Performance of the ATLAS Liquid Argon Calorimeter after three years of LHC operation and plans for a future upgrade

Pavol Strizenec

IEPSAS Košice
On behalf of the ATLAS Collaboration

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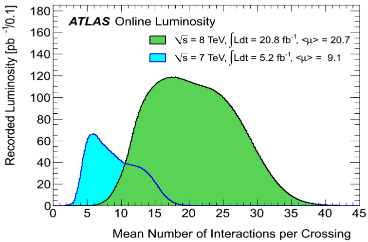
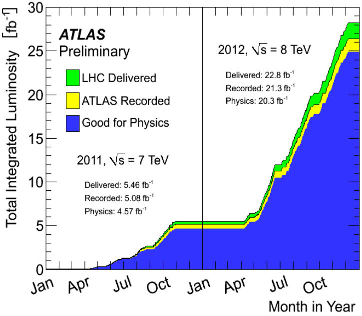
LHC beam conditions and ATLAS



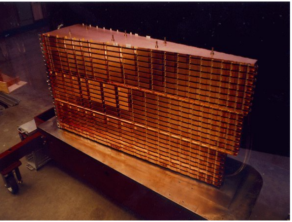
- LHC used 50ns bunch spacing (25ns nominal)
- very high peak luminosity reached 7.73×10^{33} cm^{-2}s^{-1} (nominal 10^{34}cm^{-2}s^{-1})
- High pileup environment (on average more then 20 interactions per crossing in 2012) - left figure
- High particle multiplicities, unprecedented energies, very demanding environment for the detectors

- LHC delivered part of the data at $\sqrt{s}$=7 TeV, bigger amount of data at $\sqrt{s}$=8 TeV to all experiments
- ATLAS was quite efficient 93.5% recording efficiency in 2012, out of which 95.8% GOOD quality data, used for physics

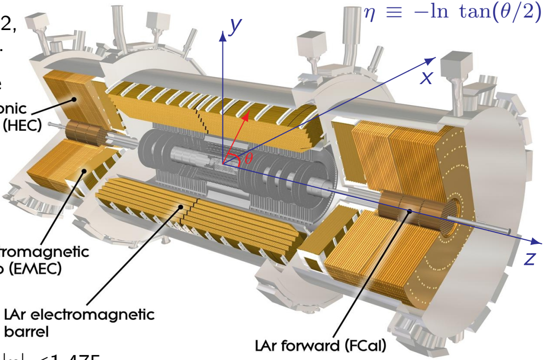
Year	$\sqrt{s}$ pp (Pb-Pb)	Recorded Lumi pp (Pb-Pb)
2010	7 (2.76) TeV	45 pb^{-1} (9.17 μb^{-1})
2011	7 (2.76) TeV	5.25 fb^{-1} (158 μb^{-1})
2012/	8 TeV	21.7 fb^{-1}
2013	5 TeV (p-Pb)	29.8 nb^{-1}



LAr System in Nutshell

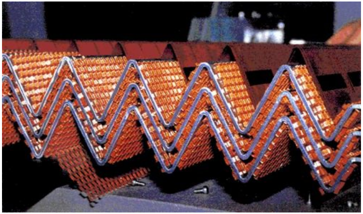


$1.5 < |\eta| < 3.2$,
$\sim$ 5.6k chan.
Cu absorber
parallel plate

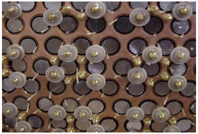


$1.375 < |\eta| < 3.2$
$\sim$ 64k chan.
Accordion geometry
Lead absorber
LAr Presampler in front of accordion for $|\eta| < 1.8$

$|\eta| < 1.475$
$\sim$ 110k chan.

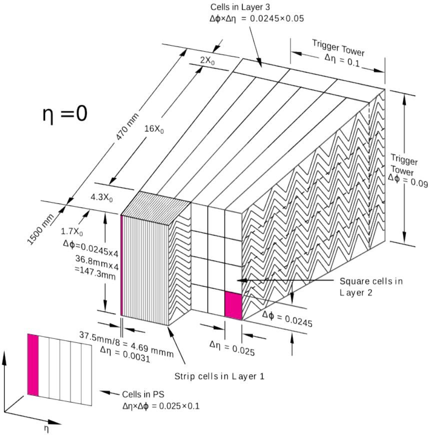


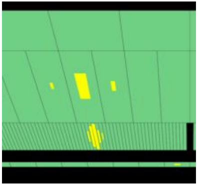
$3.1 < |\eta| < 4.9$, $\sim$ 3.5k chan.
Cu (EM), W (Had.) absorber
very narrow LAr gaps needed
novel design with cylindrical electrodes parallel to the beam



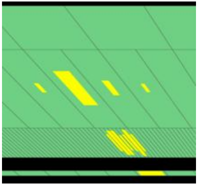
LAr Calorimeter Design Principles

- EM Calorimeter - both barrel and endcap:
  - copper/kapton electrodes
  - uniform ϕ coverage by accordion geometry
  - cells in η created by copper etching, in ϕ by ganging electrodes
  - first layer has fine segmentation - used for particle ID, and to have good angular resolution
  - presampler is used to correct energy losses in upstream material





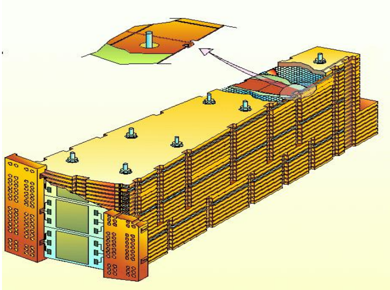
γ candidate

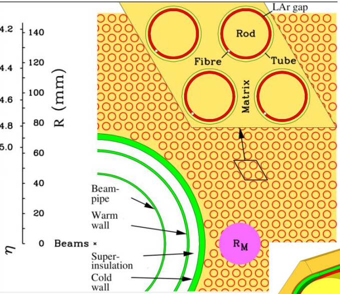


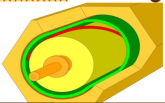
Jet candidate (π^0)

LAr Calorimeter Design Principles

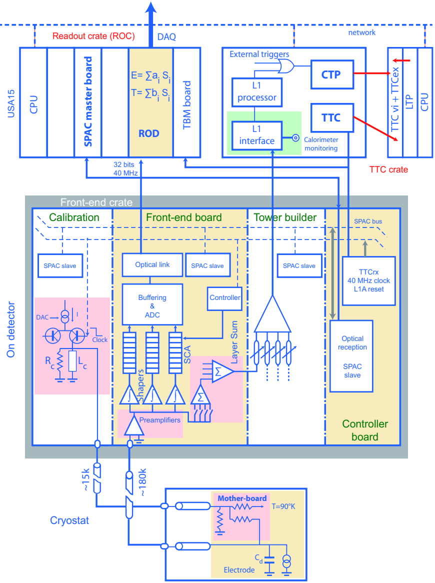
- Hadronic Endcap - behind the EM
- parallel copper plate/electrode structure (perpendicular to a beam), electrodes signal summing on detector
- novel technology of using GaAs preamplifiers and drivers in the cold, up to 4 PA's summed to a readout channel
- 4 longitudinal readout layers



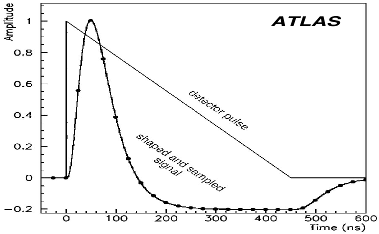




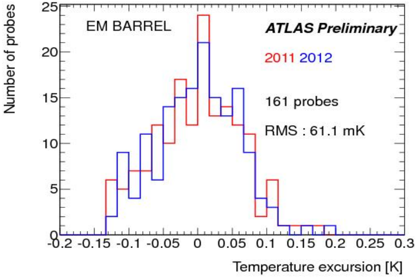
- Forward Calorimeter - high η coverage
- very high particle flux $\Rightarrow$ very narrow LAr gaps needed
- novel design of cylindrical electrodes, rods placed inside tubes parallel to the beam, gaps thickness kept with fiber wound around rods
- 3 modules, first (closest to IP) with Cu absorber, optimized for EM showers (269 μm gaps, other 2 with W absorber, optimized for hadronic measurements (375 and 500 μm gaps)



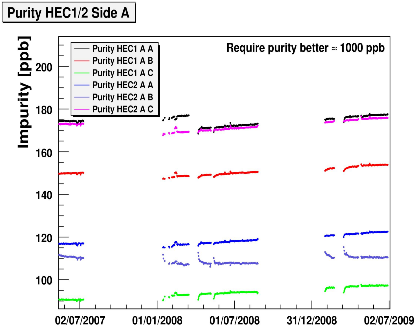
- signal is amplified outside of cryostat at 1524 **F**ront **E**nd **B**oards, with 128 channel each, (located in **F**ront **E**nd **C**rates on cryostat feed-throughts), split into 3 gain scales (1/9.9/93) and shaped
- signal is then sampled at 40MHz and stored in analogue pipelines
- with L1-accept signal arrived, the proper gain is selected, digitized and transmitted to back-end
- with ~2 mm gaps at 2kV the drift time is ~450 ns



LAr Cryogenic System Stability



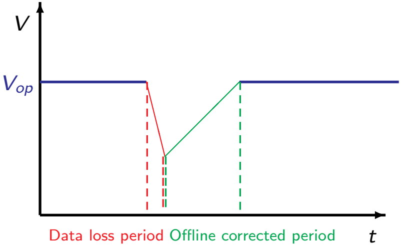
- LAr temperature variations needs to be <100 mK, because the impact on energy resolution is -2%/K
- measured uniformity is below 61 mK (plot shown for barrel, endcaps see less variations)

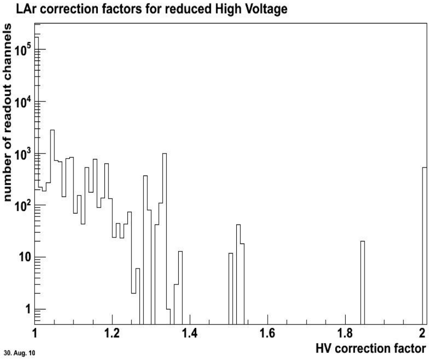


- signal in LAr is degraded by electronegative impurities (O_2)
- measured with 30 purity monitors in 10-15 min. interval
- stable and better than 200 ppb in barrel and 140 ppb in endcap cryostats (required < 1000 ppb)

LAr High Voltage System

- HV modules supplying the needed voltage on electrodes could trip during data taking, stopping the signal measurement
- there is a redundancy at EM calorimeter - each side of the electrode is powered independently
- most of the channels run in "auto-recovery" mode, bringing the operations HV back after trip automatically
- HV values stored in conditions DB, from where offline corrections are computed and applied during reconstruction
- Some adjustment of operational voltage (lowering) was done for frequently tripping channels (energy also corrected offline)
- More robust HV modules (Current Control mode instead of trip) deployed

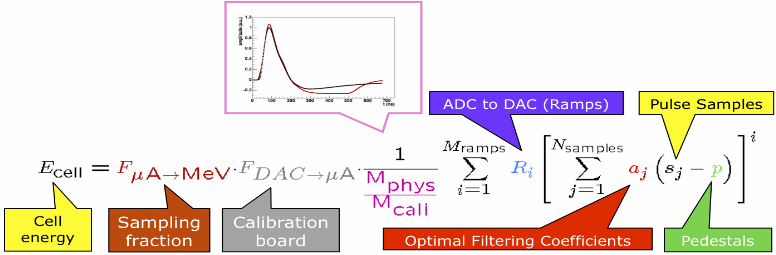




Hardware Problems during operation

- apart from HV trips, the annoying intermittent problem are the large scale coherent noise bursts, more details later in Data quality monitoring section
- there were also few persistent hardware problems, which were taken into account in Monte Carlo
  - **2010:** 30 FEBs lost optical connection to data acquisition system (broken optical transmitters), which was around 5% acceptance loss. Broken and suspicious transmitters replaced during 2010/2011 winter stop, no problems since then
  - **2011:** 6 FEBs and one calibration board in EM barrel lost trigger, clock and control signals (burnt fuse on controller board), most important FEBs (layer 2) fixed in summer, the rest fixed in winter shutdown, no problems since
  - **2012:** Leak developed in part of FEBs cooling system, 4 FEBs turned off in endcap, affecting 4.5% of the hadronic and 1.2% of the electromagnetic channels, fixed after couple of weeks (therefore not included in MC), no more problem seen since
  - **2013:** Water leak from Tile Cs calib. system stopped one HEC LV power supply, recovered, Cs. calib. system under review now
- no problems with detector itself or cryo systems during whole running period

Signal reconstruction and calibration

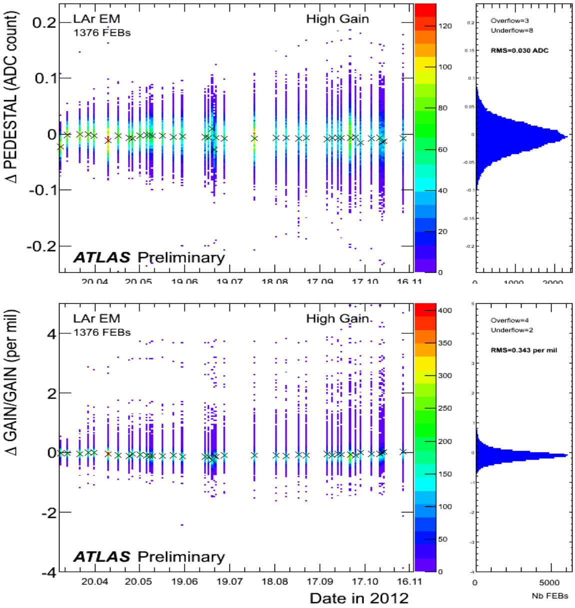


$$E_{\text{cell}} = F_{\mu\text{A}\to\text{MeV}} \cdot F_{DAC\to\mu\text{A}} \cdot \frac{1}{\frac{\text{M}_{\text{phys}}}{\text{M}_{\text{cali}}}} \sum_{i=1}^{M_{\text{ramps}}} R_i \left[\sum_{j=1}^{N_{\text{samples}}} a_j \left(s_j - p \right) \right]^i$$

- calibration runs taken regularly without beam by injecting a known exponential pulse from calibration boards, to measure the response of electronics in all three gains
- Pedestals obtained from random triggers (no input signal) runs (in addition noise & autocorrelation measured)
- OFCs computed from Delay calibration runs (signal shape measured with ∼1 ns binning), using both electronics and pileup (from MC) noise
- ADC to DAC is computed from Ramp calibration runs (gain measurement)
- $\text{M}_{\text{phys}}/\text{M}_{\text{cali}}$ is the response difference between physics (triangular) and calibration (exponential) input pulse
- Sampling fraction coefficient obtained from test beams

Calibration stability

- results from calibration runs are monitored for any variation
- calibration constants updated in database if a significant change is seen, typically once per month
- excellent stability with time observed, readout infrastructure is very reliable
- on plots the averages over FEB (128 channels) are shown for all calibration campaigns in 2012
- Pedestal stability **0.02 - 0.03 ADC** counts, relative gain stability **0.05 - 0.30 per mil**



LAr Data Quality Monitoring

- procedures to track and identify all potential problems with quality of data
- in real time during data taking monitoring all important detector parameters *(HV, temperature, purity, readout, timing, data integrity,...)*, issuing alarms to operators in case some problem appear
- more detailed checks performed offline on the recorded data
  - use a subset of data, promptly reconstructed, to identify potential "defects"
  - corrective actions (calibration change, various corrections updated,...) applied before bulk data processing (usually starts 48 hours later)
  - one more check on full statistics, once data are reconstructed
- procedures were constantly improved, seen on table of data fraction (percentage) considered GOOD quality for physics in pp collisions:

2010

LAr EM	LAr HAD	LAr FWD
90.7	96.6	97.8

$\longrightarrow$

2011

LAr EM	LAr HAD	LAr FWD
97.5	99.2	99.5

$\longrightarrow$

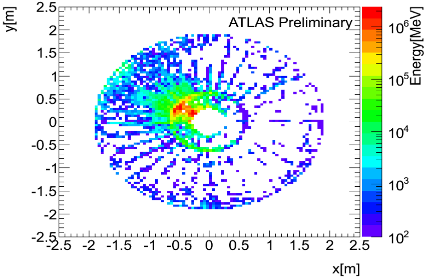
2012

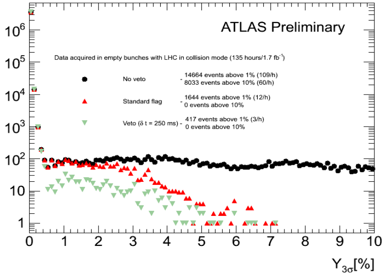
LAr
99.1

- in 2012 inefficiency comes mainly from:
  HV trips - 0.46%
  noise bursts - 0.2% (see next slide)

LAr Data Quality Monitoring - Noise Bursts

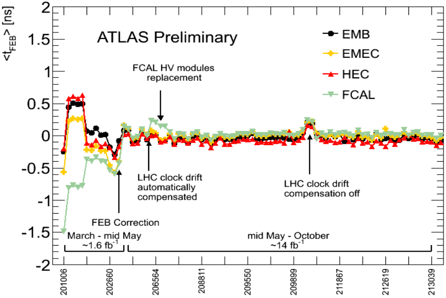
- large scale coherent noise, localized mainly in endcaps, only in the presence of collisions
- frequency of bursts scales with instantaneous luminosity, bursts are very short in time (typically $\lesssim 5\ \mu s$) with many channels noisy significantly above standard level
- example energy distribution of such noise burst on left plot
- using the shape Quality factor rejects hard noise bursts, using the time veto on events around identified noise events (in 2012 a 250 ms window was used) allowed good rejection with low inefficiency (0.2%)
- right plot shows the $Y_{3\sigma}$ (percentage of channels with signal above 3 $\times$ electronic noise measured in empty LHC bunches), which shows efficiency of two different cleaning methods used

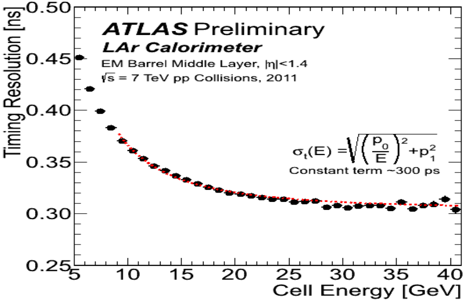




LAr signal timing

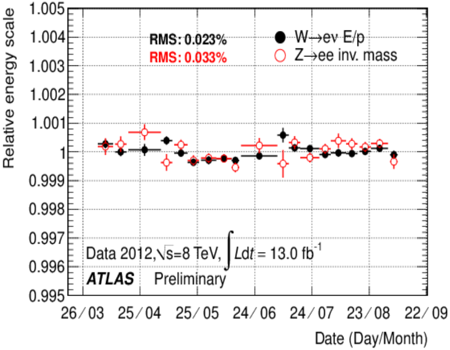
- stable and precise timing needed to measure out-of-time signals, to suppress cosmics and beam-induced background
- top plot shows the stability of FEBs timing throughout 2012
- online measured FEB to FEB dispersion has $\sigma \sim$ 0.10 - 0.17 ns, in offline channel-level corrections, calculated from $W \rightarrow e\nu$ events brings timing resolution to $\sim$ 300 ps for large energy deposits, which includes $\sim$ 220 ps correlated contribution from the beam spread

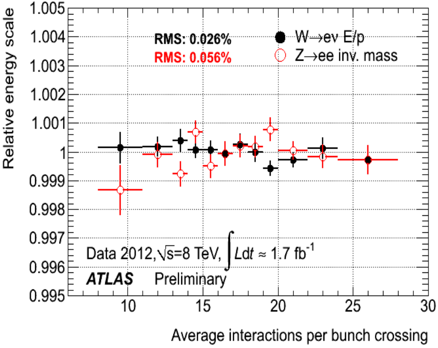




EM Energy reconstruction and resolution

- EM showers reconstructed as clusters of calorimeter cells, energy scale is set by using Z $\rightarrow$ ee events, $J/\psi \rightarrow$ ee is used to verify that MC is describing sampling and noise resolution terms well
- cross-check with W $\rightarrow$ eν events, energy compared to momentum from inner detector
- excellent stability over time (left plot), as well as with pile-up (right plot)



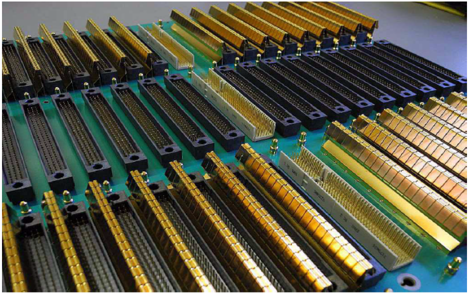


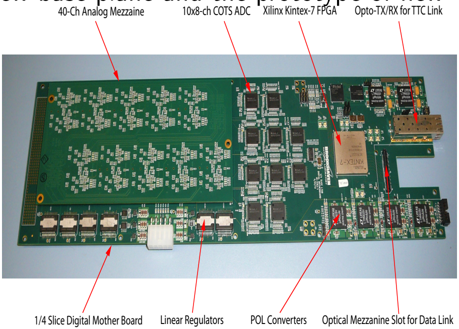
LAr upgrades Outline

- LHC already running close to design luminosity, after current shutdown (LS-1) restart in 2015 plans to exceed it (Run-2). After second shutdown (LS-2) in 2022 plan is to achieve $\sim 3 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Run-3), with ambitious plan of High Luminosity LHC beyond 2024 with luminosities $> 5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- LAr detector was not designed to run at this luminosity and some components can / may not survive planned integrated dose $\sim 3000\ \mathrm{fb}^{-1}$
- upgrade plans are accordingly grouped in 3 phases (0-2). Phase-0 currently ongoing, mainly consolidation of the electronics and installation of demonstrator for the phase-1
- phase-1 should cope with increasing trigger rates, L1 rate is limited to 100 kHz and current EM trigger selection would be 270 kHz in Run-3 lumi and pile-up conditions. Need to reduce it to 20 kHz without important acceptance loss
- phase-2 should address main issues:
  - performance of the readout electronics
  - HEC GaAs cold electronics
  - issues for the FCal, where ion buildup affects electric field in the gap, where higher current cause significant voltage drop across resistors inside cryostat and high ionization load could potentially boil the LAr

Phase-0

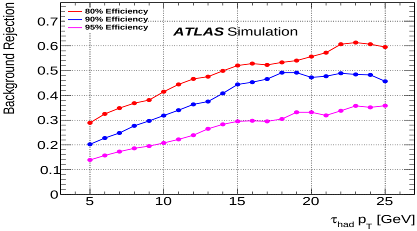
- maintenance of the electronics (repair $\sim$ 20 FEBs), update the software for online,HV, DCS, improve calibration speed, replace part of HV modules
- install new low voltage power supplies from Wiener
- L1 trigger rate will be increased to 100 kHz after LS-1, LAr is ready for this, providing only 4 samples are digitized and transmitted from readout. Performance impact is currently under study
- installation of demonstrator for the Phase-1 upgrade of the L1 calo trigger - details on next slides, here is shown the new base-plane and the prototype of new digital trigger board

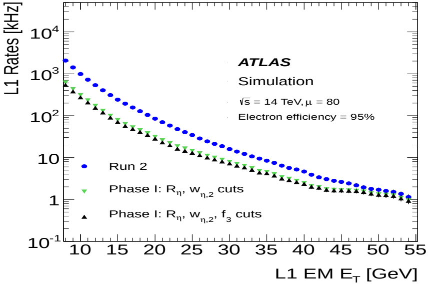




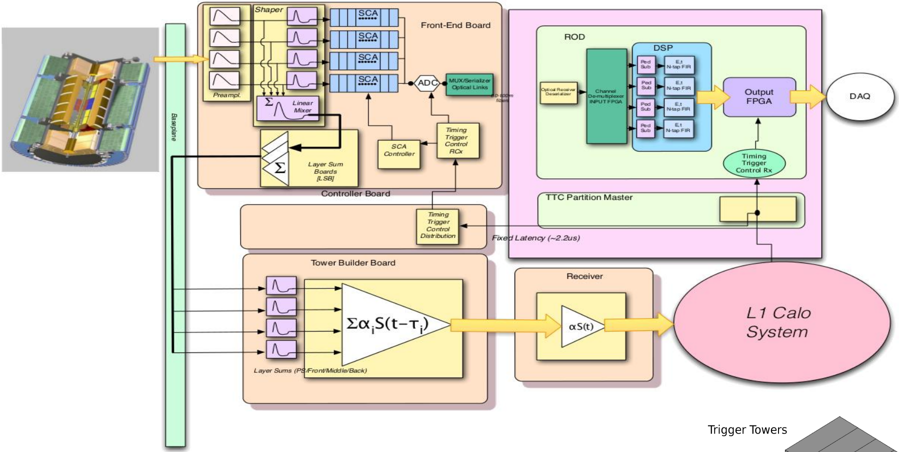
Phase-1 Trigger Upgrade

- increasing instantaneous luminosity brings very high trigger rates, increasing thresholds is not a solution - acceptance loss
- using higher granularity in trigger should maintain or even increase efficiency, reduced transverse energy (E_T) thresholds will increase the acceptance for measuring Higgs properties and looking for new physics including SUSY and extra dimensions
- using some shower shape variables (like $R_\eta = E_{3\times2}/E_{7\times2}$) allows better discriminate electrons and jets and keep E_T thresholds low (28 GeV) (right plot)
- apply rejection criteria similar to offline in order to reject the QCD background jets (left plot)

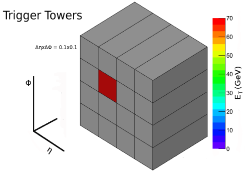




Phase-1 - Current Scheme

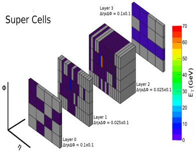


- analog energy sums for trigger input, granularity $\Delta\eta \times \Delta\Phi = 0.1\times0.1$, no longitudinal segmentation
- only "simple" algorithms possible



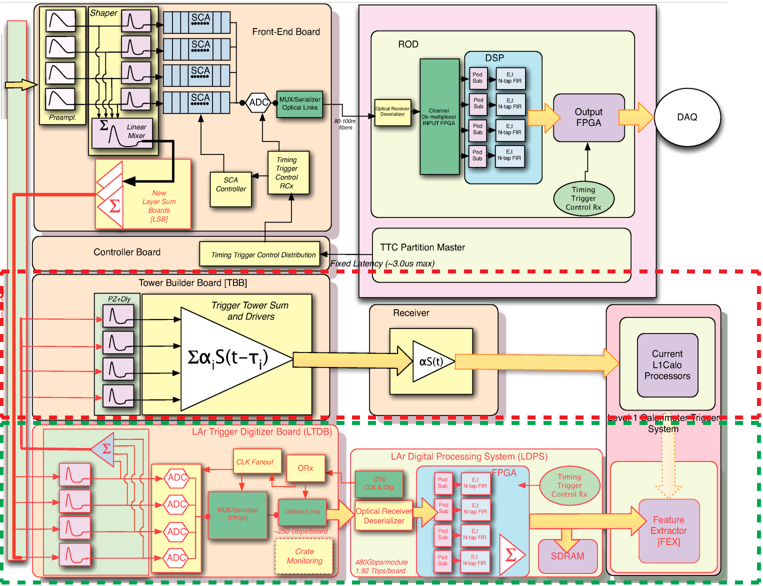
Phase-1 - L1 Trigger Upgrade

New granularity, 4 layers, $\Delta\eta \times \Delta\Phi = 0.025\times0.1$ in Front and Middle, Super Cells (SC)



Kept old boards for compatibility

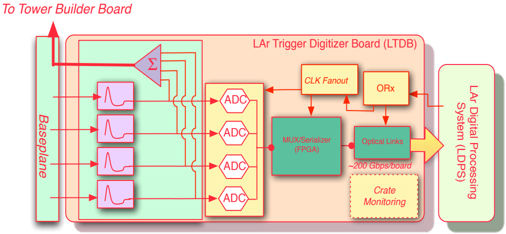
New LAr Trigger Digitizer Board (LTDB)

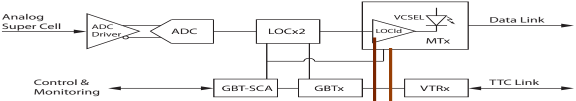


More sophisticated system allows advanced algorithms for object selection and ID

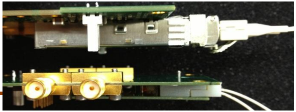
Phase-1 - Digitizer and Data Transmission

- each LTDB process up to 320 SC signal
- high performance ADC (40 MHz, low power consumption), 1 commercial and custom designs under tests
- LTDB designed for digital precision 32 MeV in Front and 125 MeV in Middle layers



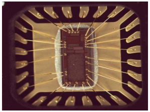


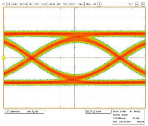
- physical size of transceiver crucial, no commercial modules with height < 6 mm available
- serialization of multiple ADC channels required - 8 multiplexed to 5.12 Gbps stream
- in total 20 2-channels transmitter modules per LTDB



SFP+ (14 mm)

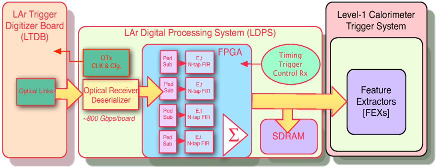
MTx (6 mm)

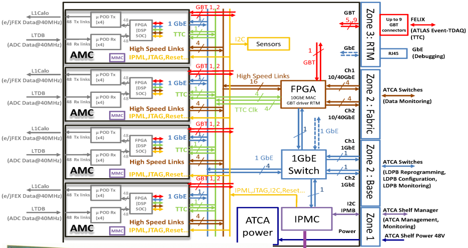


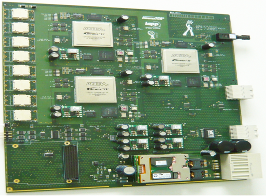


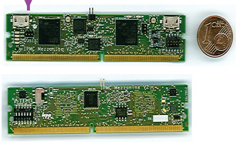
Phase-1 - Data Processing

- LAr Digital Processing System (LDPS) gets data from LTDB (~25 Tbps), reconstructs E_T, time and transmit to L1 Calo Trigger (~41 Tbps)
- LDPS providing also monitoring, TTC distribution, configuration
- LAr Digital Processing Blade (LDPB) is ATCA carrier board, with 4 Advanced Mezzanine Cards (AMC) for data processing
- 31 LDPBs required, with 124 AMCs in total
- strict latency limit for E_T and time algorithm (5 to 6 bunch crossing)
- several options for filtering investigated:*5 samples OF, OF_{max} - current L1 Calo, OF_χ, Wiener filter with forward correction*

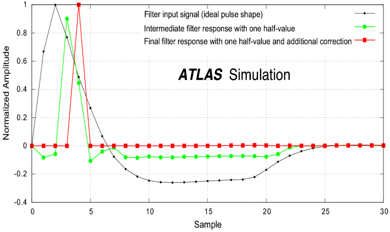


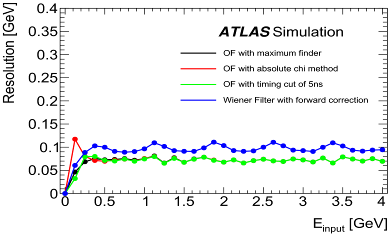




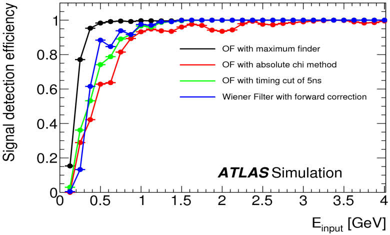


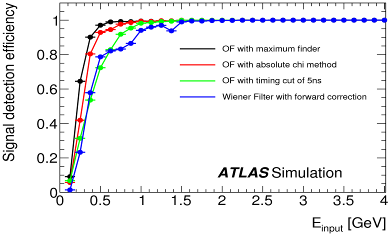
- Wiener filter working principle on left plot, intrinsically pile-up robust and bunch train independent, expected resolution (slightly worse) right plot





- Signal detection efficiency for different filters for fast (left) and slowly (right) rising pulses. In-time and out-of-time pileup effects as well as electronics noise are included





Phase-2 Readout and Detector Upgrade

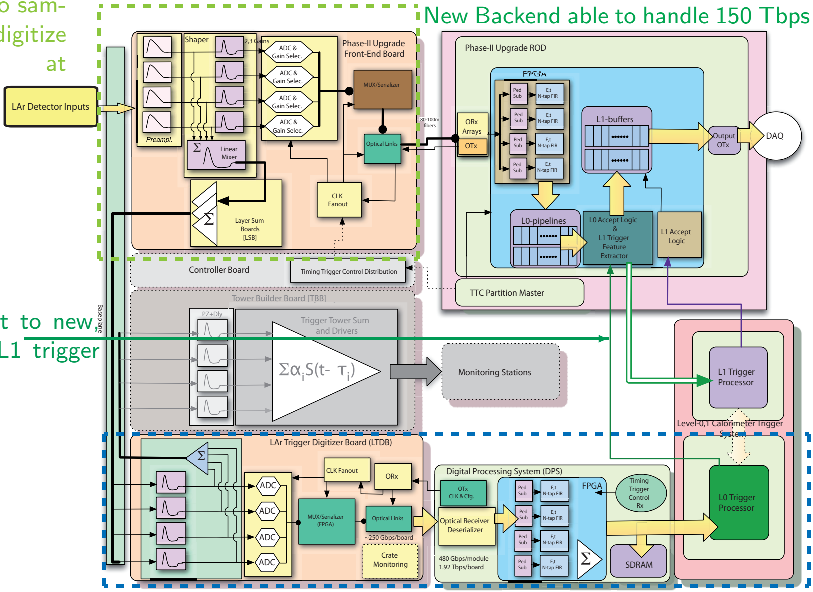
- planned HL-LHC luminosity ($\mathcal{L}_{\text{inst}}$=5-7 $\times$ 10^{34} cm^{-2}s^{-1}, $\mathcal{L}_{\text{int}}$ >3000 fb^{-1}) create issues:
  - front-end electronics performance - new readout architecture is planned. L1 trigger developed for Phase-1 become a L0 trigger in Phase-2
  - potentially for HEC cold electronics - currently intensive study of potential damage and replacement scenarios
  - potentially for the FCal detector:
    - voltage drops due to high current drawn at high rate - current limiting resistors are inside the endcap cryostat
    - increasing heat due to higher rate and ionization
    - space charge effects due to high ionization rate (*see talk by J. Rutherfoord in this session*)
  - Investigations are currently ongoing, whether the performance of the current FCal will be sufficient at HL-LHC luminosities. If not, possible FCal upgrade should maintain it, two approaches under development (replace the FCal with improved detector or place small calorimeter in front of present FCal)

Phase-2 New Readout Architecture

New FEBs to sample and digitize continuously at 40 MHz

New Backend able to handle 150 Tbps

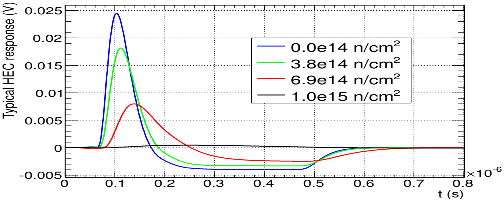
Provide input to new, fully digital L1 trigger system

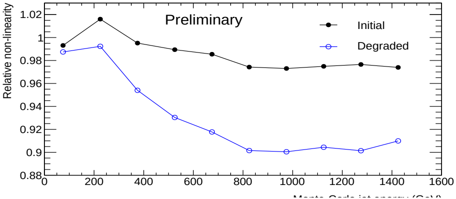


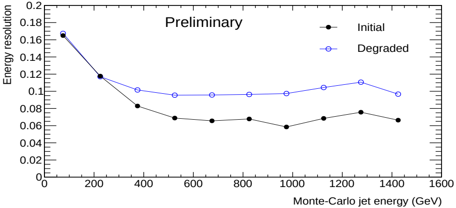
Phase-1 upgrades used to create new Level-0 trigger

Phase-2 HEC Electronics Replacement

- HEC cold electronics chips under proton and neutron irradiation tests to check degradation under HL-LHC doses
- top plot shows changes in typical signals from degraded HEC preamp (expected HL-LHC dose is in the middle between green and red)
- the most worrying issue is non-linearity in preamps,
  4 preamps are summed and calibrated together, individual preamps as well as 'system' could be measured
- effect on physics needs to be simulated, degradation on scale and resolution seen (middle and bottom plot)

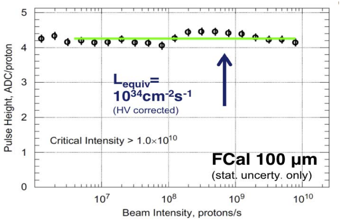


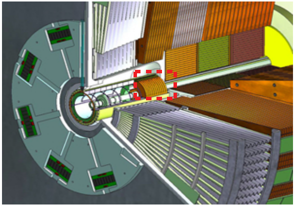


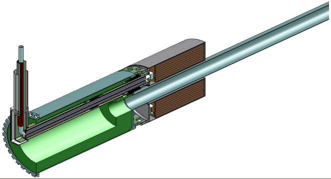


Phase-2 FCal Upgrade Options

- first option for FCal upgrade is replacement, similar to existing one, but:
  - smaller LAr gaps ≈(100/200/300 μm), small prototype tested in Protvino (top plot)
  - need new cooling loops, new summing boards with lower value resistors
- second option is small calorimeter in front (middle plot), which absorb some of the energy upstream of inner part of the FCal
  - warm option with diamond sensor was studied, but this option is closed now
  - warm option with Cu absorber and high-pressure Xenon possible (still need basic RD on gas properties up to 10 bar)
  - cold option (Cu + LAr with FCal design) seemed problematic because lot of material for piping and feed-throughs
  - new engineering studies showed possibility to put feed-through not in front of Calorimeter (bottom fig.), in progress







Conclusions

- ATLAS LAr Calorimeter has achieved excellent performance and stability during the three years of LHC operations, without any significant hardware or software problems
- Constantly improving the hardware (HV system), monitoring and data quality procedures ATLAS LAr team was able to achieve $>$99% efficiency of data GOOD for physics in 2012
- Upgrade preparations for running the ATLAS LAr Calorimeter with higher luminosities are progressing well
- Phase-1 upgrade TDR was endorsed already, demonstrator setup is already in preparation to install in ATLAS during LS-1 this year
- options for running ATLAS LAr Calorimeter in HL-LHC are intensively studied and road map is already set

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