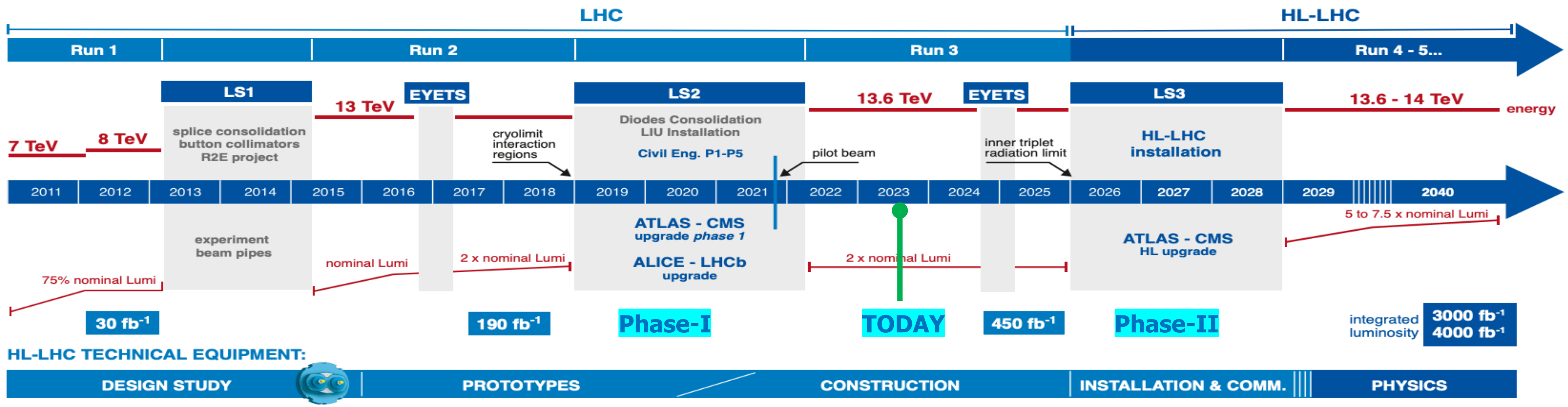
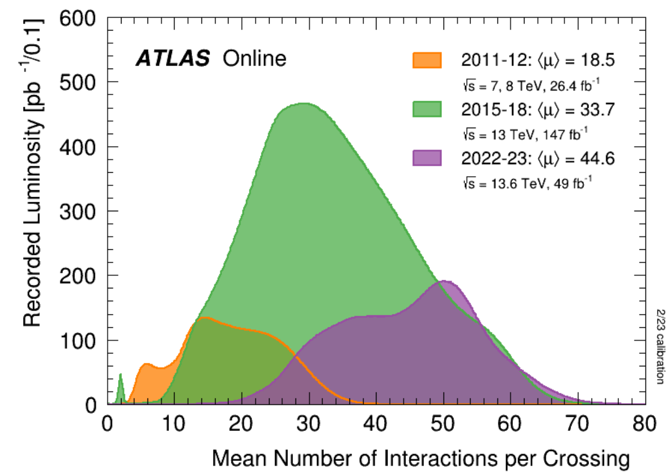
The ATLAS HL-LHC Upgrade program

Claudia Gemme (INFN Genova)
On behalf of the **ATLAS Collaboration**

The High Luminosity LHC

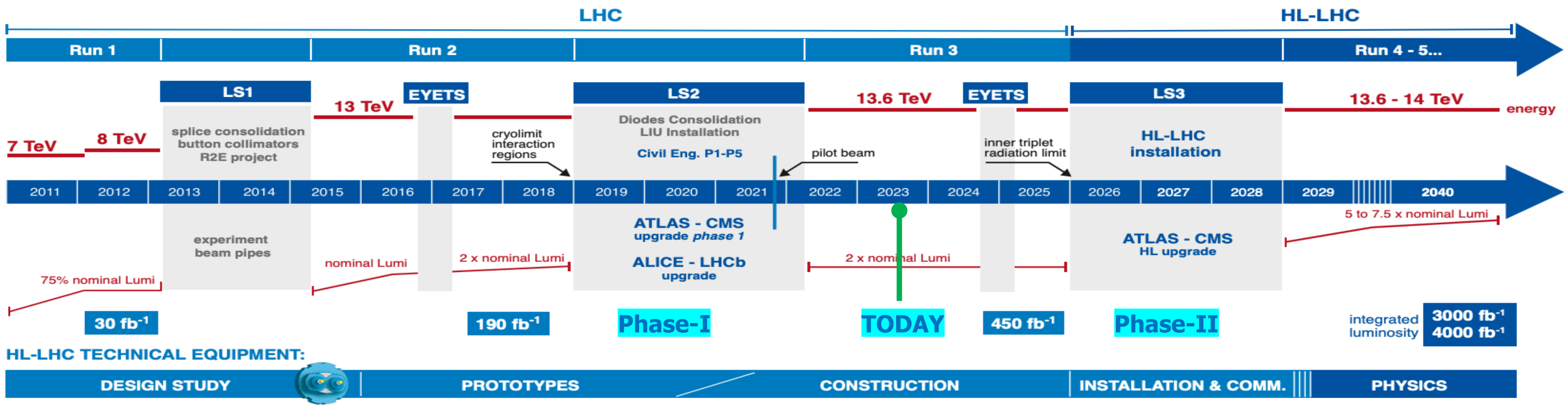


- The LHC accelerator is periodically upgraded to keep exploring the energy frontier...
  - At the same time detectors keep evolving to keep the pace.
- The "HL-LHC" period will start in ~2029, after a three years shutdown, with more than 5 times the initial nominal instantaneous luminosity (i.e. up to 5-7.5 10^{34} $cm^{-2}s^{-1}$)
  - This will increase the average pile up from current **μ~50 to μ=200**



PublicPlots

The High Luminosity LHC



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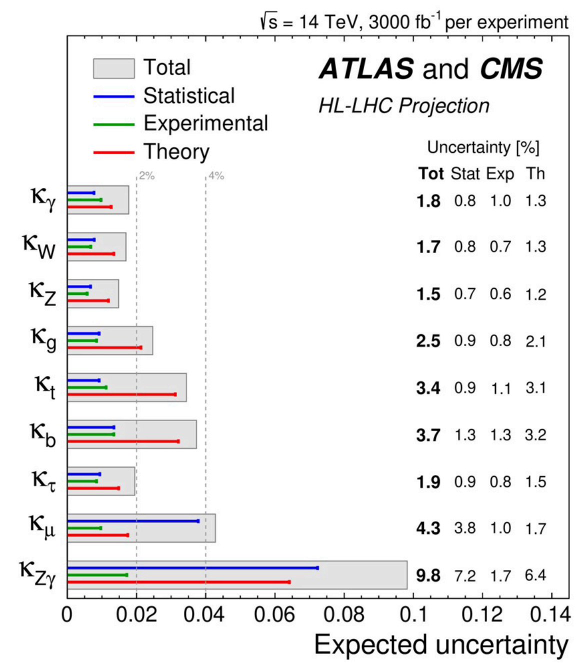
  - This will increase the average pile up from current **μ~50 to μ=200**
- A total integrated luminosity up to 4000 ifb will be collected (340 ifb so far!)
  - Data will be essential to improve the knowledge of the **Higgs couplings** from ~12% to few %, measure the Higgs self coupling, extend the searches for physics beyond the Standard model, accomplish electroweak precision measurements, etc



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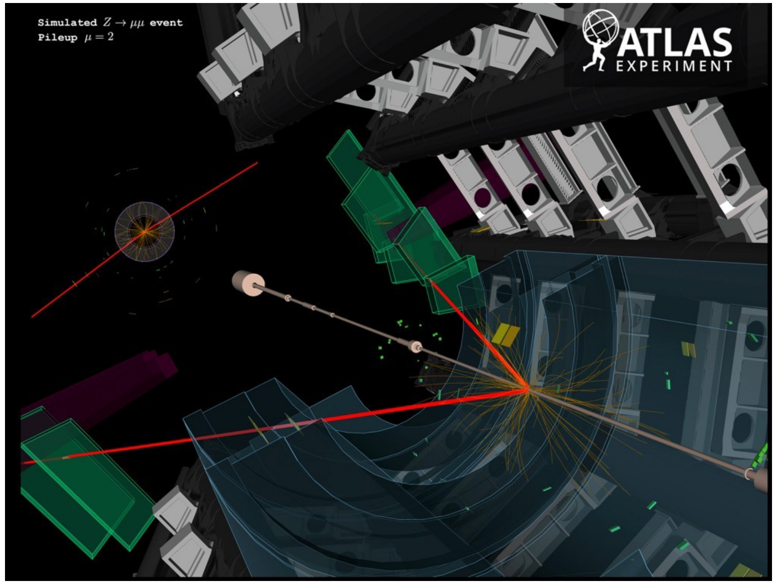
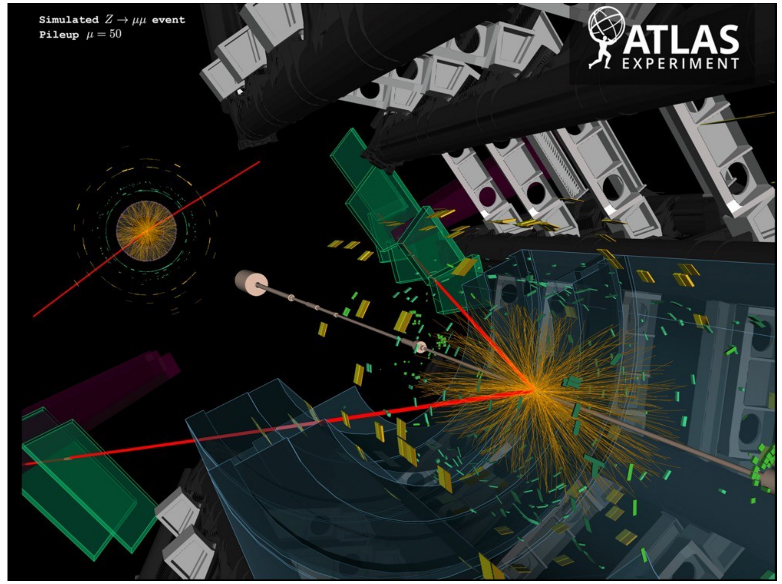
ATLAS for HL-LHC

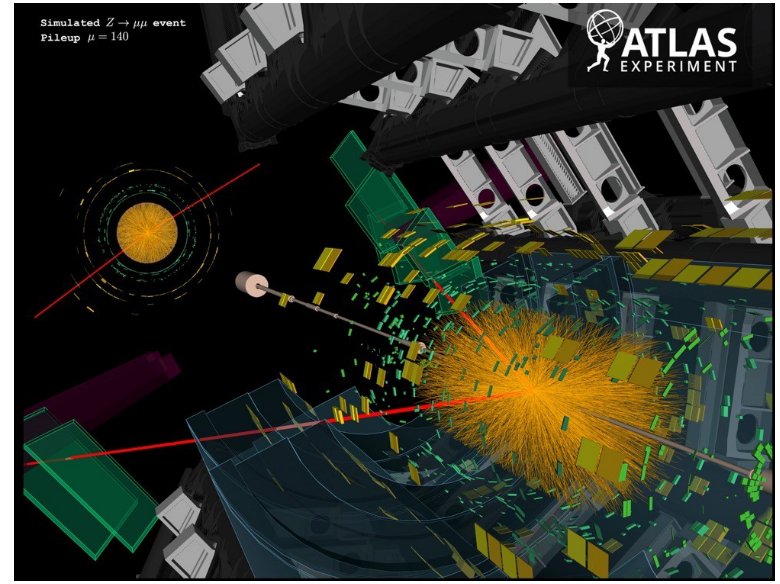
Pile-up = 2



Pile-up = 50



Pile-up = 140



- Need to **upgrade ATLAS experiment** to deal with more “messy” events, and more radiation damage.
- To fulfil the physics goals the detector should
  - Measure all relevant final states (leptons, photons, jets, missing E_T , …) with at least comparable precision as in current run, in a much harsher environment
  - Be very radiation hard, (eg: Inner Tracker ~ 10e16 n_{eq}/cm^2 i.e. ~x10 higher)
  - Improve the triggering capabilities: trigger rate x10 higher while keeping same lepton p_T threshold
  - Improve the read-out capabilities: read-out detectors at 1 MHz

Some more challenges

- Technical challenges coming from the HL-LHC are huge and complicated, examples in the next slides.

- HL-LHC phase also calls for new collaboration organization:
  - For the first time some detector **deliverables are common to the LHC experiments** (not only R&D): notably, the Pixel 65 nm readout ASIC and the CO_2 cooling systems for the trackers have been shared between ATLAS and CMS.
  - A large community is needed to build and fund such challenging "home-made" detectors. But the **management** of a such large community in our "scientific style" is not easy.
  - With respect to the initial detectors construction, now the **same community must deal** with data analysis, detector operation and maintenance, and upgrade.

- Some detectors are there since almost 20 years!
  - Beyond the upgrades, it is important also to focus on the possibility to reliably run the"legacy" detectors for more than another decade: making access easier, adding redundancy, consolidating them is vital.

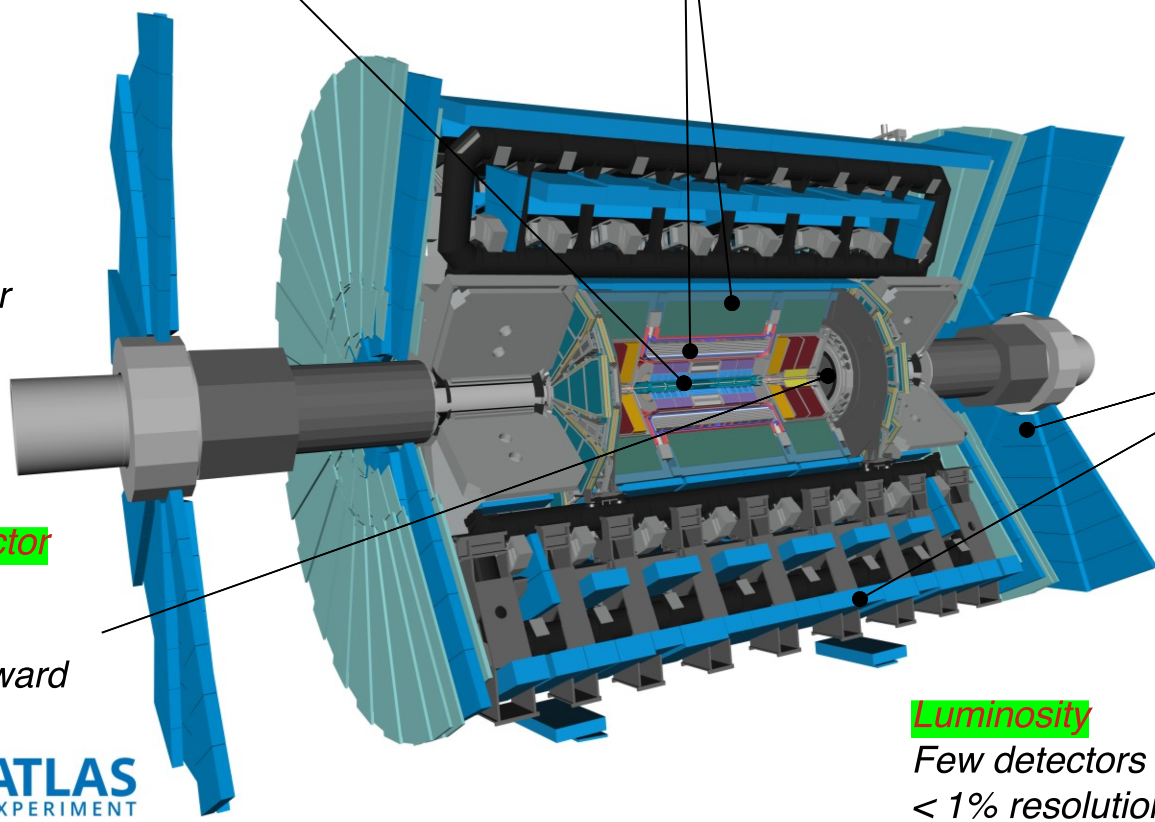
ATLAS Phase–II Upgrades

Legacy detectors

New detectors

New Inner Tracker (ITk)
All silicon with 9 layers up to $|\eta|=4$
Less material finer segmentation
Improve vertexing, tracking, b-tagging

Calorimeter Electronics
On-detector electronics upgrades of LAr and Tile Calorimeters
Provide 40 MHz readout for triggering



Trigger and DAQ Upgrade
Single level Trigger with 1 MHz output (x 10 current)
Improved DAQ system with faster FPGAs

Muon Detector
Upgrade of the detector electronics for new T/DAQ system
Upgrade of inner barrel chambers with new RPC and sMDT
Improve trigger efficiency and momentum resolution, and reduced fakes

New High Granularity Timing Detector
Precision track timing (30 ps) with LGAD in the forward region.
Improve pile-up rejection in the forward region

Luminosity
Few detectors devoted to luminosity to get < 1% resolution as ATLAS has in Run2: LUCID-3, ITk-BCM', HGTD

ATLAS EXPERIMENT

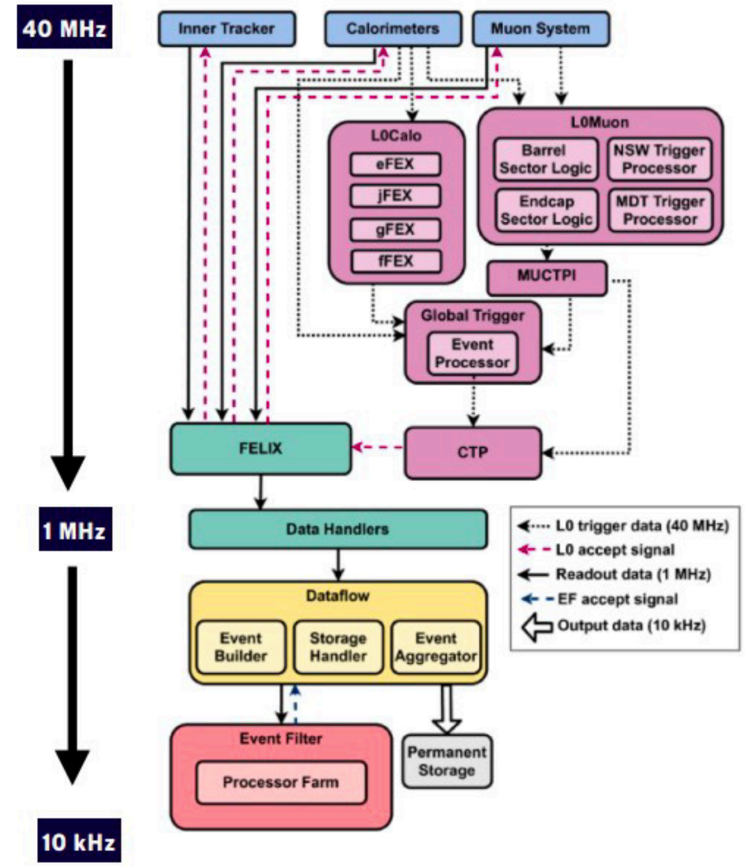
Several detailed talks at TIPP!

Development and prototype of a new luminometer for the ATLAS experiment during Run 3 and Run 4 of the LHC	Data Preparation	Marco Bruschi
Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector: laboratory and test beam campaigns	HGTD	Mei Zhao
Overview of the ATLAS High-Granularity Timing Detector: project status and results	HGTD	Shahzad Ali
Module development for the ATLAS ITk Pixel Detector	ITK system	Matthias Saimpert
ATLAS ITk Pixel Detector Overview	ITK system	Koji Nakamura
Design and prototyping of large-scale flex circuits for the ATLAS ITk Pixel detector	ITK system	Steven Welch
Loading of ATLAS ITk pixel module on multi flavour local supports	ITK system	Gabriele Chiodini
Novel pixel sensors for the Inner Tracker upgrade of the ATLAS experiment	ITK system	Stefano Terzo
System tests of the ATLAS ITk planar and 3D pixel modules	ITK system	David Vazquez
The ATLAS ITk Strip Detector for the Phase-II LHC Upgrade	ITK system	Jose Bernabeu Verdu
The ATLAS ITk Strip End-of-Substructure Card - From design to production	ITK system	Marcel Stanitzki
Development of the ATLAS Liquid Argon Calorimeter Readout Electronics for the HL-LHC	LAr detector system	Arno Straessner
Machine Learning for Real-Time Processing of ATLAS Liquid Argon Calorimeter Signals with FPGAs	LAr detector system	Etienne Marie Fortin
ATLAS MDT AMT Simulations for LHC Run3 and HL-LHC	T/DAQ system	Jiajin Ge
FELIX Phase II, the ATLAS readout system for LHC Run 4	T/DAQ system	Frans Schreuder
The ATLAS Level-1 Topological Processor: Phase-I upgrade and Phase-II adaptation	T/DAQ system	Emanuel Meuser
Long term aging studies of the new PMTs for the HL-LHC ATLAS hadronic calorimeter upgrade	Tile detector system	Fabrizio Scuri
Long-term stability uncertainty of luminosity measurements of the ATLAS detector in Run 3 during the 2022 data-taking per	Tile detector system	Phuti Rapheeha
The Phase-II Upgrade of the ATLAS Hadronic Tile Calorimeter for the High Luminosity LHC	Tile detector system	Edward Khomotso Nkadimeng
The use of Machine learning to improve quality control for the ATLAS Phase-II Upgrade LVPS bricks at CERN	Tile detector system	Khathutshelo Tony Phadagi

Trigger and DAQ

- Huge increase in data rates and thus data throughput, bringing extra complexity!
- Trigger updates
  - **Hardware based Level-0:** Trigger data input at 40 MHz from Calorimeters and Muons.
    - Output Rate 1 MHz (currently 100 kHz), latency 10 μs
    - Exploits full detector granularity with new Global Trigger component
  - **Software based Event Filter** (High-Level trigger):
    - Output Rate 10 kHz (currently 3 kHz)
    - Extended tracking range fully exploiting ITk, improved muon trigger efficiency
    - For the Event Filter use commercial hardware, either pure software solution, or GPU or FPGA card acceleration (under evaluation).
- DAQ updates
  - To achieve the requested data throughput, completely new architecture based on custom PCIe FPGA cards (FELIX) instead of VME based readout boards.
    - This evolution has started already in Phase-I.

New TDAQ architecture



FELIX Prototype

Electromagnetic Calorimeter

- General for Calorimeters
  - New on-detector and off-detector electronics
  - Continuous readout at 40 MHz (no on-detector buffering)
  - Full digital input to ATLAS trigger system
- LAr upgrade happens in two stages:
  - Phase-I (2018-21): Trigger digitization and processing, now in operation
  - Phase-II: Calibration, digitization and signal processing for energy reconstruction
- On-detector
  - New high precision frontend electronics aiming at 16-bit dynamic range and a linearity better than 0.1 %.
  - New ASICS (ADC, calibration DAC & pulser)
- Off-detector
  - ATCA boards for waveform feature extraction (E, time) with a total bandwidth of 345 Tbps

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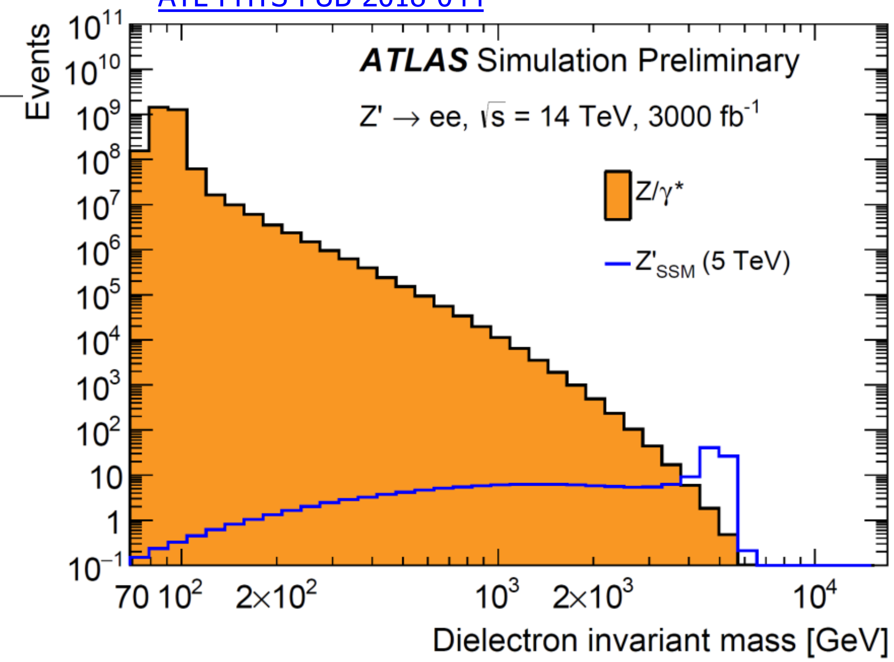
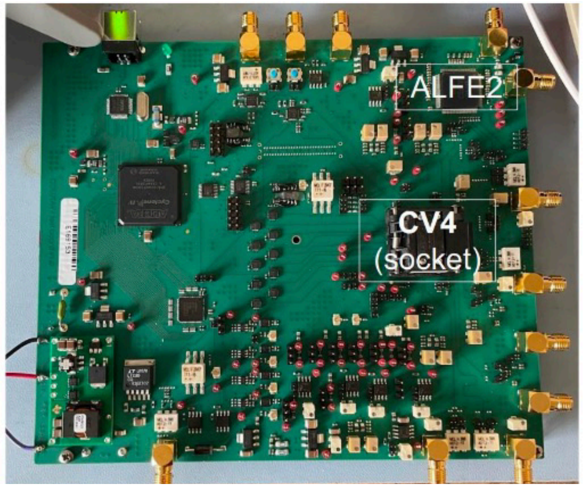


FEB2 prototype
Pre-production wafers of FE Board ASICs received



LASP demonstrator
under test

Hadronic Calorimeter

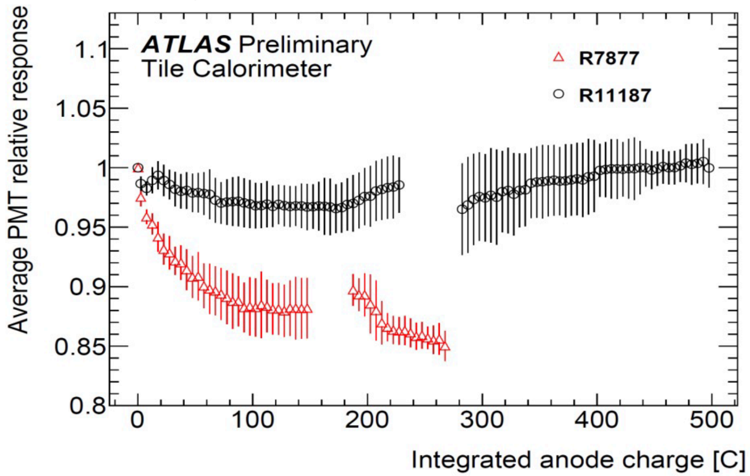
- General for Calorimeters
  - New on-detector and off-detector electronics
  - Continuous readout at 40 MHz
  - Full digital input to ATLAS trigger system

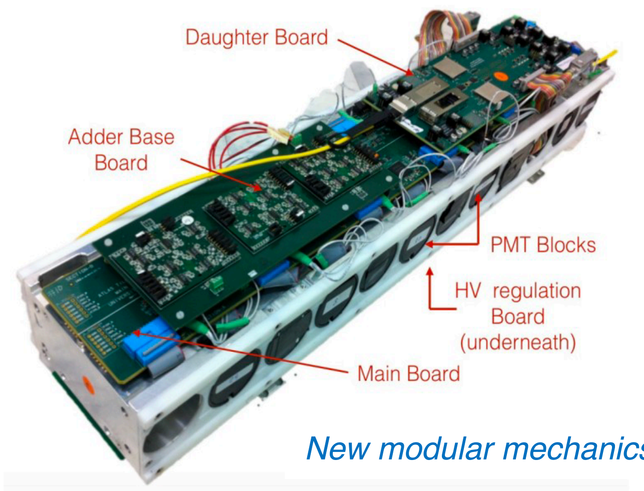
- Tile Calorimeter:
  - New modular mechanical design for **better accessibility and maintenance** and increasing redundancy.
  - Replacement of the most **exposed PMTs** (about 10%).
  - Replacement of **passive PMT HV-dividers** by active dividers for better response stability.
  - **Phase-II demonstrator** installed (July 2019) in ATLAS and is taking data during Run 3.

  - On-detector electronics at advanced stage, production ongoing.

PMT stability vs integrated charge

New vs *old*



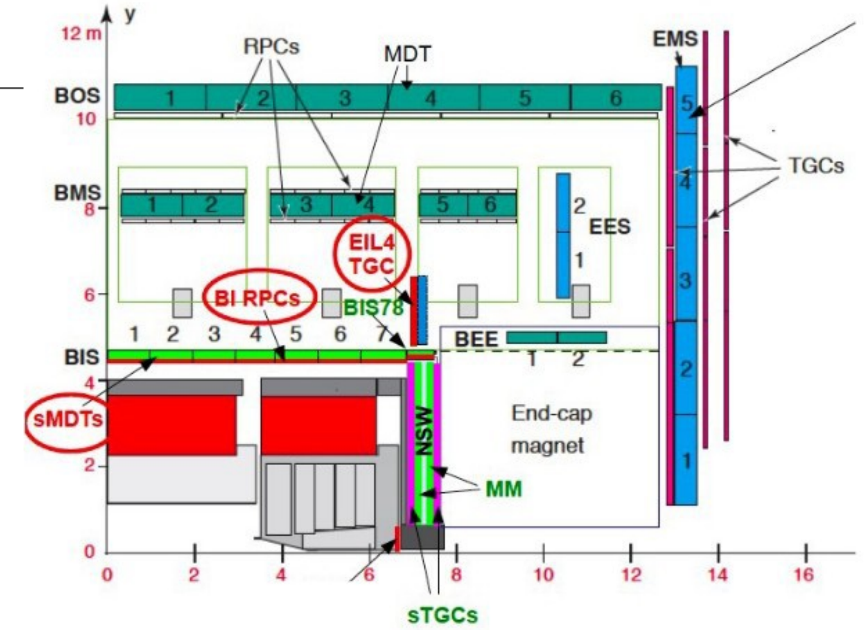


New modular mechanics

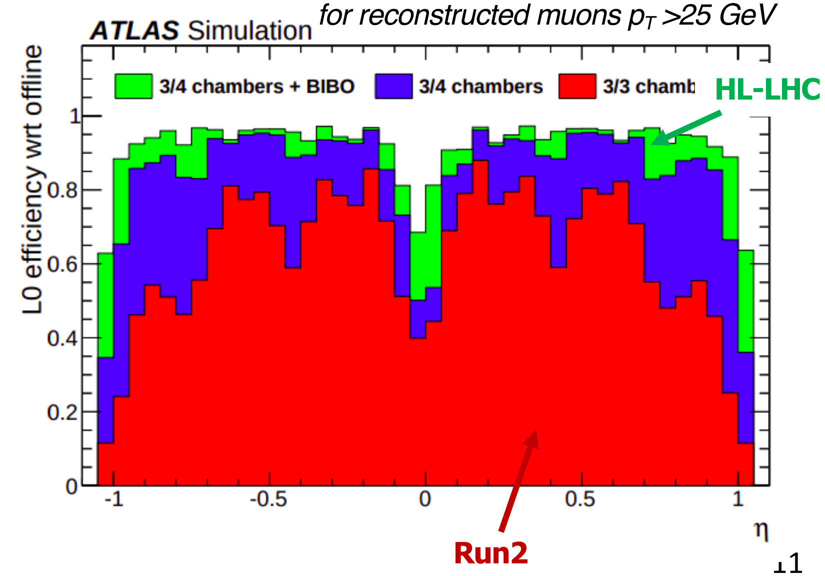
Muons Spectrometer

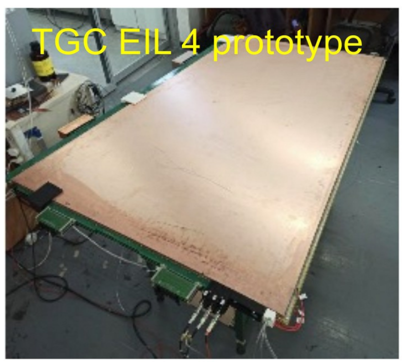
MDT: Monitored Drift Chambers
RPC: Resistive Plate Chambers
TGC: Thin Gap Chamber

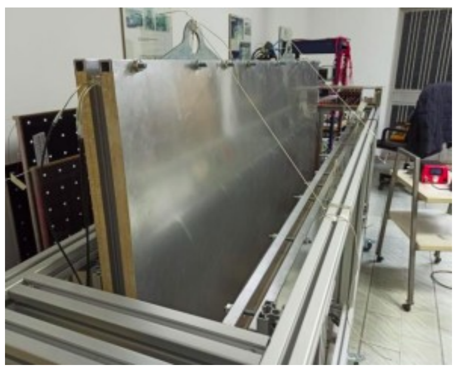
- Upgrade readout/trigger electronics
  - all hit data is sent off detector to trigger logic boards with L0 trigger rate of 1 MHz at new latency (10 μs)
  - New: **MDT** will provide L0 trigger information.
- Additional Barrel Layers of sMDT, RPC, and TGC
  - New **sMDT** BIS chambers (to make space for the RPC)
  - New **RPC** triplets in the inner layer (to improve trigger coverage)
  - New **EIL4 TGG** chambers (to improve trigger rejection)
- Current status
  - All prototypes chambers exist and sMDT production almost finished. **RPC** FE prototypes submitted but critical for the project.



L0 efficiency x acceptance
for reconstructed muons p_T >25 GeV





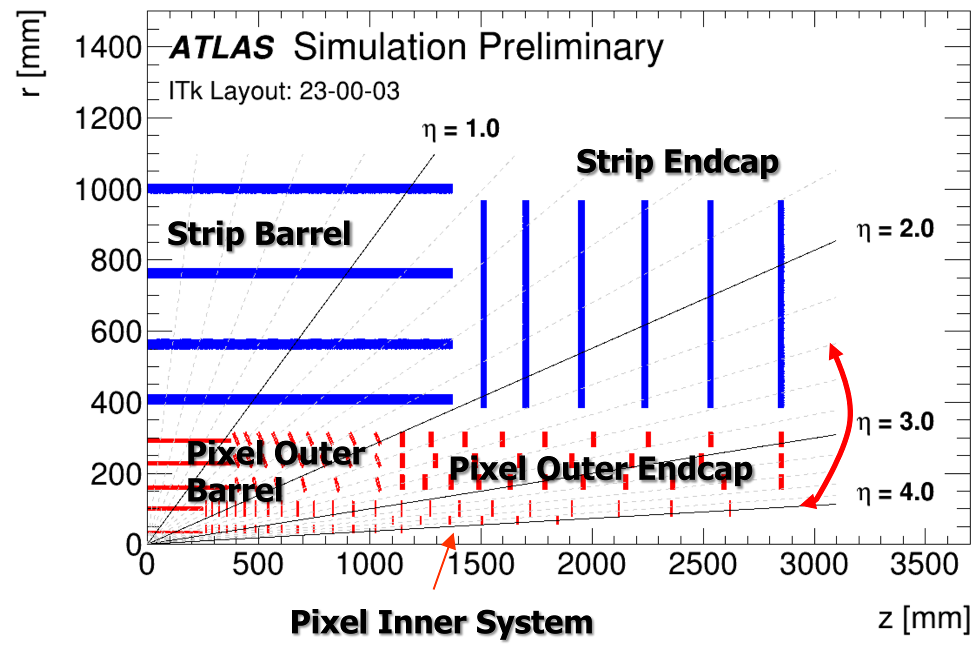


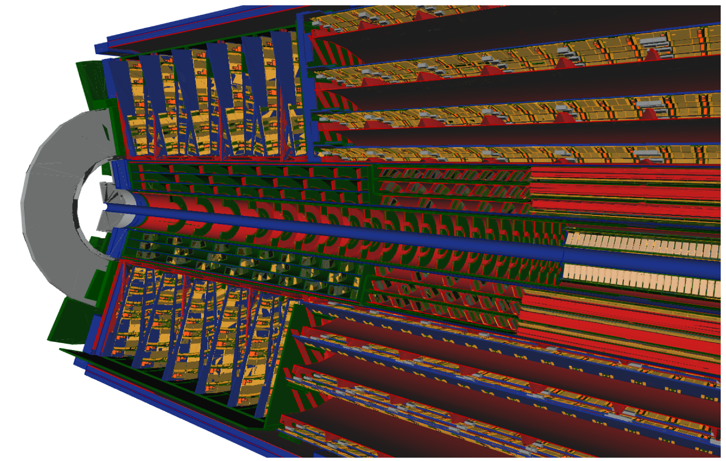
RPC prototype

sMDT

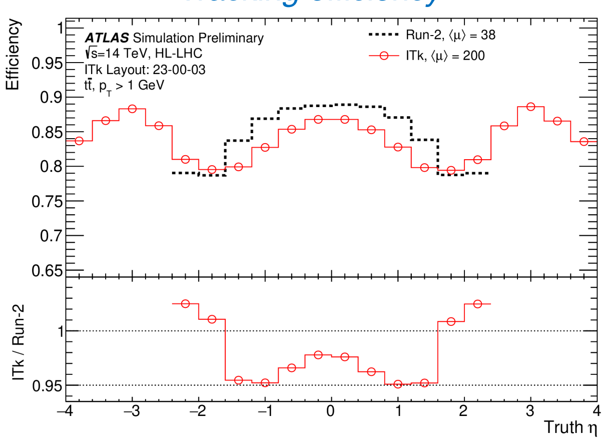
A new tracker system, ITk

- Complete replacement of the current Inner Detector with an all-silicon detector in 2T magnetic field.
  - Angular coverage increased from |η| = 2.5 to 4
- Overall significant improvement thanks to:
  - Reduced material budget → minimize material interactions
  - Finer segmentation → improved resolutions
  - Increase in overall hit counts, at least 9 silicon hits per track, and improved hermeticity → tighter track selection

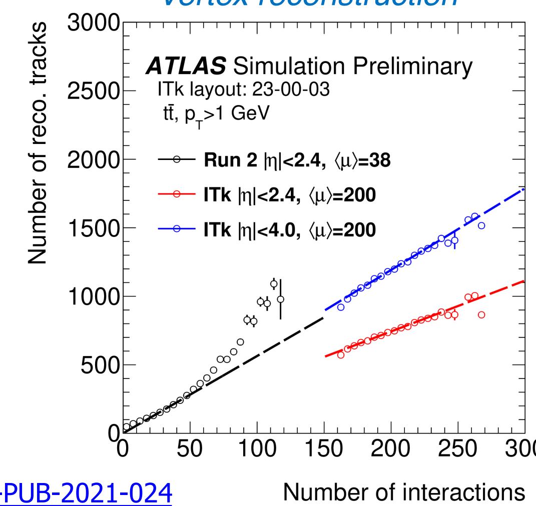




Tracking efficiency



Vertex reconstruction

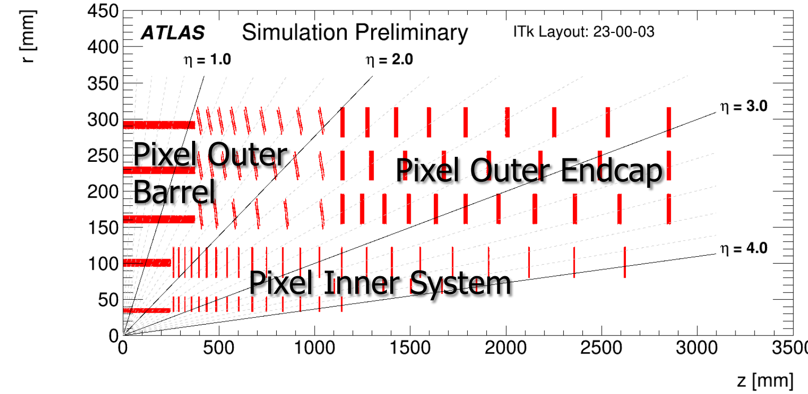


	Surface [m²]	# Channels	# modules
Strip	165	60 M	18 k
Pixel	13	5.1 G	9.2 k

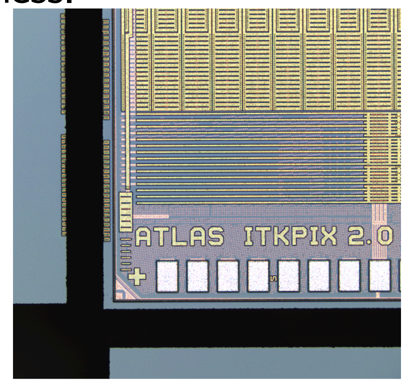
ATL-PHYS-PUB-2021-024

ITk Pixel

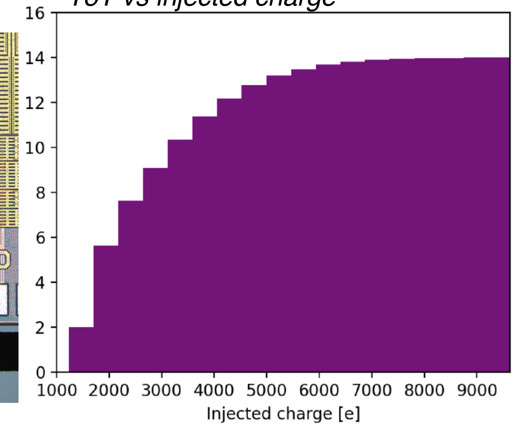
- General characteristics:
  - Organized as **three sub-systems** (inner, outer barrel, outer endcaps)
    - Pixel subsystem covering up to **|η|<4.0** with five Barrel layers + several endcap rings
    - Inner system will be **replaced** at half lifetime due to radiation hardness.
  - Almost 10 times larger than current one in terms of area and number of modules to be built.
- Modules:
  - Pixel cell size 25x100 μm^2 in L0 barrel and 50x50 μm^2 (everywhere else)
  - **3D** sensors in the innermost layer and **planar** sensors in the other layers
  - Radiation tolerant up to ~2E16 n_{eq}/cm^2
- Status:
  - All sensors are in pre-production
  - Hybridization pre-production modules started
  - The production readout chip, **ITkPixV2** has been received and is being tested
  - Demonstrators for all the sub-systems exists and preproduction of local supports, services has started.



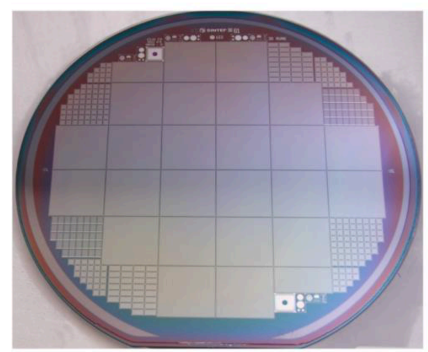
ITkPixV2
Picture of a corner



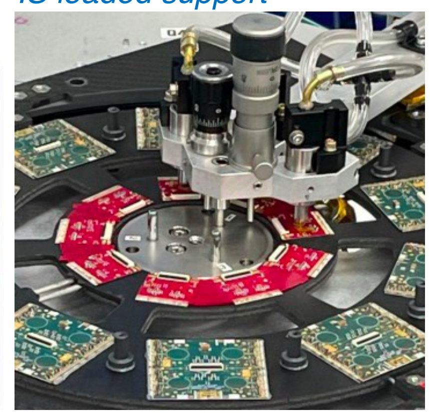
ITkPixV2
ToT vs injected charge



Sintef 3D wafer



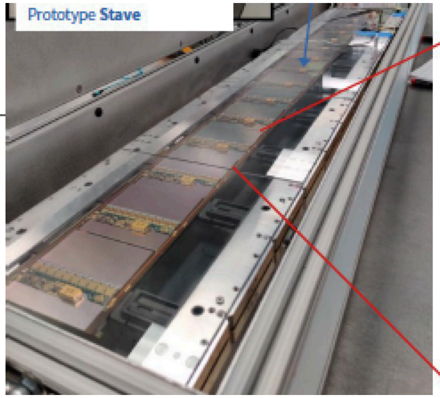
IS loaded support



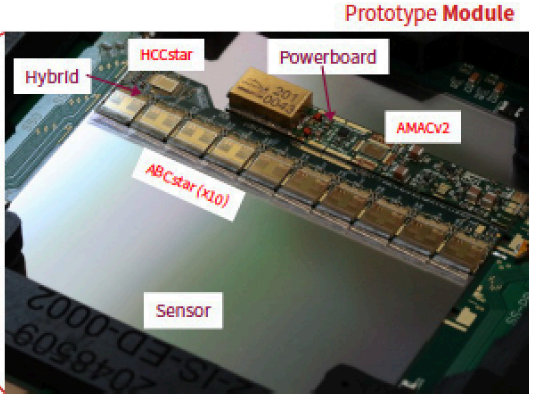
ITk Strip

- General characteristics:
  - Organized as two systems (Barrel and Endcaps)
    - Strip subsystem covering up to **$|\eta|<2.7$** with 4 Barrel layers 6 End-cap disks
  - Almost 3 times larger than current one in terms of area and 5 times as number of modules to be built.
  - Radiation hardness up to 1.6E15 n_{eq}/cm^2
- Status:
  - Sensors and ASICs, mechanics in production
  - On detector electronics and modules in preproduction
    - Issue with **large noise when operating cold** slow down the preproduction for several months, finally understood as caused by vibrations of capacitors on power boards.

Prototype Barrel Stave

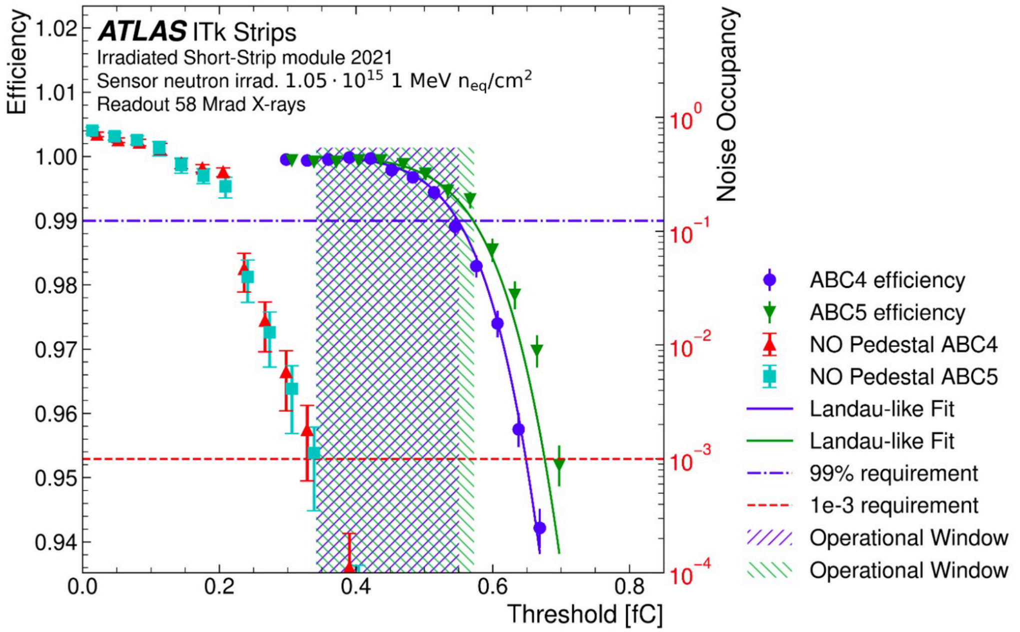


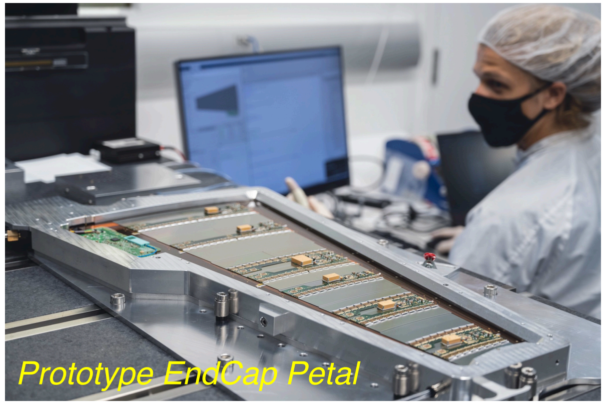
Prototype Barrel Module



Efficiency and Noise Occupancy

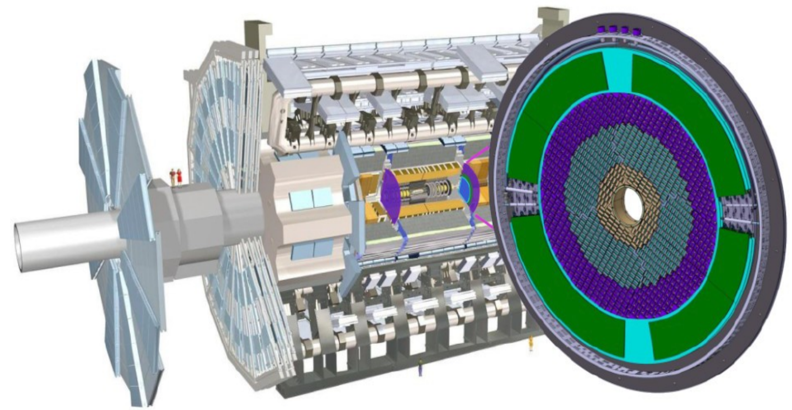
a full dose irradiated endcap module



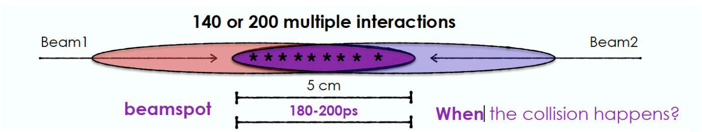


High Granularity Timing Detector (HGTD)

- HGTD designed to improve ATLAS performance in the **forward region** in view of increased pile up in the HL-LHC. Also provides **luminosity** information.
- Silicon detector modules mounted on disks.
  - Two disks/side, two sensor layers/disk → total **4 layers/side**
  - Target **time resolution: 30-50 ps/track** up to 4000 ifb
- Disk replacement plan to maintain 2.5E15 n_{eq}/cm^2 level.

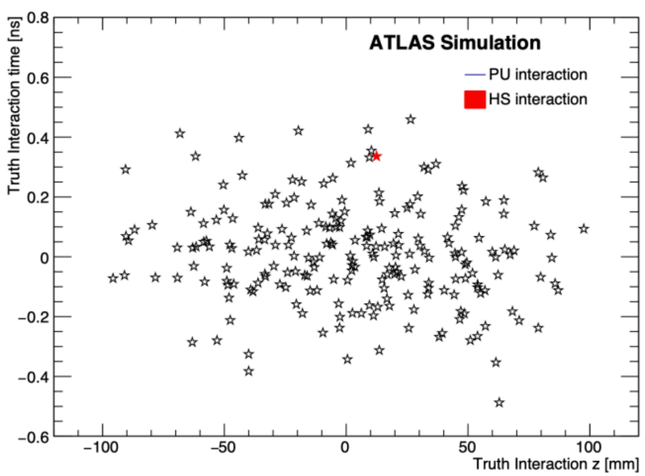


at |z|=3.5 m in front of the LAr EndCap
*at r in (12, 64) cm → **2.4 < |η| < 4.0***



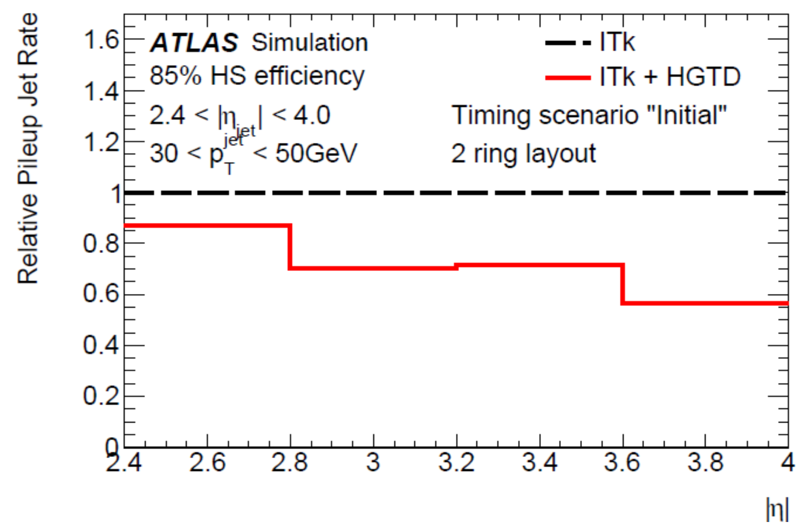
Inside a bunch crossing, interactions spread longitudinally but also in time.

Therefore, assigning a time to tracks with a good resolution allows to better reconstruct and identify pile-up vertices.



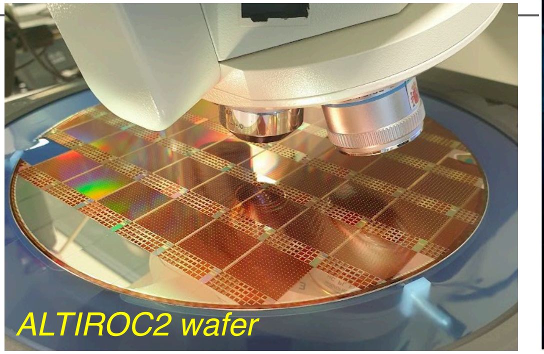
Longitudinal Primary Vertex distribution vs time

Relative Pile up Jet rate
Without or with HGTD

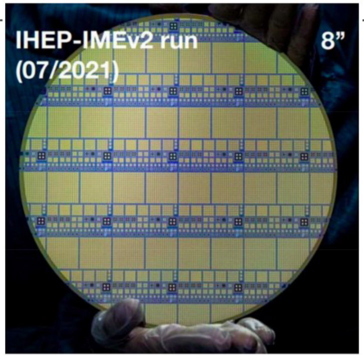


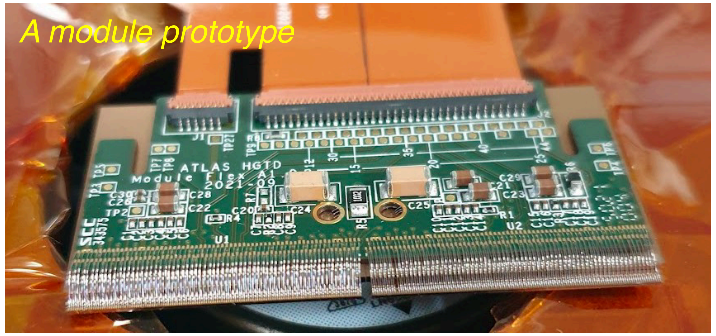
High Granularity Timing Detector (HGTD)

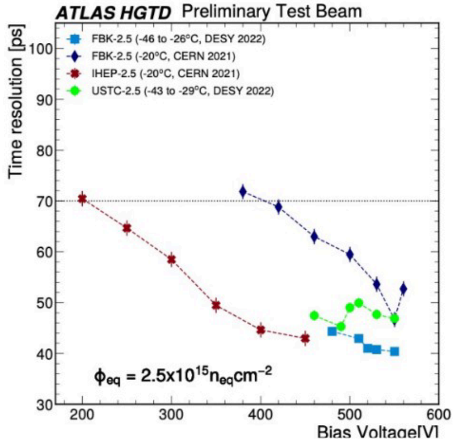
- Sensors:
  - Low Gain Avalanche Detectors (**LGAD**) arrays with pad size 1.3 x 1.3 mm^2
  - Single-event burnout (SEB) was observed on LGAD sensors during beam tests
    - Mitigated by **carbon-infused sensors** (can be operated at decreased high voltage)
  - Established maximum field per sensor thickness. Prototype sensors met radiation tolerance requirements below this critical field.
  - Preproduction mostly completed.
- ASIC:
  - First full size ALTIROC2 prototypes very successful, not fully rad hard
  - Final ASIC prototype ALTIROC3 wafers received and first tests started – rather positive
- Modules:
  - Modules (2 ALTIROCs bump bonded to 2 LGAD sensors) have been demonstrated required resolution
- System Tests:
  - Thermal demonstrator done
  - Electrical demonstrator on-going



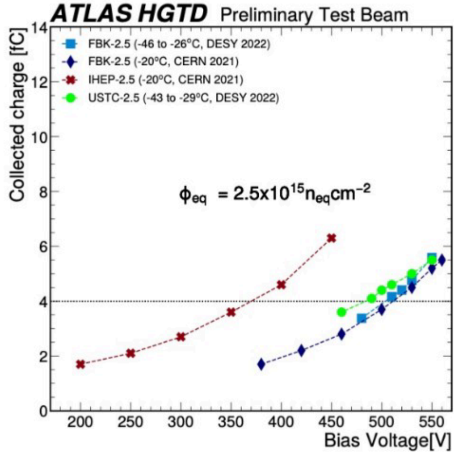
LGAD Sensor wafer







Hit Time resolution vs Bias



Collected charge vs Bias

HGTD Plots

Conclusions

- ATLAS detector currently undergoing mayor upgrade to optimize the experiment for HL-LHC data taking period
  - Objective is to **maintain or improve physics performance** in view of more demanding environment. To reach the goal:
    - A main upgrade of the trigger and readout system is ongoing
    - Most electronics (DAQ and trigger systems) of the existing detectors will be upgraded to cope with the luminosity increased and increased trigger/readout rate
    - New detectors will be installed (ITk and HGTD, part of the Muon Spectrometer)
- Challenges coming from the HL-LHC are huge and complicated: some of them have been **a common effort** together with other LHC detectors.
  - This is a **good model** that will be certainly followed in future upgrade to optimize resources
- All detectors are in production, at a different level of progress. **Schedule will also be a challenge**, both for **construction,** including delays from (single) vendors, as well for a very compact **installation** during the next long LHC shutdown.

Many interesting details and results in this conference

Additional material

Current detector configuration

Inner Tracker (ID)

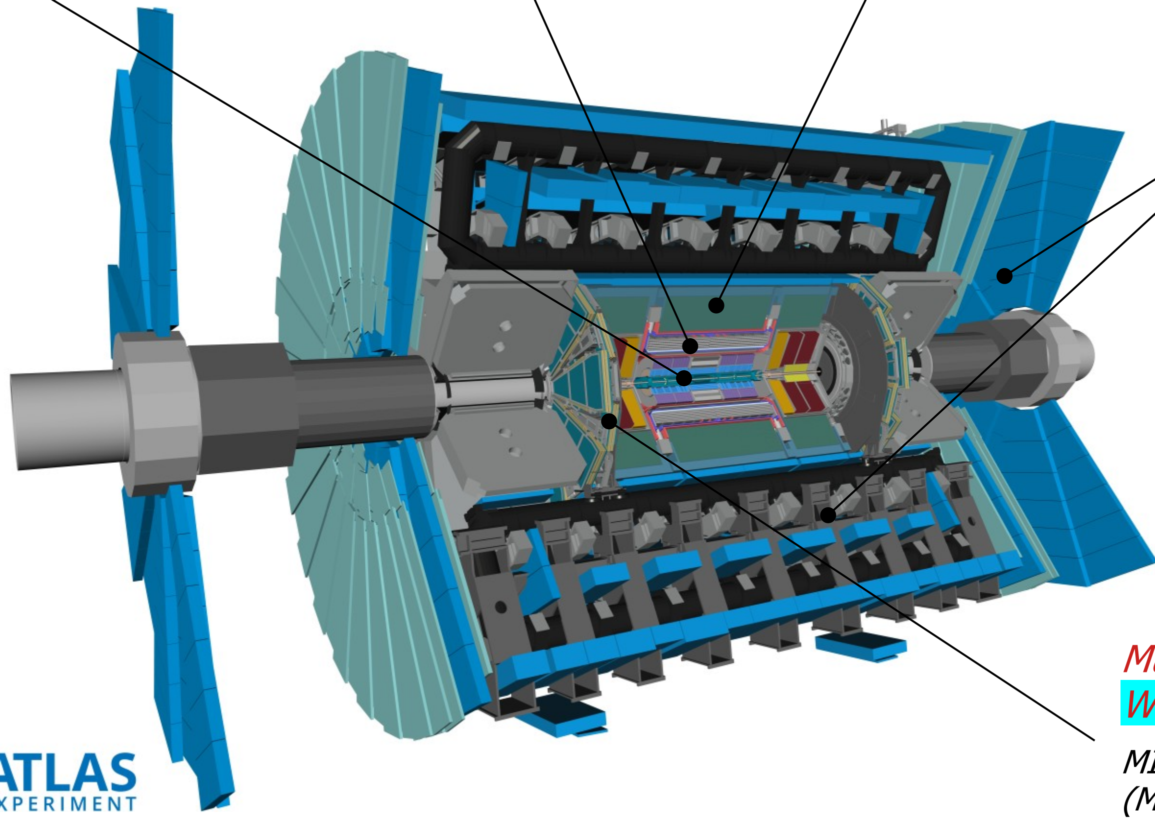
Pixel and Strip silicon detector, Transition Radiation TRT. At larger radius. A fourth additional pixel layer (IBL) added to the ID in 2014.

Electromagnetic Calorimeter

high granularity Lead/Liquid Argon (LAr)

Hadronic Calorimeter

steel/scintillator-tile



Muons Spectrometer

Barrel region: Monitored Drift Chambers (MDT) and Resistive Plate Chambers (RPC) for triggering

End-Cap region: MDT and Thin Gap Chamber (TGC) for triggering

Magnets

Toroid Magnets for the Muon Spectrometer, Solenoid magnet for the ID systems

Trigger and DAQ

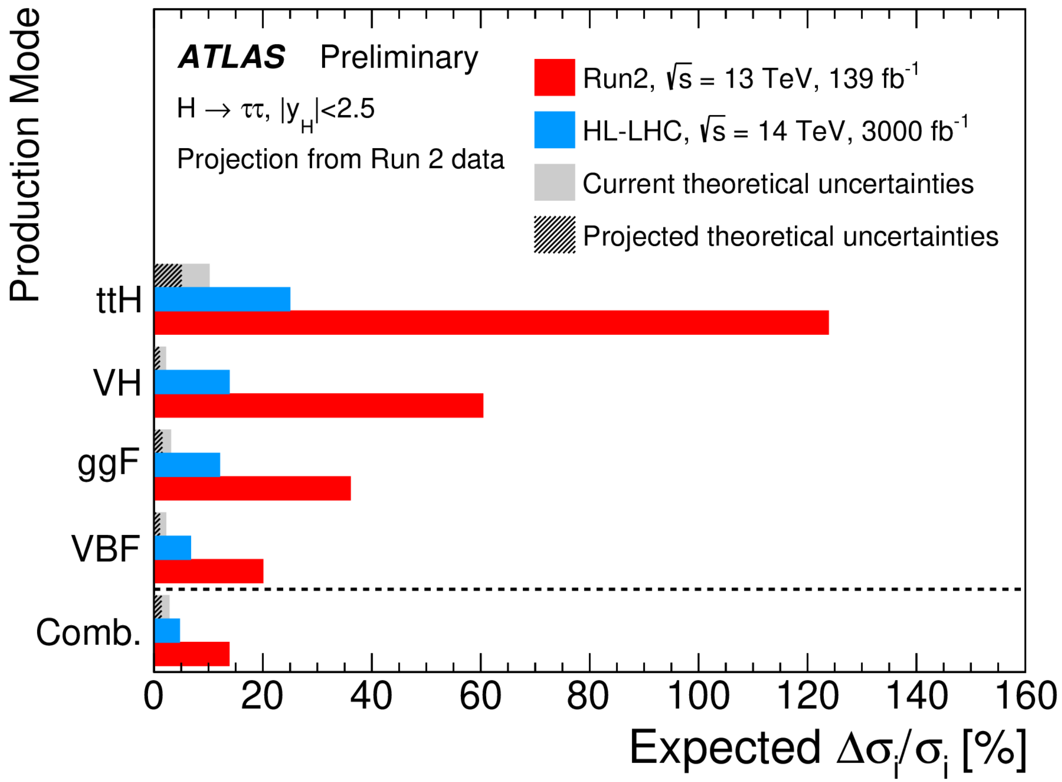
Hardware Trigger at 100 kHz fed by Calo and Muons, sw trigger at few kHz output

Muons Spectrometer – New Small Wheels in Phase-I

MICRO MEsh GAseous Structure (Micromegas) detectors, and *small-strip TGC, optimized for triggering*

Physics at HL-LHC

- Example of Higgs sector
  - Run 2 (red) and projected HL-LHC (blue) expected precision of the $H \rightarrow \tau^+\tau^-$ production mode measurements for ggF, VBF, VH and tanti-tH, scaled to their cross-section expectation values. The precision of the combined result for the inclusive cross-section, also scaled to its expectation value, is included at the bottom. The uncertainty on the predicted signal cross-section for each production mode, illustrating the current (light grey) and projected HL-LHC (hashed) precision of theory calculations, is also shown.



ATL-PHYS-PUB-2022-018