Test beam performance of a novel compact RICH detector with timing capabilities for the future ALICE 3 PID system at HL-LHC

M. Nicola Mazziotta on behalf of the ALICE 3 RICH working group

mazziotta@ba.infn.it

The 6th International Workshop on new Photon-Detectors (PD24)

Nov 19 – 22, 2024

Harbour Centre, Vancouver (BC), Canada

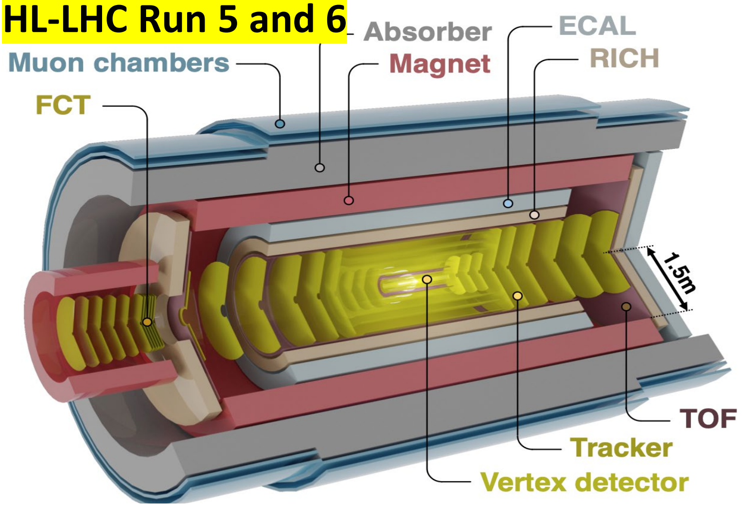
Outline

- ALICE 3 RICH layout proposal
- Beam test campaign at CERN PS@T10 in 2023 and 2024
  - We used a slightly different set-up but with different FE and read-out boards
  - Hereinafter we use “2023” and “2024” to refer to the two tests
- Results:
  - Cherenkov angle resolution
  - Timing resolution
- Outlook

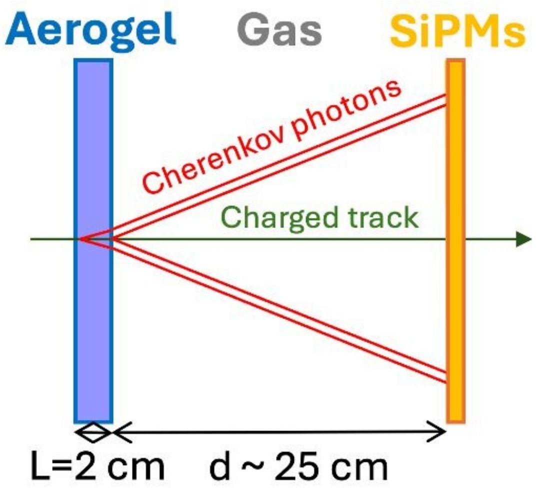
ALICE 3 proximity-focusing RICH detector

- PID goals
  - e/π separation in the *p* range 0.5 - 2 GeV/*c*
  - π/K separation in the *p* range 2 - 10 GeV/*c*
  - K/p separation in the *p* range 4 - 16 GeV/*c*
- Design concept: proximity-focusing geometry
  - Aerogel radiator tiles
    - n = 1.03, thickness = 2 cm
    - Transmission length > 6-7 cm at 400 nm
  - Photon detector based on SiPMs
    - Pixel size of 2x2 mm^2
    - PDE > 40% at 400 nm
    - BoL DCR < 50 kHz/mm^2 at RT
    - Expected NIEL of about 10^{12} MeV neq /cm^2
  - Fast front-end with SPTR < 100 ps
- R&D ongoing with on-the-shelf components
  - Hydrophobic aerogel from Aerogel Factory & co.
  - HPK SiPM S13361-* (+ thin quartz window for Cherenkov based charged track timing and better pattern recognition)
  - Petiroc 2A and Radioroc 2 Omega/Weeroc FEs + CERN pTDC

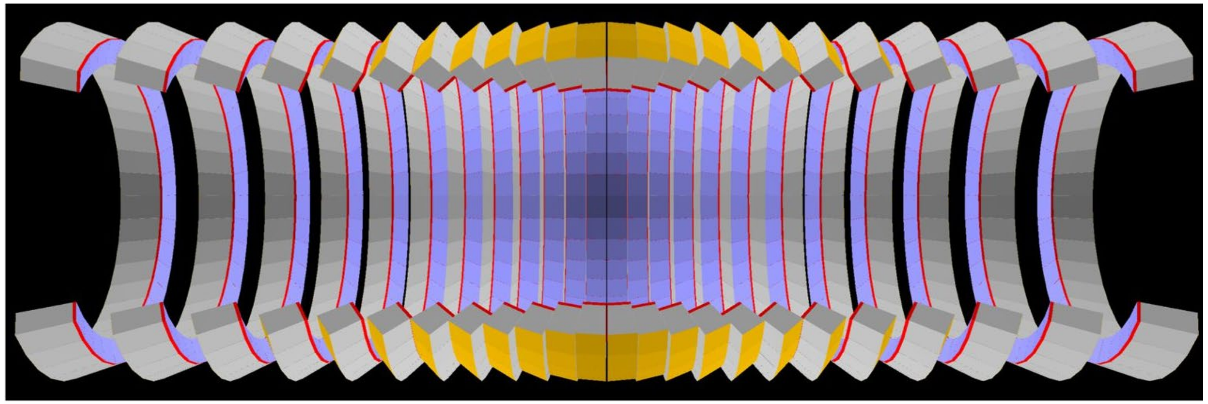
ALICE 3 baseline (LoI) B = 1-2 T
HL-LHC Run 5 and 6



Proximity-focusing geometry

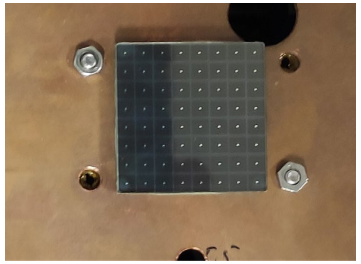


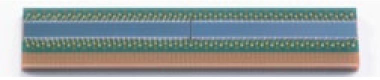
Projective geometry: modules oriented towards nominal collision vertex
24 sectors x 36 modules, sensor area ≈ 30.7 m^2, total N channels ≈ 7M



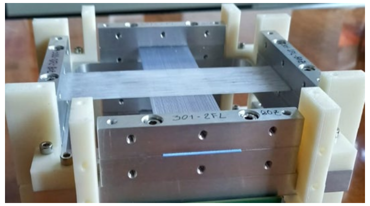
2023 beam test set-up@T10

Particle timing (M1):
S13361-3075 array
With 1 mm of SiO2



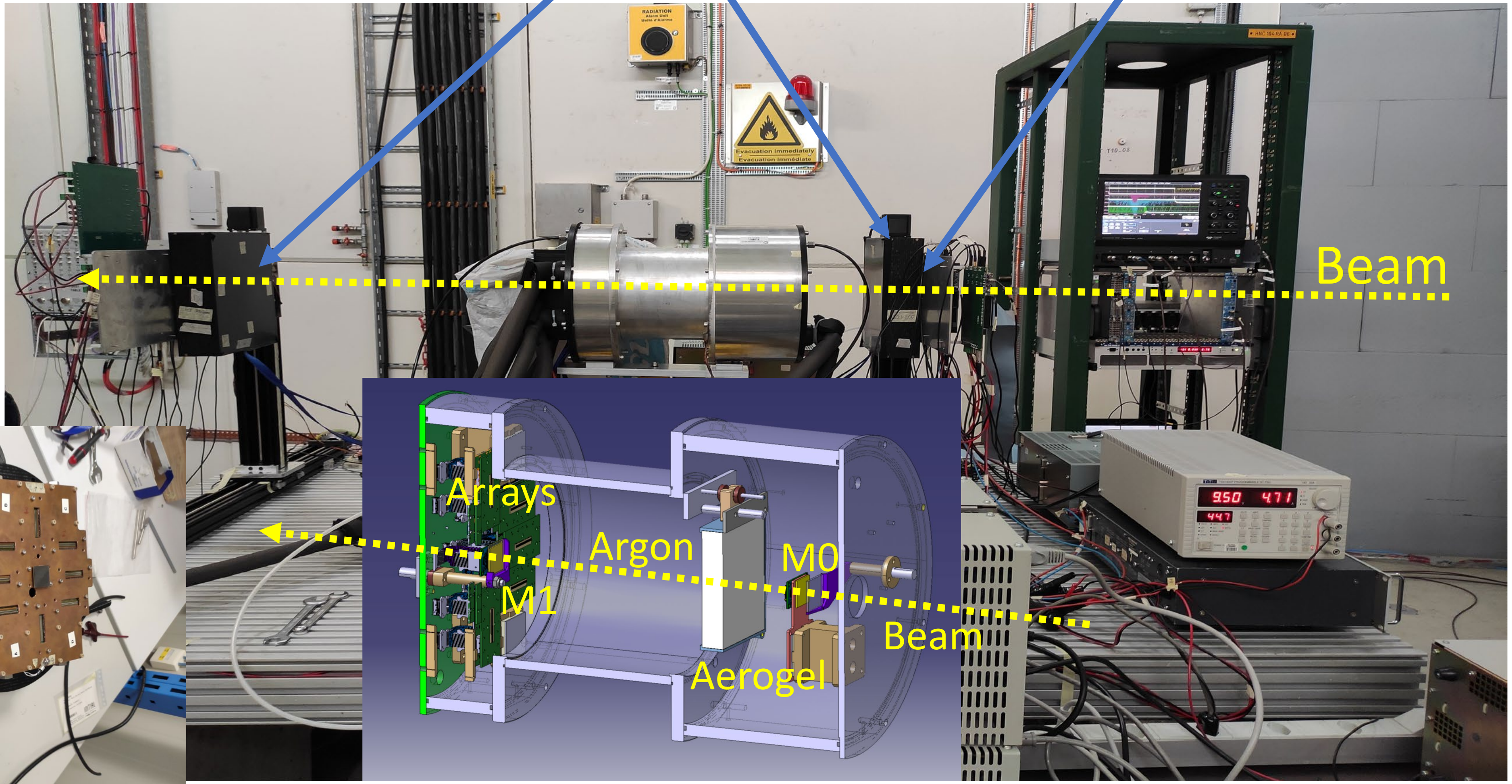


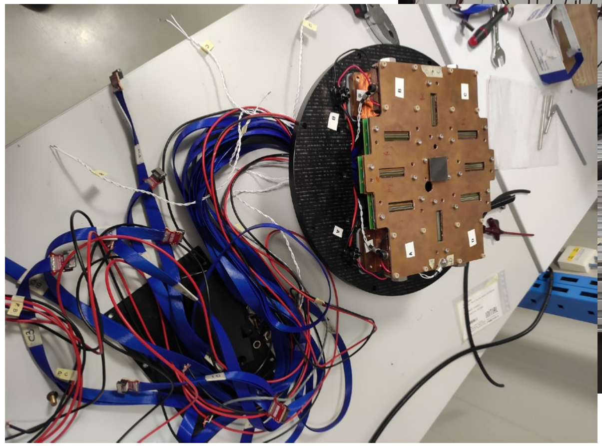
Ring: 8 HPK S13552
128 ch. arrays of 0.23x1.625 mm^2 strips, 32 ch read-out
4- ORed strips



X-Y fiber tracker box

Scintillator trigger box

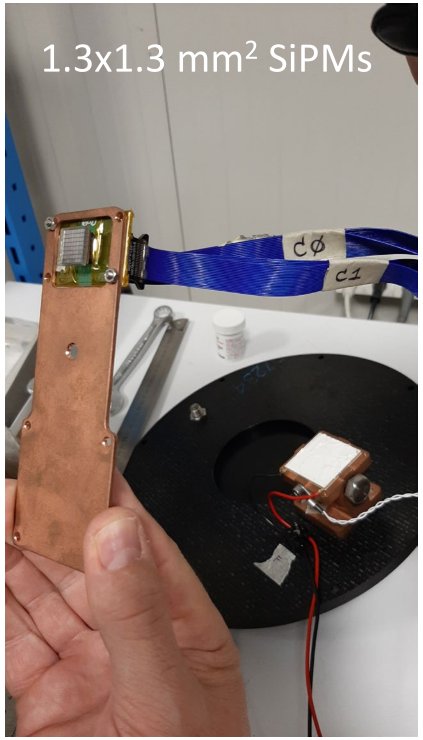




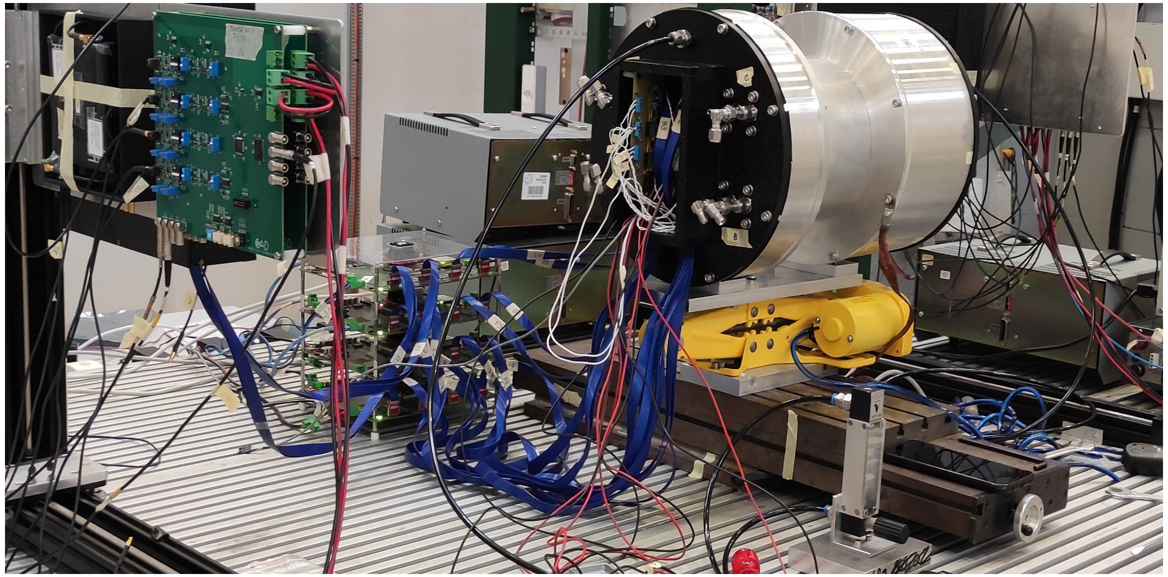
SiPM cooling: Water chiller + 5 Peltier devices: operation temperature in [-5°,0°]

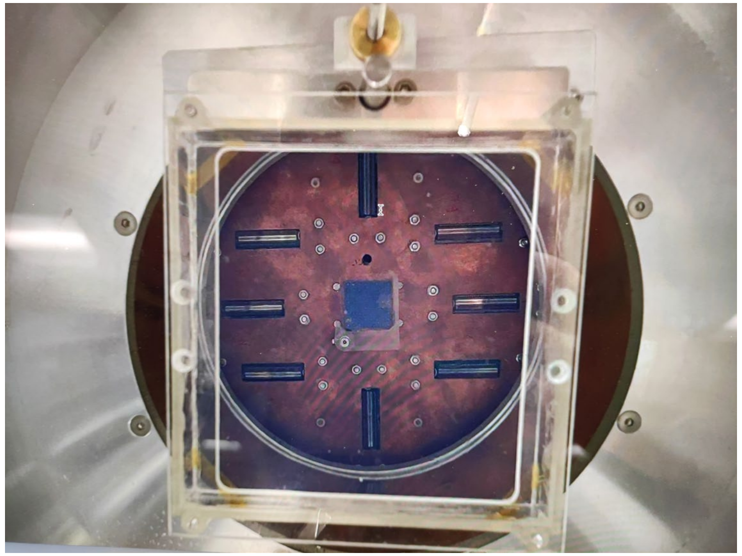
M0:

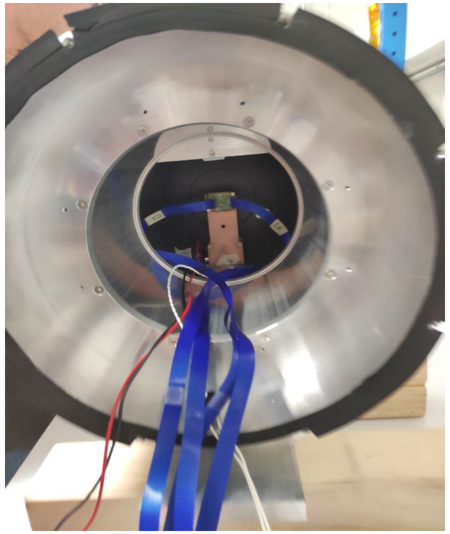
- S13361-1350 with 2 mm of SiO_2
- S13361-3075 with 1 mm of SiO_2
- S13361-3075 with 1 mm of MgF_2

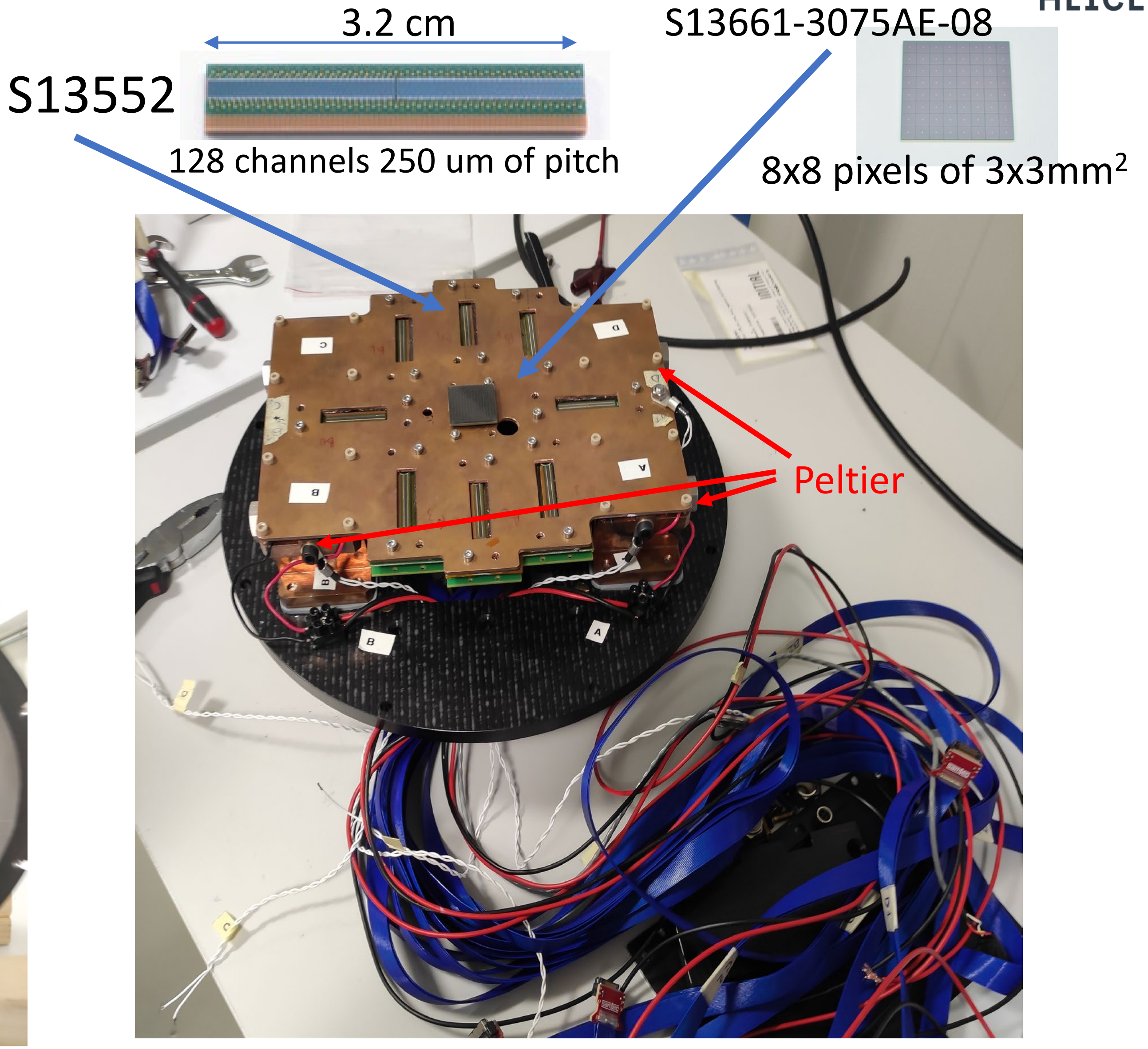


2023 - Rich set-up (1)

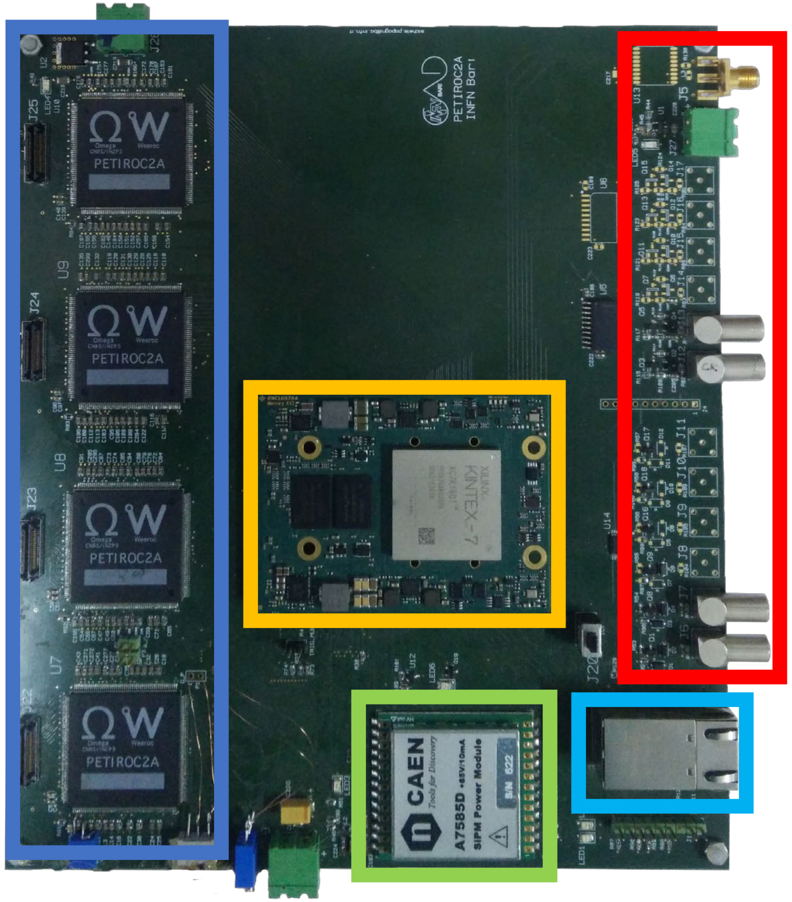






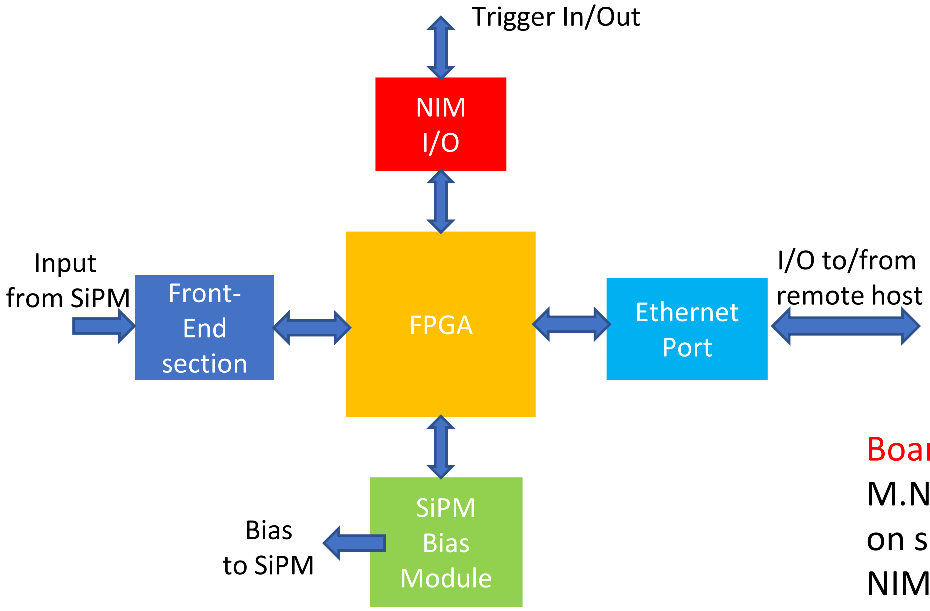


2023 - DAQ and Front-End Board (FEB)



Front-End
- Four PETIROC 2A ASICs

Ethernet port
- Data I/O to a remote host



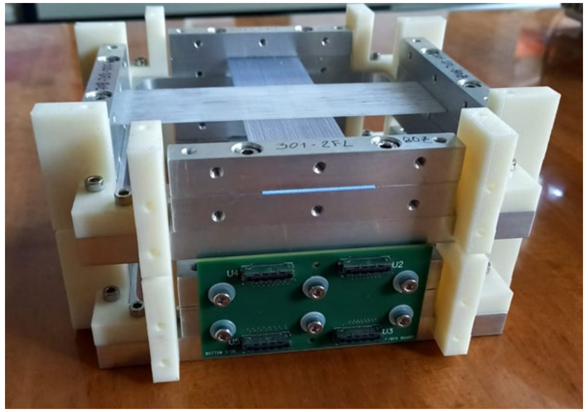
FPGA:
- I/O data management
- Trigger
- Configuration

NIM I/O
- Trigger

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

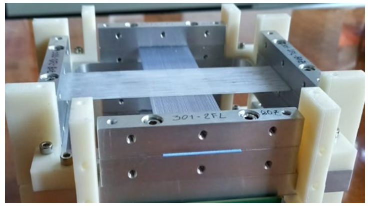
Four FEBs:
- Two FEBs for the ring read-out
- One FEB for the central matrices
- One FEB for the 2 X-Y fiber tracker

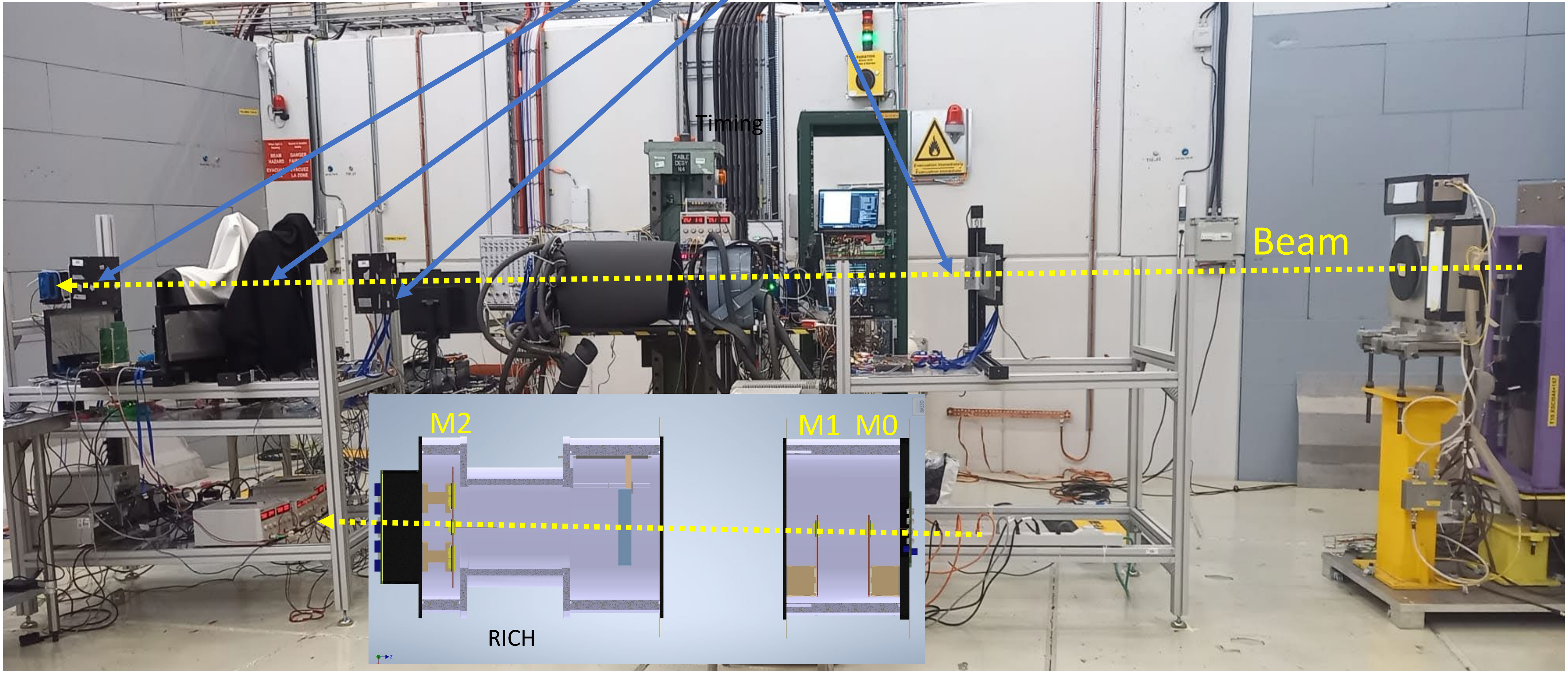
Boards developed in Bari for a fiber tracker
M.N. Mazziotta et al "A light tracker based on scintillating fibers with SiPM readout", NIMA 1039 (2022) 167040
https://doi.org/10.1016/j.nima.2022.167040



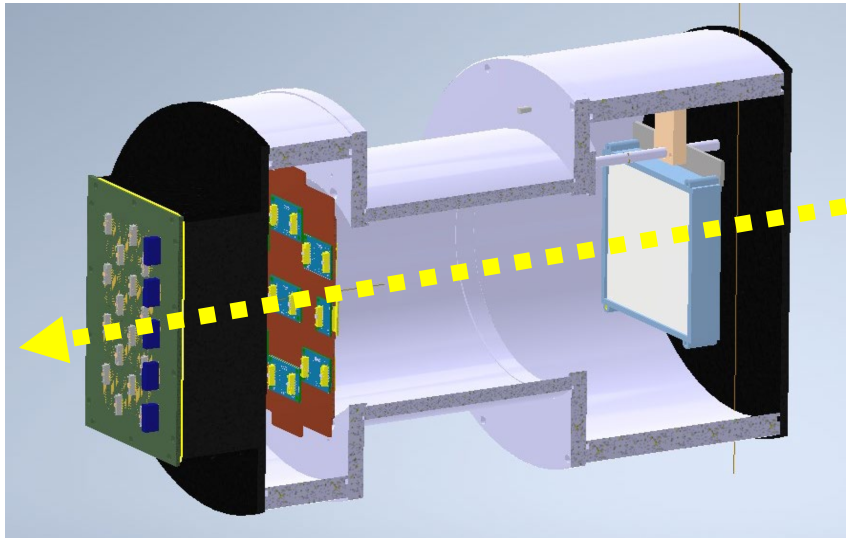
2024 Beam test set-up@T10

X-Y fiber tracker module: beam trigger and particle tracking

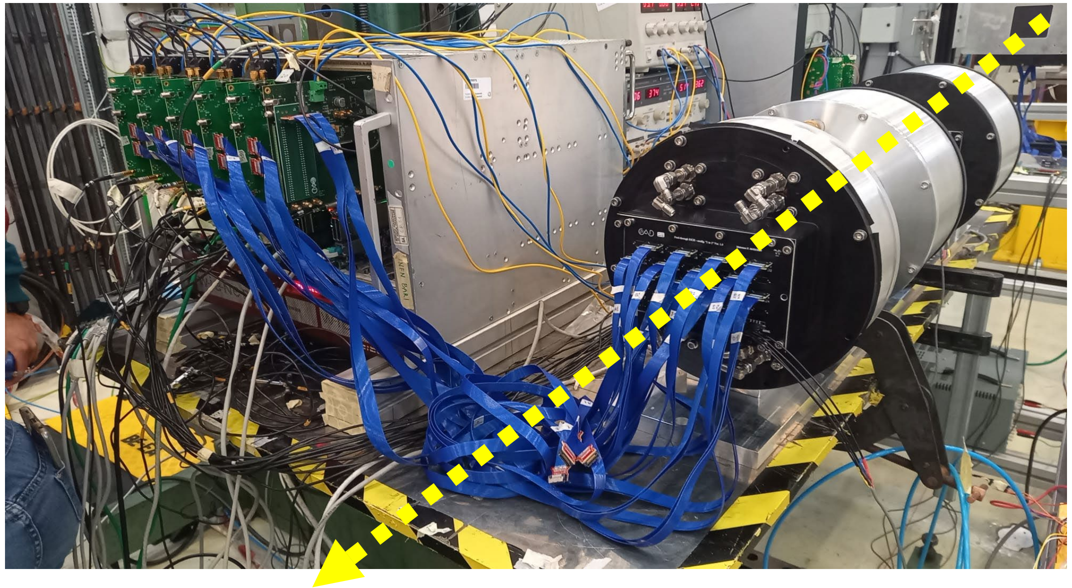


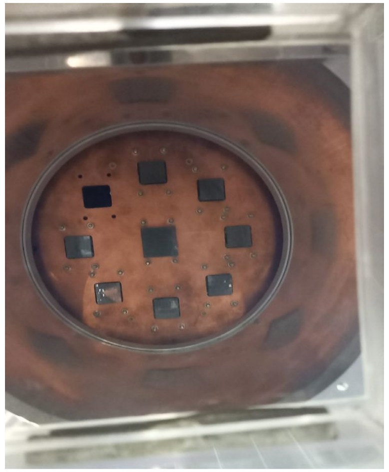


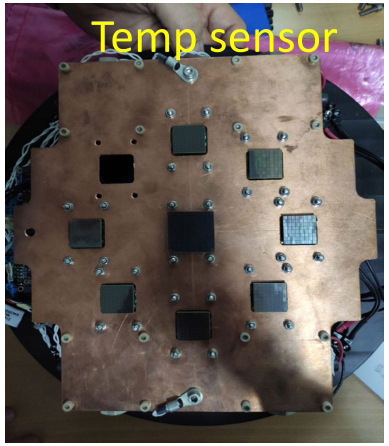
2024 RICH set-up

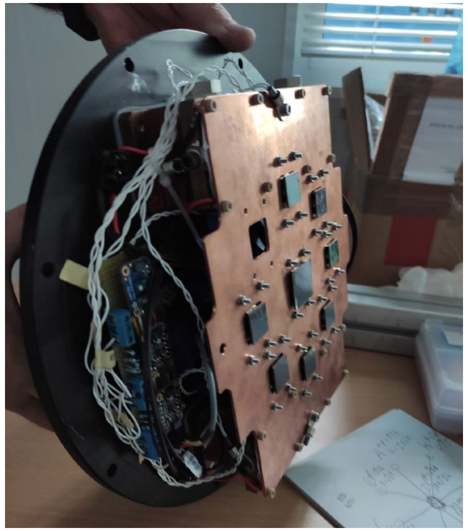


- SiPM RICH camera with a feedthrough board (SiPM signals, Peltier bias and environmental sensor signals)
  - Flushed with Argon or CO_2
- Central array: HPK SiPM S13361-3050AE-08 with 3 mm pitch and 1 mm thick quartz window (M2)
- Ring array: HPK SiPM S13361-2050AE-08 matrices
- Aerogel radiator:
  - Single tile 2 cm thick with n=1.03 (single layer)
  - Focusing aerogel tile with 1 cm n=1.030 (upstream) + 1 cm n=1.033 (downstream) (two layers aerogel)



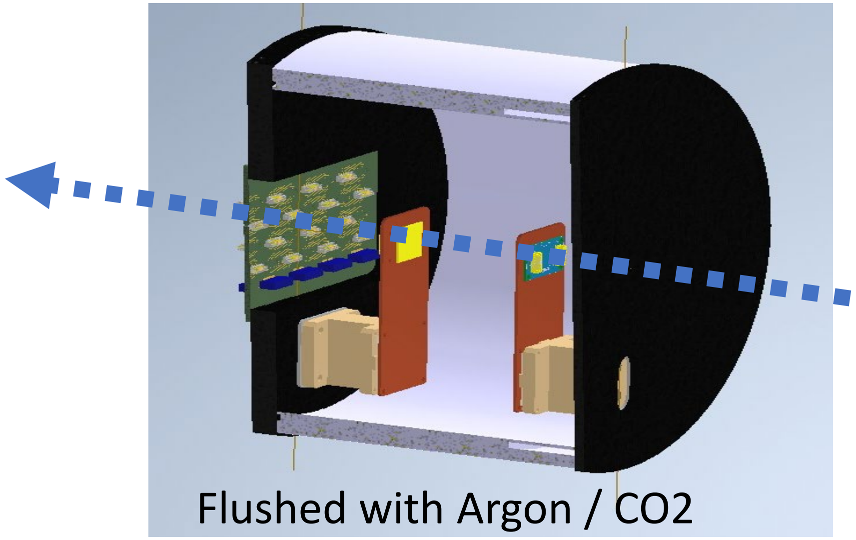


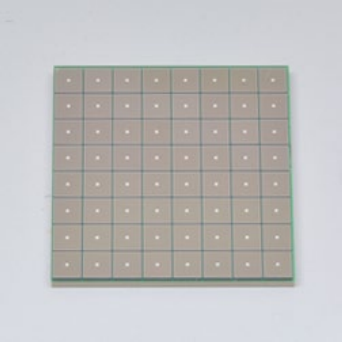


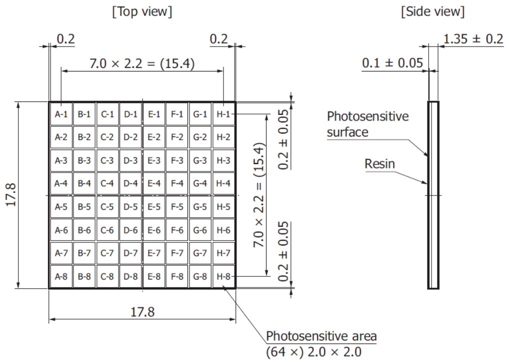


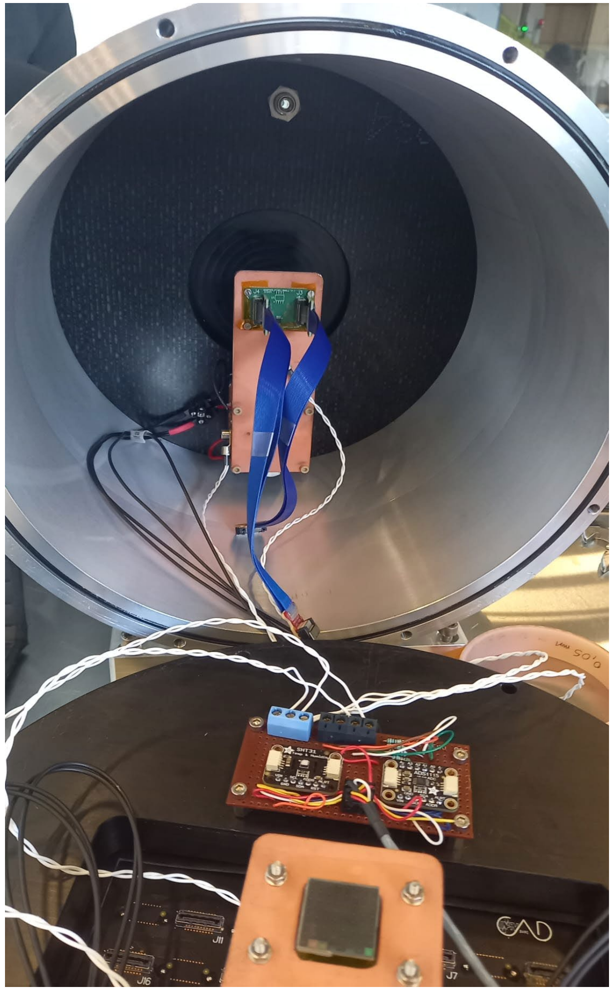
2024 - Timing set-up

- Two Hamamatsu SiPM S13361-2050AE-08 arrays (M0 and M1) with 2 mm pitch and 1 mm thick quartz window to produce a cluster of Cherenkov photons



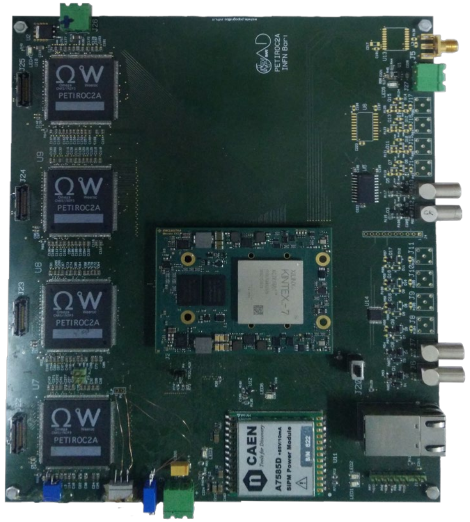


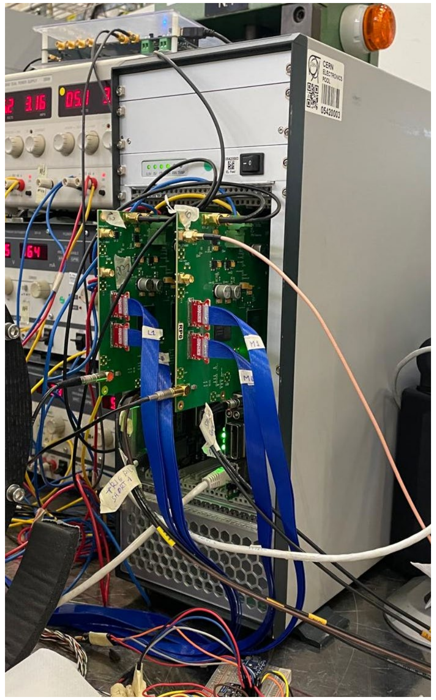


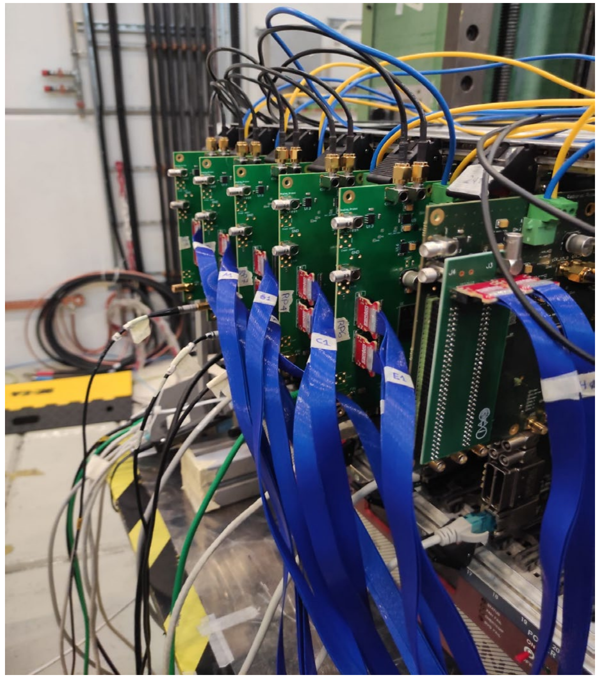


2024 - Front-end and DAQ boards

- RICH and timing systems
  - Custom board based on the Radioroc 2 FE ASIC with picoTDC (LSB ≈ 3 ps) and read-out by MOSAIC boards
  - picoTDC in multihit configuration with ToA and ToT
- Fiber tracker modules:
  - Custom boards based on the PETIROC2A FE ASICs with TDC (LSB ≈ 37 ps) and ADC and FPGA on board
    - As beam test in 2023
  - Beam particle trigger and tracking

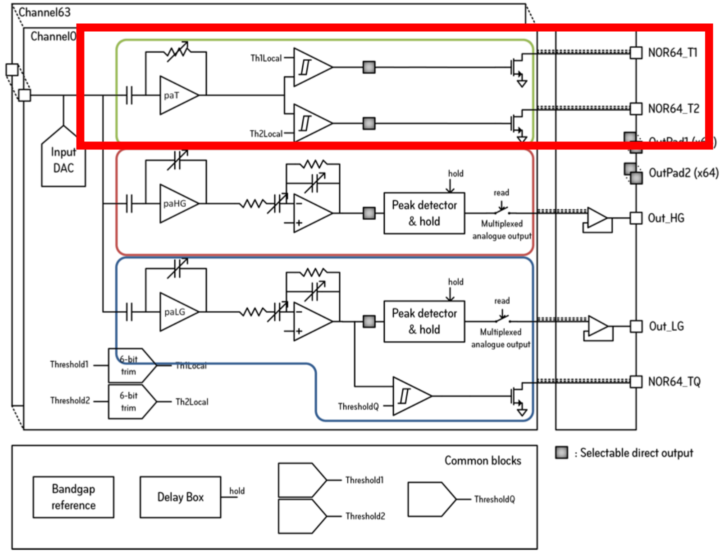


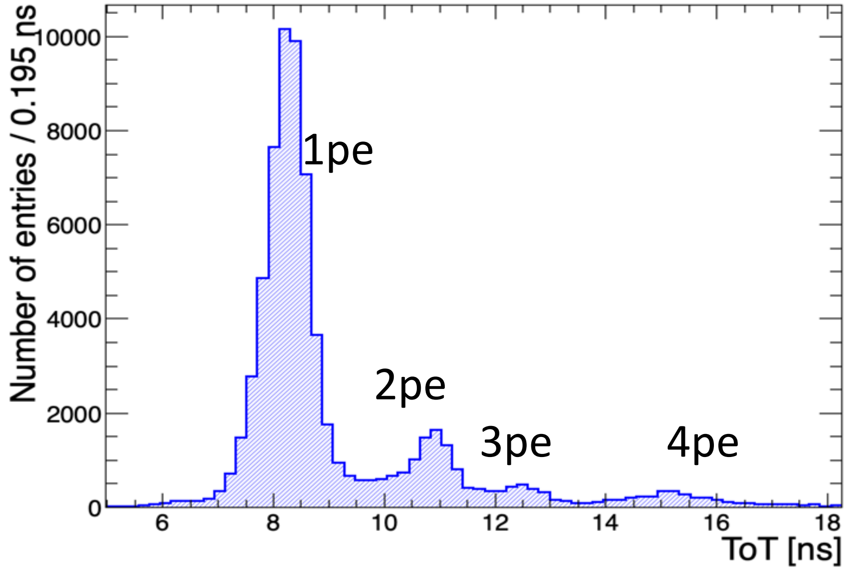




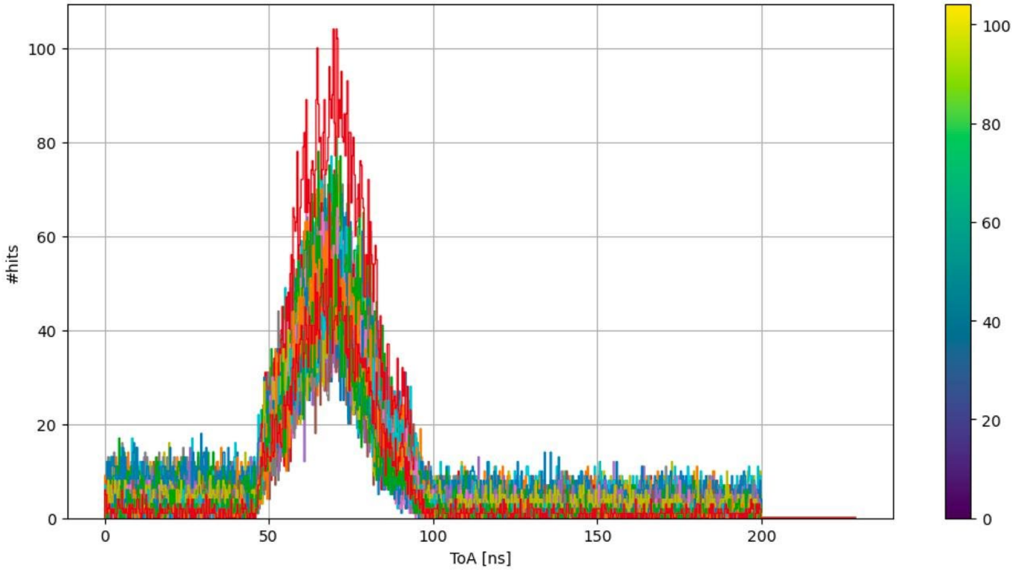
Radioroc2+pTDC board
(in collaboration with Weeroc)
+ MOSAIC

2024 - Radioroc 2 and picoTDC





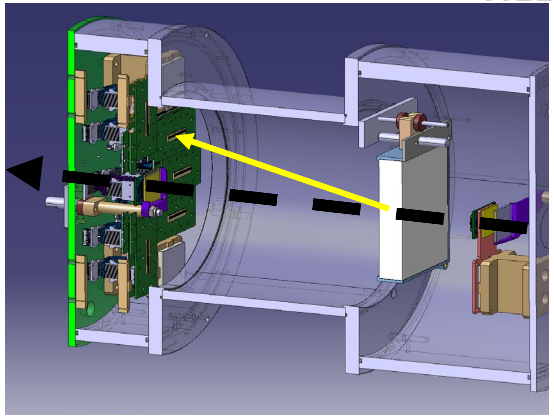
- Radioroc 2 - Weeroc
  - ToT proportional to the number of photoelectrons (P.E.)
  - Threshold at single P.E. level
- picoTDC - CERN
  - ToA LSB ≈ 3.05 ps
  - ToT LSB ≈ 195 ps
  - Acquisition window of 200 ns



RICH with timing capability

- A good timing-particle match helps aerogel pattern recognition by allowing us to discard uncorrelated hits due to the SiPM DCR
  - Crucial for long term operation in ALICE 3, with the DCR increasing with the radiation
- First, we consider the time differences between the SiPM arrays (M0, M1 and M2) with thin window (Č radiator in front) to study the timing performance of the system
  - All time offsets removed as well (including the time-of-flight)
- Then, we consider the time difference between the RING arrays and the central matrix to remove the dark counts hit in the signal region
  - A Č photons – particle hit arrival time within a narrow interval, i.e. +/- 5 ns

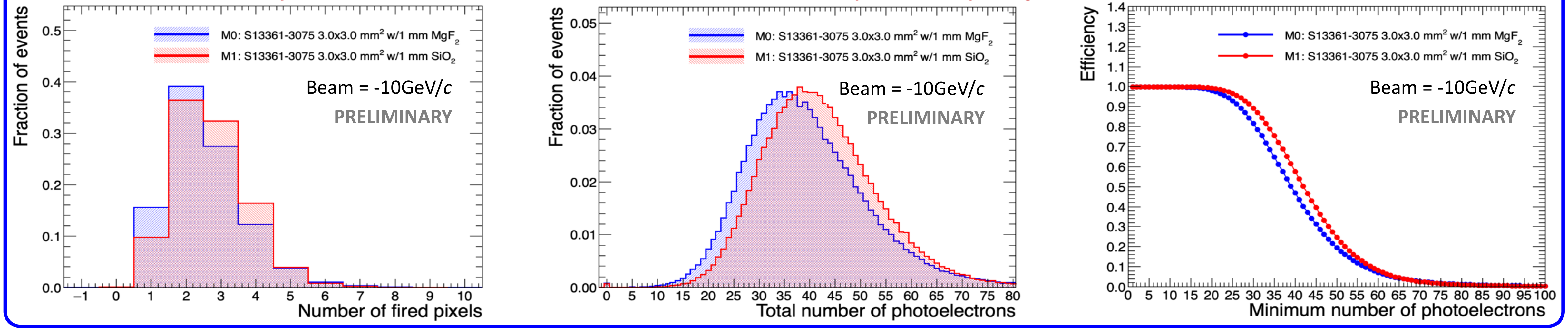
Cherenkov angle reconstruction method



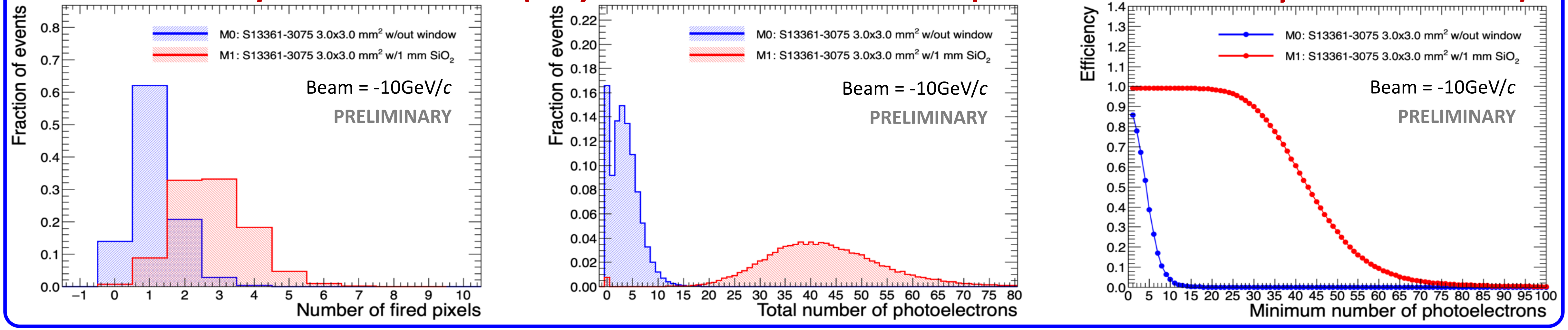
- All hits in the ring SiPM assumed as candidate Cherenkov photons
  - Emission position in the middle of the aerogel tile by means of particle track parameters
- Cherenkov angle reconstruction
  - Analytical backpropagation:
    - Pixel hit $\leftrightarrow$ Radiator by including Snell's law (at the areogel-argon surface)
- Angle resolution
  - Data fitted with $Gaus(\pi)$ (+ Gaus(p)) + background template
    - Background due to random coincidences, dark count rate hits, optical cross-talk, wrong tracking, …
    - The background hits template looking ToA values outside the signal region

2023 - M0 and M1 performance with 10 GeV/c pions

Efficiency of $\approx 100\%$ with clusters with $N > 20$ p.e. coupling thin window to the SiPMs



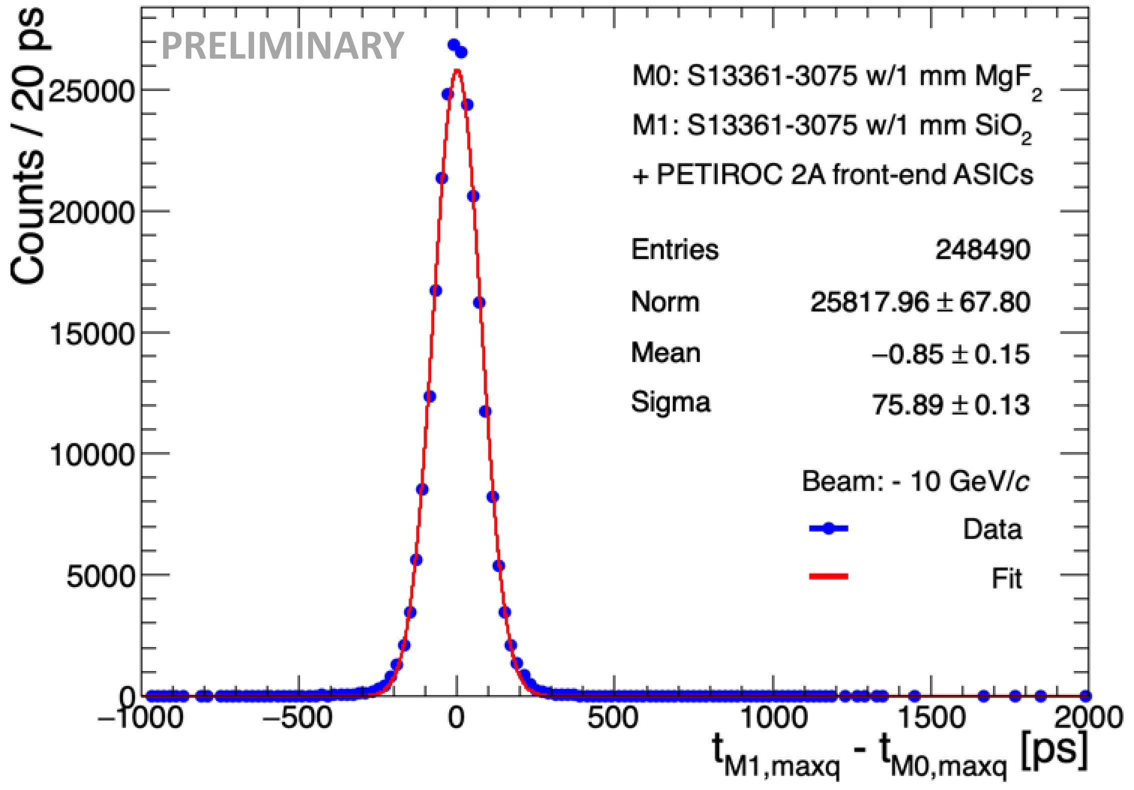
Lower efficiency without window (only direct MIP interactions or photons from ≈ 100 μm built-in resin)



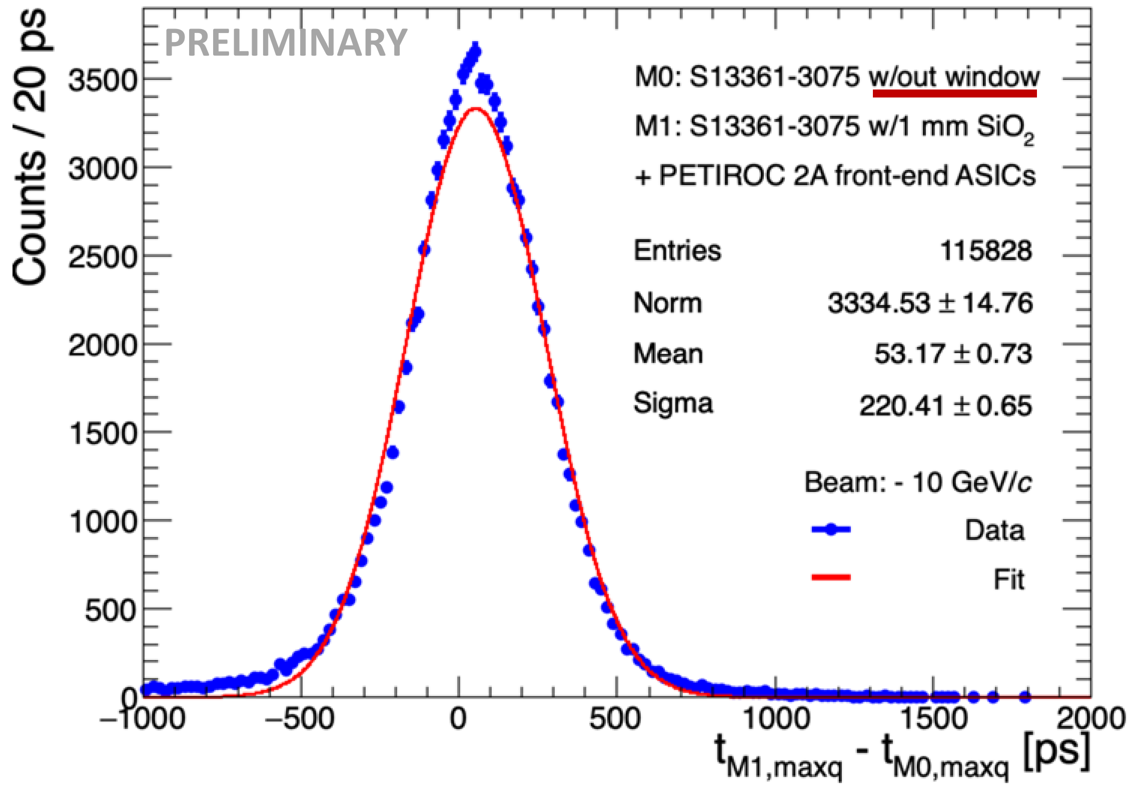
2023 - Time resolution with/without window

- Selecting tracks in fiducial area requiring hits both in the two tracker planes and in the two central arrays
- Including time walk and channel by channel offset corrections and subtracting the nominal Time-of-Flight offset at the actual beam momentum

We measured an overall resolution down to ≈ 75 ps (i.e. ≈ 50 ps single pixel resolution) adding thin window radiator with the SiPM arrays



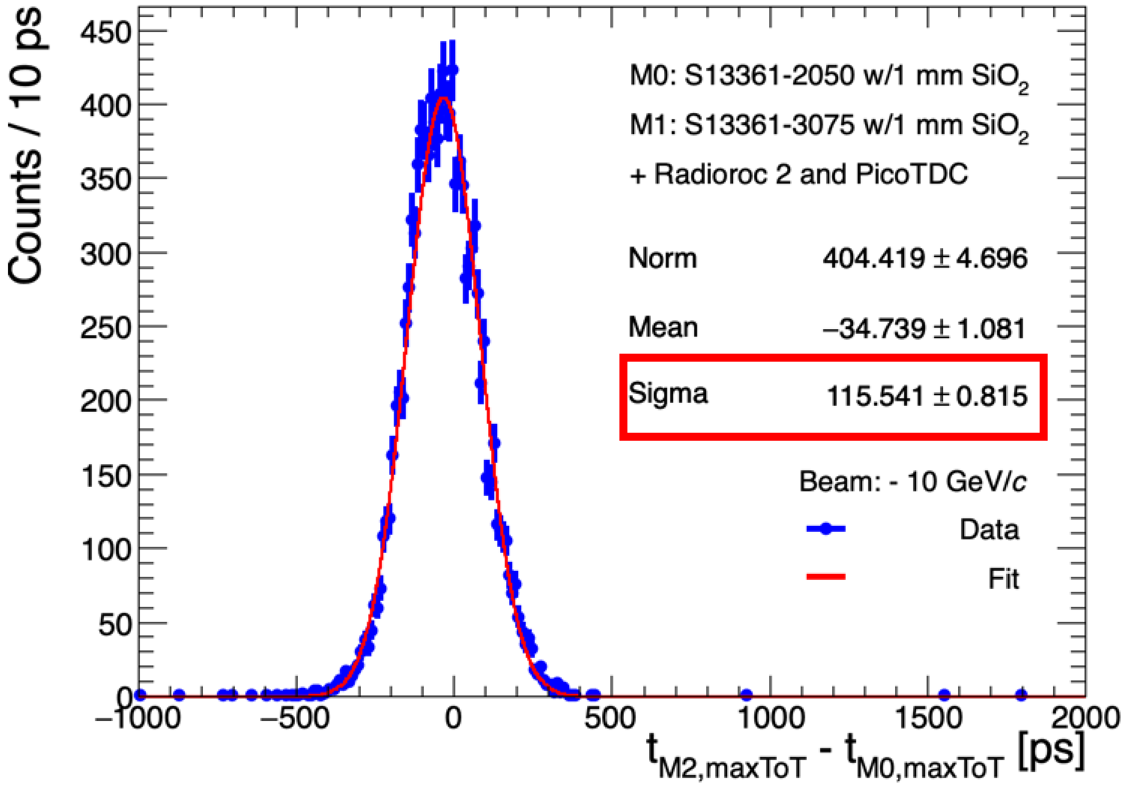
Much better performance using SiPMs coupled with radiator window w.r.t. same matrix without window



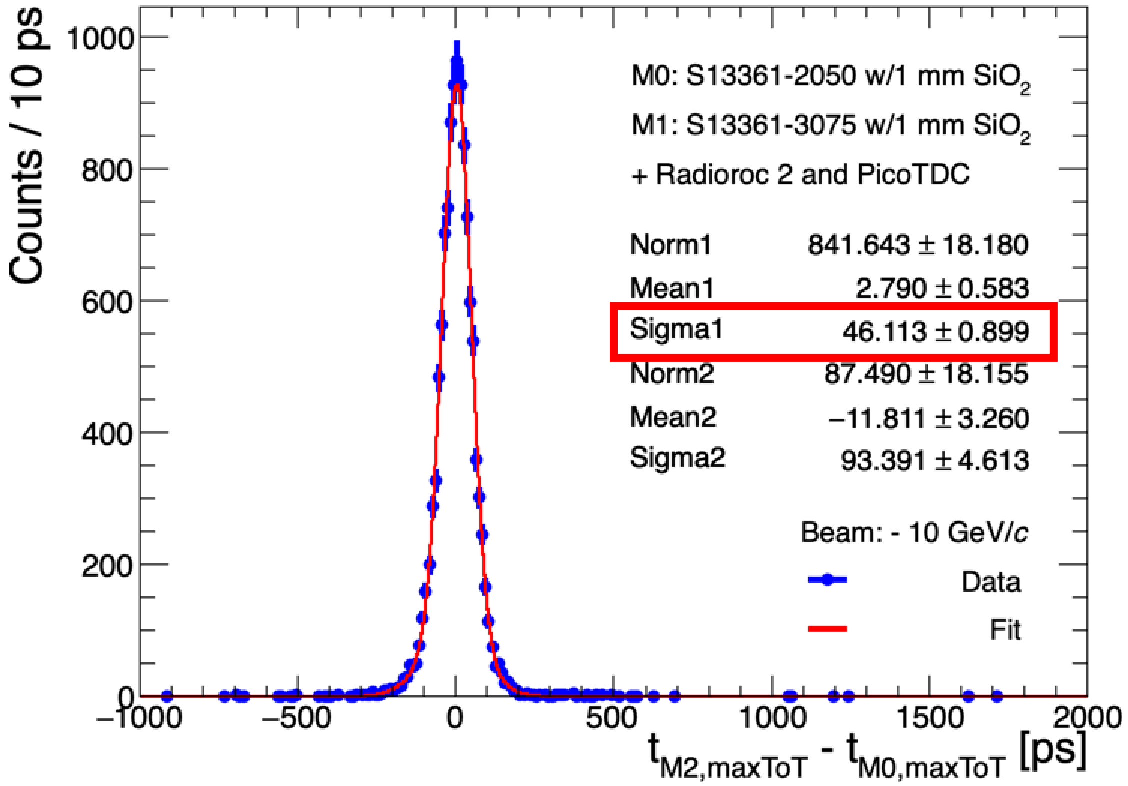
2024 - time resolution with maximum charge pixels

- Selecting tracks in fiducial area with M0 max-ToT > 20 ns, M1 max-ToT > 20 ns and M2 max-ToT > 40 ns
- Comparing results both with and without ToT-based time walk and channel by channel offset correction

We measured a Δt_{max} res. down to ≈ 120 ps with no time walk and ch by ch offset correction (but subtracting only TOF)

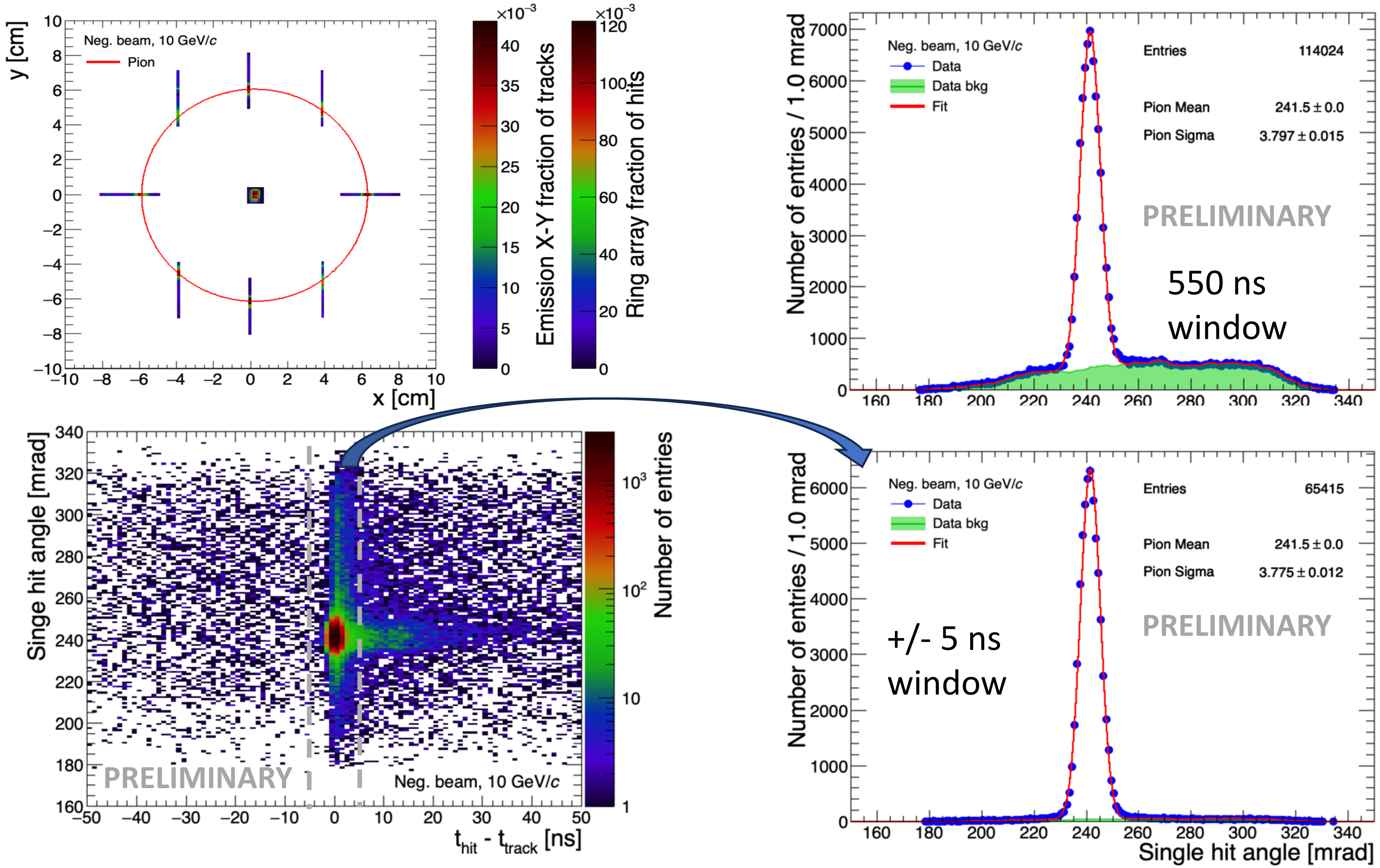


Correcting for time walk and ch by ch offset, a Δt_{max} res. down to ≈ 50 ps is achieved ⇒ Better than 35 ps at single SiPM level



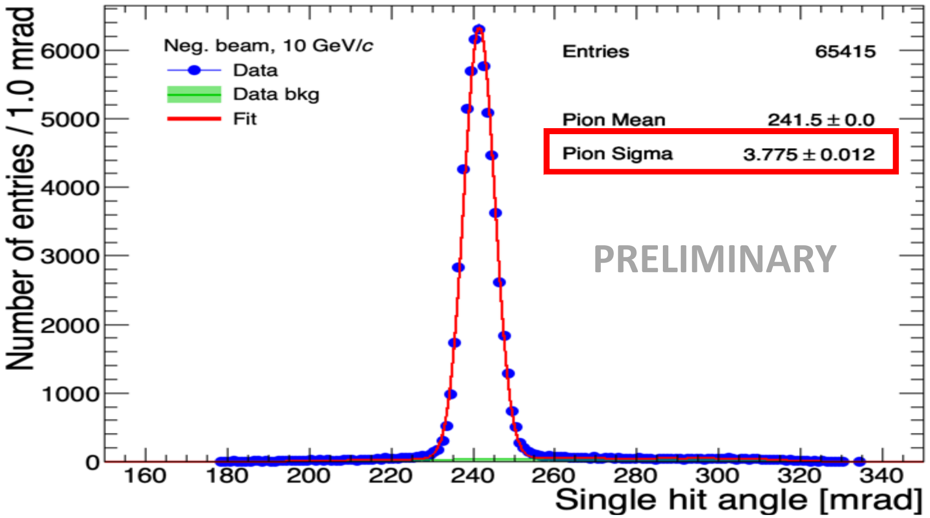
2023: Cherenkov angle and timing effects

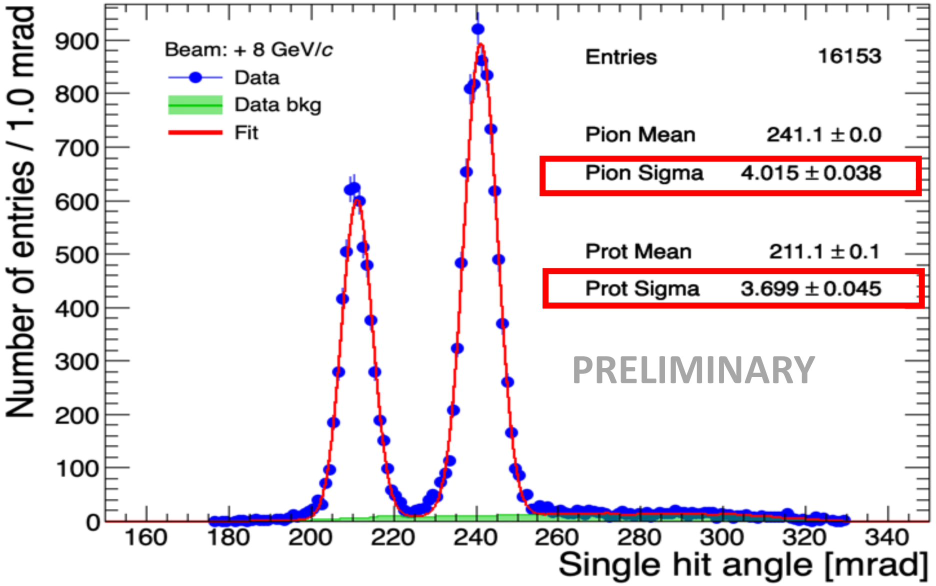
- Excellent background suppression achieved using timing information

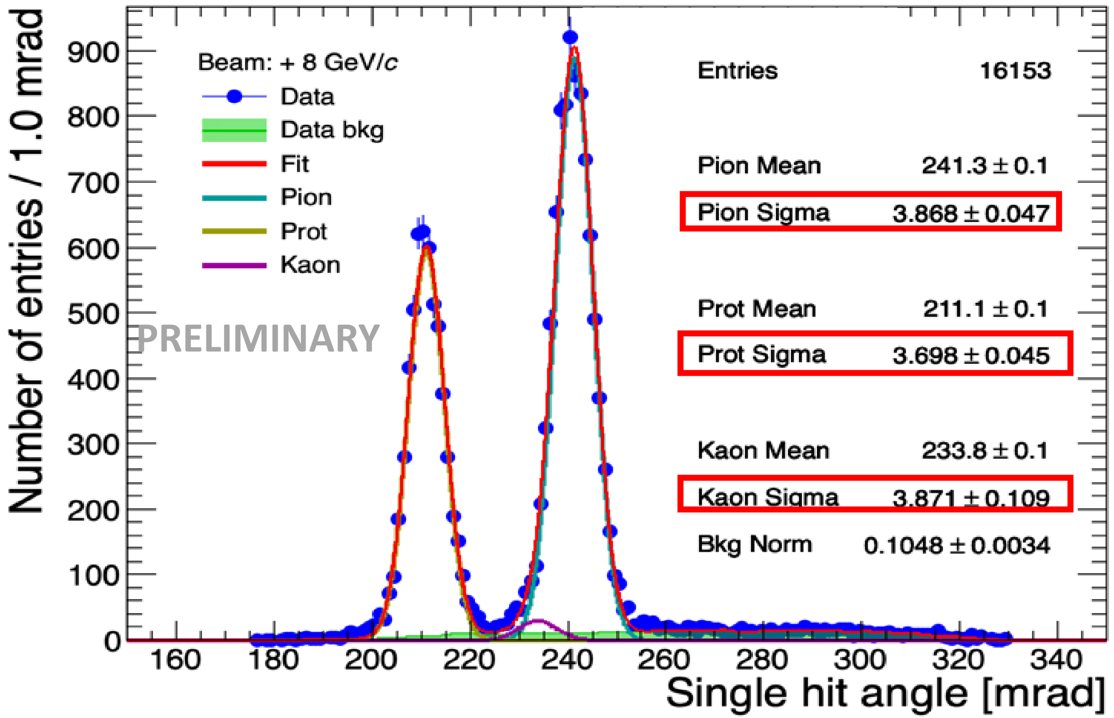


Pixel size of 1 x 1.6 mm^2

2023 Angular resolution - signal hits within a ±5 ns



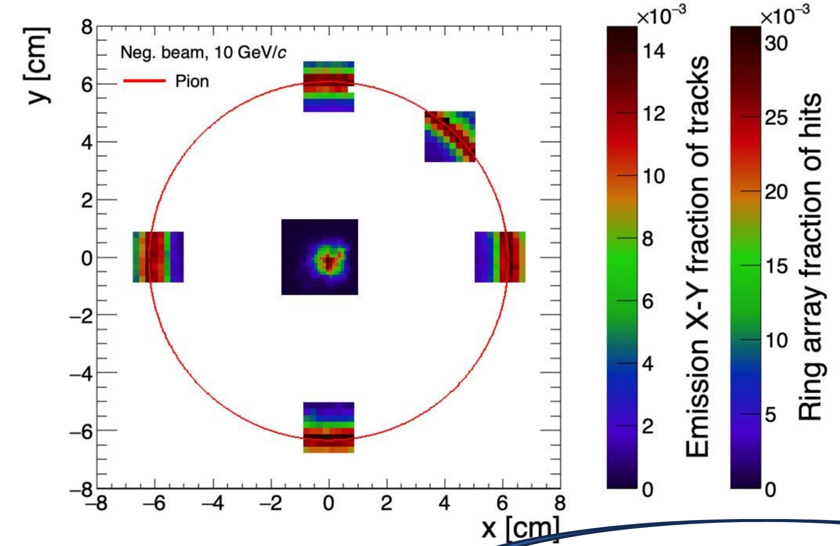


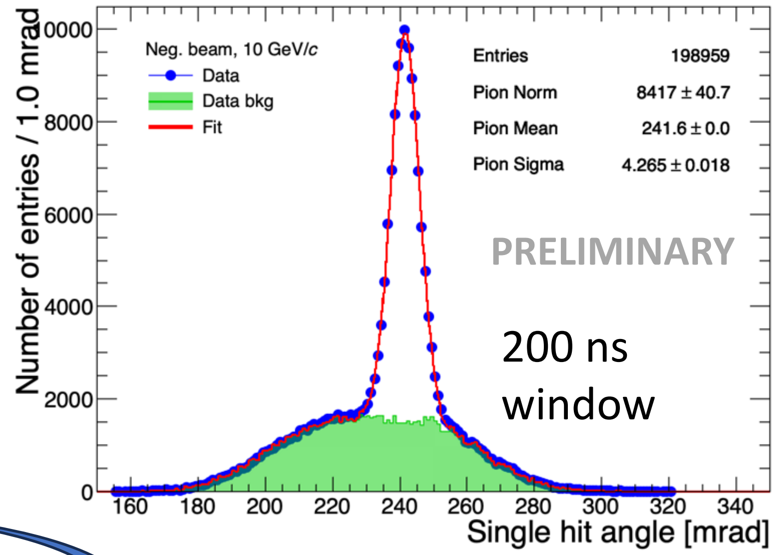


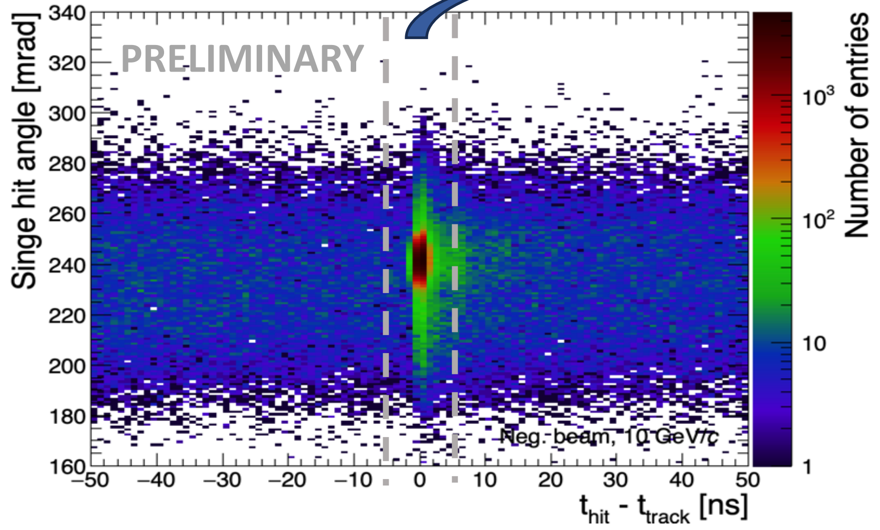
- Including kaons in the fit the pion resolution is recovered
  - The kaon fraction is compatible with the T10 particle beam composition at 8 GeV/c

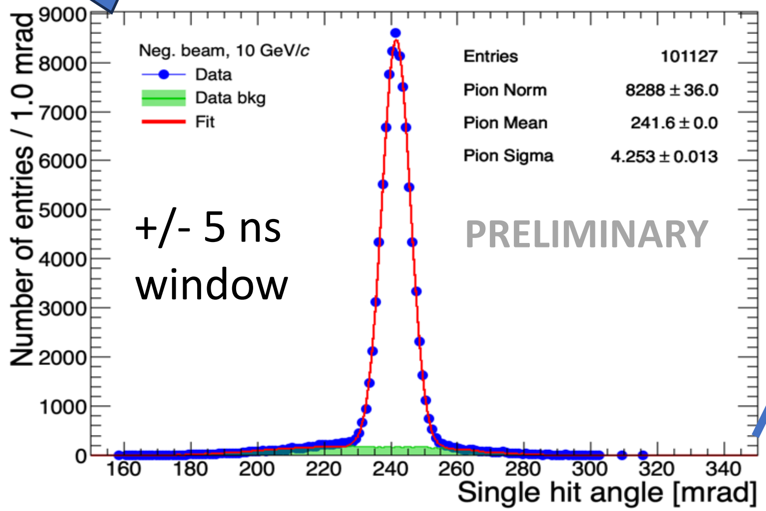
2024: Cherenkov angle and timing effects

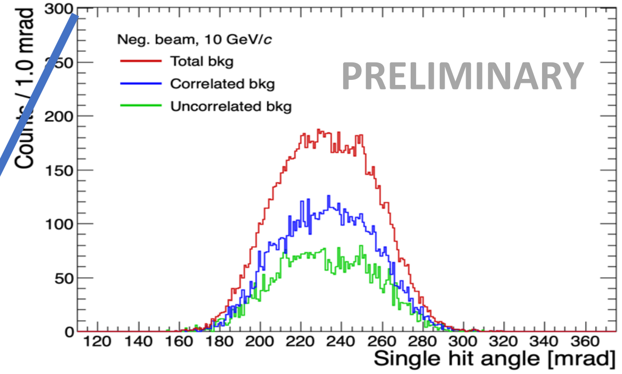
- Angular resolution of about 4.3 mrad as expected with 2x2 mm^2 pixel size



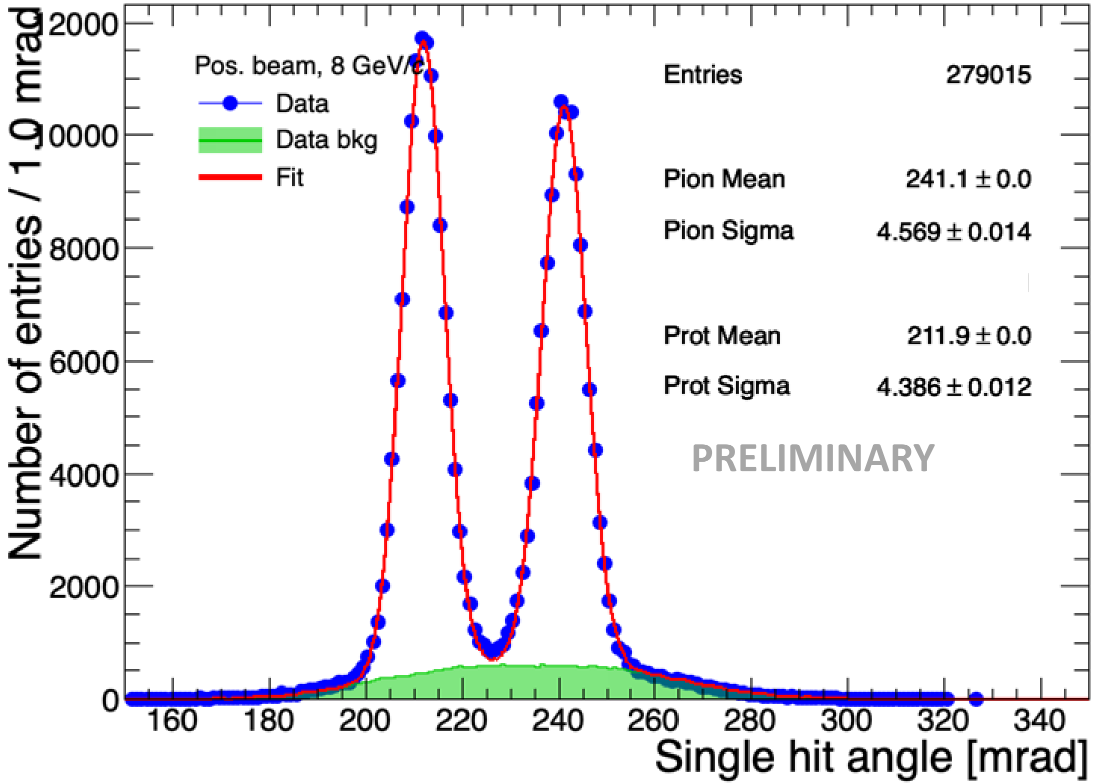


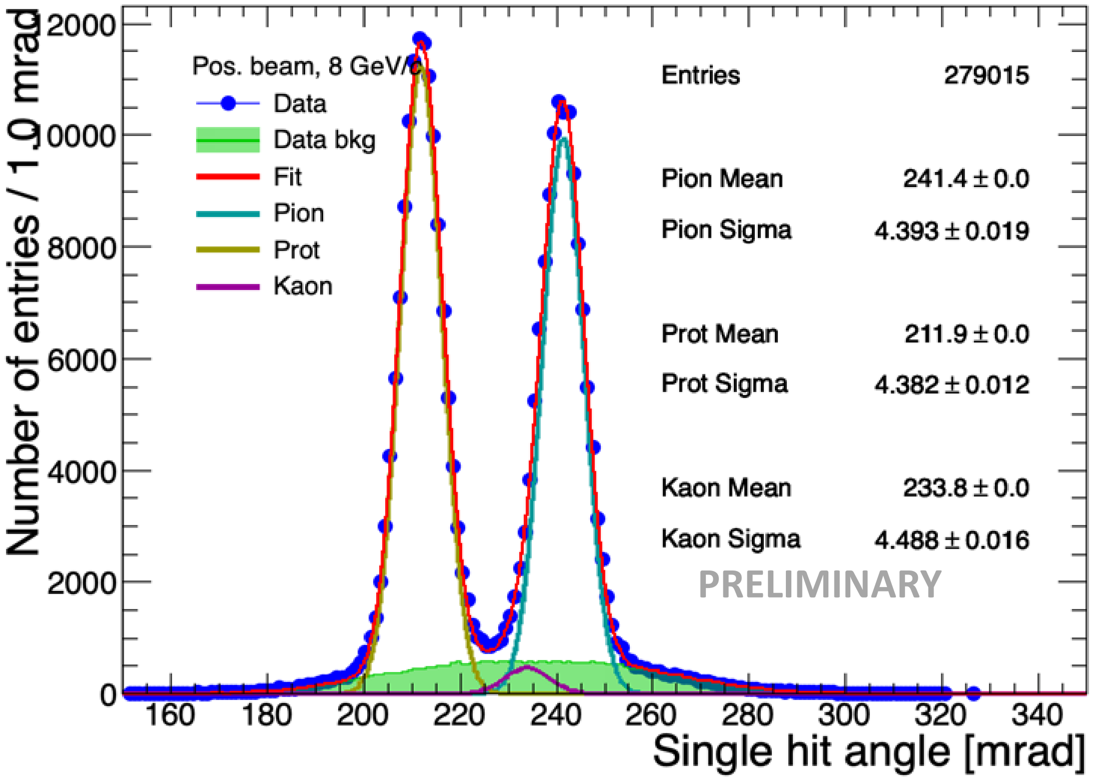






2024 - Angular resolution 8 GeV/c positive pions+protons





- Including kaons in the fit the pion resolution is recovered
  - The kaon fraction is compatible with the T10 particle beam composition at 8 GeV/c

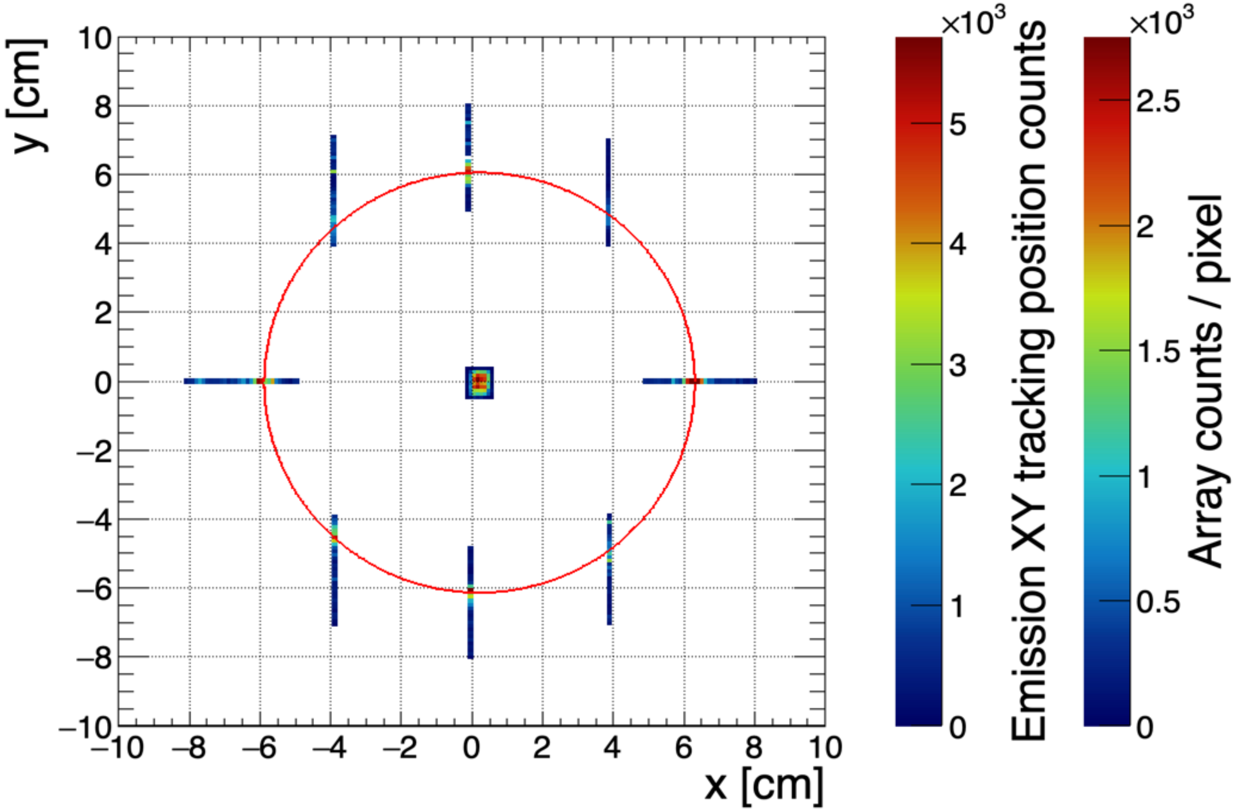
Conclusion and Outlook

- Pion and proton Cherenkov single photon angle resolution of about 4-5 mrad in 8 - 10 GeV/c beam momenta
  - 2 cm aerogel with n=1.03 and a proximity gap of about 23 cm
  - SiPM pixel pitch of 2 mm
  - Background suppression achieved using timing information
- The overall (electronic + SiPM) single pixel timing resolution of about 50 ps (sigma) / $\sqrt{2}$ or better with 1 mm of quartz radiator
- Towards ALICE 3 RICH
  - Compact SiPM + electronic layout, i.e. vertical integration with cooling (interposer)
  - Dedicated rad-hard SiPM and CMOS SPAD sensors
  - Dedicated front-end ASICs
    - Currently we are investigating to use the ALCOR chip developed by INFN Torino
  - Read-out based on the LpGBT ASIC and VTRX+ optical links
    - No local FPGAs due to the high radiation environment

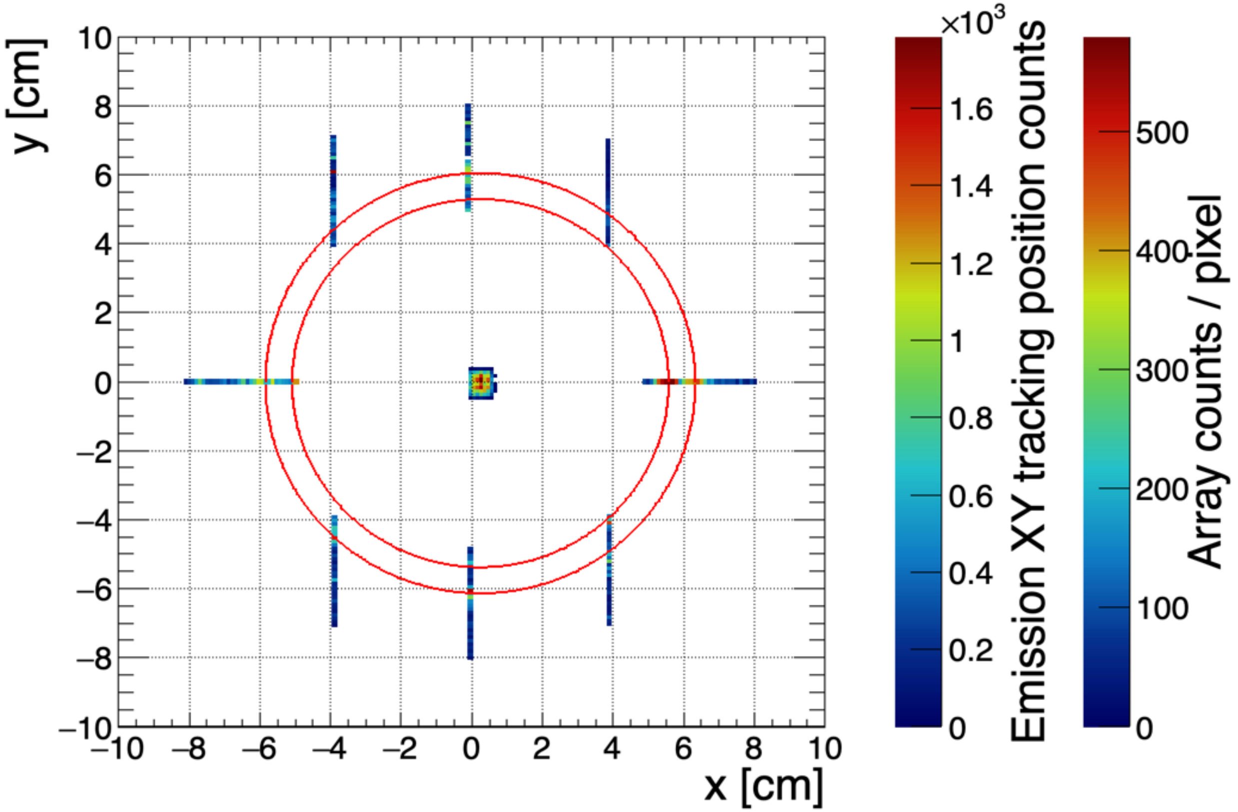
BACKUP

2023 Hit maps

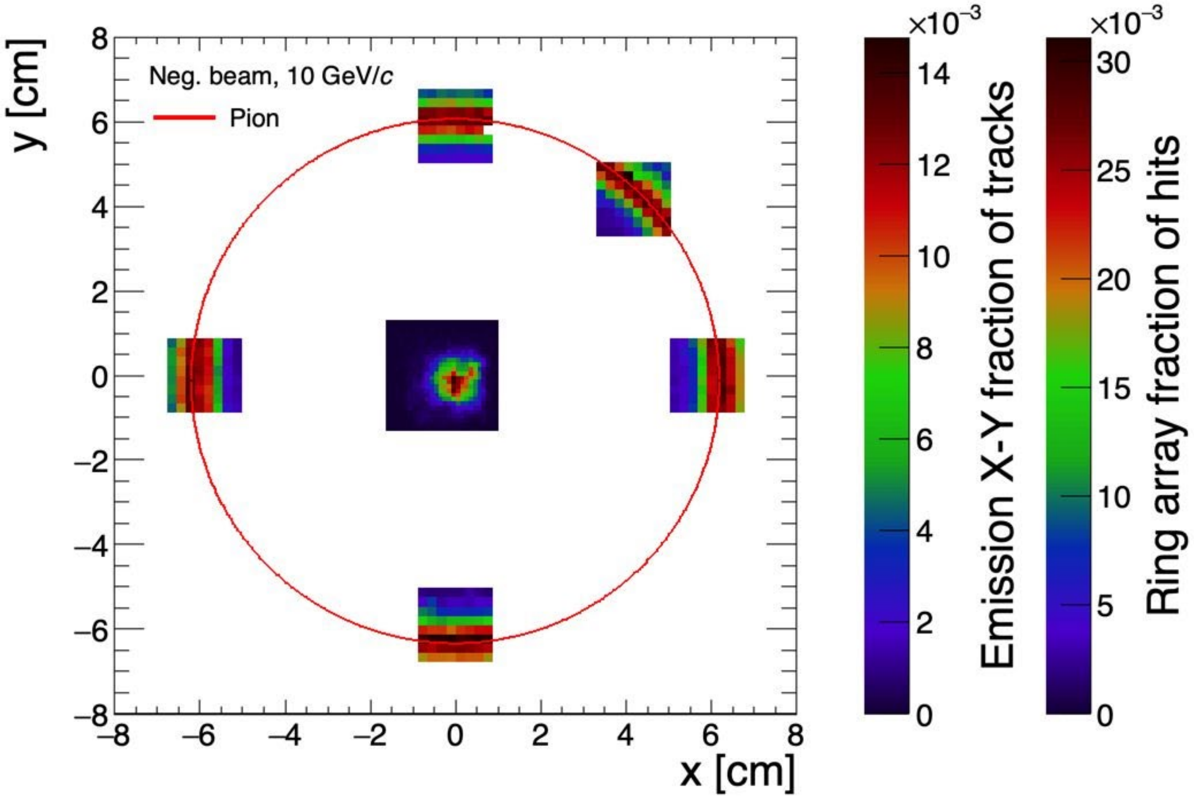
-10 GeV/c beam

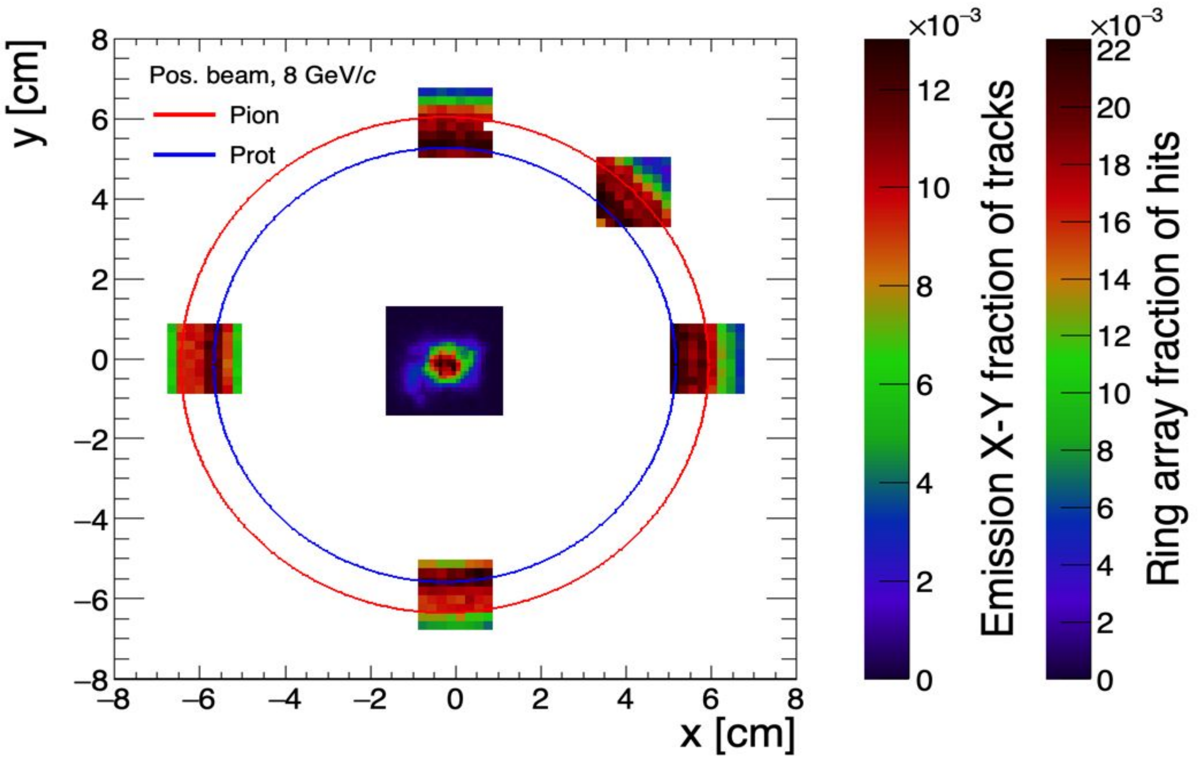


+8 GeV/c beam



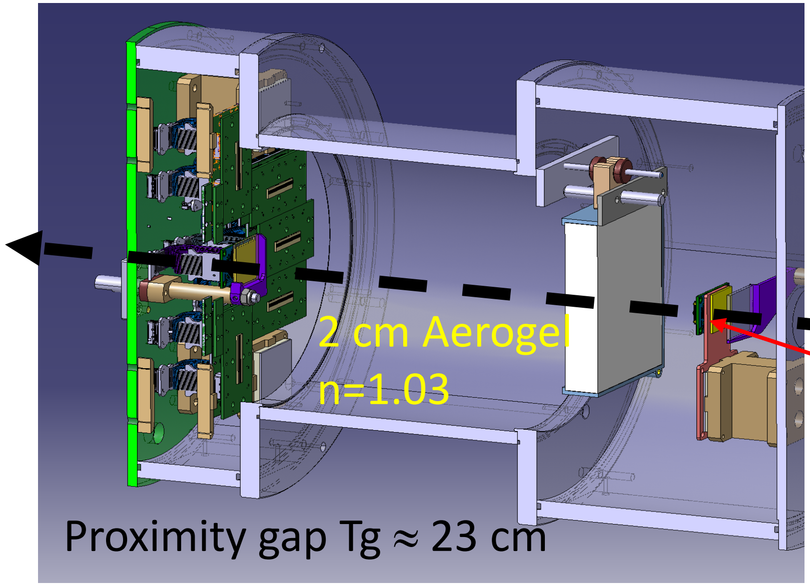
2024 BT Hits map



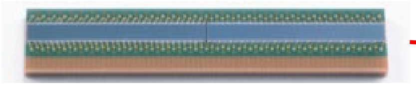


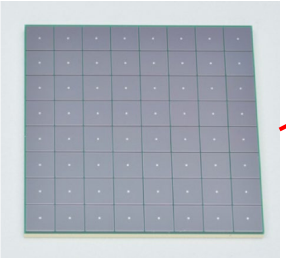
2023 - RICH set-up (3)

Copper plate removed

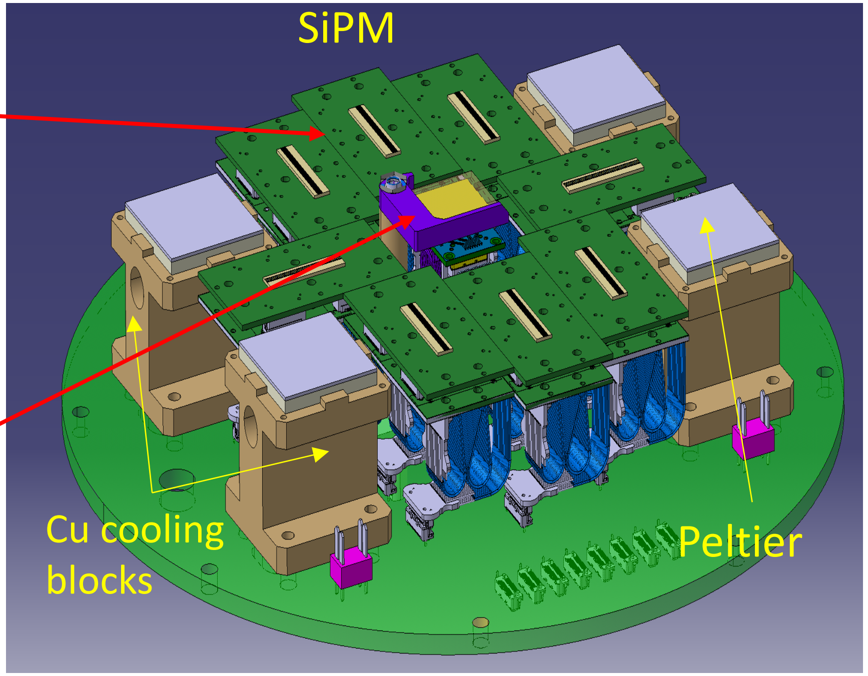


Beam





Copper plate removed

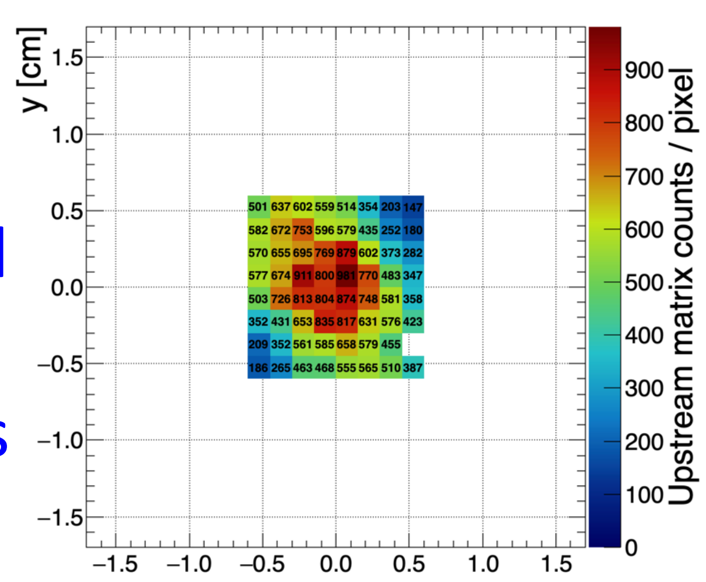


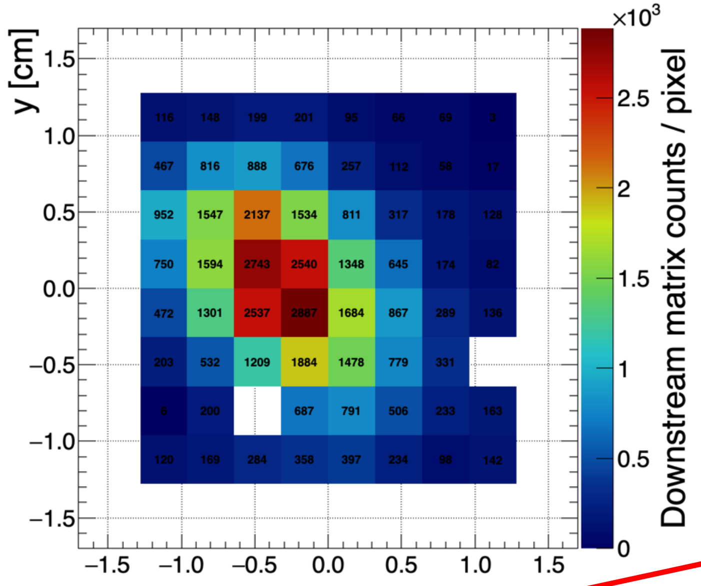
- Upstream 8x8 SiPM matrix (M0)
  - S13361-1350 1.3x1.3 mm^2 pixel with 2 mm of SiO2 and 100 um of Epoxy resin
    - The radiator was glued at CERN
  - S13361-3075 3x3 mm^2 pixel with 1 mm of SiO2
    - The radiator was glued by HPK
  - S13361-3075 3x3 mm^2 pixel with 1 mm of MgF2
    - The radiator was glued by HPK
  - S13361-3075 3x3 mm^2 pixel with 100 um Epoxy resin

- Downstream S13361-3075 8x8 SiPM matrix 3x3 mm^2 pixel (M1)
  - The radiator was glued by HPK
- Eight SiPM arrays for rings, HPK S13552: 128 strip with 250 μm of pith (active area of 0.23x1.625 mm^2)
  - 32 read-out channels 4 ORed strips with 1 mm of pitch

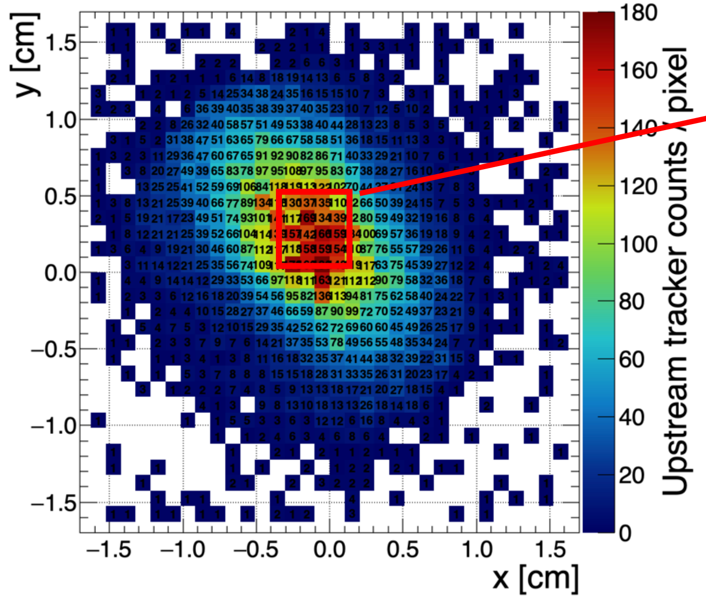
2023 - Beam spot on matrices and trackers

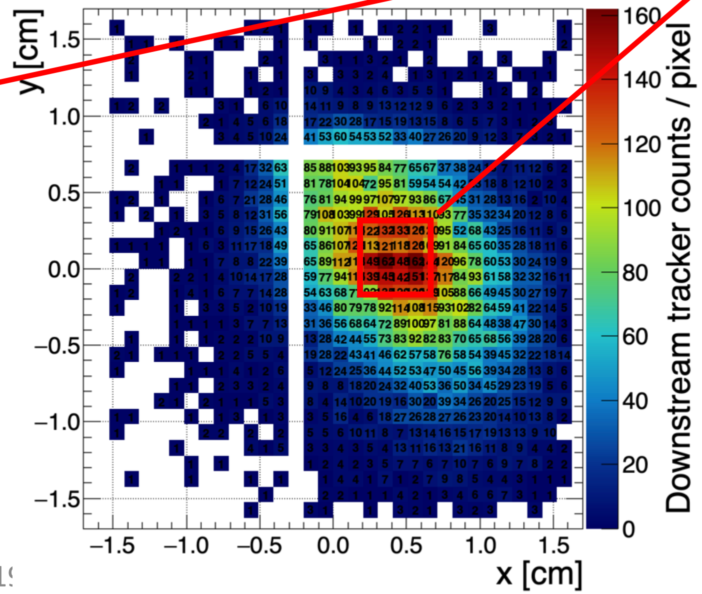
Upstream and downstream SiPM matrices





Upstream and downstream X-Y Fiber trackers





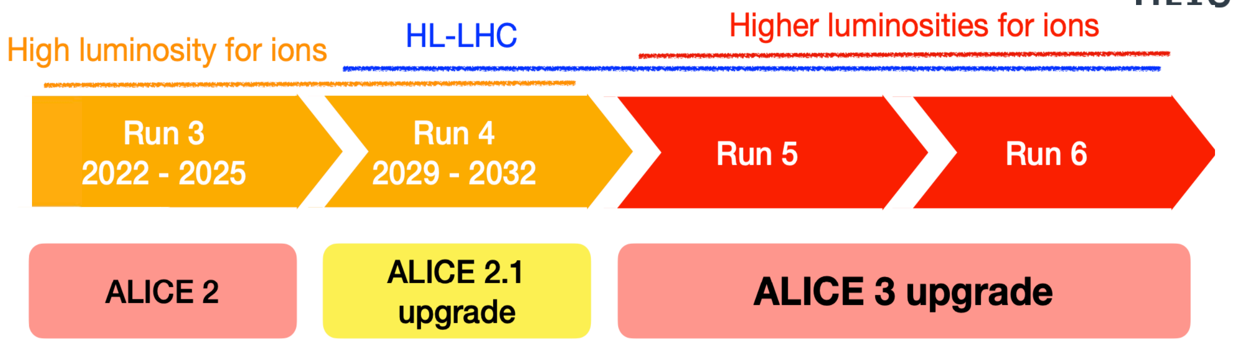
Tracker fiducial area for particle signal in both matrices

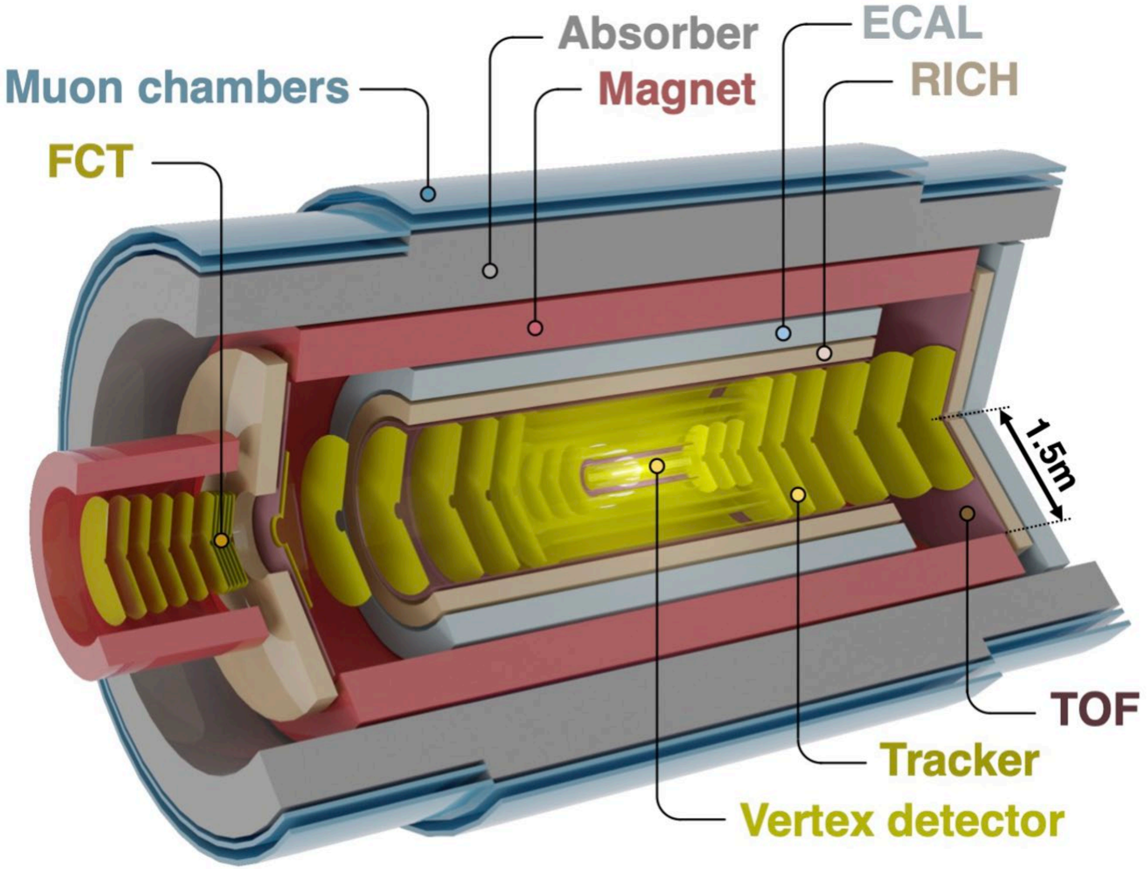
The ALICE 3 upgrade

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



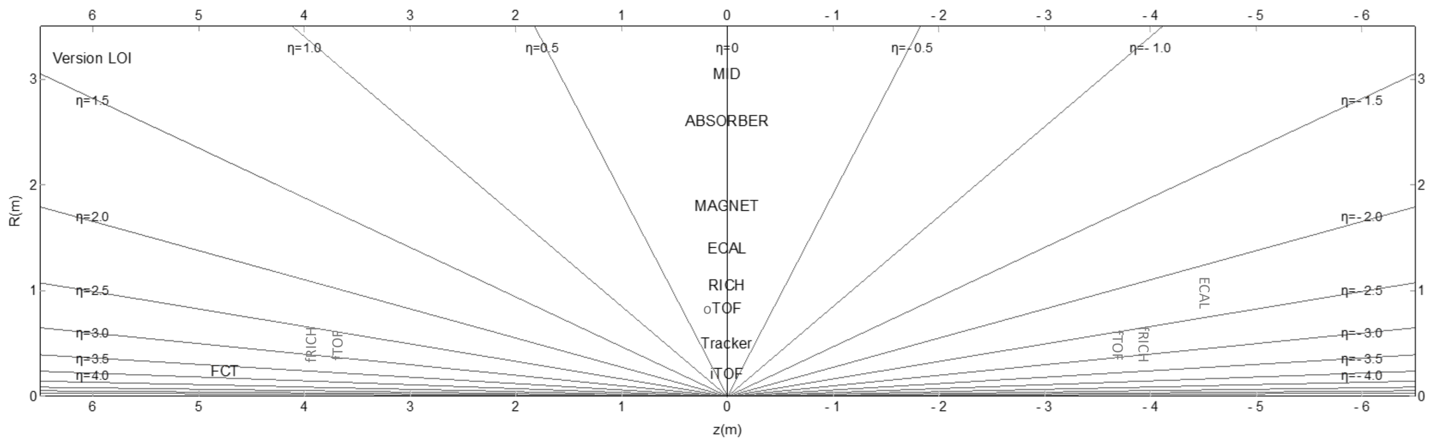


ALICE 3 barrel RICH motivation

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

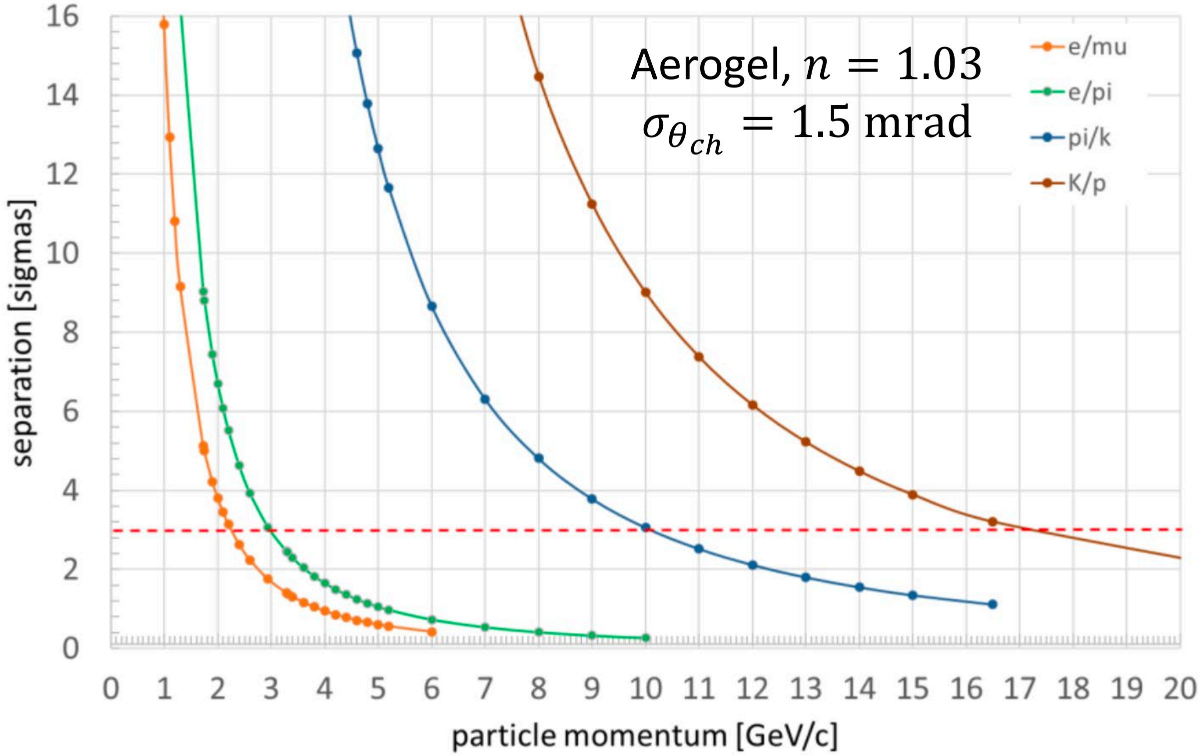
Let's focus on the bRICH



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

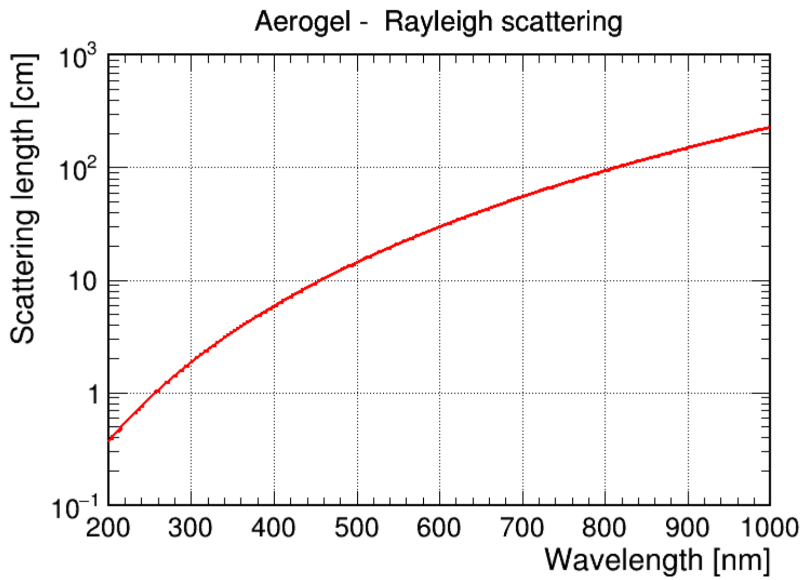
→ Achieved using aerogel radiator with $n \approx 1.03$
+ requiring angular resolution $\sigma_{\theta_{ch}} \approx 1.5$ mrad



bRICH technology

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

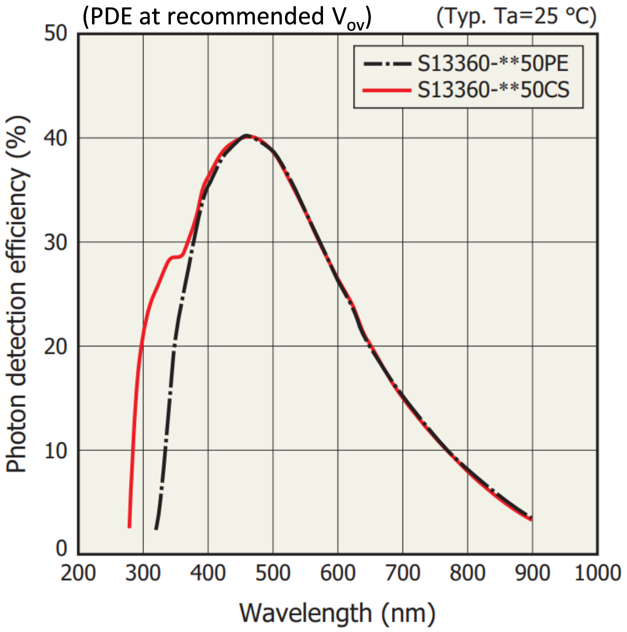
- Lattice of SiO_2 grains filled with trapped air
- Tunable index in the range 1.006-1.250
- Transmittance dominated by Rayleigh scattering
  - Transparent in the visible, opaque in the UV

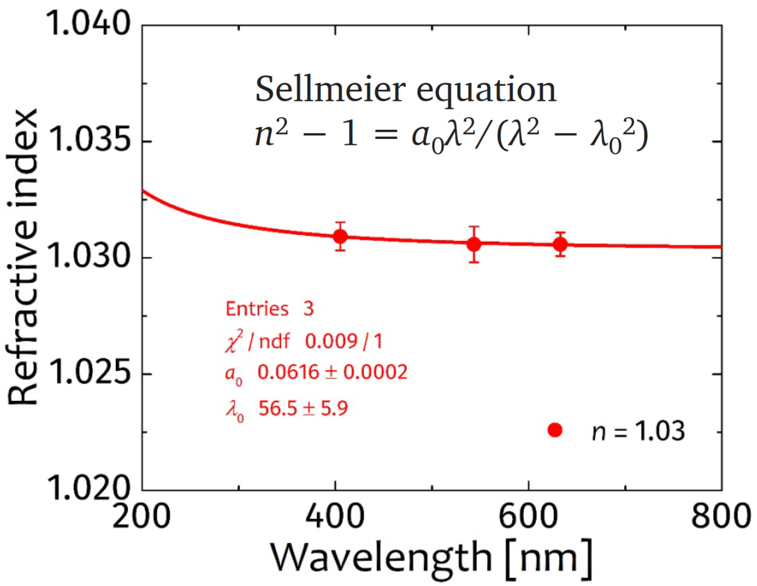


SiPM-based photodetector

- Sensors must be sensitive to visible light
- Operation in magnetic field
- Granularity from 3x3 to 1x1 mm^2
- 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





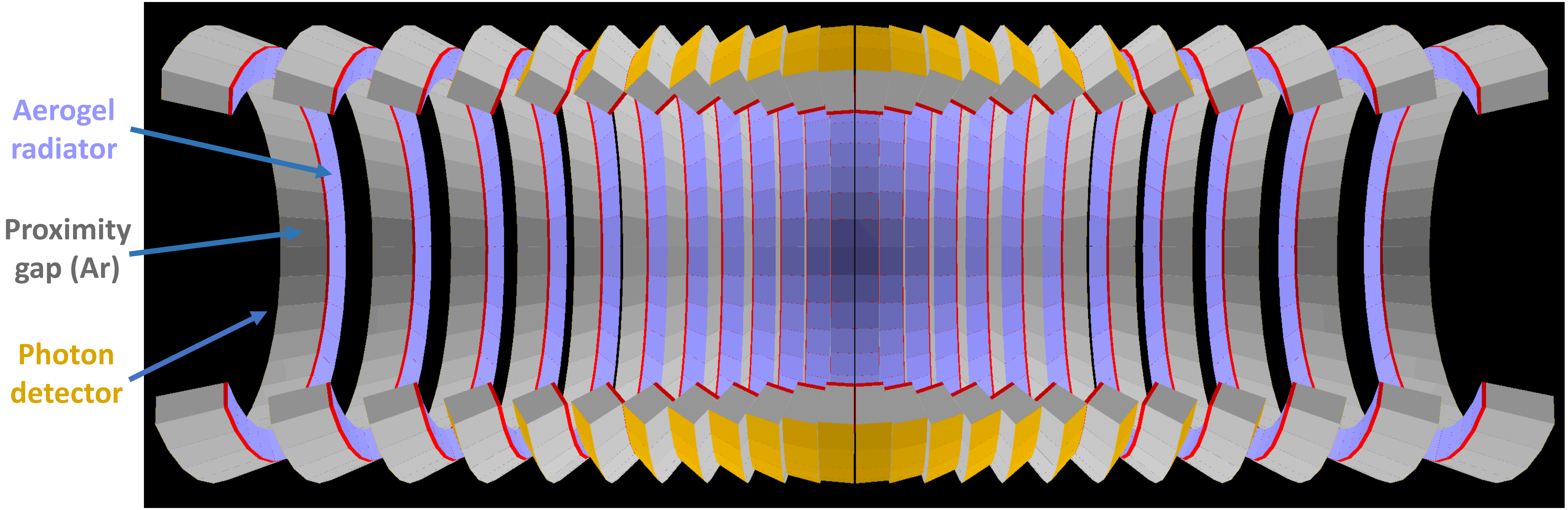
Projective bRICH layout

Assumptions

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

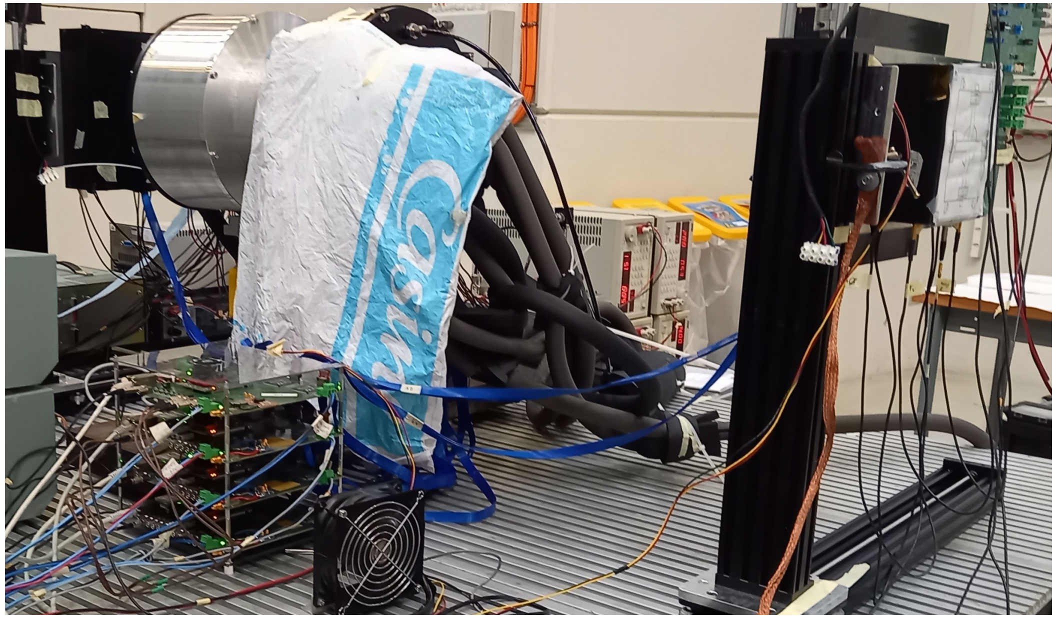
Implementation

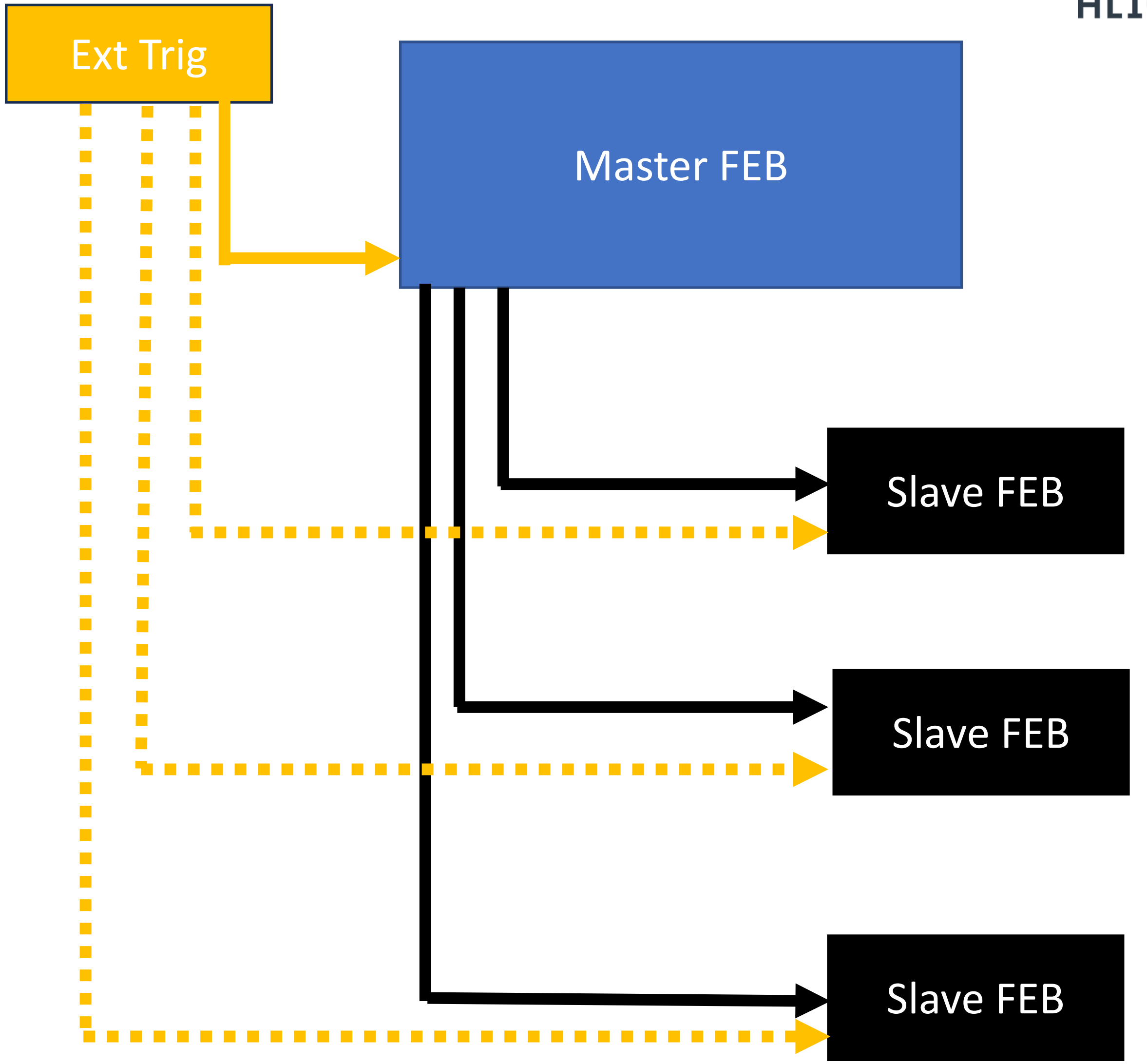
- 24 sectors in z
- 36 modules in rϕ for each sector
- Photosensitive surface: ≈ 30 m^2



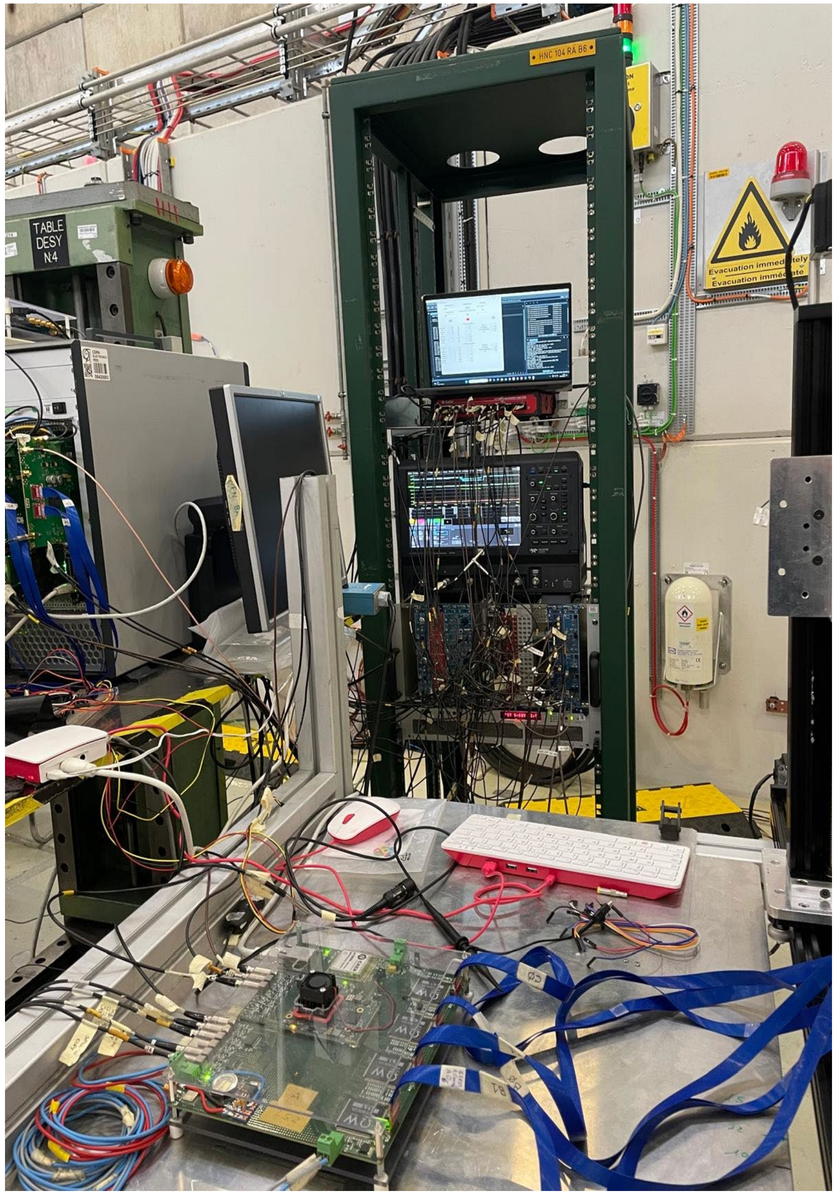
2023 - FEB configuration and synchronization

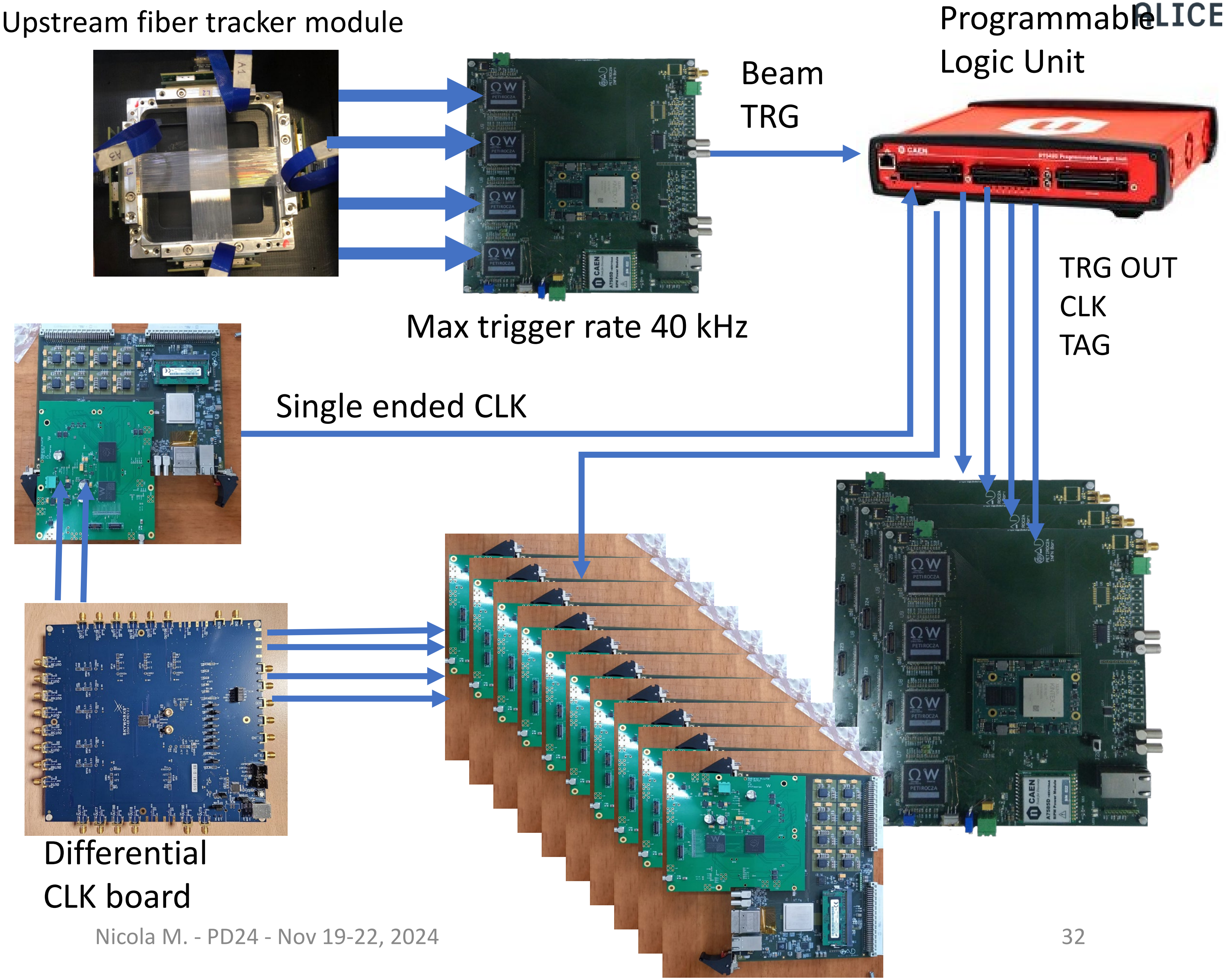
- The FEB can work in different mode
  - Alone
  - Master
  - Slave
- In the master and slave configuration the master provides a common 40 MHz clock, trigger signal and event id to slaves



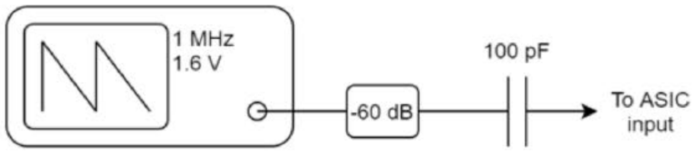


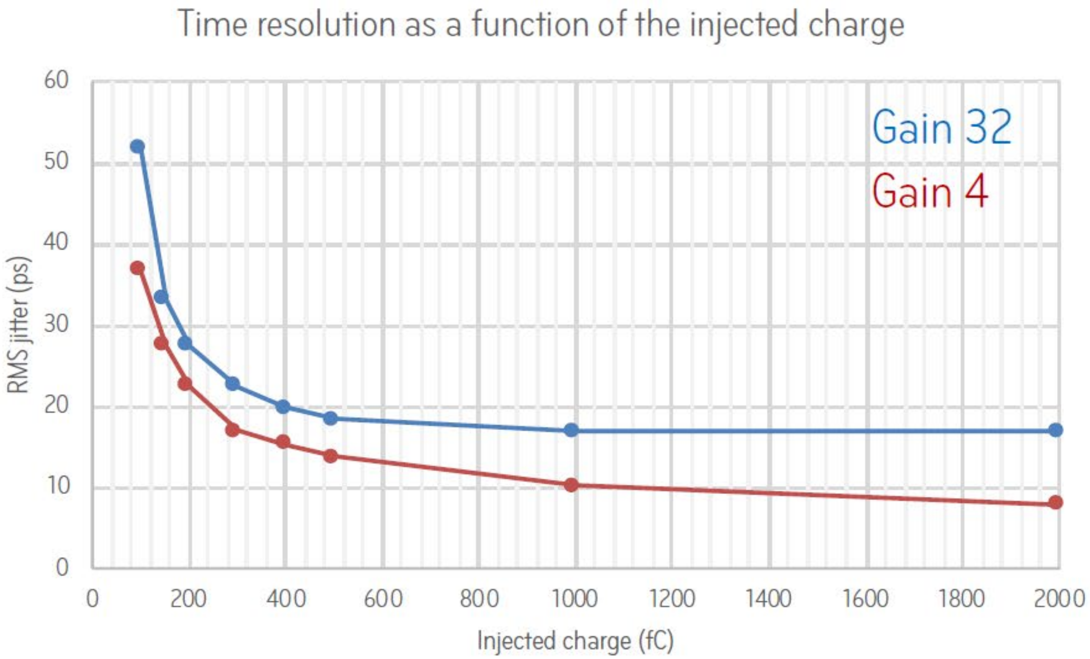
2024 - Trigger and DAQ system

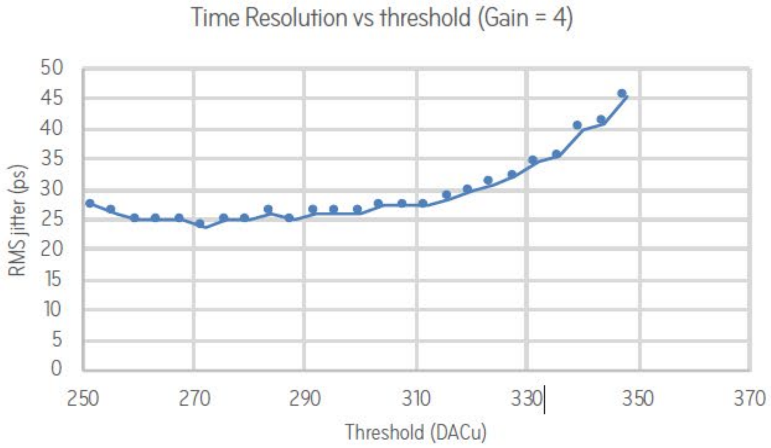


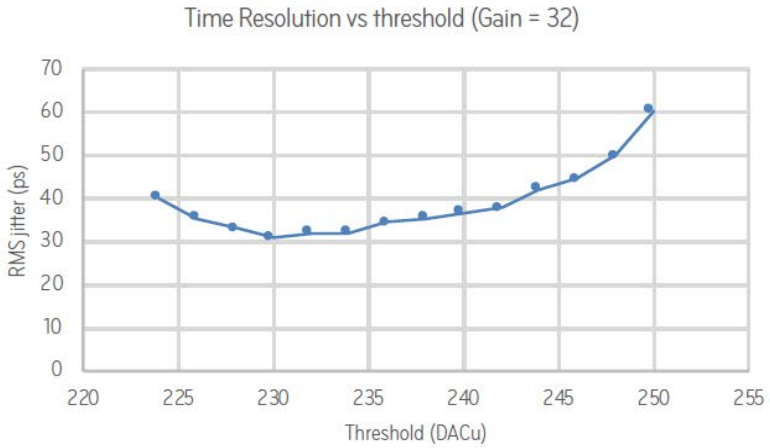


Time resolution









1 DACu = 250 µV

22

https://indico.cern.ch/event/1307202/contributions/5498756/attachments/2821938/4928175/Weeroc%2520-%2520PM4%2520-AIDAINNOVA%2520-%252018-03-24.pdf