Plans and developments for Cherenkov PID upgrade for ALICE 3

ALICE, EIC, LHCb Meeting
April 25th, 2023

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on behalf of the ALICE 3 RICH WG

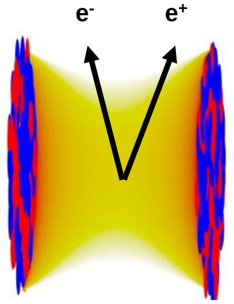
Outline

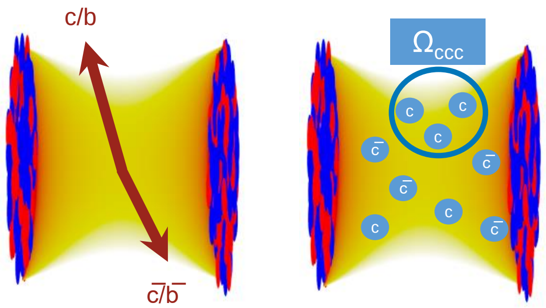
- Introduction to ALICE 3 and PID requirements
- RICH layout and performance studies in Geant4
- R&D topics
- Plans

ALICE 3: phase IIb upgrade for LHC Run 5 & 6

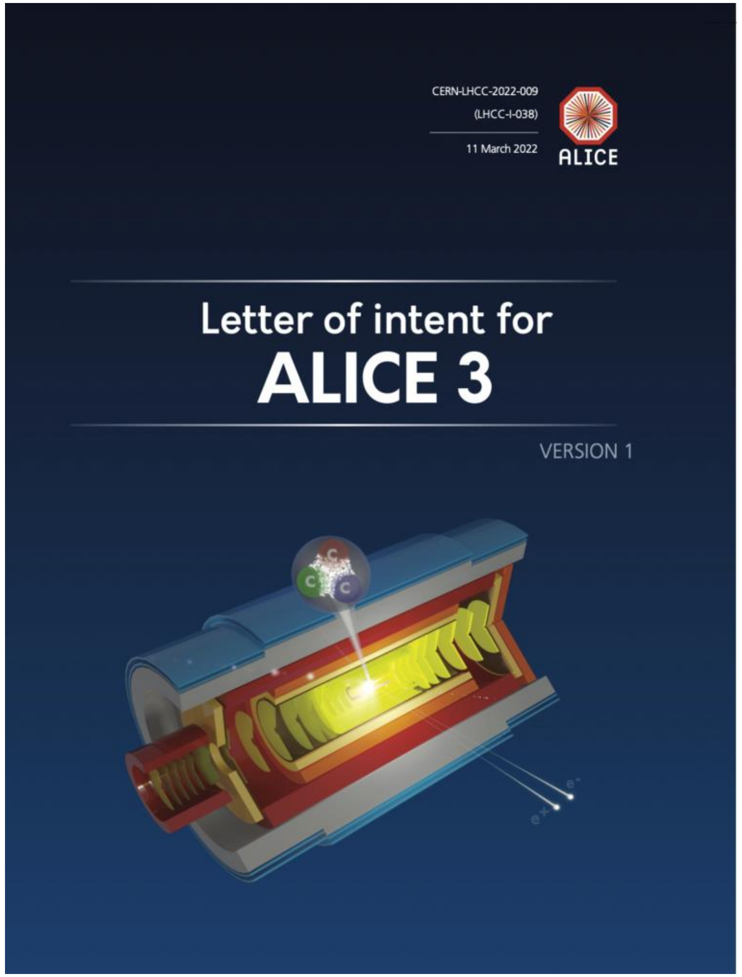
Key physics questions and drivers

- **precision measurements of dileptons**
  - ➟ evolution of the quark gluon plasma
  - ➟ mechanisms of chiral symmetry restoration in the quark-gluon plasma
- **systematic measurements of (multi-)heavy-flavoured hadrons**
  - ➟ transport properties in the quark-gluon plasma
  - ➟ mechanisms of hadronisation from the quark-gluon plasma
- **hadron correlations**
  - ➟ interaction potentials
  - ➟ fluctuations
- …





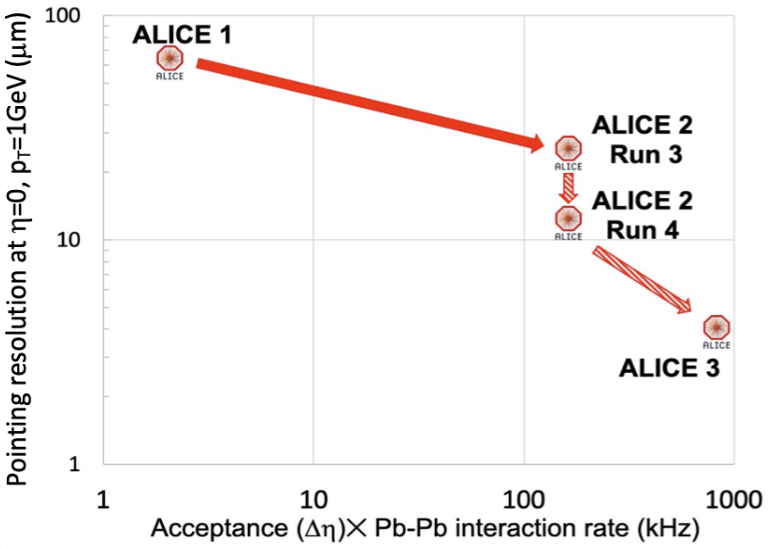
➡ Heavy-ion collisions at the LHC are ideal to address these questions, but require improved detector performance and statistics.

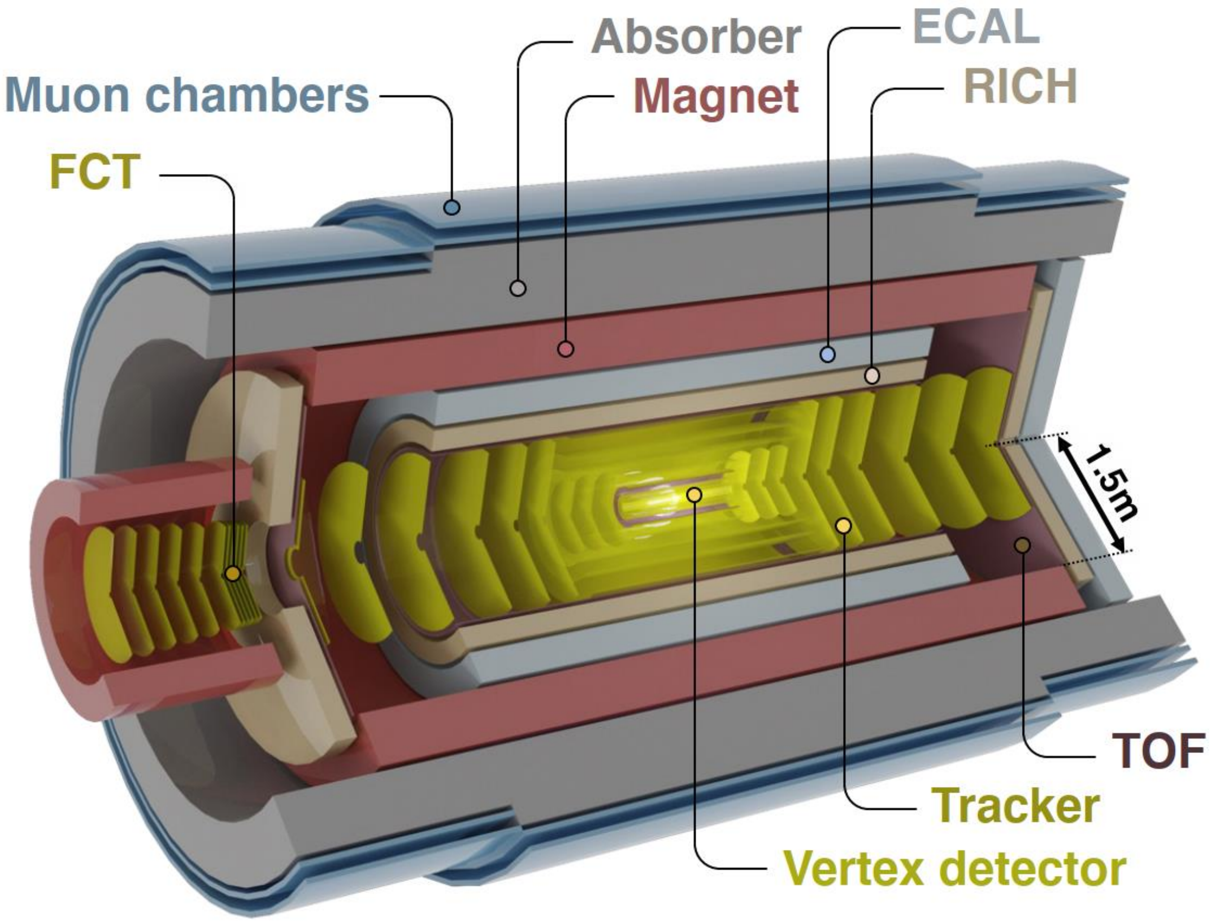


CERN-LHCC-2022-009

The ALICE3 detector

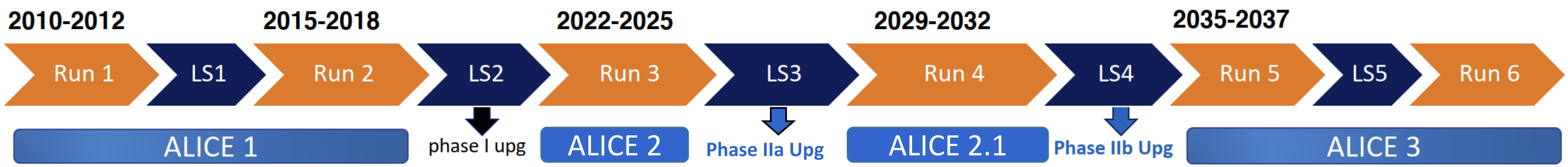
- High-efficiency for heavy-quark identification and reconstruction of low-mass dielectrons
- Compact all-silicon tracker with unprecedently low material budget, with retractable vertex detector (tracking precision x 3: 10µm at p_T = 200 MeV)
- Large acceptance with excellent coverage down to low p_T (acceptance x 4.5: $|\eta| < 4$)
- Extensive particle ID
- Superconducting magnet system
- Continuous readout and online processing (A-A rate x 5, pp x 25)





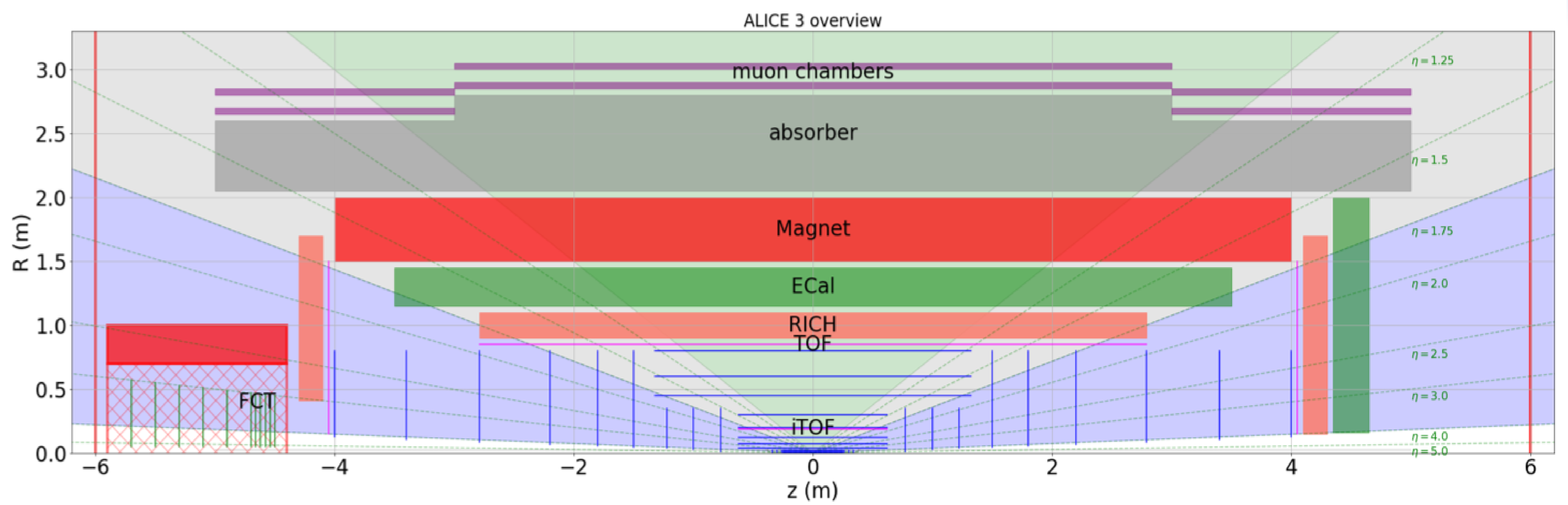
innovative technologies relevant for future HEP experiments

ALICE Phase IIb Upgrade Timeline



- 2023 – 2025: selection of technologies, small-scale proof of concept prototypes (~25% of R&D funds)
- 2026 – 2027: large-scale engineered prototypes (~75% of R&D funds) ➡ **Technical Design Reports**
- 2028 – 2030: construction and testing
- 2031 – 2032: contingency
- 2033 – 2034: installation and commissioning
- 2035 – 2042: physics campaign

ALICE 3 charged PID system



Barrel inner (outer) TOF:
- η = ±1.75 (± 1.75)
- L = 1.24 (5.6) m
- R = 0.19 (0.85) m

Barrel RICH:
- η = ±1.75
- L = 5.6 m
- R = 0.90-1.12 m

Barrel Muon-ID:
- η = ±1.3
- L = 10 m
- R = 2.8 m

Forward TOF Ecal (FCT) side:
- +1.75 (-4.0) ≤ η ≤ +4.0 (-1.75)
- Z = +4.05 (-4.05) m
- R = 0.15 (0.15) - 1.5 (1.5) m

Forward RICH Ecal (FCT) side:
- +1.75 (-3.0) ≤ η ≤ +4.0 (-1.75)
- Z = +4.10 (-4.10) m
- R = 0.15 (0.5) - 1.5 (1.5) m

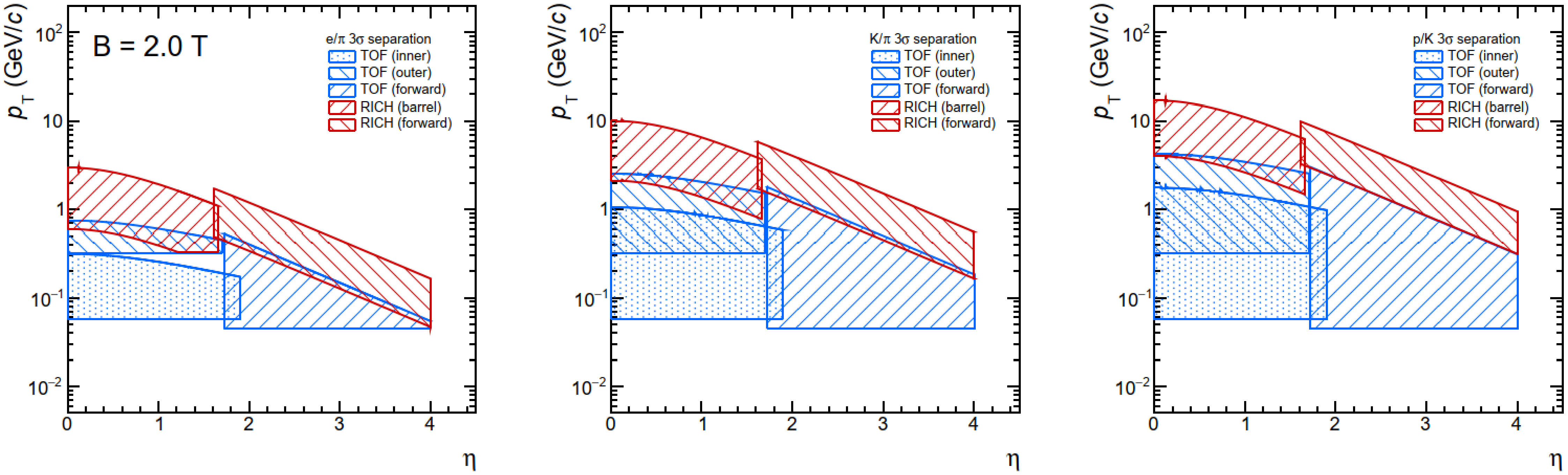
ALICE 3 charged PID requirements

Component	Observables	Barrel ($\|\eta\| < 1.75$)	Forward($1.75 < \|\eta\| < 4$)	Detectors
Hadron ID	(Multi-)charm baryons	π/K/p up to ~10 GeV/c		• TOF: σ_{TOF} ~ 20 ps • bRICH: n=1.03, σ_{θ} ~ 1.5 mrad • fRICH: n=1.006-1.03, σ_{θ} ~ 1.5 mrad
Electron ID	Dielectrons, quarkonia, $X_{c1}(3872)$	π rejection by 1000x up to 2-3 GeV/c		• TOF: σ_{TOF} ~ 20 ps • bRICH: n=1.03, σ_{θ} ~ 1.5 mrad
Muon ID	Quarkonia, $X_{c1}(3872)$	Muons from p_T ~ 1.5 GeV/c at η=0		Steel absorber: L ~ 70 cm, muon detector (scintillators)

RICH systems in the LoI: motivations

Extend electron and charged hadron ID at p 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 radiator (2cm, n=1.03) + 20 cm expansion gap + SiPM photodetector**
- **Forward RICH: idem, but lower n**



Results from “fast” parametric simulation, assuming a Cherenkov angle resolution at saturation of 1.5 mrad

Aerogel Cherenkov radiator

Cherenkov relation — *momentum threshold for Cherenkov emission*

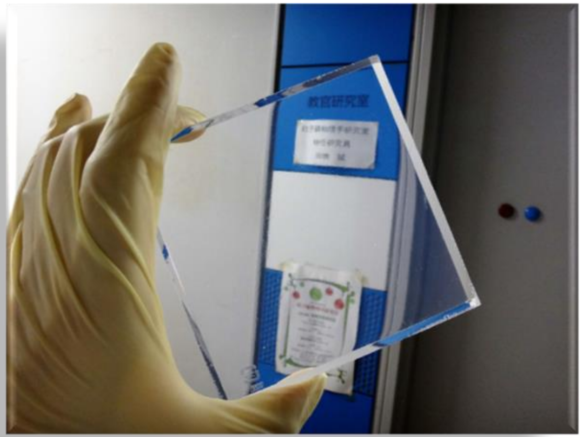
$$\cos\vartheta_c = \frac{1}{n\beta} \rightarrow \beta_{th} = \frac{1}{n} \rightarrow p_{th} = \frac{m}{\sqrt{n^2 - 1}}$$

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

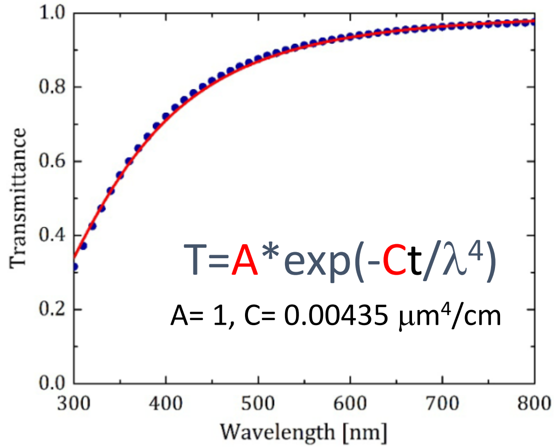
Hydrophobic silica aerogel from Aerogel Factory Co. Ltd (Chiba, Japan):

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

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



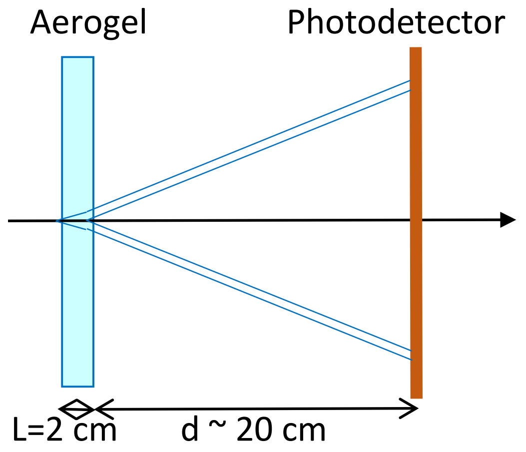
(M. Tabata – Chiba University)



Barrel RICH layout options

Proxmity focusing layout:

- Single radiator layer
- Cylindrical geometry

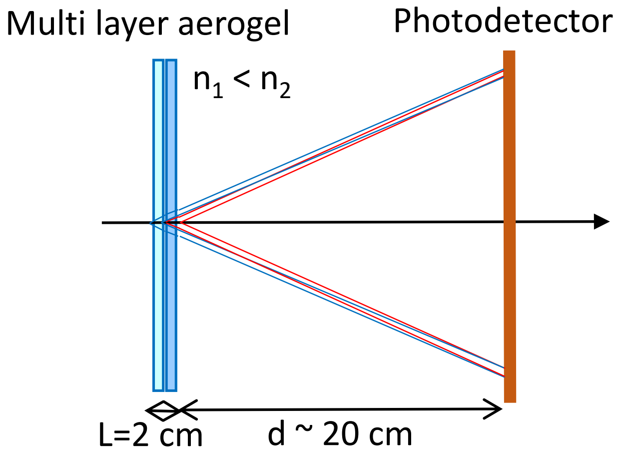


→ con's:

- Angular resolution dominated by geometrical aberration

Aerogel focusing layout:

- Two or more aerogel layers with increasing refractive index



→ pro's:

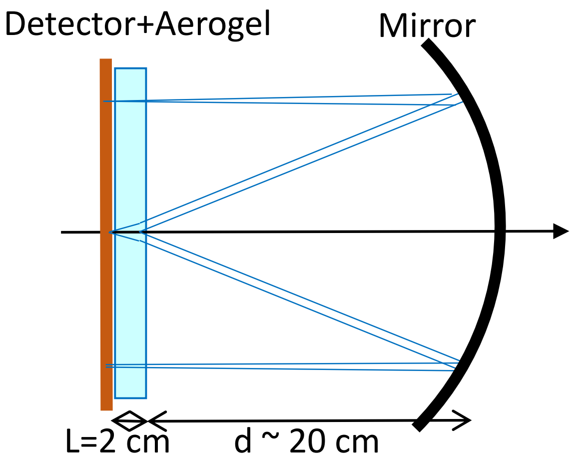
- Photons produced in the second layer reach the pd @ same radius as the first one, thus reducing the geometric aberration error at saturation

→ con's:

- Fine tuning of focusing layer indices vs track inclination must be taken into account

Mirror focusing layout:

- Spheric/parabolic mirrors
- Projective geometry



→ pro's:

- **Reduce/suppress geometric aberration**
- **Reduce p.d. area**

→ con's:

- ~ 30% photon loss due to double crossing of aerogel and mirror reflection
- spherical aberration and mirror alignment to be taken into account

The 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 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 X0
    - Cost
- **SiPM**
  - PDE ~ 50%
  - LV operation
  - Time resolution ~ 50 ps
  - ***Main limitations:***
    - Noise at room T, increase above 10^{10} MeV n_{eq} /cm^2
    - Cost (but lower than vacuum-based)

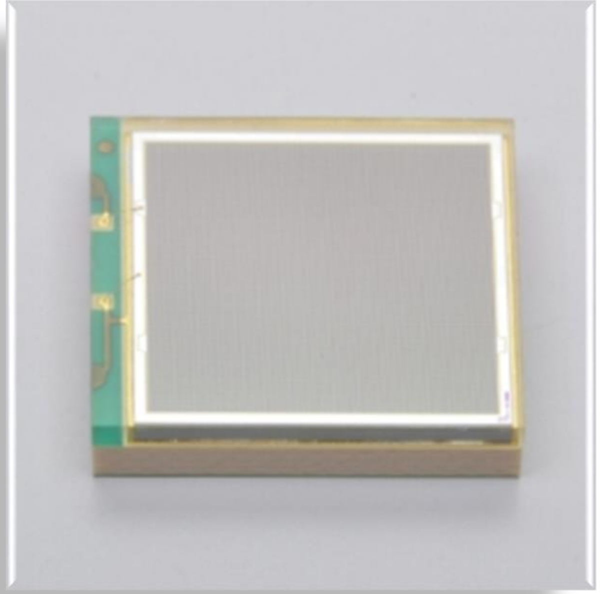
The photon detector

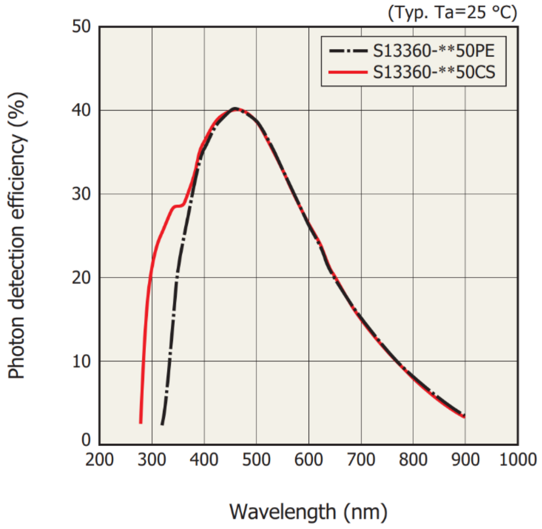
Example: SiPM HPK 13360 3050CS

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

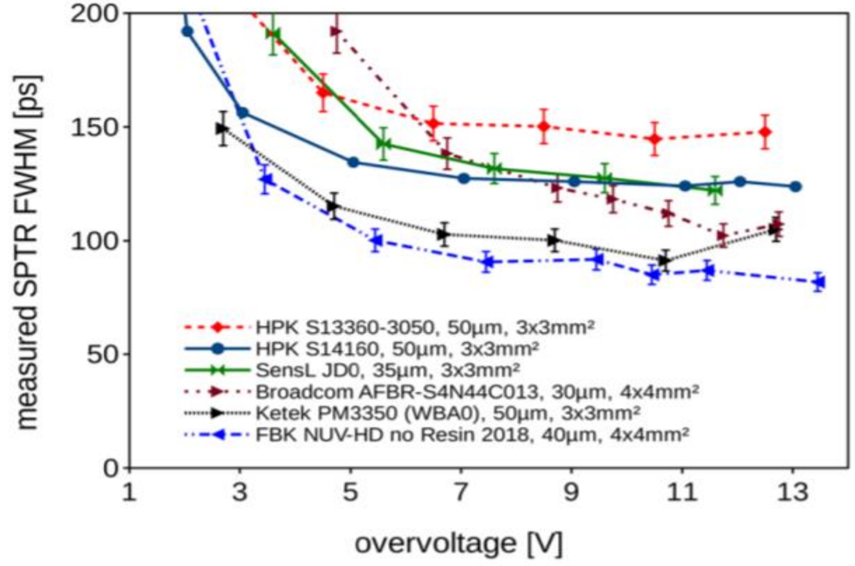
Main requirements

- Single photon sensitivity in the visible range (Photon Detection Efficiency (PDE) > 40-50%)
- Integration fill factor > 90%
- Pixel ~ 3x3 mm^2 (down 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





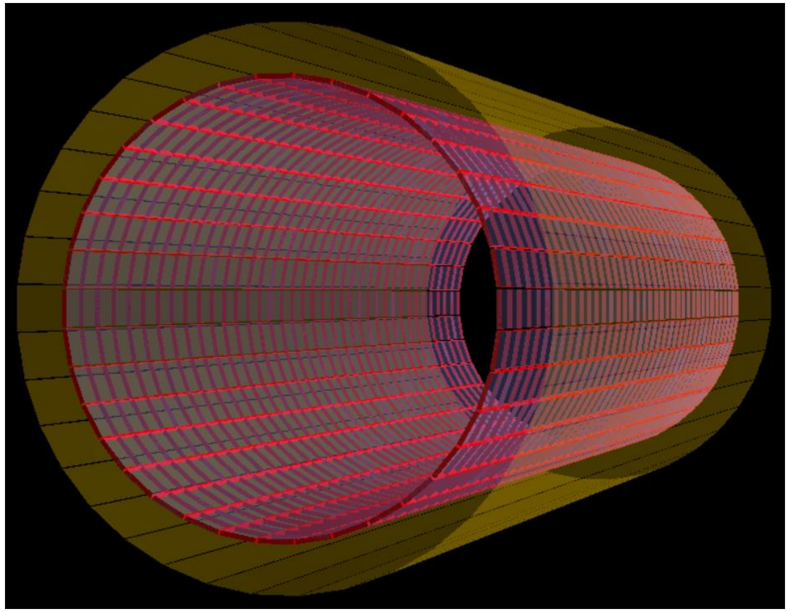
Stefan Gundacker et al 2020 Phys. Med. Biol. 65 025001



Proximity focusing studies summary

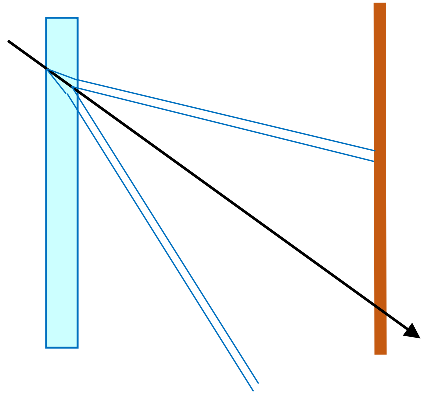
Detector parameters for Geant4

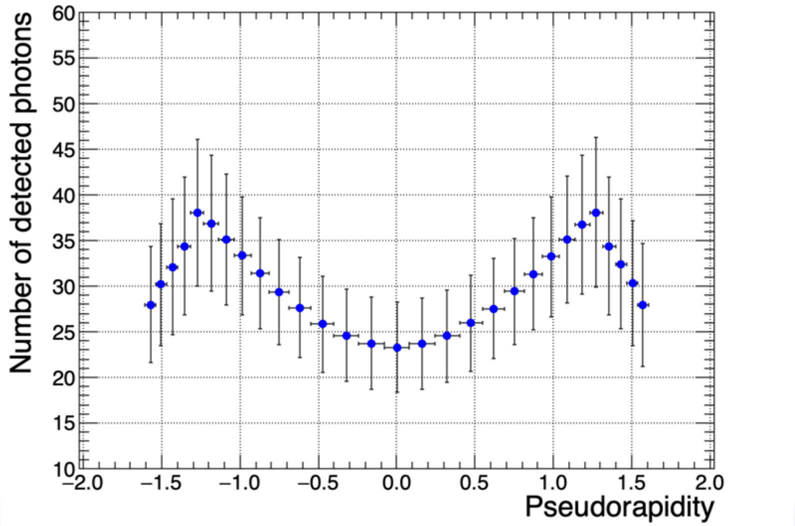
- R = 0.90-1.12 m, $|\Delta z|<2.8$ m
- 37(z) x 36 (r ϕ) tiles:
  - Radiator: 15 cm x 15 cm
  - SiPM layer: 15 cm x 19 cm
- Aerogel: T = 2 cm, n = 1.03 @ 400 nm
- SiPM pixel size: 3 x 3 mm^2
- Photosensitive area: **38 m^2**

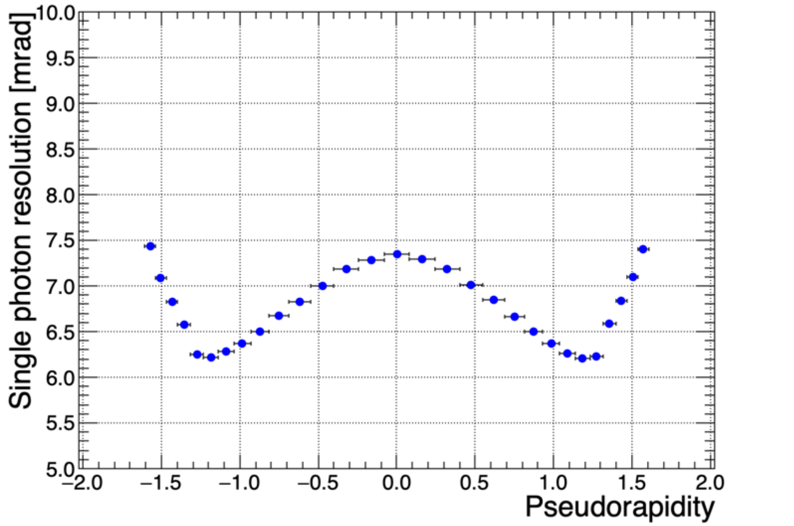


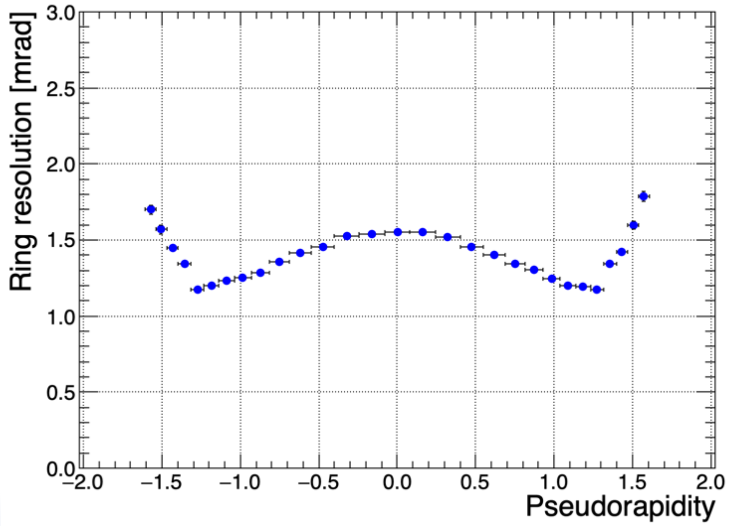
Performance η dependence, for very inclined tracks:

- geometric aberration increase
- photon losses





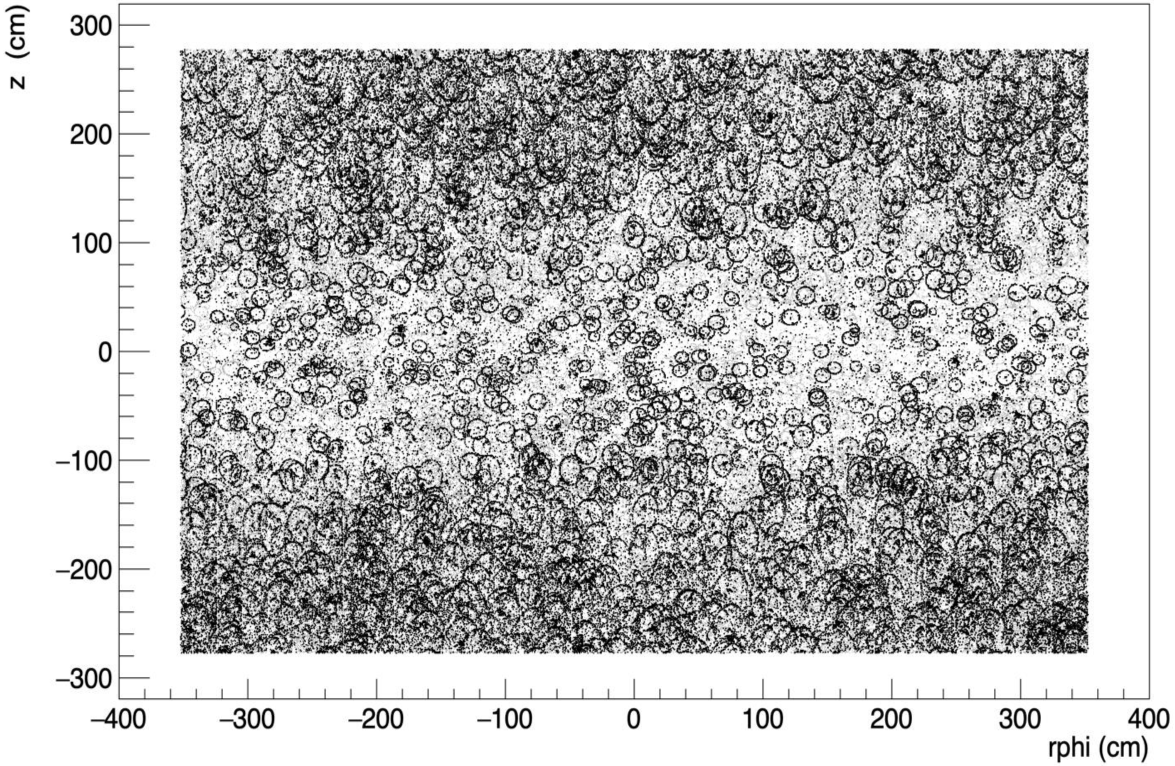




Proximity focusing studies summary

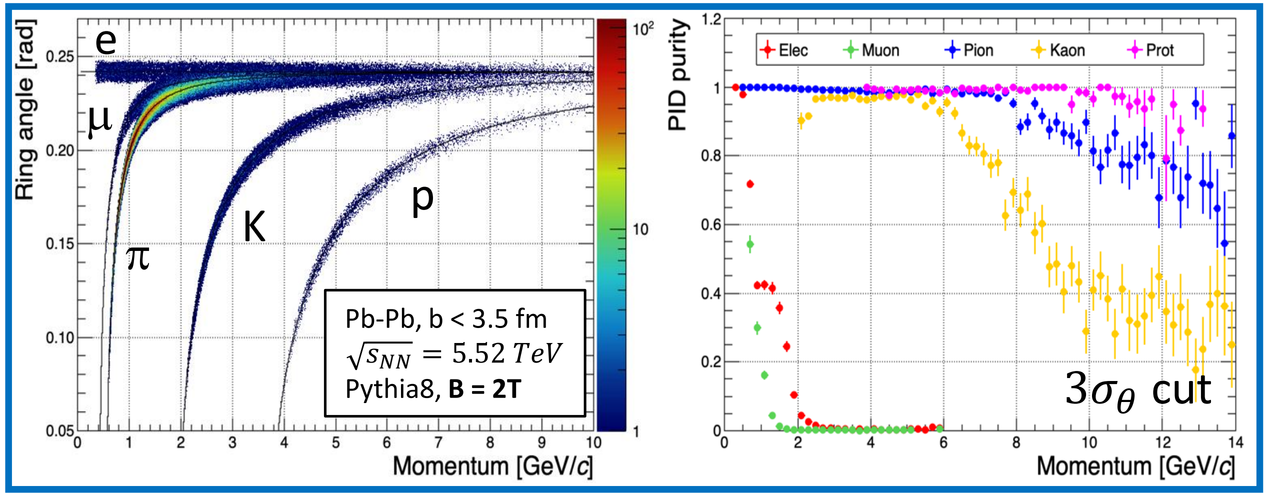
Performance in central Pb-Pb collisions

Single Pb-Pb central event, B= 2T



Selection cuts

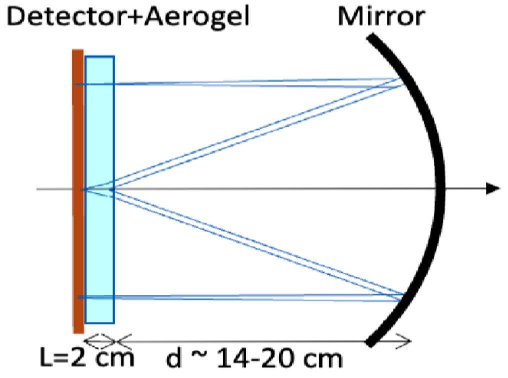
- Timing (2σ cut)
- Hough transform cut ($N_{ph,min}$ variable with track sector)

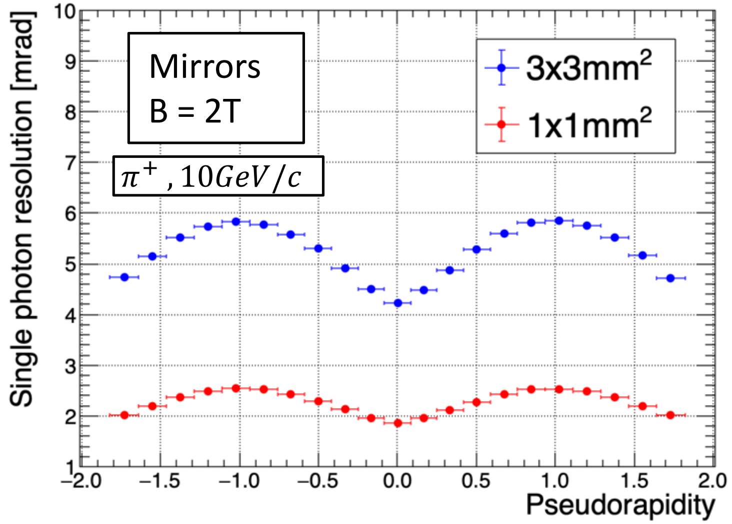


Mirror focusing studies summary

Detector parameters

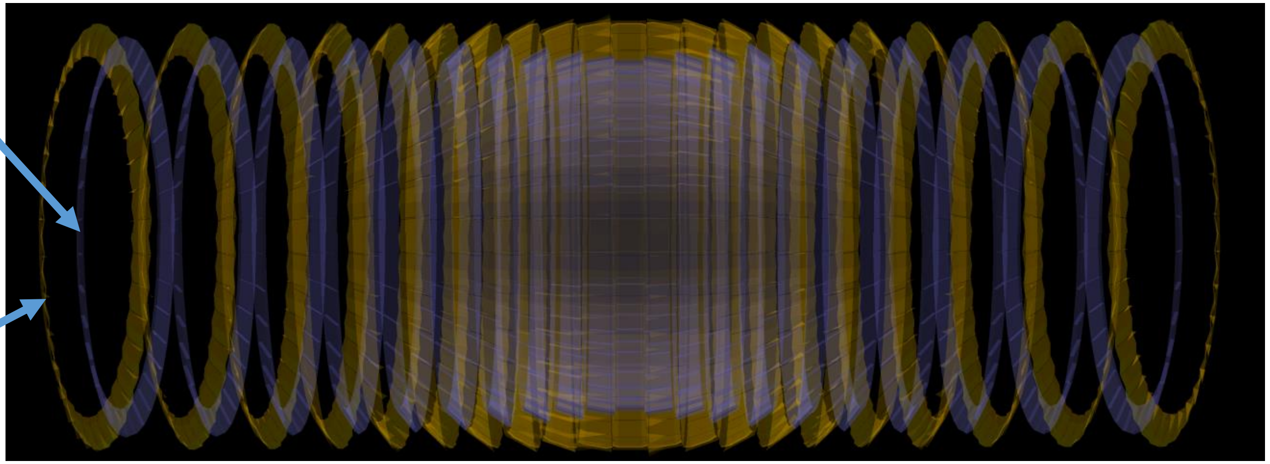
- **Projective layout** with hermeticity to tracks
- Variable mirror radius to keep ΔR = 22 cm for all sectors
- 36 sectors in rϕ, 21 sectors in Z
- 3x3 and 1x1 mm pixels
- Photosensitive area: **18.5 m^2**

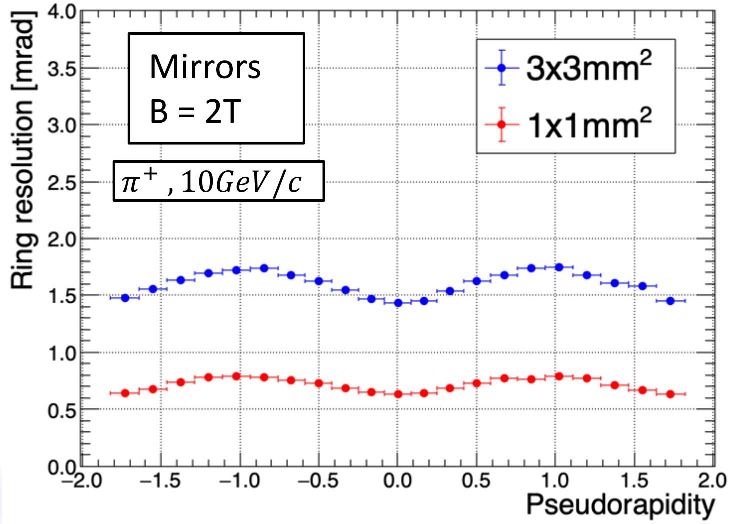




Radiator + Photodetector

Mirror

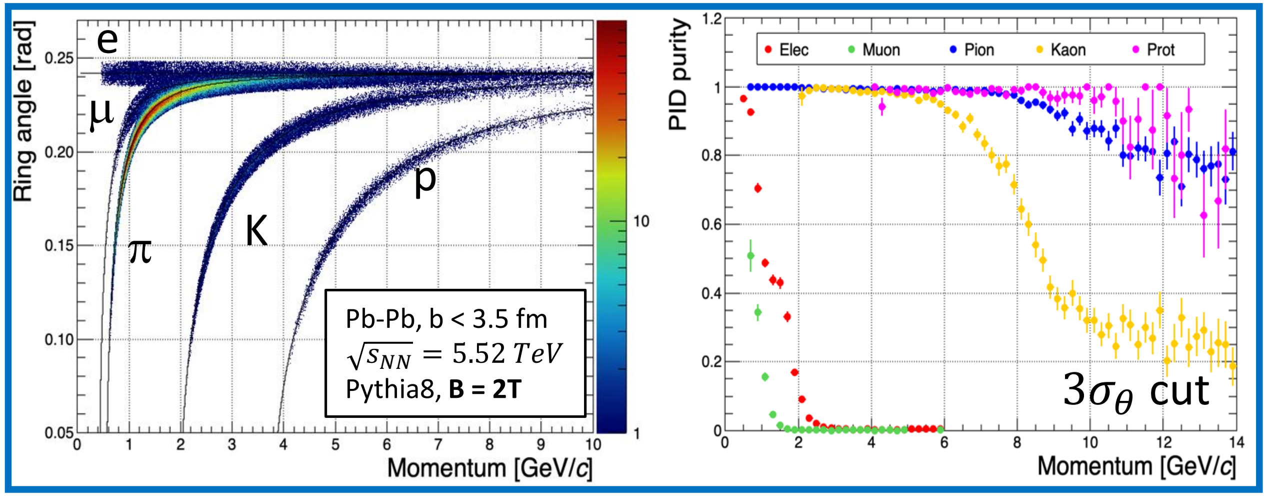




Mirror focusing studies summary

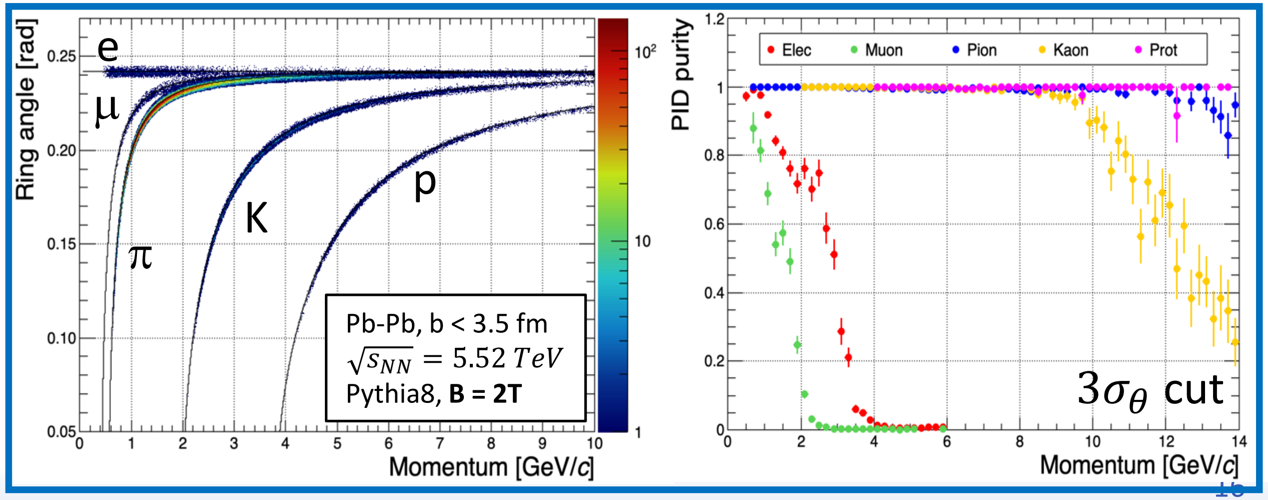
Performance in central Pb-Pb collisions

Mirror layout, **3x3 mm2** cells



Similar to proximity focusing due to lower photon detection

Mirror layout, **1x1 mm2** cells



Better performance by pixel error reduction (dominant)

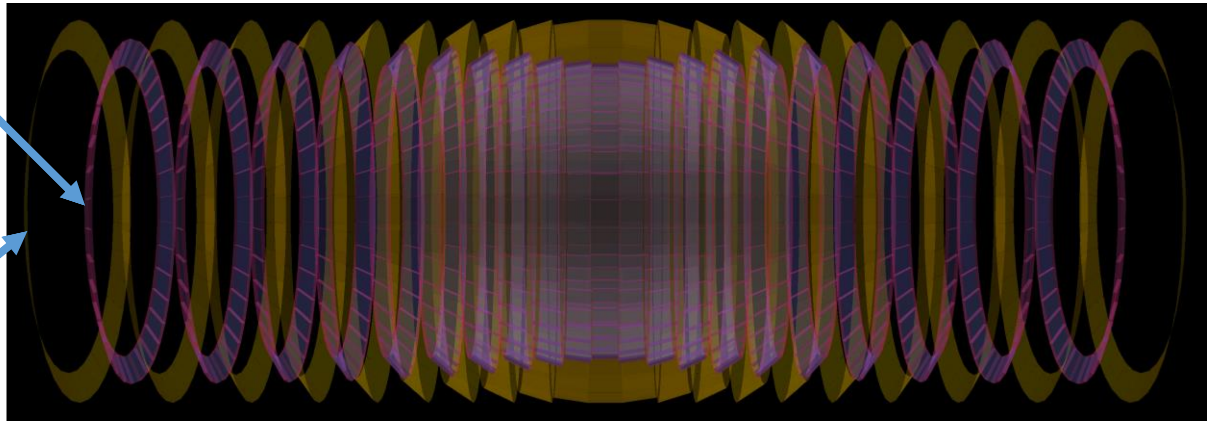
Proximity focusing TOF+RICH – Projective

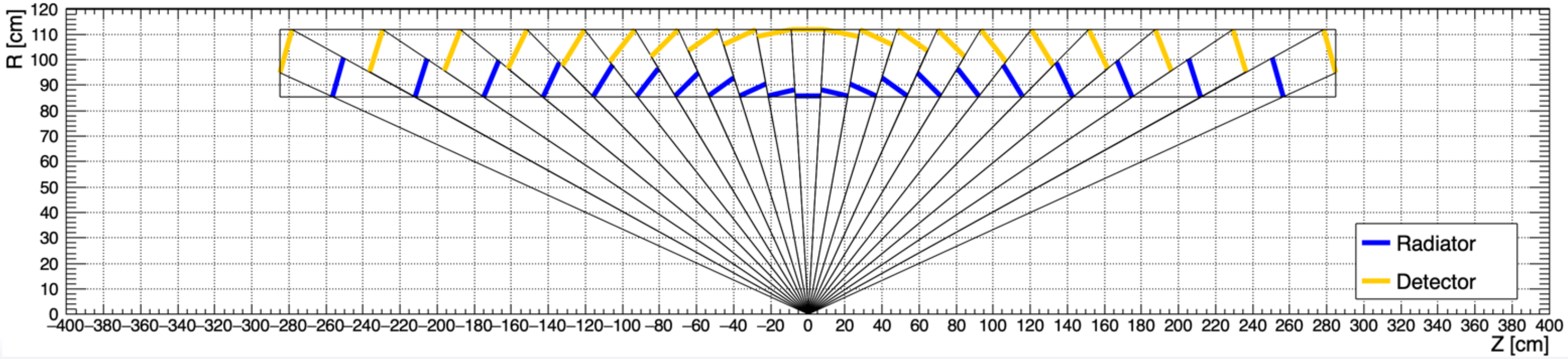
Detector parameters

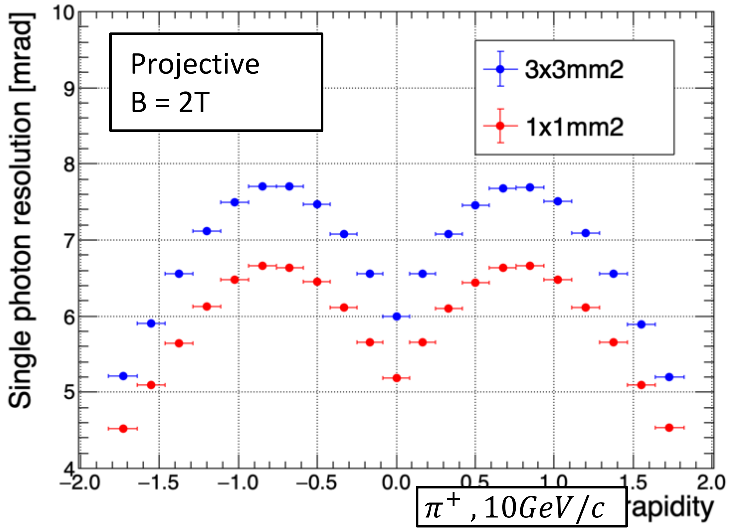
- **Projective layout** with hermeticity to tracks
- Use TOF volume and increase proximity gap to 25 cm
- 1mm SiO_2 window coupled to SiPMs for TOF
- 36 modules in r ϕ, 21 sectors in Z
- Photosensitive area: **25.7 m²**

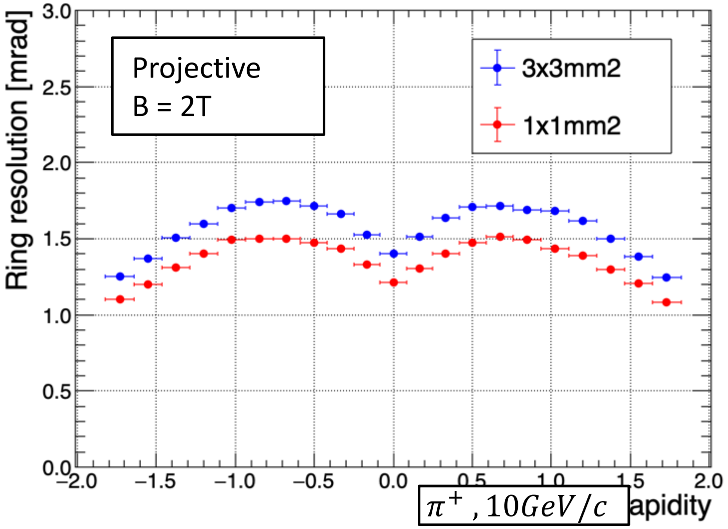
Radiator

SiPM





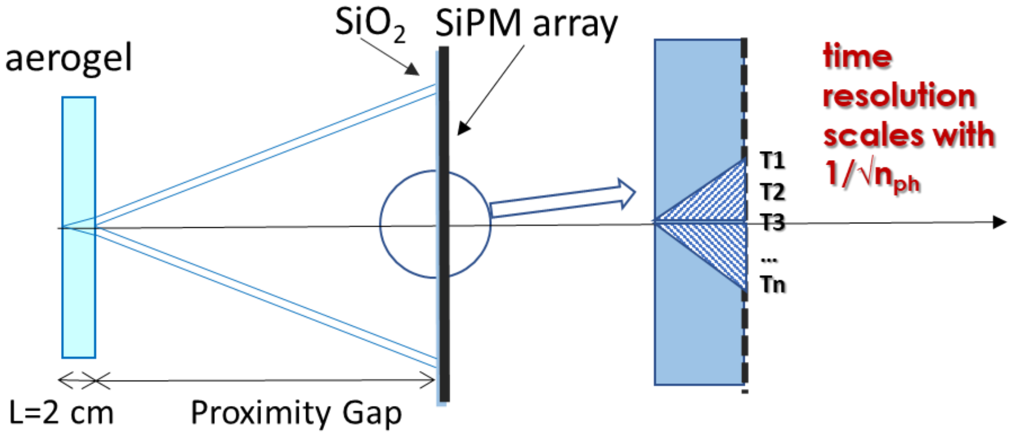




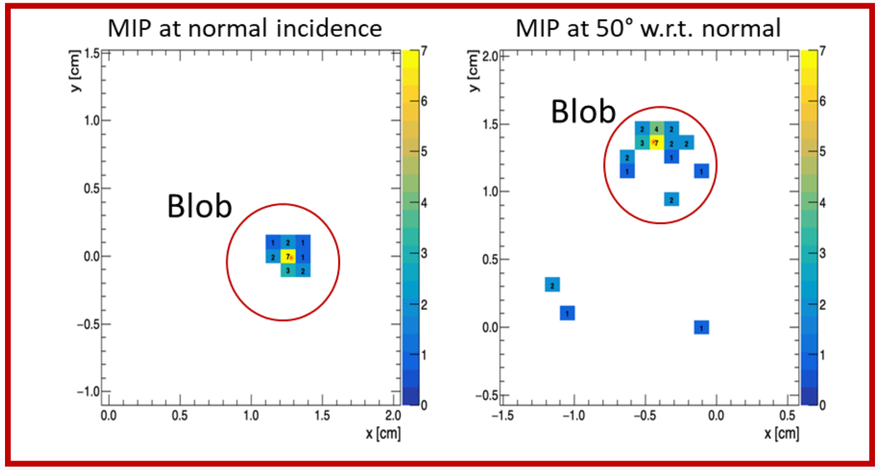
TOF measurement in RICH SiPMs

Layout option under study:

- 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)

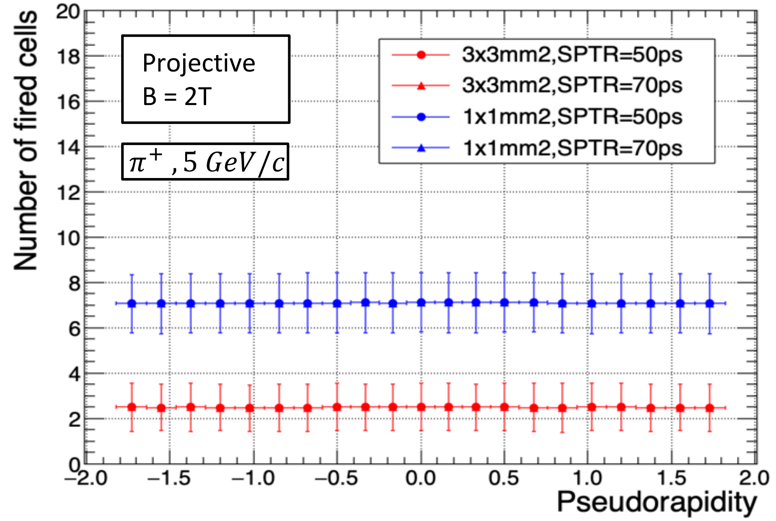


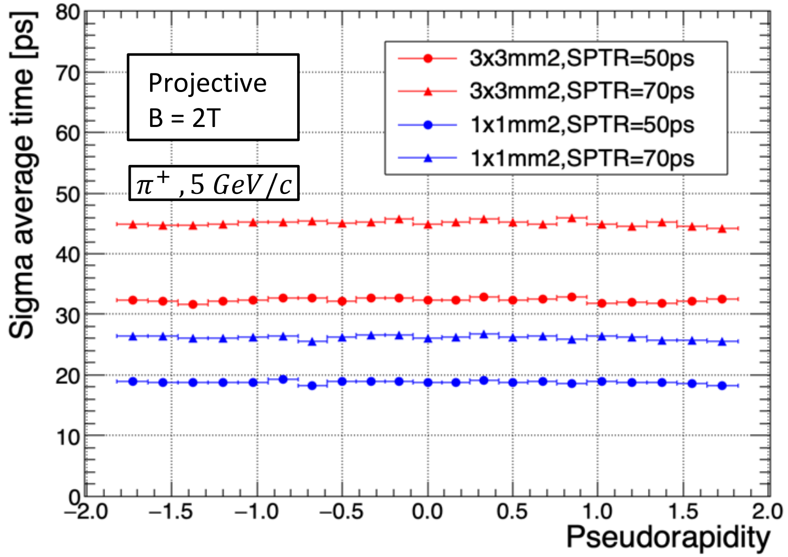
Geant4 simulation



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

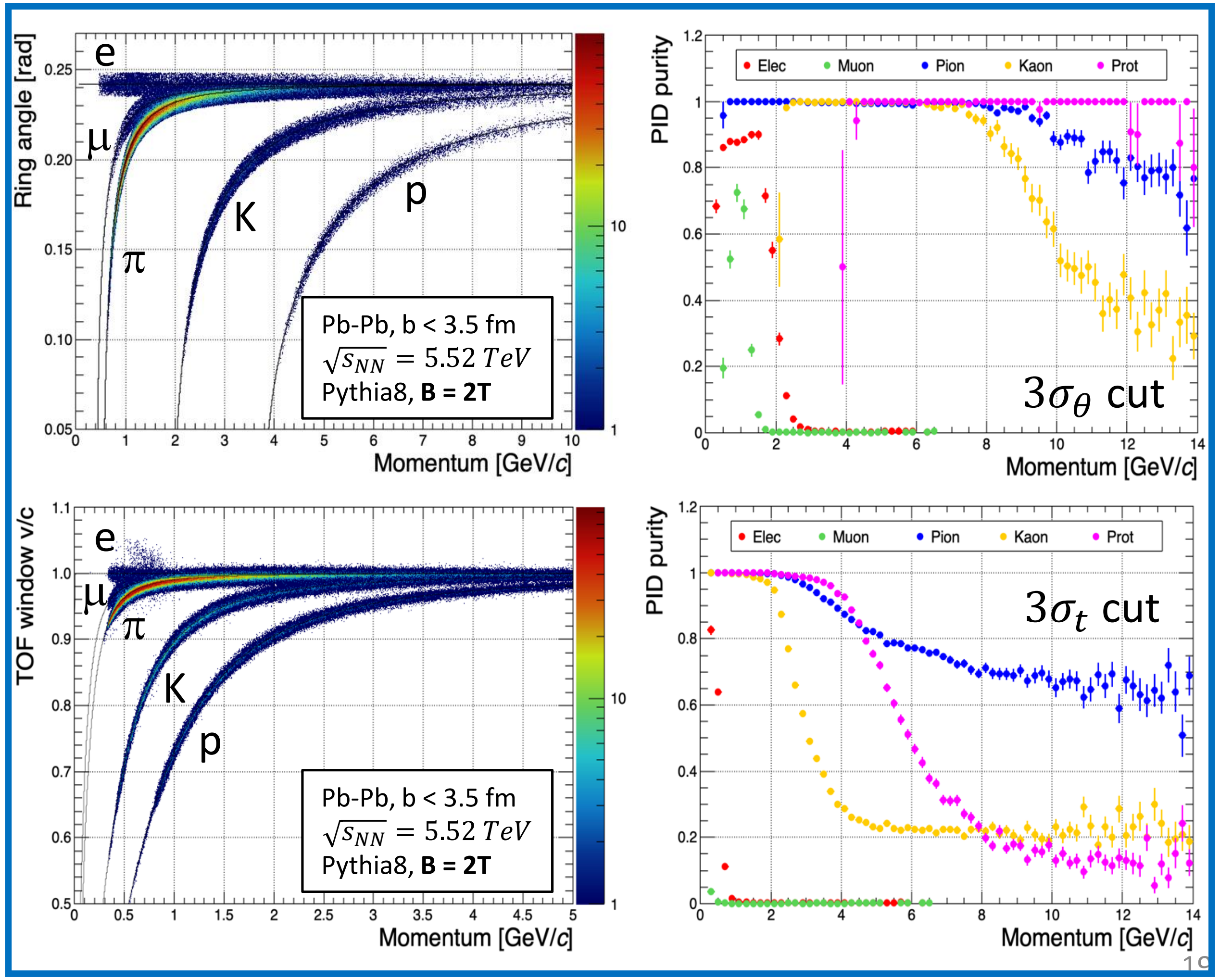
1 mm SiO_2 + 0.45 mm epoxy resin





Proximity focusing TOF+RICH – Projective

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



e-PID range extension

Goal

- Extend electron identification above 4 GeV/c

  Required for physics channels involving e.g. J/ψ→ e^+e^-

Strategy

- Implement gaseous radiator having n ≈ 1.0006
- Gaseous radiators having large GWP (CF4, C4F10, …) must be avoided

E.g.: SLD CRID approach on a $C_5F_{10}O + N_2$ mixture

- From molar frac.s $w_{1,2}$ to n of a gas mixture: $n_{mix} = w_1 n_1 + w_2 n_2$
- $n_{mix} = 1.0006 \Rightarrow w_{C5F10O} = 20\%,\ w_{N2} = 80\%$

ECal-less scenario

- Barrel ECal radial dimensions in the LoI: 1.15-1.45 m
- Possibility to increase the RICH proximity gap to 30-35 cm

(and reduce magnet radius from 1.50 m to ≈1.35 m !!!)

ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

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A sonar-based technique for the ratiometric determination of binary gas mixtures ☆

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Received 25 March 1987, Revised 17 September 1987, Available online 28 October 2002.

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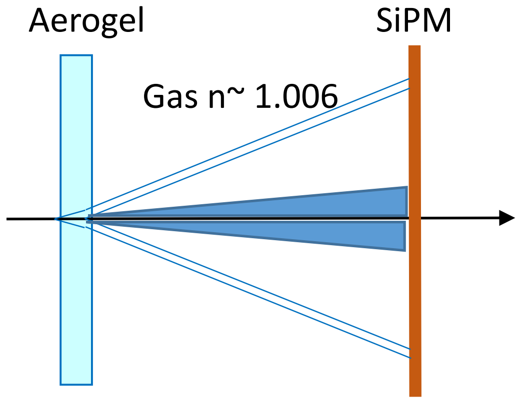
Abstract

We have developed an inexpensive sonar-based instrument to provide a routine on-line monitor of the composition and stability of several gas mixtures having application in a Cherenkov Ring Imaging Detector. The instrument is capable of detecting small (<1%) fluctuations in the relative concentration of the constituent gases and, in contrast with some other gas analysis techniques, lends itself well to complete automation.

e-PID range extension

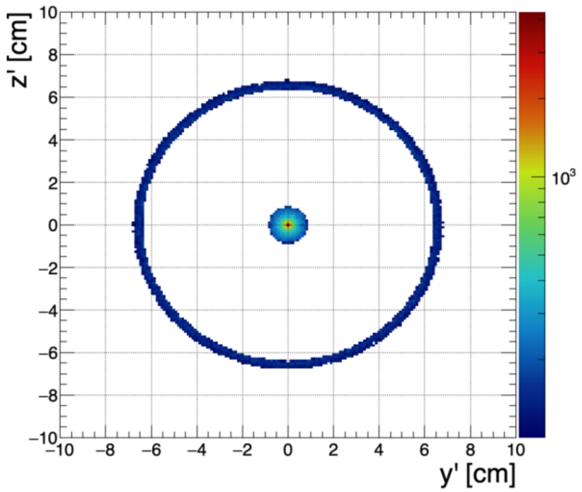
e-ID by threshold
(presence of photons blob around MIP track)

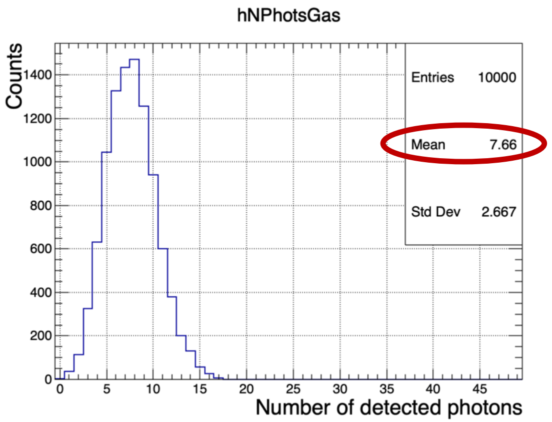


Cherenkov emission threshold in GeV/c

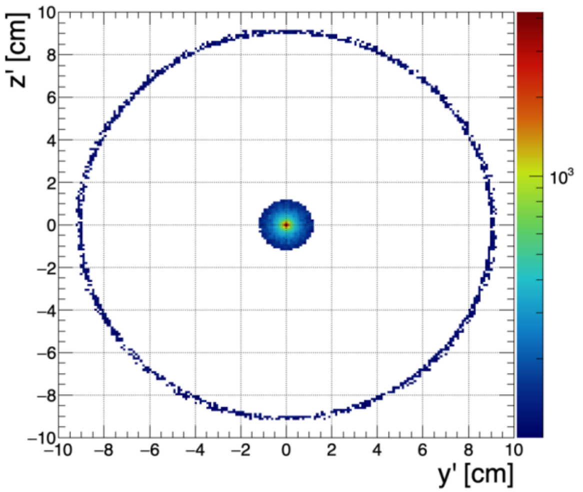
n	βth	e-	μ	π	K	p
1.0006	0.9994	0.014749	3.049626	4.028433	14.24909	27.08153
1.0005	0.9995	0.0162	3.3408	4.4130	15.6095	29.6671

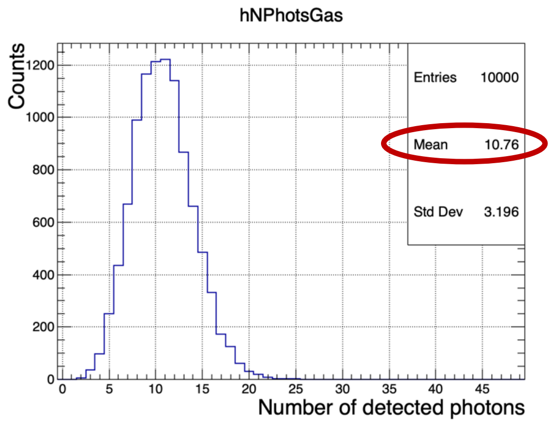
e^-, p = 3 GeV/c, **25 cm** gap, 1x1 mm^2



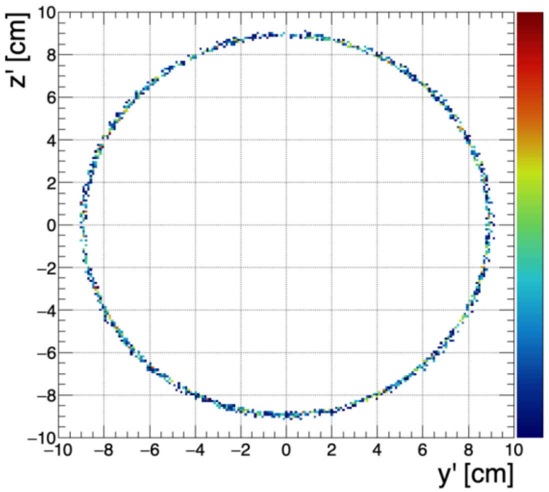


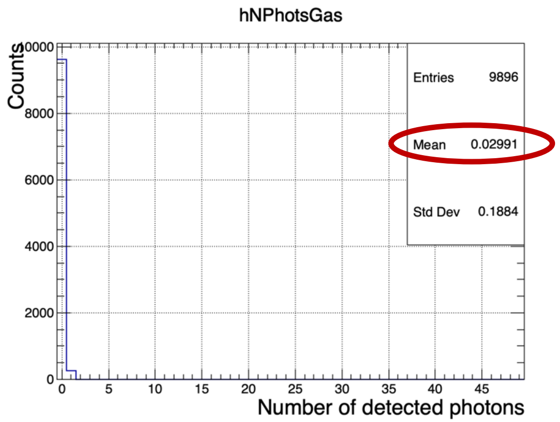
e^-, p = 3 GeV/c, **35 cm** gap, 1x1 mm^2





π^-, p = 3 GeV/c, **35 cm** gap, 1x1 mm^2





e-PID range extension

Pb-Pb central collisons

Projective Layout (ΔR = 35 cm): 2 cm **Aerogel** (1.03) + **Gas** (1.0006) + 1 mm **SiO_2** window (1.47) + 0.45 mm **Epoxy resin** (1.55)

Aerogel information

- Hit timing cut: $2\sigma_t$ matching with track
- Hough transfrom cut: $N_{ph,min} \geq 12$
- PID Above C.kov threshold: $3\sigma_\theta$ cut

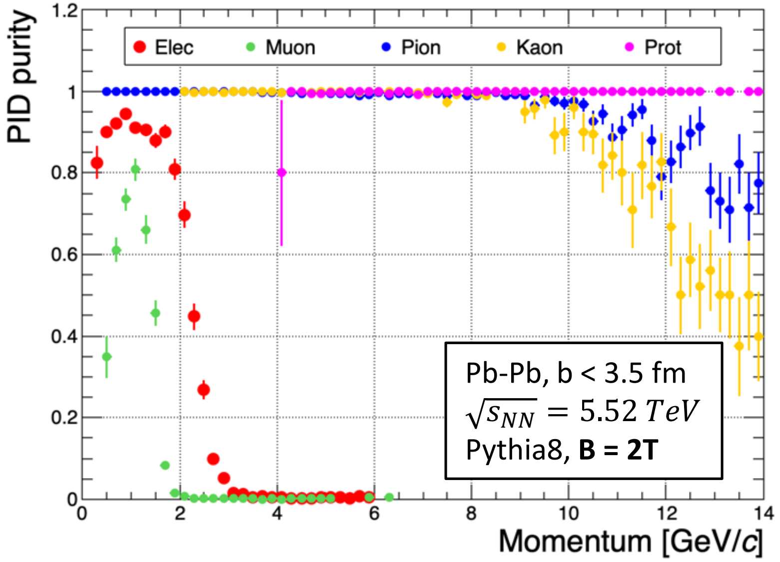
Aerogel + Gas information

- Hit timing cut: $2\sigma_t$ matching with track
- Hough transfrom cut: $N_{ph,min} \geq 12$
- PID Above C.kov threshold: $3\sigma_\theta$ cut
- **$e^\pm$ hyp. accepted ⇔ N(d_{min} * < d < d_{max}) ≥ 7**

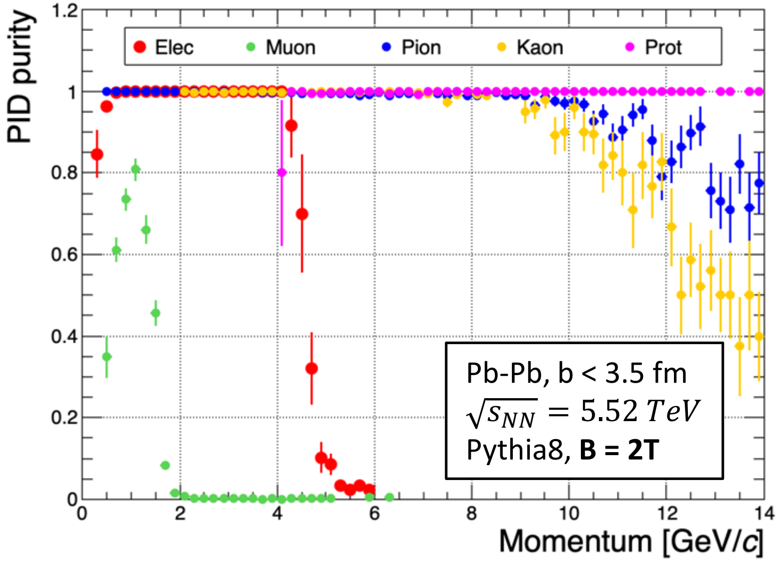
Aerogel + Gas + TOF window information

- Hit timing cut: $2\sigma_t$ matching with track
- Hough transfrom cut: $N_{ph,min} \geq 12$
- PID Above C.kov threshold: ($3\sigma_\theta$ cut & $3\sigma_t$) cut
- **$e^\pm$ hyp. accepted ⇔ N(d_{min} * < d < d_{max}) ≥ 7**

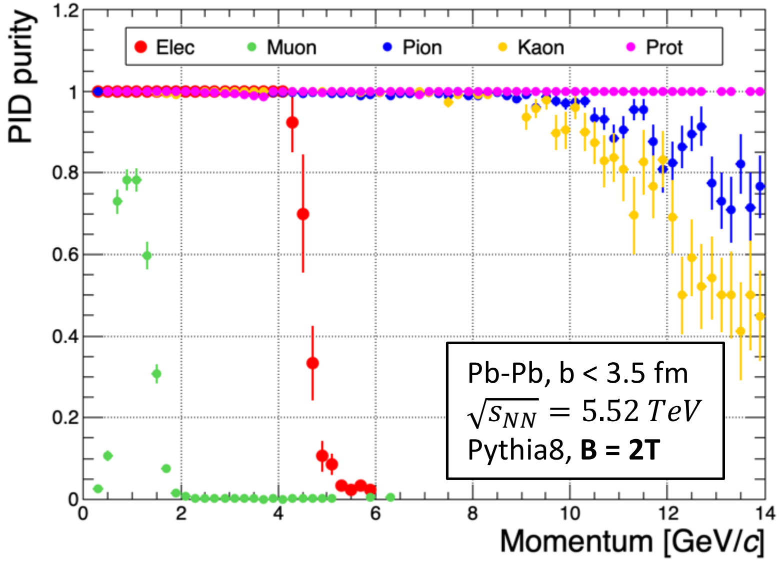
1x1 mm2 cells, **50 ps** SPTR, **real reconstruction**



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

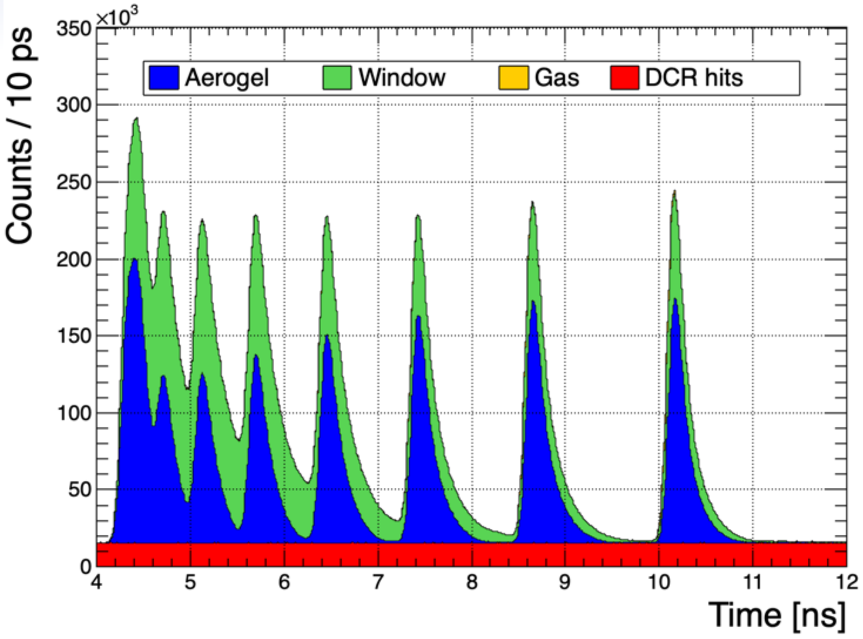


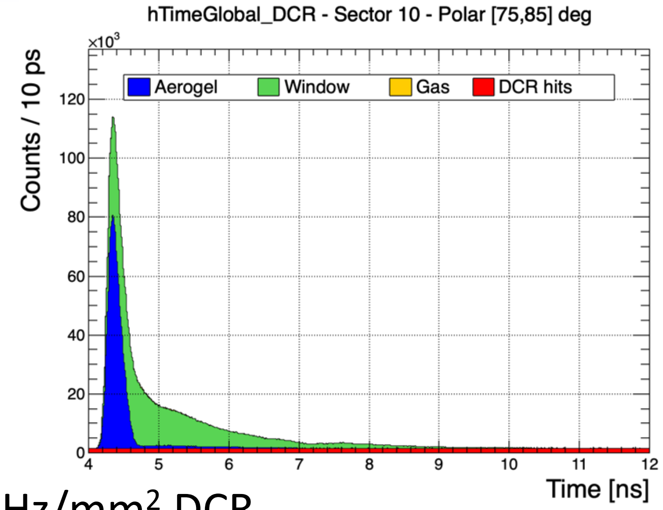
1x1 mm2 cells, **50 ps** SPTR, **real reconstruction**

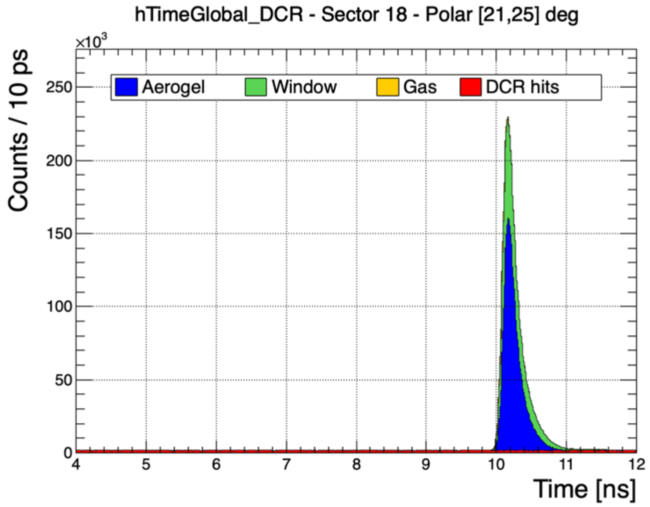


*The minimum distance **d_{min}** allows to exclude the hits due to photons from the TOF window which are present for all particle species

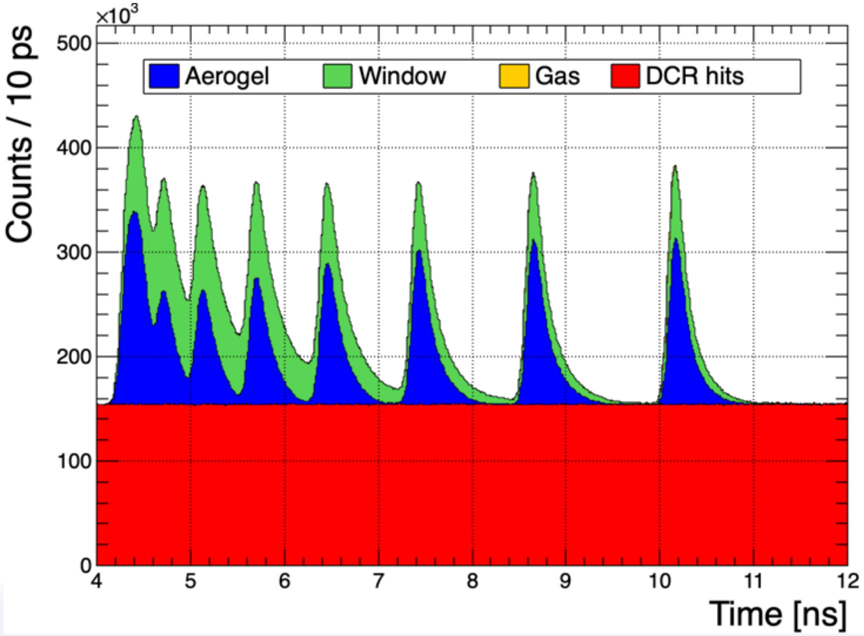
Photons timing

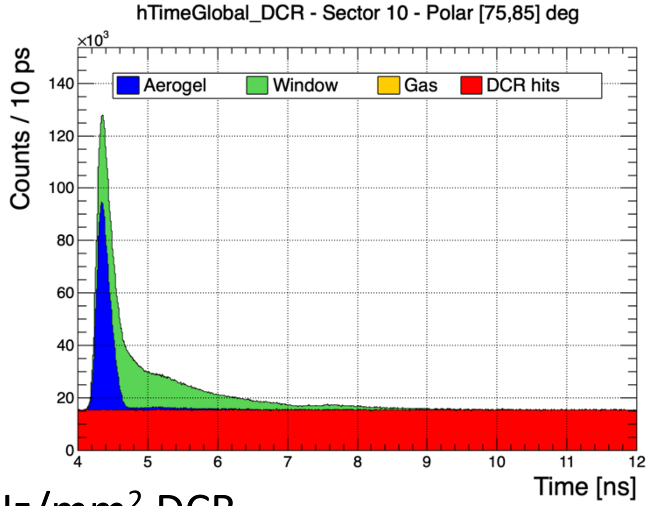


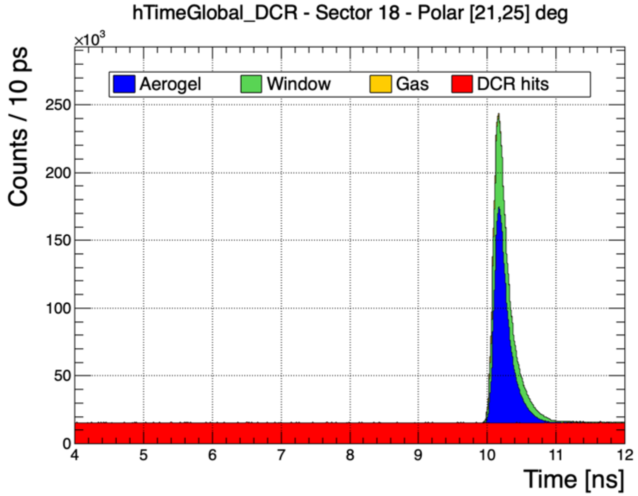




50 kHz/mm^2 DCR







500 kHz/mm^2 DCR

Online timing gate and precise time stamping mandatory!

R&D topics

- Aerogel

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

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

- Photodetection

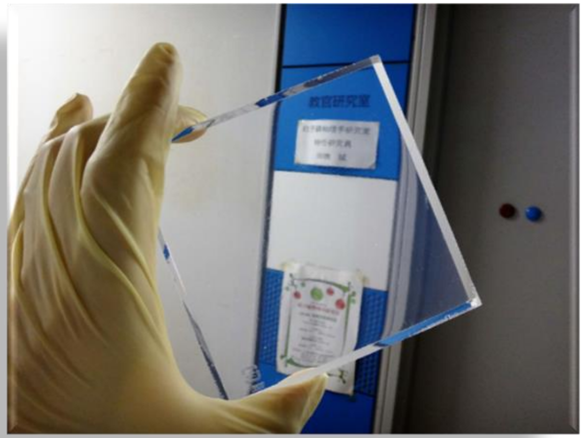
SiPM specs: Pixel 1x1 mm^2 , die (SiPM array) size ~ 1x1 cm^2, PDE > 40% at 450 nm, DCR < 50 kHz/mm^2, radiation hardness: NIEL ~ 10^{10} 1 MeV n_{eq}/cm^2 , time resolution < 100 ps, packaging fill factor > 90% (TSV interconnection)

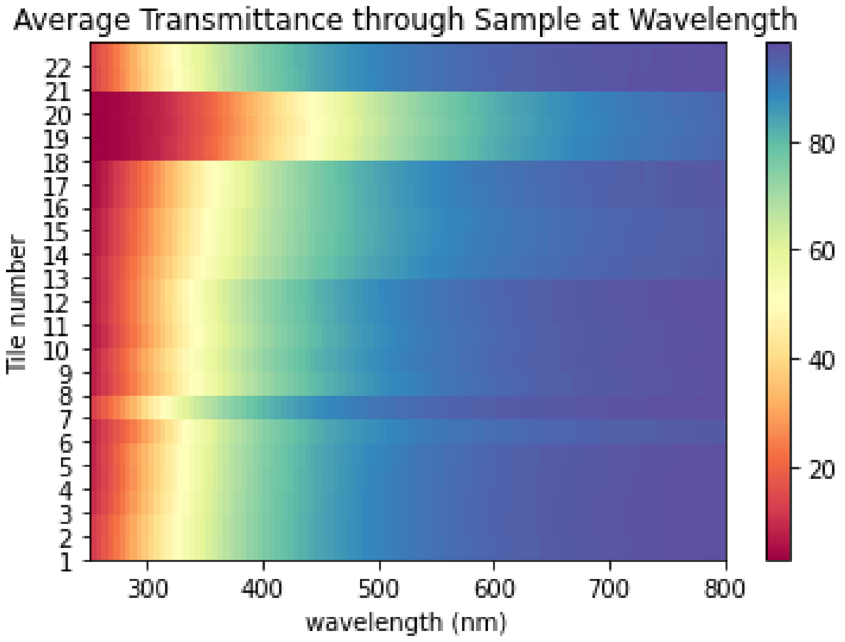
- Explore path towards monolithic (2D or 3D) SiPM in CMOS Imaging Sensor technology (massive R&D in industry on digital SPADs for consumer applications and automotive), to reduce costs, <u>customize sensor and improve performance</u>:
- MIP detection by thin radiator window for TOF
- Module concept and cooling integration

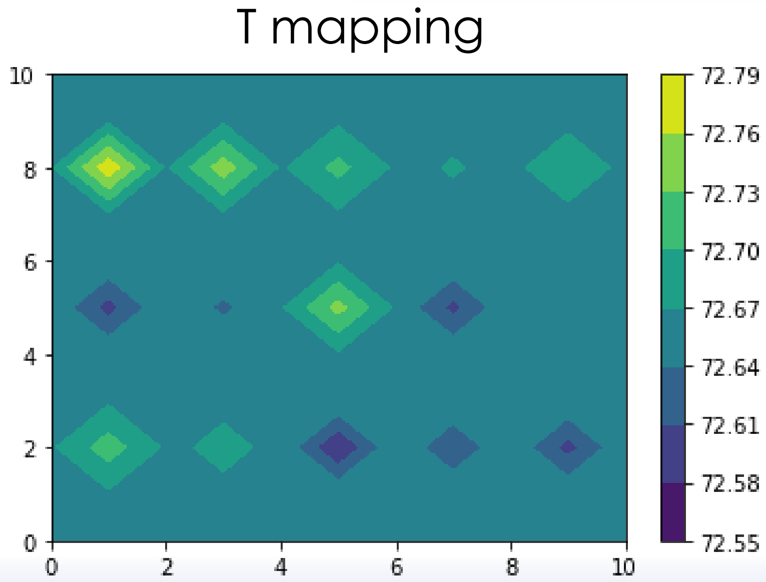
Ongoing R&D: aerogel characterization

#	Sample	n
1	LEC4-1b	1.03
2	LEC4-2a	1.03
3	LEC6-1a	1.03
4	LEC6-1b	1.03
5	LEC6-2b	1.03
6	SP3-0	1.03
7	SP3-1	1.03
8	LEC11-6	1.04
9	LEC11-7	1.04
10	LEC12-1	1.04
11	LEC12-4	1.04
12	LEC12-6	1.04
13	LEC8-1	1.05
14	LEC8-2	1.05
15	LEC8-6	1.05
16	LEC9-1	1.05
17	LEC9-2	1.05
18	TSA41-2a	1.00539
19	TSA41-2b	1.00544
20	TSA41-3a	1.00548
21	TSA38-2	1.0312
22	TSA38-8	1.0311

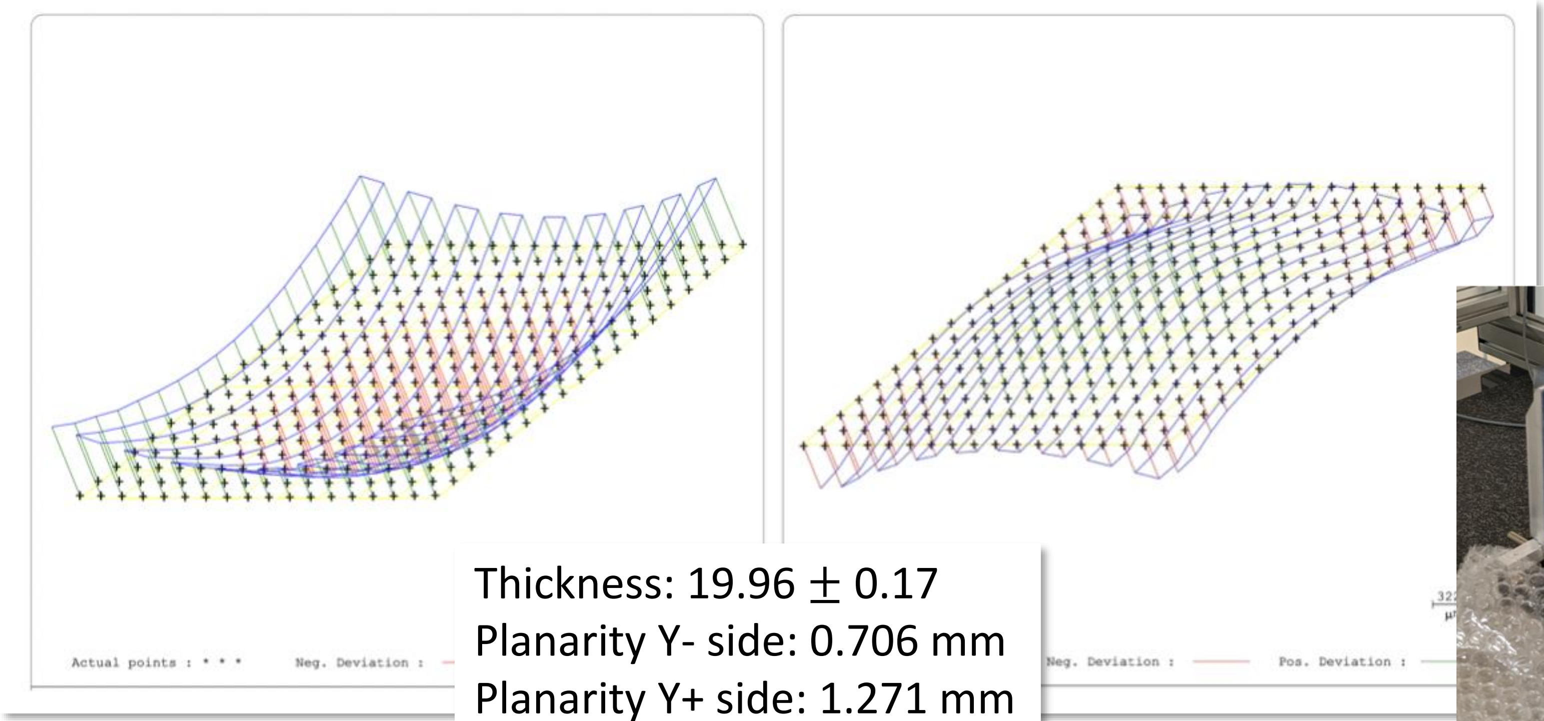
- 22 samples available from Aerogel Factory LTD, Chiba, JP (purchased with LHCb)
- Four n: 1.005, 1.03, 1.04, 1.05
- Two sizes: 11x11 cm^2 and 15x15 cm^2
- Measurement of transaparency and uniformity
- Dimensional/shape characterization



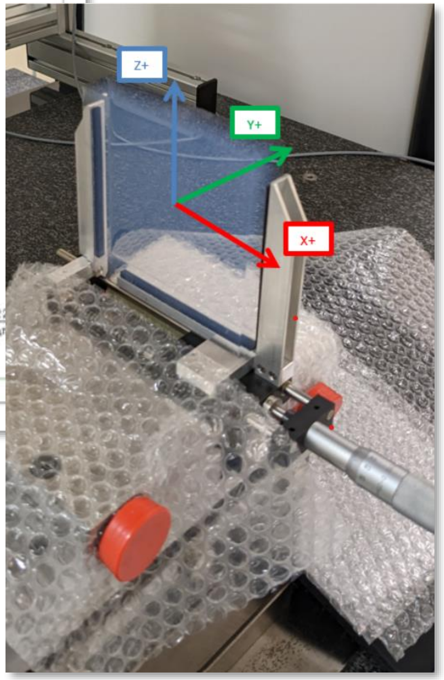


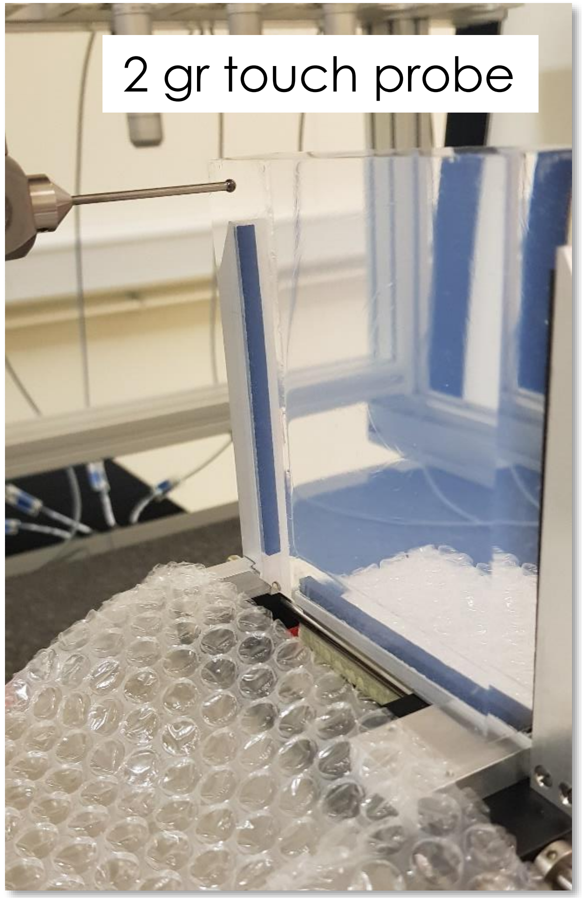


Ongoing R&D: aerogel characterization



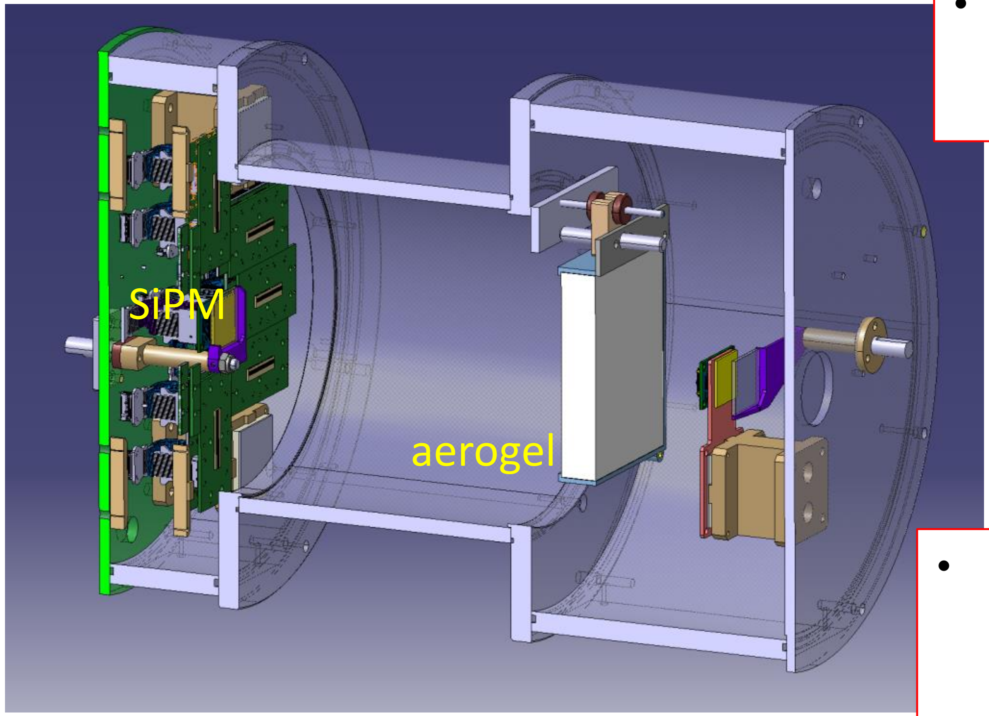
Thickness: 19.96 ± 0.17
Planarity Y- side: 0.706 mm
Planarity Y+ side: 1.271 mm



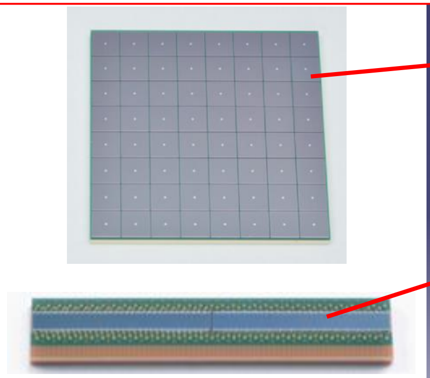


- Thickness variation: no impact on performance
- Planarity defect:
  - Can be included in Cherenkov angle reconstruction
  - According to supplier, there is margin for improvement

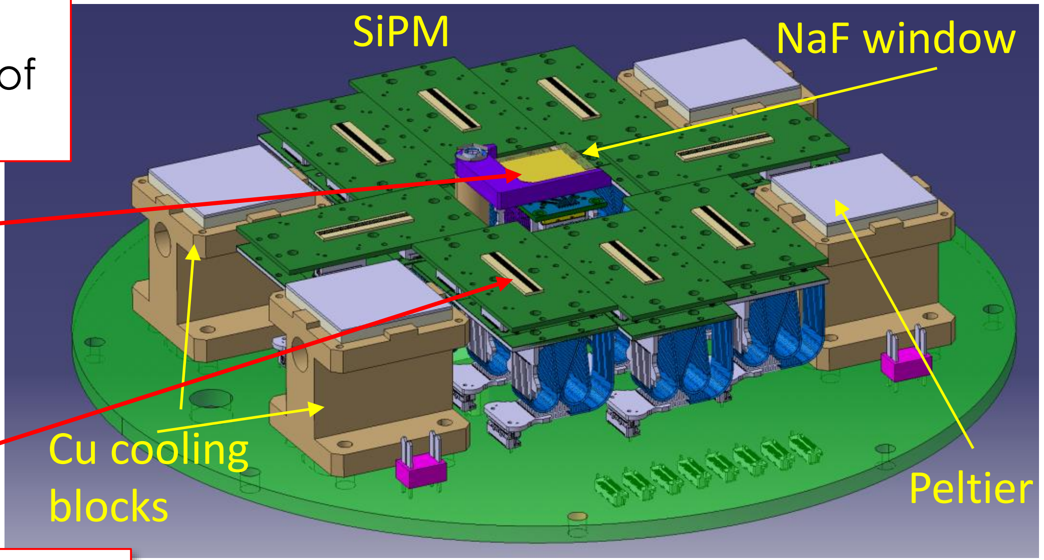
Ongoing R&D: prototype @ testbeam PS/T10

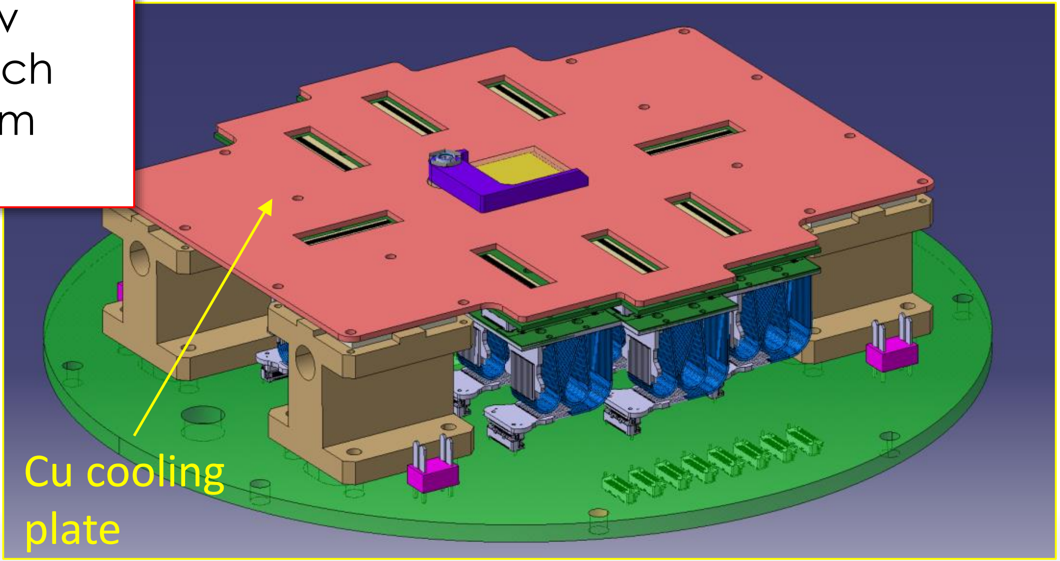


- 1 card for MIPs, HPK S13361 : 64 ch array of 3x3 mm pads



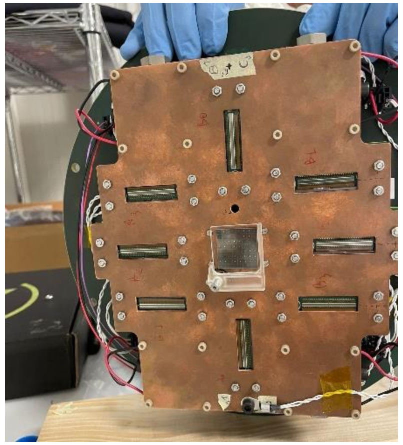
- 8 cards for Cherenkov ring, HPK S13552: 128 ch array of 0.23x1.625 mm strips

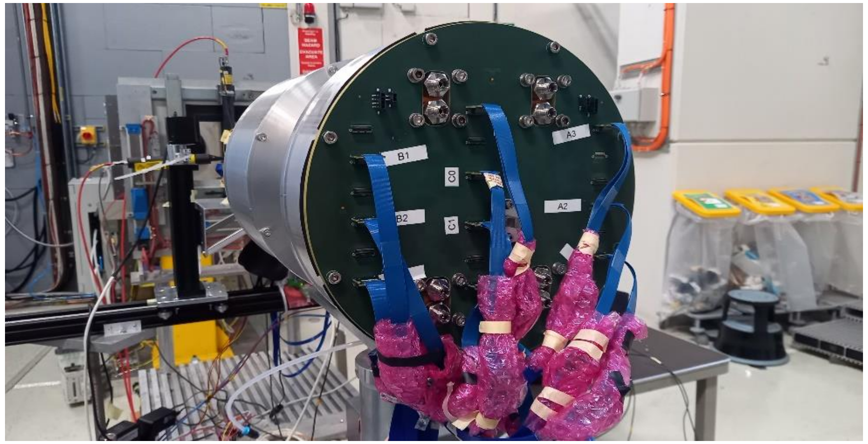


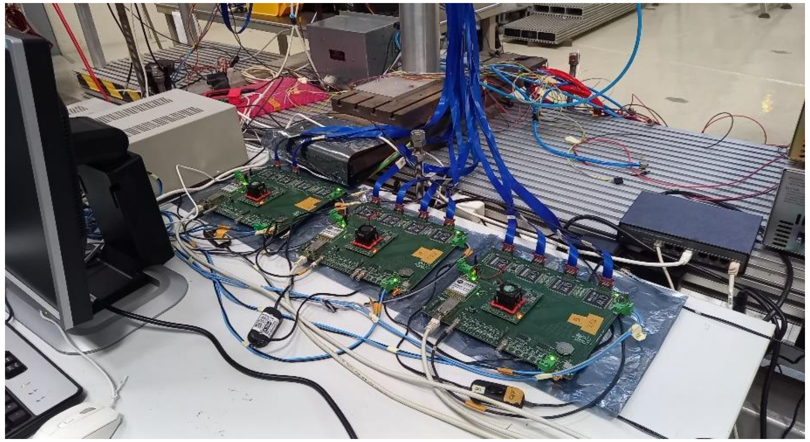


- Testbeam from Oct 19 to Nov 2 2022
- Verify aerogel performance (photon yield)
- Test Cherenkov radiator NaF window

Ongoing R&D: prototype @ testbeam PS/T10

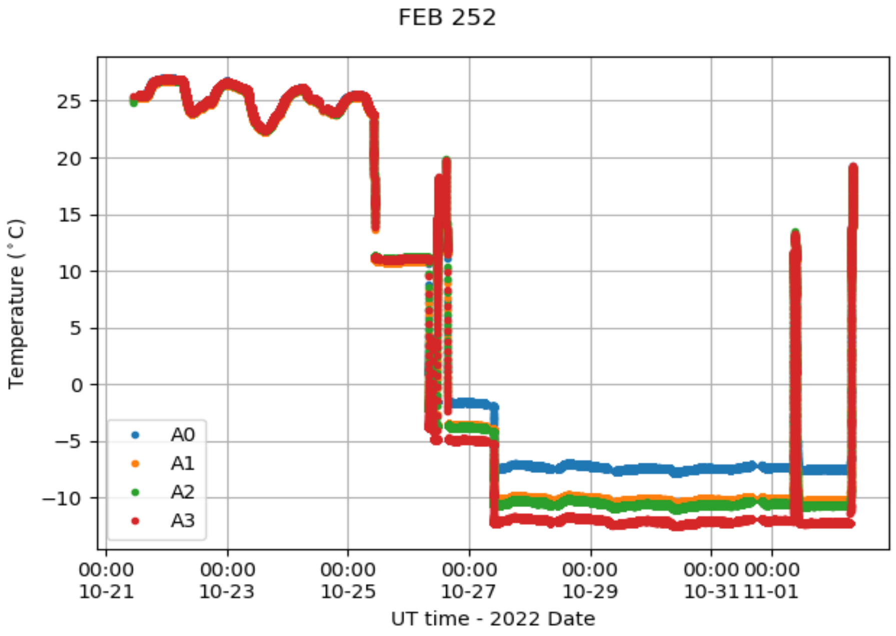


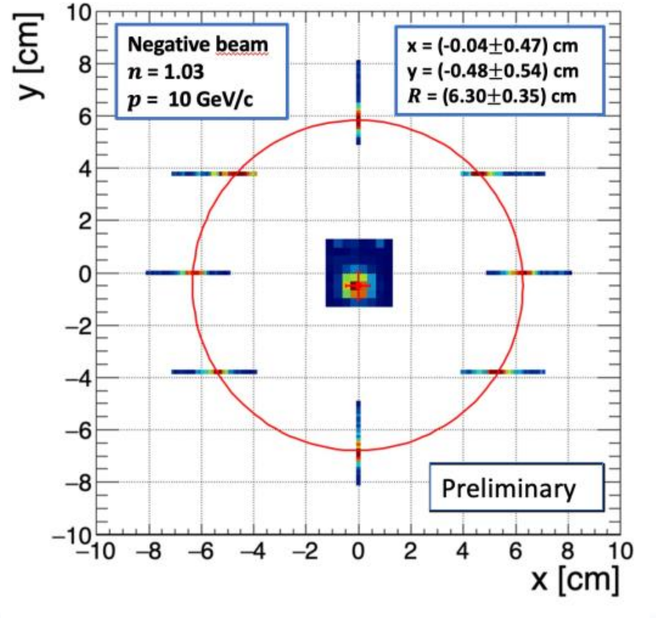




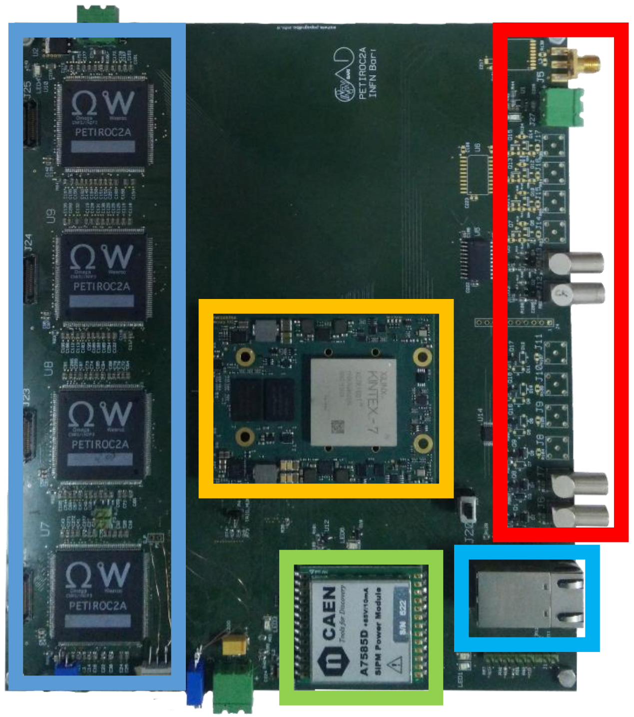
Detector parameters

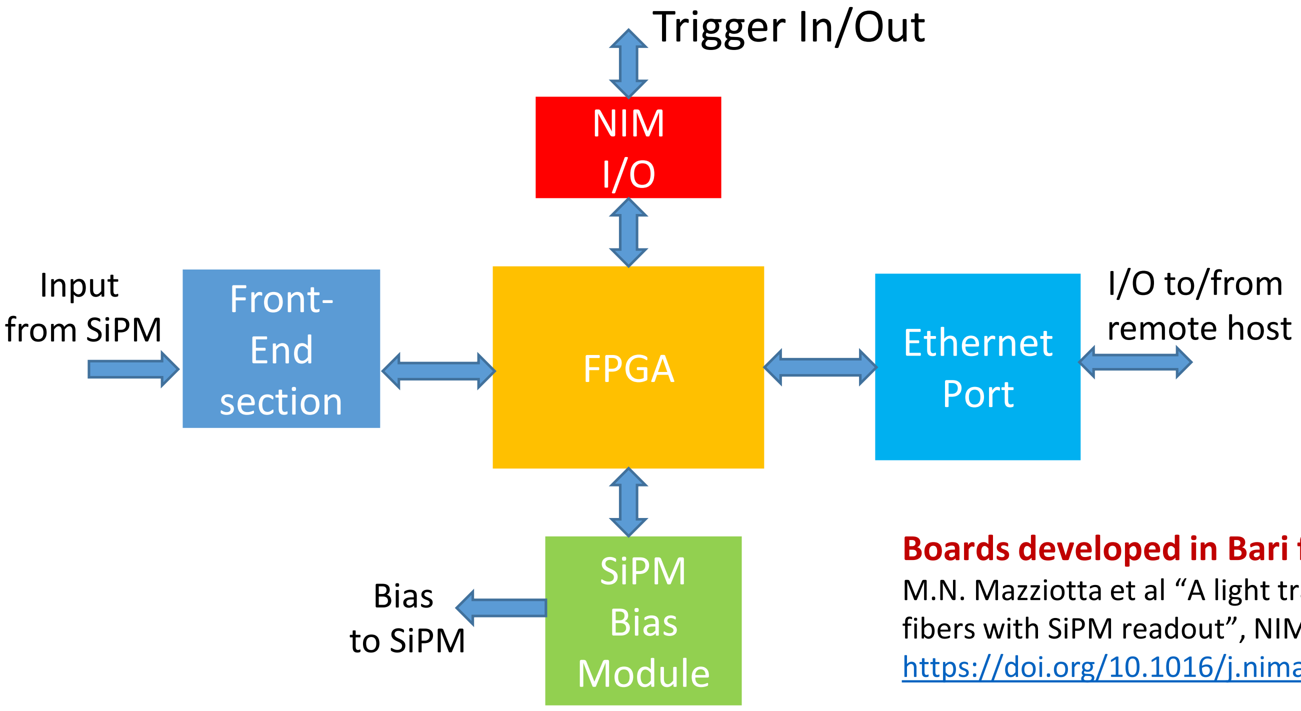
- Radiator: T_r = 2 cm, n = 1.03-1.04
- Proximity gap: T_g =23.4 cm, Ar
- SiPM cooling: -12° < T < -5°
- $V_{ov,matrix}$ = 4.4 V, $V_{ov,strips}$ = 6.9 V





DAQ and Front-End Board (FEB)





Boards developed in Bari for GAMMA experiment

M.N. Mazziotta et al "A light tracker based on scintillating fibers with SiPM readout", NIMA 1039 (2022) 167040
https://doi.org/10.1016/j.nima.2022.167040

Front-End
- 4 PETIROC ICs:
  - 32 front-end channels
  - ADC for charge measurements - 10 bit
  - TDC to measure the arrival time - 37 ps LSB
    PA time jitter about 45 ps (>4 p.e.)
  - 32 digital outputs for triggering

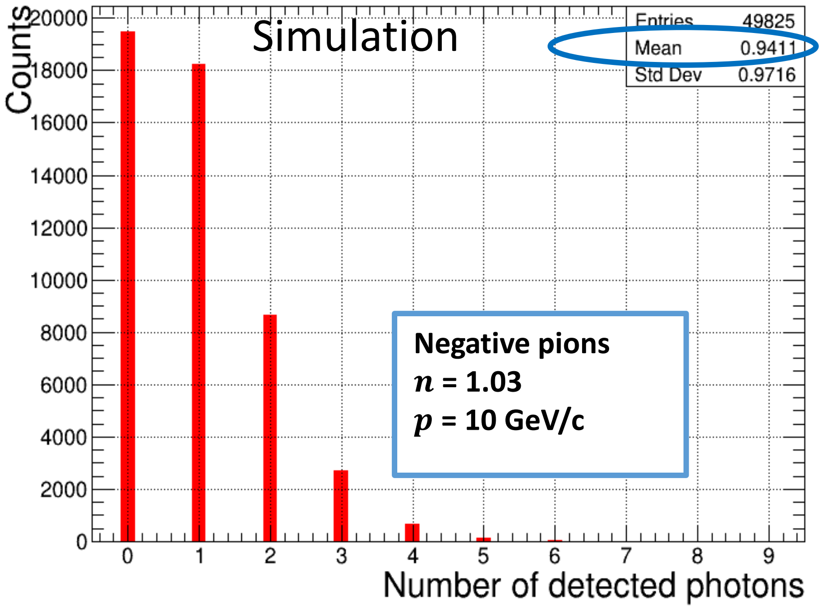
FPGA:
- I/O data managment
- Trigger
- Coincidence

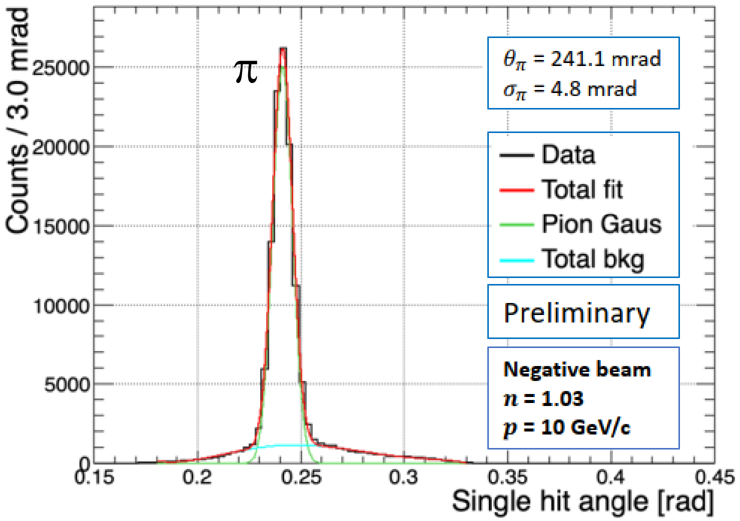
SiPM Bias Module:
- SiPM bias voltage regulation up to 80 V

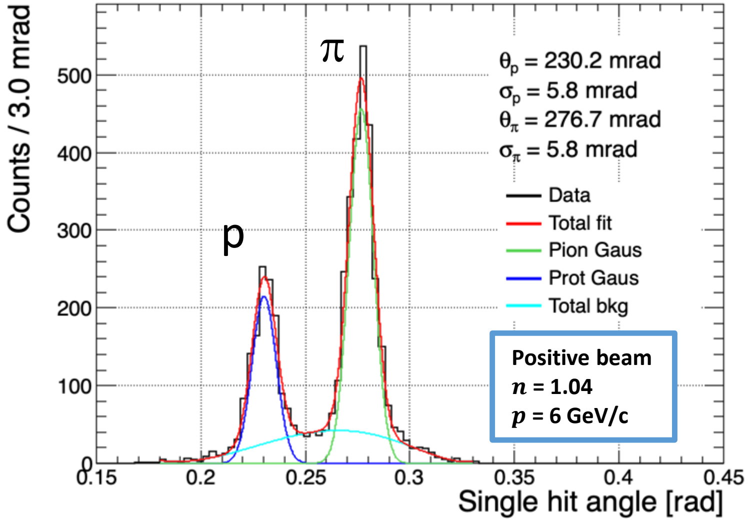
NIM I/O
- Trigger

Ethernet port
- Data I/O to a remote host

Ongoing R&D: prototype @ testbeam PS/T10







Extrapolation of # detected photons/ring

- $N_{det} = \frac{\#\ hits\ in\ the\ strips\ under\ the\ \pi\ Gaussian}{\#\ events\ with\ a\ cluster\ in\ central\ matrix} = \frac{56184}{59879} = 0.938$
- $N_{ring} = \frac{N_{det}}{Frac.\pi\ circumference} = N_{det} \cdot \frac{2\pi\langle R_\pi \rangle}{8\Delta s} = 28.6$

N.B.: Excess with respect to full barrel sim. due to larger strip SiPM PDE

Angles and resolution consistent with expectations

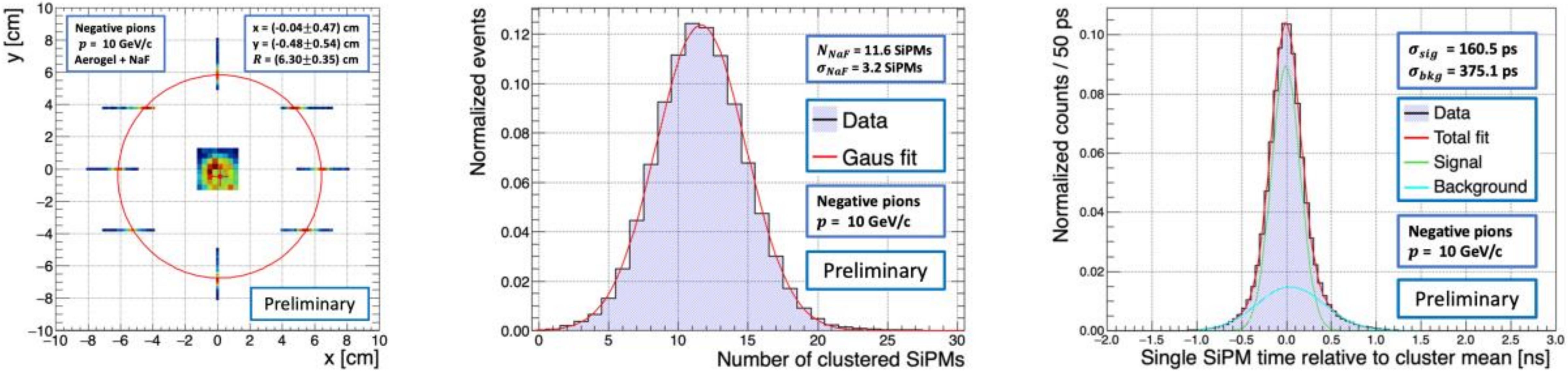
p= -10 GeV/c $\theta_{\pi,th} = 242\ mrad, \sigma_{sim} \approx 5.5\ mrad$

P= + 6 GeV/c $\theta_{p,th} = 232\ mrad, \sigma_{sim} \approx 5.3\ mrad$

$\theta_{\pi,th} = 277\ mrad, \sigma_{sim} \approx 6.1\ mrad$

Time resolution measurements

3 mm thick NaF radiator (n = 1.3319 @ 400 nm), 4 mm apart from the central matrix



Limitation

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

Test beam results

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: $\sigma_{\langle t \rangle} = \frac{\sigma_{SiPM}}{\sqrt{N_{NaF}}} \approx 47\ ps$

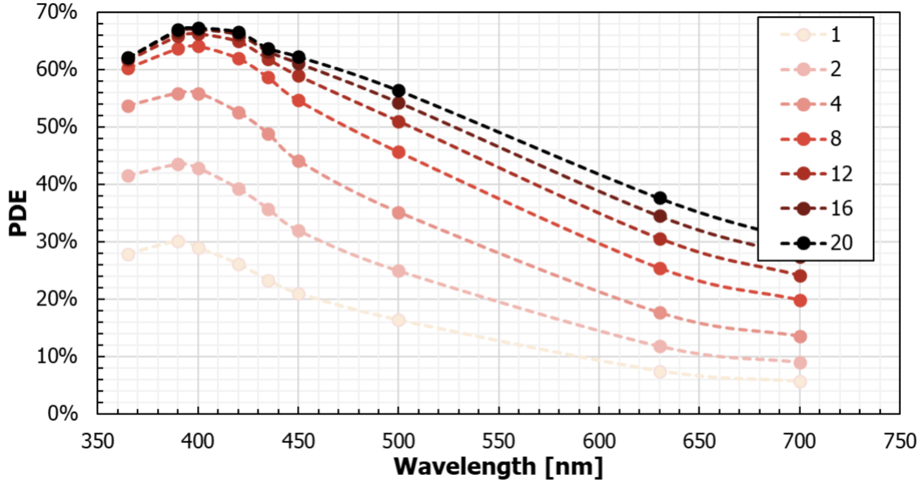
There is room for improvement

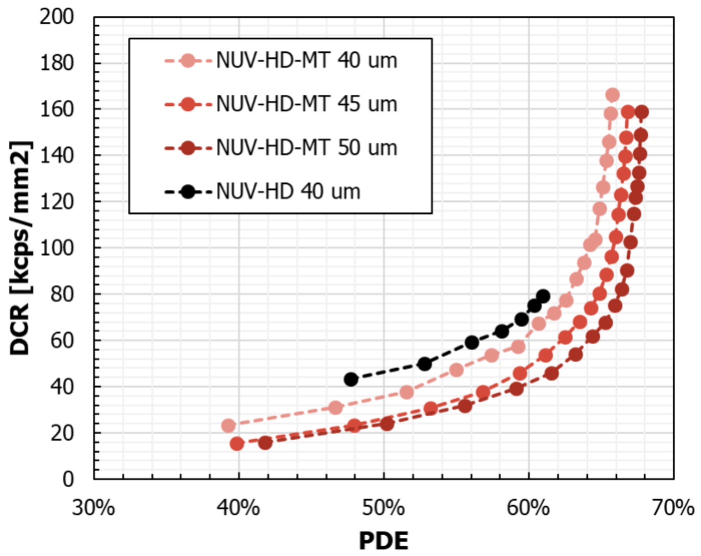
Further investigations are being carried out for improving timing results: offsets and slewing corrections, thresholds for data acquisition, ASIC syncronization, etc.

SiPM R&D

- 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 microlenses)
  - 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 wrt DCR): cell layout

FBK NUV-HD technology

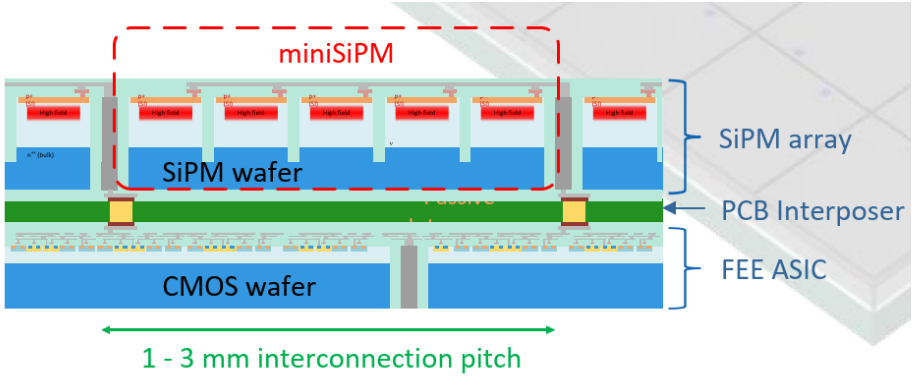




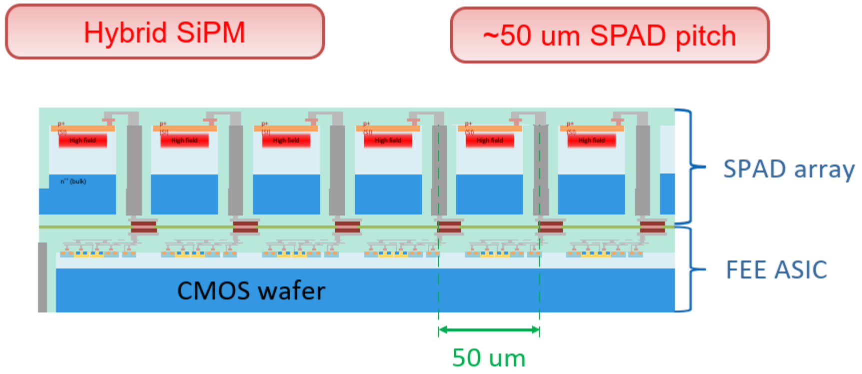
SiPM packaging

- 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



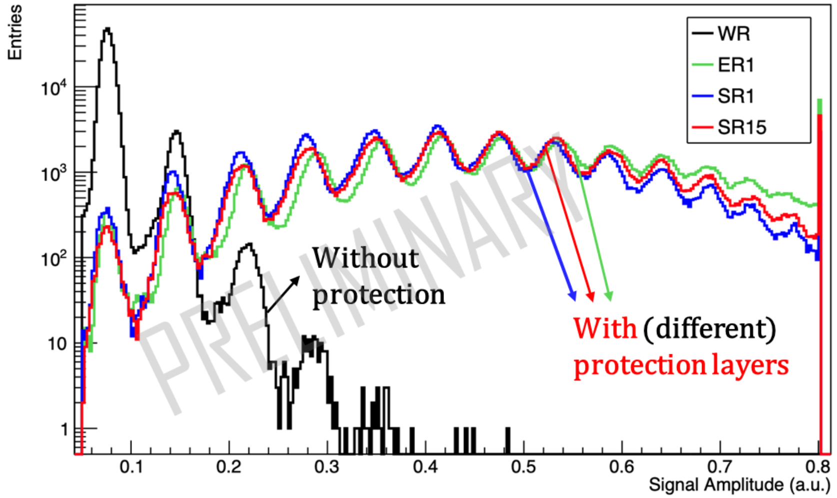
Direct detection of charged particles with SiPM

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

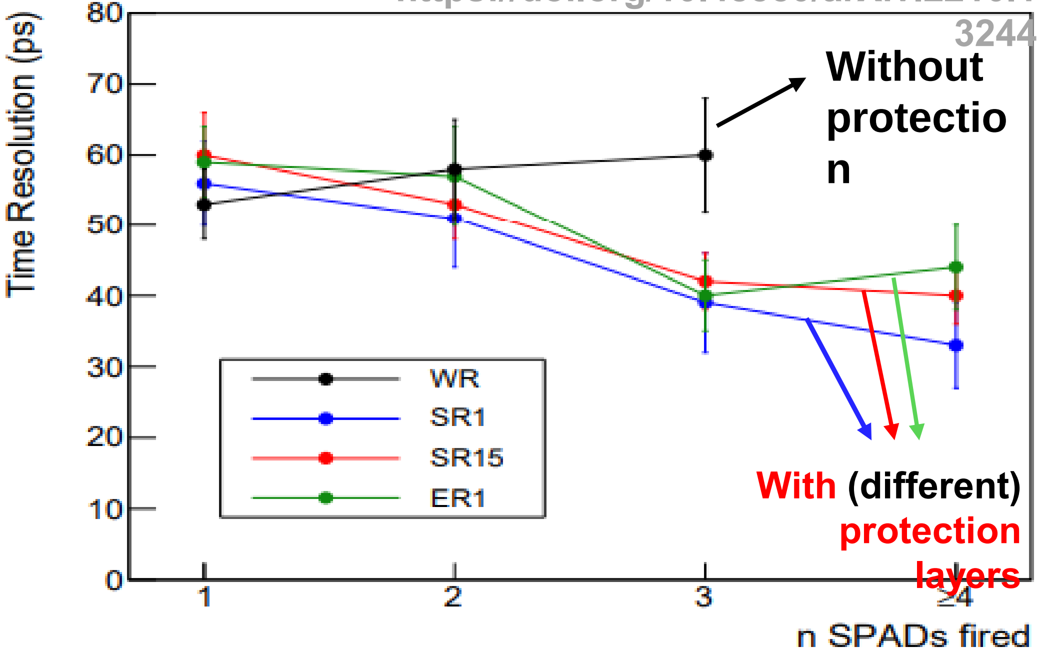
Effect (due to **Cherenkov light** produced in the protection layers
https://doi.org/10.48550/arXiv.2210.13244

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



https://doi.org/10.48550/arXiv.2210.13244



Anti-reflective coating

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

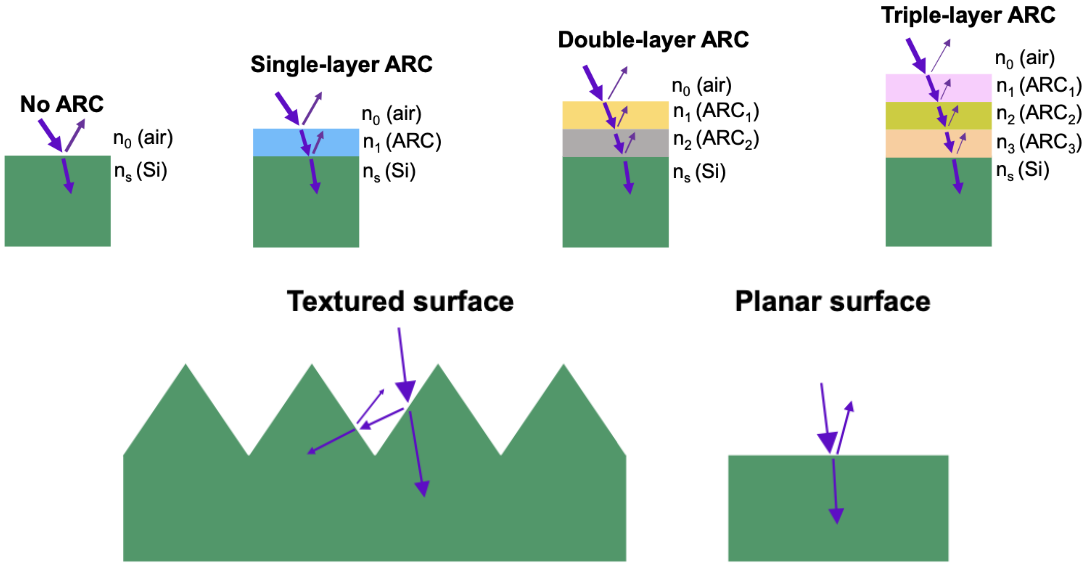
Solutions:

- 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.

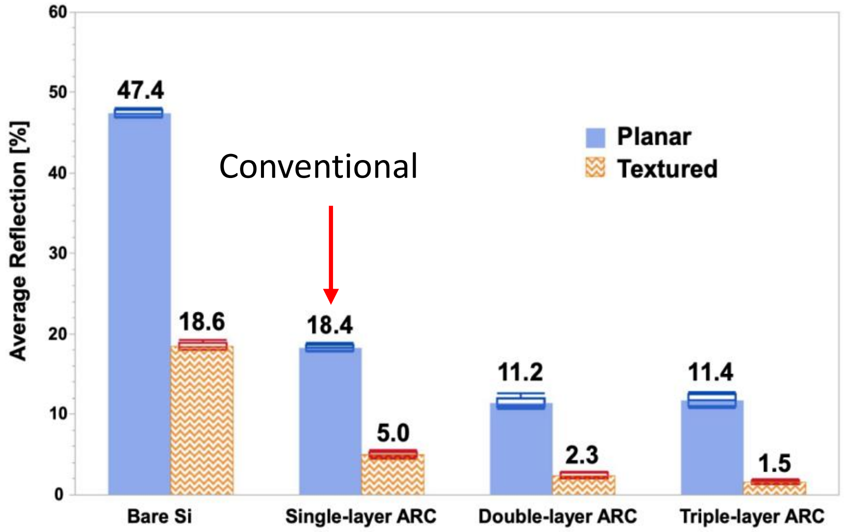
Additional benefits:

- The PDE increase allows operation at lower V_{OV} hence lowerd DCR
- Limitation of crosstalk from reflection at Si interface of Cherenkov photons produced inside TOF window

SiPM Anti Reflective Coating



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



Plans towards TDR

	2023	2024	2025	2026	2027
Design	• Performance/ optimization studies • Mechanical structure design	• Mechanical structure design • Integration	Prototype modules	Engineering modules	Engineering modules
Aerogel	Optical and mechancial studies	Optical and mechancial studies	Integration and mechanics	Integration and mechanics	**TDR**
D-SiPM	• Test available devices • photod. module • cooling	• Characterization of test structures • 1st submission • photod. module • cooling	• Characterization of D-SiPM prototype • 2nd submission • photod. module • Cooling	• Validation of D-SiPM • cooling integration	