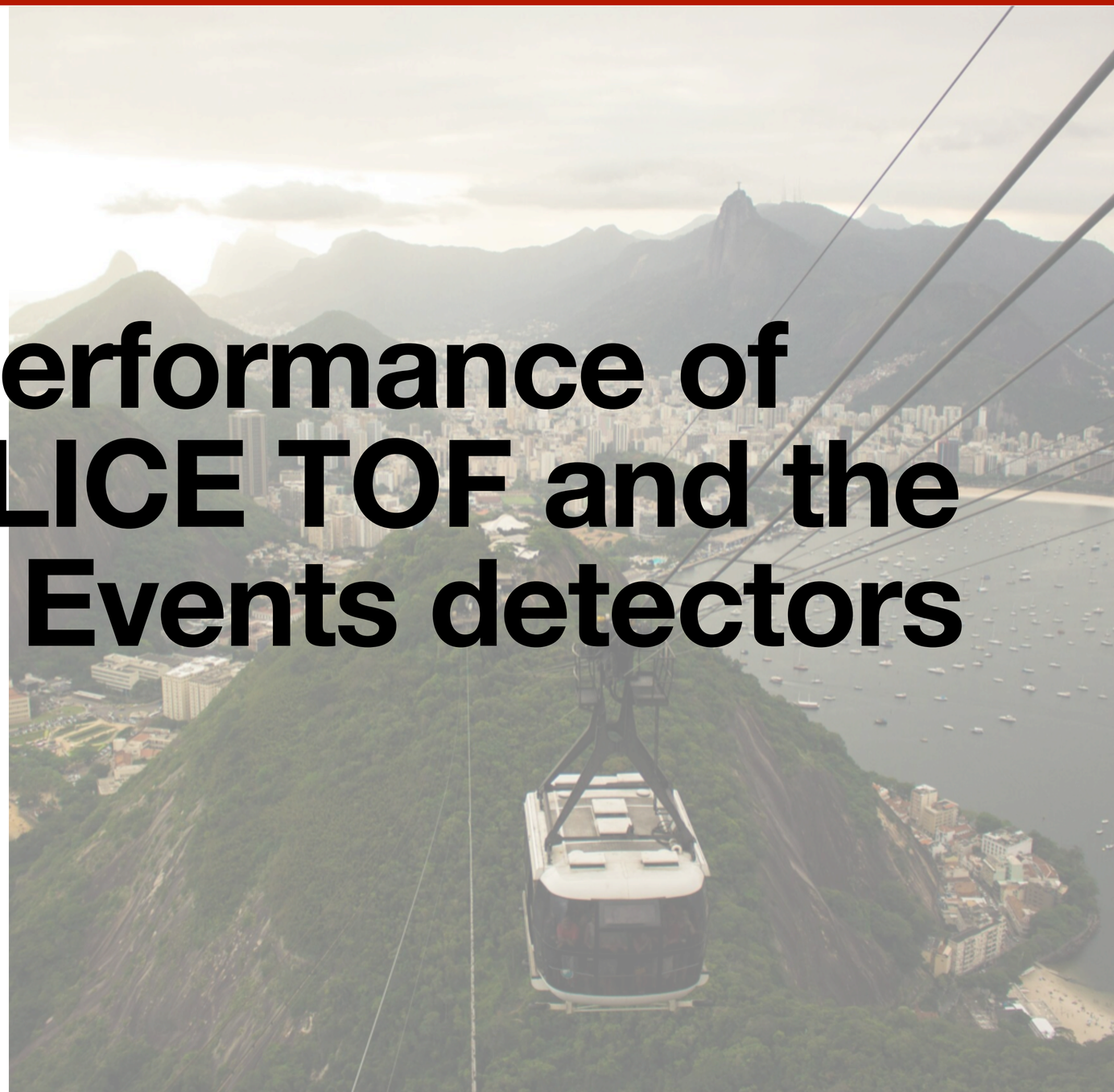
The long-term performance of MRPCs in the ALICE TOF and the Extreme Energy Events detectors

Bianca Sabiu[1]
On behalf of the ALICE and the EEE Collaborations

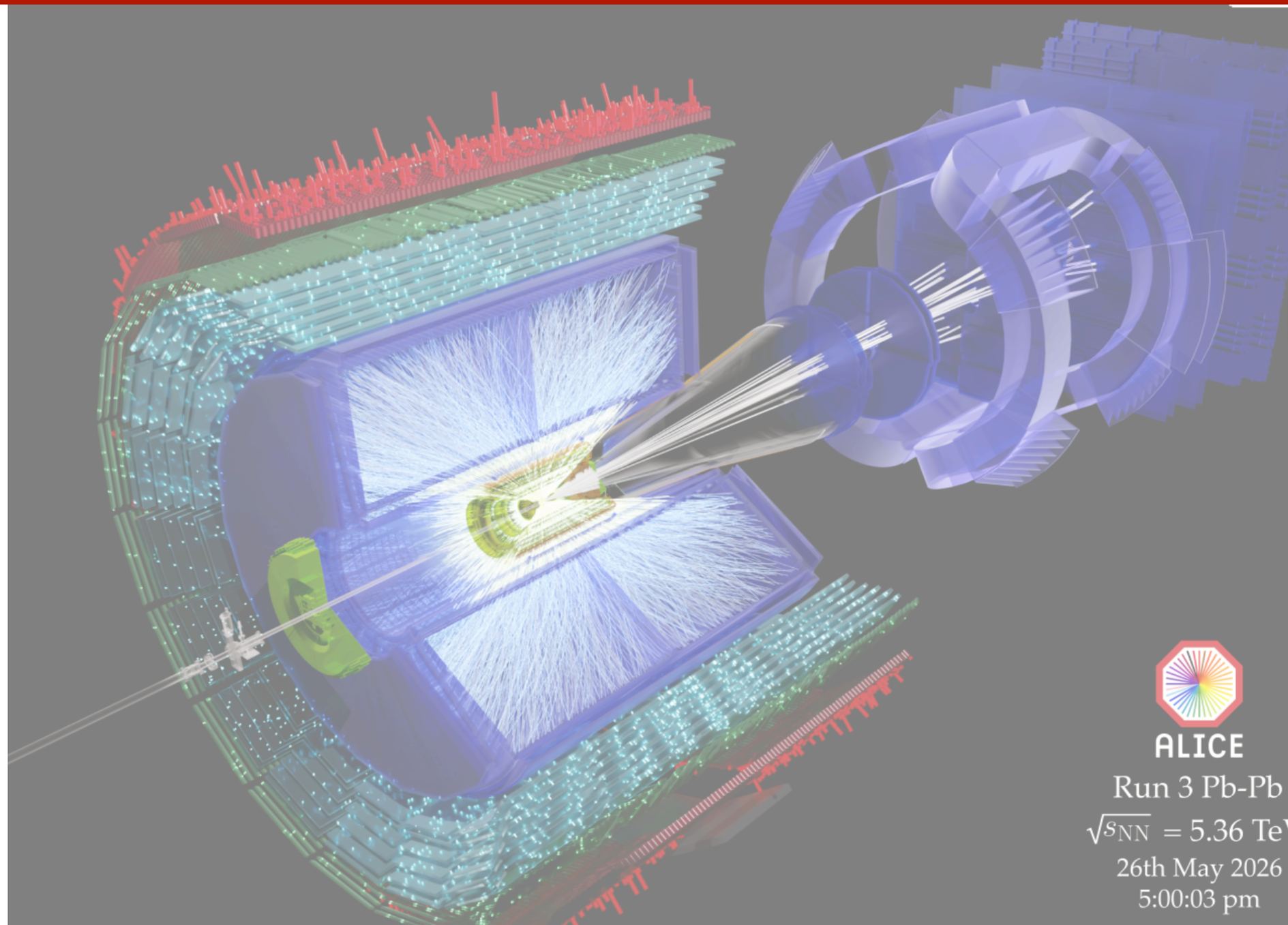
[1]University and INFN Bologna, CERN



RPC 2026
RIO DE JANEIRO

Overview

- **The ALICE TOF detector**
  - The ALICE detector
  - TOF MRPCs
  - TOF detector and LS2 upgrades
  - Run 3 performance
- **The EEE detectors**
  - MRPCs
  - Performance
  - Recent tests on gas mixture
  - Recent scientific results
- **Conclusions**


ALICE
Run 3 Pb-Pb
$\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV
26th May 2026
5:00:03 pm

The ALICE Detector in Run 3

- Dedicated **heavy-ion experiment** at the LHC designed for very high multiplicities (up to $dN_{ch}/d\eta$=8000)
- B=0.5 T, low material budget, continuous readout
- In Run 3 Pb-Pb 5.36 TeV total luminosity collected 6.9 nb^{-1}: ~120x (Run 1 + Run 2) total!
- Many new experimental techniques developed for Run 3

Tracker for low-p_T tracking down to 150 MeV/c, 35 μm pointing resolution at 1 GeV/c

ITS2 since Run 3

Two arrays of Cherenkov radiators with MCP PMTs for event time t_0 with intrinsic time resolution ~5-15 ps depending on collision system

FT0 since Run 3

GEM-based energy loss measurement up to 100 GeV/c

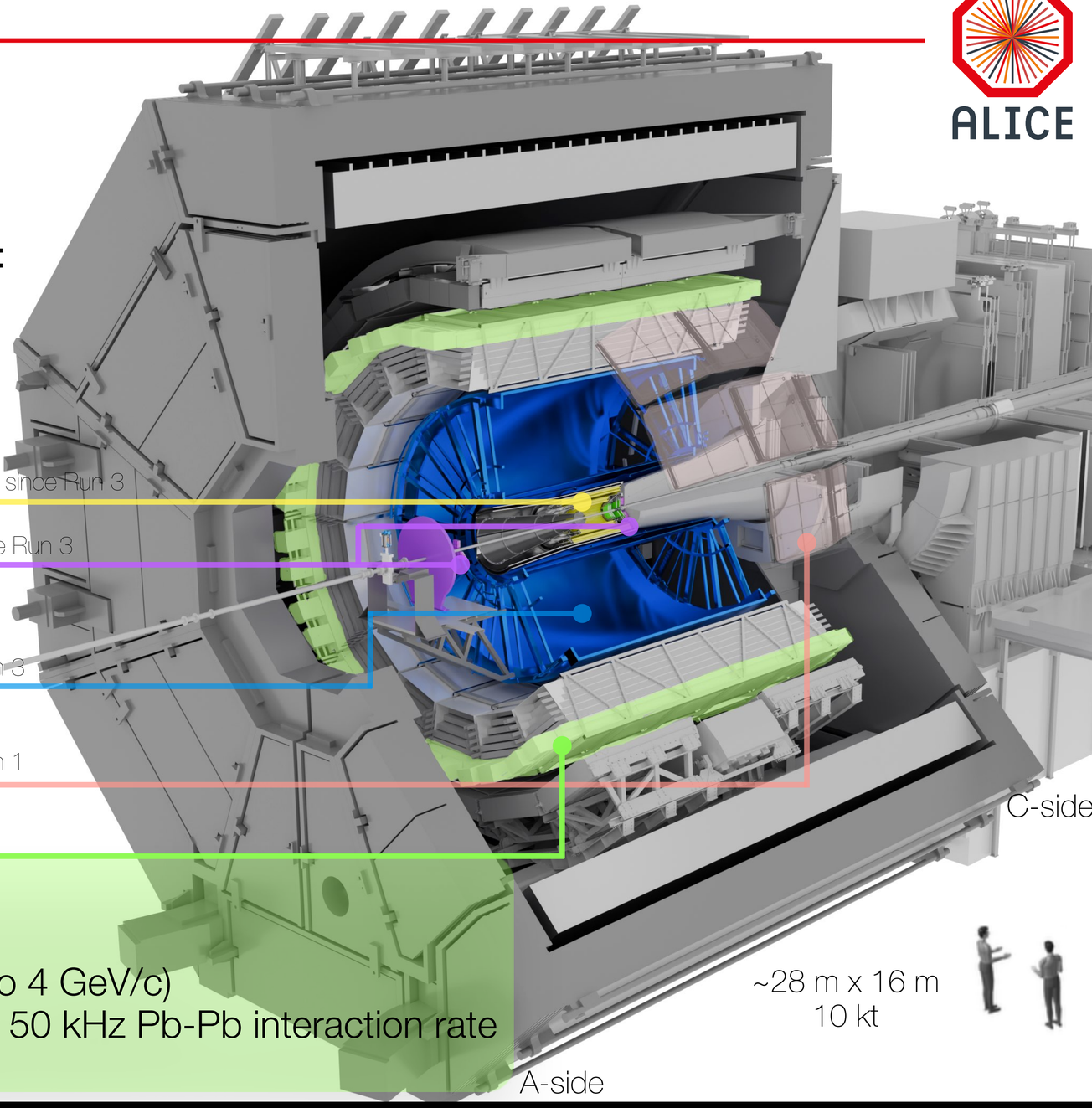
TPC since Run 3

RICH detector for high-momentum particles identification (π/K up to 3 GeV/c, K/p up to 5 GeV/c)

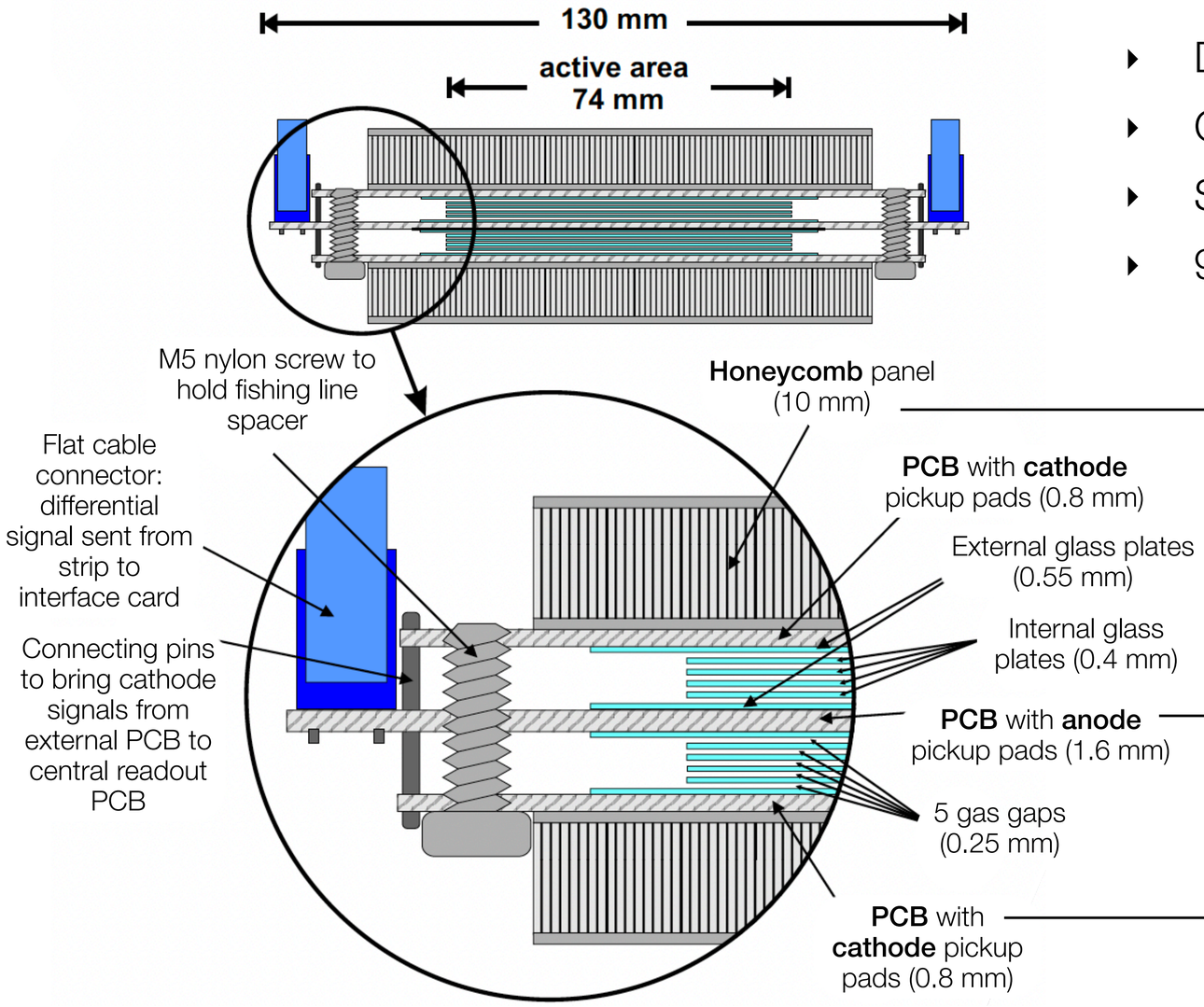
HMPID since Run 1

TOF since Run 1

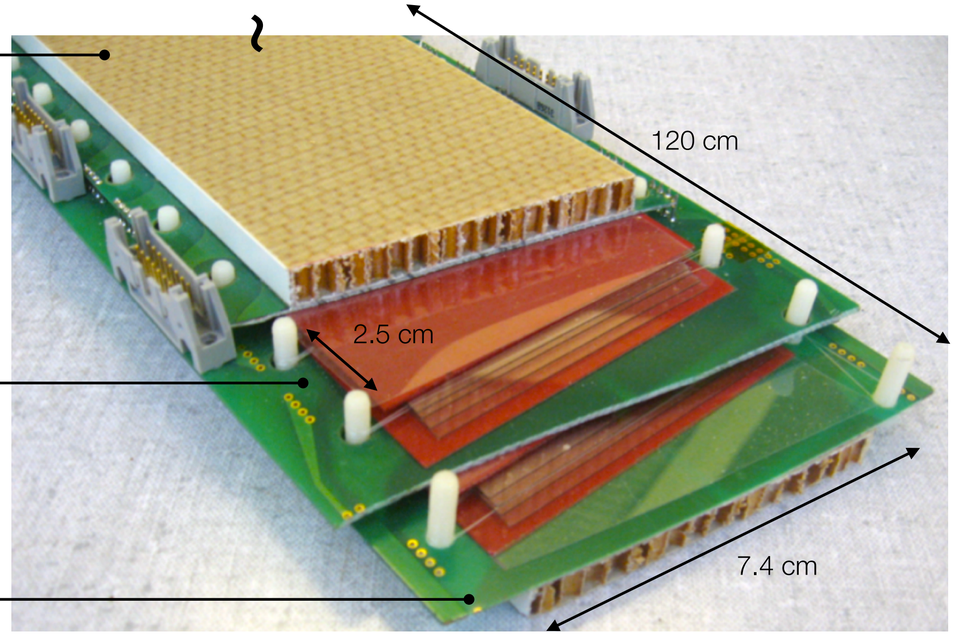
- ~140 m^2 , -0.9 < η < 0.9, 3.7 m < r < 4 m
- Low noise, high granularity, high efficiency
- PID at intermediate momenta (π/K up to 2.5 GeV/c, K/p up to 4 GeV/c)
- Continuous readout scheme (upgraded during LS2) to target 50 kHz Pb-Pb interaction rate
- **15 years of operation!**



The ALICE TOF MRPCs strip



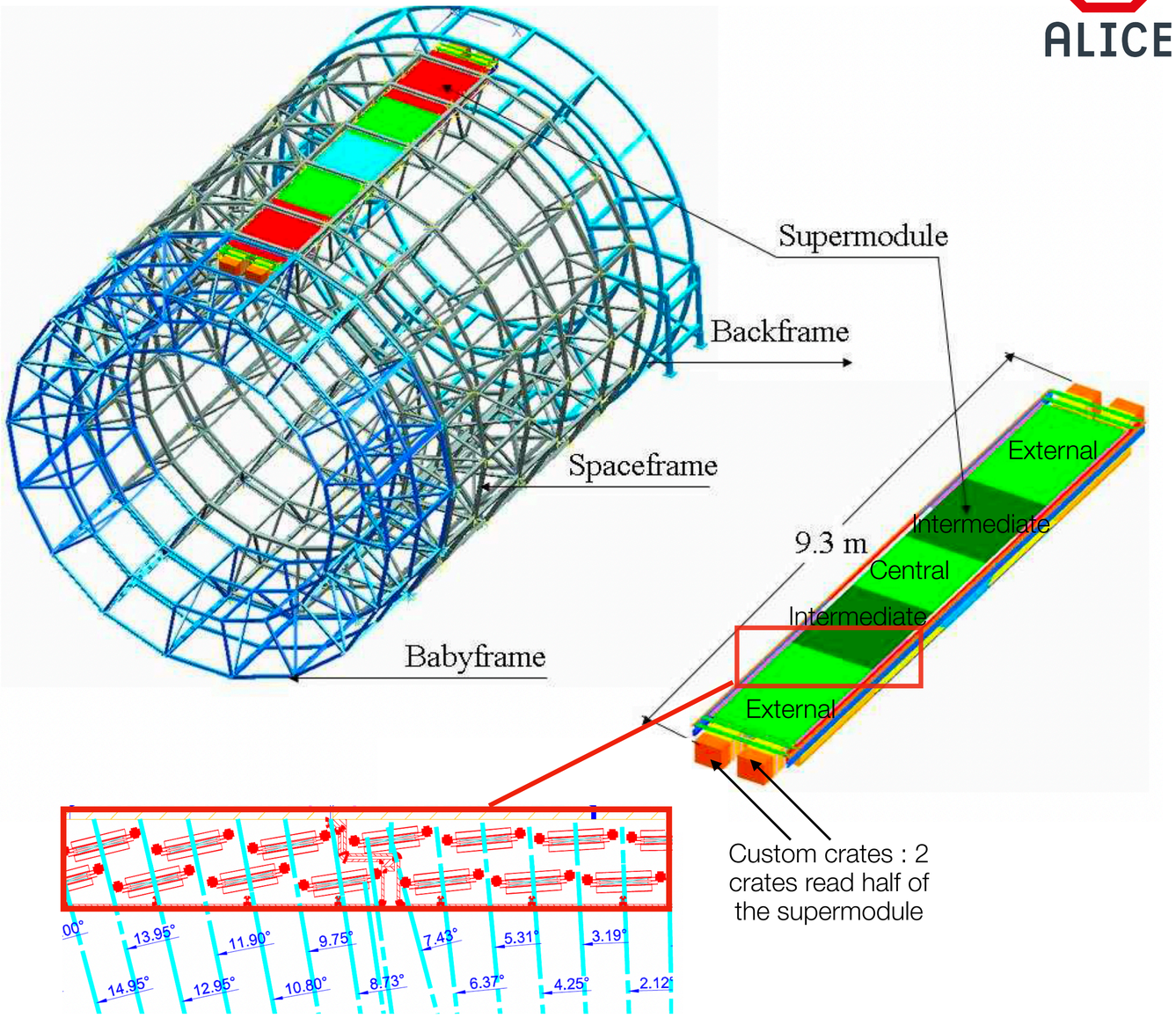
- Double-stack **M**ulti-gap **R**esistive **P**late **C**hambers
- Gas mixture: 93% Freon (R-134a) + 7% SF_6
- Strip of 120×7.4 cm^2 active area (~900 cm^2)
- 96 pickup pads per strip (~3.5×2.5 cm^2) on 2 rows



Thickness are reported in (mm)

The ALICE TOF detector (I)

- **18 supermodules** along ϕ for full 2π coverage
- Each supermodule has **5 modules** (x1 central, x2 intermediate, x2 external)
- Central module has 15 MRPC strips, intermediate and external modules have 19 strips each: 4x19+15=**91 strips per supermodule**
- 18x91=1638 strips in total facing the interaction point
- 3 central modules (45 strips) removed at ϕ=0 to reduce material budget in front of the PHOS (electromagnetic calorimeter for photons)
- (96 pickup pads×1638)-45x96=**152 928 readout channels**



The ALICE TOF detector (II)

- MRPC production finished in 2006
- Installation completed in 2008
- **First data taking in mid-2008**
- Low dark noise (~0.1 Hz/cm^2) and small intrinsic dead time (~10 ns) detector



Photo of an intermediate module

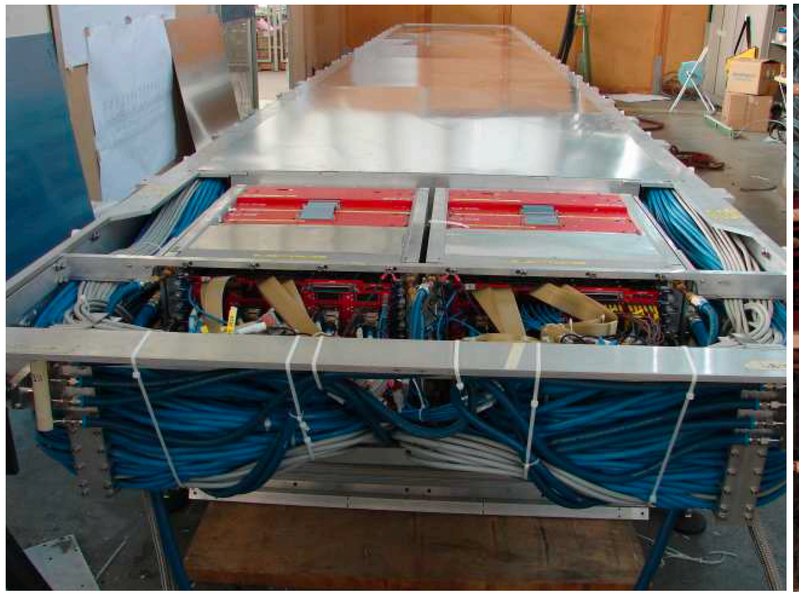
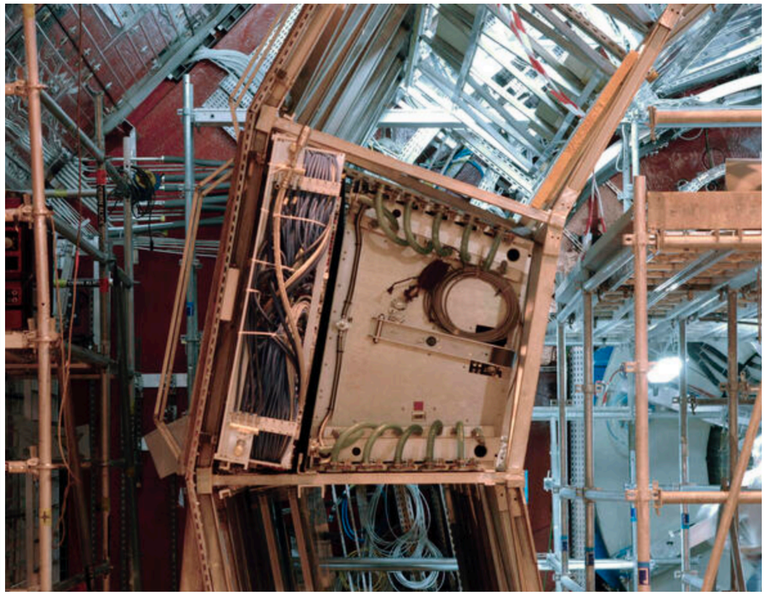


Photo of a fully assembled supermodule

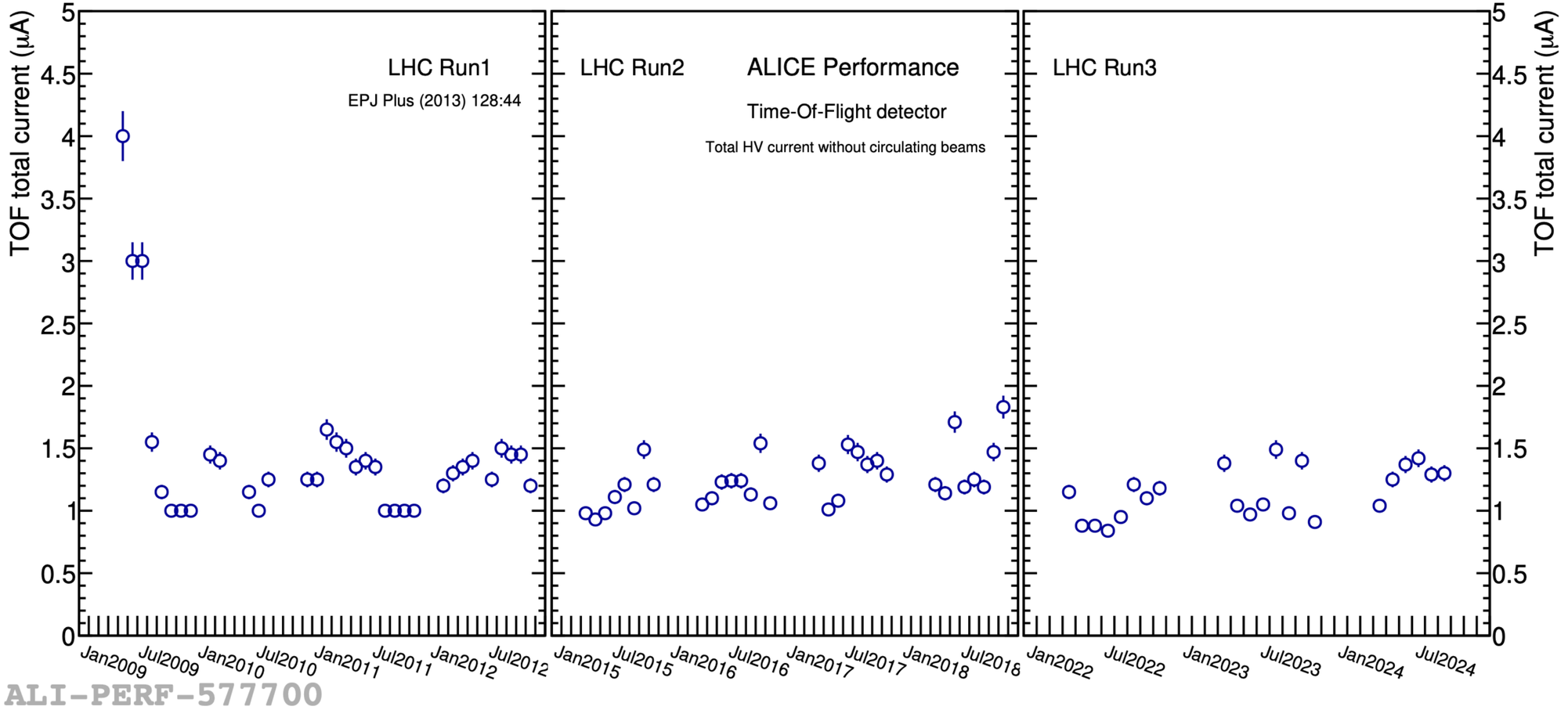


Two supermodules of the Time of Flight (TOF) and of the Transition Radiation Detectors (TRD) installed in their final position.

Recently published performance papers

- "15 years young: the ALICE TOF detector in the LHC Run 3", Strazzi S. for the ALICE Collaboration, NIMA 1077 170521 (2025) *https://doi.org/10.1016/j.nima.2025.170521*
- "Time resolution of the ALICE time-of-flight detector with the first Run 3 pp collisions at $\sqrt{s}$ =13.6 TeV", ALICE Collaboration, EPJ Plus 141 914 (2026) *https://doi.org/10.1140/epjp/s13360-026-07626-4*

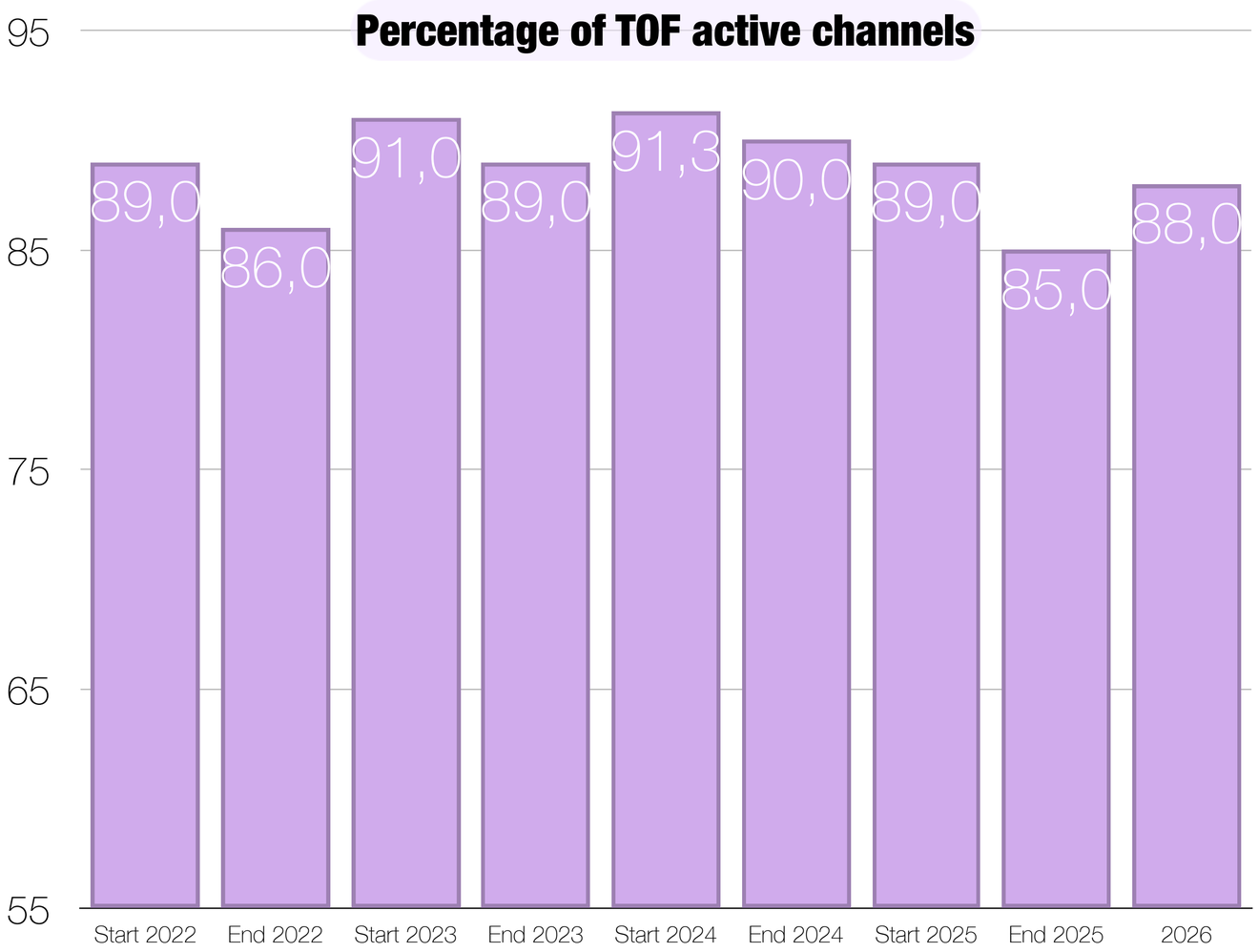
TOF operation: current



- Few nA average current per MRPC
- Current measured without circulating beams

Current is low and stable since 2009: **no signs of aging**

TOF operation: active channels and availability during beam time



Percentage of availability during beam time

- 2018 → ~98%
- In 2025-2026 **Run 3 pp** → 99.9%
- in 2025-2026 **Run 3 Pb-Pb** → stable at **~98%** at **top interaction rate for ~400 hours of readout**

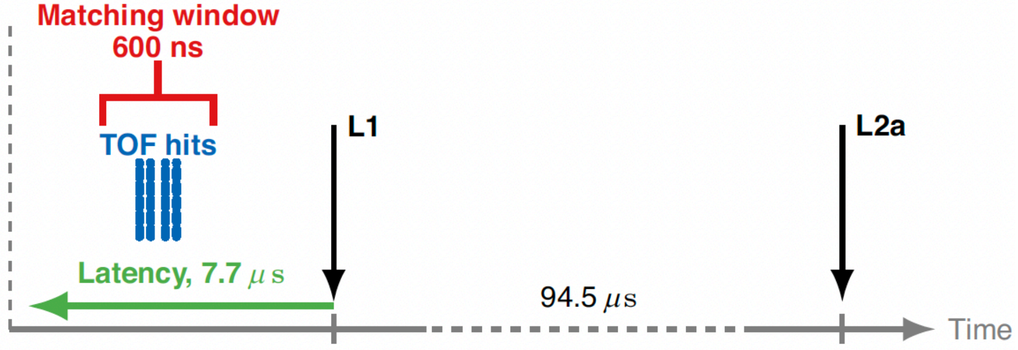
- the missing ~2% is due to readout inefficiency (triggers in pause to reset the electronics while running): ***not to MRPCs***!

Stable number of active channels and availability during beam time throughout the years

Upgrade during LS2

During LS2 (2019-2021), many ALICE detectors upgraded to a **continuous readout scheme** to cope with increased luminosity and handle the (targeted) **50 kHz Pb–Pb** interaction rate

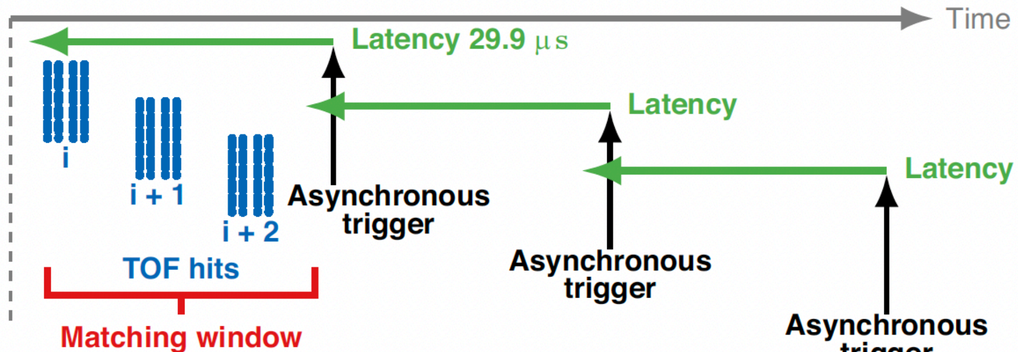
Run 1 - Run 2



Eur. Phys. J. Plus (2026) 141:914

- **TOF** readout in Run 1 and 2:
  - Trigger was received by Central Trigger Processor (CTP)
  - The TDC opened a latency window of ~8 μs with a matching window of 600 ns
  - One single collision event

Run 3



Eur. Phys. J. Plus (2026) 141:914

- **TOF upgraded** readout in Run 3:
  - Periodic trigger, asynchronous wrt physics events
  - 30 μs large latency window and periodic triggers at $f=3/t_{LHC_{orbit}}$ ~33 kHz to cover the full LHC orbit time
  - New Digital Readout Module (DRM2) designed and commissioned
  - In continuous readout, the event definition coincides with the **collision vertex of reconstructed tracks**

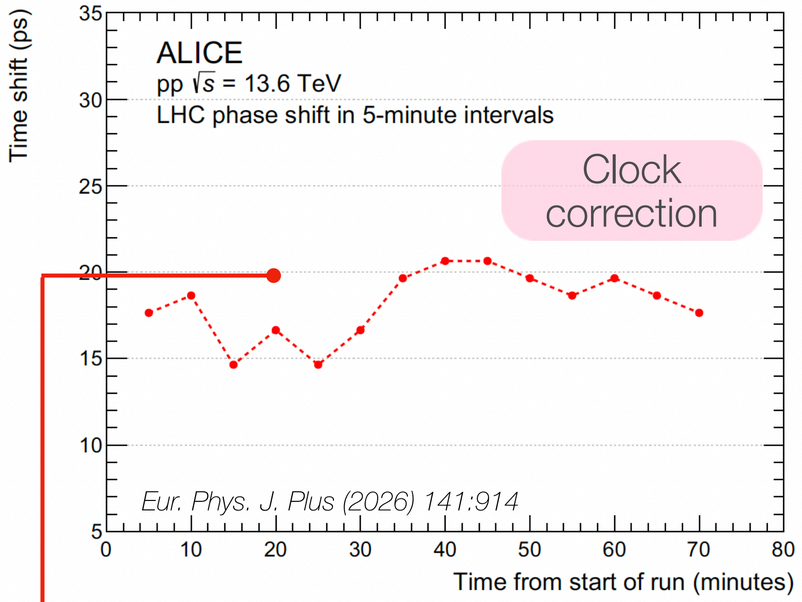
The timing information from FT0 must match the LHC bunch crossing time

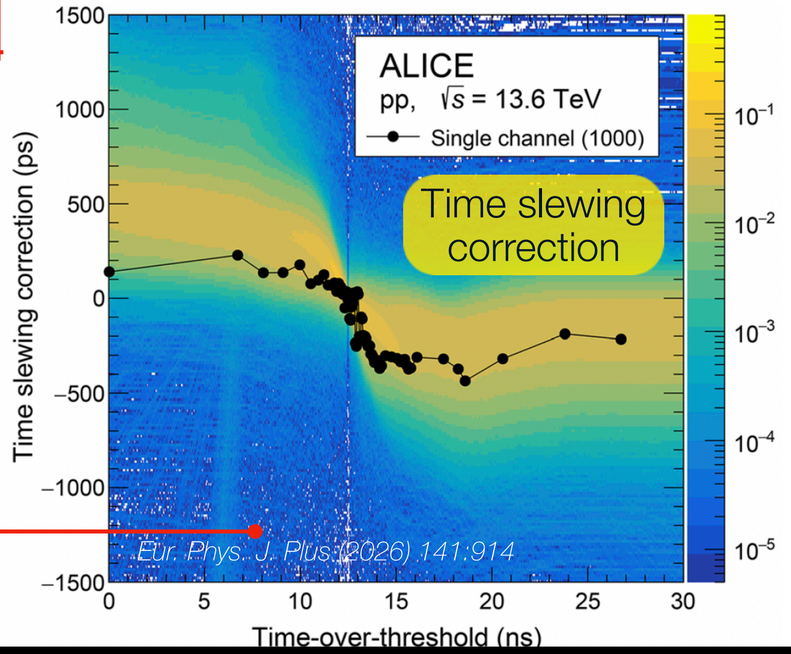
TOF online and offline calibrations

- **General calibration:**
  - At the start of each Run (*DCS calibration*) to get active channels map
  - During the data taking (*sync calibration*)
    Tracking detectors are also calibrated at this stage
  - Offline (*async calibration*) with better tracking reconstruction quality and with time slewing correction

- **Time calibrations:**
  - TOF/ALICE **clock shift** relative to the LHC clock (every 5 min)
  - **Channel-by-channel** calibrations (global offsets run-by-run, charge dependence via TOT determined over several runs)
    Usually 100 entries needed per channel i.e. 5 10^6 pp collisions (~15 mins of data taking)

✳ From Run 1 to Run 2 improvement of the event time resolution **from ~80 ps to ~60 ps** thanks to the refined time slewing calibration procedure





TOF discrimination power

- The TOF measures the time of arrival of particles at the detector t_{TOF}
- Under the mass hypothesis:

$$m_{TOF} = \frac{p}{c}\sqrt{\frac{c^2 t^2}{L^2} - 1}$$

$$\left(\frac{\delta m_{TOF}}{m}\right)^2 = \left(\frac{\delta p}{p}\right)^2 + \left(\gamma^2 \frac{\delta L}{L}\right)^2 + \left(\gamma^2 \frac{\delta t}{t}\right)^2$$

Dominant at high momenta

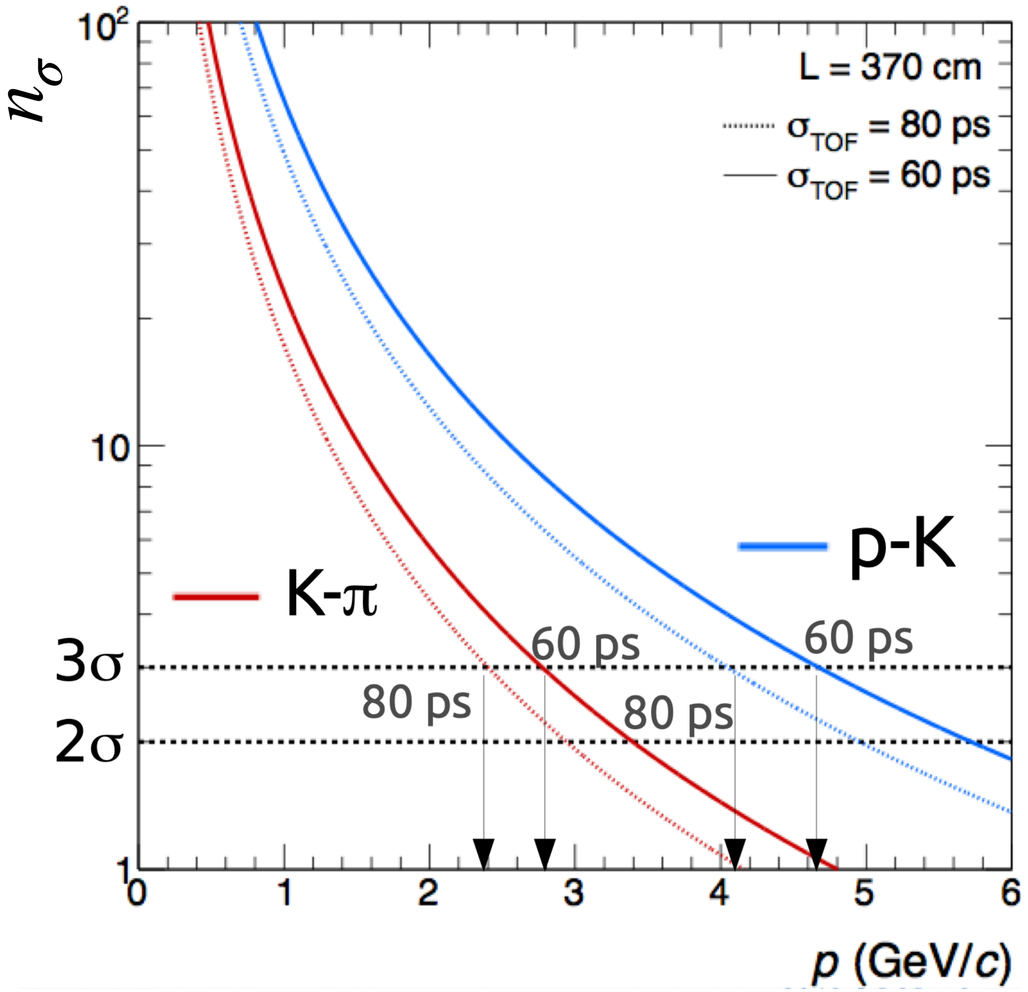
- Considering two different particle masses:

$$\Delta t_{i,j} = t_i - t_j \simeq \frac{Lc}{2p^2}(m_i^2 - m_j^2)$$

the discrimination power can be written as

$$n_\sigma = \frac{\Delta t_{i,j}}{\sigma_{TOF}}$$

Intrinsic TOF resolution: MRPC (~50 ps), FEE, calibration



↓ resolution, ↑ momentum limit for PID

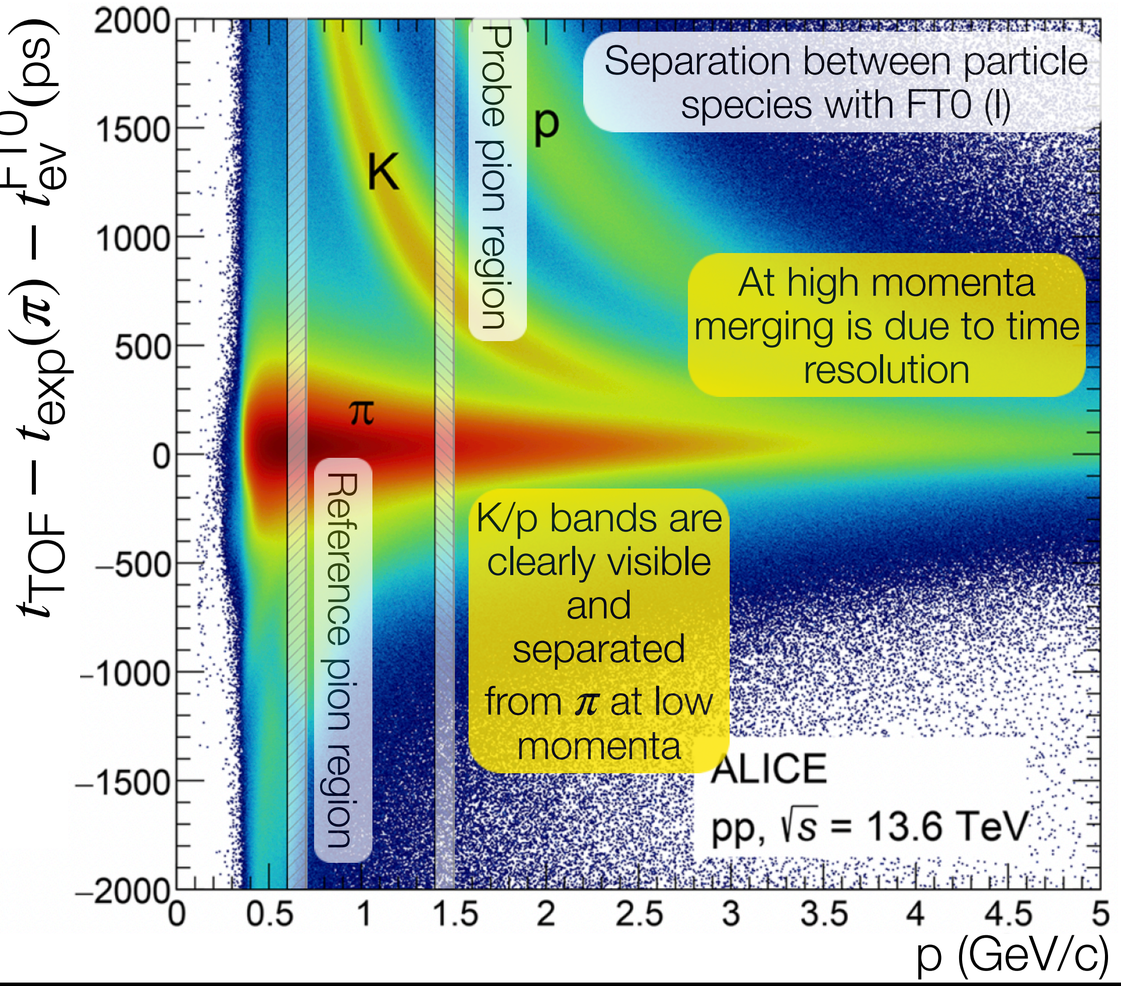
Performance: time resolution (I)

- σ_{TOF} can be computed (for any collision system) via 2 different methods:

(I) via time difference with **event collision time** from FT0 reference trigger detector (used in plot below)

(II) In a **self-consistent** measurement: with time difference between 2 tracks matched with TOF in same event under given mass hypothesis

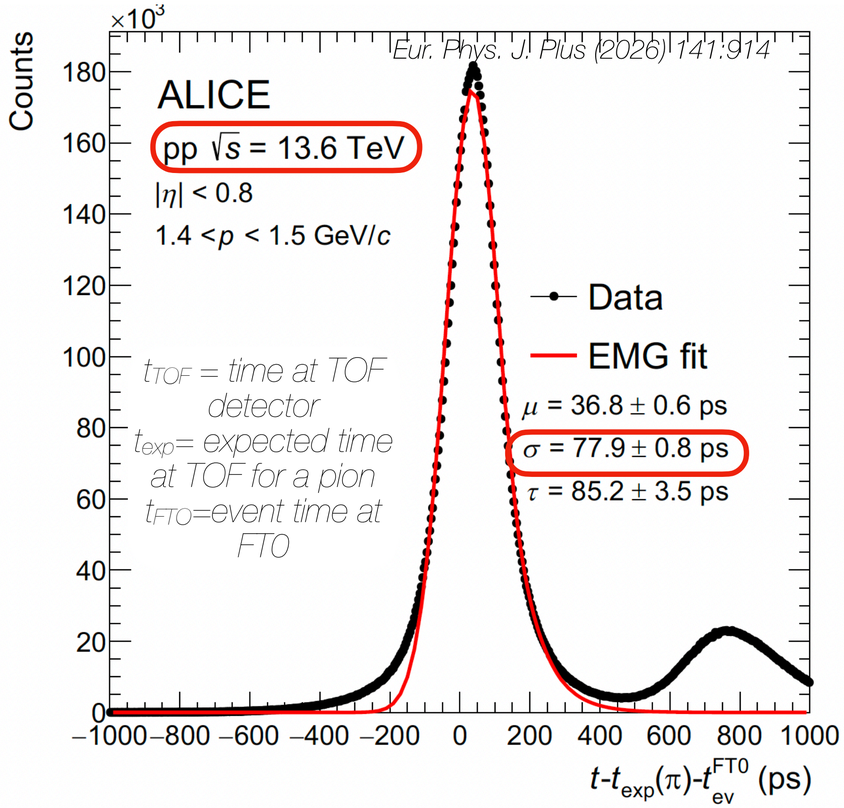
Ex. under π mass hypothesis: considering as reference pion region 600-700 MeV/c → time difference between two pions→ reference time resolution σ_{ref} (square root of the sigma of the fit on time difference)→from probe pion region you subtract the reference time resolution from the fit sigma



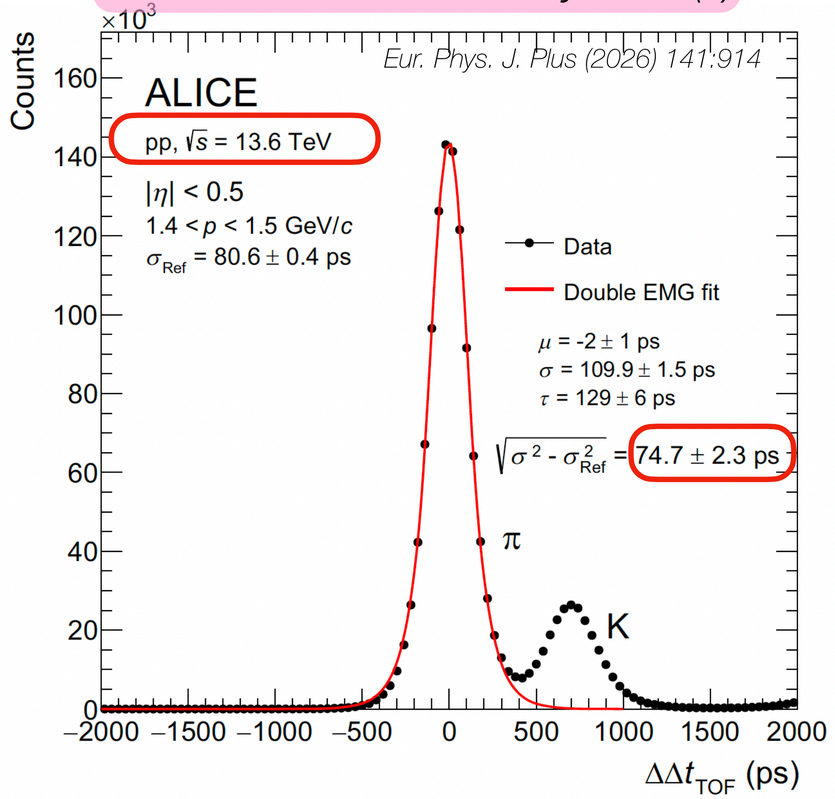
Performance: time resolution (II)

- σ_{TOF} can be computed (for any collision system) via 2 different methods:
  - (I) via time difference with **event collision time** from FT0 reference trigger detector (used in plot below)
  - (II) In a **self-consistent** measurement: with time difference between 2 tracks matched with TOF in same event under given mass hypothesis

Time resolution with FT0 (I)



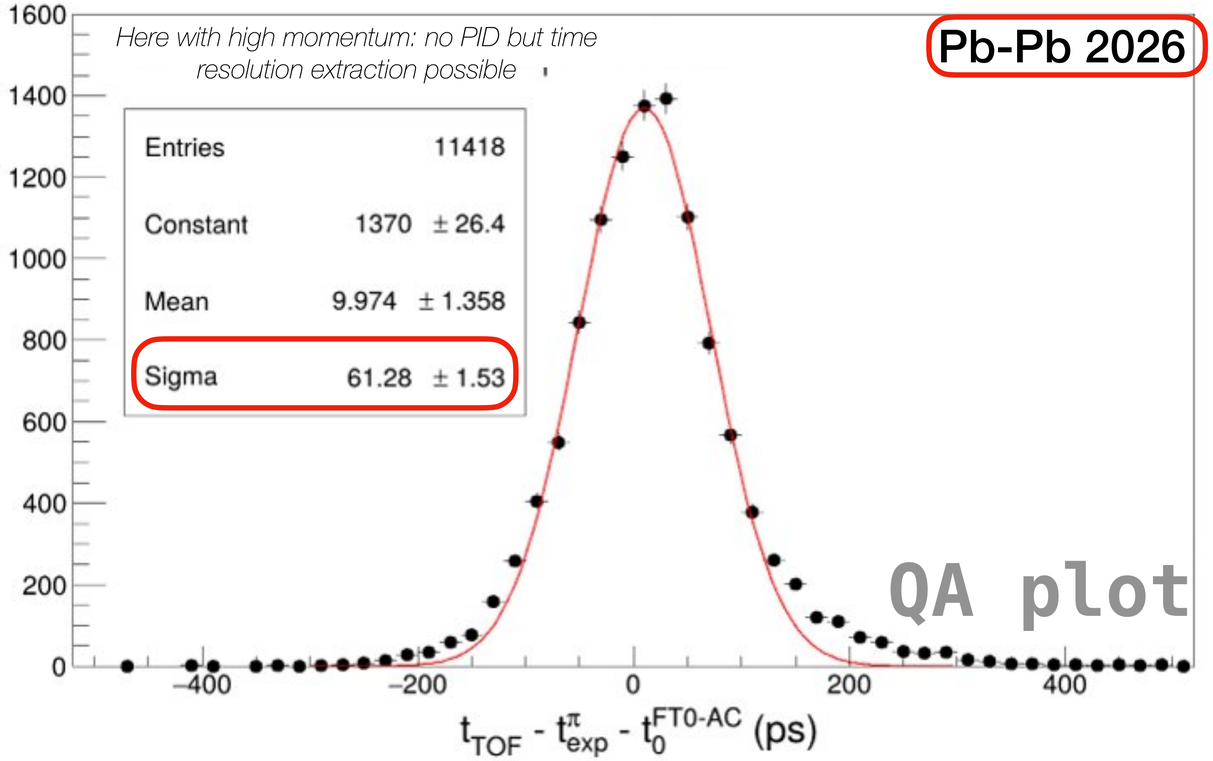
Time resolution with only TOF (II)



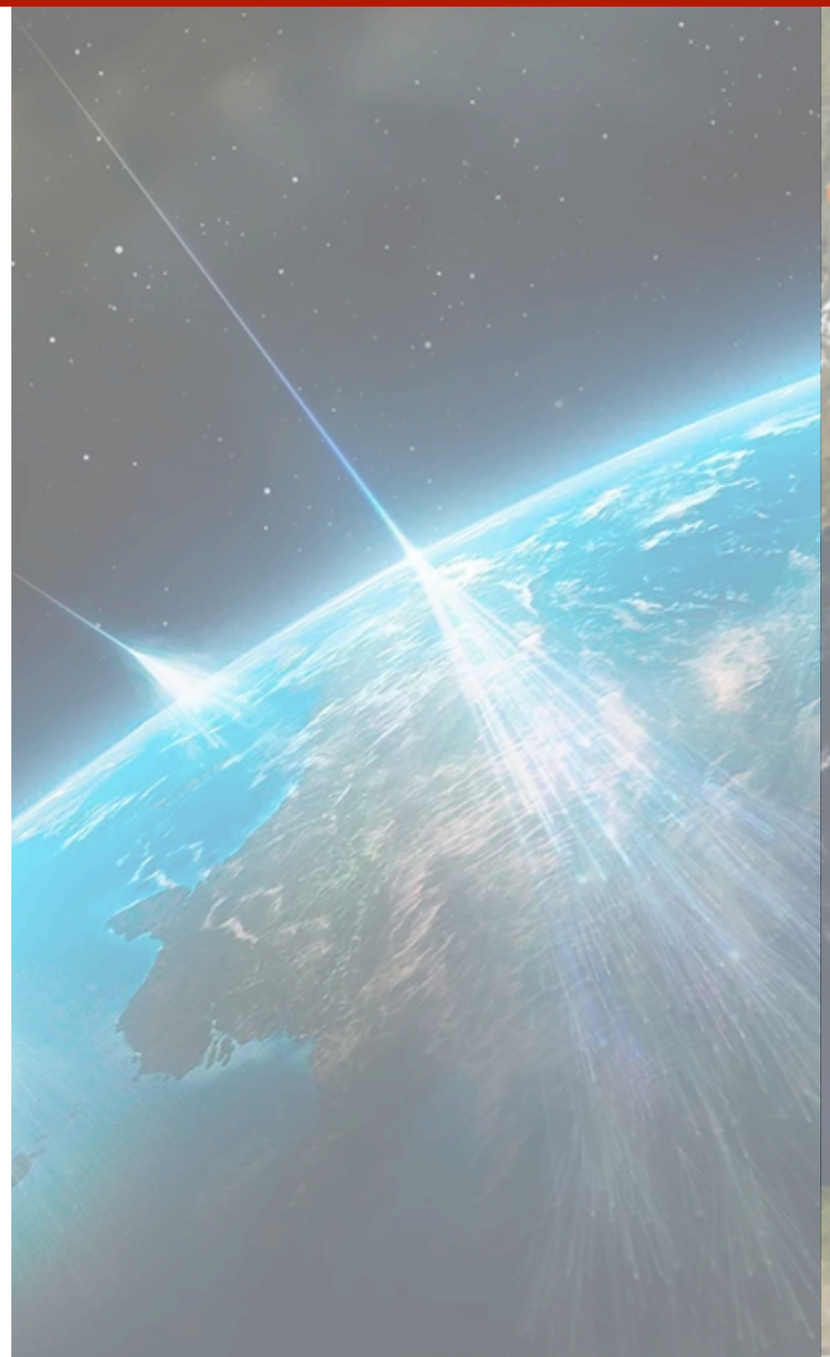
The two methods are in agreement!

Performance: time resolution (III)

- σ_{TOF} via event collision time in Run 3 with **Pb-Pb collision**
  - Because $\sigma_{event} = \sigma_{TOF}/\sqrt{N_{\text{tracks}}}$ in high multiplicity events many more tracks are produced per collision: TOF time resolution driven by event multiplicity reference/start time precision not by MRPC performance
- Time resolution of ~ 61 ps for high momentum range after refined calibration
- In agreement with Run 2 ~57 ps (with refined TOT calibration)



Excellent and stable time resolution of **~60 ps** after more than 15 years of operation!





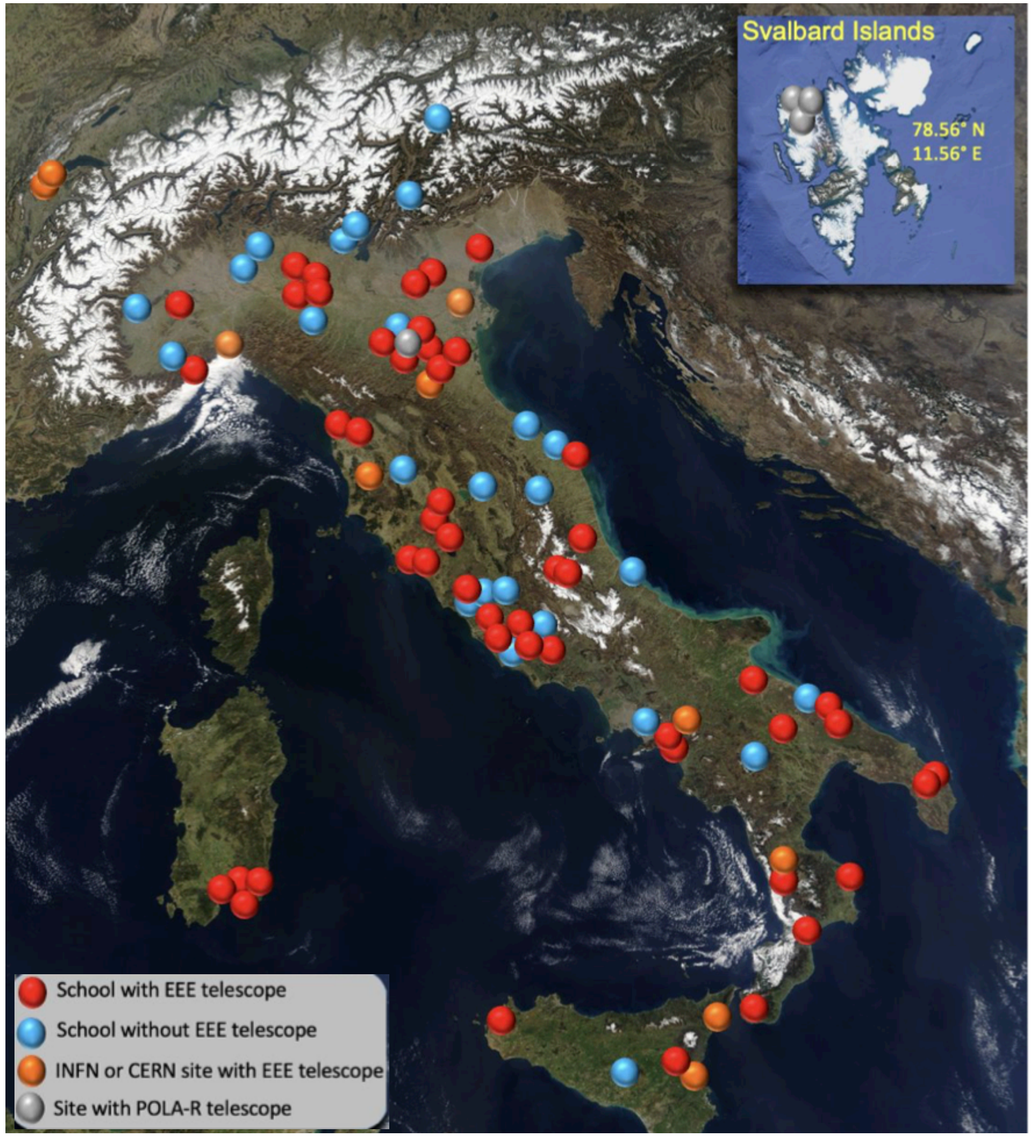
The EEE project

The **Extreme Energy Events Project** is a Centro Ricerche Enrico Fermi (CREF) & INFN Experiment with dual role

- **Cosmic ray experiment**: detection and study of high energy cosmic rays at ground level, detecting extensive air showers produced by primary interaction in the atmosphere
- **Scientific education**: involve high school students in *all* the phases of the experiment

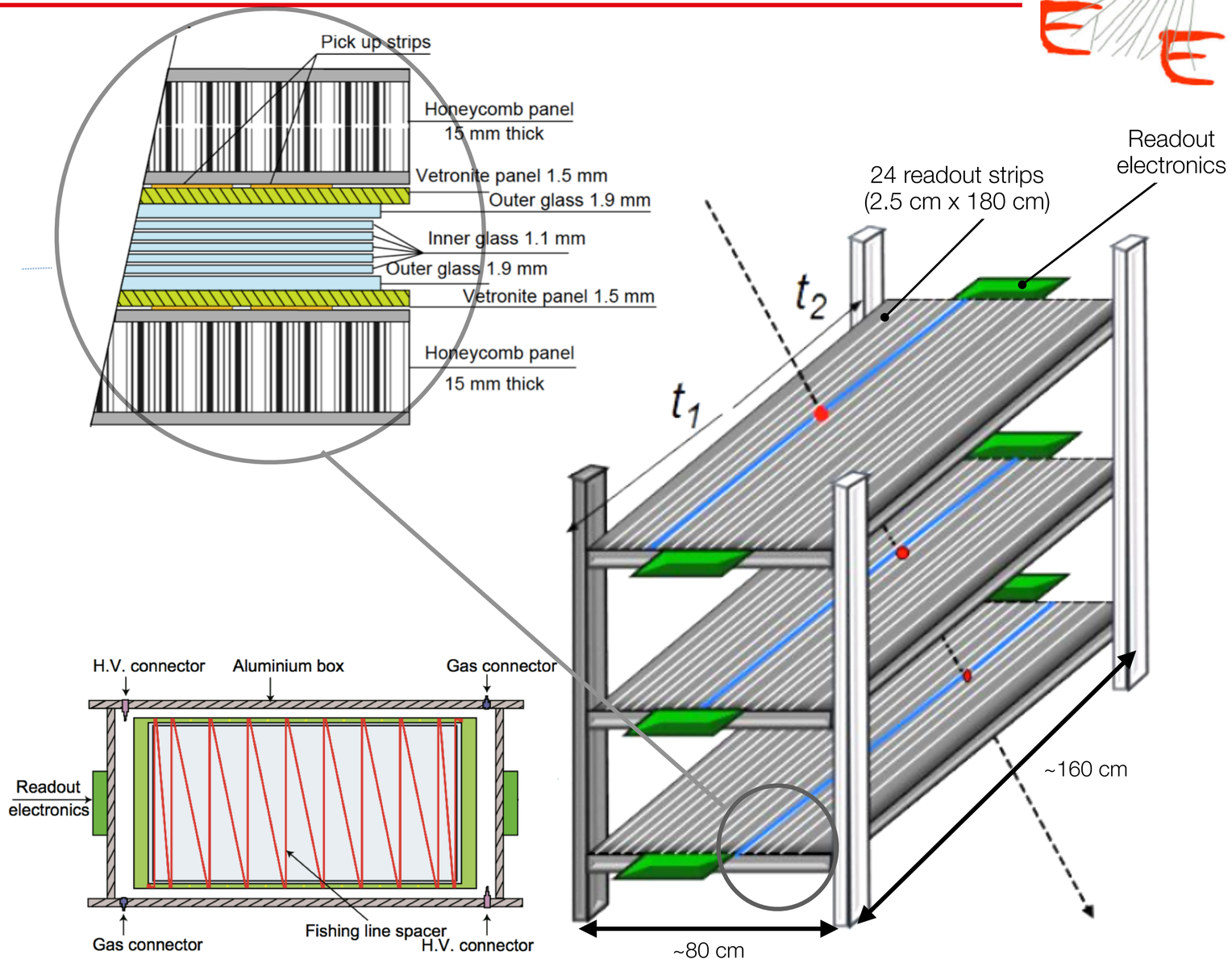
A network of **>50 muon tracking telescopes**, GPS synchronized, installed inside Italian high schools, INFN laboratories, CREF and CERN over an area larger than $3x10^5$ km^2

+ since 2019, some telescopes at Svalbard Islands with scintillators and SiPMs are installed as northernmost permanent monitor



The EEE telescope

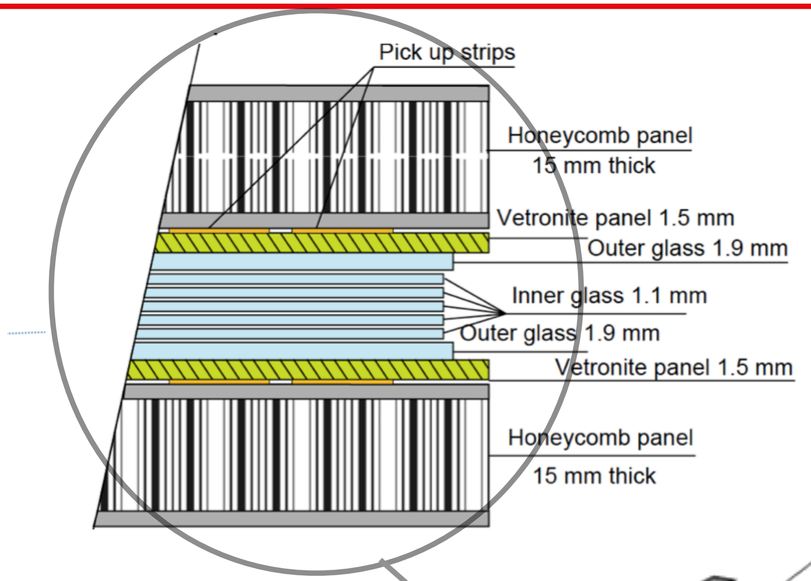
- The telescopes are constituted by 3 large area (~160x80 cm^2) **single stack** MRPCs
- Each MRPC has **six gas gaps** and is built **similarly** to **ALICE TOF MRPCs**
- MRPC signal pick-up electrodes segmented in 24 strips
- ~1 cm spatial resolution and **~240 ps* time resolution** with cosmic rays (after time slewing correction) *De Gruttola et al. JINST 14 C05022 (2019)*

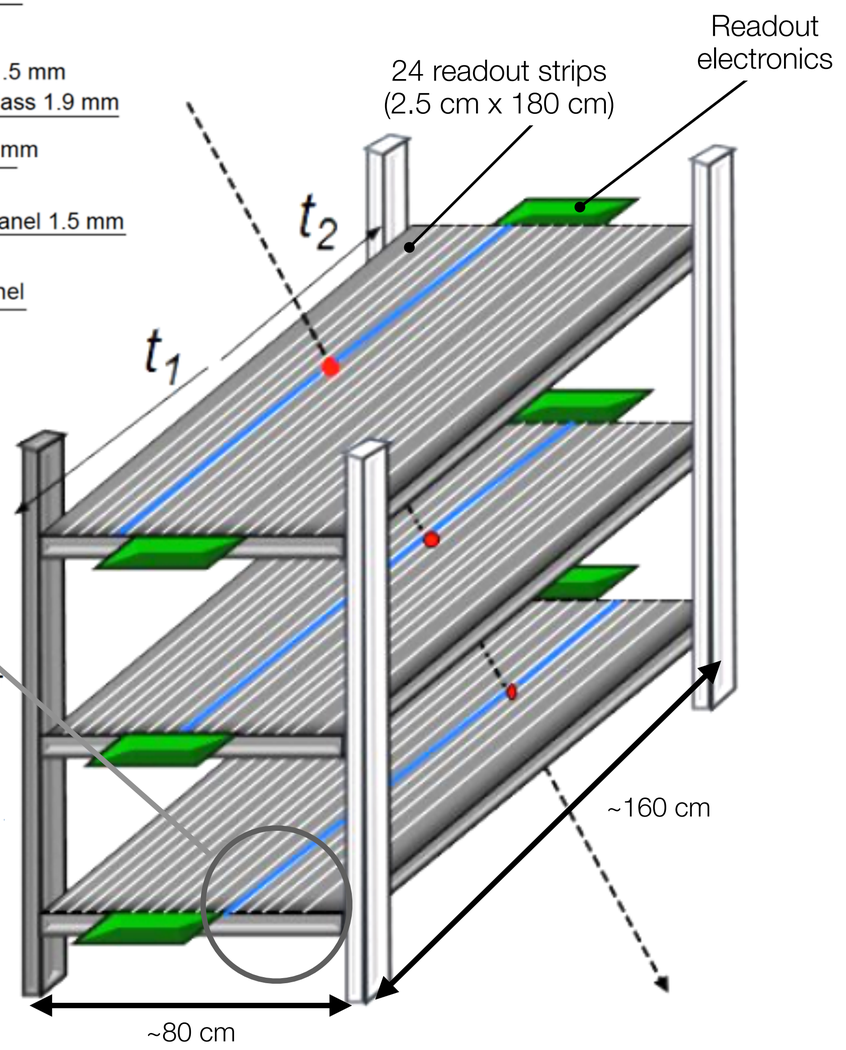


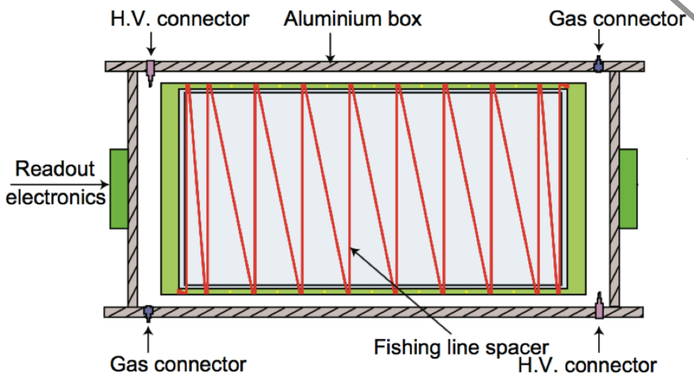
** The MRPC time resolution in beam test is ~70-100 ps*

The EEE telescope

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- MRPC signal pick-up electrodes segmented in 24 strips
- ~1 cm spatial resolution and **~240 ps* time resolution** with cosmic rays (after time slewing correction) *De Gruttola et al. JINST 14 C05022 (2019)*







- Until 2020 gas mixture **98% $C_2H_2F_4$** (R-134a) **and 2% SF_6**

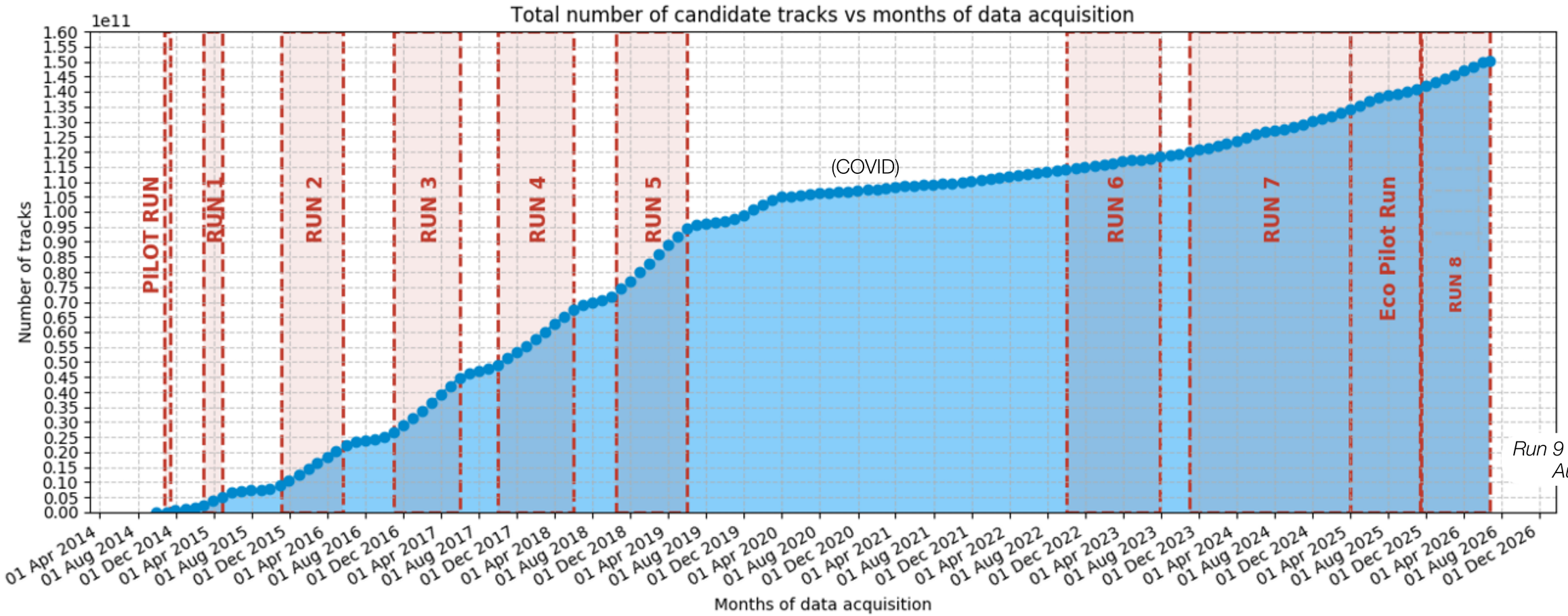
From 2020, the telescopes have a **new gas mixture** based on **eco-friendly** solutions

M. Abbrescia et al 2024 JINST 19 P11003

  - Helium at 50%
  - $C_3F_4H_2$ (R-1234ze) (*ECO Freon*) at 50%
- Open loop with ~1 L/h gas injection

** The MRPC time resolution in beam test is ~70-100 ps*

Runs overview from 2014 until now



Run 9 to start this Autumn!

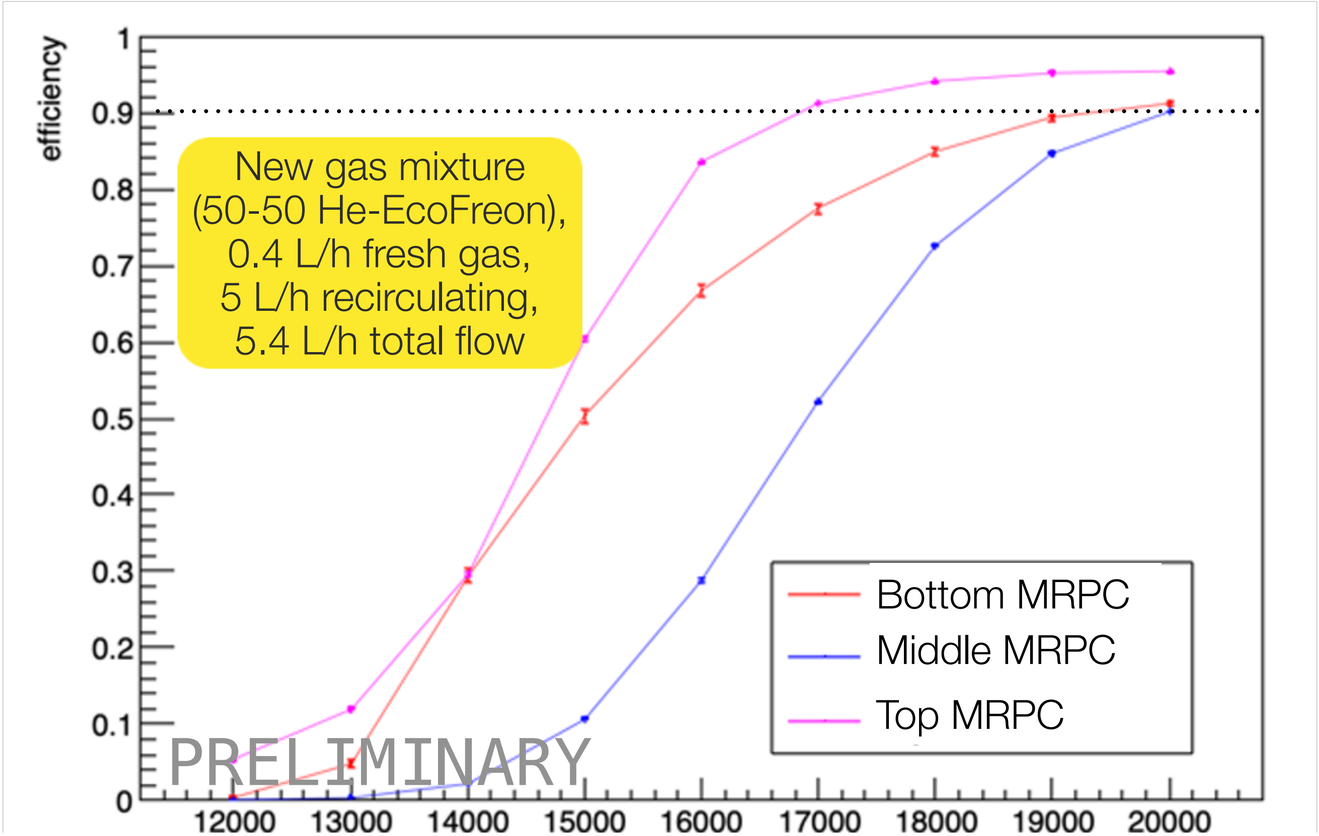
Stable data taking since 2014 with a total of >150x10^9 candidate tracks!

Recent tests with gas recirculating system

- Together with **CERN Gas Group** new prototype of telescope with a low cost recirculating system featuring
  - Input/loop rotameters
  - Humidity sensors before and after the detector
  - Pressure sensors and buffer volumes before and after the pump
  - Bubblers
- Recent tests with different L/h injection in the recirculating system
  - Fresh gas flux of **0.4 L/h (93% recirculating!)**

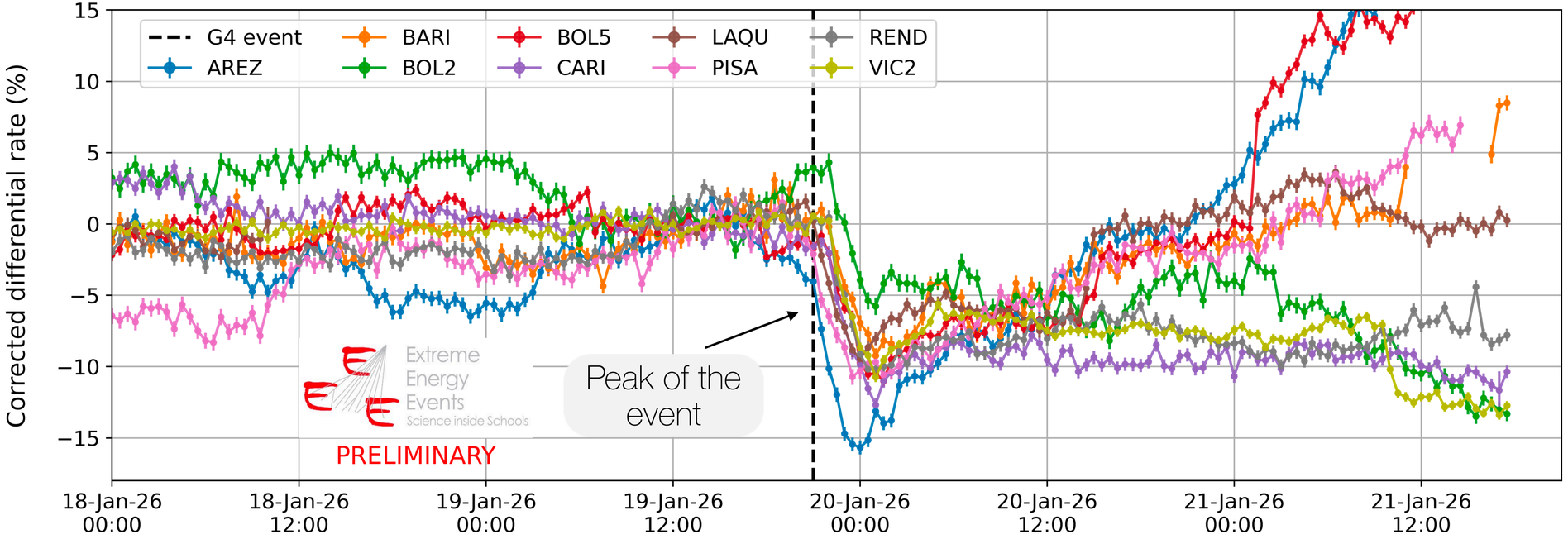
Stable operation and efficiency **>90%,** in agreement with standard and new mixture performance

  - Now trying to go to 0.2 L/h and to have a small transportable setup in the schools!



Example of recent scientific results

- Observation of **Forbush decrease** in 2024 with uniform response and performance with eco-friendly gas mixtures (*Abbrescia et al. EPJ Plus 141 790 2026*)
- **Preliminary results** from a new Forbush decrease in **2026** (see *M. Rasà talk at CRIS-MAC Conference 2026*)



A ***Forbush decrease*** is a sharp temporary drop in the intensity of cosmic rays (few to ~20%) caused by coronal mass ejections (CMEs) or high-speed solar wind streams

The differential rates are pressure-corrected by the barometric coefficient

Summary

- >1600 MRPC strips with >150 000 readout channels: **large area stable and efficient high-performance detector** in operation since 2008
  - ➡ More than **15 years of operation**
- Currents low and stable since 2009
  - ➡ **no signs of aging of MRPCs**
- LS2 upgrade to continuous readout
  - ➡ No performance loss
- Via reliable calibration procedures, event time resolution is improved and stable over time
  - ➡ **~60 ps time resolution** in Run 2 and Run 3 Pb-Pb with refined calibration and through different analysis methods

WHAT'S NEXT: Consolidation works during **LS3**: among others, production, validation and installation to replace faulty TOF TDC Readout Modules (TRMs) with new TDC card based on PicoTDC (instead of HPTDC)

- Network of **muon tracking telescopes based on MRPCs**
- Stable data taking since 2014 with >150x10^9 candidate tracks collected
- Transition to **eco-friendly gas** mixture since 2020 matching the performance of standard mixture
- Ongoing R&D on a **gas-recirculating system** with CERN showing promising >90% efficiency with 93% recirculation
  - ➡ Toward compact and transportable to schools telescope units
- **Rich and growing scientific output**
  - ➡ Network's long-term value as a genuine research instrument not only educational tool

WHAT'S NEXT: Complete for all the telescopes the passage to eco-friendly gas system

Two very different scales but common MRPC technology which continues to prove itself as a robust, reliable and long-lived detector technology, more than 20 years after its original design

Thank you



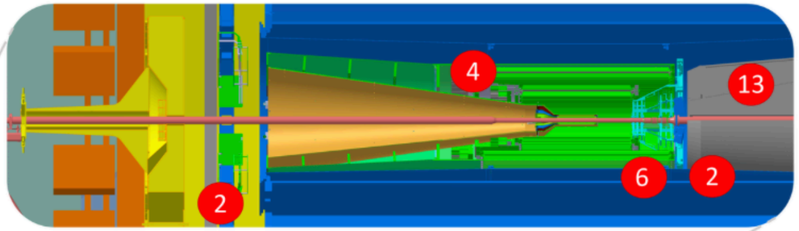
"The title of your talk makes me think of the long and close cooperation and friendship"

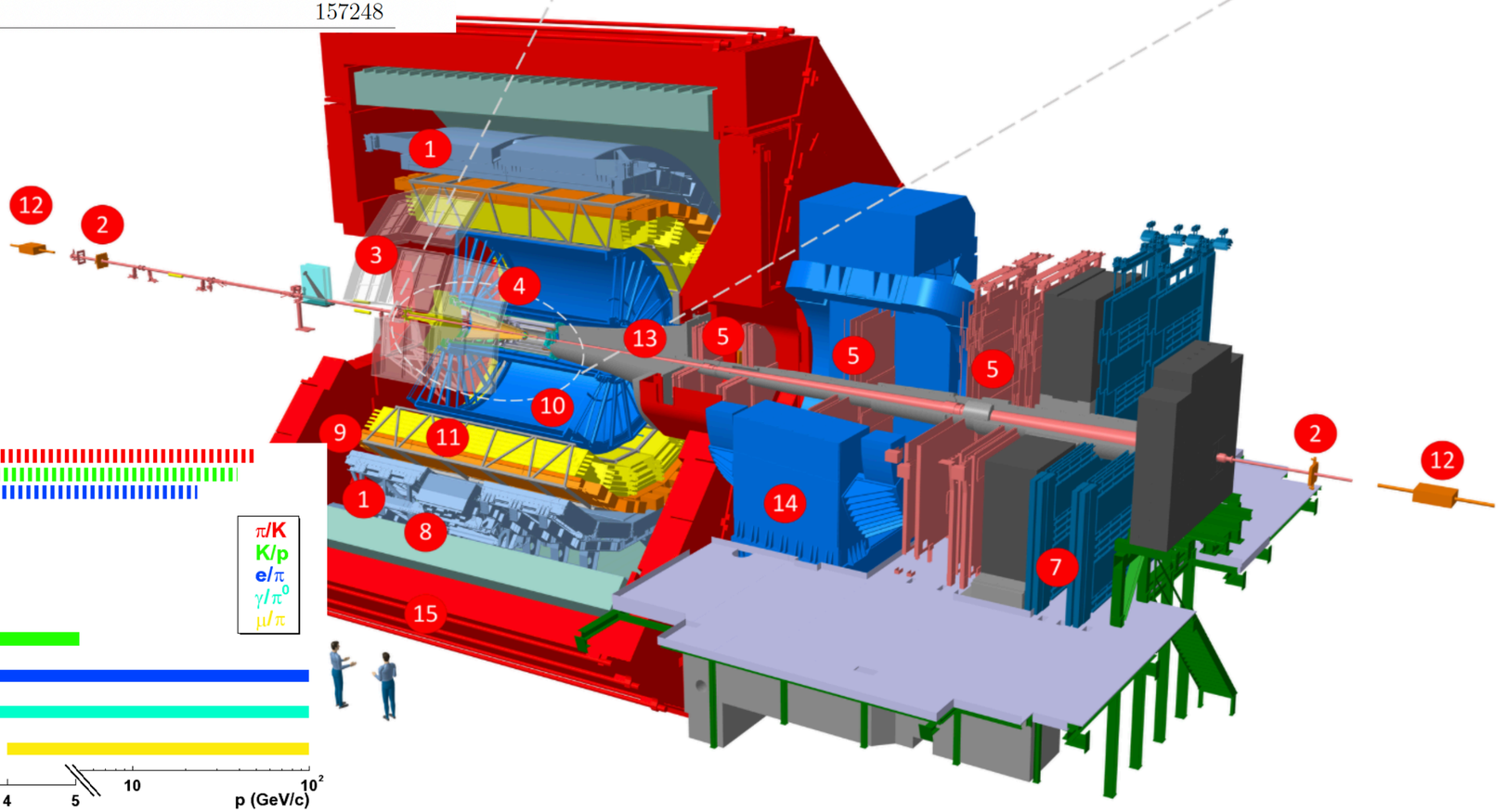
Backup

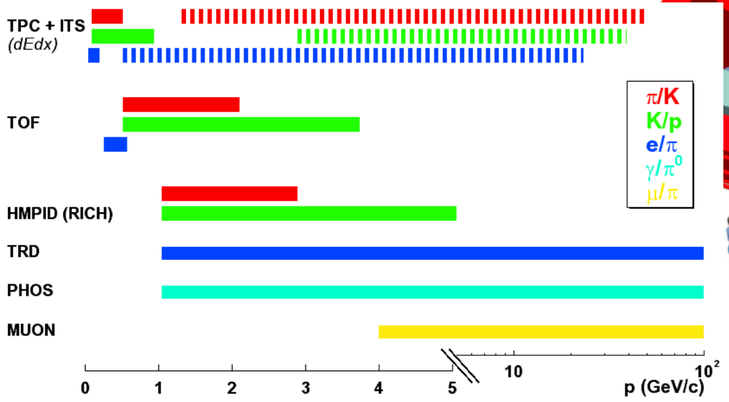
ALICE

TOF parameters

Pseudorapidity coverage	$-0.9 < \eta < 0.9$
Azimuthal coverage	2π
Radial position	$370 < r < 399$ cm
Radial thickness	$X/X_0 = 29.5\%$
Active area (total area)	141 m^2 (171 m^2)
ϕ-segmentation	18-fold
z-segmentation	5-fold
Readout pad geometry	3.5×2.5 cm^2
Total number of modules	90
Total number of strips	1638
Number of readout channels	157248



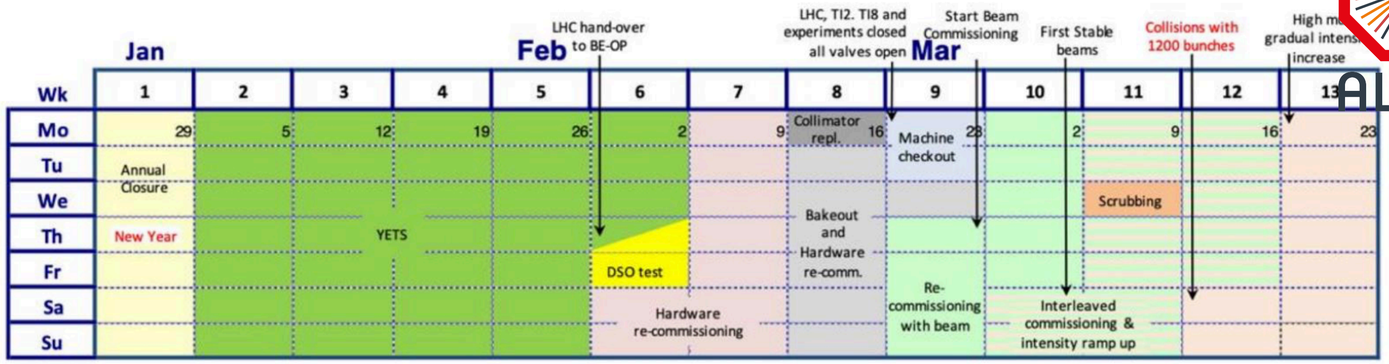


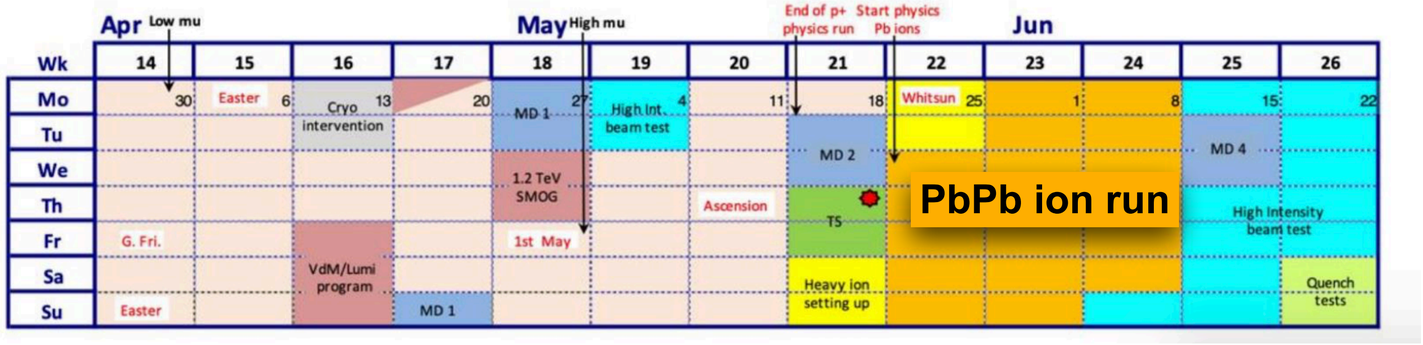


1. **EMCAL |** Electromagnetic Calorimeter
2. **FIT |** Fast Interaction Trigger
3. **HMPID|** High Momentum Particle Identification Detector
4. **ITS|** Inner Tracking System
5. **MCH|** Muon Tracking Chambers
6. **MFT|** Muon Forward Tracker
7. **MID|** Muon Identifier
8. **PHOS/CPV|** Photon Spectrometer
9. **TOF|** Time Of Flight
10. **TPC|** Time Projection Chamber
11. **TRD|** Transition Radiation Detector
12. **ZDC|** Zero Degree Calorimeter
13. **Absorber**
14. **Dipole Magnet**
15. **L3 Magnet**

2026 Pb Pb overview

- 27th May 2026 - 13rd June 2026 PbPb: 18 **Ion days** of physics run
- **LHC performance**: 49.4% stable beam time with average fill lenght ~5.32h
- ALICE **~89.3% data taking efficiency** (eval as total time in SB / tot running time)
- **Background**: preliminary test during ion setup in -/- magnet polarity configuration (collimator setting at IP8, introduced in 2025 for LHCb)
  - ➡ In the end same setting as 2025 as the test showed no difference so ALICE took data in -/- configuration up to the end of Run 3
- **EOR** dominated by beam dump

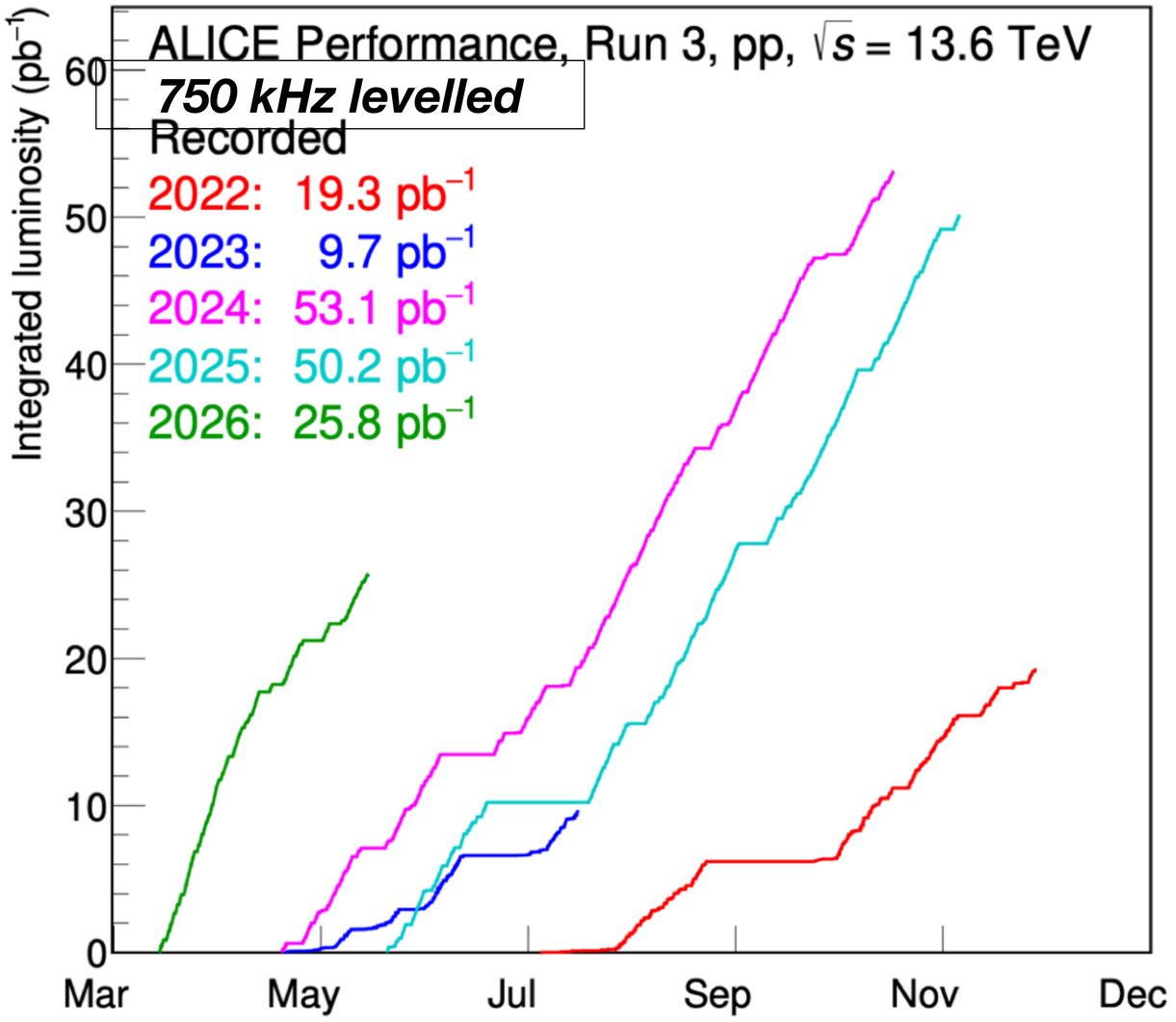


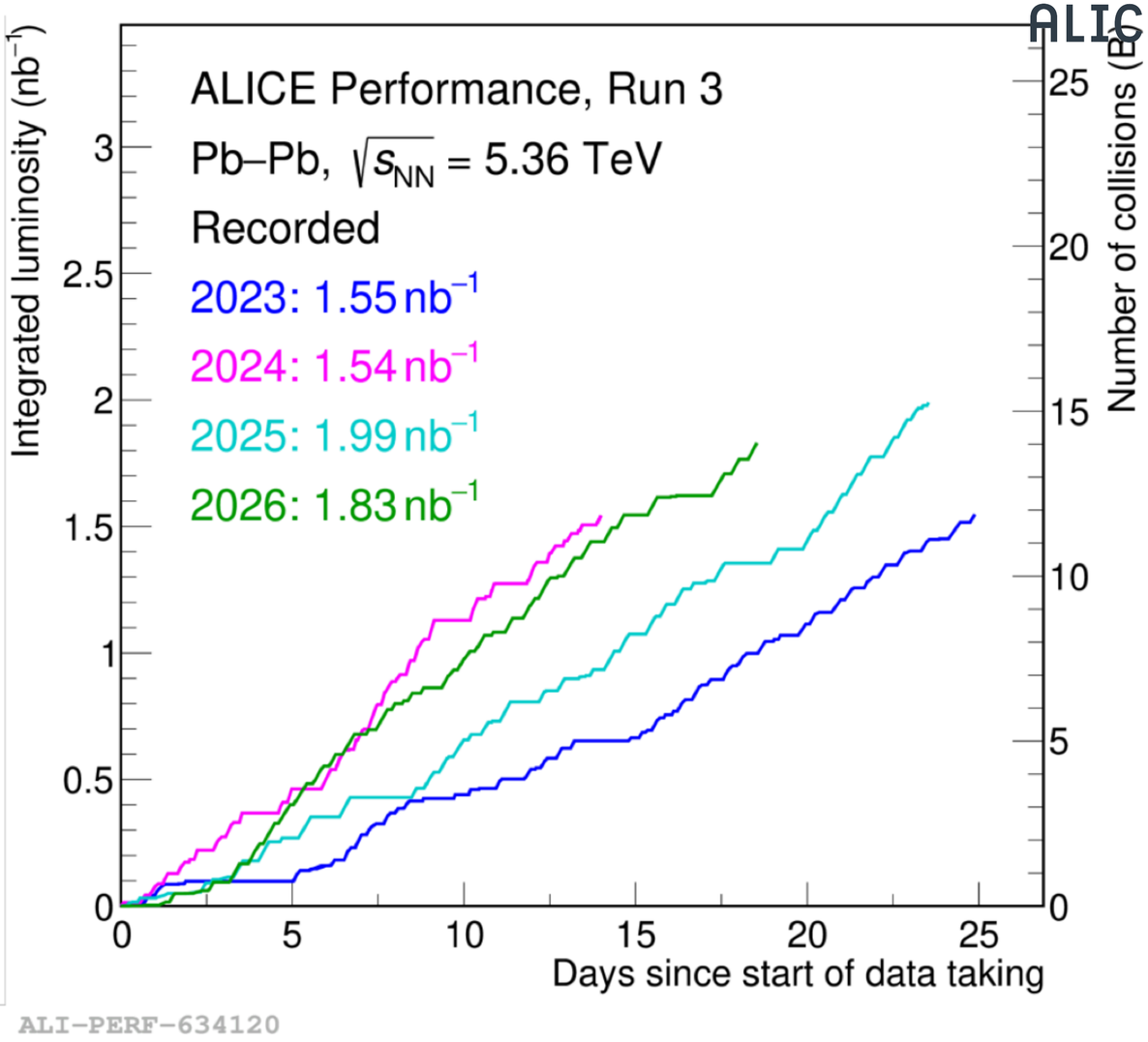


System	Luminosity in Run 3
Pb-Pb 5.36 TeV	6.9 nb^{-1} (collected) **~120x Run 1+2 total**
pp 13.6 TeV	158.1 pb^{-1} (inspected via software triggers) **~1000x Run 1+2 total**

Extra: 5.0 nb^{-1} **OO,** 0.8 nb^{-1} **Ne-Ne,** 7.2 nb^{-1} **pO**

ALICE in Run 3 : pp overview and PbPb 2026





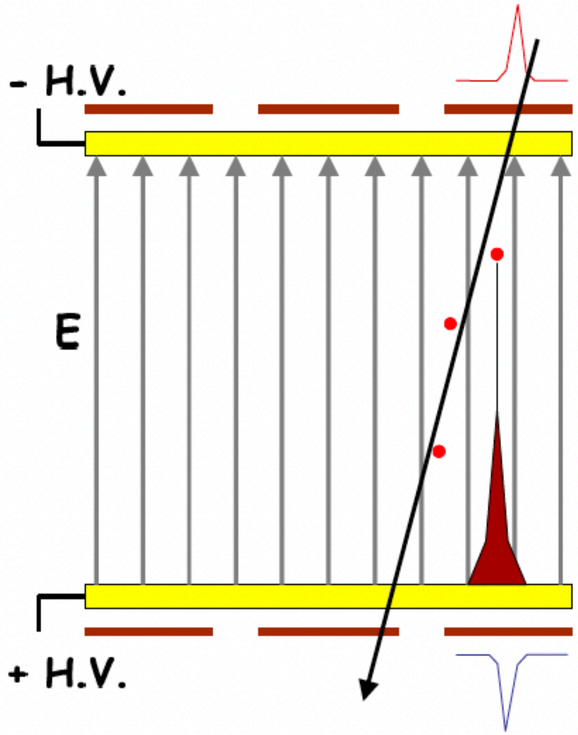
Minimum : 100 pb-1
Reached: 158 pb-1 (x1000 run1 + run 2!)

Run 3: Delivered: 7.96 nb-1
Total **Recorded: 6.91 nb-1 (x120 run1+run2!)**

RPC vs MRPC vs ALICE TOF double stack MRPC

Standard RPC

R. Santonico, R. Cardarelli NIM 187 (1981) 377

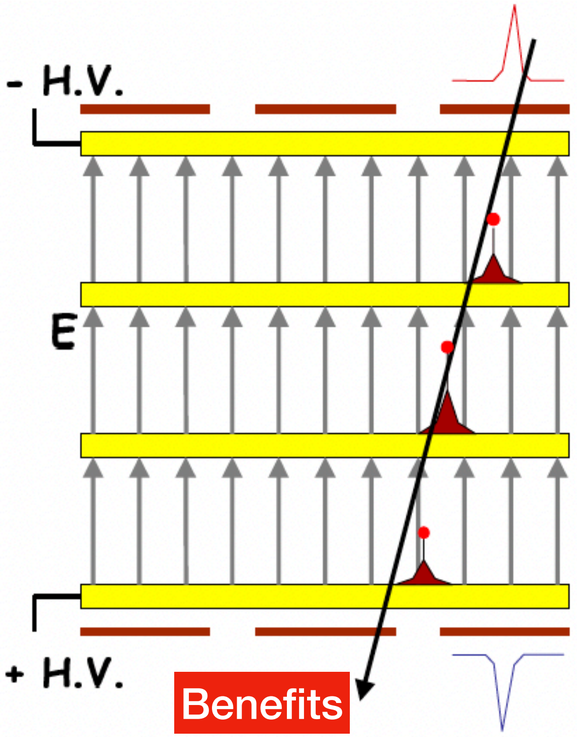


In the simplest configuration the RPC is composed by two parallel resistive plates (electrodes), tipically bakelite (volumic resistivity ρ = 10^9 – 10^{11} Ωcm).

- **The electric field E is uniform and is ~ 50 kV/cm**

MRPC

NIM A 374 (1996) 132, A. Zichichi, C. Williams et al.

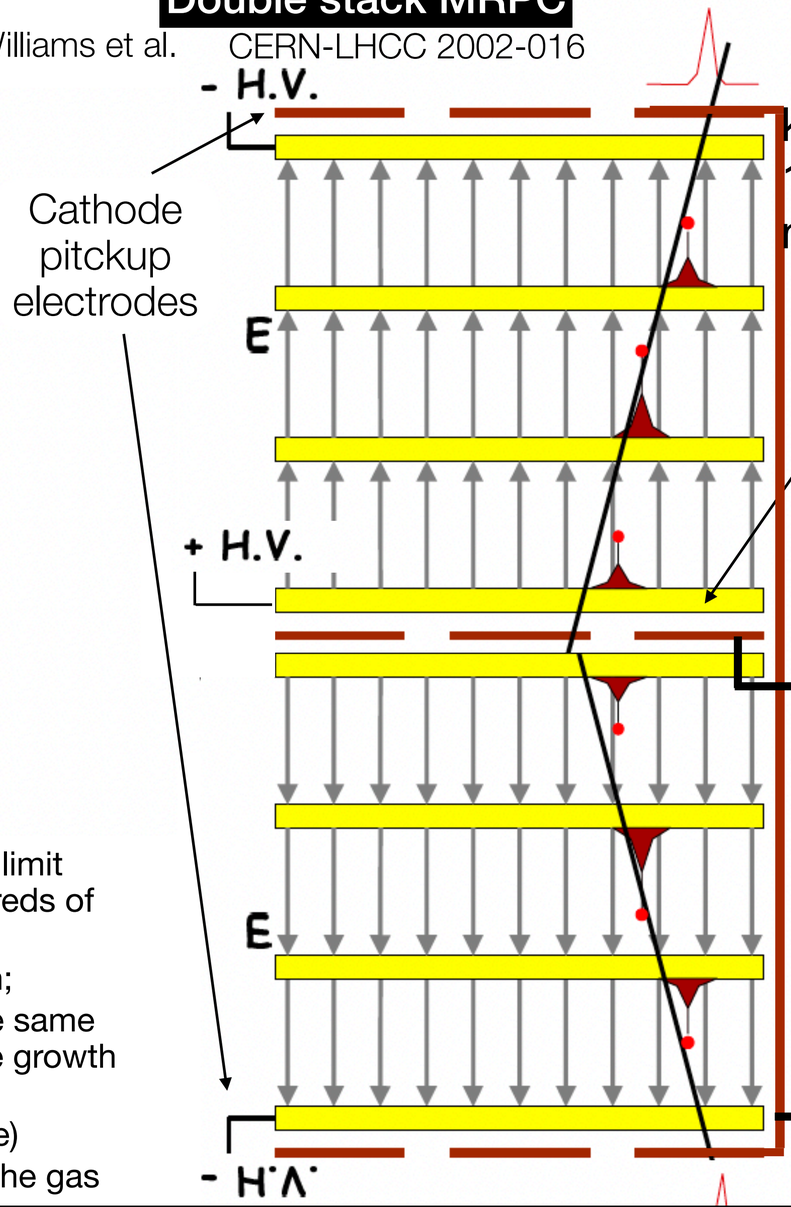


Benefits

- increase the rate capability limit (from few tens to few hundreds of Hz/cm2);
- improve the time resolution;
- increase the gain but at the same time to find a way to stop the growth of the avalanche (no streamer mode)
- reduce the current across the gas

Double stack MRPC

CERN-LHCC 2002-016

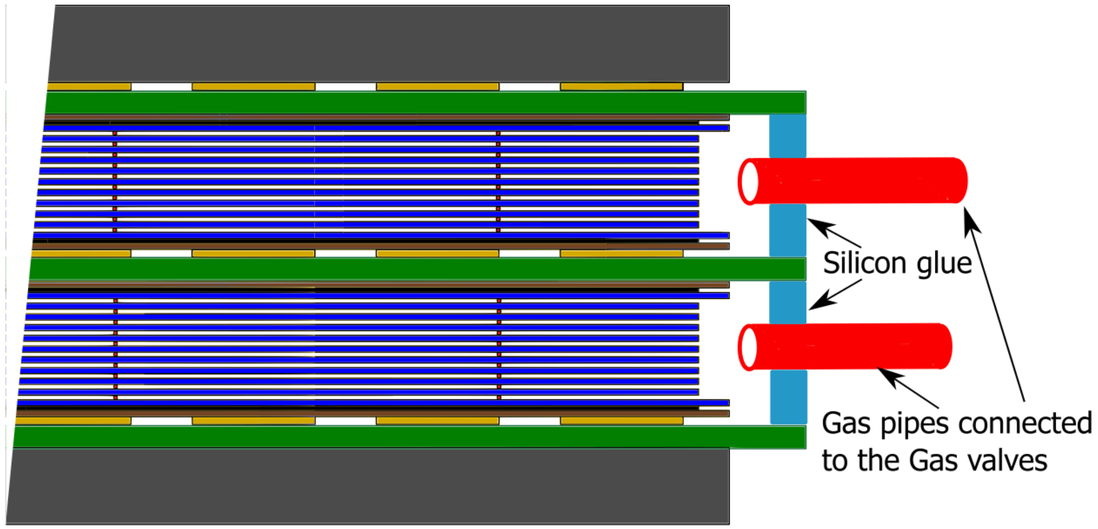


(+) and (-) HV (-6.5 kV, +6.5 kV to get 13kV for every module in TOF

Anode pitckup electrode

DIFFERENTIAL SIGNAL TO FRONT-END electronics

TOF gas sealing and overlap between two modules



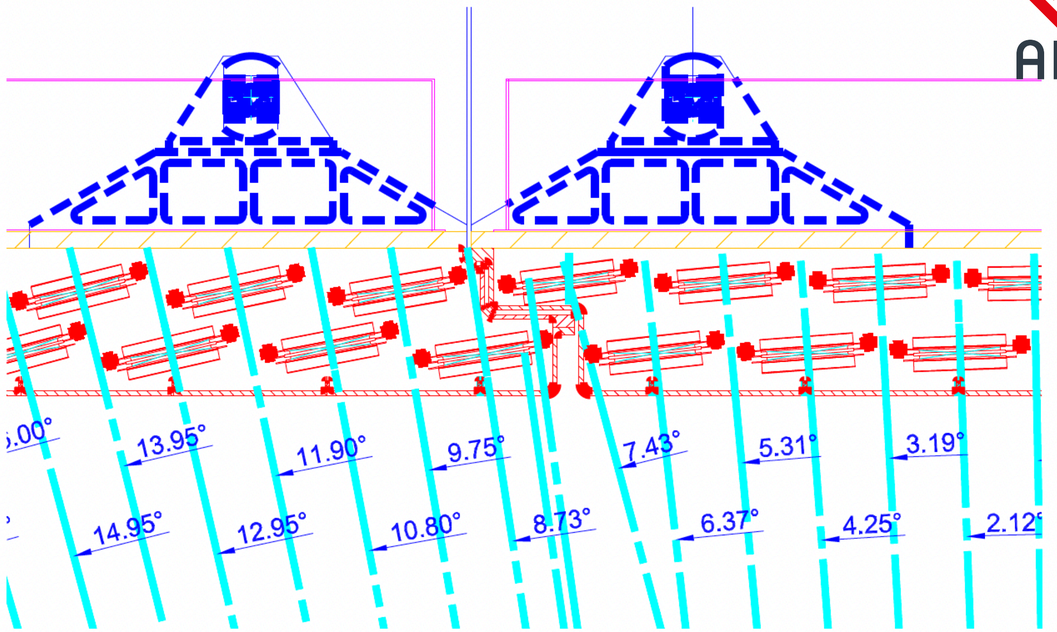
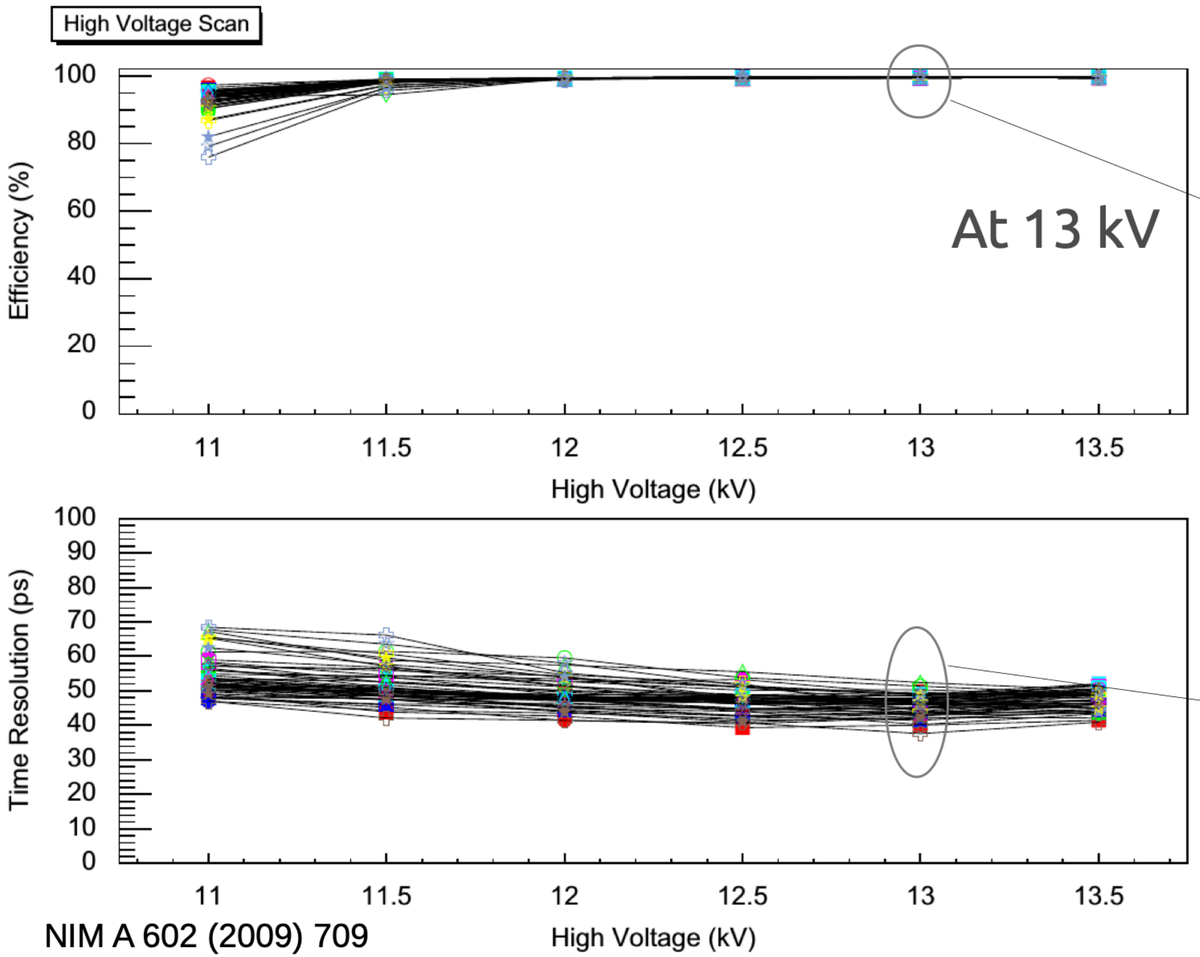
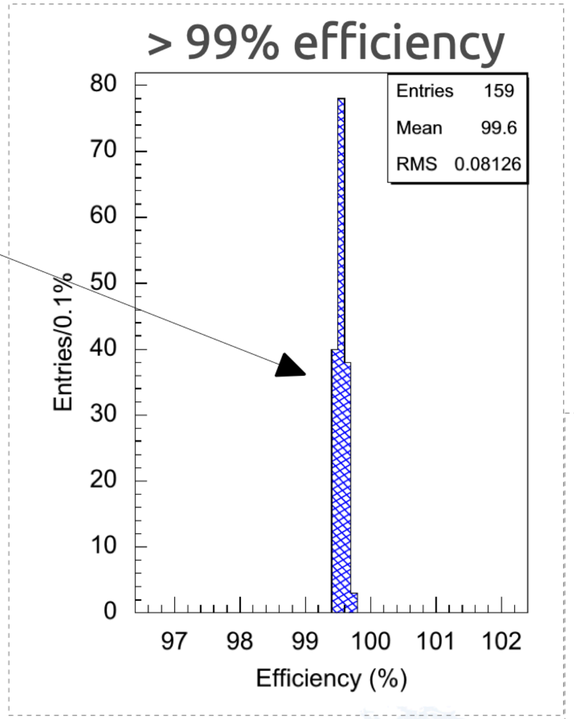


Figure 2.9: Detail of the overlap region between two modules and strip positioning.

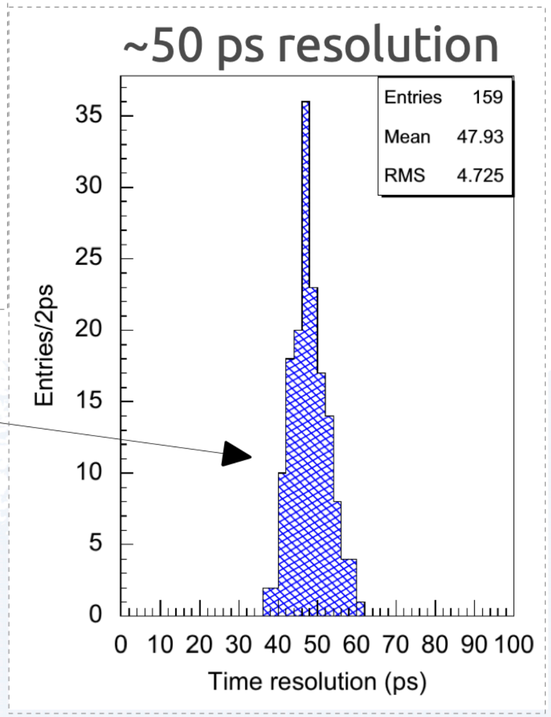
R. Preghenella - PhD thesis

TOF before commissionig: test beam results





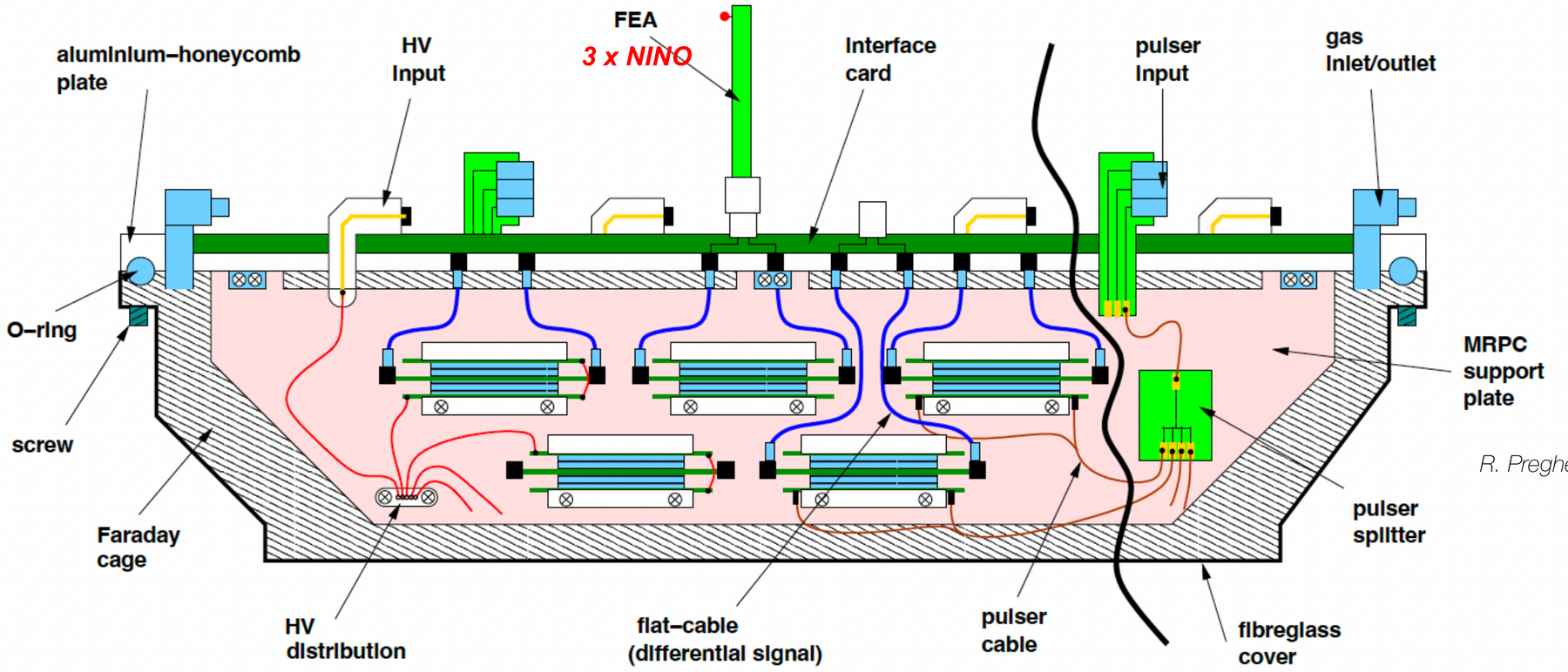
At 13 kV



NIM A 532 (2004) 611

Nuovo Cim. B 124 (2009) 235

TOF module mockup

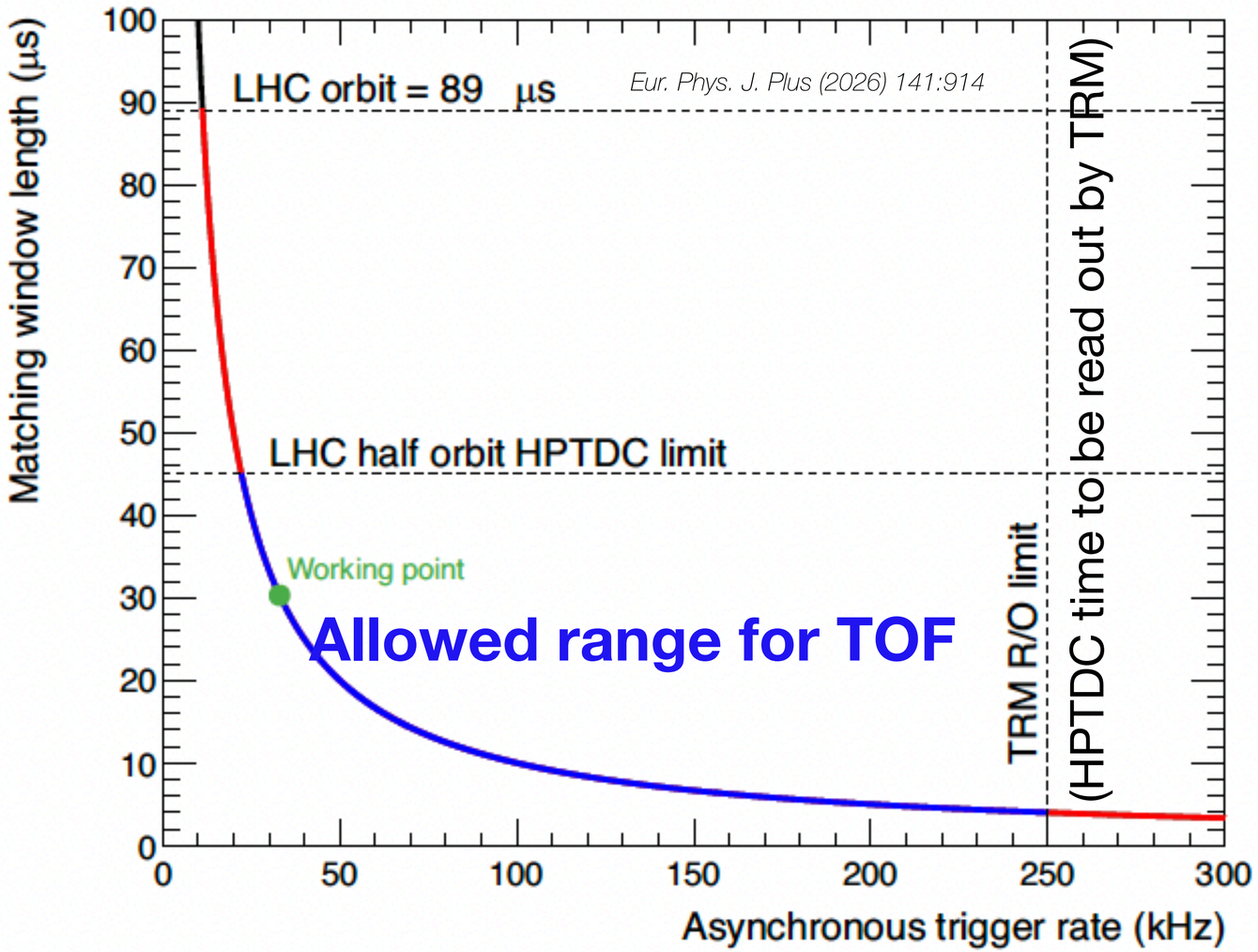


R. Preghenella PhD thesis

Analog signal*→ *3 x NINOs (amp.+discr.) on every FEA (3 x 8 CHs = max 24 CHs) → *you have* ***10 FEAs/TRM → Considering 10 HPTDCs/TRM → 240 CHs/TRM*** *(pads/TRM)*
12 FEAs supplied by a single FEAC.

240 channels/TRM
every TRM 10 FEAs
DRM —>dstirbutes clock to all TRMs and send hits to FLPs (optic fiber)

Continous readout of TOF



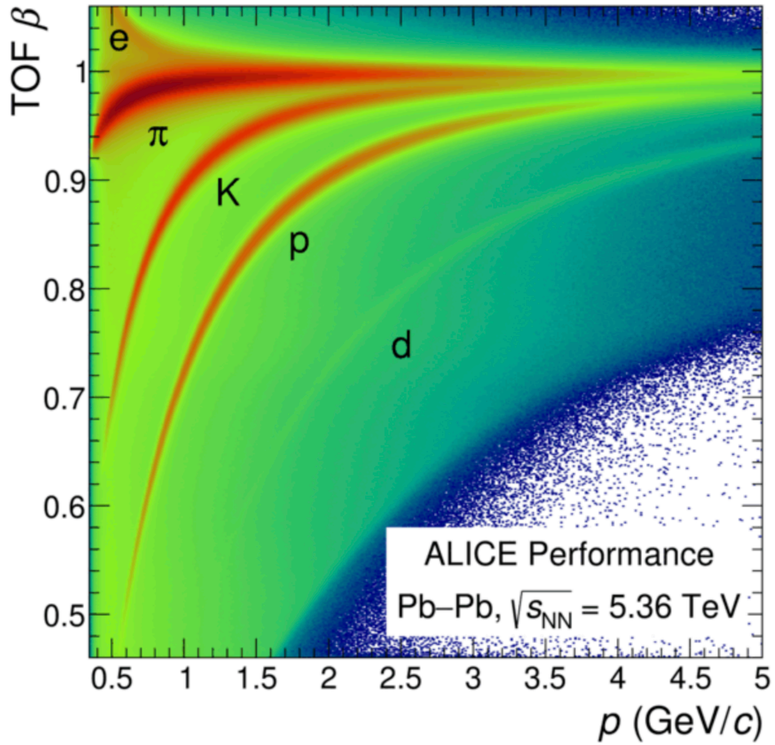
Requirements for tof track Hit

Reconstruction requires the use of both the ITS and the TPC information.

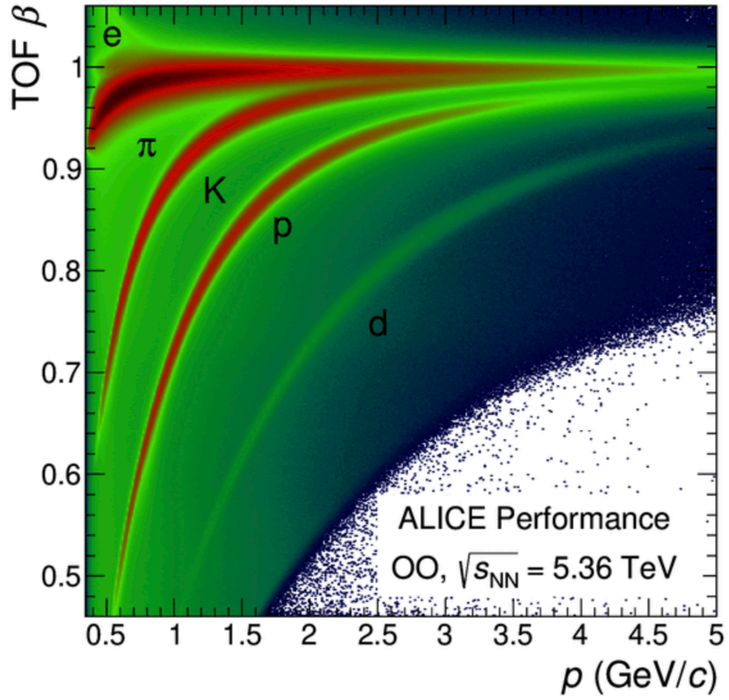
- A minimum of **four ITS hits** is needed, with **at least two** located **in the first three layers**.
- Tracks with < 70 (out of 152) crossed rows in the TPC are discarded
- To further ensure quality, the reduced chi-squared of the track fit quality must be $\chi^2/NDF < 2$.
- Only primary tracks used for resolution (cuts on DCA)

Special runs in 2025 PID

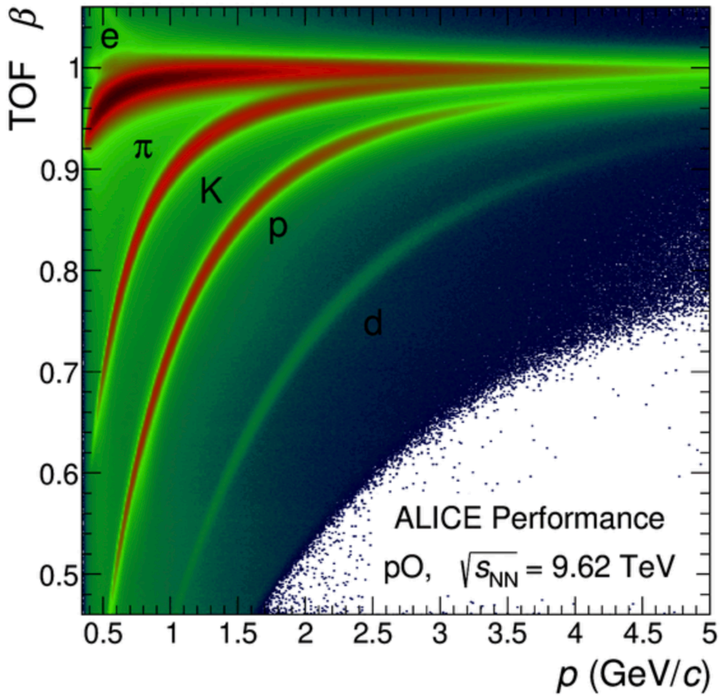
Consistent for NeNe, OO, pO runs of 2025



ALI-PERF-619478



ALI-PERF-609017



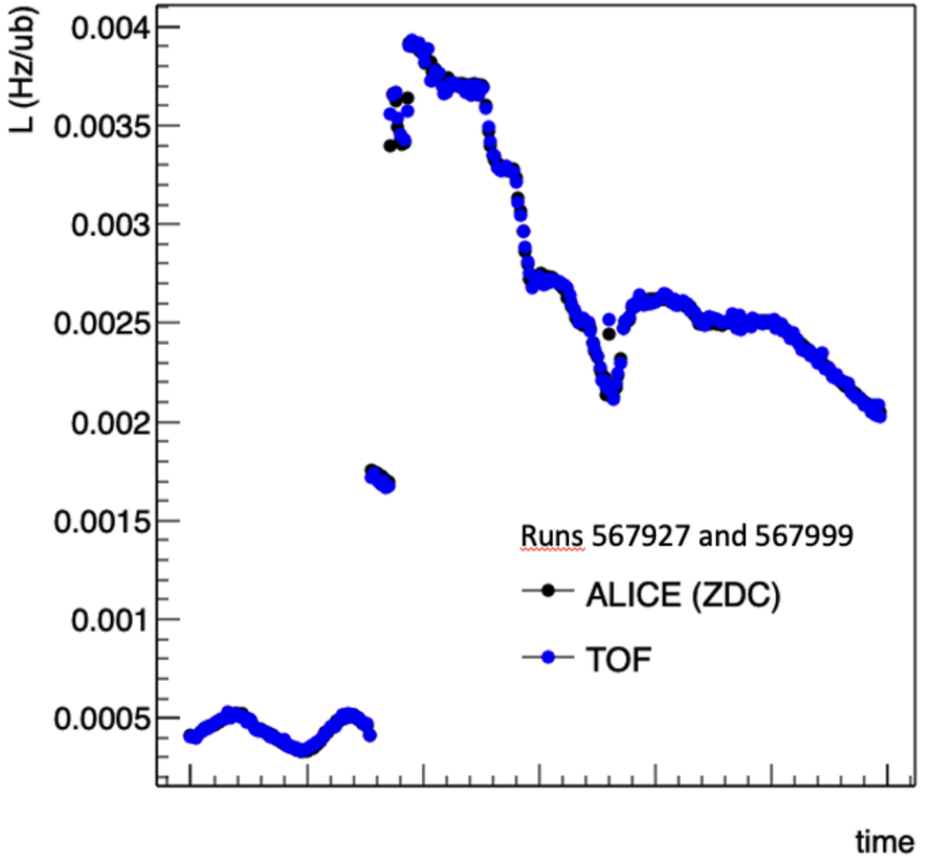
ALI-PERF-609021

TOF operation: TOF as luminometer

- Estimate of the interaction rate using average **TOF hit multiplicity** in 1 min windows corrected by
  - Crate and TRM efficiency
  - acceptance
  - constant empirical factor, estrapolated by comparing TOF luminosity to ALICE luminosity via ZDC (Zero Degree Calorimeter) in the same time window

- The TOF hit rate increases linearly with the LHC luminosity with no signs of ageing

TOF is an effective luminometer for ALICE!



Self-consistent TOF time resolution evaluation

Sum in quadrature of the uncertainty on the 2 tracks

$$\sigma_{11t_{\mathrm{TOF}}} = \sigma(p) \oplus \sigma_{\mathrm{Reference}}$$

$$\sigma(p) = \sigma_{\mathrm{TOF}} \oplus \sigma_{\mathrm{t-exp}}(p)$$

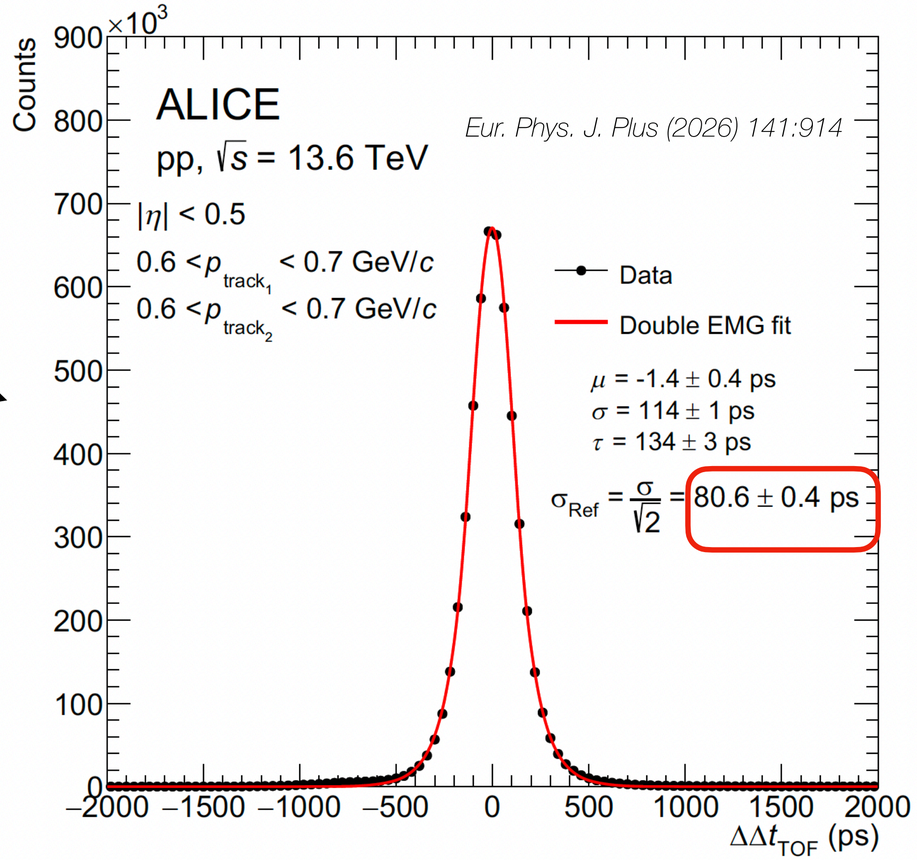
The individual uncertainty contributions come from the TOF resolution and the one from the p dependent time from tracking (strongly depending on mass of particle, uncertainties are larger for heavier particles)

! When p>1GeV/c, the second term is negligible

$$\sigma^{\mathrm{Reference}}_{11t_{\mathrm{TOF}}} = \sigma_{\mathrm{Reference}} \oplus \sigma_{\mathrm{Reference}} = \sqrt{2} \cdot \sigma_{\mathrm{Reference}}$$

$$\sigma_{\mathrm{Reference}} = \sigma^{\mathrm{Reference}}_{11t_{\mathrm{TOF}}} / \sqrt{2}$$

With 2 particles in the reference region 600<p<700 MeV/c



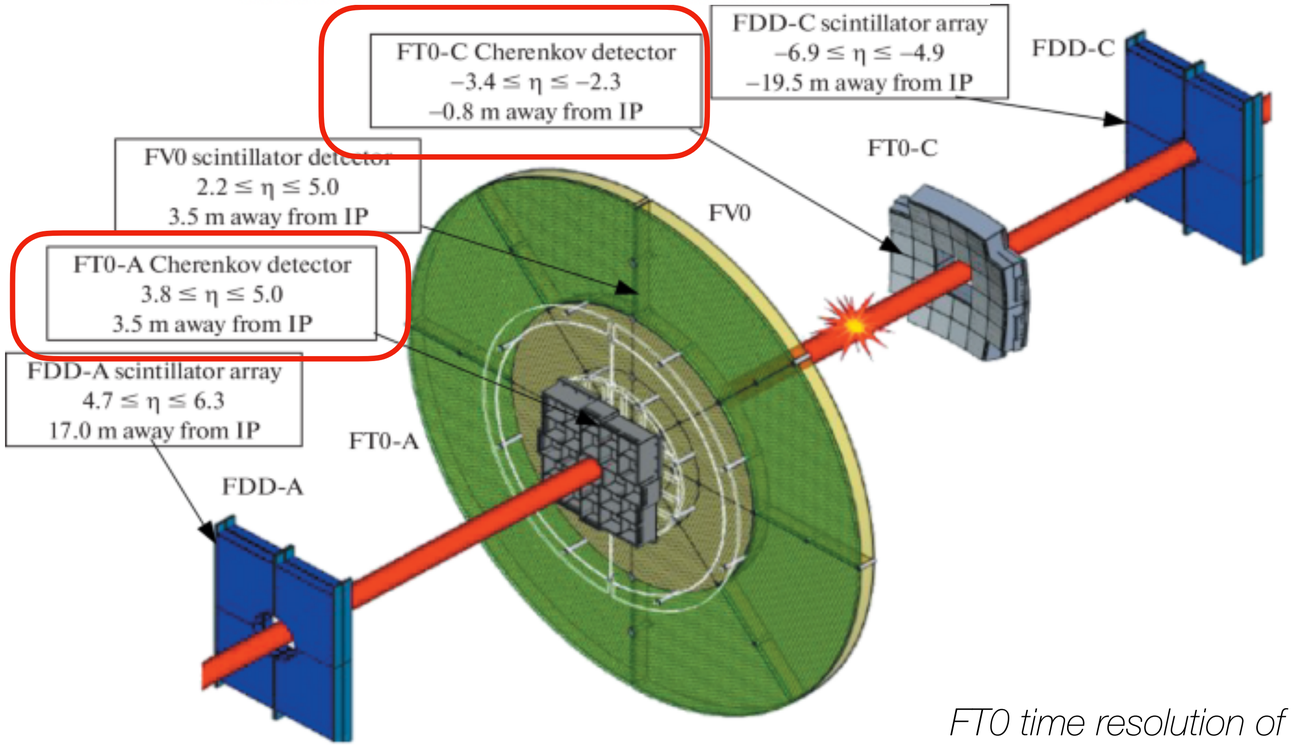
$$\sigma(p) = \sigma_{\mathrm{TOF}} \oplus \sigma_{\mathrm{t-exp}}(p) = \sqrt{\sigma^2_{\Delta\Delta}(p) - \sigma^2_{\mathrm{Reference}}}$$

the analysis can be repeated by varying the momentum of the particles under study to extract: single particle time resolution

Time resolution with FT0

Event collision time

$$t_{\mathrm{ev}}^{\mathrm{FT0}} = \left(t_{\mathrm{ev}}^{\mathrm{FT0A}} + t_{\mathrm{ev}}^{\mathrm{FT0C}}\right)/2$$

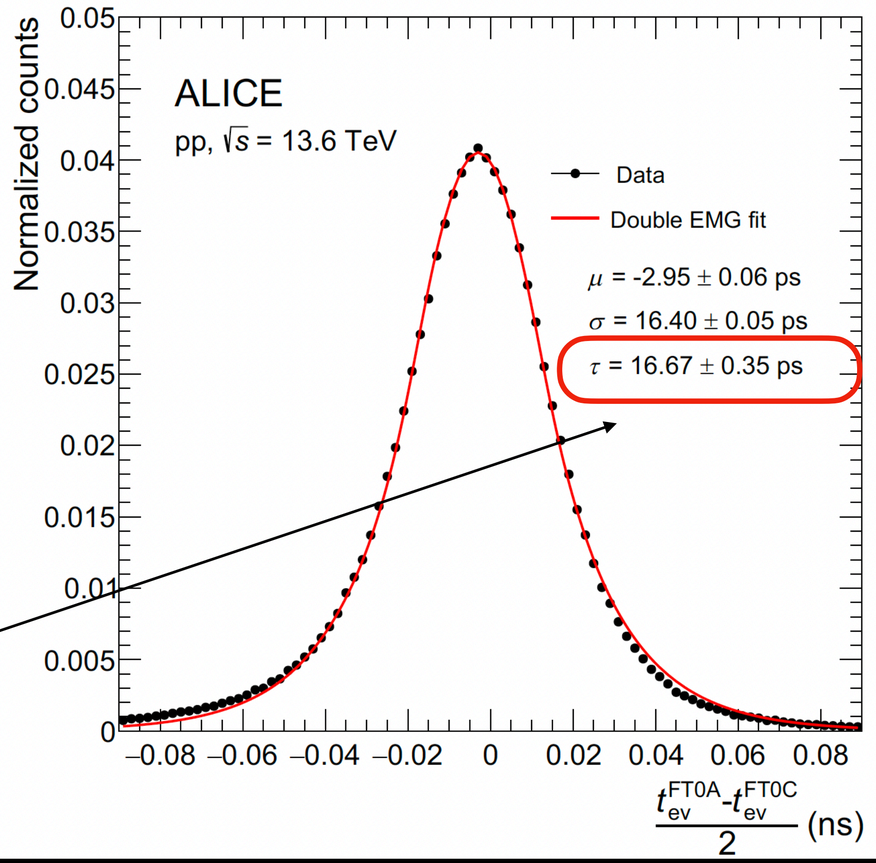


$$\sigma_{t_{\mathrm{TOF}}-t_{\mathrm{exp}}-t_{\mathrm{ev}}^{\mathrm{FT0}}} = \sigma_{\mathrm{TOF}} \oplus \sigma_{\mathrm{t-exp}}(p) \oplus \sigma_{t_{\mathrm{ev}}^{\mathrm{FT0}}}$$

!Assuming at p>1GeV/c, the tracking term is negligible :

$$\sigma_{t_{\mathrm{TOF}}-t_{\mathrm{exp}}-t_{\mathrm{ev}}^{\mathrm{FT0}}} = \sigma_{\mathrm{TOF}} \oplus \sigma_{t_{\mathrm{ev}}^{\mathrm{FT0}}}$$

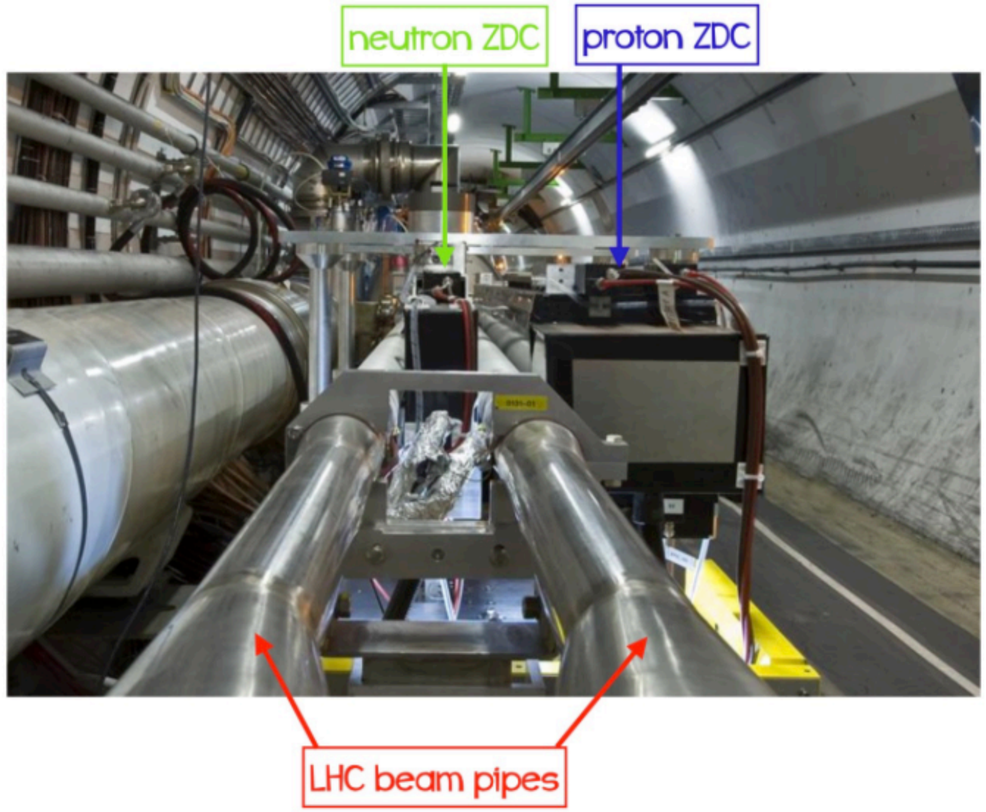
FT0 time resolution of ~17 ps is subtracted to get the TOF time resolution: basically negligible in quadratura



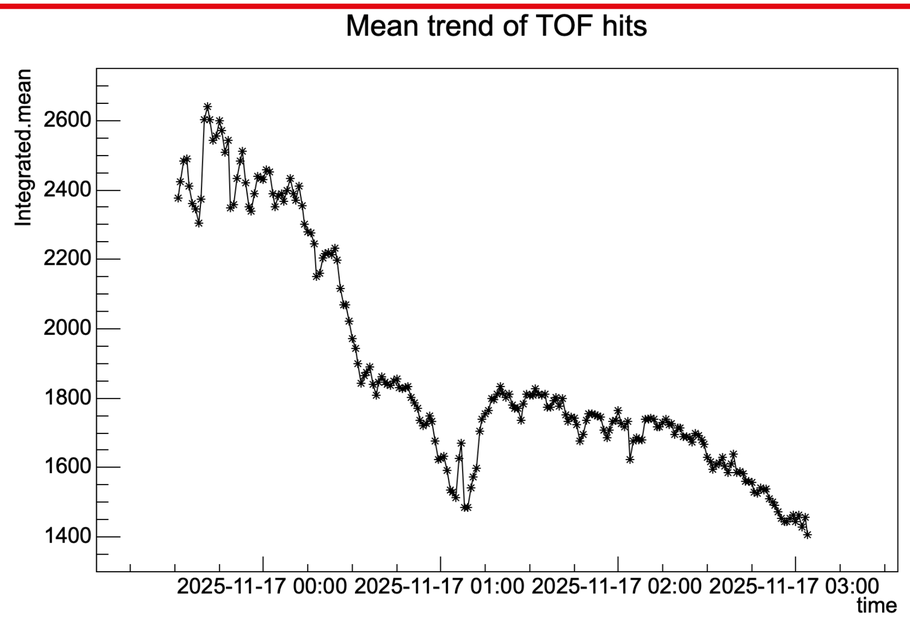
ZDC (Zero Degree Calorimeter)

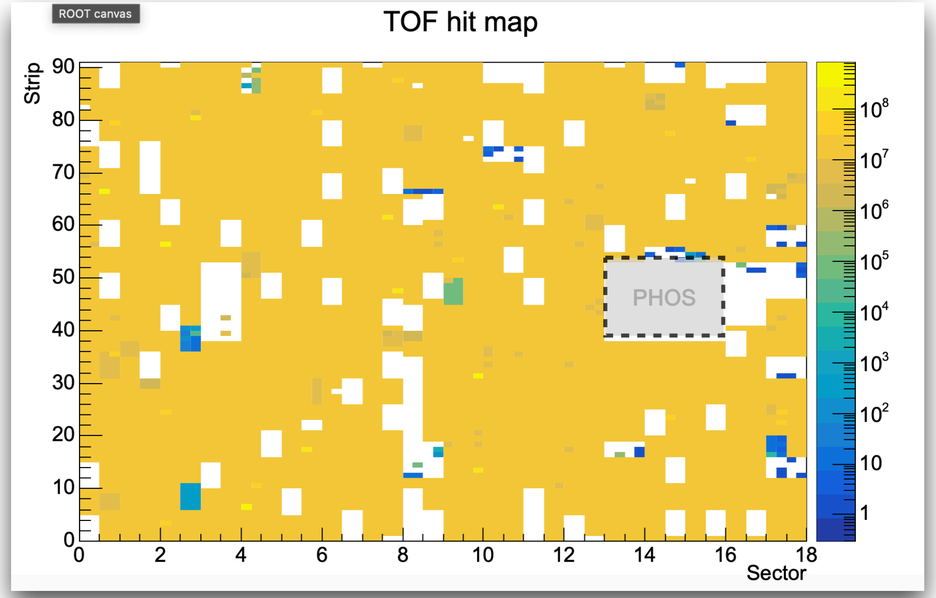
The ZDC consists in two identical sets of calorimeters located on both sides relative to the interaction point IP2, 112.5 meters away from it. In that region the two LHC beams circulate in two different pipes. Each set of detectors consists of a **neutron (ZN) and a proton (ZP) calorimeter.** The **ZN is placed at zero degree with respect to the LHC axis,** between the two beam pipes, while the **ZP is positioned externally** to the outgoing beam pipe. The **spectator protons** are **separated** from the ion beams **by means of the dipole** magnet D1, while **spectator neutrons fly at zero degree** without further changing direction. The ZDC detector is completed by 2 forward EM calorimeters (ZEM) placed at about 7.35 m from I.P.2, on A side, covering the pseudorapidity range $4.8 < \eta < 5.7$.

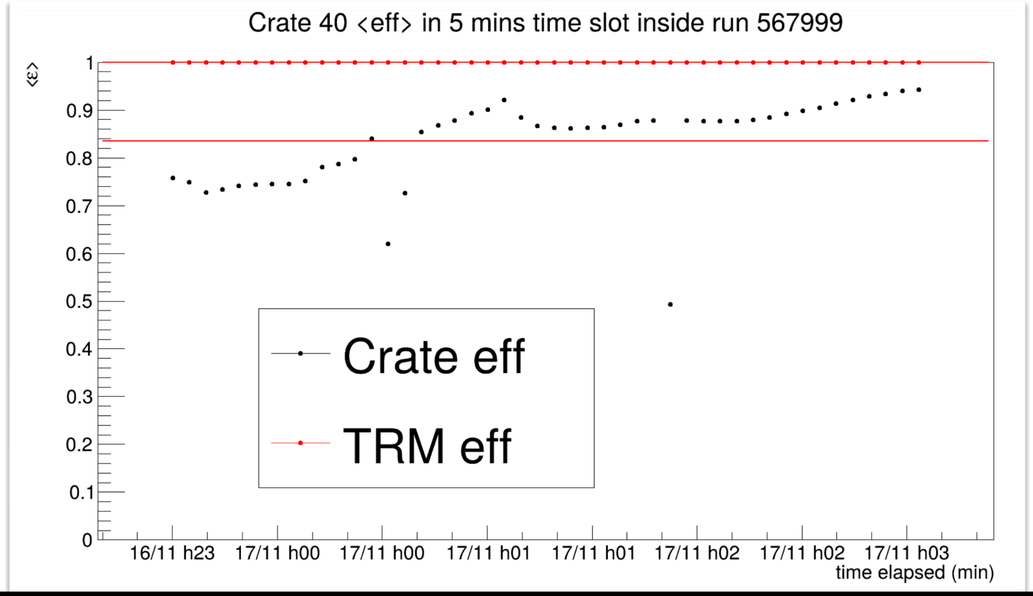
Made by **quartz-fiber** spaghetti **calorimeters** with **silica optical fibers** as active material embedded in a dense absorber. Their principle of operation is based on the **detection of Cherenkov light produced by the charged particles of the shower in the fibers**. The response is very fast thanks to the intrinsic speed of the emission process, making such detectors suitable for triggering purposes.

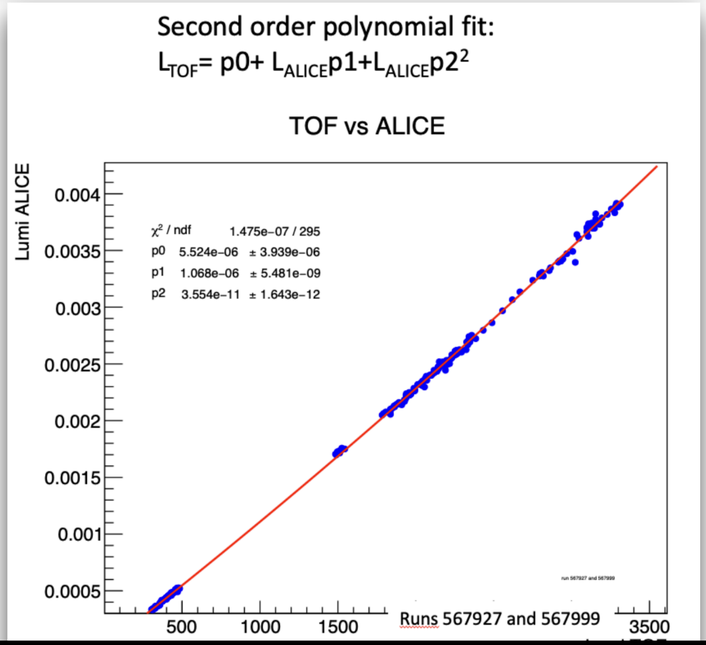


TOF as luminometer: relevant parameters

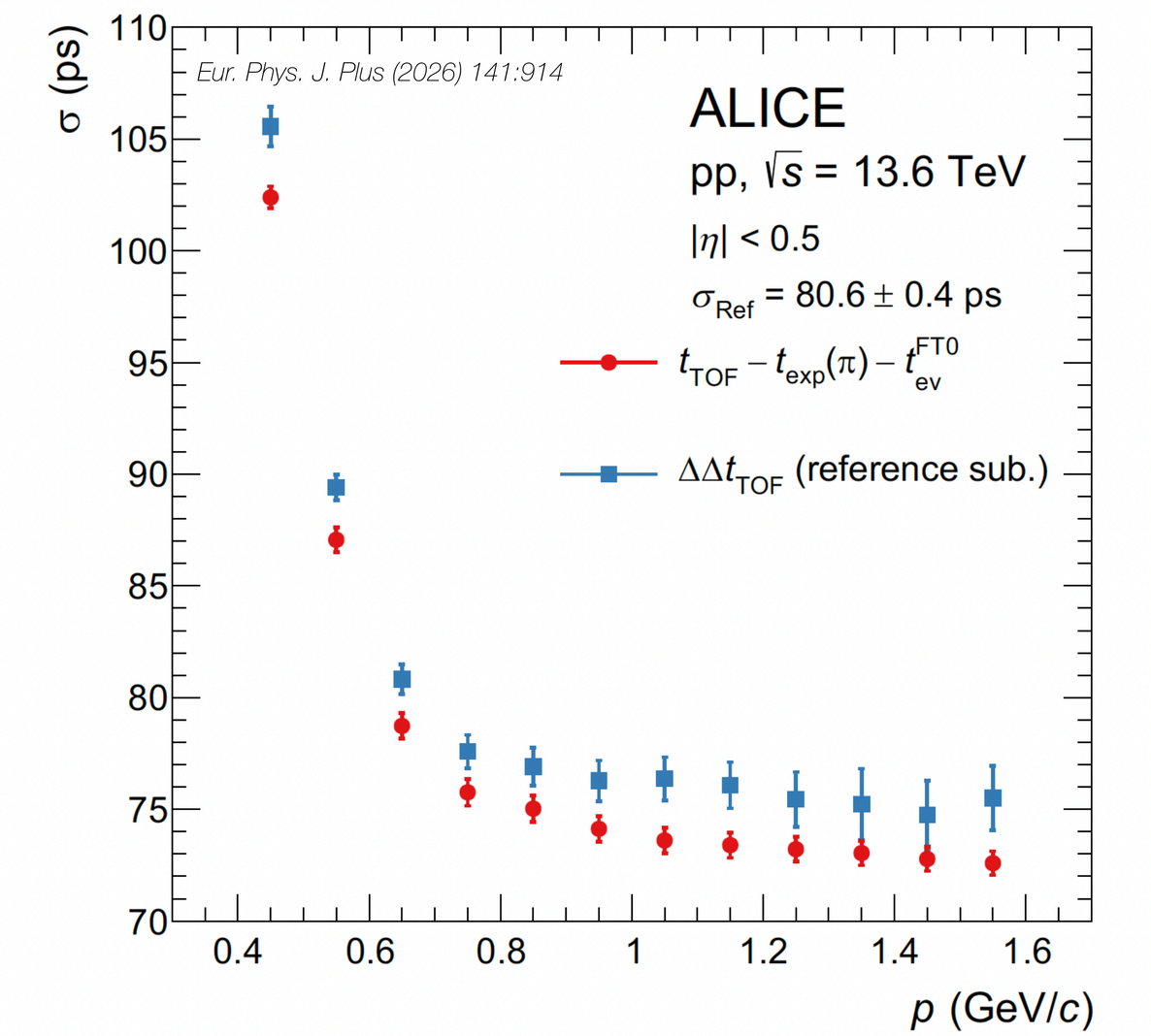






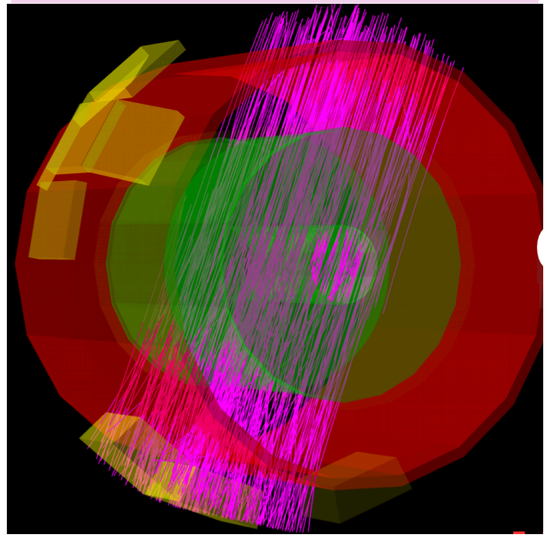


Agreement between the 2 techniques

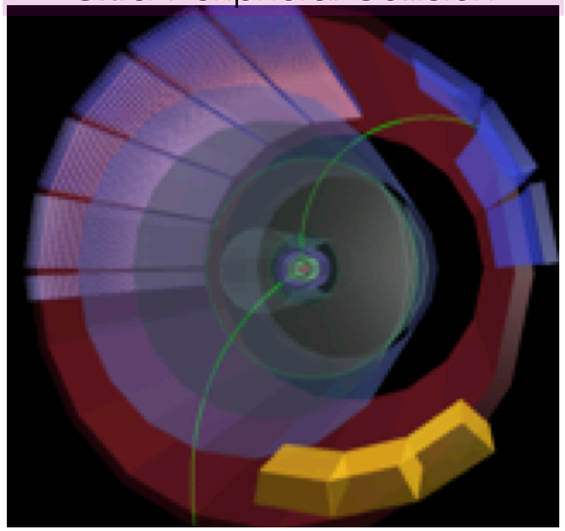


Performance in Run 3: trigger

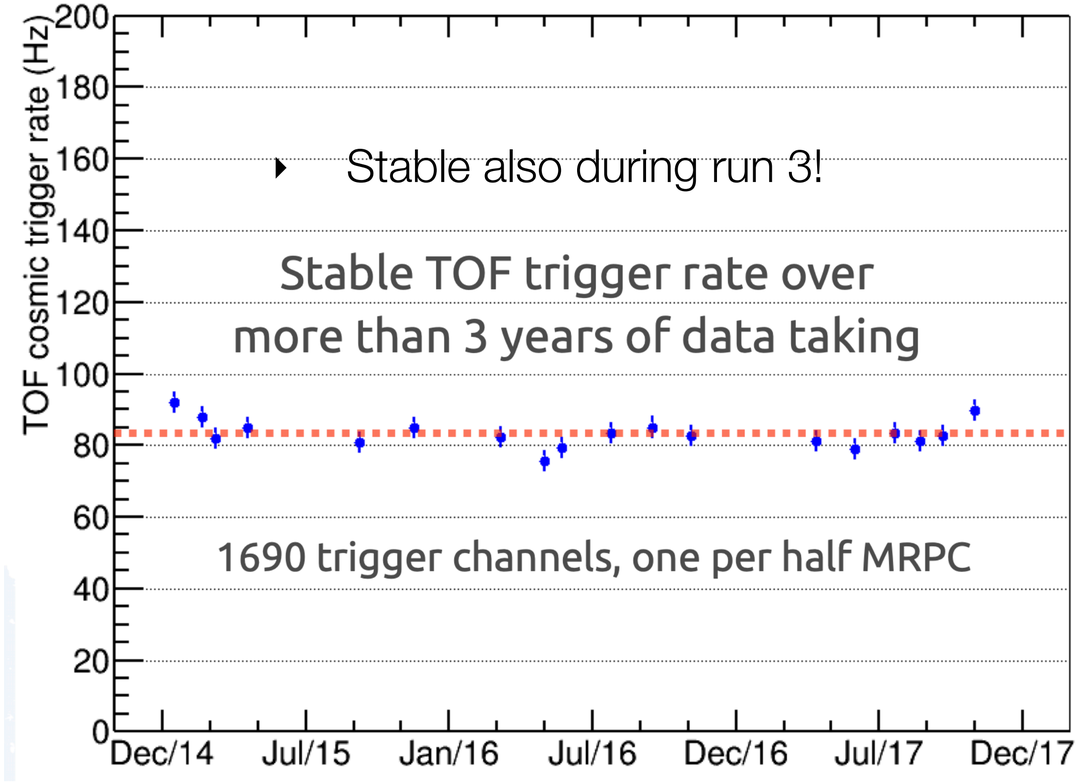
Cosmic rays



Ultra-Peripheral Collision

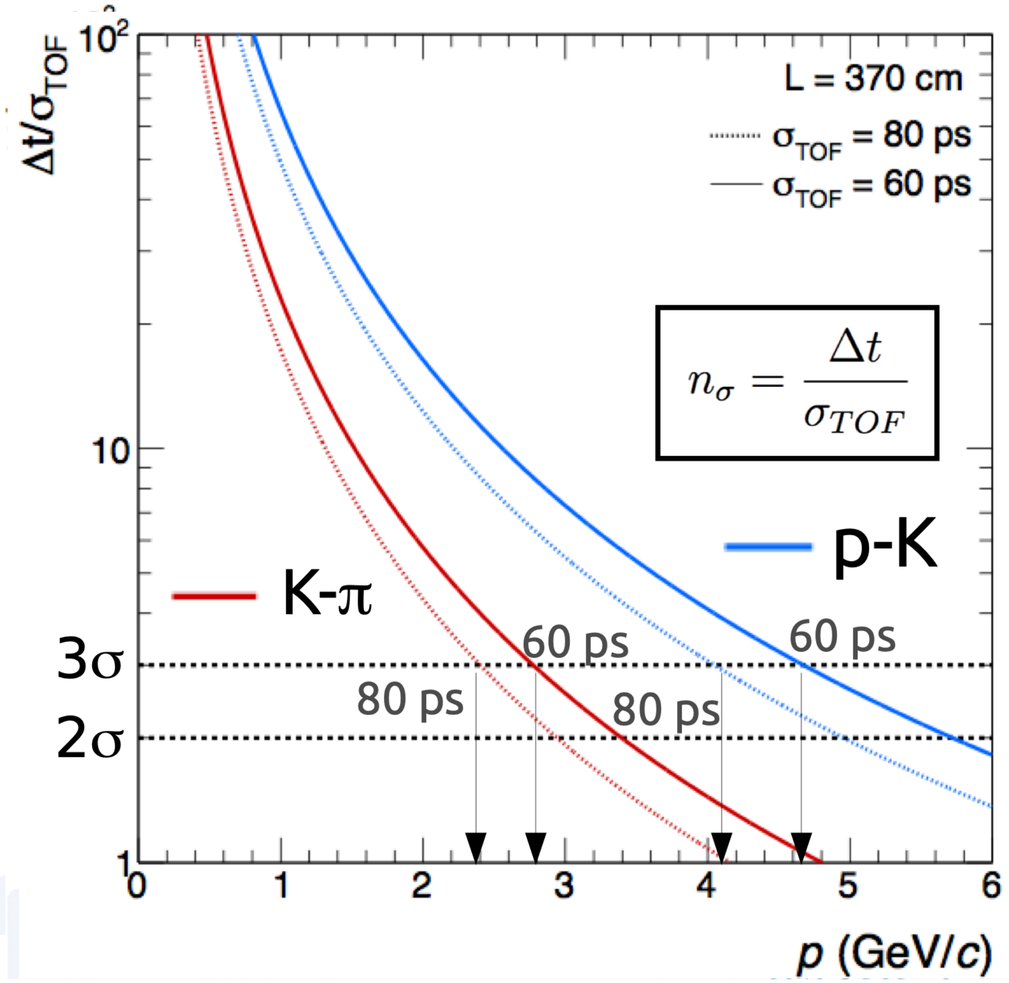


- TOF provides a dedicated trigger for **cosmic events** and **UPCs**
- Stable TOF trigger rate



Discrimination power

Mass hypothesis



P with tracker — *t measured by TOF* — *L with TPC*

$$m_{TOF} = \frac{p}{c}\sqrt{\frac{c^2 t^2}{L^2} - 1}$$

$$\left(\frac{\delta m_{TOF}}{m}\right)^2 = \left(\frac{\delta p}{p}\right)^2 + \gamma \cdot \left(\frac{\delta L}{L}\right)^2 + \gamma \cdot \left(\frac{\delta t}{t}\right)^2$$

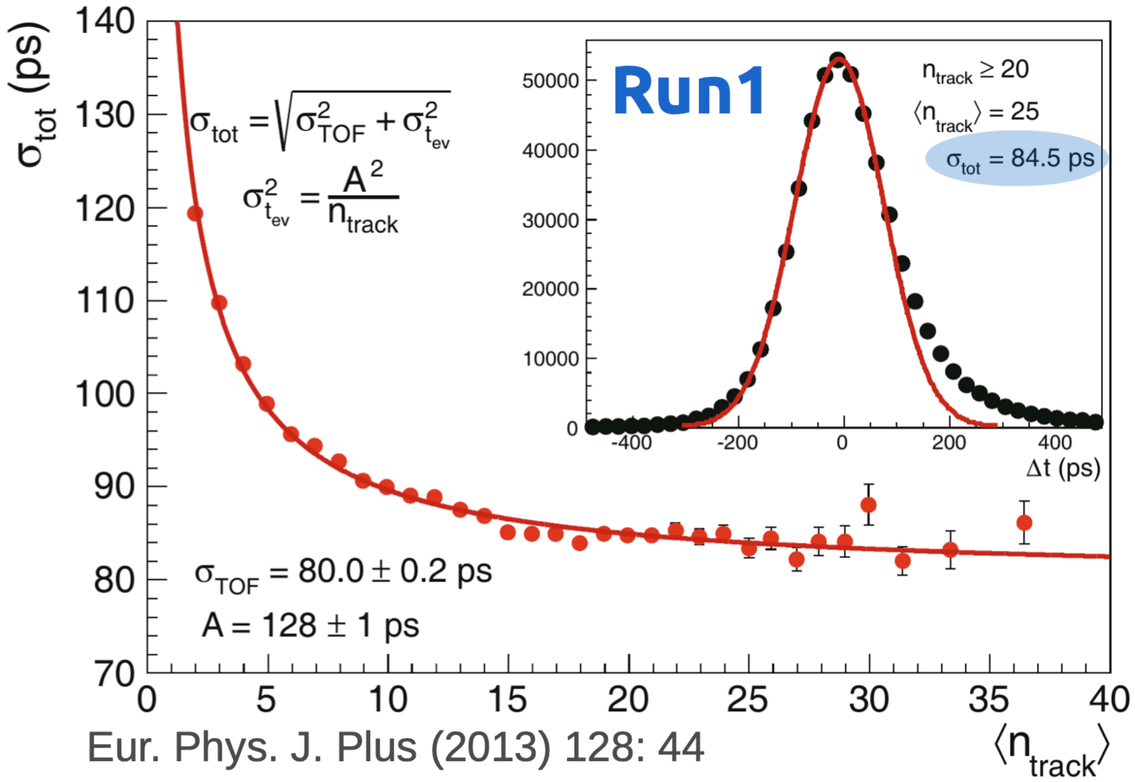
Dominant term at high momentum

$$\Delta t_{i,j} = t_i - t_j \simeq \frac{Lc}{2p^2}\left(m_i^2 - m_j^2\right)$$

PID separation power of the TOF detector depends mainly on the intrinsic time resolution

N. Jacazio - FATA 2019

Time resolution contributions, pp VS PbPb



Eur. Phys. J. Plus (2013) 128: 44

Asymptotic value for large track multiplicities → best event collision time precision

Time-Of-Flight

$$TOF = t_{TOF} - t_{event} - t_{\exp_i}$$

Time-Of-Flight resolution

$$\sigma_{TOF} = \sigma_{t_{TOF}}^2 + \sigma_{trk}^2 + \sigma_{event}^2$$

Associated to intrinsic MRPC (~50ps)

In Run1 = 84.5 ps

Negligible for p>1 GeV/c

Intrinsic time resolution

$$\sigma_{t_{TOF}}^2 = \sigma_{MRPC}^2 + \sigma_{TDC}^2 + \sigma_{FEE}^2 + \sigma_{Calib.}^2$$

Constant terms

Fixed by calibration proc. —> refined for Run 2

Event collision time resolution

$$\sigma_{event} \sim \sigma_{t_{TOF}} / \sqrt{TOF\ track\ multiplicity}$$

Eur.Phys.J.Plus 132 (2017) no.2, 99

N. Jacazio - FATA 2019

Time resolution : pp VS PbPb

Time-Of-Flight

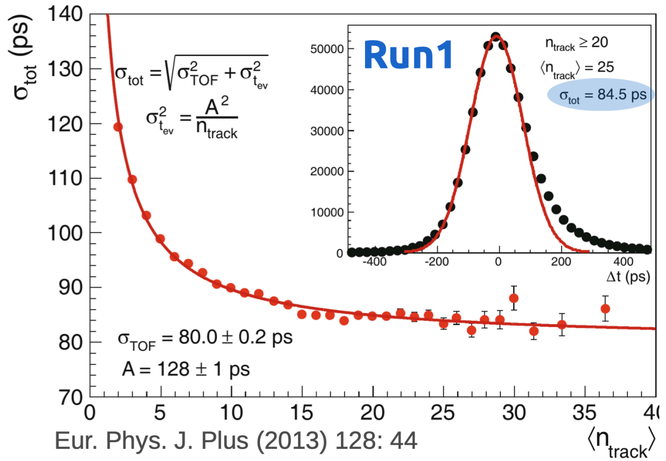
$$TOF = t_{TOF} - t_{event} - t_{\exp_i}$$

Time-Of-Flight resolutio

$$\sigma_{TOF} = \sigma^2_{t_{TOF}} + \sigma^2_{trk} + \sigma^2_{event}$$

Associated to **intrinsic** *MRPC (MRPC, TDC, FEE electronics, calibration) (~50ps)*

Negligible at >1 GeV



From FT0 or multiple TOF matched tracks.

In PbPb, central/high multiplictiy events, many more particles are produced per collision. Averaging over many hits/tracks pushes this contribution down as $1/\sqrt{N}$

In pp, multiplicity is low: few tracks: less redundancy to pin down t_{event} : FT0 has fewer hits to average, the combinatorial TOF method has few tracks: the resolution is higher

Resolution is driven by <u>event multiplicity</u> via start-time precision, not by MRPC performance itself

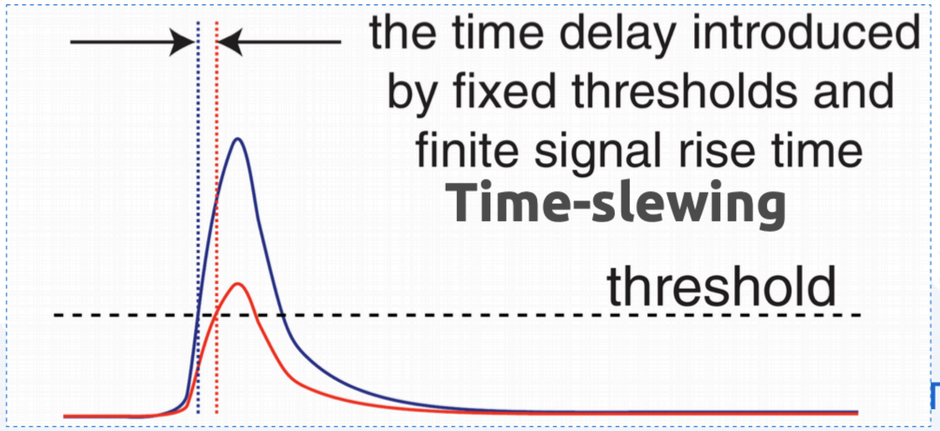
Time slewing correction

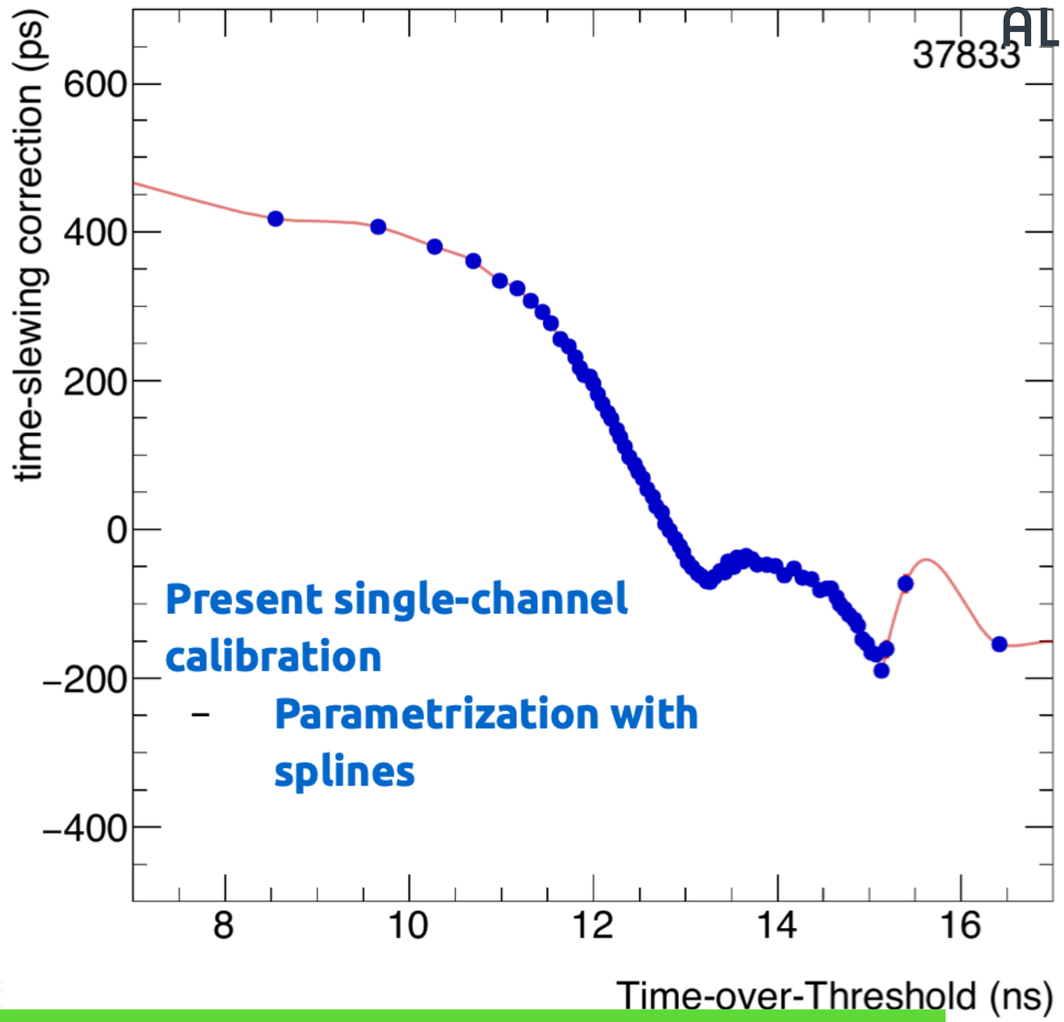
TOF time calibration is based on **3 components**:

1) Global offset, common to all channels (clock)

2) Channel-by-channel offset (cables lengths,…)

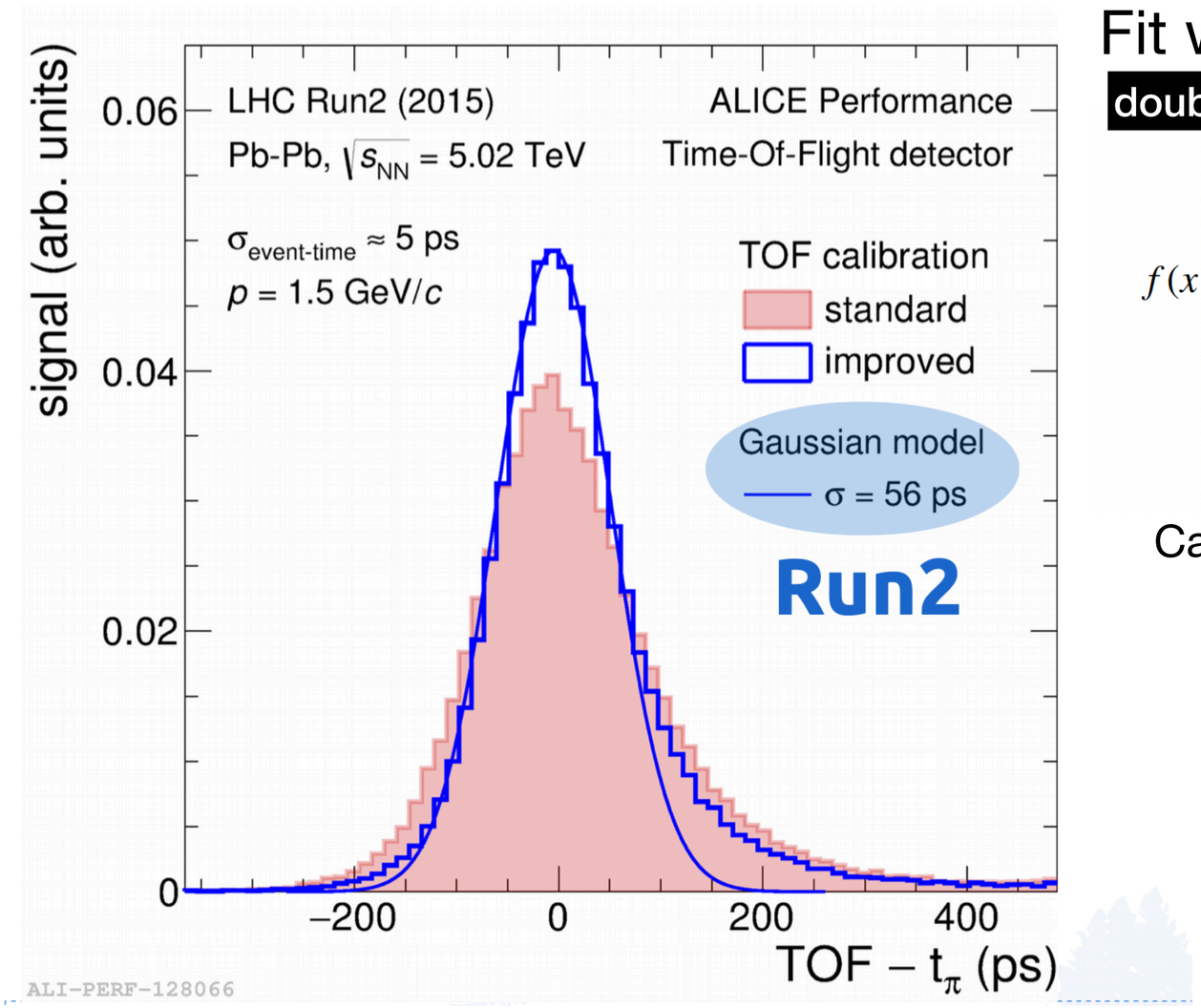
3) Time-slewing correction:
correlation between the time and charge
→ TOF system uses *Time-Over-Threshold* (**ToT**) as a proxy for the charge





N. Jacazio - FATA 2019

Run2 time resolution



Fit with non-gaussian tails (exponential)

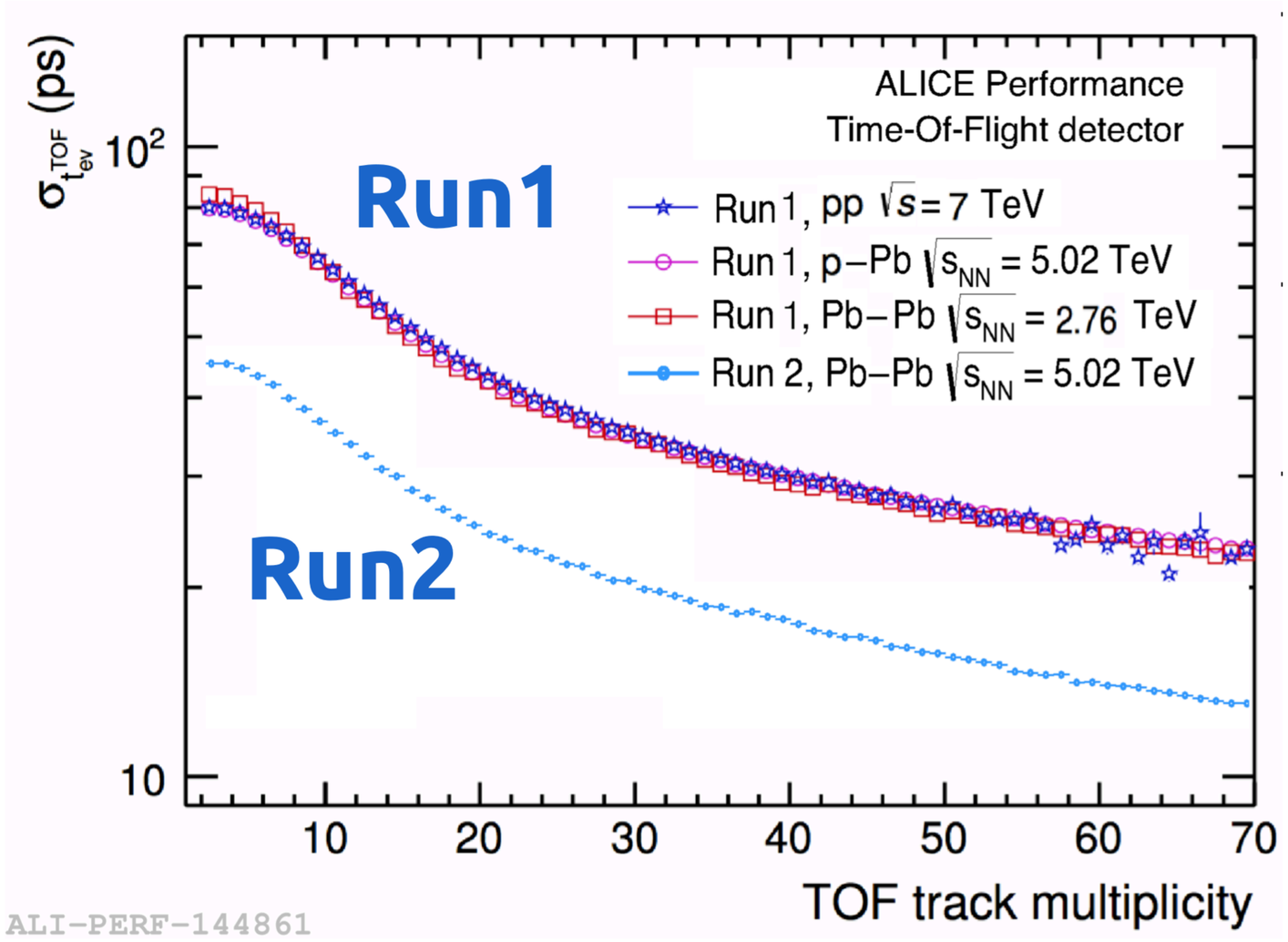
double exponentially modified Gaussian distribution

$$f(x) \propto \begin{cases} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} & \text{if} \quad \mu - \tau \le x \le \mu + \tau \\ \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\tau}{\sigma}\right)^2 - \frac{\tau}{\sigma^2}(x-\mu-\tau)} & \text{if} \quad x > \mu + \tau \\ \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\tau}{\sigma}\right)^2 - \frac{\tau}{\sigma^2}(\mu-\tau-x)} & \text{if} \quad x < \mu - \tau \end{cases}$$

Calibration procedure refined—> significant improvement!

56 ps time resolution

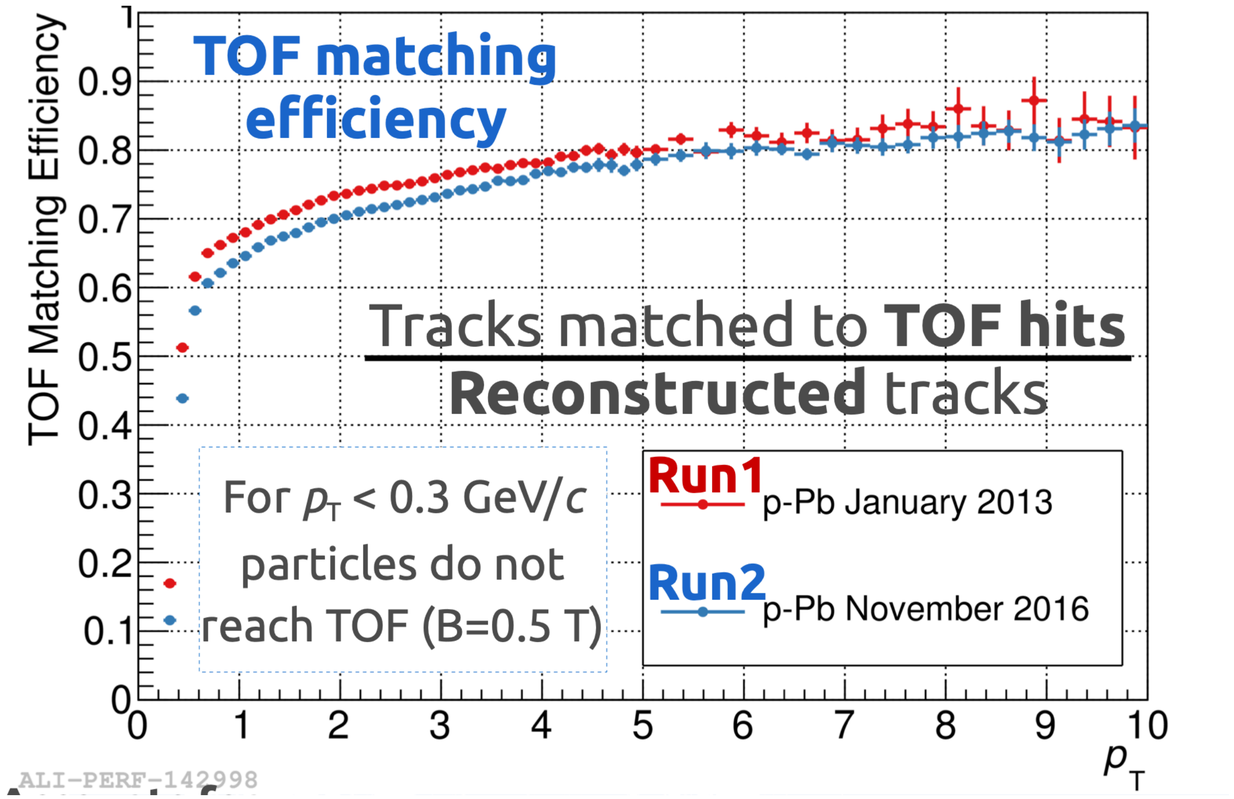
Run2 time resolution



- If multiplicity>2, TOF time resolution is a self-consistent measurement
- Independently from other detectors and collision systems (pp, p-Pb, Pb-Pb)
- Depends just on track multiplicity

$$\sigma_{event} \sim \frac{\sigma_{t_{TOF}}}{\sqrt{TOF\ track\ multiplicity}}$$

Performance: matching efficiency



$$\text{TOF matching efficiency}^* = \frac{\text{tracks matched to TOF}}{\text{total reconstructed tracks}}$$

*accounts for TOF geometrical acceptance (active channels, dead space…)

Run3 : published results

pp

Measurement of the B0-meson production cross section in proton-proton collisions at $\sqrt{s}$ =13.6 TeV
https://alice-publications.web.cern.ch/node/13173

Time resolution of the ALICE Time-Of-Flight detector with the first Run 3 pp collisions at $\sqrt{s}$ =13.6 TeV
https://alice-publications.web.cern.ch/node/12796

Multiplicity dependence of the size of the common hadron emission source in pp collisions at the LHC
https://alice-publications.web.cern.ch/node/13402

Three-baryon femtoscopy as an effective 3→3 scattering experiment
https://alice-publications.web.cern.ch/node/13447

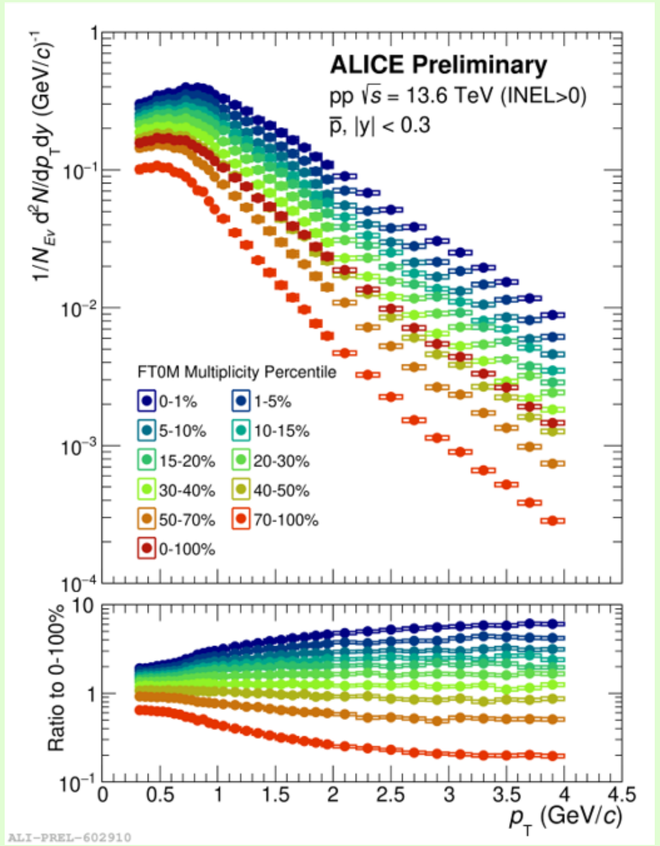
PbPb

Evidence of different Λ_c -baryon and D-meson elliptic flow in Pb-Pb collisions at $\sqrt{s}_{NN}$ = 5.36 TeV with ALICE at the LHC
https://alice-publications.web.cern.ch/node/13174

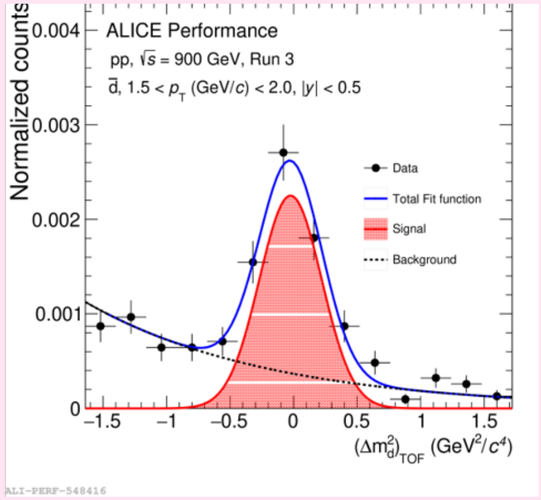
Physics with TOF: recent highlight (not comprehensive!)

TOF is employed for identification of light hadrons as well as of light (anti)nuclei in many analyses across ALICE and several Physics Working Groups (PWGs)

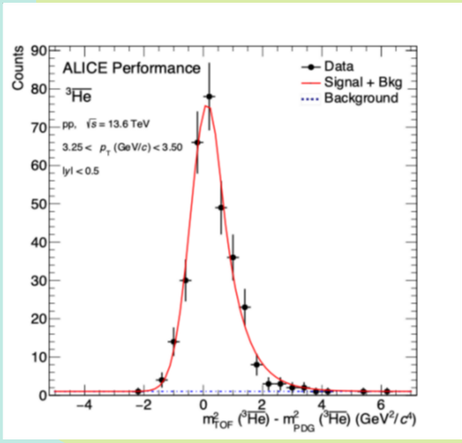
$\bar{p}$ in pp 13.6 TeV (+π, K) [QM25 prel.]



Antideuteron in pp $\sqrt{s}$ =900 GeV [paper proposal approved by PB]

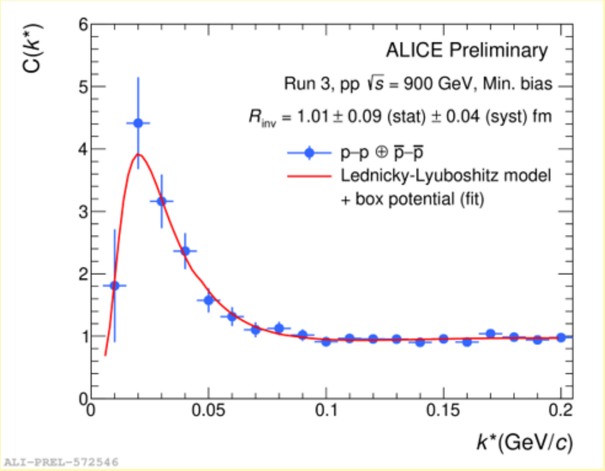


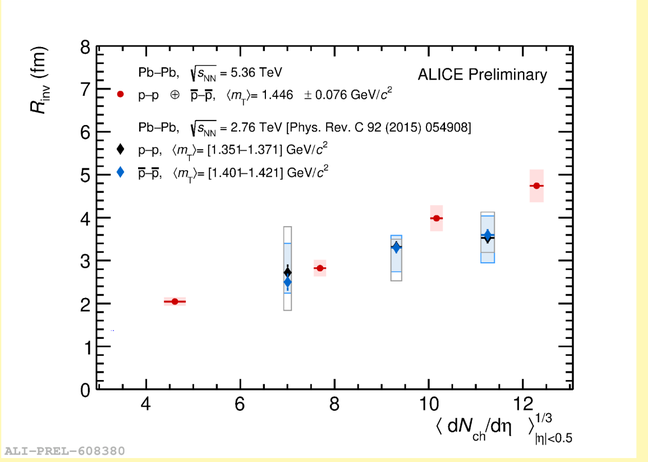
Anti-^{3}He in pp 13.6 TeV [QM23, ongoing analysis]



Femtoscopy:

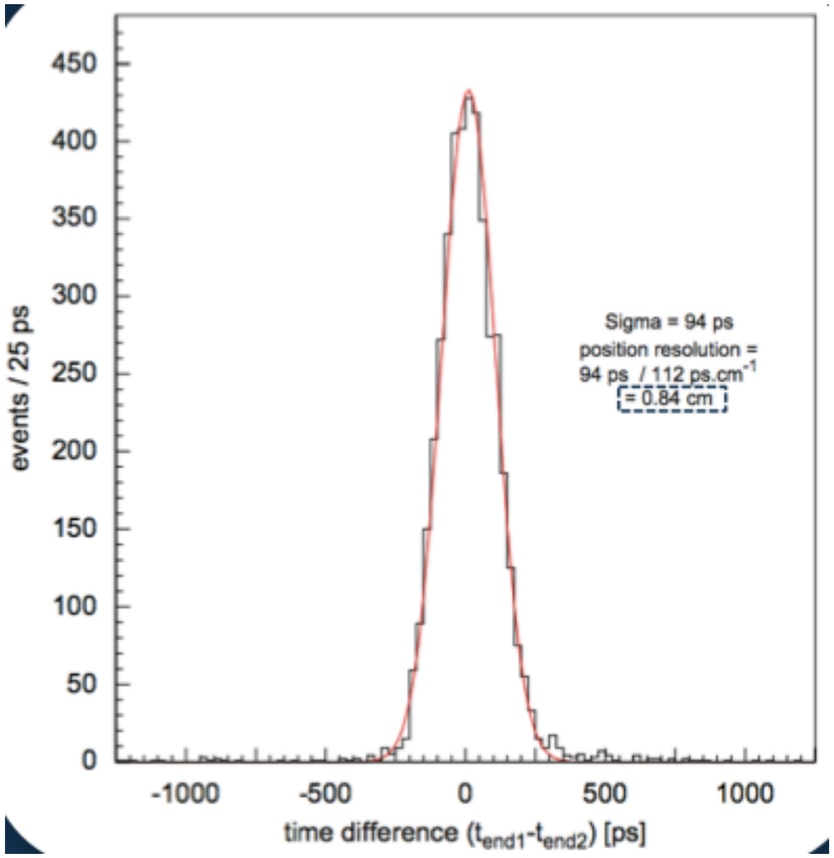
- Proton source radius via femtoscopy in pp $\sqrt{s}$ =900 GeV [paper proposal approved by PB]
- Proton source radius via femtoscopy in Run 3 Pb-Pb [preliminary at ICHEP24]

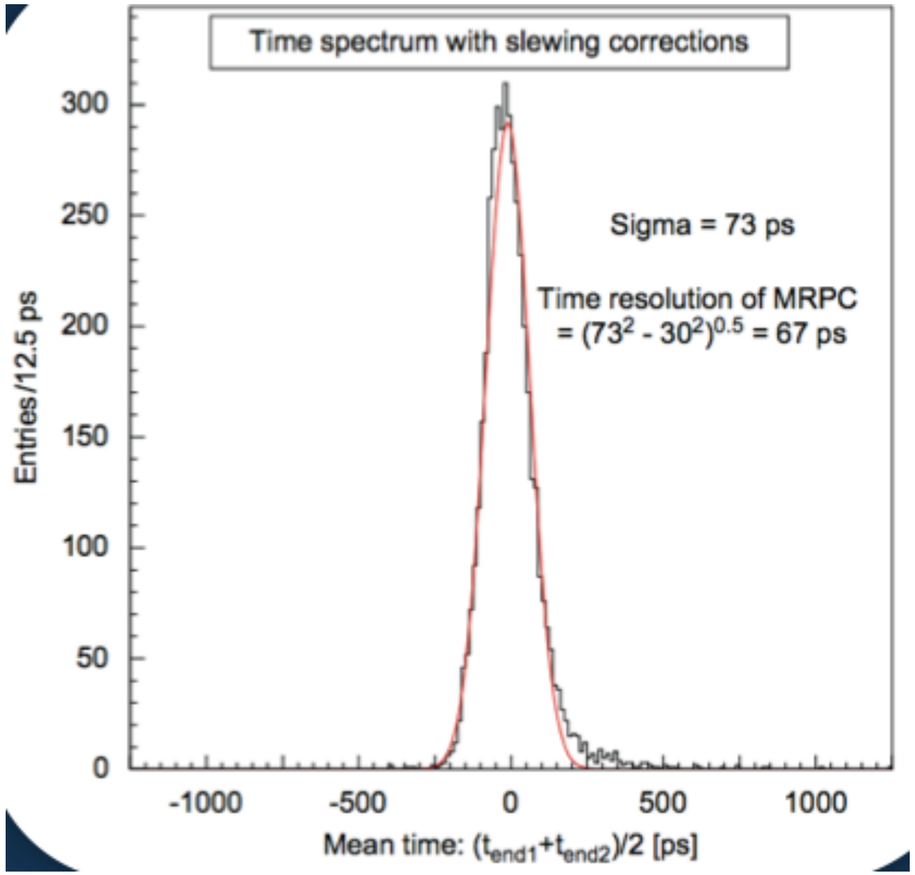




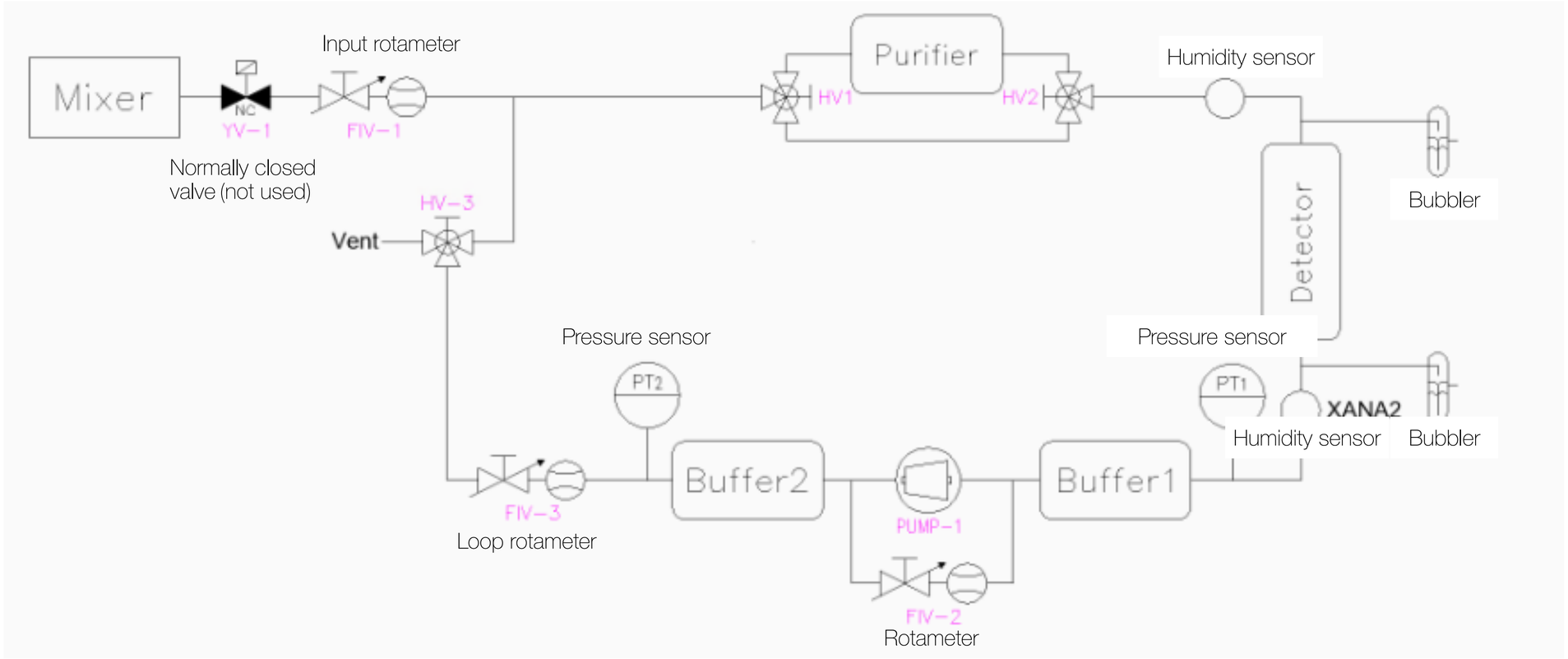
EEE : performance of MRPCs

https://cds.cern.ch/record/2669839/files/PoS(EPS-HEP2017)820.pdf





EEE telescope: recirculating system

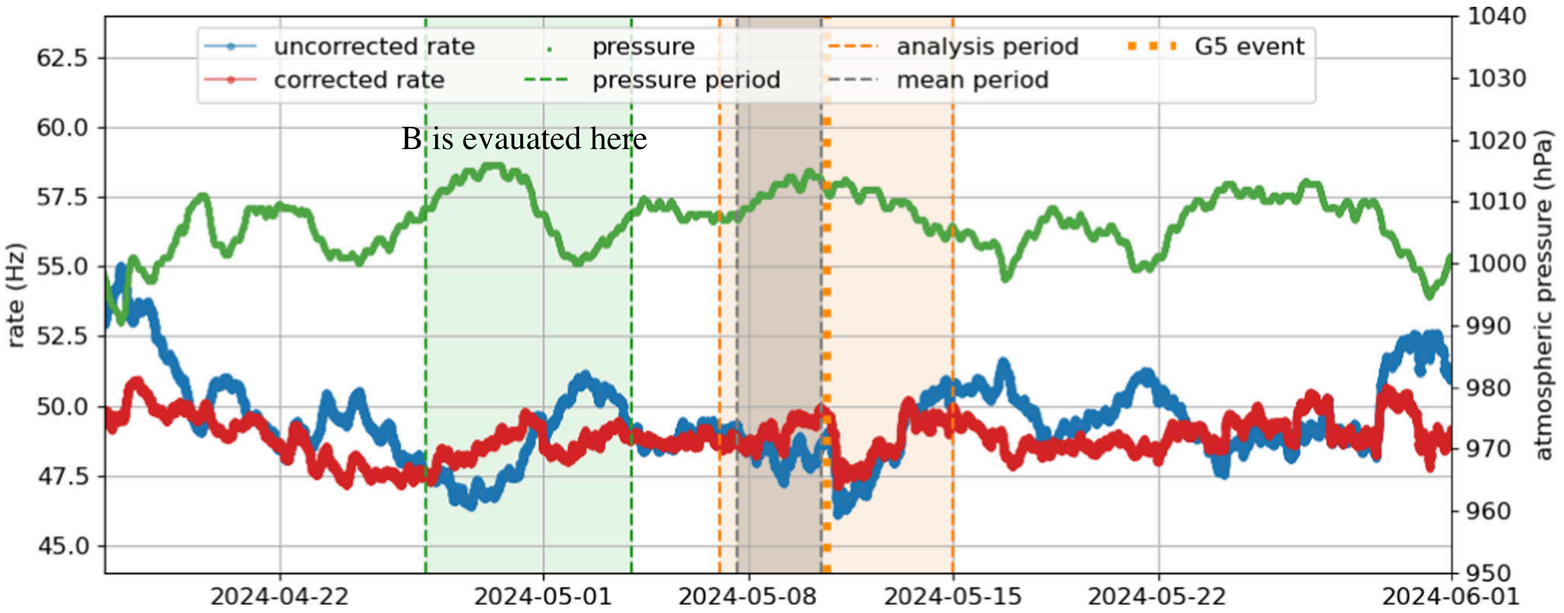


Methods for correction in Forbush decrease analysis

- *Abbrescia et al. EPJ Plus 141 790 2026*

$$I_P = I_0\, e^{-0.01\ \beta\ (P-P_0)}$$

pressure influence on the muon intensity observed at ground level: Ip=muon count rate at P; I0=initial count rate at P0; β=barometric coefficient (%/hPa) taking into account the magnitude of the pressure influence



BAROMETRIC COEFF.

β=slope of linear regression between

$\log(\Delta I/\langle I\rangle)$ and $\Delta P = P - \langle P\rangle$

Where <I> and <P> are the mean rate and mean pressure in the green region

$$I_{PC}(t) = I_{OBS}(t)\, e^{0.01\ \beta\ (P(t)-\langle P\rangle)}$$

Correction with β

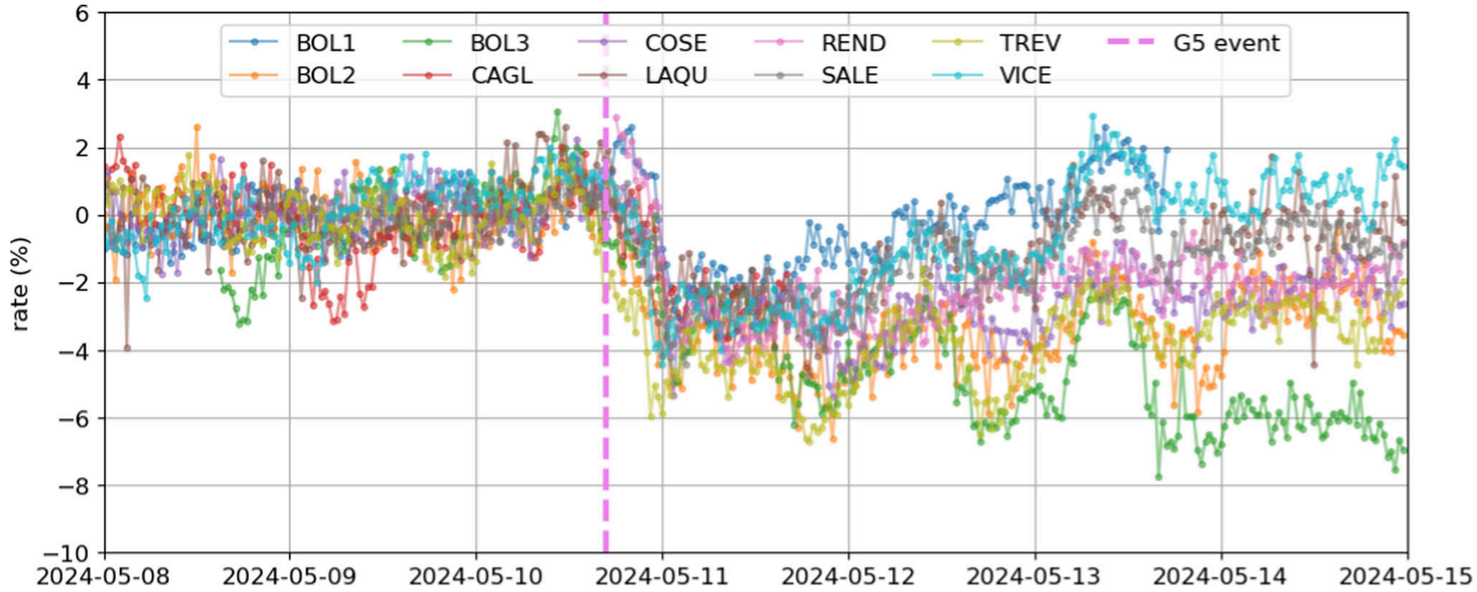
$$\Delta I(t) = \frac{I_{PC}(t) - \langle I_{PC}\rangle}{\langle I_{PC}\rangle} \times 100$$

Differential rate to compare different telescopes

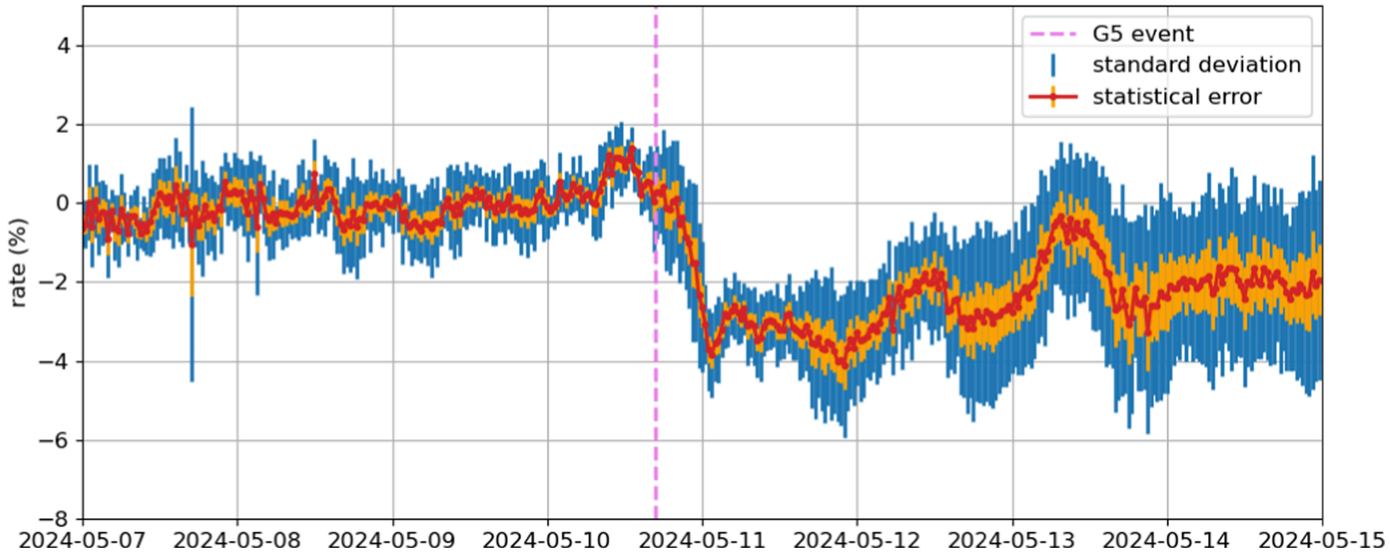
Where Ipc is reported above and <Ipc> is the mean value estimated in the grey region (just before the Forbush event)

Methods for correction in Forbush decrease analysis

- *Abbrescia et al. EPJ Plus 141 790 2026*



+- 2% of spread before the Forbush event



Mean