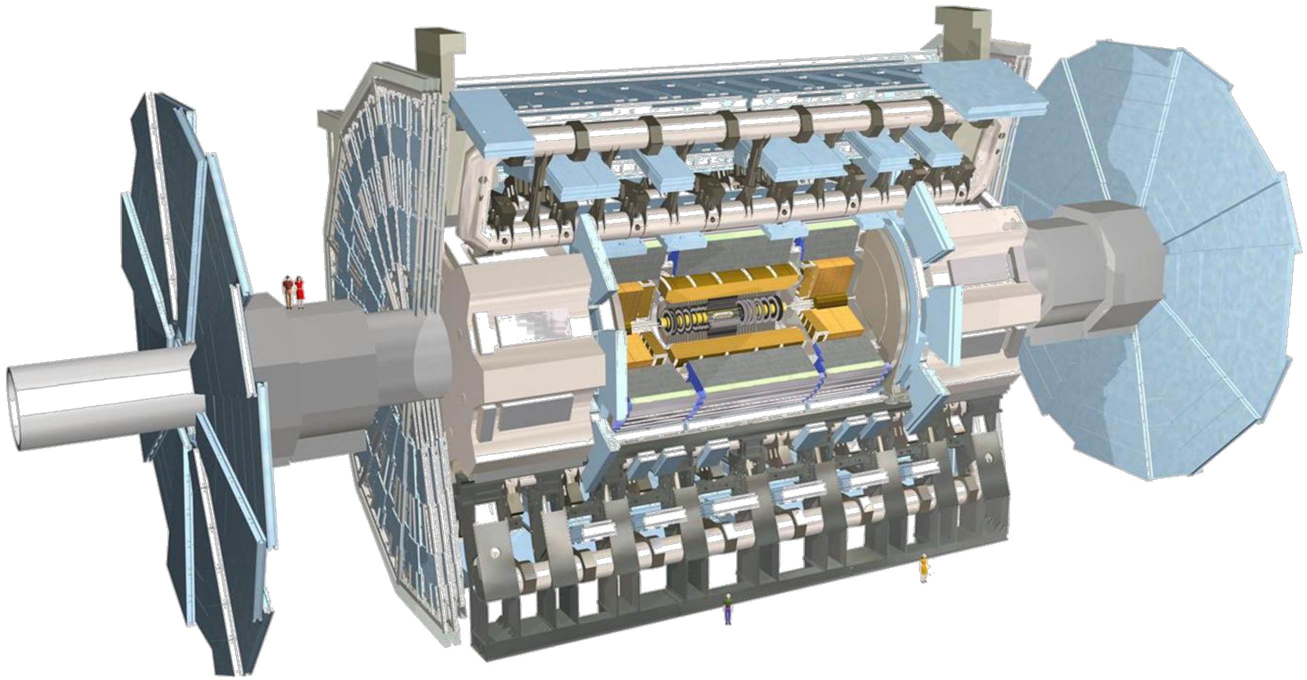
ATLAS Upgrades



Vincenzo Izzo - INFN Napoli

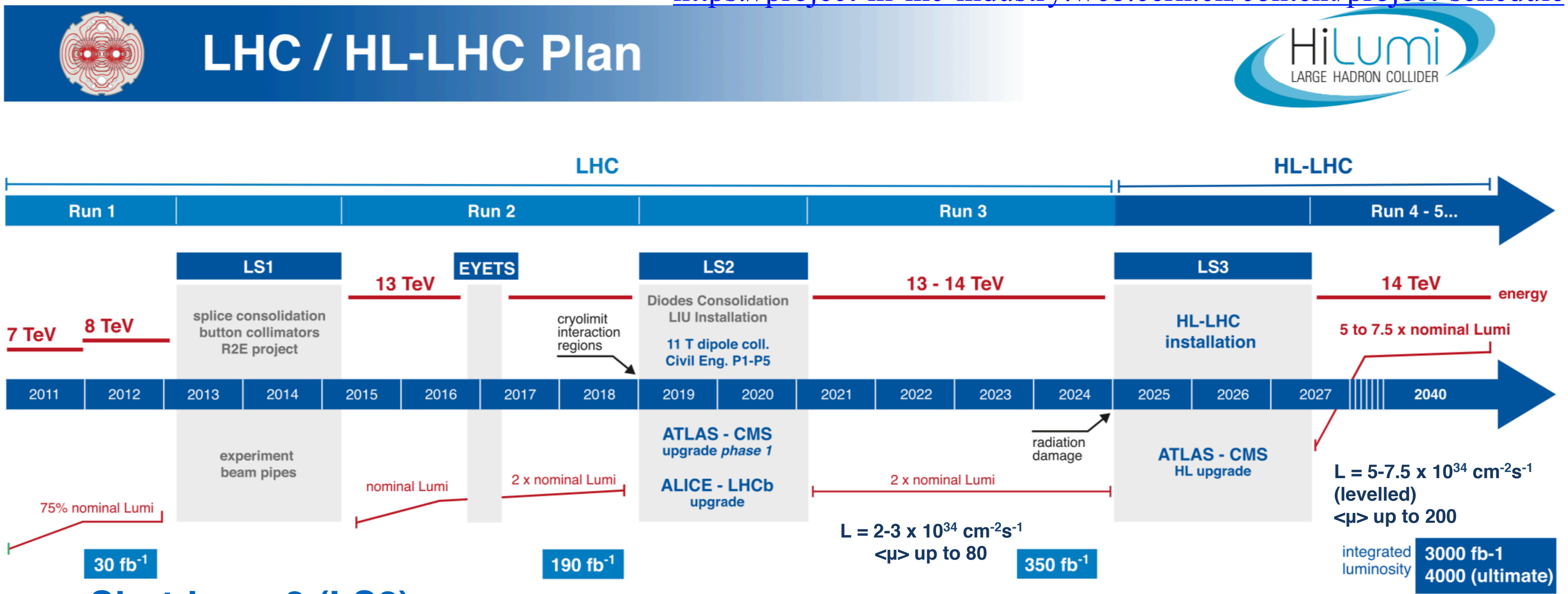
on behalf of the ATLAS collaboration

The 8th Annual Large Hadron Collider Physics conference

25 May 2020

ATLAS and LHC upgrades

https://project-hl-lhc-industry.web.cern.ch/content/project-schedule



Long Shutdown 2 (LS2):

LHC: cryomagnets replacement, bending magnets, PS Booster injection system, etc.

ATLAS Phase-I upgrades: New Small Wheel, Muon, LAr electronics, L1 Calo, TDAQ

Long Shutdown 3 (LS3):

High Luminosity-LHC (HL-LHC):

Improved injectors: more protons per bunch, all-new Linac-4, better focusing

Center-of-mass energy= 14 TeV, **instantaneous luminosity** up to 7.5 × 10^{34} $cm^{-2}s^{-1}$

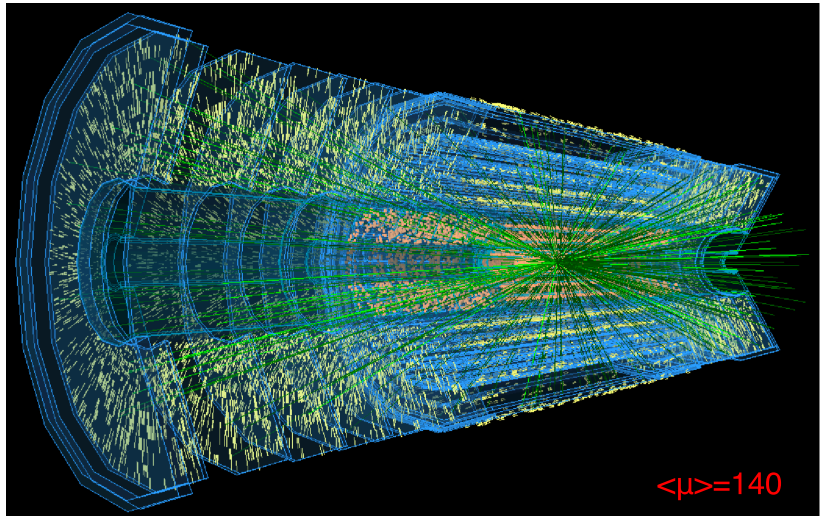
ATLAS Phase-II upgrades: Inner tracker, Muon detectors, HGTD, L1 Calo, TDAQ

***Long Shutdown 1 (LS1) ATLAS**:
RPC in barrel feet region, MDT at |η| ~ (1.1-1.3), pixel IBL, HLT

High luminosity impact on the experiment

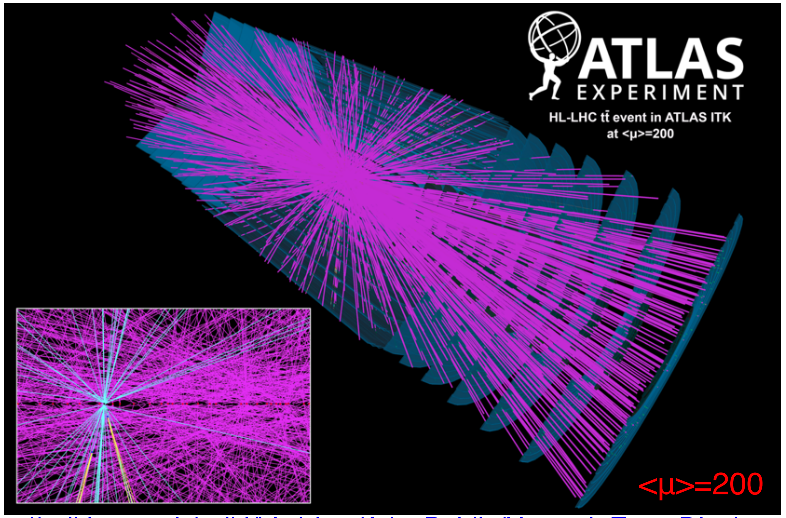
- High luminosity is needed to achieve physics goals

- **Requirements**:
  - All parts of the experiment have to stand a peak levelled **luminosity** of 7.5x10^{34} $cm^{-2}s^{-1}$
  - keep **good physics performances** in this challenging environment, as good as in run 2 and 3
  - keep acceptable **trigger rate** with low p_T threshold
  - mitigate **pile-up** up to high η



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

- **Detector challenges**:
  - high **pileup** (<μ> up to ~200 collisions/bunch crossing)
    - → larger event sizes
    - → higher trigger rate
    - → higher detector occupancy
    - → readout limitations
    - → increasing reconstruction complexity
  - high **radiation** levels (~$10^{16} n_{eq}/cm^2$; 10 MGy)
    - → increased radiation damage
    - → increased activation of materials



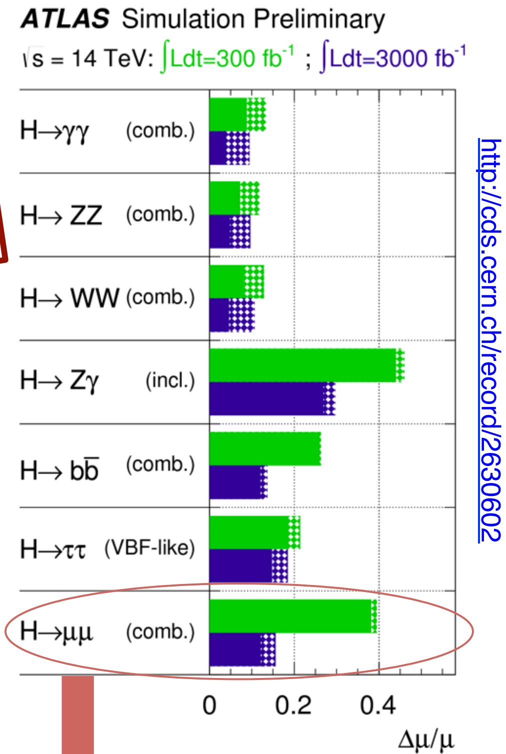
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradeEventDisplays

Motivation for the upgrades

Maximise physics performance for:

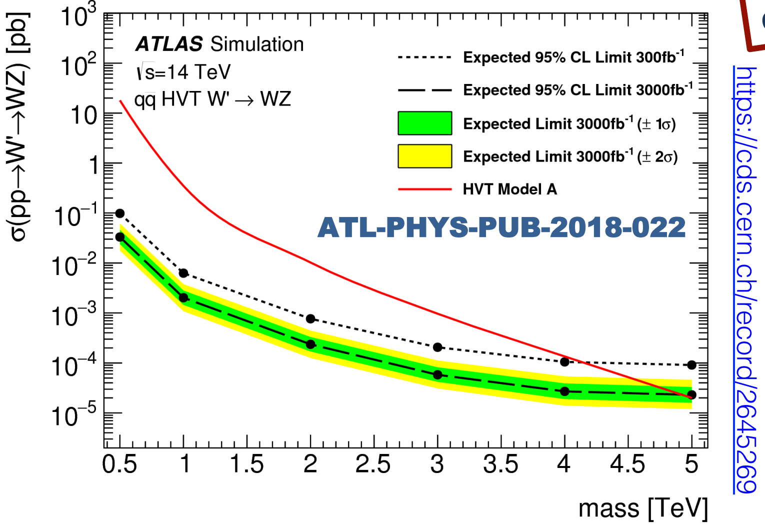
- **Precision measurements** of Higgs coupling and other SM processes:
  - search for **SM rare decays/effects** (like **H→μμ**)
  - **Higgs self-coupling** in SM accessible at HL-LHC
  - Higgs boson couplings measured with precision of 2-10%

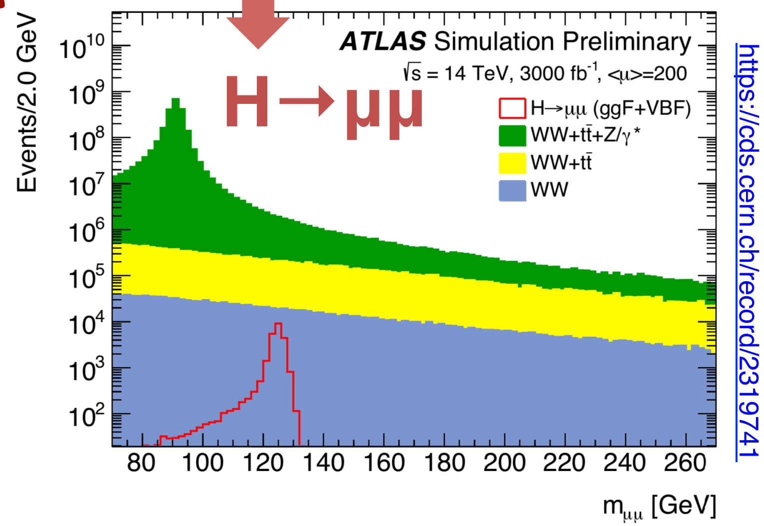
See Higgs physics sessions on 26/05 and 28/05



- Continue the LHC scientific programme with the search of **Beyond Standard Model physics (BSM):**
  - Resonances: Searches for new massive states on HL-LHC will extend mass reach by ~20%
  - SUSY and Exotic benchmark significantly extended
  - Dark sector
  - Long lived particles

See TeV-scale BSM sessions on 27/05 and 28/05

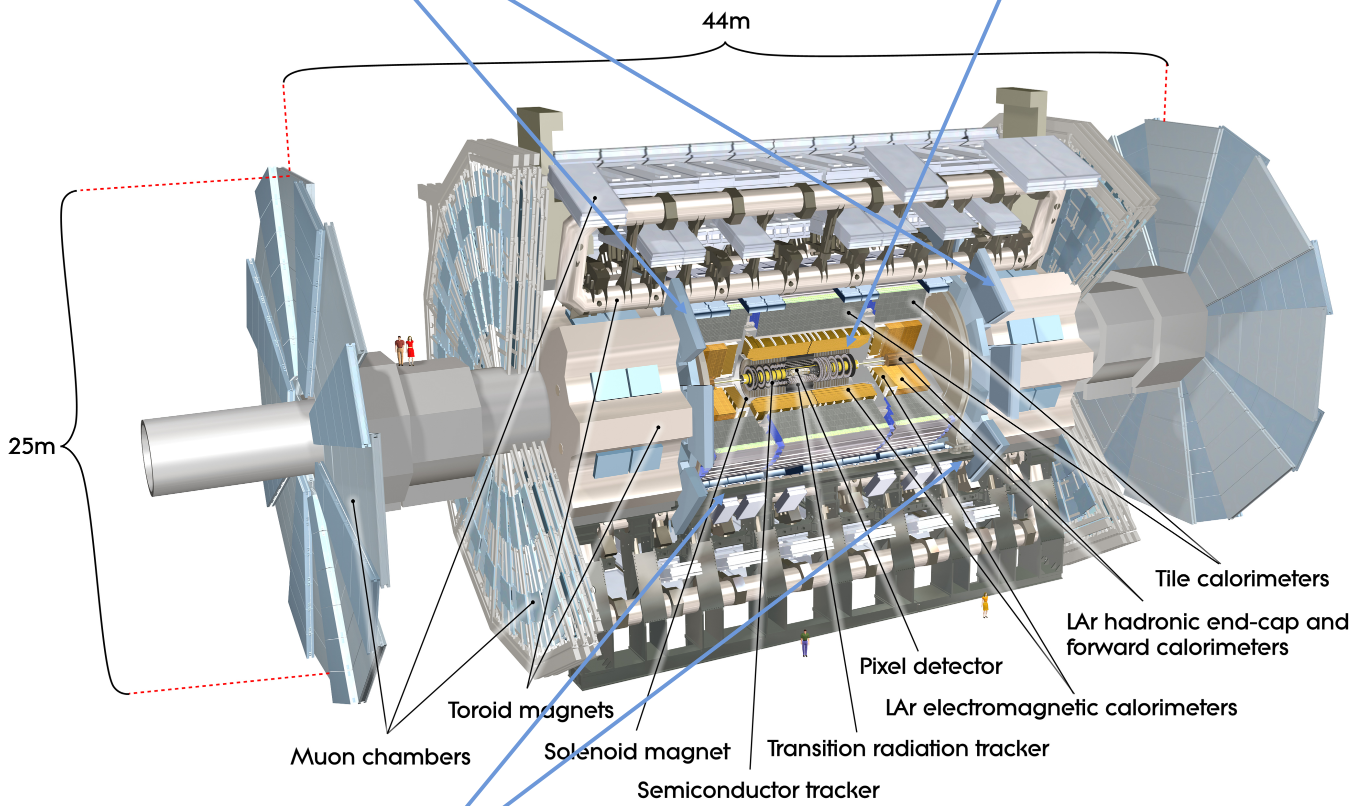




ATLAS Phase-I upgrades

New Small Wheel detector

LAr front-end electronics



New **Muon RPC** detector (**BIS78**)

TDAQ off-detector electronics:

- **L1 hardware trigger**:
  - L1 calorimeter
  - L1 topological
  - L1 NSW trigger
  - L1 endcap trigger
  - L1 MuCTPi
- **Readout system**
- **HLT**

New Small Wheel Overview

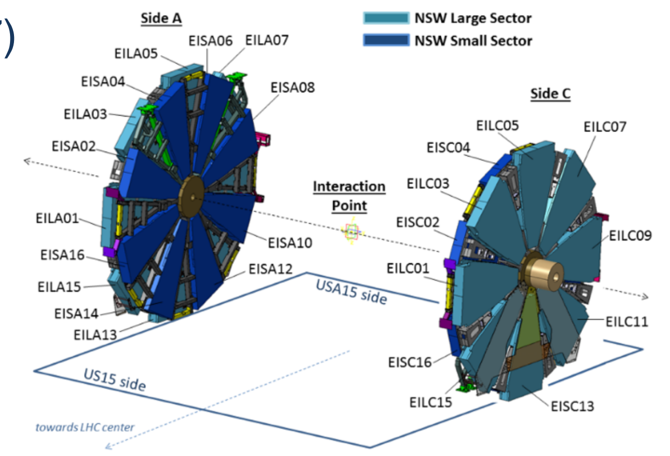
- Two 5m radius wheels in **the inner end-cap** region (1.3 < Iηl < 2.7)

- Each wheel is formed by:
  - 2 external **sTGC** wedges (mainly trigger, bunch crossing identification + vector tracking with < 1 mrad resolution)
  - 2 internal **MicroMega** wedges (mainly tracking, spatial resolution <100 μm)

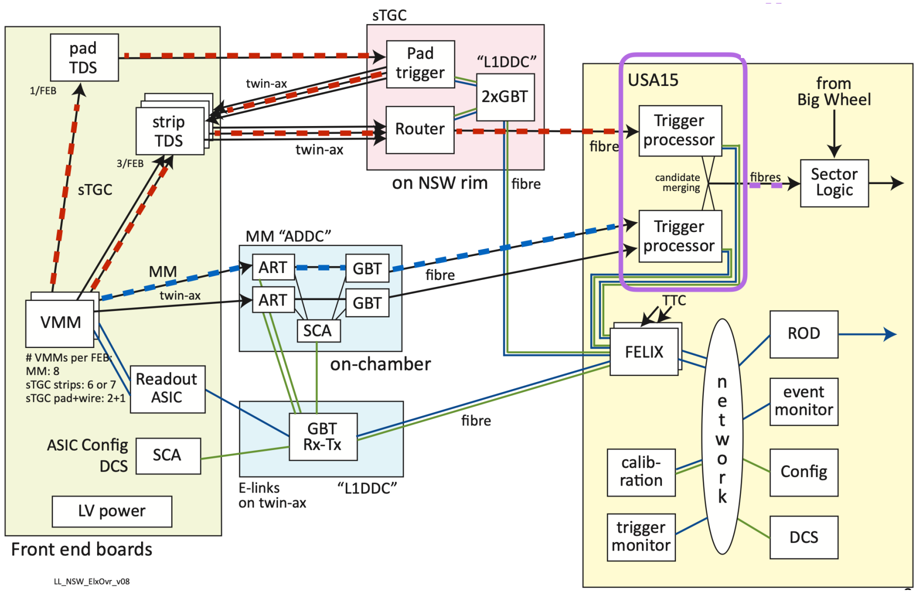
- Needed to **reduce fake muon triggers in the end-cap region**, thanks to the coincidence endcap-NSW

- **Electronics** based on many custom elements:

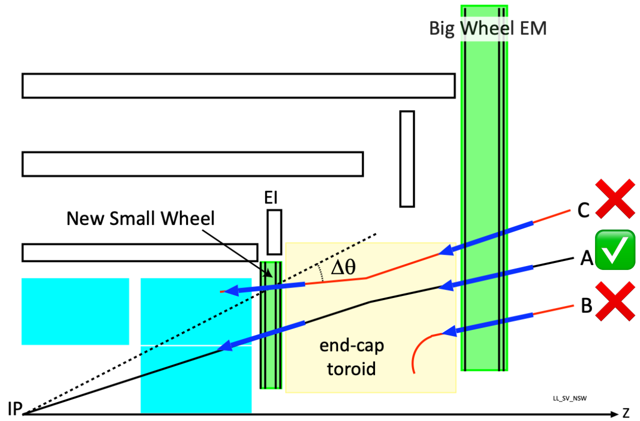
4 ASICs, **Front-End boards**, **on-rim boards**, **off-detector ATCA module**



Chambers built in Institutes in 4 continents



NSW trigger and readout schema



ATLAS-TDR-020-2013

L1MU threshold (GeV)	Level-1 rate (kHz)
$p_T > 20$	60 ± 11
$p_T > 40$	29 ± 5
$p_T > 20$ barrel only	7 ± 1
$p_T > 20$ with NSW	22 ± 3
$p_T > 20$ with NSW and EIL4	17 ± 2

Expected L1 muon rate for L = 3×10^{34} $cm^{-2}s^{-1}$

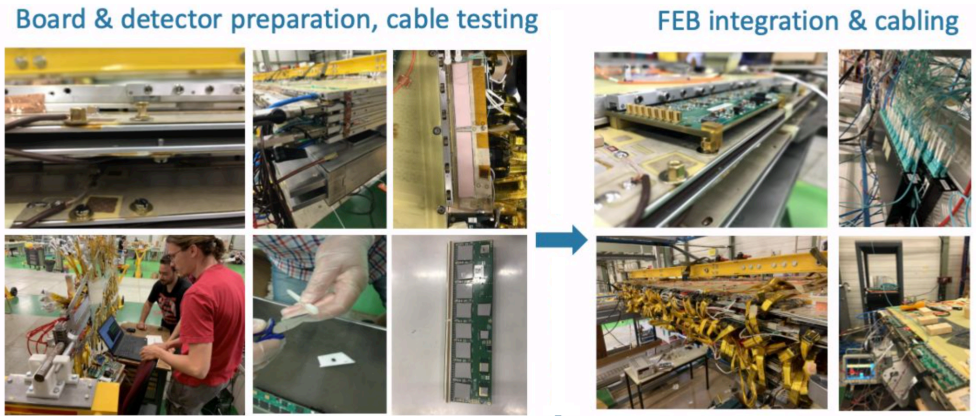
New Small Wheel Status

- Chambers and electronics for first NSW almost all produced, and well on track for 2nd wheel
  - for many electronics part, indeed already completed full production

2 posters on this! Thursday 28th

- Integration activities @ CERN in full swing (assembly, installation, connections), both for Micromegas and sTGC

MicroMegas Integration

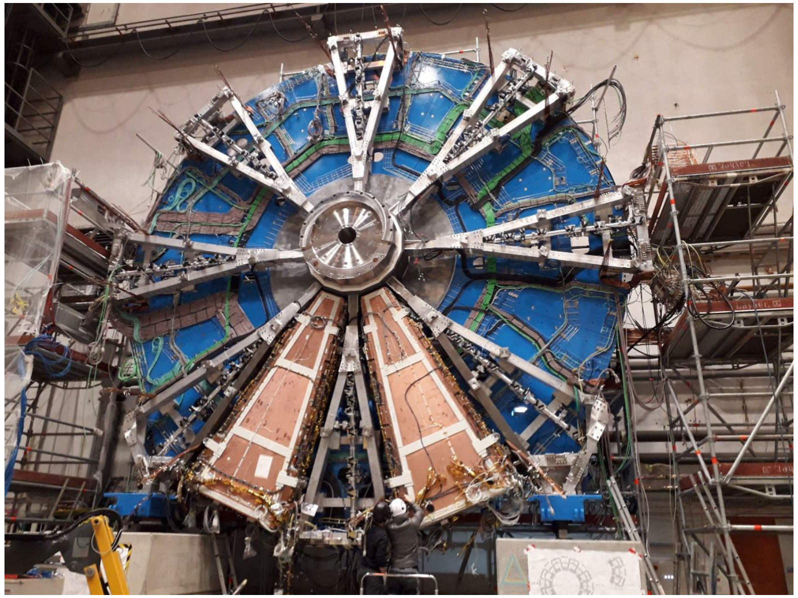


sTGC Integration

- In parallel implementing DAQ, Readout, Trigger software etc.

- Prior to COVID-19 crisis, were on track for installing first wheel before end of this year

Sectors 12&14 installed since March '20



BIS78

- NSW covers the region (1.3 < Iηl < 2.7), while the big wheel covers (1.0 < Iηl < 2.7)

- Half of the region 1.0 < Iηl < 1.3 is covered by the existing EIL4 TGC end-cap trigger chambers

- **New detectors in the BIS region** will cover the rest

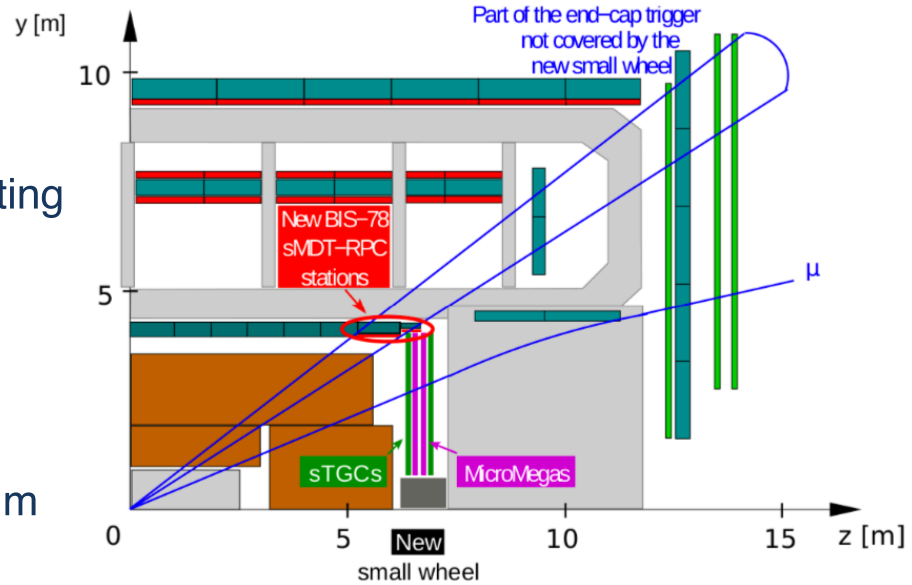
- 16 **RPC** trigger chambers: thin gap RPC triplets ⇒ 1 mm gas-gap width (instead of 2 mm), new FE elx.

- replacement of 16 existing MDT with **sMDT**⇒ drift tube diameter 15 mm instead of 30 mm

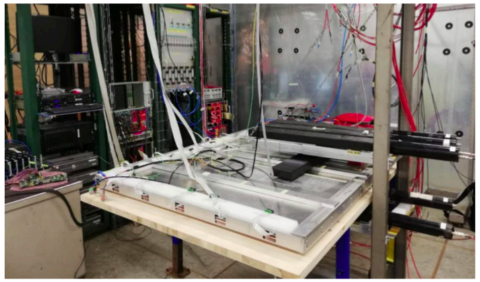
- The additional RPC chambers can significantly **reduce the foreseen fake rate**

- Detector production ongoing, installation of A side by summer, BIS78 C-side postponed until LS3

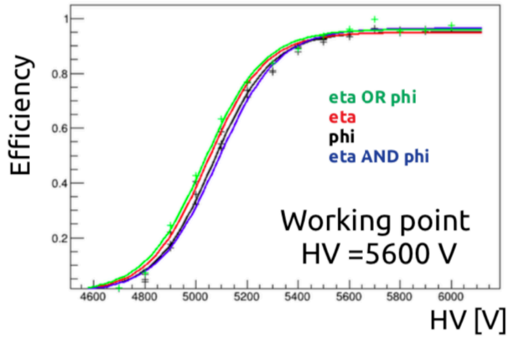
- **Phase-II pilot project:** same MDT and RPC detector technology that will be used for Phase-II, when the full BI layer will be equipped



Triplet

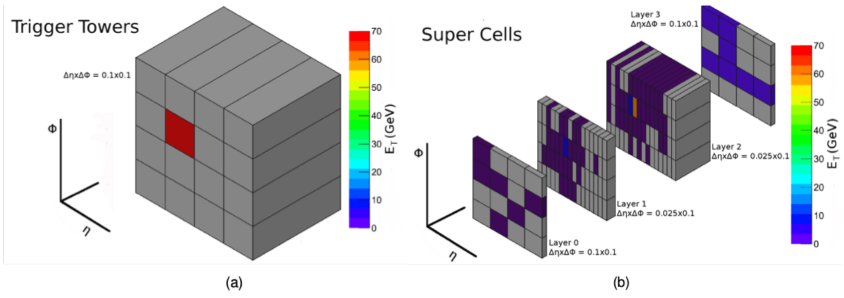


Efficiency ~ 95% at plateau



LAr calorimeter and L1calo new electronics

- **LAr calorimeter**:
  - New **front-end** (Trigger Digitiser Board LTDB) and **back-end** (Digital Processing System LDPB) boards
  - **Increased trigger tower granularity** ($\Delta\eta x \Delta\phi$ = 0.025x0.1)
  - Good **trigger performances** with the increasing luminosity and pile-up:
    - lower **trigger rate** thanks to the background rejection
    - low **thresholds** and better **turn-on curves** thanks to the higher geometrical resolution

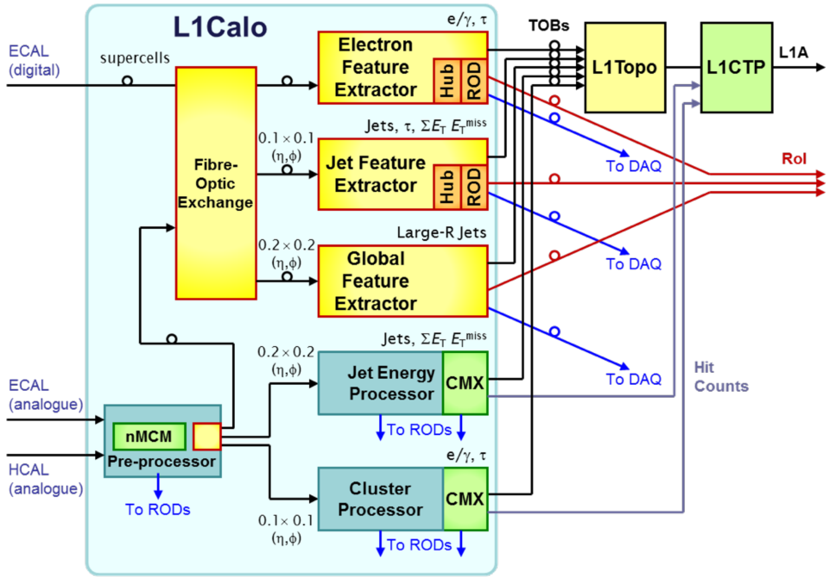


Run1 & Run2 Granularity   Run3 Granularity

3 posters on this!
Thursday 28th

- **L1Calo**:
  - New **Feature Extractor boards**: eFEX, jFEX, gFex
  - More refined processing of electromagnetic calorimeter information at **higher granularity**
  - **Better discrimination** between photons, electrons, taus and jets
  - Efficient single object triggers for electroweak-scale physics

ATLAS-TDR-023-2013

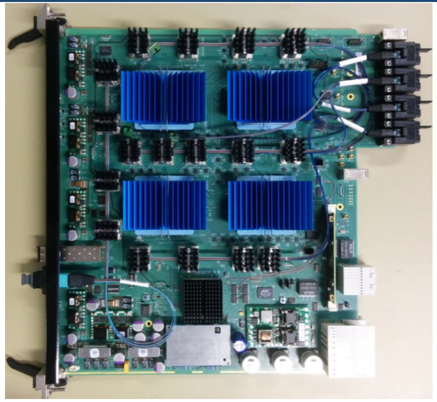


TDAQ Phase-I

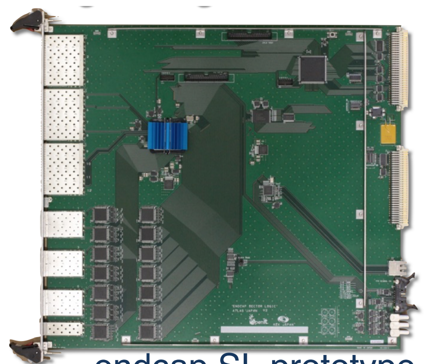
- **L1 calo**:
  - new trigger and readout electronics, new fibre optics system
  - finer granularity data, more efficient algorithms
- **L1 topo**:
  - new board: topological algorithms on data from calorimeters and muons
- **L1 end-cap**:
  - new muon end-cap Sector Logic board with new inputs:
    - New Small Wheel muon system (trigger processor boards)
    - RPC new BIS78 trigger boards
    - outer layer of the extended barrel of the Tile Calorimeter
    - reduce the fake trigger rate

see poster on this! Thursday 28th

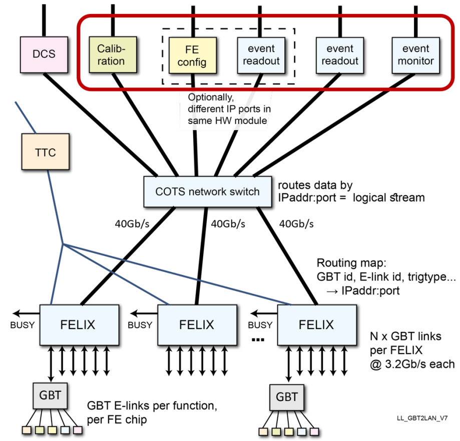
- **L1 MuCTPi**:
  - new Muon to Central Trigger Processor interface board
    - Data transfers with the new boards: L1Topo and new end-cap SL
    - Optical links provide higher bandwidth → additional data to be transfered
- **FELIX** readout system:
  - it works as a router between the FE links and commercial multi-gigabit network technology, transmitting data to the appropriate destination node (readout, DCS,..)
  - it interfaces with the TTC and busy system
  - Used in Phase-I for the upgrades: NSW, BIS78, L1calo, LAr.
  - Phase-II Felix will be the standard system for Run4



eFEX prototype



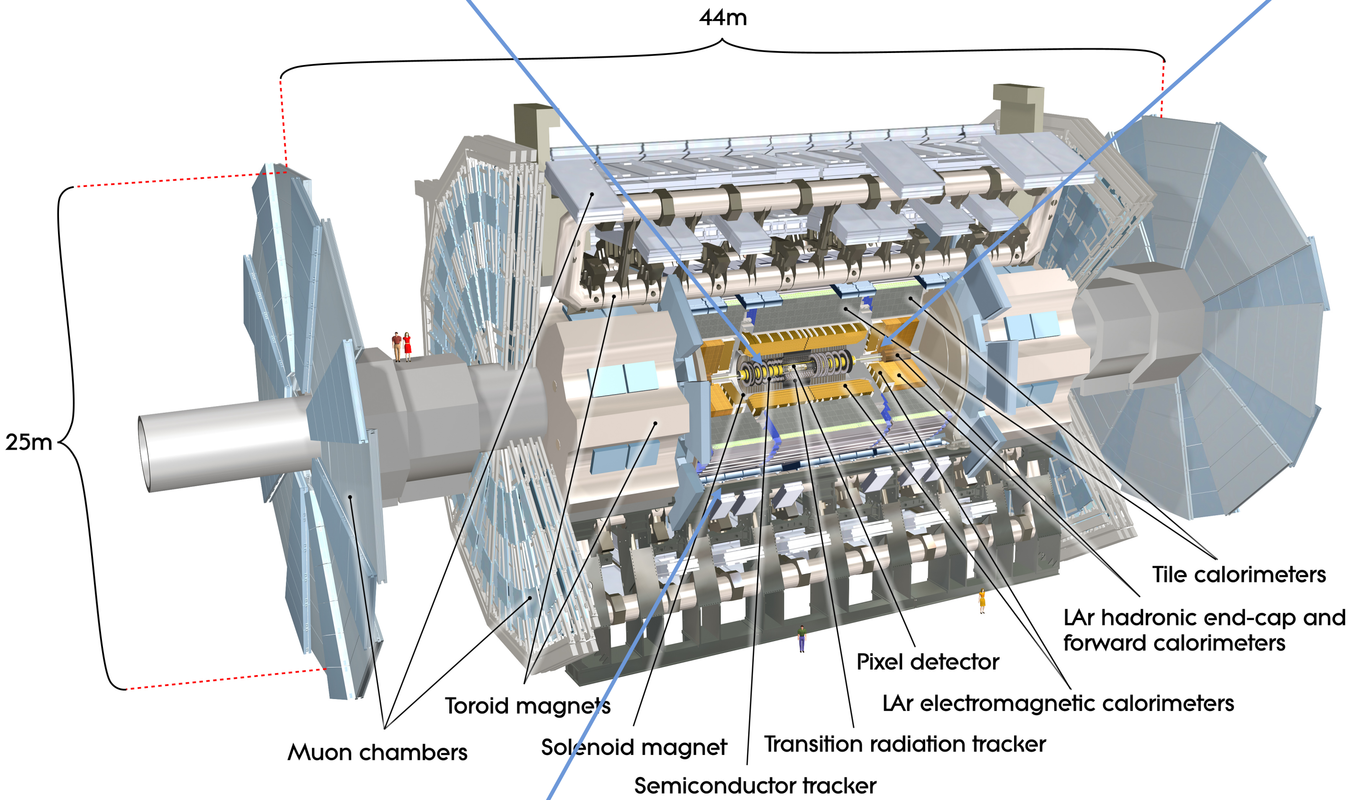
endcap SL prototype



ATLAS upgrades for Phase-II

New **all-silicon inner tracker** (**ITK**) with eta coverage up to 4

Calorimeters and High Granularity Timing Detector (**HGTD**) in forward region

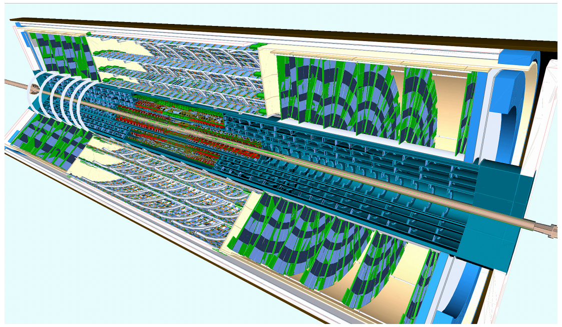


TDAQ off-detector electronics:

- **L0 hardware trigger**:
  - L0 calorimeter
  - L0 topological
  - L0 muon
  - L0 global
- **Readout system**
- **HLT**

New **muon chambers** in the barrel inner region (BI)

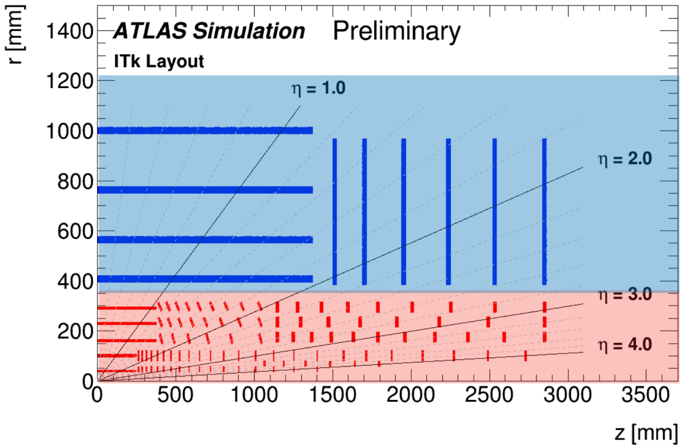
Inner tracker: Overview



- Current ATLAS Inner Detector was designed to operate for 10 years at $L=1x10^{34}\ cm^{-2}\ s^{-1}$ with <μ>=23, @25ns, L1=100kHz

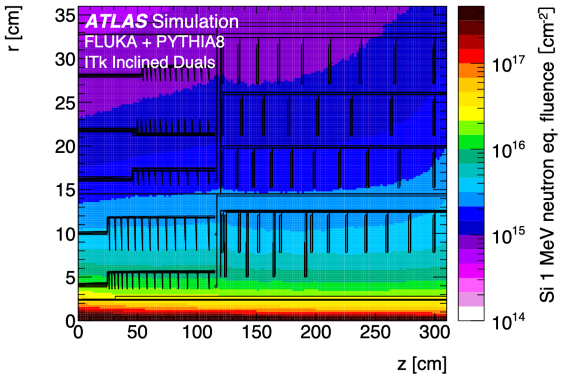
- Limiting factors at HL-LHC
  - Increased occupancies & Bandwidth saturation
  - Radiation damage (Run1-2 Pixels designed for 400 fb^{-1})

- **New all-silicon Inner TracKer system**



- **Strip subsystem covering |η| < 2.7**
  - 4 Barrel layers
  - 6 End-cap disks

- **Pixel subsystem covering |η| < 4.0**
  - 5 Barrel layers + Inclined modules
  - Barrel + End-cap rings



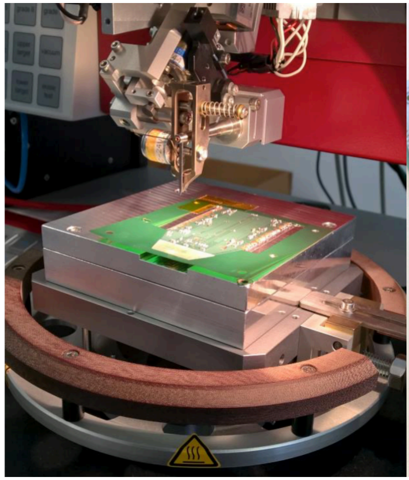
- equal or better **performances** than the existing detector in a much more **difficult tracking environment**
  - high track reconstruction efficiency and low rate of fake tracks

https://cds.cern.ch/record/2285585

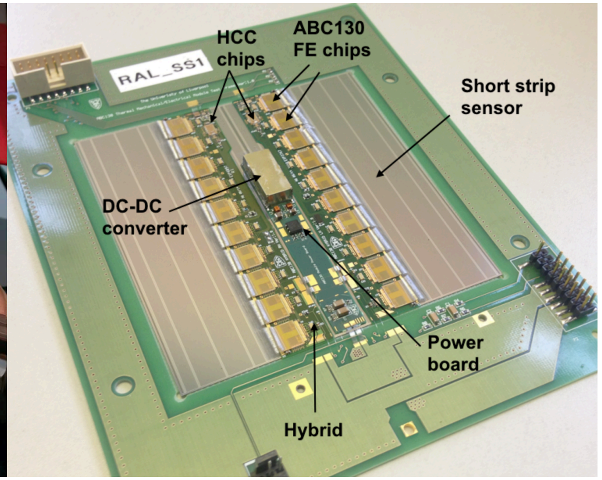
Inner tracker: details

CERN-LHCC-2017-021

- **Pixel** system
  - Active area: 12.7 m^2
  - Pixel size: 50x50 (or 25x100) μm^2
  - 10276 modules
  - 33184 FE chips
  - # of channels: ~$5x10^9$
  - Radiation tolerance up to: $1.3x10^{16}$ n_{eq}/cm^2
  - TID 9,9MGy

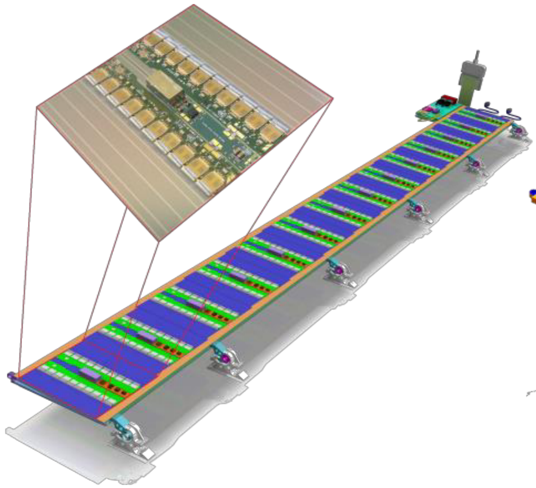


Pixel module
on automated machine

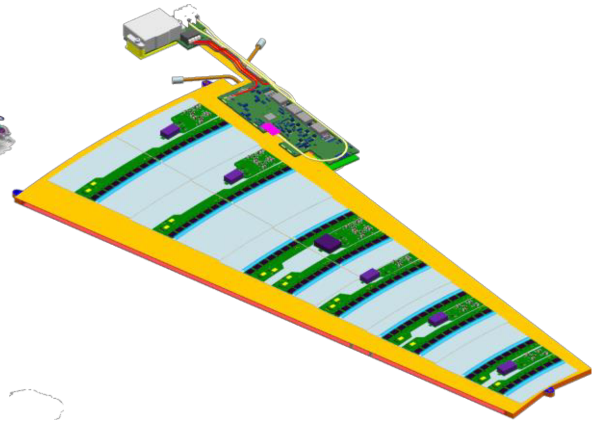


Strip Barrel module

- **Strip** system
  - ~18K Modules
  - Strip width about 75 µm
  - Resolution 22 µm rms.
  - 59.87 million channels
  - 165 m^2 of Silicon



Barrel: Stave is loaded with 28 modules
Length ~ 140 cm

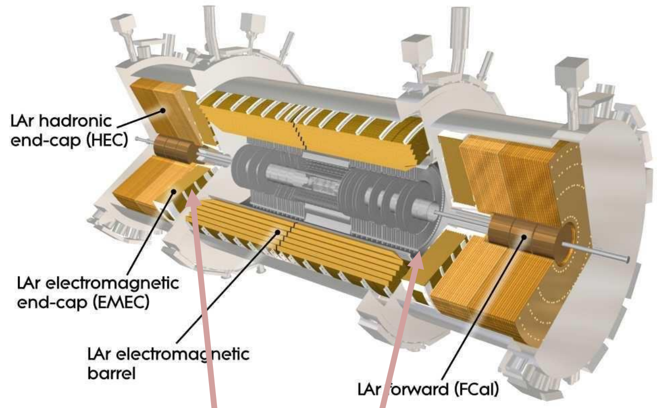


Endcap: Petal is loaded with 18 modules
Length ~ 60cm

Liquid Argon Calorimeter + High-granularity timing detector (HGTD)

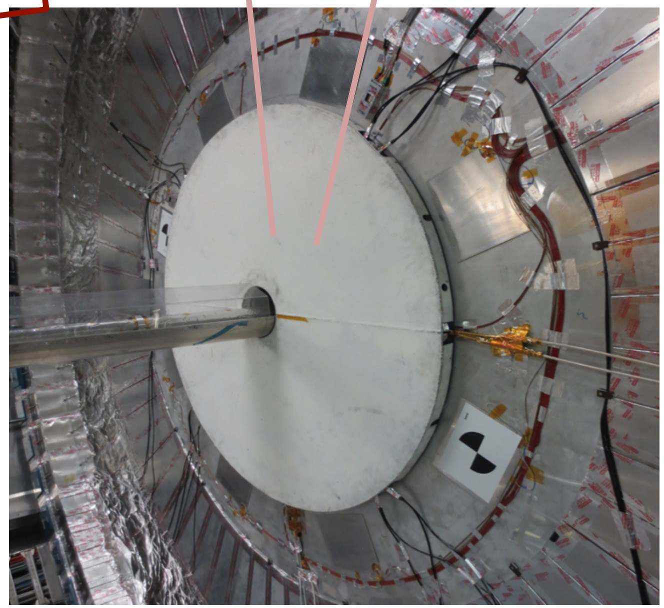
- **LAr:**
  - Current electronics is not compatible with phase-II requests (latency and trigger rate)
  - Radiation hardness requirements are above original design
  - phase-I upgraded boards will continue to be used
  - **new front-end and back-end electronics**
  - **full granularity calorimeter signals will be digitized and sent to the Back End at 40 MHz**

see poster on this!
Thursday 28th



Presented Today
by Dr. D. Boumediene

- **High Granularity Timing Detector (HGTD):**
  - **pileup mitigation** using high-precision timing information to distinguish between collisions
  - installed in space between ID and calorimeter end-caps and based on silicon Low Gain Avalanche Detector (LGAD) technology
  - $2.4 < \eta < 4.0$; $R_{min} = 12$ cm; $R_{max} = 64$ cm; **Δt = 30-50 ps**
  - Improves the pileup reduction to improve the forward object reconstruction, complementing the capabilities of ITk in the forward regions, leading to an improved performance for both jet and lepton reconstruction
  - offers unique capabilities for the online and offline luminosity

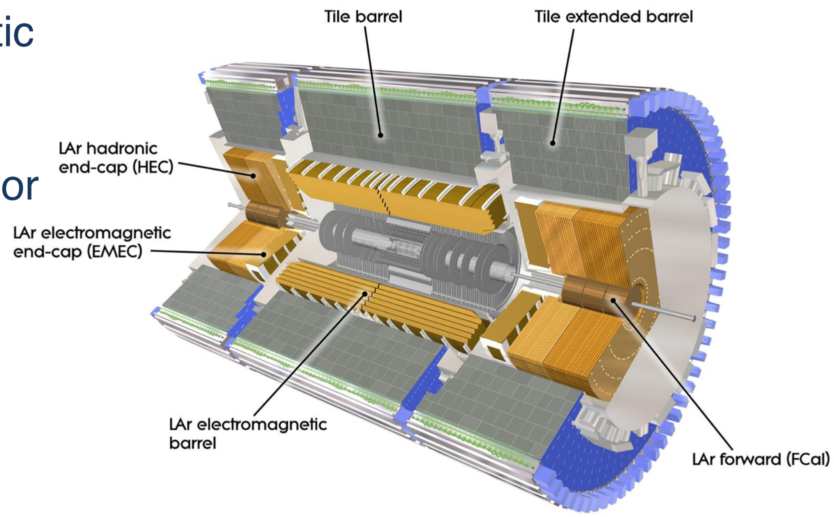


Tile Calorimeter

TileCal is a segmented calorimeter of steel plates and plastic scintillator tiles, comprising 10k readout channels

For Phase-II Upgrade a complete replacement of on-detector and off-detector electronics is foreseen:

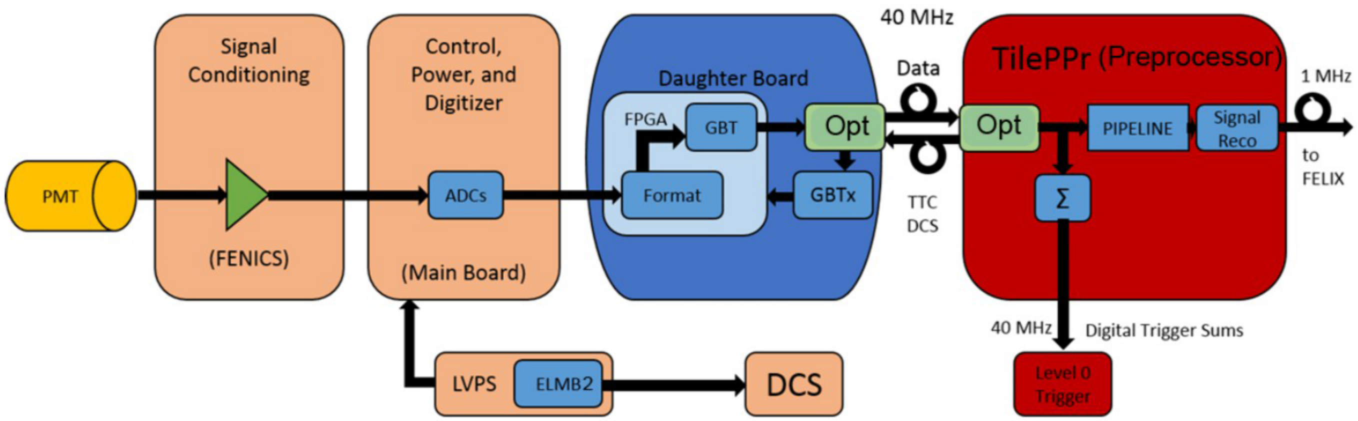
- due to **radiation** and **time aging**;
- to fulfill Phase-II radiation requirements;
- to be compatible with TDAQ and processing at 40 MHz;
- high speed optical communication for **full data transmission at 40 MHz** to off-detector electronics.



In addition:

- PMTs reading out the most exposed cells will be replaced (about 10% of the total PMTs)
- Upgrade of LVPS system to reduce single point failure is foreseen
- High Voltage to be distributed remotely from off-detector

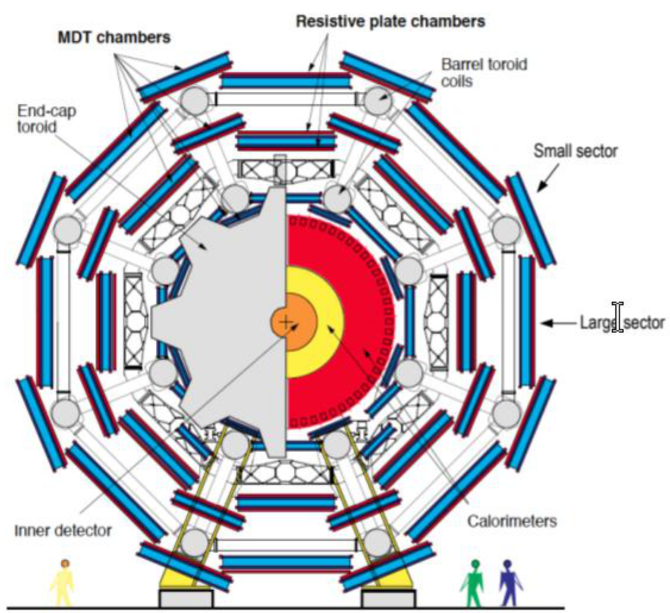
Project in very mature state. Pre-production expected this year for several sub-systems



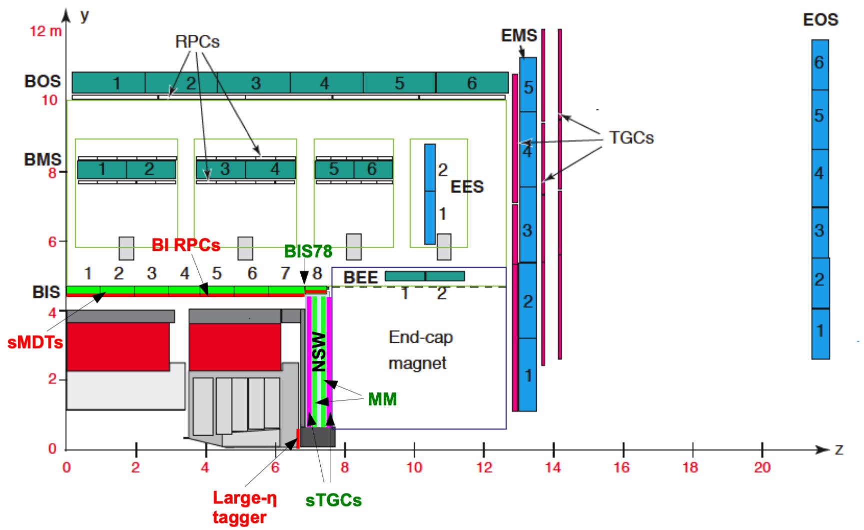
TileCal acquisition schema

Muon detectors

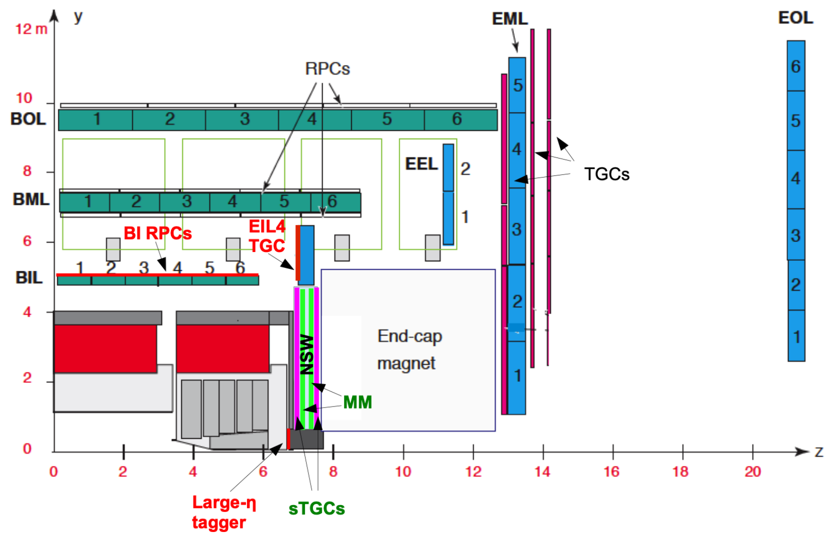
- The muon spectrometer is made of gaseous detectors in the outer part of ATLAS, and covers barrel and end-cap regions
- Requirements for Phase-II:
  - **reduce the trigger fake rate** in barrel and end-cap regions
  - increase geometrical **coverage** in the barrel
- **New detectors**:
  - **barrel inner RPC + sMDT**:
    - old BIS MDT replaced by new (sMDT + RPC)
    - new RPC mounted on top of existing BIL MDT
  - **TGC EIL4** (triplet instead of doublet)



Muon spectrometer in the barrel region
(section orthogonal to beam axis)



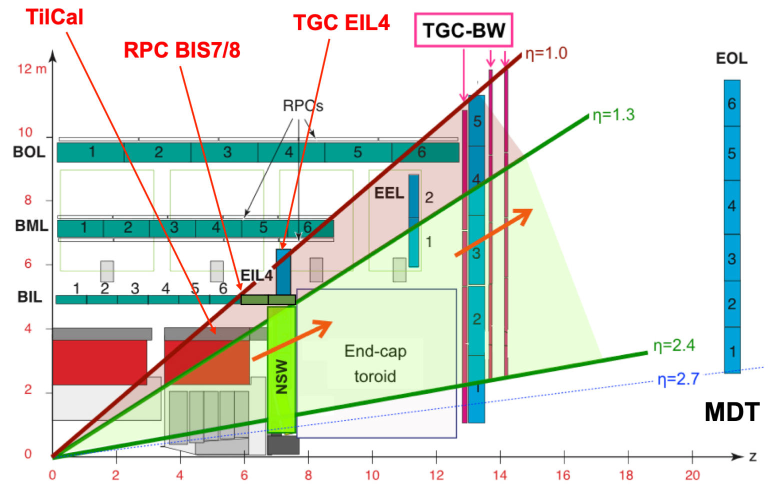
Muon spectrometer small sectors



Muon spectrometer large sectors

Level-0 muon trigger (L0muon)

- The data from the **RPC**, **TGC**, and **NSW** detectors used in the Phase-I system will be complemented with data from:
  - **BI RPC**,
  - **EIL4 TGC**,
  - **Tile** calorimeter outer cells,
  - **sMDT.**
- **Increase the geometrical acceptance in the barrel**, from ~78% to ~95%
- Increased **selection efficiency** and reduce **fake triggers**
- New on-detector boards: **full digital detector data sent off-detector @ 40 MHz**
- **Barrel** and **end-cap** new off-detector boards perform the trigger algorithm + send the seed to the MDT trigger processors
- New **MDT trigger processor boards** match MDT hits with the RPC/TGC seed vectors in space and time (different algorithms for segment finding under study)
- New **MDT trigger** sharpens **turn-on curve** and increase rejection power



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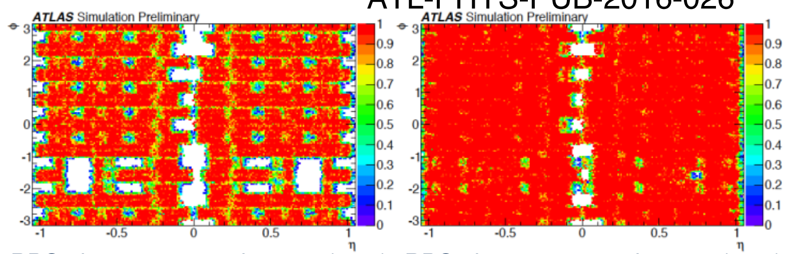
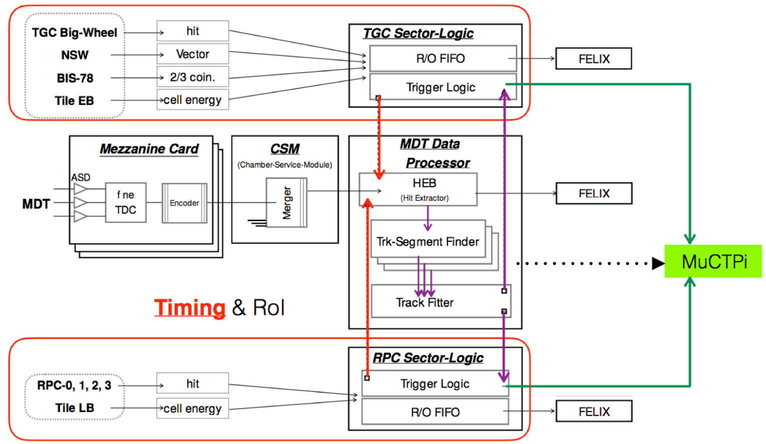


RPC trigger coverage in run-1 (78%) RPC trigger coverage in run-4 (96%)



TDAQ system in Phase-II

CERN-LHCC-2017-020

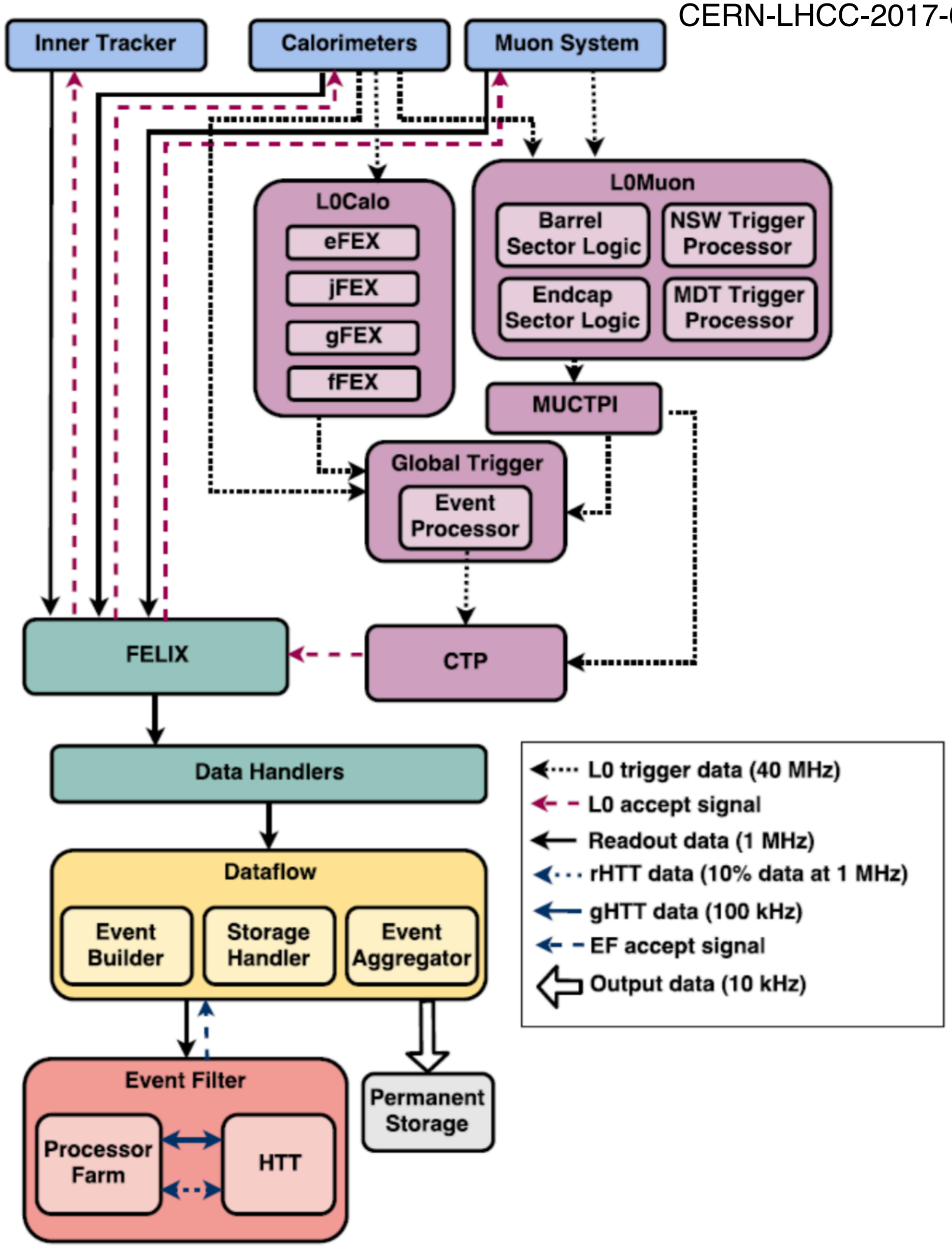
- Two-level trigger architecture:
  - L0
    Central Trigger Processor (CTP) processes candidates from L0Calo & L0Muon, issues a *L0Accept* and data from Inner Tracker, Calorimeters & Muons are sent to FELIX for readout
  - High Level Trigger (HLT)
    tracking data is used @ Event Filter by custom hardware (Hardware Track Trigger, HTT)

- L0 Trigger Rate 1 MHz
  - was 100 kHz in Run1 & Run2

- L0 latency < 10 µs
  - was 2.5 µs in Run1 & Run2

- Permanent storage @10 kHz

- Considers a L0/L1 evolution system, allowing scaling TDAQ later, if demanded be physics/HL-LHC performance
  - System has to be designed now in order to allow evolution at a later stage



TDAQ Level-0 architecture

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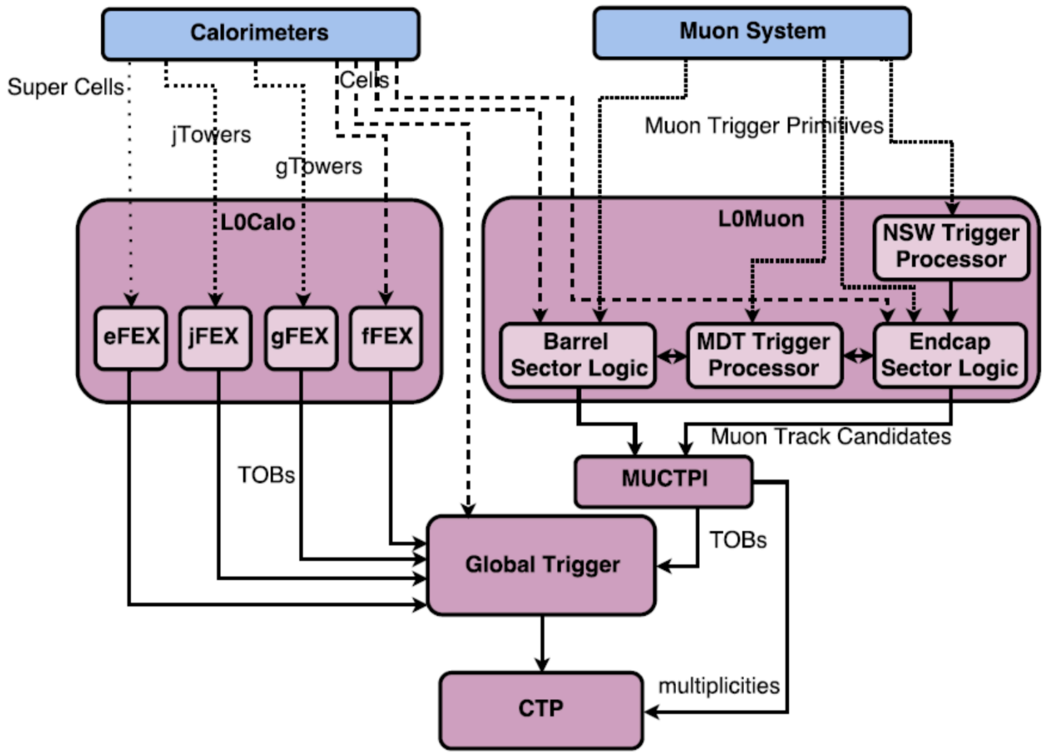
- **Level-0** upgrade:
  - Additional data from Calorimeters and Muons, wrt Run1 & Run2
- **L0calo**
  - new in Phase-I and extending Feature Extraction (FEXs) in Phase-II for forward EM and jets (fFEX)
- **L0Muon**
  - data from New Small Wheel, Tile & MDT included, to improve the muon trigger coverage
- **Global** Trigger
  - new subsystem of the Level-0 Trigger, will perform offline-like algorithms on full granularity calorimeter data
  - use of topological criteria: clustering, electron and photon identification, lepton isolation.



- **Central Trigger**
  - Muon-to-CTP Interface (MUCTPI) designed for Phase-I to be used also in Phase-II:
    - upgraded firmware to handle increased input bandwidth requirements
  - new Central Trigger Processor (CTP) to be developed for Phase-II:
    - increased input bandwidth requirements (data from MUCTPI and Global Trigger)
    - more logic resources to handle bigger trigger menus

Upgraded DAQ & HLT

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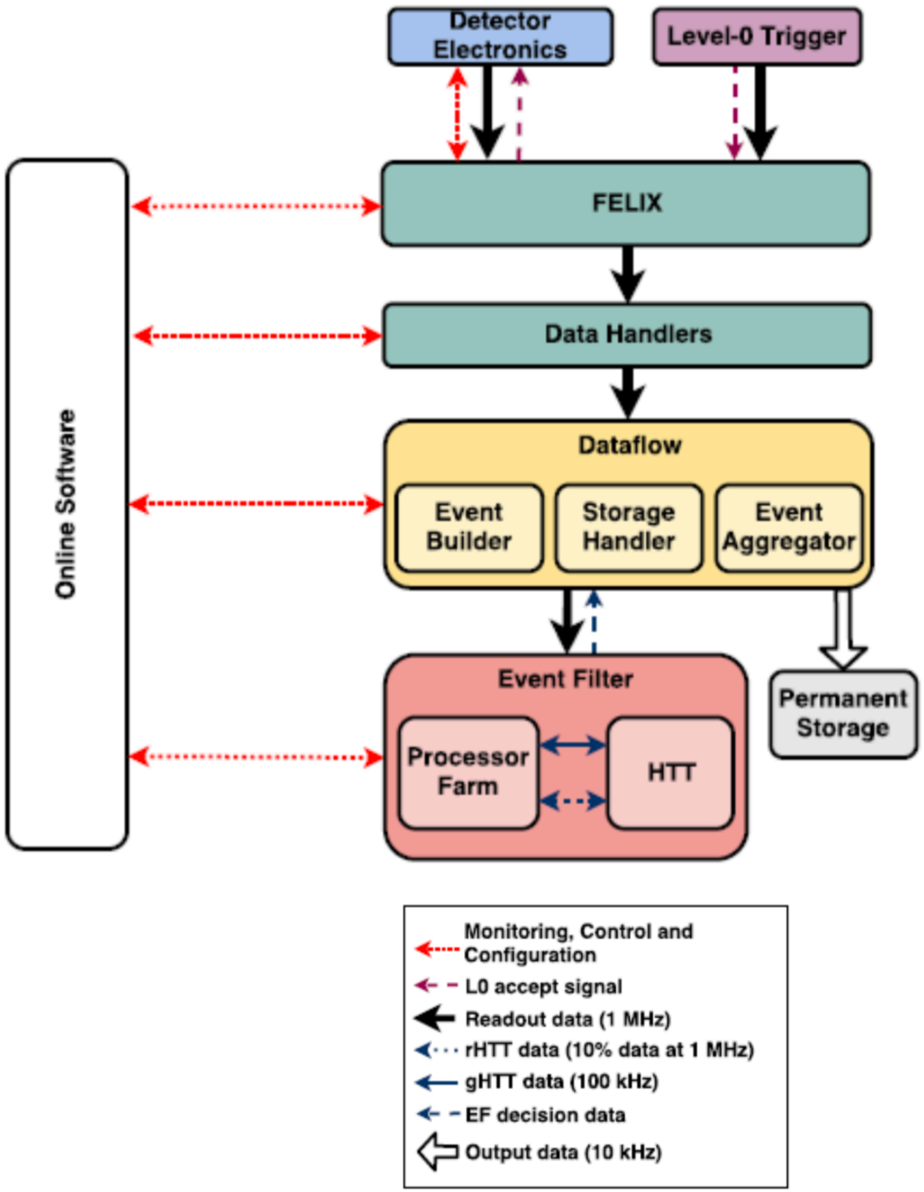
- Detector read-out at **1 MHz**:
  10 x more than today's.
- Read-out throughput: **5.2 TB/s**:
  20 x more than today's.
- **DAQ system:**
  based on FELIX universal network-based interface for TTC and all DAQ functions.
- **Dataflow**:
  - Buffers readout data for O(10) minutes: **3+ PB**
  - Event building
  - Records selected events at 60 GB/s @10 kHz
- **Event Filter** consists of Hardware-based Tracking for the Trigger (**HTT**) (based on Associative Memory technology for track finding and FPGAs for track fitting) and **processor farm** for sophisticated HLT event selection.



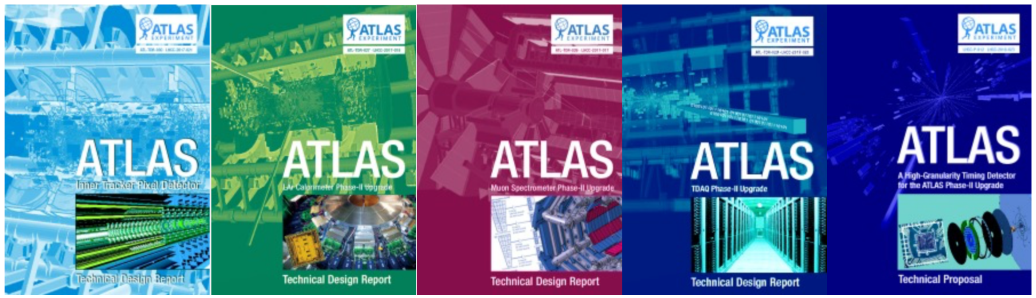
Conclusions

- The large datasets that can be collected with the LHC upgrades will allow to perform **precision measurements** in the 125 GeV Higgs boson sector, the exploration of extremely rare **Standard Model processes**, as well as the search for **new phenomena** beyond Standard Model

- **Phase-I upgrades**:
  - Provide improved rate capabilities and background rejection to stand with L = 2-3 x 10^{34} $cm^{-2}s^{-1}$
  - Production completed for most of the systems, installation will be completed this year

- **Phase-II upgrades**:
  - Designed for L = 5-7.5 x 10^{34} $cm^{-2}s^{-1}$ and 3000 fb^{-1}
  - Up to factor 10 increase in radiation hardness
  - Improved pile-up handling with new tracker and timing detector
  - Increased Trigger and readout capabilities due to muons and TDAQ upgrades
  - Work on all the major upgrades is well advanced and documented in TDRs:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Upgrade_Pro



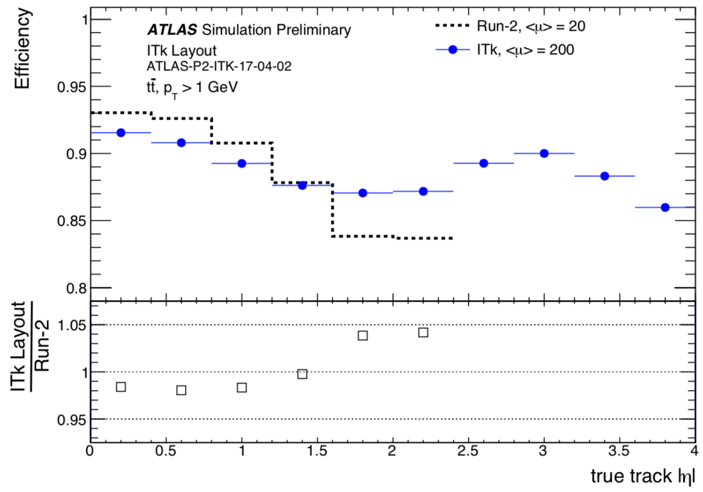
Backup

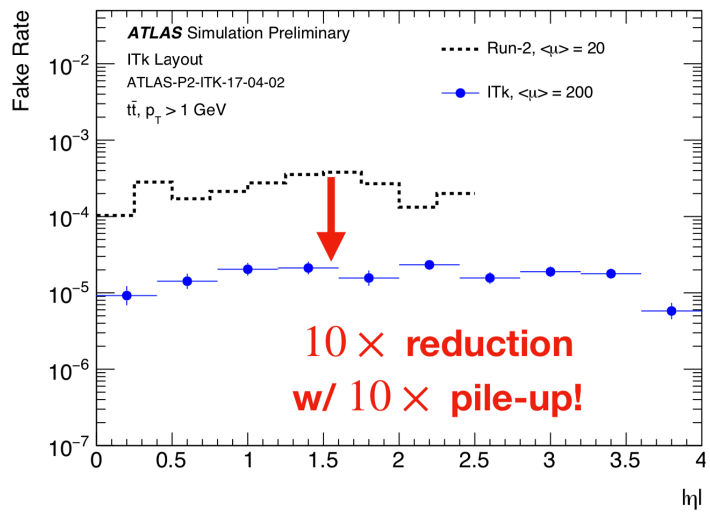
ITk Backup: Efficiency & Fake Rate

- **Efficiency** is the fraction of all **reconstructed true prompt particles**
  - Maintain **over 85%** efficiency up to $|\eta| = 4.0$, efficiency is comparable with Run-2 ID at $\langle \mu \rangle = 20$

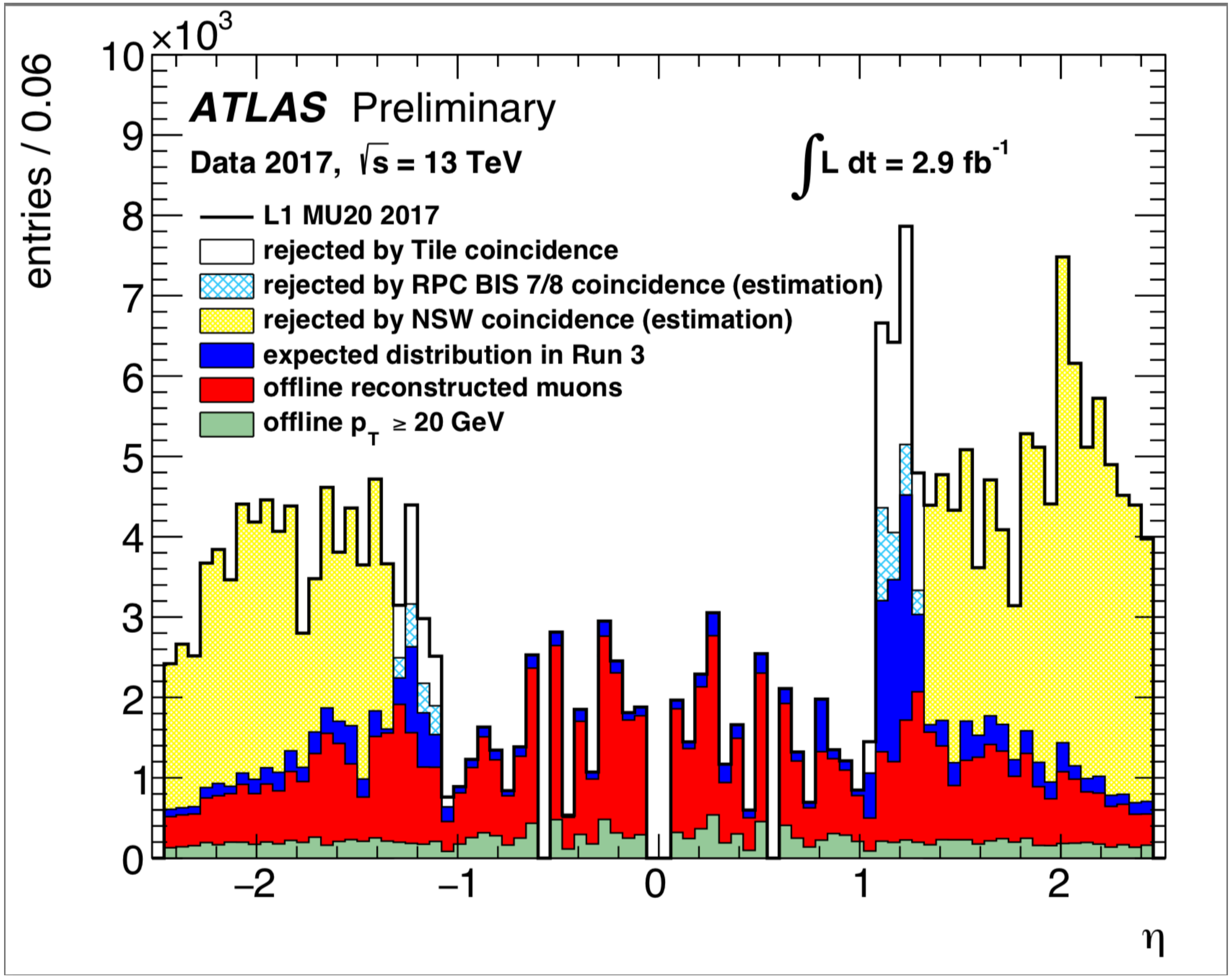
- **Fake rate** is the fraction of all **reconstructed tracks unmatched** to a **true particle**
  - Excellent improvements over Run-2 ID, even considering 10 × increase in pile-up

- Overall significant improvements in forward region up to extent of Run-2 ID, plus extended coverage!
  - Reduced **material budget** → minimize material interactions
  - Increase in overall **hit counts** → tighter track selections
  - Improved **hermiticity** → more hits + fewer holes on track





BIS78 Backup



- The pseudo-rapidity (η) distributions of the Level-1 MU20 RoI.
- The expected distribution in Run 3 shows the final distribution in Run 3 after enabling all TileCal, RPC BIS7/8, and NSW coincidences.

Phase-II Muons Backup

- Present MS has three RPC layers.
- Addition of fourth RPC layer (triplet) for Phase-2

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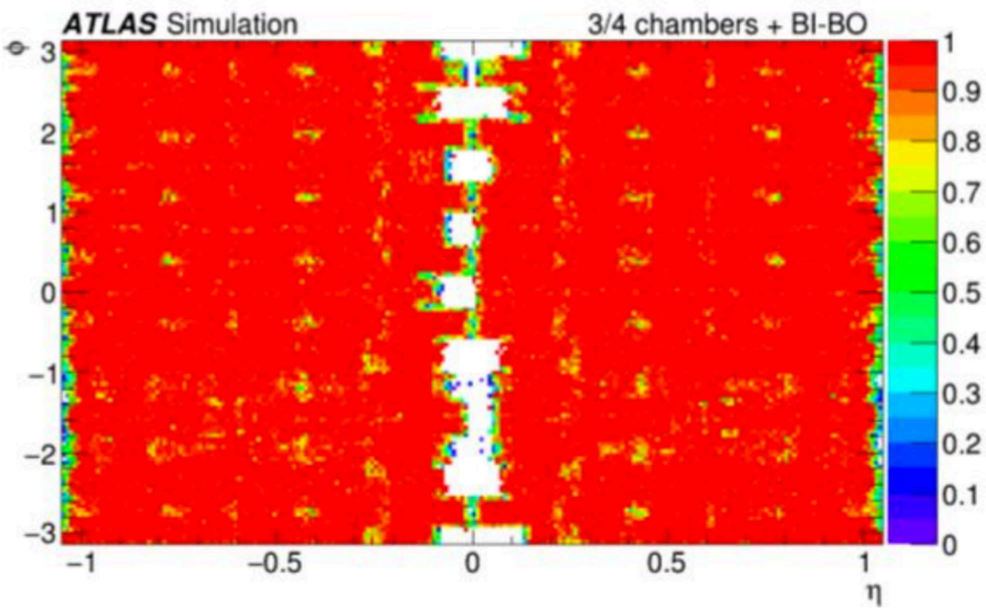
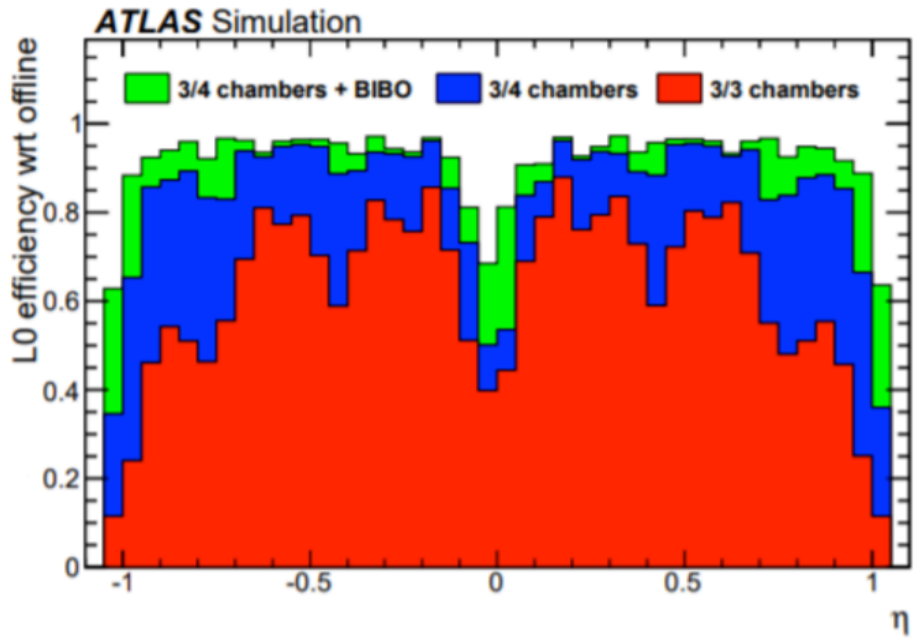


- Geometrical acceptance of the L0 barrel trigger with respect to reconstructed muons



- Efficiency times acceptance of the L0 barrel trigger with respect to reconstructed muons.
- Plot assumes worst-case RPC aging scenario for original chambers (only 65% single-hit efficiency)

Level-0 Global trigger

- **High granularity full data** digital transmission from calorimeters

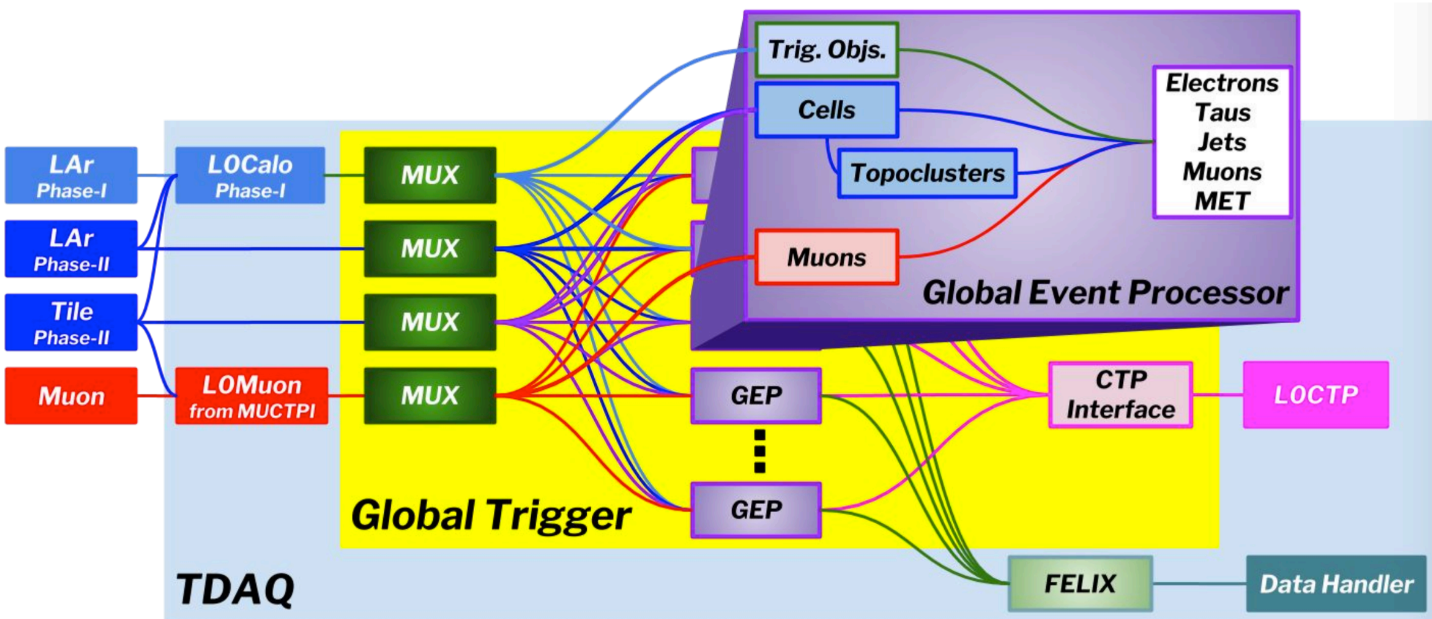
- **HGTD** new input to extend the electron and jet identification capabilities and to provide pileup rejection in the forward region

- LAr and Tile calorimeter are sent separately to Feature Extractors

  - fFEX new addition to L0Calo (eFEX, gFEX, jFEX) trigger system, to increase coverage to |η|>3.2

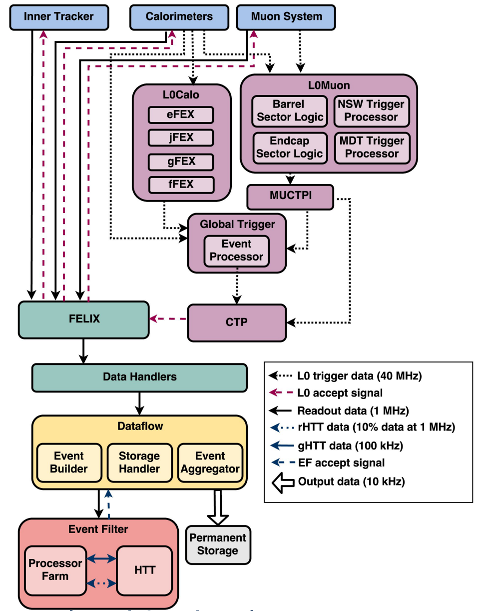
- Global Trigger consists of a layer of incoming multiplexing (**MUX**) nodes that feed data into a layer of Global Event Processor (**GEP**) nodes

- Each GEP node receives the **complete detector data** from the calorimeters and muon system for each event at 40 MHz

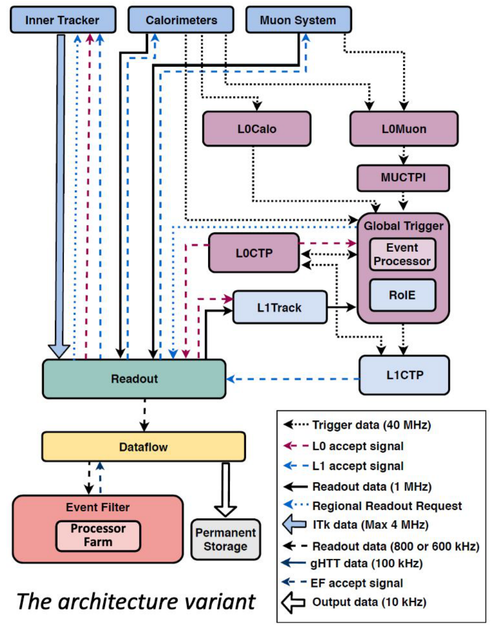


Level-0 and Level-0/Level-1 TDAQ options

- L0 trigger rate = **1 MHz**; L0 latency = **10 μs**
- The **Global Event processor** replaces the existing L1Topo and integrates topological functions with additional selection algorithms using additional information from the calorimeters
- L0/L1 schema introduces a **second level of hardware track trigger** (pattern recognition with AM chips + track fitting with FPGA)
- L0 trigger rate = **4 MHz**; L0 latency = **10 μs**
- L1 trigger rate = **800 kHz**; L1 latency = **35 μs**
- the **L0 Global Event processor** generates the commands Request for the read out of the corresponding data from the ITk detector
- The **L1Track** receives ROI data from ITk and performs track finding
- The **L1 Global Event processor** refines e/γ, τ, jets and E_{Tmiss} signatures and improves rejection by combining the refined calorimeter signature information with the tracking information from L1Track



Level-0 only schema



Level-0 /Level-1 schema