Particle identification in ALICE 3

EMMI Workshop: Soft photons – the higher orders
26 May 2025

Antonello Di Mauro (CERN)
on behalf of the ALICE Collaboration

ALICE upgrade plans

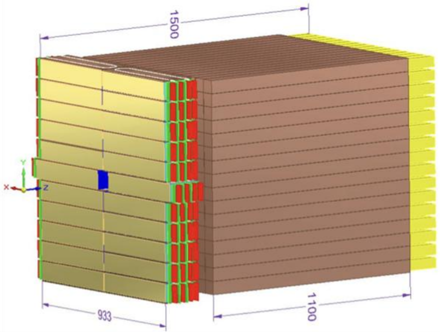
LS3: FoCal & ITS3

- Specific upgrades for Run 4
- TDRs approved last year
- Moving towards production phase

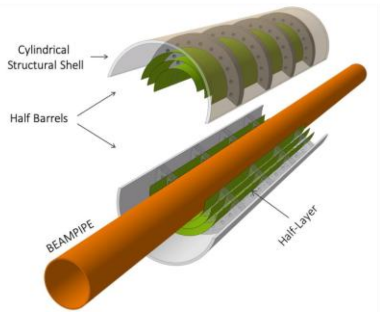
LS4: ALICE 3

- Next-generation heavy-ion experiment for Run 5
- Letter of Intent reviewed in 2022
- Scoping Document just reviewed

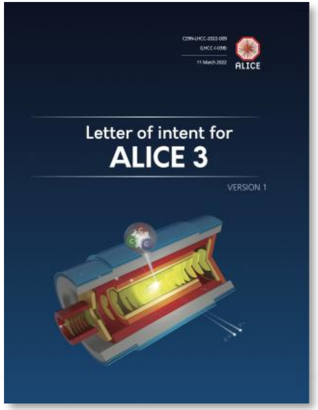
FoCal TDR: CERN-LHCC-2024-004



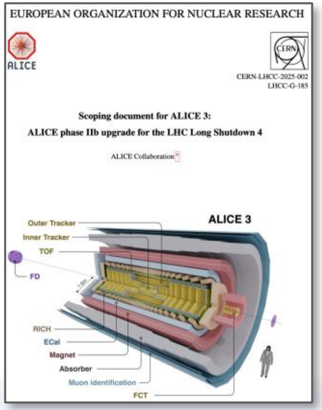
ITS3 TDR: CERN-LHCC-2024-003



LOI: CERN-LHCC-2022-009



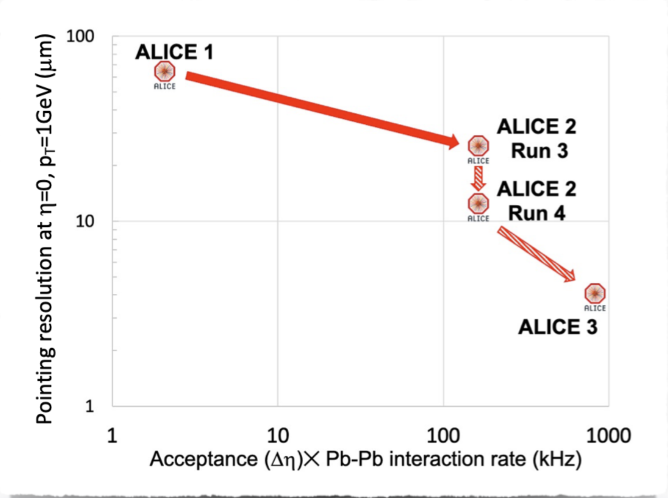
SD: CERN-LHCC-2025-002

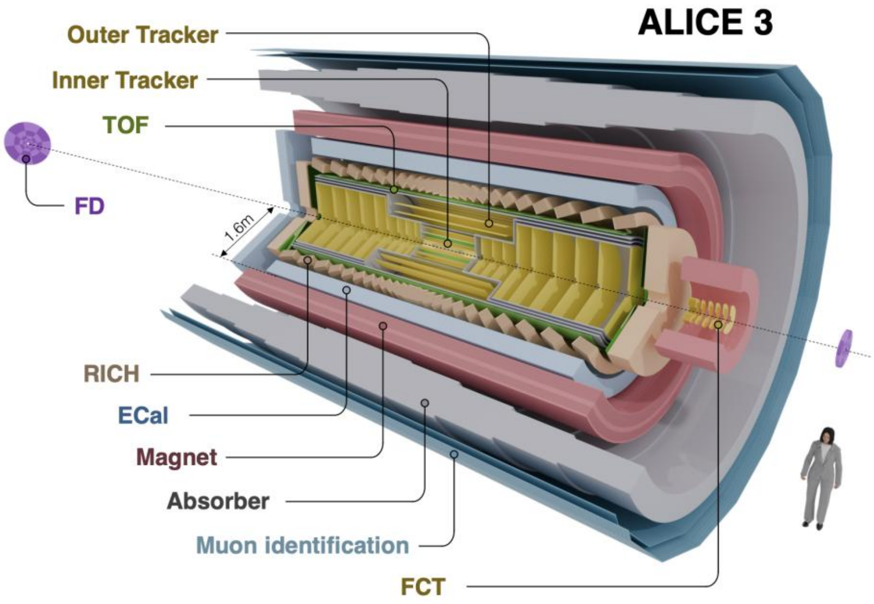


The ALICE 3 upgrade

➡ Novel all-silicon compact detector

- Ultra-light all-pixel tracker with retractable vertex detector inside the beam pipe
- Extensive particle identification: TOF, RICH, MID
- Large acceptance $|\eta|<4$
- Superconducting solenoid magnet B= 2 T
- Continuous read-out and online processing





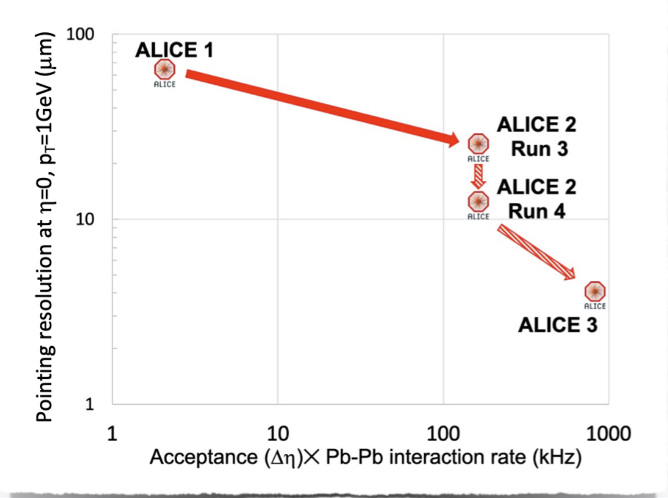
Interaction rates	ALICE Run 3, 4	ALICE 3
pp	500 kHz-1 MHz	**24 MHz**
Pb-Pb	50 kHz	**100 kHz***

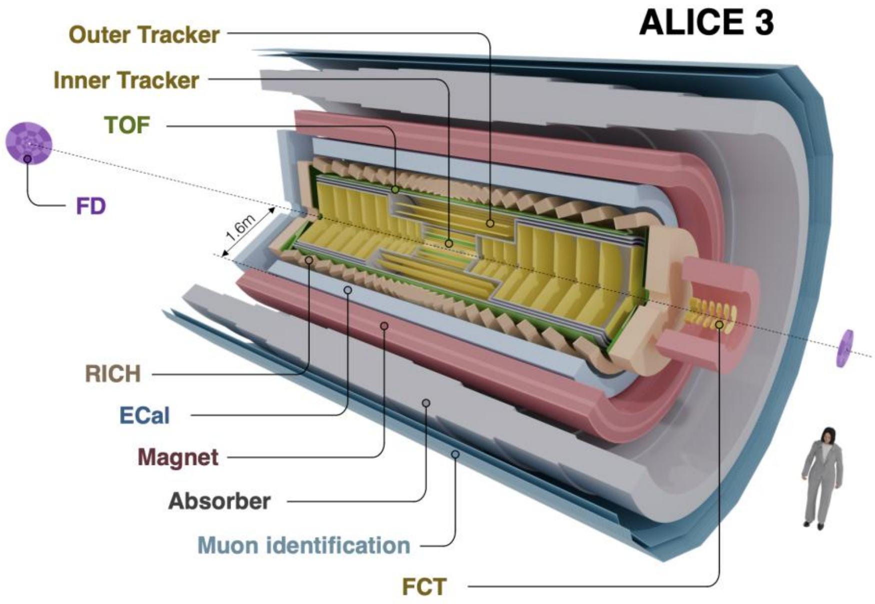
* not limited by detector

The ALICE 3 upgrade

Key objectives :

- **Access to QGP temperature vs. time**
  → Precision measurement of dileptons
- **Understanding thermalization in QGP**
  → beauty and (multi-)charm hadrons
- **Fundamental aspects of QCD phase transition**
  → chiral symmetry restoration: di-electron mass spectrum
- **Laboratory for hadron physics**
  → hadron-hadron interaction potential, exotic hadrons





Interaction rates	ALICE Run 3, 4	ALICE 3
pp	500 kHz-1 MHz	**24 MHz**
Pb-Pb	50 kHz	**100 kHz***

* not limited by detector

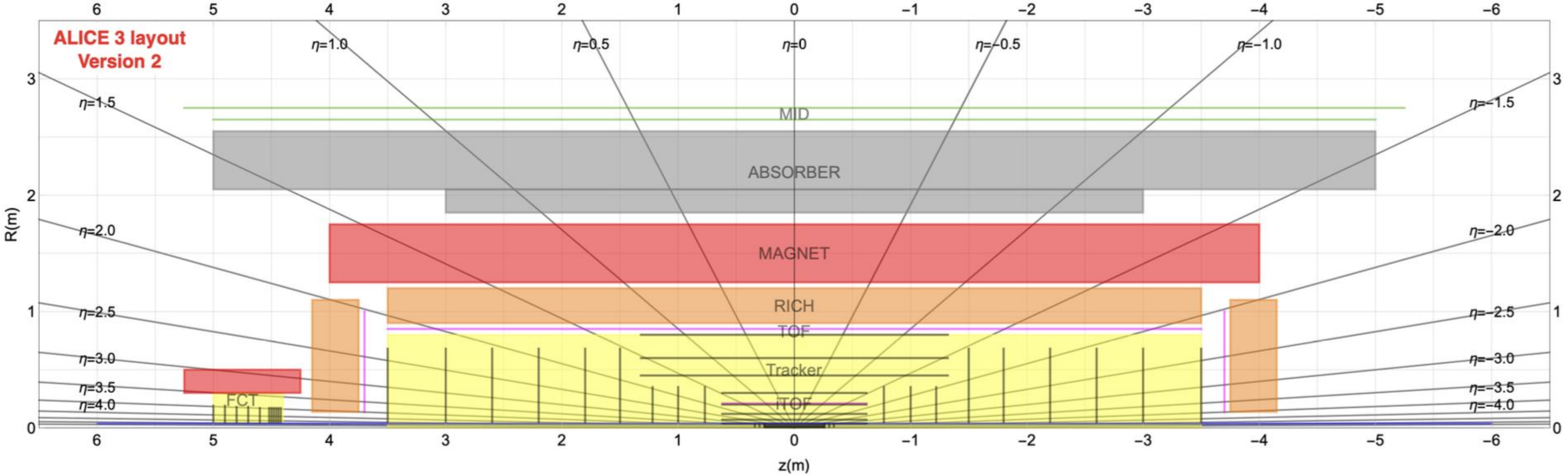
ALICE 3 detector requirements

PID

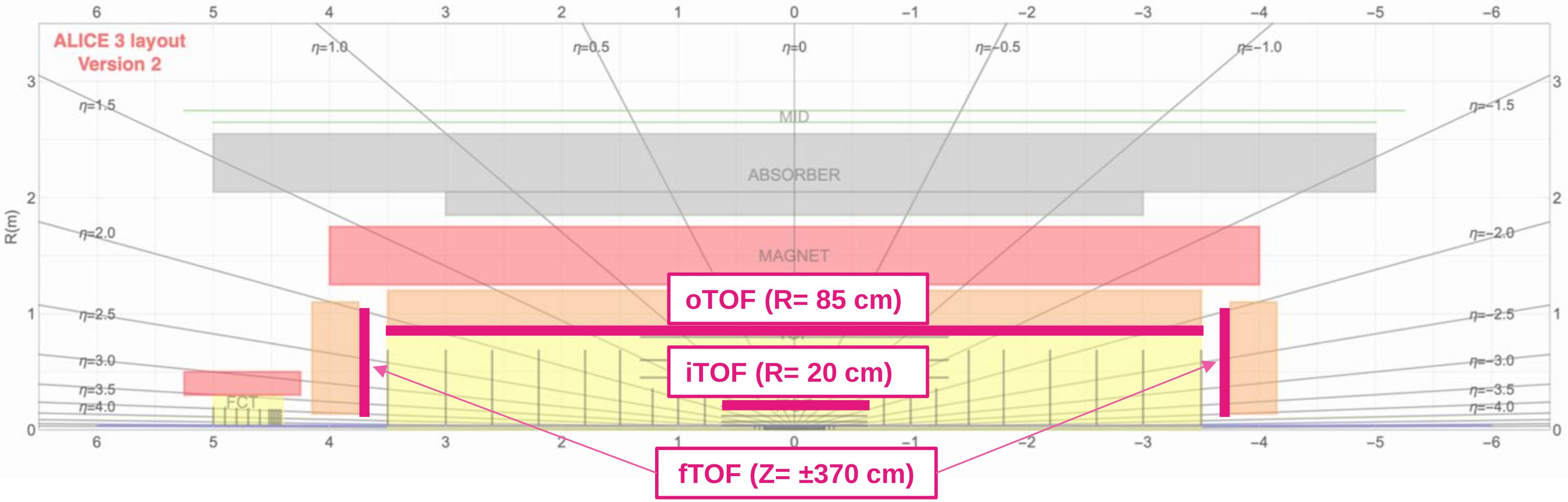
Component	Observables	Barrel ($\|\eta\| < 1.75$)	Forward ($1.75 < \|\eta\| < 4$)	Detectors
Vertexing	(Multi-)charm baryons, dielectrons	Best possible DCA resolution, $\sigma_{DCA} \approx 10\,\mu m$ at $p_T = 200\,MeV/c$, $\eta = 0$	Best possible DCA resolution, $\sigma_{DCA} \approx 30\,\mu m$ at $p_T = 200\,MeV/c$, $\eta = 3$	retractable Si-pixel tracker: $\sigma_{pos} \approx 2.5\,\mu m$, $R_{in} \approx 5\,mm$, $X/X_0 \approx 0.1\,\%$ for first layer
Tracking	(Multi-)charm baryons, dielectrons, photons ...	$\sigma_{p_T}/p_T \approx 1--2\,\%$		Silicon pixel tracker: $\sigma_{pos} \approx 10\,\mu m$, $R_{out} \approx 80\,cm$, $L \approx \pm 4\,m$, $X/X_0 \approx 1\,\%$ per layer
Hadron ID	(Multi-)charm baryons	$\pi/K/p$ separation up to a few GeV/c		Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Electron ID	Dielectrons, quarkonia, $\chi_{c1}(3872)$	pion rejection by 1000x up to 2–3 GeV/c		Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/ψ at rest, i.e. muons from $p_T \sim 1.5\,GeV/c$ at $\eta = 0$		steel absorber: $L \approx 70\,cm$ muon detectors
ECal	Photons, jets	large acceptance		Pb-Sci sampling calorimeter
ECal	χ_c	high-resolution segment		$PbWO_4$ calorimeter
Soft photon detection	Ultra-soft photons		measurement of photons in p_T range 1–50 MeV/c	Forward conversion tracker based on silicon pixel tracker

(from ALICE 3 LoI)

ALICE 3 PID detector requirements



ALICE 3 TOF detector requirements



3σ TOF PID ranges

$e/\pi \lesssim$ 500 MeV/c

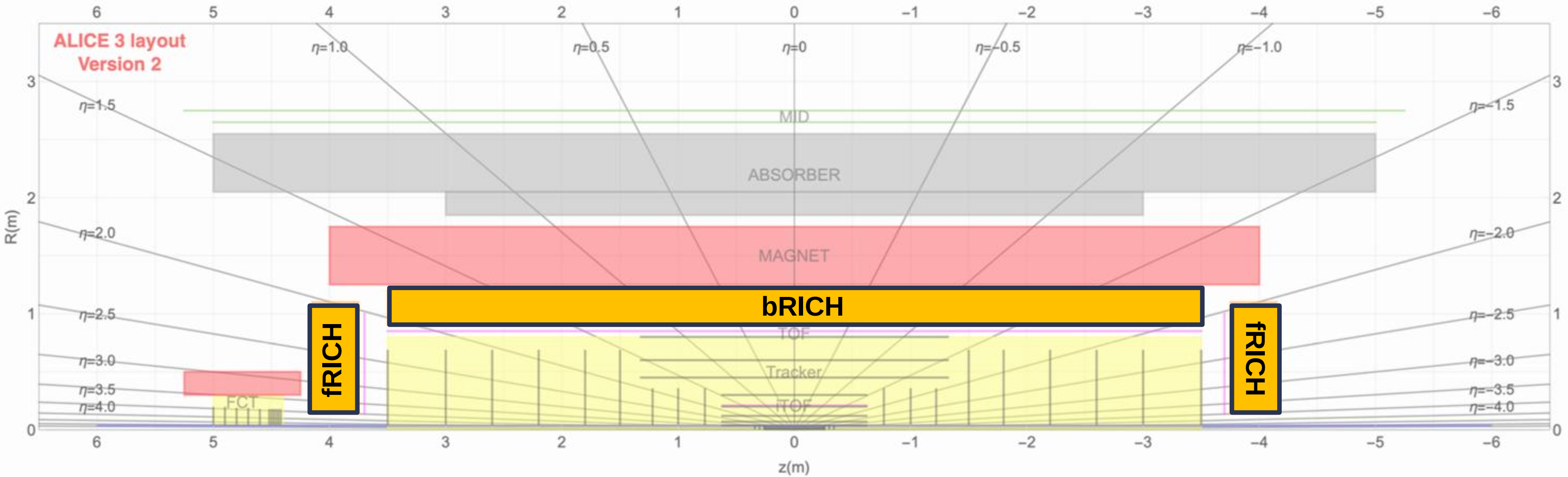
$K/\pi \lesssim$ 2.5 GeV/c

$p/K \lesssim$ 4 GeV/c

Separation power $\propto L/\sigma_{TOF}$

→ required **time resolution: $\sigma_{TOF} \approx 20$ ps**

ALICE 3 RICH detector requirements



Extend TOF PID ranges

$e/\pi \lesssim$ 2 GeV/c

$K/\pi \lesssim$ 10 GeV/c

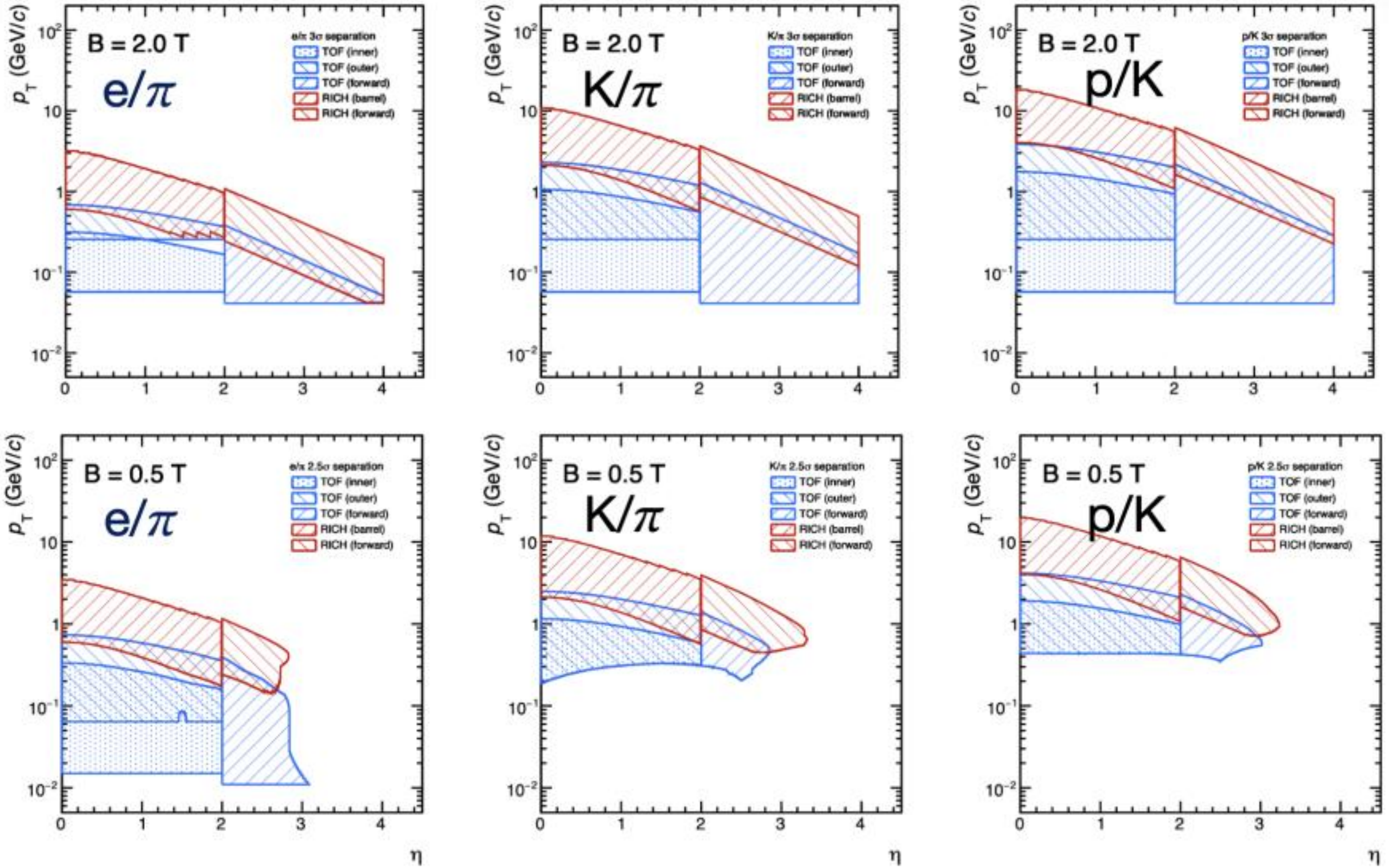
$p/K \lesssim$ 16 GeV/c

Aerogel radiator

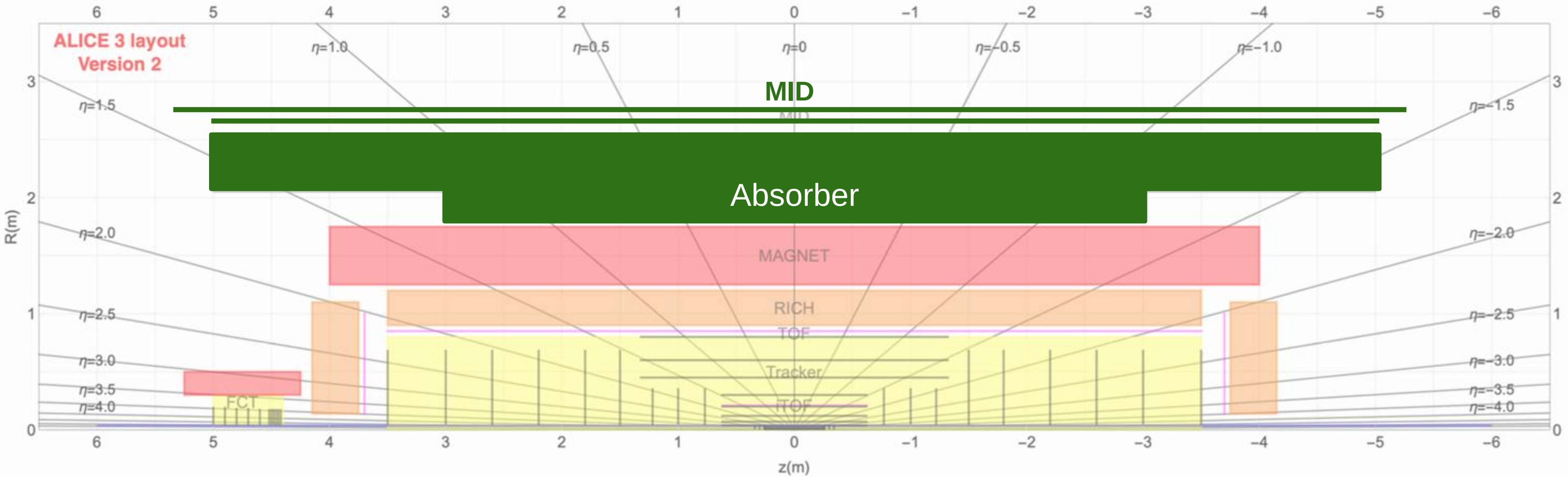
- bRICH: n=1.03
- fRICH : n=1.006

+ Cherenkov angle resolution $\sigma_{\theta c}$ = 1.5 mrad

TOF+RICH p_T vs η coverage



ALICE 3 MID detector requirements



μ identification from p_T ~1.5 GeV/c at η=0
→ J/ψ down to p_T = 0

- Steel absorber, 70 cm at η=0
- Granularity ~ 5x5 cm^2
- π, K rejection factor ~ 100

Silicon-based TOF detector specs

	Inner TOF	Outer TOF	Forward TOF disks
Area (m^2)	1.5	37	6
Granularity (mm^2)	1×1	5×5	1×1 to 5×5
Hit rate (kHz/cm^2)	200	15	280
Material budget ($\%X_0$)	1 to 3	1 to 3	1 to 3
Power density (mW/cm^2)	50	50	50
System time resolution (ps)	20	20	20
Radiation tolerance NIEL (1 MeV n_{eq}/cm^2)	$7 \cdot 10^{12}$	$9 \cdot 10^{11}$	$1 \cdot 10^{13}$
Radiation tolerance TID (rad)	$3 \cdot 10^5$	$2 \cdot 10^4$	$4 \cdot 10^5$

Two barrel layers ($|\eta|<2$) → inner-TOF: R ≈ 19 cm, |z| < 62 cm, 1x1 mm^2 pixels
outer-TOF: R ≈ 85 cm, |z| < 350 cm, 5x5 mm^2 pixels

Two forward disks ($2<|\eta|<4$) → forward-TOF: z ≈ ±370 cm, R ≈ 15-100 cm, 1x1 mm^2 pixels

Total surface (TOF) ~ **45 m^2**

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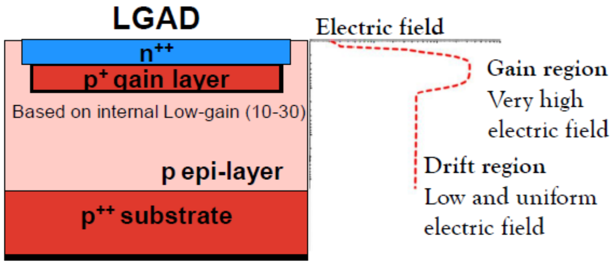
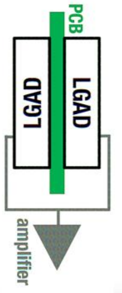
Three sensor technologies: LGAD, monolithic CMOS-LGAD (baseline), SiPM

Silicon-based TOF detector R&D

1. LGADs: R&D on thinner sensors and double layer

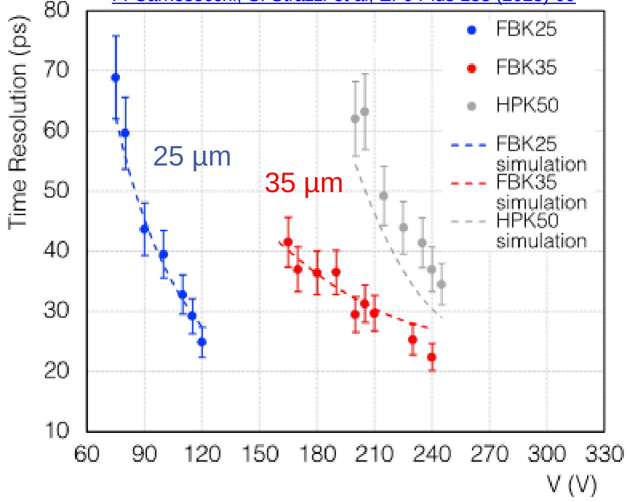




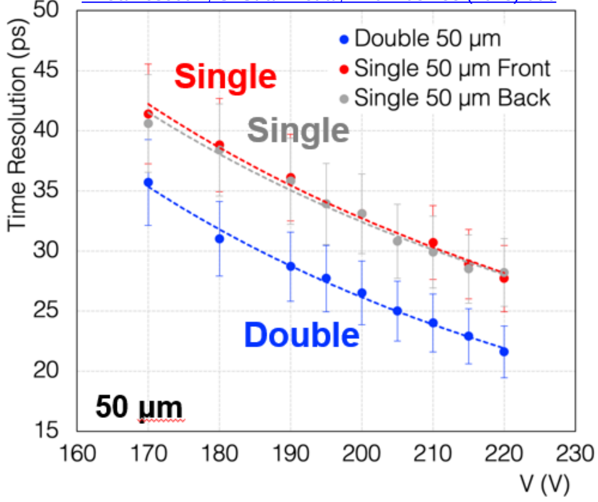
double-LGAD introduced and tested *for the first time*

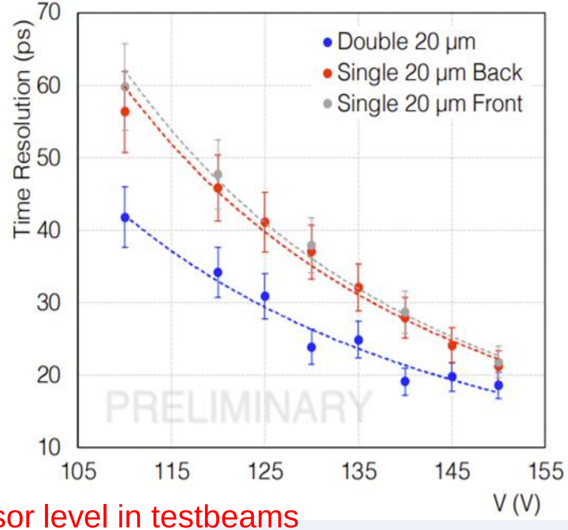
→ signals of both layers summed up using a *single* front-end amplifier

F. Carnesecchi, S. Strazzi et al, EPJ Plus 138 (2023) 99



F. Carnesecchi, S. Strazzi et al, EPJ Plus 138 (2023) 990



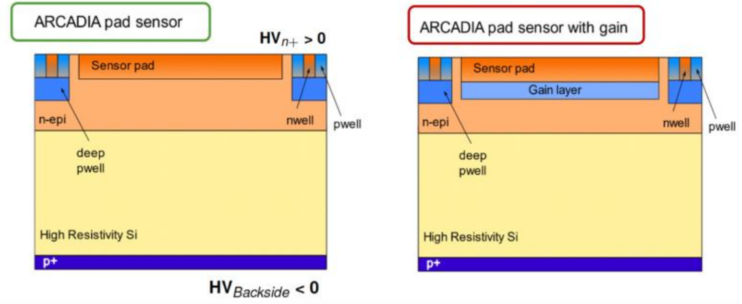


Close to target resolution at sensor level in testbeams

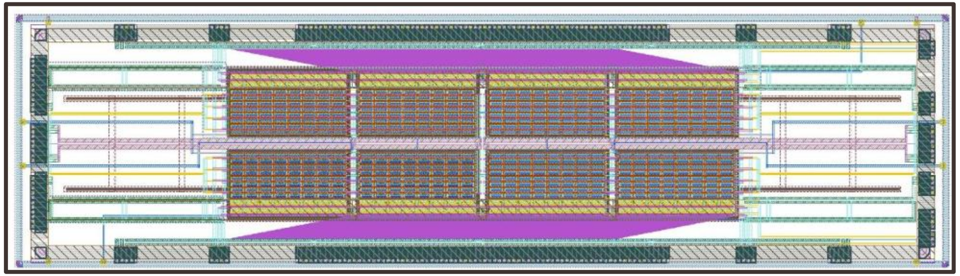
Silicon-based TOF detector R&D

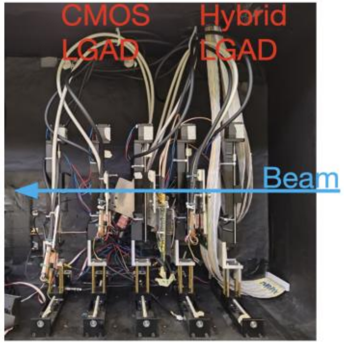
2. Monolithic CMOS LGADs:

- Sensor and FEE integrated in the same chip→ cost reduction
- Based on INFN ARCADIA MAPS 110 nm LFoundry, with additional gain layer

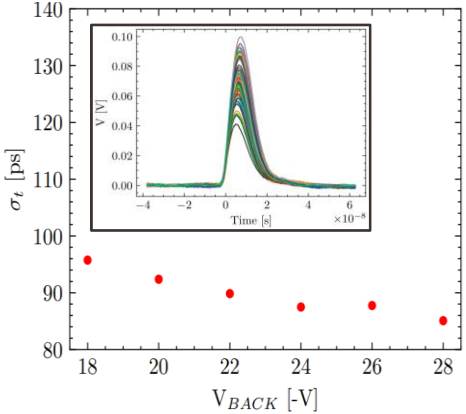


*MADPIX (**M**onolithic CMOS **A**valanche **D**etector **PIX**elated Prototype)*





Beam-test results on 50 μm thick sensor (Oct. 2024)



Time res. sensor + front-end (@0.18mW/ch): 88 ps

Time resolution sensor: ≈ 75 ps

Silicon-based TOF detector R&D

2. Monolithic CMOS LGADs:

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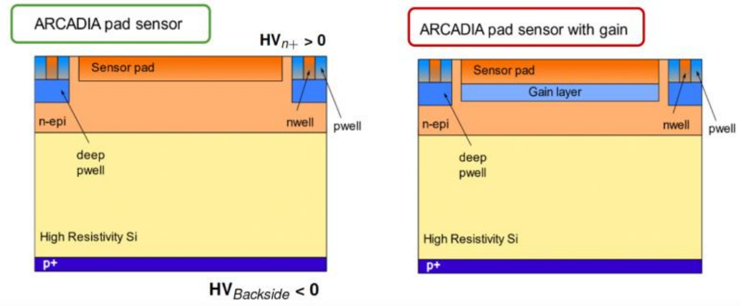
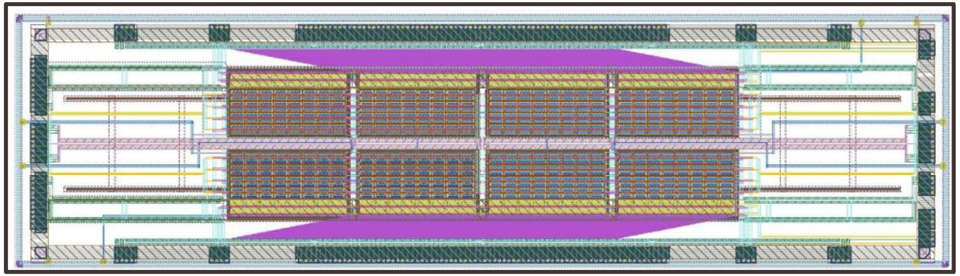
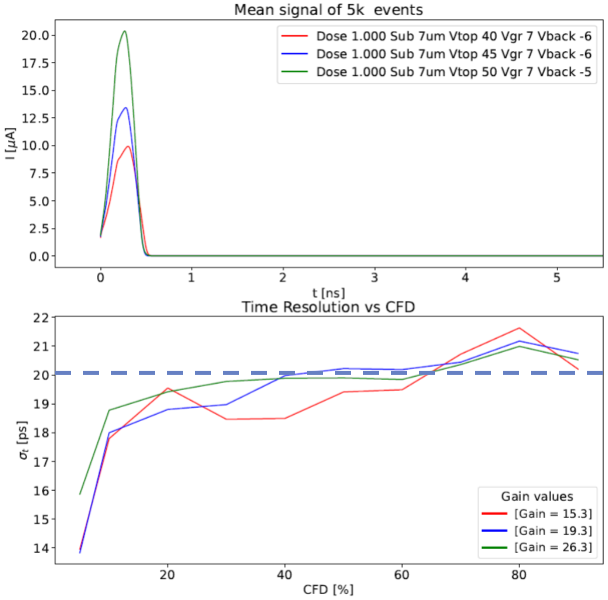


MADPIX (Monolithic CMOS Avalanche Detector PIXelated Prototype)



TCAD simulation of new short-loop sensor, 15 μm thick

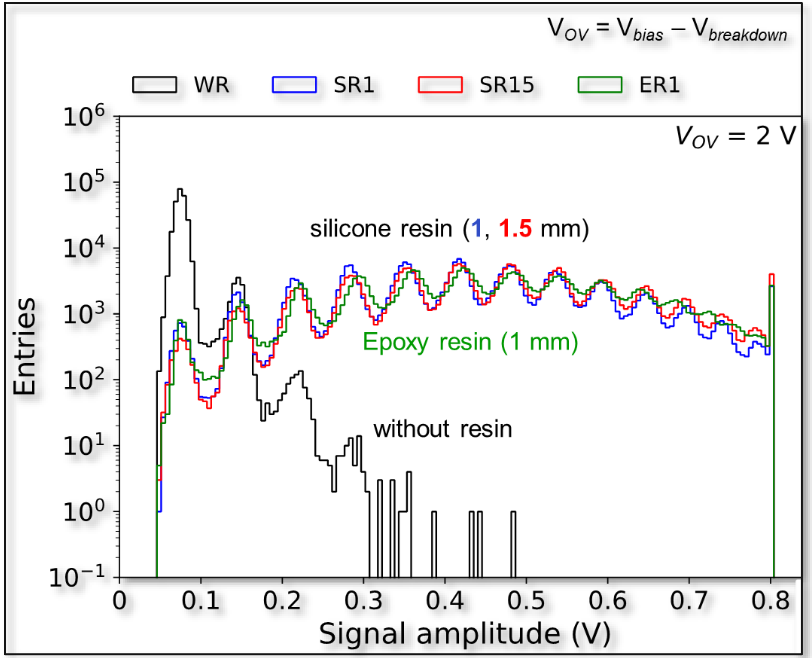


New prototypes planned for this summer expected to reach 20 ps

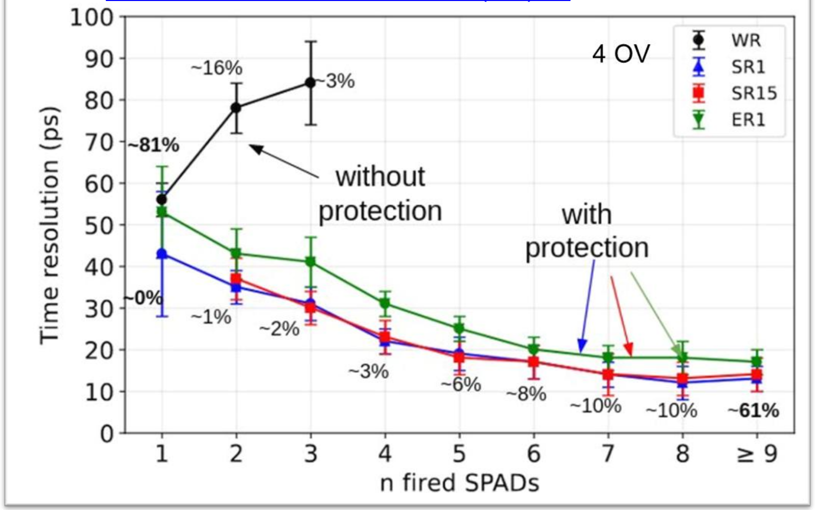
Silicon-based TOF detector R&D

3. SiPMs for timing:

- First demonstration of direct detection of charged particles exploiting Cherenkov photons generated inside protective layer



F. Carnesecchi, B. Sabiu et al, EPJ Plus 138 (2023) 788



Measured ~ 20 ps jitter at sensor level

RICH with Si photon sensors specs

	Barrel RICH	Forward RICH disks
Area (m^2)	28	9
Granularity (mm^2)	2×2	2×2
Hit rate (kHz/cm^2)	15	280
Photon detection efficiency at 400 nm (%)	40	40
Material budget ($\%X_0$)	1 to 3	1 to 3
Power density (mW/cm^2)	50	50
Time resolution (ps)	50	50
Radiation tolerance NIEL (1 MeV n_{eq}/cm^2)	$6.2 \cdot 10^{11}$	$1 \cdot 10^{13}$
Radiation tolerance TID (rad)	$1.5 \cdot 10^4$	$3 \cdot 10^5$

Barrel RICH ($|\eta|<2$) → R ≈ 90 - 120 cm, |z| < 350 cm, 2x2 mm^2 pixels

Two forward RICH discs ($2<|\eta|<4$) → z ≈ ±380 cm, R ≈ 15-110 cm, 2x2 mm^2 pixels

Total surface ~ **37 m^2**

Cherenkov radiator: aerogel + photon detectors: SiPM

RICH with Si photon sensors specs

Cherenkov radiator materials

	Material	Refractive index	$p_{threshold}$ [GeV/c]				λ_{cutoff} [nm]
			e	π	K	p	
gases	He	1.000035	0.061	16.68	59.01	112.14	112
gases	Ar	1.000283	0.021	5.87	20.75	39.44	124
gases	CO_2	1.000449	0.017	4.66	16.47	21.48	175
gases	C_4F_{10}	1.0015	0.009	2.5	9.0	17	136
	Aerogel*	1.03	0.002	0.55	2.0	3.8	300**
liquids	C_6F_{14}	1.3	0.0006	0.174	0.614	1.168	165
liquids	H_2O	1.333	0.00058	0.158	0.56	1.065	190
solids	NaF	1.41	0.00051	0.161	0.567	1.079	125
solids	LiF	1.46	0.00048	0.144	0.509	0.969	105
solids	quartz	1.58	0.00047	0.132	0.465	0.884	158

* n can be tuned in range ~ 1.001-1.1

**Aerogel needs photon detection in the visible

RICH requirements: extend TOF PID

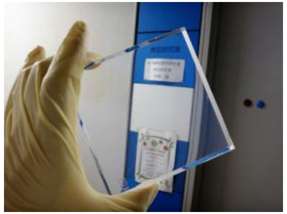
3σ TOF PID ranges

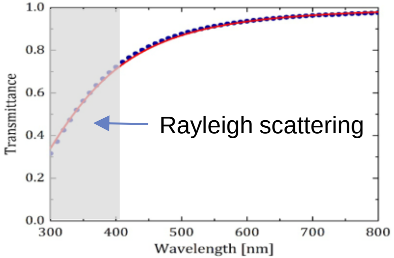
$e/\pi \lesssim$ 500 MeV/c

$K/\pi \lesssim$ 2.5 GeV/c

$p/K \lesssim$ 4 GeV/c

Aerogel with n= 1.03 optimal radiator choice





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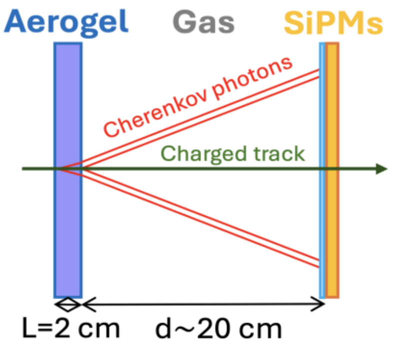
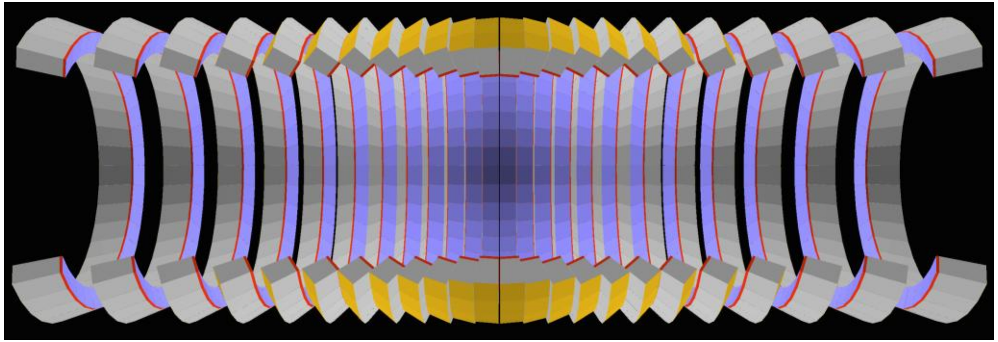
SiPM: 2x2 mm^2, PDE > 40% @ 400 nm

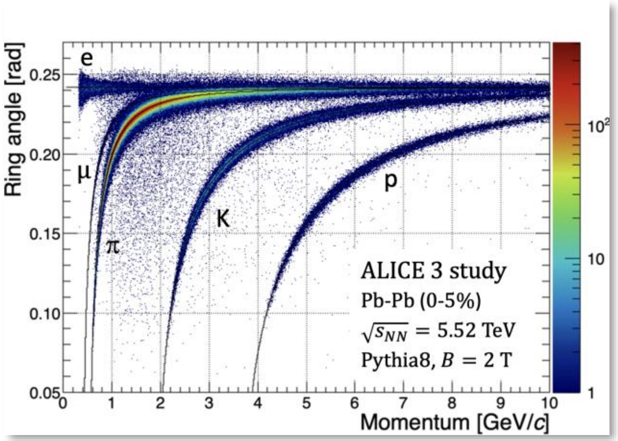
RICH with Si photon sensors R&D

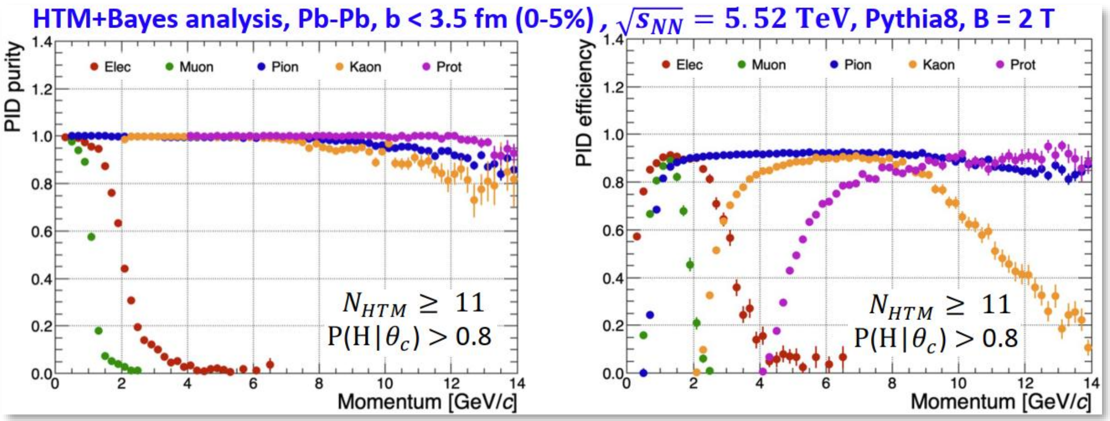


"Projective" layout with modules pointing to collision point



Performance simulations

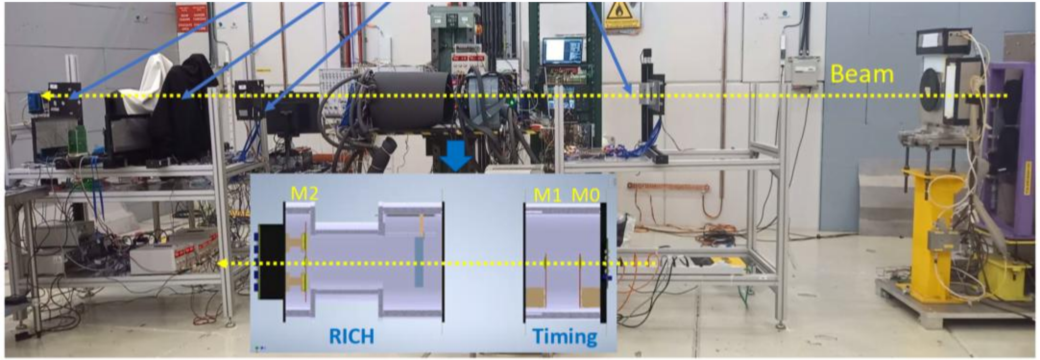


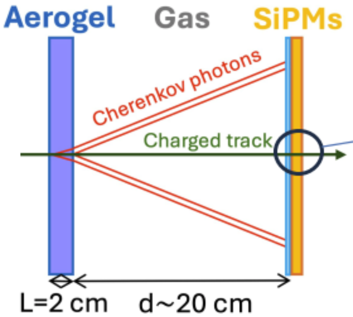


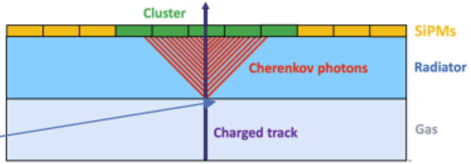
RICH with Si photon sensors R&D

R&D focuses on:

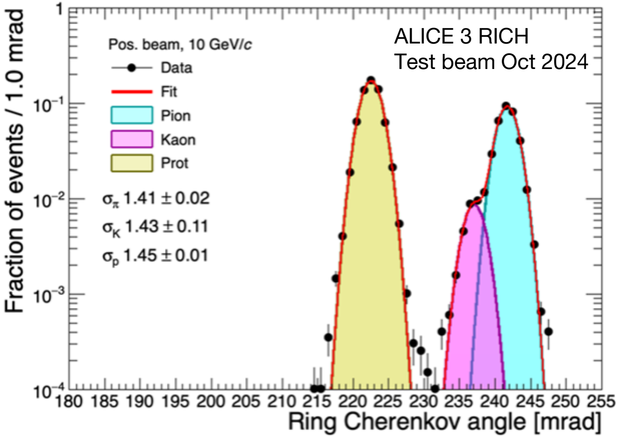
- Aerogel characterization
- SiPM DCR (< 1 MHz/mm^2) and radiation hardness (NIEL ~ 7 x 10^{11} 1 MeV n_{eq}/cm^2):
  - CO_2 cooling @ - 40 ºC and annealing
  - backside illuminated SiPM
  - microlenses and light concentrators





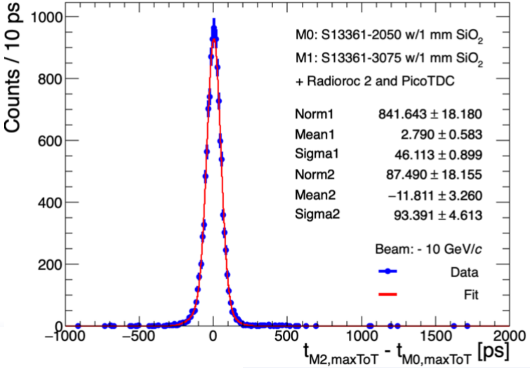


Cherenkov angle of pions, kaons and protons:
~ 1.5 mrad angular resolution



- SiPM equipped with SiO_2 window for MIP timing

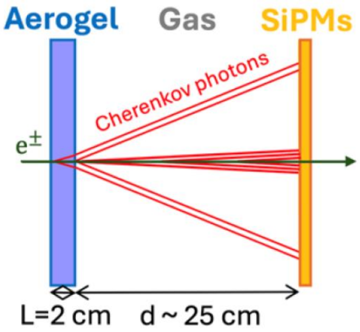
→ ~ 35 ps time jitter on SiPM+R/O

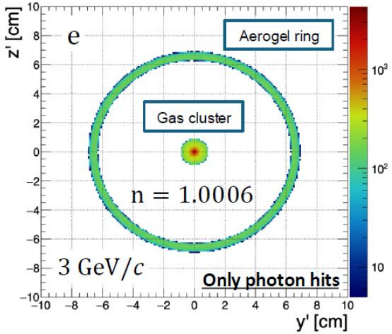


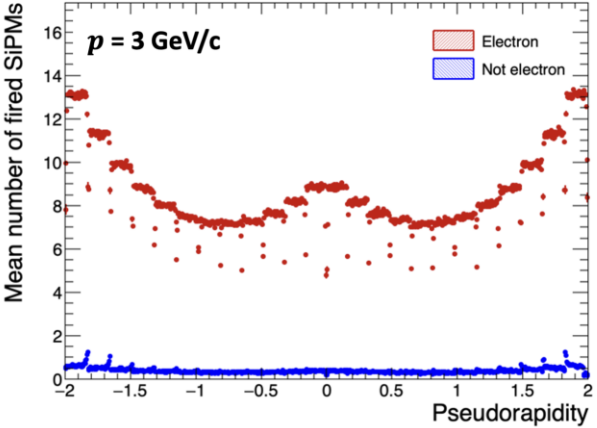
RICH with Si photon sensors R&D

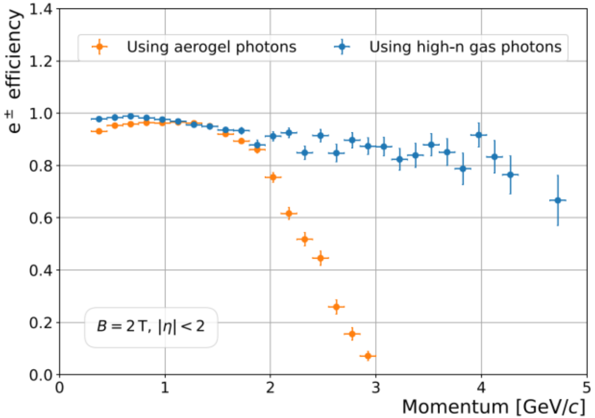
- e-ID extension using gaseous radiator having n ~ 1.0006:
  - avoid high GWP fluids (CF_4, C_4F_{10},…)
  - blend of CO2 (n=1.00045) and $C_5F_{10}O$ or i-C_4H_{10}

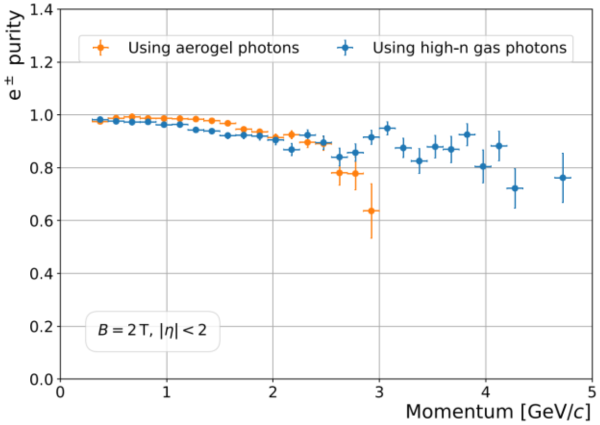
n	β_{th}	p_{th} (GeV/c)				
		e	μ	π	K	p
1,00045	0,9996	0,017	3,522	4,652	16,454	31,272
1,00060	0,9994	0,015	3,050	4,028	14,249	27,082









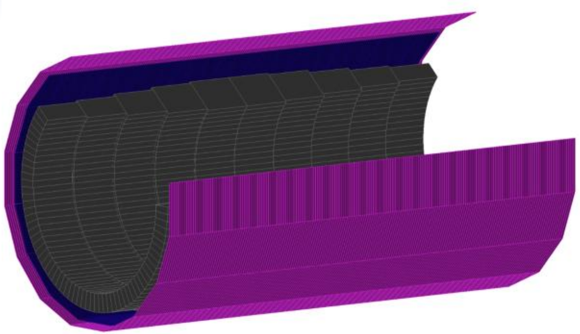


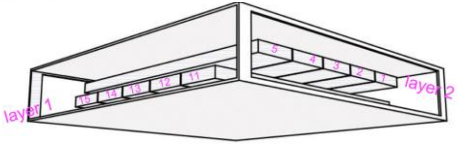
MID detector specs and R&D

Muon chambers
- 160 chambers of 1x1 m^2
- $\Delta\eta \times \Delta\phi$ granularity → 5x5 cm^2 cells
- 2 layers of plastic scintillator bars
- SiPMs readout
- Alternative option: MWPC

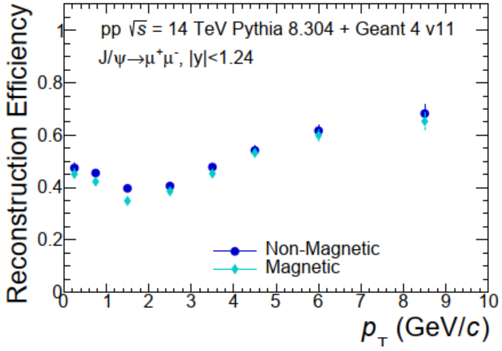
Absorber outside SC magnet
- Standard magnetic steel absorber
- Thickness of ≈ 70 cm at $\eta = 0$

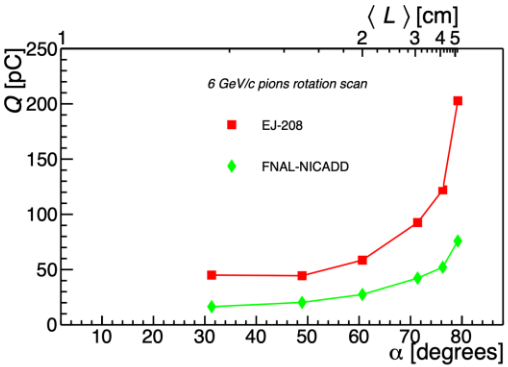
R&D focuses on:
- scintillator material selection
- layout optimization for π rejection

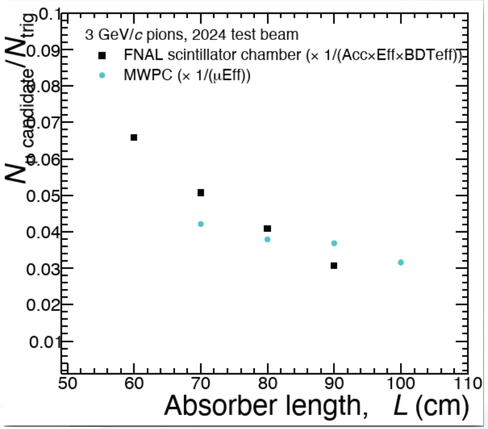




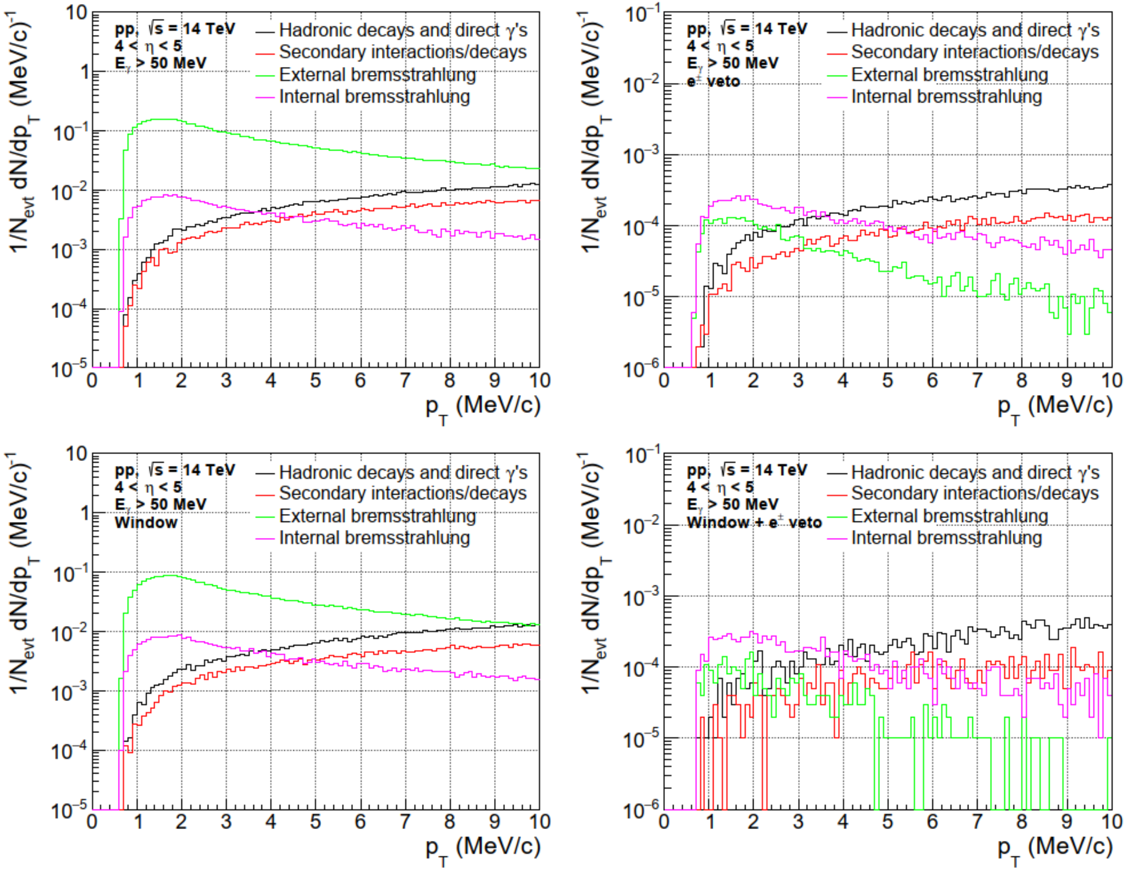
Testbeam in Oct 24 of Scintillators/SiPM and MWPC prototypes using final size iron absorber







Thoughts on e-ID for FCT



+ e veto
- conical beam pipe

- e veto
+ conical beam pipe

+ e veto
+ conical beam pipe

(from Scoping Document)

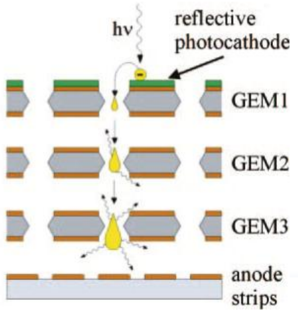
Thoughts on e-ID for FCT

Goal: identify $e^{+/-}$ from few 10's of MeV/c up to few GeV/c

Material	Refractive index	$p_{threshold}$ [GeV/c]				λ_{cutoff} [nm]
		e	π	K	p	
He	1.000035	0.061	16.68	59.01	112.14	112
Ar	1.000283	0.021	5.87	20.75	39.44	124
CO_2	1.000449	0.017	4.66	16.47	21.48	175
C_4F_{10}	1.0015	0.009	2.5	9.0	17	136

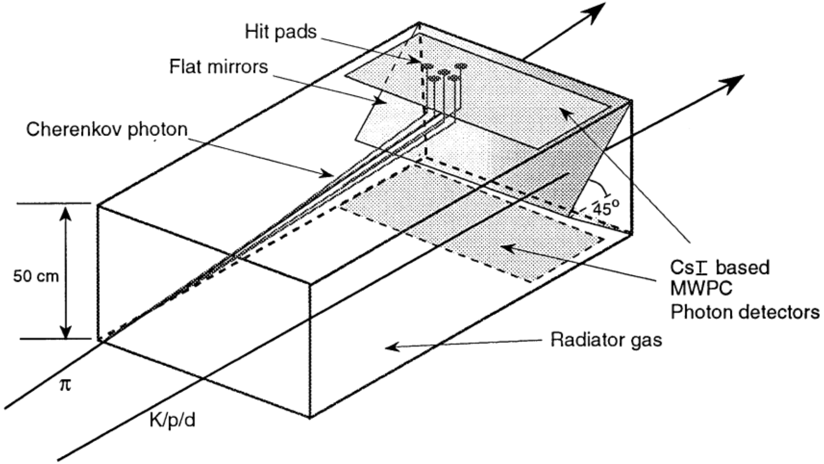
Gaseous radiator

CsI-based gaseous photon-detector (e.g. with GEMs)



Thoughts on e-ID for FCT

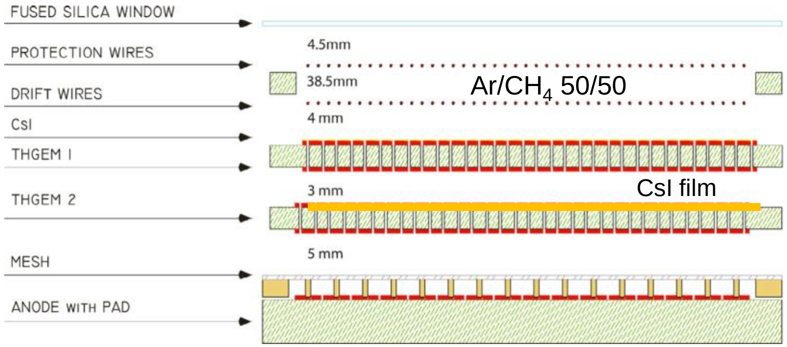
Threshold Imaging Cherenkov detector (NA44)



A. Braem et al., Nucl. Instr. & Meth. A 409 (1998) 426-431

- Depending on radiator gas, hadrons will produce Cherenkov photons only above a certain momentum (e.g. in CO_2 for π: p_{th} = 4.7 GeV/c) → work in threshold mode
- Using flat mirrors one can detect photons generated by $e^{+/-}$ using photo-detectors placed outside the acceptance
- Simple and cheap technology for the photon-detector: CsI +GEMs (or THGEMs)

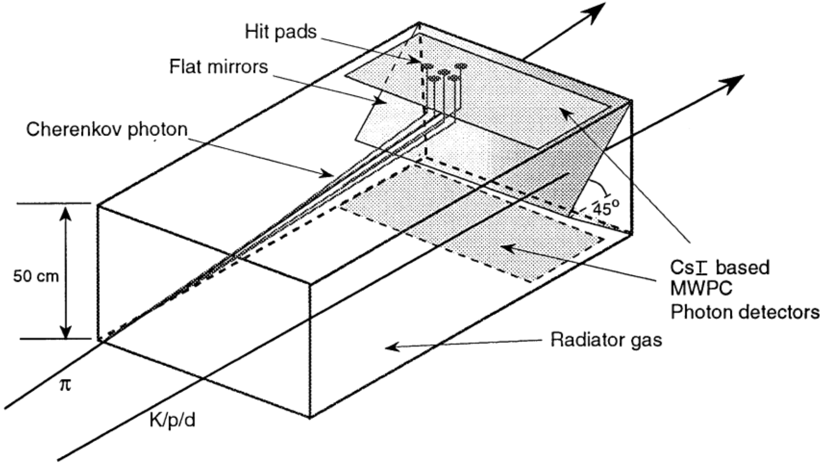
For example: COMPASS MPGD (Hybrid THGEM+MICROMEGAS)



S. Dalla Torre, Nucl. Instr. & Meth. A 970 (2020)

Thoughts on e-ID for FCT

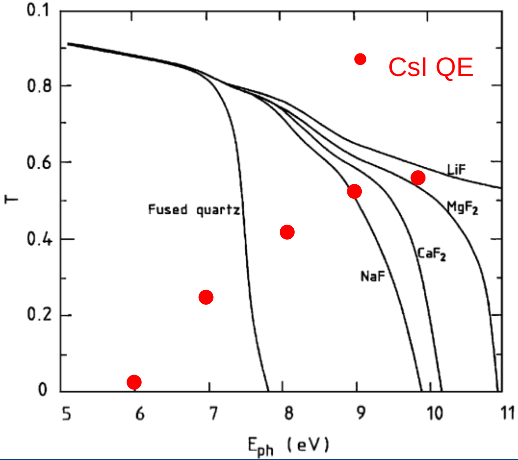
Threshold Imaging Cherenkov detector (NA44)



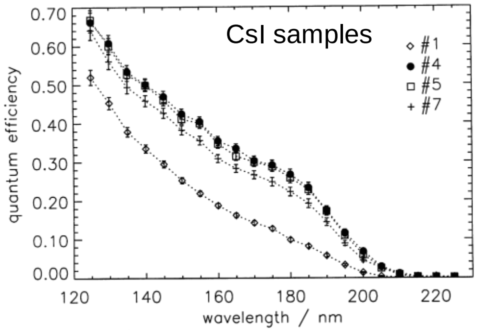
A. Braem et al., Nucl. Instr. & Meth. A 409 (1998) 426-431

The choice of the optical window of the PD has a strong impact on the number of detected photons hence on the length of the radiator gas volume, which in turn defines the area of the PD

H. Rabus et al., Nucl. Instr. & Meth. A 438 (1999) 94-103



H. Rabus et al., Nucl. Instr. & Meth. A 438 (1999) 94-103



Frank-Tamm relation

$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

Optical window	Fused silica	CaF_2	MgF_2
Wavelength range	160-210 nm	121-210 nm	113-210 nm
No. of Cher. phot. In 1 m CO_2	**63**	**146**	**173**
No. of Cher. phot. In 1 m He	**5**	**11.5**	**13.7**

Summary

- The ALICE collaboration has proposed a new experimental apparatus to fully exploit the excellent LHC performance as HI collider starting from Run 5.
- PID plays a central role in the achievement of the rich physics programme aiming at ultimate insights on QGP through studies of dielectrons, heavy quarks and more.
- Extensive R&D in key areas, such as MAPS for timing and radiation-hard SiPMs, is driving sensor technology forward in ways that will also benefit future applications.
- The “versatility” of Cherenkov imaging offers interesting options for implementing e-ID in the FCT detector.