dRICH SiPM photodetector electronics and integration

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PID Parallel Session at Lehigh Collaboration Meeting
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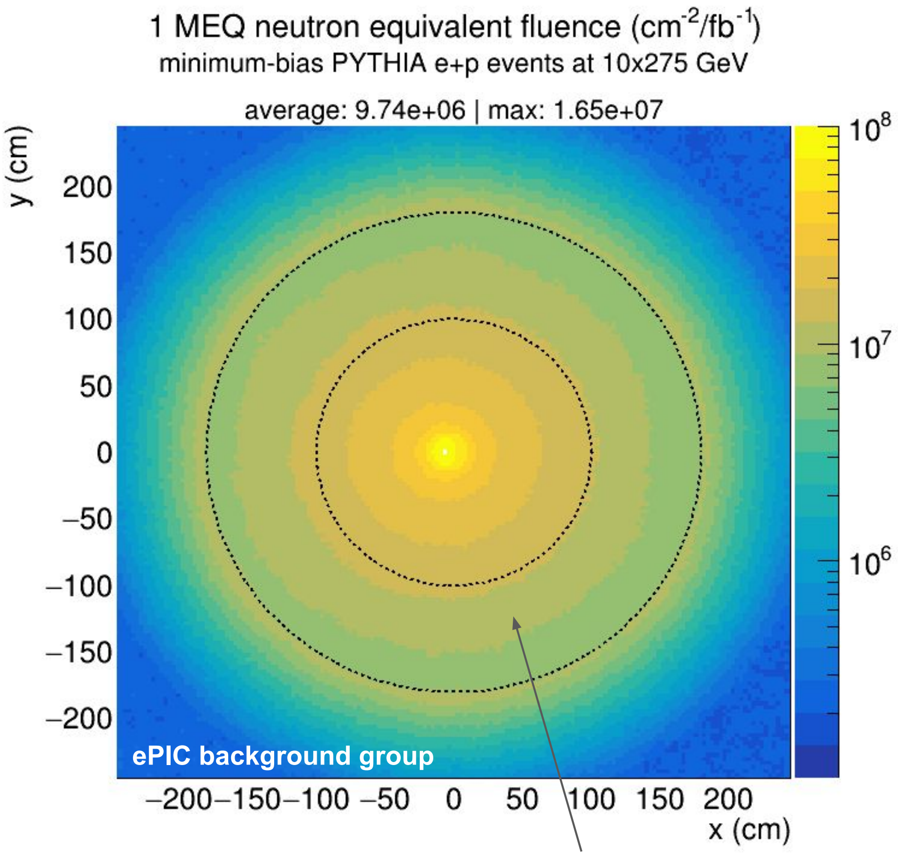
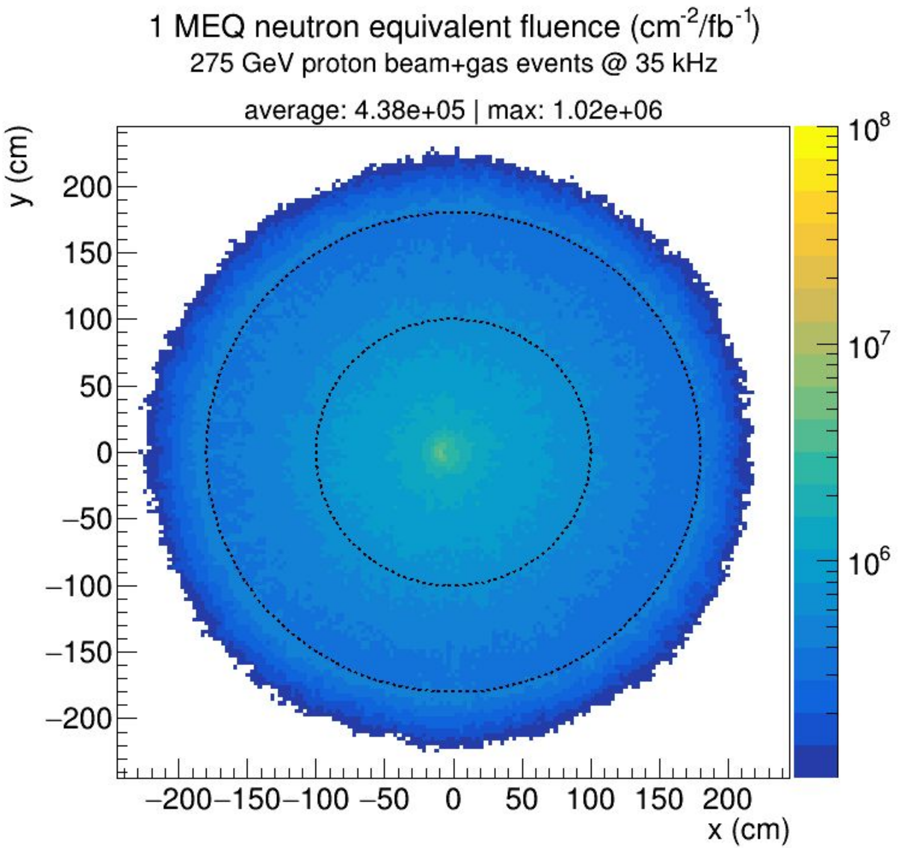
Radiation damage estimates (March 1st, 2024 update)





max fluence = 1.75 10^7 neq/fb^{-1} at the location of dRICH photosensors

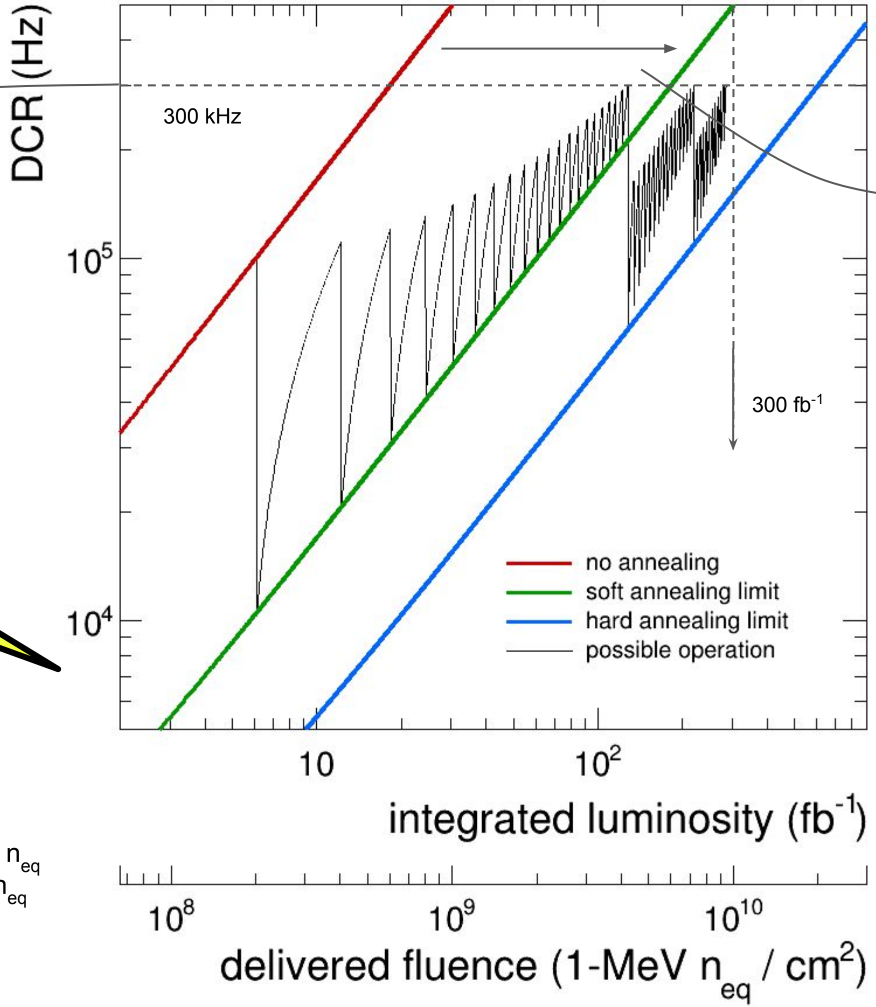
210 < z < 260 cm, 100 < R < 180, including fluence from proton beam-background interactions

Ageing model

max acceptable DCR for
Physics performance
~ 10 noise hits / sector within 500 ps

the "possible operation" scenario shown here has 44 soft-annealing cycles and 3 hard-annealing cycles

Hamamatsu S13360-3050 @ Vover = 4 V, T = -30 C



in-situ annealing significantly extends SiPM lifetime

up to 300 fb^{-1} without need of touching/replacing SiPM
working on optimisation of annealing protocol, maybe one could reach beyond that

model input from R&D measurements (up to 2022)

- DCR increase: 500 kHz/10^9 n_{eq}
- residual DCR (online annealing): 50 kHz/10^9 n_{eq}
- residual DCR (oven annealing): 15 kHz/10^9 n_{eq}

1-MeV neq fluence from background group

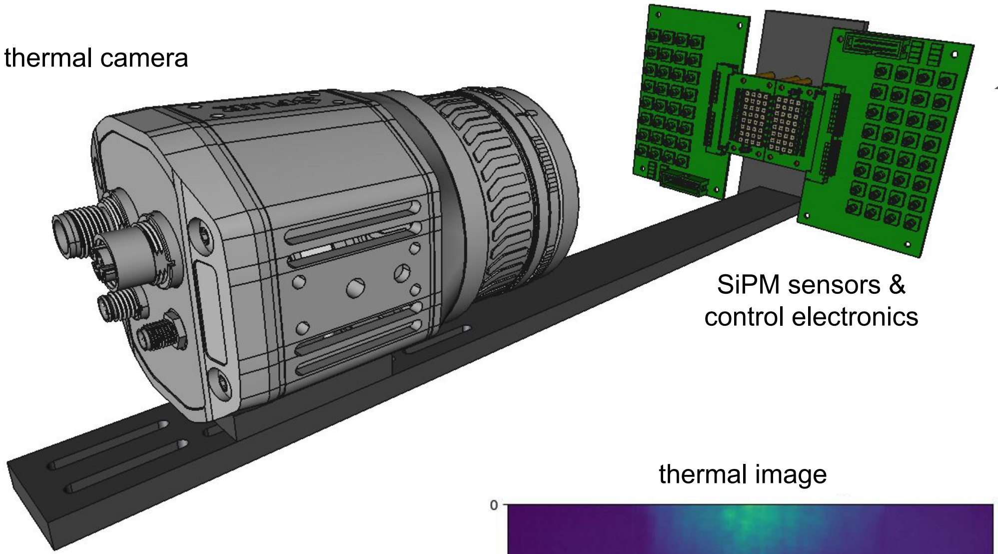
- 1.75 10^7 n_{eq} / fb^{-1}
- add an extra 2x safety factor

these predictions are according to present knowledge / tested solutions
there are more handles to further mitigate DCR
lower Vover, 3V
lover T operation -40 C or below

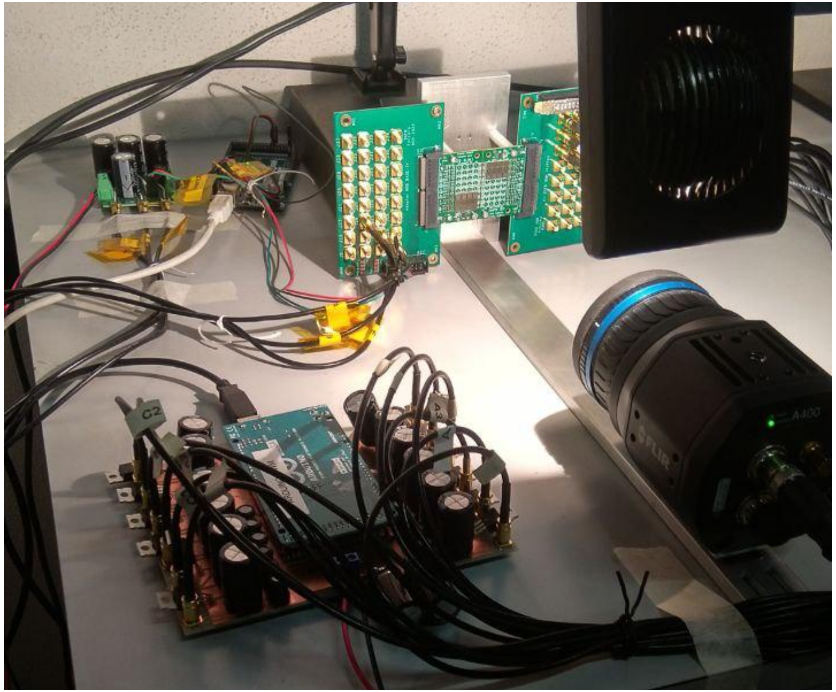
Automated multiple SiPM online self-annealing

system for online self-annealing with temperature monitor and control of each individual SiPM

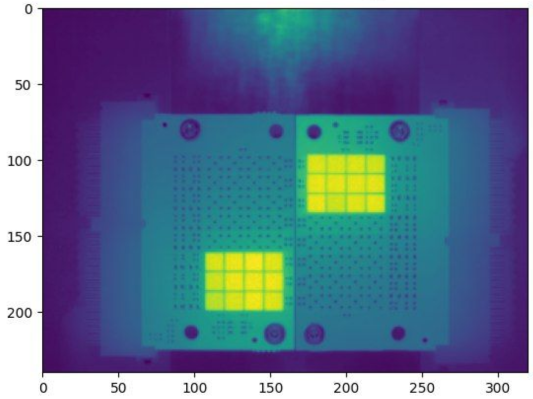
thermal camera



SiPM sensors & control electronics



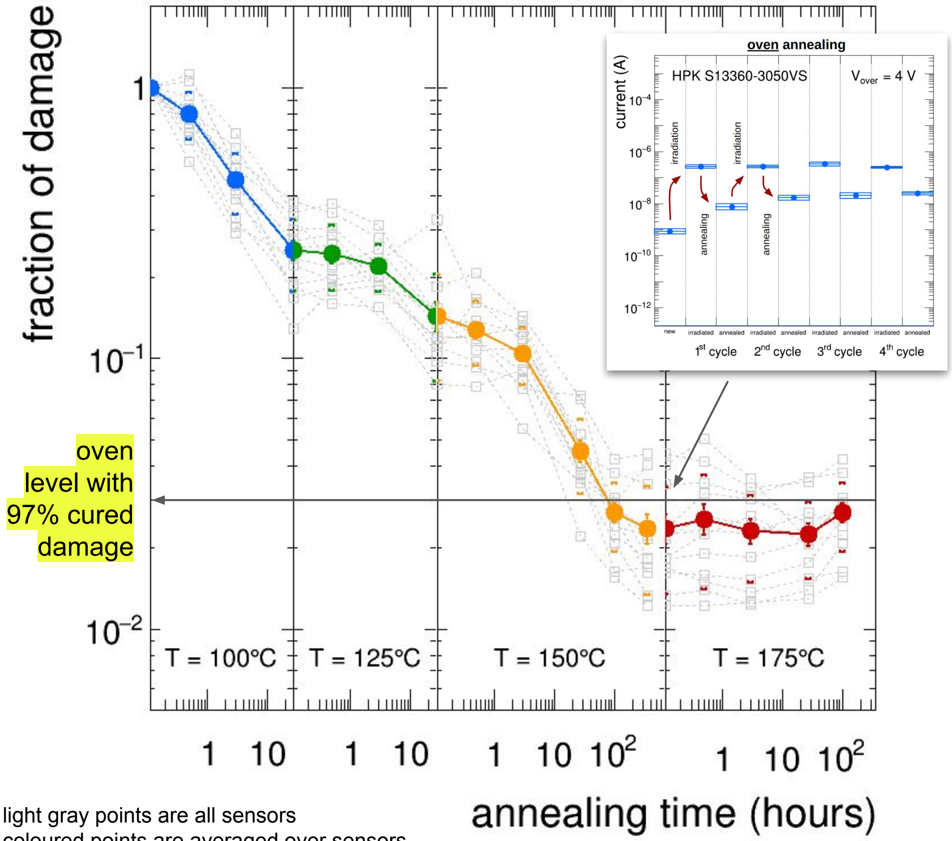
thermal image



monitor and logging system

Detailed studies of SiPM online self-annealing

online self-annealing with forward bias



light gray points are all sensors
coloured points are averaged over sensors
coloured brackets is the RMS

test on a large number SiPM sensors how much damage is cured as a function of temperature and time

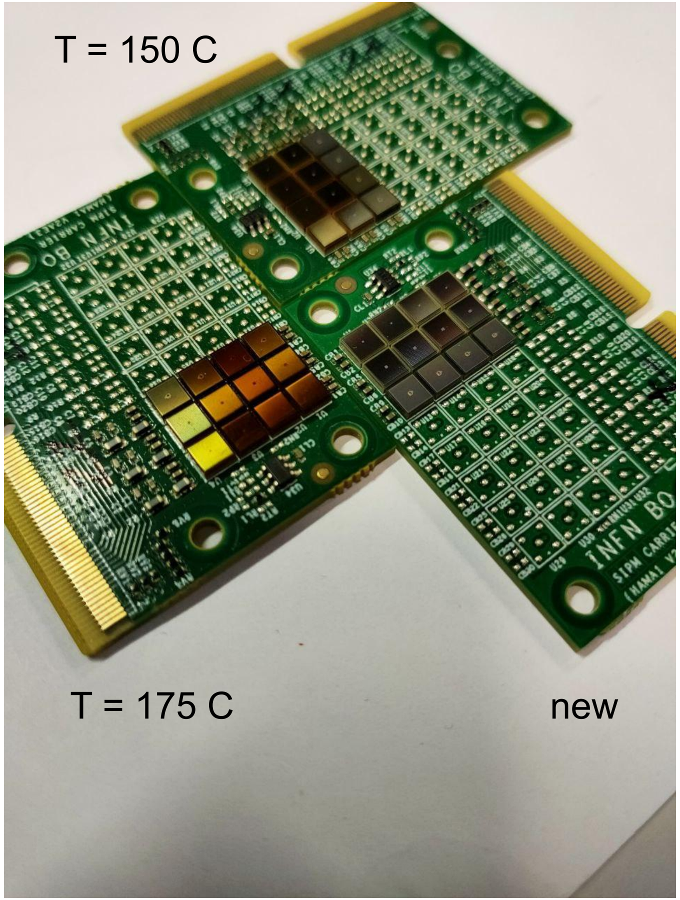
the same sensors have undergone self-annealing
increasing temperature steps
increasing integrated time steps

- started with T = 100 C annealing
  - performed 4 steps up to 30 hours integrated
- followed by T = 125, 150 and 175 C

fraction of residual damage seems to saturate at 2-3% after ~ 300 hours at T = 150 C

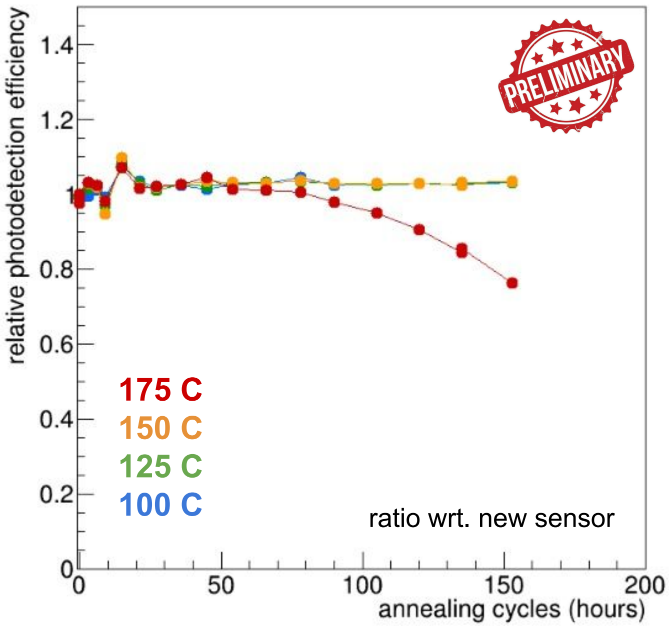
continuing at higher T = 175 C seems not to cure more than that

Detailed studies of SiPM online self-annealing



after many hours of online annealing

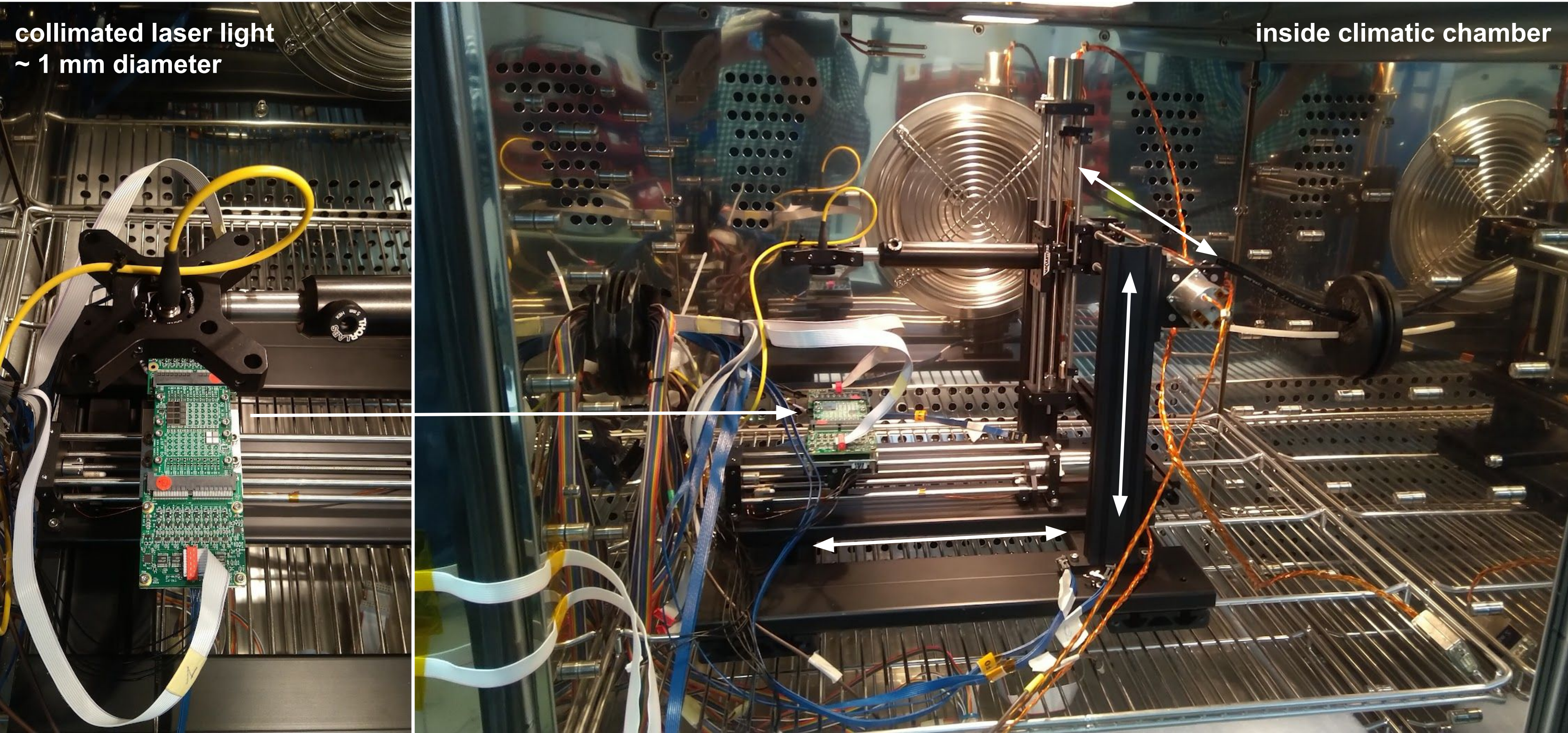
we noticed alterations on the SiPM windows
in particular in one board that underwent
500 hours of online annealing at T = 175 C
the sensors appear "yellowish" when compared to new



detailed studies are ongoing, preliminary results indicate efficiency loss after 100 hours of annealing at T = 175 C. lower temperatures unaffected up to 150 hours

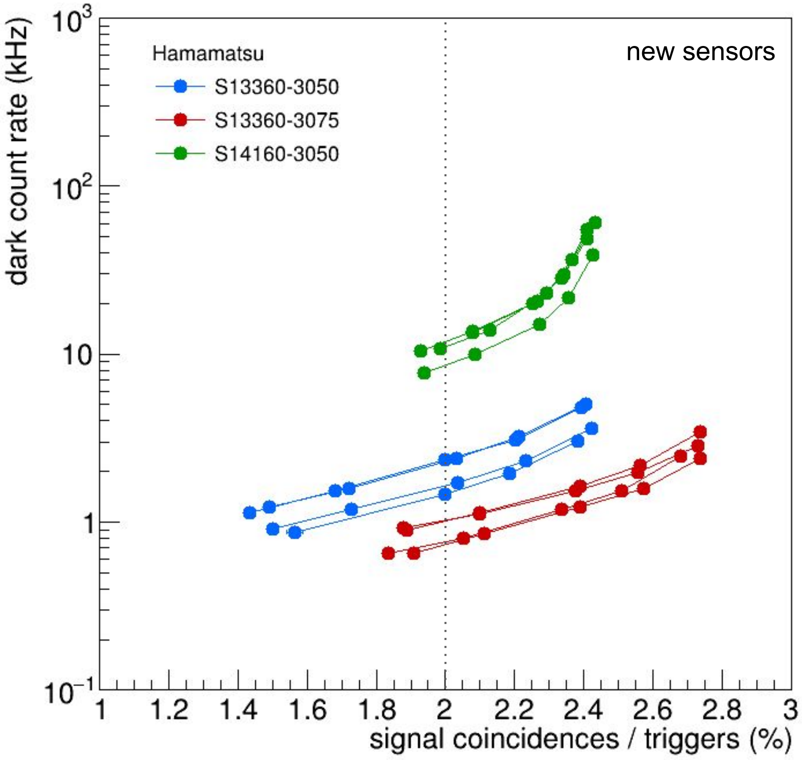
Upgraded laser setup at INFN Bologna

new xyz moving stage that can operate at low temperature (down to T = -40 C) within a 200 mm range



DCR vs. PDE comparison between sensors

3 Hamamatsu sensor types, 4 sensors each measured as NEW



proxy for photodetection efficiency

at the same level of detection efficiency

namely, the probability to detect light from laser pulse

different sensors have different DCR level

<u>best</u>: S13360-3075

most promising sensors, large pitch SPADs (75 μm)

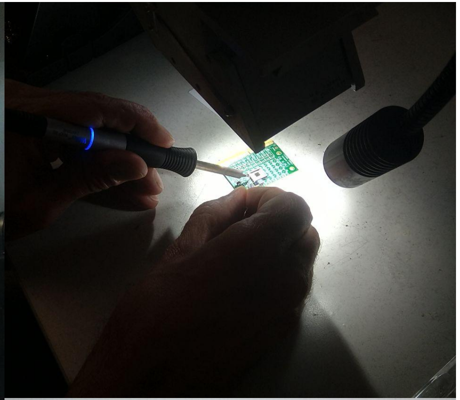
<u>second</u>: S13360-3050

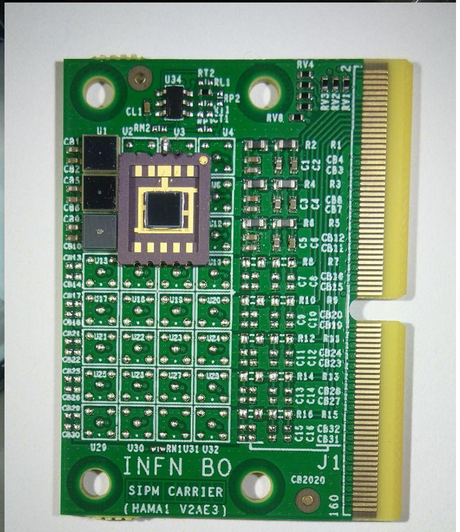
same technology, medium pitch SPADs (50 μm)

<u>worst</u>: S14160-3050

different technology, medium pitch SPADs (50 μm)

New Hamamatsu SiPM prototypes





S13360-3050UVE

newly-developed Hamamatsu SiPM sensors

based on S13360 series

few samples of 50 μm and 75 μm SPAD sensors

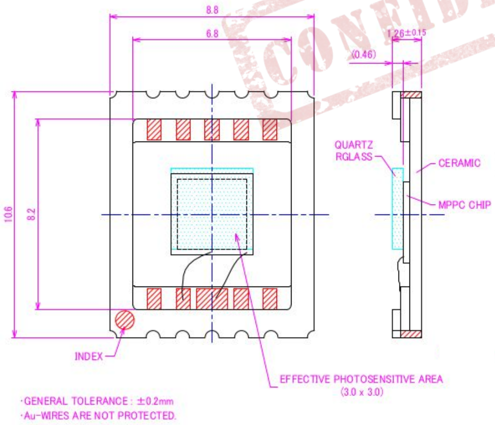
on paper they look VERY promising

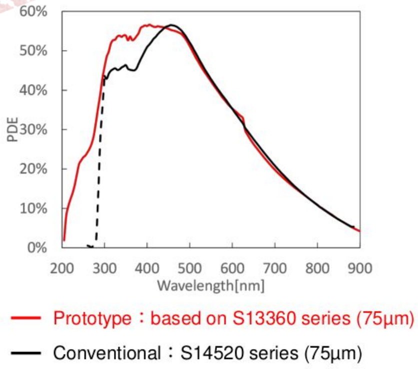
- improved NUV sensitivity
- improved signal shape
- improved recharge time

mounted on EIC SiPM test boards

we will characterise and test them in full

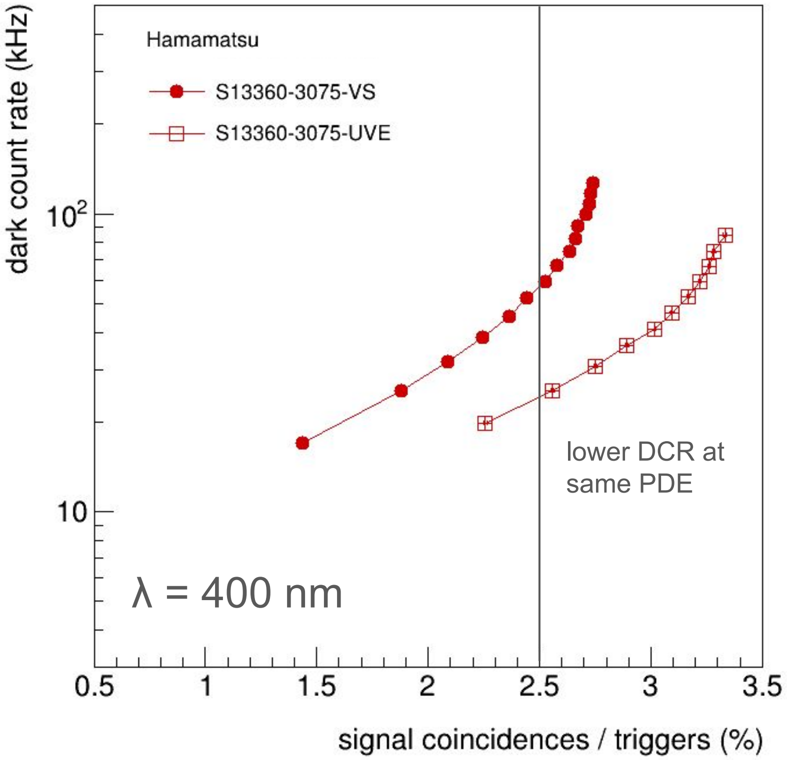
irradiation, annealing, laser, …

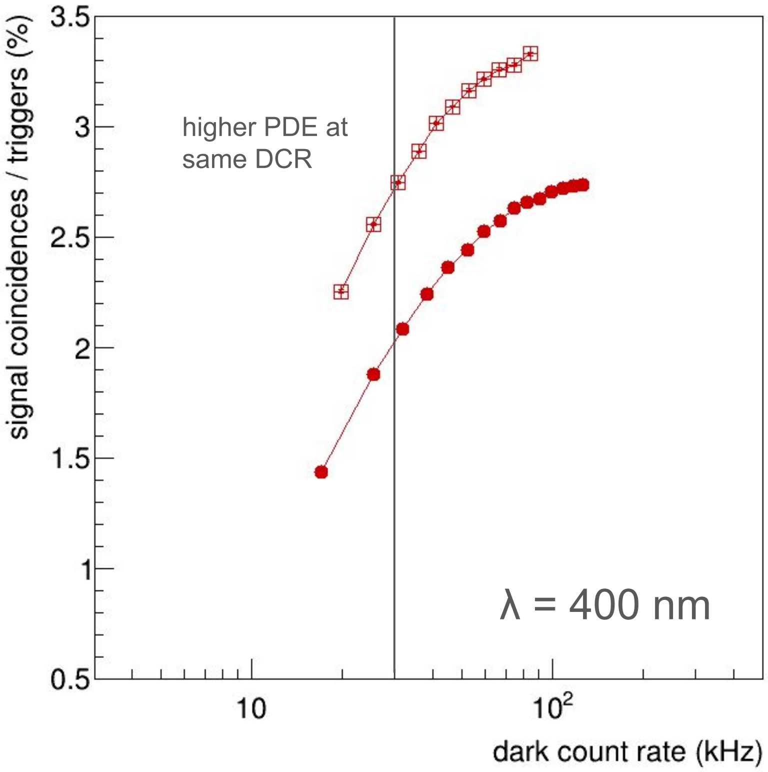




prototype Hamamatsu sensors (10^9 neq after oven annealing)

PRELIMINARY

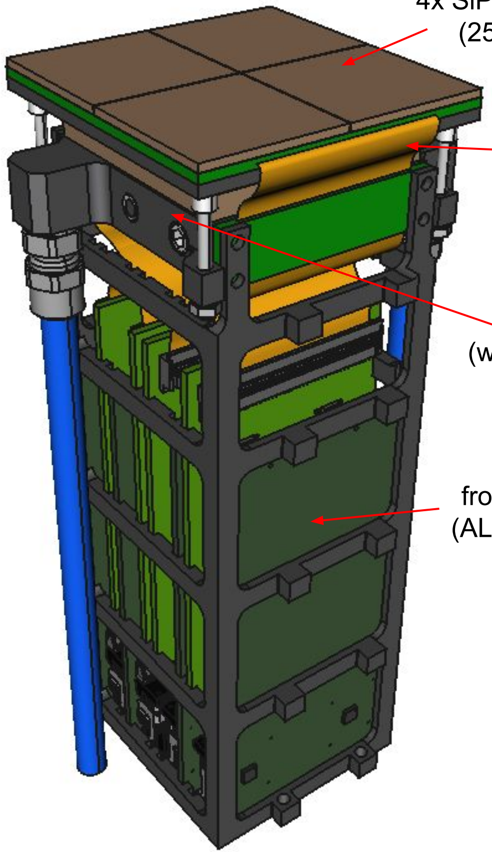


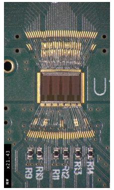


prototype Hamamatsu UVE sensors have significantly higher efficiency than standard sensors
caveat: we only measure PDE at the fixed **laser wavelength of ~400 nm**, larger PDE expected because…
prototype sensors have a NUV-enhanced behaviour.
we will study them further, currently asking Hamamatsu status for production and quotation of this product

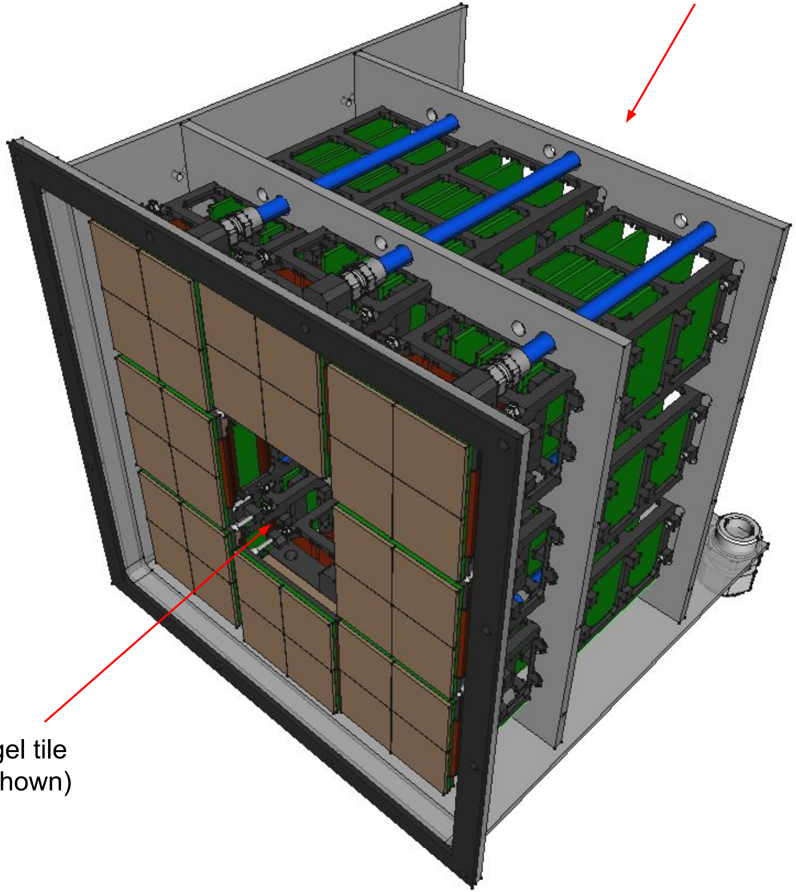
detector prototype and beam tests

EIC ePIC-dRICH SiPM photodetector prototype



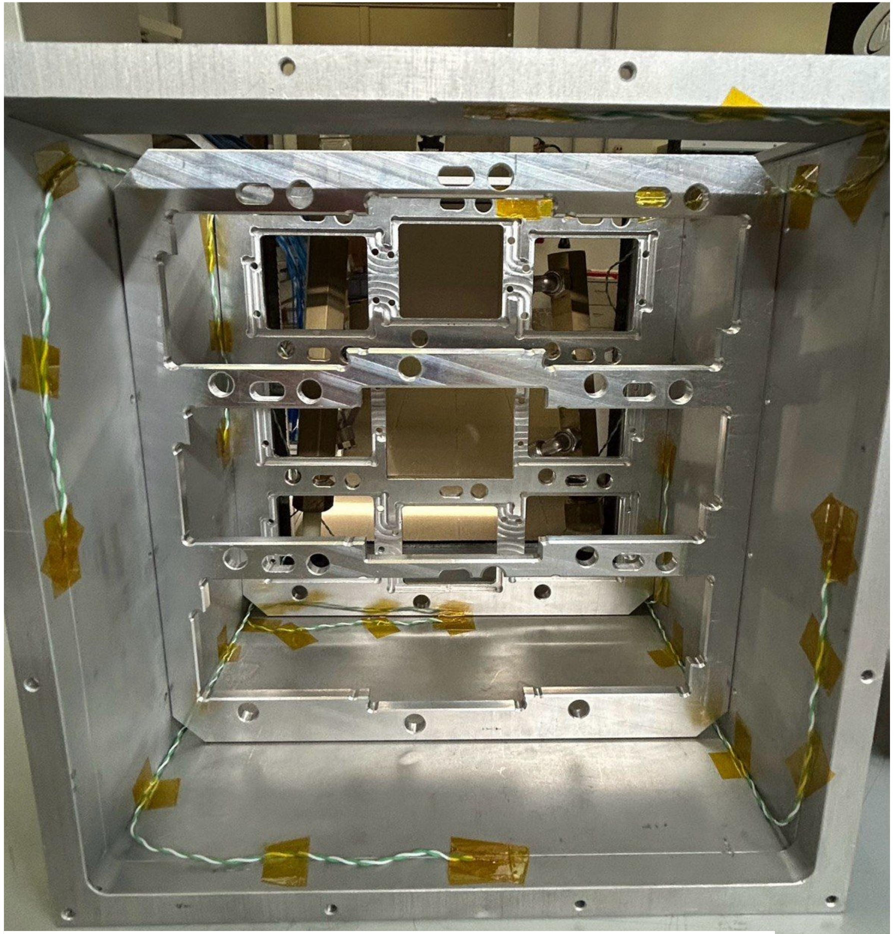


PhotoDetector Unit (PDU)

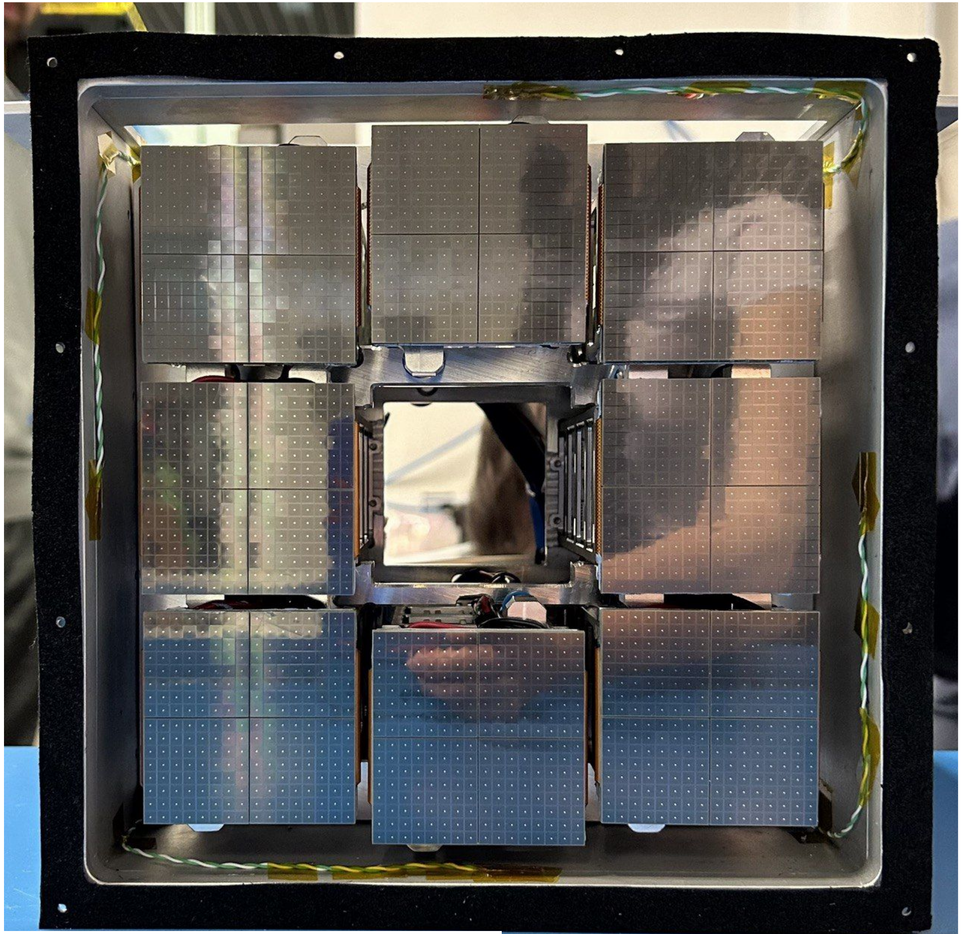


Readout Box

From an empty box to a full detector



empty readout box with PDU housing and monitor thermocouples



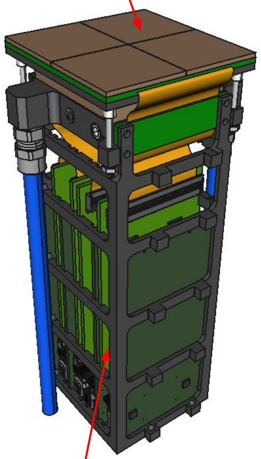
readout box filled with 8 PDUs ready to go

2024 test beam at CERN-PS

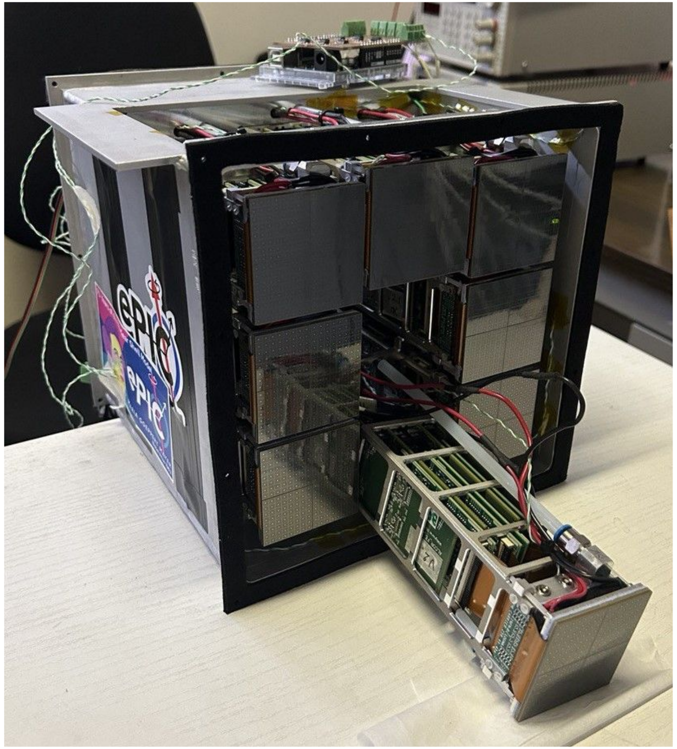
another successful beam test with prototype SiPM photodetector units (CERN-PS, ended on 5th June)

PDU

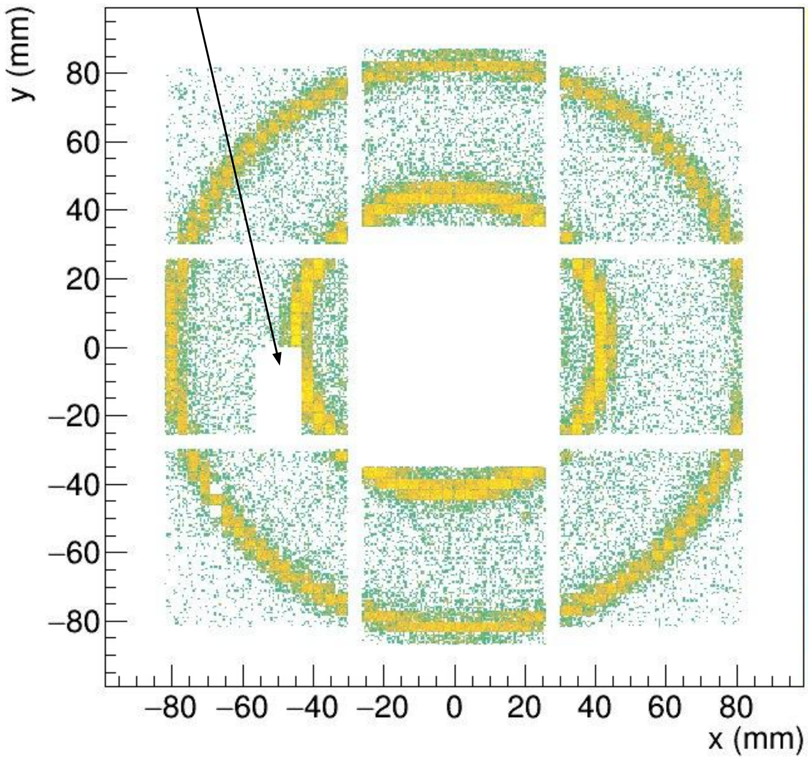
4x SiPM matrix arrays
(256 channels)



front-end electronics
(ALCOR ASIC inside)



unfortunately one ASIC chip (32 ch) had some front-end problems



all the rest was rather full of photons

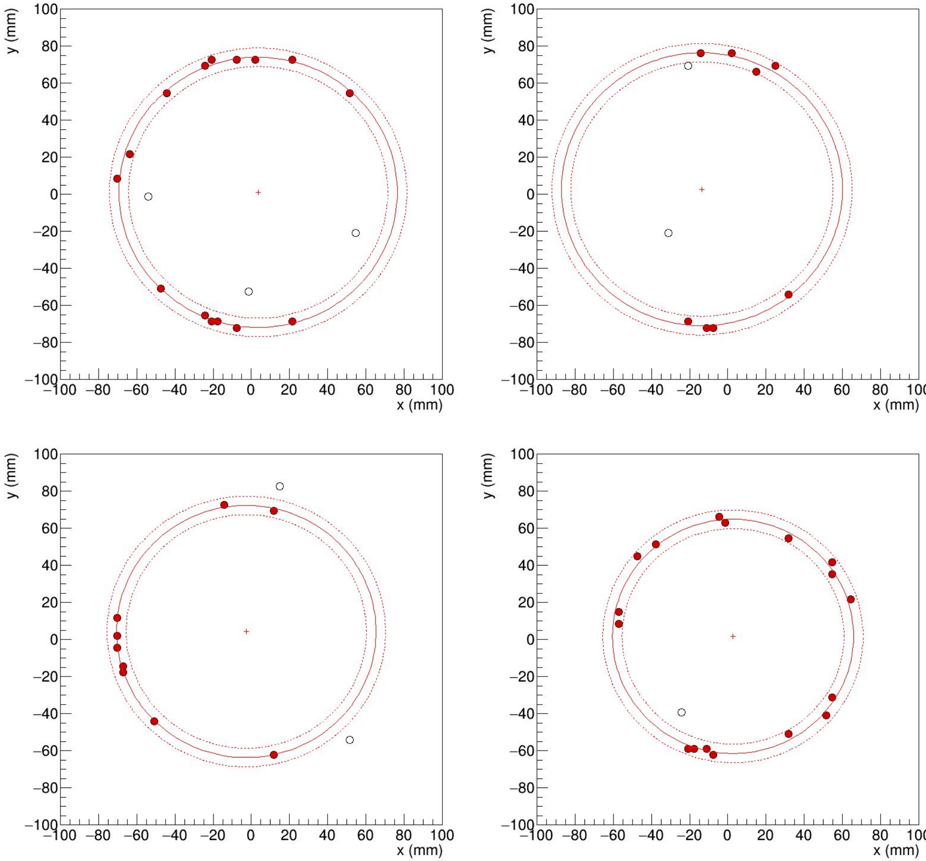
> 2000 SiPMs with TDC readout at work

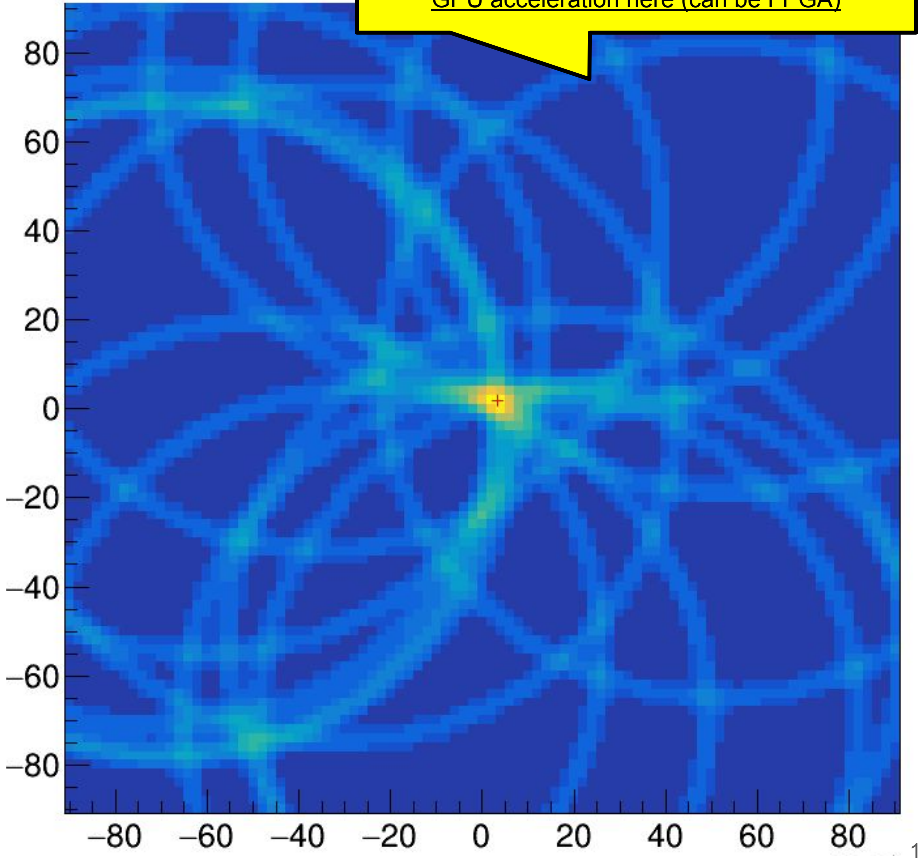
Test beam data analysis is ongoing

event-by-event pattern recognition with Hough Transform Method

4D (including time) Hough transform can detect rings in a streaming detector

GPU acceleration here (can be FPGA)



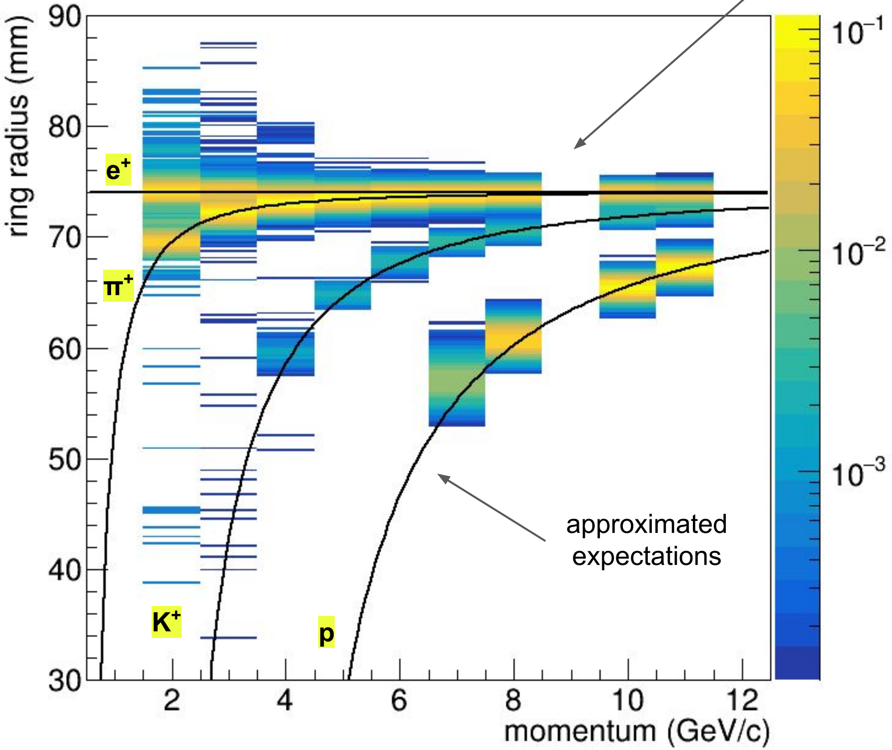


Beam momentum scan

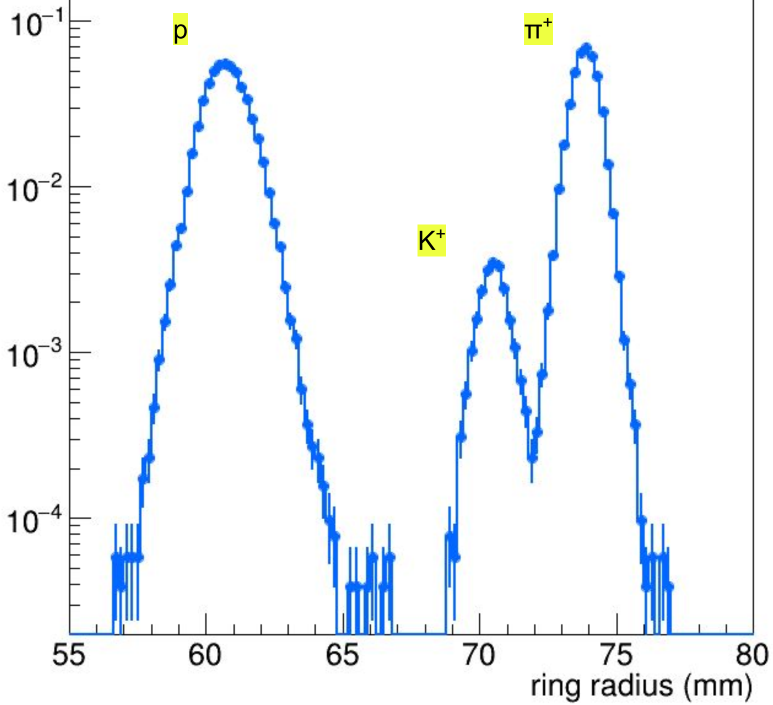
positive particles, aerogel only

something went wrong with the
beam configuration for 9 GeV
(that's a pity, data seems not good)

reconstructed radii vs. beam momentum



reconstructed ring radius at 8 GeV/c beam momentum



nice!

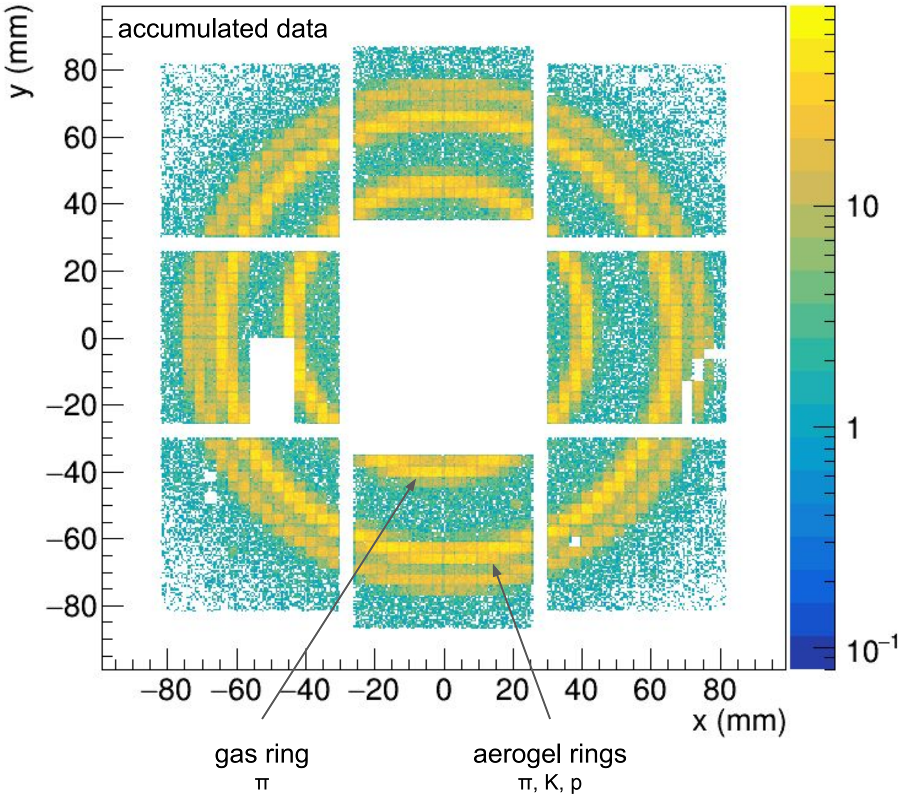
asdasdasd

Interplay between aerogel and gas radiators

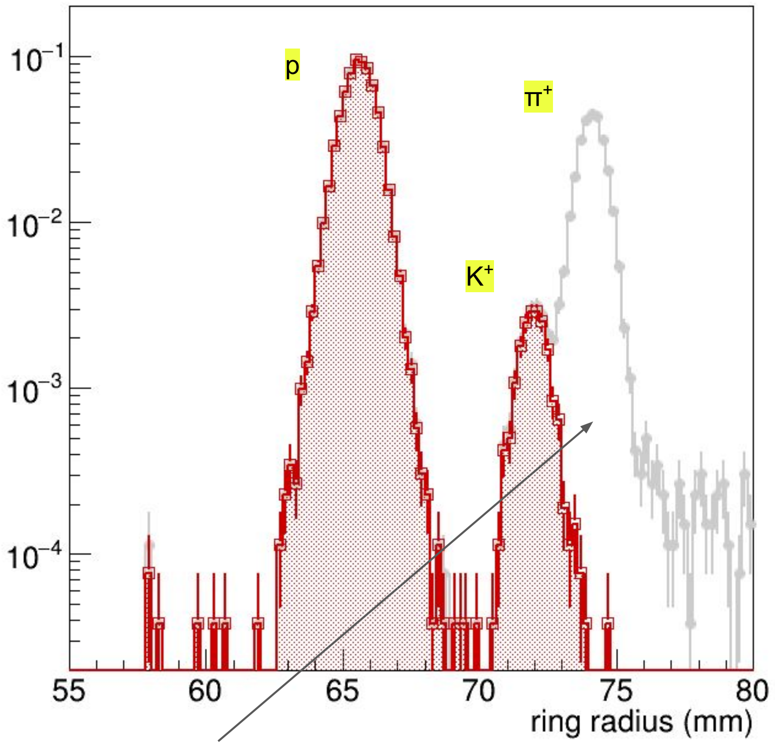
gas ring tags pions, at 10 GeV/c kaons and protons are below C_2F_6 gas threshold

Nicola Rubini

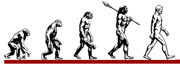
10 GeV/c positive beam with no selection applied



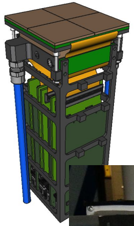
reconstructed ring radius at 10 GeV/c with gas veto

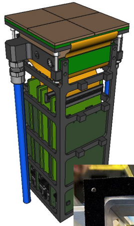


gas-ring veto removes pions, clean kaon identification at 10 GeV/c



towards construction



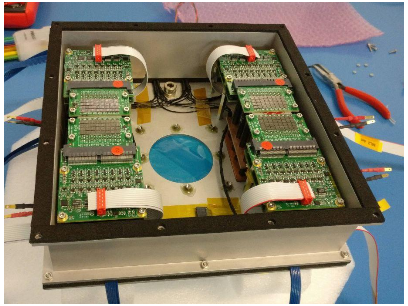


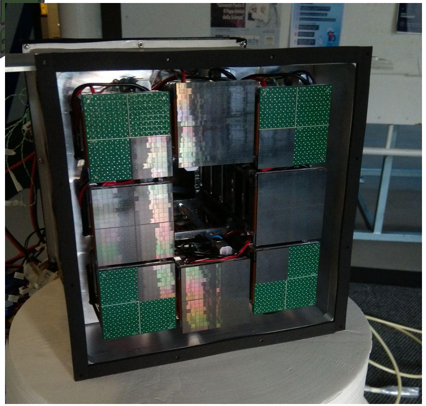
2022
electronics v1

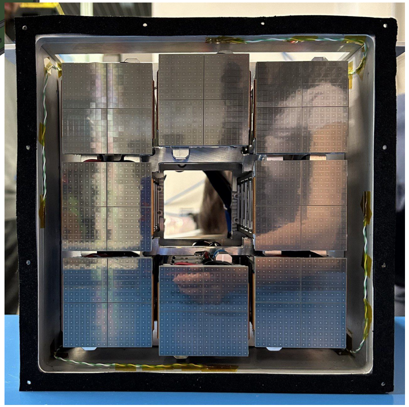
2023
electronics v2

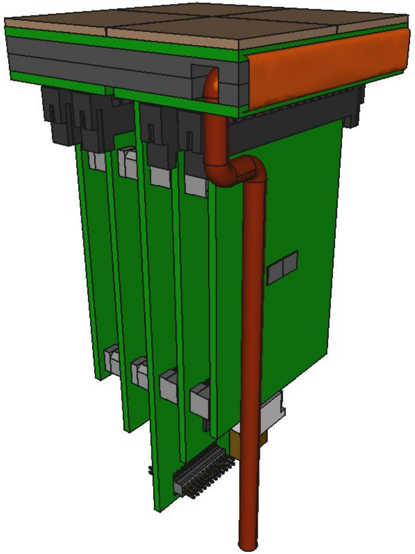
2024
electronics v2.1

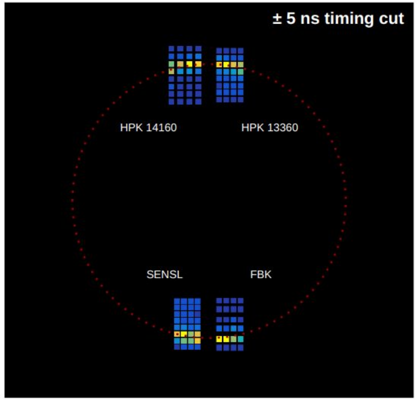
2025
electronics v3
final prototype

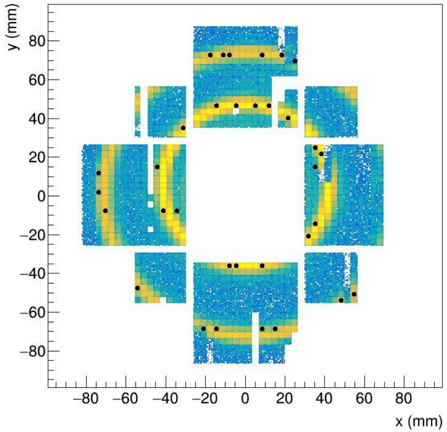


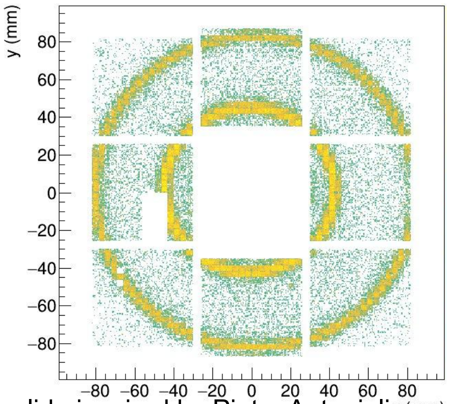










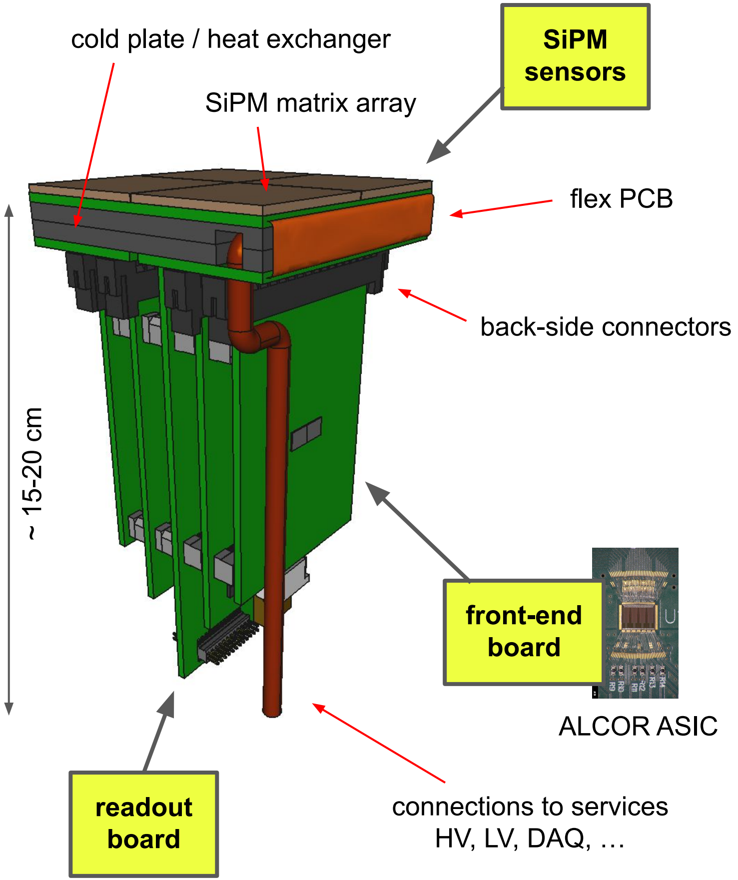


slide inspired by Pietro Antonioli

detector integration
and electronics

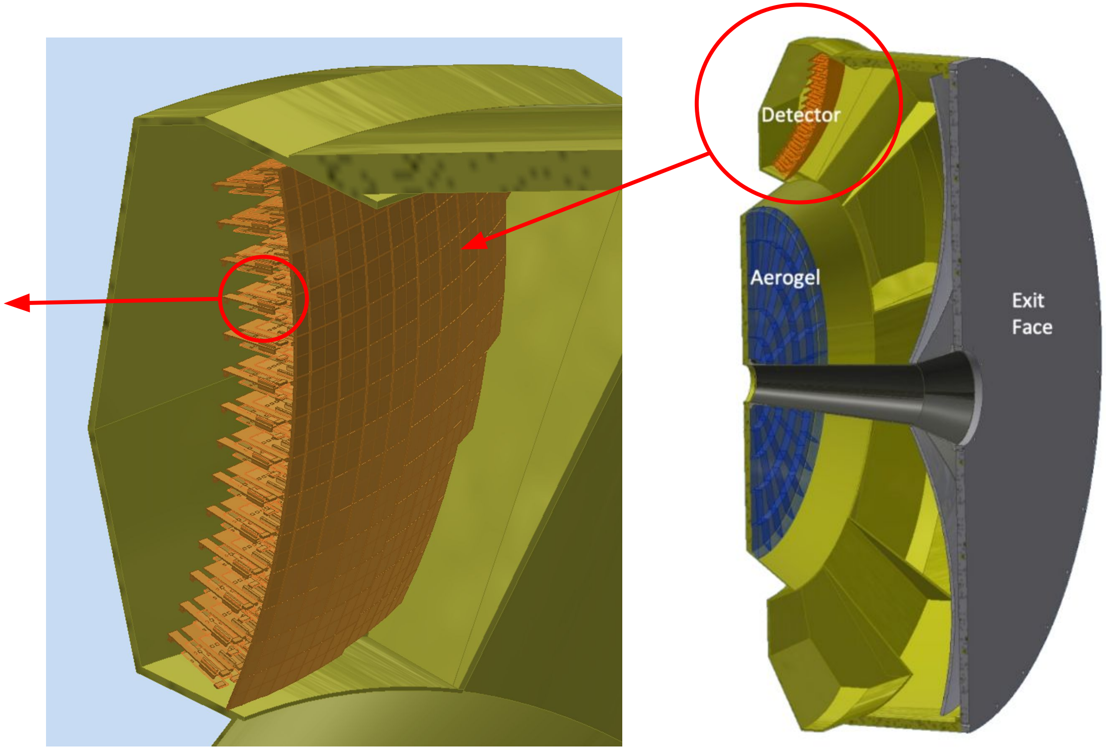
Photodetector unit

conceptual design of PDU layout



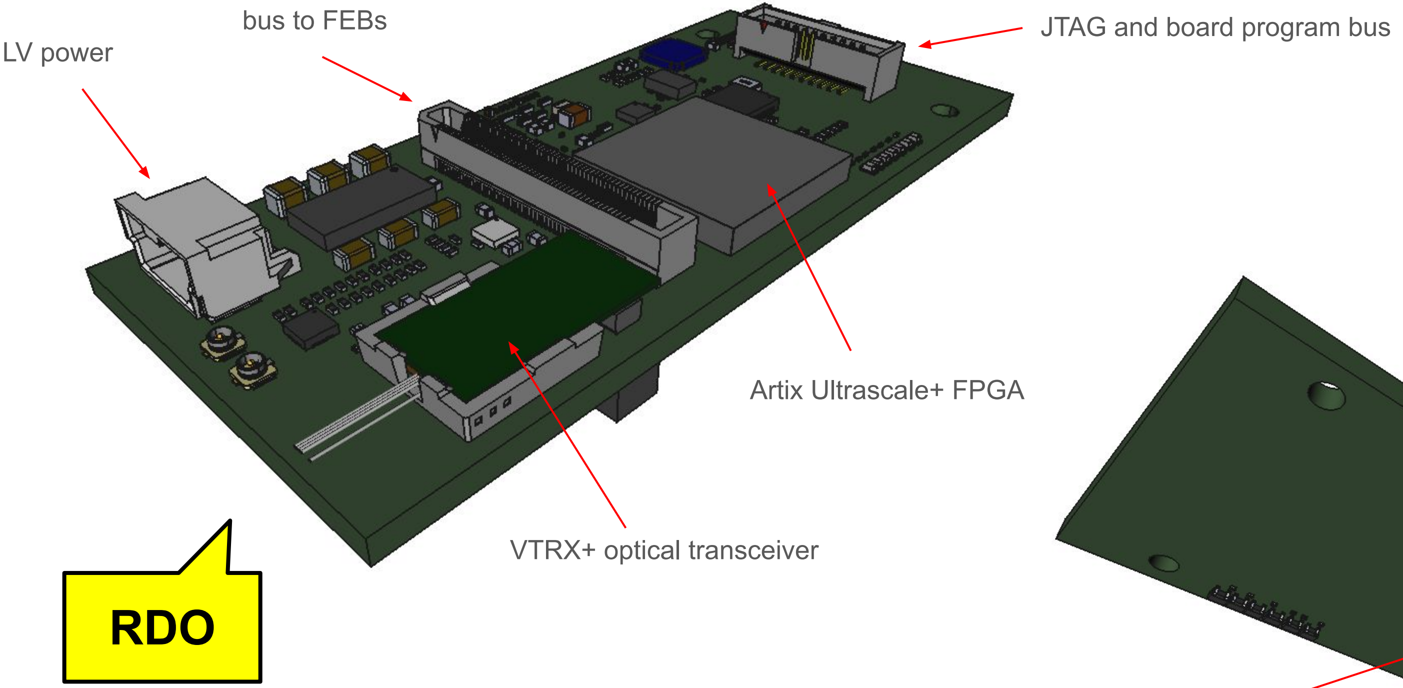
SiPM sensor matrices mounted on carrier PCB board

- 4x 64-channel SiPM array device (256 channels) for each unit
  - need modularity to realise curved readout surface
- 1248 photodetector units for full dRICH readout
  - 4992 SiPM matrix arrays (8x8)
  - 319488 readout channels

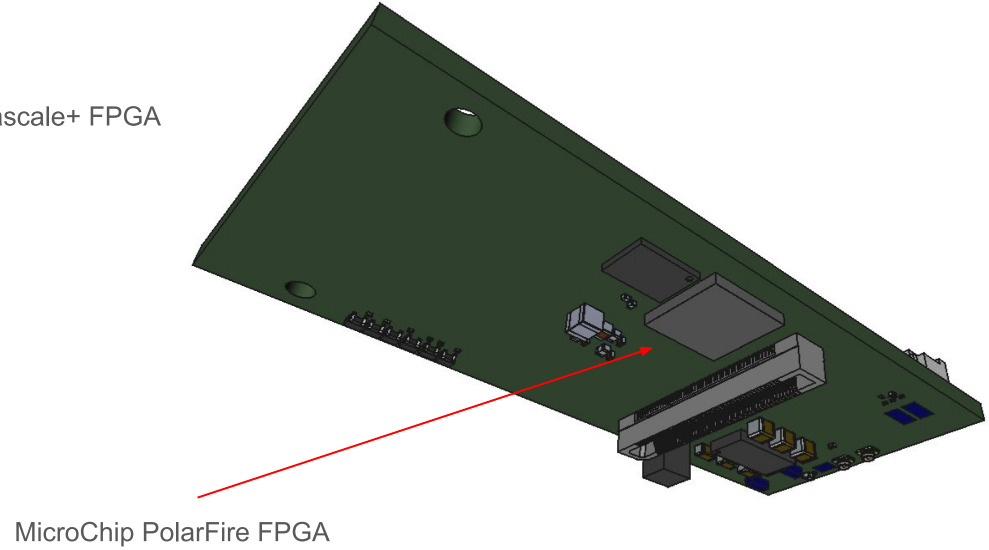


RDO is in advanced design stage

project will be soon sent for board layout by external company and production of first prototypes



Davide Falchieri

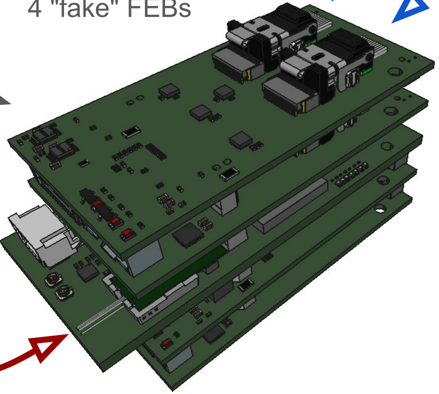


RDO readout architecture for next beam test

8x stacks of electronics
each with
- 1 RDO
- 4 "fake" FEBs

"fake" FEBs

RDO

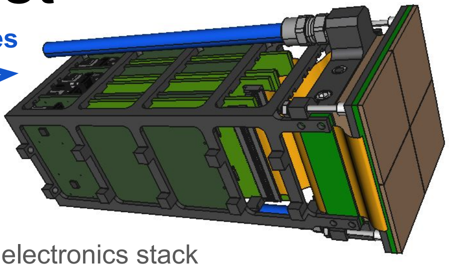


VTRX+ optical link to commercial SFP

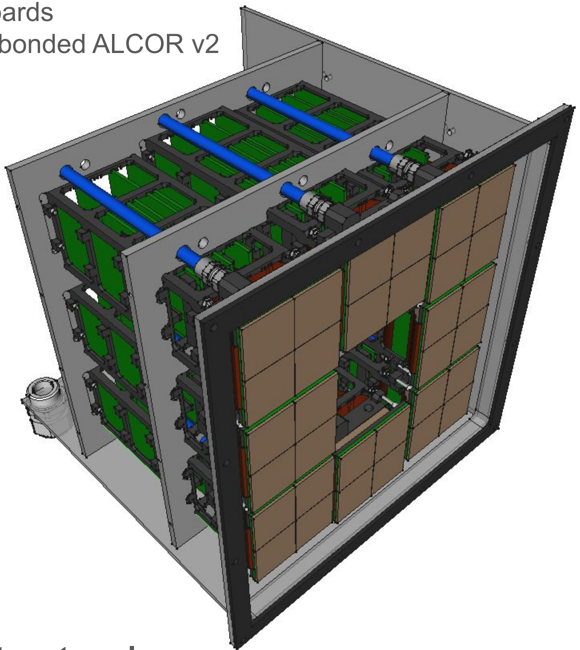
high-performance computer with 8 SFP optical links

outside

8x FireFly cables



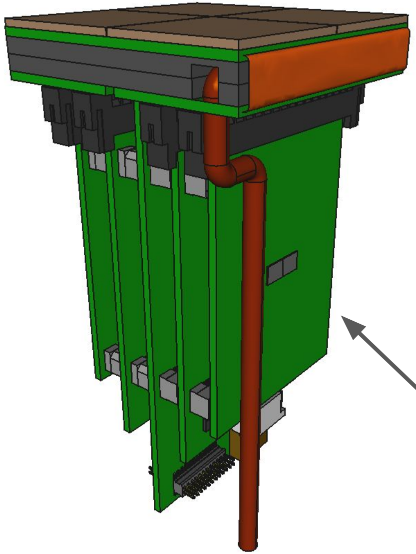
existing front-end electronics stack
4 ALCOR-dual boards
each with 2x wirebonded ALCOR v2



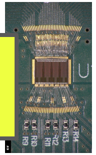
inside detector box

The front-end board (FEB) and ALCOR v3

taking ALCOR chip to the ultimate dRICH requirement with 64 channels and a BGA package



front-end board

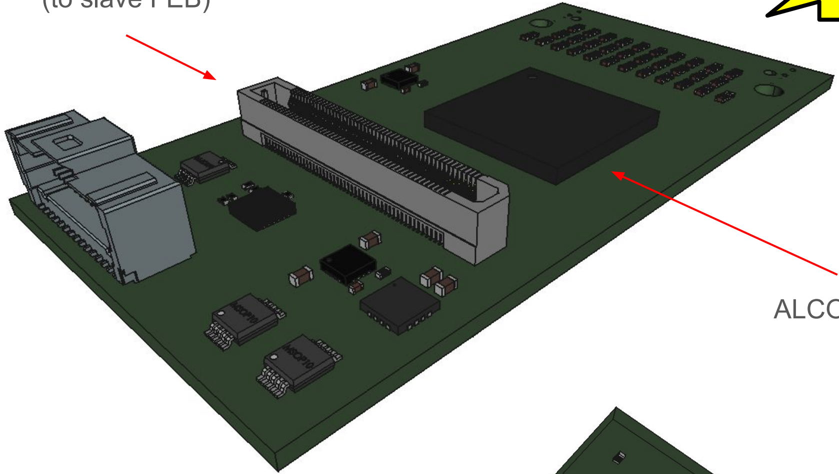


ALCOR ASIC

FEB

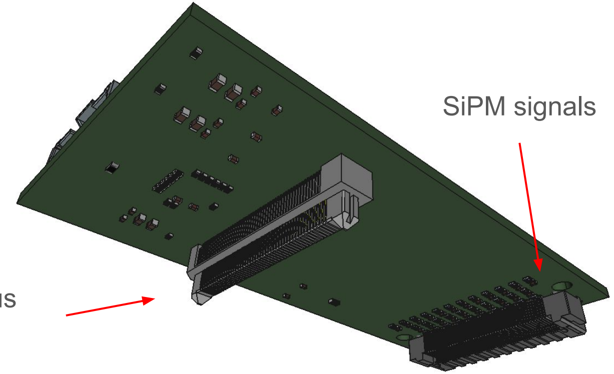
LV power

digital data bus
(to slave FEB)



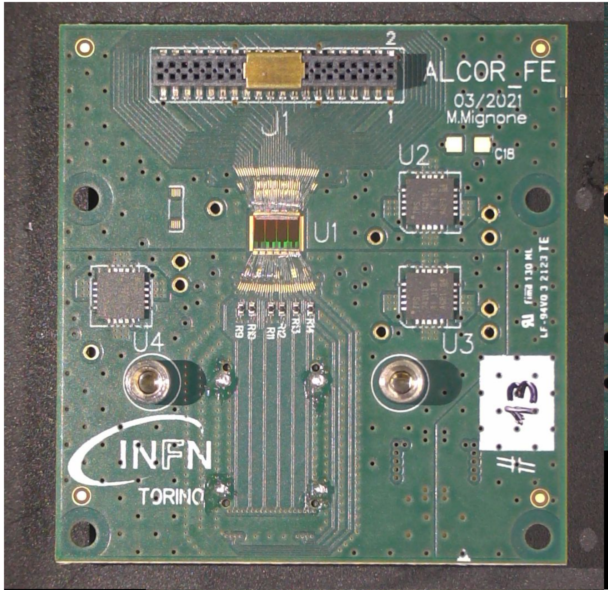
ALCOR v3

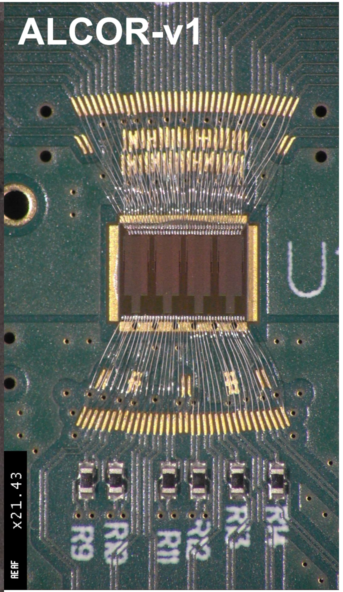
SiPM signals

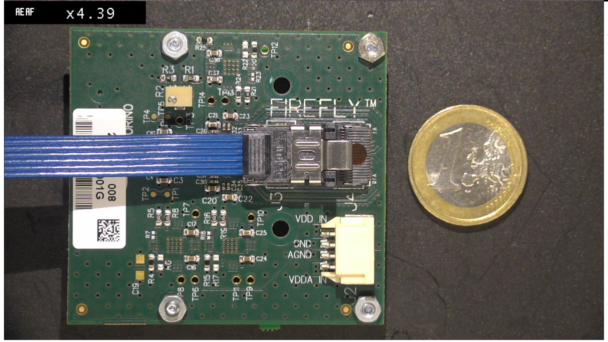


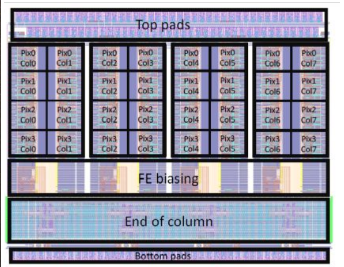
digital data bus
(to RDO)

ALCOR ASIC: integrated front-end and TDC









developed by INFN-TO

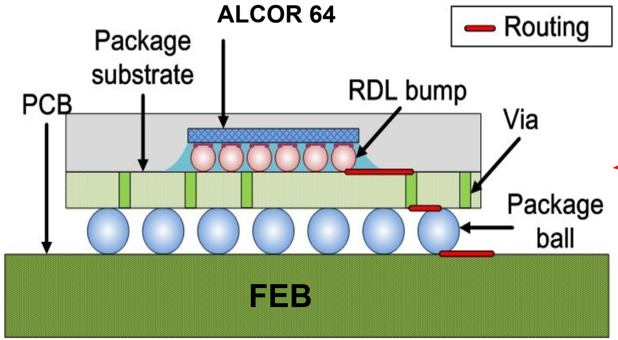
64-pixel matrix mixed-signal ASIC

current versions (v1,v2,v2.1) have 32 channels, wirebonded
final version will have 64 channels, BGA package, 394.08 MHz clock

- **the chip performs**
  - signal amplification
  - conditioning and event digitisation
- **each pixel features**
  - 2 leading-edge discriminators
  - 4 TDCs based on analogue interpolation
    - 20 or 40 ps LSB (@ 394 MHz)
  - digital shutter to enable TDC digitisation
    - suppress out-of-gate DCR hits
    - 1-2 ns timing window
    - programmable delay, sub ns accuracy
- **single-photon time-tagging mode**
  - continuous readout
  - also with Time-Over-Threshold
- **fully digital output**
  - 8 LVDS TX data links

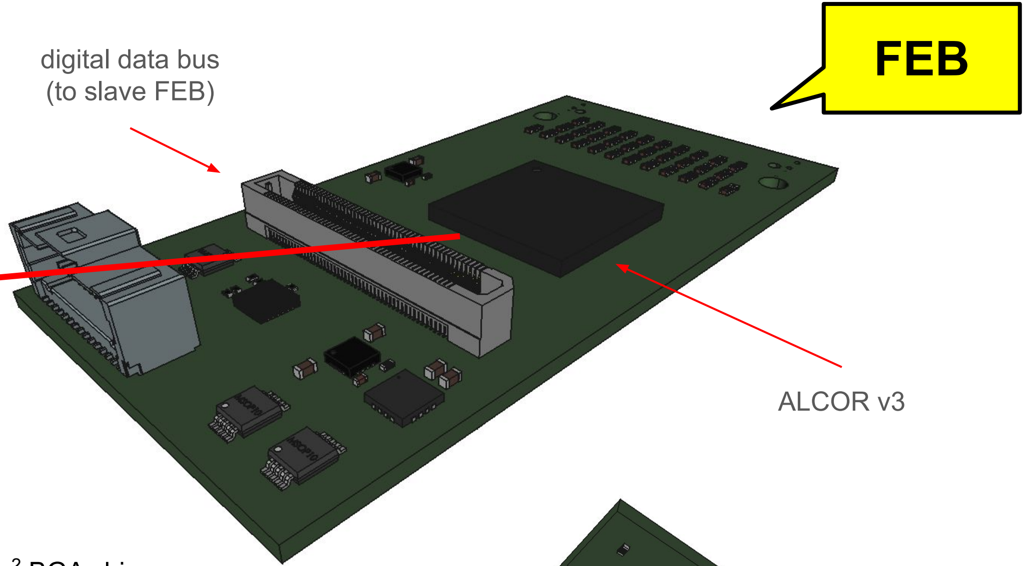
The front-end board (FEB) and ALCOR v3

taking ALCOR chip to the ultimate dRICH requirement with 64 channels and a BGA package



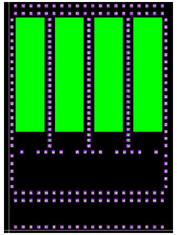
LV power

digital data bus
(to slave FEB)



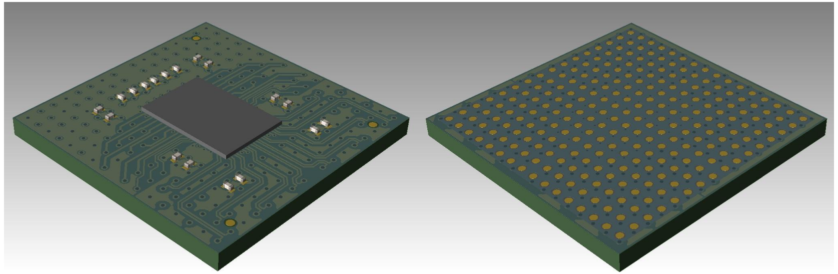
ALCOR v3

ALCOR v3
silicon chip



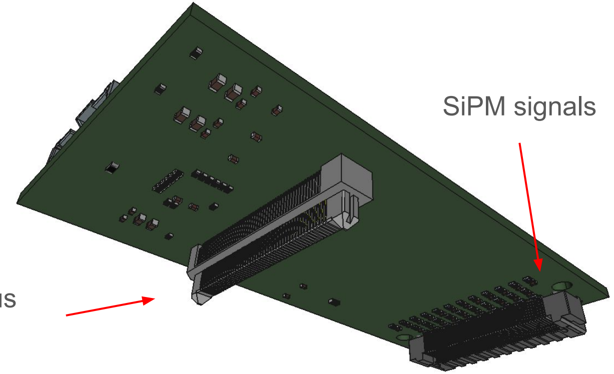
flip-chipped onto interposer
complex PCB RDL, design is ready

17x17 mm^2 BGA chip
package with 256 balls, 1 mm pitch



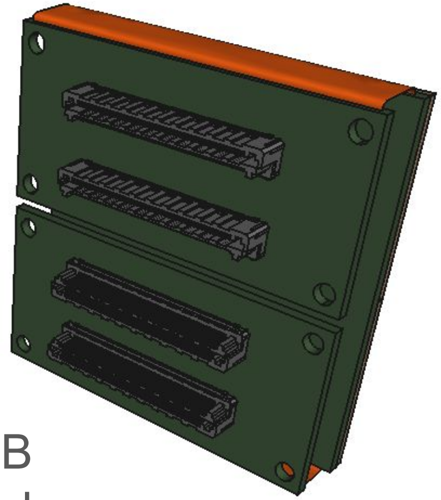
SiPM signals

digital data bus
(to RDO)



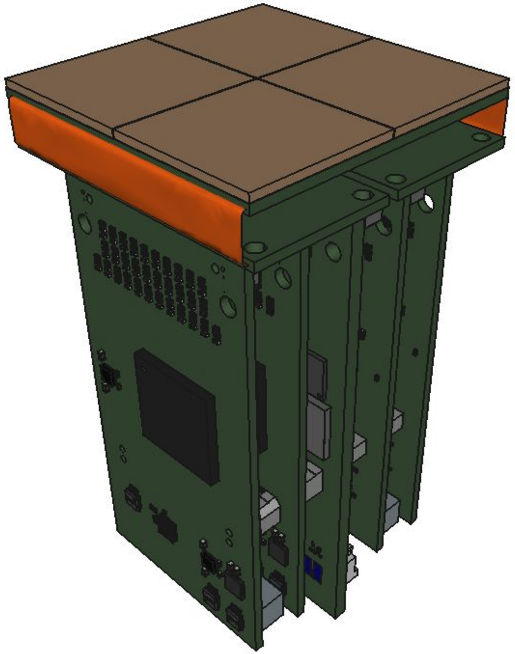
dRICH SiPM photodetector unit engineering and design

evolution from conceptual to final design: in progress



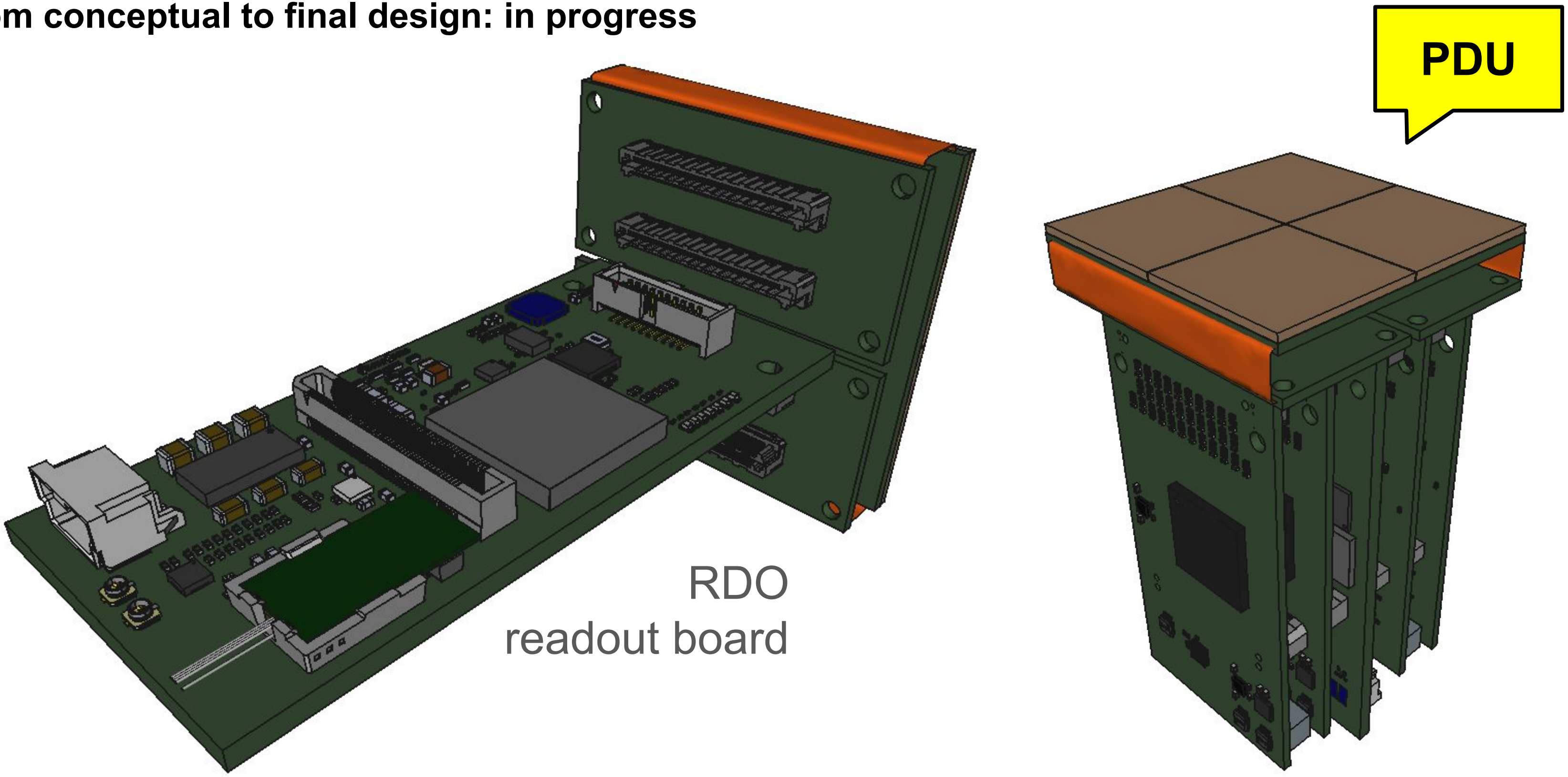
flex-PCB
SiPM carrier board

PDU



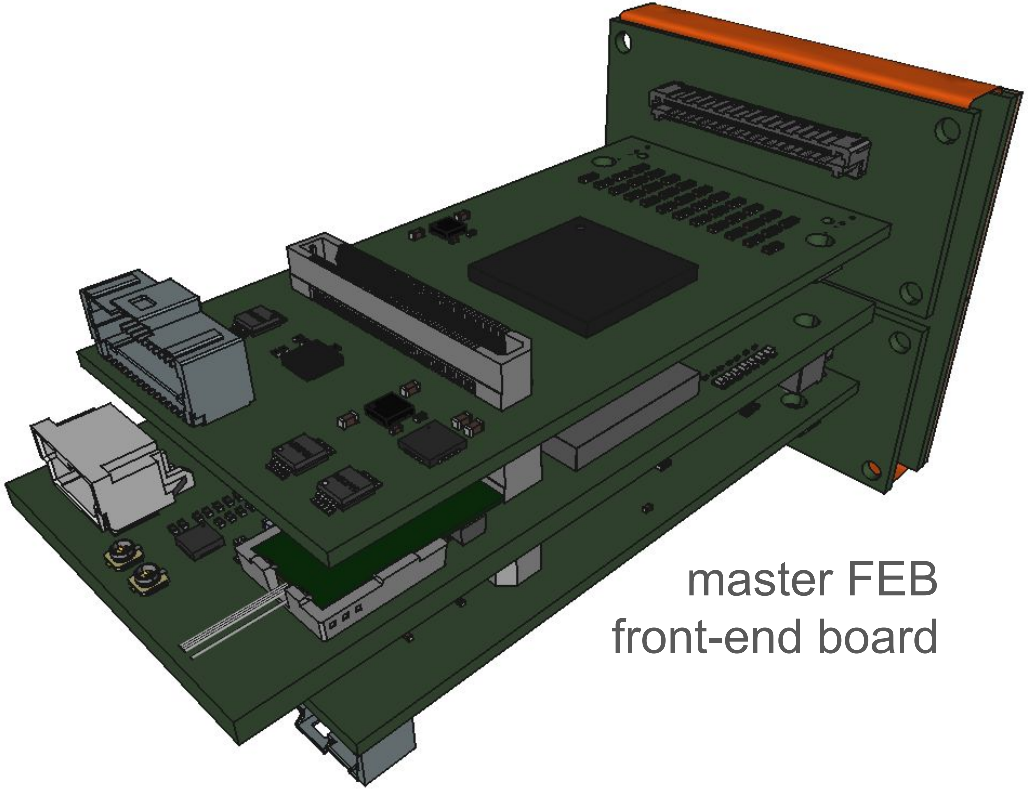
dRICH SiPM photodetector unit engineering and design

evolution from conceptual to final design: in progress



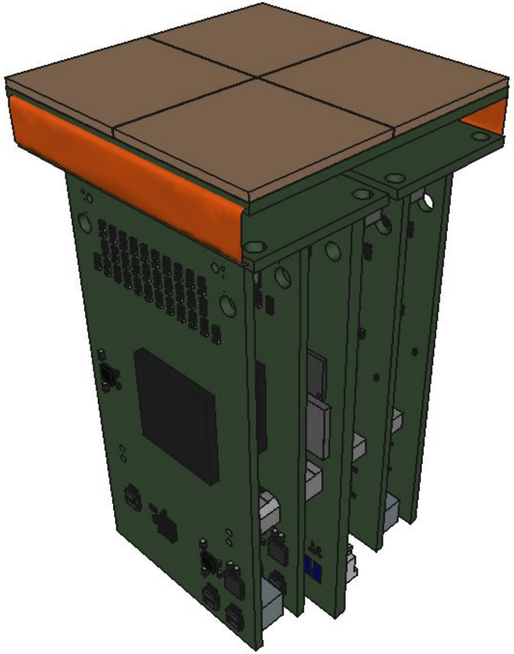
dRICH SiPM photodetector unit engineering and design

evolution from conceptual to final design: in progress



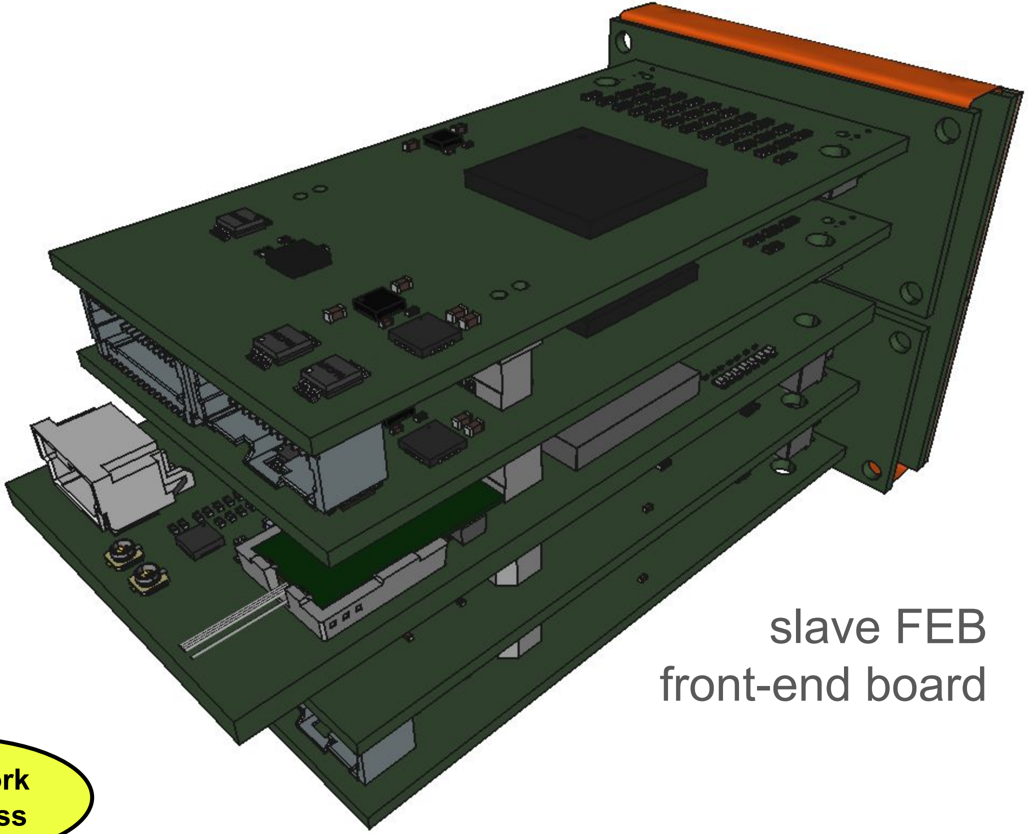
master FEB
front-end board

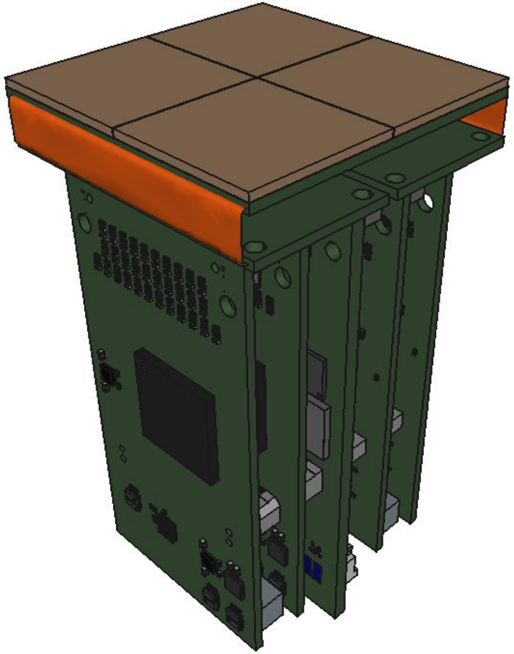
PDU



dRICH SiPM photodetector unit engineering and design

evolution from conceptual to final design: in progress





lots of work in progress

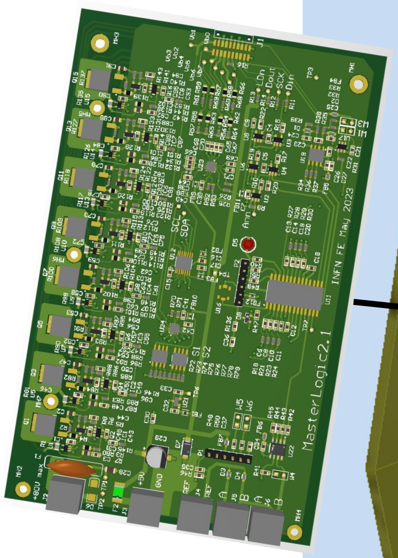
The dRICH MasterPanel board

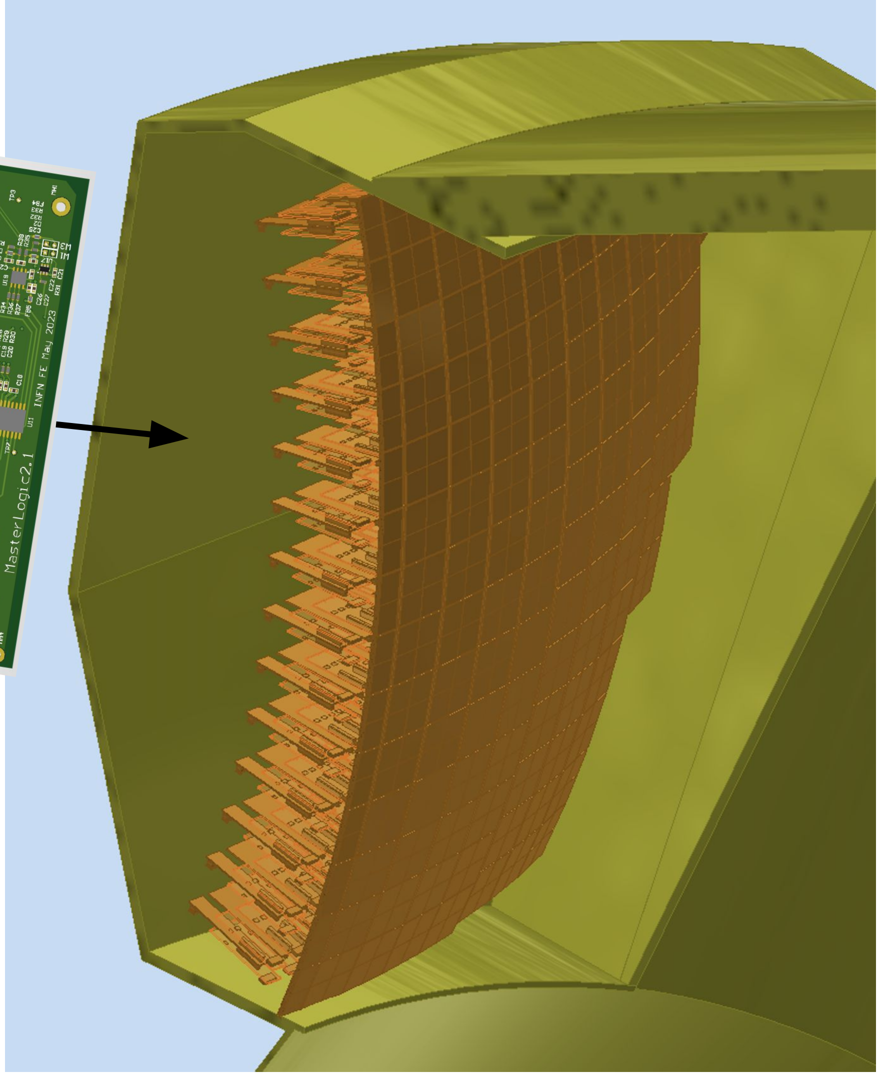
we developed and operated in the dRICH beam test in October 2023 and May 2024 the MasterLogic v2 card (evolution of the MasterLogic v1 card).

the card hosts

- 8 channels made of identical circuits for linear regulation of Vbias from 0 to Vin (80 V max)
- a microcontroller (PIC) for external communication (RS485)
- current monitor

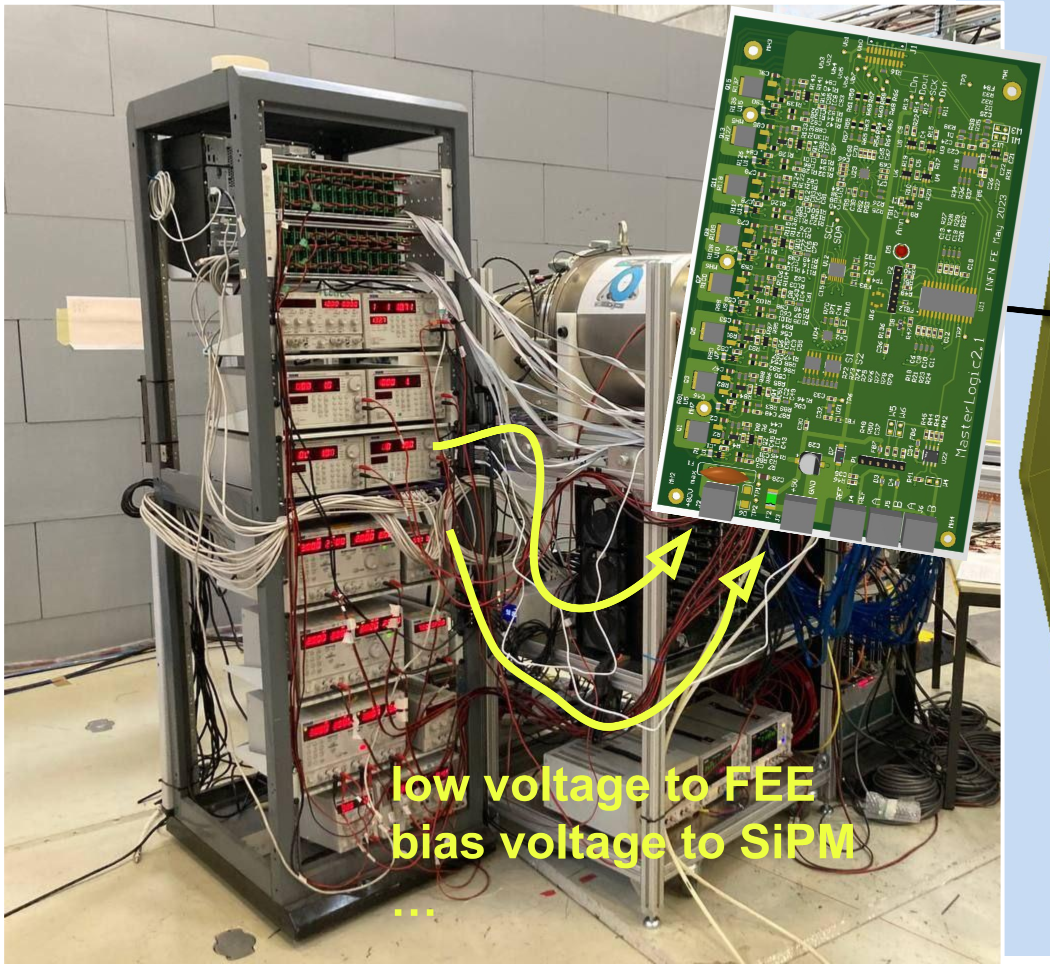
future evolution: MasterPanel card to plug onto the dRICH readout box patch panel for Vbias and Vann control and distribution (and perhaps more features).

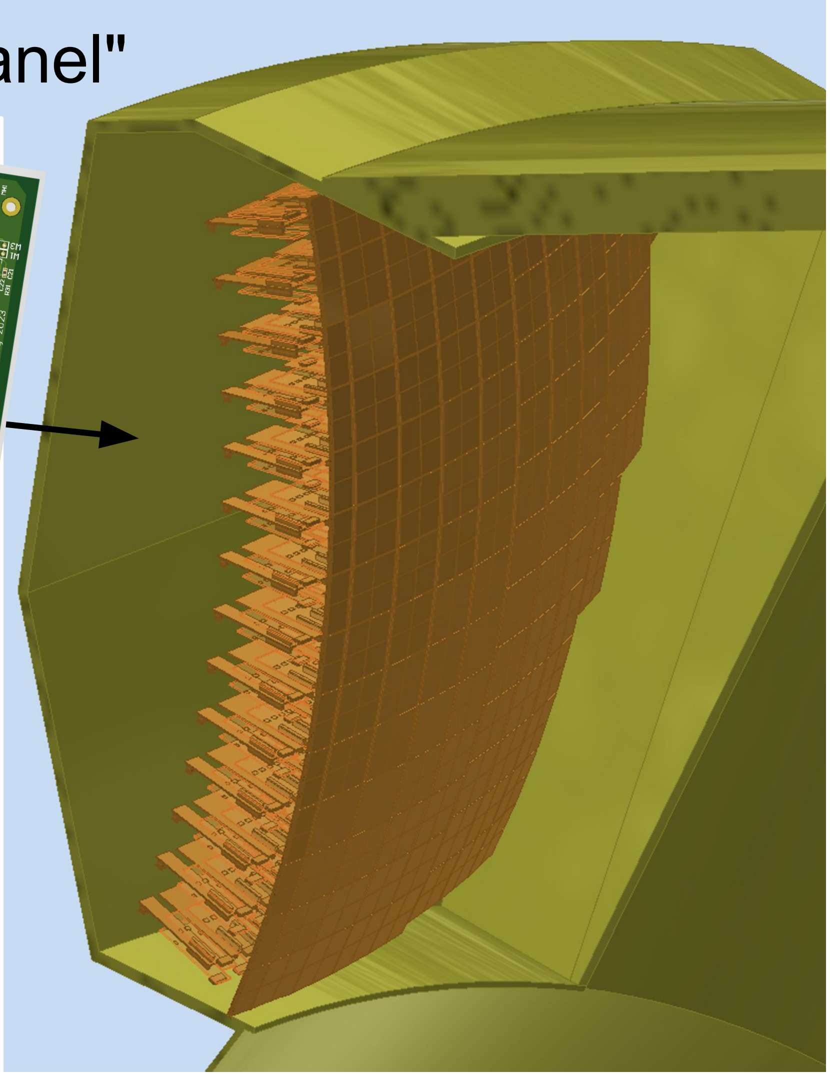




MasterPanel

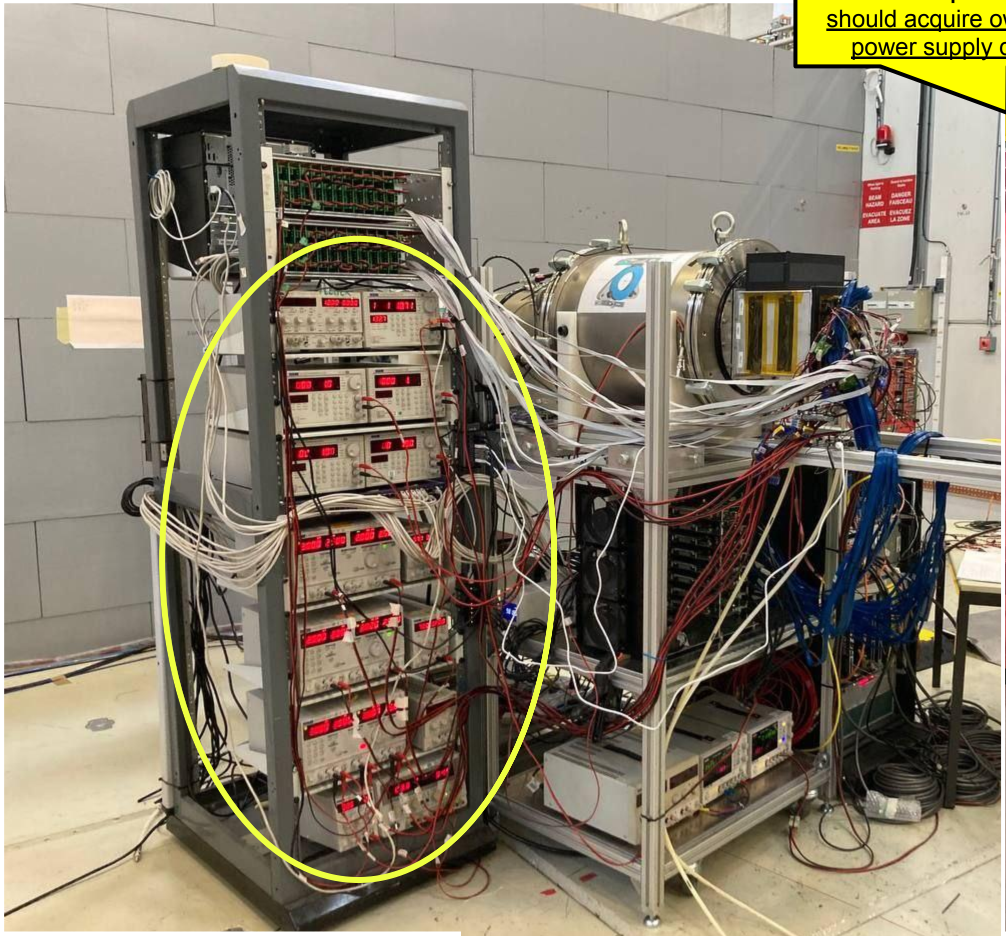
The dRICH MasterPanel "patch panel"



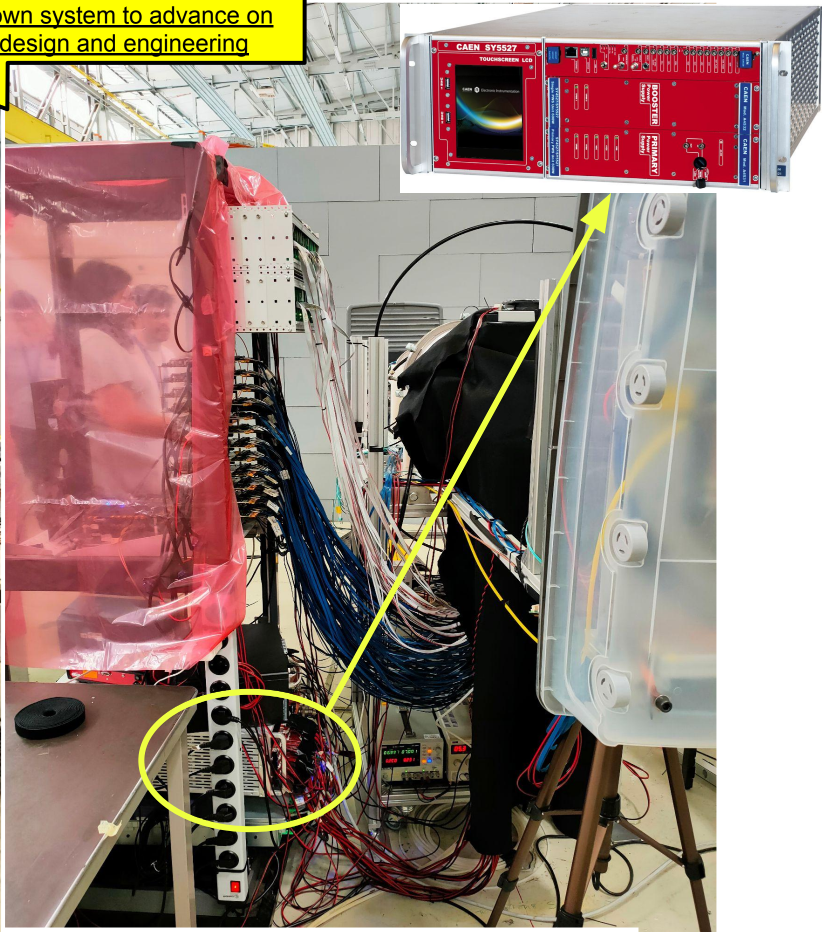


Power supply system

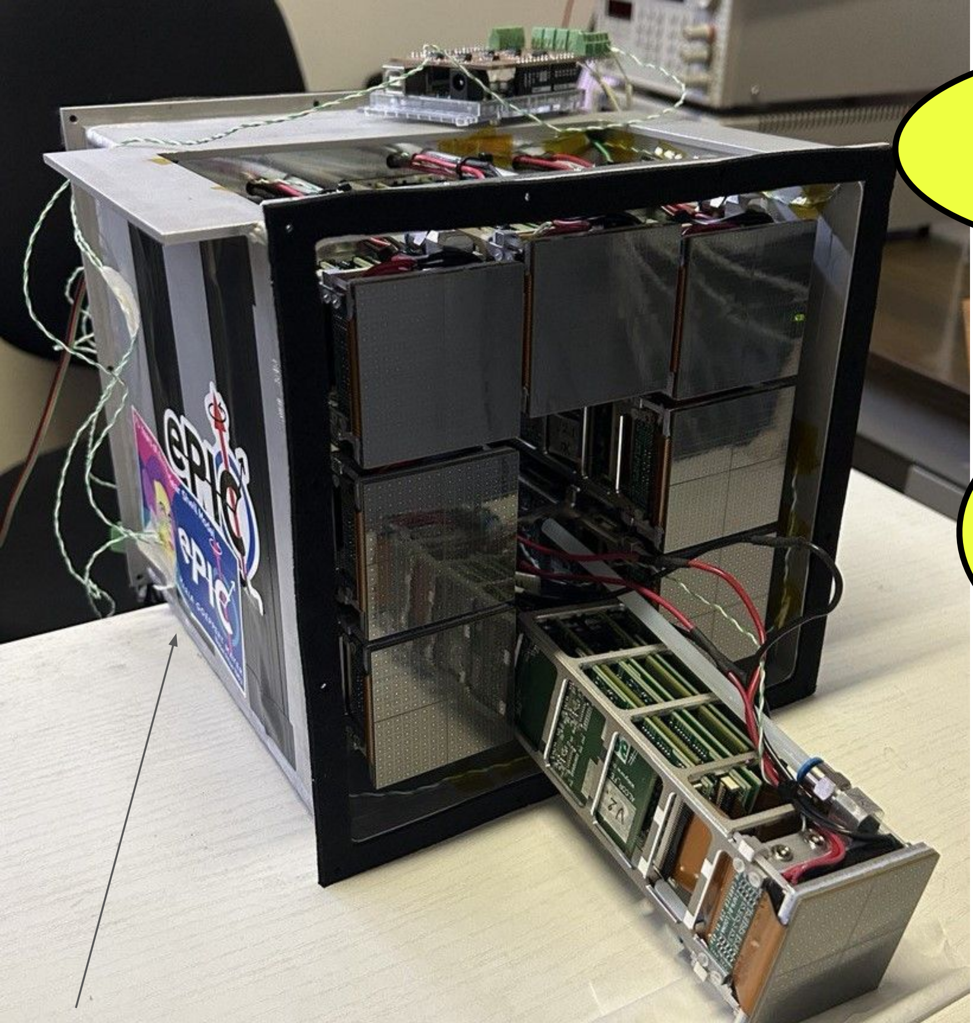
in beam test 2024 used rented CAEN power supply system
<u>should acquire own system to advance on power supply design and engineering</u>



many table-top power supplies in 2023



first test with rented CAEN power-supply units in 2024

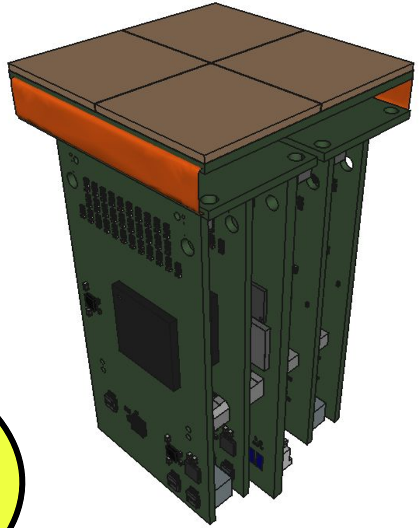


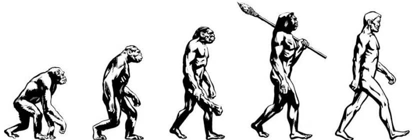
ePIC stickers

lots of work done

lots of work in progress

lots of work to be done



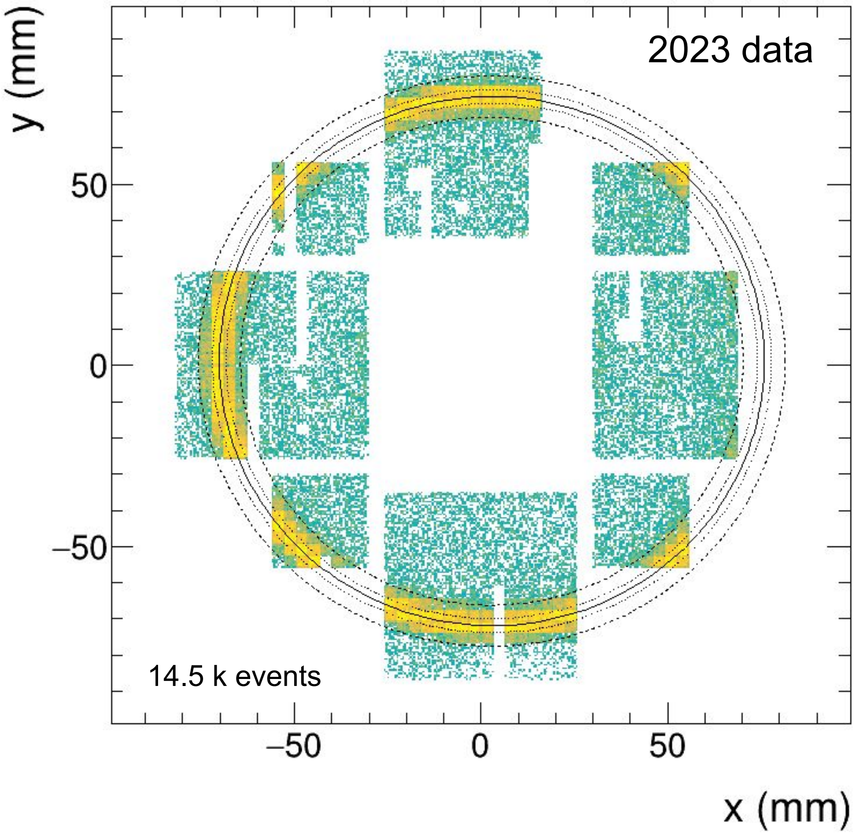


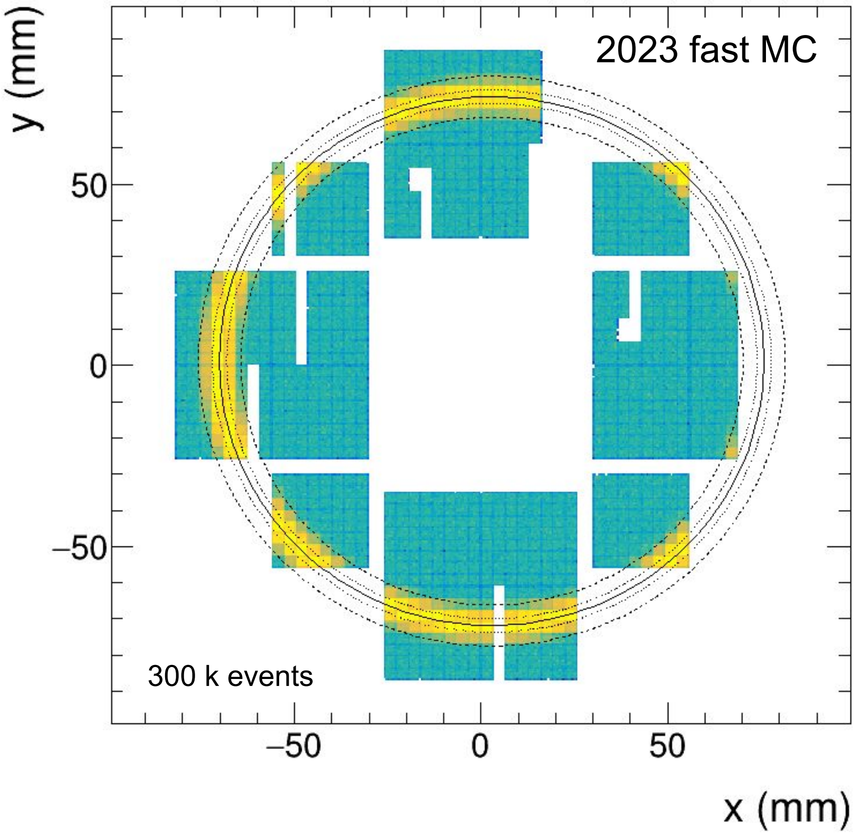
some
beam-test
results

Number of photoelectrons

2D fit parameters match accurately fast MC input
notice redefinition of Nsig and Nbkg

Nsig	=	23.6048	+/-	0.0154101
X0	=	2.87125	+/-	0.00255149
Y0	=	1.18834	+/-	0.00193679
R	=	73.0013	+/-	0.00166626
sigmaR	=	1.88591	+/-	0.00123206
Nbkg	=	10.3538	+/-	0.0133316





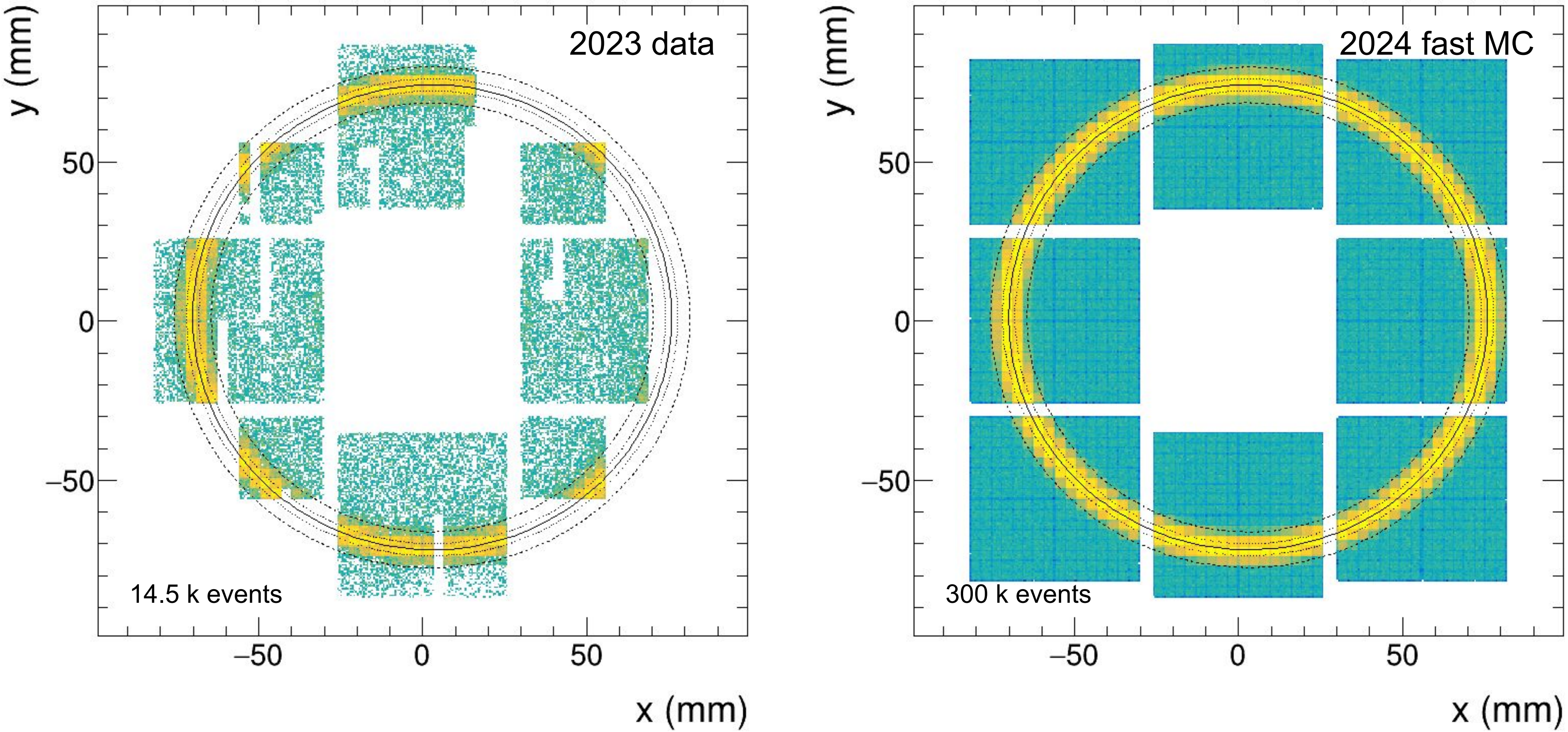
large number of detected aerogel photons in 2023, on average **more than 9 photoelectrons over the active area**

Number of photoelectrons

2D fit parameters match accurately fast MC input

notice redefinition of Nsig and Nbkg

Nsig	=	23.6048	+/-	0.0154101
X0	=	2.87125	+/-	0.00255149
Y0	=	1.18834	+/-	0.00193679
R	=	73.0013	+/-	0.00166626
sigmaR	=	1.88591	+/-	0.00123206
Nbkg	=	10.3538	+/-	0.0133316

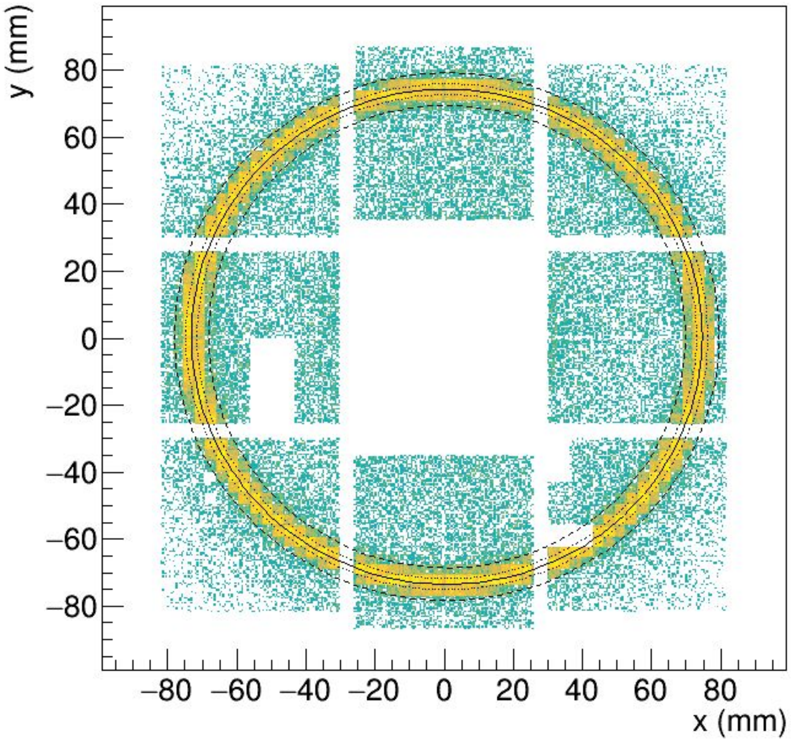


fast MC expectation for a 2024 beam test with 8x full PDUs is a **very large average number of photoelectrons for aerogel > 18**

Number of photoelectrons

is large as expected

11.5 GeV/c negative beam, n = 1.02 aerogel (accumulated events)



$X_0 = 0.75 \pm 0.01$ mm

$Y_0 = 0.45 \pm 0.01$ mm

$R = 73.87 \pm 0.00$ mm

$\sigma_R = 1.63 \pm 0.00$ mm

average number of signal photons for 100% acceptance
includes SiPM efficiency

$N_{sig} = 29.13 \pm 0.07$

$N_{bkg} = 8.47 \pm 0.05$

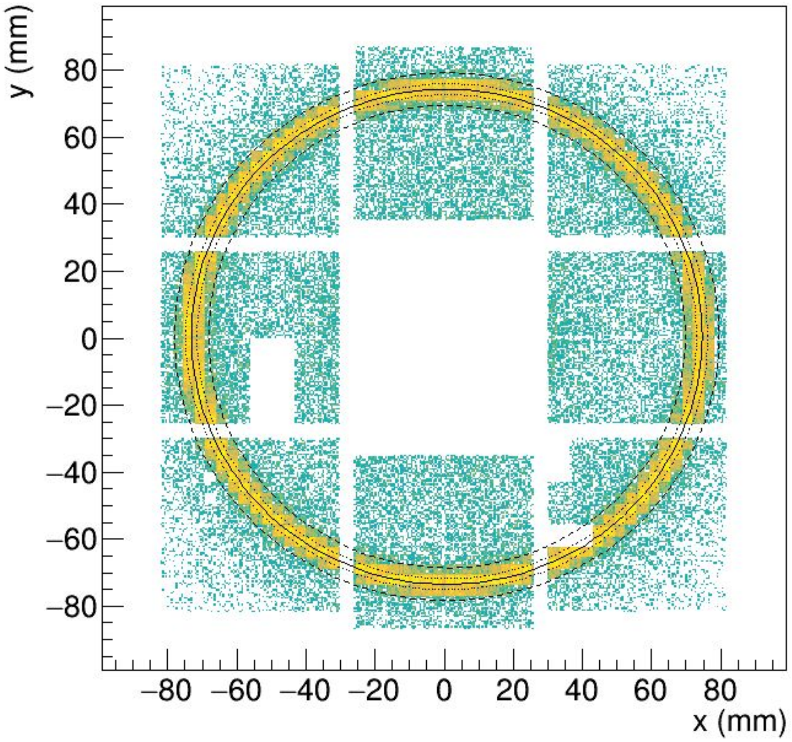
2D fit to accumulated data with realistic model (ring + background)

global ring parameters and performance, running also online

Number of photoelectrons

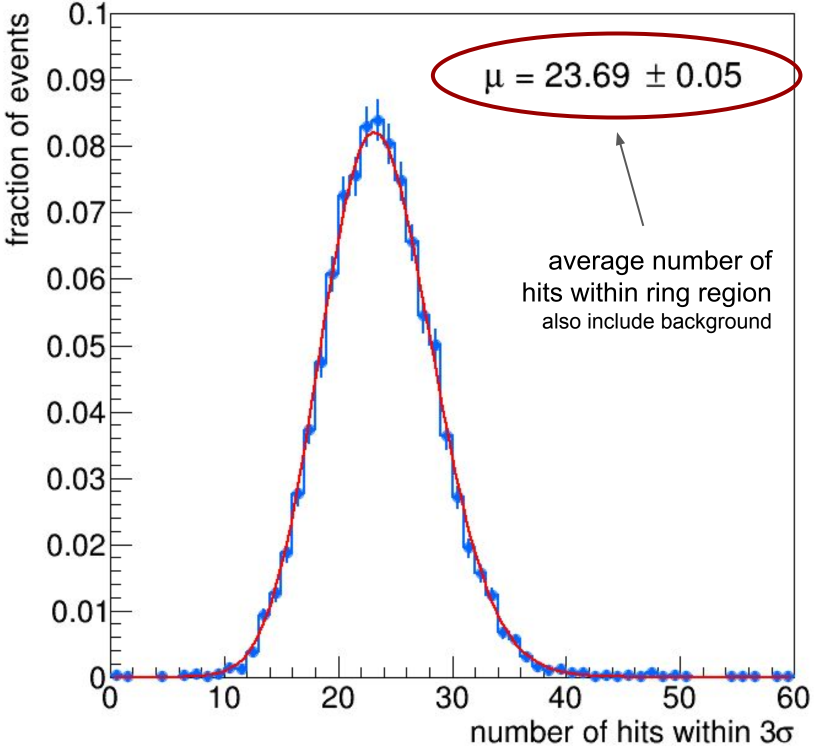
large as expected

11.5 GeV/c negative beam, n = 1.02 aerogel (accumulated events)



2D fit to accumulated data with realistic model (ring + background)

event-by-event distribution of hits in the ring

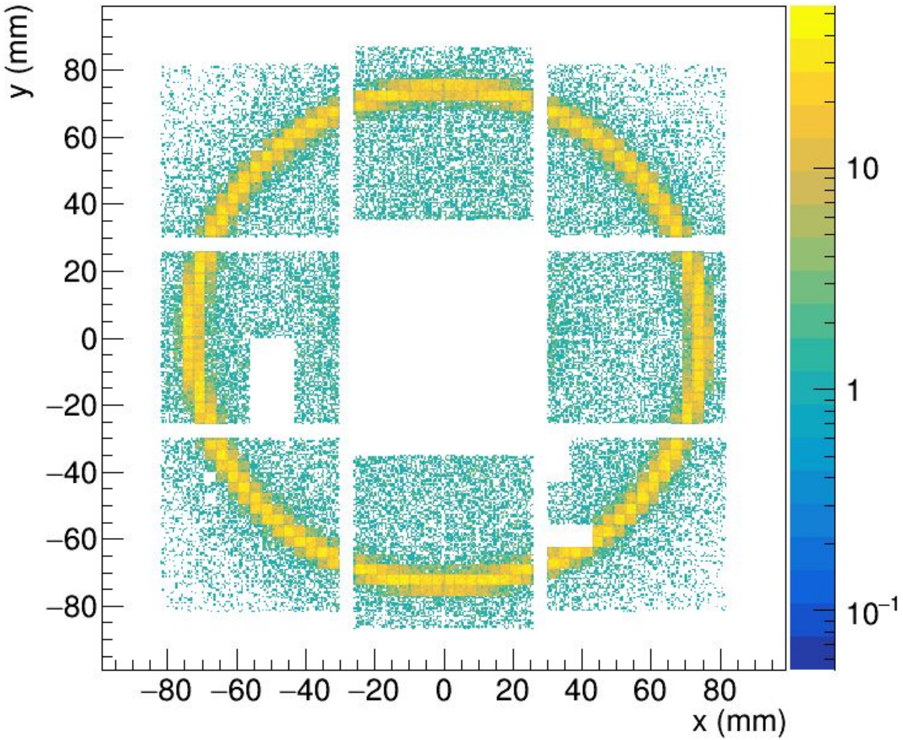


Poisson fit to data, average number of hits is large

Background studies

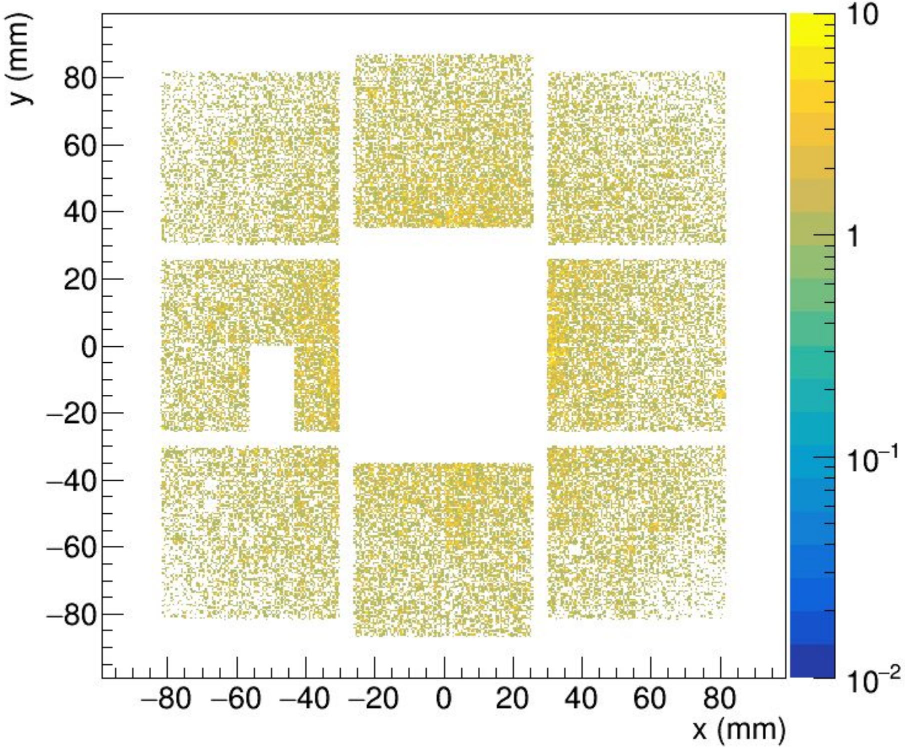
data taken without aerogel radiator

with two n = 1.02 aerogel tiles (accumulated events)



with timing cuts applied, large background as seen in past years

without aerogel (accumulated events)

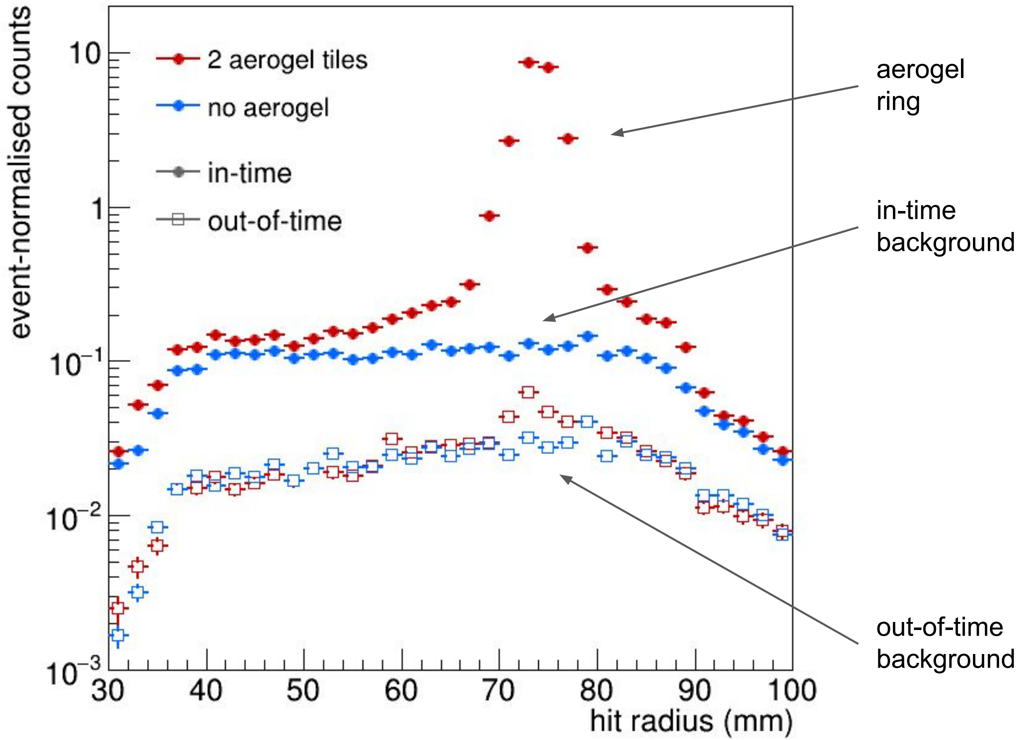


removed the aerogel tile, background remains

Background studies

basically all the background remains after removing aerogel, not from DCR

distribution hit radii with and without aerogel

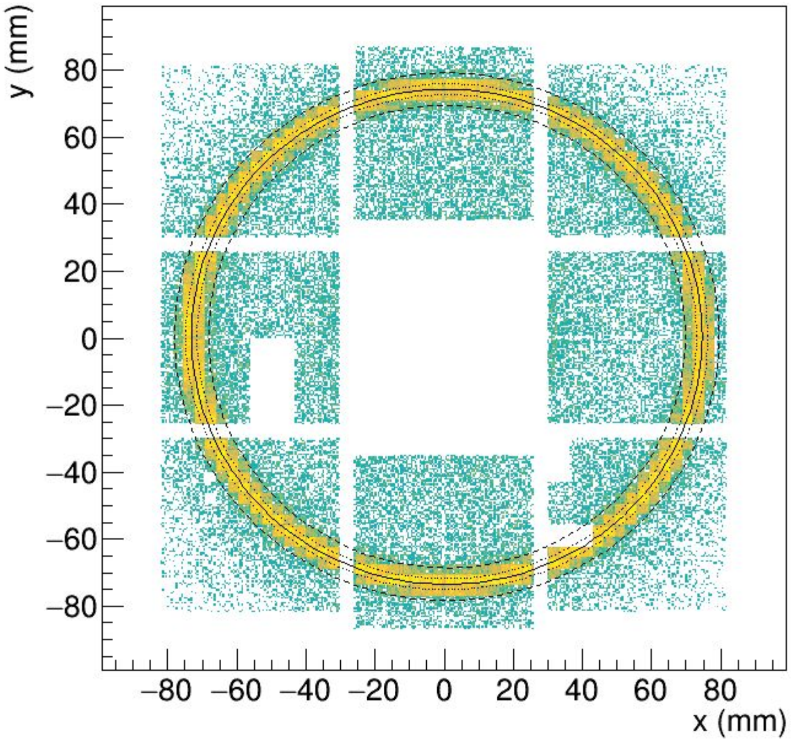


in-time (40 ns window) background is ~ 10x larger than out-of-time (40 ns window) background (mostly DCR) | origin still unclear | to be understood

Background studies

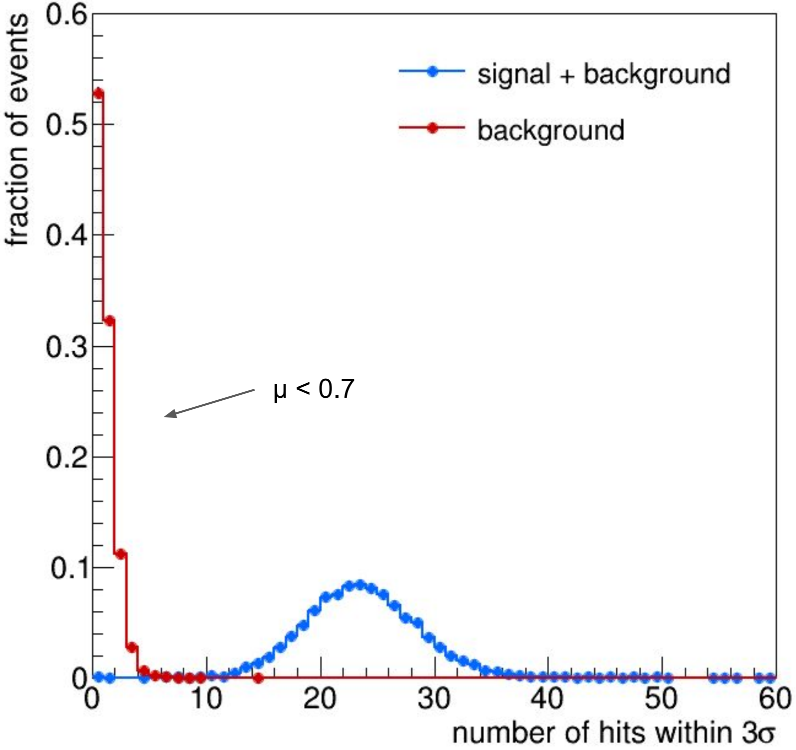
there is often one background hit in the ring, this will impact resolution

11.5 GeV/c negative beam, n = 1.02 aerogel (accumulated events)



2D fit to accumulated data with realistic model (ring + background)

event-by-event distribution of hits in the ring

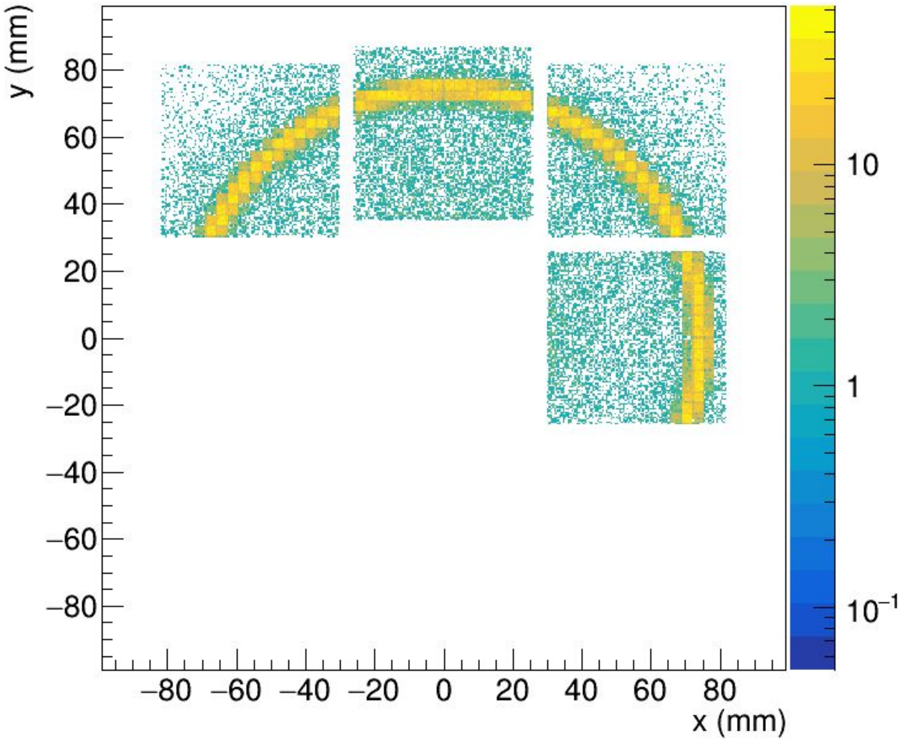


background in ring region estimated with data taken without aerogel

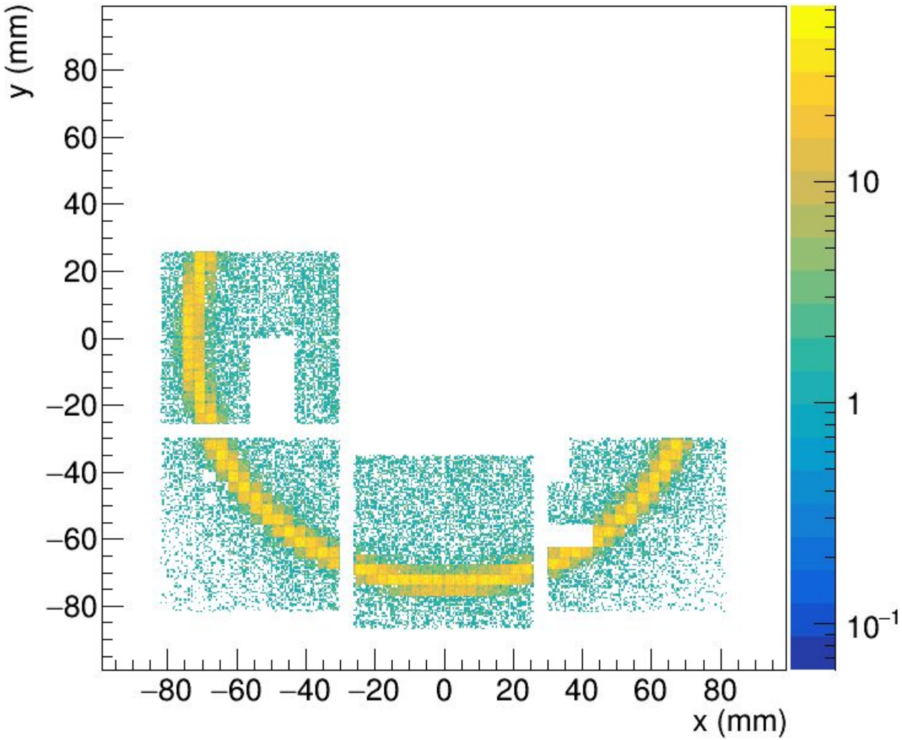
Comparison between different SiPM sensors

same Hamamatsu technology, different SPAD sizes

Hamamatsu S13360-3050 (50 µm)



Hamamatsu S13360-3075 (75 µm)

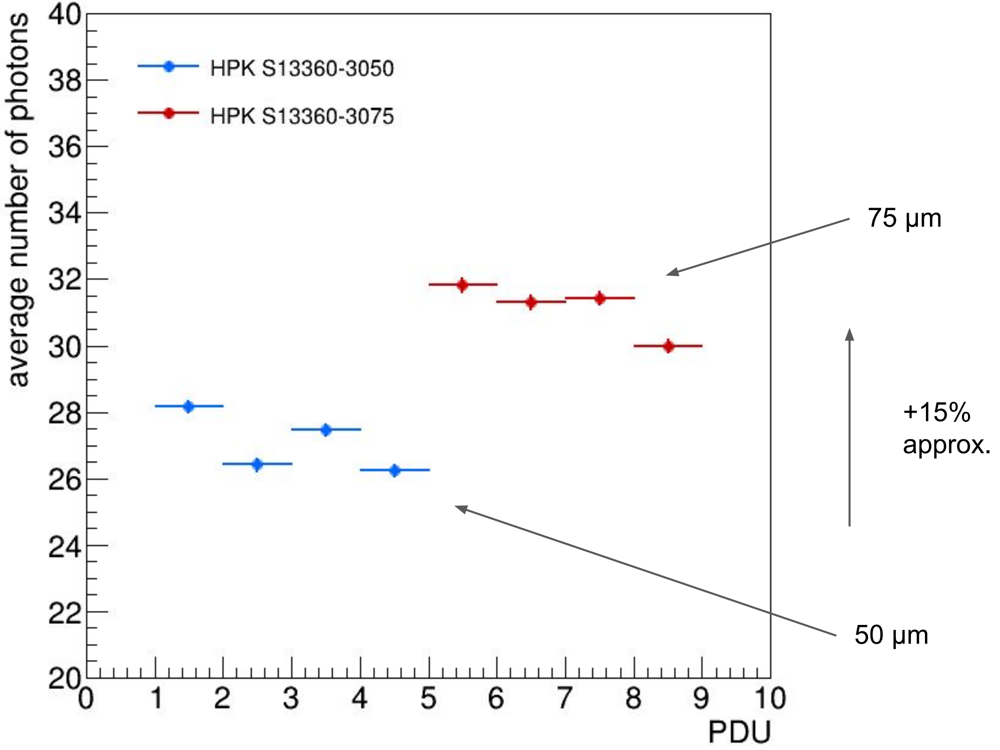


4 PDUs were equipped with one type of sensors symmetrically, the other four with different sensors

Comparison between different SiPM sensors

same Hamamatsu technology, different SPAD sizes

estimated average number of photoelectrons per event

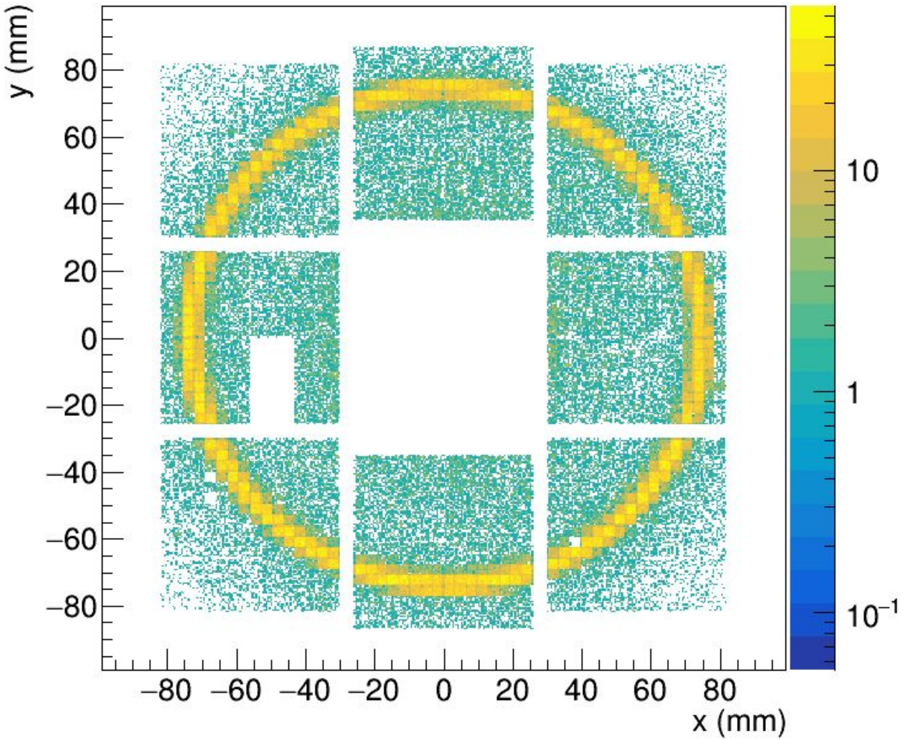


larger SPADs see more light (at the same overvoltage) than smaller SPADs | observed 15% more light | expected 25% higher PDE from datasheet

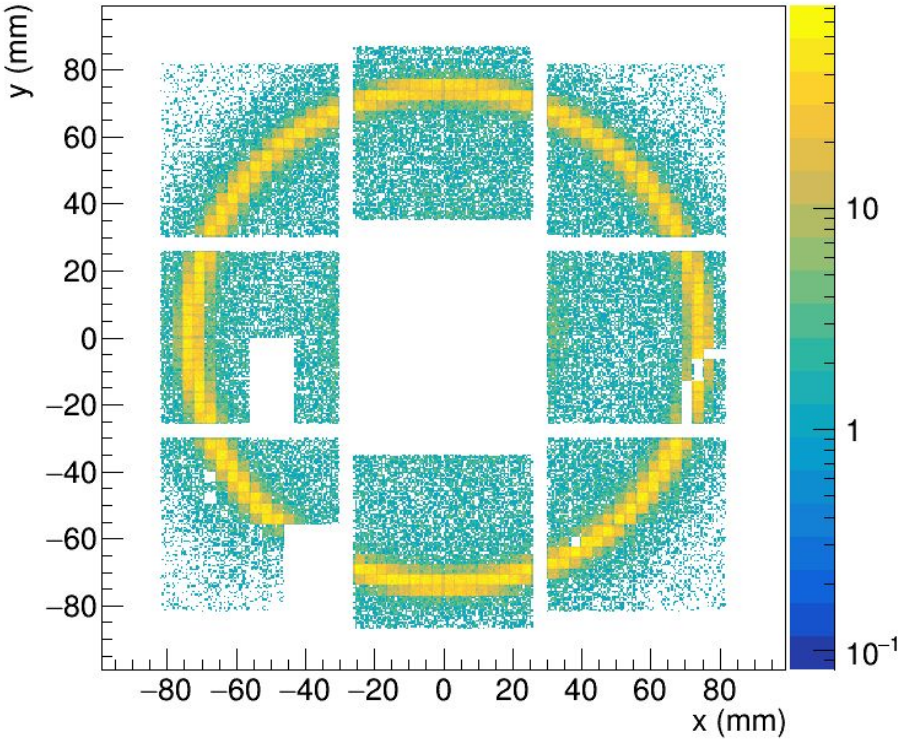
Increasing number of aerogel tiles

n = 1.02 aerogel tiles of L = 2 cm thickness

one aerogel tile (n = 1.02, L = 2 cm)



four aerogel tiles (n = 1.02, L = 2 cm)

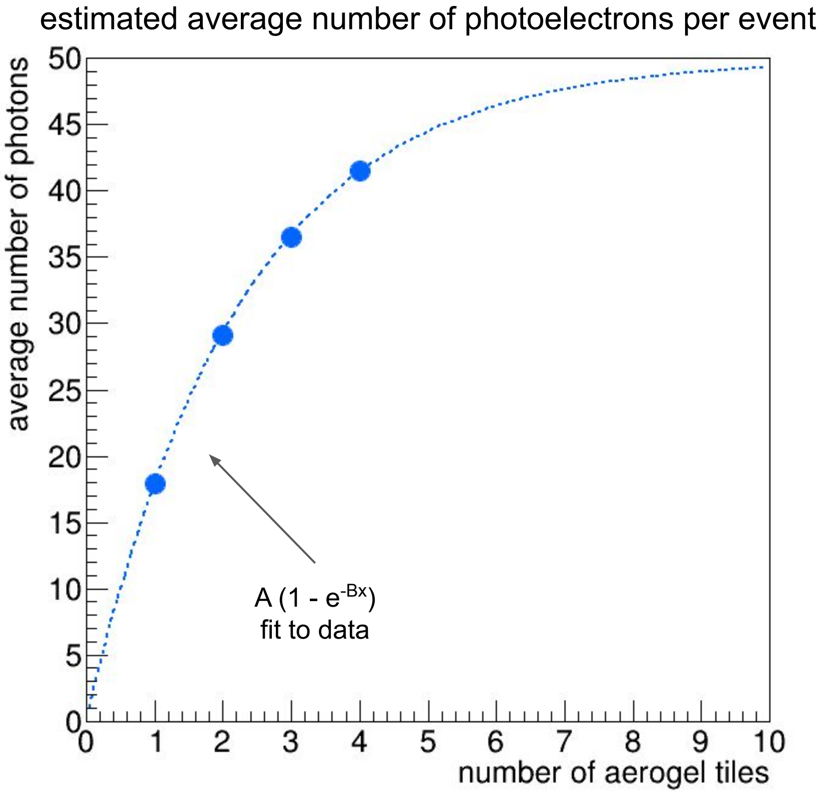


from 1 aerogel tile

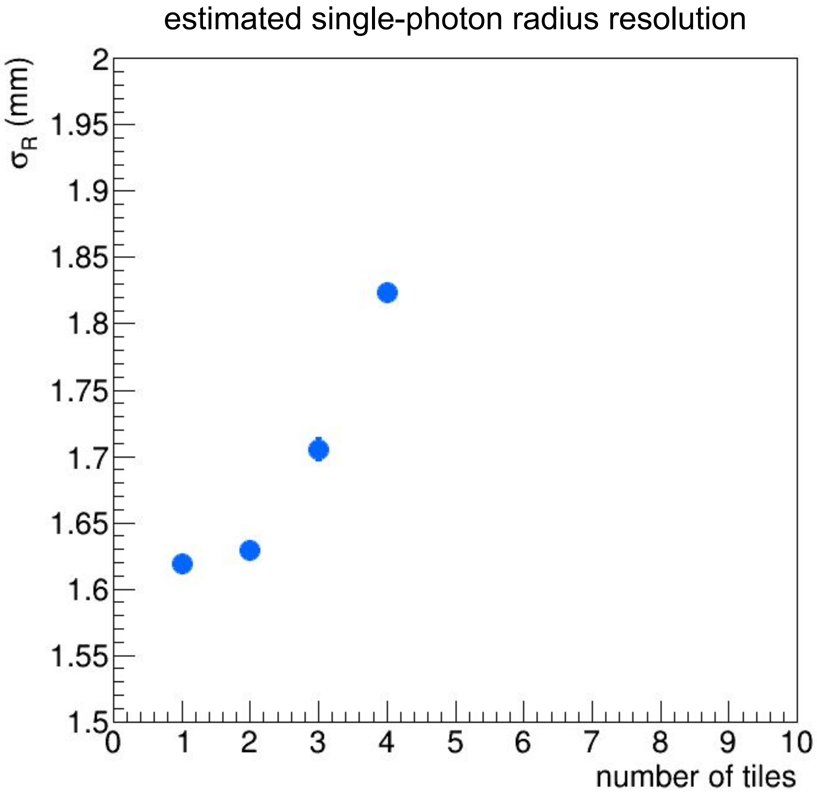
up to four tiles

Increasing number of aerogel tiles

n = 1.02 aerogel tiles of L = 2 cm thickness



adding tiles increases light, less and less effectively (absorption)



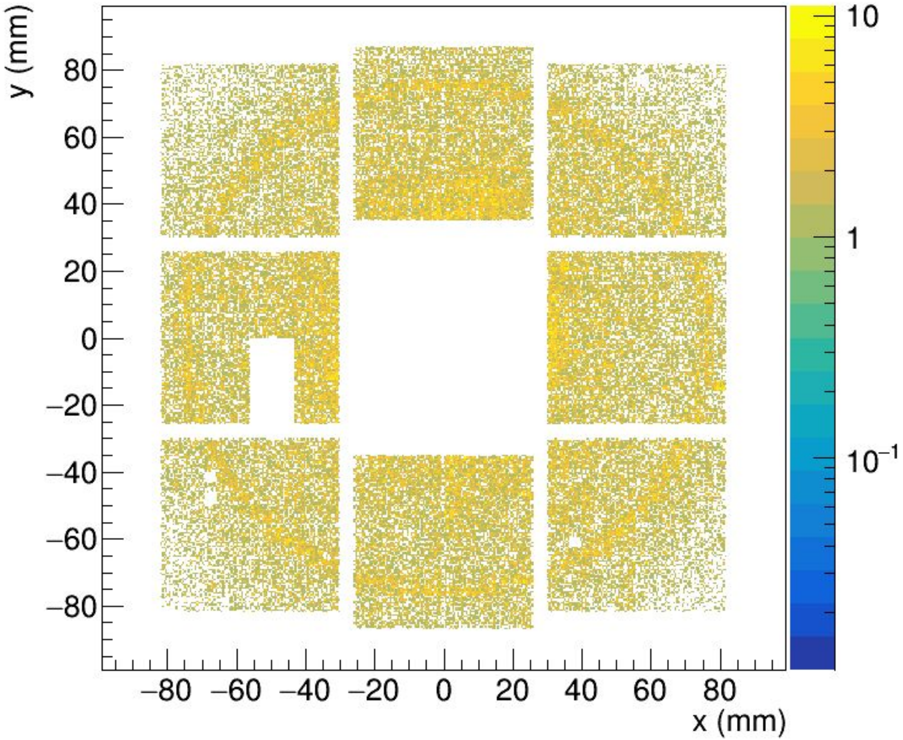
looks like single-photon resolution is degrading, not clear why

Wavelength filters

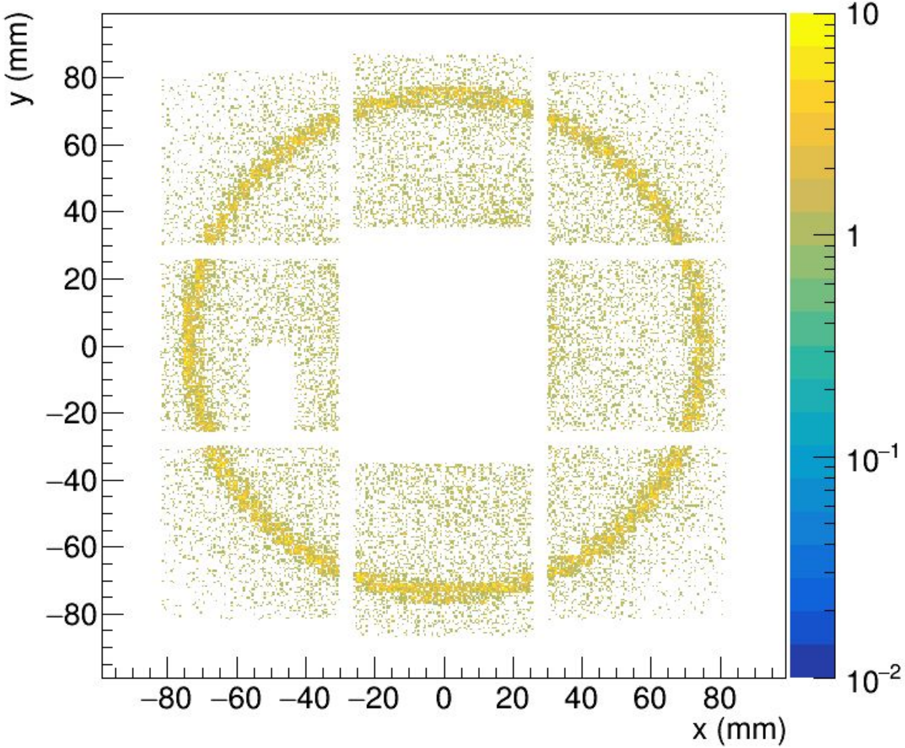
several filters used to select specific wavelength bands

PRELIMINARY

near ultra-violet filter (λ ~ 350 nm)



blue filter (450 < λ < 500 nm)

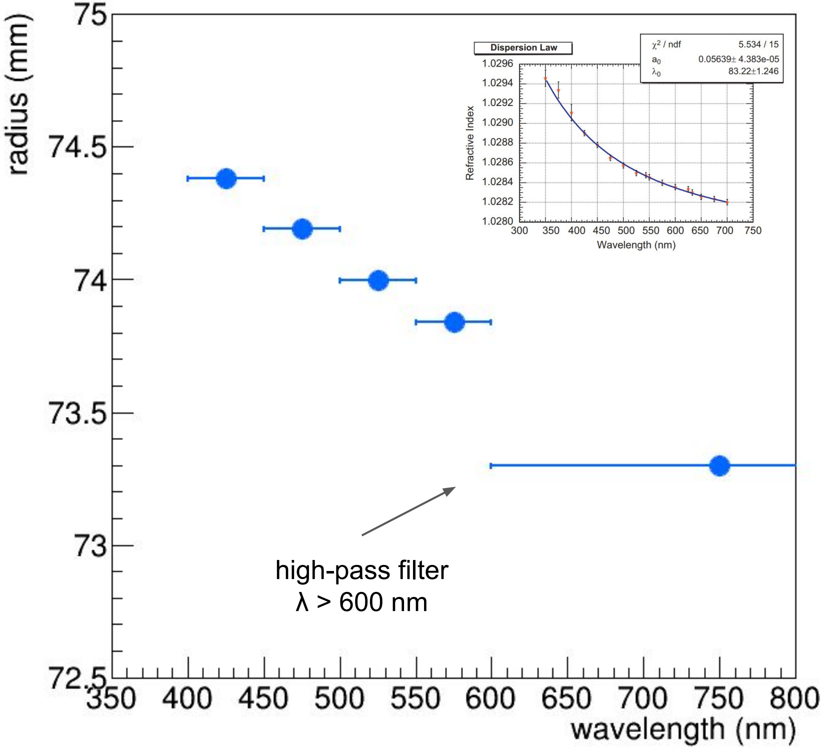


we still see the ring, but the "beam background" makes life difficult

Wavelength filters

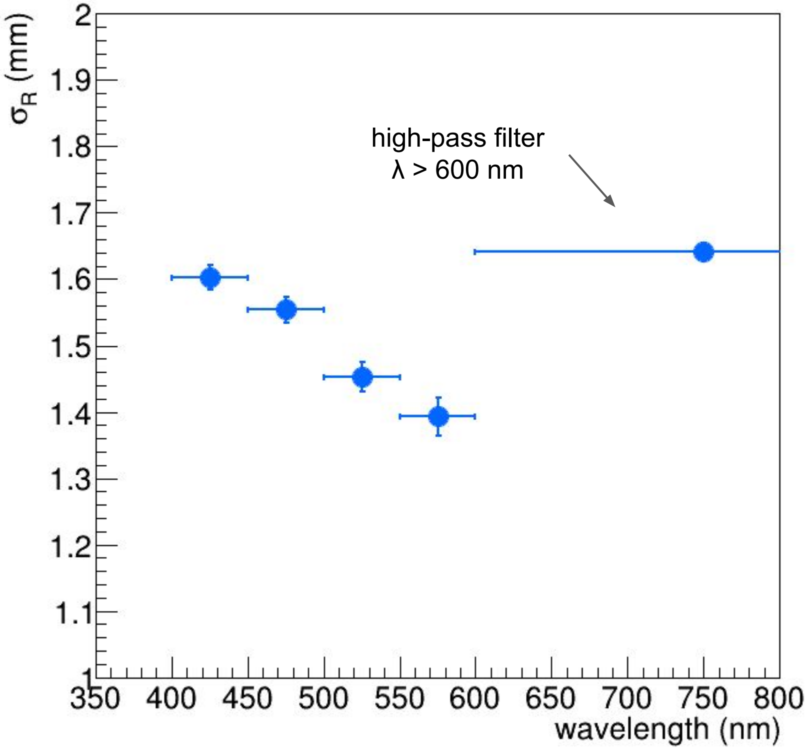
several filters used to select specific wavelength bands

estimated ring radius



ring radius decreases with increasing wavelength

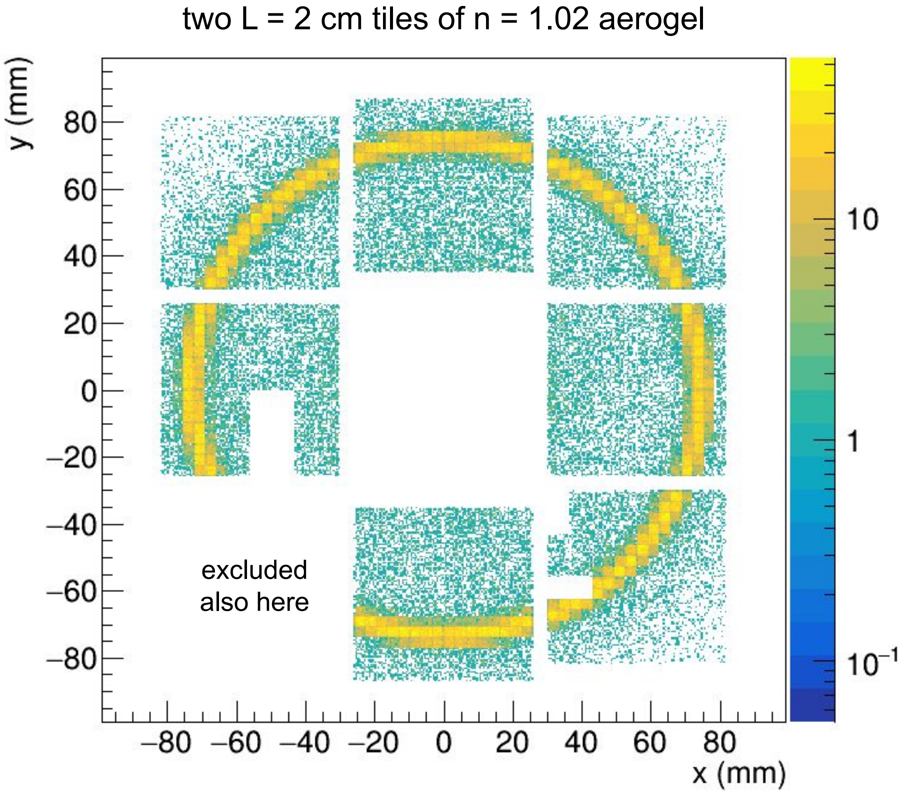
estimated single-photon radius resolution

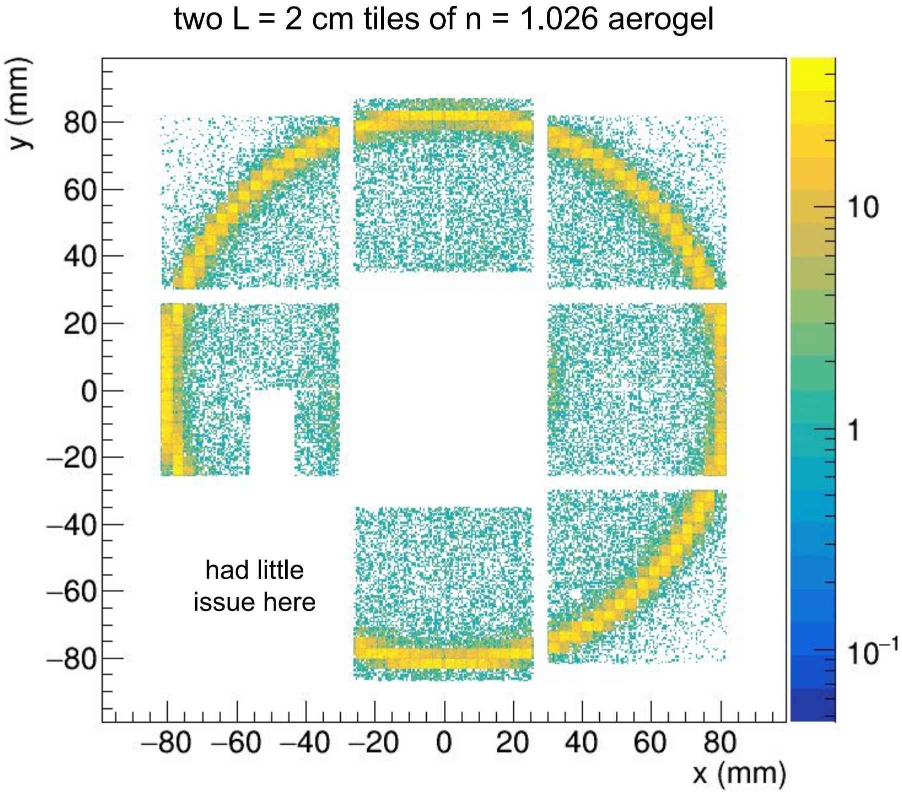


single-photon resolution improves, not clear why

n = 1.026 aerogel samples

larger refractive index, expected larger rings and more light





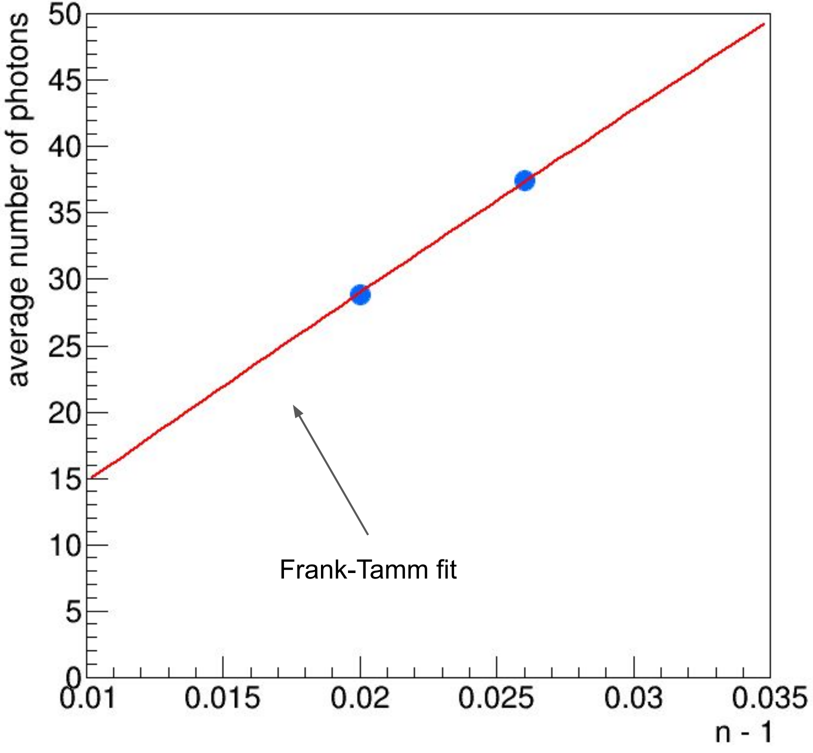
excluded bottom-left corner in these runs because of little issue

ring is larger, at the limit of the detector acceptance

n = 1.026 aerogel samples

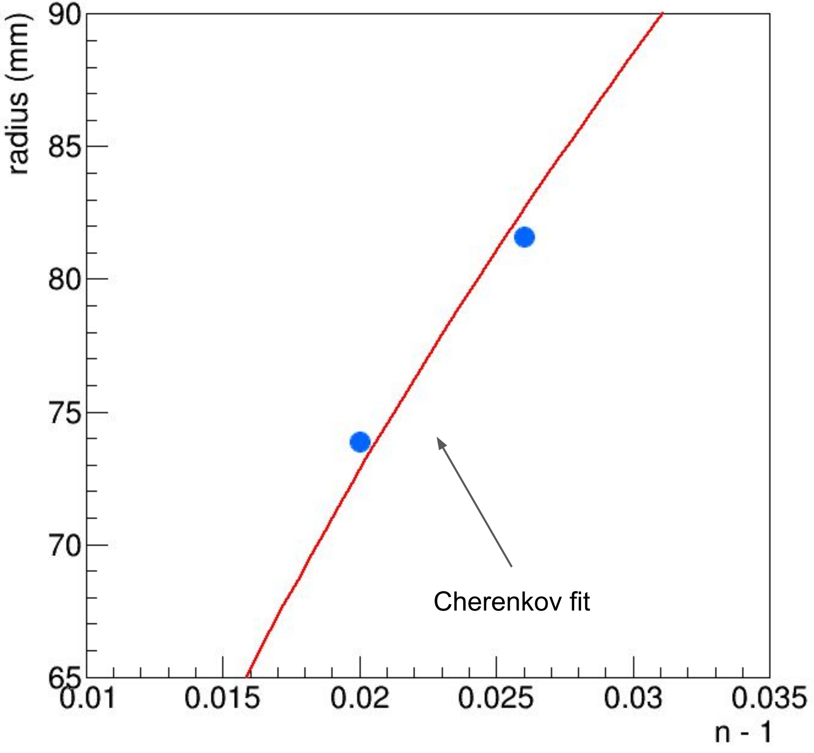
larger refractive index, expected larger rings and more light

estimated average number of photoelectrons per event



increases with refractive index (angle)

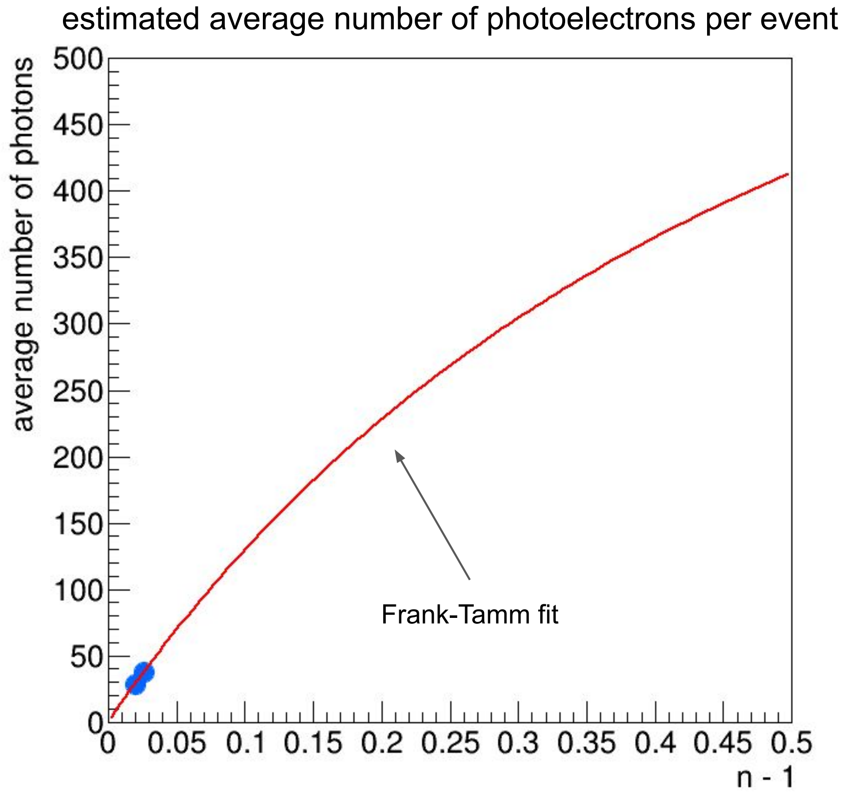
estimated ring radius

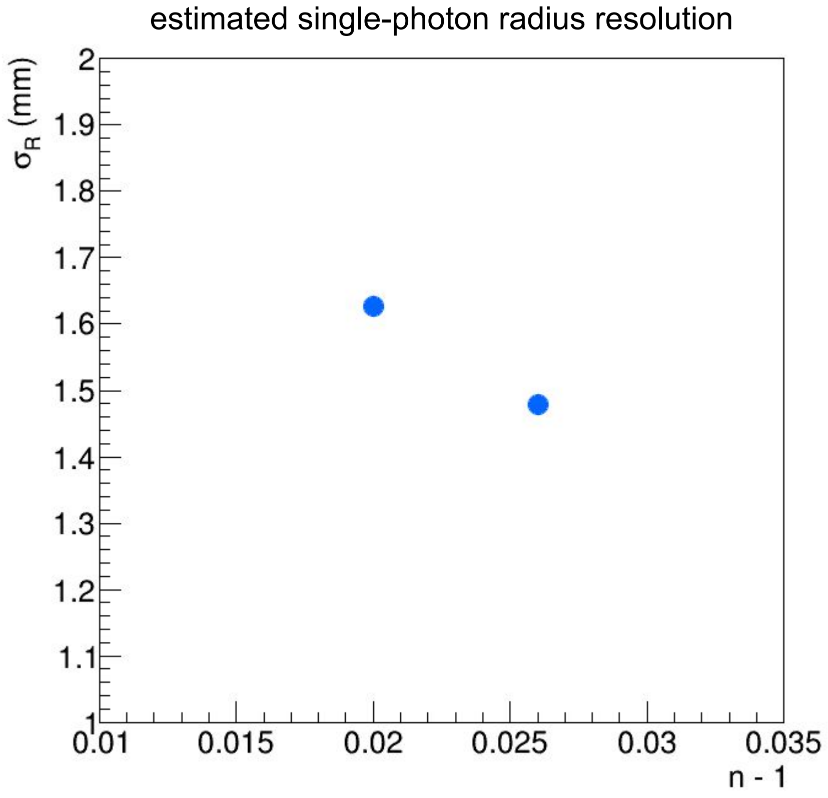


radius increases

n = 1.026 aerogel samples

larger refractive index, expected larger rings and more light





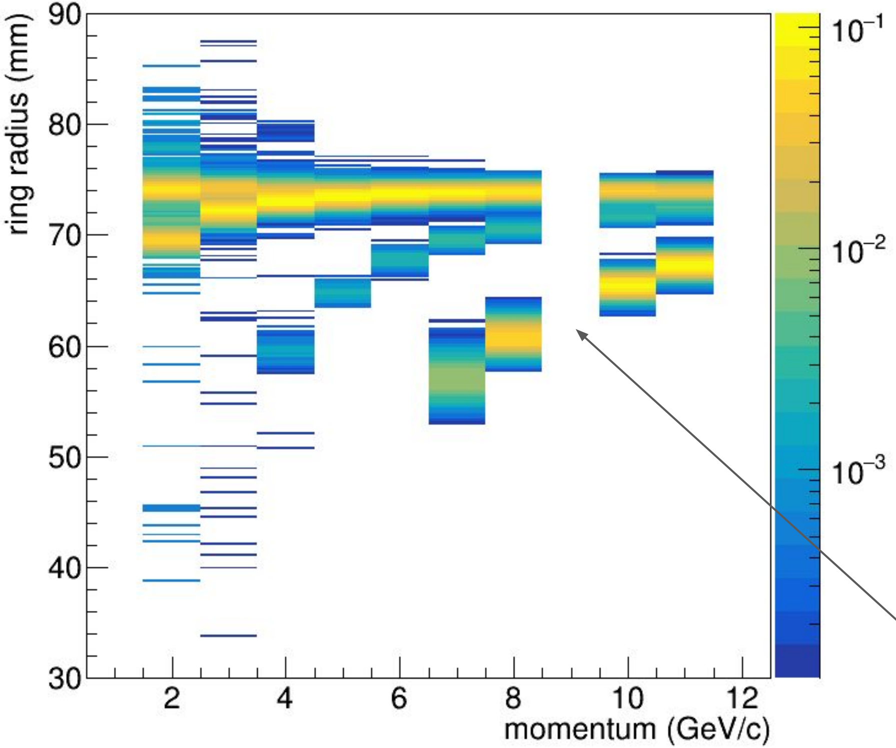
same view with extended range

single-photon resolution improves

Beam momentum scan

positive particles, aerogel only

reconstructed radii vs. beam momentum



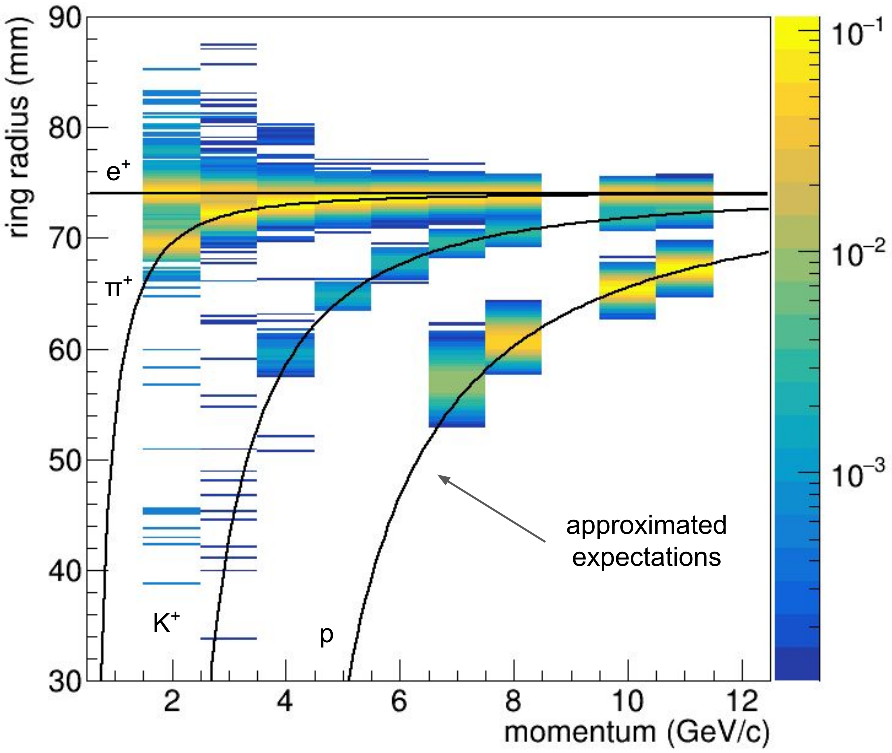
something has gone wrong with the beam configuration for 9 GeV (data not show)

nice!

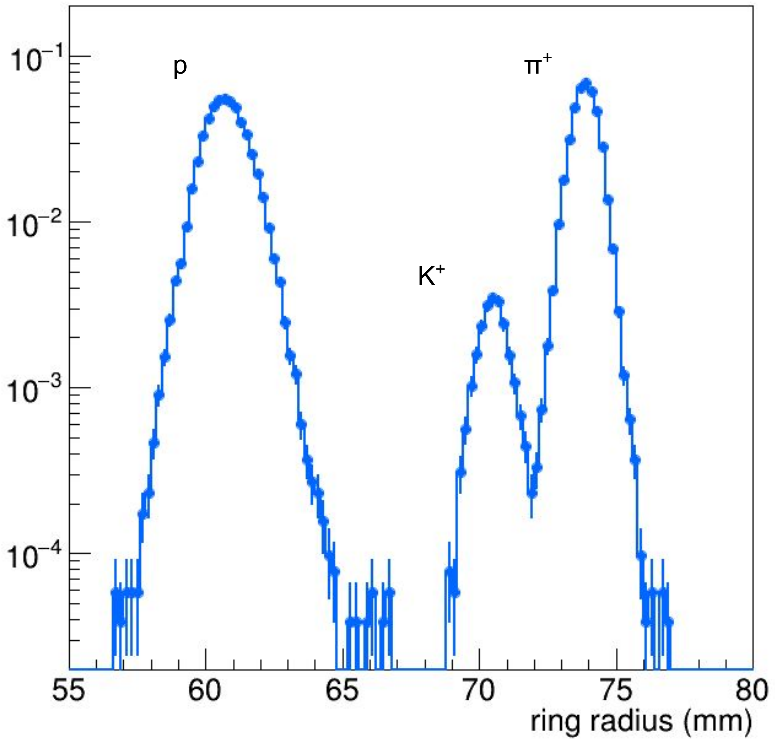
Beam momentum scan

positive particles, aerogel only

reconstructed radii vs. beam momentum



reconstructed radii at 8 GeV/c beam momentum



nice!

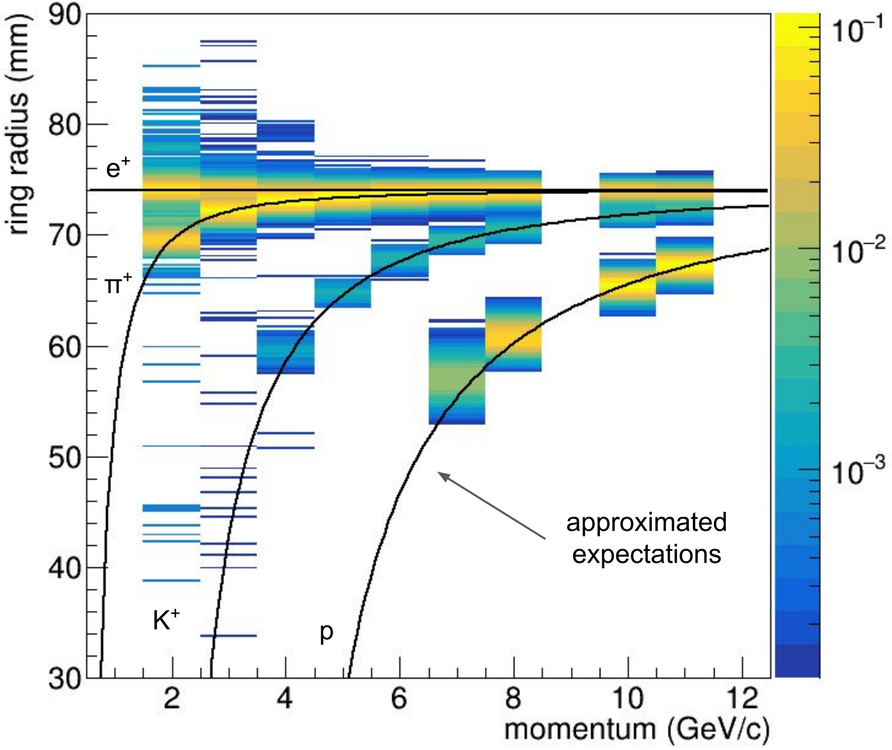
asdasdasd

Beam momentum scan

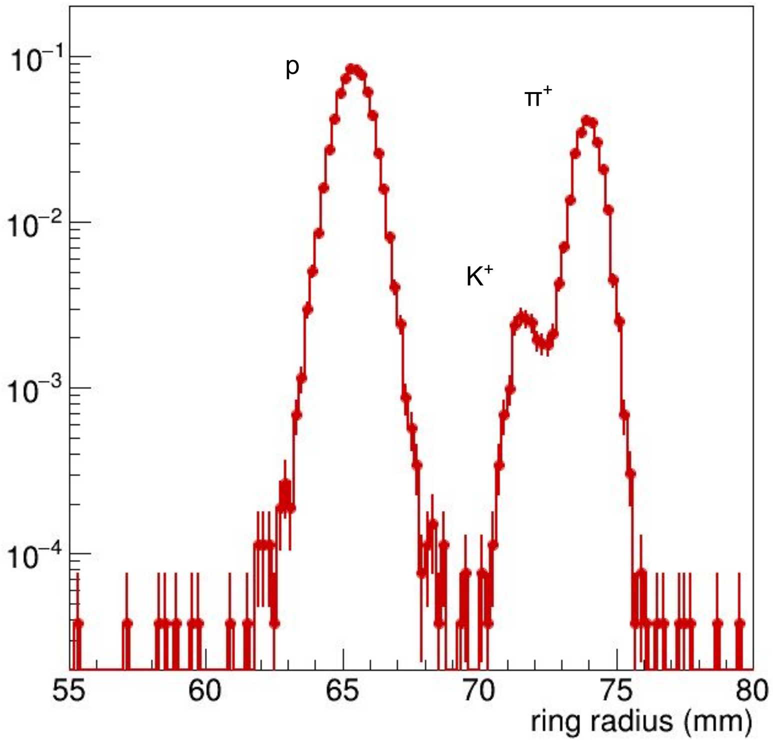
positive particles, aerogel only

PRELIMINARY

reconstructed radii vs. beam momentum



reconstructed radii at 10 GeV/c beam momentum



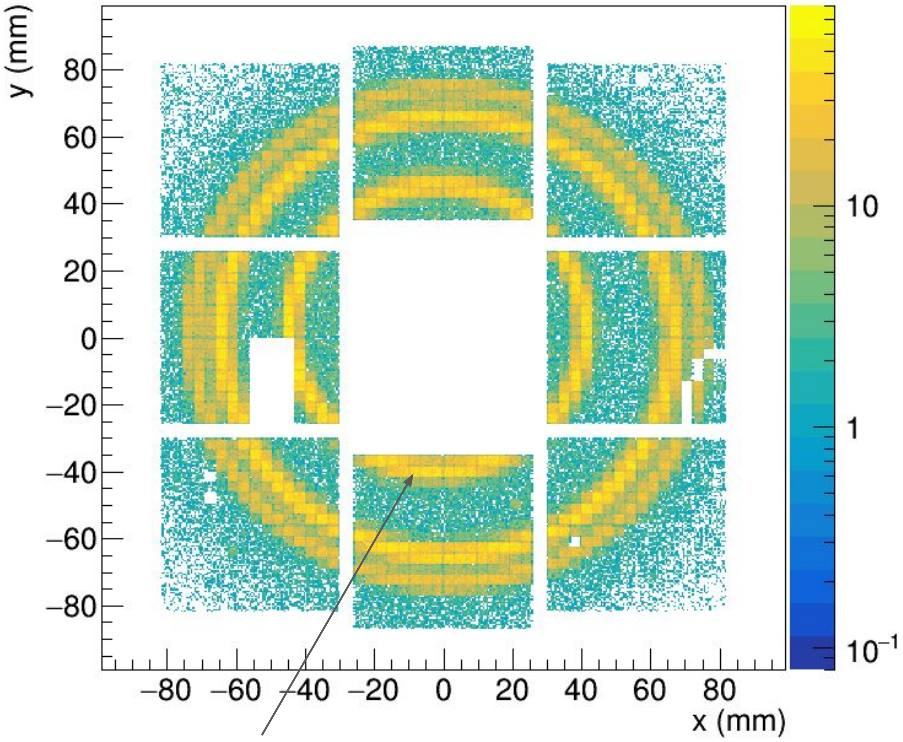
nice!

asdasdasd

Interplay between radiators

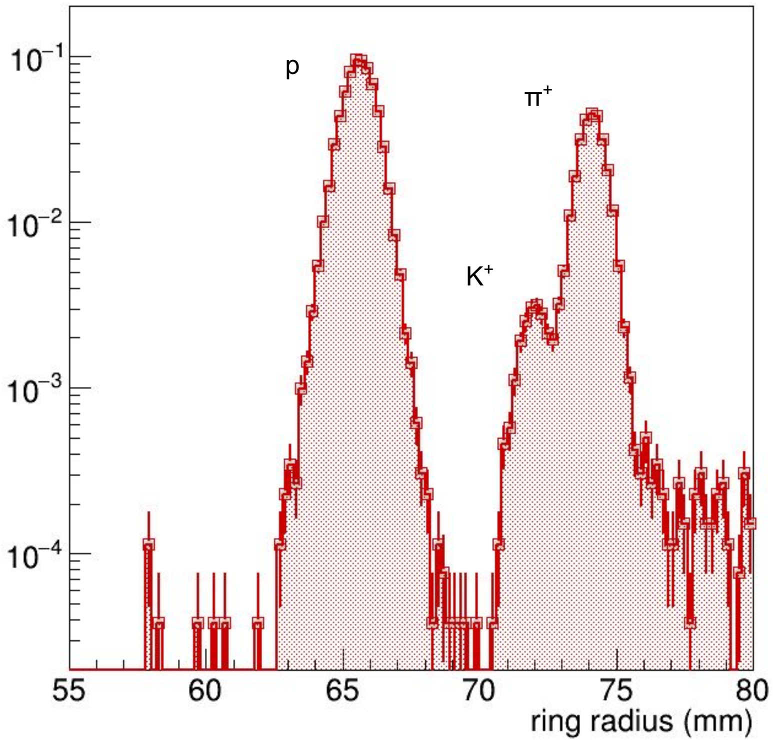
gas ring tags pions, kaons and protons are below threshold

10 GeV/c positive beam with no selection applied



gas ring

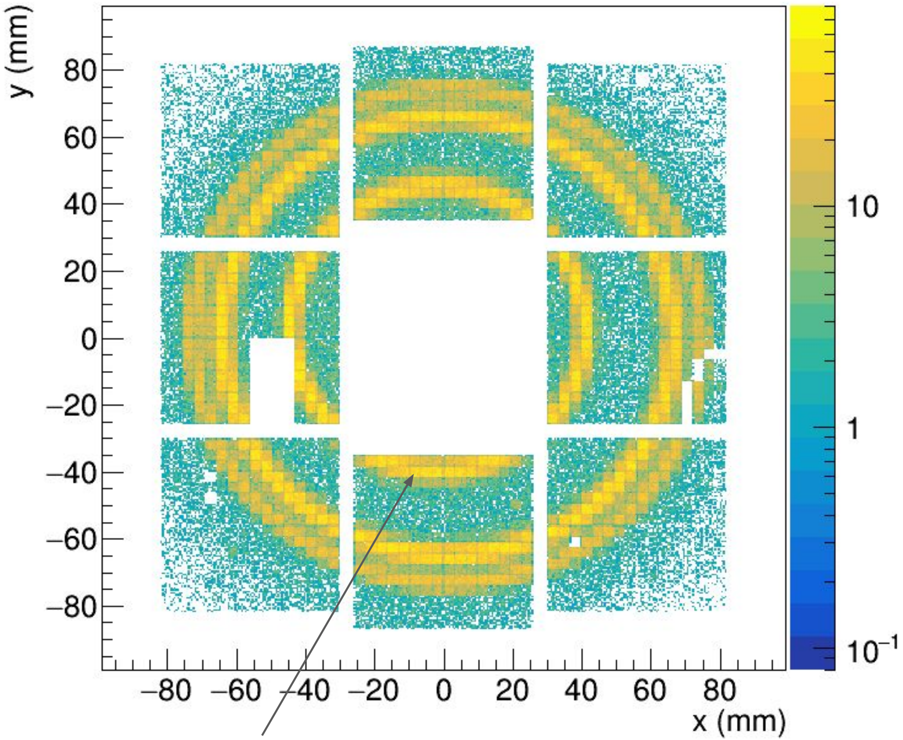
reconstructed radii at 10 GeV/c with no selection applied



Interplay between radiators

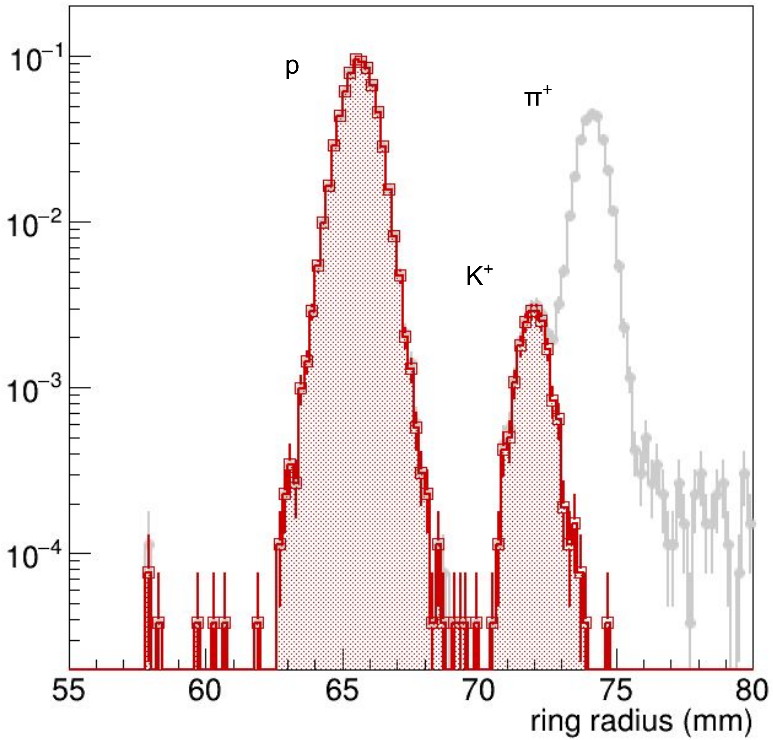
gas ring tags pions, kaons and protons are below threshold

10 GeV/c positive beam with no selection applied



gas ring

reconstructed radii at 10 GeV/c with gas veto

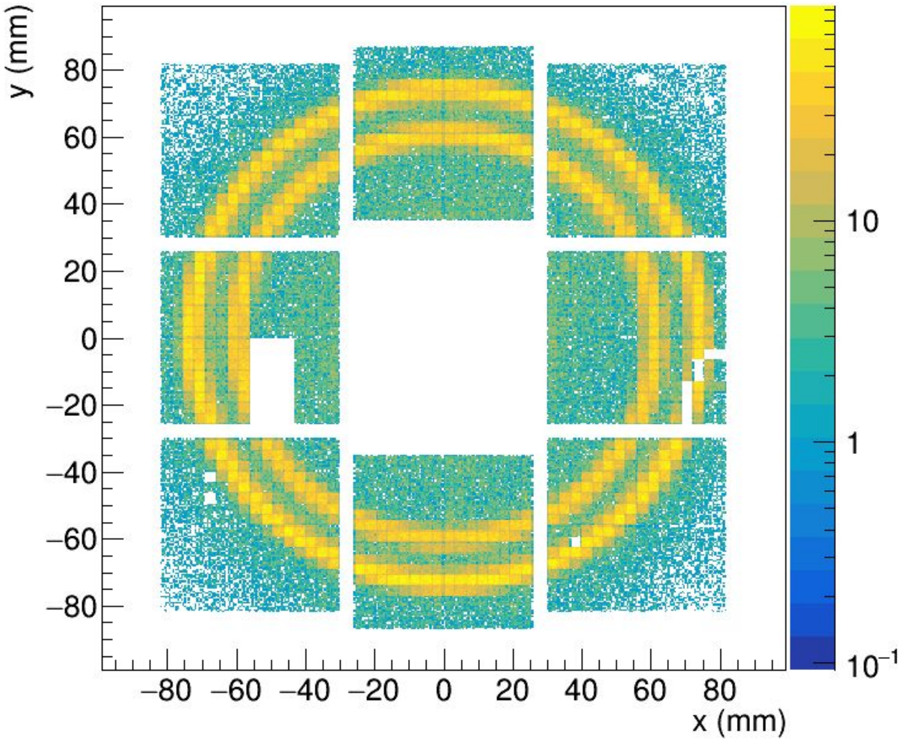


clean kaon identification at 10 GeV/c

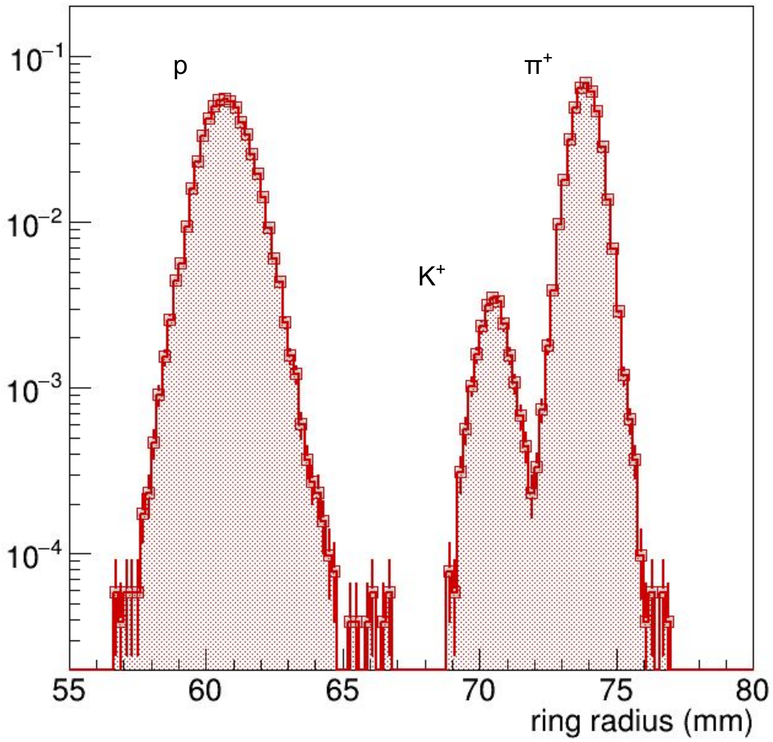
Threshold Cherenkov beam counters

TCh-1 set below kaon threshold, TCh-2 set below proton threshold

8 GeV/c positive beam with no selection applied



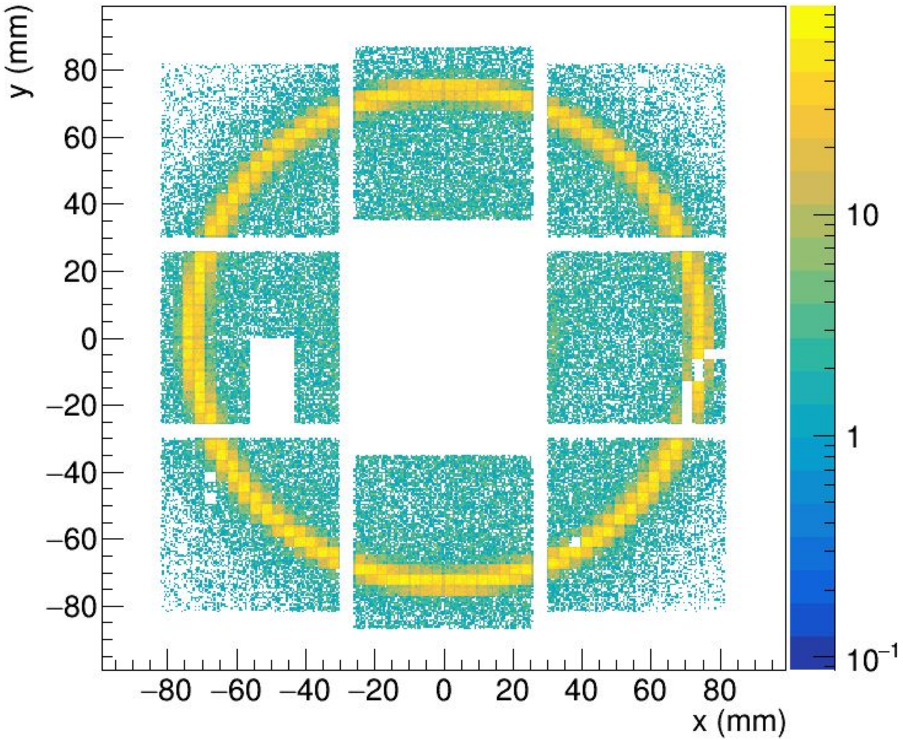
reconstructed radii at 8 GeV/c with no selection applied



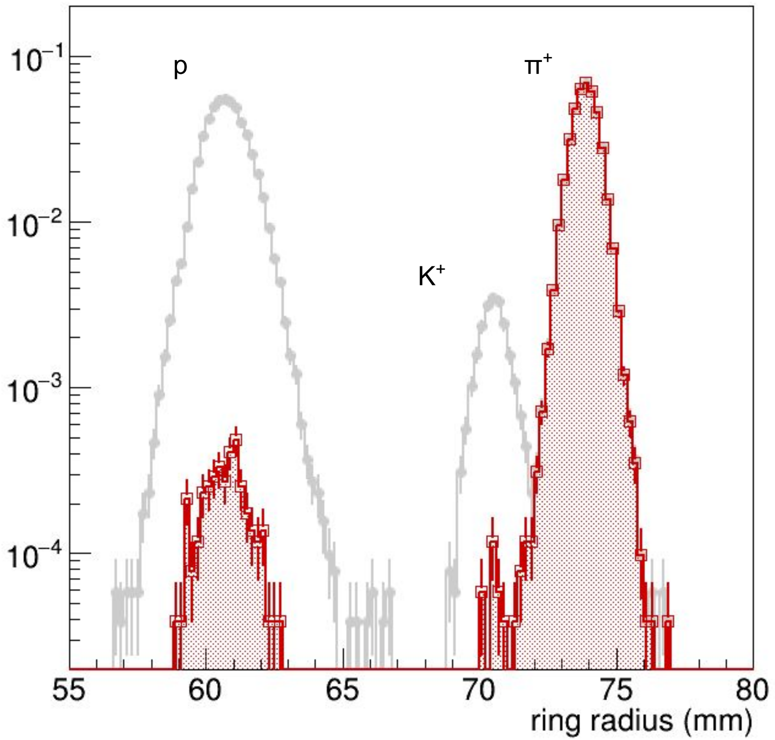
Threshold Cherenkov beam counters

TCh-1 set below kaon threshold, TCh-2 set below proton threshold

8 GeV/c positive beam with pion tag



reconstructed radii at 8 GeV/c with pion tag

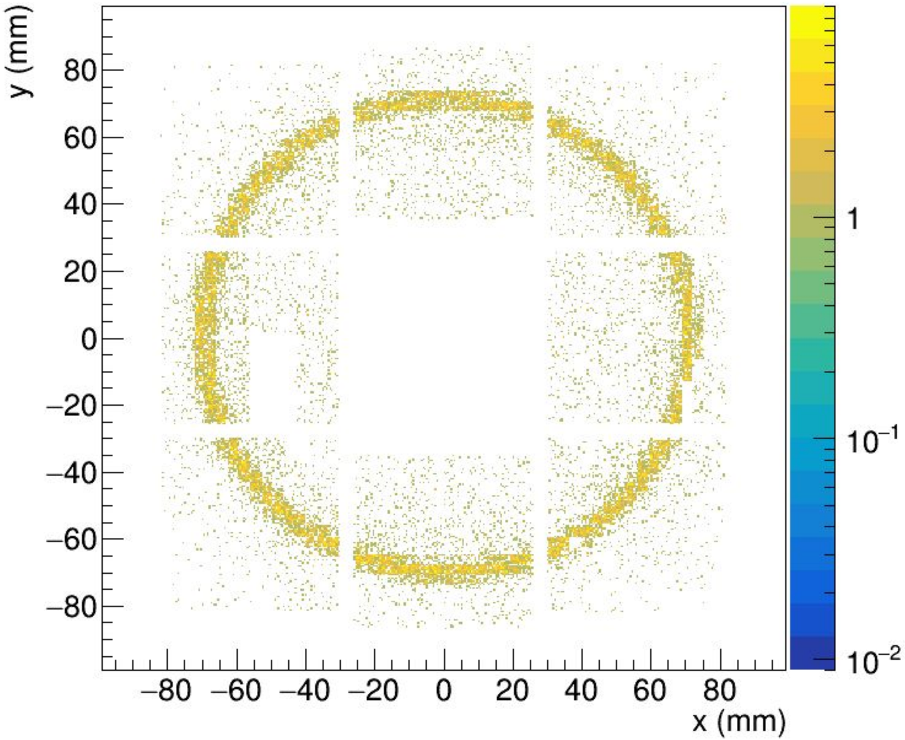


pion tag: TCh-1 required

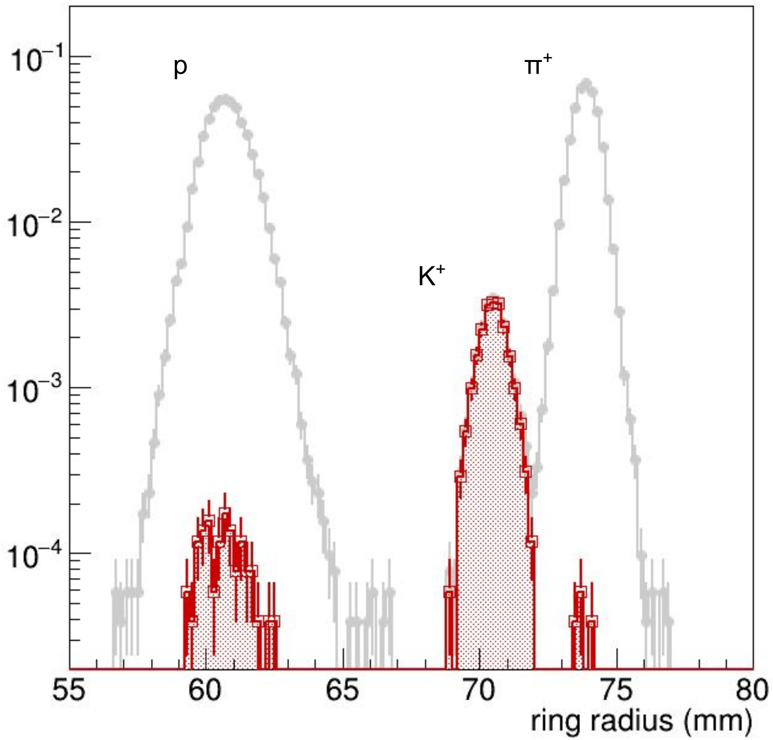
Threshold Cherenkov beam counters

TCh-1 set below kaon threshold, TCh-2 set below proton threshold

8 GeV/c positive beam with kaon tag



reconstructed radii at 8 GeV/c with kaon tag

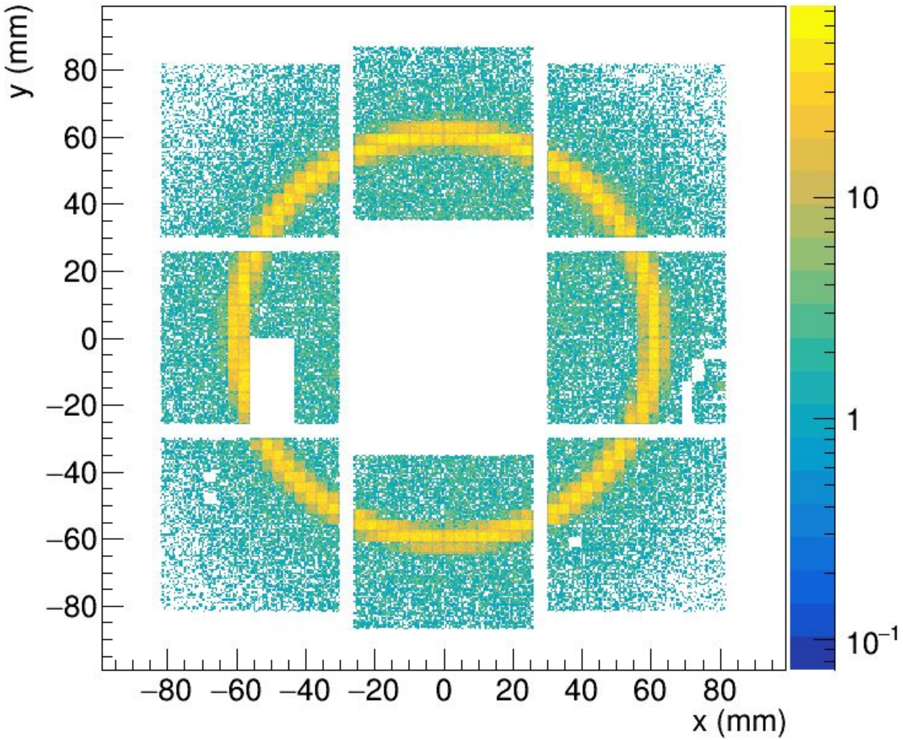


kaon tag: TCh-1 veto and TCh-2 required

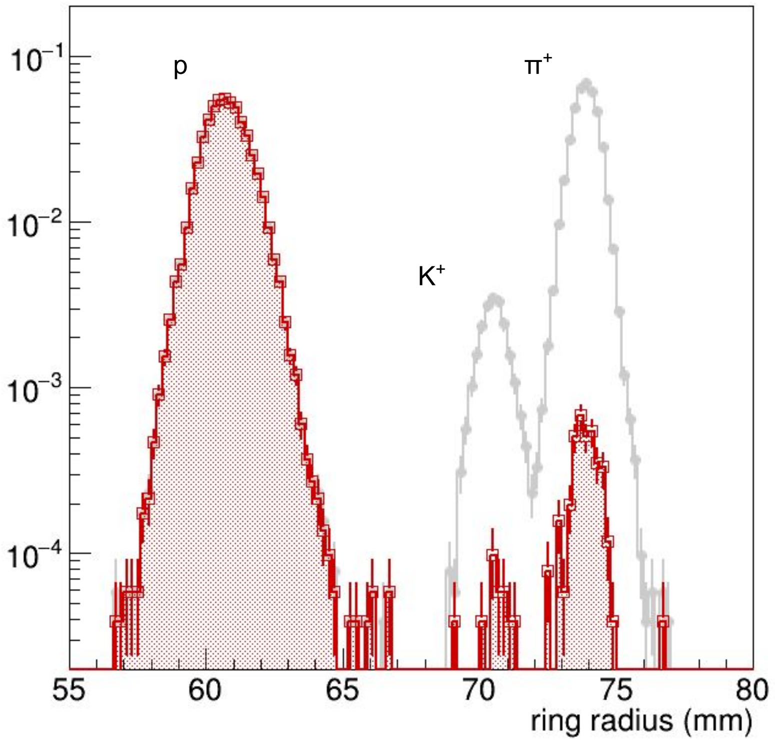
Threshold Cherenkov beam counters

TCh-1 set below kaon threshold, TCh-2 set below proton threshold

8 GeV/c positive beam with proton tag



reconstructed radii at 8 GeV/c with proton tag

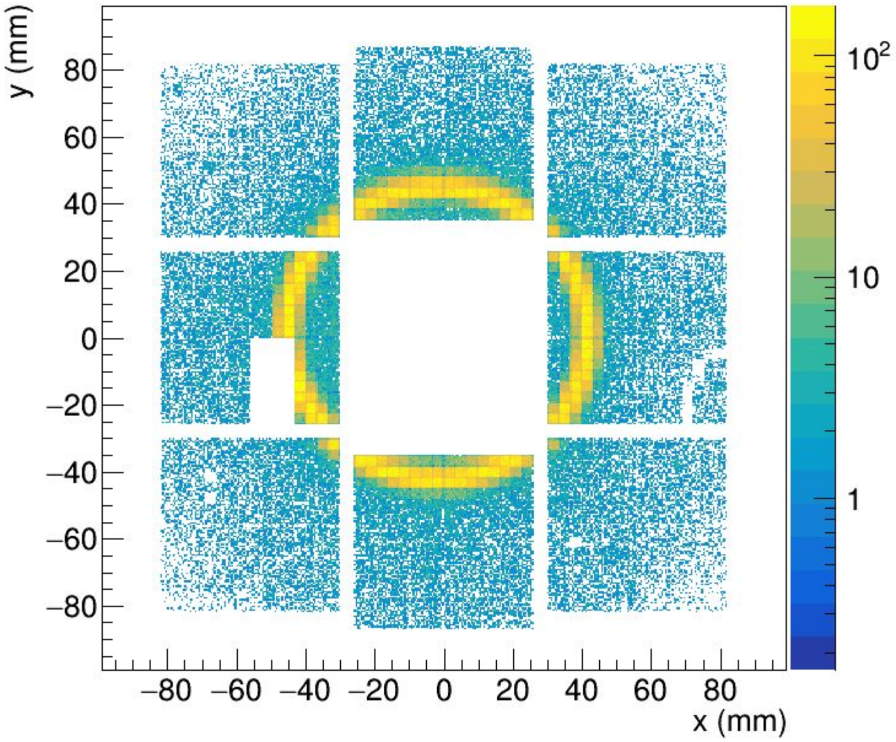


proton tag: TCh-1 veto and TCh-2 veto

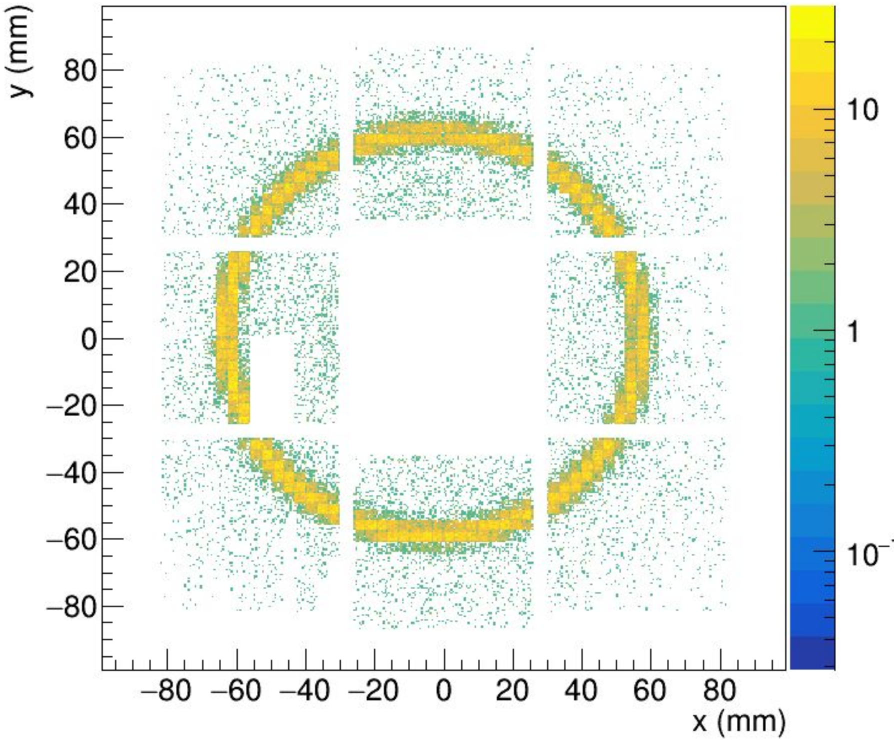
Gas radiators

standard gas C_2F_6 (n = 1.0008) and heavier C_4F_{10} (n = 1.0014)

C_2F_6 (n = 1.0008)



C_4F_{10} (n = 1.0014)



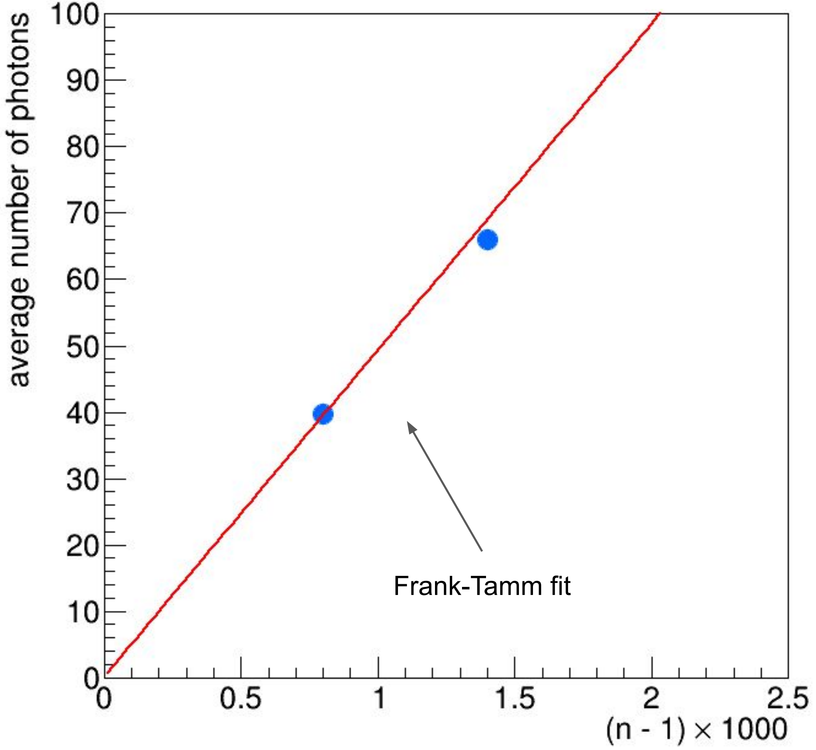
no aerogel in these data

heavier gas, larger refractive index, larger ring

Gas radiators

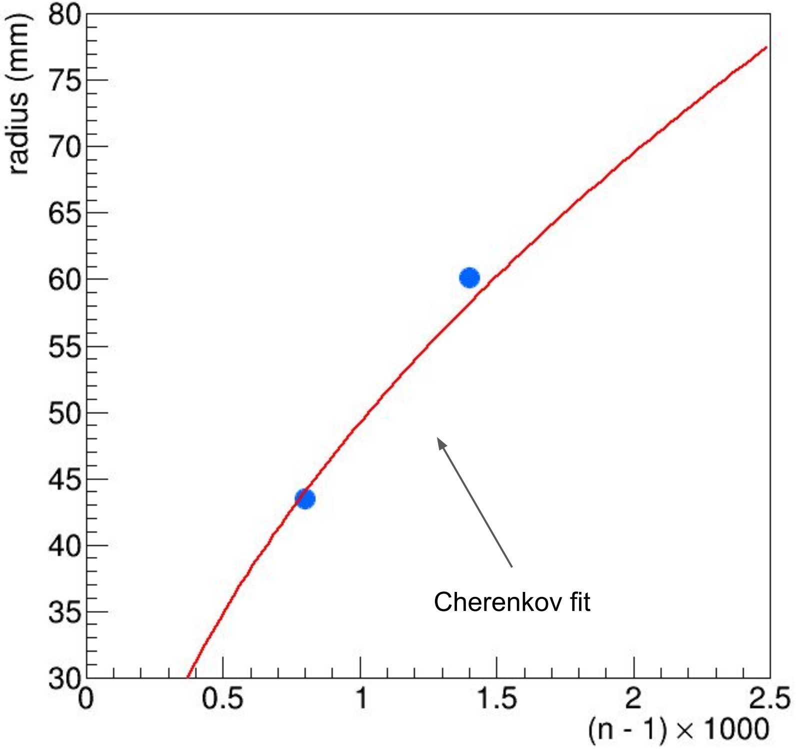
standard gas C_2F_6 (n = 1.0008) and heavier C_4F_{10} (n = 1.0014)

estimated average number of photoelectrons per event



increases with refractive index (angle)

estimated ring radius



radius increases