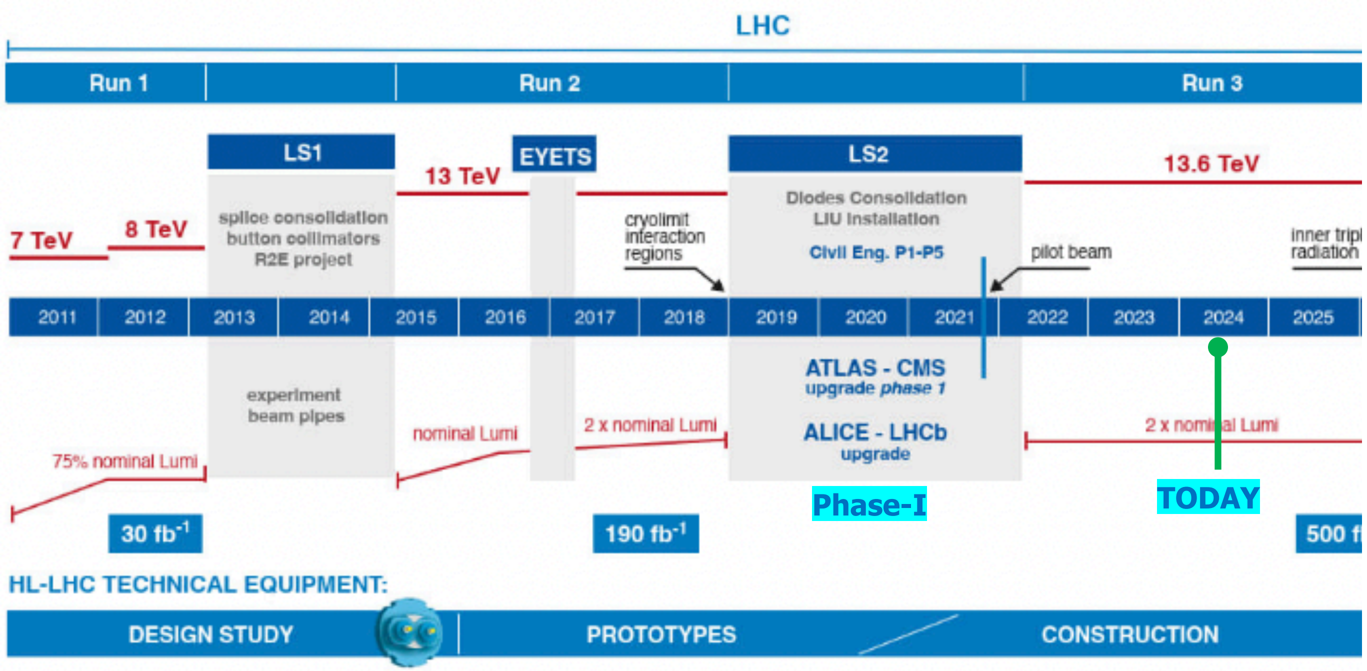
# The ATLAS HL-LHC Upgrade program

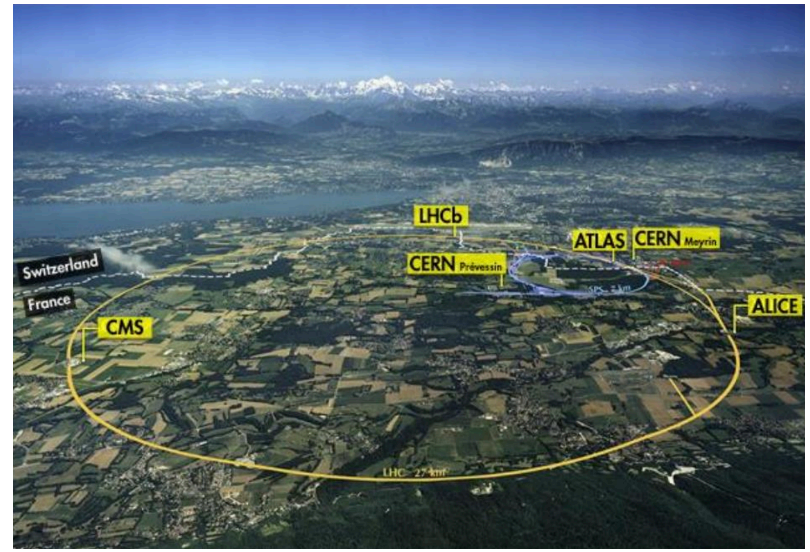
Claudia Gemme (INFN Genova)

***Outline***

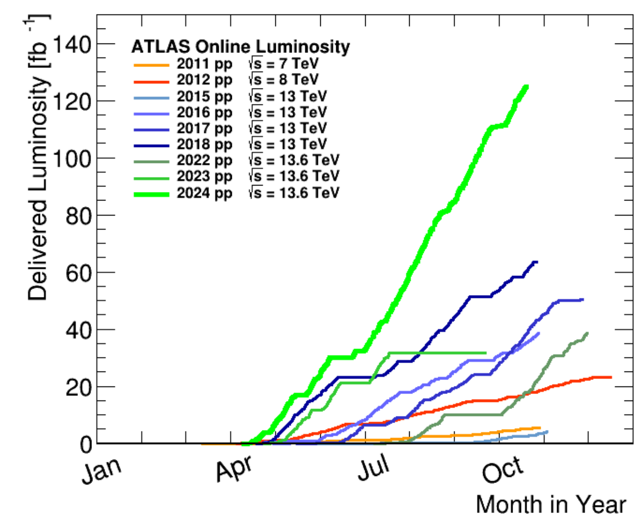
- *ATLAS@LHC*
- *HL-LHC motivations and challenges*
- *ATLAS@HL-LHC*

# The Large Hadron Collider



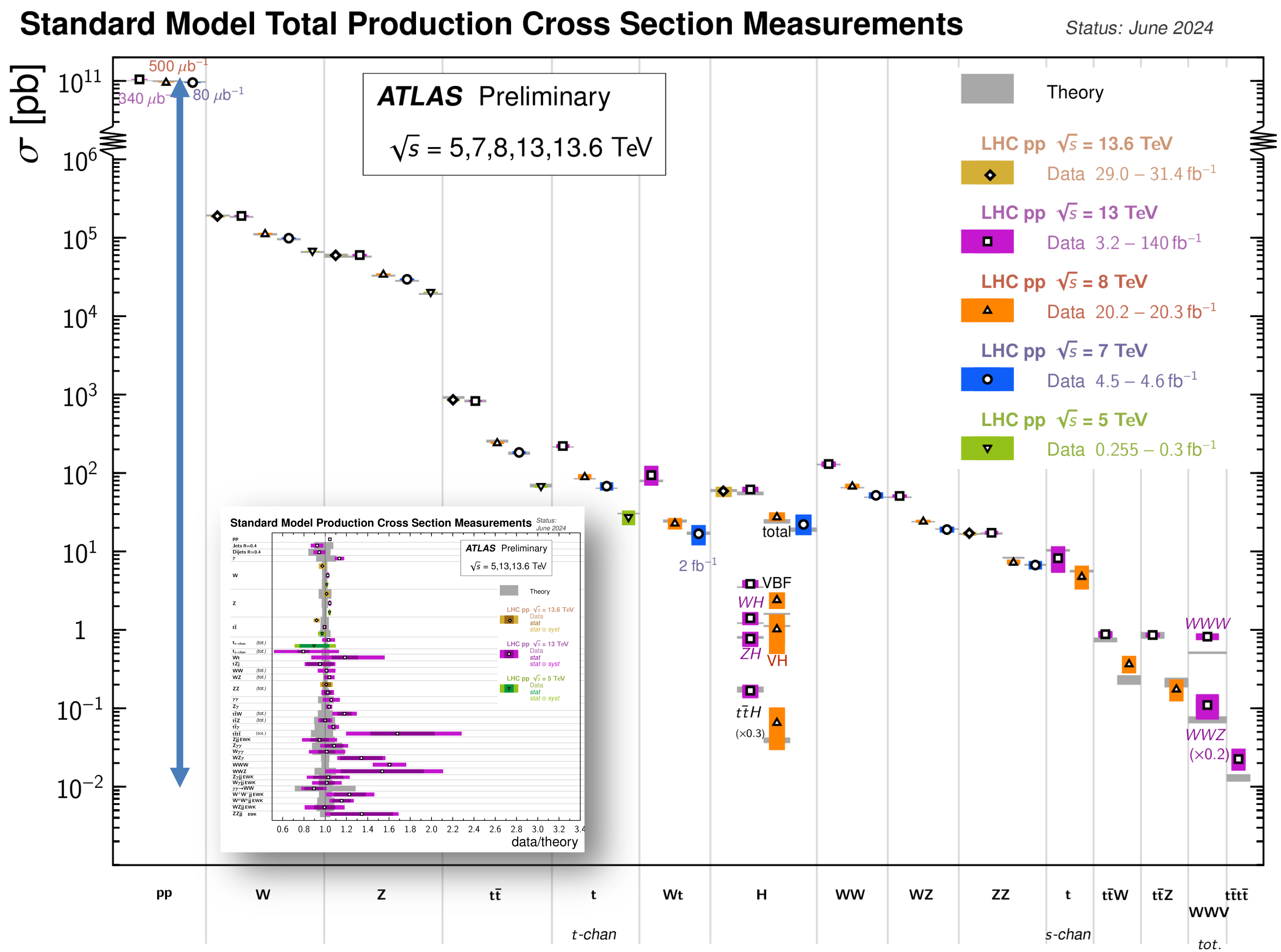

- The LHC accelerator is periodically upgraded to keep exploring the energy frontier.
  - **Run1** 2008-2012:
    - $E_{cm}$ = 7-8 TeV, Average pileup ~18, $L_{int}$ = 26 fb$^{-1}$
  - **Run2** 2015-2018:
    - $E_{cm}$ = 13 TeV, Average pileup ~34, $L_{int}$ = 147 fb$^{-1}$
  - **Run3** 2022-2024:
    - $E_{cm}$ = 13.6 TeV, Average pileup ~64, $L_{int}$ = 183 fb$^{-1}$




PublicPlots

# ATLAS Physics reach

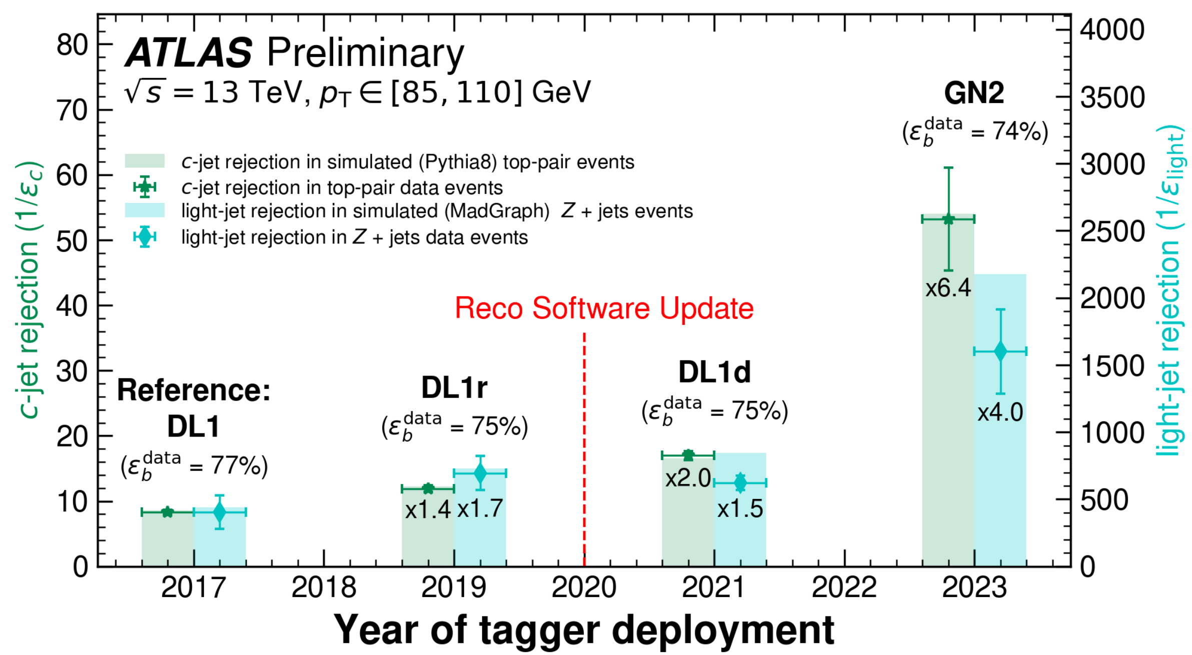
- SM studied over 13 orders of magnitude
- Higgs:
  - After observation in Run1, all major production mechanisms observed and coupling to bosons and to 3rd generation fermions
- Probing SM:
  - pQCD tests in production of jets, photons, W, Z, top;
  - Precision measurements: $m_W$, $m_t$, $\alpha_s$, $\sin^2\theta_W$ …
  - Rare processes …
- Physics program greatly benefitted from advances in theory calculations and event generators:
  - Calculations up to N3LO in QCD and NLO in EW corrections




[Public plots](#)

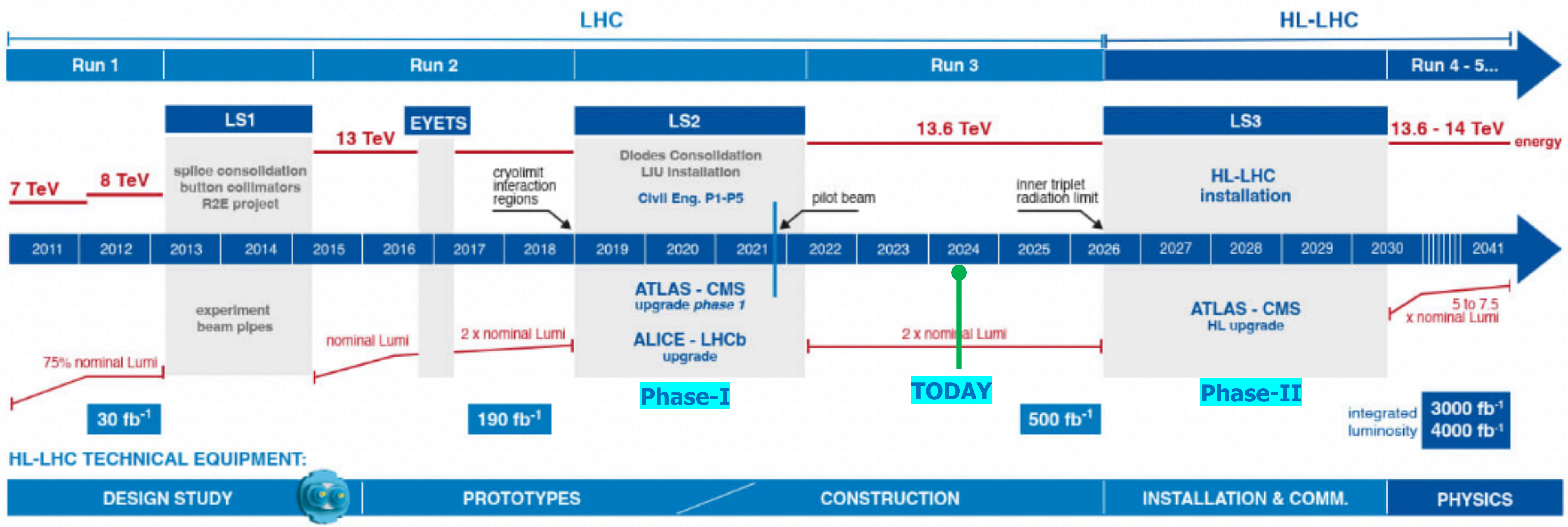
# ATLAS detector performance

- Detector performance is constantly improving with time, often beyond original expectations, even thanks to the **safety margins** adopted in the design.
  - Very large calibration samples give the possibility to calibrate object momentum scales with very small uncertainty (<0.1% for leptons, <1% for jets)
  - Impressive improvement in jet flavour tagging and tau identification thanks to state of-the-art deep learning techniques, calibrated using real data samples
- Learning process: large effort for taking high quality data, performing calibrations, brings to a better understanding of detectors and thus to new ideas to improve beyond initial expectations.



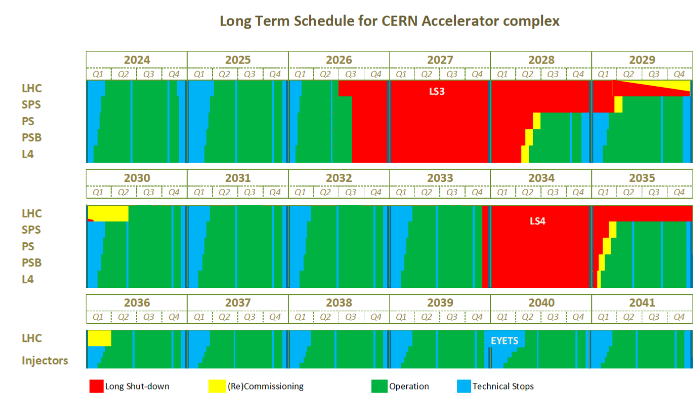

*Example:*
*Heavy flavour tagging*

# The High Luminosity LHC




*HL-LHC schedule, October 2024*

- The "HL-LHC" period will start in ~2030, after an almost four years shutdown:
- A total integrated luminosity up to 3000-4000 ifb will be collected
    - i.e. almost 10 times the current luminosity!



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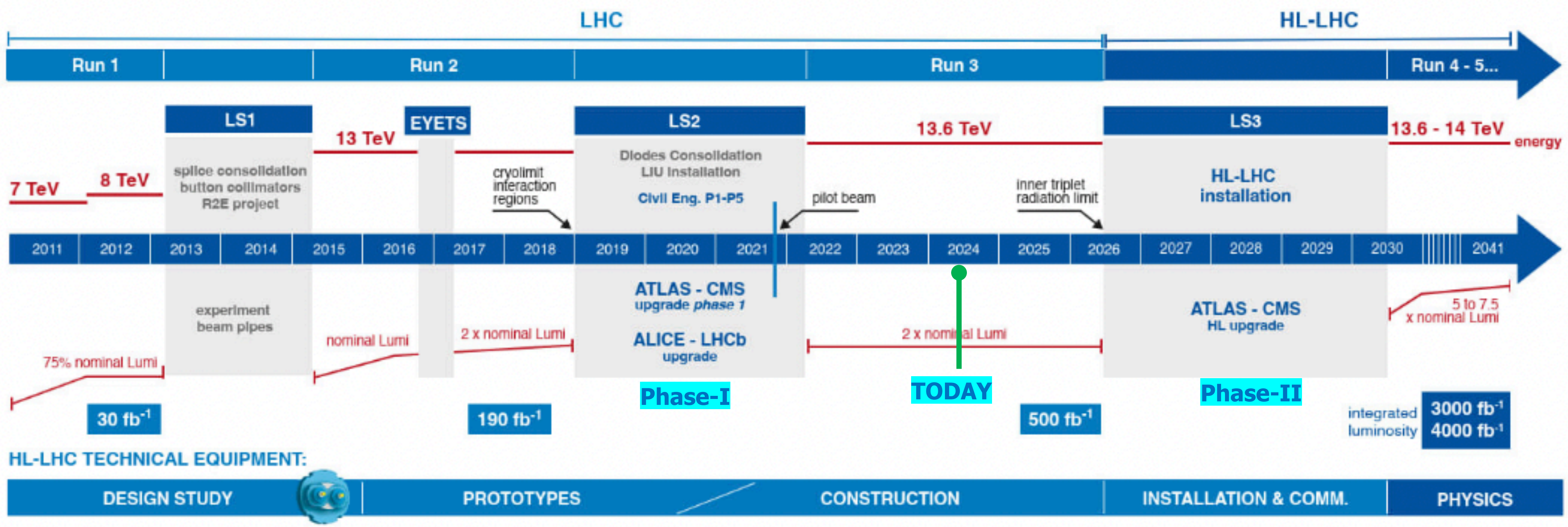
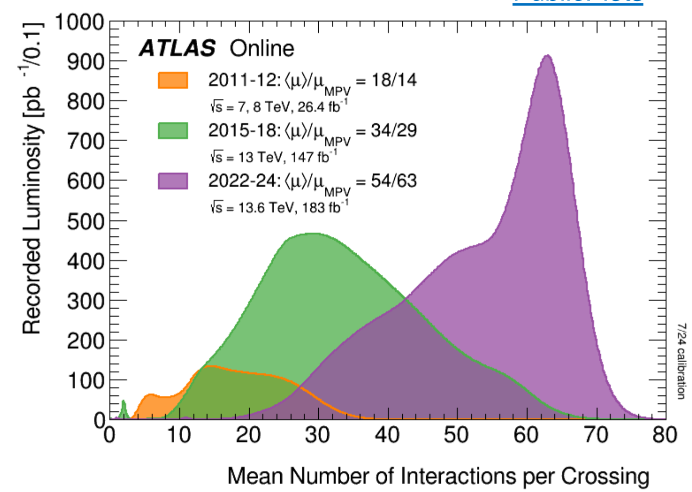



*HL-LHC schedule, October 2024*

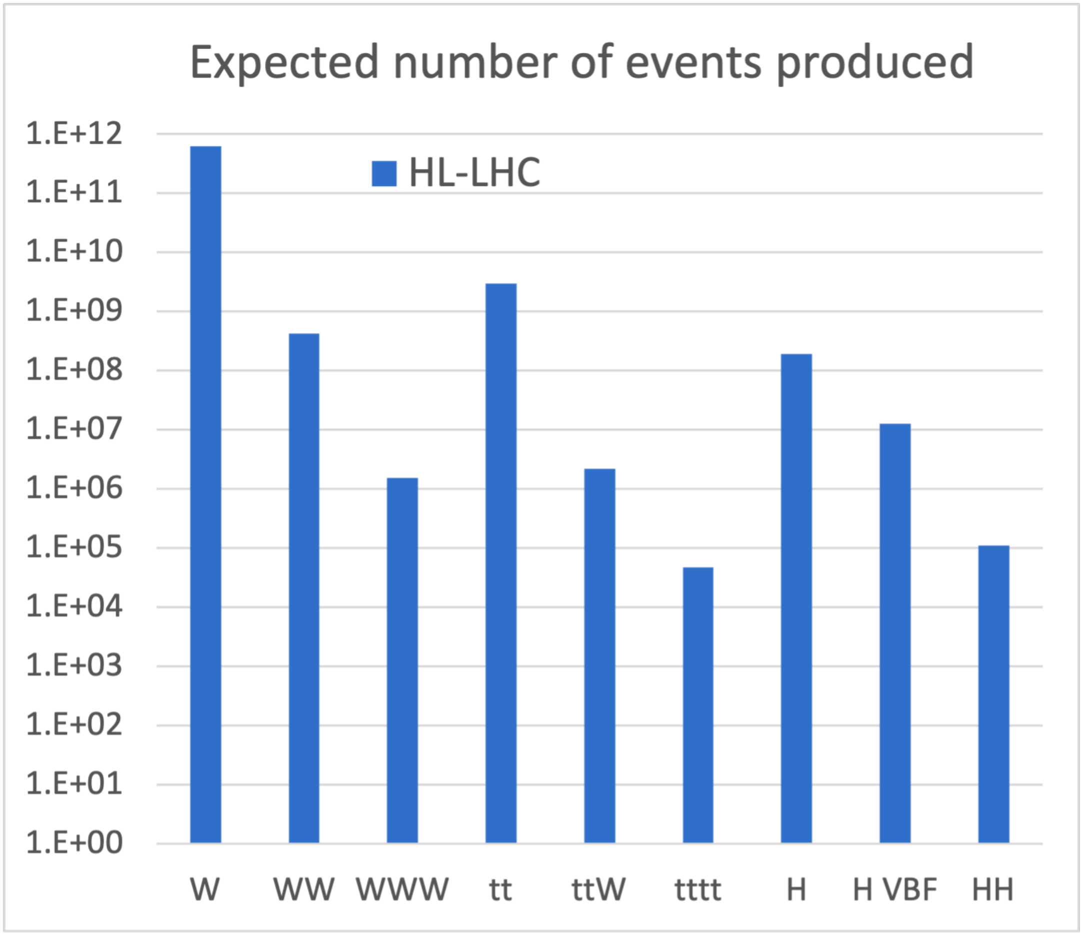
PublicPlots




- The "HL-LHC" period will start in ~2030, after an almost four years shutdown
- A total integrated luminosity up to 3000-4000 ifb will be collected
  - i.e. almost 10 times the current luminosity!
- 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~60* up to *μ*=200**

# *HL-LHC is a Higgs, W/Z/top … factory*

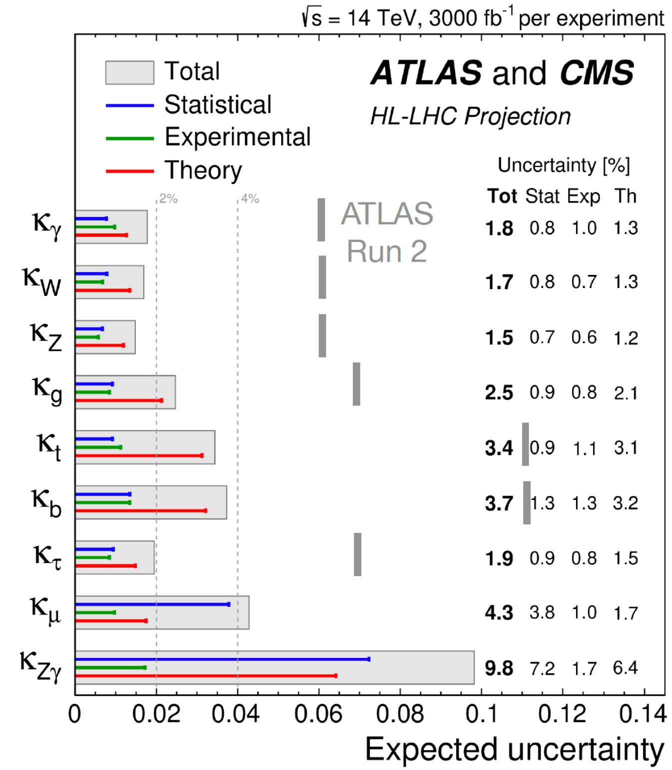
- **Huge statistical power for heavy particles!**
- Number of particles produced in ATLAS with 3,000 $fb^{-1}$ at 14 TeV
  - 600,000 Millions W bosons
  - ~3,000 Millions tt pairs
  - ~190 Millions Higgs bosons
  - ~0.12 Millions HH pairs
- Gives access to "rare" processes
  - ~50,000 tttt
  - exotic Higgs decays down to BF ~$10^{-6}$
- **HL-LHC allows exploration at both energy frontier and intensity frontier.**



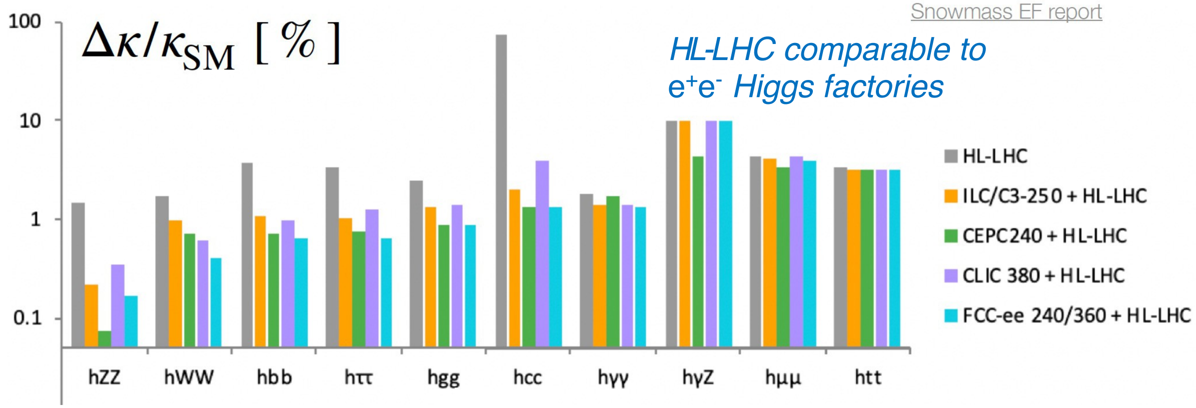
# Physics reach at HL-LHC – Higgs properties

- Higgs boson couplings quantified with precision on tree-level coupling modifiers ($k_i$)
  - 1.5 - 1.8% for couplings to bosons ($\gamma$, w, Z)
  - 1.9 - 4.3% for couplings to fermions (μ, tau, b, t)
  - Coupling to charm difficult due to BR = 2.9% , large background and c-tagging performance: $k_c$ < 1.75 x SM @ 95% CL
  - $BR_{inv}$<2.5% @95% CL: strong constraints on Dark Matter in Higgs portal models
- The main challenge is to reduce systematic uncertainties exploiting large data sets: a thorough work!
- HL-LHC is a Higgs factory, in several cases results will not be improved by future $e^+e^-$ colliders.

CERN-2019-007 (YR18)




Snowmass EF report



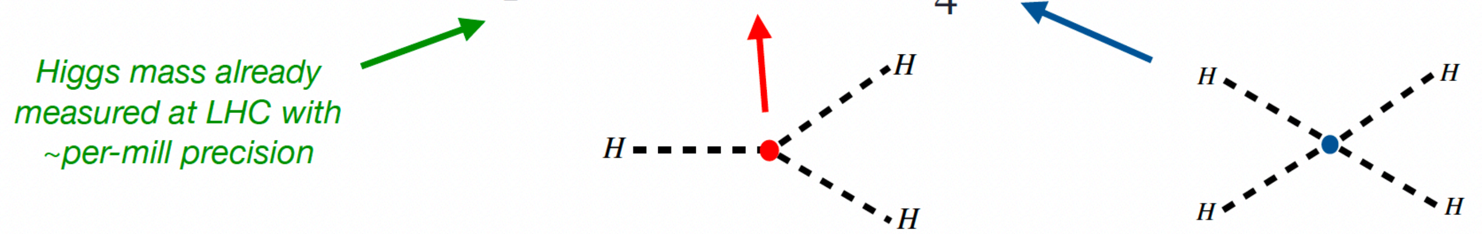

*Main sources: CERN yellow report (2018) updated by Snowmass white paper (2022), further update in preparation for European Strategy.*

# Physics reach at HL-LHC – Di-Higgs

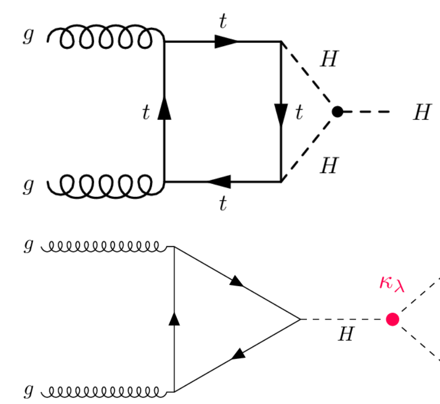
- **Measurement of Higgs potential a science driver for HL-LHC,** largely unconstrained so far.

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4}H^4$$

$$\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}$$




- Single Higgs measurements sensitive to $\lambda$ via higher-order corrections.
- Tri-linear coupling directly accessible via Higgs pair production
  - pp→ HH cross section 3 orders of magnitude lower than single Higgs



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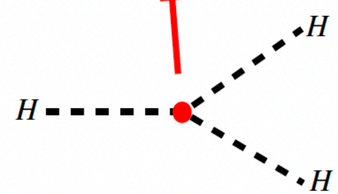
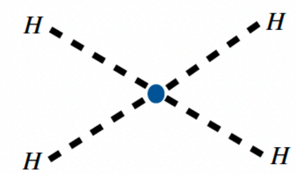
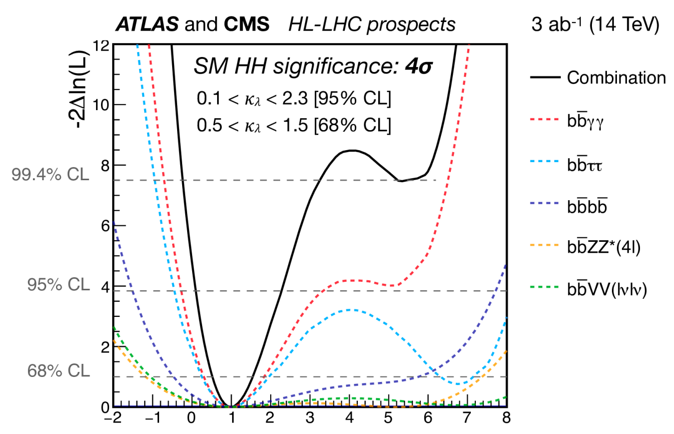
*Higgs mass already measured at LHC with ~per-mill precision*

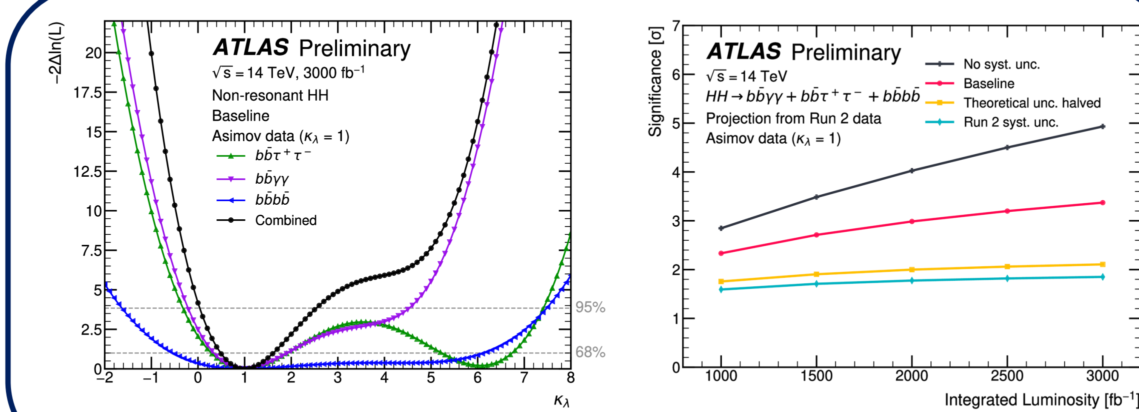



- Snowmass ATLAS-CMS combination expects a 4σ observation (4.5 stat. only)
  - New ATLAS-only expectation (improved after this combination): pp→ HH 3.4σ (4.9 stat only)
  - Expecting improvements from progress on b/tau tagging and ML techniques and reduction of associated systematic uncertainties, we can probably pass the 5σ



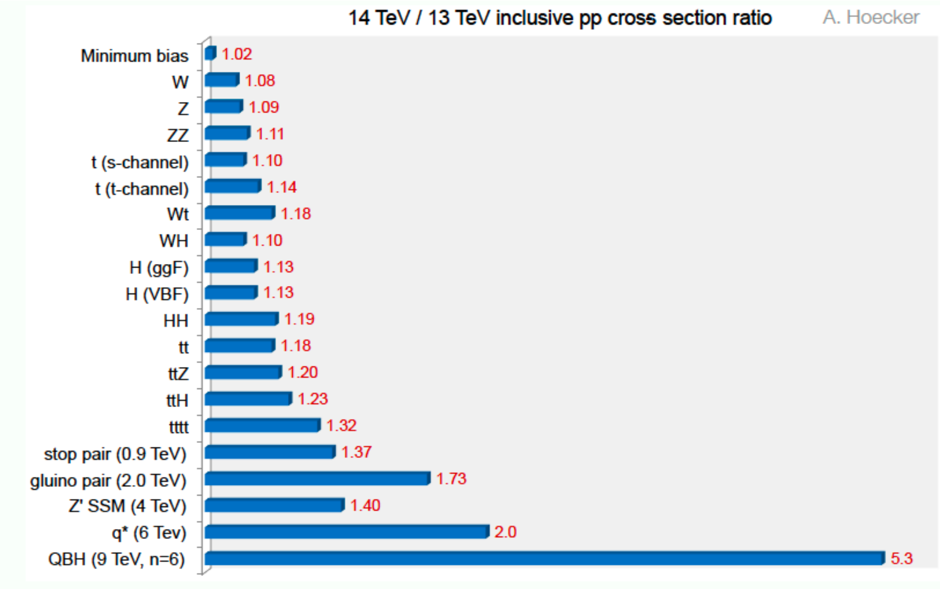

[CERN-2019-007 (YR18)](#)




ATLAS-only update [ATLAS-PHYS-PUB-2022-053](#)

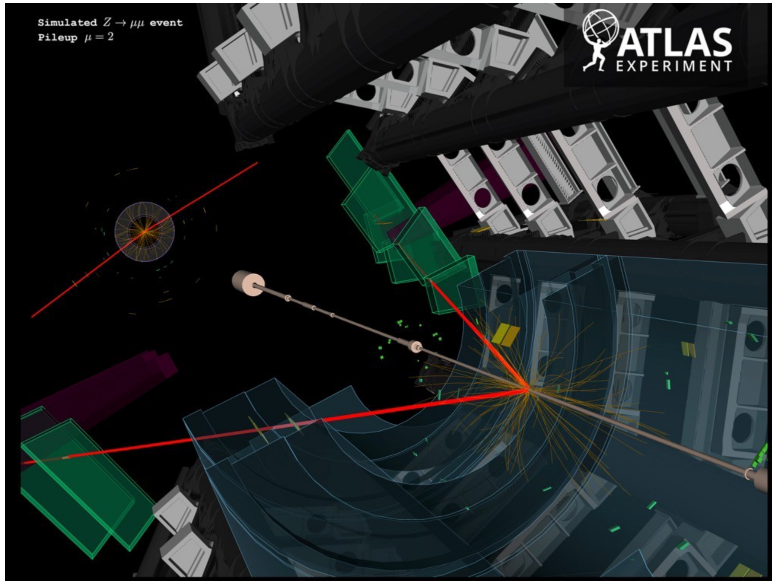
# *Physics reach at HL-LHC – Searches*

- Increase in mass reach for new states just from luminosity is significant (but not huge: cross sections decreases steeply)
  - e.g. Z'SSM from 5.5 → 7 TeV, gauginos 1.1 → 1.6 TeV
- Difference between 13.6 and 14 TeV for resonances with mass close to kinematical limit:
  - e.g. for a 9 TeV quantum black hole cross section increase by factor 5.3
- Expect improvements for LLPs and channels involving b/tau-jets, low-$p_T$ objets, thanks to improved trigger and detector capabilities

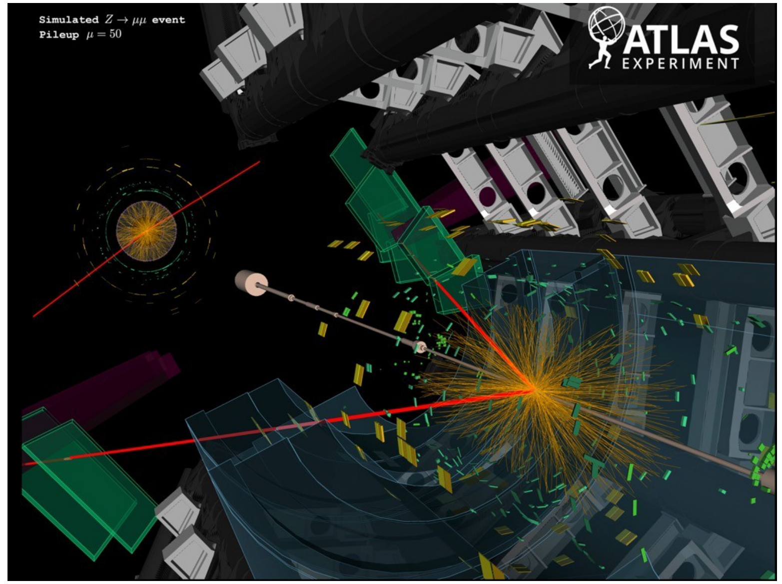


# *HL-LHC detector challenges*

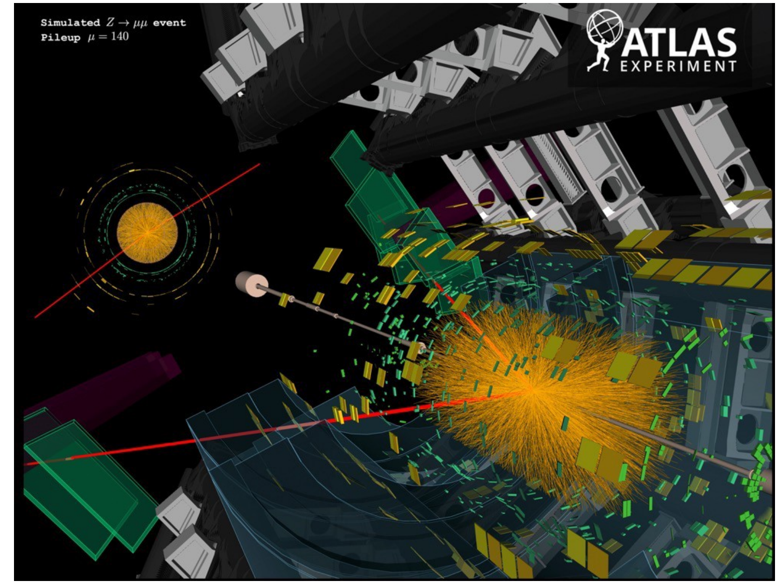
*Pile-up = 2*




*Pile-up = 50*



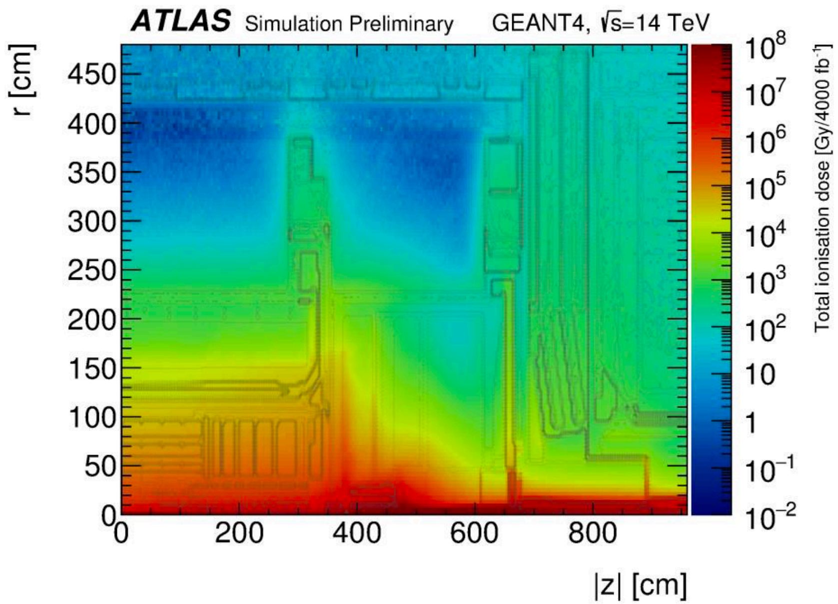

*Pile-up = 140*

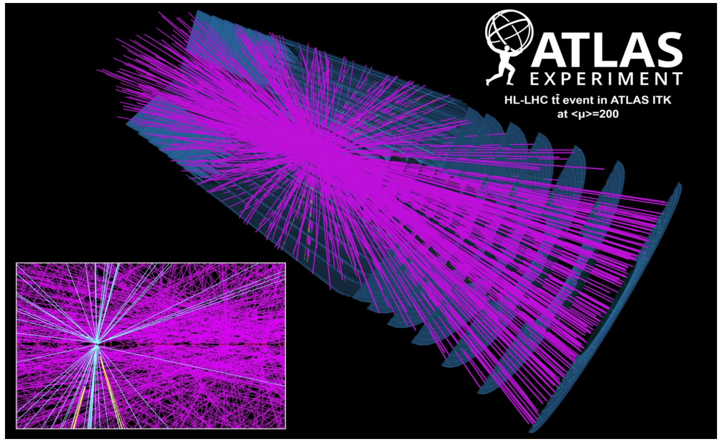



- Need to **upgrade ATLAS experiment** to deal with more “messy” events, and more radiation damage.
- The goal is to keep (if possible, improve) current performance despite new challenges:
  - Measure all relevant final states (leptons, photons, jets, missing $E_T$ , … ) with at least comparable precision as in current run, in a much harsher environment.

# Detector challenges

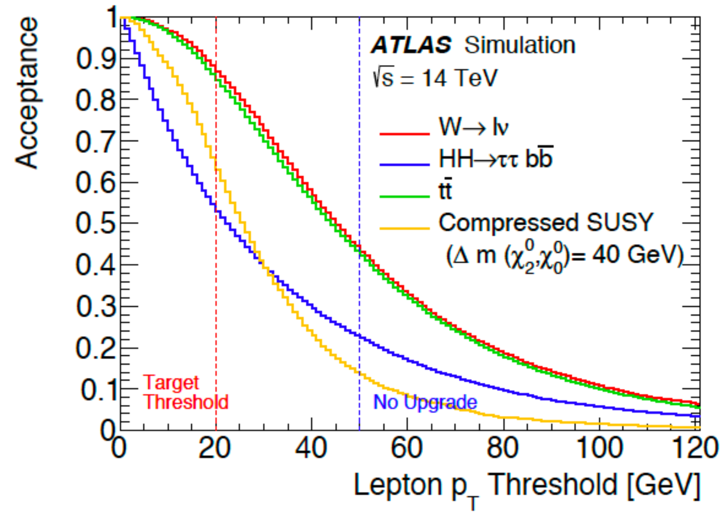
- Radiation damage
  - 4 times larger radiation doses than original ATLAS → Radiation ageing of detectors and electronics (up to 10 MGy, $2\times10^{16}$ $n_{eq}$ $cm^{-2}$ in the tracker innermost layers)
- Pileup is an experimental challenge
  - reconstruct charged-particle tracks in this busy environment, keep **fake** under control
  - distinguish tracks originating from the vertex of the interesting interaction (or from sec. vertices from b decays) from the others coming from pileup vertices
  - Minimize the energy from pileup interactions in the reconstruction of jets, MET, isolation and reject pileup jets



# Detector challenges

- Readout challenges
  - Larger event sizes
  - Hit rates may reach the limits of detector rate capability or saturate readout bandwidth
- Trigger challenges
  - Keep object $p_T$ thresholds low (without increasing rates too much) to fully exploit the high luminosity physics potential
  - Add signatures that have been in part sacrificed in Run2 because of rate limitations e.g. low-$E_T$ multi-jets for di-Higgs searches, low mass di-leptons…
- Experiment lifetime extended from 10 to approximately 30 years:
  - Keep technologies up to date
  - Robustness and maintenance (including sociology)




*Single-lepton signature plays a central role in LHC data analyses*
*The no-upgrade scenario, assumes a ~100 kHz Level-0 output rate, the Phase-I hardware selections unchanged, and rate allocations comparable to those planned for Phase-I.*

# *Detector upgrade design*

- HL-LHC challenges require the **re-design of our current detector** (or at least large parts of it) for our physics programme
  - Higher detector **occupancy**
    - need a detector with higher granularity
  - Higher **trigger** rates
    - redesign of our trigger architecture and readout system for a trigger rate at 1 MHz , i.e. x10 higher, while keeping same lepton $p_T$ threshold
  - Increasing **reconstruction** complexity
    - run more complex software online
    - extend tracking to forward regions (to match forward jets)
    - improve capability to associate tracks to vertices exploiting timing
  - High **radiation** environment
    - need silicon with higher tolerances (eg: Inner Tracker ~ 10e16 $n_{eq}/cm^2$ i.e. ~x10 higher)
    - replacement for electronics
- **A staged approach:**
  - Upgrade towards HL-LHC has started in the Phase-I with inclusion of New Small wheel and the upgrade of the calorimetric trigger

# 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 detector 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.

# Current detector configuration

New detectors

*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). Trigger upgrade

*Hadronic Calorimeter*

steel/scintillator-tile

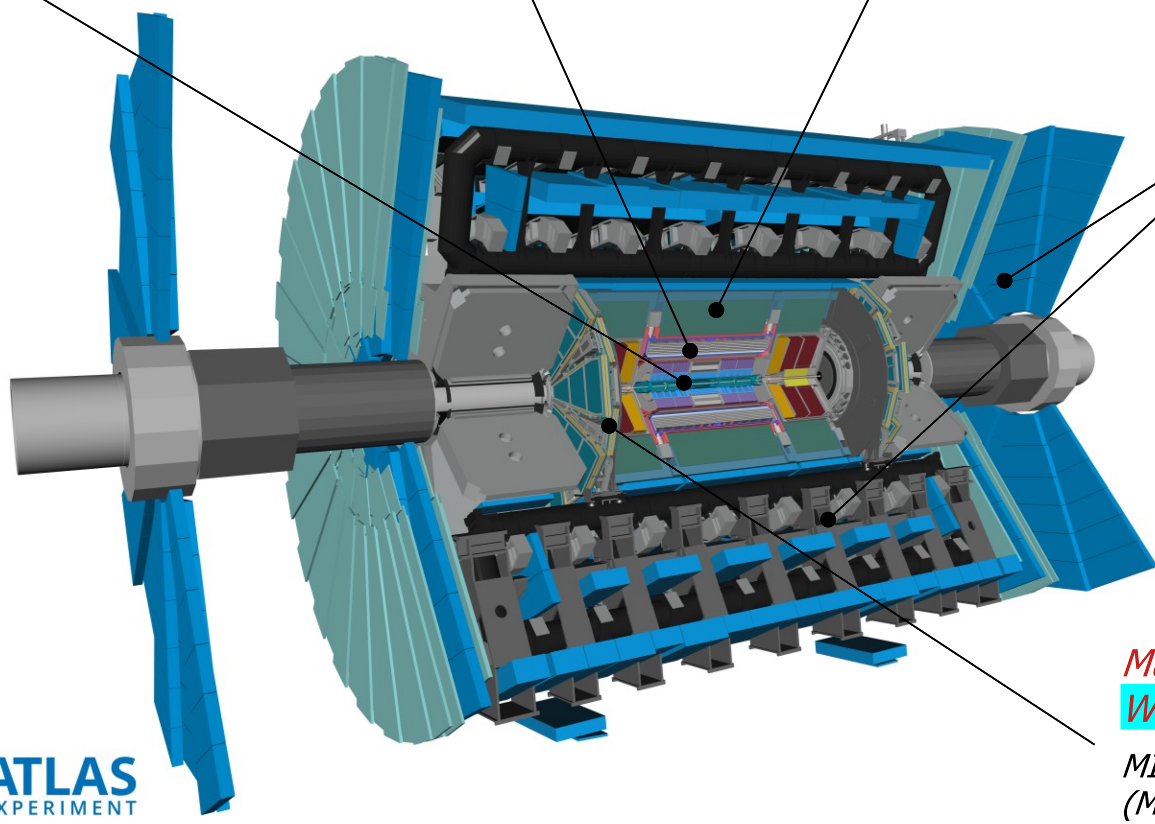
*Muons Spectrometer*

**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

ATLAS EXPERIMENT

*Muons Spectrometer – New Small Wheels in Phase-I*

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

# *ATLAS Phase–II Upgrades*

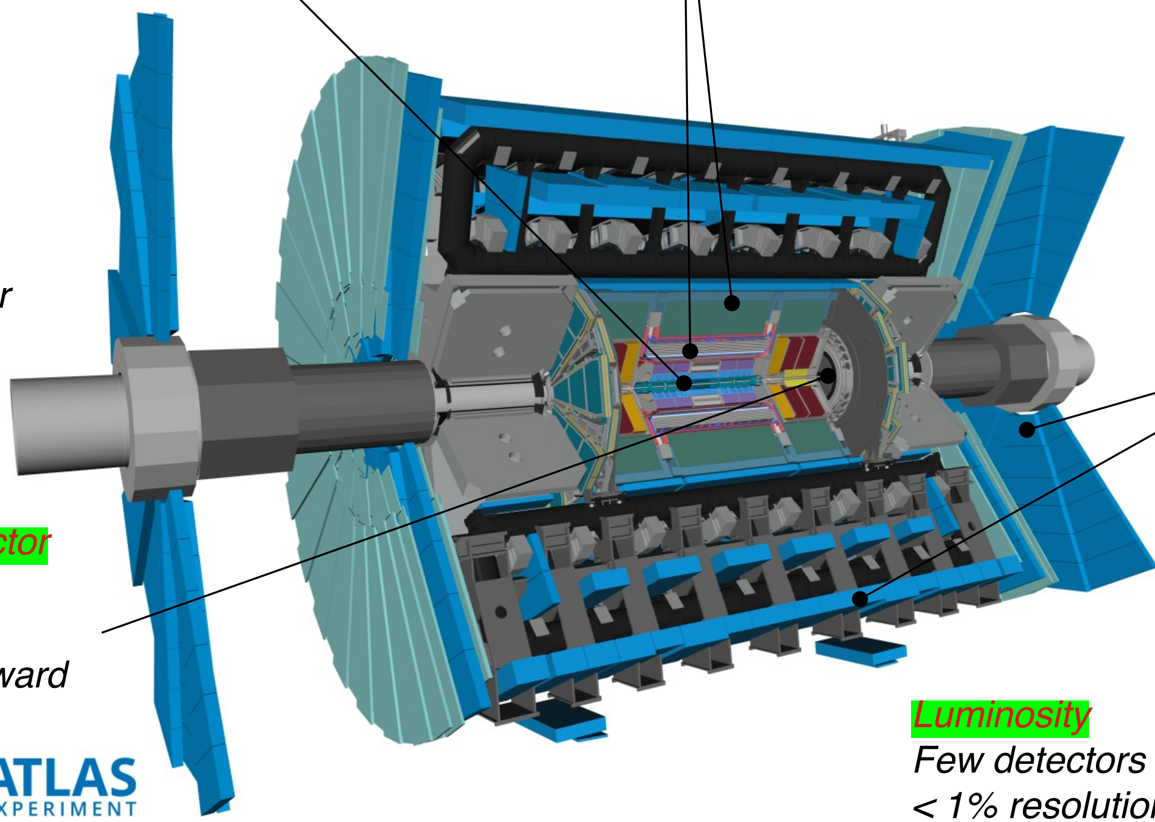
Legacy detectors

New detectors

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

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

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



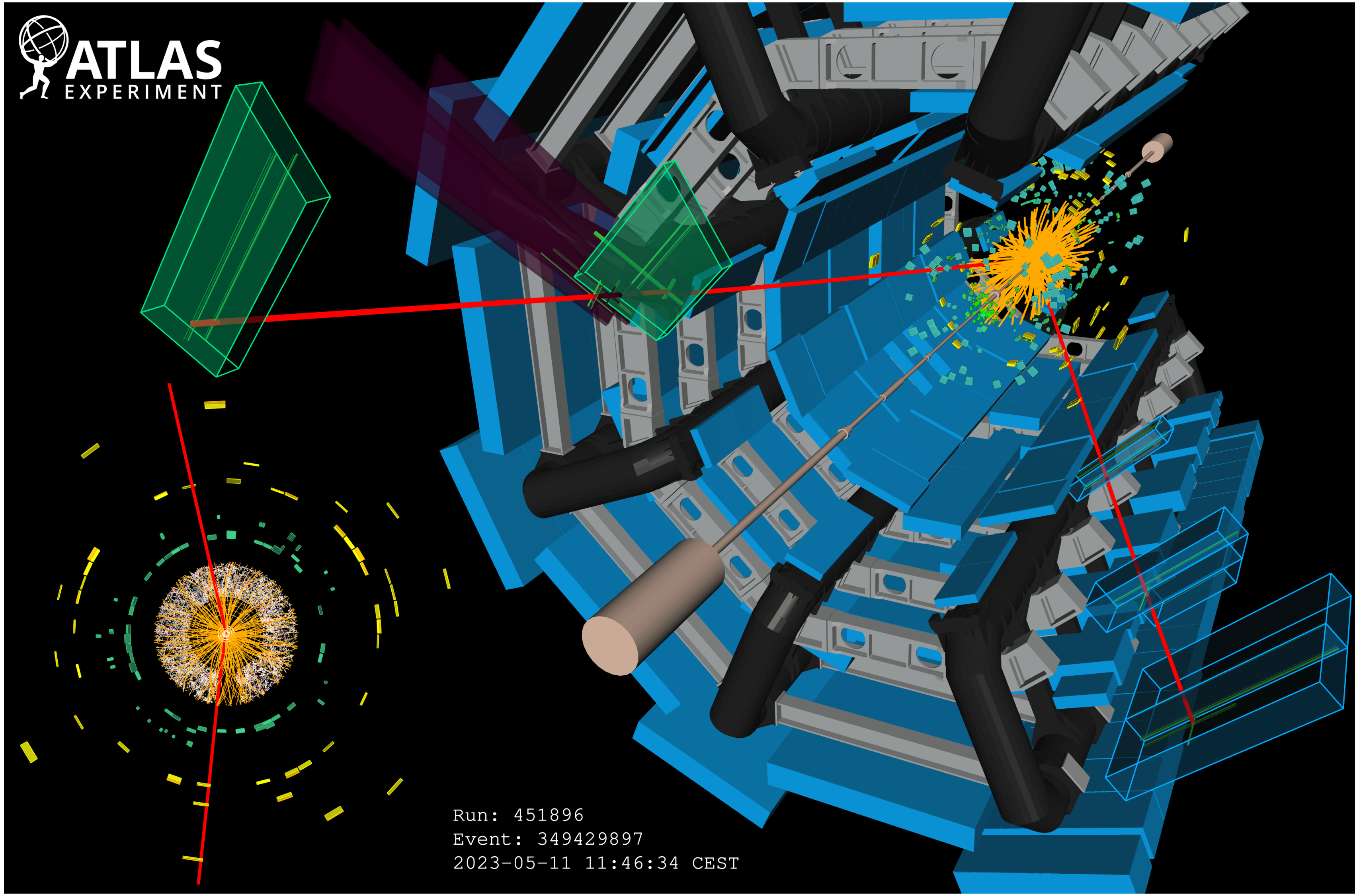
*Muon Detector*
*Upgrade of the detector electronics for new T/DAQ system*
*Upgrade of inner barrel chambers with new RPC and sMDT*
*Improve trigger efficiency and momentum resolution, and reduced fakes*

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

ATLAS EXPERIMENT

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

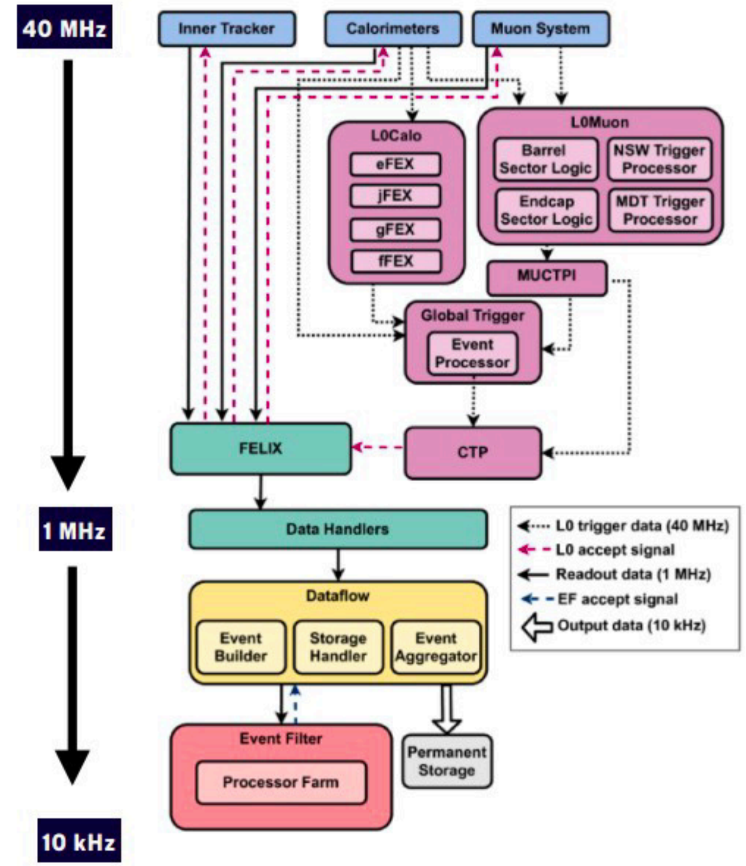
# Subsystems


ATLAS
EXPERIMENT
Run: 451896
Event: 349429897
2023-05-11 11:46:34 CEST

# Trigger and DAQ

- Huge increase in data rates and thus data throughput, bringing extra complexity!
- **TDAQ has 3 systems,** updates
  - **Hardware based Level-0:** Trigger data input at 40 MHz from Calorimeters and Muons.
    - Output Rate of L0Accept 1 MHz (100 kHz in Run3), latency 10 µs (2.5 µs in Run3)
    - Exploits full detector granularity with new Global Trigger component
  - **DAQ updates**
    - Completes event-data from all detectors at 1MHz
    - 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.
  - **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).

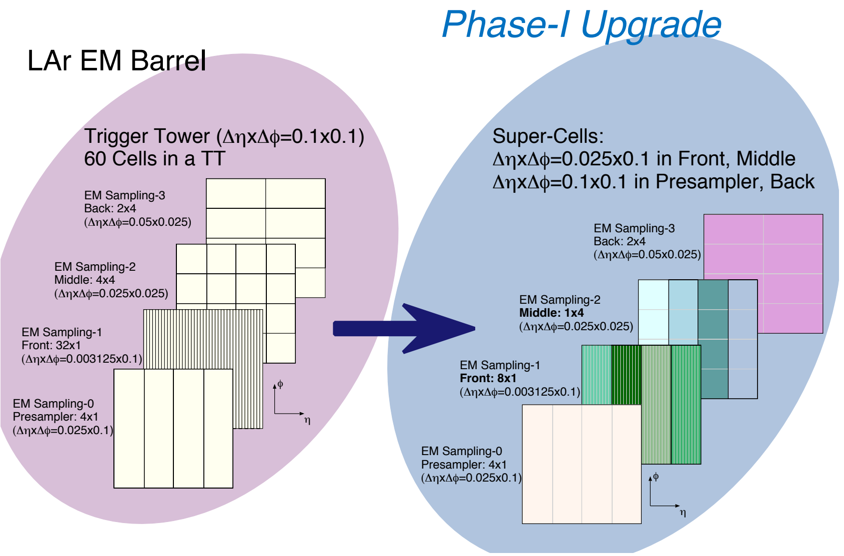
*New TDAQ architecture*




*FELIX Prototype*

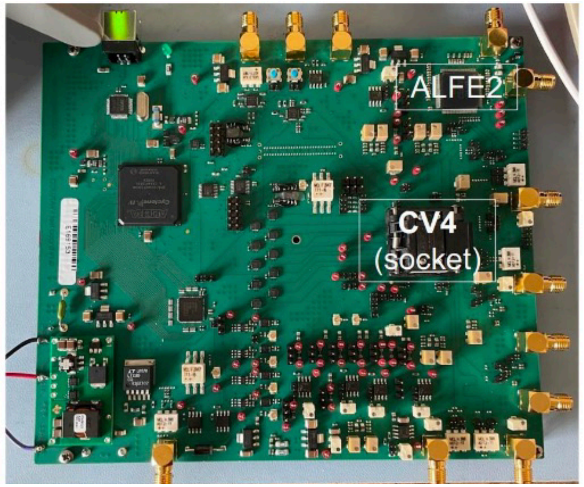
# Electromagnetic Calorimeter

- 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: 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



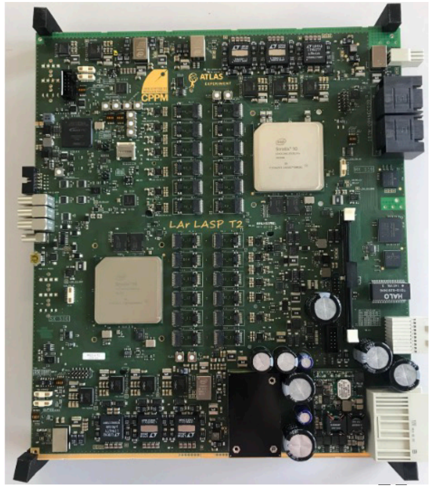

*FEB2 prototype*

*Pre-production wafers of FE Board ASICs received*




*LASP demonstrator*

*under test*

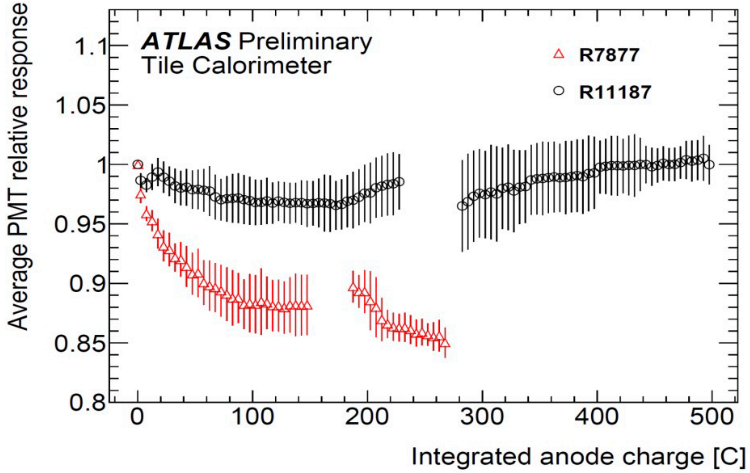


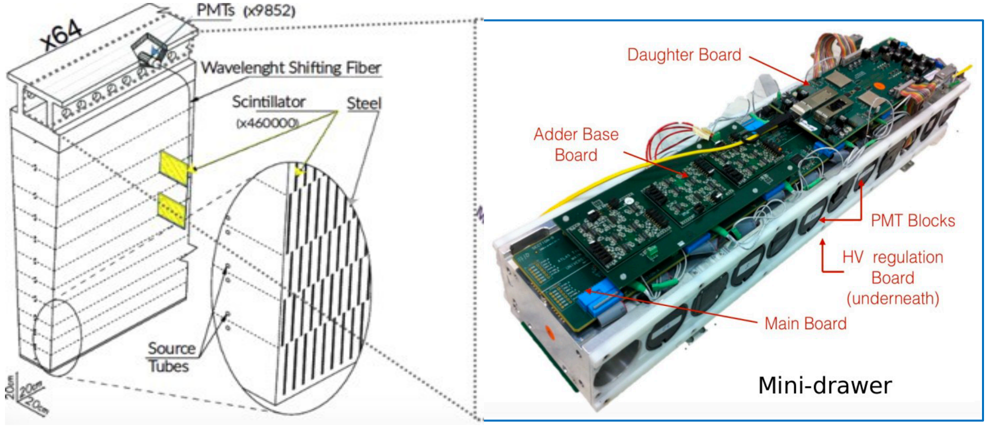
# Hadronic Calorimeter

- 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*

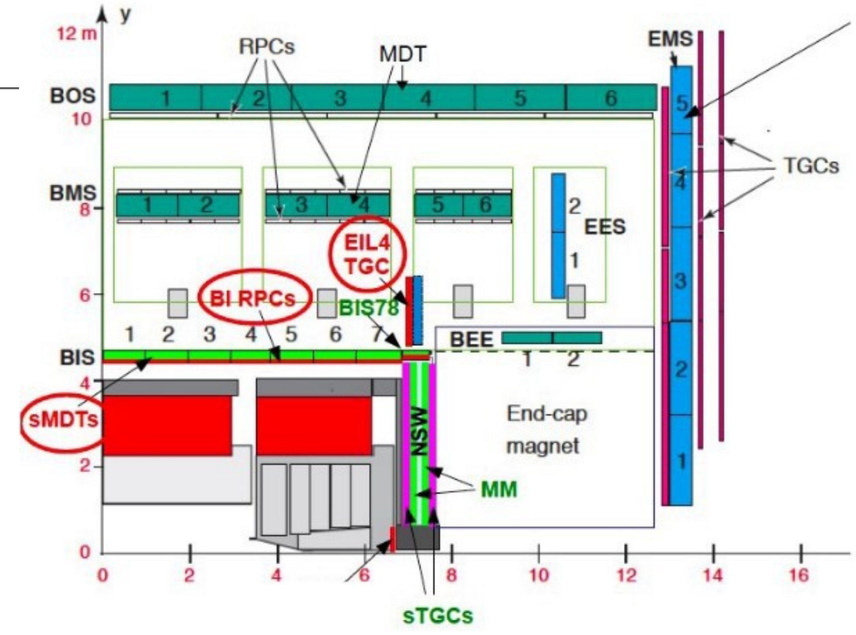


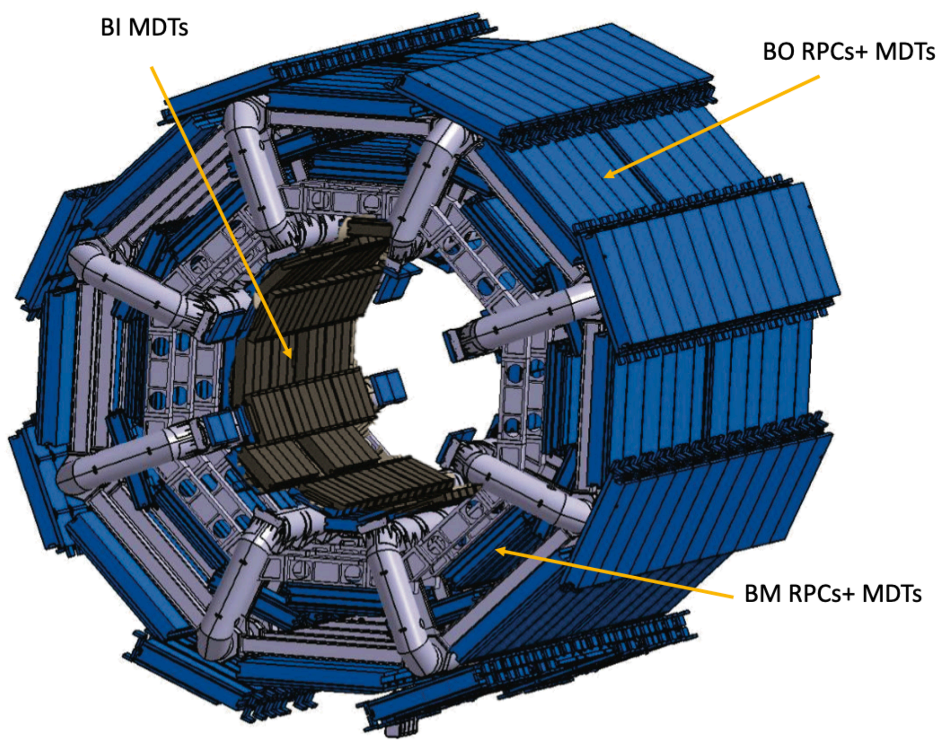

*New modular mechanics*

# 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** data be included in L0 trigger.




## Additional Barrel Layers of sMDT, RPC, and TGC

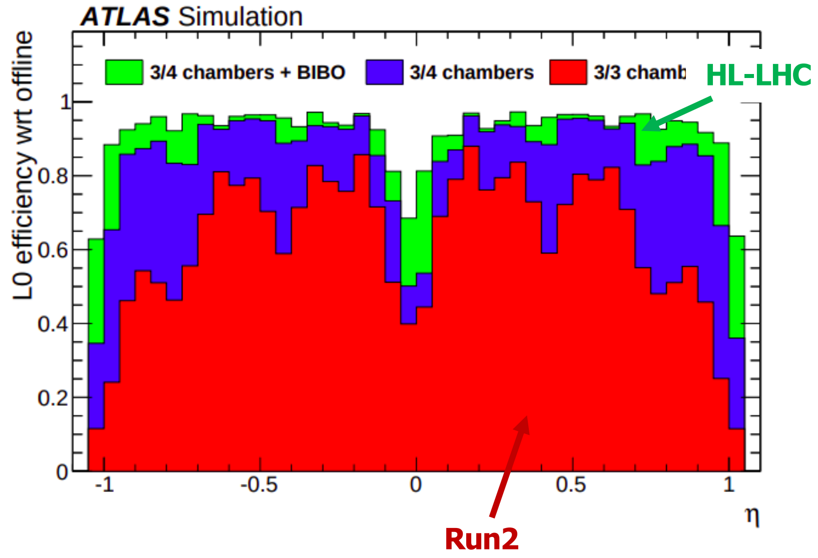
- New **RPC** triplets in the inner layer (to improve trigger coverage and efficiency)
- New **sMDT** BIS chambers with smaller diameter (to make space for the RPC)
- New **EIL4 TGC** chambers (to improve trigger rejection)

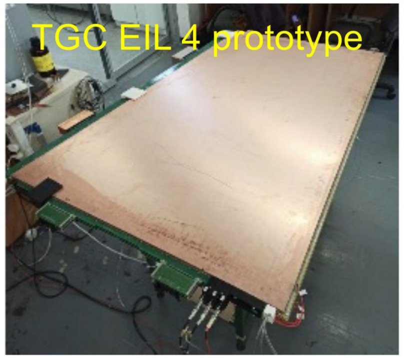
# Muons Spectrometer

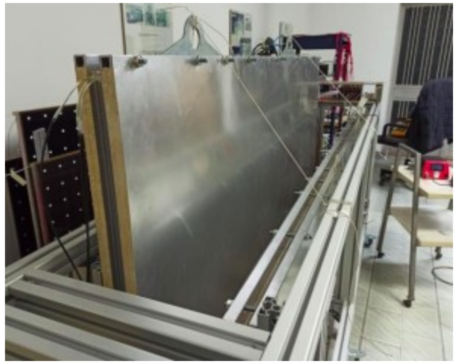
*MDT: Monitored Drift Chambers*
*RPC: Resistive Plate Chambers*
*TGC: Thin Gap Chamber*

- Current status
  - sMDT production finished, chambers at CERN for integration.
  - RPC gas volume production is restored at vendor after addressing gas leaks related to not optimal design.
  - RPC FE electronics (ASIC and DCT) decision to be taken after completing RPC+ FE electronics + Cable + DCT tests.
  - Production of TGC (EIL4) and TGC electronics is moving along.

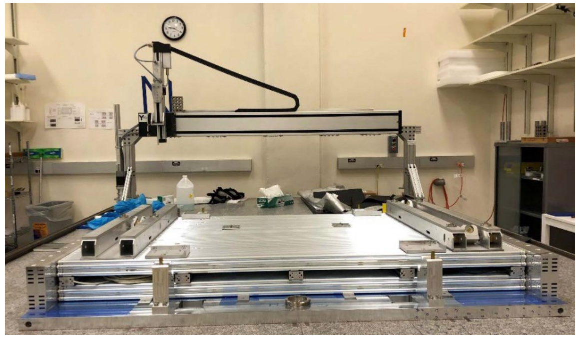
*L0 efficiency x acceptance*
*for reconstructed muons $p_T$ >25 GeV*



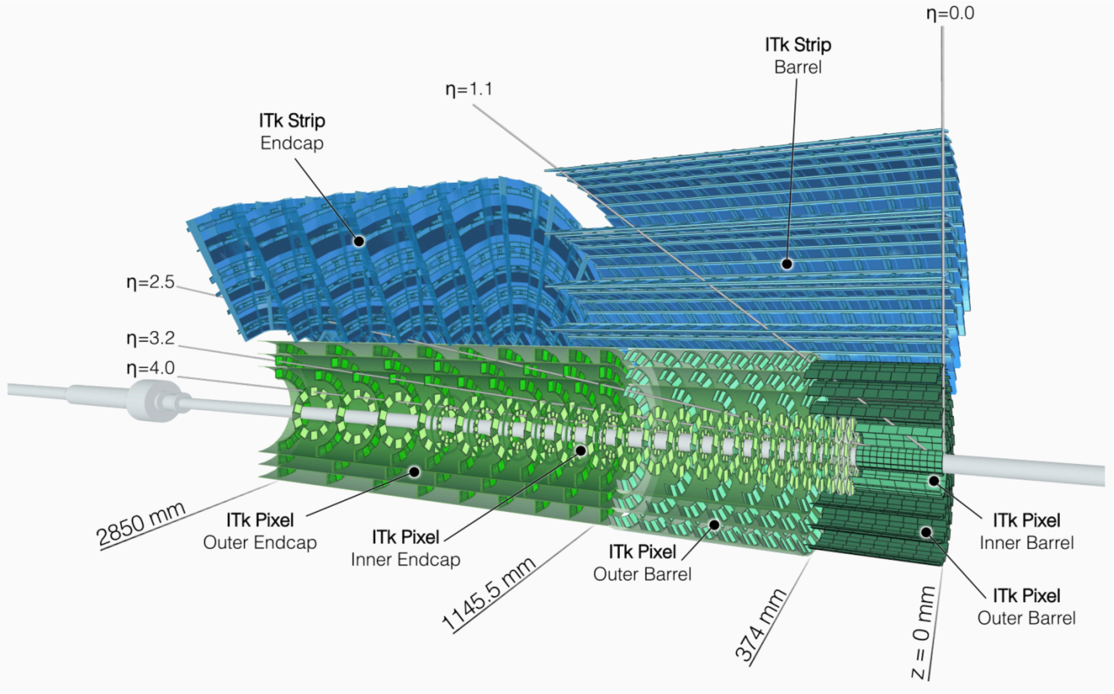
*RPC prototype*



*sMDT*

# A new tracker system: ITk

- Complete replacement of the current Inner Detector with an all-silicon detector in 2T magnetic field.



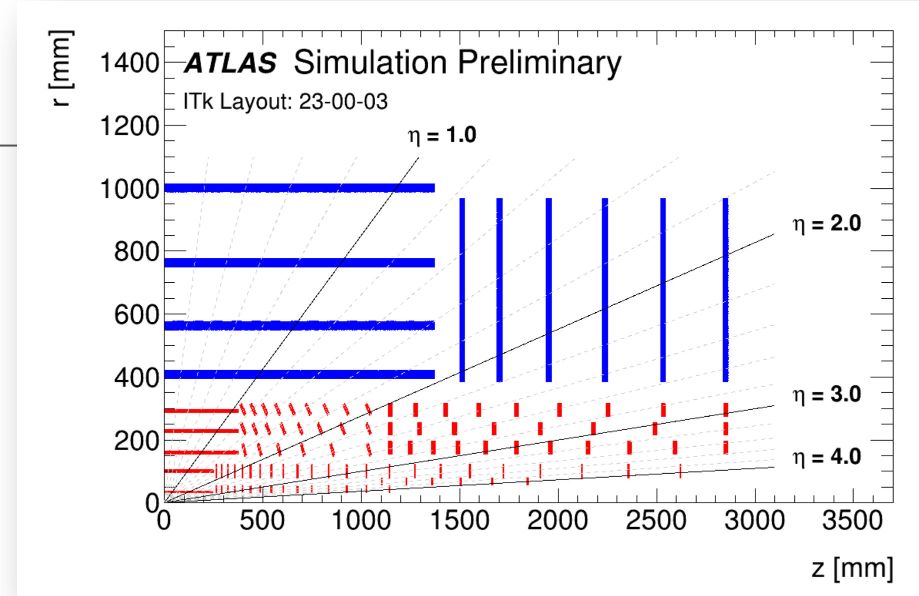

- 4 **strip** and 5 **pixel** barrel layers + 2x6 **strip disks** and several **pixel ring** layers
- Overall dimensions: ~ 6 m length and 2 m diameter.
- Angular coverage increased from |η| = 2.5 to 4

| | Surface [$m^2$] | # Channels | # modules |
|---|---|---|---|
| **Strip** | 165 | 60 M | 18 k |
| **Pixel** | 13 | 5.1 G | 9.2 k |

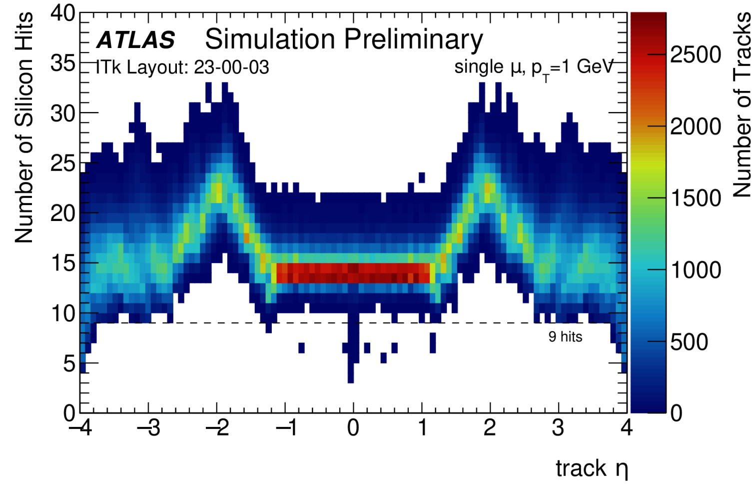
- Overall significant improvement thanks to:
  - Reduced material budget → minimize material interactions
  - Finer segmentation → improved resolutions
  - Increase in overall hit counts, at least 9 silicon hits per track, and improved hermeticity → tighter track selection

# A new tracker system: ITk

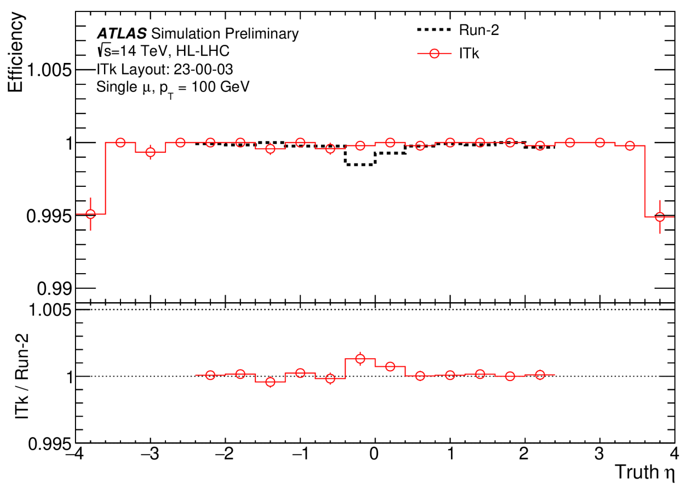
ATL-PHYS-PUB-2021-024



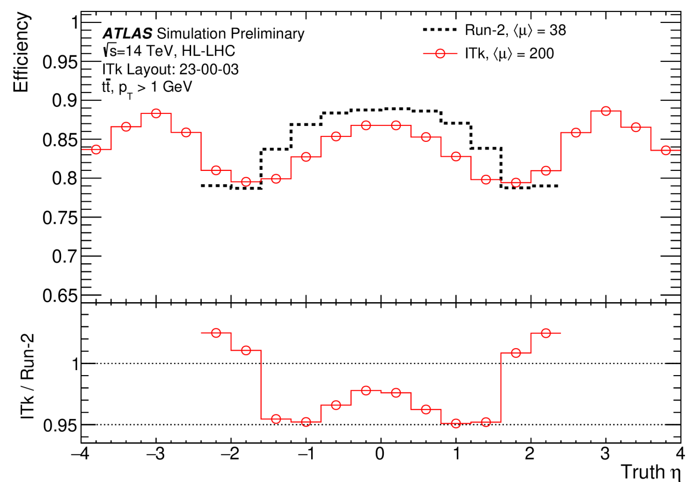

*Number of Si hits on track*



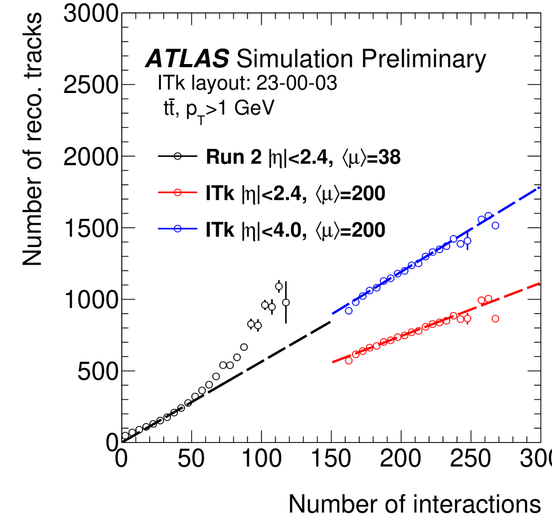

*High $p_T$ Muon Tracking efficiency*




*Tracking efficiency in tt*



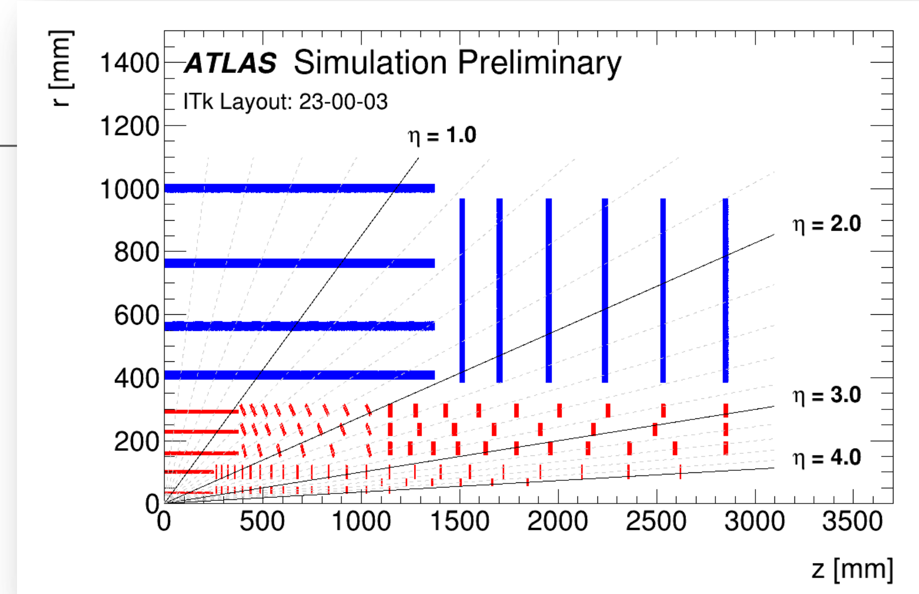

*Vertex reconstruction*



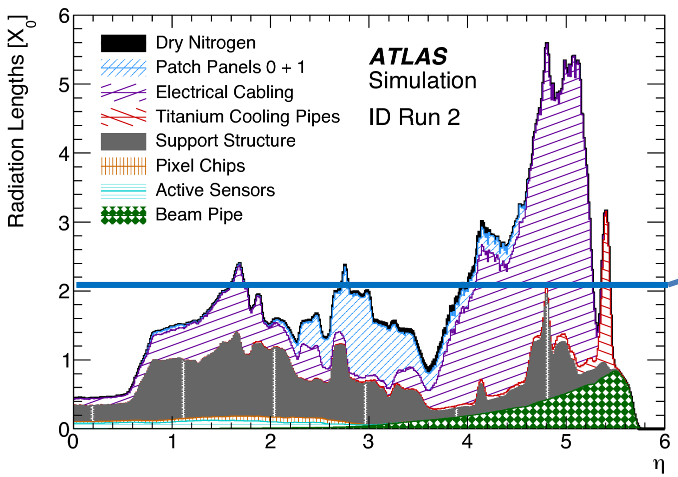
# A new tracker system: ITk

[ITK-2023-001](ITK-2023-001)

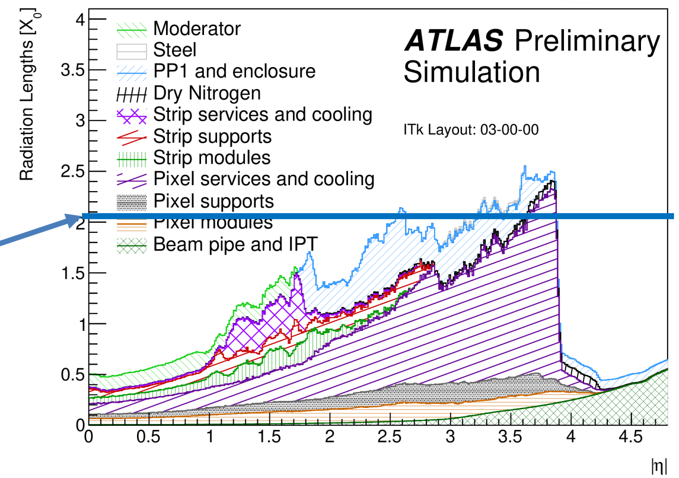
- Reduce the material as far as possible
  - Evaporative $CO_2$ cooling system with titanium pipes
  - Light carbon structures (mechanical stability) and radiation-hard
  - Usage of optical links wherever possible
  - Reduction of services for the detector

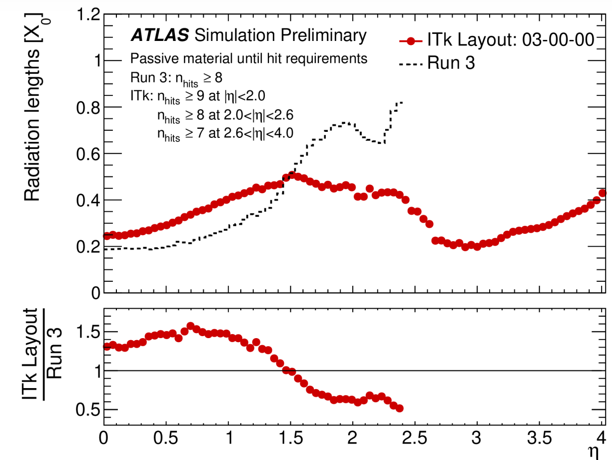



Material thickness in Radiation lengths




CERN-LHCC-2017-005



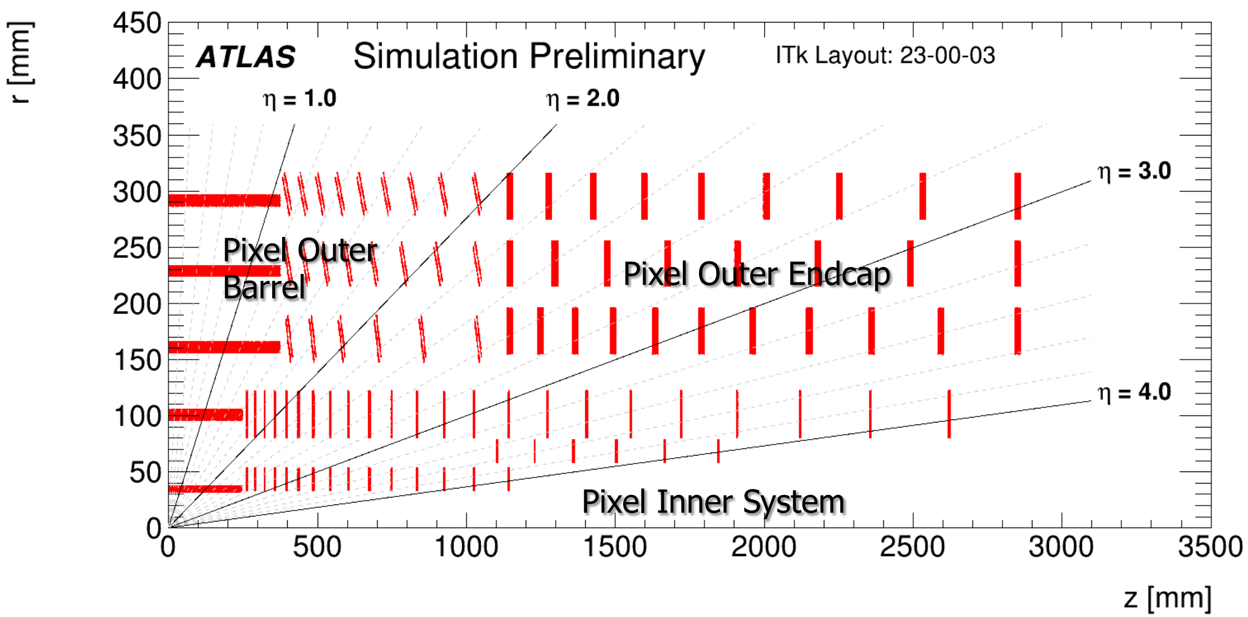




*Material thickness in radiation lengths (X0) seen by particles until reaching the minimum number of hits required for track reconstruction (at least 8 silicon hits on a track in Run3, while the ITk reconstruction requires at least 9 hits for |η|<2.0, 8 for |η|<2.6 and 7 otherwise).*

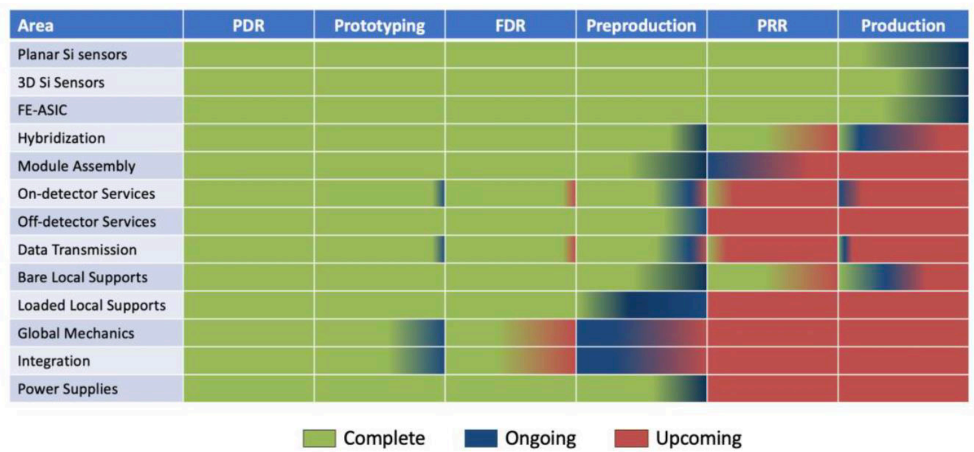
# ITk Pixel



- General characteristics:
  - Organized as **three sub-systems**:
    - Inner system  (IS) will be **replaced** at half lifetime due to radiation hardness.
    - **IS** built in US, Outer Endcap **OEC** in UK/Italy, Outer Barrel **OB** integrated at CERN with parts from France, Germany, Japan, Switzerland.



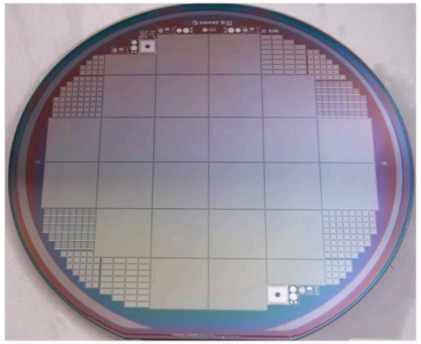

- Status of the project:
  - Preproduction completed for the majority of the objects ...



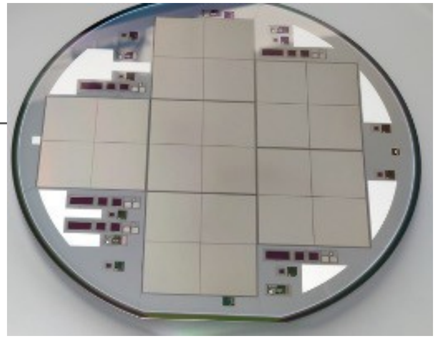
# ITk Pixel

- Sensors - all in production
  - **Pixel cell size** is 100x25 µm² in L0 barrel and 50x50 µm² (everywhere else)
  - **3D sensors** in innermost layer – due to better radiation hardness. Single tile.
    - SINTEF (Nw) 50x50 and FBK (Italy) 100x25 and 50x50
    - Radiation tolerant up to ~2E16 $n_{eq}/cm^2$
  - **Planar** n-in-p sensors in other layers: **100 $\mu$m** thick in L1, **150 $\mu$m** thick elsewhere. Quad tiles.
    - HPK (Japan): ~90% of 150$\mu$m
    - MICRON (UK): 10% of 150$\mu$m and ~~60% of 100$\mu$m~~ [cancelled due to leakage-current stability issue → Fewer100um sensors required due to switch to 150um in Layer-1 rings
    - FBK (Italy): 40% of 100$\mu$m

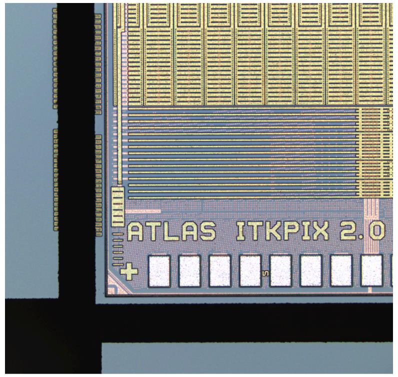
*Sintef 3D wafer*



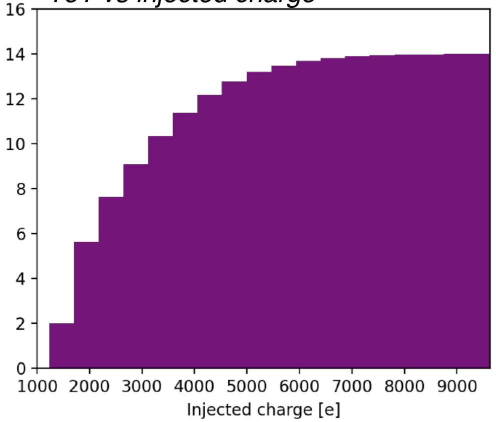
*HPK planar wafer*



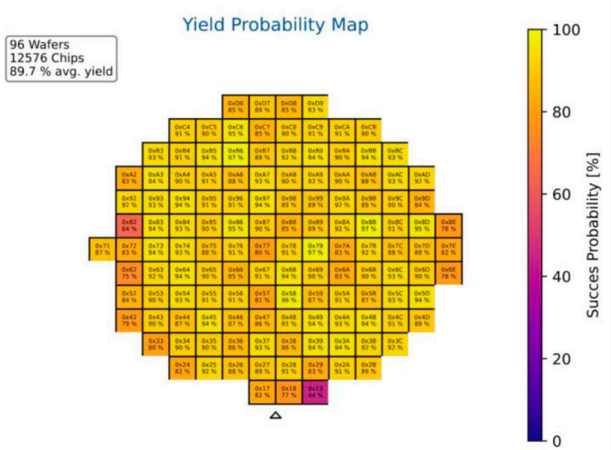
*ITkPixV2*
*Picture of a corner*




*ITkPixV2*
*ToT vs injected charge*



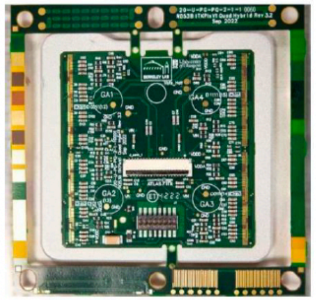

- Front-End ASIC: ITkPixV2 in production
  - Largely delivered. Wafer testing ongoing with high yield (~90%)
- Hybridization:
  - 2 out 4 hybridization vendors (HPK and IZM) are in production
  - Two more have technical issues and we working with them: Advafab and Leonardo.



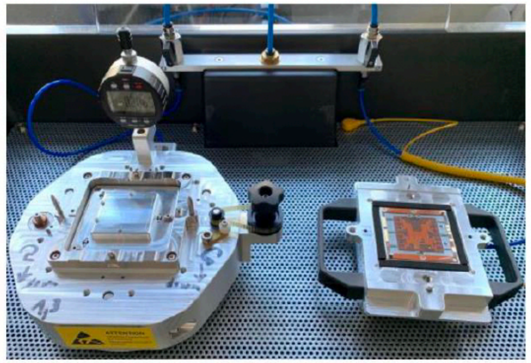
# ITk Pixel

## Quad Modules – Outer System (L1-L2-L3-L4)

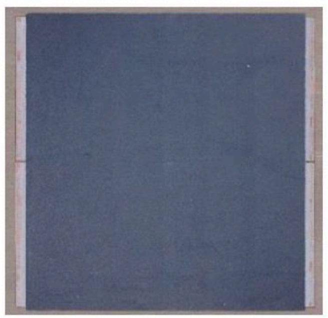
Flex Quad



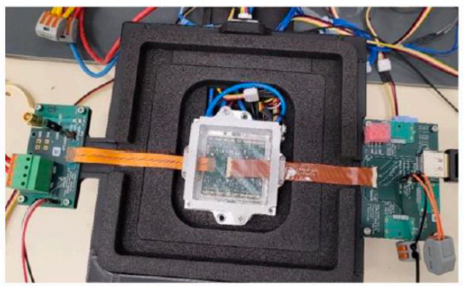
Assembly jig



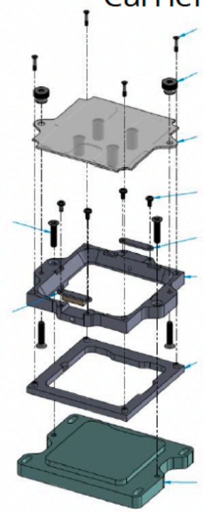
Bare Module

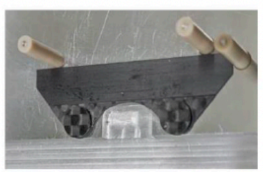


Testing



Carrier

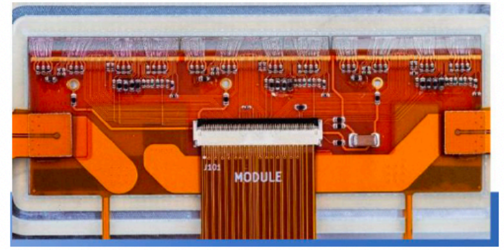




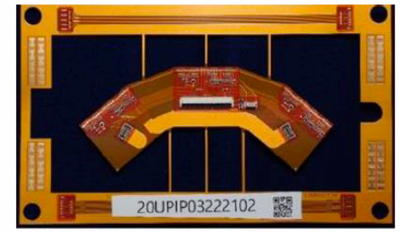
OB wire bonding protection

## Triplet Modules – Innermost layer

Linear Triplet

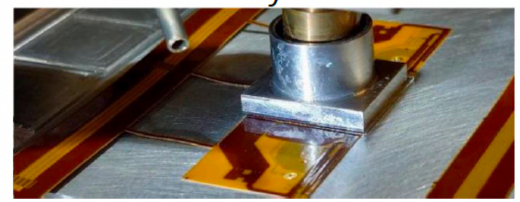



Flex Triplet

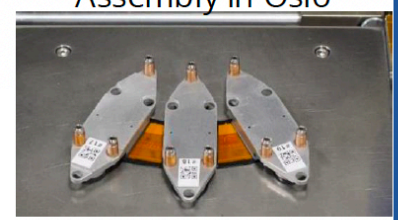



Bare Modules

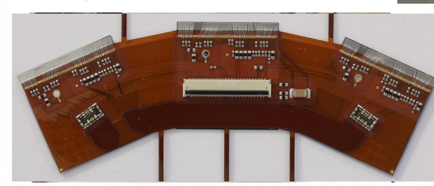
Assembly in BCN



Assembly in Oslo



Ring triplet in Genova

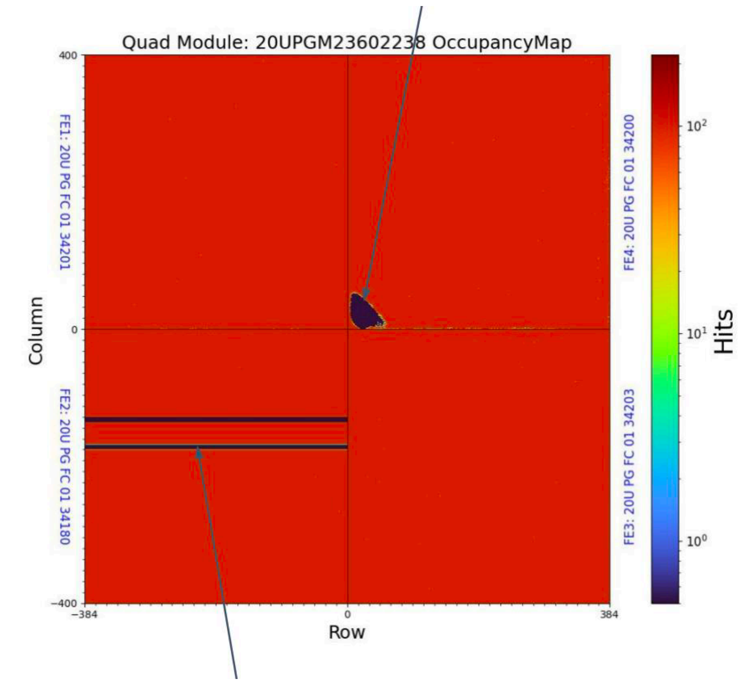


*Assembly in 16 sites and Test in 23 sites, organized in national clusters*

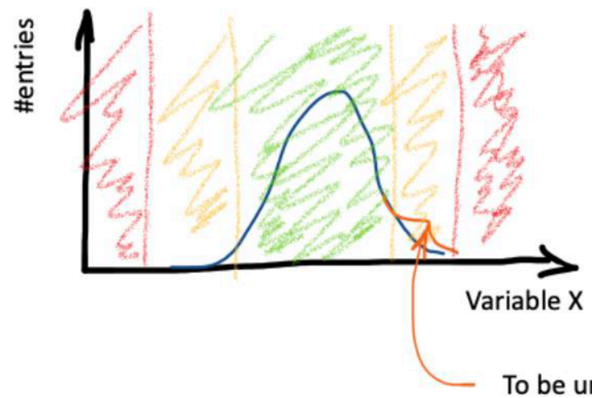
*Assembly in 4 sites and Test in 7 sites, in Italy, Spain and Norway*

# *ITk Pixel*

- Modules is entering production with some concerns
- The "**Core Column (CC) Issue**" refers to the observation that unless specific core columns (1 core column is about 2% of the Chip) are disabled the chip will malfunction when operated → **Task force** including CMS and RD53 members
  - Rate is lower (~9% for V2 vs. ~25% for V1) but not negligible
  - **Preliminary conclusion:** The **CC issue** is introduced via **mechanical damage** to the chip during the hybridization process (dicing/flip-chip?), that leads the complex circuitry to fail in a severe way.




- Quantify the yield of the module production → Yield Task Force.
  - Review the cuts applied in the module QC, and re-estabilish the ones deemed important for the final module operation. This review affects cuts on bare modules, assembled modules and electrical tests.
  - For the latter, needed to determine procedure to qualify how a module will work in a SP, without operating it in a SP chain.

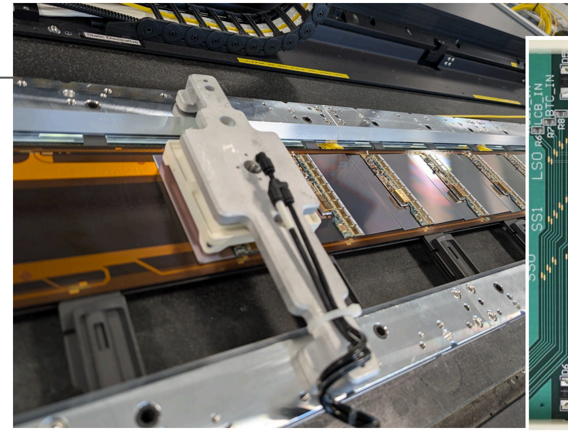


New Systems

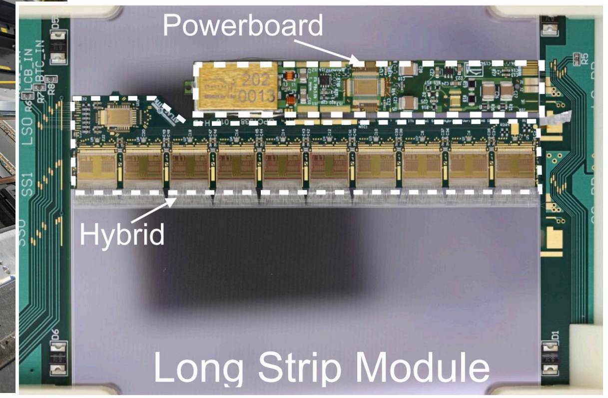
# ITk Strip

- **General characteristics:**
  - Organized as two systems (Barrel and Endcaps)
    - Strip subsystem covering up to **|η|<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
  - Modules production halted for a long time
    - Issue with **large noise when operating cold** slowed down the preproduction for several months, finally understood as caused by vibrations of capacitors on power boards.

Barrel Stave

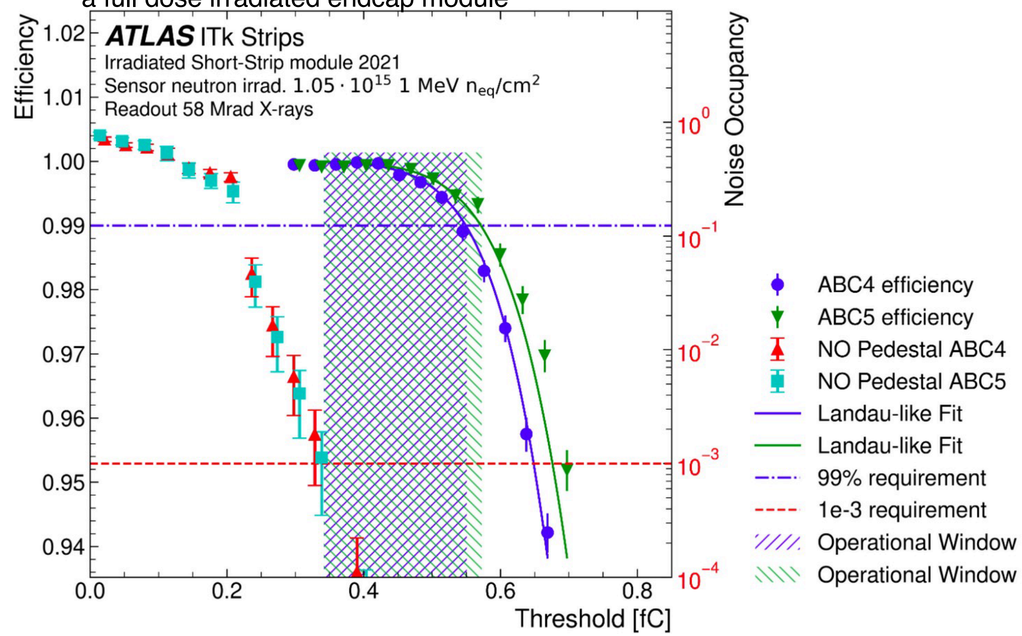


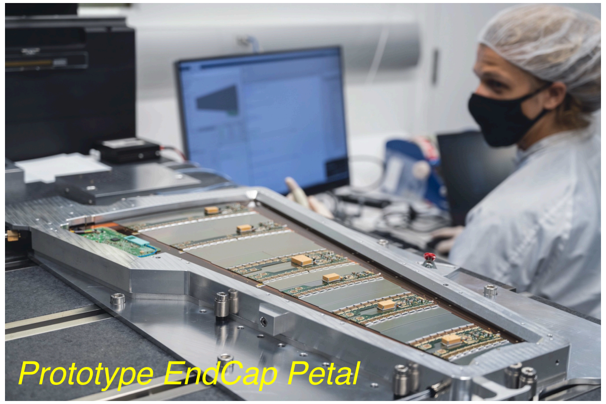
Barrel Module



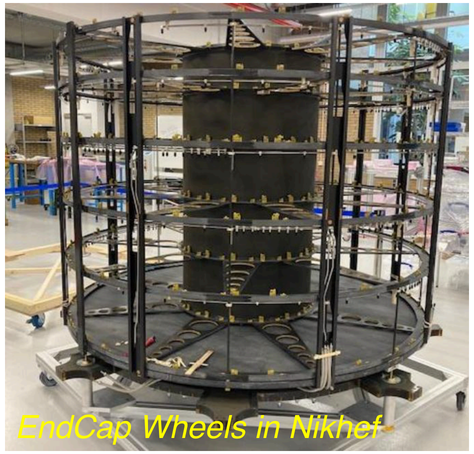

Efficiency and Noise Occupancy

a full dose irradiated endcap module



Prototype EndCap Petal

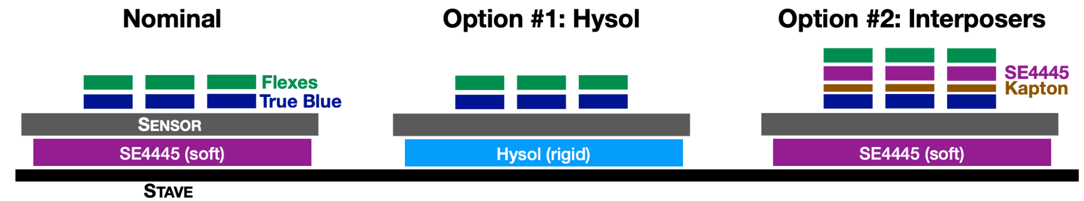


EndCap Wheels in Nikhef

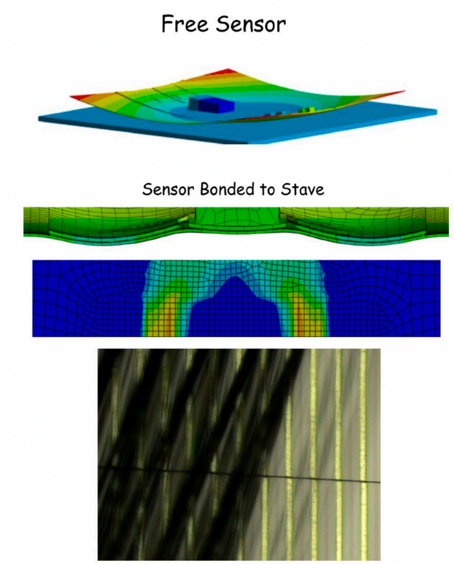
n-in-p sensors, ~320 μm thickness by HPK;
8 different sensor types (2 barrel, 6 end-cap)

# ITk Strip

A barrel strip module

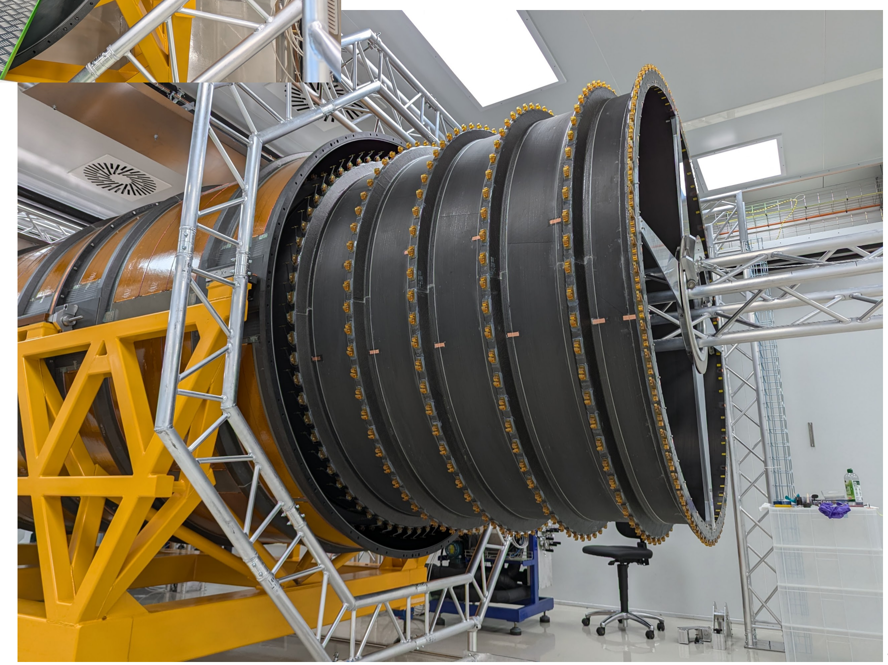




- Early Breakdown (Cracking)
  - Modules are silicon sensors glued to carbon fiber local supports below and PCBs (both readout and power) above. Upon deep cooling stress builds due to mismatching coefficients of thermal expansion → physically crack sensor, *only happens when sensor is constrained both to flexes above and stave/petal below.*



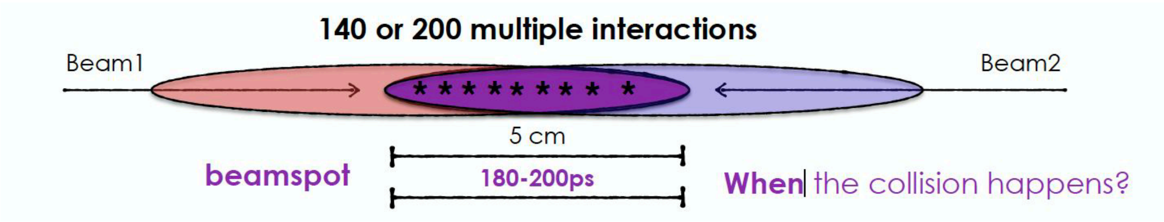

- The interposer decision.
  - Decouple the PCB from the sensor mechanically with an interposed layer (Kapton and soft SE4445 glue) →Requires adding a delicate step to a critical activity → cause for production delays.
  - 1.5 interposed Staves and 1 interposed petal have been constructed and no cracks are observed down to -70° C / -55° C
  - Barrel module **production relaunched** in November; Endcap is still evaluating a glue-only solution (*interposers for endcap modules is far more complex*).

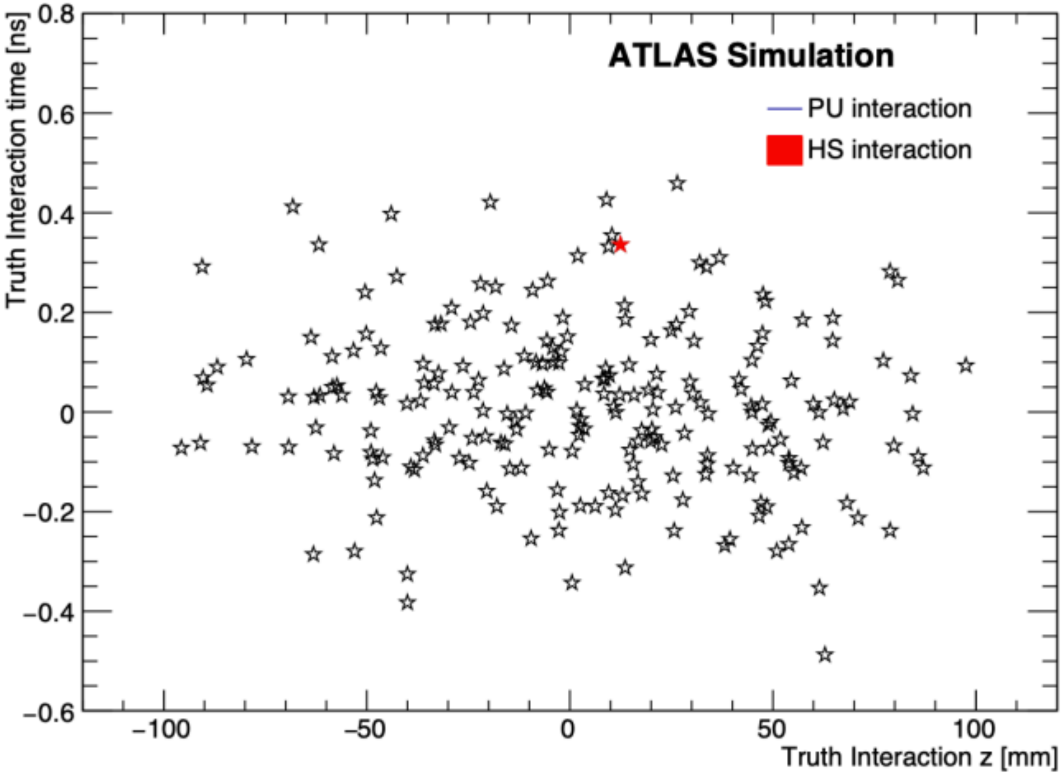
# *ITk integration being prepared at CERN*



- Outer Cylinder received, assembled and delivered to SR1 in June
- Polymoderator tiles installed in July
- Layer 3 inserted July, Layer 2 and all mount brackets for L3/L2 support installed in September

# Adding time into the game!

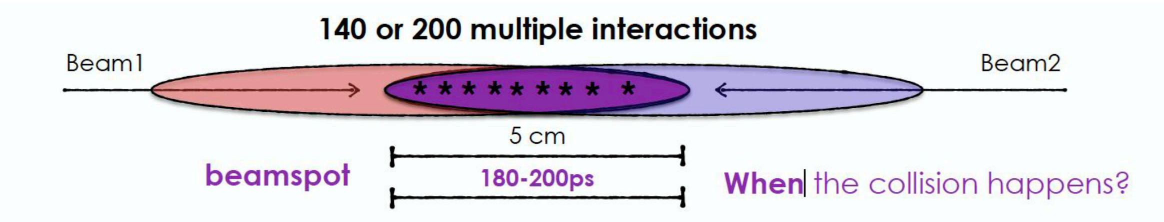


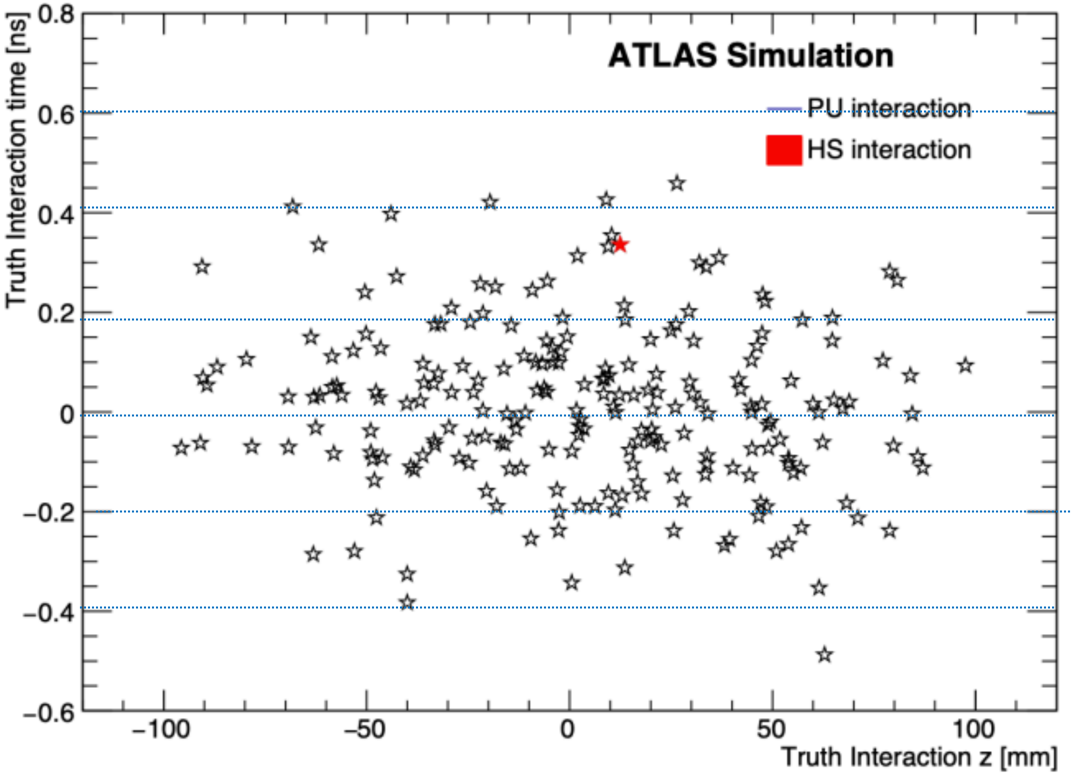




*Longitudinal Primary Vertex distribution vs time*

- Inside a bunch crossing, interactions spread longitudinally but also in time.
- In very high pileup density, timing can be exploited to resolve p-p interactions, i.e., to help associate tracks to vertex.

# Adding time into the game!



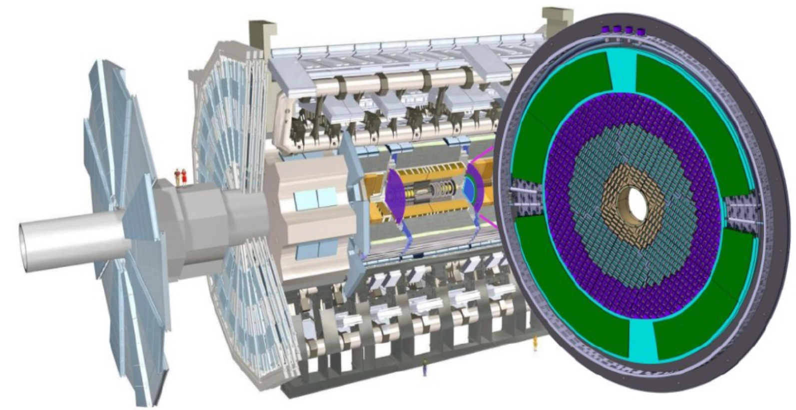




*Longitudinal Primary Vertex distribution vs time*

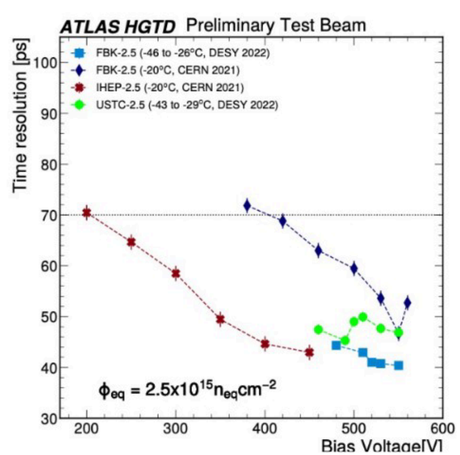
- Inside a bunch crossing, interactions spread longitudinally but also in time.
- In very high pileup density, timing can be exploited to resolve p-p interactions, i.e., to help associate tracks to vertex.
- Therefore, assigning a **time to tracks with a good resolution** allows to better reconstruct and identify pile-up vertices.

# High Granularity Timing Detector (HGTD)

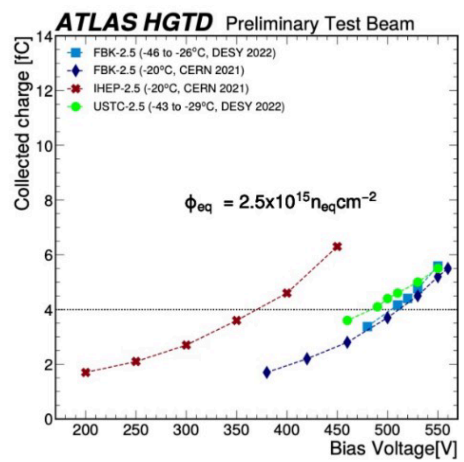
- HGTD designed to improve ATLAS performance in the **forward region**.
  - **Provides timing information to tracks**
  - **improves in areas where resolution of tracker-only tracks is degraded**
  - Also provides **luminosity** information.
- Silicon detector modules mounted on disks.
  - Two disks/side, 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 to maintain adequate time resolution.



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



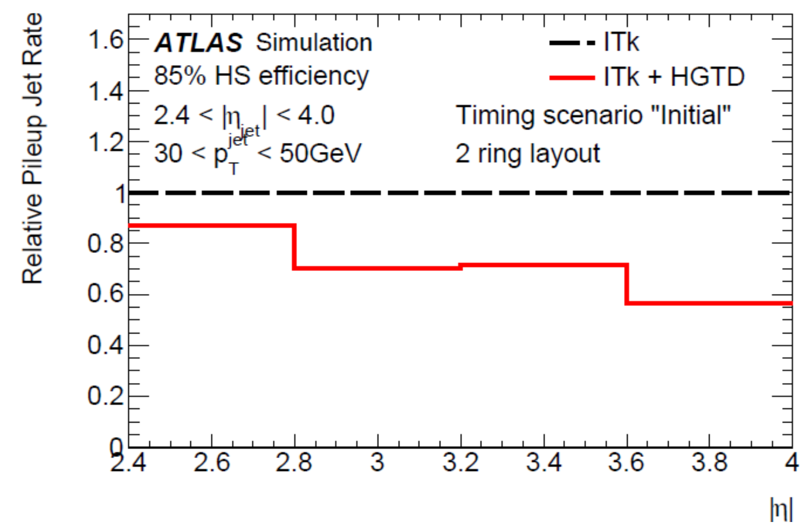

*Hit Time resolution vs Bias*




*Collected charge vs Bias*

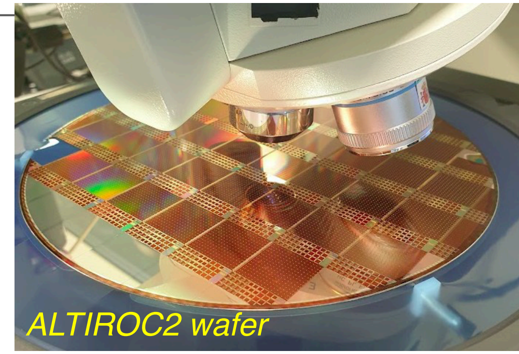
HGTD Plots

*Relative Pile up Jet rate*
Without or with HGTD

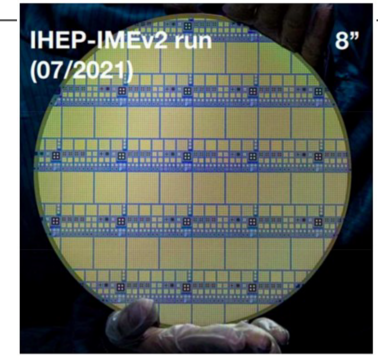


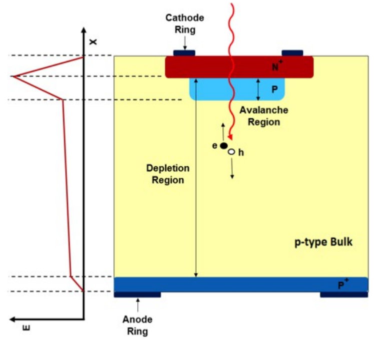
# *High Granularity Timing Detector (HGTD)*

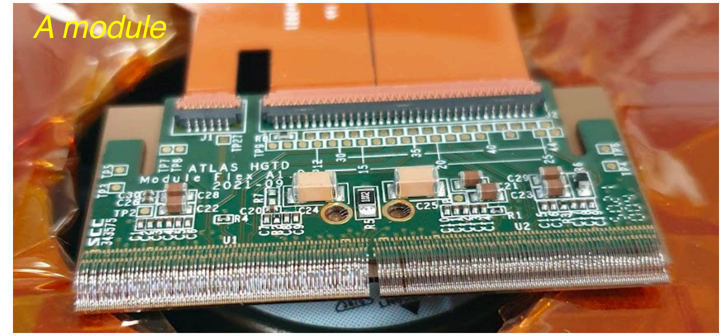
- ## Sensors:
  - Low Gain Avalanche Detectors (**LGAD**) arrays with pad size 1.3 x 1.3 $mm^2$ to keep occupancy low (< 10 % in inner most radius)
    - Single-event burnout (SEB) was observed on LGAD sensors during beam tests. Mitigated by **carbon-infused sensors** (can be operated at decreased high voltage)
- ## ASIC:
  - probing of production chip ALTIROC3 ongoing
- ## Modules:
  - Modules (2 ALTIROCs bump bonded to 2 LGAD sensors) have been demonstrated required resolution
- ## System Tests:
  - Demonstrator currently testing 39 modules on cooling plate down to -30C with CO2 cooling successfully over the last several months




*LGAD Sensor wafer*

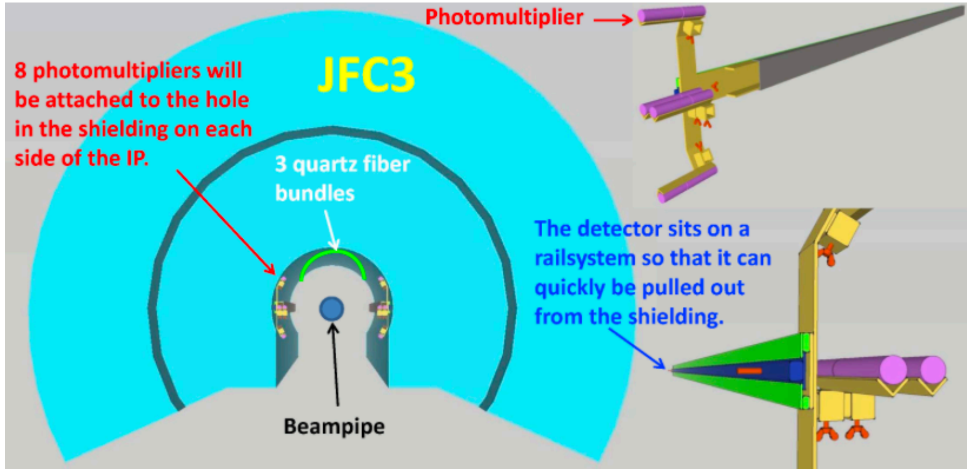



# Luminometry

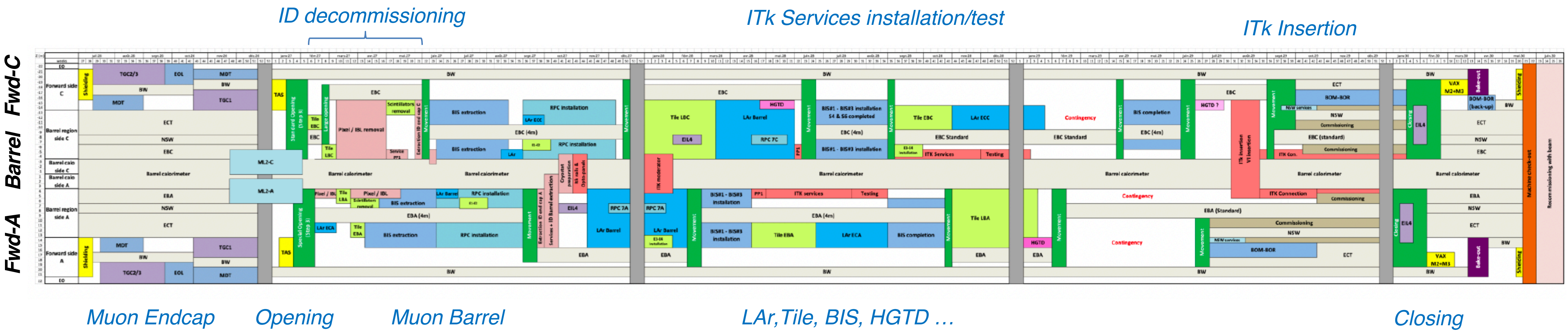
- Goal is to measure luminosity with **1% accuracy** at the HL-LHC
  - Vital for precision physics measurements at the HL-LHC
  - Achieved unprecedent uncertainty 0.83 % at a hadron collider in Run 2, thanks to complementary measurements from LUCID, Inner detector and Calorimeters [back-up]
- Same strategy at HL-LHC, based on several detectors.
- New LUCID-3 to solve hit saturation that would occur, need to lower acceptance
  - Already taking data with different prototypes to find best solution for HL-LHC in terms of geometrical acceptance, radiation exposition, accessibility for replacement and maintenance)




- **HGTD** will perform luminosity measurement in highest radial locations
- **BCM'** will have dedicated thresholds for luminosity determination
- *Other R&D projects (Pixel Luminosity Ring, BMA, etc…) to add other small luminosity detectors.*

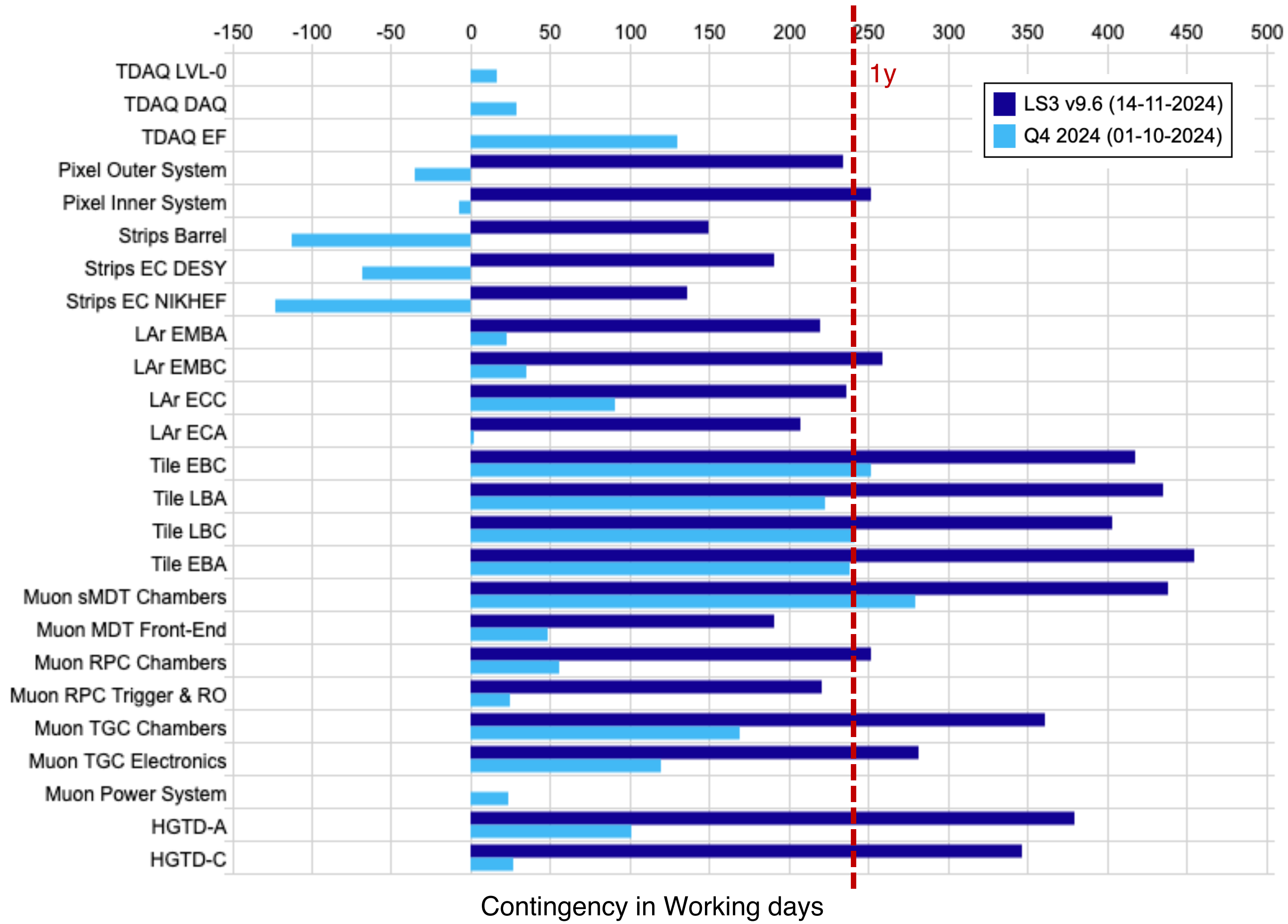
# LS3 schedule in the cavern

- Schedule and planning for decommissioning, installation and commission of detectors and services is within Technical Coordination responsible for activities at P1
  - 14 steps corresponding to different configurations of the detector
- New official schedule for LS3 gives us some more contingency
  - Run3 extension until end of June 2026 (+ 7.5 months) → LS3 start on June 29th, 2026
  - Closure of experimental caverns mid-May 2030 (+ 1 year)
    - Duration beam to beam: 47 months



# *Critical path*

- LS3 schedule determines the need-dates for the detector and their services.




Added overall ~1.5y to the Start of Run 4 schedule in the recent discussions.

It brings all the detectors in a better situation: **still challenging,** from not possible!

# 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

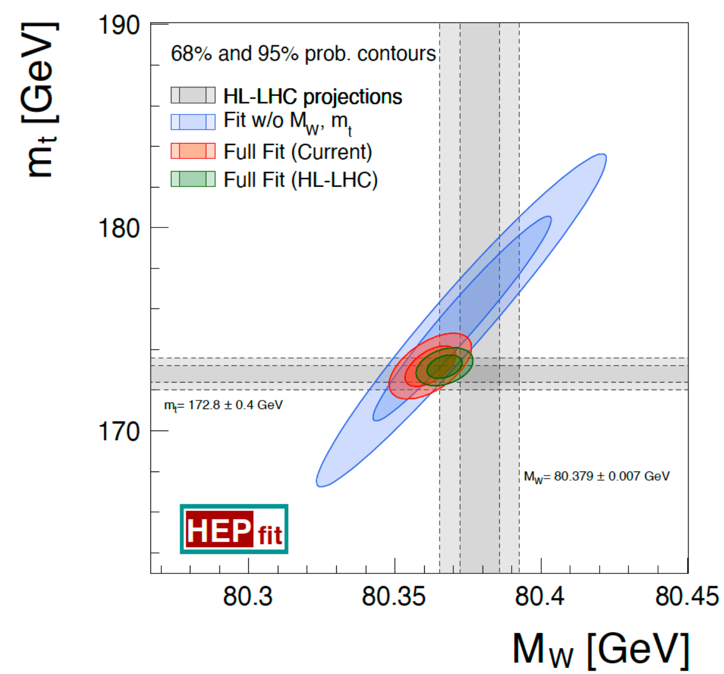
- All detectors are in production, at a different level of progress. **Schedule remains a challenge**, both for **construction,** including delays from (single) vendors, as well for a very compact **installation** during the next long LHC shutdown.

# *Additional material*

# Physics reach at HL-LHC – Precision

- SM physics measurements such as $m_W$, $\sin^2\theta_W$, $\boldsymbol{\alpha}_s$, etc. are dominated by systematics rather than by statistical uncertainties
  - difficult to estimate possible improvements
- Often the main uncertainty in these measurements are PDFs. A more focused effort to make measurement useful for the determination of PDFs at (HL-) LHC and new constraints from latest fixed target DIS experiments may indeed bring to improvements.

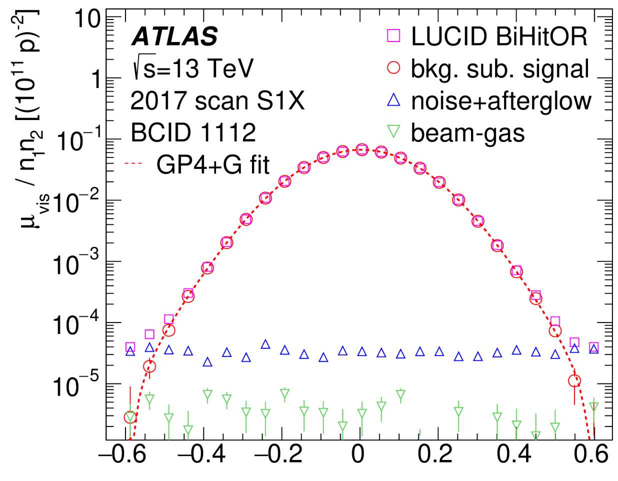
- $\sigma(m_W) \simeq 5$ MeV (CDF: 9.4 MeV)
- $\sigma(m_t) \simeq 0.2$ GeV (LHC: 0.6 GeV)
- $\sigma(\sin^2\theta^{\ell}_{\rm eff}) \simeq 10 \times 10^{-5}$ (LEP+SLD: $16 \times 10^{-5}$)



# Run-2 pp Luminosity

arXiv:2212.09379, CERN LHC Seminar

- ## Luminosity in ATLAS
  - Based on complementary measurements from LUCID, ID and Calos
  - Absolute calibration of LUCID from dedicated vdM scan sessions each year
  - Transported to physics data-taking using track-counting measurements
  - Stability verified using electromagnetic and hadronic calorimeters




*Van der Meer scan*

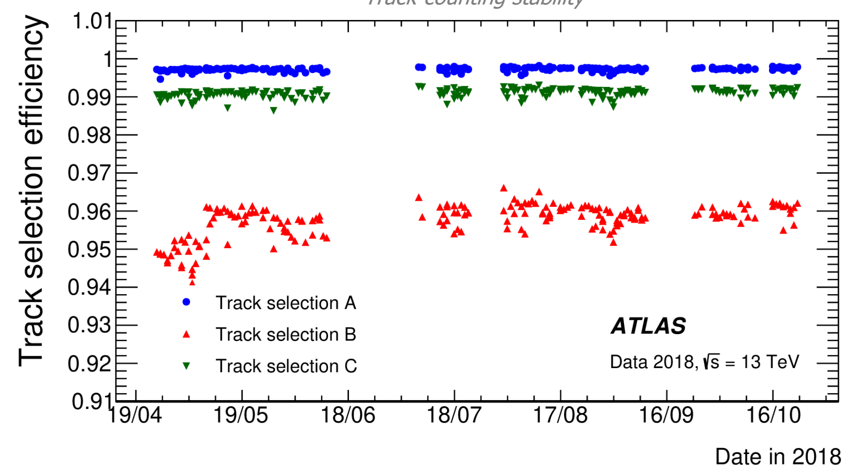
- ## Final result for high pile-up sample:

  $L_{int}=140.1\pm1.2\ fb^{-1}$

  - **Unprecedented uncertainty of 0.83% .** The most precise determination at a modern hadron collider to date
  - Enables significantly more precise x-section measurements from Run-2 legacy analyses: first application will be $\sigma$(t-tbar) to ~1.7% from 2.4%

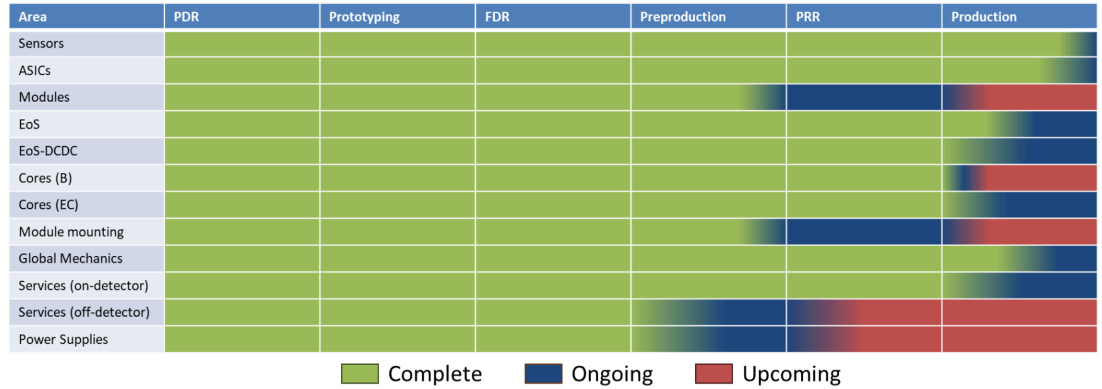
| Data sample | 2015 | 2016 | 2017 | 2018 | **Comb.** |
|---|---|---|---|---|---|
| Integrated luminosity [$fb^{-1}$] | 3.24 | 33.40 | 44.63 | 58.79 | **140.07** |
| Total uncertainty [$fb^{-1}$] | 0.04 | 0.30 | 0.50 | 0.64 | **1.17** |
| Uncertainty contributions [%]: | | | | | |
| Subtotal vdM calibration | 0.96 | 0.70 | 0.99 | 0.93 | 0.65 |
| Calibration transfer* | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Calibration anchoring | 0.22 | 0.18 | 0.14 | 0.26 | 0.13 |
| Long-term stability | 0.23 | 0.12 | 0.16 | 0.12 | 0.08 |
| Total uncertainty [%] | 1.13 | 0.89 | 1.13 | 1.10 | **0.83** |

*Track-counting stability*

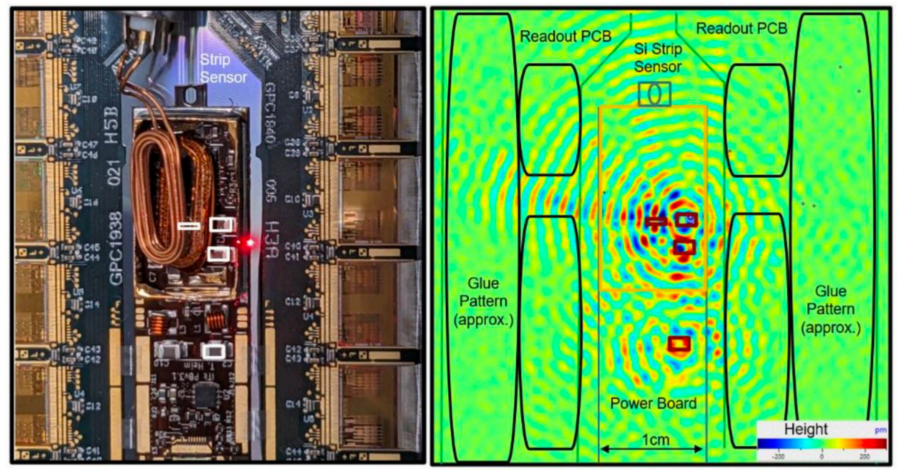


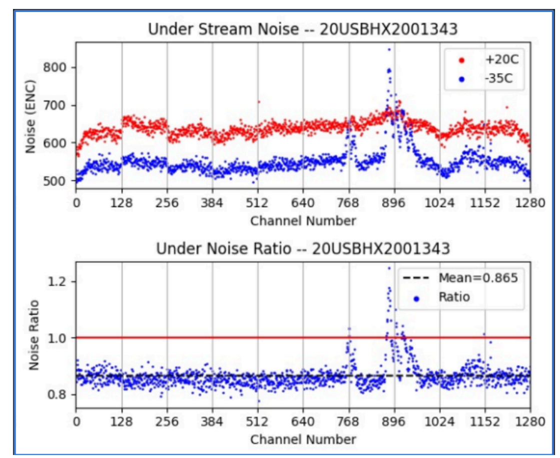
# Strip

- Readiness




- Cold noise
  - Noise in barrel modules at cold temperatures discovered to be due to 2MHz physical oscillation of capacitors on powerboards (coupled to the switching of the DC/DC converter) on top of the sensor.
  - Great effort taken to understand this subtle mechanism and mitigate it (highly dependent on module-PCB interface glue, geometry of PCB)
  - Never observed in any endcap modules. Cold noise eliminated in LS modules with glue choice, ameliorated in SS modules…
  - Completely invisible in modules created with an interposing layer of kapton and soft glue between PCBs and sensor



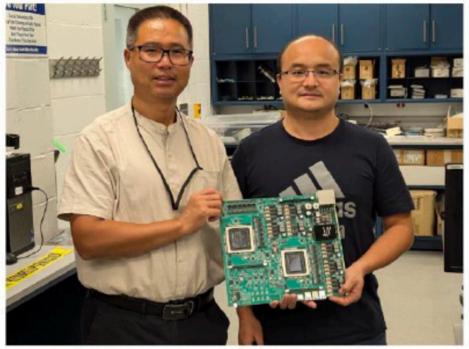



# Trigger and DAQ: Highlight

## TDAQ Progress Highlights

ATLAS EXPERIMENT

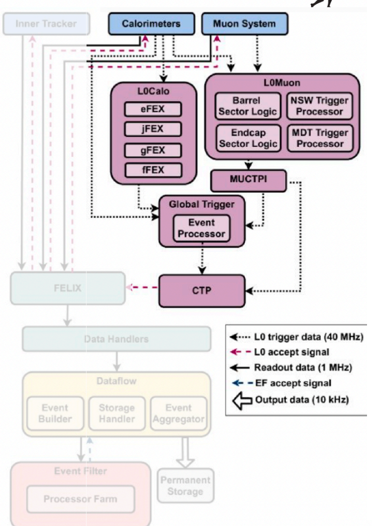
- L0 Trigger good progress with hardware prototyping
  - Firmware development proceeding well as hardware becomes available (Global Trigger, L0MDT, etc)
  - Availability of LTI prototype important for early integration testing with detectors in 2025
  - NSW-TP updating schedule and identifying additional effort
- DAQ good progress in readout, dataflow, network and online software
  - Incorporated additional prototype in the schedule
    - First batch of FLX-182 available, finalized FELIX FPGA choice and first prototype of FLX-155 under testing
- Event Filter technical work leading to technology choice yielding promising results across all candidate implementations
  - EF Tracking completing the second “integration”-themed demonstrator cycle, finalizing the document to define requirements and set process for technology choice



# Trigger and DAQ: More details

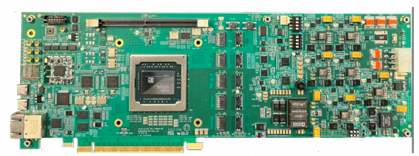
## Hardware based L0 system

- Data from calorimeters and muon detectors processed by dedicated trigger systems
  - **L0Calo and L0Muon**
- **L0Calo:**
- Feature Extractors **(FEX)**
  - FPGA-based trigger boards optimized to trigger on different physics objects
- **L0Muon:**
- Sector Logic
  - FPGA-based off-detector trigger logic
- **Global trigger** runs full granularity offline-like reconstruction: HLT-like object-level and event-level
  - Event Processor at 40 MHz
- Outputs sent to Central Trigger Processor **(CTP)** to make L0 decision
  - Accepted events sent to **Event Filter**

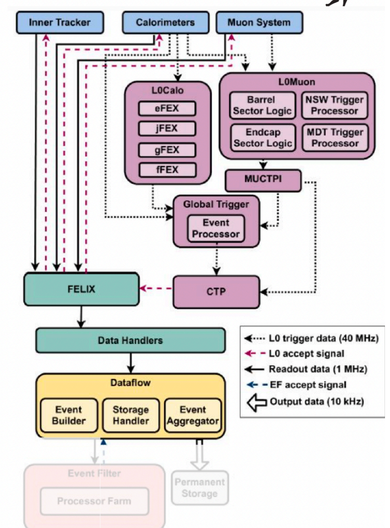



## Readout and DataFlow

- **Front-End LInk eXchange**
  - PC-based gateway
- **FELIX interfaces**
  - Custom optical links to/from front-end
  - Partially deployed in Run 3
- **Dataflow** provides full events (from readout) to EF and storage



*FLX-182 prototype*




## Event Filter

- Multiple types of computational units
  - CPU-servers
  - Possibly of accelerators: GPU, FPGA
  - Decision on EF expected in 2025
- **1 MHz data input rate**
  - Running event reconstruction algorithm
  - Integration with ACTS
- **EF tracking:** Many ongoing FPGA & GPU studies for track seeding from ITk inputs
- **EFCalo:** Studies with GPUs for topological clustering
- **EFMuon:** Muon reconstruction using ML algorithms
- **Final event selection: 10 kHz**
  - *3 kHz in Run-3*

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