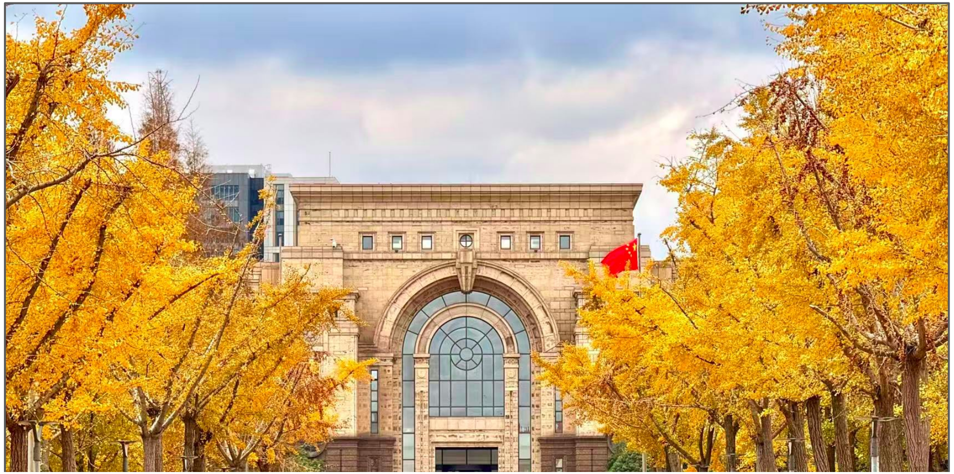

ALICE-TOF

2nd lecture

F. Noferini* on behalf of the ALICE-TOF group

*INFN Bologna

Shanghai, China, 5th November 2025

The 1st ALICE Experiment and Heavy-Ion Physics Workshop

Outline

1st lecture

- Role of PID in HEP physics
- PID in ALICE
- The Time Of Flight Det.
- Multigap Resistive Plate Chambers (MRPC) →TOF
- TOF performance in ALICE Run 1/2
- Physics with TOF in Run 2 (few highlights)

2nd lecture

- Usage of TOF PID (+ with other Dets.)
- TOF upgrade in Run 3
- TOF in continuous readout era
- TOF operations in Run 3
- TOF performance in Run 3

ALICE and PID

Different and complementary techniques in a “low” magnetic field (B=0.2/0.5 T) →high acceptance down to very low momenta

(O(100 MeV))

TOF operates in the intermediate momentum region (hadron separation and more)

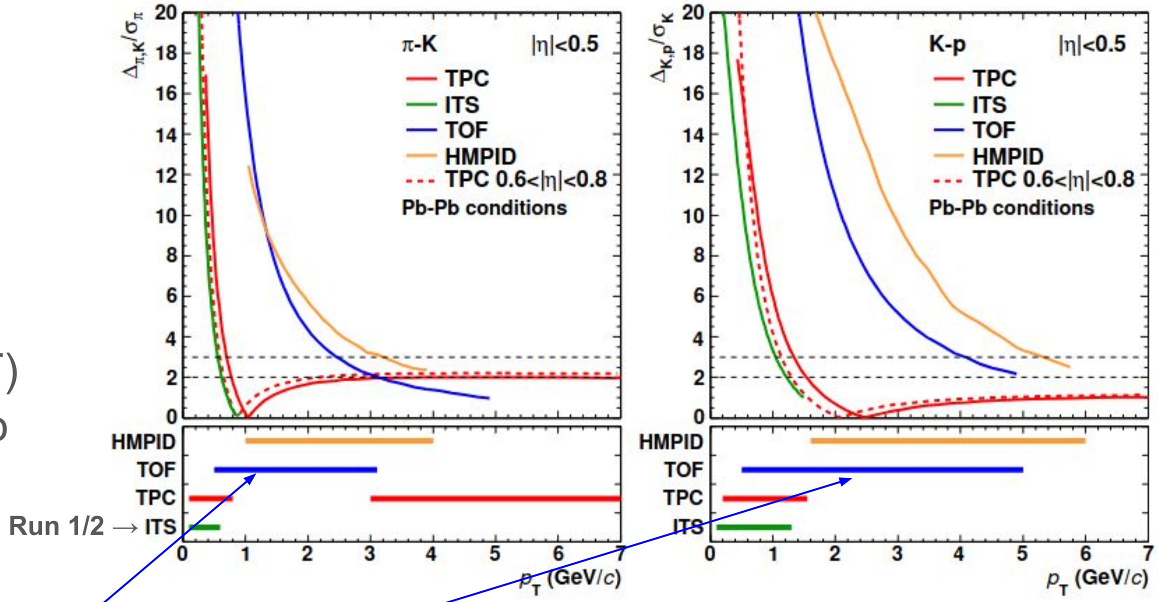

Fig. 46: Separation power of hadron identification in the ITS, TPC, TOF, and HMPID as a function of p_T at midrapidity. The left (right) panel shows the separation of pions and kaons (kaons and protons), expressed as the distance between the peaks divided by the resolution for the pion and the kaon, respectively, averaged over $|\eta| < 0.5$. For the TPC, an additional curve is shown in a narrower η region. The lower panels show the range over which the different ALICE detector systems have a separation power of more than 2σ.

ALICE and PID

Different and complementary techniques in a “low” magnetic field (B=0.2/0.5 T) →high acceptance down to very low momenta

(O(100 MeV))

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Run 1/2 →

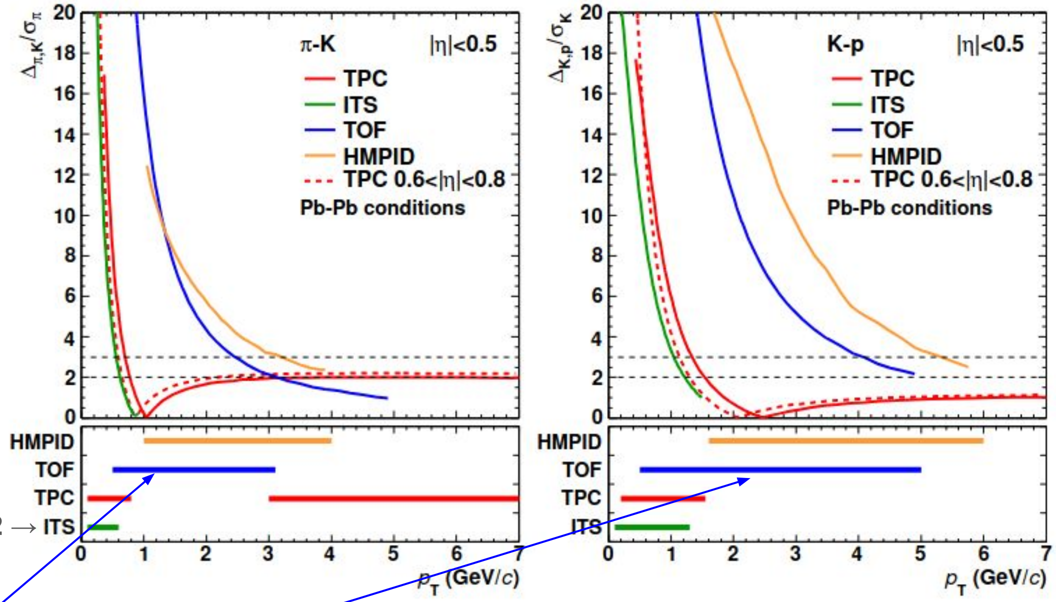
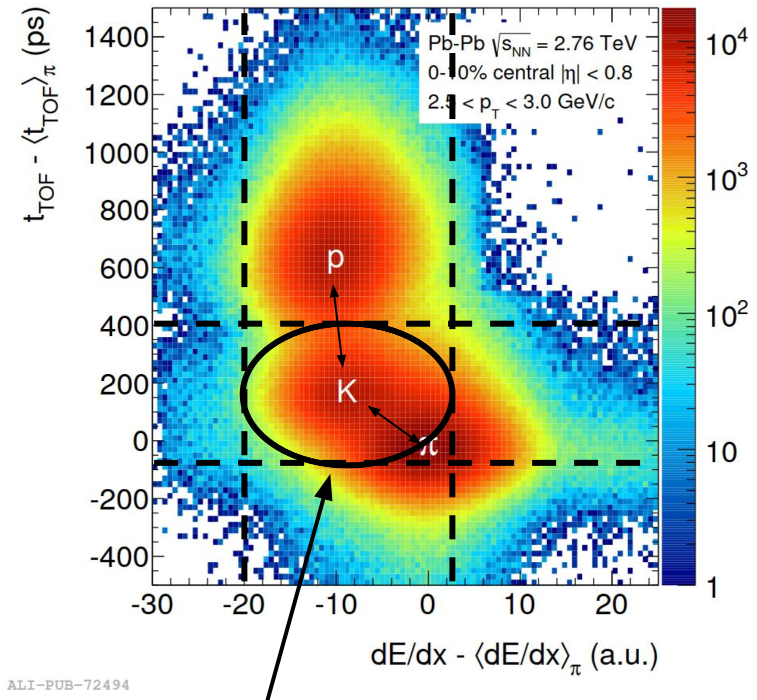


Fig. 46: Separation power of hadron identification in the ITS, TPC, TOF, and HMPID as a function of p_T at midrapidity. The left (right) panel shows the separation of pions and kaons (kaons and protons), expressed as the distance between the peaks divided by the resolution for the pion and the kaon, respectively, averaged over $|\eta| < 0.5$. For the TPC, an additional curve is shown in a narrower η region. The lower panels show the range over which the different ALICE detector systems have a separation power of more than 2σ.

Can we combine information from many detector (e.g. TPC+TOF)?

Combined PID



Elliptic cut corresponds to a cut on the variable:

$$n^2_{\sigma,comb} = n^2_{\sigma,TOF} + n^2_{\sigma,TPC}$$

In the intermediate p_T region one single detector may be not sufficient to provide a good PID. However **the combination of the information allows a good PID performance**.

Such an approach was largely used using TPC and TOF in the p_T region up to 4 GeV/c.

Definition in the Bayesian language (I)

Let's define a detector response for a given mass hypothesis, H_i, is given, for simplicity, by a Gaussian distribution (Bayesian approach doesn't require necessary Gaussianity!):

$$P(S|H_i) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\mathrm{n}_\sigma{}^2} = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(S-\hat{S}(H_i))^2}{2\sigma^2}}$$

This represents, in the case of a single detector, the so called **conditional probability**, i.e. the probability that a particles crossing how detector "releases" that signal.

S = measured signal (dE/dx, tof, …)

S(H_i) = expected signal for a given mass hypothesis

If we generalize to the multi-detector case it can be written as a product:

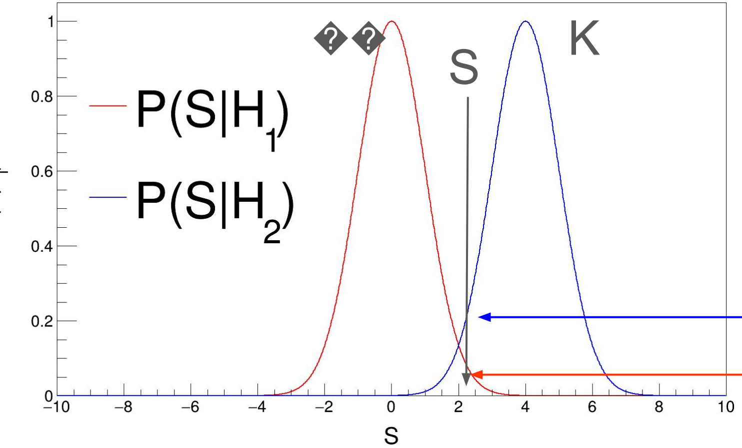
$$P(\vec{S}|H_i) = \prod_{\alpha=\mathrm{ITS,TPC,...}} P_\alpha(S_\alpha|H_i)$$

Where $\vec{S} = (S_{ITS}, S_{TPC}, S_{TOF}, ...)$ is now a vector →probability to have those measured signals

Conditional probability

Conditional probability refers to the probability that a given hypothesis could produce that signal.

If we assume a Gaussian probability distribution each hypothesis has a maxim for a specific value and then probability decreases quite fast.



Let's suppose to have two hipotesis (one peaked at 0 and one peaked at 4, same width)

Our problem is the following:
Is it correct to associate the identity to a track accordingly to the higher conditional probability? **If $P(S|H_2) > P(S|H_1)$, does it mean that H_2 is more probable when we register a signal S?**
Answer: **No, because if particle 1 is much more abundant in nature it can be still the most favorite hypothesis**.

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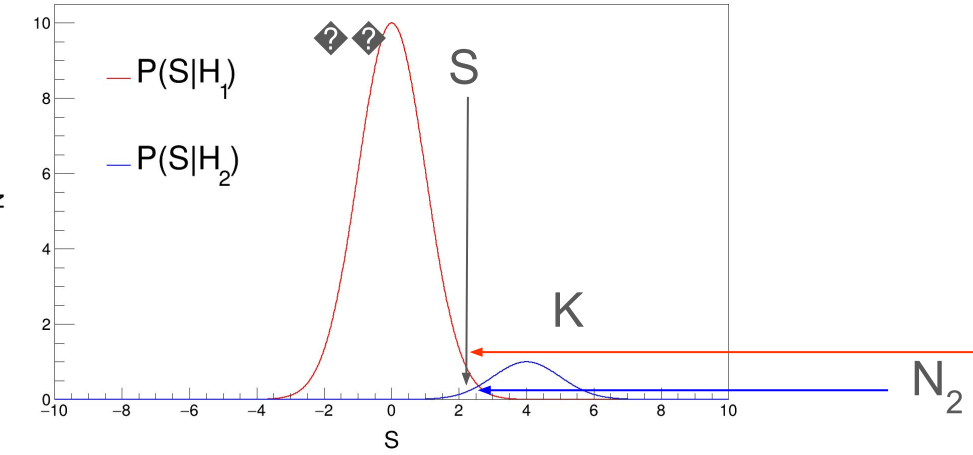

N_1 = frequency of hypotesis 1

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Is it correct to associate the identity to a track accordingly to the higher conditional probability? **If $P(S|H_2) > P(S|H_1)$, does it mean that H_2 is more probable when we register a signal S?**
Answer: **No, because if particle 1 is much more abundant in nature it can be still the most favorite hypothesis**.

Also abundances (proportional to the AREA of curves) play a relevant role

Definition in the Bayesian language (II)

If we know how detectors we can easily calculate $P(\vec{S}|H_i)$, the probability that assuming a given particle (mass hypothesis) it can produce the signals we measured.

But our problem is different: we need to know what is the probability that the assuming a measurement the signal was generated by a given particle (mass hypothesis) $\rightarrow P(\vec{H}_i|S)$ or **posterior probability**

Ther relation of the quantities is established by the Bayesian theorem in this form:

$$P(H_i|\vec{S}) = \frac{P(\vec{S}|H_i)C(H_i)}{\sum_{k=e,\mu,\pi,\ldots} P(\vec{S}|H_k)C(H_k)}$$

$C(H_i)$, **prior probability** or priors, represents the fraction of H_i-particle in the data sample we consider
… simplifying: in case of an ambiguous detector response we have a higher probability to be right if we identify the particle accordingly to the hypothesis most abundant in the sample

Definition in the Bayesian language (II)

If we know how detectors we can easily calculate $P(\vec{S}|H_i)$, the probability that assuming a given particle (mass hypothesis) it can produce the signals we measured.

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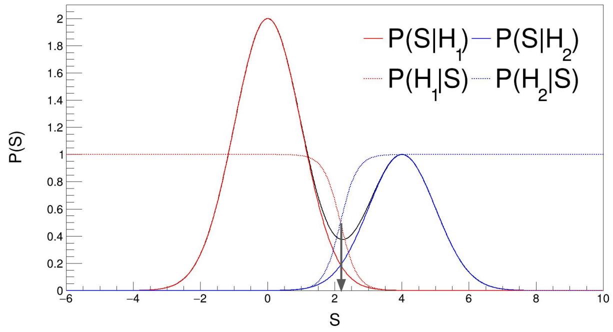
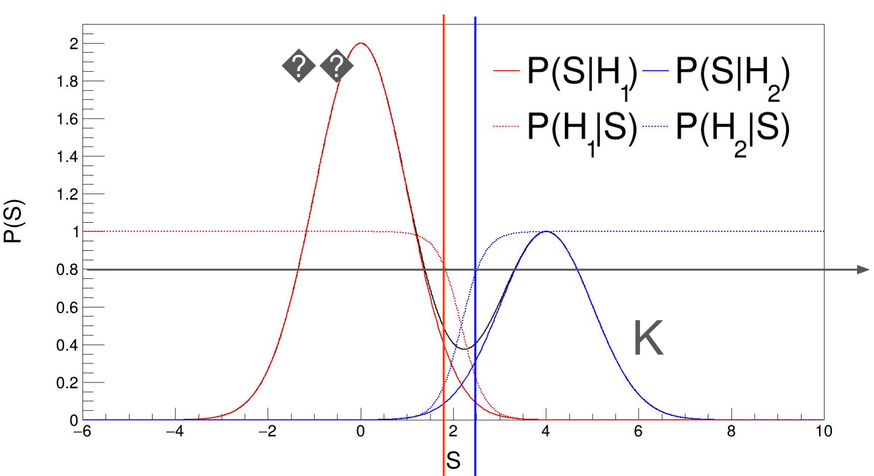
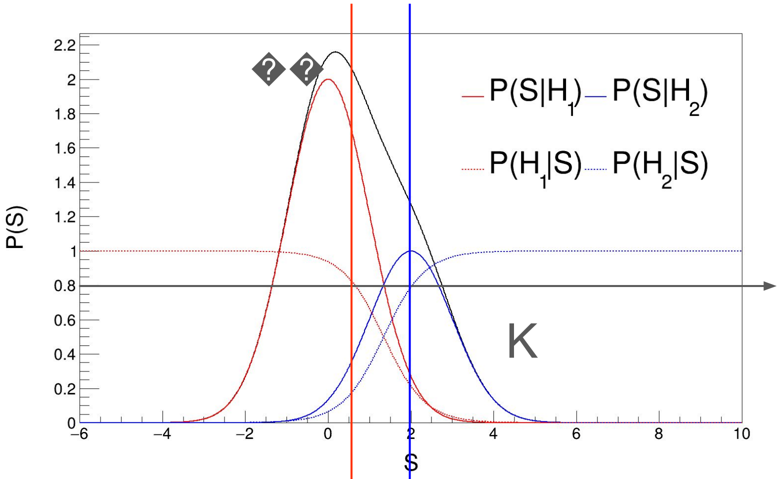


Bayesian probability tells you what is the purity of the signal you would have if you accept the track with a given mass hypothesis.





If you want a pure sample you have to cut here if the separation is at 4σ

If you want a pure sample you have to cut here if the separation is at 4σ

If you want a pure sample you have to cut here if the separation is at 2σ

If you want a pure sample you have to cut here if the separation is at 2σ

Note that when losing particle separation the efficiency decreases when requiring higher purities.

ALICE Bayesian PID in Run 2

$$P(H_i|\vec{S}) = \frac{P(\vec{S}|H_i)C(H_i)}{\sum_{k=e,\mu,\pi,\ldots} P(\vec{S}|H_k)C(H_k)}$$

$$P(\vec{S}/H_i) = \prod_{\alpha=ITS,TPC,\ldots} P(S_\alpha / H_i)$$

$$P(S/H_i) = P(n_\sigma) = \frac{1}{2\pi\sigma}\exp(-n_\sigma^2/2)$$

This is the critical part. If there are non Gaussian effects we need to parametrize them properly in the detector response function → this is why in Run 2 we needed to validate the technique!

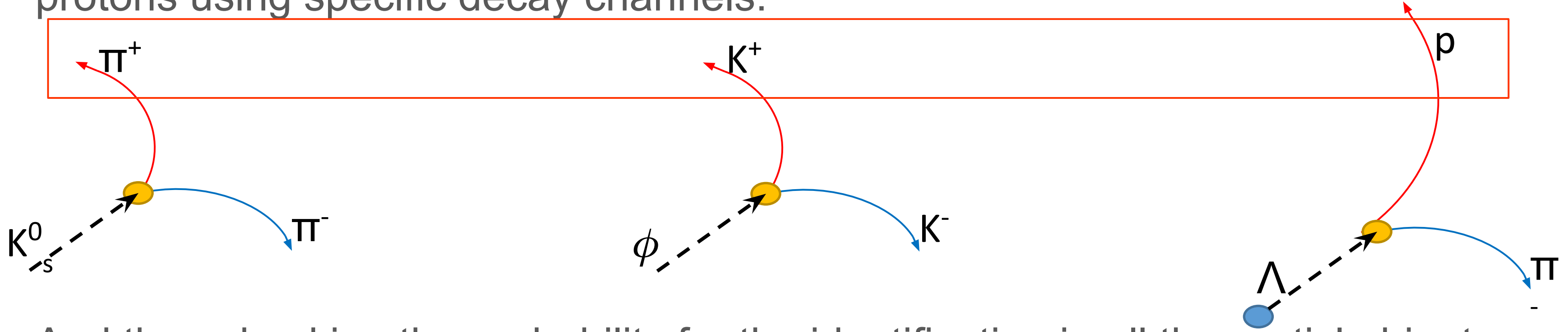
Bayesian approach is a powerful tool…

BUT it has to be treated carefully

Validation of Bayesian PID

- The use of Bayesian probability easily allows to **manage multi-detector scenarios in a natural way** **typically by applying a cut on the probability for our particle of interest.**
- PID efficiencies are extracted via simulations **the simulation of our detector has to be well under control**

The validation strategy was based on the selection pure samples of pions, kaons and protons using specific decay channels:



And then checking the probability for the identification in all the particle hipoteses

→ BOTH IN DATA AND SIMULATIONS (MC)

Data and sims have to agree in order to prove that everything is under control

Results for TPC and TOF combined PID

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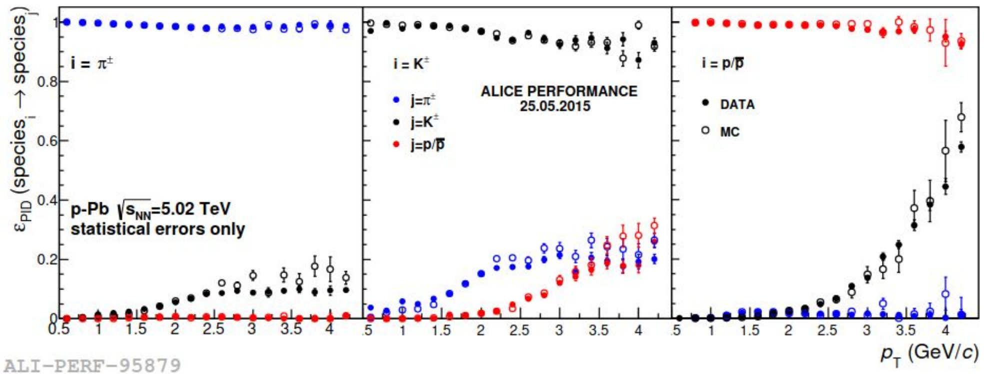
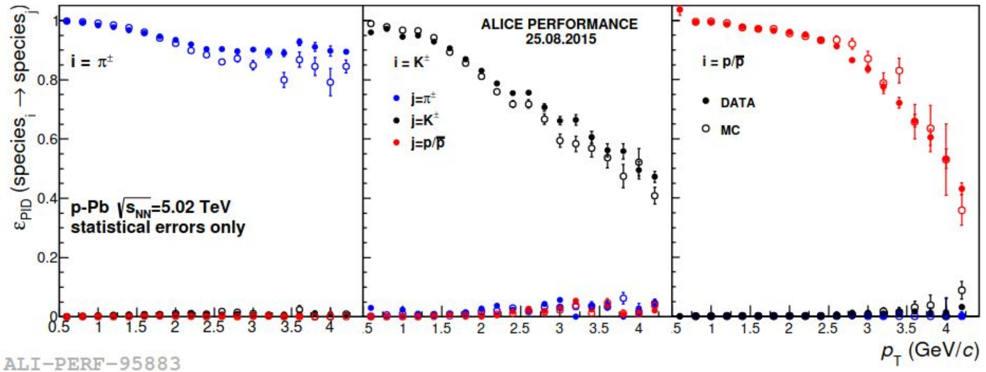
P(j) > 0.2



ALI-PERF-95879

P(j) > 0.8



ALI-PERF-95883

High efficiency

High purity

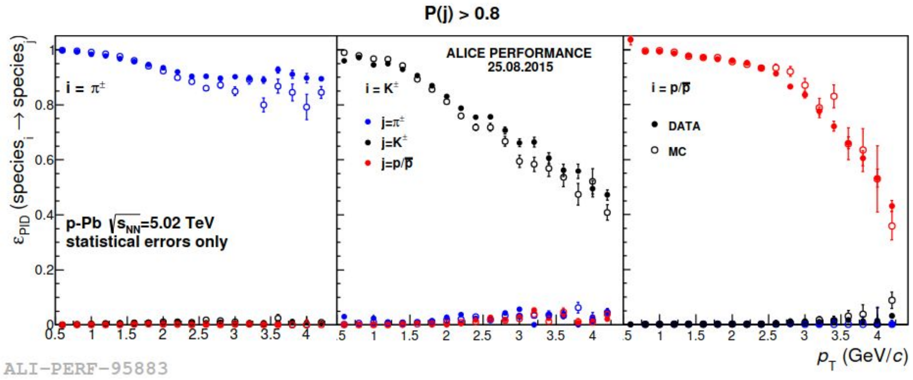
The combined PID using TPC and TOF PID signals were validated using Run 1 data (p-Pb) with different requests (cut on probability values) on the Bayesian probability.

The consistency between data and MC, in different scenario, was better than 5% □ **very good understanding of our detector responses**.

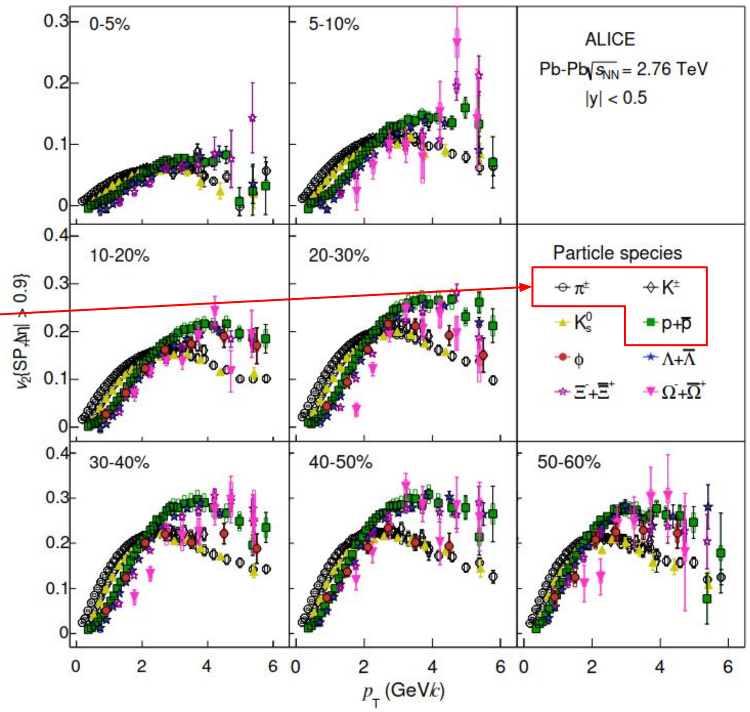
Such an approach was extensively used in Run 2 and hass to be extended also in Run 3.

Bayesian PID →physics

The first use case was the elliptic flow of identified hadrons but then the technique was extensively used in many Run 2 analyses.



Elliptic flow of identified particles (π, K ,p) was done with a TPC-TOF Bayesian PID



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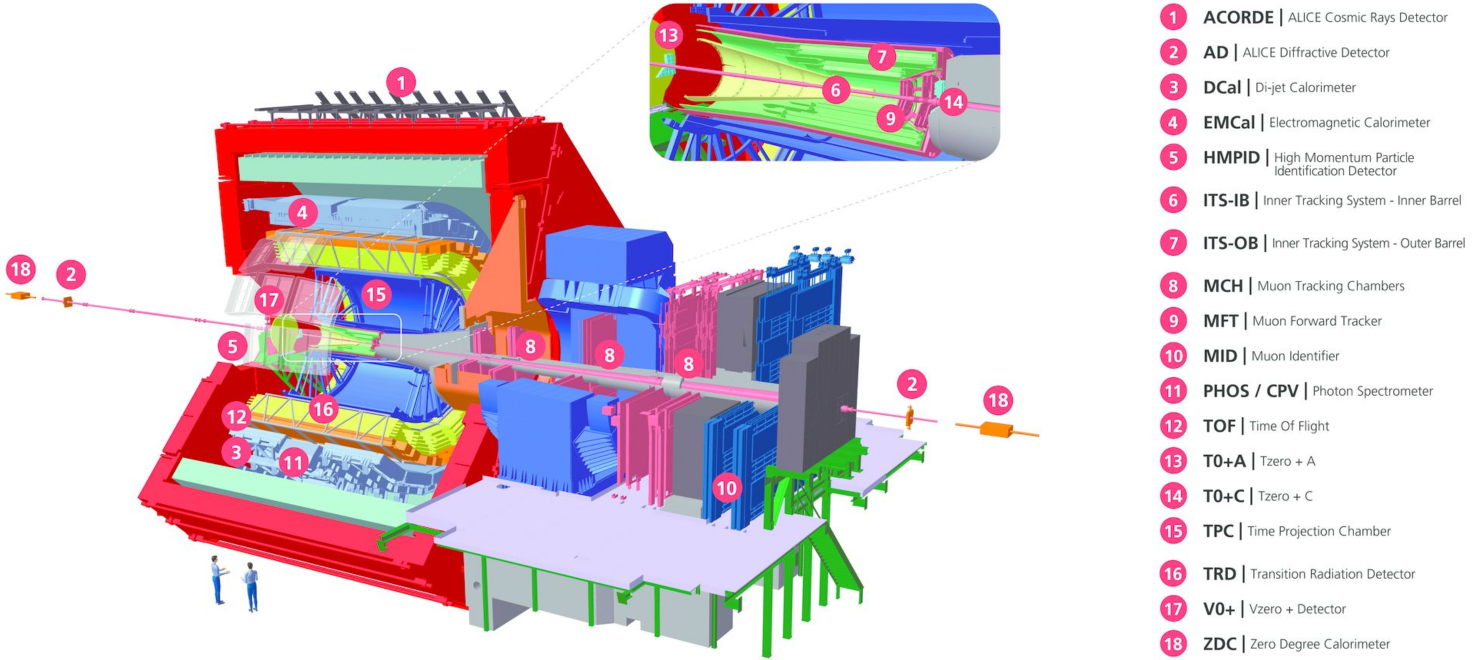
ALICE in Run 3



ALICE detector in Run 3

The **ALICE detector underwent a series of upgrades during the LS2** to enable future advancements focused on precision measurements of statistics-limited rare probes in both large (Pb–Pb) and small collision systems (pp) → **to sustain data taking in high interaction rate conditions up to 1 MHz in pp collisions and 50 kHz in Pb–Pb collisions**

TOF in Run 3

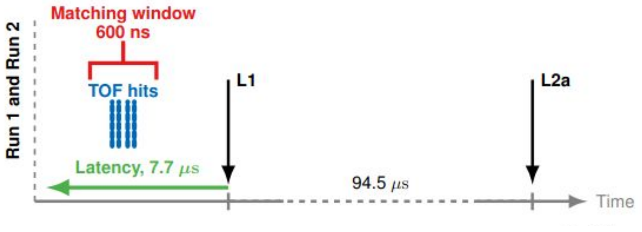
In order to sustain higher interaction rates ALICE changed the paradigm for data acquisition and processing moving to **continuous readout** mode (this is indeed a major upgrade) and TOF should adapted at the new scheme as well → upgrade of TOF readout electronic:

- ALICE TOF detector completed the readout electronics upgrades in early July 2022
- This involved the production of a new readout board designed by INFN Bologna and using high-speed optical links (GBTx) to achieve a high bandwidth, 400 Mb/s, and high quality clock

Data Readout Module 2

Figure 1: The DRM2 board

TOF in continuous readout era

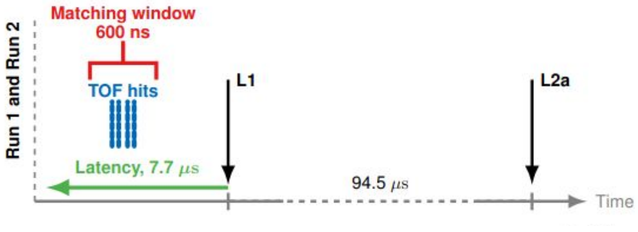


TOF was conceived as a triggered detector. In Run 1 and 2 data were read when a trigger* signal (from a collision) was received → typically few kHz trigger rate

* trigger is defined as a condition determined by a detector condition (e.g. at least N channels fired in one event), or a combination of conditions from many detectors, which tells us than an interesting event is occurred and tht we want to register it:

- It should be fast (we need to take a decision in a short time… other events are coming)
- It should be distributed to all the detectors

TOF in continuous readout era



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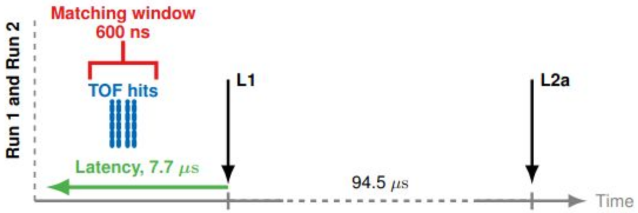
When TOF receives a trigger, the Data Readout Module collects all the information contained in the Trigger Readout Module (hits) which were collected so far. To be sure the whole event is registered there is a latency is set (since we always read in the past) and then all data within a matching window (much larger than the typical collision time distribution) are stored

TOF in continuous readout era

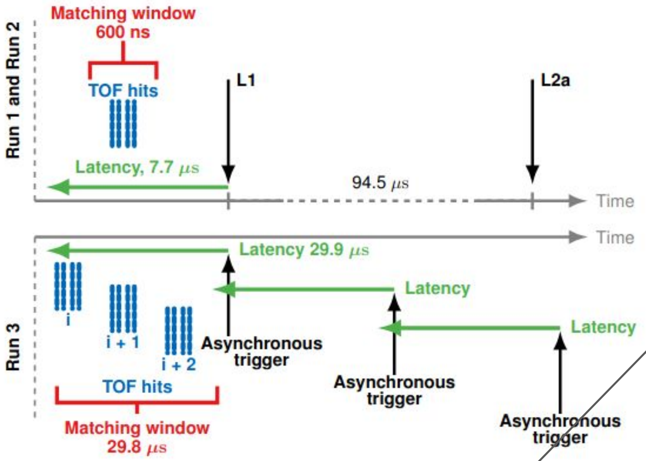


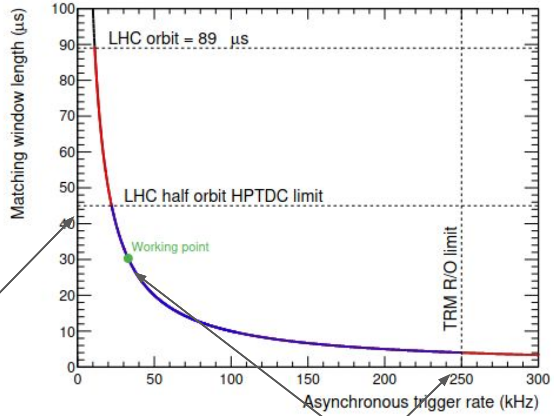
Fraction of time read and stored by TOF at 1 kHz trigger rate
= 1 kHz x 600 ns
= 0.06%

TOF was conceived as a triggered detector. In Run 1 and 2 data were read when a trigger signal (from a collision) was received → typically few kHz trigger rate

When TOF receives a trigger, the Data Readout Module collects all the information contained in the Trigger Readout Module (hits) which were collected so far. To be sure the whole event is registered there is a latency set to be sure we don't cut anything (since we always read in the past) and then all data within a matching window (much larger than the typical collision time distribution) are stored

TOF in continuous readout era





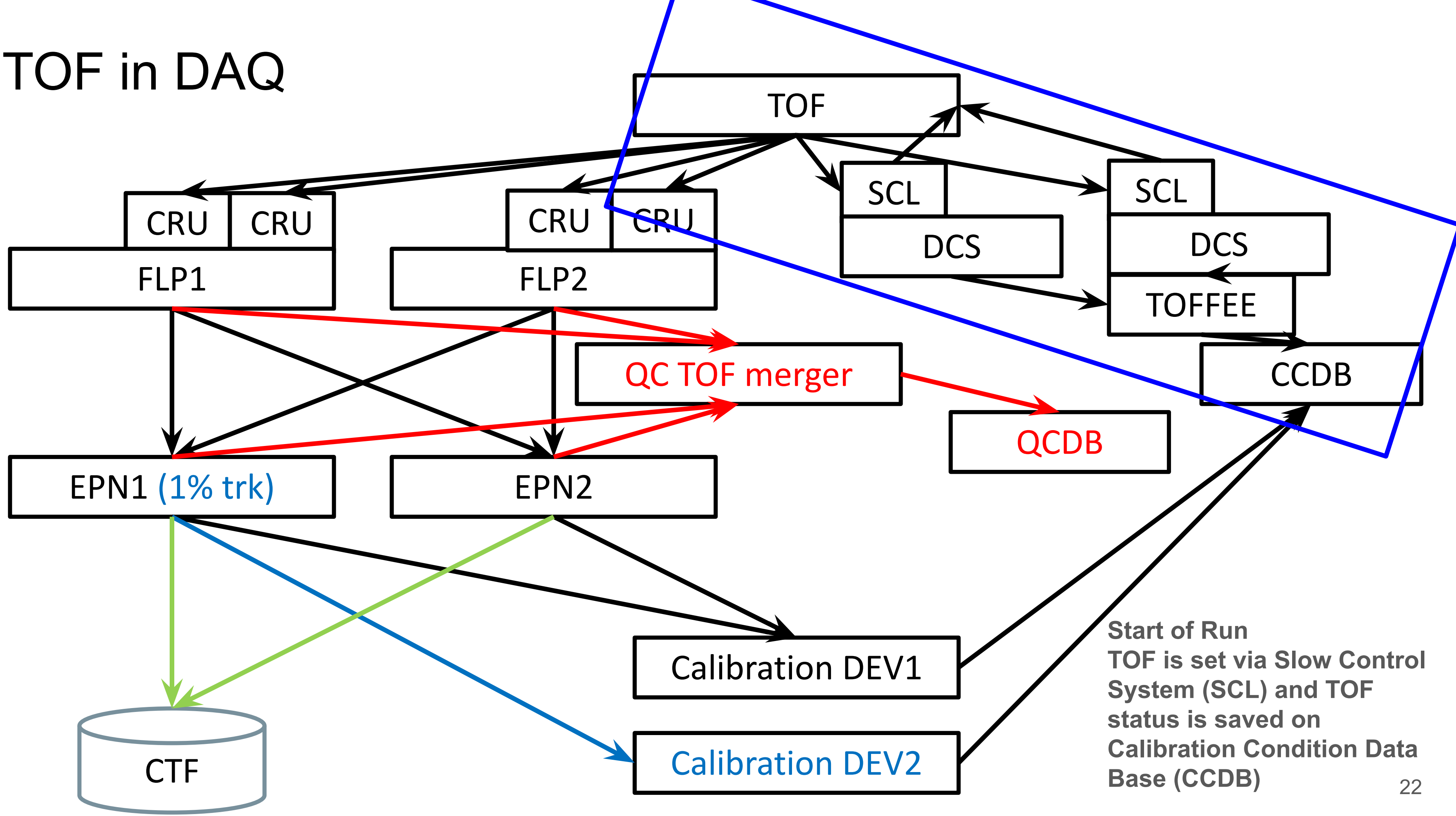
In Run 3 we replaced the physics trigger (typically few kHz rate) with a periodic trigger given at fixed time intervals and storing all the hits collected in the whole interval →actually ⅓ orbit (every ~30 μs)
→ ~ 33 kHz trigger rate and reading ~30 μs of data at each trigger

the latency window cannot be set at a value larger than half of an LHC orbit

the trigger frequency cannot be too high, due to the HPTDC readout time inside the TDC readout module (TRM)

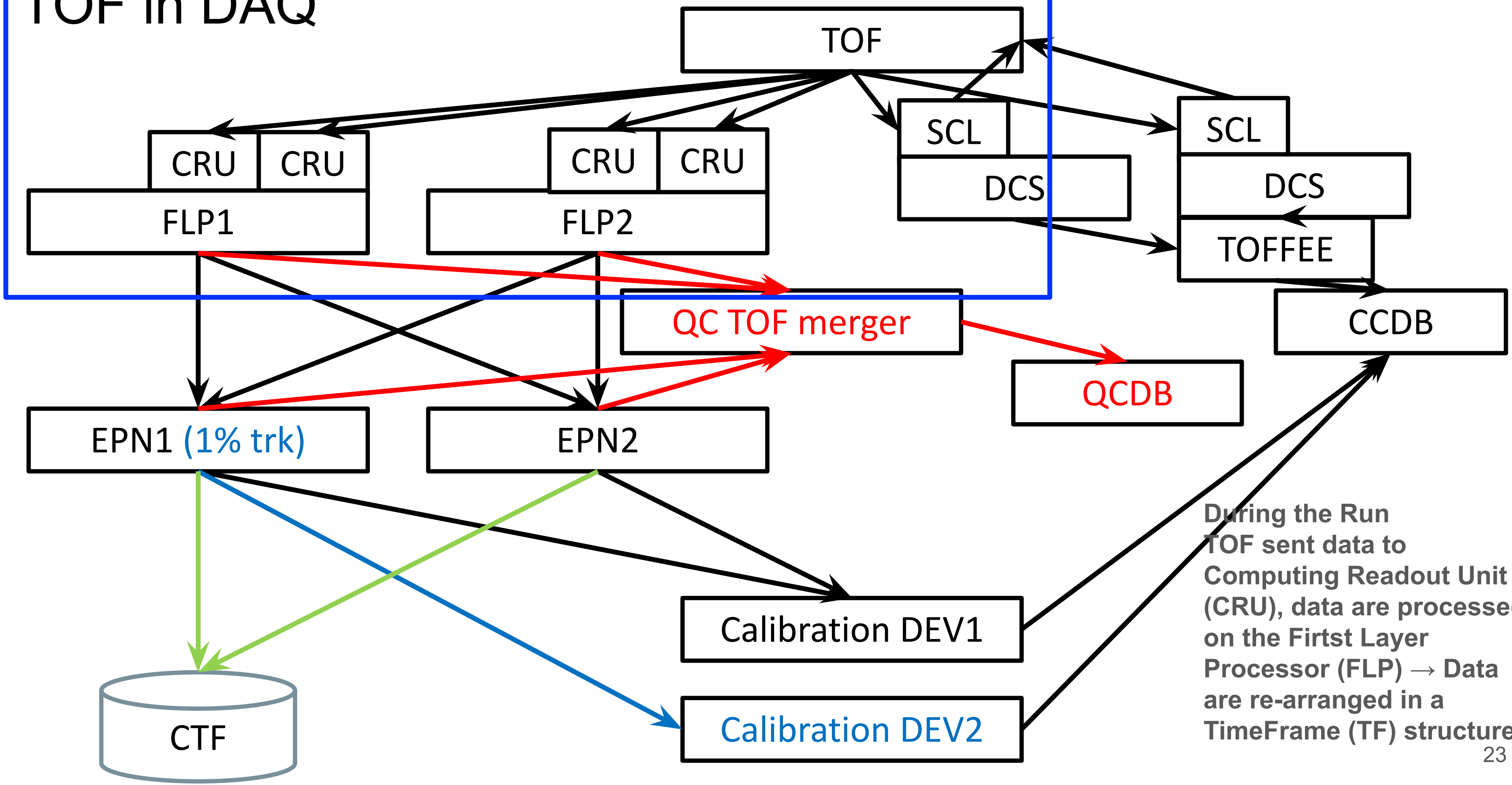
33 kHz x 30 μs = 100% (we read and store all!)

TOF in DAQ



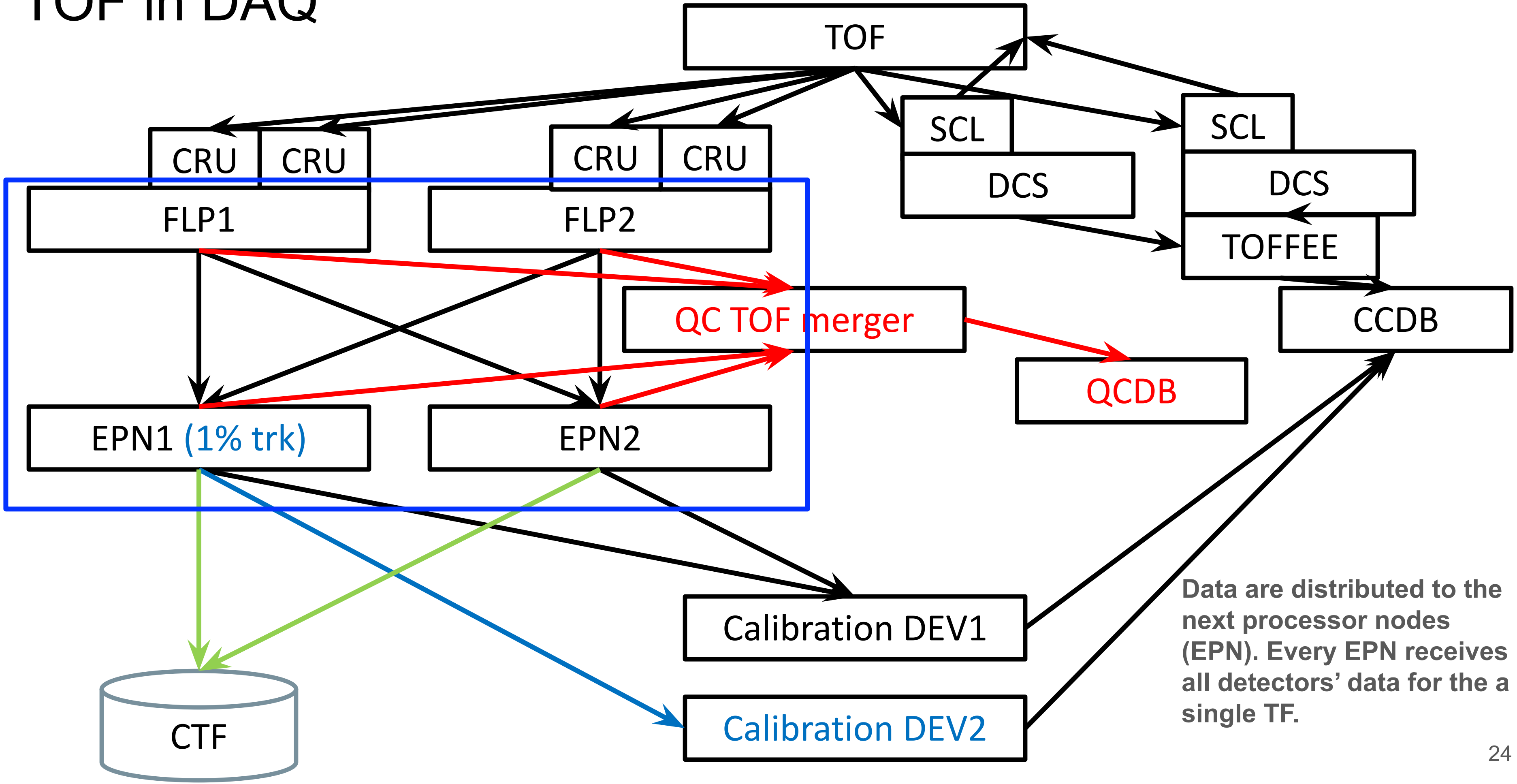
Start of Run
TOF is set via Slow Control System (SCL) and TOF status is saved on Calibration Condition Data Base (CCDB)

TOF in DAQ



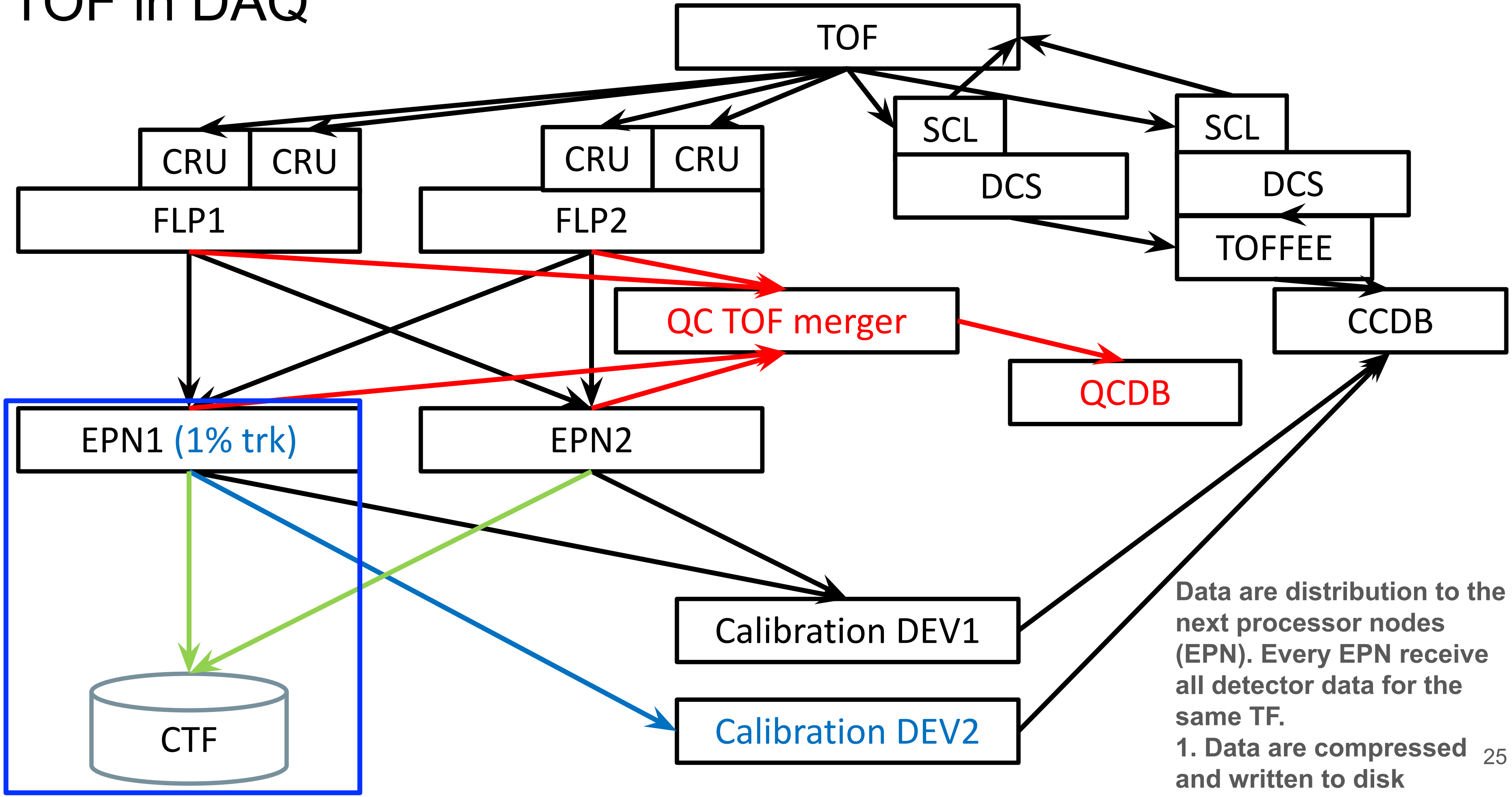
During the Run TOF sent data to Computing Readout Unit (CRU), data are processed on the Firtst Layer Processor (FLP) → Data are re-arranged in a TimeFrame (TF) structure

TOF in DAQ



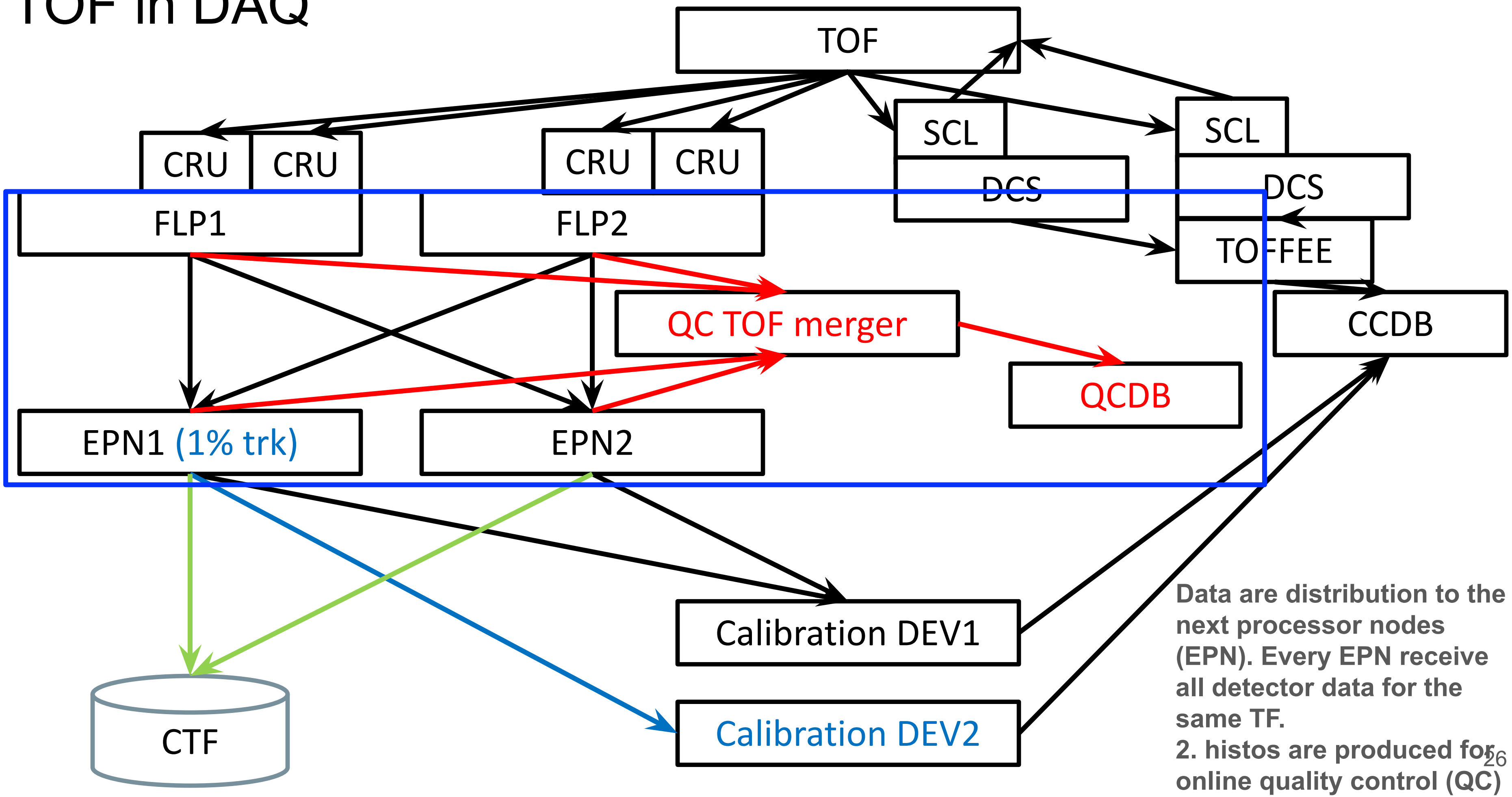
Data are distributed to the next processor nodes (EPN). Every EPN receives all detectors' data for the a single TF.

TOF in DAQ



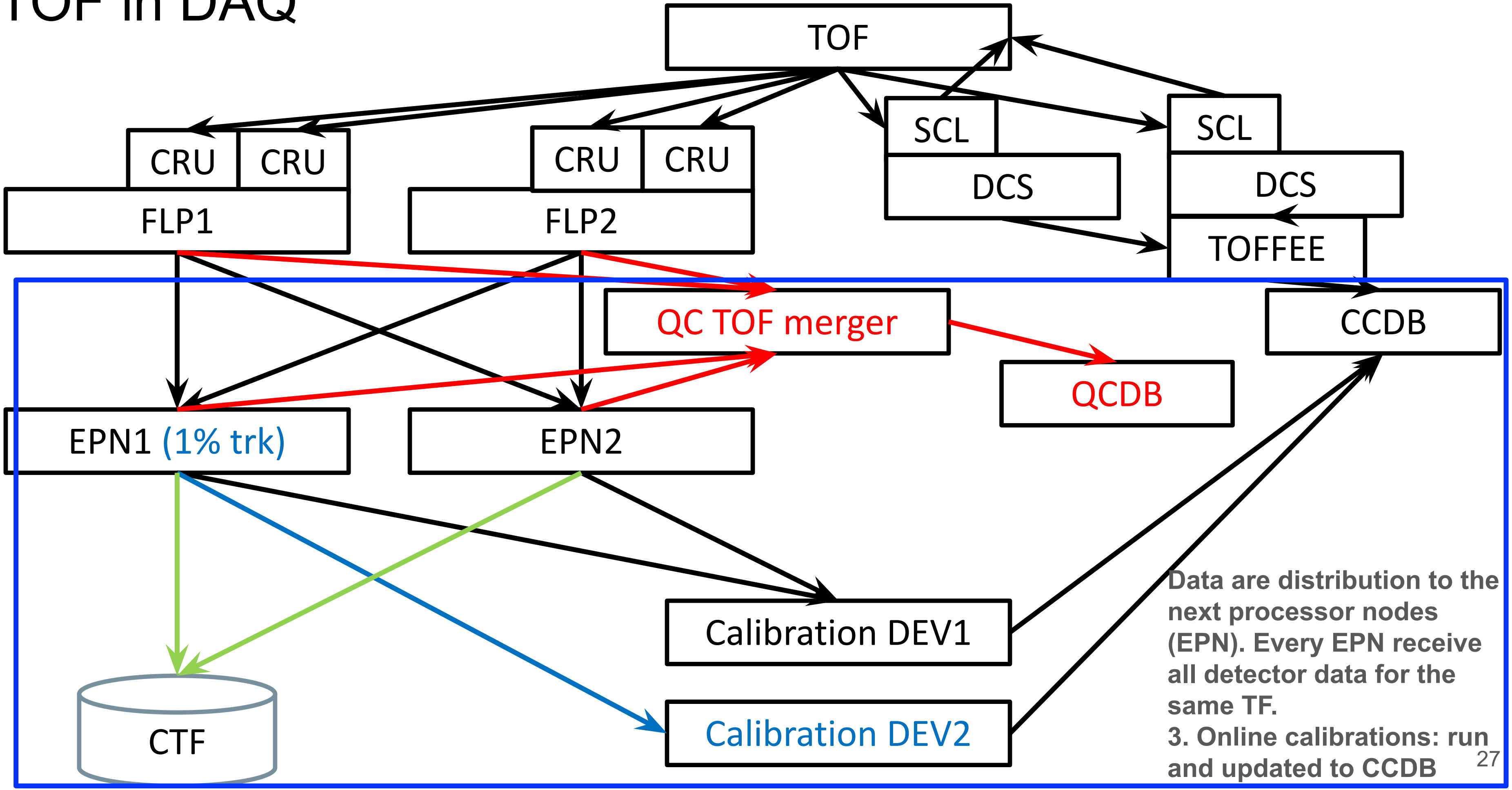
Data are distribution to the next processor nodes (EPN). Every EPN receive all detector data for the same TF.
1. Data are compressed and written to disk

TOF in DAQ



Data are distribution to the next processor nodes (EPN). Every EPN receive all detector data for the same TF.
2. histos are produced for online quality control (QC)

TOF in DAQ

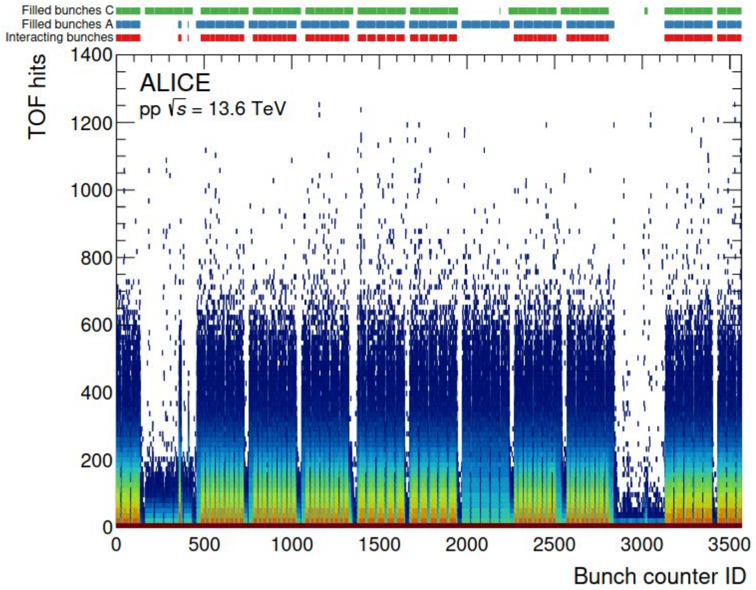


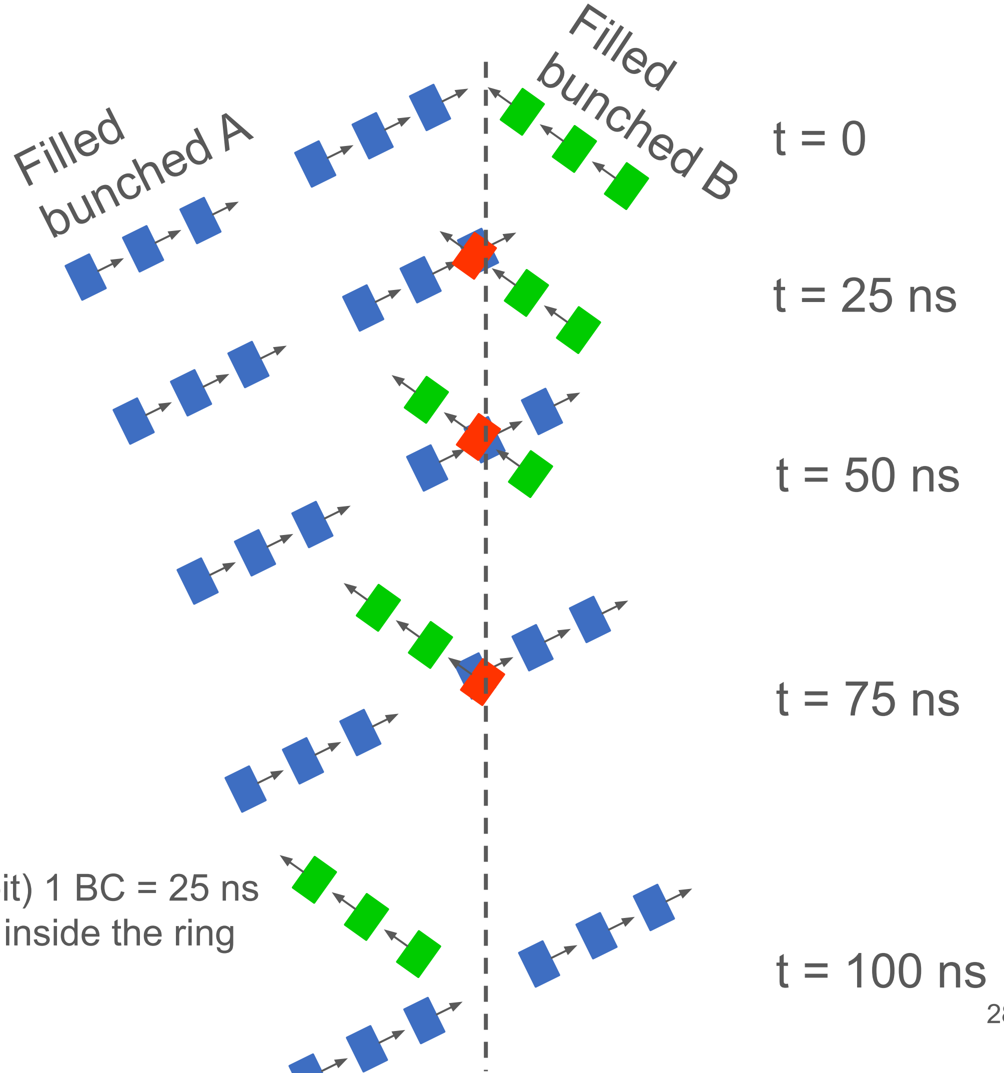
Data are distribution to the next processor nodes (EPN). Every EPN receive all detector data for the same TF.

3. Online calibrations: run and updated to CCDB

Online Quality Control

Online we check several quantities:

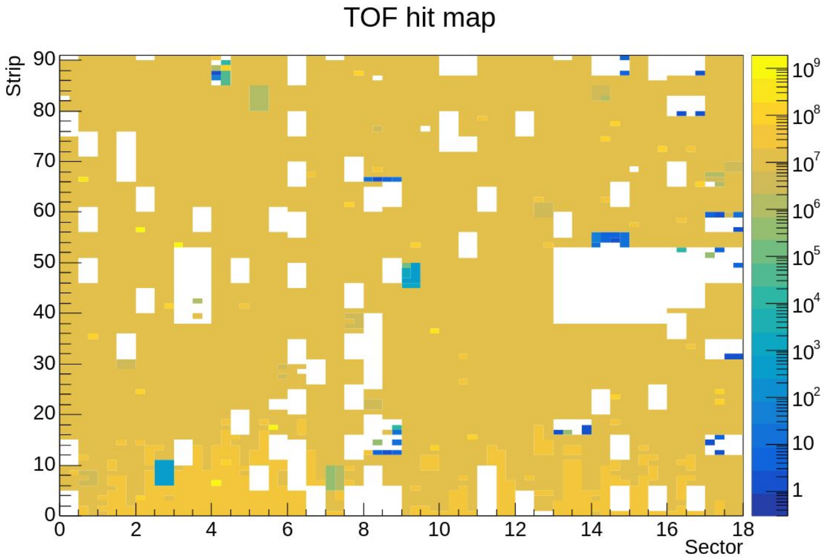




Filling scheme (BC structure inside one LHC orbit) 1 BC = 25 ns
LHC orbit (time for a proton to cover to full cycle inside the ring ~ 90 μs)

Online Quality Control

Online we check several quantities:

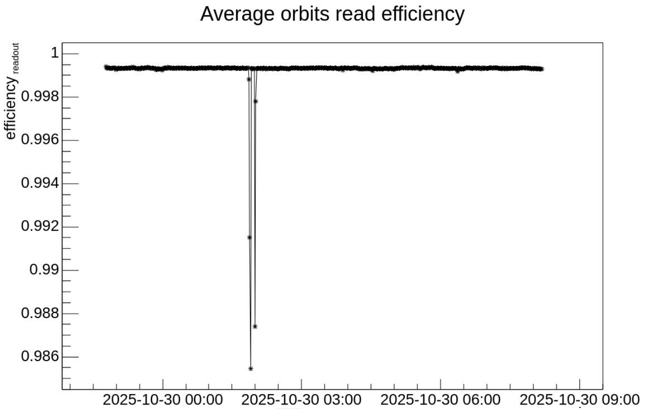


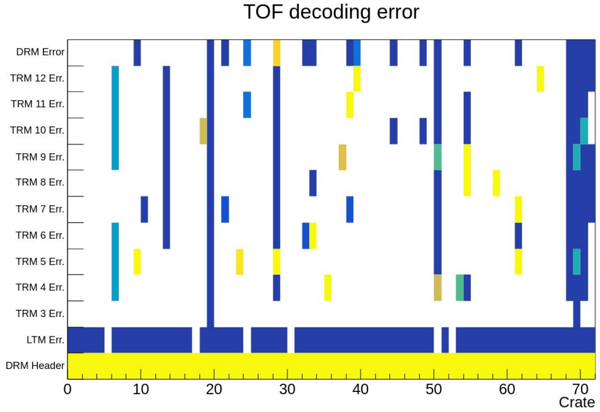
During data acquisition TOF hit map is always checked and compared with the expected maps for active channel maps.

Unexpected holes can trigger an intervention.

Note that:
If we are not able to control data acquisition conditions we cannot use data to do physics.

Online Quality Control



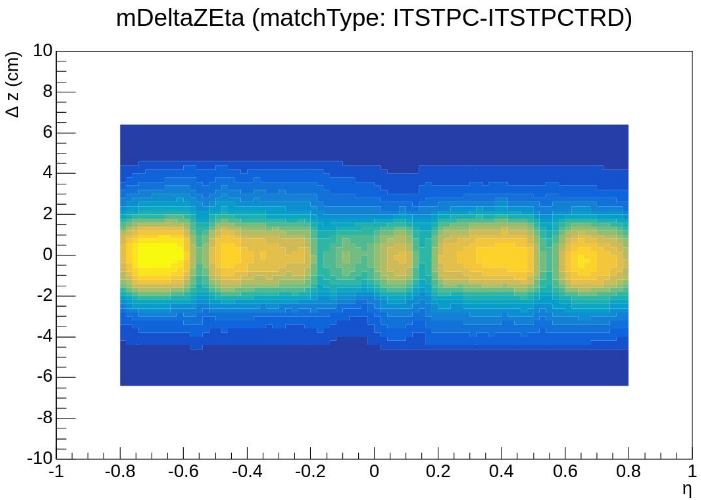


Our electronics, time to time, can have failures. We need to monitor the efficiency and quality of the data to trace any source of error continuously (trending along time).

→ again, any error which can produce inefficiency has to be considered in our simulations.

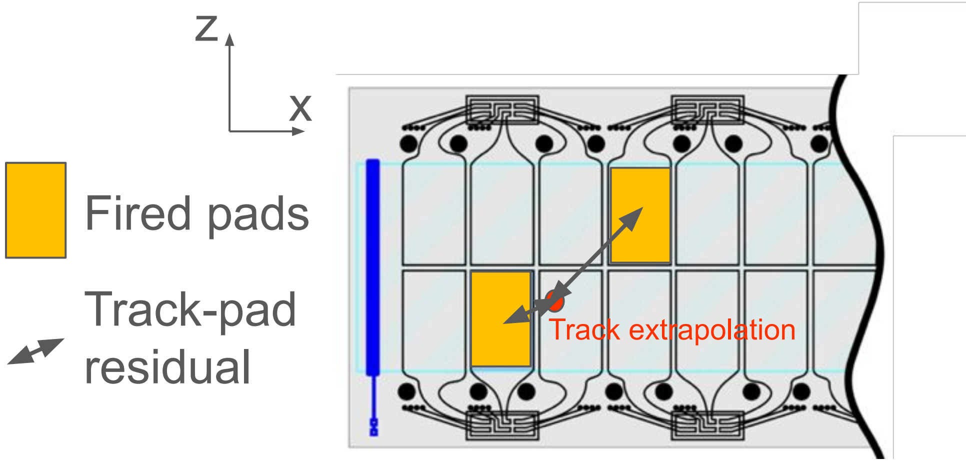
Online Quality Control

Online we check several quantities:



For a fraction of events → full reconstruction (~1%) → Quality of the track-TOF matching (e.g. track extrapolation residuals at TOF)

Remember: track extrapolation has to be well aligned with TOF (on average residuals at zero!)



In case of multiple matching-pad candidates a minimization on residuals is applied to select the better association

Calibrations

Along the full chain of the data taking/reconstruction, there are three subsequent calibration stages:

1. DCS calibration performed during the start of the run from the TOF slow control system
2. synchronous calibration done during the data taking on the EPN farm
3. asynchronous calibration required in the offline reconstruction

Sync calibrations:

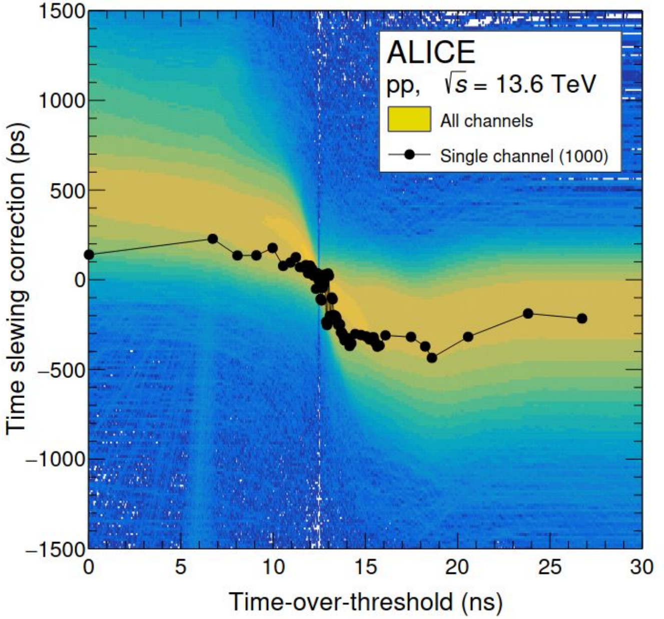
1. Diagnostic: all decoding errors are traced in 5 minutes slot (to be used in MC)
2. Time aligned (global offset with respect LHC clock) is computed in 5 minutes slots
3. Single channel offsets are calibrated

Async calibrations:

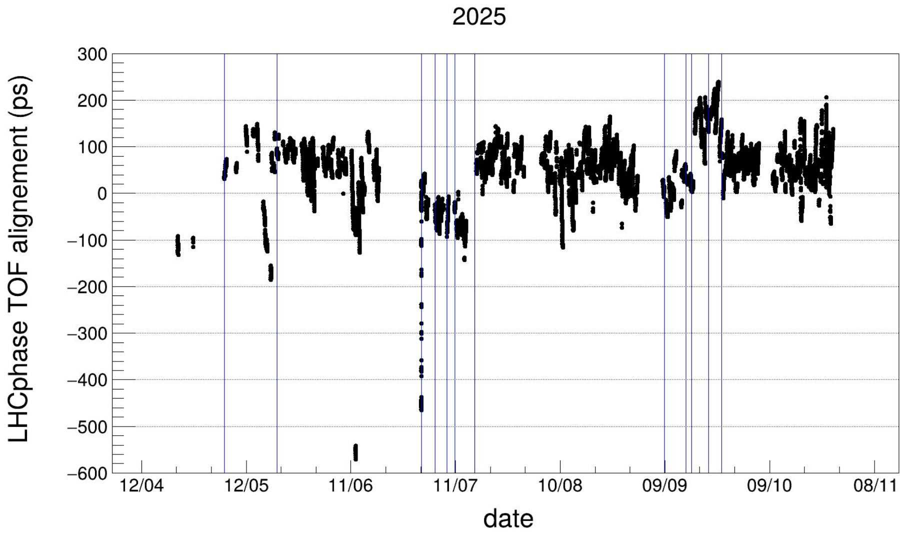
1. Refined time aligned (global offset with respect LHC clock) is computed in 5 minutes slots
2. Single channel offsets are calibrated and also time slewing calibrations (requiring large stats) are done

Async calibrations rely on the first offline reconstruction (calibration pass) done on 10% of each good run

Calibrations (II)

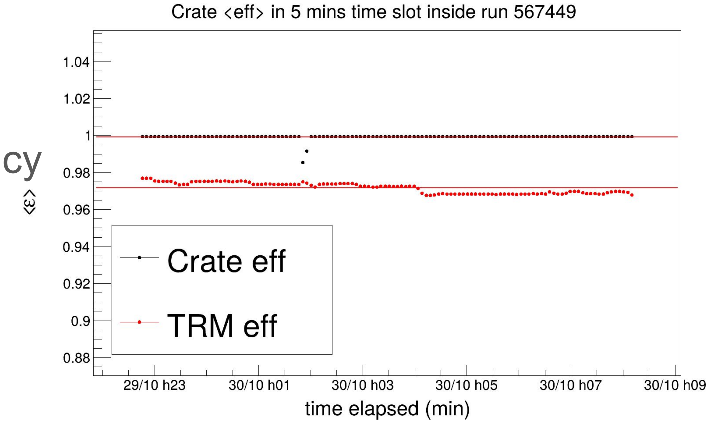


Time slewing corrections (2022 pp data)

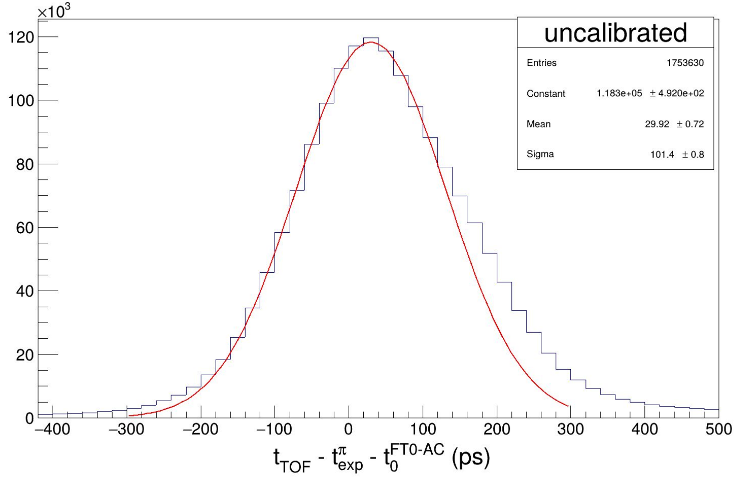


TOF - LHC clock alignment in 2025 pp data

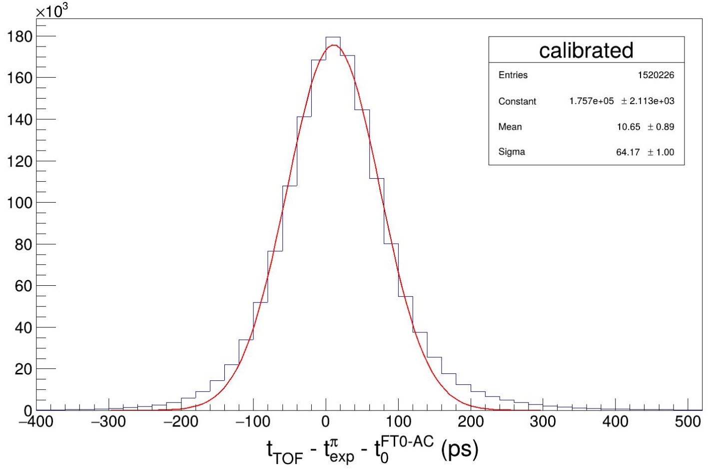
Readout efficiency with one run (example)



TOF calibration in Run 3 (2025)

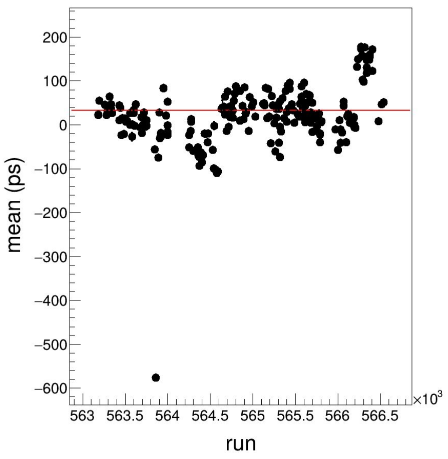


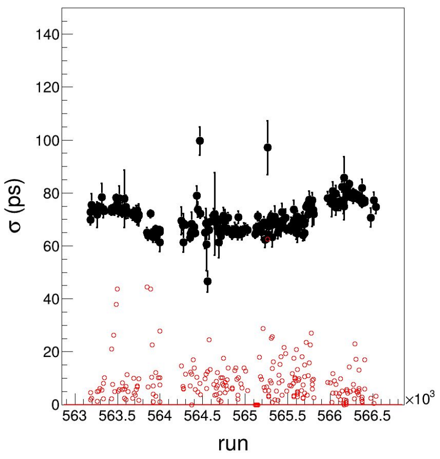
Before offline calibrations

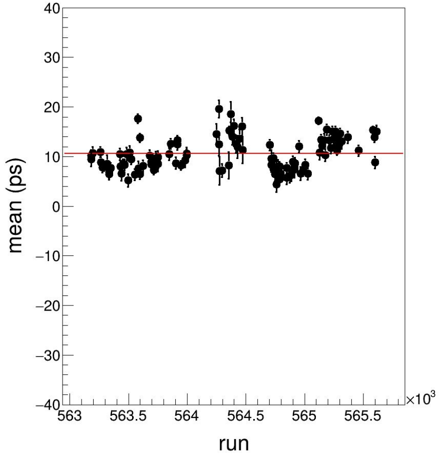


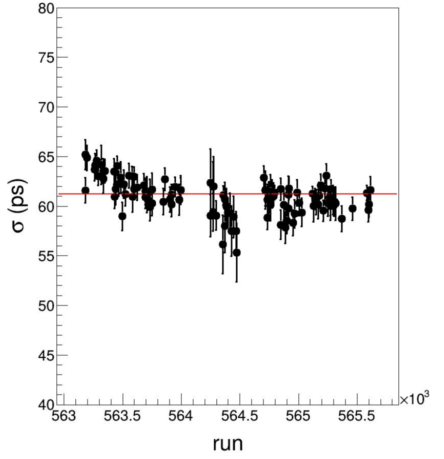
After calibration pass (1 week after first reconstruction pass is over, run-by-run)

TOF calibration in Run 3 (2025)





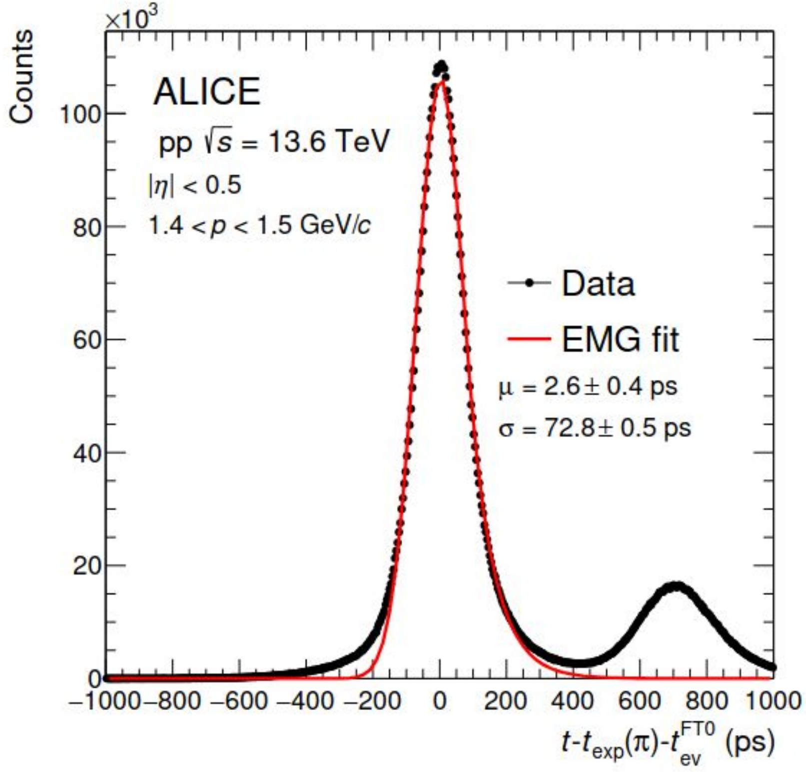




Before offline calibrations (in red the spread introduced to the uncalibrated TOF - LHC clock alignment)

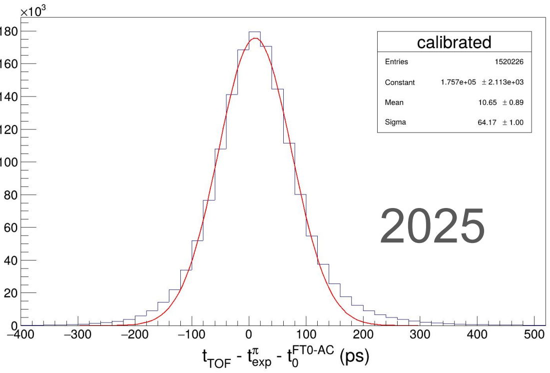
After calibration pass (1 week)

TOF performance

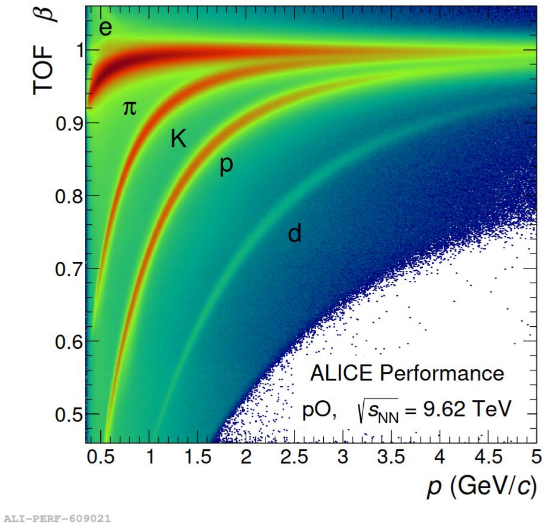


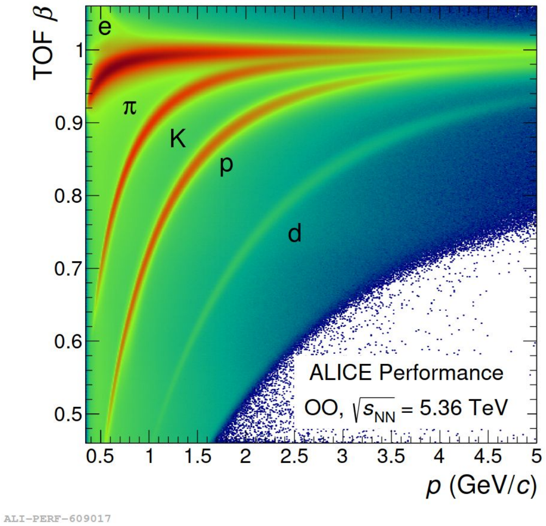
A paper on TOF performance is close be published on the first data we collected in Run 3 (pp in 2022).

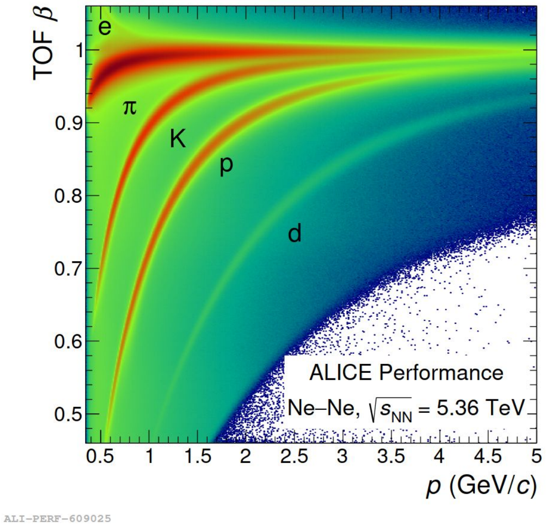
As shown, in the meantime quality improved (also thanks to the big improvement on tracking, TPC calibrations, which determines the quality of t_{exp})



TOF performance (II)

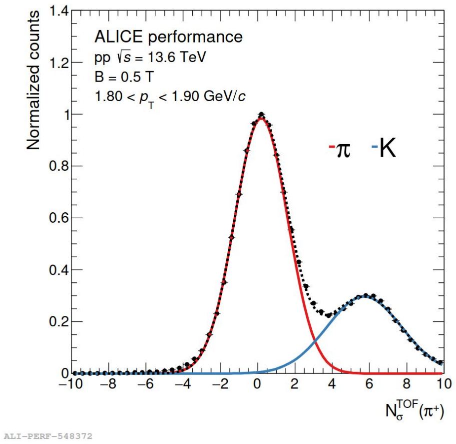


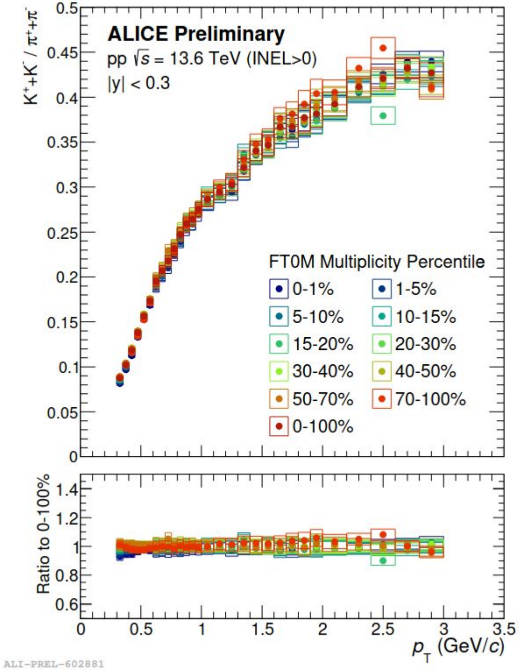


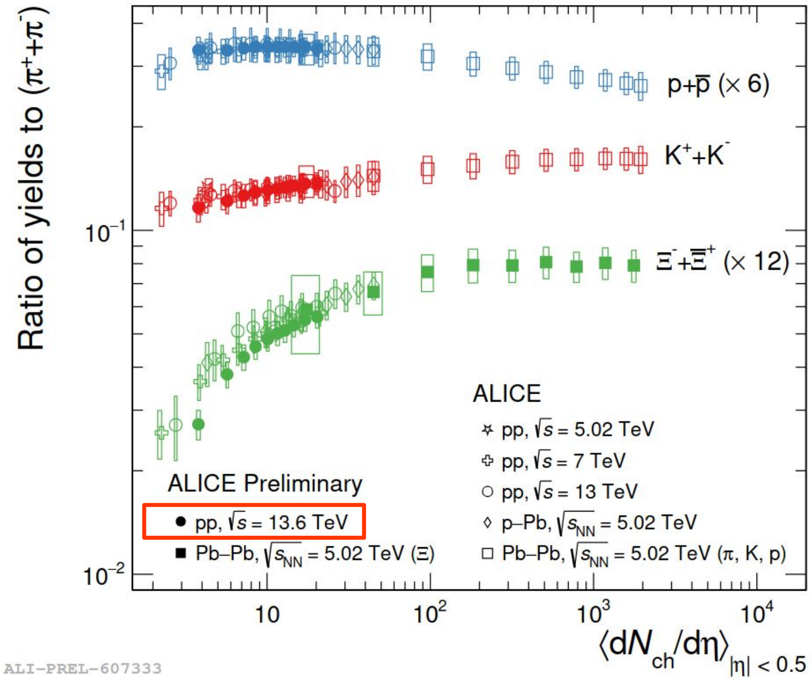


Excellent and uniform performance achieved so far for all data sample and for different colliding system. Also in the recent campaigns for pO, OO and Ne-Ne

Few highlights of physics with TOF (ALICE preliminary)

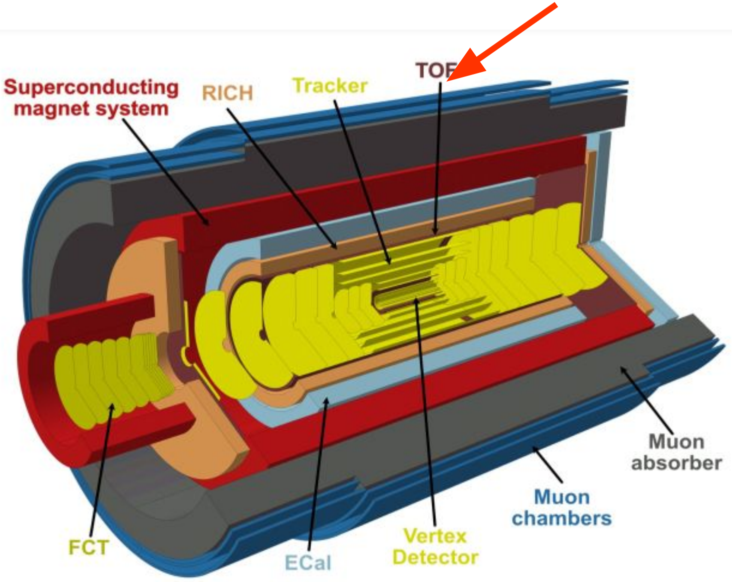






Hadron production in pp@13.6 TeV

What next



ALICE 3 a next generation heavy-ion experiment

Time-Of-Flight System (TOF)

Separation Power $\propto \frac{L}{\sigma_{TOF}}$

- inner TOF R ≈ 19 cm
- outer TOF $\boxed{R \approx 85\ \text{cm}}$
- forward TOF z ≈ 375 cm

Requirements:

- Moderate rad. hardness
  - inner TOF: NIEL ~6.1·10^{12} 1-MeV n_{eq} /cm^2
  - outer TOF: NIEL ~9·10^{11} 1-MeV n_{eq} /cm^2
  - forward TOF: NIEL ~8.5·10^{12} 1-MeV n_{eq} /cm^2
- Low material budget ~1-3% X_0
- **Time resolution**: $e/\pi \lesssim 500$ MeV/c, $K/\pi \lesssim 2.5$ GeV/c, $p/K \lesssim 4$ GeV/c → **20ps**

Extensive R&D on the most advanced silicon technologies:

LGADs, SiPMs, CMOS-LGADs

New exciting opportunities for the study of:

✦ **Multi-charm hadrons at low momenta**

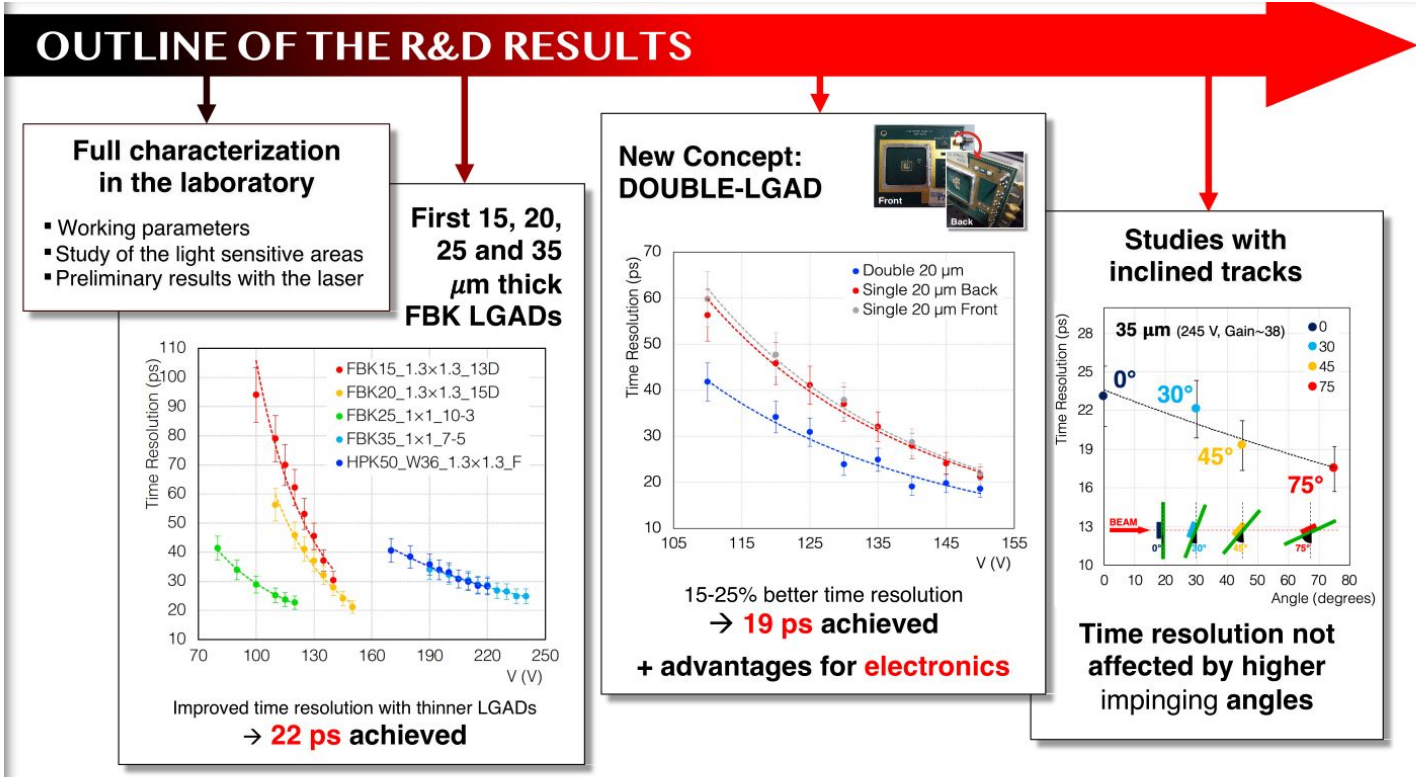
→ Crucial test for coalescence models

✦ **EM radiation** produced in the first evolution phases of QGP

Progress on R&D…

S. Strazzi PhD thesis
http://cds.cern.ch/record/2929067/files/CERN-THESIS-2025-027.pdf

Note that there is a dedicated lecture on ALICE 3 by J. Klein



Thanks for your attention!!!