Run 3 performance of new hardware in ALICE

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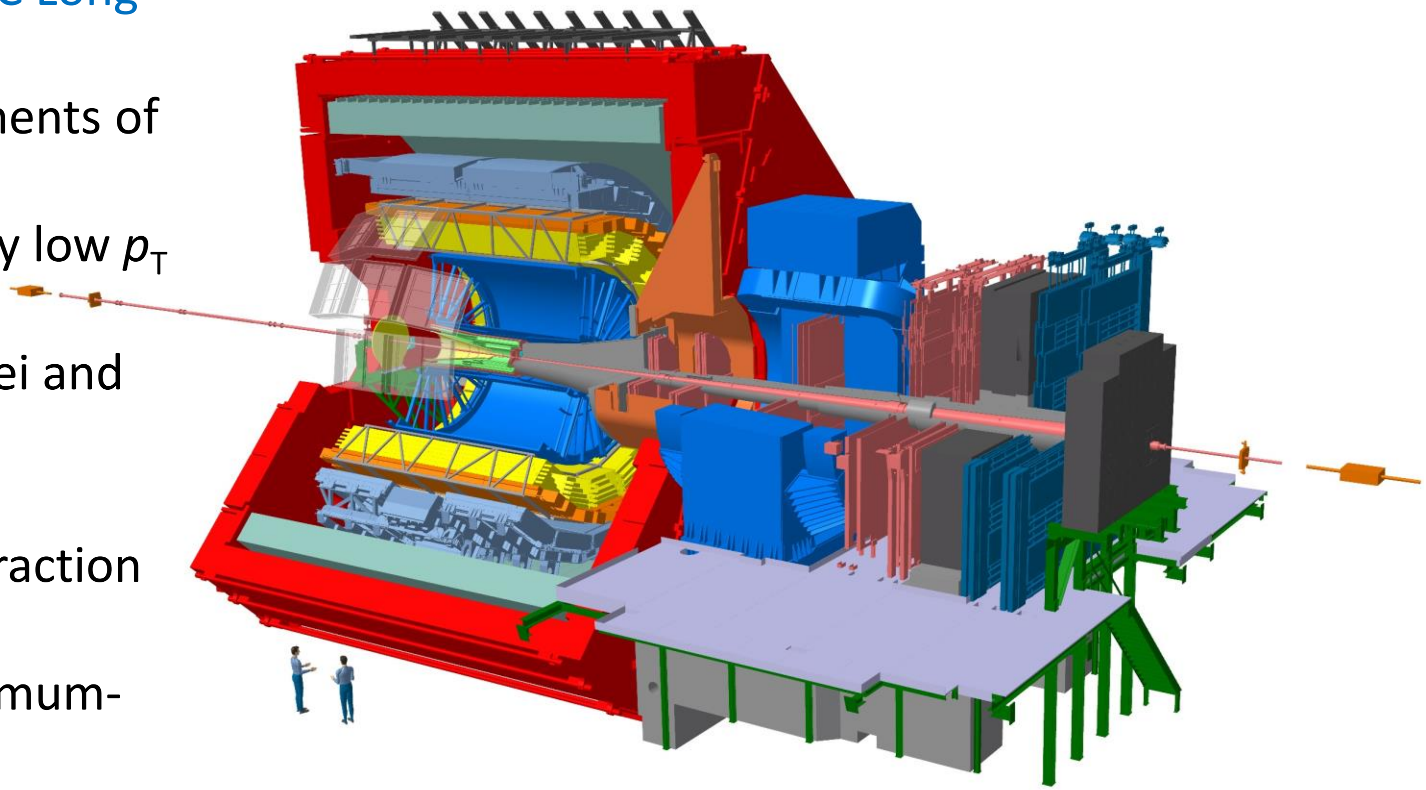
on behalf of the ALICE Collaboration

Large Hadron Collider Physics Conference 2023

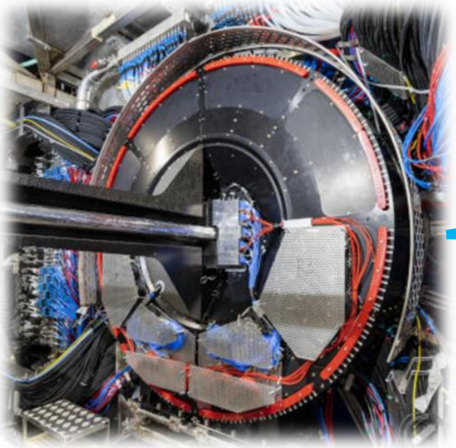
22-26 May 2023, Belgrade, Serbia

ALICE upgrades for LHC Run 3

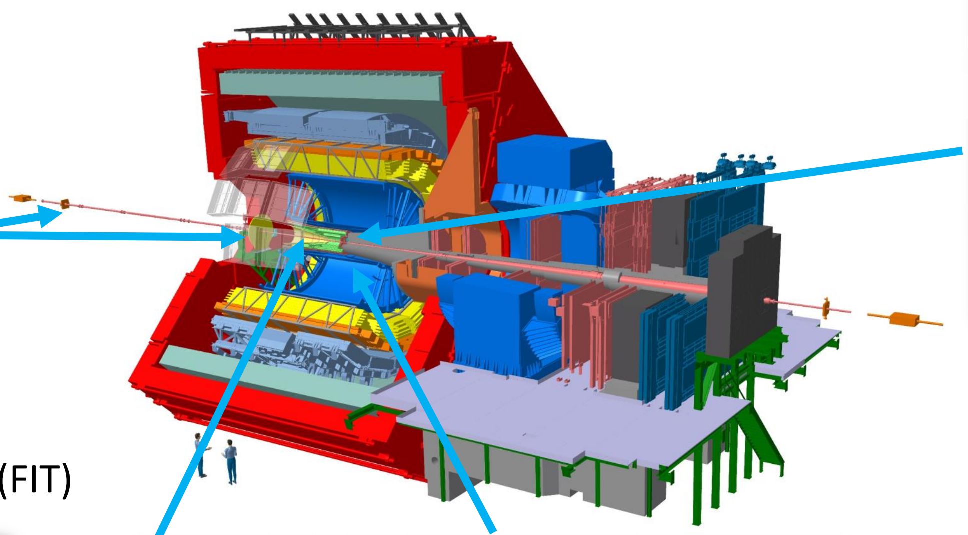
- Major upgrades completed for ALICE during LHC Long Shutdown 2 (2019 - 2021)
- Physics motivation → high-precision measurements of quark-gluon plasma (QGP) properties
  - Heavy-flavor hadrons and quarkonia at very low p_T
  - Vector mesons and low-mass dileptons
  - High-precision measurements of light nuclei and hypernuclei
- Requirements
  - Increase minimum-bias Pb-Pb data → interaction rate of 50 kHz (~1 kHz in Run 2)
  - Collect 13 nb^{-1} in Run 3 and 4 → x100 minimum-bias statistics with respect to Run 1 and 2
  - Improve tracking resolution at low p_T

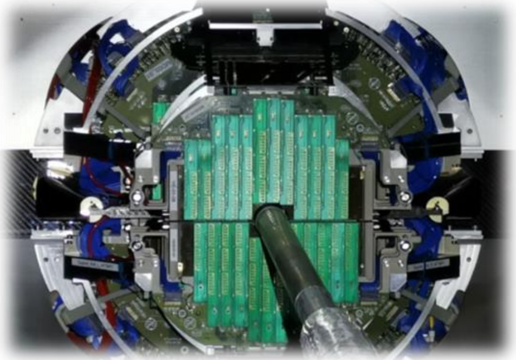


ALICE upgrades for LHC Run 3



New Fast Interaction Trigger (FIT)

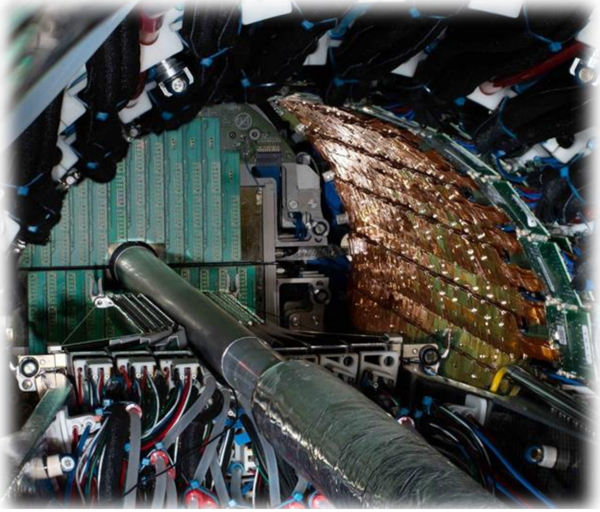




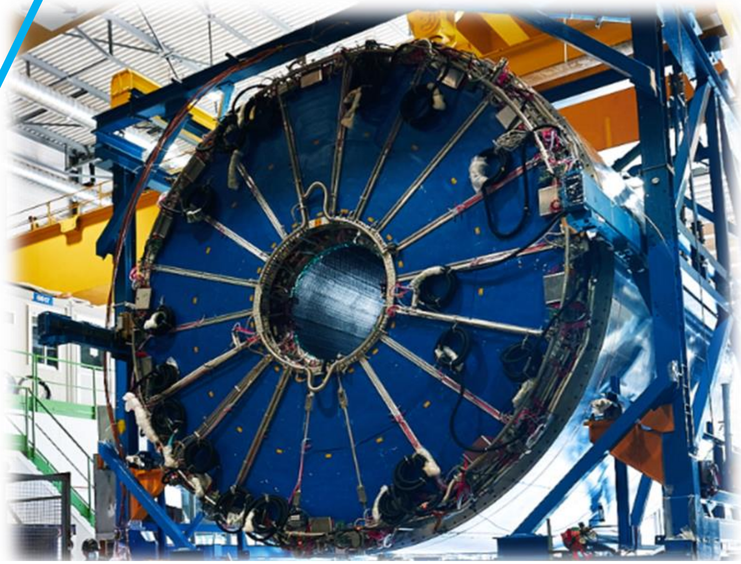
New Muon Forward Tracker (MFT)

New Trigger and Readout systems

New Online/Offline (O^2) system



New Inner Tracking System (ITS2)

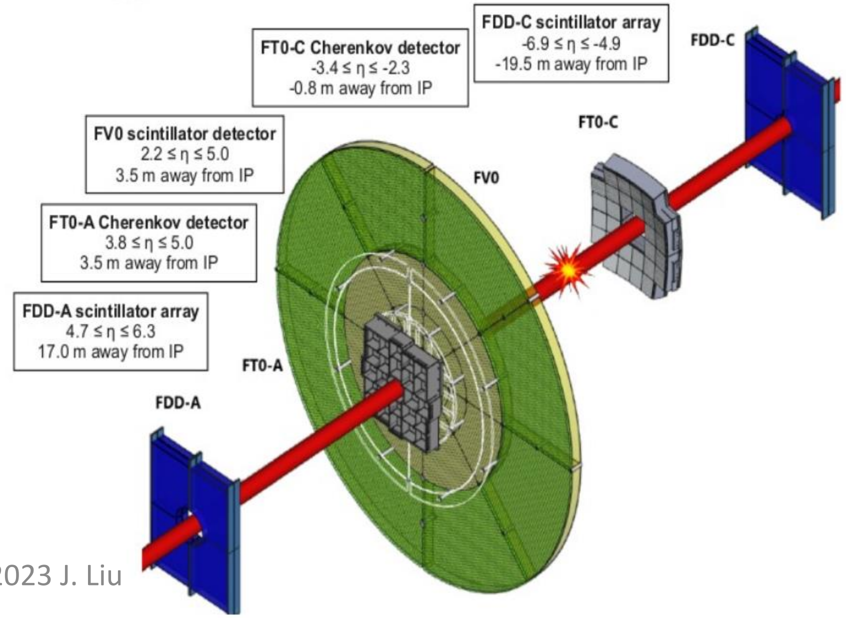


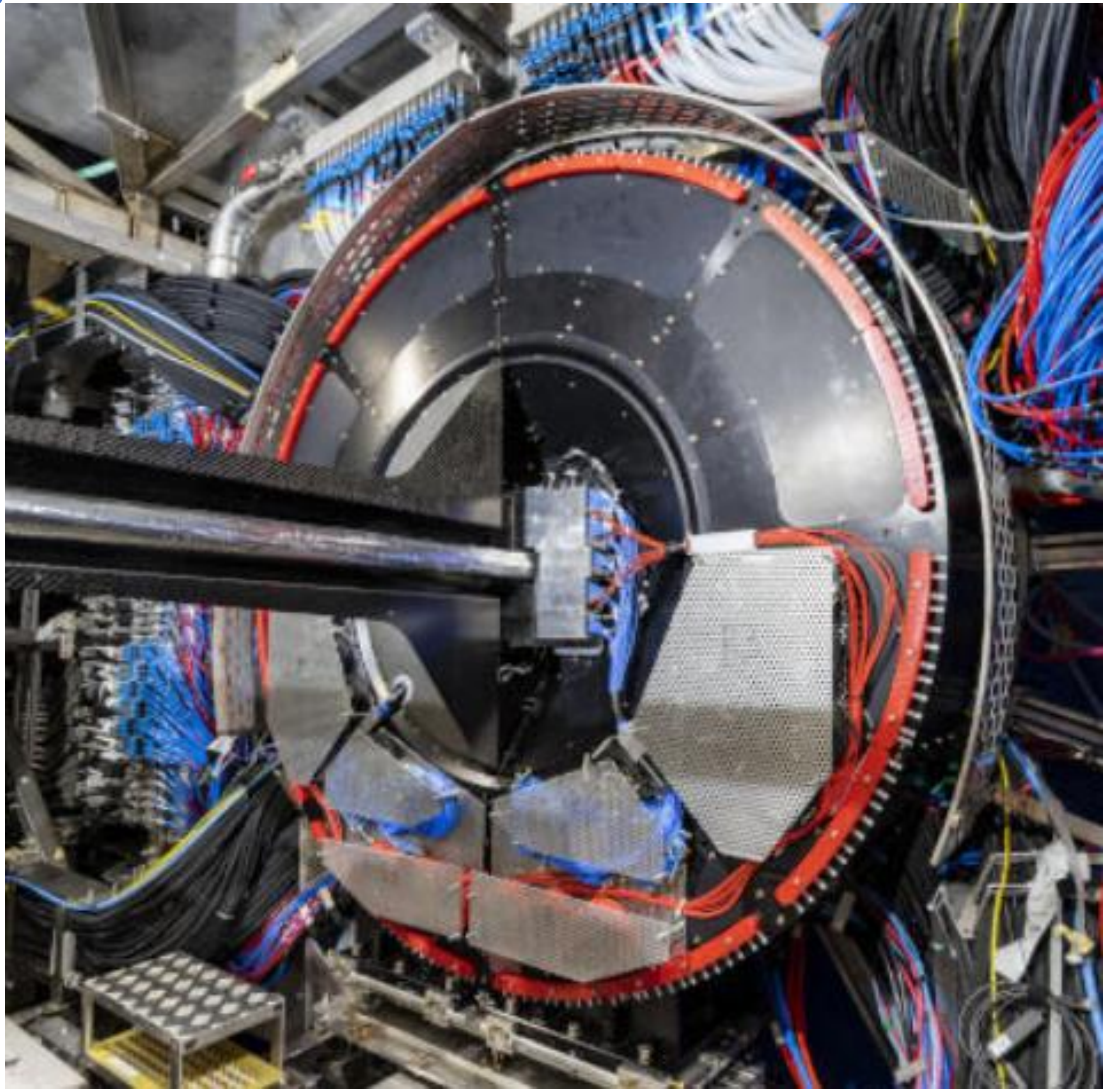
New GEM-based Time Projection Chamber (TPC) readout

Fast Interaction Trigger

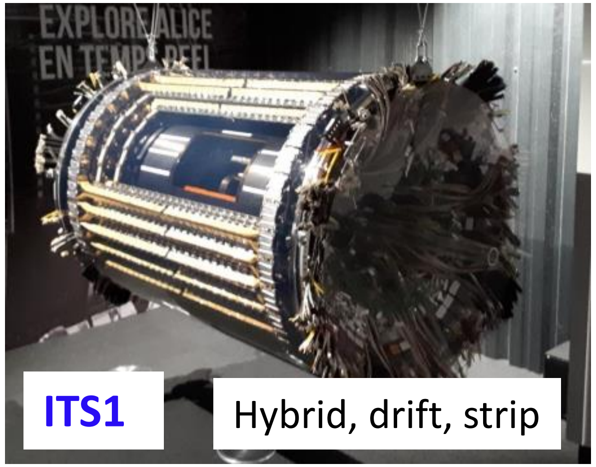
Three new sub-detectors: FT0, FV0 and FDD (Forward Diffractive Detector)

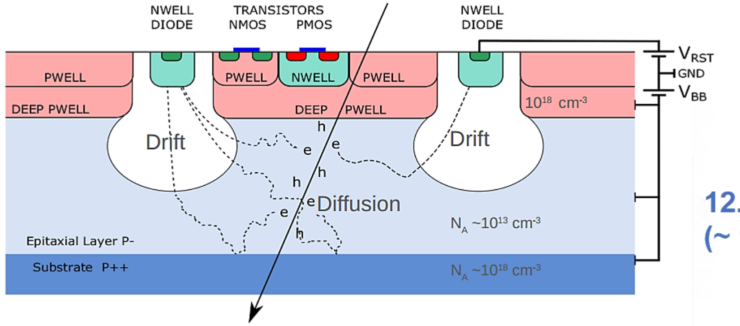
- FT0: 2 arrays of Cherenkov radiators, optically coupled to micro-channel plate photomultiplier tubes (PMTs)
  - Fast minimum-bias trigger generation
  - High precision measurement for collision time and vertex position
  - Luminosity and background monitoring
- FV0: 5 large segmented scintillator rings with PMT readout
  - Background, interaction rate, and luminosity monitoring
  - Multiplicity, centrality, and event plane
- FDD: 2 double layer scintillator arrays with PMT readout
  - Background monitoring
  - Forward vetoes for diffractive studies





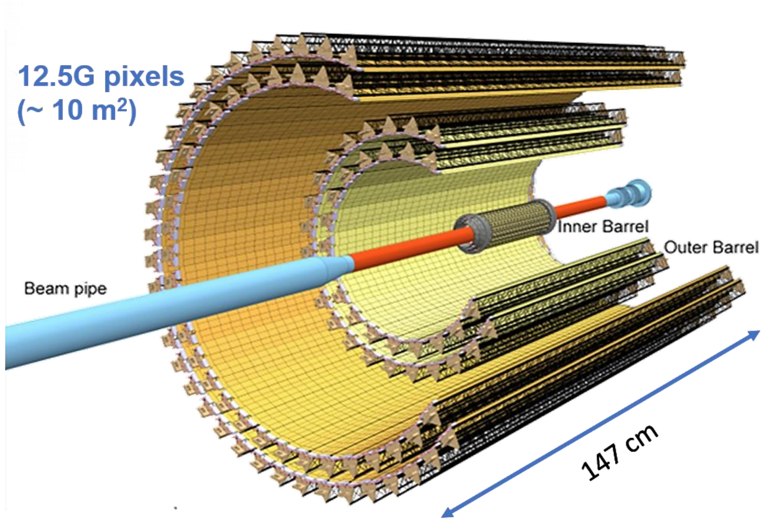
Inner Tracking System





ALPIDE specification:

- TowerJazz 180 nm CiS Process, full CMOS
- Sensor size: 1.5 cm x 3 cm
- Pixel pitch: 27 µm x 29 µm
- Thickness: 50 µm (IB), 100 µm (OB)



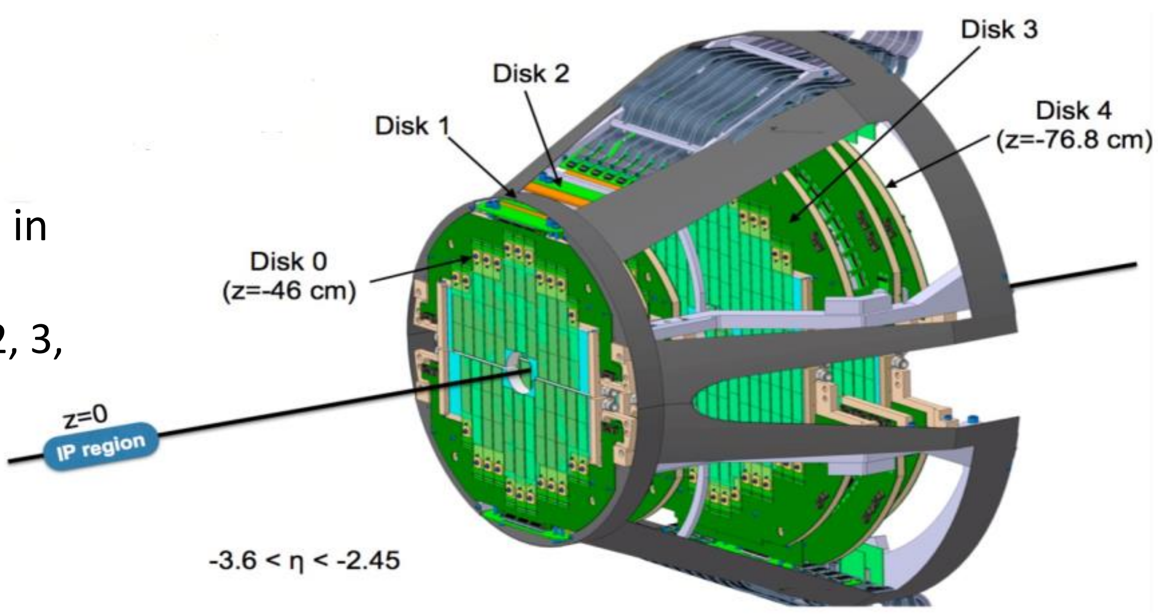
Entirely monolithic active pixel sensor (MAPS) based

- 7 cylinders covering ~10 m^2 area
- ALPIDE sensor with continuous or triggered readout
- Fake-hit rate (FHR) requirement: < 10^{-6} /event/pixel
- Detection efficiency requirement: > 99%
- Radiation tolerance (qualified up to)
  - 270 kRad total ionising dose (TID)
  - 1.7 x10^{13} 1MeV/n_{eq} non-ionising energy loss (NIEL)

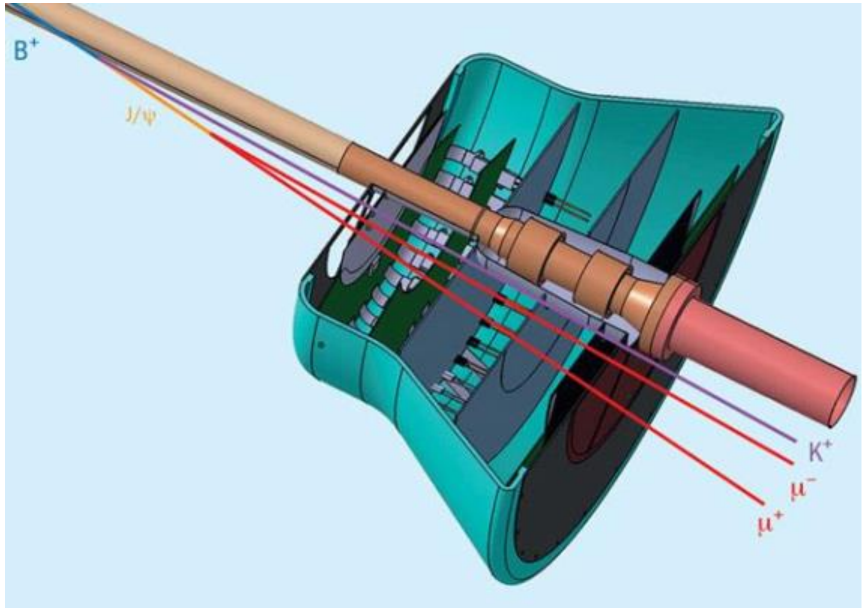
	ITS1	ITS2
Technology	Hybrid, drift, strip	MAPS
Layers	6	7
Spatial resolution	12 µm x 100 µm	5 µm x 5 µm
Radius	39 – 430 mm	22 – 400 mm
Pseudorapidity	$-1 \leq \eta \leq 1$	$-1.4 \leq \eta \leq 1.4$
Material budget	~ 1.14% X_0	~ 0.3% X_0 (inner barrel), ~ 1% X_0 (outer barrel)
Readout capability	1 kHz	>100 kHz (Pb-Pb), >1 MHz (pp)

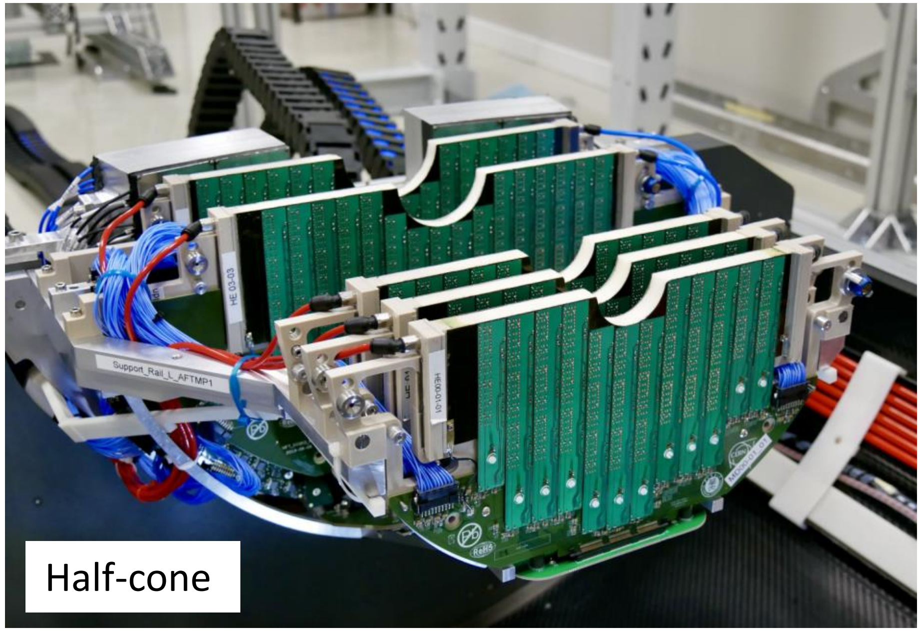
Muon Forward Tracker

- New high-resolution silicon tracking detector installed in front of the Muon Spectrometer
  - 920 silicon pixel sensors (0.4 m^2) on 280 ladders of 2, 3, 4 or 5 sensors each
  - The same sensor as in ITS, 50 μm thickness
  - 10 half-disks: 2 detection planes each
  - Precise secondary vertexing capabilities to muon tracking at forward rapidity



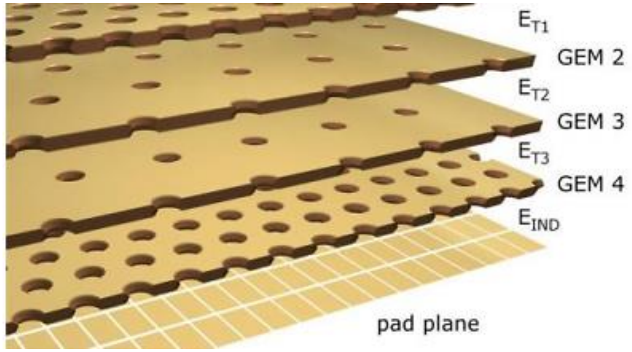
ALICE

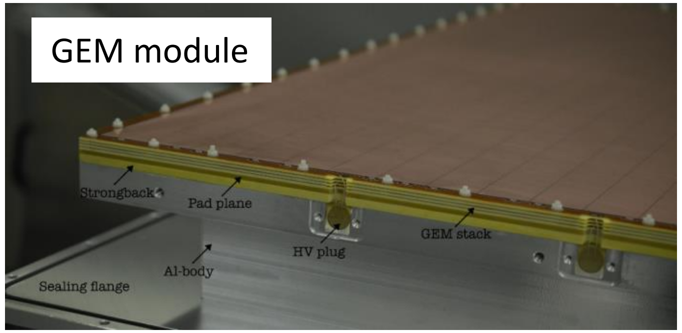


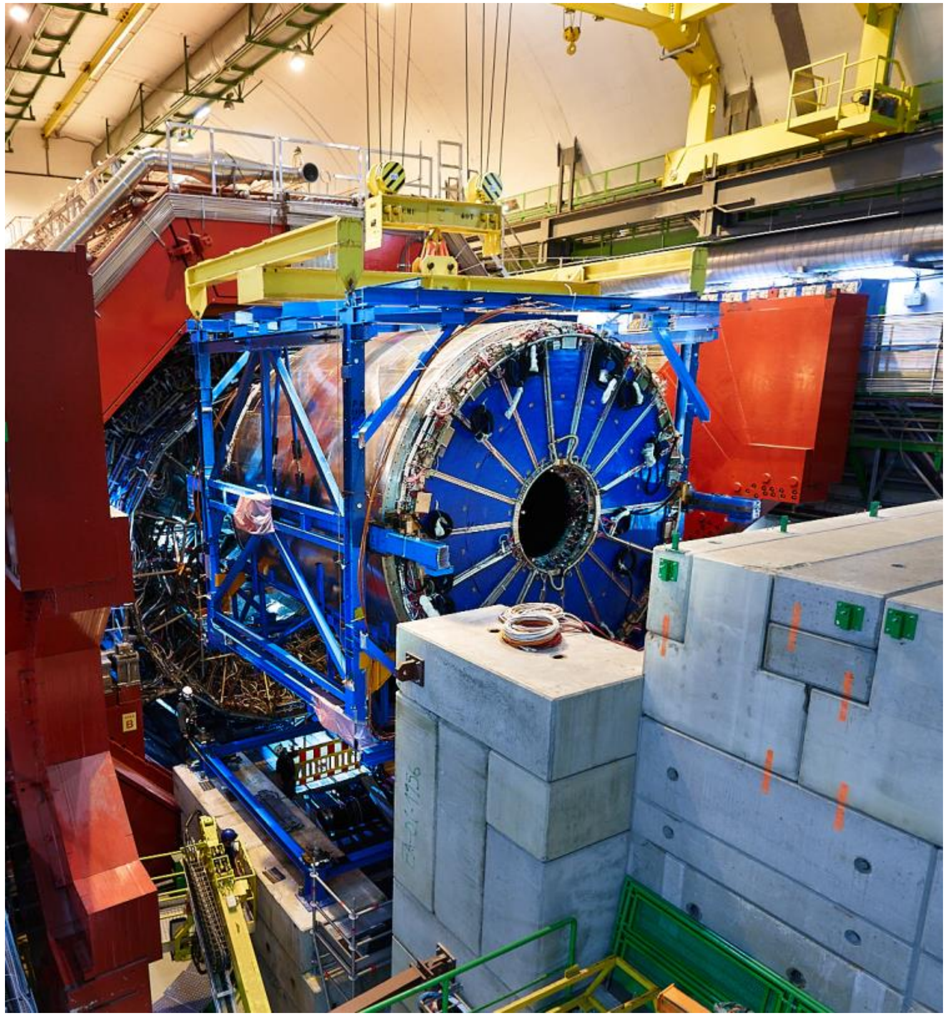


Time Projection Chamber

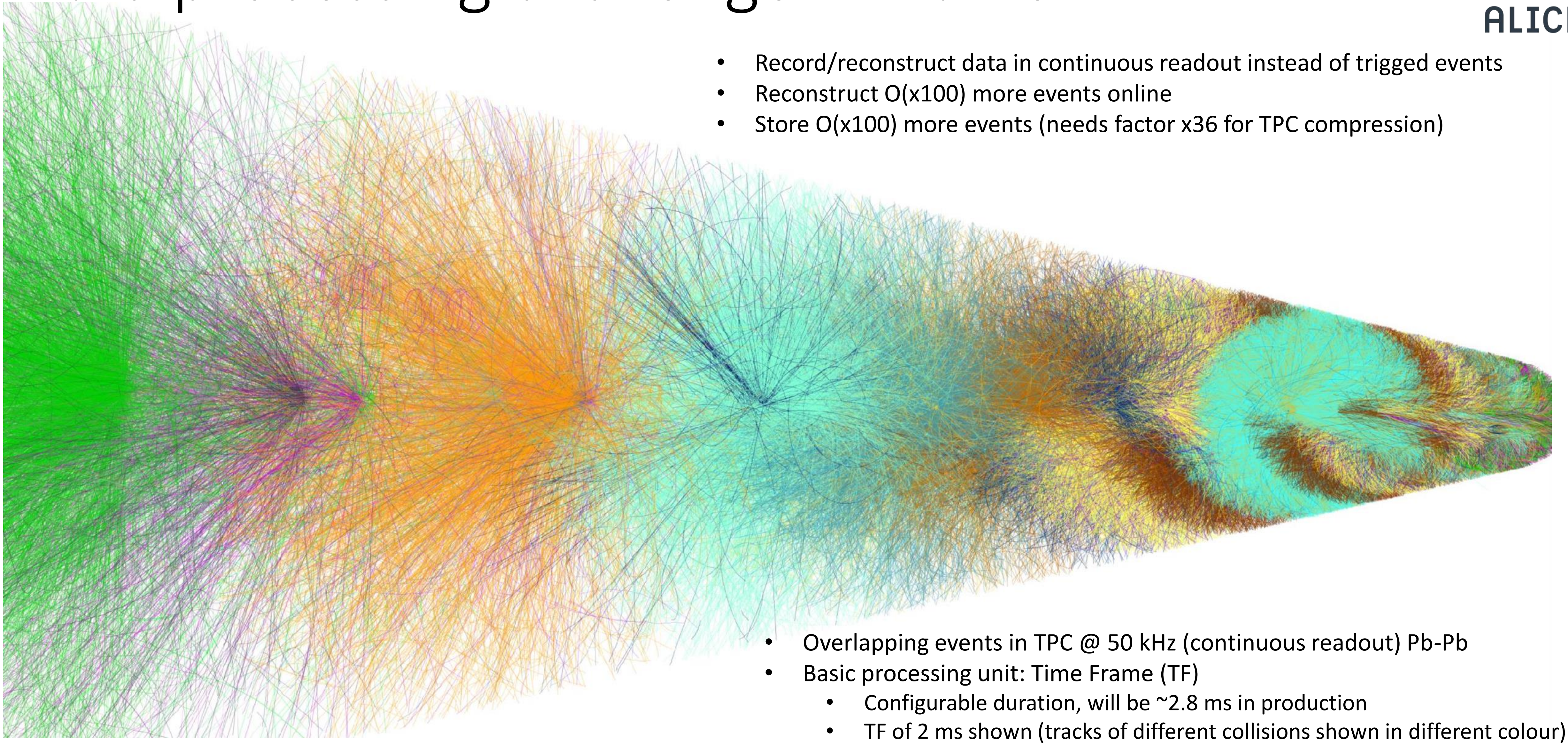
- MWPC (Multi-Wire Proportional Chamber) → GEMs (Gas Electron Multiplier) → removing rate restriction
- 36 inner and outer readout chambers (IROC and OROC)
- Specific configuration of GEM stack to keeping Ion backflow below 1% → preserving PID capabilities
- Pb–Pb collisions at 50 kHz: 5 pile-ups on average → continuous readout







Data processing challenge in Run 3



- Record/reconstruct data in continuous readout instead of trigged events
- Reconstruct O(x100) more events online
- Store O(x100) more events (needs factor x36 for TPC compression)

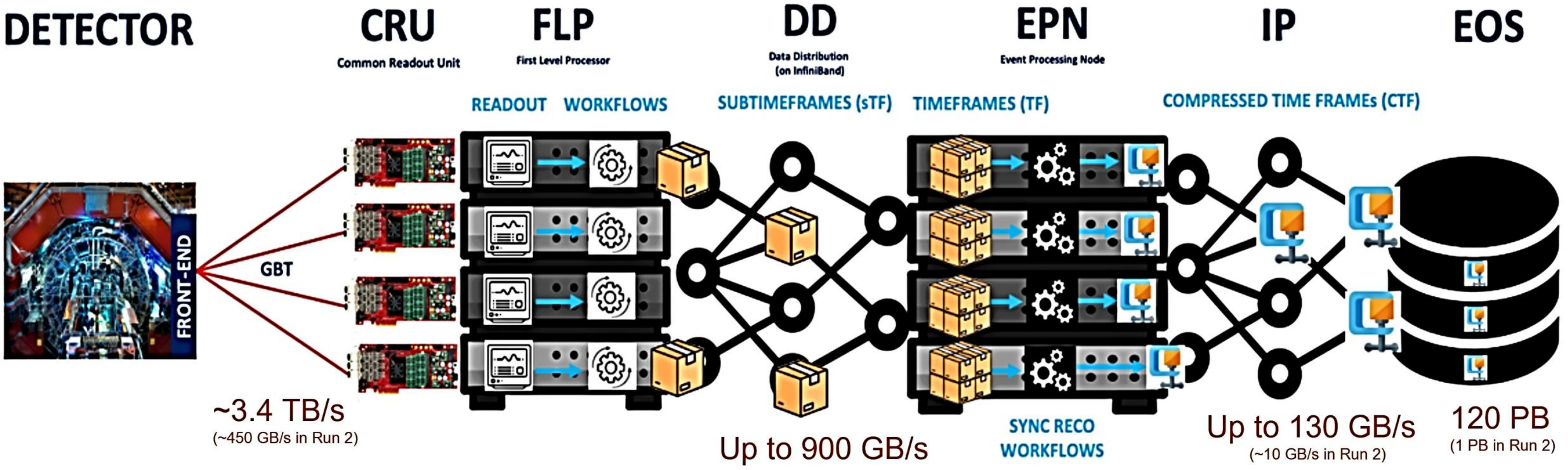
- Overlapping events in TPC @ 50 kHz (continuous readout) Pb-Pb
- Basic processing unit: Time Frame (TF)
  - Configurable duration, will be ~2.8 ms in production
  - TF of 2 ms shown (tracks of different collisions shown in different colour)

Online/Offline (O^2)

Targeting to record large minimum-bias sample

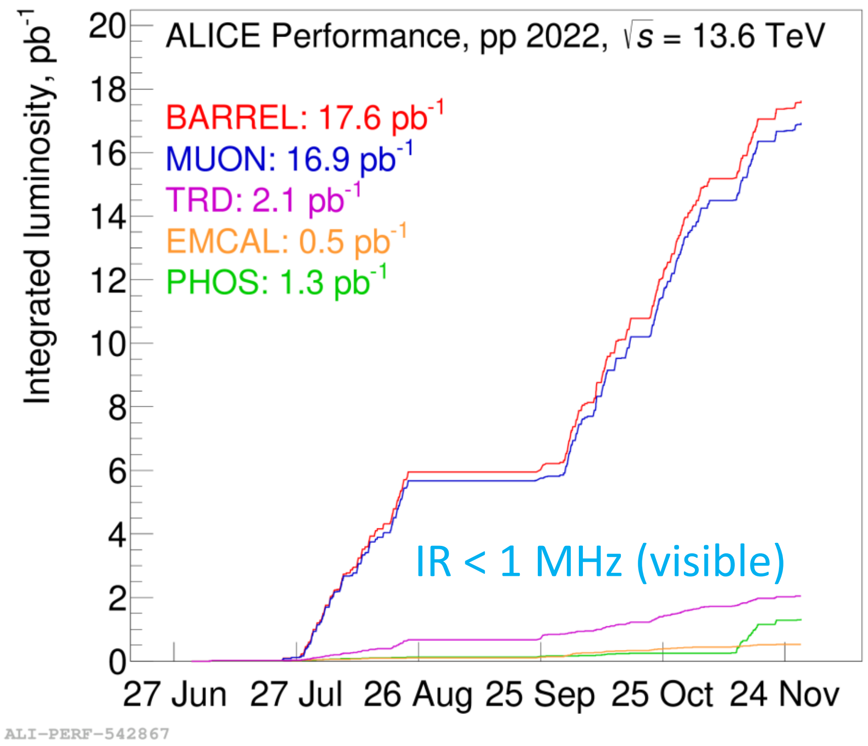
- All collisions stored for main detectors with continuous readout in combination with triggered detectors
- Extreme online data compression (~3.4 TB/s → ~0.1 TB/s) → GPUs to speed up online (and offline) processing

- First level processors (FLP)
  - Readout of detectors (3 TB/s) and raw data processing
  - 200 nodes in total
- Event processing nodes (EPN)
  - Synchronous/asynchronous event reconstruction
  - 280 nodes each with 8 GPUs (extending to 350 nodes)



Data taking and processing from 2022 to 2023

- Regular pp production running at 500 kHz interaction rate (IR) → running stable
- In 2022, 13.8 pb^{-1}, 56 PB of 13.6 TeV pp data @ 500 kHz (visible) collected
  - Asynchronous data processing completed in April → ~1 trillion INEL collisions reconstructed
- Preparation for Pb-Pb data taking in 2023
  - Pilot tests in Nov. 2022 with low rate at 5.36 TeV per nucleon → validation of online reconstruction and calibration
  - Detector readout firmware optimization, adding more FLP and EPN nodes → ~30% processing margin according to experience from 2022 data and MC data replay
  - Regular high-rate tests up to ~4 MHz (visible) with pp collisions
    - 3.5 MHz visible corresponds to 50 kHz Pb-Pb



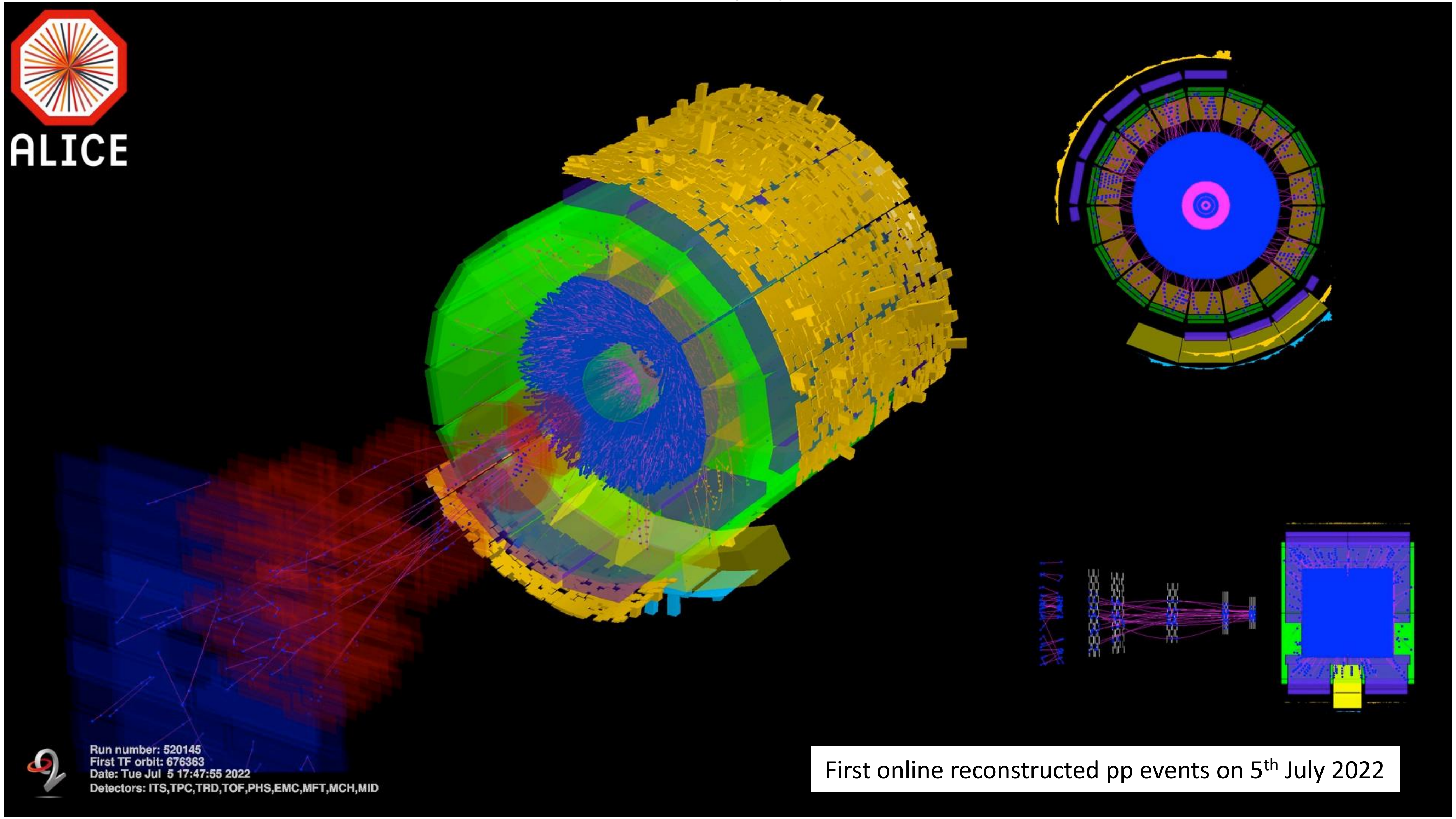
First high-rate test on May 9th, 2023

IR	μ (VTX)	Duration	Data rate
500 kHz	6%	~40 min	210 GB/s
1 MHz	12%	~30 min	360 GB/s
2 MHz	24%	~30 min	620 GB/s
3 MHz	36%	~60 min	856 GB/s
4 MHz	58%	~45 min	1.11 TB/s

2 MHz:
- Full online processing and quality control with 130 EPNs
- Data rate reduced from 1.25 TB/s to 620 GB/s compared with 2022

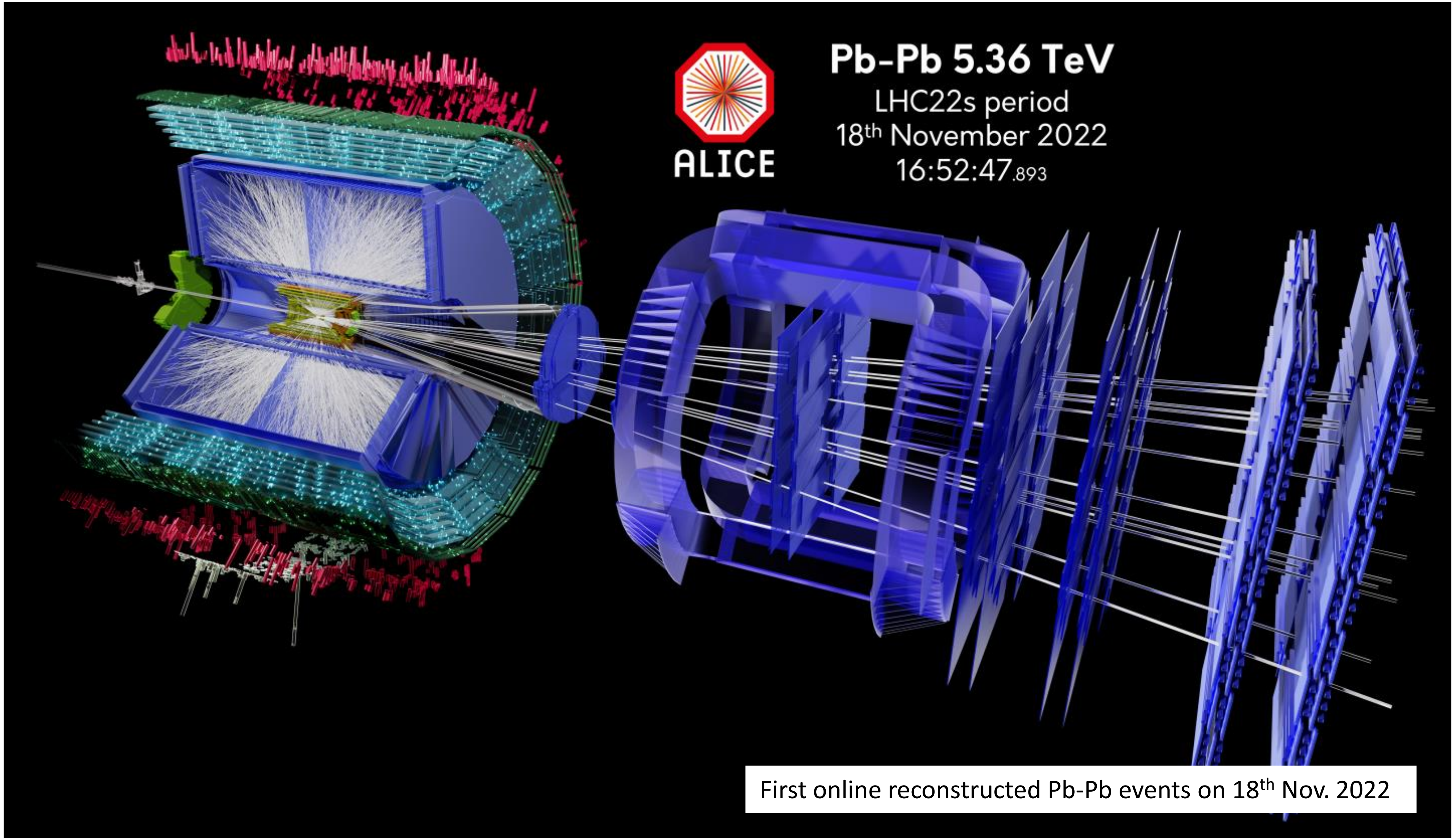
4 MHz:
- Data aggregation without online processing
- Maximum FLP rate < 10 GB/s

Online reconstruction for pp collisions



First online reconstructed pp events on 5th July 2022

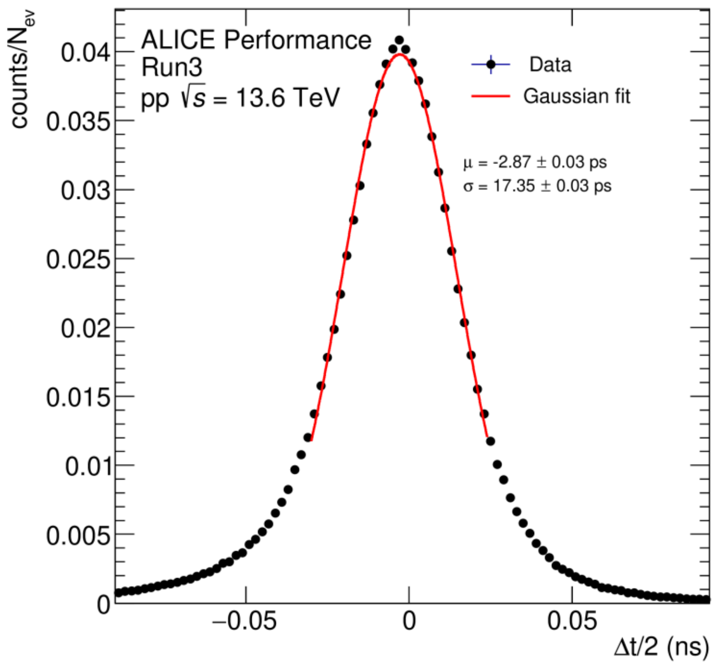
Online reconstruction for Pb-Pb collisions



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

FIT collision time resolution and correlation

- The time resolution: 9 ps for Pb-Pb collisions and 18 ps for pp collisions → expected to be improved with software and calibration optimizations
- Good correlation with the primary vertex reconstructed by the central tracking detectors



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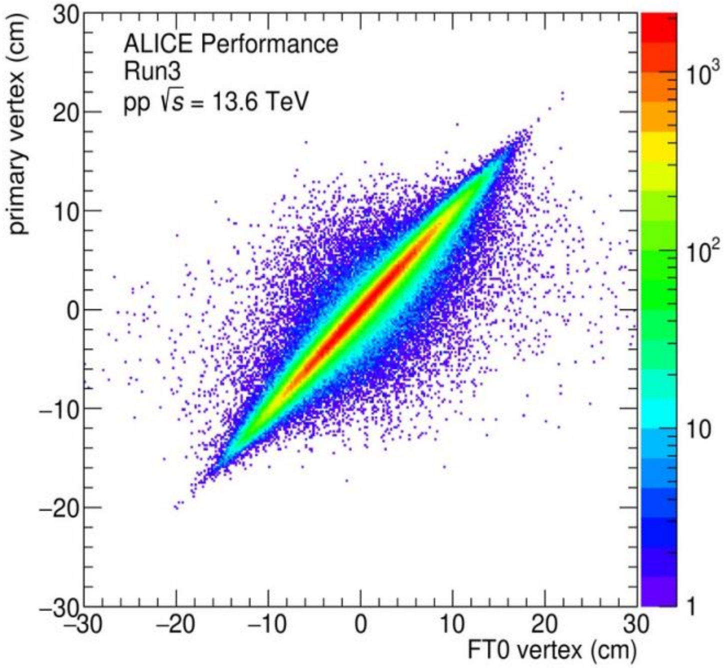

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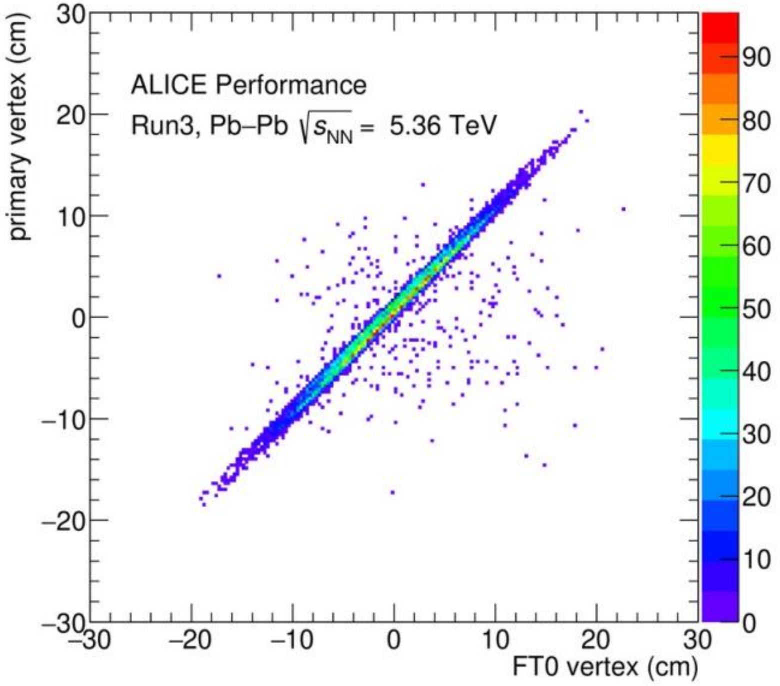

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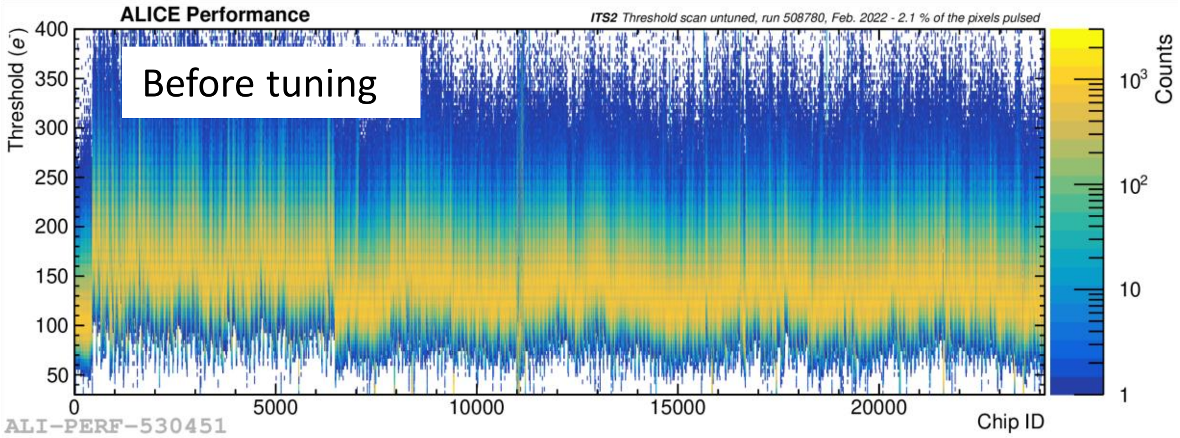
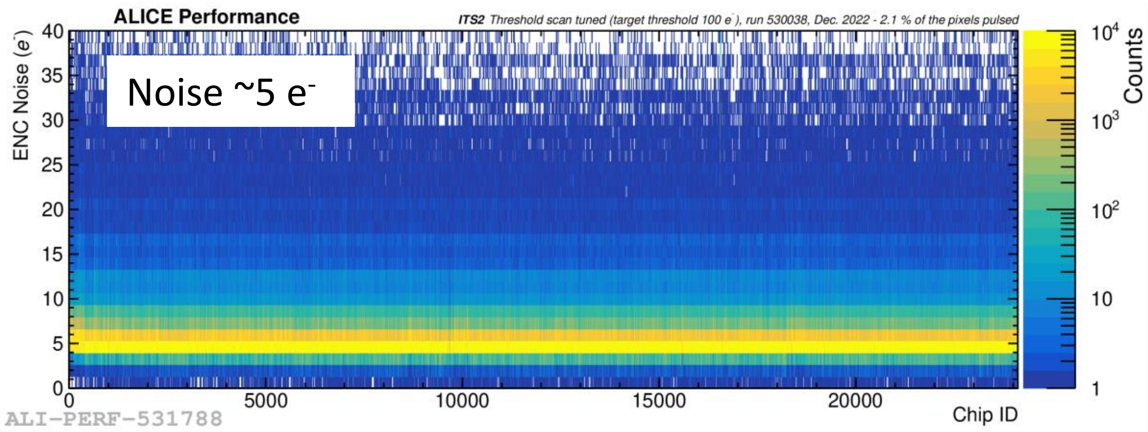
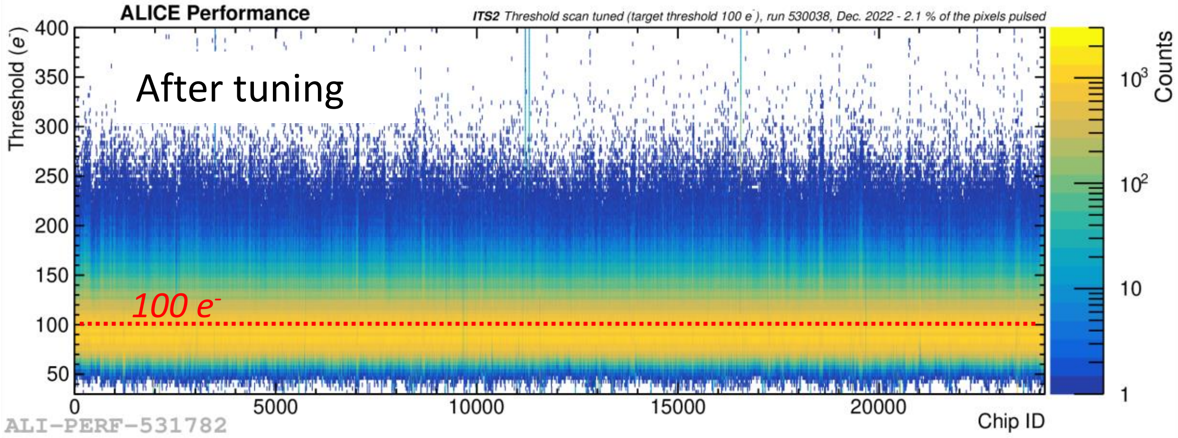
See Mikael Andreas Molander's poster: "The new ALICE Fast Interaction Trigger in LHC Run 3", 23/05 17:00

ITS threshold

- Tuning of analog DACs setting the averaged chip charge threshold
- Online calibration on a representative subset of pixels
- Uniform response across the detector achieved (target to 100 e^-). Noise ~5 e^- (compatible with production measurements)
- Very satisfying threshold stability over time for 24 k chips



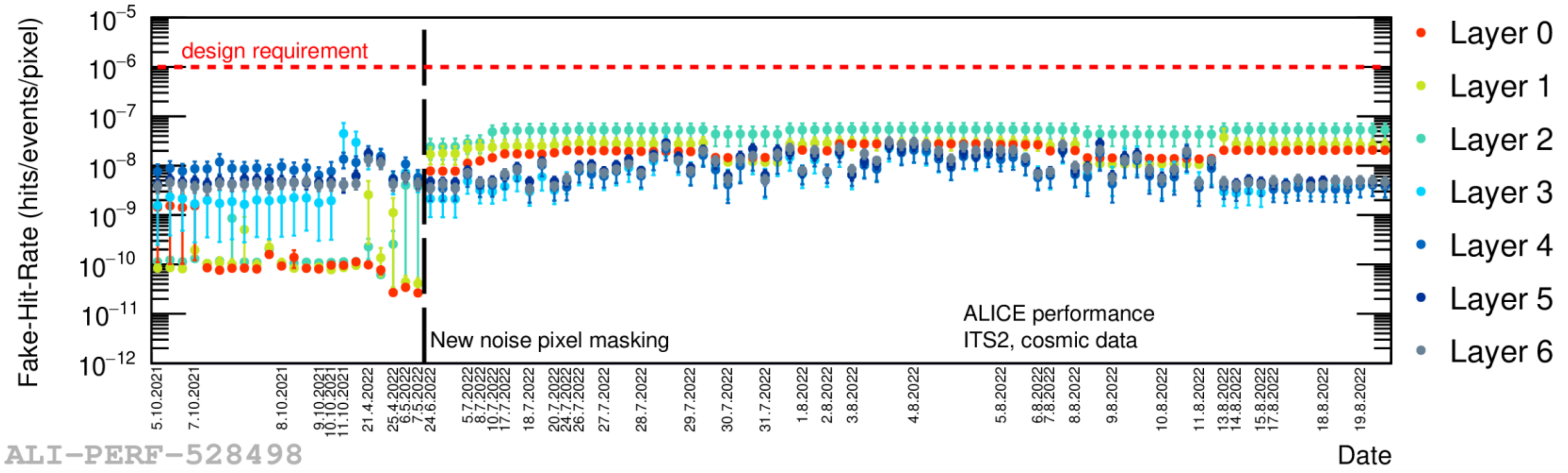


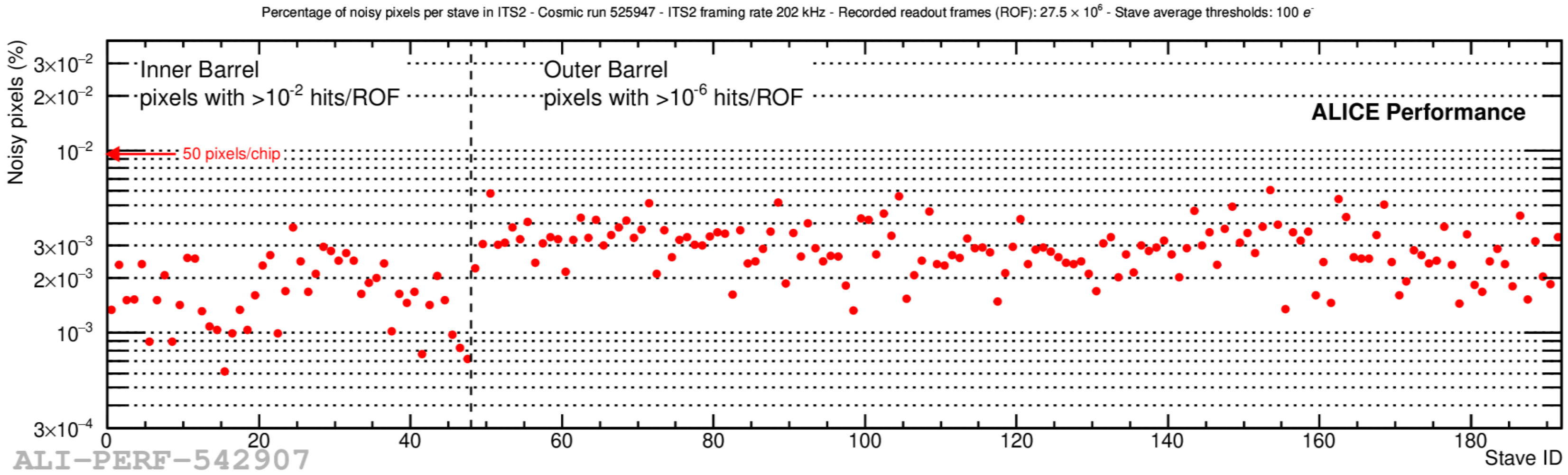


ITS noise

- Possibility to run with static masks already proven during surface commissioning
- OB masking: pixels with 10^{-6} hits/event
- IB masking: almost no mask (10^{-2} hits/event + stuck pixels) → prioritization of efficiency over data rate reduction
- Fraction of masked pixels: 0.15‰
- Stable noisy pixel map → occasionally noise calibration is sufficient

Dead chips on OB from production resulted in a loss of acceptance of 1.5‰



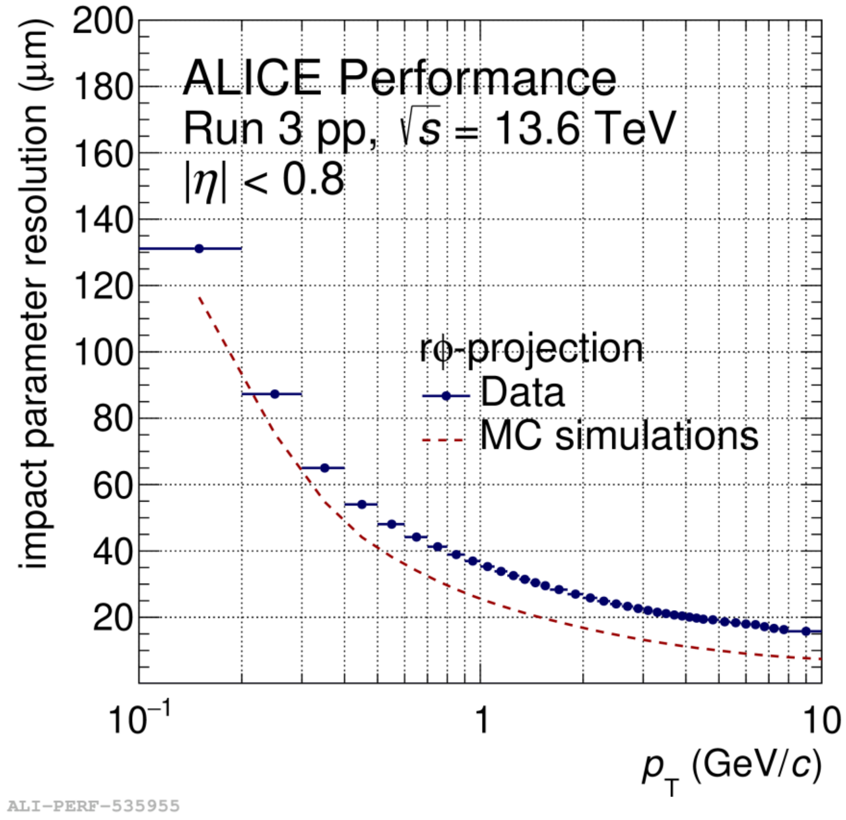


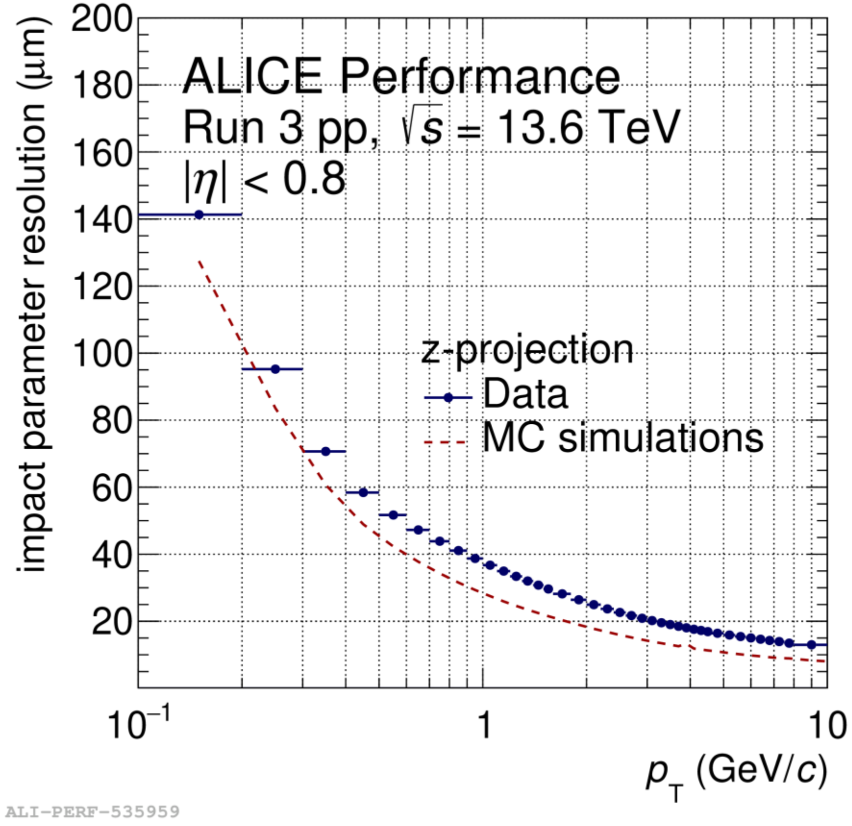
Extremely quiet detector

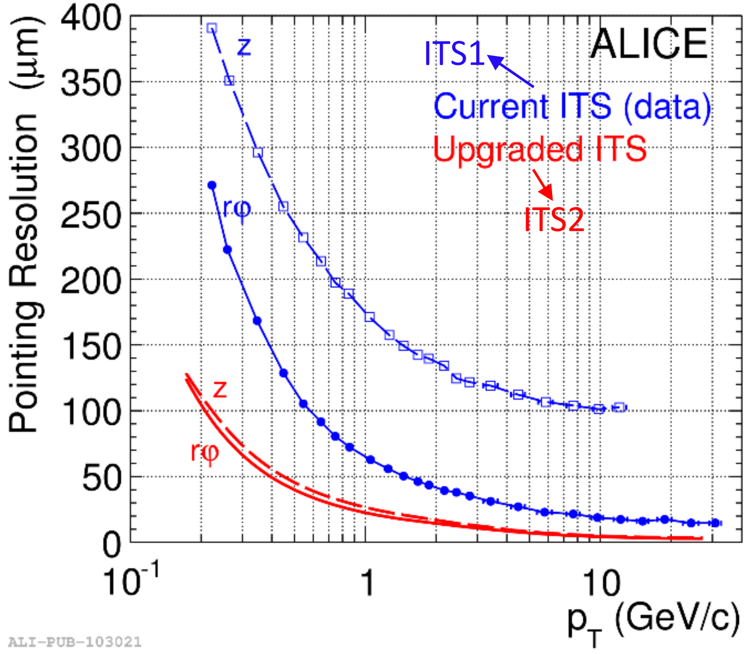
IB: Inner Barrel
OB: Outer Barrel

Impact parameter resolution

- Significant improved pointing resolution with new ITS2 alignment → comparable to simulations
  - x3 and x6 improvement in rφ and z at low p_T
- Remaining difference with respect to simulation attributed to residual misalignment



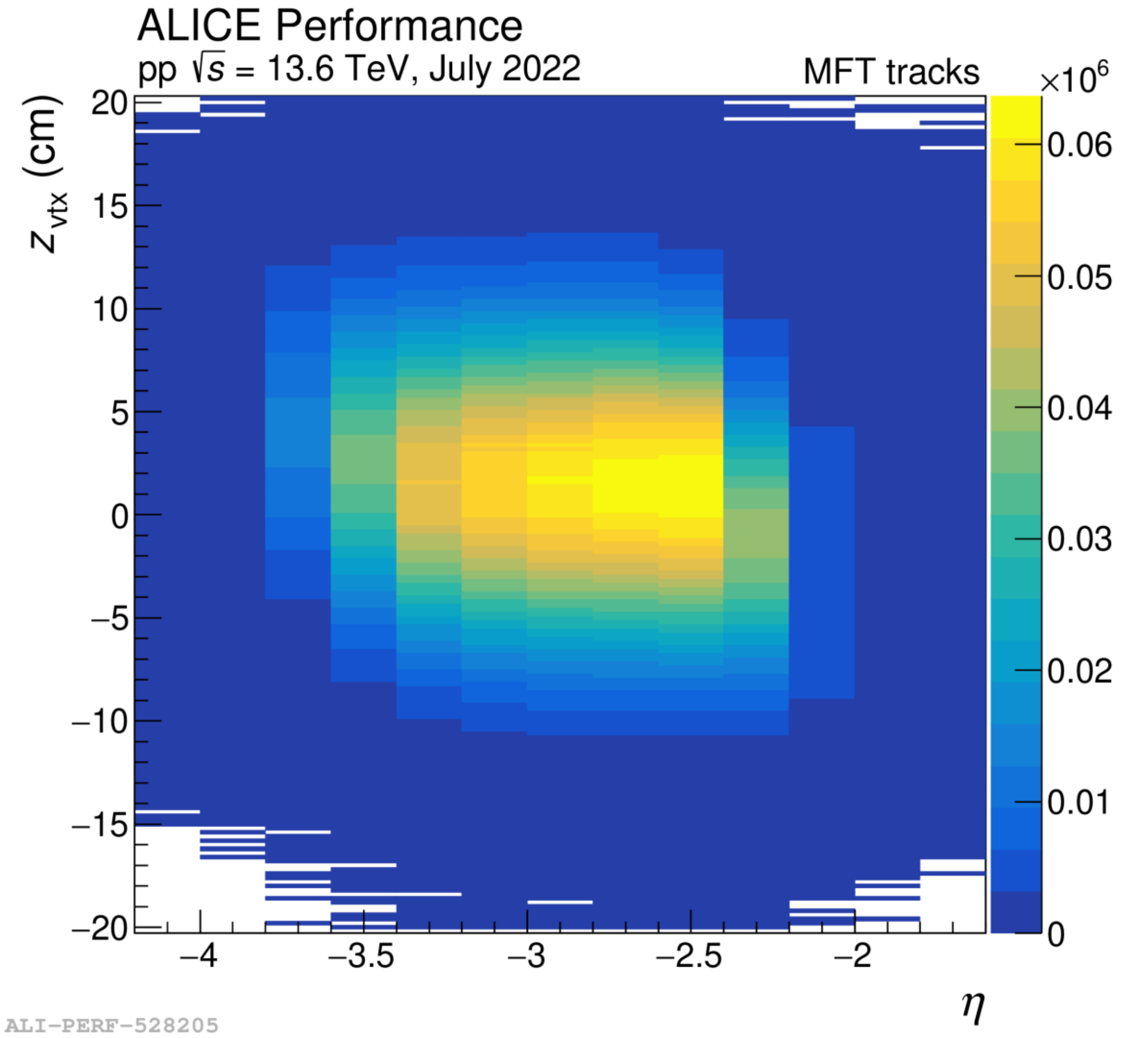




See Mattia Faggin's talk: "Tracking and vertexing", 25/05 12:24

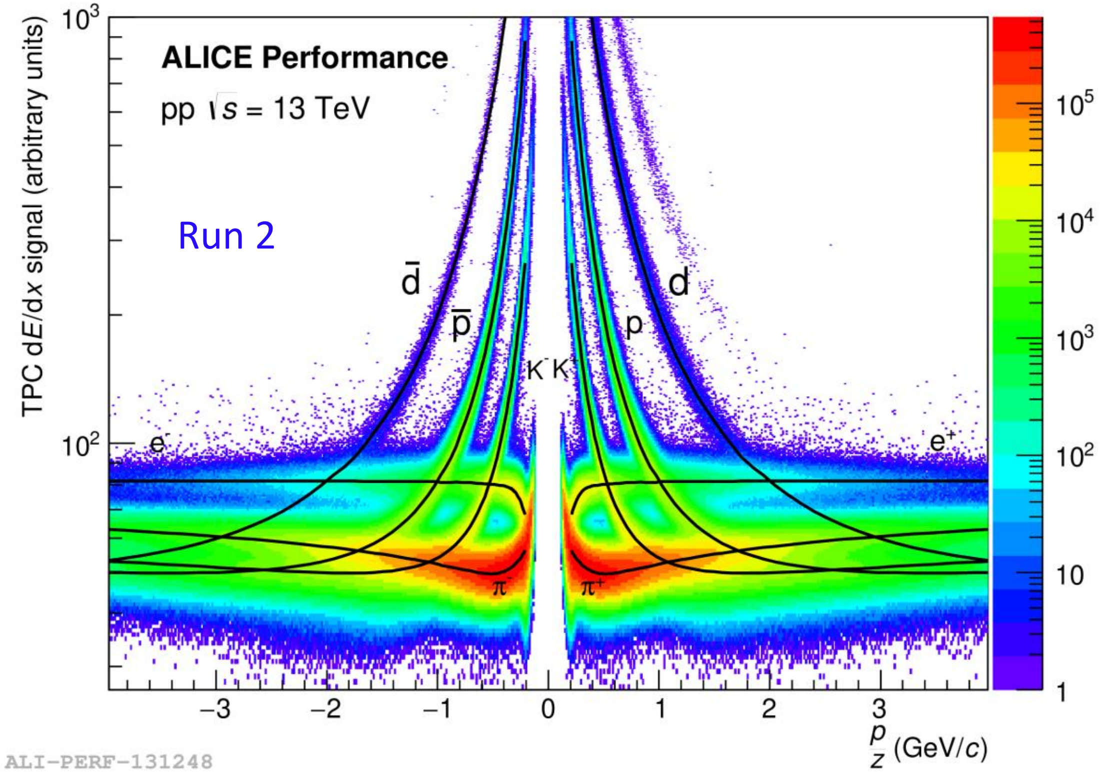
MFT noise and tracking

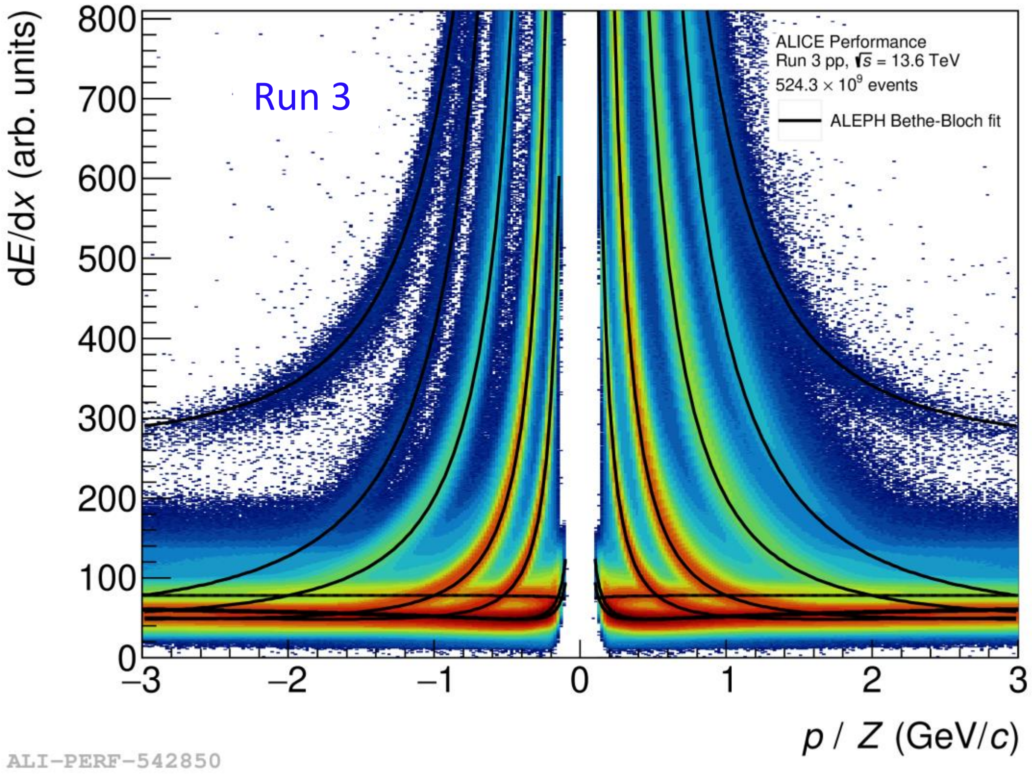
- Extremely low noise by masking only few pixels → fake-hit rate < 10^{-10}/event/pixel
- Good tracking performance of the new Muon Forward Tracker in pp and Pb-Pb collisions



TPC PID

- GEM-based TPC achieved comparable PID performance with respect to the MWPC
- Improvements on calibration and reconstruction in progress

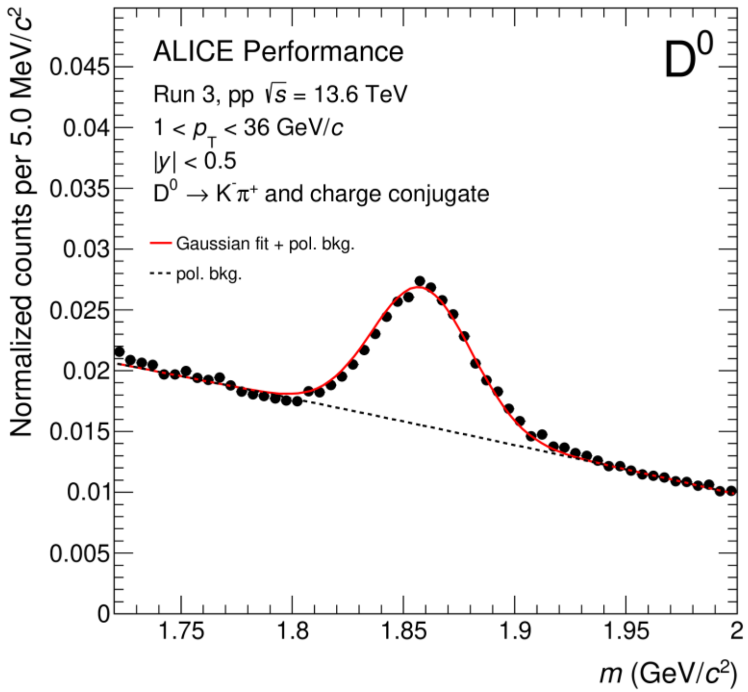




See Christian Sonnabend's talk: "Particle identification", 25/05 12:42

First look at Run 3 data

- Good reconstruction and improved signal/background ratio observed with latest tunings → further optimizations ongoing, significant improvements expected with updated TPC calibrations



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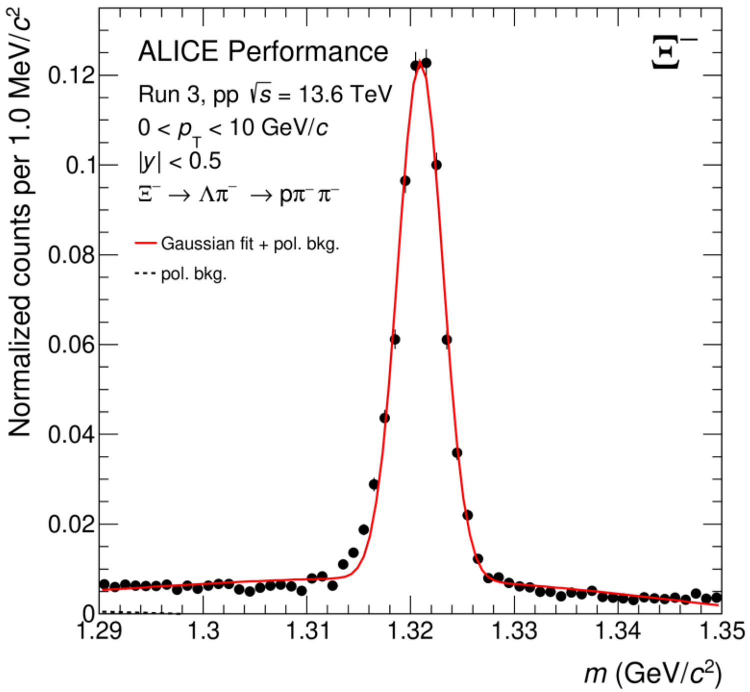

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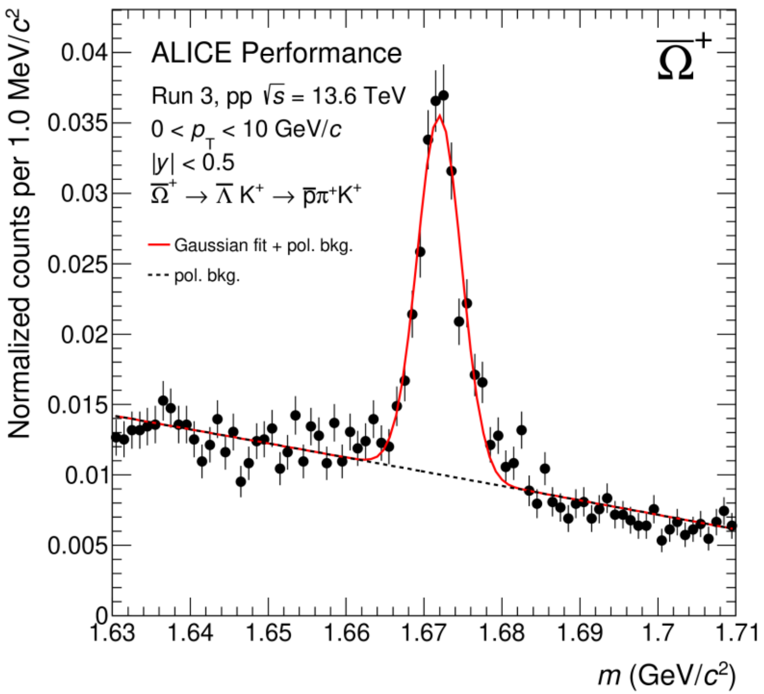

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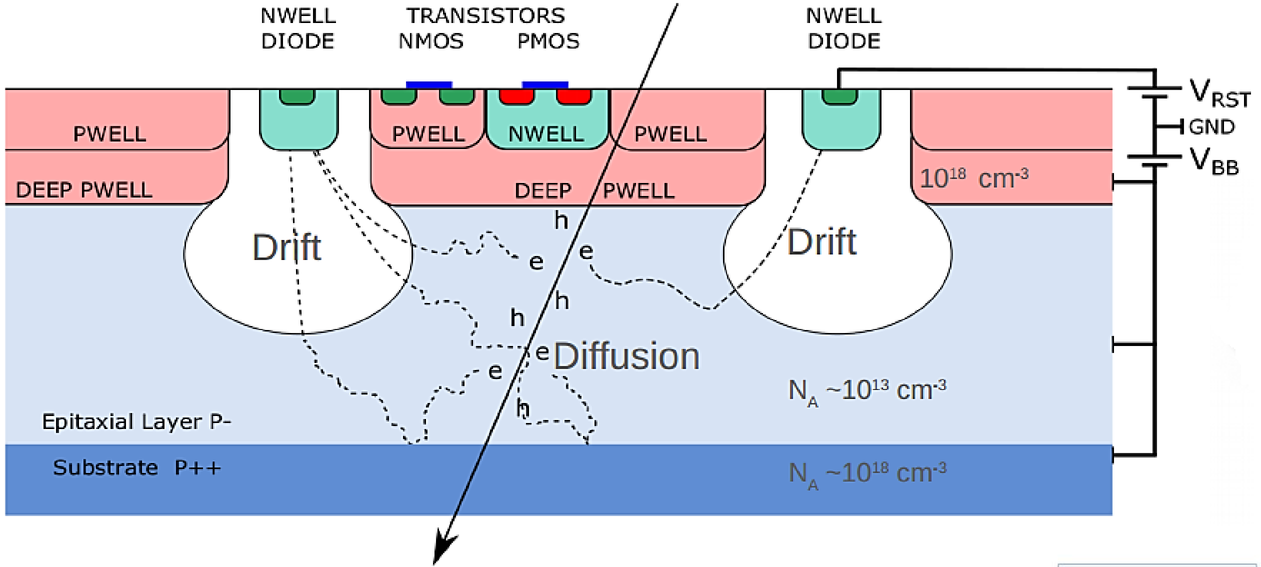
Summary

- Major upgrades for ALICE completed in 2021 during the LHC Long Shutdown 2
- The first phase of data taking in Run 3 successful with significantly enhanced capabilities
- Upgraded detectors, readout/trigger systems and O2 show excellent performance
- Data in 2022 reconstructed and physics analysis ongoing
- Resumed production data taking with pp collisions in May 2023
- Huge effort of performance tuning/improvements ongoing and looking forward to the first Pb-Pb collisions in October 2023!

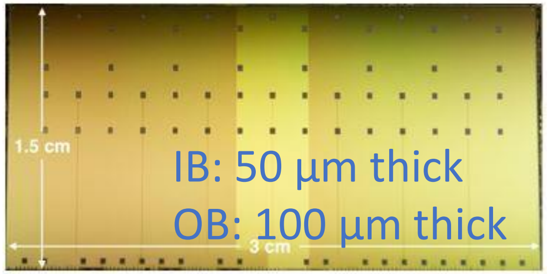
Backup

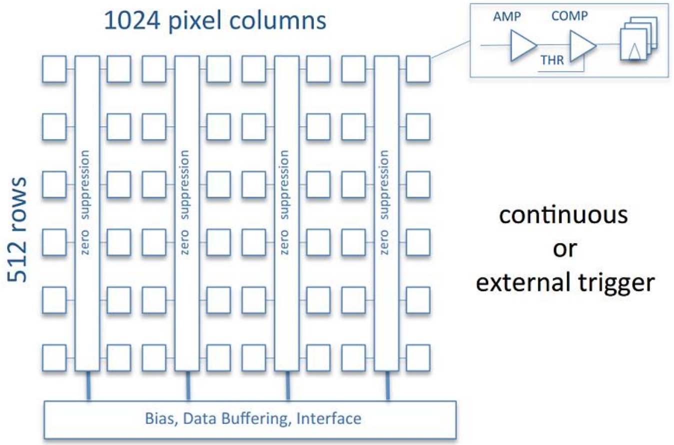
ALPIDE: **AL**ICE **PI**xel **DE**tector



ALPIDE technology features:

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





Sensor specification:

- Pixel pitch 27 µm x 29 µm → spatial resolution 5 µm x 5 µm
- Priority Encoder Readout
- Power: 40 mW/cm^2
- Trigger rate: 100 kHz
- Integration time: < 10 µs
- Read out up to 1.2 Gbit/s
- Continuous or triggered read-out