Queen Mary University of London, London, UK, 01-04 Sept 2026

Pushing TOF timing to the limit with Cherenkov light and SiPM arrays

Istituto Nazionale di Fisica Nucleare
Sezione di Bari

Nicola Nicassio (INFN Unit of Bari)

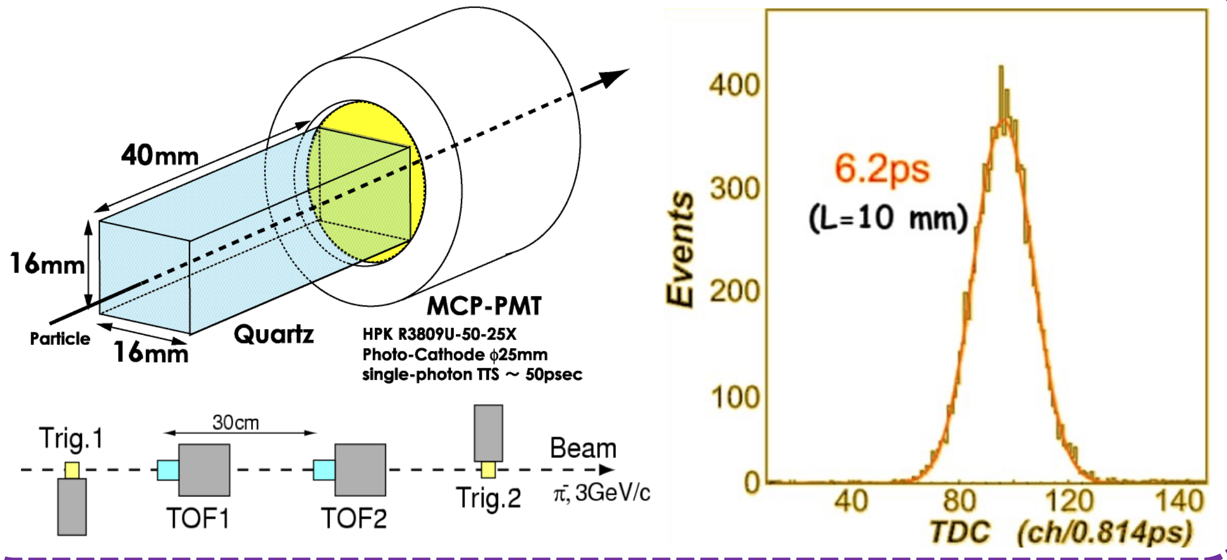
on behalf of the ECFA-DRD4 Bari group

TOF detectors based on Cherenkov light

Why Cherenkov light for TOF devices?
- Prompt emission O(ps): ultimate timing
- Constrained direction: Almost no jitter

Compared to scintillation (many photons)
- O(ns) decay time + photon path jitter

… or LGADs (based on direct ionization)
- Landau fluctuations in deposited charge



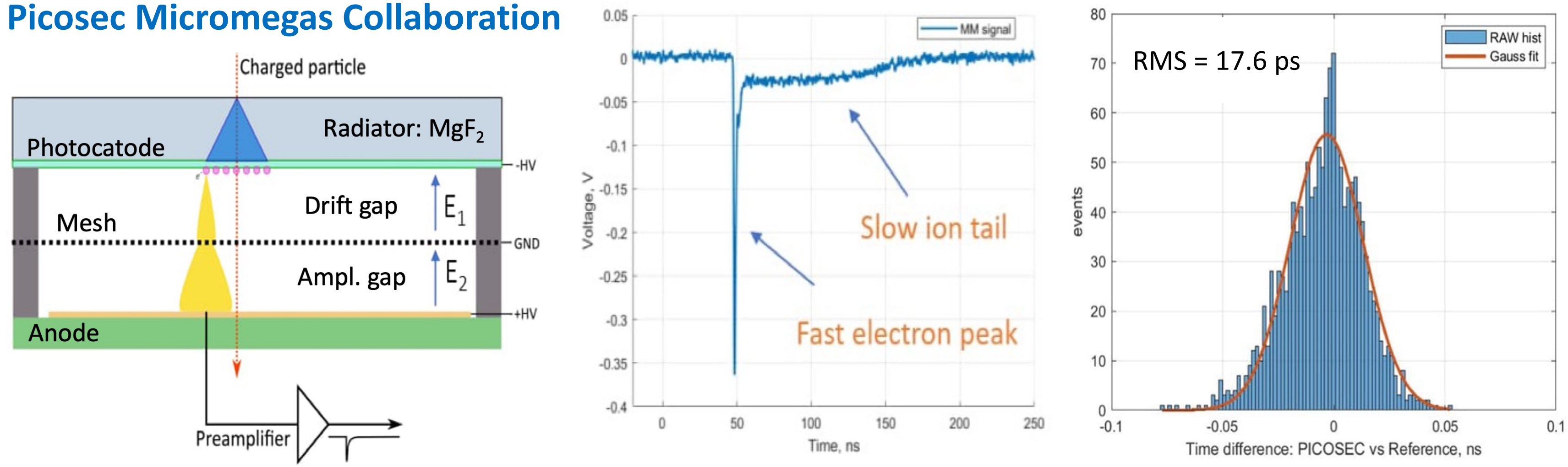
Y.Enari NIM A 547 (2005) 490

K.Inami NIM A 560 (2006) 303

Several concepts with MCPs or gaseous detectors validated

M. Lisowska NIM A 1046 (2023) 167687

Picosec Micromegas Collaboration



Why using SiPMs?

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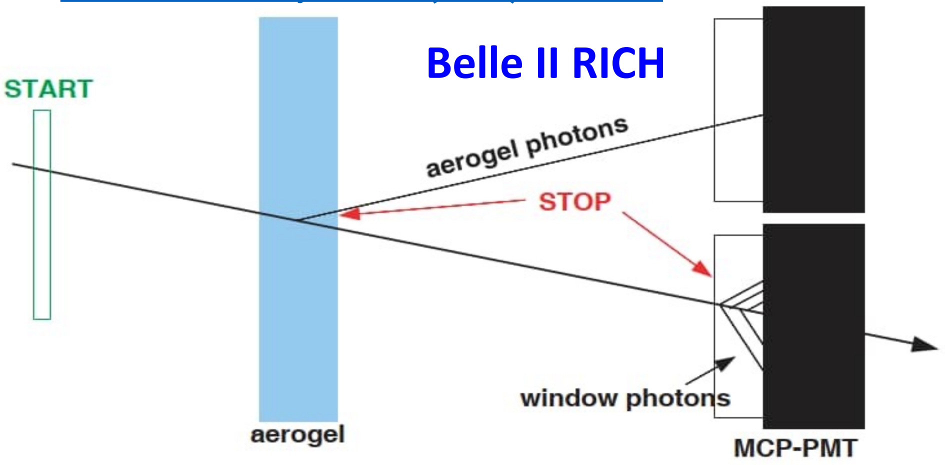
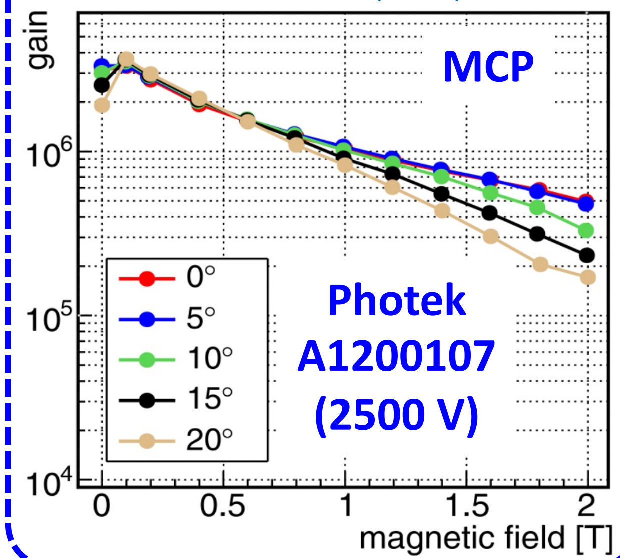
P. Krizan Nucl. Phys. B 172 (2007) 227–230

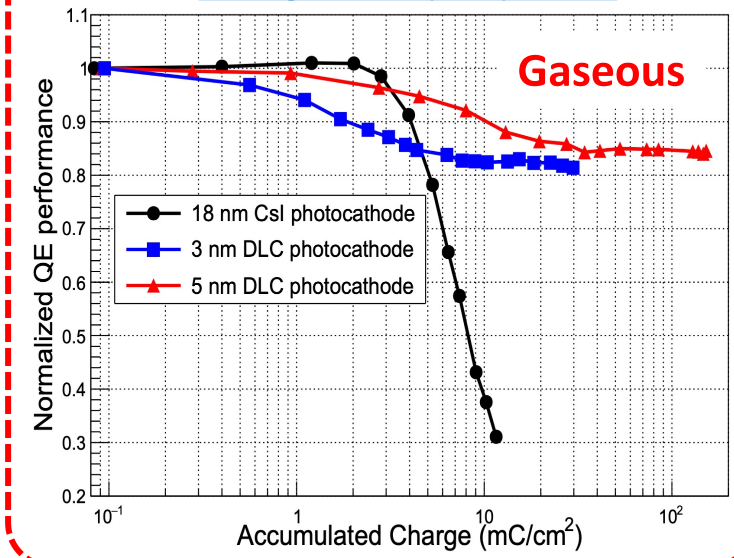
Belle II RICH



A.Lehmann NIM A 1065 (2024) 169536

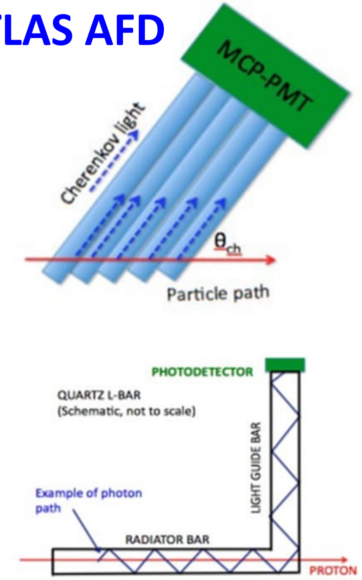


X.Wang JINST 19 (2024) P08010

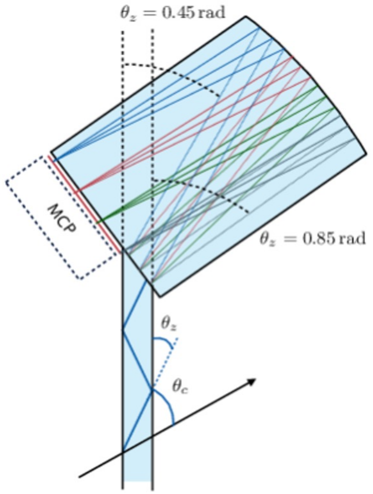


ATLAS AFD

M.G.Albrow JINST 7 (2012) P10027



N.Harnew NIM A 936 (2019) 595-597



LHCb TORCH

Vacuum photon detectors (MCPs, LAPPDs)

- **Main limitation: magnetic field sensitivity**

Gaseous Photon detectors (Picosec MM)

- **Main limitation: Photocathode ageing**

Both detector types are bulky (large x/X_0)

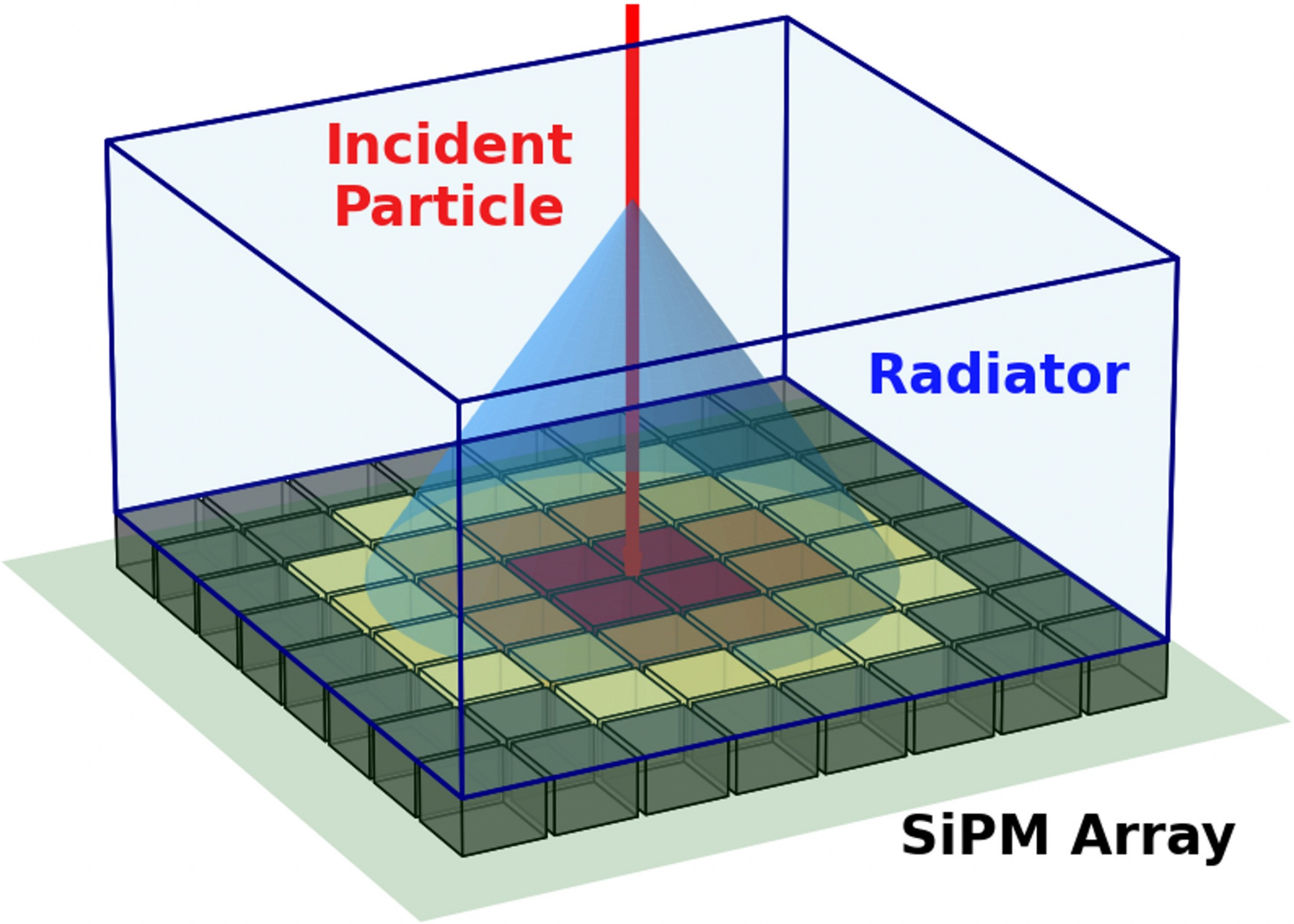
→ These limitations do not affect SiPMs

Principle of operation

Coupling to a SiPM array a thin O(mm) window serving as Cherenkov radiator

Using SiPM clusters by Cherenkov photons for charged particle timing

- Achieving a charged particle detection efficiency of 100%
- Achieving time resolutions of tens of ps at full system level
- Improving time resolution by combining the timestamps of multiple SiPMs in the cluster

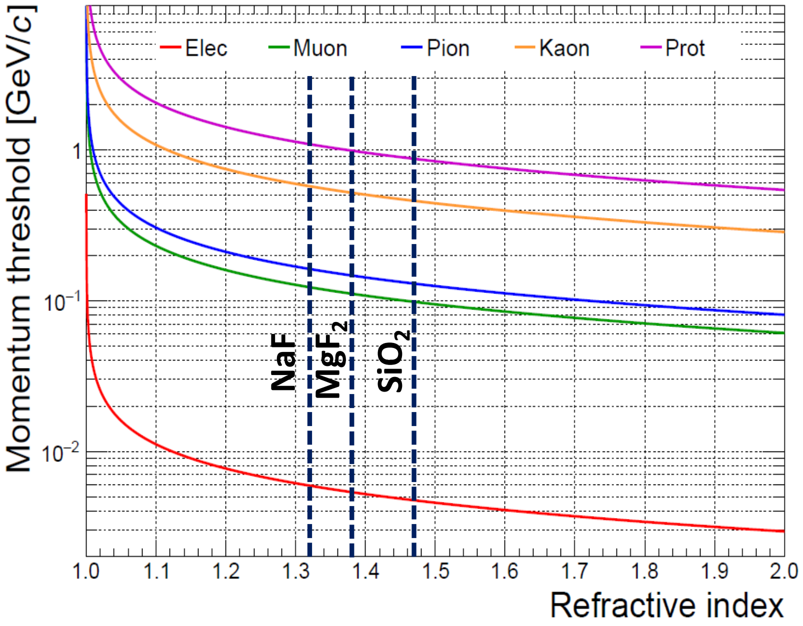


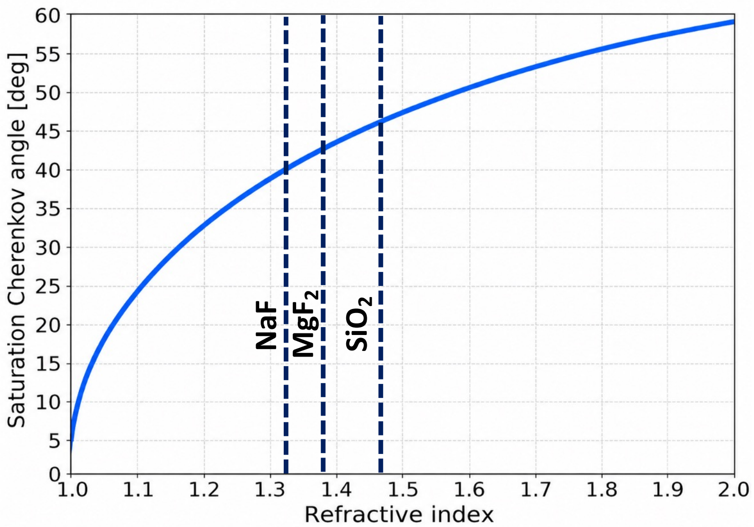
Choice of the radiator material

Emission threshold

$$\beta > \frac{1}{n(\lambda)} \Rightarrow p_{th} = \frac{m}{\sqrt{n^2(\lambda) - 1}}$$

Sufficiently high n to ensure Cherenkov emission for the particle species of interest





Emission angle

$$\cos\theta_c = \frac{1}{n(\lambda)\beta} = \frac{\sqrt{p^2 + m^2}}{n(\lambda)p}$$

Number of photons

$$\frac{d^2 N_{Ch}}{dE dx} = \left(\frac{\alpha}{\hbar c}\right) Z^2 \sin^2\theta_c$$

High n to maximize both N photons and cluster size

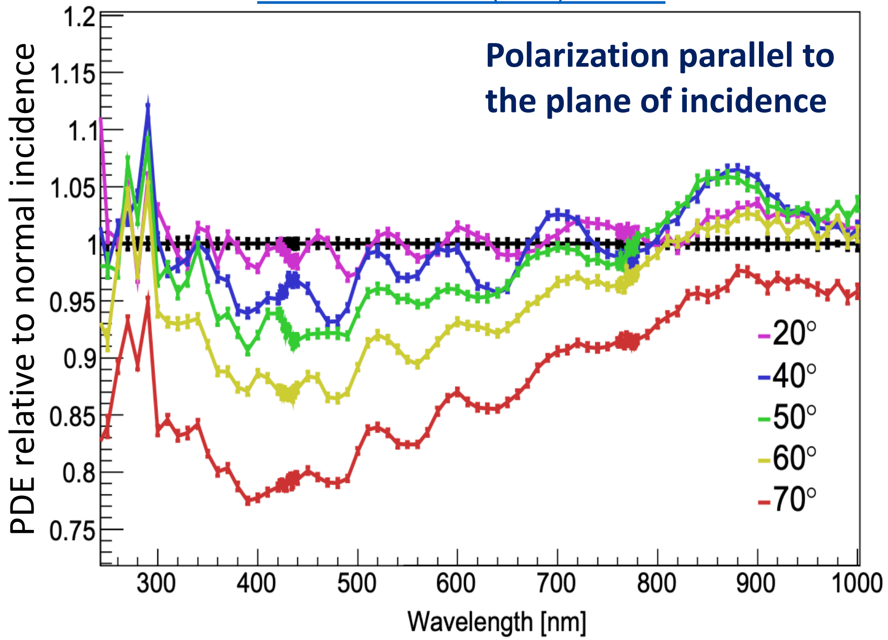
Number of photoelectrons

$$N_{PE} = N_{Ch} \oplus \text{Acc.} \oplus Tr \oplus \text{PDE}$$

... but no so high due to PDE worsening at large angles

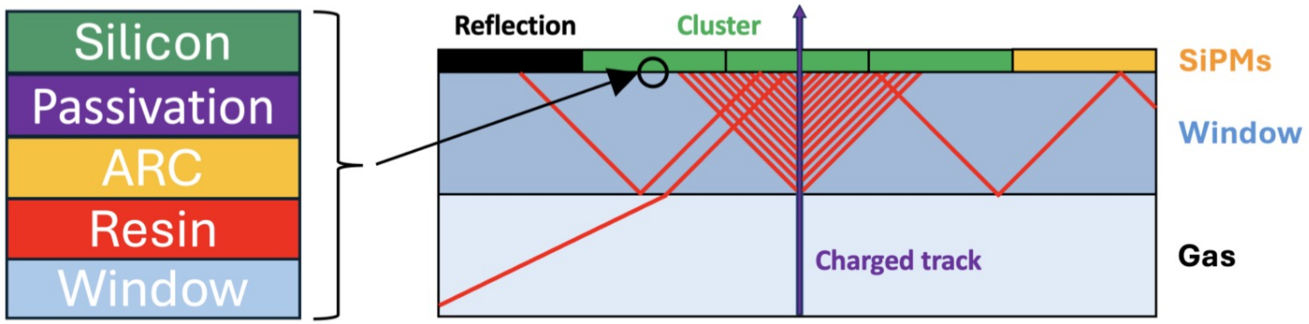
Best compromise: SiO_2, MgF_2

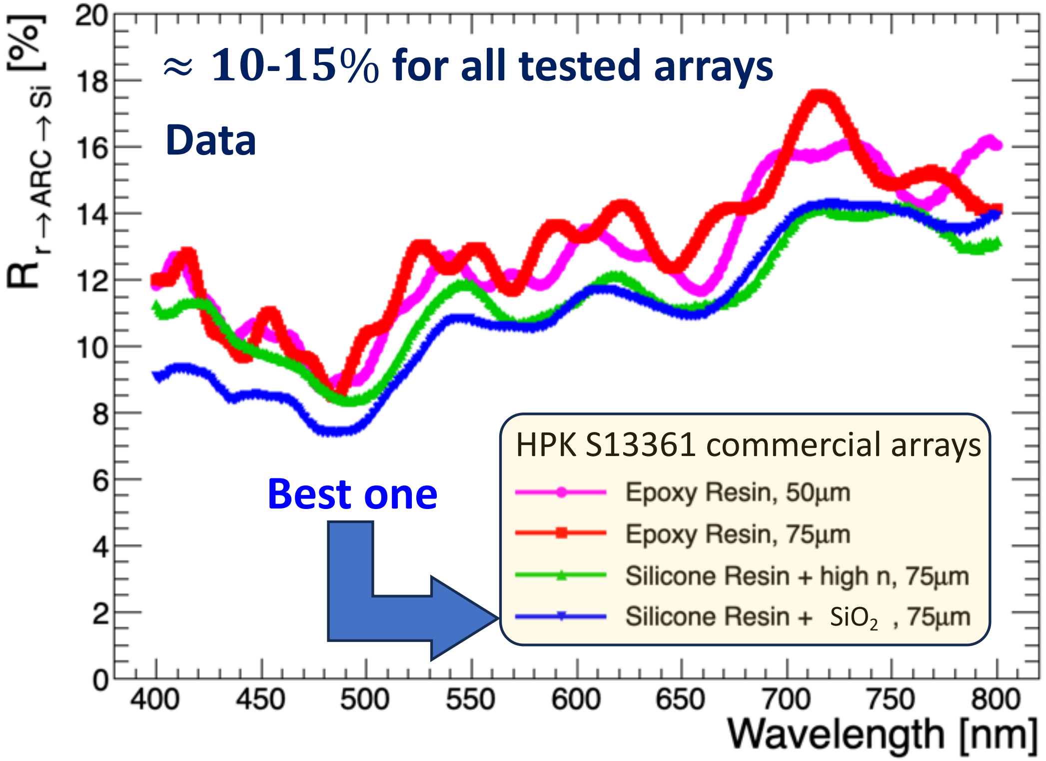
A.N.Otte NIM A 846 (2017) 106-125



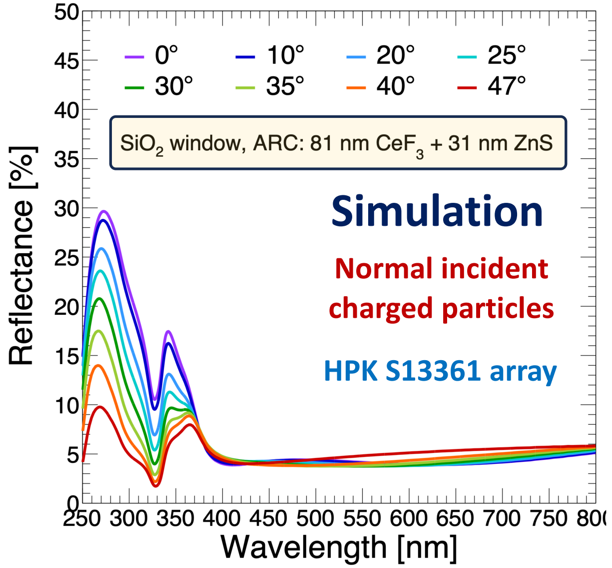
Optical coupling Window ⇔ SiPM

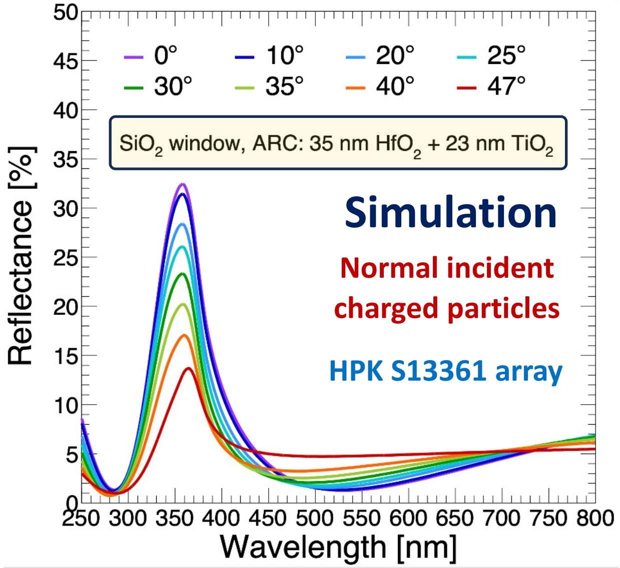
- Complex system with several interfaces between window and SiPM active area
- Reflection effects worsen the PDE and may result in delayed background hits





- Reflections ultimately controlled by SiPM ARC
- Measured R for commercial HPK arrays ≈ 12%
- Custom ARC may reduce reflectance below 5%





Simulation-based design optimization

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Resolution at single SiPM level

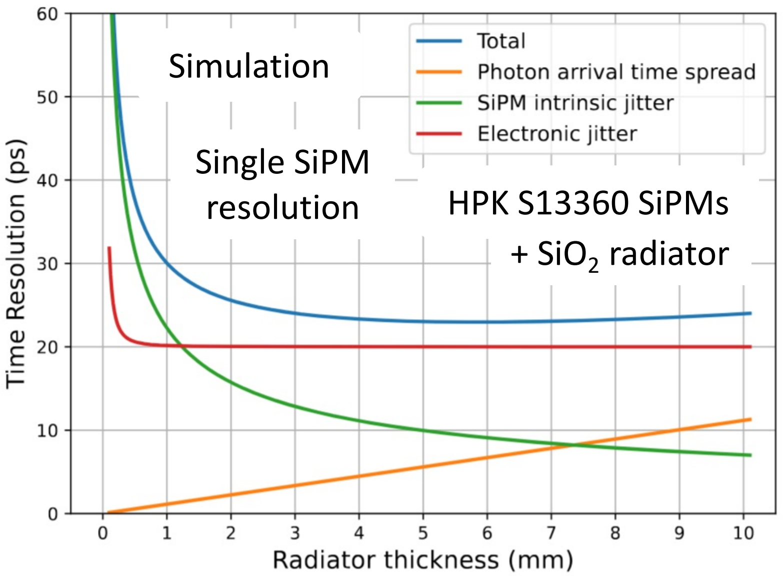
$$\sigma_t^2 = \sigma_{\mathrm{Geom}}^2 + \sigma_{\mathrm{SiPM}}^2 + \sigma_{\mathrm{FE}}^2 + \sigma_{\mathrm{TDC}}^2$$

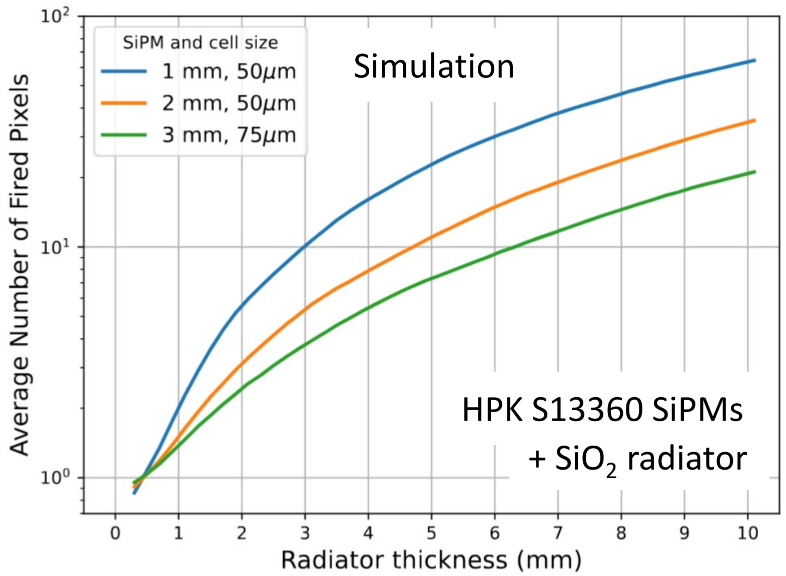
$$\left(\begin{array}{ll} \sigma_{\mathrm{SiPM}} \approx a N_{pe}^{-1/2} & \sigma_{\mathrm{FE}} \approx b\, N_{pe}^{-1} \oplus c \\ \sigma_{\mathrm{geom}} \propto \mathrm{thick} & \sigma_{\mathrm{TDC}} \approx LSB/\sqrt{12} \end{array} \right)$$

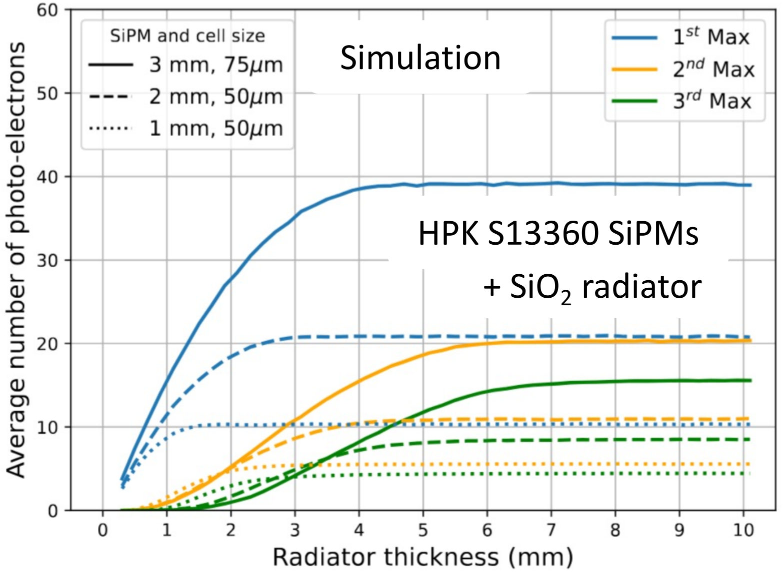
For thin windows, the dominant contributions are the intrinsic SiPM resolution and the FE contribution

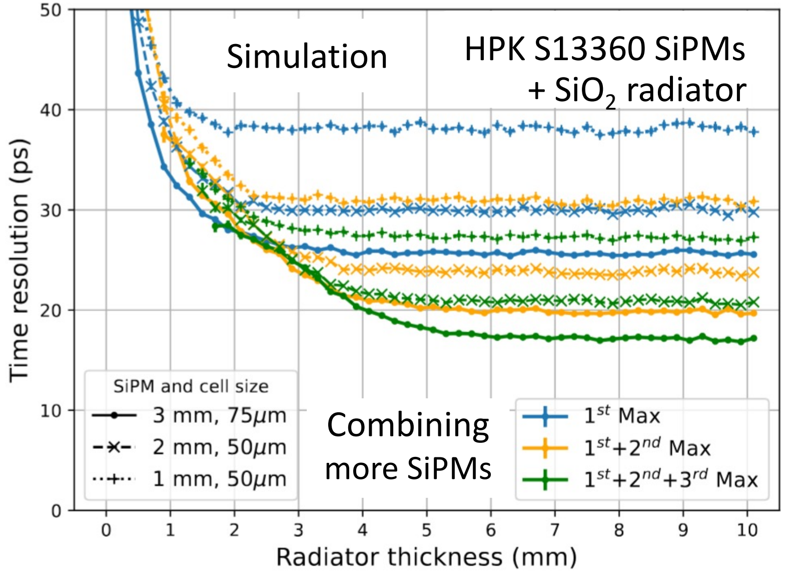
Best contribution to timing by channel with max. charge

Combining more timestamps improves σ_t IF enough PEs are detected in each SiPM









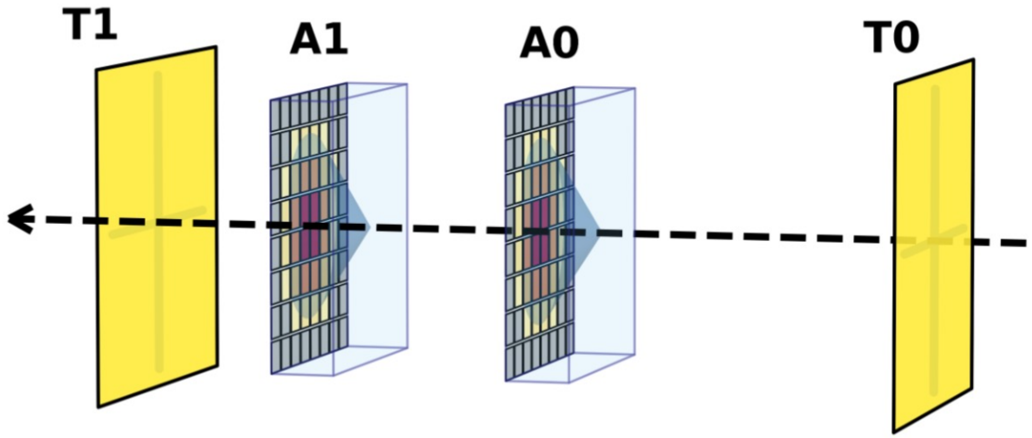
Beam test campaigns @ CERN-PS T10

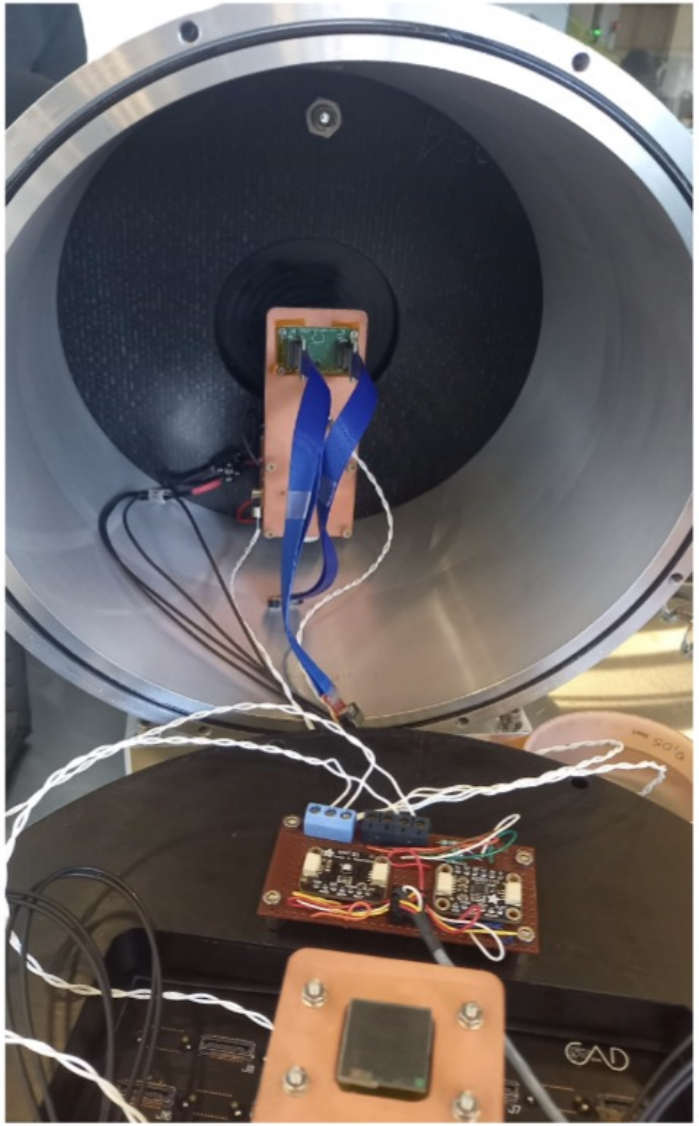
We tested various arrays + windows …

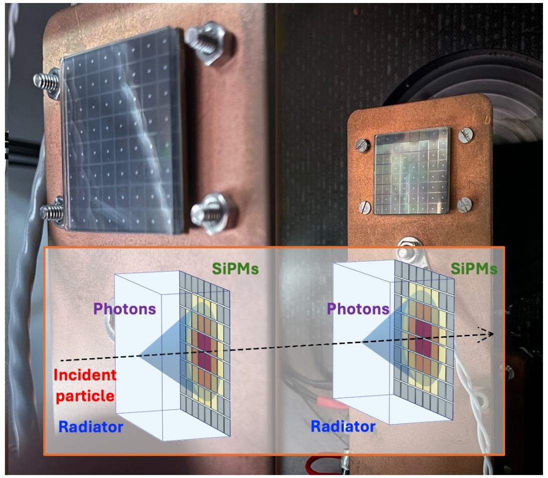
- SiPM size: 1.3 mm, 2 mm, 3 mm
- SPAD pitch: 50 um, 75 um
- Window materials: SiO_2, MgF_2
- Thickness: 1 mm, 2 mm, 3 mm

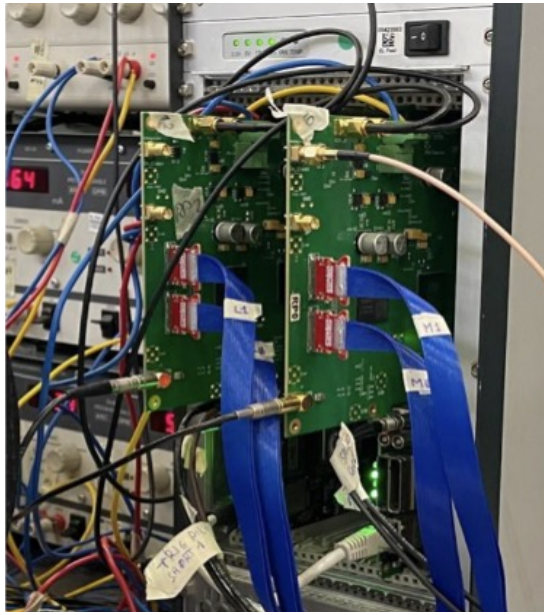
… and two different FE architectures

- Petiroc 2A (charge, ToA)
- Radioroc 2 + picoTDC (ToA , ToT)









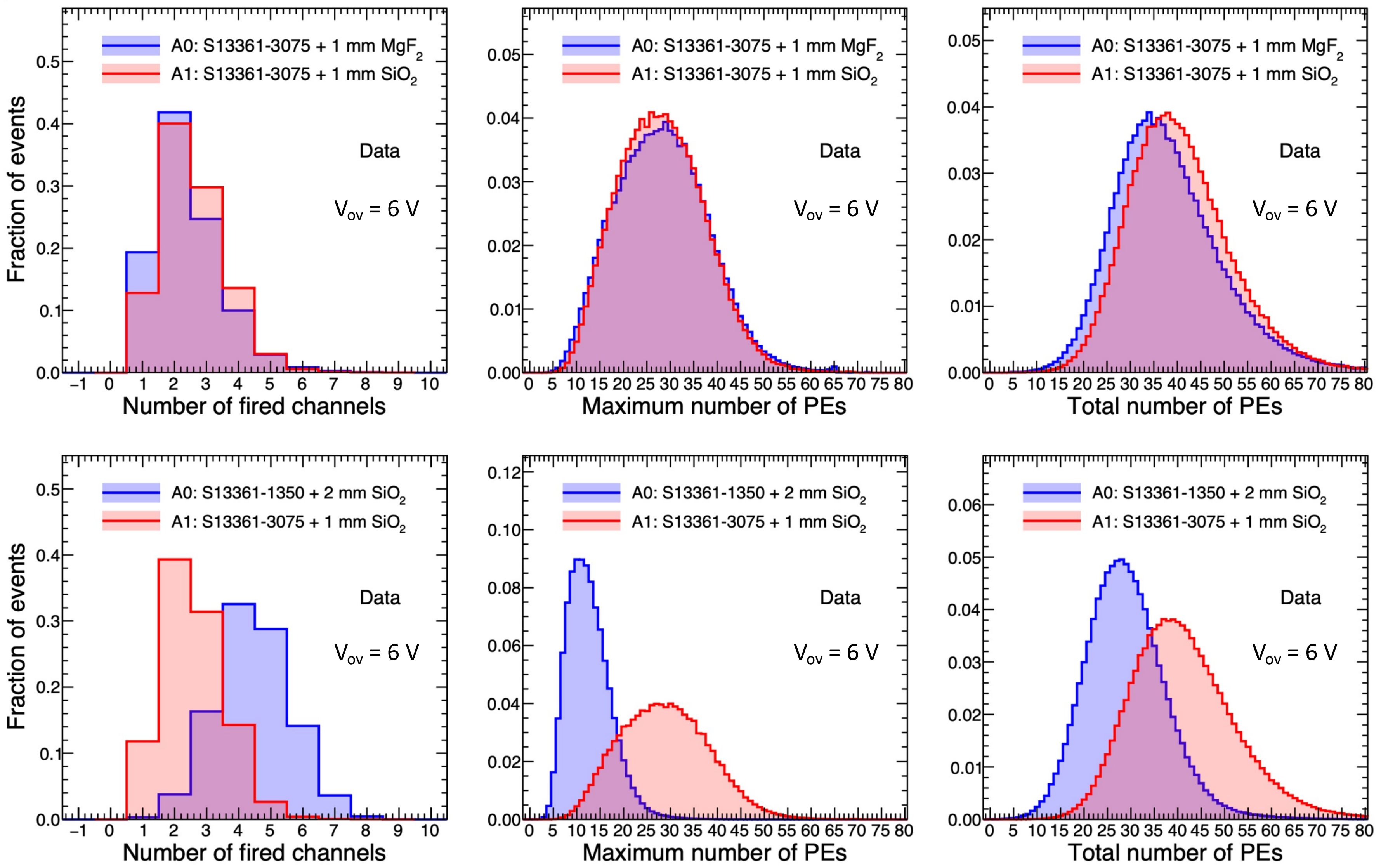
Features of radiator clusters

Measurement of SiPM clusters with more than 25 PE on average

SiO_2 and MgF_2: similar results due to their very close optical properties

Smaller SiPMs result in more fired channels with smaller charge

Measurement results are well reproduced by GEANT4 simulations

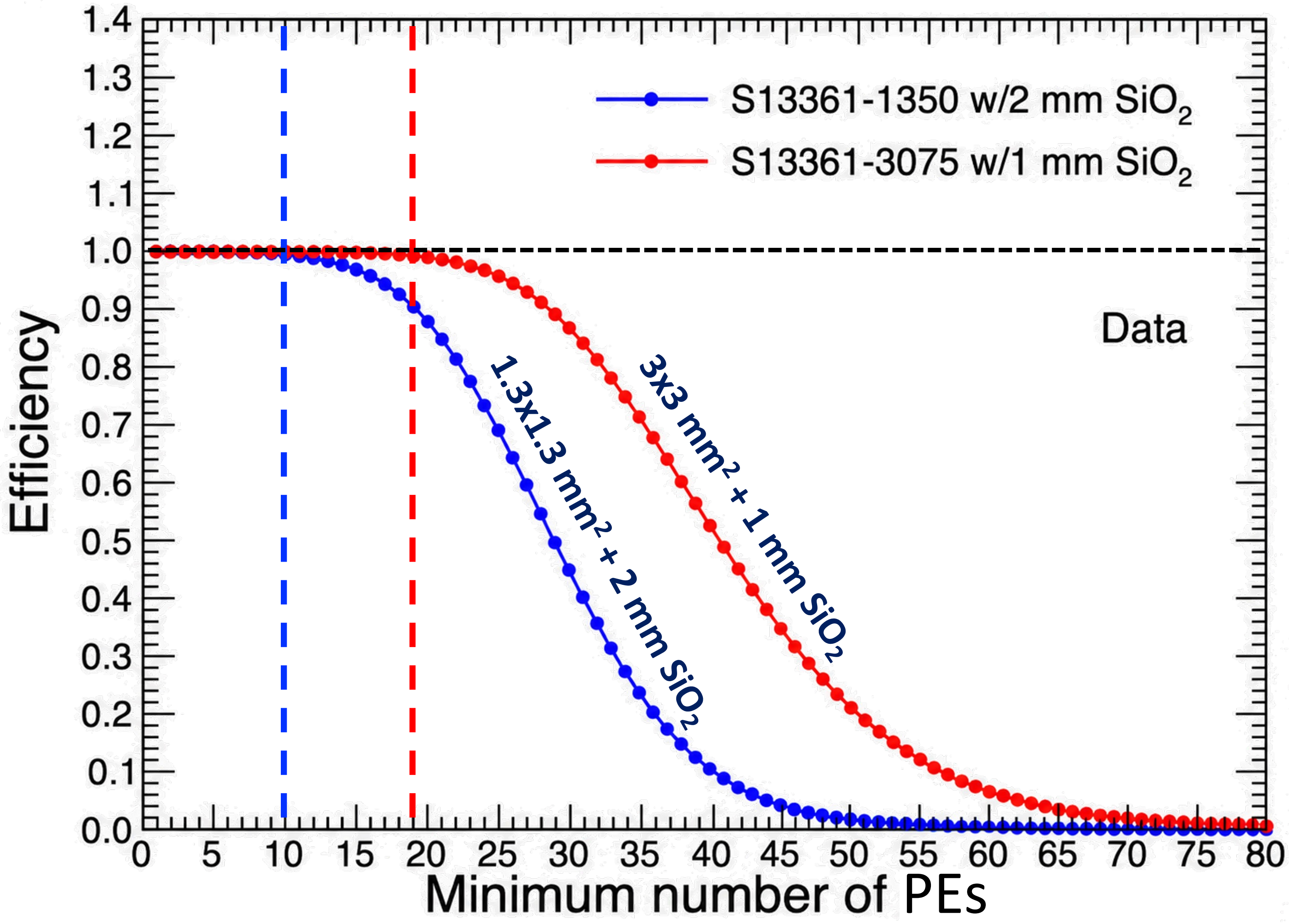


Charged particle detection efficiency

Measured efficiency of 100% at thresholds much larger than the single PE

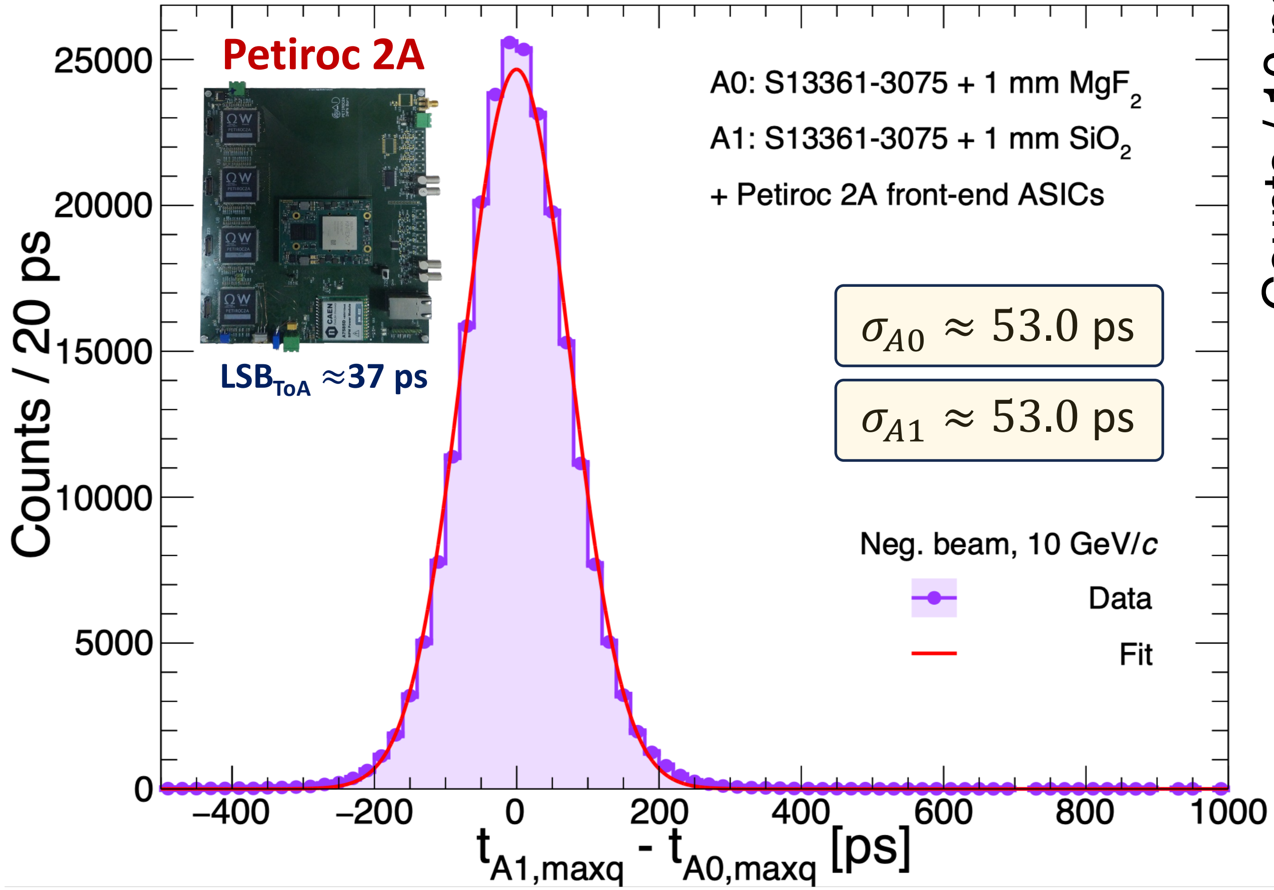
Allows stable operation at threshold that can suppress the bkg from the SiPM DCR

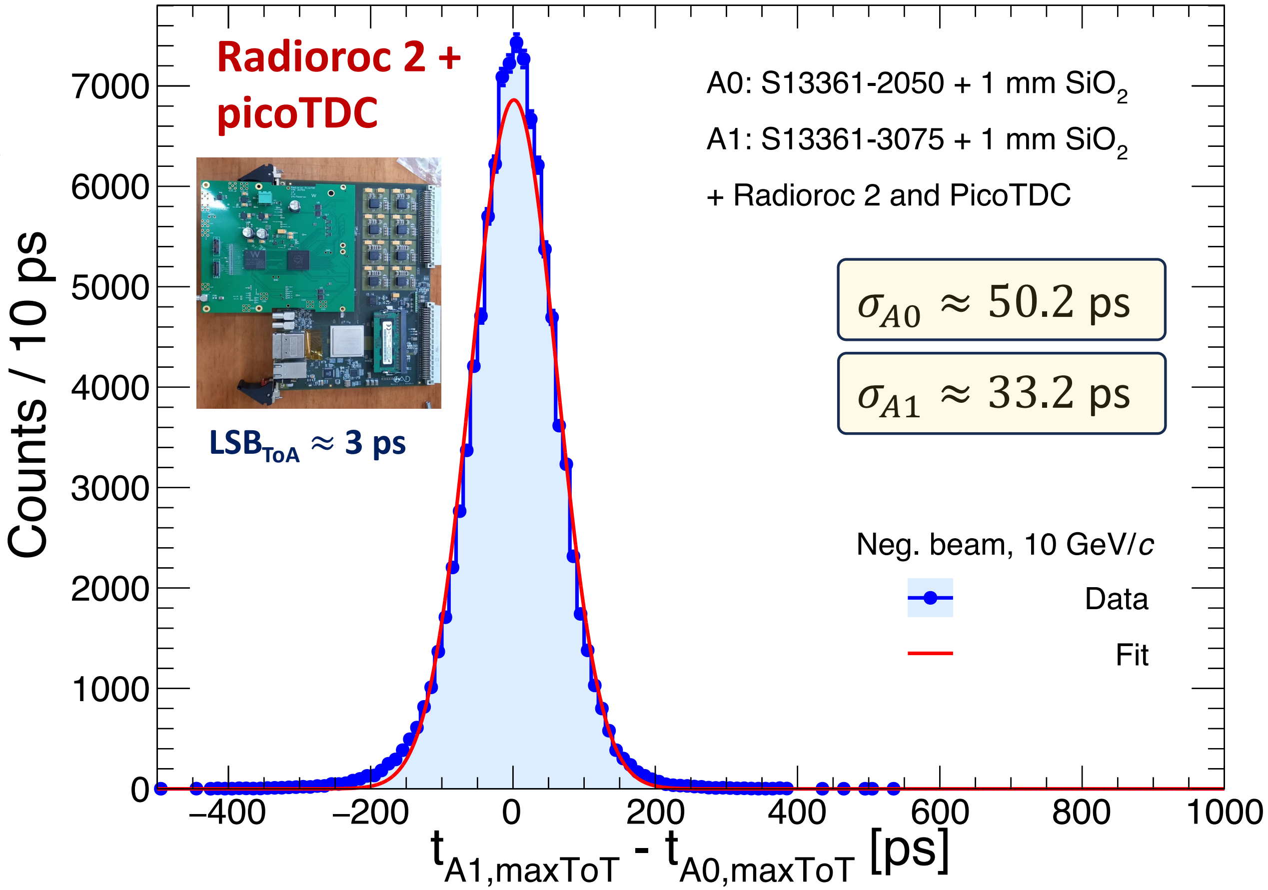
Robust option for timing in future HEP experiments where radiation tolerance is crucial



Measured time resolution

- **Correcting measured times for time-walk, channel-by-channel offsets and the π TOF**
- **Extracting σ from multi-Δt comparisons**





- **Best measured time resolution ≈ 33 ps (SiPM intrinsic res. ⊕ electronics jitter)**

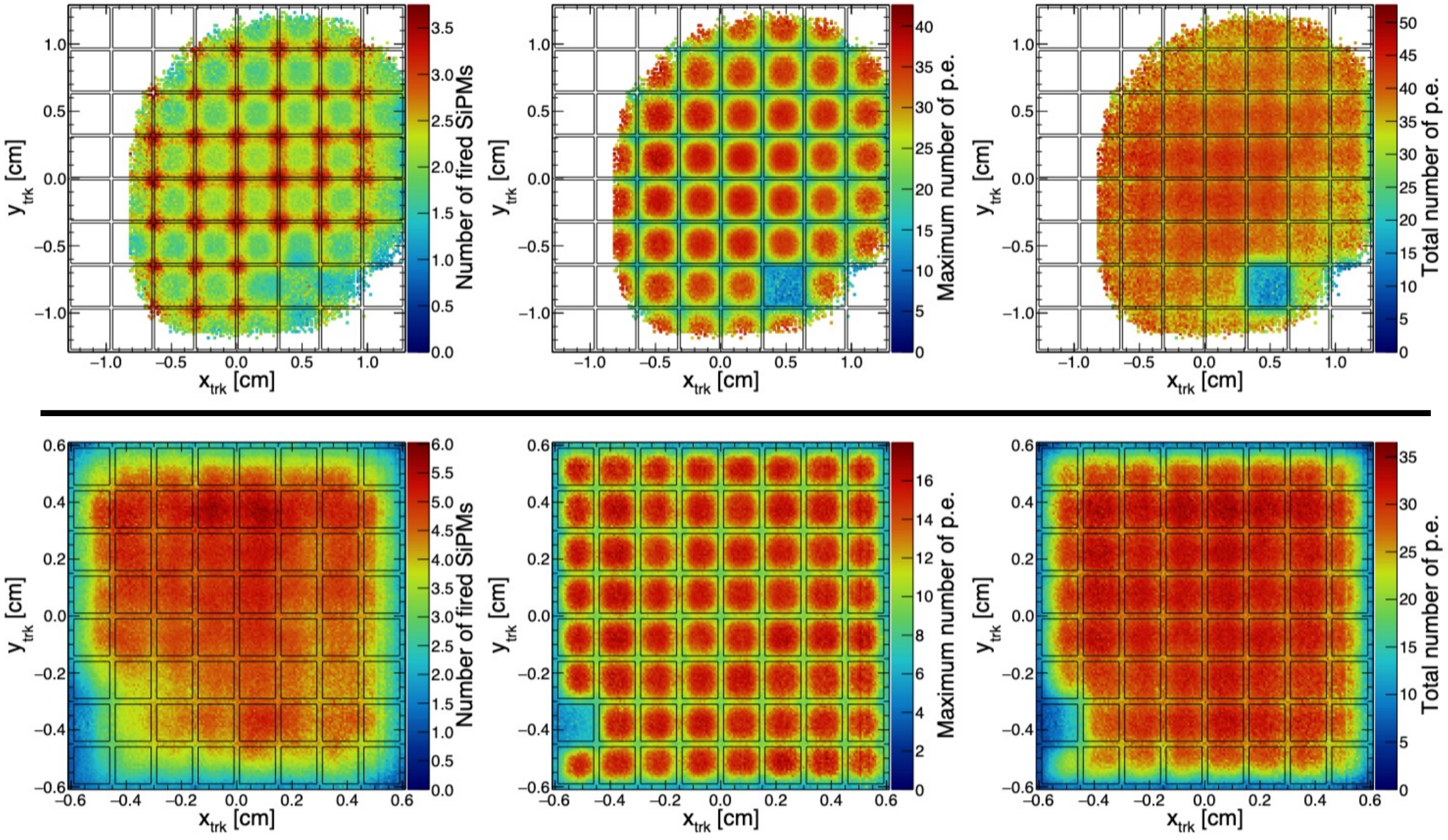
Analysis vs track impact point

Multiple channels are fired mainly for track incidence at the SiPM corners/edges

More fired SiPMs ⇒ Same total charge, but lower 1-SiPM maximum charge

Charge sharing particularly relevant for smaller SiPMs and/or thicker windows

3x3 mm^2 SiPMs + 1 mm SiO_2



1.3x1.3 mm^2 SiPMs + 2 mm SiO_2

Time resolution vs cluster mean

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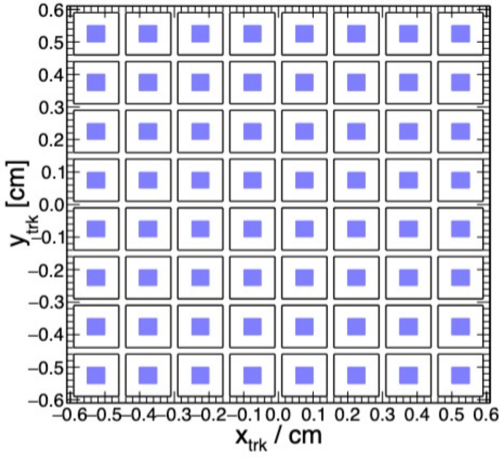
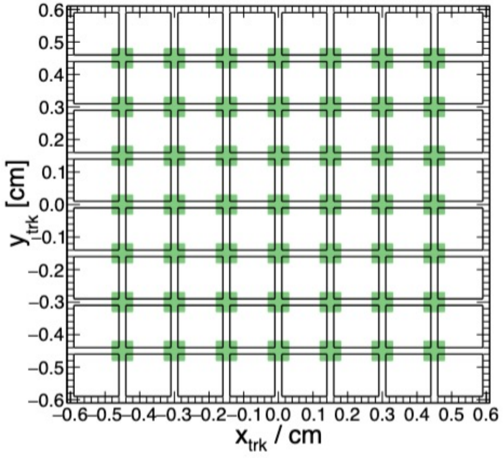
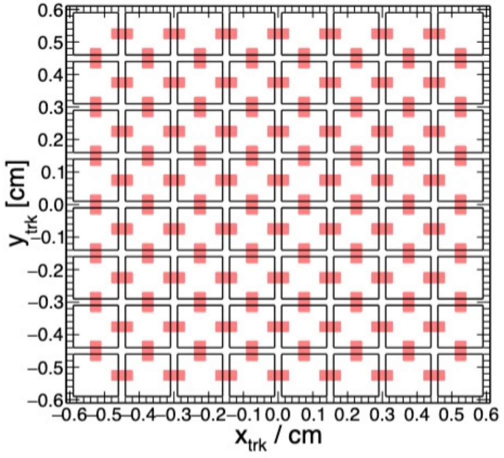
Using single SiPMs, time resolution worsens from center to eges/corners

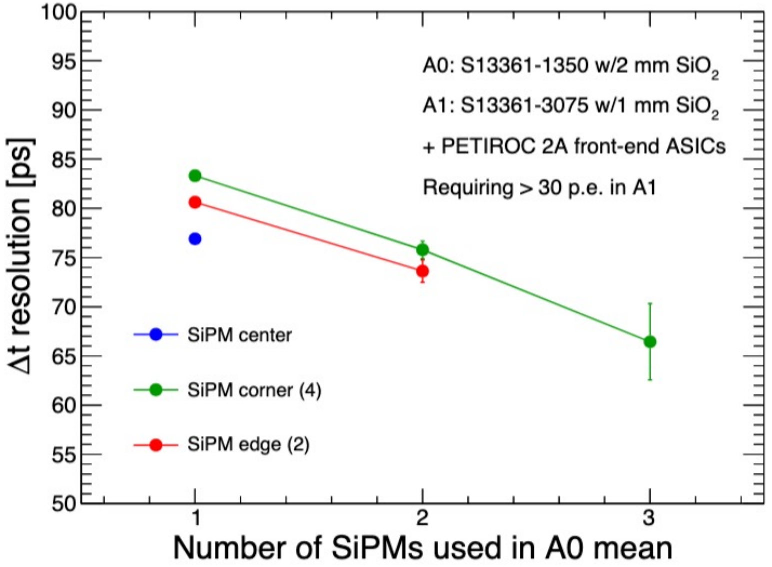
Averaging the timestamps for tracks at edges/corners improves the resolution

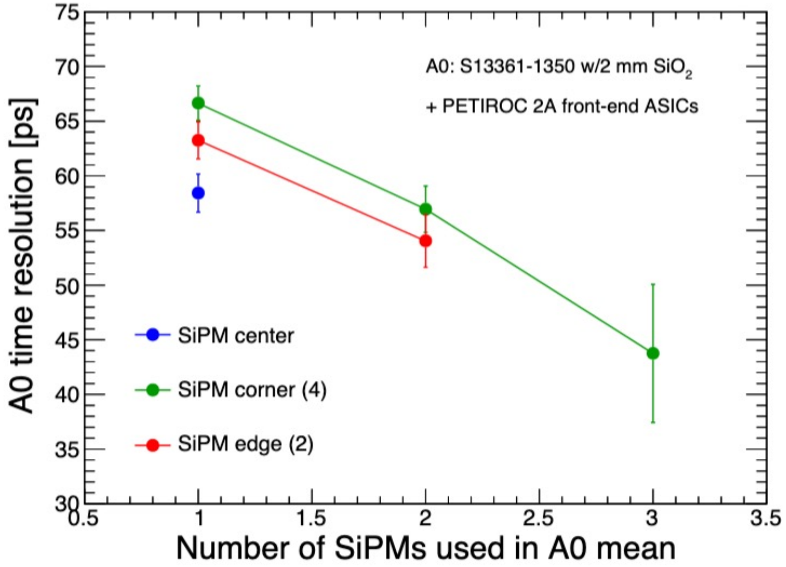
The measured resolution requiring many PE in each SiPM scales as $\approx 1 / \sqrt{N_{SiPMs}}$







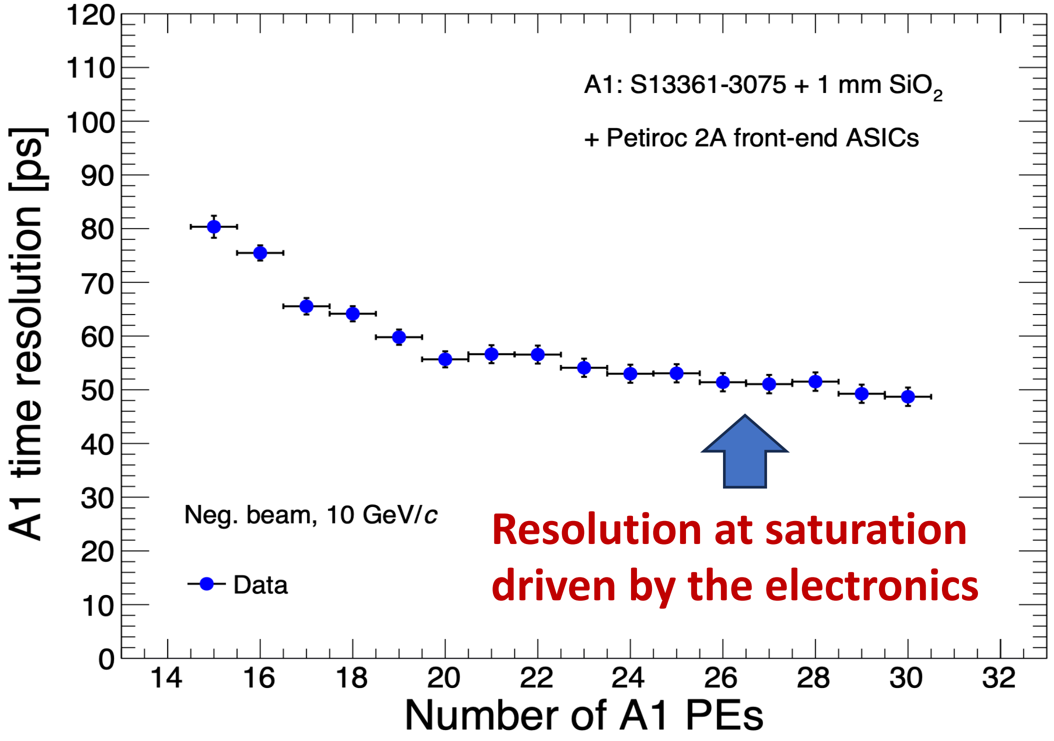




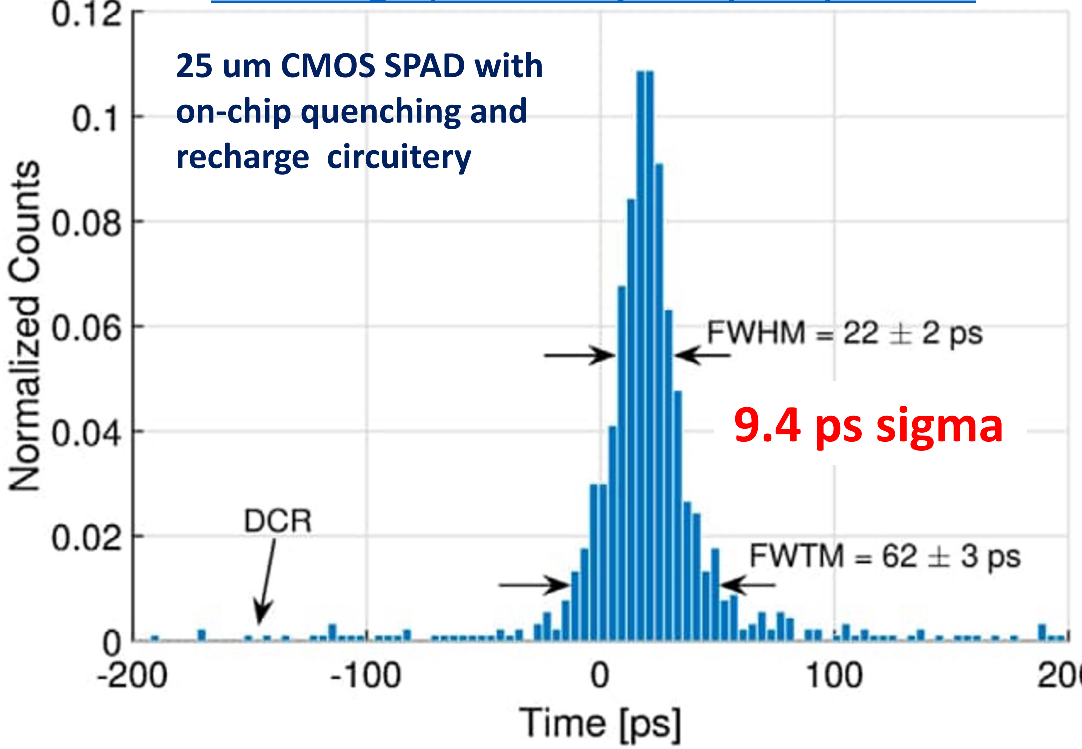
Ultimate improvement in system timing

Need for integrated electronics, including time digitizers for each SPAD (group) in a 3D layout

- **Reducing the noise, parasitic inductances and capaitances of the interconnections**



F. Gramuglia, Front. Phys. 10 (2022) 849237



The ultimate system resolution is limited by output capacitance and elec. noise/bandwidth

- **The larger the SiPM area used for timing the more important this effect becomes**

Next step: improving intrinsic res.

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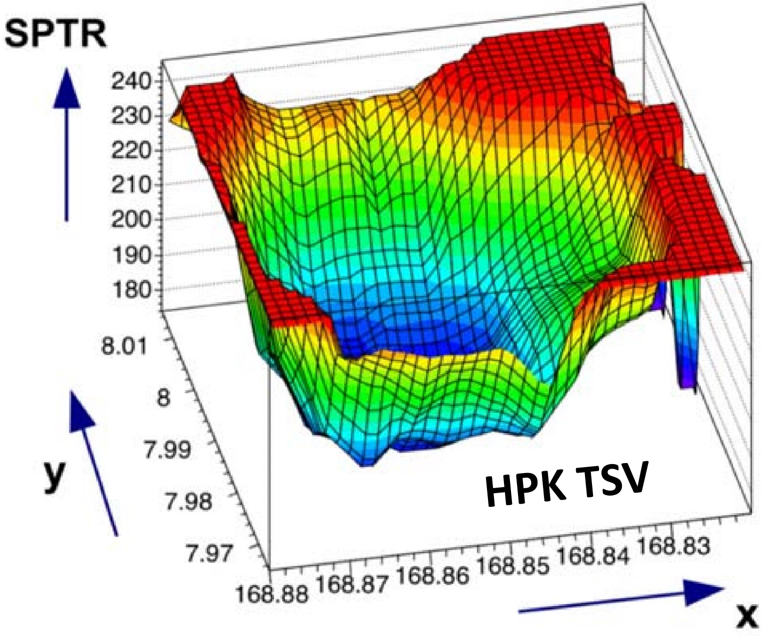
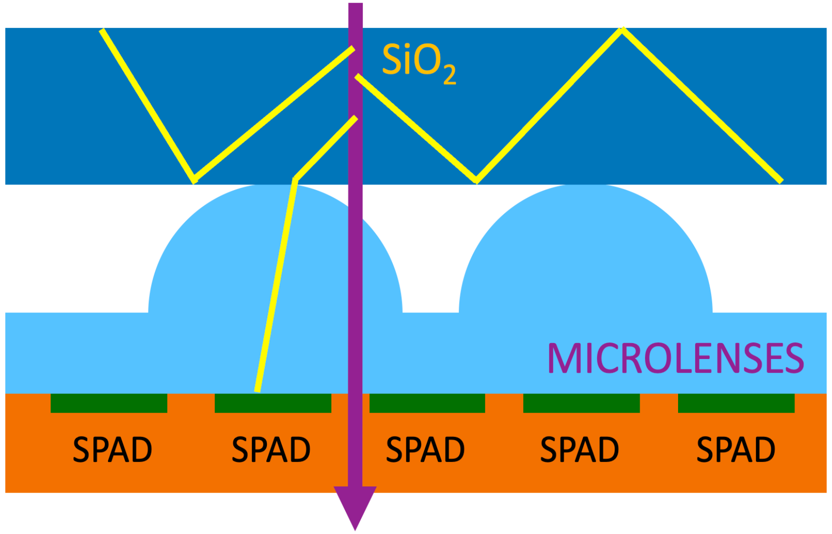
Intrinsic SiPM limit: worst timing at SPAD borders

Masking borders improves timing, BUT worsens PDE

S.Gundaker Phys. Med. Biol. 68 (2023) 165016





Idea: using focusing optics

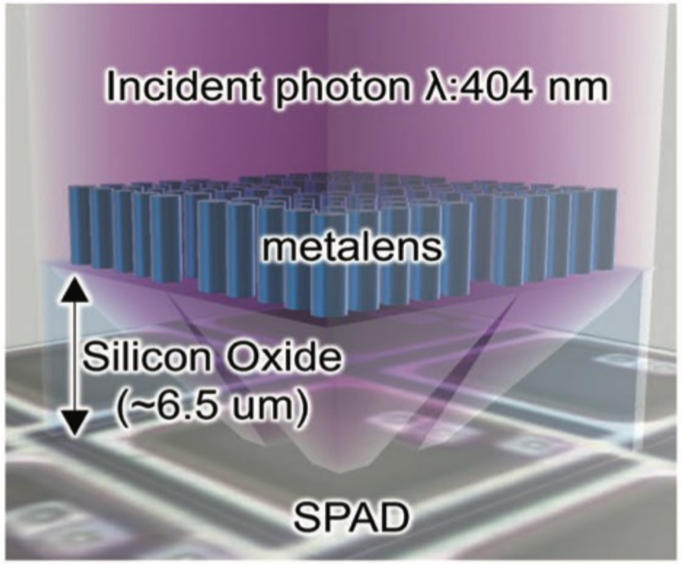
Problem: Refractive μ-lenses not compatible with radiator coupling (gaps → reflections)

Solution: using metalenses

Metalenses: thin planar lenses based on nanostructures

Already validated for scintillation light

S.Uenoyama Adv. Optical Mater. 10 (2022) 2102707



CHRONOS (submitted for INFN-ECR grant)

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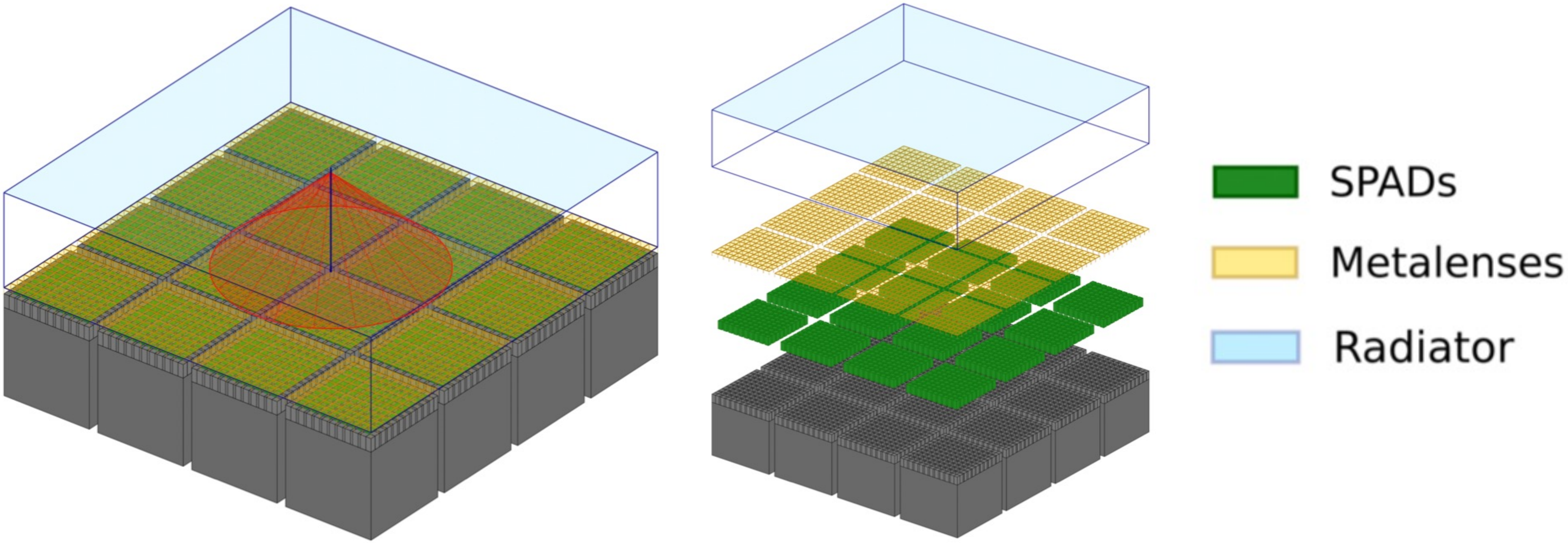
CHRONOS: CHerenkov RadiatOr integrated Nanophotonic Optics for fast SiPM timing



Conclusions

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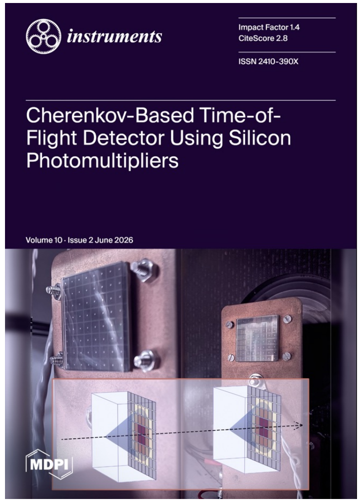
- **Proved the effectiveness of coupling thin windows to SiPMs for improving MIP timing capabilities with an efficiency of 100%**
- **Measured an overall time resolution at full system level of ≈ 30 ps including both the intrinsic SiPM res. and off-the shelf electronics**
- **Next steps: metalenses to achieve the ultimate intrinsic resolution and optimized front-end to minimize the resulting electronic jitter**

Article https://doi.org/10.3390/instruments10020028

Development of a Cherenkov-Based Time-of-Flight Detector Using Silicon Photomultipliers

Liliana Congedo [1], Giuseppe De Robertis [1], Antonio Di Mauro [2], Mario Giliberti [1,3], Francesco Licciulli [1], Antonio Liguori [1,3], Rocco Liotino [1,3], Leonarda Lorusso [1], Mario Nicola Mazziotta [1,*], Eugenio Nappi [1], Nicola Nicassio [1,2,3,*], Giuliana Panzarini [1], Roberta Pillera [1] and Giacomo Volpe [1,3]

1 Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Bari, via Orabona 4, 70125 Bari, Italy
2 European Organization for Nuclear Research (CERN), Esplanade des Particules 1, 1211 Geneva, Switzerland
3 Dipartimento di Fisica dell'Università e del Politecnico di Bari, via Amendola 173, 70126 Bari, Italy
* Correspondence: marionicola.mazziotta@ba.infn.it (M.N.M.); nicola.nicassio@ba.infn.it (N.N.)



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Thank you for your attention

Nicola.Nicassio@ba.infn.it

Backup

Cherenkov radiation

Charged particles traversing a medium with velocity greater than the phase velocity of light in the medium radiate prompt photons with defined angle and polarization

- **Emission threshold**

$$\beta > \frac{1}{n(\lambda)} \Rightarrow p_{\mathrm{th}} = \frac{m}{\sqrt{n^2(\lambda) - 1}}$$

- **Emission angle**

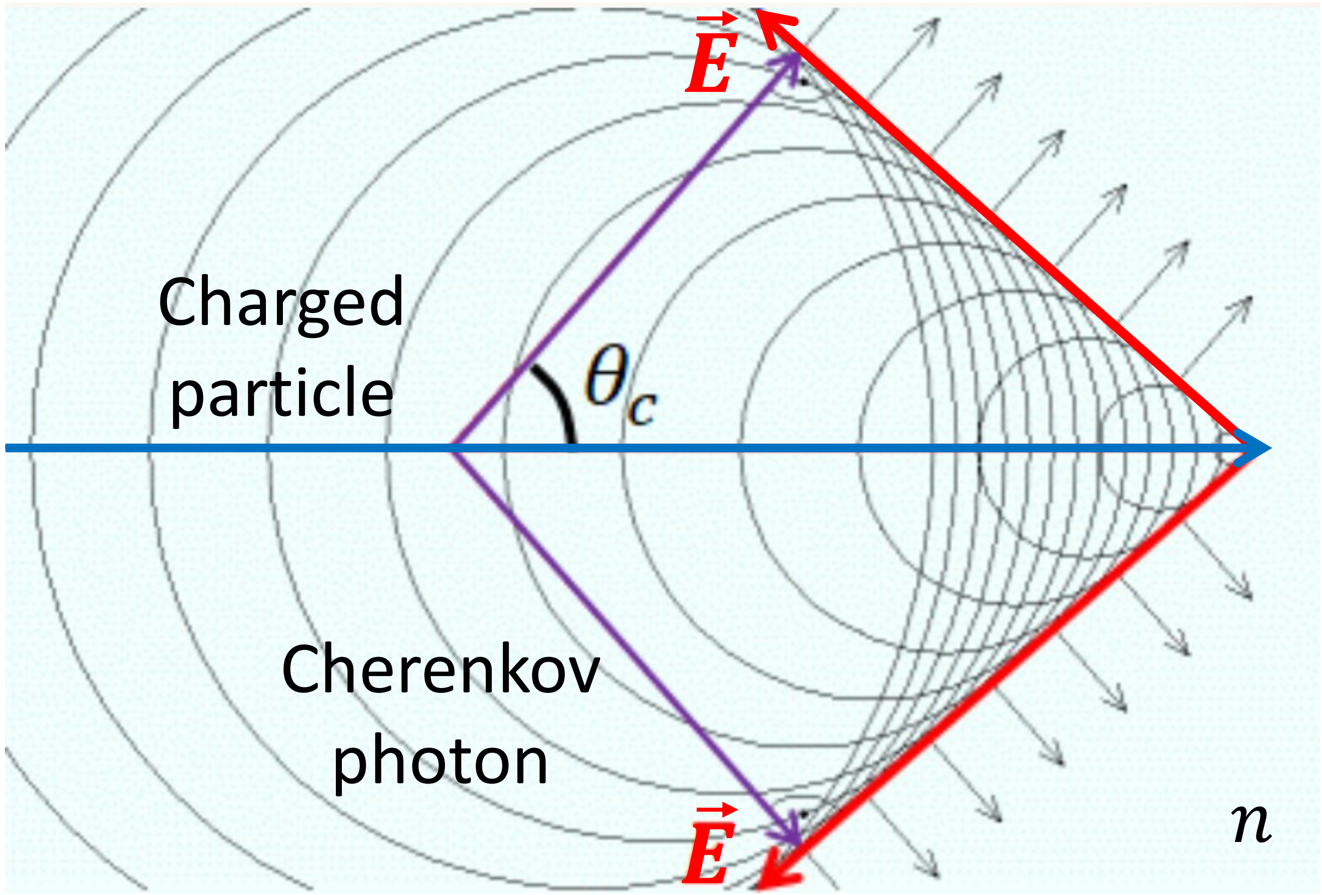
$$\cos\theta_c = \frac{1}{n(\lambda)\beta} = \frac{\sqrt{p^2 + m^2}}{n(\lambda)p}$$

- **Number of photons**

$$\frac{\mathrm{d}^2 N}{\mathrm{d}E\mathrm{d}x} = \left(\frac{\alpha}{\hbar c}\right) Z^2 \sin^2\theta_c$$

- **Polarization**

  $\vec{E}$ normal to the cone surface

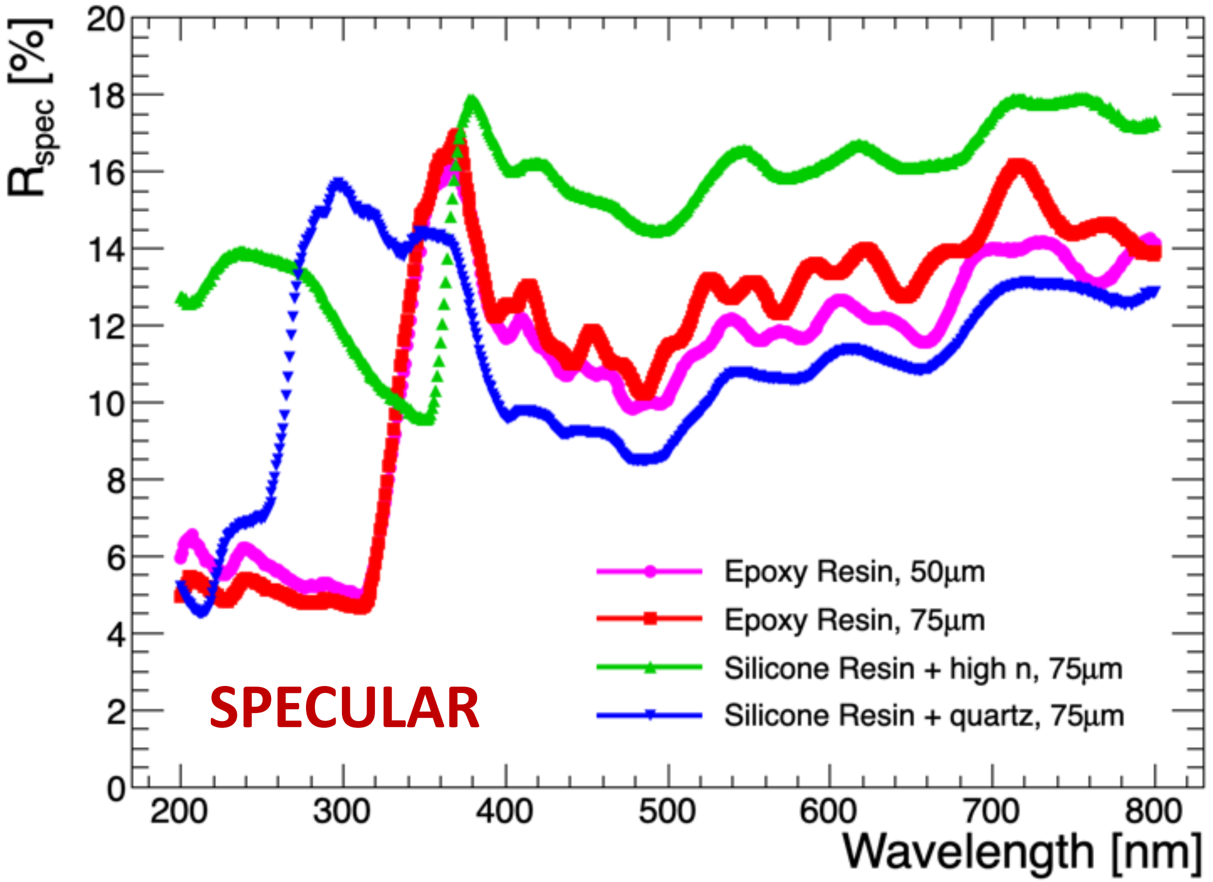


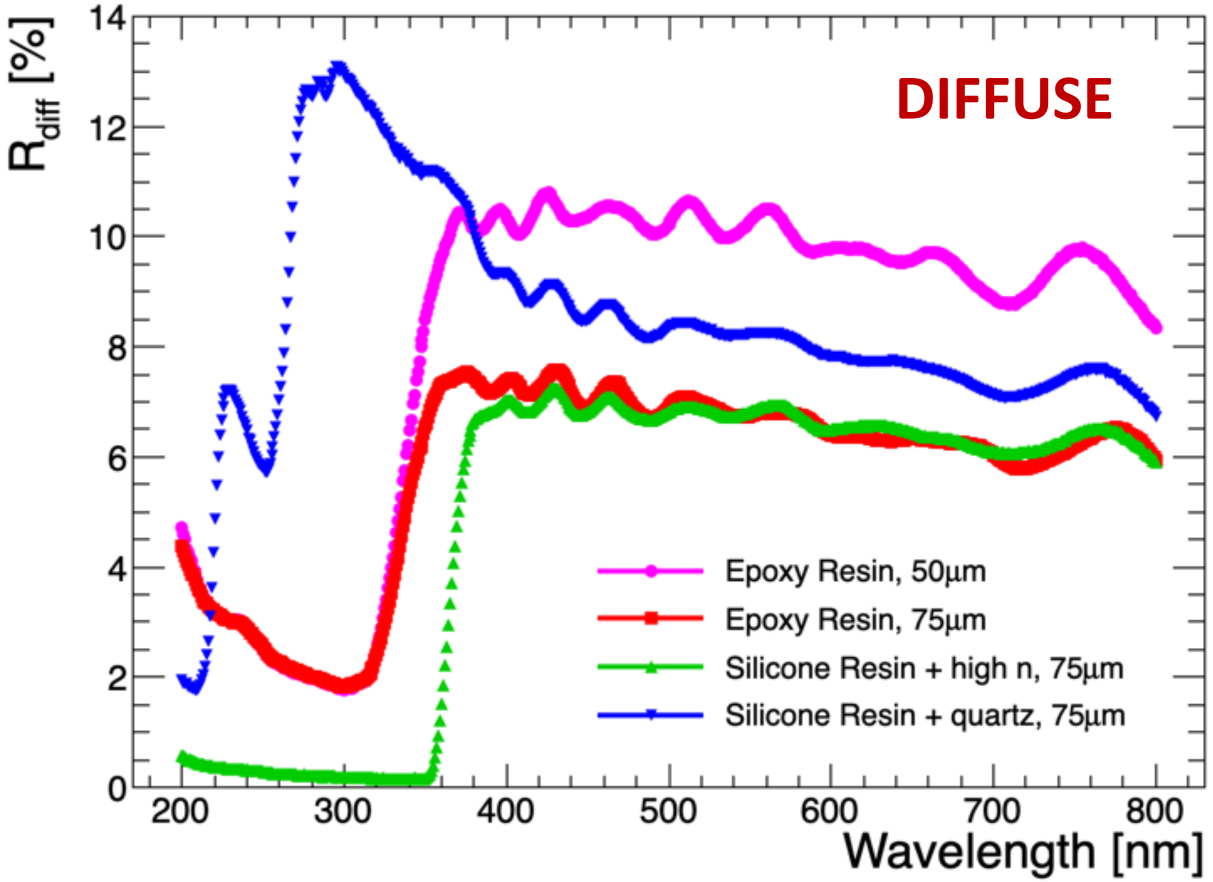
Reflectance measurements

We measured the specular and diffuse relfectance of various Hamamatsu arrays

We tested various SiPM sizes, SPAD sizes, protective layers and radiator windows

Best performance using silicone resin + SiO_2 (best coupling + UV transmission)





Simplified SiPM reflection model

Reflection model assuming no window

$$R_{spec} = R_{a\to r} + (1 - R_{a\to r}) \cdot IF \cdot FF \cdot \boldsymbol{R_{r\to ARC\to Si}} \cdot (1 - R_{r\to a})$$

$$R_{diff} = (1 - R_{a\to r}) \cdot [(1 - IF) \cdot \boldsymbol{R_{diff2}} + \cdot IF \cdot (1 - FF) \cdot \boldsymbol{R_{diff1}}] \cdot (1 - \langle R_{diff,r\to a} \rangle)$$

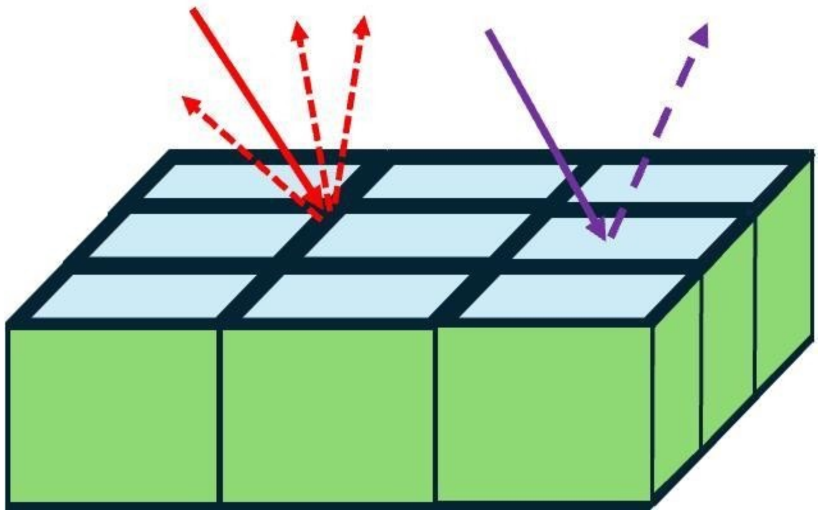
Reflection model including window

$$R_{spec} = R_{a\to w} + (1 - R_{a\to w})R_{w\to r} + (1 - R_{a\to w})(1 - R_{w\to r}) \cdot IF \cdot FF \cdot \boldsymbol{R_{r\to ARC\to Si}} \cdot (1 - R_{r\to w})(1 - R_{w\to a})$$

$$R_{diff} = (1 - R_{a\to w})(1 - R_{w\to r}) \cdot [(1 - IF) \cdot \boldsymbol{R_{diff2}} + \cdot IF \cdot (1 - FF) \cdot \boldsymbol{R_{diff1}}] \cdot (1 - \langle R_{diff,r\to w\to a} \rangle)$$

Assumptions of the model

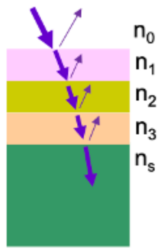
- Only specular reflection at the optical inferfaces $a \leftrightarrow r, a \leftrightarrow w, w \leftrightarrow r$
- Only specular reflection $\boldsymbol{R_{r\to ARC\to Si}}$ **in SiPM active area** (fraction = $IF \cdot FF$)
- Only diffuse reflection $\boldsymbol{R_{diff1}}$ **in SiPM dead area** (fraction = $IF \cdot (1 - FF)$)
- Only diffuse reflection $\boldsymbol{R_{diff2}}$ **in matrix dead area** (fraction = $(1 - IF)$)



Notation:
- a = air
- w = window (SiO_2 layer)
- r = resin
- IF = Integration factor
- FF = Fill factor of the single SiPM
- ARC = Anti-Reflective-Coating
- $R_{x\to y}$ calculated using Fresnel equations
- $\langle R_{diff,x\to\cdots\to z} \rangle$ calculated from Monte Carlo assuming random isotropic reflection angle

Simulating multi-layer thin-film reflectance

Thin films: Matrix formalism



- Consider light incident at angle θ_i on stack:
  - Incident medium: $n_0 = \mathrm{Re}(n_0) + i\,\mathrm{Im}(n_0)$
  - N films (j = 1,…,N) : $n_j = \mathrm{Re}(n_j) + i\,\mathrm{Im}(n_j)$
  - Substrate medium : $n_s = \mathrm{Re}(n_s) + i\,\mathrm{Im}(n_s)$
- Extract the resulting 2x2 thin-film transfer matrix

$$F = F_1 F_2 F_3 \ldots F_N = \begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

where for layers j = 1,…, N having thickness d_j

$$F_j = \begin{bmatrix} \cos(\delta_j) & \dfrac{-i\sin(\delta_j)}{\alpha_j} \\ -i\alpha_j \sin(\delta_j) & \cos(\delta_j) \end{bmatrix}$$

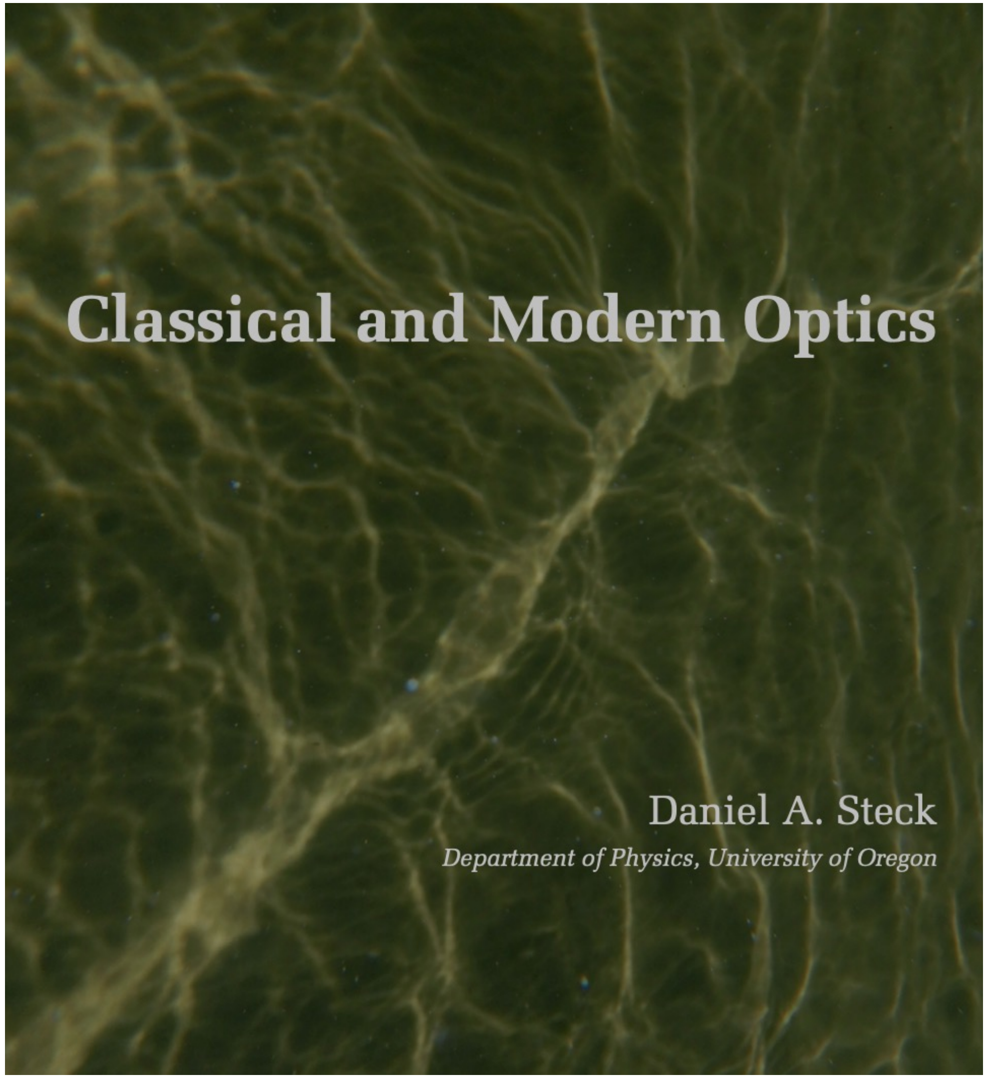
$$\alpha_j = n_j \cos(\theta_{tj}) \ (\mathrm{P-polarization})\ (\mathrm{Also\ for\ j = 0, s})$$
$$\alpha_j = n_j / \cos(\theta_{tj}) \ (\mathrm{S-polarization})\ (\mathrm{Also\ for\ j = 0, s})$$
$$\delta_j = \frac{2\pi}{\lambda} n_j d_j \cos(\theta_{tj}) \quad \mathrm{with} \quad \theta_{tj} = \sin^{-1}\left(\frac{n_i}{n_j}\sin(\theta_0)\right)$$

- Calculate reflection coefficient and reflectance

$$r = \frac{\alpha_0 A + \alpha_0 \alpha_s B - C - \alpha_s D}{\alpha_0 A + \alpha_0 \alpha_s B + C + \alpha_s D} \Rightarrow R = rr^*$$

- For thick layers ($d_j \gg \lambda$ e.g. for $\approx 100\ \mu m$ SiPM resin) coherence is lost and R must be averaged over δ_{resin}

Reference: Chapter 10 from



Optimizing radiator coupling

Assumptions

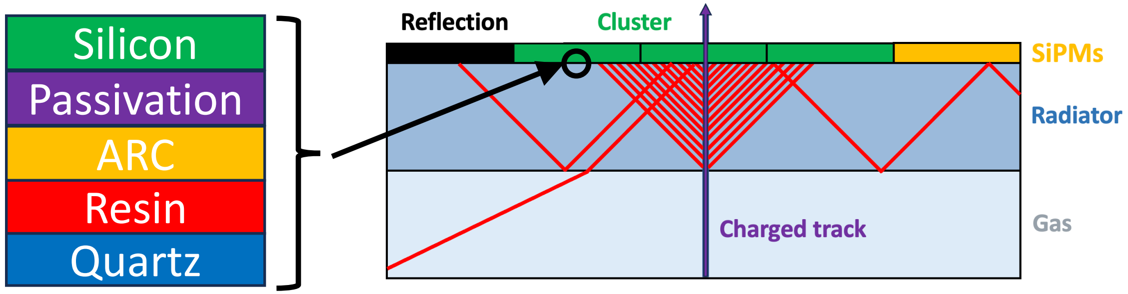
- Quartz radiator material: incoherent layer
- Silicone resin: 100 μm incoherent layer
- (ARC: CeF_3 + ZnS : thickness to be optimized)
- (SiO_2 passivation layer: assuming 10 nm)
- Silicon substrate: semi-infinite approximation
- SiPM PDE(λ) profile of HPK S13360-3050CS

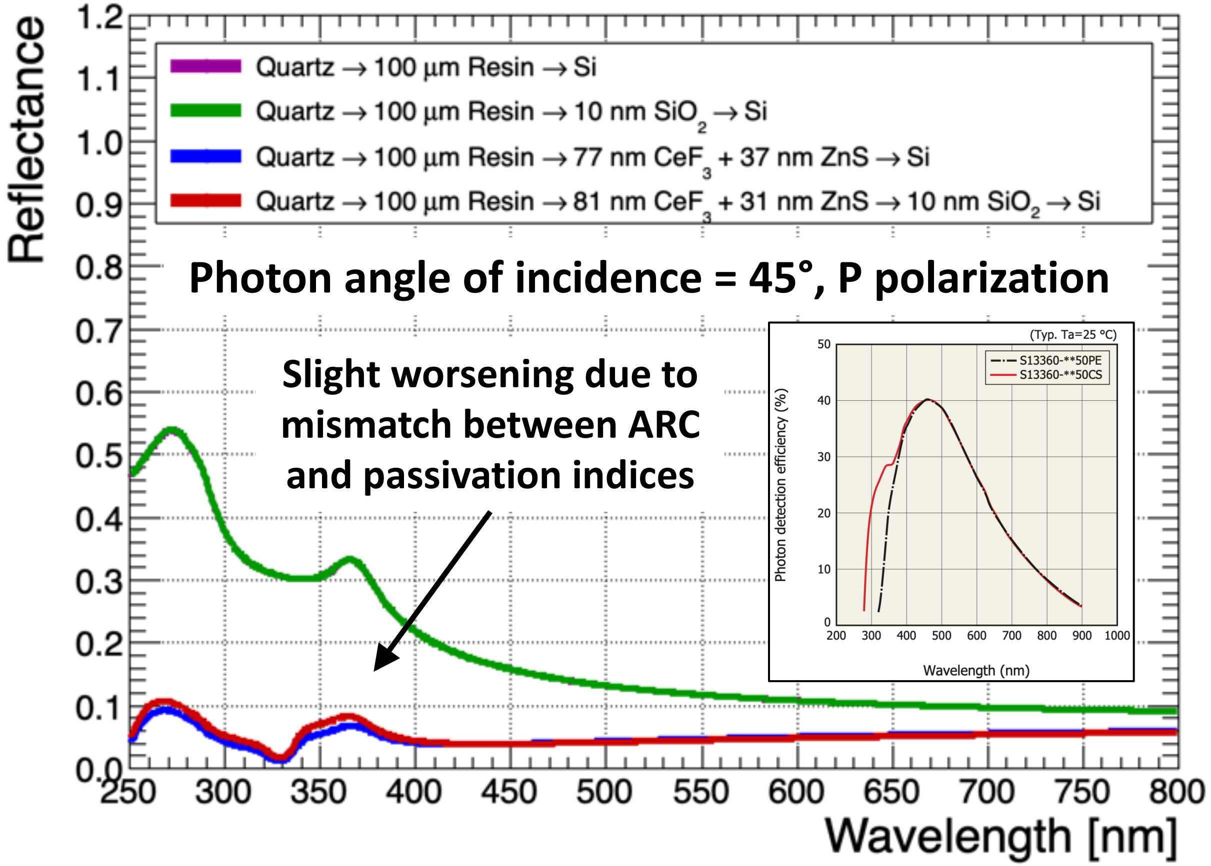
Remember

- Cherenkov photon yield $dN/d\lambda$ scales as λ^{-2}
- Cherenkov photons have inherent polarization perpendicular to Cherenkov cone's surface

Optimization criterion

- Quartz C.kov photons by normal MIP: $\theta_i \approx 45°$
  ➔ P polarization, but in case of not normal incidence a S component also appears
- **Taking ARC thicknesses minimizing reflectance weigthing each λ contribution by $PDE(\lambda) \cdot \lambda^{-2}$**





Beam tests: Front-end & DAQ boards

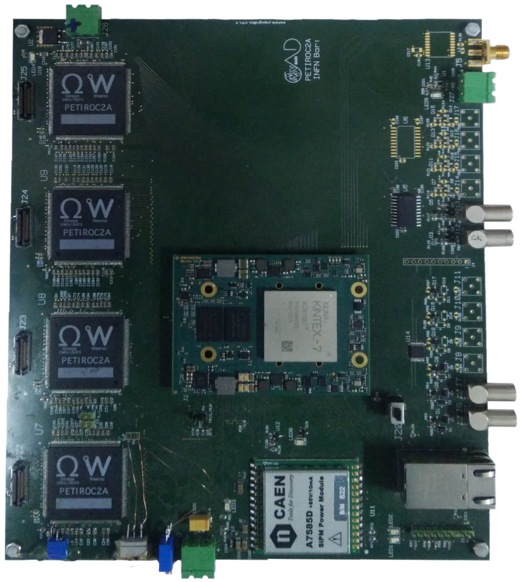
Petiroc 2A

TDC (LSB ≈ 37 ps) and ADC (10 bits)

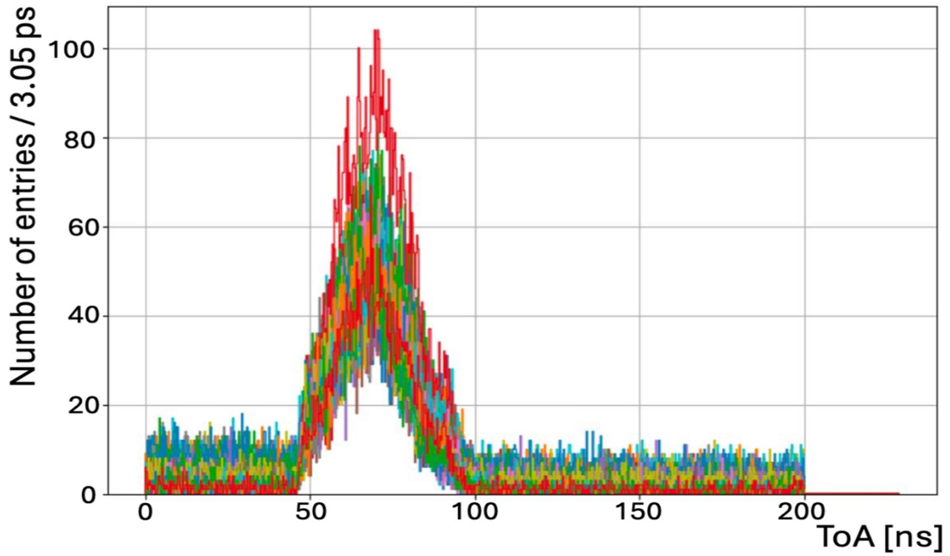
Radioroc 2 + picoTDC

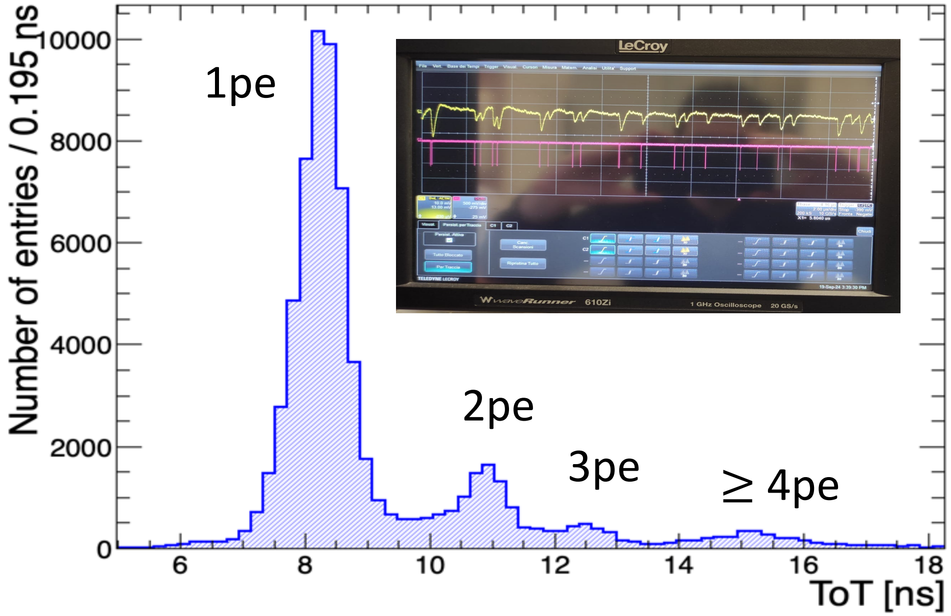
ToA LSB ≈ 3 ps, ToT LSB ≈ 195 ps

Petiroc board



RadioPico board





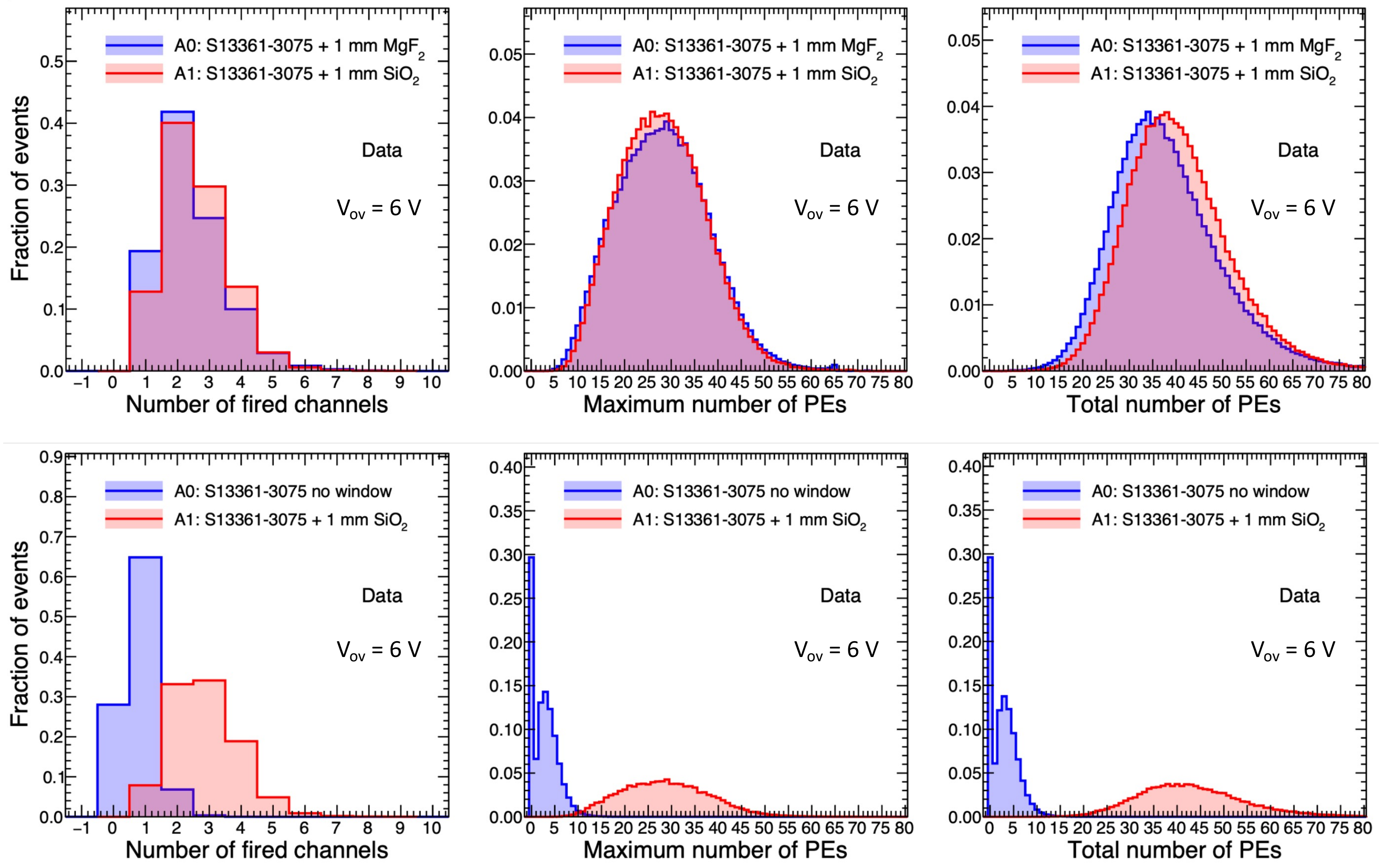
Comparison with «bare» arrays

«Bare» arrays ≡ only ≈100 μm built-in resin

N_{pe} of bare array also includes extra DCR due to lower op. threshold

Confirmation that the observed excess mostly comes from the window

Measurement results are well reproduced by GEANT4 simulations



Less PEs with double rad thickness?

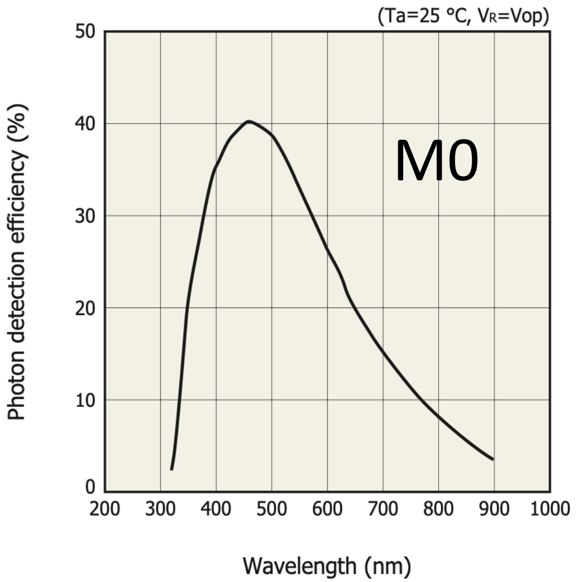
INFN BARI
Istituto Nazionale di Fisica Nucleare
Sezione di Bari

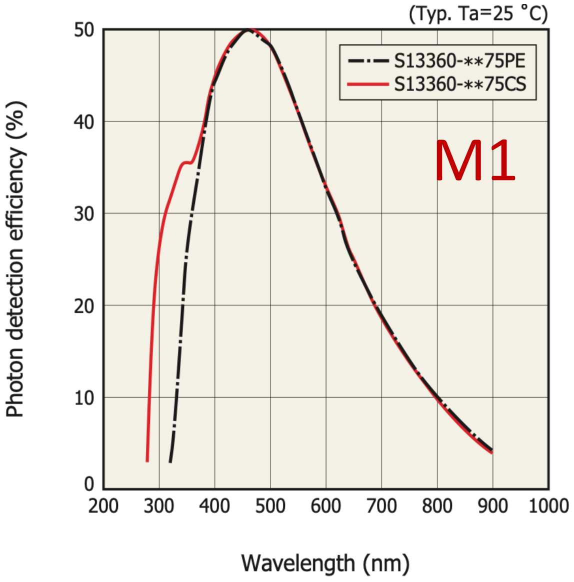
Case: M0 1.3x1.3 mm^2 w/2mmSiO_2 window, M1 3.0x3.0 mm^2 w/1mmSiO_2 window

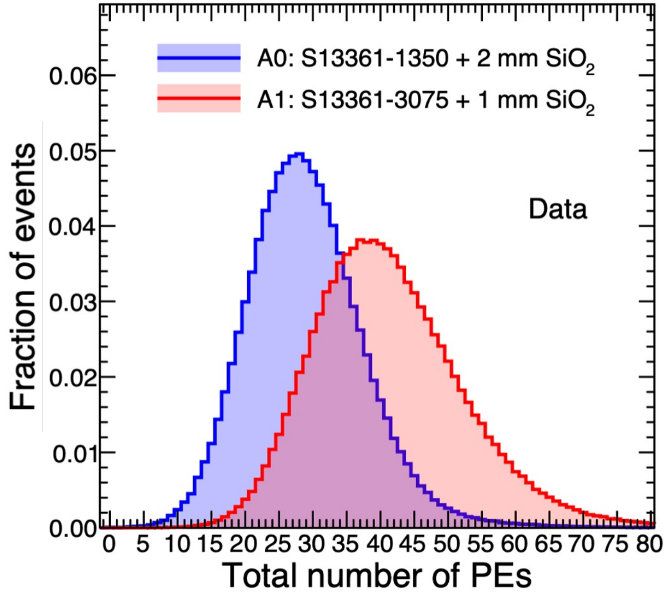
Why 2 mm of SiO2 in M0 results in less photon than 1 mm of SiO_2 in M1?

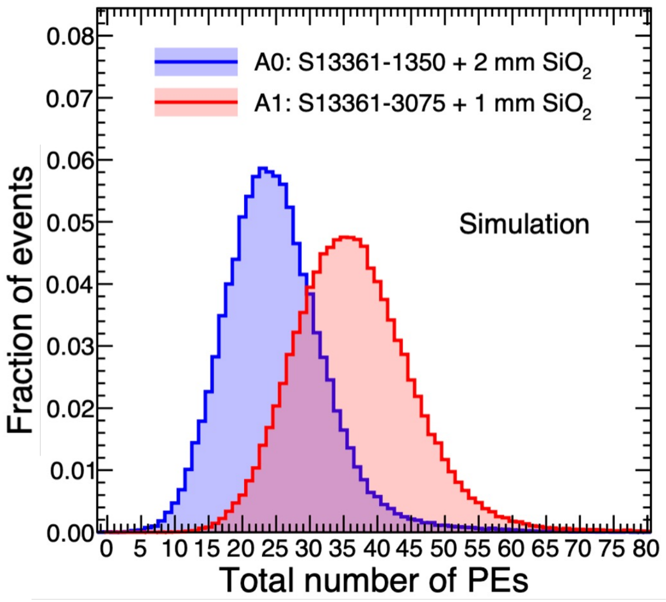
1) **Fill factor: M1 has larger fill factor whan M0 (75um vs 50 um SPADs)**
2) **Response to UV photons: higher for M1 than M0 (resin for window coupling)**
3) **Packaging fill factor: M0 = 1.3x1.3/1.5x1.5 = 75% M1 = 3x3/3.2x3.2 = 88%**
4) **Photons from argon ($n_{Ar} \approx$1.000283): M1 sees x(4-5) times Ar photons wrt M0**
5) **SiPM cross-talk: At operating Vov: $CT_{M0} \approx$ 6%, $CT_{M1} \approx$ 17%**

Accounting for all these effects, measurements are consistent with simulation predictions !!!





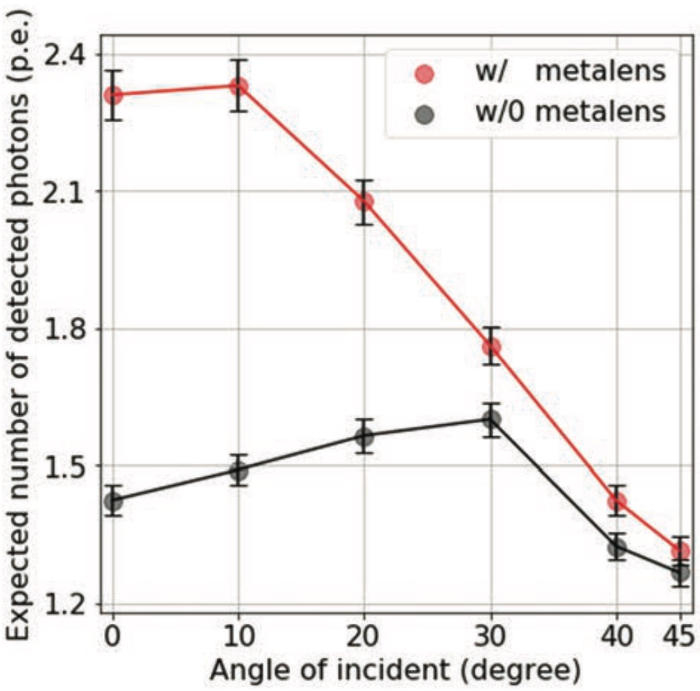


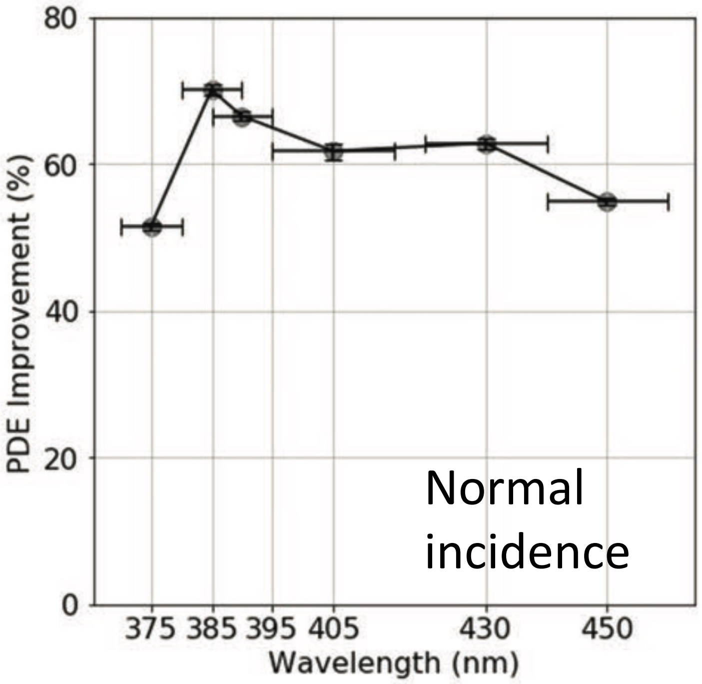


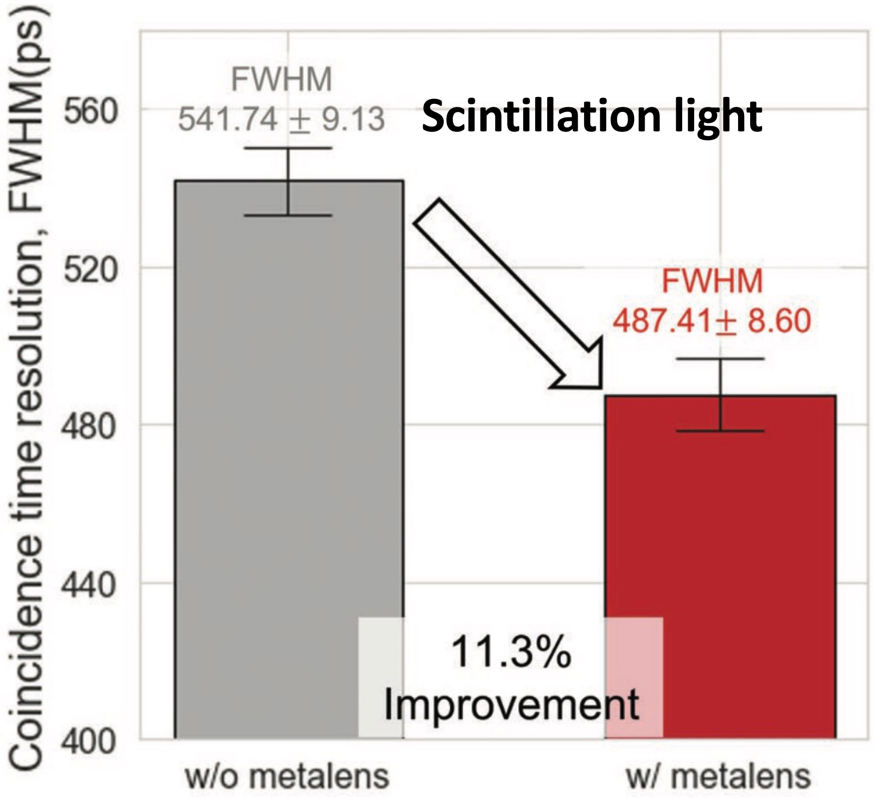
Early metalens + SiPM results

Early metalens results prove the intrinsic improvement of PDE & SPTR

3x3 mm^2 SiPM with 25x25 um^2 SPADs







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