ATLAS HL-LHC Upgrade

TIDC Annual Meeting 2025
January 7th 2026

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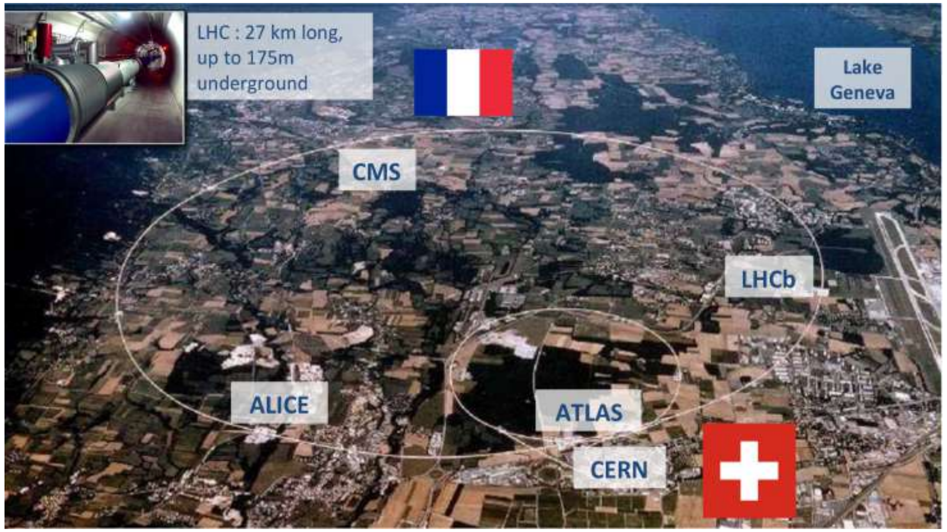
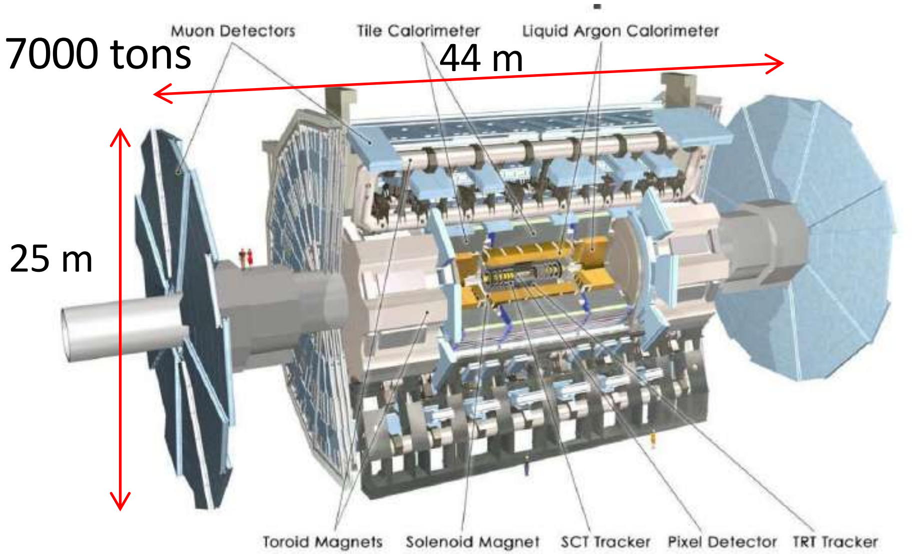
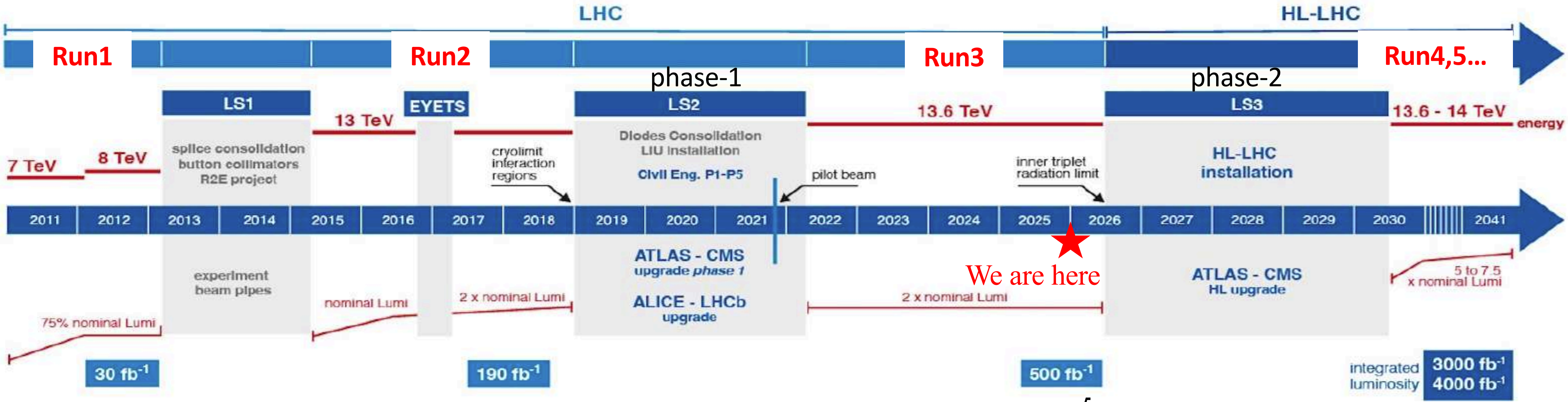
Academia Sinia

ATLAS Experiment





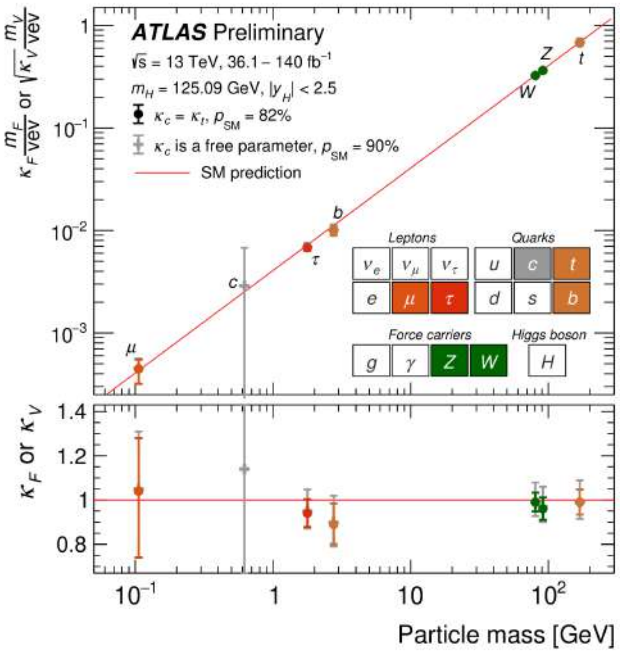
- ATLAS collaboration: ~3000 physicists

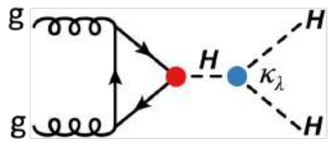


- First pp collision on Nov 23rd 2009
- Commissioning run in 2010
- Run1: 2011-2012 ($\sqrt{s}$=7,8 TeV)
- Run2: 2015-2018 ($\sqrt{s}$=13 TeV, $\int L$=140 fb^{-1})
- Run3: 2022-2026 (June) ($\sqrt{s}$=13.6 TeV)
  - Already collected $\int L$~300 fb^{-1}

Higgs Reach @ LHC

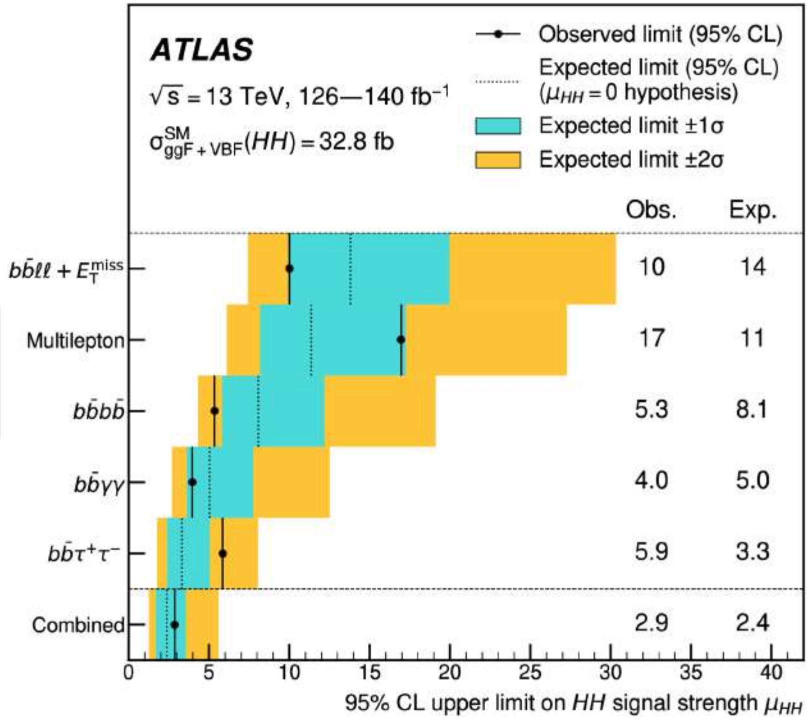
Single Higgs (H)





$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

Di-Higgs (HH)



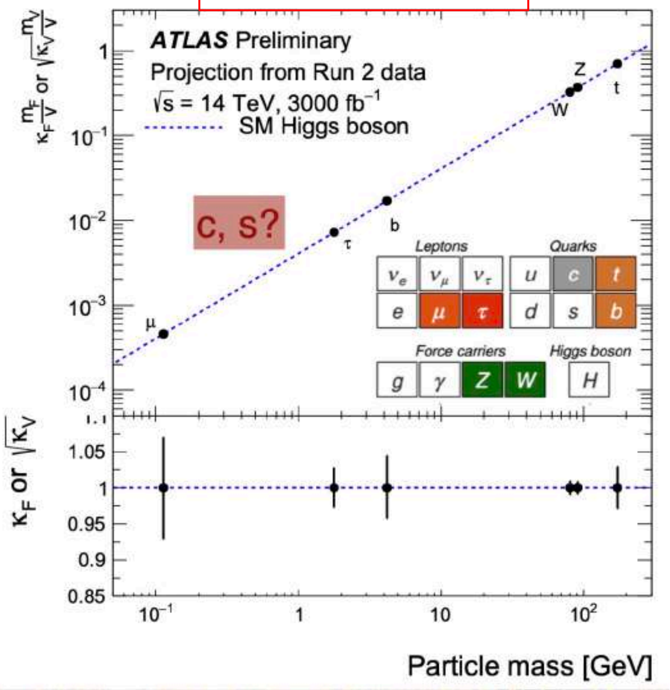
- Observed main production channels (ggF, VBF, VH, ttH), and couplings to gauge bosons ($\gamma\gamma$,WW,ZZ) and 3rd gen. fermions (τ, b, t)
  - Measured at O(10%) precision in best channels
- Probing couplings to 2nd gen. fermions and rare decay
  - H→ $\mu\mu$ (@ 3.4σ *obs.*) , H→ $Z\gamma$ (@ 2.2σ)
  - $\sigma(VH(\rightarrow cc))$: < 11.3 × SM observed (95%CL)

- Limits on HH production rate at 95% CL
  - Obs (exp) = 2.9 (2.4) × SM
- Significance : Obs (exp) = 0.4 (1.0) σ
- κ_λ constrained at 95% CL interval:
  - Obs (exp) = [-1.2, 7.2] ([-1.6, 7.2])

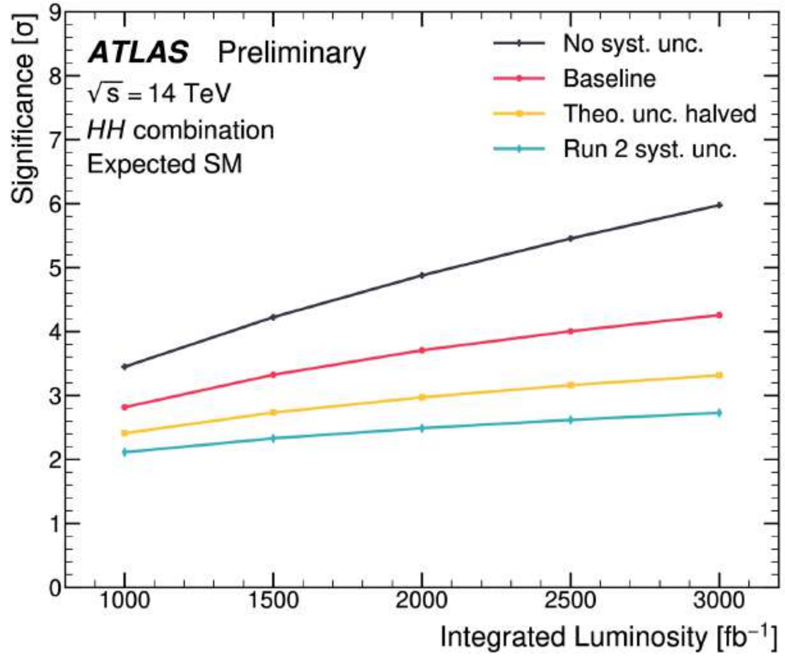
ATLAS-CONF-2025-006 | PRL 135 (2025) 231802 | PRL 133 (2024) 101801

Projected Higgs Reach @ HL-LHC

Single Higgs (H)



Di-Higgs (HH)



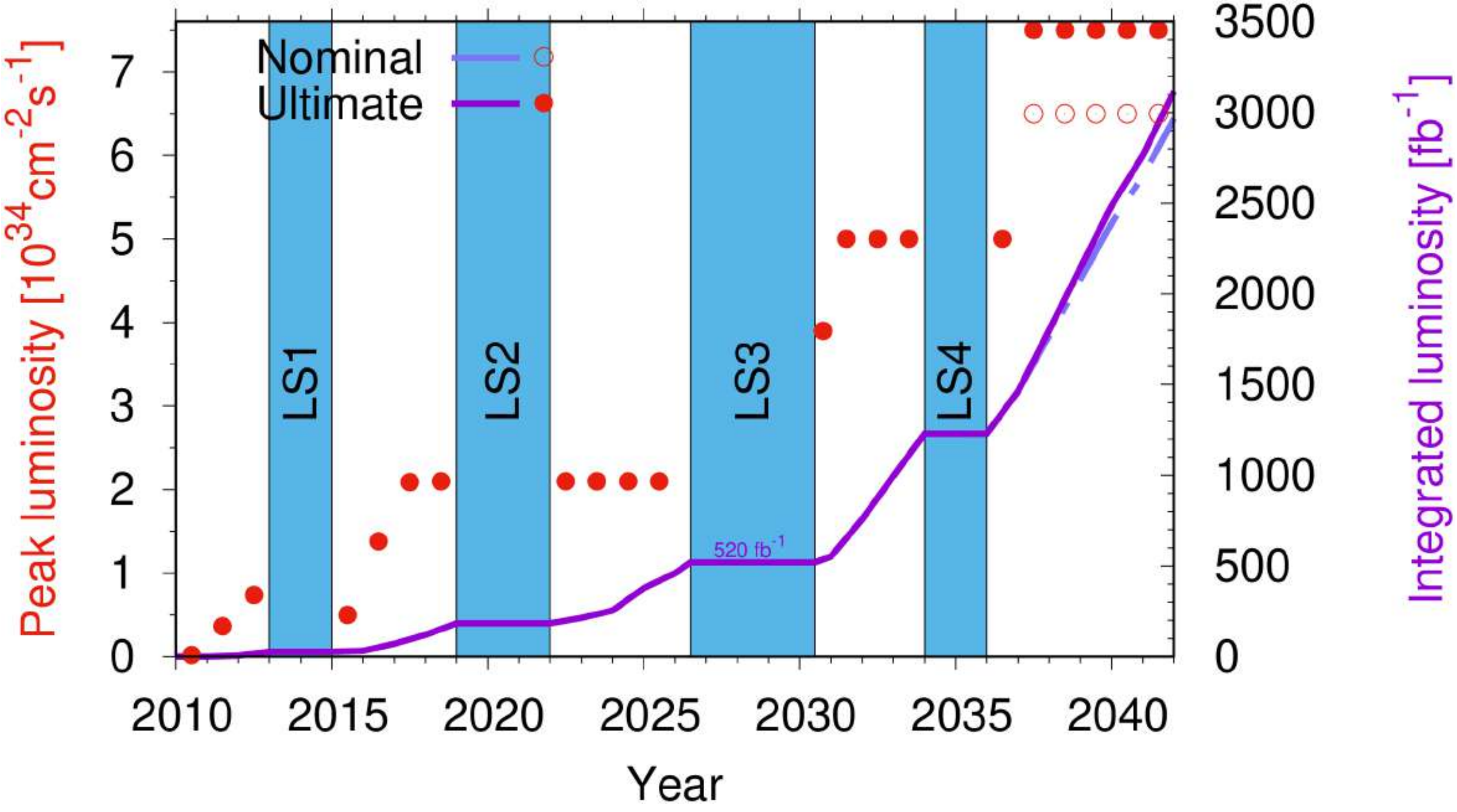
- ~2-5% precision for many of the Higgs couplings
- Larger uncertainties for $Z\gamma$ and charm

- Expected Significance : ~4.2 σ (Baseline)
- κ_λ (self-coupling modifier) expected to be measured as 1.0 +0.48 -0.42

ATL-PHYS-PUB-2025-006

HL-LHC era will dramatically expand the reach for Higgs physics, Standard Model measurements, and New Physics searches !

HL-LHC

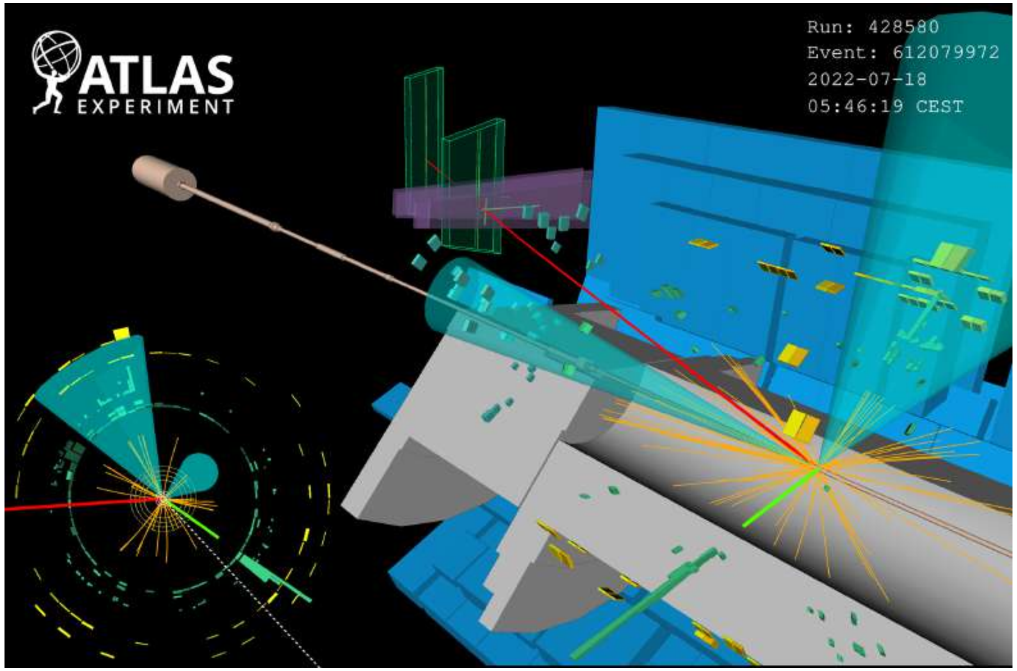


- $\sqrt{s}$=13.6-14 TeV
- $L \sim 5\text{-}7\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\int L \sim 3000\ \mathrm{fb}^{-1}$
- Ave. #of interactions per bunch crossing (pile-up): ~140-200

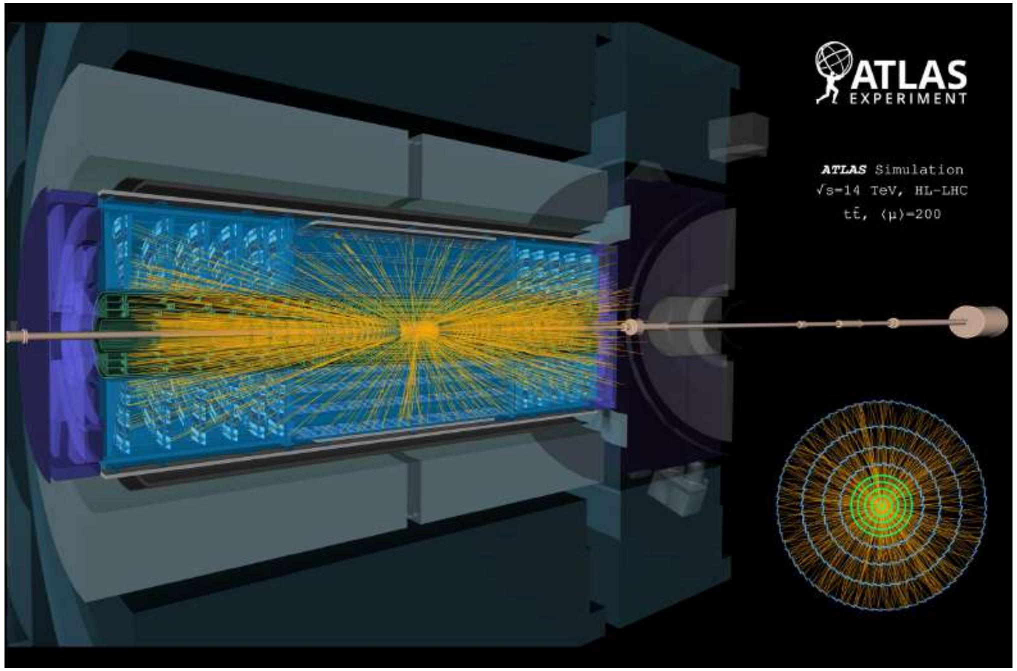
- High lumi and pileup pose challenging conditions to the experiment
  - Larger beam background and detector irradiation, higher trigger rates, higher particle density in detector
- Require improvements in many areas of the experiment:
  - Detector, trigger and readout electronics, software and computing, analysis techniques

Challenges at HL-LHC

ttbar, Run3

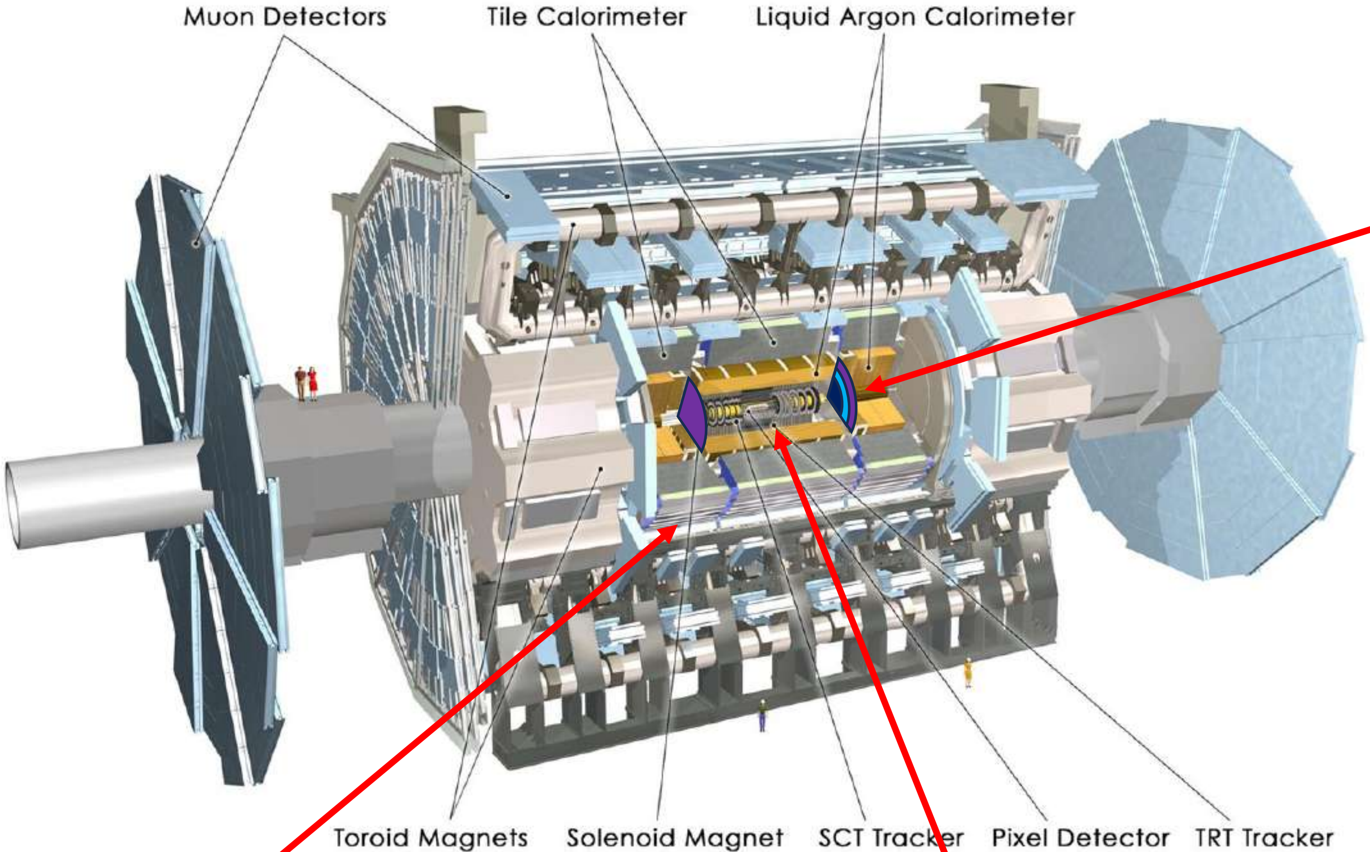


ttbar, HL-LHC, <μ>=200



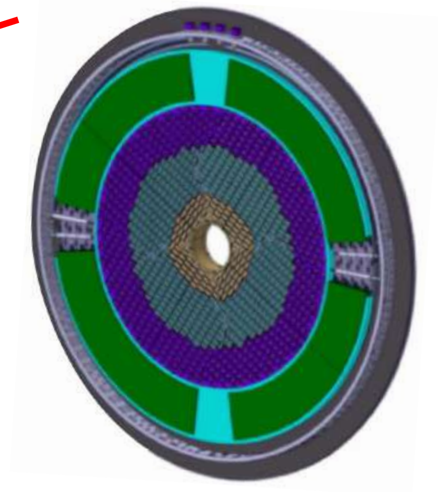
- High particle multiplicity ~10000 tracks/event => need improved granularity
- ~10 times more particle fluence and total ionizing doses => need improved radiation tolerance
- Need faster electronics and larger data throughout (trigger rate increase: 100 kHz → 1 MHz)

ATLAS Upgrade for HL-LHC



High Granularity Timing Detector (HGTD)

Forward region ($2.4<|\eta|<4.0$)
Low-Gain Avalanche Detectors (LGAD)
with 30 ps track resolution



Upgraded Trigger and Data Acquisition system

Level-0 Trigger at 1 MHz
Improved High-Level Trigger
(150 kHz full scan tracking)

Electronics Upgrades

LAr Calorimeter,
Tile Calorimeter, Muon System

New Muon Chambers

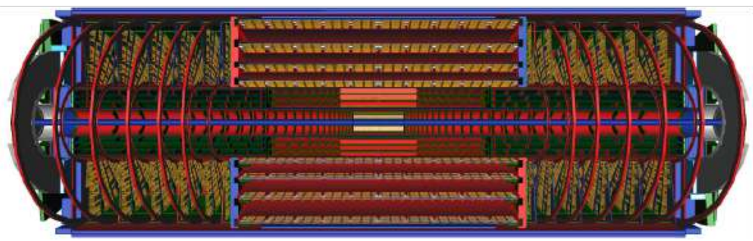
Inner barrel region with new
RPC and sMDT detectors

Additional small upgrades

Luminosity detectors (1% precision goal)
HL-ZDC

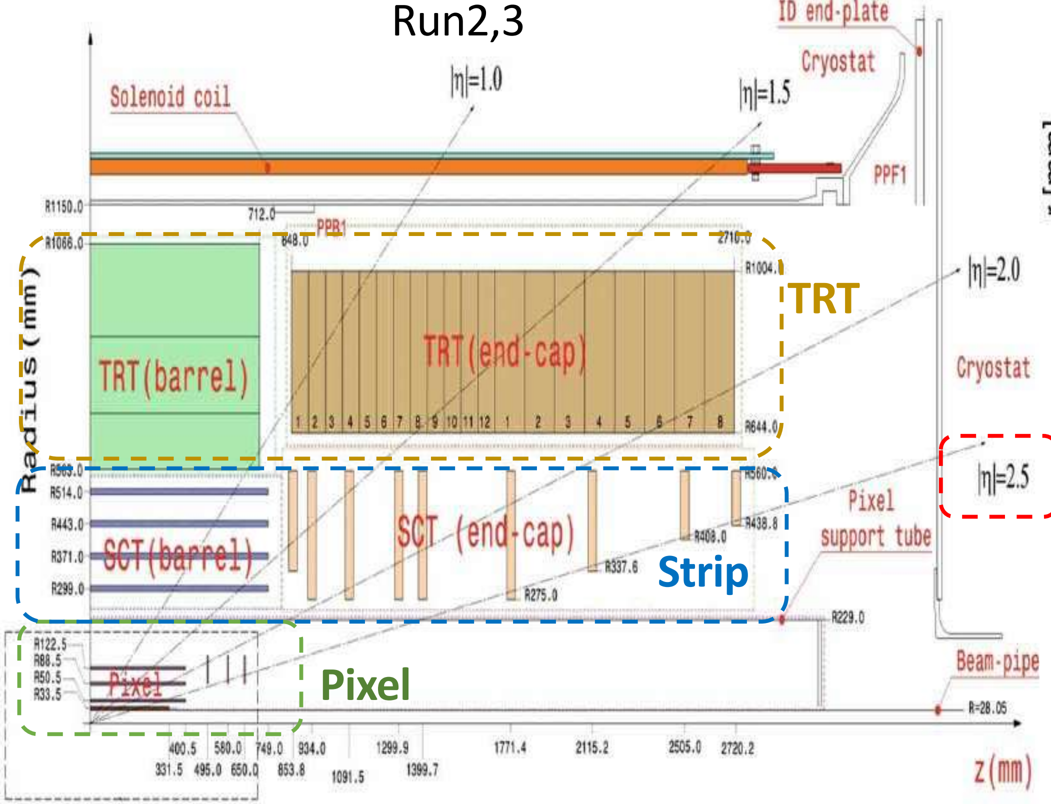
New Inner Tracking Detector (ITK)

All silicon, up to $|\eta|=4$

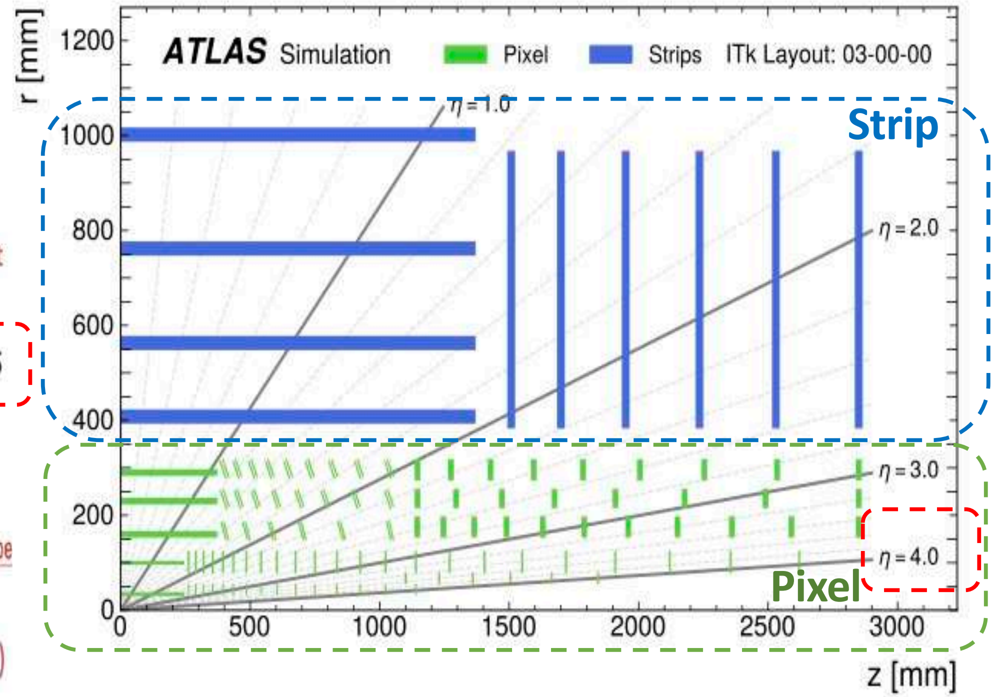


Inner Tracking Detector

Run2,3



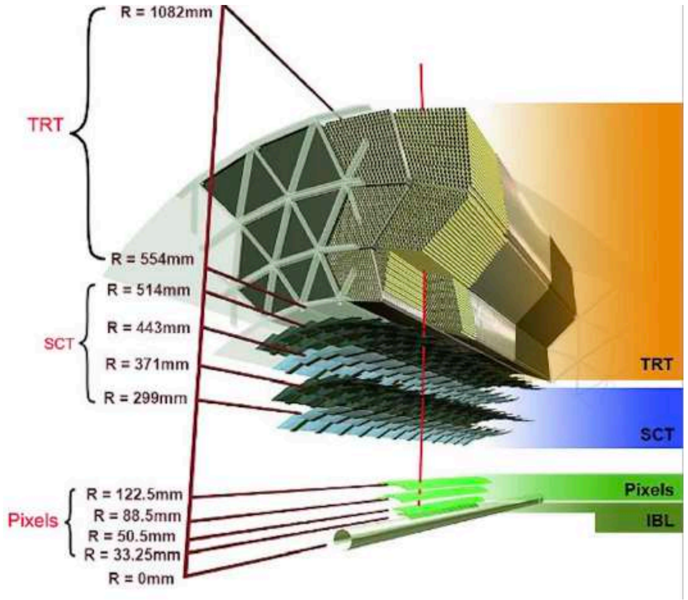
HL-LHC

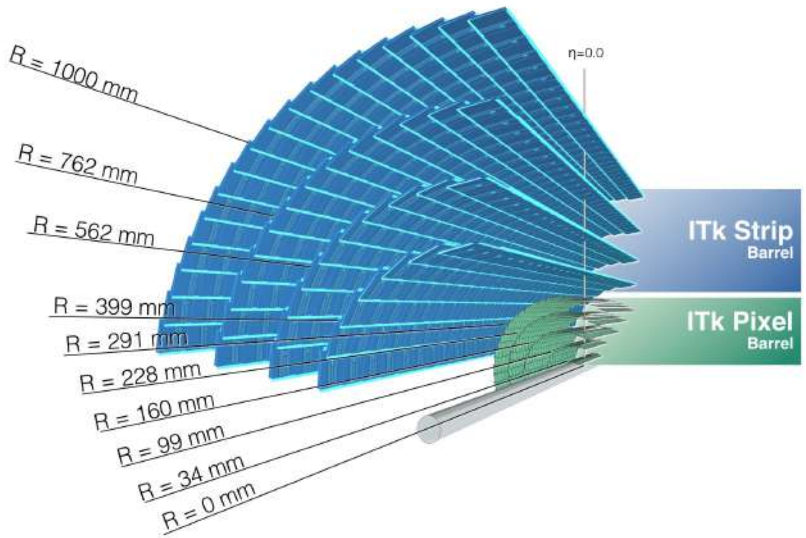


- Run2,3:
  - Silicon Tracker (pixel, strip) + Transition Radiation Tracker (TRT)
  - Coverage: |**η**|<2.5
- HL-LHC:
  - Replace with all silicon tracker
    - TRT cannot withstand high particle rates at HL-LHC
  - Extend coverage to |**η**|<4

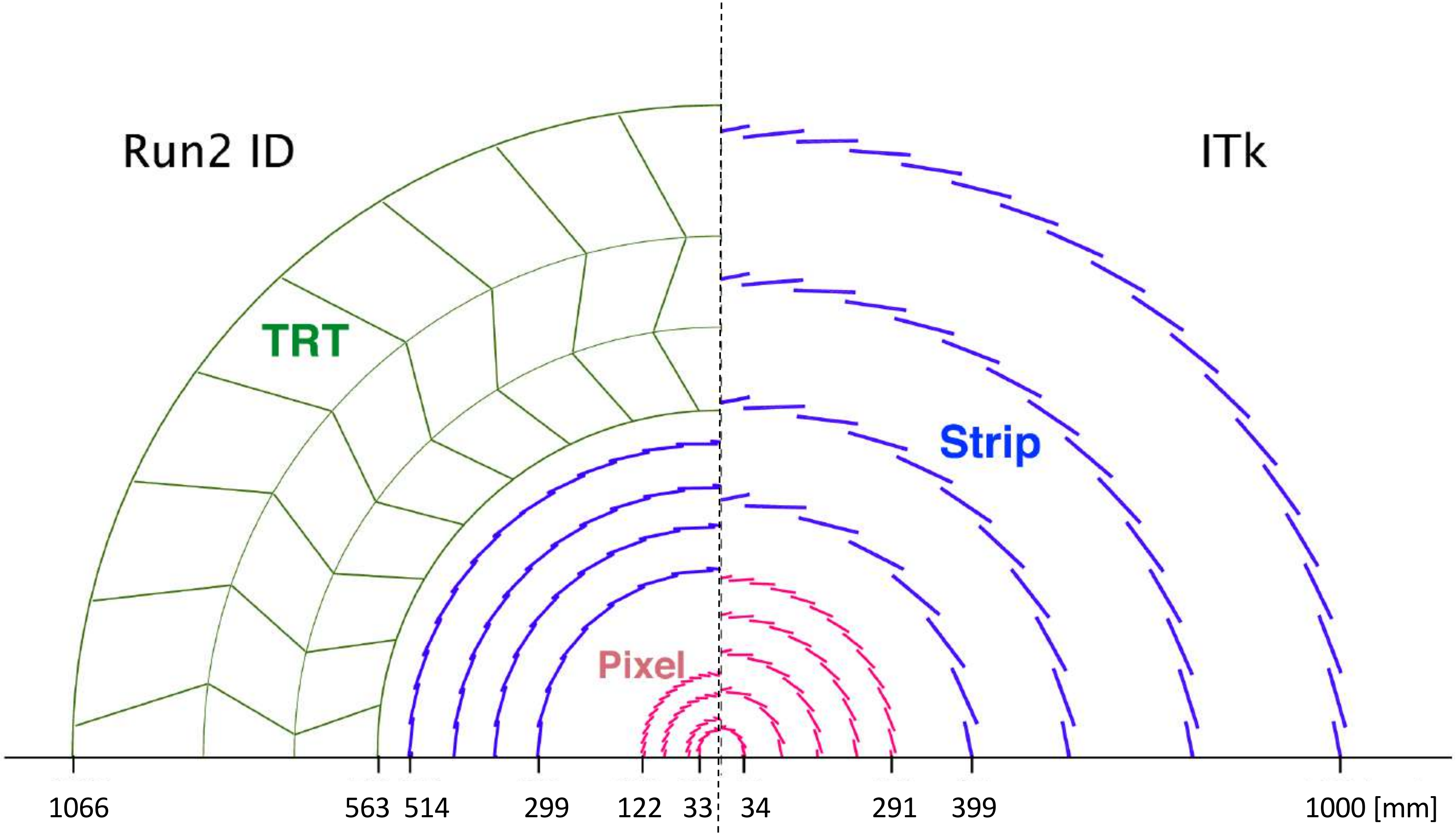
Inner Tracking Detector

		Run2,3	HL-LHC	
Pixel	Total silicon area (m^2)	2	13	~6.5x
	Layers	4	5	
	Pixel size (μm)	50x400, 50x250	50x50, 25x100	
	# channels	92 M	5.1 B	~50x
Strip	Total silicon area (m^2)	68	165	~2.4x
	Layers	4 (double sided)	4 (double sided)	
	Pitch size (μm)	80 (barrel), 57 - 94	70 - 80	
	# channels	6.3 M	60 M	~9.5x

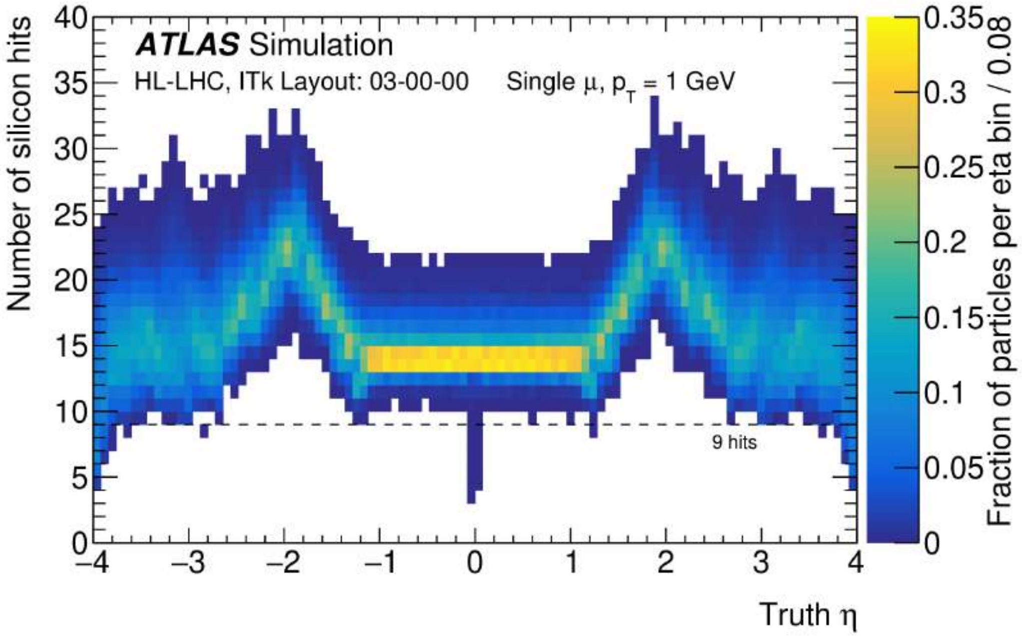


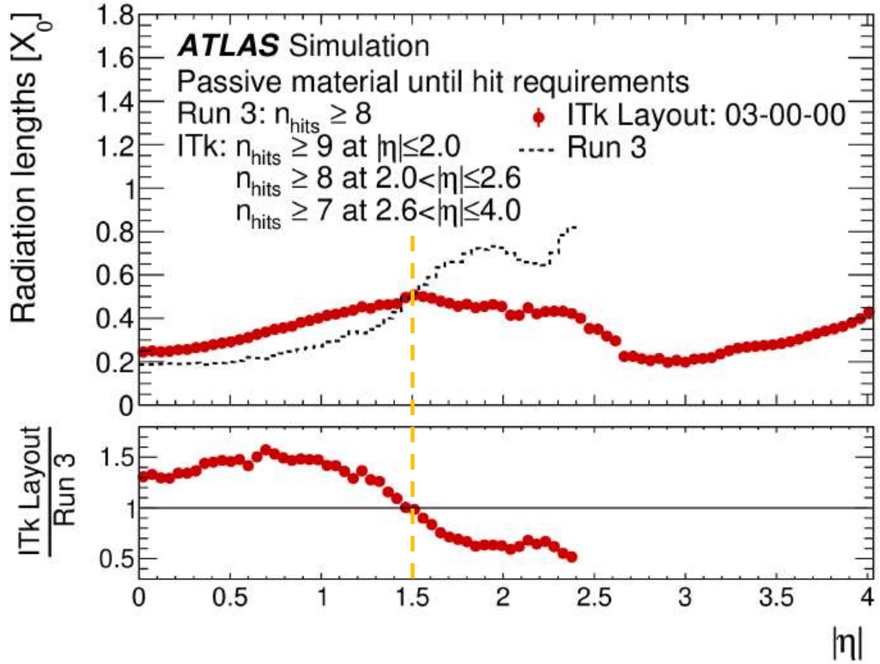


Inner Tracking Detector



Inner Tracking Detector Performance

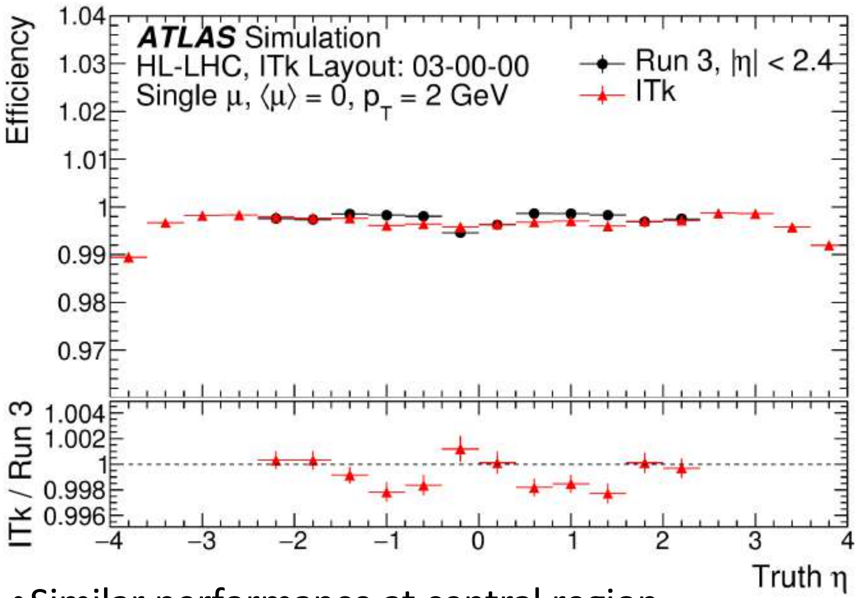




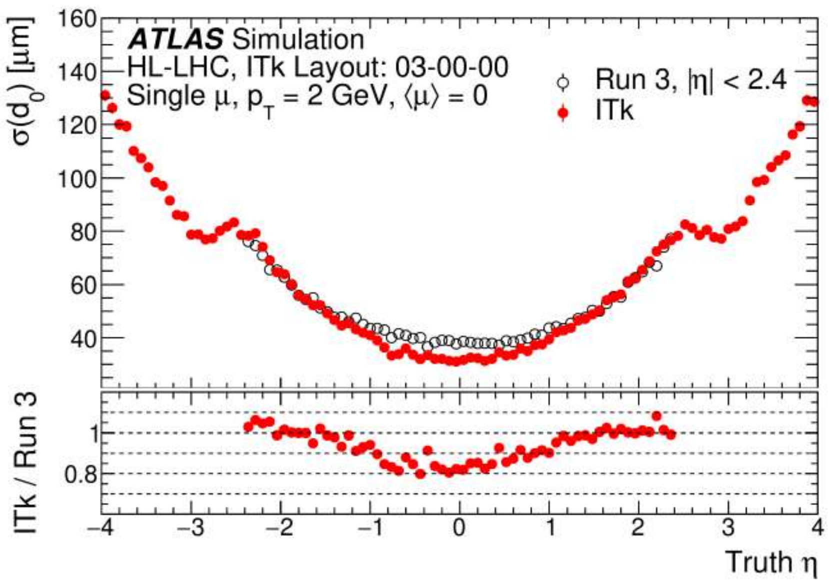
- Most of the charged particles from collisions will register about ~13-14 hits in the silicon tracker

- Amount of materials (in radiation length) traversed by particles before reaching minimum number of hits required for track reconstruction
- Passive material compare to Run2,3:
  - Not significant increase in central region
  - Reduction in forward region

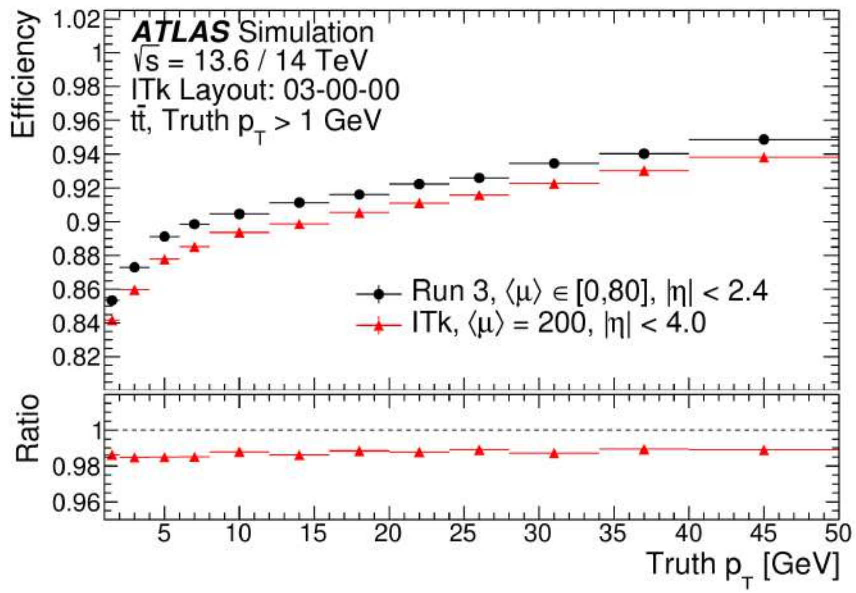
Inner Tracking Detector Performance



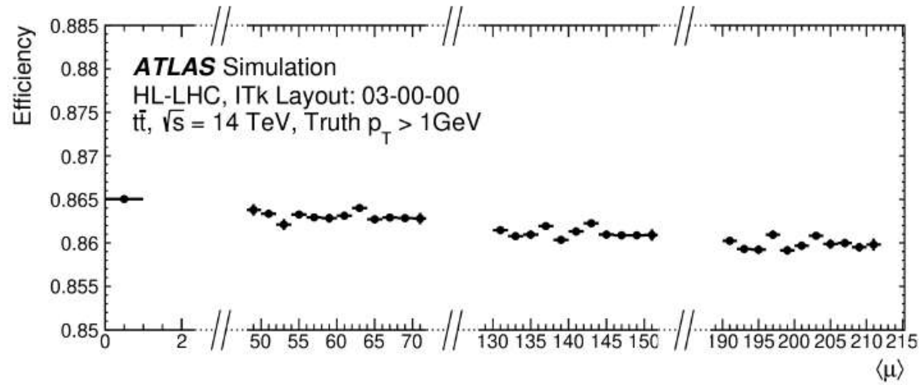
- Similar performance at central region



- Better impact parameter resolution at central region



- Slight degradation of tracking efficiency ~2%

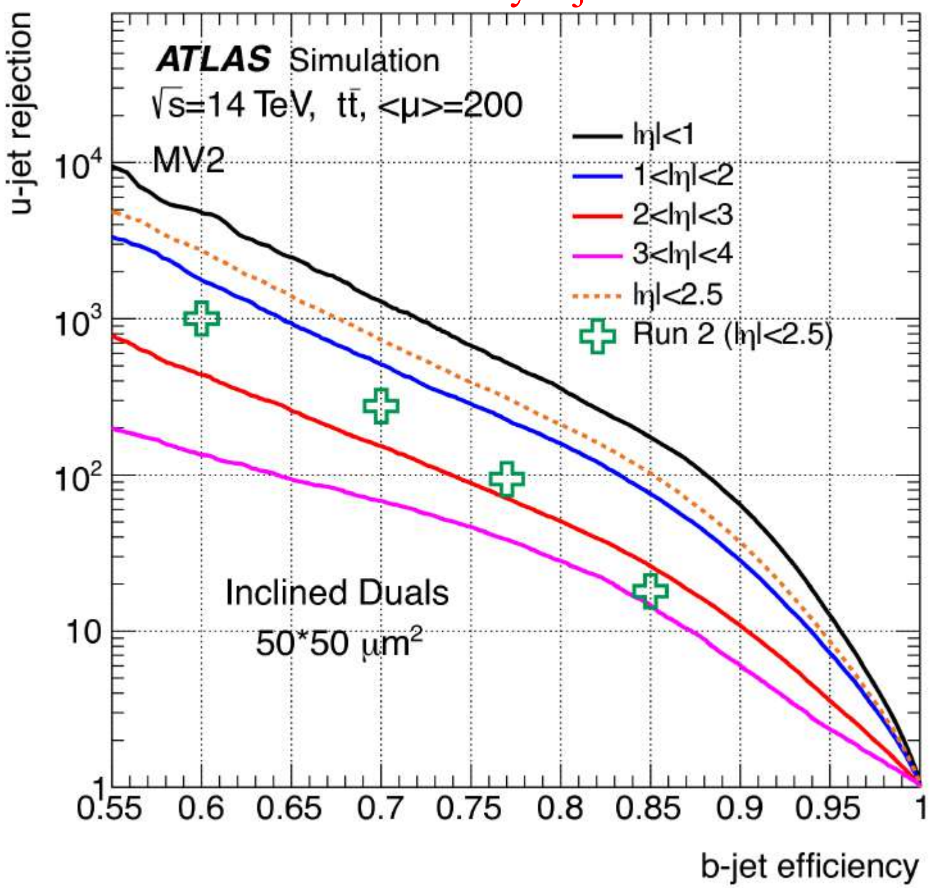


- Slow degradation in tracking efficiency with increase with pile-up

Detector Performance

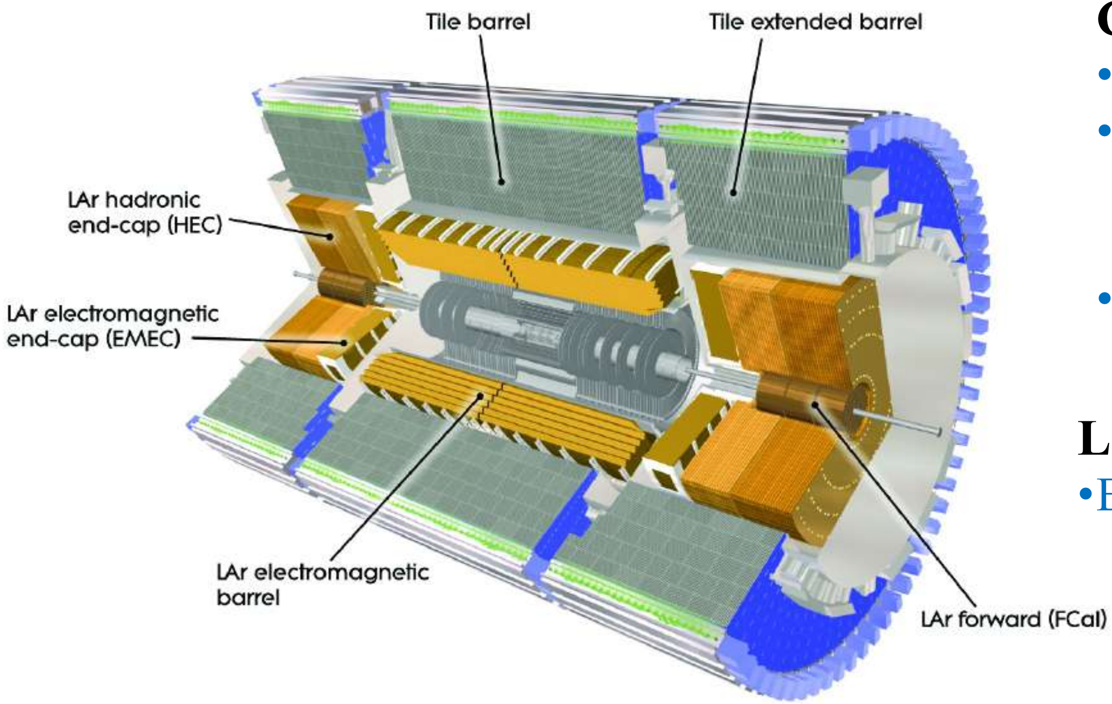
ATL-PHYS-PUB-2019-005

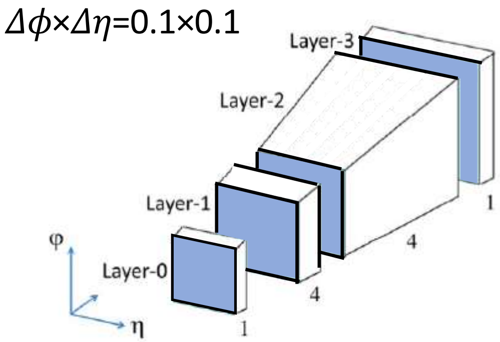
Identify b-jets



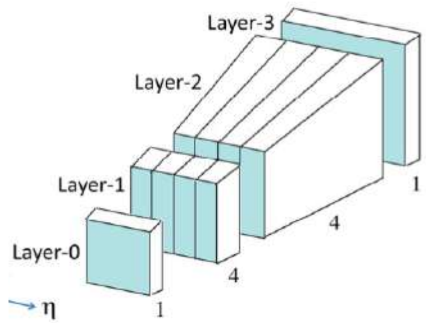
- Trained with similar b-jet identification algorithm:
    - Better performance with ITK (HL-LHC) tracking detector than Run2 tracking detector

Liquid Argon and Tile Calorimeters





Trigger Tower



Trigger Tower using super cell info

Calorimeters:

- Expect to fully operational at HL-LHC
- Complete replacement of on- and off detector electronics to meet new radiation, trigger and readout performance criteria
- To improve detector granularity and readout rate

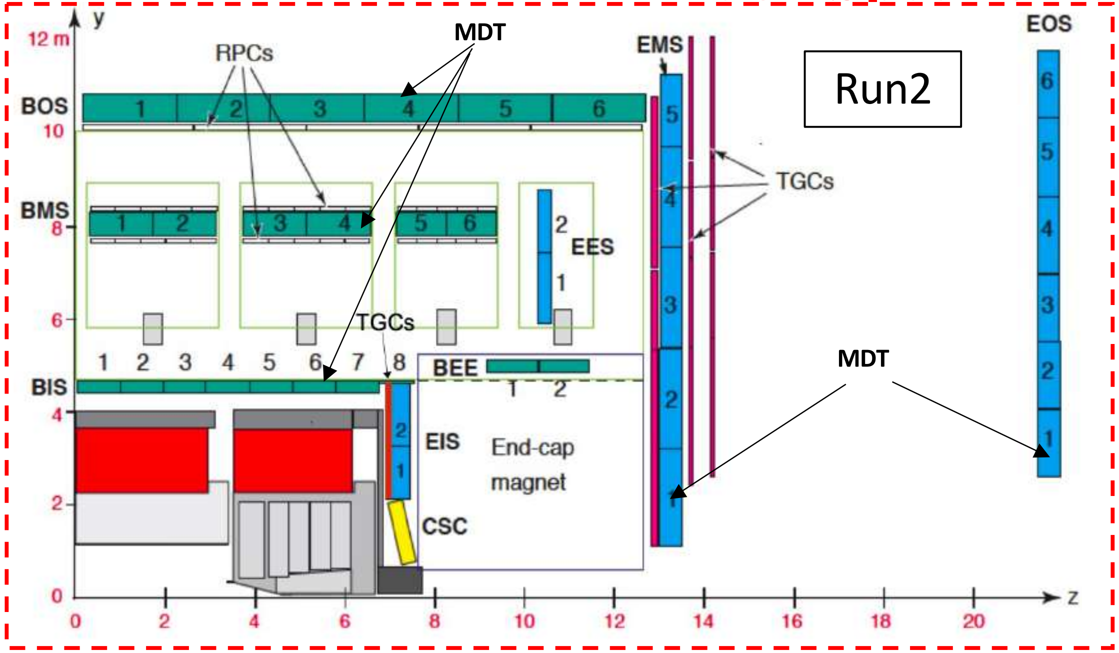
LAr:

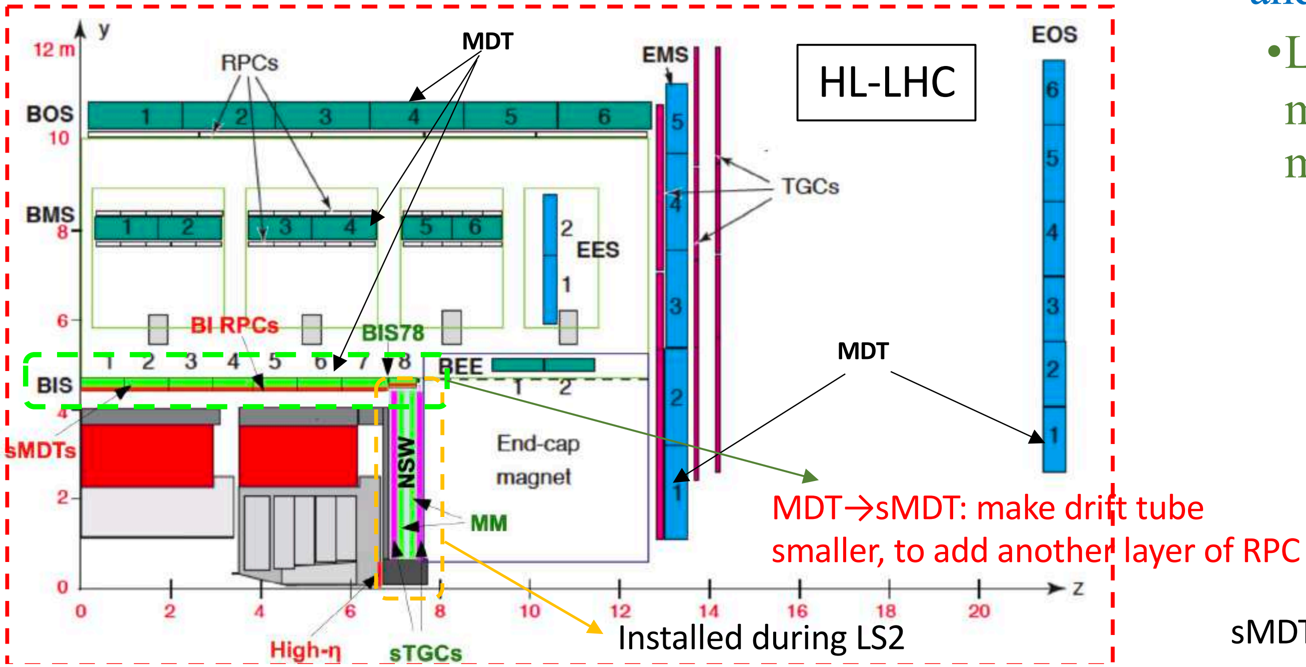
- Exploit "super cell" scheme introduced in Run3
  - Provide information with finer segmentation ($\Delta\phi\times\Delta\eta$=0.1×0.025) in front and middle layers of the barrel and endcaps
  - Perform particle ID (e.g. isolation) at L0 trigger
- Detector signals digitized at 40 MHz, use for L0Calo trigger

Tile:

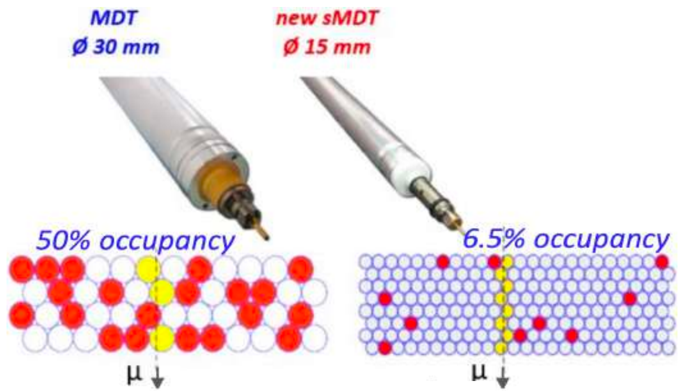
- PMTs on the most exposed cells will also be replaced,
- Upgrade LV/HV power systems
- Upgrade calibration systems

Muon Spectrometers (MS)



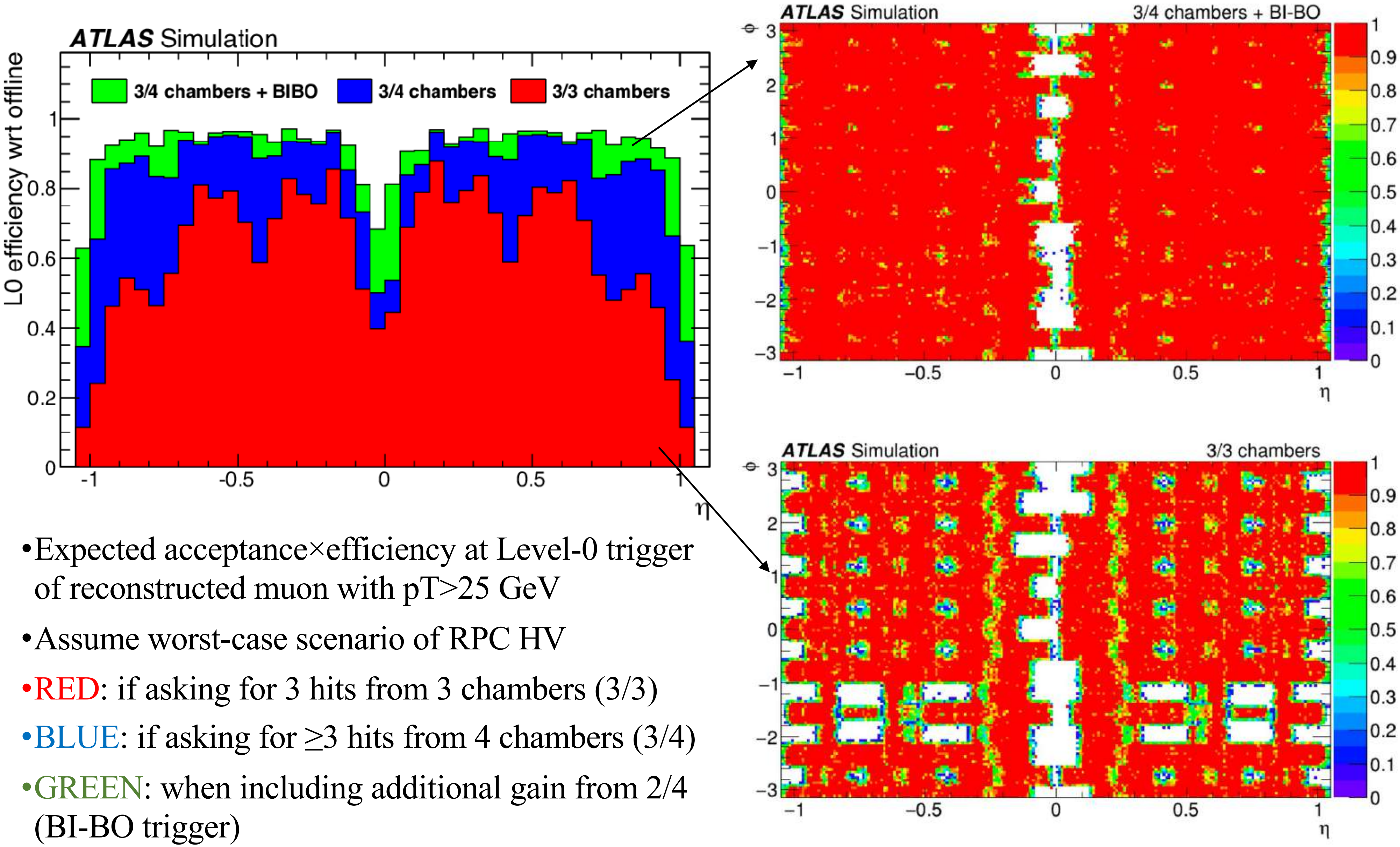


- MS consist of sub-systems for precision pT measurement (MDTs, NSW) and for fast trigger selection (RPC, TGC, NSW)
- **HL-LHC upgrade comprises:**
  - Installation of new chambers, and replacement of some existing chambers by new ones
    - To increase trigger acceptance and efficiency
  - Replacement of a large part of front-end and trigger and readout electronics
    - Low trigger thresholds can be maintained and trigger rates remain manageable



sMDT: 8X lower background occupancy than MDT

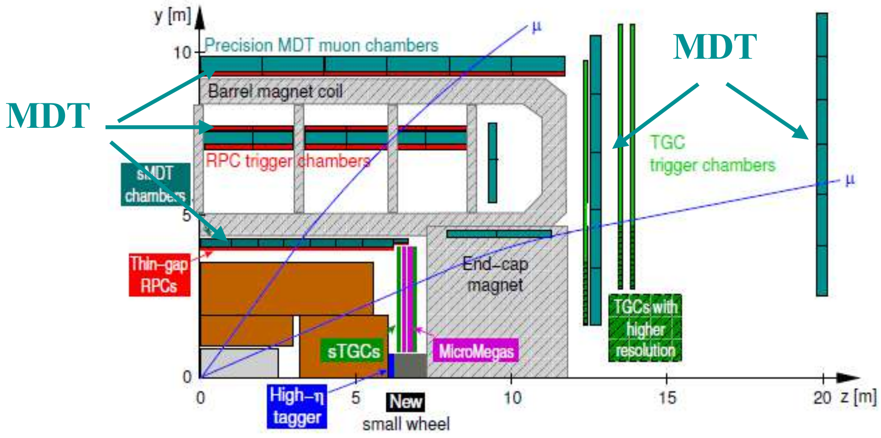
Muon Spectrometers (MS)

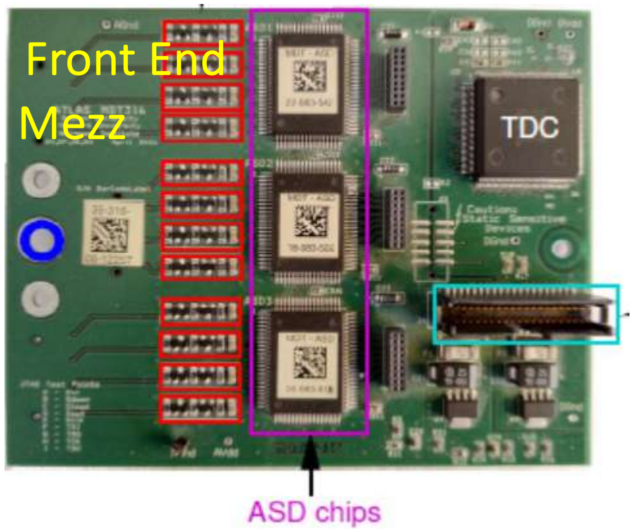


- Expected acceptance×efficiency at Level-0 trigger of reconstructed muon with pT>25 GeV
- Assume worst-case scenario of RPC HV
- RED: if asking for 3 hits from 3 chambers (3/3)
- BLUE: if asking for ≥3 hits from 4 chambers (3/4)
- GREEN: when including additional gain from 2/4 (BI-BO trigger)

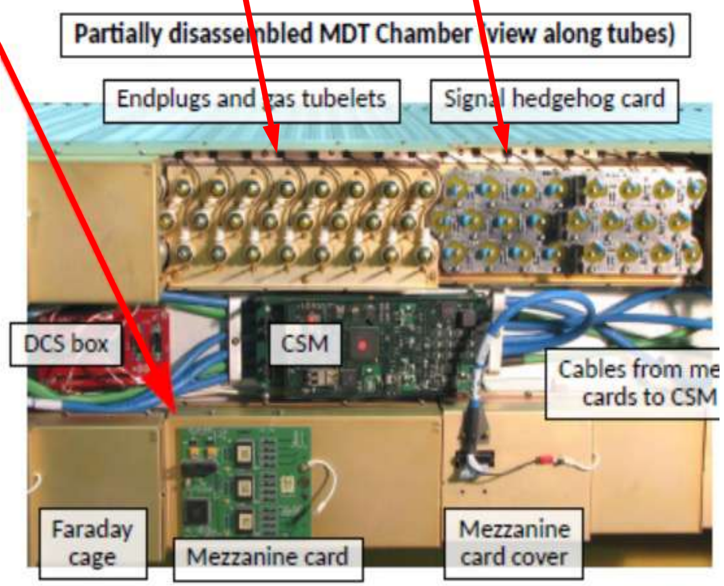
AS Contributions to Muon Upgrade

- **Muon detector: Monitored Drift Tube (MDT)**
- Upgrade readout electronics
- AS is building the MDT front end mezzanine cards
  - Process raw signals from detector
  - Amplified/digitized/discriminate, extract arrival time



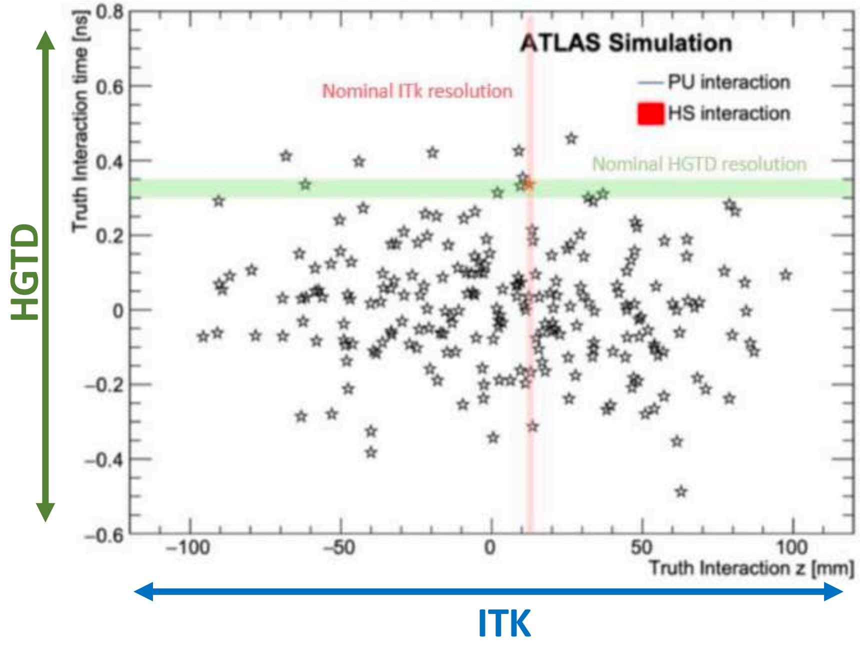


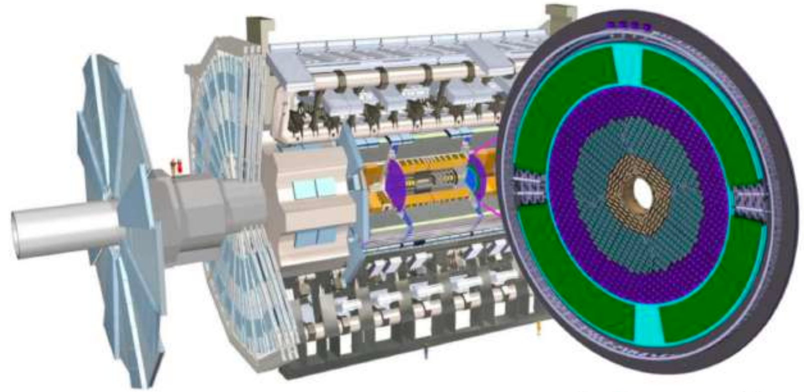
MDT chamber
Mezz tube ends, HV bias



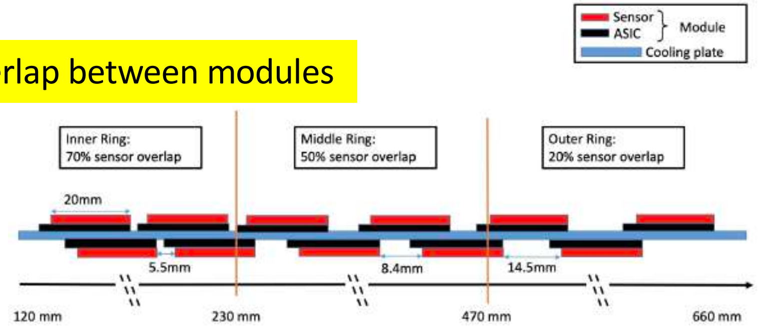
High Granularity Timming Detector (HGTD)

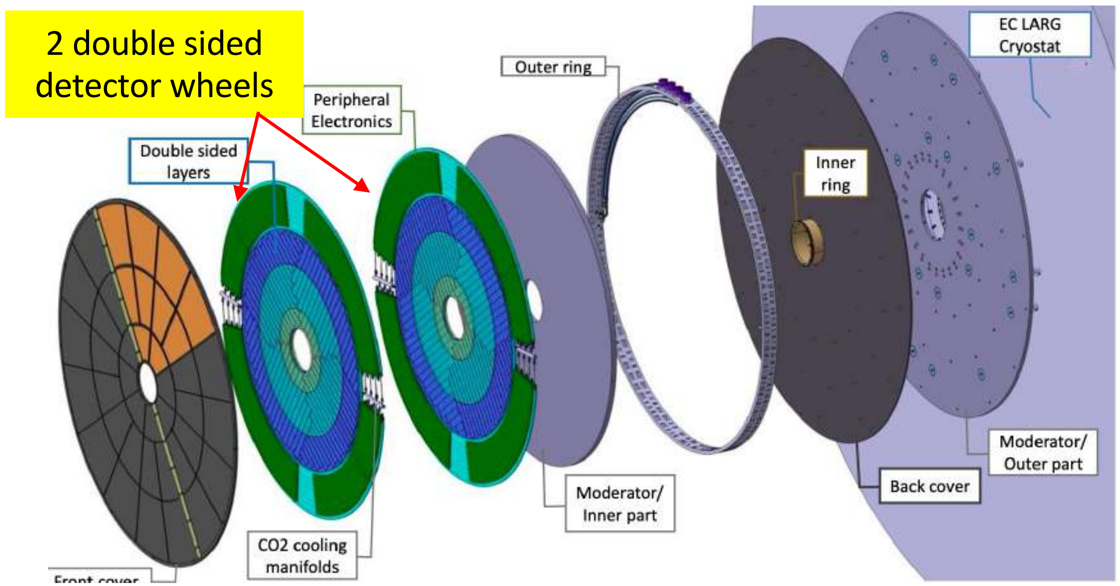
- Highest rates in forward detector regions, where tracker resolution is poorest
- Challenging to assign correct tracks to vertices
- HGTD can provide an extra dimension (time) to separate the individual interactions
  - Improves pile-up rejection and vertex reconstruction
- Place between ITK and LAr, |z|=3.5m, cover $2.4<|\eta|<4.0$
- Detector build with 8032 silicon modules





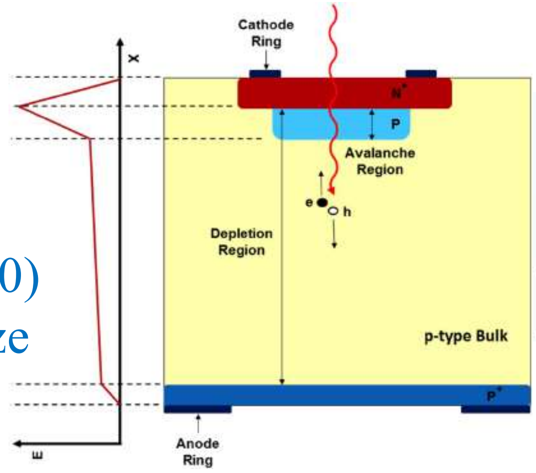
Overlap between modules

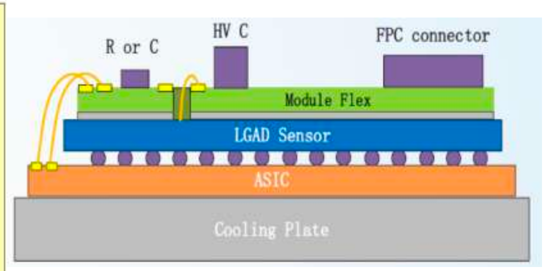




High Granularity Timming Detector (HGTD)

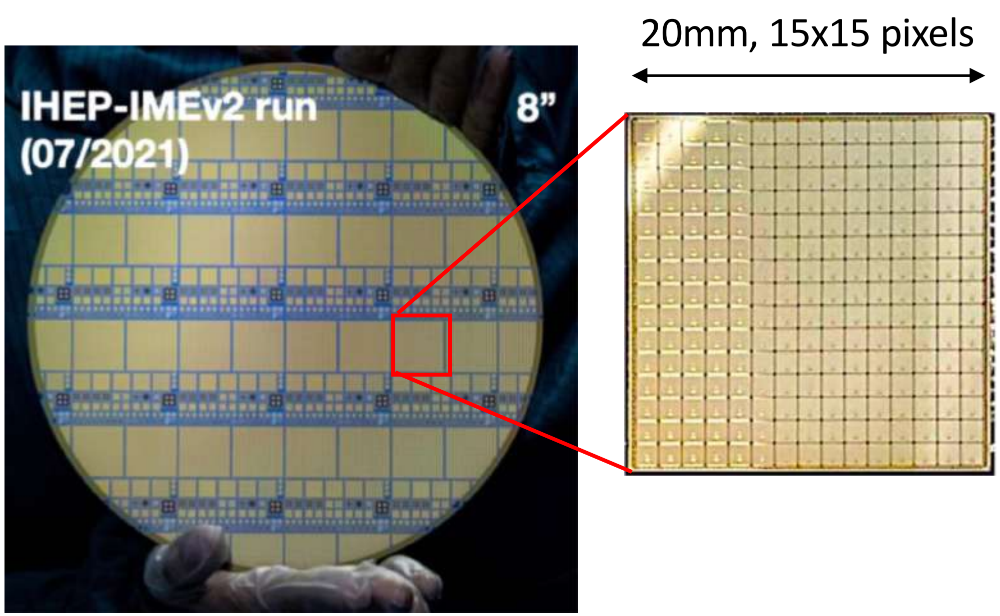
- •HGTD silicon sensors based on Low Gain Avalanche Detector (LGAD) technology
- •Thin depleted layer: 50 um, with extra gain-layer (10-40 gain)
- •Fast rise time and high signal-to-noise (15-30)
- •Each sensor contains 15x15 pixels , pixel size $1.3\times1.3\ mm^2$
- •Sensors bump-bonded to front-end ASIC readout chips





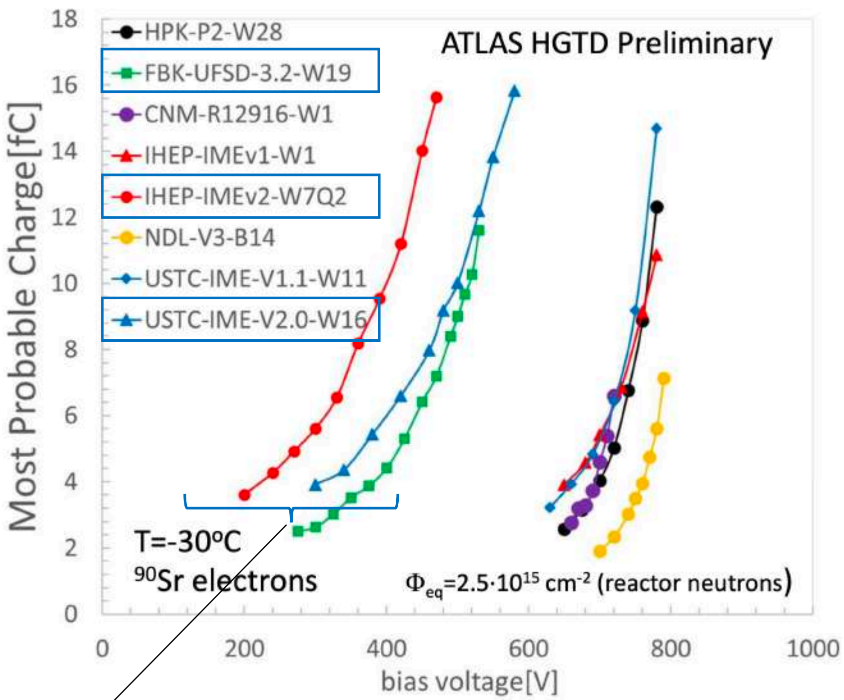
•Sensor requirements:

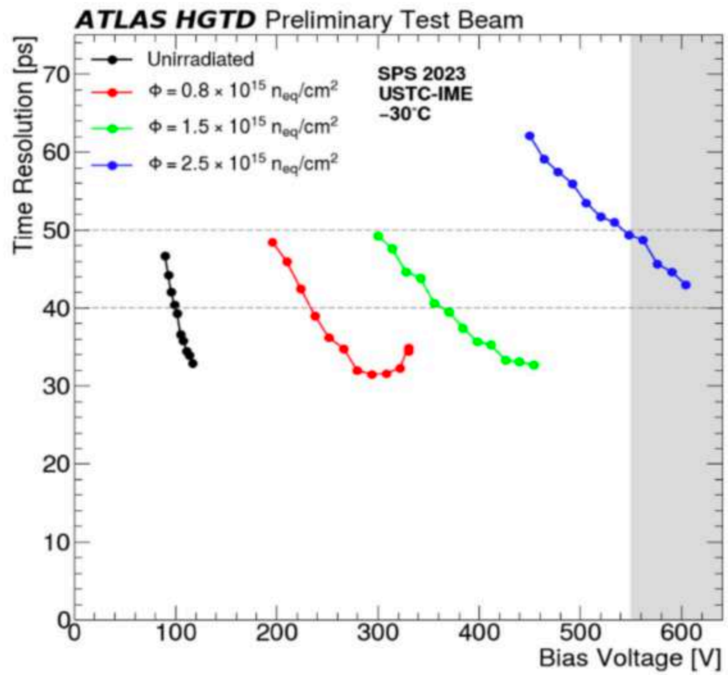
- •Collect charge/hit : 10 fC (start) – 4 fC (end)
- •Achieve 30-50 ps/track resolution
- •Operates at low temp (-30 C) to mitigate the impact of irradiation
- •Total channels: 3.6 M



•HGTD: also provides bunch-by-bunch luminosity measurement

High Granularity Timming Detector (HGTD)

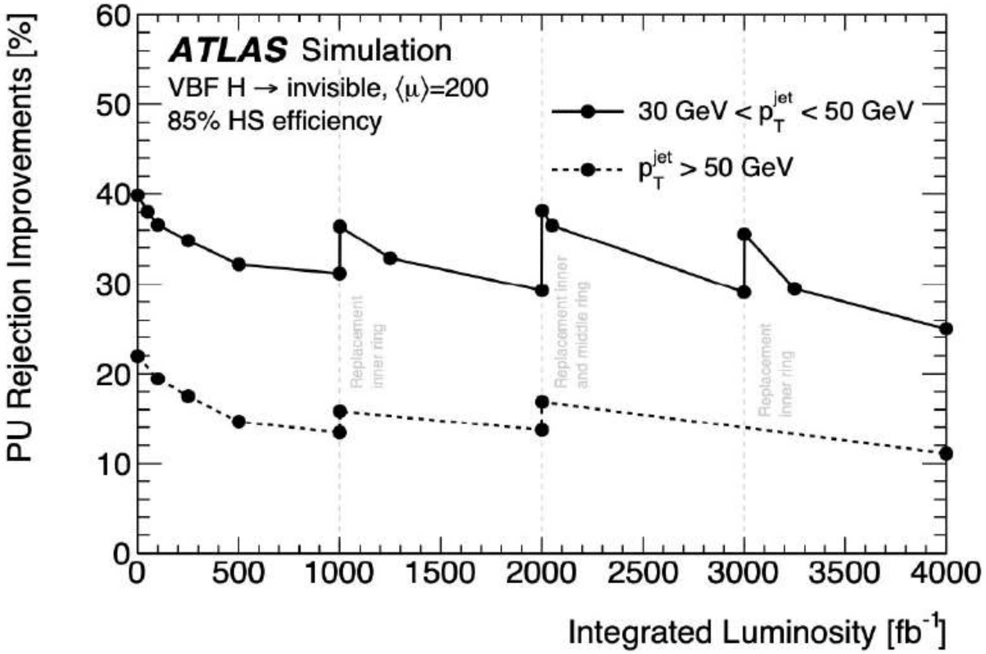


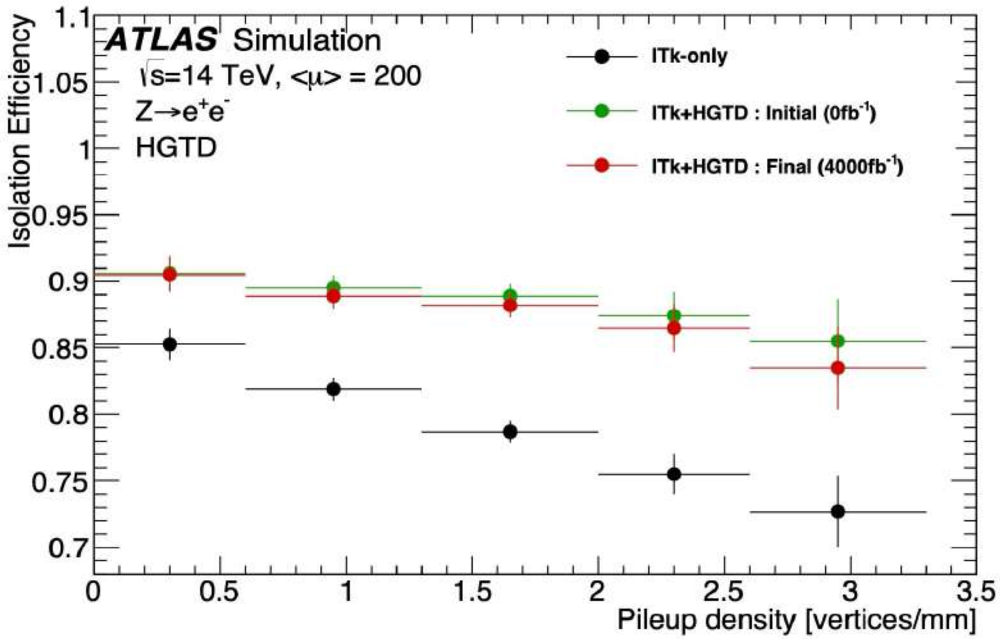


- Carbon infused sesnors more robust against Single Event Burn-out (SEB) with stable operation at lower voltage

- LGAD performance degrades with radiation exposure due to loss of gain
  - Recover by increasing operation voltage

High Granularity Timming Detector (HGTD)

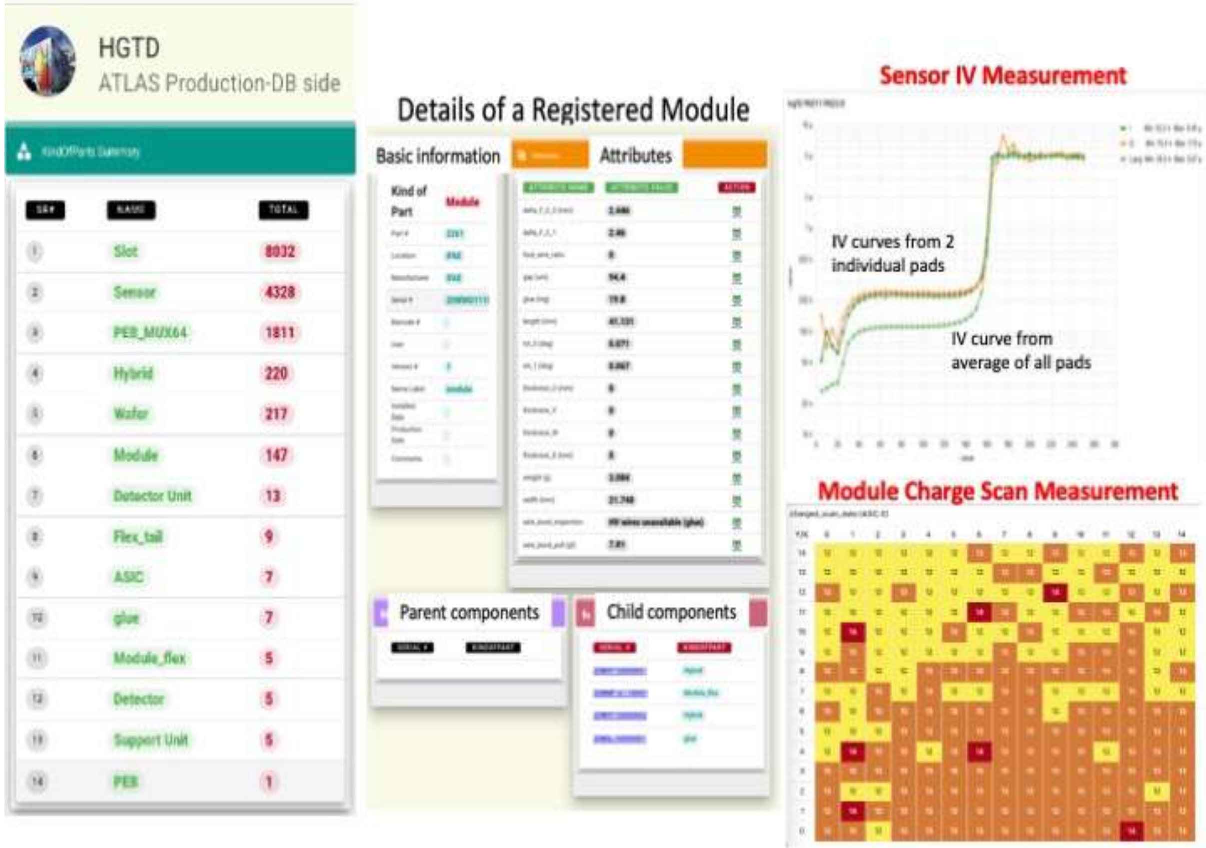




- Track-timing information from HGTD will allow to recover the performance in the forward detector region:
  - Improve pile-up (PU) rejection
  - Increase lepton-isolation efficiecny

AS and NTHU Contributions to HGTD

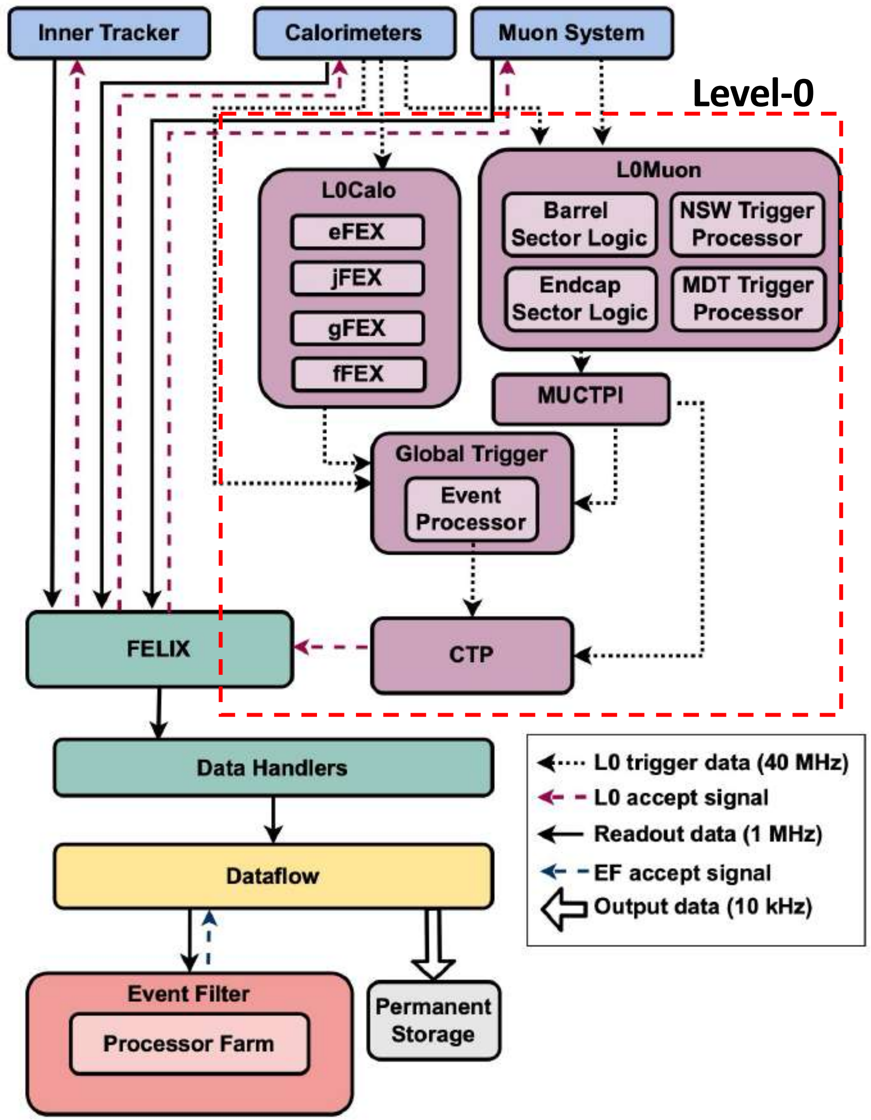
- AS+NTHU contributes to
  - optical fibers and cables production
  - simulation studies and test beam
  - demonstrator setup
  - production database and data quality
- HGTD going into pre-production soon
  - We will participate in detector installation and testing



- **Production Database**
- HGTD: ~8k sensor modules, assembled together and connected to front end electronics boards and HV/LV power supplies
- Need a Database to record all these parts, store test measurements and Quality Control info
  - Record need to keep until end of HL-LHC
- Implemented majority functions of Database
- Ready in 2026 for pre-production

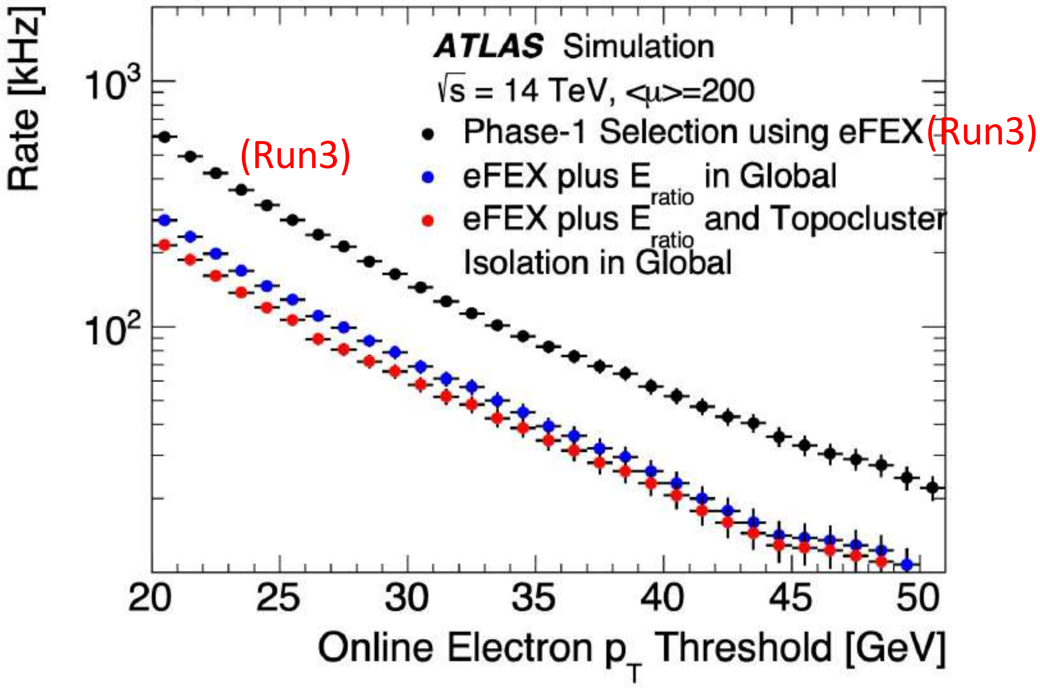
Trigger Upgrade for HL-LHC

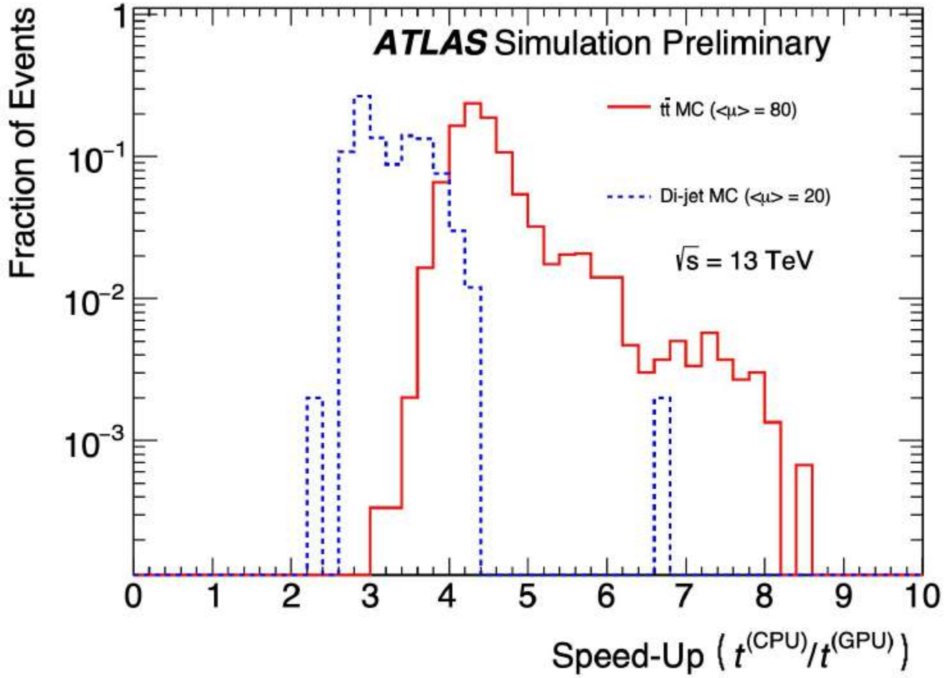
- Consists of Hardware and Software level Triggers
- **Hardware Trigger (Level-0)**
  - Receive higher granularity detector information from Calorimeter and Muon at input rate of 40 MHz
  - Use calorimeter cell info to do particle ID
  - Output rate at 1 MHz, 10× higher than Run3
- **Software Trigger (Event Filter)**
  - Base on a large farm of commodity computers
  - Potential to be augmented by commercial accelerators (FPGA or GPU)
  - Run offline-like algorithms at input rate 1 MHz
  - Reduces the event rate to a maximum of 10 kHz
  - Purchases of commodity hardware will be done as late as possible to profit from latest developments



L0 Global Trigger prototype

Trigger Upgrade for HL-LHC

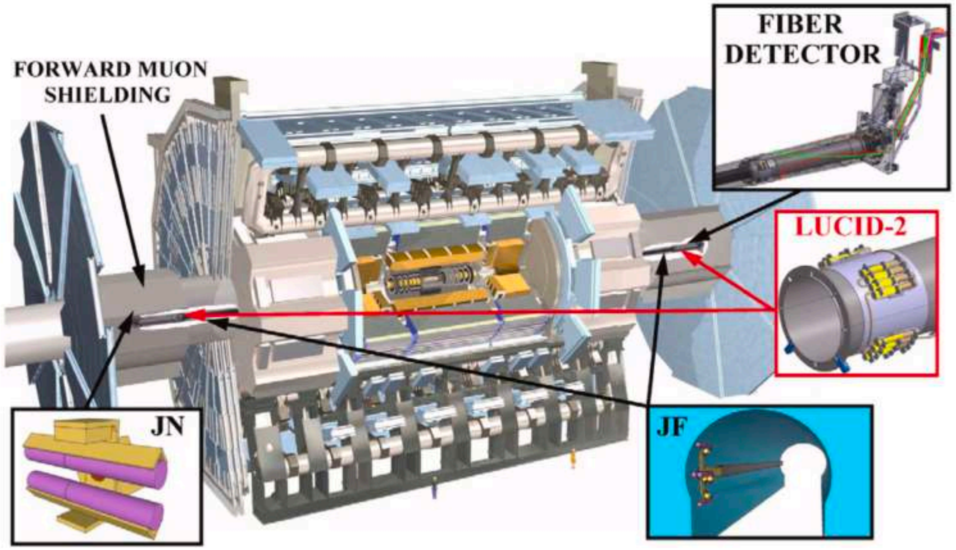




- **Hardware Trigger (Level-0)**
  - Can reduce single-electron trigger rate by ~2-3X using higher granularity calorimeter information to perform topo-clustering and isolation
- **Software Trigger (Event Filter)**
  - Speed up of topo-clustering in ttbar and di-jet events with GPU compare to only CPU

Luminometers for HL-LHC

- Luminosity: measurement of p-p collision rate
- **Importance:**
  - Has direct impact on many data analyses
  - Use for operation of accelerator and optimization of data taking
- Aim to achieve uncertainty < 1%
- Several luminometers for L measurement



- **LUCID-3:**
  - LUCID-2: main ATLAS luminometer for Run2,3
    - Consists of few PMTs, at 17m from interaction point, 12 cm around the beam pipe
    - Will suffer from "saturation" (blind to further increase in luminosity) at high pile-up of HL-LHC
    - Suffered radiation damage, need replacement
  - LUCID-3: to avoid "saturation" by reducing detector occupancy
    - Use smaller PMTs, or quartz fiber
    - Relocate further from beamline to lower particle flux
    - Choice of PMTs/fiber and location are to be finalized

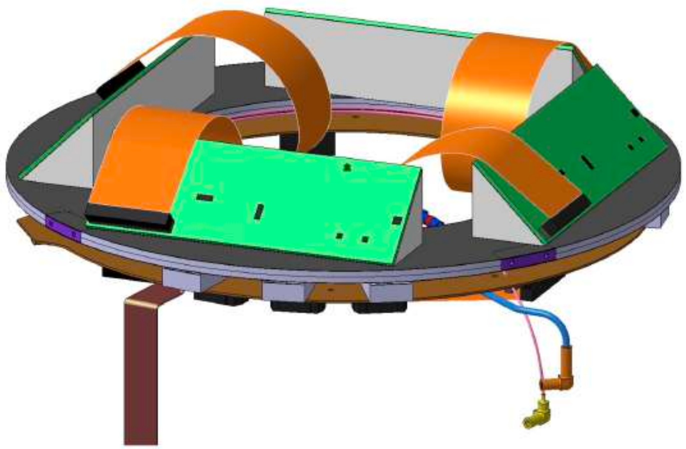
LUCID-3 JN prototype

LUCID-3 JF prototype

Luminometers for HL-LHC

- Other luminometers for HL-LHC:

BCM’



- **HGTD**:
  - Also provide bunch-by-bunch luminosity measurement

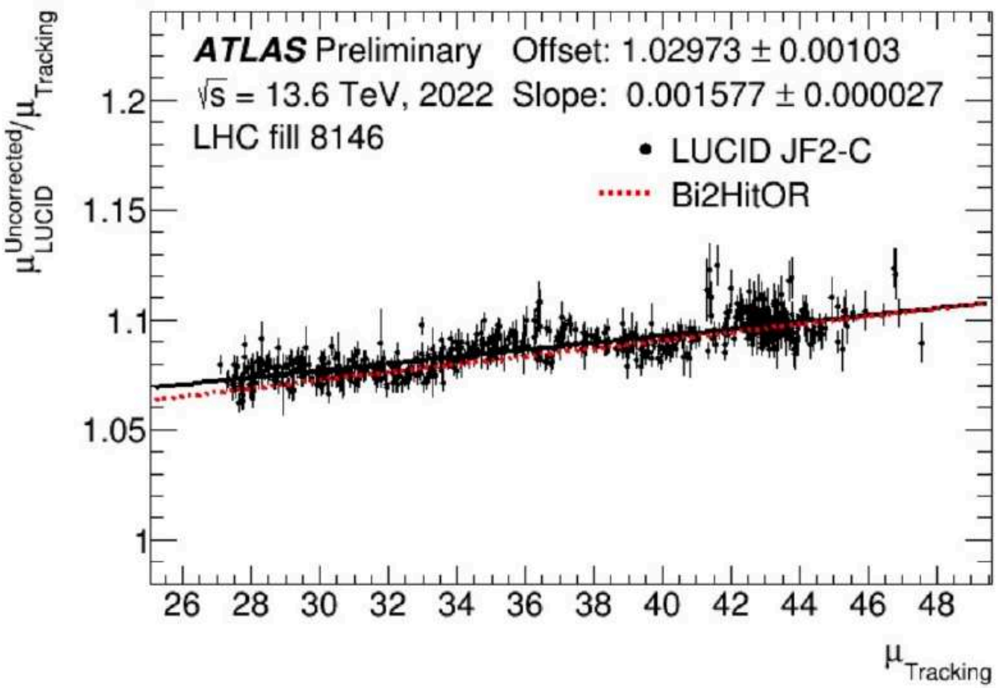
- **BCM’:**
  - Diamond based beam conditions monitor
  - Located inside ITK
  - To monitor beam conditions and provide bunch-by-bunch luminosity measurement
  - Academia Sinica is contributing to:
    - Analyze test beam data
    - Assemble BCM’ at TIDC, build test stand at AS

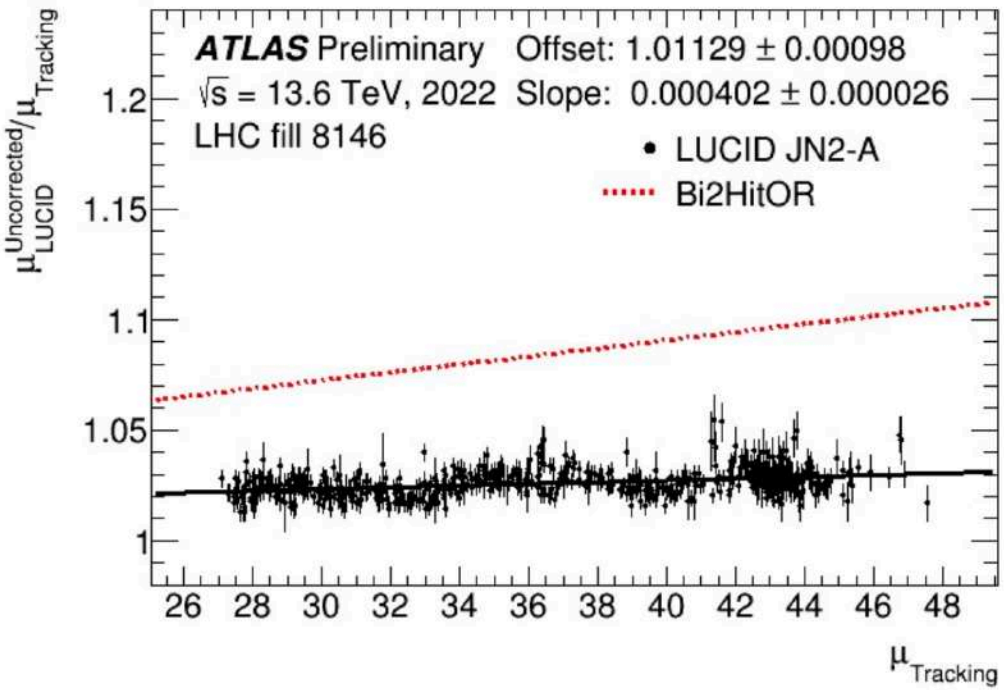
Summary

- ATLAS is performing several major upgrades to cope with the challenging conditions pose by the HL-LHC
- The inner tracking tracking will be completely replaced by an all-silicon tracker with coverage extended to $|\eta|<4$
- The High Granularity Timming Detector (HGTD) will help to mitigate pile-up effect through precise timming measurement
- The upgrade of the muon sub-system will improve the trigger geometry coverage
- The on- and off-detector electronics of the sub-systems are to be replaced to handle higher trigger and readout rates, and to provide higher granularity detector informarion for the trigger
- Soon these upgrades will start the installation and testing after the end of Run3 (June 29th 2026) data taking

BackUp

Requirements	Pseudorapidity interval		
	$\|\eta\| \leq 2.0$	$2.0 < \|\eta\| \leq 2.6$	$2.6 < \|\eta\| \leq 4.0$
Pixel + strip hits	≥ 9	≥ 8	≥ 7
Pixel hits	≥ 1	≥ 1	≥ 1
Holes	≤ 2	≤ 2	≤ 2
p_T [MeV]	> 900	> 400	> 400
$\|d_0\|$ [mm]	< 2.0	< 2.0	< 10.0
$\|z_0\|$ [cm]	< 20.0	< 20.0	< 20.0


ATLAS Preliminary
√s = 13.6 TeV, 2022
LHC fill 8146
Offset: 1.02973 ± 0.00103
Slope: 0.001577 ± 0.000027
LUCID JF2-C
Bi2HitOR
μ LUCID Uncorrected/μ Tracking
μ Tracking


ATLAS Preliminary
√s = 13.6 TeV, 2022
LHC fill 8146
Offset: 1.01129 ± 0.00098
Slope: 0.000402 ± 0.000026
LUCID JN2-A
Bi2HitOR
μ LUCID Uncorrected/μ Tracking
μ Tracking