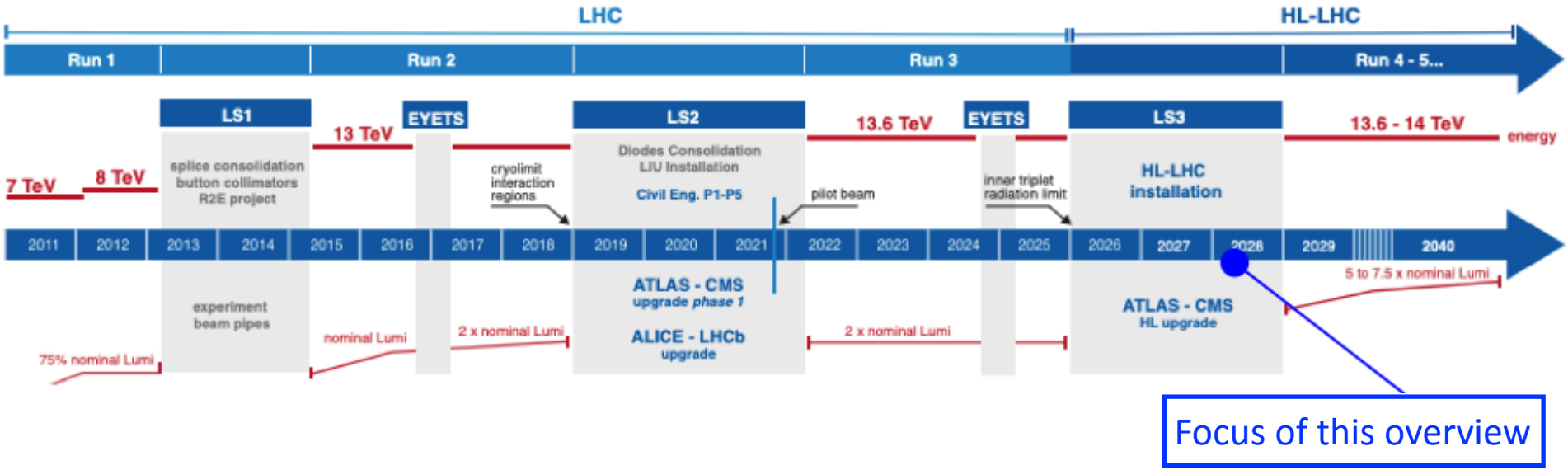
General overview of the ATLAS Upgrade Projects for HL-LHC

Heinz Pernegger (CERN) on behalf of the ATLAS Collaboration

15th Pisa Meeting, May 22-28, 2022

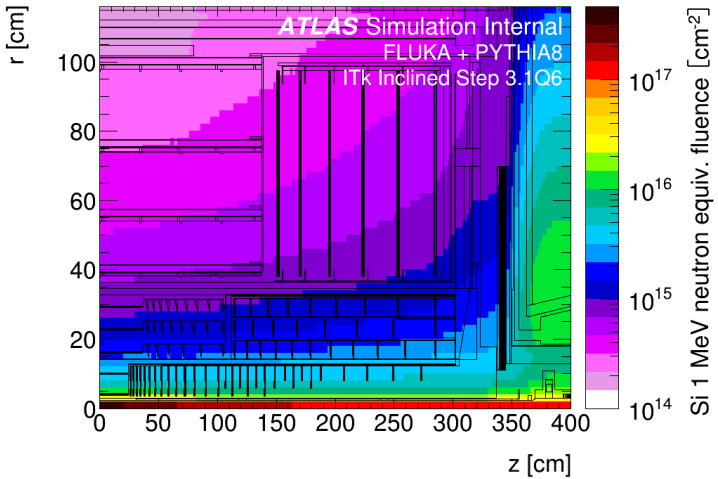
The ATLAS Upgrade Programme for HL-LHC

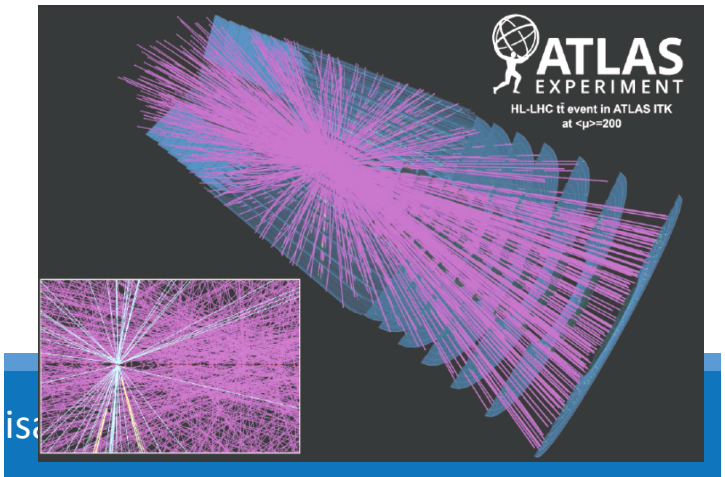


- HL-LHC enables a broad physics programme through a 10-fold increase in luminosity starting after Long-shutdown 3 (LS3)
  - recently CERN approved LS3 start with December 2025 and will last 36 months
  - ATLAS just completed its Phase-I upgrade (e.g. New Small Wheel muon detector) and pursues all HL-LHC Phase-II Upgrade projects now in parallel to Run-3 data taking

Challenges for pp-experiments at HL-LHC

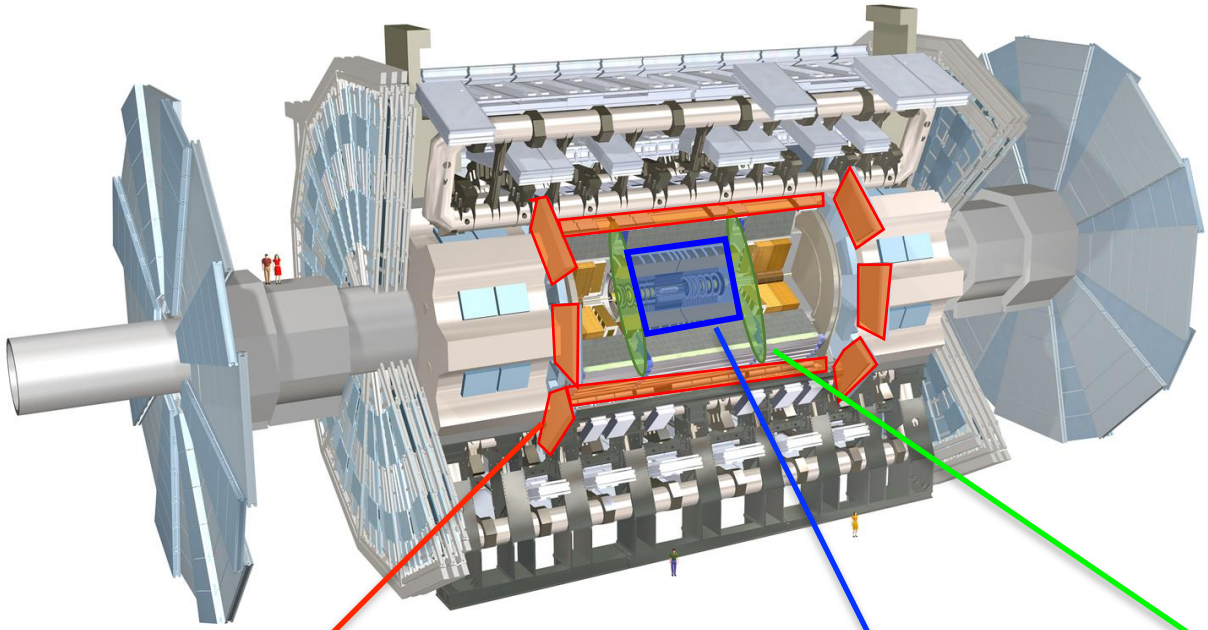
- → Instantaneous nominal luminosity x 5-7 and integrated luminosity x10
  - New radiation hard sensors - complete new tracker
  - Finer sensor granularity
- → Increase of overlapping proton-proton events (pile-up) from <μ> ~ 50 now to <μ> ~ 200
  - Additional energy in calorimeters, accumulation of “pile-up” jets especially in the forward region
  - High hit rates of up to 3GHz/cm^2 in tracker center
- → Increase readout rate 10-fold (L0 trigger rate 1 MHz)
  - requires new front-end and/or back-end electronics for many sub-detectors
  - new DAQ and trigger system to cope with complex high-rate trigger and band-width requirements





Simulated event with ttbar events and average pile-up of 200 collisions per bunch crossing

ATLAS Phase-II Upgrade Projects



Upgraded Trigger and Data Acquisition System

- Single Level Trigger with 1 MHz output
- Improved 10 kHZ Event Farm

Electronics Upgrades

- On-detector/off-detector electronics upgrades of LAr Calorimeter, Tile Calorimeter & Muon Detectors

Talk by F. Tartarelli: Friday Electronics

Forward detector upgrades

- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

New Muon Chambers

- Inner barrel region with new RPCs, sMDTs, and TGCs
- Improved trigger efficiency/ momentum resolution, reduced fake rate

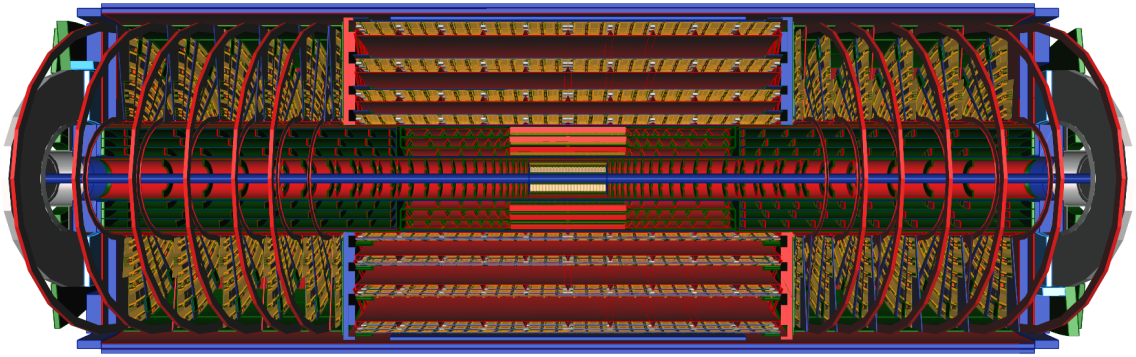
New Inner Tracking Detector (ITk)

- All silicon with at least 9 layers up to $|\eta| = 4$
- Less material, finer segmentation

High Granularity Timing Detector (HGTD)

- Precision time reconstruction with Low-Gain Avalanche Detectors (LGAD)
- Improved pile-up separation and bunch-by-bunch luminosity

ITk Tracker Upgrade



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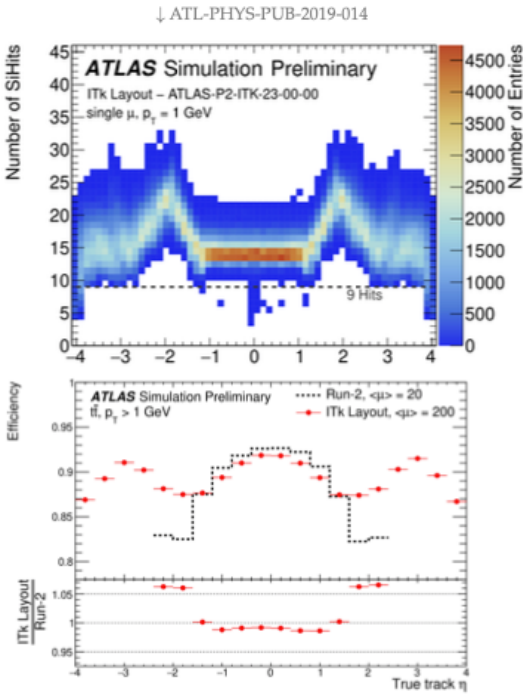
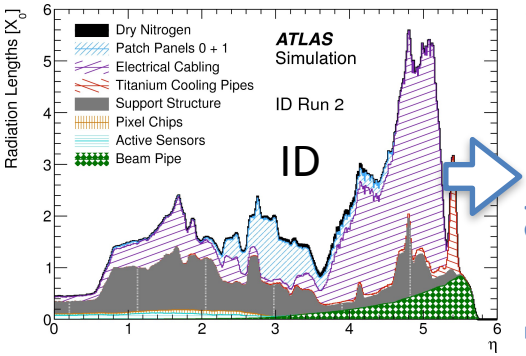
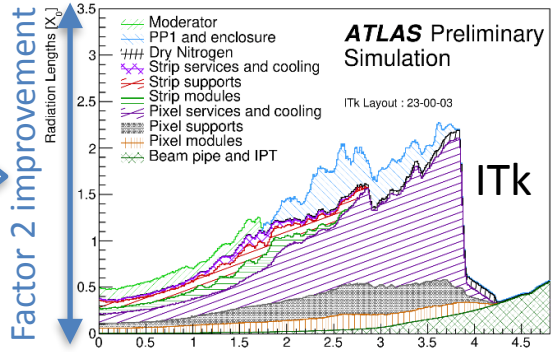


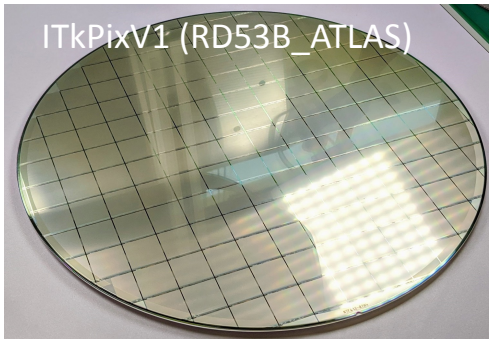
- ITk tracker consists of outer strip tracker and inner pixel tracker to replace current ATLAS "Inner Detector"
  - 168 m² of silicon strip and 10 m² of silicon pixel
  - designed to withstand up to 10^{16} n_{eq}/cm^2 on inner most pixel
- Improve impact parameter resolution and robust tracking
  - Coverage increases from $|\eta|<2.5$ (ID) to $|\eta|<4$ (ITk)
  - Provides >9 silicon hits per track
  - Reduced material and finer segmentation
- Current status & activities
  - Global ITk support mechanics in production
  - CO_2 Cooling studies and optimisation
  - Preparation for ITk integration in ATLAS Point 1

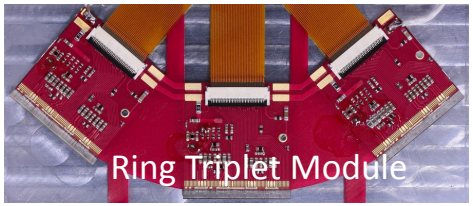


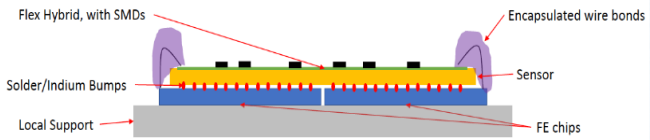


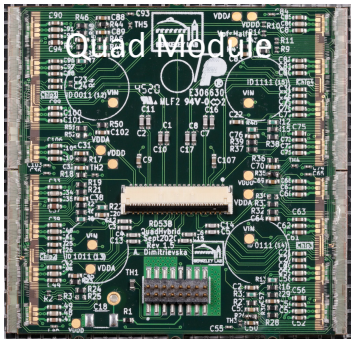
ITk Pixel Detector Modules

- 5-Layer pixel system with a total of ~ 10000 pixel modules
  - 2-layer inner system replaceable (e.g. after 2ab-1) ATLAS-TDR-030
- Pixel Front-end chip: Joint development for ATLAS and CMS by RD53 collaboration
  - 50×50 μm² pixel size, 153k pixel per FE, pixel module consists of 3 or 4 FE chip
  - Successful prototyping with RD53A and ITKPIXV1 chips
  - Chip yield on after after 50 wafer tested ~ 80%
  - Currently finalise ITKPIXV2 production FE-chip for submission
- Sensors - Hybridization - Modules
  - 3D sensors with 25×100 μm² pixel size in L0 barrel and 50×50 μm² pixel size in L0 disks
  - Planar n-in-p detectors of 100 μm (L1) or 150 μm (L2-4) sensor thickness
  - All sensors are in pre-production with most pre-production batches received
  - Hybridization (= bump-bonding) to ITKPIXV1 pre-production modules has started
  - RD53A electrical modules and first ITKPIXV1 electrical modules tested successfully



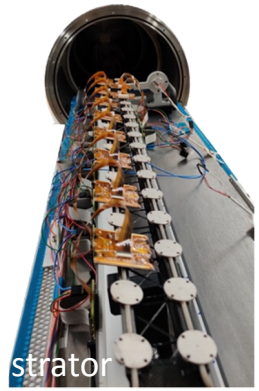


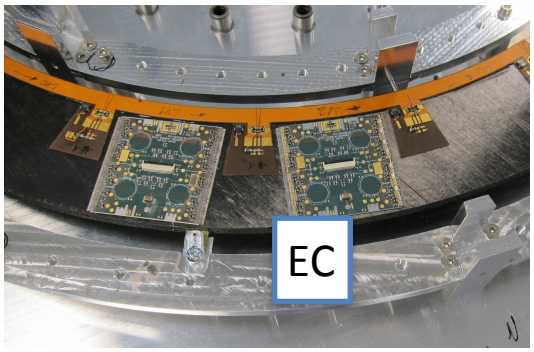


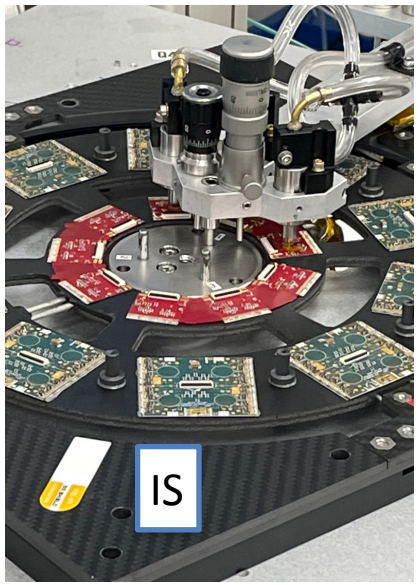


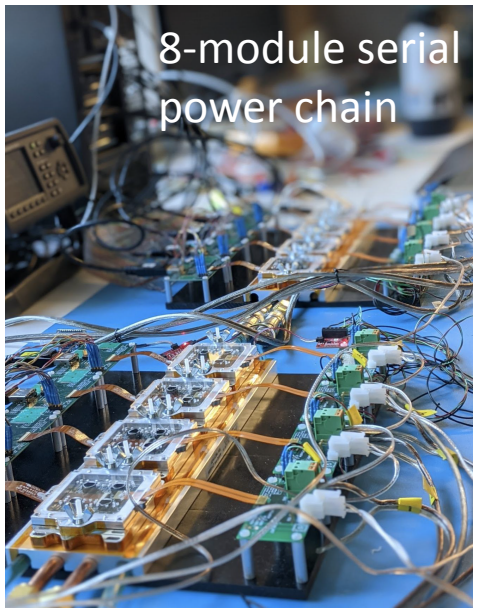
ITk Pixel Detector Mechanics and System

- Carbon fibre support for pixel modules passed thermal and mechanical qualification
  - first prototype staves & rings are currently loaded with RD53A modules
  - qualify module loading and electrical tests on support mechanics
  - prototype services for electrical readout at 1.28Gbps in hand
- Powering based on serial powering concept
  - chain of up to 13 modules are fed with constant current and chip voltage produced inside FE-chip
  - First two 8-quad module long serial powering chains built and under test



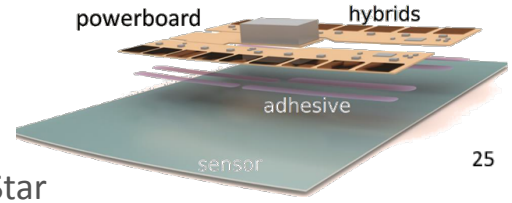


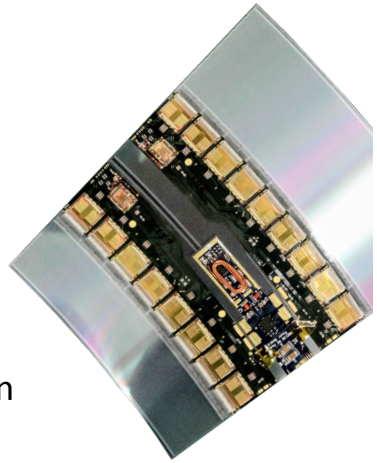




ITk Strip Detector Modules

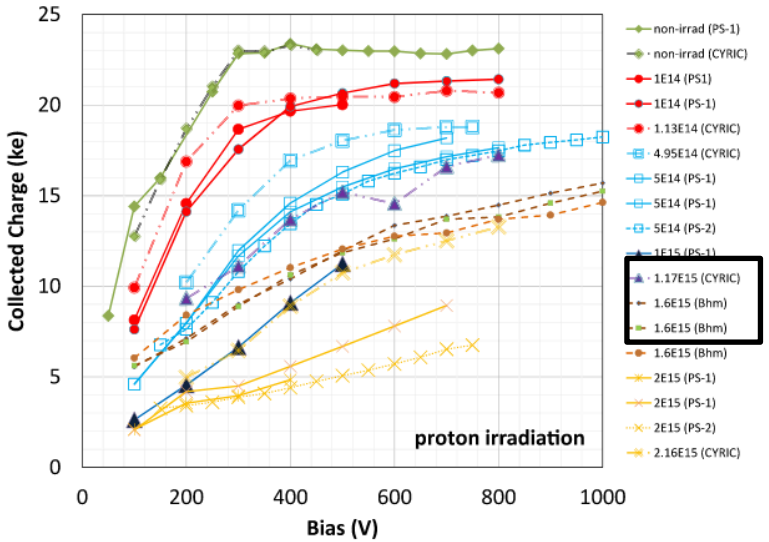
- 18000 silicon strip modules
  - 2560 or 5120 strips/modules
  - developed 3 dedicated ASICs ABCStar (FE), HCCStar (hybrid controller) and , AMACStar (analog monitor/ctrl)
  - sensors in production
- Three dedicated ASIC
  - ABCStar extensively SEE tested in heavy-ion and proton beams production order placed
  - HCCStar andAMACStar pre-production delivered and currently under test
- Sensors in production
- Hybrid and modules in pre-production
  - performance and yield as expected

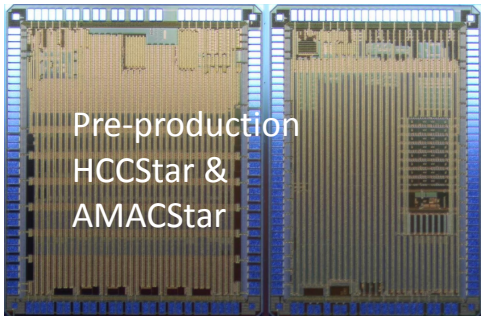


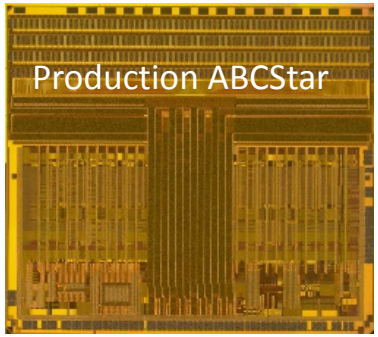


Max expected + safety:
1.6 x 10^{15} n_{eq}/cm^2

Nucl. Inst. Meth, A 983 (2020) 164422

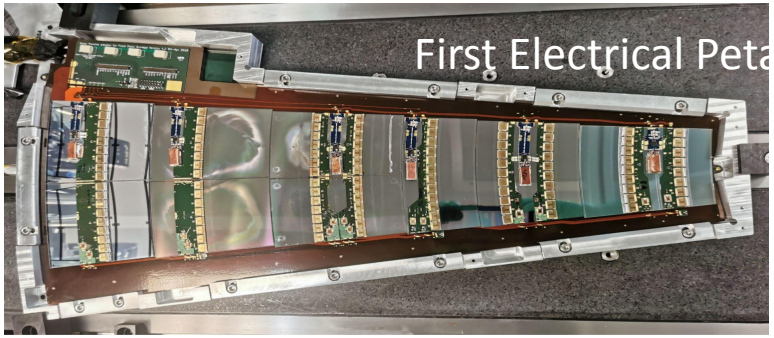


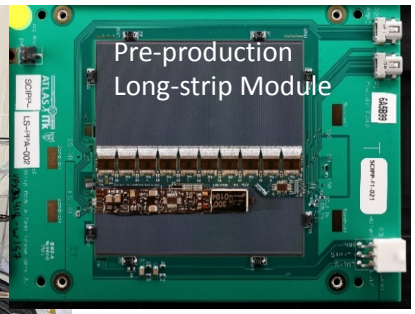


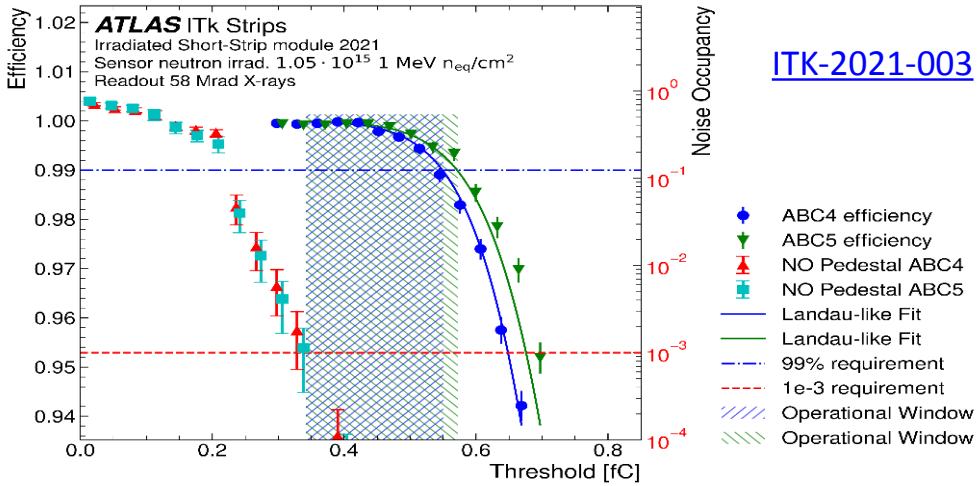


ITk Strip Detector Barrel and Endcaps

- Strong progress in modules & mechanics
  - First electrical petal complete (13 hybrid, 9 module types)
  - Irradiated short-strip modules with production ABCStar had wide operating window after 150% maximum fluence
- Local mechanics also in pre-production
  - Endcap petal cores assembled successfully in industry
- Global mechanics are in production
  - Most elements nearing completion in end-cap







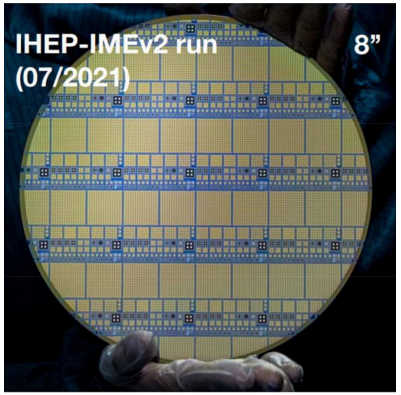
ITK-2021-003

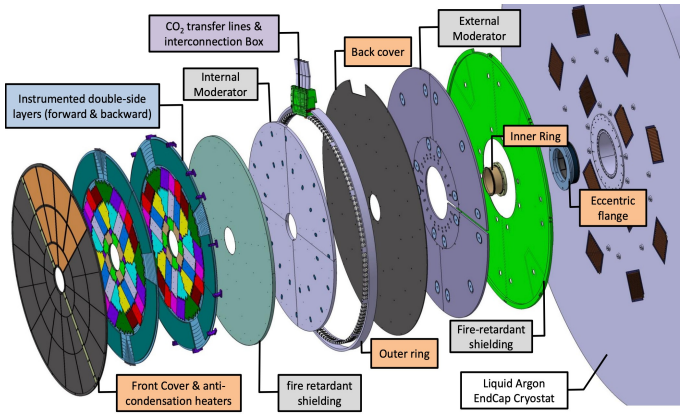
Talk by L. Gonella: Tuesday Silicon session

High-Granularity Timing Detector

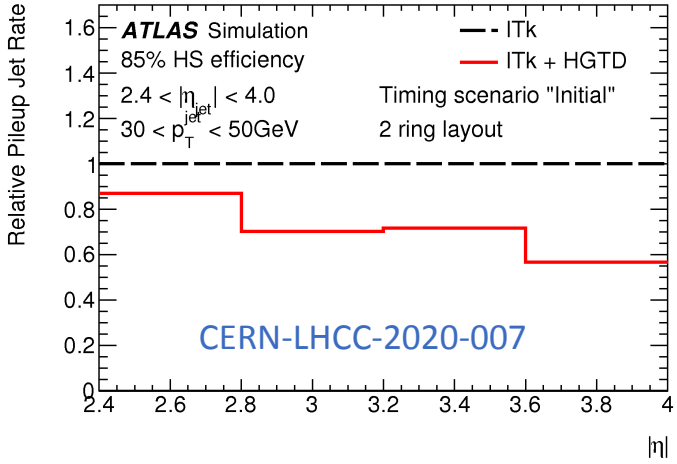
- New HGTD detector to resolve pile-up through hit timing information
  - installed between ITK and EC calorimeter $2.4<|\eta|<4.0$
  - 4 layer of LGAD to achieve 30ps-50ps timing resolution (70ps per hit)
  - also provides bunch-by-bunch luminosity measurement
- HGTD modules
  - LGAD sensor with 1.3x1.3 mm² pixel size
  - bump-bonded to FE-ASIC ALTIROC

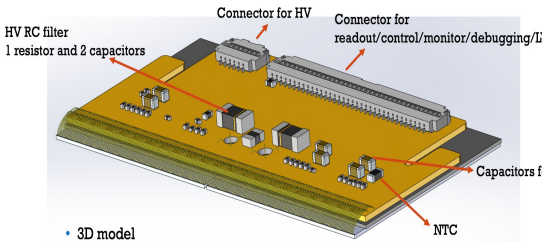
[ATLAS-TDR-031]





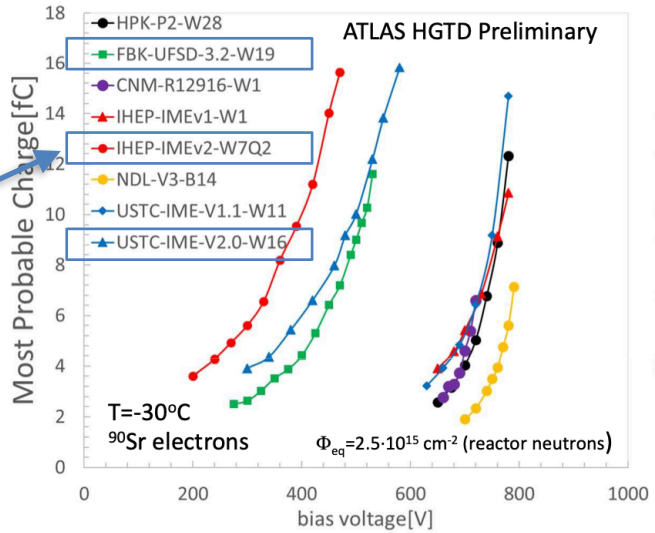
Pileup Jet rejection with and with out HGTD



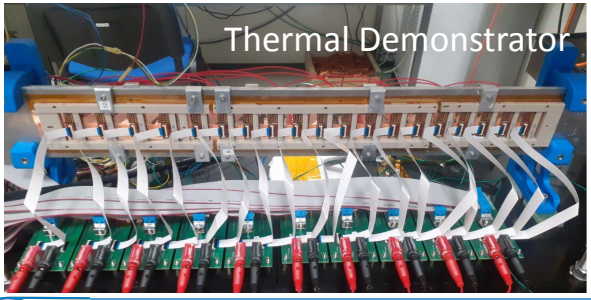


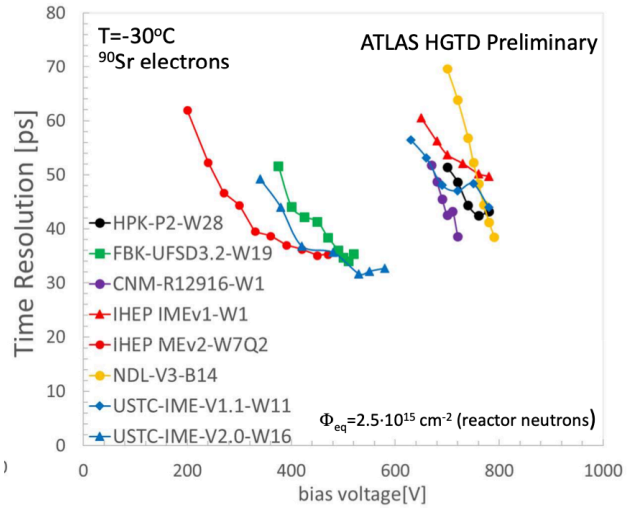
High-Granularity Timing Detector

- Present status sensors & modules
  - first hybrids with ALTIROC2 FE chip and FE-chip functionality demonstrated
  - Carbon infused sensors more robust against Single Event Burn-out (SEB) with stable operation at lower voltages
- Services and mechanics
  - construct thermal demonstrator to qualify cooling and mechanics support



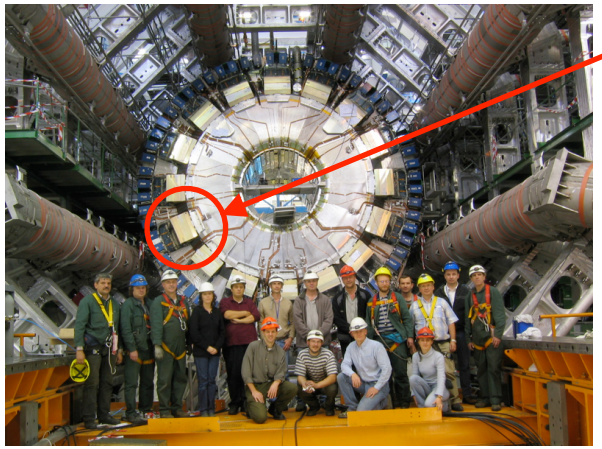
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HGTDPublicPlots



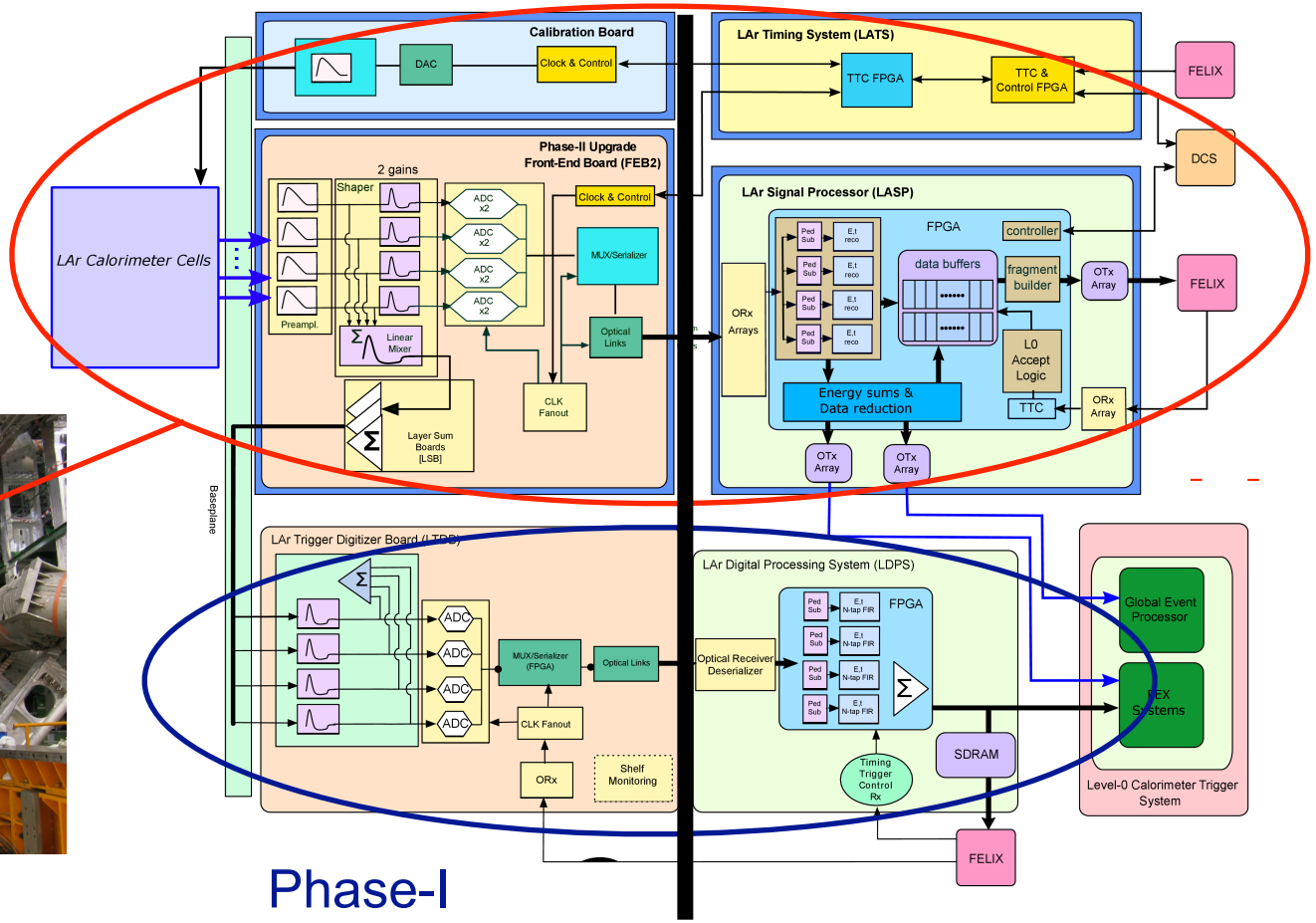


LAr calorimeter: Upgrade Front-end and readout

Fine-grained lead/copper/ tungsten - liquid Argon sampling calorimeter
-~180,000 cells
-At shower max,
Δη x Δφ = 0.025 x 0.025



Phase-II

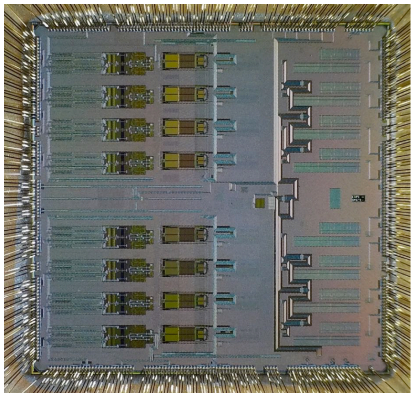


Phase-I

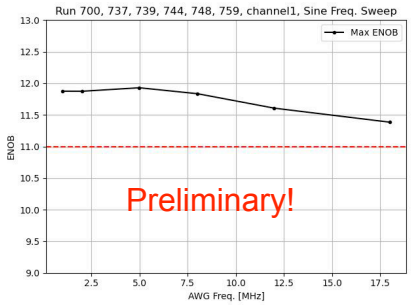
~10x fewer boards, less stringent analog requirements

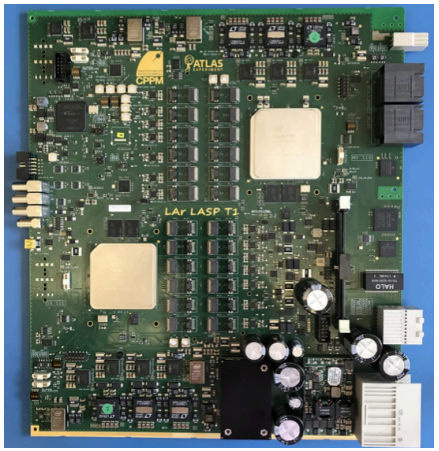
LAr calorimeter Upgraded Front-end and readout

- Need linearity ~0.1% up to 300 GeV (for precision physics, e.g. Higgs and W mass), electronics noise < MIP (for calibration), minimal saturation for large signals $\Longrightarrow$ 16-bit dynamic range with 11-bit precision (implemented in 2 overlapping 14-bit gains)
- Four LAr-specific ASICs:
  - Preamp[pre-shaper for HEC]/shaper
  - ADC
  - Calibration DAC and pulser
- Transmit data off-detector at 40 MHz
  - 225 Gbps/board: lpGBT + VL+ chipset
  - (345 Tbps full calorimeter)
- Filter digital waveform to extract energy and time
  - LAr Calorimeter timing resolution ~200 ps!
  - High-end FPGAs on ATCA boards, ~33k inputs at 10 Gbps
- Transmit data to L0 trigger and DAQ
  - 25 Gbps links

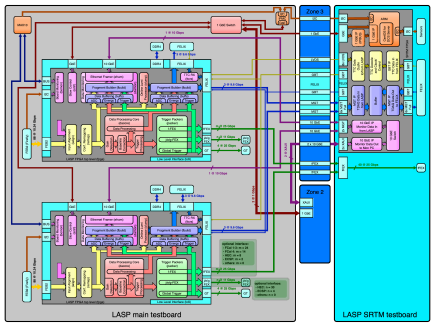


ADC prototype (65 nm CMOS):
octal, 15 bit, 11+ ENOB

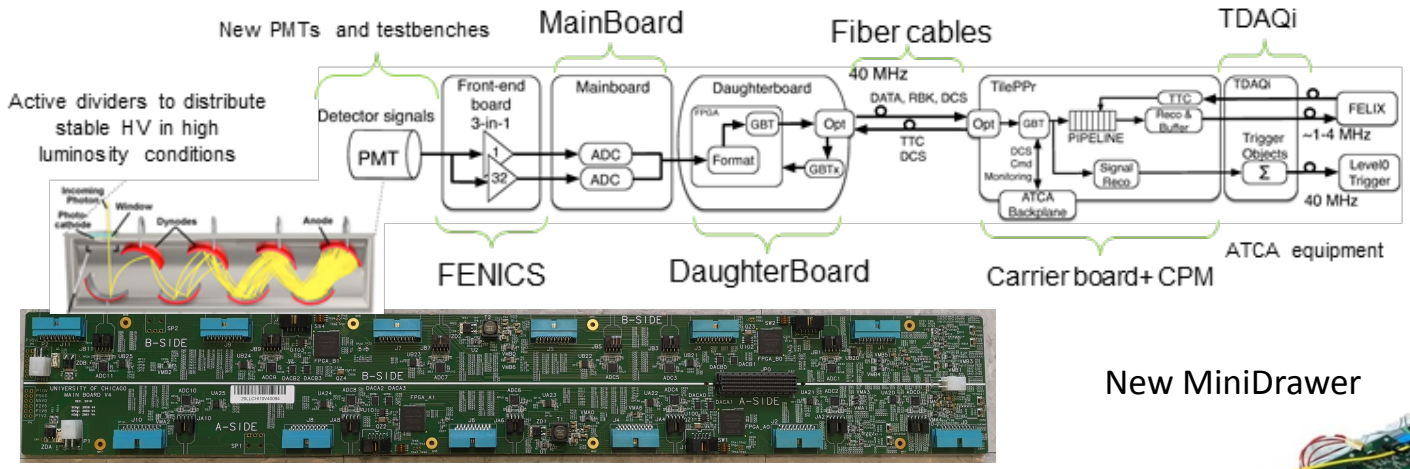


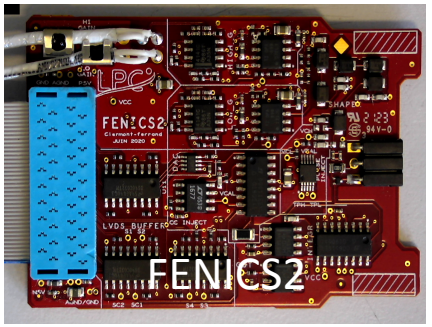


ATCA Test Board:
2 STRATIX 10, 24 Fireflies

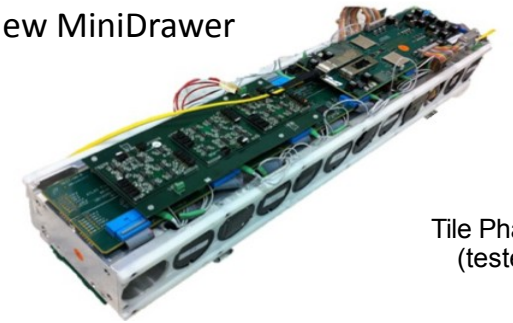


Hadron Calorimeter (Tile) Upgrade electronics



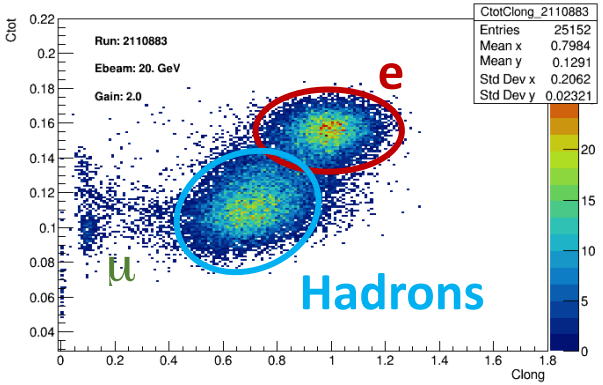


New MiniDrawer

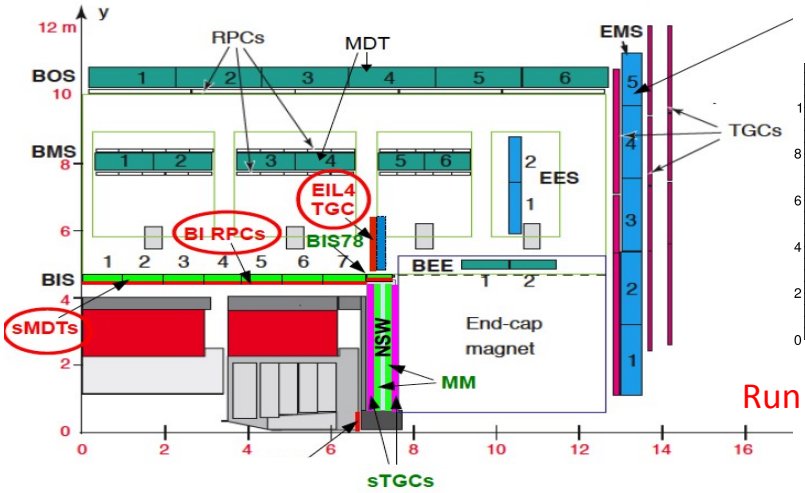


Tile Phase-II demonstrator (tested in test beams)

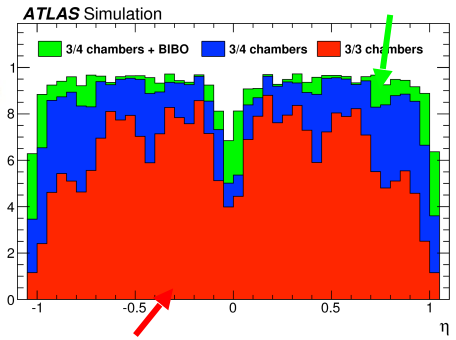
- Full replacement of front-end and back-end electronics
  - Modified mechanics for easier access/maintainability
  - Fully digital readout data and input to trigger system
  - Replacement of 10% of the PMTs
- Most on-detector items are in pre-production
  - Daughter board prototype evaluation nearly complete
  - Mini-Drawer Mechanics well into production
- Pre-production electronics operated together at SPS test-beam
  - And performs as expected
- Off-detector electronics prototype under evaluation



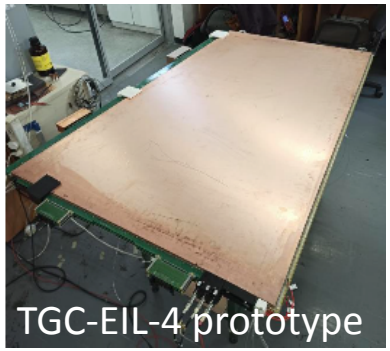
Muon Detector and Electronics upgrade

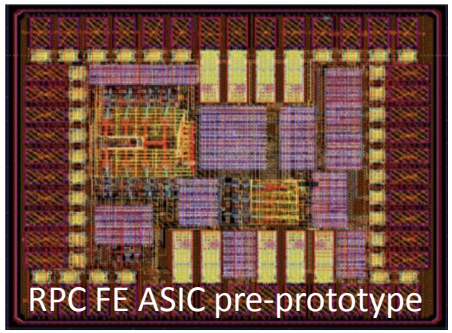


trigger acceptance upgrade



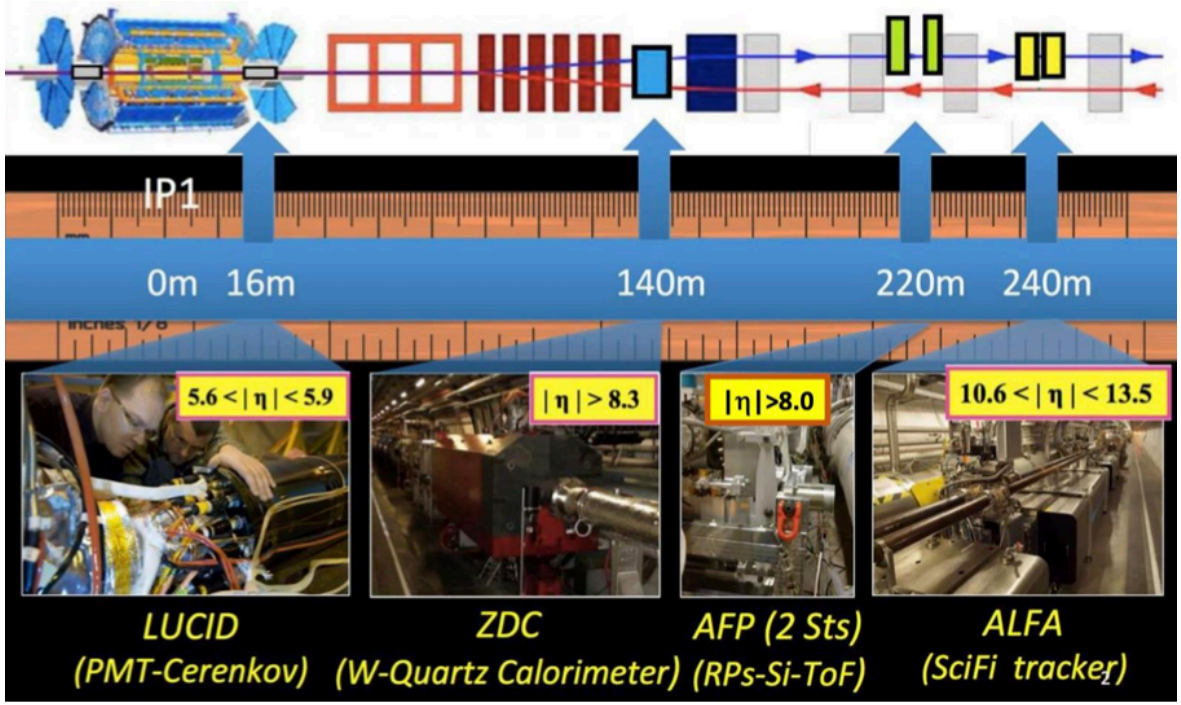
Run 2-trigger in HL-LHC conditions

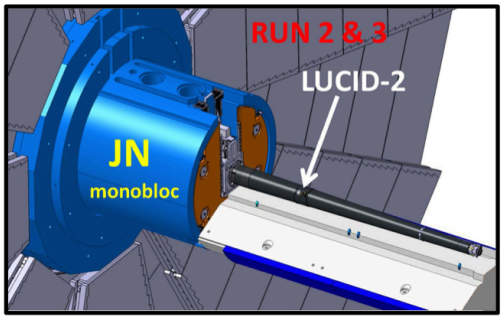


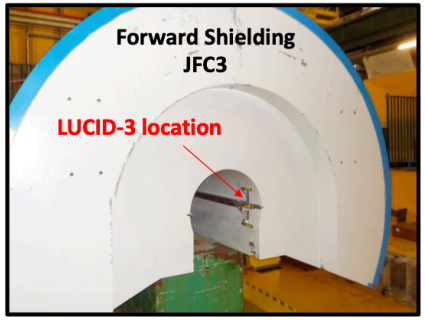


- Upgrade readout/trigger electronics
  - all hit data is sent off detector to trigger logic boards with L0 trigger rate of 1MHz
- Addition layers of sMDT, RPC, and TGC to
  - improve coverage, trigger uniformity & momentum resolution, reduce fake rates
- Current status
  - sMDT: chambers in production, electronics near pre-production
  - RPC: FE prototypes submitted, prototype chamber nearly complete
  - TGC: Triplet prototype completed, FE ASIC production complete

Forward Detector system



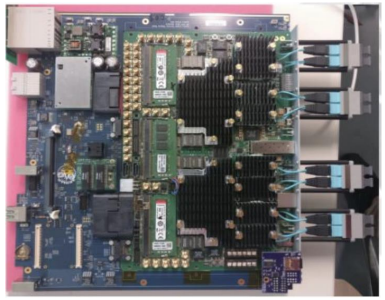




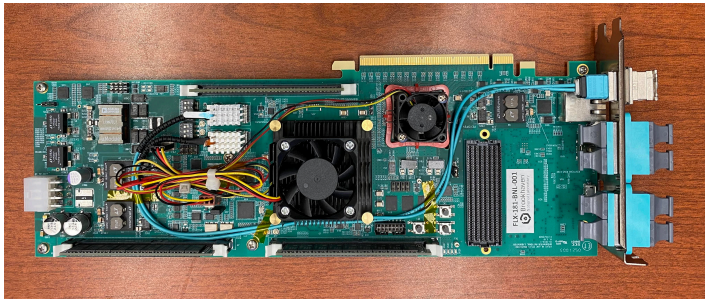
- Stable and precise luminosity measurement in forward direction
  - BCM' : diamond based beam conditions monitor to monitor beam and provide bunch-by-bunch luminosity measurement (inside ITk)
  - HGTD also provides bunch-by-bunch luminosity measurement
  - PLR: Pixel luminosity rings based on silicon pixel detector (inside Ink volume)
  - New LUCID3: Cherenkov integrating luminosity monitor based on Cherenkov hit counting in new location
- Heavy Ion Physics programme
  - New Zero-Degree-Calorimeter (ZDC) in development for HL-LHC Run 4

DAQ and Trigger upgrade for HL-LHC

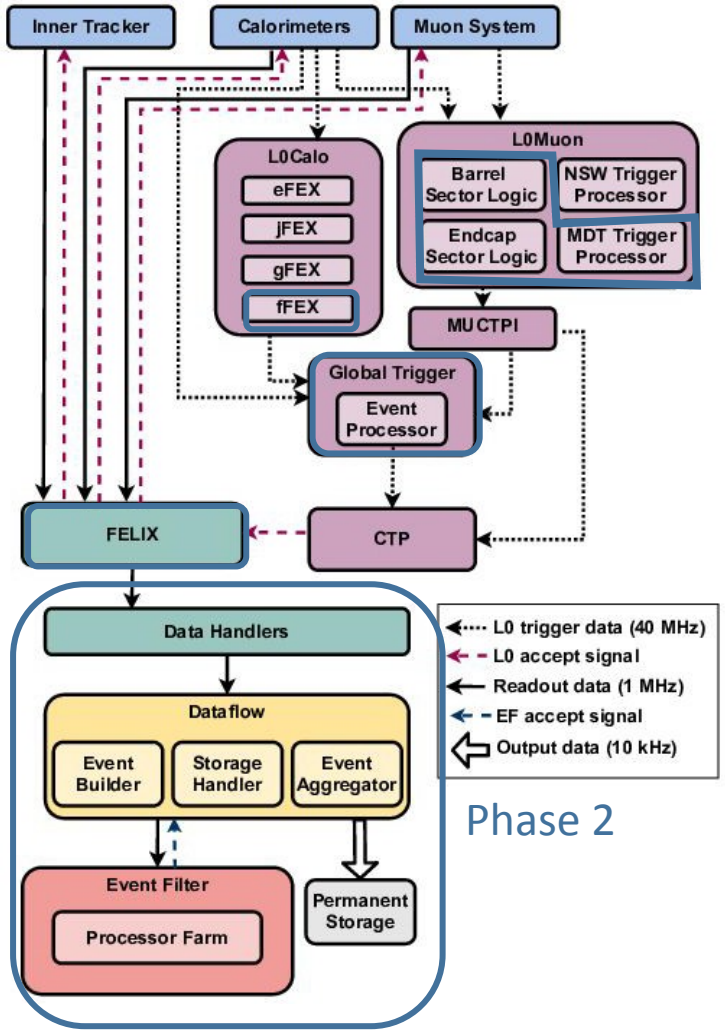
- Move to 1 MHz single-level HW trigger for all systems
  - Level 0: 1 MHz, ~5.2 TB/s, latency 10 μs
  - Event Farm: 10 kHz, ~52 GB/s
- Exploit full detector granularity and extended tracking range, improve muon trigger efficiency
- FE electronics linked via FELIX readout to DAQ
- Prototypes of FELIX, jFEX, L0Muon Trigger, & Global Trigger under evaluation



L0 muon trigger prototype



FELIX Phase-II prototype



ATLAS Upgrade presentations and poster

- **Laura Gonella : Solid State Detector session on Tuesday - The ATLAS ITk Detector System for the Phase-II LHC Upgrade**
- **Francesco Tartarelli : Electronics session on Friday - ATLAS toward the High Luminosity era: challenges on electronic systems**
- Daniela Bortoletto : Detector Systems poster - Expected tracking and readout performance of the ATLAS Phase-II Inner Tracker Upgrade
- Nicolas Viaux : Detector Systems poster - The ATLAS New Small Wheel new Muon Stations Ready for LHC Run3
- Tobias Bisanz : Detector Systems poster - Operational Experience and Performance with the ATLAS Pixel detector at the Large Hadron Collider
- Federico Lasagni Manghi : Detector Systems poster - The upgrade of the ATLAS Luminosity detector (LUCID) for HL-HLC
- Maciej Trzebinski : Solid State Detector poster - Overview of ATLAS forward proton detectors for LHC Run 3 and plans for the HL-LHC
- Marianna Testa : Solid State Detector poster - Expected reconstruction performance with the new ATLAS Inner Tracker at the High-Luminosity LHC
- Jiri Kroll : Solid State Detector poster - Effect of irradiation and annealing performed with bias voltage applied across the coupling capacitors on the interstrip resistance of ATLAS ITk
- Vera Letonova : Solid State Detector poster - Characterization of the polysilicon resistor in silicon strip sensors for ATLAS Inner Tracker as a function of temperature, pre- and post-irradiation
- Abhishek Sharma : Solid State Detector poster - Module development for the ATLAS Phase II Pixel Inner Tracker
- David Rousso : Solid State Detector poster - Test and extraction methods for the QC parameters of silicon strip sensors for ATLAS upgrade tracker
- Punit Sharma : Solid State Detector poster - Electrical performances of pre-productions staves for the ATLAS ITk Strip Detector Upgrade
- Nicola Pacifico : Solid State Detector poster - An environmental monitoring and control system for the ATLAS Outer Barrel QC and Integration
- Javier Fernandez-Tejero : Solid State Detector poster - Analysis of humidity sensitivity of silicon strip sensors for ATLAS upgrade tracker, pre- and post-irradiation
- Matthew Addison : Solid State Detector poster - The development of high precision, fast-timing 3D silicon sensors with a focus on the high luminosity upgrades of the ATLAS detector
- Tingyu Zhang : Calorimetry poster - ATLAS LAr Calorimeter Commissioning for LHC Run-3
- Antonio Jesus Gomez Delegido : Calorimetry poster - Upgrade of ATLAS Hadronic Tile Calorimeter for the High Luminosity LHC
- Giorgio Chiarelli : Calorimetry poster - Long term aging test of the new PMTs for the HL-LHC ATLAS hadron calorimeter upgrade
- Nina Wenke : Calorimetry poster - Performance studies of single-particles uncertainties and Local Hadron Calibration for Particle-Flow jets in ATLAS
- Kristina Mihule : Calorimetry poster - Time calibration, monitoring and performance of the ATLAS Tile Calorimeter in Run 2
- Giorgio Chiarelli : Calorimetry poster - Long term aging test of the new PMTs for the HL-LHC ATLAS hadron calorimeter upgrade
- Kevin Nelson : Gas detector poster - Construction and testing of the sMDT system for the HL-LHC ATLAS muon detector upgrade
- Robert Faure : Trigger/DAQ poster - Machine Learning for Real-Time Processing of ATLAS Liquid Argon Calorimeter Signals with FPGAs
- Liangliang Han : Trigger/DAQ poster - Demonstration System of the HGTD Peripheral Electronics Board (PEB) for ATLAS Phase II Upgrade
- Davide Cieri : Trigger/DAQ poster - Upgrade of the first-level muon trigger for the ATLAS experiment at the HL-LHC
- Damir Raßloff : Trigger/DAQ poster - The phase-1 upgrade of the ATLAS level-1 calorimeter trigger
- Antonio Cervello Duato : Trigger/DAQ poster - The TileCal PreProcessor Interface with the ATLAS Global Data Acquisition System at the HL-LHC
- Mengqing Wu: Trigger/DAQ poster - FELIX: readout upgrade for the ATLAS Trigger DAQ system in HL-LHC
- Will Kalderon: Trigger/DAQ poster - FPGA-based techniques to improve fast track finding in the ATLAS Trigger
- Will Kalderon: Trigger/DAQ poster - The ATLAS Forward Proton Real-Time Time-of-Flight Trigger and Trigger Decoder for LHC Run 3
- Jan Zich: Trigger/DAQ poster - FPGA-based techniques to improve fast track finding in the ATLAS Trigger

Summary

- ATLAS currently develops and constructs major upgrades to its detector system to optimise the experiment for HL-LHC data taking
- An all-new silicon tracker (ITk) with 5 layer pixel and 4 layer strips improves tracking up to $|\eta|<4$
- The High Granularity Timing Detector (HGTD) based on LGADs will help to resolve pile-up through timing measurements
- Additional muon detector upgrade will follow the LS2 New small wheel installation
- Most detector electronics, DAQ and trigger systems will be upgrades to cope with the luminosity increased and increased trigger/readout rate