A novel SiPM-based aerogel RICH detector for the future ALICE 3 apparatus at LHC

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for the ALICE Collaboration

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Outline

Detector concept

Simulation studies

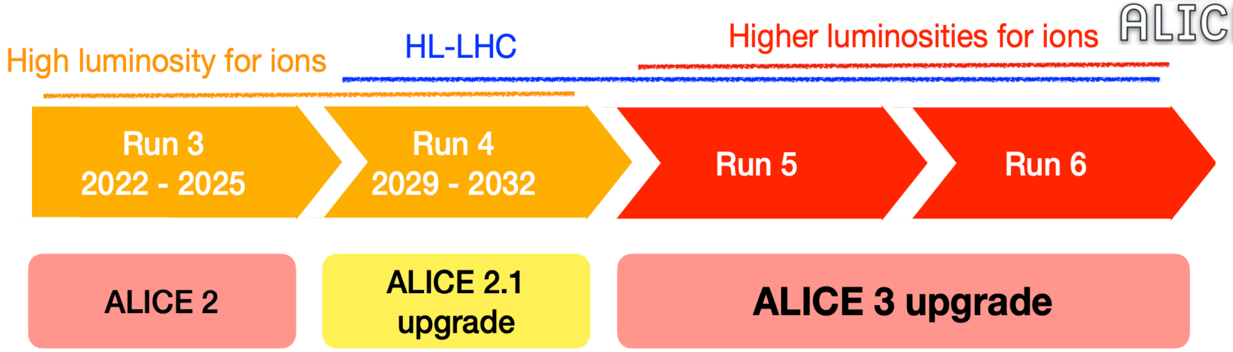
Test beam results

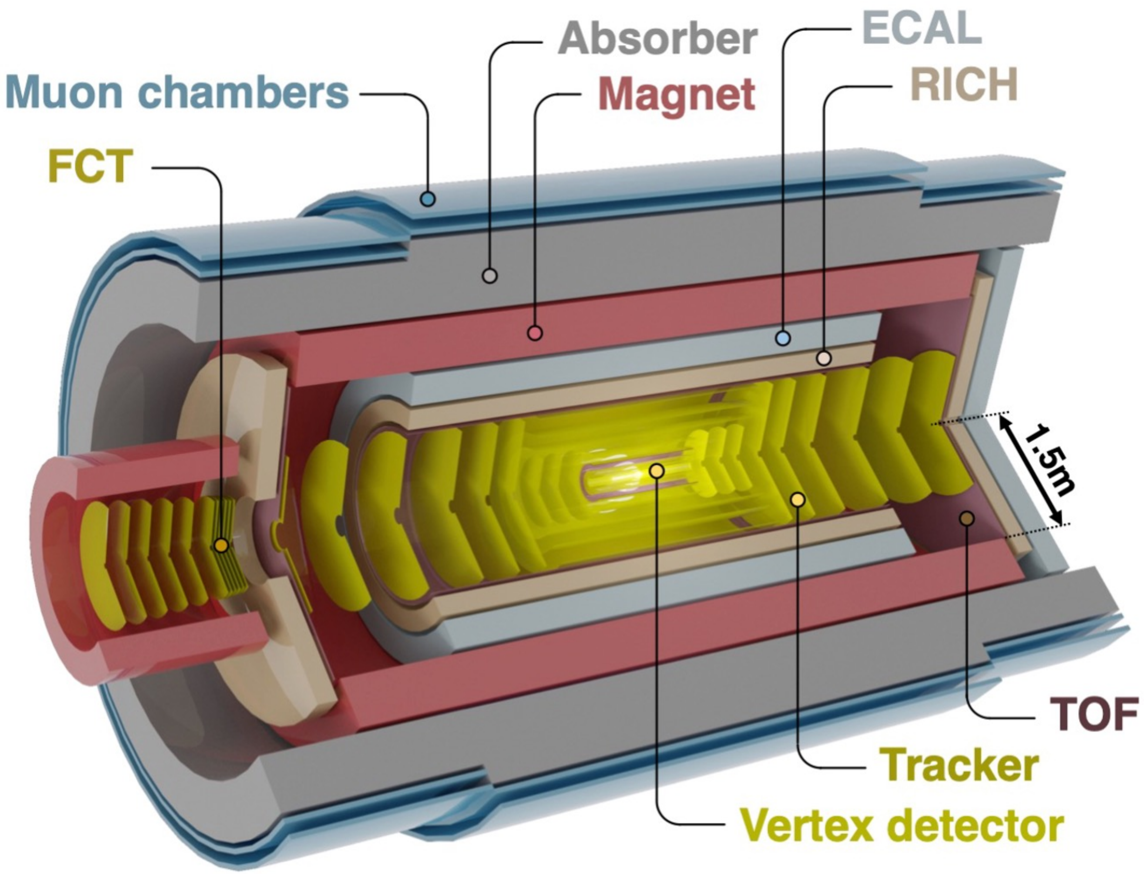
The ALICE 3 upgrade

ALICE 3 motivation and concept

- **ALICE main goal**: access the dynamics of the strongly interacting matter produced in heavy-ion collisions
- **Fundamental questions will remain open** after LHC Run 4, demanding for a next-generation experiment
- **Letter of Intent** for ALICE 3 submitted in March 2022
  ALICE CERN-LHCC-2022-009
- **Scoping document** submission by March-April 2024

Processes	Observables
Early stages	Dilepton and photon production and flow
Diffusion	Heavy-flavour correlations and flow
Hadronization	Multi-charm baryons, quarkonia
Detector requirements	Pointing resolution: $\approx$ 10 μm at 200 MeV/c
	Tracking relative p_T resolution: $\approx$ 1-2 %
	Extensive identification of e, μ, π, K, p, γ
	Large pseudorapidity coverage: $\lvert\eta\rvert$ < 4

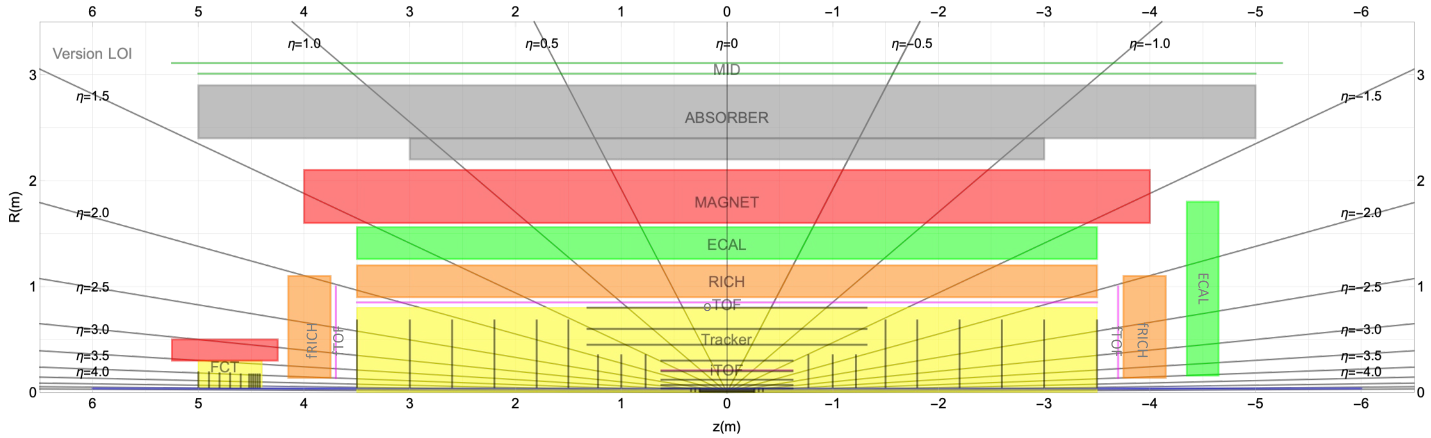




ALICE 3 barrel RICH motivation

ALICE 3 charged PID systems

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

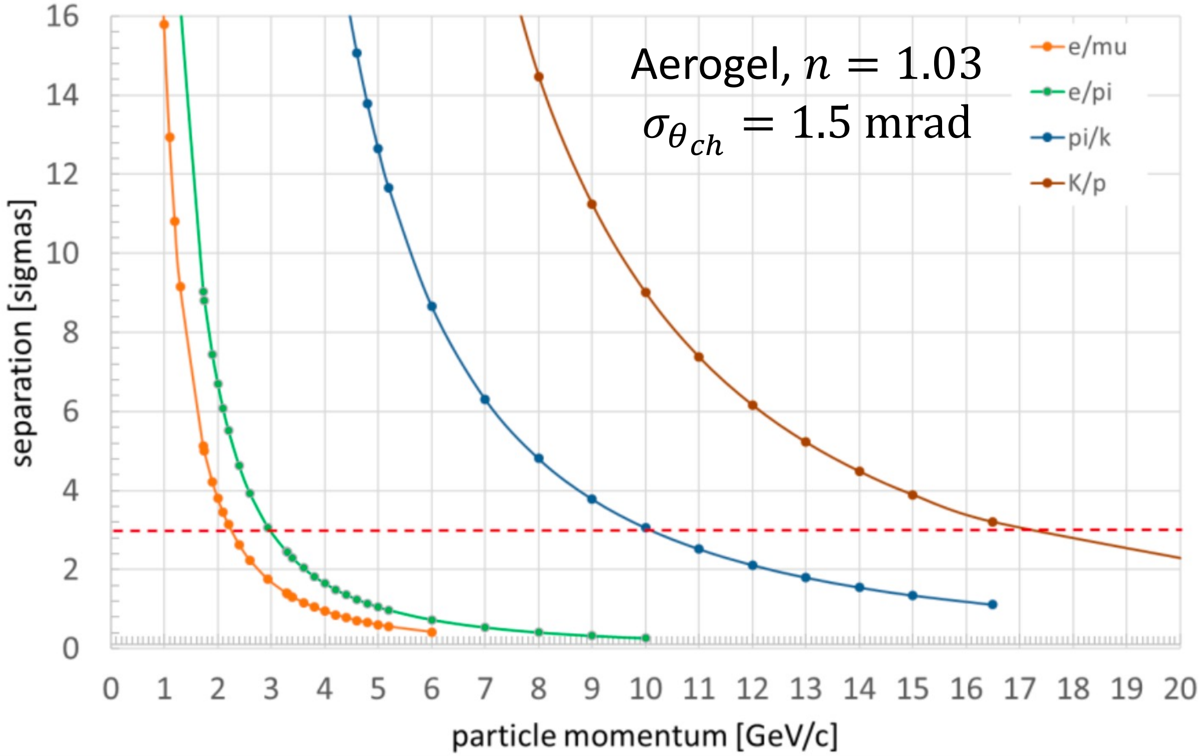


Let's focus on the bRICH

bRICH motivation

- Extend charged PID beyond the TOF limits
  - π/e in the p range 0.5 – 2.0 GeV/c
  - K/π in the p range 2.0 – 10.0 GeV/c
  - p/K in the p range 4.0 – 16.0 GeV/c

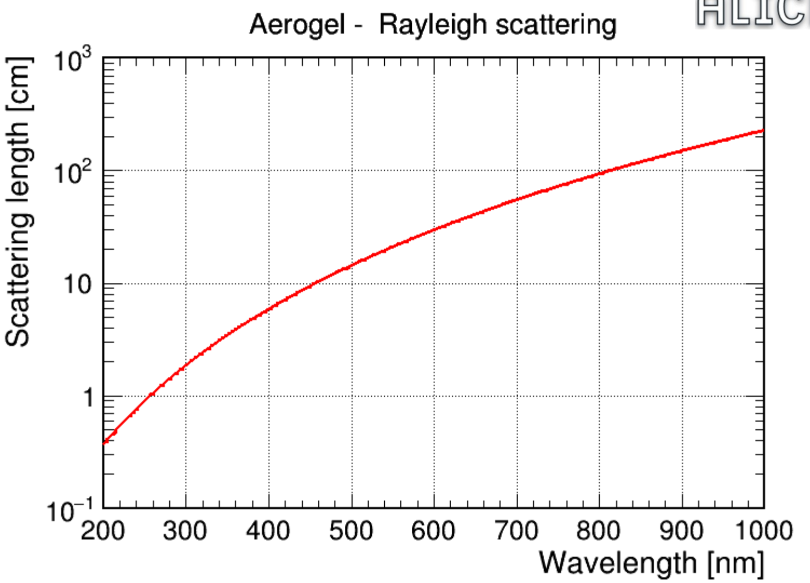
→ Achieved using aerogel radiator with $n \approx 1.03$
+ requiring angular resolution $\sigma_{\theta_{ch}} \approx 1.5$ mrad



bRICH technology

Aerogel radiator (n=1.03, L = 2 cm)

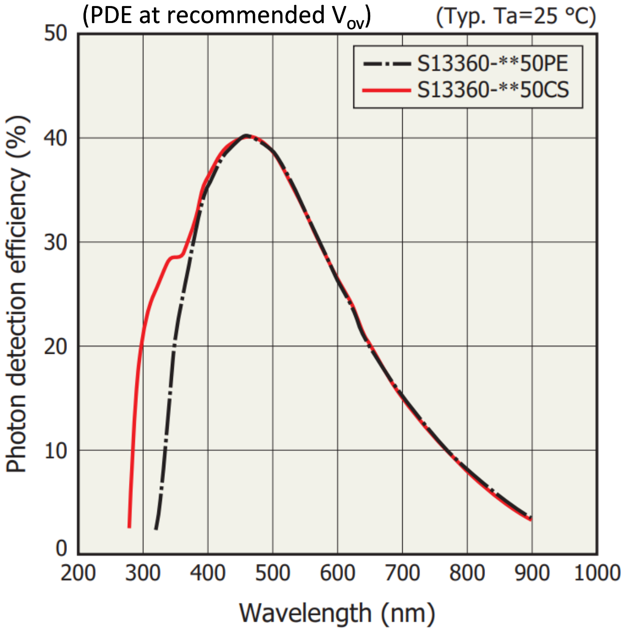
- Lattice of SiO_2 grains filled with trapped air
- Tunable index in the range 1.006-1.250
- Transmittance dominated by Rayleigh scattering
  - Transparent in the visible, opaque in the UV

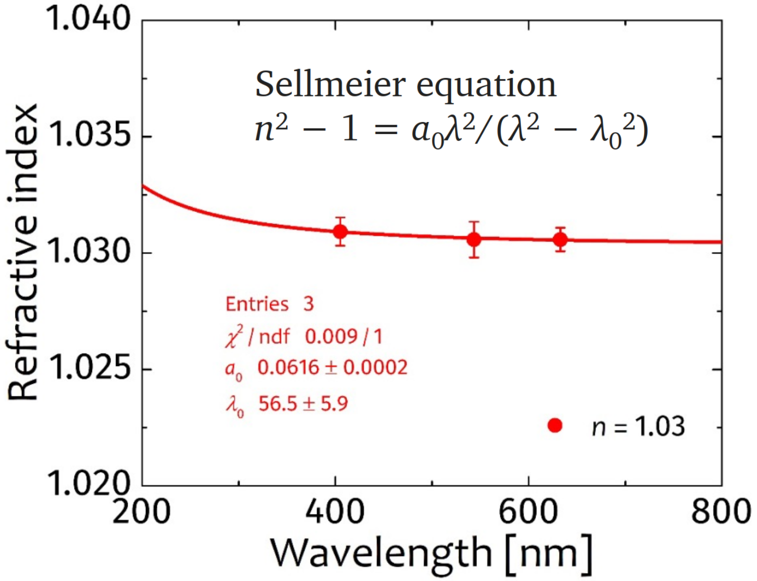


SiPM-based photodetector

- Sensors must be sensitive to visible light
- Operation in magnetic field
- Granularity from 3x3 to 1x1 mm²
- Simulations: HPK 13360-3050CS SiPMs

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





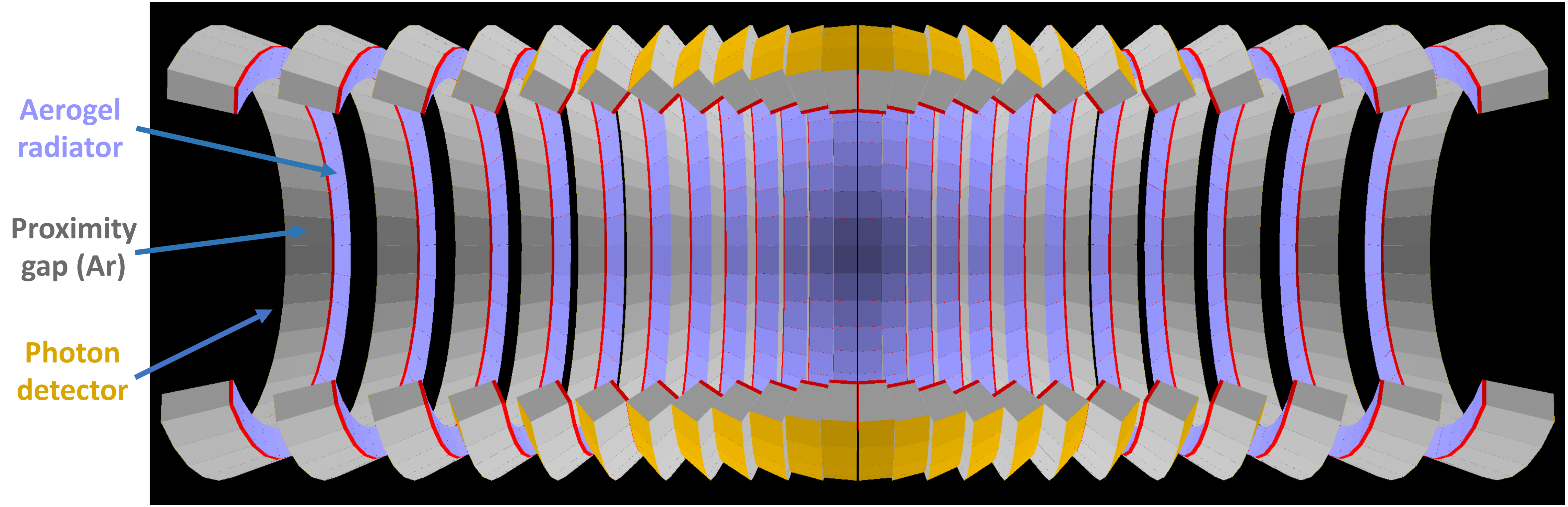
Projective bRICH layout

Assumptions

- All tiles oriented toward nominal interaction point
- Full coverage to charged particles without overlaps
- Trapezoidal tile profile to maximize the acceptance

Implementation

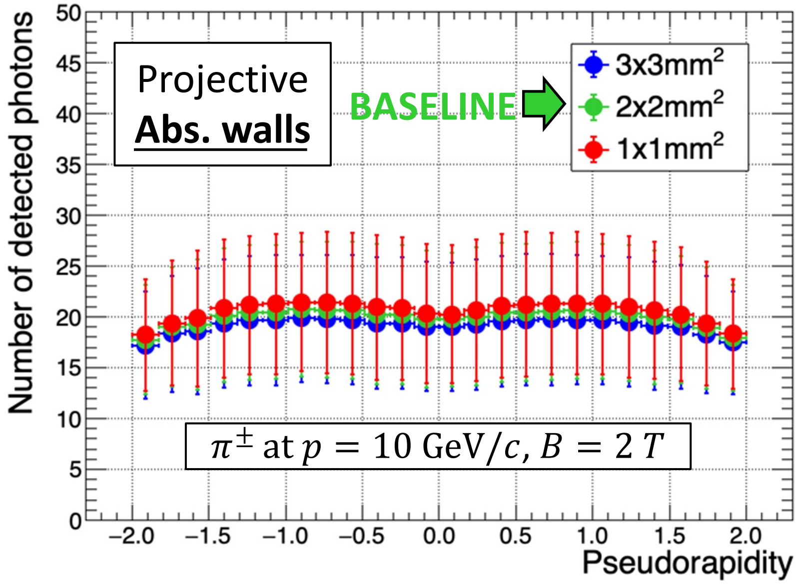
- 24 sectors in z
- 36 modules in rϕ for each sector
- Photosensitive surface: ≈ 30 m^2



bRICH performance vs η

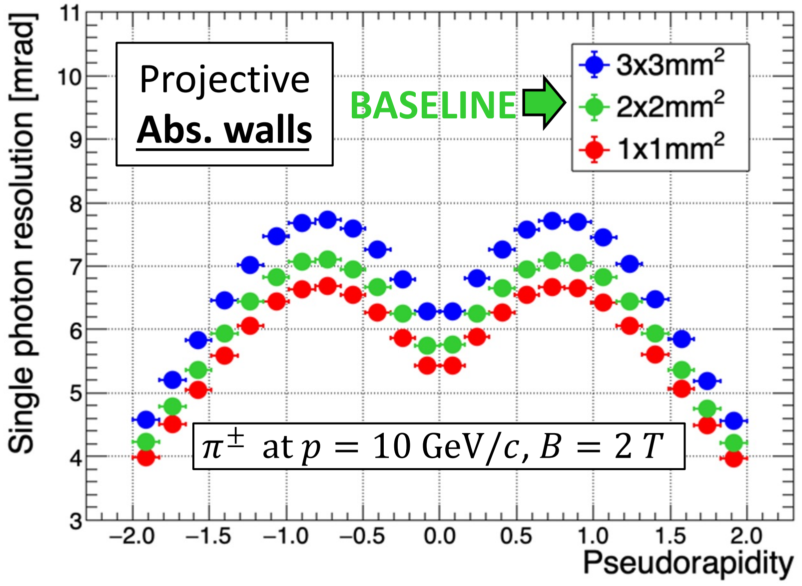
Number of detected photons

- $N_{p.e.} \propto \sin^2\theta_c \oplus \text{phot. acceptance}$
  - Remember: $\cos\theta_c = 1/n\beta$
- Ph. absorbing walls between sectors
  → Loss of some photons boundaries



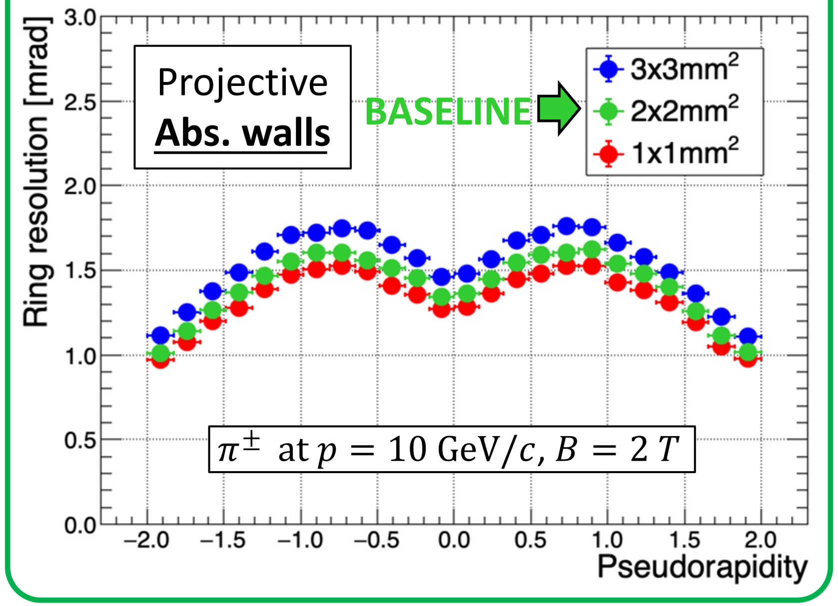
Single photon resolution

- Expected: $\sigma_{\theta_c}^{p.e.} = \sqrt{\sum_i \sigma_{\theta_c}^2(i)}$
  - i = chrom, geom, pixel, tracking
- Worst $\sigma_{\theta_c}^{p.e.}$ at $\eta \approx 0.9$ for sectors where the gap thickness is smaller



Ring angular resolution

- Expected: $\sigma_{\theta_c}^{ring} = \frac{\sigma_{\theta_c}^{p.e.}}{\sqrt{N_{p.e}}}$
- Excellent $\sigma_{\theta_c}^{ring}$ for $|\eta| < 2$
- Minor worsening at $\eta \approx 0.9$



bRICH PID purity in p-p and Pb-Pb

Angle reconstruction

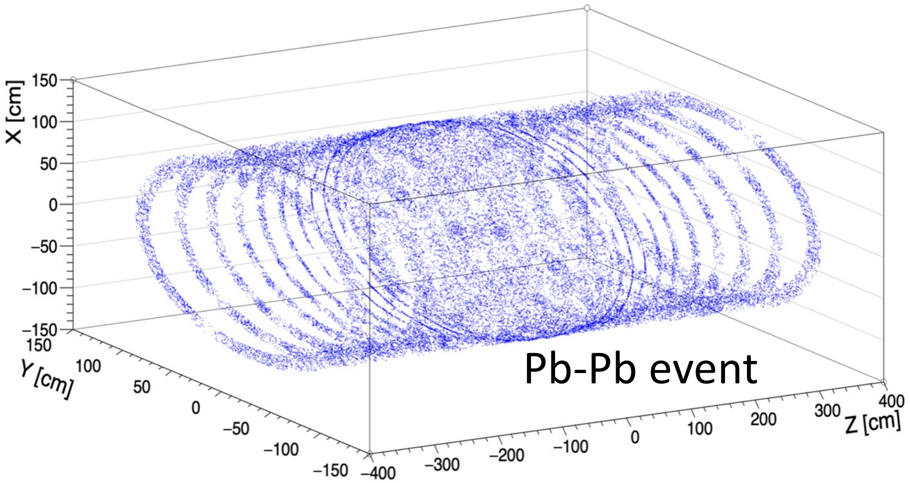
- Based on Hough Transform method
- Timing cut on hit-track matching
- HTM $N_{ph,min}$ cut on clustered hits

Particle identification

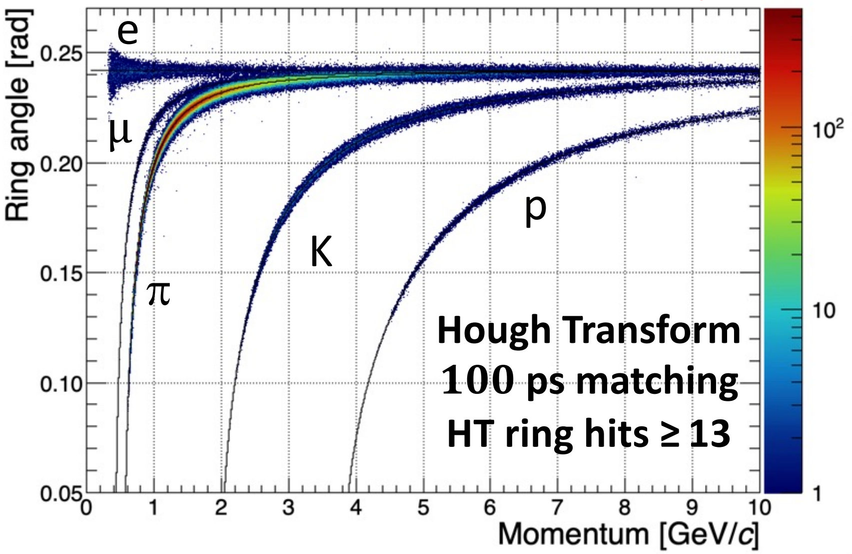
- Bayesian approach + probability cut

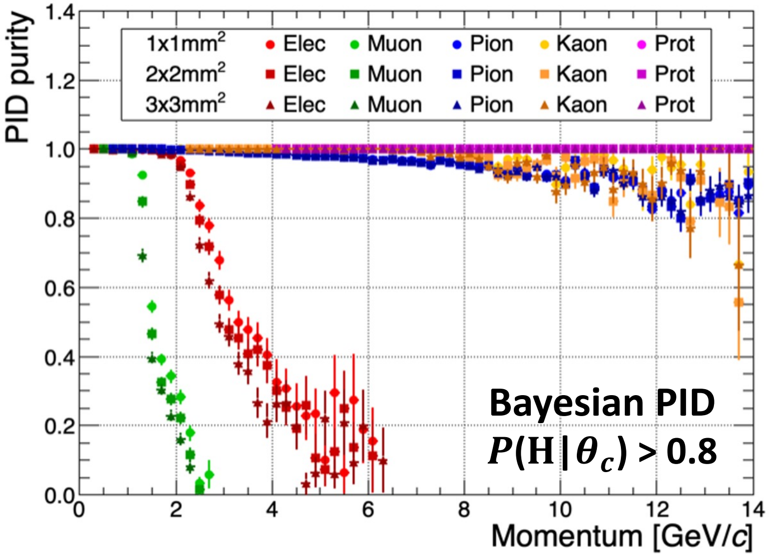
Background

- Photons emitted by different tracks
- Aerogel Rayleigh scattered photons
- SiPM dark count hits (50 kHz/mm^2)

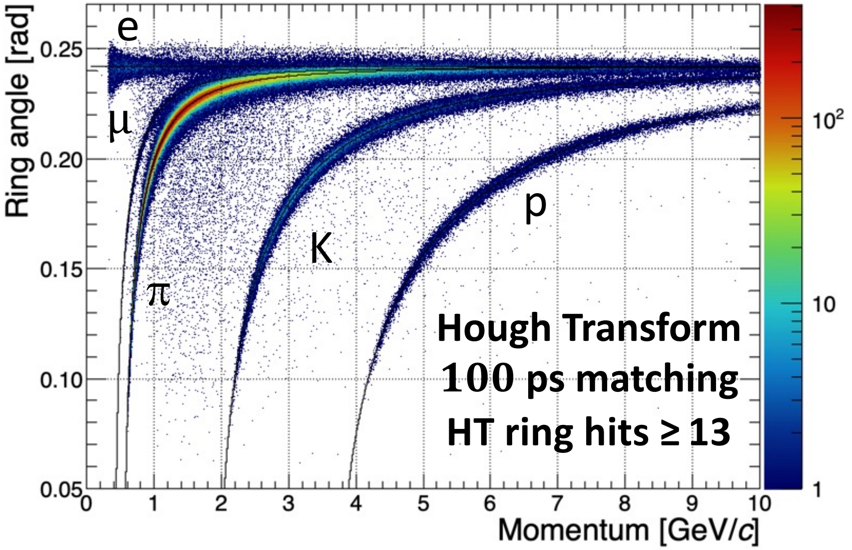


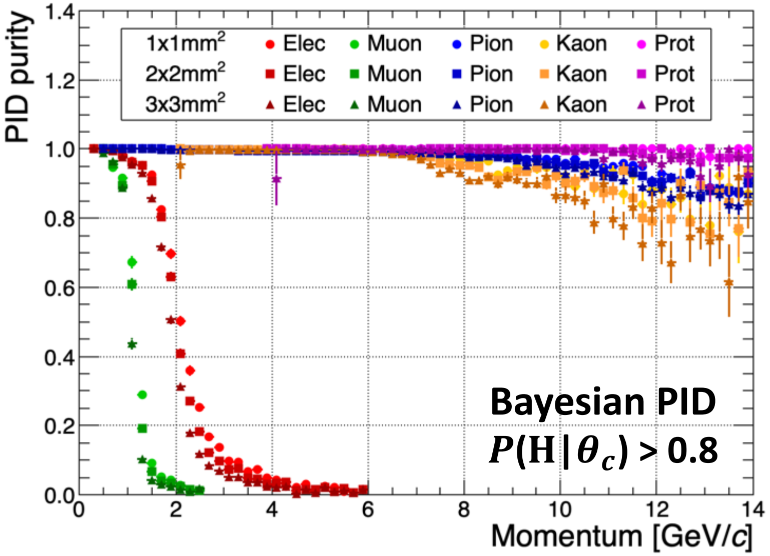
p-p , $c\bar{c}$ biased, $\sqrt{s_{NN}} = 14$ TeV, Pythia8, B = 2 T





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





R&D activities: aerogel radiator

Baseline bRICH option

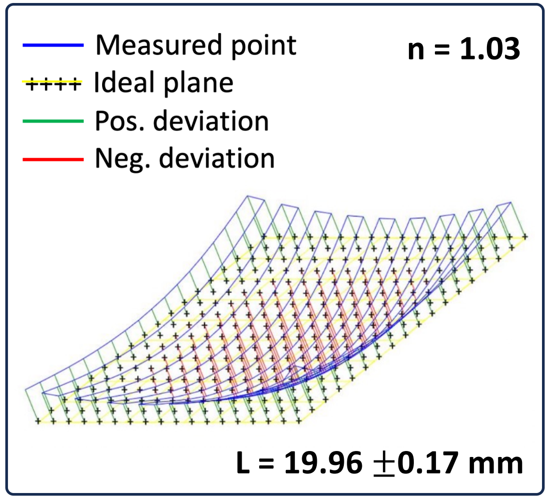
- Tiles from Aerogel Factory Co. LTD (Chiba, JP)

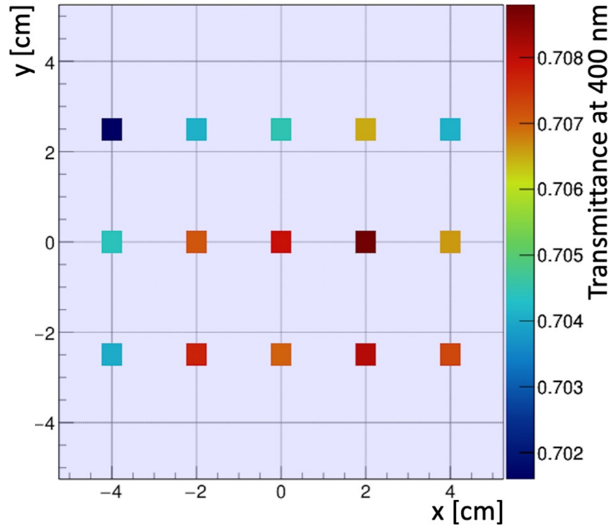
Aerogel characterization

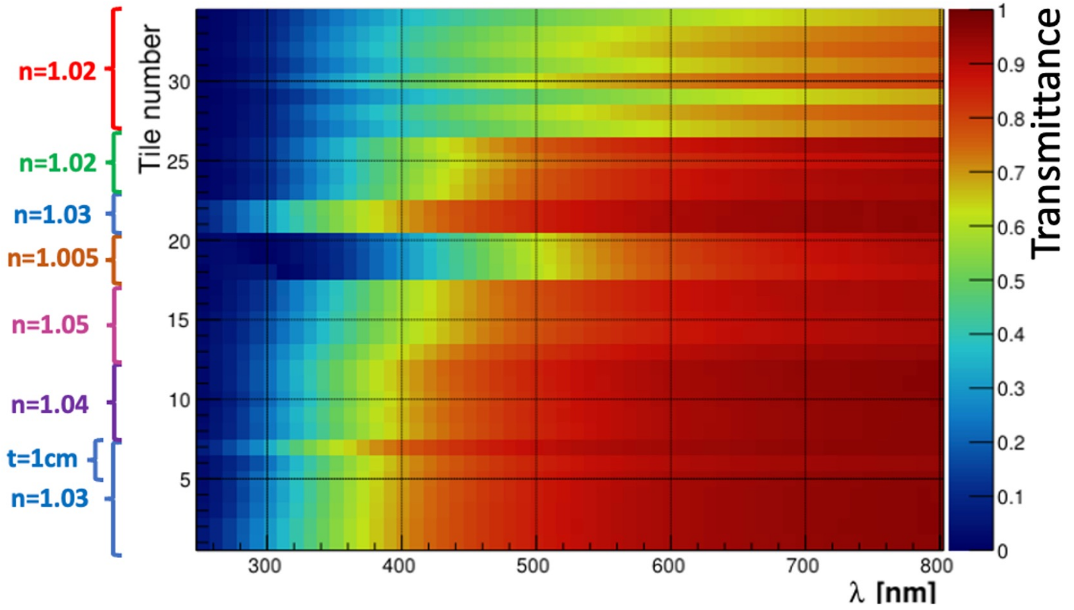
- Refractive index uniformity and reproducibility
- Transmittance, Rayleigh scattering, absorption
- Tile dimensional and shape characterization

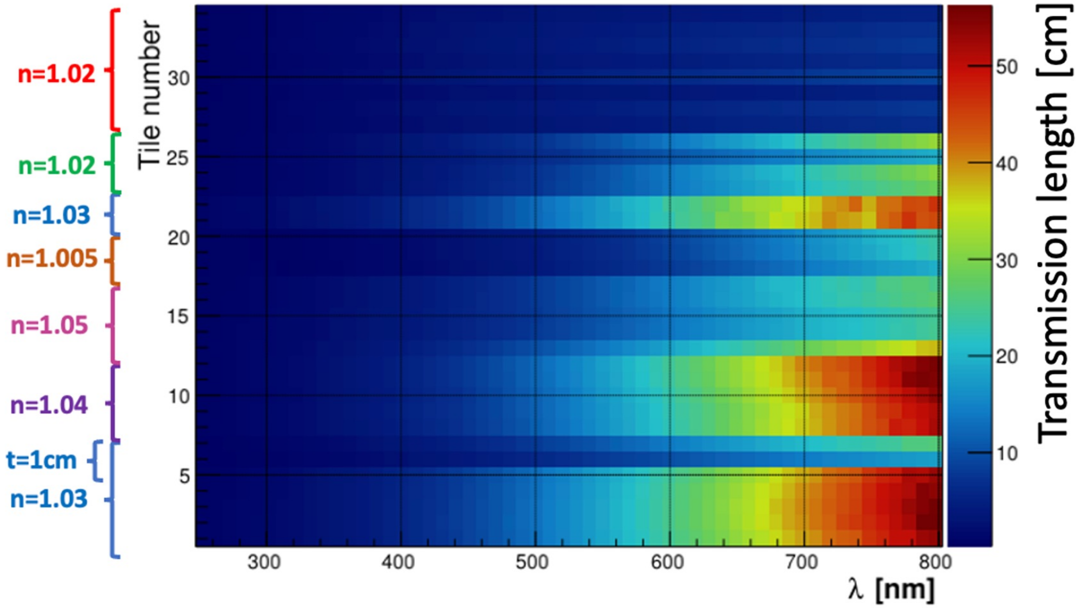
For details: see contribution by Anna Rita Altamura

Meniscus structure at tile edges affects transmittance uniformiy









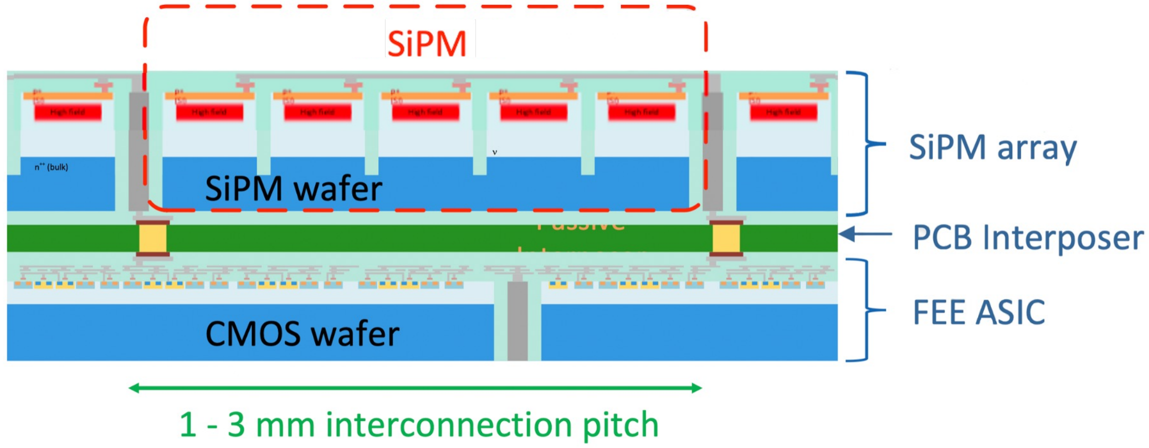
R&D activities: photon detector

Simulations based on commercial SiPMs
- Custom devices already available with better PDE, DCR

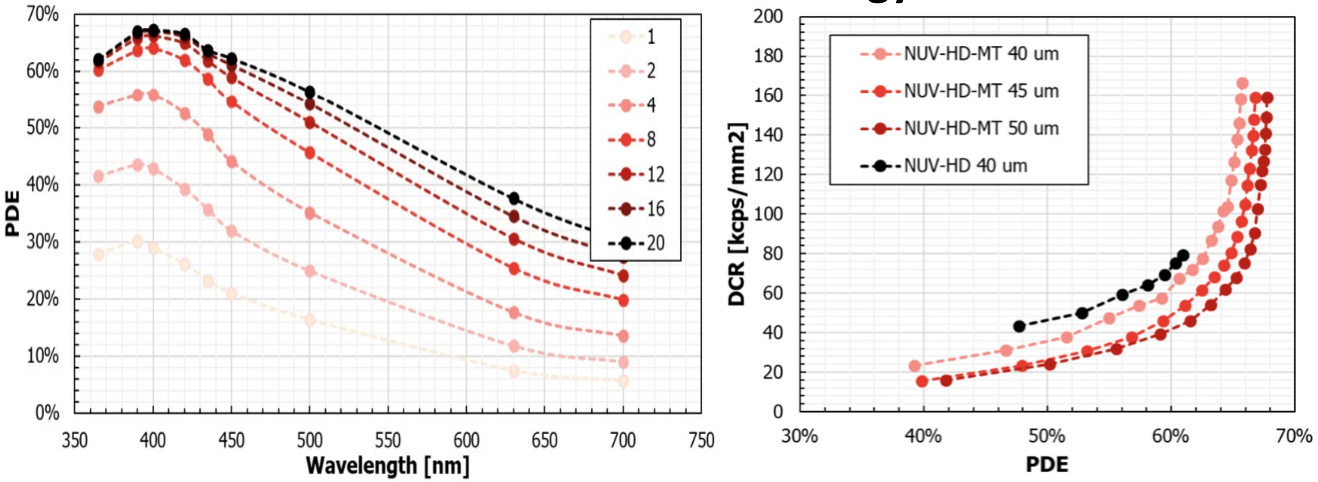
SiPM R&D key topics
- Fill factor and timing: active quenching, SPAD layout
- PDE improvement: E-field engineering, A/R coating
- DCR reduction: E-field engineering, single SPAD access
- Radiation hardness: SPAD layout, cooling, annealing

SiPM packaging option
- 2.5D packaging (using passive silicon interposer)

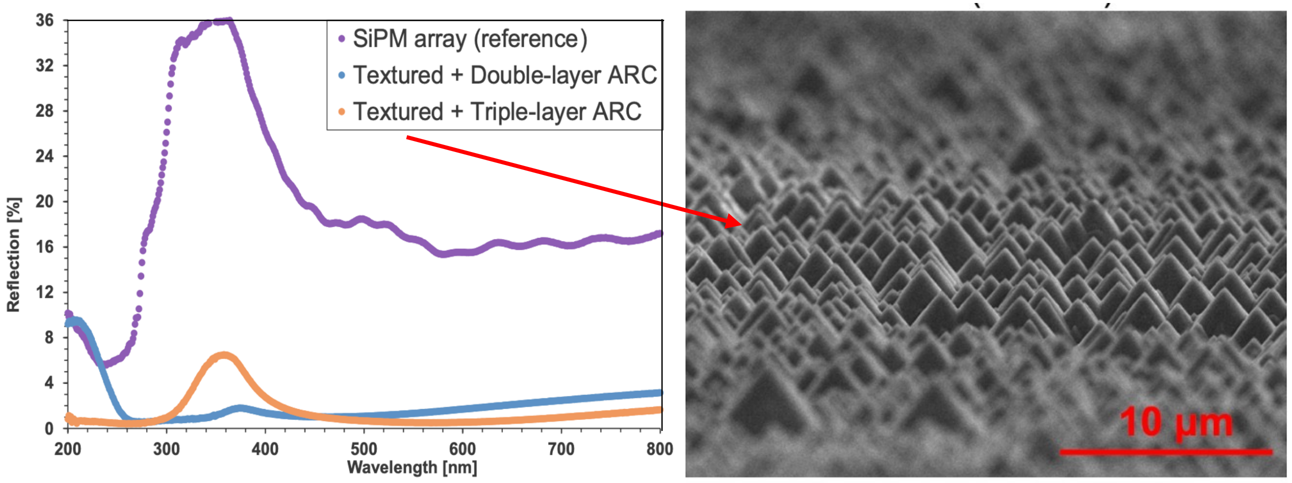
Cooling/annealing circuit embedding in silicon interposer



FBK NUV-HD technology



Fresnel reflections at Si interface: A/R coating and texturing



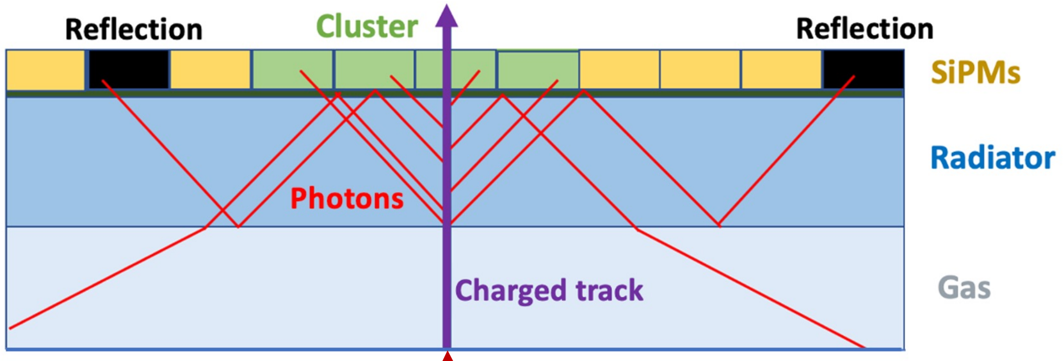
Yuguo Tao at al. doi: 10.1038/s41598-022-18280-y

Option: MIP timing using bRICH SiPMs

Principle of operation

- Introduction of Cherenkov radiator coupled to SiPM layer
- Use SiPM clusters due to radiator photons for MIP timing

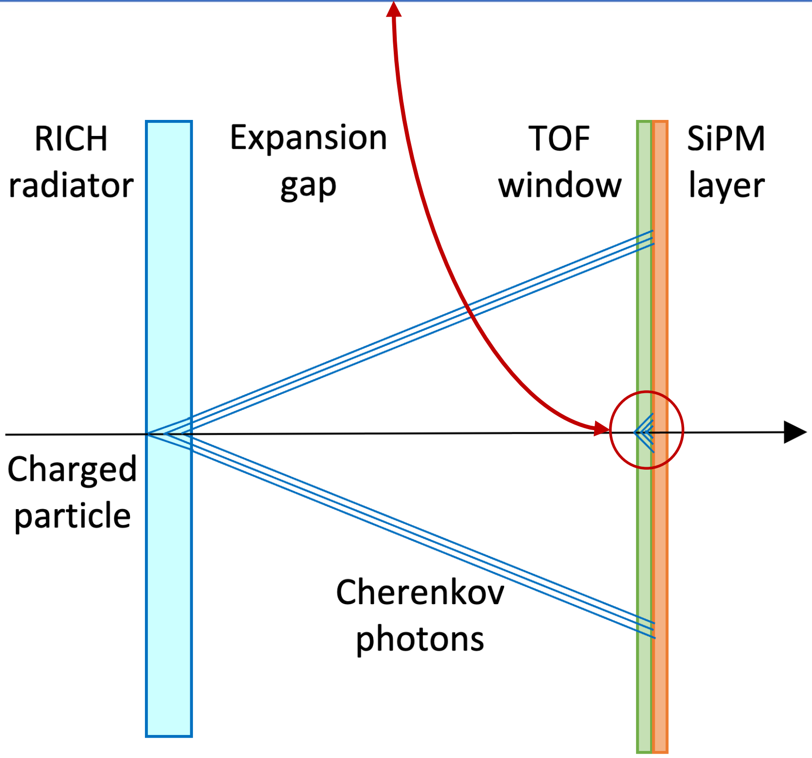
Possibility of achieving time resolutions down to ≈ 20 ps with ≈ 100 % charged particle detection efficiency !!!



See also talks and posters by Bianca Sabiu, Giulia Gioachin

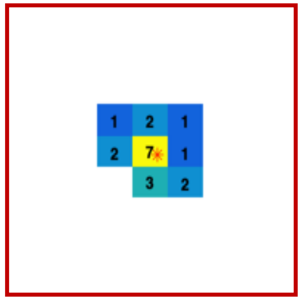
Radiator choice

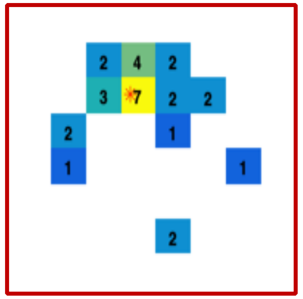
- Use high refractive index material to minimize Cherenkov thresholds and to enhance both photon yield and spread



1 mm SiO_2 (n=1.47) + 0.45 mm epoxy resin (n=1.55), 1x1 mm^2 SiPMs

*MIP at 0° incidence



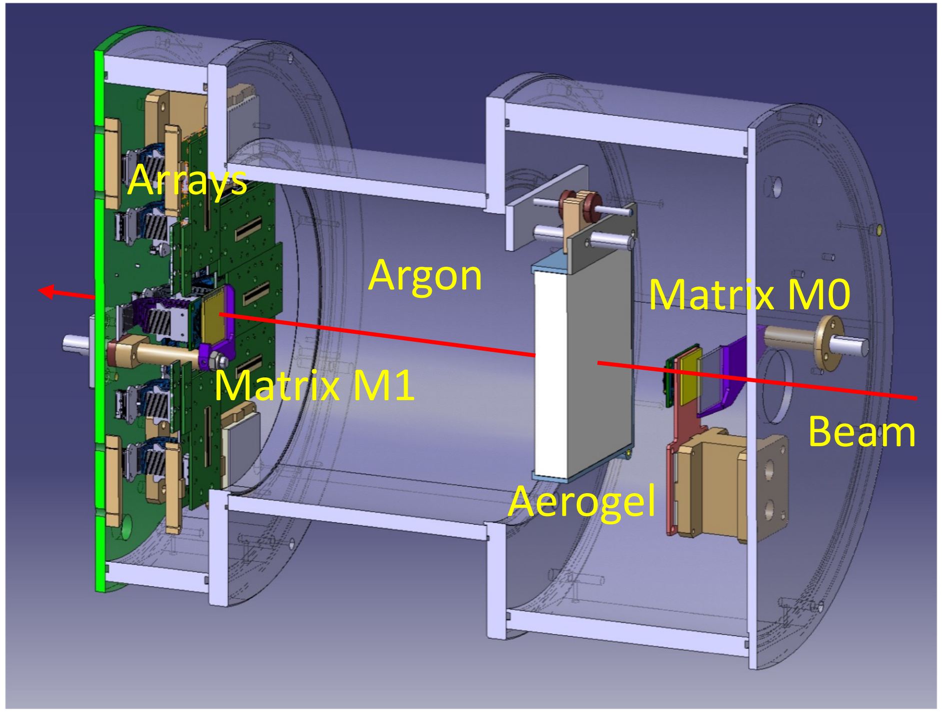


*MIP at 50° incidence

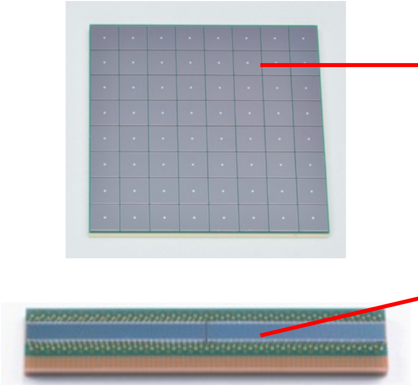
Assuming PDE of S13360-50CS SiPMs at recommended overvoltage**

2022/2023 beam tests @ PS/T10

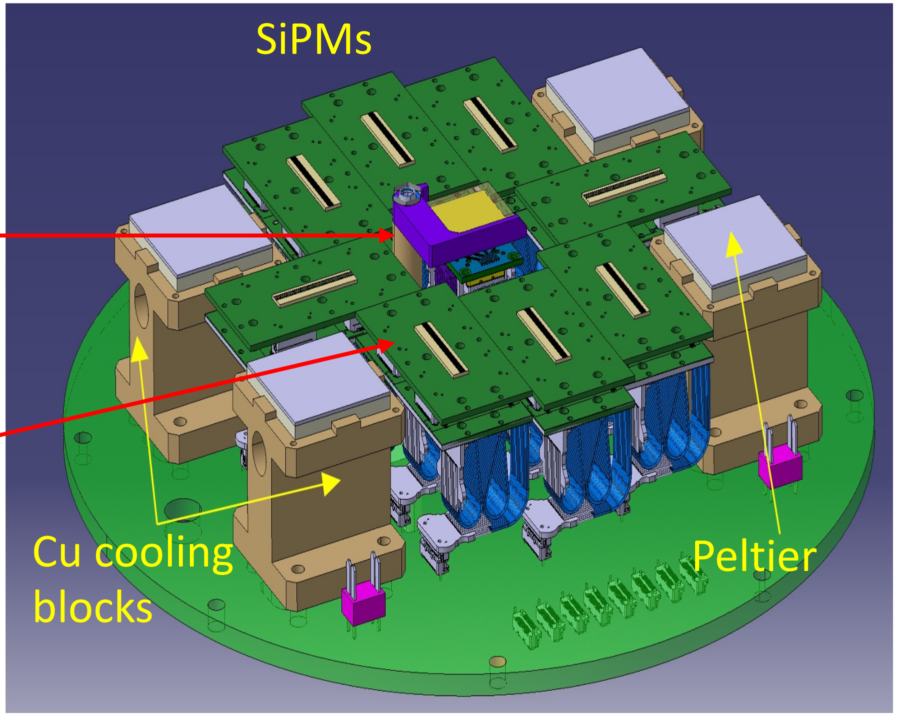
In collaboration with Mario Nicola Mazziotta, Leonarda Lorusso, Giuliana Panzarini, Roberta Pillera et al. (INFN Bari)



Card for MIPs, HPK S13361-3075AE-08
8x8 ch. matrix of 3x3 mm^2 pads
64 ch. read-out



8 cards for rings, HPK S13552
128 ch. array of 0.23x1.625 mm^2 strips
32 ch read-out x 4 ORed strips



Angular measurements

- **Radiator**: Aerogel, n = 1.03, T_r = 2 cm
- **Gap**: Argon, n = 1.00028, T_g =23.0 cm
- **Sensors**: 8 x HPK S13552, V_{ov} = 4.6 V

Timing measurements

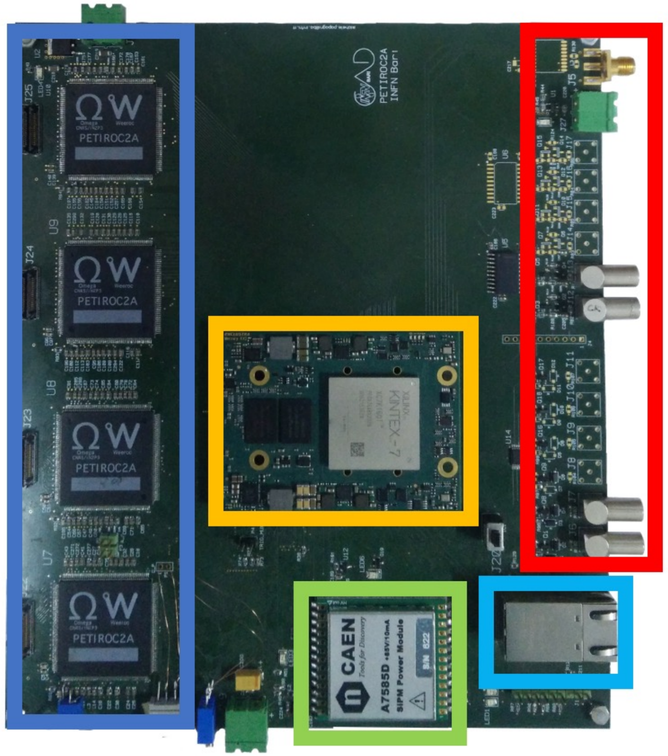
- HPK S13361-3075 + 1mm quartz/MgF_2
- HPK S13361-3075 + no window
- HPK S13361-1350 + 2mm quartz

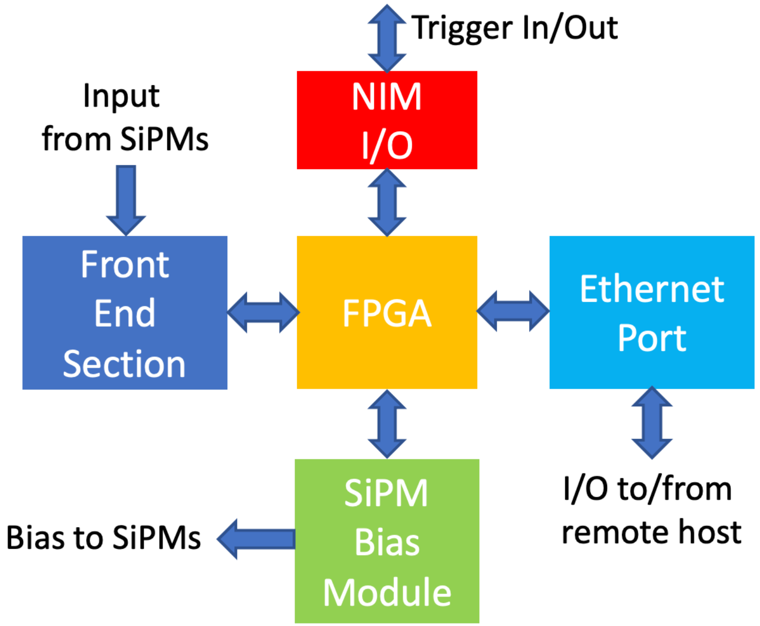
Ancillatory detectors

- **Triggering**: Beam plastic scintillator
- **Tracking**: 2 X-Y fiber tracker module
  - 1 mm read-out pitch

SiPM cooling: **Water chiller + 5 Peltier devices** ⇒ Measured operation temperature in [-5°,0°]

Beam test Front-End and DAQ





Four different FEBs

- Two FEBs for the 8 array read-out
- One FEB for the 2 central matrices
- One FEB for the 2 X-Y fiber trackers

Boards developed in Bari for a fiber tracker

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

Front-End

- 4 PETIROC 2A ASICs:
  - 32 front-end channels
  - PA - time jitter about 45 ps (>4 p.e.)
  - TDC for time measurements - 37 ps LSB
  - ADC for charge measurements - 10 bit
  - 32 digital outputs for triggering

FPGA

- I/O data management
- Trigger
- Coincidence

SiPM Bias Module

- SiPM bias voltage regulation up to 80 V

NIM I/O

- Trigger

Ethernet port

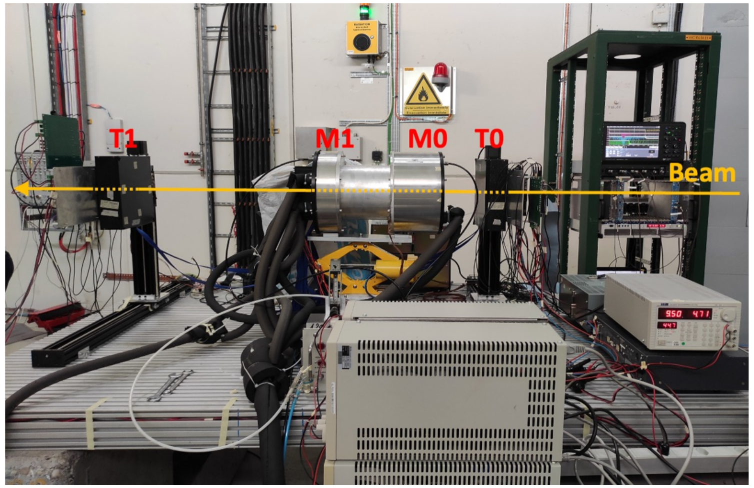
- Data I/O to a remote host

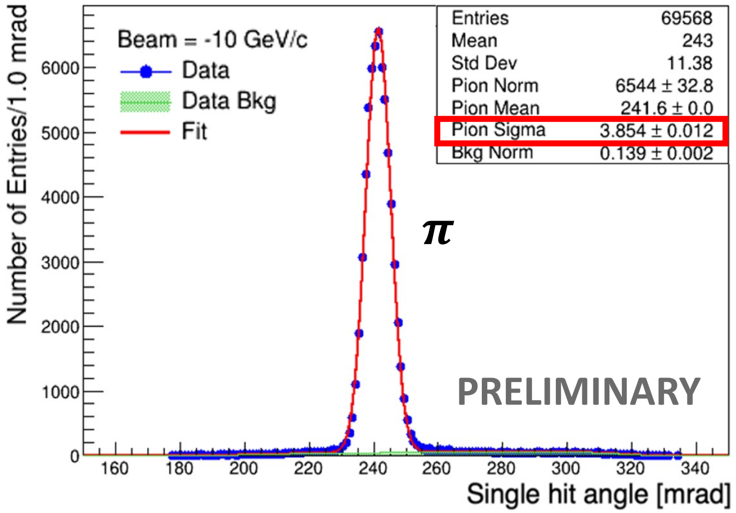
Angular resolution measurements

Analysis strategy

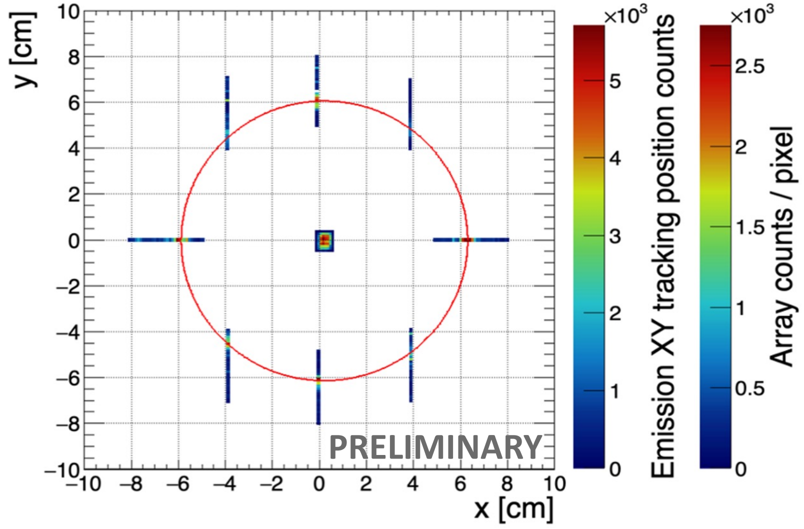
- **Event selection**
  Requiring signal in a fiducial area of the fiber tracker planes (T0,T1) and the SiPM matrices (M0,M1)
- **Charged particle tracking**
  4-points straight line fit to extract the track position in the middle of aerogel and track director cosines
- **Single photon Cherenkov angle**
  Hit geometric backpropagation from all hit positions to the median plane of the aerogel tile
- **Time cut for DCR suppression**
  $$|t_{hit,array} - t_{max-q,M0}| < 5 \text{ ns}$$
- **Fit model for angular distribution**
  Assuming Gaussian signals and template bkg. distribution from time-uncorrelated hits w.r.t. MIP

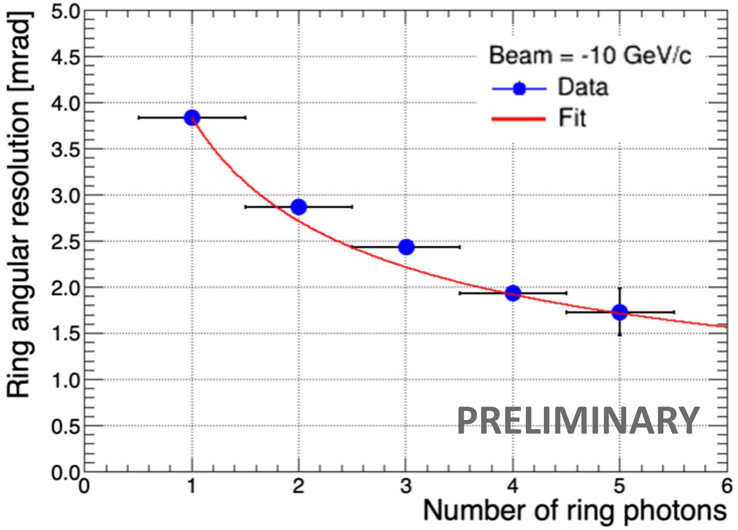
We measured a single photon resolution $\sigma_\theta \approx 3.8$ mrad





Ring resolution better than 1.5 mrad for N > 6 photons





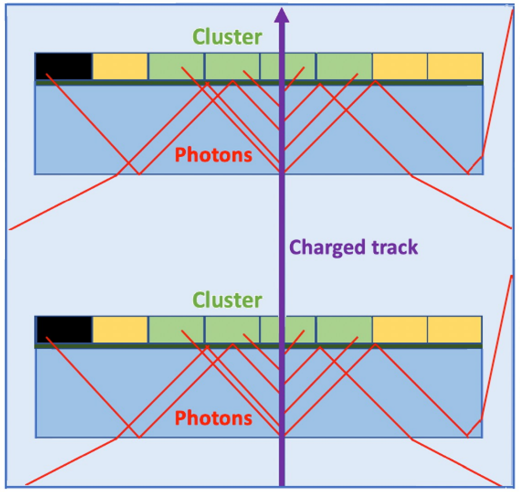
Charged particle timing measurements

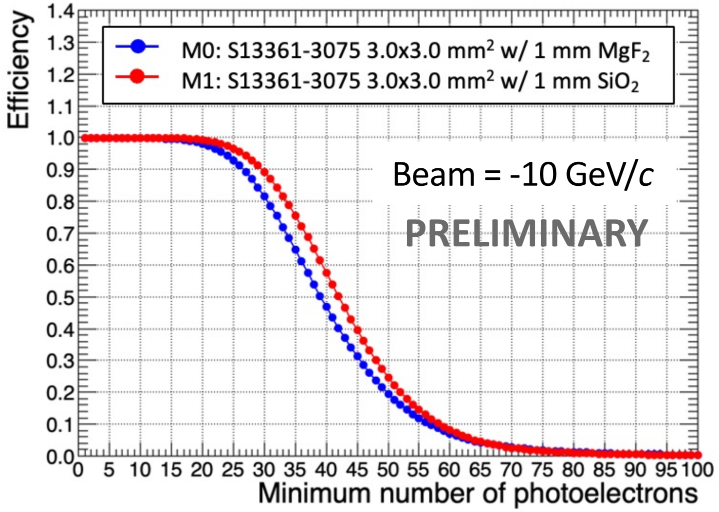
Analysis strategy

- **Event selection**
  Signal in fiducial area of tracker (T0,T1) and matrices (M0,M1)
- **Fine time calibration**
  Channel-by-channel level
- **Channel intrinsic offset correction**
  Different delays for different SiPMs: routing, cabling, etc.
- **Time walk correction**
  Intrinsic offset between signals with a different number of p.e.
- **Timing operations**
  Comparing M0 and M1 response
  Extrapolating M0 / M1 resolution

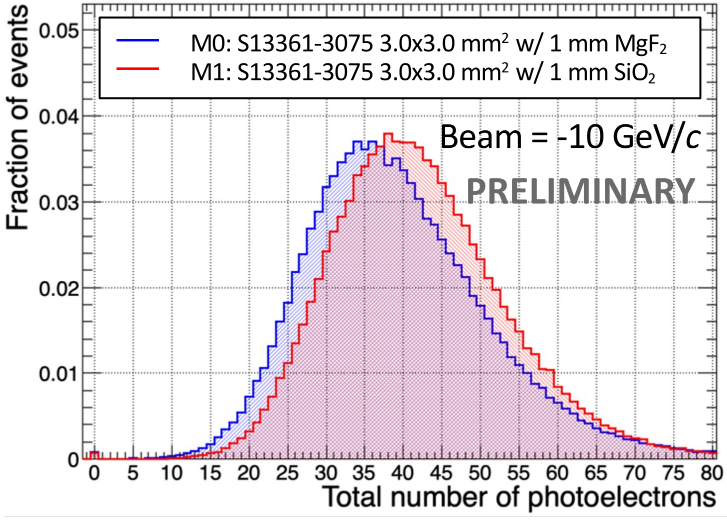
Note: The results on timing include both the intrinsic SiPM resolution and the electronics (jitter, TDC, etc.)

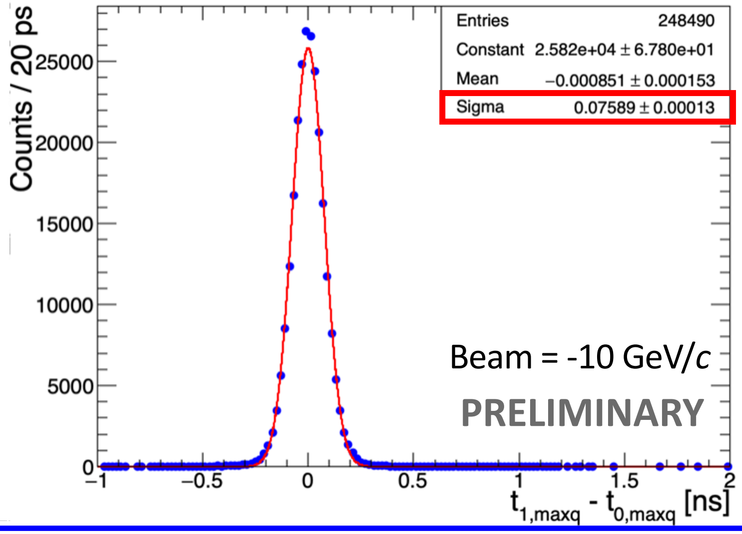
Measured charged particle detection efficiency $\varepsilon \approx 100\%$





Resolution: $\sigma(\Delta t) \approx 75$ ps $\Rightarrow \sigma(t) \approx \sigma(\Delta t)/\sqrt{2} \approx 53$ ps





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Conclusions

Summary

- Simulation studies show that the **proposed bRICH** fulfills the ALICE 3 PID requirements, in particular in the extreme high-multiplicity environment expected in central Pb-Pb events
- Breakthrough concept of **TOF measurements** using bRICH SiPMs is currently under study and very promising results on the achievable arrival time resolution have been obtained
- **R&Ds**: Aerogel and SiPM characterization, radiation hardness, bRICH mechanics, cooling

Outlook

- **2024-2025**: Selection of technologies, small-scale prototypes
- **2026-2027**: Large-scale prototypes, Technical Design Report

Thank you for your attention!

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