Operation and performance of the upgraded ALICE Inner Tracking System

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on behalf of the ALICE Collaboration

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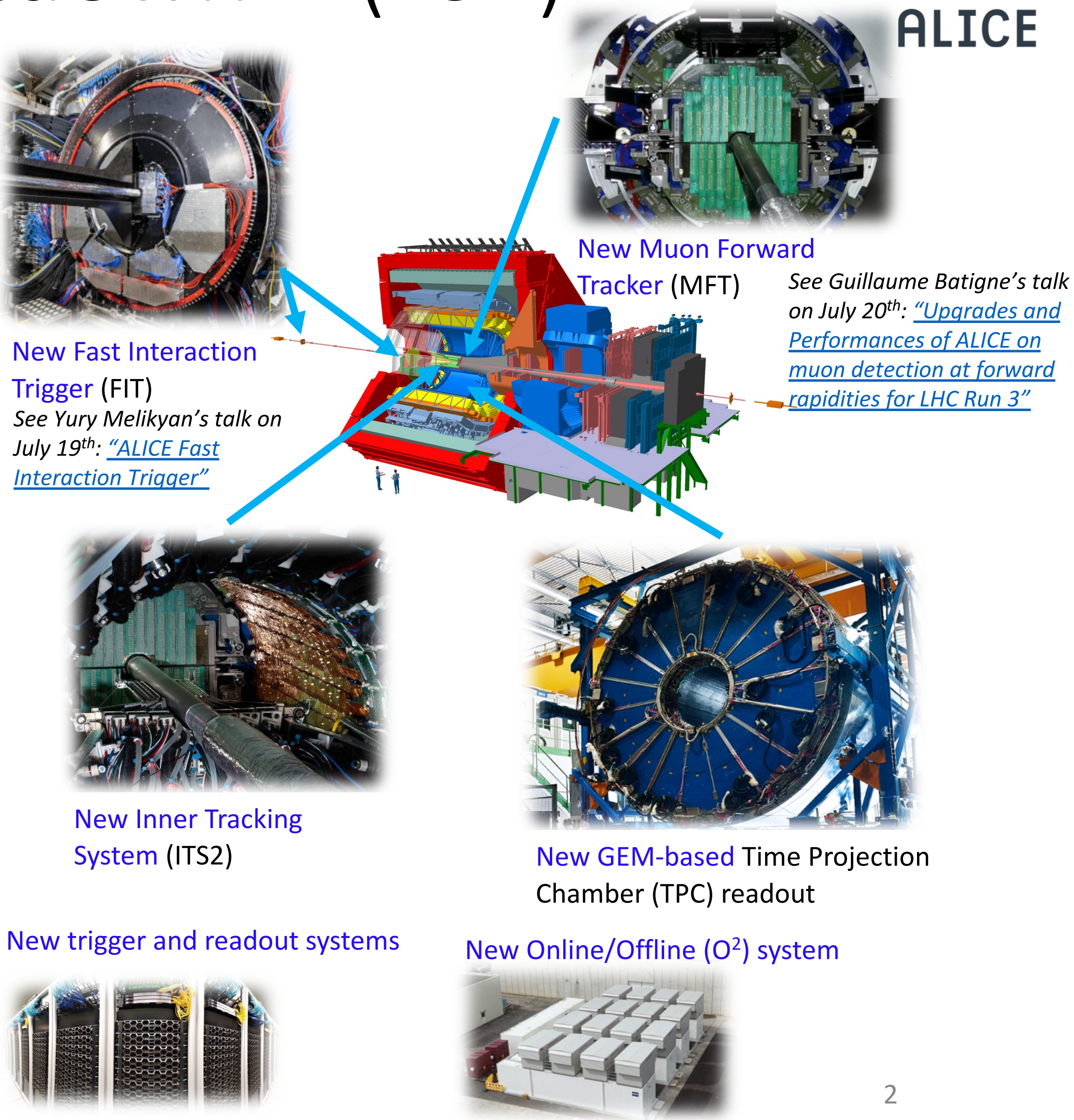
ALICE upgrades in Long Shutdown 2 (LS2)

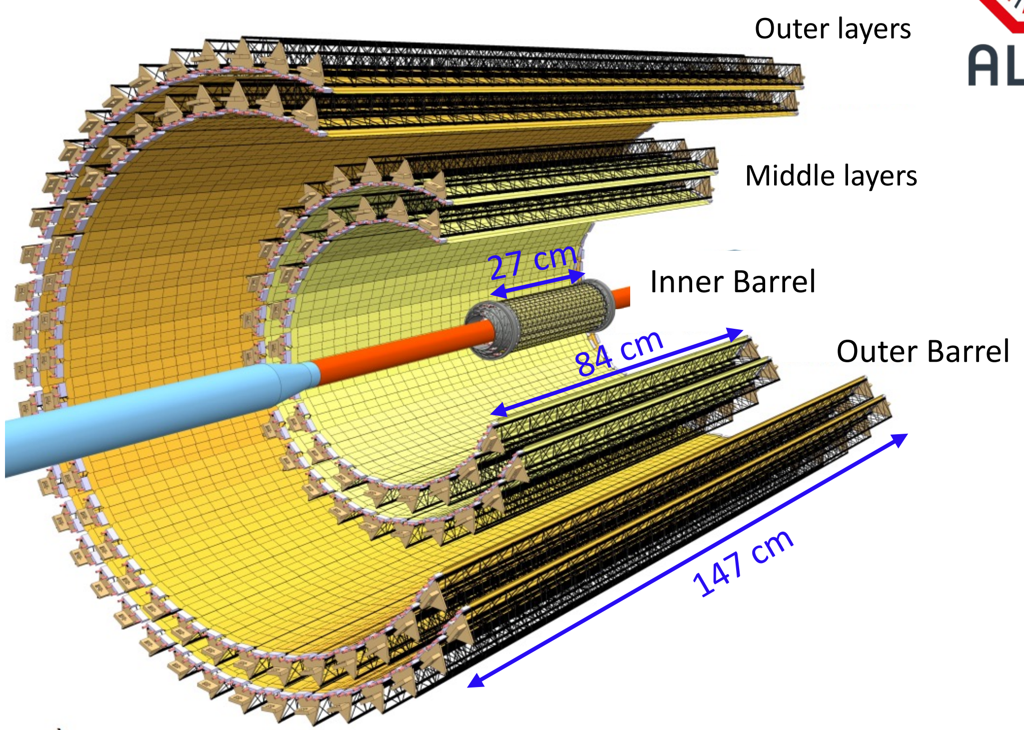
- Major upgrades completed for ALICE during LHC LS2 (2019 - 2021)
- Motivation
  - High-precision measurements of rare probes at low p_T
    - Cannot be selected by hardware trigger
    - Need to record large minimum-bias data sample
      → read out all Pb-Pb interactions up to the maximum collision rate of 50 kHz
- Goal
  - Pb-Pb integrated luminosity > 10 nb^{-1} (plus pp, pA and O-O data)
    → gain factor 100 in statistics for minimum-bias sample with respect to Run 1 and 2
  - Improved vertex reconstruction and tracking capabilities
- Strategy
  - New ITS, MFT, FIT and TPC readout chambers
  - New readout of most detectors and new trigger system
  - New integrated Online-Offline system (O^2)

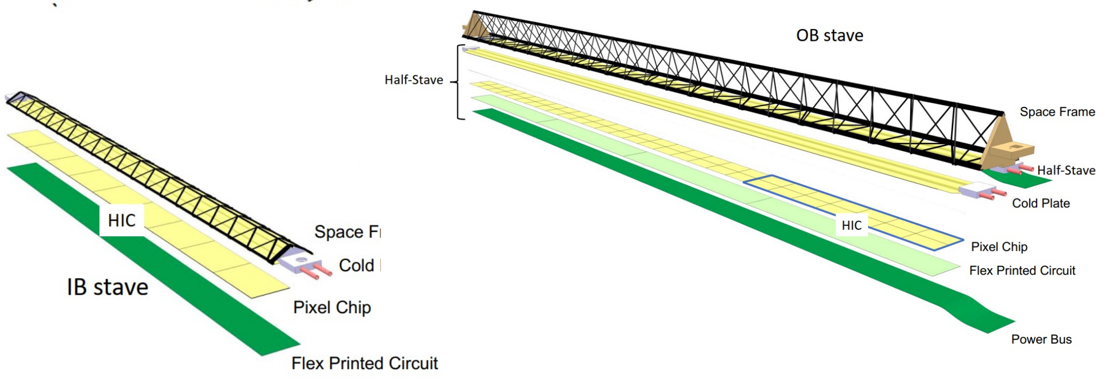


ALICE upgrades during the LHC Long Shutdown 2, JINST 19 P05062

ITS2 objectives and layout

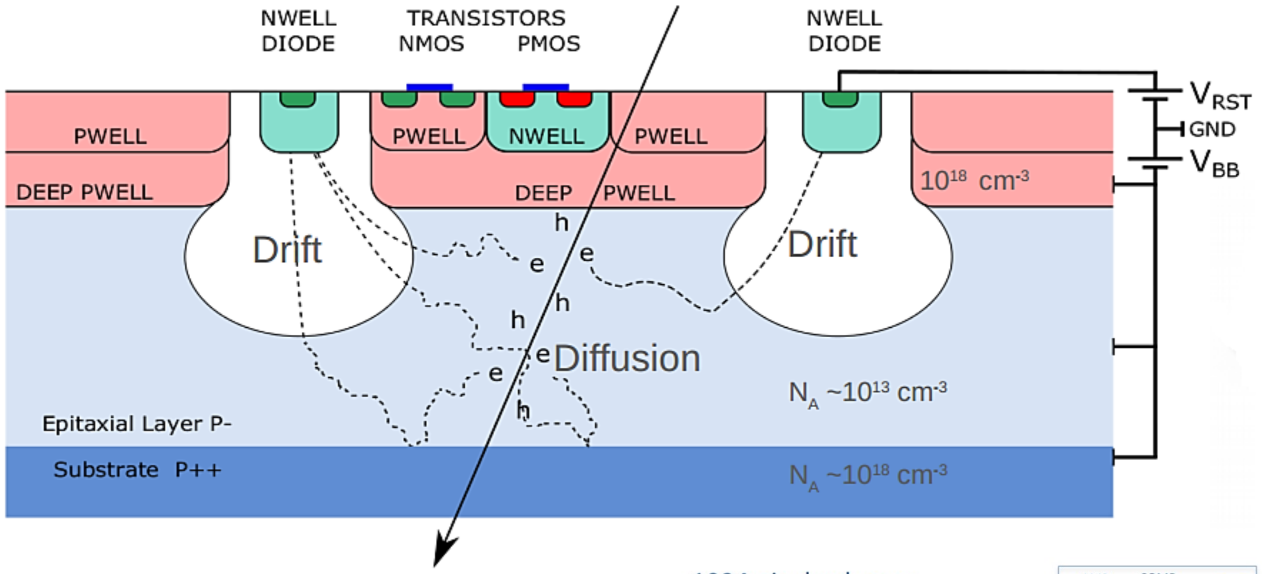
- Improve impact parameter resolution by factor ~3 in rφ and factor ~5 in z at p_T = 500 MeV/c
  - Get closer to IP: 39 mm → 23 mm
  - Reduce material budget:
    - 1.14% X_0 → 0.36% X_0 per layer (inner layers)
  - Reduce pixel size: 50 x 425 μm^2 → 29 x 27 μm^2
- Improve tracking efficiency and p_T resolution at low p_T
  - Increase number of track points: 6 → 7 layers
- Fast readout
  - Detector readout rates up to 100 kHz (Pb-Pb, was 1 kHz for ITS1) and 400 kHz (pp)
- 7 cylinders covering ~10 m^2 area with 12.5 billion pixels
  - Inner Barrel (IB)
    - 3 Inner Layers (48 staves)
  - Outer Barrel (OB)
    - 2 Middle Layers (54 staves) + 2 Outer Layers (90 staves)





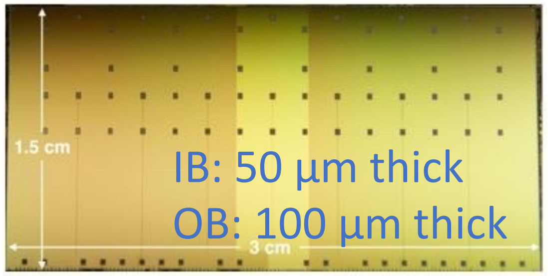
Technical Design Report for the Upgrade of the ALICE Inner Tracking System, J. Phys. G: Nucl. Part. Phys. 41 087002

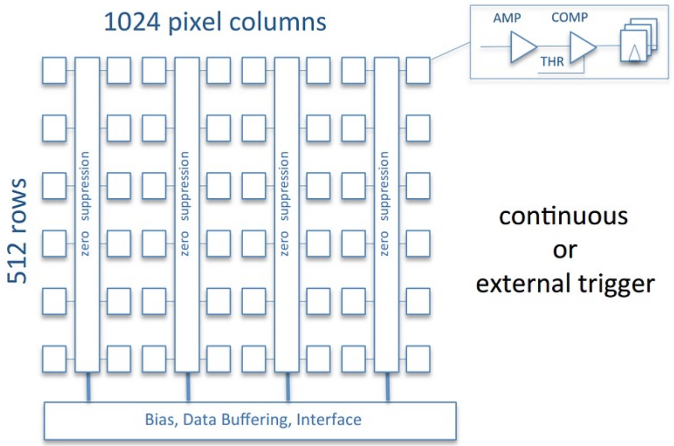
ALPIDE: ALICE PIxel DEtector



ALPIDE technology features:

- TowerJazz 180 nm CiS Process
- Deep p-well implementation available → full CMOS
- High resistivity (>1 kΩ·cm), 25 µm thick, p-type epi-layer
- Possibility of reverse biasing
- Smaller charge collection diode
  → lower capacitance → higher S/N
- Substrate can be thinned down

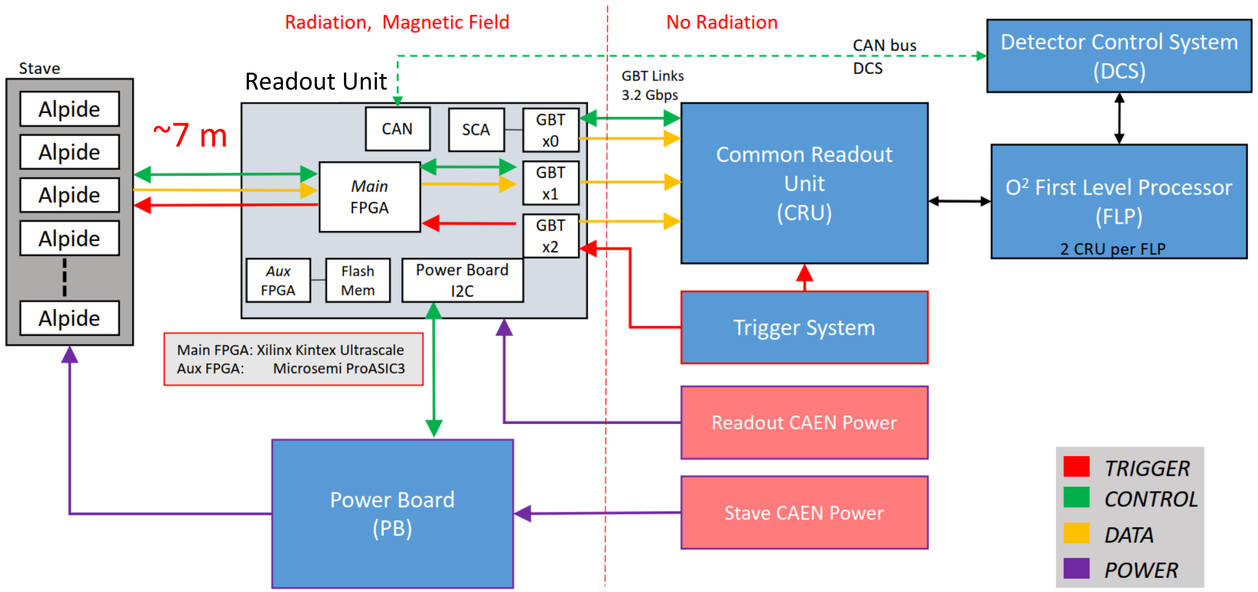


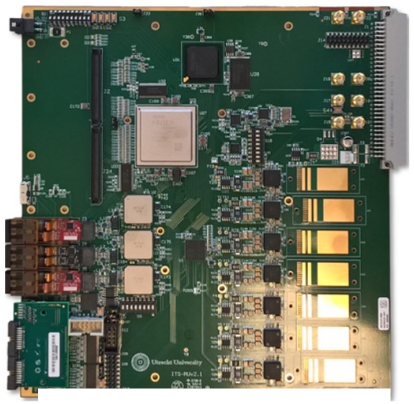


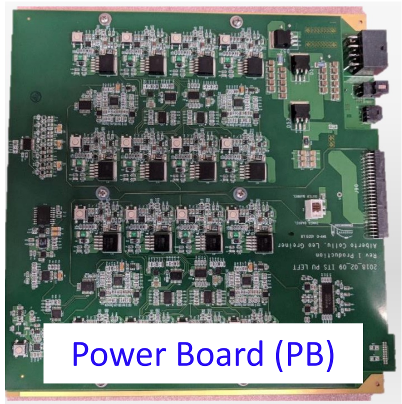
Sensor specification:

- Pixel pitch: 27 µm x 29 µm → spatial resolution: ~5 µm
- Priority Encoder Readout
- Power consumption: 47.5 mW/cm^2 (IB) and 35 mW/cm^2 (OB)
- Integration time: < 10 µs
- Fake-hit rate: << 10^{-6} /pixel/event
- Readout bandwidth up to 1.2 Gbit/s (IB) and 400 Mbit/s (OB)
- Continuous or triggered readout

ITS2 system architecture




Readout Unit (RU)

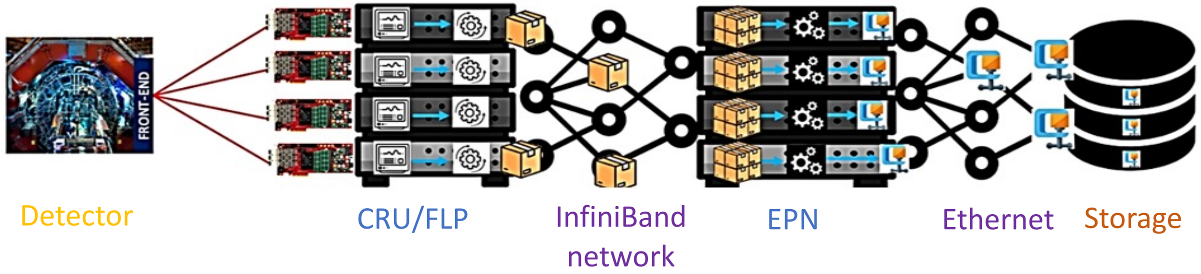

Power Board (PB)


Common Readout Unit (CRU)


CAEN power system

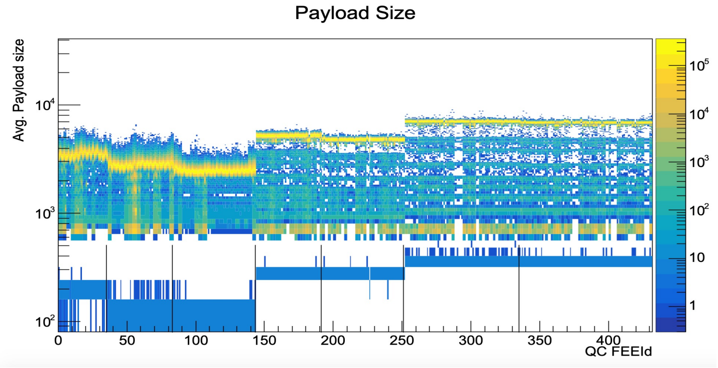
- Electrical links (~7 m) between the detector and the RU
- FPGA in radiation environment controlling detector, packaging data, electrical optical conversion using Versatile Link controlling powering
  - Needs scrubbing and TMR (Triple Modular Redundancy) to mitigate radiation effects
- Connecting to 22 CRUs hosting on 13 FLPs via the optical Versatile Link for raw data processing
- Detector Control System (DCS) communicates with the detector via CRU and RU
  - Automatic in-run recovery maximizes detector acceptance and data-taking efficiency

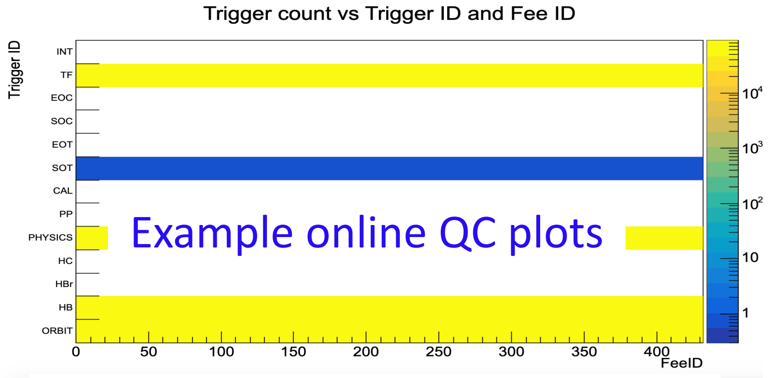
Data processing and quality control (QC)



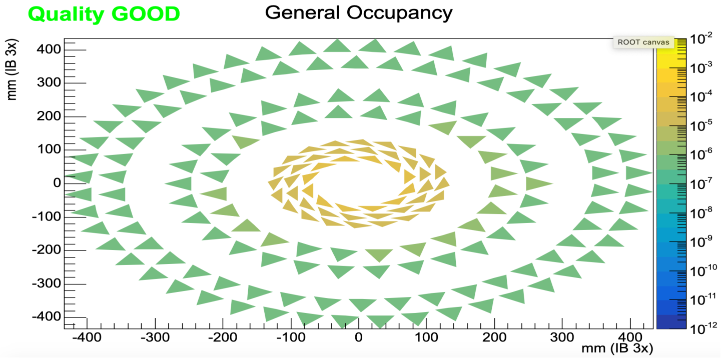
Synchronous

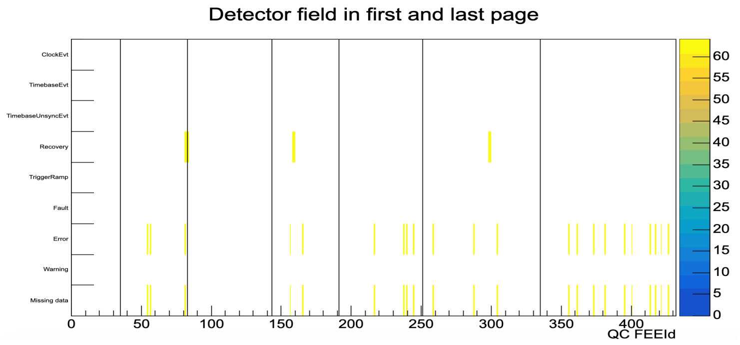
- 13 ITS First Level Processors (FLPs)
  - Data aggregation
  - QC: data integrity and detector occupancy

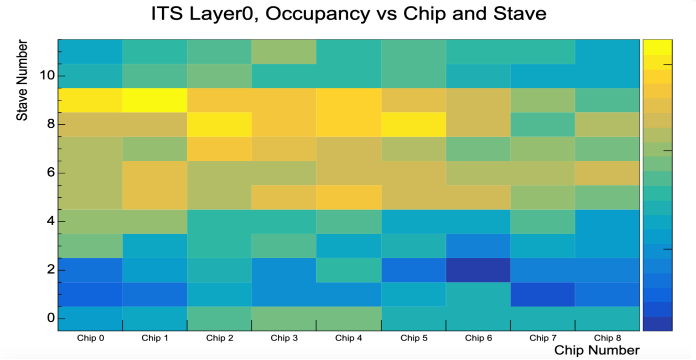


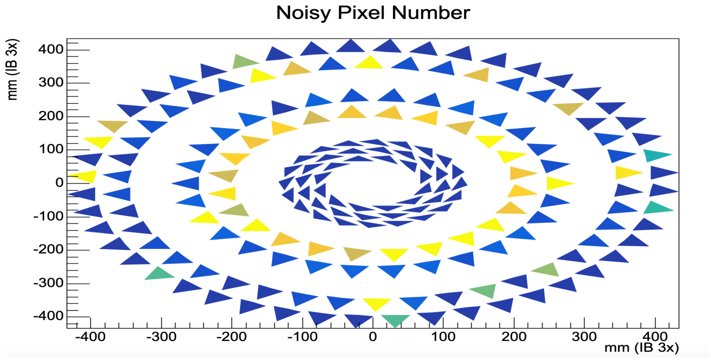


Example online QC plots



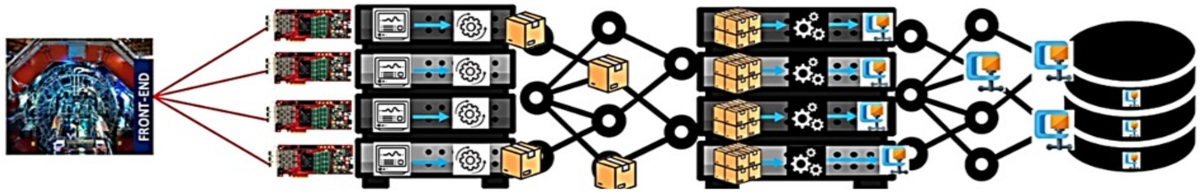






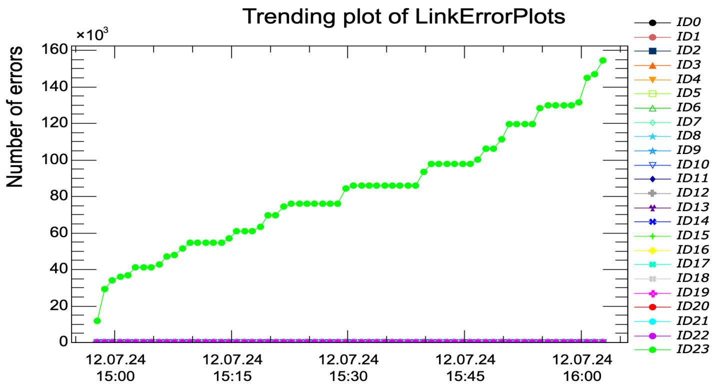
See Svetlana Kushpil's poster on July 19th: "Data Quality Control of the ALICE Inner Tracking System in the LHC Run 3"

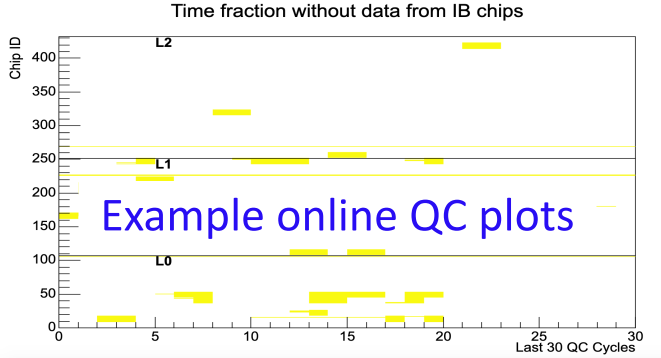
Data processing and quality control (QC)



Synchronous

- 340 Event Processing Nodes (EPNs, shared by all ALICE detectors)
    - Synchronous reconstruction and data compression
    - Detector calibration: threshold scan/tuning, noisy pixel masking etc
    - QC: decoding errors, dead-chip maps, clustering and tracking, threshold and noisy pixels
- Aggregated QC flags with trending on dedicated QC servers





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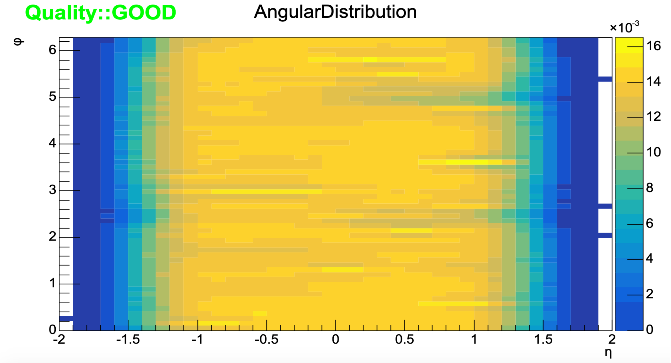

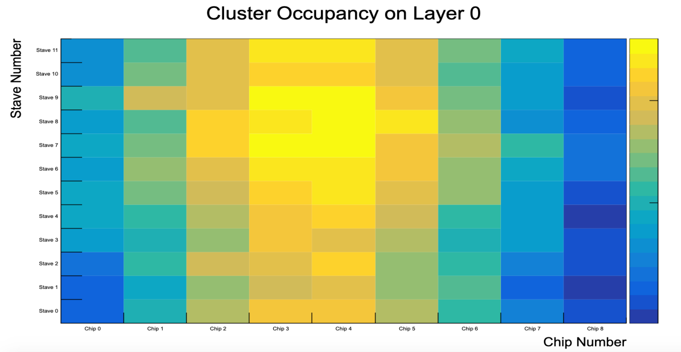

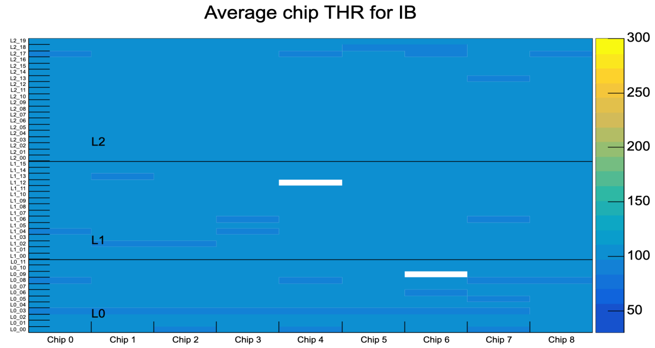

GLOBAL ITS QUALITY

ITS Quality : Good
All checks are OK

ITS DETAILS

Hit Occupancy : Good
Link Decoding Errors : Good
Lanes into ERROR and FAULT : Good
Lanes into WARNING : Good
Lane status summary : Good
Trigger count Vs FeeID : Good
Cluster occupancy : Good
Track angular distribution : Good
NClusters : Good
Internal triggers per Orbit : Good

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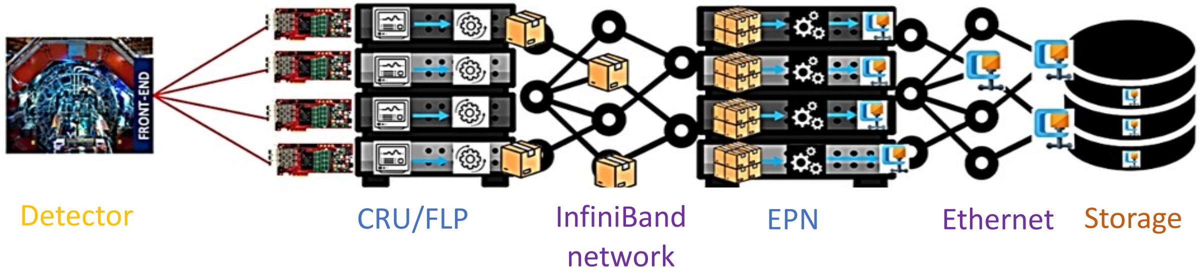
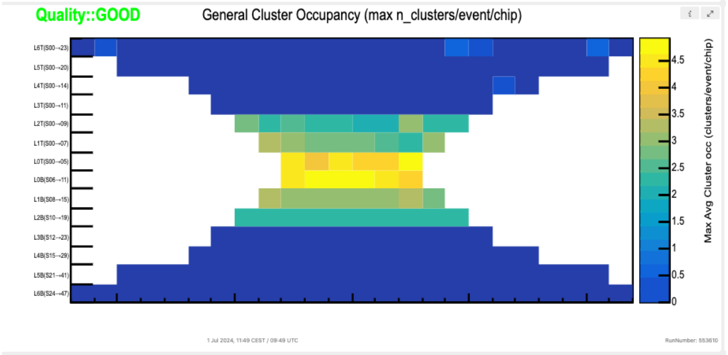
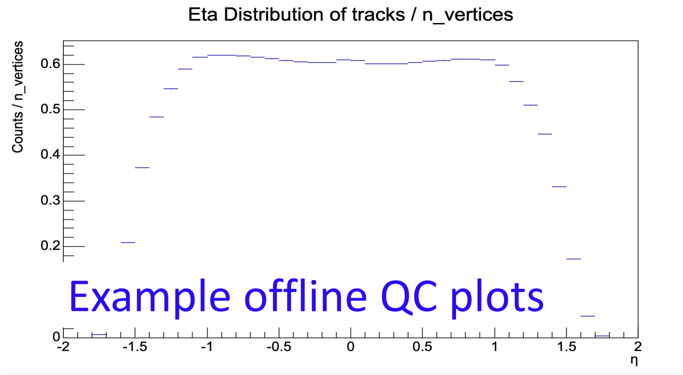
Data processing and quality control (QC)



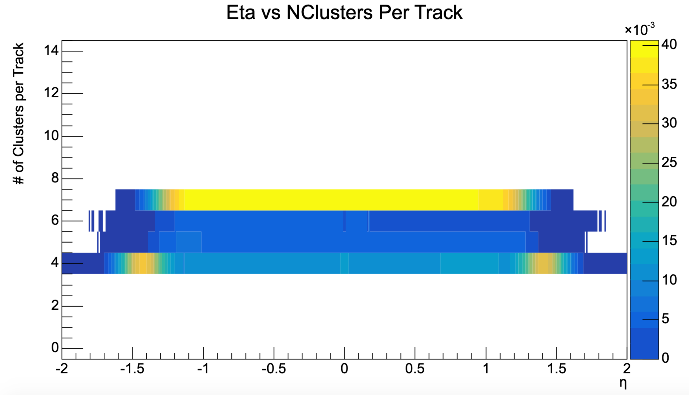
Asynchronous

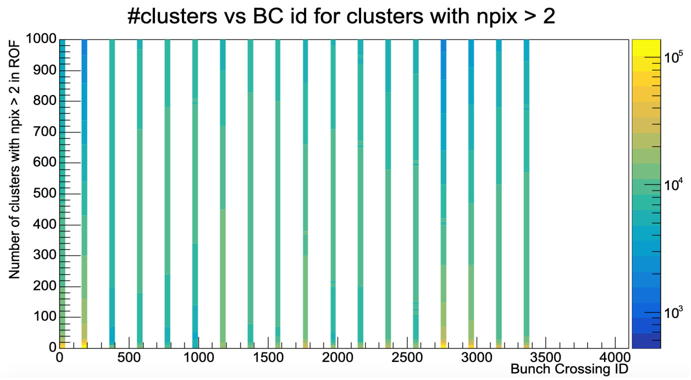
- Physics reconstruction with QC on the EPNs not used for synchronous and on GRID → final Analysis Object Data (AOD)
  - QC: cluster occupancy/topology, track distribution and length
- Monte Carlo (MC) simulations anchored to physics runs with ITS dead-chip maps

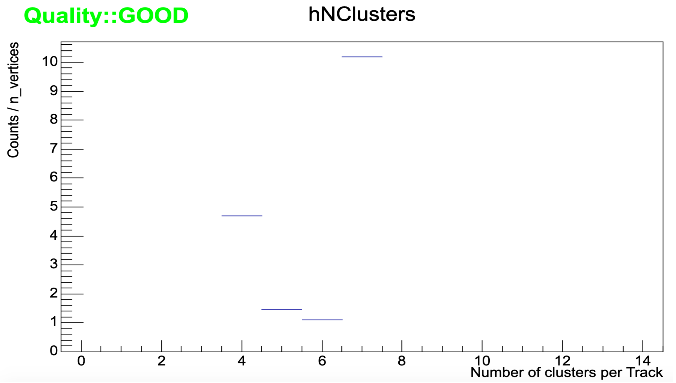


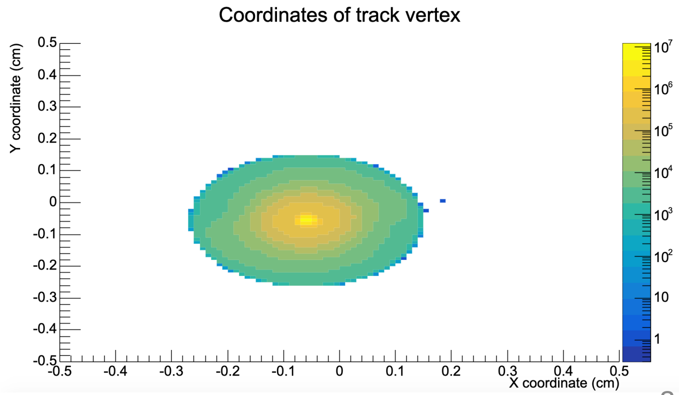


Example offline QC plots









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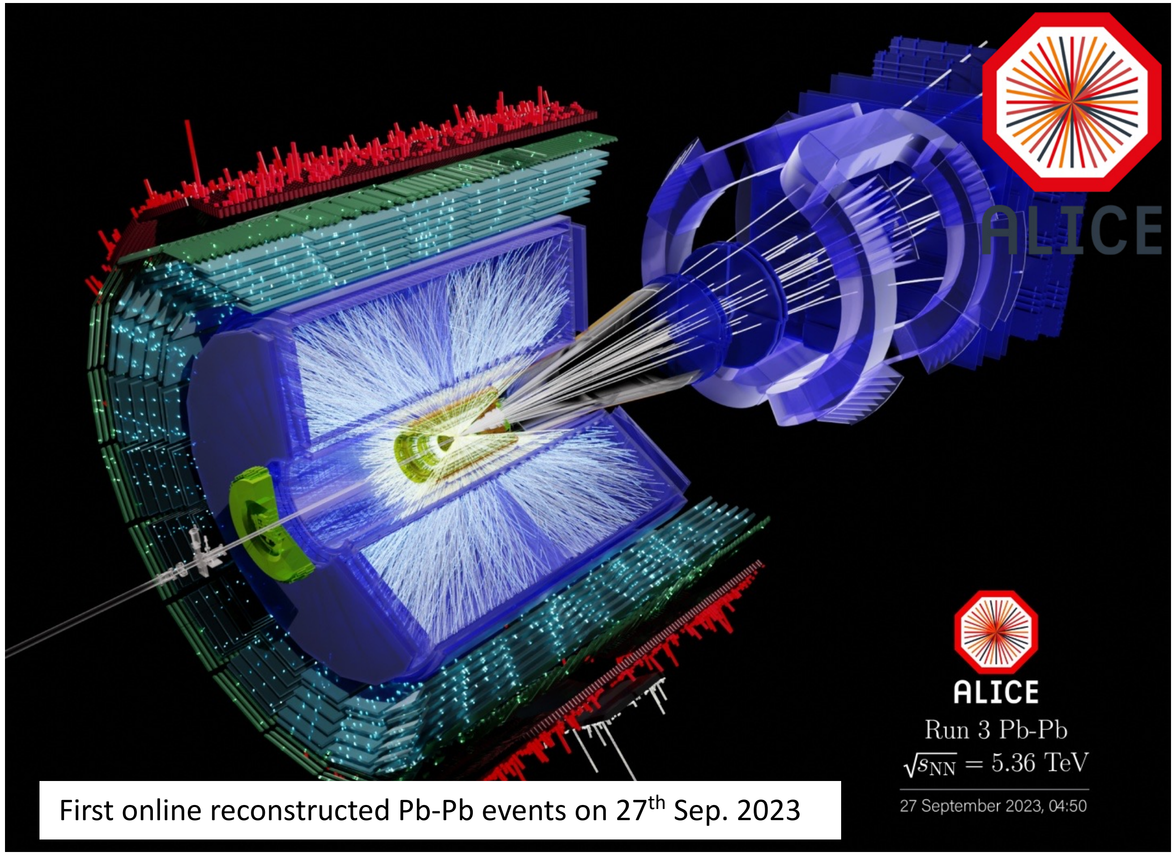
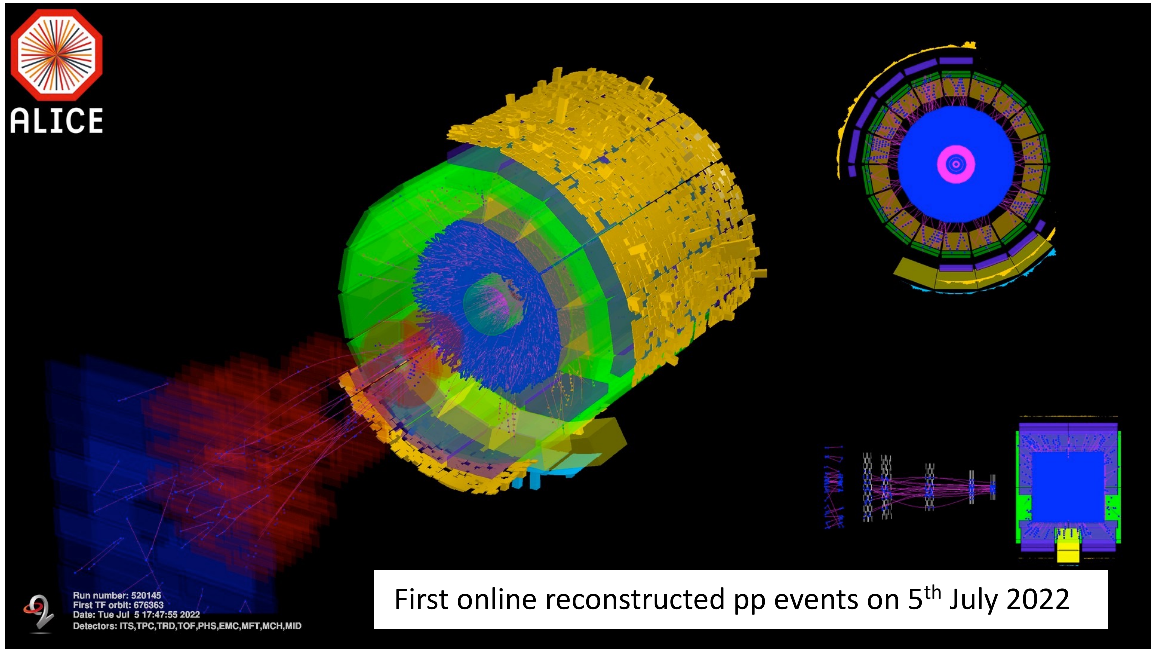
ITS2 in Run 3

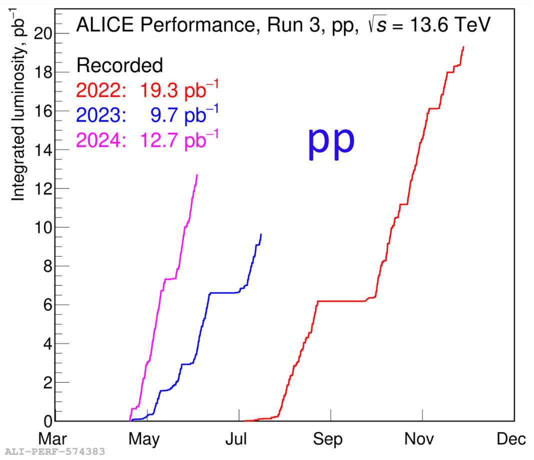
- Integrated luminosity so far (pp collisions): ~42 pb^{-1}
- Integrated luminosity for Pb-Pb in 2023 Oct.: ~1.5 nb^{-1}
  - Recorded Minimum Bias sample of ~12 billion collisions, ~40 times larger than Run 1+2
- ALICE standard interaction rate: 500 kHz (pp) – peaking at 47 kHz in Oct. 2023 (Pb-Pb)
  - Instantaneous luminosity: ~10^{31} (pp) – 10^{27} (Pb-Pb) $cm^{-2}s^{-1}$

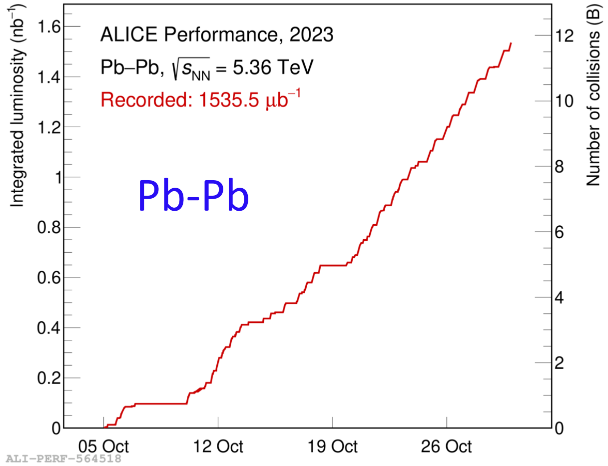


First online reconstructed Pb-Pb events on 27th Sep. 2023



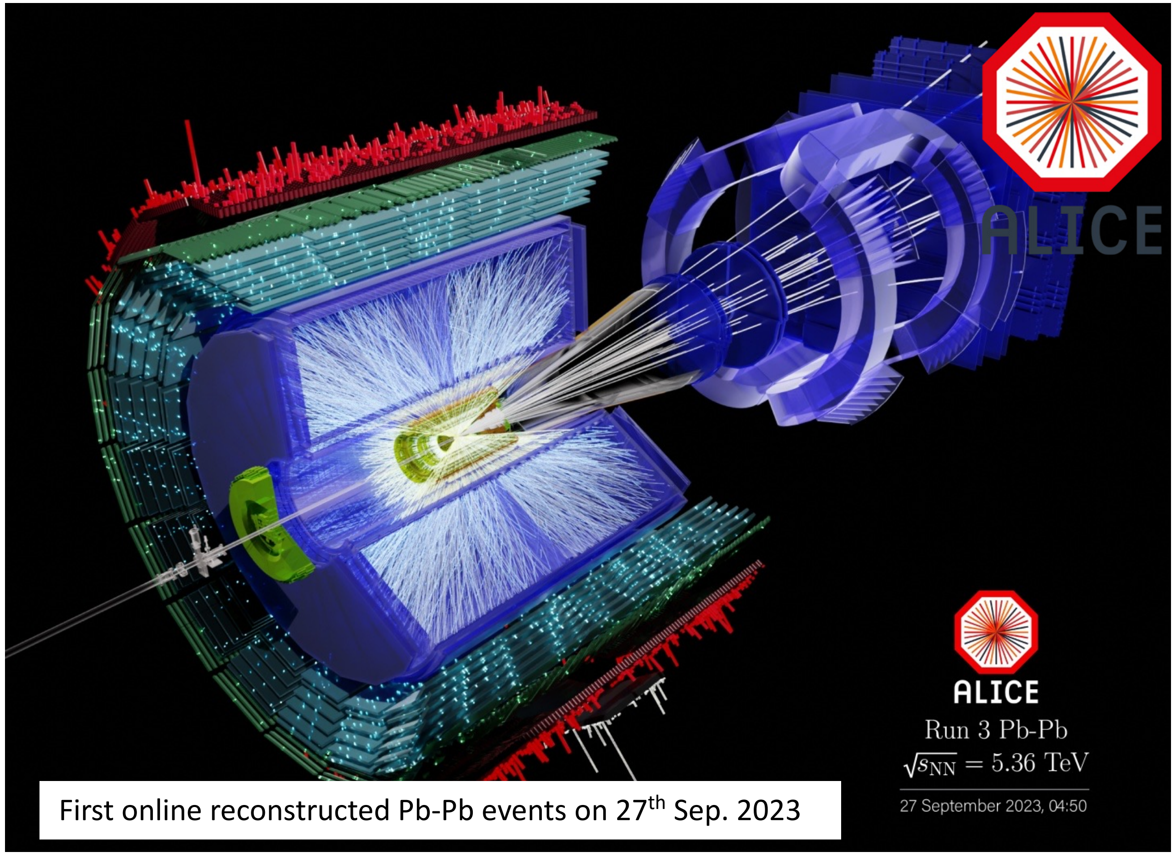
First online reconstructed pp events on 5th July 2022



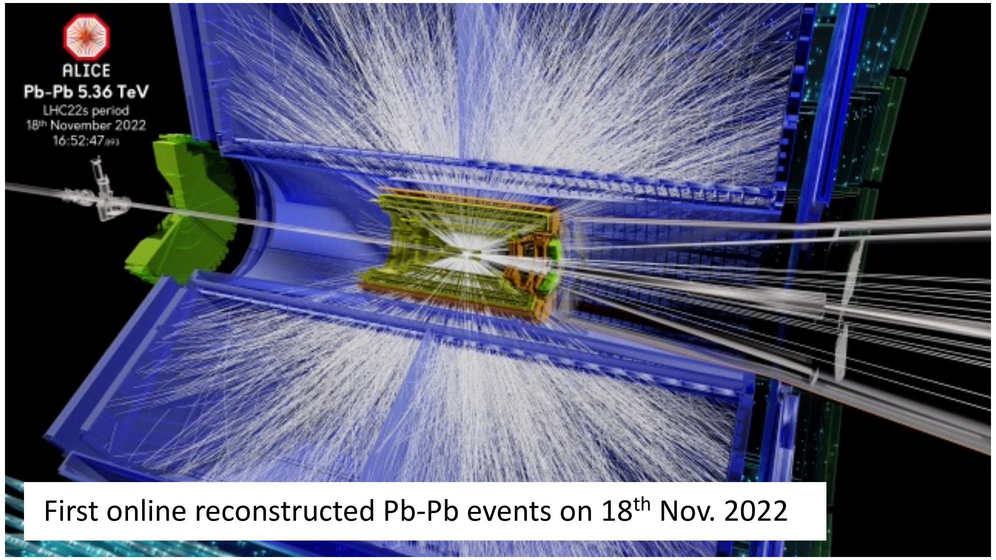


ITS2 in Run 3

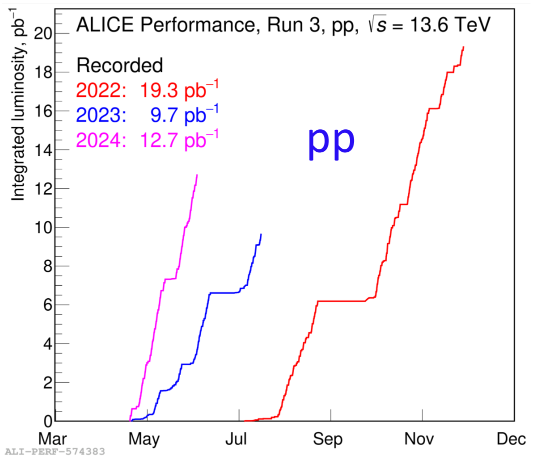
- ITS2 successfully tested up to 4 MHz interaction rate in pp
- 99.6% pixel active in the whole detector
  - 94 chips broken/excluded, 970 k dead pixels and 500 k noisy pixels
- Beam-induced background observed in the first minutes of the stable beams → largely mitigated by prompt LHC adjustment
  → Improved ITS RU firmware to better cope with such events
- Loss of acceptance during run auto-recovered by DCS
- Sporadic data corruption events not affecting overall performance
  - Dominated by SEU induced issues; further consolidations ongoing

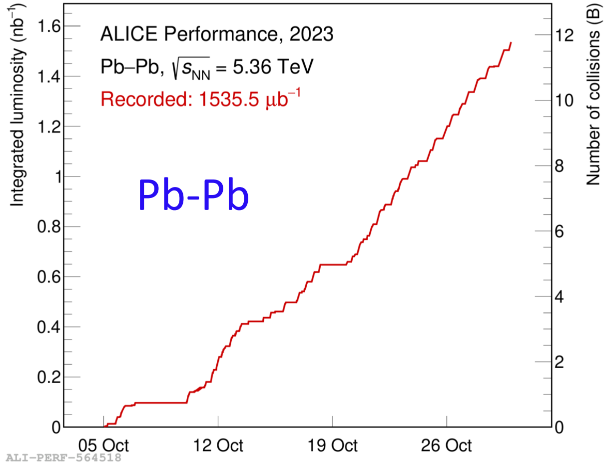


First online reconstructed Pb-Pb events on 27th Sep. 2023



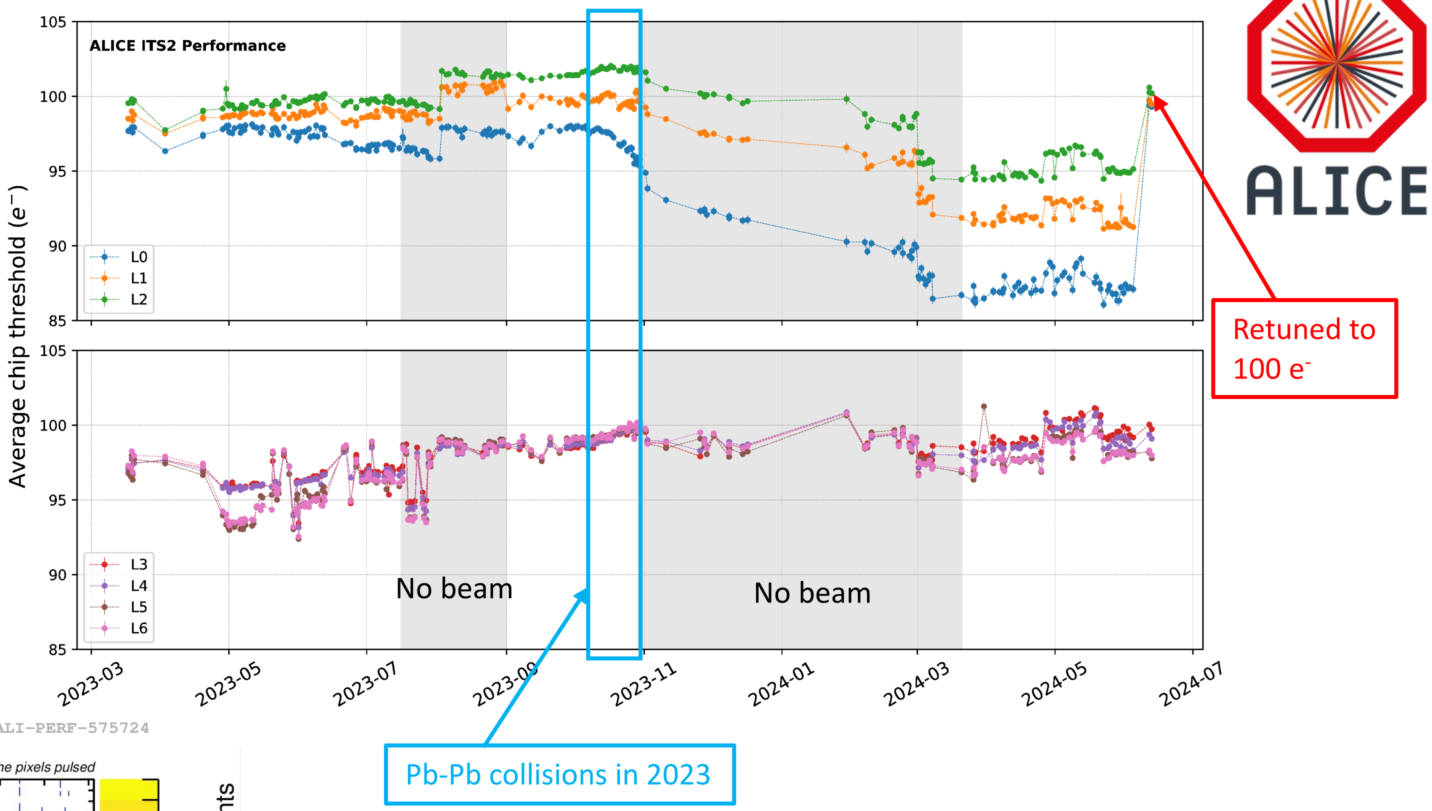
First online reconstructed Pb-Pb events on 18th Nov. 2022

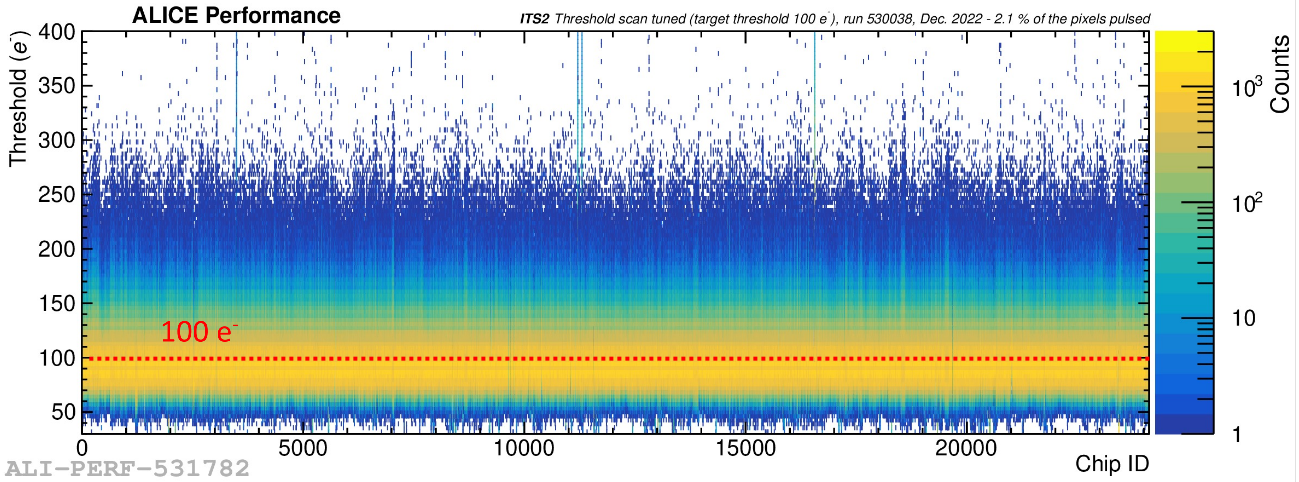




Calibration (1/2)

- Main ITS calibrations
  - Threshold tuning
  - Noisy pixel masking
- Threshold & noise re-calibration: ~1/year
- Fast threshold scan (~1% pixels) at each beam dump
- Full threshold scan (100% pixels): ~1/year



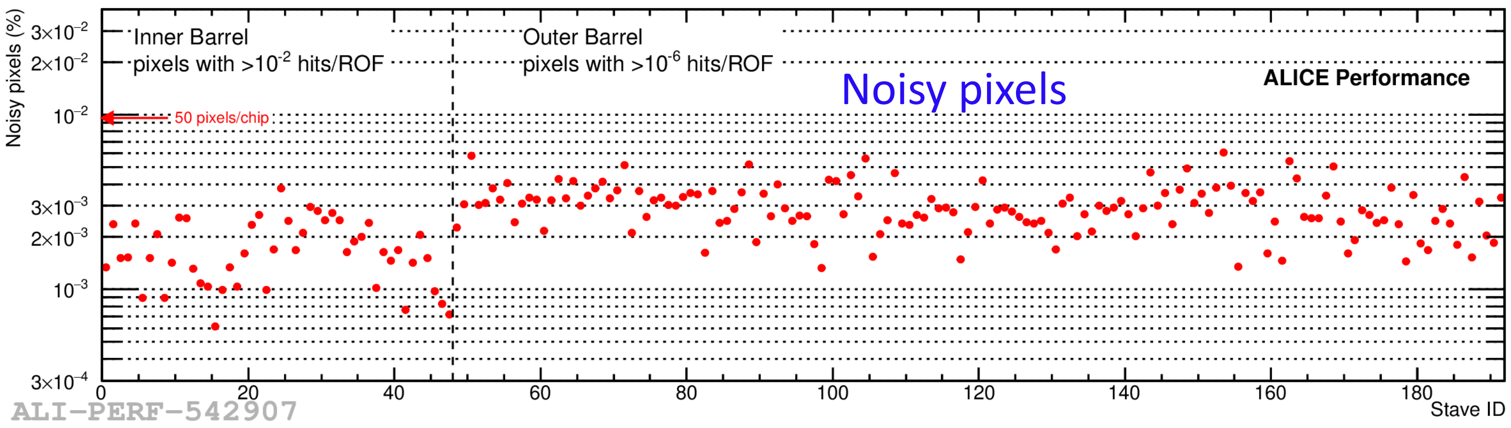


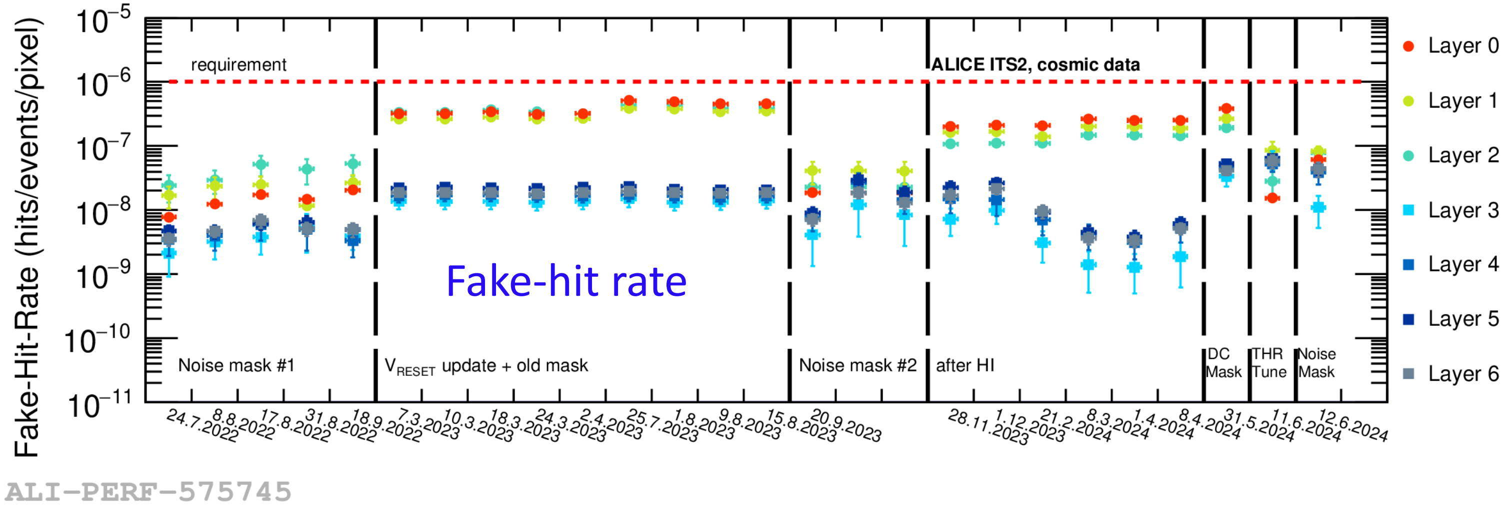
- Uniform response across the detector achieved (100 e$^-$ target)
- Noise ~5 e$^-$ (compatible with production QA measurements)
- Very satisfying threshold stability over time for 24 k chips
  - Minor fluctuations due to supply voltage optimizations
- Radiation effect observed in IB after Pb-Pb runs in 2023
  - Effect compensated with a new tuning in June 2024

Calibration (2/2)

- Possibility to run with static masks already proven during surface commissioning
- OB masking: pixels with 10^{-6} hits/event
- IB masking: 10^{-2} hits/event → almost no masking → prioritization of efficiency over data rate reduction
- Fraction of masked pixels: 0.004%
- Stable noisy pixel map → occasionally noise calibration is sufficient

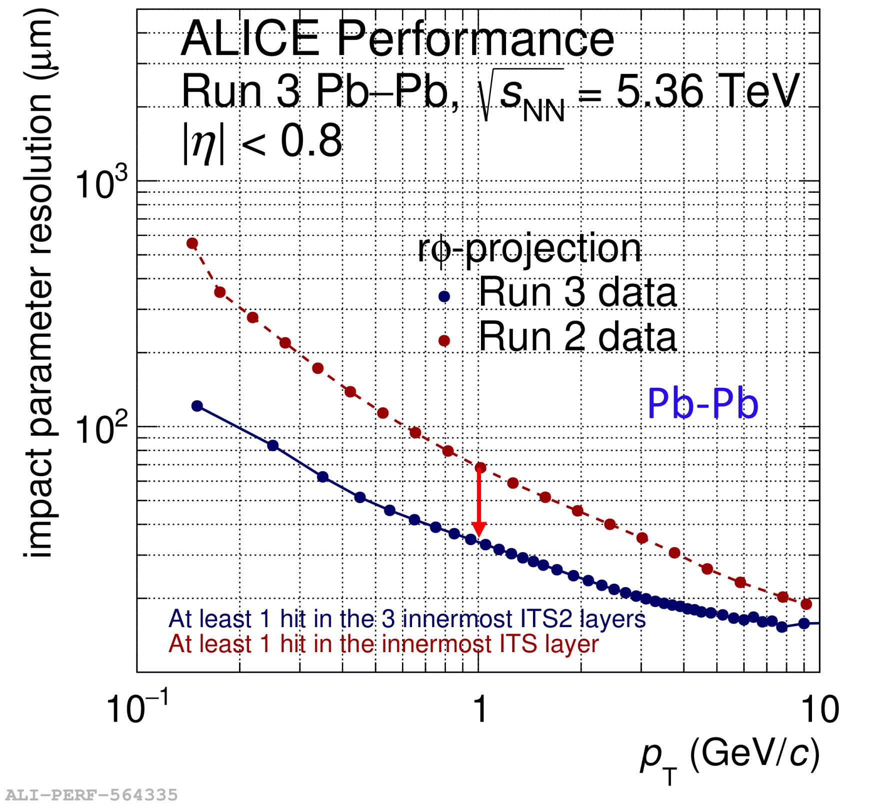
Extremely quiet detector!

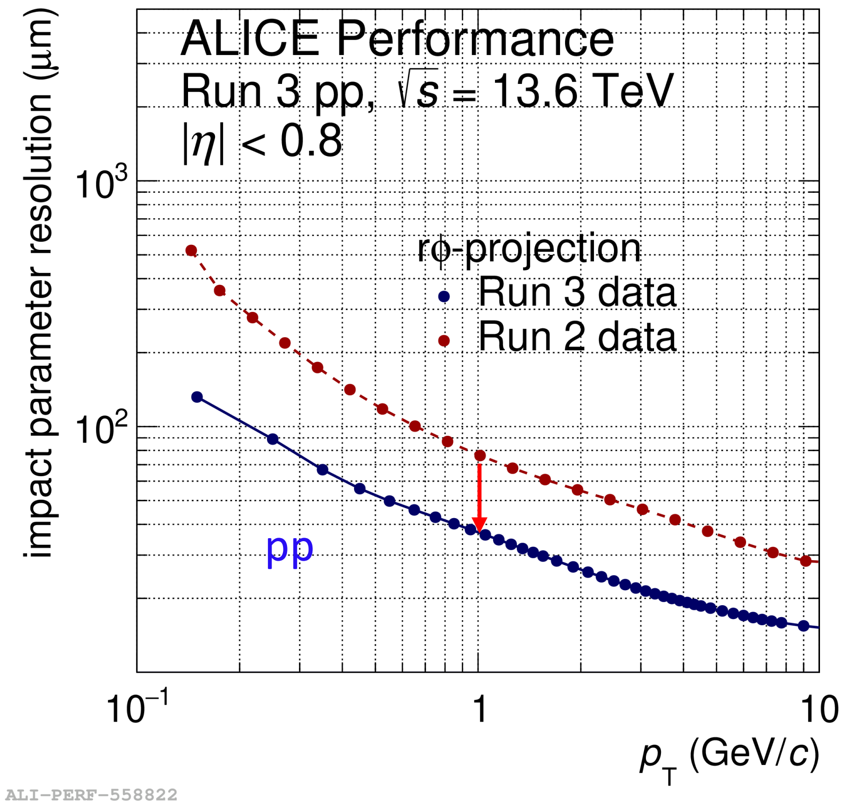




Impact parameter resolution

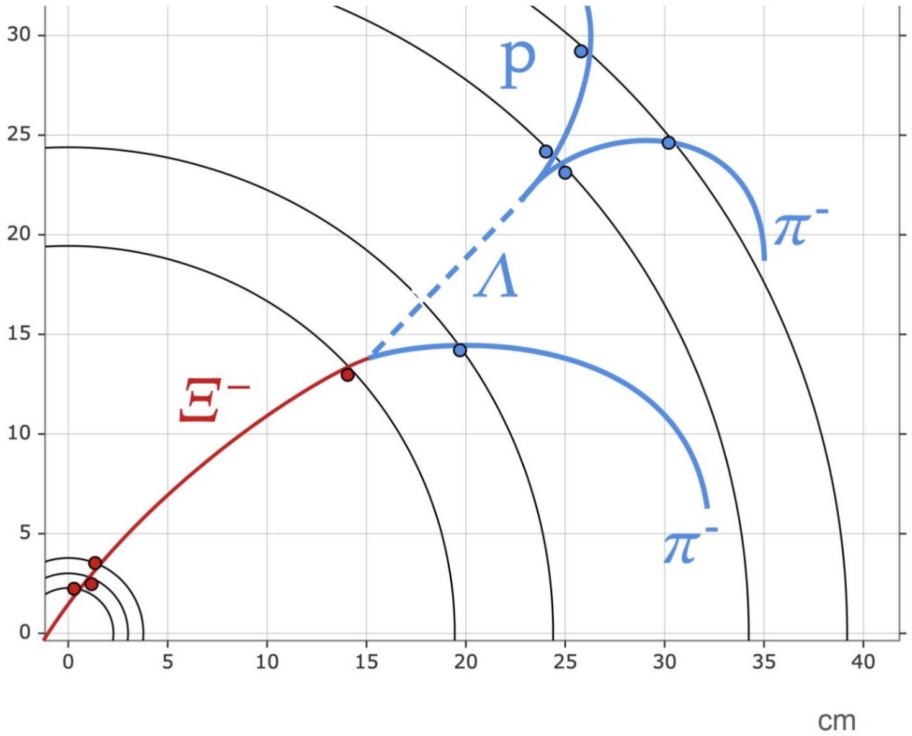
- Impact parameter resolution measured with Run 3 pp and Pb–Pb data
  - ITS updated alignment + TPC space-charge distortion calibration
  - ~2x improvement at p_T = 1 GeV/c with respect to Run 2

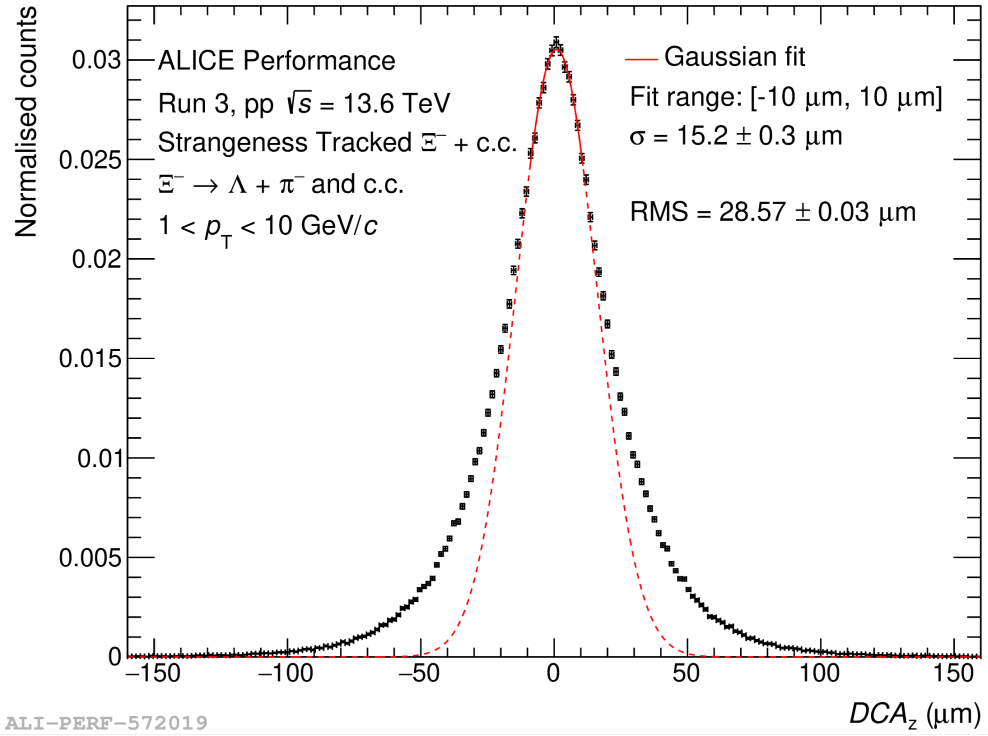




Detection of weakly decaying particles

- ITS2 Inner Barrel has the first three layers within 4 cm
  - Direct tracking of charged weak-decaying particles before their decay via strangeness tracking
  - New possibilities of studies: non-prompt cascades, hypernuclei, exotic bound states

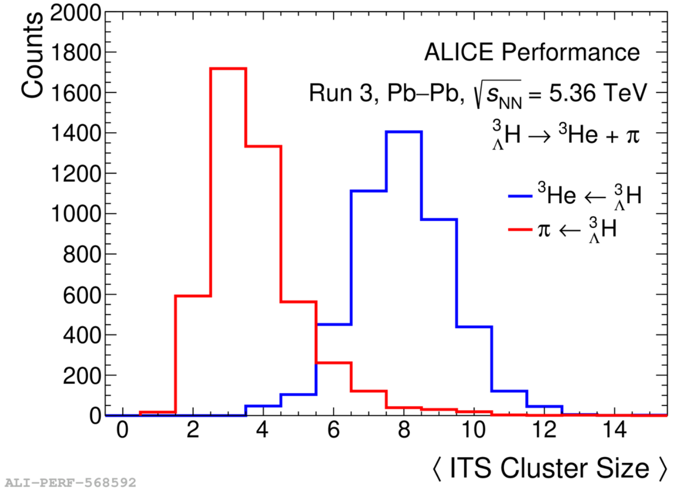




Impact parameter resolution of strangeness tracked Ξ^- baryons along the z-axis

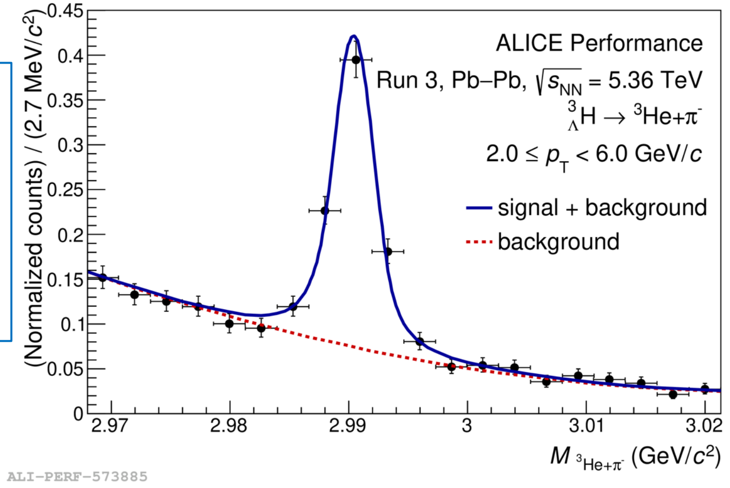
Studies on particle identification (PID)

- Hypernuclei and heavy-ionizing particles
  - Measured in Pb-Pb data recorded in 2023 with standard ITS2 setting

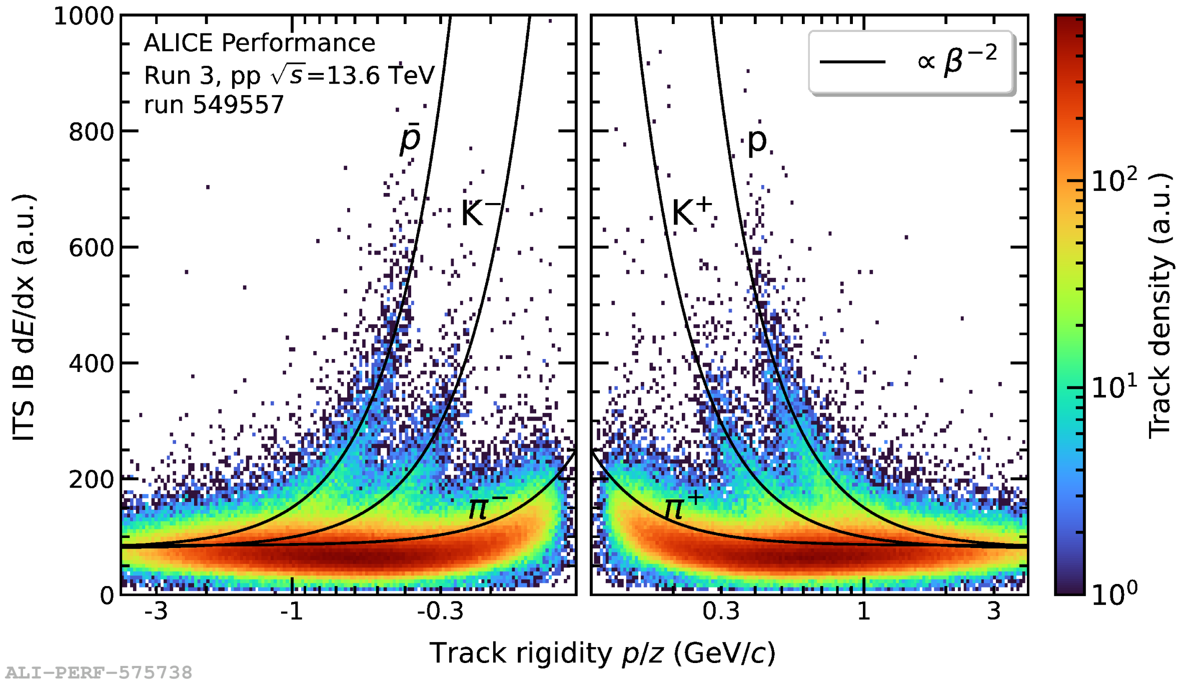


Use of ITS2 cluster size to tag ^3He daughter track and reduce ITS-TPC fake matchings

Invariant mass of the sum of hypertriton and antihypertriton, measured from the two-body mesonic decay

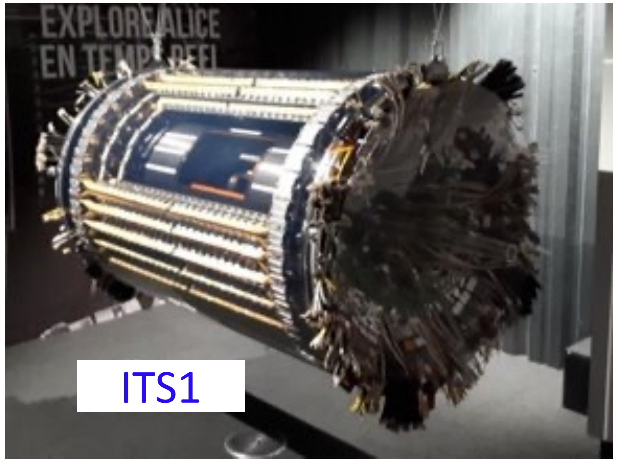


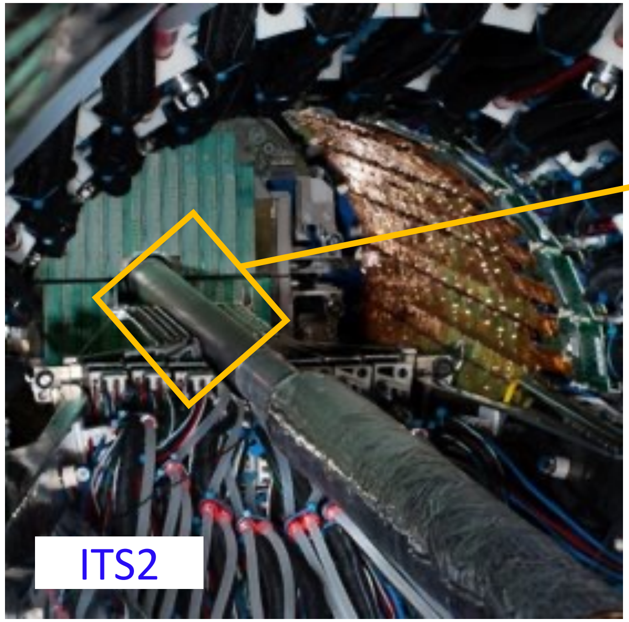
- Proof of concept for PID with thin binary readout
  - Dedicated ITS2 runs in pp with interaction rate at ~1kHz
    - 2.2 MHz framing rate on IB → oversampling ALPIDE response
    - Front-end tuned for charge-proportional analogue pulse length
  - First dE/dx spectrum observed!

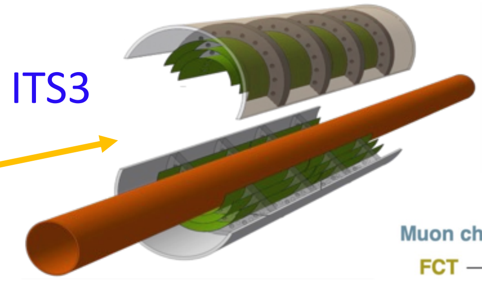


Summary

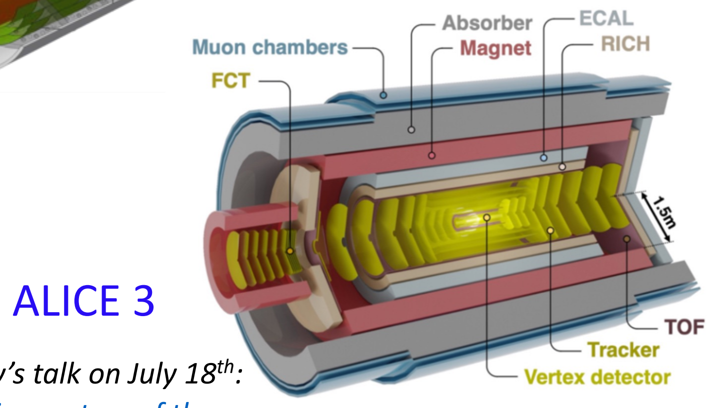
- ITS2, the first Monolithic Active Pixel Sensor based detector at LHC, was installed in ALICE during the LS2
  - ITS2 is operational since the first day of Run 3
- Excellent performance observed in both pp and Pb-Pb collisions
  - Uniform pixel threshold distribution and extremely low noise; stable over time
  - Significantly improved tracking capabilities, 30 μm at p_T = 1 GeV/c
- Proof of concept of highly ionising particle identification using cluster size in standard operation as well as dE/dx via time-over-threshold information in special runs
- MAPS is a key element in the upcoming ITS3 and ALICE 3 upgrades







See Felix Schlepper's talk on July 18th: [*"The ITS3 detector and physics reach of the LS3 ALICE Upgrade"*]



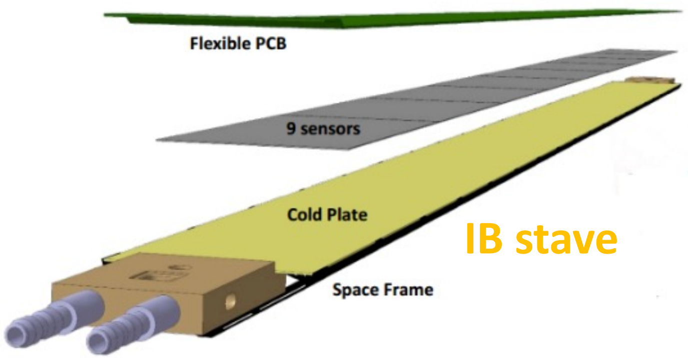
See Igor Altsybeev's talk on July 18th: [*"The silicon tracking system of the future ALICE 3 experiment at the LHC"*]

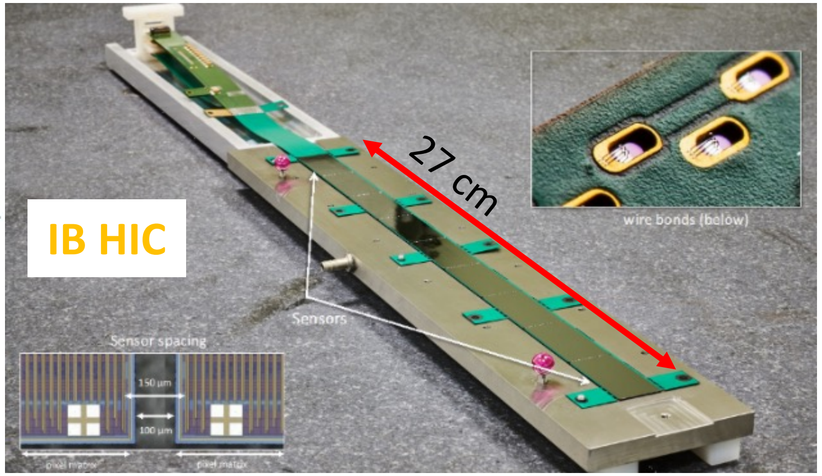
Backup

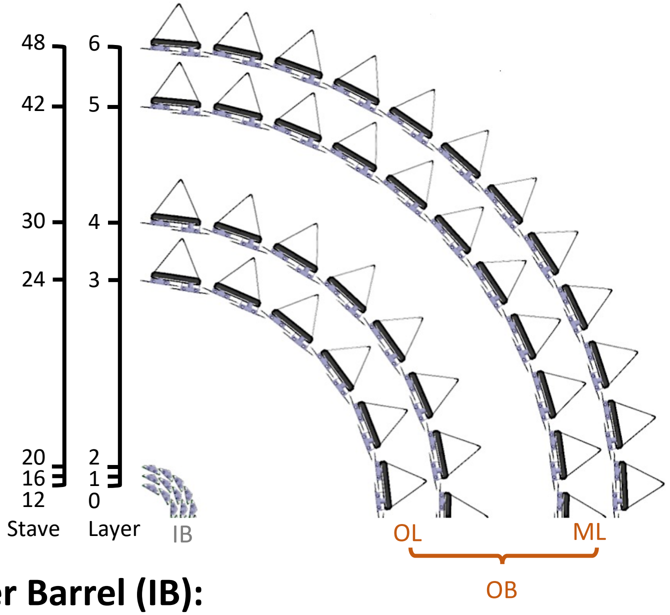
ITS1 vs ITS2

	ITS1	ITS2
Technology	Hybrid pixel, strip, drift	MAPS
No. of layers	6	7
Radius	39–430 mm	22–395 mm
Rapidity coverage	$\lvert \eta \rvert \leq 0.9$	$\lvert \eta \rvert \leq 1.3$
Material budget / layer	1.14% X_0	inner barrel: 0.36% X_0 outer barrel: 1.10% X_0
Pixel size	425 μm × 50 μm	27 μm × 29 μm
Spatial resolution ($r\varphi \times z$)	12 μm × 100 μm	5 μm × 5 μm
Readout	Analogue (drift, strip), Digital (Pixel)	Digital
Max rate (Pb-Pb)	1 kHz	50 kHz

ITS2 Barrels





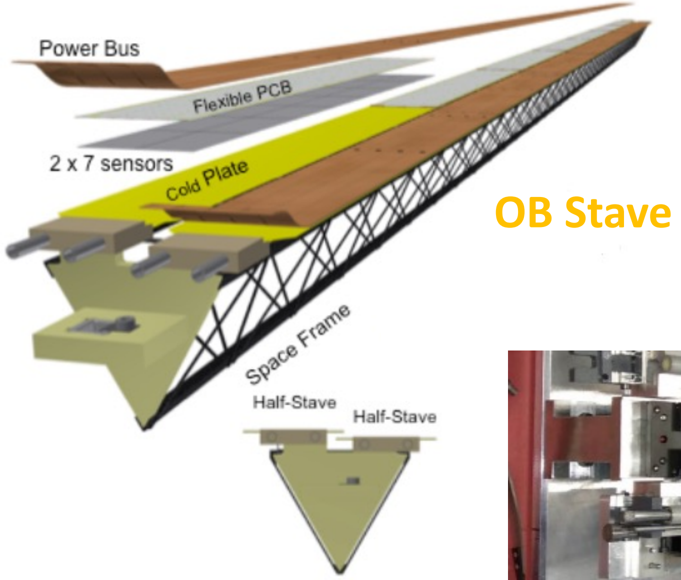


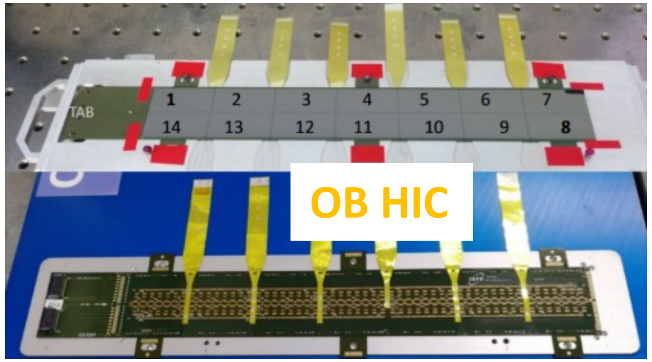
Inner Barrel (IB):

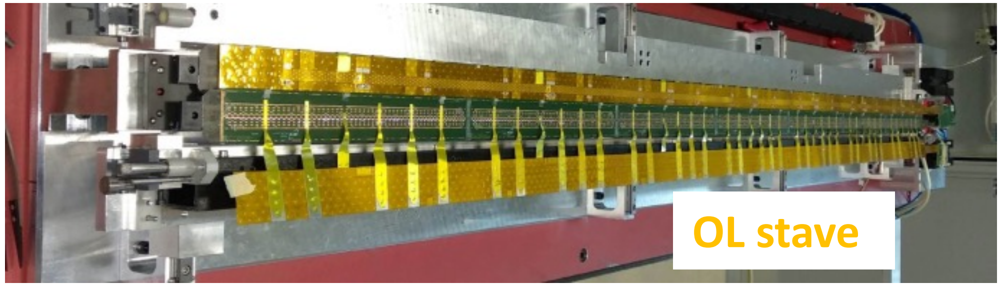
- Hybrid Integrated Circuit (HIC): 9 sensors glued onto Al Flexible Printed Circuit (FPC)
- Wirebonds electrically connect FPC to chips
- Stave: a HIC glued onto cold plate and space frame
- Each sensor is read out individually

Outer Barrel (OB):

- OB HIC:
  - 7x2 sensors (2 rows) glued onto Cu FPC
  - Power delivered via 6 Al cross-cables soldered to the FPC
  - Data and control are transferred through 1 master chip per row
- OB stave:
  - 4x2 HICs (for ML) or 7x2 HICs (for OL) glued onto cold plate and space frame

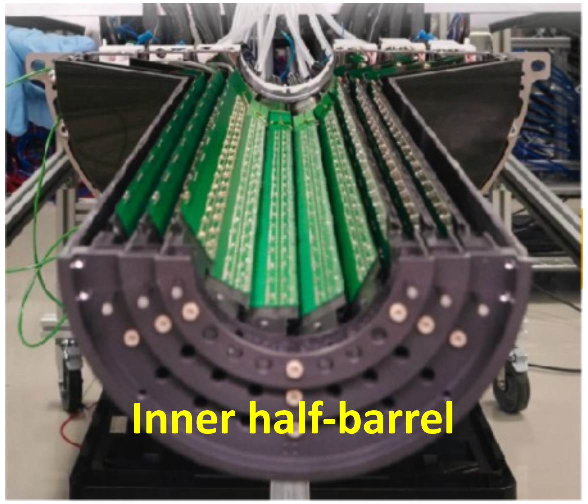


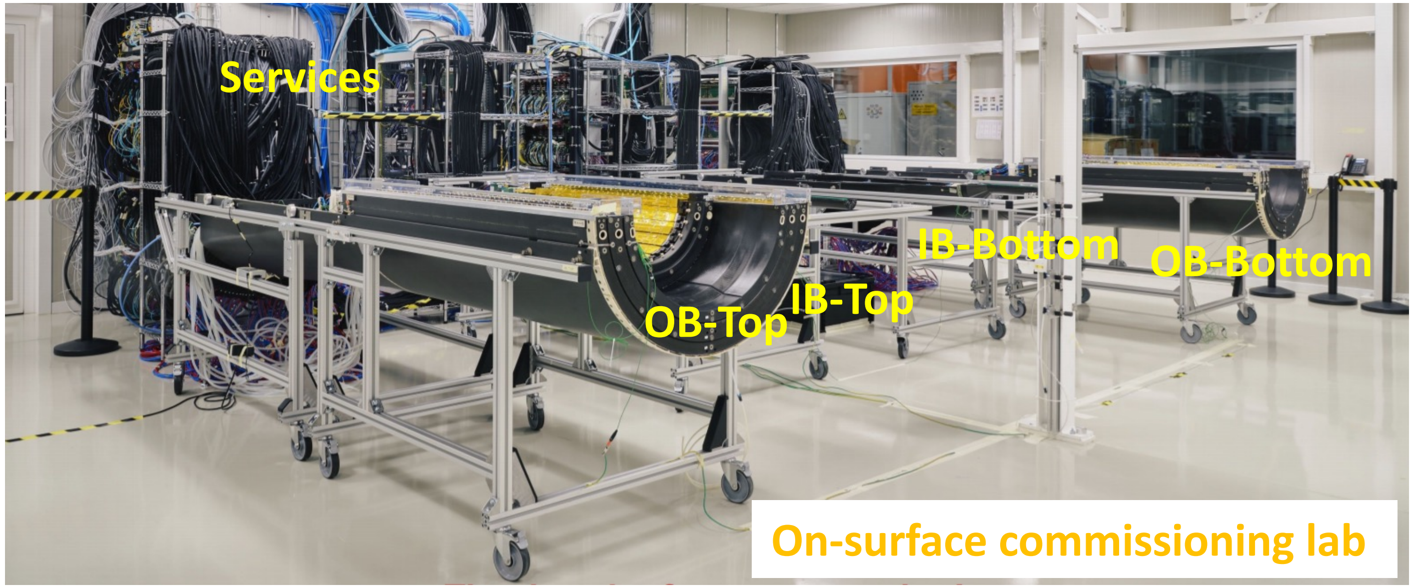




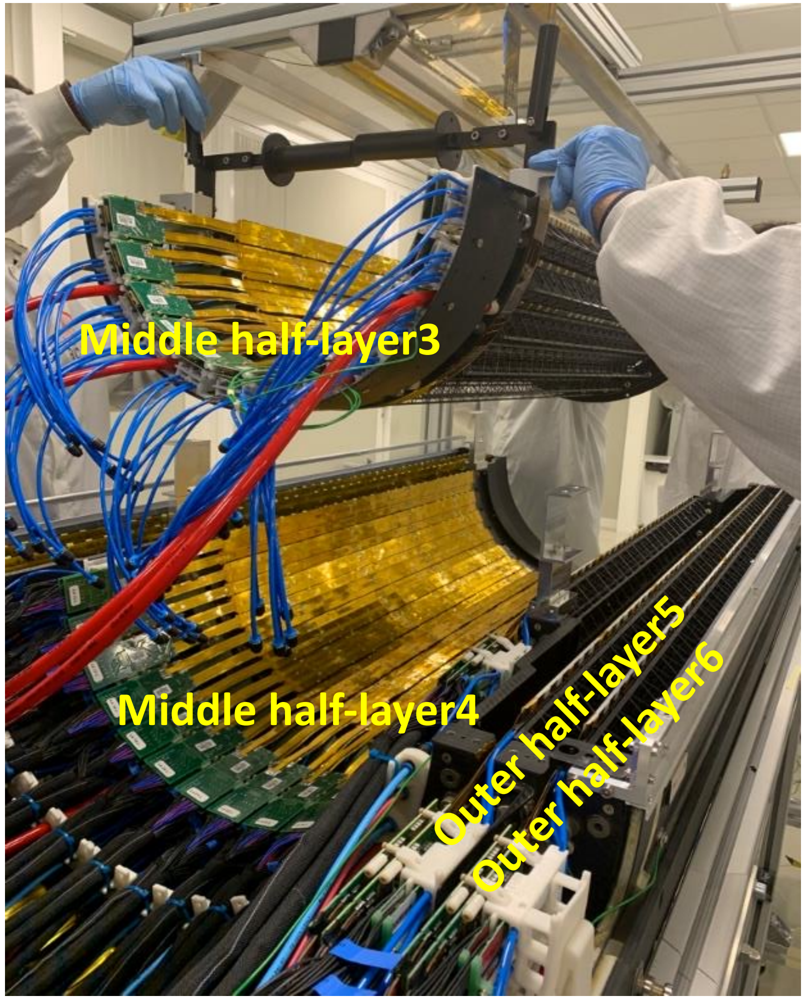
Layer and Barrel Assembly

Inner Barrel assembly



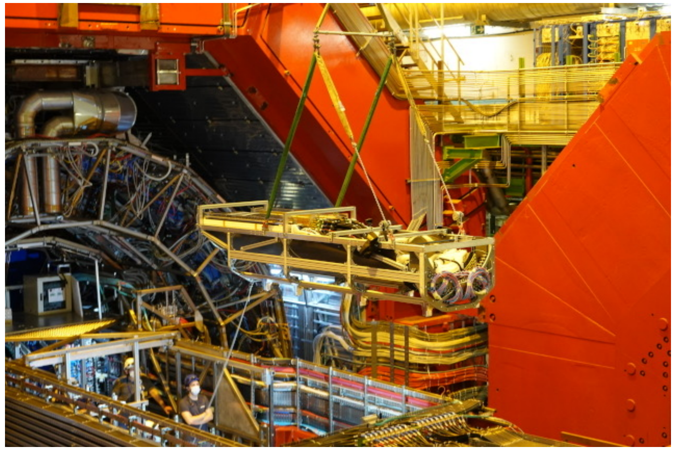


Outer Barrel assembly

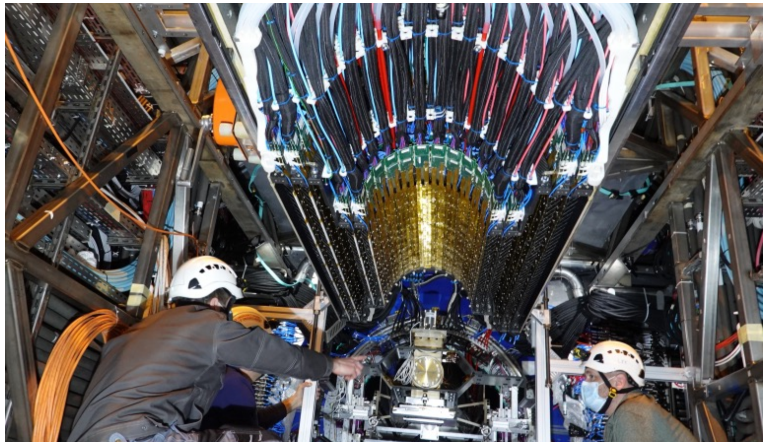


Detector fully assembled in Dec. 2019

Installation

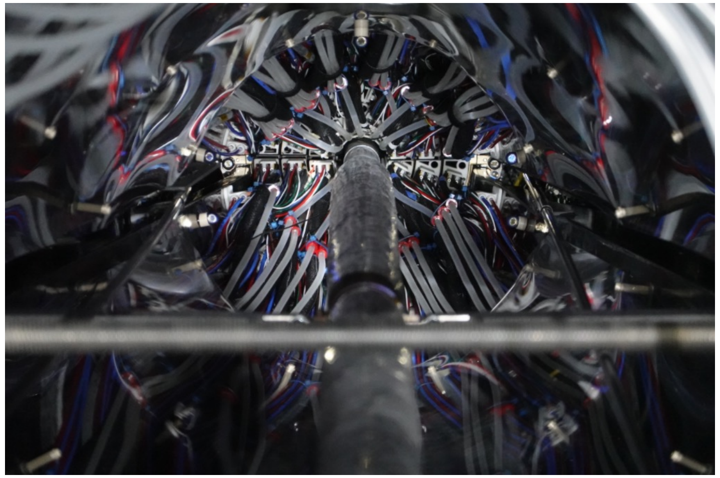


OB-Bottom being loaded to mini-frame

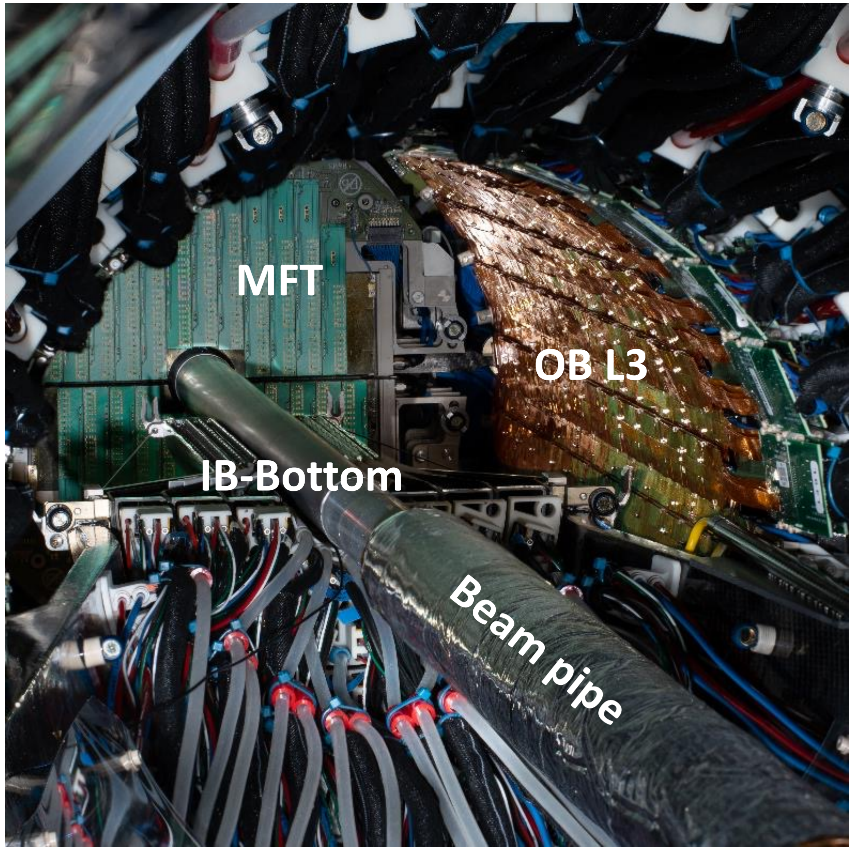


OB-Bottom being positioned

IB being installed



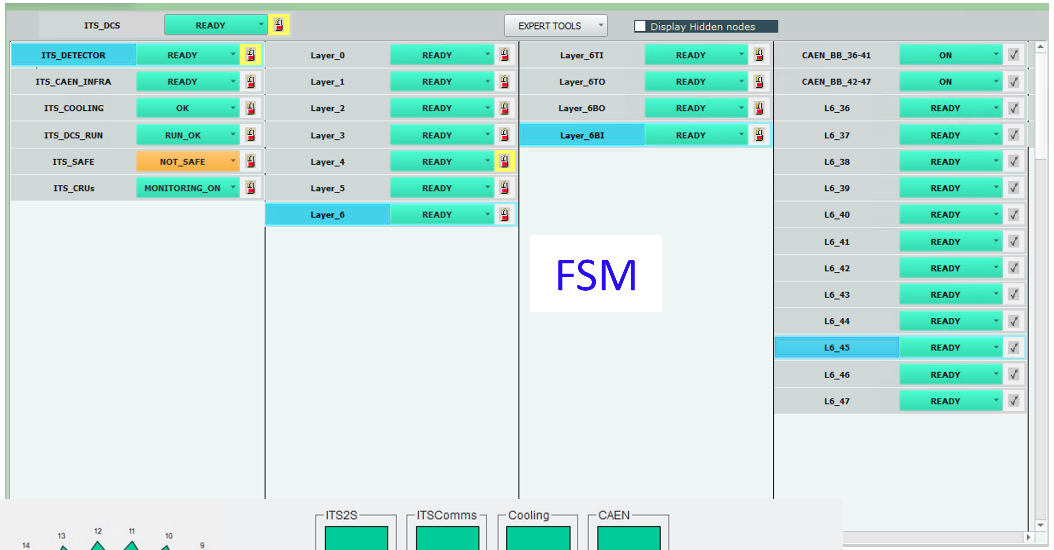
IB installed

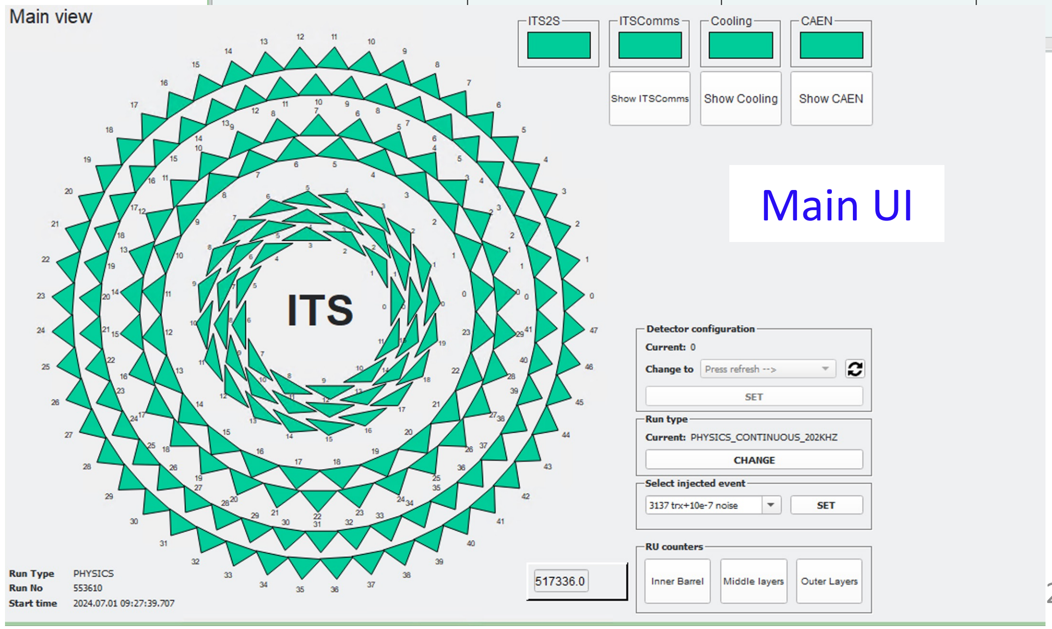


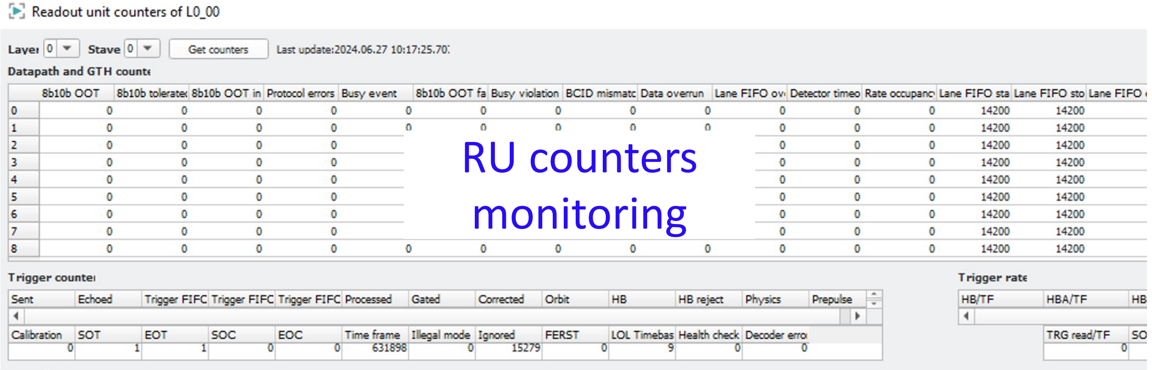
OB installation completed – mid March 2021
IB installation completed – mid May 2021

DCS and safety system

- DCS
  - User interface (UI) developed in WINCC OA SCADA
  - Logics implemented as a Finite State Machine (FSM)
  - Detector operation and monitoring
    - Control the detector itself and its infrastructure, like RU/PB and cooling system
    - Monitoring > 100 k data points with data archiving
    - Automatic in-run recovery maximizes detector acceptance and data-taking efficiency
- ITS2S
  - Independent safety system
  - Interlocks CAEN power channels based on stave temperatures and cooling plant loop status

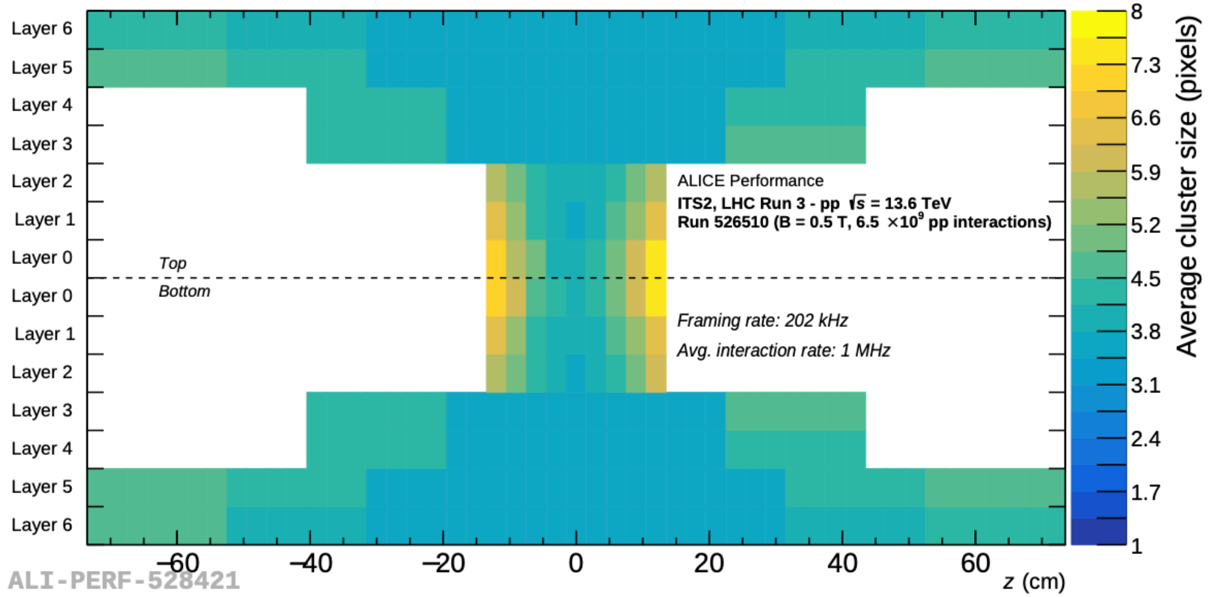




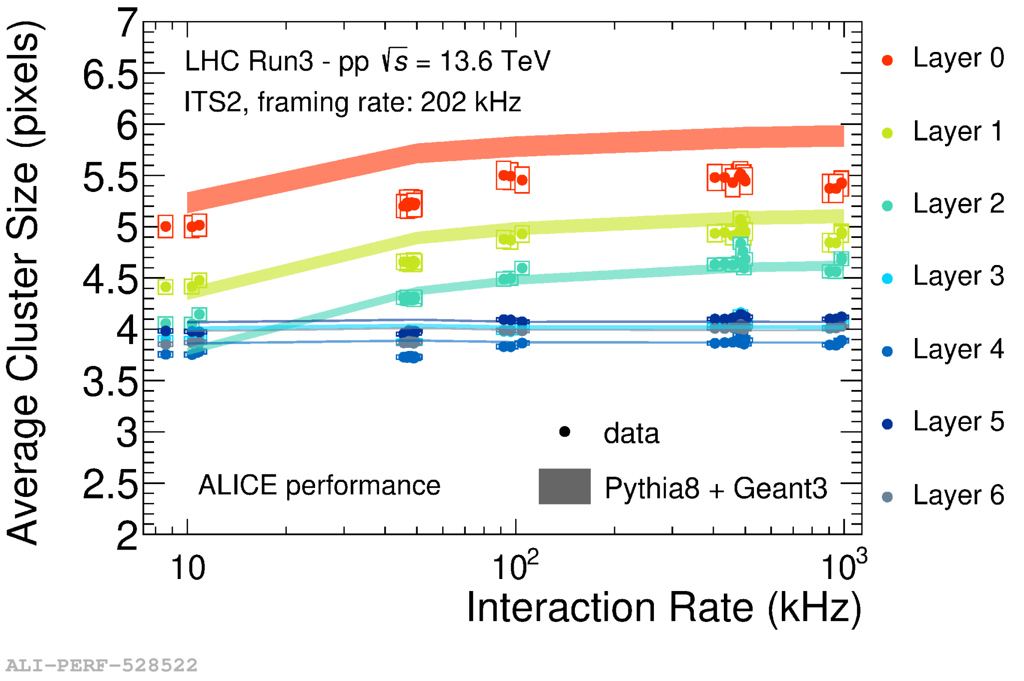


Cluster size

- Cluster size averaged for half layers (pp)
  - 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

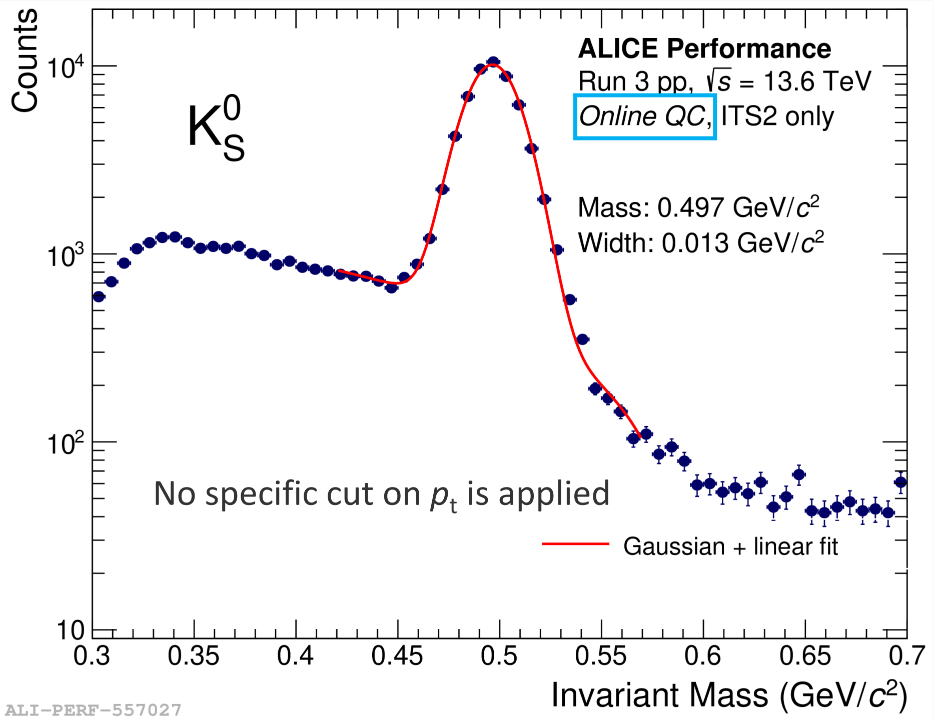


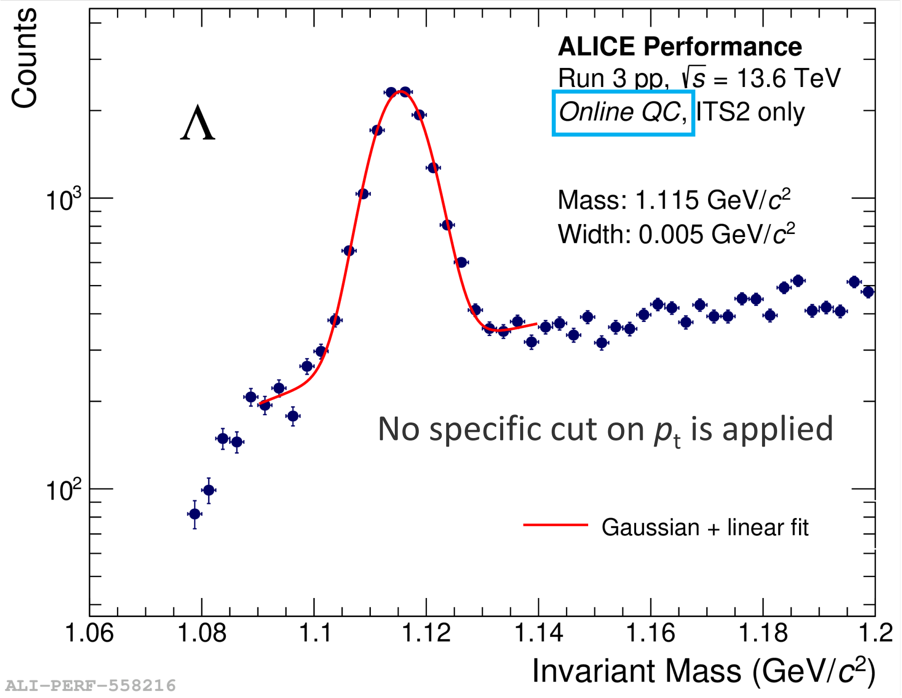
- Simulation with Pythia 8 + Geant 3 (pp)
  - Simulated noise: $2x10^{-8}$ hits/event/pix (IB), $3x10^{-9}$ hits/event/pix (OB)
  - Good agreement with data considering approximations
    - Average noise per barrel and not per stave/chip
    - Limited statistics in MC: ~20 k events



Tracking

- Excellent performance in both pp and Pb-Pb runs with the current updated detector alignment
  - Good angular distribution of tracks
  - Time-dependent acceptance maps accurately describe acceptance loss in MC simulations



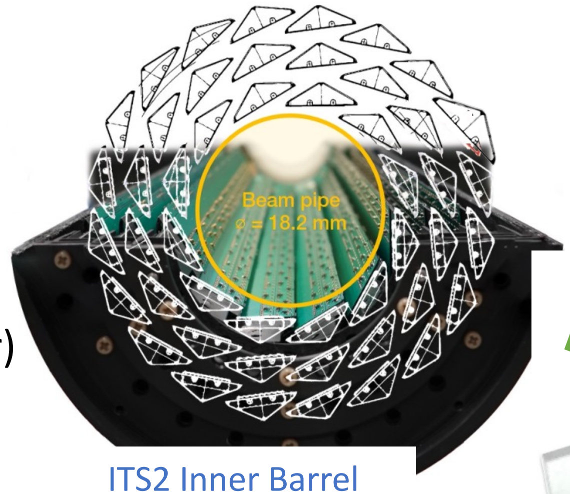


ITS3

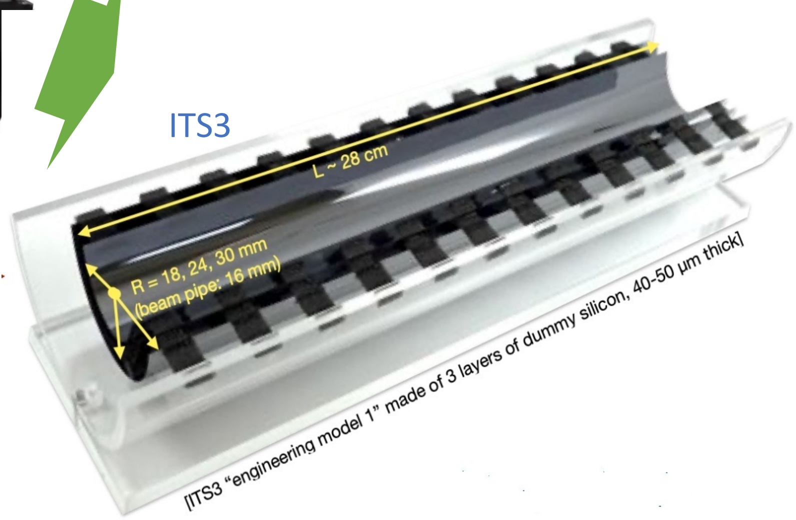
Replacing the 3 innermost layers with new ultra-light, truly cylindrical layers

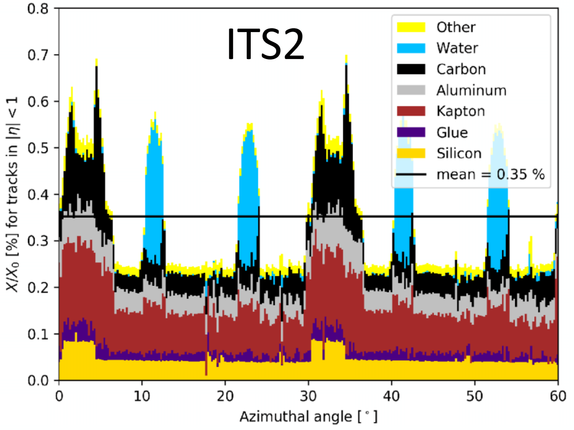
- Reduced material budget (from 0.36% to 0.07% X_0 per layer) with a very homogenous material distribution by removing water cooling, circuit boards and mechanical support
- Closer to the interaction point (from 23 to 19 mm)

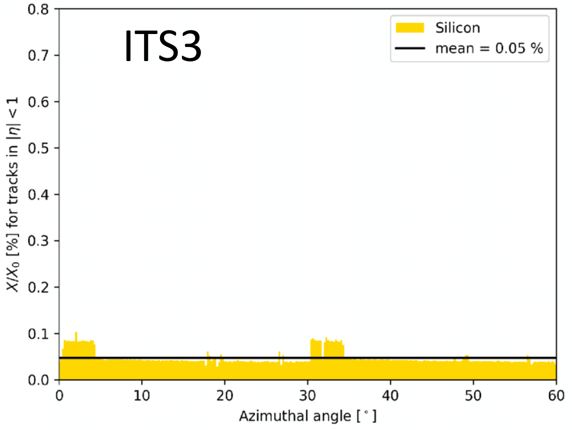
Improved vertexing performance and reduced backgrounds for heavy-flavour signals and for low-mass dielectrons



ITS2 Inner Barrel







IB Layer Parameters	Layer 0	Layer 1	Layer 2
Sensor length [mm]		265.992	
Sensitive length [mm]		259.992	
Sensor azimuthal width [mm]	58.692	78.256	97.820
Radial position [mm]	19.0	25.2	31.5
Equatorial gap [mm]		1.0	
Max thickness [µm]		50	

Table 3.3: Design dimensions of the sensor dies and radial position.