ATLAS LAr Calorimeter Performance in LHC Run 2

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INSTR20

NEVIS LABORATORIES
COLUMBIA UNIVERSITY

ATLAS EXPERIMENT

Outline

- Detector Overview

- Data Quality

- Run 2 Studies:

  ‣ Purity Stability

  ‣ Pulse Shapes

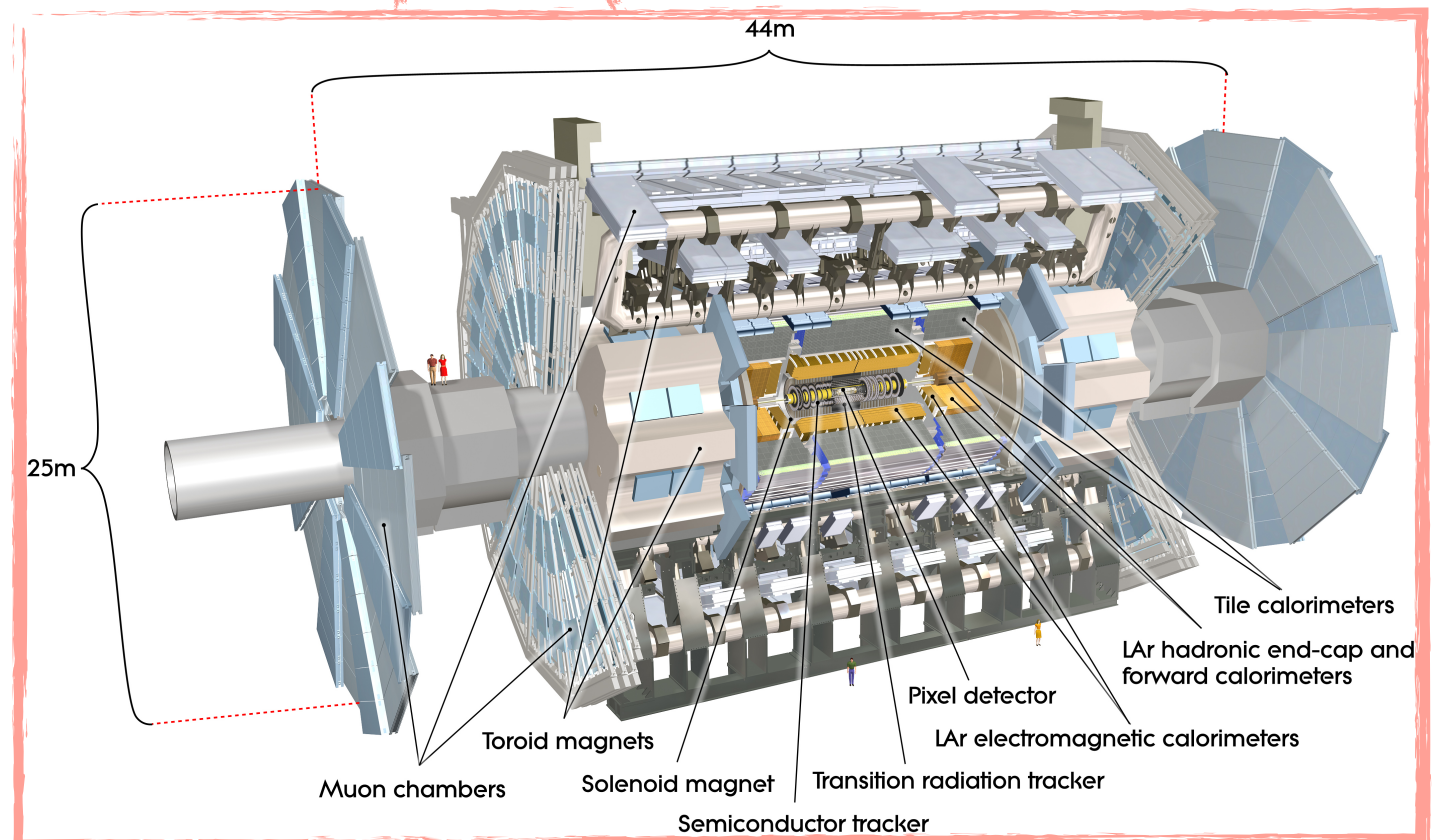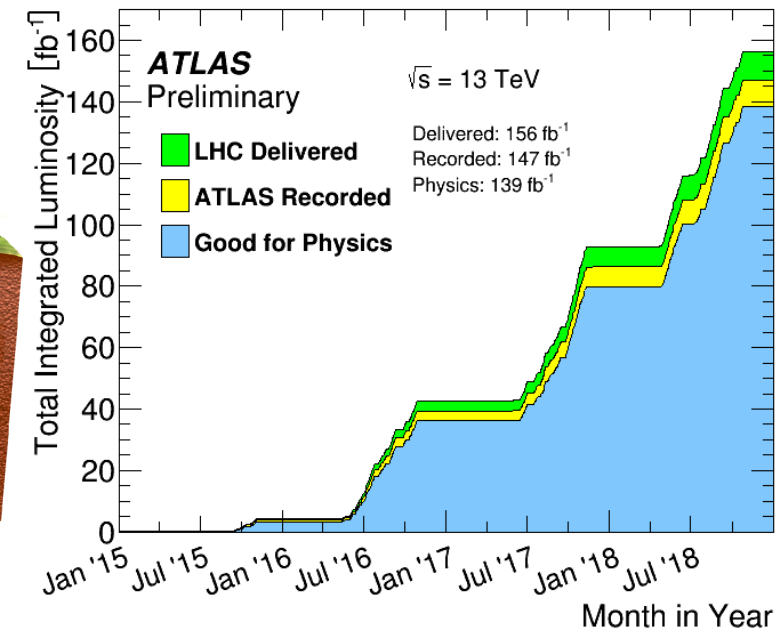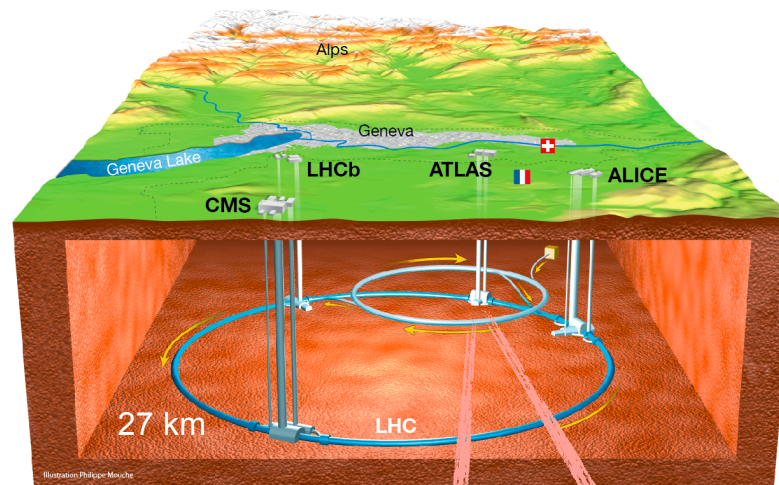 ‣ Energy Resolution

  ‣ Timing

- Phase I Upgrade for Run 3

ATLAS and the LHC

- CERN's Large Hadron Collider (LHC)

  ‣ Proton-proton (pp) and heavy ion collision modes

  ‣ Center-of-mass energy: $\sqrt{s}$ = 13 TeV

  ‣ Bunch crossing rate: 40 MHz

  ‣ Peak luminosity in Run 2 (2015-2018): 2.1 x 10^{34} $cm^{-2}s^{-1}$

  ‣ Pileup (μ, interactions per bunch crossing): $\bar{\mu}$ = 33.7, μ_{max} ~80

- ATLAS

  ‣ One of two general-purpose detectors at the LHC

  ‣ Tracking, calorimetry, muon spectrometry

  ‣ 139 fb^{-1} of recorded data good for physics in Run 2 (~89% efficiency)

Alps

Geneva

Geneva Lake

CMS   LHCb   ATLAS   ALICE

27 km   LHC

Illustration Philippe Mouche

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV

Delivered: 156 fb⁻¹
Recorded: 147 fb⁻¹
Physics: 139 fb⁻¹

- LHC Delivered
- ATLAS Recorded
- Good for Physics

Total Integrated Luminosity [fb⁻¹]

Month in Year

44m

25m

Tile calorimeters

LAr hadronic end-cap and forward calorimeters

Pixel detector

LAr electromagnetic calorimeters

Toroid magnets

Muon chambers

Solenoid magnet

Transition radiation tracker

Semiconductor tracker

- Liquid argon sampling calorimeter
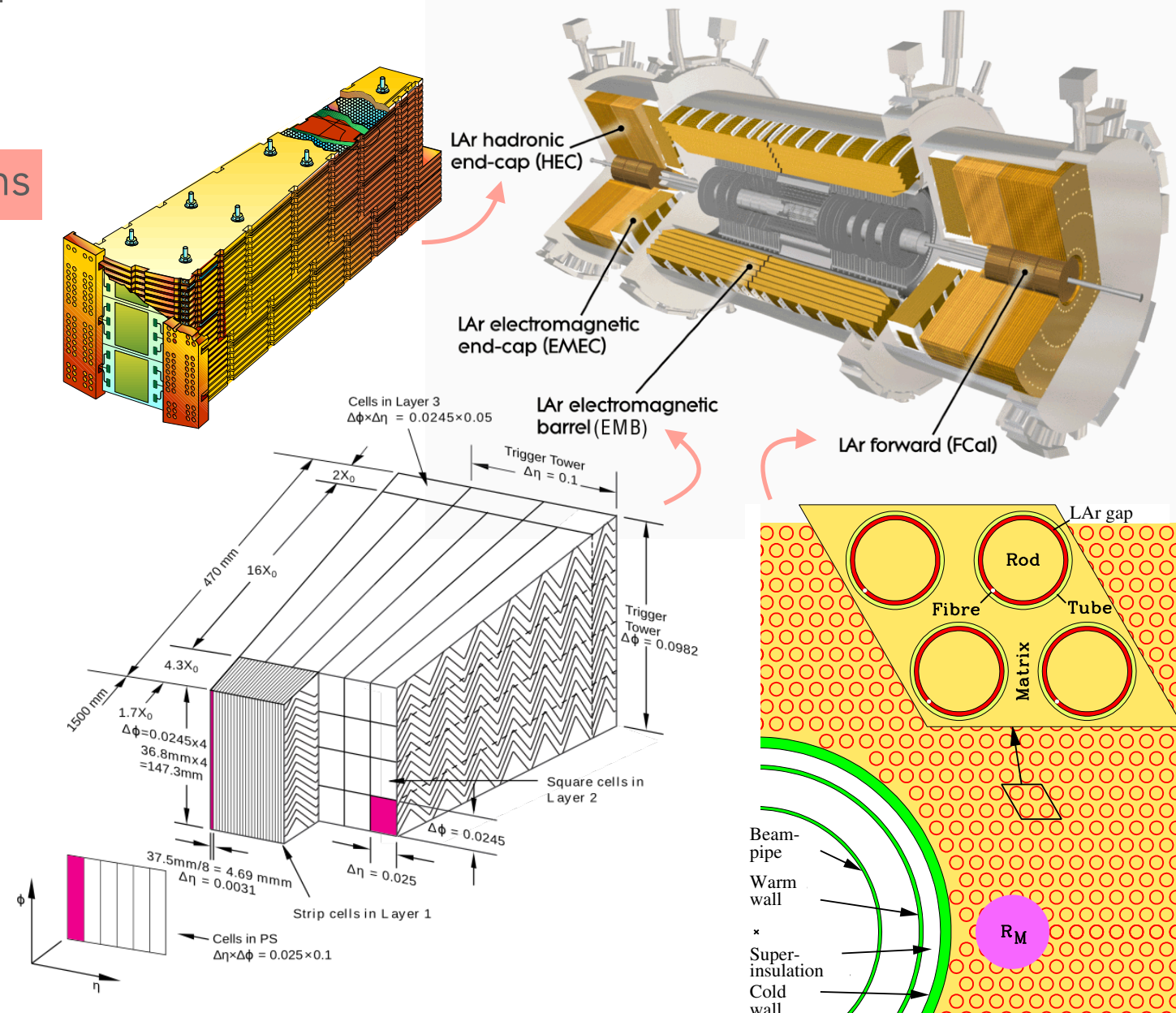 - Cooled with 3 cryostats to ~90 K
  - Linear response, uniform, stable, radiation-tolerant
  - ~182,000 channels (>99.9% operational)
- Electromagnetic (EM) and hadronic sections
  - EM barrel (EMB) and end-cap (EMEC)
    - Lead plates interspaced as the passive material
    - Arranged in accordion-like structures
    - Fast readout and full, uniform azimuthal coverage
  - Forward calorimeters (FCal)
    - Copper and tungsten absorber matrices with rod electrode structures
  - Hadronic end-cap (HEC)
    - Conventional parallel copper plate electrodes

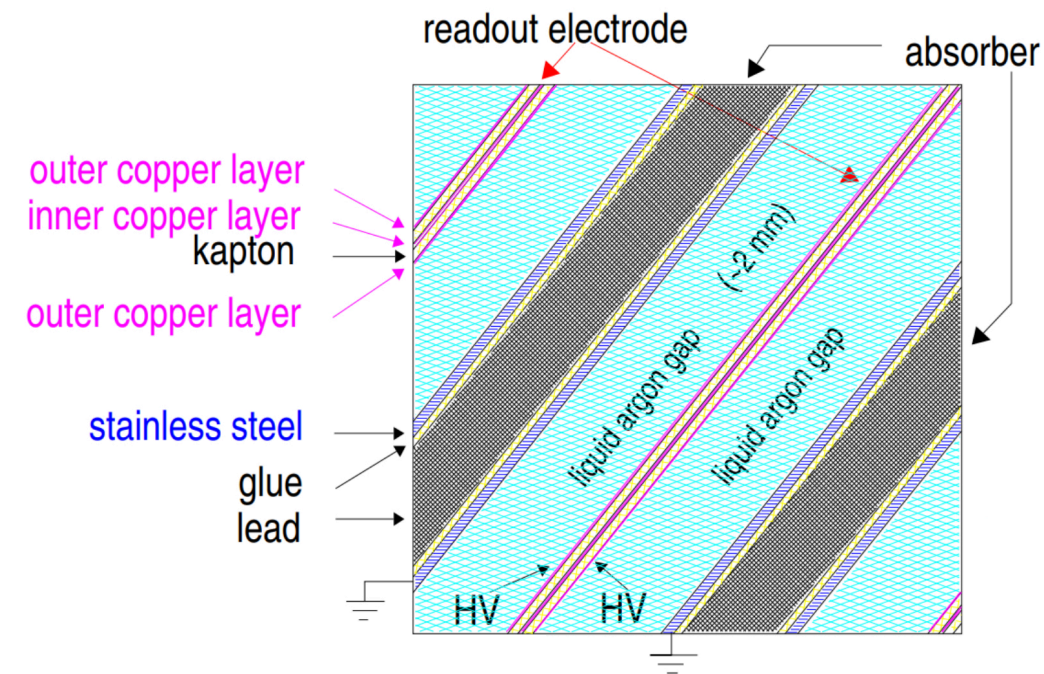| Detector component	Required resolution
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$
Hadronic calorimetry (jets) barrel and end-cap forward	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$ $\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$

	Coverage in Pseudorapidity (η)
EMB	$|\eta| < 1.475$
EMEC	$1.375 < |\eta| < 3.2$
HEC	$1.5 < |\eta| < 3.2$
FCal	$3.1 < |\eta| < 4.9$

LAr hadronic end-cap (HEC)

LAr electromagnetic end-cap (EMEC)

LAr electromagnetic barrel (EMB)

LAr forward (FCal)

Cells in Layer 3
$\Delta\phi \times \Delta\eta = 0.0245 \times 0.05$

Trigger Tower $\Delta\eta = 0.1$

$2X_0$

470 mm

16X_0

Trigger Tower $\Delta\phi = 0.0982$

4.3X_0

1500 mm

1.7X_0
$\Delta\phi=0.0245x4$
36.8mmx4
=147.3mm

Square cells in Layer 2

$\Delta\phi = 0.0245$

$\Delta\eta = 0.025$

37.5mm/8 = 4.69 mmm
$\Delta\eta = 0.0031$

Strip cells in Layer 1

ϕ

Cells in PS
$\Delta\eta \times \Delta\phi = 0.025 \times 0.1$

η

LAr gap
Rod
Fibre
Tube
Matrix

Beam-pipe
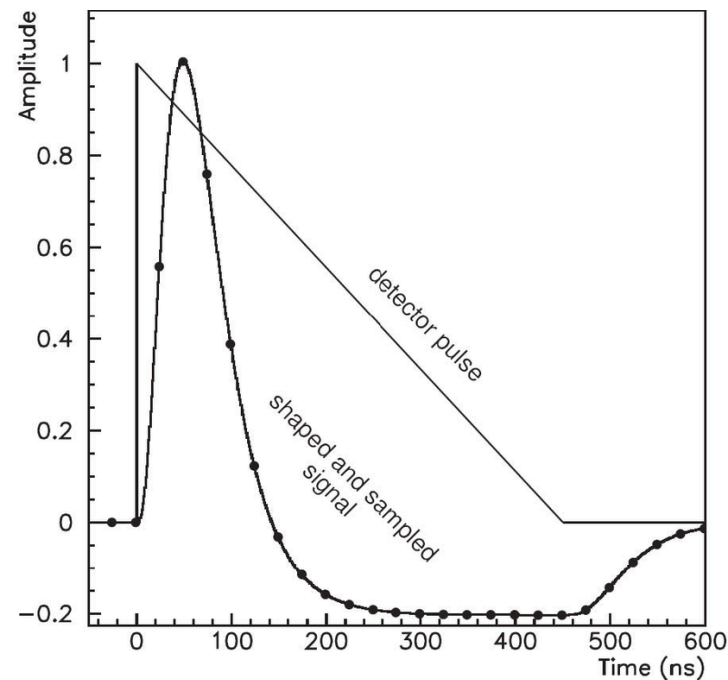Warm wall
Super-insulation
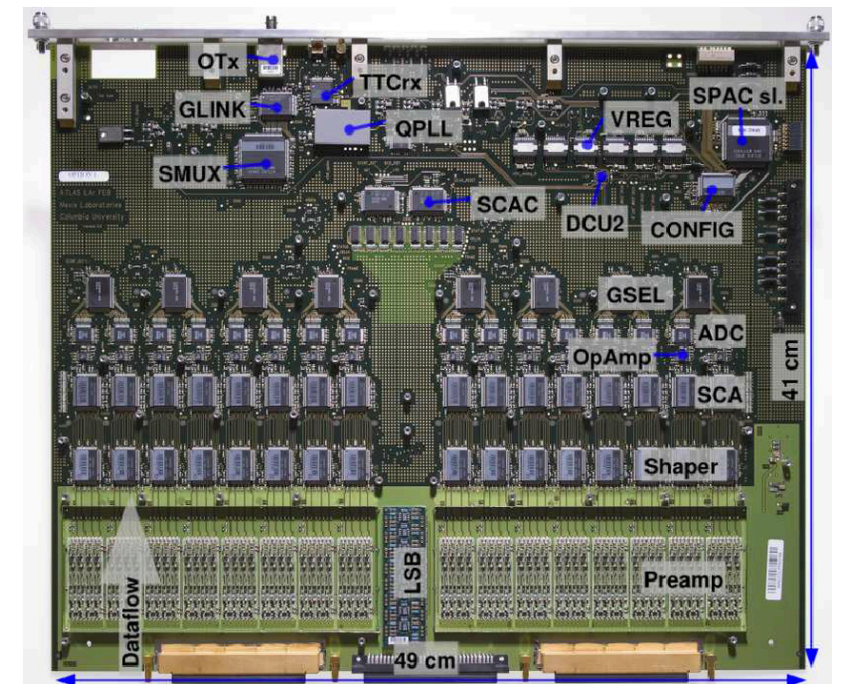Cold wall

R_M

Signal Measurement & Readout

### Signal Production & Collection
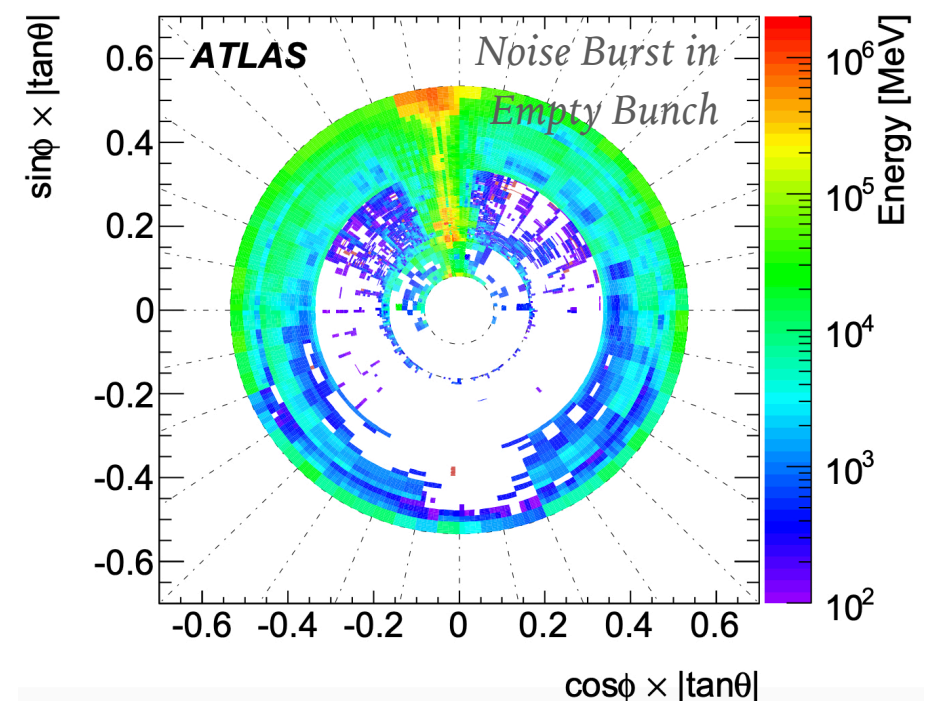

Ionization Pulse

Front-End Board

- Signal production
  - ‣ Incoming EM particle hits lead absorber, producing a shower in LAr, whose current is collected by electrodes
- On-detector electronics
  - ‣ Signal is amplified, split into 3 overlapping linear gain scales, and shaped on Front-End Boards (FEBs)
  - ‣ Sampled at 40 MHz and stored in analog buffer awaiting trigger decision
  - ‣ If triggered, gain is selected, and 4 samples are digitized and read out via optical fiber
- Off-detector electronics
  - ‣ Using optimal filtering coefficients (OFCs), amplitude (~energy) and time are computed
  - ‣ Quality factor measures consistency with in-time pulse, mitigates effects of out-of-time pileup

Devin Mahon

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LAr Offline Data Quality

- 99.6% overall data-taking efficiency for LAr in Run 2
- 2 categories of inefficiencies:
  - ‣ Defect rejection: reject full "long" block of data (> 1 min.)
  - ‣ Veto rejection: issues in a "short" time period (< 1 min.), reject event-by-event
- Main veto rejection data losses:
  - ‣ Noise bursts
    - ‣ Well-studied noise phenomenon affecting a large fraction of the detector for a short time (~1 µs)
    - ‣ Suspected to be induced by unshielded HV cables
  - ‣ Mini noise bursts
    - ‣ Noise in a small region of the detector for a very short time (tens of ns)
    - ‣ Improved identification and HV tuning virtually eliminated their effect by 2018
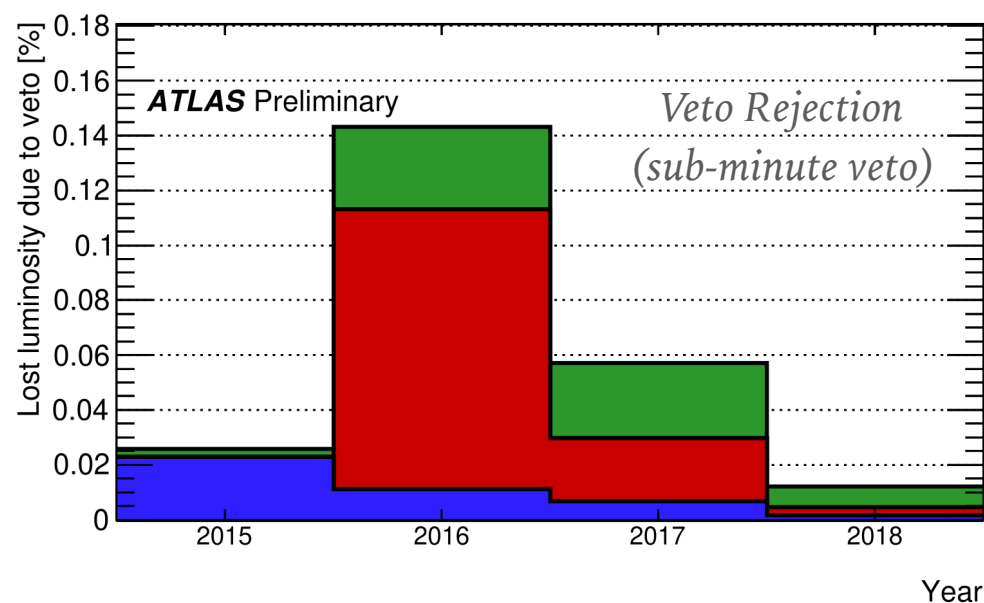
	2015	2016	2017	2018
Luminos. :	3.4 fb^{-1}	34.3 fb^{-1}	45.5 fb^{-1}	61.2 fb^{-1}
Total loss:	0.03%	0.14%	0.06%	0.01%
data corruption	0.00%	0.03%	0.03%	0.01%
mini noise burst	-	0.10%	0.02%	0.00%
noise burst	0.02%	0.01%	0.01%	0.00%

ATLAS Preliminary — *Veto Rejection (sub-minute veto)*

Lost luminosity due to veto [%] vs Year

ATLAS — *Noise Burst in Empty Bunch*

Energy [MeV], $\sin\phi \times |\tan\theta|$ vs $\cos\phi \times |\tan\theta|$

LAr Offline Data Quality

- Main defect rejection data losses:
  - Noisy channels
    - Individual channels masked due to noise from pulses incompatible with LAr ionization
  - Noise bursts
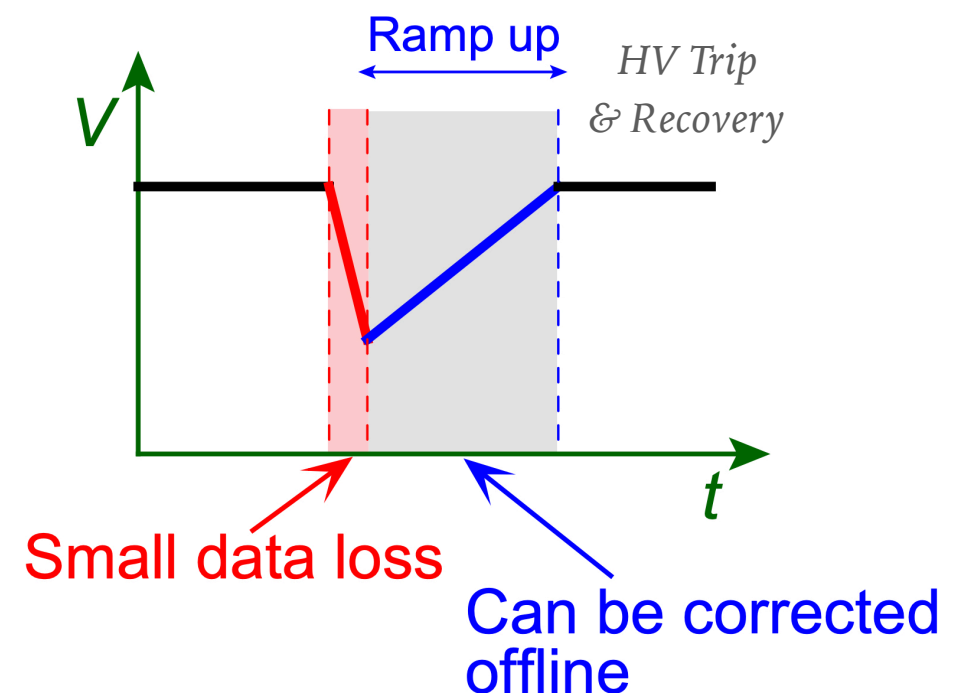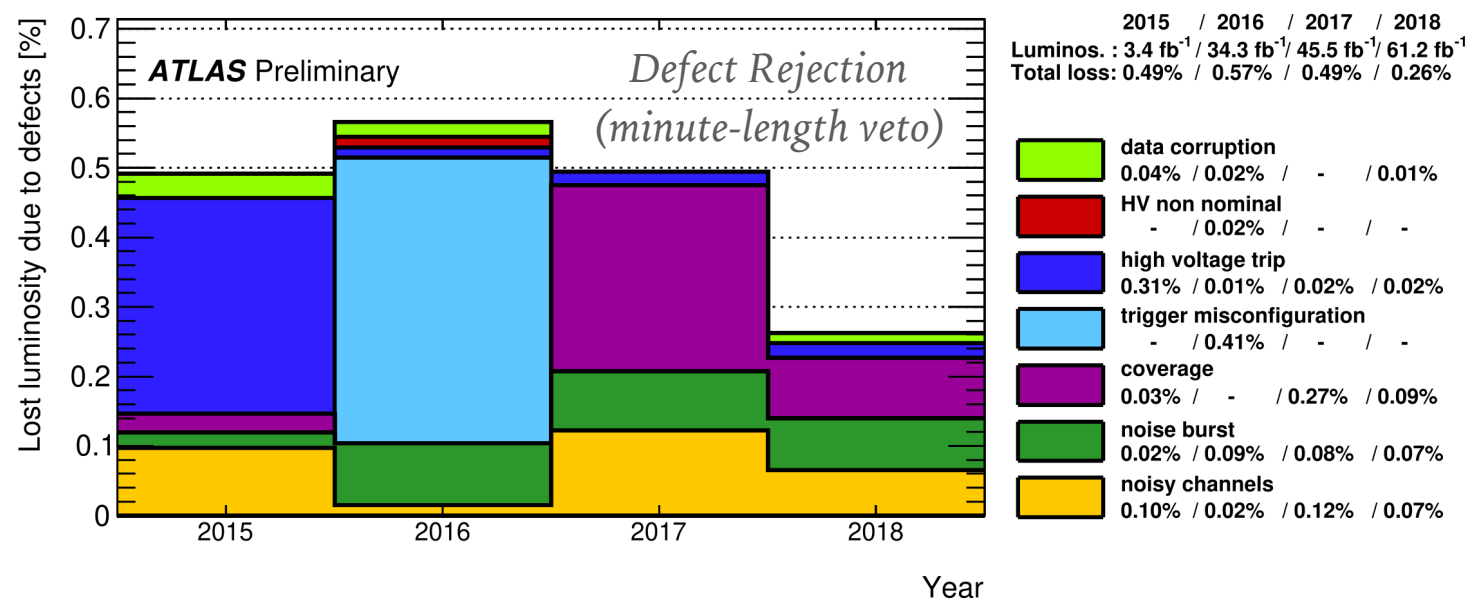   - Previously discussed widespread coherent noise phenomenon
  - Coverage
    - Temporary improper readout in an area of >512 cells due to a single hardware failure
  - High voltage (HV) trip
   - Sudden HV drop making energy correction unreliable
   - Reduced significantly with new power supplies in 2016

Online Tools & Operations

- High efficiency and smooth operations thanks to:
  - ‣ Very stable system performance and a dedicated operations team
  - ‣ Real-time (online) monitoring tools to quickly identify issues
    - ‣ Noise, timing, trigger rates, and other data integrity checks
    - ‣ Configuration and hardware status
  - ‣ Automated recovery procedures
    - ‣ e.g. LAr Trigger Tower Noise Killer (LTTNK): automatically searches for and disables noisy cells from being used in Level-1 trigger
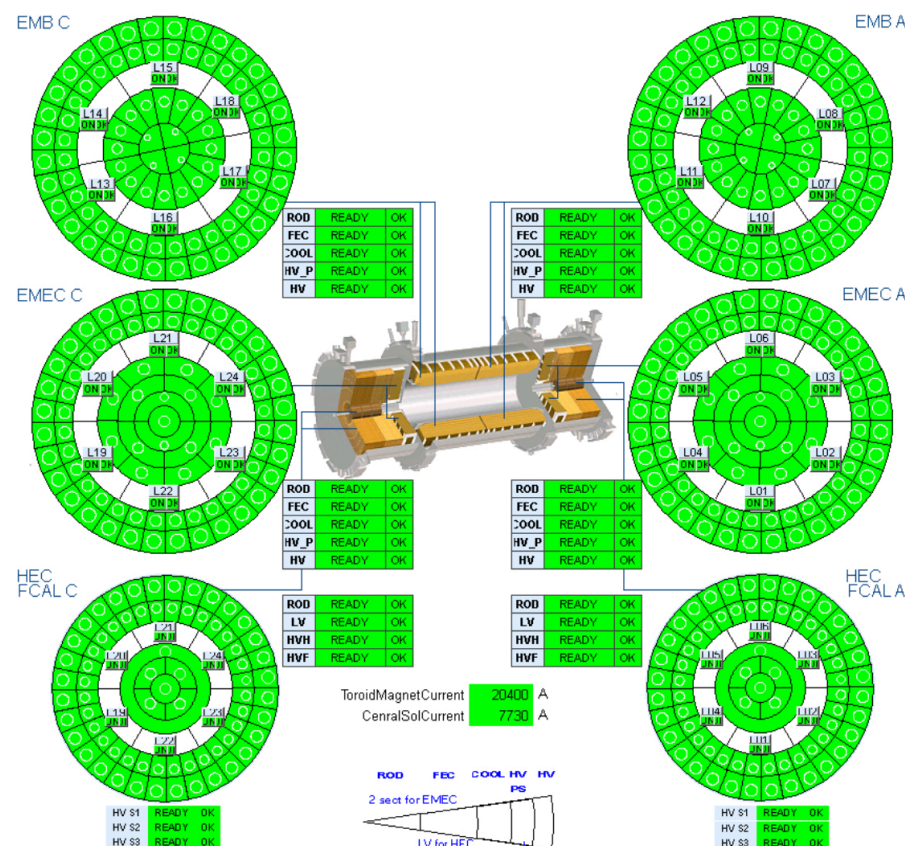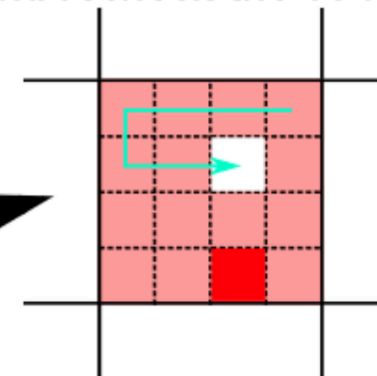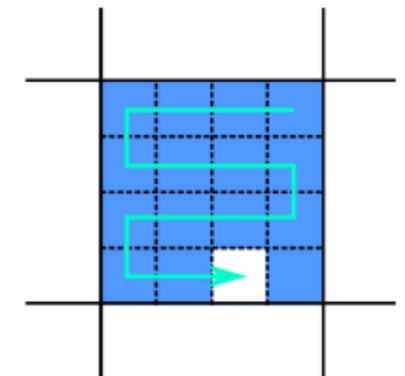

In case of trigger tower with too high rates
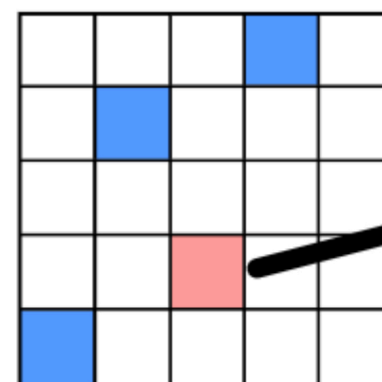
LTTNK disables cells of the tower one by one and recheck the TT rate

Until it finds the cell causing the noise

C. Camincher CALOR 2018

Purity Stability Studies

- LAr impurities:
  - Electronegative molecules (primarily O_2 and N_2) capture signal electrons, preventing them from being collected at the electrodes
  - Reduces signal-to-noise ratio
  - Must be monitored to ensure good, stable conditions
- Impurity measurement:
  - α- and β-source chambers in the cryostats measure electron lifetime in LAr
  - Laser chambers in contact with LAr measure electron lifetime and drift velocity and provide calibration for source chambers
  - Measured in oxygen equivalent
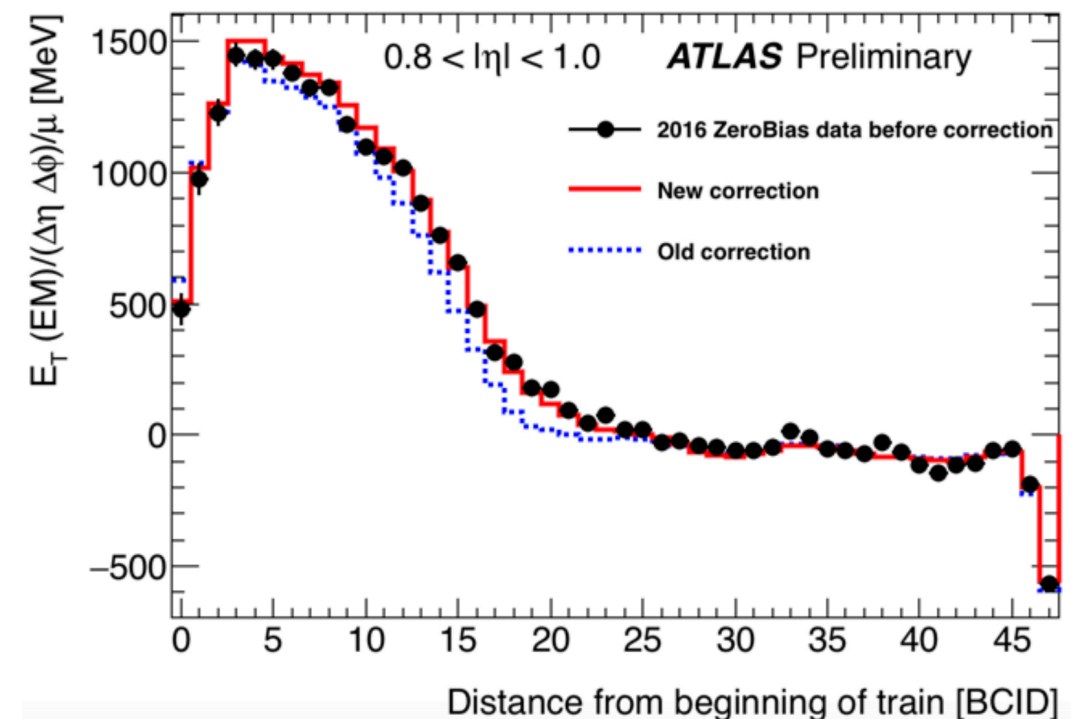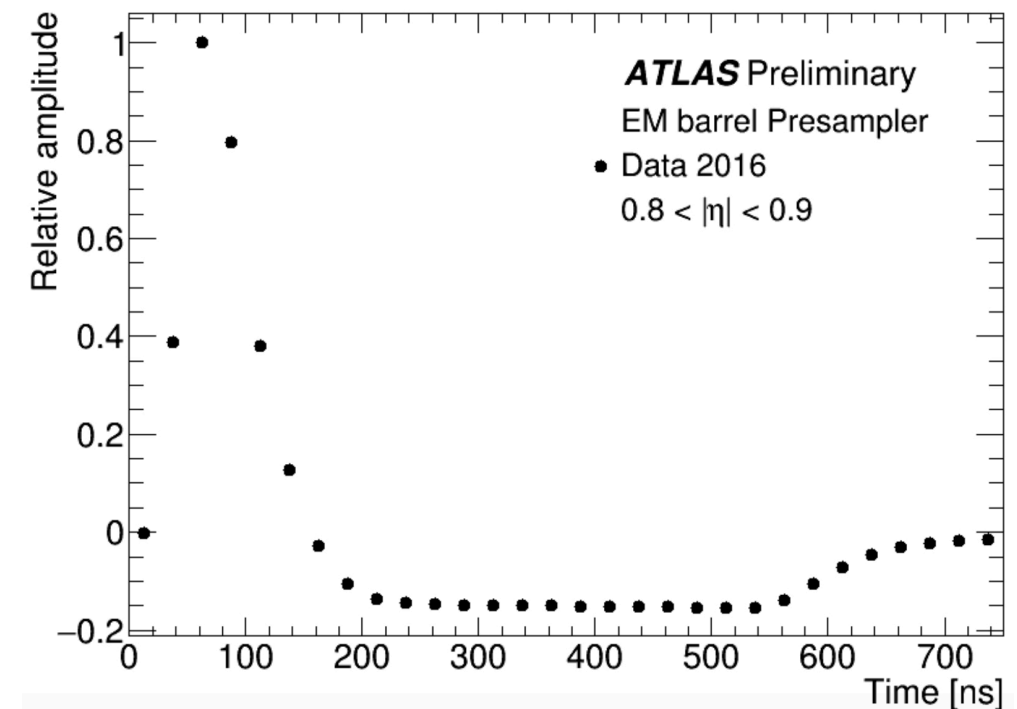 - Measurements during collisions excluded due to signals from radiation in the ionization chambers
- Impurity remained stable in Run 2 for the end-caps and decreased for the barrel
  - Always < 0.25 ppm
  - Clear explanation for decrease unknown, but change of other input parameters (e.g. temperature or HV of the ionization chambers) is excluded
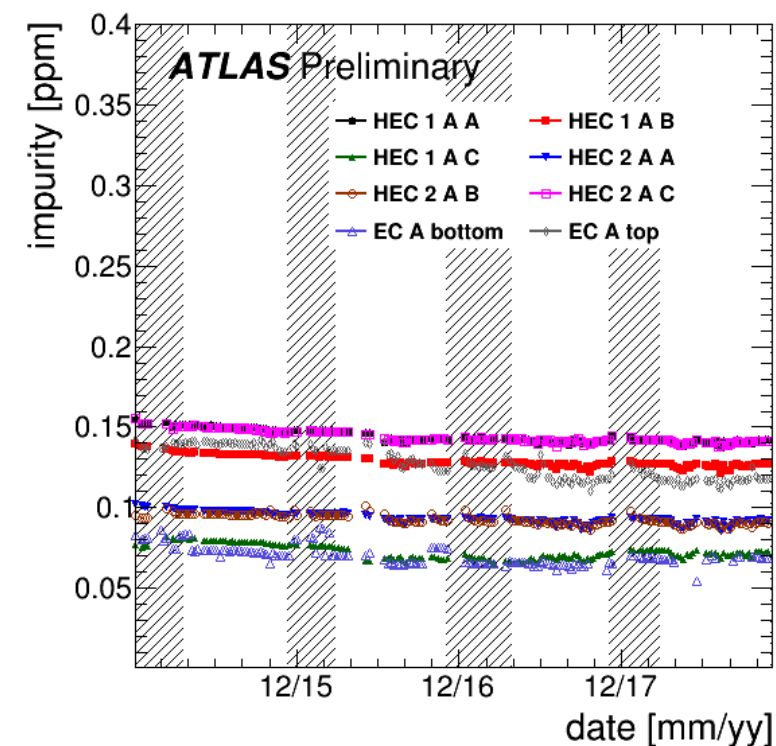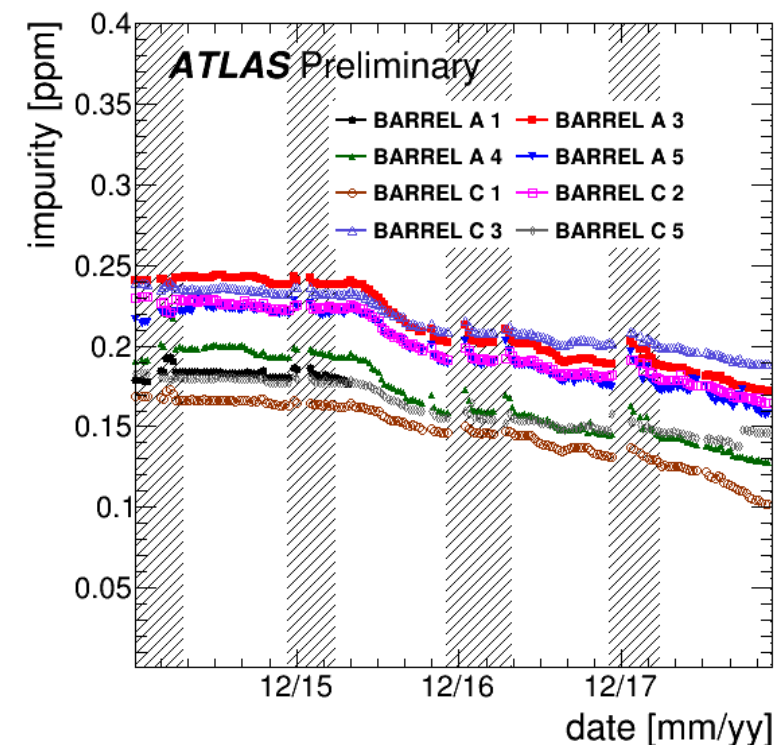
Pulse Shape Studies

- Dedicated measurements taken during special runs
  - ‣ 2016: 4 samples recorded with random trigger around a single colliding bunch
  - ‣ 2017 & 2018: 32 samples recorded, shifting readout in steps of ~3 ns
  - ‣ Physics pulse shape now sampled precisely at 256 points in various detector regions
- Precise knowledge of the pulse shape is important to:
  - ‣ Reduce uncertainties on shape corrections in energy computation
  - ‣ Cross-check LAr purity by examining distortions in the tail of the pulse caused by captured electrons
  - ‣ Improve the baseline correction for bunch structure
    - ‣ Bipolar pulse shape cancels in- and out-of-time pileup contributions to energy for infinite bunch trains
    - ‣ But finite trains and different bunch structures cause an energy shift
    - ‣ Applied as a pedestal correction
    - ‣ For a typical EM cluster and pileup, maximum baseline shift ~800 MeV, reduced to <30 MeV after correction

ATLAS Preliminary
EM barrel Presampler
• Data 2016
$0.8 < |\eta| < 0.9$

$0.8 < |\eta| < 1.0$ ATLAS Preliminary
- 2016 ZeroBias data before correction
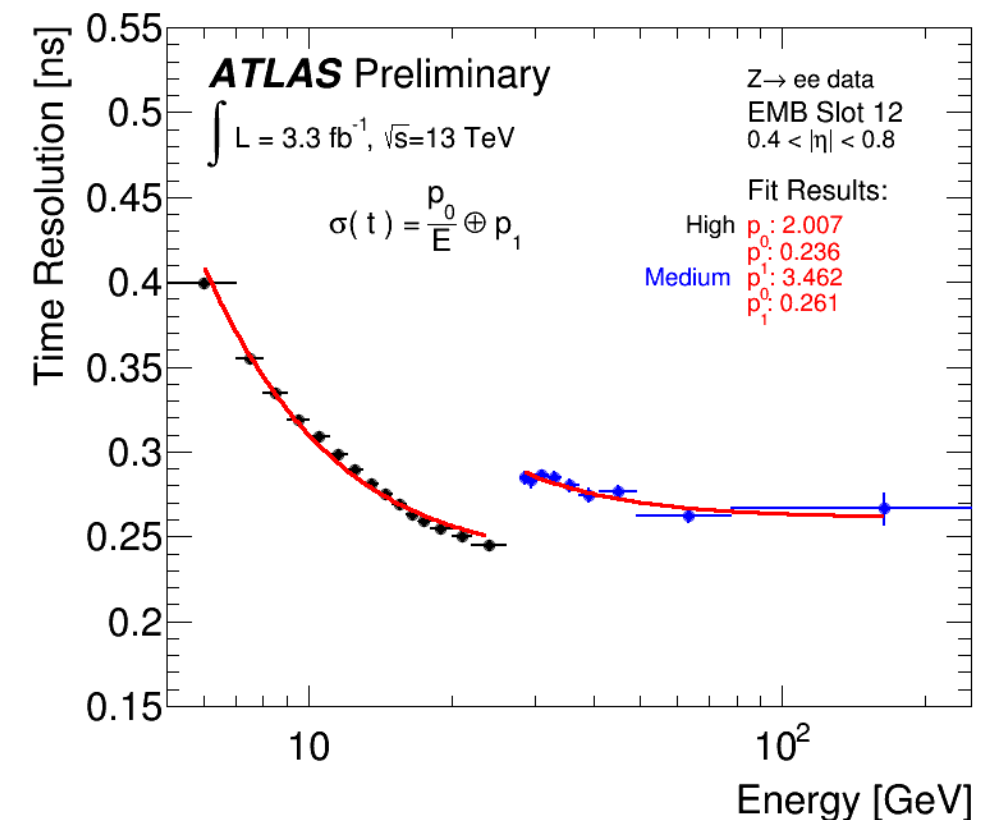- New correction
- Old correction

Energy Resolution Studies

- Modeling of energy resolution
  - ▸ Mis-modeling of energy scale and resolution calibrated with $Z \rightarrow ee$ data and MC
  - ▸ Corrections verified with $Z \rightarrow ee\gamma$ and $Z \rightarrow \mu\mu\gamma$ data with precision $\lesssim 0.5\%$
- Higher pileup (μ) increases noise and thus worsens the energy resolution ($\propto \sqrt{\mu}$)
  - ▸ Stability is especially relevant for Run 3 and beyond with much higher pileup environments
  - ▸ Overall stability with $Z \rightarrow ee$ data: within ~0.05%
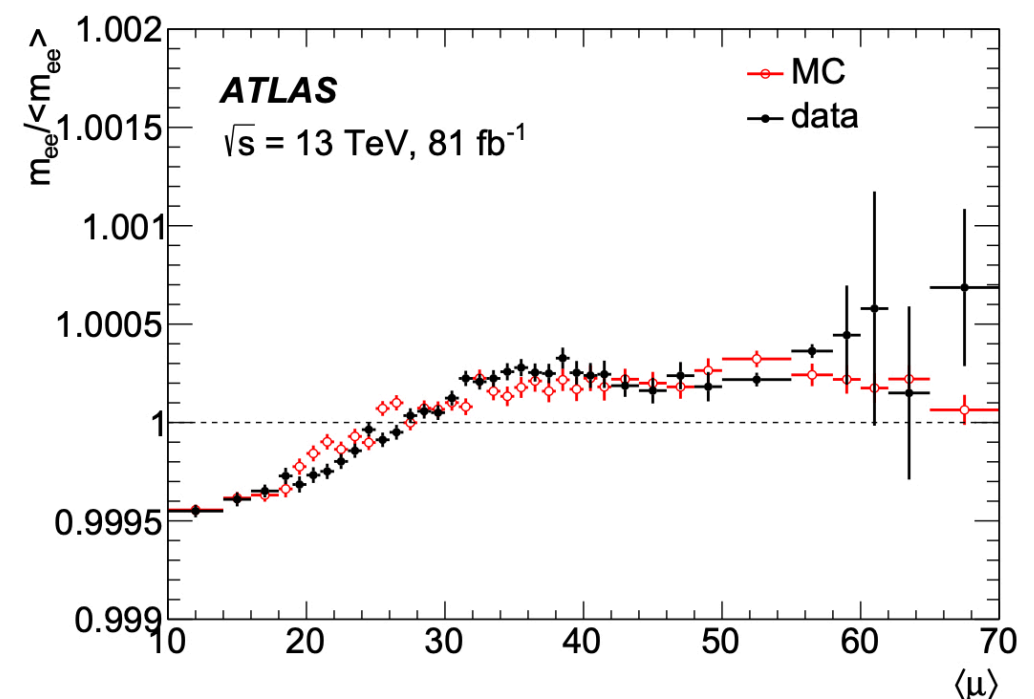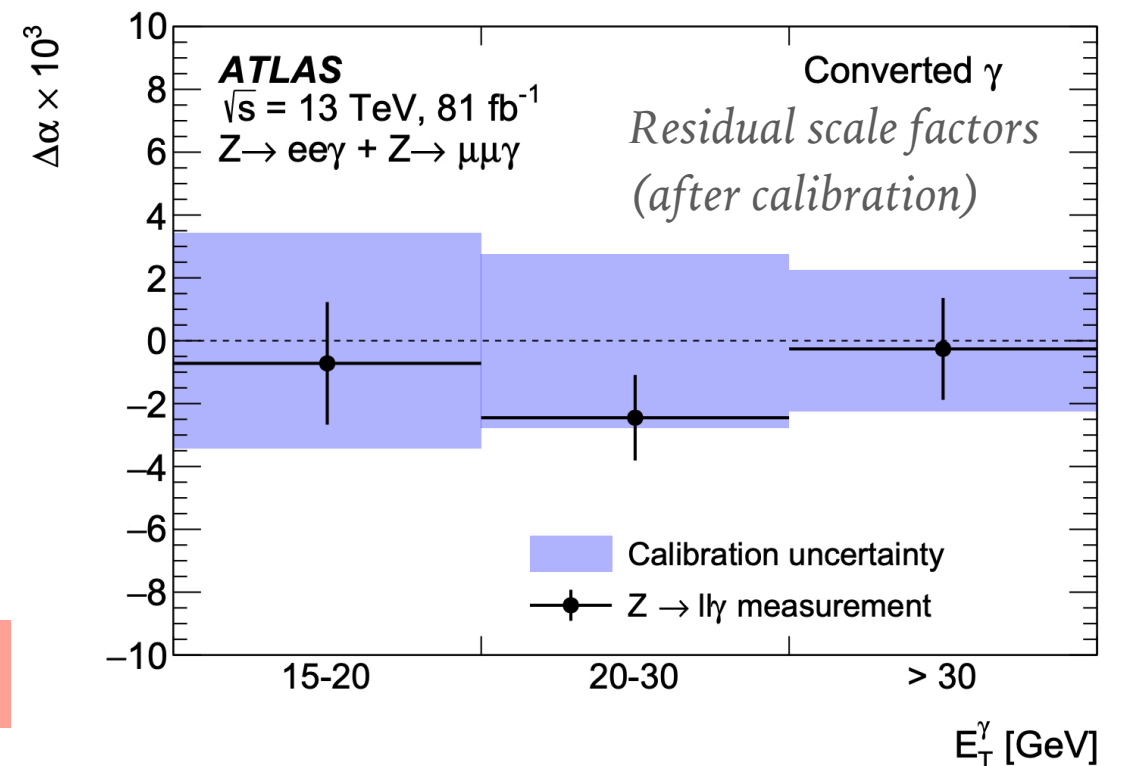
Timing Studies

- Timing is calculated online with ~1 ns resolution
  - Computed using optimal filtering coefficients (OFCs)
  - Tuned with FEB fine delays and monitored during data-taking
  - Sufficient for triggering and vetoing background
- Performance is significantly improved offline via calibration with electrons from W and Z boson decays
  - Removes timing variations from known detector effects
  - Improves resolution to as low as ~220-270 ps for high-energy electrons and photons
  - Powerful discriminant for long-lived particle searches
  - Computed beam spread timing component: ~200 ps
- Uncorrelated contribution to constant term (p_1) attributed to LAr: ~65-185 ps (varies in η and gain)
- LAr provides the most precise timing in ATLAS
  - New, updated calibration improves performance even further (results not yet released)

$$A = \sum_{i=1}^{4} a_i(s_i - p)$$

$$A\tau = \sum_{i=1}^{4} b_i(s_i - p)$$

$$\chi^2 = \sum_{i=1}^{4} [a_i(s_i - p) - Eg_i - E\tau g_i']^2$$

ATLAS Preliminary

$\int L = 3.3\ fb^{-1},\ \sqrt{s}=13\ TeV$

$\sigma(t) = \dfrac{p_0}{E} \oplus p_1$

Z→ ee data
EMB Slot 12
$0.4 < |\eta| < 0.8$

Fit Results:
High p_0: 2.007
p_0: 0.236
Medium p_1: 3.462
p_1: 0.261
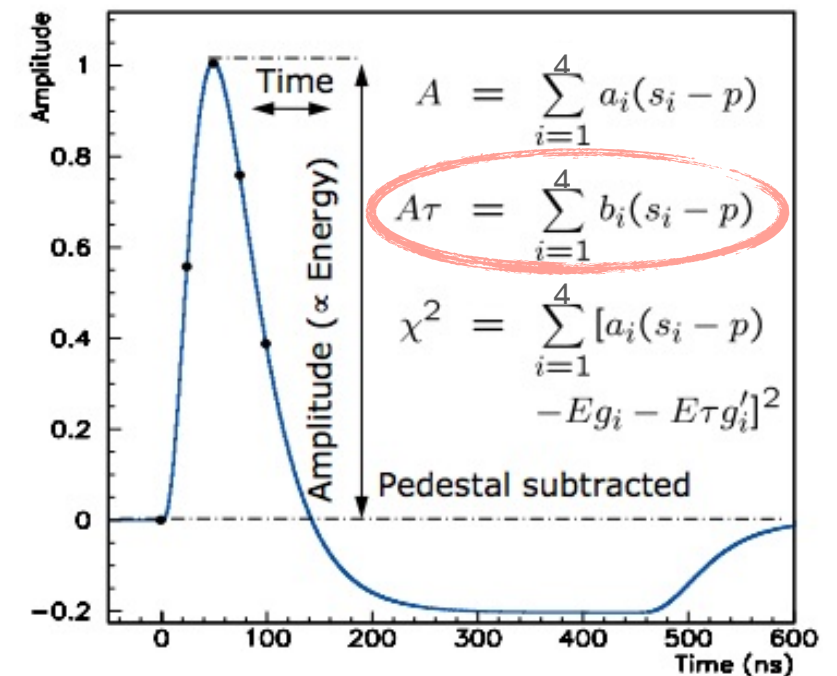
LAr Calorimeter Physics Applications

- Provides precise measurements of EM objects for a wide variety of crucial applications
  - ‣ Higgs discovery and precision measurements:
    - ‣ $H \rightarrow \gamma\gamma, H \rightarrow ZZ^* \rightarrow 4e, H \rightarrow WW^* \rightarrow e\nu e\nu$
  - ‣ Many searches for physics beyond the Standard Model
- Provides strong rejection of jet background and measurement of the EM component of jets
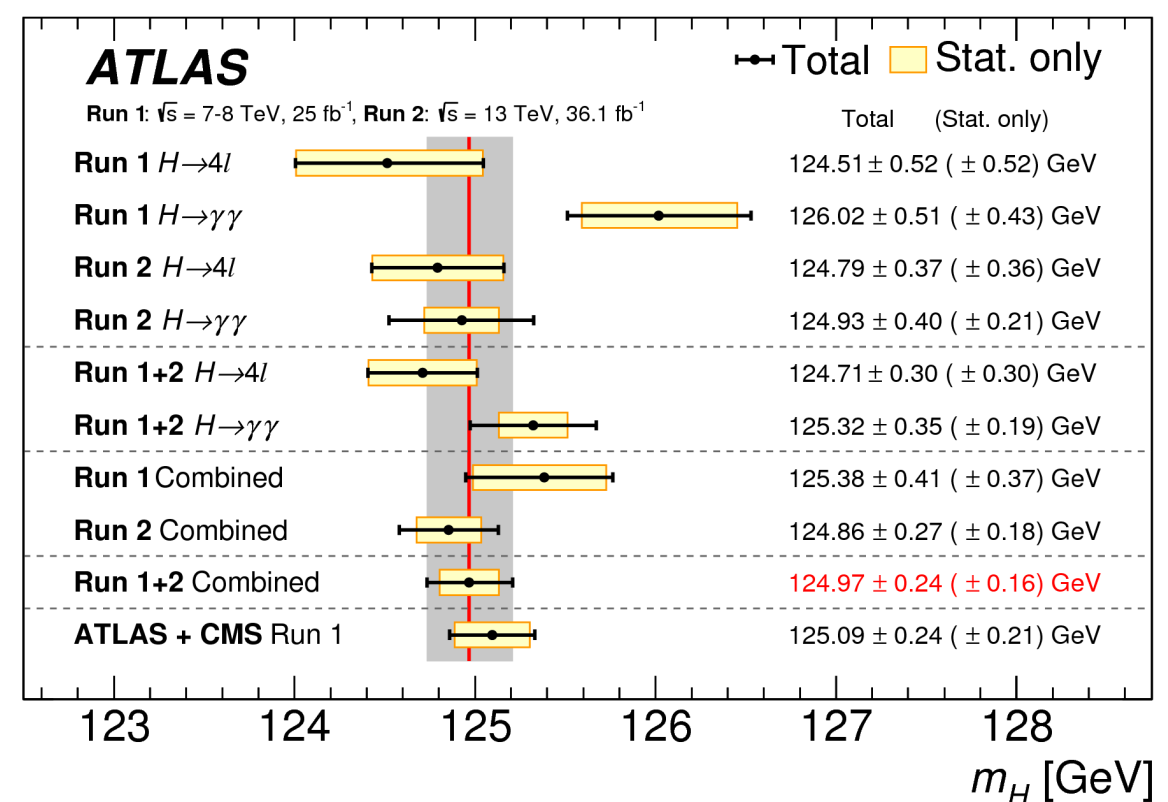
Photon Timing in BSM Search
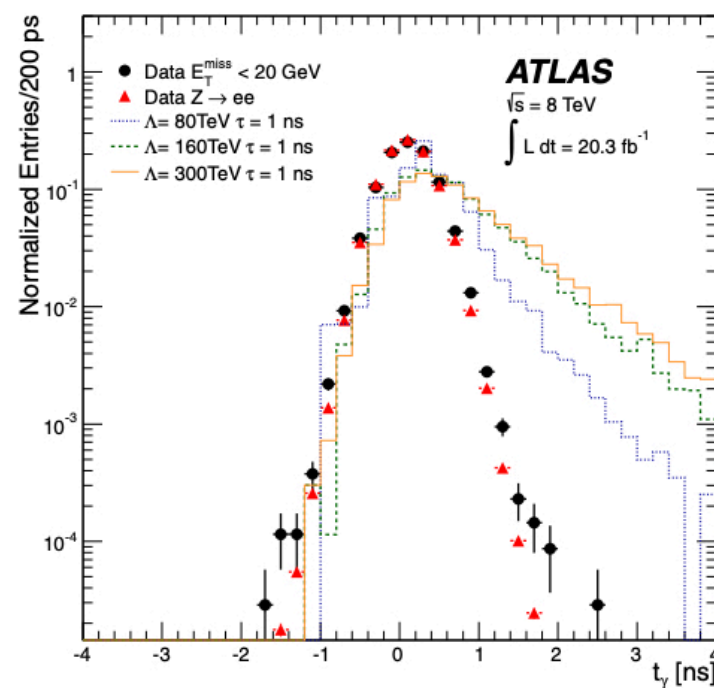
$H \rightarrow \gamma\gamma$ Peak
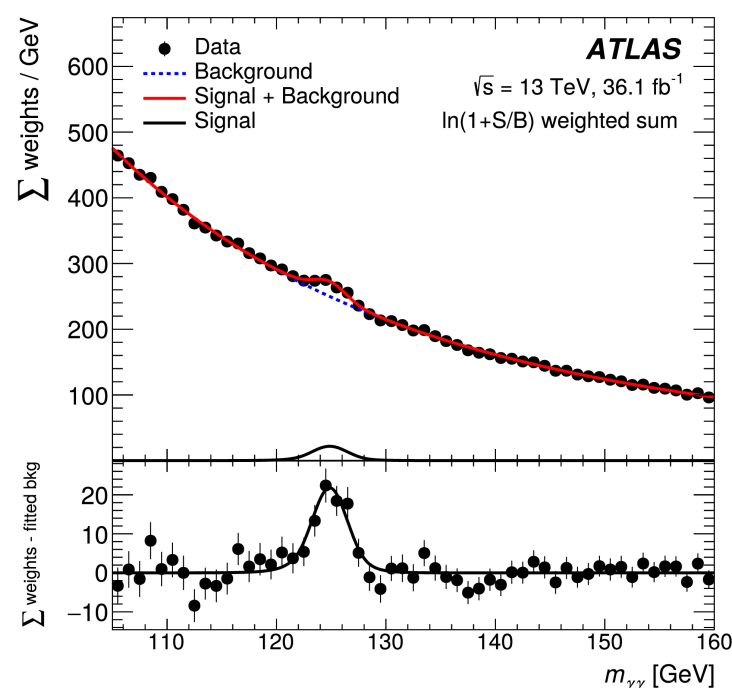
Higgs Mass Measurements
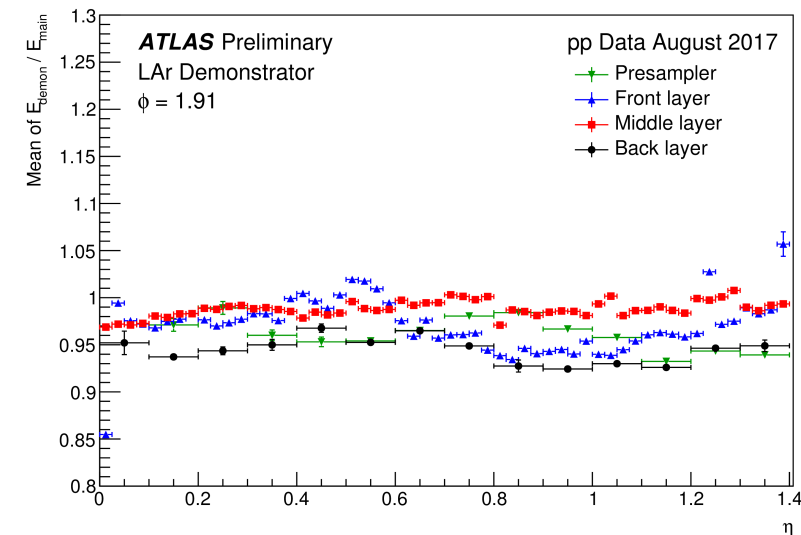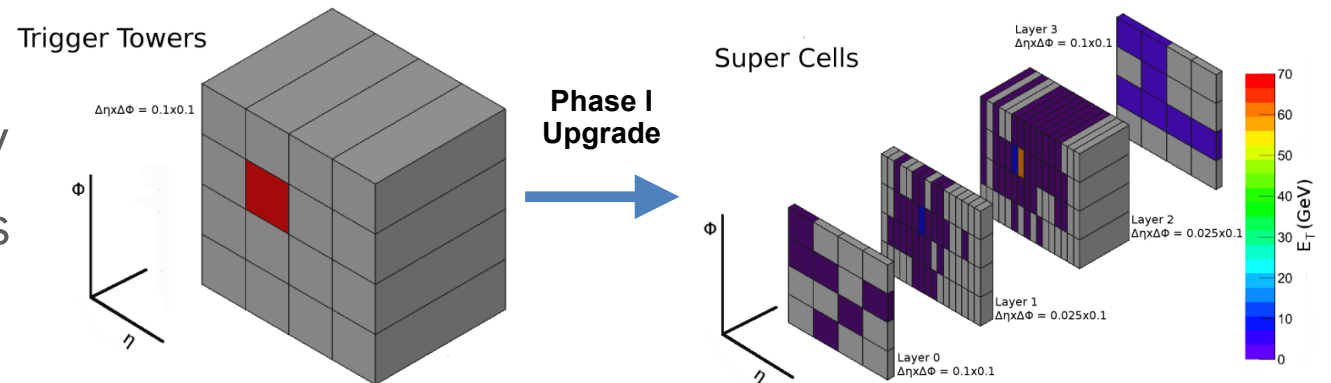
Ongoing Phase I Upgrade

- Run 3 (2021-2024) challenge:
  ‣ Higher pileup and instantaneous luminosity
  ‣ But maintain same Level-1 (L1) trigger rates and thresholds
  ‣ Better discrimination in trigger is needed

- Solution: upgrade of L1 trigger electronics
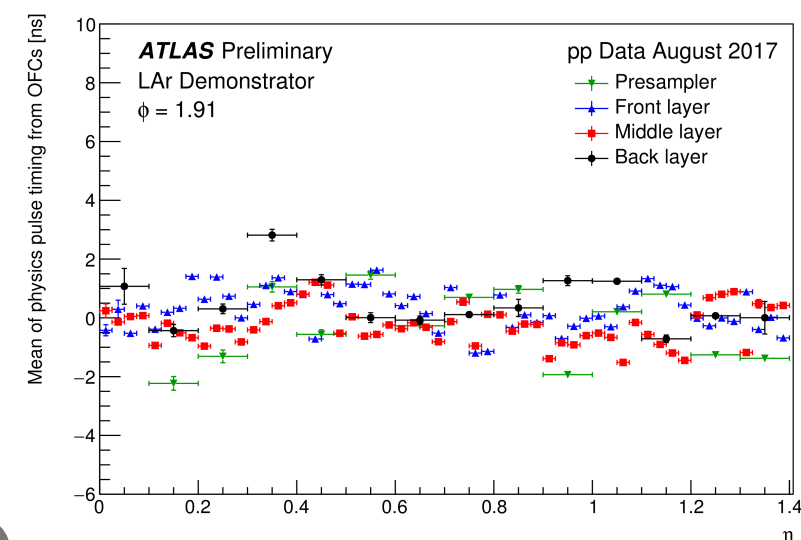 ‣ 10x greater L1 readout granularity
  ‣ Improved L1 discrimination of e, γ, τ, jets based on shower shape, isolation, etc.
  ‣ Improved L1 jet E_T and E_T^{miss} resolutions
  ‣ Greatly reduces effects of dominant QCD background and pileup

- Run 2 In-Situ Demonstrators
  ‣ 2 generations of demonstrator systems ran parasitically in the barrel throughout Run 2
  ‣ Validated design, observed good agreement with main readout

Trigger Towers

$\Delta\eta \times \Delta\Phi = 0.1 \times 0.1$

Phase I Upgrade

Super Cells

Layer 3
$\Delta\eta \times \Delta\Phi = 0.1 \times 0.1$

Layer 2
$\Delta\eta \times \Delta\Phi = 0.025 \times 0.1$

Layer 1
$\Delta\eta \times \Delta\Phi = 0.025 \times 0.1$

Layer 0
$\Delta\eta \times \Delta\Phi = 0.1 \times 0.1$

E_T (GeV)

Energy Agreement

ATLAS Preliminary
LAr Demonstrator
$\phi = 1.91$
pp Data August 2017
Presampler
Front layer
Middle layer
Back layer

Mean of E_{demon} / E_{main}

Time Agreement

ATLAS Preliminary
LAr Demonstrator
$\phi = 1.91$
pp Data August 2017
Presampler
Front layer
Middle layer
Back layer

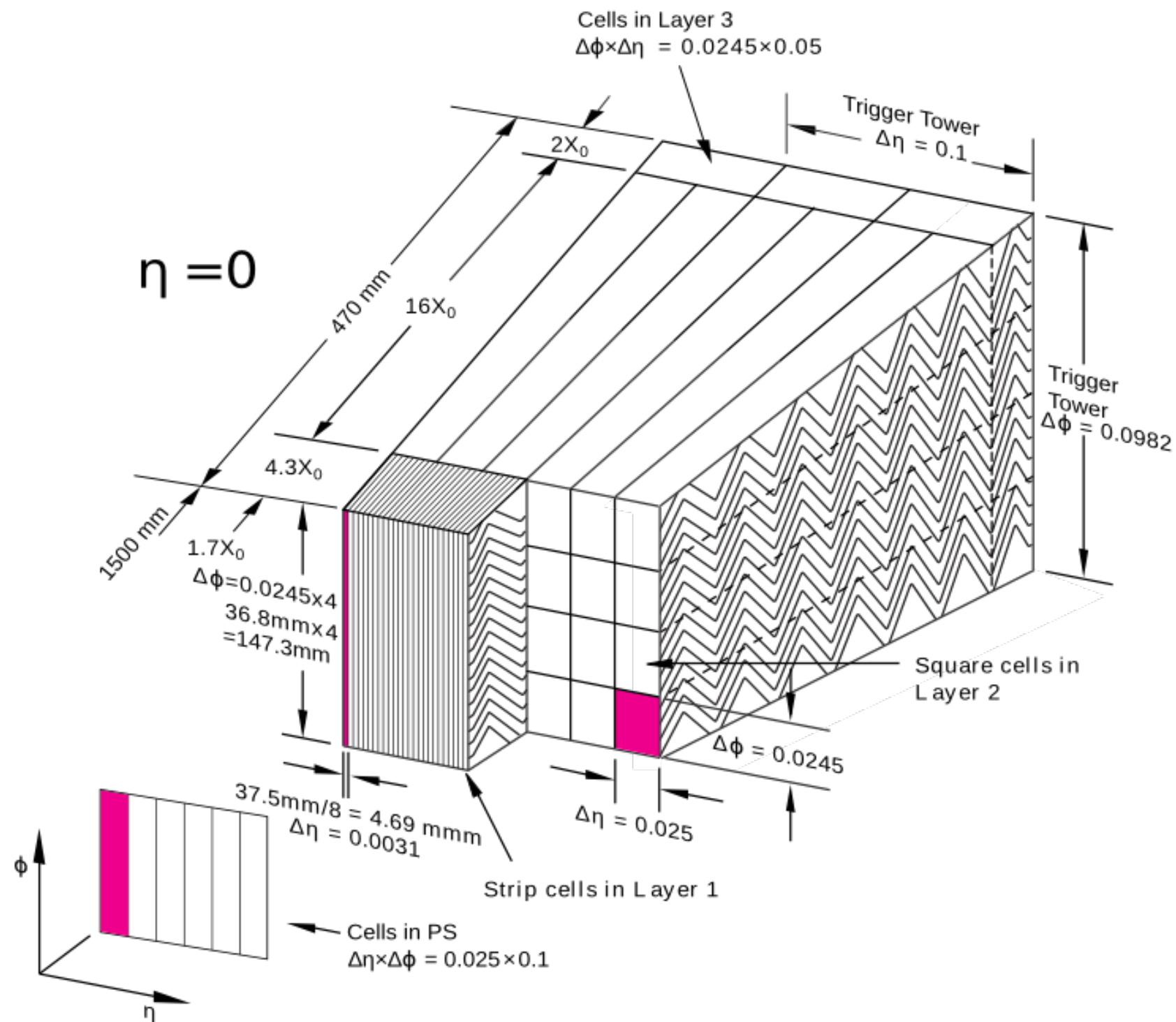Mean of physics pulse timing from OFCs [ns]

Summary

- The ATLAS LAr Calorimeters operated very successfully throughout Run 2 with 99.6% overall data-efficiency

- Various Run 2 studies demonstrate the excellent quality of physics data collected and the commitment to continually improving operations and performance

- LAr has contributed greatly to many important physics measurements and searches during Run 2

- Ongoing upgrades to handle conditions in Run 3 are well underway
 - ‣ Dedicated Phase I and HL-LHC upgrade talks on Friday

Backup

Cells in Layer 3
$\Delta\phi \times \Delta\eta = 0.0245 \times 0.05$

Trigger Tower
$\Delta\eta = 0.1$

$2X_0$

$\eta = 0$

470 mm

$16X_0$

Trigger Tower
$\Delta\phi = 0.0982$

$4.3X_0$

1500 mm

$1.7X_0$
$\Delta\phi = 0.0245 \times 4$
$36.8mm \times 4$
$= 147.3mm$

Square cells in Layer 2

$\Delta\phi = 0.0245$

37.5mm/8 = 4.69 mmm
$\Delta\eta = 0.0031$

$\Delta\eta = 0.025$

Strip cells in Layer 1

ϕ

η

Cells in PS
$\Delta\eta \times \Delta\phi = 0.025 \times 0.1$

Energy Resolutions

Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\, p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < |\eta| < 4.9$	$3.1 < |\eta| < 4.9$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV	± 2.7	± 2.4

Table 1. General performance goals of the ATLAS detector. Note that, for high-p_T muons, the muon-spectrometer performance is independent of the inner-detector system. The units for E and p_T are in GeV.
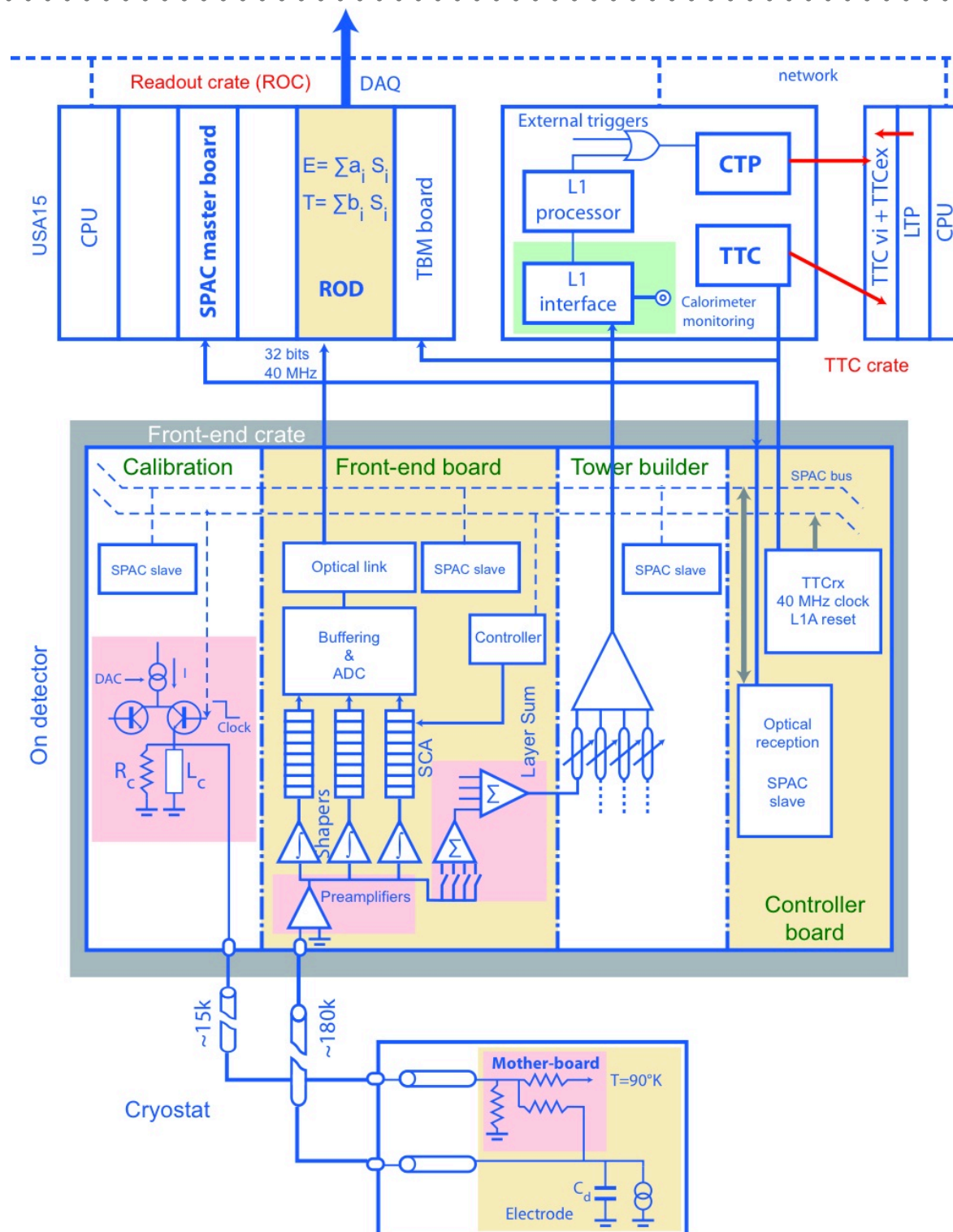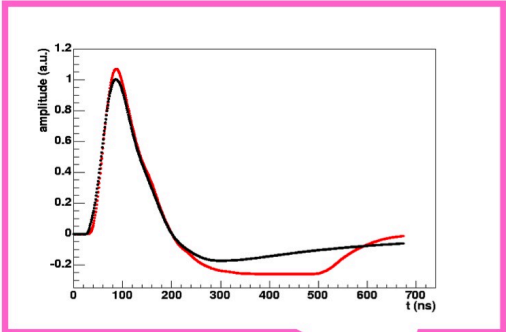
Front-End Board Schematic
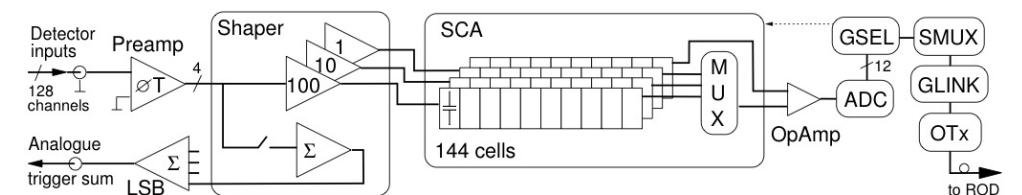
Energy Reconstruction

ADC to DAC (Ramps)

Pulse Samples

$$E_{\text{cell}} = F_{\mu A \to MeV} \cdot F_{DAC \to \mu A} \cdot \frac{1}{\frac{M_{\text{phys}}}{M_{\text{cali}}}} \sum_{i=1}^{M_{\text{ramps}}} R_i \left[\sum_{j=1}^{N_{\text{samples}}} a_j \left(s_j - p \right) \right]^i$$

Cell energy

Sampling fraction

Calibration board

Optimal Filtering Coefficients

Pedestals

The above formula describes the LAr electronic calibration chain (from the signal ADC samples to the raw energy in the cell. Note that this version of the formula uses the general M_{ramps}-order polynomial fit of the ramps. We use a linear fit as the electronics are very linear, and we only want to apply a linear gain in the DSP in order to be able to undo it offline, and apply a more refined calibration. In this case, the formula is simply:

$$E_{\text{cell}} = F_{\mu A \to MeV} \cdot F_{DAC \to \mu A} \cdot \frac{1}{\frac{M_{\text{phys}}}{M_{\text{cali}}}} \cdot R \left[\sum_{j=1}^{N_{\text{samples}}} a_j \left(s_j - p \right) \right]$$