INFN BARI
Istituto Nazionale di Fisica Nucleare
Sezione di Bari

Efficient and precise Cherenkov-based charged particle timing using SiPMs

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Intro/Outline

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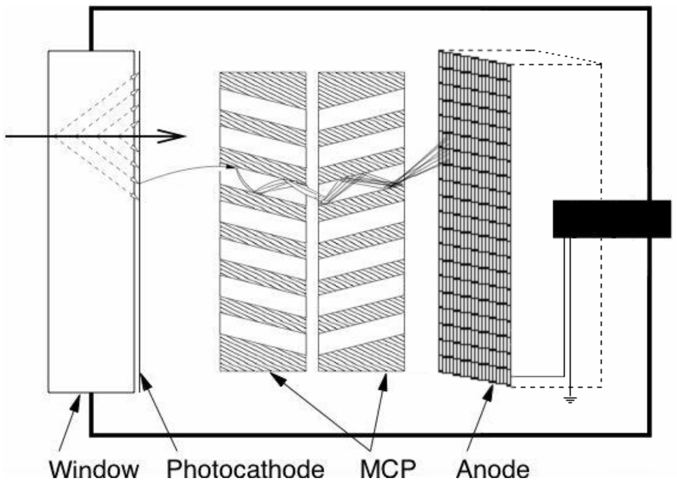
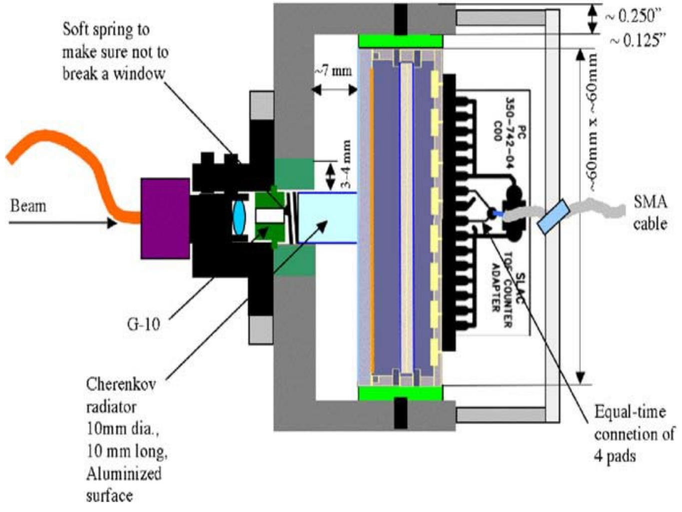
- Cherenkov prompt radiation emission is currently exploited for charged particle Time-of-flight (TOF) measurements
- Cherenkov photons emitted by charged particles in PMT thin windows provide fast signals, that can be used for triggering purpose
  - The photodetector can also be used for direct charged particle detection
  - In case of pixelated sensors (i.e. SiPM) it also provides position information
- The results achieved with a SiPM-based system in beam test campaigns will be reported
- The perspectives of a TOF (and a combined TOF + RICH layout) and its optimization are discussed



T. Credo et al. *IEEE Symp. Conf. Rec. Nuc. Sci. 2004*

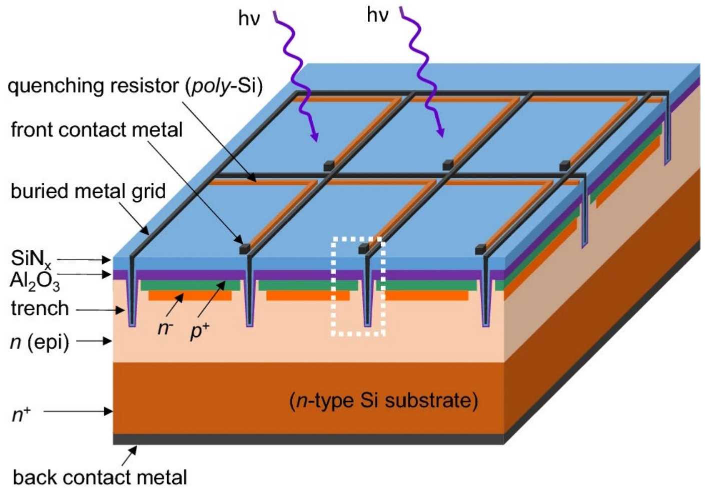


J. Va'vra et al. NIMA 606 (2009) 404

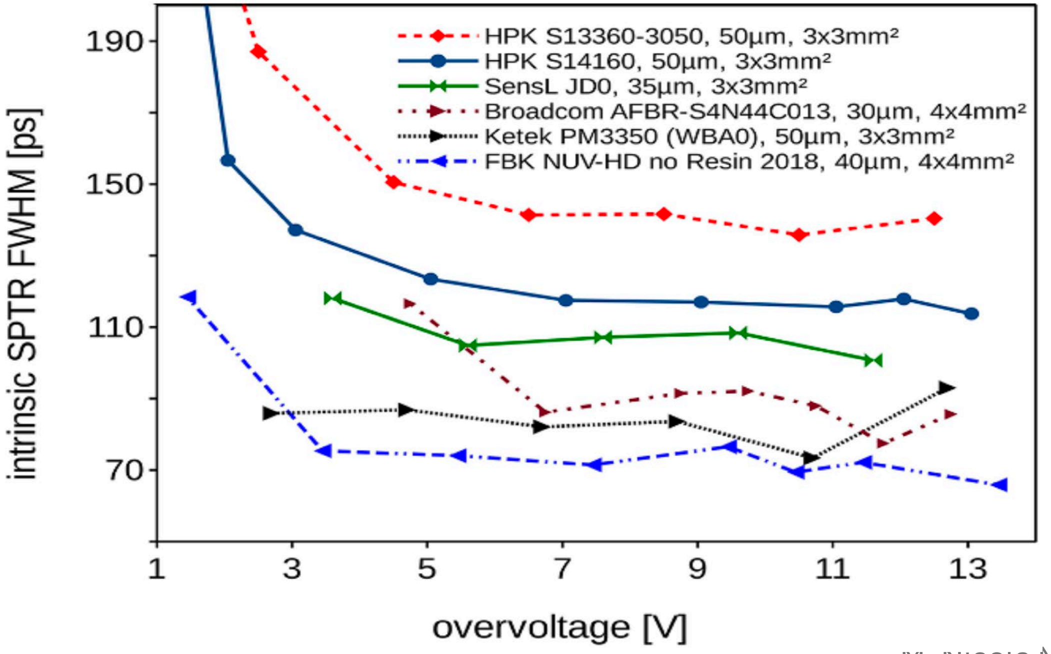
* See also Yuri Melikyan's talk Long-term performance of non-ALD MCP-PMTs in the high-radiation environment of ALICE

SiPMs as photodetector

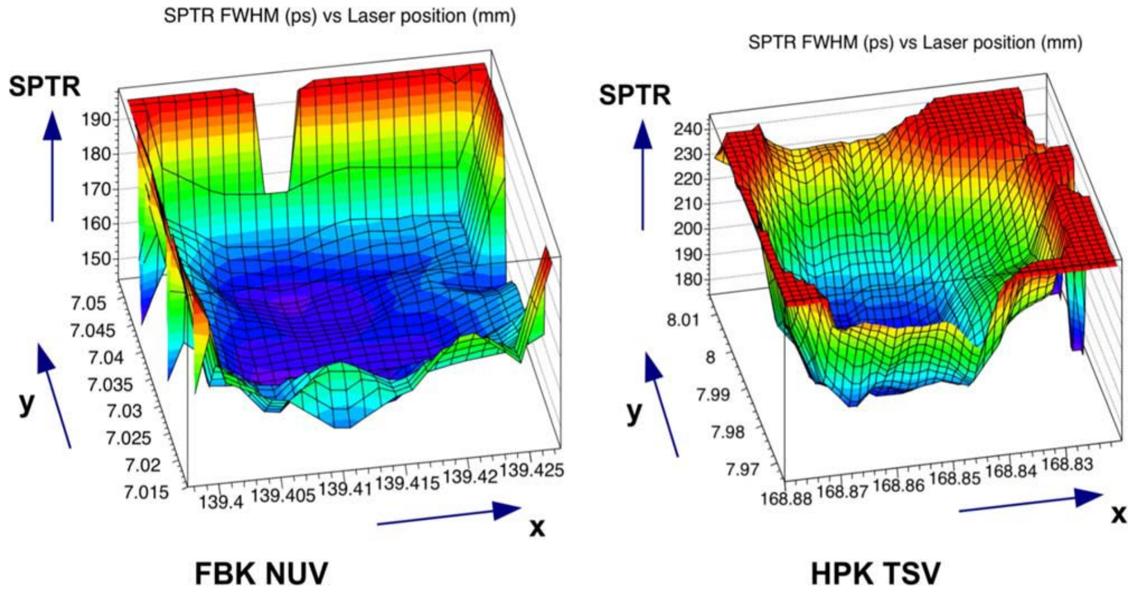
- SiPMs are fast photon detectors
  - Multi-pixel photon counter (MPPC) where each pixel (microcell) is an avalanche photodiode (APD) connected in parallel
- Single photon time resolution (SPTR) < 100 ps RMS for commercial SiPMs
  - Improves with increasing bias voltage
  - Worse resolution measured at the micro-cell edges
    - SPTR is improved by masking microcell edges or by suing microlens



Y. Tao et al. *Sci Rep* **12**, 13906 (2022)



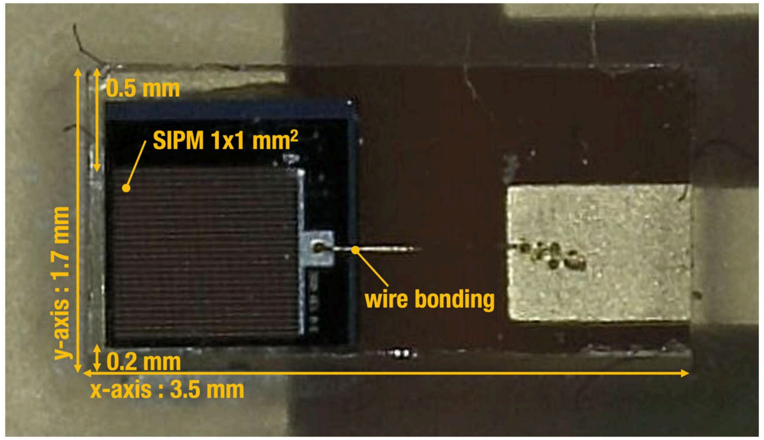
S. Enoch *et al* 2021 *JINST* **16** P02019



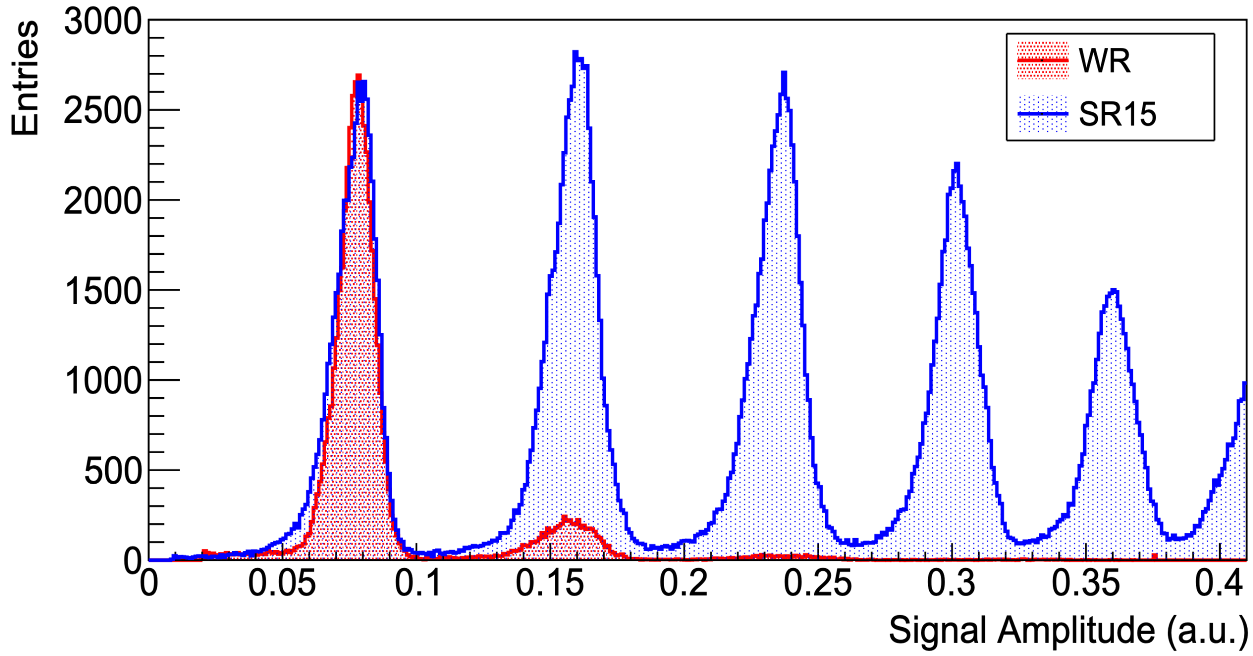
F. Acerbi and S. Gundacker NIMA 926 (2019) 16

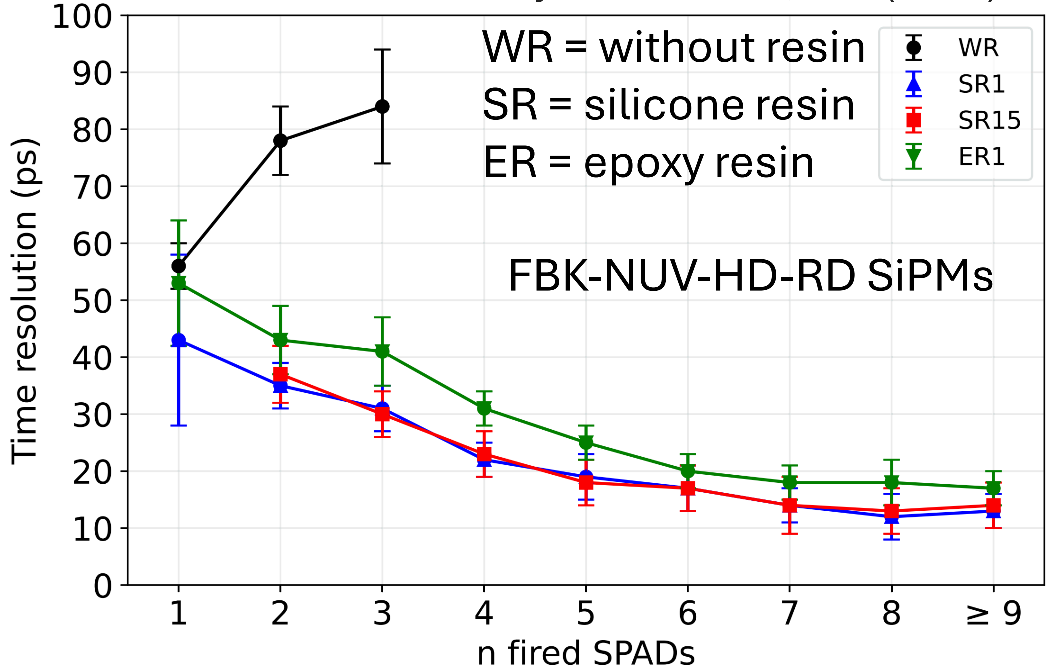
SiPMs as charged-particle detectors

- Cherenkov photons from materials coupled with SiPM can be efficiently detected as many-P.E. signals
  - These photons can also be produced in the $\mathcal{O}(100\mu m)$ thick SiPM protection resin
    - However, a low efficiency is measured



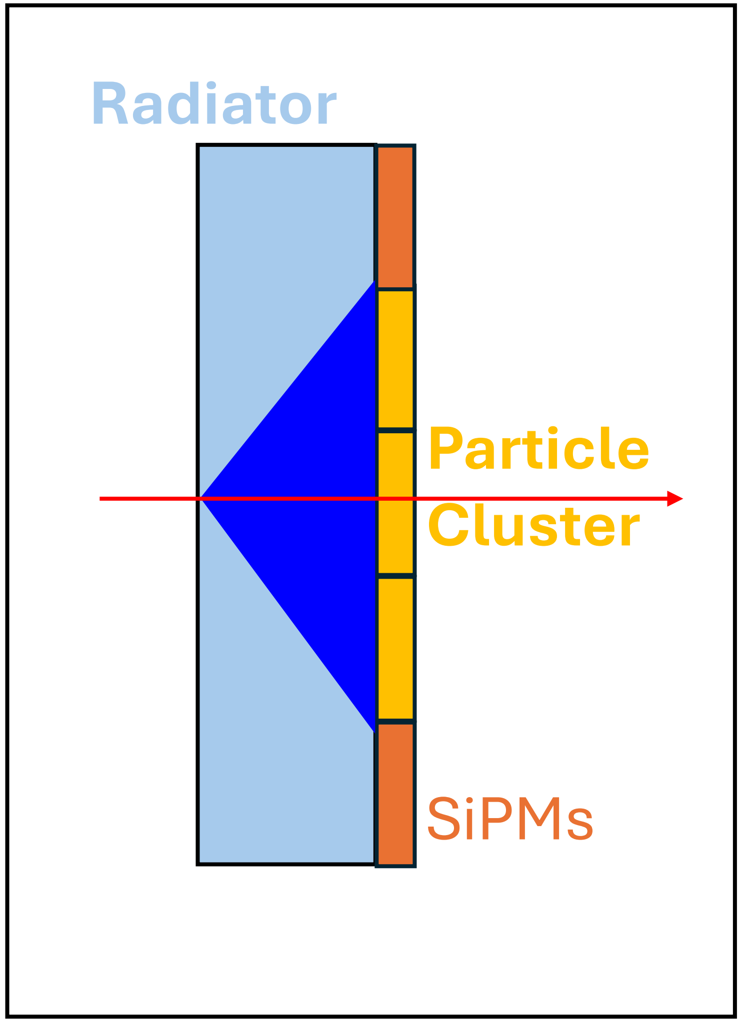
F. Carnesecchi et al. Eur. Phys. J. Plus **138**, 788 (2023)





SiPM-based charged particle timing

- Principle of operation: thin $\mathcal{O}(1mm)$ radiator + SiPM arrays
- Impinging particles above Cherenkov threshold result in a cluster of fired SiPM channels
  - Multi-photoelectron signals
    - Majority of pe collected by pixels hit by the track
    - The cluster size increases with the radiator thickness
  - Track position reconstructed from pixel charge information
  - Detection efficiency close to 100% bypassing dead areas between SiPMs
- Possibility of achieving an intrinsic time resolution of few ps
  - High number of photoelectrons
  - However, charge sharing among multi pixel could affect the time resolution
    - Few photoelectrons in far pixels



Main factors that affect the time resolution

- Spread in the arrival times of Cherenkov photon to SiPM (normal incidence, neglecting absorption, scattering and chromatic dispersion):

$$\Delta t_{max} = \frac{d}{\beta c}(\beta^2 n^2 - 1) \propto d$$

Assuming uniform photon production: $\sigma_t(d) = \frac{\Delta t_{max}}{\sqrt{12}} \propto d$

$d = 1\,mm, n = 1.5, \beta = 1 \Rightarrow \Delta t_{max} \approx 4\,ps\ (\sigma_t \approx 1.2\,ps)$

- Photodetector time resolution (e.g. jitter photo-electron creation, transit time, multiplication)

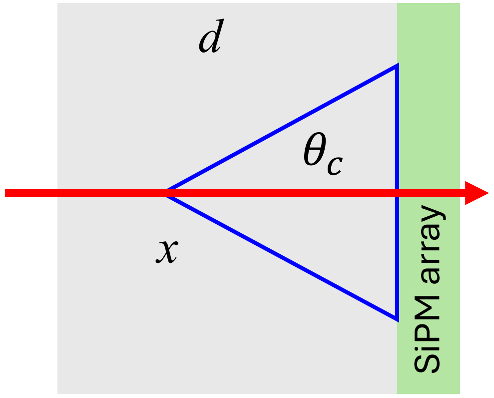
$$\sigma_{pe} = \frac{\sigma_{SPTR}}{\sqrt{N_{pe}}} \oplus const \propto \frac{1}{\sqrt{d}}$$

SPTR < 100 ps

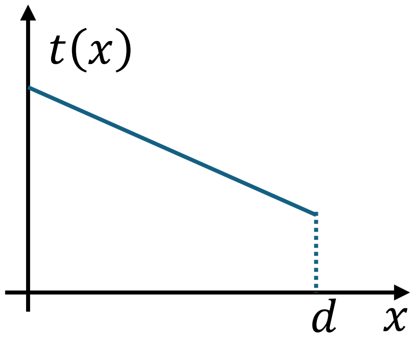
- Electronic time jitter: $\sigma_{ele}^2 = \sigma_{FE}^2 + \sigma_{TDC}^2$

$$\sigma_{FE} \propto \frac{1}{N_{pe}} \oplus const \propto \frac{1}{d}, \sigma_{TDC} = \frac{LSB}{\sqrt{12}}$$

- N_{pe} is the number of photoelectrons detected in each read-out channel

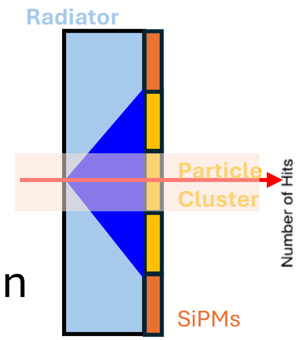


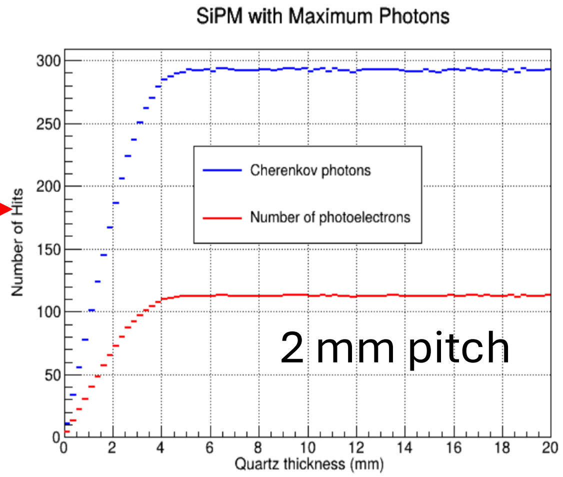
$$t(x) = \frac{x}{\beta c} + \frac{n(d-x)}{c\cos\theta_c}$$

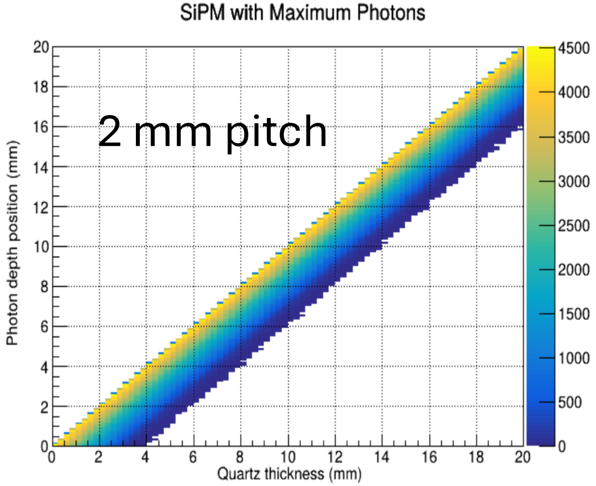


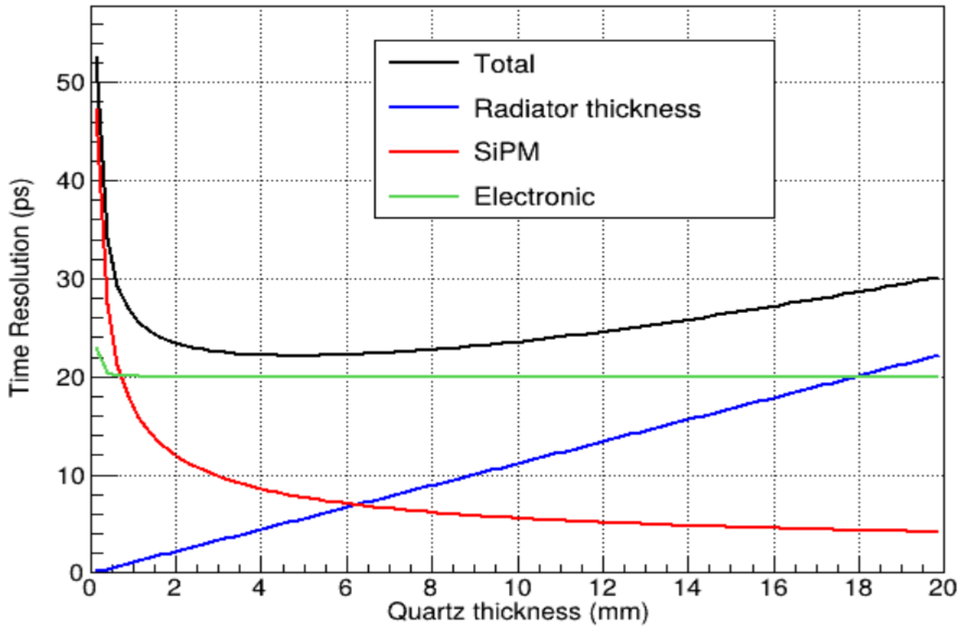
Expected time resolution – a fast MC

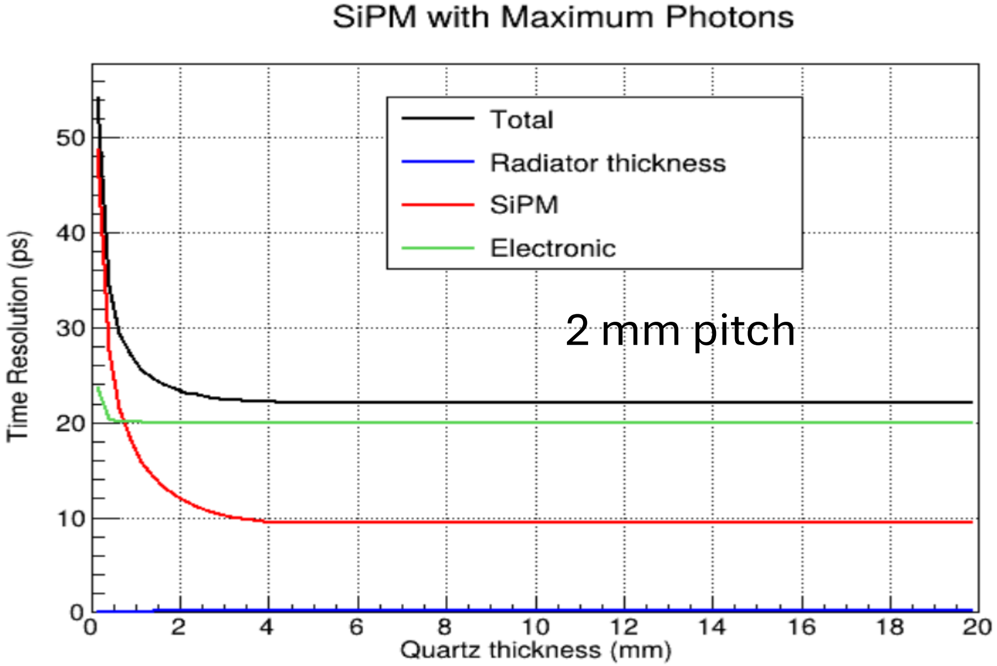
- SiPM model:
  - SPTR of 100 ps
  - Pixel pitch of 2 mm
  - PDE of 40% (cell size of 50 μm)
- Electronic time jitter: $\sigma_{FE} = \frac{50\ ps}{N_{pe}} \oplus 20\ ps$
- Number of Cherenkov photons/mm based on the beam test dat (see next slides)
  - No reflection, absorption, dispersion, etc.







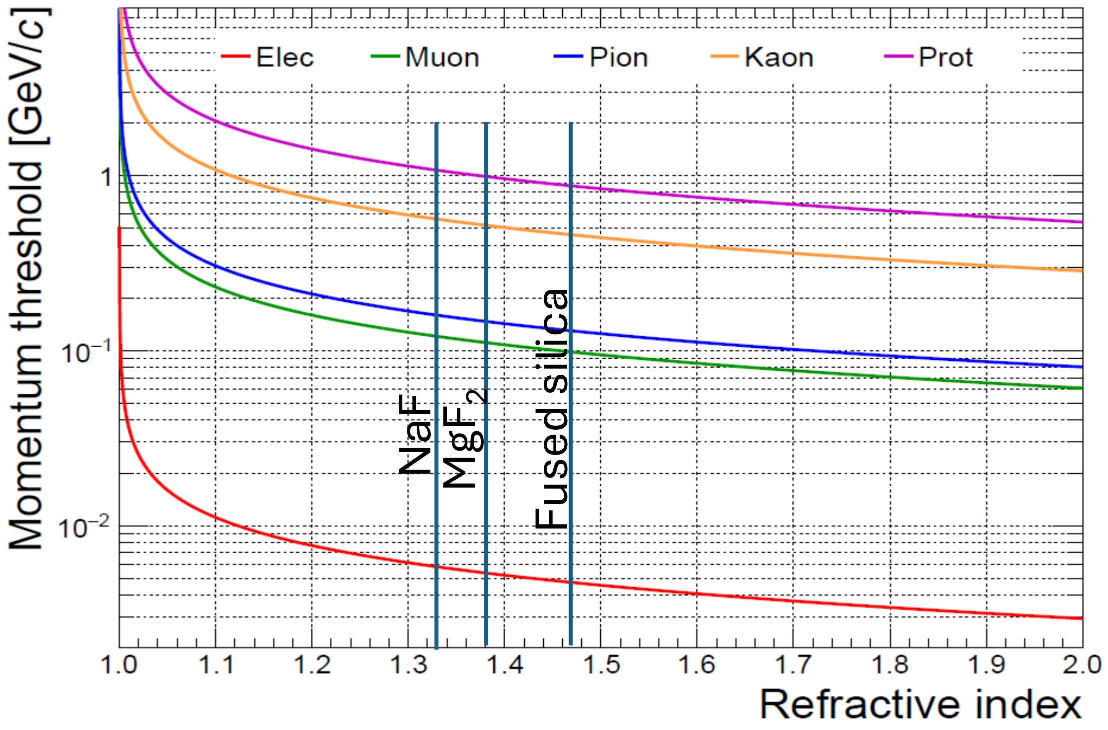




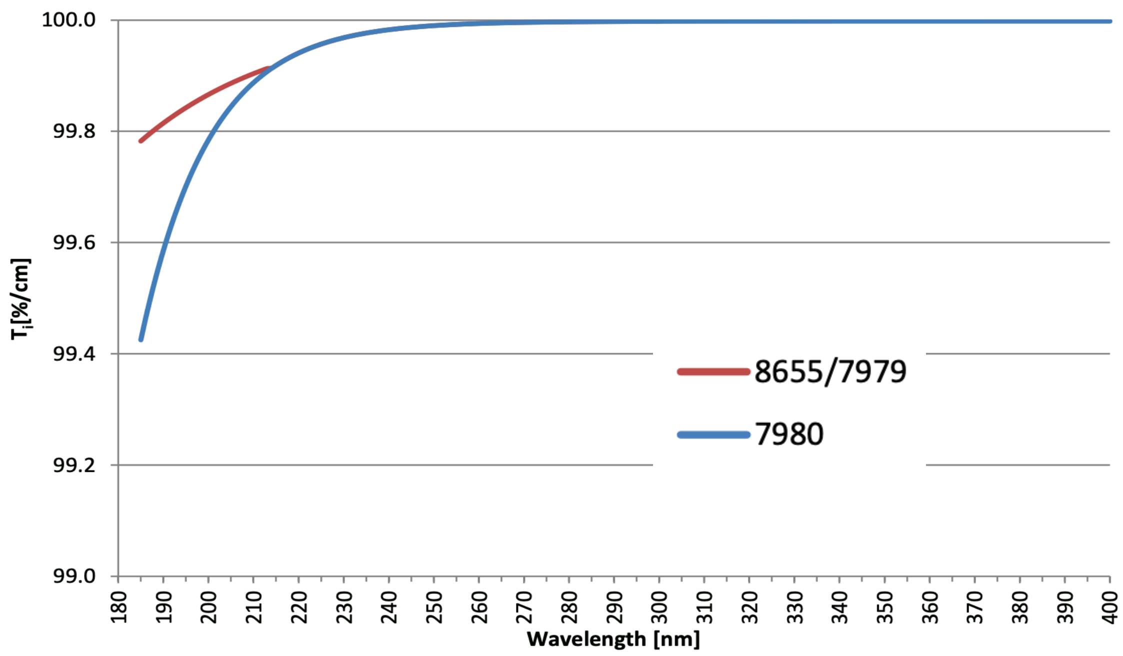
Assuming that all photons are collected by the SiPM (i.e. no pixeleted sensors)

Radiator material

- High-n material for lower Cherenkov thresholds and to enhance photon yield and cluster size
- Good NUV transmittance to fully exploit Cherenkov spectrum ⊕ SiPM PDE
  - Materials as fused silica, NaF or MgF_2 also provide optimal optical coupling



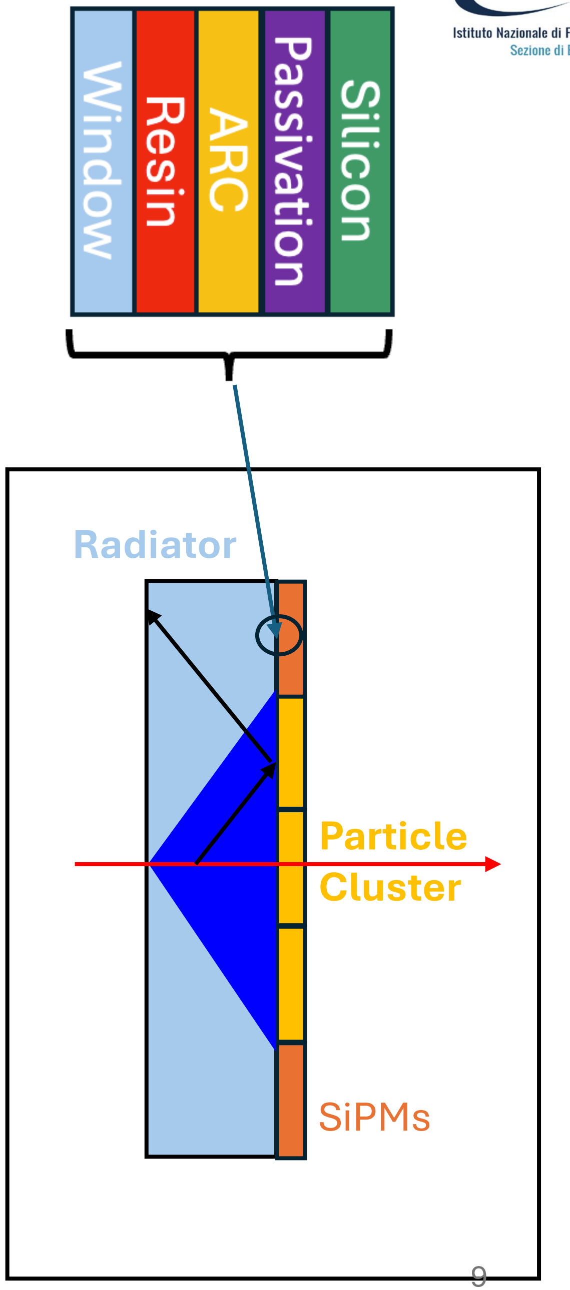
Corning® HPFS® 7979, 7980, 8655 Fused Silica



HPFS_Product_Brochure_All_Grades_2015_07_21.pdf

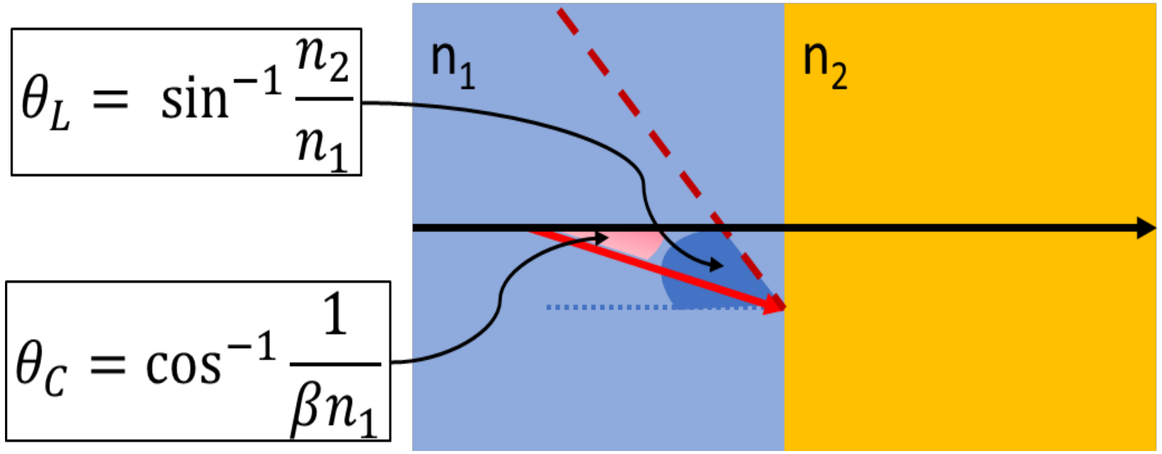
Radiator + SiPM (1)

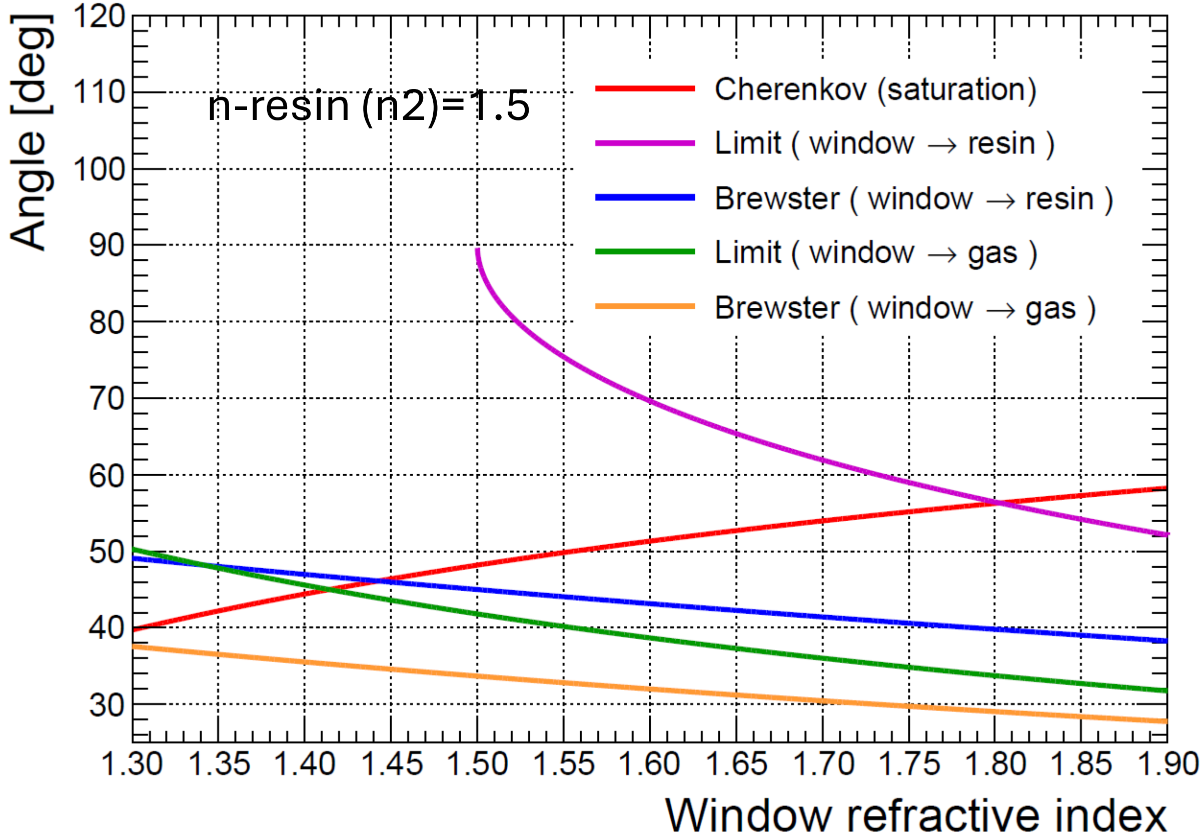
- Needs optimal refractive index for coupling with the SiPM to suppress reflections
  - Many interfaces are present
    - Radiator-SiPM resin, antireflection coating (ARC), passivation layer, silicon, …
- Optical couplings should be optimized
  - To suppress reflections
  - To avoid loss of photons, also due to the Cherenkov polarization effect
  - To avoid signal delays
  - The particle incidence angle should be also taken into account



Radiator + SiPM (2)

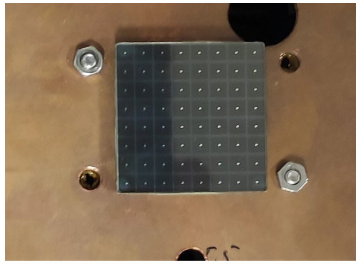
- The Cherenkov angle emission should be compared with the other characteristic angles such as the total internal reflection angle and Brewster's angle
- Typical resin refractive index of 1.4 – 1.6
- Multiple reflections should be accounted for collecting photons in the SiPM

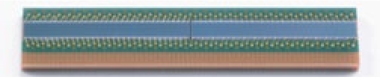


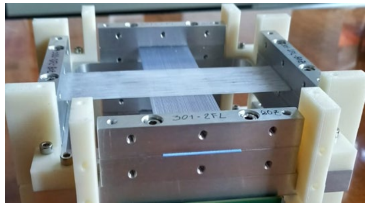


2023 beam test set-up@T10

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



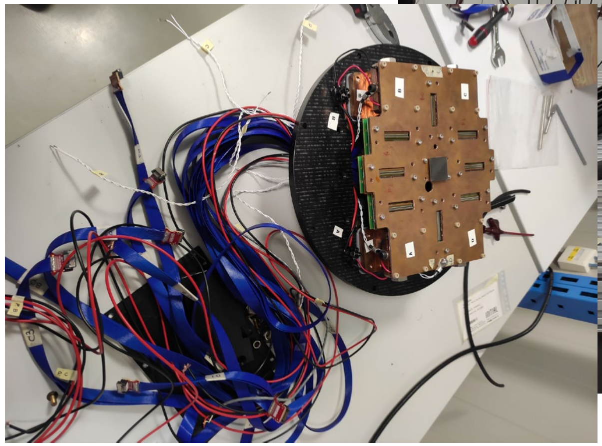


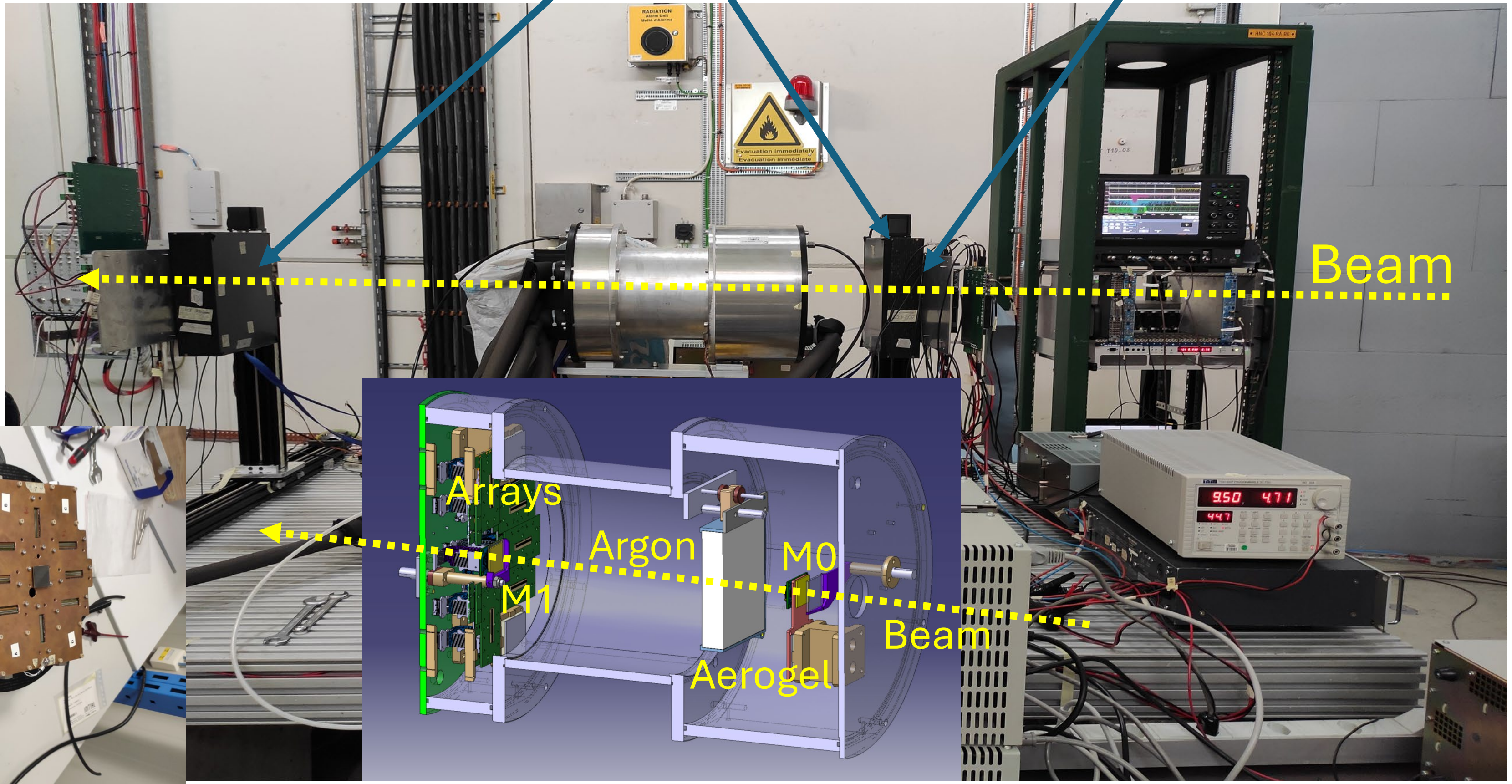


Ring: 8 HPK S13552
128 ch. arrays of
0.23x1.625 mm^2 strips, 32
ch read-out 4- ORed strips

X-Y fiber tracker box

Scintillator trigger box

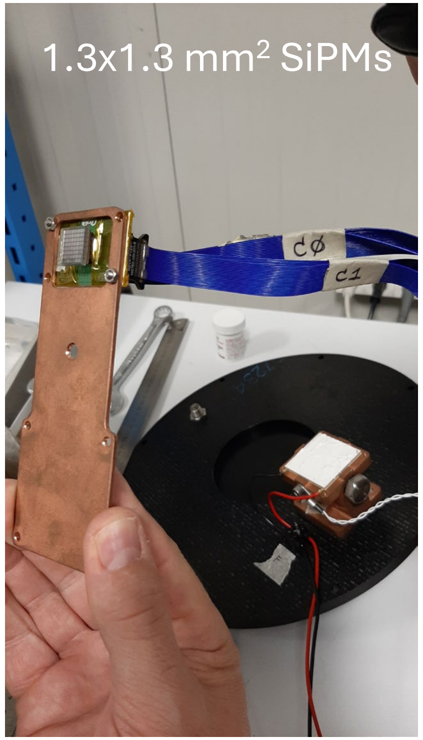




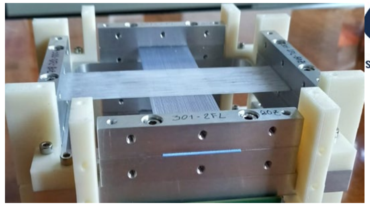
SiPM cooling: Water chiller + 5 Peltier devices: operation temperature in [-5°,0°]

M0:

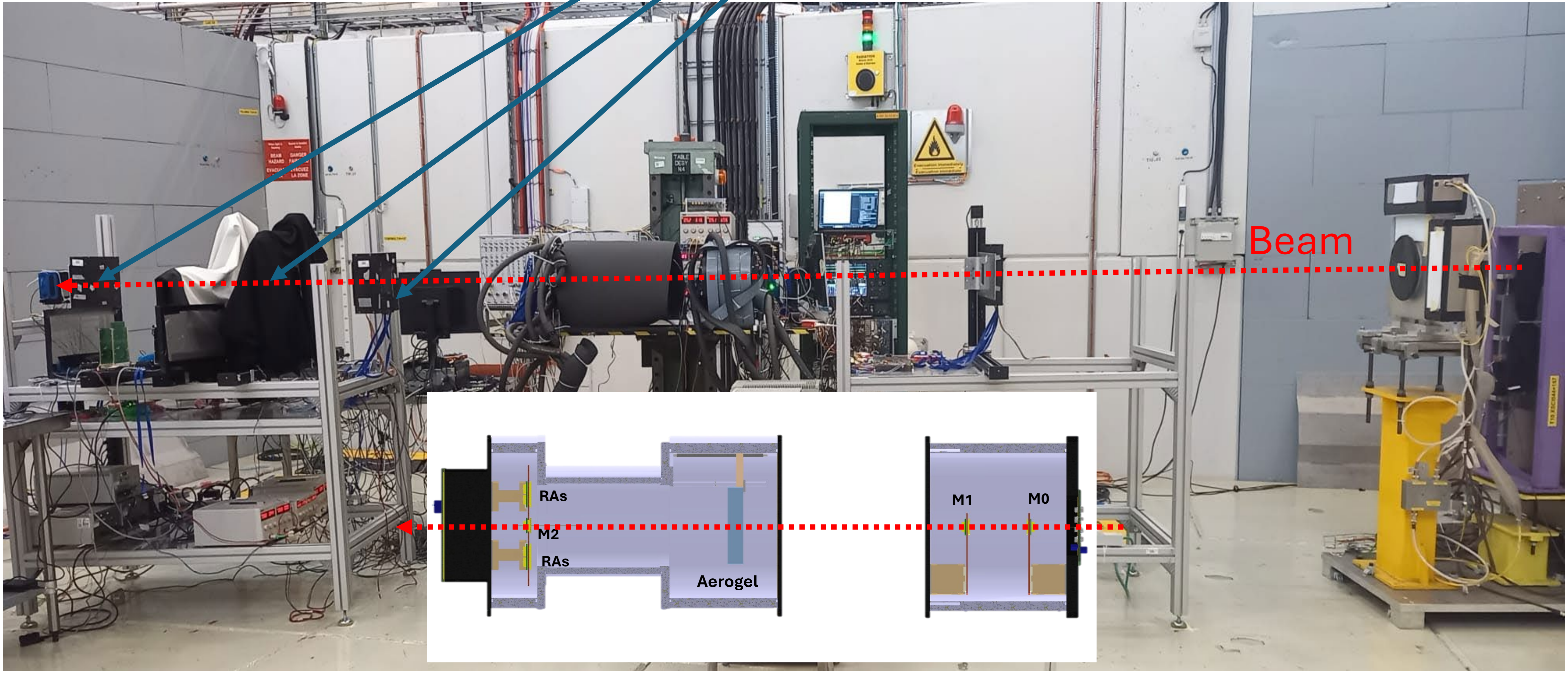
- S13361-1350 with 2 mm of SiO_2
- S13361-3075 with 1 mm of SiO_2
- S13361-3075 with 1 mm of MgF_2



2024 Beam test set-up@T10

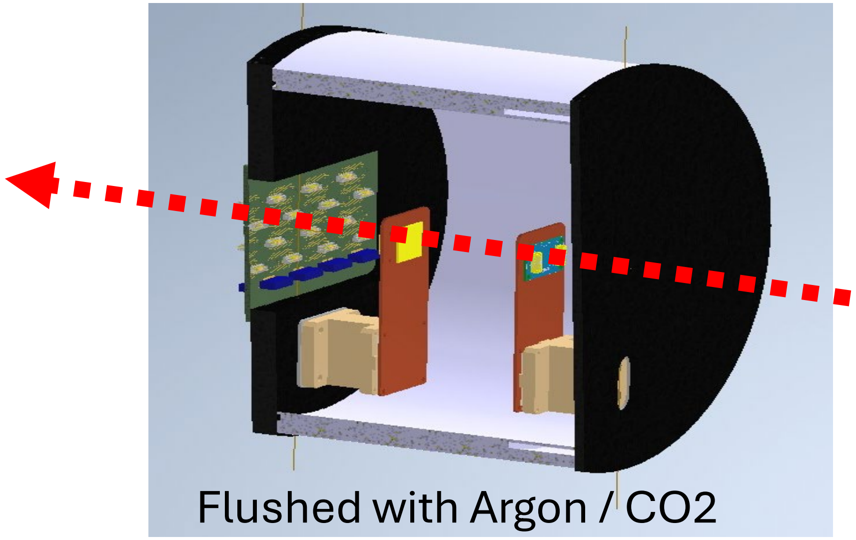


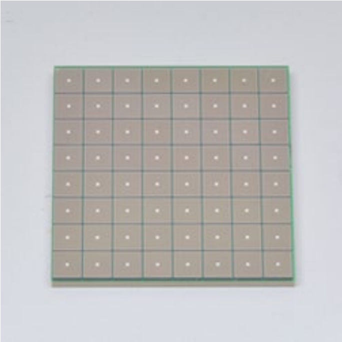
X-Y fiber tracker module: beam trigger and particle tracking

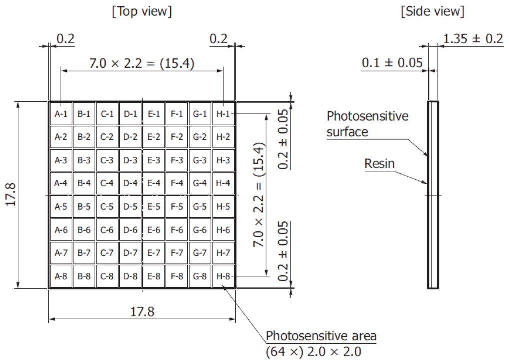


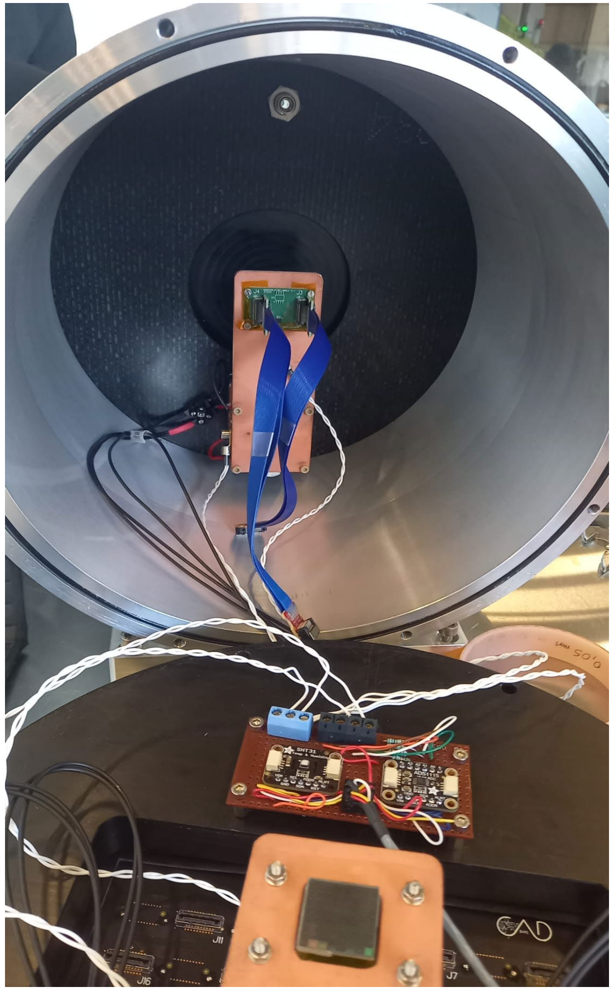
2024 - Timing set-up (upstream cylinder)

- 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



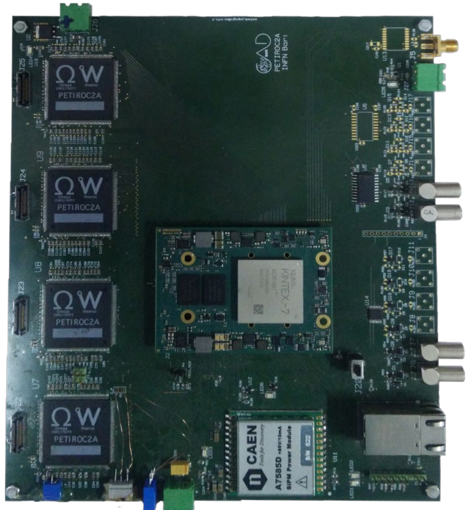


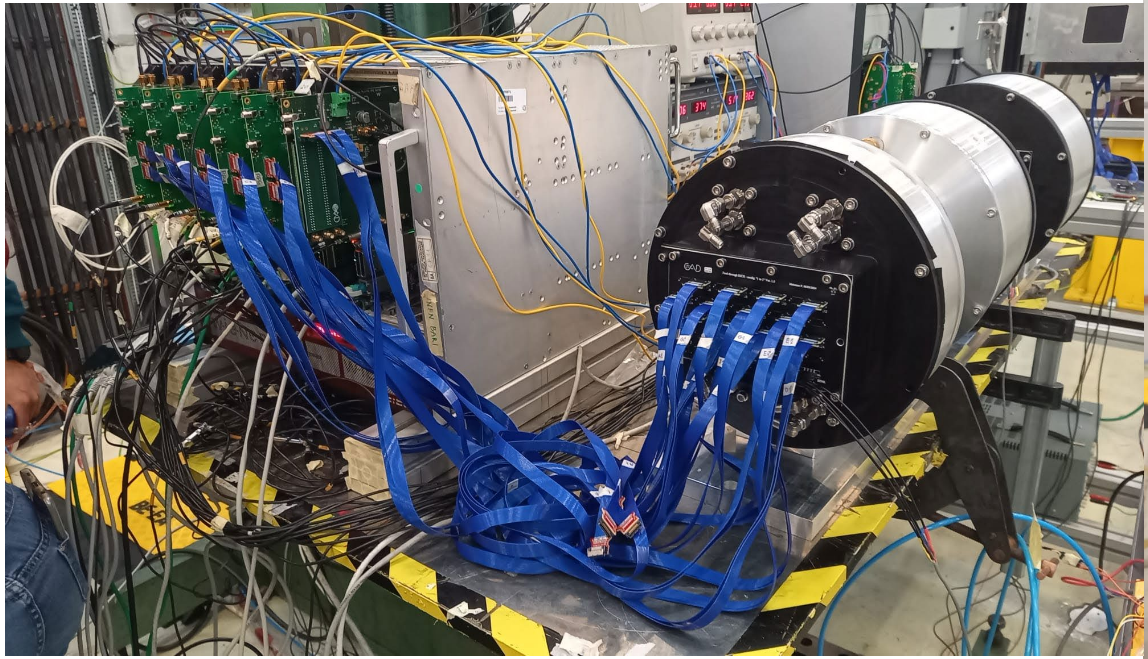


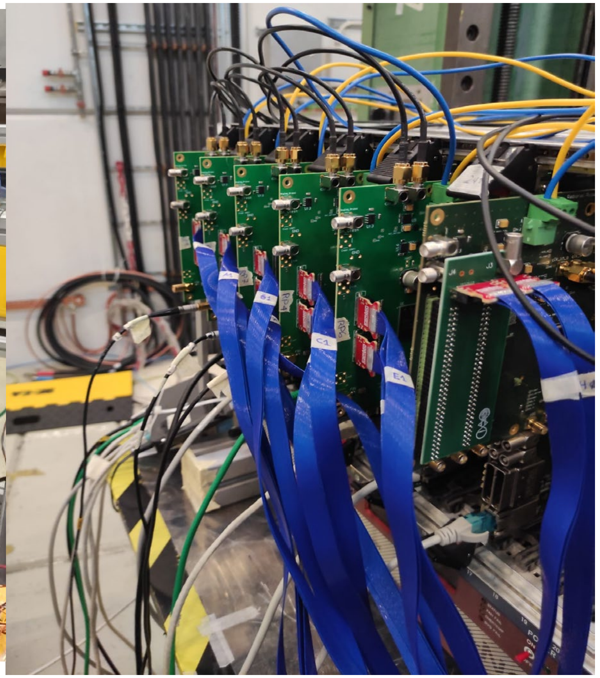


Front-end and DAQ boards

- Custom boards based on
  - PETIROC2A FE ASICs with TDC (LSB ≈ 37 ps) and ADC and FPGA on board
  - Radioroc 2 FE ASIC with picoTDC (LSB ≈ 3 ps) and read-out by MOSAIC boards
  - picoTDC in multihit configuration with ToA (≈ 3.05 ps LSB) and ToT (≈ 200 ps LSB)
- SiPM inside the vessels ($\approx -5°$) + 1.2 m Samtec HLCD cable to the FEB at room temperature







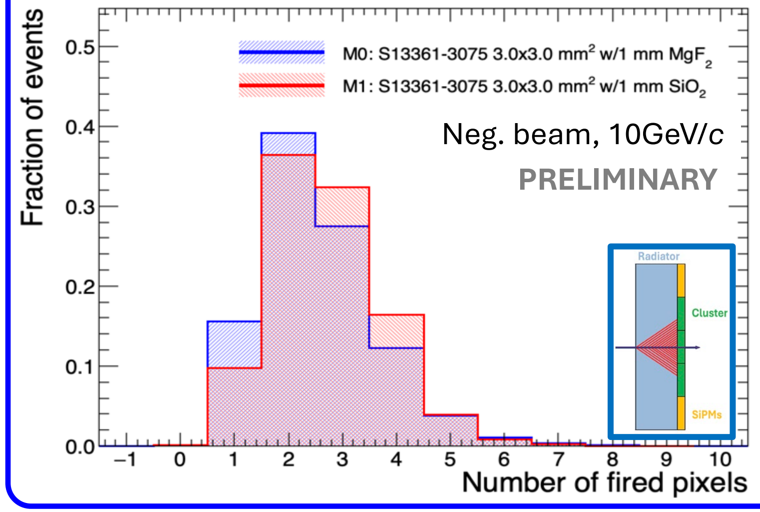
Radioroc2+pTDC board
(in collaboration with Weeroc)
+ MOSAIC

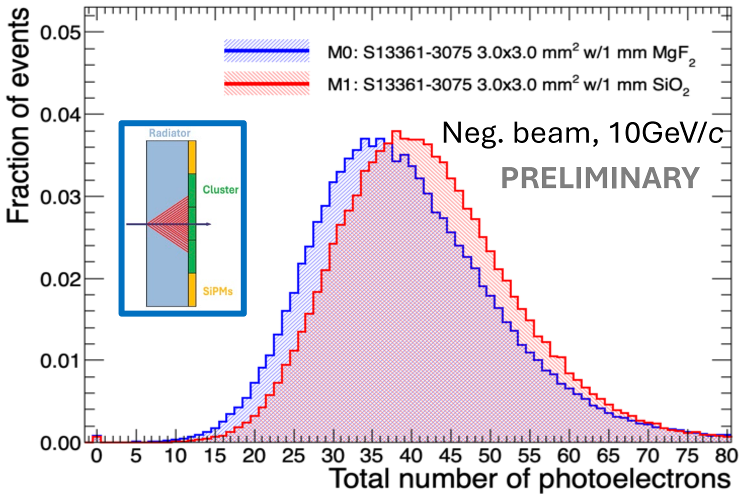
Data analysis

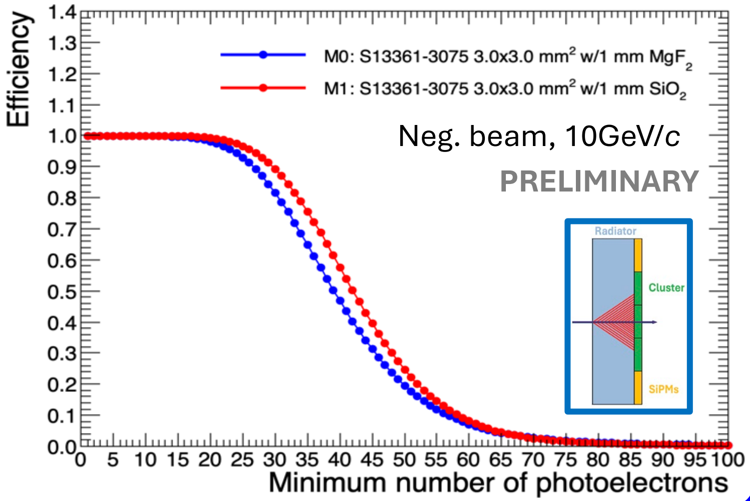
- In the set-up there are three SiPM arrays along the beamline with thin quartz/MgF2 window
  - M0 upstream TIME cylinder
  - M1 downstream TIME cylinder
  - M2 RICH cylinder
- All time offsets removed as well, included the time of flight and time walk
- Timing resolution evaluated comparing the M0, M1 and M2 time responses
  - Currently we have selected the pixel with the maximum observed charge (ToT) value in each of those SiPM arrays

Time performance with 10 GeV/c pions – Petiroc2A

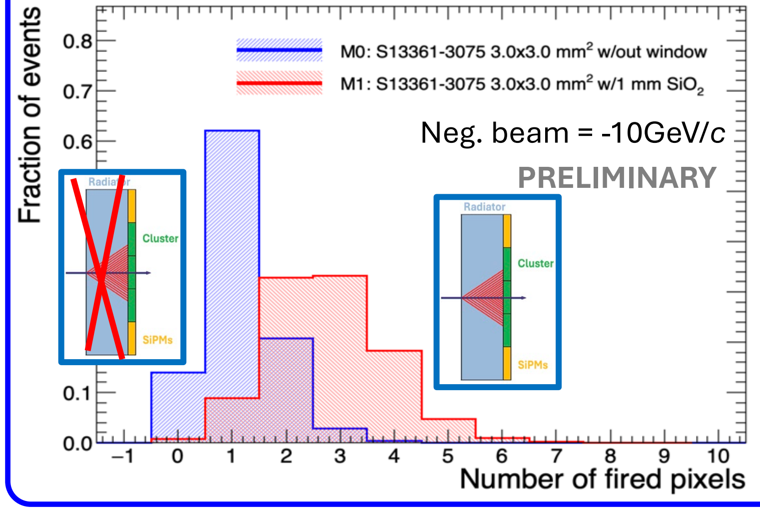
Efficiency of $\approx 100\%$ with clusters with $N < 20$ pe coupling thin window to the SiPMs

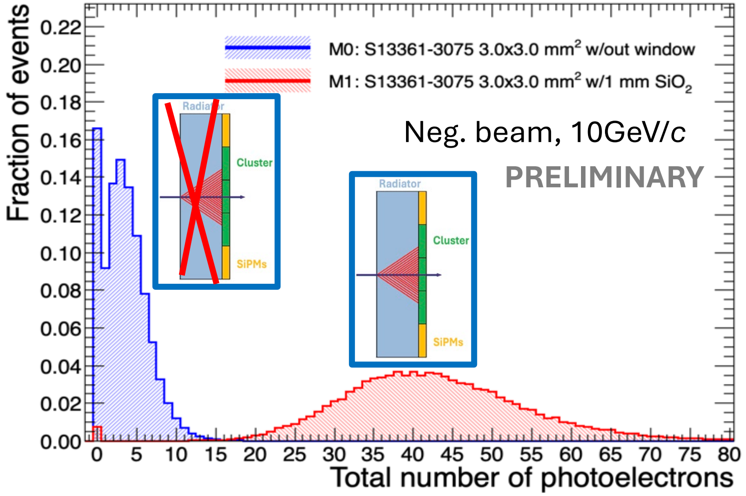


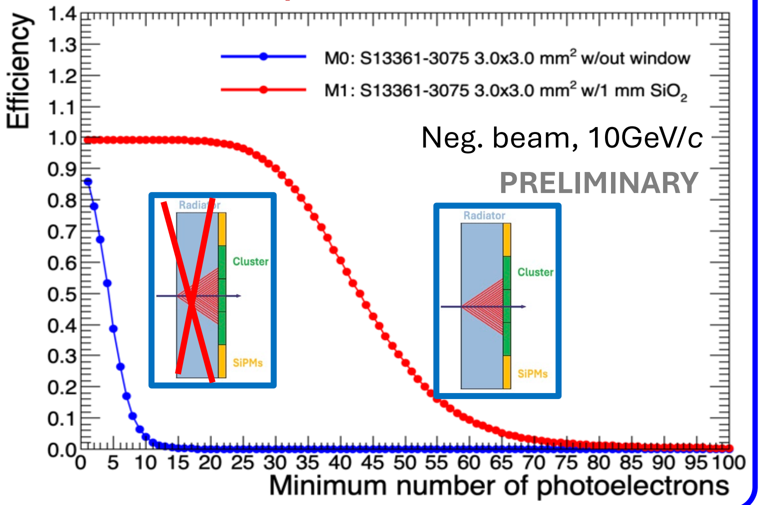




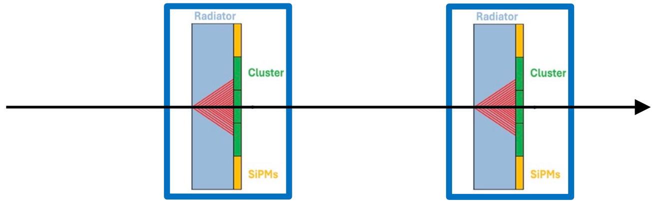
Lower efficiency without window (only direct MIP interactions or photons from $\approx 100\ \mu m$ built-in resin)

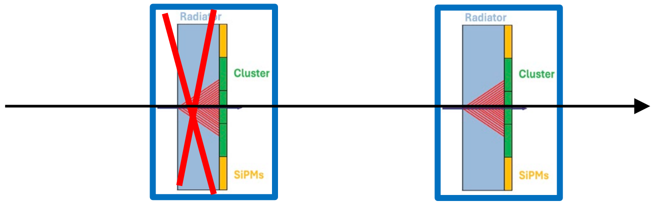




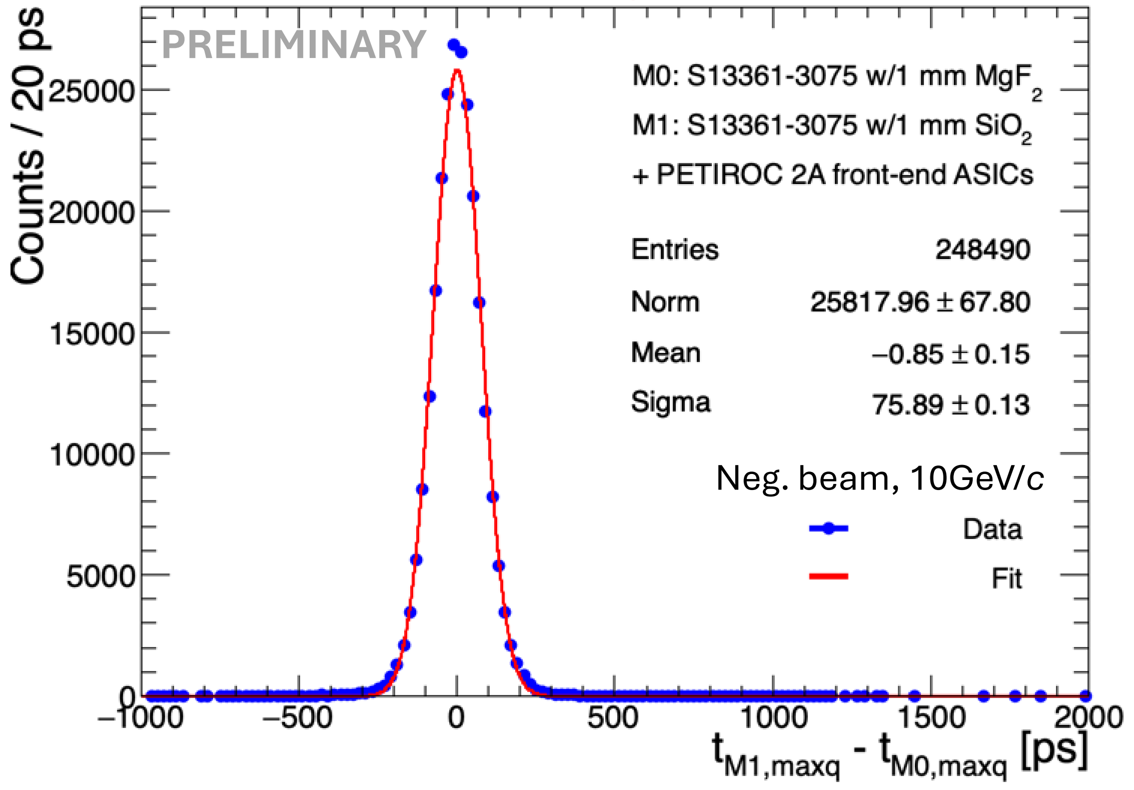


Time resolution with/without window – Petiroc2A

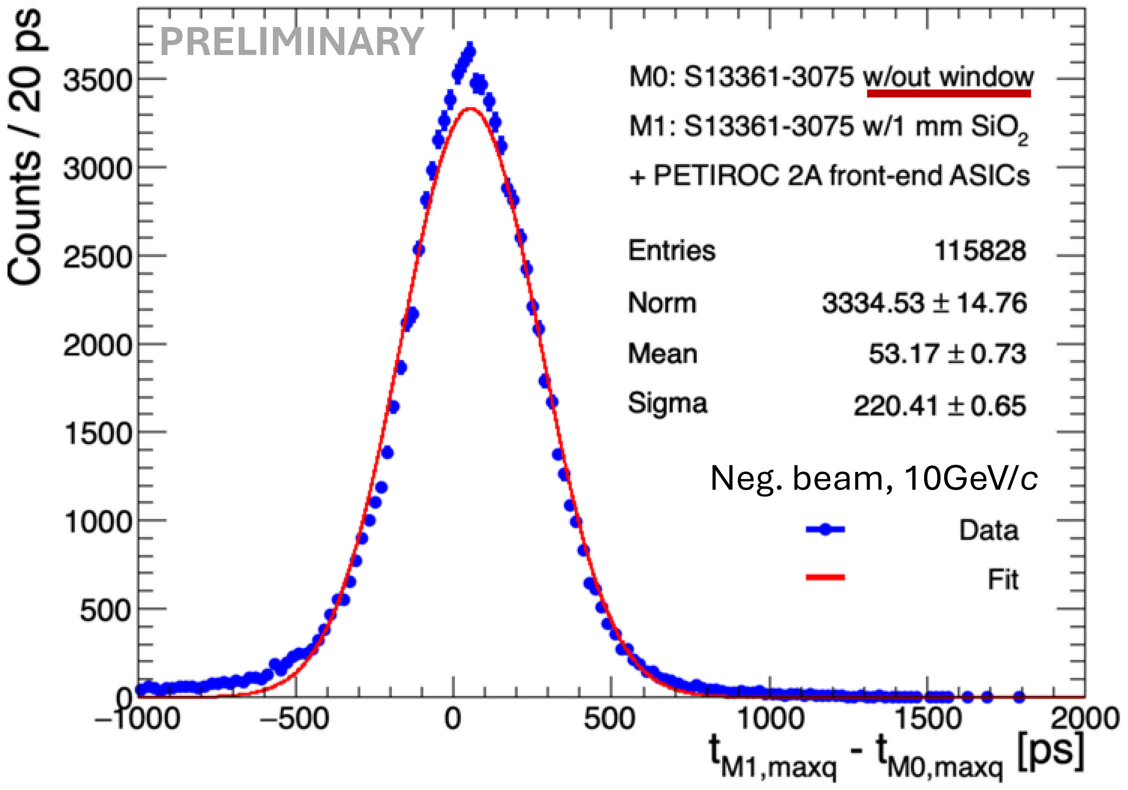




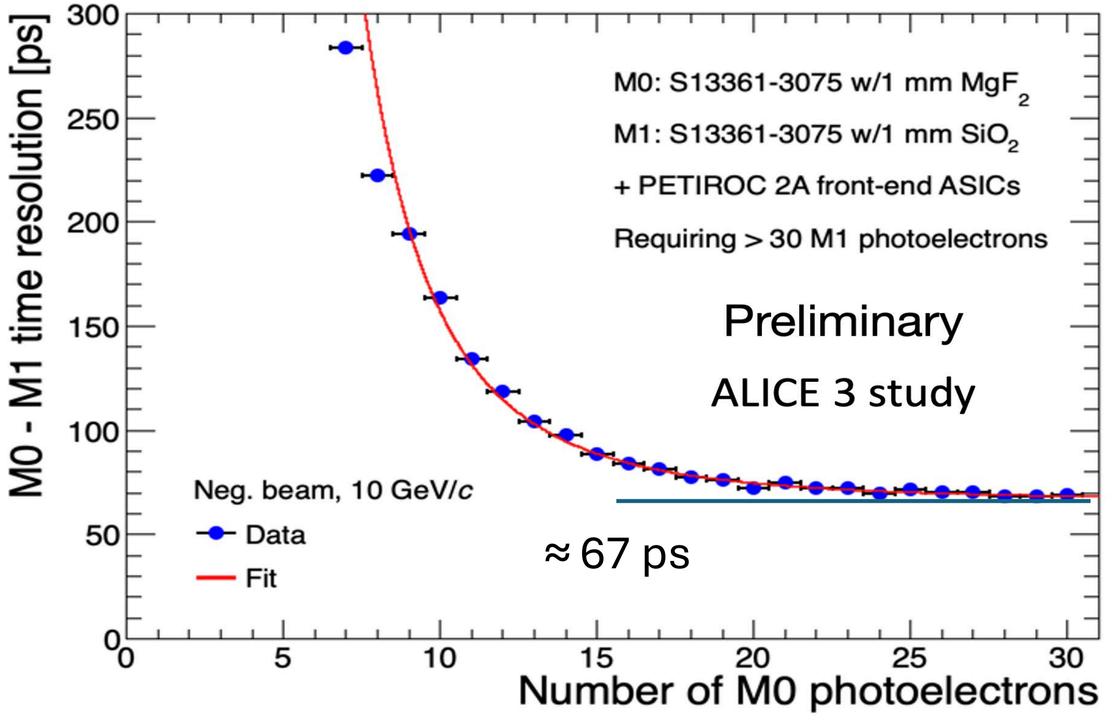
We measured an overall resolution down to ≈ 75 ps (i.e. ≈ 50 ps single pixel resolution) adding thin window radiator with the SiPM arrays

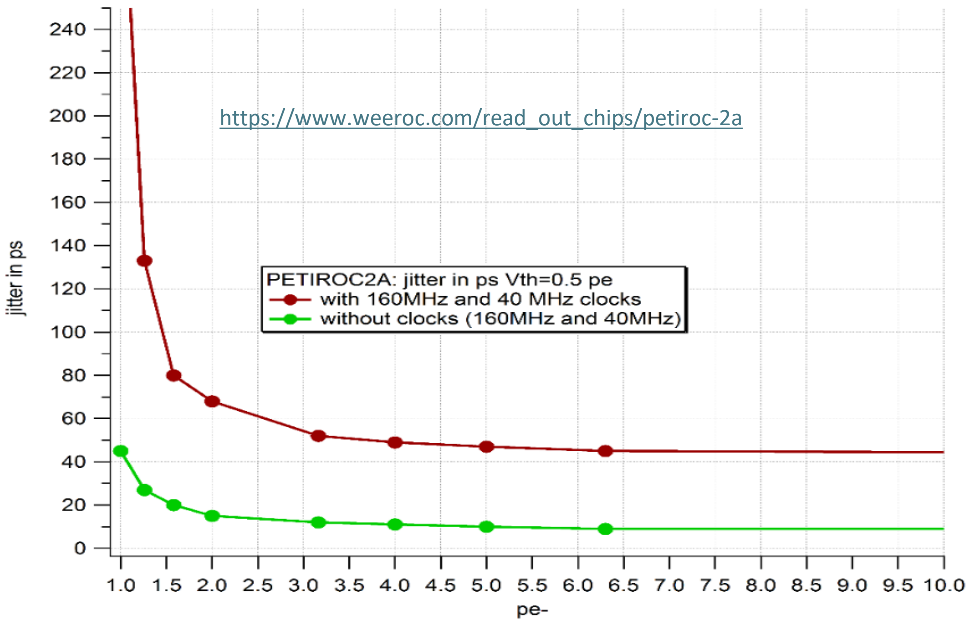


Much better performance using SiPMs coupled with radiator window w.r.t. same matrix without window



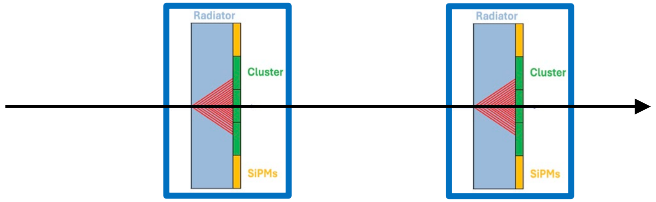
Time resolution– Petiroc2A





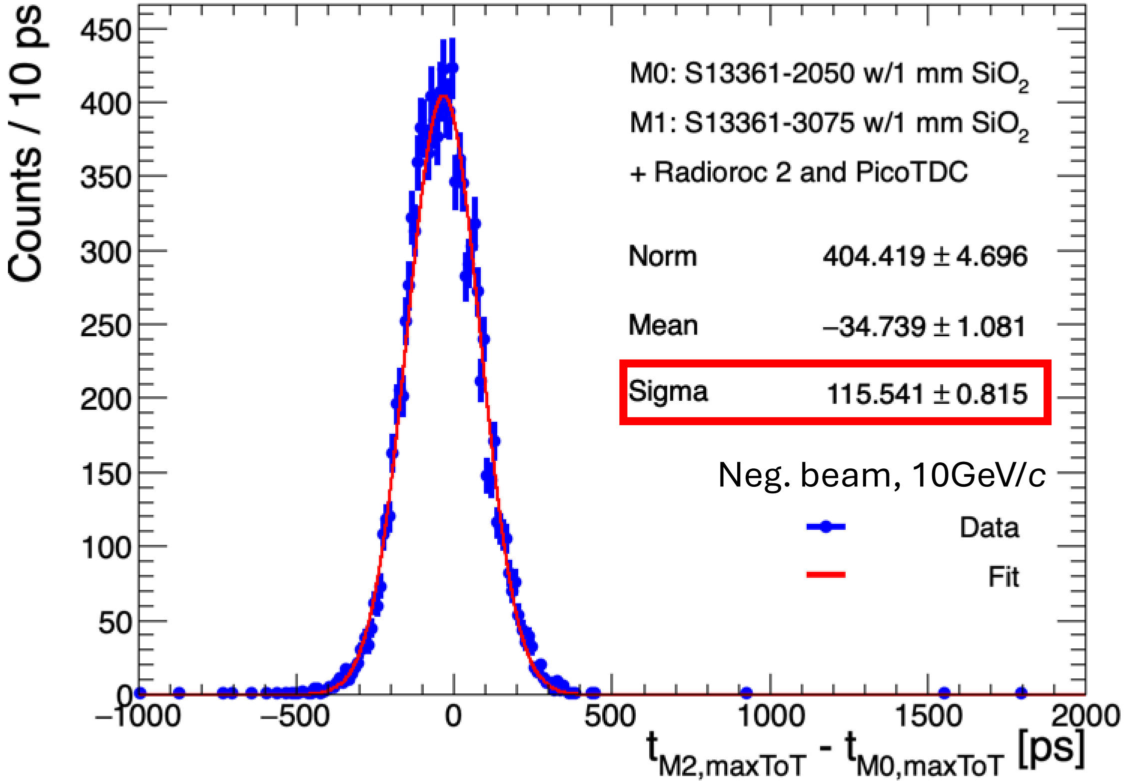
- Single pixel time resolution of $\sigma \approx \frac{67}{\sqrt{2}} \approx 47ps$ (SiPM + FE)
- Assuming the FE jitter of about 40 ps we have $\sigma_{SiPM} \approx 25\ ps$ at 5-6V over voltage

Time resolution – Radioroc2 + picoTDC

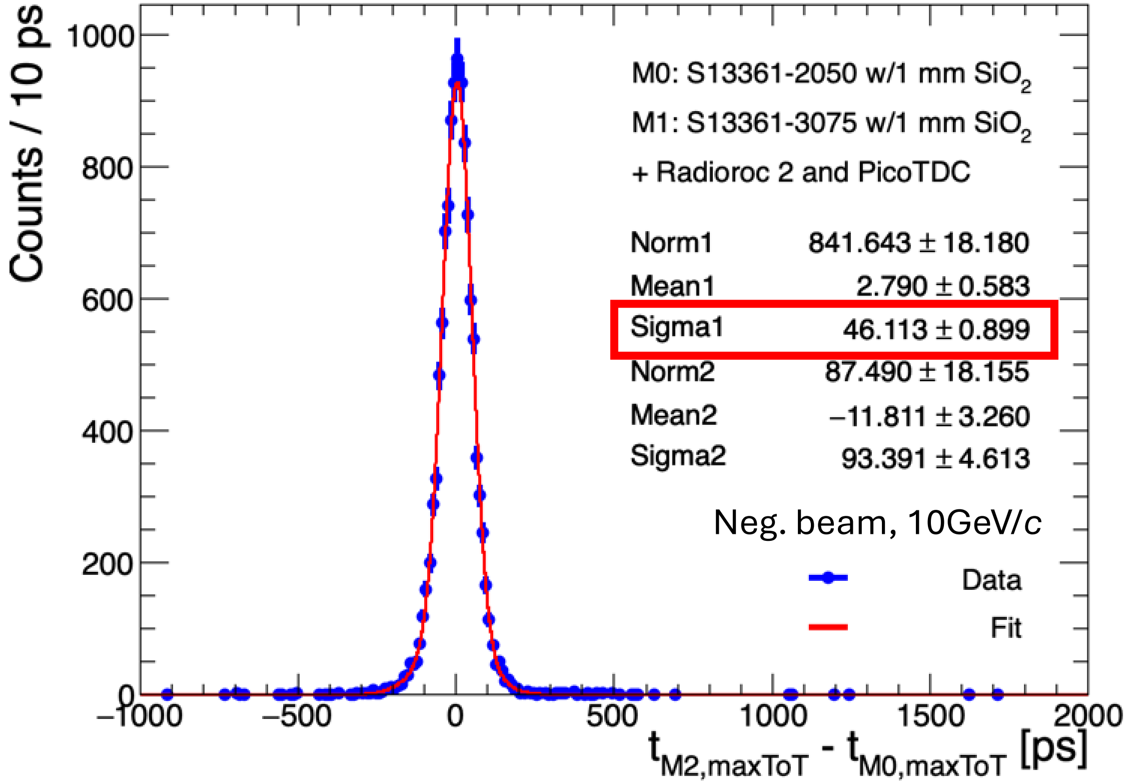


Radioroc2 FE jitter of about 20 ps or less: $\sigma_{SiPM} \approx 25\ ps$ at 5-6V over voltage

We measured a $\Delta t_{\max}$ res. down to $\approx$ 120 ps with no time walk and ch by ch offset correction (but subtracting only TOF)

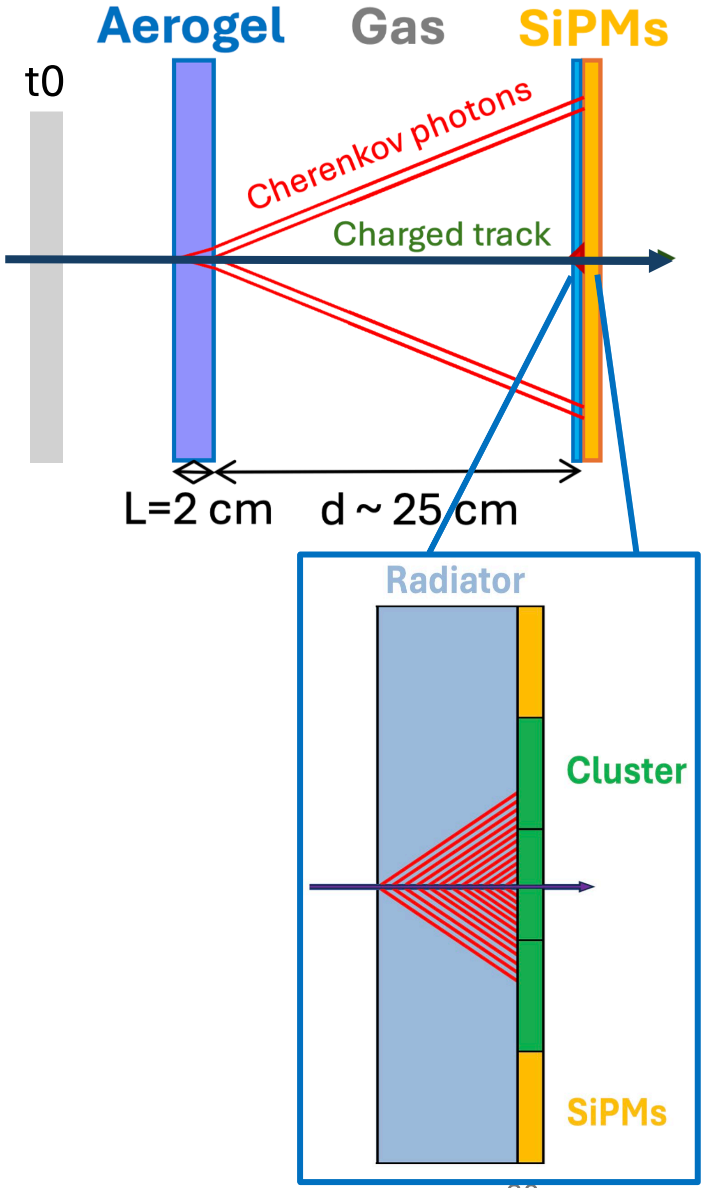


Correcting for time walk and ch by ch offset, a Δt_{max} res. down to $\approx$ 50 ps is achieved $\Rightarrow$ Better than 35 ps at single SiPM level

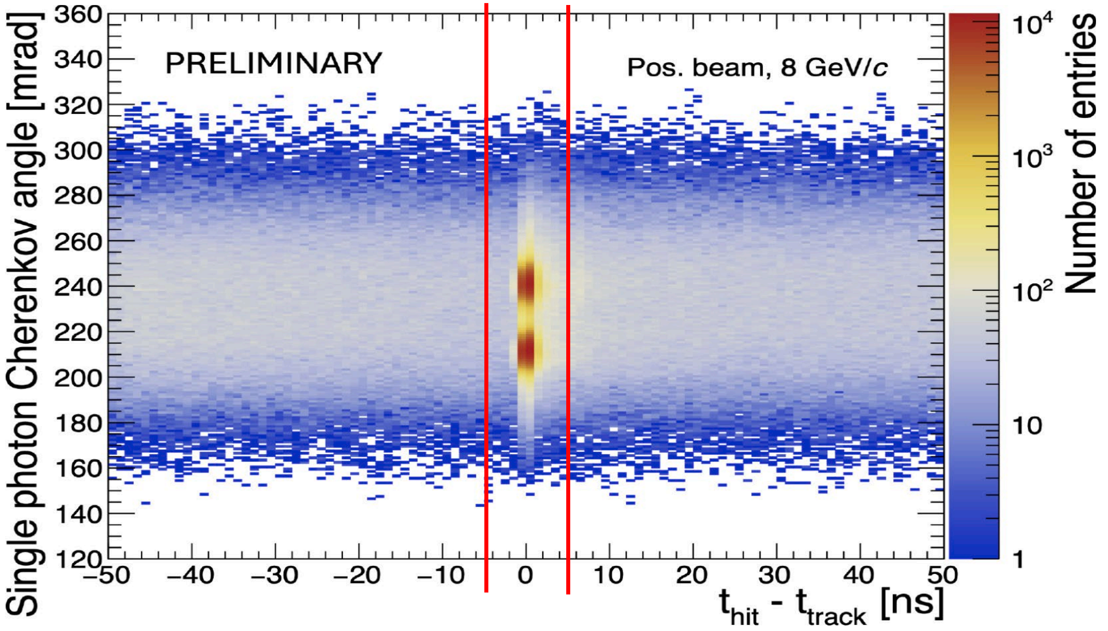


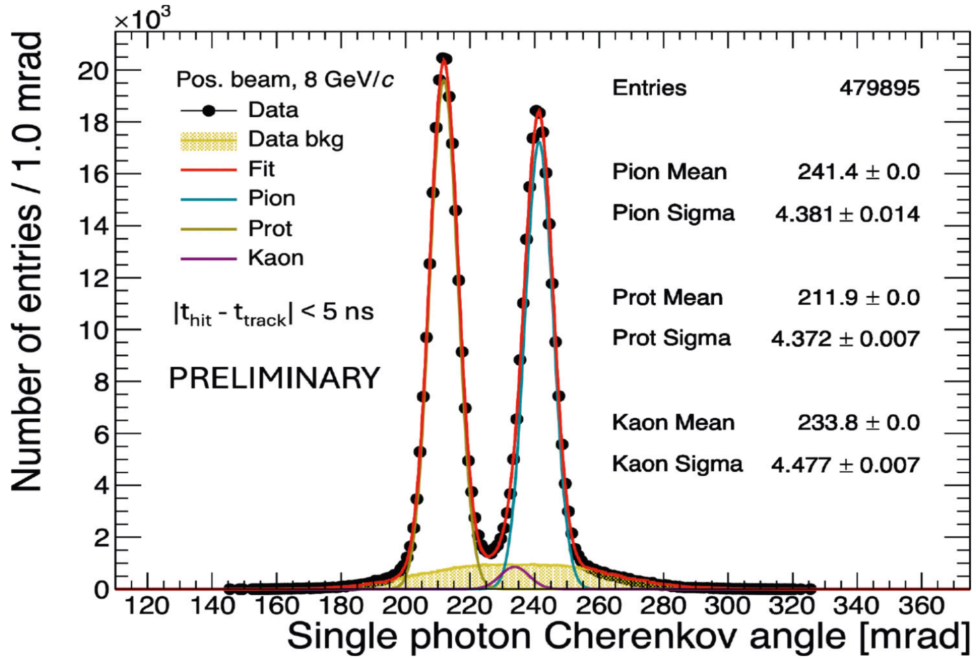
Combined RICH+TOF layout

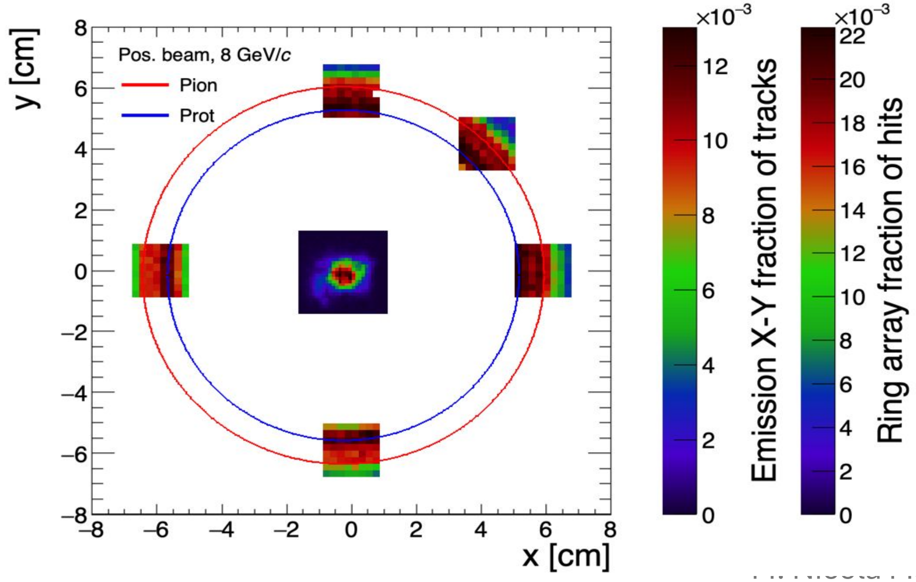
- Particle identification up to tens of GeV/c momenta with RICH in a proximity configuration
  - Single radiator (e.g. aerogel)
    - Few cm thick to limit the geometrical aberration effect to the angular resolution
  - Single photodetector layer made by SiPM
    - Timing jitter of tens of ps
    - Pixel pitch of 1-3 mm
    - PDE > 40% at 400 nm
- Possibility to glue thin (mm) high refractive window (e.g. synthetic quartz) to SiPM layer for TOF measurements
- A good timing-particle match improves RICH pattern recognition
  - Disregarding uncorrelated hits due to the SiPM DCR
  - See Nicola Nicassio's talk for more details here
- RICH-TOF layout as an option for the ALICE 3 PID system

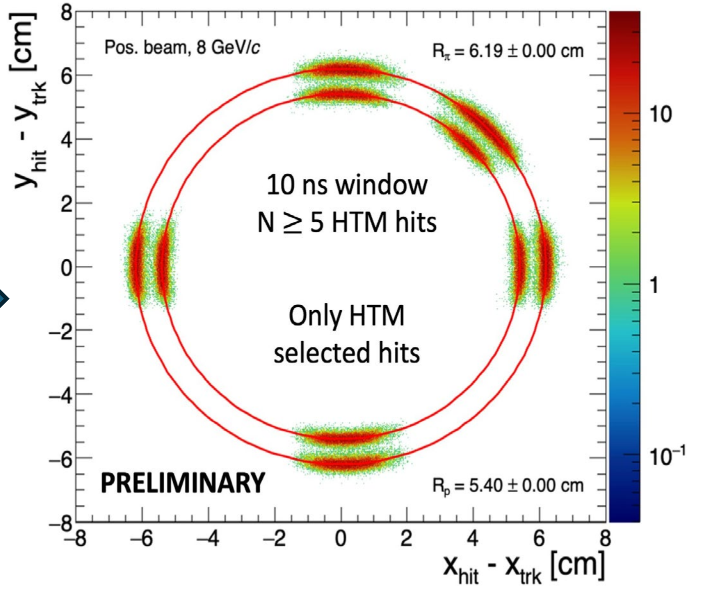


ALICE 3 RICH-based timing option









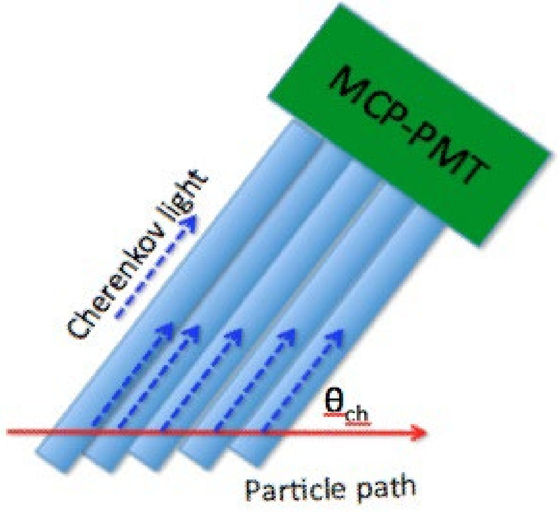
Conclusions and outlook

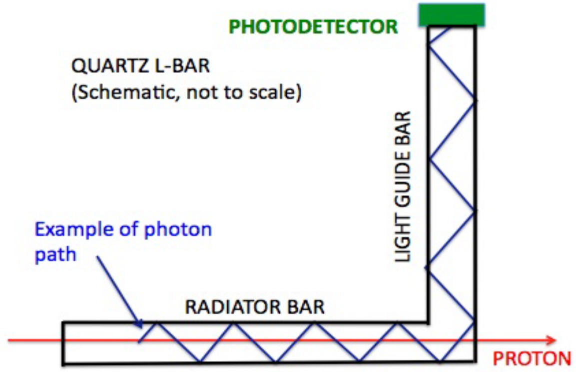
- SiPM coupled with thin Cherenkov radiators can be used for charged particle tracking and TOF measurements
  - Several beam tests performed since 2022 at CERN PS
  - The overall (electronic + SiPM) single pixel timing resolution (sigma) of about 35ps (=50ps/$\sqrt{2}$) or better with 1 mm of synthetic quartz radiator has been achieved (including electronic time jitter)
- A SiPM-based RICH detector with good timing capabilities can be combined with a ToF system in a compact configuration for a PID system operating in a wide momentum range
  - ALICE 3 PID option
  - A possible application is the measurement of isotopic composition of light nuclei

BACKUP

Radiator geometry

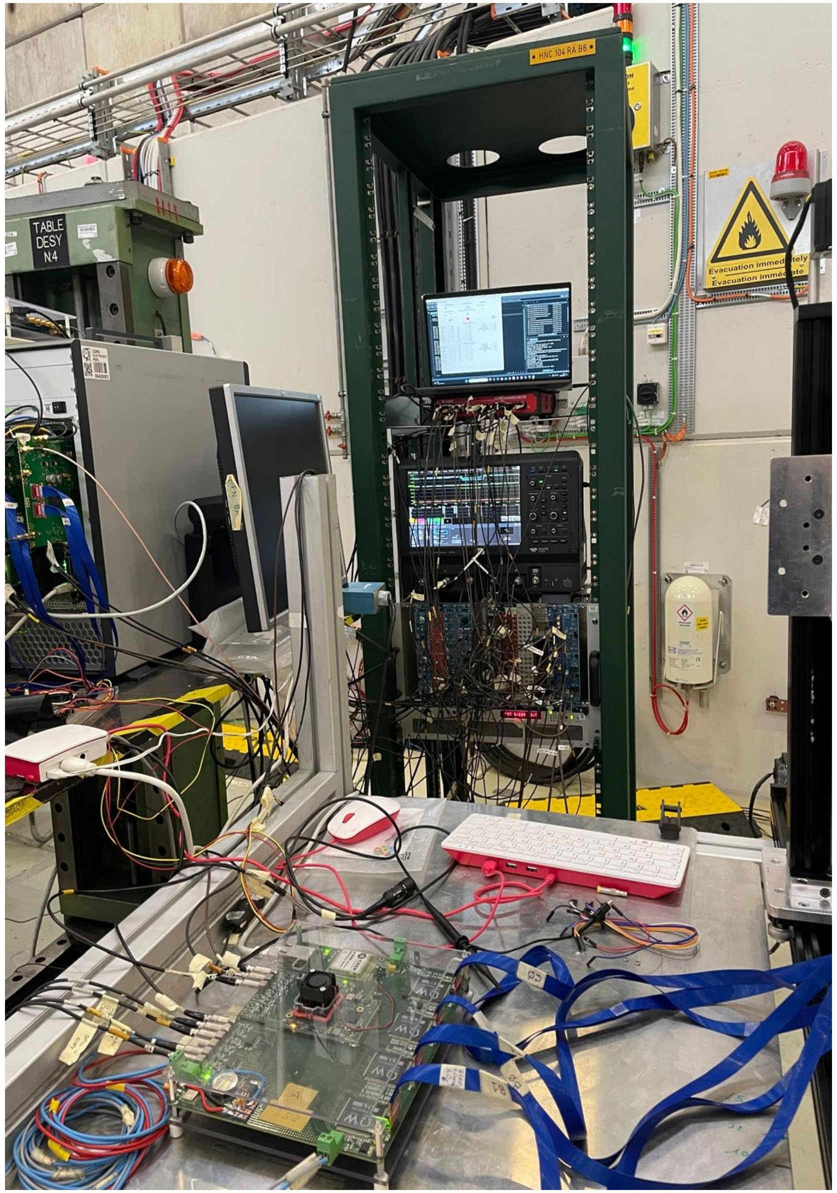
- Radiation geometry affects the signal collection
  - Angled-bar: radiator bar tilted as the Cherenkov angle
  - L-bar: radiator bar and a lightguide bar at 90°

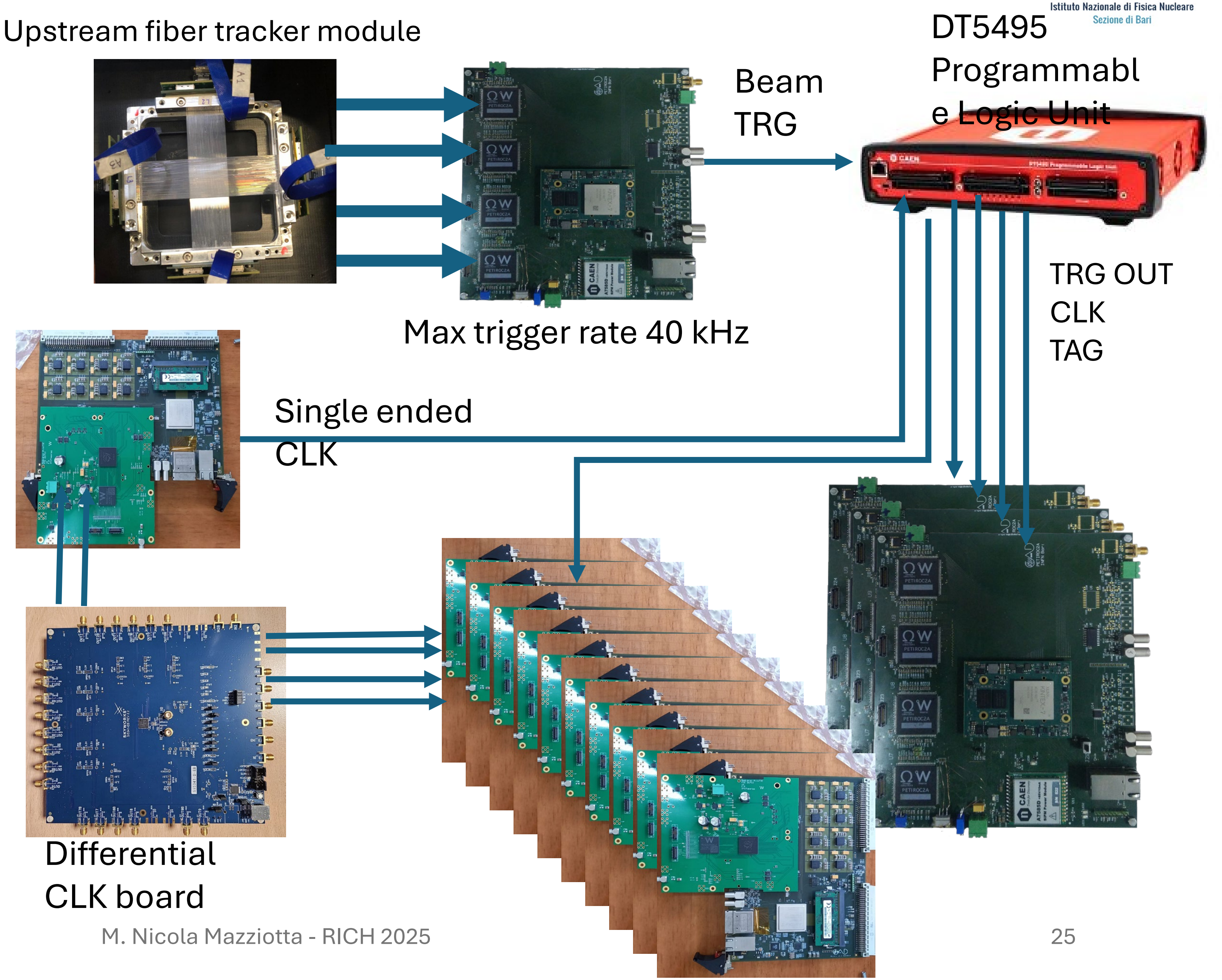




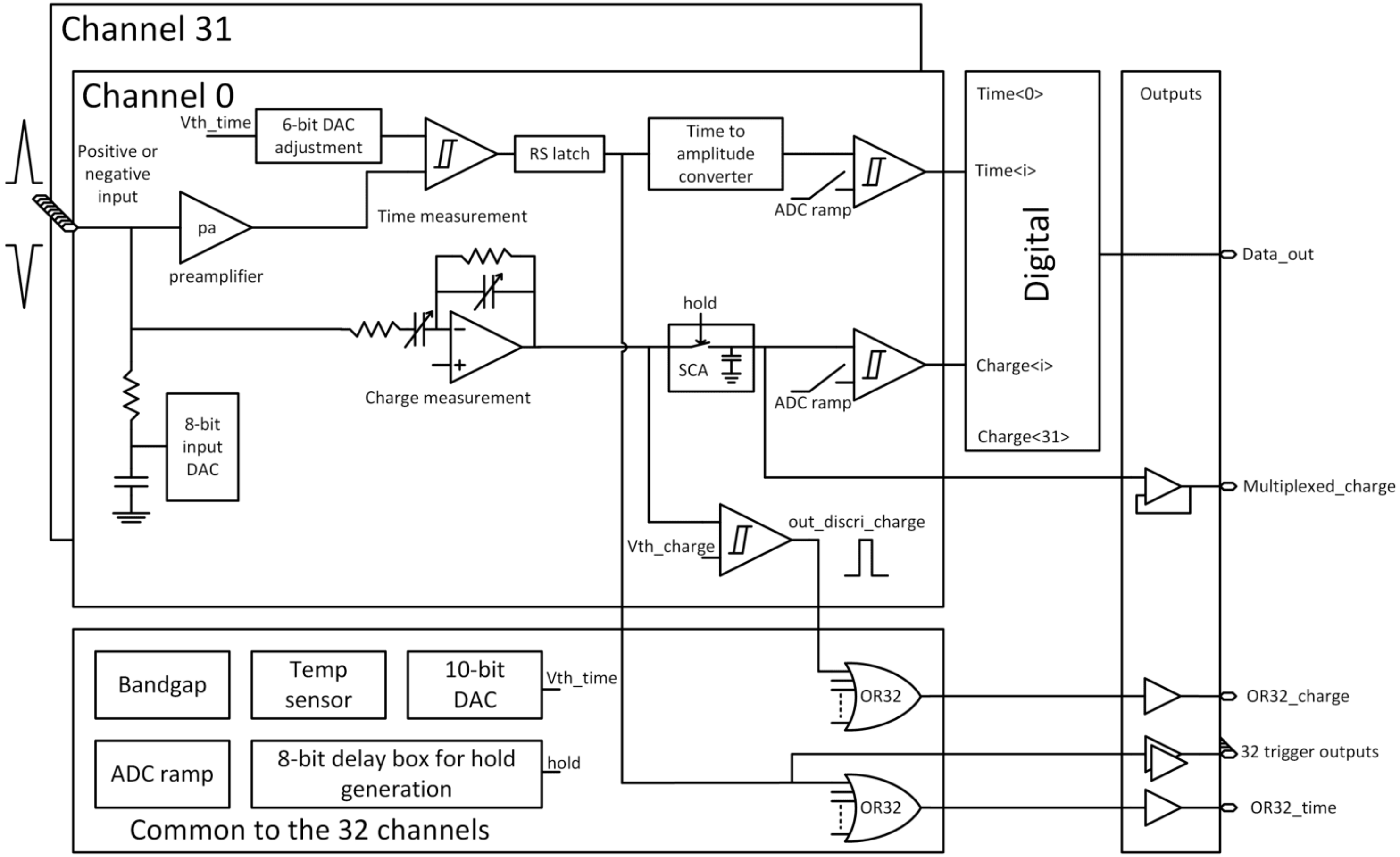
M G Albrow et al 2012 JINST 7 P10027

2024 - Trigger and DAQ system



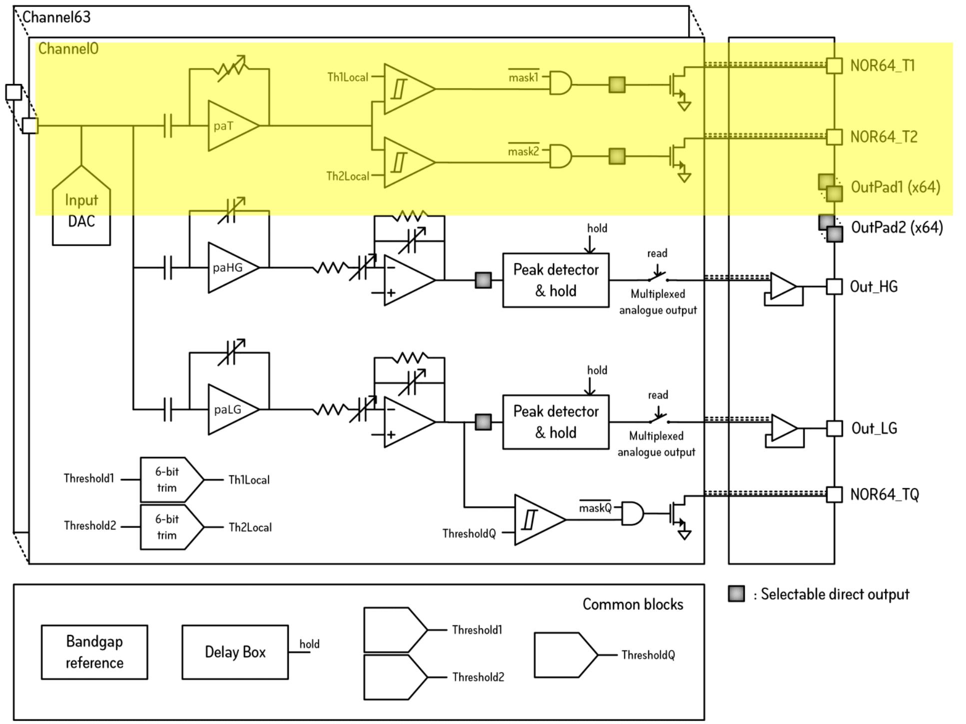


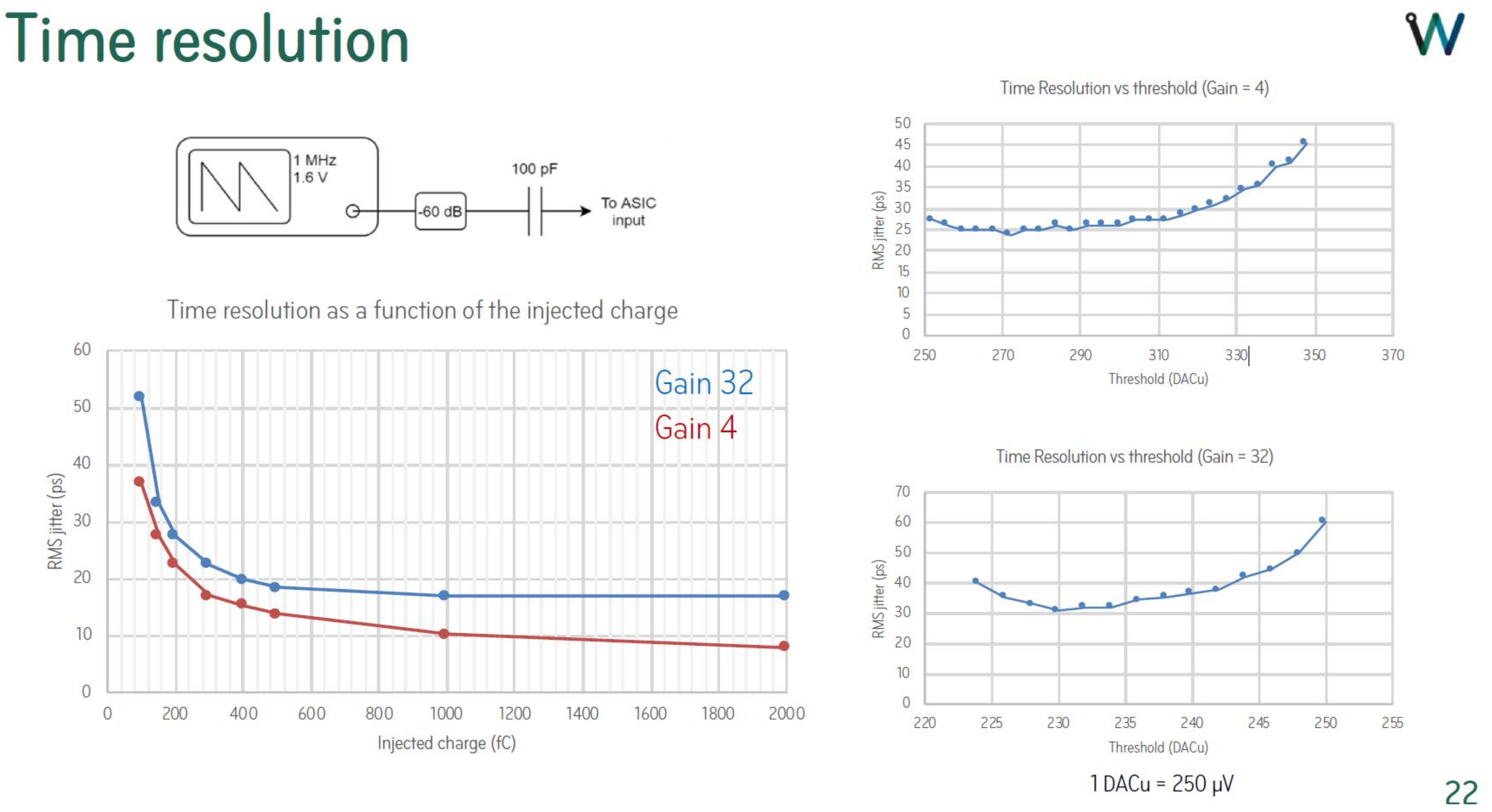
Petiroc 2A



- Digital output:
  - ADC on 10 bits
  - TDC on 10 bits - ≈ 37ps LSB
- 32 trigger outputs

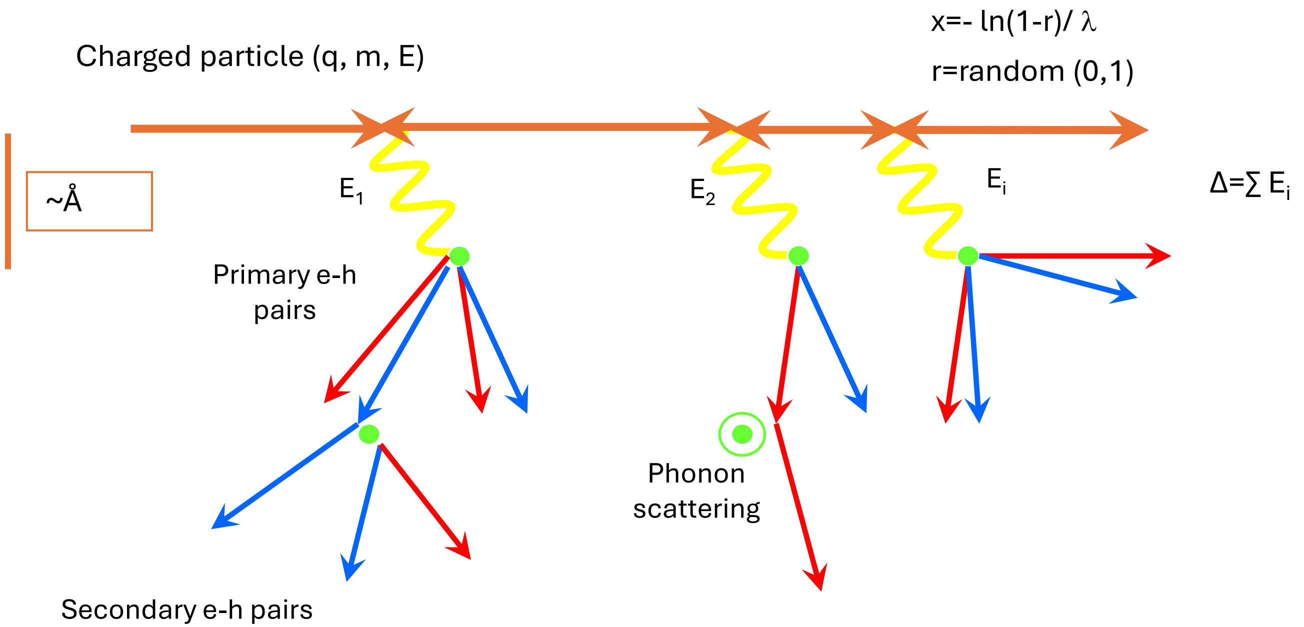
Radioroc 2



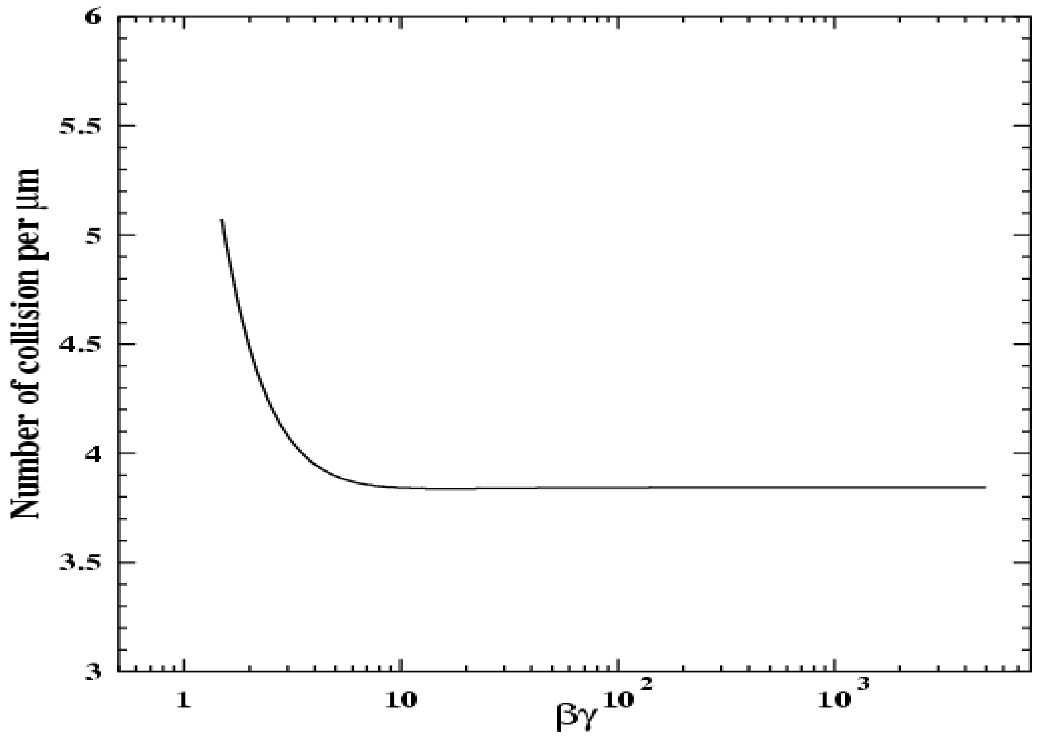


https://indico.cern.ch/event/1307202/contributions/5498756/attachments/2821938/4928175/Weeroc%2520-%2520PM4%2520-AIDAINNOVA%2520-%252018-03-24.pdf

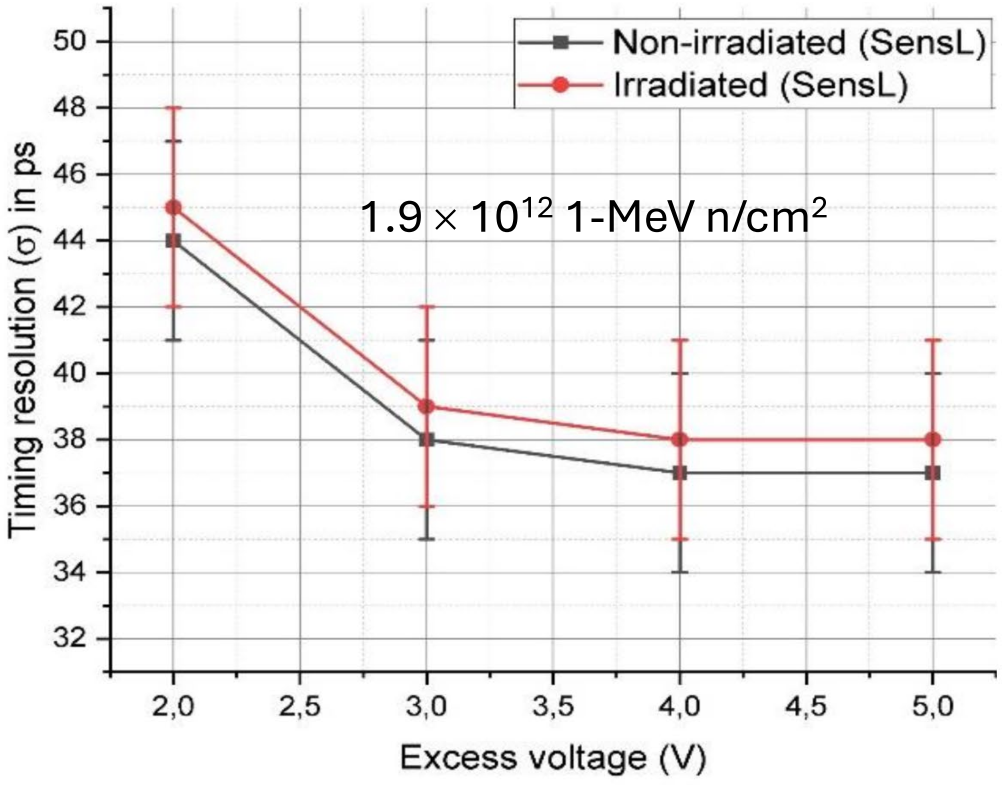
Energy loss in silicon



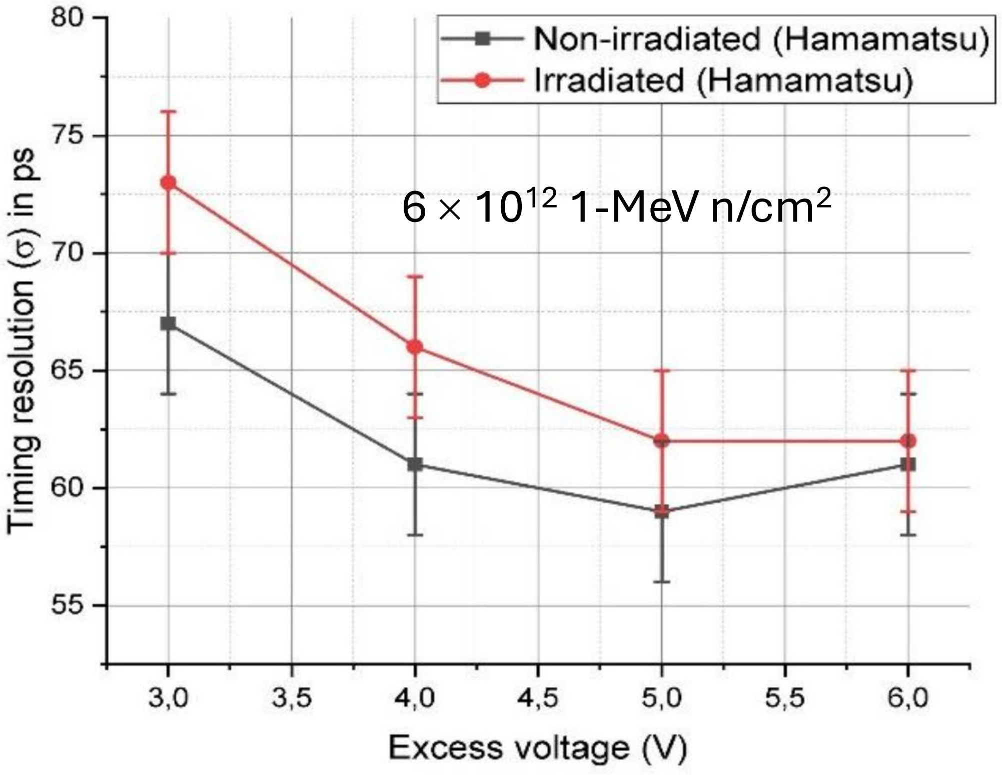
M.N. Mazziotta et al. NIMA 533 (2004) 322
M.N. Mazziotta NIMA 584 (2008) 436



Timing resolution of SiPM after neutron irradiation



(a)



(b)

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See also Marco Guarise's poster in the poster session