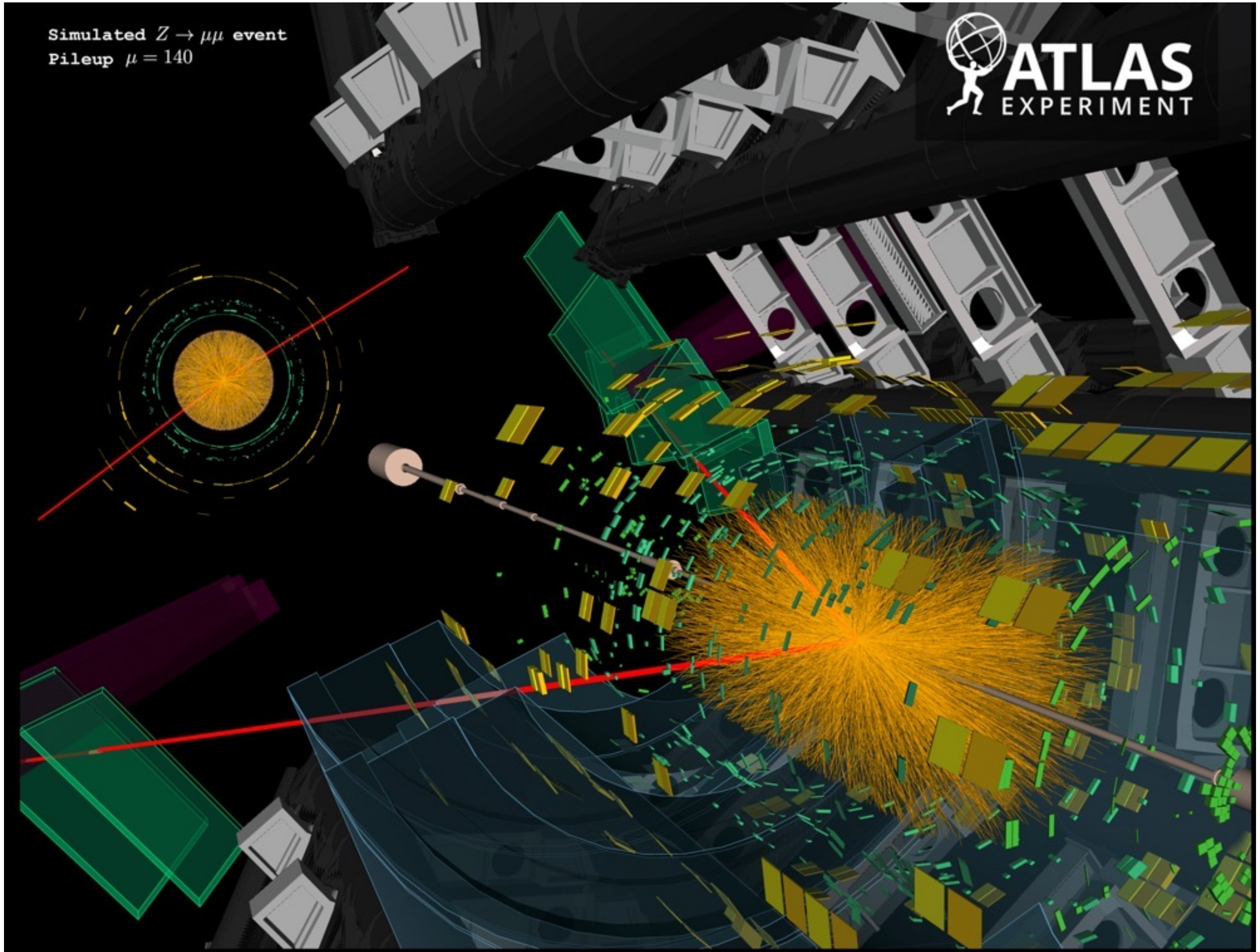
The ATLAS Phase II Upgrade program

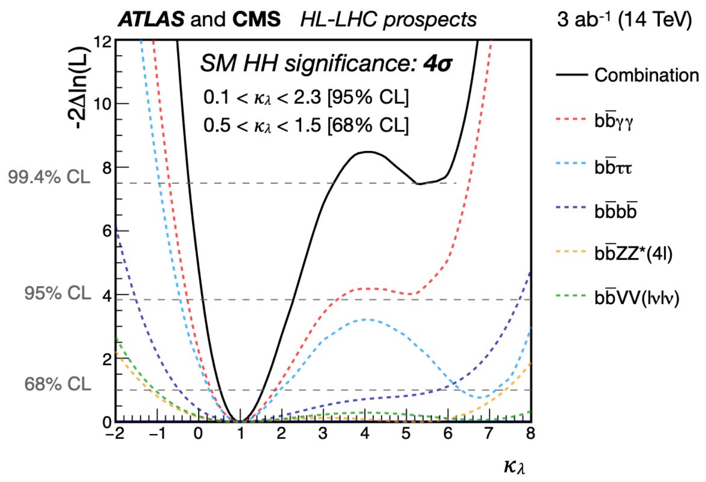


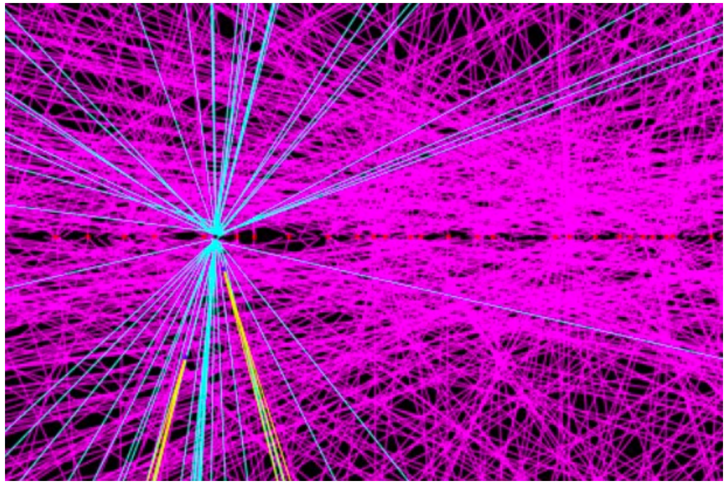
Ludovico Pontecorvo (CERN)
On behalf of the ATLAS collaboration

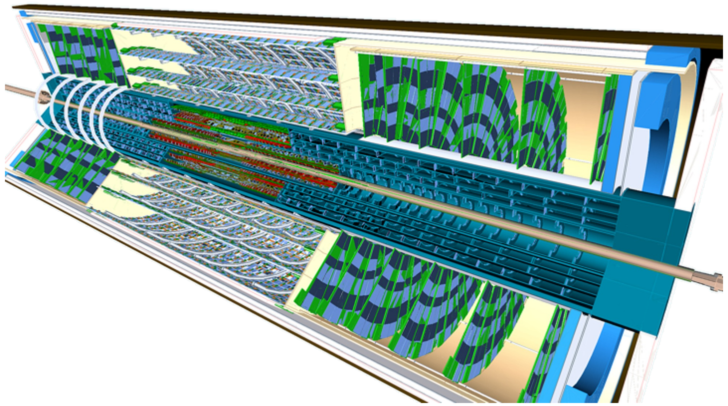
EPS 2023 (Hamburg)

Outline

- The Physics case
- Challenges at HL-LHC
- The ATLAS Upgrade Program

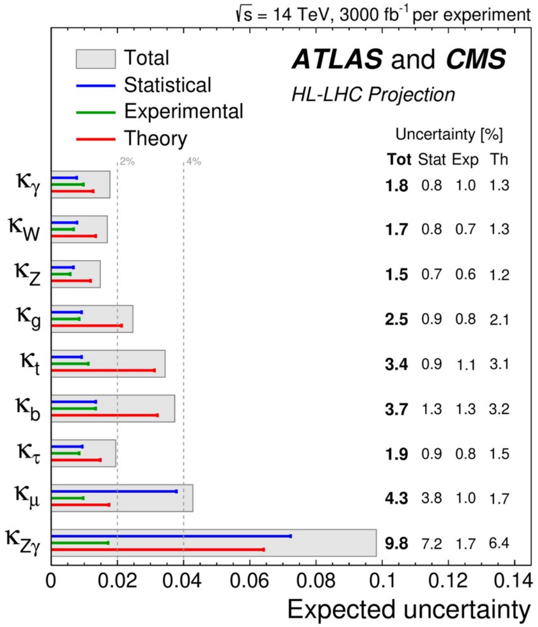


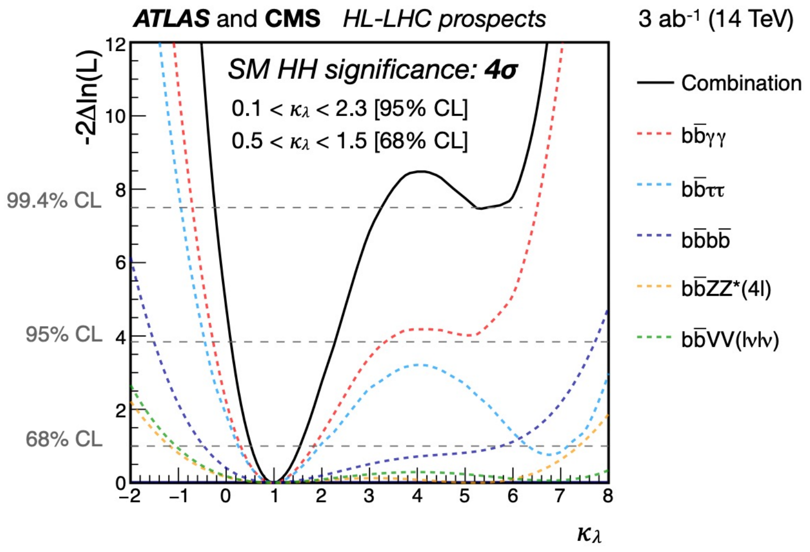




Physics objectives for HL-LHC (in a nutshell)

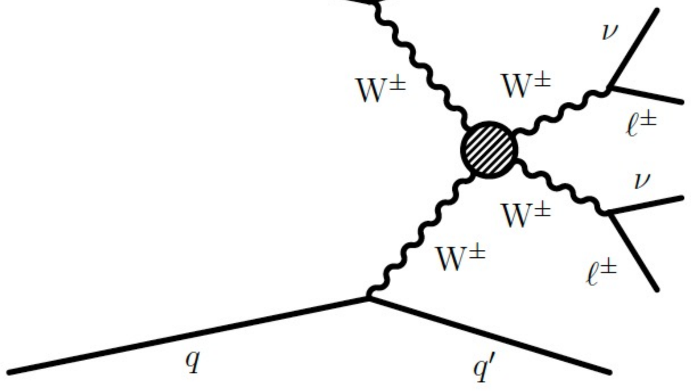
- The HL-LHC program aims at collecting at least 3 ab^{-1} of 14 TeV pp collisions (~ 15 times the present sample)
- This data will be essential to:
  - **Improve the understanding of the Higgs Boson couplings**
    - Major couplings measured at % level precision
    - Excellent sensitivity to rare decays eg H->Zγ
  - **Shed light on the Higgs potential through the measurement of the self coupling**
    - With 3 ab^{-1} the double Higgs production can be observed if the rate is SM like, combining ATLAS and CMS

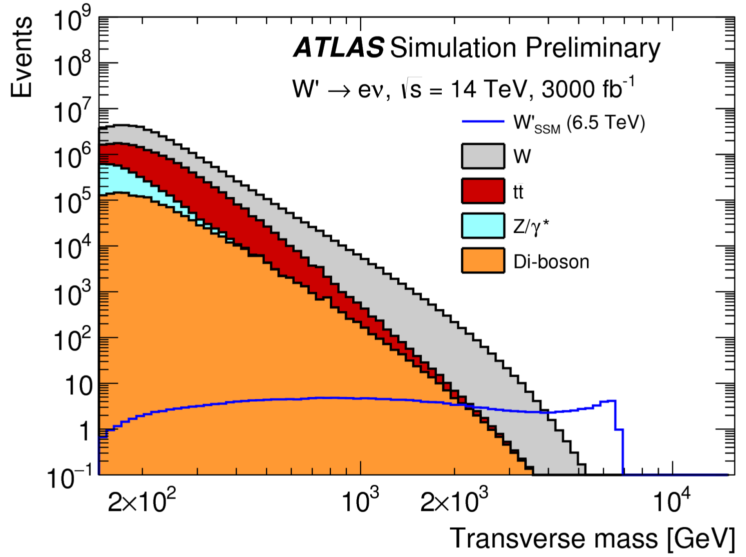




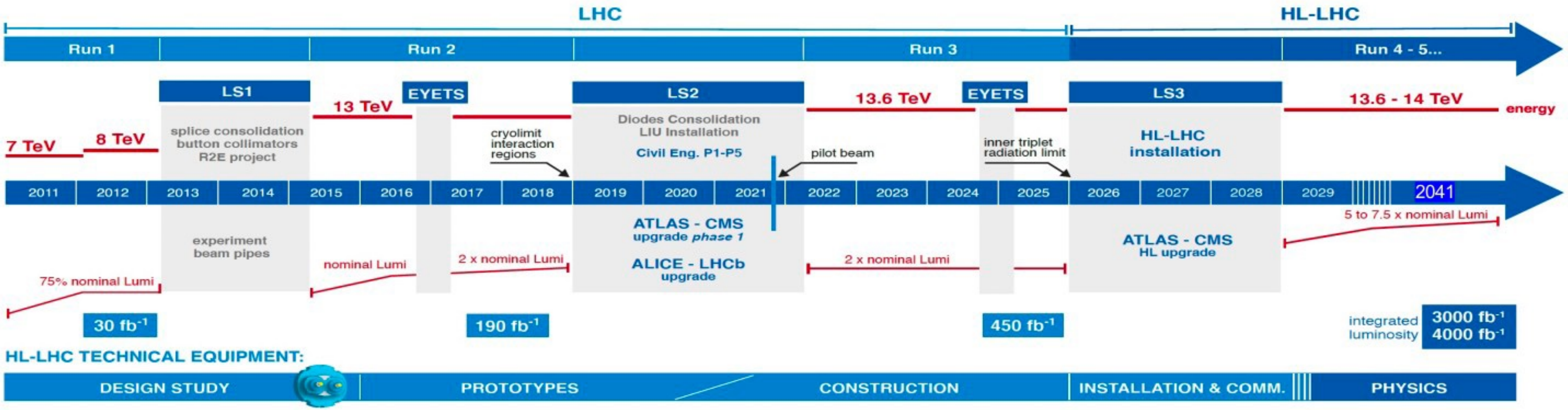
Physics objectives for HL-LHC (in a nutshell)

- The HL-LHC program aims at collecting at least 3 ab^{-1} of 14 TeV pp collisions (~ 15 times the present sample)
- This data will be essential for:
  - **Precision electroweak measurements**:
    - Longitudinal polarised vector boson scattering, triboson couplings, electroweak processes involving top quarks, rare processes…..
  - **Searches for Beyond Standard Model physics**:
    - SUSY, dark matter, new resonances, long-lived particles
  - **Flavour physics studies**:
    - Rare bottom and top decays, constraints on CKM





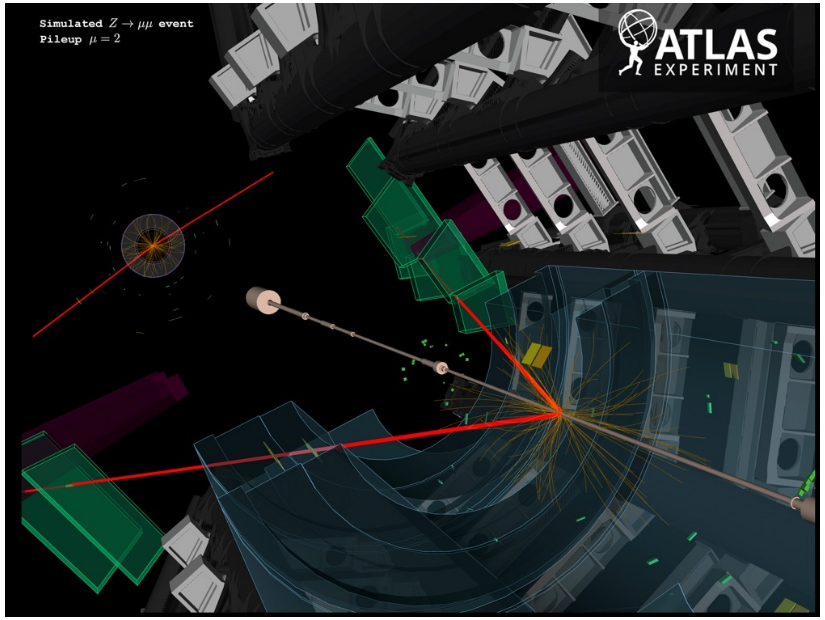
Challenges at HL-LHC



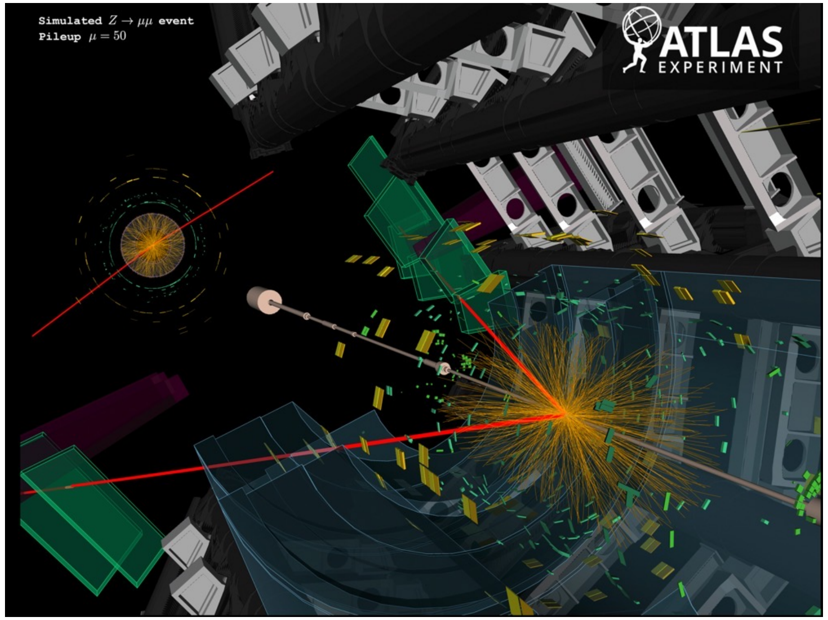
- The HL-LHC will provide higher instantaneous luminosity (5-7.5 10^{34} $cm^{-2}s^{-1}$)
- The pile up will increase from μ=60 (now) to μ=140-200 (levelled)
- Much larger radiation to detectors
- The beam induced cavern background will increase linearly with the luminosity
- Very large collected data sample : big challenges for computing and data storage

Challenges at HL-LHC

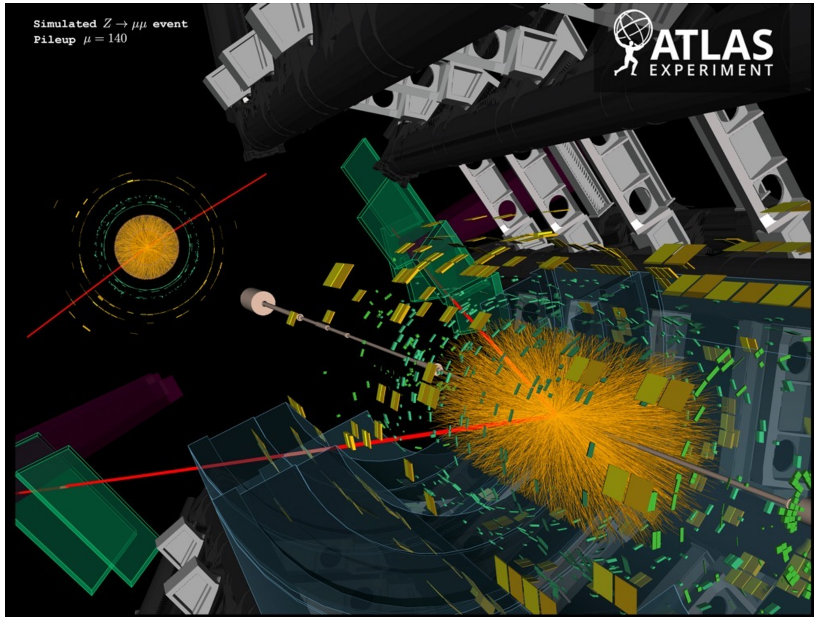
Pile Up = 2



Pile Up = 50



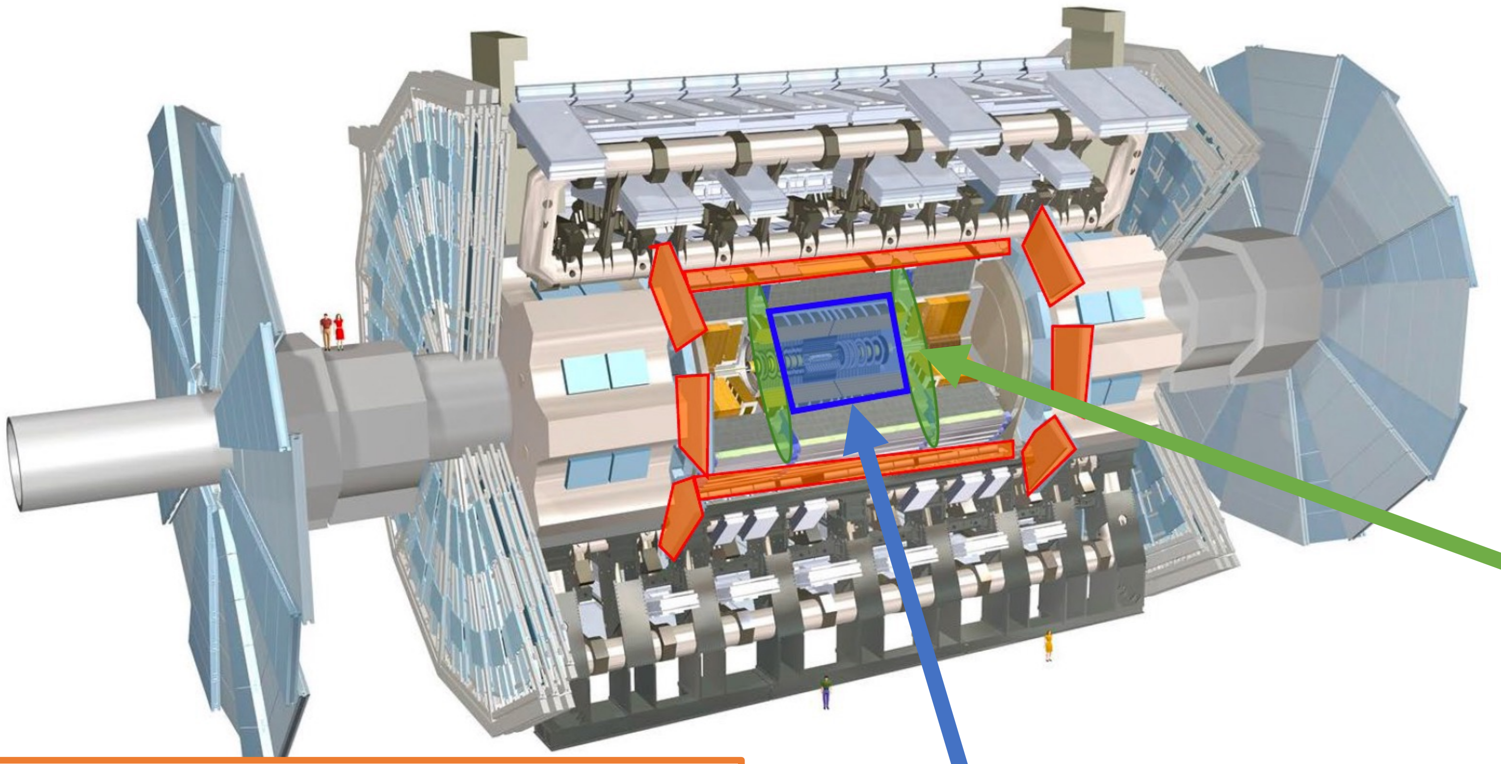
Pile Up = 140



- To fulfil the physic goals the upgraded detectors should
  - Measure all relevant final states (leptons, photons, Jets, Missing Et etc.) aiming at better performance wrt now, in a much harsher environment
  - Be very radiation hard (eg: Inner Tracker ~ 10^{16} n/cm^2)
  - Improve the triggering capabilities, trigger rates X10 higher while keeping same lepton Pt threshold
  - Improve the read-out capabilities (Read-out detectors at 1 MHz)

Overview of the ATLAS upgrade program

Very ambitious and complex upgrade program on all the ATLAS systems



Trigger and DAQ Upgrade

Single level Trigger with 1MHz output (x 10 current)

Improved system with faster FPGAs

HLT output rate (up to 10 kHz) and EF with 150 kHz full tracking

Calorimeter Electronics

On-detector electronics upgrade of LAr and Tile Calorimeters

Provide 40 MHz readout for triggering

High Granularity Timing Detector

Precision track timing (30 ps)

improve pile-up rejection in the forward region

New Muon Chambers and Electronics

Improved trigger efficiency/momentum resolution, reduced fake rates

New Inner Tracker (ITk)

All silicon with 9 layers up to |η|=4

Less material finer segmentation

Improve vertexing, tracking, b-tagging

Additional small upgrades

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

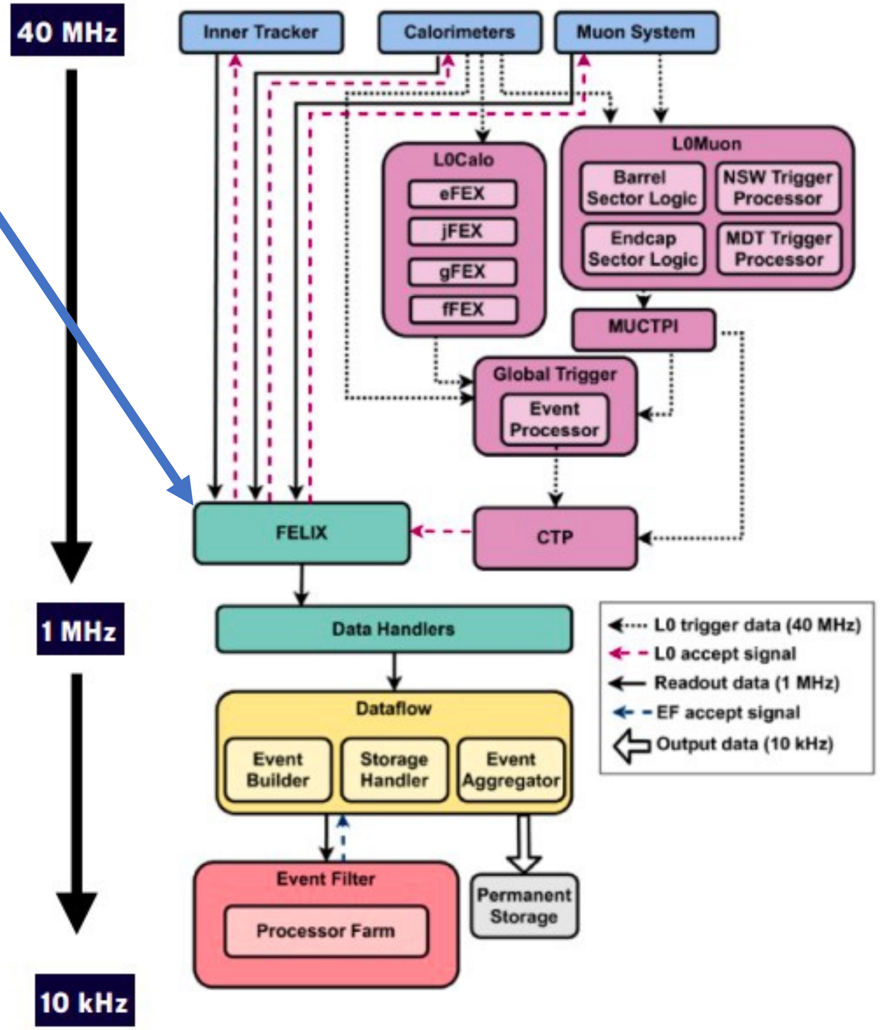
Not Covered in this talk

Trigger and DAQ upgrade

- DAQ:
  - Completely new architecture based on custom FPGA cards (FELIX)
    - *Data input form detectors at 40 MHz*

Felix Prototype

New TDAQ architecture



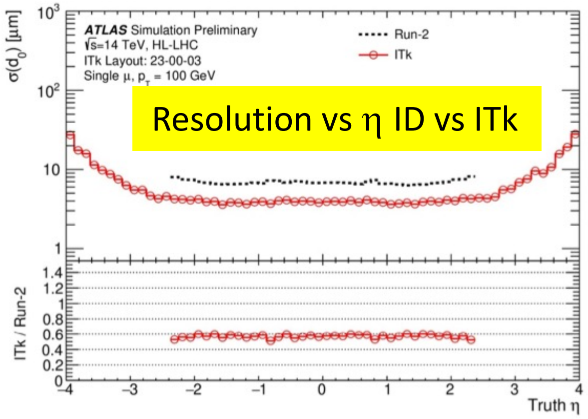
- Trigger:
  - Level-0 Trigger data input at 40 MHz from Calorimeters and Muons
  - Level-0: Rate 1 MHz, latency 10 µs
    - Exploits full detector granularity with new Global Trigger component
  - Software based Event Filter: Rate 10 kHz
    - Extended tracking range fully exploiting ITk, improves muon trigger efficiency
    - Based on CPU and accelerators (technologies under evaluation)

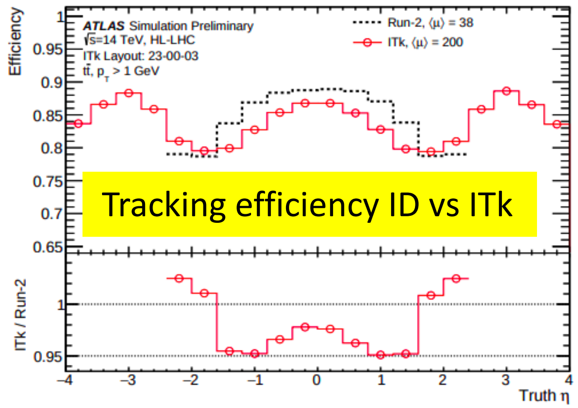
The Inner Tracker (ITk)

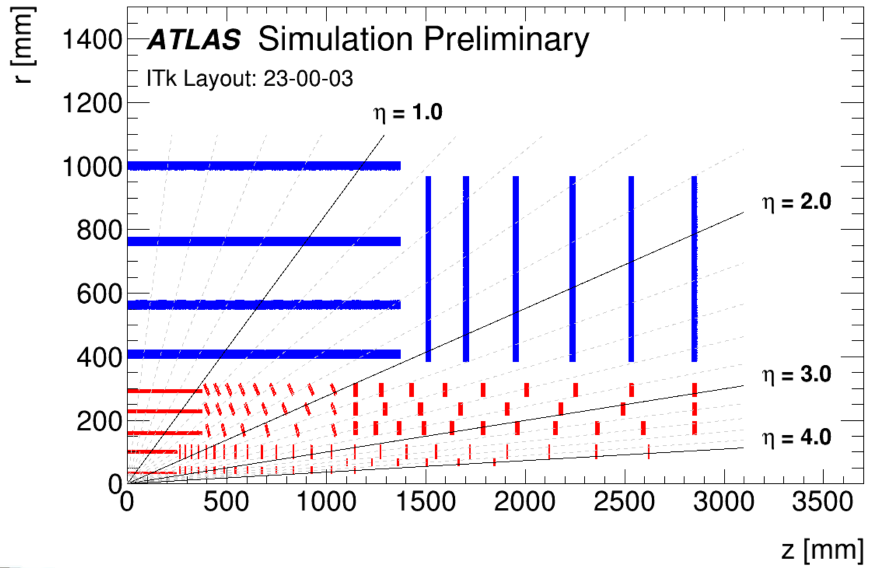
Completely replace the current Inner Detector (ID) with an all silicon Inner Tracker with much larger acceptance

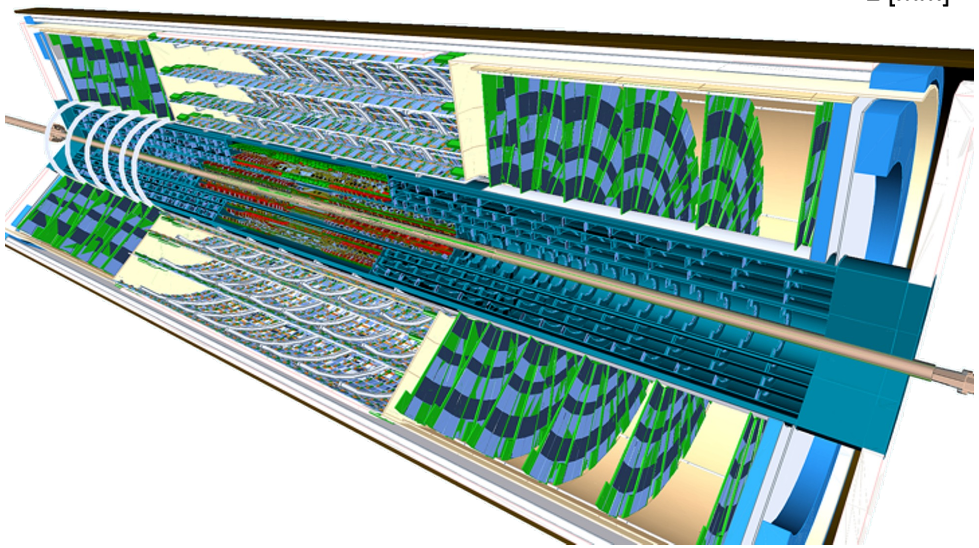
Schematic view of ITk systems

- ID $|\eta| < 2.5$ → ITk $|\eta| < 4$
- Better Pt resolution
- Similar Tracking efficiency but at pile-up of 200









- Very large and complex structure including:
  - 13m² of Pixel detectors (Inner System, Outer barrel and Outer End Cap)
  - 168 m² of Strip Detectors (Barrel and End Caps)
  - 5.1 Billions channels
- Reduced material and finer segmentation
  - Smaller pitch for inner pixel layer: 25x100 μm² (50x50 mμ² in other layers)
  - Improved vertex reconstruction (d_0 and z_0)
- At least 9 silicon hits per track
- Radiation tolerant up to 1E16 neq/cm² (inner Pixel layer)

ITk Photo Gallery

L3 Strip Barrel Shell

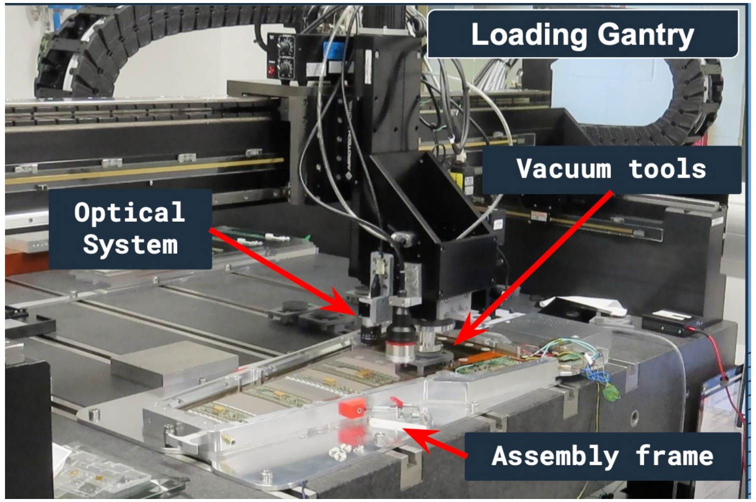
ITk Pixel loaded local support

ITk Strip pre-production Petal

Outer Cylinder Barrel

L2 Strip Barrel Shell

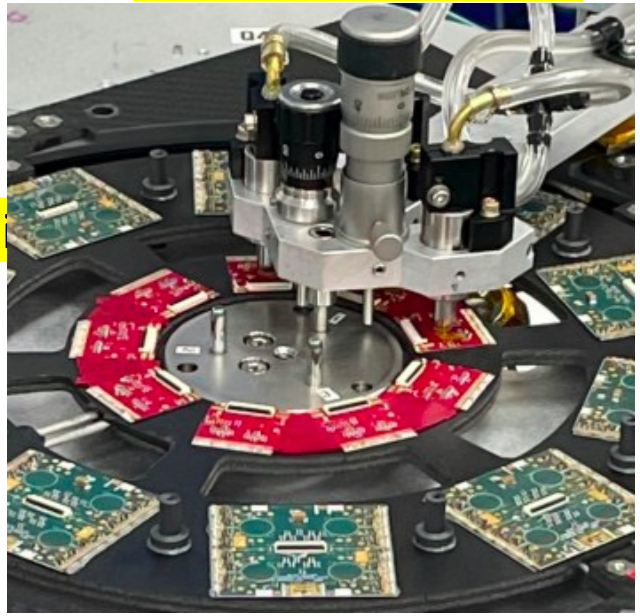
Petal assembly Loading Gantry



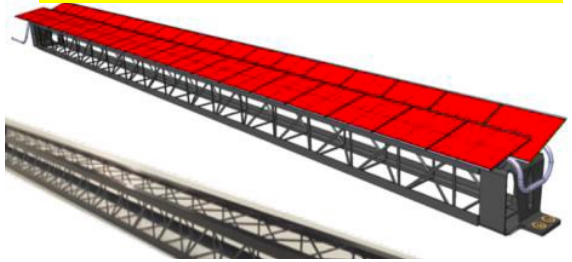
ITk Pixel

- General features:
  - Five barrel-layers + inclined and standard rings i End Cap
  - More than 5 Billions pixels, ~10 k modules
  - Inner system replaceable (due to expected radiation damage)
  - Serial powering (less material)
  - Carbon fiber supports, thermal demonstrators
- Sensors:
  - Pixel sizes
    - 25 x 100 µm² (innermost barrel)
    - 50 x 50 µm² (everywhere else)
  - 3D sensors in innermost barrel/disks
  - Planar sensors in the other layers
  - 3 or 4 FE chips/module
- Production status:
  - All sensors are in pre-production
  - Hybridization pre-production modules started
  - ITkPixV2 readout chip has been received and is being tested

Inner System loading

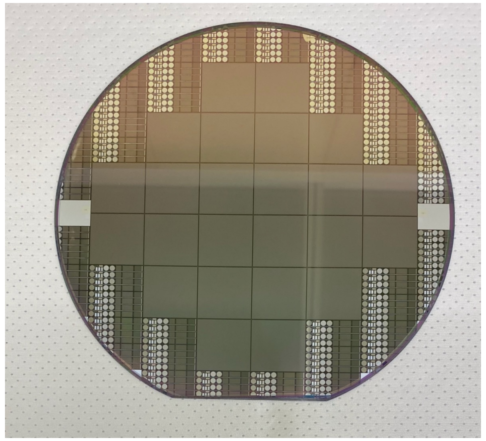


Pixel Outer System Stave

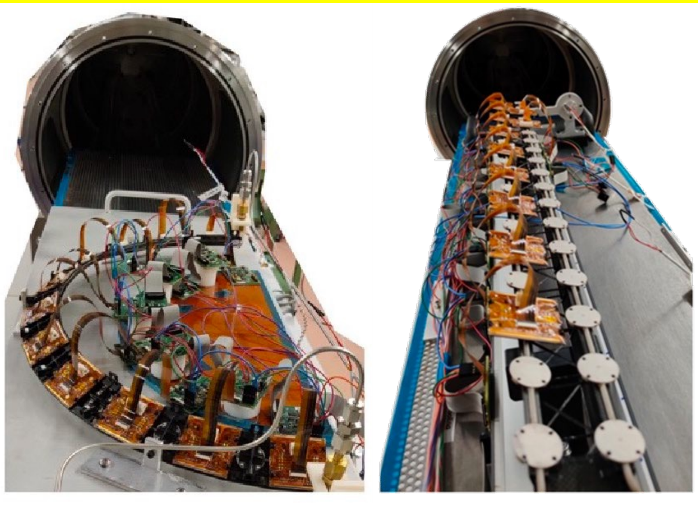


Pixel inclined ring

FBK 3D sensors

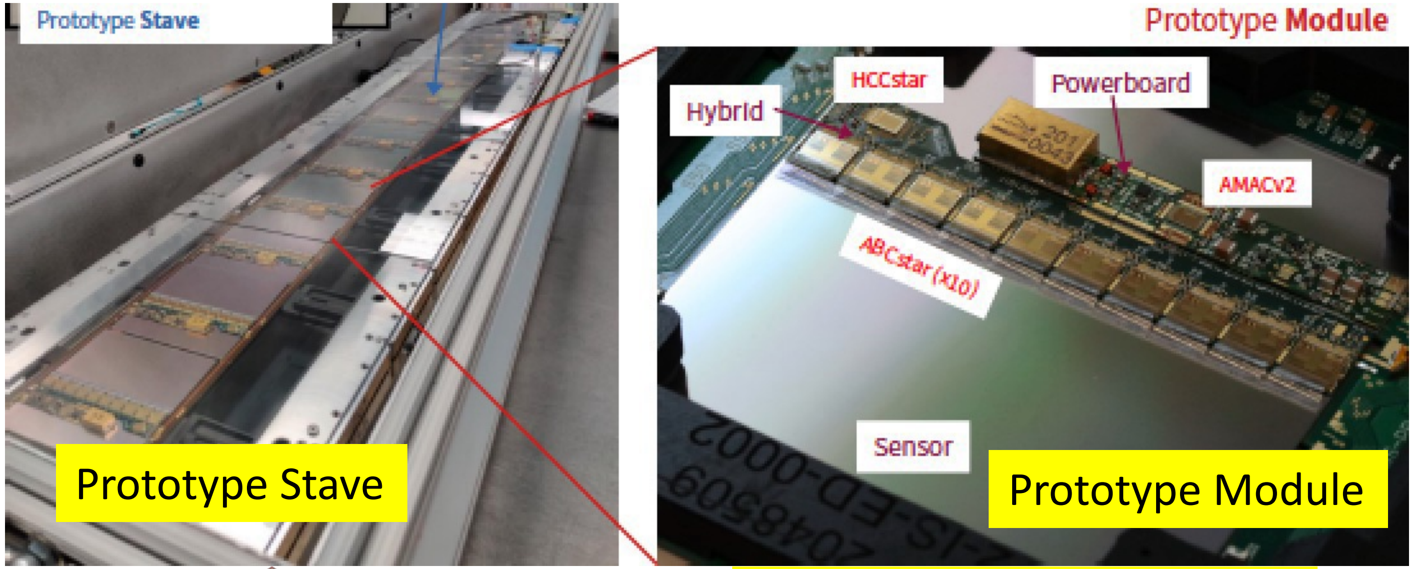


Thermal Studies for the outer barrel



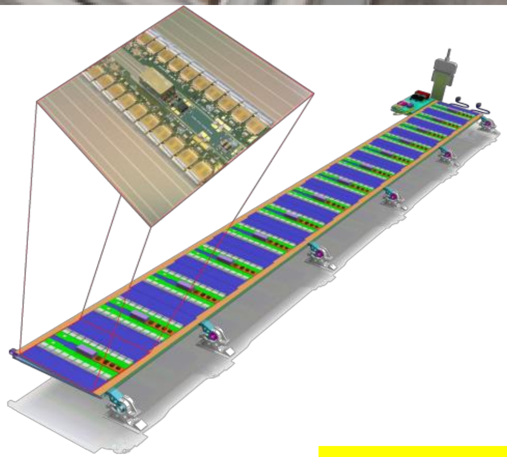
ITk Strip

- General features:
  - Four-layer barrel and two six-disk endcaps
  - Angular coverage of |η| < 2.7
  - 18 k modules
- Sensors/ASICs:
  - Strip width ~75 μm
  - ~60 M channels
  - 3 front-end ASICS: ABCStar, HCCStar and AMAC
  - Radiation: 1.6E15 neq/cm^2
- Production status:
  - Sensors: In production.
  - ASICs: in production
  - Hybrids and modules in pre-production
    - Issue with noise when operating at cold caused by vibrations of capacitors on Power bards
    - Possible mitigation found
  - Mechanics in production



Prototype Stave

Prototype Module



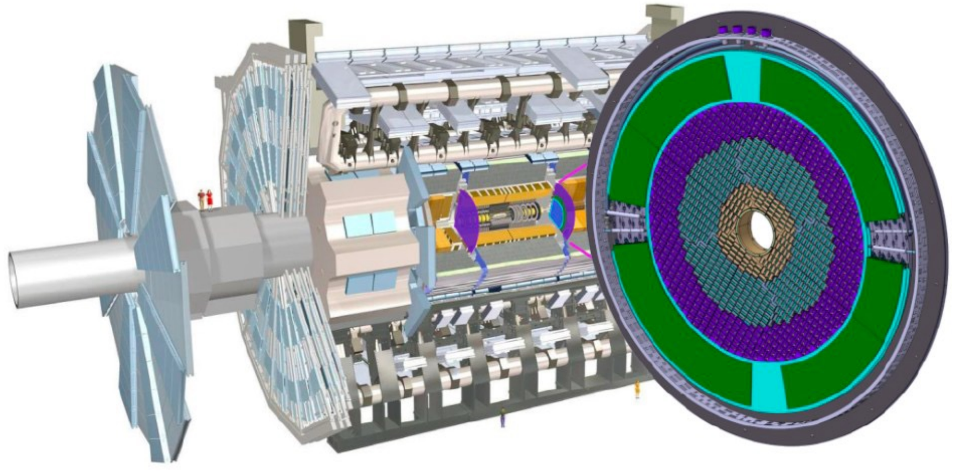
Production End Cap Wheels

Pre-production Petal

High Granularity Timing Detector (HGTD)

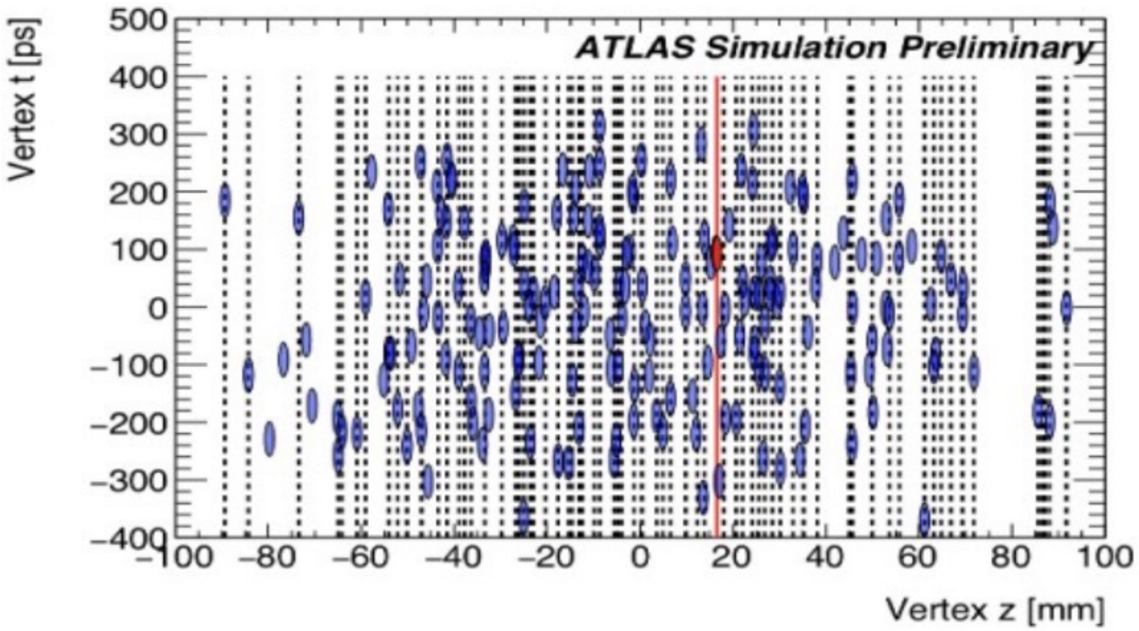
- HGTD improves pile-up rejection in the forward region and provides luminosity measurement
- Located at |z|=3.5 m in front of the LAr End Cap
- Active area: 12 cm < r < 64 cm; 3.6M Channels

  2.4 <|η|< 4.0



- Silicon detector modules mounted on disks
  - Rad Hard Carbon infused LGAD sensors to mitigate single event burnout
    - 1.3x1.3 mm^2 pads
  - Two sensor layers/disk
  - Two disks/side (total 4 layers/side)
  - Target time resolution:
    - 30-50 ps/track up to 4000/fb
- Current Status:
  - Final front-end ASIC prototype (ALTIROC3) received and initial tests started
  - Established maximum field per sensor thickness
  - Prototype sensors met radiation tolerance requirements below this critical field
  - Design of modules, services, mechanics progressing

4D tracking using precise vertex timing for Pile-Up rejection



LAr Calorimeter

- General for all calorimeters
  - New on-detector and off-detector electronics.
  - Continuous readout at 40 MHz.
  - Full digital input to ATLAS trigger system
- LAr Upgrade in 2 Phases:
  - Phase I : Trigger digitization and processing (in operations)
  - Phase II: Calibration, digitization and signal processing for energy reconstruction.

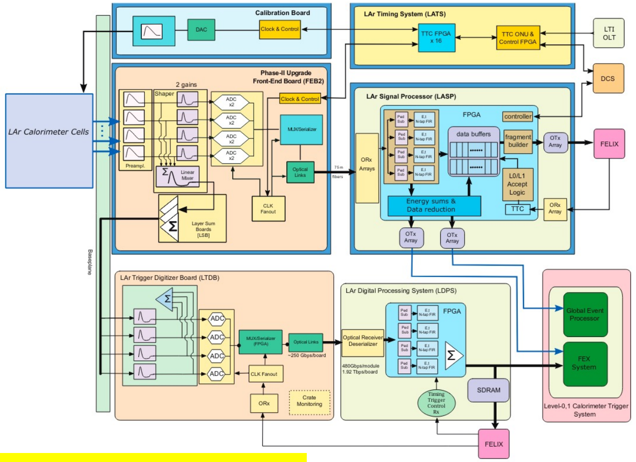
Phase II

On detector:

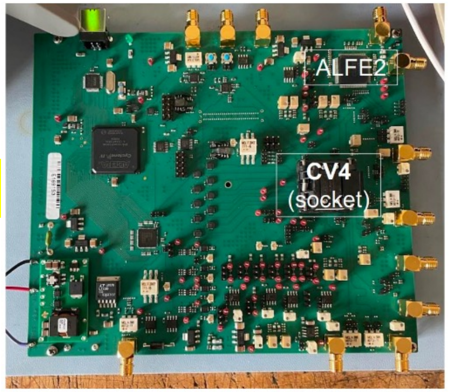
- New high precision frontend electronics aiming at 16-bit dynamic range and linearity better than 0.1 %.
  - Two new ASICS housed on a new Front End Board (FEB2):
  - Two new ASICS housed in new Calibration Board:

- Off Detector:
  - LAr Signal Processor (LASP) and LAr Timing System (LATS)
    - Total bandwidth of 345 Tbps.
    - ATCA boards for waveform feature extraction with ~33k links at 10 Gbps.

On-detector *Off-detector*



FEB2 prototype



LAr Signal Processing (LASP) demonstrator under testing

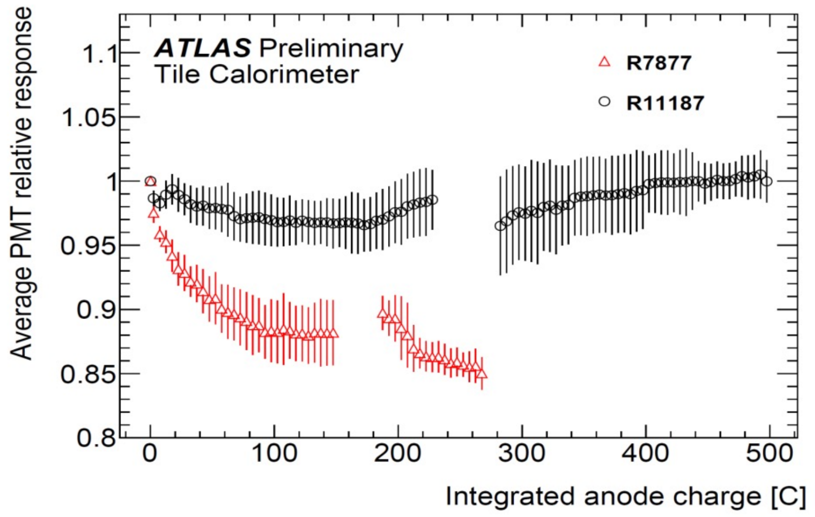
Status:

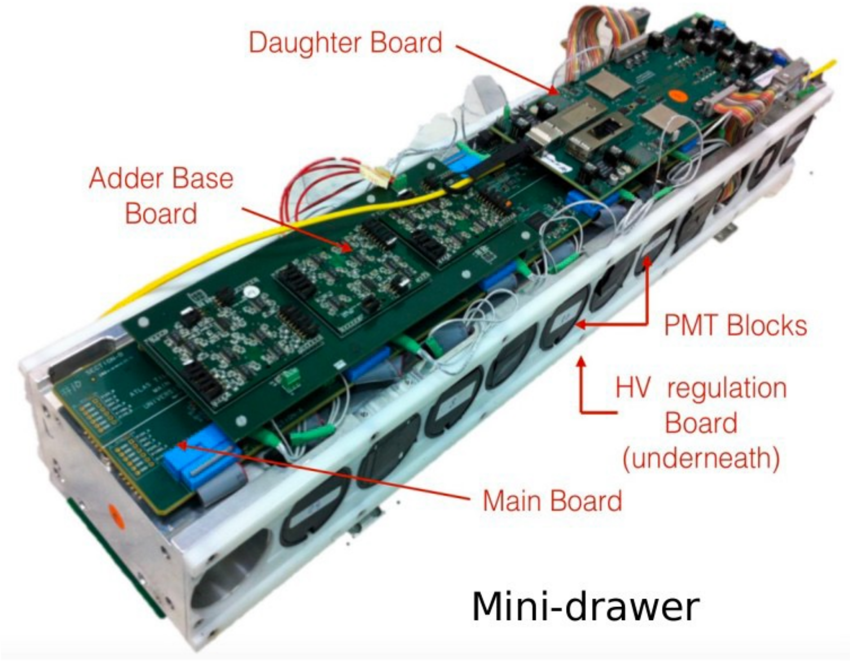
- Major technical progress in all areas
  - Pre-production wafers of FE Board ASICs received
- FE Preamp/shaper ASIC (ALFEv2) & ADC ASIC (COLUTAv4
  - Prototype off-detector elements proceeding

Tile Calorimeter

- New modular mechanical design of the front-end housing 4 mini drawers 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.
- **F**ront **E**nd board for the **N**ew **I**nfrastructure with **C**alibration and **S**ignal Shaping (FENICS)
  - Shaping and amplification (2 gains) of the PMT signal and calibration (9852 boards in total)
  - Built in charge injection systems for ADC calibration
- Phase-2 demonstrator has been installed in ATLAS and is taking data.
  - Has proven to be very useful to test the electronics and identify problems early on
  - Demonstrator gives stable performance, low noise and good CIS and laser signal
- Status:
  - Most on-detector items are in production
    - First production batch of FENICS to be received soon
    - Mainboard production close to completion
    - Mini-Drawer Mechanics production completed
    - Design of DaughterBoard is being finalized

New vs old PM stability vs int. charge

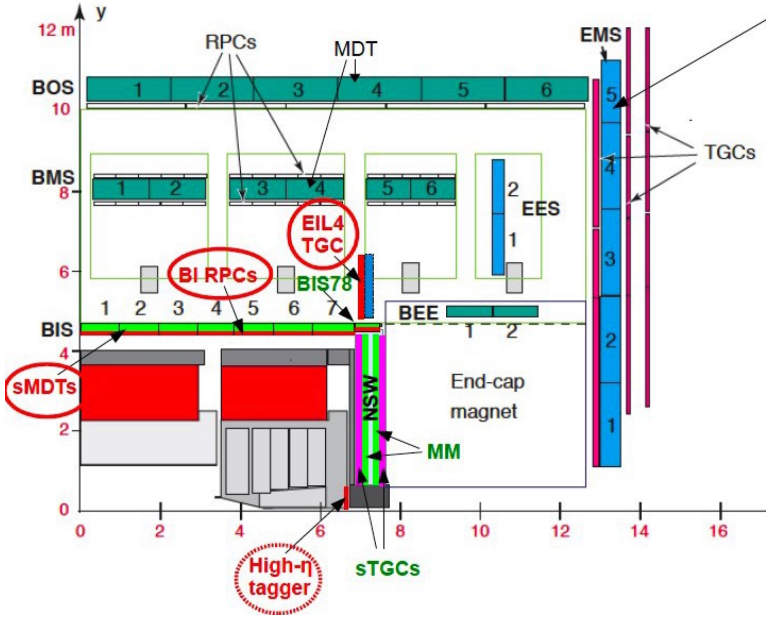


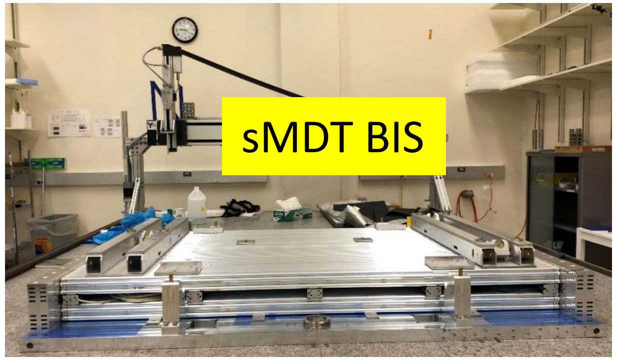


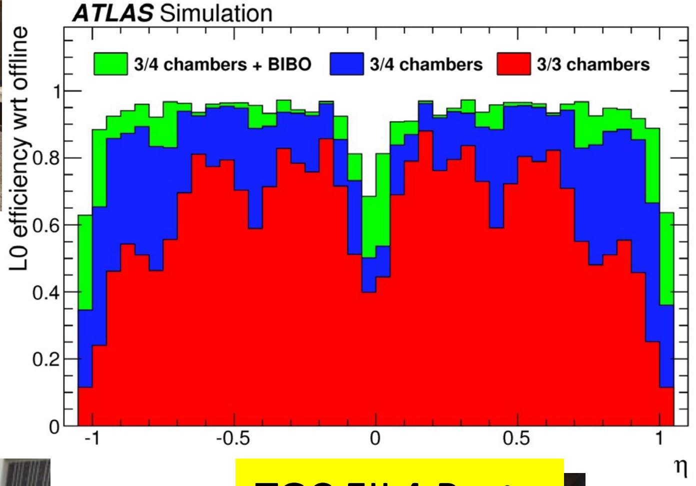
Mini-drawer

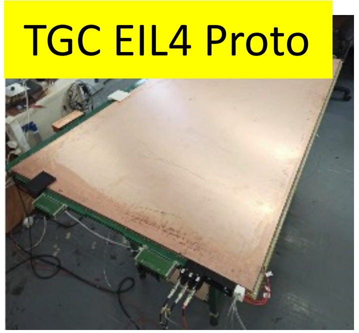
Muons

- Muon upgrade aims at Improving trigger coverage and fake rates+ new electronics to be compliant with the 1 MHz LVL0 and new latency (10 µs)
  - Addition of layers of sMDT, TGC, RPC in the Barrel region (NSW Phase I upgrade for End Cap)
    - To Improve trigger coverage
  - Change all the on-detector front-end electronics
    - Readout/trigger upgrade to send data at 40 MHz.
  - MDT will provide L0 trigger to improve Turn-On
- Production status:
  - sMDT:
    - Chamber production almost finished, two thirds of the chambers already at CERN. Frontend-boards to be produced in the fall.
    - Start of commissioning in early 2024.
  - RPC:
    - Second FE prototype delivered and under test.
    - ASIC engineering run submitted.
    - Prototype chambers under test.
  - TGC:
    - Design passed FDR, Completion of two pre-production modules





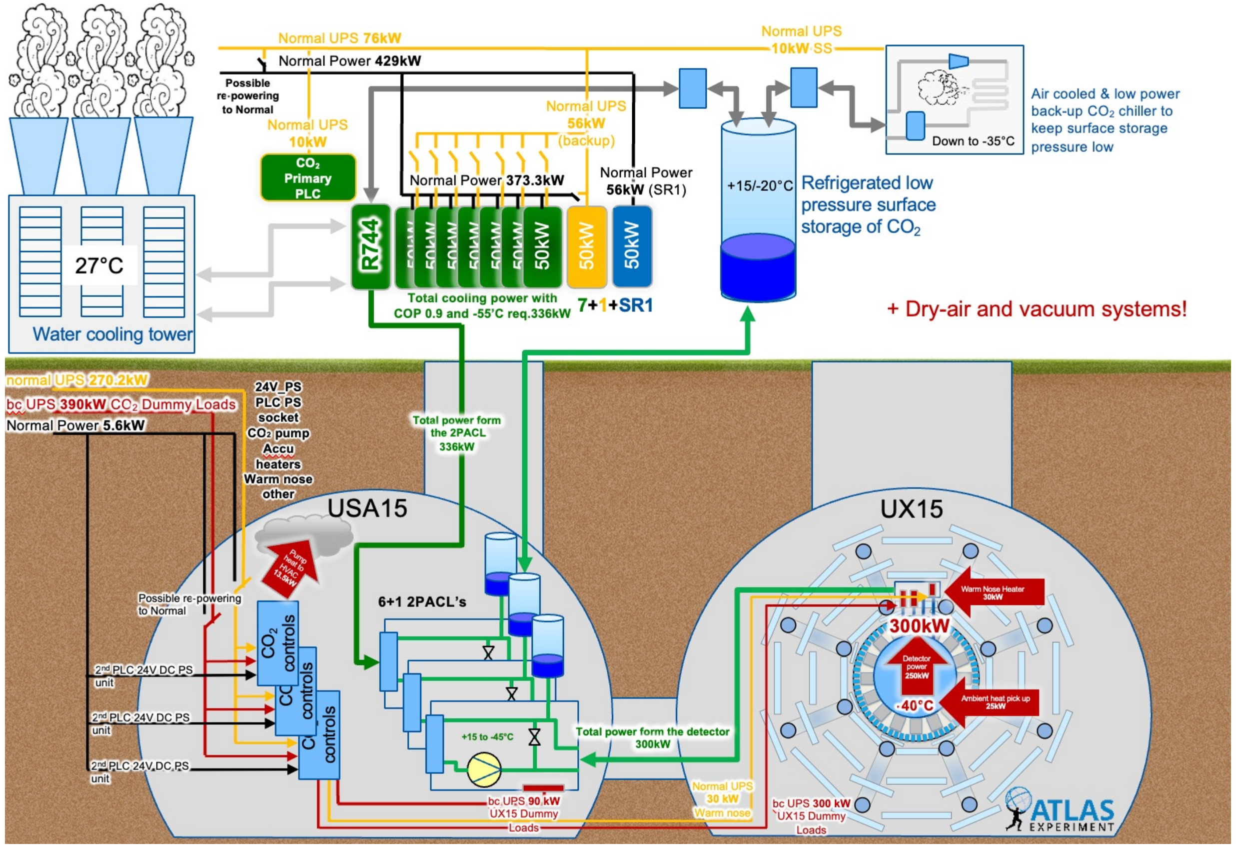




Infrastructure Upgrade

- Need to upgrade all ATLAS infrastructures to support the new upgraded detector

- Largest and more innovative project is the new CO2 Cooling plant for the ITk and HGTD detector cooling
  - 300 kW of cooling power at -40 C
    - >20X largest CO2 cooling systems to date



Huge project in collaboration with CMS, CERN EP-DT and EN-CV
Based on 2PACL technology developed at CERN
Will allow to decrease by 30% the CO2e emissions of the experiments by replacing the cooling systems based on greenhouse gasses C3F8 and C6F14

C3F8 GWP =8830
C6F14 GWP= 9300 → CO2 GWP =1

Conclusions

- ATLAS has an ambitious upgrade program to fully exploit the physics potential of HI-Lumi LHC
- The upgraded detector is designed to, have better performance in a much harsher environment, and it will also provide exciting new physics opportunities (increased acceptance, improved low-level triggering, enhanced timing information, deeper use of machine learning in trigger and reconstruction)
- New detectors are being produced (ITk, HGTD, Muons)
- New electronics are developed for all systems
- The Trigger and Data acquisition will be running at X10 the present rate
- All projects are entering the production phase
  - Huge progress in the last year for all systems but still it is a very technically challenging project with a very tight schedule for several systems

Back Up

Computing needs for HL-LHC

- Computing Resource Estimates show need for major R&D (and/or budgetary) effort to realize the HL-LHC physics potential.
  - Two scenarios defined : *Conservative R&D* and *Aggressive R&D*
    - Conservative should be achievable with today’s effort and people
    - Aggressive requires more people, more R&D projects bringing resource savings
  - The black lines indicate the “flat budget” of 10% (lower line) and 20% (upper line)