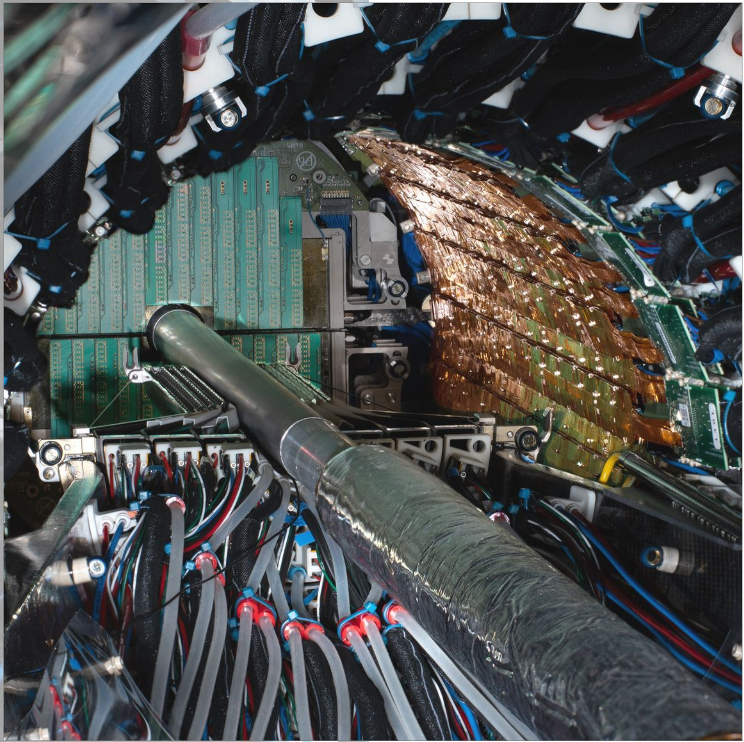
The ALICE Inner Tracking System performance during the first two years of Run 3 at LHC

Ivan Ravasenga[1]
for the ALICE Collaboration
[1]CERN *(Geneva, CH)*

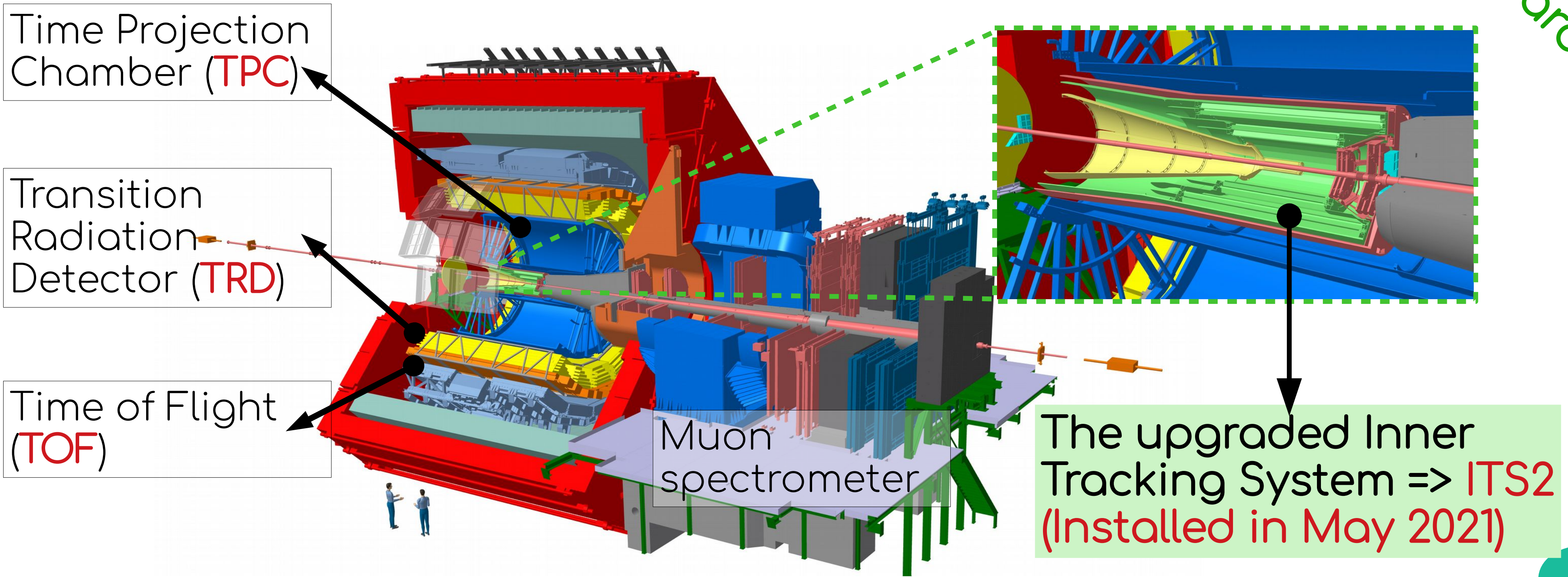


Current and future tracking and vertexing detectors 2023 – 7/8 Nov.

Introduction – ALICE experiment

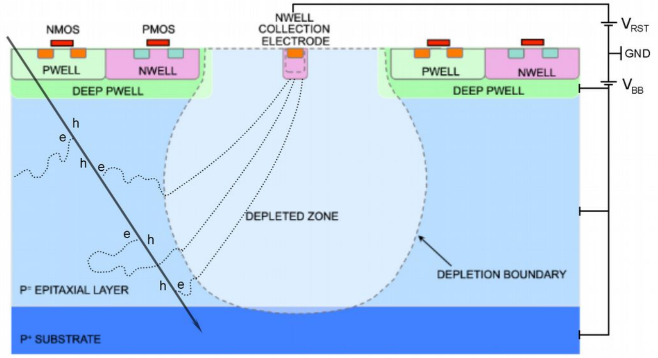
- Run 2 of LHC completed in 2018 with Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- Long-shutdown 2 started in 2018 to allow detector & computing system upgrades

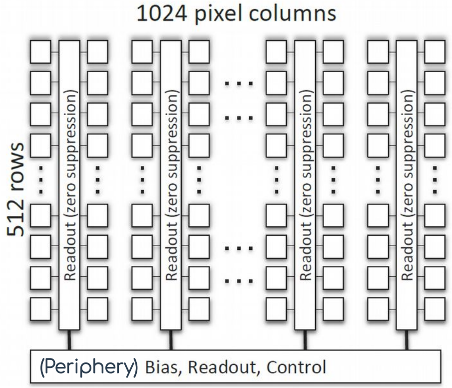
Run 3 apparatus



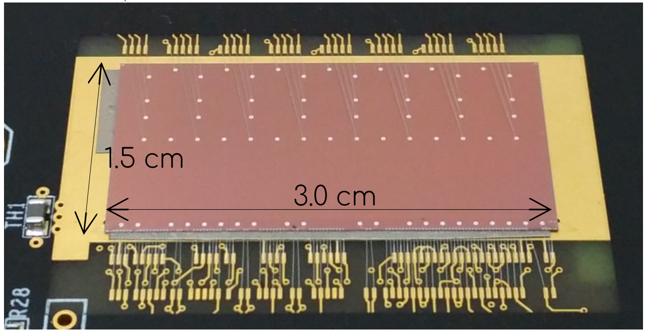
ALPIDE chip – the detector core

→ ALice PIxel DEtector





ALPIDE chip bonded on its carrier board

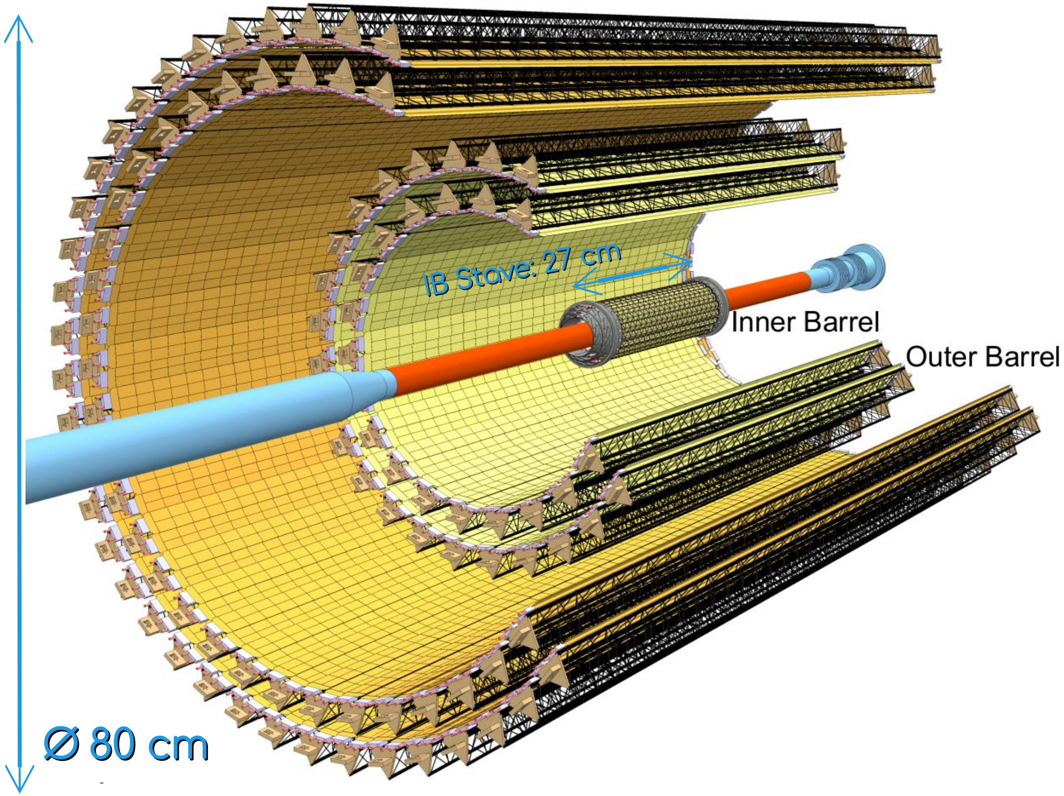


- TowerJazz 0.18 μm CMOS imaging process – a Monolithic Active Pixel Sensor (MAPS)
  - High resistivity p-type epitaxial layer on p-type substrate
  - Small n-well diode → small capacitance ~fF
  - In-matrix sparsification using priority encoder
  - Pixel signal amplified and digitized at a pixel level
  - 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/cm²
Pixel size	27x29 μm²
Spatial resolution (rφ,xz)	5x5 μm²

Introduction – The Upgraded Tracker (ITS2)
→ 10 m² of monolithic active pixel sensors (12.5 GPixels)



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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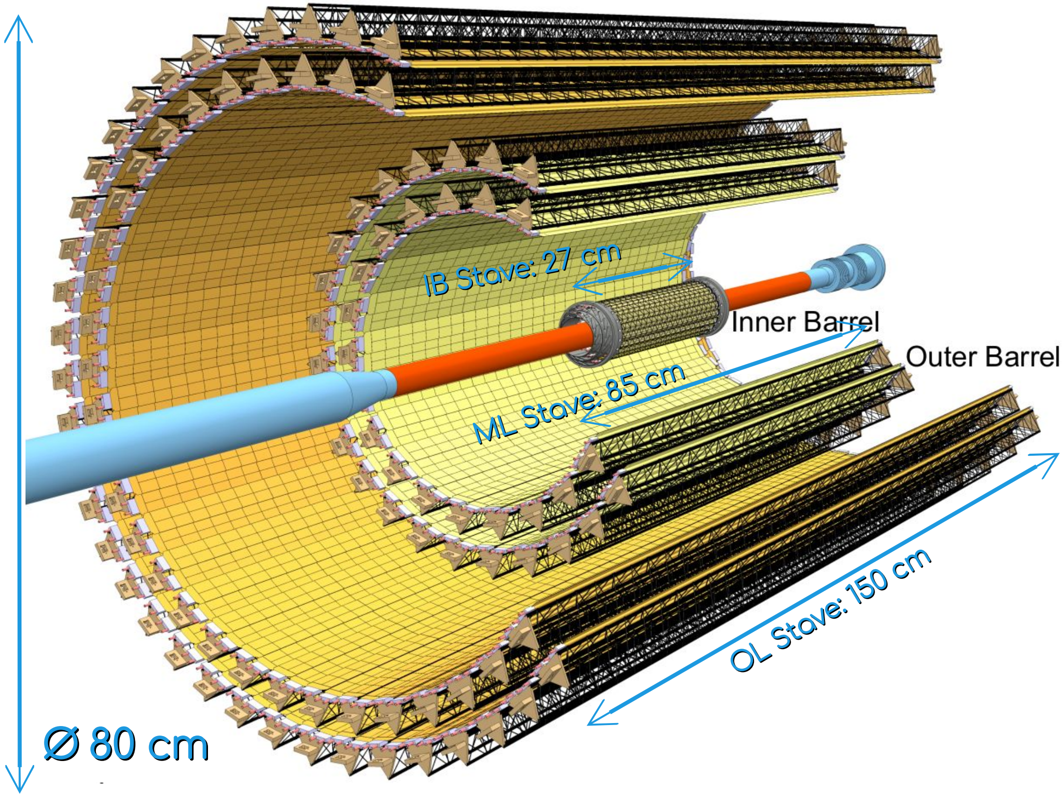
ALICE



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- **Readout at 1200 Mb/s per chip**

<u>Outer Barrel (OB)</u>

- 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**

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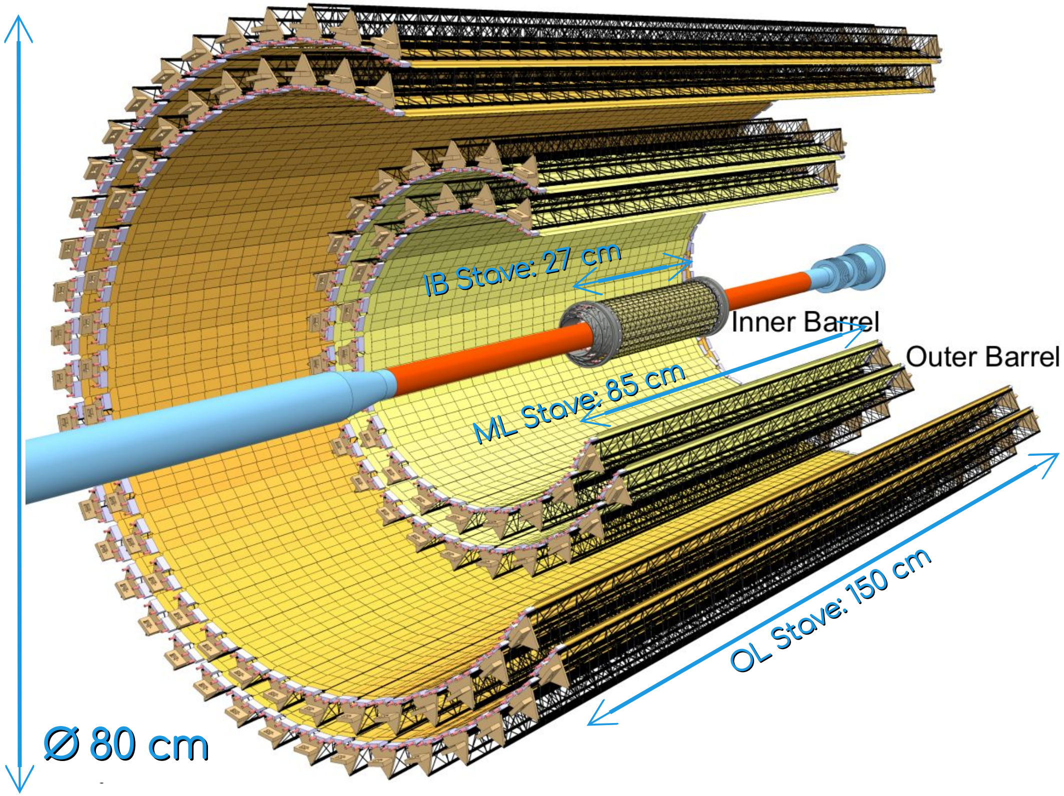
ALICE



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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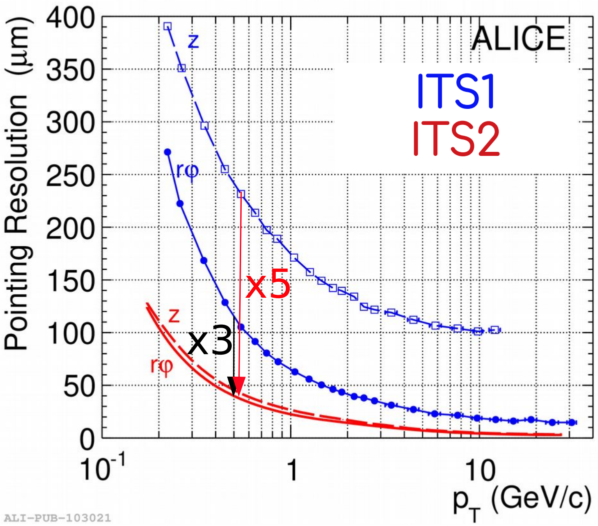
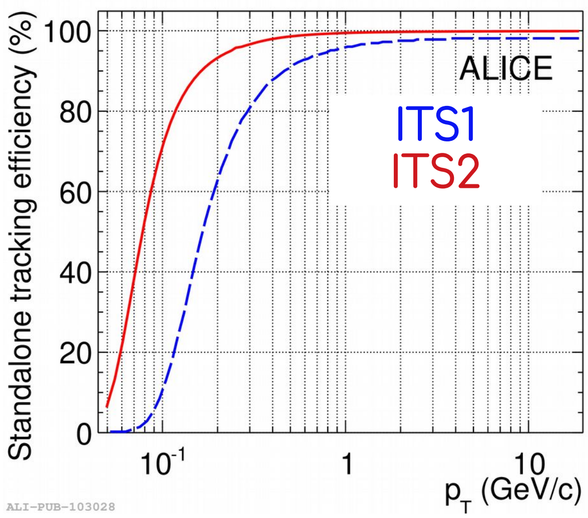
Expected improvements with ITS2

Pointing resolution (rφ & z)



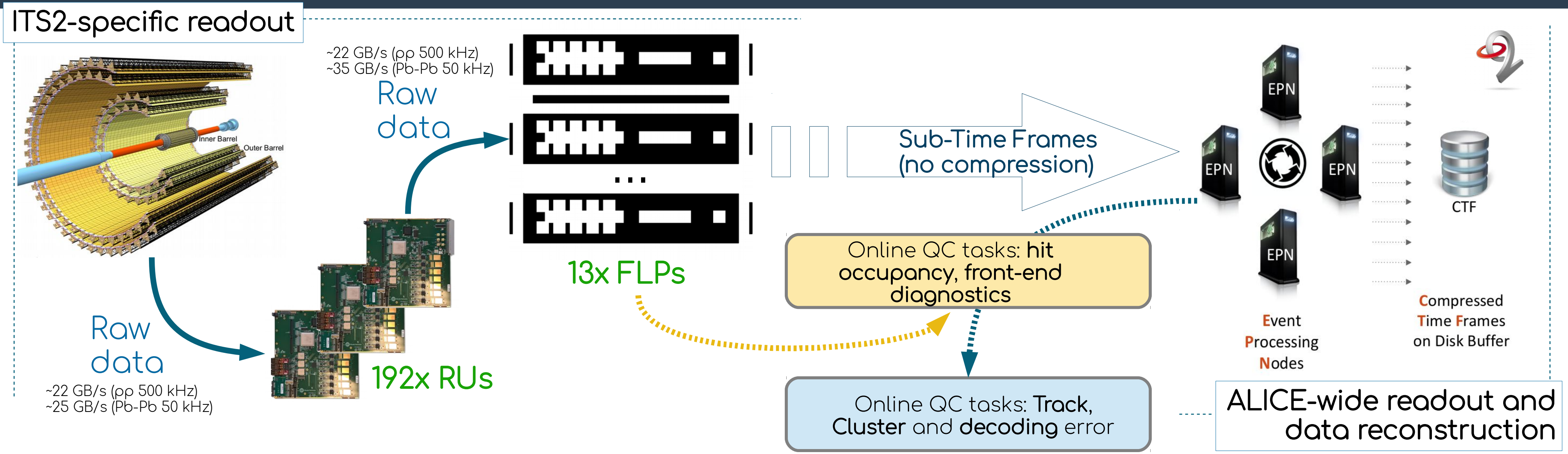
Tracking efficiency



- **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

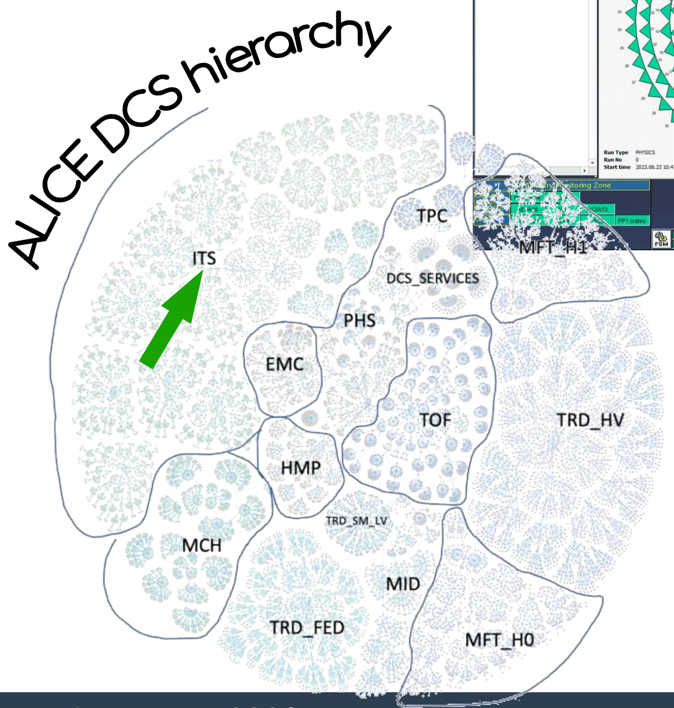


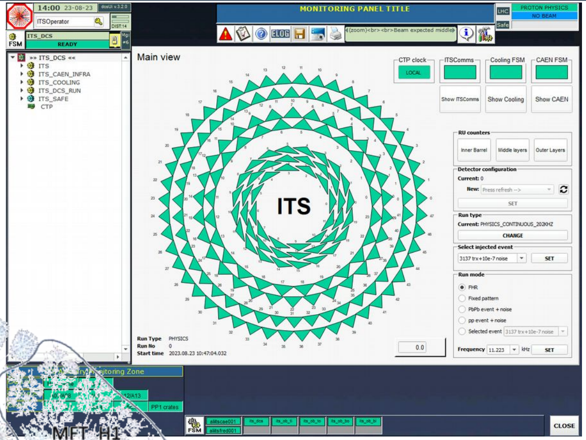
- 13 ITS First Level Processors (FLPs)
  - Online data quality control tasks: hit occupancy and front-end electronics diagnostics.
- 350 Event Processing Nodes (total EPNs from ALICE farm)
  - Online quality control tasks: reconstructed ITS2 tracks, clusters and decoding errors.
- Synchronous reconstruction, 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 in the ALICE hierarchy
- An independent safety system interlocks power channels based on stave temperatures and cooling status

ALICE DCS hierarchy



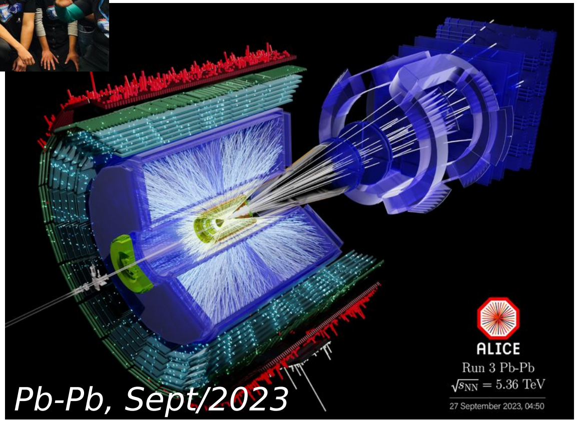


ITS DCS UI

Run 3 overview

- Started on 2022, July 5th with first pp collisions at $\sqrt{s}$ = 13.6 TeV (*stable beams*)
- Integrated luminosity so far (pp collisions): ~28 pb^{-1}
- Integrated luminosity Oct/2023 Pb-Pb: ~1.5 nb^{-1}
- ITS fully operational
  - 0.4% of total pixels excluded = dead and noisy
- ALICE & ITS2 numbers in data taking
  - Nominal ITS framing rate: 202 kHz (pp) – 67 kHz (Pb-Pb)
  - ALICE standard luminosity: 500 kHz (pp) – 47 kHz (Pb-Pb)
    → Instantaneous luminosity: ~10^{31} (pp) – 10^{27} (Pb-Pb) $cm^{-2}s^{-1}$
  - ITS2 successfully tested up to 4 MHz interaction rate in pp (~ 50 GB/s data rate).
  - Loss of acceptance during runs auto-recovered by DCS
  - Very sporadic data corruption events not affecting overall performance
- At every beam dump: fast ITS threshold scan on 2% of the pixels to evaluate the quality of the detector calibration

Pb-Pb collisions were the main event this year!



- We are now in Technical Stop till March 2024 -

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
- Threshold calibration of 24120 chips is challenging:
  - Online calibration workflow runs on ~1/9 of the EPN farm with parallel processing
  - Pulsing of ~1% of the pixels: ~252Ghits
  - Thresholds: tuned to 100e-
(in-layer RMS < 5-6 e-)
- When
  - Threshold & Noise re-calibration: <1 /year
  - Fast threshold scan (for verification): 1 /day
  - Full threshold scan (100% pixels): 1 /year

How do we tune the thresholds?

Tune of ALPIDE VCASN registers of every chip (*coarse tuning*) to get 100 e^-

1/9 of EPN farm: ~ 10 mins
DCS & ECS: config & start/end of run

↓

Tune of ALPIDE ITHR registers of every chip (*fine tuning*) to get 100 e^-

1/9 of EPN farm: ~ 10 mins
DCS & ECS: config & start/end of run

↓

Prepare detector configuration in ORACLE

WinCC panel

↓

Fast threshold scan – **tuning validation**

1/9 of EPN farm: ~ 10 mins
DCS & ECS: config & start/end of run

~35 min

Fit in-between 2 LHC fills in case of issues

Performance results in Run 3

→ *ITS2 full calibration (2)*

- Main ITS calibration parameters:
  - Masking of noisy pixels
  - Tuning of in-pixel discriminating thresholds
  - Power supply voltage
  - On-chip temperatures
- Threshold calibration of 24120 chips is challenging:
  - Online calibration workflow runs on ~1/9 of the EPN farm with parallel processing
  - Pulsing of ~1% of the pixels: ~252Ghits
  - Thresholds: tuned to 100e- (in-layer RMS < 5-6 e-)
- When
  - Threshold & Noise re-calibration: <1 /year
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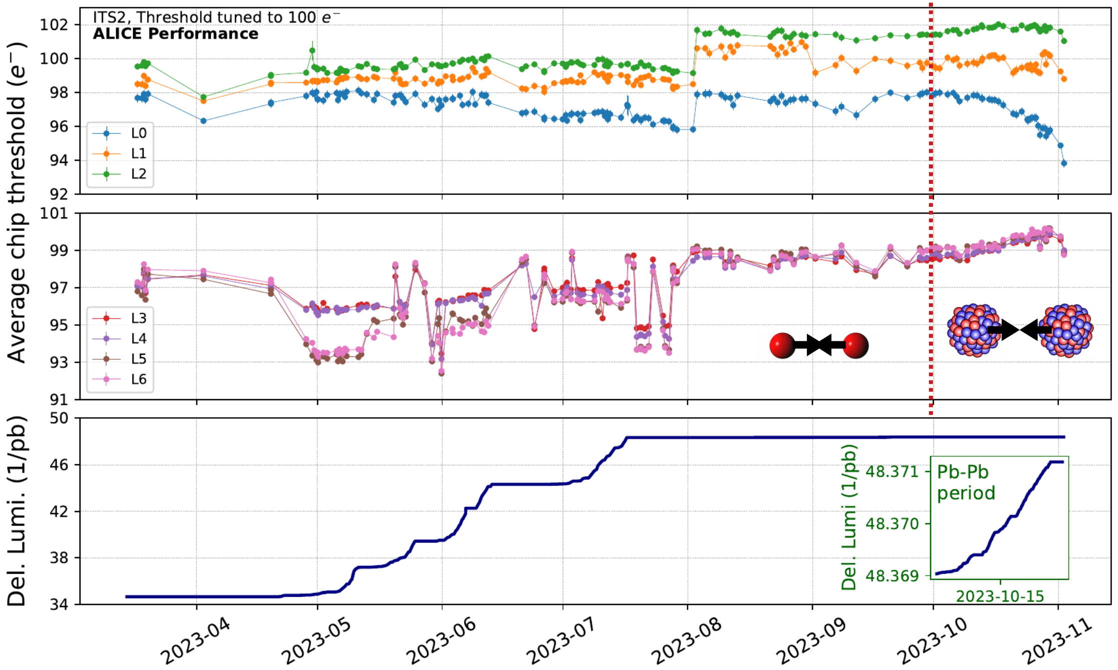
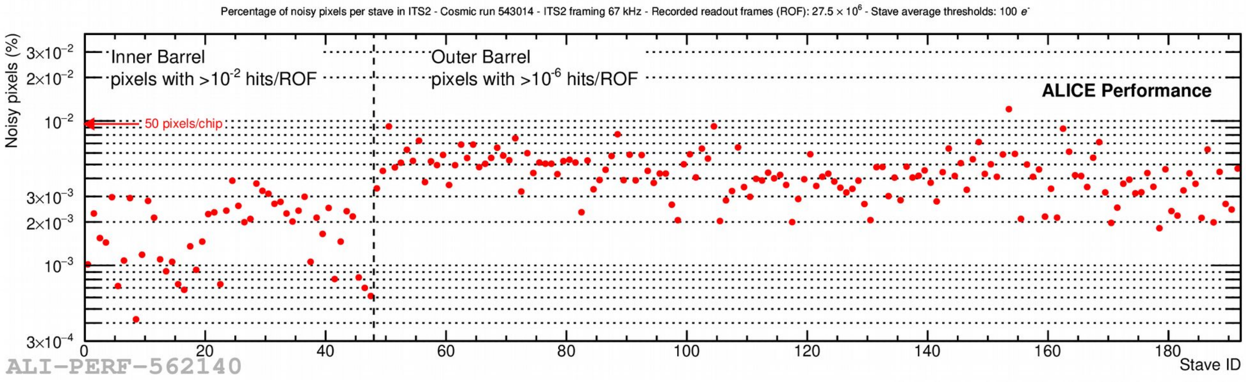


Thresholds are observed to be stable during 2023 operations without re-tuning

Fluctuations of 2-3 e- due to optimizations of the voltage to chips: *radiation effects under study*

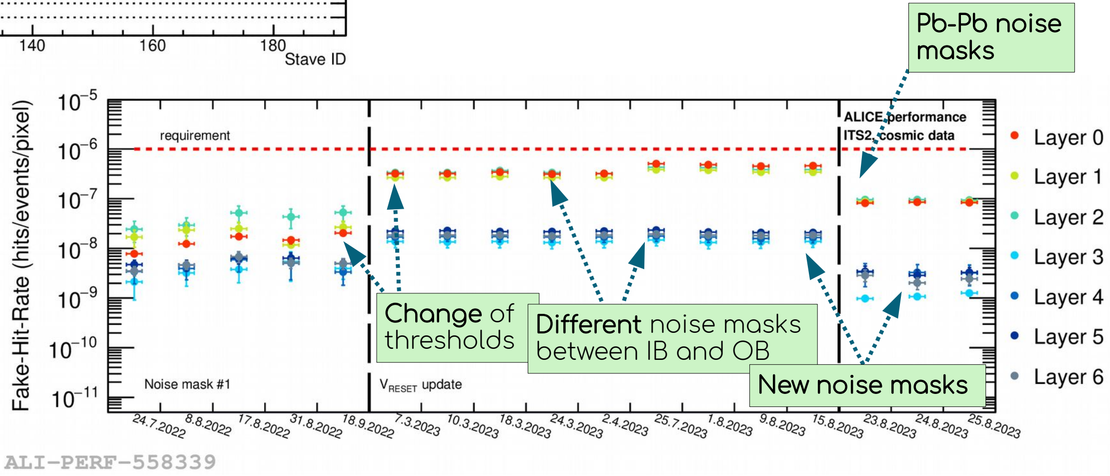
Performance results in Run 3

→ ITS2 full calibration (3)



- Noise calibration: 1/9 of the EPN farm needed (10-30 mins depending on ITS2 framing rate)
- 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: ~0.02-0.05 ‰

- 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

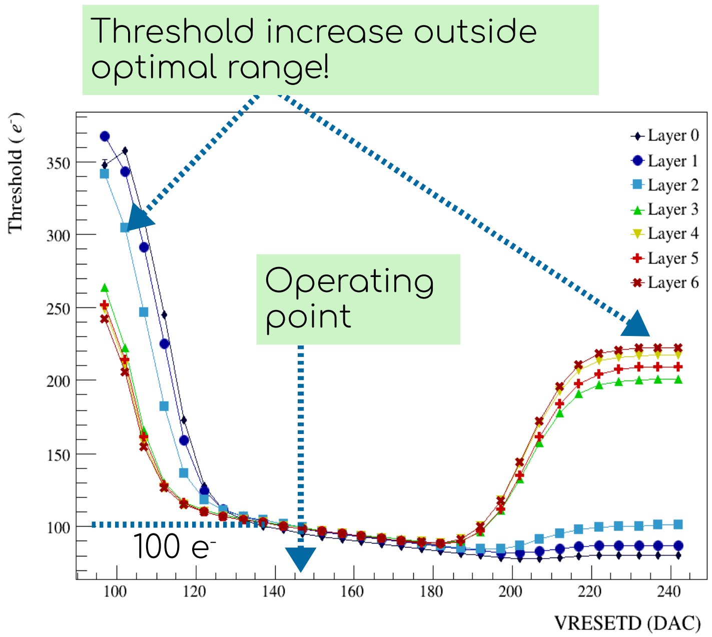


2022 → 03/2023 → 08/2023

Performance results in Run 3

→ *ITS2 full calibration (4)*

- The calibration framework allows us to monitor the optimal range of VRESETD ALPIDE register
  - Influence on leakage current and reset voltage of the pixel charge collecting node
  - Influence of radiation visible on the discriminating thresholds when outside operational range: clear radial trend based on the accumulated dose
- Operating point: 147 DAC Units → 100 electrons

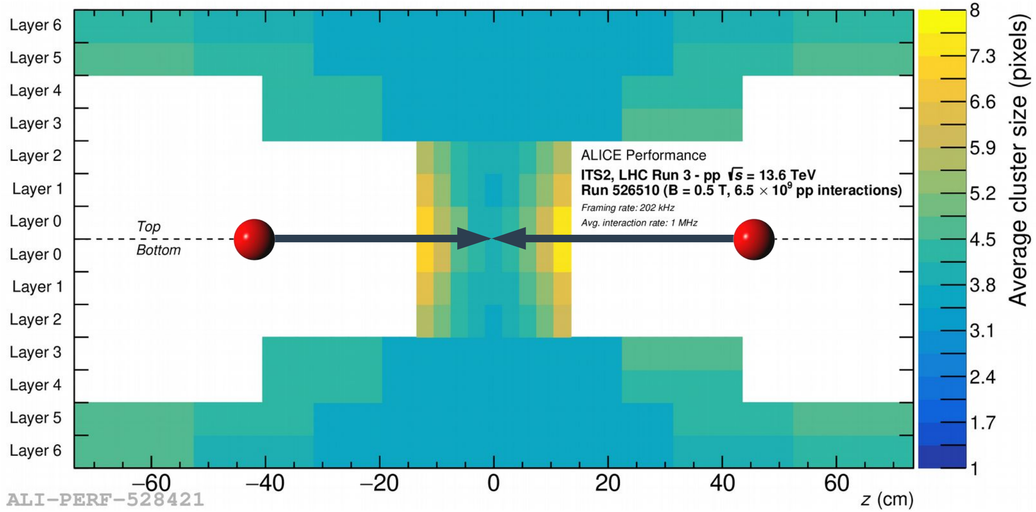


- Physics performance results
  - Comparison of pp vs Pb-Pb results → very first look into Pb-Pb after 1 week from the end of the data taking

Preliminary performance results in Run 3

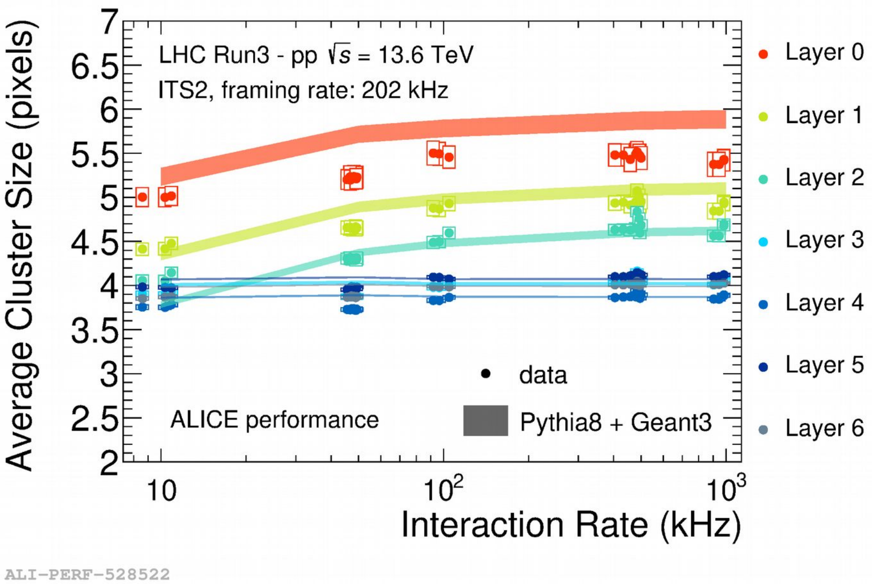
→ Cluster size and simulation in pp collisions

- 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 in pp (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.



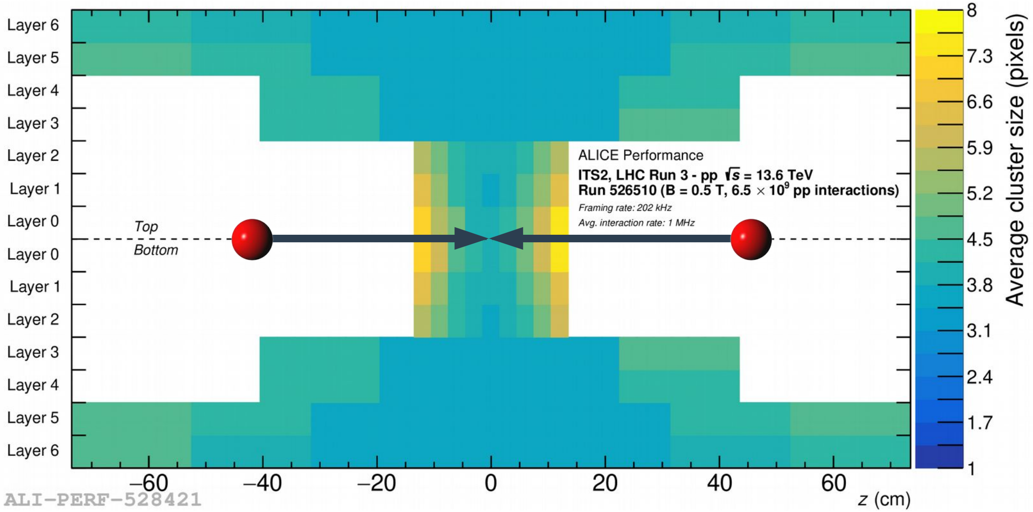
Cluster size vs IR in pp

Preliminary performance results in Run 3

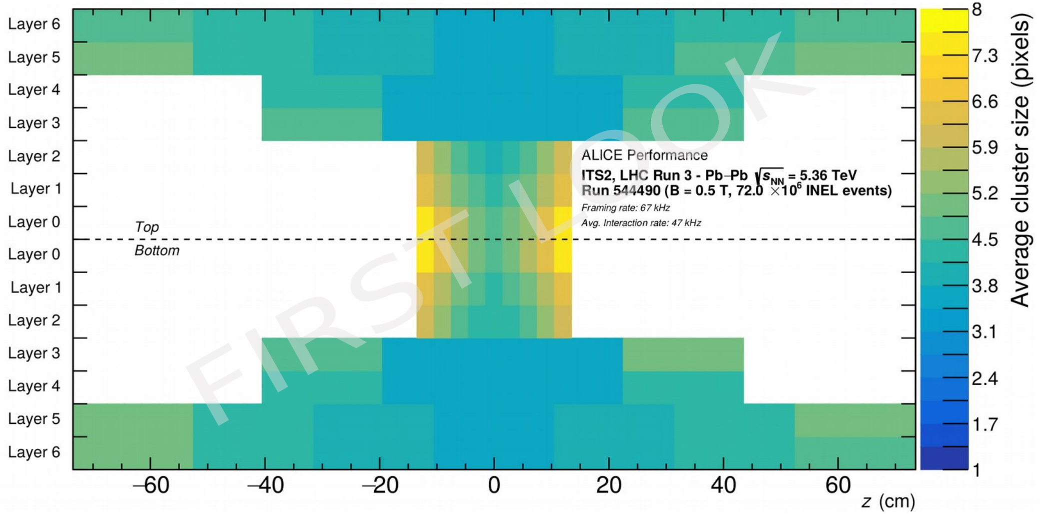
→ Cluster size and simulation in pp collisions vs Pb-Pb

- 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

Pb-Pb cluster size evolution with the detector geometry is comparable to pp: *study of contributions from background in Pb-Pb ongoing*



Cluster size in pp (pix)



Cluster size in Pb-Pb (pix)

Preliminary performance results in Run 3

→ Cluster occupancy and simulation in pp collisions

- Cluster occupancy per readout frame (ROF) and per chip
  - Between 0.1 and 10 clusters/ROF/chip @ 500 kHz (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)
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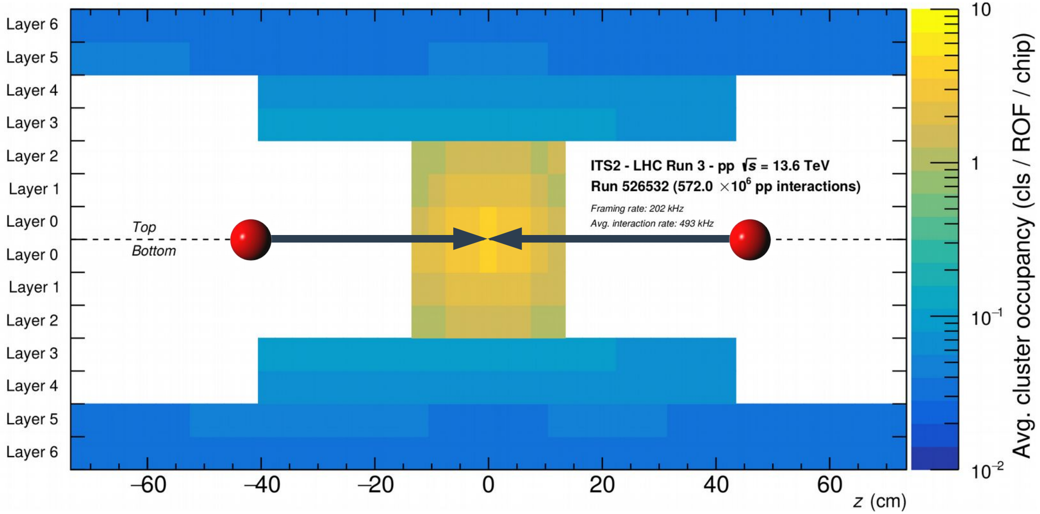
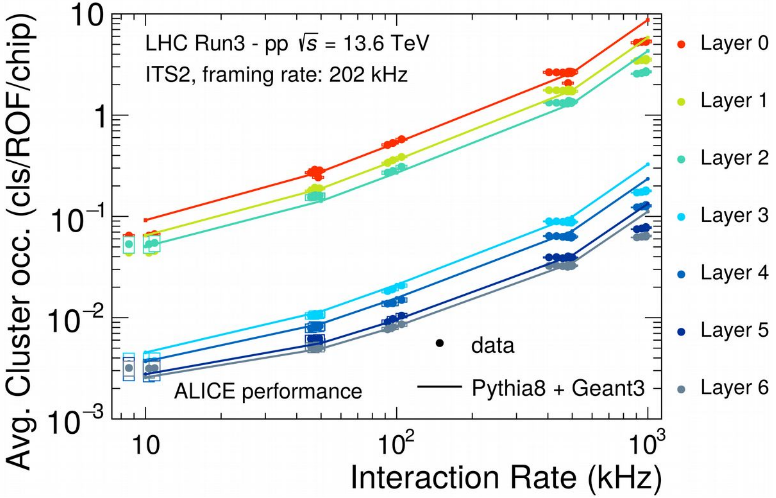


Cluster occupancy in pp



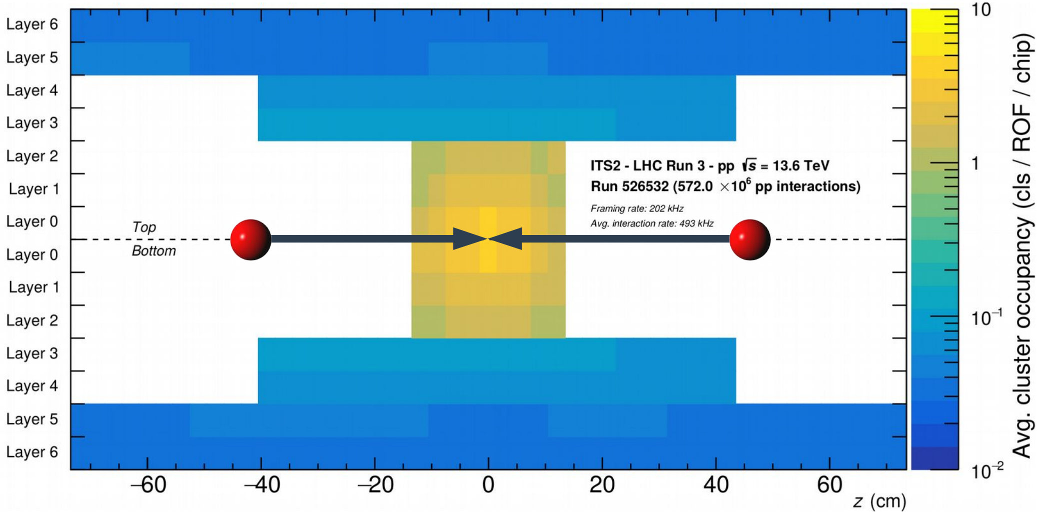
Cluster occ. vs IR

Preliminary performance results in Run 3

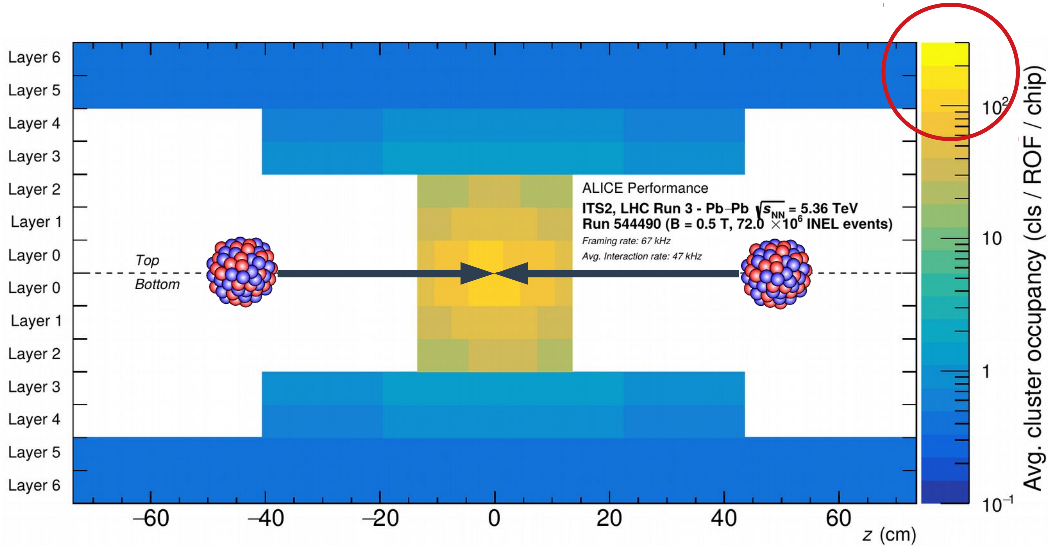
→ Cluster occupancy and simulation in pp collisions

- Cluster occupancy per readout frame (ROF) and per chip
  - Between 0.1 and 10 clusters/ROF/chip @ 500 kHz (202 kHz framing rate)
  - Observed to be stable over time (at the same IR)
  - Dependent on the interaction rate

Between 0.3 and 100 clusters/ROF/chip @47 kHz Pb-Pb (67 kHz framing rate)



Cluster occupancy in pp

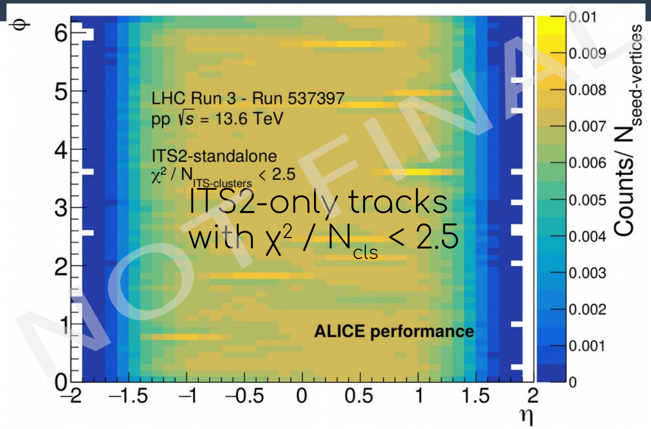


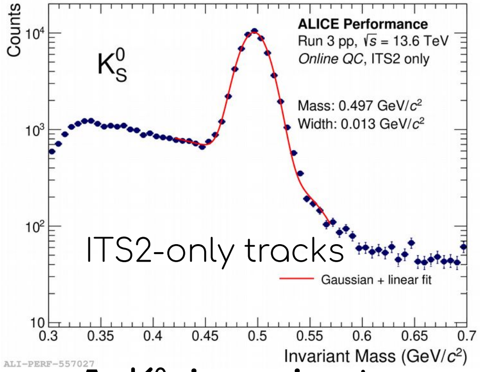
Cluster occupancy in Pb-Pb

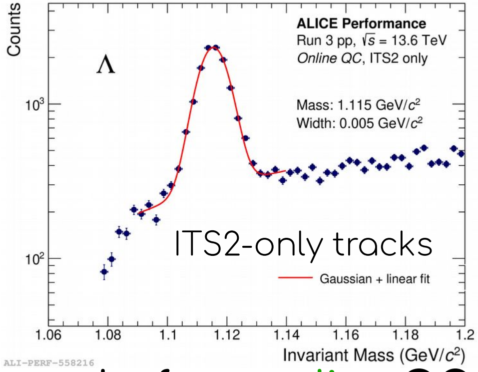
Preliminary performance results in Run 3

→ *Detector alignment and reconstructed tracks*

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







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

Preliminary performance results in Run 3

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ALICE

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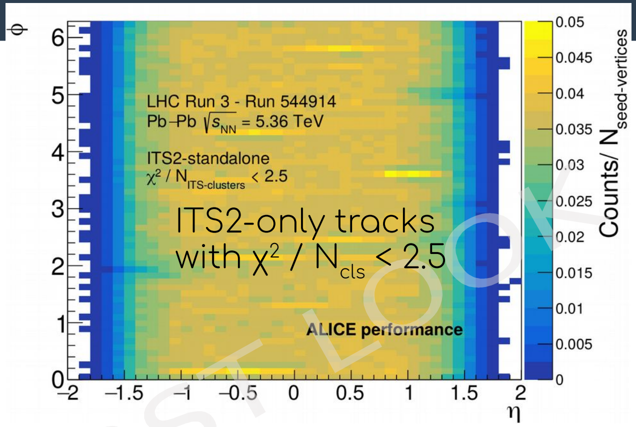
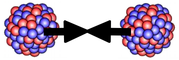
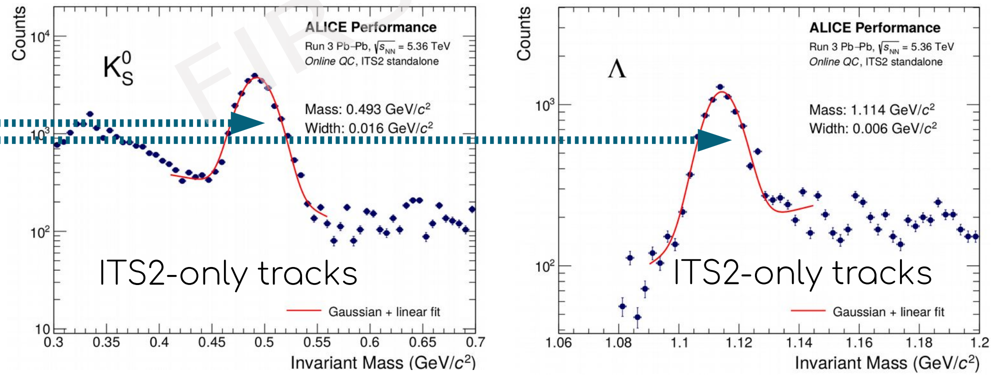




Peak widths ~15-20% larger than pp (higher background contribution → *identical tracks cuts to pp, not optimized for Pb-Pb*)



Λ, K^0_S invariant mass peaks from online QC in Pb-Pb collisions

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→ Detector alignment and reconstructed tracks

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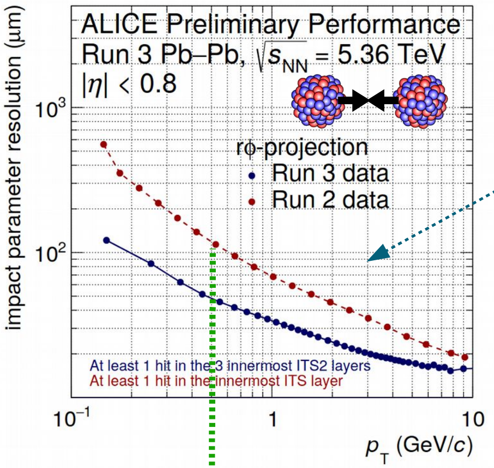
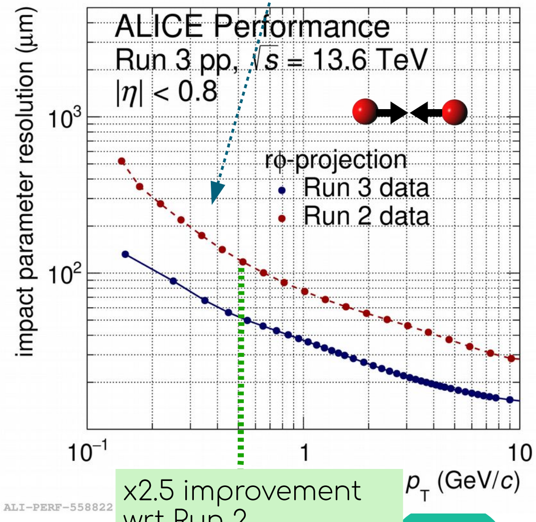
  - Cellular automaton algorithm
  - Online tracking for quick QA of the data
  - Angular distribution of tracks of good quality → good detector acceptance
- Online physics performance from QC through Λ and K^0_S invariant mass peaks
- Impact parameter resolution measured with Run 3 pp/Pb-Pb data → excellent performance
  - About 2.5x improvement at p_T = 500 MeV/c
    → Detector alignment, space charge corrections and calibrations still continuously improving



x2.5 improvement wrt Run 2

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



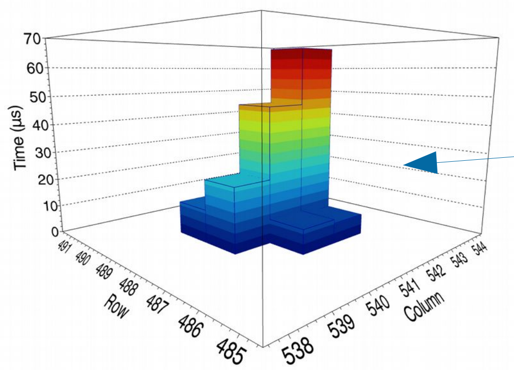
x2.5 improvement wrt Run 2

Ongoing studies with ITS2 – Color runs

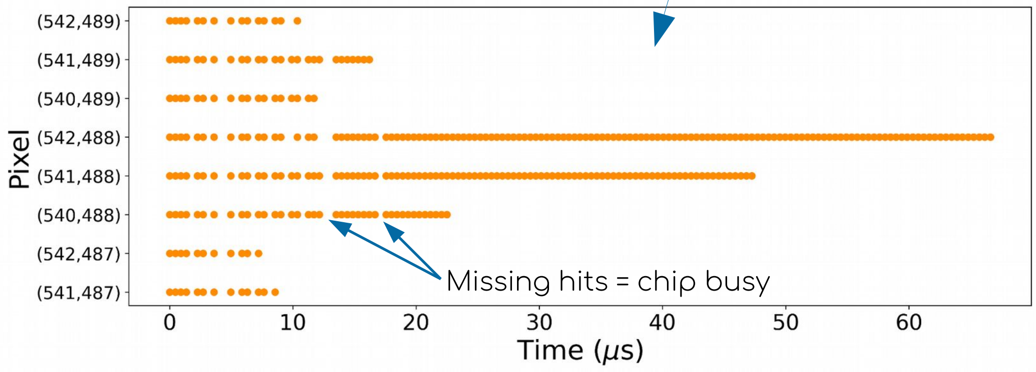
→ Preliminary

ALICE

- Special ITS-standalone run in pp collisions with very low interaction rate (900 Hz):
  - Oversampling of ALPIDE analog signal in Inner Barrel: 2.2 MHz trigger rate
- Objective: particle identification with MAPS
  - Measurement of the time-over-threshold
  - Time-over-threshold → Charge calibration available for all IB pixels



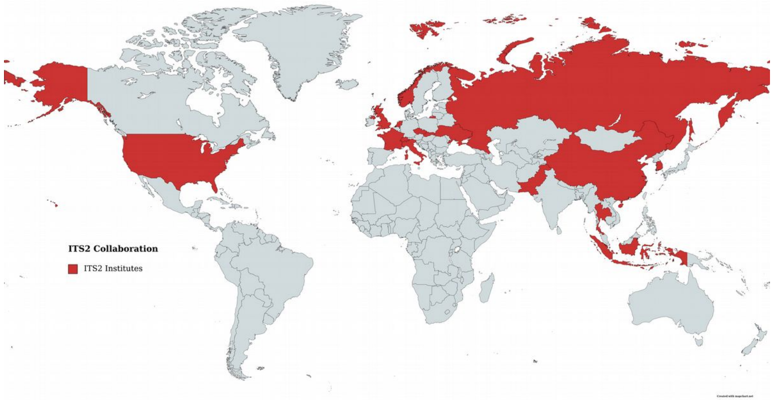
Data validation done by looking at cluster evolution vs time



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 at $\sqrt{s_{NN}}$ = 5.36 TeV, interaction rate up to 47 kHz
- Excellent performance of ITS2 in Run 3
  - ITS2 performance is within expectations: both in pp and Pb-Pb collisions at top energy
- No need of recurrent detector calibration for stable operations
- Detector Control System and Quality Control system
  - Ready and constantly in use to monitor the detector hardware and data in Run 3

The ITS2 Collaboration

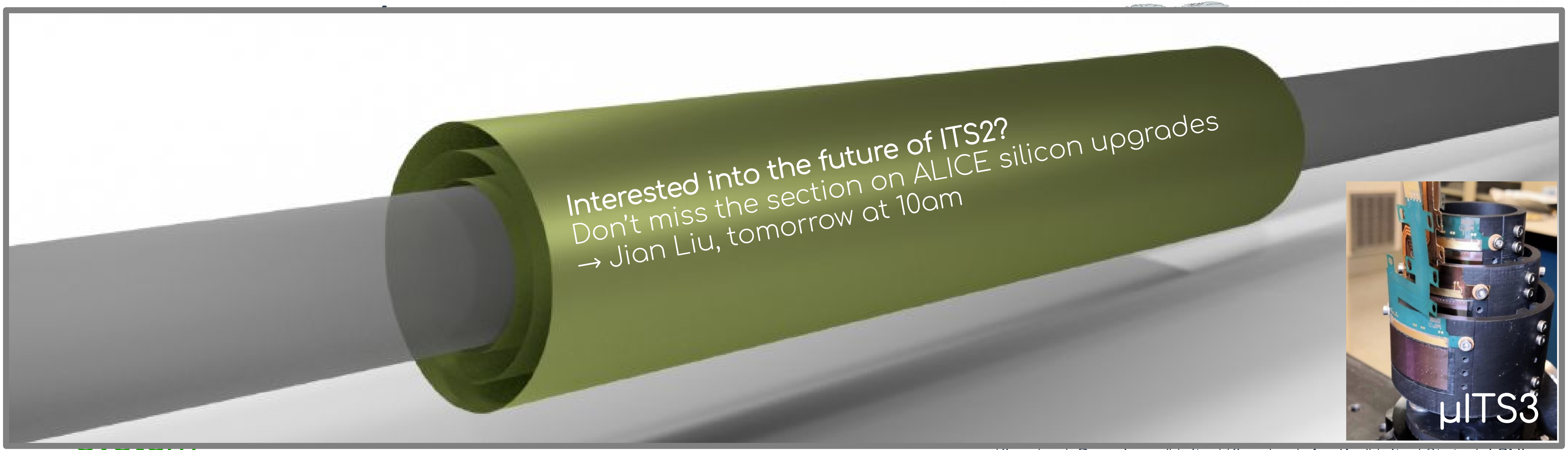


CERN (Switzerland), **CCNU** (China), **Řež u Prahy** (Czech Republic), **Strasbourg** (France), **LIPI** (Indonesia), **Alessandria** (Italy), **Bari** (Italy), **Cagliari** (Italy), **Catania** (Italy), **LNF** (Italy), **Messina** (Italy), **Padova** (Italy), **Pavia** (Italy), **Torino** (Italy), **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



Kingdom), **Daresbury** (United Kingdom), **Austin** (United States), **LBNL** (United states), **ORNL** (United States)

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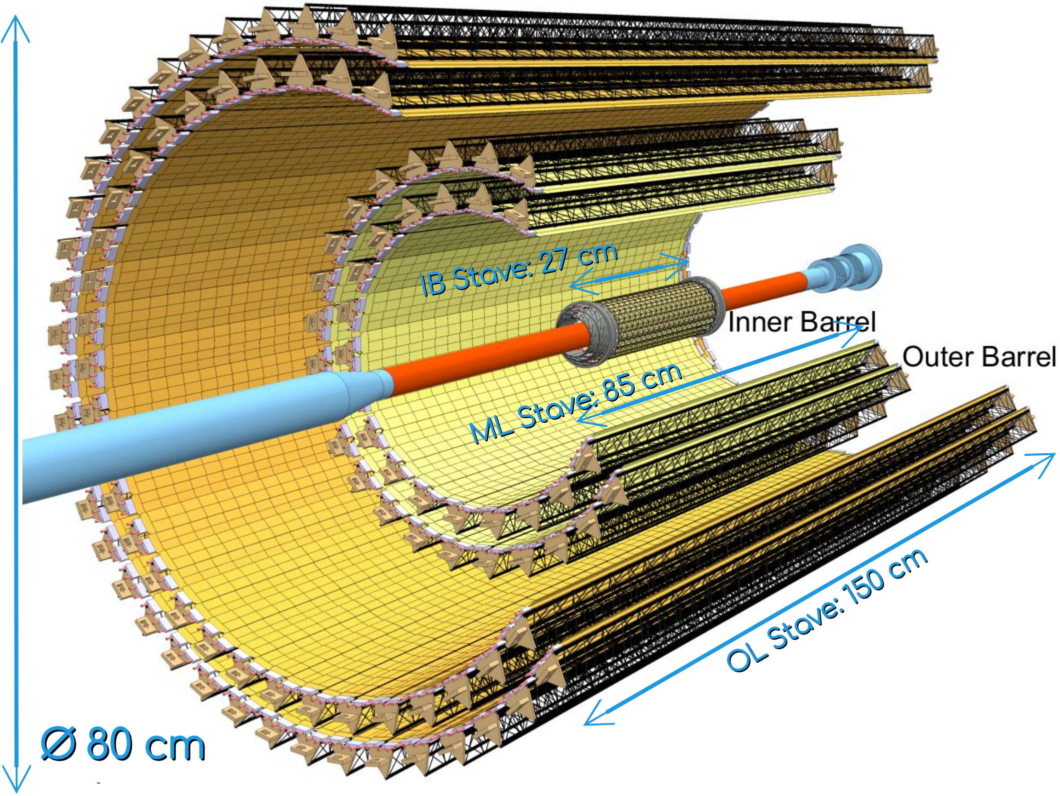
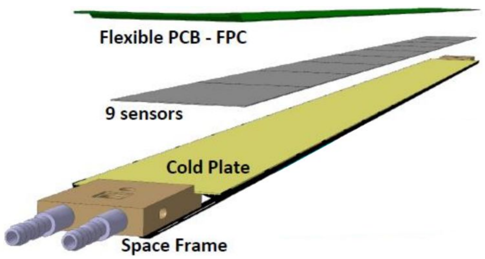
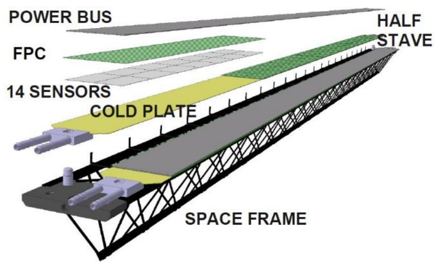
Backup slides

ITS2 – details on components



Inner Tracking System (ITS)





Detector Control System (DCS) - a quick view

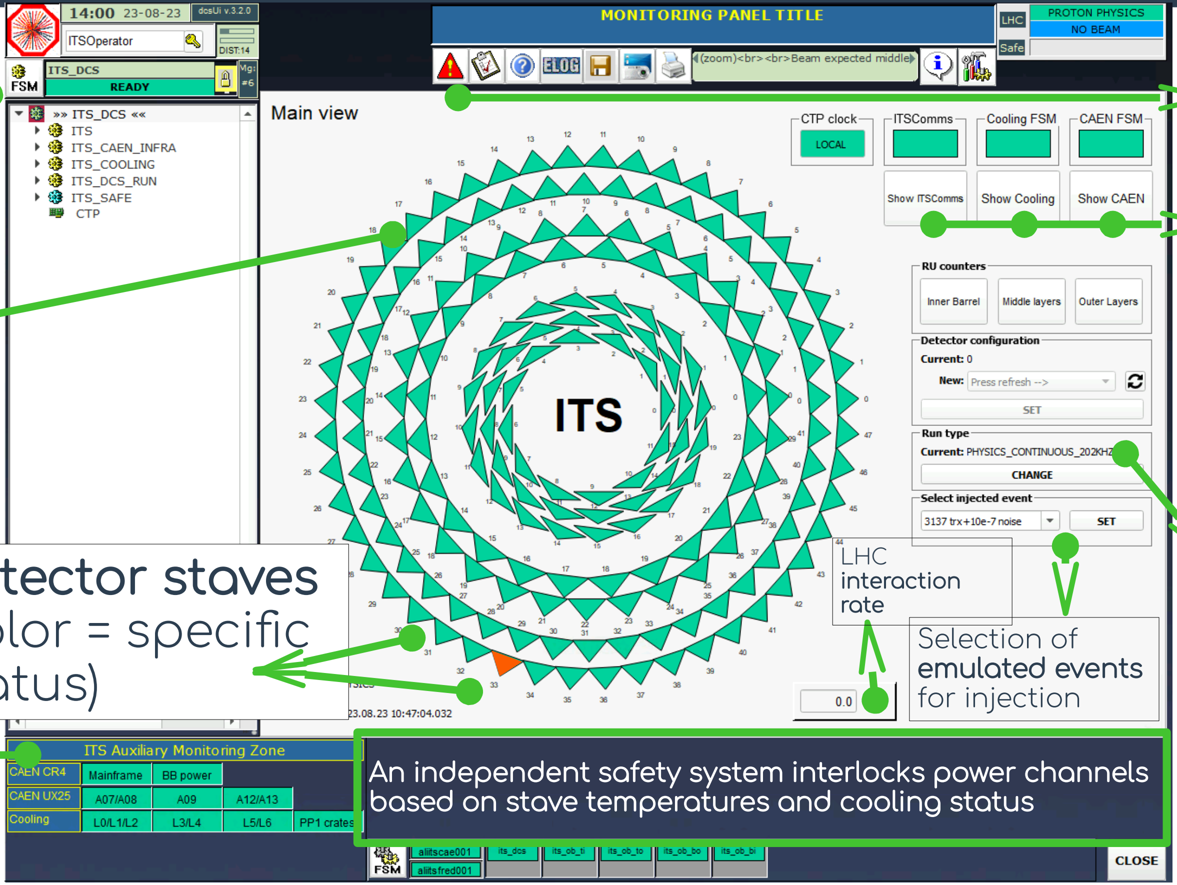
ALICE

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, ...



LHC interaction rate

Selection of emulated events for injection

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

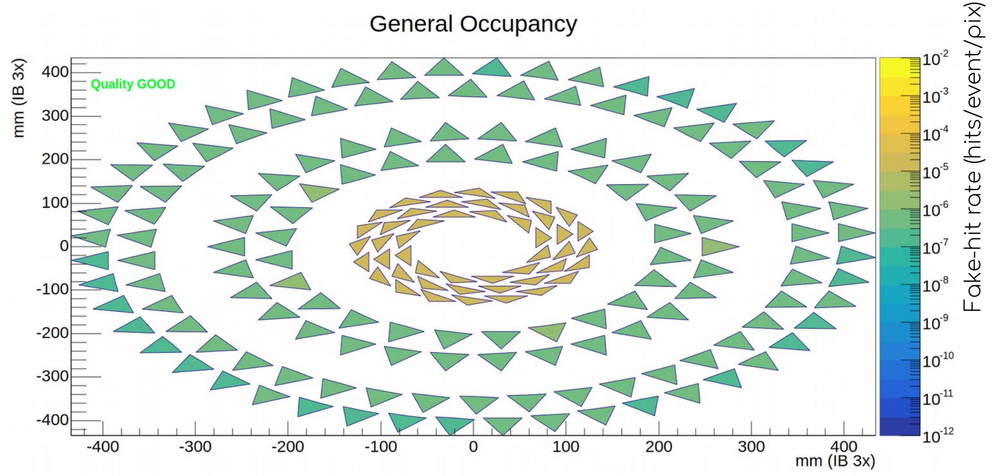
Detector configuration and selection of **run types** (physics, calibration)

(Data) Quality Control (QC)

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



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

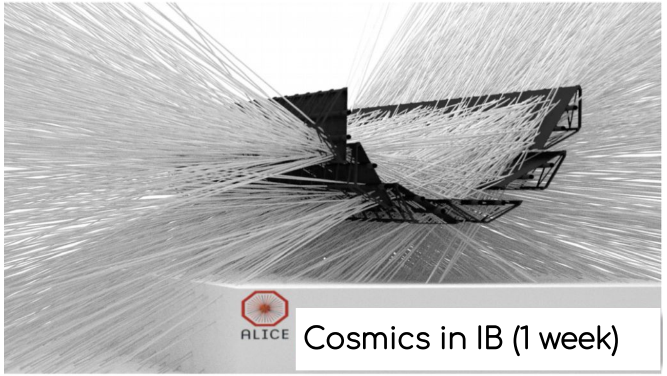
5 online post-processing tasks + offline post-processing framework/macros → trending vs run

QA of data done on a daily basis

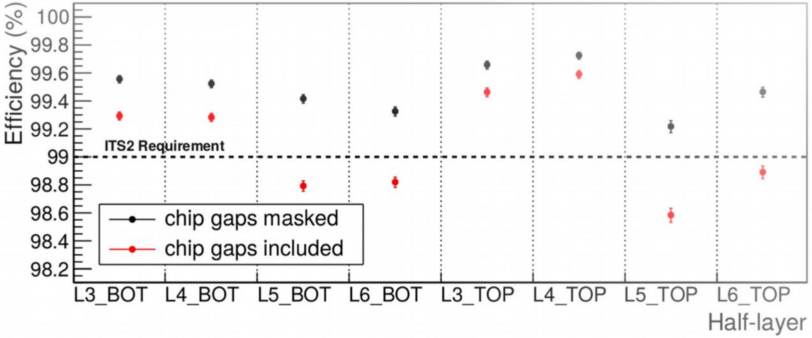
On-surface commissioning overview - 2019/2020

- 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)



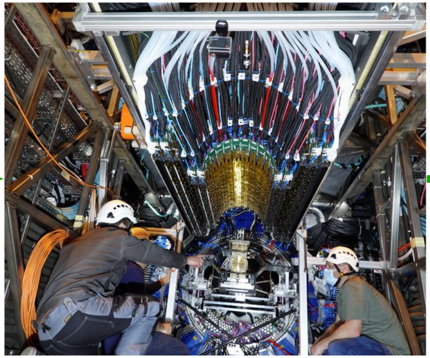
Efficiency with cosmic tracks (OB)

ITS installation inside ALICE cavern - 2021

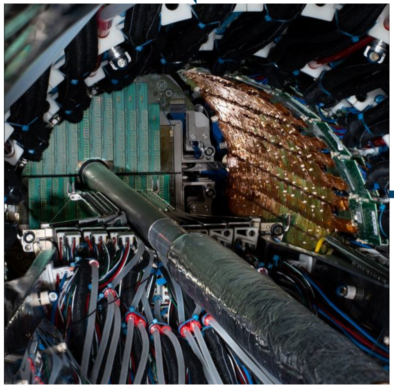
→ a trip from lab to ALICE cavern

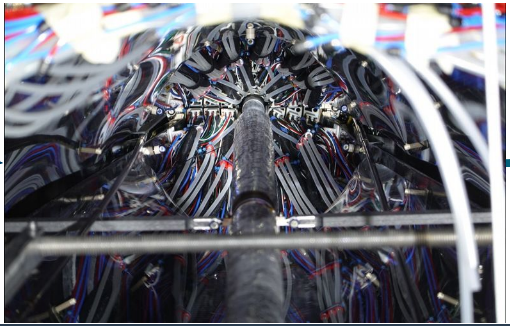
- ITS installation in ALICE cavern started in 2021 after a **successful on surface commissioning from Sept/2019 to Dec/2020**
- OB installation completed in March 2021 → IB installation completed in May 2021

OB

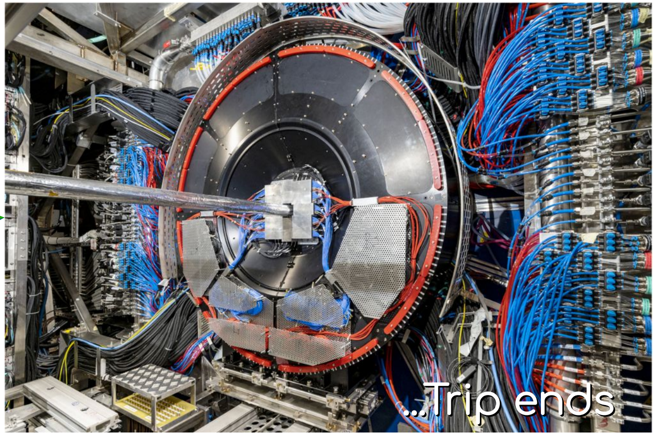


IB



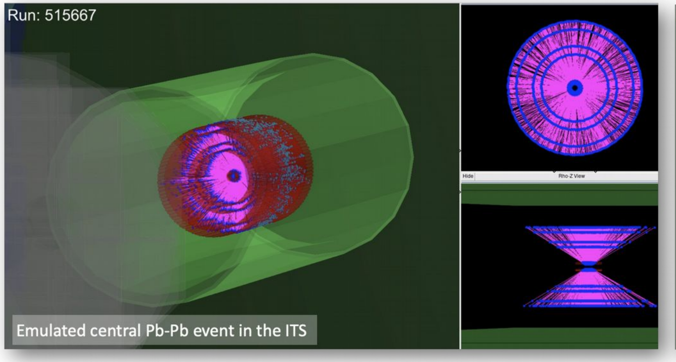


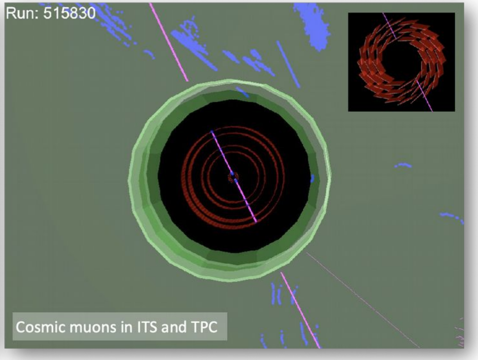
Fast Interaction Trigger (FIT) in front of ITS2

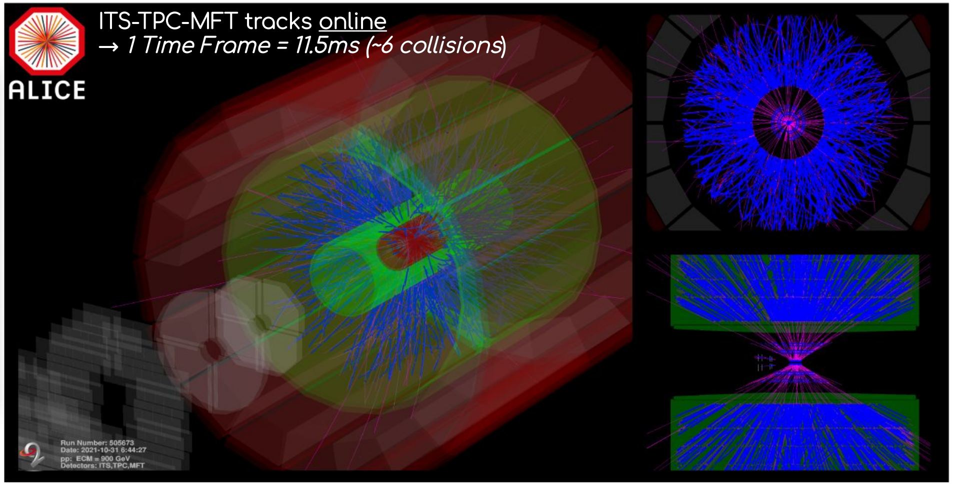


The challenge:
- Clearance around beam pipe: **~2 mm**
- Clearance between adjacent staves: **~1.2 mm**
- Manipulation from **4m distance**

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

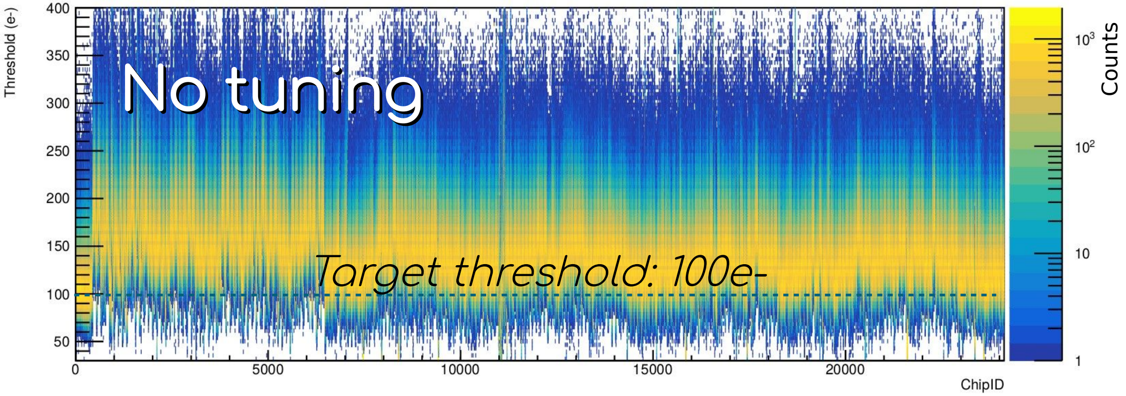
Verification of barrels after installation and preparation for data taking - 2021

ALICE

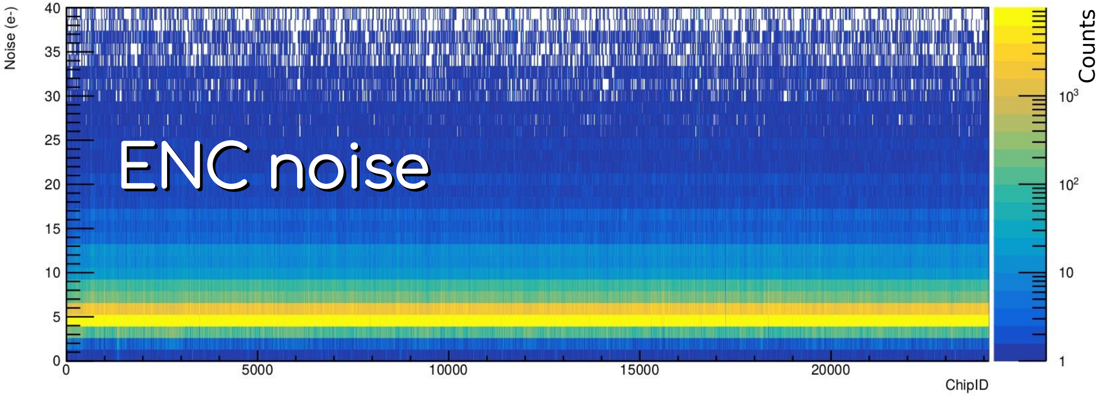
- OB installation (March 2021)
  - Full detector powered and monitored till mid-April
  - Various issues spotted and solved:
    - Problematic cables giving loose contacts or with wrong wire configuration (replaced)
    - Unstable power supplies (replaced)
    - Optimization of cooling for staves and 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

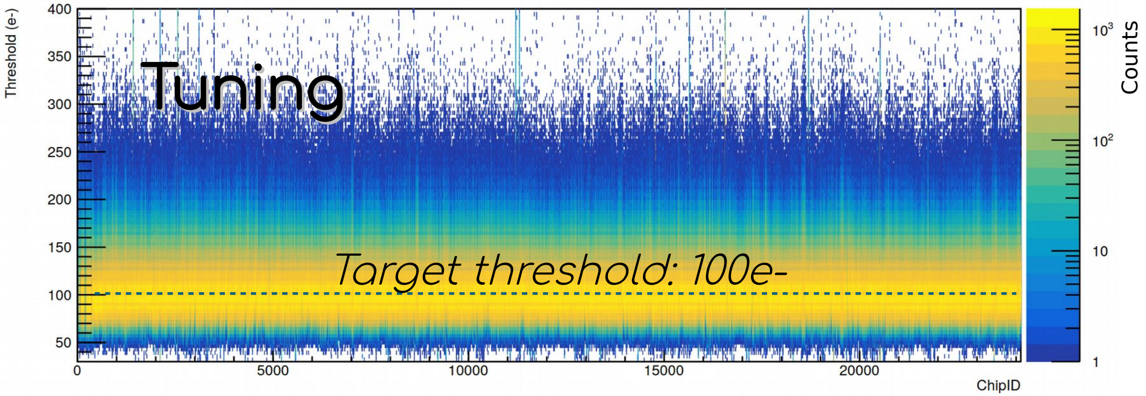
→ ITS2 full calibration (2)



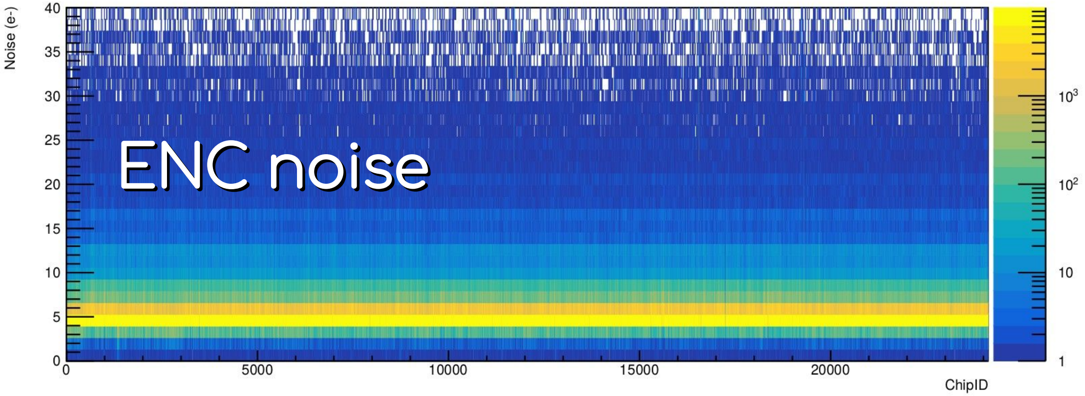
- Distribution of pixel thresholds per chip
- Thresholds not tuned: detector already ~100% efficient
- ENC noise: ~5e- (stable for 24k chips)



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)

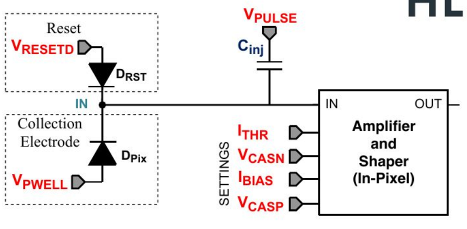


Influence of VRESETD on the ALPIDE performance

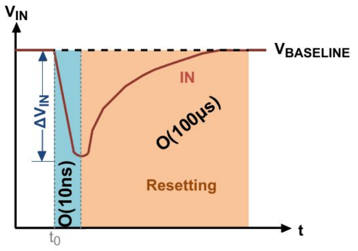
A Large Ion Collider Experiment

Influence of V_{RESETD} on the ALPIDE performance

- ALPIDE uses a diode based reset:
  - Reset current depends exponentially on the forward bias of the diode D_{RST}
  - Baseline of V_{IN} depends on V_{RESETD} and the leakage current in the pixel (shown as reversed-biased D_{Pix})
- V_{IN} needs to fit the working range of the amplifier/shaper in the pixel
- Working point (V_{IN}) and working range influenced by radiation:
  - Pixel leakage current increased by NIEL (Non-Ionizing Energy Loss)
    → lower V_{IN} due higher larger current through D_{RST}
  - Transistor properties altered by TID (Total Ionizing Dose)
    → changes working range (in terms of V_{IN}) of the amplifier/shaper
  - Effects (so far) not studied independently, as chips are exposed simultaneously to NIEL and TID during operation at LHC
    → No direct observation of V_{IN}



Input section of the ALPIDE Front-End



Voltage excursion during charge collection (blue) and resetting (orange)

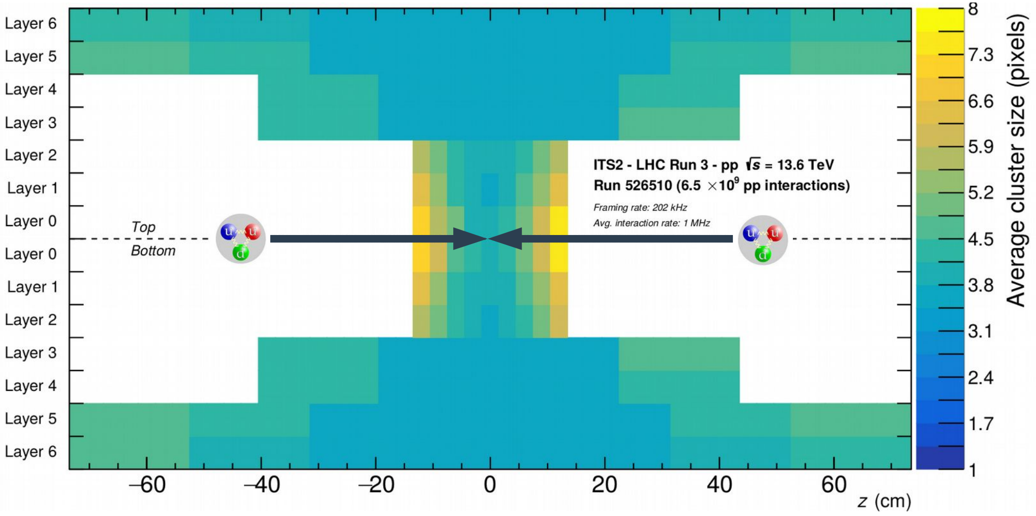
Correct working range of VRESETD is fundamental (VRESETD scan)

- Courtesy of Felix Reidt

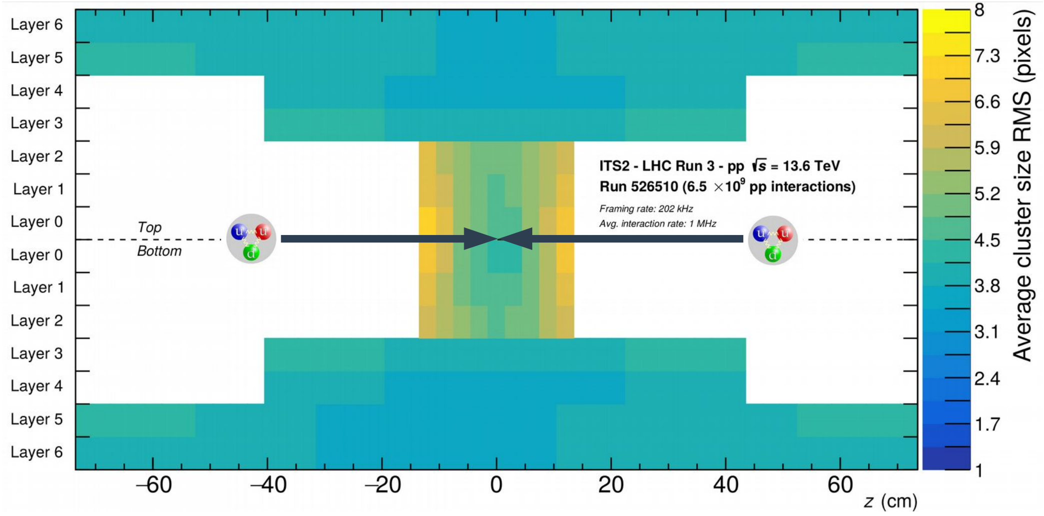
Preliminary performance plots in Run 3

→ 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



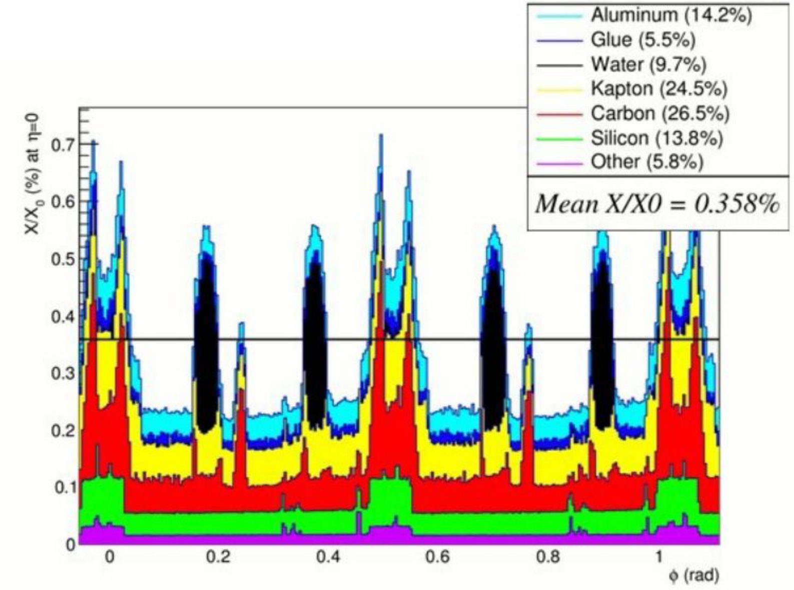
Cluster size (pix)



Cluster size RMS (pix)

ITS2 material budget

Inner Barrel



Outer Barrel