Calibration and Performance of the Upgraded ALICE Inner Tracking System

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for the ALICE collaboration

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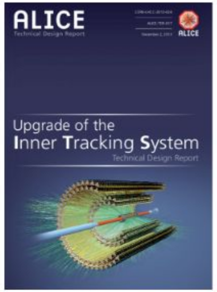
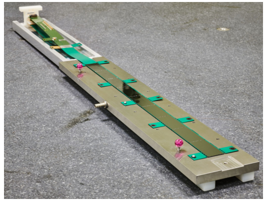
iWoRiD 2024 - 1st July 2024

- Improve the improve the **tracking efficiency** and the **p_T resolution**
  - 7 pixel layers instead of 6 (SSD, SDD, SPD) layers
- Improve the **impact parameter resolution**
  - Reduced beam pipe diameter → First layer closer to the interaction point
  - Reduced material budget in the innermost layers: 1.14% X_0/layer → 0.36% X_0/layer
- Improve the **readout**
  - 1 kHz → up to 100 kHz (Pb–Pb), 400 kHz (pp)



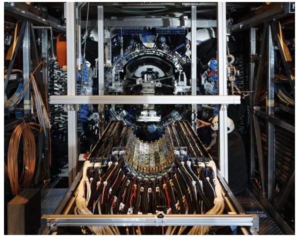
CDR 2012

TDR 2013

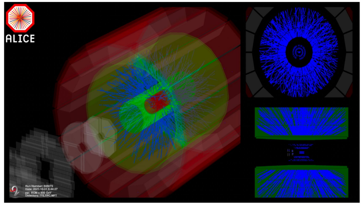


Start of ITS2 construction and assembly 2016

Start of on-surface commissioning 2019



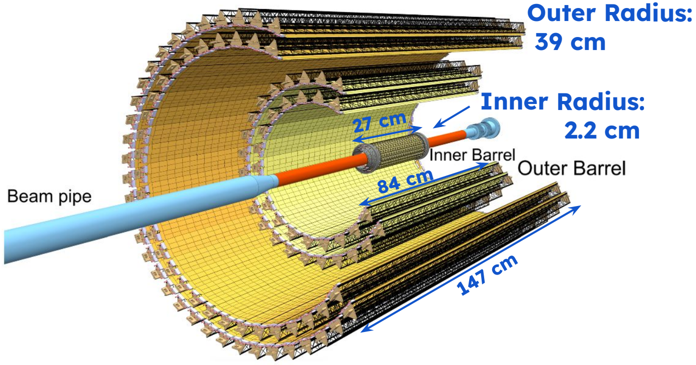
ITS2 installation in the cavern Spring 2021

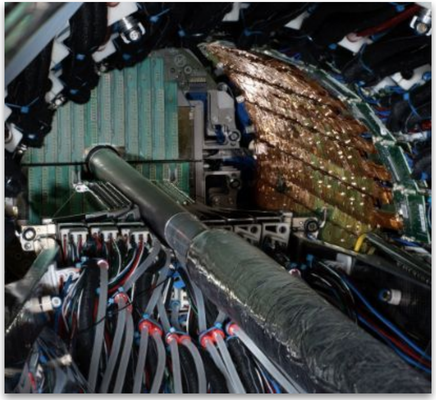


Pilot beam Oct 2021

Introduction: The Upgraded Inner Tracking System

- ITS1 upgraded to **ITS2** during LHC Long Shutdown 2.
- Requirements achieved with 7 layers of **MAPS** chips **ALPIDE** and a reduced beam pipe diameter





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

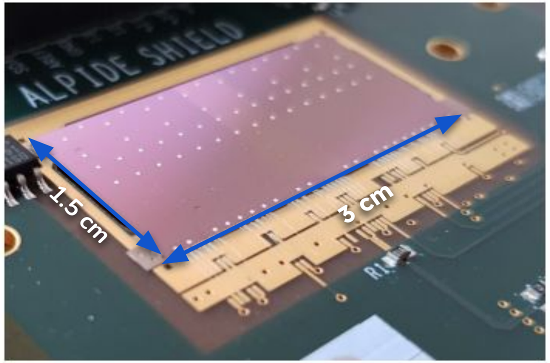
4 Outer Barrel (**OB**) layers:
- Middle Layers: **3,4**
  - Number of staves: **54** (24+30)
- Outer Layers: **5,6**
  - Number of staves: **90** (42+48)
- Material budget: **1.1%** X_0**/layer**

192 staves
24120 chips
12.5 Giga pixels
10 m^2 active area

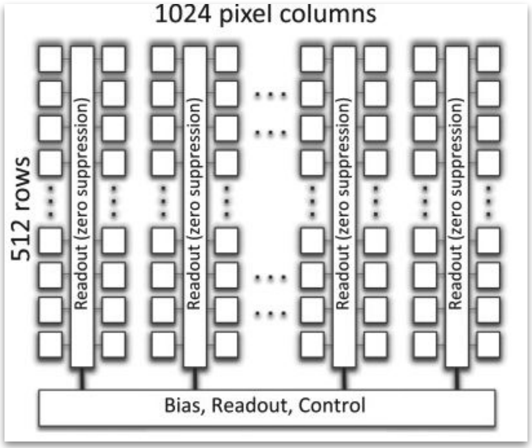
↓

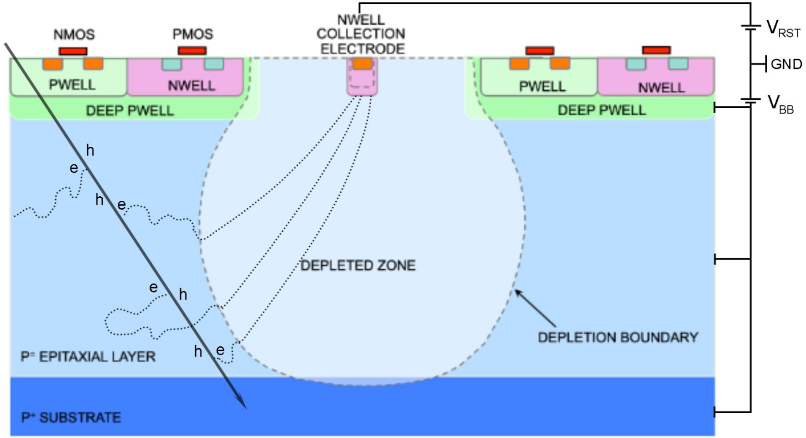
Largest pixel detector
in High-Energy Physics

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

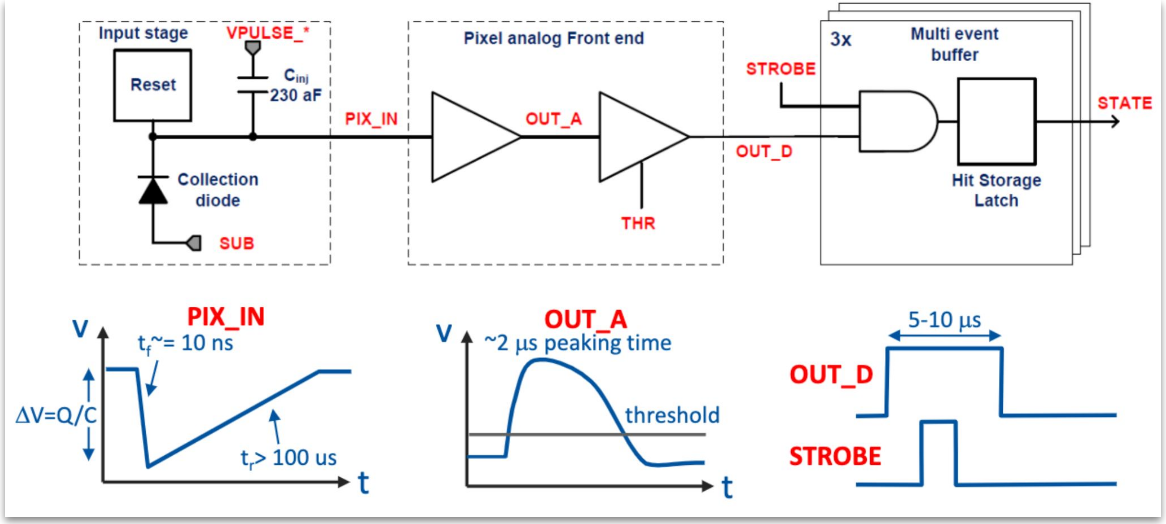


- **512x1024** pixels
- Readout of pixel hit data based on the Priority Encoder
- Pixel size ~ **27 x 29 μm²**
- Spatial resolution (rφ, z) ~ **5x5 μm²**



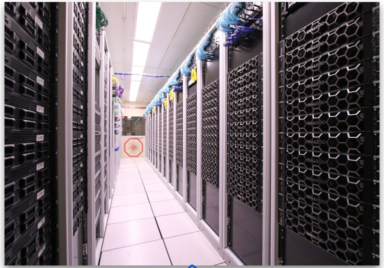


- **Deep p-well → Full CMOS circuitry within active area**
- High resistivity (1-6 kΩcm) p-type epitaxial layer (25 μm) on p-type substrate
- Small n-well diode (ø = 2μm), ~100 times smaller than pixel → low capacitance ~fF
- Reverse bias voltage to substrate: -6 V < V_{BB} < 0 V → increase the depletion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



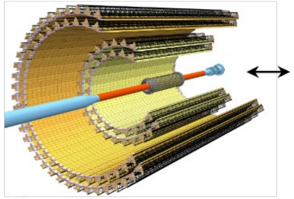
Pixel signal amplified and digitized at pixel level:

- Sensing **diode**
- Pulse **injection capacitor**
  → inject test charges during calibration
- Front-end **amplifying and shaping stage**
  - Always active with power consumption **< 7 mW/cm^2**
- **Discriminator**
  → binary readout
- **Digital section**
  - 3 hit **storage register** (Multi Event Buffer)
  - **Pixel masking register**
  - **Pulsing logic**
- Total chip power consumption **< 47 mW/cm^2**

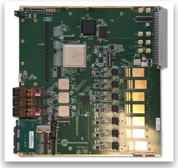


Detector Control System (DCS)

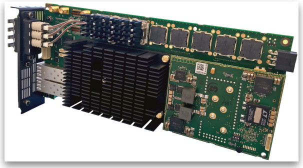
ITS configuration and calibration



192 x Readout Units (RUs)



22 x Common Readout Units (CRUs)



13 x First Level Processors (FLPs)

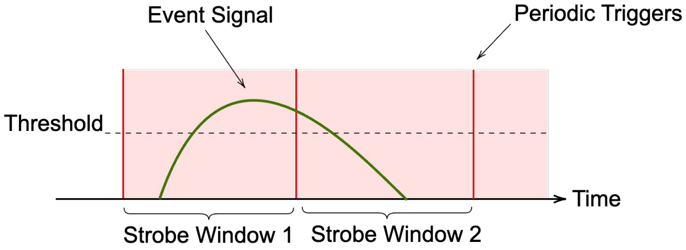
Online data QC tasks:
- hit occupancy
- front-end electronic diagnostic

340 x Event Processing Nodes (EPNs)

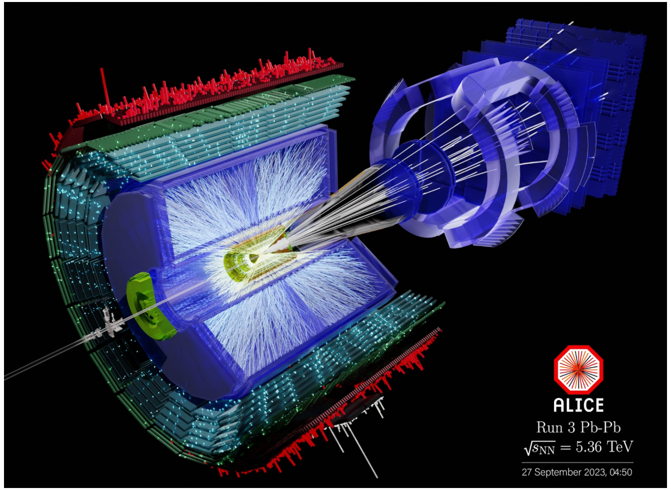
Online data QC tasks:
- Reconstructied tracks and clusters
- Decoding errors

Decoding
Hit counting
Threshold extraction
Data aggregation
...

- **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 (100 ns)



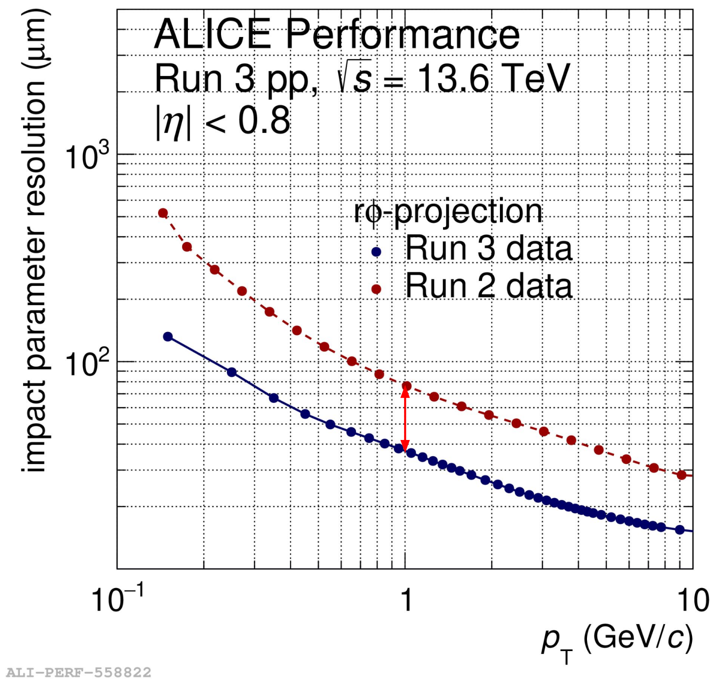
	Run 2 pp	Run 2 Pb–Pb	Run 3 pp	Run 3 Pb–Pb
Recorded luminosity	~0.059 pb^{-1}	~2.2 nb^{-1}	~38 pb^{-1} (so far)	~2 nb^{-1} (so far)
Interaction rate	200 kHz	8 kHz	500 kHz	45 kHz (so far)

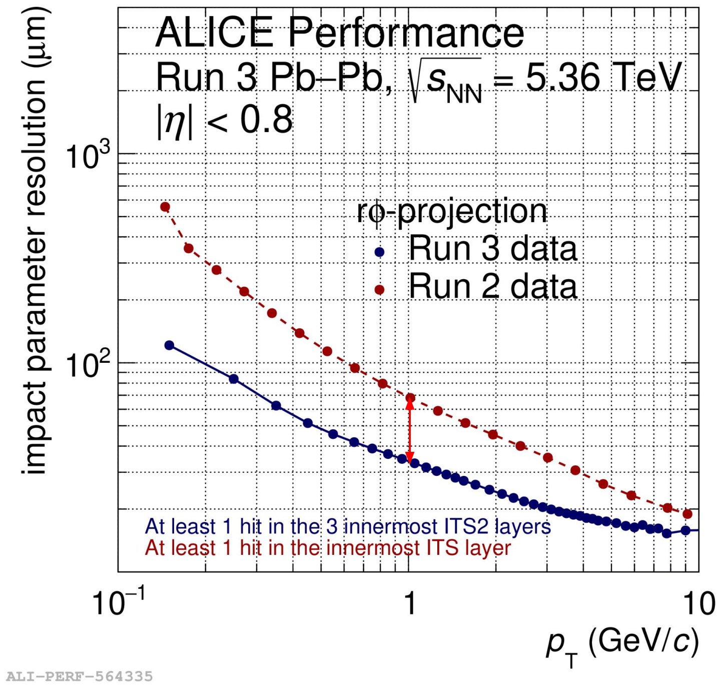


- ITS2 successfully tested up to **4 MHz** pp interaction rate (~**50 GB/s** data rate)
- **ITS fully operational**
  - Except for **0.4%** of the 12.5 billions pixel excluded in the whole detector

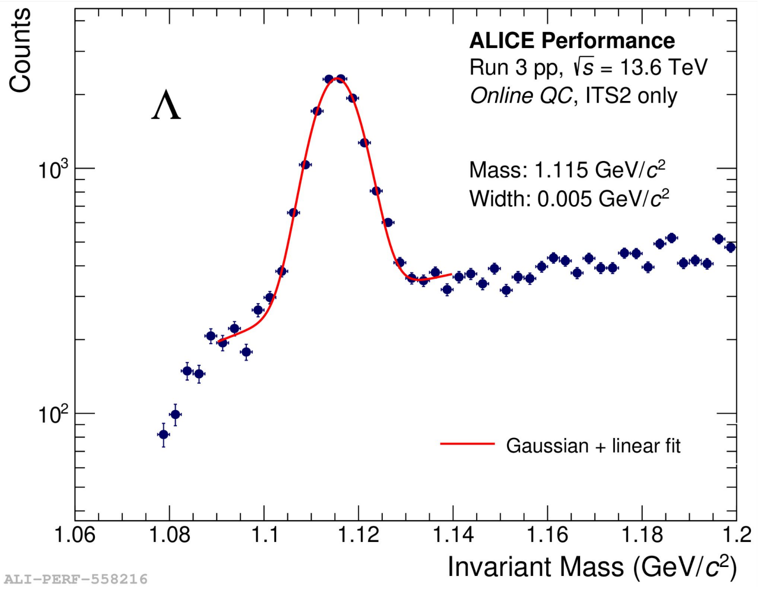
    (**94 over 24120 chips** dead/excluded, **1.5M over 12.5B** pixels dead/noisy)

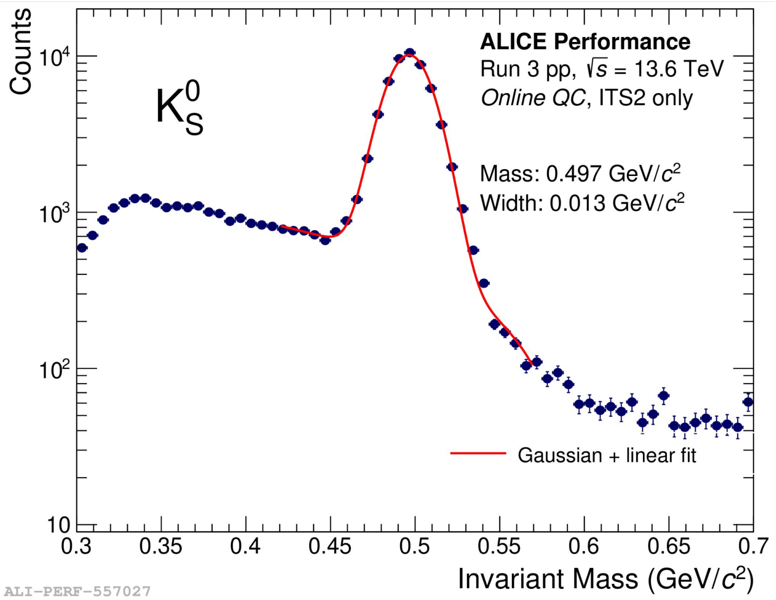
- **Impact parameter resolution** measured with Run 3 pp and Pb–Pb data:
  - **~2x improvement** at p_T = 1 GeV/c with respect to Run 2



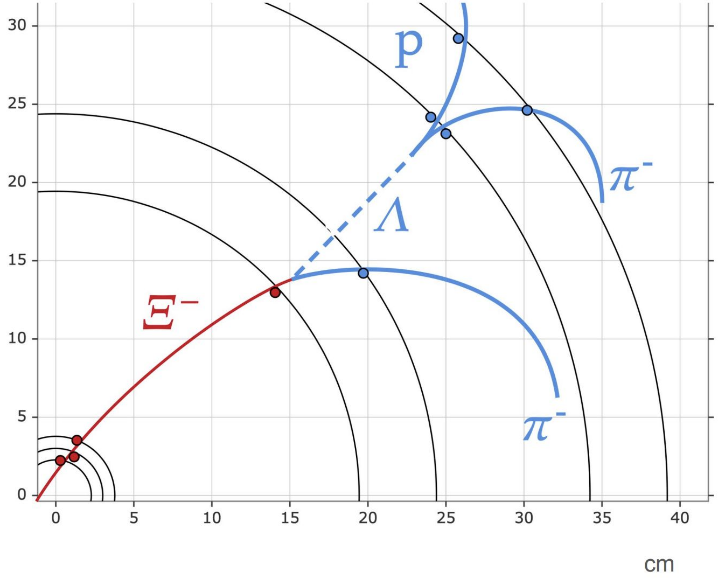


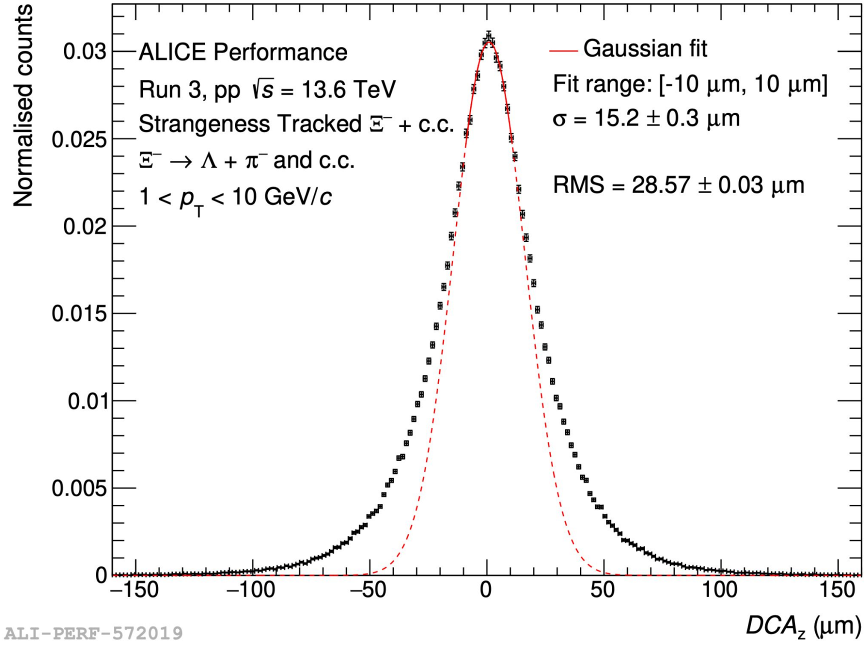
- **Online physics performance** from QC through Λ baryon and K_s^0 meson invariant mass peaks using ITS standalone tracks





- ITS innermost layers radius range from 2.2 cm to 4 cm
- Possibility to track charged weak-decaying particles before their decay via the **strangeness tracking** algorithm
  - Associating hits in the IB to the tracks of the decay daughters in the OB
  - New possibilities of studies: **non-prompt cascades**, hypernuclei, exotic bound states





Main calibration procedures:

- **Threshold calibration**
- **Noise calibration**

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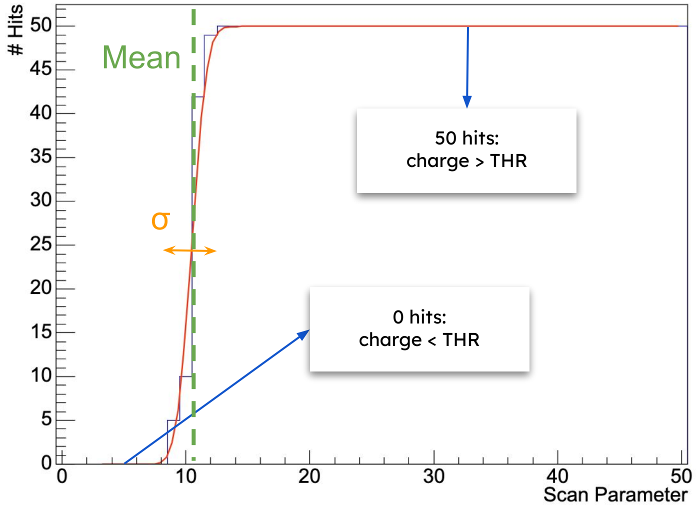


- **Threshold tuning** and **threshold scan**
- General threshold calibration operations:
  - **Inject charge** into single pixels
  - **Vary scan parameter** and repeat
  - Measure **response** (hits per injection) as a function of the scan parameter
  - **Fit** response vs scan parameter with error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

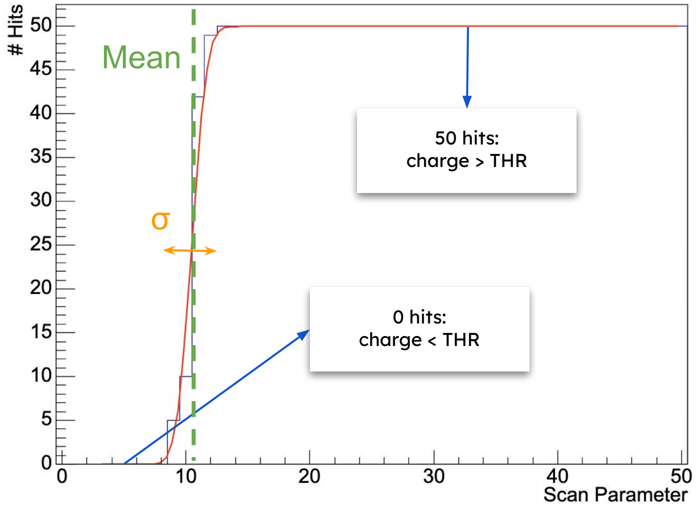
Calibration scan	Scan duration	How often
Threshold scan (short)	10 min	1/day
Threshold scan (full)	1h30 min	If needed, ~1/year
Threshold tuning	10 min	1/year

Challenging procedure:

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

Main calibration procedures:

- **Threshold calibration**
- **Noise calibration**



Threshold tuning:

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

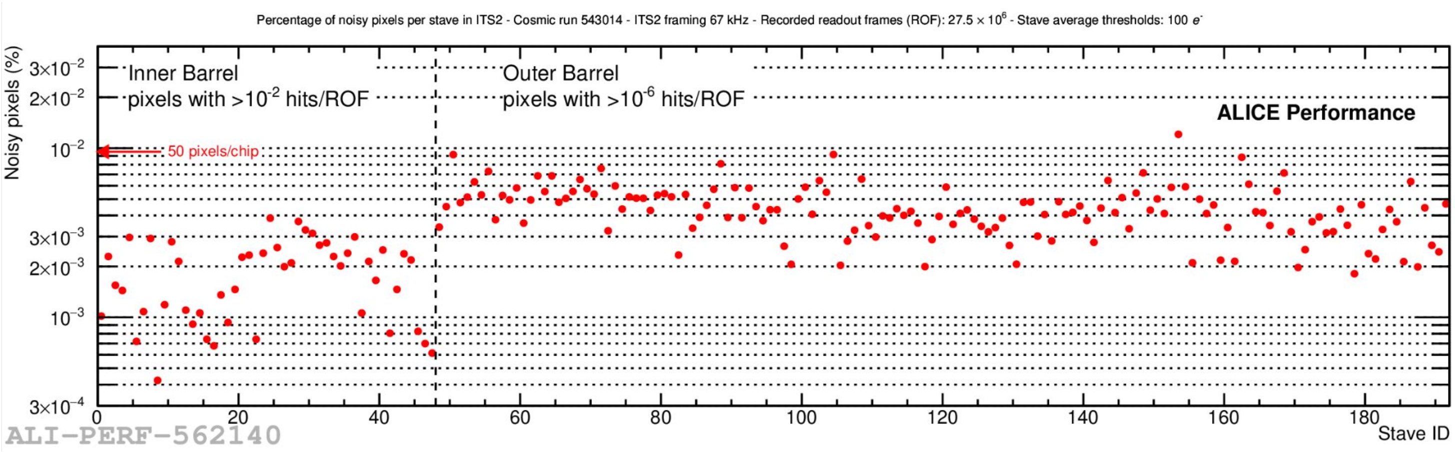
Threshold scan:

- Goal: Measure the **average threshold** per chip
- **Vary the charge injected keeping fixed the DACs setting**
- Pixel threshold = inflection point of S-curve
- **Chip threshold** = mean of pixel thresholds
- Data stored for monitoring of **detector stability** over time
- **~2% of representative pixels** per chip are scanned (daily threshold verification)

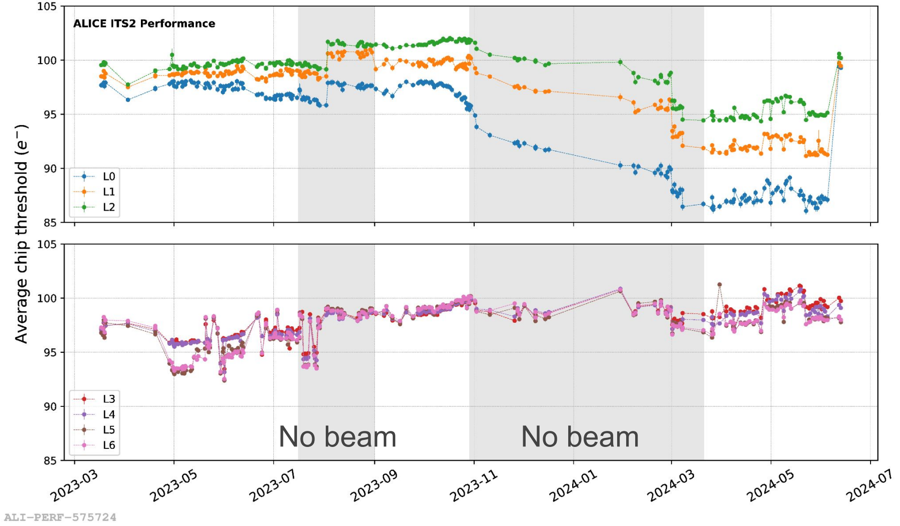
Main calibration procedures:

- Threshold calibration
- **Noise calibration**

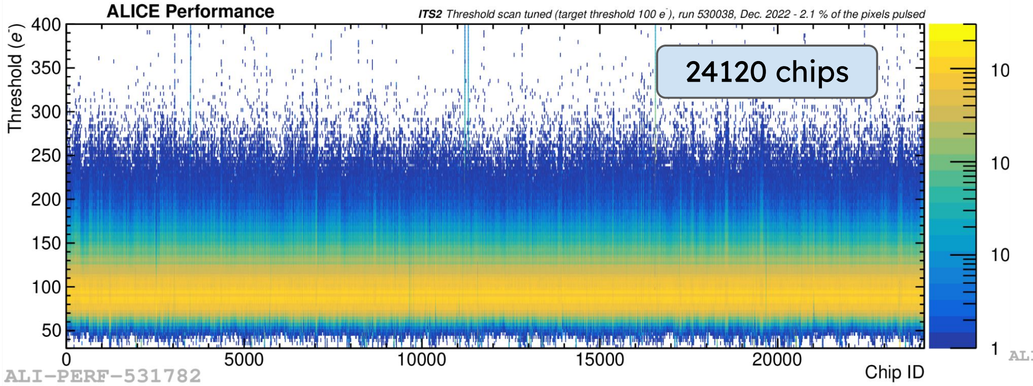
- Goal: find **noisy pixels** with the threshold currently set
- **Cosmic run**
- Masking pixels exceeding:
  - $\mathbf{10^{-2}}$ hits/event/pixel in **IB**
  - $\mathbf{10^{-6}}$ hits/event/pixel in **OB**
- Resulting fake-hit rate meets the requirements

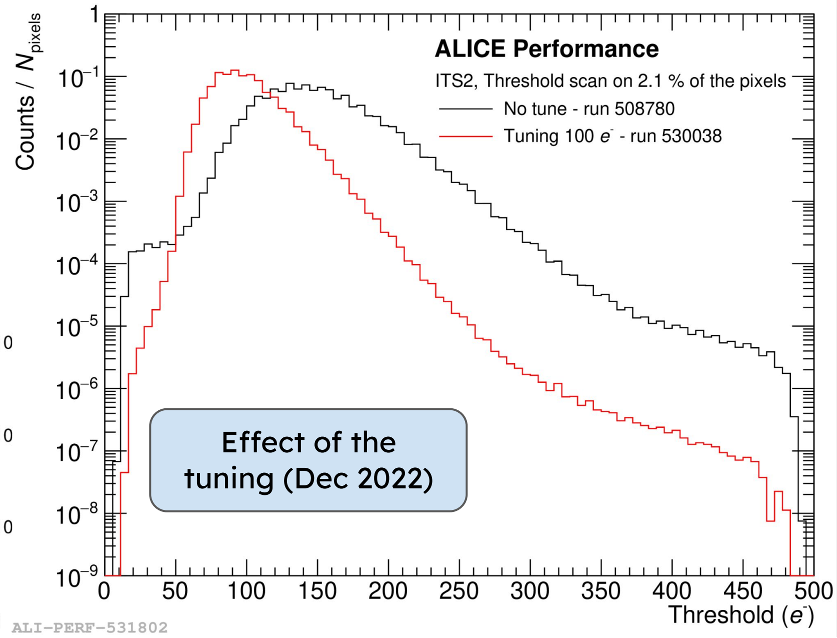


ITS Calibration results: Threshold calibration



- Threshold tuned to **100 e^-** in December 2022
- Radiation effect made the threshold decrease in IB layers
- Effect compensated with a new tuning in June 2024
- Minor fluctuations due to supply voltage optimizations





ITS Calibration results: Threshold tuning and calibration

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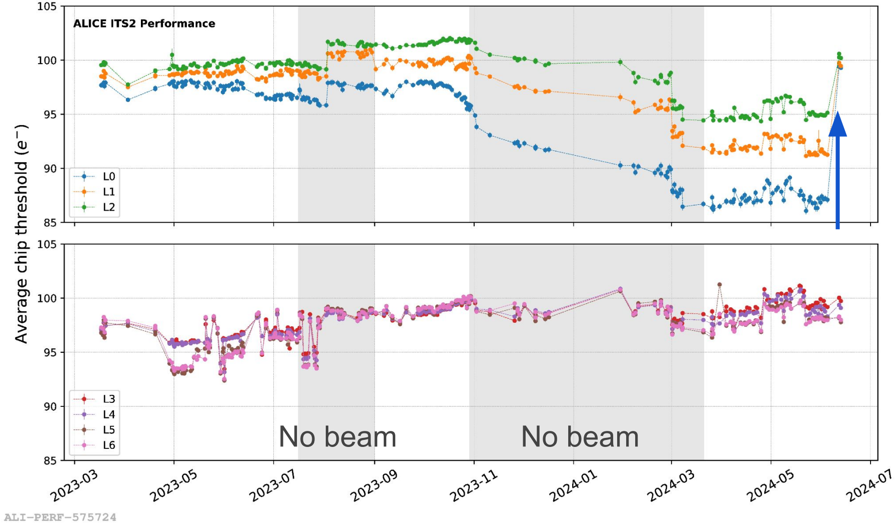

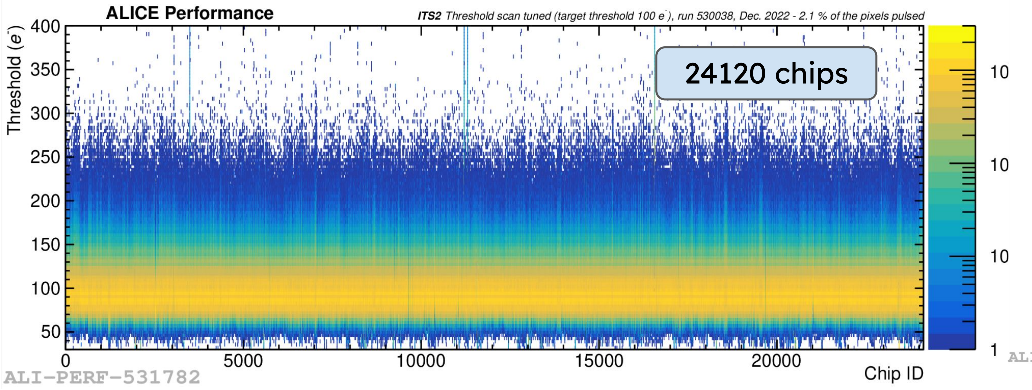

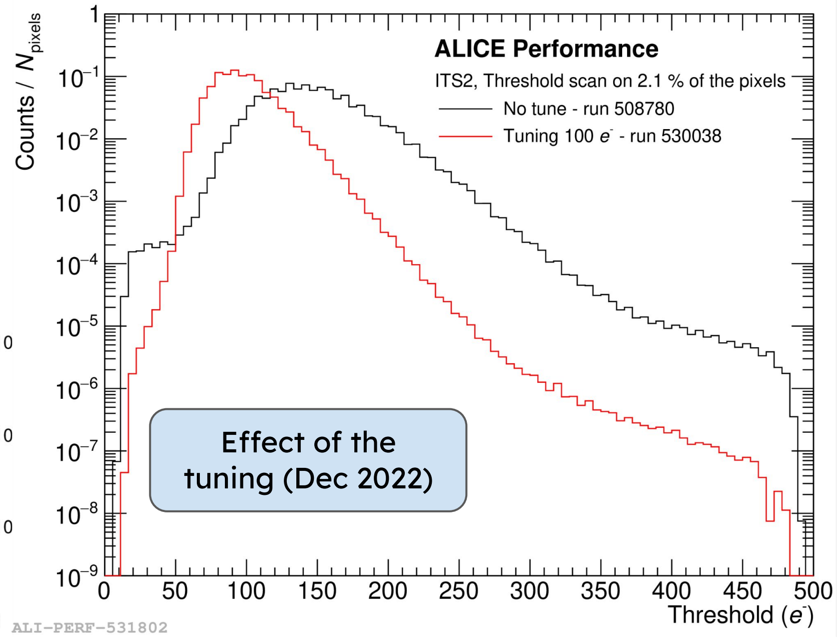

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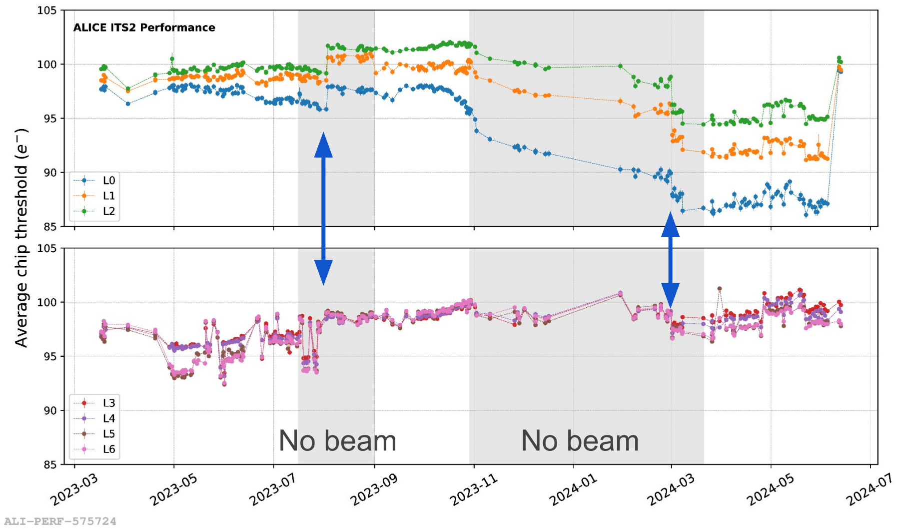
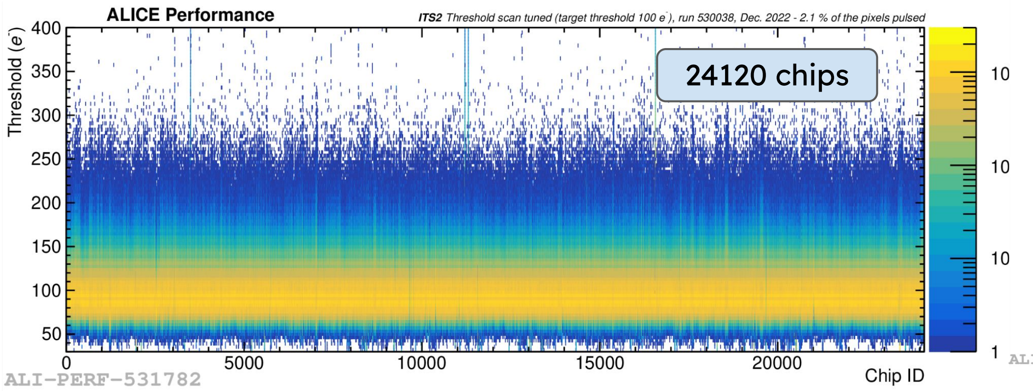
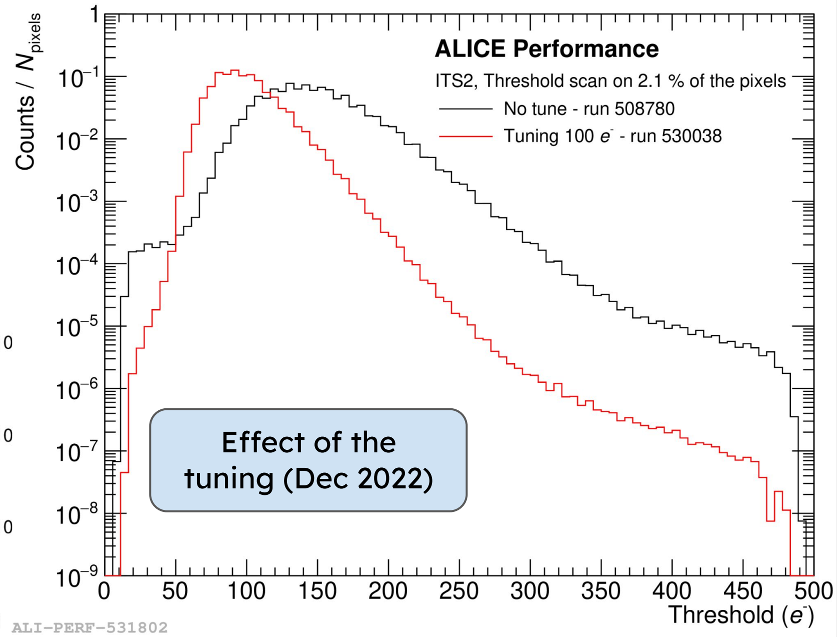
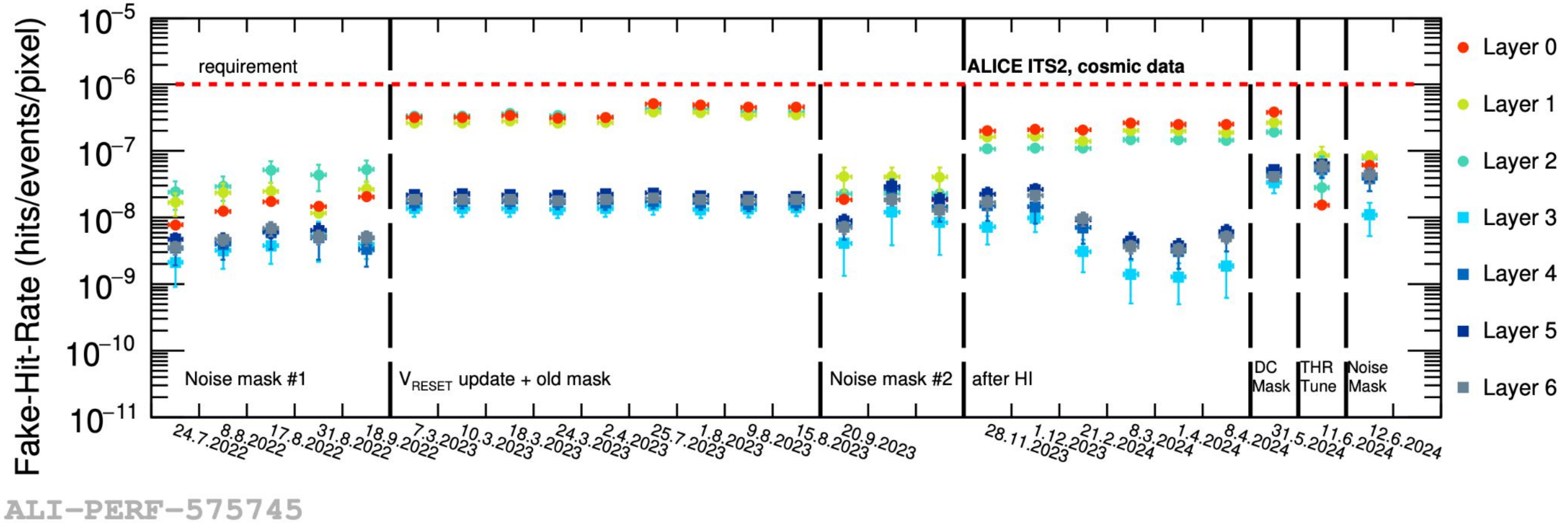






- Masked noisy pixels on the full detector:
  ~ 546k → ~0.004%
- Fake-hit rate after masking:
  - **$\sim 10^{-7}$** hits/event/pixel for **IB**
  - **$\sim 10^{-8}$** hits/event/pixel **OB**

    → orders of magnitude better than requirement (**$\sim 10^{-6}$** hits/event/pixel)



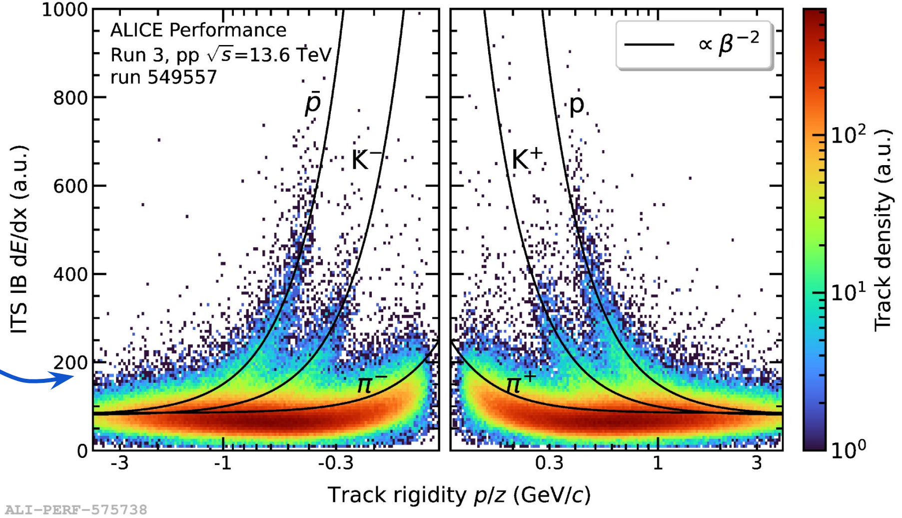
- **Proof of concept** for **PID** with MAPS detectors
- Starting point: measuring Time over Threshold in MAPS during non-standard ALICE operation:

Standard operations	**Dedicated ITS run**
ALPIDE signal clipping activated → time-over-threshold independent of the charge deposit	**ALPIDE signal clipping deactivated** → time-over-threshold proportional to the charge deposited
202 kHz ITS framing rate	**2.2 MHz ITS framing rate** → oversampling ALPIDE response
500 kHz pp interaction rate	**~ 1 kHz pp interaction rate** → fit into bandwidth

- Time-over threshold calibrated using pulse injection measurement

First dE/dx spectrum observed!

- Charge deposit measured in the ALPIDEs of the Inner Barrel
- Proof of concept for PID with binary readout MAPS



- The ALICE Inner Tracking System is composed by **24120 ALPIDE MAPS** distributed over **7 concentric layers**.

- **Fundamental detector** for the ALICE experiment.

- **Largest and successfully operating silicon-pixel detector** in high-energy physics.

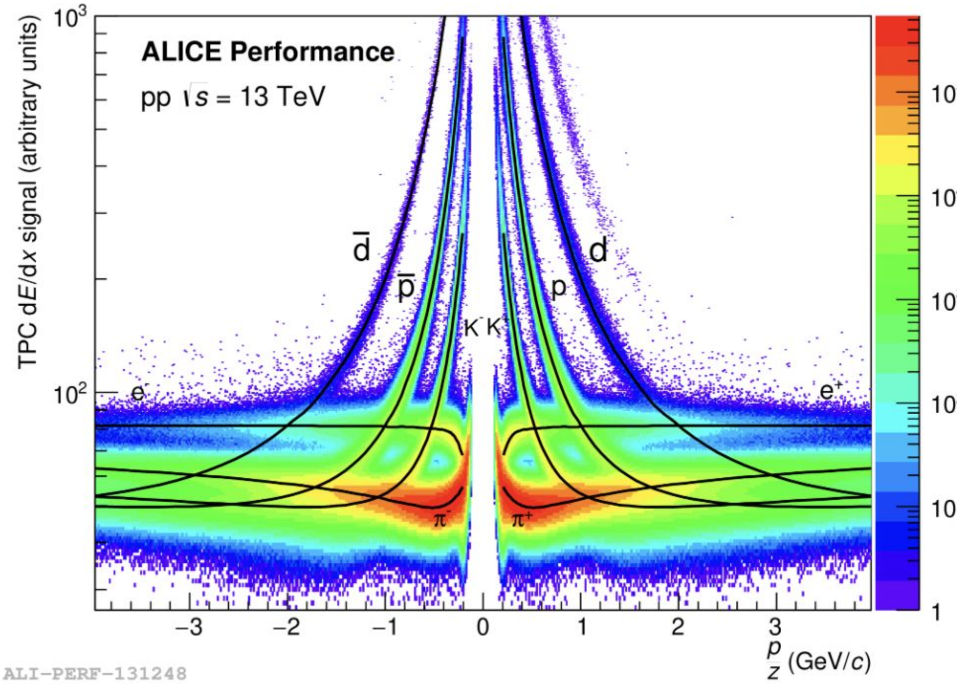
- Unprecedented impact parameter resolution of **30 μm at p_T = 1 GeV/c**.

- Successful operation and high data quality are ensured with **regular monitoring and calibration**.

- Proof of concept for **energy loss measurement using binary readout MAPS**.

Thanks for your attention!

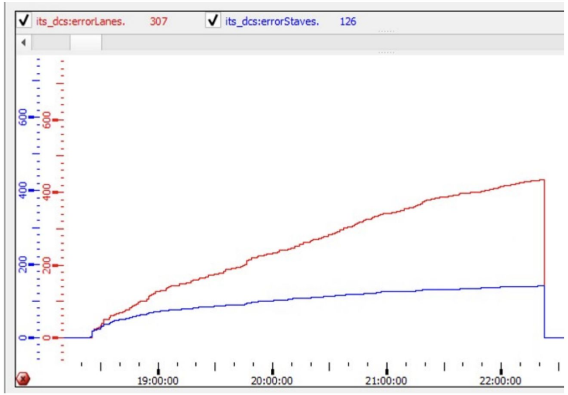
Backup



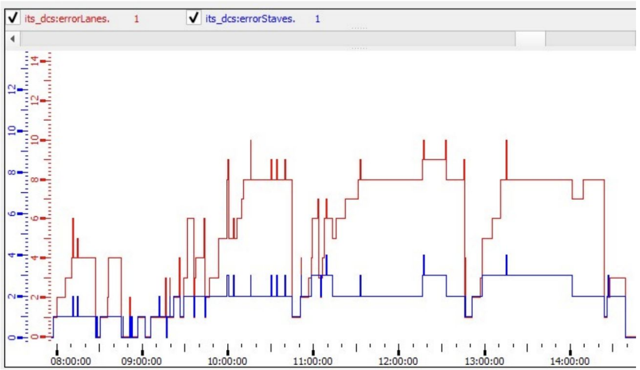
ALICE Performance
pp √s = 13 TeV
TPC dE/dx signal (arbitrary units)
10^3
10^2
d̄
p̄
K⁻ K⁺
d
p
e⁻
e⁺
π⁻
π⁺
−3
−2
−1
0
1
2
3
p/z (GeV/c)
10
1
ALI-PERF-131248

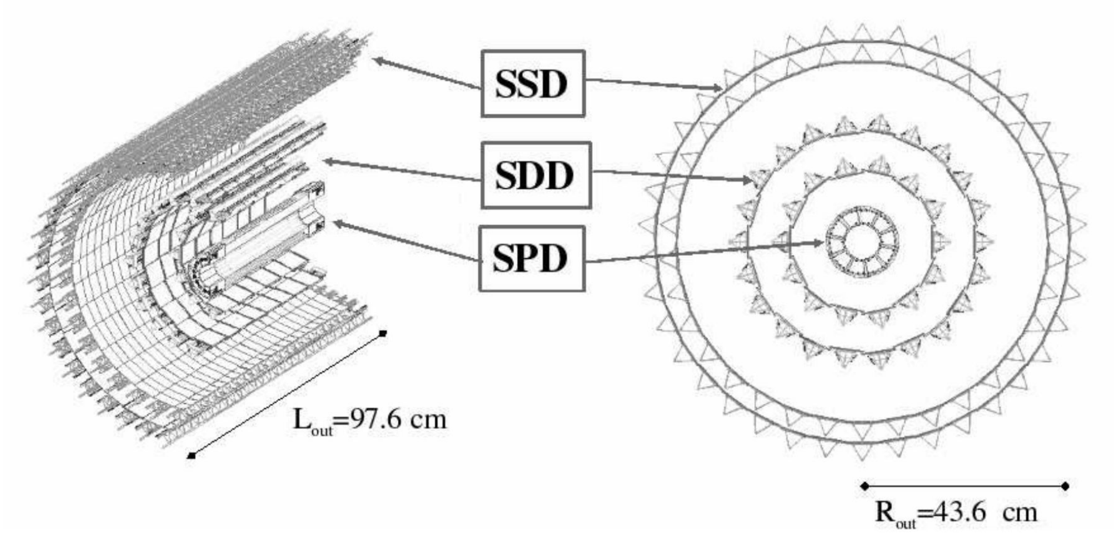
- **Voltage check and correction**:
  → each time the output voltage is modified, in case of errors, an automatic correction of the Power Unit output voltage is done
- **Voltage drop correction**:
  → automatic correction of the voltage drop on staves changing state due to extra current at the start of trigger
- **Stave auto-recovery**
  → automatic recovery of high-speed links and lanes into error
- **In-run recovery of data corruption**

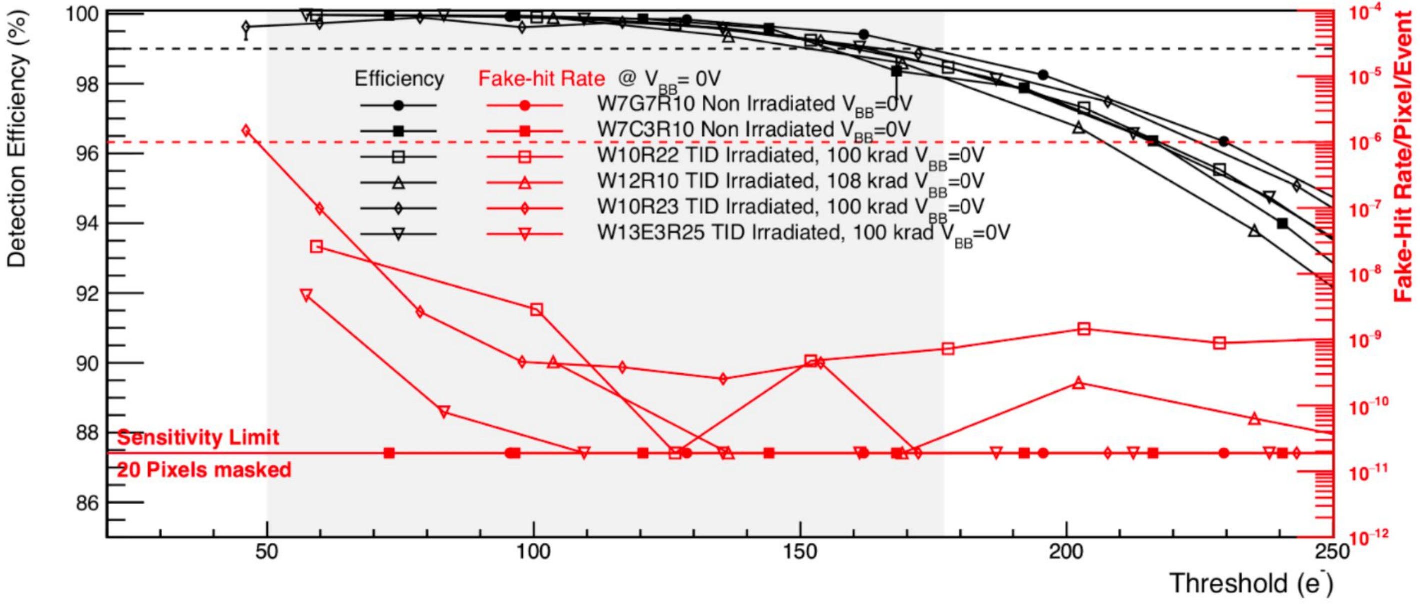
4-hour run without auto-recovery:



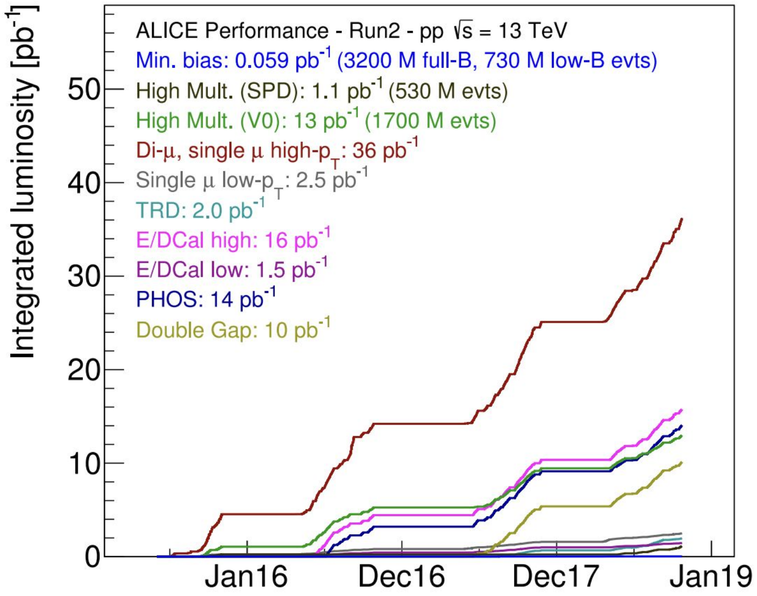
6-hour run with auto-recovery:

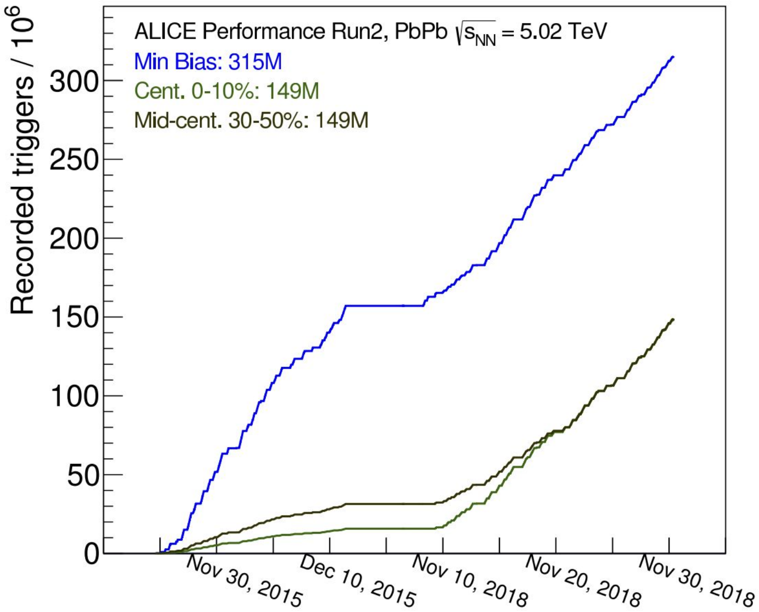



SSD
SDD
SPD
L_out=97.6 cm
R_out=43.6 cm

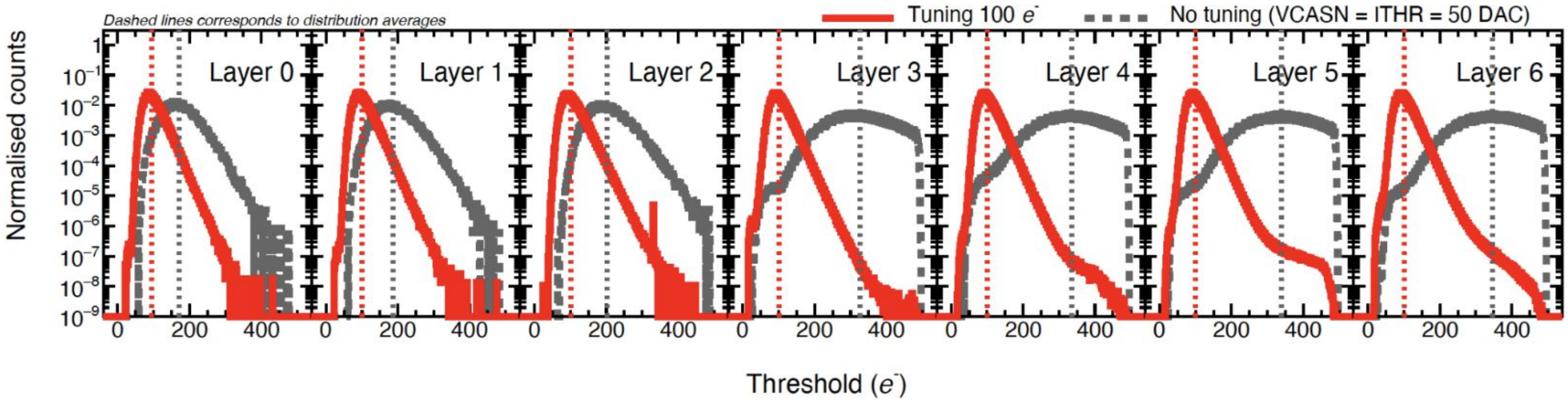


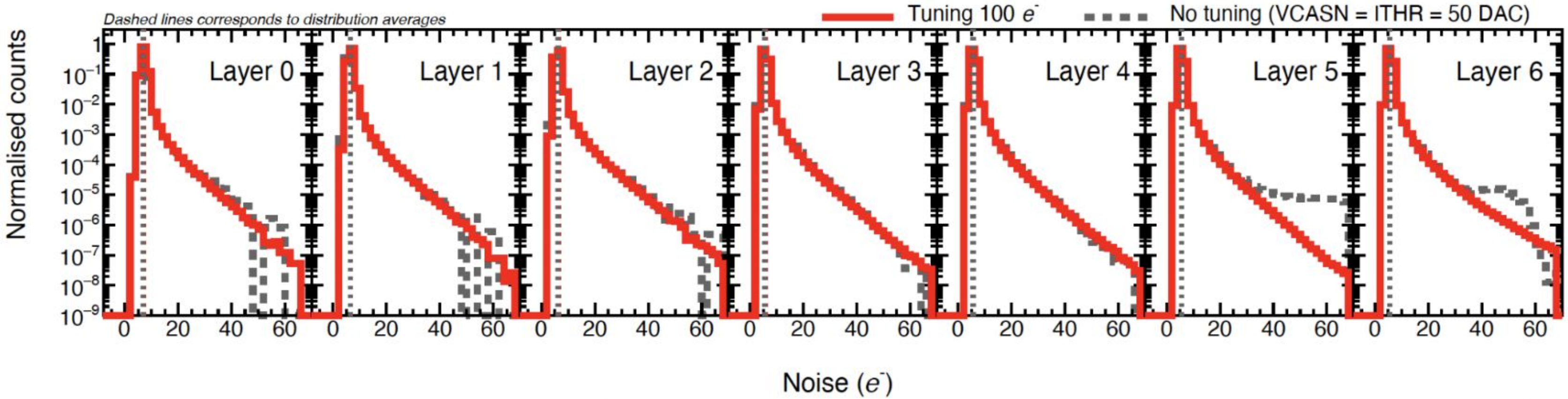
- Beam test: single chips
- Efficiency better than 99% : up to ~150 e^-
- Recurring threshold scans are important to evaluate if a new calibration is needed

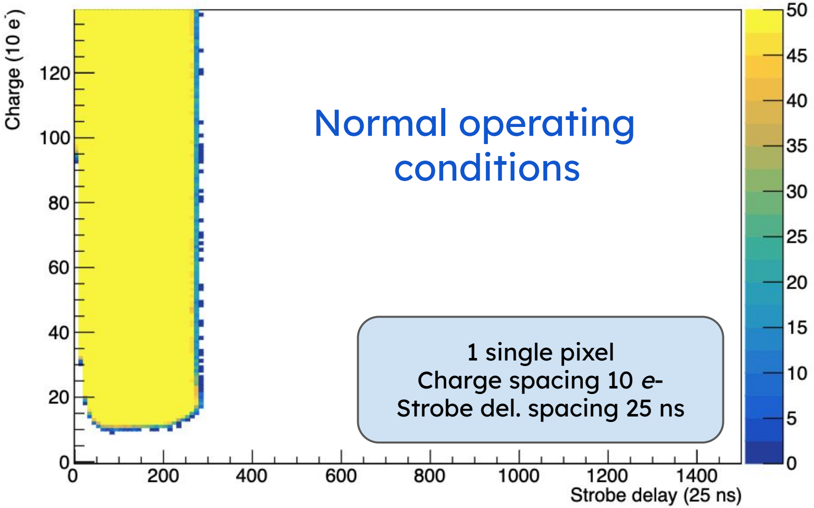

ALICE Performance - Run2 - pp √s = 13 TeV
Min. bias: 0.059 pb-1 (3200 M full-B, 730 M low-B evts)
High Mult. (SPD): 1.1 pb-1 (530 M evts)
High Mult. (V0): 13 pb-1 (1700 M evts)
Di-μ, single μ high-pT: 36 pb-1
Single μ low-pT: 2.5 pb-1
TRD: 2.0 pb-1
E/DCal high: 16 pb-1
E/DCal low: 1.5 pb-1
PHOS: 14 pb-1
Double Gap: 10 pb-1
Integrated luminosity [pb-1]
0
10
20
30
40
50
Jan16
Dec16
Dec17
Jan19

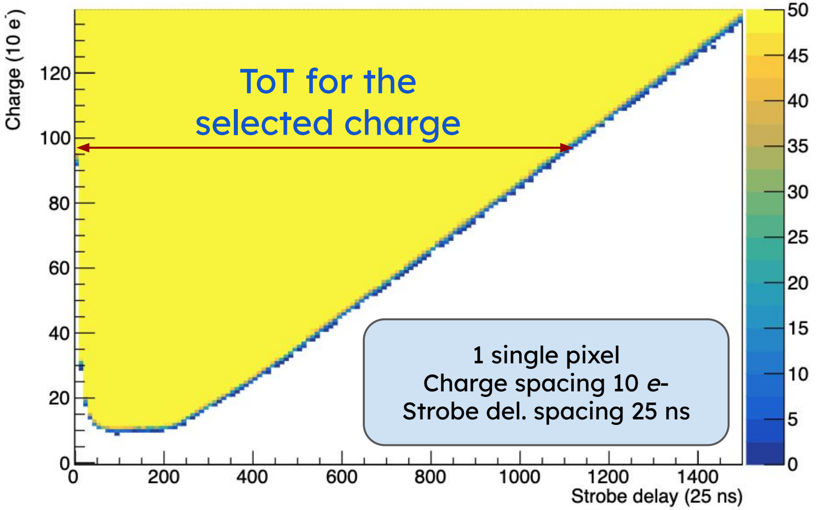

ALICE Performance Run2, PbPb √sNN = 5.02 TeV
Min Bias: 315M
Cent. 0-10%: 149M
Mid-cent. 30-50%: 149M
Recorded triggers / 10^6
0
50
100
150
200
250
300
Nov 30, 2015
Dec 10, 2015
Nov 10, 2018
Nov 20, 2018
Nov 30, 2018

ITS Calibration results: Threshold calibration - before and after tuning

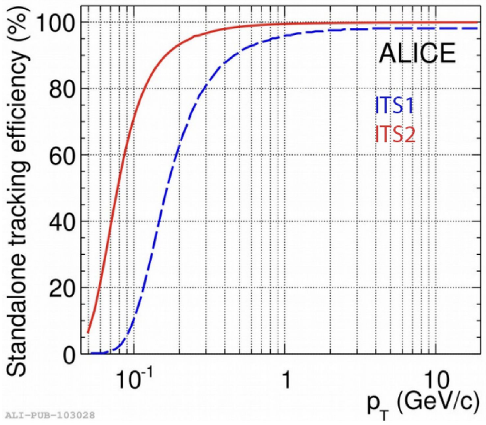





Charge (10 e⁻)
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
Strobe delay (25 ns)
50
45
40
35
30
25
20
15
10
5
0
Normal operating conditions
1 single pixel
Charge spacing 10 e-
Strobe del. spacing 25 ns

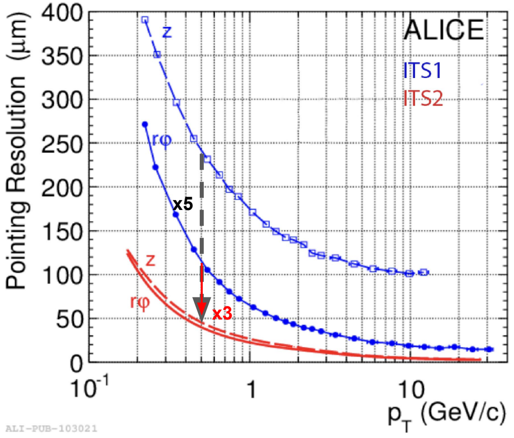

Charge (10 e⁻)
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
Strobe delay (25 ns)
50
45
40
35
30
25
20
15
10
5
0
ToT for the selected charge
1 single pixel
Charge spacing 10 e-
Strobe del. spacing 25 ns

- Tracking efficiency improved



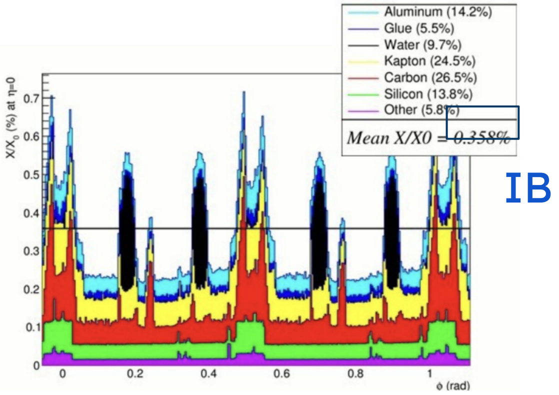
- 60%→90% at p_T=200 Mev/c

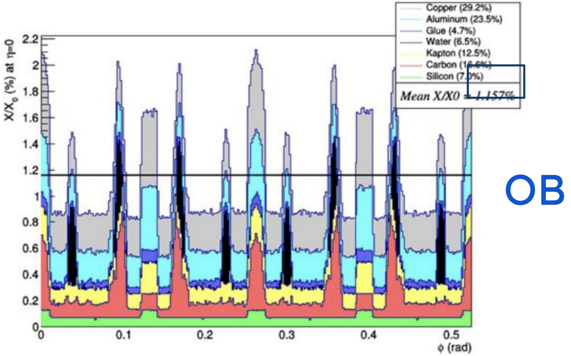
- Pointing resolution improved



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

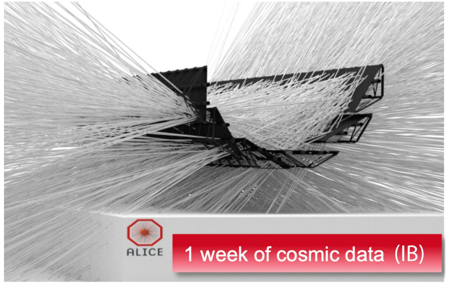
- Material budget: from 1.1%X_0 to:

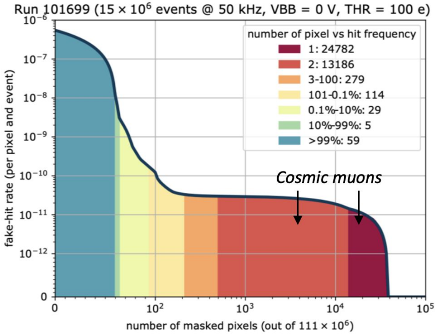




- Reduced beam pipe diameter
  - First layer closer to the Interaction point: 3.9 cm → 2.2 cm
- Increased readout rate
  - 1kHz→100 kHz Pb-Pb and 400 kHz pp
  - More granularity and smaller pixel size wrt old SDD

- 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

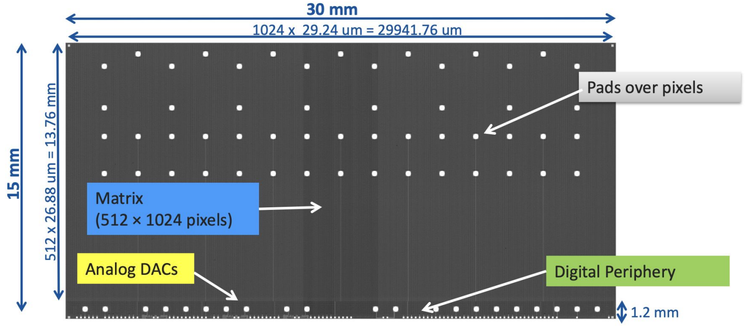




- Installation and commissioning in the ALICE cavern
  - January 2021 → Services installation
  - March 2021 → OB installed
  - May 2021 → IB installed
  - July 2021 → start of ALICE global commissioning with central shifts
  - October 2021 → first pilot collision: pp $\sqrt{s}$ = 900 GeV
  - 5th July 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.

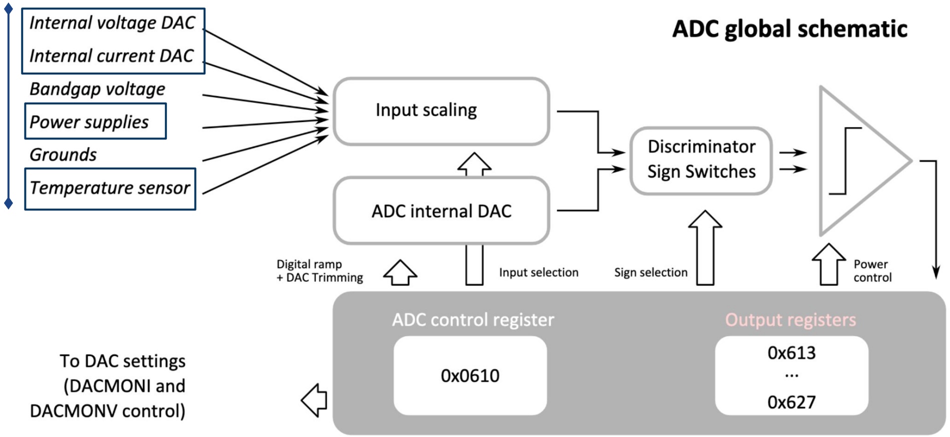
- Analog monitoring pads are available to monitor the outputs of the internal DACs.

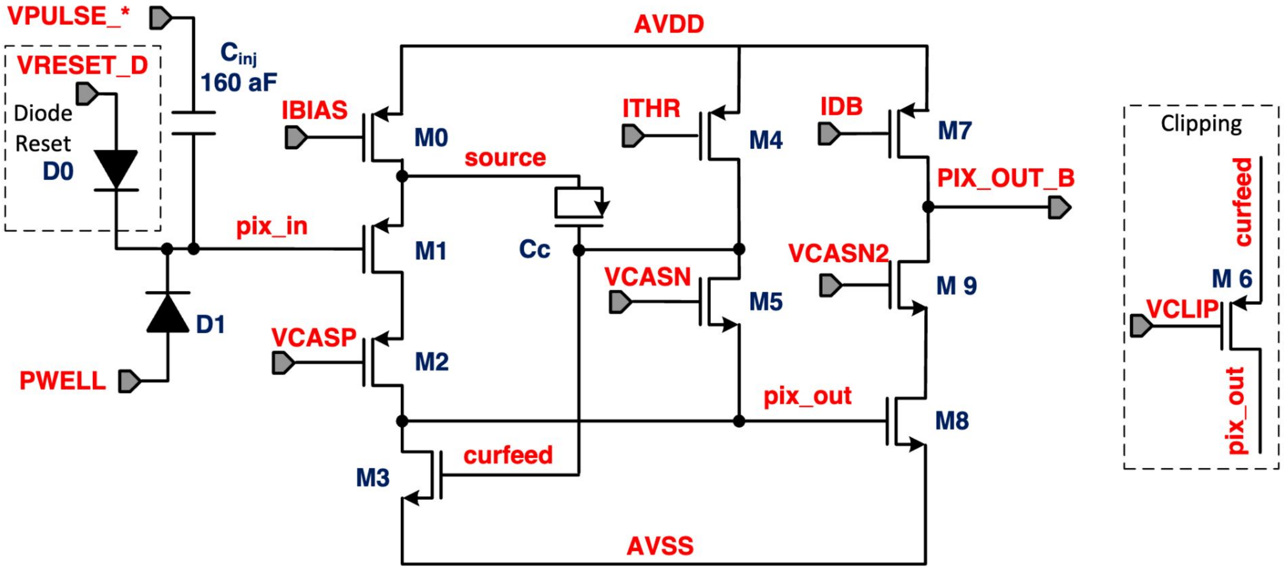


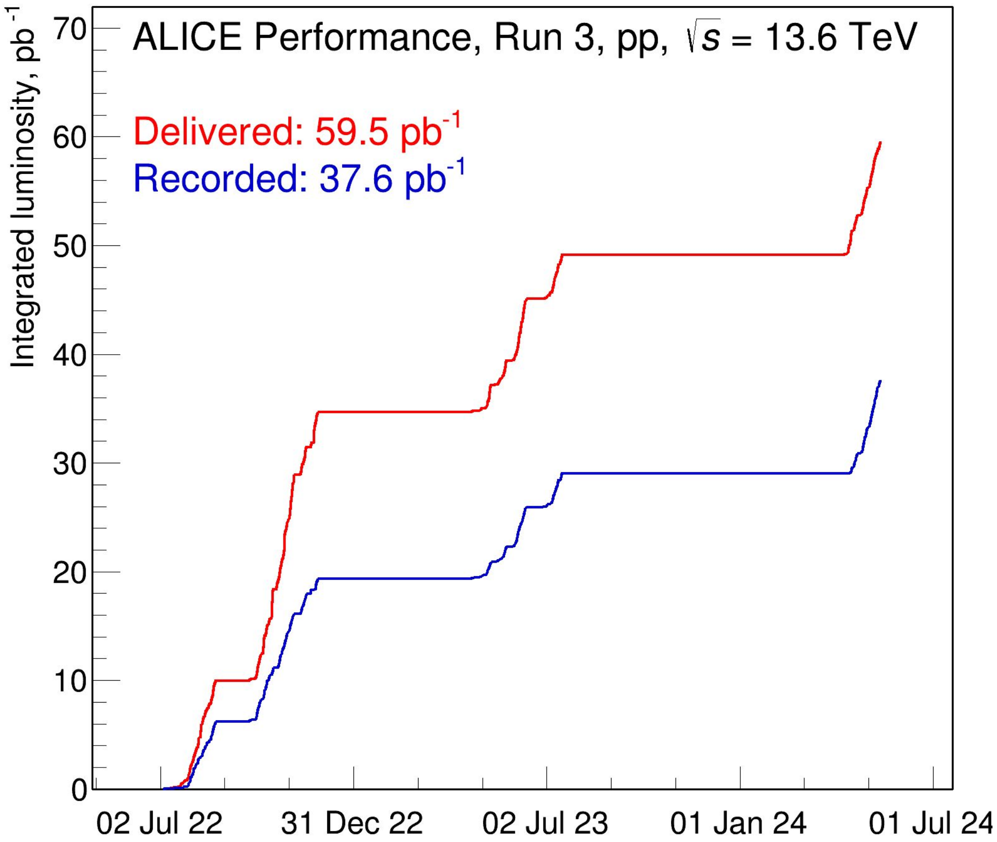
- The analog section of the periphery also contains a 10 bits resolution ADC to monitor quasi-static internal signals

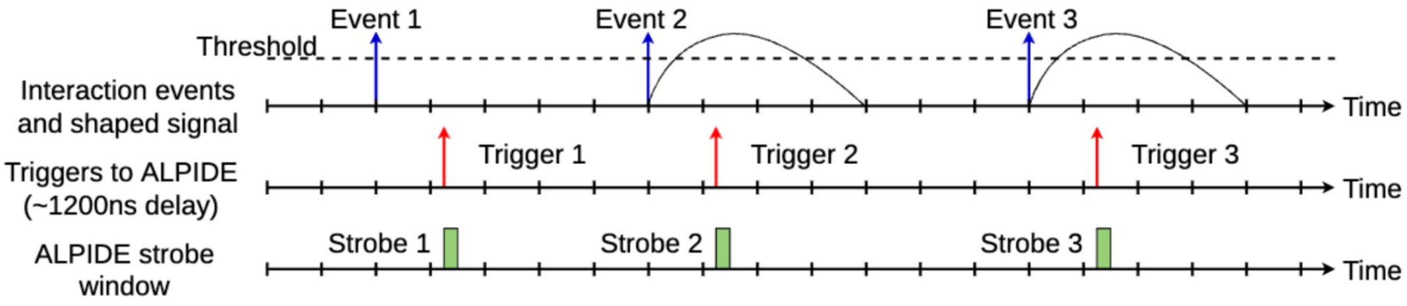
- Voltage DAC: ex. VCASN
- Current DAC: ex. ITHR

Threshold regulation

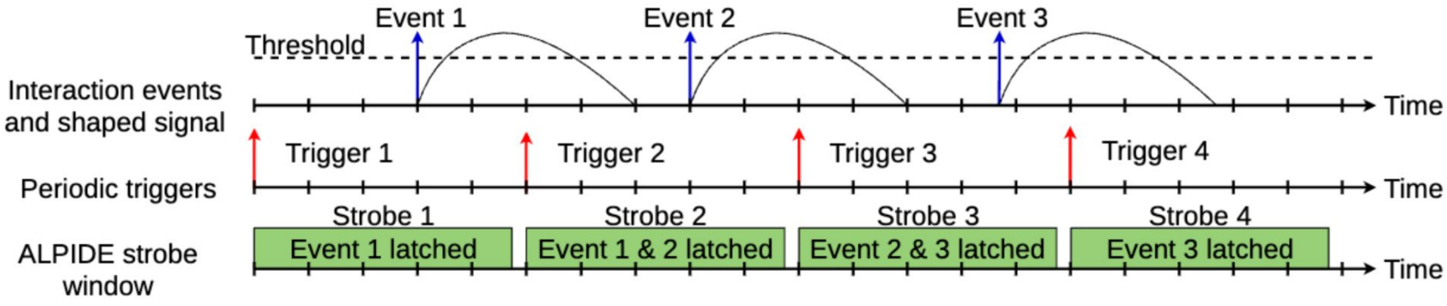



VPULSE_*
VRESET_D
Diode
Reset
D0
Cinj
160 aF
AVDD
IBIAS
M0
source
ITHR
M4
IDB
M7
PIX_OUT_B
pix_in
M1
Cc
VCASN
M5
VCASN2
M 9
D1
VCASP
M2
PWELL
pix_out
M8
curfeed
M3
AVSS
Clipping
curfeed
M 6
VCLIP
pix_out


ALICE Performance, Run 3, pp, $\sqrt{s}$ = 13.6 TeV
Delivered: 59.5 pb^{-1}
Recorded: 37.6 pb^{-1}
Integrated luminosity, pb^{-1}
0
10
20
30
40
50
60
70
02 Jul 22
31 Dec 22
02 Jul 23
01 Jan 24
01 Jul 24



(a) Triggered mode



(b) Continuous mode