Attività 2024

Richieste 2025

ALICE 3-RICH project

Rome, 19/07/2024

Giacomo Volpe (University & INFN, Bari)
On behalf of the ALICE 3 RICH WG

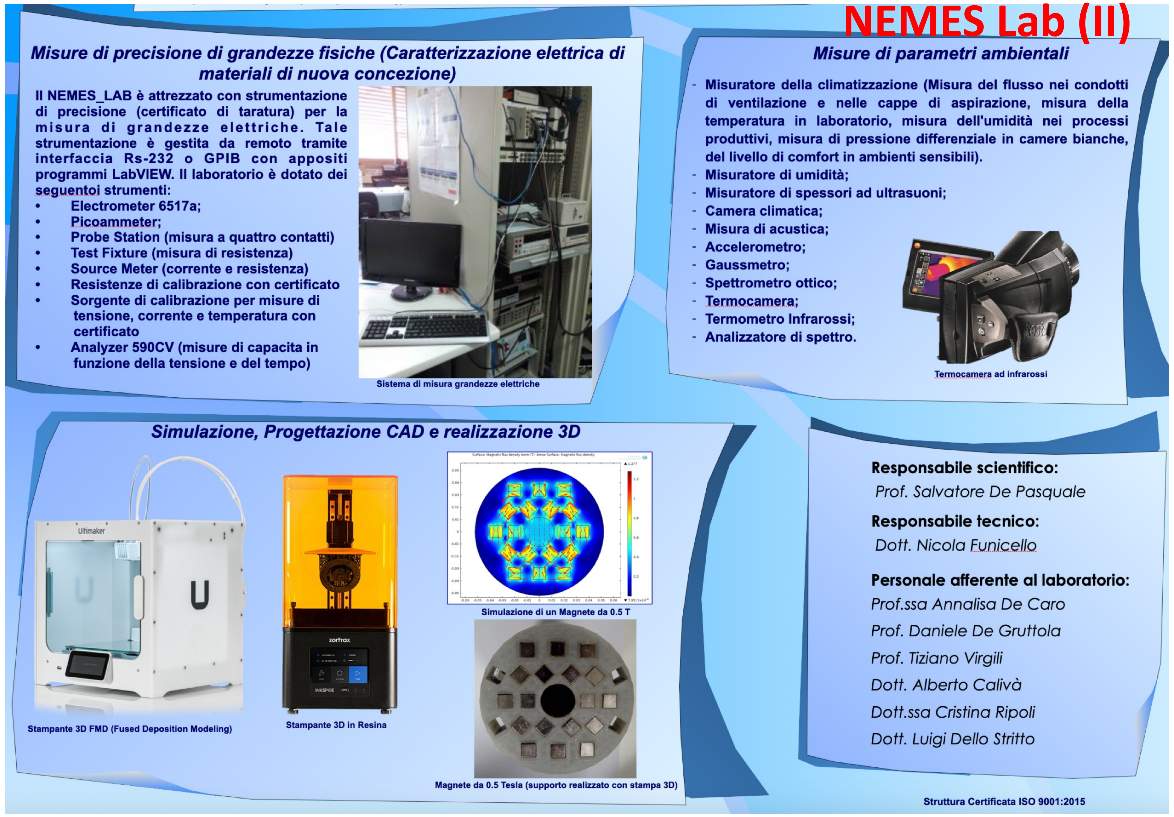
Italian participating institutes

Institute	Interest
INFN, University, Politecnico Bari	SiPM R&D, module, mechanics, aerogel characterization
INFN, University Salerno	SiPM R&D, module (sensor characterization also in cryogenic condition)
INFN-To (Italy)	FEE ASIC

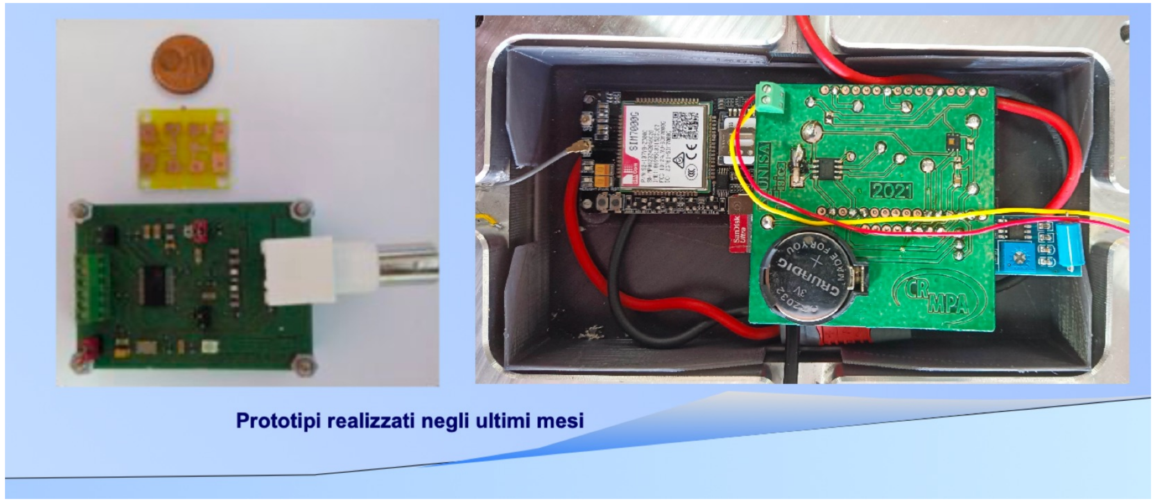
In collaboration with LNGS-NOA for the packging and with FBK for the SiPM R&D

ALICE Salerno group joined to the project

NEMES Lab (II)

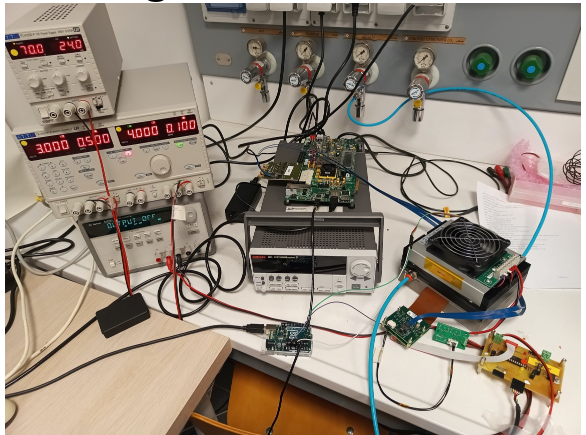


NEMES Lab (I): prototipazione e produzione, su piccola scala, di schede elettroniche multistrato



Reaching low temperature with liquid N

Testing SiPMs for ePIC dRICH



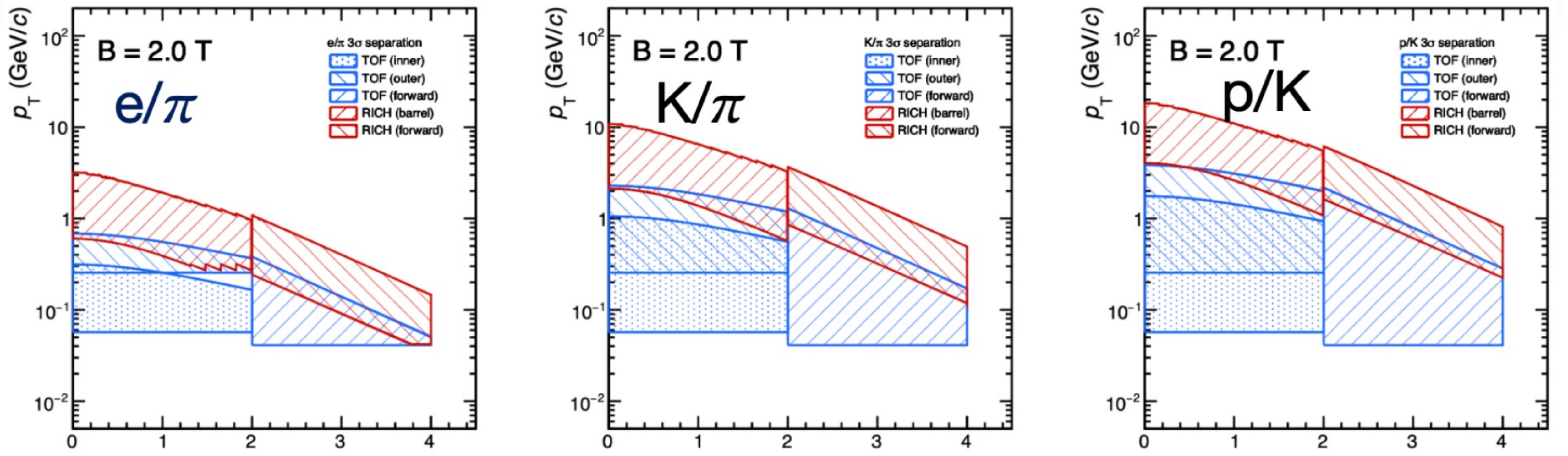
Cosmic ray telescope

ALICE 3 - RICH

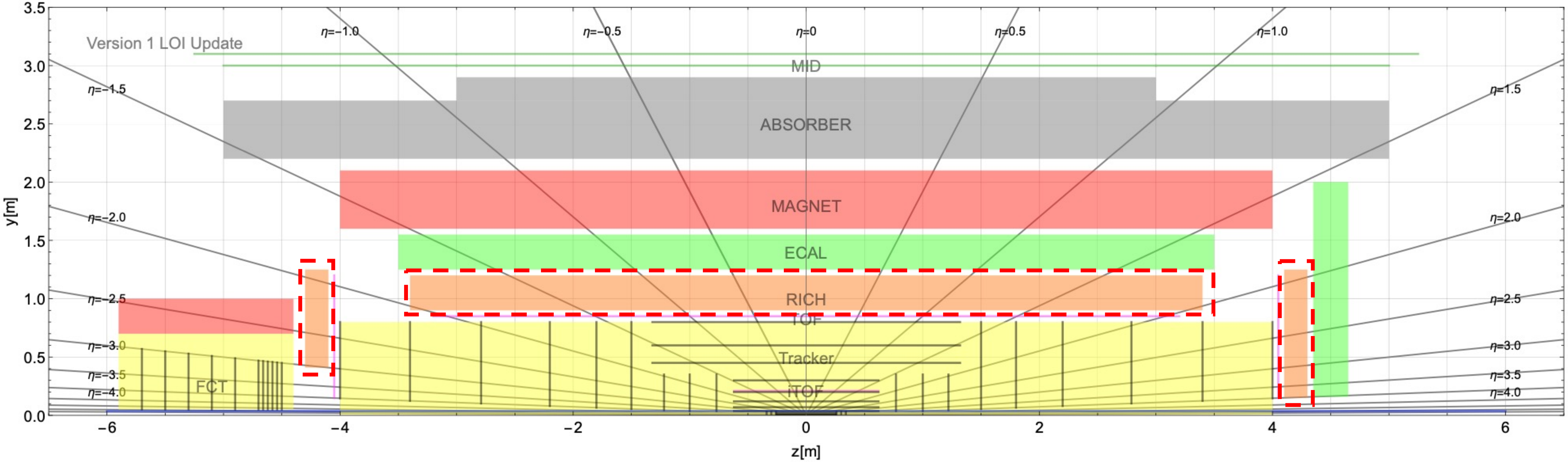
Extend electron and charged hadron ID at momenta higher than the TOF range, e.g in the barrel:
e/π : 0.5 - 2 GeV/c
π/K : 2.0 - 10.0 GeV/c
K/p : 4.0 – 16.0 GeV/c

Barrel RICH: aerogel Cherenkov radiator (2cm, n=1.03) + 20 cm expansion gap + SiPM photon detector
Forward RICH: idem, but aerogel n = 1.006

Results from "fast" parametric simulation, assuming a Cherenkov angle resolution at saturation of 1.5 mrad and a TOF time resolution of 20 ps



ALICE 3 - RICH

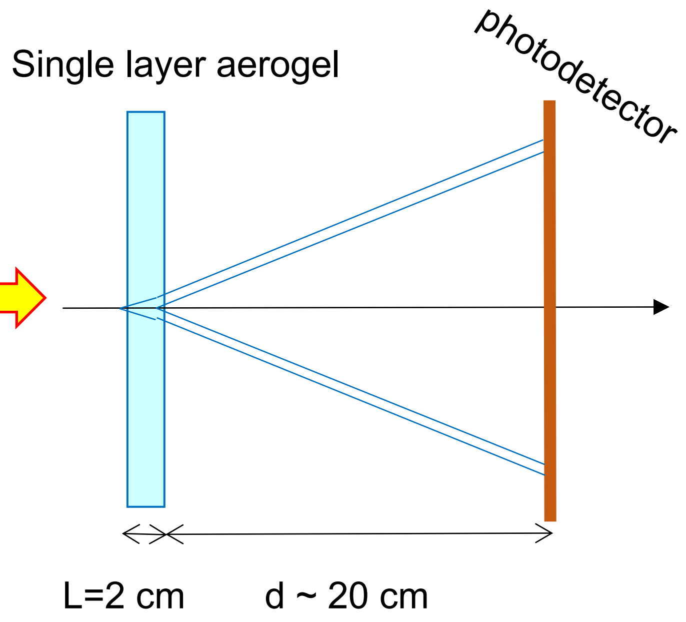


	Barrel RICH	Forward RICH disks
Radius (m)	0.9 to 1.2	0.15 to 1.2
z range (m)	−3.50 to 3.50	±4.3
Surface (m^2)	28	9
Acceptance	$\|\eta\| < 2$	$2 < \|\eta\| < 4$
Granularity (mm^2)	1×1 to 2×2	1×1 to 2×2

bRICH layout	bRICH number of modules	fRICH number of modules	bRICH SiPM area [m^2]	bRICH aerogel area [m^2]	fRICH SiPM area [m^2]	fRICH aerogel area [m^2]
Projective $\|\eta\| < 2$	864	220	30.7	22.7	7.5	6.6

ALICE 3 - RICH

Baseline option

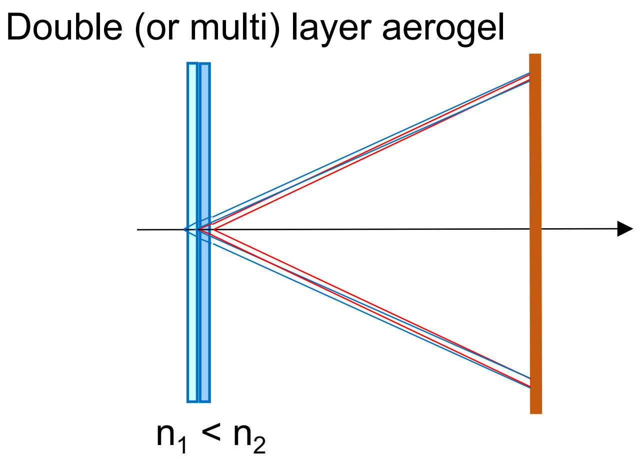


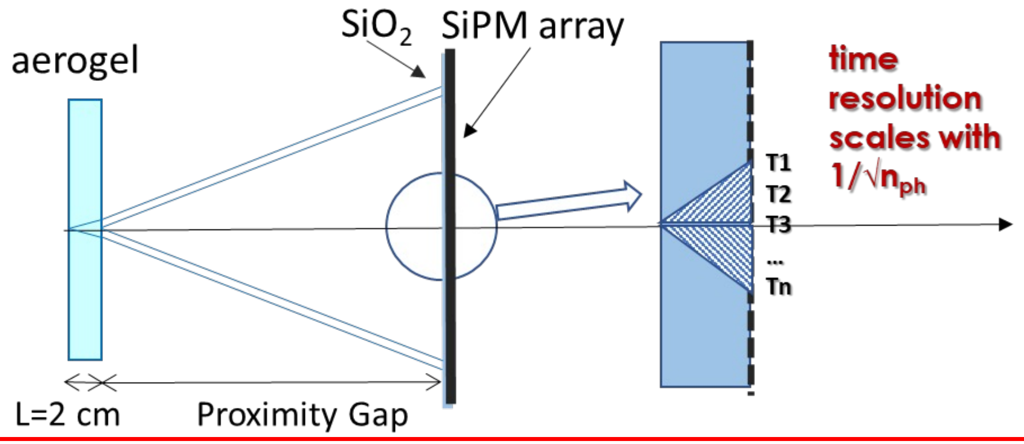
The Cherenkov radiator comprises hydrophobic aerogel tiles (15 × 15 × 2 cm^3 refractive index n = 1.03)

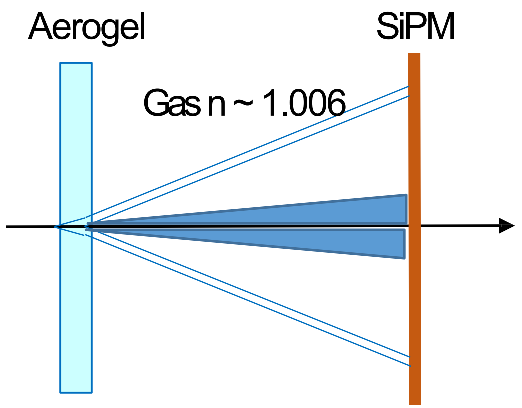
The photodetection layer, positioned 20 cm from the radiator, relies purely on proximity focusing.

Each photon detector module covers an area of approximately 20 × 20 cm^2 , featuring an optimized SiPM pixel size of 2 × 2 mm^2, 1x1 cm^2 die.

Alternative options







Simulation studies (by N. Nicassio): assumptions

Radiator

- Aerogel, n = 1.03
- Tickness: 2 cm
- Transmittance and n vs wavelenght from Aerogel Factory Co., Ltd. (Chiba, Japan) data

Photon sensor

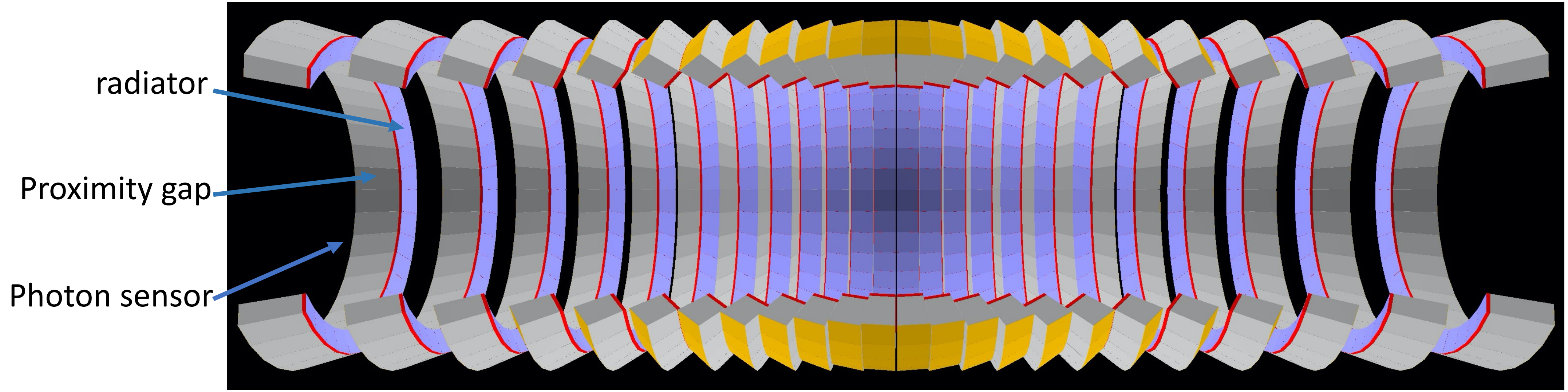
- Silicon Photon Multiplier (SiPM)
- Pixel size: 2x2 mm2
- PDE ≅ 40 % at 450 nm
- Intrinsic single SiPM time resolution: 50 ps
- DCR: 50 kHz/mm^2

Cylindrical projective geometry

- All aerogel tiles oriented toward nominal interacion point
- Full coverage to charged particles without ovelaps
- Trapeizoidal tile profile to maximize the acceptance

→ 24 sectors in z

36 modules in $r\phi$ for each sector



Simulation studies (by N. Nicassio): PID purity in p-p and Pb-Pb

Angle reconstruction

- Based on Hough Transform method (HTM)
- Timing cut on hit-track matching
- HTM $N_{ph,min}$ cut on clustered hits

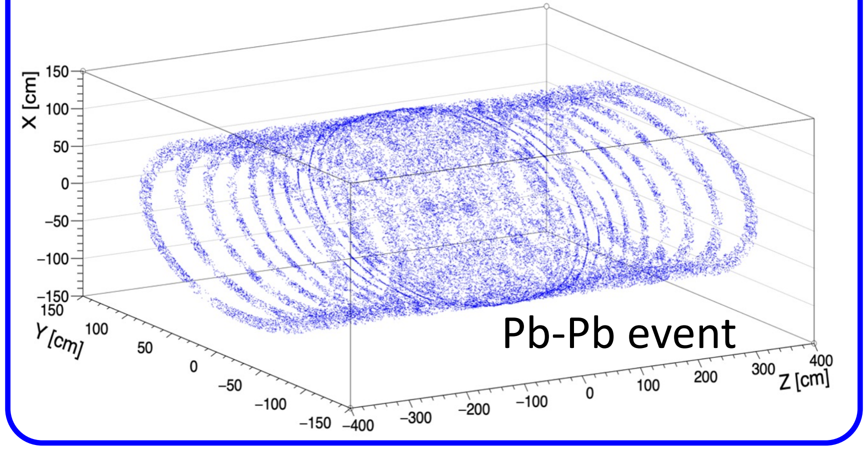
Particle identification

- Bayesian approach + probability cut

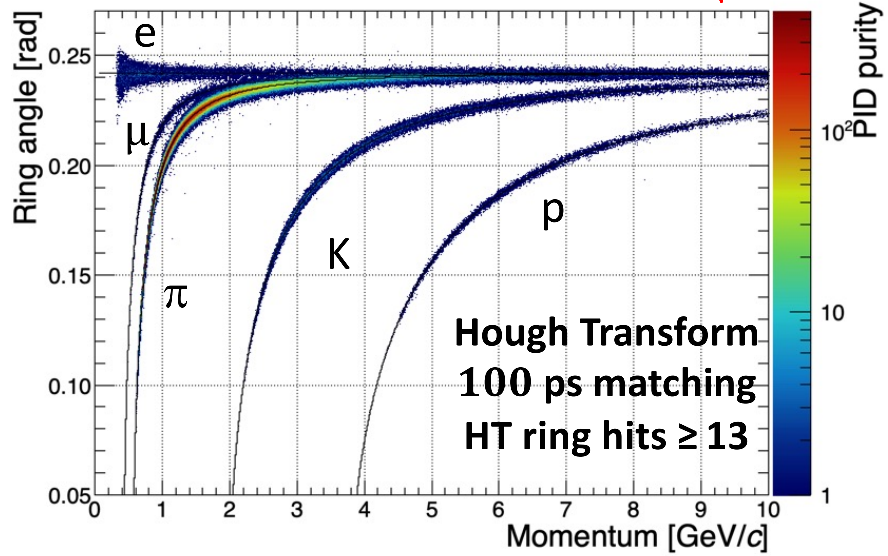
Background

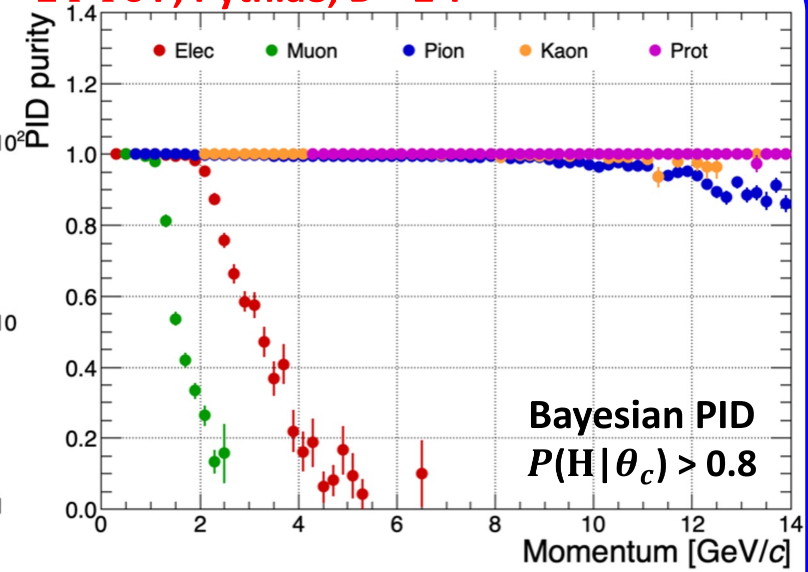
- Photons emitted by different tracks
- Aerogel Rayleigh scattered photons
- SiPM dark count hits (in DAQ gate)

Photodetector hit map of Pb-Pb event

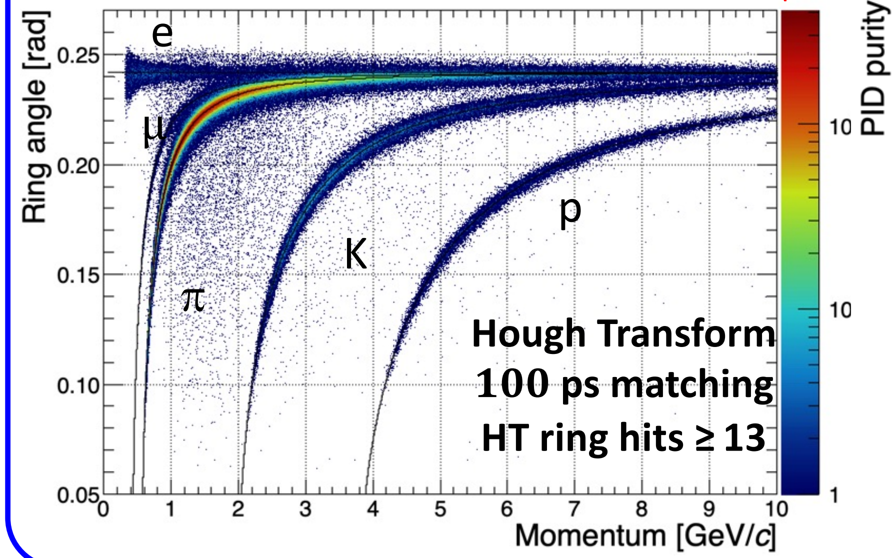


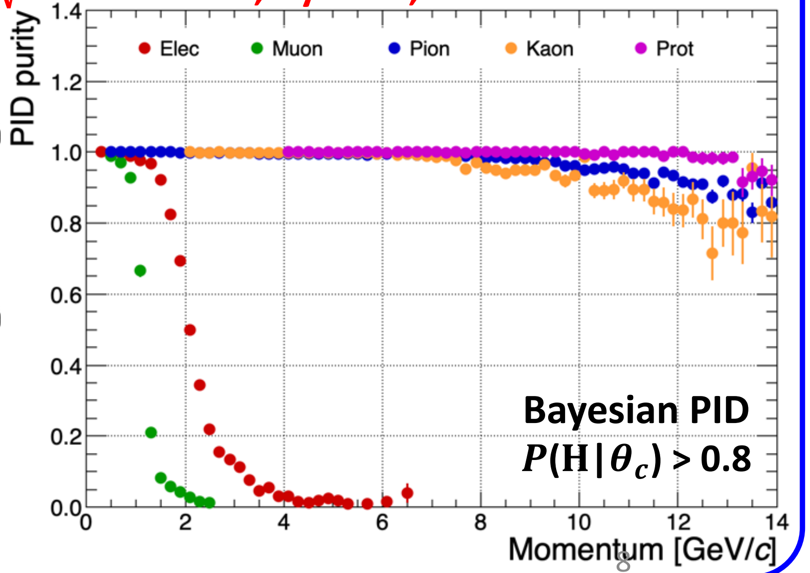
p-p , $c\bar{c}$ biased, $\sqrt{s_{NN}} = 14$ TeV, Pythia8, B = 2 T





Pb-Pb, b < 3.5 fm (0-5%) , $\sqrt{s_{NN}} = 5.52$ TeV, Pythia8, B = 2 T





Simulation studies (by N. Nicassio): Machine learning vs HTM

Dataset

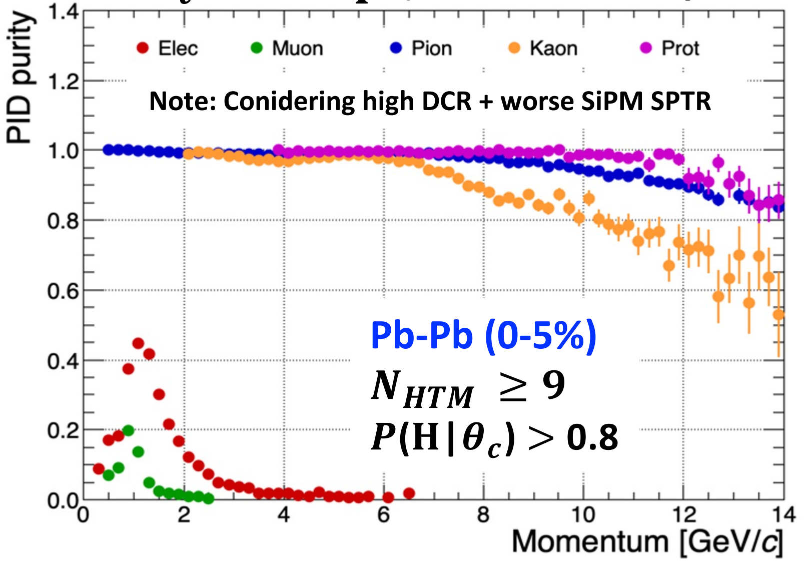
- 5k Pb-Pb (b < 3.5 fm), B = 2T
- $\approx$ 20.0 M charged tracks at bRICH
- Composition: $\pi^{\pm}, K^{\pm}, p^{\pm}, e^{\pm}, \mu^{\pm}$

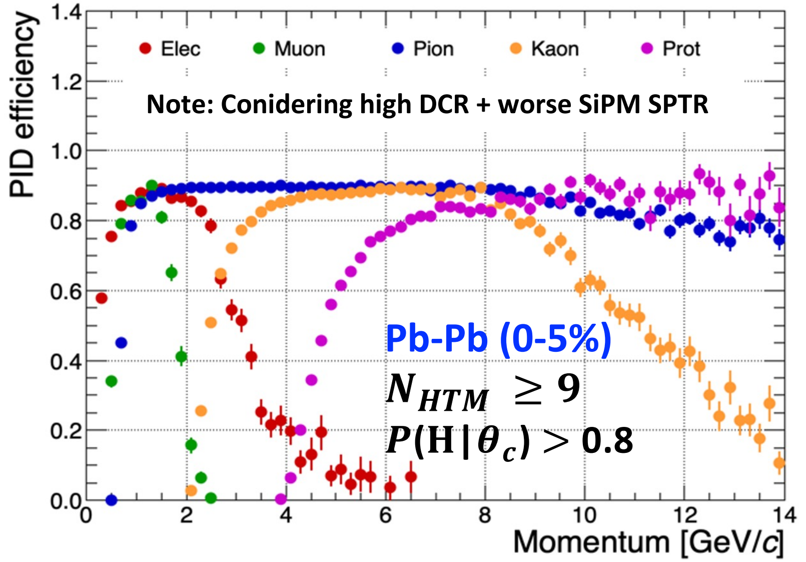
ML vs HTM-based PID

- Overall better effciency*purity achieved using ML w.r.t. HTM
  - Note: Efficiency limits in HTM due boundary effects: need for refined N_{HTM} conditions
  - The effect is automatically learned by my ML algorithm
- Better $e^{\pm}$ & $\mu^{\pm}$ purities with ML
- ML worsening above $\approx$ 10 GeV/c
  - Limited statistics of high-p particles in training dataset

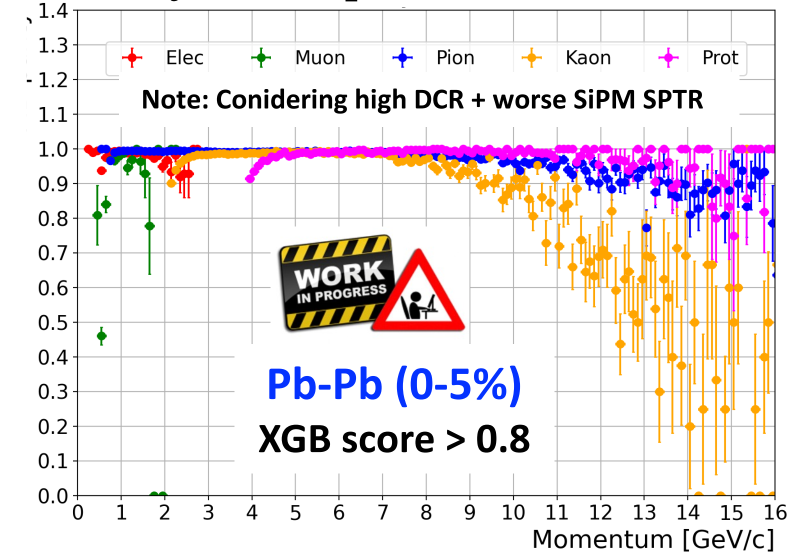
Next step: Training on larger sample

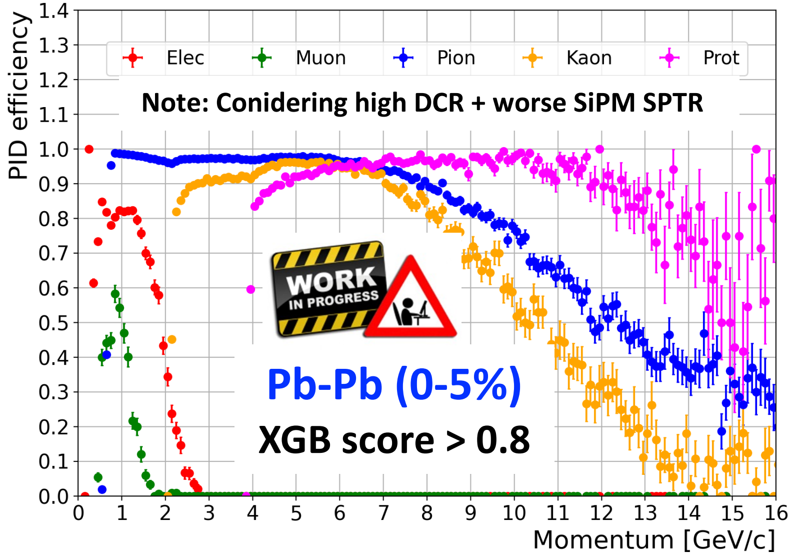
HTM: $\sigma_t = 200$ ps, DCR = 1 MHz/mm²





ML: $\sigma_t = 200$ ps, DCR = 1 MHz/mm²





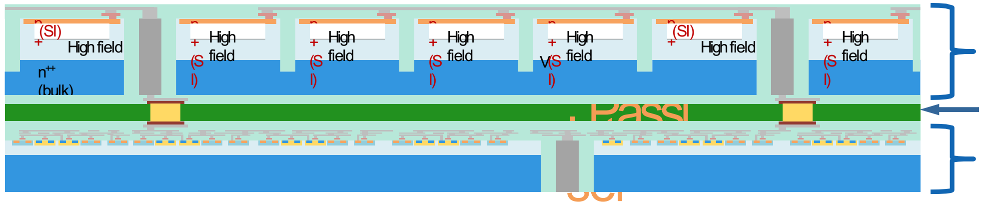
Can be improved a lot training with more statistics

Photon detector

SiPM specifications:

pixel size = 2x2 mm^2 , die (SiPM array) size ~ 1x1 cm^2, PDE > 40% at 450 nm, DCR < 50 kHz/mm^2,
radiation hardness: NIEL ~ 10^{12} 1 MeV neq/cm^2, time resolution < 100ps,
packaging fill factor > 90% (TSV interconnection)

- Explore custom solutions for 2.5D configuration in CMOS Imaging Sensor technology (partnership with FBK)
- MIP detection by thin radiator window for TOF
    - Anti-reflecting coating
- FEE ASIC
- Module concept and cooling integration (cool down up to -30/-40 °C to reduce the DCR).



SiPM Array

PCB Interposer with embedded CO2 cooling and annealing

FEE ASIC

The barrel RICH challenges – Radiation Load

Radiation load for Run 5+6 in pp collisions

Element	R (m)	TID (rad)	NIEL (1 MeV neq/cm²)	HEH (kHz/cm²)	Ch. particle fluence (kHz/cm²)
Barrel RICH	0.9	3.3×10^4	8.3×10^{11}	8.3	12
Barrel RICH	1.2	1.4×10^4	6.1×10^{11}	4.3	5
Forward RICH disk	0.15	7.1×10^5	8.5×10^{12}	2.0×10^2	2.8×10^2

Evaluated with FLUKA (assuming 65% running efficiency)

Radiation load for Run 5+6 in Pb-Pb collisions

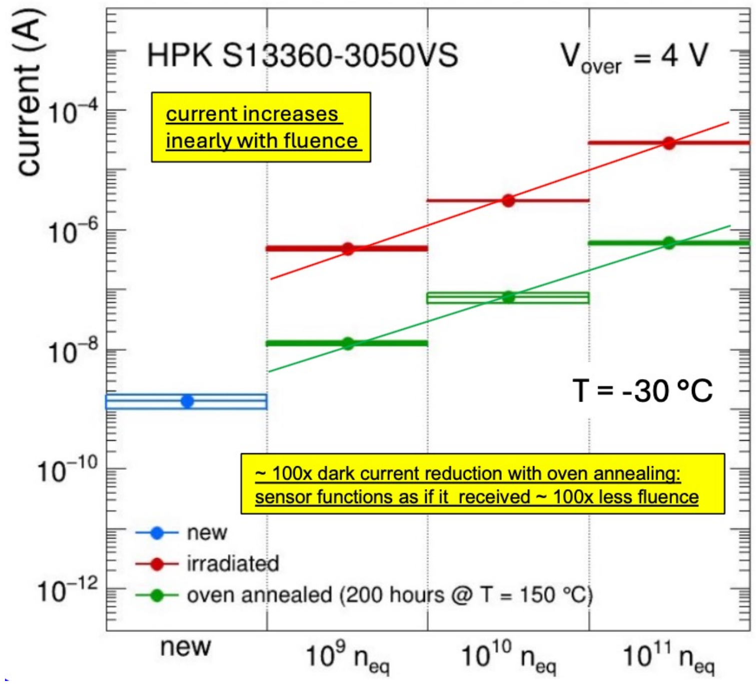
Element	R (m)	TID (rad)	NIEL (1 MeV neq/cm²)	HEH (kHz/cm²)	Ch. particle fluence (kHz/cm²)
Barrel RICH	0.9	4.7×10^2	1.2×10^{10}	2.5	3.5
Barrel RICH	1.2	2.0×10^2	8.8×10^9	1.3	1.5
Forward RICH disk	0.15	1.0×10^4	1.2×10^{11}	57	81

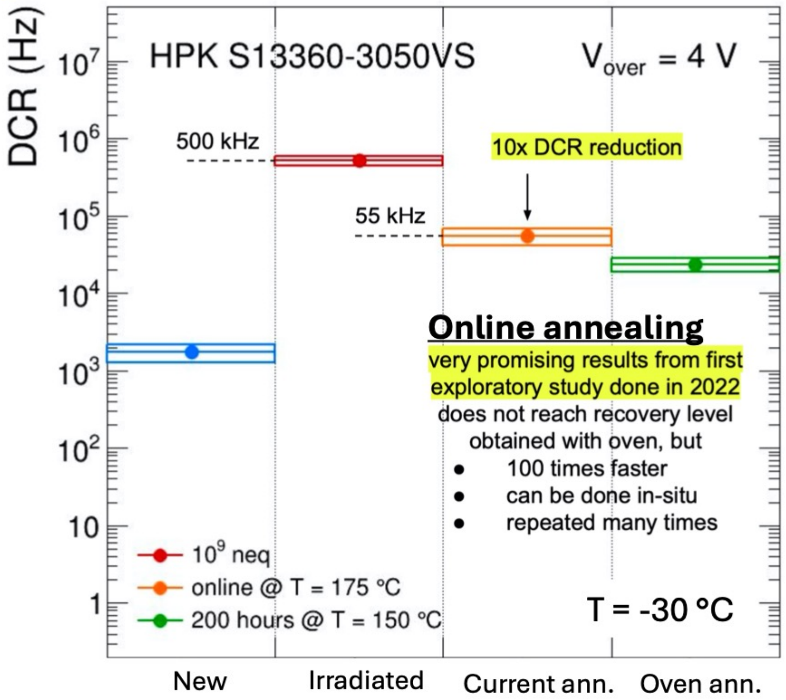
For the Barrel RICH: NIEL ~ 8.4×10^{11} 1 MeV n_{eq}/cm^2 (even worse with ECal, ~10^{13})

The barrel RICH challenges – Radiation Load

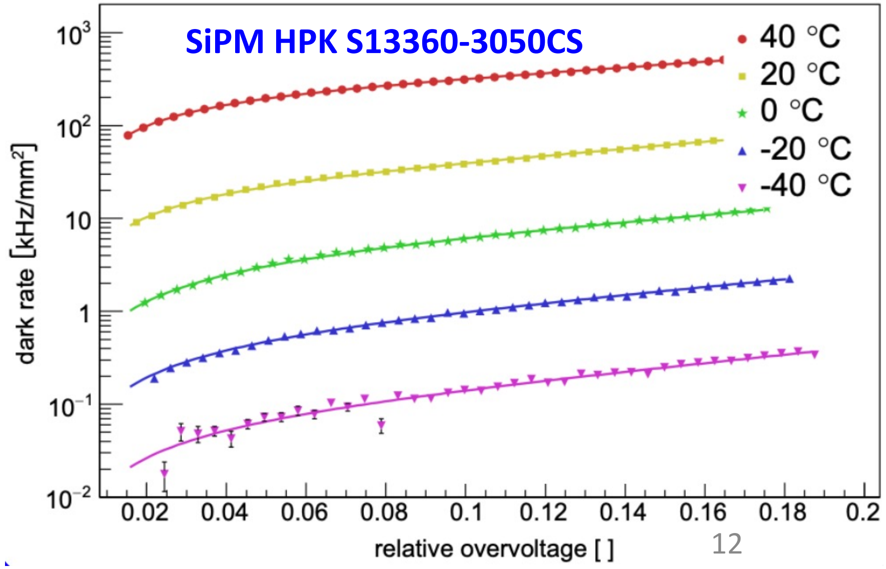
- High radiation load expected in the barrel (**NIEL ~ 8.4 x 10^{11} 1 MeV neq/cm^2**) → SiPM DCR increases to not tollerable values (> 1 MHz/mm^2)
  - Improve SiPM radiation hardness
  - Development of cooling/annealing strategy

From R. Preghenella





NIMA 846 (2017) 106–125



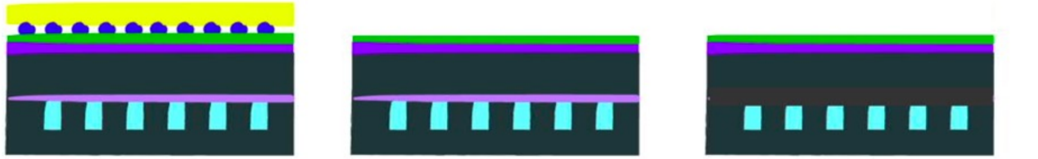
Cooling option

Detector cooling, 16th Terascale Detector Workshop 2024 | Jan-Hendrik Arling & Sergio Diez, 21.02.2024

Dual-phase CO2 cooling - A good choice for HEP applications

- advantages of dual-phase CO_2 cooling for HEP applications:
  - **large latent heat transfer** due to the phase change energy for the transition of liquid to gas
  - operation with **low mass flow** of the coolant is possible
  - **low mass flow as well as a low liquid viscosity results in a low pressure drop along cooling pipe**
    - **a low pressure drop allows the use of small pipe diameters or technical solutions like micro-**
  - **channel cooling, which allows new detector design concepts**
  - high **heat transfer capability** (typical ~8000 W/Km) is possible despite small pipe diameters
  - practical **temperature range** of −40 °C to 25 °C for detector application
  - CO_2 is a **natural**, non-toxic, non-flammable, radiation resistant and non-magnetic gas

Micro-channel cooling on Si - A silicon-embedded technology



Hybrid pixel detector & micro-channel cooling plate — Monolithic CMOS detector — Monolithic CMOS detector with integrated micro-channels

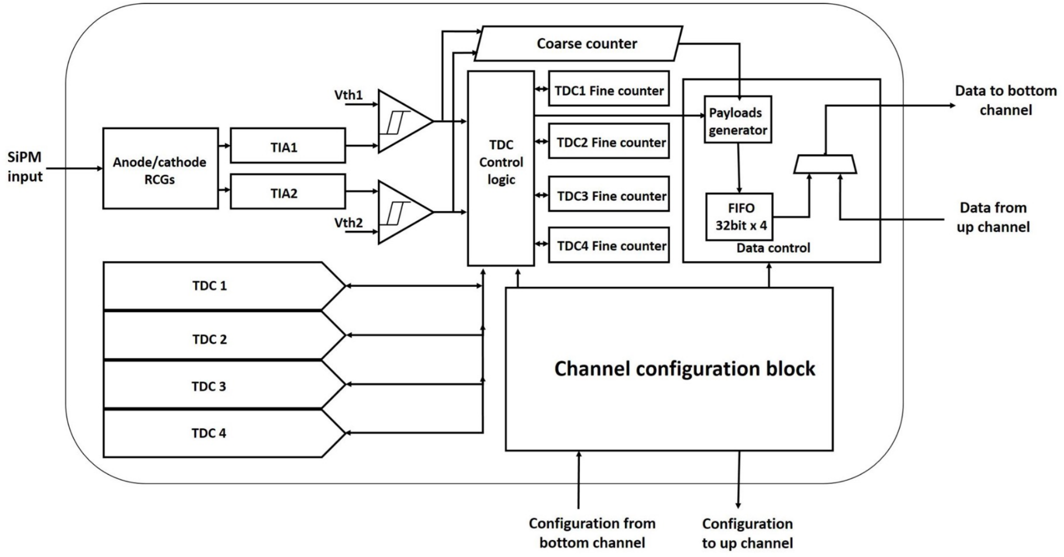
- micro-channel cooling in Si is a favorable technology
  - **optimized thermal contact with heat sources**
  - heavily simplified assemblies
  - reduction of material
  - **efficient for cooling "chip-like" heat densities**
- basic technological process: deep RIE + (anodic, eutectic, fusion) wafer bonding
- further integrations also possible!
  - example: metal Re-Distribution Layers (RDL) (*M. Ullán et al. (HSTD13, 2023)*)

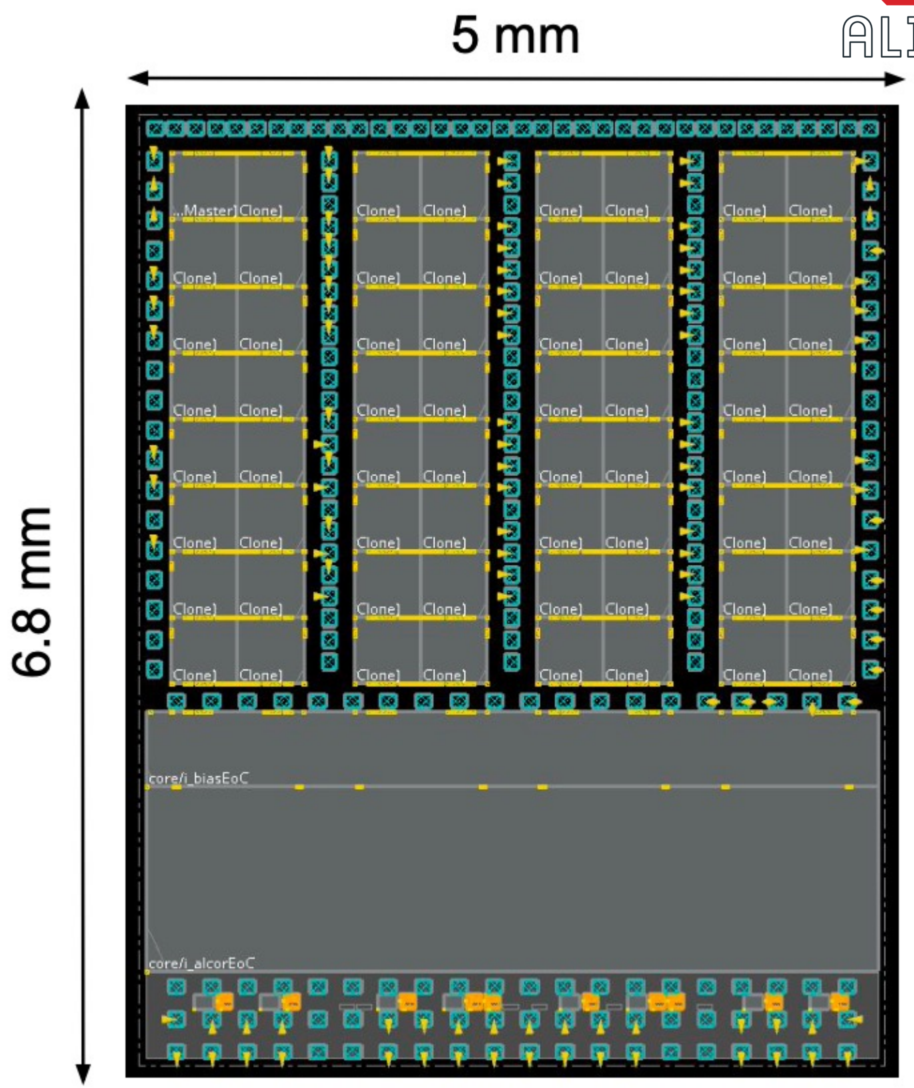
ASIC FEE development

ALCOR (A Low Power Chip for Optical sensors Readout) is a ASIC developed to readout silicon photomultipliers at low temperature. The chip is designed in a 110 nm CMOS technology

Developed by INFN-Torino for SiPM sensors used in the dRICH detector of the ePIC experiment at EIC.

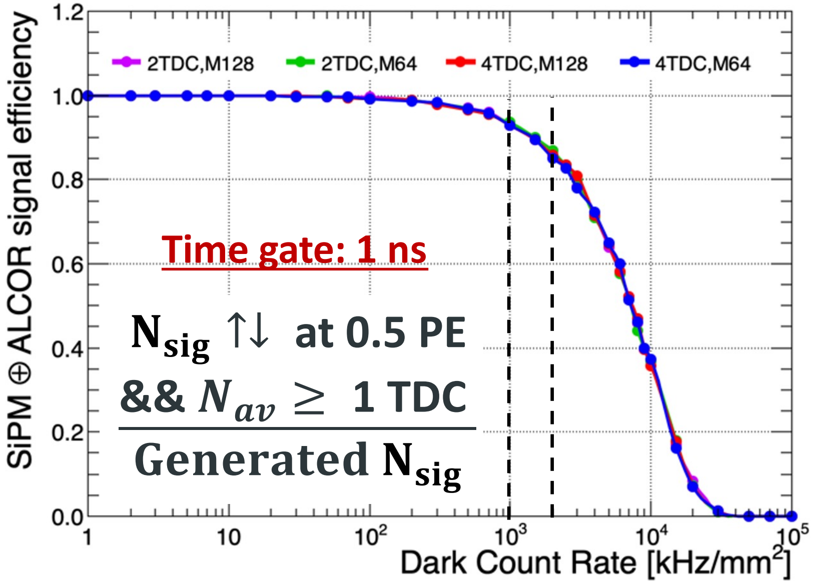
Current plan for the RICH FEE ASIC
- Use ALCOR chip with modularity optimized for the RICH
- Already started a collaboration between INFN Bari, INFN Torino and INAOE (Mexico)
- If ALCOR TDC is suitable also for TOF/RICH purpose only further minor modifications will be needed
- ePIC Run for 64 channel ASIC foreseen beginning 2025

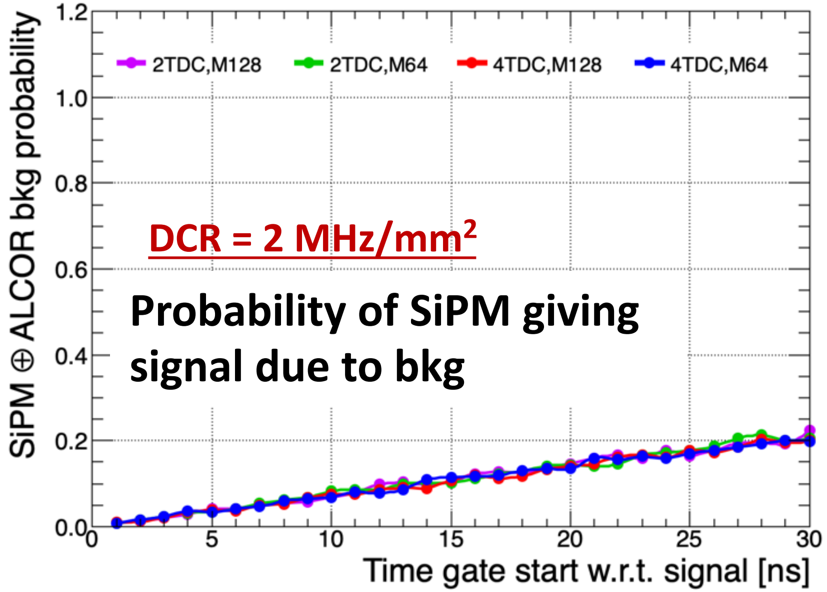




8x8 pixel matrix ASIC ePIC version (64 channels)

FEE ASIC: simulation results





Dead time effects of ALCOR TDCs not an issue provided to keep the SiPM DCR below 2 MHz/mm^2

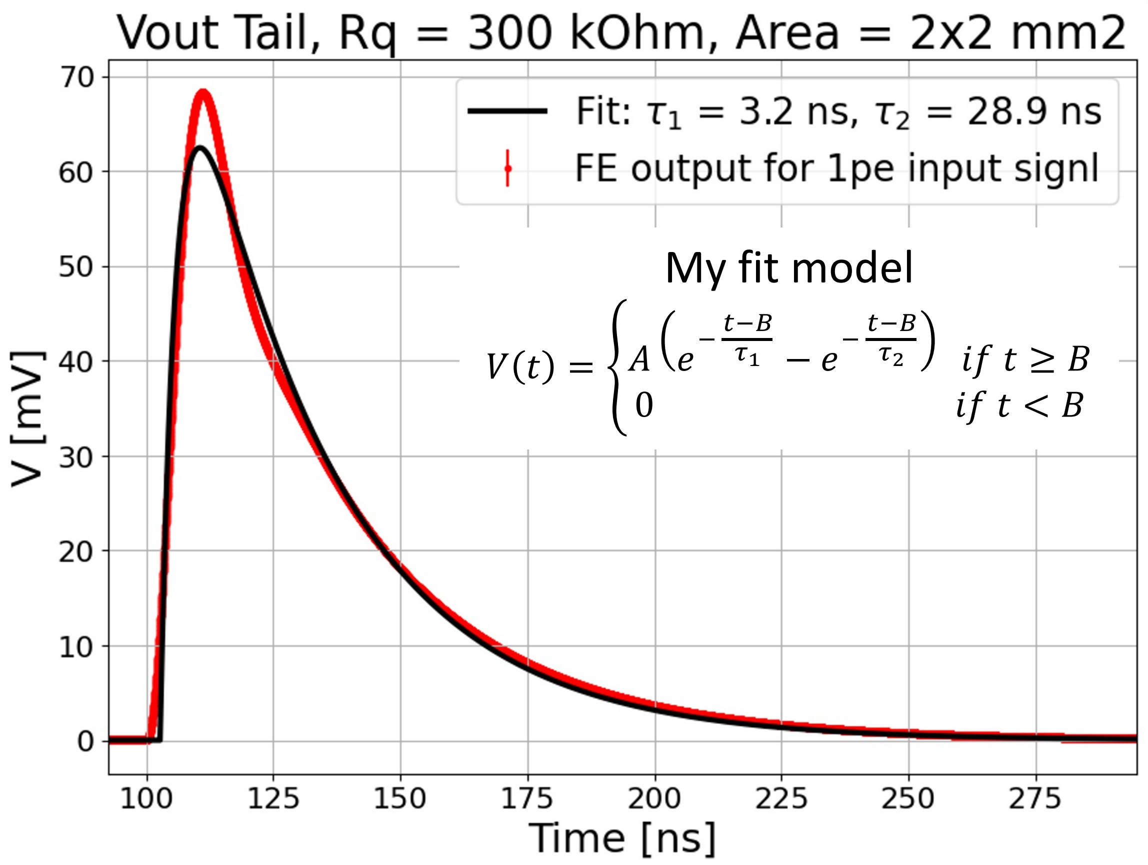
If a reset is applied to the TDCs from 1 ns to tens of ns before signal arrival, significant efficiency loss mitigation is achieved even with very high DCR

Using a proper time gate for the reset of TDCs is possible to keep excellent efficiency not only in LeadingEdge mode, but also in ToT/SlewRate mode

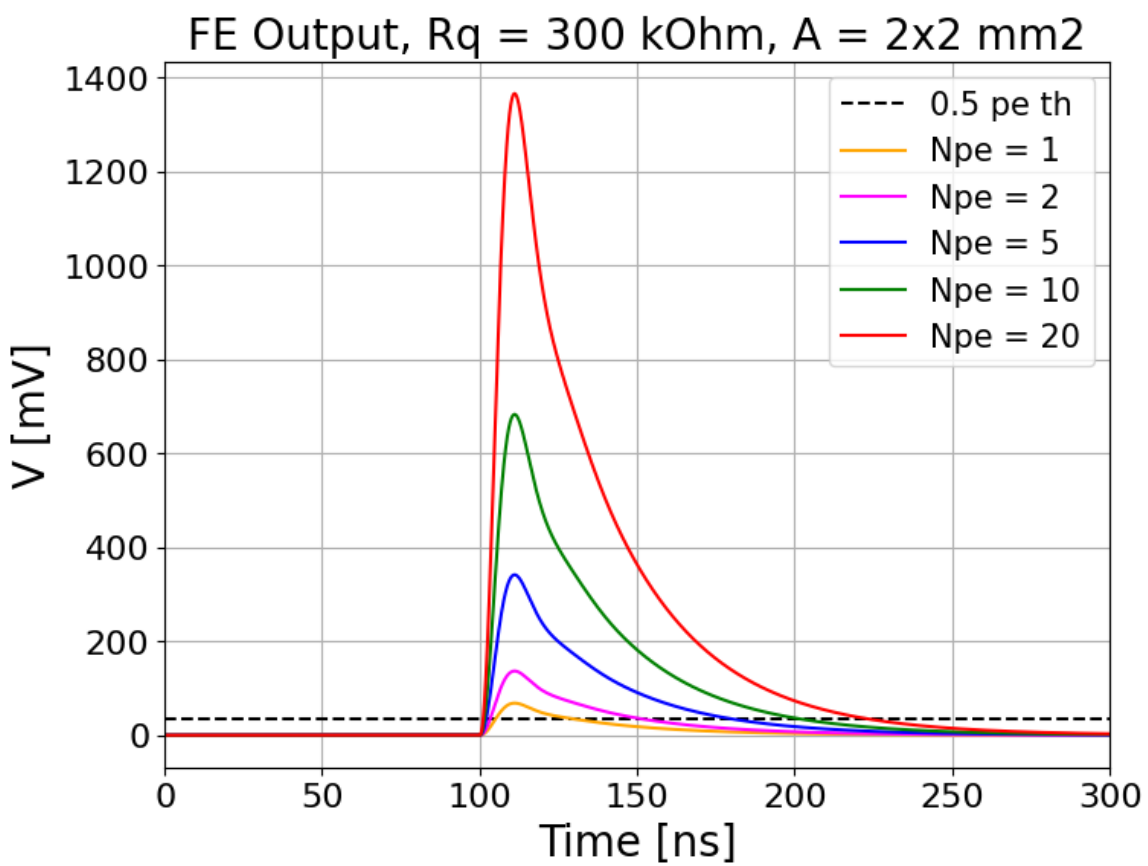
The ultimate efficiency limits vs DCR set by the recovery time of the SiPM →Possible improvements by including signal shaping by the electronics

FEE ASIC: simulation results

FE output signal time constants



FE response to many PE signals



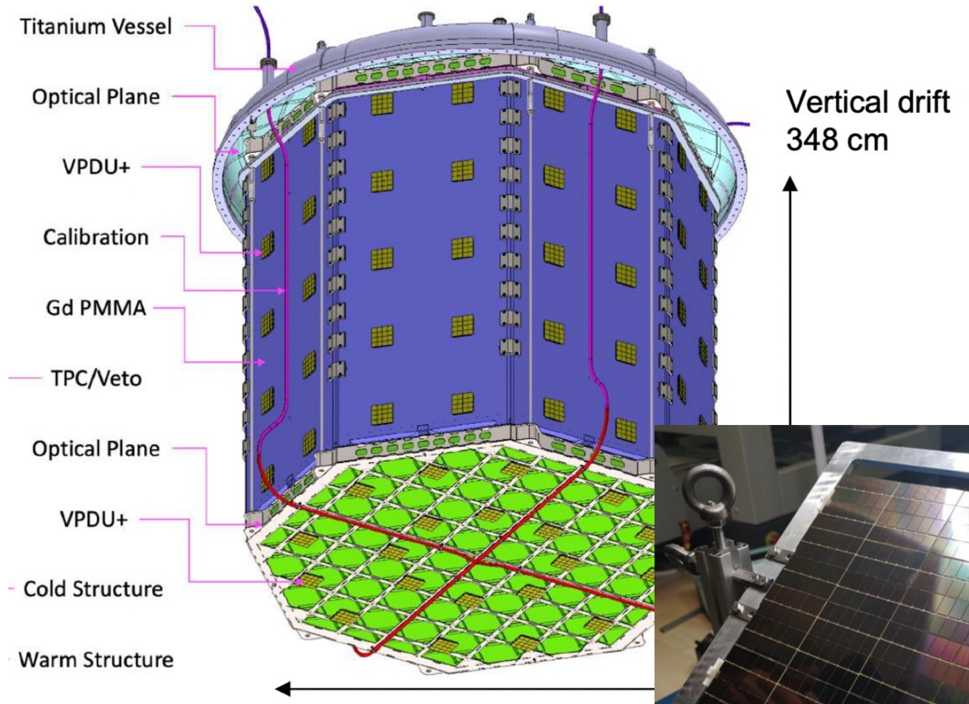
Next step: Studying pile-up of multiple photons and SiPM DCR bkg at FE level

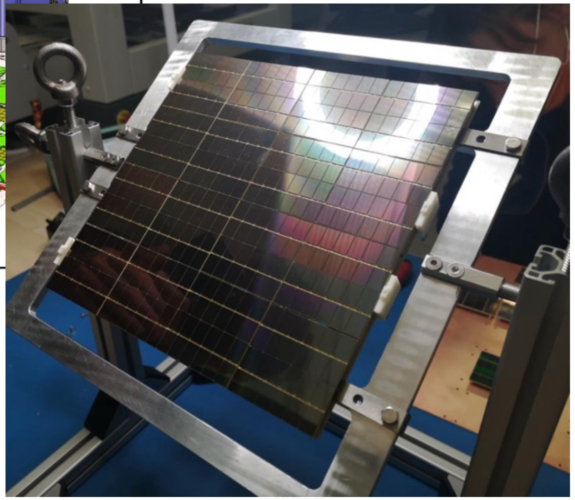
Packaging: NOA facility at LNGS (Gran Sasso, Italy)

The DarkSide-20k experiment at LNGS

Dual-phase argon TPC for searching direct evidence of dark matter at the INFN underground laboratory LNGS, foreseen to begin operations in 2026

The TPC is equipped with SiPMs for detecting the prompt scintillation light





SiPMs based on FBK NUV-HD-Cryo Design, manufactured by LFoundry

- **~21 m^2 TPC PDU** (2 optical planes, Top and Bottom of the TPC)
- **~5 m^2 Veto PDU** (all around the TPC)
- Total = **26 m^2 of SiPM**
  - **1400 wafers** (200 mm, **268 SiPM per wafer**, 7.9 x 11.7 mm^2)
  - SPAD size = 30µm
  - Yield by contract= 80%, **actual is ~95%**
  - Cathode on the backside, anode pads for wire bonding
- Photodetector Module **(PDM) is 5 x 5 cm^2** single output
- **PDU 20 x 20 cm^2 = 16 PDM** with 4 differential output channels (1 channel = 4 PDMs summed)

SiPMs surface comparable to that needed for the ALICE 3 RICH!!

Packaging: NOA facility at LNGS (Gran Sasso, Italy)

ALICE

We can benefit from the DarkSide experience!

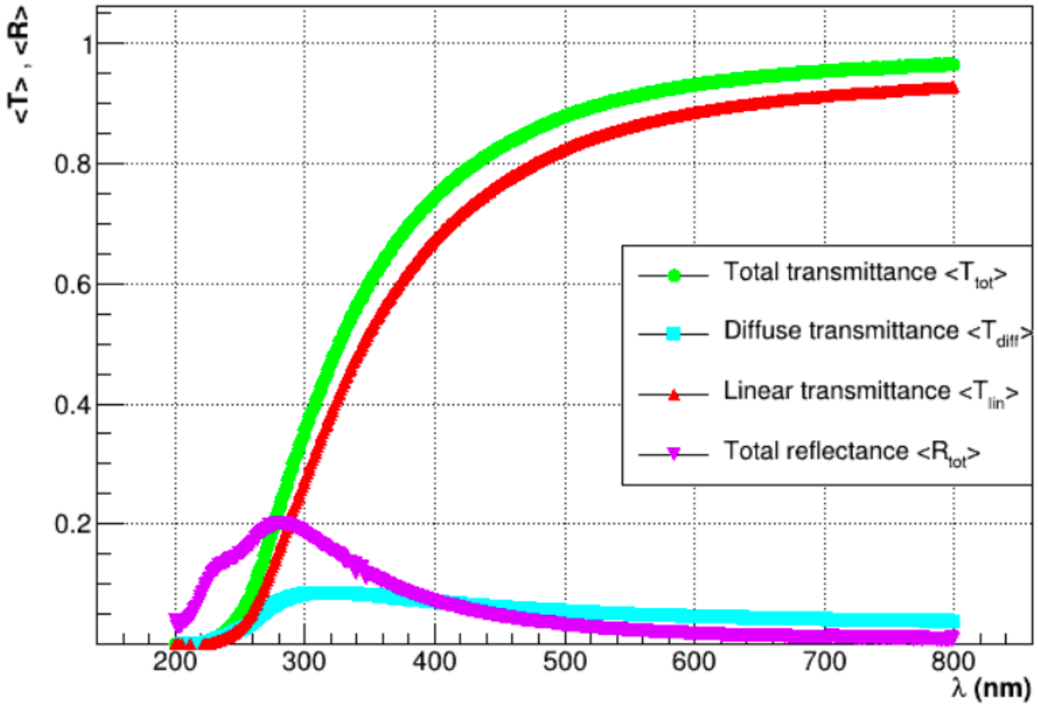
Already in contact with LNGS director and NOA responsible!!

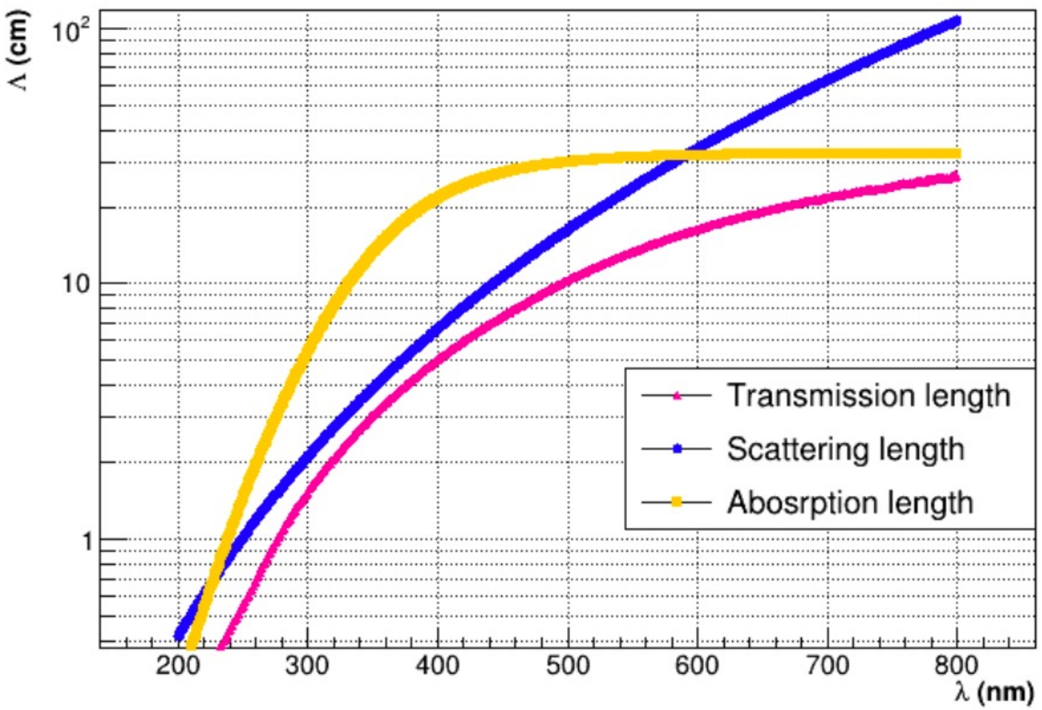
***The Nuova Officina Assergi: future perspectives beyond DarkSide-20k** (https://doi.org/10.22323/1.441.0310)*

Aerogel characterization

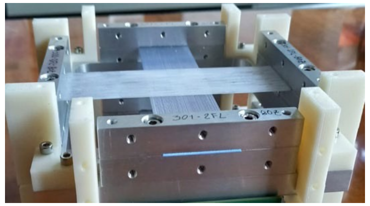
- Agilent – Cary 4000 – Series UV-Vis Spectrophotometer acquired by Bari INFN unit beginning 2024.
  - Equipped with an integration sphere

- Transparency measurement on aerogel samples already started





2023 prototype beam test (PS T10 2-18 October)

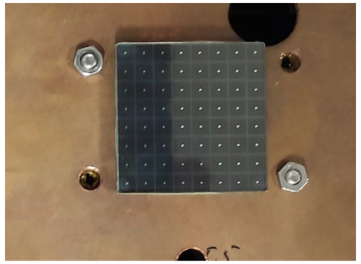


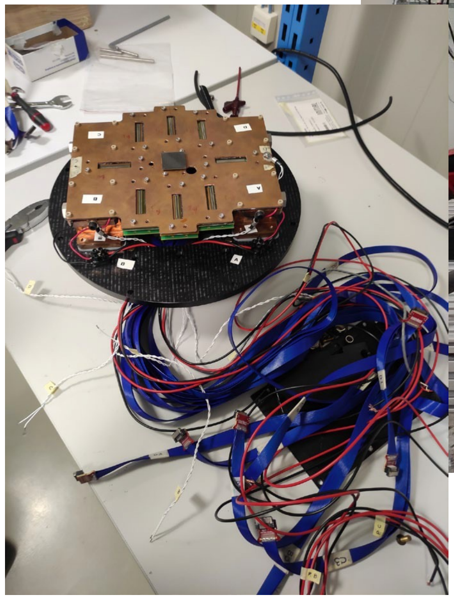
X-Y fiber tracker box

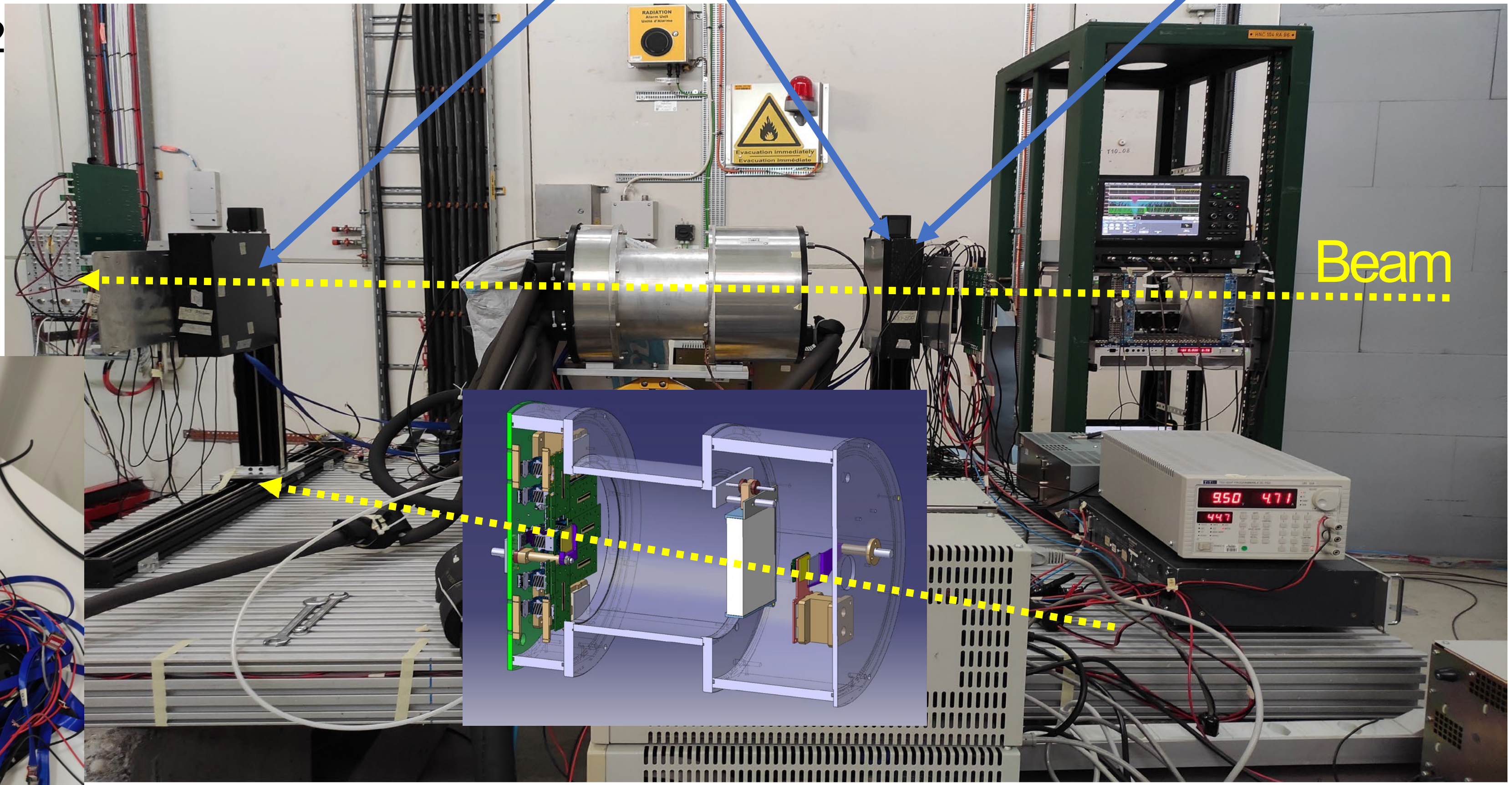
Scintillator trigger box

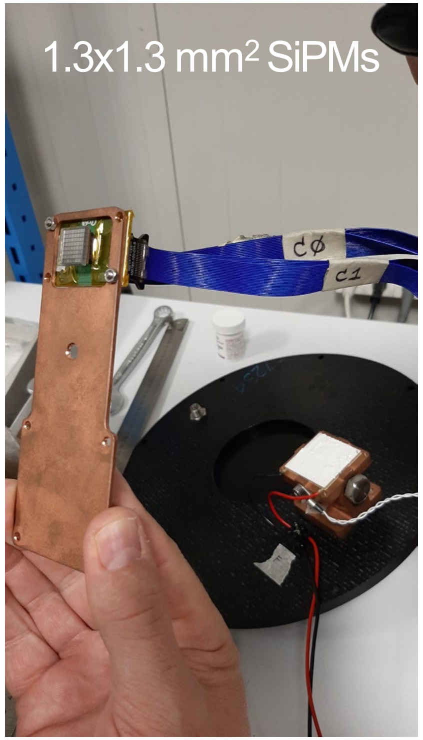
- S13361-1350 with 2 mm of SiO_2
- S13361-3075 with 1 mm of SiO_2
- S13361-3075 with 1 mm of MgF_2

S13361-3075
With 1 mm of SiO_2



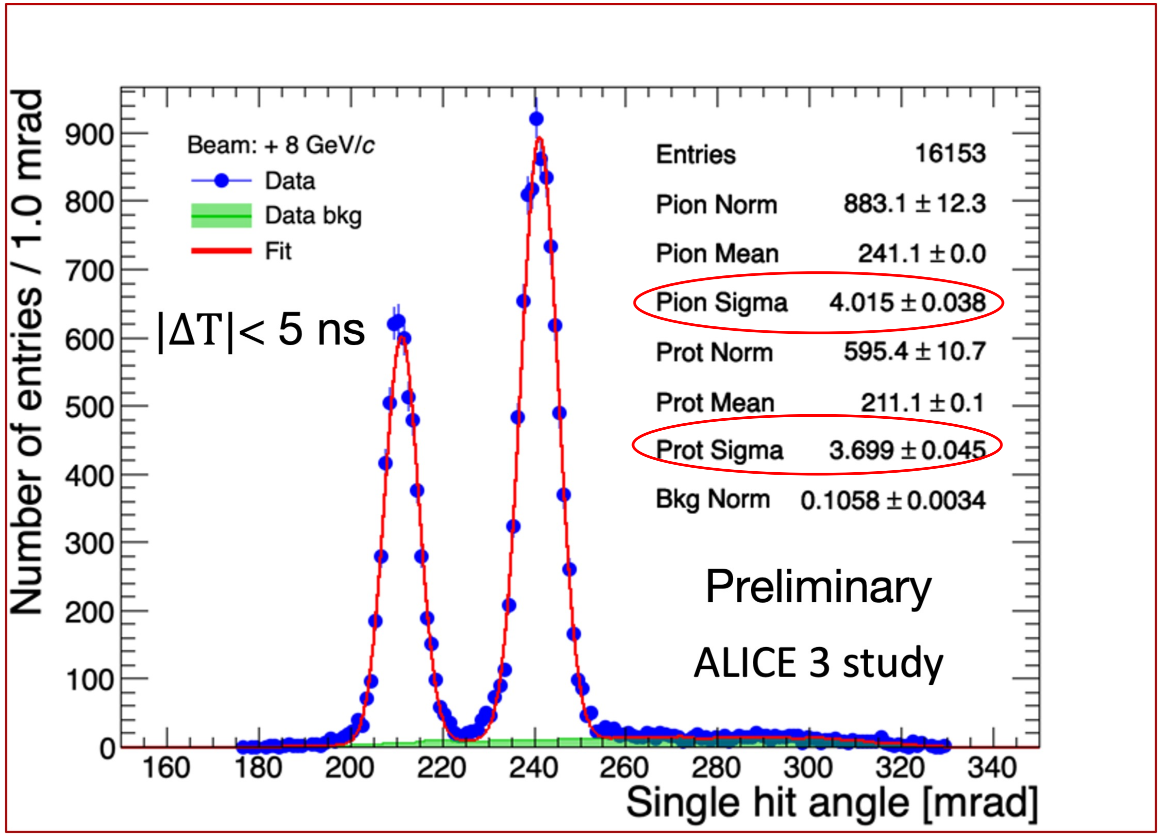


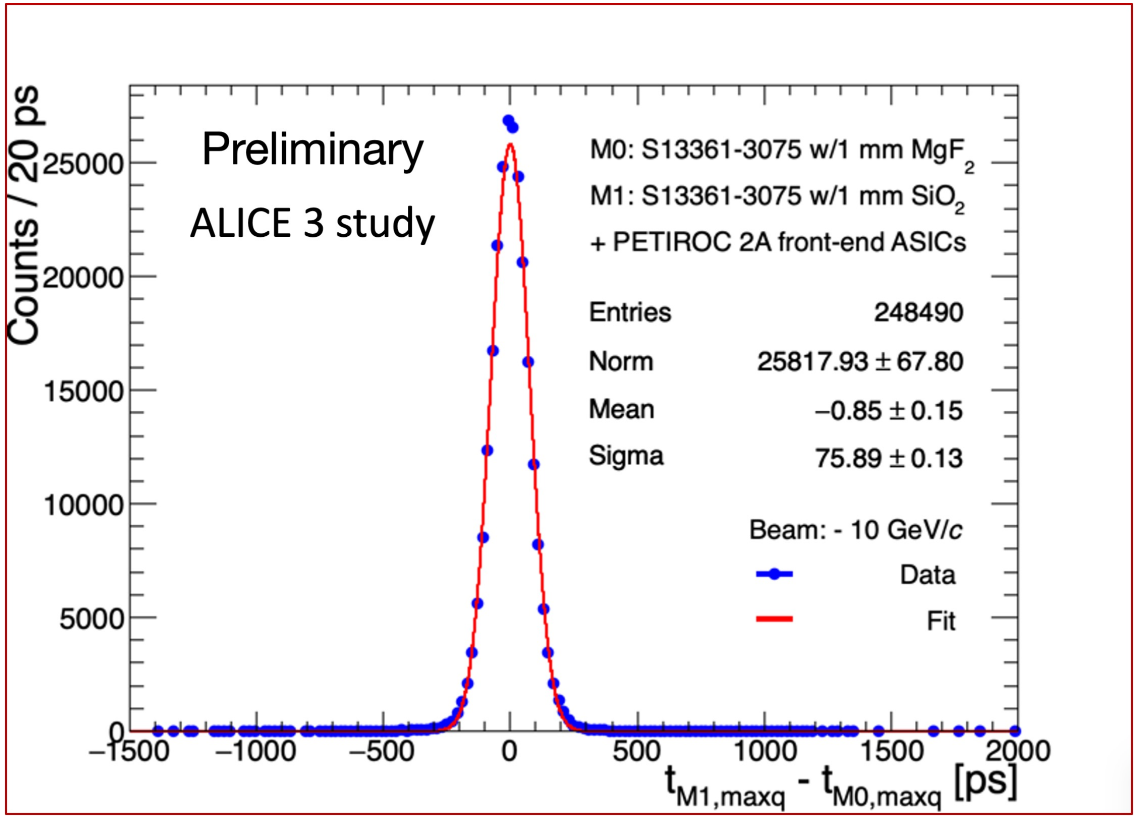




Cherenkov angle and timing

Beam test results in term of angular resolution and number of detected photo-electron using commercial SiPM and electronic, in agreement with simulation!!



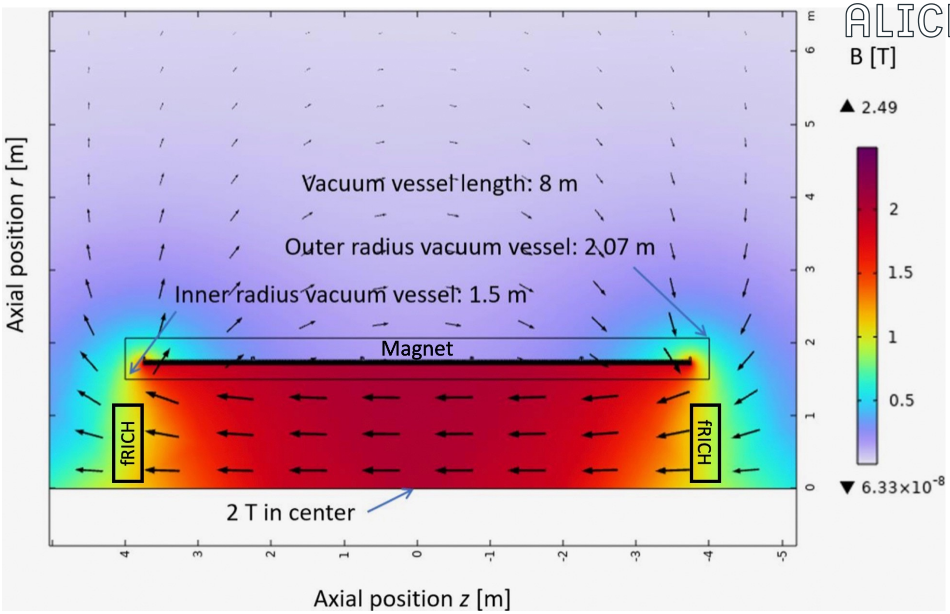


***Paper in preparation:** "A compact and fast SiPM-based RICH detector for the future high-energy physics experiments"*

LAPPD option for fRICH

Radiation load for Run 5 + 6 in pp collisions

Element	R (m)	TID (rad)	NIEL (1 MeV neq/cm²)	HEH (kHz/cm²)	Ch. particle fluence (kHz/cm²)
Forward RICH disk	0.15	9.7×10^5	3.9×10^{13}	2.1×10^2	4.4×10^2



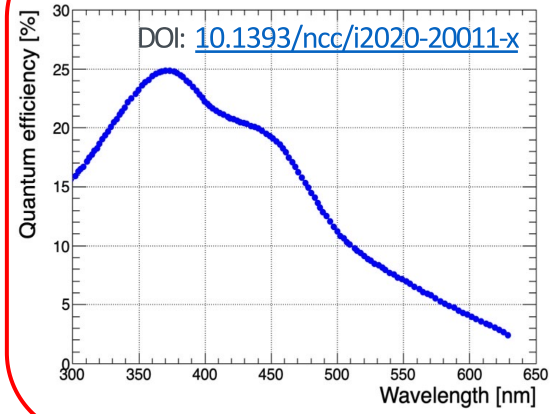
Operation beyond **10^{13} MeV neq/cm²** leads to SiPM DCR increase above tens of MHz/mm²

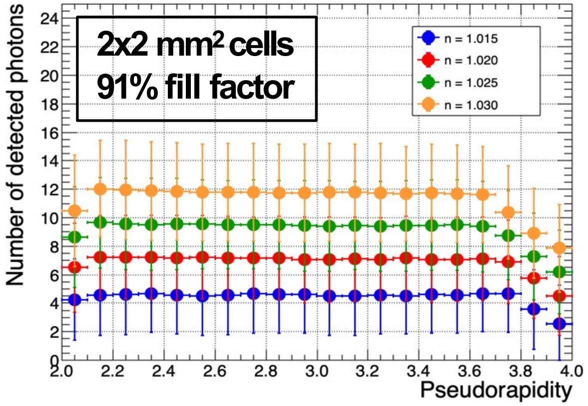
- SiPM-based single photon detection not trivial even accounting cooling + annealing

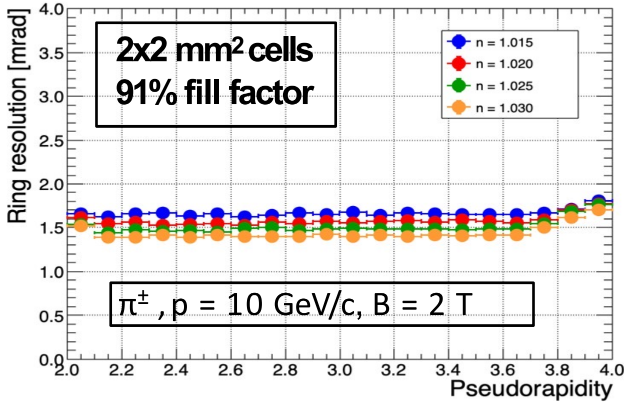
The expected radiation load is not an issue for vacuum-based devices like MCPs and LAPPDs

- Excellent time resolution, low DCR and high radiation hardness make them ideal for the fRICH

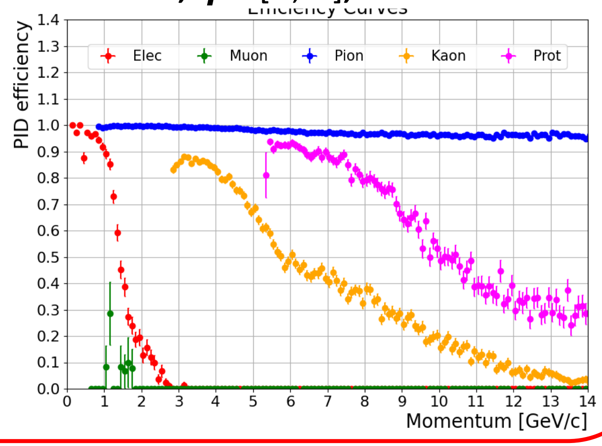
Preliminary studies with LAPPDs





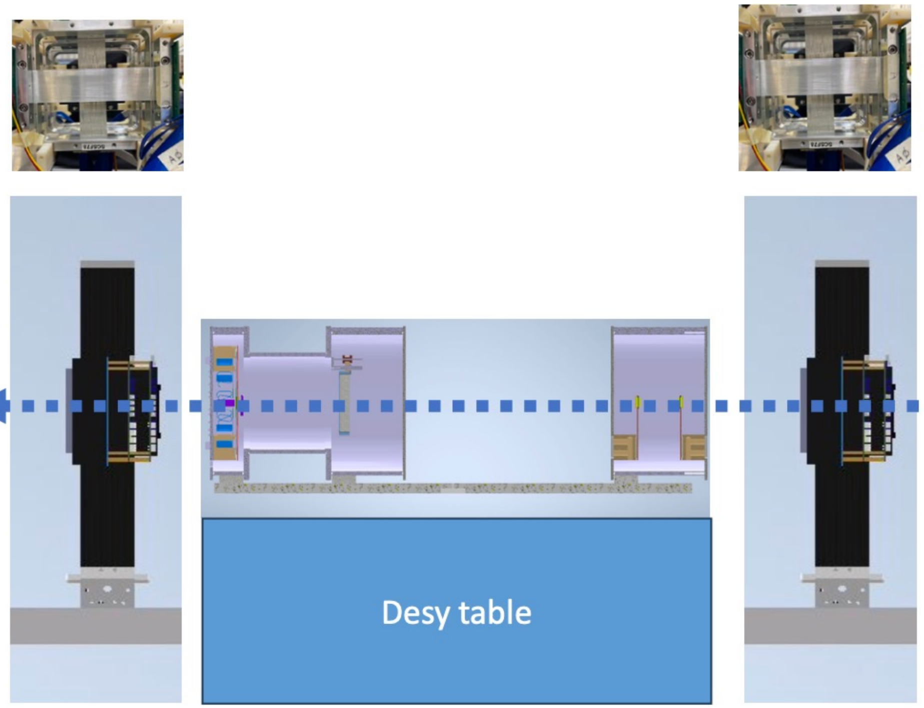


n = 1.015, $\eta \in [2, 4]$, central Pb-Pb



Expression of interest from the Yale University group!

2024 beam test



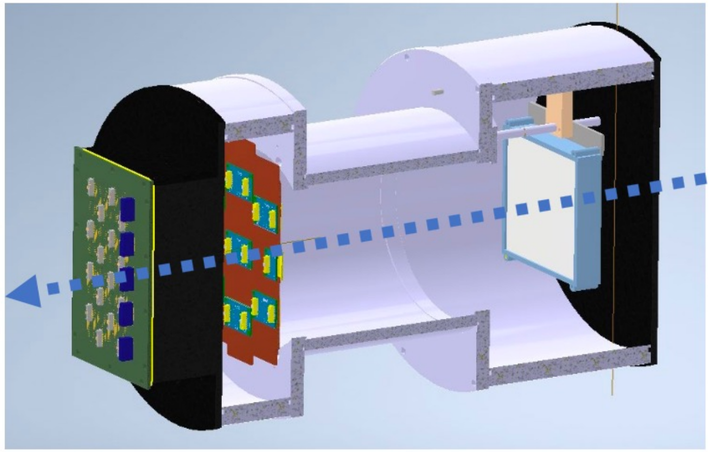
New PS beam test forseeen for Oct 24!

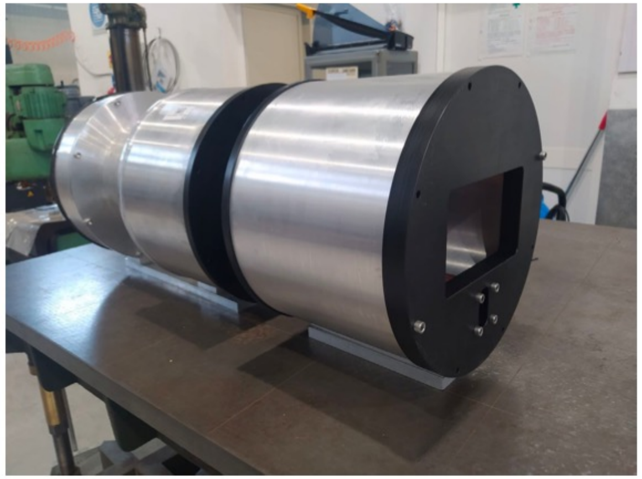
Upgrading the set-up with

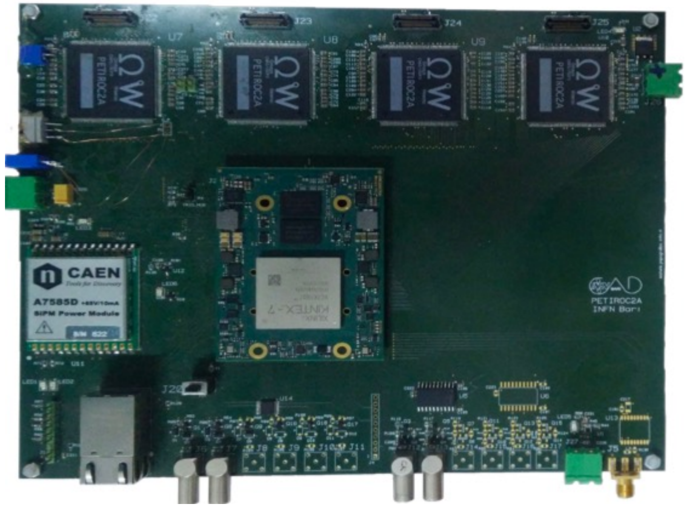
- SiPM array with 2 mm of pitch → Target sensor for ALICE 3 RICH
- Timing measurement:
  - New custom front-end boards based on Radioroc/Weeroc and picoTDC/CERN
    - The first version is under test
  - Read-out and DAQ with Mosaic boards
- Position measurement still based on the Petiroc 2A boards
- All the boards with common clock and trigger signals

Prototype still based on on-the-shelf components

- Test aerogel focusing configuration

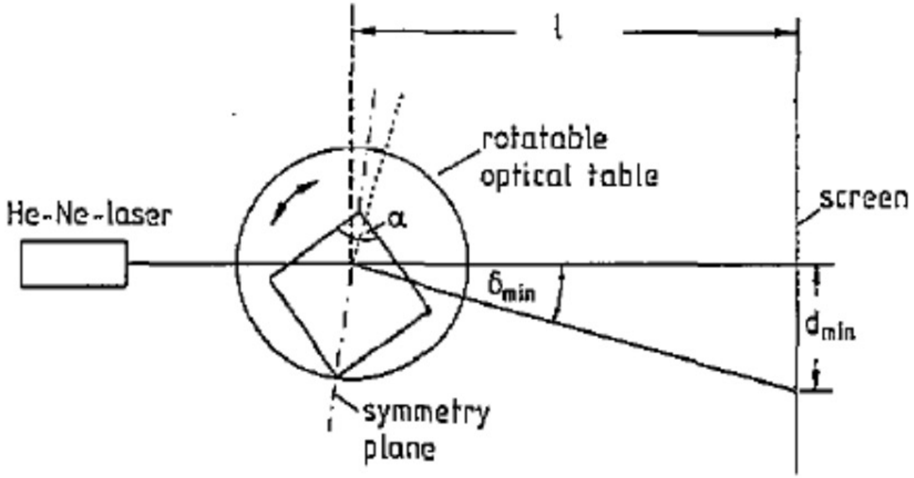






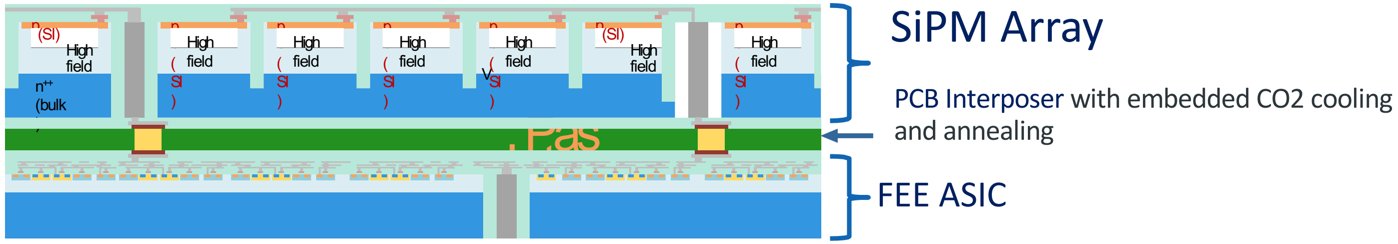
RICH 2025 plans

- Aerogel Characterization (ePIC synergy)
  - Setup for measuring the aerogel refractive index will be implemented, enabling comprehensive optical characterization of the Cherenkov radiator.



Setup of the refractive index measurement shown in [2].

- Study of the prototype interposer and cooling system
- **Milestone: ottimizzazione configurazione interposer con annesso sistema di cooling a microcanali**

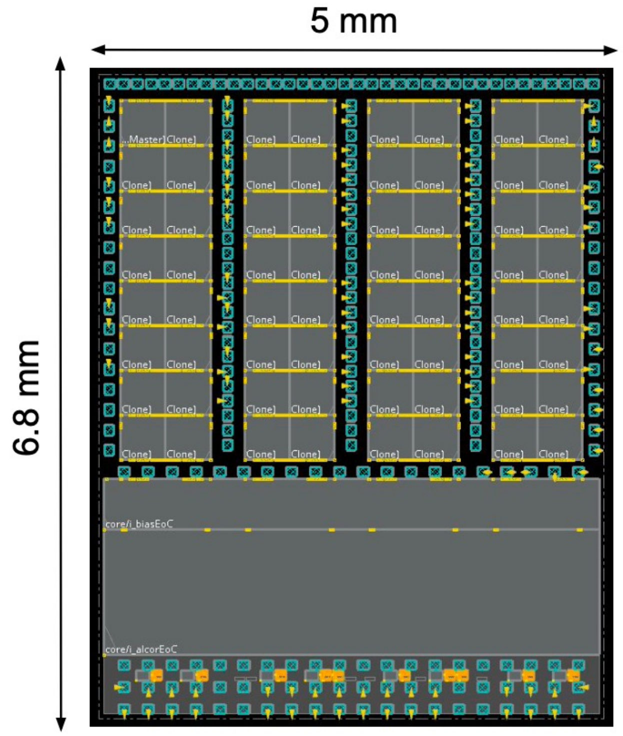


- Test new prototype at CERN-PS
  - Position measurement: new FEE/RO to improve single photon detection efficiency
  - Increase photon sensor acceptance (25 modules, 2.5 k€ each)

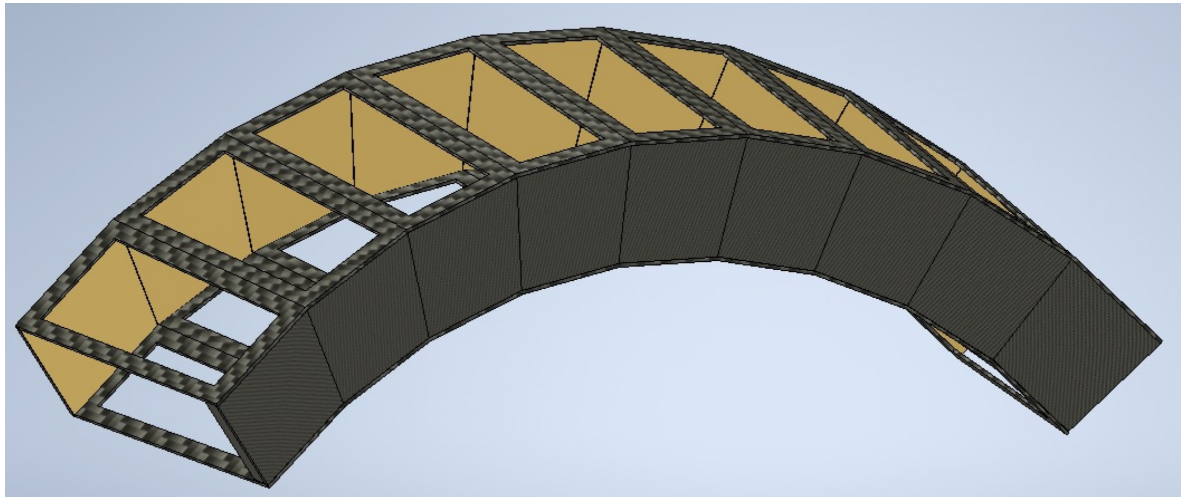
RICH 2025 plans

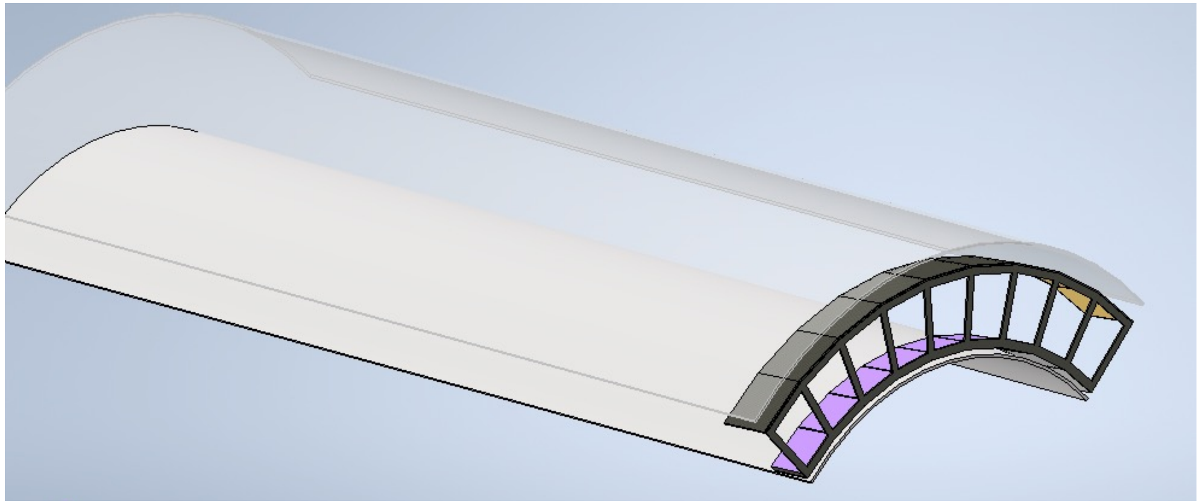
- RUN ASIC ALCOR
  - One wafer of ALCOR v3 from the ePIC RUN for testing purpose
  - Packaging studies for the ALICE RICH configuration

- RICH module mock-up construction for installation test



Drawing realized by INFN Bari CAD service





ECFA DRD4 activities

***DRD4 WP 4.4.1:* Coupling of a thin Cherenkov radiator to SIPMs, for TOF of charged particles**

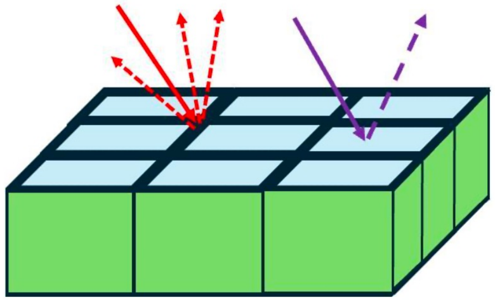
***DRD4 WP 4.4.2*: SiPM array, with mm-scale pixelization, suitable for use in TOF prototypes**

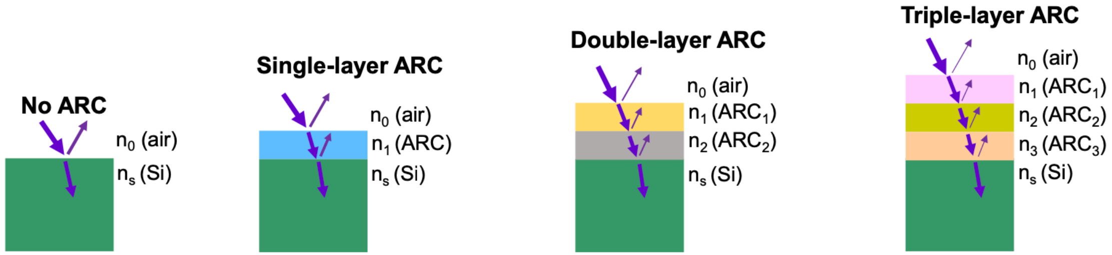
Reflections at the SiPM interface: reduce reflection to increase PDE

DRD4 WP 4.4.1

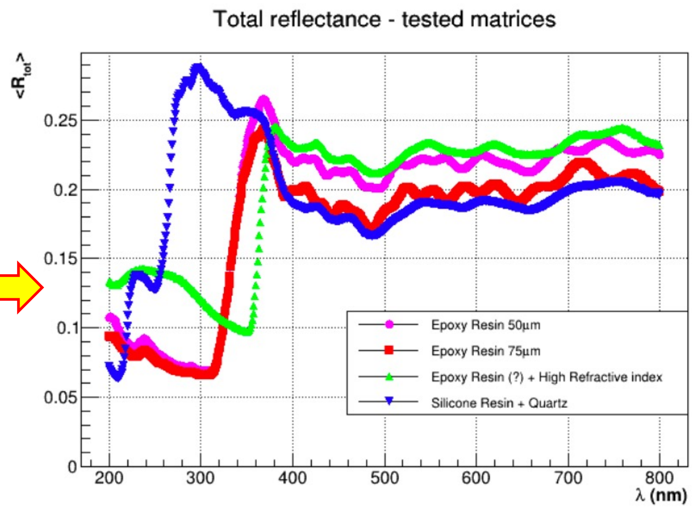
Solutions:

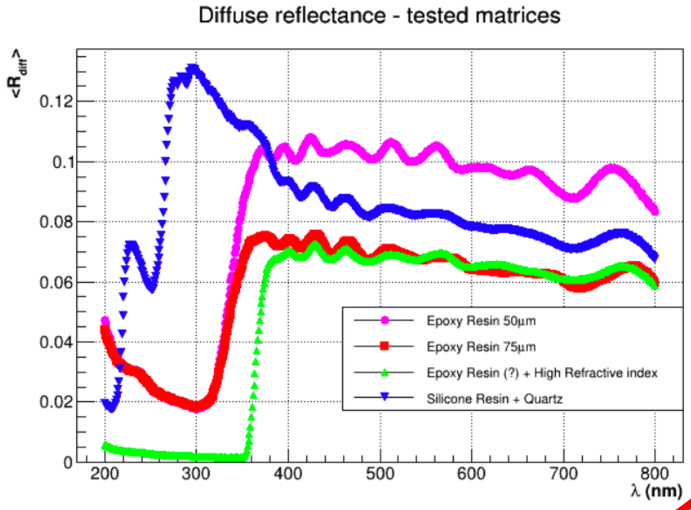
- Conventional single-layer antireflection coating (ARC)
- (Multi-layer) ARC: double-layer ARC and triple-layer ARC
- Textured Si surface with upright random nano/micro pyramids formed by anisotropic etching.



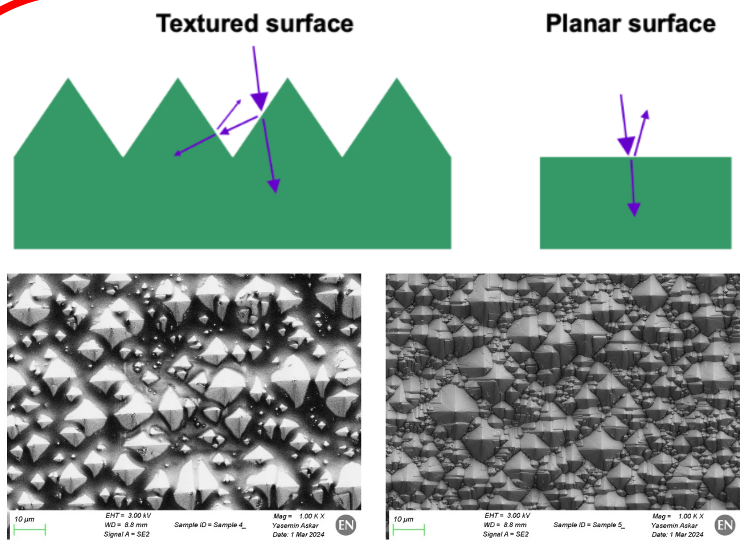


SiPM matrices have 64 channels, 3x3 mm^2 cells and 50 or 75 µm micro-cells.
Three matrices have an epoxy resin (n ~ 1.55), while the last one has a silicone resin (n ~ 1.41).
The total and diffuse reflectance have been measured using **the Agilent - Cary 4000 - Series UV-Vis Spectrophotometer** available in INFN laboratories in Bari.

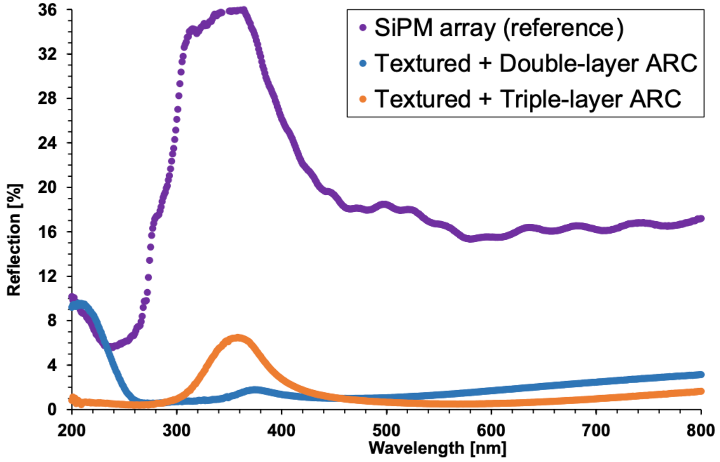


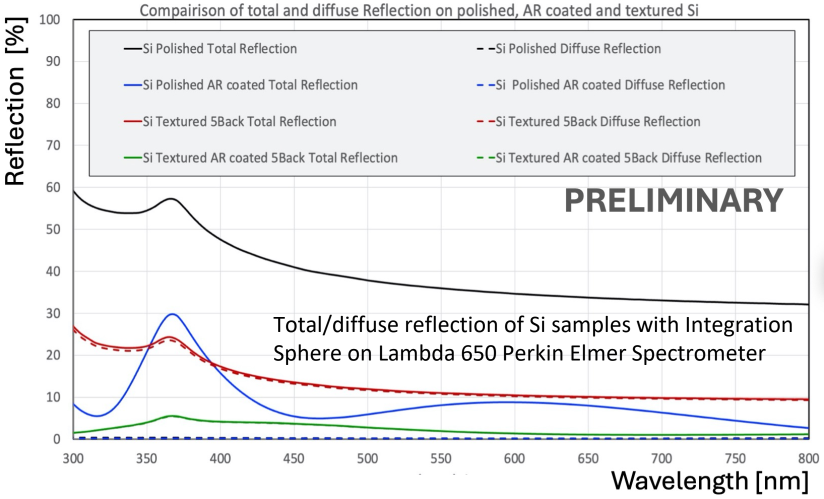


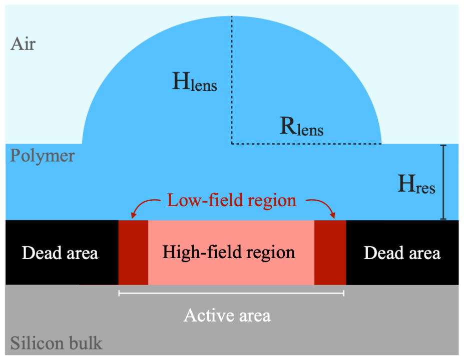
ECFA DRD4 activities

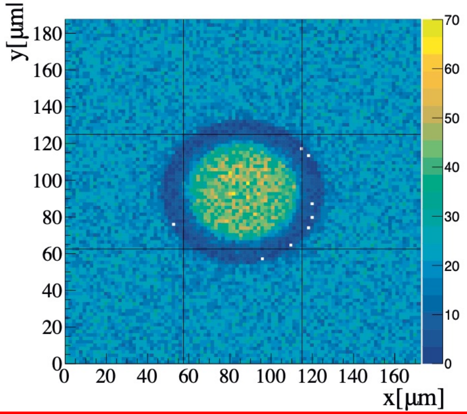


Yuguo Tao at al. doi: 10.1038/s41598-022-18280-y









Improving sensor timing response

Plans for 2025: creation of micro lenses to optimize SPAD timing response

DRD4 WP 4.4.1

DRD4 WP 4.4.2

Realization of fast electronic boards for timing measurements with TDC FE integrated as WEEROC/OMEGA and/or FastIC+

Budget request

Missioni		
Sezione	**Importo**	**Descrizione**
Bari	40 k€	2 Test beam da 2 sett. al CERN x 8 pers.
	5 k€	partecipazione riunioni al CERN (2 riunioni di 5 gg ciascuna) **(DRD4 WP 4.4)**
Salerno	10 k€	2 Test beam da 2 sett. al CERN x 2 pers.

Consumo, inventario, etc		
Sezione	**Importo**	**Descrizione**
Bari	60 k€	SiPMs ed elettronica di FE/RO per prototipo da testare sul fascio
	20 k€	Studio prototipo interposer e sistema di cooling
	40 k€	One wafer of ALCOR v3 from the ePIC RUN + packaging studies for ALICE 3 - RICH configuration
	10 k€	Costruzione mock-up modulo RICH
	5 k€	Realizzazione micro lenti per ottimizzare risposta temporale SPAD **(DRD4 WP 4.4.1)**
	30 k€	realizzazione di schede elettroniche per misure di timing con FE della WEEROC/OMEGA e/o FastIC+ **(DRD4 WP 4.4.2)**

Sigla in gruppo 5

ASPIDES: A CMOS SPAD and Digital SiPM Platform for High Energy Physics (ASPIDES)

The goal of this research activity is the development of a technology platform for the design, production and commissioning of dSiPMs, detectors with single-photon sensitivity and embedded functionalities. The activity will target applications to light detection for dual-readout calorimetry at future leptonic collider experiments, RICH and neutrino experiments.

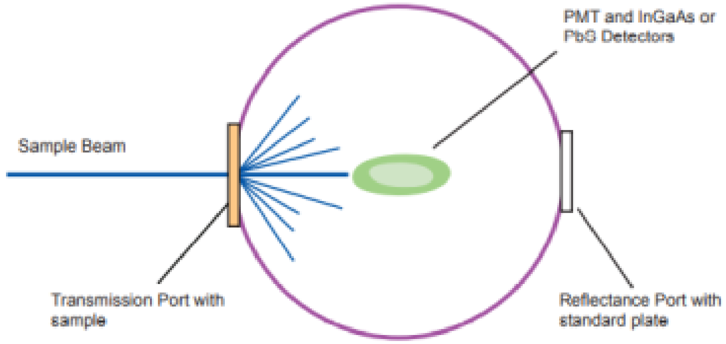
In the research activity, the collaboration will pursue the development of a planar detector in a standard CMOS technology, naturally lending itself to the design of a monolithic sensor, where the front-end electronics and the sensitive element lie in the same substrate.

Backup

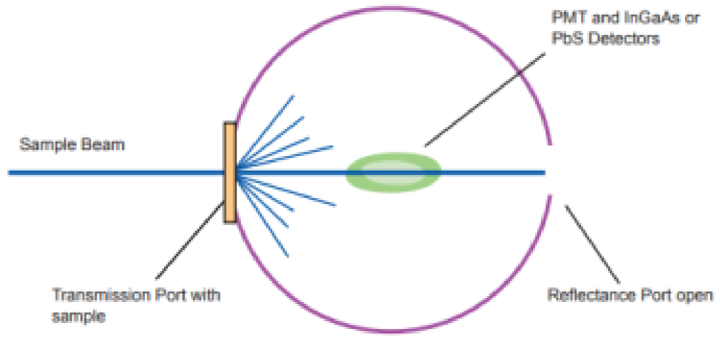
Aerogel characterization

Measurements performed with a Perkin Elmer spectrometer: integrating sphere and two different light source to cover the range 250 - 800 nm

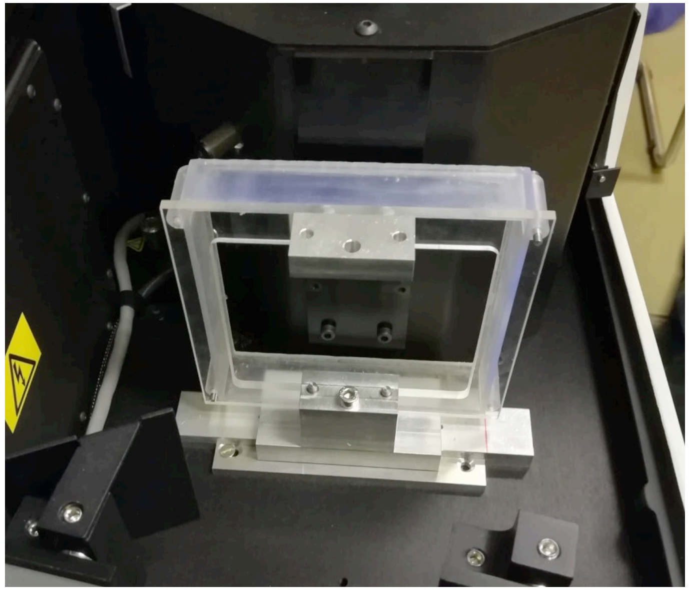
TOTAL TRANSMITTANCE



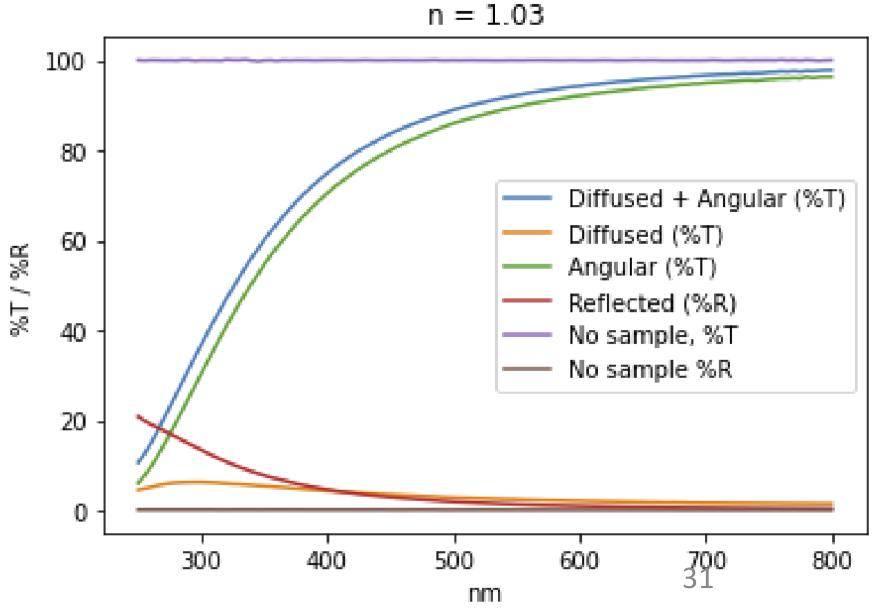
DIFFUSE TRANSMITTANCE



Linear TRANSMITTANCE = total T. – diffuse T.



Each tile was placed into a holder (10x10 cm^2) and mounted onto a metal ridge sliding perpendicular to the beam to explore different positions of the samples



Aerogel characterization

$$T(\lambda) = e^{-\frac{t}{\Lambda_{trasm}}} = e^{-t\left(\frac{1}{\Lambda_A}+\frac{1}{\Lambda_S}\right)} = A \cdot e^{-\frac{B\,t}{\lambda^8}} \cdot e^{-\frac{C\,t}{\lambda^4}}$$

TRANSMISSION LENGTH:

$$T(\lambda) = e^{-\frac{t}{\Lambda_{trasm}}}$$

$$\Lambda_{trasm} = -\frac{t}{\ln(T)}$$

SCATTERING LENGTH:

$$e^{-\left(\frac{t}{\Lambda_S}\right)} = e^{-\frac{C\,t}{\lambda^4}}$$

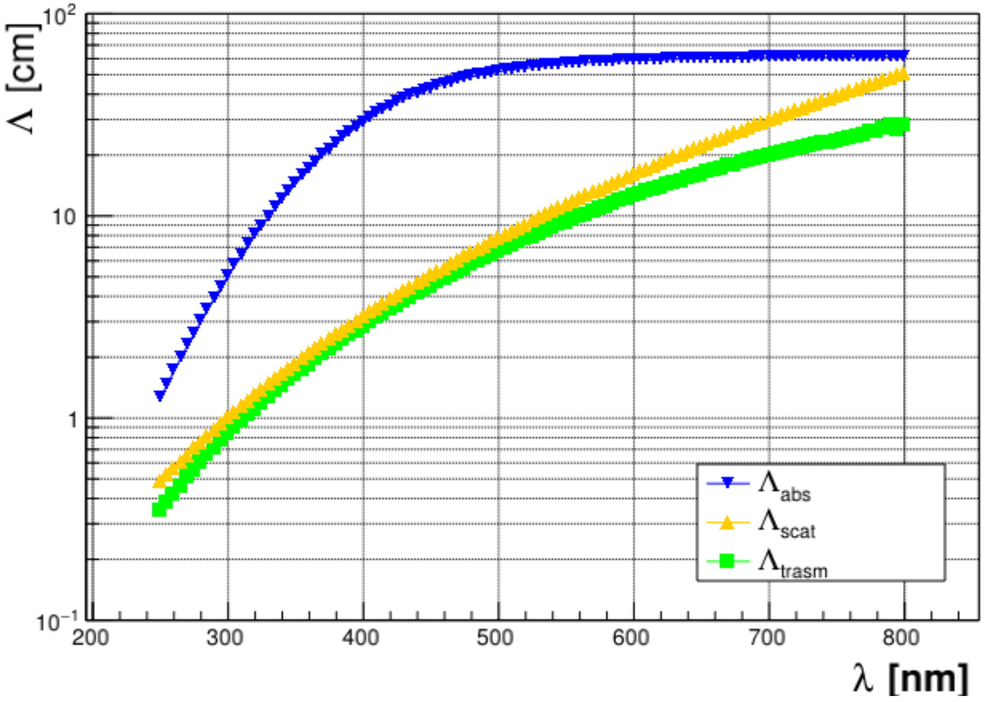
$$\Lambda_{scat} = \frac{\lambda^4}{C}$$

ABSORPTION LENGTH:

$$e^{-\left(\frac{t}{\Lambda_A}\right)} = A \cdot e^{-\frac{B\,t}{\lambda^8}}$$

$$\Lambda_{abs} = \frac{\lambda^8 \cdot t}{B\,t - \lambda^8 \cdot \ln(A)}$$

Lengths evaluated from average transmittance values.

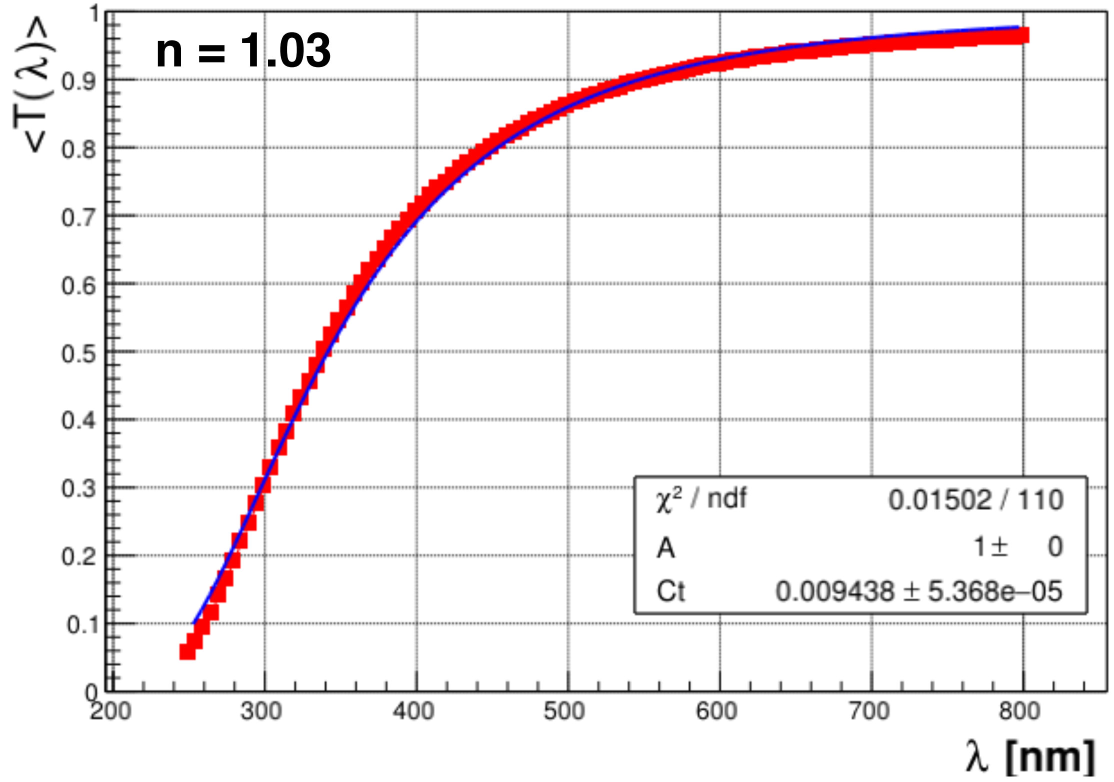


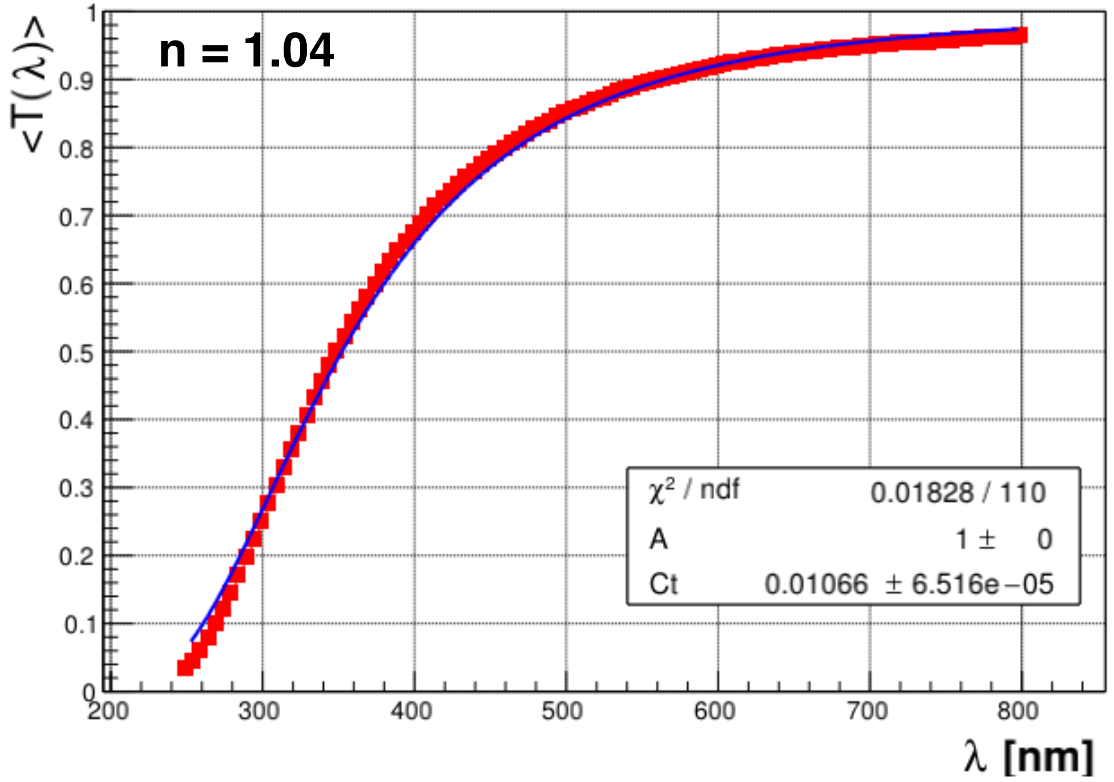
SMALL IMPACT OF THE ABSORPTION ON THE TRANSMISSION LENGTH

Aerogel characterization

Transmittance fitted by ***Hunt formula*** [NIM A 440 (2000) 338-347]

$$T(\lambda) = e^{-\frac{t}{\Lambda_{trasm}}} = e^{-t\left(\frac{1}{\Lambda_A}+\frac{1}{\Lambda_S}\right)} = A \cdot e^{-\frac{C\,t}{\lambda^4}}$$





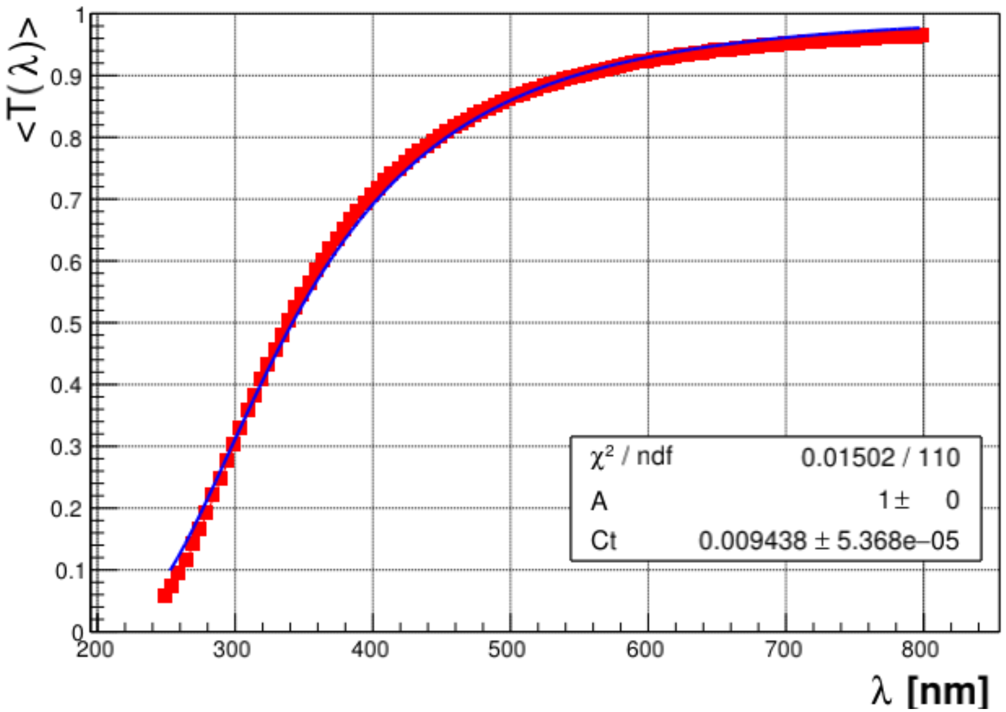
Aerogel characterization

ALICE

Transmittance fitted by **Hunt basic**:

$$T(\lambda) = e^{-\frac{t}{\Lambda_{trasm}}} = e^{-t\left(\frac{1}{\Lambda_A}+\frac{1}{\Lambda_S}\right)} = A \cdot e^{-\frac{C\,t}{\lambda^4}}$$

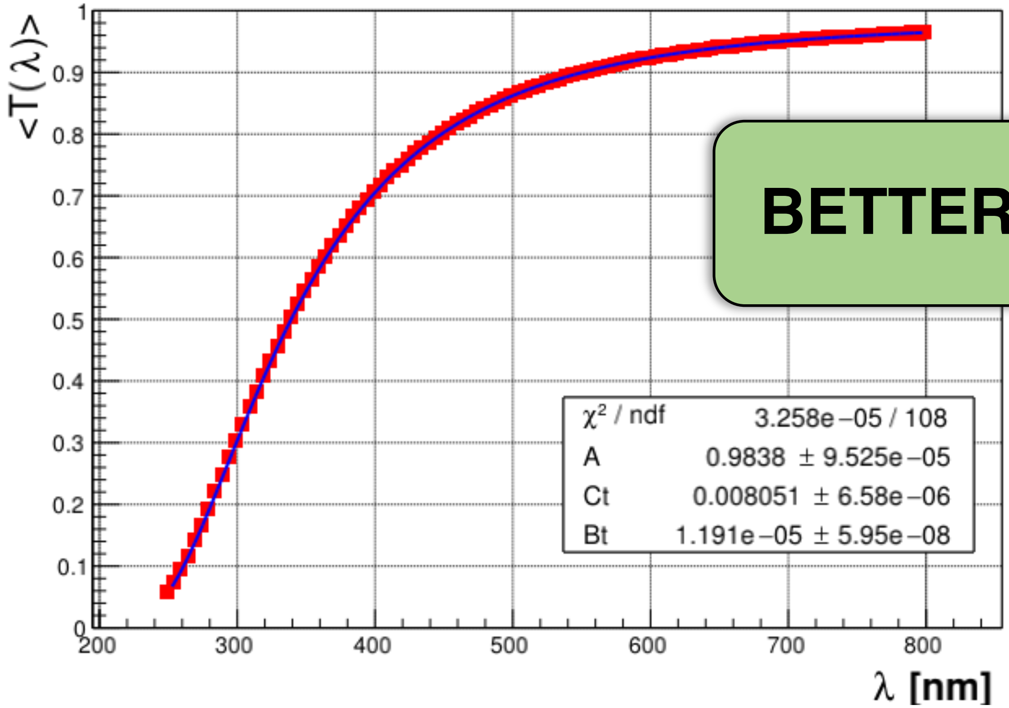
Assuming:
$\boldsymbol{\Lambda_A}$ ***negligible***
$\boldsymbol{\Lambda_S \sim \lambda^4}$



Transmittance fitted by **Hunt extended**:

$$T(\lambda) = e^{-\frac{t}{\Lambda_{trasm}}} = e^{-t\left(\frac{1}{\Lambda_A}+\frac{1}{\Lambda_S}\right)} = A \cdot e^{-\frac{B\,t}{\lambda^8}} \cdot e^{-\frac{C\,t}{\lambda^4}}$$

Assuming:
$\boldsymbol{\Lambda_A \sim \lambda^8}$
$\boldsymbol{\Lambda_S \sim \lambda^4}$

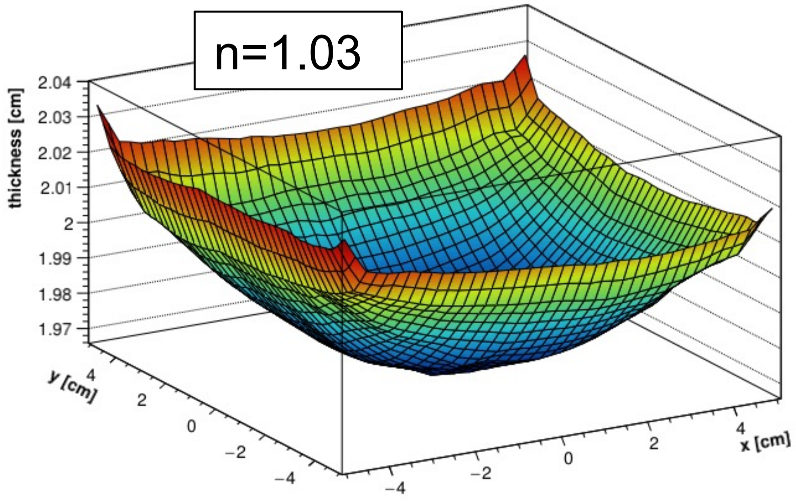


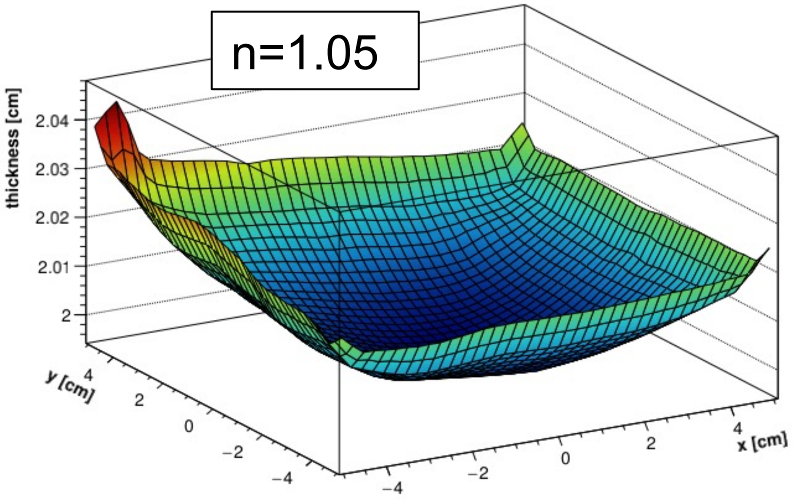
BETTER FIT

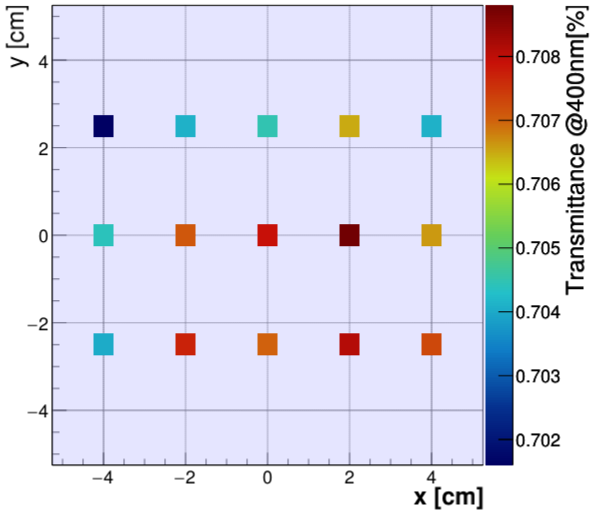
<T> = average of the transmittance values at the different points on the tile #1 (n = 1.03)

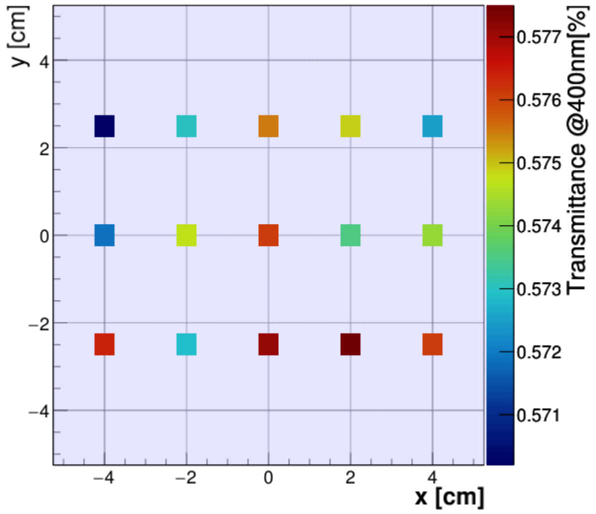
Aerogel characterization

The shape of the tile has implications on the transmittance.









n=1.03	
min tickness (mm):	19.690
max tickness (mm):	20.385
standard deviation:	0.172
average (mm):	19.955
n=1.04	
min tickness (mm):	19.271
max tickness (mm):	21.798
standard deviation:	0.335
average (mm):	19.641
n=1.05	
min tickness (mm):	19.965
max tickness (mm):	20.479
standard deviation:	0.098
average (mm):	20.106

Aerogel characterization

Thickness and flatness measurement in metrology lab at CERN!

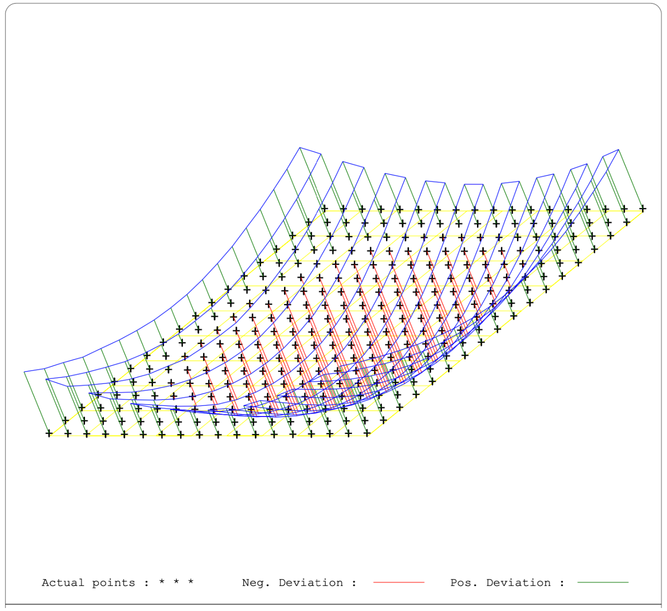
- Results obtained on a tile of n = 1.03 with the touch probe system (force applied by the probe is 2 gr).
- The measuring system is the LEITZ PMMC with ± 0.3 μm of precision

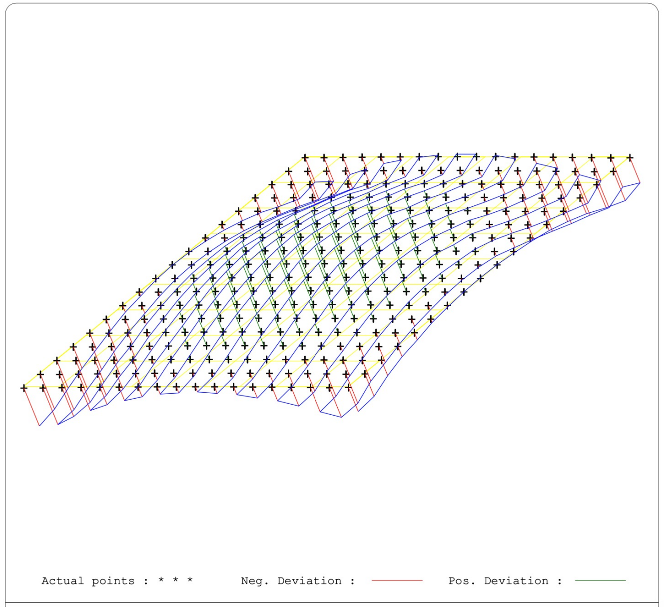
Thickness = 19.96 ± 0.17

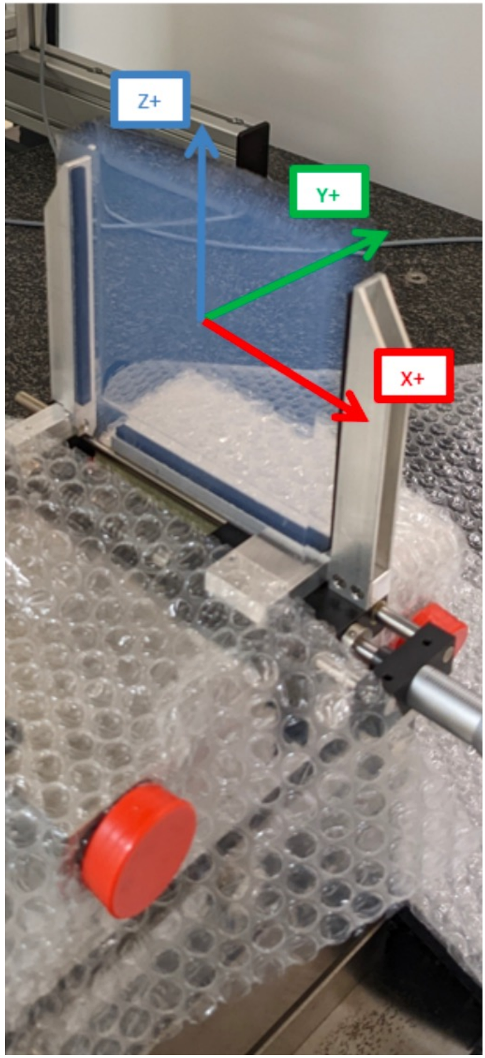
Plane Y- side = 0.7060

Plane Y+ side = 1.2716

Meniscus shape due to fabrication process







There is a variation in thickness from the centre to the edges, of the order of 0.4 mm, and a different planarity in the two faces, one 0.7 mm, the other 1.27 mm. In general the tiles have the shape of a dome.

- The manufacturer (Aerogel Factory Ltd, Chiba, JP) stated that it is possible to improve the flatness and the thickness uniformity;
- the planarity can be mapped, to include the defect in the reconstruction of the Cherenkov angle.

Simulation studies (by N. Nicassio)

Single photon angular resolution