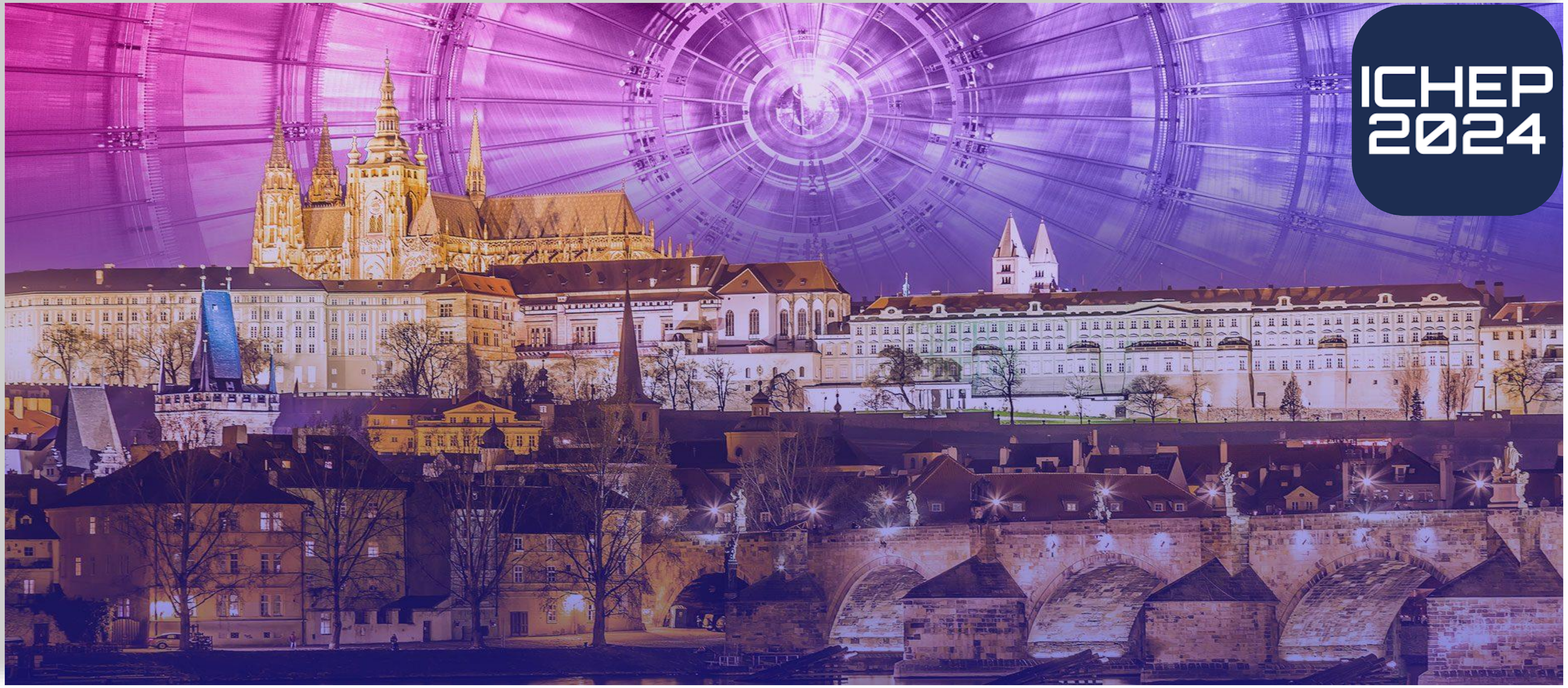
The ALICE 3 Particle IDentification system

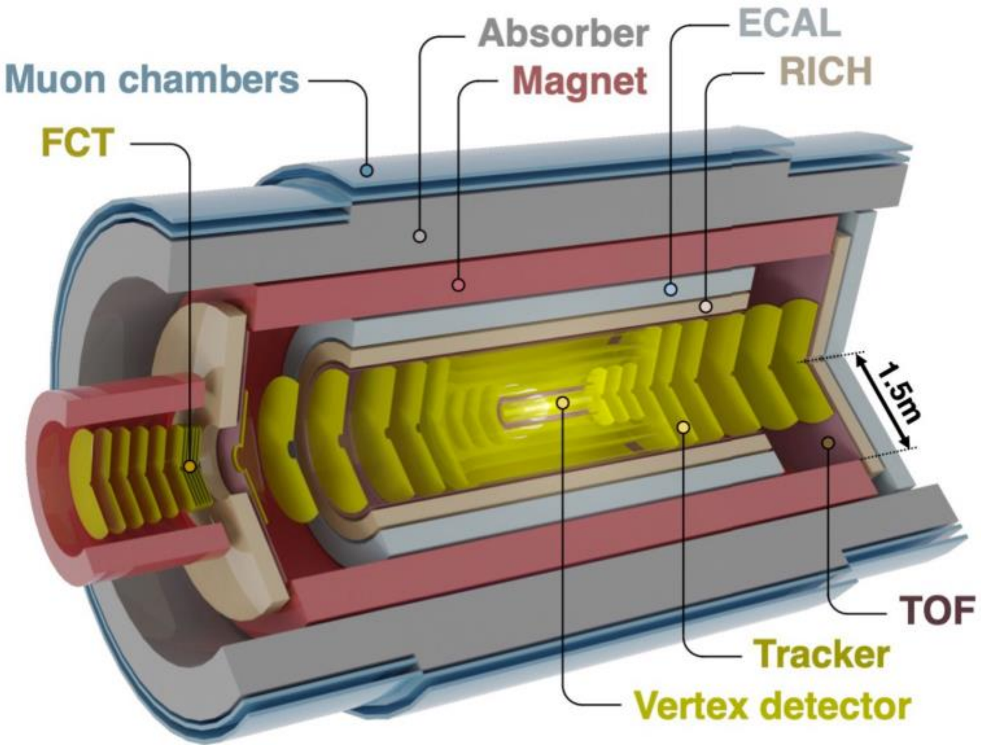
Giulia Gioachin
On behalf of ALICE Collaboration



18 – 24 July 2024 – Prague

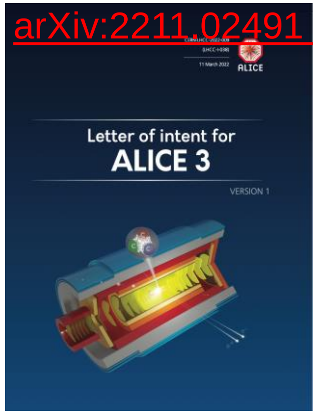
The ALICE 3 Upgrade

Run 1 2009 - 2013 → Run 2 2015 - 2018 → Run 3 2022 - 2025 → Run 4 2029 - 2032 → Run 5 2035 - 2038 → Run 6 2040 - 2041



ALICE 3 main goal: access the dynamics of the strongly interacting matter produced in heavy-ion collisions

arXiv:2211.02491



ALICE 3 Upgrade

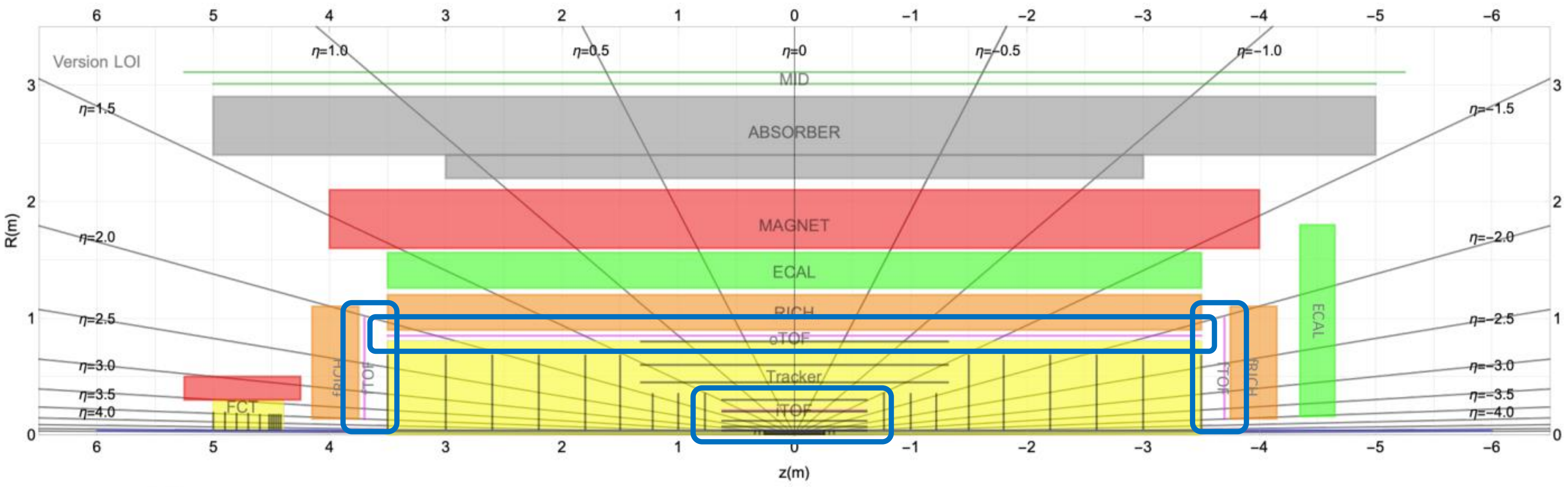
a next-generation heavy-ion experiment at the *LHC*

→ **innovative detector concept**

- ❑ Compact and lightweight all-silicon tracker
- ❑ Retractable vertex detector
- ❑ **Extensive particle identification**
- ❑ Large acceptance
- ❑ Superconducting magnet system
- ❑ Continuous read-out and online processing

See I. Altsybeev Talk

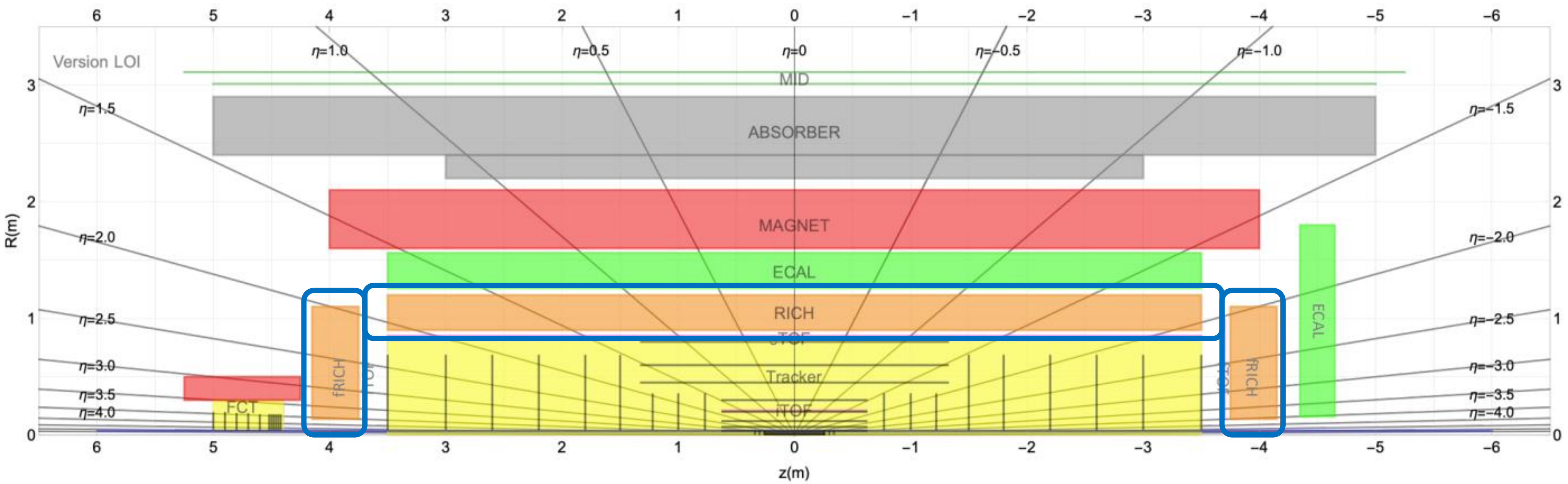
The ALICE 3 PID System



ALICE 3 PID system:

Time-Of-Flight: InnerTOF, OuterTOF, Forward TOF disks

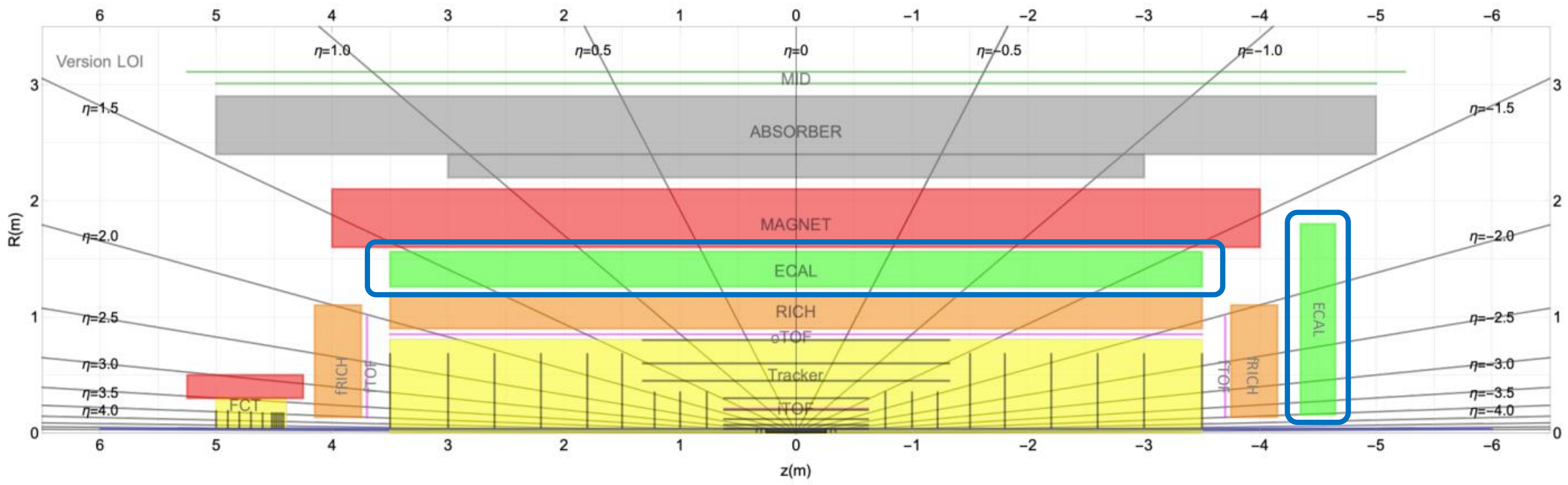
The ALICE 3 PID System



ALICE 3 PID system:

Time-Of-Flight: InnerTOF, OuterTOF, Forward TOF disks
Ring-Imaging Cherenkov: Barrel RICH, Forward RICH

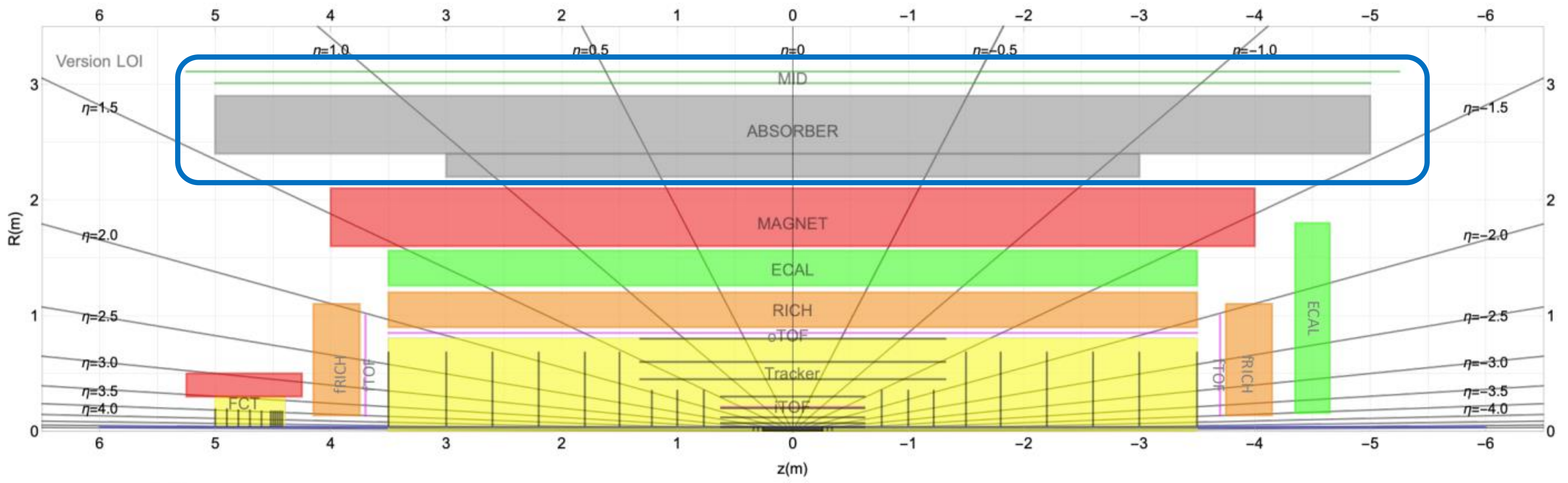
The ALICE 3 PID System



ALICE 3 PID system:

Time-Of-Flight: InnerTOF, OuterTOF, Forward TOF disks
Ring-Imaging Cherenkov: Barrel RICH, Forward RICH
EM Calorimeter: Barrel + Forward ECAL

The ALICE 3 PID System



ALICE 3 PID system:

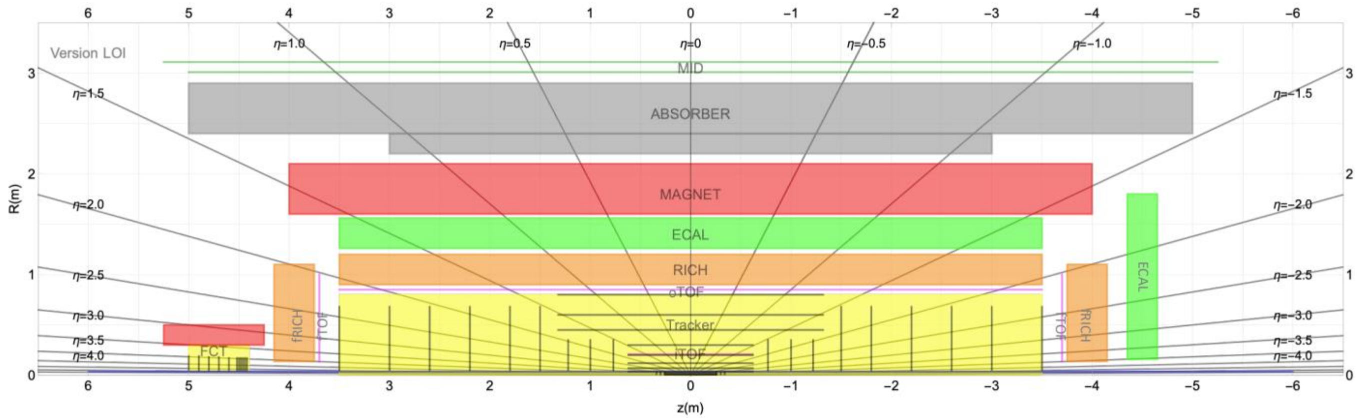
Time-Of-Flight: InnerTOF, OuterTOF, Forward TOF disks
Ring-Imaging Cherenkov: Barrel RICH, Forward RICH
EM Calorimeter: Barrel + Forward ECAL
Muon Identifier Detector: Barrel Muon Identification Detector

The ALICE 3 PID System

Component	Observables	$\|\eta\|< 4$	Detectors
Hadron ID	Multi-charm baryons	π/K/p separation up to a few GeV/*c*	**Time Of Flight:** $\sigma_{tof} \approx 20$ ps **RICH:** aerogel, $\sigma_\theta \approx 1.5$ mrad
Electron ID	Dielectrons, Quarkonia, χ_{c1}(3872)	pion rejection by 1000x up to ~2 - 3 GeV/*c*	**Time Of Flight:** $\sigma_{tof} \approx 20$ ps **RICH:** aerogel, $\sigma_\theta \approx 1.5$ mrad Possibily preshower detector
Muon ID	Quarkonia, χ_{c1}(3872)	reconstruction of J/Ψ at rest, i.e. muons from 1.5 GeV/*c*	steel absorber: L ≈ 70 cm **Muon detectors**
Electromagnetic calorimetry	Photons, jets χ_c	Large acceptance High-resolution segment	**Pb-Sci calorimeter** **$PbWO_4$ calorimeter**

ALICE 3 PID system:

Time-Of-Flight: iTOF, oTOF, fTOF
Ring-Imaging Cherenkov: bRICH, fRICH
EM Calorimeter: Barrel + forward ECAL
Muon Identifier Detector: Barrel MID



The ALICE 3 PID System

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ALICE 3 PID system:

Time-Of-Flight: iTOF, oTOF, fTOF
Ring-Imaging Cherenkov: bRICH, fRICH
EM Calorimeter: Barrel + forward
Muon Identifier Detector: Barrel MID

Exploit **Time-Of-Flight** and **Cherenkov Imaging techniques** → essential for Particle IDentification

ALICE 3 Time Of Flight Detector

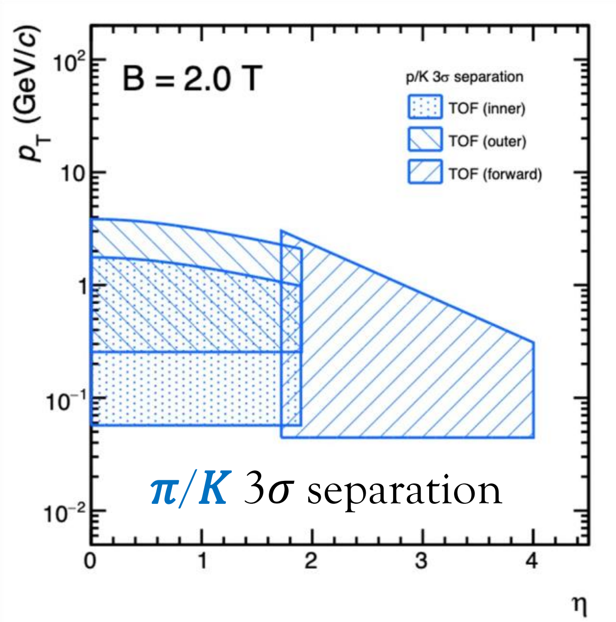
The **Time-Of-Flight system** provides particle identification over the full acceptance ($|\eta| < 4$)

2 barrel + 1 forward TOF layers:

- Two layers → **InnerTOF** and **OuterTOF** located at 20 cm and 85 cm from the beam pipe
  - Barrel TOF ($|\eta|<2$)
- **Forward TOF** located at 405 cm on either side of the interaction point
  - Forward TOF ($2<|\eta|<4$ and $-4<|\eta|<-2$)

Total silicon surface ~ 45 m^2

- e/π separation up to ≈ 500 MeV/c
- π/K separation up to ≈ 2 GeV/c
- K/p separation up to ≈ 4 GeV/c
- separation power $\propto L/\sigma_{TOF}$, → σ_{TOF}≈ 20 ps



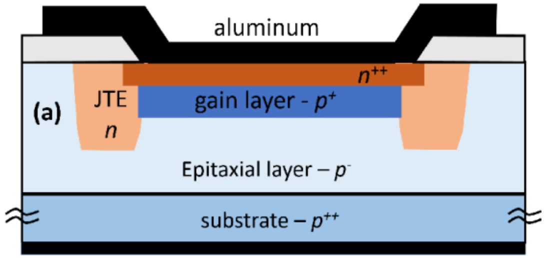
Detector Specifications

- ❑ Time resolution σ_{TOF} ≈ 20 ps r.m.s.
- ❑ Low material budget of 1-3% X_0
- ❑ Power density of 50 mW/cm^2

R&D for Time Of Flight Detector

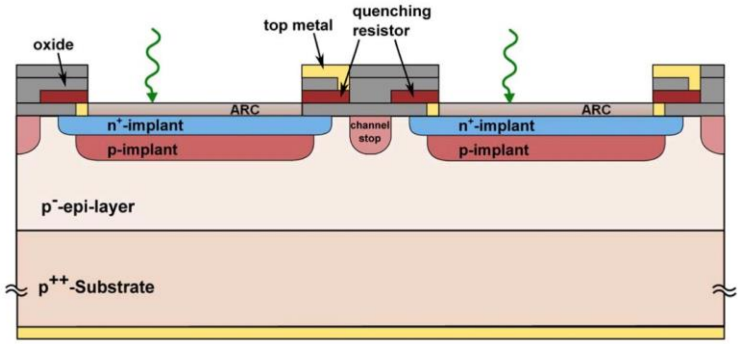
3 candidate sensor technologies for ALICE 3 TOF

LGAD



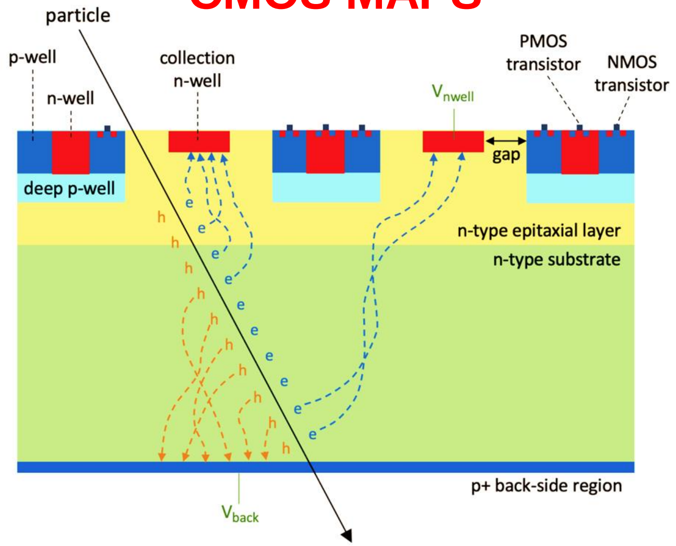
- **Timing resolution of ~30 ps** demonstrated with 50 μm up to (1-2)10^{15} 1-MeV-neq/cm^2
- Thinner LGADs produced by different manufacturers

SiPM



- Timing resolution of 40 ps for single photons detection so far
- Very promising results on MIP detection
- Dark count issue → no radation hardness

CMOS MAPS

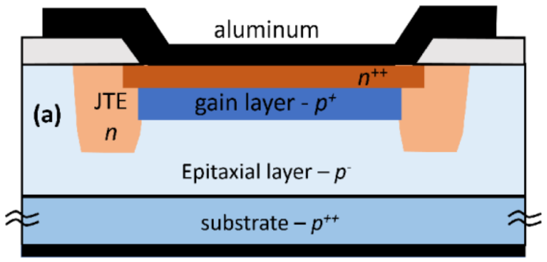


- Low material budget
- Cheap and easy assembly
- Low power
- Investigation on innovative design to proof timing performance

R&D for Time Of Flight Detector

3 candidate sensor technologies for ALICE 3 TOF

LGAD



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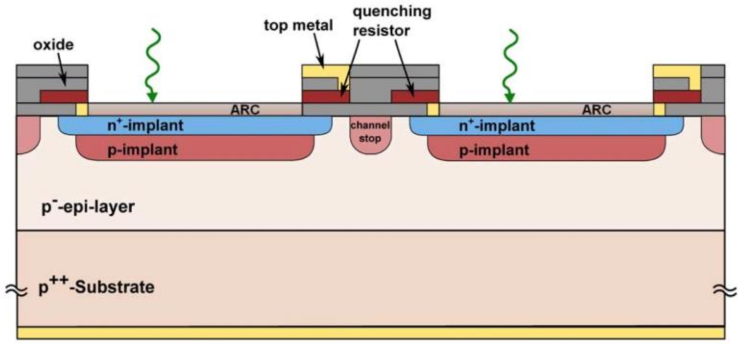

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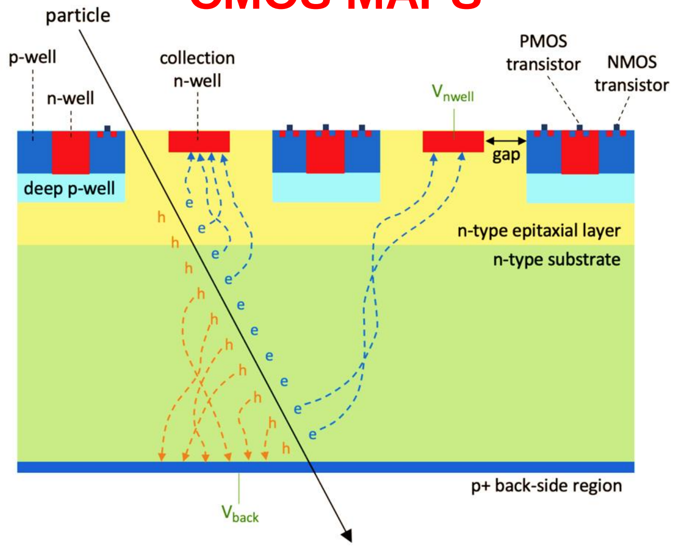


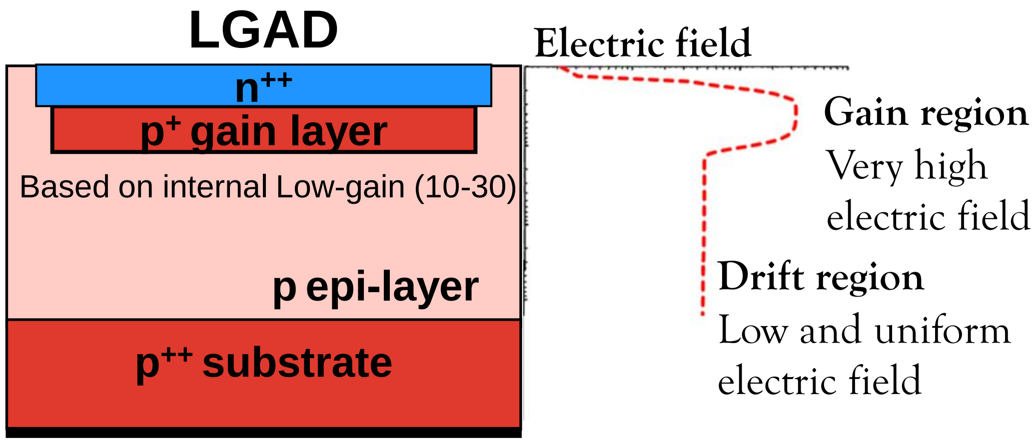
- Low material budget

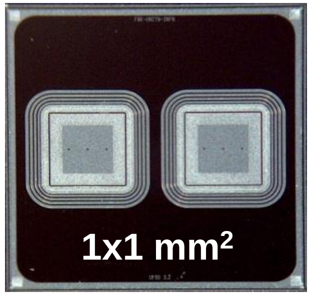
to proof timing performance

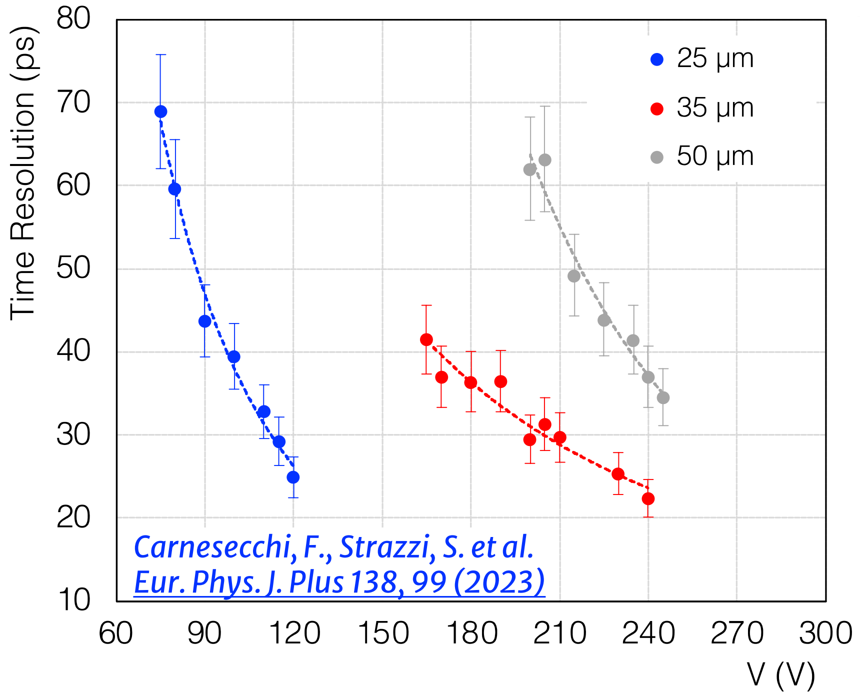
R&D for the addition of a gain layer → extensive activities of sensor simulation and design

R&D for Time Of Flight Detector

LGAD







$$\sigma_t^2 = \sigma^2_{\text{Time Walk}} + \sigma^2_{\text{Landau Noise}} + \sigma^2_{\text{Distortion}} + \sigma^2_{\text{Jitter}} + \sigma^2_{\text{TDC}}$$

- $\sigma^2_{\text{Time Walk}}$: Can be **corrected** (e.g. with Constant Fraction Discriminator, CFD)
- $\sigma^2_{\text{Landau Noise}}$: Fundamental limit
- $\sigma^2_{\text{Distortion}}$: Non saturated velocity and non-uniform weighting field
- σ^2_{Jitter}: $\sigma_{Jitter} \propto \frac{\sigma_V}{dV/dt}$ — Low input capacitance, high preamp. transconductance; Large signal (gain); Short signal rise time
- σ^2_{TDC}: Can be made **negligible**

H. F.-W. Sadrozinski et al 2018 Rep. Prog. Phys. 81 026101

Standard LGAD (50 μm) in line with the expectations

25μm	**25 ps** : Slightly worse time resolution than what expected
35μm	**22 ps** : In agreement with MC simulations

Improved time resolution with thinner LGAD detectors

R&D for Time Of Flight Detector

Monolithic CMOS Sensor

- **Front-end electronics** in the same silicon substrate
  → lower material budget + cheaper technology
- **Fully depleted** sensor → **fast charge collection** by drift
- **Large electrode** → uniform *E* field

↳ Drawback: the present time resolution is too low (~ns) due to limited SNR (no gain)

↳ Solution: LGAD - MAPS

⇩

Highly doped p-type region (gain layer)

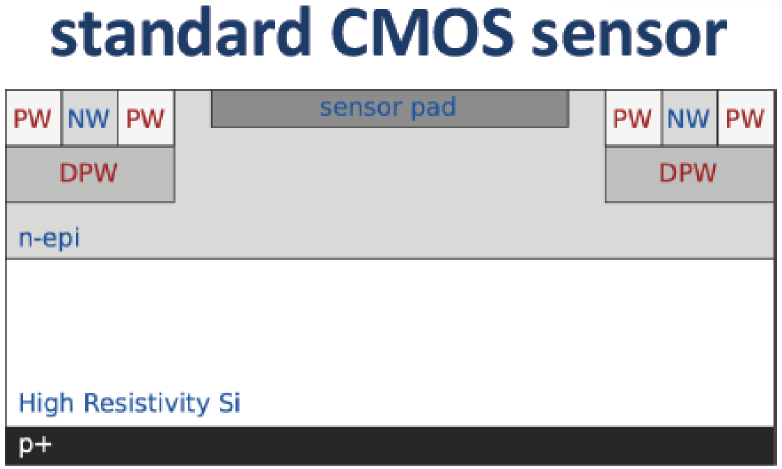
⇩

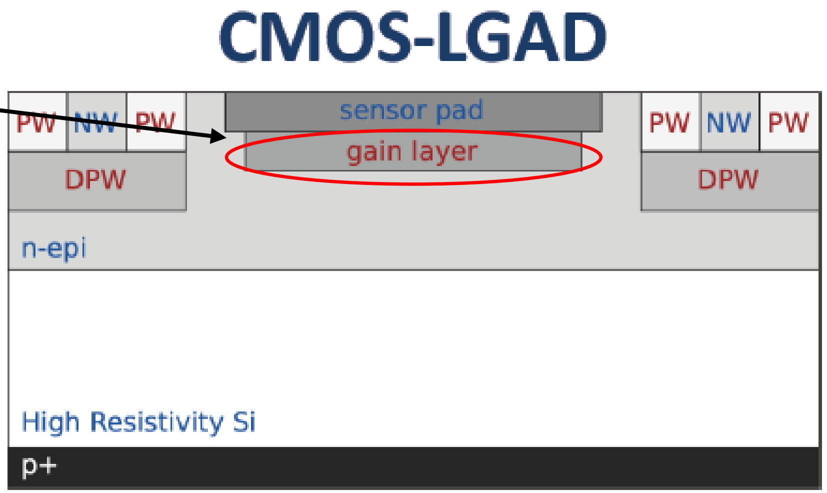
Avalanche process

⇩

Larger SNR → improvement of the time resolution

↳ First prototype with **integrated electronics** and **gain layer**
→ produced by LFoundry 110 nm

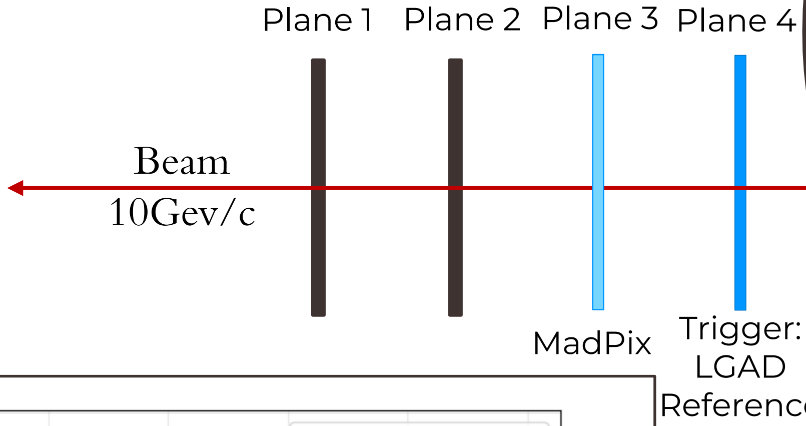


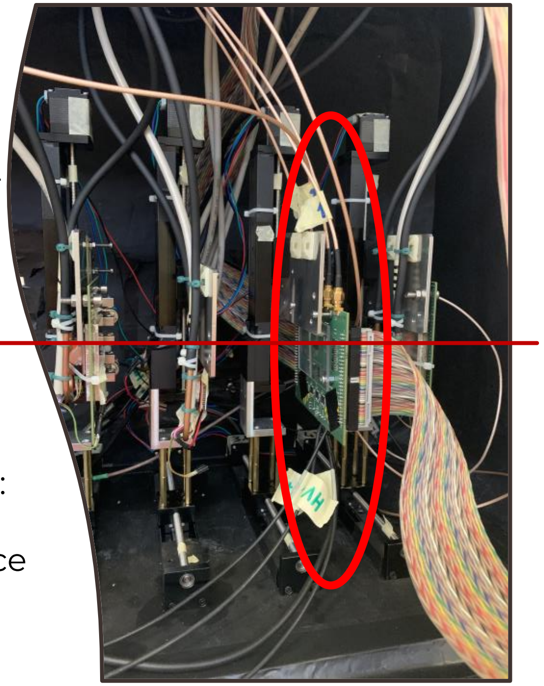


R&D for Time Of Flight Detector

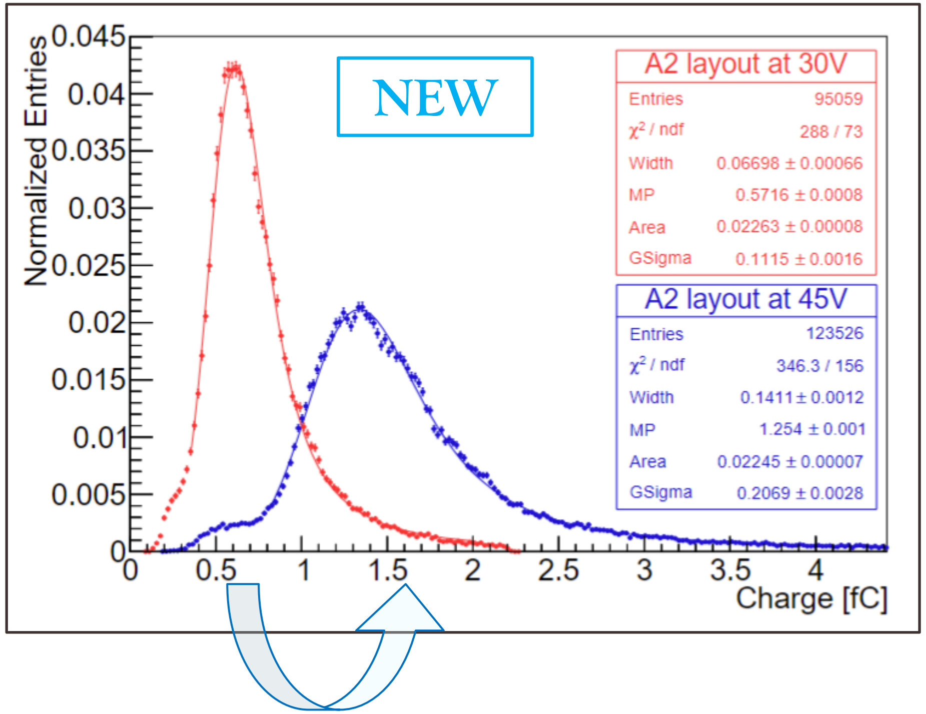
Monolithic CMOS Sensor

In October 2023 ***first test beam*** with ***MadPix at PS***

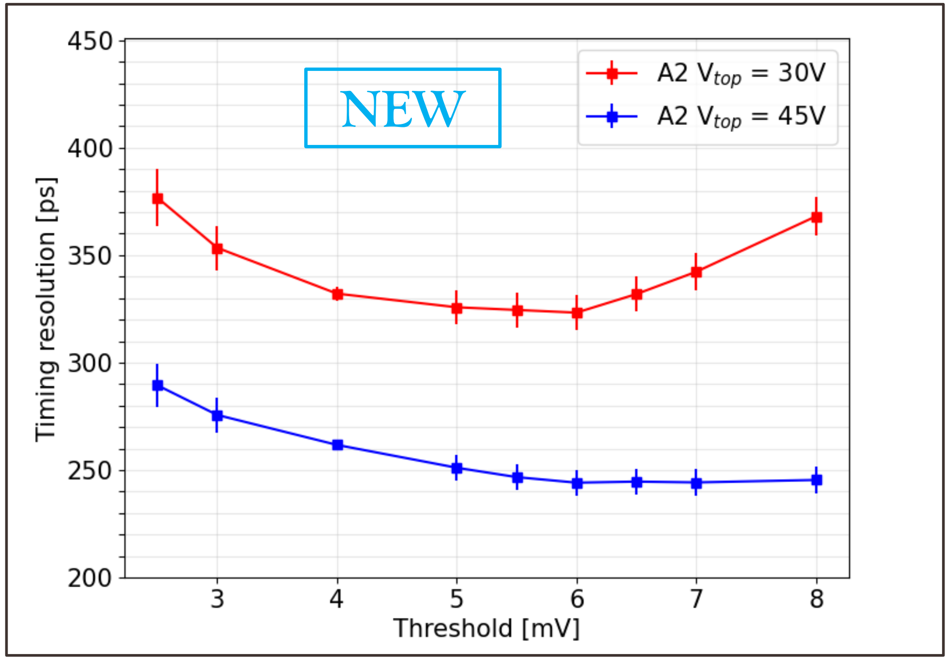




Collected Charge Distribution



Gain ~ 2

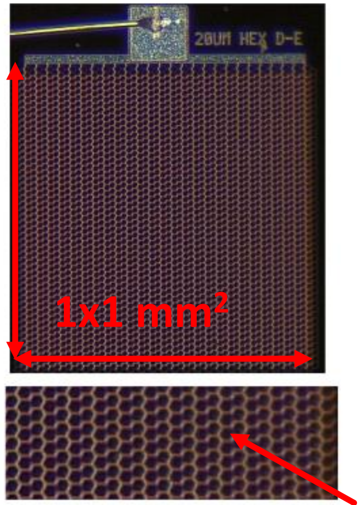


Follo U., Gioachin G. et al.
arXiv:2406.19906

Measured gain lower than expected (10-20)
New monolithic devices with higher gain to be tested this year

R&D for Time Of Flight Detector

SiPM



SPAD i.e. pixel

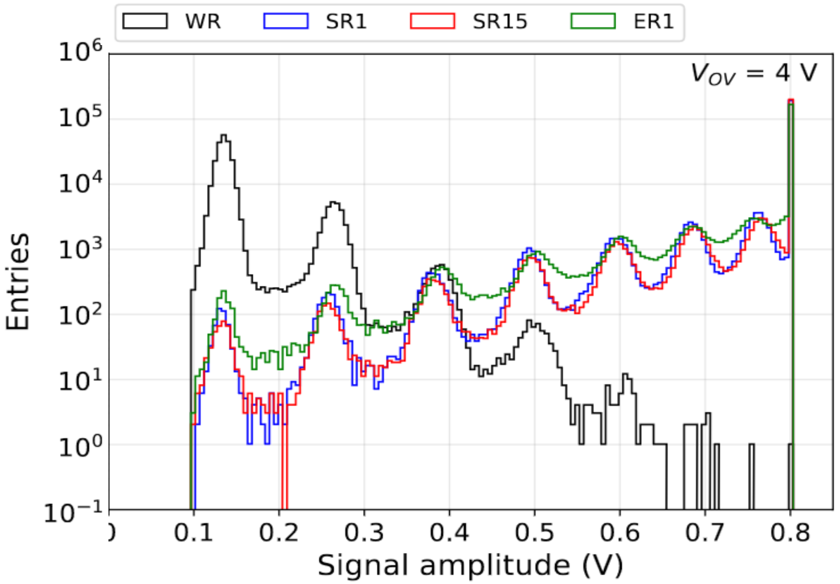
Microscope photograph of SiPM with 20um exagonal SPADs

Active area	1x1 mm^2
Pixel pitch	20um
#SPADs	2444
Fill Factor	72%
V breakdown	33.0±0.1 V
Dark Count Rate (before TB)	~ 2÷6 x 10^4 Hz/mm^2

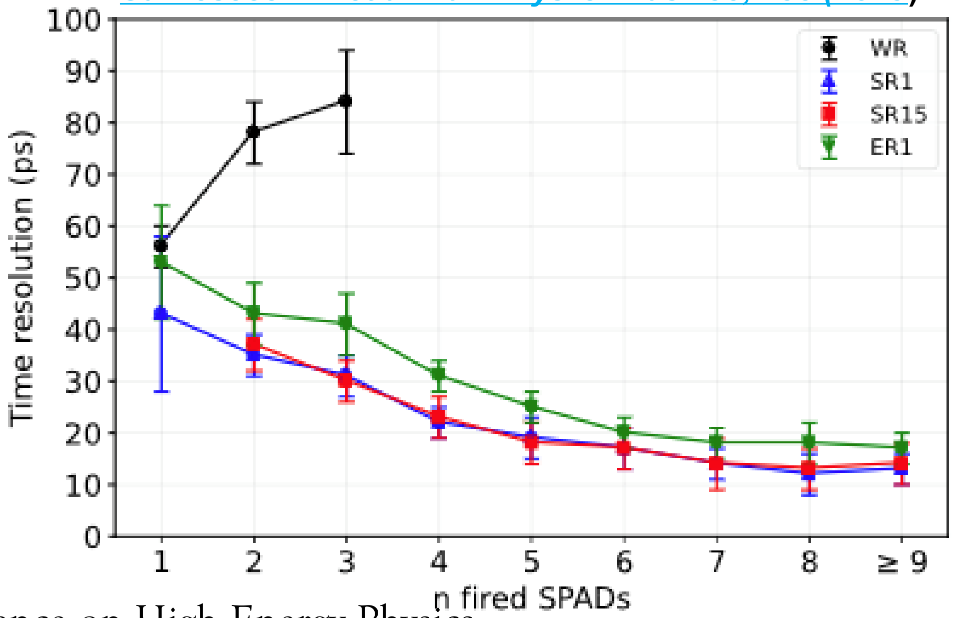
FBK NUV-HD-RH SiPM prototypes with different protection layers

- Silicone Resin 1 mm (SR1) (n=1.5)
- Silicone Resin 1.5 mm (SR15)
- Epoxy Resin 1 mm (ER1) (n=1.53)
- Without resin **(WR)**

Time resolution SiPMs with protection resin improves as number of fired SPADs increases

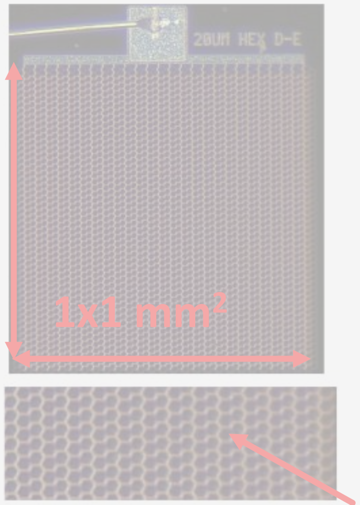


Carnesecchi F. et al. Eur. Phys. J. Plus 138, 788 (2023))



R&D for Time Of Flight Detector

SiPM



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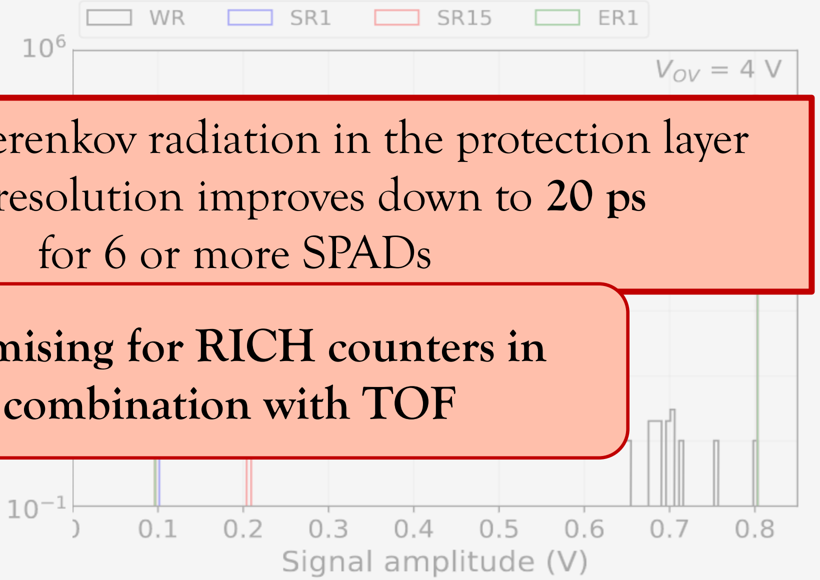
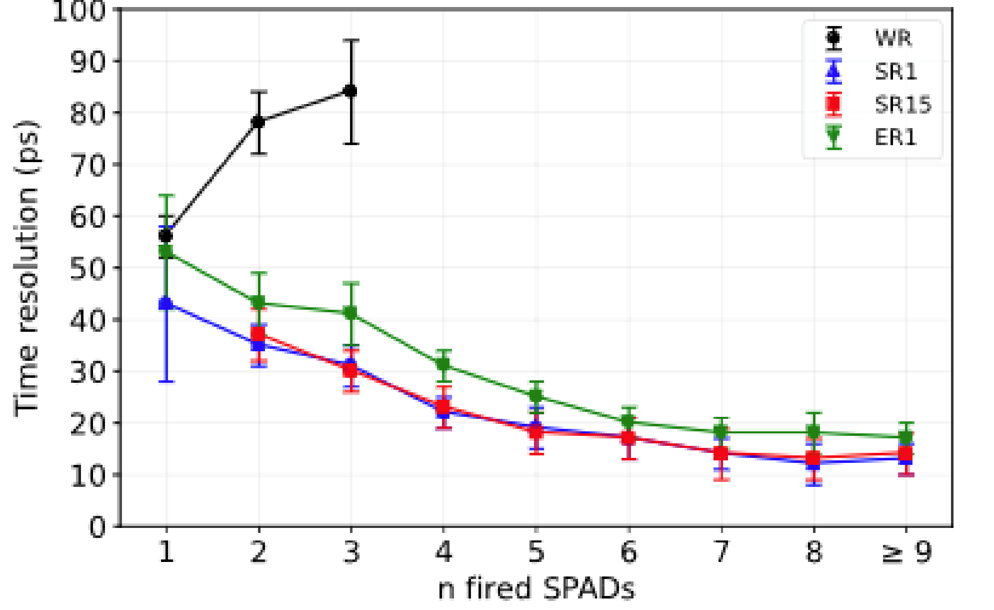


Exploiting Cherenkov radiation in the protection layer the time resolution improves down to **20 ps** for 6 or more SPADs

Promising for RICH counters in combination with TOF

Carnesecchi F. et al. Eur. Phys. J. Plus 138, 788 (2023)



ALICE 3 RICH Detector

ALICE

Requirements:

Extend PID reach of outer TOF to higher p_T

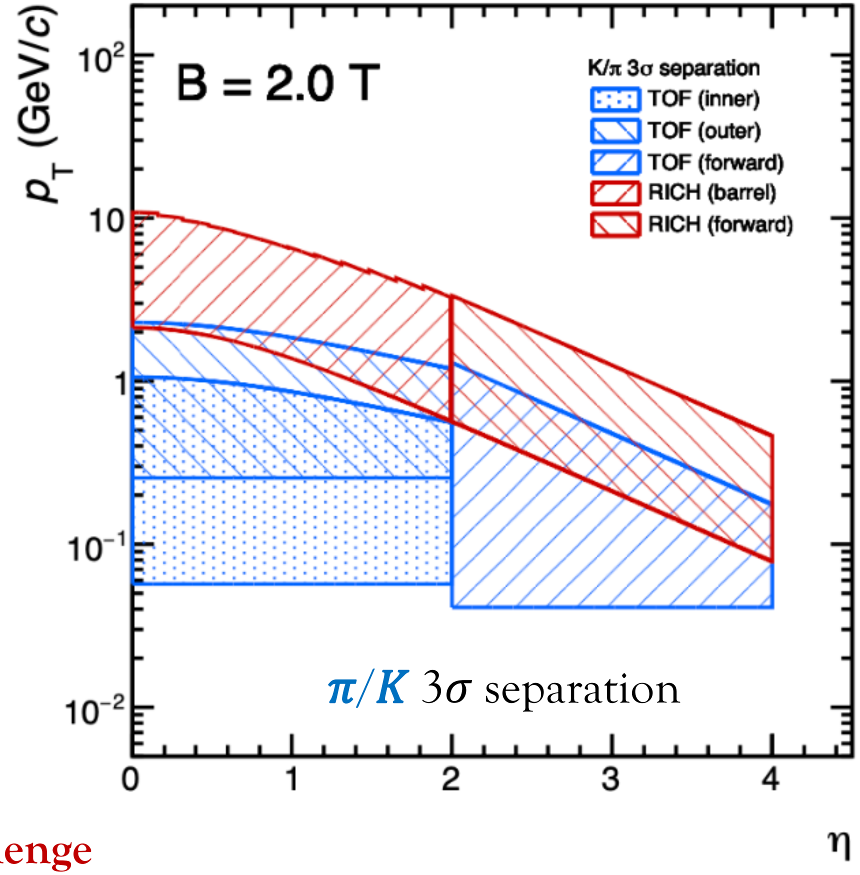
- e/π up to ≈ 2 GeV/c
- π/K up to ≈ 10 GeV/c
- K/p up to ≈ 16 GeV/c

Aerogel radiator to ensure continuous coverage from TOF

→ refractive index n = 1.03 (barrel)

→ refractive index n = 1.006 (forward)

+ Requiring angular resolution $\sigma_{\theta_{ch}} \approx 1.5$ mrad



Implementation

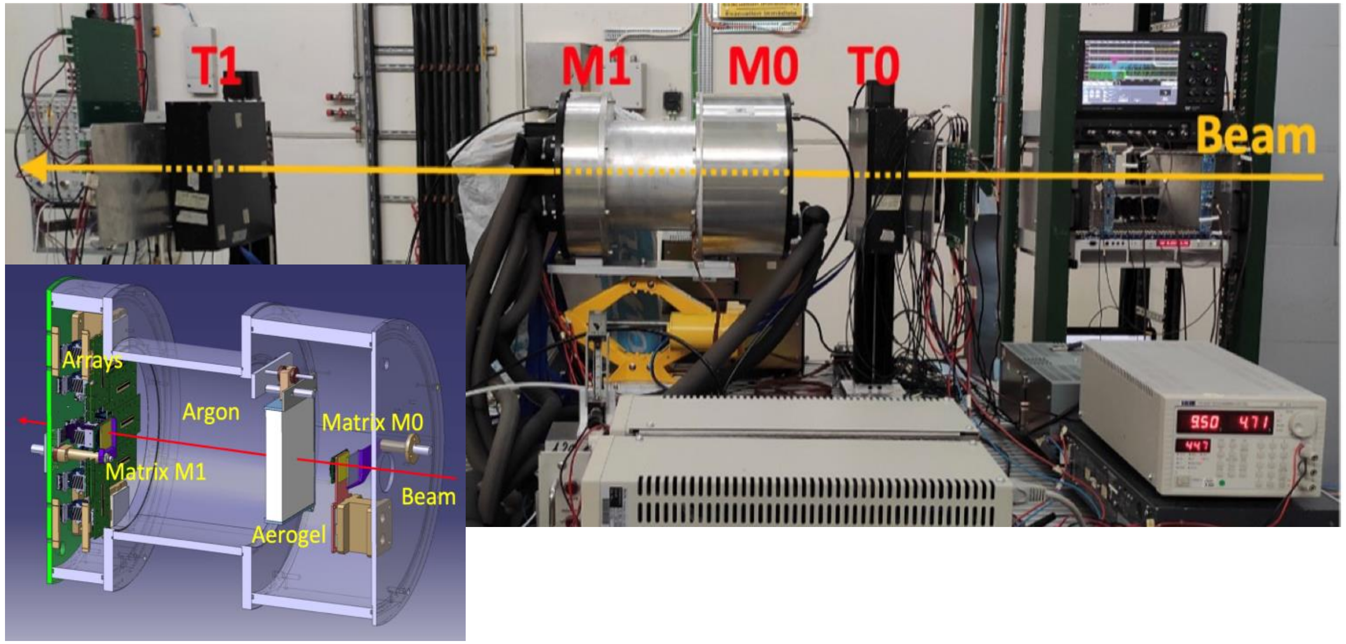
- 1(barrel)+1·2(disk) layers
- Barrel RICH at $R \approx 0.30$ m, $z < 3.50$ m
- Forward RICH at z ≈ 4.10 m, $R < 1.00$ m
- Silicon Photomultipliers (SiPMs)

R&D challenge

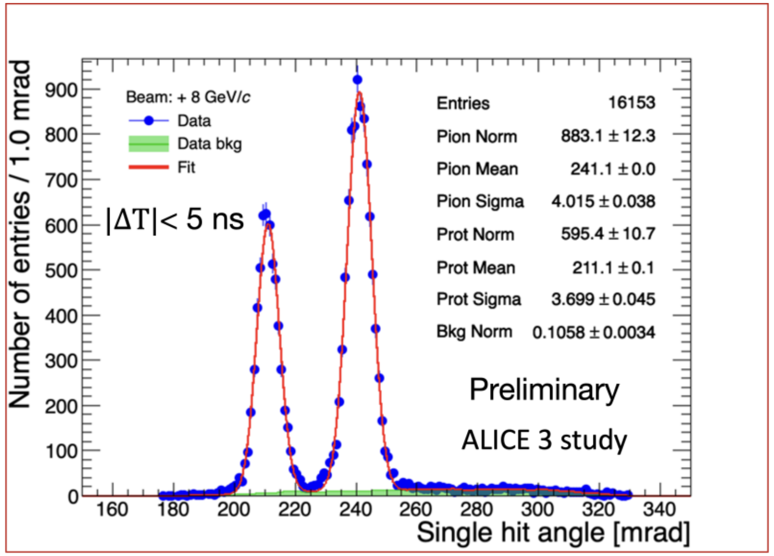
Merged oTOF+bRICH system using a common SiPM layer

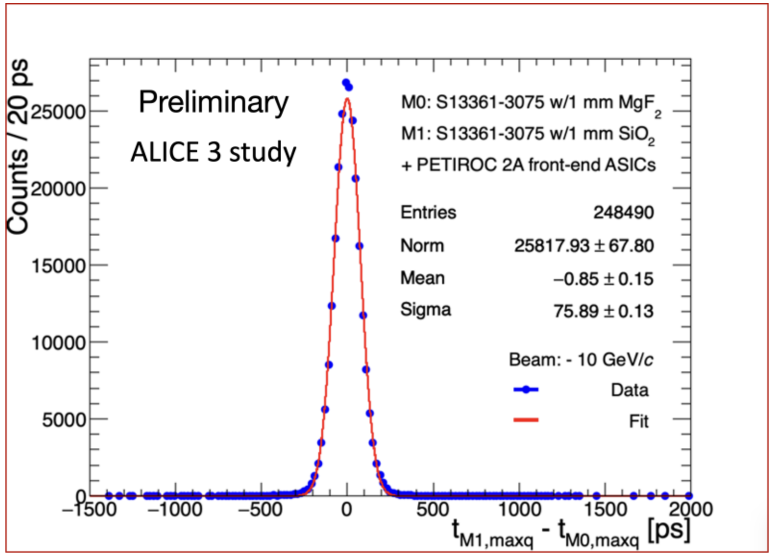
coupled to a thin radiator window

ALICE 3 RICH Detector



Cherenkov angle of pions and protons

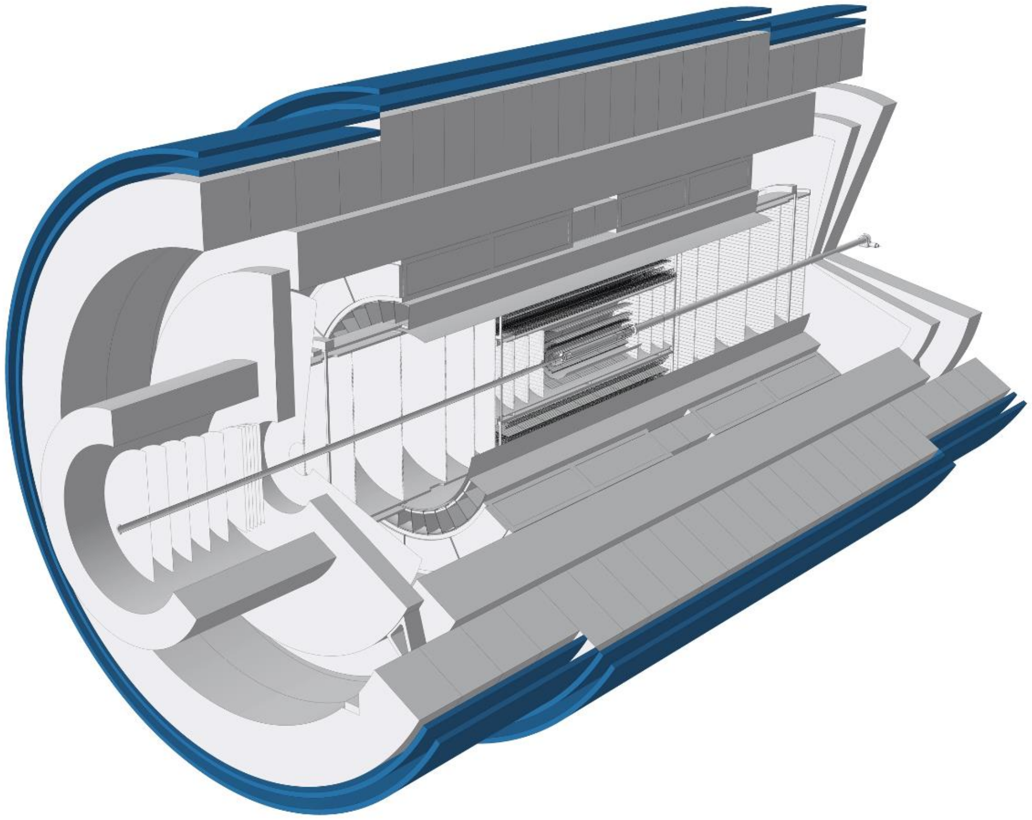




Test beam in Oct 2023 at CERN PS

- Aerogel radiator by Aerogel Factory LTD (Japan)
- 8x8 SiPM matrices from HPK and FBK, various pixel sizes
- Different radiator windows coupled to SiPM to test TOF+RICH integrated concept

ALICE 3 MID Detector



Requirements

- Muon ID down to $p_T \approx 1.5$ GeV/c
- Pseudorapidity coverage $|\eta| < 1.3$

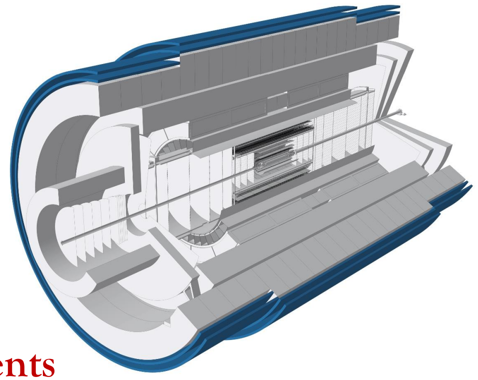
↳ Hadron absorber outside of the magnet:

- Standard magnetic steel absorber
- Thickness of ≈ 70 cm at $|\eta| = 0$

↳ Muon chambers

- 160 chambers
- $\Delta\eta$ x $\Delta\phi$ granularity → 5 x 5 cm^2 cells
- 2 layers of plastic scintillator bars
- Silicon Photomultiplier readout
- Coupling to WLS fibers is under study
- Alternative options:
  - MWPCs: 160 chambers
  - RPCs: 320 chambers

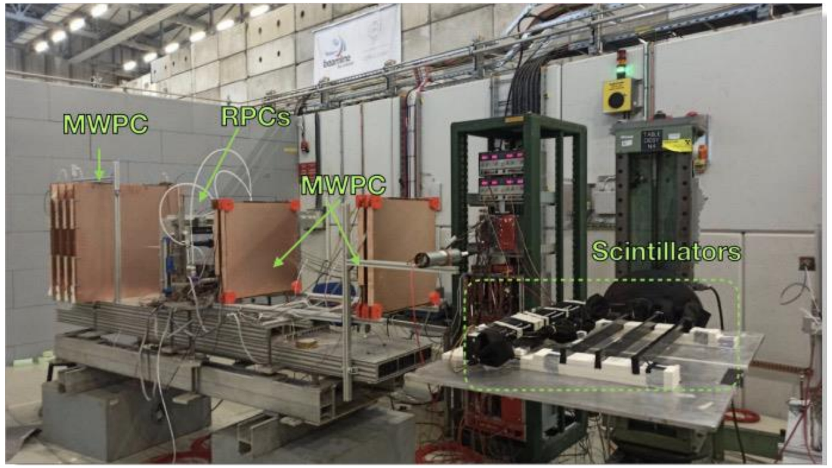
ALICE 3 MID Detector



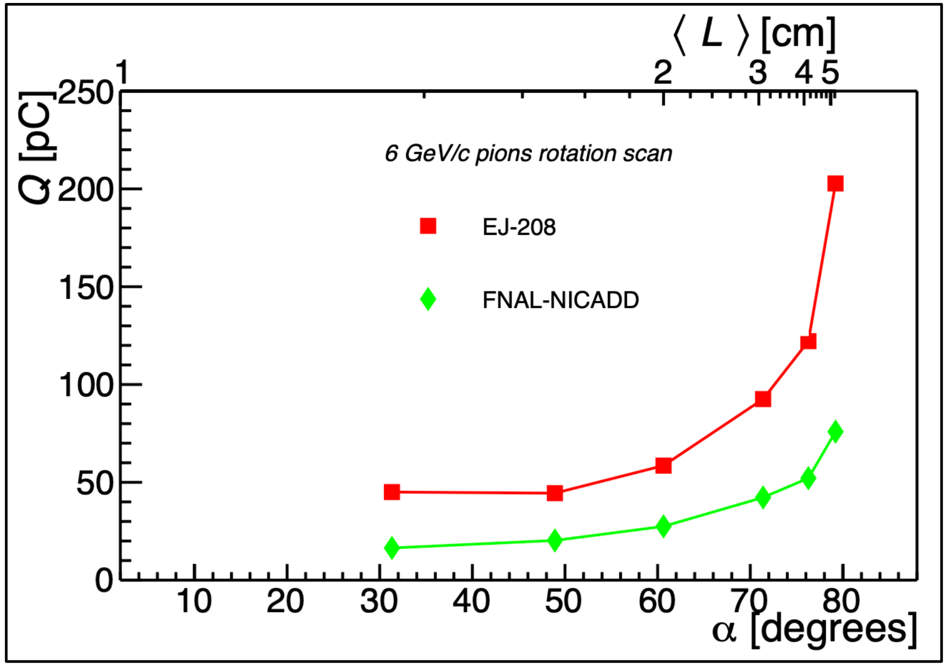
Requirements

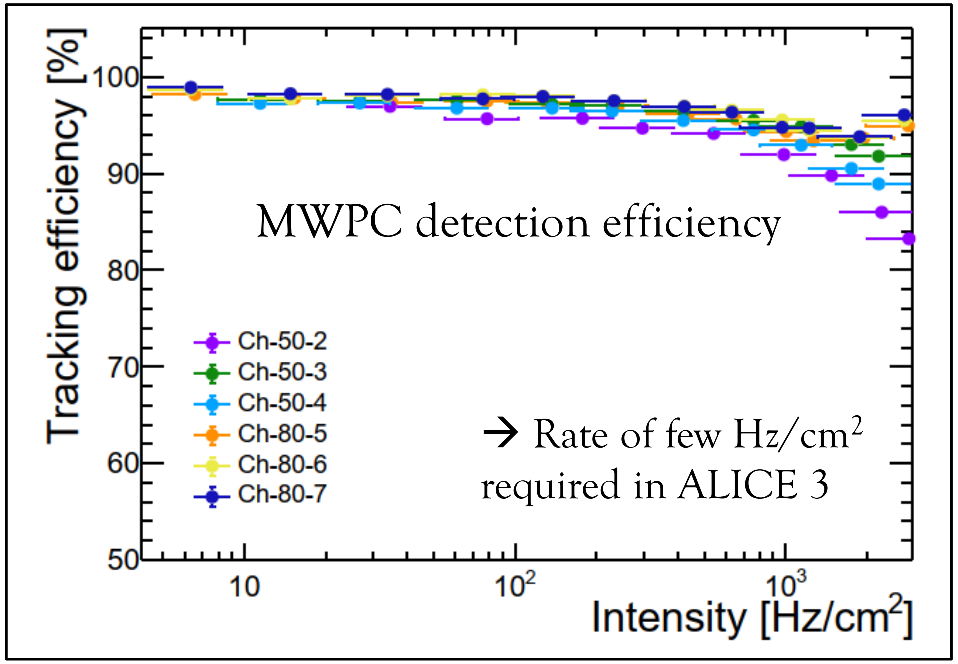
- Muon ID down to $p_T \approx 1.5$ GeV/c
- Pseudorapidity coverage $|\eta| < 1.3$

Test beam in July 2023 at CERN PS



Ortiz A. et al. JINST 19 (2024) 04, T04006





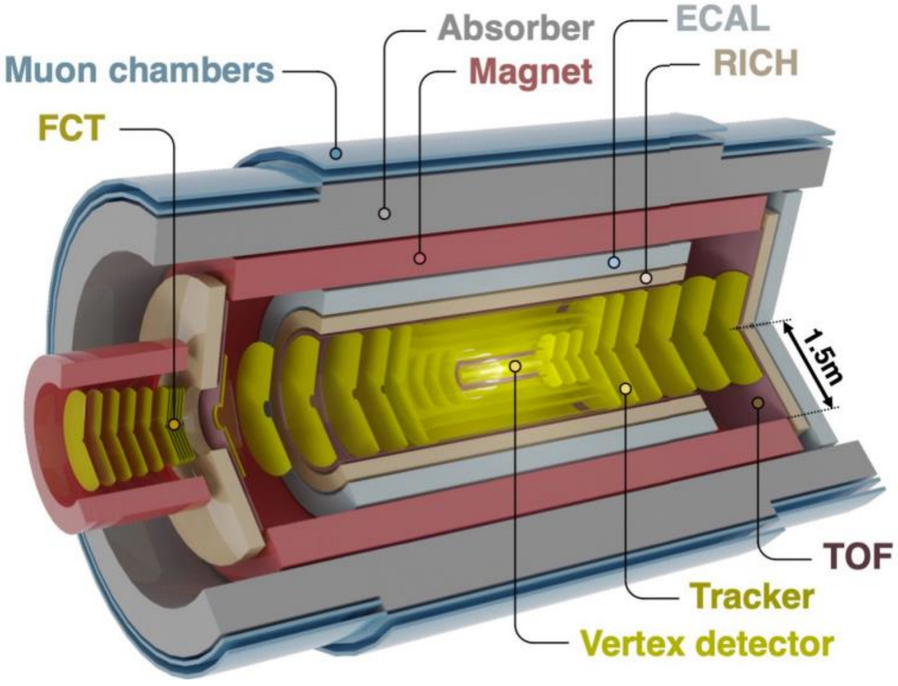
Charge vs the incidence angle and path length (⟨L⟩) in Plastic scintillator bars

Summary

To fulfill the rich physics program, ALICE 3 is being designed with excellent PID capability exploiting several PID techniques

- ❖ The PID performance and the several ongoing novel detector R&D have been presented
- ❖ They will have a broad impact on the future HEP and nuclear experiments

- ❖ Requiring extensive R&D activities in several strategic areas
  → e.g. Monolithic pixel with additional gain



Outlook

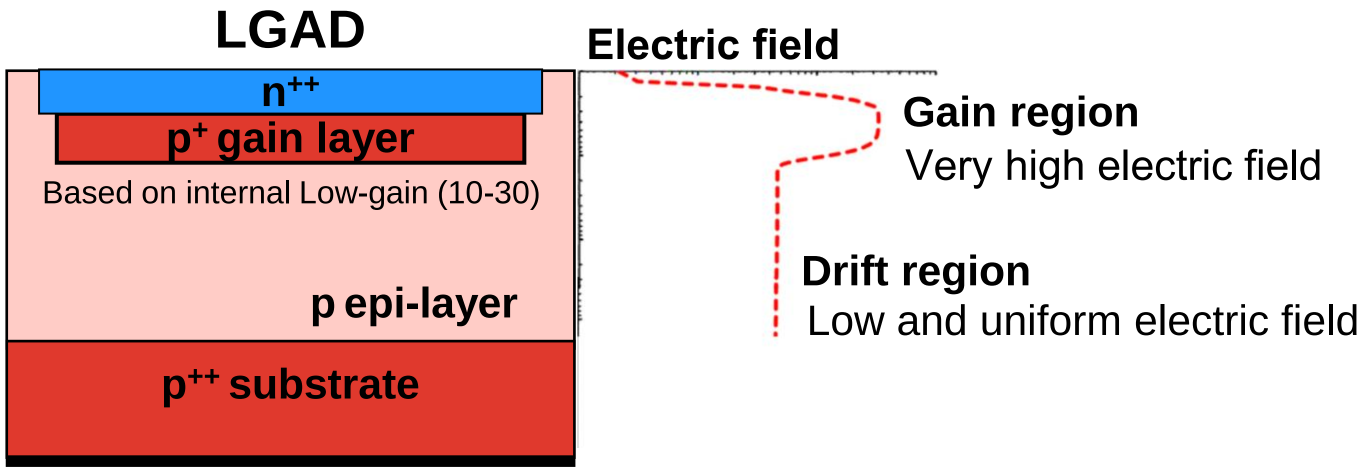
- **R&D activities** have started
- **2025**: selection of technologies, small-scale proof of concept prototypes
- **2026-27**: large-scale engineered prototypes → Technical Design Reports
- **2033-34**: Preparation of cavern and installation of ALICE 3

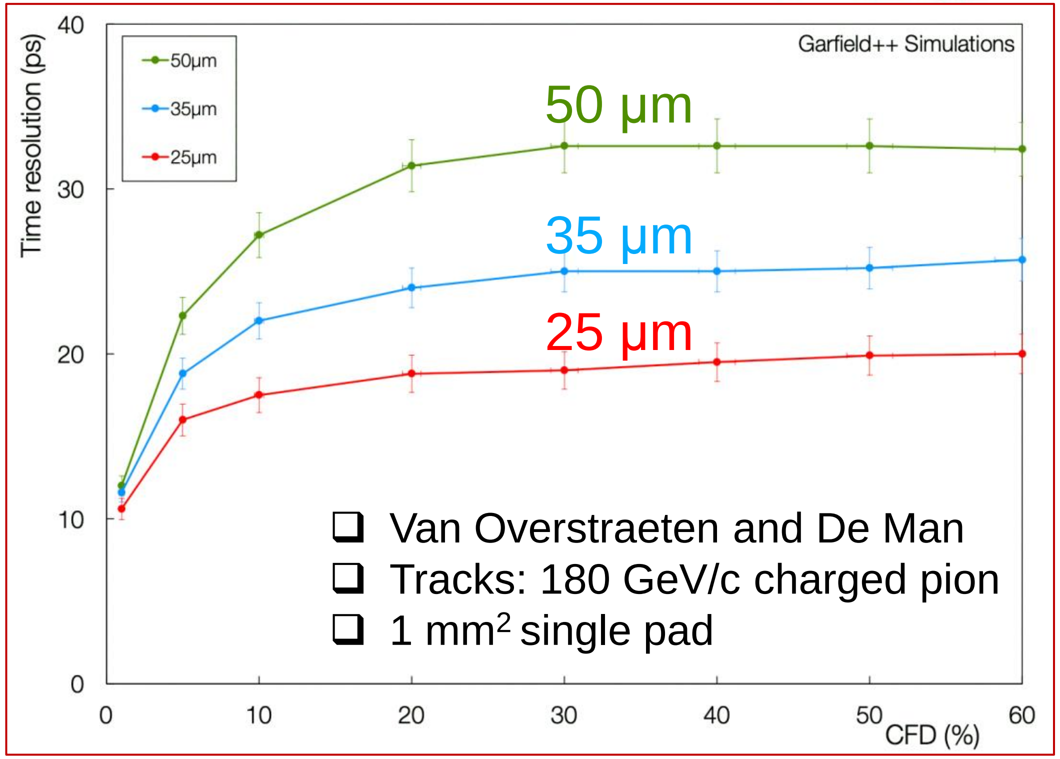
Thank you for the attention!

Backup slides

R&D for Time of Flight Detector

LGAD





$$\sigma_t^2 = \sigma_{\text{Time Walk}}^2 + \sigma_{\text{Landau Noise}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{TDC}}^2$$

- $\sigma_{\text{Time Walk}}^2$: Can be **corrected** (e.g. with Constant Fraction Discriminator, CFD)
- $\sigma_{\text{Landau Noise}}^2$: Fundamental limit
- $\sigma_{\text{Distortion}}^2$: Non saturated velocity and non-uniform weighting field
- σ_{Jitter}^2: $\sigma_{Jitter} \propto \frac{\sigma_V}{dV/dt}$ — Low input capacitance, high preamp. transconductance; Large signal (gain); Short signal rise time
- σ_{TDC}^2: Can be made **negligible**

H. F.-W. Sadrozinski et al 2018 Rep. Prog. Phys. 81 026101

→ Potential of a **thinner layout of LGAD**

- Contribution of electronic noise can be reduced by increasing the gain
- Fundamental limitation: **Landau fluctuations**

R&D for Time of Flight Detector

Monolithic CMOS Sensor

MADPIX ***M**onolithic CMOS **A**valanche **D**etector **PIX**elated Prototype for ps Timing Application*

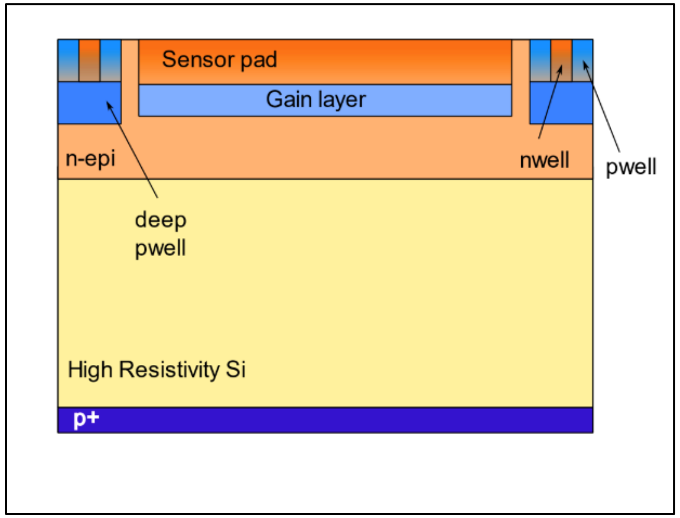
First prototype with **integrated electronics** and **sensor gain**

→ produced by LFoundry 110 nm

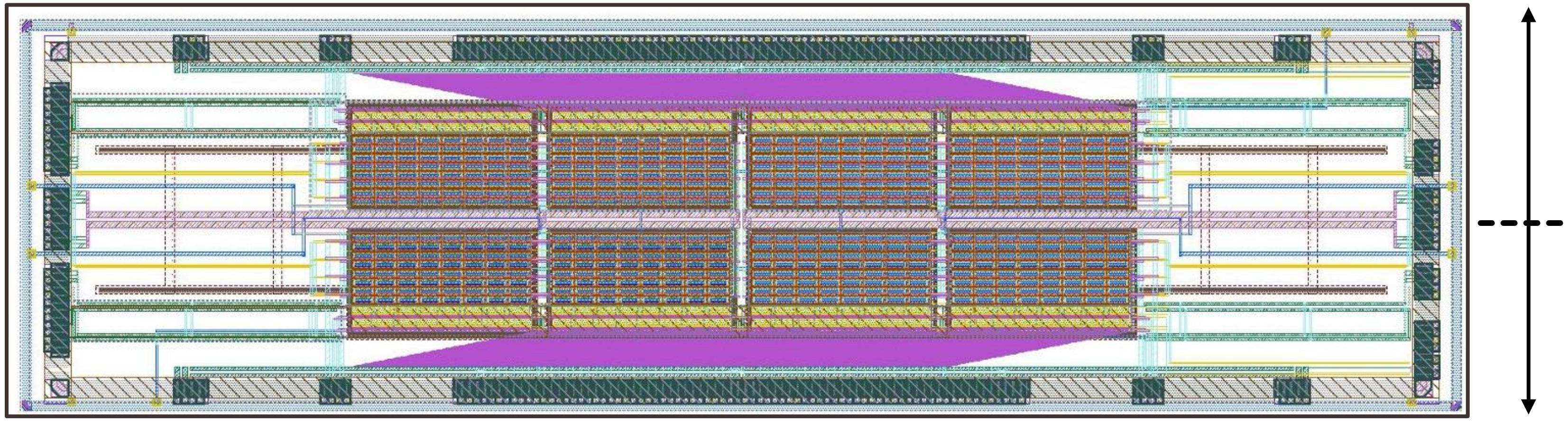
- Active thickness: 48µm
- **Backside HV**: allow full depletion → -25 V to -40 V
- **Topside HV**: manage the gain → 30 V to 50 V

» 8 matrices of 64 pixels each
» 4 flavours
» 64 x 2 analogue outputs
» Pixels of 250µm x 100µm

ARCADIA pad sensor with gain



Lucio Pancheri



Symmetrical

TOF Specifications

	Inner TOF	Outer TOF	Forward TOF
Radius (m)	0.19	0.85	0.15–1.5
z range (m)	−0.62–0.62	−2.79–2.79	4.05
Surface (m^2)	1.5	30	14
Granularity (mm^2)	1×1	5×5	1×1 to 5×5
Hit rate (kHz/cm^2)	74	4	122
NIEL (1 MeV n_{eq}/cm^2) / month	1.3×10^{11}	6.2×10^{9}	2.1×10^{11}
TID (rad) / month	4×10^{3}	2×10^{2}	6.6×10^{3}
Material budget ($\%X_0$)	1–3	1–3	1–3
Power density (mW/cm^2)	50	50	50
Time resolution (ps)	20	20	20

Table 11: TOF specifications.

RICH Specifications

Inner Radius (m)	0.9
Proximity gap (m)	0.2
Length (m)	5.6
Aerogel surface (m^2)	32
NIEL (1 MeV n_{eq}/cm^2) / month	4.5×10^9
TID (rad) / month	1.4×10^2
Material budget (% X_0)	3
Power density (mW/cm^2)	50
Cherenkov angle resolution (mrad)	1.5

PD area (m^2)	39
PDE in visible range	$\geq 40\%$
Pixel size (mm^2)	3x3
Integration fill factor	$\geq 90\%$
Time jitter (ps)	≤ 100
Occupancy (dark count)	5×10^{-4}
Occupancy (photons)	5×10^{-3}
Hit rate (kHz/cm^2)	1.5×10^2

Table 13: (Left) RICH and (Right) photon detector specifications

	barrel RICH	forward RICH disks
Radius (m)	0.9 to 1.2	0.15 to 1.15
z range (m)	−3.50 to 3.50	$3.75 < \|z\| < 4.15$
Surface (m^2)	28	9
Acceptance	$\|\eta\| < 2$	$2 < \|\eta\| < 4$
Granularity (mm^2)	2×2	2×2

MID Specifications

	Absorber	MID layer 1	MID layer 2
Inner radius (m)	2.20	3.01	3.11
Outer radius (m)	2.90	3.02	3.12
Total length (m)	10	10	10.5
No. of sectors in z	9	10	10
No. of sectors in φ	1	16	16
Scintillator bar length (cm)	-	99.8	123.5
Scintillator bar width (cm)	-	5.0	5.0
Scintillator bar thickness (cm)	-	1.0	1.0

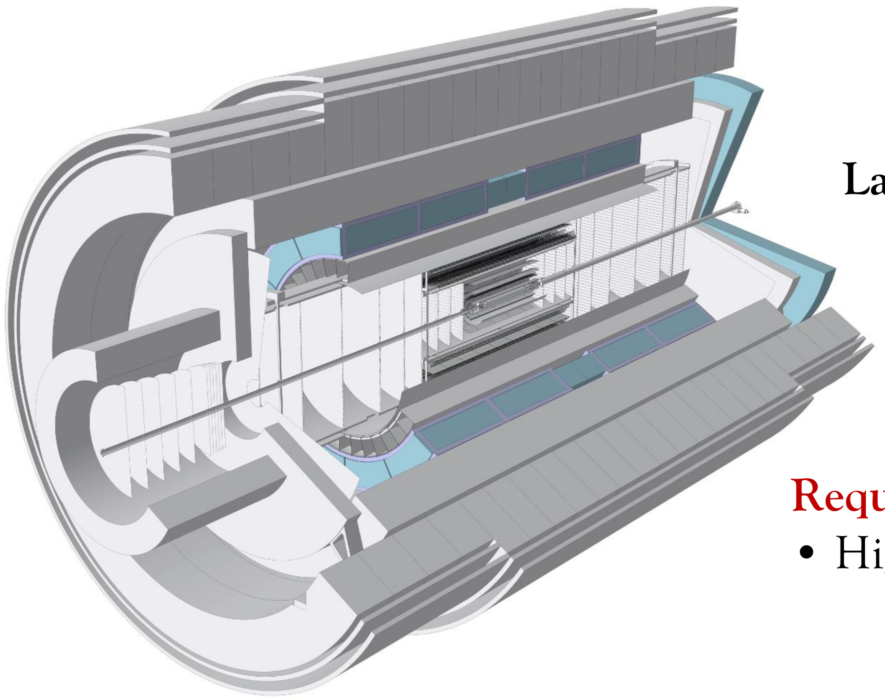
ECAL Specifications

ECal module	Barrel sampling	Endcap sampling	Barrel high-precision
acceptance	$\Delta\varphi = 2\pi$, $\|\eta\| < 1.5$	$\Delta\varphi = 2\pi$, $1.5 < \eta < 4$	$\Delta\varphi = 2\pi$, $\|\eta\| < 0.33$
geometry	$R_{in} = 1.15$ m, $\|z\| < 2.7$ m	$0.16 < R < 1.8$ m, $z = 4.35$ m	$R_{in} = 1.15$ m, $\|z\| < 0.64$ m
technology	sampling Pb + scint.	sampling Pb + scint.	$PbWO_4$ crystals
cell size	30×30 mm^2	40×40 mm^2	22×22 mm^2
no. of channels	30 000	6 000	20 000
energy range	$0.1 < E < 100$ GeV	$0.1 < E < 250$ GeV	$0.01 < E < 100$ GeV

Table 15: ECAL parameters.

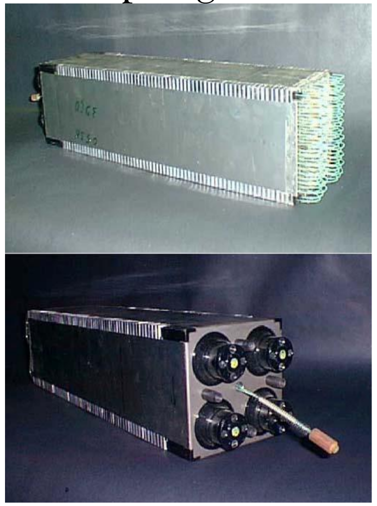
ECal segment	η range	Cell technology	Cell size	N_φ	N_η	N_{tot}
Central barrel	$\|\eta\| < 0.45$	$PbWO_4$	2.2×2.2 cm^2	348	57	19836
Outer barrel	$0.45 < \|\eta\| < 1.6$	Pb-Sci sampling	3×3 cm^2	256	120	30720
End cap	$1.6 < \eta < 4$	Pb-Sci sampling	4×4 cm^2			6000

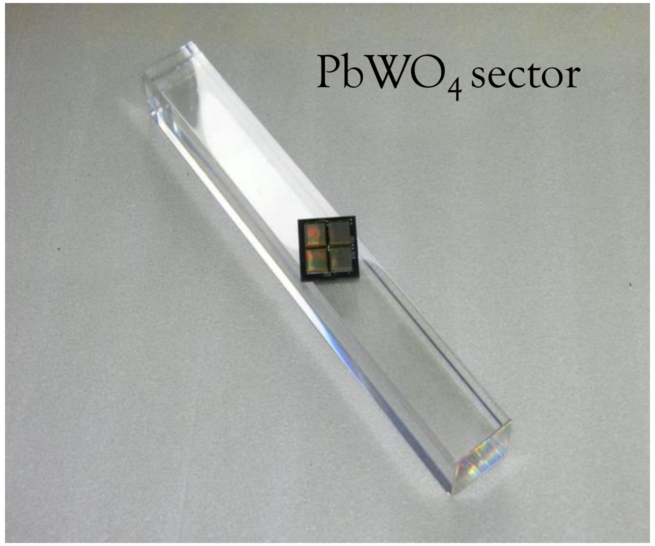
ALICE 3 Electromagnetic Calorimeter



Large acceptance calorimeter

Sampling sector





Requirements

- High-energy electron and photon ID
  - Up to 100 GeV for $\eta < 1.5$
  - Up to 250 GeV for $1.5 < \eta < 4$

Implementation

- 2 (barrel) + 1(disk) layers
  - Sampling calorimeter: 1mm Pb + 1.5 mm plastic scintillator
  - High energy resolution segment based on $PbWO_4$ crystals, $\eta < 0.22$
  - Silicon Photomultiplier readout