033-34**: Preparation of cavern, installation

Next steps:
- R&D and proof of concept for all systems
- Prepare funding and resource plan (including construction phase)



ALICE Calorimeters – Future plan

- Calorimeters for ALICE 3, Run 5 and beyond (2035-)

- **Large acceptance sampling calorimeter**
  O(100) layers (1 mm Pb + 1.5 mm plastic scintillator)

- **High energy resolution segment** at mid-rapidity
  → reuse of $PbWO_4$ crystals

R&D challenges

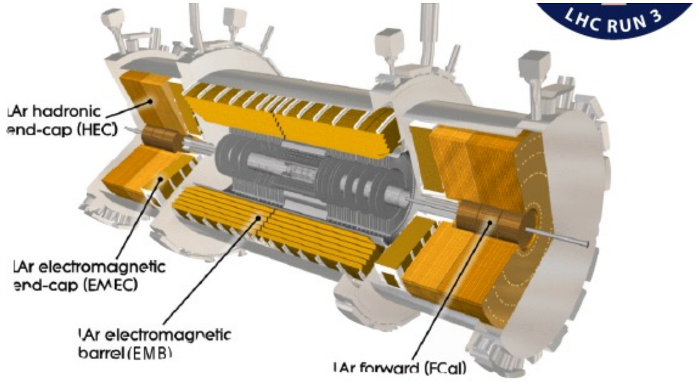
- **Optimisation of sampling stack** (geometry, no. of layers, sampling ratio, ...) in view of
  - performance
  - ease of manufacturing
- **Performance of sampling calorimeter**
  - impact of shower overlaps
  - performance outside magnet
- **Readout design** (large dynamic range)
  - Simulation of event sizes → data aggregation, readout segments
- **Mechanical concept** (support, stability, ...)
- **Physics performance** (jet and γ-jet performance, electron ID with ECAL, direct photons)

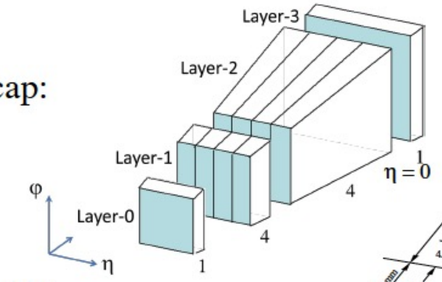
ALICE 3 open forum | Sep 22, 2022 | MvL, jkl

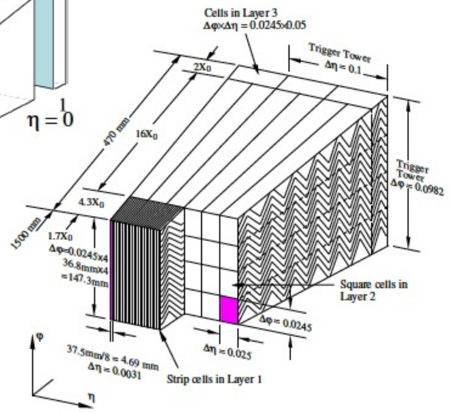
ECal module	Barrel sampling	Endcap sampling	Barrel high-precision
acceptance	$\Delta\varphi = 2\pi$, $\lvert\eta\rvert < 1.5$	$\Delta\varphi = 2\pi$, $1.5 < \eta < 4$	$\Delta\varphi = 2\pi$, $\lvert\eta\rvert < 0.33$
geometry	$R_{in} = 1.15$ m, $\lvert z\rvert < 2.7$ m	$0.16 < R < 1.8$ m, $z = 4.35$ m	$R_{in} = 1.15$ m, $\lvert z\rvert < 0.64$ m
technology	sampling Pb + scint.	sampling Pb + scint.	$PbWO_4$ crystals
cell size	30×30 mm^2	40×40 mm^2	22×22 mm^2
no. of channels	30 000	6 000	20 000
energy range	$0.1 < E < 100$ GeV	$0.1 < E < 250$ GeV	$0.01 < E < 100$ GeV

ATLAS Calorimeters – LAr module design

- Liquid argon calorimeter
  - Sampling calorimeter:
    - Absorber material: lead, copper and tungsten.
    - Active material: liquid Argon (LAr).
  - Four major components:
    - Electromagnetic calorimeter in the barrel (**EMB**) and endcap (**EMEC**), hadronic endcap calorimeter (**HEC**) and forward calorimeter (**FCAL**).
    - Separated by A ($\eta > 0$) and C side ($\eta < 0$).
  - LAr detector comprises four layers in the barrel and most of the endcap:
    - **Presampler**: measure energy loss before the calorimeter.
    - **Front layer**: fine segmentation, used to distinguish π^0 from γ.
    - **Middle layer**: deepest layer, most of the EM shower deposits energy here
    - **Back layer**: catch the tail of EM shower.

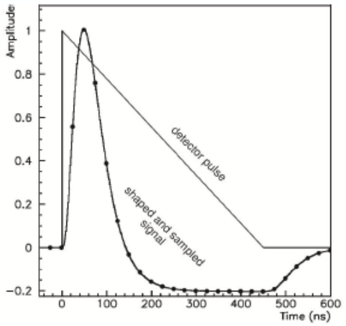






ATLAS Calorimeters – LAr module design

- Liquid argon calorimeter
  - Front-end boards (FEBs):
    - 1524 FEBs, with 128 channels on each FEB.
    - Split into 3 gains scales (low/medium/high) and shapes.
    - The triangular pulse shaped and digitised at 40MHz and stored in a buffer.



  - Signal Level-1 calorimeter (L1Calo) trigger:
    - Receives analog signal build by tower builder boards (TBBs) and send L1 accept (L1A) back to FEB.
    - FEB select the proper gain, digitise the signal and transmit to read out drivers (RODs), and further to ATLAS DAQ system.

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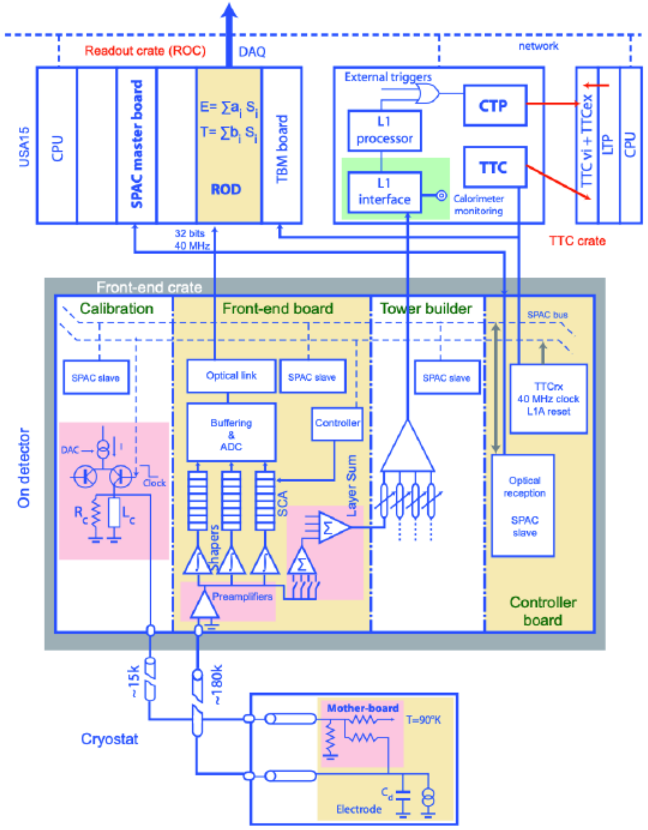


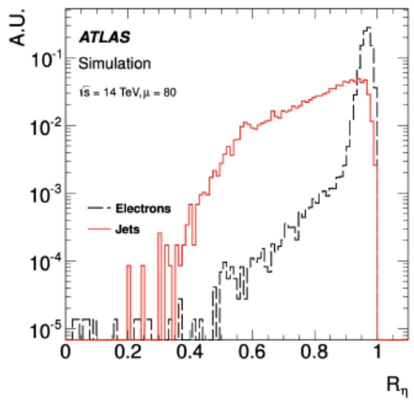
ATLAS Calorimeters – LAr Phase-I upgrade

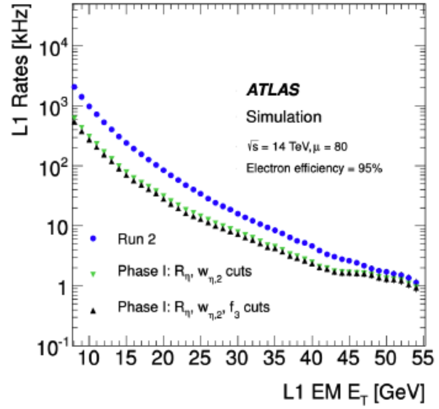
- Liquid argon calorimeter

  - First thing first: Run 2 operation was a huge success…

Year	2015	2016	2017	2018
ATLAS data efficiency	87.1%	93.0%	93.6%	95.7%
LAr data efficiency	99.4%	99.8%	99.5%	99.5%

  - However, in LHC Run 3:
    - Instantaneous luminosity and pile-up will increase, but the sustainable ATLAS L1 trigger will remain the same as Run 2.
      - 100kHz at maximum, **20kHz for electrons and photons**.
    - Using shower shape variables, such as R_η, $w_{\eta,2}$, f_3.
      - Better distinguish electrons and jets
      - Remains a low E_T thresholds ~28 GeV, 7 GeV lower than Run 2 algorithm.
    - So, how can we retrieve better shower shape information?



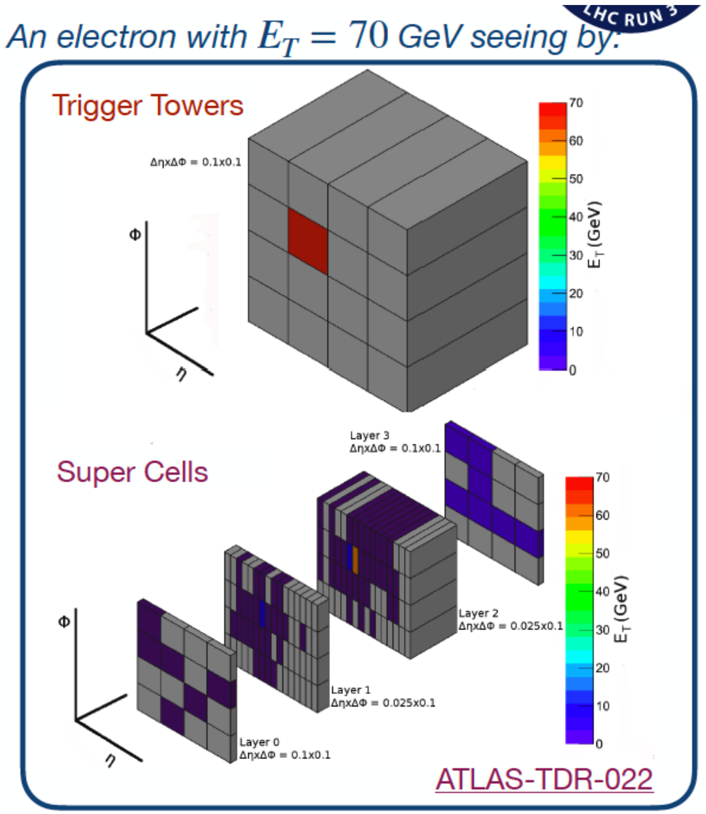


ATLAS-TDR-022

ATLAS Calorimeters – LAr Phase-I upgrade

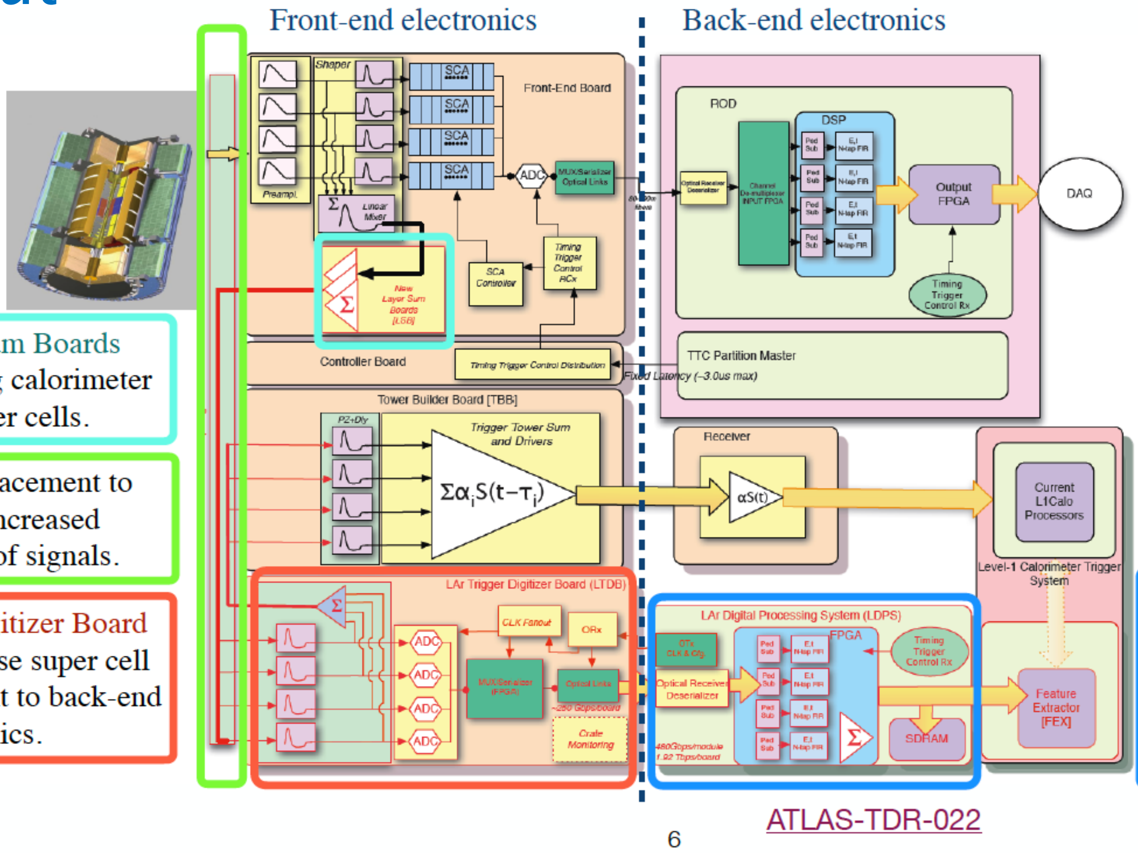
- Super cells
  - In the legacy system, L1Calo trigger decision is based on ~5.4k trigger towers from 180k cells.
    - Transverse energy E_T in all four layers are summed.
      - Losing the shower shape information.
    - Using analog signals, digitised on trigger backend.
  - Super cells (SC) proposed for the Phase-I upgrade
    - Using ~34k SC from 180k cells.
      - Finer granularity for triggering, by a factor of 10.
    - Increased resolution in front and middle layer. E_T in each layer is retained.
      - Access to the longitudinal shower shapes.
    - Move to digitised signals → **LAr digital trigger system**.

An electron with $E_T = 70$ GeV seeing by:



ATLAS Calorimeters – LAr Phase-I upgrade

- Electronics readout



New Layer Sum Boards (LSBs) summing calorimeter cells to super cells.

Baseplane replacement to handle the increased transmission of signals.

LAr Trigger Digitizer Board (LTDB) to digitise super cell signals and send it to back-end electronics.

ATLAS-TDR-022

In case of unforeseen issues, both legacy and digital trigger system will be running concurrently in early Run 3!

LAr Digital Processing Blade (LDPB) to reconstruct transverse energy with LATOME, and send to L1Calo system

ATLAS Calorimeters – LAr Phase-I upgrade

- Electronics readout

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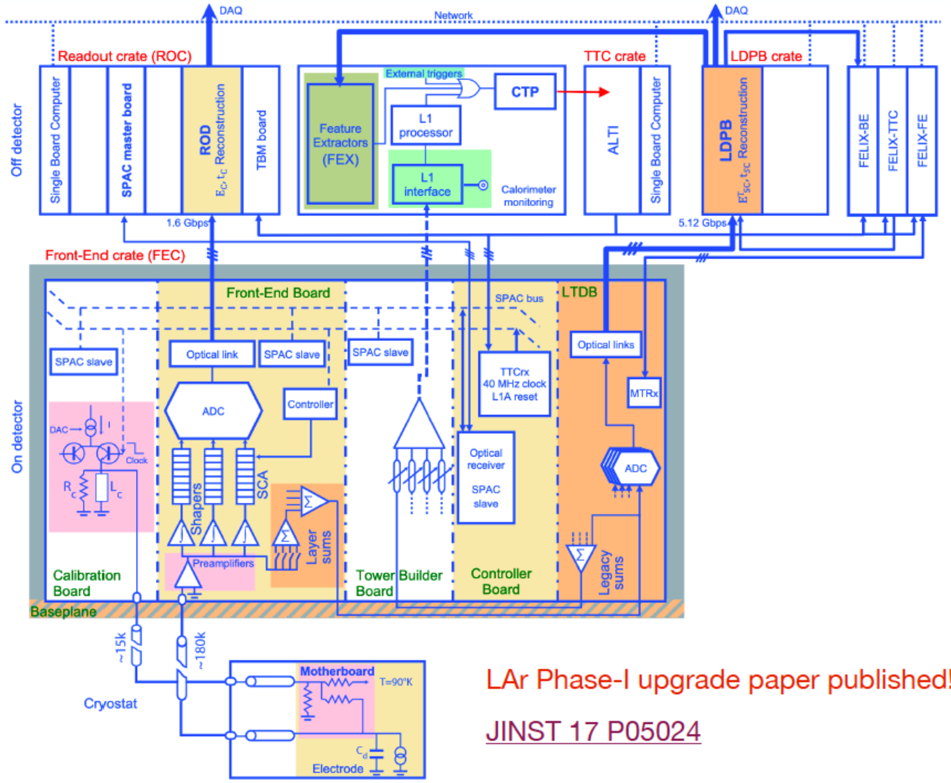


LAr Phase-I upgrade paper published!

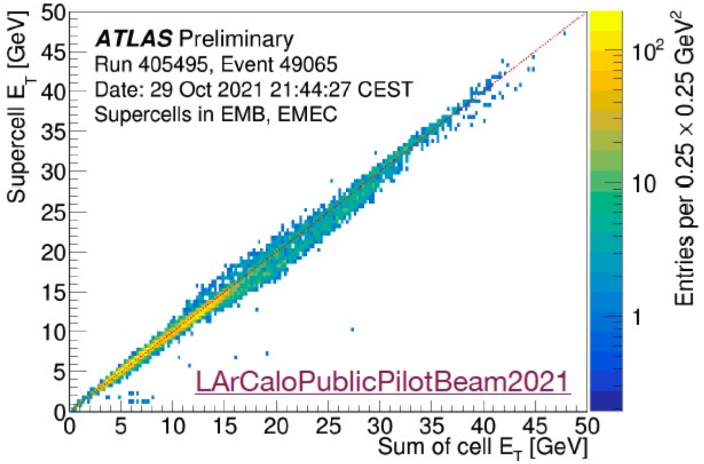
JINST 17 P05024

In case of unforeseen issues, both legacy and digital trigger system will be running concurrently in early Run 3!

LAr Digital Processing Blade (LDPB) to reconstruct transverse energy with LATOME, and send to L1Calo system

ATLAS Calorimeters – LAr Phase-I upgrade

- LHC pilot run fall 2021
  - Fruitful outcome during the LHC pilot run in October, 2021
    - First LHC beam delivered after Run 2, after 3 years of LS2.
    - Used to test system after Phase-I upgrade, for both main readout and digital trigger system.
      - Good agreement between supercell (digital trigger system) and summed cell energy obtained from the main readout.



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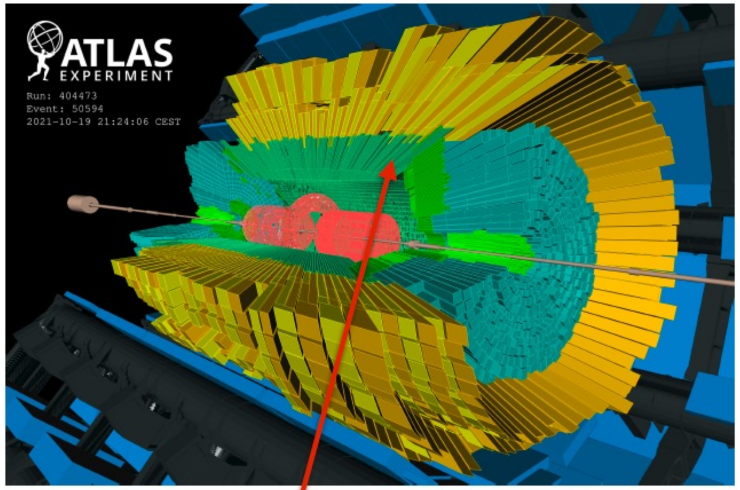
EventDisplayPilotBeam2021

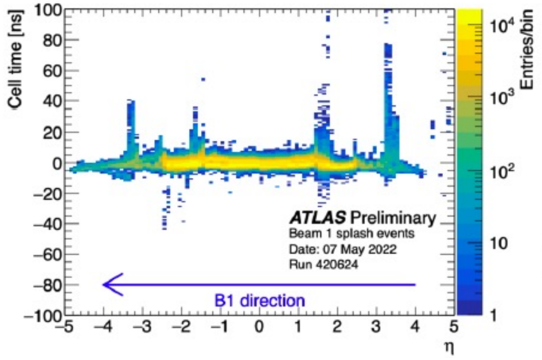


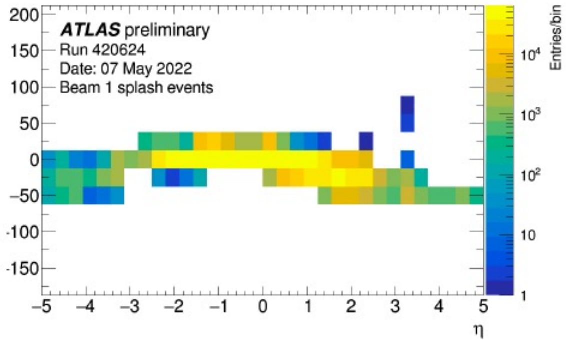
Green boxes show energy deposits in the LAr calorimeter.

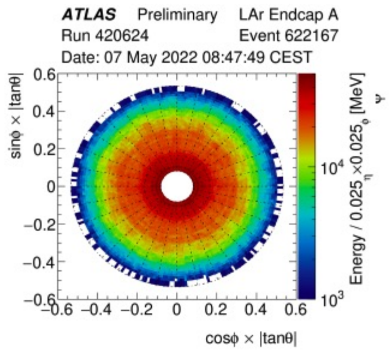
ATLAS Calorimeters – LAr Phase-I upgrade

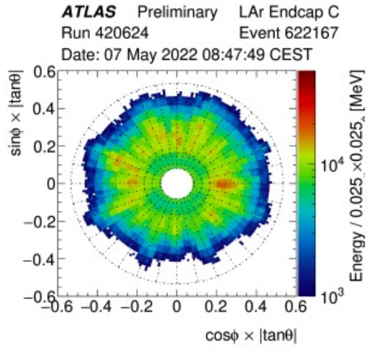
- beam splash

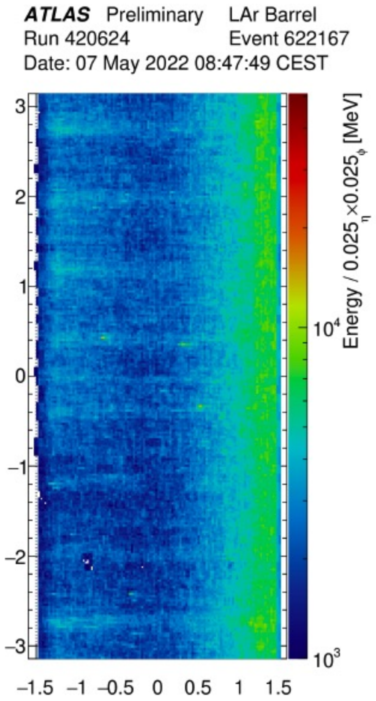
  - Beam splash delivered by LHC during the pilot run in fall 2021 and test run early 2022.
  - Using beam splash to align the timing for the full LAr system.
    - Main readout aligned to ns level.
    - Digital trigger system aligned at BCID level (25ns), will be aligned to ns level in the future.









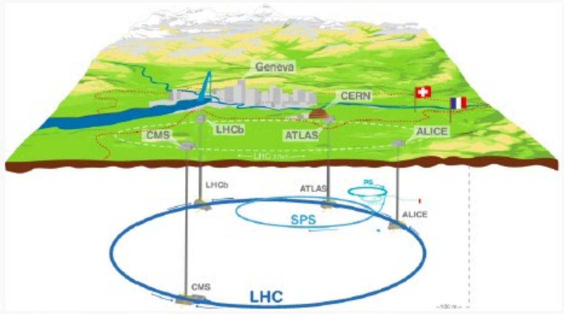


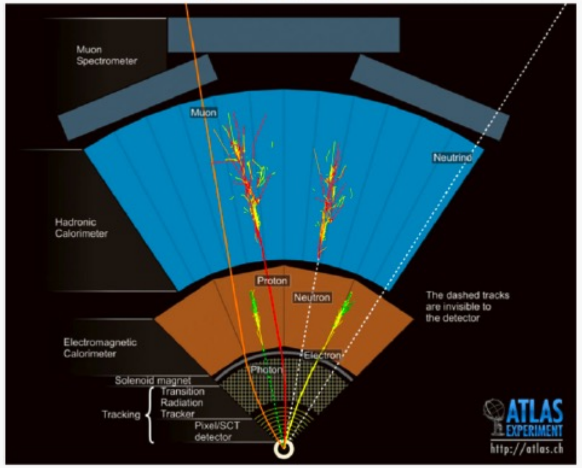
LArCaloPublicBeamSplashMay2022

ATLAS Calorimeters – TileCal module design

- Hadronic Tile Calorimeter

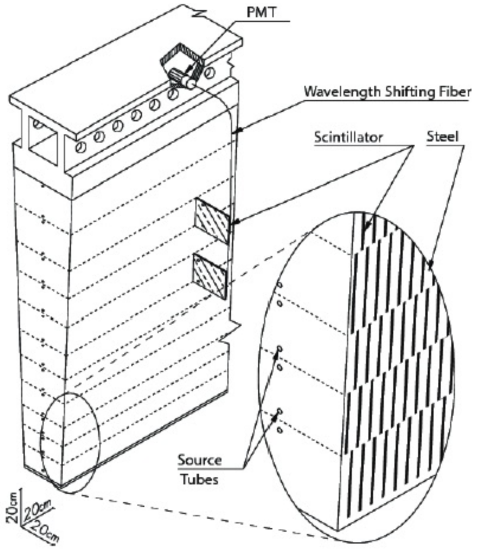
- The Hadronic Tile calorimeter (TileCal) is the outermost calorimeter in the ATLAS detector on the Large Hadron Collider (LHC) at CERN
  - Hadronic sampling calorimeter, covering $|\eta| < 1.7$
  - Important in jet, τ, E_T^{miss} and μ identification and triggering
  - Scintillating tile with steel absorber
  - $\Delta\eta x \Delta\phi = 0.1x0.1$ in two innermost layers
    - $\Delta\eta x \Delta\phi = 0.2x0.1$ in outermost layer
  - Designed with a stand-alone energy resolution for jets of $\frac{\sigma}{E} = \frac{50\%}{\sqrt{E(GeV)}} \oplus 3\%$
  - Technical Design Report : 10.17181/CERN.JRBJ.7O28



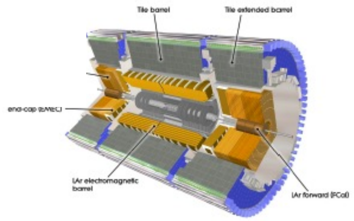


ATLAS Calorimeters – TileCal module design

- Hadronic Tile Calorimeter



- the on-detector electronics is located inside the electronics drawers

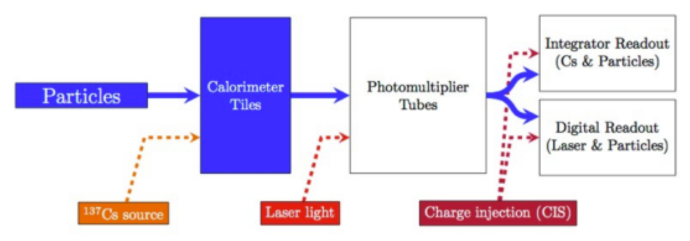


- Central hadronic calorimeter ($|\eta| < 1.7$)
- Sampling calorimeter : plastic scintillators and steel absorbers
- 5182 cells (9836 PMTs) : double photomultiplier readout using wave length shifting fibres
- Readout granularity (η, φ) : 0.1×0.1 (in the outer layer 0.2×0.1)
- Energy resolution $\sigma/E \sim 50\%/E \oplus 3\%$
- Critical sub-detector for most physics signatures
  - jets and missing p_T
  - electrons and photons

ATLAS Calorimeters – TileCal calibration

- Hadronic Tile Calorimeter

  - Cesium (Special runs)
    - Cs_{137} source is hydraulically moved throughout detector, calibrates entire readout chain ($\sim$ 0.3% precision)
  - Laser (daily)
    - Measures response of PMTs w.r.t. last Cs scan ($\sim$ 0.5% precision)
    - Taken during LHC collision empty bunches and individual calibration runs
  - Charge Injection (daily)
    - Measures response of digitizers and readout electronics via a range of controlled charges ($\sim$ 0.7% precision)



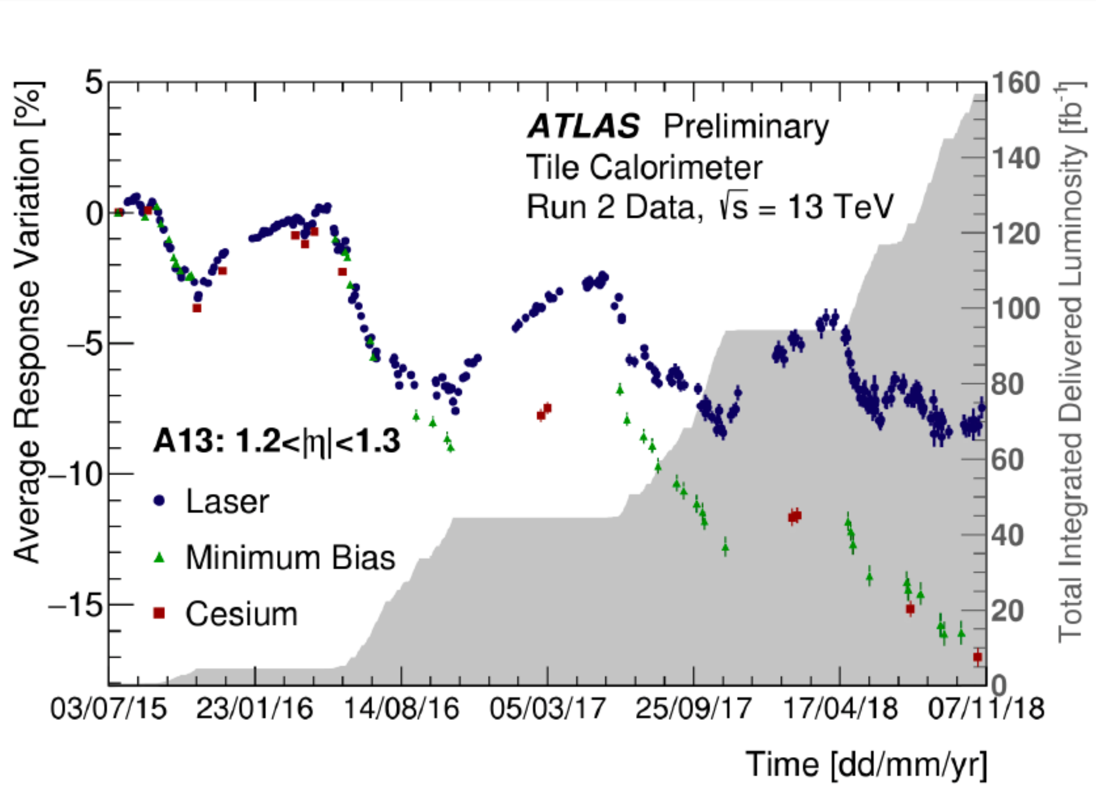
  - Minimum Bias
    - Integrates signal over $\sim 10-20$ ms during physics data taking
    - Provides corrections in absence of Cs calibration
  - Energy reconstructed at the EM scale

$$E = \frac{A[ADC\ Counts]}{C_{Cs} \cdot C_{Las} \cdot C_{CIS}[ADCcounts/pC] \cdot C_{TB}[pC/GeV]}$$

C_{TB} determined at dedicated test beams

ATLAS Calorimeters – TileCal calibration

- Hadronic Tile Calorimeter

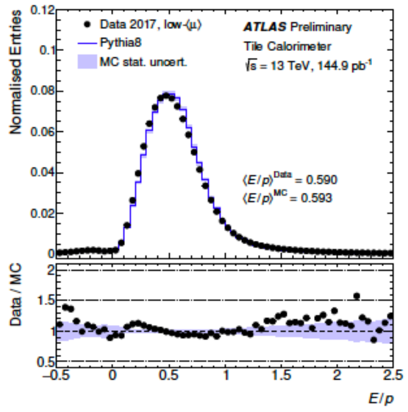


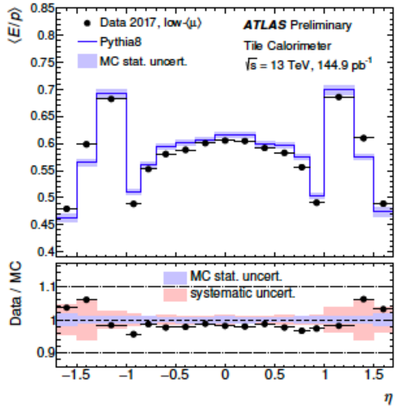
- Laser system probes PMT response
  - Down-drift during collisions
  - Recovery seen during beam-off periods
- Cs and Minimum Bias both measure the drift in PMTs, optical fibers, and scintillators
- Difference between Laser and Cs (or Laser and Minimum Bias) is due to degradation of tiles and WLS fibers

ATLAS Calorimeters – TileCal performance

- Hadronic Tile Calorimeter

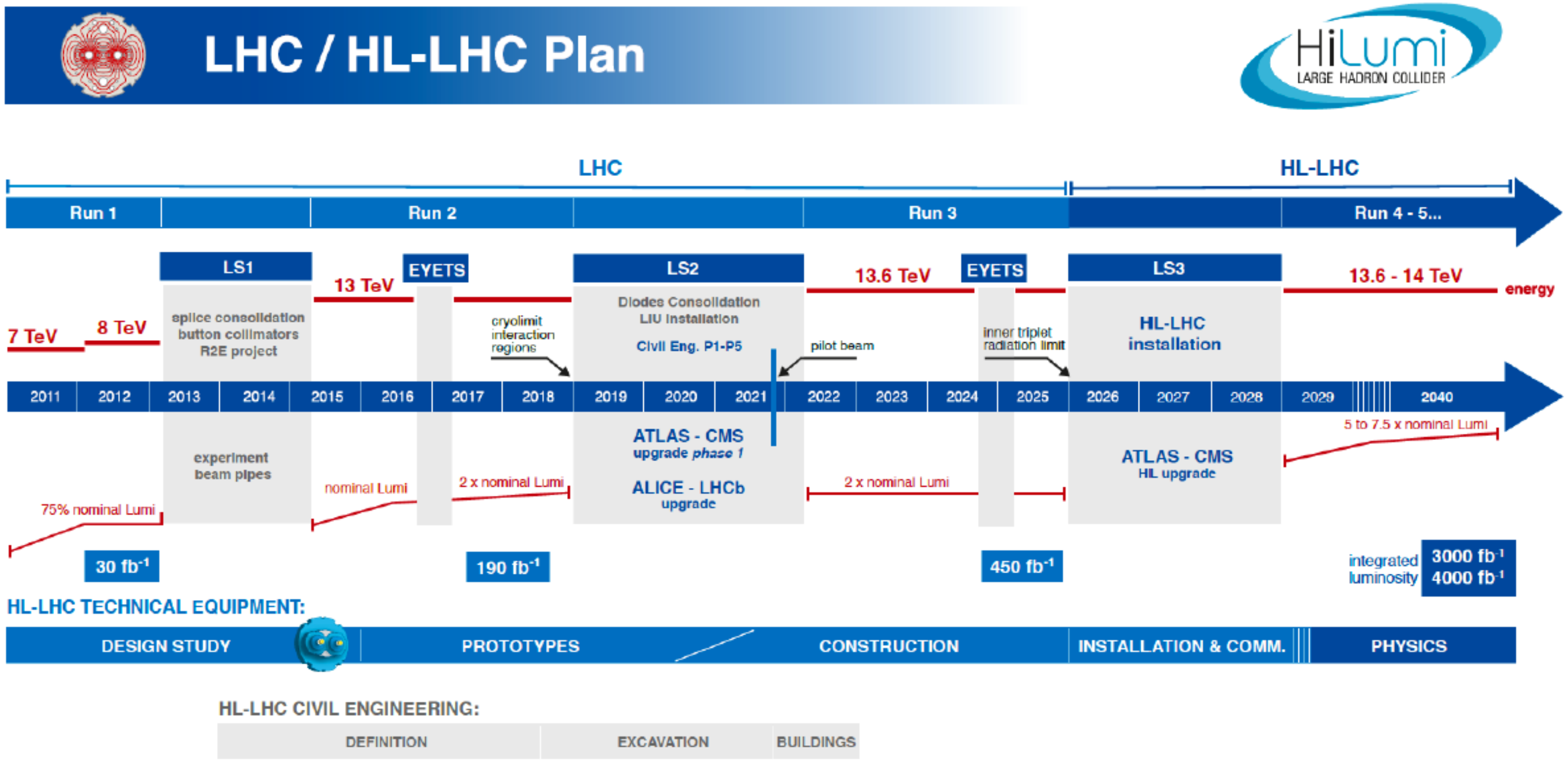
- Clusters in the calorimeter with associated tracks are used
  - Tracks in the Inner Detector measure momentum
  - Cluster energy is measured in TileCal
- Ratio of calorimeter energy and track momentum (E/p)
  - TileCal is a non-compensating, so $E/p < 1$
- Performed in three pileup bins
  - $< \mu \approx 0 >$, $< \mu \approx 2 >$, $< \mu \approx 10 - 20 >$
- Results
  - Good Data/MC agreement in all bins
  - In highest pileup bin, $\sim 3\%$ differences due to pileup mismodelling





ATLAS Calorimeters – TileCal upgrade schedule

- Hadronic Tile Calorimeter

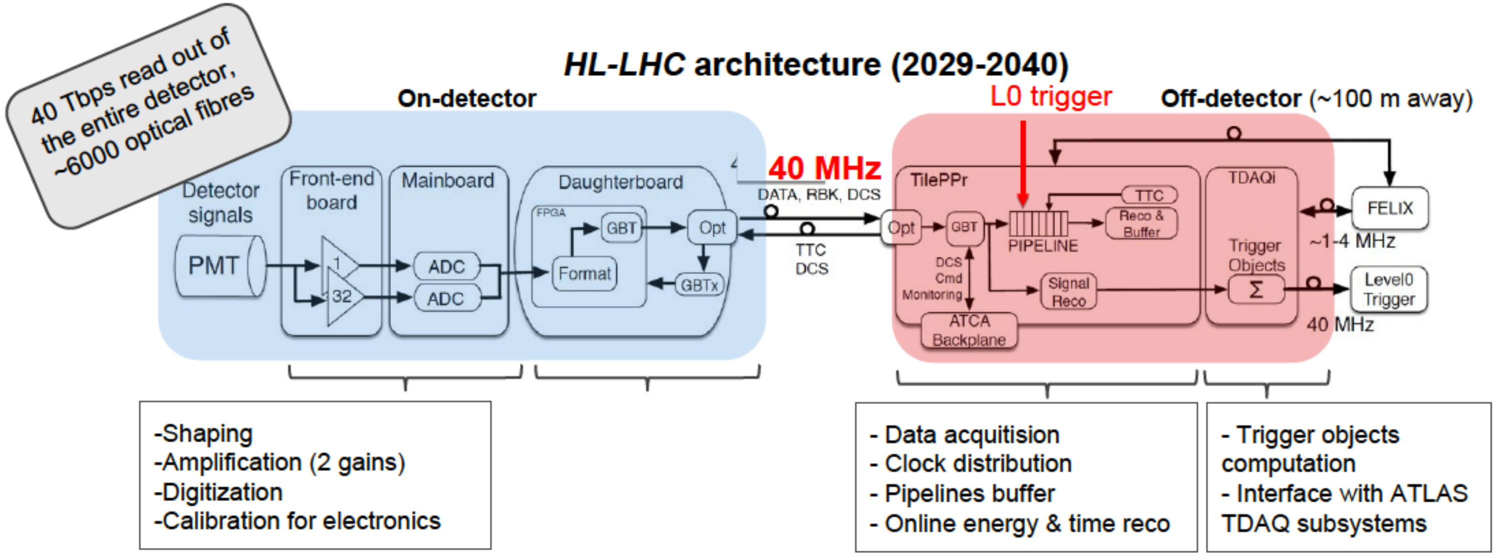


ATLAS Calorimeters – TileCal upgrade motivation

- At HL-LHC, the instantaneous luminosity will increase by a factor $\sim$ 7, leading to around 200 simultaneous proton-proton collisions per bunch crossing
- Increased particle flux through TileCal (2 to 24 Gy for 4 ab^{-1} integrated luminosity)
- Readout electronics is ageing due to operation time and to radiation.
- Current readout architecture is not compatible with the new fully digital TDAQ system of ATLAS and with the timing requirements for trigger and data flow.
- Detector components (steel absorbers, scintillating tiles, fibres and almost all the PMTs) will not be replaced, but detector optics performance has to match the physics requirements.

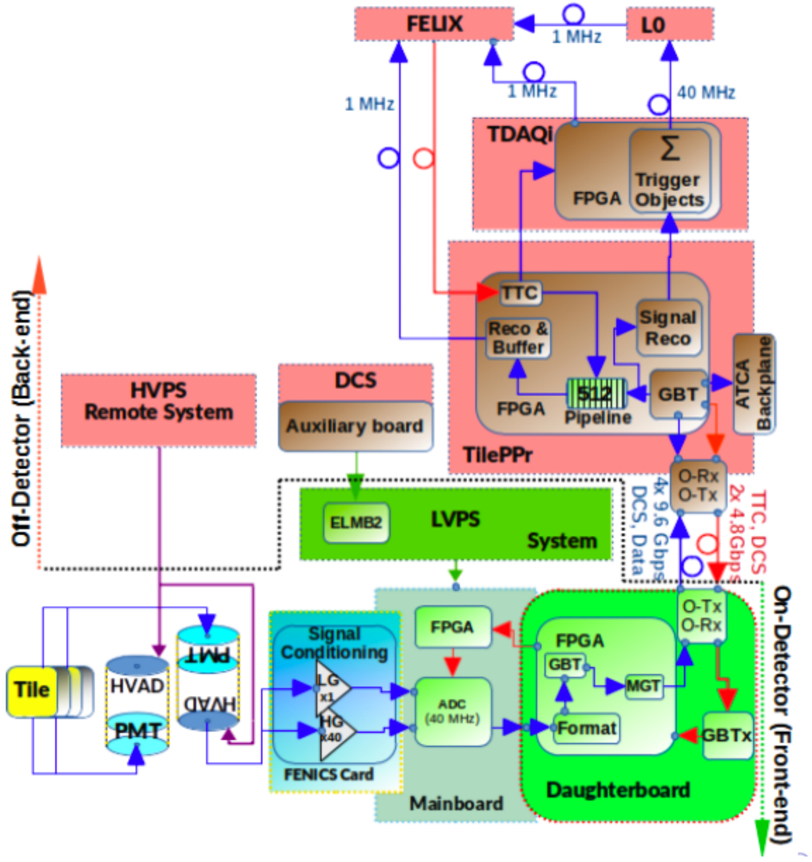
ATLAS Calorimeters – TileCal upgrade items

- High Luminosity LHC, starting around 2029, will achieve an instantaneous luminosity 5-7 larger than the LHC nominal value.
- This requires an upgrade of the ATLAS detector (Phase-II upgrade), which is in progress.
- Upgrade of the Tile Calorimeter:
  - Active dividers for all PMTs and replacement of the 10% most exposed PMTs.
  - Complete replacement of on-detector and off-detector electronics.
  - New digital ATLAS trigger system up to 40 (1) MHz read-out (accept) rate.
  - Increased detector read-out bandwidth – 40 Tbps for the entire TileCal.
  - Improved LV and HV system.



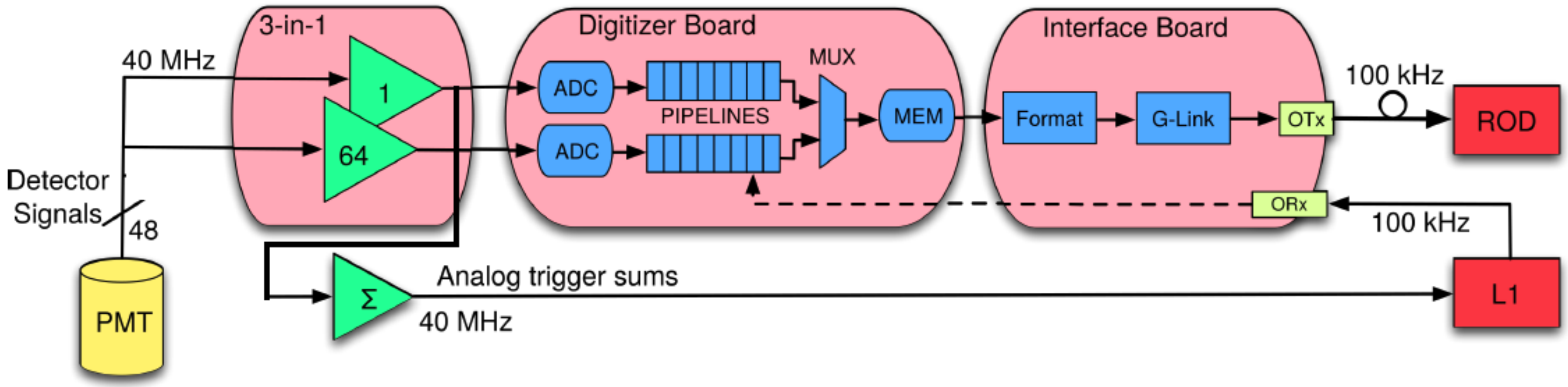
ATLAS Calorimeters – TileCal upgrade strategy

- use electronics parts tolerant to the expected radiation level
- Improve reliability through redundancy $\Rightarrow$ reduces impact of component failures
- readout electronics architecture must sustain the higher trigger rate ($\sim$1 MHz) and allow for larger event buffer ($> 10\mu$s) $\Rightarrow$ move buffers and pipelines off detector and read out at the LHC crossings rate 40 MHz
- Replace PMTs that are reading-out the most exposed detector cells (high response losses)

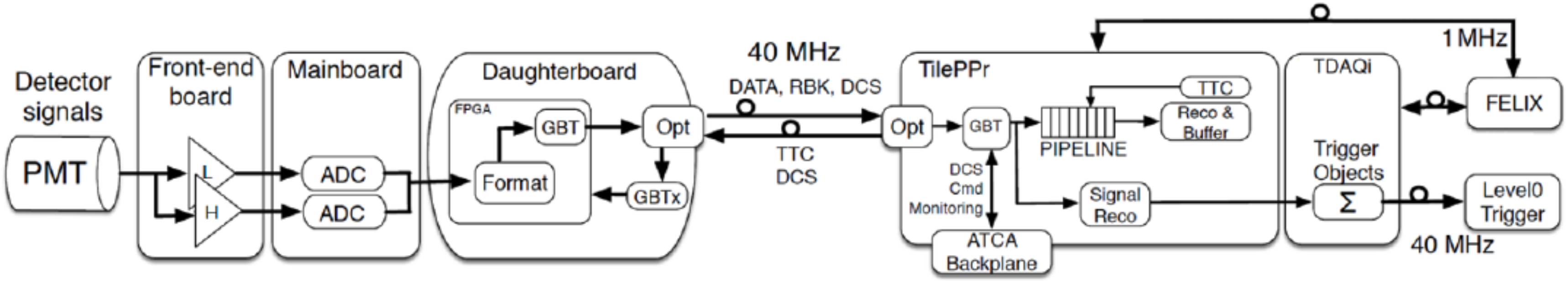


ATLAS Calorimeters – TileCal upgrade readout

Current read-out

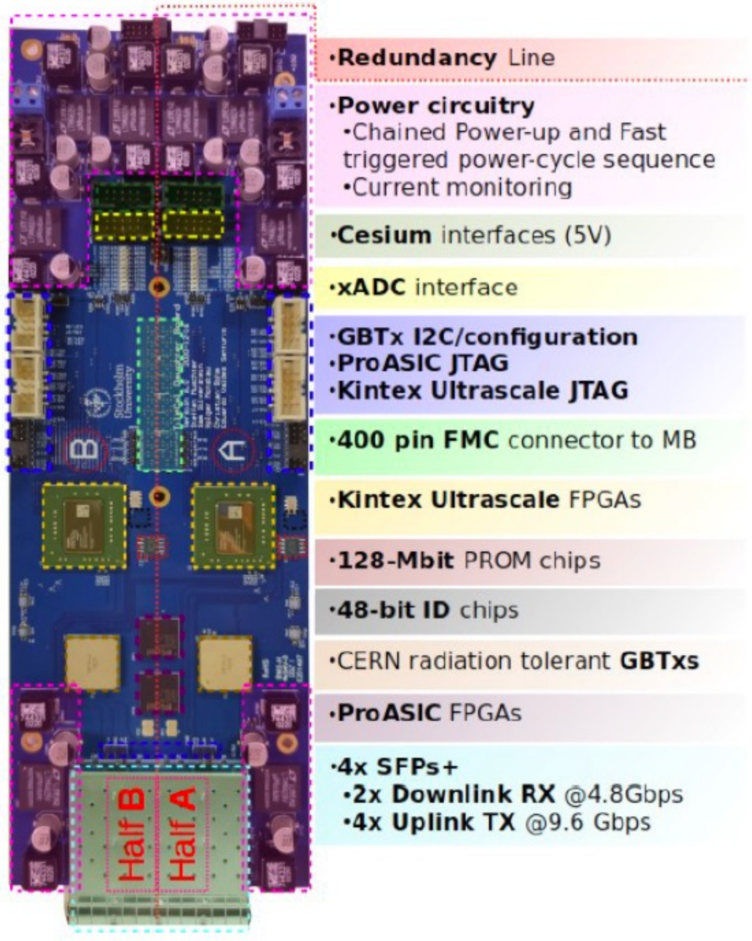


HL-LHC read-out



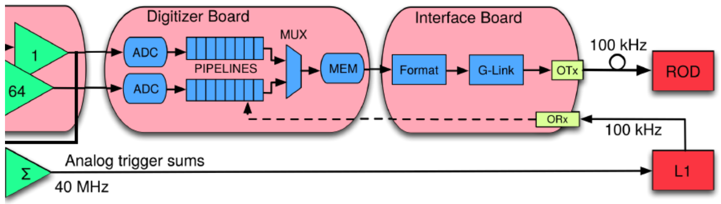
ATLAS Calorimeters – TileCal upgrade readout

- High-speed interface with the off-detector electronics: **Daughterboard**
- Collects PMT digitized data from Mainboards
- Data transmission to off-detector electronics
- Clock and command distribution to FENICS
- Implements data link redundancy
- DaughterBoard specs:
  - 2 × GBTx chips for LHC clock recovery and distribution
  - 2 Kintex Ultrascale FPGAs for communication and data processing (SEL tolerance)
  - Each side serving 6 PMTs (12 in total)
  - 2 × QSFP high-speed optical modules

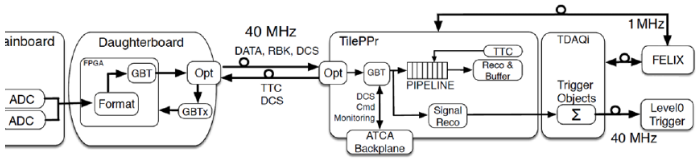


DaughterBoard

Current read-out

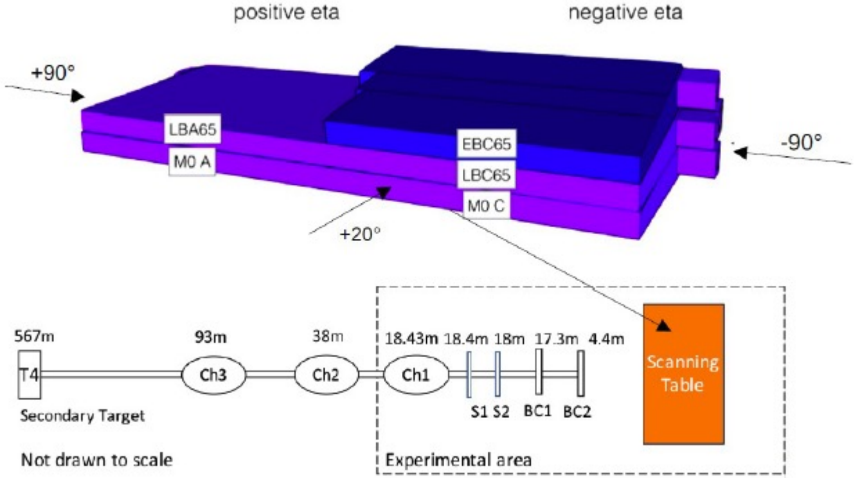


HL-LHC read-out



ATLAS Calorimeters – TileCal upgrade testbeam

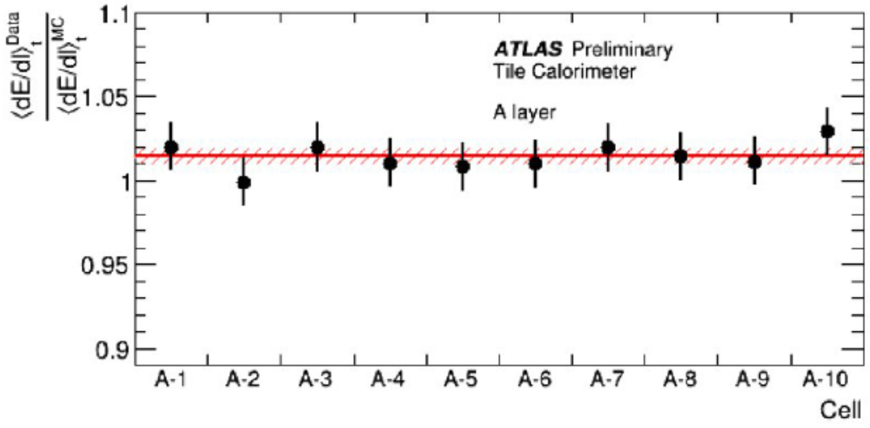
- 8 **Testbeams** at CERN SPS between 2015-2018 and 2021-2022 to validate the hardware with beam data and perform physics studies.
- 3 modules from the calorimeter (two Long-Barrel and one Extended-Barrel)
- The read-out uses different upgraded front-end electronics proposed for the ATLAS Phase-II upgrade.
- A half-module equipped with a prototype of the new Phase-II upgrade electronics.
- Exposed to electron, muon and hadron beams at various energy ranges.
- Hadron beams of 16-290 GeV energy.

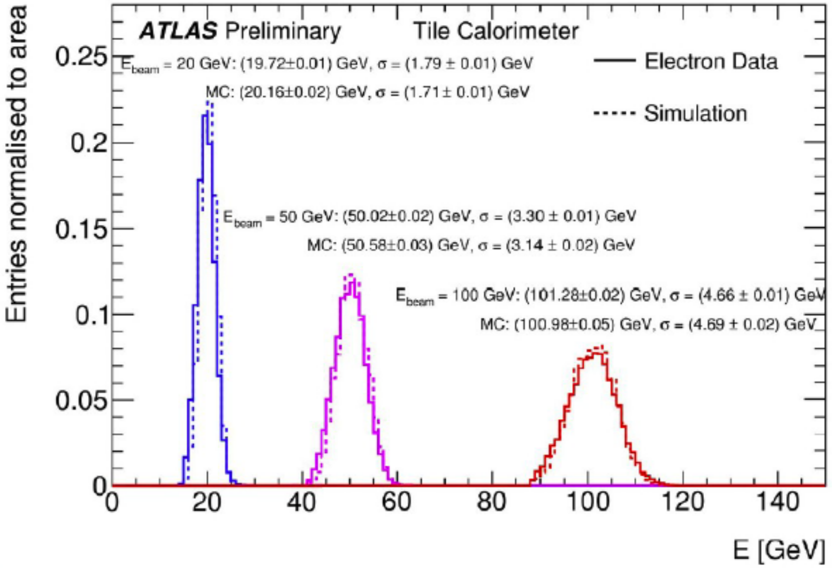


ATLAS Calorimeters – TileCal upgrade testbeam

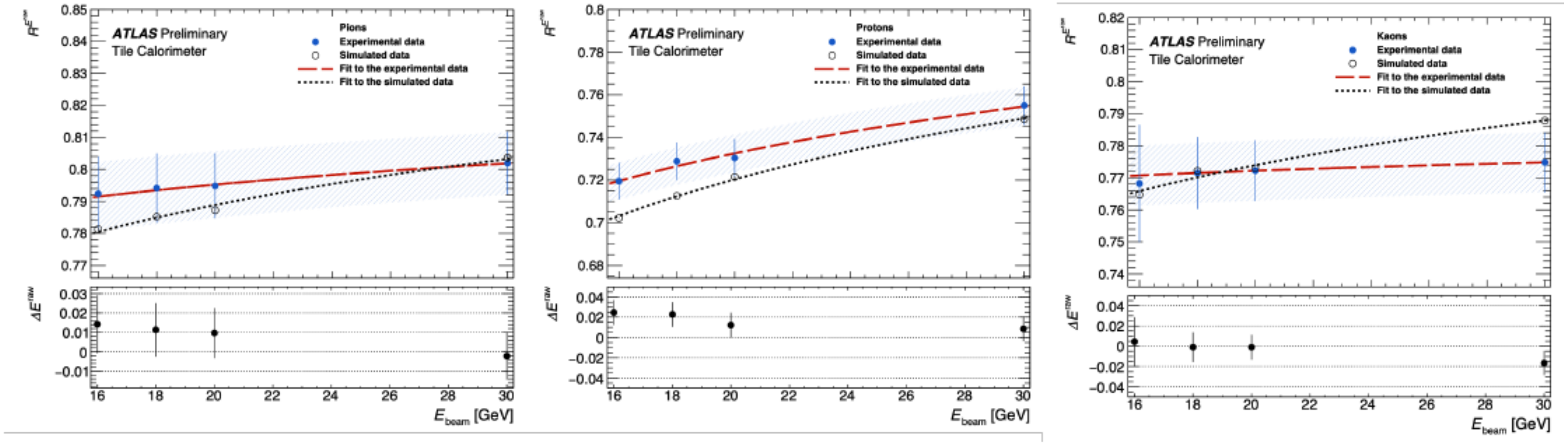
- **Muons** of 160 GeV traverse the entire TileCal modules with an angle of 90º.
- Energy loss is ~proportional to the muon track path length in the calorimeter → Checking the equalization of the cell response.
- Layer uniformity within 1%.
- Max offset of 1.4% for Data/Simulation.

- **Electrons** to determine the EM scale by calculating the average charge-to-energy conversion factor, (pC/GeV) using electrons of different energies.
- Verify the linearity of the response vs. energy and to test the uniformity and energy resolution.





ATLAS Calorimeters – TileCal upgrade testbeam



- Kaon content is smaller in the beam - dominated by statistical errors
- Protons have high statistics - low systematic and statistical uncertainties
- More results in the last year publication : EPJ C81 (2021) 549

Summary

- Calorimeters at the ALICE and ATLAS experiments performed well throughout Run 1 and Run 2
  - Detailed operation and performance paper for Run 2 coming out
- Great physics output from all calorimeters: photon, hadron, charm/bottom, jet...
- Ready for Run 3: Many maintenance items taken care of over the long shutdown of last few years
- Exciting upgrades on the way: Run 3, Run 4, and beyond (2035–)