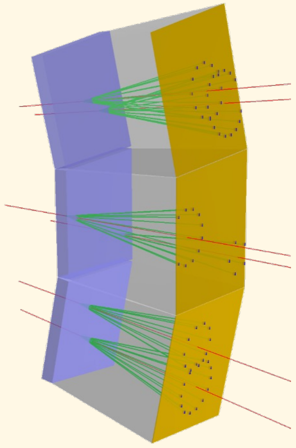
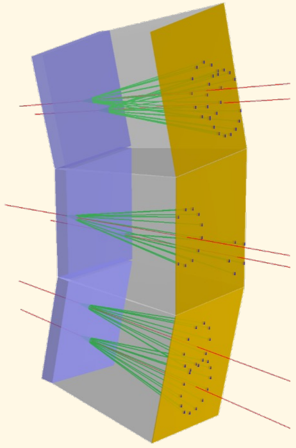
Designing the ALICE 3 bRICH detector: simulation studies and beam test results



Nicola Nicassio (University and INFN Bari*)

on behalf of the ALICE Collaboration

RICH 2025 – September 15-19, 2025



* CERN/INFN fellowship from 01/03/2025 to 28/02/2026

Outline

Detector concept

Simulation studies

Test beam results

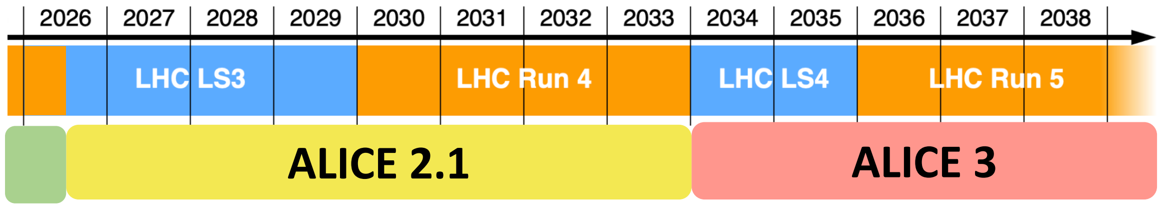
The ALICE 3 upgrade

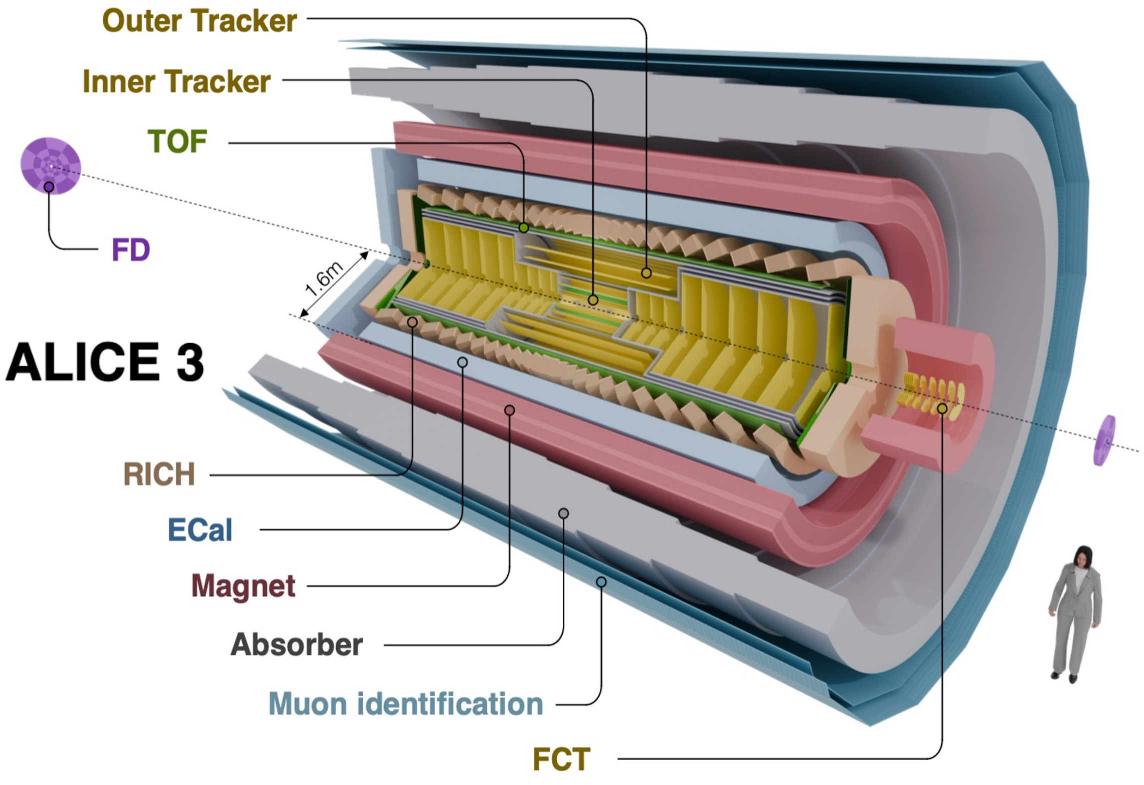
ALICE 3 motivation and concept

- **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

A RICH system covering the barrel (bRICH, $|\eta| < 2$) and forward region (fRICH, $2 < |\eta| < 4$) is planned

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: ≈ 10 μm at 200 MeV/c
	Tracking relative p_T resolution: ≈ 1-2 %
	$\boxed{\text{Extensive identification of e, μ, π, K, p}}$ γ
	Large pseudorapidity coverage: $|\eta| < 4$





ALICE 3 Scoping document: CERN-LHCC-2025-002

bRICH baseline

Proximity-focusing RICH based on aerogel + SiPMs in a projective geometry

Goal

- π/e, K/π and p/K in the p intervals [0.5, 2], [2, 10] and [4, 16] GeV/c

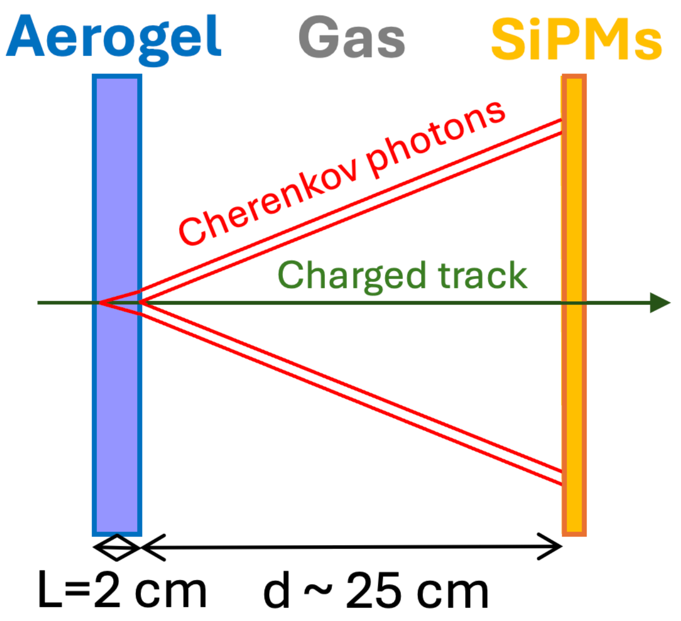
$\Rightarrow$ Need for $n \approx$1.03, $\sigma_\theta^r \approx$ 1.5 mrad

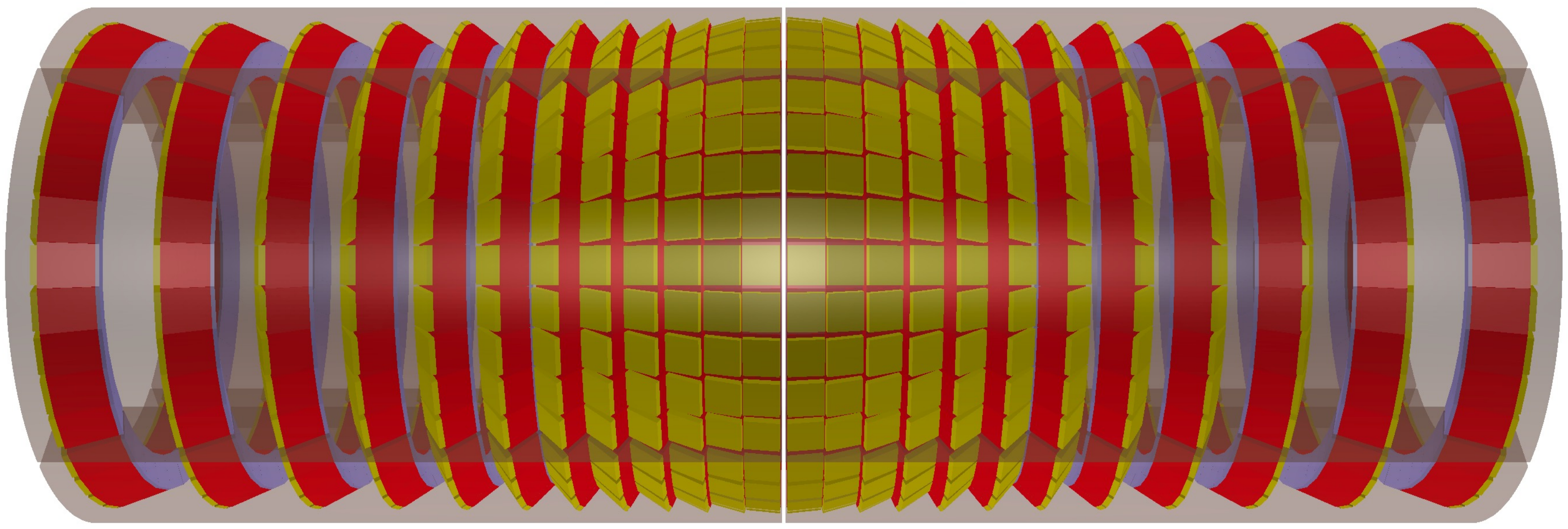
Technology

- Aerogel: L ≈ 2 cm, n = 1.03
- SiPMs: 2x2 mm^2, T = -40 °C
- DENEB FE ASIC: 1024 chan.

Geometry

- 24 sectors x 36 modules, active area ≈ 18.6 m^2
- All modules oriented toward the interaction point
- Trapezoidal tile profile for maximum acceptance





Aerogel radiator

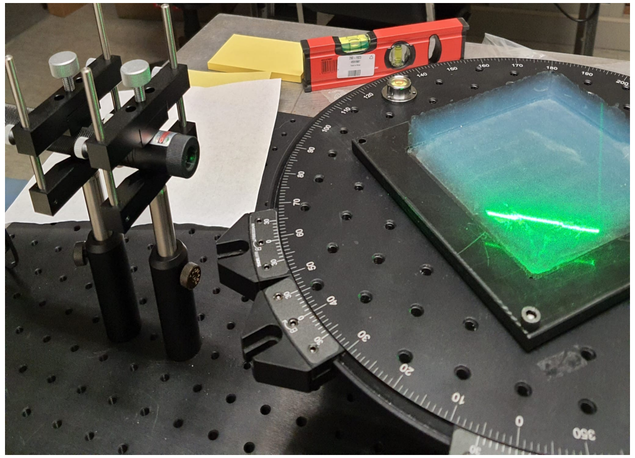
Reference bRICH option

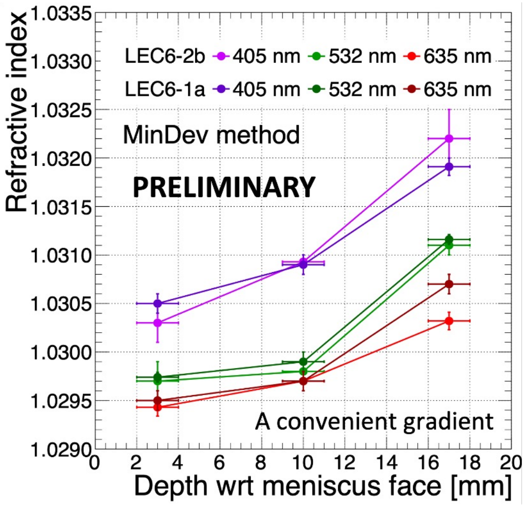
- Hydrophobic tiles from Aerogel Factory Co. Ltd. (JP)

Characterization studies

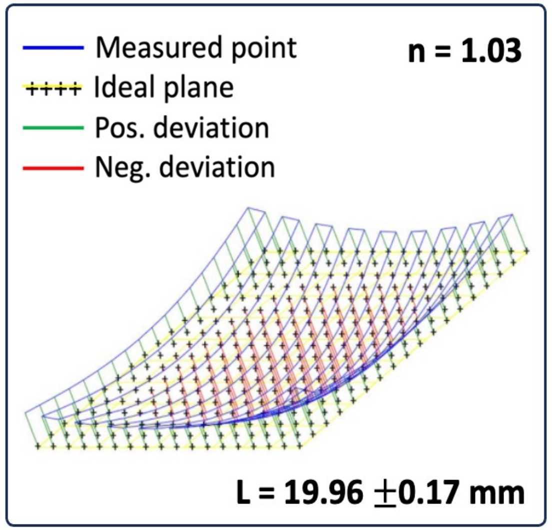
- Refractive index uniformity and reproducibility
- Transmittance, Rayleigh scattering, absorption
- Tile dimensional and shape characterization

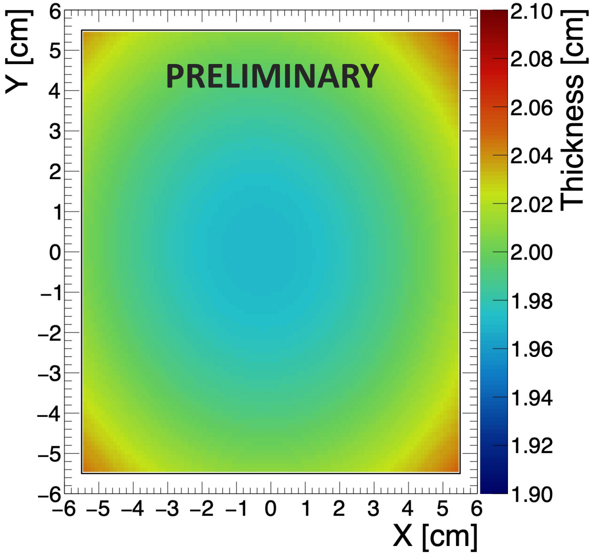
For details: see poster by Rocco Liotino

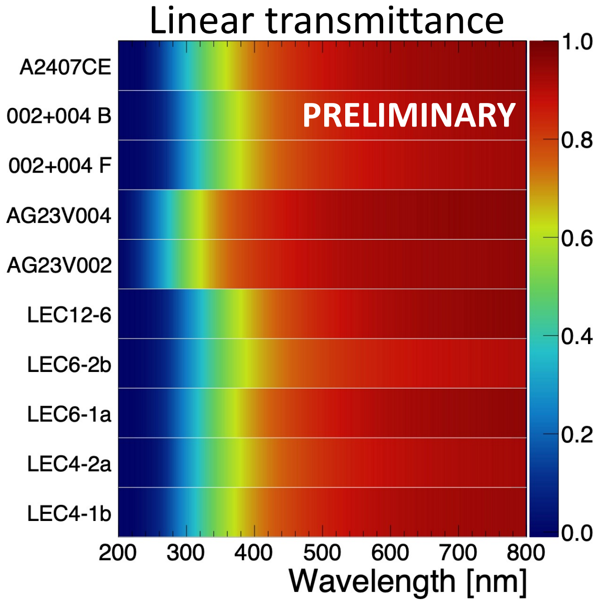


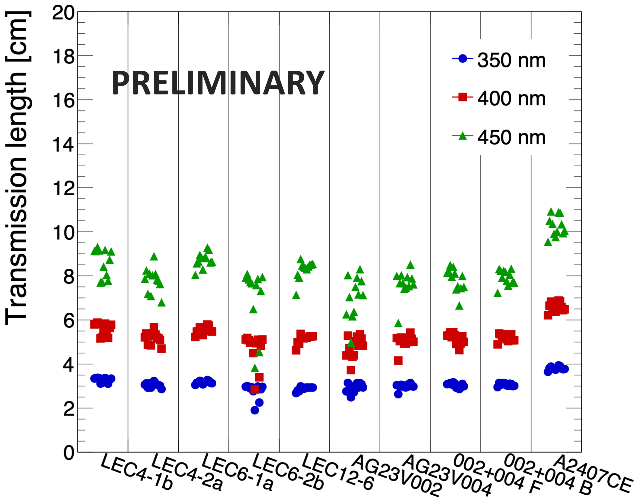


Meniscus structure at tile edges affects transmittance uniformity









SiPM-based photodetector

Reference bRICH option

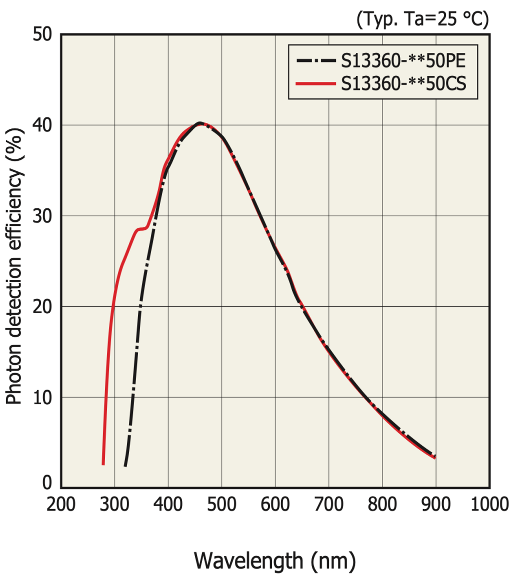
- HPK S13361-2050 SiPMs operated at $V_{ov} = 3$

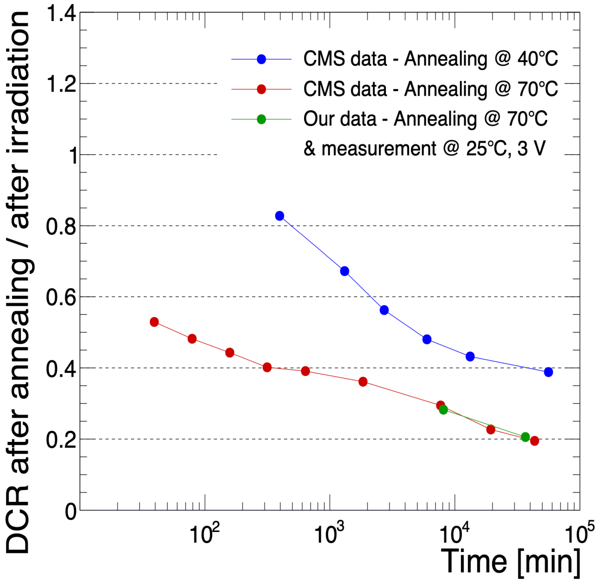
Radiation damage studies

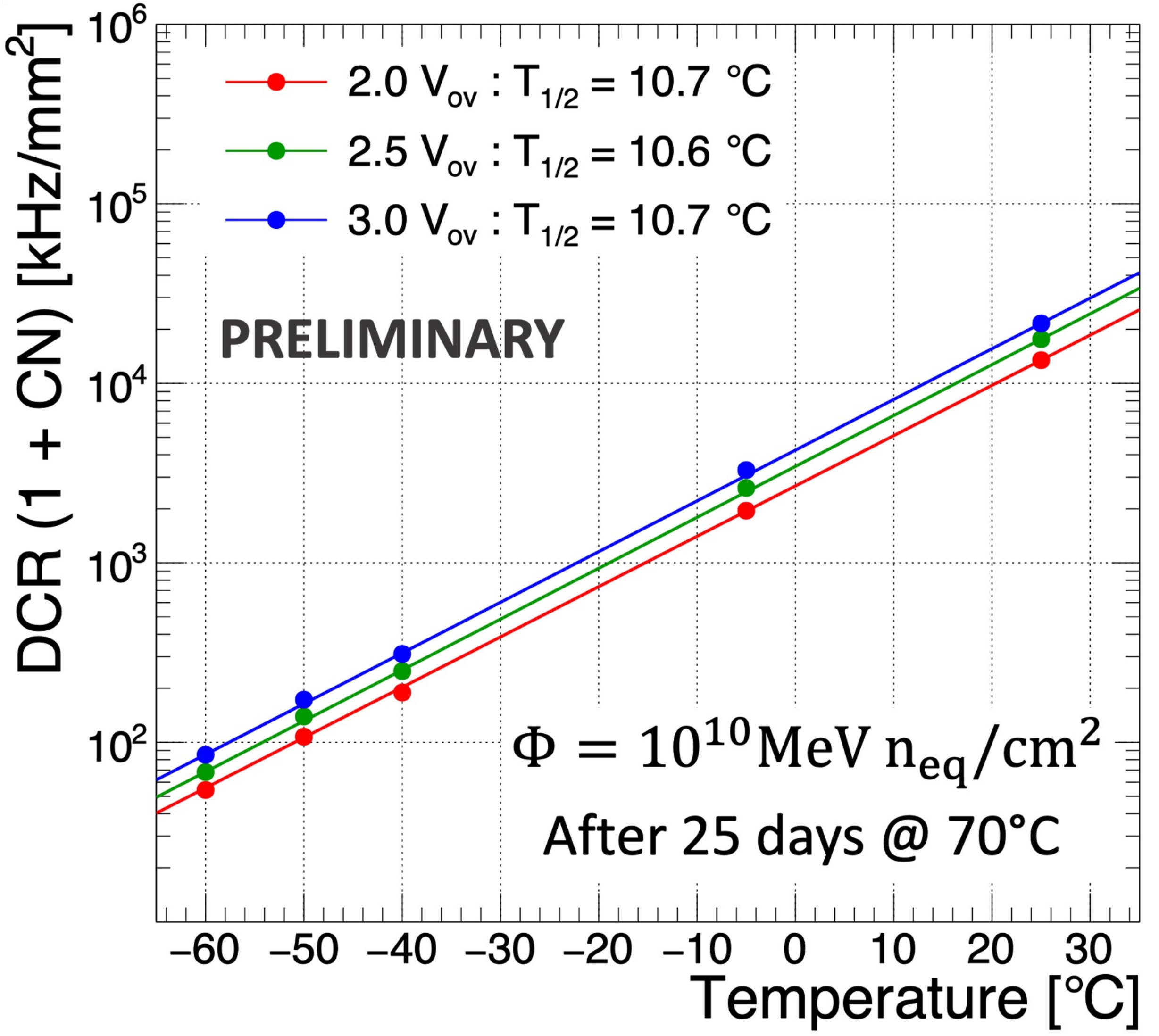
- Expecting fluence up to units of 10^{11}MeV n_{eq}/cm^2
- We identified a DCR safety limit of 1 MHz/mm² per ch.

⇒ Cooling at T < -40°C + annealing at T > 70°C crucial

- Testing of arrays irradiated up to 10^{12} MeV n_{eq}/cm^2



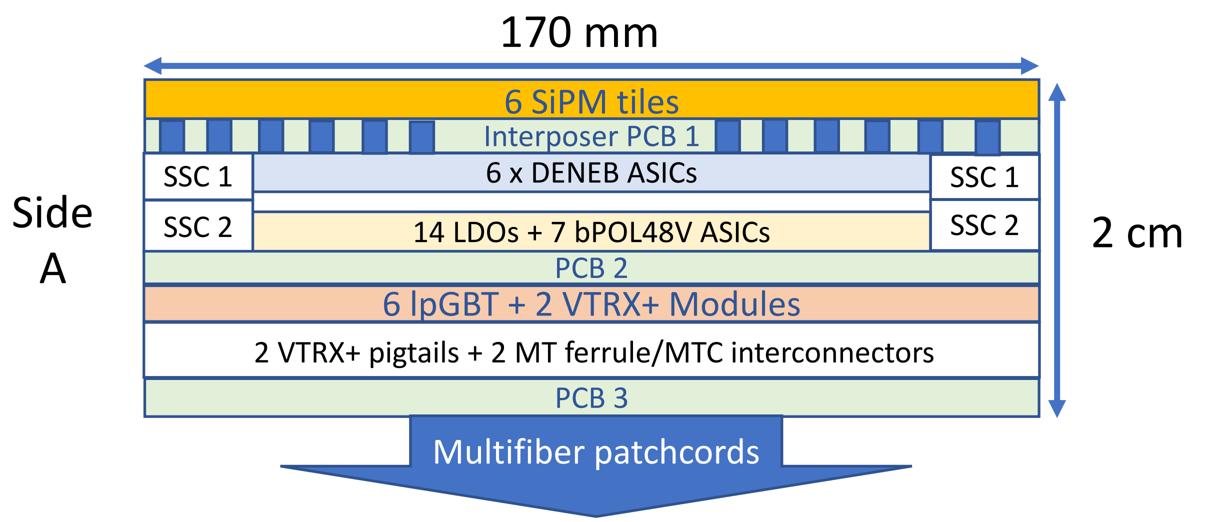


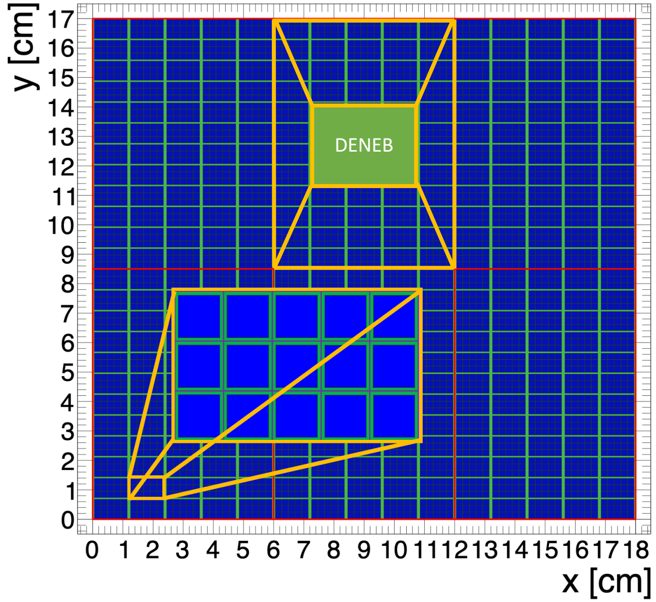


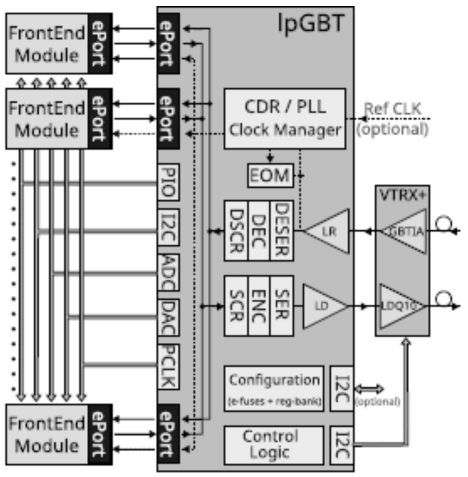
Module concept

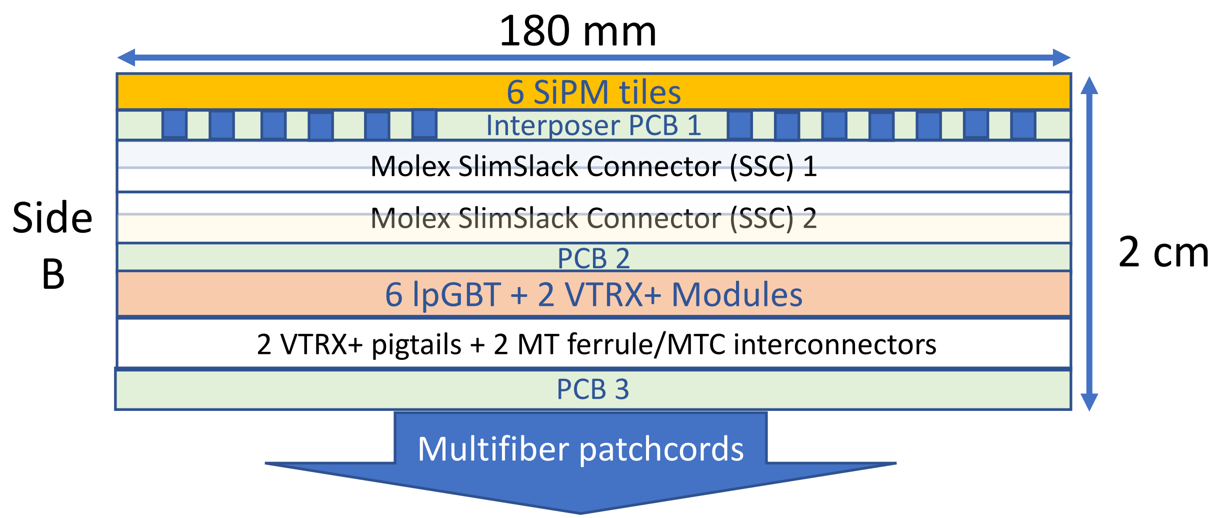
FEE-module reference

- SiPM layer with an area of 17x18 cm^2 connected to the FEE layer via a PCB / ceramic interposer integrating cooling via microchannel bi-phase CO_2
- FEE layer segmented in 6 DENEB 1024-ch. ASICs (under development for DUNE based on ALCOR)
- Read-out based on 6 lpGBT & 2 VTRX+ per module





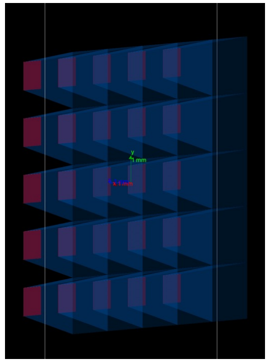




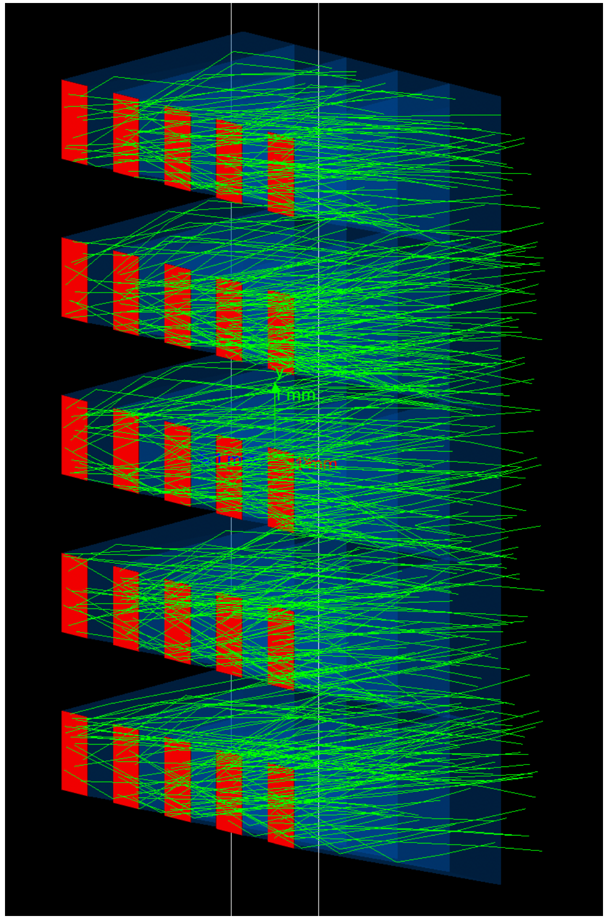
Option: Smaller SiPMs + concentrators

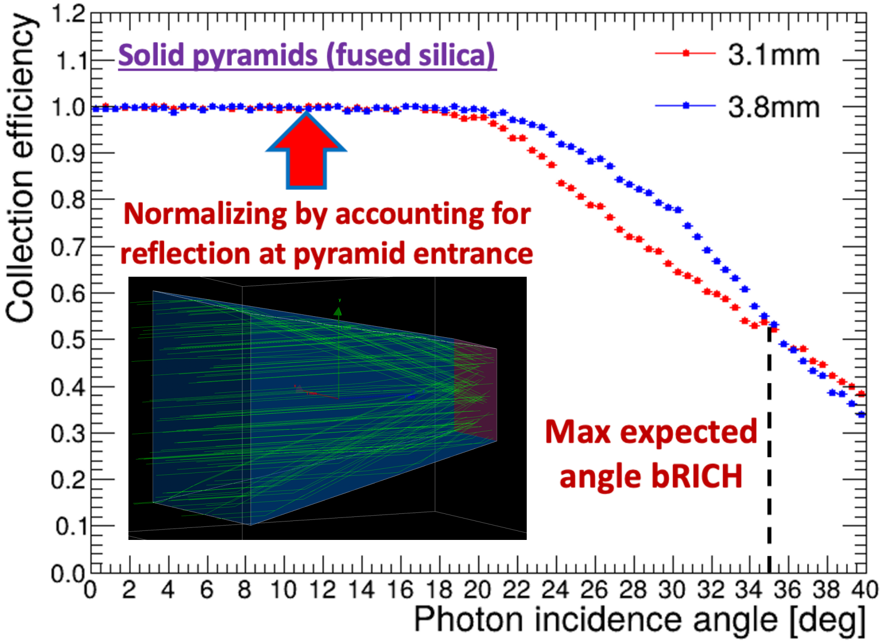
DCR mitigation using light concentrators

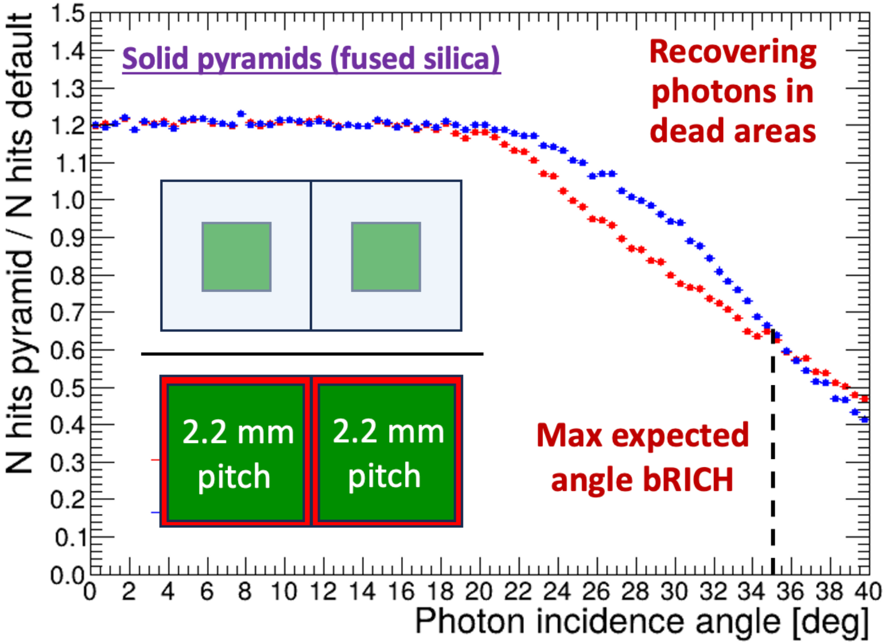
- Light guides concentrating photons from an area of 2.2x2.2 mm^2 onto SiPMs with an area of 1x1 mm^2
- Reducing DCR/ch., active area and cost by $\approx \times 4$
- Keeping the same number of ch. and module layout
- Recovering photons in dead regions between SiPMs



Sensor active area (m^2)
18.58 (baseline 2x2 mm^2)
4.64 (light conc.+1x1 mm^2)



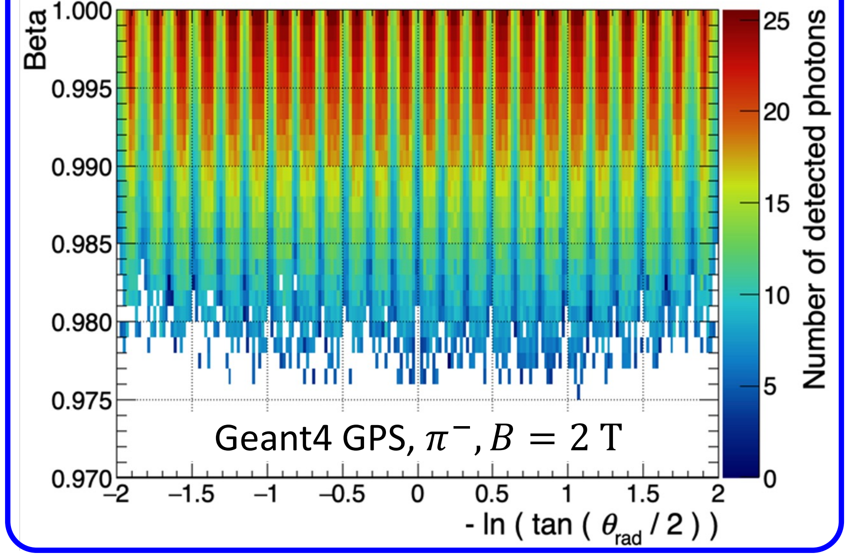




Simulation: yield and resolution

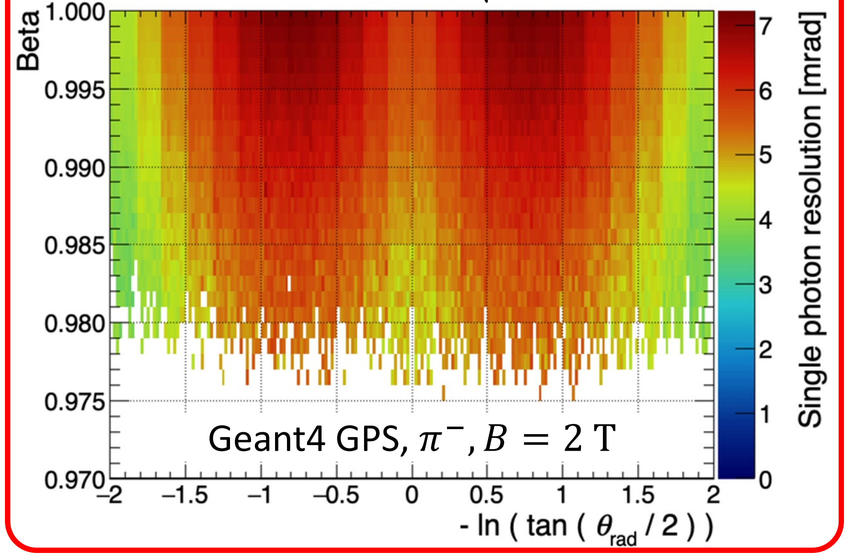
Number of detected photons

- $N_{p.e} \propto \sin^2\theta_c \oplus \text{phot. acceptance}$



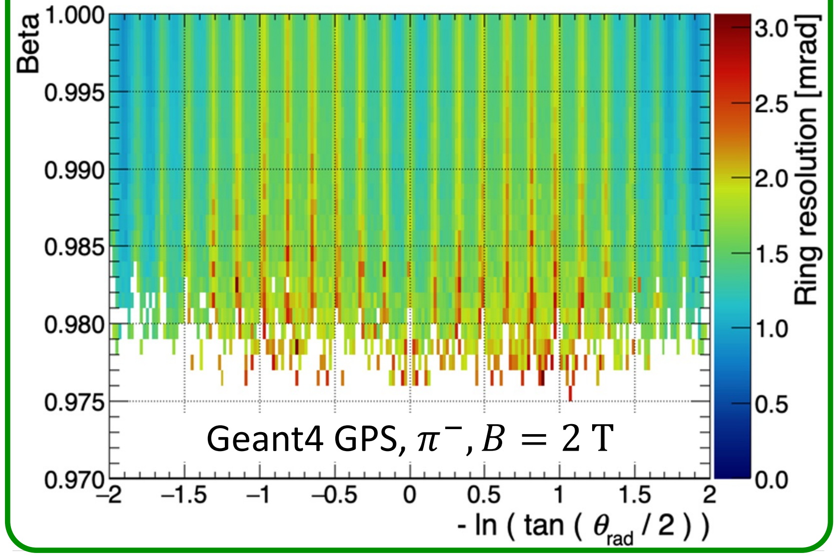
Single photon resolution

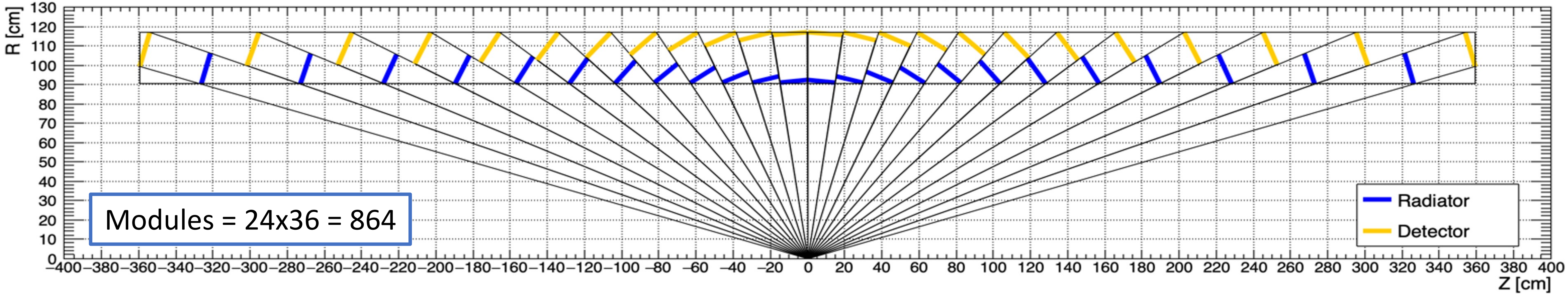
- Expected: $\sigma_{\theta_c}^{p.e.} = \sqrt{\sum_i \sigma_{\theta_c}^2(i)}$



Ring angular resolution

- Expected: $\sigma_{\theta_c}^{ring} = \sigma_{\theta_c}^{p.e.} / \sqrt{N_{p.e}}$



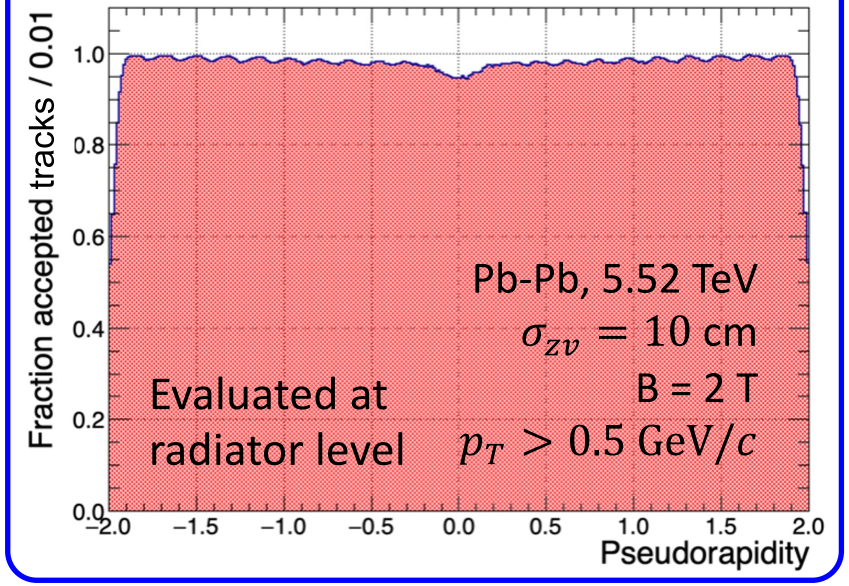


Modules = 24x36 = 864

Simulation: acceptance and timing

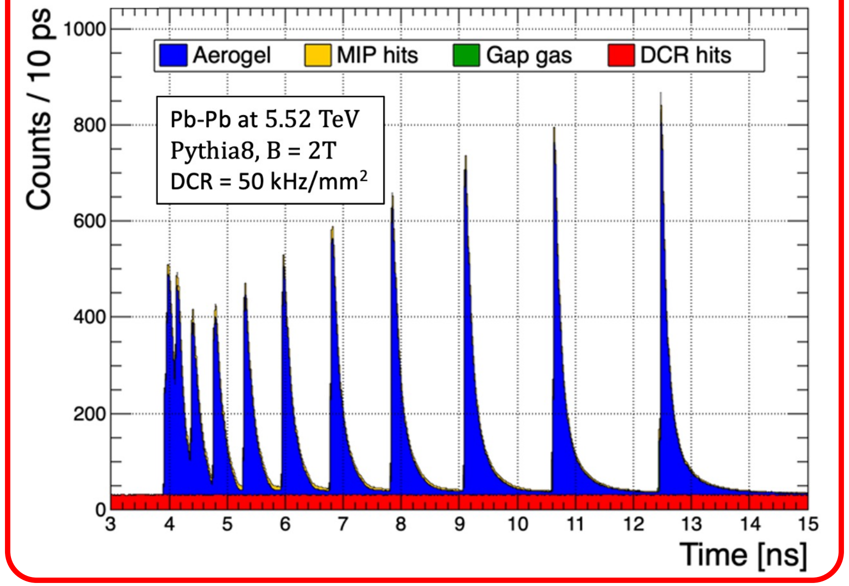
Charged track acceptance

- Minor losses at sector boundaries



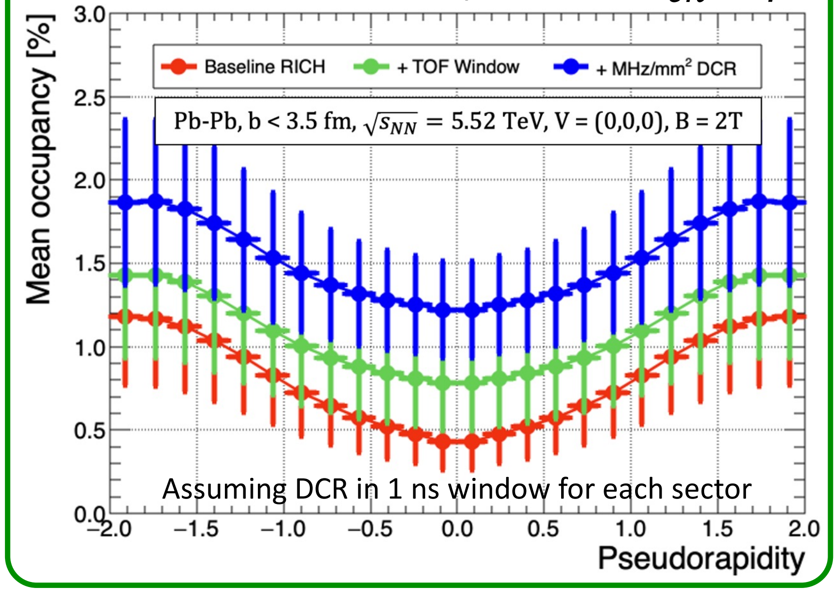
Time profile of Pb-Pb events

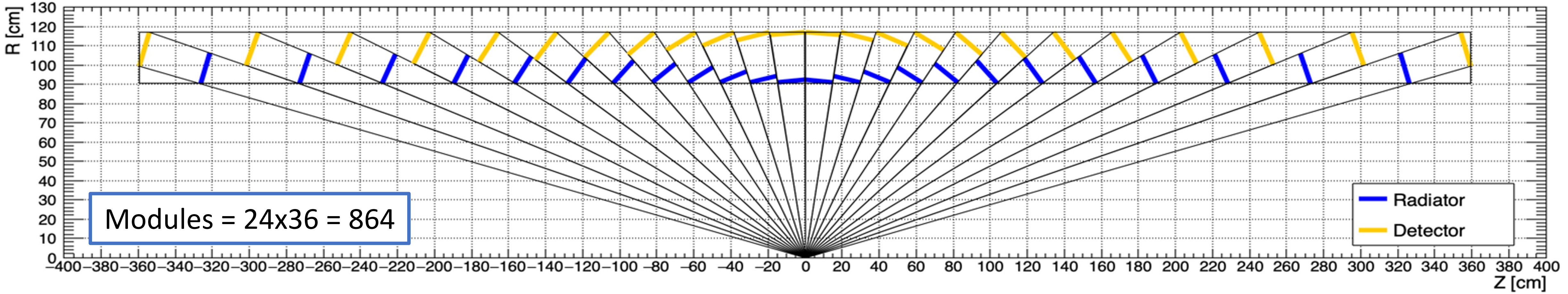
- Signal hits clustered in ≈ ns intervals



Photodetector occupancy

- Consistent with expected $dN_{ch}/d\eta$

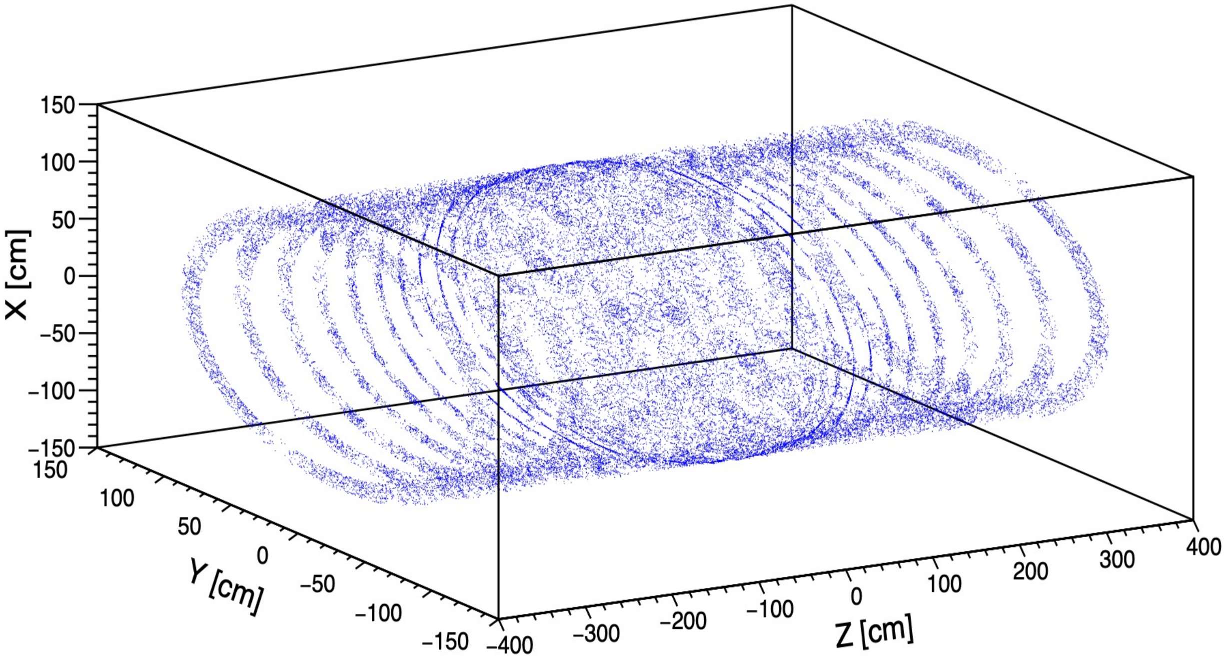


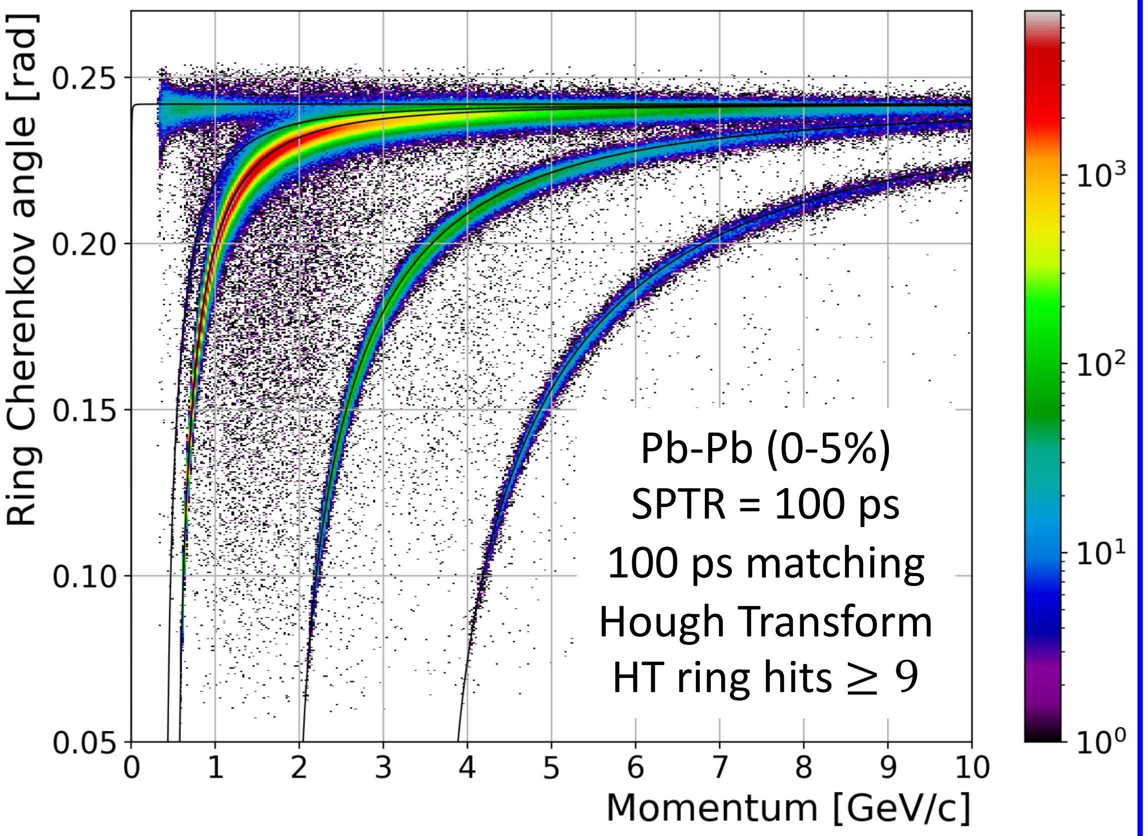


Simulation: Performance in Pb-Pb

- **Challenge: Pattern recognition in high-multiplicity central Pb-Pb events**
  - **Background: Photon hits from different tracks, DCR, Rayleigh scattering**
  - **Precise photon timing (SPTR < 100 ps) crucial for background suppression**

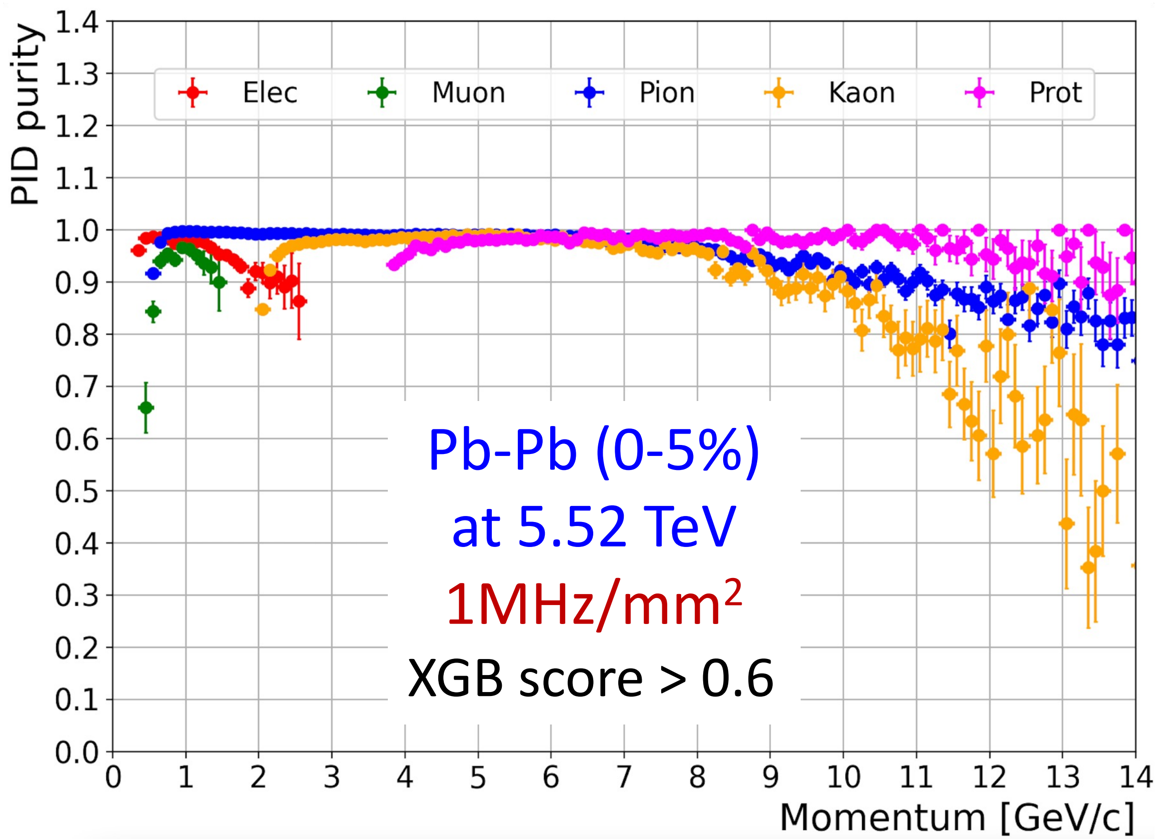
Hit map of a single central Pb-Pb event

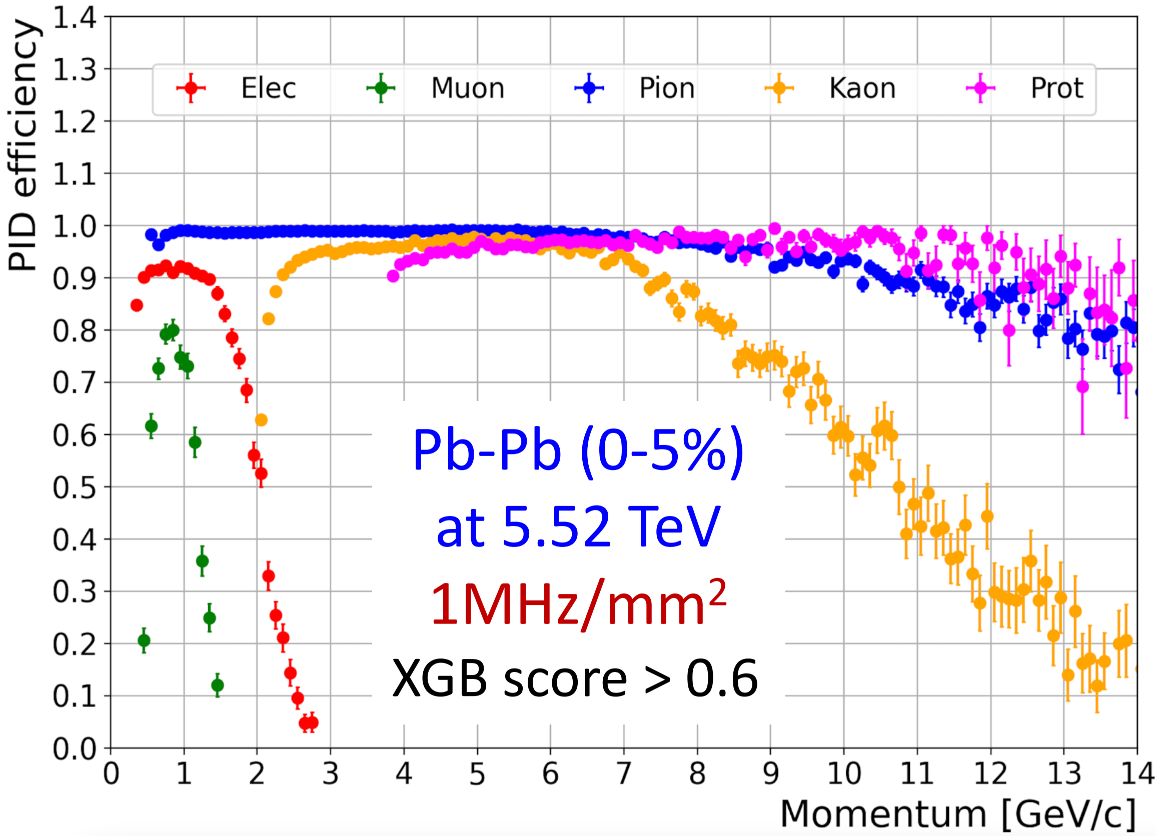




Simulation: Performance in Pb-Pb

- **PID analysis: ML algorithm based on XGBoost trained to optimize eff x pur**
- **Features: trk parameters, N photons in various $N\sigma_{\theta c}^{\gamma}$, ϕ_c, $\Delta t_{hit-trk}$ intervals**
- **Topology of C.kov rings in projective geometry automatically learnt by ML**





Option: Gas-based $e^{\pm}$ ID enhancement

Goal

- Extend electron/positron identification above 2 GeV/c
- Required for dielectrons and quarkonia, e.g. J/ψ → $e^{+}e^{-}$

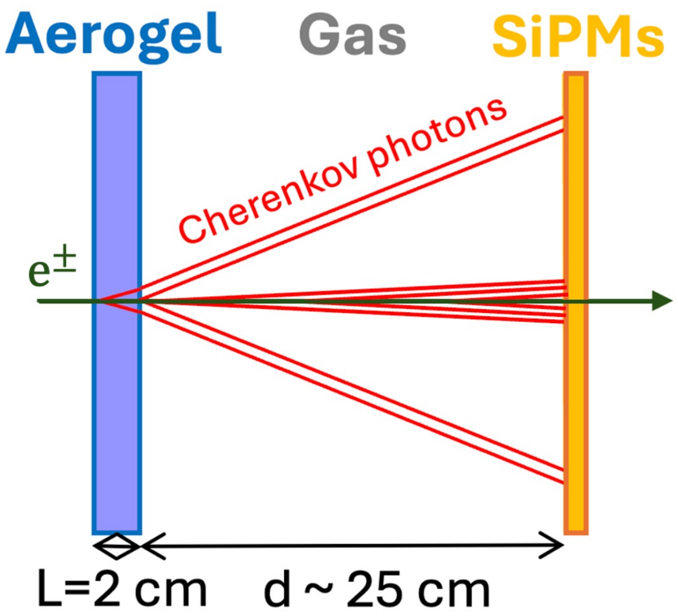
Strategy

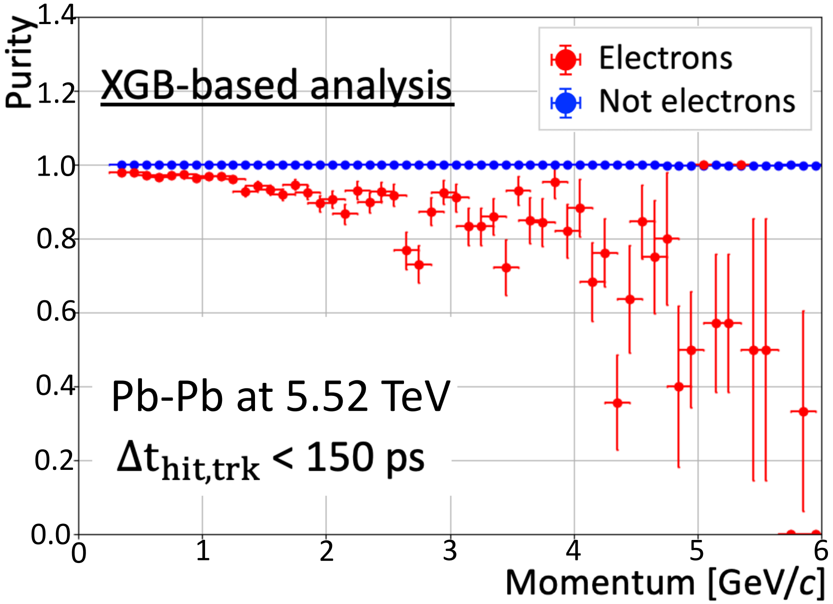
- Flushing the RICH gap with gas radiator having n ≈ 1.0006
- **$e^{\pm}$ ID enhanced by C.kov threshold-based discrimination**

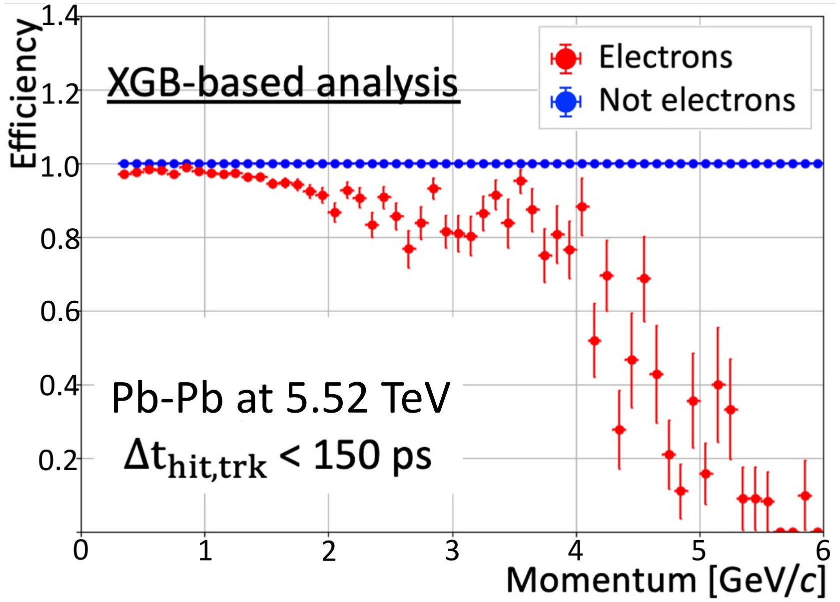
Gas options

- Gases with large GWP (CF_4, C_4F_{10}, …) must be avoided
- Solution: Mixtures of CO_2 and e.g $C_5F_{10}O$ or i-C_4H_{10}

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







2024 beam test set-up@PS-T10

Aerogel radiator: 2 cm thick tile with n=1.03, $\Lambda \approx$5.5 cm @ 400 nm

Central array: 1 HPK SiPM S13361-3050AE-08 (64 3x3 mm^2 SiPMs)

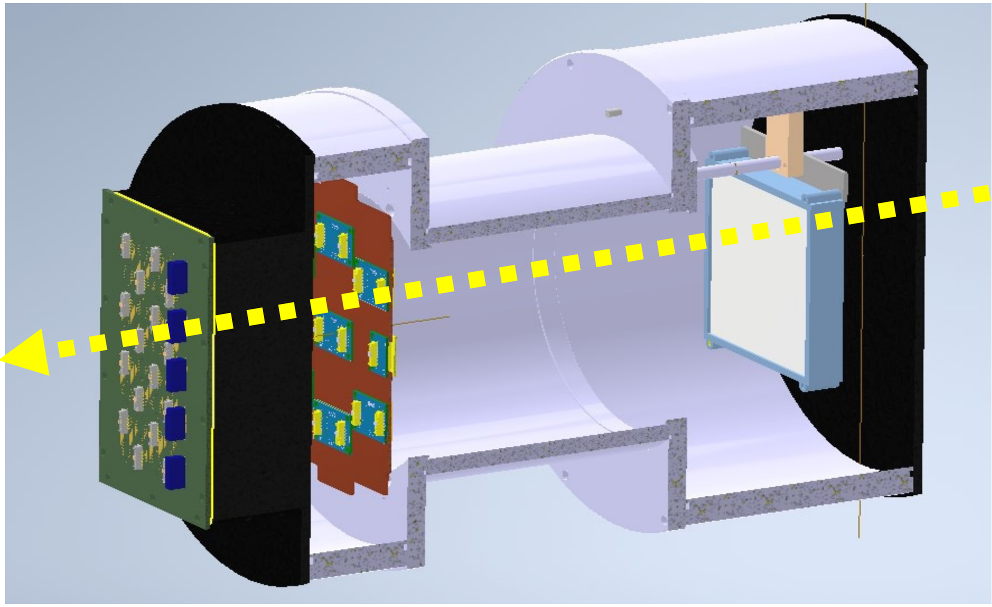
Ring arrays: 7 HPK SiPM S13361-2050AE-08 (64 2x2 mm^2 SiPMs)

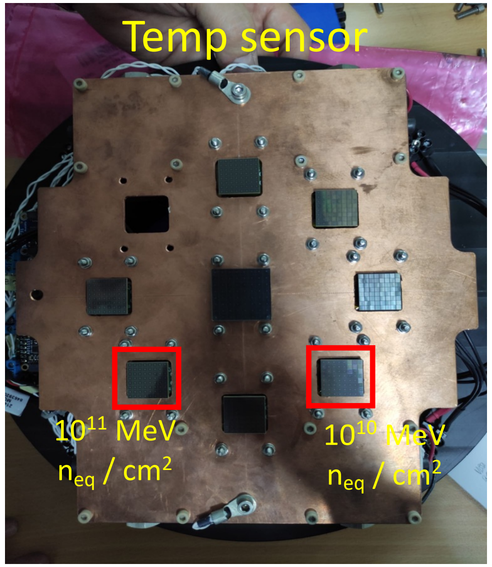
SiPM cooling: Down to -5 °C using water chiller + Peltier Cells

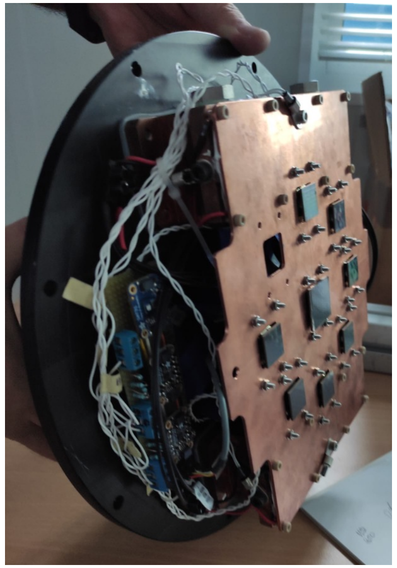
Proximity gap: 23.4 cm between aerogel and SiPMs flushed with Ar

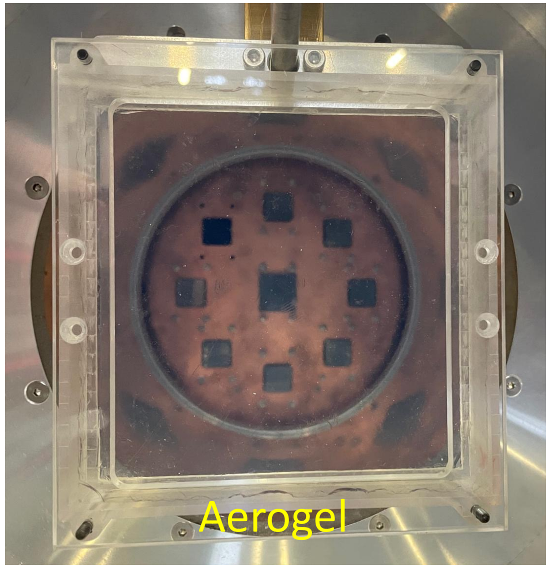
Front-end: Custom board based on Radioroc 2 FE ASIC and picoTDC

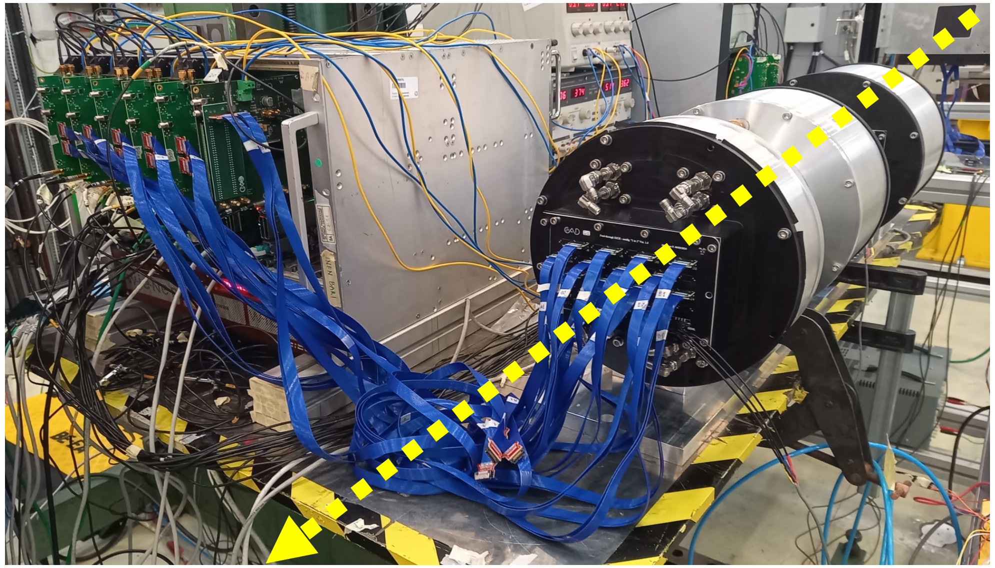
Additional vessel equipped with 2 extra HPK SiPM S13361-2050AE-08 for timing studies of charged-particle tracks ⇒ See talk by N. Mazziotta







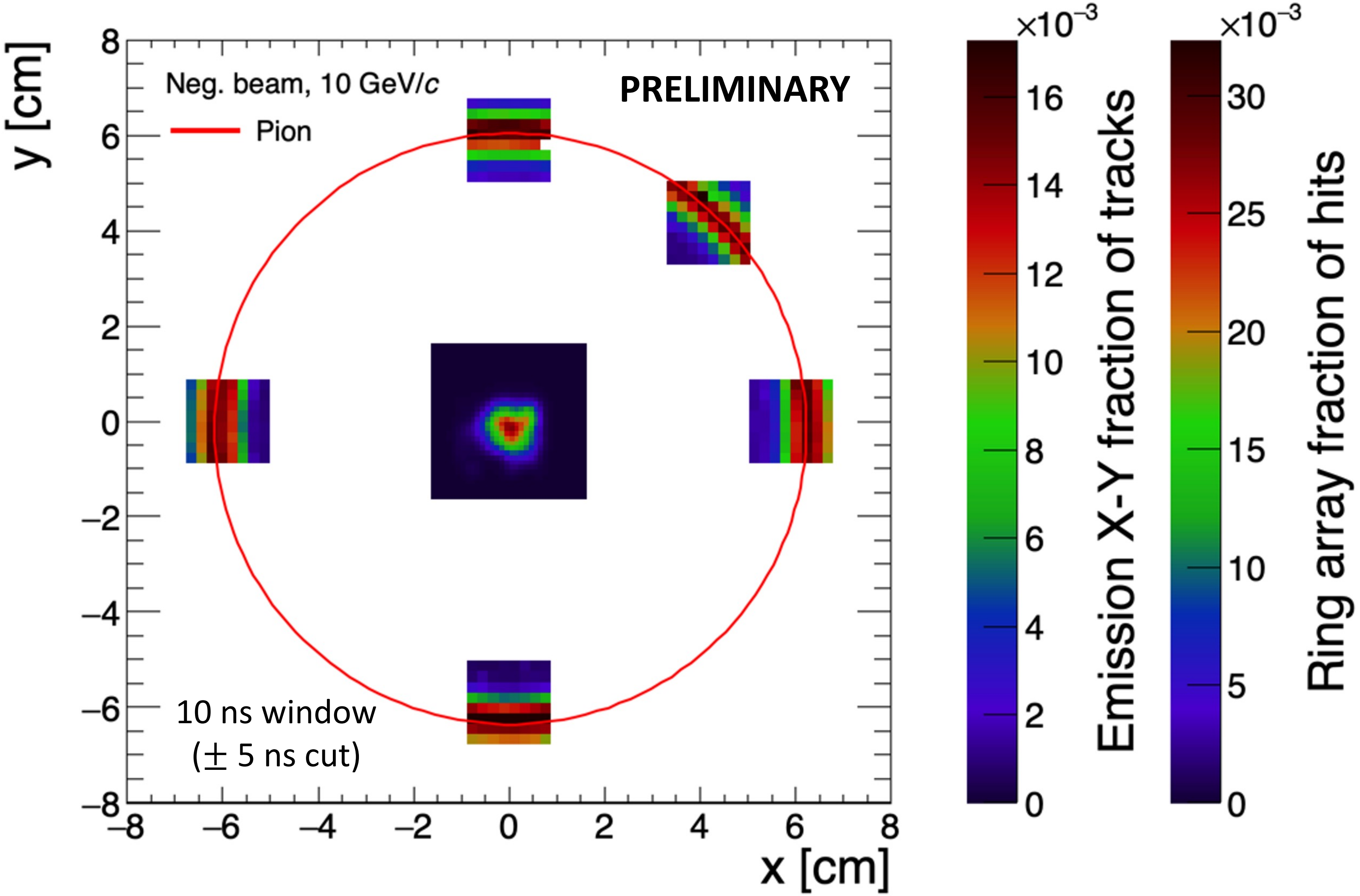




Single hit analysis strategy

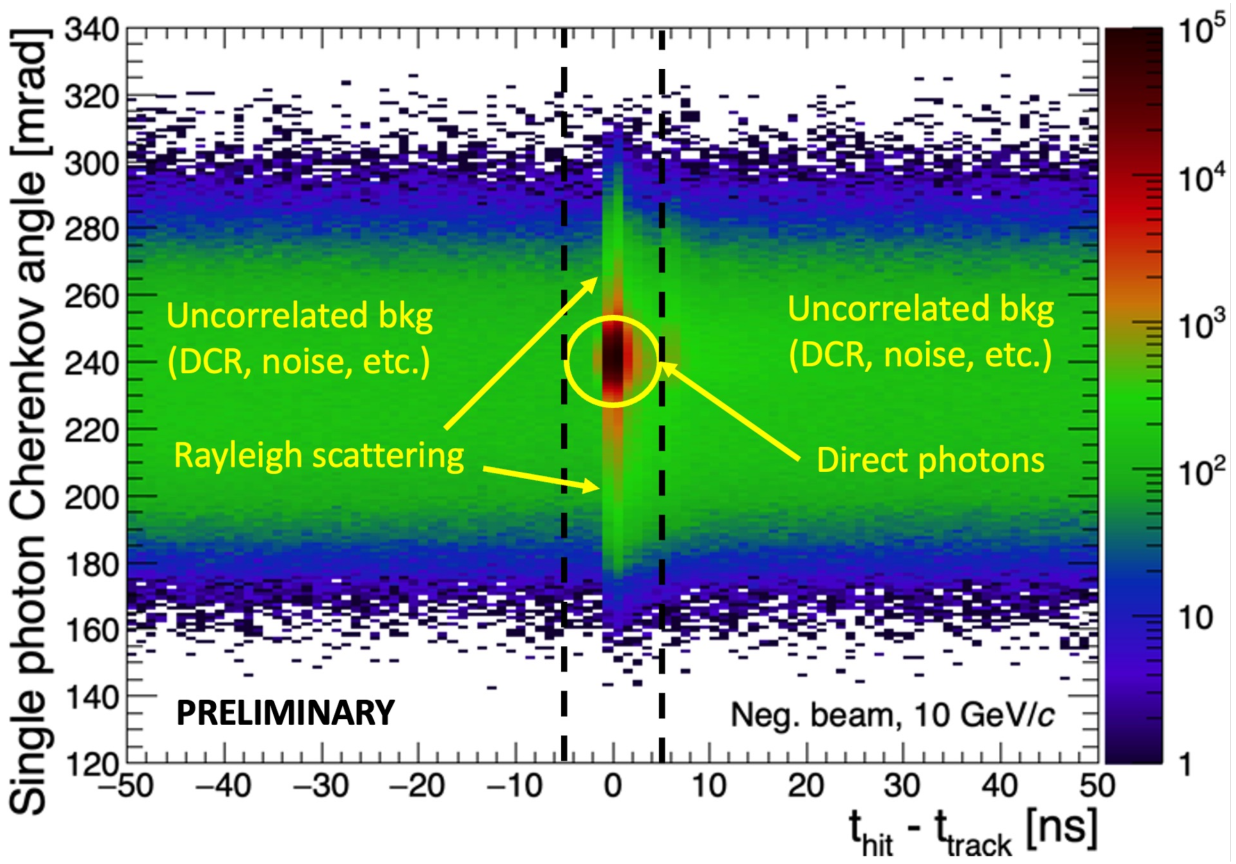
- **Event selection**
  Requiring signal in a fiducial area of the fiber tracker planes (T0,T1) and the SiPM arrays (M0,M1,M2)
- **Charged particle tracking**
  Straight line fit to extract the track position in the middle of aerogel and the track direction cosines
- **Single photon Cherenkov angle**
  Geometric backpropagation of all hit positions to the most probable emission point in the aerogel tile
- **Time cut for DCR suppression**
  $$\left| t_{hit,array} - t_{max-ToT,M2} \right| < X\ \mathrm{ns}$$
- **Fit model for sig / bkg analysis**
  Assuming Gaussian signals and template bkg. distribution from time-uncorrelated hits w.r.t. MIP

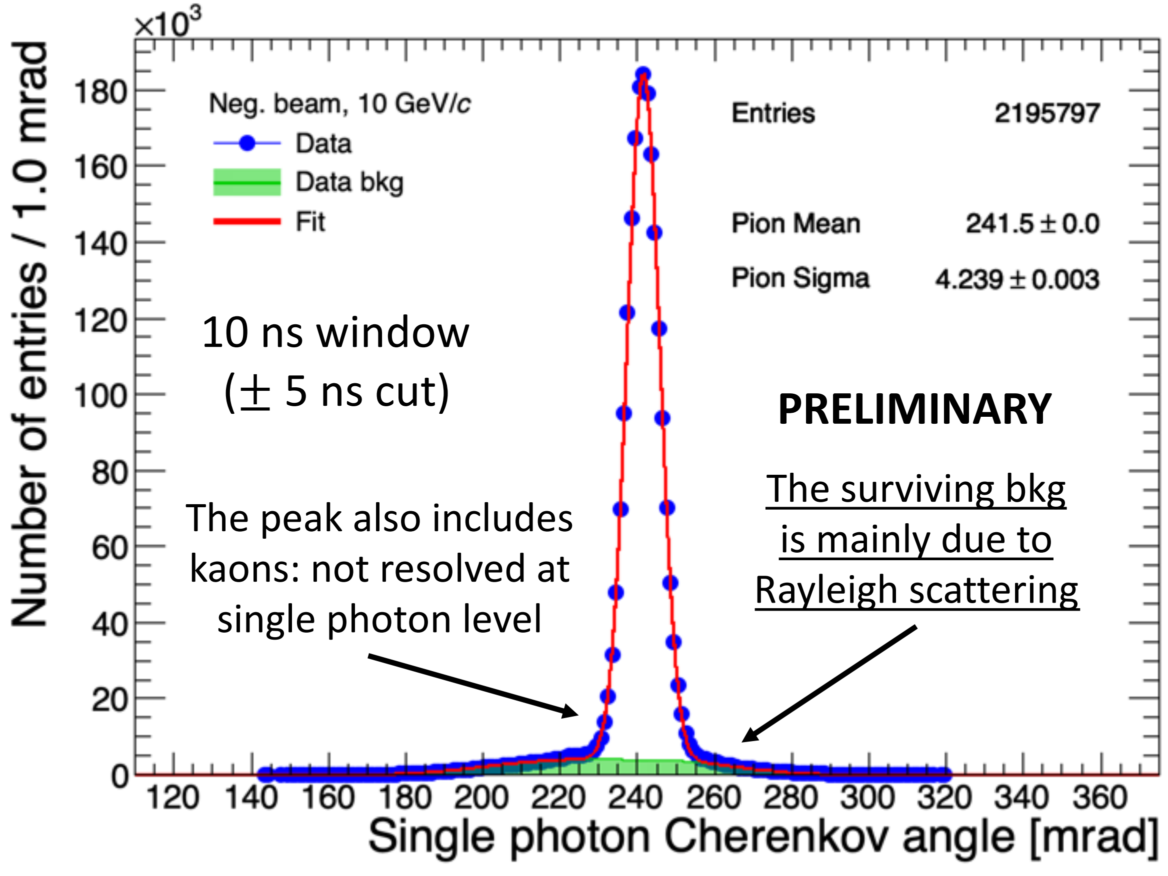
Ring acceptance ≈ 25% ⇒ Good for ring reconstruction studies



Performance at single hit level

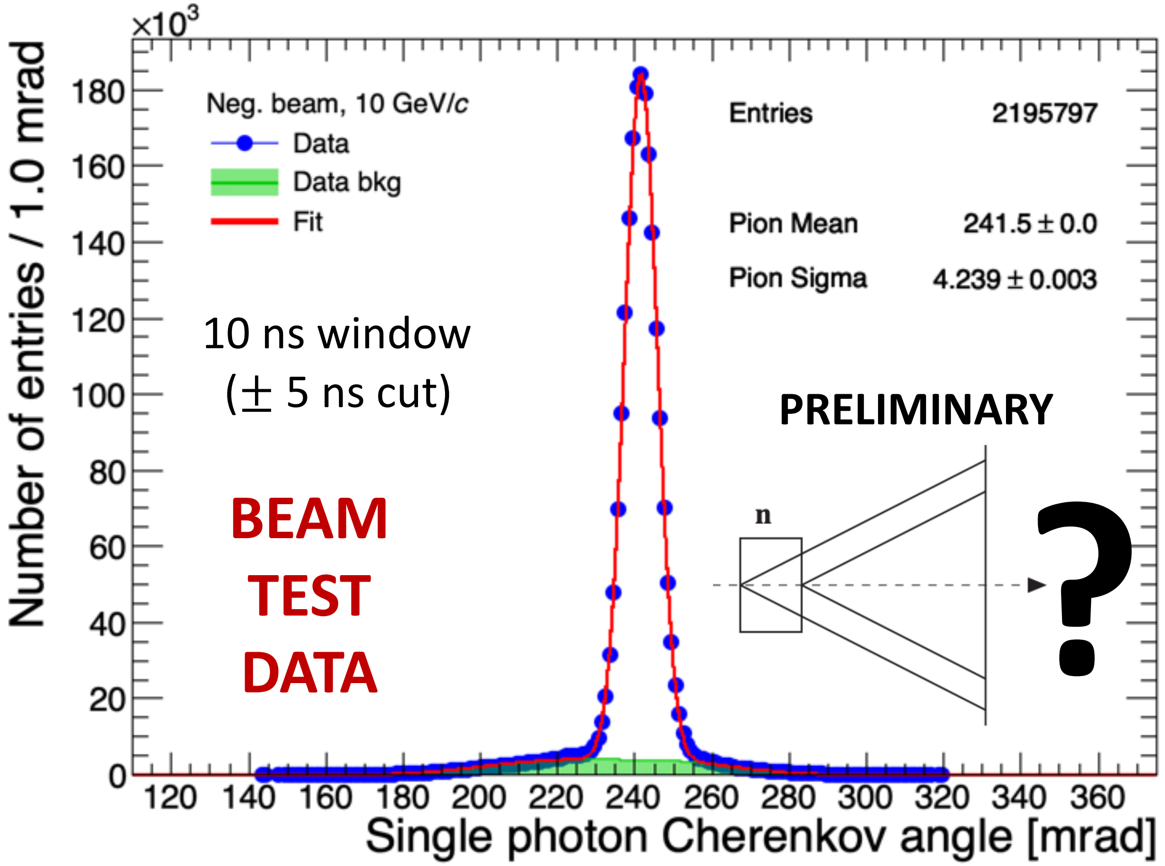
- **Angular resolution of about 4.2 mrad as expected with 2x2 mm^2 pixel size**
- **Background level consistent with expectations @ the operation T and V_{ov}**
- **Excellent uncorrelated bkg suppression achieved using time matching**

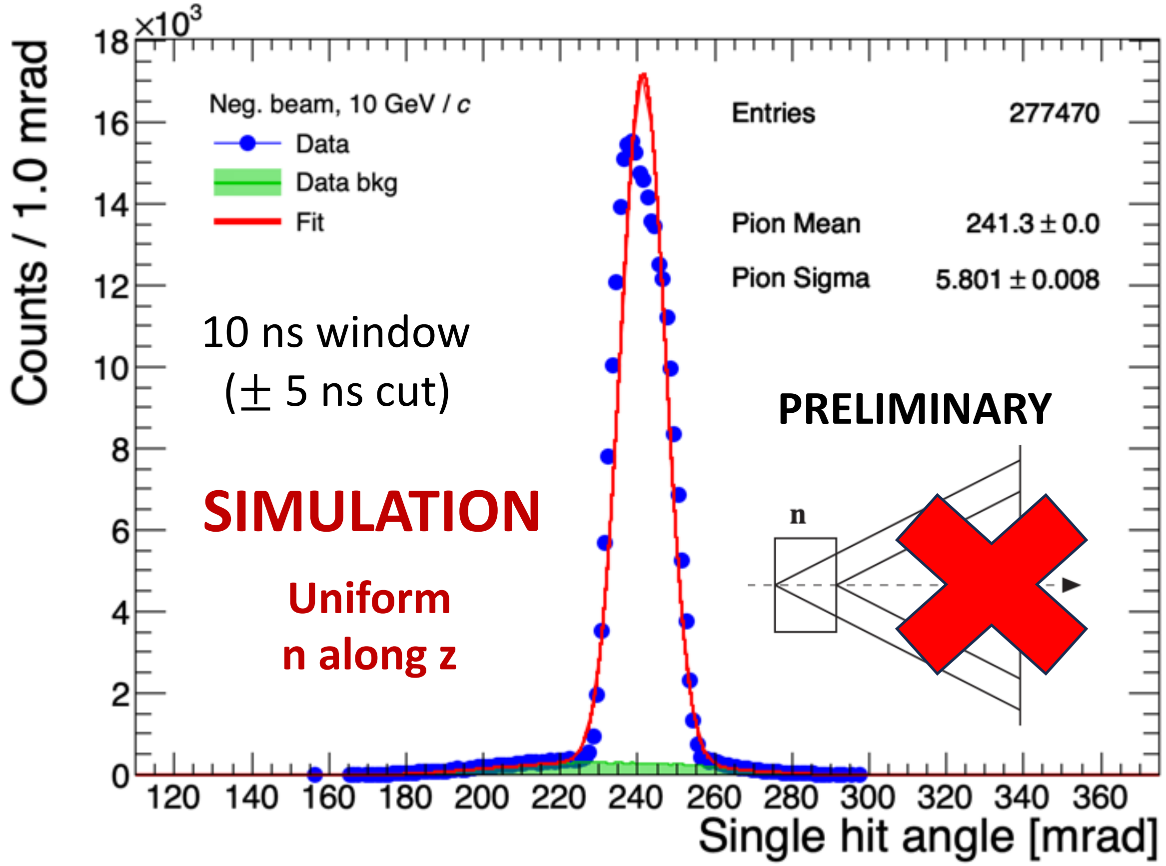




Data vs sim: angular resolution puzzle

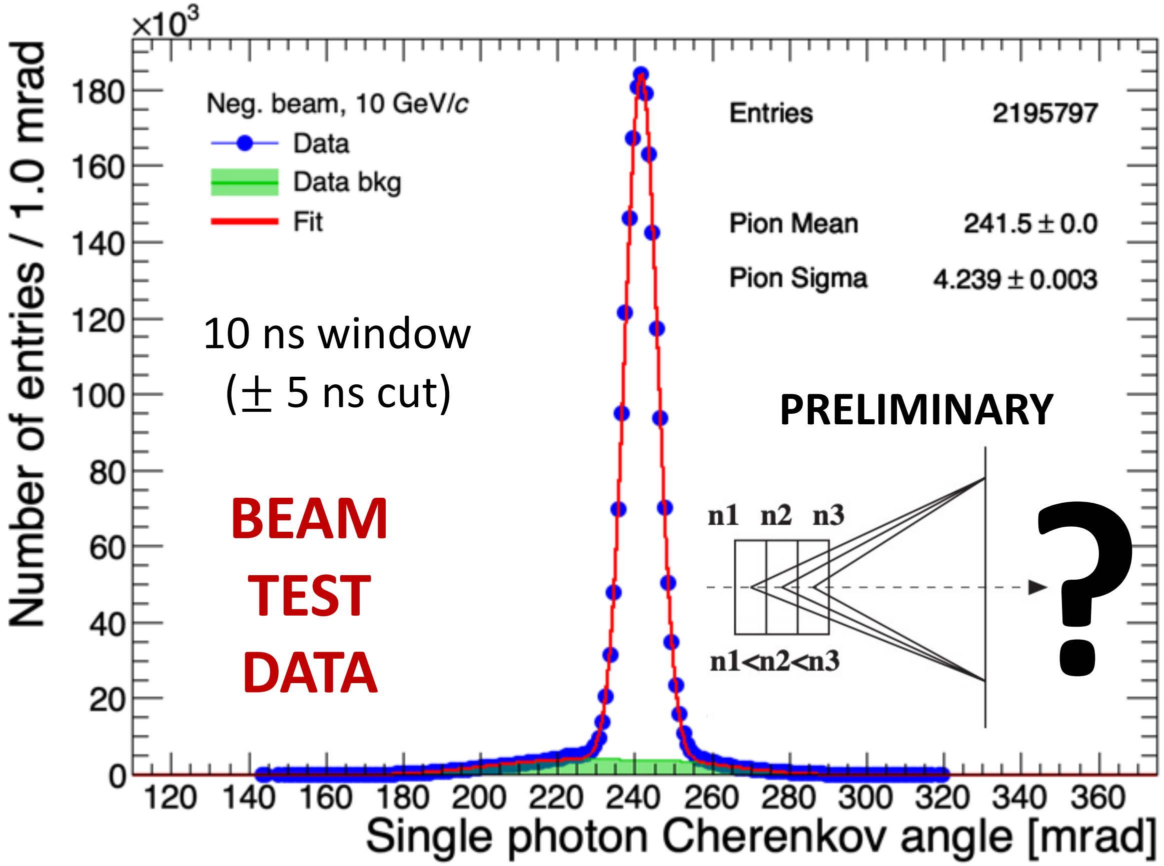
- Simulation with measured aerogel optical properties and uniform n along z
- Non-Gaussian shape: expected due to geometric error uniform distribution
- "Problem": Data with various tiles better than simulation by ≈ 1.6 mrad

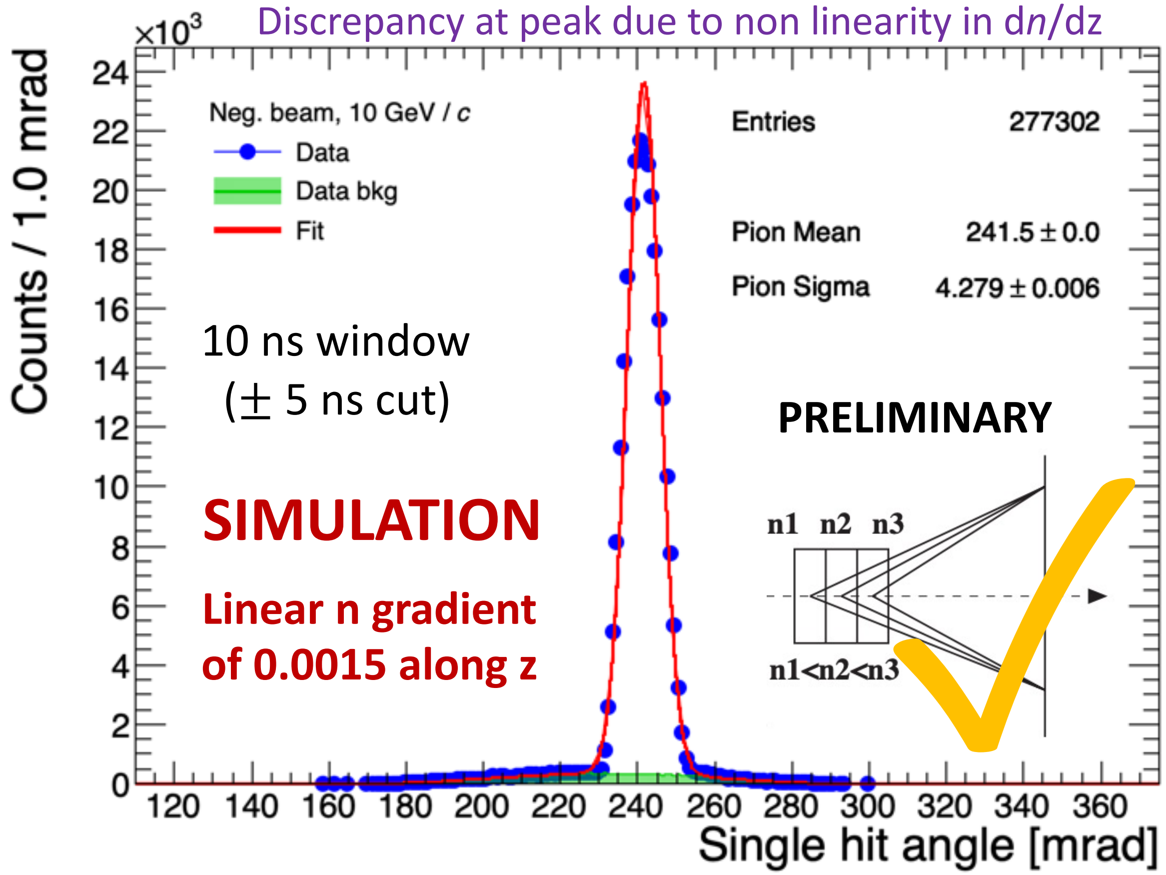




Hypothesis: gradient in aerogel n

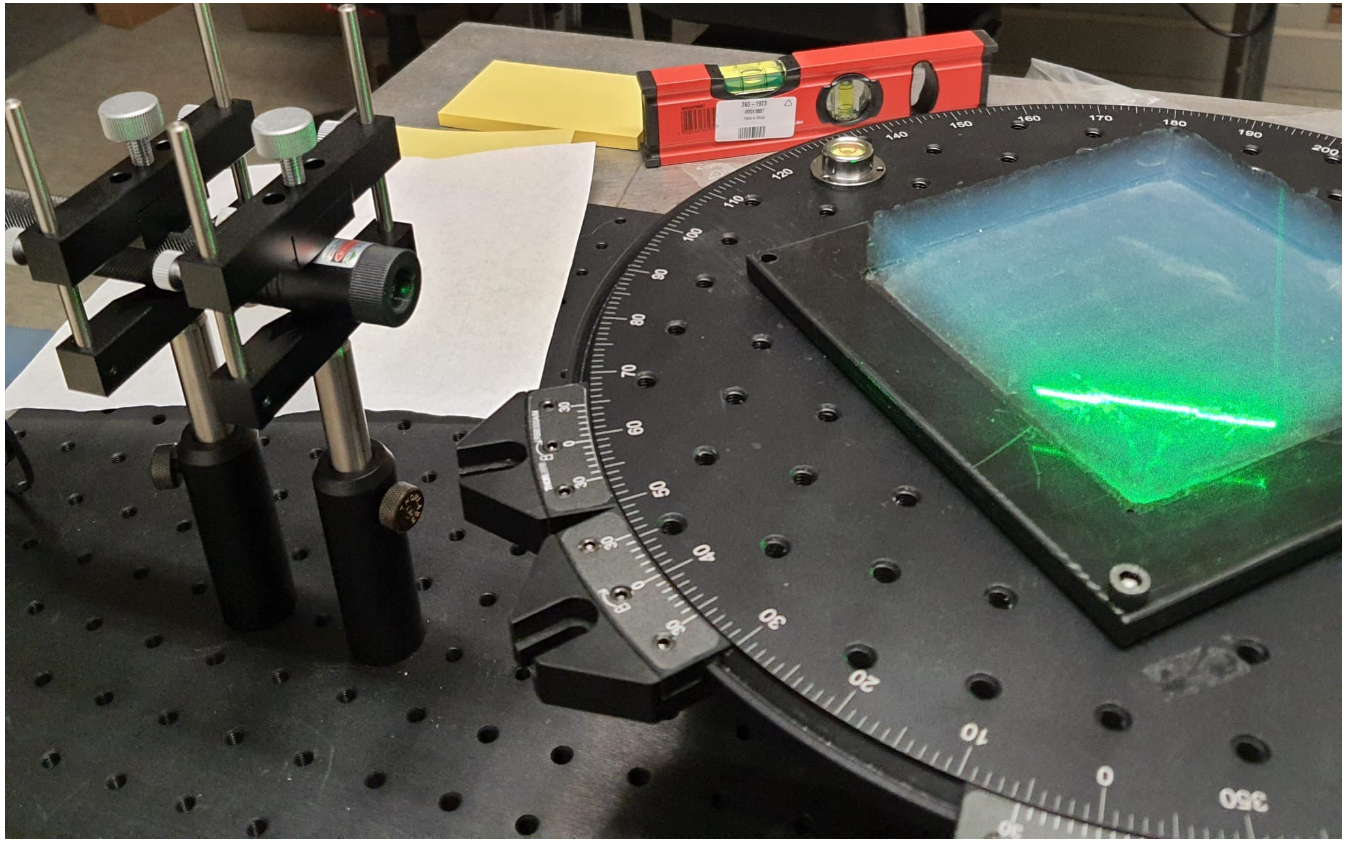
- Discussing with Aerogel Factory @ Co, Ltd: possible n gradient along z
- A kind of self-focusing, suppressing the dominant geometric uncertainty
- If reproducible, much better PID than current simulations for free !!!

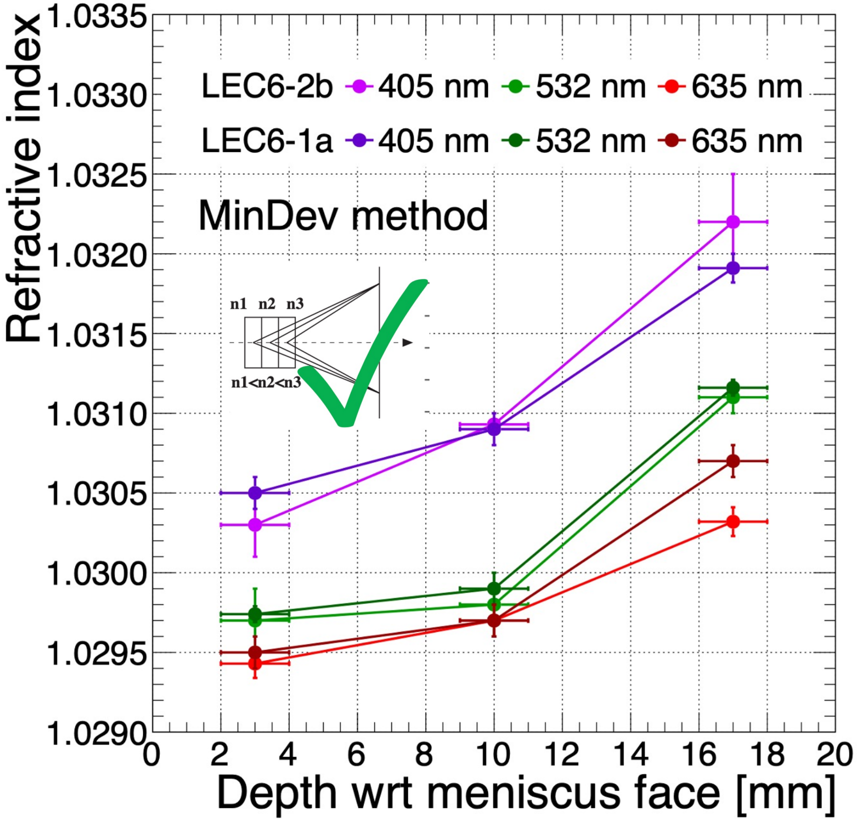




Measurements of aerogel index

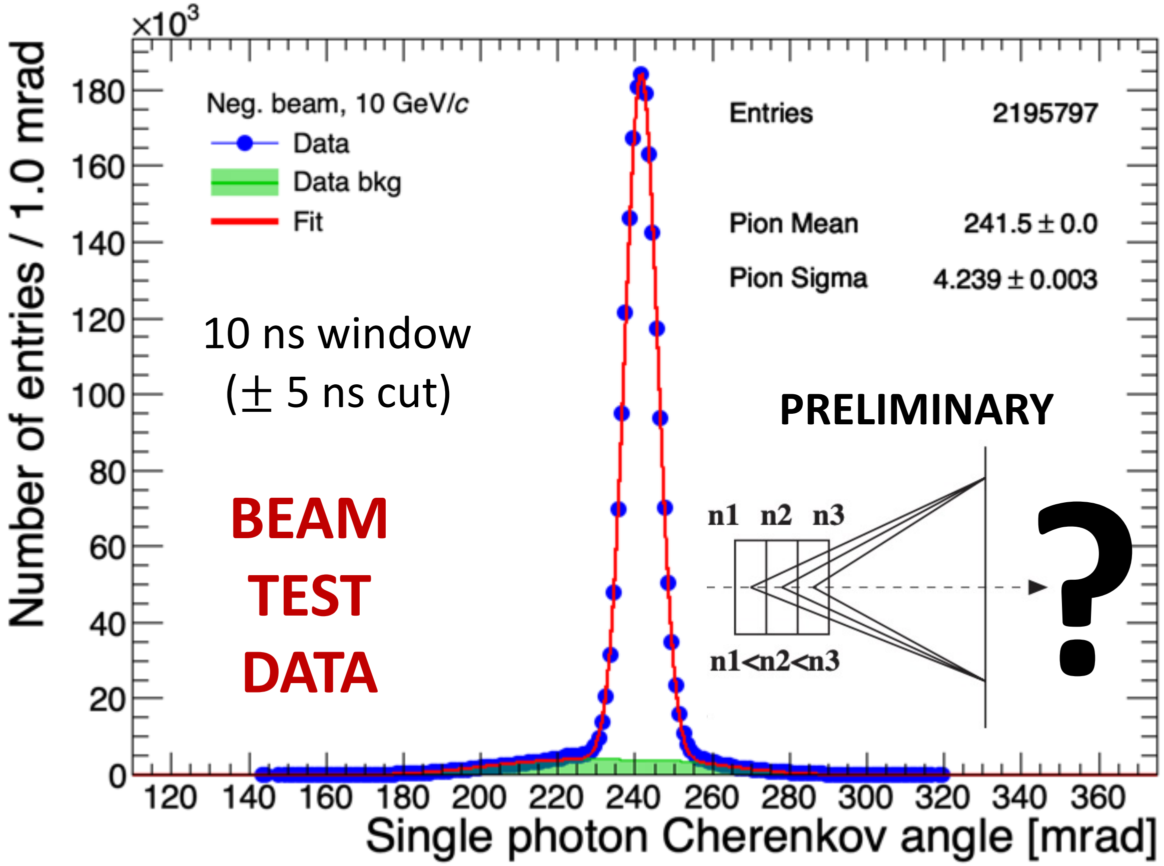
- **Chromatic dispersion:** **using lasers with wavelengths 405, 523 and 635 nm**
- **Depth dependence:** **measuring n at $\approx$ 3, 10 and 17 mm wrt upstream face**
- **Results: The expected gradient is confirmed, reproducible, but non-linear**

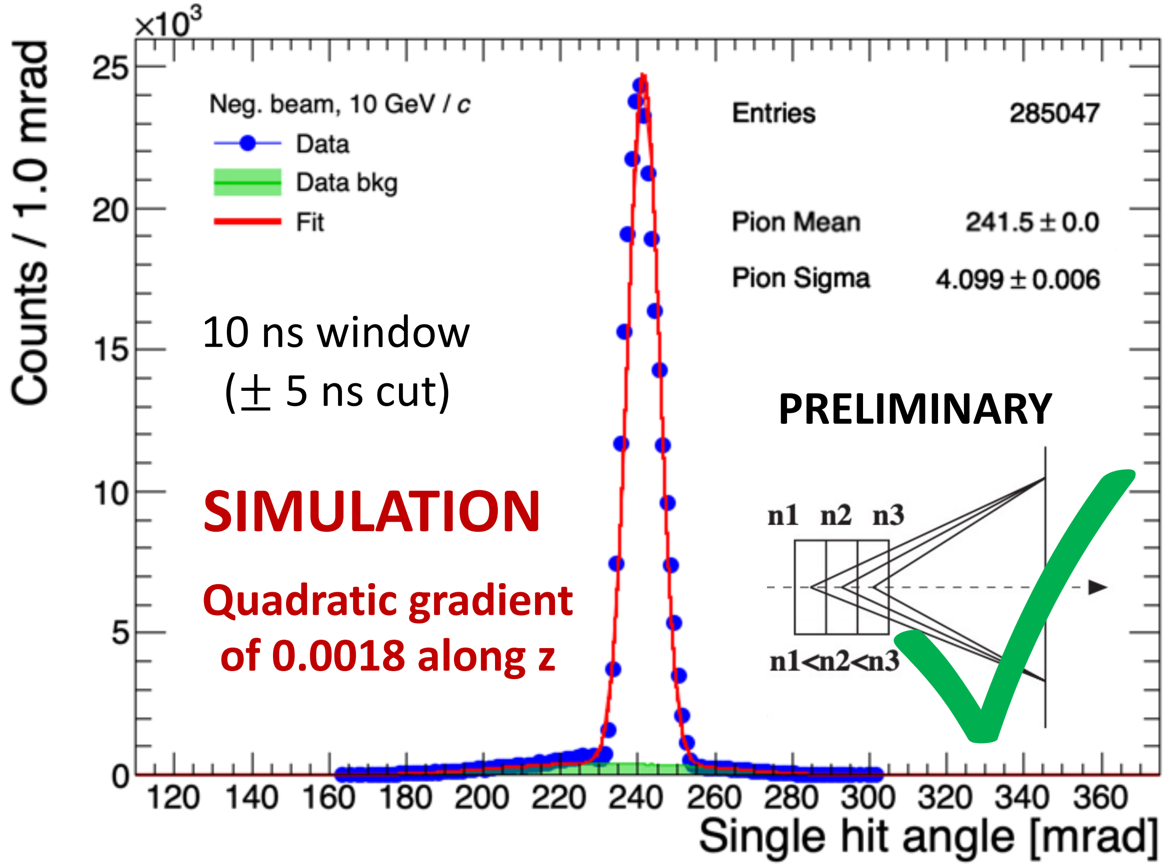




Puzzle solved: quadratic n gradient

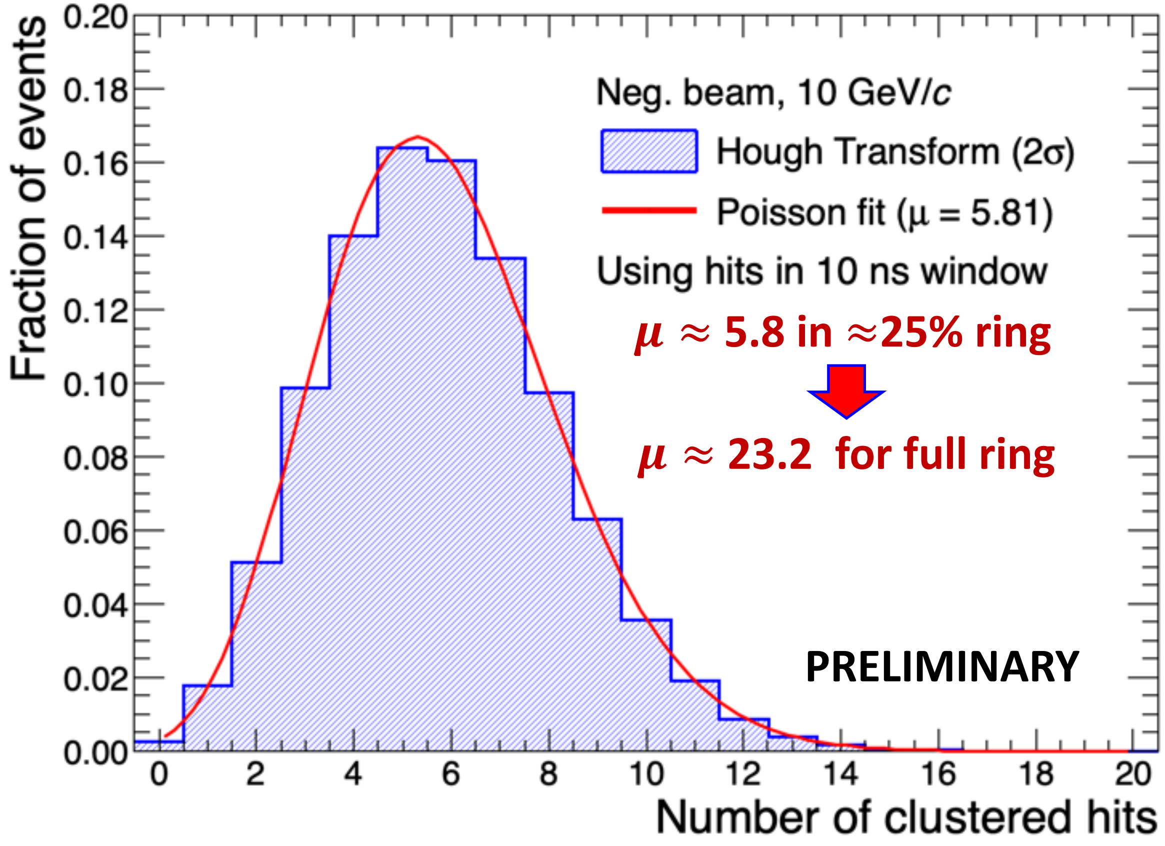
- **Chromatic dispersion: using lasers with wavelengths 405, 523 and 635 nm**
- **Depth dependence: measuring n at ≈ 3, 10 and 17 mm wrt upstream face**
- **Extracting n(z) from three-point quadratic interpolations of measured points**

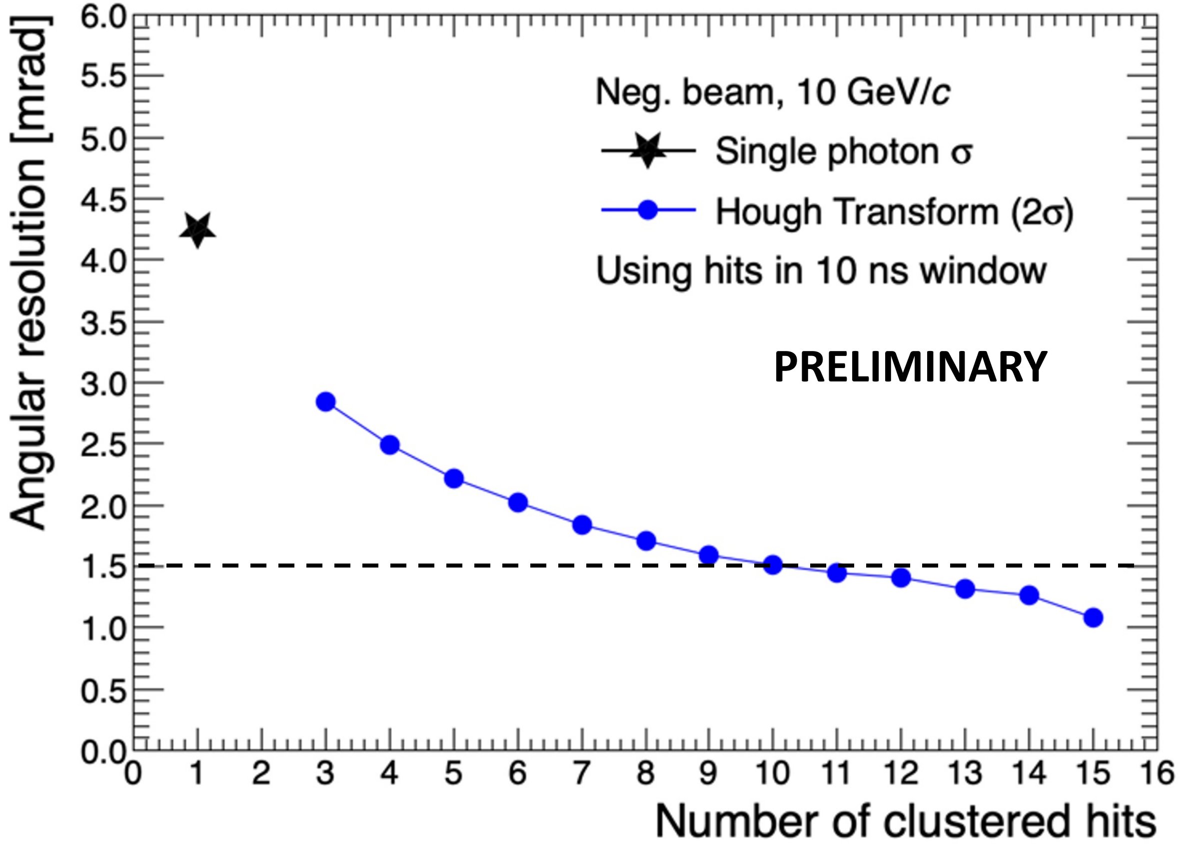




Pattern recognition performance

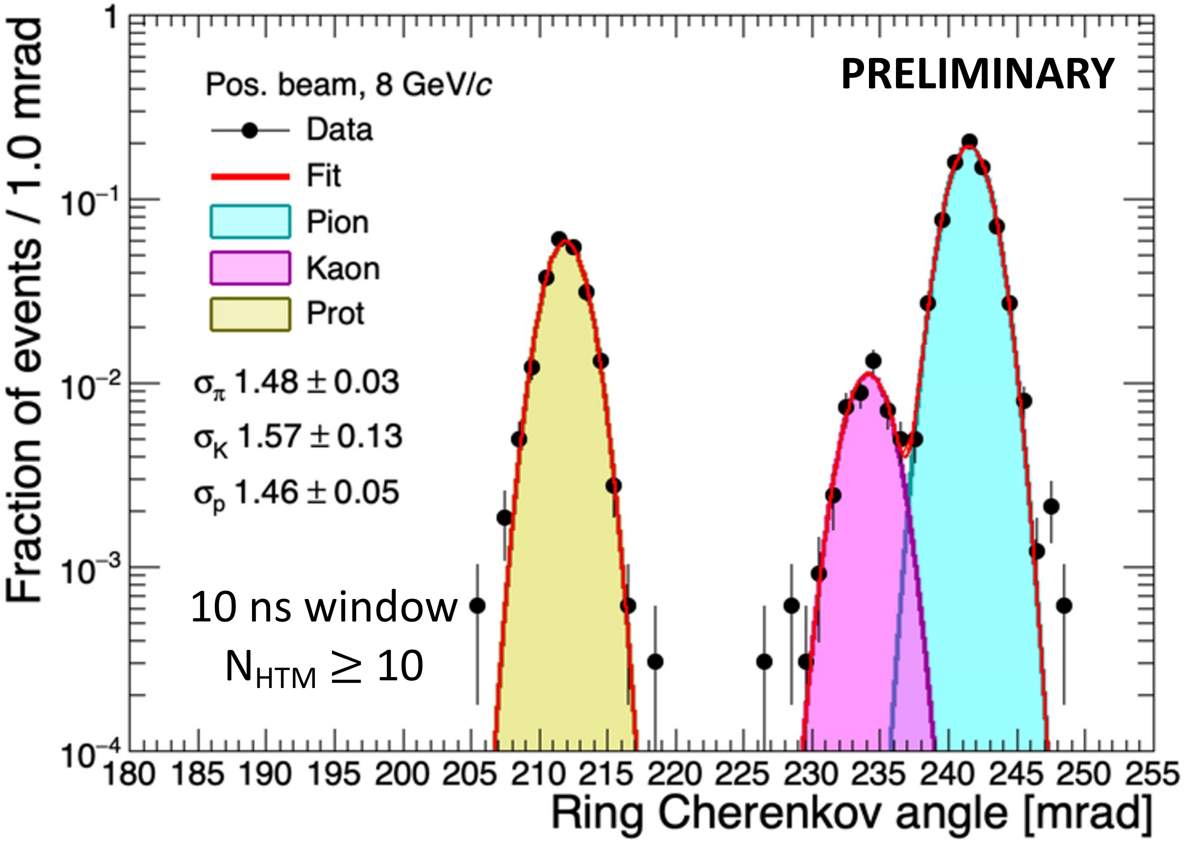
- Using Hough Transform method (HTM) for candidate photon clustering
- We measured on average 5-6 HTM selected hits per track at saturation
- Ring angular resolution better than 1.5 mrad for ≥ 10 HTM selected hits

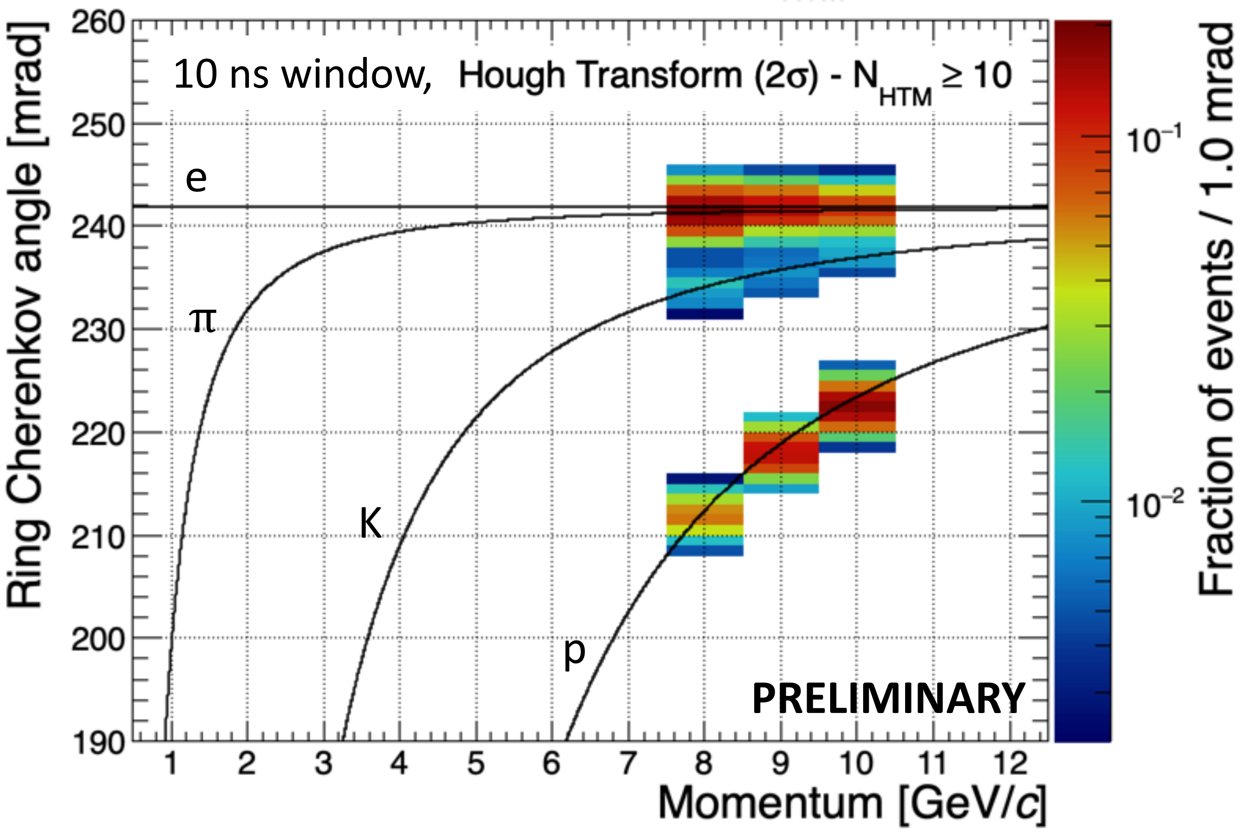




Separation power vs momentum

- Comparing results with positive beam @ 8,9,10 GeV/c with $N_{HTM} \geq 10$
- Reconstructed ring angles follow the expected scaling with momentum
- Separation of π, K and p beyond 3σ, with π/K limit at 10 GeV/c as required





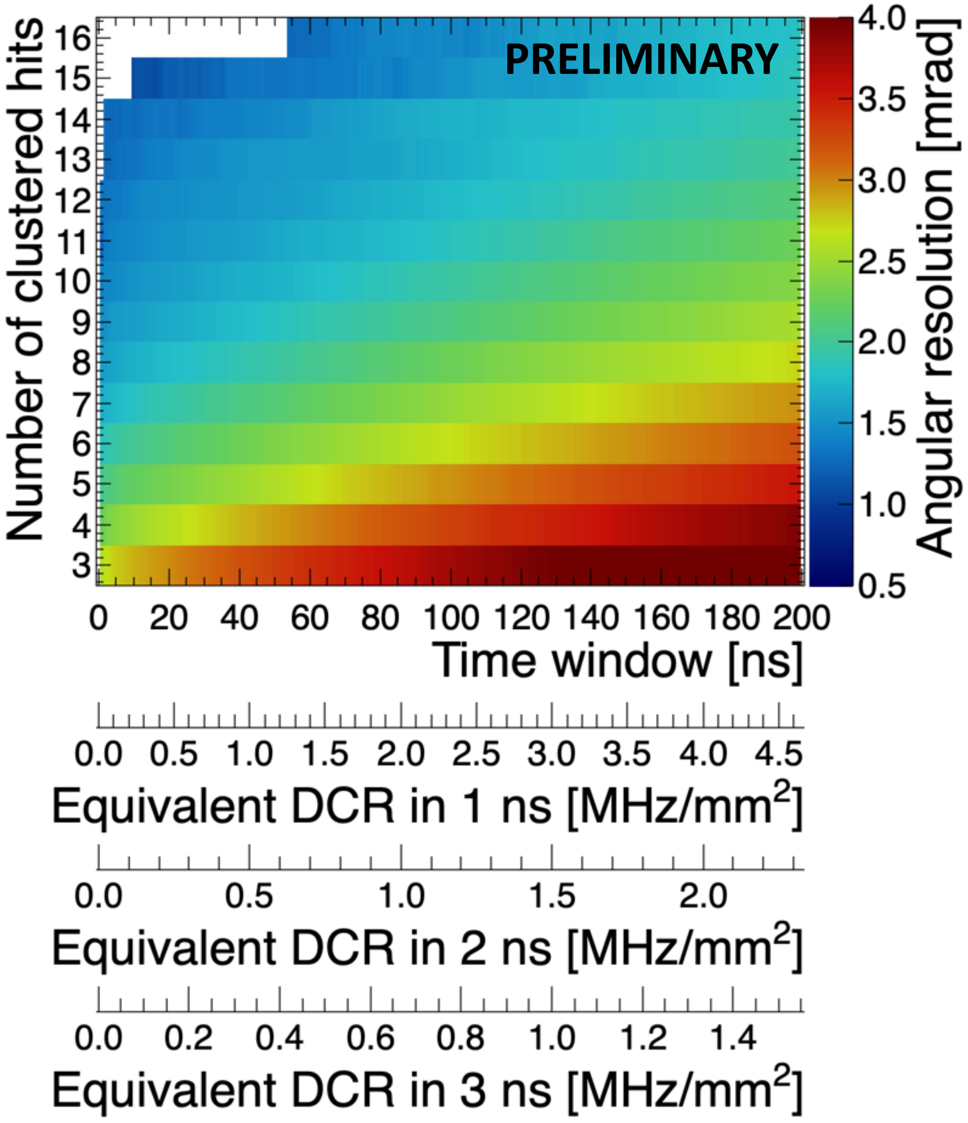
Stability with increasing background

Performance vs time window and DCR

- We studied the pattern recognition stability in wider and wider time windows with the nominal 23.3 kHz/mm^2
- We scaled the resulting mean number of background hits in terms of the **equivalent DCR bkg** we would have in the target **1-2-3 ns acquisition window** for the ALICE 3 RICH

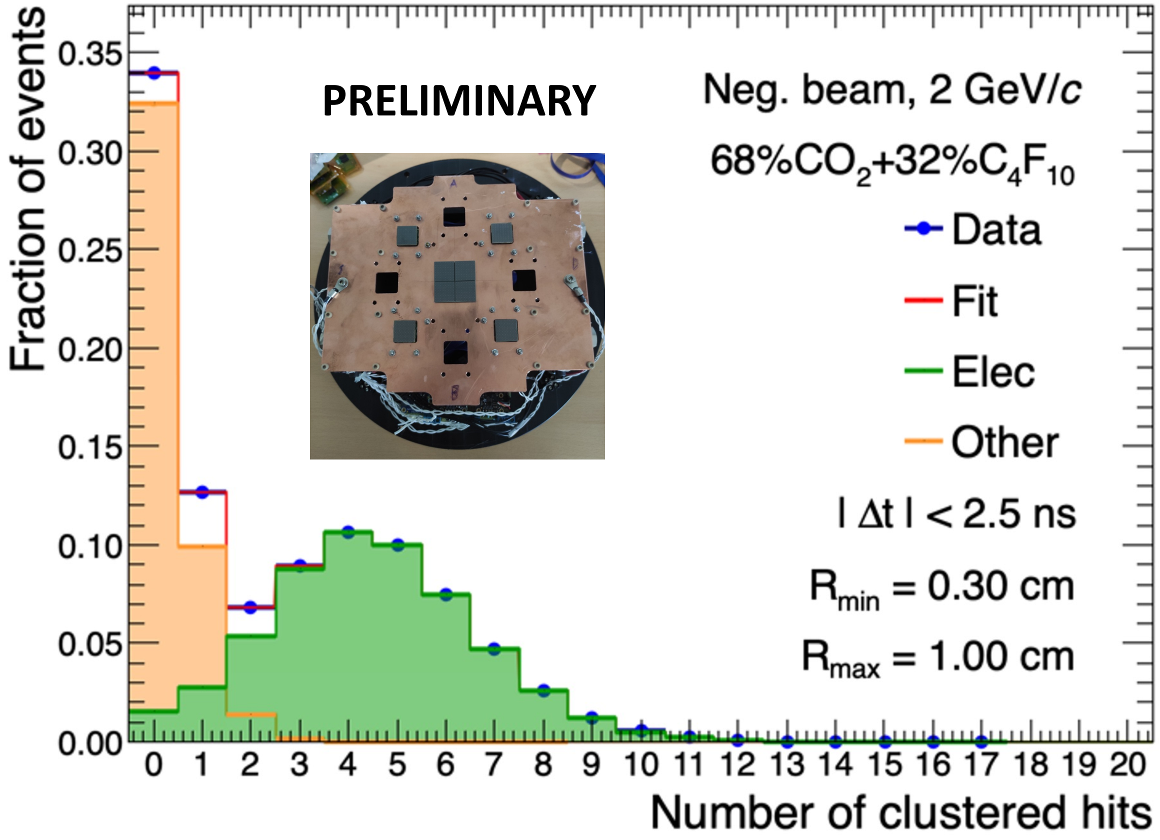
Results

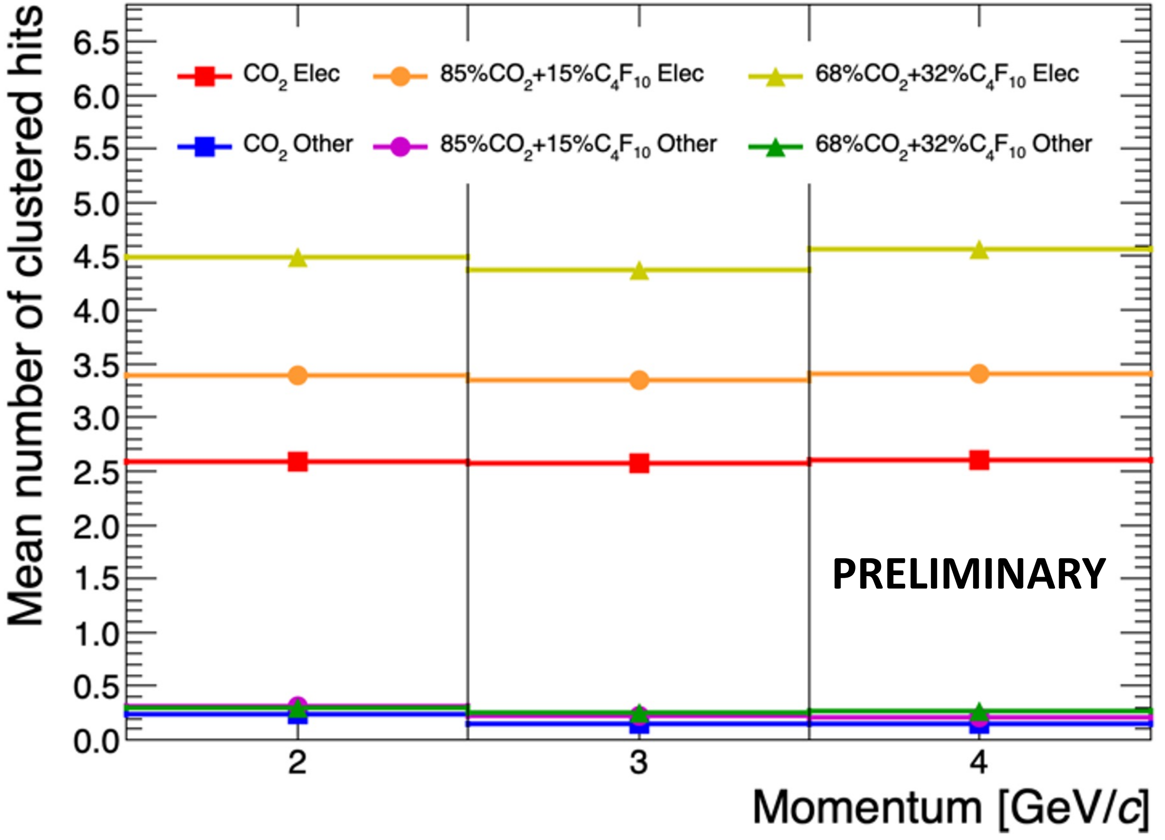
- $\approx$ **0.5 mrad worsening** up to **1 - 4 MHz/mm^2 equivalent** depending on the considered acquisition time window
- **This study proves the stability of the reconstruction and physics performance up to the considered DCR levels**
    - **Modulo** bandwidth limitations and SiPM dead time effects



Gas based e-ID

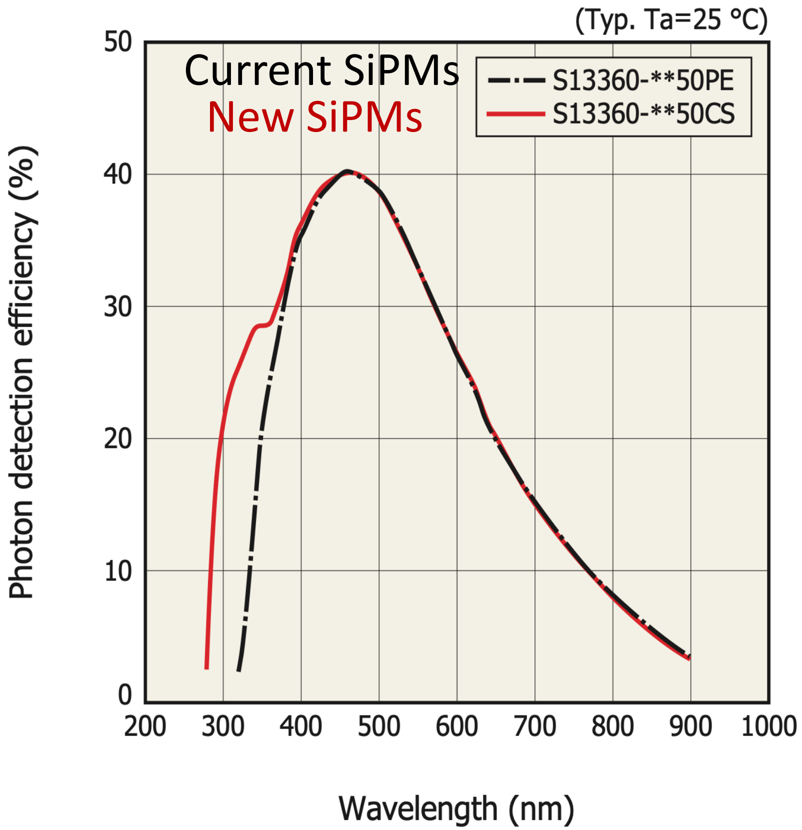
- **Gas studies were performed with CO_2 gas mixtures varying the r. index**
- **Cuts on R_{min}, R_{max} and $|t_{\mathrm{hit}} - t_{\mathrm{trk}}|$ to discard track hits and DCR bkg hits**
- **By looking at cluster size a clear separation can be seen between e and π**

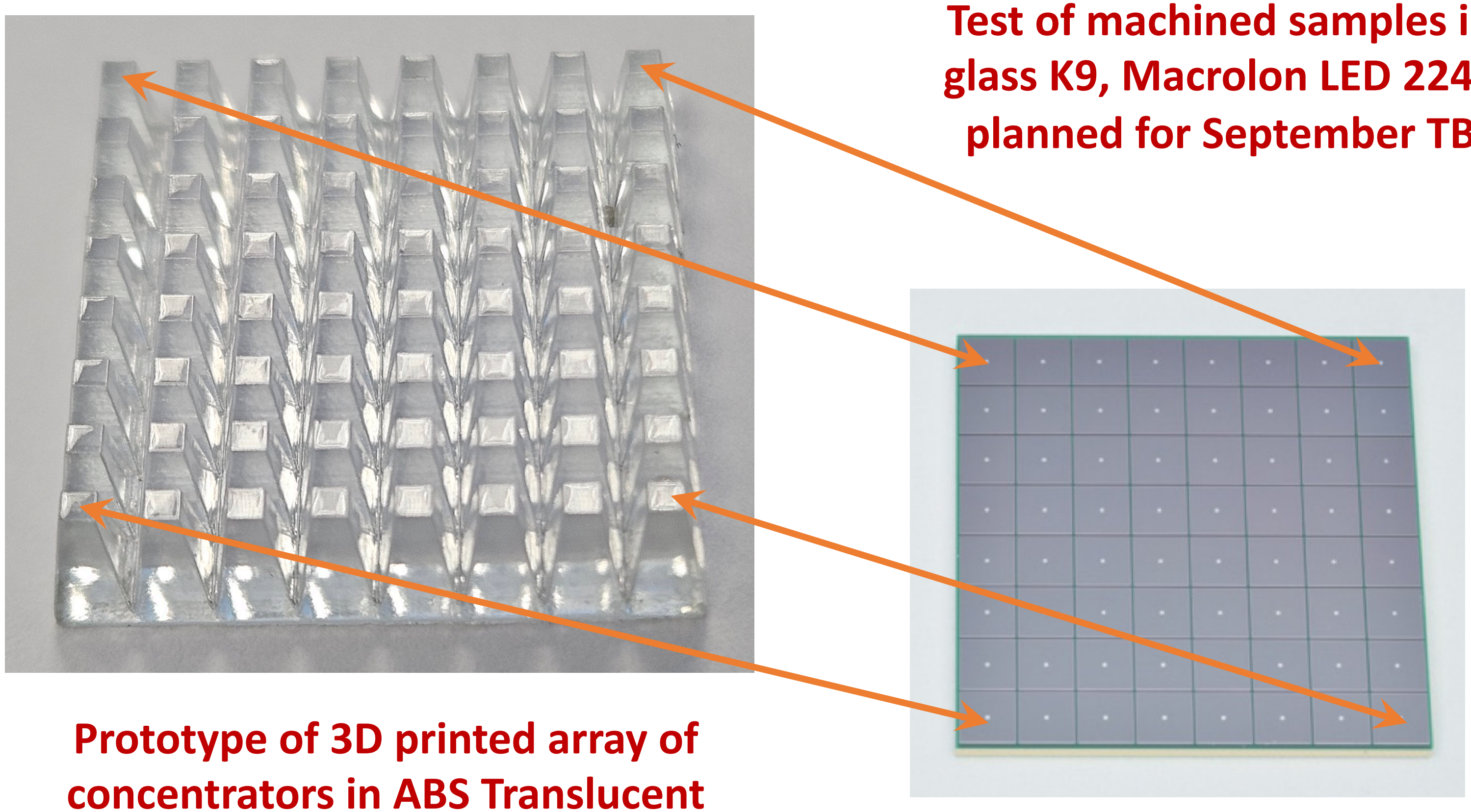




New test beam starting on Sept 25th

- Testing new arrays with silicone resin instead of epoxy for improved yield
- Systematic study of e-ID capabilities vs momentum with various mixtures
- Testing efficiency and resolution using SiPMs mounting light concentrators





Test of machined samples in glass K9, Macrolon LED 2245 planned for September TB

Prototype of 3D printed array of concentrators in ABS Translucent

Conclusions

Summary

- Simulation studies show that the proposed layout fulfills the ALICE 3 requirements in central Pb-Pb
- Measured photon yield, angular resolution and separation power consistent with ALICE 3 target
- Stable reconstruction beyond MHz/mm^2 DCR values considering proper DAQ / time matching windows

Outlook

- Refining the mechanics, as well as cooling, annealing and other handles to mitigate SiPM radiation damage
- Preparation of RICH Technical Design Report in 2027

Thank you for your attention

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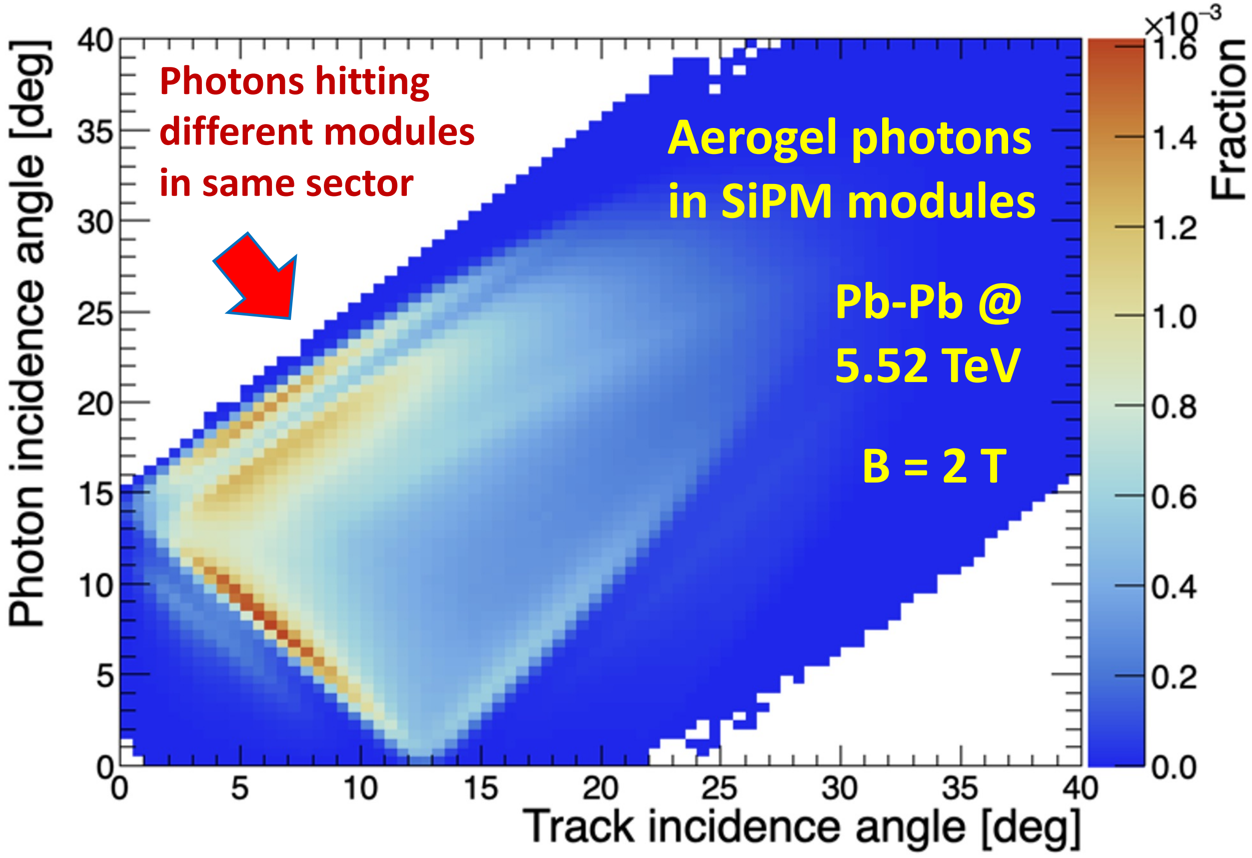
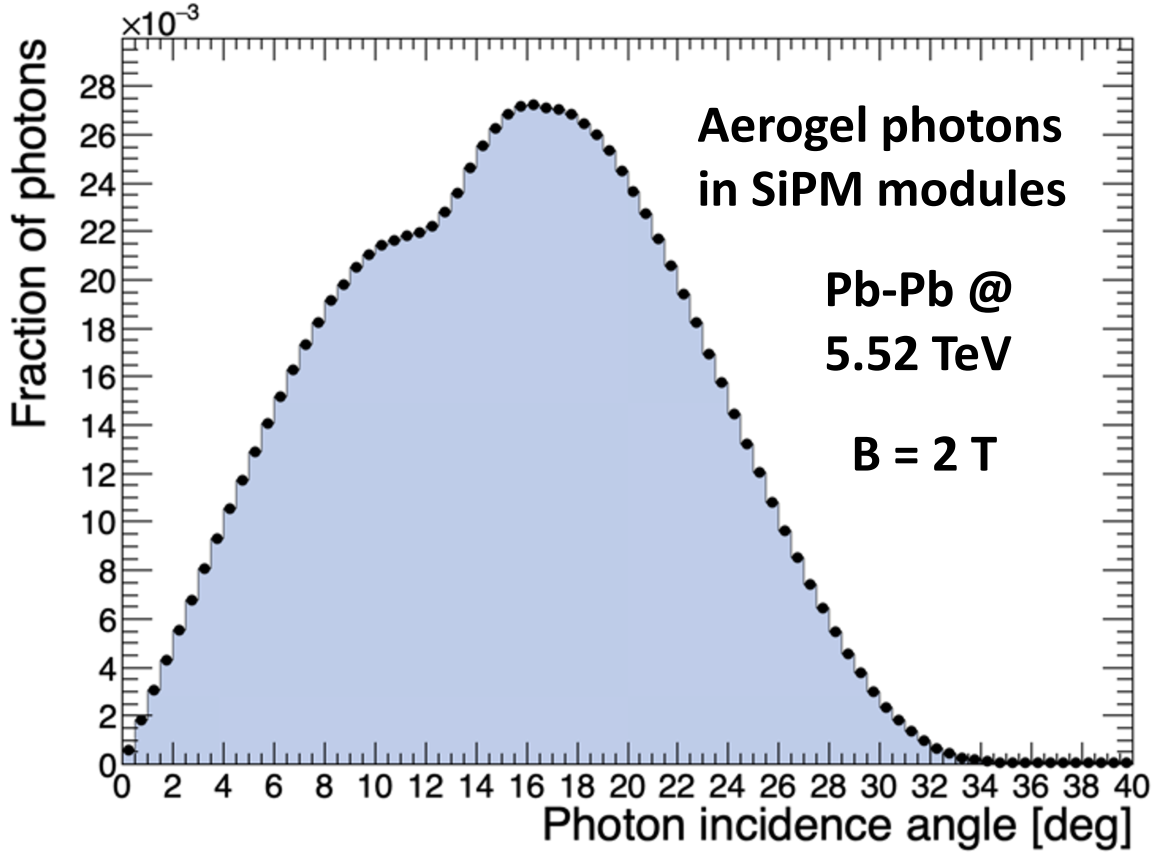
Backup

Concentrators: collection efficiency

- Concentrator light collection efficiency depends on photon incidence angle
  - Need to ensure good efficiency for all physical bRICH indicence angles
- All useful aerogel (and gas) photons reach bRICH SiPMs with angle < 35°



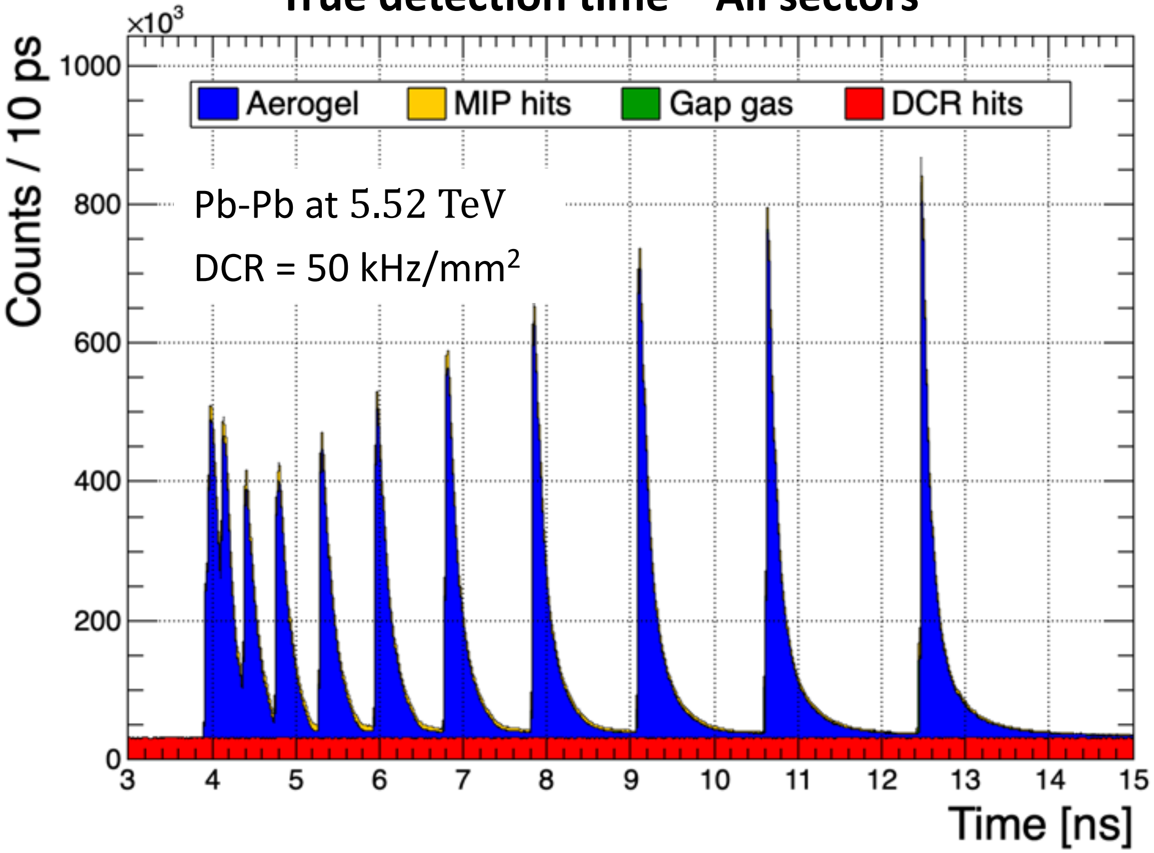


DCR bkg suppression via hit timestamp

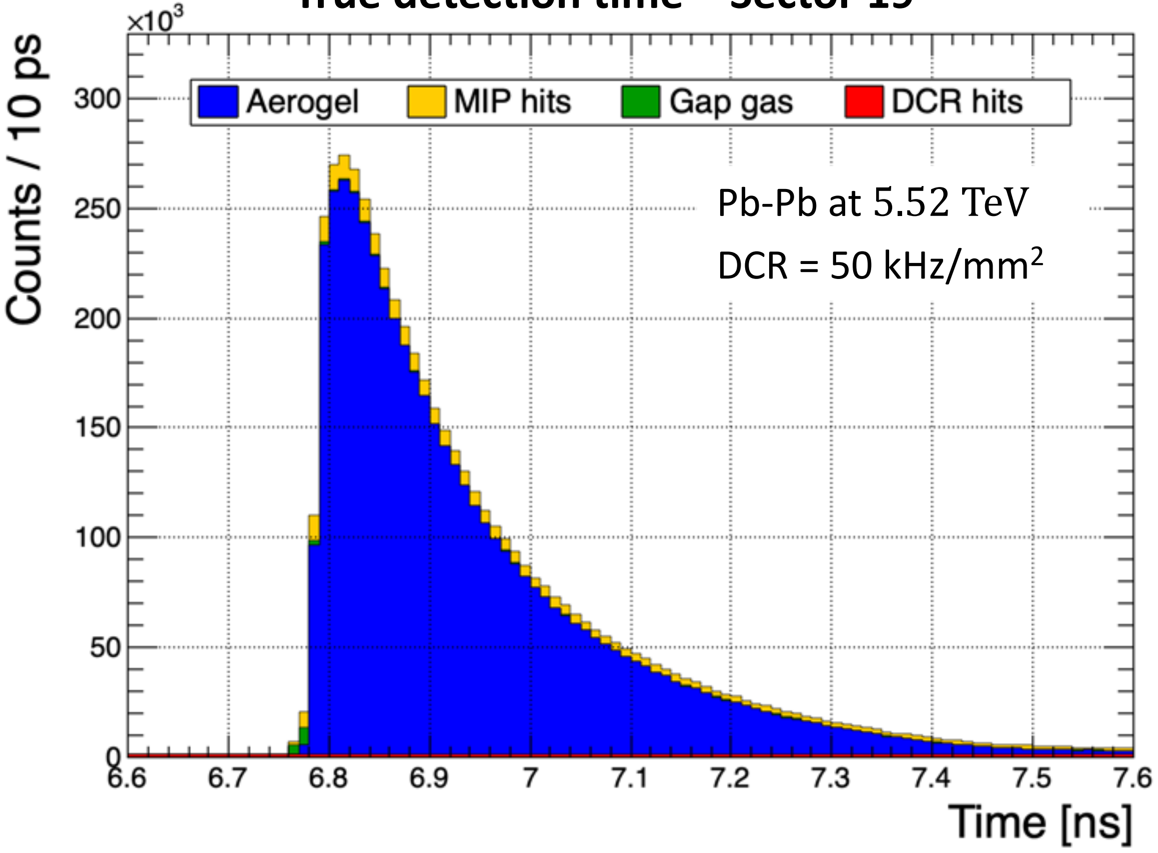
Projective RICH geometry ⇒ Photons in each sector reach SiPMs in ≈ ns intervals

- **DCR signals are time uncorrelated from photon signal hits in each sector**
- **Excellent DCR bkg suppression selecting hits in ≈ 1-2 ns signal intervals**

True detection time – All sectors



True detection time – Sector 19

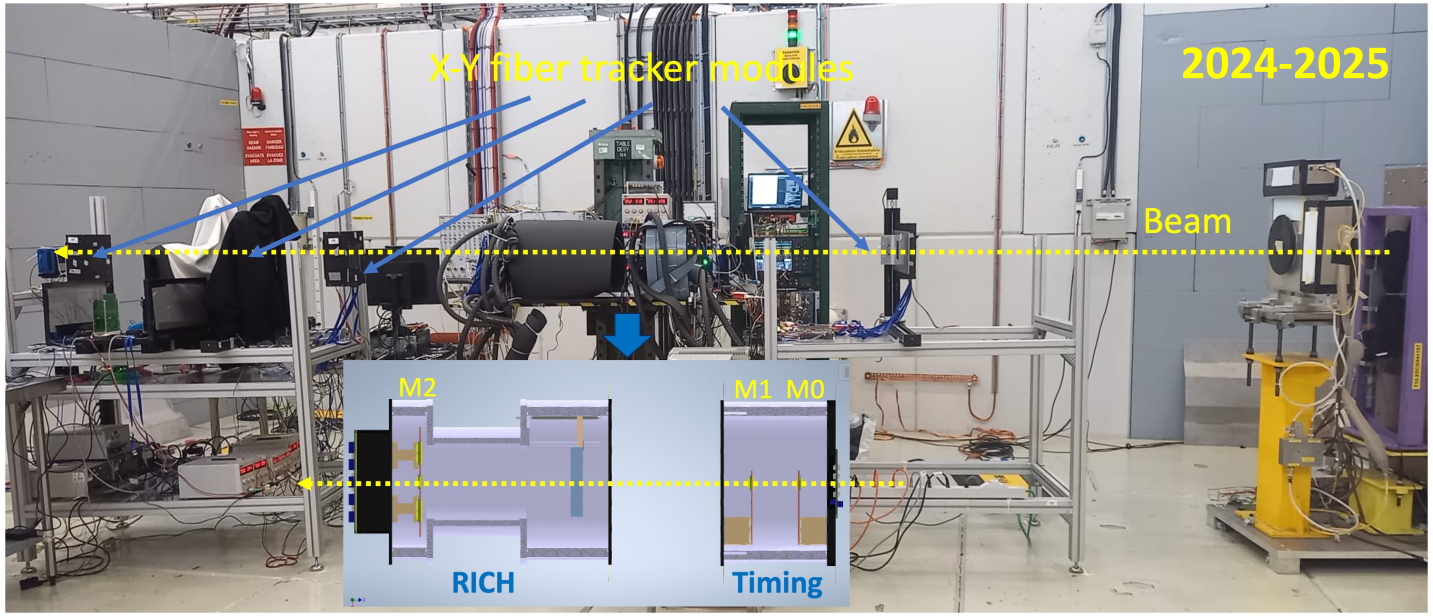


Beam test activities

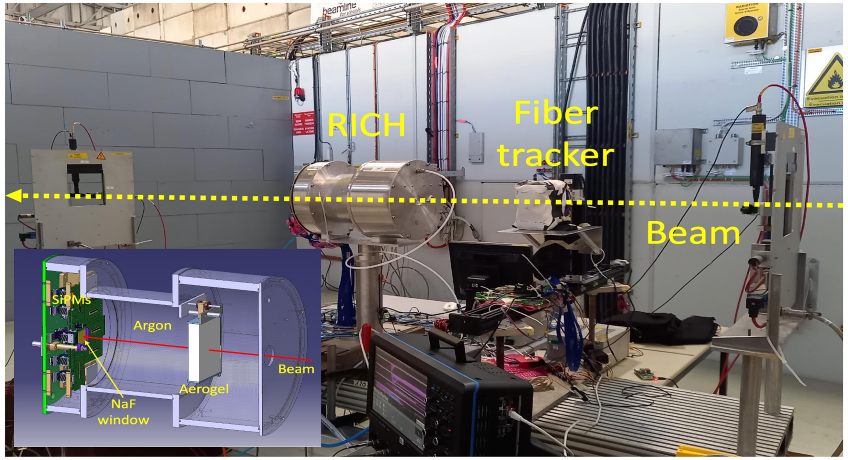
A long journey since 2022

- Various prototypes were tested on beam at PS-T10 beamline
- Various SiPM arrays, aerogel tiles and FE boards were used
- Measurements validated the baseline bRICH specifications
- Very promising results for the timing and gas-eID options

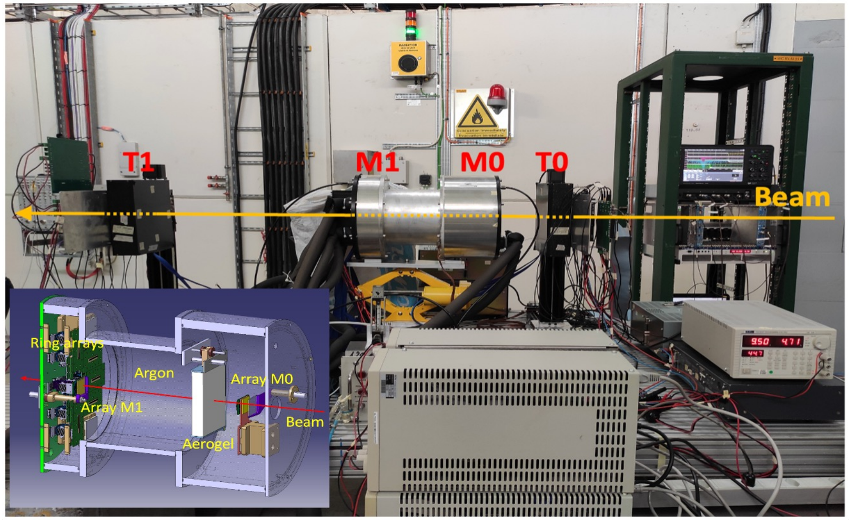
Let's focus on 2024-2025 results



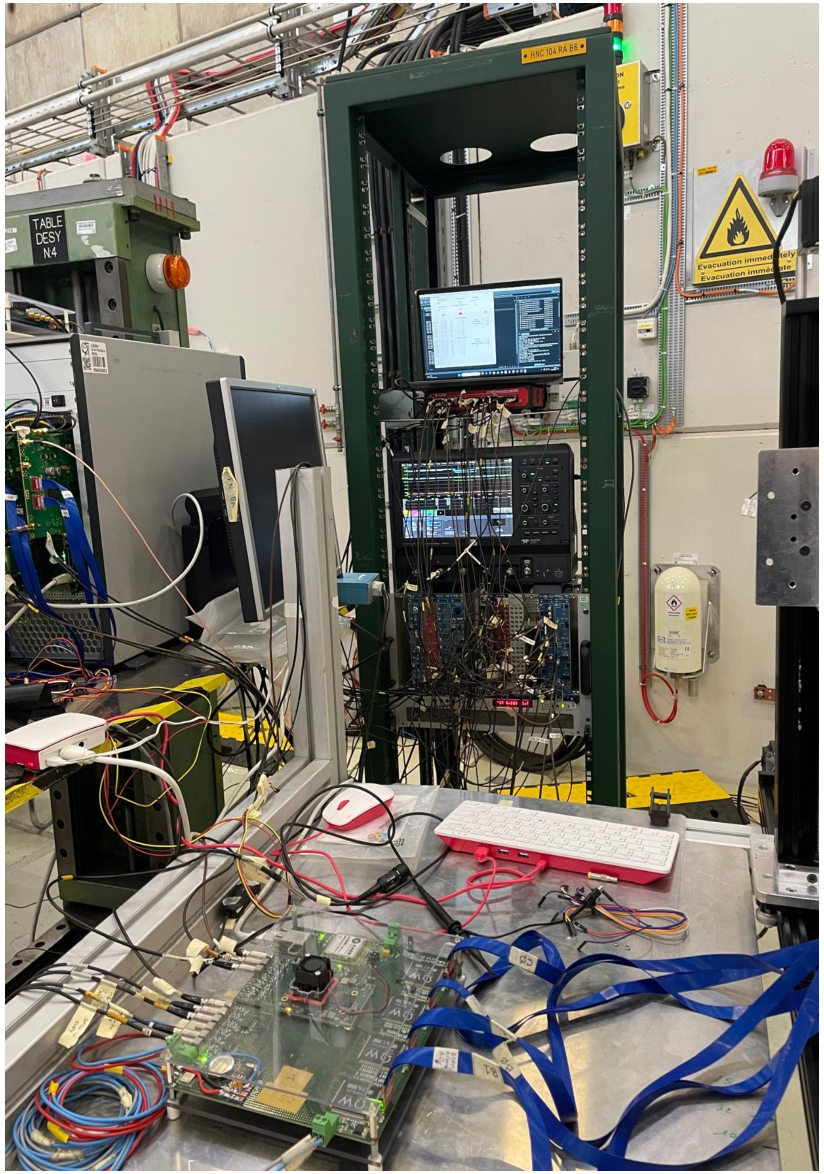
2022 A. R. Altamura et al., EPJ C 85, 578(2025)

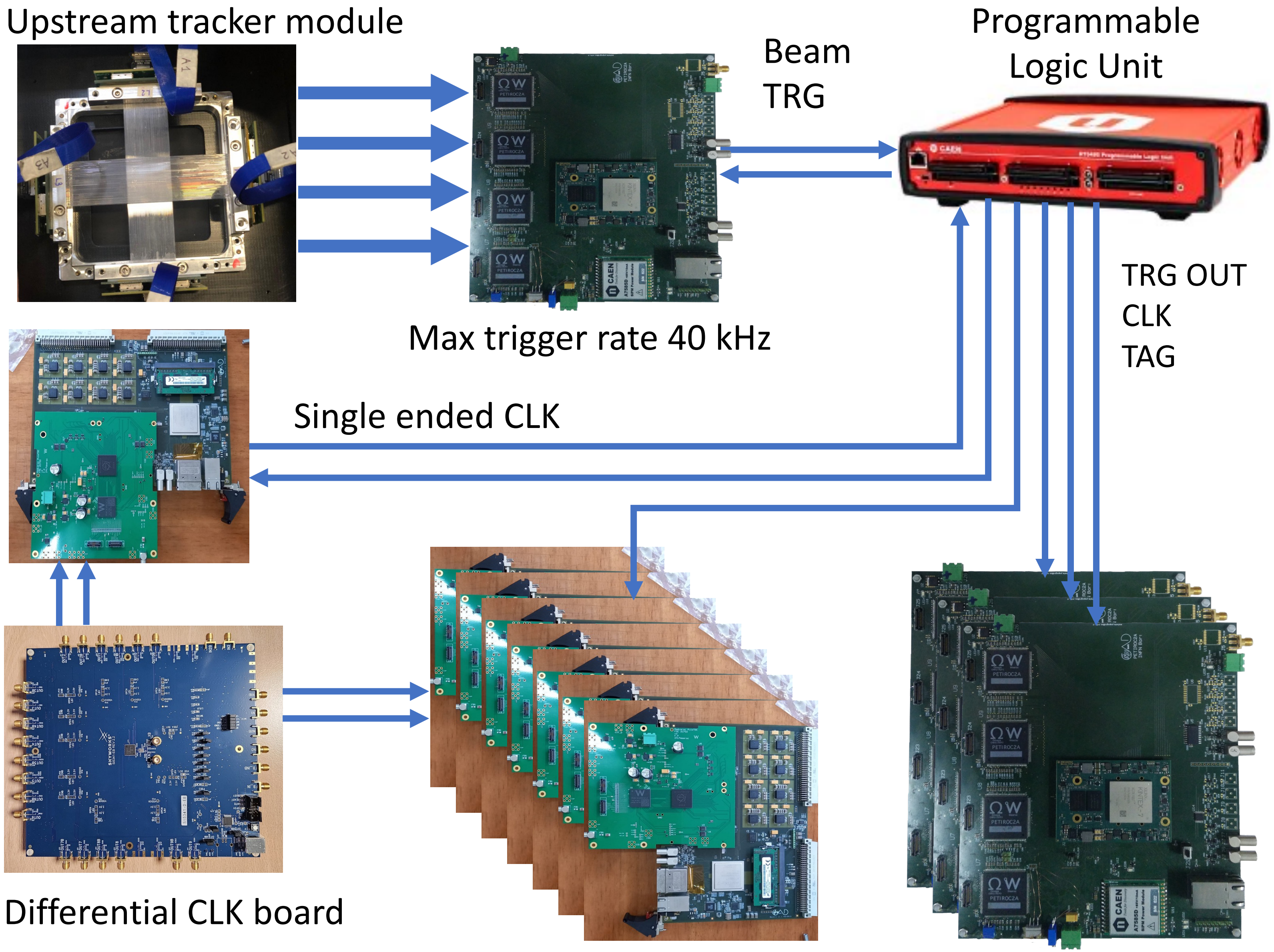


2023 N. Nicassio et al., IWASI 2023 (2023)



Trigger and DAQ system

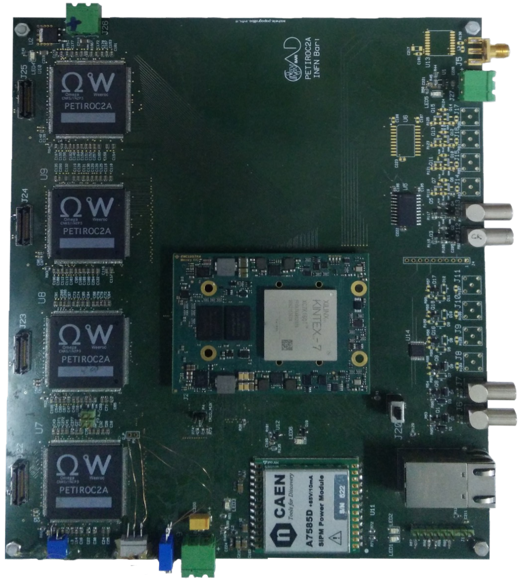




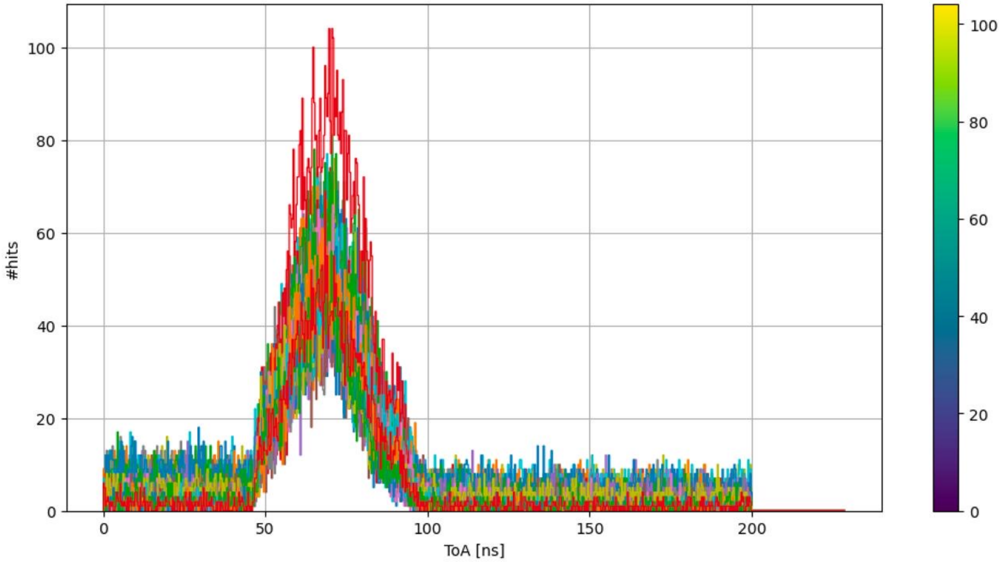
Front-end and DAQ boards

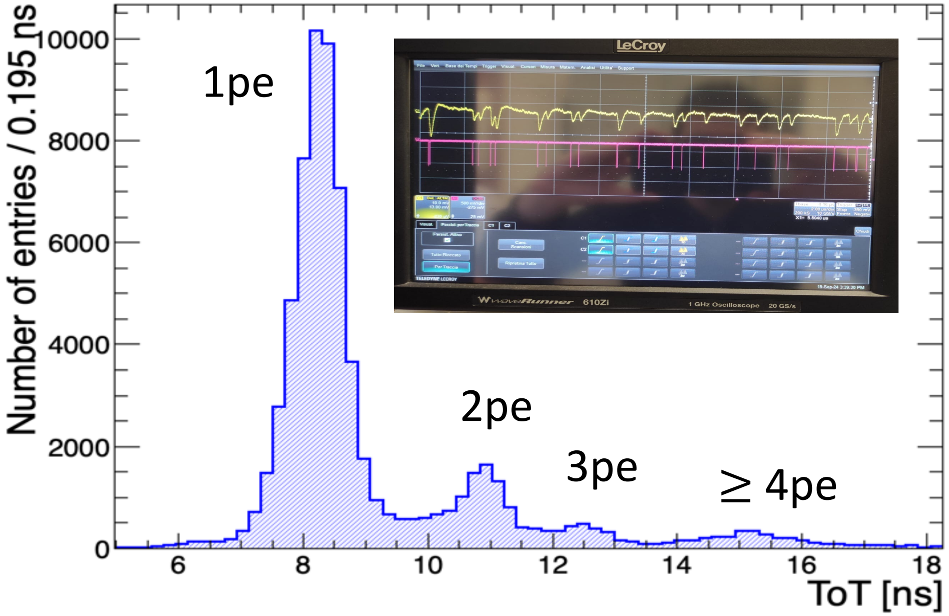
- **Fiber tracker modules**
  - Custom board based on PETIROC 2A FE ASIC with TDC (LSB ≈ 37 ps) and ADC (10 bits)
- **RICH and timing system**
  - Custom mezanine based on Radioroc 2 FE ASIC + picoTDC, read-out by MOSAIC board
  - Opeation: ToA LSB ≈ 3 ps, ToT LSB ≈ 195 ps

PETIROC 2A board



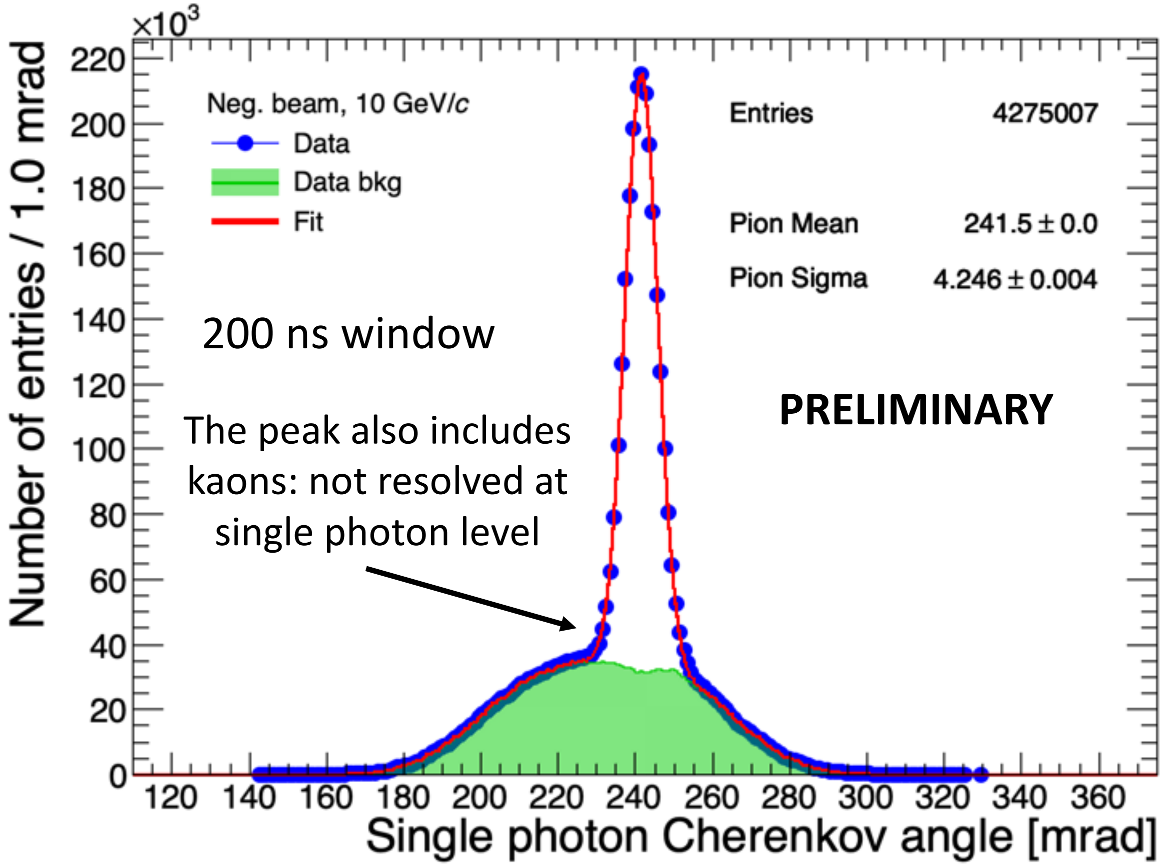
Radioroc2+picoTDC board

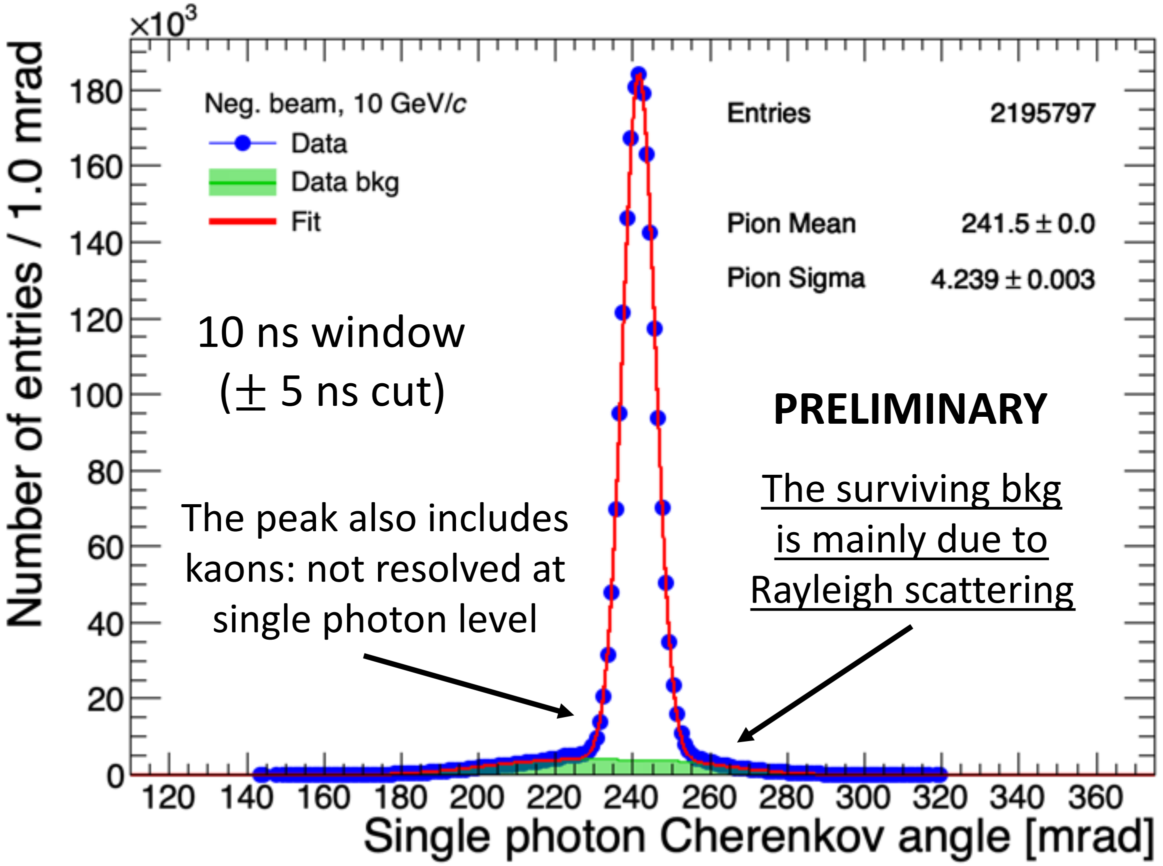




2024: Performance at single hit level

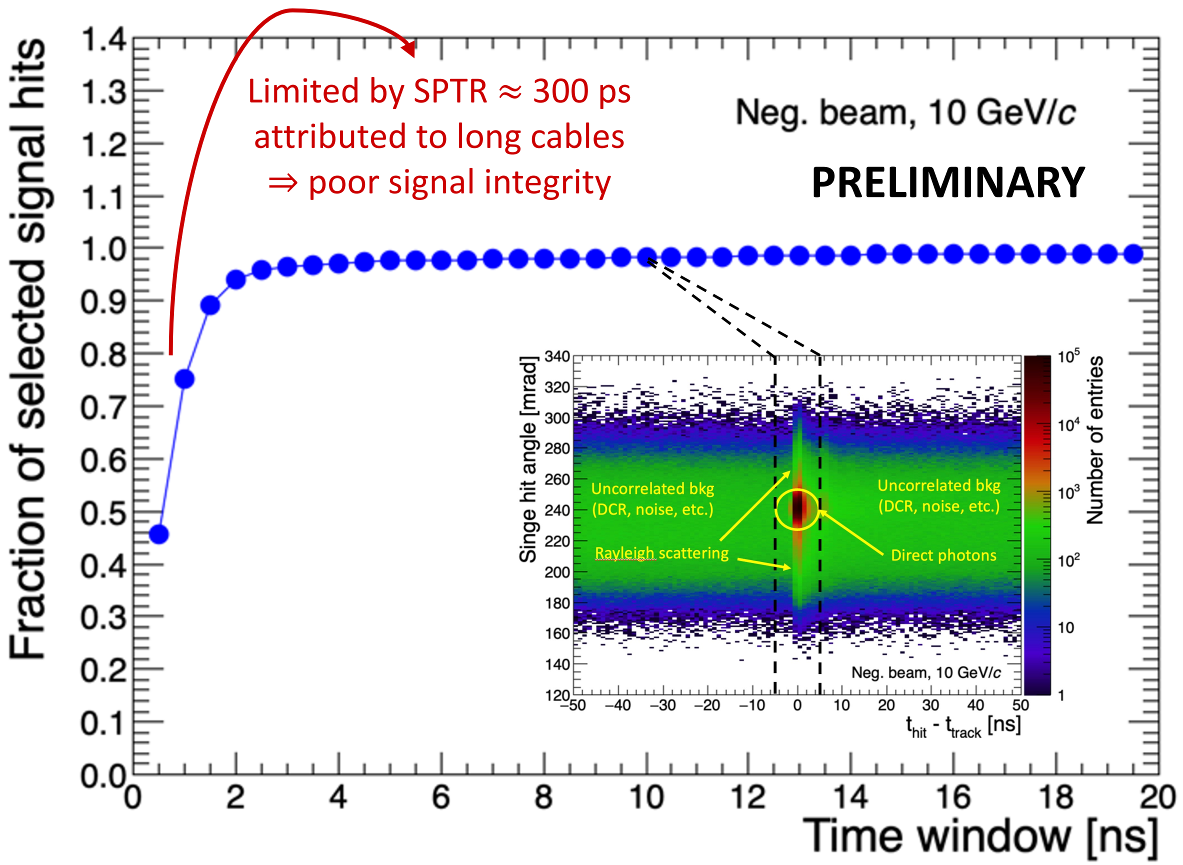
- **Angular resolution of about 4.2 mrad as expected with 2x2 mm^2 pixel size**
- **Background level consistent with expectations @ the operation T and V_{ov}**
- **Excellent uncorrelated bkg suppression achieved using time matching**

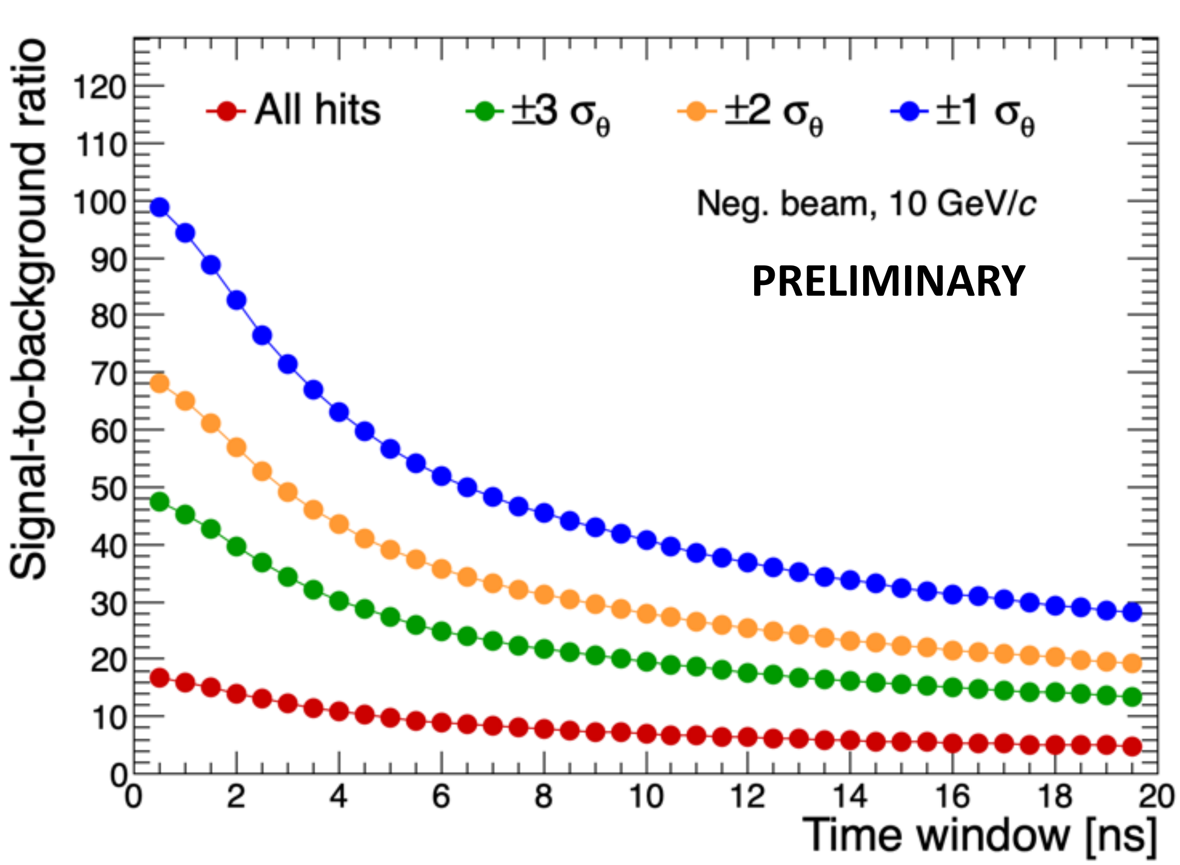




Efficiency and signal/background

- Signal efficiency (≡ fraction of signal hits) > 95 % for time windows ≥ 2 ns
- Sig-to-bkg ratio > 20 for $|\theta_{\mathrm{hit}} - \theta_{\mathrm{trk}}| < 3\sigma_\theta$ and $|t_{\mathrm{hit}} - t_{\mathrm{trk}}| < 10$ ns
- Bkg for small Δt: mainly Rayleigh scattering, Bkg for large Δt: mainly DCR





Extrapolation to full acceptance

- **Using template based on ring mean and sigma radius to extrapolate the track-by-track acceptance loss based on the track position in central array**
- **We get 24 signal photons on average, as expected @ operation conditions**