Attività 2023
Richieste 2024

ALICE 3 RICH

Rome, 21/07/2021

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

Requirements and specifications

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

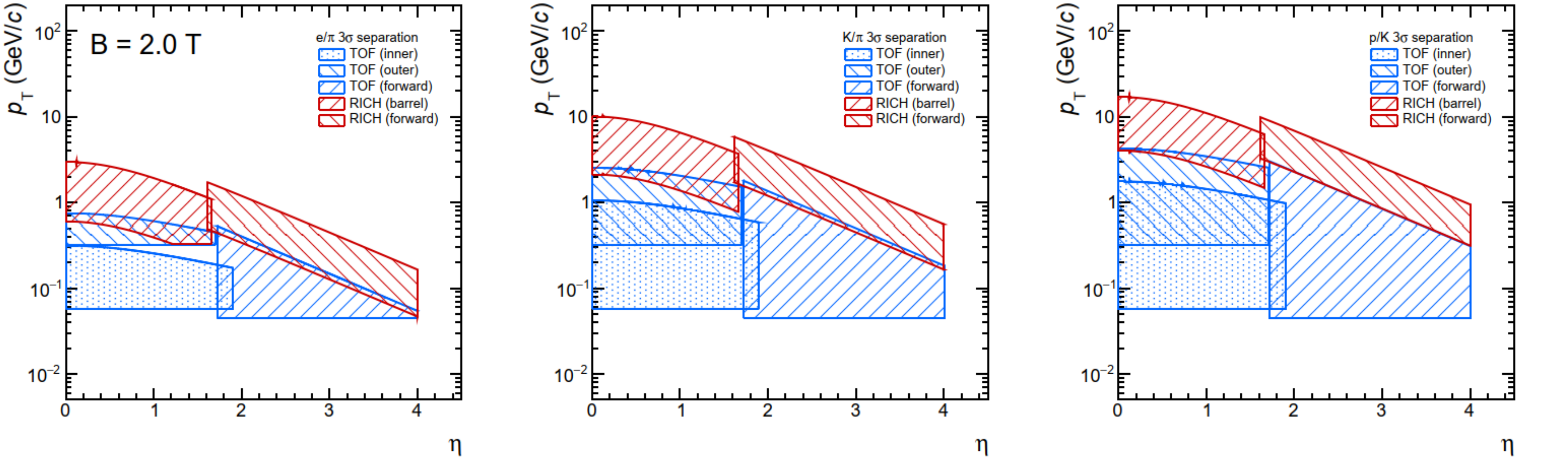
π/K : 2.0 - 10.0 GeV/c

K/p : 4.0 – 16.0 GeV/c

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

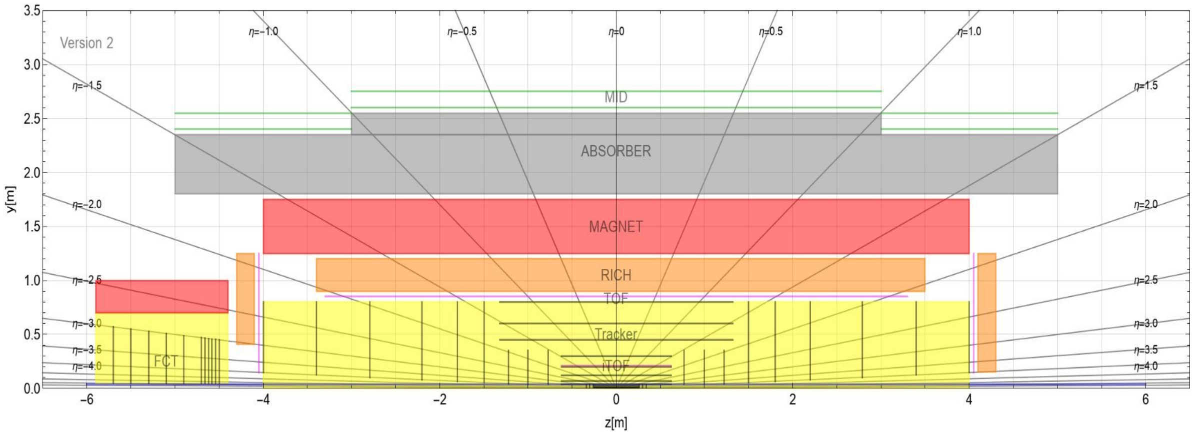
Forward RICH: idem, but aerogel n = 1.006

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

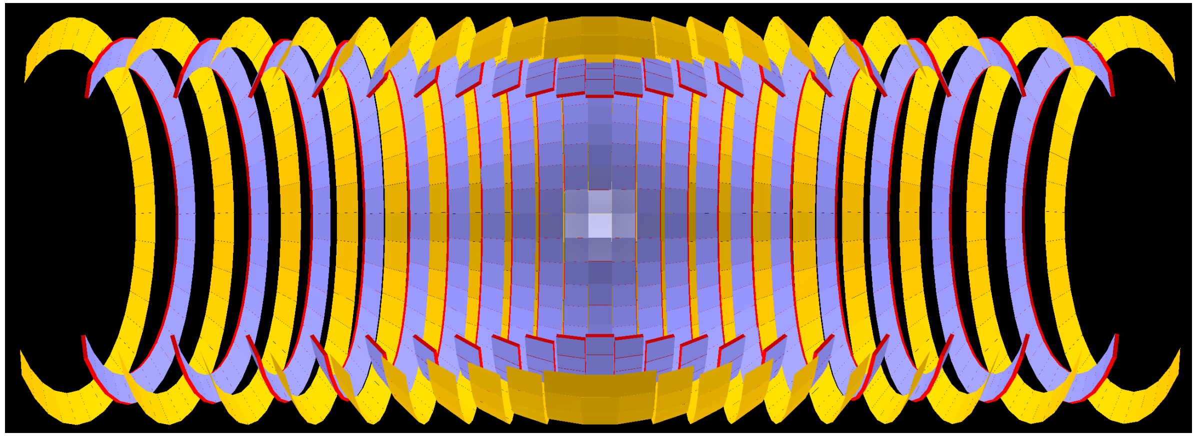


Subsystem description

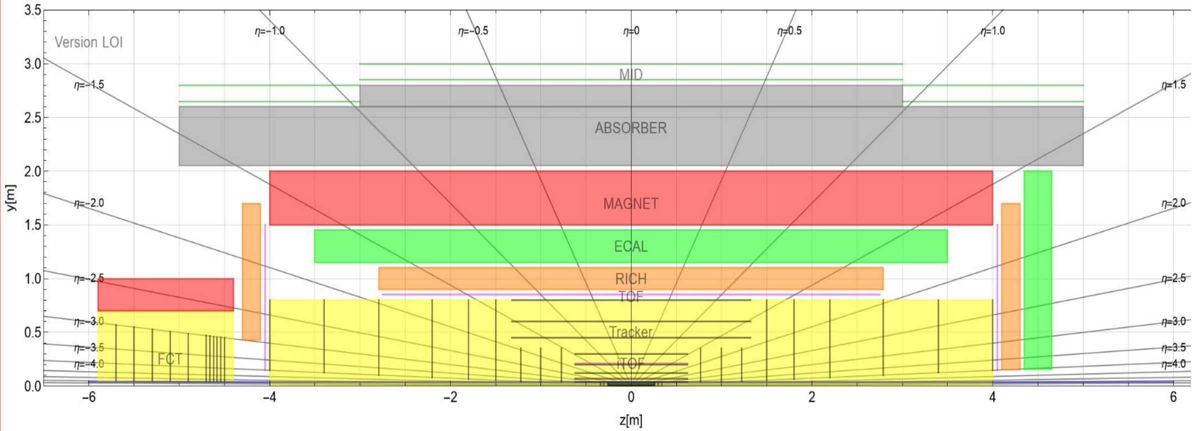
Extended layout

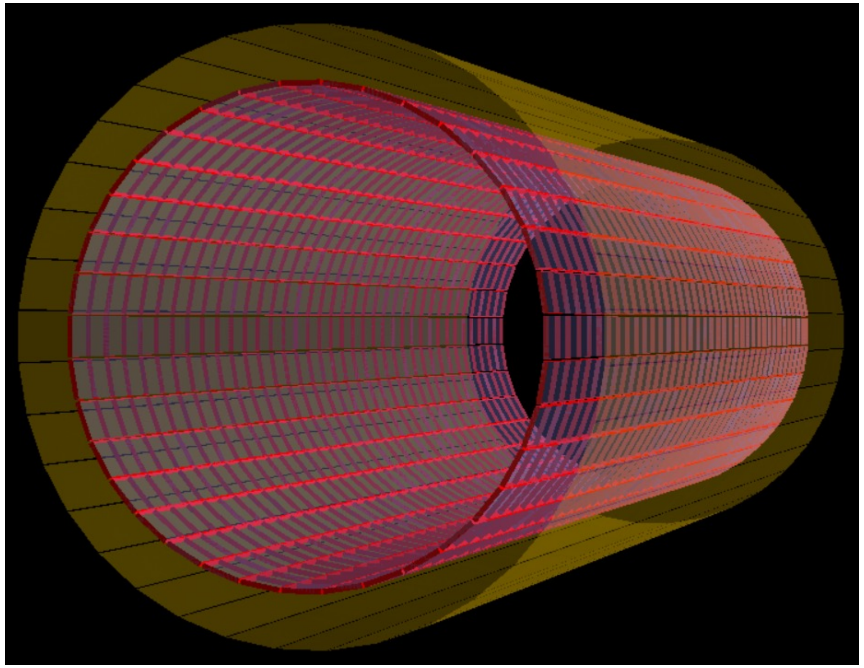


Proximity focusing projective layout



LoI layout



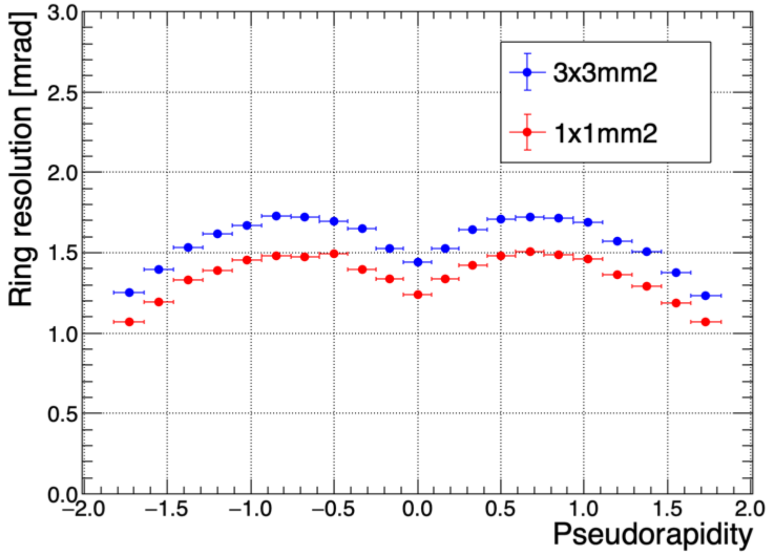


Proximity focusing projective layout

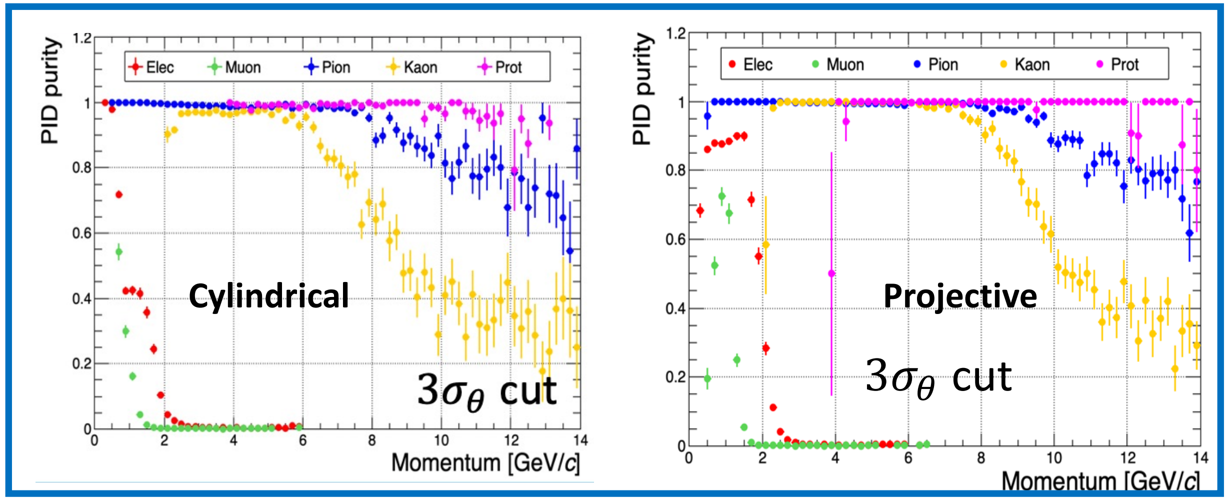
Aerogel and photon sensor surfaces decreasing and better performance

bRICH layout	bRICH number of modules	bRICH SiPMs area [m²]	bRICH aerogel area [m²]	fRICH SiPMs area [m²]	fRICH aerogel area [m²]
LoI Cylindrical (|η|<1.64)	1332 SiPM 1044 aerogel	38.96	24.43	19	17
Projective (|η|<2.00)	828 SiPM 828 aerogel	28.12	21.65	9	8

$\sigma_z^{int.point}$ = 10 cm



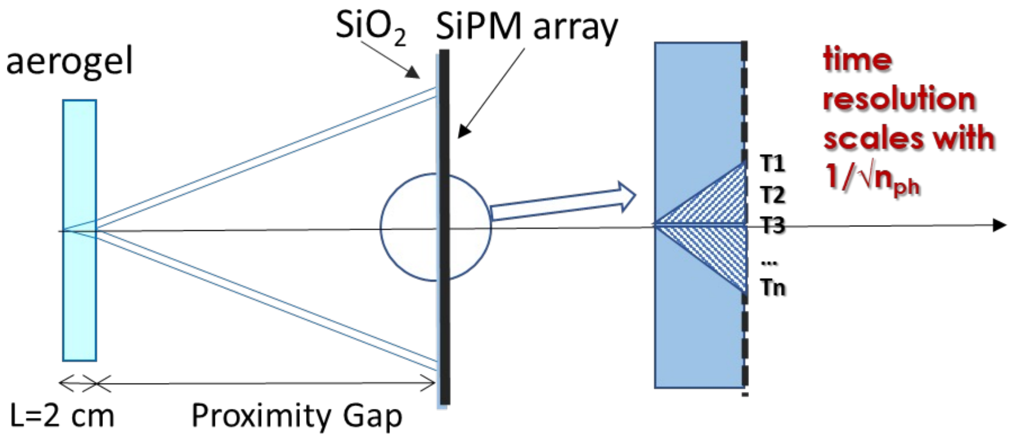
Central Pb-Pb collisions, Projective layout, **1x1 mm² cells**

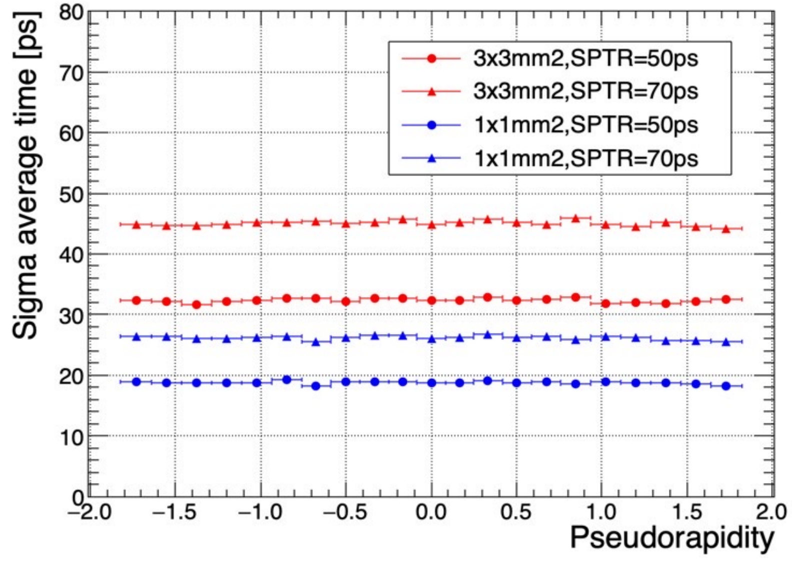


Alternative layouts

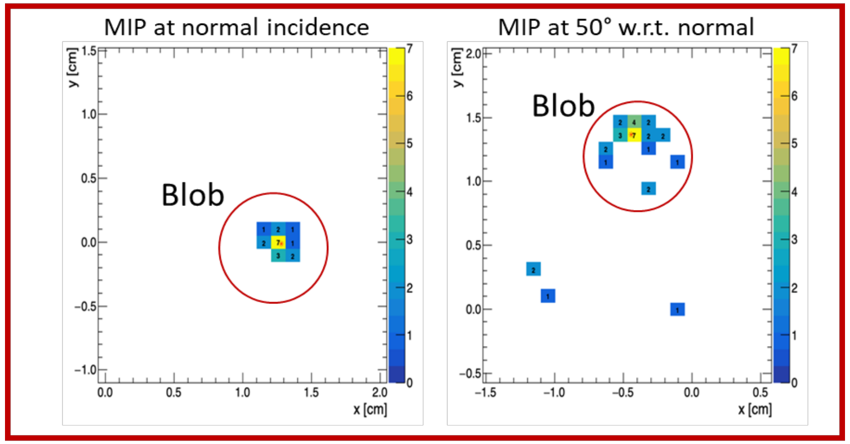
TOF measurement by RICH SiPMs

- Reduction of costs and material budget, two PID techniques in one device
- Performance improvement both for TOF (increase of lever arm: 0.85 -> 1.1 m) and RICH (increase of proximity gap: 20 -> 25 cm)

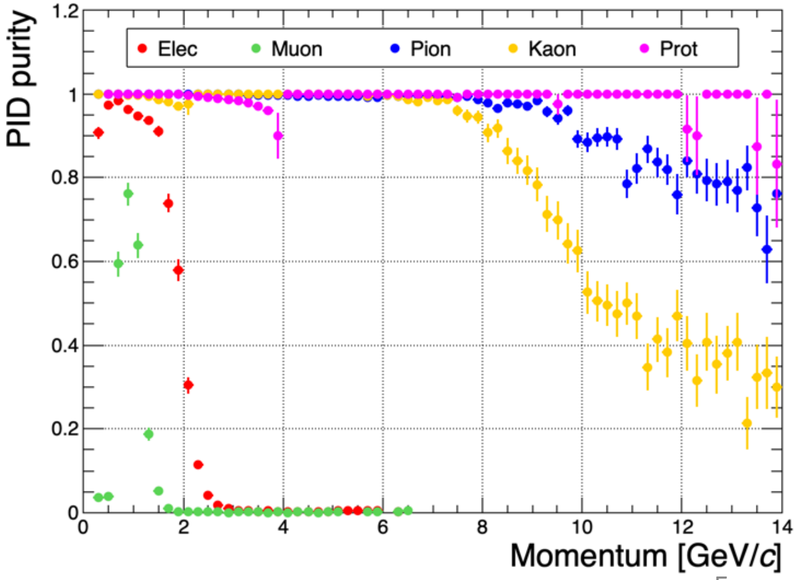




Geant4 simulaiton



1 mm SiO_2 + 0.45 mm epoxy resin, 1x1 mm^2 cells



Alternative layouts

e-PID range extension

Goal

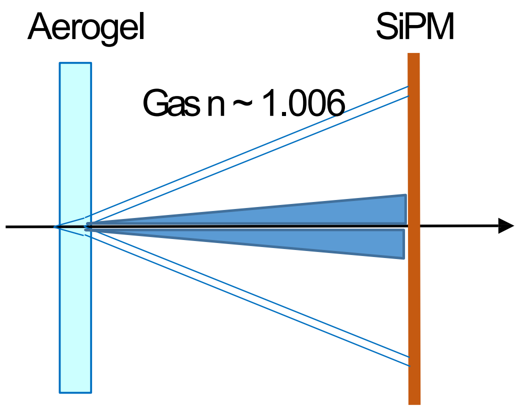
- Extend electron identification up to 4 GeV/c
  - Required for physics channels involving e.g. dielectrons

Strategy

- Implement gaseous radiator having n ≈ 1.0006
- Solution avoiding gases with large GWP to be studied
  E.g.: SLD CRID approach on a C_5F_{100} + N_2 mixture
- $n_{mix} = 1.0006 \Rightarrow w_{C5F100} = 20\%$, $w_{N2} = 80\%$

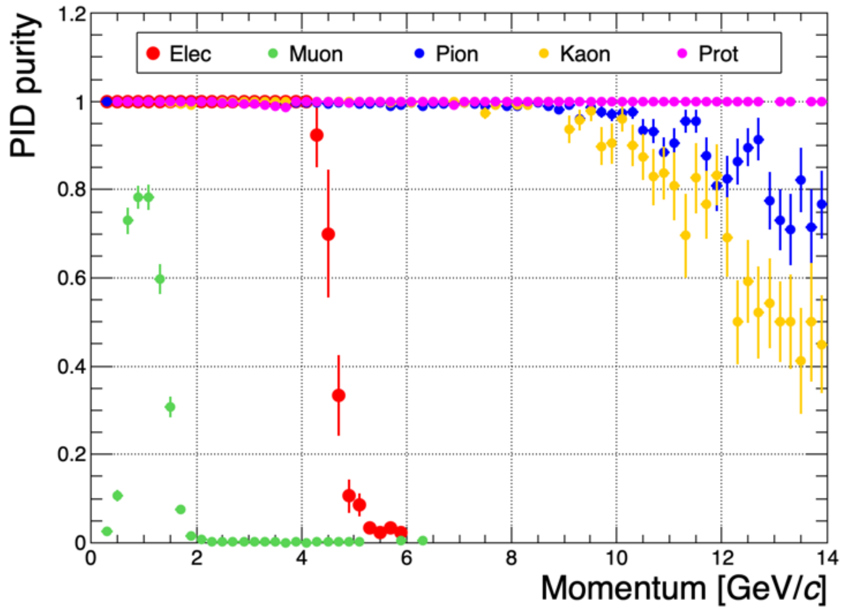
Caveat

- Requires to increase the proximity gap (35 cm) to increase the photon yield in gas

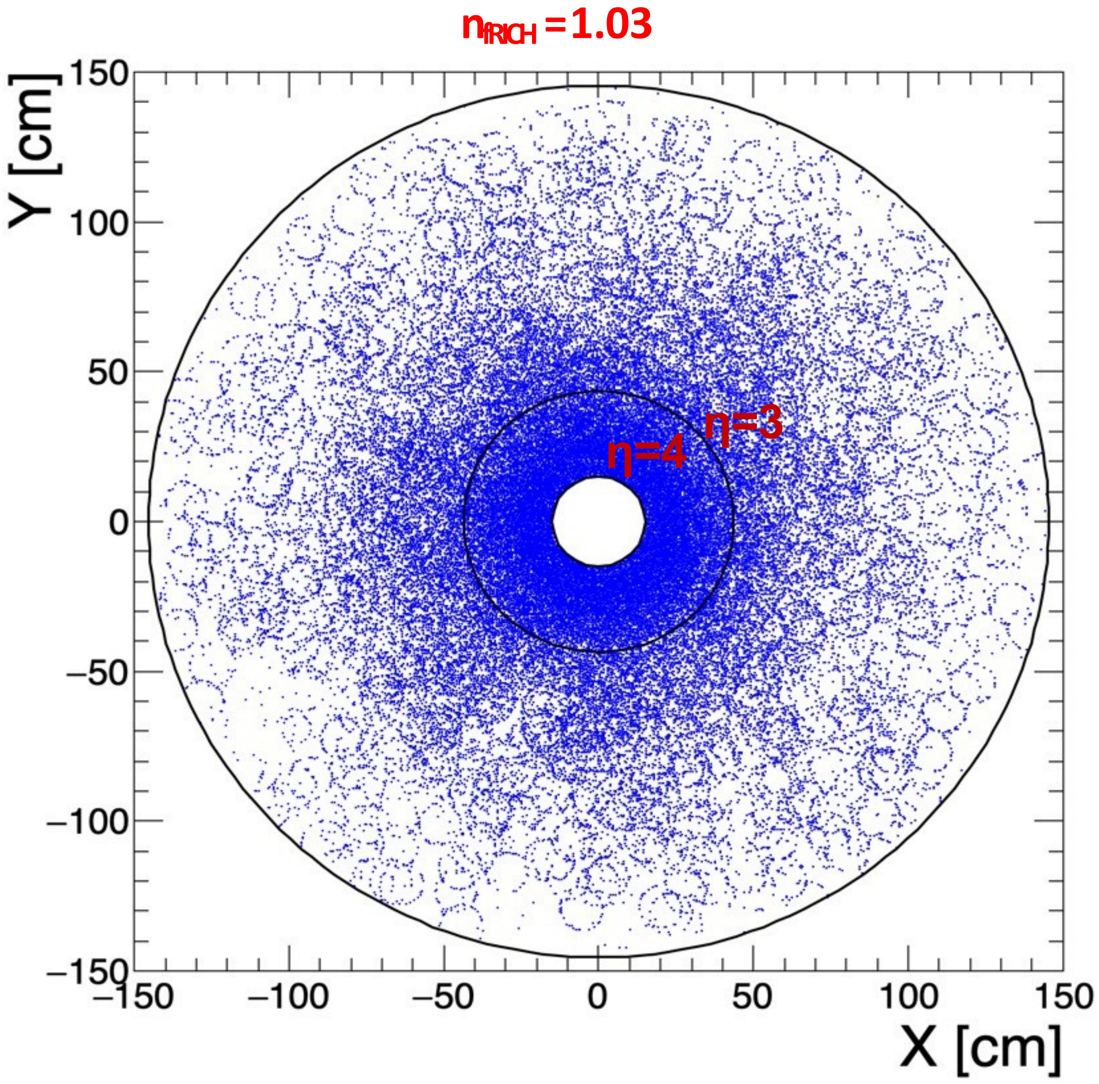


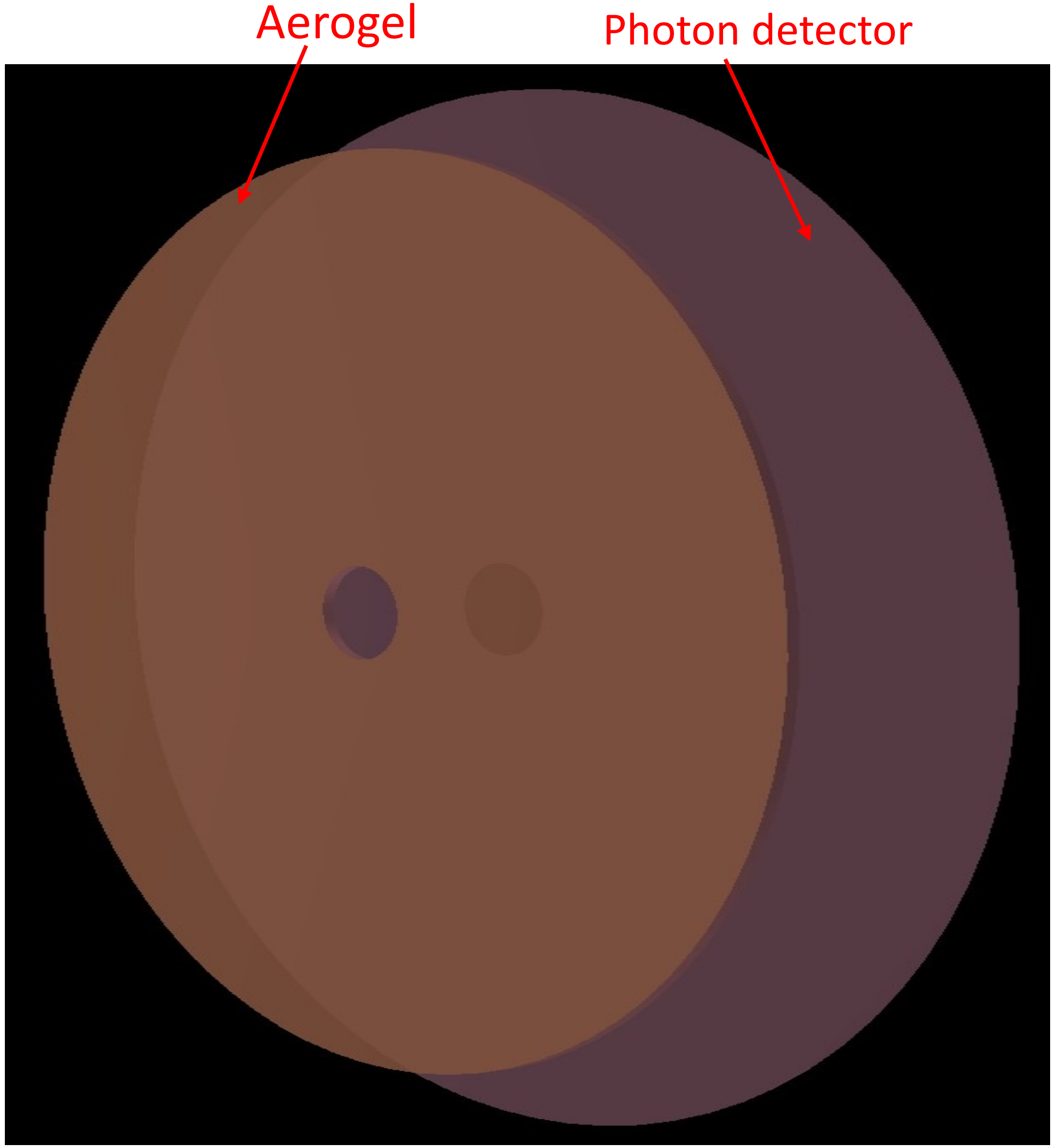
e-ID by Cherenkov threshold (hadron blind)
(presence of photons blob around MIP track)

1x1 mm2 cells, **50 ps** SPTR, **real reconstruction**



Forward RICH



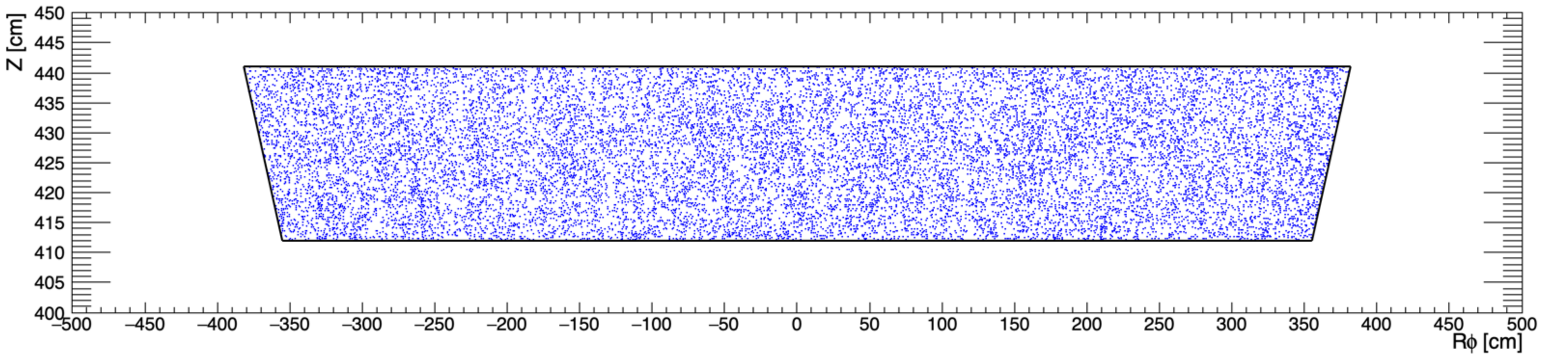


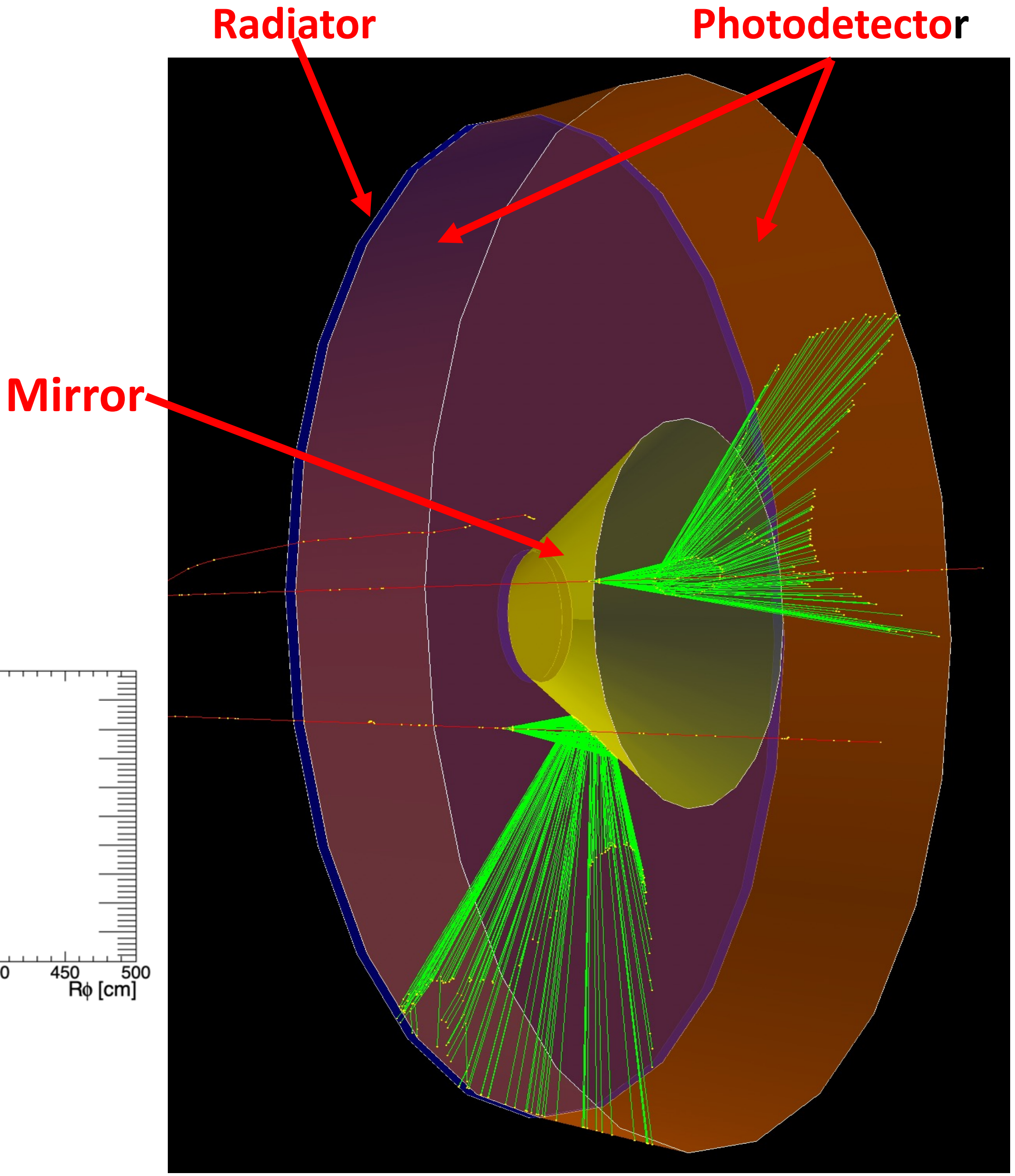
Forward RICH: towards mirror layout

Optimazing forward RICH layout to cope with large occupancy at $3 < \eta < 4$

- Replace photon detector with flat mirror at 45° incliantion

$n_{fRICH} = 1.03$





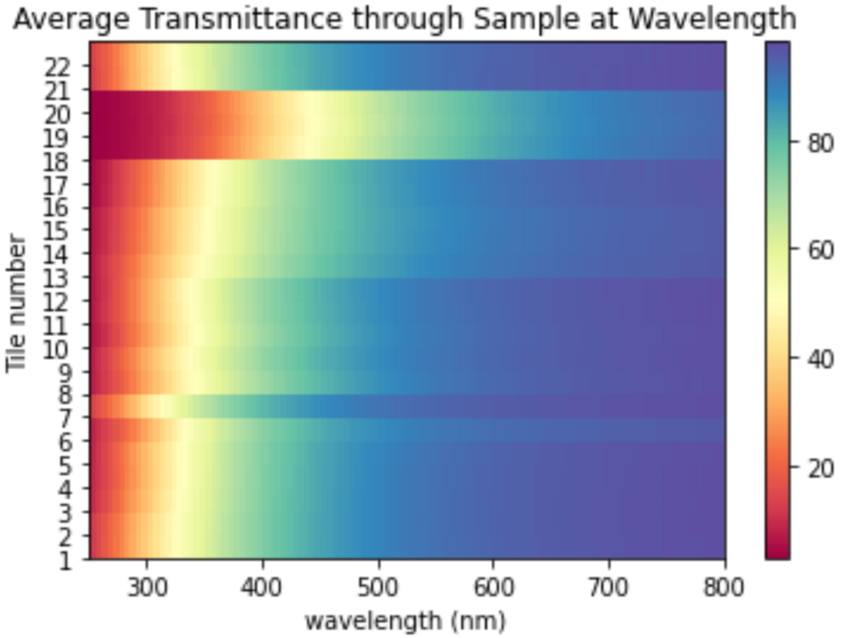
R&D activities: aerogel characterization

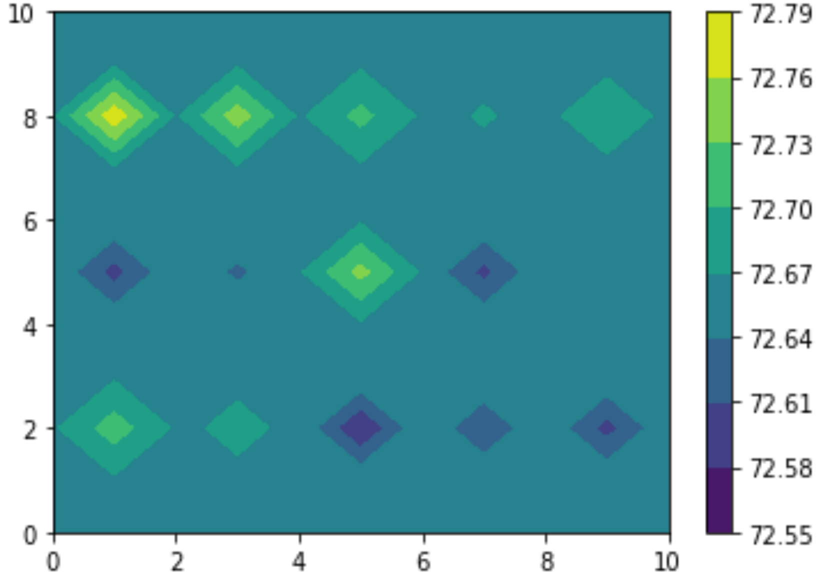
Aerogel specs: hydrophobic, T> 80% @ 400 nm, 15 x 15 cm^2.

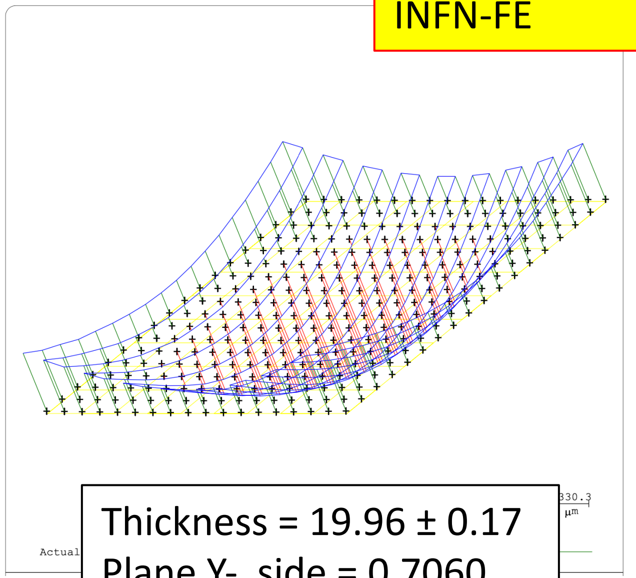
- Optical properties (refractive index and transmittance homogeneity and reproducibility)
- Tile size (up to 20x20 cm^2) and shape
- Multi-layer focusing (also monolithic?)

Sinergy with EIC INFN-FE

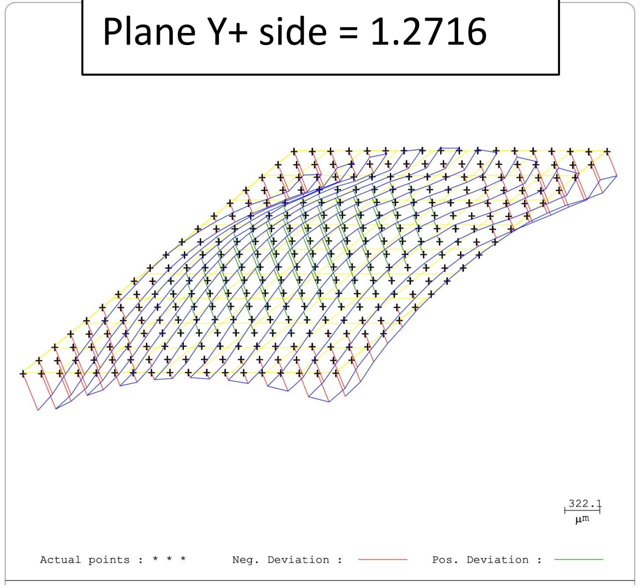
- 22 samples available from Aerogel Factory Co. LTD (Chiba, JP) (purchased with LHCb)
- Four n: 1.005, 1.03, 1.04, 1.05
- Two sizes: 11x11 cm^2 and 15x15 cm^2
- Measurement of transparency and uniformity
- Dimensional/shape characterization







Thickness = 19.96 ± 0.17
Plane Y- side = 0.7060
Plane Y+ side = 1.2716

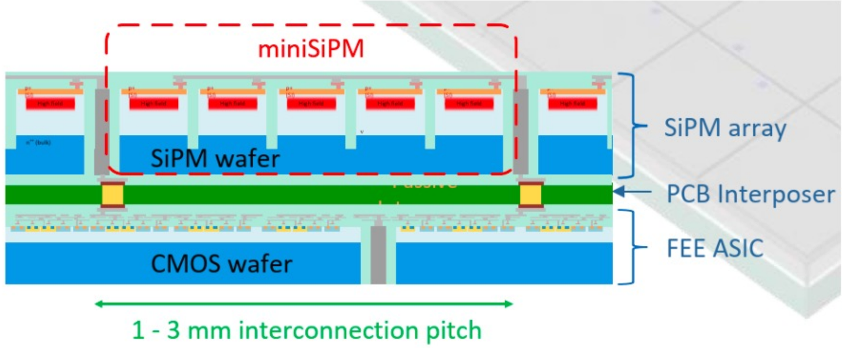


R&D activities: photon detector

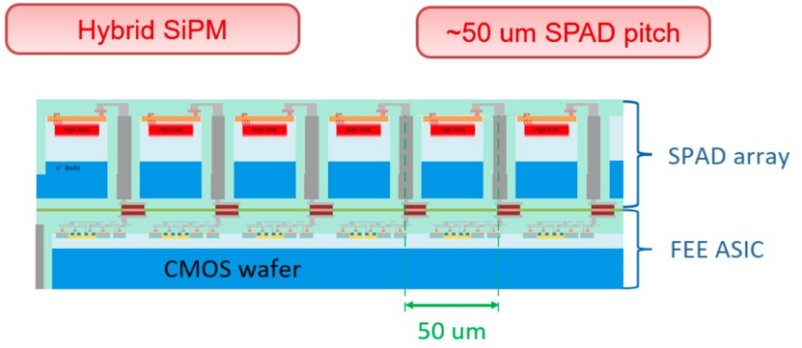
SiPM specs: Pixel 2x2 mm^2 , die (SiPM array) size ~ 1x1 cm^2, PDE > 40% at 450 nm, DCR < 50 kHz/mm^2, radiation hardness: NIEL ~ 10^{10} 1 MeV neq/cm^2, time resolution < 100 ps, packaging fill factor > 90 (TSV interconnection)

- Explore custom solutions for 2.5 or 3D SiPM in CMOS Imaging Sensor technology (partnership with FBK?)
- MIP detection by thin radiator window for TOF (see TOF presentation)
  - Anti-reflecting coating
- Module concept and cooling integration

2.5 D



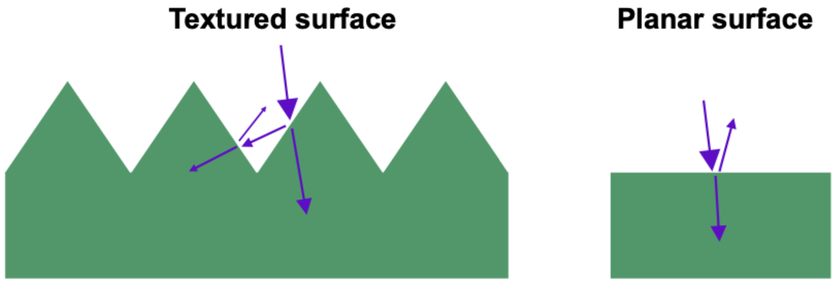
3 D

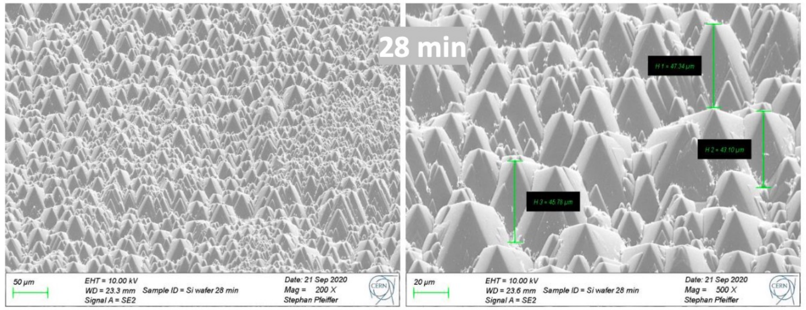


R&D activities: ECFA DRD4 (Photon Detectors and Particle ID)

Activities

- Detailed GEANT4 simulations emulating the time spread introduced by the optical cross/talk to neighboring pixels
- Laboratory tests with SiPMs equipped with high refractive materials with entrance face textured with micro-pyramids or micro-lenses.





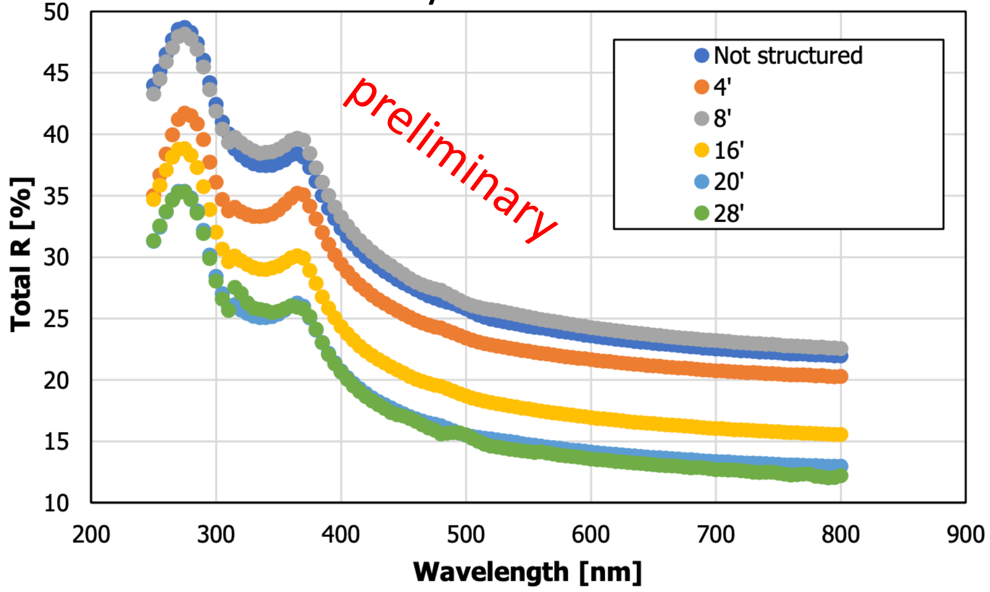
Reflection effects:

- Fresnel reflection between window and resin or resin and Silicon + total reflection between window and Ar
- Loss of photons from aerogel (accounted in the PDE)
- A larger PDE could be achieved by limiting reflection effects

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.

Ethced Si reflectivity measured at CERN TFG lab

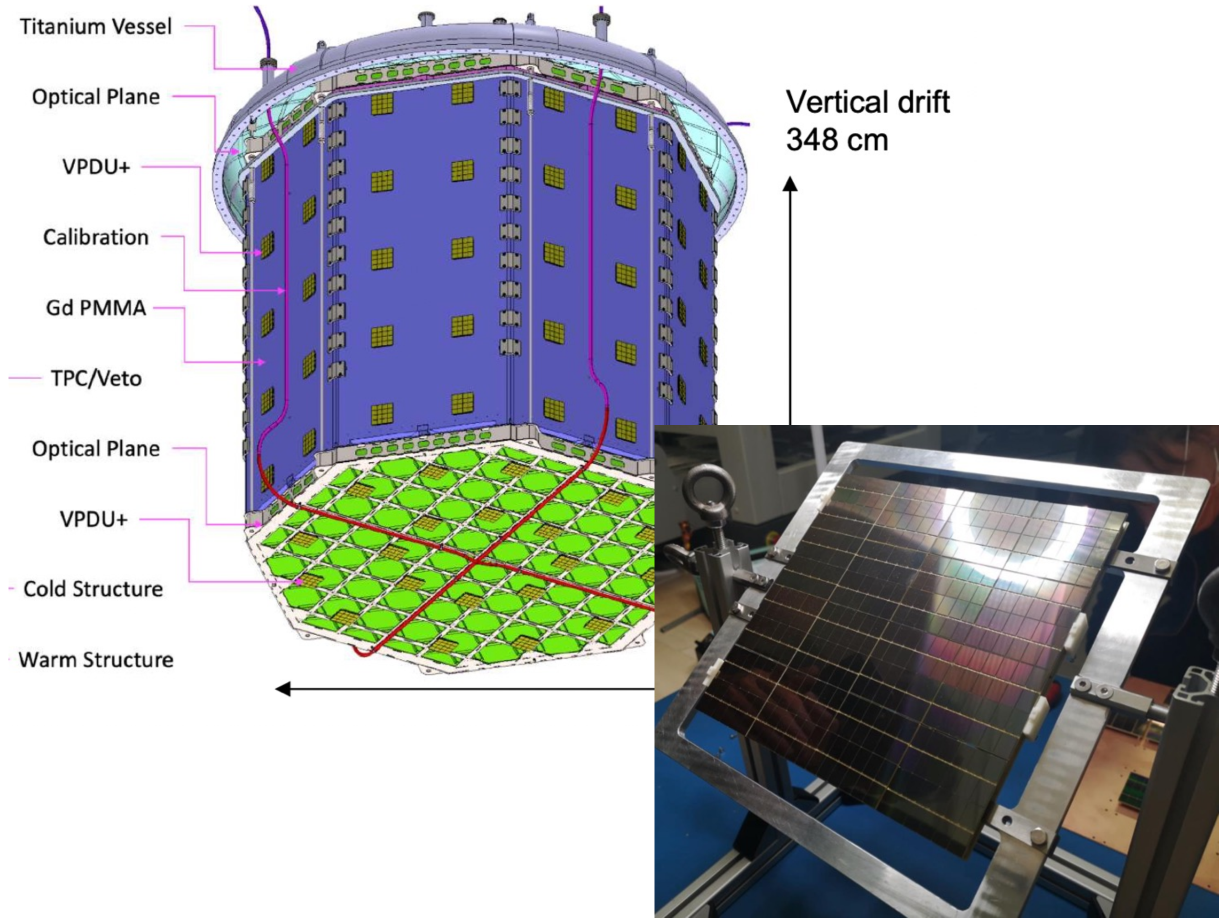


Example of a large scale SiPM packaging

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



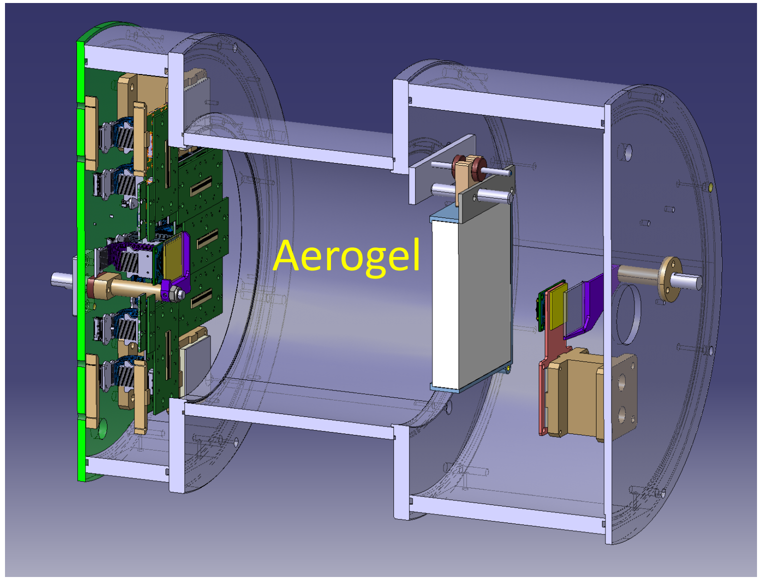
SiPMs based on FBK NUV-HD-Cryo Design, manufactured by LFoundry

- **~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)

Example of a large scale SiPM packaging

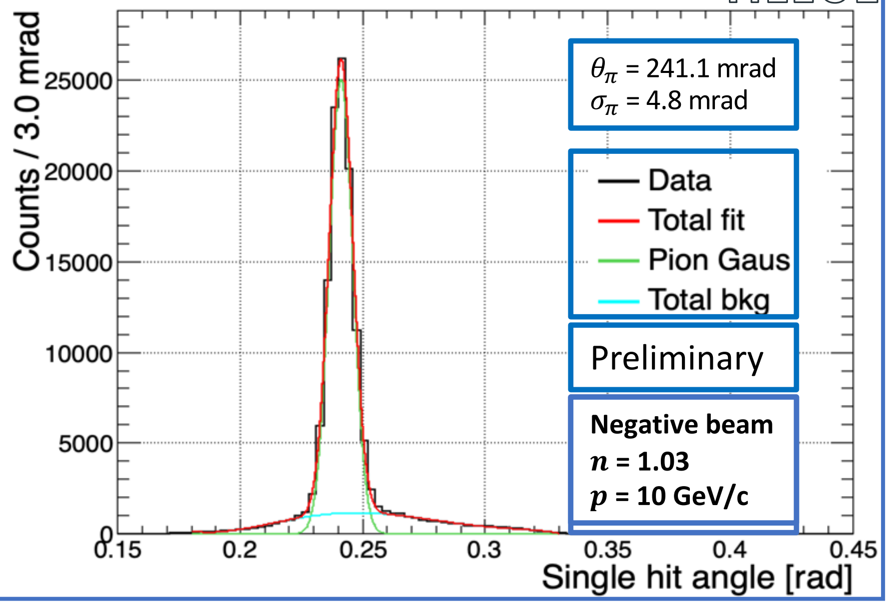
NOA faciltiy at LNGS (Gran Sasso, Italy)

R&D activities: prototype @ testbeam PS/T10



Measured angular resolution

σ_{π} = 4.8 mrad



Testbeam from 19/10 to 02/11 2022

- Verify aerogel performance
- Study electronics effects on the detector response
- DCR dependence on cooling

Detector parameters

- Radiator: T_r = 2 cm, n = 1.03-1.04
- Proximity gap: T_g = 23.8-23.4 cm, Ar
- SiPM cooling: -12° < T < -5°

1 card for MIPs, HPK S13361: 64 ch array of 3x3 mm² pads

8 cards for rings, HPK S13552: 128 ch array of 0.23x1.625 mm² strips, 32 ch read-out

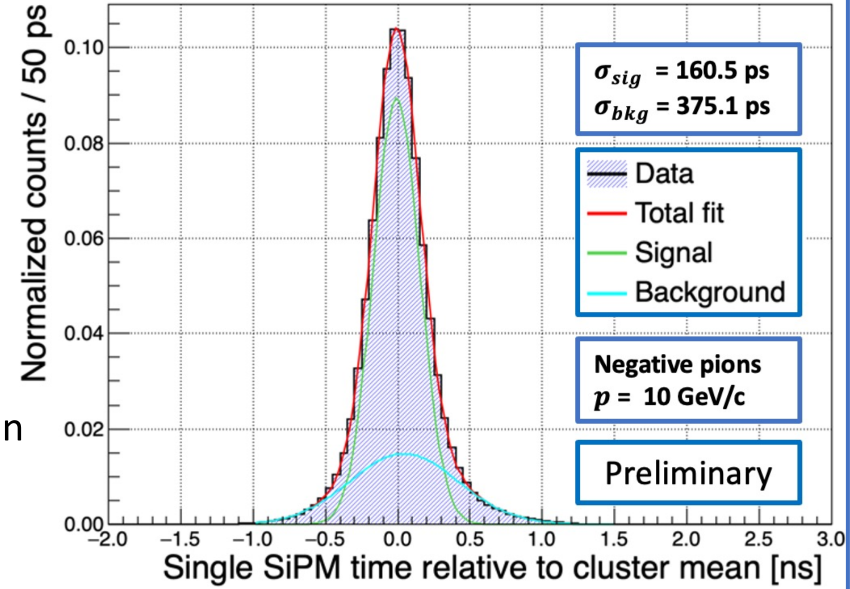
Measured time resolution

σ_{sig} = 160.5 ps

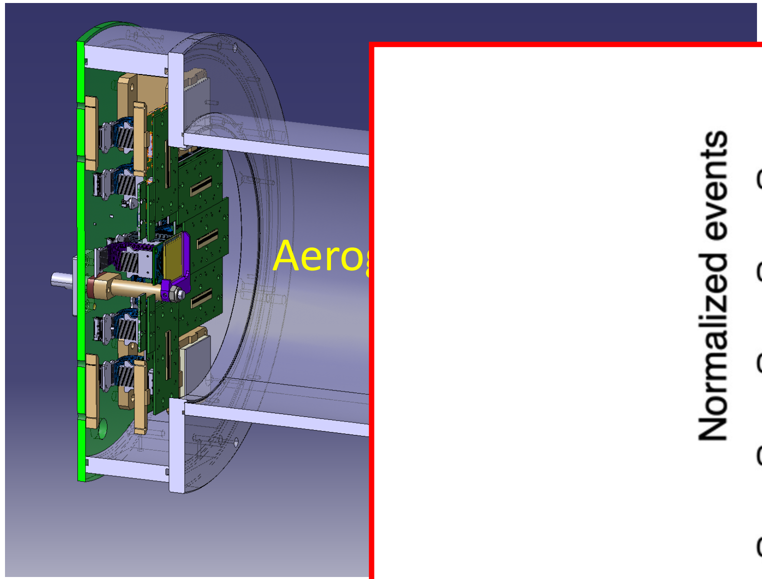
Limitation

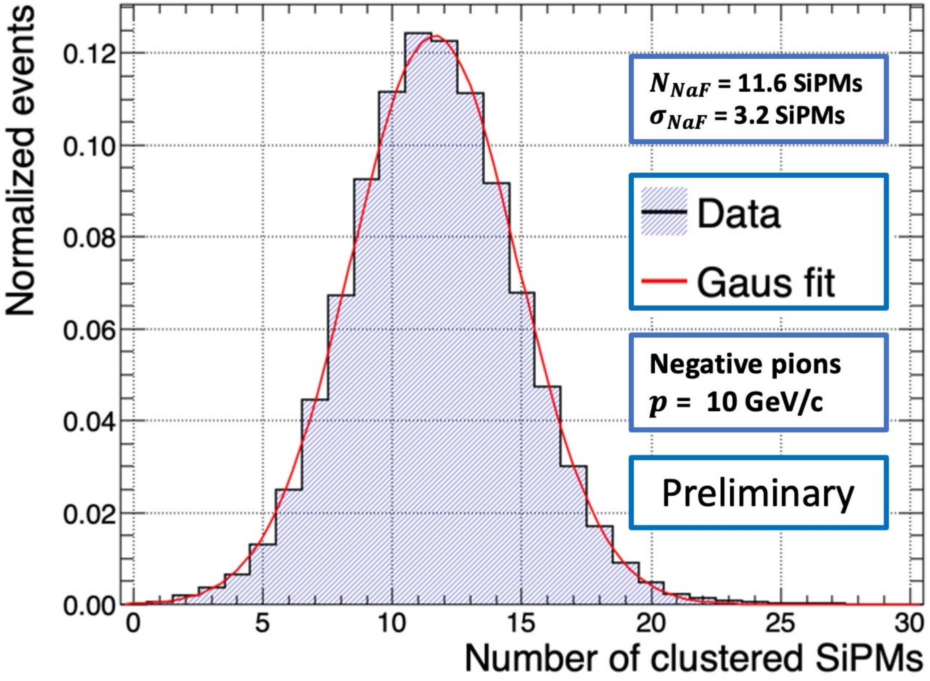
No reference time available ⇒ times referred to the cluster mean time

There is room for improvement!



R&D activities: prototype @ testbeam PS/T10

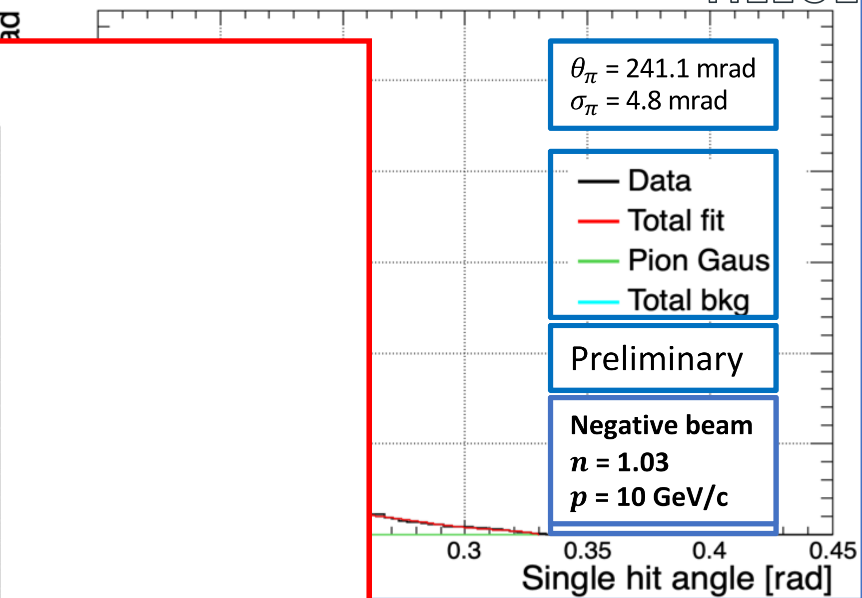


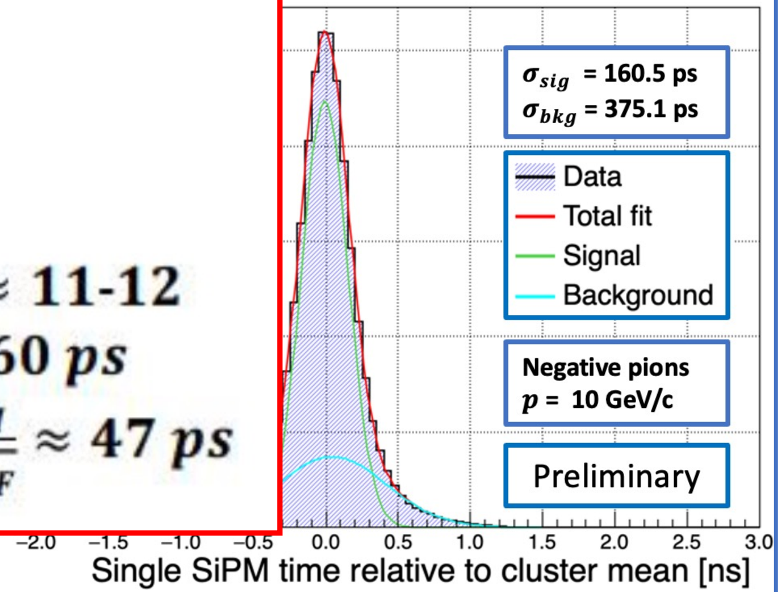


Measured mean number of clustered SiPMs : $N_{NaF} \approx$ **11-12**

Measured single SiPM time resolution: $\sigma_{SiPM} \approx 160\ ps$

Extrapolated mean cluster time resolution: $\sigma_{\langle t \rangle} = \frac{\sigma_{SiPM}}{\sqrt{N_{NaF}}} \approx 47\ ps$





Testbeam from 19/10 t
- Verify aerogel perfo
- Study electronics ef
- DCR dependence o

Detector parameters
- Radiator: T_r = 2 cm,
- Proximity gap: T_g = 2
- SiPM cooling: -12°

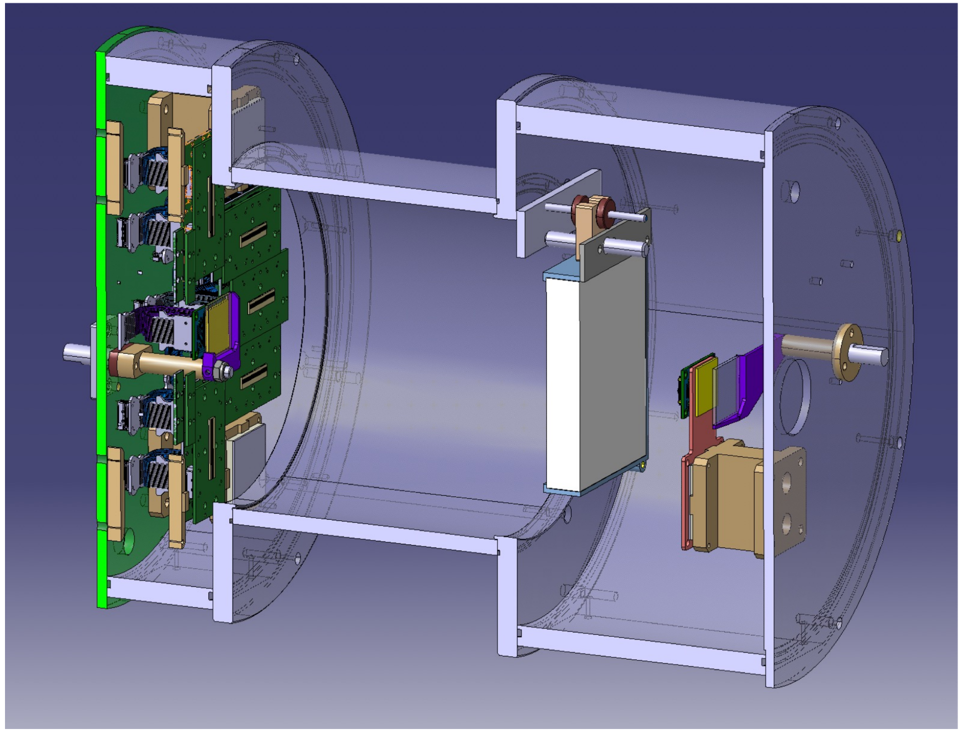
1 card for MIPs, HPK S13361: 64 ch array of 3x3 mm² pads

32 ch read-out

R&D activities: prototype @ testbeam PS/T10

2023 test

- Similar to the 2022 beam test, but with some upgrades:
  - Adding a SiPM matrix upstream (with SiO_2 and high n Corning glass glued window)
  - Board synchronization
  - External tracking detector:
    - Two X-Y upstream/downstream fiber tracker module
    - Option: two ALPIDE pixel modules
  - Some mechanical reworks
  - Further read-out electronic developments ongoing
    - Not sure that new cards will be available



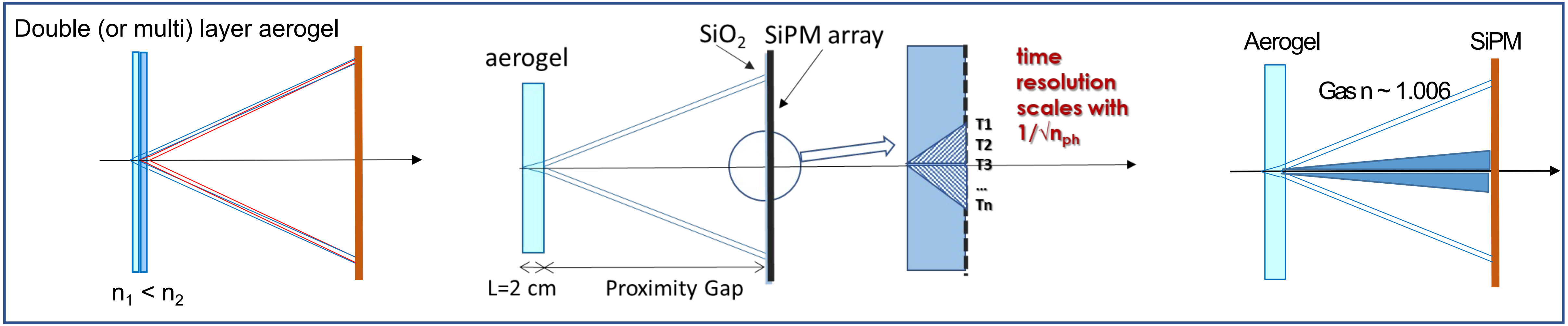
- Main goals of the 2023 test:
  - Improving time measurement
  - Photon yield and timing studies with 1 mm radiator glued on the SiPM matrix
  - PID studies with $N_2/C_5F_{10}O$ gas radiator and focusing aerogel double layer

Toward the scoping document

- Proximity focusing with projective geometry → baseline
  - LoI cylindrical layout not an option anymore

Scoping document layout options

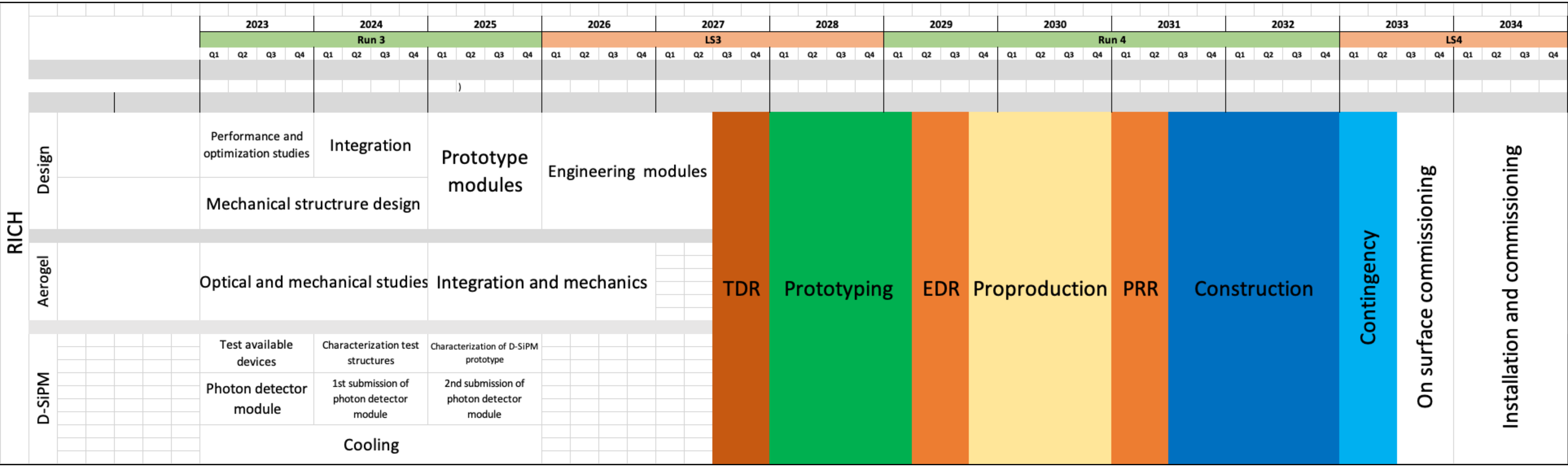
- Aerogel focusing with projective geometry (2x2 mm^2 pixels)
- RICH + TOF: TOF measurements in RICH SiPMs
- Implement also gas radiator with $n \approx 1.0006$, for e-ID in threshold mode



2024

- Simulation studies for the optimization of detector geometry and parameters.
- Optical characterization studies of SiPM and radiator coatings.
- Studies of the mechanical structure.
- In addition, for sensor R&D, it is planned to commission a first CMOS SPAD engineering run to LFoundry/FBK.
- Another beam test of a prototype will also be planned, with the aim of further improving time measurements with the use of a newly developed WEEROC board with pico-TDC.

Preliminary conceptual schedule



Financial requests

Missioni	
Importo	Descrizione
10 k€	test beam x 4 persone x 2 sett. + contatti con Malta, Messico, LFoundry e NOA
4 k€	DRD4

Consumo, inventario, etc	
Importo	Descrizione
10 k€	SiPM (1.3x1.3 mm2 e 2x2 mm2, 2+2 con SiO2 e 2+2 con Corning)
10 k€	acquisto scheda WEEROC con picotdc x 5
60 k€	Engineering RUN FBK/LFoundry CMOS SPAD
4.5 k€	scheda FPGA (Mouser electronics EK-Z7-ZC706-G o simili)
6 k€	DRD4

RICH WG organization

Coordinator: G. Volpe

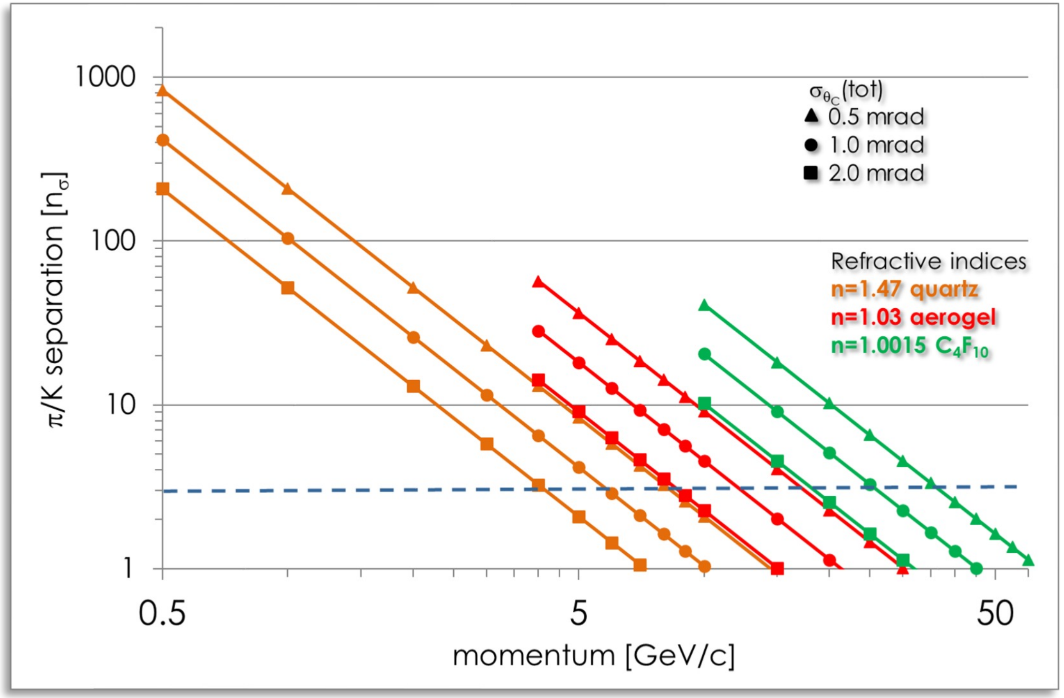
Tasks	Institutes
Design studies (simulations)	INFN Bari
SiPM R&D, readout electronics, module development and integration	INFN Bari, Mexico, Malta + ?
Aerogel characterization, procurement and quality assurance	INFN Bari + ?
Cooling	?
Mechanics and integration	Malta + ?

Hungary: involvement to be defined

Backup

Requirements and specifications

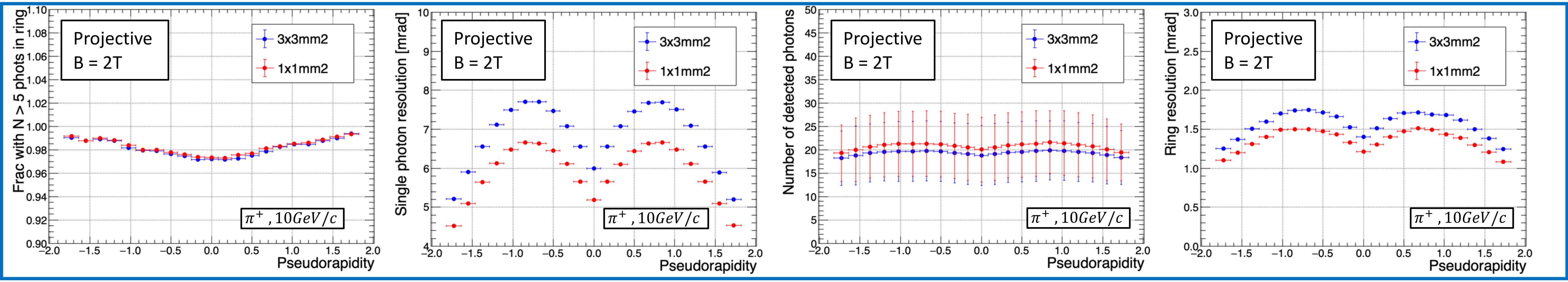
Material	Refractive index	$p_{threshold}$ [GeV/c]				λ_{cutoff} [nm]
		e	π	K	p	
He	1.000035	0.06	16.68	59.01	112.14	112
Ar	1.000283	0.021	5.87	20.75	39.44	124
CO_2	1.000449	0.017	4.66	16.47	21.48	175
C_4F_{10}	1.0015	0.009	2.5	9.0	17	136
Aerogel	1.03	0.002	0.57	2.0	3.8	300
C_6F_{14}	1.3	0.0006	0.168	0.594	1.13	165
H_2O	1.333	0.00058	0.158	0.56	1.065	190
NaF	1.41	0.00051	0.140	0.497	0.944	125
LiF	1.46*	0.00048	0.131	0.464	0.882	105
quartz	1.47*	0.00047	0.129	0.458	0.87	158



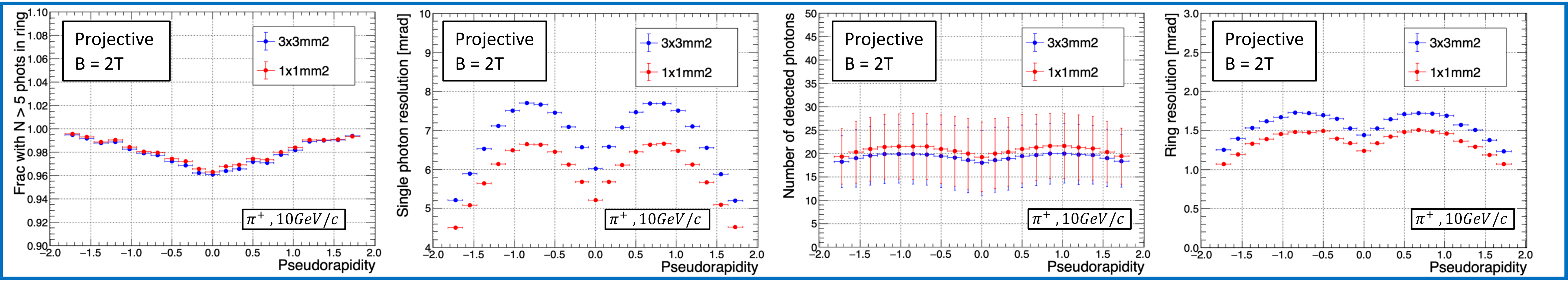
- Required PID momentum range covered by aerogle radiator
- While transparent in the visible range, aerogel becomes opaque for wavelengths shorter than 300 nm, where most of the incident radiation is diffused by Rayleigh scattering.
- A photon counter sensitive to visible light is required to detect the Cherenkov photons
- Silicon-based photon sensors represent an interesting and commercially available option.

Projective: Performance vs spread of Z vertex

$\sigma_z = 0\ cm$



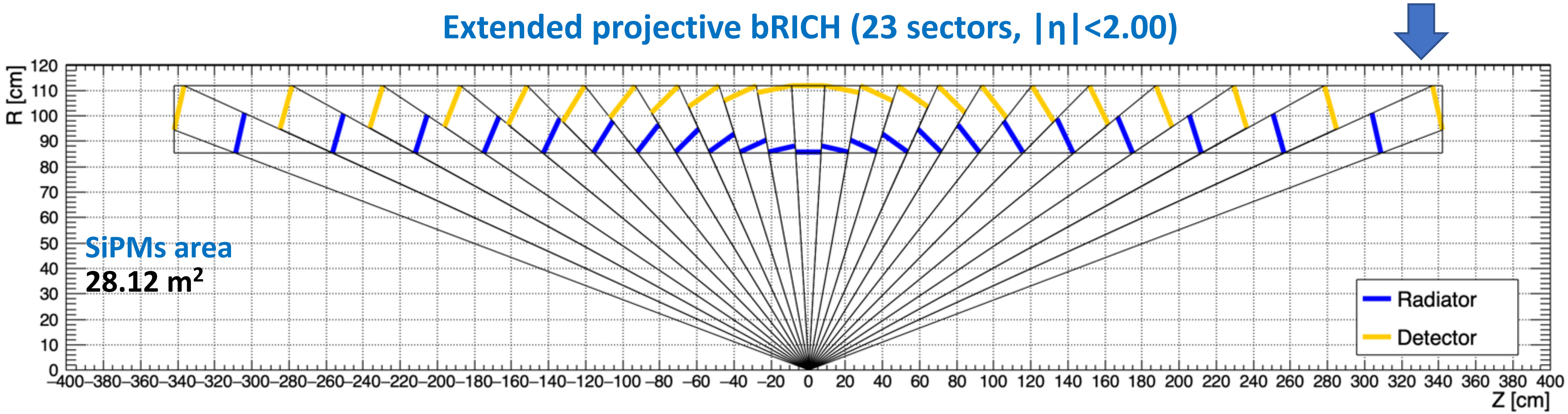
$\sigma_z = 10\ cm$



Summary: Some photons are lost for MIPs close to midrapidity, but the effect on the performance seems negligible !!!

Extended projective layout

- Number of aerogel tiles: 23*36 = 828
- Number of photodetector modules: 23*36 = 828
- Total photosensitive surface: 28.12 m^2
- Total aerogel area: 21.65 m^2 (max. rectangles)
- Effective aerogel area: 20.43 m^2 (exact trapezoid size)



Baseline cylindrical bRICH (|η|<1.64)

Zrad = 410 cm
Zdet = 437 cm
Rrad,out = 165.28 cm
Rdet,out = 176.17 cm

Rrad,in = 15.0 cm
Rrad,in = 15.0 cm

$$A_{rad} = \pi\left(R^2_{rad,out} - R^2_{rad,in}\right) = 8.51\ m^2$$
$$A_{det} = \pi\left(R^2_{det,out} - R^2_{det,in}\right) = 9.68\ m^2$$

Basic projective bRICH (|η|<1.82)

Zrad = 410 cm
Zdet = 437 cm
Rrad,out = 136.44 cm
Rdet,out = 145.42 cm

Rrad,in = 15.0 cm
Rrad,in = 15.0 cm

$$A_{rad} = \pi\left(R^2_{rad,out} - R^2_{rad,in}\right) = 5.77\ m^2$$
$$A_{det} = \pi\left(R^2_{det,out} - R^2_{det,in}\right) = 6.57\ m^2$$

Ext/hybrid projective bRICH (|η|<2.00)

Zrad = 410 cm
Zdet = 437 cm
Rrad,out = 113.04 cm
Rdet,out = 120.49 cm

Rrad,in = 15.0 cm
Rrad,in = 15.0 cm

$$A_{rad} = \pi\left(R^2_{rad,out} - R^2_{rad,in}\right) = 3.94\ m^2$$
$$A_{det} = \pi\left(R^2_{det,out} - R^2_{det,in}\right) = 4.49\ m^2$$

bRICH layout	bRICH number of modules	bRICH SiPMs Area [m²]	Max. radiator area [m²]	Effective radiator area [m²]	fRICH Rmin [cm]	fRICH Rmax [cm]	fRICH radiator area [m²]	fRICH SiPMs area [m²]
Cylindrical (|η|<1.64)	1332 SiPM 1044 aerogel	38.96	24.43	24.43	Rad: 15 Det: 15	Rad: 165.28 Det: 176.17	2·8.51	2·9.68
Projective (|η|<1.82)	756	25.74	19.55	18.50	Rad: 15 Det: 15	Rad: 136.44 Det: 145.42	2·5.77	2·6.57
Projective (|η|<2.00)	828	28.12	21.65	20.43	Rad: 15 Det: 15	Rad: 113.04 Det: 120.49	2·3.94	2·4.49
Hybrid (|η|<2.00)	972	31.32	21.97	21.08	Rad: 15 Det: 15	Rad: 113.04 Det: 120.49	2·3.94	2·4.49

Technology options (baseline and alternatives)

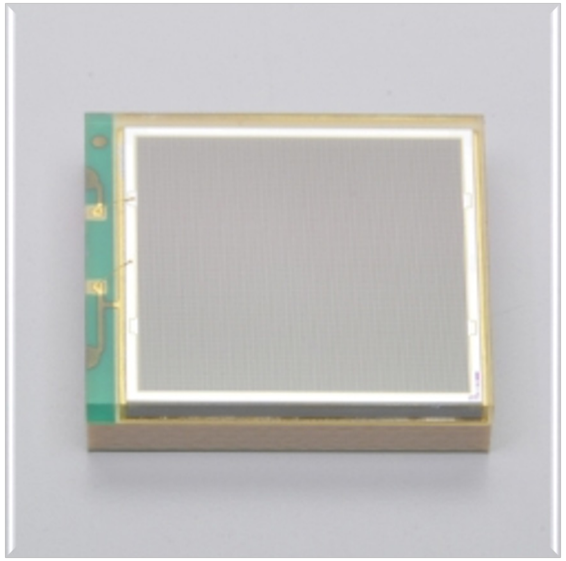
Photon detector

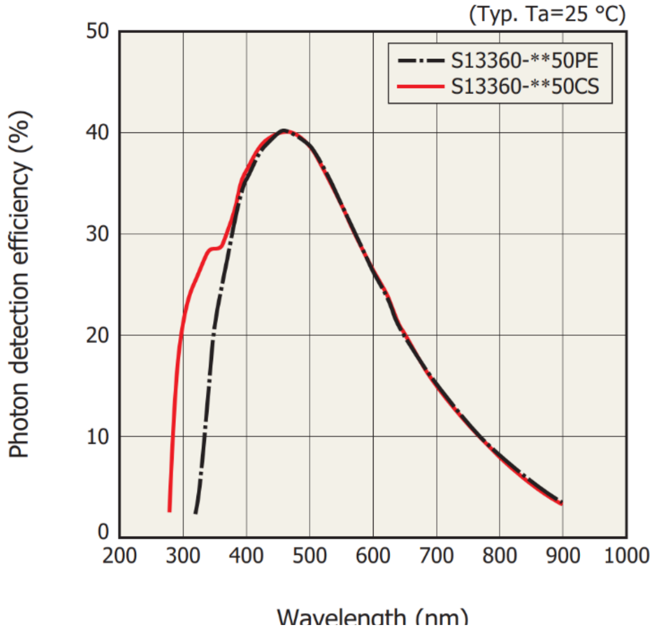
Example: SiPM HPK 13360 3050CS

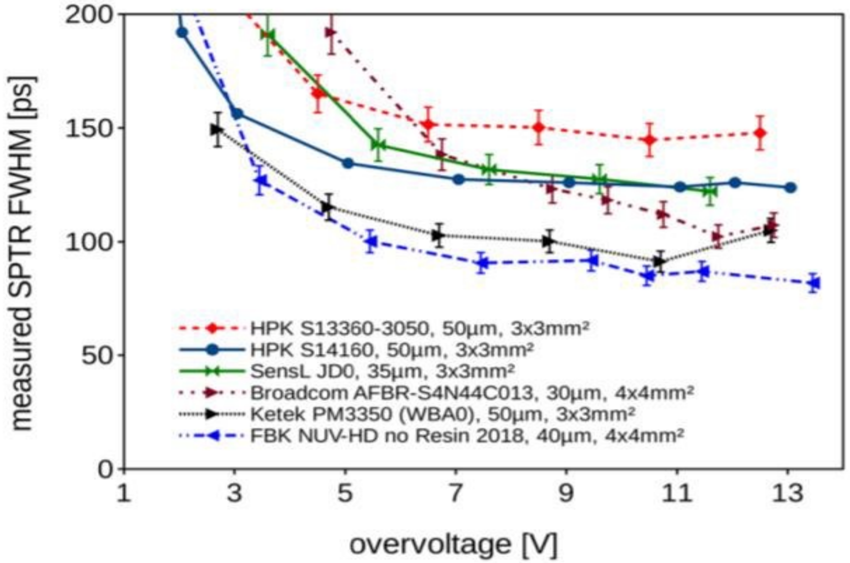
- 3x3 mm^2 pixel (3600 SPADs with 50 μm pitch)
- Dark count rate (DCR) ~ 50 kHz/mm^2
- 50 ps time resolution

Main requirements

- Single photon sensitivity in the visible range (Photon Detection Efficiency (PDE) > 40-50%)
- Integration fill factor > 90%
- Pixel ~ 3x3 mm^2 (down up to 1x1 mm^2)
- Time resolution σ < ~ 100 ps
- Magnetic field: up to 2 T
- Expected radiation load: NIEL ~ 10^{12} 1-MeV n_{eq} /cm^2







Necessary and ongoing R&D

Photon detector

Direct detection of charged particles with SiPM

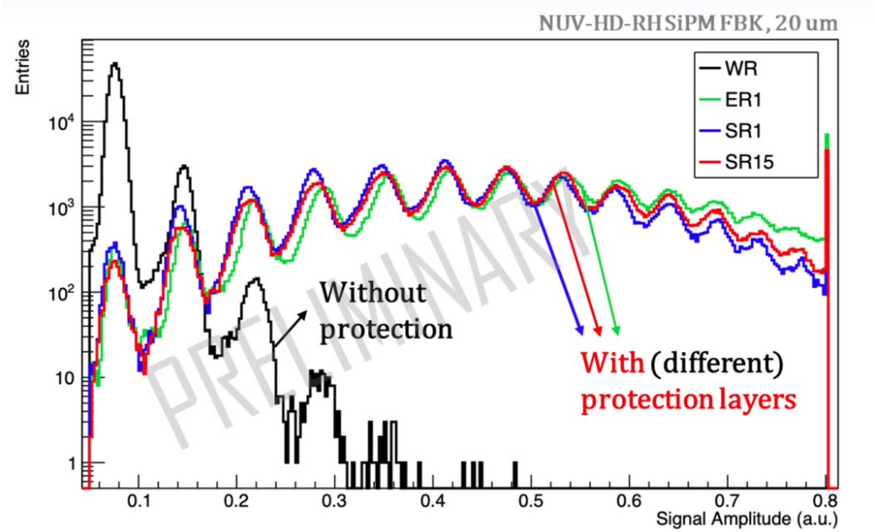
At the passage of a single charged particle very **high number of SPADs** fire (**https://dx.doi.org/10.1088/1748-0221/17/06/P06007)**

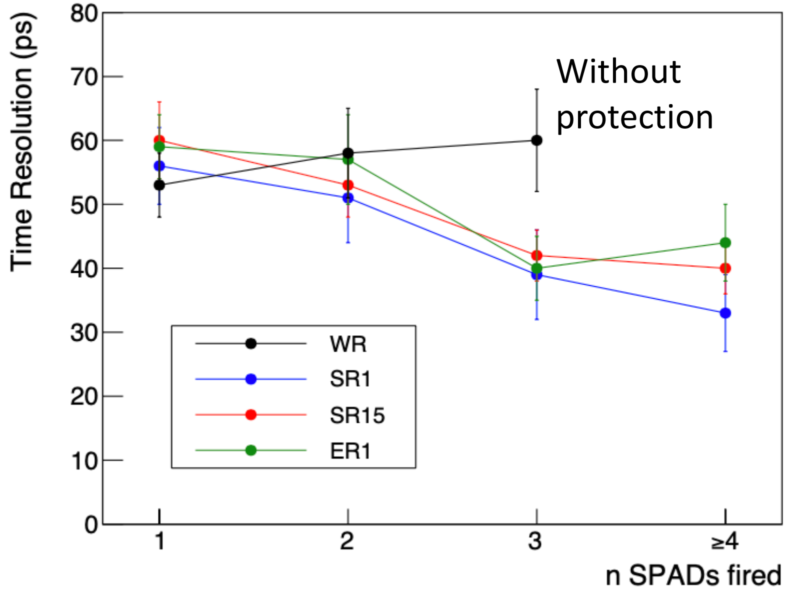
- Effect due to **Cherenkov light** produced in the protection layers **https://doi.org/10.48550/arXiv.2210.13244**

As a consequence:

- Higher **efficiency** (wrt what expected from simple Fill Factor, FF)
- And also **time resolutions** around/below 30 ps

Further step: exploit SiPM for TOF measurements by detection of Cherenkov photons produced in a thin window





Technology options

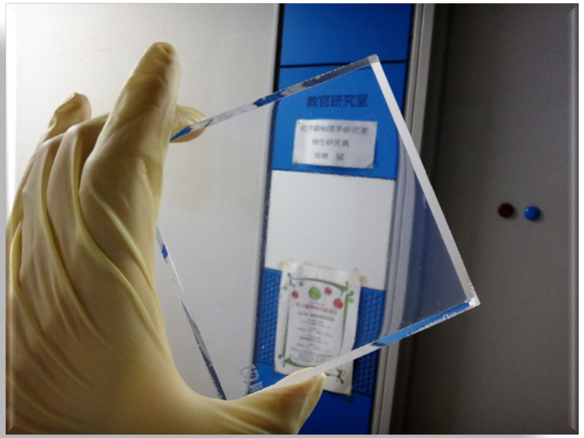
Aerogel radiator

- **Best match with PID requirements, large choice of refractive indexes**
- **Possibility to fine tune PID threshold and range**

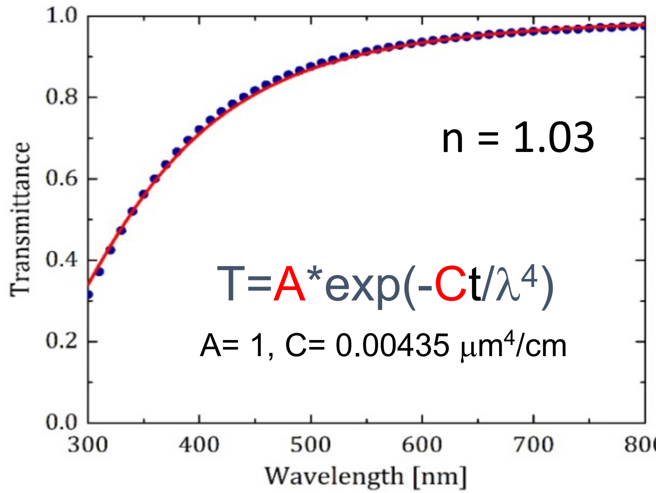
Cherenkov relation — *momentum threshold for Cherenkov emission*

$$\cos\vartheta_c = \frac{1}{n\beta} \rightarrow \beta_{th} = \frac{1}{n} \rightarrow p_{th} = \frac{m}{\sqrt{n^2-1}}$$

aerogel n	βth	momentum threshold [GeV/c]				
		e	μ	π	K	p
1.01	0.99009901	0.0036	0.7453	0.9845	3.4821	6.6181
1.02	0.98039216	0.0025	0.5257	0.6944	2.4561	4.6681
1.03	0.97087379	0.0021	0.4281	0.5656	2.0005	3.8021
1.04	0.96153846	0.0018	0.3699	0.4886	1.7282	3.2846
1.05	0.95238095	0.0016	0.3300	0.4359	1.5420	2.9307
1.06	0.94339623	0.0015	0.3005	0.3970	1.4042	2.6688
1.07	0.93457944	0.0013	0.2776	0.3667	1.2969	2.4649
1.08	0.92592593	0.0013	0.2590	0.3421	1.2102	2.3001
1.09	0.91743119	0.0012	0.2436	0.3218	1.1383	2.1634
1.14	0.87719298	0.0009	0.1930	0.2550	0.9019	1.7142



(M. Tabata – Chiba University)



Hydrophobic silica aerogel from Aerogel Factory Co. Ltd (Chiba, Japan):

- No degradation for exposure to humidity, easy storage
- Excellent transparency in the range 1.02-1.05
- Stable up to 10 Mrad

Technology options

Photon detector

Main requirements

- Single photon sensitivity in the visible range (Photon Detection Efficiency (PDE) > 40-50%)
- Integration fill factor > 90%
- Pixel ~ 3x3 mm^2 (down up to 1x1 mm^2)
- Time resolution σ < ~ 100 ps
- Magnetic field: up to 2 T
- Expected radiation load:

NIEL ~ 10^{12} 1-MeV n_{eq} /cm^2

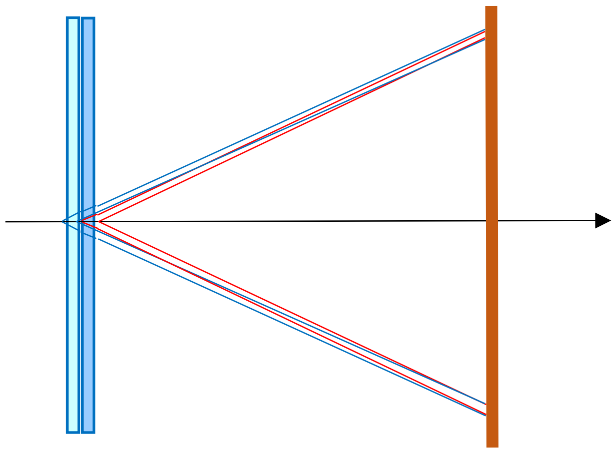
- **Vacuum-based devices (MCPs, LAPPDs)**
  - Single photon detection efficiency ~ 25-30%
  - Low noise and good radiation tolerance
  - Time resolution ~ 30 ps
  - ***Main limitations:***
    - Sensitivity to B (x10 gain drop above 0.5 T, no gain for ⊥ B)
    - HV operation
    - Bulky, reduced fill factor ~ 70%, large X_0
    - Cost of commercial devices
- **SiPM**
  - PDE ~ 50%
  - LV operation
  - Time resolution ~ 50 ps
  - ***Main limitations:***
    - Noise at room temperature, increase above 10^{11} 1-MeV n_{eq} /cm^2
    - Cost of commercial devices

Technology options

Aerogel focusing layout:

- Two or more aerogel layers with increasing n
- Aerogel layers @ 0.9 m from IP
- Photodetector @ 1.1 m
- Aerogel ≅ 22 m^2, p.d. ≅ 29 m^2

Alternative layouts

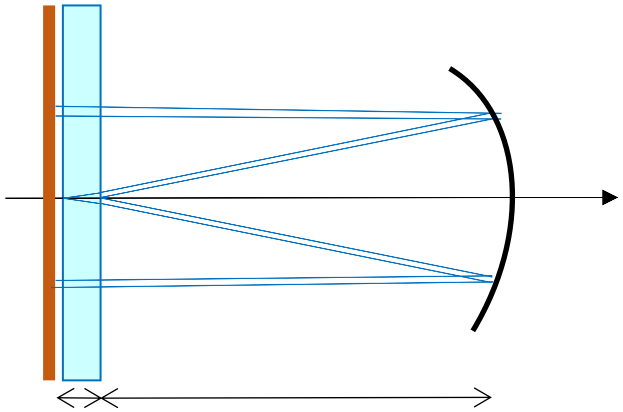


→ pro's:

- ○ photons produced in the second layer reach the pd @ same radius as the first one, thus reducing the geometric aberration error in saturation

Mirror layout:

- With or w/o aerogel focusing
- aerogel layers @ 0.95 m from IP
- photodetector @ 0.9 m
- Aerogel ≅ 22 m^2, p.d. ≅ 22 m^2



→ pro's:

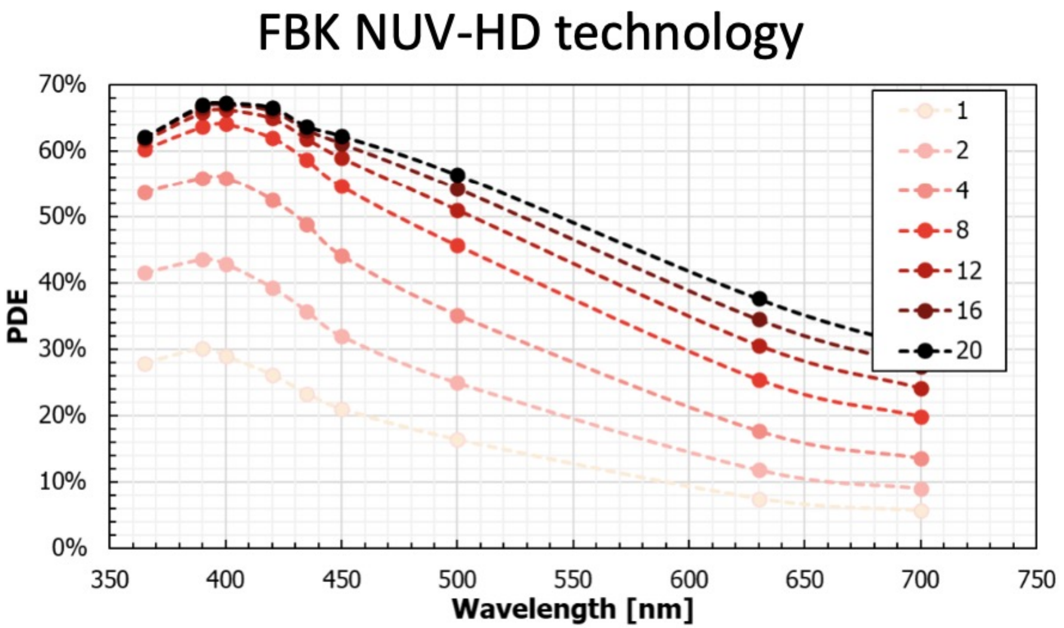
- ○ **Reduce/suppress geometric aberration** depending on mirror:
  - ○ flat: doubling of gap
  - ○ cylindrical: focusing in one direction + doubling of gap
  - ○ parabolic: full focusing
- ○ **reduce p.d. area by 60%**

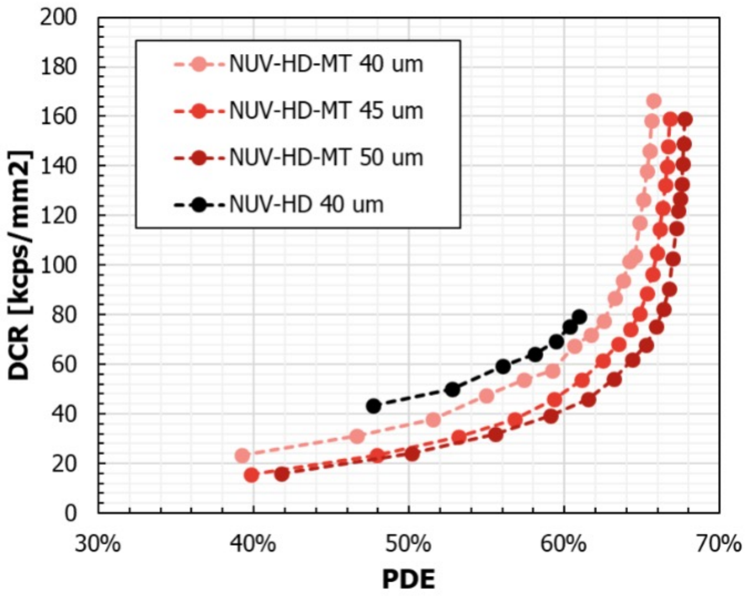
→ con's:

- ○ ~ 20% photon loss due to double crossing of aerogel and mirror reflection
- ○ spherical aberration and mirror alignment to be taken into account

R&D activities: photon detector

- All performance simulations have been based conservatively on commercial analogue SiPMs, while custom devices are already available with better PDE, DCR
- The access to customized SiPM opens the possibility of developing innovative technologies and detector applications
- Some key topics:
  - Single cell access (for screamer SPADs disabling and DCR reduction), active quenching (to improve fill factor and timing)
  - PDE improvement by: E-field engineering, A/R coating , max fill factor (BSI or micro-lenses)
  - DCR reduction by: E-field engineering, operation at lower V_{OV} if large enough PDE, cooling integration
  - Radiation hardness: cell layout, cooling/annealing
  - Timing performance, precise event time stamping for online and offline filtering (also w.r.t. DCR): cell layout



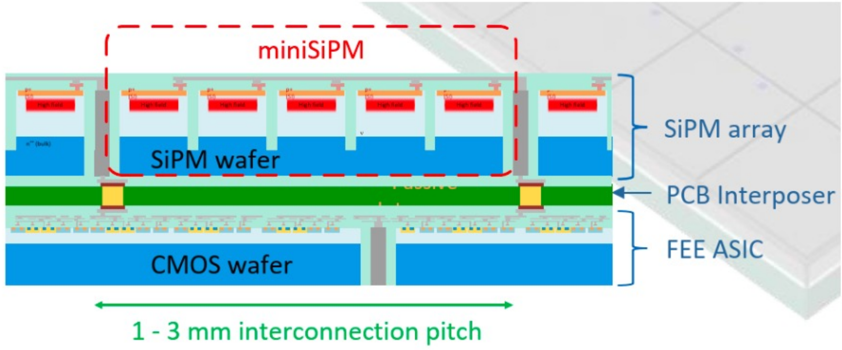


R&D activities: photon detector

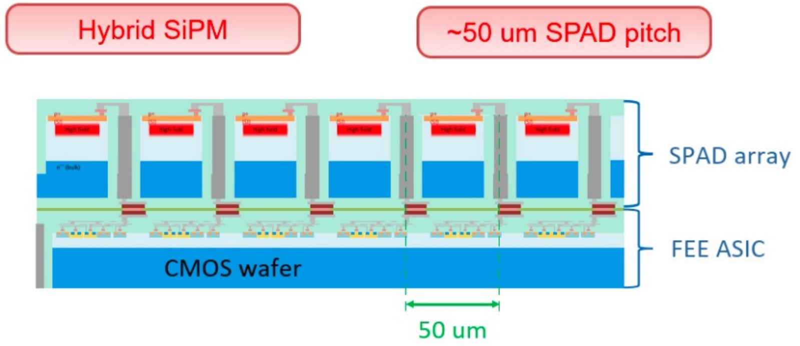
SiPM packaging

- Module size ~ 20.4x20.4 cm^2 (0.02 cm spacing between dies,) -> fill factor > 99%
- Area to be covered: ~ 30 m^2 -> ~ 750 modules (950 assuming 80% yield), 380000 SiPM dies (630000 SiPM dies assuming 60% yield)
- Packaging options:
  - 2D (monolithic digital SiPM, SPAD fill factor? PDE? DCR? RH?)
  - 2.5D (using silicon interposer or PCB)
  - 3D (wafer to wafer bonding, requires further assembly on PCB)
- Cooling/annealing circuit embedding in PCB or silicon interposer (linked to DCR and radiation hardness)

2.5 D



3 D



First CMOS SPAD engineering run to LFoundry/FBK

Area: 15 mm^2

Price unit: 2520 €

FBK SPAD License fee for one time usage on MPW: 8400 €