Results of the new MAPS-based ALICE inner tracker operation in the LHC Run 3

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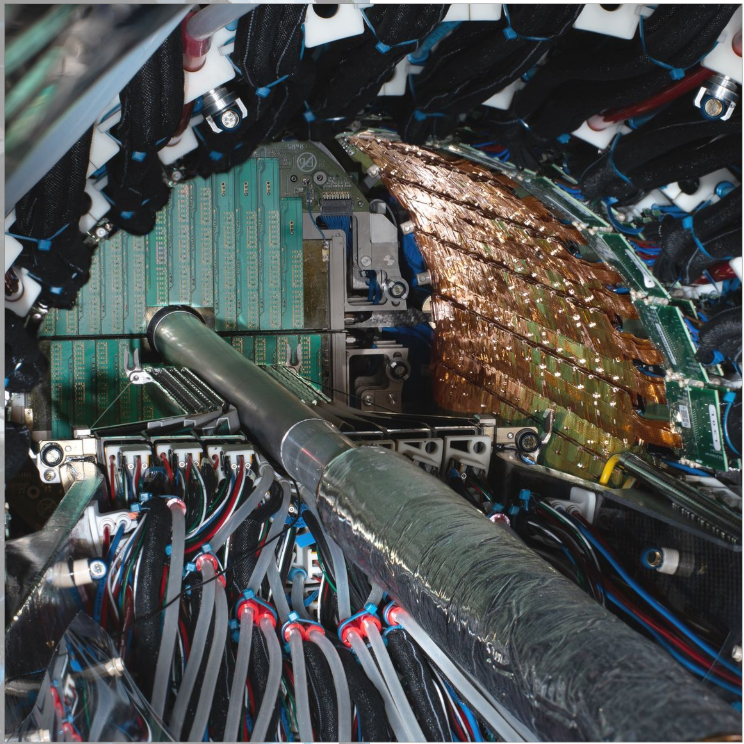
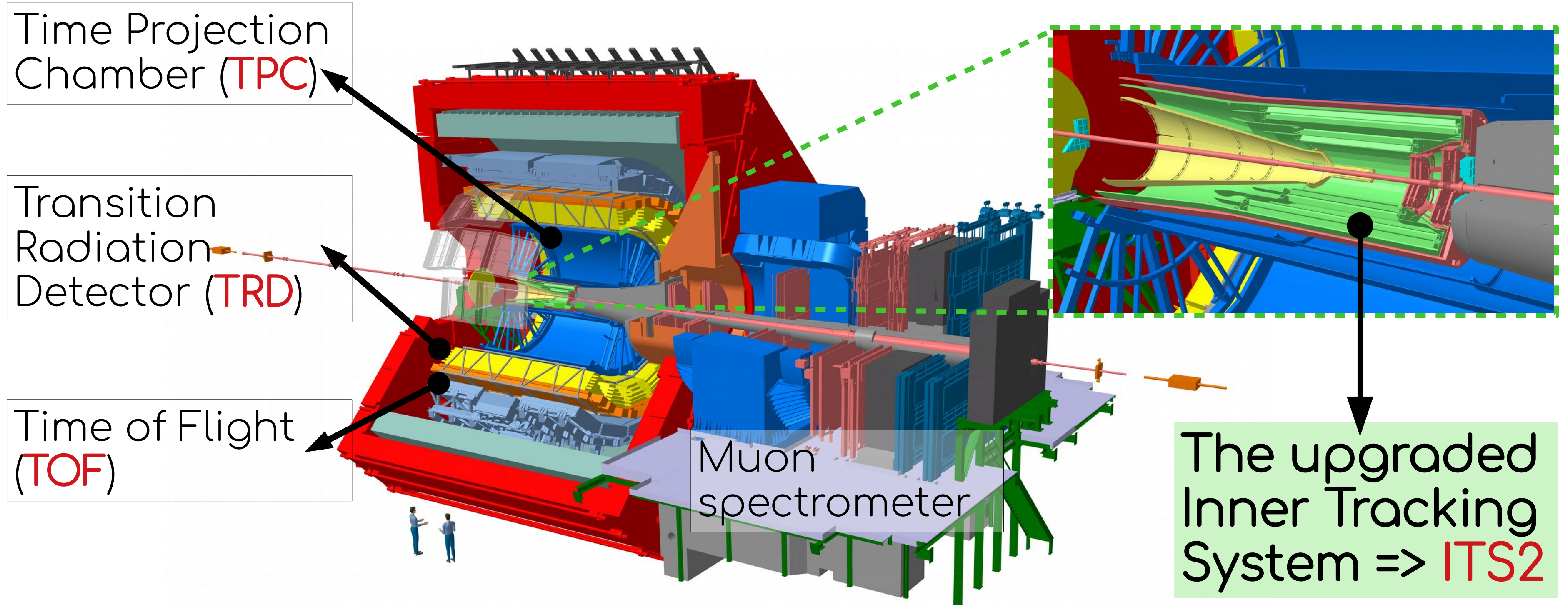


Introduction – ALICE experiment

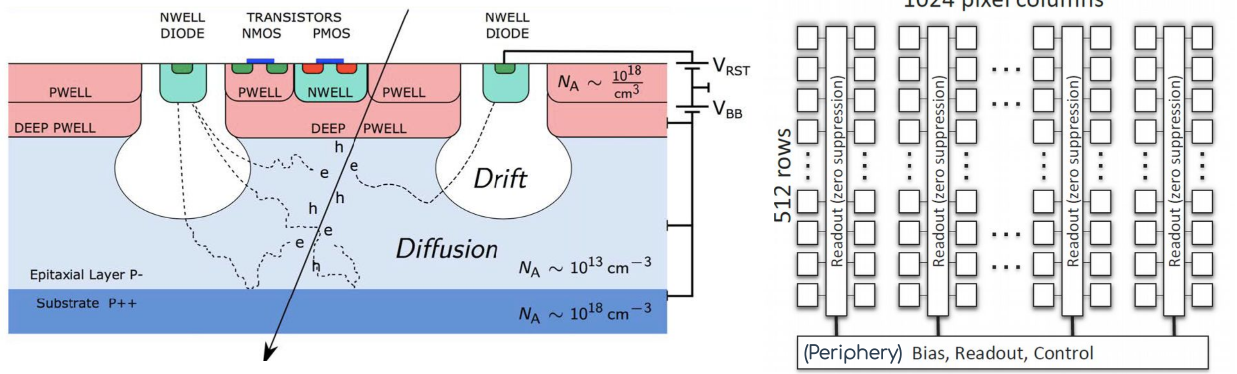
- Run 2 of LHC completed in 2018 with Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- Long-shutdown 2 started in 2018 to allow detector & computing system upgrades

Run 3 apparatus

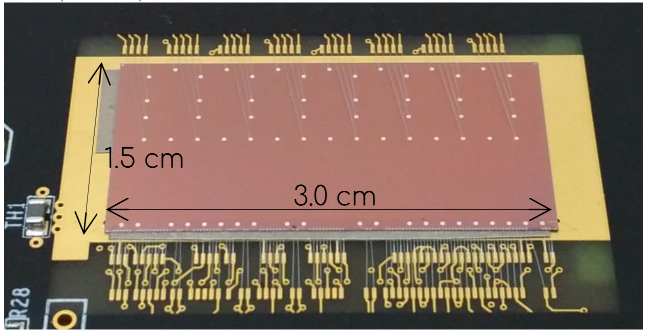


ALPIDE chip – the detector core

→ ALice PIxel DEtector



Example: chip bonded on its carrier board



- TowerJazz 0.18 µm CMOS imaging process – a Monolithic Active Pixel Sensor (MAPS)
  - High resistivity p-type epitaxial layer on p-type substrate
  - Small n-well diode → small capacitance ~fF
  - In-matrix sparsification using priority encoder
  - Pixel signal amplified and digitized at a pixel level
  - Low power consumption
  - Pixel data sent towards periphery to the Data Transmission Unit (Serializer + PLL + LVDS driver)

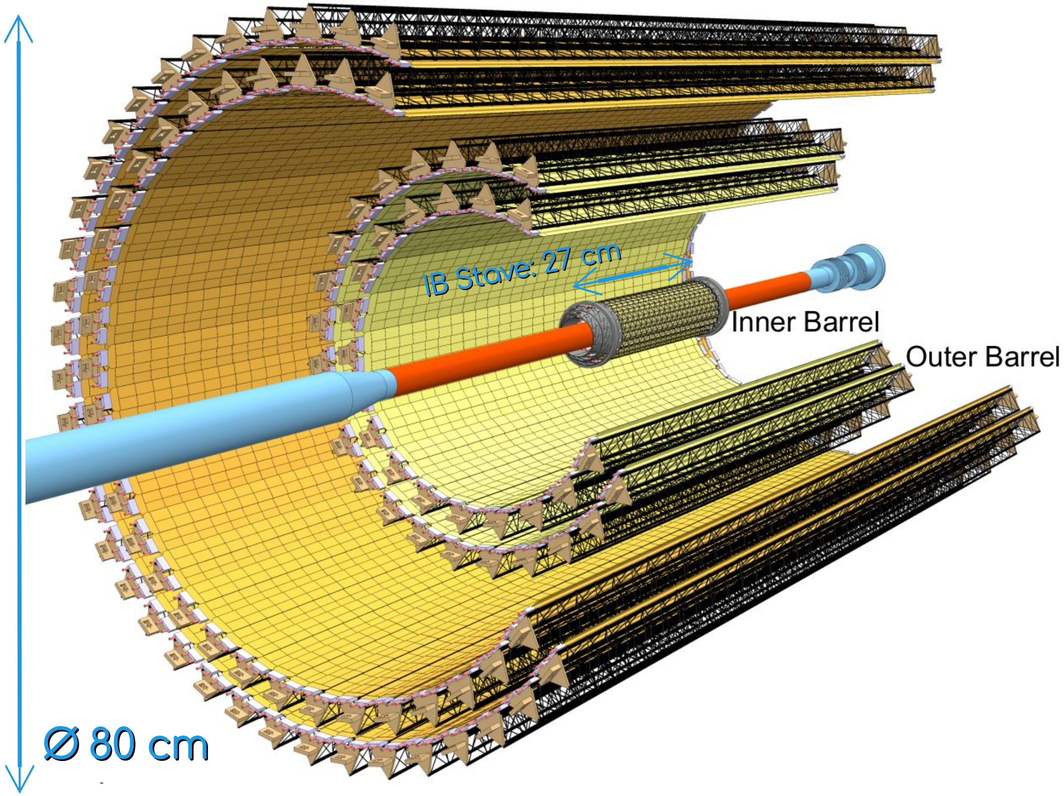
Key numbers

Resistivity	1 ÷ 6 kΩcm
Epitaxial layer thickness	25 µm
N-well diode diameter	2 µm
Power consumption	≤ 47 mW/cm^2
Pixel size	27x29 µm^2
Spatial resolution (rφ,xz)	5x5 µm^2

Introduction – The Upgraded Tracker (ITS2)

→ 10 m² of monolithic active pixel sensors (12.5 GPixels)

ALICE



Inner Tracking System (ITS)

Inner Barrel (IB)

- 3 layers (**L0 → L2**)
- 48 Staves made of 9 ALPIDE chips each
- Material budget: **0.36%** X_0
- **Readout at 1200 Mb/s per chip**

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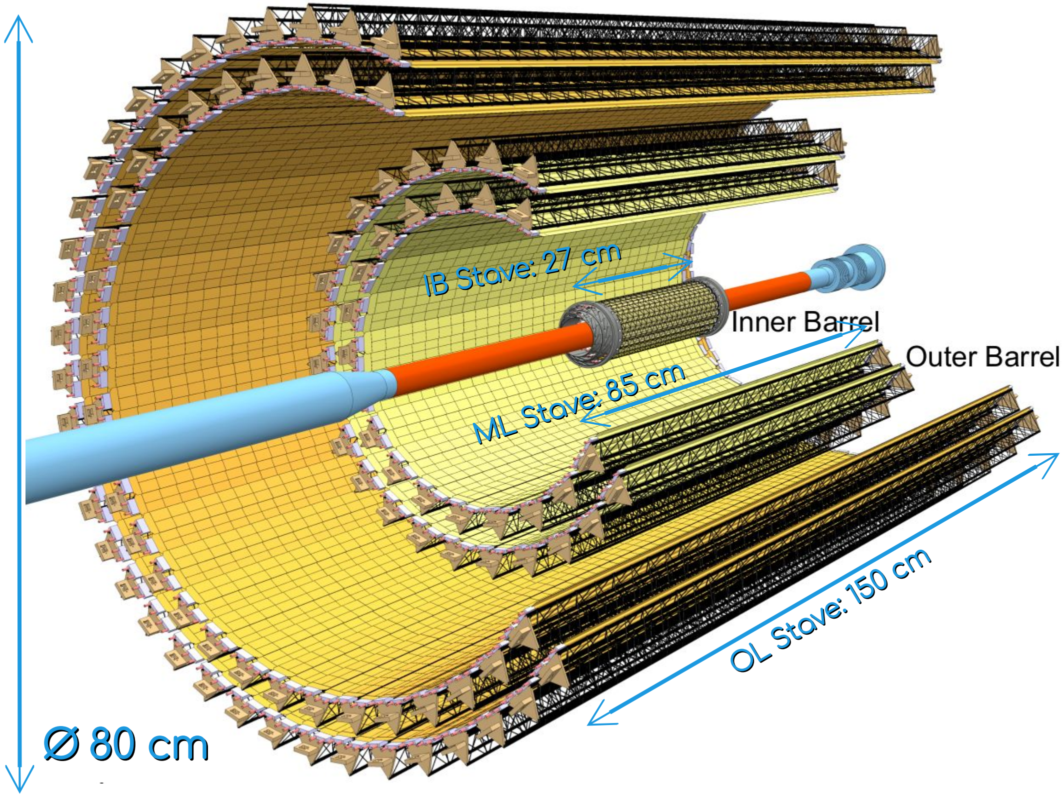
ALICE



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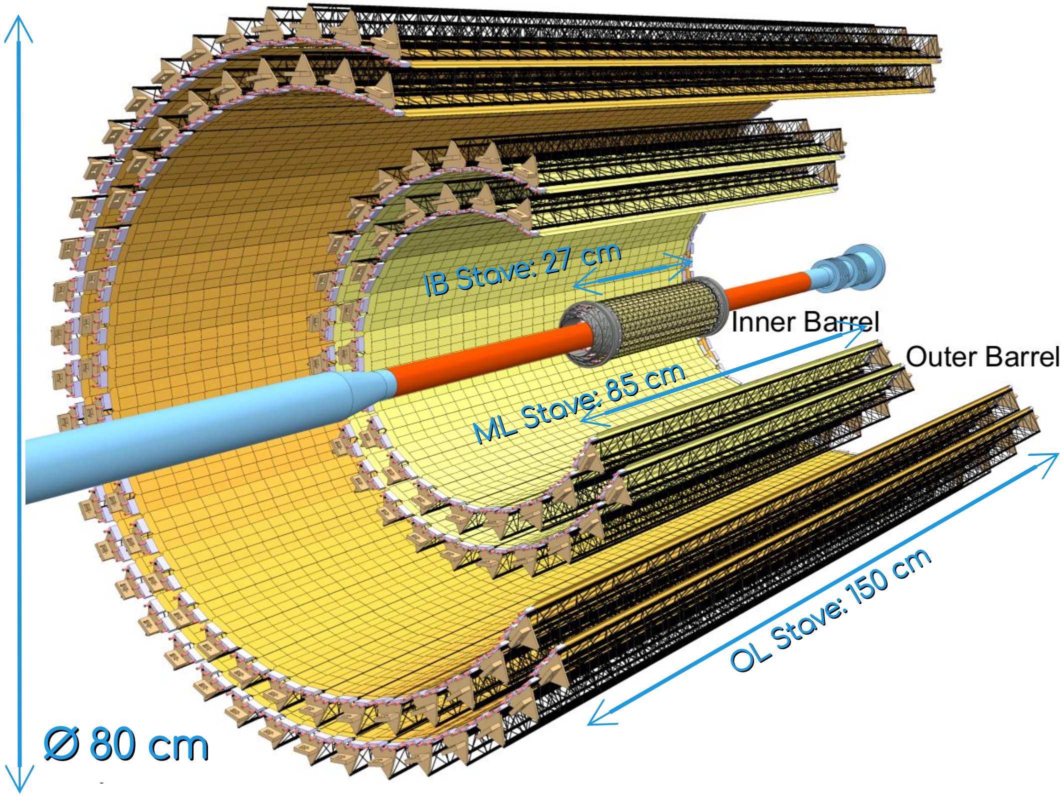
Outer Barrel (OB)

- 4 layers – 2 Middle + 2 Outer Layers (**L3 → L6**)
- ML(OL): 54(90) Staves with 112(196) ALPIDE chips each
- Material budget: **~1.1% X_0**
- **Readout of 7 chips with single link at 400 Mb/s**

Introduction – The Upgraded Tracker (ITS2)

→ 10 m² of monolithic active pixel sensors (12.5 GPixels)

ALICE



Inner Tracking System (ITS)

24k chips
12.5 Gpix

Inner Barrel (IB)

- 3 layers (**L0 → L2**)
- 48 Staves made of 9 ALPIDE chips each
- Material bu
- **Read**

The largest MAPS-based detector ever built in HEP experiments

Outer Ba

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- ML(OL): 54(90) Staves with 112(196) ALPIDE chips each
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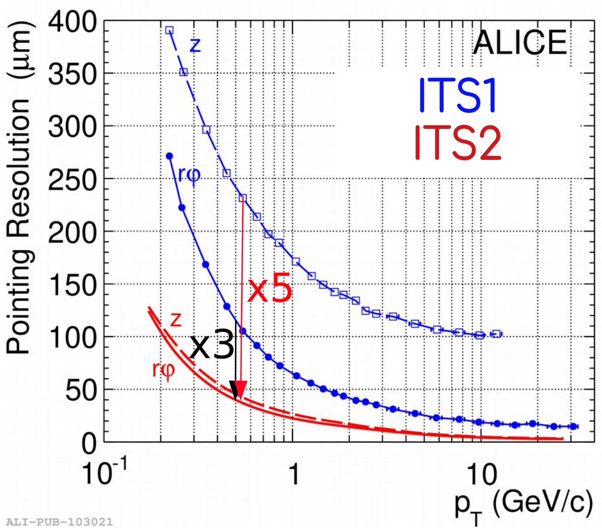
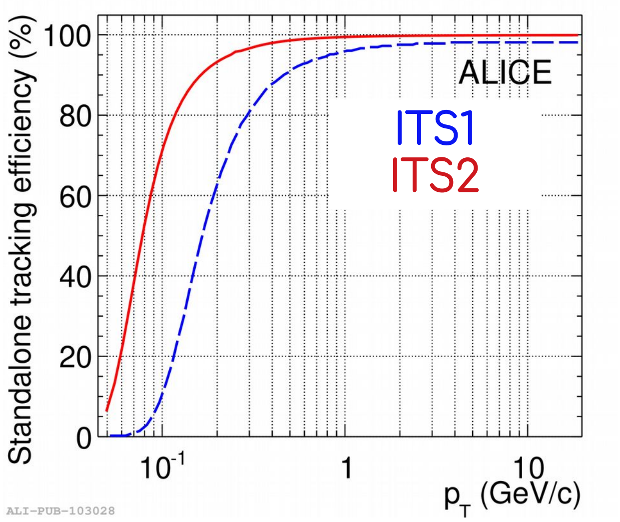
Expected improvements with ITS2

Pointing resolution ($r\varphi$ & z)



Tracking efficiency

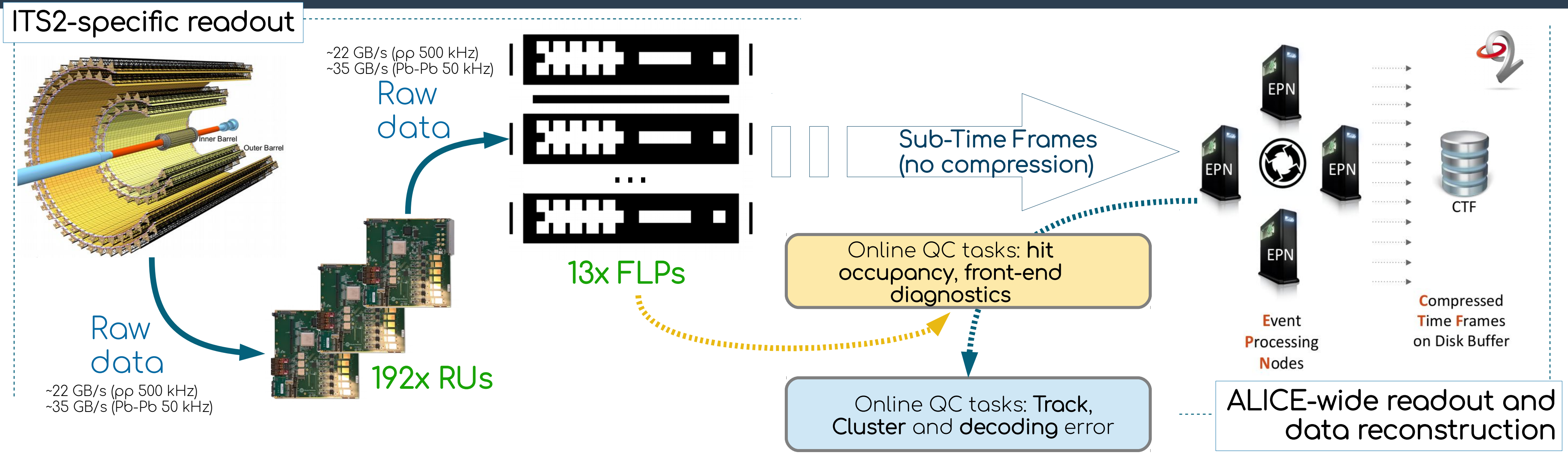


- **Improved impact parameter resolution**: factor ~5 (z), factor ~3 ($r\varphi$) at p_T = 500 MeV/c
- **Improved standalone tracking efficiency:** 60% → 90% at p_T = 200 MeV/c

Data readout architecture and quality control (QC)

→ a simplified view

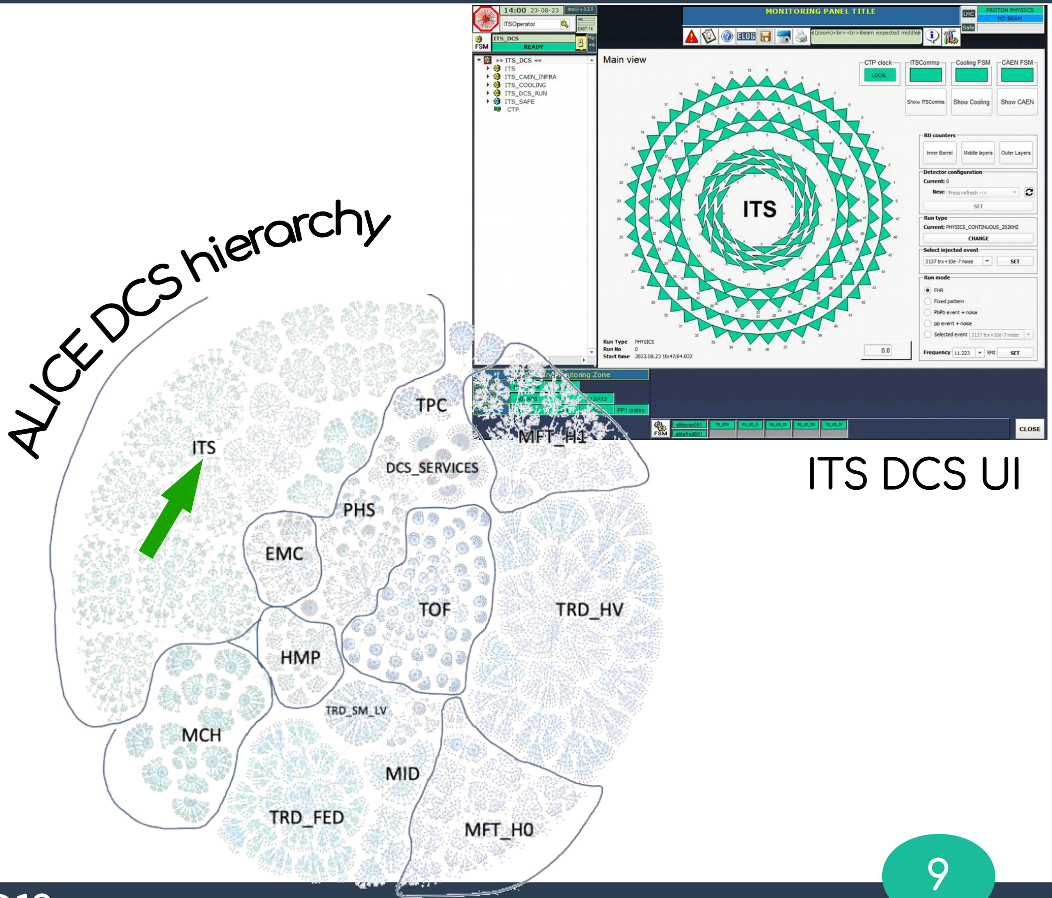
ALICE



- 13 ITS First Level Processors (FLPs)
  - Online data quality control tasks: hit occupancy and front-end electronics diagnostics.
- 340 Event Processing Nodes (total EPN from ALICE farm)
  - Online quality control tasks: reconstructed ITS2 tracks, clusters and decoding errors.
- Synchronous reconstruction, calibration and data compression (→ GPUs)
- Asynchronous stage: reconstruction with final calibration → final Analysis Object Data (AOD)

Detector Control System (DCS) - a quick view

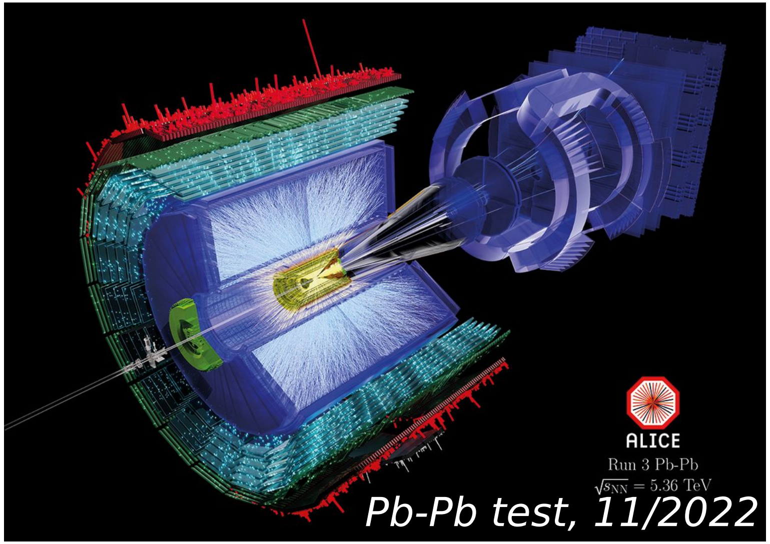
- User Interface developed in **WinCC** – detector logic implemented in a **Finite State Machine**
- **Detector operation, monitoring and archiving of detector data.**
- Deal with **~110000 data points (ITS only)** → **typical monitoring frequency of 1 Hz.**
- **Built as a hierarchical system** (partitioned with system of locks) → ITS occupies a big slice of the ALICE hierarchy
- An **independent safety system** interlocks power channels based on stave temperatures and cooling status



ITS DCS UI

Run 3 overview

- Started on 2022, July 5th with first pp collisions at √s = 13.6 TeV (*stable beams*)
- Pb-Pb ion test in November 2022: record energy 5.36 TeV
- Integrated luminosity so far (pp collisions): ~28 pb^{-1}
- ALICE & ITS2 numbers in data taking
  - Nominal ITS framing rate: 202 kHz
  - ALICE standard luminosity: 500 kHz (instantaneous luminosity ~10^{31} cm^{-2} s^{-1})
  - ITS2 successfully tested up to 4 MHz interaction rate (~ 50 GB/s data rate).
  - Loss of acceptance during runs auto-recovered by DCS
- At every beam dump: fast ITS threshold scan on 2% of the pixels to evaluate the quality of the detector calibration



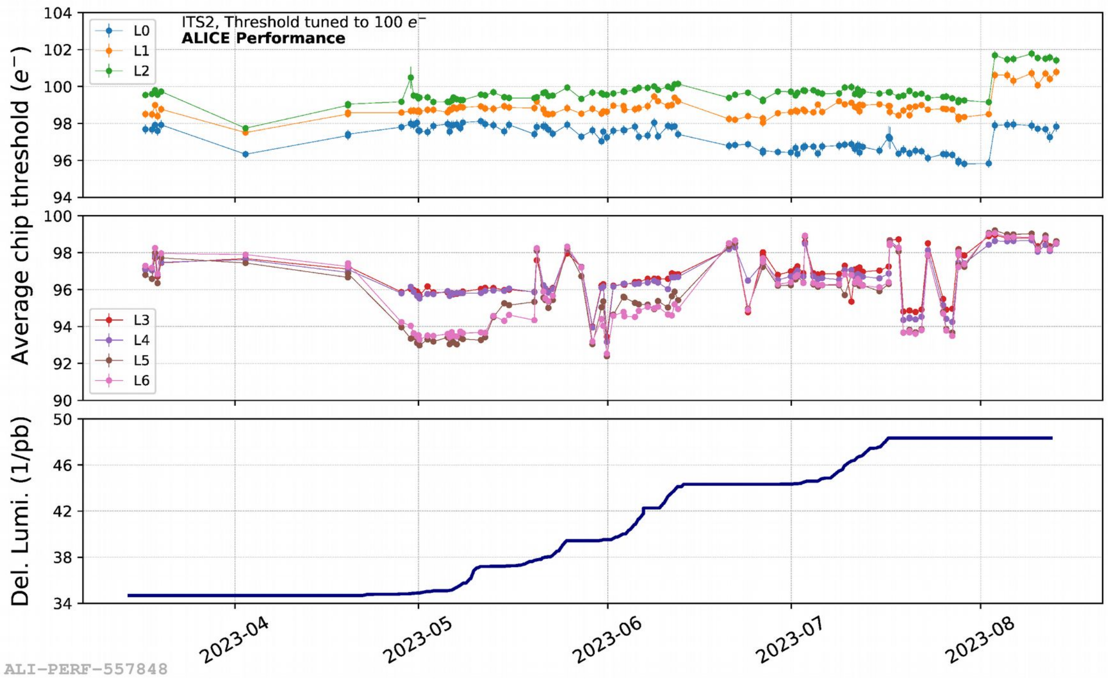
- Main events till next technical stop
  - Week 37: pp reference runs
  - October: Pb-Pb ion runs

Performance results in Run 3

→ ITS2 full calibration (1)

ALICE

- Main ITS calibration parameters:
  - Masking of noisy pixels
  - Tuning of in-pixel discriminating thresholds
  - Power supply voltage
  - On-chip temperatures
- Percentage of non-working pixels: ~0.2 %
- Threshold calibration of 24120 chips is challenging:
  - Online calibration workflow runs on 40 EPNs with parallel processing
  - Pulsing of ~1% of the pixels: ~252Ghits
  - Thresholds: tuned to 100e- (in-layer RMS < 5-6 e-)

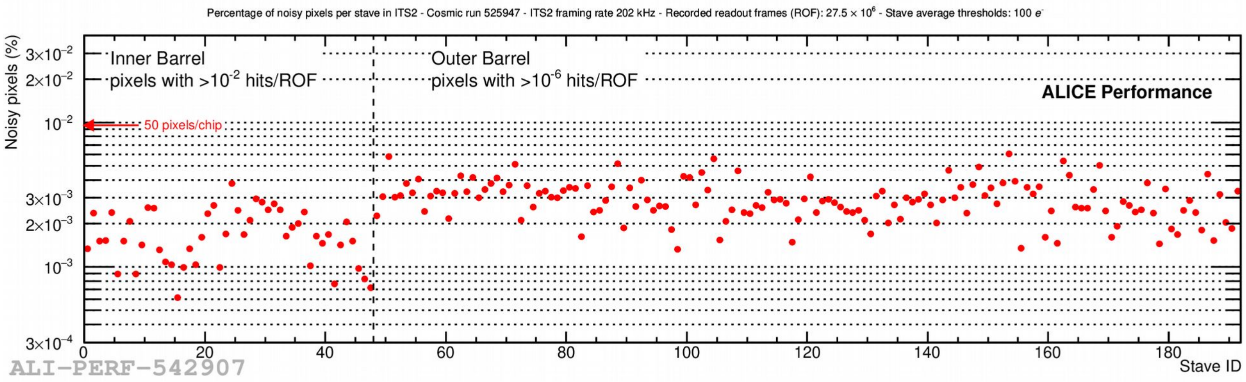


Thresholds are observed to be stable during 2023 operations without retuning

Fluctuations of 2-3 e- due to optimizations of the voltage to chips

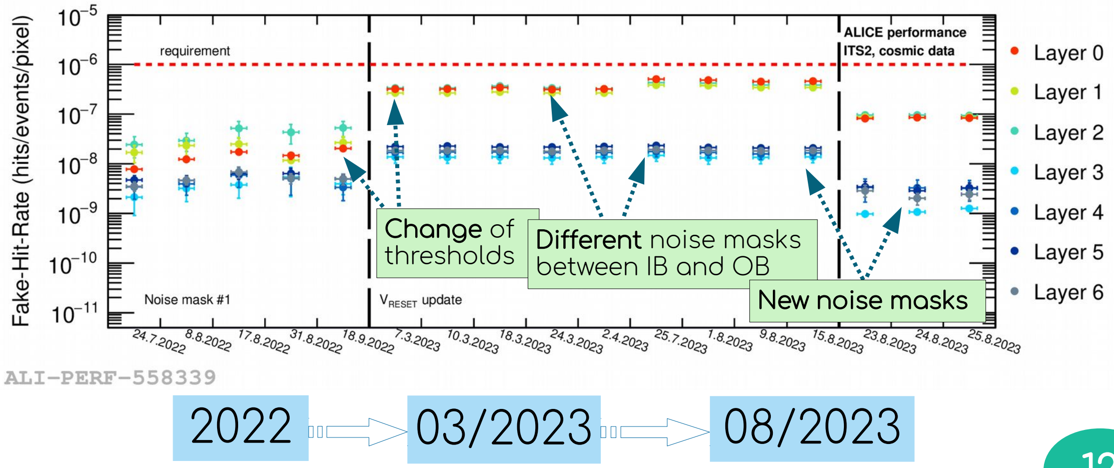
Performance results in Run 3

→ ITS2 full calibration (2)



- Noisy pixel definition:
  - IB: occupancy > 10^{-2} hits/event
  - OB: occupancy > 10^{-6} hits/event
- Percentage of noisy pixels masked per stave is extremely small: ~0.02-0.03 ‰

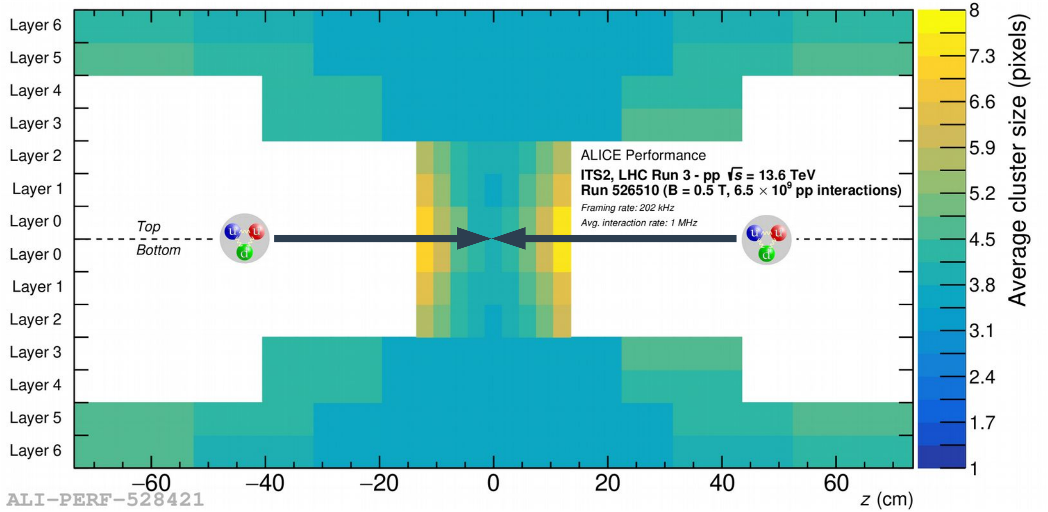
- Fake-hit rate trend during cosmic runs (tuned thresholds + noise masks)
- Stable and < 10^{-6} hits/event/pixel (*design requirement*) by masking only ~0.03‰ of the pixels



Preliminary performance results in Run 3

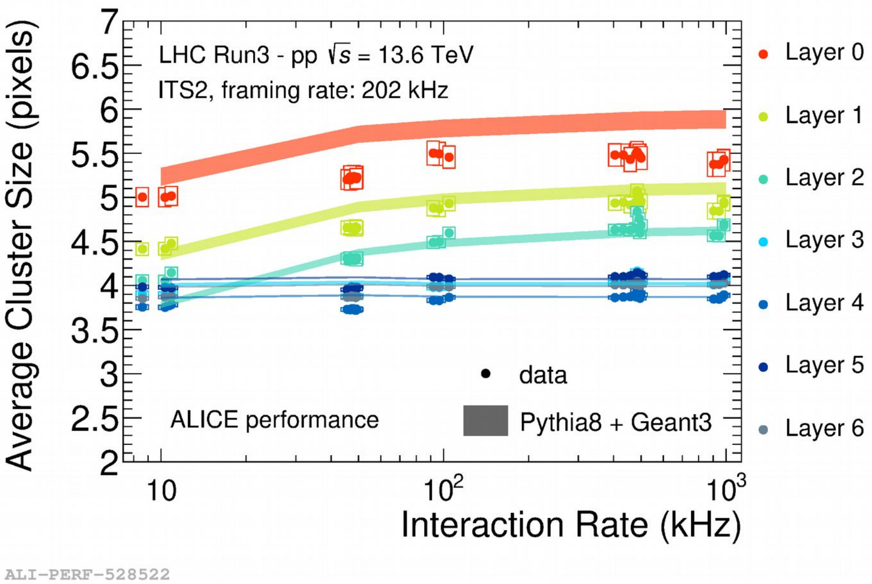
→ *Cluster size and simulation*

- Cluster size averaged for half barrels
  - Between 3 and 8 pixels depending on η
  - RMS ranging on the same interval
  - Observed to be stable over time
  - Independent of the interaction rate



Cluster size (pix)

- Simulation with Pythia 8 + Geant 3
  - Simulated noise: $2x10^{-8}$ hits/event/pix (IB), $3x10^{-9}$ hits/event/pix (OB)
  - Good agreement with data considering approximations:
    - Average noise per barrel and not per stave/chip.
    - Limited statistics in MC: ~20k events.

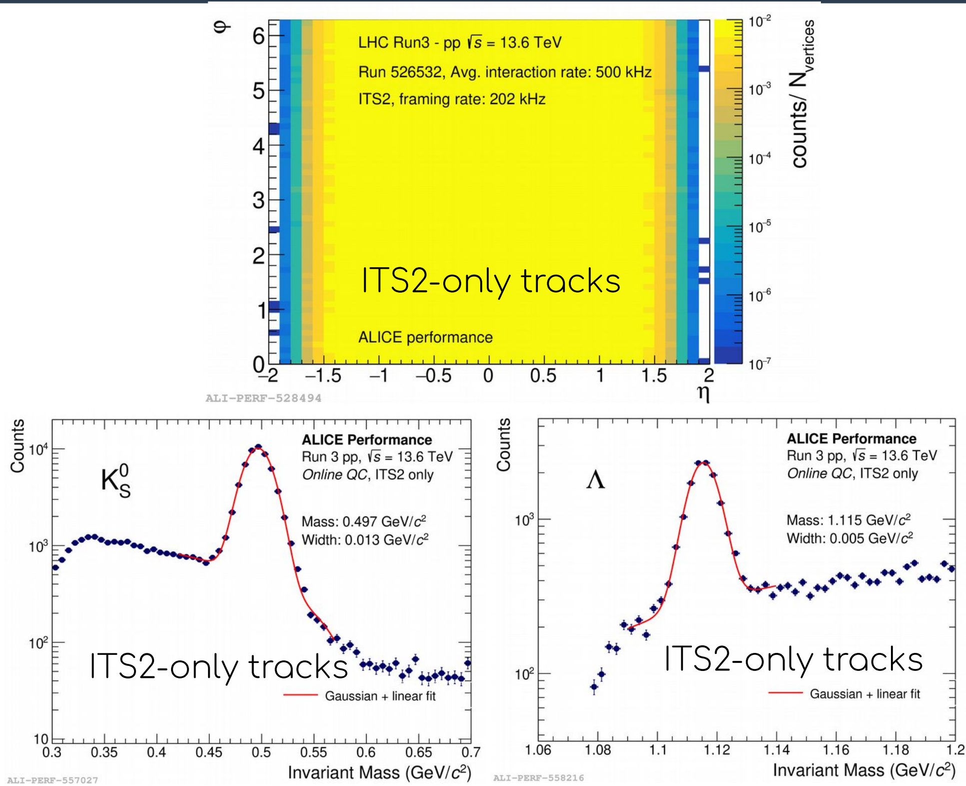


Cluster size vs IR

Preliminary performance results in Run 3

→ Detector alignment and reconstructed tracks

- ITS tracking: excellent performance with current detector alignment
  - Cellular automaton algorithm
  - Online tracking for quick QA of the data
  - Angular distribution of tracks of good quality → good detector acceptance
- Online physics performance from QC through Λ and K^0_S invariant mass peaks

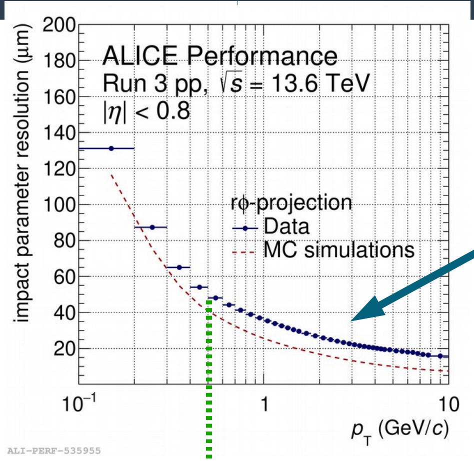


Λ, K^0_S invariant mass peaks from online QC

Preliminary performance results in Run 3

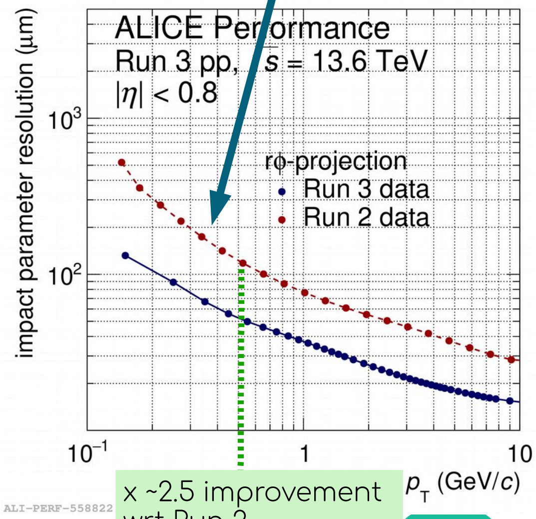
→ Detector alignment and reconstructed tracks

- ITS tracking: excellent performance with current detector alignment
  - Cellular automaton algorithm
  - Online tracking for quick QA of the data
  - Angular distribution of tracks of good quality → good detector acceptance
- <u>Online</u> physics performance from QC through Λ and K^0_S invariant mass peaks
- Impact parameter resolution measured with Run 3 pp data → <u>excellent performance</u>
  - About 2.5x improvement at p_T = 500 MeV/c ⟶ **Detector alignment, space charge corrections and calibrations still continuously improving**
  - ~20% discrepancy with MC could be related to a mismatch of sensor response in simulation and residual misalignments in data



~20% discrepancy with MC

Global tracks with at least 1 hit in Inner Barrel (Run 3) or in the two innermost pixel layers (Run 2)



x ~2.5 improvement wrt Run 2

Conclusions

- **Run 3 started on July 5th 2022**
  - pp collisions at $\sqrt{s}$ = 13.6 TeV, nominal interaction rate at 500 kHz.
- **Pb-Pb collisions in October 2023 before the year-end closure**
  - Major event of the year for ALICE
- **Excellent performance of ITS2 in Run 3**
  - ITS2 performance is within expectations → no showstoppers for upcoming Pb-Pb.
- **Detector Control System and Quality Control system**
  - Ready to monitor the detector hardware and data in Run 3

The ITS2 Collaboration

CERN (Switzerland), **CCNU** (China), **Řež u Prahy** (Czech Republic), **Strasbourg** (France), **LIPI** (Indonesia), **Alessandria** (Italy), **Bari** (Italy), **Cagliari** (Italy), **Catania** (Italy), **LNF** (Italy), **Messina** (Italy), **Padova** (Italy), **Pavia** (Italy), **Torino** (Italy), **Trieste** (Italy), **Nikhef** (The Netherlands), **UoB/BUC** (Bergen, Norway), **Oslo** (Norway), **COMSATS** (Pakistan), **Inha** (Republic of Korea), **Yonsei** (Republic of Korea), **PNU** (Republic of Korea), **St. Petersburg** (Russia), **Kosice TU** (Slovakia), **Kosice Slovak Academy** (Slovakia), **SUT** (Thailand), **Kiev BITP** (Ukraine), **Liverpool** (United Kingdom), **Daresbury** (United Kingdom), **Austin** (United States), **LBNL** (United states), **ORNL** (United States)

Conclusions

- Run 3 started on July 5th 2022

The ITS2 Collaboration

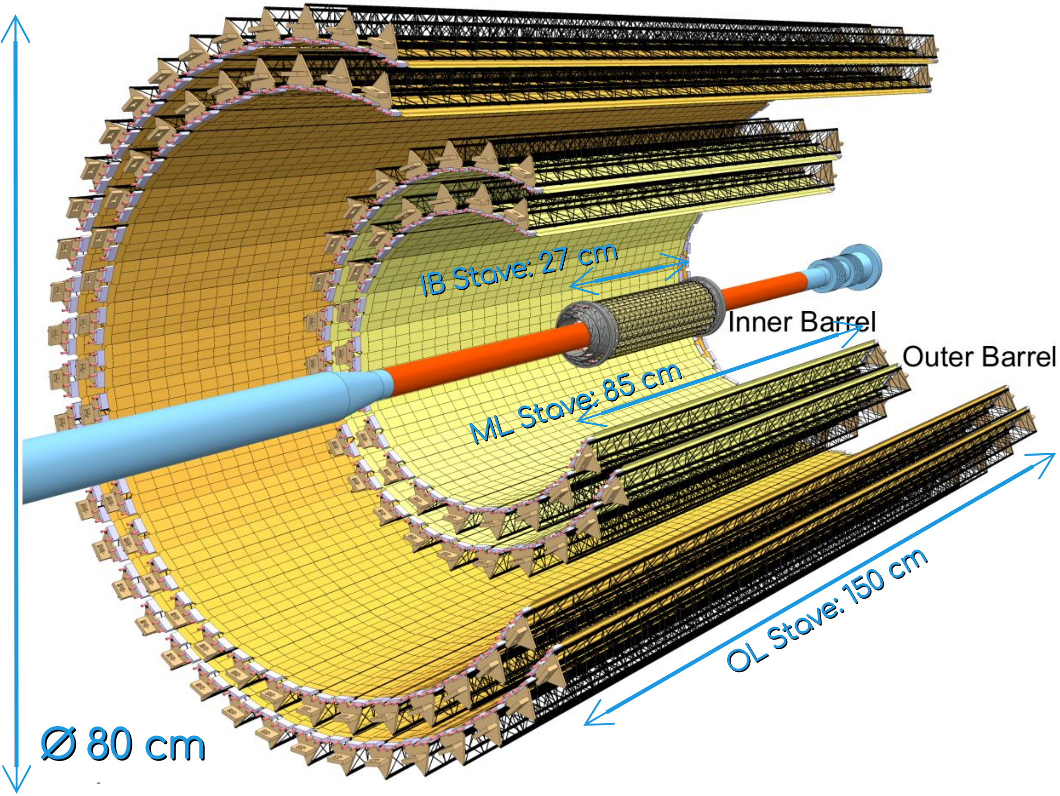
system

  - Ready to monitor the detector hardware and data in Run 3

(Slovakia), **SUT** (Thailand), **Kiev BITP** (Ukraine), **Liverpool** (United Kingdom), **Daresbury** (United Kingdom), **Austin** (United States), **LBNL** (United states), **ORNL** (United States)

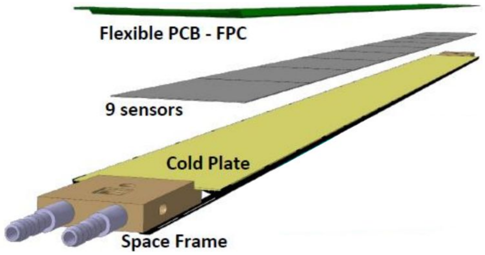
Backup slides

ITS2 – details on components

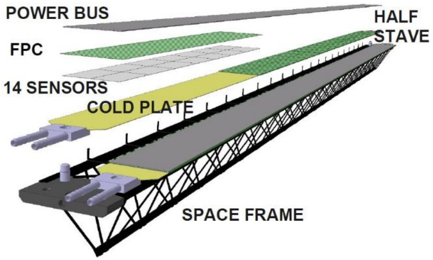


Inner Tracking System (ITS)

Inner Barrel Stave



Outer Barrel Stave



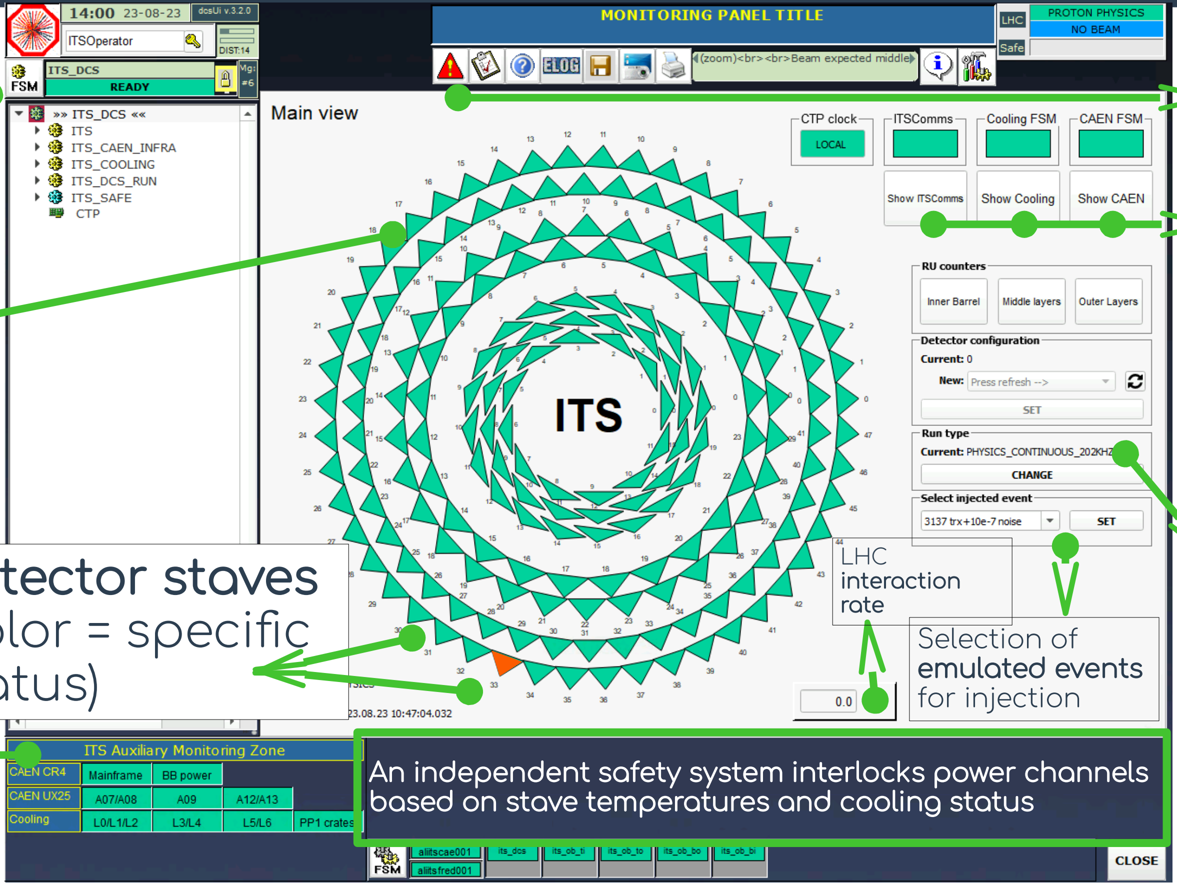
Detector Control System (DCS) - a quick view

Finite State Machine (FSM): detector status and operations

Click: **stave status** (voltages, currents, temperatures, readout electronics)

Detector staves (color = specific status)

Auxiliary monitoring: CAEN, cooling, ...



An independent safety system interlocks power channels based on stave temperatures and cooling status

Alarm screen: list of alarms

CAEN, Cooling and monitoring software statuses

Detector configuration and selection of **run types** (physics, calibration)

(Data) Quality Control (QC)

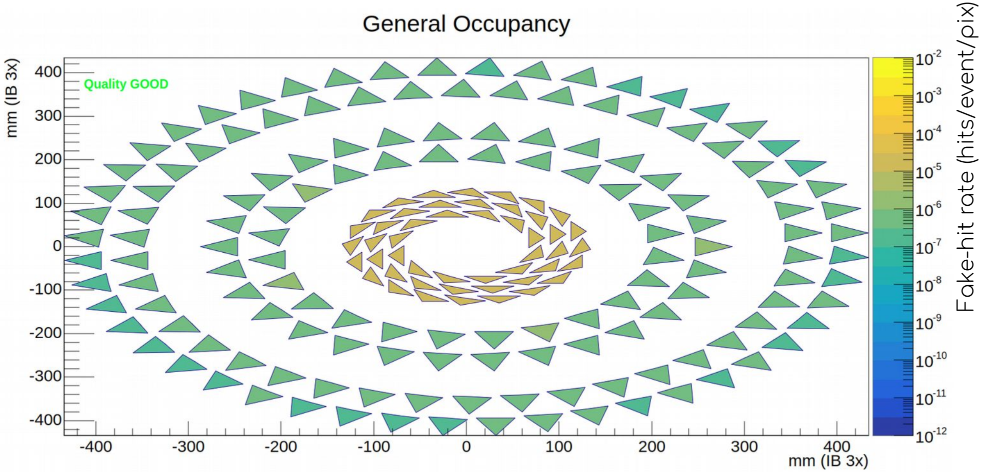
ALICE

7 QC online tasks
(online monitoring on data subsets)

- **Fake-hit rate**: monitoring of detector FHR and noisy pixels
- **Noisy pixels**: for detector noise calibration
- **Calibration**: monitoring of pixel threshold and dead pixels.
- **Cluster**: monitoring cluster size, topology, etc.
- **Tracks**: monitoring of track multiplicity, angular track distribution, clusters, etc.
- **Front-end Electronics**: chips in error, trigger flags
- **Decoding errors:** summary of decoding errors per chip

... and

5 online post-processing tasks + offline post-processing framework/macros → trending vs run



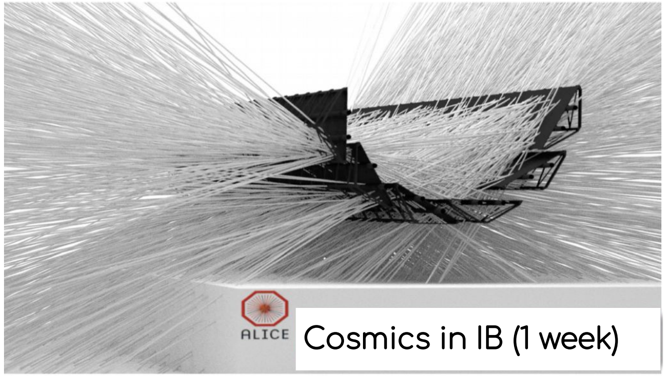
Example: detector average occupancy per stave in pp $\sqrt{s}$ = 13.6 TeV (500kHz IR, 202 kHz framing rate)

QA of data done on a daily basis

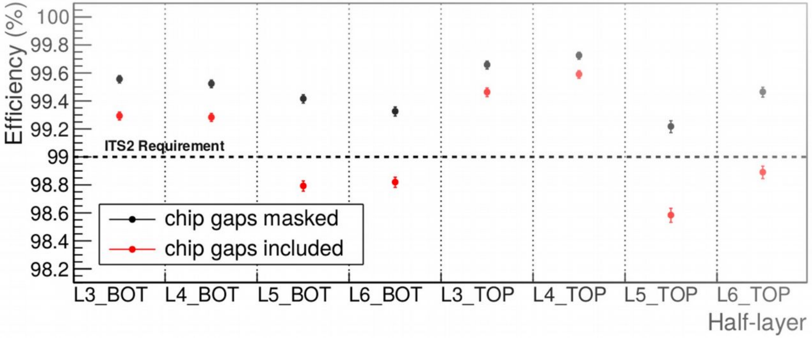
On-surface commissioning overview - 2019/2020

- Commissioning of the full detector in the laboratory before installation in the ALICE cavern
  - Sept 2019 → Dec 2020
- Continuous data taking: cosmic + calibration runs
  - 24/7 shifts + operations by detector experts

Half-barrels in the CERN cleanroom



Cosmics in IB (1 week)



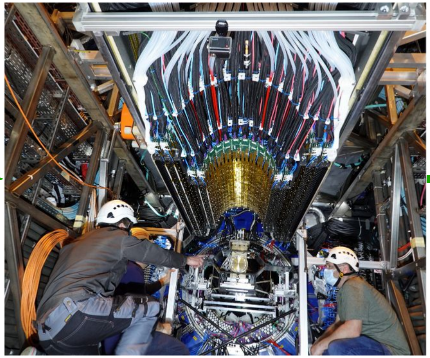
Efficiency with cosmic tracks (OB)

ITS installation inside ALICE cavern - 2021

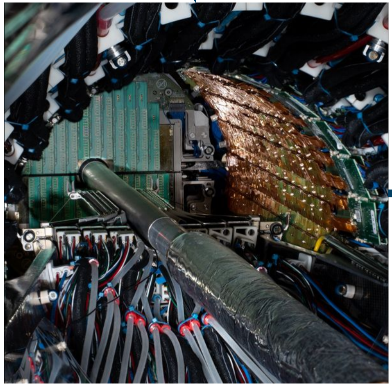
→ a trip from lab to ALICE cavern

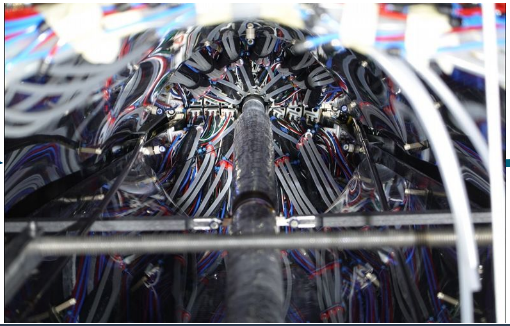
- ITS installation in ALICE cavern started in 2021 after a **successful on surface commissioning from Sept/2019 to Dec/2020**
- OB installation completed in March 2021 → IB installation completed in May 2021

OB

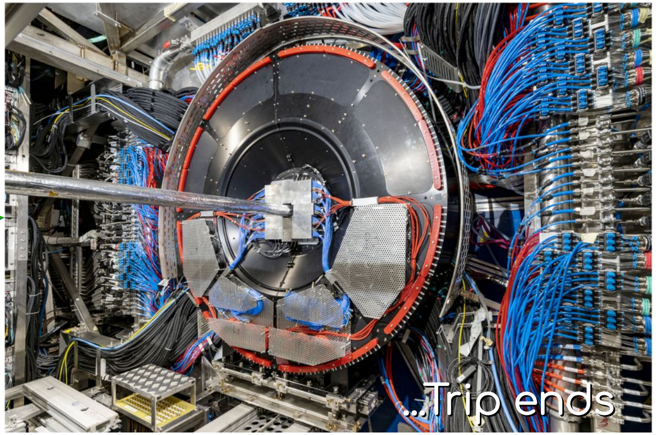


IB



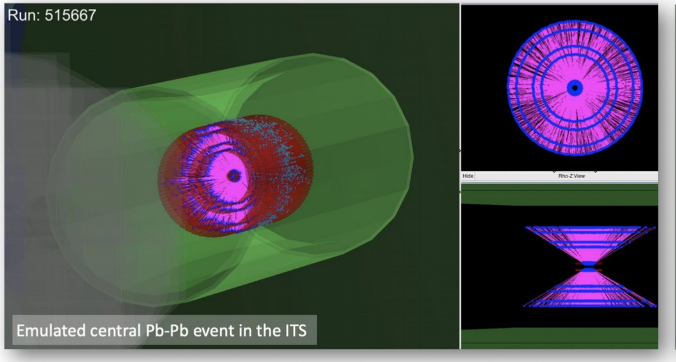


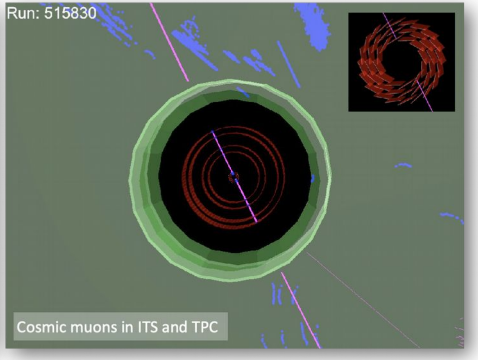
Fast Interaction Trigger (FIT) in front of ITS2

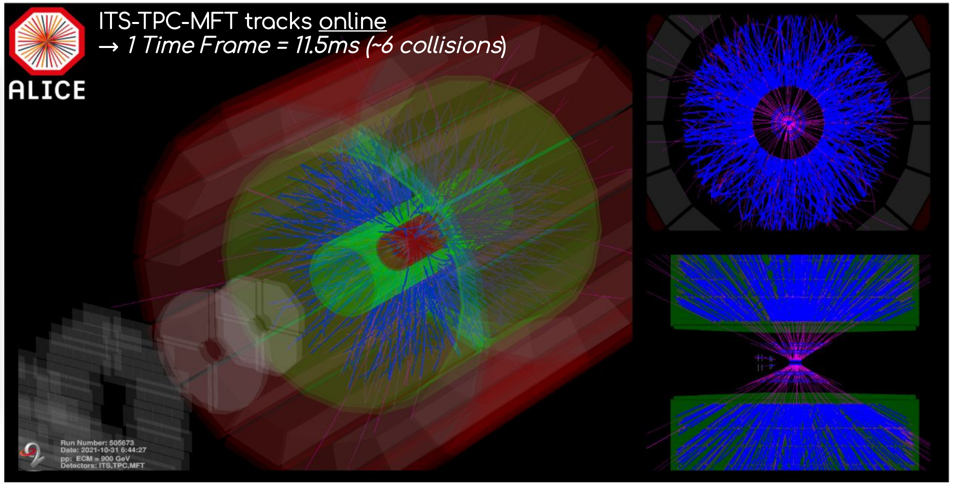


The challenge:
- Clearance around beam pipe: **~2 mm**
- Clearance between adjacent staves: **~1.2 mm**
- Manipulation from **4m distance**

Verification of barrels after installation and preparation for data taking - 2021 / 2022







Data taking preparation

- pp @ 202 kHz
- Pb-Pb @ 45 kHz
- cosmics

→

Successful data taking

- pp @ $\sqrt{s}$ = 900 GeV

→

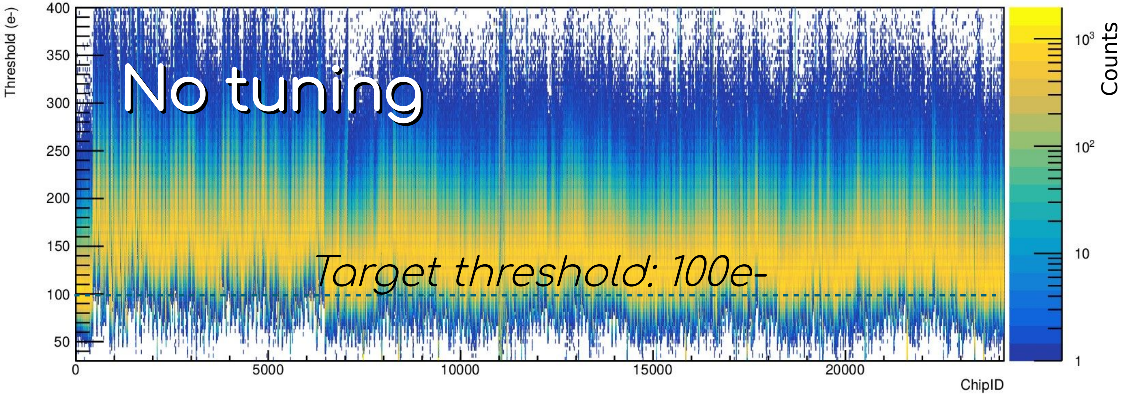
19/07/2021: start of ALICE global commissioning with central shifts
End October 2021: first pilot collisions (pp $\sqrt{s}$ = 900 GeV)
January 2022 – June 2022: pilot collisions, cosmics, software validation with emulated data

Verification of barrels after installation and preparation for data taking - 2021

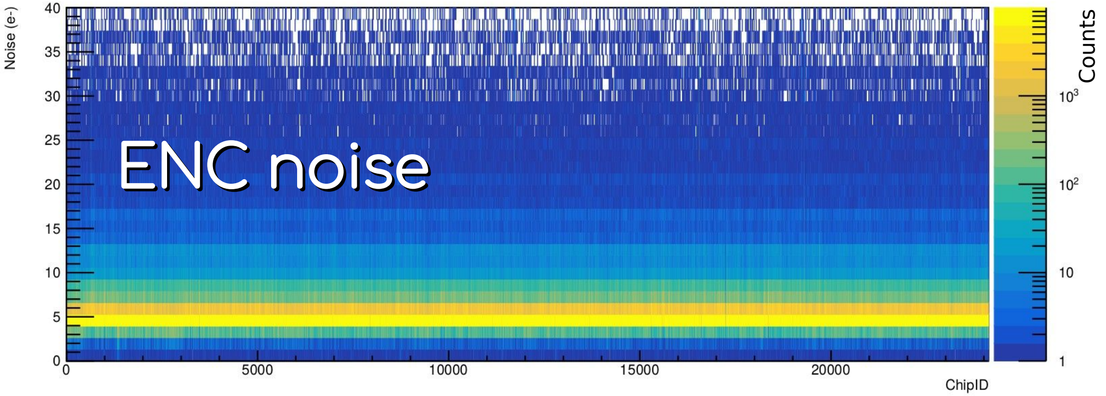
- OB installation (March 2021)
  - Full detector powered and monitored till mid-April
  - Various issues spotted and solved:
    - Problematic cables giving loose contacts or with wrong wire configuration (replaced)
    - Unstable power supplies (replaced)
    - Optimization of cooling for staves and electronics
    - Resolution of bugs into control-system user interface and code.
- IB installation (May 2021)
  - Basic verification of IB: readout tests + resistance measurement to check connections.
  - Basic verification of OB after IB installation: power and communication tests
- ITS standalone commissioning in the cavern (till July 2021)
  - Full verification of the detector: cosmic runs, data taking with emulated data patterns (pp, Pb-Pb), calibration runs.

Preliminary performance results in Run 3

→ ITS2 full calibration (2)

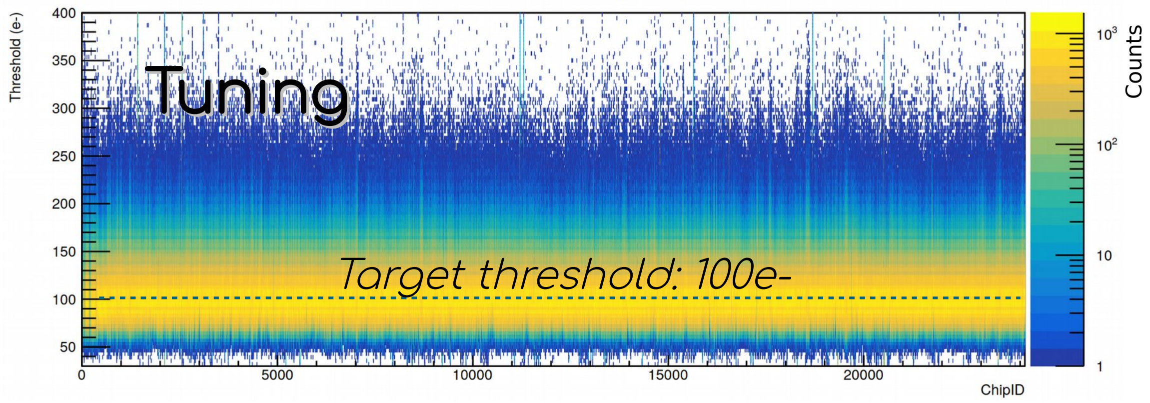


- Distribution of pixel thresholds per chip
- Thresholds not tuned: detector already ~100% efficient
- ENC noise: ~5e- (stable for 24k chips)

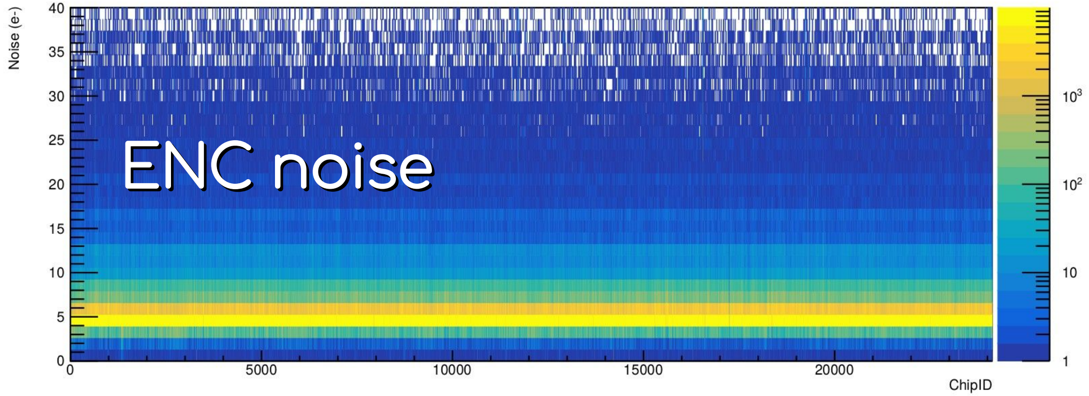


Preliminary performance results in Run 3

→ *ITS2 full calibration (3)*



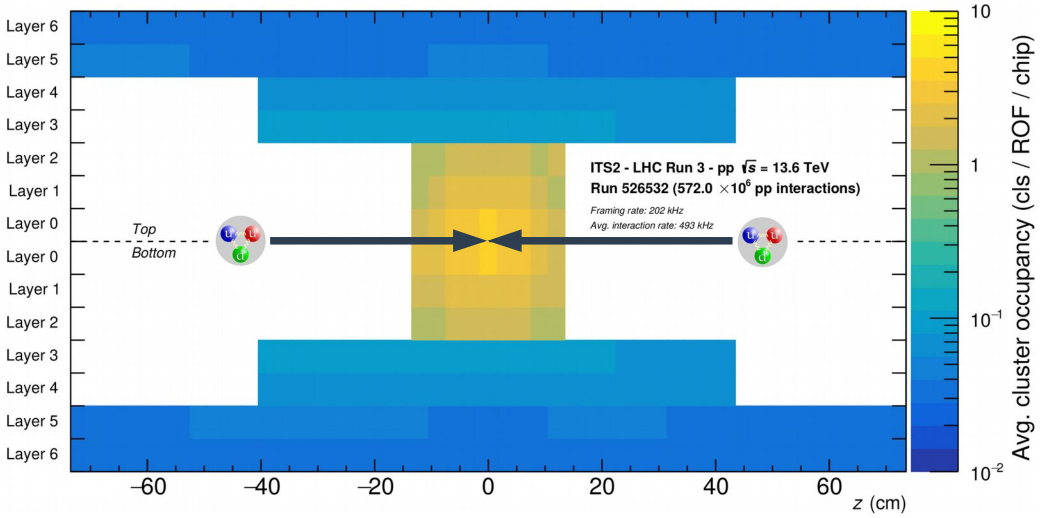
- Distribution of pixel thresholds per chip
- Thresholds not tuned: detector already ~100% efficient
- ENC noise: ~5e- (stable for 24k chips)
- Threshold tuned: 100e- (stable for 24k chips)
- RMS ~20e- (compatible with what measured during production)



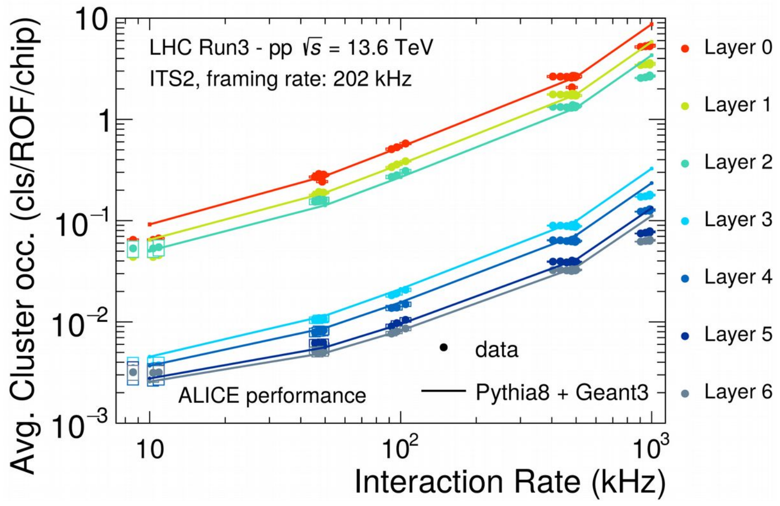
Preliminary performance results in Run 3

→ *Cluster occupancy and simulation*

- Cluster occupancy per readout frame (ROF) and per chip
  - Between 0.1 and 10 clusters/ROF/chip @ 1 MHz (202 kHz framing rate)
  - Observed to be stable over time (at the same IR)
  - Dependent on the interaction rate
- Simulation with Pythia 8 + Geant 3
  - Simulated noise: 2×10^{-8} hits/event/pix (IB), 3×10^{-9} hits/event/pix (OB)
  - Good agreement with data considering approximations:
    - Average noise per barrel and not per stave/chip.
    - Limited statistics in MC: ~20k events.



Cluster occupancy

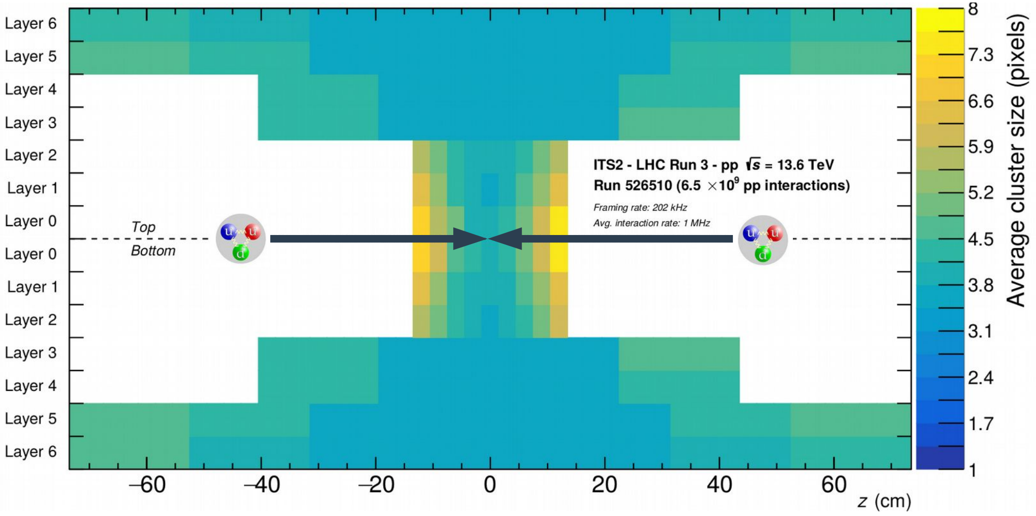


Cluster occ. vs IR

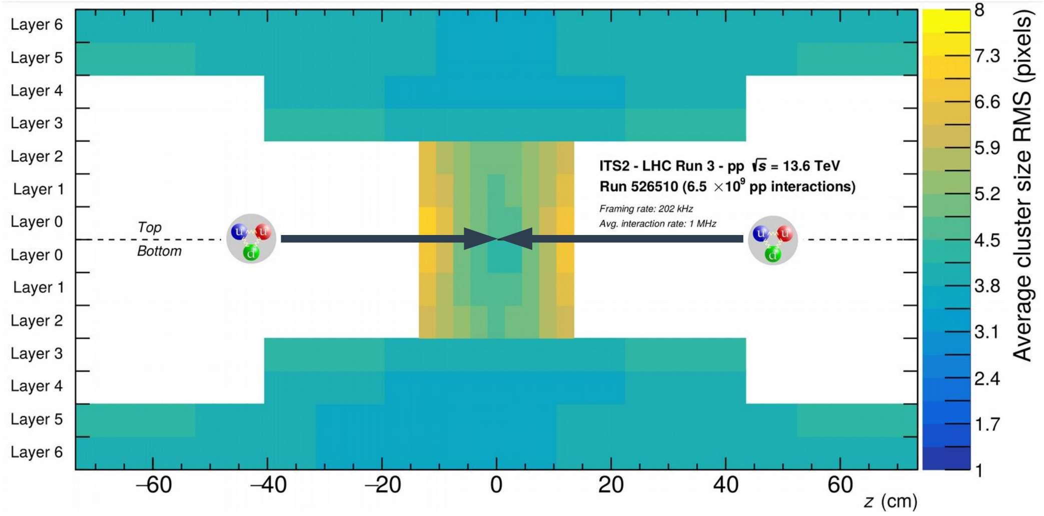
Preliminary performance plots in Run 3

→ Cluster size

- Cluster size averaged for half barrels
  - Between 3 and 8 pixels depending on η
  - RMS ranging on the same interval
  - Observed to be stable over time
  - Independent of the interaction rate
  - PID studies with machine learning techniques are ongoing



Cluster size (pix)

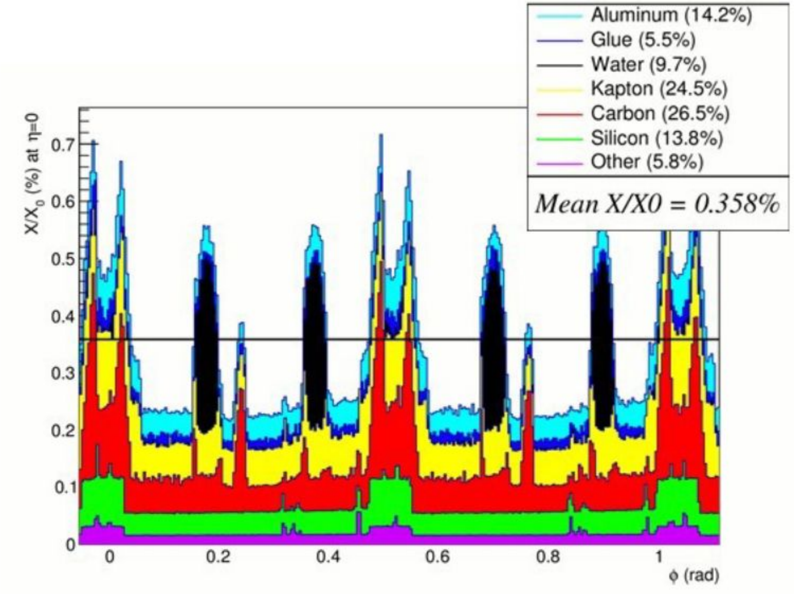


Cluster size RMS (pix)

ITS2 material budget

ALICE

Inner Barrel



Outer Barrel