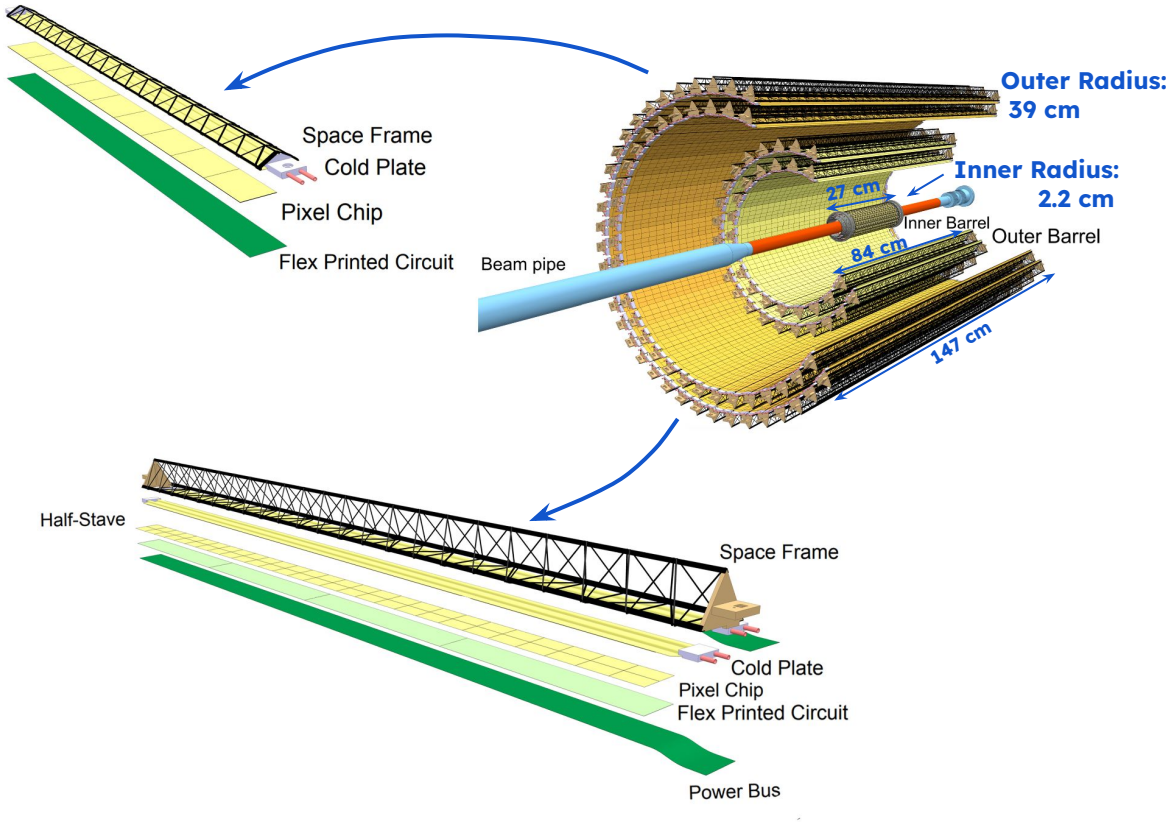
Operation and Performance of the Upgraded ALICE Inner Tracking System

Andrea Sofia Triolo [1,2]
for the ALICE collaboration

VERTEX 2023 - 16th October 2023

[1] CERN
[2] University of Messina

- ITS upgraded to **ITS2** during LHC Long Shutdown 2 and installed in 2021.
- 7 layers of **MAPS** chips **ALPIDE**



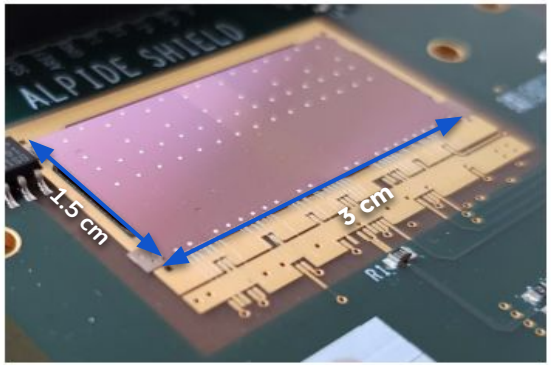
3 Inner Barrel (**IB**) layers:
- Layers: **0,1,2**
- Number of staves: **48** (12+16+20)
- Material budget: **0.36% X_0/layer**

4 Outer Barrel (**OB**) layers:
- Middle Layers: **3,4**
  - Number of staves: **54** (24+30)
- Outer Layers: **5,6**
  - Number of staves: **90** (42+48)
- Material budget: **1.1% X_0/layer**

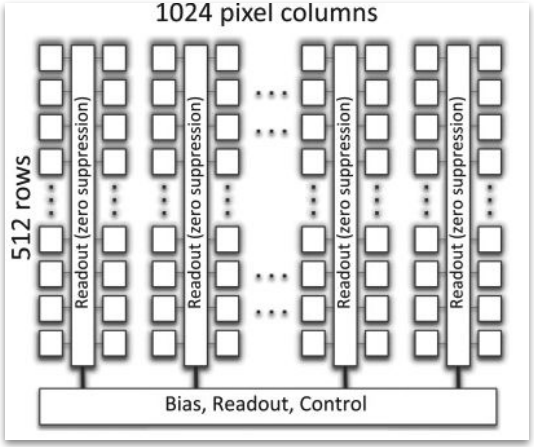
192 staves
24120 chips
12.5 Giga pixels
10 m² active area

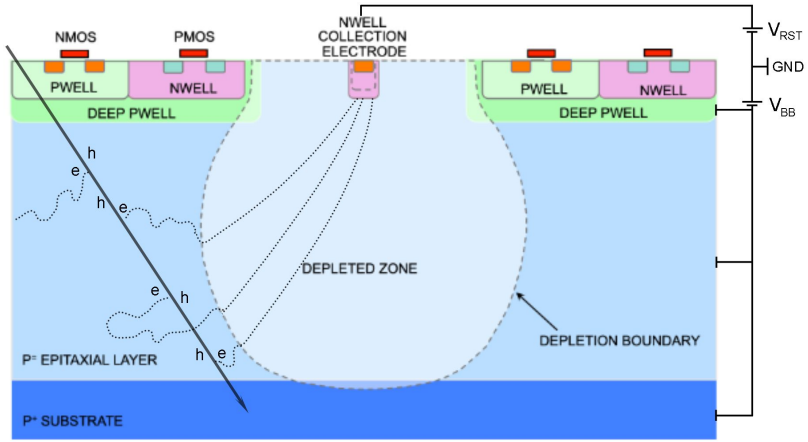
Largest pixel detector
in High-Energy Physics

- **Monolithic Active Pixel Sensors** (MAPS) implemented using the 180 nm CMOS technology of TowerJazz.

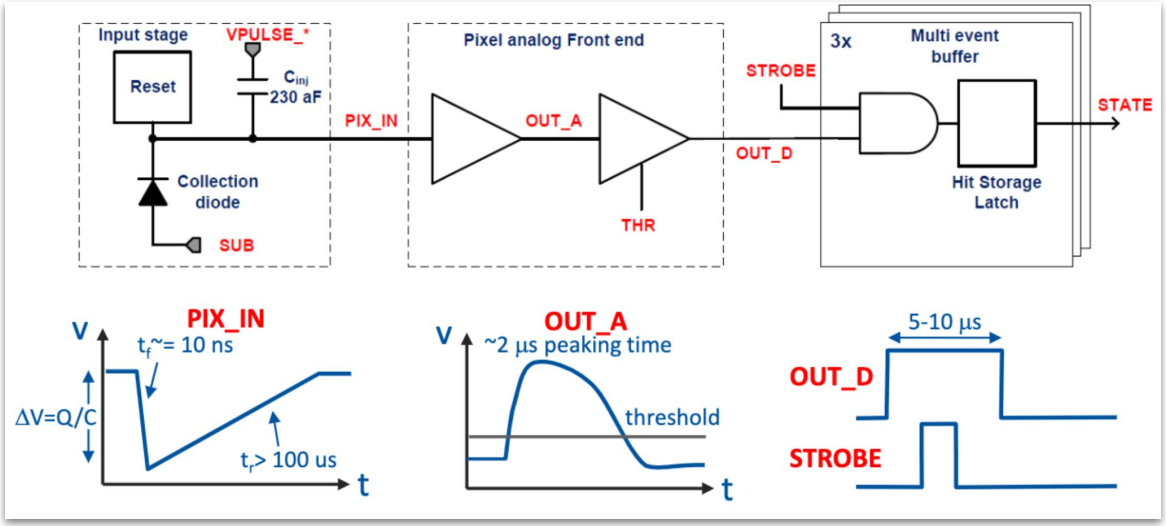


- **512x1024** pixels
- Readout of pixel hit data based on the **Priority Encoder**
- Pixel size ~ **27 x 29 µm²**
- Spatial resolution (rφ, z): **5x5 µm²**



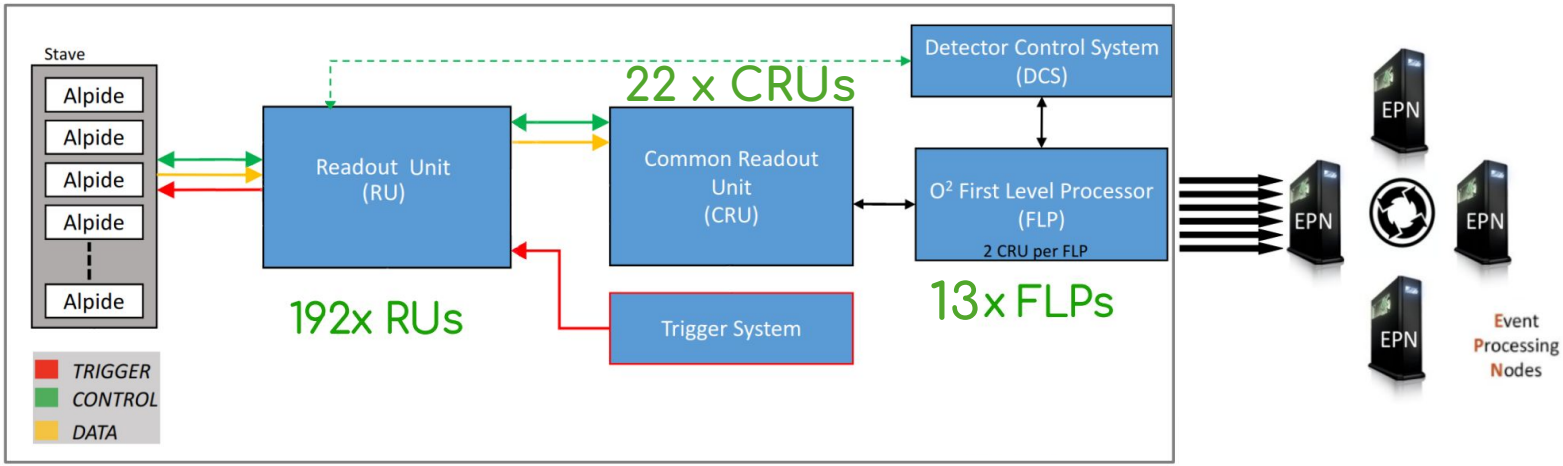


- **Deep p-well** → Full CMOS circuitry within active area
- High resistivity **(1-6 kΩcm)** p-type epitaxial layer **(25 µm)** on p-type substrate
- Small n-well diode **(ø = 2µm)**, ~100 times smaller than pixel → low capacitance **~fF**
- Reverse bias voltage to substrate: **$-6\ V < V_{BB} < 0\ V$** → increase the depletion volume around the n-well collection diode



Pixel signal amplified and digitized at pixel level:

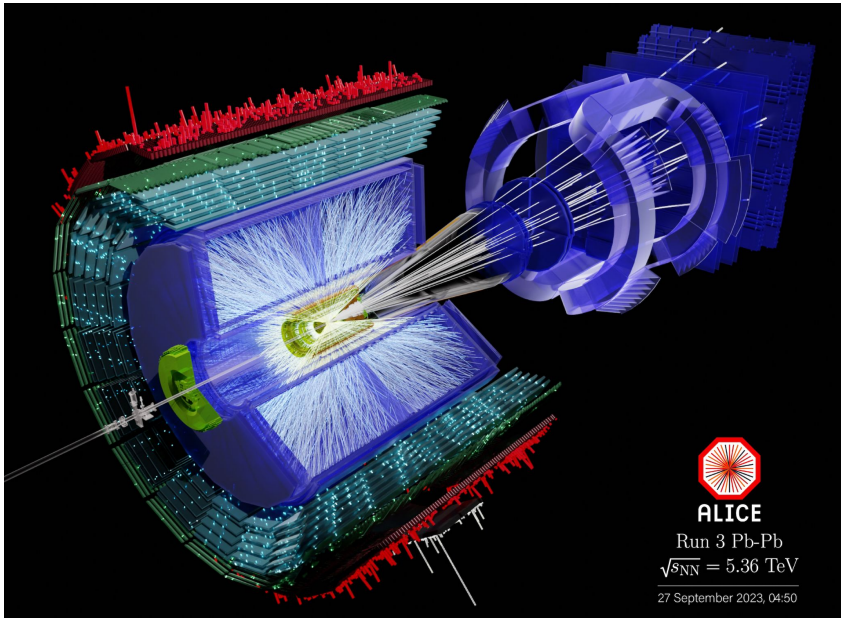
- Sensing **diode**
- Pulse **injection capacitor**
- Front-end **amplifying and shaping stage**
  - Always active with power consumption **< 7 mW/cm²**
- **Discriminator** → binary readout
- **Digital section**
  - 3 hit **storage register** (Multi Event Buffer)
  - **Pixel masking register**
  - **Pulsing logic**
- Total chip power consumption **< 47 mW/cm²**



ITS2 readout

- ITS configuration (chips + Readout Units) and calibration managed by the **ITS Detector Control System (6 Worker Nodes)**
- **13 ITS First Level Processors** (FLPs)
  - Online data quality control tasks: hit occupancy and front-end electronics diagnostics
- **340 Event Processing Nodes** (EPN from ALICE farm)
  - Online quality control tasks: reconstructed ITS2 tracks, clusters and decoding errors
- **O2**: ALICE computing framework for Run 3

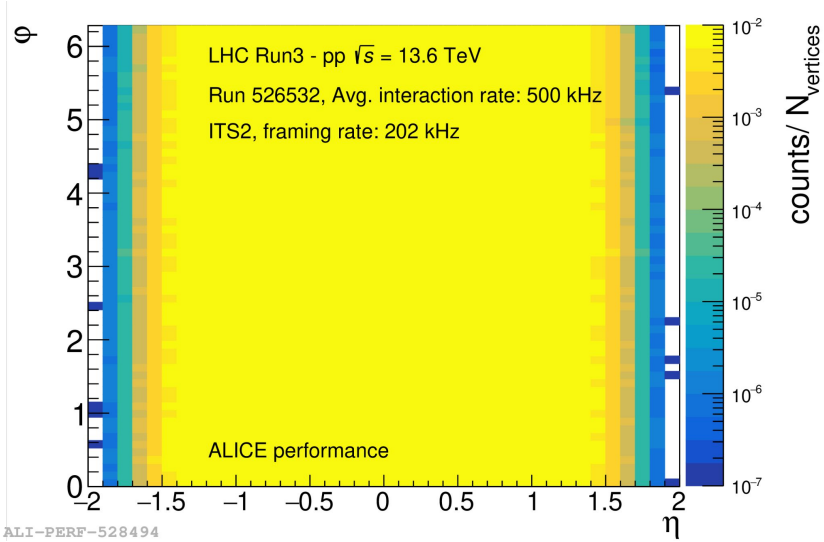
- **Operated in continuous integration**
  - Long strobe window (1/trigger frequency)
  - Minimal gap between each strobe
- Possibility to run in triggered mode:
  - Trigger from an external interaction trigger
  - Short strobe window



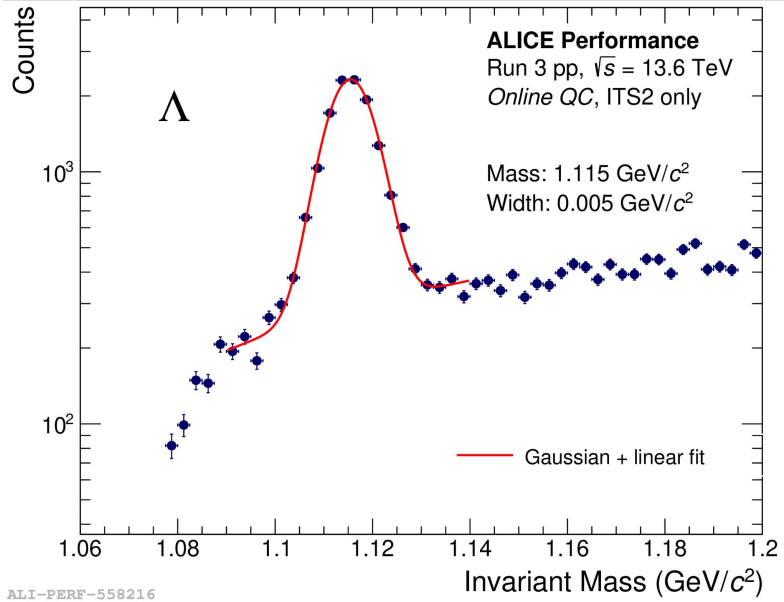
- Recorded luminosity so far (pp collisions)~**28 pb^{-1}**
- Nominal ITS framing rate (pp): **202 kHz**
- ALICE standard interaction rate (pp): **500 kHz**
- Instantaneous luminosity: **~10^{31} $cm^{-2}s^{-1}$**
- ITS2 successfully tested up to **4 MHz** pp interaction rate (~**50 GB/s** data rate)
- **ITS fully operational**
  - Except for **0.4%** pixel excluded in the whole detector (94 chips dead/excluded, 970k dead pixels, 500k noisy pixels)

- **September 2023: Pb-Pb collisions ongoing**
  - Interaction rate up to **45 kHz**
  - Default Framing rate **67 kHz**
  - ~ **20 GB/s** data rate
  - Machine rump up ongoing

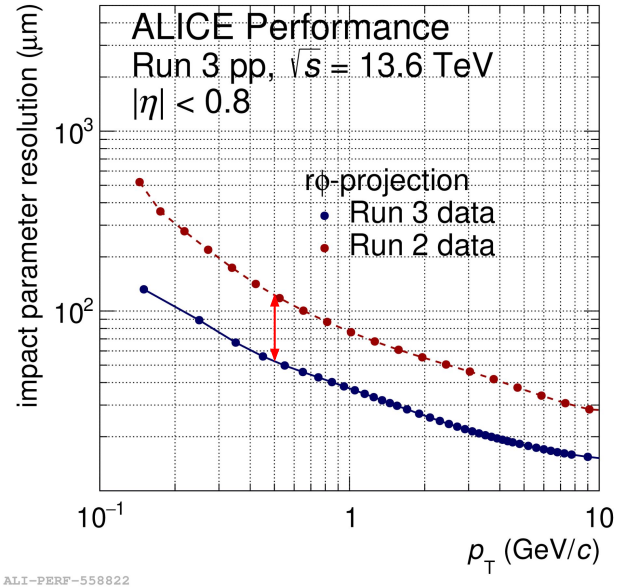
- **ITS tracking**:
  - Online tracking task for quick data QA
  - Good quality of the angular distribution of the tracks

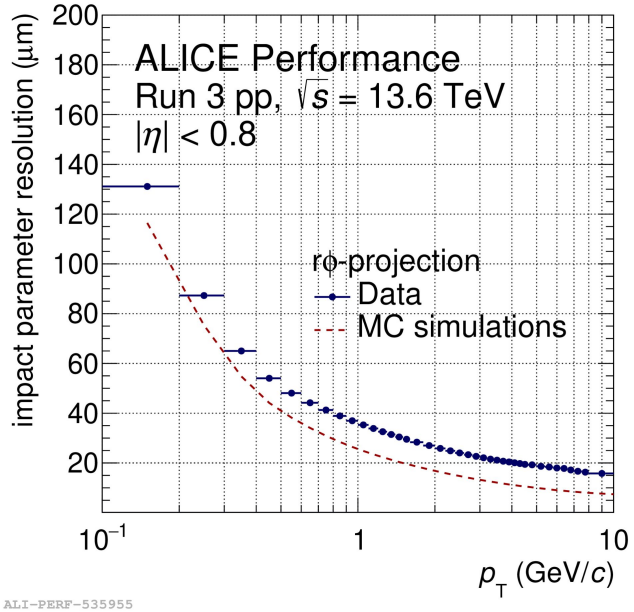


- **Online physics performance** from QC through Λ and K_s^0 invariant mass peaks
  - ITS standalone tracks

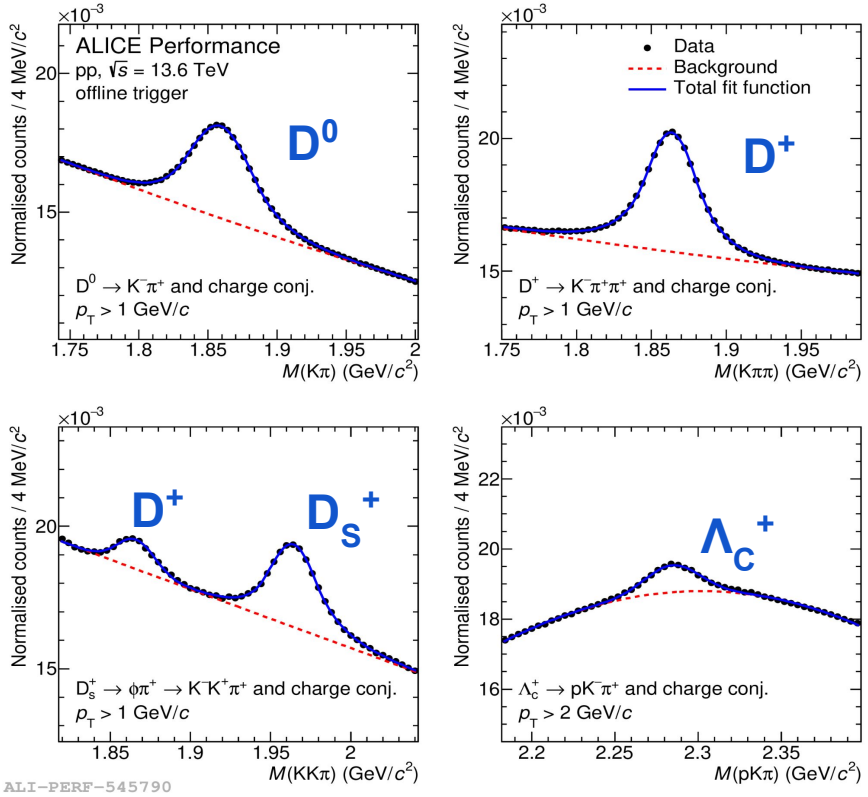


- **Impact parameter resolution** measured with Run 3 pp data:
  - Global tracks with at least 1 hit in Inner Barrel (Run 3)
  - Global tracks with at least 1 hit in the two innermost ITS1 layers (Run 2)
- **2.5x improvement** at p_T = 500 MeV/c with respect to Run 2
- **~20% discrepancy with MC** could be related to a mismatch of sensor response in simulation and residual misalignments in data
  - Resolution and alignment checks ongoing





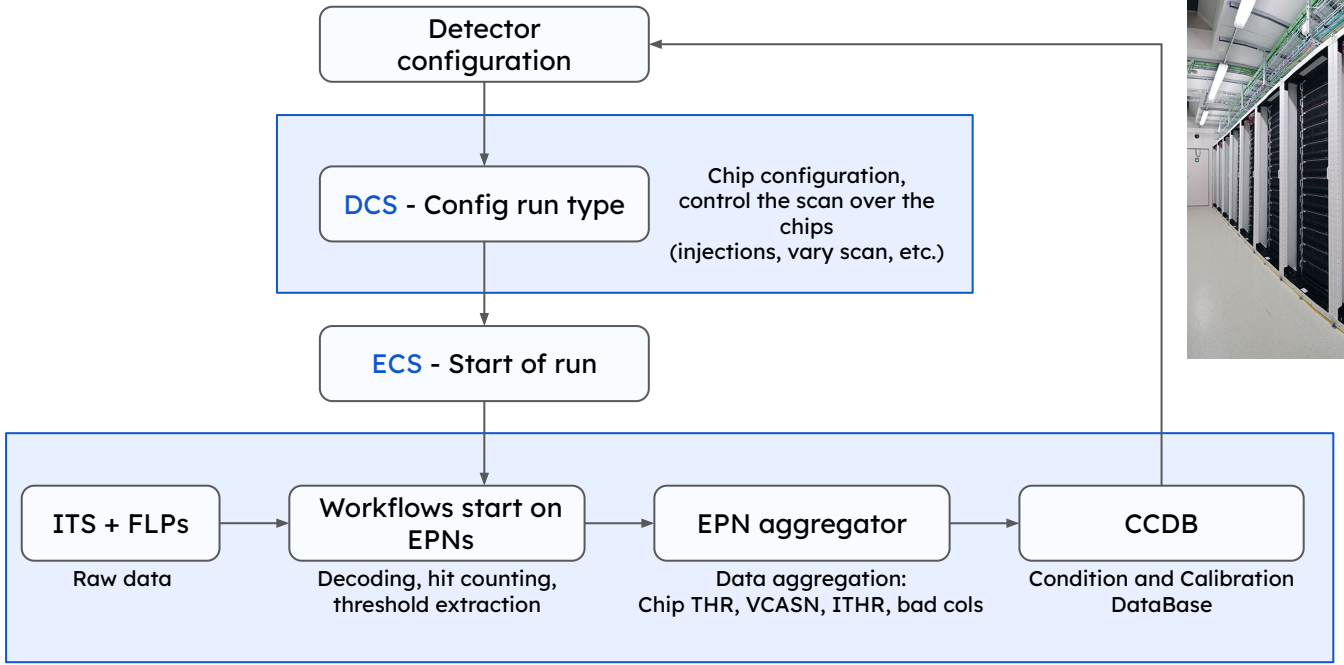
- First measurements of **charm mesons and baryon production** with LHC Run 3 data from pp collisions at $\sqrt{s}$ = 13.6 TeV



General calibration operations:
- **Inject charge** into single pixels
- **Vary scan parameter** and repeat
- Measure **response** (hits per injection) as a function of the scan parameter
- **Fit** response vs scan parameter with error function to extract 50%-point and σ

Calibration scan	Scan duration	How often
Threshold scan (short)	10 min	1/day
Threshold scan (full)	1h30 min	If needed
Threshold tuning	10 min	1/year
Noise calibration	10-30 min	If needed

Other scans available for detector studies.



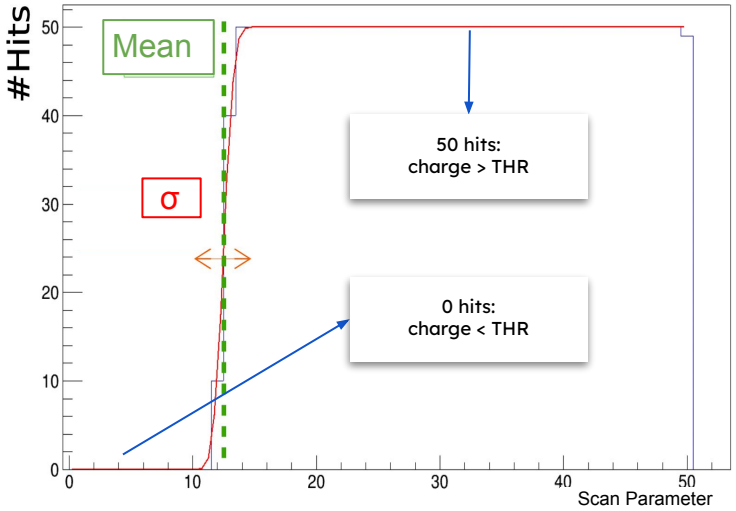
EPN racks in the ALICE computing farm

Challenging procedure:
- **24120** chips with **524288** pixels each → **12.5 Giga** pixels → ~ **60 TB** of event data (Threshold scan)
- Online calibration workflows runs on **40 EPNs** (Threshold calibration)

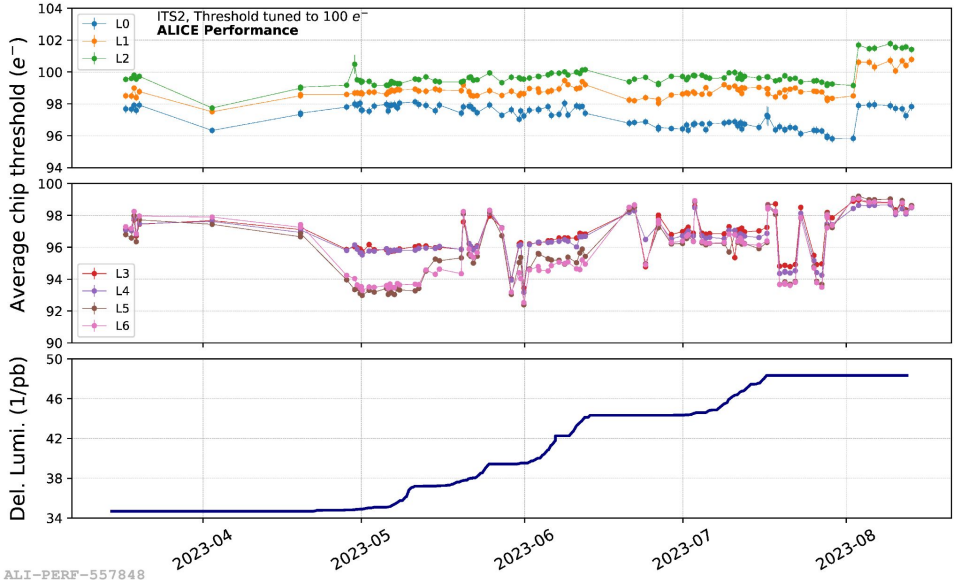
DCS: Detector Control System
ECS: Experiment Control System
FLP: First Level Processors
EPN: Event Processing Nodes

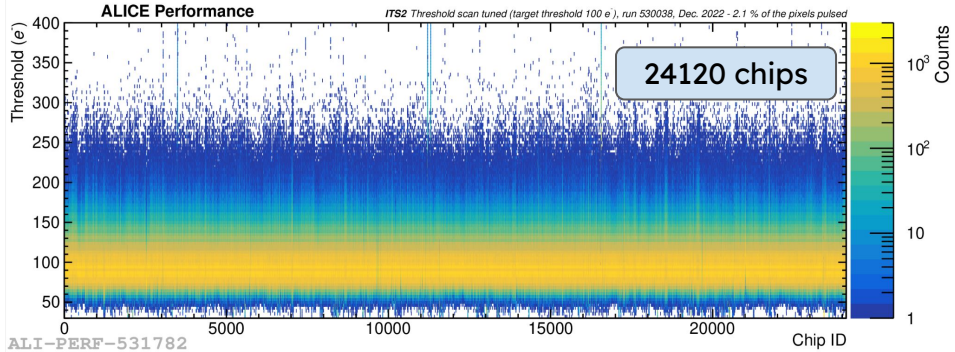
Threshold tuning:
- Goal: Set the **operation point** of the detector
- Threshold influenced by the setting of 2 DACs: VCASN and ITHR
- 2 different scans: **VCASN + ITHR tuning** (chip level):
  - **50 charge injections** repeated for **50 DAC settings**
  - Inject fixed charge corresponding to desired threshold (**~100 e^-**)
  - Tuned DAC values = inflection point of **S-curve**
- **~1% of pixels** per chip are scanned

Threshold scan:
- Goal: Measure the **average threshold** per chip
- **50 charge injections** repeated for **50 charge values**
- Pixel threshold = inflection point of S-curve
- **Chip threshold** = mean of pixel thresholds
- Scan performed at every beam dump to monitor the calibration
- Data stored for monitoring of **detector stability** over time
- **~2% of pixels** per chip are scanned (daily threshold verification)

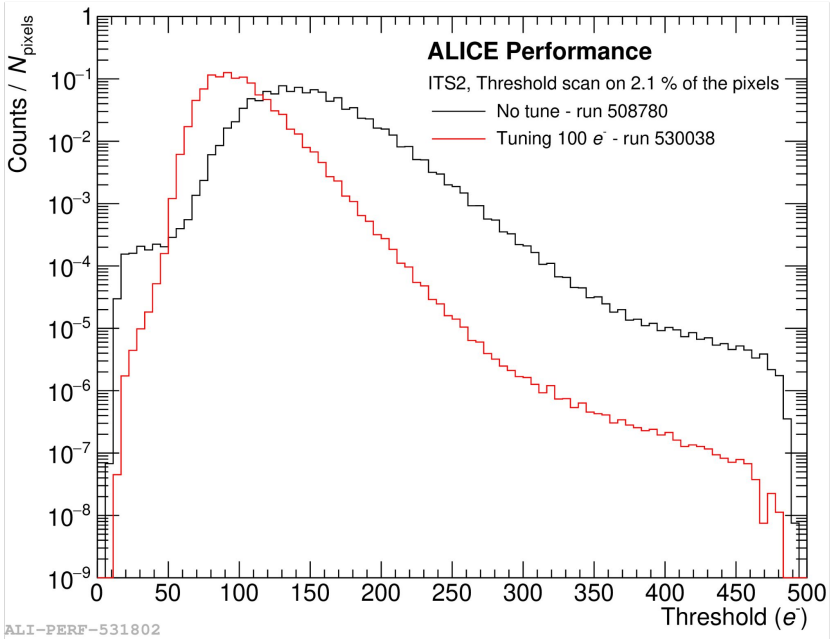


ITS Calibration results: Threshold tuning and calibration



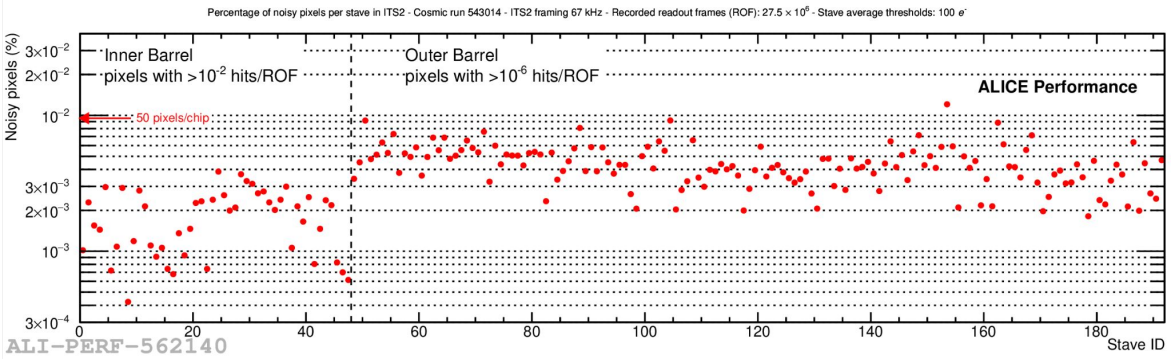


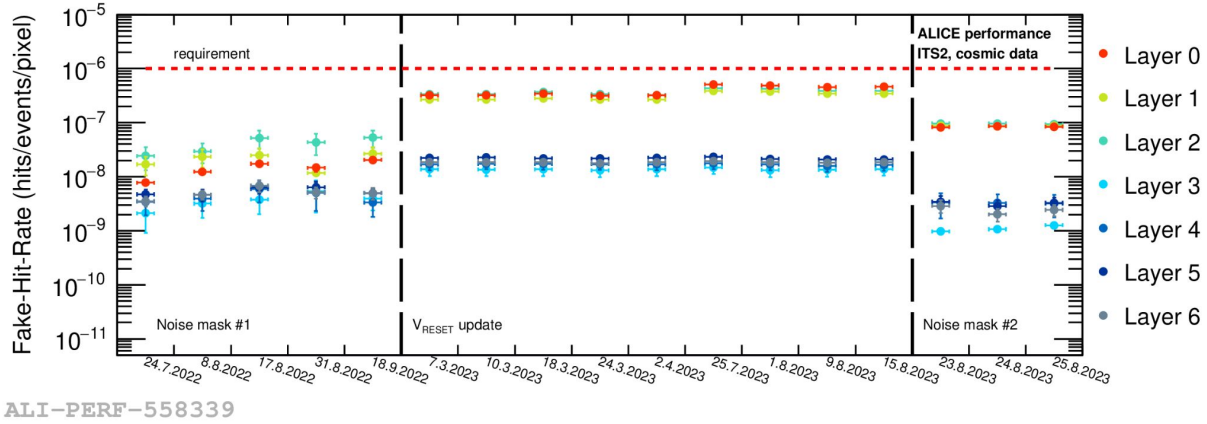
- Threshold tuned to **100 e^-** in December 2022
  → stable after months of operations
  → not affected by radiation
- Minor fluctuations due to supply voltage optimizations
  → **ITS2 calibration very stable**



Noise calibration:

- Goal: find **noisy pixels** with the threshold currently set
- **Cosmic Run**
- Noise threshold for a stable detector:
  - **10^{-2} (IB)**, **10^{-6} (OB)** hits/event/pixel

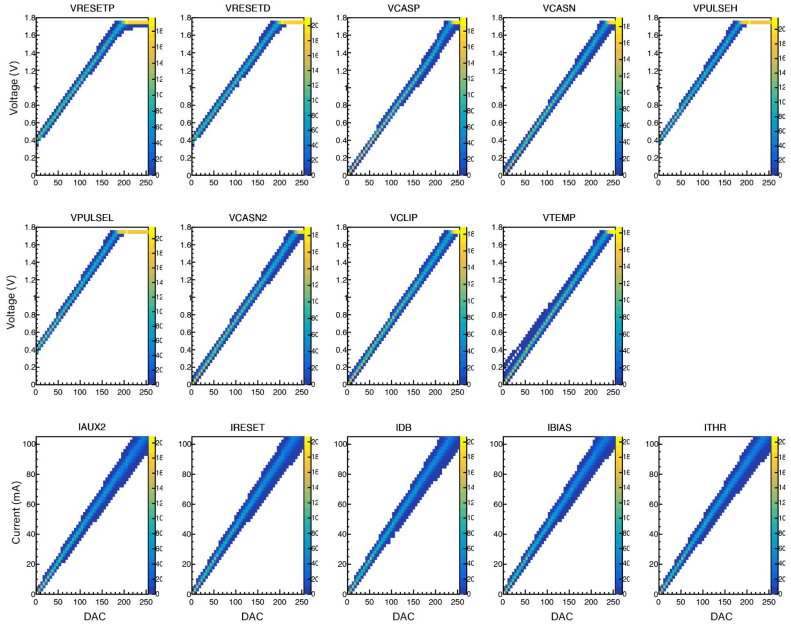




- Masked noisy pixels on the full detector: **~ 546k → ~0.004%**
- Fake-hit rate after masking: **~10^{-8} (OB)**, **~10^{-7} (IB)** hits/event/pixel → orders of magnitude better than requirement (**~10^{-6}** hits/event/pixel)

DAC scan:

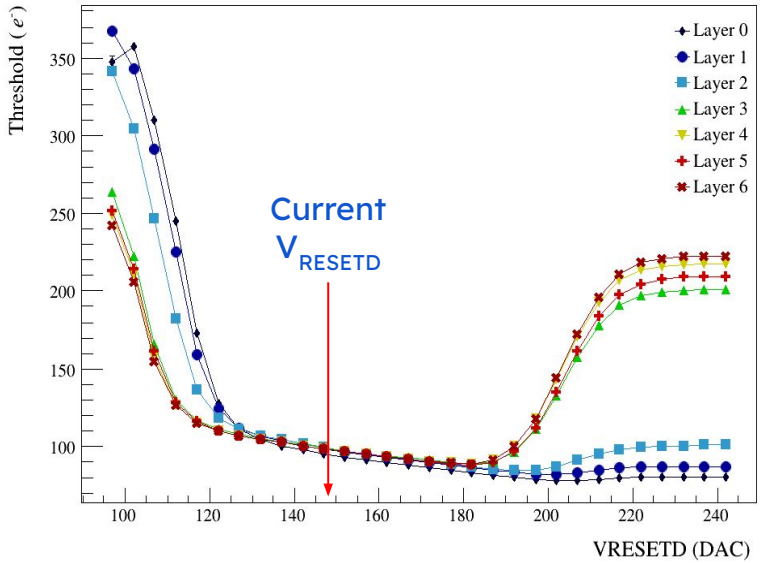
- Goal: Monitor on-chip **DACs output**
- Outputs measured through on-chip ADC
- **14 DAC channels**: 9 voltage DACs and 5 current DACs
- **Linearity** between Digital Input and Analog Output



- All chips from IB

V_{RESETD} scan:

- Goal: Monitor the **optimal operational range** of the chips
- Influence of leakage current and **reset voltage** of the pixel charge collecting node
- Influence of **radiation** outside operational range
  - Ordering of layers based on accumulated radiation
- **2D scan**: Threshold scan for each V_{RESETD} selected
  - Threshold scan of 1 row of pixels per chip every 5 DACs setting
- Same setting for all the chips: **147 DAC Units → 100 e^-**



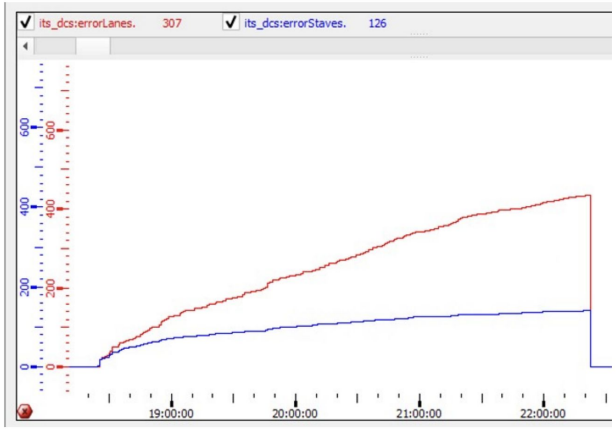
Radiation tolerance:

- Scrubbing: DCS regularly performs single scrubbing cycles controlled by software on the Readout Units
- SEU in ALPIDE chips: peripheral logic is SEU hardened, DCS procedure implemented to periodically rewrite pixel masks
- Latch-up: not observed

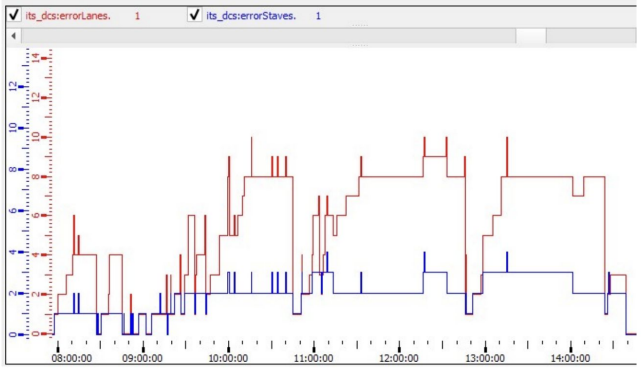
Operations during the run:

- Voltage check and correction: each time the output voltage is modified, in case of errors, an automatic correction of the Power Unit output voltage is done
- Voltage drop correction: automatic correction of the voltage drop on staves changing state due to extra current at the start of trigger
- High-speed links into error → Lanes NOK of faulty
  → Stave Auto-Recovery triggered:
  - Level 1 (automatic): Reconfigure RU only (sufficient in most cases)
  - Level 2 (automatic): Reconfigure chips and RU
  - Level 3 (manual): Powercycle chips, then reconfigure chips and RU

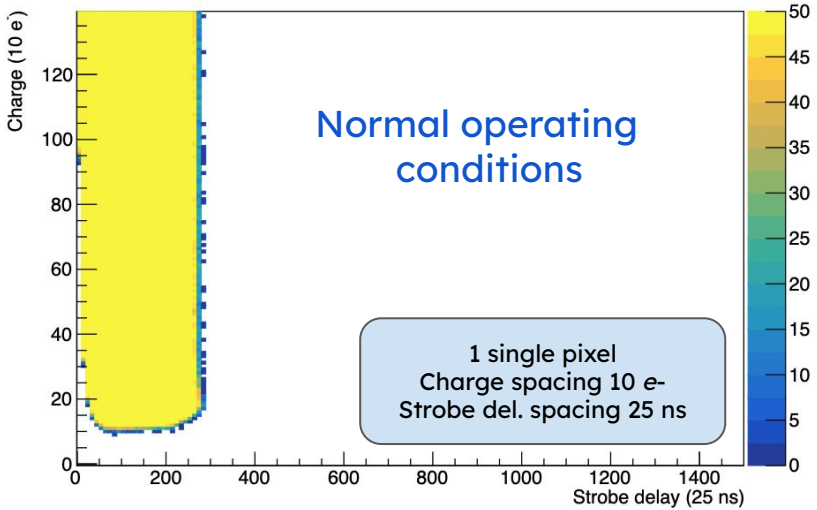
4-hour run without auto-recovery:

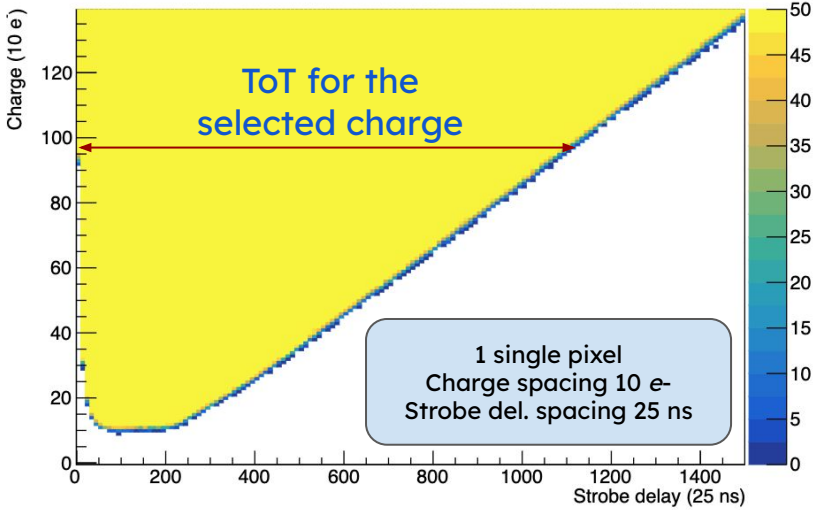


6-hour run with auto-recovery:



- **Proof of concept** of the **Time Over Threshold** (TOT) measurement with MAPS detectors
- Normal operating conditions → pulses clipped
- ToT measurement → clipping removed: linear dependence between the charge and the length of the pulse

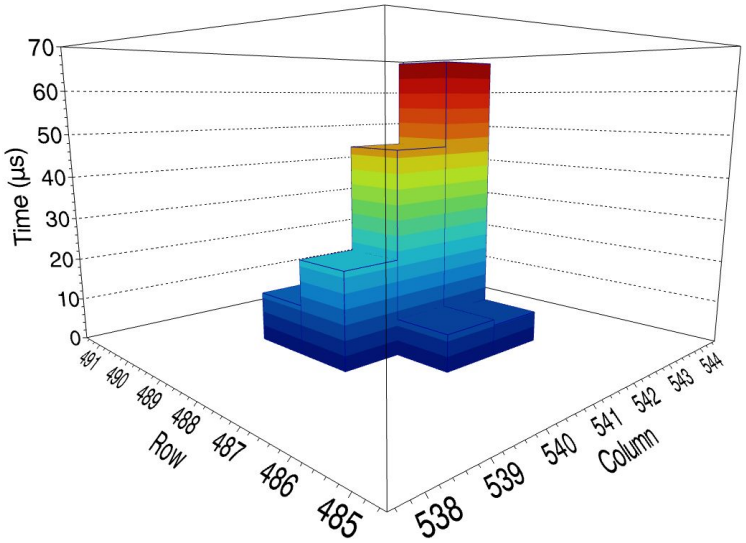


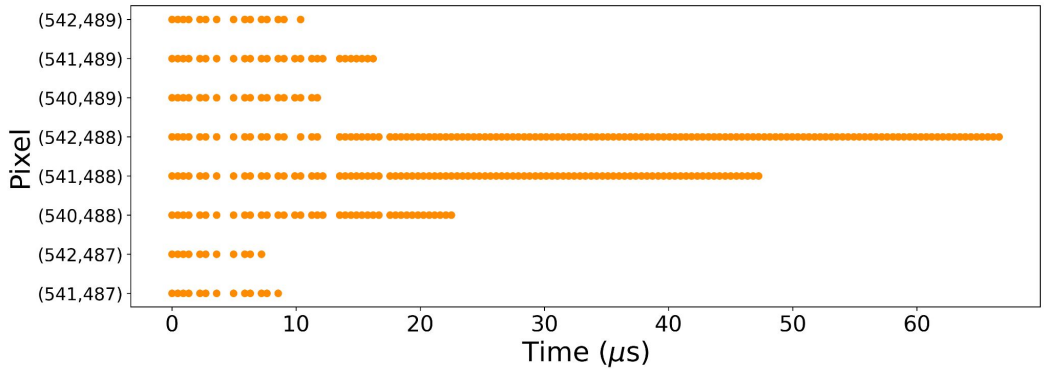


- Goal: extract **PID** information from ITS2 with the charge obtained after calibration

- Dedicated ITS run (IB only) → **ITS2 Color run**:
  - Signal clipping removed from each chip → signal present in multiple subsequent events
  - **~ 900 Hz** pp interaction rate → fit into bandwidth
  - **2.2 MHz** framing rate → oversampling ALPIDE response

Clusters observed in data
→ Integrity of data verified





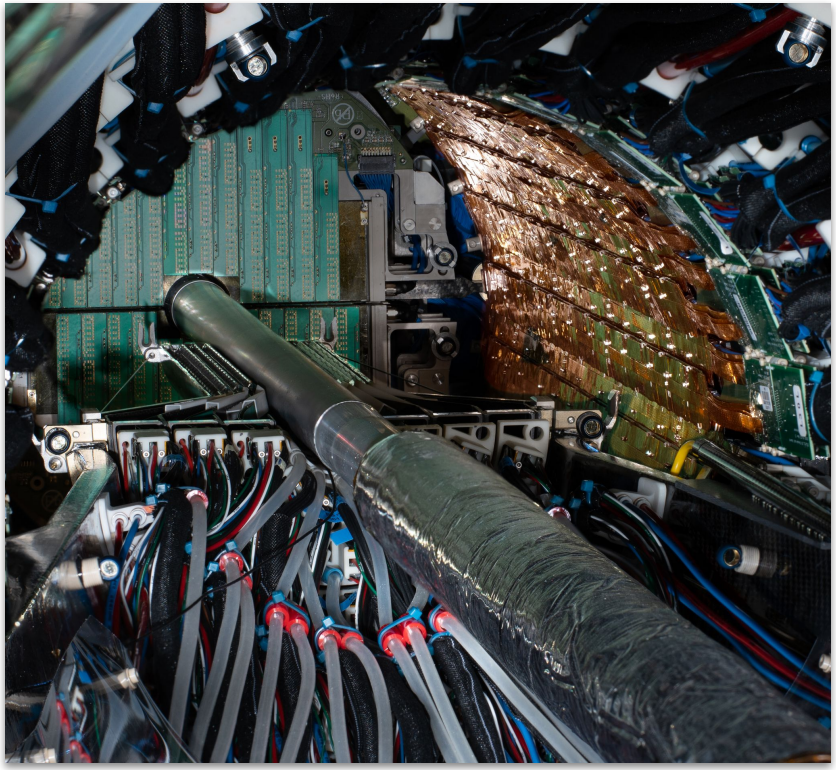
- Next: extract time over threshold to measure the charge released on each pixel

- The ALICE Experiment has replaced its Inner Tracking System with a 7-layer pixel-only tracker made out of more than 24000 monolithic active pixel sensor chips (ALPIDE) during the Long Shutdown 2.
- Largest successfully operating pixel-based detector in high-energy physics.
- A regular monitoring of the calibration of the detector is performed to ensure stable operation and high data quality. Results show excellent stability of threshold and noise over time.
- Studies performed during Run 3 show an improvement in the impact parameter resolution with respect to Run 2 and an excellent quality of the ITS2 tracking.

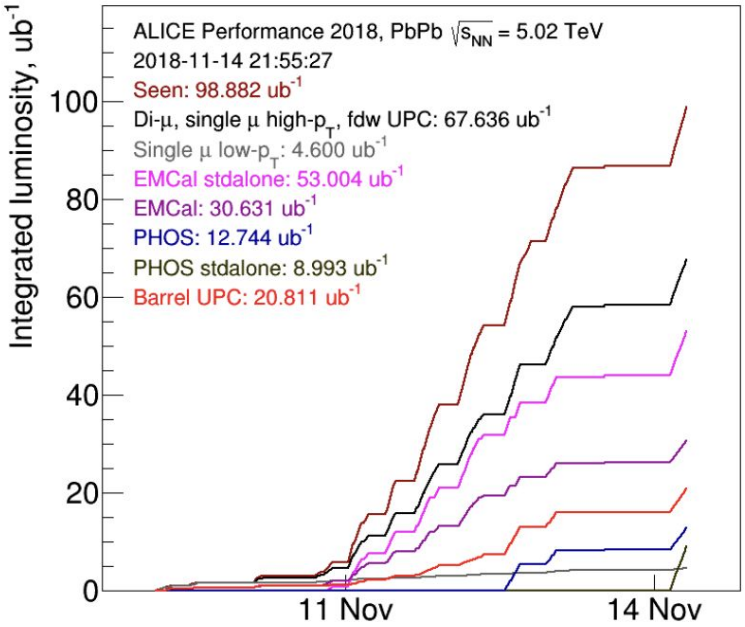
Future ITS Upgrade:

- ITS3: next ALICE upgrade for the Inner Tracking System - F. Krizek - Tue 17:25
- Recent results from MAPS prototypes for ITS3 - A. Villani - Wed 11:30

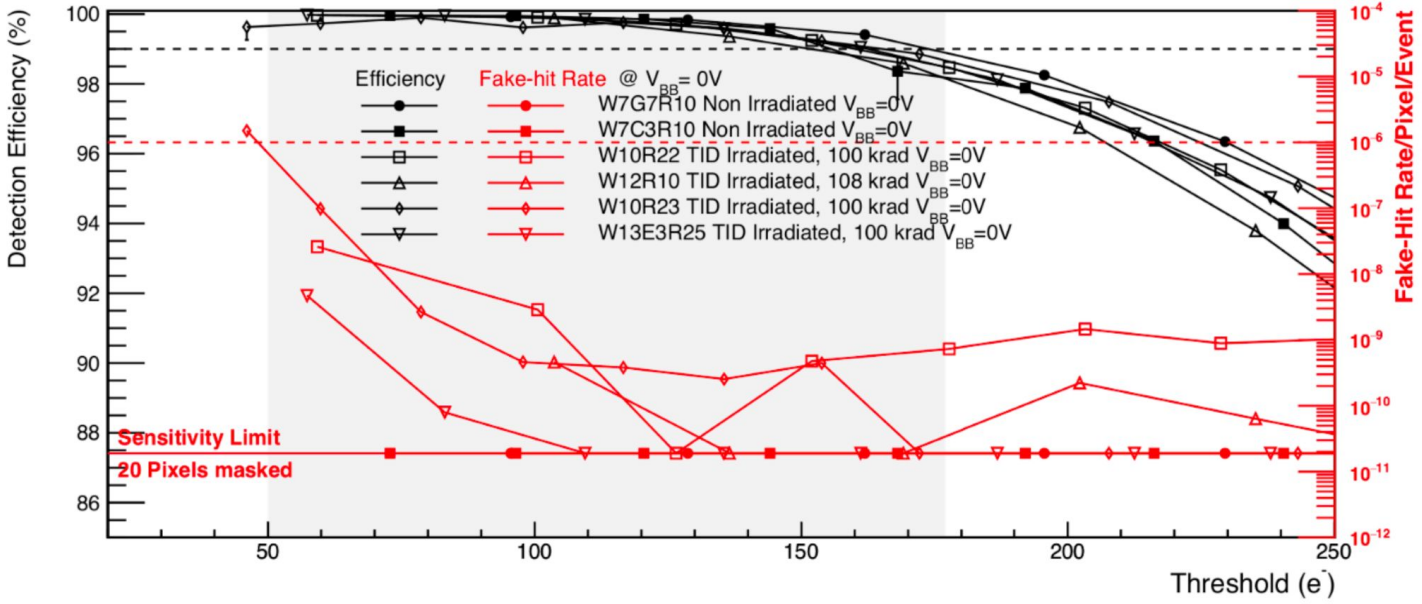
Thanks for your attention!



Backup

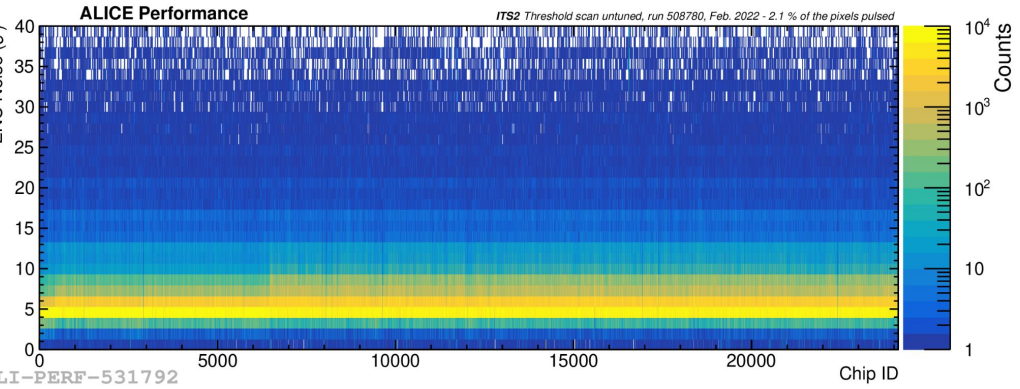


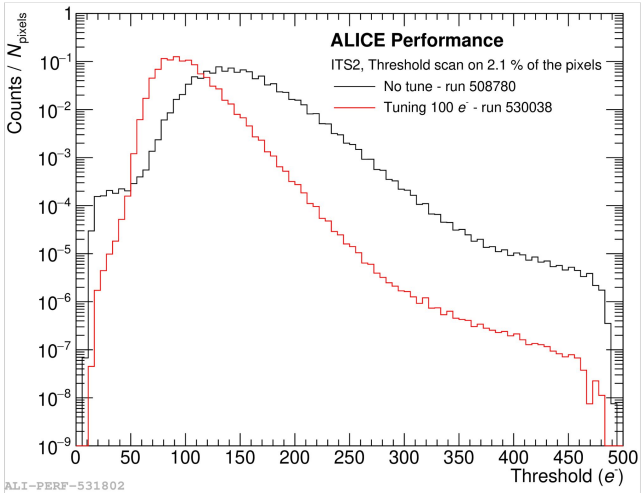
- Nominal ITS framing rate: **1 kHz**
- ALICE standard interaction rate (pp): **100 kHz**
- ALICE standard interaction rate (Pb-Pb): **8 kHz**

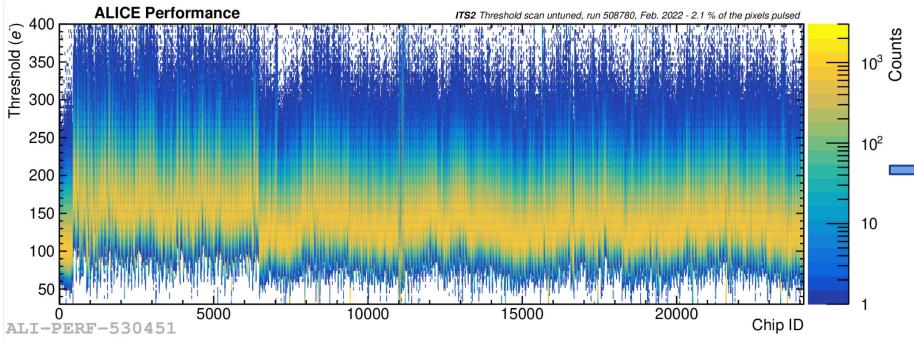


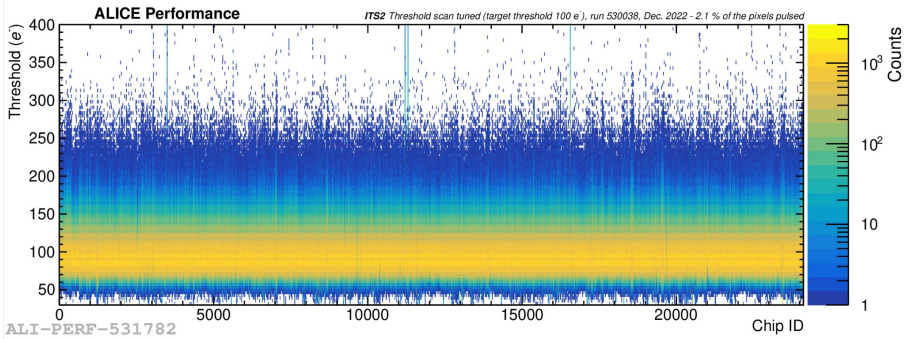
- Beam test: single chips
- Efficiency better than 99% : up to ~150 e^-
- Recurring threshold scans are important to evaluate if a new calibration is needed

ITS Calibration results: Threshold calibration - before and after tuning

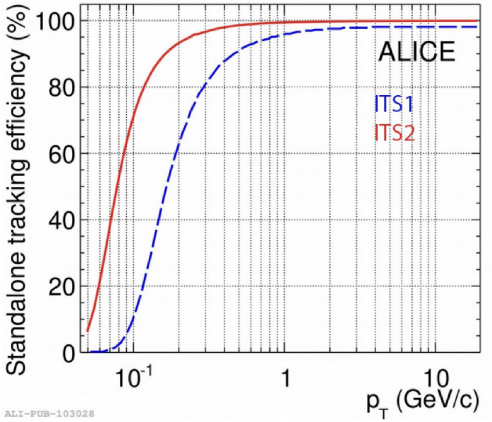






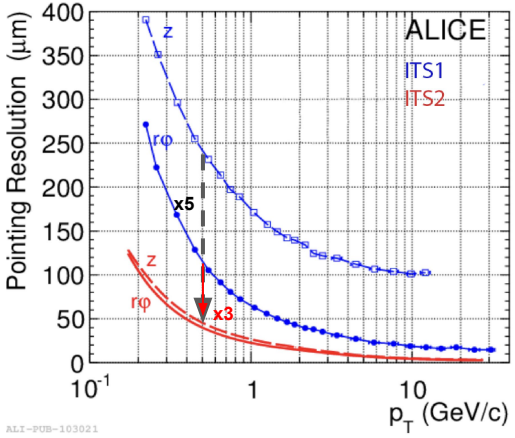


- Tracking efficiency improved



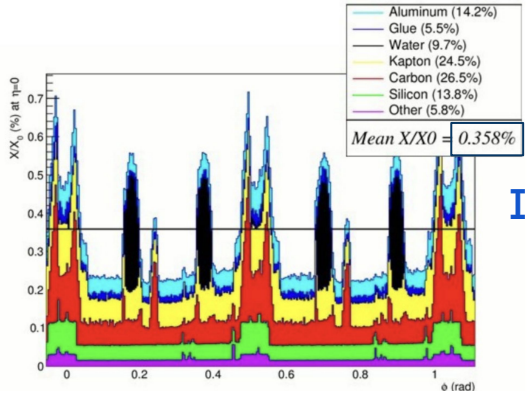
- 60%→90% at p_T=200 Mev/c

- Pointing resolution improved

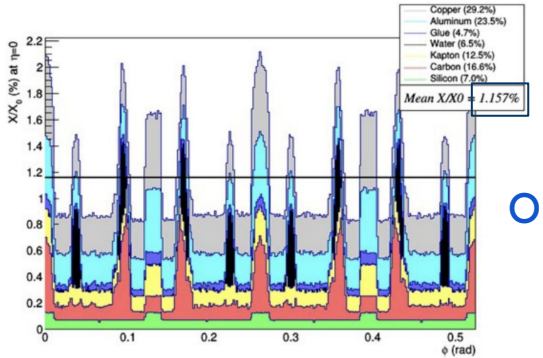


- ~5 factor (z), ~3 factor (rφ) at p_T = 500 MeV/c

- Material budget: from 1.1%X_0 to:



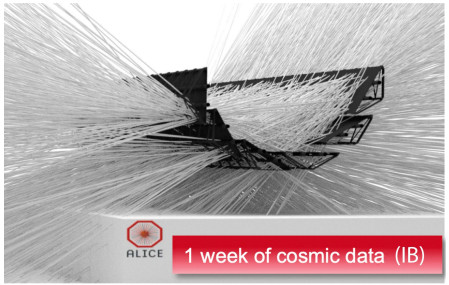
IB

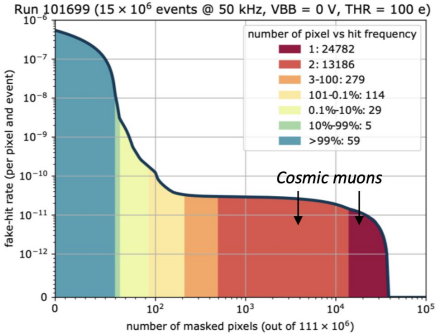


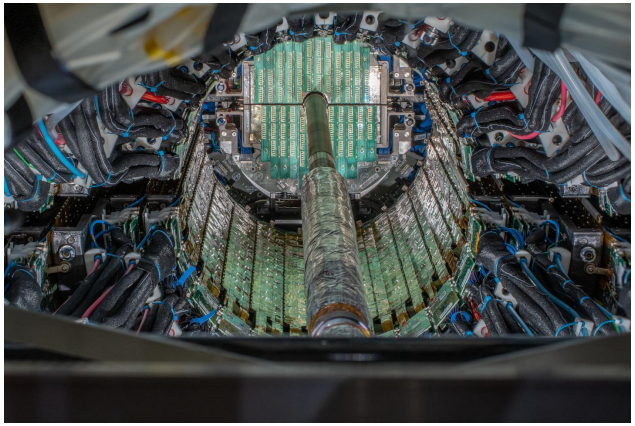
OB

- Reduced beampipe diameter
  - First layer closer to the Interaction point: 3.9 cm → 2.2 cm
- Increased readout rate
  - 1kHz→100 kHz Pb-Pb and 200 kHz pp
  - More granularity and smaller pixel size wrt old SDD

- Detector commissioning in the lab
  - June 2019 - December 2020 → Full detector commissioning in the lab
    - 24/7 shifts → monitor + cosmic data taking + calibration runs
  - Fake Hit Rate ~ 10^{-10} hit/pixel/event
  - Detector efficiency >99%
  - Stable chip threshold over time
  - Cosmic tracks successfully reconstructed



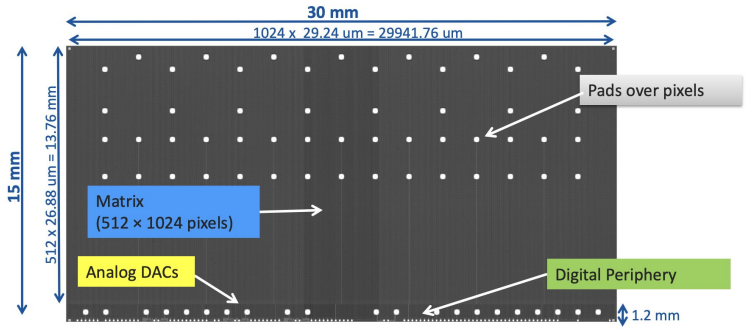




- Installation and commissioning in the ALICE cavern
  - January 2021 → Services installation
  - March 2021 → OB installed
  - May 2021 → IB installed
  - July 2021 → start of ALICE global commissioning with central shifts
  - October 2021 → first pilot collision: pp $\sqrt{s}$ = 900 GeV
  - 5th July 2022 → start of Run 3: first pp collision at $\sqrt{s}$ = 13.6 TeV
  - 18 November 2022 →first Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.36 TeV

- All the analog signals required by the frontends are generated by a set of on-chip 8 bit DACs.

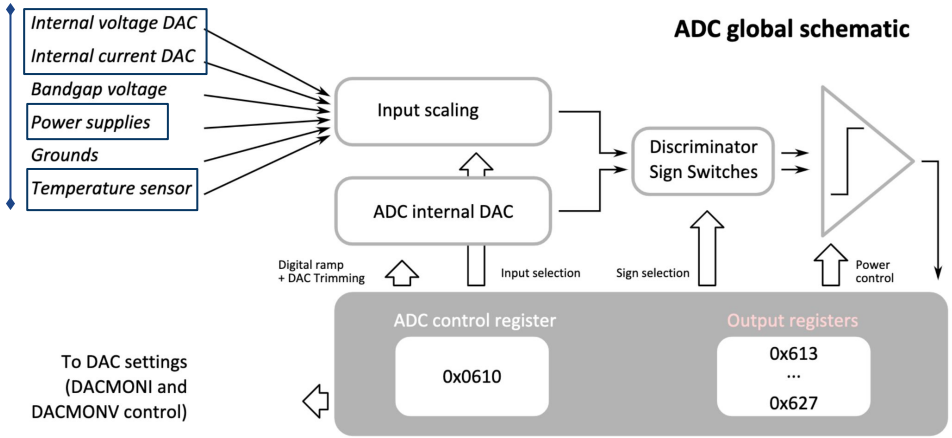
- Analog monitoring pads are available to monitor the outputs of the internal DACs.

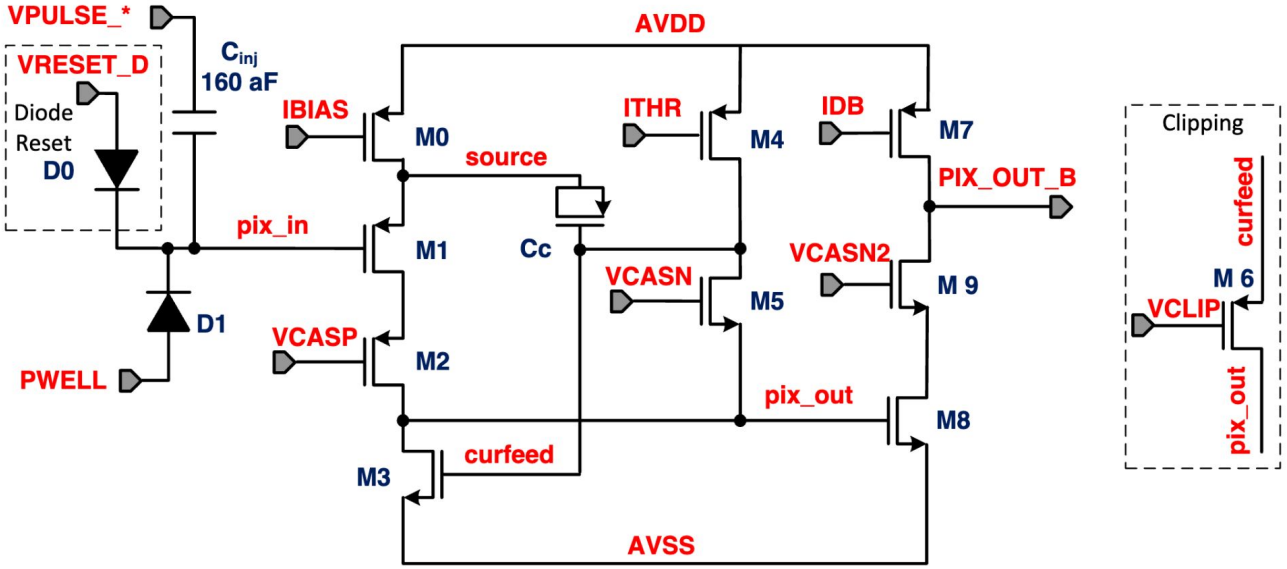


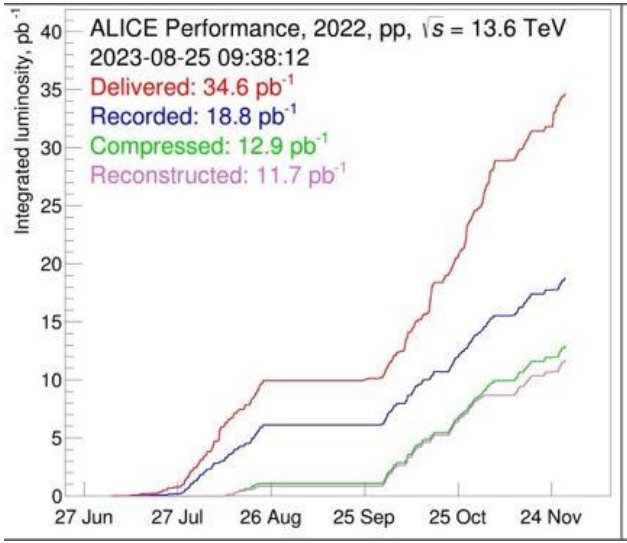
- The analog section of the periphery also contains a 10 bits resolution ADC to monitor quasi-static internal signals

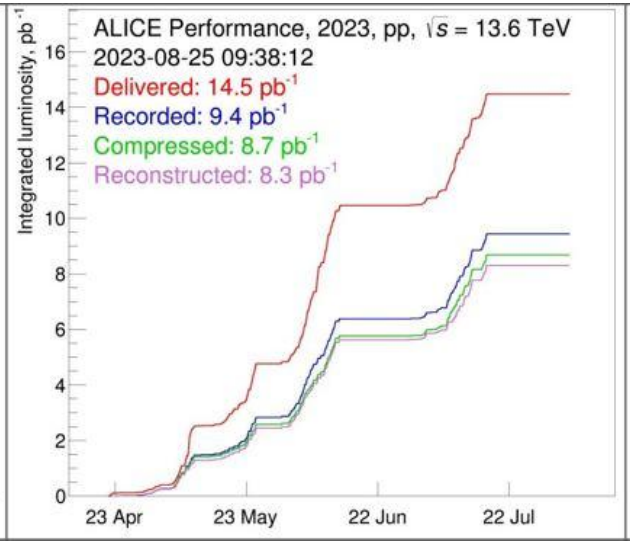
- Voltage DAC: ex. VCASN
- Current DAC: ex. ITHR

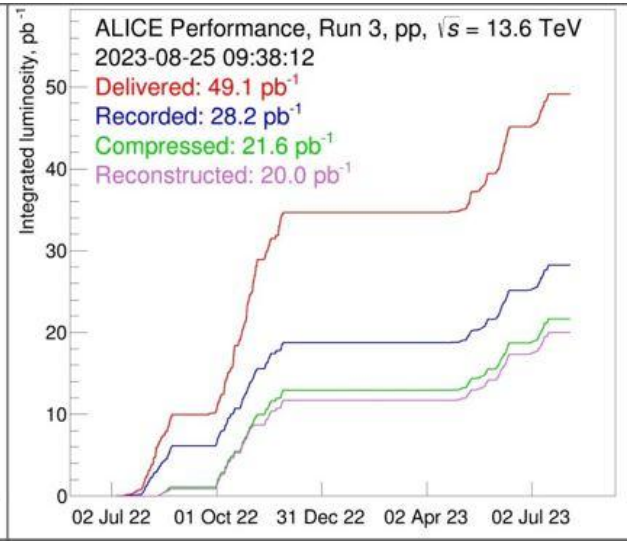
Threshold regulation

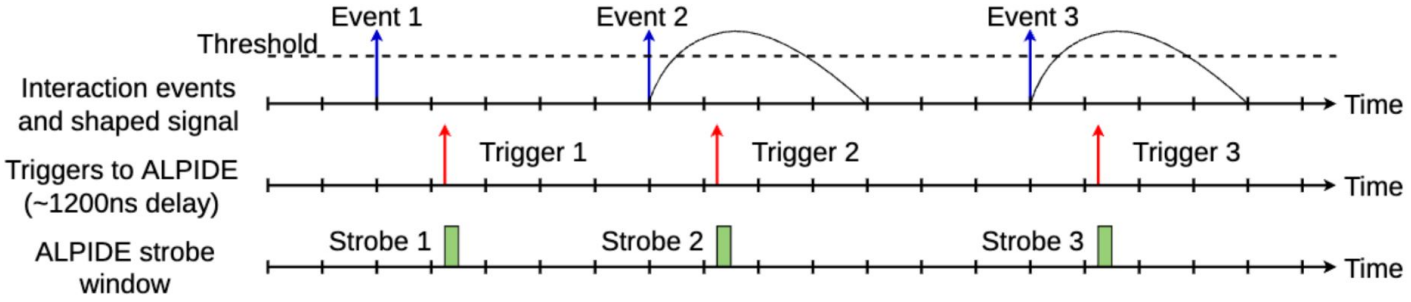



VPULSE_*
VRESET_D
Diode
Reset
D0
C_{inj}
160 aF
D1
PWELL
AVDD
IBIAS
M0
source
ITHR
M4
IDB
M7
PIX_OUT_B
pix_in
M1
Cc
VCASN2
M 9
VCASN
M5
VCASP
M2
pix_out
M8
curfeed
M3
AVSS
Clipping
curfeed
M 6
VCLIP
pix_out

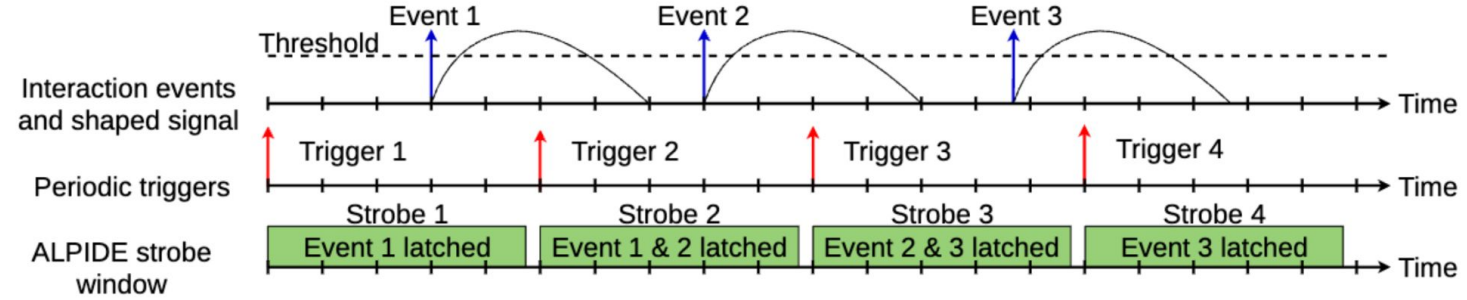

ALICE Performance, 2022, pp, √s = 13.6 TeV
2023-08-25 09:38:12
Delivered: 34.6 pb-1
Recorded: 18.8 pb-1
Compressed: 12.9 pb-1
Reconstructed: 11.7 pb-1
Integrated luminosity, pb-1
0
5
10
15
20
25
30
35
40
27 Jun
27 Jul
26 Aug
25 Sep
25 Oct
24 Nov


ALICE Performance, 2023, pp, √s = 13.6 TeV
2023-08-25 09:38:12
Delivered: 14.5 pb-1
Recorded: 9.4 pb-1
Compressed: 8.7 pb-1
Reconstructed: 8.3 pb-1
Integrated luminosity, pb-1
0
2
4
6
8
10
12
14
16
23 Apr
23 May
22 Jun
22 Jul


ALICE Performance, Run 3, pp, √s = 13.6 TeV
2023-08-25 09:38:12
Delivered: 49.1 pb-1
Recorded: 28.2 pb-1
Compressed: 21.6 pb-1
Reconstructed: 20.0 pb-1
Integrated luminosity, pb-1
0
10
20
30
40
50
02 Jul 22
01 Oct 22
31 Dec 22
02 Apr 23
02 Jul 23



(a) Triggered mode



(b) Continuous mode