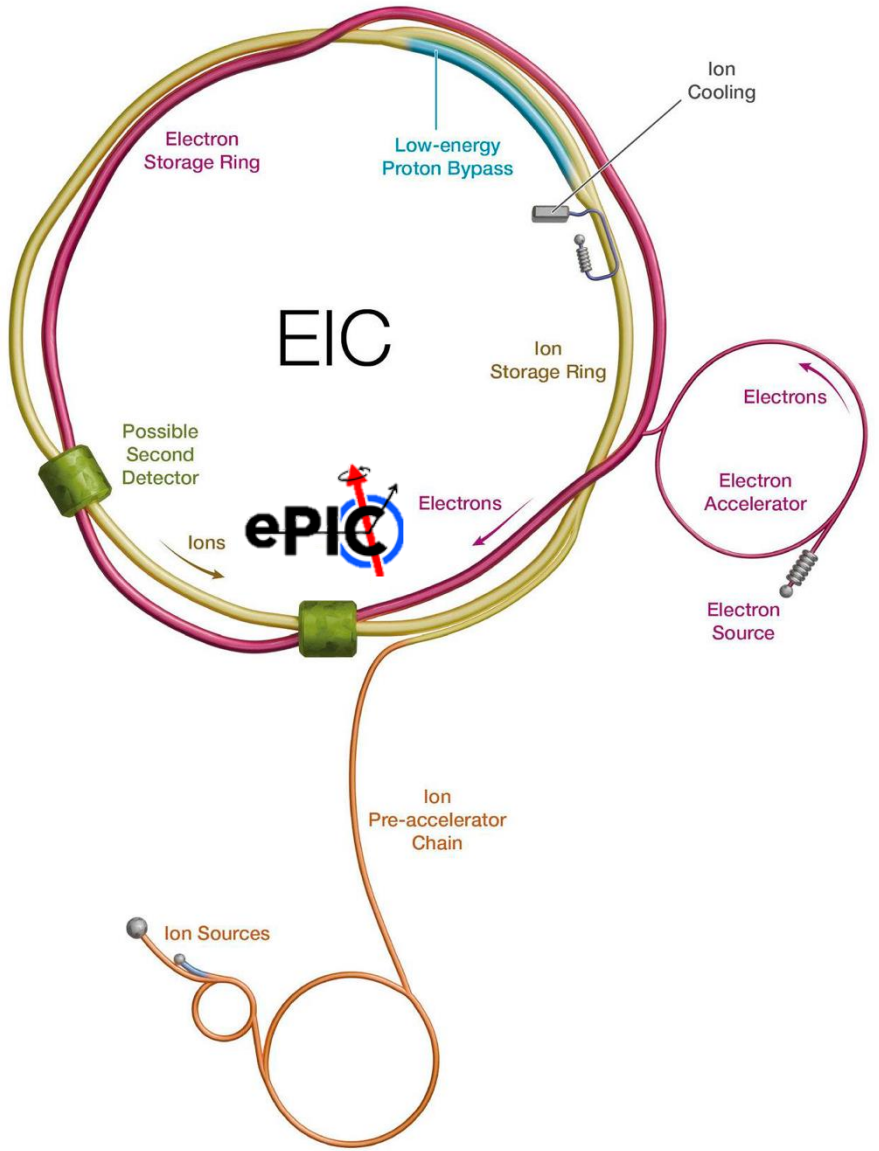


Development and performance of the dRICH SiPM-based photodetector for the ePIC experiment at the EIC

Luigi Rignanese on behalf of the **ePIC dRICH** collaboration

Outline:

- The **Electron-Ion Collider** and the **ePIC** detector
- **SiPMs** and **radiation damage**
- **The Photodetector unit**
- **Prototype and test beams**



The Electron-Ion Collider

Brookhaven National Laboratory

www.bnl.gov/eic

The major US project in the field of nuclear physics

- Operating in the early 2030s

The world's first collider for

- Polarized electron-proton (and light ions)
- Electron-nucleus collisions

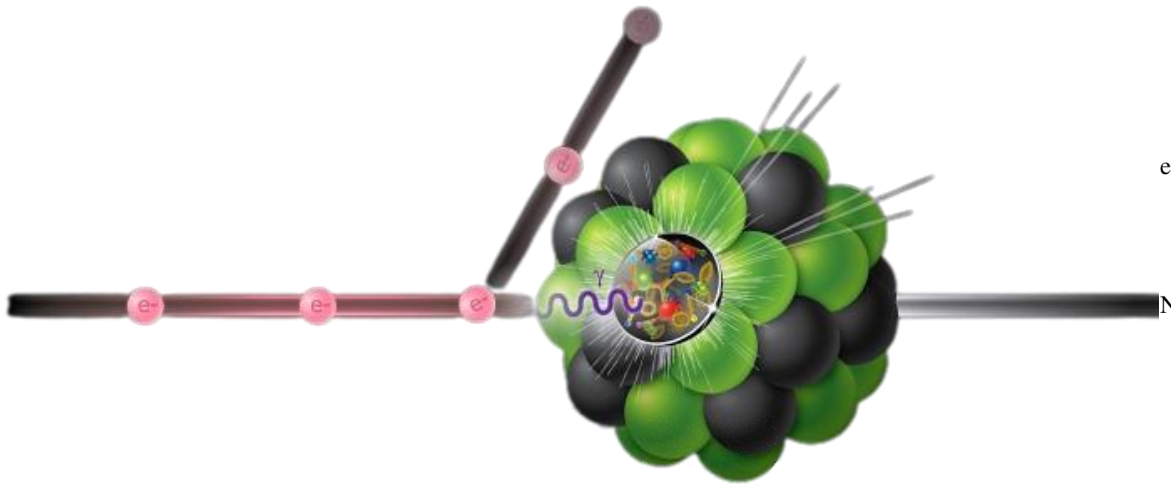
High Luminosity: 10^{34} $cm^{-2}s^{-1}$

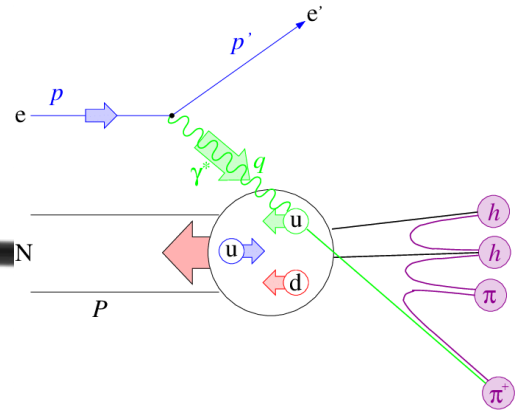
Wide energy span → $\sqrt{s}$ = 20-140 GeV

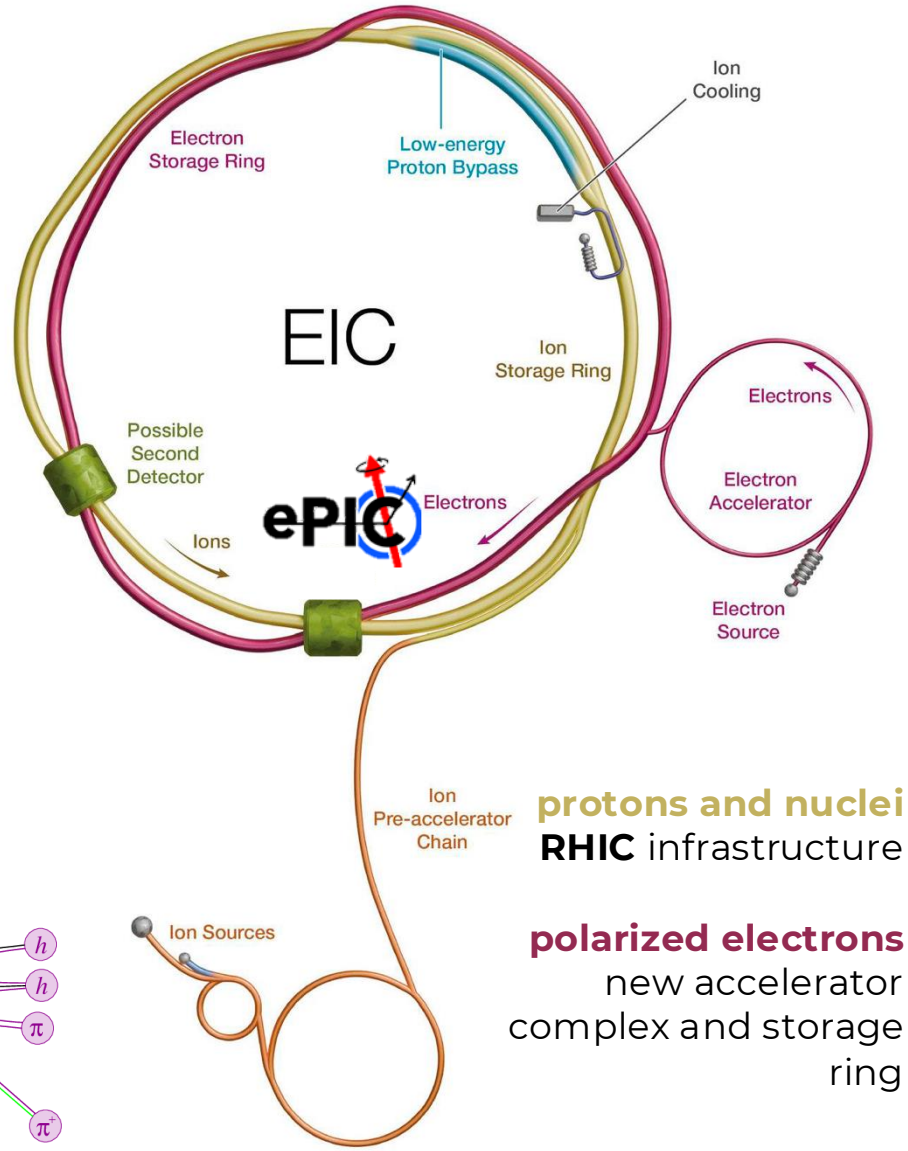
Inclusive/semi-inclusive DIS

- understand origin of mass & spin of the nucleons

3D images of the nuclear structure (GPD)







protons and nuclei
RHIC infrastructure

polarized electrons
new accelerator complex and storage ring

ePIC

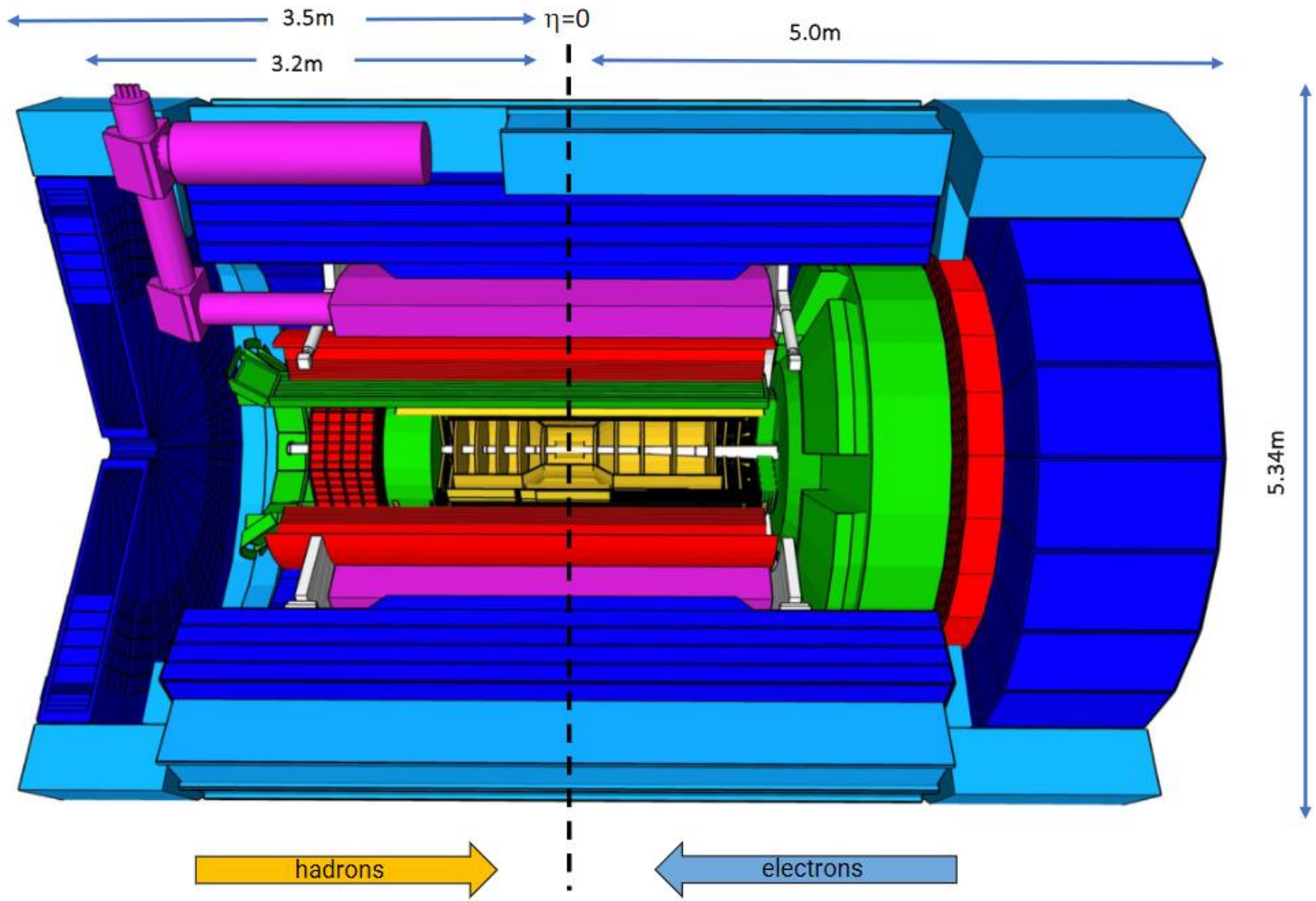
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

Tracking
- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS barrel and disks
- Gaseous tracker: MPGDs (μRWELL, MMG) cylindrical and planar

PID
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

EM Calorimetry
- imaging EMCal (barrel)
- W-powder/SciFi (forward)
- $PbWO_4$ crystals (backward)

Hadron calorimetry
- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)



ePIC

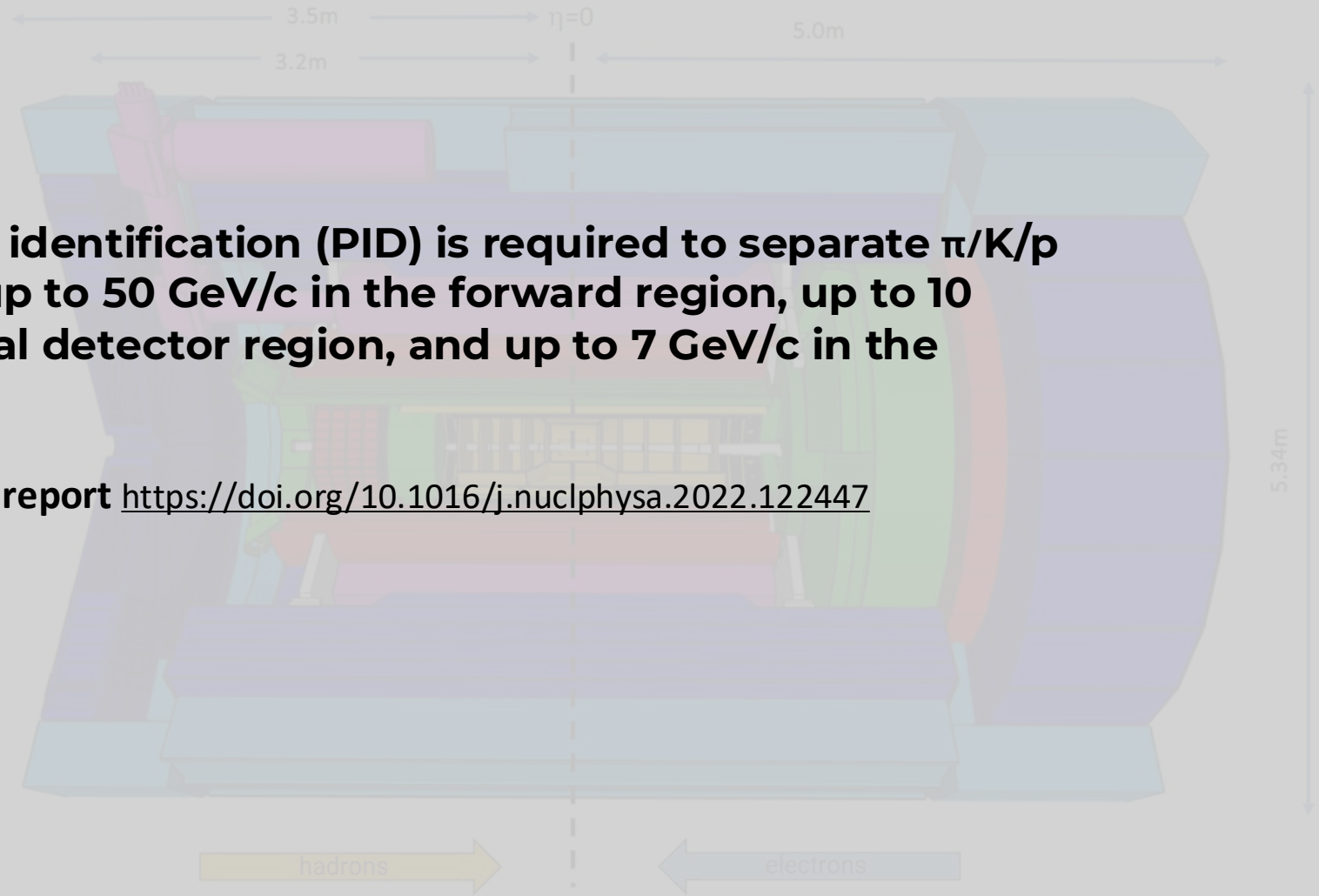
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

Tracking
- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS
- Gaseous tracker: MPGDs (

PID
- high performance DIRC (barrel)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

EM Calorimetry
- imaging EMCal (barrel)
- W-powder/SciFi (forward)
- $PbWO_4$ crystals (backward)

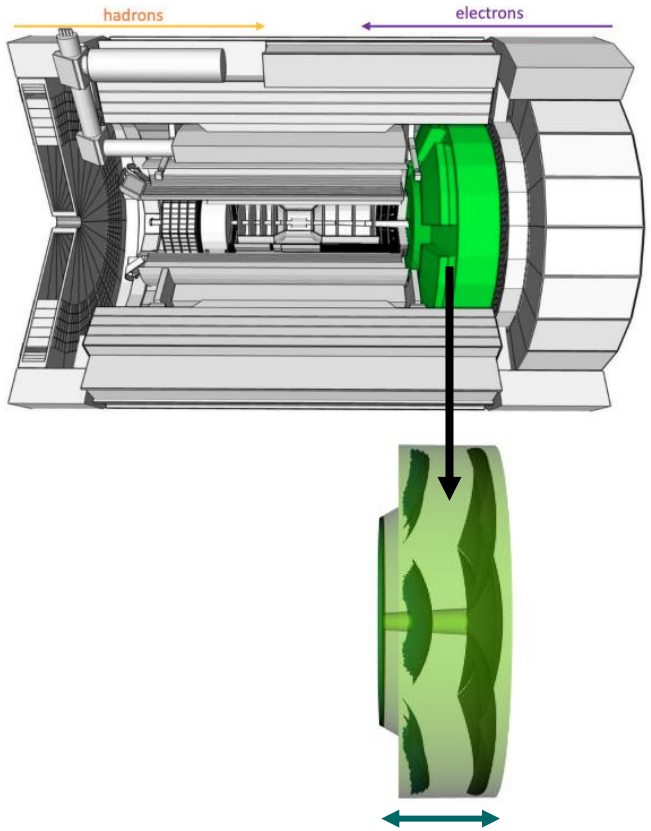
Hadron calorimetry
- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)



“Excellent particle identification (PID) is required to separate π/K/p at the level of 3 σ up to 50 GeV/c in the forward region, up to 10 GeV/c in the central detector region, and up to 7 GeV/c in the backward region”

EIC yellow report https://doi.org/10.1016/j.nuclphysa.2022.122447

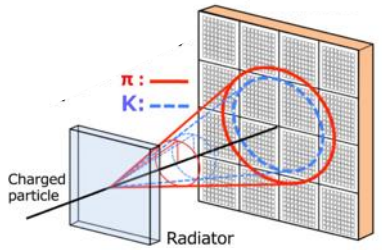
The dual-radiator (dRICH)

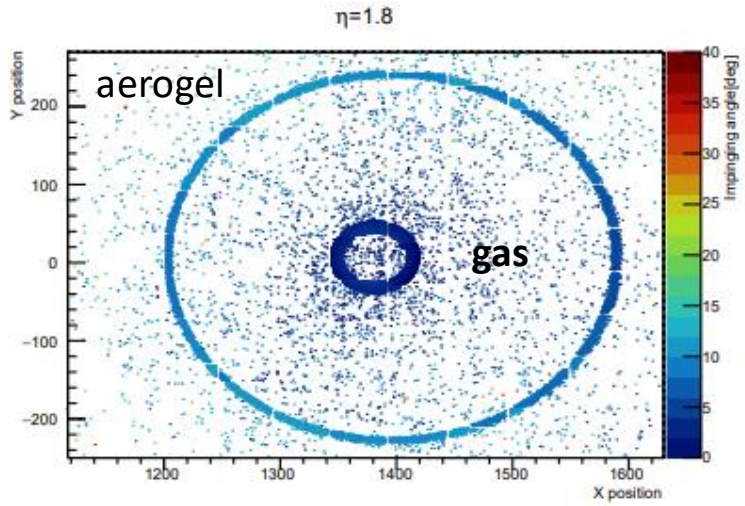


Compact and **cost-effective** solution for **broad momentum** (1-50 GeV/c) coverage at forward rapidity **π/K 3σ separation at 50 GeV/c** and **wide acceptance** (+- 300 mrad/ 1.5 < η < 3.5)

Gas volume 120 cm
C_2F_6 (n ~ 1.0008)

6 spherical mirrors
Backward-reflecting
Radius = 220 cm





Aerogel (n ~ 1.026) **4 cm**
Radius = 110 cm

Photosensors 3x3 mm² pixels 0.5 m² per sector in 1 T magnetic field and radioactive environment for low light levels.

SiPMs are the best candidates

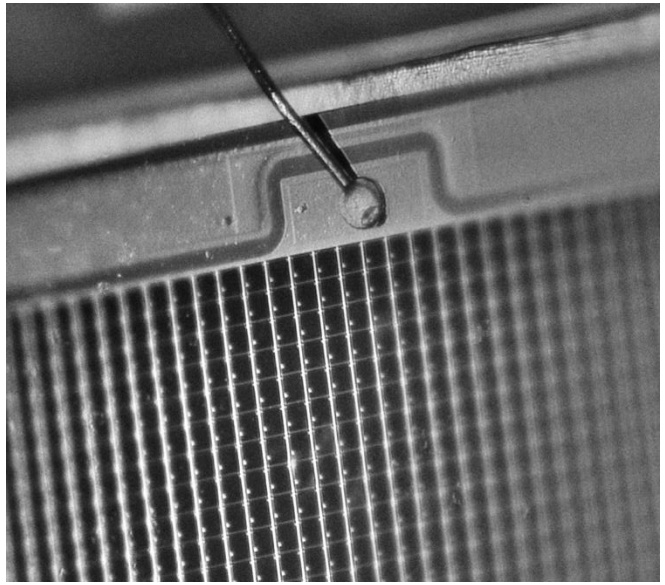
- **Small** and **cheap**
- **Insensitive** to **magnetic field**
- **High** photo-detection efficiency (**PDE**)
- High gain-**single photon** detection
- **Low voltage** operation
- Excellent **timing** performance

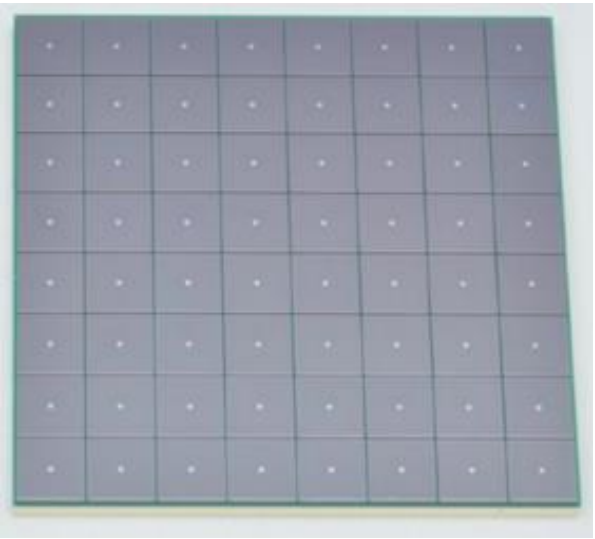
But:

x **High DCR** @ room temperature

x **Low** radiation **tolerance**

DCR increases with **dose**



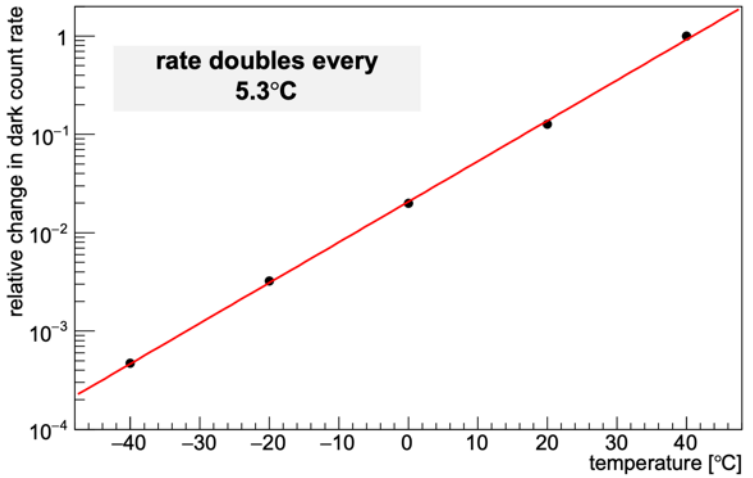


Strategy for SiPMs in the dRICH

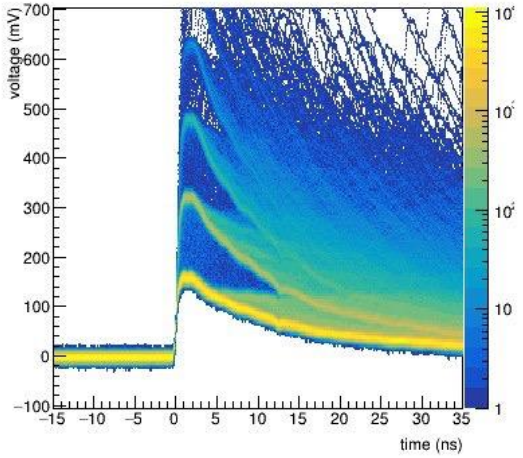
Cooling the sensors down to **– 40° C reduces** the **DCR** by a factor **~ 200**

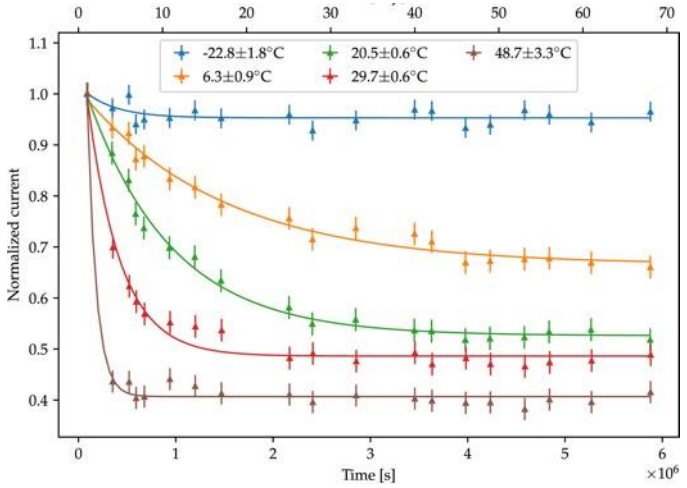
Sub ns time resolutions allow **coincidence** cuts that greatly reduce **DCR** contribution in the measurements

Annealing techniques (**high temperature process**) to recover **DCR** performance loss



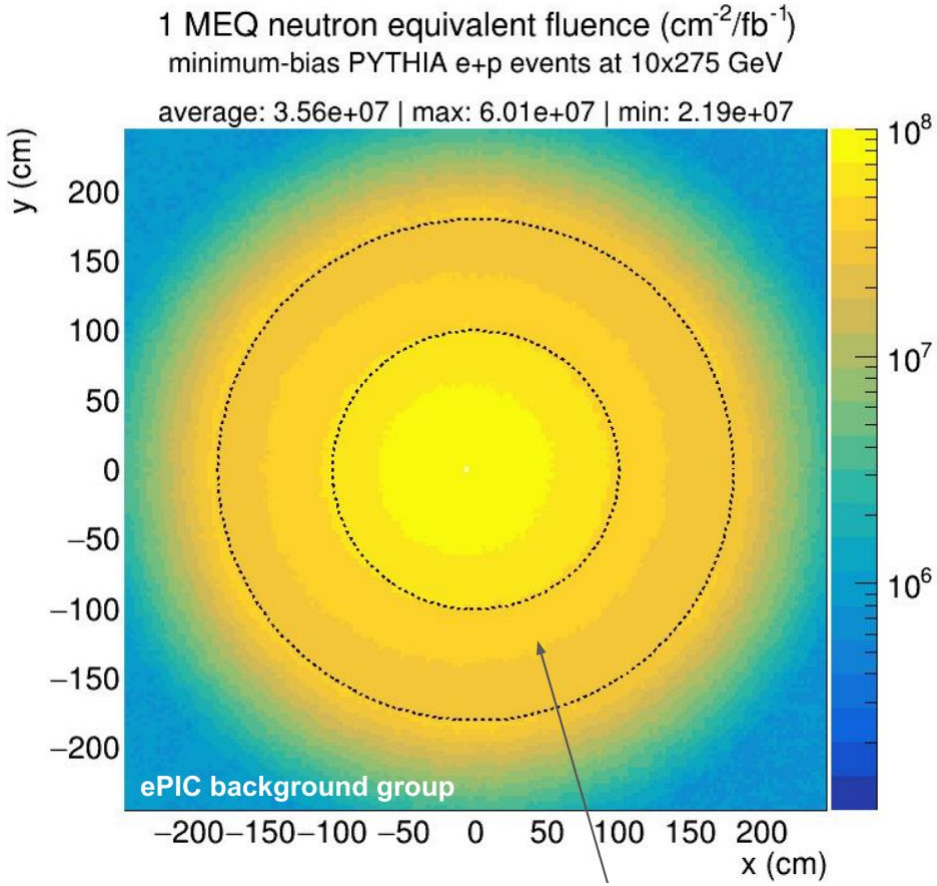
A. N. Otte et al., Nucl.Instrum.Meth.A 846 2016





N. De Angelis et al., Nucl.Instrum.Meth.A 1048 2023

Radiation levels on the dRICH



dRICH photosensors location:
Max fluence ≈ 6.38 10^7 n_{eq}/cm^2 per fb^{-1}
(including bkg)

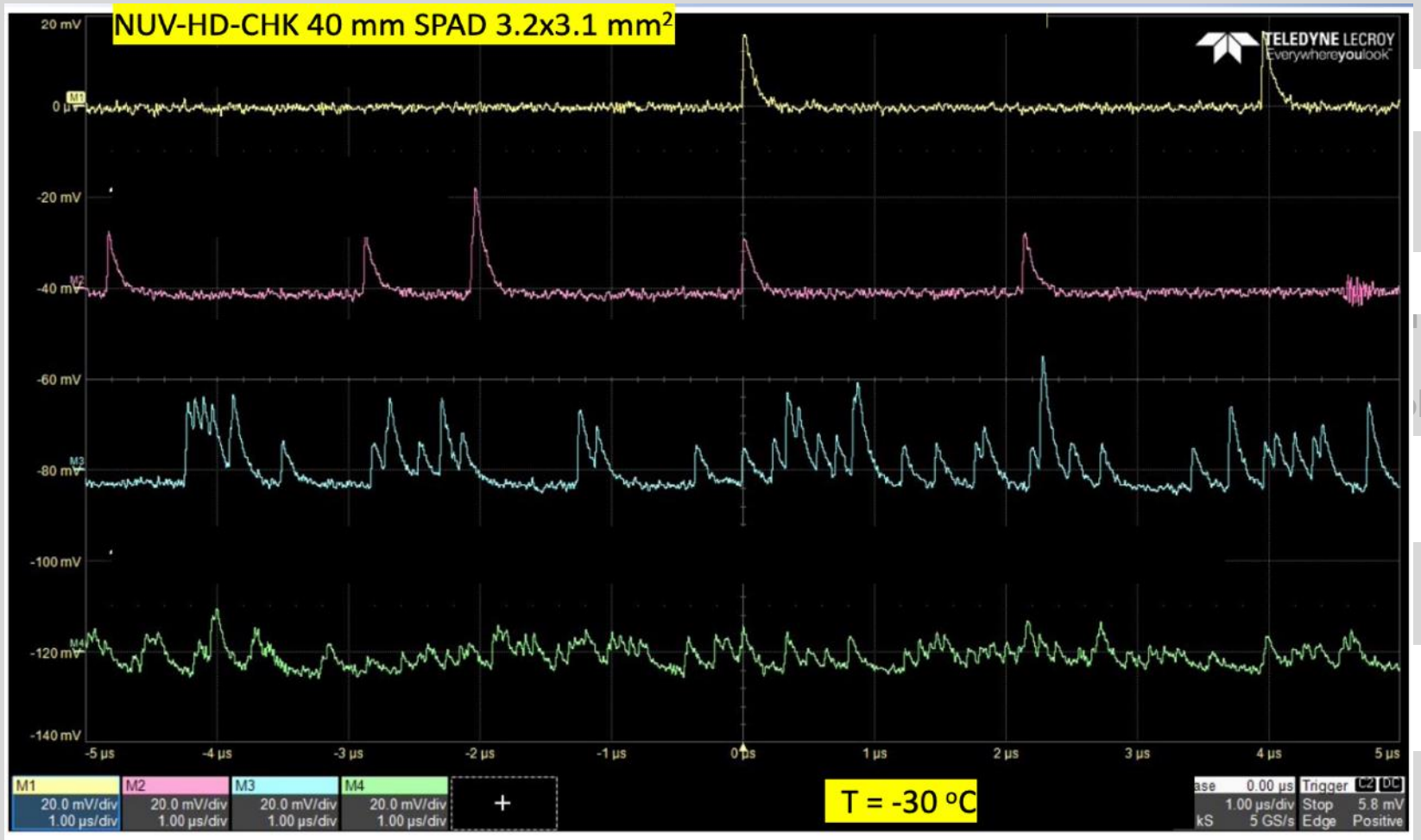
n_{eq} = 1-MeV neutron equivalent (NIEL model)

Integrated luminosity and **radiation levels**

- 30 fb^{-1} for **most** of the **physics topics** **~ 10^9 n_{eq}/cm^2**
- 10^2 fb^{-1} **GPDs** and statistically eager topics **~ 10^{10} n_{eq}/cm^2**
- 10^3 fb^{-1} may **never** be reached **~ 10^{11} n_{eq}/cm^2**



Radiation levels on the dRICH



new

10^{9} n_{eq}/cm^2

...nosity and radiation levels

...hysics topics ~ 10^{9} n_{eq}/cm^2

10^{10} n_{eq}/cm^2
(single PE detection affected)

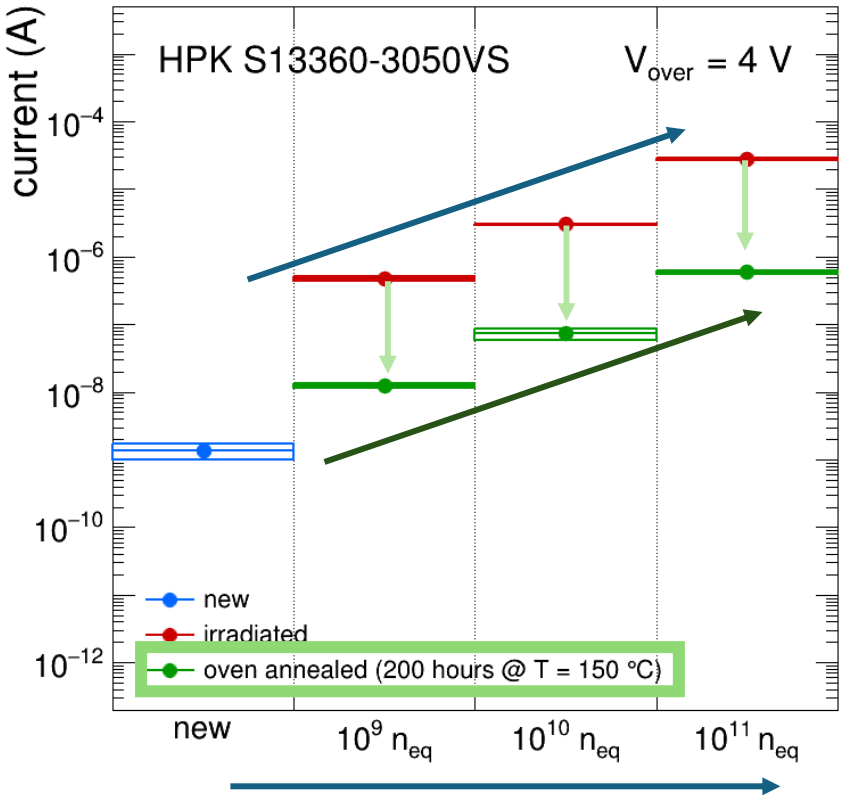
10^{11} n_{eq}/cm^2
(baseline affected)

Max fluence ≈ 6.38 10^{7} n_{eq}/cm^2 per fb^{-1}
(including bkg)

n_{eq} = 1-MeV neutron equivalent (NIEL model)

SiPMs radiation damage studies and annealing

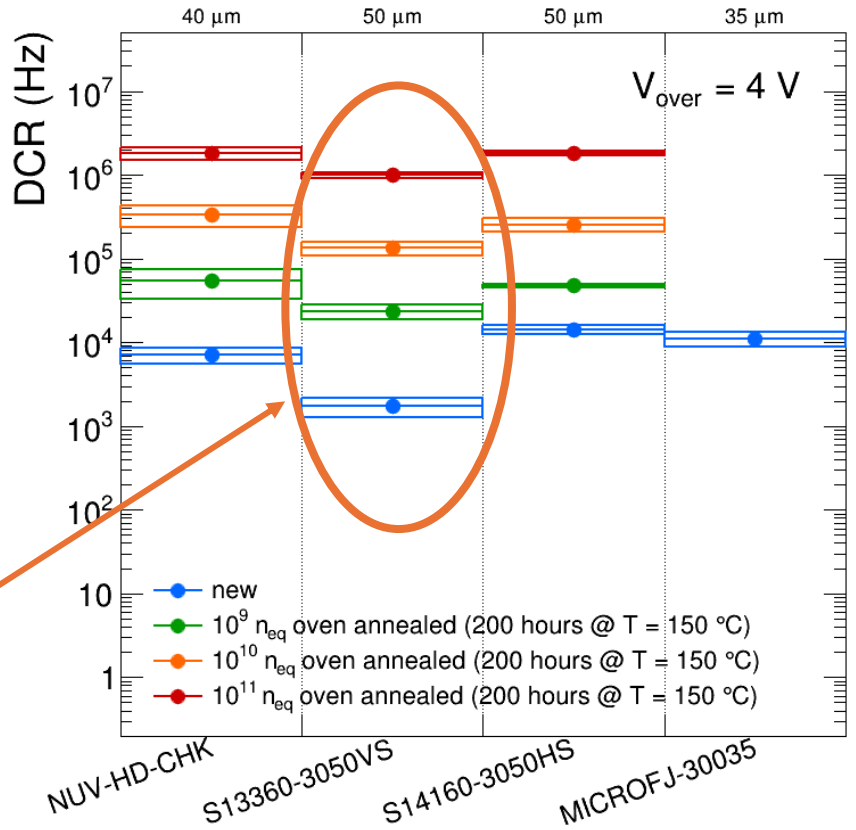
Irradiation campaigns with protons at TIFPA (TN)



Linear **increase** of dark current/**DCR** with the dose

~50x reduction of dark current/**DCR** with **150° C** oven **annealing**

All sensors behave similarly but **HAMAMATSU s13360-3050** shows the **lowest DCR** and **best PDE**

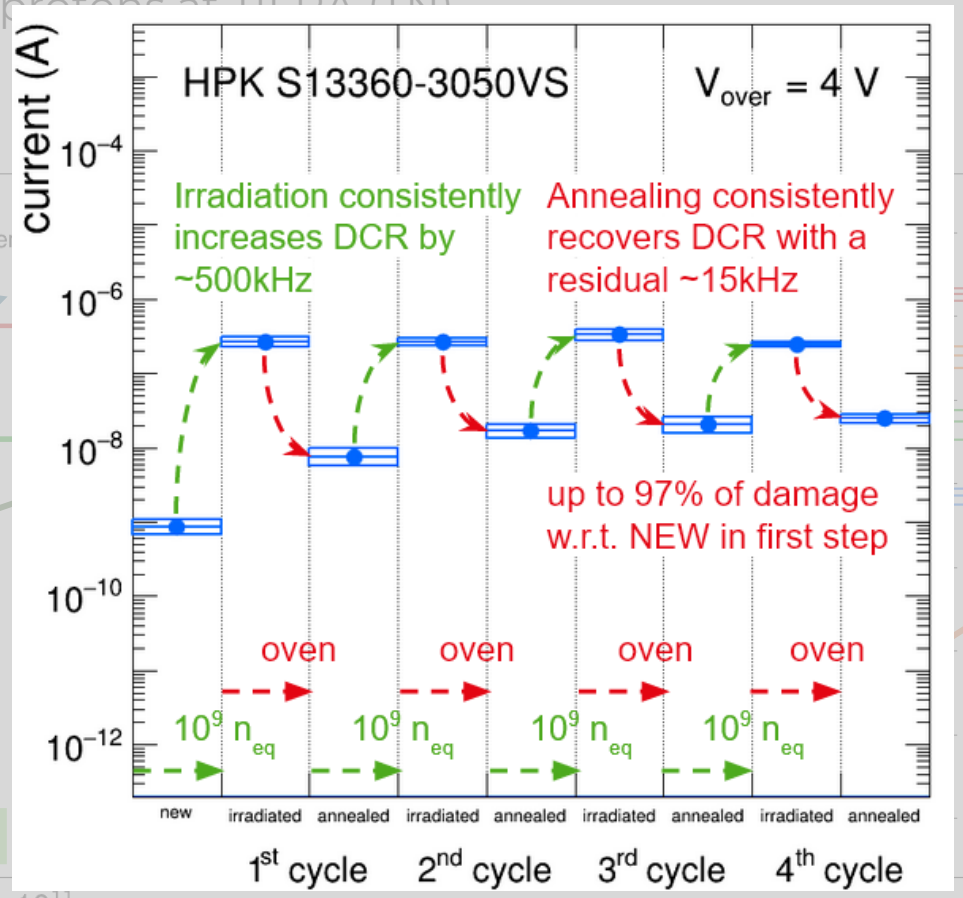


Measurements taken @ -30° C

R. Preghenella et al., Nucl.Instrum.Meth.A 1056 2023

SiPMs radiation damage studies and annealing

Irradiation campaigns with protons at TIFPA (TN)



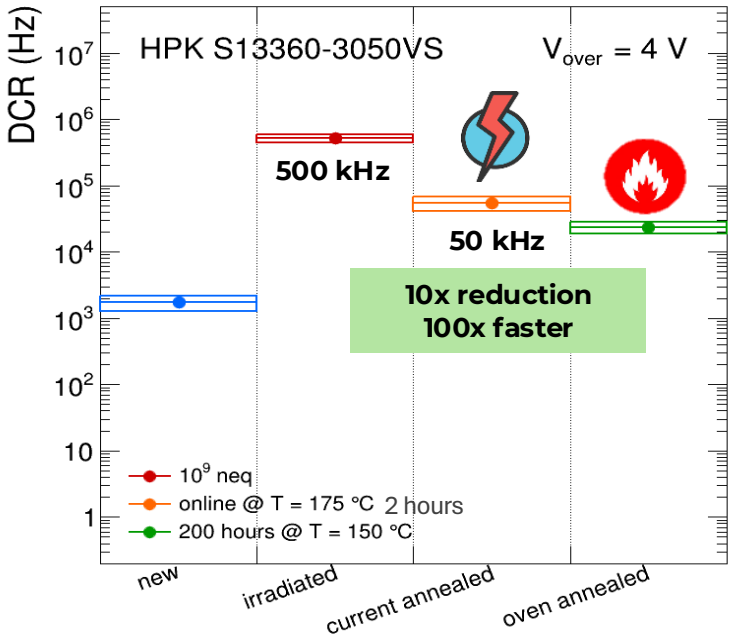
Residual increase in **DCR** is **proportional** to the dose

Measurements taken @ -30° C

R. Preghenella et al., Nucl.Instrum.Meth.A 1056 2023

SiPMs current annealing

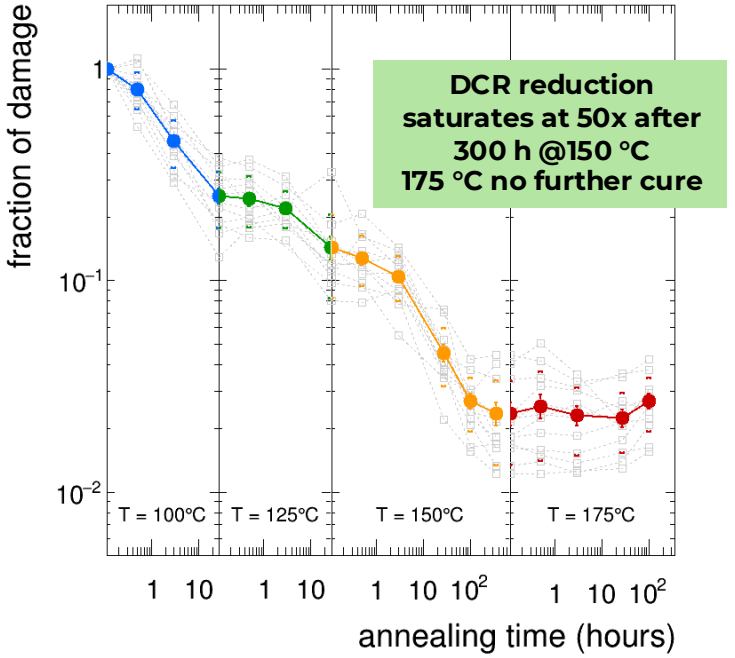
Annealing by heating up the sensors. Forward-biased diode. “High” current flowing into the SiPM. 175° C with 10 V and ~100 mA (**~ 1 W**) per sensor.

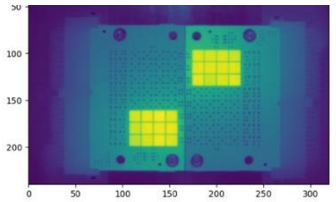




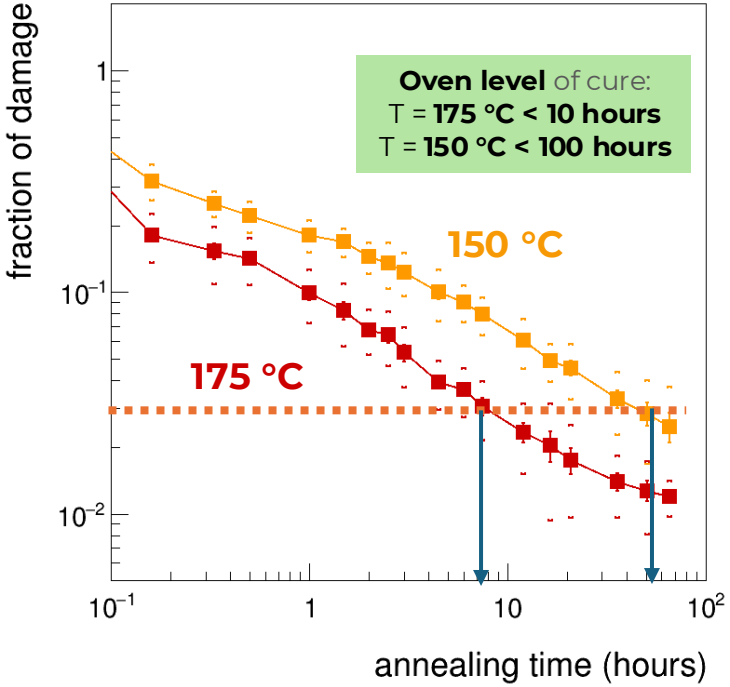
Preliminary studies in 2022 demonstrated the feasibility

R. Preghenella et al., Nucl.Instrum.Meth.A 1056 2023



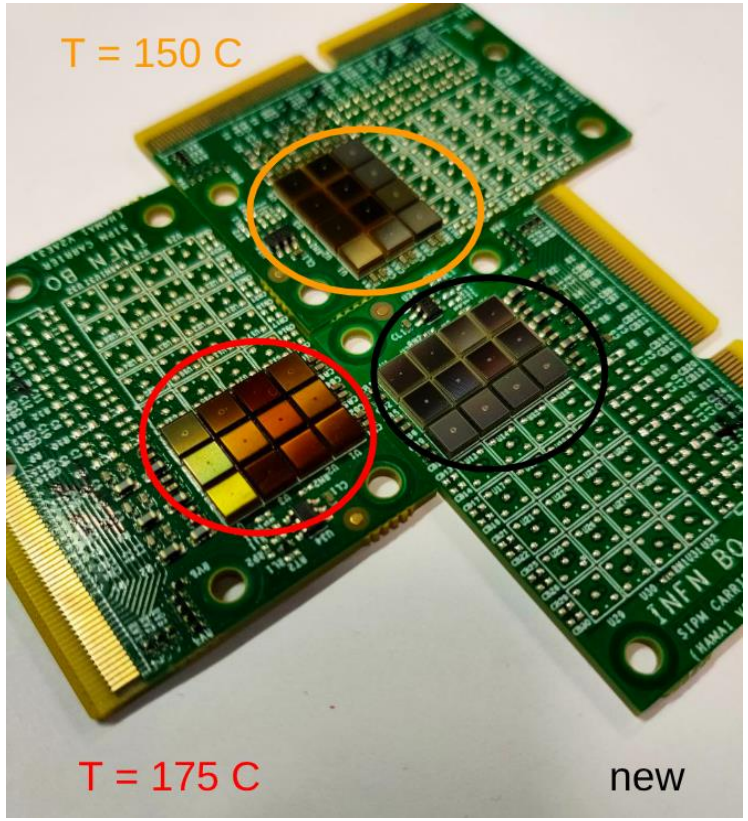


Test on a large number SiPM. Automated test at different temperatures and time intervals

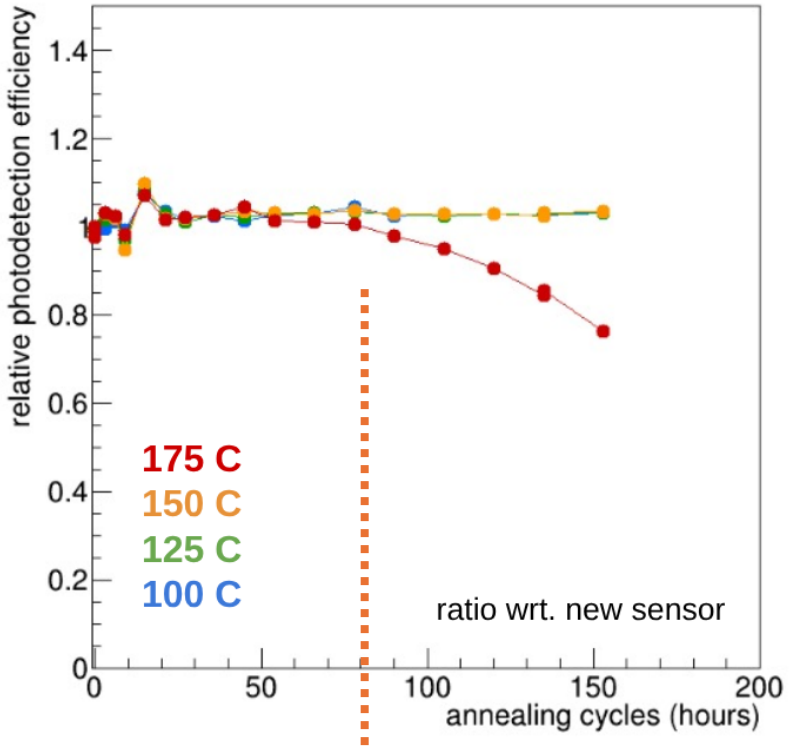


SiPMs current annealing

After more than 500h at high temperature direct current annealing clear alterations of the resin window show up.



Efficiency loss after 80 hours of annealing at T = 175° C
T = 150° C unaffected up to 150 hours

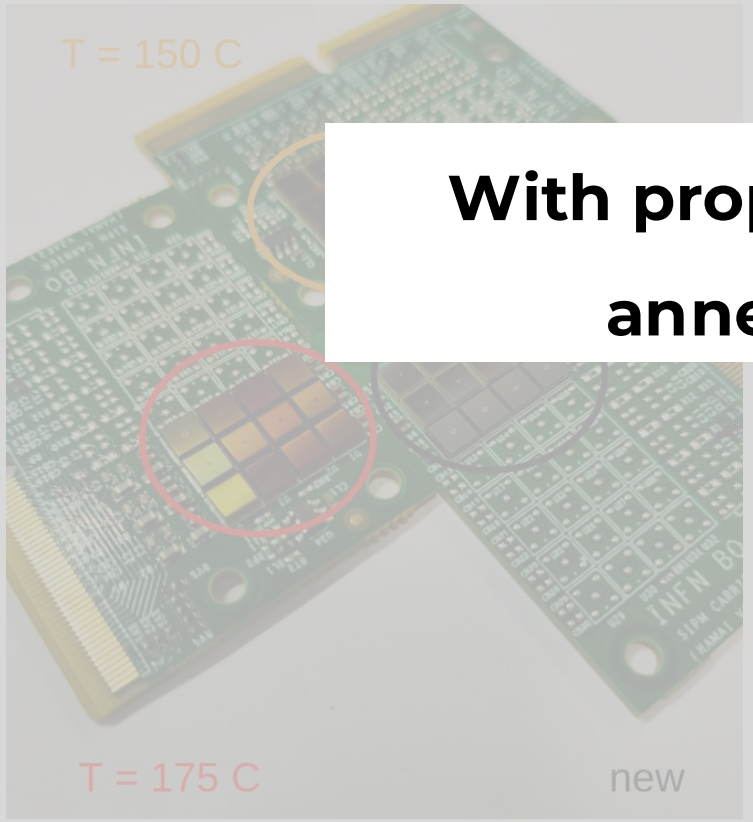


Oven annealing didn't show this problem

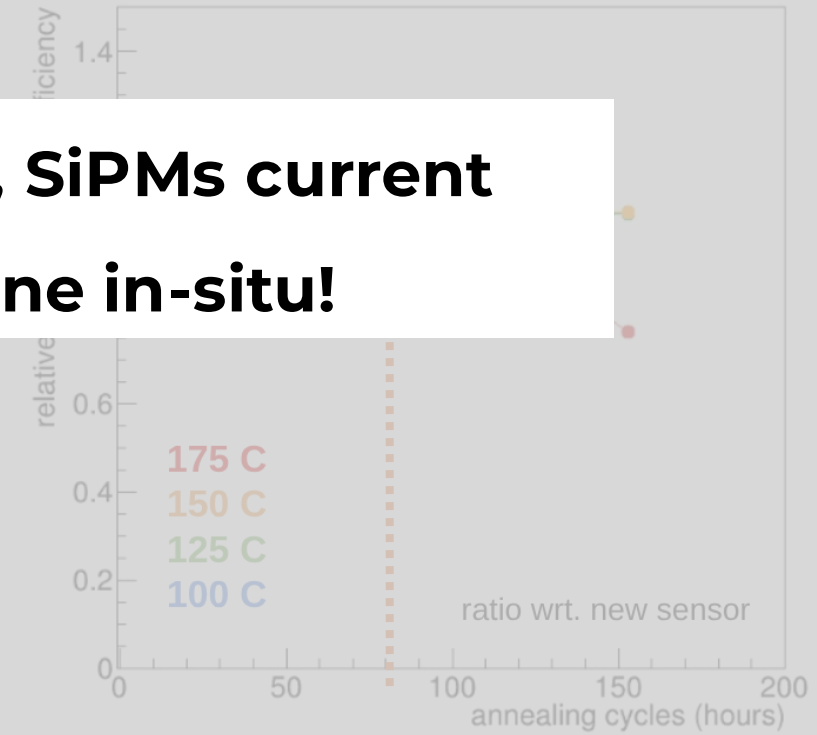
B. R. Achari et al., Journal of Instrumentation 20(08):C08025

SiPMs current annealing

After more then 500h at high temperature direct current annealing clear alterations of the resin window show up.



Efficiency loss after 80 hours of annealing at T = 175 C
T = 150 unaffected up to 150 hours



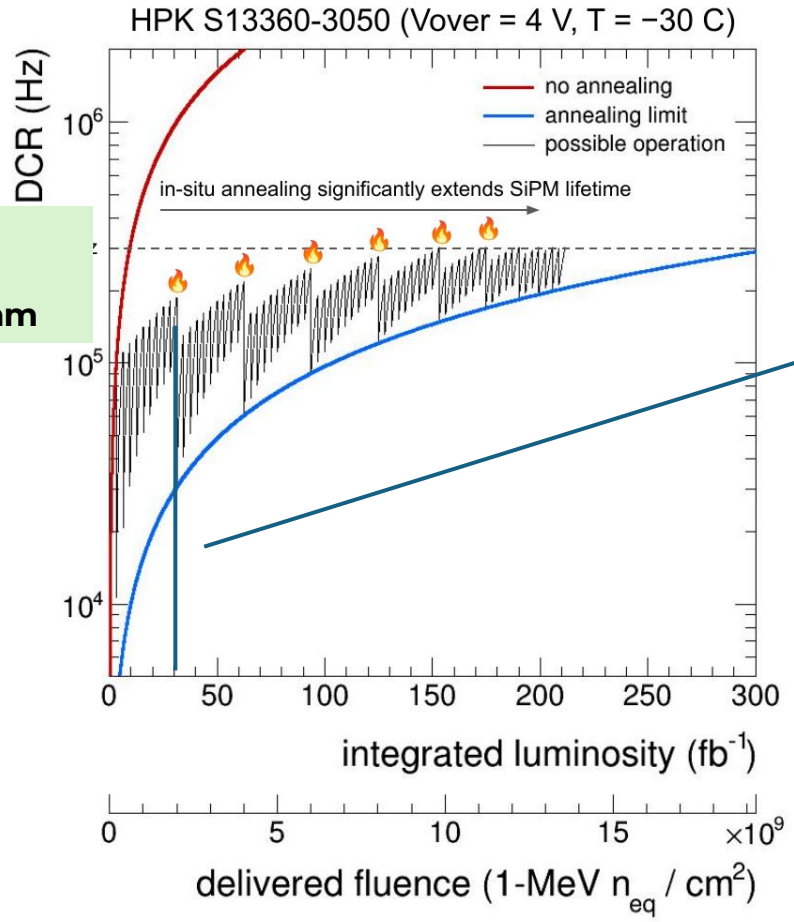
With proper precautions, SiPMs current annealing can be done in-situ!

B. R. Achari et al., Journal of Instrumentation 20(08):C08025

SiPMs aging model

possible scenario for first 5 years of EIC Phase-1					
Year	**1**	**2**	**3**	**4**	**5**
Beams (GeV)	e^- Ru 10 x 115	e^- d 10 x 130	e^- p 10 x 130	e^- Au 10 x 100	e^- ^{3}He 10 x 166
$\int$ **Lumi** (fb^{-1})	0.9	11.4	5.33	0.84	8.65

<u>300 kHz DCR</u> limit
per **sensor**
SNR and **physics program**

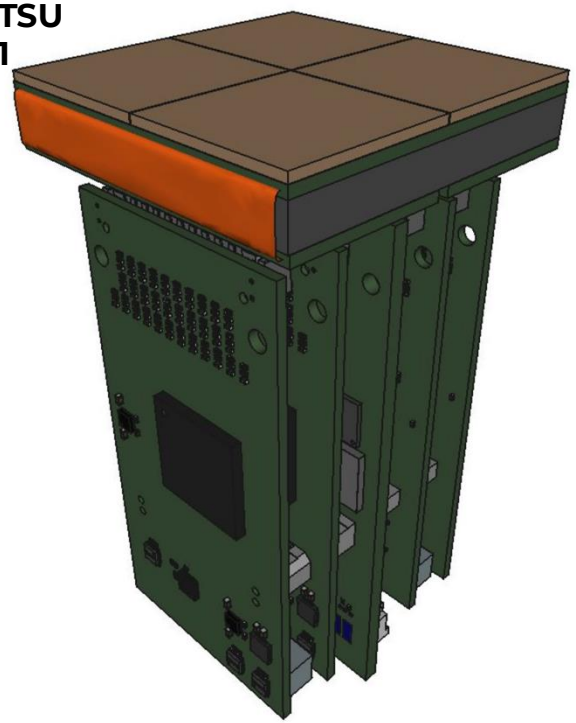


Frequent «**soft annealing**» cycles ~10 h @ 100° C
Rare «**full annealing**» cycles ~50 h @ 150° C
SiPMs life extended

Photodetector design and layout

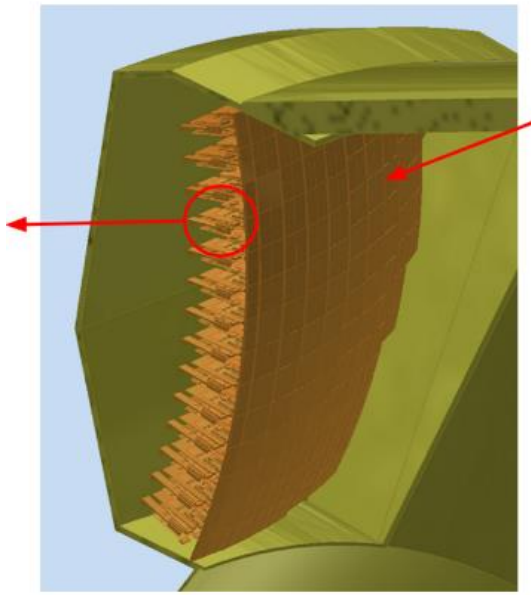
PDU

SiPMs matrix
4x HAMAMATSU
8x8 s13361

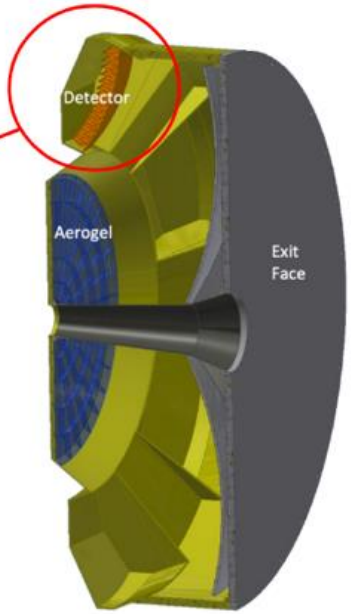


15 cm

Curved SiPM readout plane (sector)



dRICH

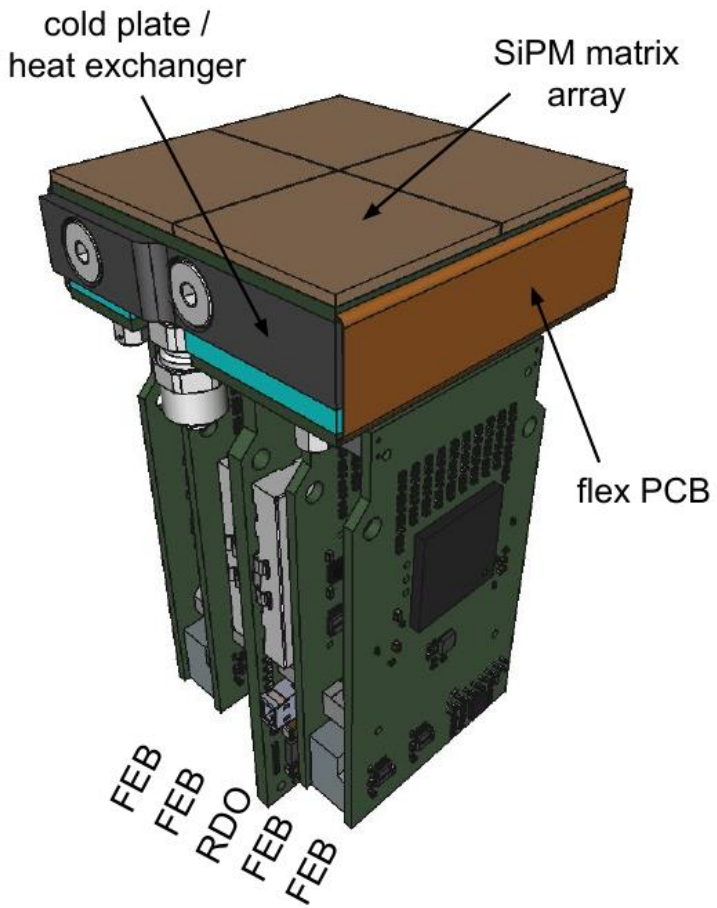


PDU · 5×5 cm²
4 matrices · **256 SiPMs**

Sector · 0.5 m²
208 PDUs · 832 matrices · **~50k SiPMs**

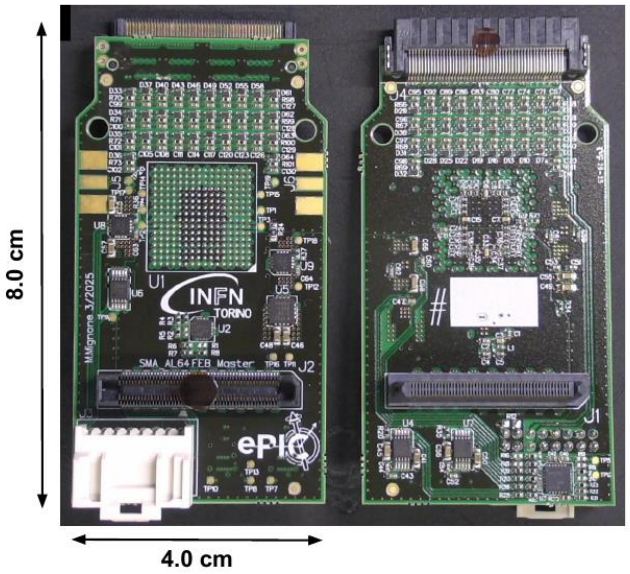
dRICH · ~3 m²
1248 PDUs · 4992 matrices · **~320k SiPMs**

The integrated detection system: the PDU

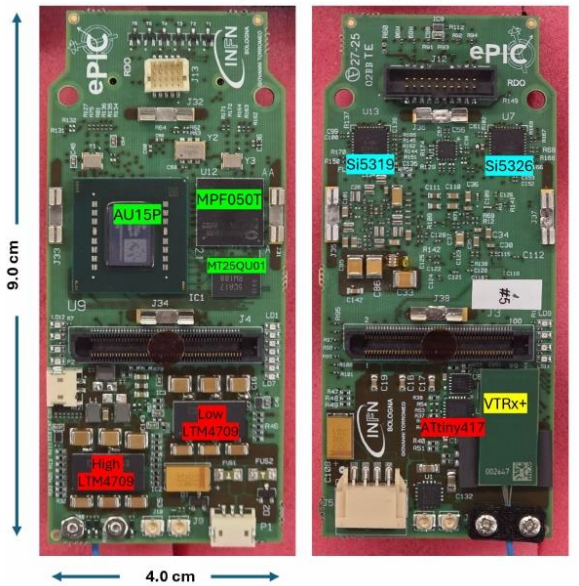


- Hosts and reads out **4× 8x8 Hamamatsu TSV S13361 - 3050/75NE-08**
- **Cooling/heating** to the sensors and routing for **HV** and **signals**
- **4 ALCOR-64 front-end boards** (FEB, INFN Torino) + **1 FPGA-based readout board** (RDO, INFN Bologna)

FEB (INFN Torino)



RDO (INFN Bologna)

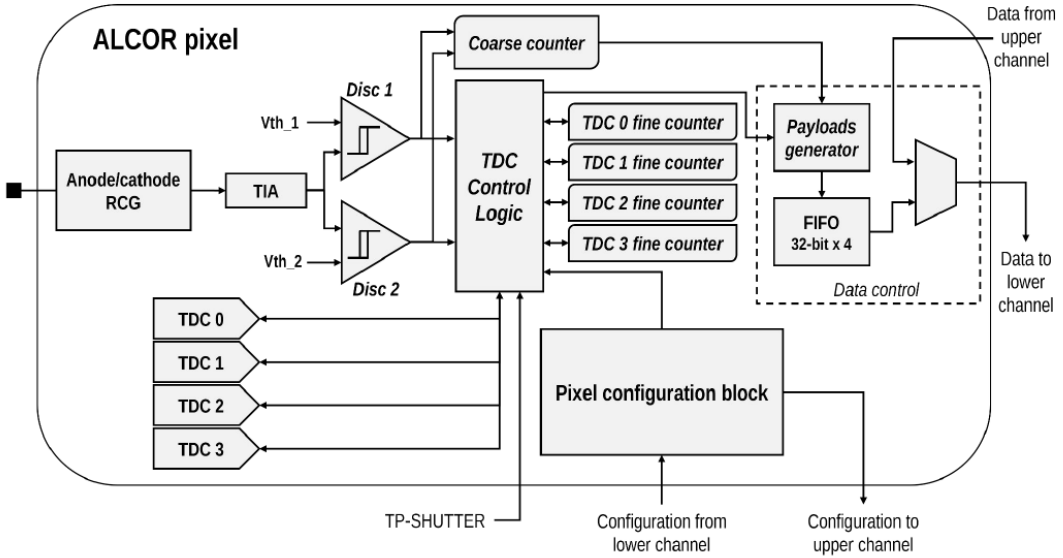


ALCOR: A Low power Chip for Optical sensor Readout

Requirements for the ePIC dRICH

➢ **Single-photon time tagging** of SiPM signals
➢ Cope with **SiPM DCR up to 300 kHz/channel** (max radiation damage)

- **32- or 64-pixel** mixed-signal ASIC (INFN-Torino), **110 nm CMOS**, **~12 mW/channel**
- Dual-polarity **RCG input stage** (*Zin* = 10–20 Ω) + **TIA with 4 gain settings**
- **2 leading-edge discriminators**, per-pixel 6-bit thresholds → *Vth* = 0.5 p.e.
- **4 TDCs** with analogue interpolation: 50 ps LSB @ 320 MHz (ALCOR-32), **20–40 ps** @ 394 MHz (ALCOR-64)
- **Triggerless**, fully digital output: ToA + **ToT** or **slew rate** for time-walk compensation
- Test-pulse injection + **shutter** to suppress out-of-time DCR hits · SPI configuration, 64-bit event data

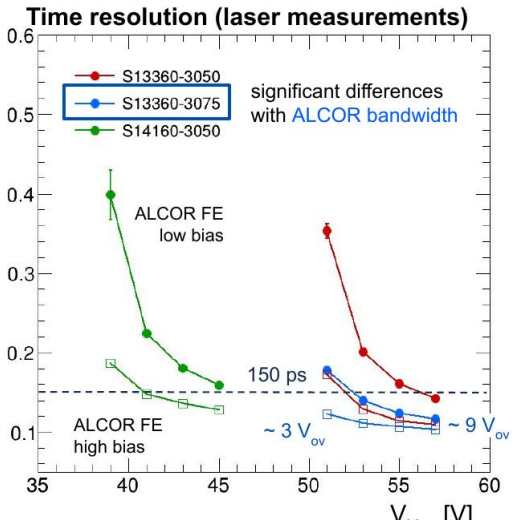


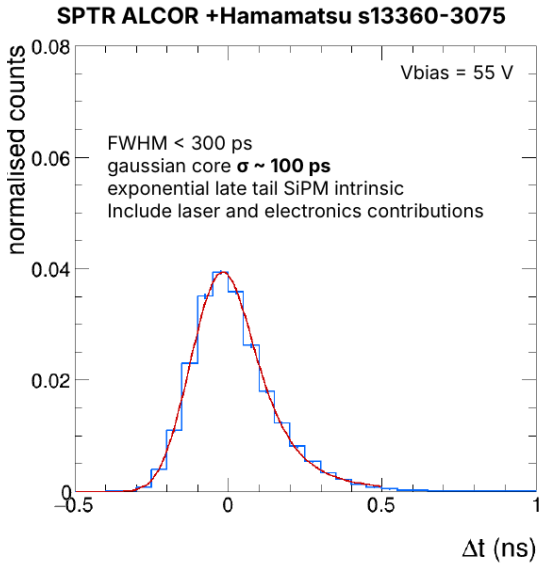
pixel size: 440 x 440 μm²

R. Kugathasan PoS TWEPP2019 (2020) 011

ALCOR-32 performance

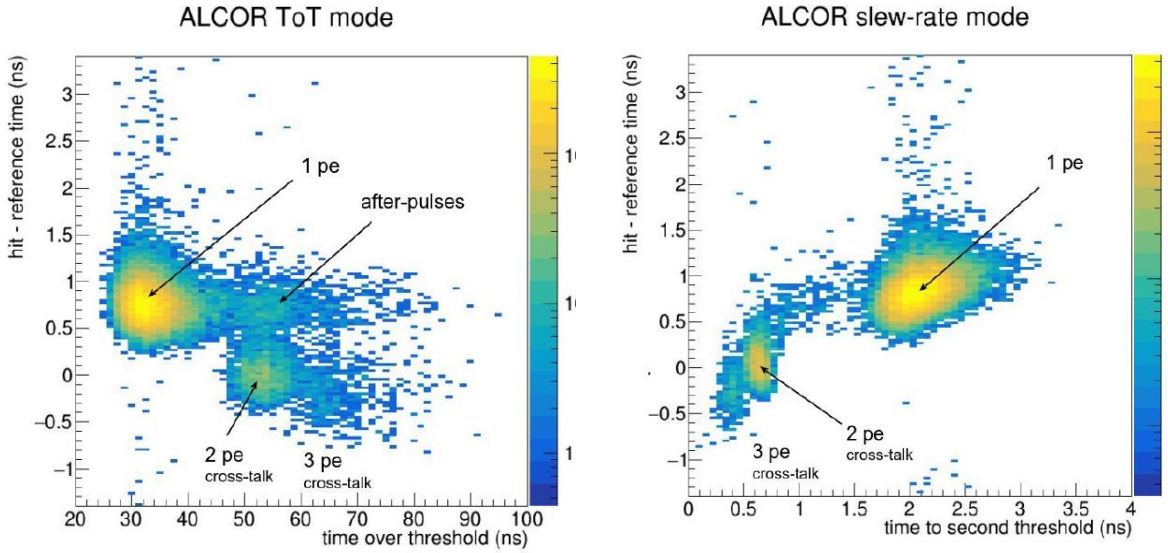
Time resolution (laser)





- SPTR: gaussian core **σ ≈ 100 ps**, FWHM < 300 ps
- **σt < 150 ps** with 75 µm SPADs, also at low V*bias*

Time-walk compensation

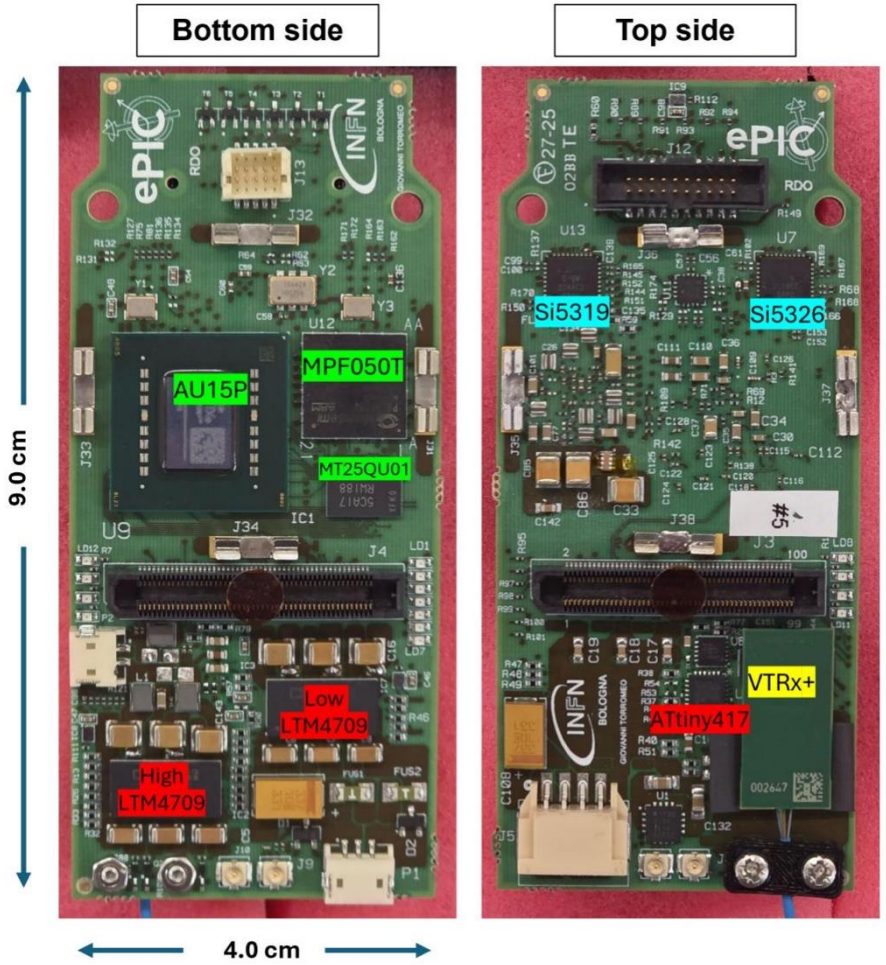


✗ **ToT mode** cannot distinguish afterpulses (slow rise, large ToT) from cross-talk (fast rise, large ToT)

✓ **Slew-rate mode** measures the signal slope → better separation

F. Cossio et al, Journal of Instrumentation 21(06)

The RDO: FPGA-based readout card of the PDU



Data concentrator for 4 ALCOR-64 FEBs

AMD Artix UltraScale+ AU15P: ALCOR readout, control and time-ordering

VTRx+ 10 Gb/s optical link to the back-end (≈6 Gb/s at 300 kHz DCR), streaming readout

ALCOR clock (394 MHz) **reconstructed from the link**: ~5 ps RMS jitter

Radiation tolerance

AU15P configuration memory **scrubbed** by a PolarFire MPF050T

RDO v1.1: ATSAMD21J18 µC as power monitor, tested to 24 krad

Proton irradiations at TIFPA (Dec 2024 – Mar 2026)

Validated in the 2025–2026 beam tests

8 RDOs in the prototype DAQ (IPbus, 1 Gb/s Ethernet), ~800 Mb/s each

S. Geminiani et al, Journal of Instrumentation 21(04)

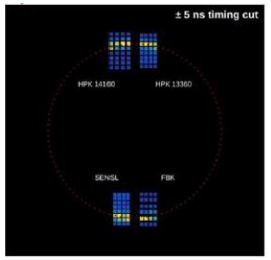
Photodetector evolution towards construction

towards construction ▶

2022

electronics v1

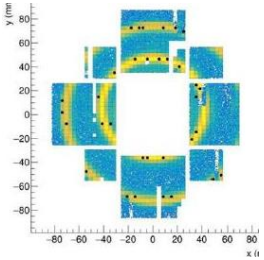




2023

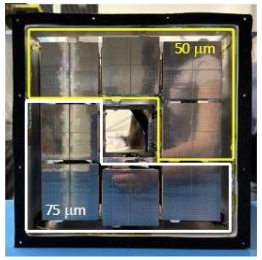
electronics v2

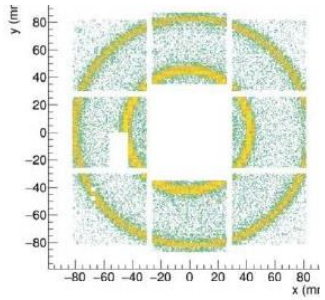




2024

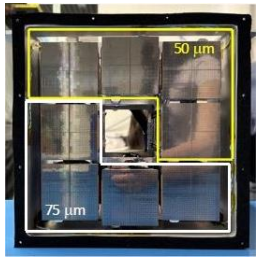
electronics v2.1

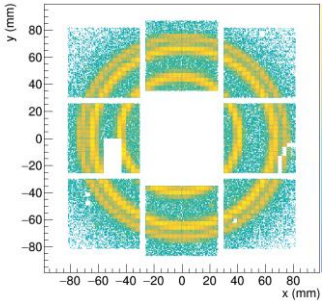




2025

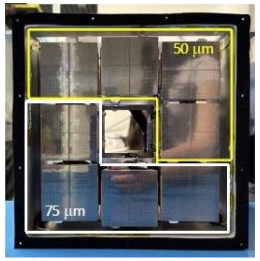
electronics v2.1 **+ RDO**

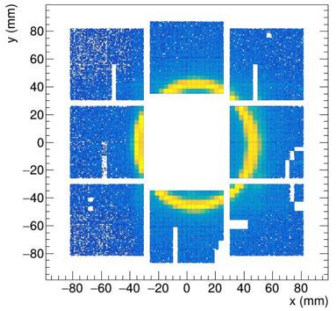




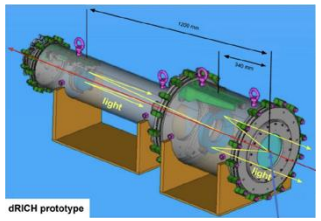
2026

electronics v2.1 **+ RDO**





dRICH prototype · 2022–2025



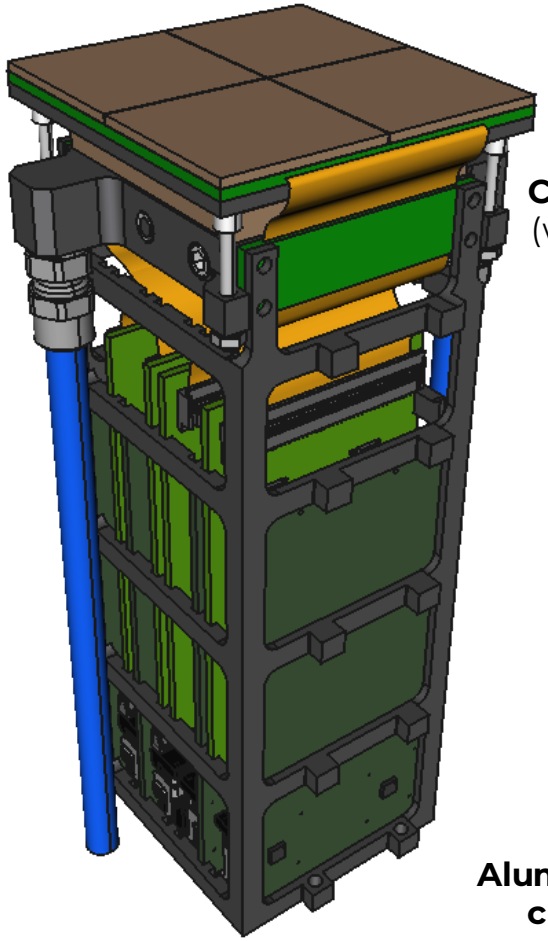


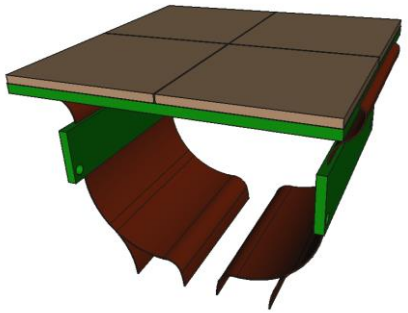
Real-scale prototype



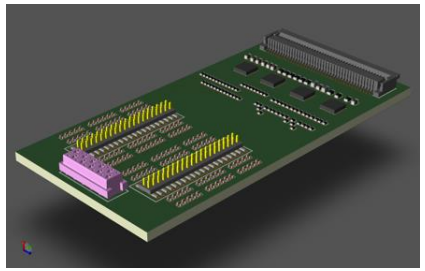
PDU prototype

SiPMs, **cooling** and **TDC electronics** integrated in a compact volume

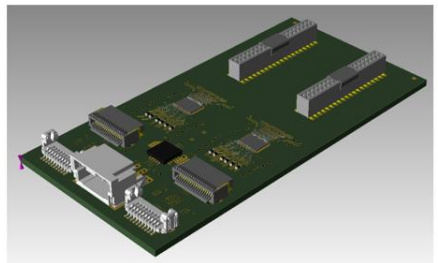




Carrier board
4 matrices of 8×8 **Hamamatsu S13361** SiPMs (256) on rigid-flex PCB · **4 NTC** sensors on the back



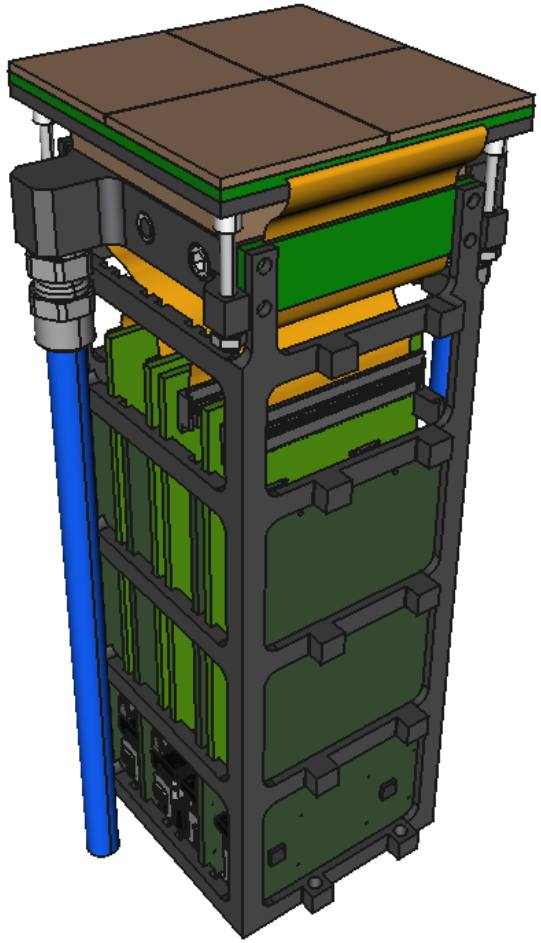
4× adapter boards
HV regulation · AC coupling to ALCOR



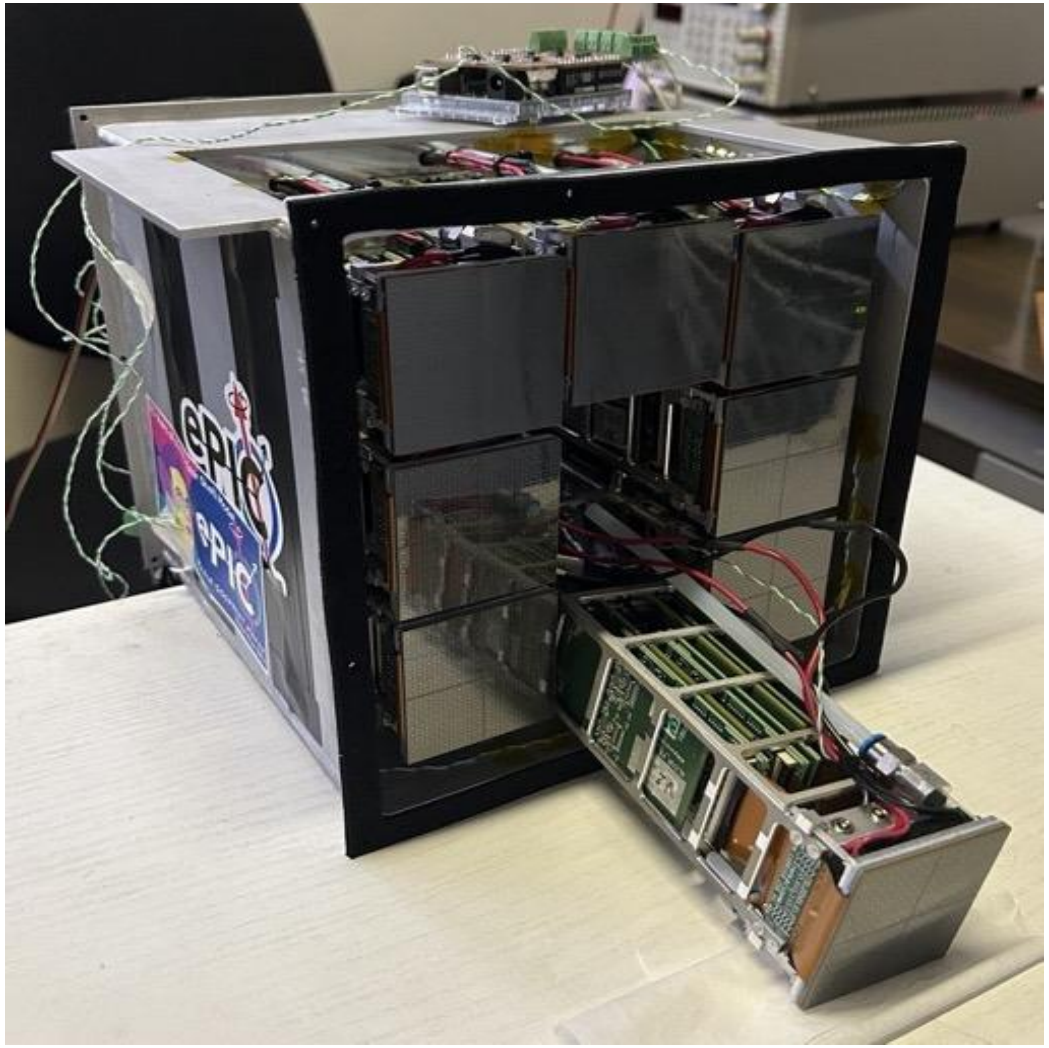
4× FE boards
2× ALCOR-v2 each (8 total) · 2× **FireFly** connectors

L. Rignanese et al., JINST 19 (2024) 02, C02062

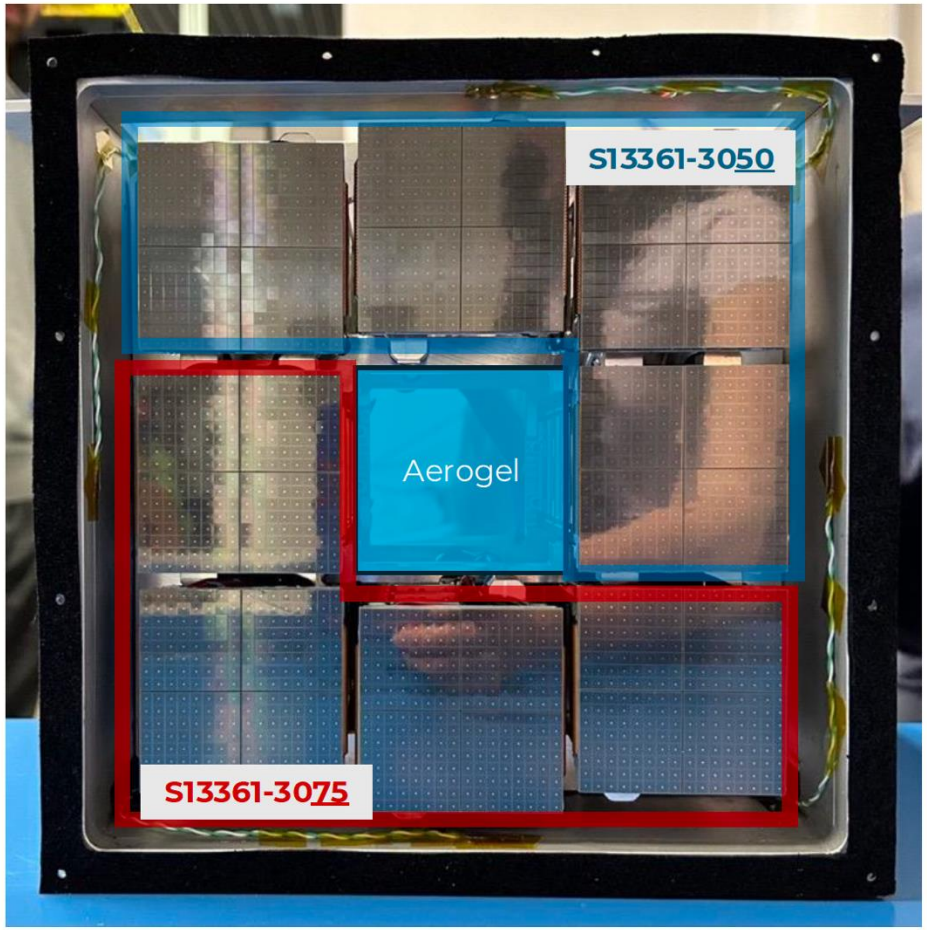
Detector box prototype



8x



Detector box prototype



20x20x20 cm^3

≈**400** cm^2 optical surface (1/10 of a dRICH sector)

2048-Hamamatsu S13360 SiPMs

2 different SPAD sizes (**50** and **75** um)

2 mm dead layer between PDUs

64 ALCOR v2 ASICs

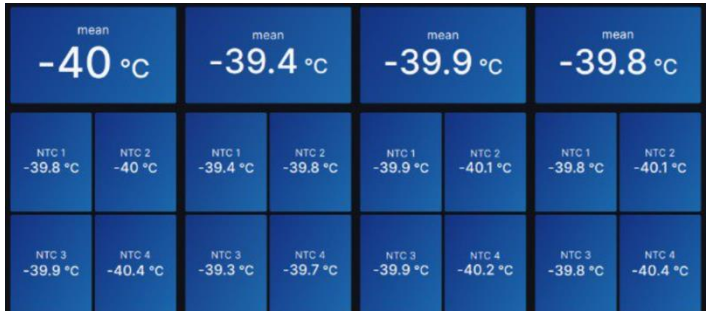
2048 TDC channels electronics

800 Mb/s data rate

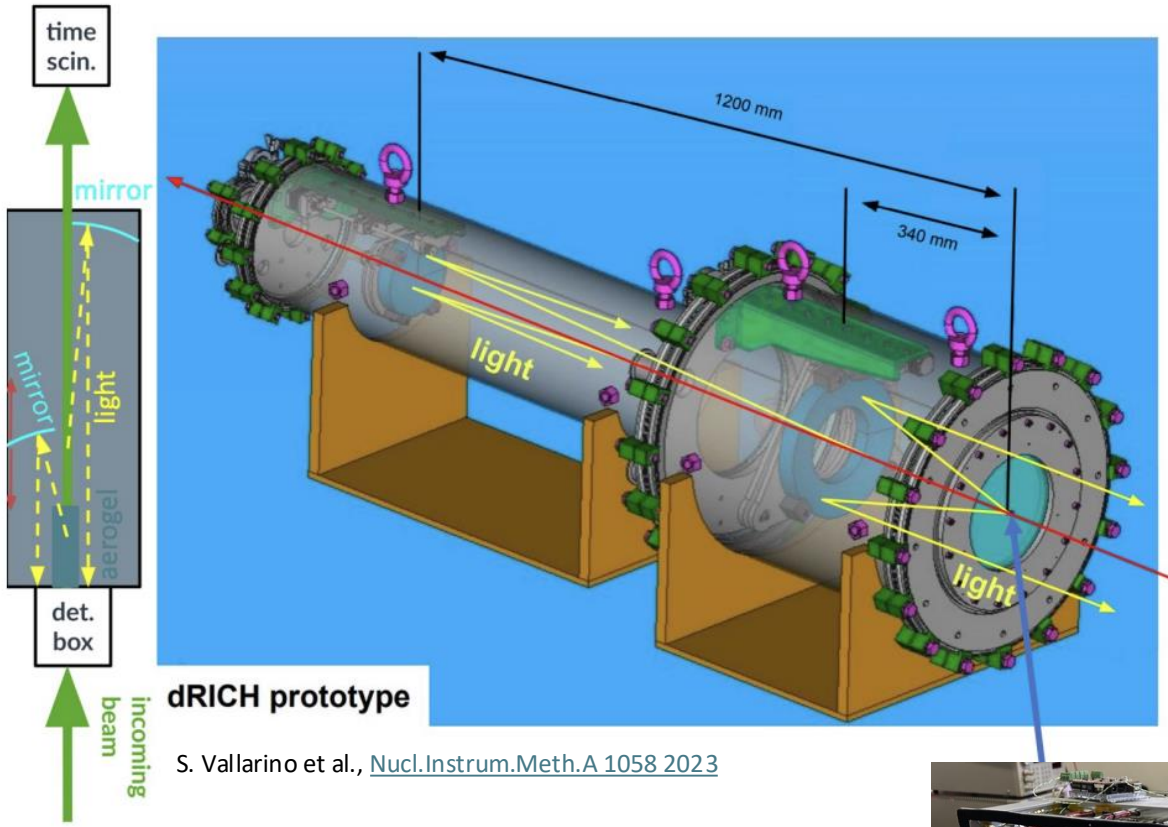
TEC active cooling (≈400 W)

Automatically controlled temp down to -**40 °C**

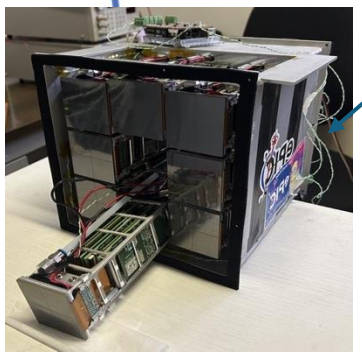
10 °C water cooling

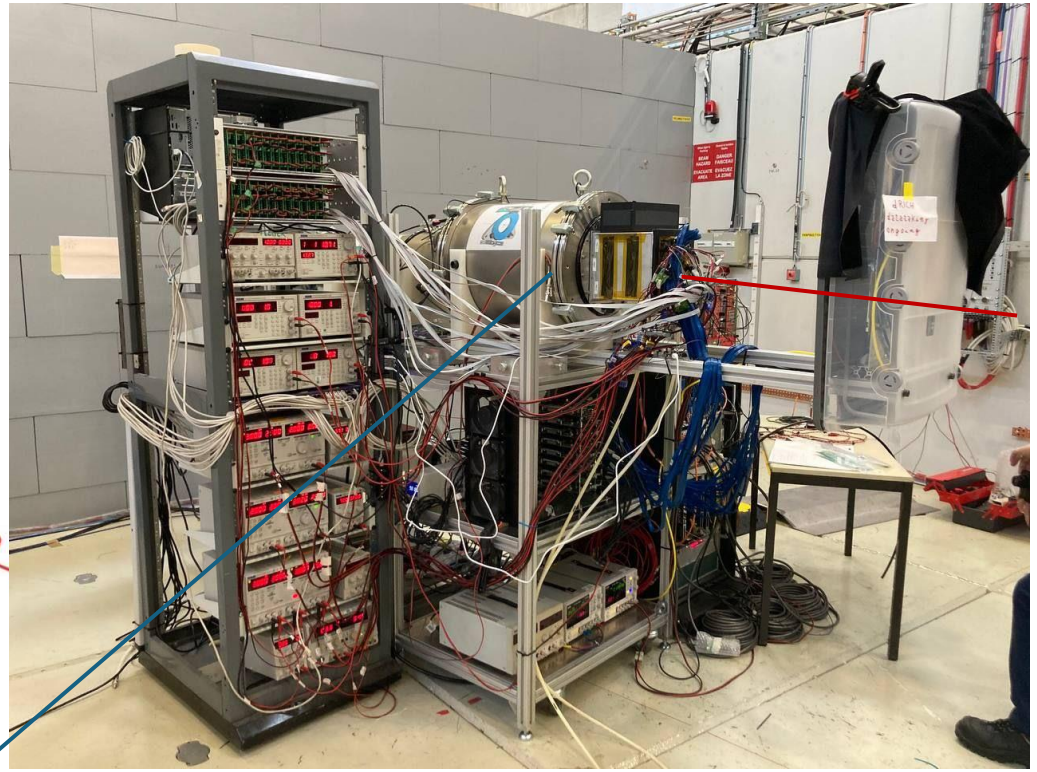


2023-4-5 test beams at CERN



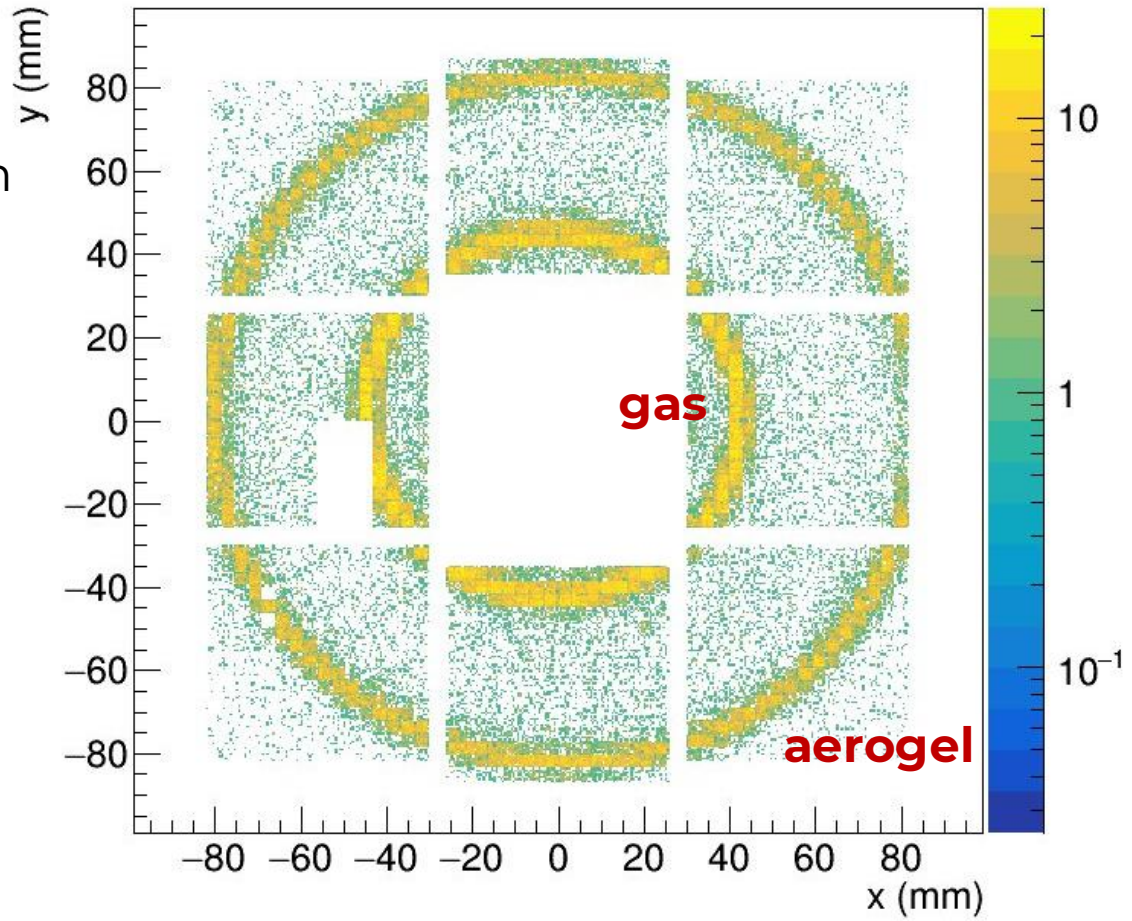
S. Vallarino et al., Nucl.Instrum.Meth.A 1058 2023

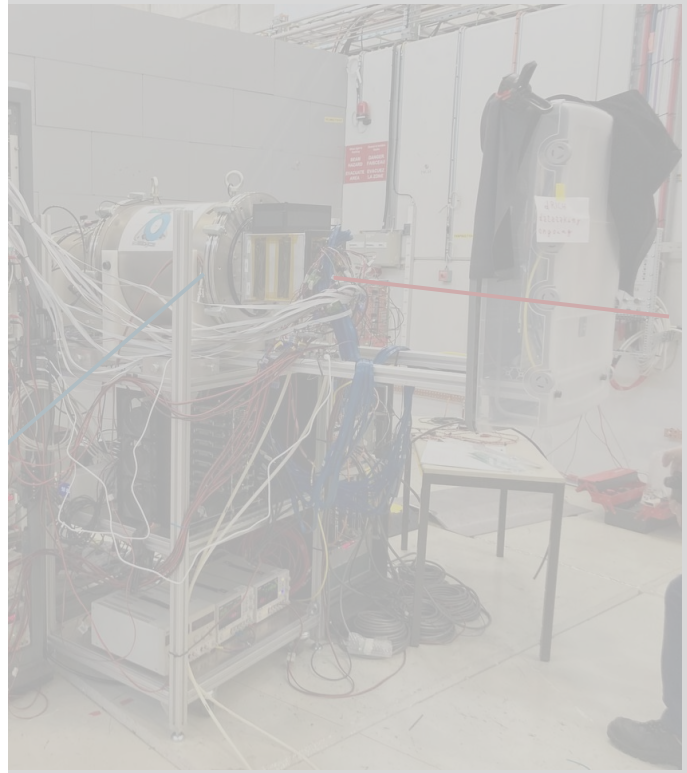




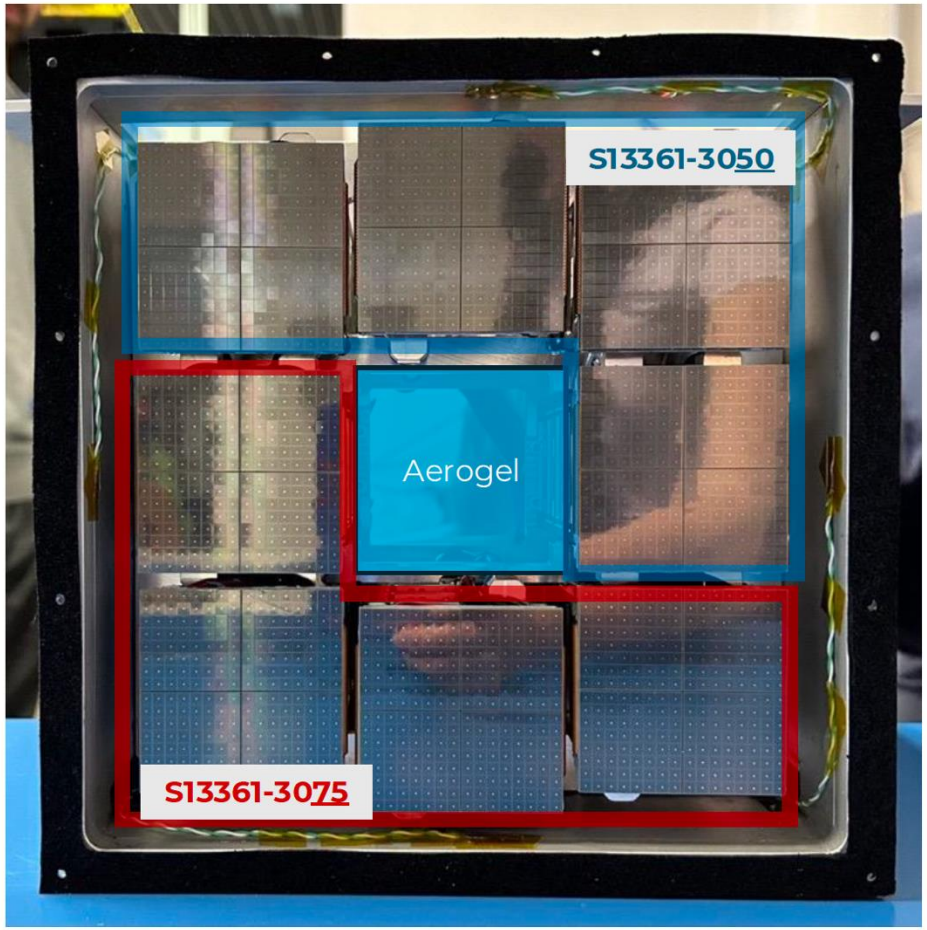
2023-4-5 test beams at CERN

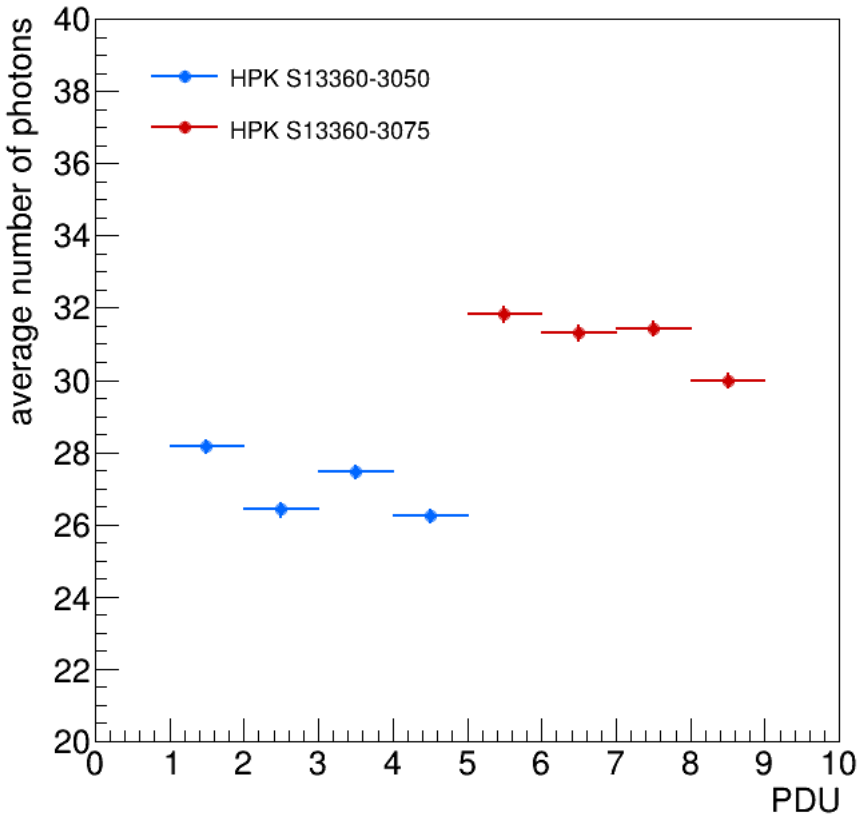
10 GeV/c
negative beam
e- only





Comparison between different SPAD sizes

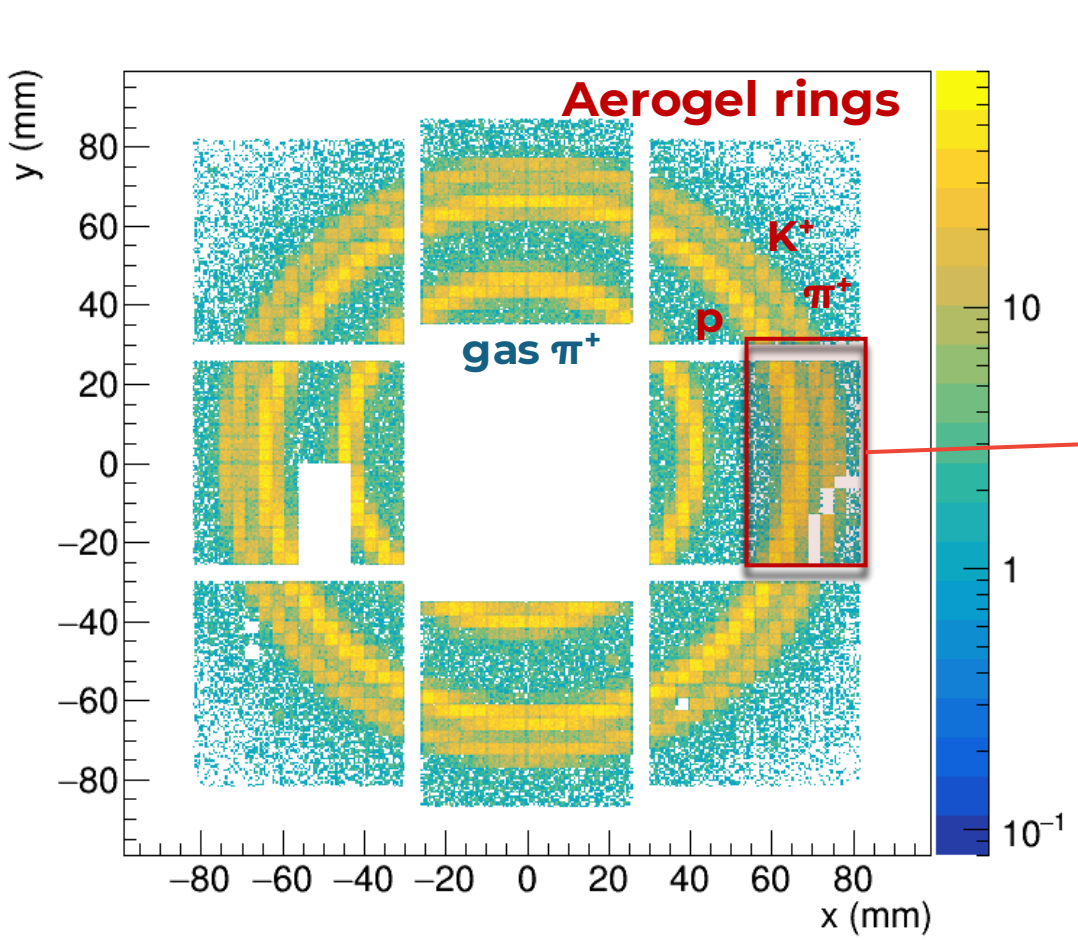


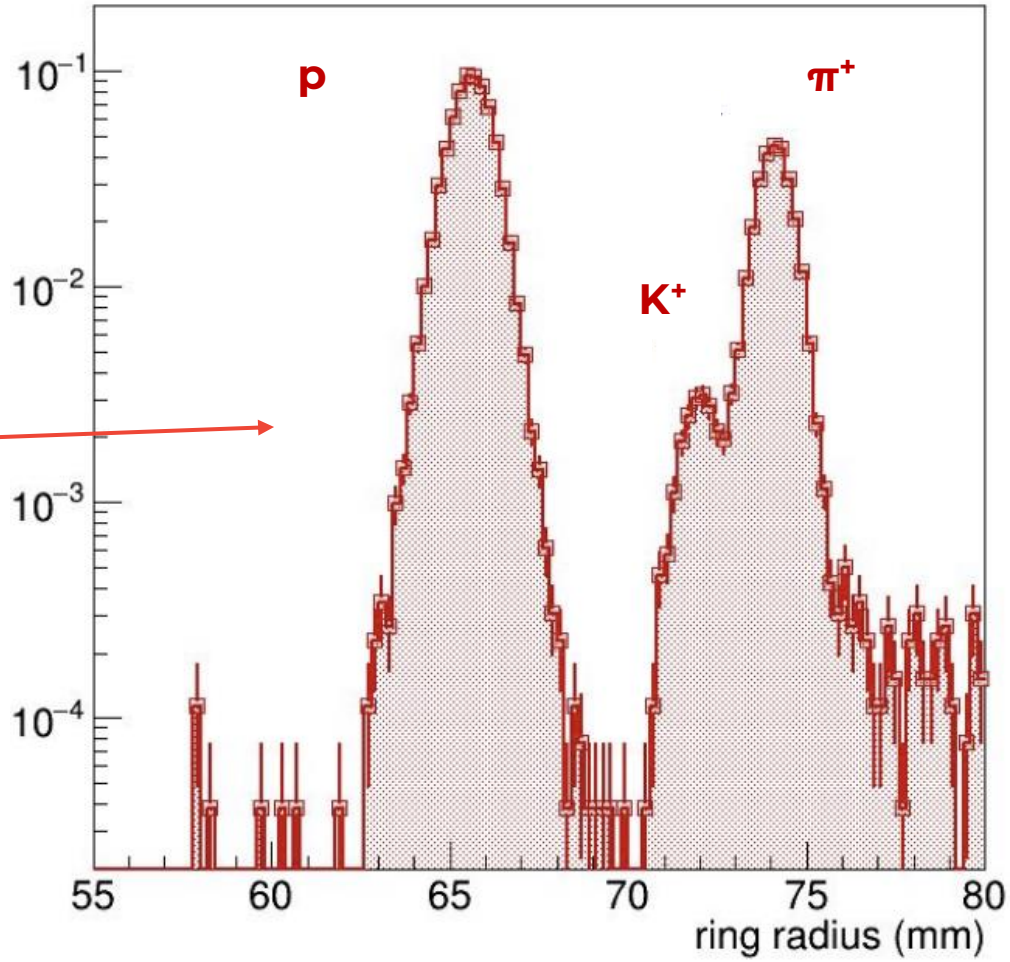


15% increase in number of detected photons
25% increase in PDE

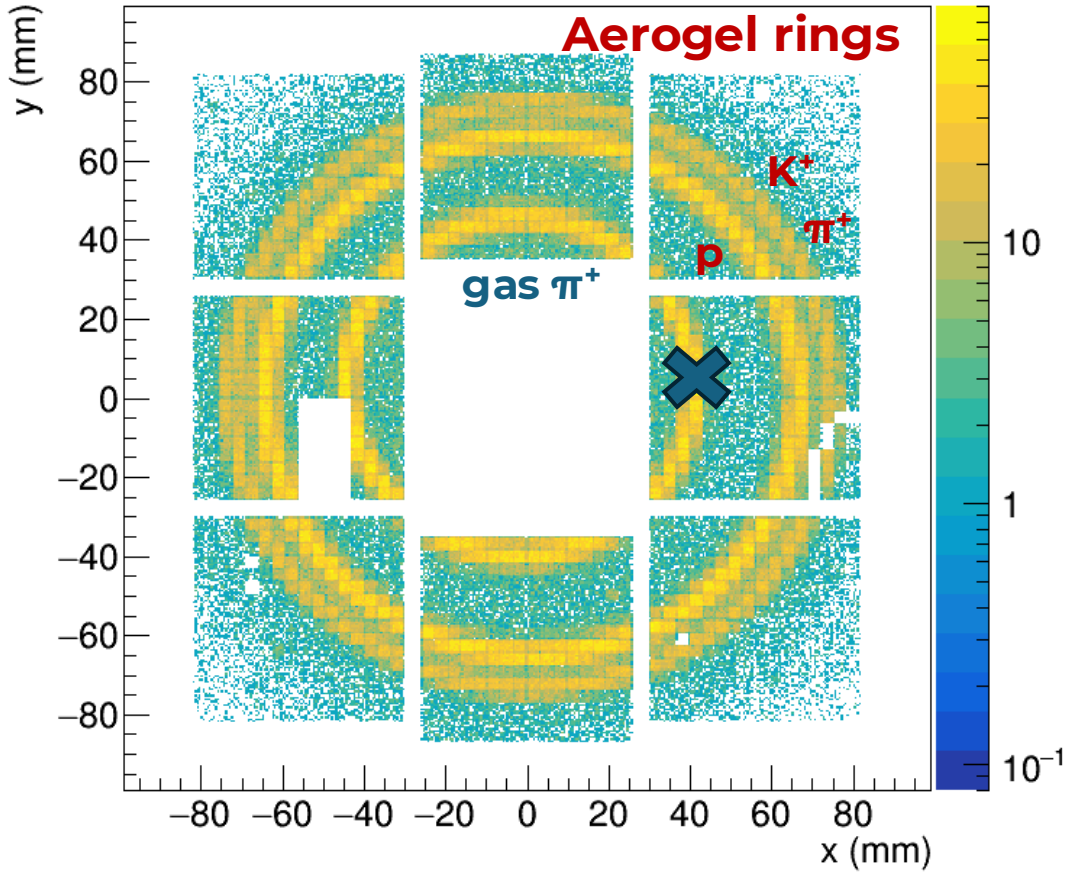
Power of the ”dual” radiator

10 GeV/c positive beam with no selection applied

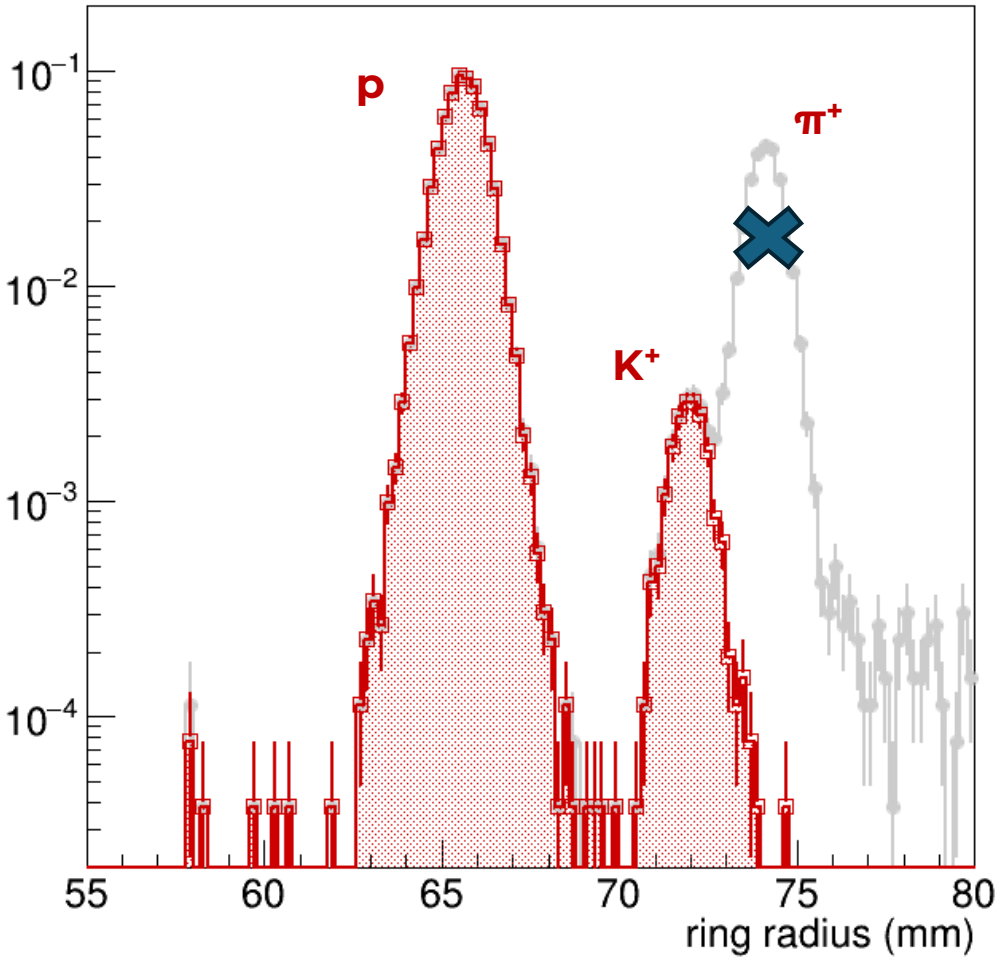




Power of the ”dual” radiator

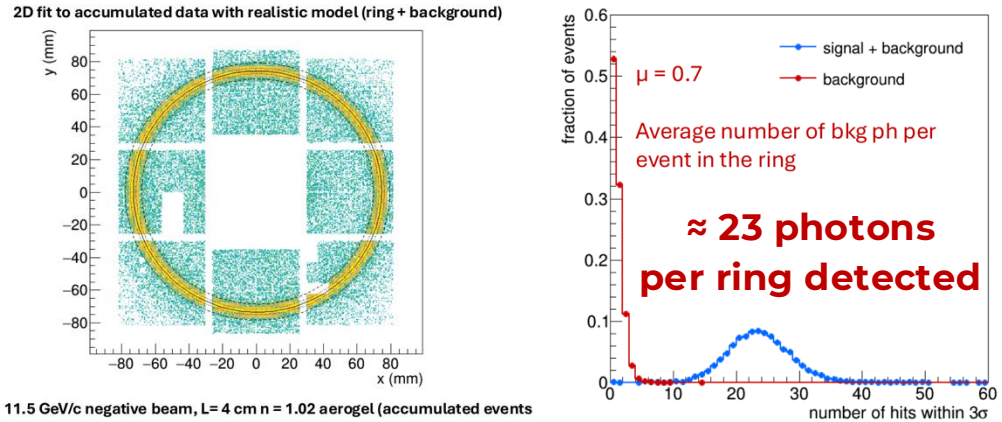


10 GeV/c positive beam with π in gas as veto



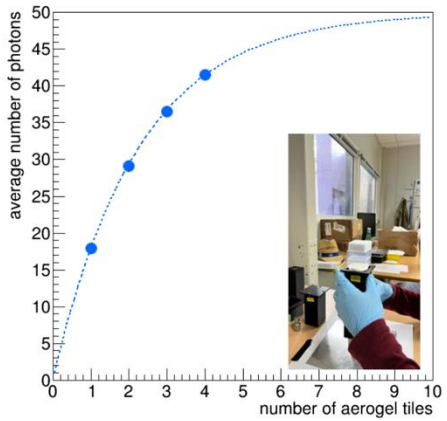
Test beams performance summary

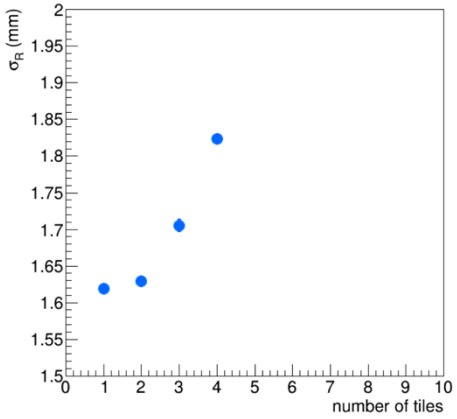
11.5 GeV/c negative beam · n = 1.02 aerogel



Aerogel thickness scan (n = 1.02, 2 cm tiles)

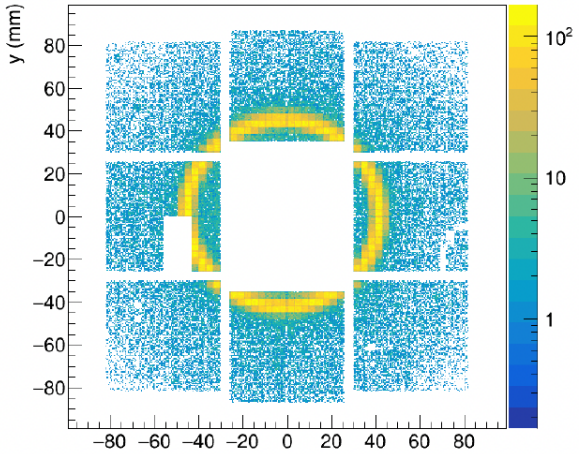
Adding tiles increases the light, less effectively (**absorption**)



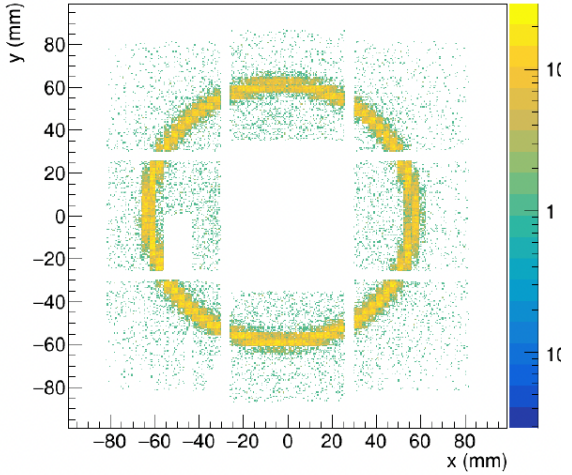


Single-photon radius resolution **degrades** with thickness (**dispersion**)

Explore alternative gases



Nominal C_2F_6 (n = 1.0008)

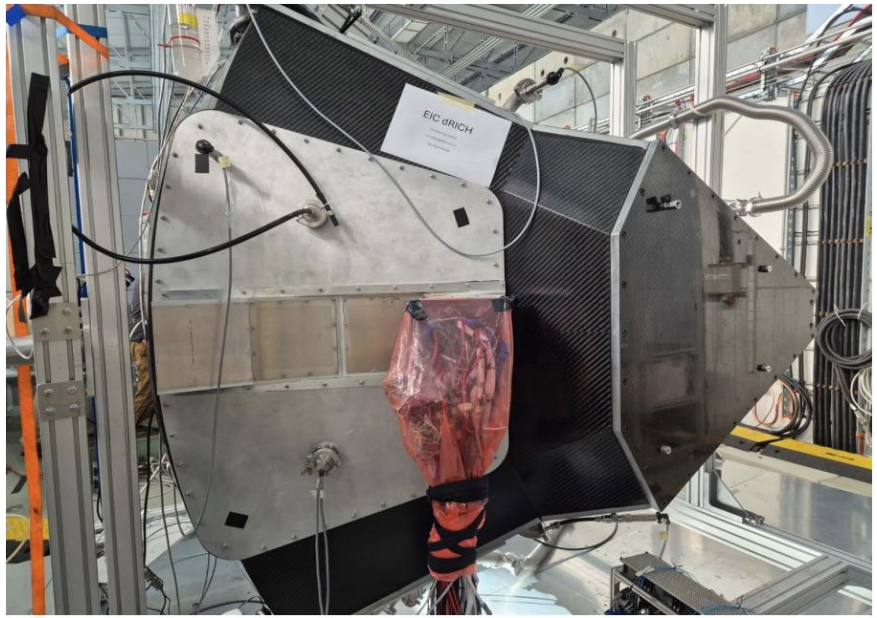


Alternative C_4F_8 (n = 1.0014)

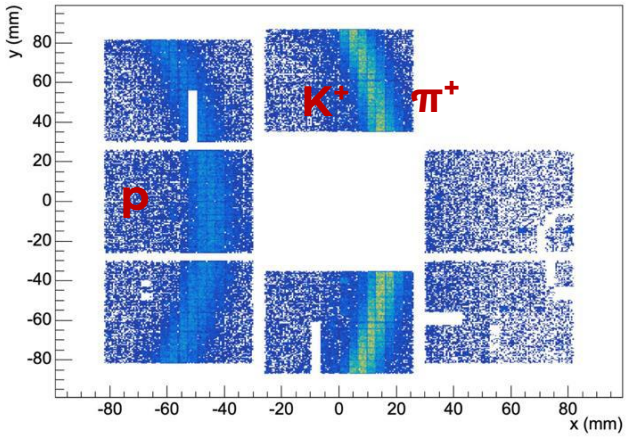
2026 real scale prototype test beam

PRELIMINARY

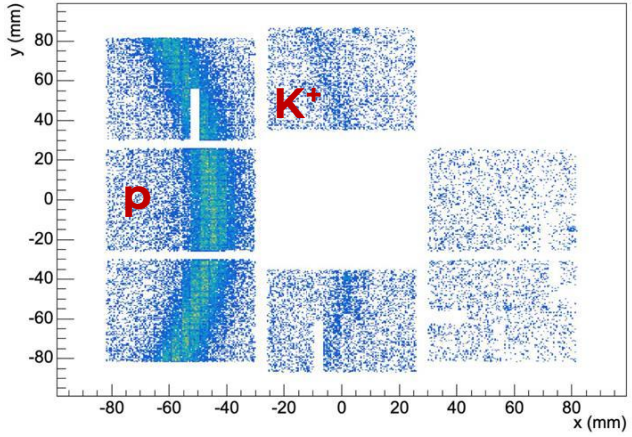
TEST:
Mechanical stability
Gas & light tightness



Before vetoing pions in the gas

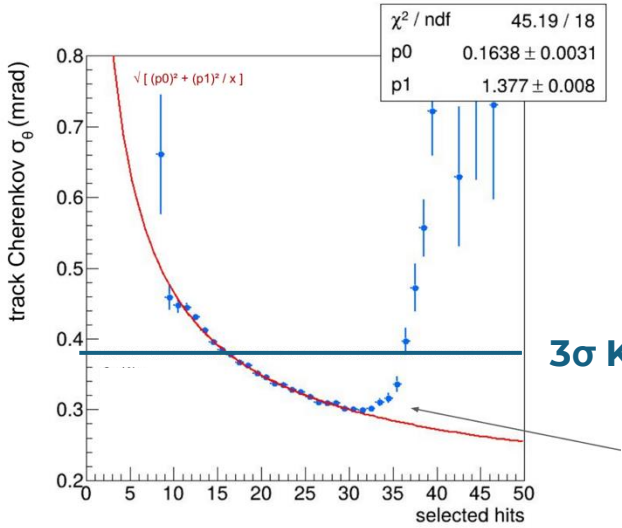


After vetoing pions in the gas



Track angular resolution vs. 3σ K/π at 50 GeV/c

26 ph per ring
σθ single ph 1.38 mrad



3σ K/π separation

One-ring classification error

Summary

- **First large-scale use of SiPMs for single-photon detection in a collider experiment:** ~3 m^2, 3×3 mm^2 pixels, ~320k channels, ~1 T field.
- **Radiation damage under control:** cooling to −40 °C, sub-ns timing, and **in-situ annealing by Joule self-heating**, which reaches oven-level recovery and is safe up to 150 °C.
- **Integrated PDU:** 256 SiPMs, cooling, 4 ALCOR-64 FEBs and the RDO in a compact module. ALCOR-32 gives $\sigma t < 150$ ps; 8 RDOs were validated in beam tests.
- **2048-channel prototype, beam tests 2023–2025:** ≈23 detected photons per ring, clear π/K/p separation with the dual radiator, +15% light with 75 µm SPADs.
- **2026 real-scale prototype (SPS, preliminary):** ~26 photons/track, single-photon $\sigma\theta \approx 1.4$ mrad, track $\sigma\theta \approx 0.34$ mrad. This is **within the 3σ π/K requirement at 50 GeV/c**.
- **Next steps:** final PDU (ALCOR-64, FEB64, UVE SiPMs), sensor procurement and QA towards construction.


CEPC2026
The 2026 International Workshop on the
High Energy Circular Electron Positron Collider
October 22-26, 2026
Shanghai, China

Thank you