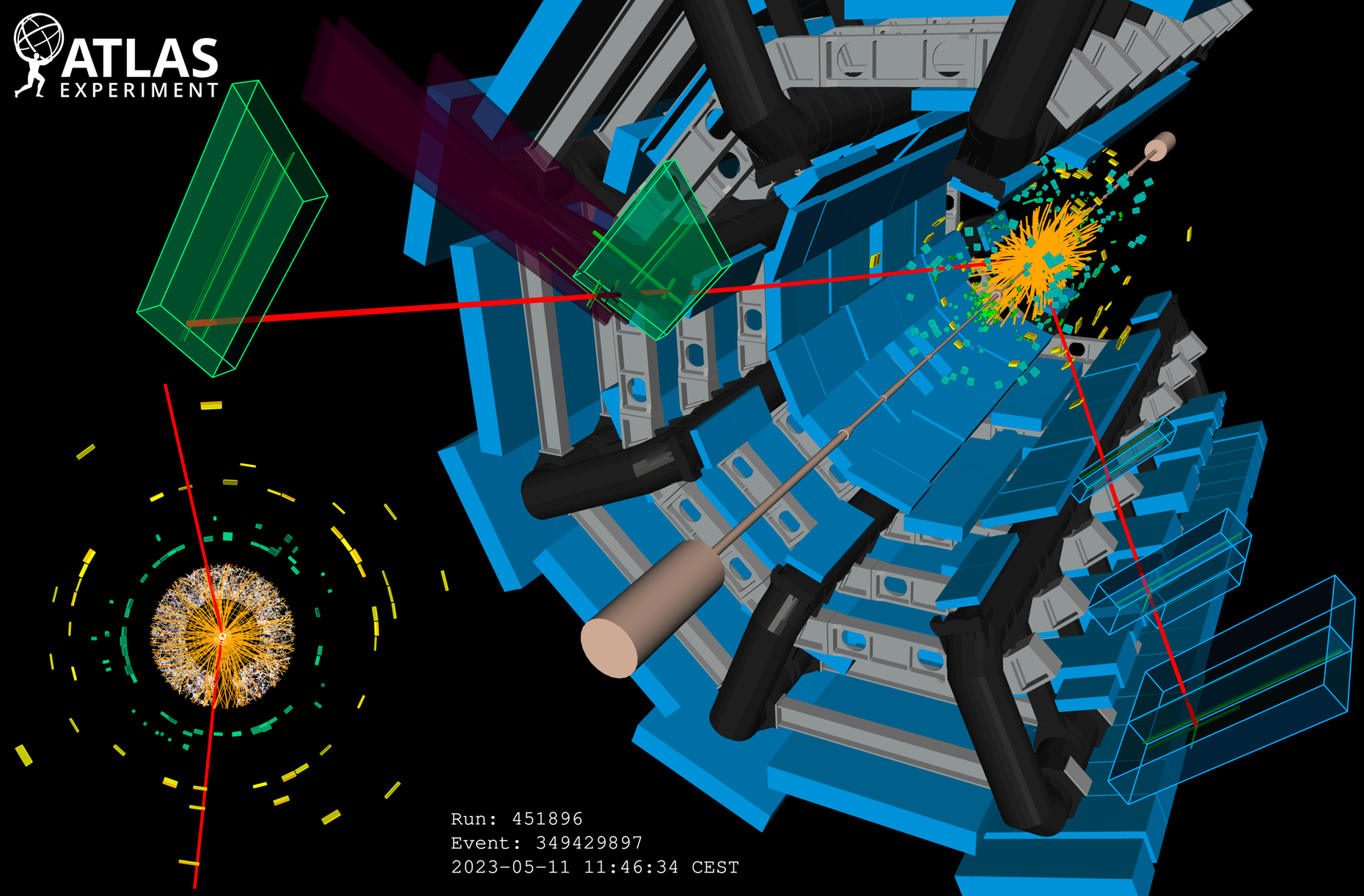



# The ATLAS experiment - Where are we now?

Stéphane Willocq
(U. Massachusetts - Amherst)

SA-CERN 15th anniversary — 20-21 Jan 2025 — iThemba LABS

# Outline

- **South Africa in ATLAS**
  - Groups and activities
- **Run 3 data taking**
  - Operations and data taking
  - Detector, trigger, software & computing
- **Run 2 & Run 3 analysis**
  - Physics & performance highlights
- **HL-LHC and Phase-II upgrade**
  - Progress with detector upgrade for HL-LHC

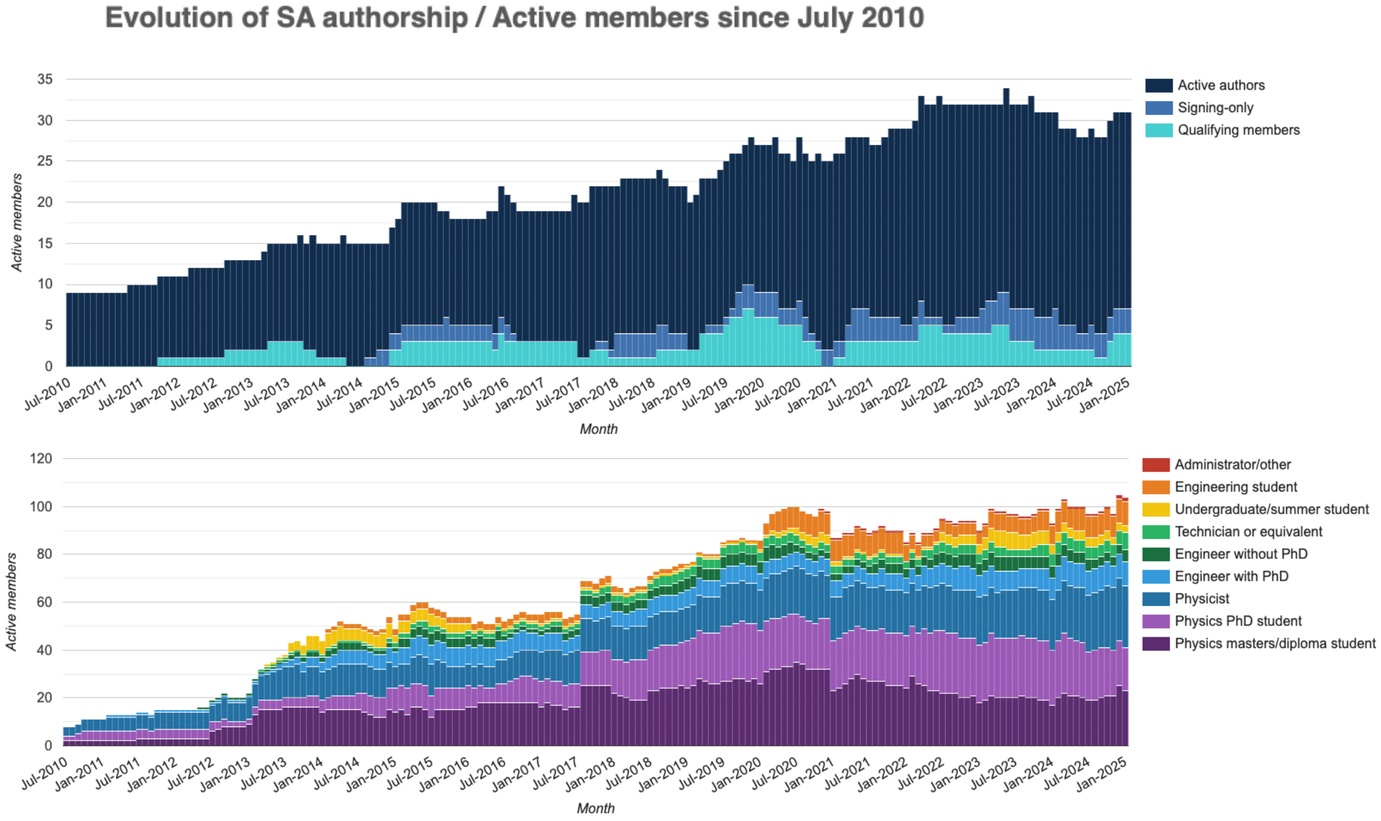
# ATLAS: A vast physics program

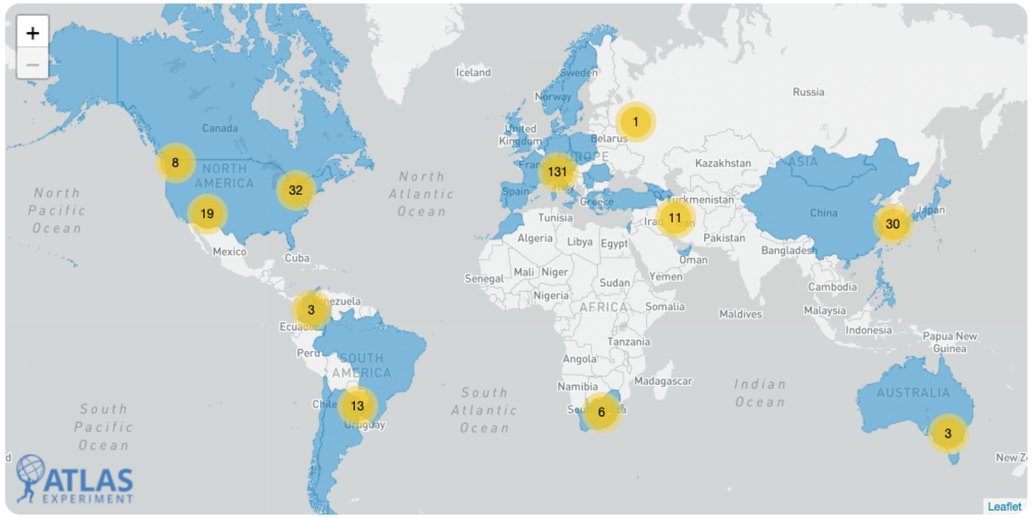
- Physics@LHC is most ambitious and farthest reaching HEP program ever
- **Huge dataset with well understood detector performance** allows
  - Precision measurements $\mathscr{L}_{\mathrm{SM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\,\bar{\psi}\not{D}\,\psi + \psi_i\,y_{ij}\,\psi_j\,\phi + \mathrm{hc} + |\,D_\mu\phi\,|^2 - V(\phi)$
    - Determine fundamental parameters, probe higher-order QCD and EW effects
    - Deep dive into role of Higgs bosons (EWSB, self-interactions -> Higgs potential)
  - Access to rare processes (e.g. production of $WWW$ or $t\bar{t}t\bar{t}$)
    - Probe poorly or untested corners of SM
  - Broad search program at TeV scale and beyond (high energy frontier)
    & feeble interactions (low coupling frontier)
    - Directly address compelling issues: naturalness, dark matter, flavor puzzles, etc.
  - Study of new states of matter —> quark-gluon plasma

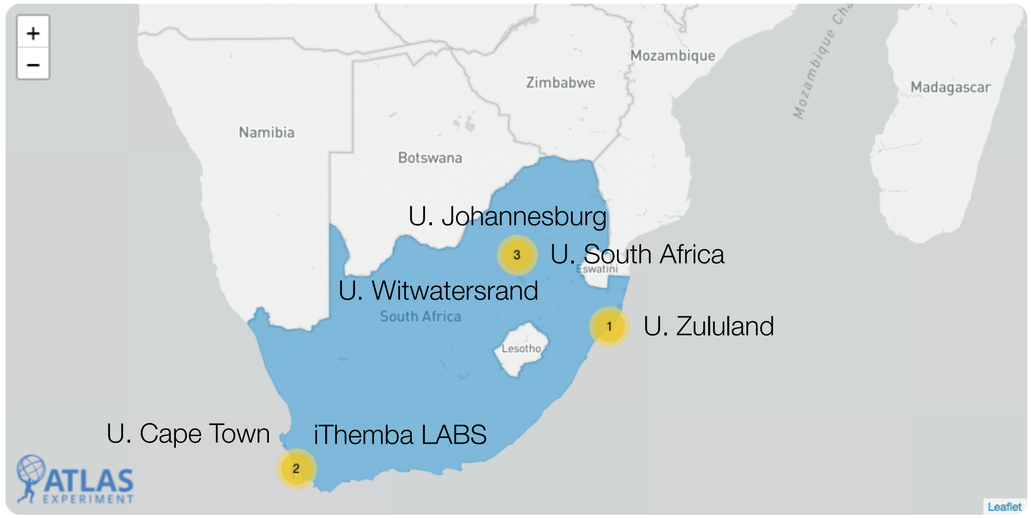
# South Africa in ATLAS

- **South Africa cluster:** 6 institutes
  - U. Cape Town, iThemba LABS, *U. Johannesburg*, U. South Africa, *U. Witwatersrand*, U. Zululand

    Founding institutes in *italics*
  - 104 active members, incl. 26 physicists, 18 PhD students

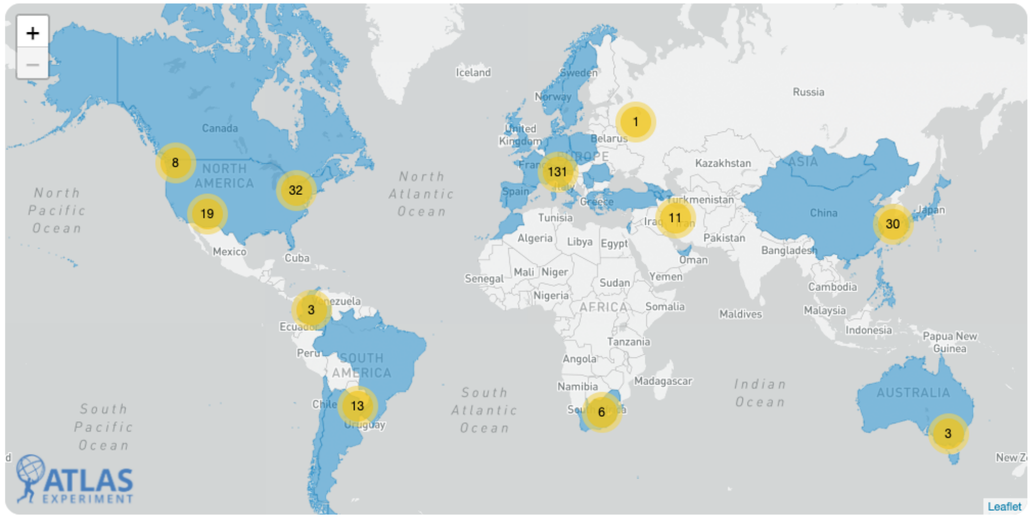


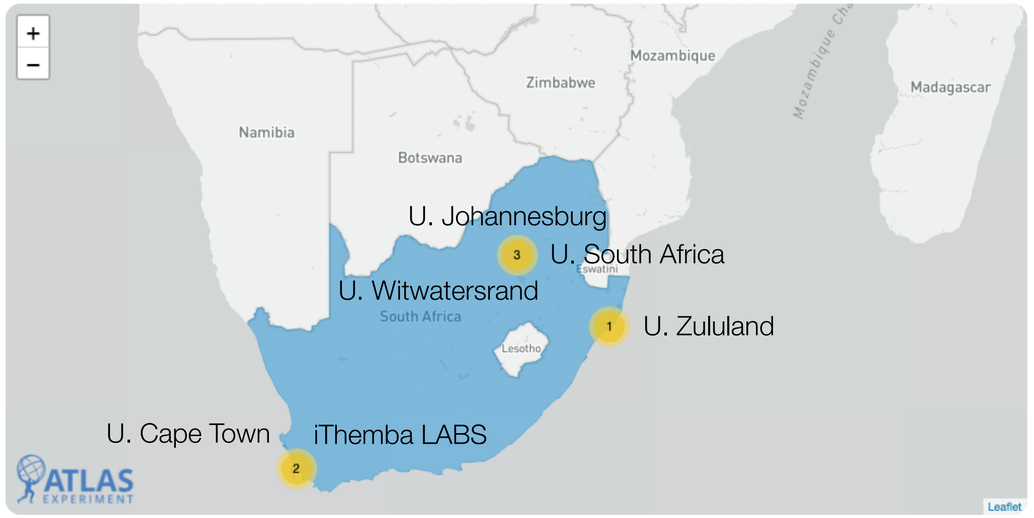



# South Africa in ATLAS

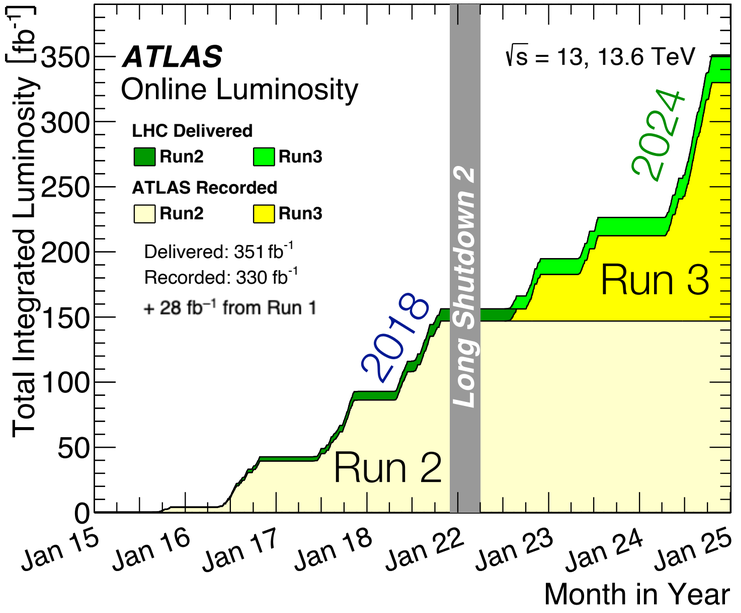
- **Detector focus**
  - Strong contributions to operations: control room shifts, SCT, Tile Calorimeter
  - Upgrade detector systems: ITk Strips (fibre-optic humidity sensors, poly-moderator and EoS cards) and Tile Calorimeter (off-detector electronics components, low voltage power supplies)
- **Physics analysis**
  - Higgs boson measurements and searches, dark matter searches, top-quark physics, strong interactions and physics modeling
- **Coordination roles / Committees**
  - Tile Calorimeter (IB & Deputy Project Leader), SCT (Run Coordinator), Top Cross-section (Subgroup Convener), Collaboration Board Advisory Group (member), D&I (Contact)

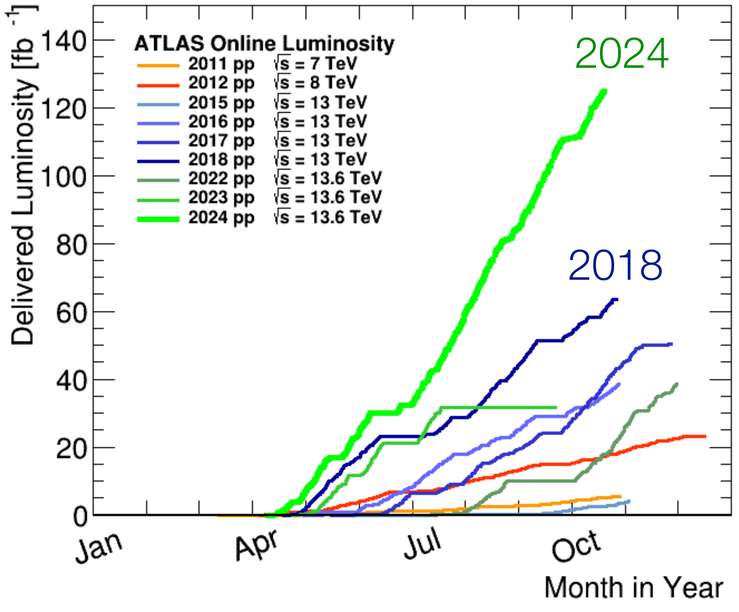


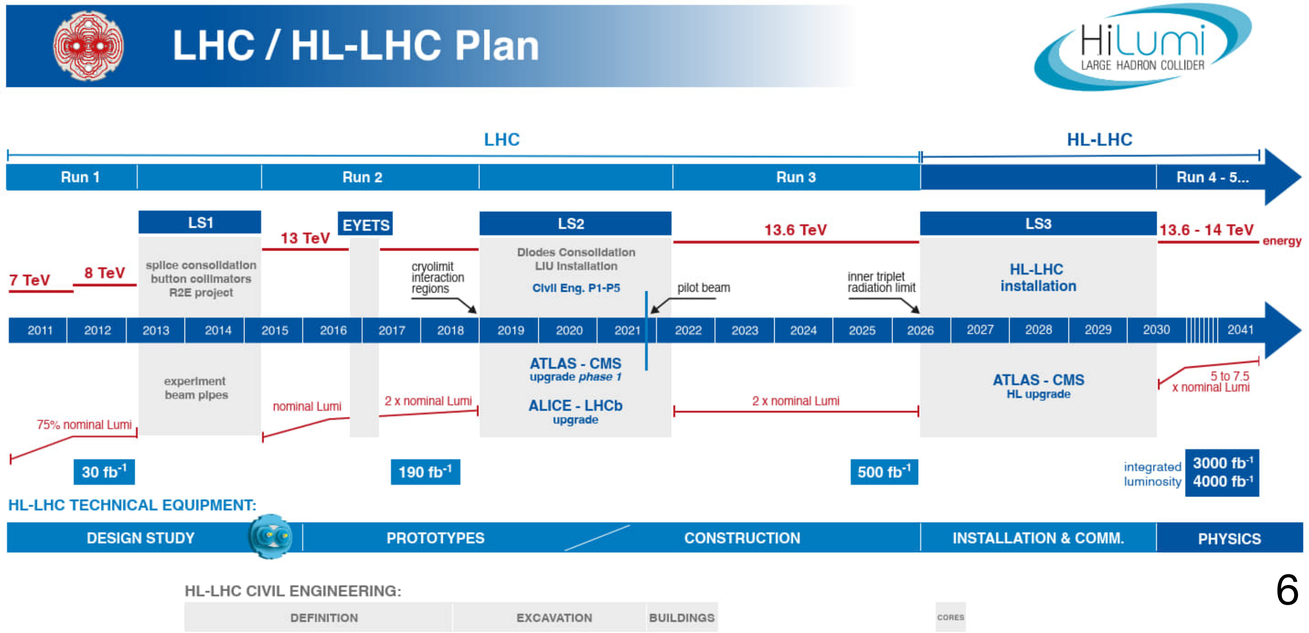



# LHC data taking

- **A gold mine for physics**
- Recorded luminosity (pp)
  - 147 fb$^{-1}$ (*Run 2*) + 183 fb$^{-1}$ (*Run 3*)
    at $\sqrt{s}$ = 13 TeV 13.6 TeV
- Good for Physics (pp)
  - 140 fb$^{-1}$ (*Run 2*) + 169 fb$^{-1}$ (*Run 3*)
- Also heavy-ion collisions
  - Pb+Pb, p+Pb, Xe+Xe
  - O+O, p+O (planned for 2025)
- **Record year in 2024**
  - Nearly 2x lumi best previous year (2018)
- **Run 3 continues in 2025 & 2026**
  - Run 3 up to 370 fb$^{-1}$ recorded (pp)
  - Run 3 up to ~7 nb$^{-1}$ recorded (Pb+Pb)

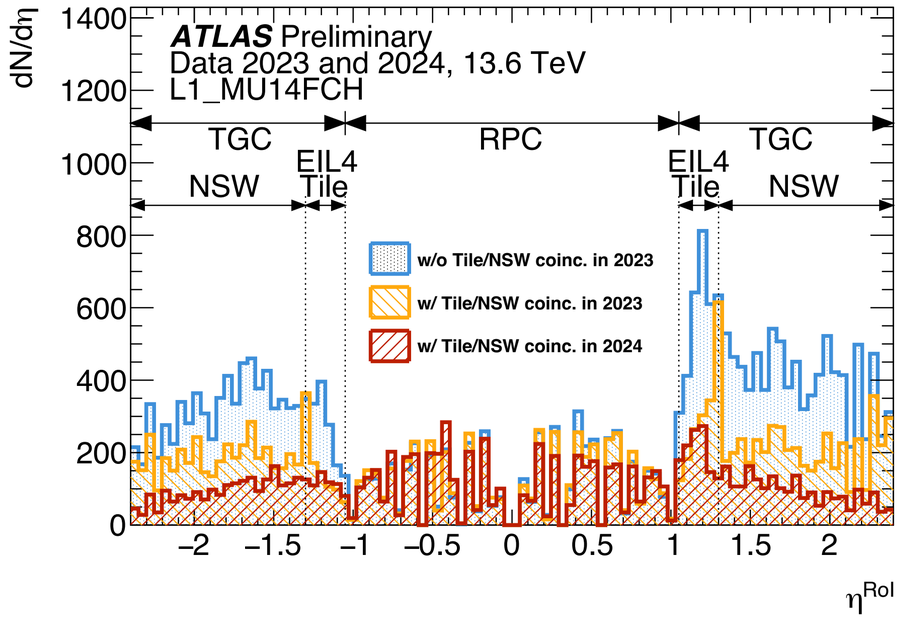


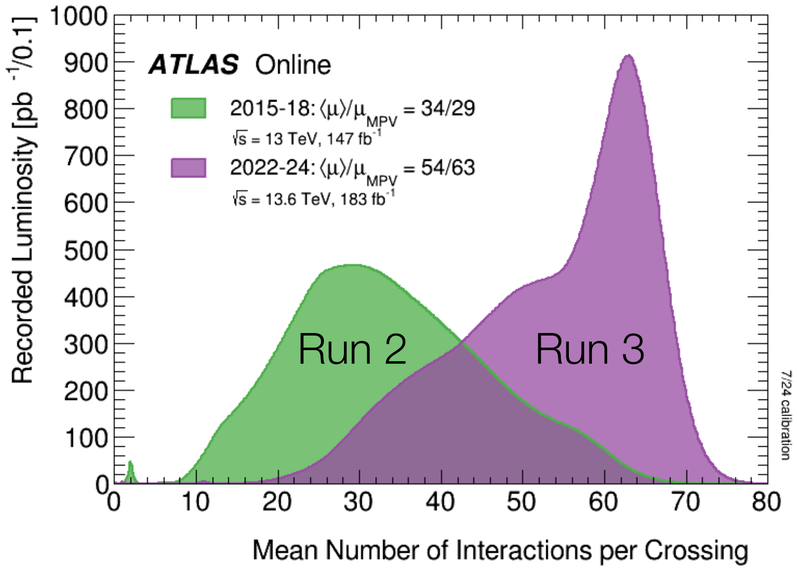



# Run 3 data taking: Pileup and Trigger

- **Increased luminosity in Run 3** brings new challenges
  - **Pileup interactions** up to ~70 / pp bunch crossing
  - **Trigger rates**
    - ~94 kHz at Level 1 (hardware trigger)
    - ~3 kHz at High-Level Trigger (~3x Run 2)
    - Phase-I detector upgrades: muon new small wheel (NSW), LAr calorimeter digital readout + L1 calorimeter trigger electronics —> keep trigger rates at acceptable levels (and dead time at ~4%)

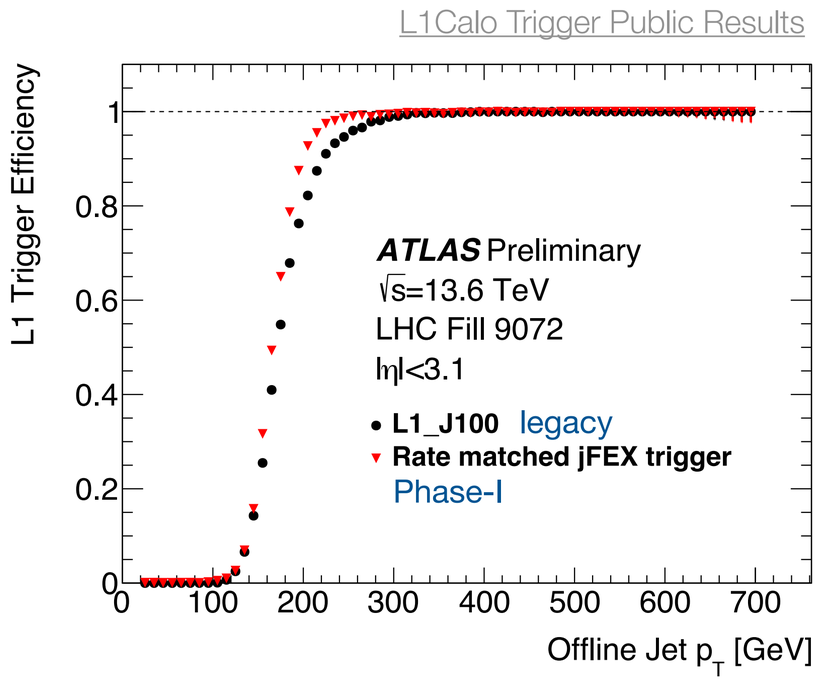


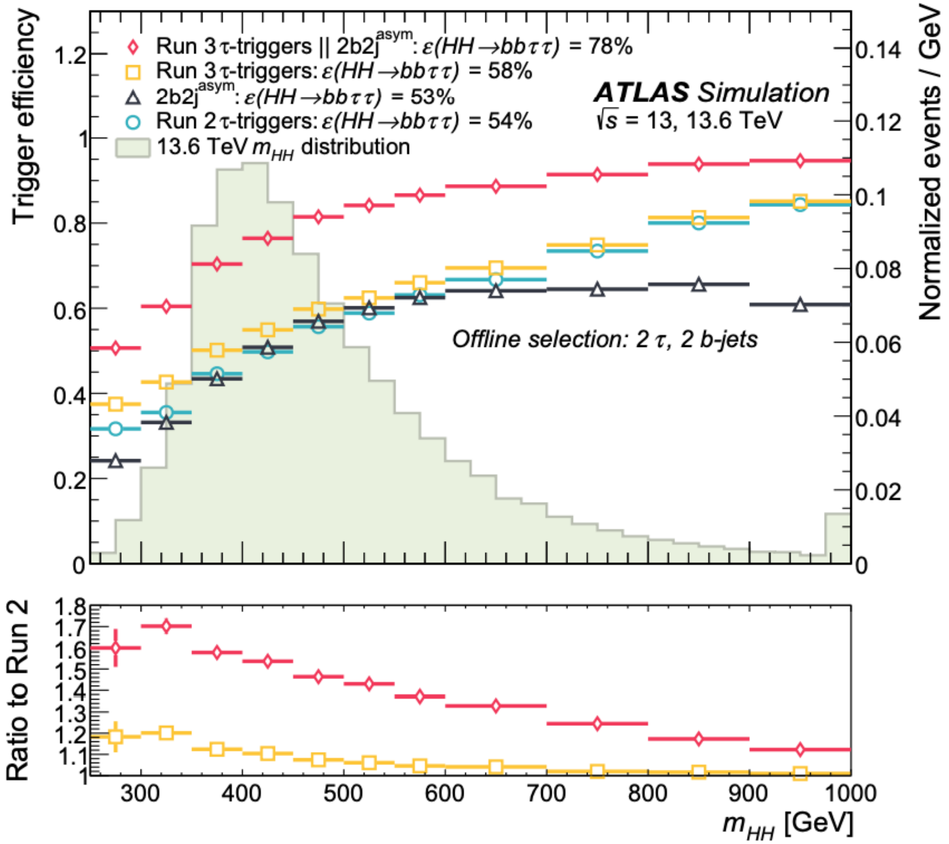

New Small Wheel (NSW)
Installation prior to Run 3

# Run 3 data taking: Trigger

- **L1 Trigger**
  - **Phase-I upgrade fully commissioned** in 2024
    Provides default triggers for physics
    - EM, muon, jets, tau, ETmiss




  - **High-Level Trigger:** Improved algorithm and *b*-tagging for Di-Higgs events in most sensitive $HH \rightarrow bb\tau\tau$ final state
    - Gain of up to factor of 1.7 wrt Run 2



# Run 3: Detector & Trigger status

**Pixel**: good, incl. B layer up to μ ~ 65!

**SCT:** OK, but several technical issues

**TRT**: some acc. loss, but FE cooling stable

**LAr**: good, cryogenics good

**Tile**: FE electronics cooling leaks at limit but so far stable, 3.5 modules switched off (1.4%)

**Muon**: MDT & TGC good; RPC inlet repairs and resin application during last EYETS did not reduce leak rate

**NSW**: DAQ stability fixed, sTGC pad & MM triggers operating, sTGC strips under work, rising number of sTGC HV failures

**Forward**: LUCID good; AFP: suffers from backgrounds (ToF inoperational); ALFA programme completed; ZDC for PbPb run

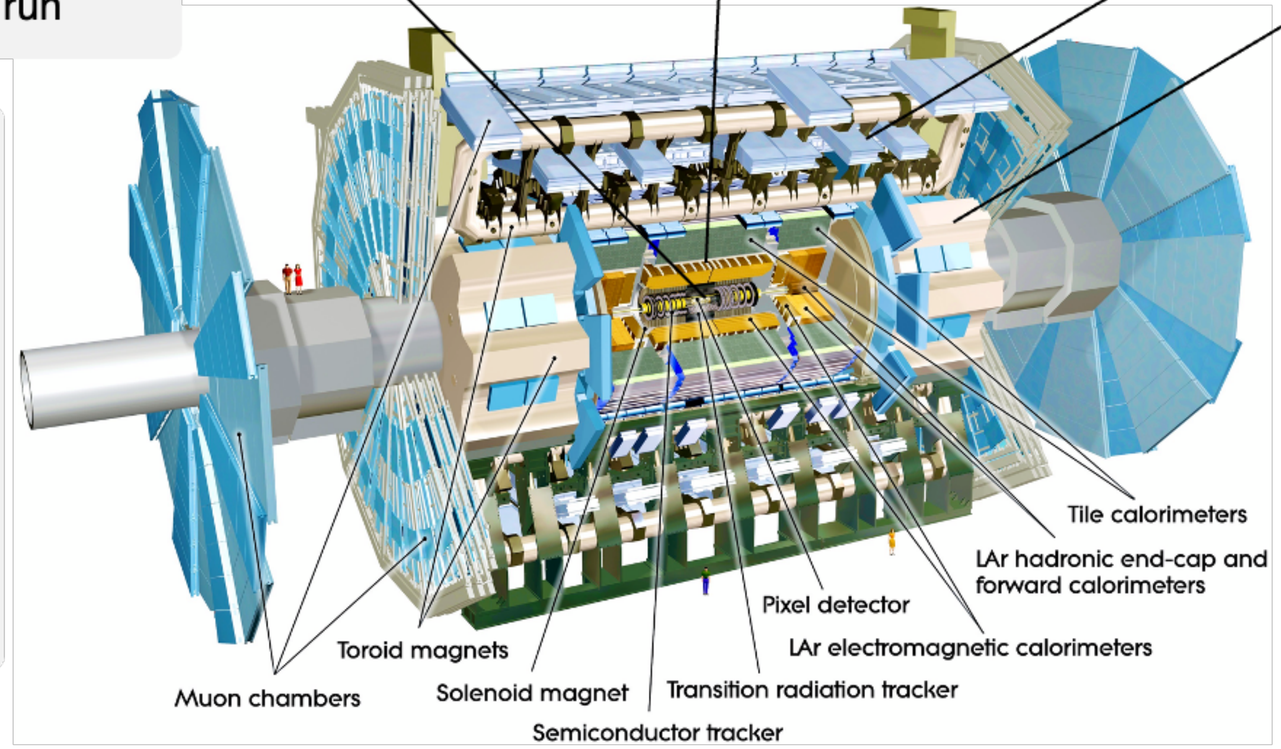
**Magnets**: cryogenics stable, but 8 toroid cycles in 2024

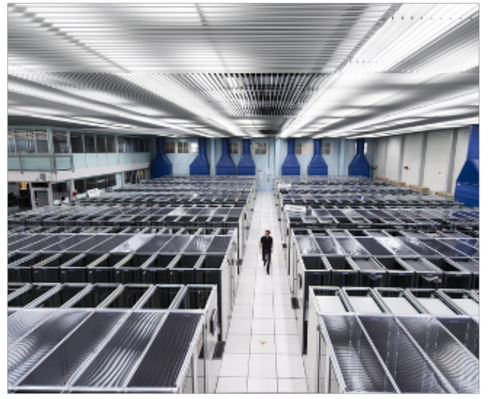
**DAQ**: no limitations

**Trigger**: L1 & HLT deal well with higher lumi and pileup; HLT CPU sufficient

**Phase-I systems**: all in operation, better efficiency with reduced fake trigger rates

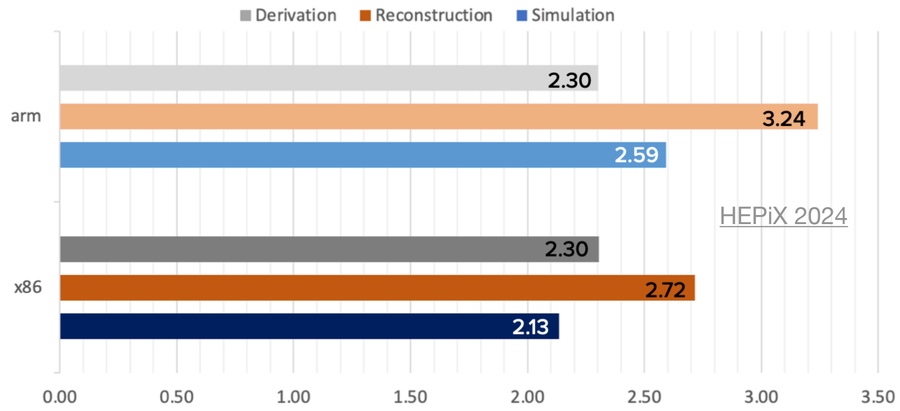
**Offline**: Tier-0 reconstruction operating smoothly (8 GB/s)



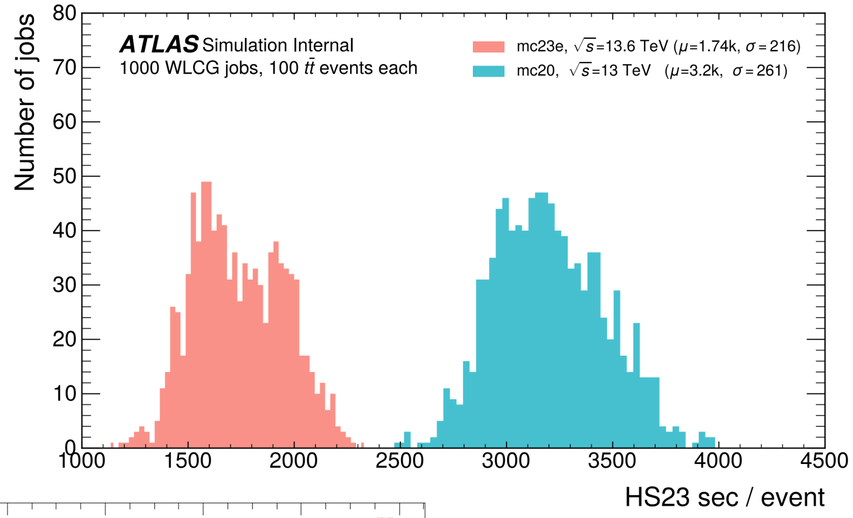
# Run 3: Software & Computing

- **ARM processors** (deployed at 4 grid sites)
  - Improved computing-work / power
  - Tested with different workloads
- **Simulation**
  - Factor of 2 speed-up of full simulation: Run 3 vs. Run 2
- **Data (real + simulated)**
  - ATLAS exceeded 1 ExaByte on July 10
- **First release of open data for research**
  - 36 fb$^{-1}$ from 2015+2016 pp collisions data and MC in PHYSLITE format at https://opendata.cern.ch/record/80020
  - News item




HEPScore/Watt

Link

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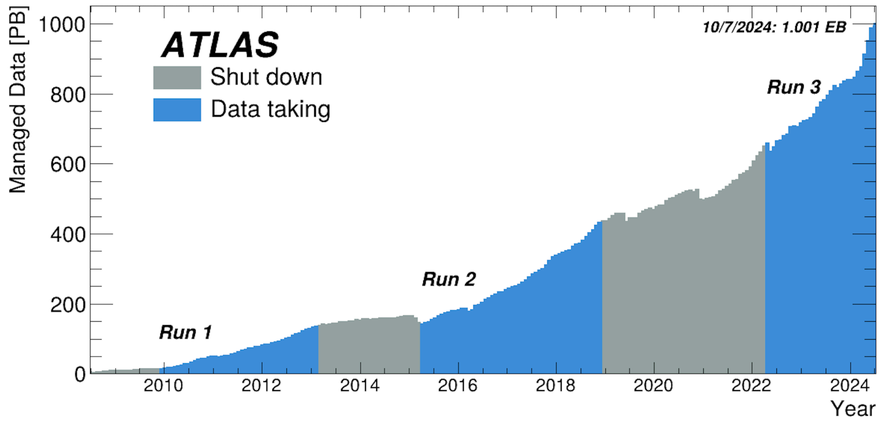
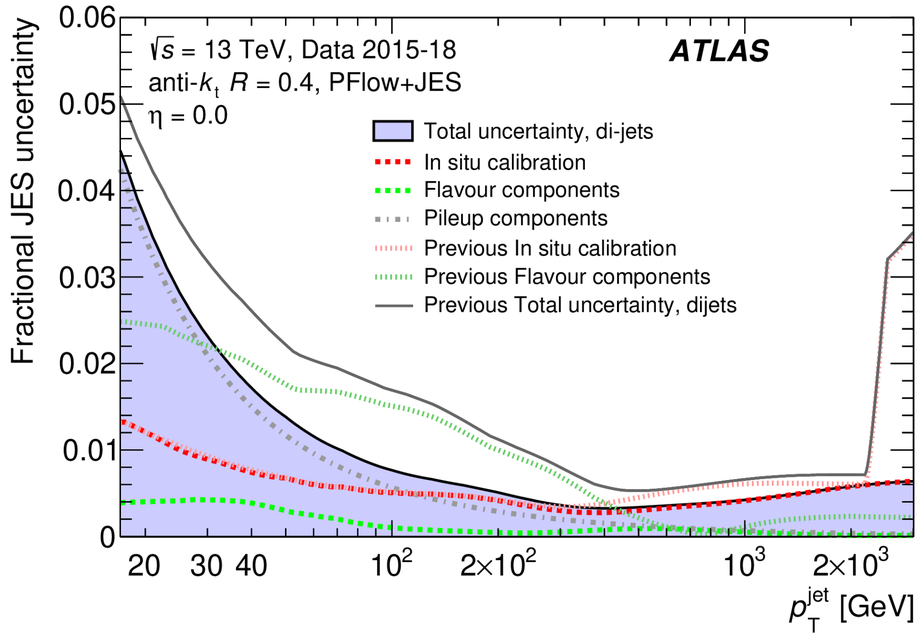



ARM = advanced RISC machine

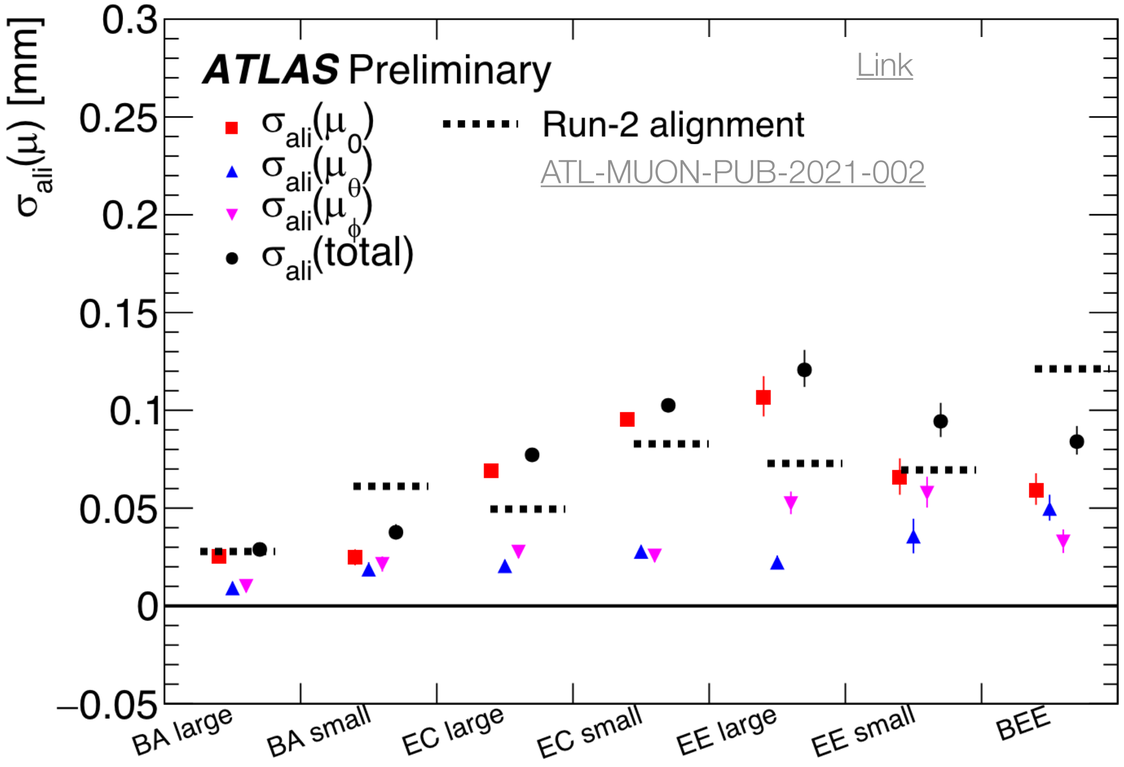
# Recent performance highlights

- **PFlow jet energy scale uncertainty improvements**
  - Use isolated pion E/p measurements from τ lepton decay
    —> JES: 0.3% at $p_T$ = 300 GeV, 0.6% at 4 TeV

arXiv:2407.15627



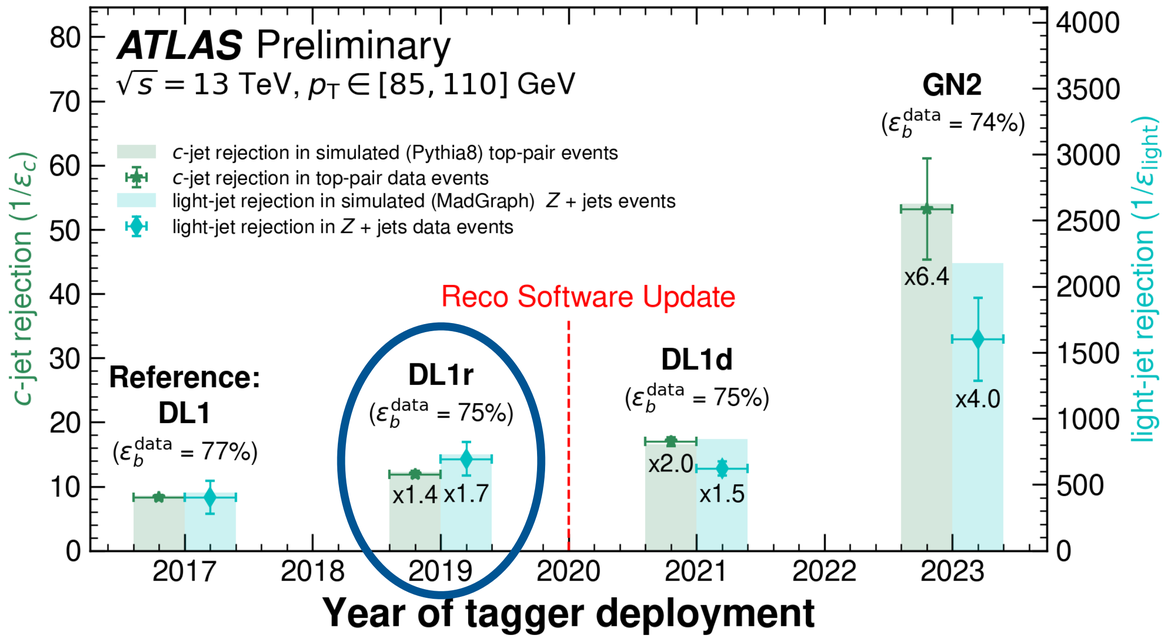

- **Muon spectrometer alignment for Run 3**



# Recent performance highlights

- **Continuing the machine learning revolution**
  - GNN for flavor tagging

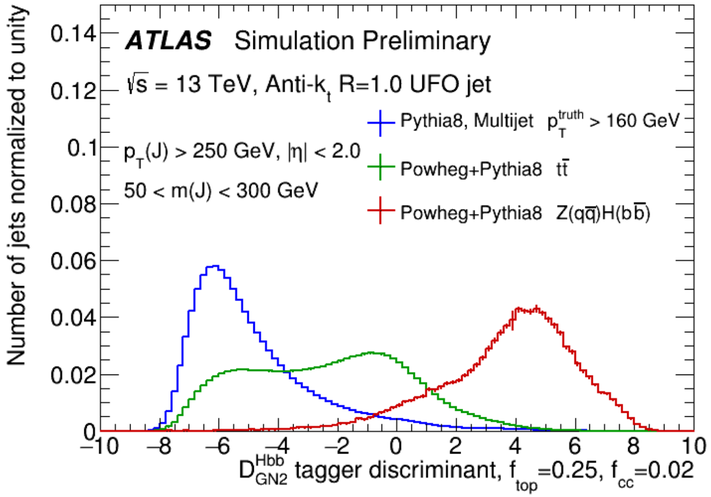
Link




Current (Run 2) results still
based on DL1r flavor tagging

Impressive leap in performance with GNNs

  - GNN for large-R jets from $H \to b\bar{b}$

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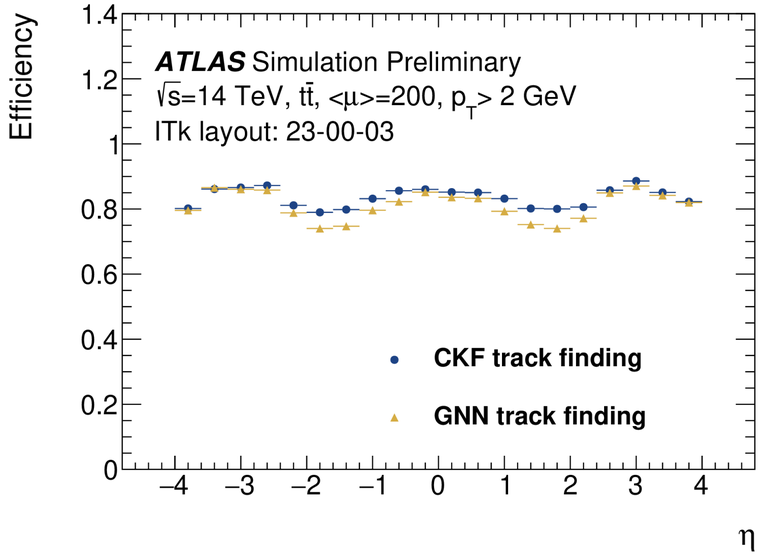
  - GNN for track reconstruction



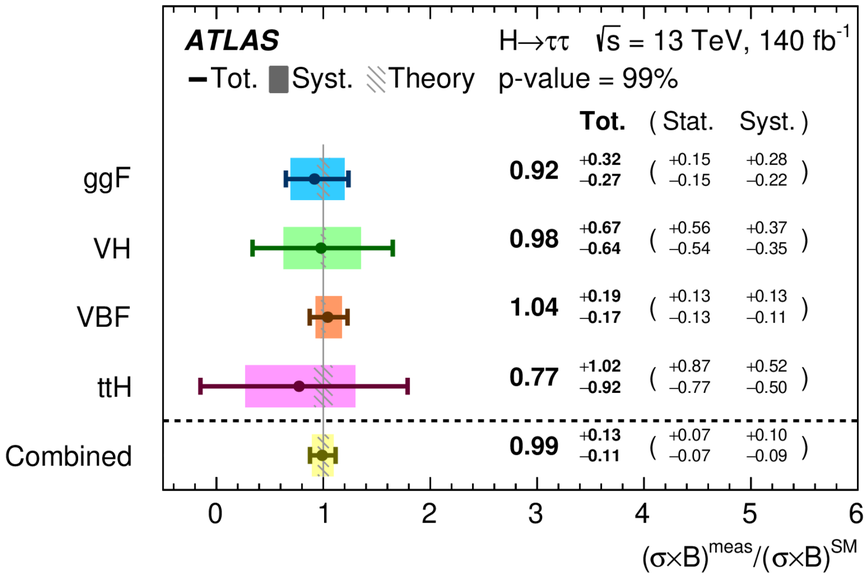

Link

GNN = graph neural network

# Recent Run 2 physics highlights

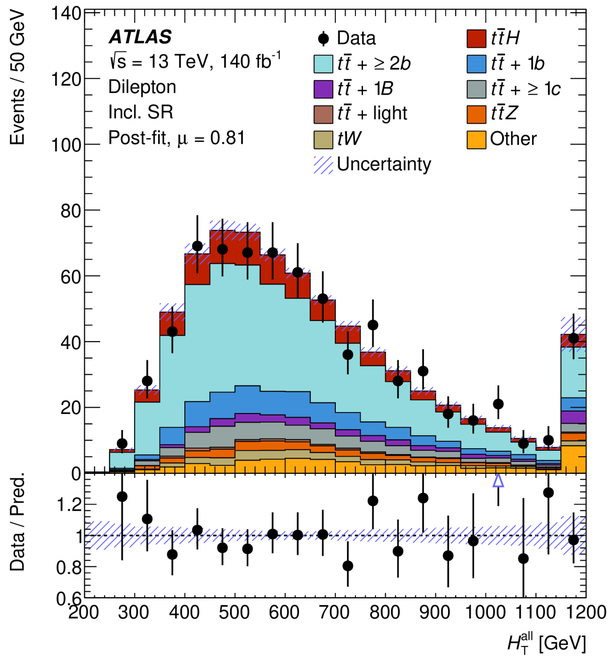
- **Precise Higgs Run 2 "legacy" measurements**

arXiv:2407.16320 H —> ττ




- Most precise VBF in single H decay mode
- Most stringent constraints on CP-odd Wilson coefficient $c_{H\tilde{W}}$

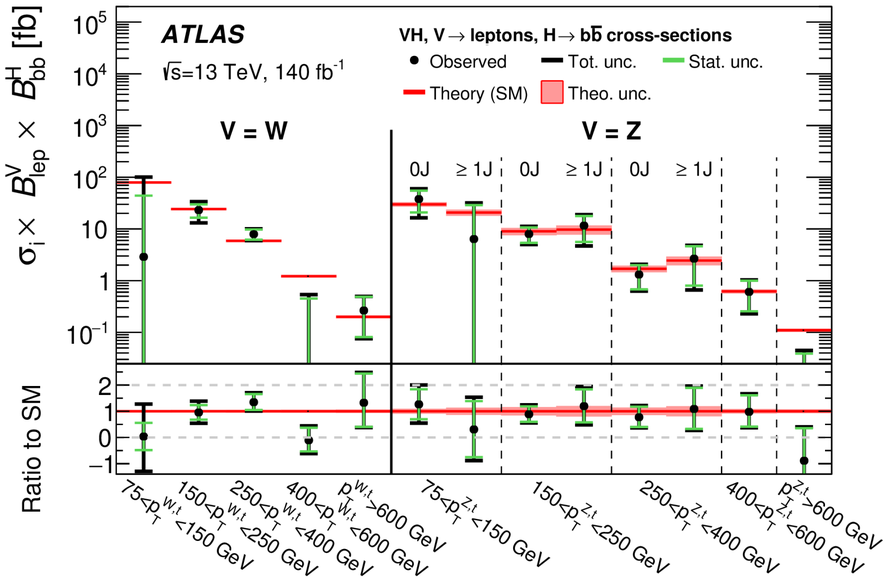
arXiv:2407.10904 ttH, H —> bb




ttH(bb) obs. with 4.6σ

$$\mu(t\bar{t}H) = 0.81^{+0.22}_{-0.19}$$

arXiv:2410.19611 VH, H —> bb




Simultaneous measurements of VH(bb) and VH(cc), upper limit on $\kappa_c$ improved by factor 3, $|\kappa_c/\kappa_b| < 3.6$

—> weaker H coupling to charm than bottom

*Results benefit from improved flavor tagging and analysis techniques*

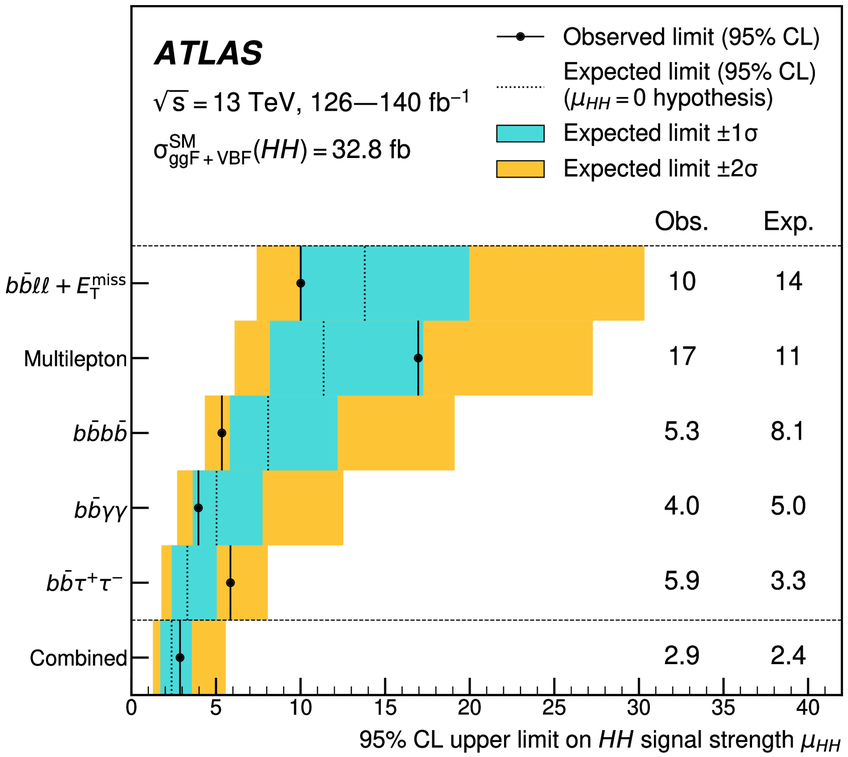
VBF = vector boson fusion

# Recent Run 2 physics highlights

- **Di-Higgs production** —> Higgs self-coupling
  - Combination of 5 analyses covering ~half of all HH final states
  - $\mu_{HH} < 2.9\ (2.4)\ \text{obs}\ (\text{exp})$ exp on $\mu_{HH} = 0$ hypothesis

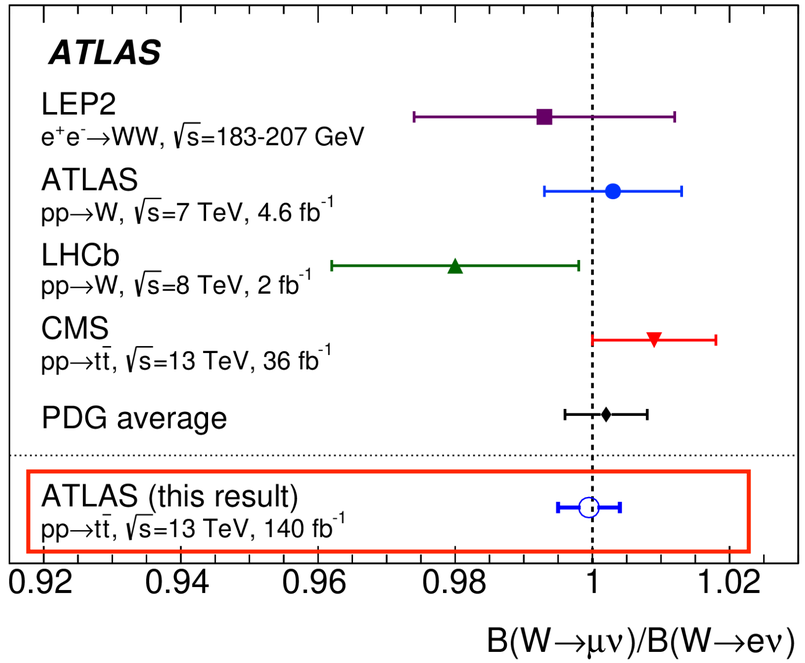
    $\mu_{HH} = 0.5^{+1.2}_{-1.0}\ (1.0^{+1.2}_{-1.0})$

arXiv:2406.09971



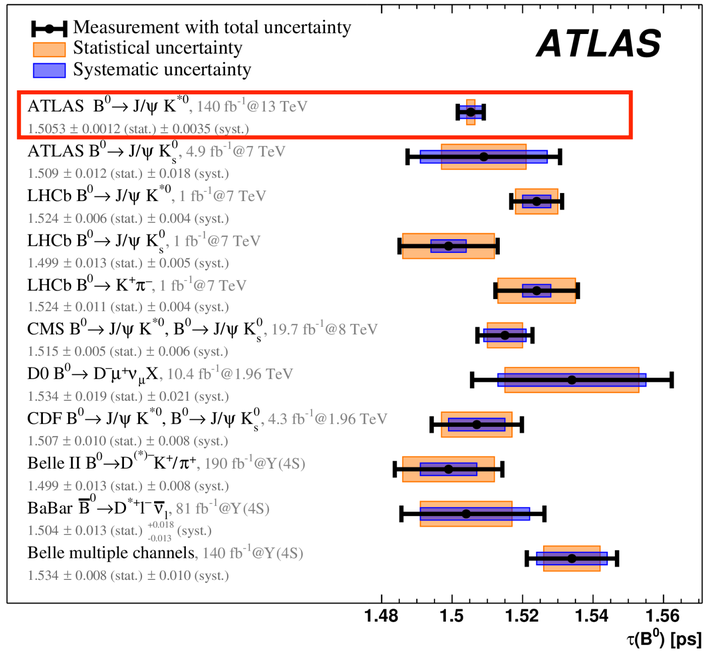

- **High-precision measurements**
  - Lepton universality test: $W \to e\nu$ vs. $W \to \mu\nu$
  - precision: 0.45%, factor of 2 improvement over best previous meas. & more precise than world avg

arXiv:2403.02133

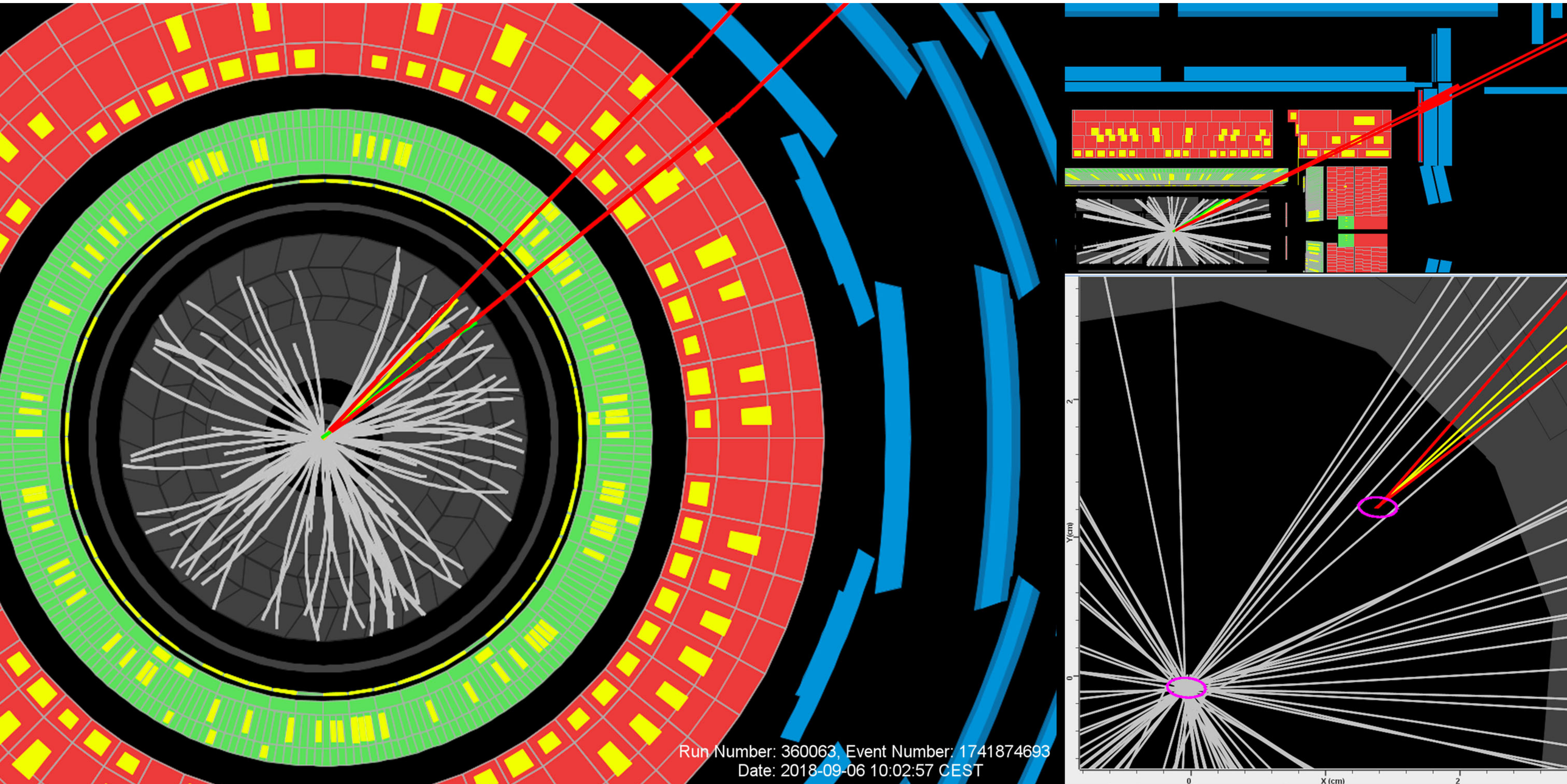



- B0 lifetime

arXiv:2411.09962



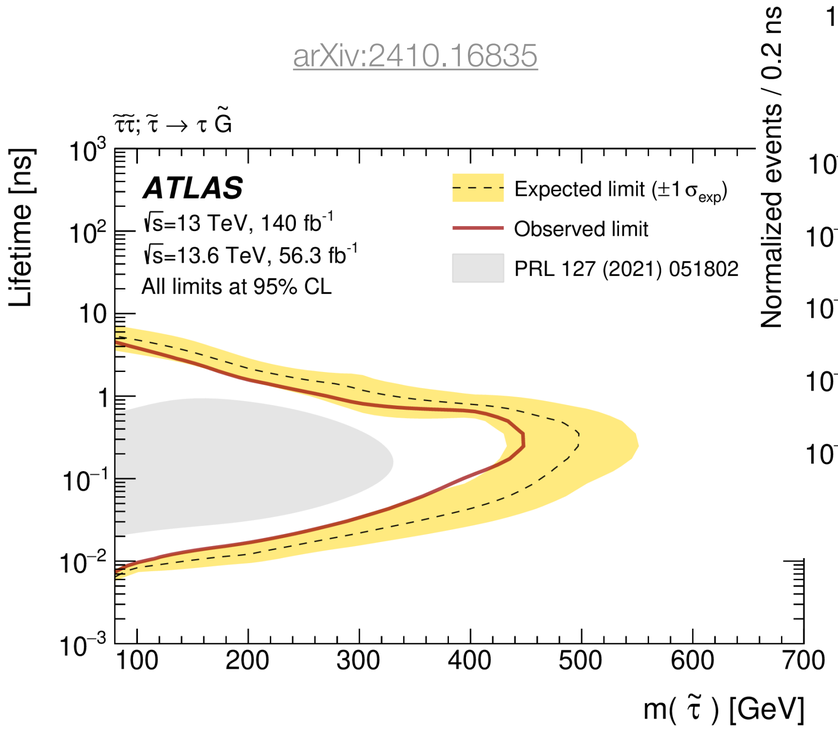
# Precise B⁰ Lifetime via $B^0 \to J/\psi\, K^{*0} \to \mu\mu\, K\pi$

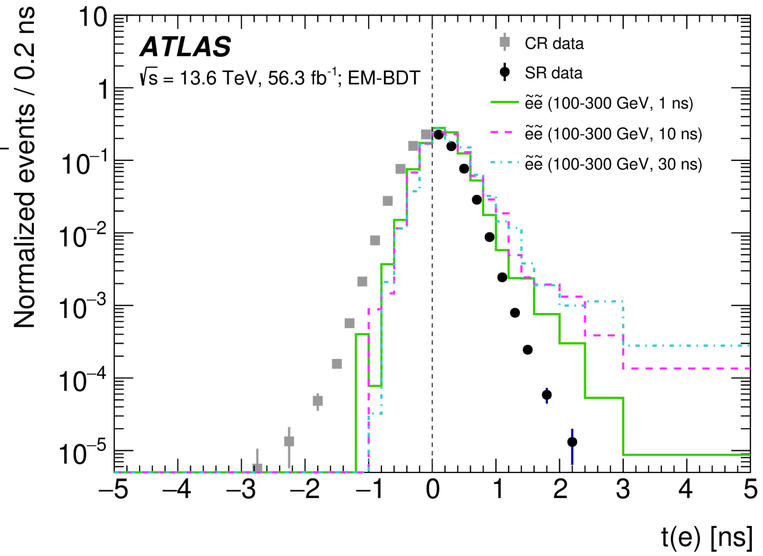


# Recent Run 3 physics highlights

- **First search results with Run 3 data**

arXiv:2410.16835



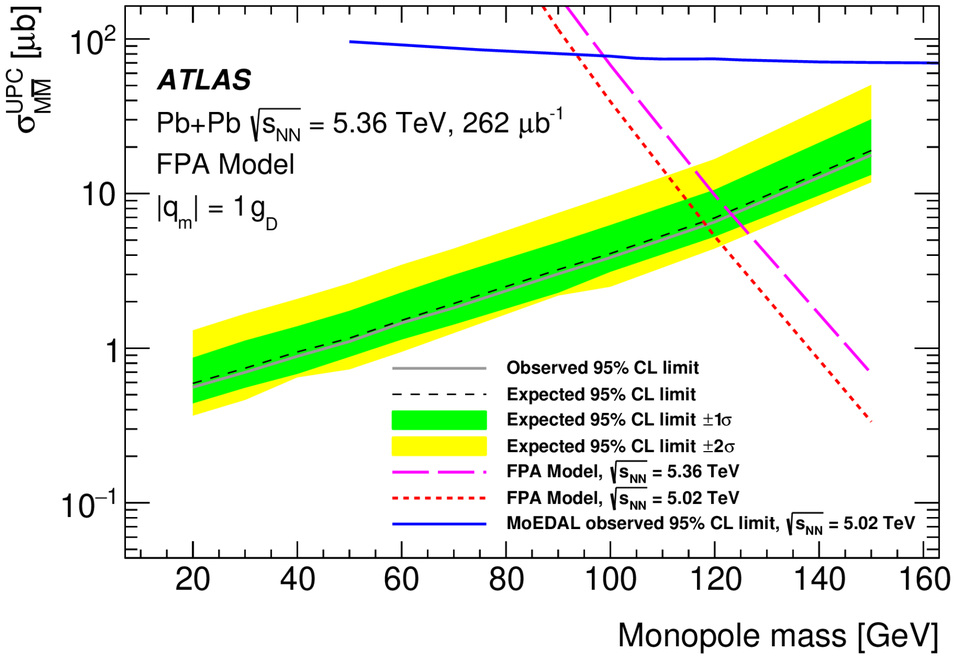




LLP search w/ large impact parameter e or μ track also using LAr timing measurements

*Results benefit at low $p_T$ from new Run 3 triggers based on large-radius tracking*

LLP = long-lived particle

arXiv:2408.11035




Search for magnetic monopoles via high ionization in Pixels

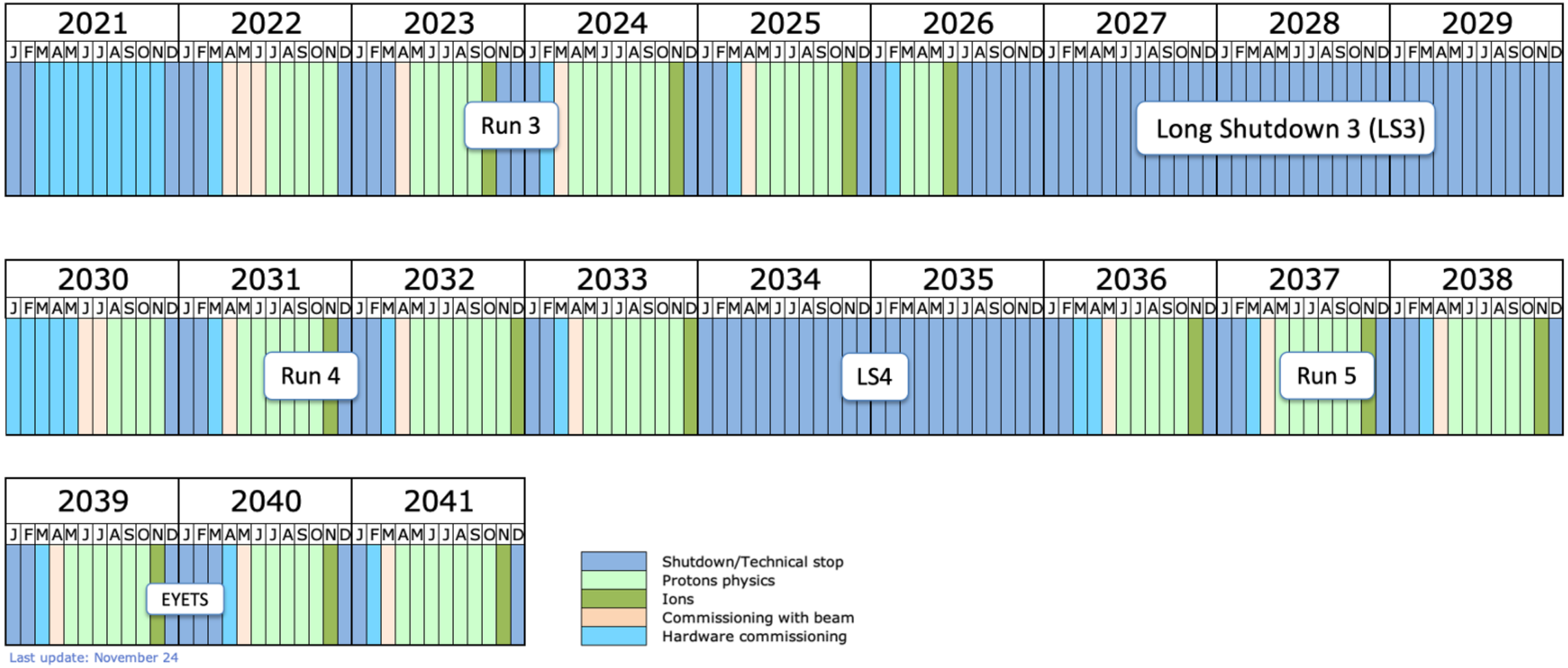
Exploit large EM fields in ultra-peripheral Pb+Pb collisions collected in 2023

*Results benefit from new Run 3 trigger based on ZDC at L1 + Pixel clusters at HLT*

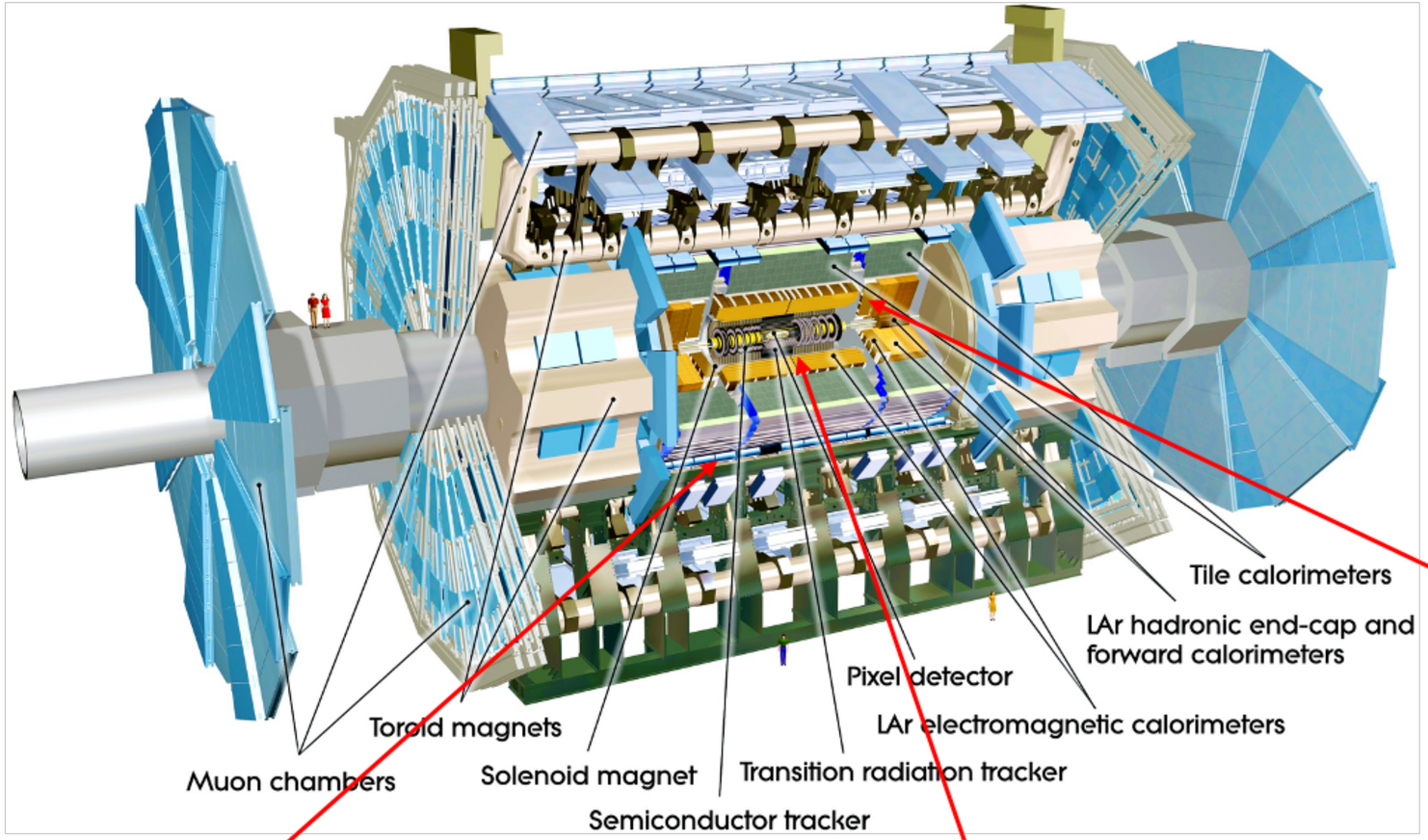
ZDC = zero-degree calorimeter

# High-Luminosity LHC (HL-LHC)

- **Higgs factory**: 190M Higgs bosons produced, precise Higgs couplings, self-interaction, VBS
- Sensitivity to rare processes and new physics
- Unique physics for many decades, complementary to FCC-ee Higgs / EW / Top Factory



# HL-LHC Upgrade




## 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

## High Granularity Timing Detector (HGTD)

Forward region ($2.4 < |\eta| < 4.0$)

Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

## New Muon Chambers

Inner barrel region with new RPC and sMDT detectors

## New Inner Tracking Detector (ITk)

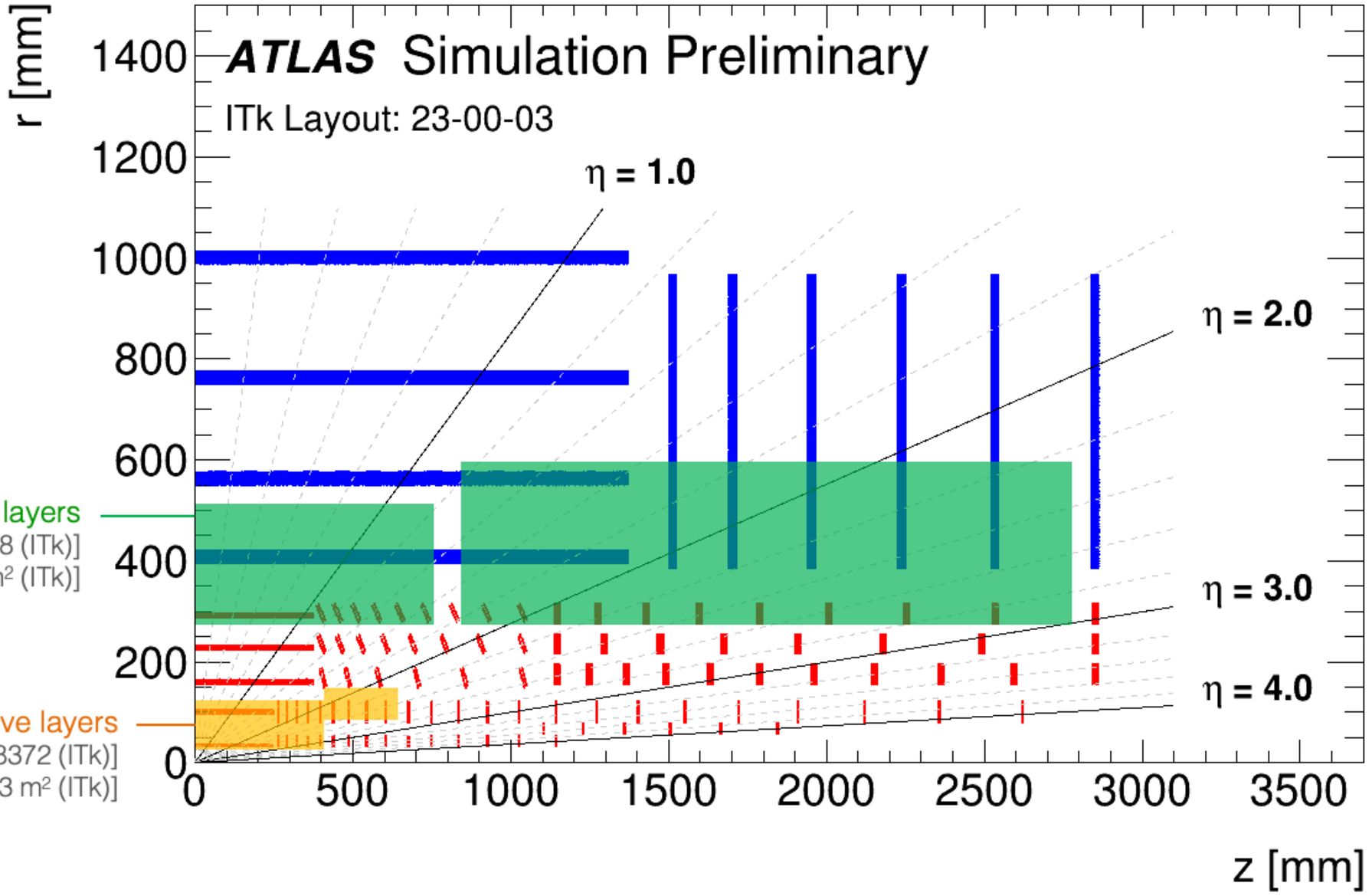
All silicon, up to $|\eta| = 4$

## Additional small upgrades

Luminosity detectors (1% precision goal)

HL-ZDC

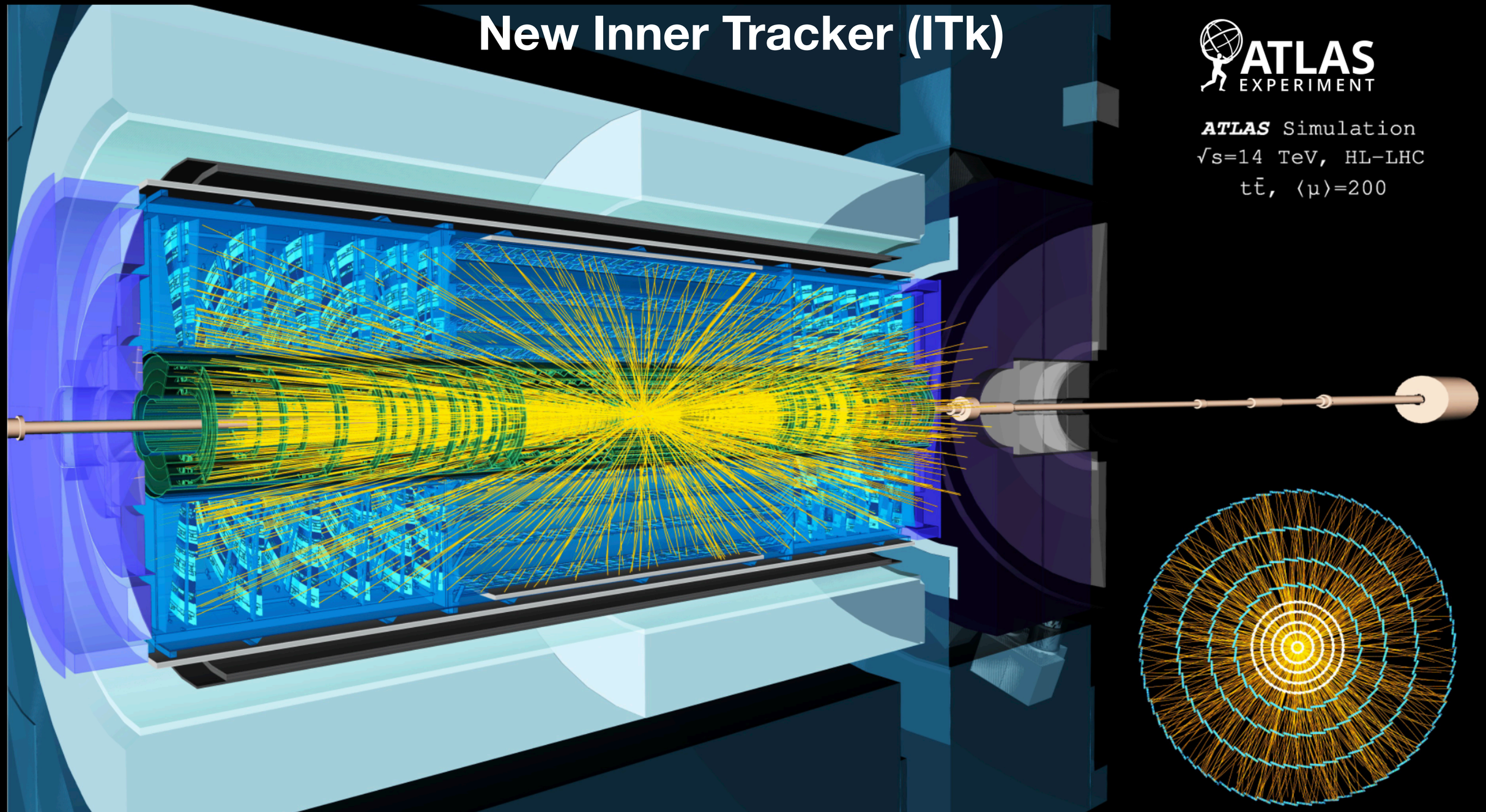
# HL-LHC Upgrade: New Inner Tracker (ITk)




Current SCT active layers
[4,088 modules → 17,888 (ITk)]
[61 m² silicon → 165 m² (ITk)]

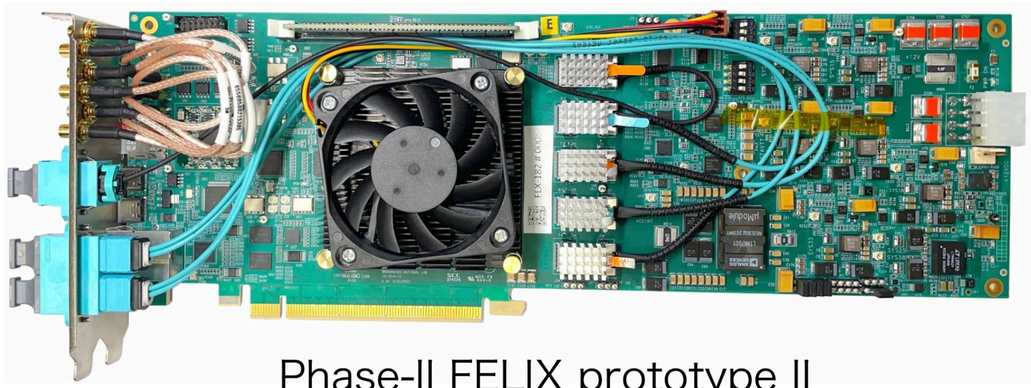
Current Pixel active layers
[2024 modules → 8372 (ITk)]
[1.7 m² silicon → 13 m² (ITk)]

# New Inner Tracker (ITk)

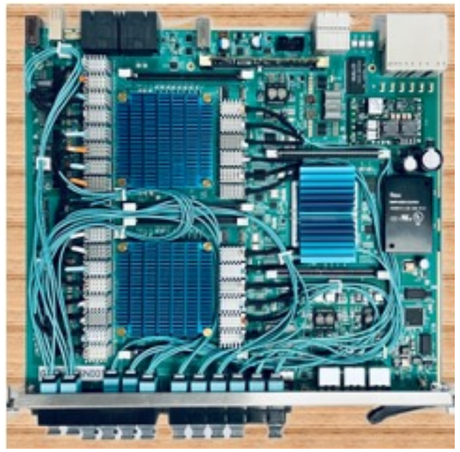



Display of a simulated ttbar event with μ = 200 (1600 tracks) in the ATLAS ITk

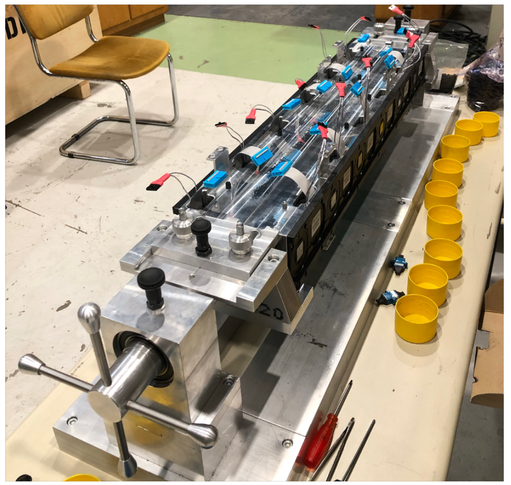
# HL-LHC Upgrade



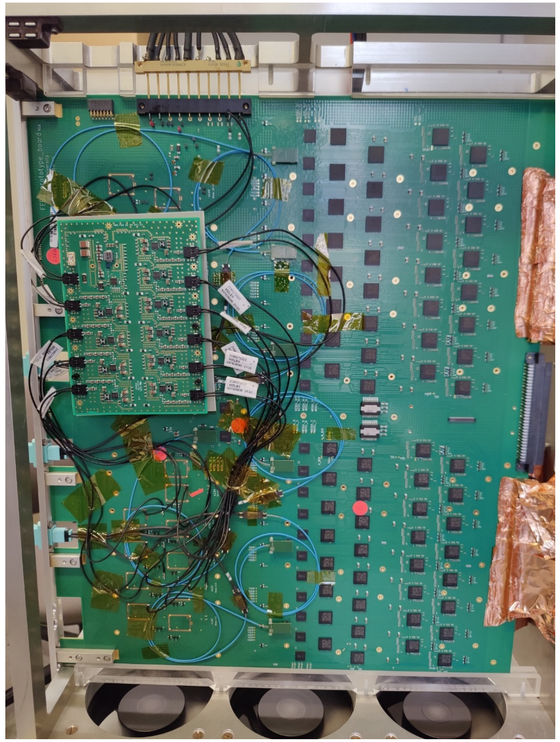
Phase-II FELIX prototype II



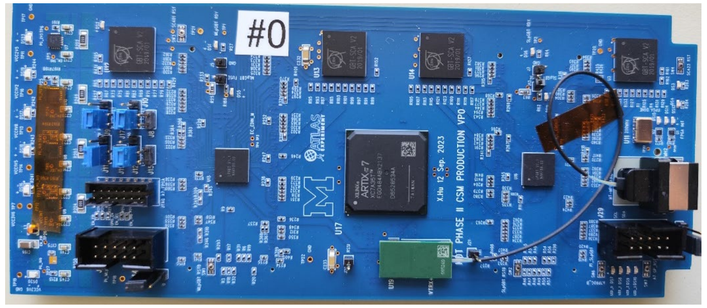
Global Trigger main board prototype



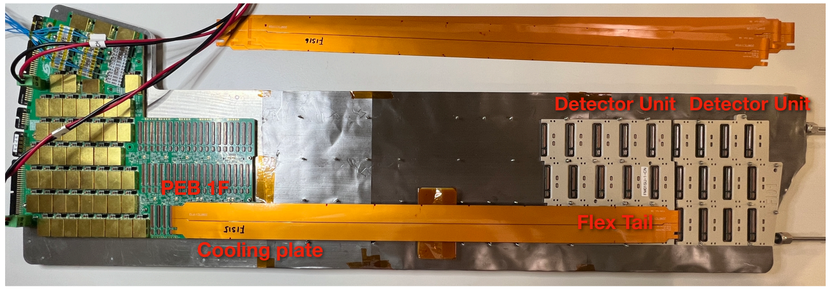
Tile Cal mini-drawer assembly



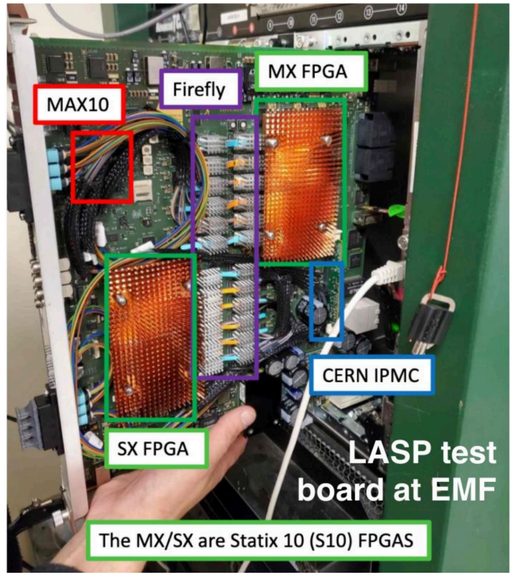
LAr FE board prototype



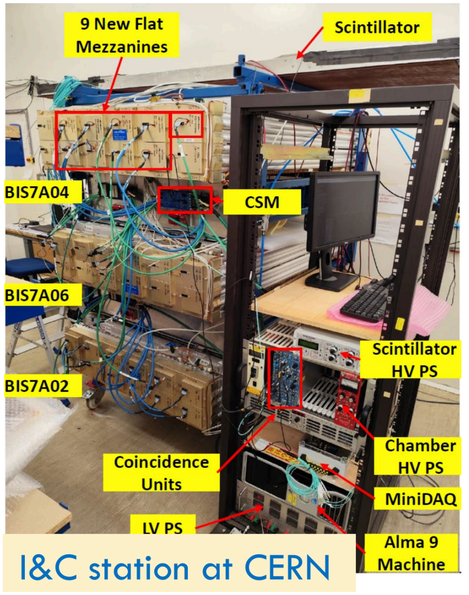

Muon Chamber Service Module board




HGTD peripheral elx board prototype

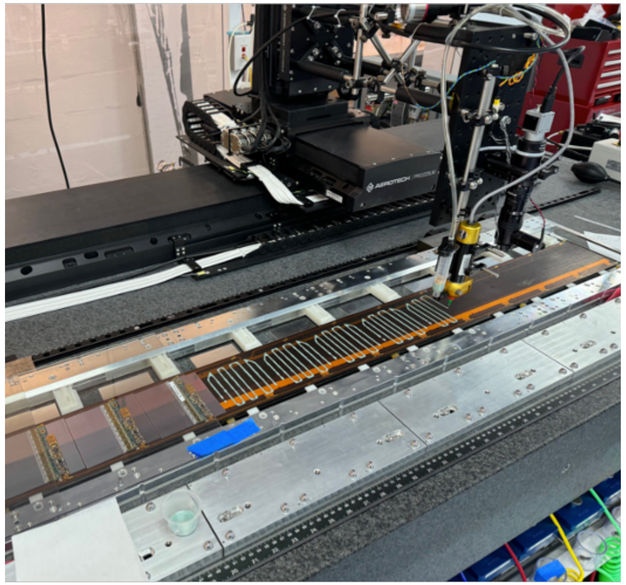



LAr Signal Processing test board



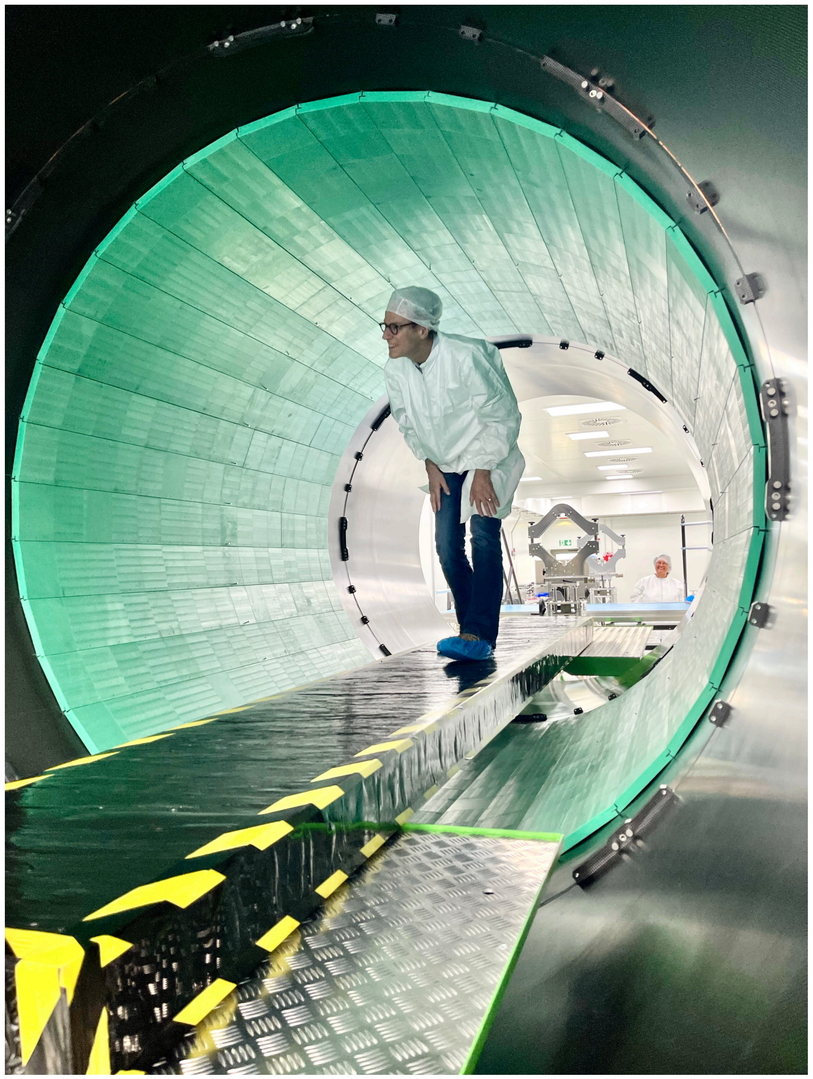

Muon test stand

# HL-LHC Upgrade

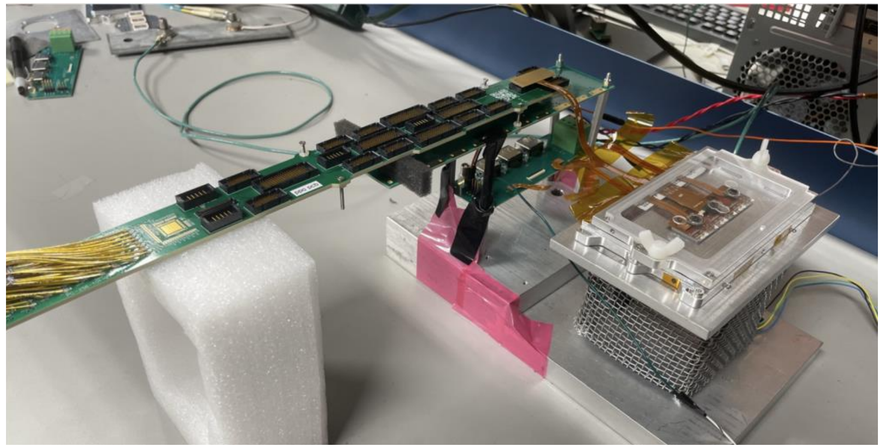


ITk Strip stave loading

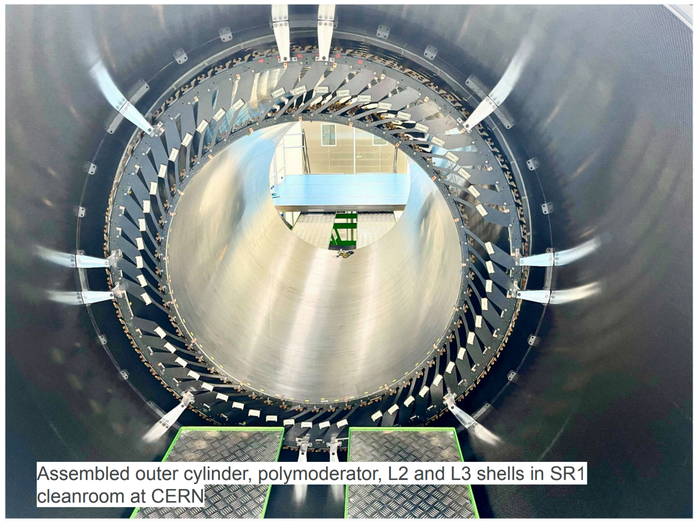
ITk surface assembly cleanroom @SR1



ITk outer cylinder polymoderator @SR1



ITk Pixel full data transmission test

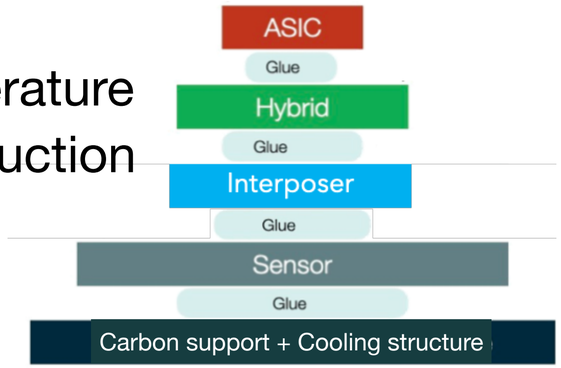


Assembled outer cylinder, polymoderator, L2 and L3 shells in SR1 cleanroom at CERN

ITk outer cylinder @SR1

# HL-LHC Upgrade

- **Status**
  - A lot of progress on all upgrade projects!
  - Many final design and production readiness reviews passed
- **ITk**
  - **ITk Pixel**: Production underway for sensors and ASICs, 2 (of 4) hybridization vendors started production, module assembly site qualification ongoing
  - **ITk Strip**: solution found for sensor cracking of mounted modules at low temperature Sensors, ASICs, EOS, bus-tapes, cores, etc. in production, sites ready for production




- **Other systems**
  - **LAr**: ASICs in production, finalizing electronic board design (FEB2, LASP)
  - **Tile**: good progress overall, comfortable contingency
  - **HGTD**: pre-production LGAD and ALTIROC hybrids under test; demonstrator tested w/ CO2 cooling
  - **Muon**: good progress on sMDT, finalise RPC readout electronics, gas-gap leaks fixed
  - **TDAQ**: good progress (online software, dataflow, EF Tracking technology choice, etc.)

# Conclusion

- **Run 2 & Run 3 performance & physics**
  - Many beautiful results continue to be released
  - Benefits from improvements in software, performance, analysis techniques, novel approaches
- **Run 3**
  - Phase-I upgrade complete —> enabling new trigger capabilities + data taking at unprecendented luminosities
  - Impressive LHC performance —> **Huge dataset for physics analysis, many opportunities**
- **HL-LHC**
  - Much progress in Phase-II upgrade efforts
  - **Top priority for particle physics** (2020 European Strategy and 2023 US P5)
  - Crucial physics program for particle physics, stepping stone toward future colliders
- ***Looking forward to continued and growing strong contributions from South Africa***

# Auxiliary material

# Run 3: What's new?

- **Upgraded ATLAS detector & TDAQ**
  - **New Small Wheel** of Muon Spectrometer $(1.3 < |\eta| < 2.7)$ for level-1 trigger rate reduction and increased redundancy (16 layers instead of 4 for CSC)
  - **Liquid-argon calorimeter digital electronics / TDAQ** with 10x increase in granularity for L1 trigger —> improved $e, \gamma, \tau$, jet triggers + enhanced L1Topo
  - **TDAQ upgrades** (Run 2 —> Run 3)
    - HLT physics stream: 1 kHz —> 1.7 kHz
    - HLT delayed stream: 0.2 kHz —> 1.6 kHz (e.g. VBF H —> inv., HH —> 4b)
    - Increased use of trigger-level analysis, full-detector tracking for hadronic signatures, large-impact parameter tracking (online & offline)