

Operation and performance of the ALICE Muon IDentifier RPCs during LHC Run 3

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Overview

- The ALICE experiment at CERN and its Muon IDentifier (MID)
- Run 3 upgrades
- Run 3 operations and performance
 - Efficiency
 - Dark current/rate
 - Integrated charge
- (Short) selection of physics results
- Conclusions and outlook

The ALICE detector at CERN



- ALICE = A Large Ion Collider Experiment at the LHC
 - Multipurpose detector taking data for all collision systems (pp, Pb–Pb,...)
 - Mainly focused on the study of quark-gluon plasma (QGP) in heavy-ion collisions

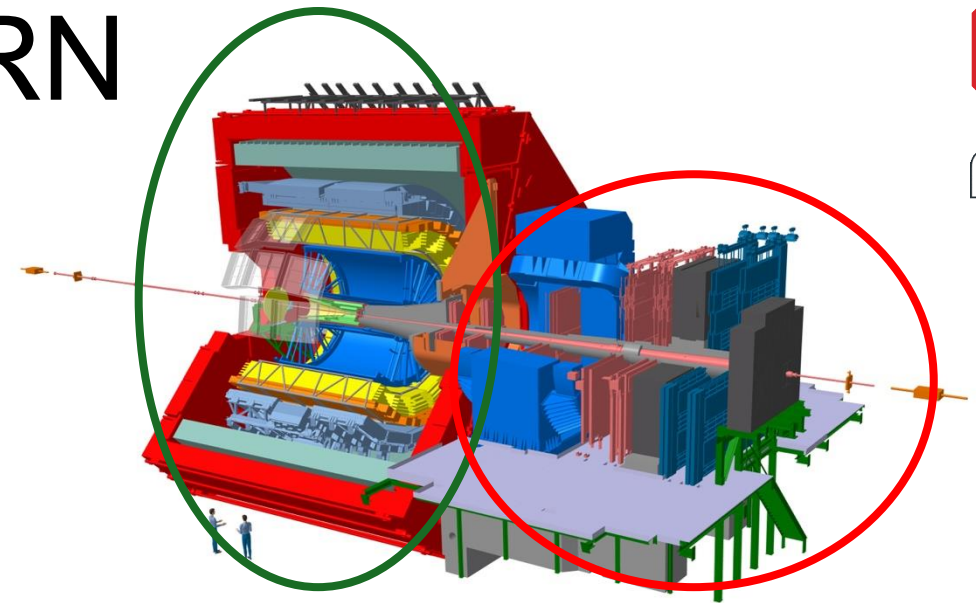
- Two spatially distinct detection regions

➤ **Central barrel:** $|\eta| < 0.9$

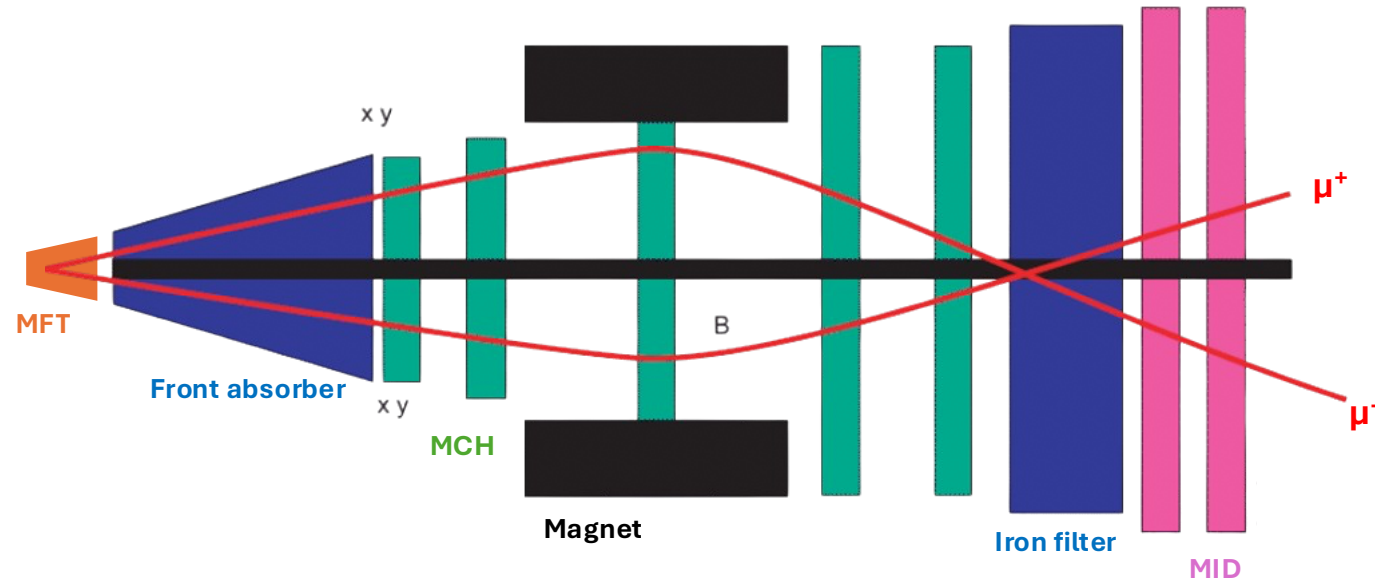
- Particle identification
- Hadron tracking, e^-/γ detection

➤ **Muon spectrometer:** $-4 < \eta < -2.5$

- Set of two **absorbers** to reduce the flux of hadrons in the muon spectrometer
- Tracking detectors: Muon Forward Tracker (**MFT**) + Muon Chambers (**MCH**)
- Dipole magnet to bend the muon tracks
- Muon Identifier (**MID**): **4 planes of single-gap RPC detectors, used for offline muon identification and bunch crossing determination**



3D view of the ALICE detector

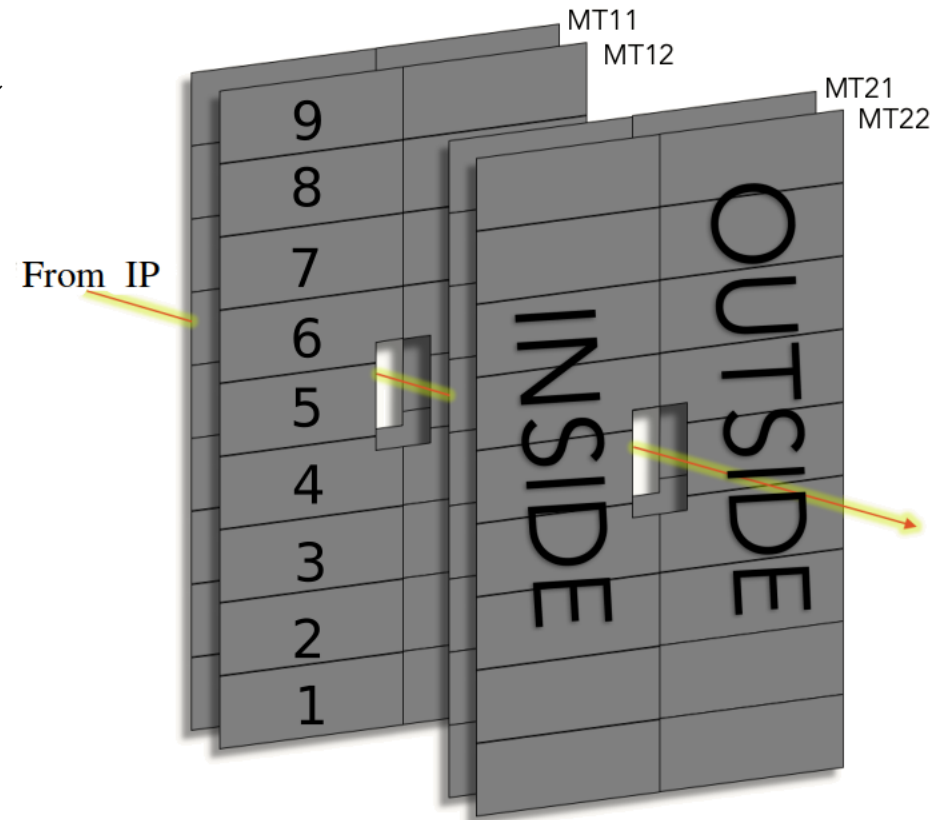


ALICE muon spectrometer

The ALICE Muon IDentifier

- 72 single gap RPCs arranged in 4 detection planes
 - 2 mm single gas gap + 2 mm Bakelite electrodes with $\rho \sim 10^9 - 10^{10} \Omega \cdot cm$
 - Located at 16/17 m from the interaction point
- Gas mixture: 89.7% $C_2H_2F_4$, 10% $i-C_4H_{10}$, 0.3% SF_6
 - 37% RH and a recirculation fraction of $\sim 88\%$
 - Total gas volume $\sim 0.3 m^3$
- Total area covered $\sim 140 m^2$ ($\sim 5.5 \times 6.5 m^2$ per plane)
 - Different RPC geometry to allow for beam pipe
- Three different strip pitches to keep occupancy uniform
 - $\sim 21k$ readout channels with 2D readout
 - **Horizontal strips:** bending-plane (BP)
 - **Vertical strips:** non-bending-plane (NBP)

} Muon tracks bent vertically by dipole



Sketch of the ALICE MID RPCs

ALICE running conditions in Run 3

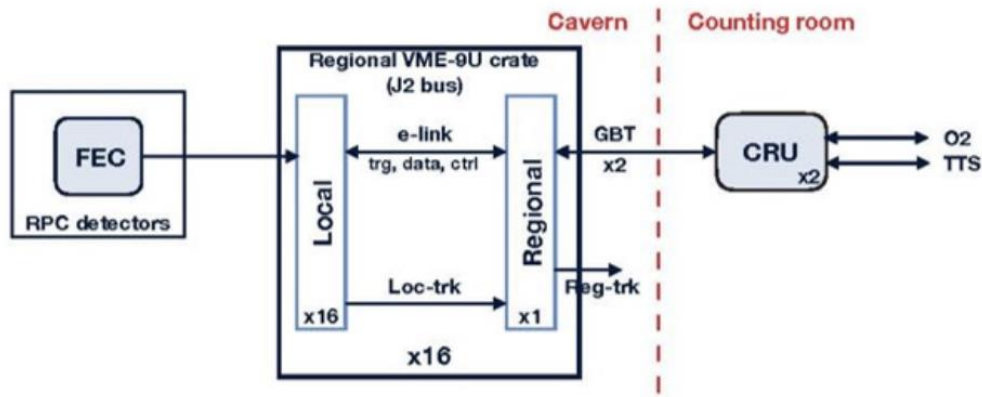
- 2022
 - pp @ $\sqrt{s} = 13.6$ TeV
- 2023
 - pp @ $\sqrt{s} = 13.6$ TeV
 - Pb-Pb @ $\sqrt{s_{NN}} = 5.36$ TeV
- 2024
 - pp @ $\sqrt{s} = 13.6$ TeV, pp @ $\sqrt{s} = 5.36$ TeV
 - Pb-Pb @ $\sqrt{s_{NN}} = 5.36$ TeV
- 2025
 - pp @ $\sqrt{s} = 13.6$ TeV
 - Pb-Pb @ $\sqrt{s_{NN}} = 5.36$ TeV
 - pO @ $\sqrt{s_{NN}} = 9.62$ TeV
 - OO @ $\sqrt{s_{NN}} = 5.36$ TeV
 - Ne-Ne @ $\sqrt{s_{NN}} = 5.36$ TeV
- 2026
 - pp @ $\sqrt{s} = 13.6$ TeV
 - Pb-Pb @ $\sqrt{s_{NN}} = 5.36$ TeV
- Total recorded luminosity in Run 3:
 - pp @ $\sqrt{s} = 13.6$ TeV -> $L_{int} = 174.4 \text{ pb}^{-1}$, pp @ $\sqrt{s} = 5.36$ TeV -> $L_{int} = 5.3 \text{ pb}^{-1}$
 - Pb-Pb @ $\sqrt{s_{NN}} = 5.36$ TeV -> $L_{int} = 6.91 \text{ nb}^{-1}$
 - pO @ $\sqrt{s_{NN}} = 9.62$ TeV -> $L_{int} = 7.3 \text{ nb}^{-1}$
 - OO @ $\sqrt{s_{NN}} = 5.36$ TeV -> $L_{int} = 5.0 \text{ nb}^{-1}$

Maximum instantaneous luminosity in Run 3 (Hz/cm²)

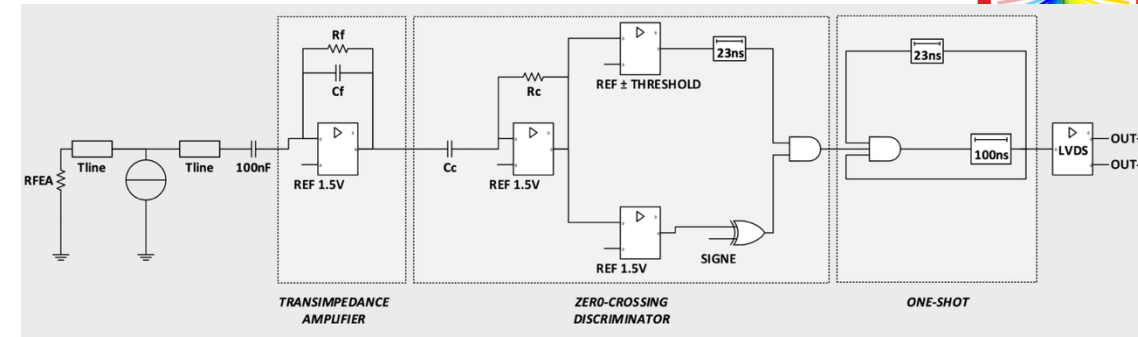
pp 5.36 TeV	1.62×10^{31}
pp 13.6 TeV	1.27×10^{31}
Pb-Pb 5.36 TeV	6.5×10^{27}
O-O 5.36 TeV	3.46×10^{28}
p-O 9.62 TeV	8×10^{28}
Ne-Ne 5.36 TeV	2.65×10^{28}

Run 3 upgrades - 1

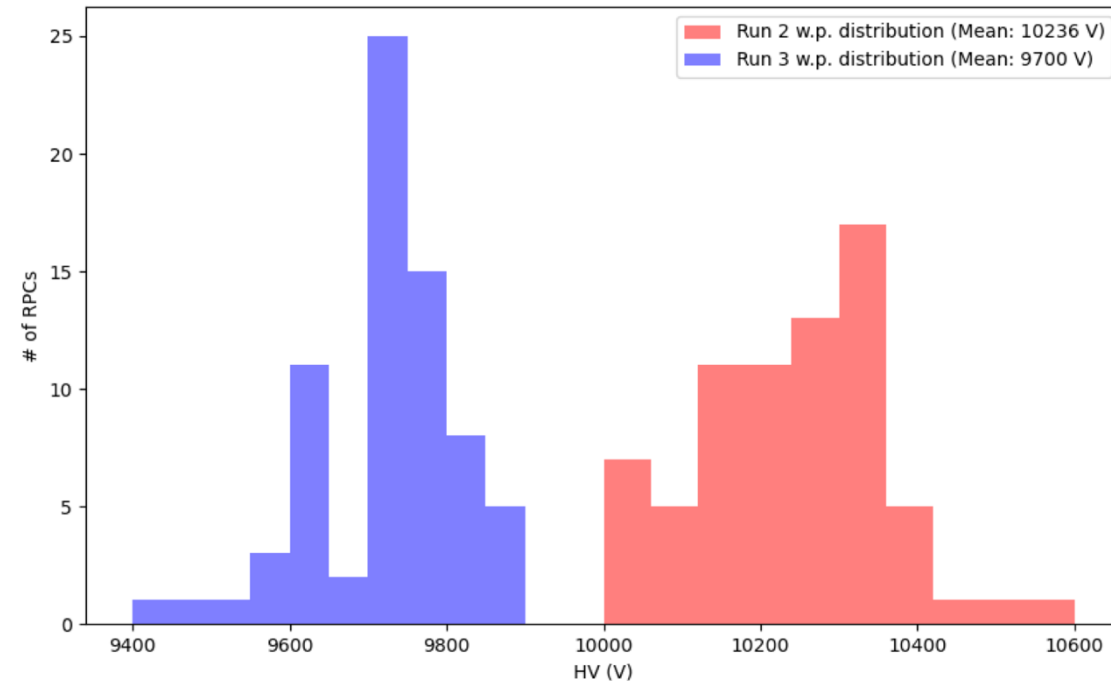
- Run 3 = ALICE running in triggerless mode
 - RPCs upgraded from muon triggering to identification for offline event selection
- New front-end electronics (FEERIC) to replace ADULT
 - Pre-amplification stage included, lower discrimination threshold (~ 150 fC)
 - Lower HV working point to improve rate capability and limit ageing
 - Working point reduced by ~ 500 V
 - Transition from maxi-avalanche mode to avalanche mode without changing the gas mixture
- Back-end readout adapted to work in triggerless mode



Simplified scheme of the MID readout in Run 3



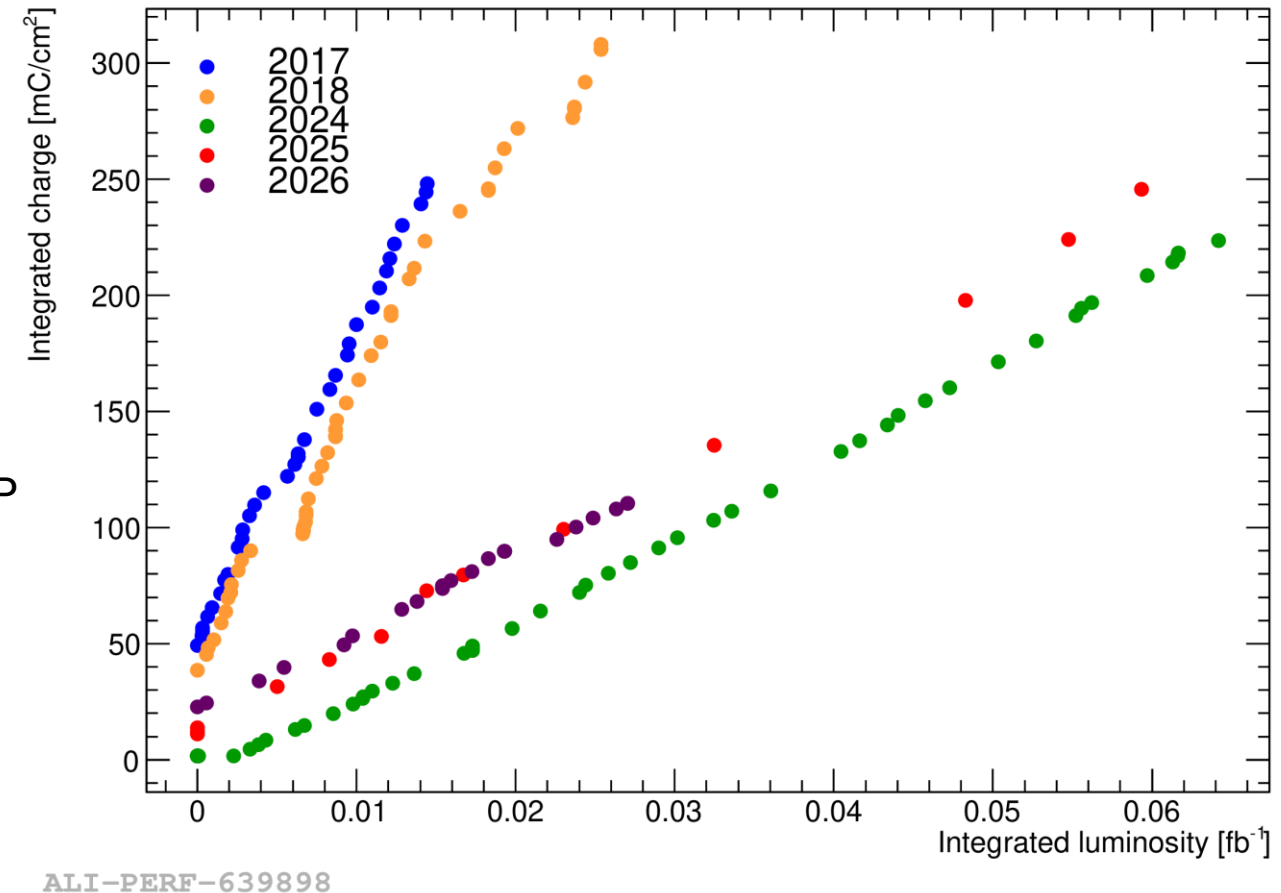
Architecture of the FEERIC chip



MID RPCs HV working point distribution in Run 2 vs Run 3

Run 3 upgrades - 2

- Trend of the total integrated charge (summed over all RPCs) vs delivered luminosity in **pp collisions**
- Clear reduction in the slope between Run 2 (2017-18) and Run 3 (2024-2026) thanks to the lowering of the WP
=> **FEERIC upgrade was a success!**



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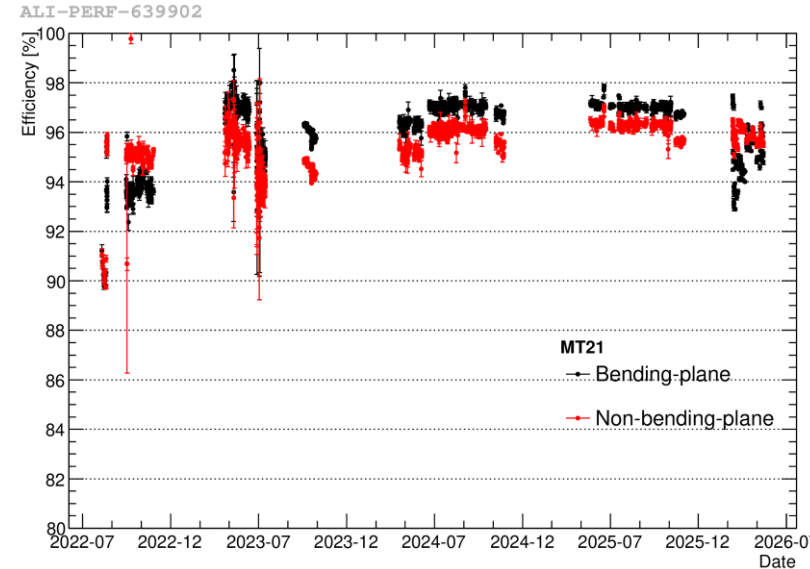
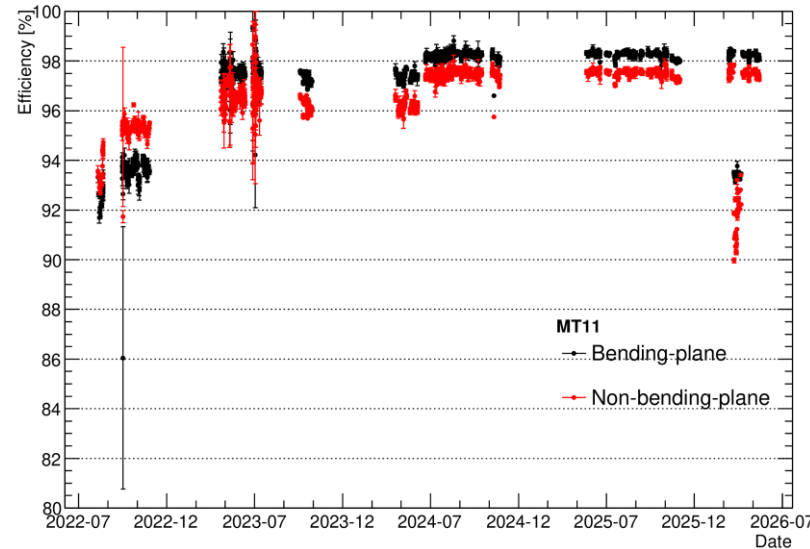
Total integrated charge as a function of delivered luminosity: Run 2 and Run 3 comparison

Run 3 operation and performance

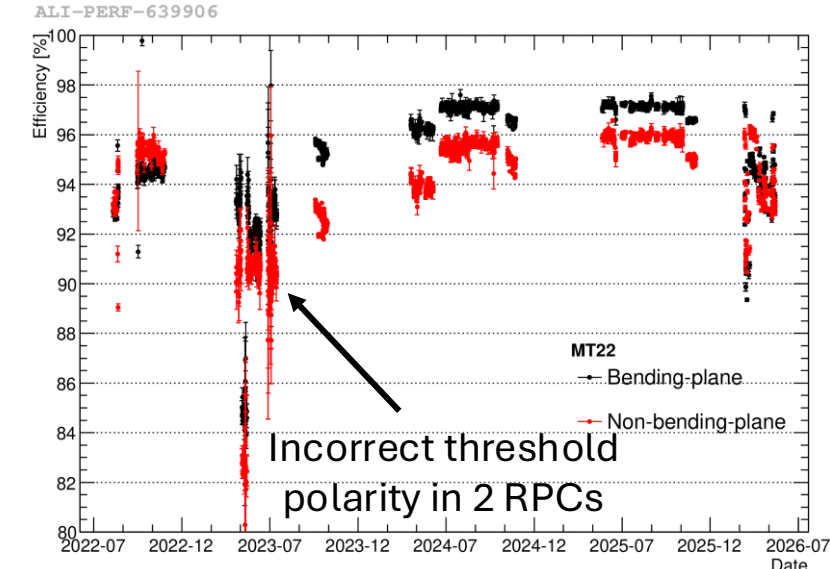
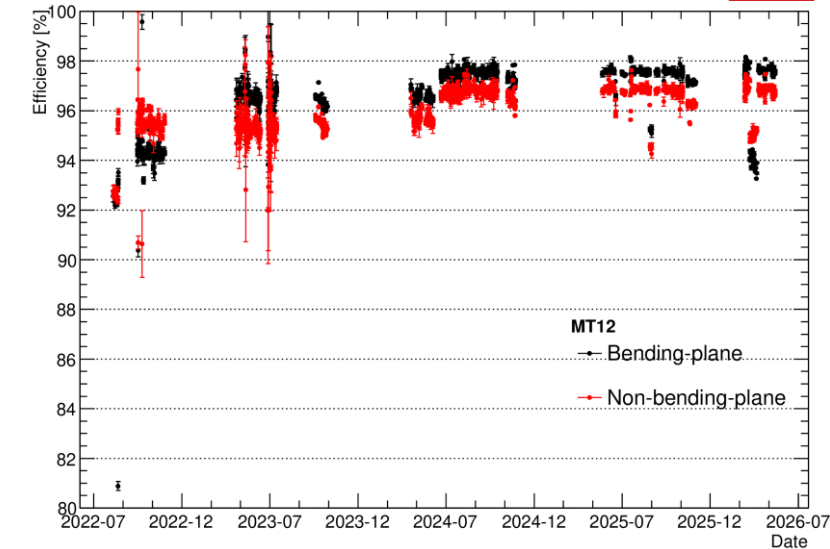


RPC detection efficiency

- Average efficiency per detection plane estimated with reconstructed tracks matched between MID and the tracking detectors in the muon spectrometer (MCH)
- Two curves for each detection plane
 - **Bending-plane efficiency**
 - **Non-bending-plane efficiency**
- Working point fine-tuning in 2024
 - Efficiency > 96% everywhere
- Excellent stability over time



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ALI-PERF-639914

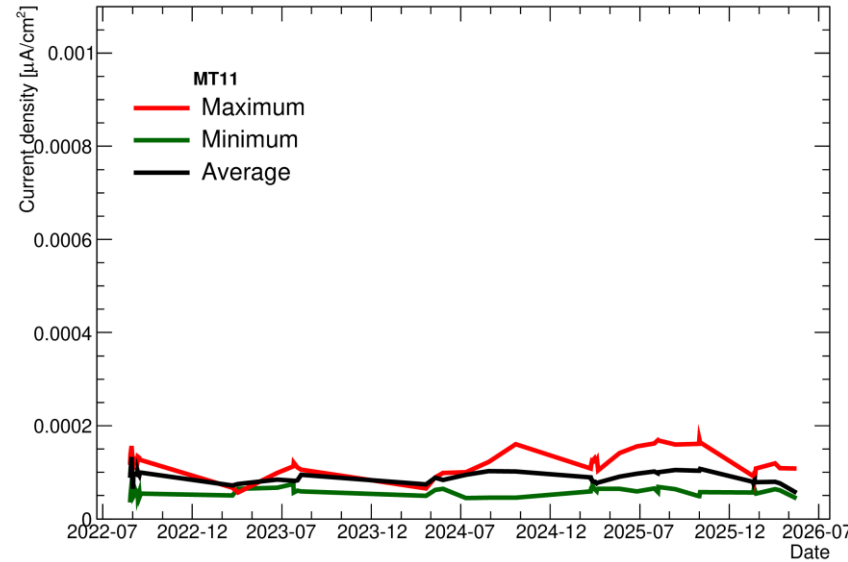
Dark current - 1

- Dark current = current absorbed when no collisions are ongoing
 - Studied during cosmic data taking, i.e. HV at nominal working point and NO BEAM in LHC
- Currents extracted from database
 - Filtered only in periods corresponding to cosmic runs
 - Average current per run computed for each RPC
 - Average current computed across all RPCs and for each run
 - Evolution between 2022 and 2026

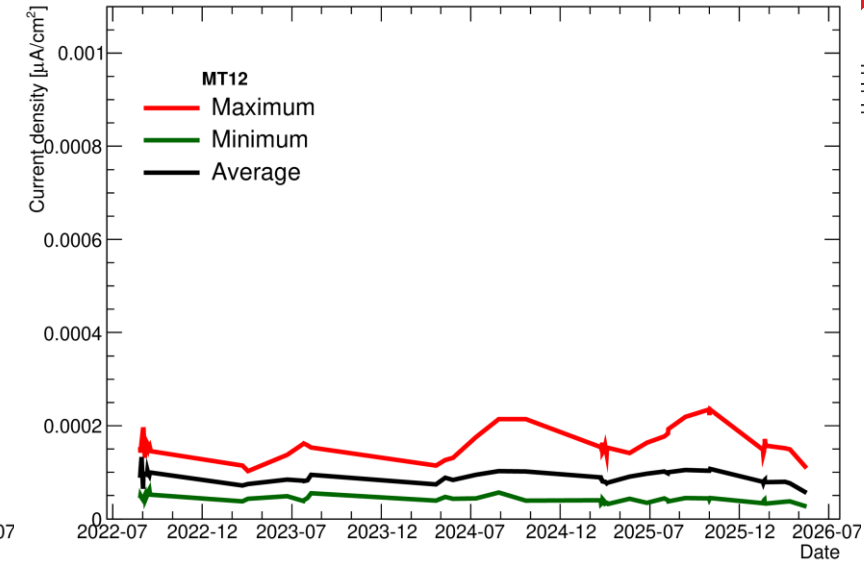


Dark current - 2

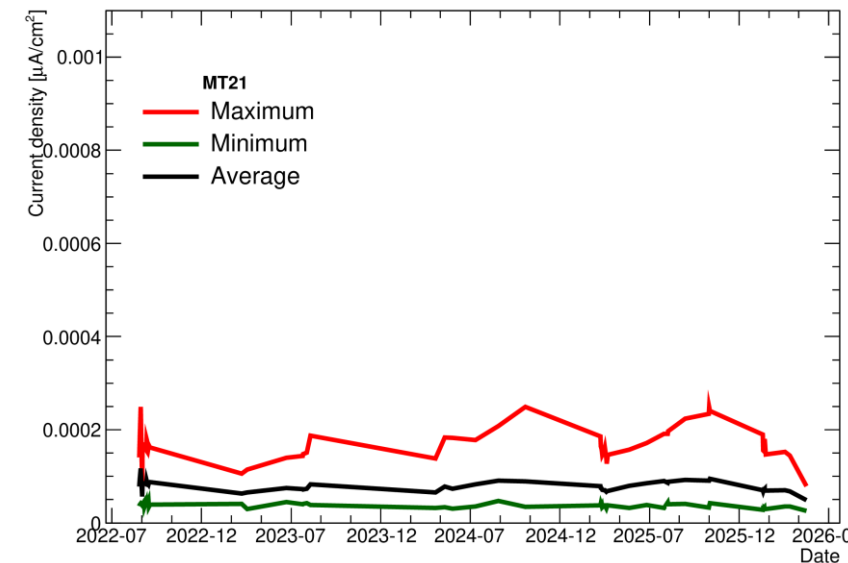
- Three curves for each detection plane
 - **Average dark current per plane**
 - **RPC with the lowest dark current at the end of Run 3**
 - **RPC with the highest dark current at the end of Run 3**
- Generally dark current is low ($< 2 \mu\text{A}$) and stable over time, similar values to Run 2
- MT22 plane: one problematic RPC with highest dark current. Known issue, under investigation (no decrease in efficiency and no increase in dark rate)



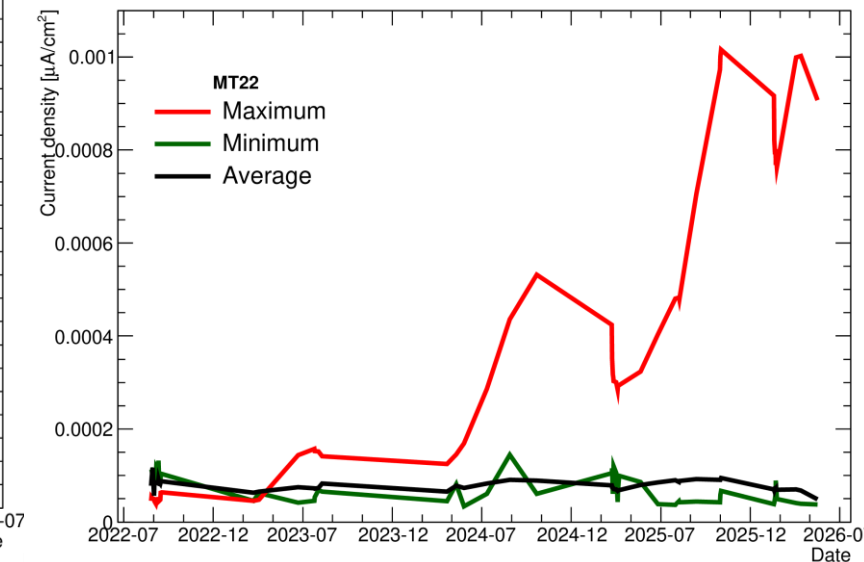
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ALI-PERF-639886



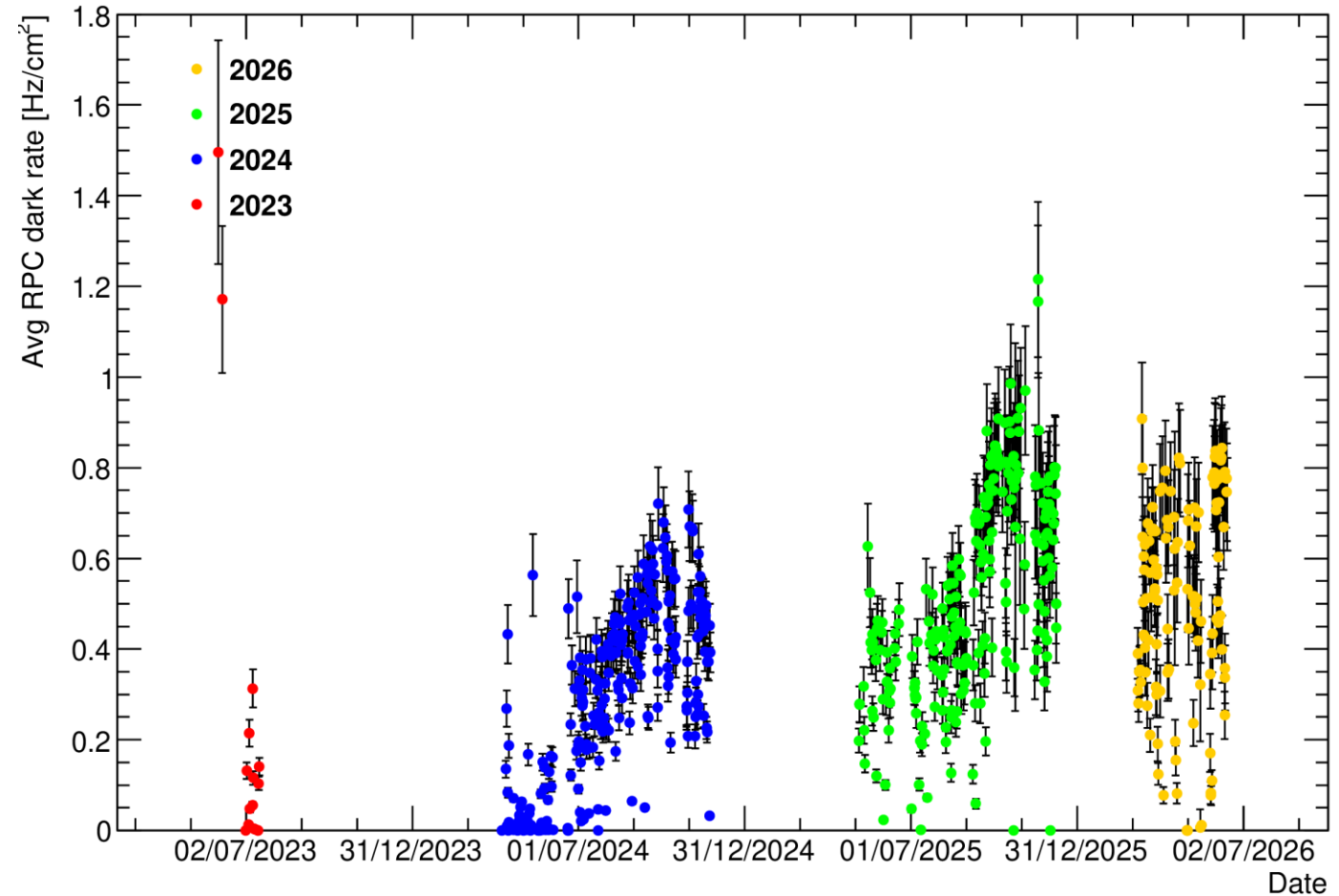
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Dark rate - 1

- Dark rate = RPC counting rate when NO BEAM is present in LHC
 - Electronic noise + detector noise
- Can be estimated using calibrations runs
 - Always one run before and one after each LHC fill
 - **Before fill:** HV ~ 8 kV in preparation for the fill, counting rate dominated by electronic noise
 - **After fill:** HV ~ 9.7 kV after nominal data-taking, counting rate dominated by detector noise
- Data available from all calibration runs from 2023 to 2026
 - Counting rate per strip measured over five LHC orbits
 - Subtraction of electronic noise carried out but negligible wrt RPC noise
 - RPC noise rate after fill depends strongly on material activation

Dark rate - 2

- Average **strip dark counting rate** computed after each fill
- Calculated only for non-bending plane (NBP)
 - Cluster size of noise hits unknown
 - Larger strips on NBP,
 - Noise **strip rate** is a better proxy for noise **cluster rate**
- Slightly higher than in Run 2
 - Lower electronics threshold



ALI-PERF-639894

Average RPC dark counting rate on NBP only

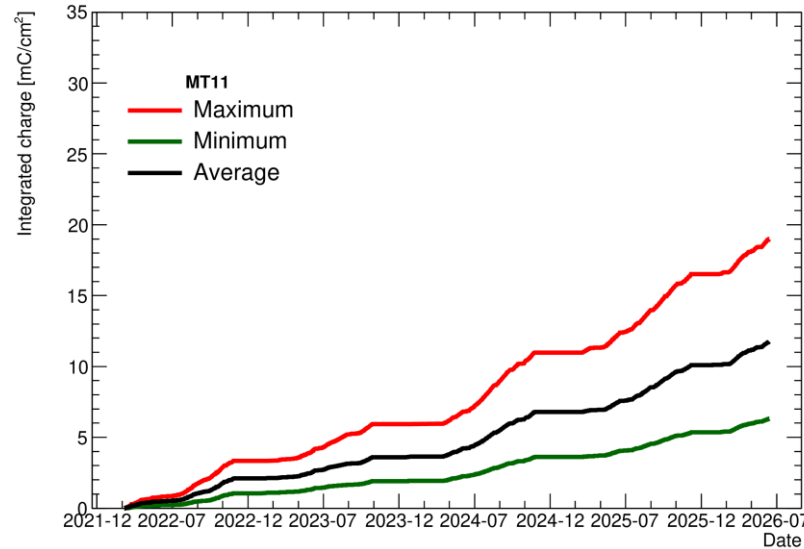
Integrated charge - 1

- Integrated charge used as *proxy* for detector *ageing*
- Computed as the integral of the current over time, without dark current subtraction (for most RPCs it is negligible wrt current with collisions)
 - Trend of integrated charge computed for each RPC + average for each detection plane
- Some (4) RPCs have been replaced during Run 3 but the plots show the total exposure of all the RPCs

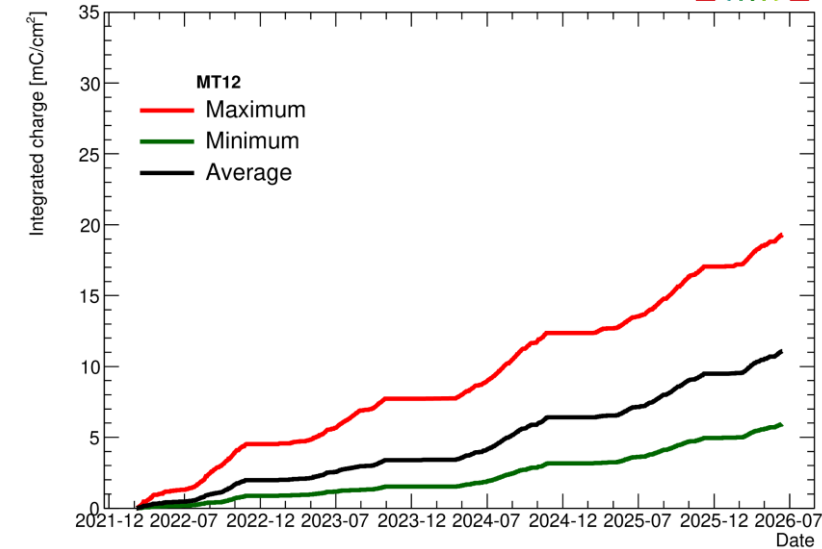


Integrated charge - 2

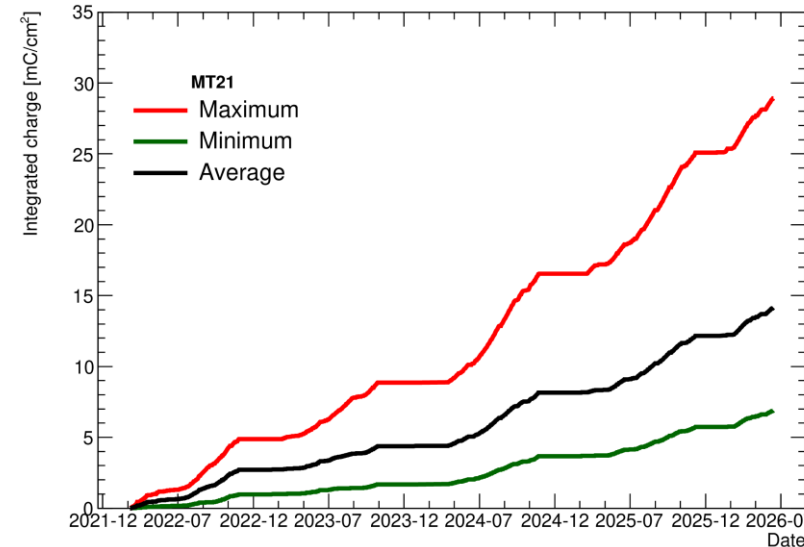
- Integrated charge per detection plane presented with the same color code as the dark current
- Values in the plots correspond to **Run 3 only**
- R&D ageing tests carried out up to 50 mC/cm^2
- Summing Run 2 values some RPCs are reaching the end of their certified lifetime
 - Spare RPC production and testing ongoing
 - **No performance degradation observed so far**



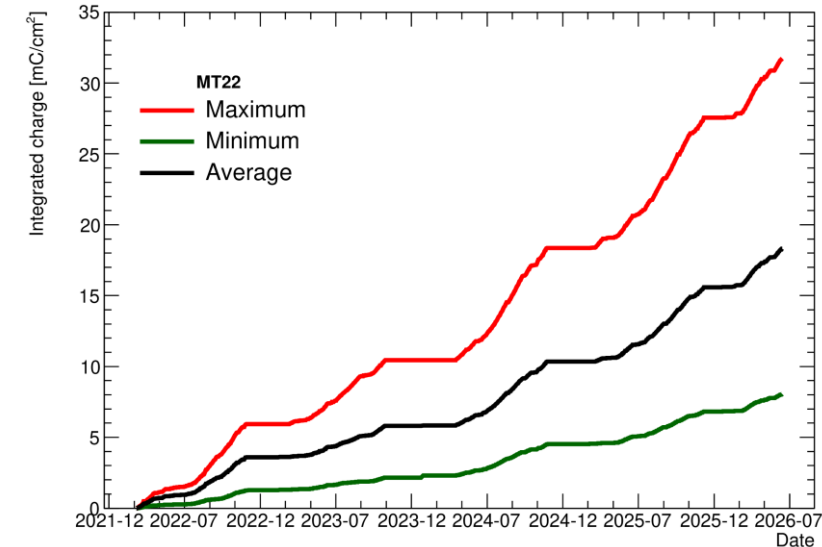
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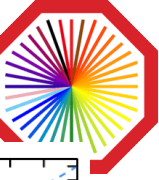
ALI-PERF-639854



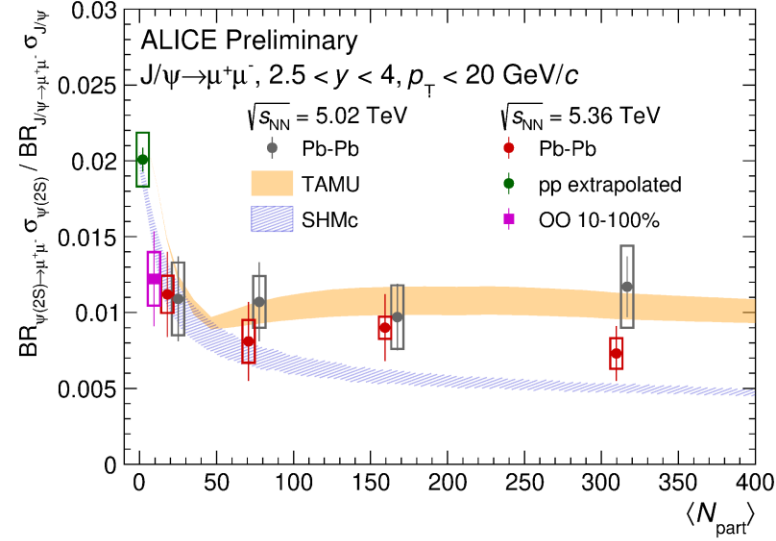
ALI-PERF-639858



ALI-PERF-639874

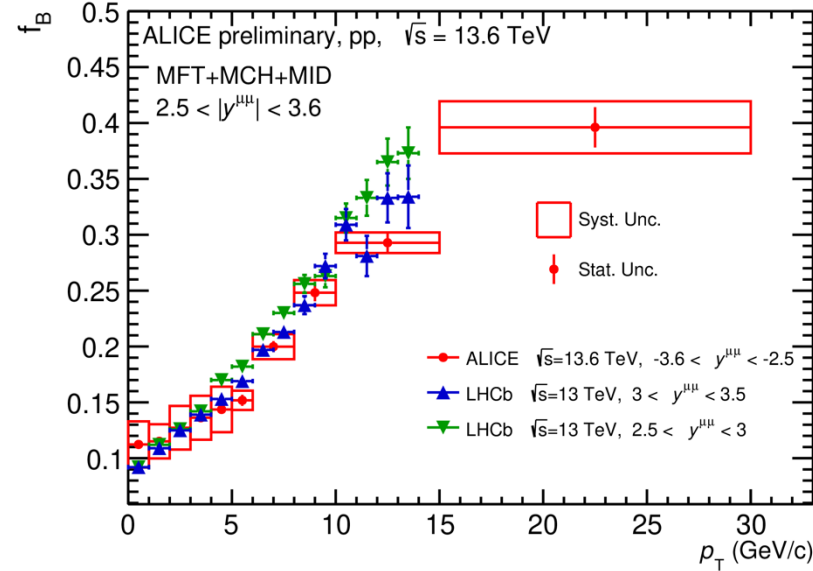


(Short) selection of physics results



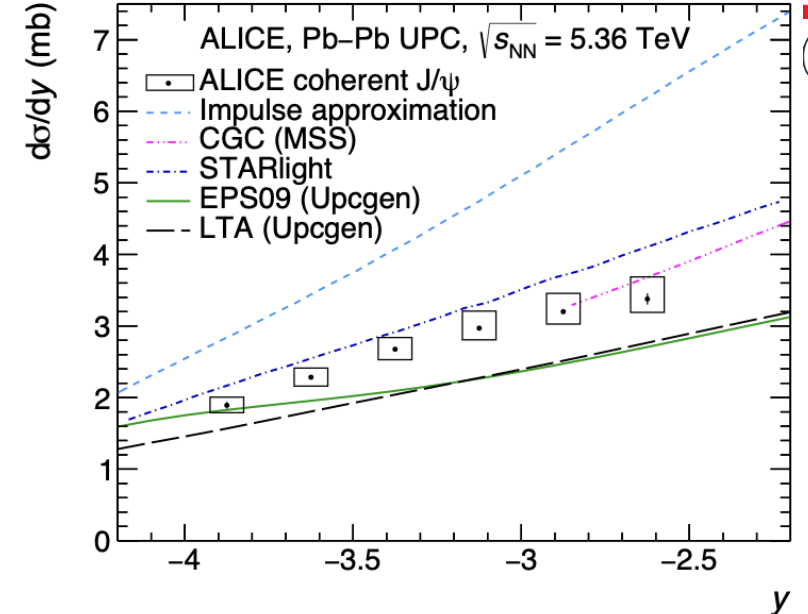
ALI-PREL-633459

$\psi(2S)$ to J/ψ ratio in Pb-Pb and O-O collisions

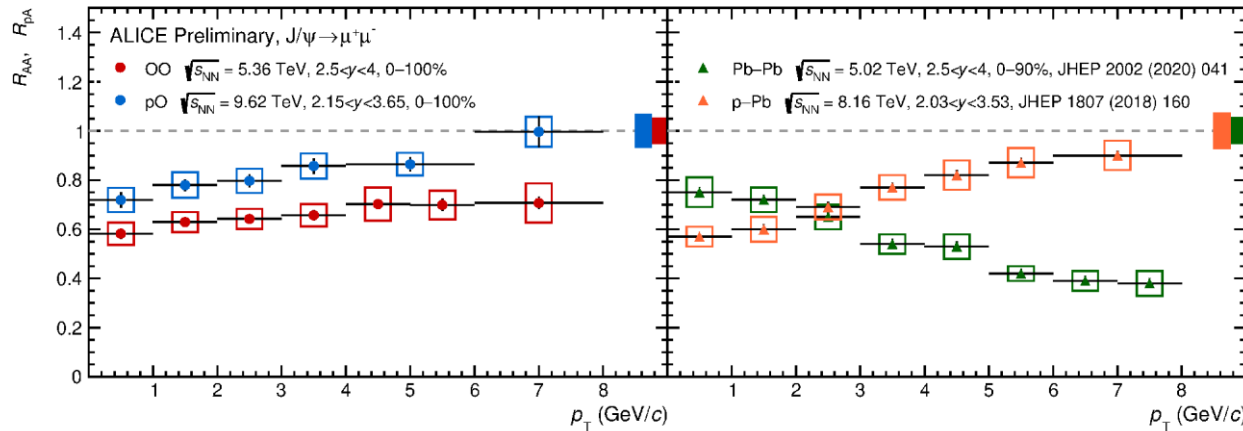


ALI-PREL-598305

Prompt/non prompt J/ψ fraction vs p_T



Rapidity-differential cross sections of the coherent J/ψ production in Pb-Pb UPCs at $\sqrt{s_{NN}} = 5.36$ TeV. Figure taken from [ALICE collaboration 2026](#) (Accepted for publication on JHEP)

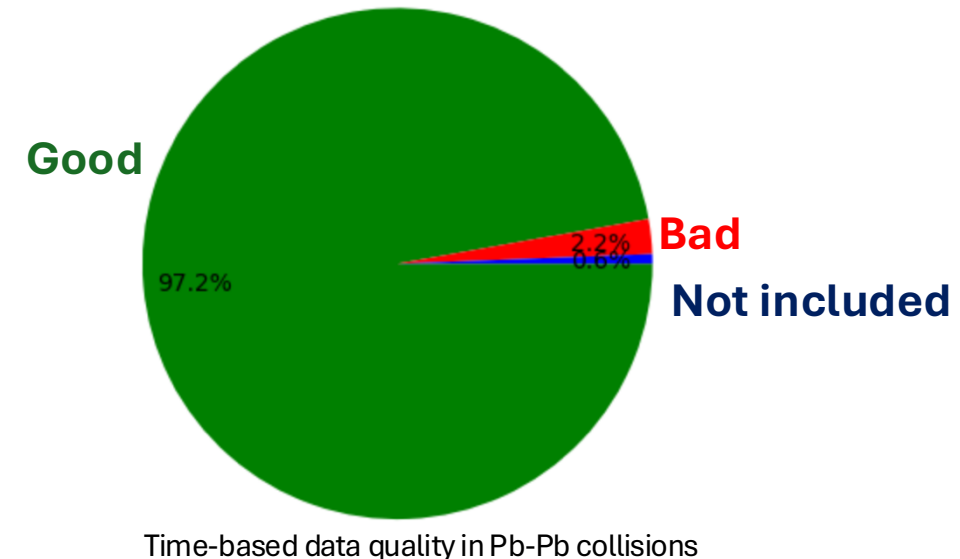
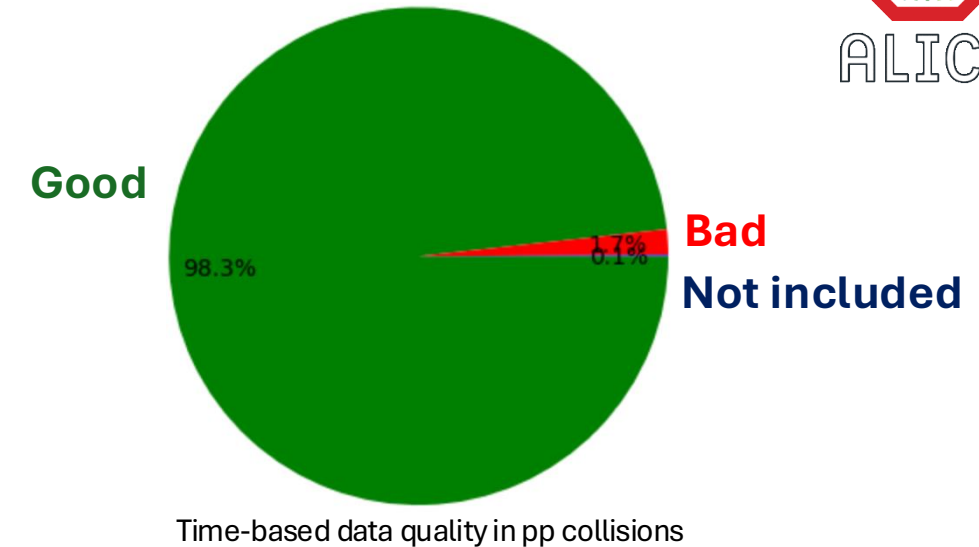


ALI-PREL-623785

J/ψ nuclear modification factor in different colliding systems

Conclusions

- MID RPCs performed extremely well throughout LHC Run 3
 - 98% good runs and detector availability throughout
- Few minor issues along the way promptly fixed by experts
- Production and testing of new spares are currently ongoing in preparation for the potential replacement of the most aged RPCs before or during Run 4 (see [Alessandro's talk](#))
- No major hardware activities foreseen during the Long Shutdown 3
 - Minor software improvements/maintenance
 - Possible threshold fine-tuning at the start of Run 4



Thank you so much for your attention!!!



Backup

RPC detection efficiency

- Efficiency estimated with reconstructed tracks matched between MID and the tracking detectors in the muon spectrometer (MCH)
- Muon track reconstructed if at least 3/4 detection planes detected a muon
- Average efficiency per detection plane and its uncertainty computed as:

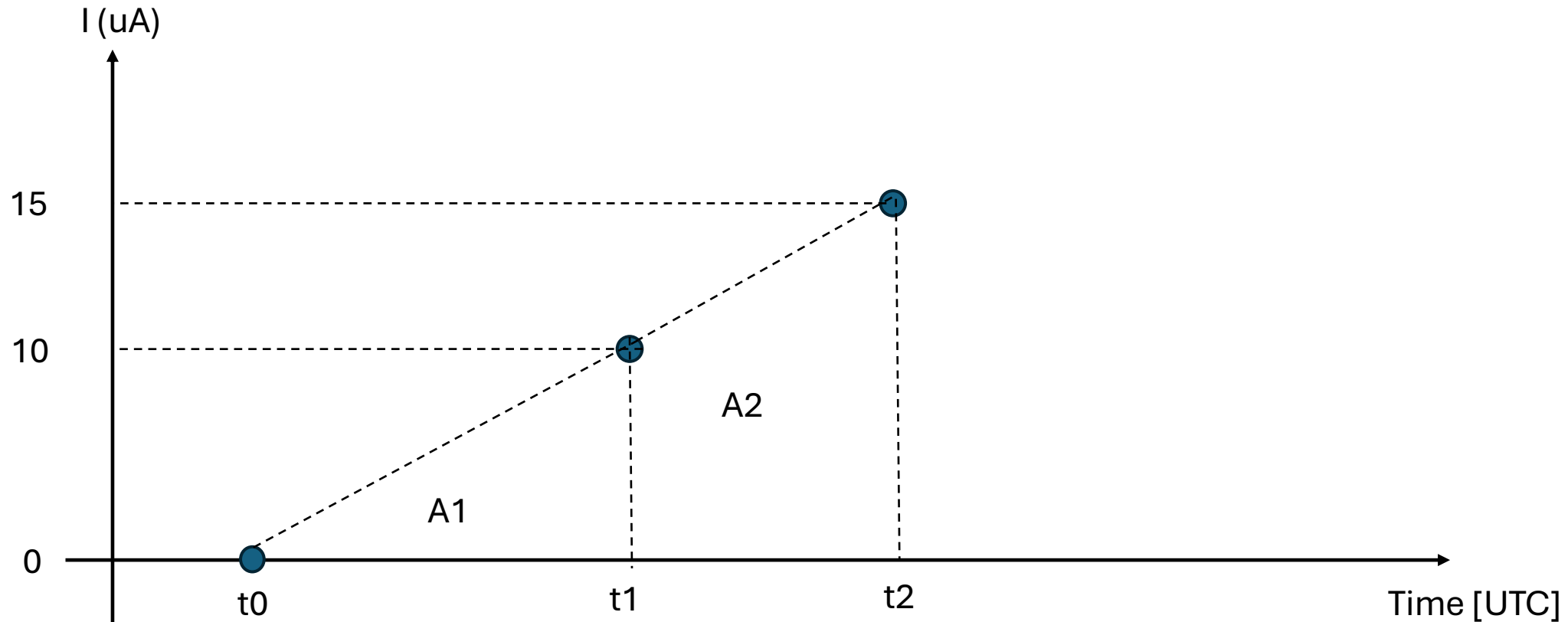
$$\varepsilon_{plane} = \frac{\text{\# of detected tracks in the plane}}{\text{\# of reconstructed tracks}}$$

$$\sigma_{\varepsilon-plane} = \sqrt{\frac{\varepsilon * (1 - \varepsilon)}{\text{\# of reconstructed tracks}}}$$

- Efficiency can also be computed at the RPC and *local board* (16 strips-groups, smallest *detection unit*) level

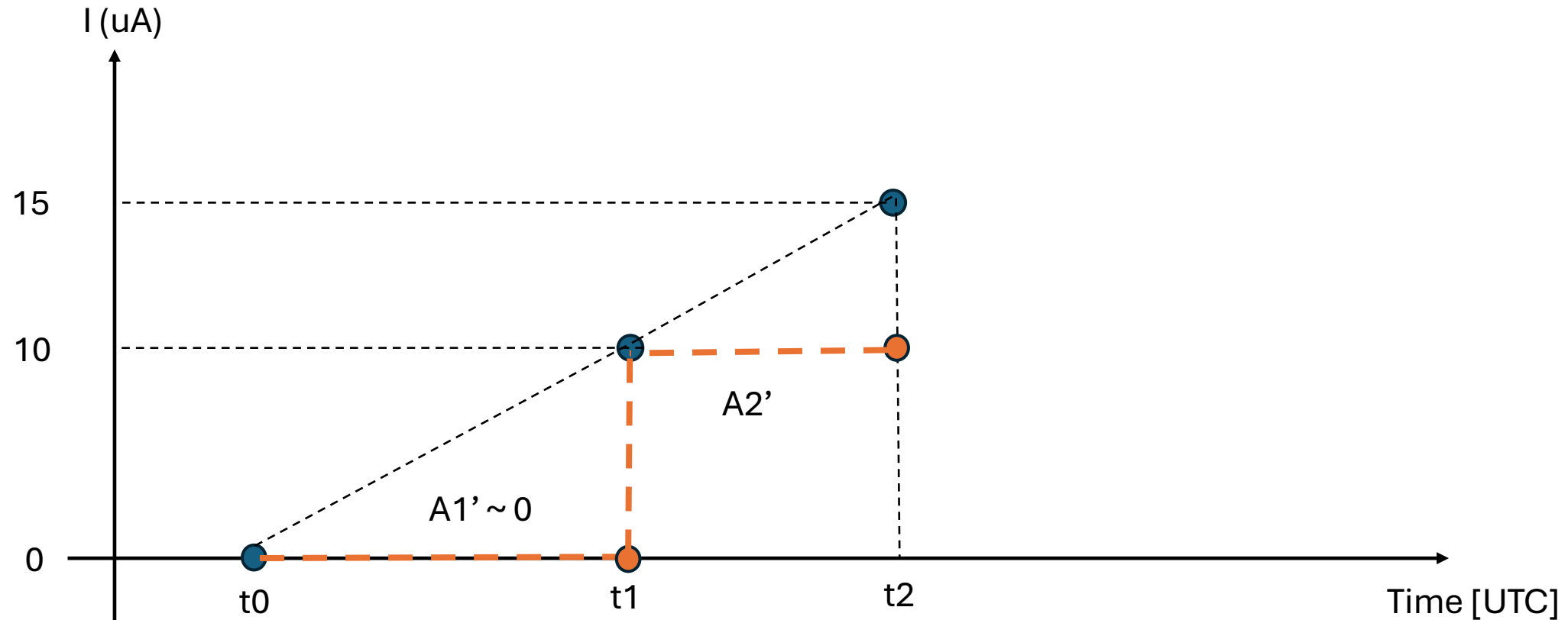
Integrated charge - 1

- Starting from DARMA database
- Usual issue -> current and voltages are saved only if there is a given change between consecutive values. Simple integration could be misleading



Integrated charge - 2

- This trend does not mean that current went from 0 to 10 and from 10 to 15
- In actuality the current started going from 0 to 10 some time close to t_1



Integrated charge - 3

- To fix the problem, start from normal values from db, load them in a dataframe
- Add two columns (start and end) which represent the time interval in which the current didn't change

	current	rpc	start	end	delta
date					
2026-01-19 11:29:31	0.0001	INSIDE_MT11_RPC1	2026-01-19 11:29:31	2026-01-21 11:07:43	171492.0
2026-01-21 11:07:43	0.0000	INSIDE_MT11_RPC1	2026-01-21 11:07:43	2026-01-21 11:21:08	805.0
2026-01-21 11:21:08	0.0027	INSIDE_MT11_RPC1	2026-01-21 11:21:08	2026-01-21 11:21:26	18.0
2026-01-21 11:21:26	0.0001	INSIDE_MT11_RPC1	2026-01-21 11:21:26	2026-01-21 12:08:50	2844.0
2026-01-21 12:08:50	0.0012	INSIDE_MT11_RPC1	2026-01-21 12:08:50	2026-01-21 12:08:52	2.0
...	...	...	...	...	...
2026-06-14 03:37:58	0.0035	INSIDE_MT21_RPC2	2026-06-14 03:37:58	2026-06-14 03:40:15	137.0
2026-06-14 03:40:15	0.0017	INSIDE_MT21_RPC2	2026-06-14 03:40:15	2026-06-14 03:40:17	2.0
2026-06-14 03:40:17	0.0034	INSIDE_MT21_RPC2	2026-06-14 03:40:17	2026-06-14 04:12:29	1932.0
2026-06-14 04:12:29	0.0000	INSIDE_MT21_RPC2	2026-06-14 04:12:29	2026-06-14 04:12:51	22.0
2026-06-14 04:12:51	0.0007	INSIDE_MT21_RPC2	2026-06-14 04:12:51	2026-06-14 04:15:20	149.0

Integrated charge - 4

- Calculate integrated charge in each interval where current does not change by multiplying current (converted to mA) by delta (in s) and dividing by RPC area
- **N.B. no dark current subtraction**

	current	rpc	start	end	delta	A	charge_A	cumulative_charge_per_RPC
date								
2026-01-19 11:29:31	0.0001	INSIDE_MT11_RPC1	2026-01-19 11:29:31	2026-01-21 11:07:43	171492.0	1.8496	9.271843e-04	0.000927
2026-01-21 11:07:43	0.0000	INSIDE_MT11_RPC1	2026-01-21 11:07:43	2026-01-21 11:21:08	805.0	1.8496	0.000000e+00	0.000927
2026-01-21 11:21:08	0.0027	INSIDE_MT11_RPC1	2026-01-21 11:21:08	2026-01-21 11:21:26	18.0	1.8496	2.627595e-06	0.000930
2026-01-21 11:21:26	0.0001	INSIDE_MT11_RPC1	2026-01-21 11:21:26	2026-01-21 12:08:50	2844.0	1.8496	1.537630e-05	0.000945
2026-01-21 12:08:50	0.0012	INSIDE_MT11_RPC1	2026-01-21 12:08:50	2026-01-21 12:08:52	2.0	1.8496	1.297578e-07	0.000945
...	...	...	...	...	...	...	...	...
2026-06-14 03:37:58	0.0035	INSIDE_MT21_RPC2	2026-06-14 03:37:58	2026-06-14 03:40:15	137.0	2.1025	2.280618e-05	2.180518
2026-06-14 03:40:15	0.0017	INSIDE_MT21_RPC2	2026-06-14 03:40:15	2026-06-14 03:40:17	2.0	2.1025	1.617123e-07	2.180518
2026-06-14 03:40:17	0.0034	INSIDE_MT21_RPC2	2026-06-14 03:40:17	2026-06-14 04:12:29	1932.0	2.1025	3.124281e-04	2.180830
2026-06-14 04:12:29	0.0000	INSIDE_MT21_RPC2	2026-06-14 04:12:29	2026-06-14 04:12:51	22.0	2.1025	0.000000e+00	2.180830
2026-06-14 04:12:51	0.0007	INSIDE_MT21_RPC2	2026-06-14 04:12:51	2026-06-14 04:15:20	149.0	2.1025	4.960761e-06	2.180835

Integrated charge - 5

- Area of all detectors implemented in this way

```
def extract_rpc(value):  
    if "RPC5" in value:  
        return value.split('_')[-2] + "_" + value.split('_')[-1]  
    else:  
        return value.split('_')[-2]  
  
area_dict = {  
    'MT11_RPC5': 2.210*0.680,  
    'MT12_RPC5': 2.210*0.680,  
    'MT21_RPC5': 2.356*0.725,  
    'MT22_RPC5': 2.356*0.725,  
    'MT11': 2.720*0.680,  
    'MT12': 2.720*0.680,  
    'MT21': 2.900*0.725,  
    'MT22': 2.900*0.725  
}
```

Radiation levels in the cavern – new FEE

- Total Ionizing Dose (TID), mainly due to photons, electrons and positrons. The values are meant for the full ALICE program after the LS2;
- Non-Ionizing Energy Loss (NIEL), conventionally expressed as bulk damage that would be caused by a given flux of 1 MeV neutrons (1 MeV neutron equivalent flux). The values are meant for the full ALICE program after the LS2;
- Flux of hadrons with kinetic energy > 20 MeV. It determines the rate of single event upsets in the microelectronics circuitry. The values are meant for Pb-Pb at 50 kHz interaction rate;
- Flux of all charged particles. It is not directly linked to radiation-induced effect, nevertheless it determines the detector occupancy and influences track reconstruction and particle identification. The values are meant for Pb-Pb at 50 kHz interaction rate.

From FEERIC production readiness review!

Such level of radiation does not represent any potential problem for modern electronics. The test of the pre-series in cavern on a long time scale is expected to confirm this affirmation.

	From IP collisions	From beam-gas
TID (krad)	6.4×10^{-3}	9.7×10^{-4}
NIEL (cm ⁻²)	8.4×10^9	8.4×10^8
Hadron flux (kHz/cm ²)	0.14	5.2×10^{-4}
Charged particles (kHz/cm ²)	0.013	4.1×10^{-4}

Table 5: Expected radiation level for the most exposed MID area (at r=60 cm and z=1720 cm)