Plans and developments for Cherenkov PID at ePIC

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Istituto Nazionale di Fisica Nucleare, Sezione di Bologna

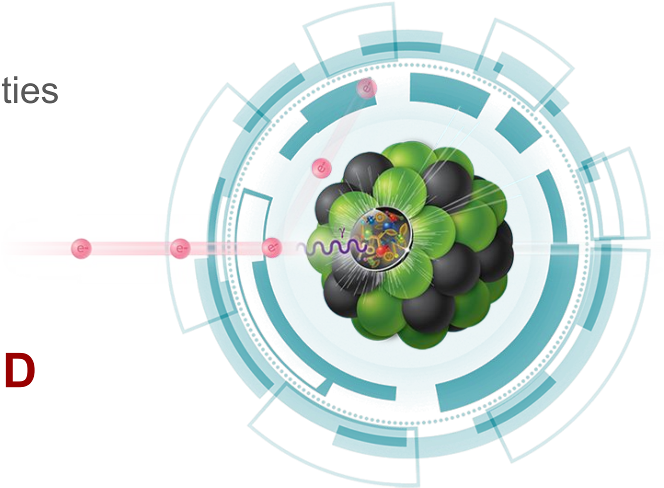
CERN-EIC synergies for Cherenkov PID, 25 April 2023

The Electron-Ion Collider

a machine that will unlock the secrets of the strongest force in Nature

is a future electron-proton and electron-ion collider to be constructed
in the United States in this decade and foreseen to start operation in 2030

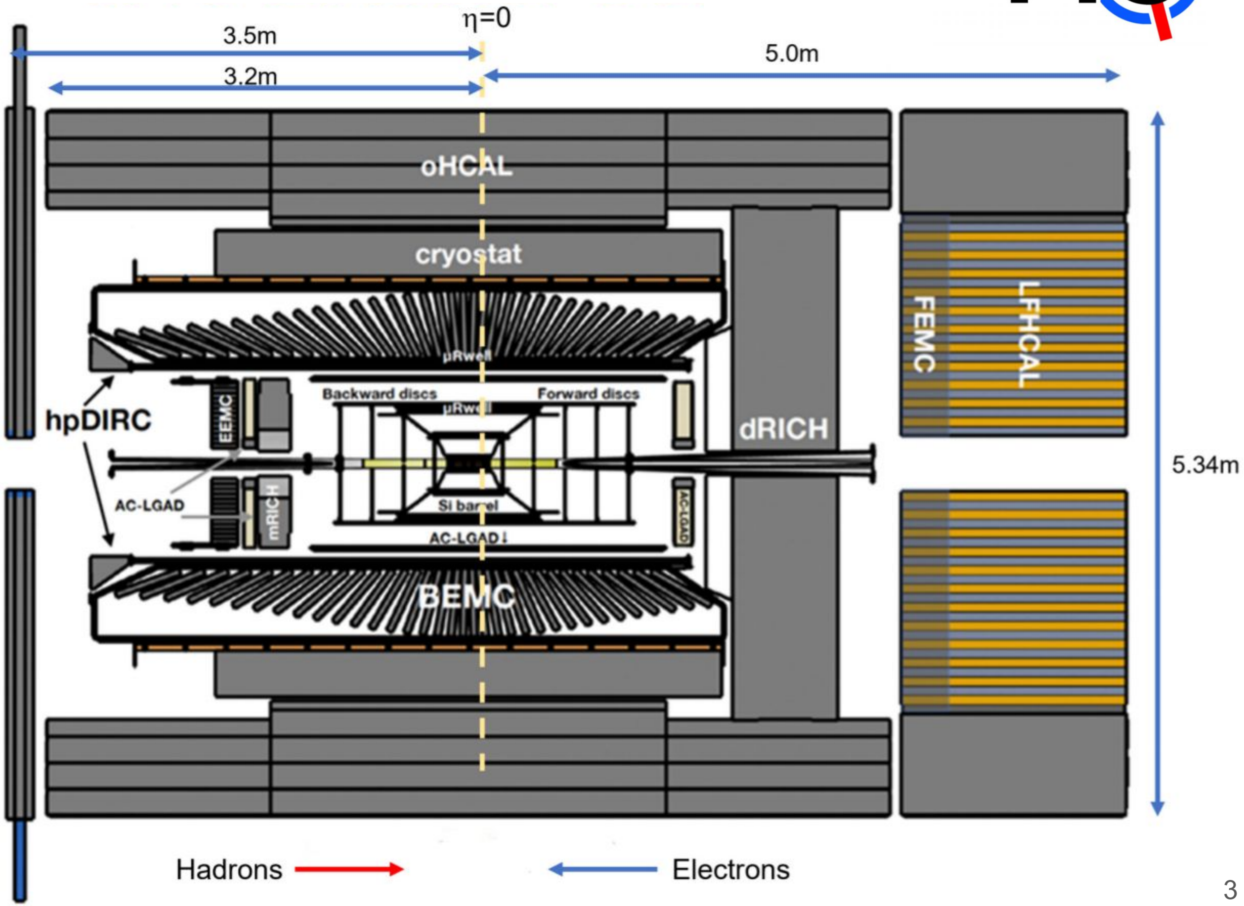
- **EIC constitutes the major US project in the field of nuclear physics**
  - and will surely be one of the most important scientific facilities for the future of nuclear and subnuclear physics
- **EIC will be the world's first collider for**
  - polarised electron-proton (and light ions)
  - electron-nucleus collisions
- **EIC will allow one to explore the secrets of QCD**
  - understand the origin of mass and spin of the nucleons
  - provide extraordinary 3D images of the nuclear structure



www.bnl.gov/eic

The ePIC barrel detector

- **tracking**
  - new 1.7 T magnet
  - Si-MAPS + MPGDs
- **calorimetry**
  - e-side: $PbWO_4$ EMCal
  - barrel: imaging EMCal
  - h-side: finely segmented
  - outer barrel HCal
- **particle ID**
  - AC-LGAD TOF
  - pfRICH
  - hpDIRC
  - dRICH



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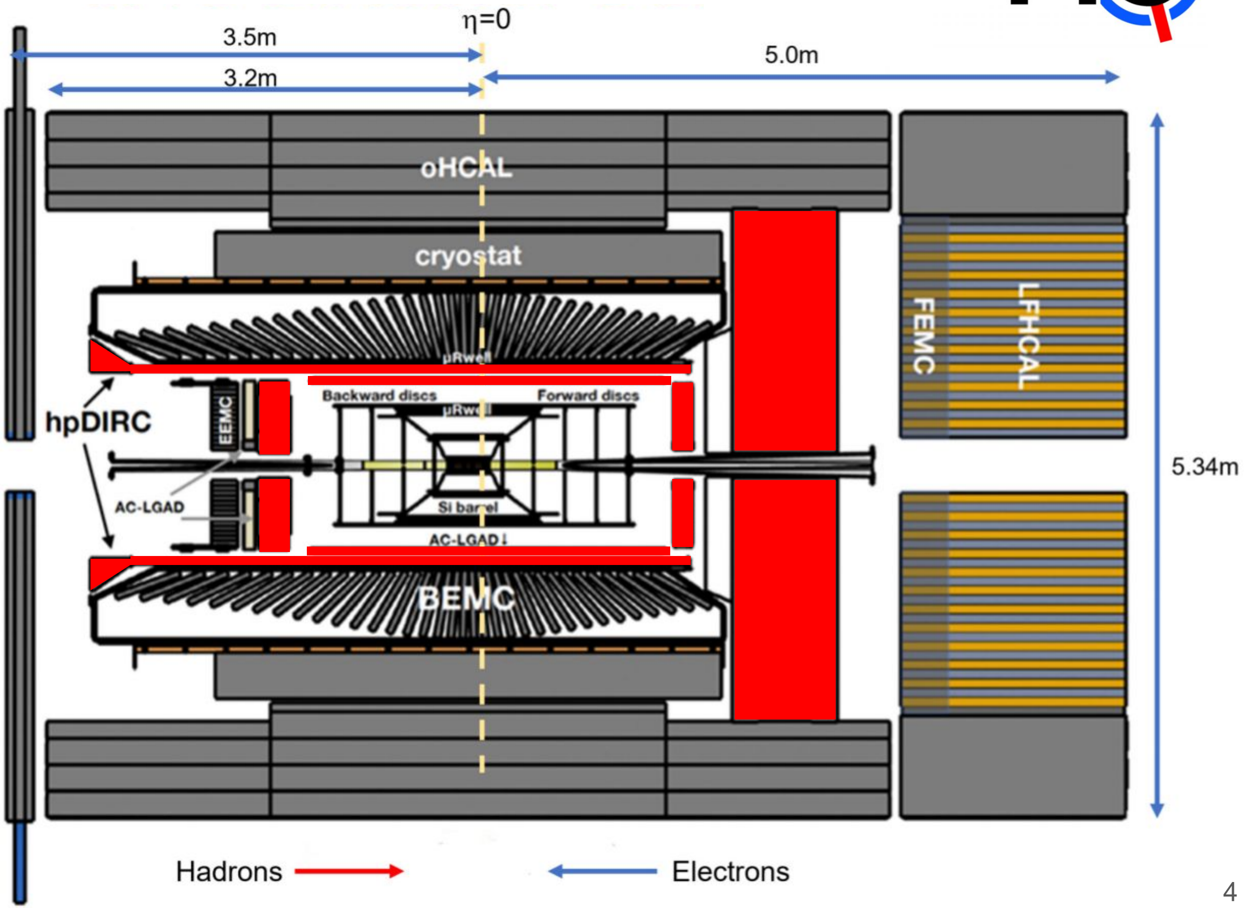
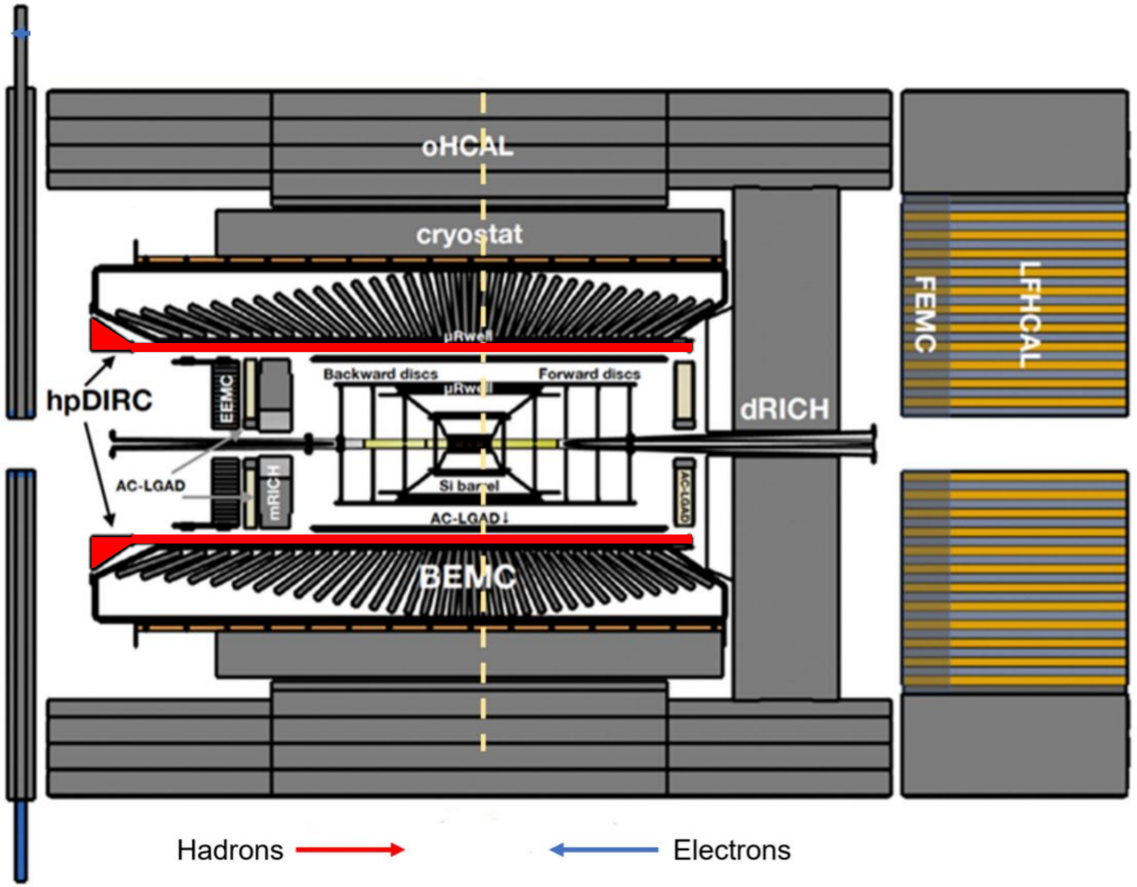


ePIC

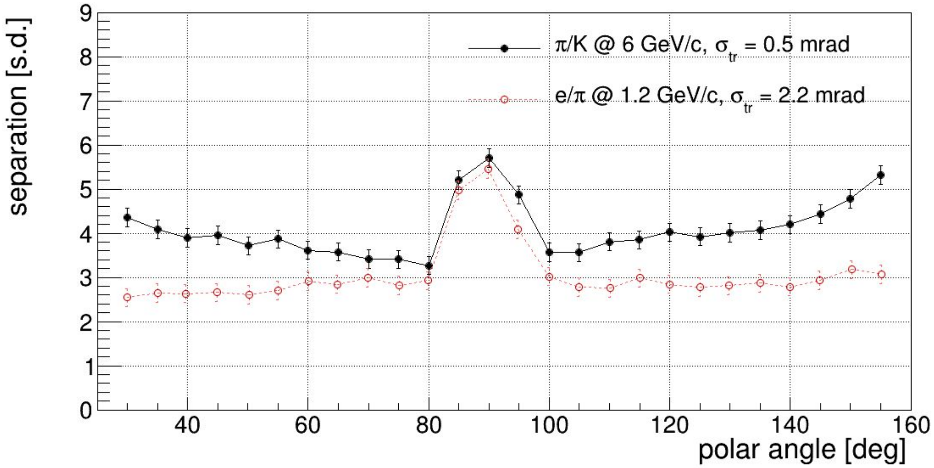
hp DIRC

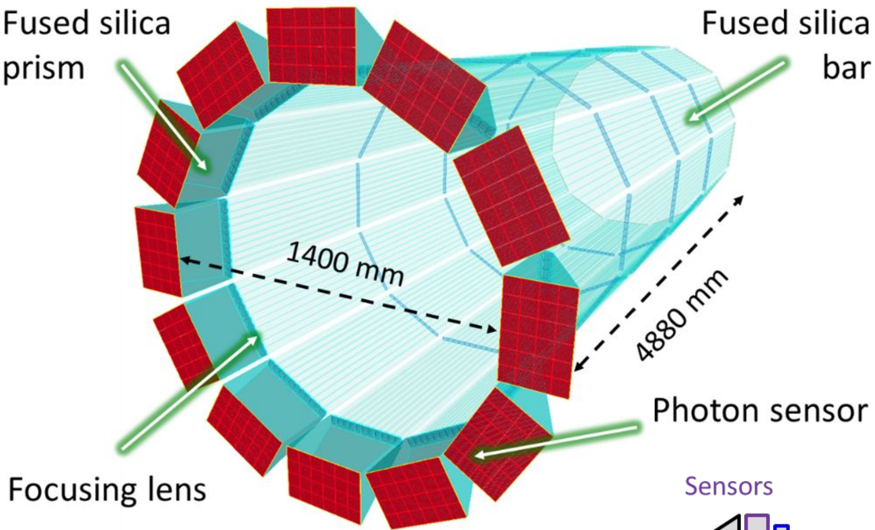

oHCAL
cryostat
μRwell
Backward discs
Forward discs
μRwell
hpDIRC
EEMC
AC-LGAD
mRICH
Si barrel
AC-LGAD
AC-LGAD
BEMC
dRICH
FEMC
LFHCAL
Hadrons
Electrons

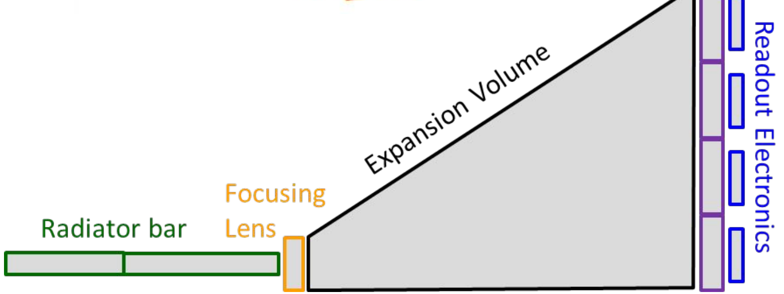
hpDIRC – high-performance DIRC

fast focusing DIRC with high-resolution 3D (x,y,t) reconstruction

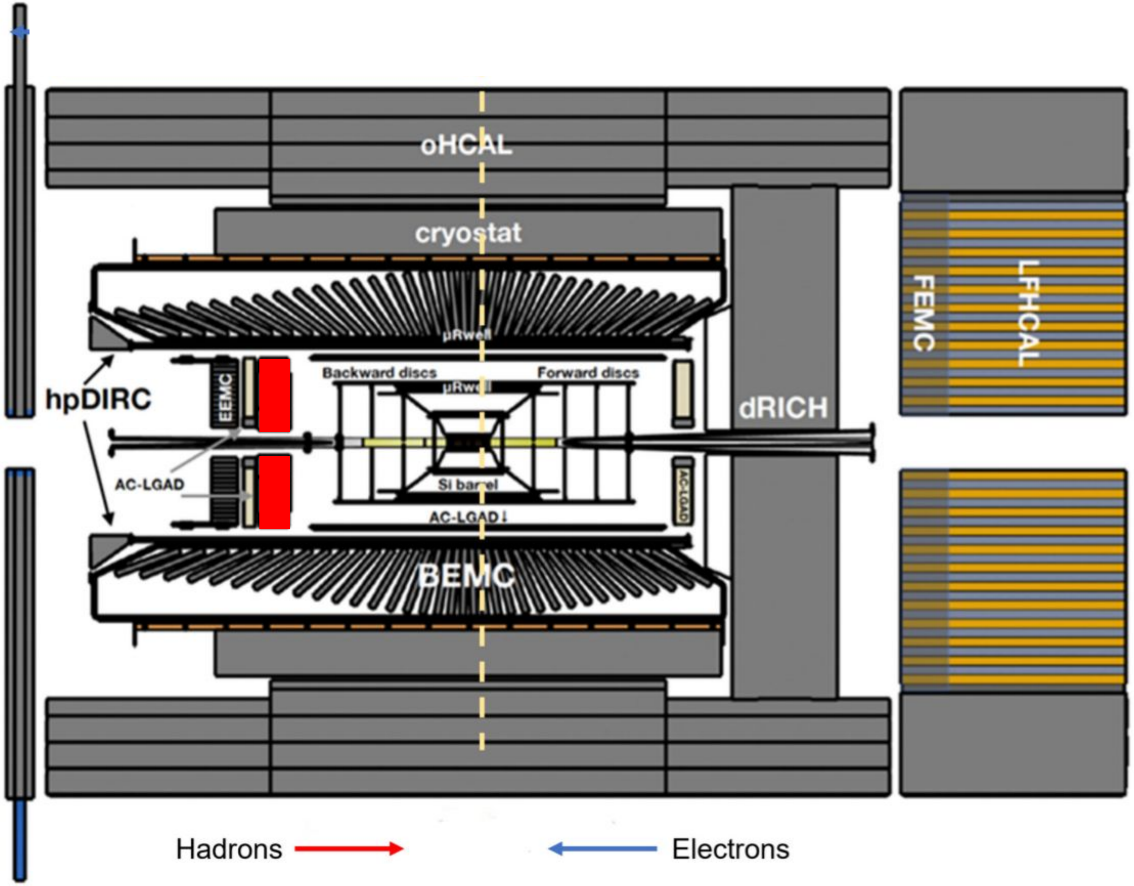
- **crucial components**
  - innovative 3-layer spherical lenses
  - compact fused silica expansion volumes
  - fast photodetection, small pixel MCP-PMT
- **hpDIRC creates focused images**
  - significantly improved resolution







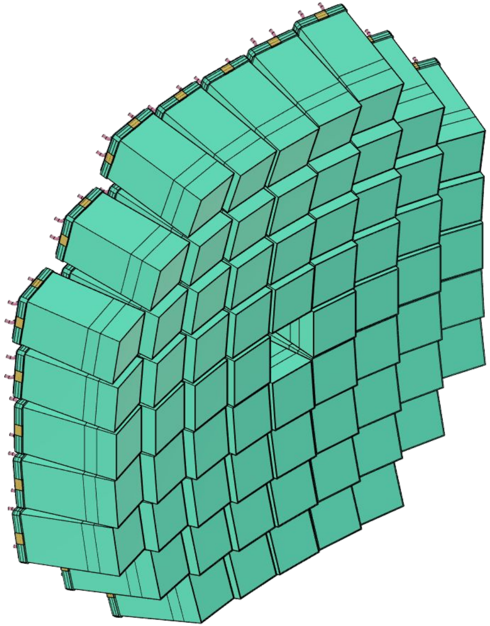
backward RICH

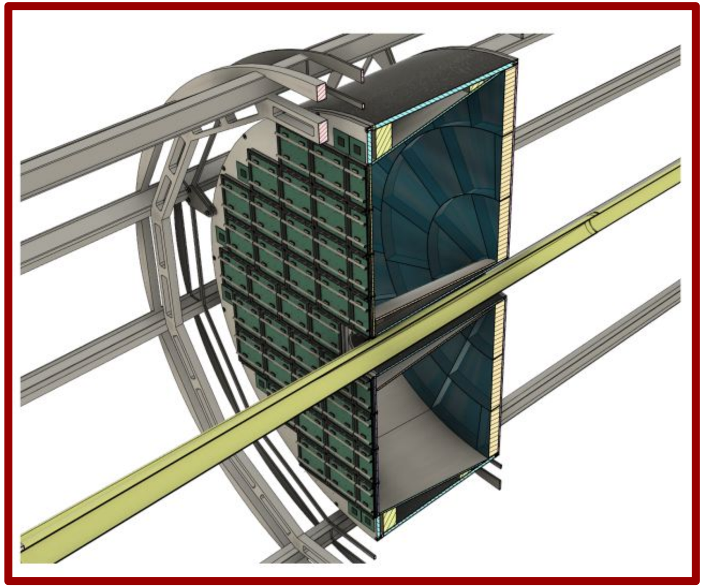


Backward RICH selection

two candidate technologies for PID in the electron-side direction
recommendation to use pfRICH as the baseline technology

mRICH



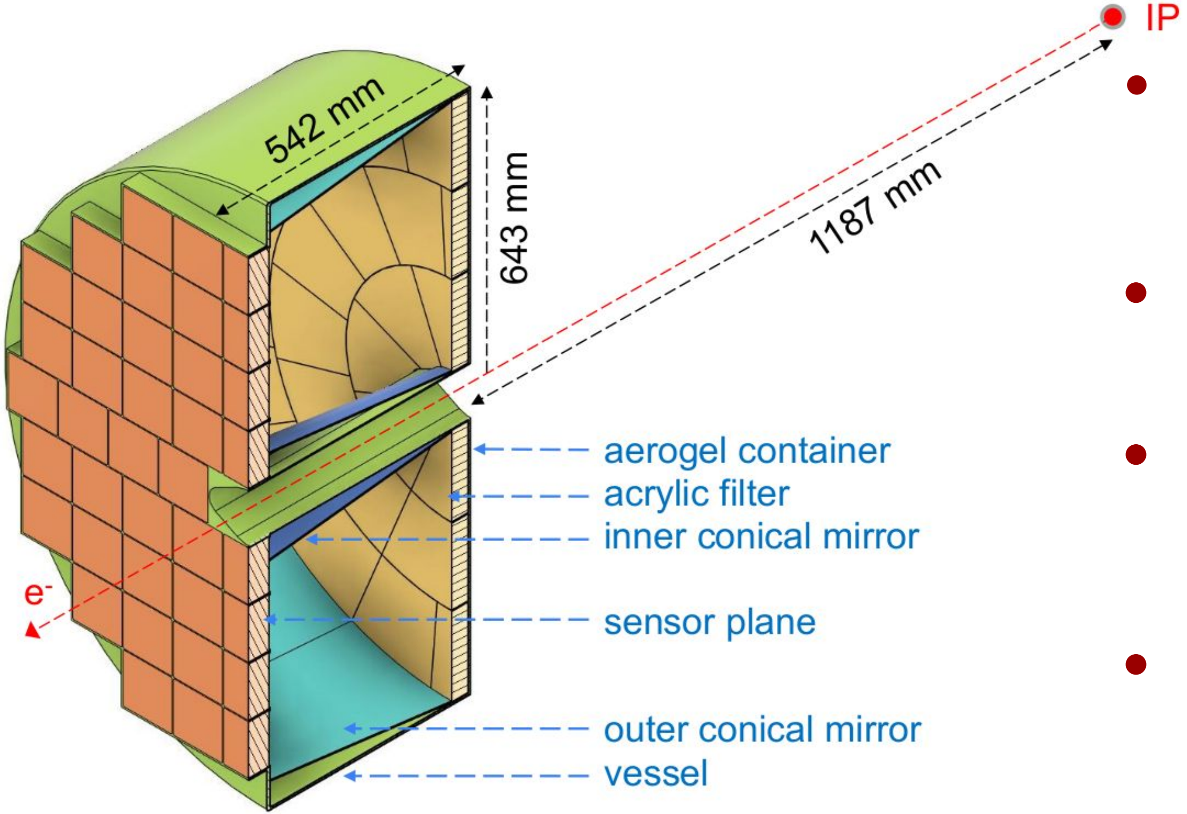


pfRICH

technologies have been reviewed (ePIC review on 20-21 March 2023)
mRICH and pfRICH costs are nearly the same, but pfRICH carriers a lower risk

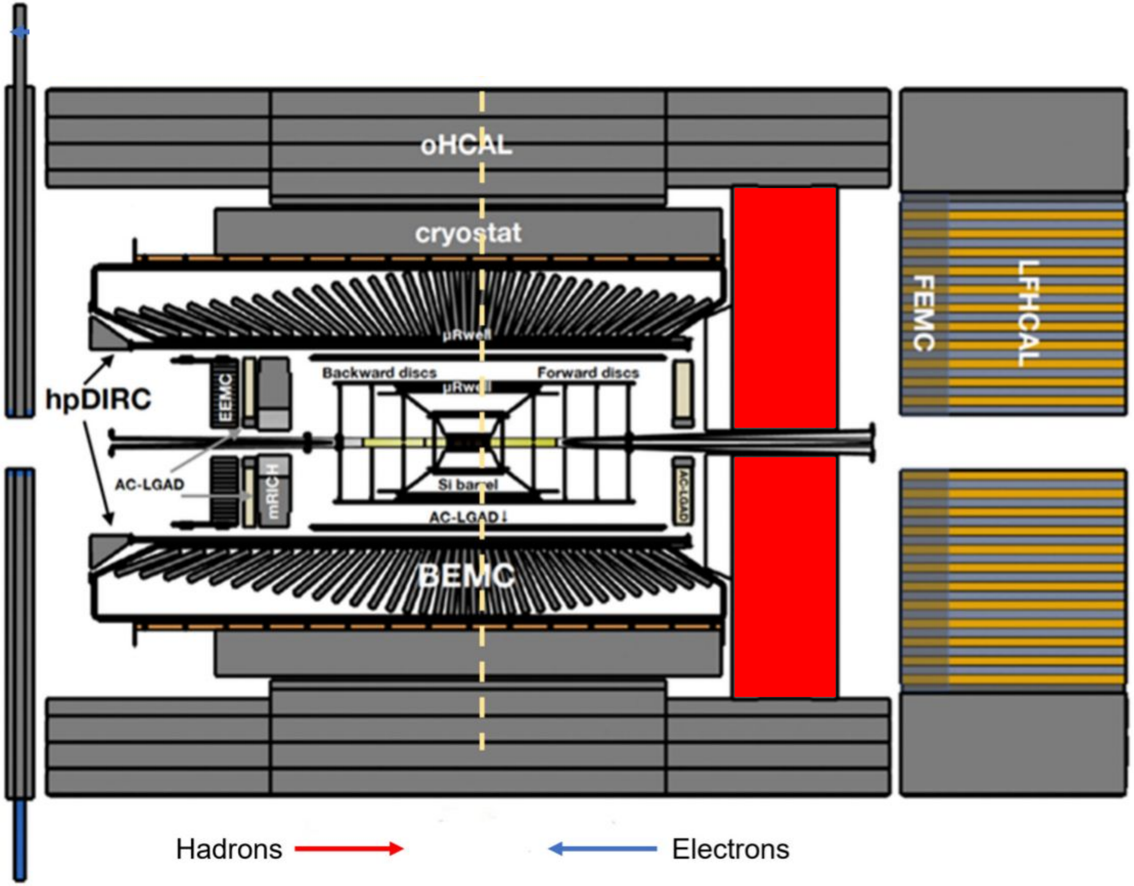
pfRICH – proximity focusing RICH

a classical proximity focusing RICH with timing capability for MIPs



- **Cherenkov radiator**
  - 2.5 cm thick aerogel (n = 1.04-1.05)
  - with 300 nm acrylic filter
  - $\langle N_{pe} \rangle \sim 11\text{-}12$
- **proximity gap**
  - 45 cm long
  - nitrogen filled
- **HRPPD photosensors**
  - 120 x 120 mm tiles
  - pixelation: 32 x 32 pads
  - DC-coupled
- **timing capability**
  - MIP produces UV light (dozens of pe) in the HRPPD window
  - provide time with $\sigma < 20$ ps

dual RICH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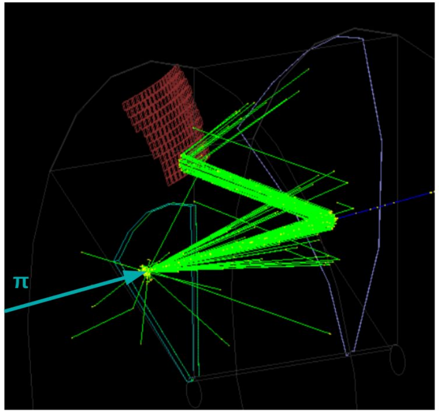
LFHCAL
Hadrons
Electrons

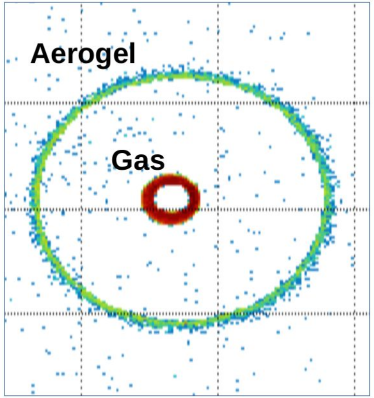
dRICH – dual-radiator RICH

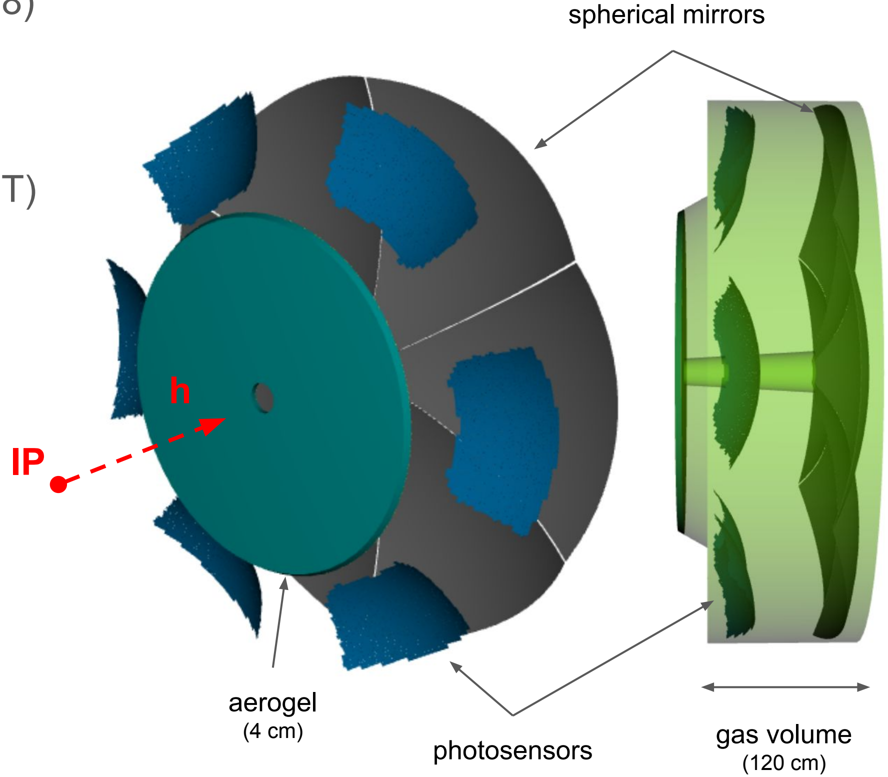
compact and cost-effective solution for broad momentum coverage at forward rapidity

- **radiators:** aerogel (n ~ 1.02) and C_2F_6 (n ~ 1.0008)
- **mirrors:** large outward-reflecting, 6 open sectors
- **sensors:** 3x3 mm^2 pixel, 0.5 m^2 / sector
    - ○ single-photon detection inside high B field (~ 1 T)
    - ○ outside of acceptance, reduced constraints
    - ○ best candidate for SiPM option

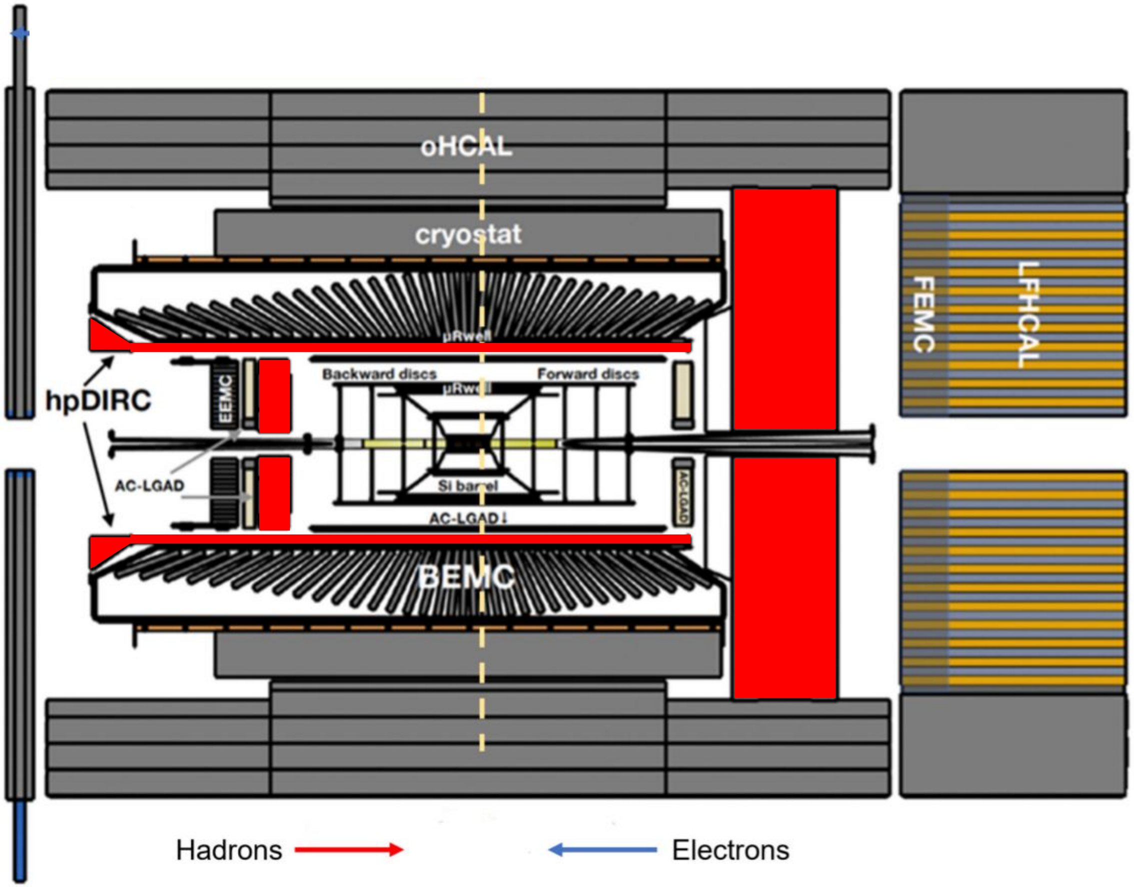


example event (accumulated hits)





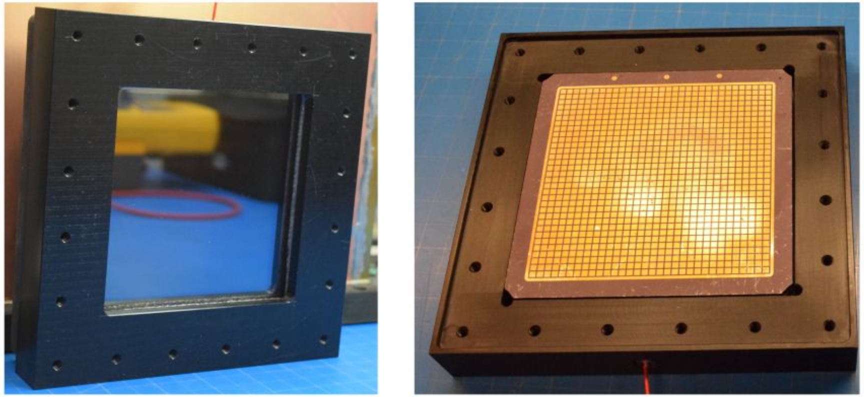
ePIC photosensors

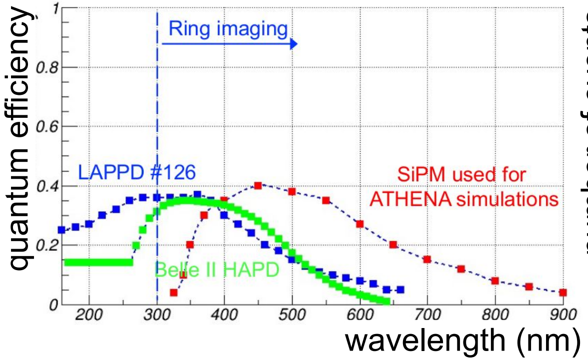


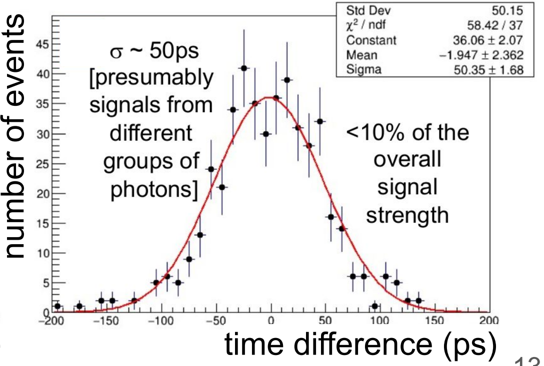
Photosensors – HRPPD

smaller version of LAPPD MCP-PMT technology, being developed with Incom Inc.

- **DC-coupled HRPPD**
  - choice for backward RICH detector
    - for both mRICH and pfRICH layout
  - 108 x 108 mm^2 active area (120 x 120 mm^2 total)
  - high intrinsic time resolution
  - low DCR (compared to SiPM) ~ 1 kHz/cm^2
  - low cost (compared to other MCP-PMT)
    - possible application for DIRC
- **ongoing R&D**
  - optimisation of QE and pixelation
  - characterisation in B field
    - gain and time resolution
  - mechanical / electrical interface
    - with direct pixel readout







LAPPD workshop last week

LAPPD Workshop

Thursday 20 Apr 2023, 16:00 → 21:00 Europe/Rome

the 3rd in the series

Description Organizers: Silvia Dalla Torre (INFN), Alexander Kiselev (BNL), Simona Malace (JLab), Deb Sankar Bhattacharya (INFN), Junqi Xie (ANL)

Hosted by CFNS: https://stonybrook.zoom.us/j/99257031544?pwd=VDhvbi9RT3B5RkJPZWRkQldPcE4wdz09

Argonne NATIONAL LABORATORY Brookhaven National Laboratory INFN Center for Frontiers in Nuclear Science Jefferson Lab

https://indico.bnl.gov/event/18642/

following slides make very large use of material from A Kiselev

Open LAPPD R&D questions before CD-3

- We need to come up with a detailed assessment of the current state of the art and projected LAPPD photosensor performance, evaluate their potential use in various EIC PID detector subsystems, and assist Incom in modifying their existing product line to meet EIC requirements

EIC requirements

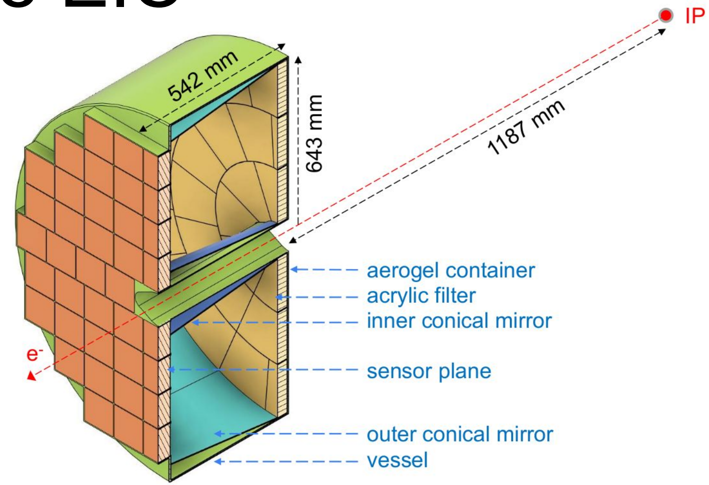
- Spatial resolution for Cherenkov imaging applications in a variety of fine pixellation schemes
- Timing resolution in a single photon mode, for a selected subset of pixellation scenarios
- Timing resolution for Time-of-Flight purposes
- Performance in a strong (inhomogeneous) magnetic field
- QE spectrum tuning and evaluation for ePIC detectors
- Overall PDE and gain uniformity tuning and measurement
- Geometric formfactor optimization
- Prospects of integration in particular ePIC detector subsystems (together with the respective groups and / or consortia), as well as the on-board electronics integration

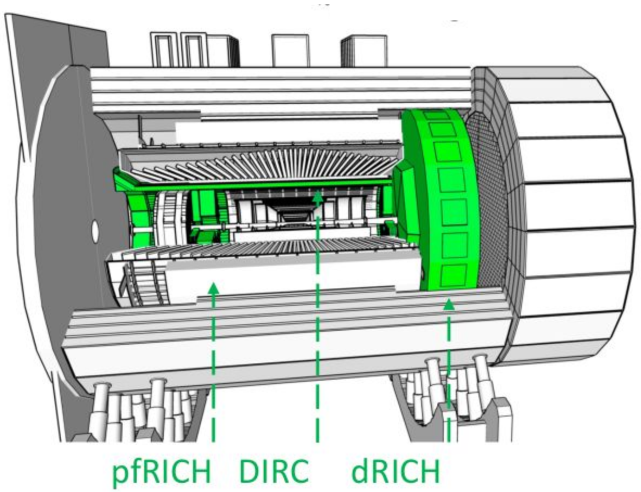
slide from the EIC Detector Advisory Committee review in October 2022

Possible HRPPD applications for the EIC

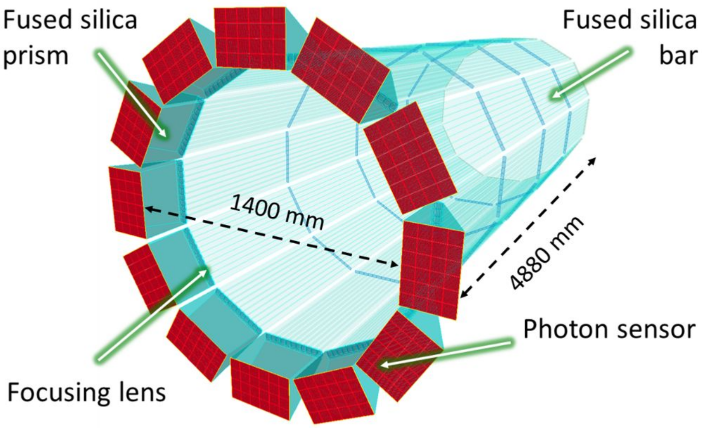
- **backward RICH (pfRICH)**
  - low DCR noise (wrt. SiPM) and timing capability
  - HRPPD is baseline photosensors as of November 2022
- **barrel DIRC (hpDIRC)**
  - MCP-PMT are the leading sensor candidate technologies
    - established (PHOTONIS), more recent (PHOTEK)
  - HRPPD expected to be more cost-effective
- **forward RICH (dRICH)**
  - use is problematic
    - large magnetic field
    - with field lines ~ perpendicular to MCP channel

pfRICH: total 68 HRPPD





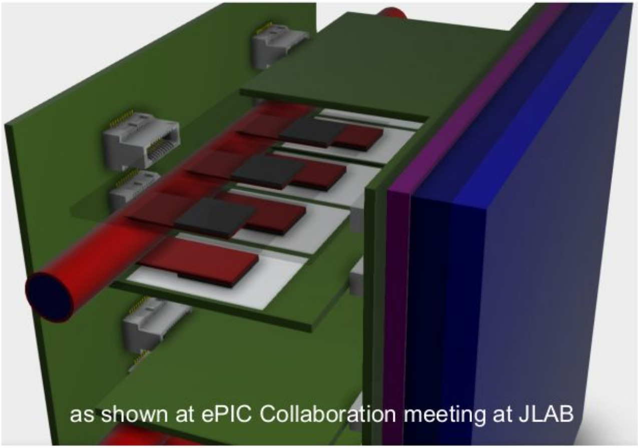
perspective for a sizeable production of ~ 150 HRPPDs
if also hpDIRC adopts it



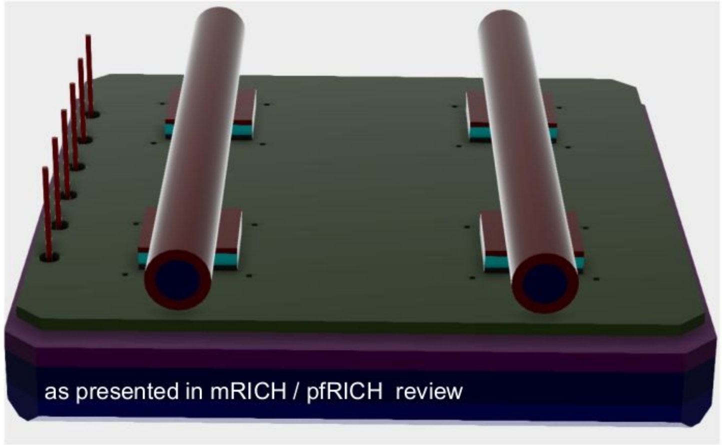
hpDIRC: total 72 HRPPD

Status of photosensor selection

conceptual evolution from January 2023



as shown at ePIC Collaboration meeting at JLAB



as presented in mRICH / pfRICH review

- ➢ Capacitively coupled HRPPDs
- ➢ 24x24 pad pixellation
- ➢ Waveform digitizer ASIC (Nalu)
- ➢ Vertical integration + a backplane

- ➢ DC-coupled HRPPDs
- ➢ 32x32 pad pixellation
- ➢ TOA / ADC ASIC (EICROC)
- ➢ Flat integration

Status of photosensor selection

conceptual evolution from January 2023

- **pfRICH choice: HRPPD by Incom Inc.**
  - High intrinsic SPE timing resolution: <50 ps
  - Low Dark Count Rate (compared to SiPMs): ~1 kHz/cm^2
  - Low cost (compared to other MCP-PMTs): <$20k for a 120mm x 120mm sensor

Capacitively coupled (Gen II)

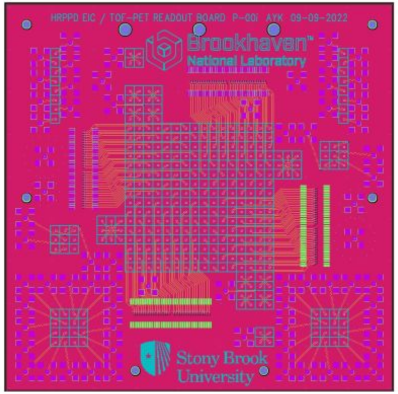
- Pros
  - All our experience is based on Gen II LAPPDs
  - Flexibility in the readout board design
- Cons
  - Broad clusters -> occupancy, overlaps, etc
  - Resistive layer -> additional R&D topic
  - Somewhat smaller amplitudes

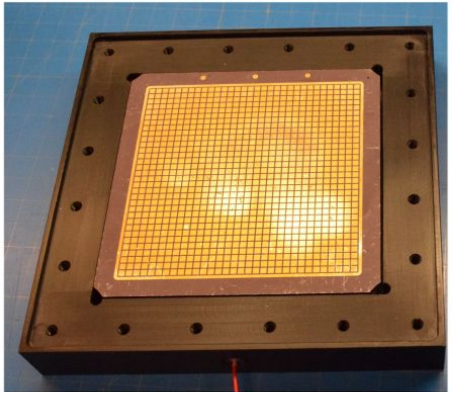
DC-coupled

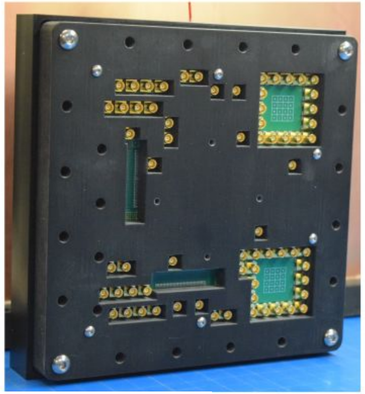
- Pros
  - Single pad hits -> better for timing
  - Same design for pfRICH & DIRC
- Cons
  - Missing interface to the readout board
  - Performance yet to be verified
  - Spatial resolution limited by pitch/√12

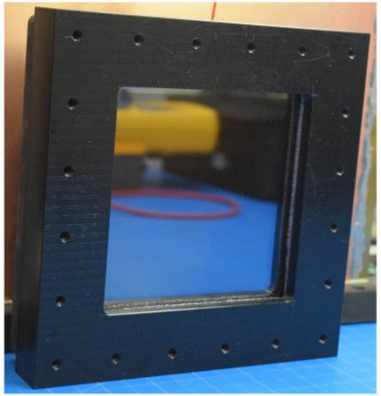
Photosensor development

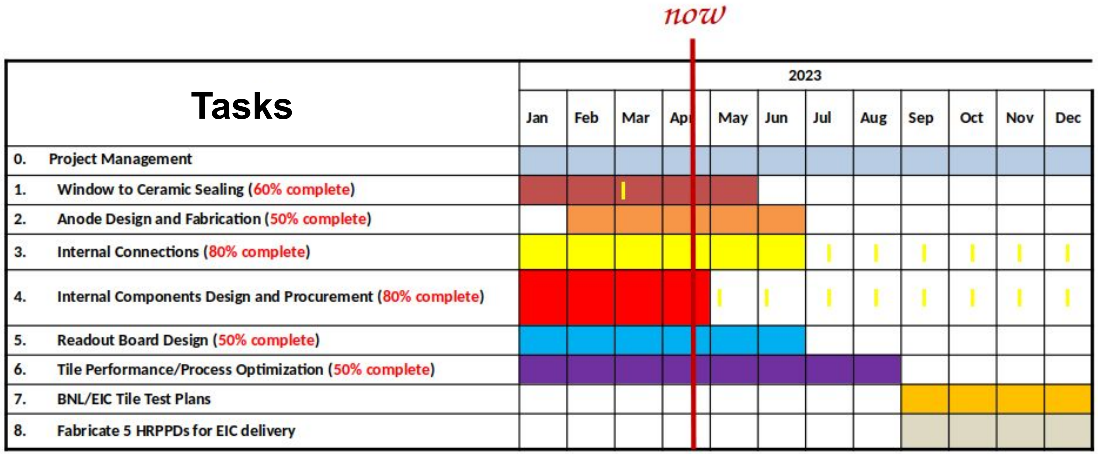
developing HRPPD with Incom Inc. as part of the eRD110 (photosensors) consortium activities











Tasks	2023											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0. Project Management	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
1. Window to Ceramic Sealing (60% complete)	🟥	🟥	🟥 ǀ	🟥	🟥							
2. Anode Design and Fabrication (50% complete)		🟧	🟧	🟧	🟧	🟧						
3. Internal Connections (80% complete)	🟨	🟨	🟨	🟨	🟨	🟨	ǀ	ǀ	ǀ	ǀ	ǀ	ǀ
4. Internal Components Design and Procurement (80% complete)	🟥	🟥	🟥	🟥	ǀ	ǀ	ǀ	ǀ	ǀ	ǀ	ǀ	ǀ
5. Readout Board Design (50% complete)	🟦	🟦	🟦	🟦	🟦	🟦						
6. Tile Performance/Process Optimization (50% complete)	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪				
7. BNL/EIC Tile Test Plans									🟧	🟧	🟧	🟧
8. Fabricate 5 HRPPDs for EIC delivery									🟫	🟫	🟫	🟫

first five HRPPD tiles for the EIC to be produced by Incom in 2023

after the final round of design modifications
manufacturing expected to start in August

Front-end ASIC

- **A standard requirement list**
  - Provide timing resolution <20ps and amplitude measurement
  - Work with collected charge from few dozens to few hundred fC
  - Work with a relatively high detector capacitance up to 10 pF
  - Have high channel density (64 channels per ASIC and more) and few mW/ch power dissipation
  - Streaming mode

<u>Waveform digitizer (by Nalu Scientific)</u>

- Pros
  - Expect higher timing resolution overall
  - Performance less affected by signal shape
- Cons
  - High expected power dissipation
  - None is readily available with a high channel density
  - Therefore realistically one should consider more space

<u>TOA/ADC (by OMEGA group)</u>

- Pros
  - EICROC is supported by the EIC project
  - Expected power dissipation <3mW/ch
  - Should work with HRPPDs at a lower gain
  - Should provide <20ps timing for C_d ~ 5pF
- Cons
  - Assumes signals have a “regular” shape

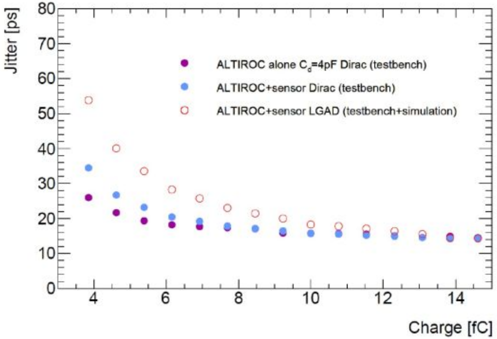
Front-end ASIC

- **A standard requirement list**
  - Provide timing resolution <20ps and amplitude measurement
  - Work with collected charge from few dozens to few hundred fC
  - Work with a relatively high detector capacitance up to 10 pF
  - Have high channel density (64 channels per ASIC and more) and few mW/ch power dissipation
  - Streaming mode

- **pfRICH ASIC choice: EICROC by OMEGA group**
  - Meets the overall requirements
  - Will be available in 256+ channel configuration
  - Will be developed for ePIC AC-LGADs anyway

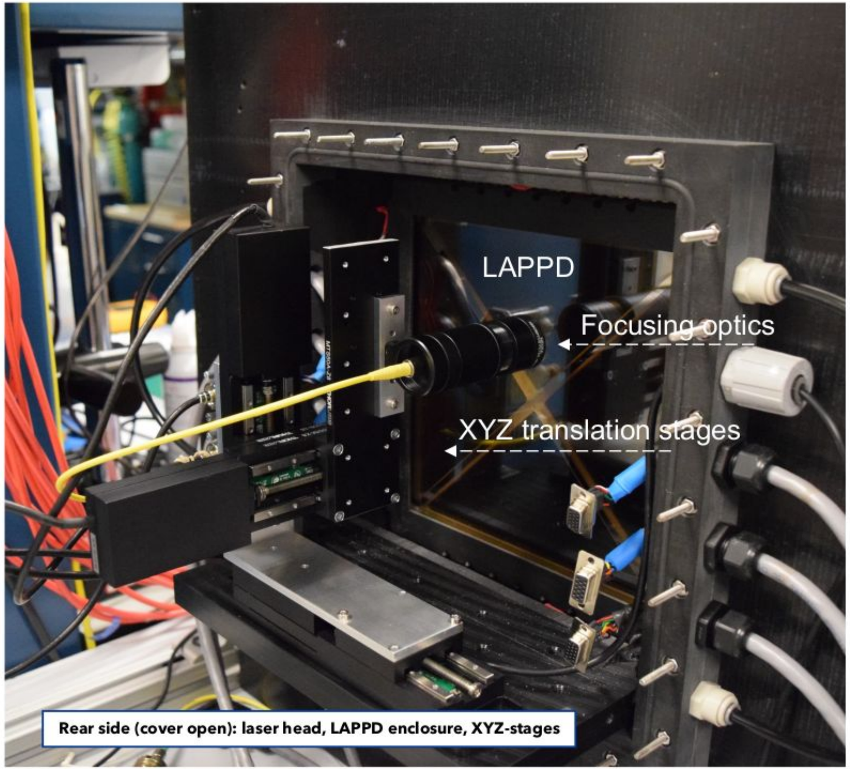
One pixel design

- Preamp, discri taken from ATLAS ALTIROC
- I2C slow control taken from CMS HGCROC
- TOA TDC adapted by IRFU Saclay
- ADC adapted to 8bits by AGH Krakow
- Digital readout : FIFO depth 8 (200 ns)



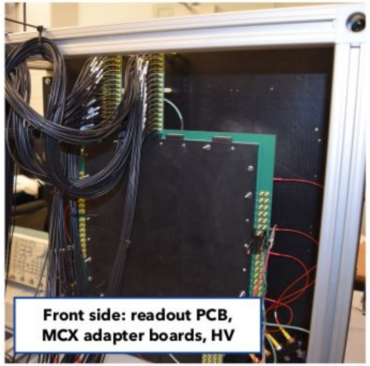
- 16 channels COB
- Sensor : AC LGAD Cd~1 pF
- Dyn range 0.3 fC to 100 fC
- Noise : 0.3 fC
- TOA Min threshold ~4 fC (Cd=4 pF)
- Time walk ~0.7 ns (Cd=4 pF)
- Jitter ~100 ps/Q(fC) (Cd=4 pF)
- Pd = 3 mW/ch

Test bench setup at BNL

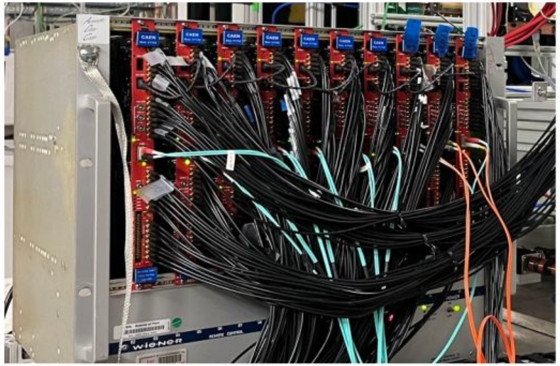


Rear side (cover open): laser head, LAPPD enclosure, XYZ-stages

- Picosecond PiLas laser
- Coming soon: Menlo Systems femtosecond laser
- Compact light-tight enclosure
- 512 DRS4 channels (V1742 digitizers)
- MCX to high-density Samtec adapter cards
- 8 GHz analogue bandwidth 50 GS/s scope

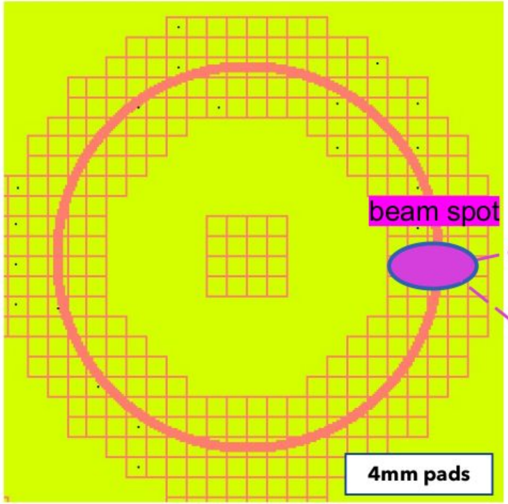


Front side: readout PCB, MCX adapter boards, HV

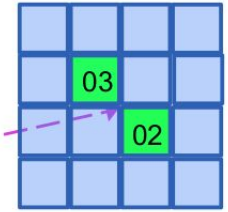


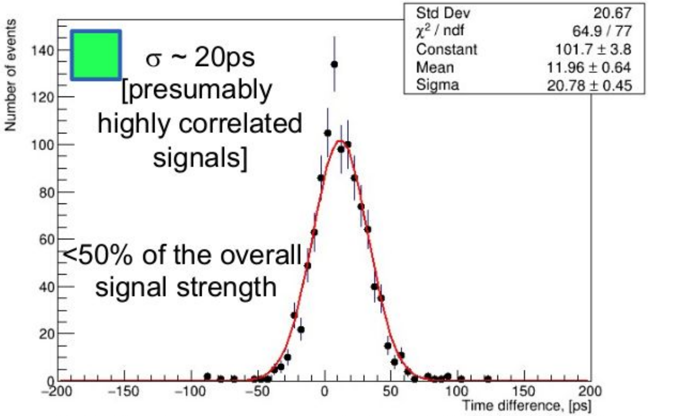
Similar type of equipment exists at INFN Trieste

Best tests at Fermilab (BNL & co.)



Event selection (A)



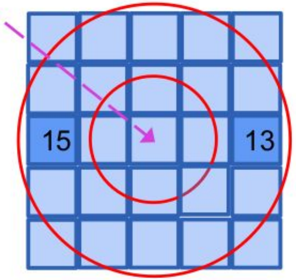


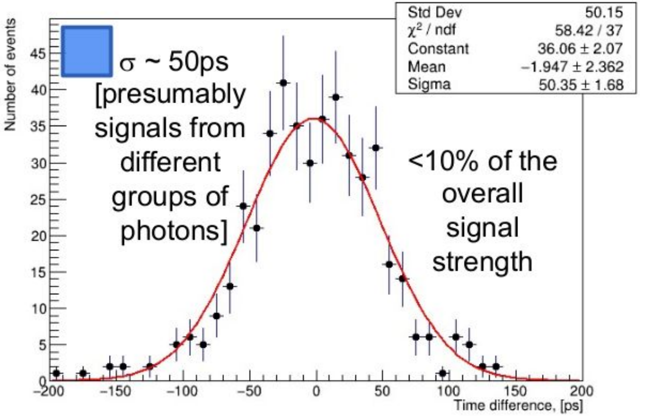
🟩 σ ~ 20ps [presumably highly correlated signals]

<50% of the overall signal strength

DRS4 chip#0: time(ch#03) – time(ch#02

Event selection (B)





🟦 σ ~ 50ps [presumably from signals from different groups of photons]

<10% of the overall signal strength

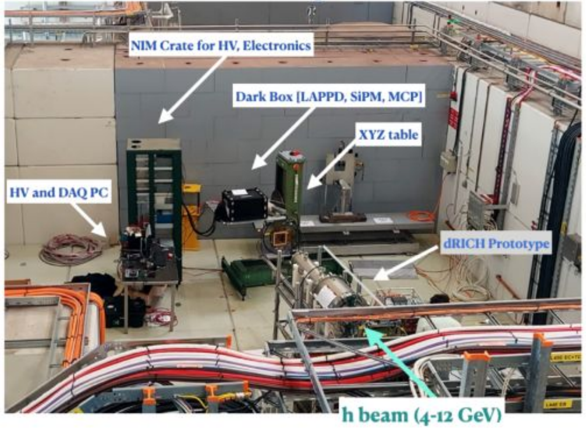
DRS4 chip#1: time(ch#15) – time(ch#13

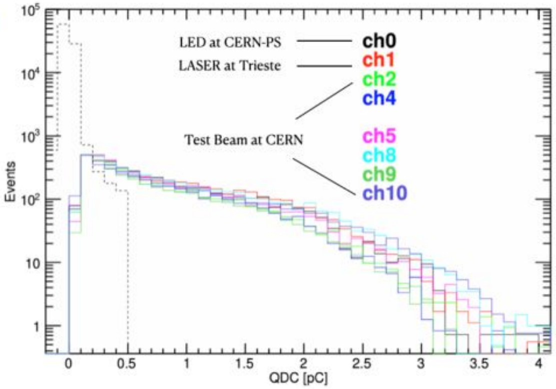
- *Single* photon TTS <50 ps
- 5mm thick UV grade quartz window: a 120 GeV proton produces a **blob of ~100 p.e.'s**

Due to the TIR, photons only hit the PC in a radial band ~[5.5 .. 12.0] mm

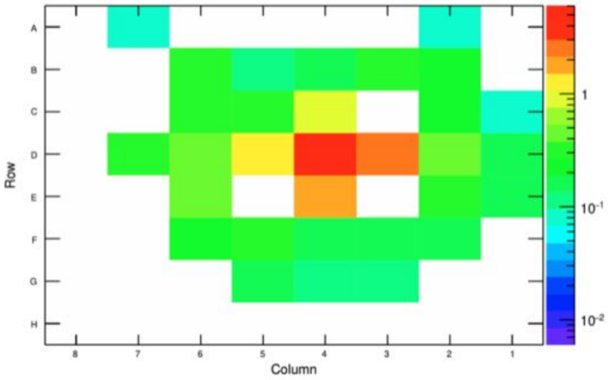
Best tests at CERN (INFN TS,GE & co.)

First Beam Test of LAPPD in parasitic mode at CERN-PS

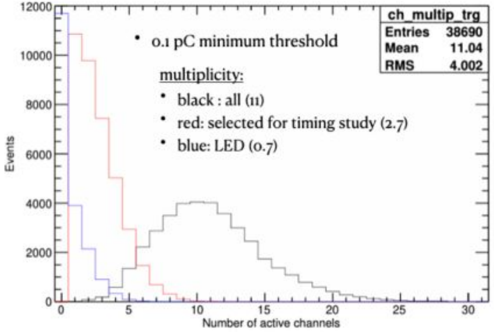




- Primary charge-spectra calibration in SPE is performed.



- Average charge collected in the Ring is lower that the SPE .

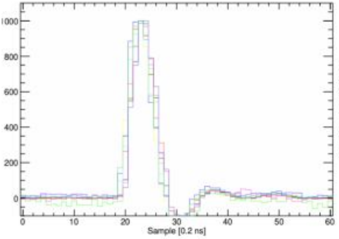


- 0.1 pC minimum threshold

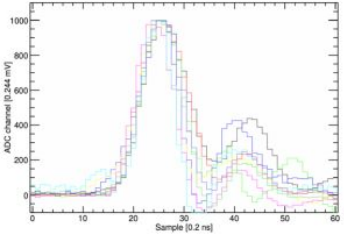
multiplicity:

- black : all (11)
- red: selected for timing study (2.7)
- blue: LED (0.7)

- Central Pad was flooded
- Only 24% of the hits were selected for timing

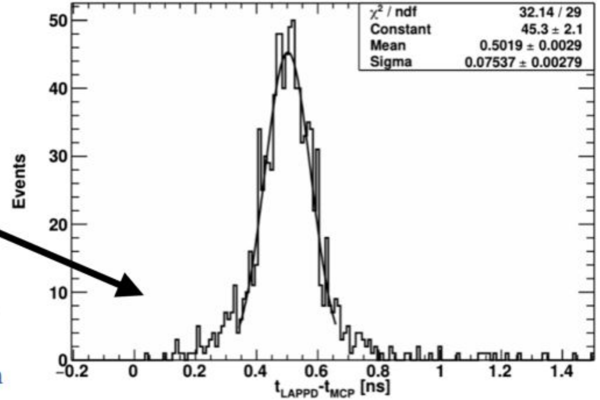


- Digitised MCP signal



- Digitised LAPPD signal

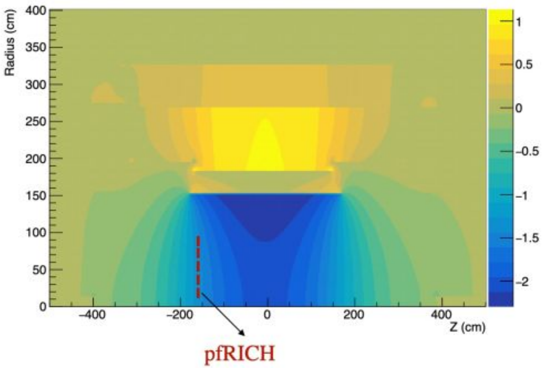
- The time difference is fitted by a Gaussian within 2σ
- The mean of 0.5 ns agrees with a preliminary GEAN4 simulation
- The obtained σ varies within 80-130 ps, within <10 ps error
- The best resolution found in Channel 2 is 75 +-3 ps

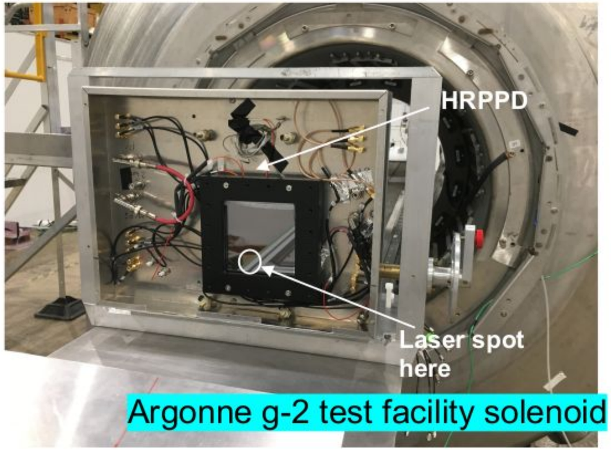


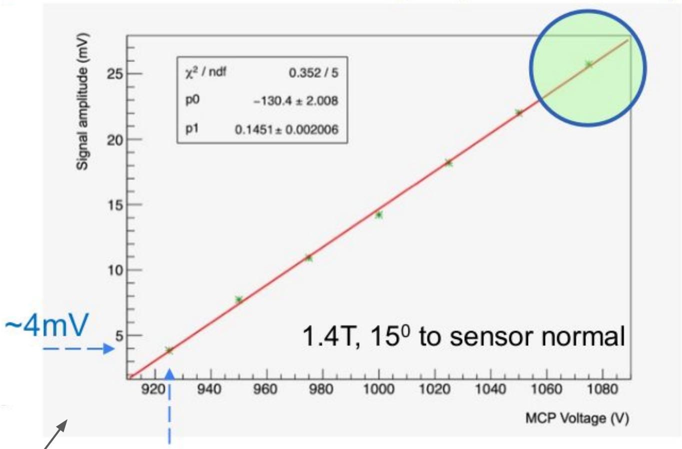
- Timing difference between channel 2 and MCP

HRPPD tests in magnetic field

ePIC solenoid magnetic field (Tesla) in **Z direction**;



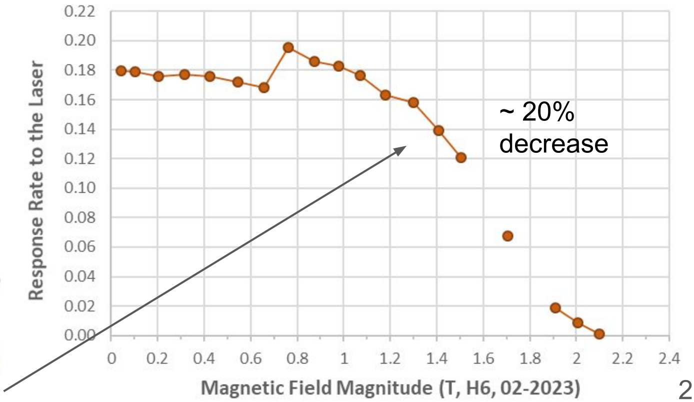




Nominal HV to achieve 25mV signals at B=0T

- ➢ In ePIC pfRICH HRPPDs will be exposed to a magnetic field of ~1.4 Tesla at an angle up to 12.6 degrees
- ➢ Tests of a HRPPD prototype in a high magnetic field were carried out by Argonne and Incom using g-2 calibration solenoid
- ➢ Data analysis by eRD110 members of pfRICH team

Preliminary conclusion: gain in this high magnetic field can be fully restored by increasing HV from 925V to ~1075V

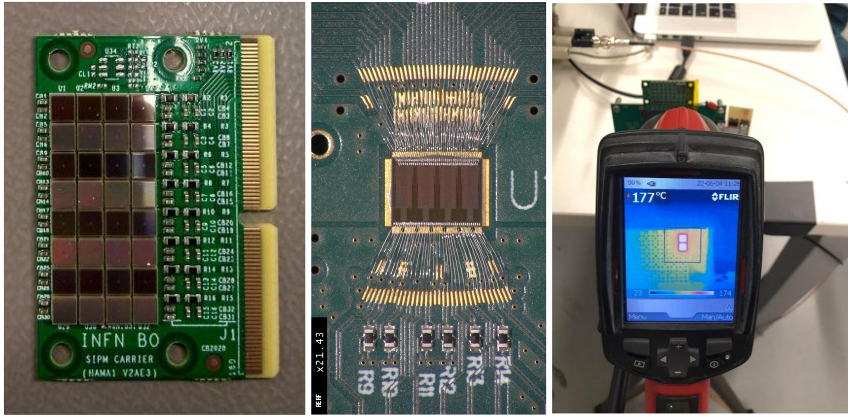


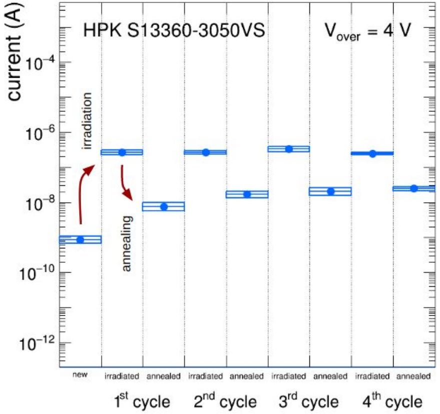
Detection efficiency decrease with increasing magnetic field strength

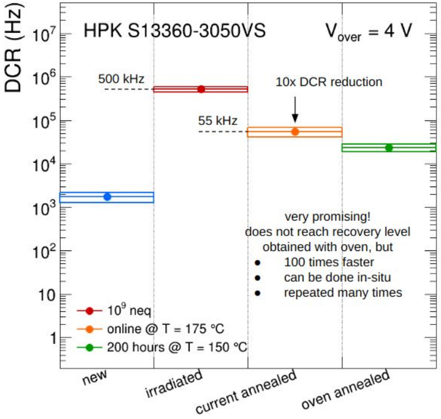
Photosensors – SiPM

magnetic-field insensitive and cheap solution for the dRICH

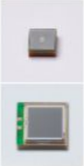
- **pros**
    - cheap
    - high photon efficiency
    - excellent time resolution
    - insensitive to B field
- **cons**
    - large DCR, ~ 50 kHz/mm^2 @ T = 24 °C
    - not radiation tolerant
        - moderate fluence < 10^{11} n_{eq}/cm^2
- **R&D on mitigation strategies**
    - reduce DCR at low temperature
        - operation at T = -30 °C (or lower)
    - recover radiation damage
        - in-situ high-temperature annealing
    - exploit timing capabilities
        - with ALCOR (INFN) front-end chip



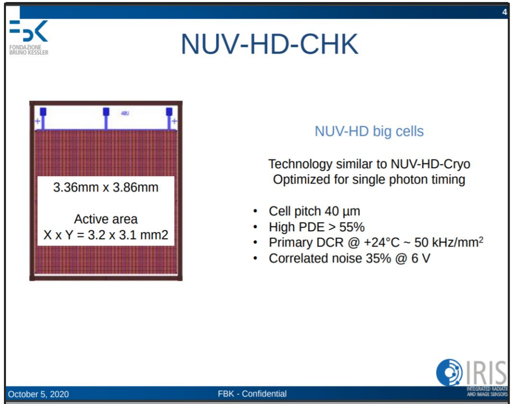




Commercial SiPM sensors and FBK prototypes



board	sensor	uCell (μm)	V_{bd} (V)	PDE (%)	DCR (kHz/mm^2)	window	notes
HAMA1	S13360 3050VS	50	53	40	55	silicone	legacy model Calvi et. al
	S13360 3025VS	25	53	25	44	silicone	legacy model smaller SPAD
HAMA2	S14160 3050HS	50	38	50		silicone	newer model lower V_{bd}
	S14160 3015PS	15	38	32	78	silicone	smaller SPADs radiation hardness
SENSL	MICROFJ 30035	35	24.5	38	50	glass	different producer and lower V_{bd}
	MICROFJ 30020	20	24.5	30	50	glass	the smaller SPAD version
BCOM	AFBR S4N33C013	30	27	43	111	glass	commercially available FBK-NUVHD



4

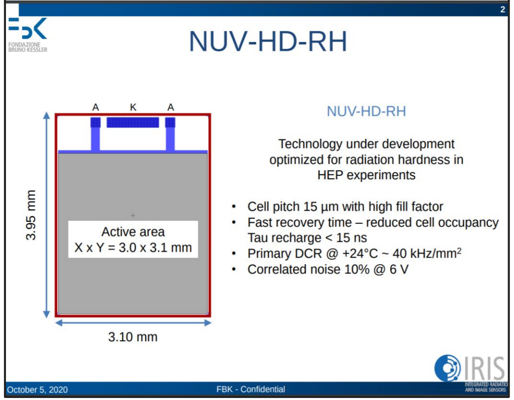
NUV-HD-CHK

NUV-HD big cells

Technology similar to NUV-HD-Cryo
Optimized for single photon timing

- Cell pitch 40 μm
- High PDE > 55%
- Primary DCR @ +24°C ~ 50 kHz/mm^2
- Correlated noise 35% @ 6 V

October 5, 2020 FBK - Confidential



2

NUV-HD-RH

NUV-HD-RH

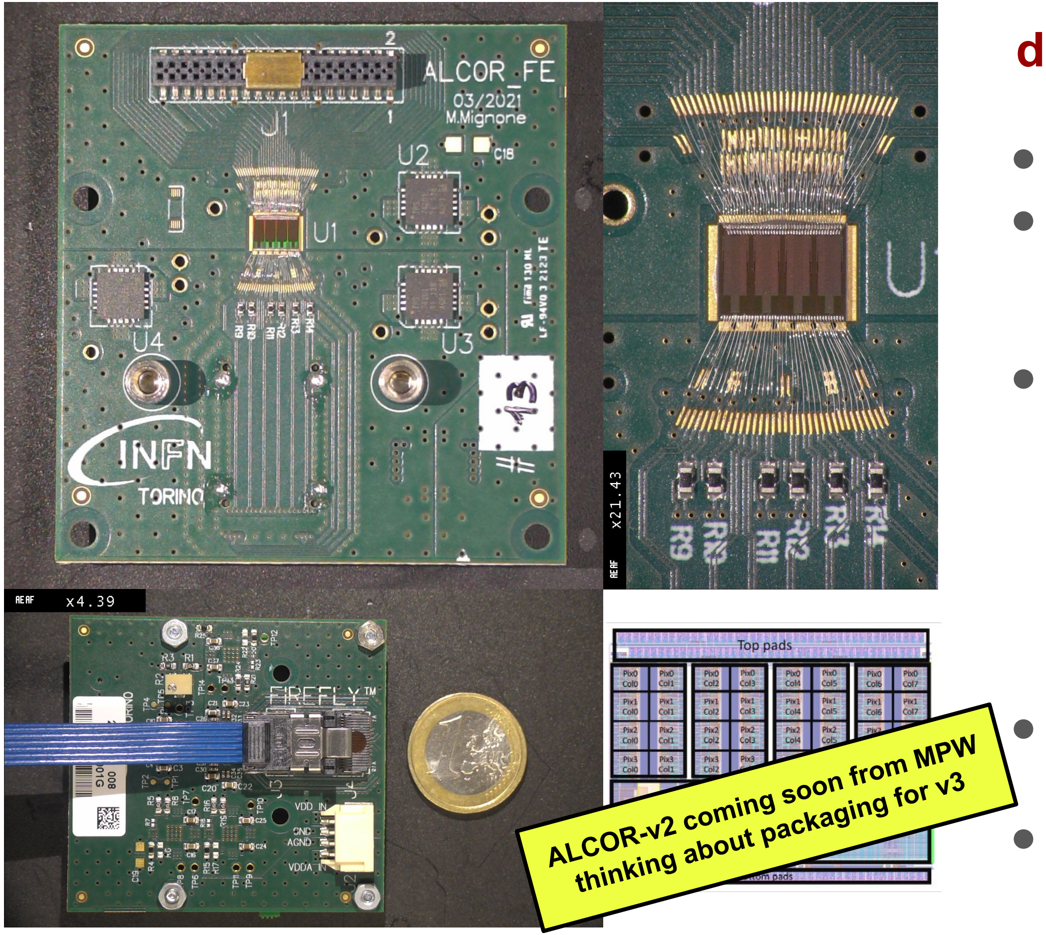
Technology under development
optimized for radiation hardness in
HEP experiments

- Cell pitch 15 μm with high fill factor
- Fast recovery time – reduced cell occupancy Tau recharge < 15 ns
- Primary DCR @ +24°C ~ 40 kHz/mm^2
- Correlated noise 10% @ 6 V

October 5, 2020 FBK - Confidential

multiple producers: different technologies, SPAD dimensions, V_{bd}, electric field …

ALCOR: A Low Power Chip for Optical sensor Readout

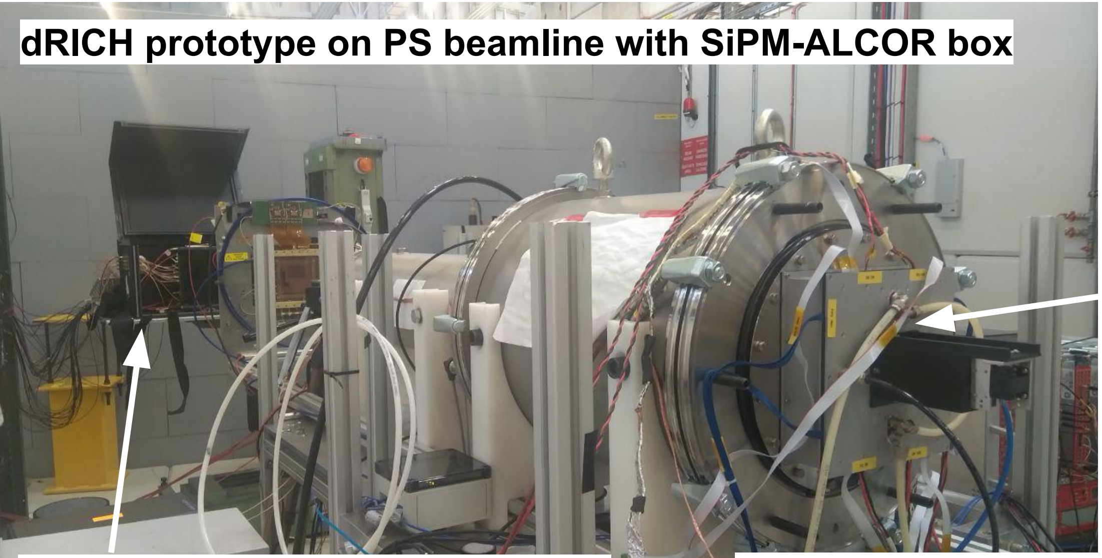


ALCOR-v2 coming soon from MPW
thinking about packaging for v3

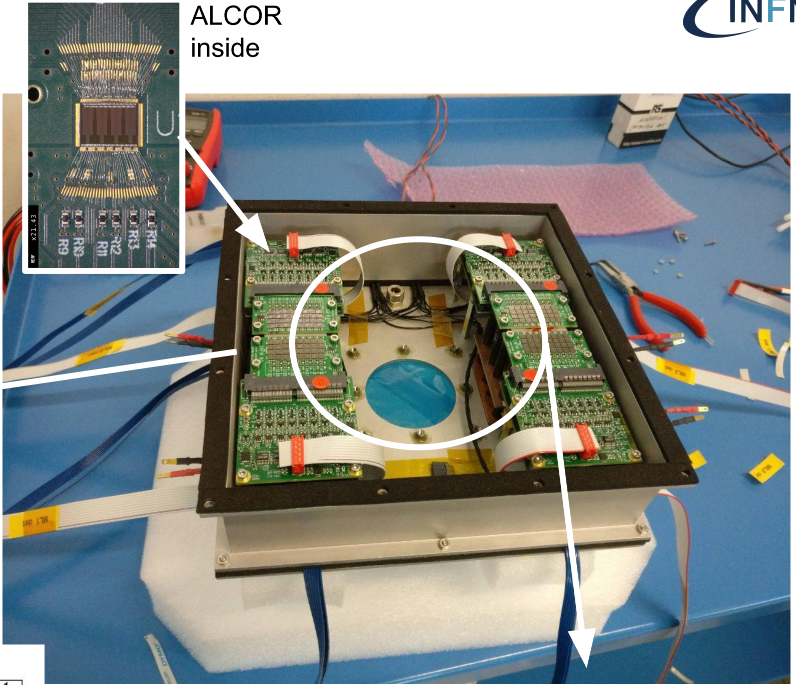
developed by INFN-TO for DarkSide

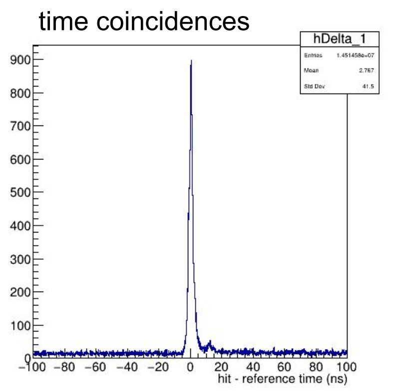
- 32-pixel matrix mixed-signal ASIC
- the chip performs
  - signal amplification
  - conditioning and event digitisation
- each pixel features
  - dual-polarity front-end amplifier
    - low input impedance
    - 4 programmable gain settings
  - 2 leading-edge discriminators
  - 4 TDCs based on analogue interpolation
    - 25 ps LSB (@ 320 MHz)
- single-photon time-tagging mode
  - also with Time-Over-Threshold
- fully digital output
  - 4 LVDS TX data links

2022 test beam at CERN-PS

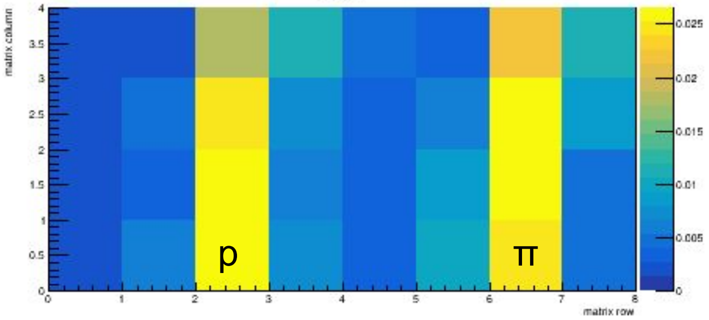

dRICH prototype on PS beamline with SiPM-ALCOR box

beamline shared with LAPPD test


ALCOR
inside

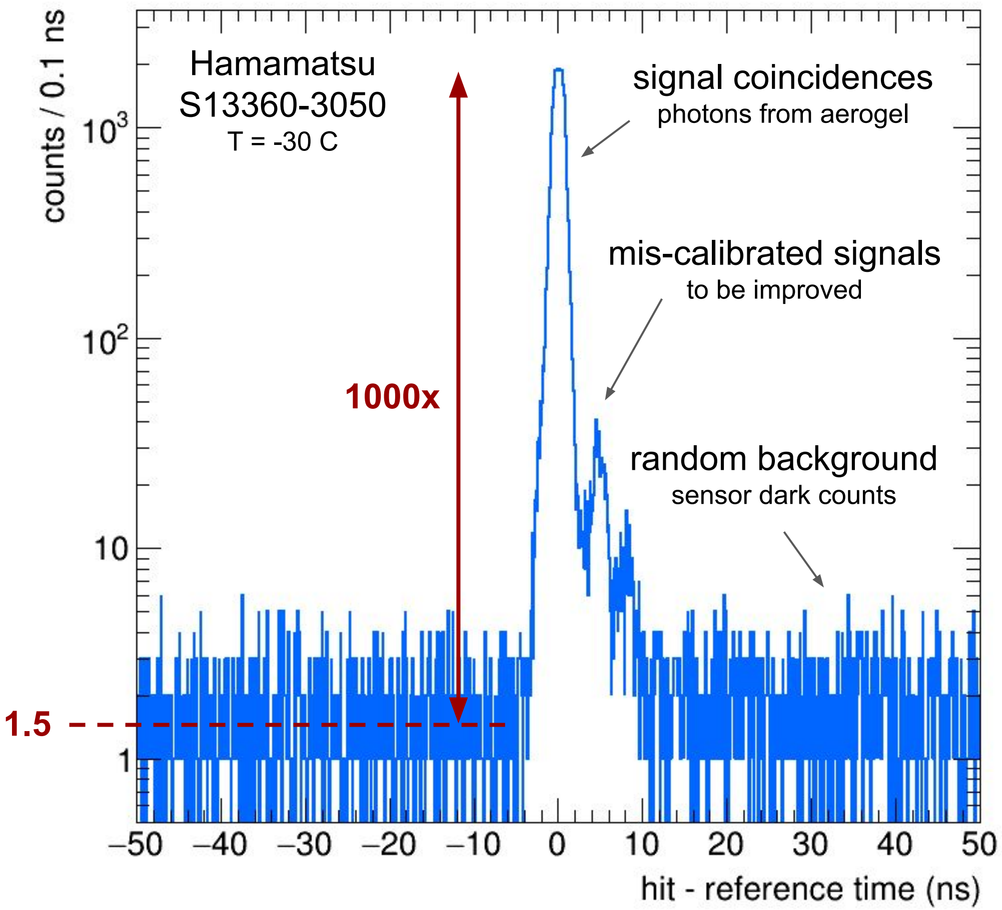

time coincidences

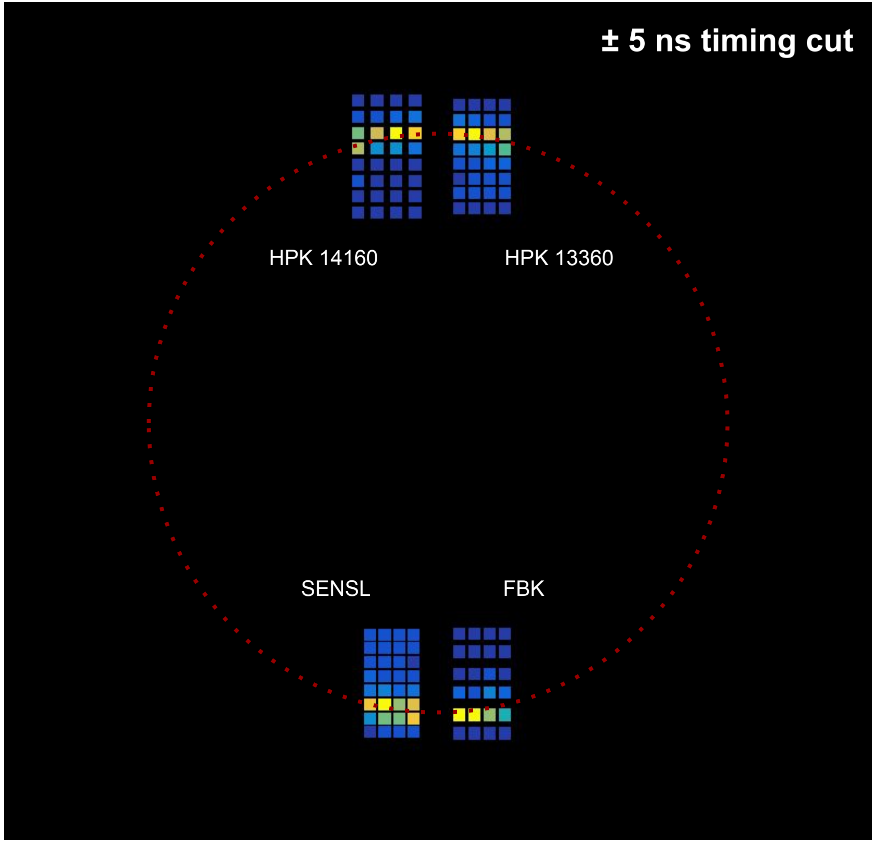
8 GeV positive beam (aerogel rings)



successful operation of SiPM <u>irradiated</u> (with protons up to 10^{10}) and <u>annealed</u> (in oven at 150 C)

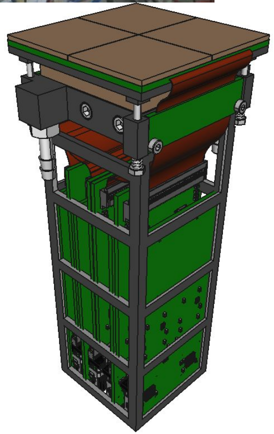
after irradiation with $2\cdot10^{9}$ n_{eq}/cm^{2} fluence (protons)
and oven annealing at T = 150 C for 150 hours



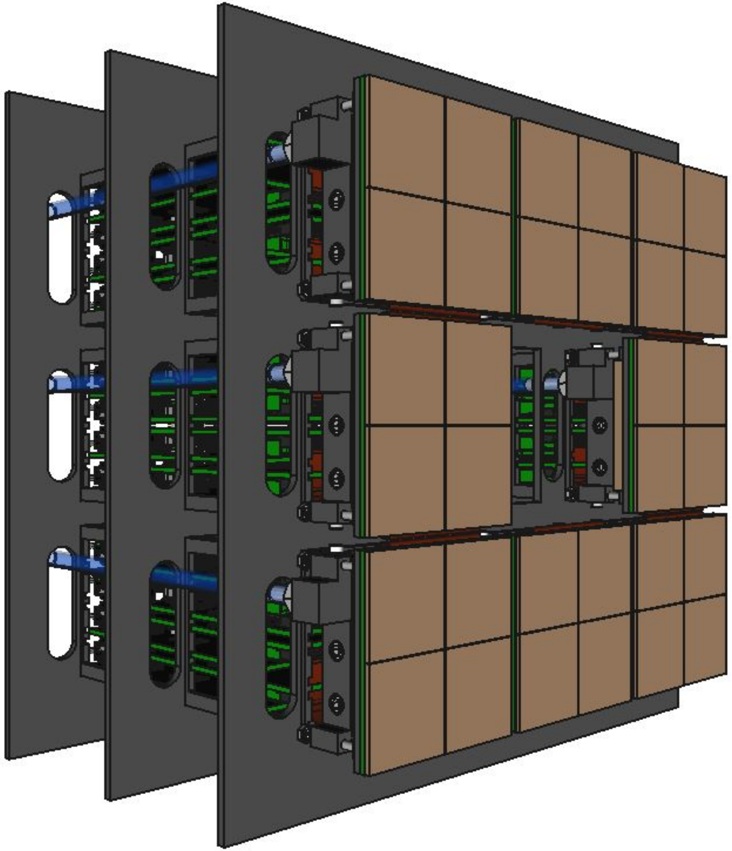


sensor DCR ~ 15 kHz

developing mechanical layout, readout electronics for SiPM-ALCOR-based dRICH prototype



new SiPM readout unit based on
Hamamatsu S13360-3050 arrays
integrated with cooling and electronics



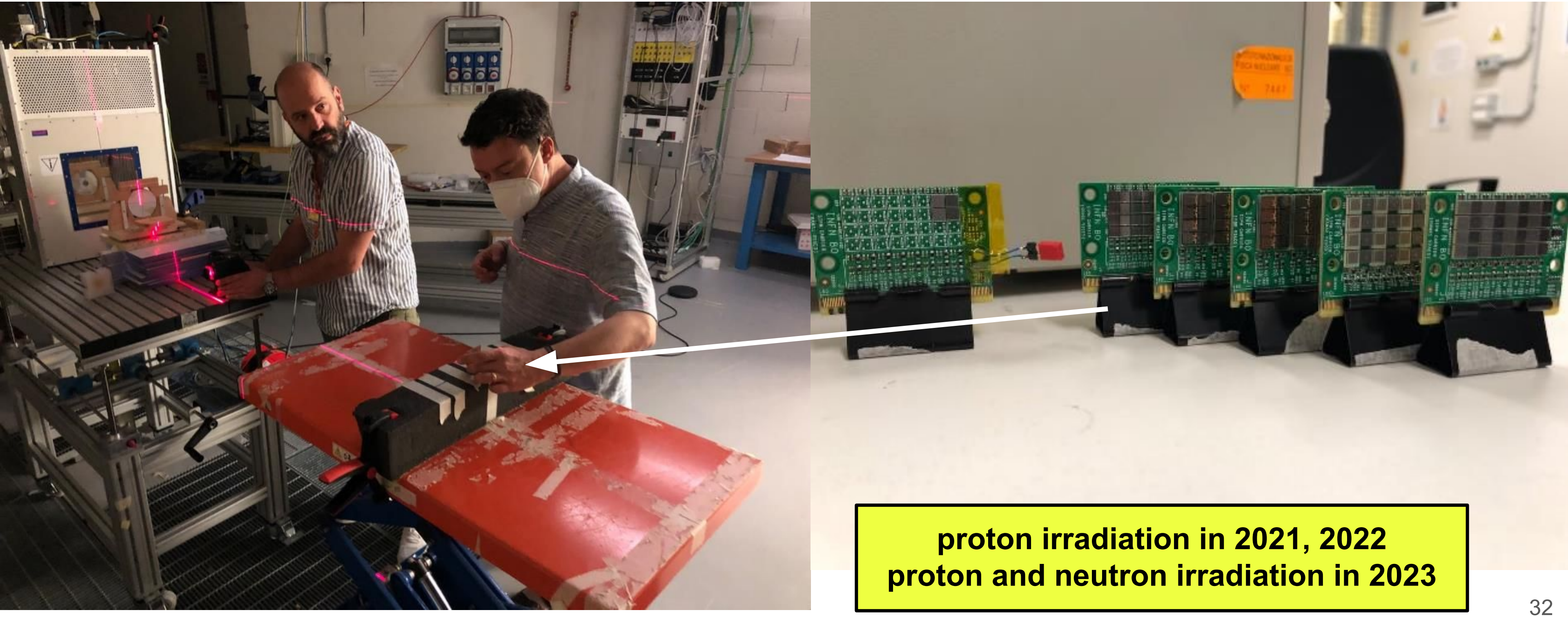
dRICH beam tests in August and October
(with ALICE RICH) at CERN

Irradiation at Trento Proton-Therapy hall (TIFPA)

3x3 mm^2 SiPM sensors
4x8 “matrix” (carrier board)

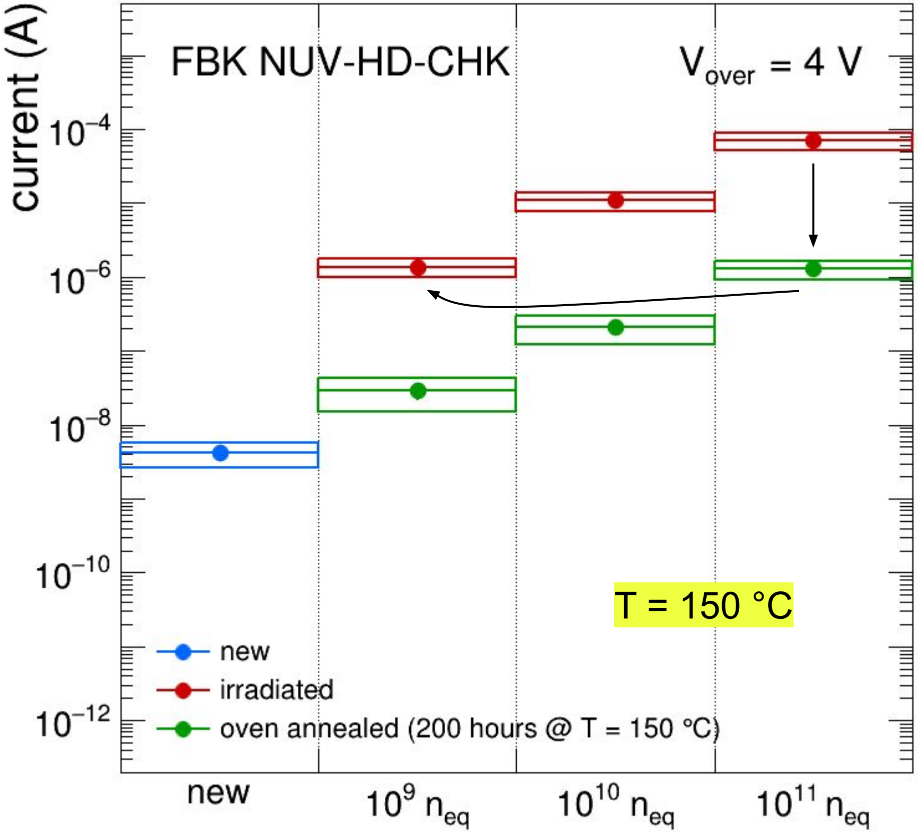
multiple types of SiPM: **Hamamatsu** commercial (13360 and 14160)
FBK prototypes (rad.hard and timing optimised)

148 MeV protons → scattering system → ~~collimation system~~ → carrier board



proton irradiation in 2021, 2022
proton and neutron irradiation in 2023

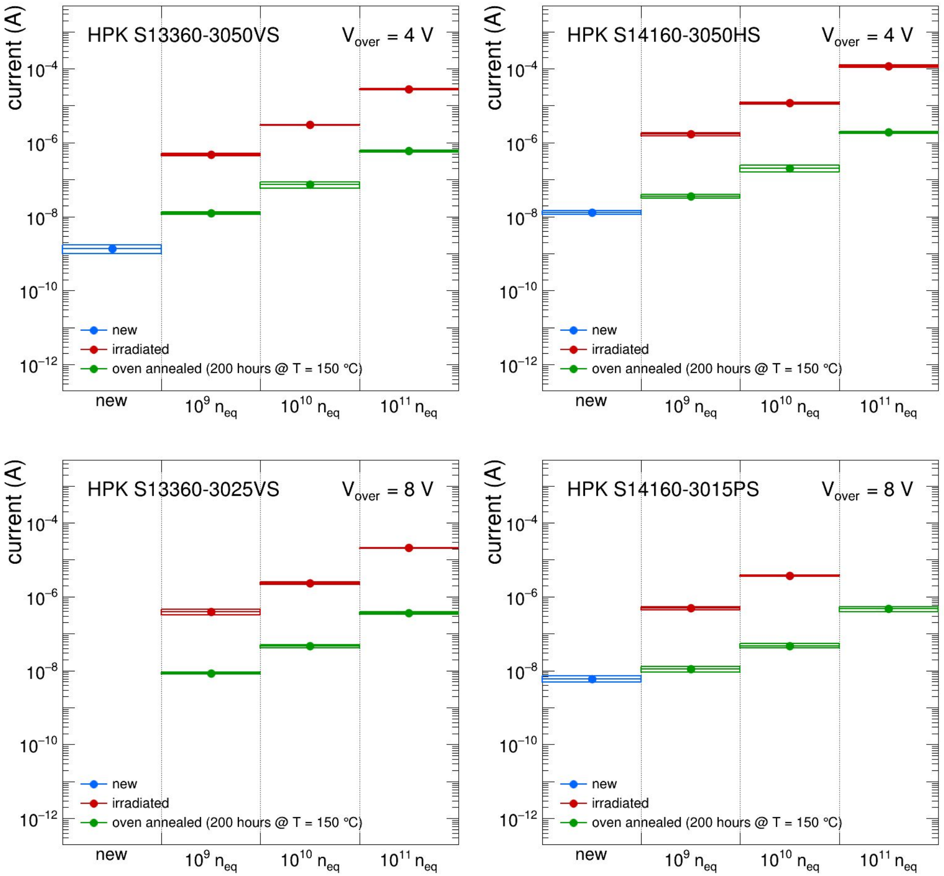
High-temperature annealing recovery



T = 150 °C

~ 100x current reduction

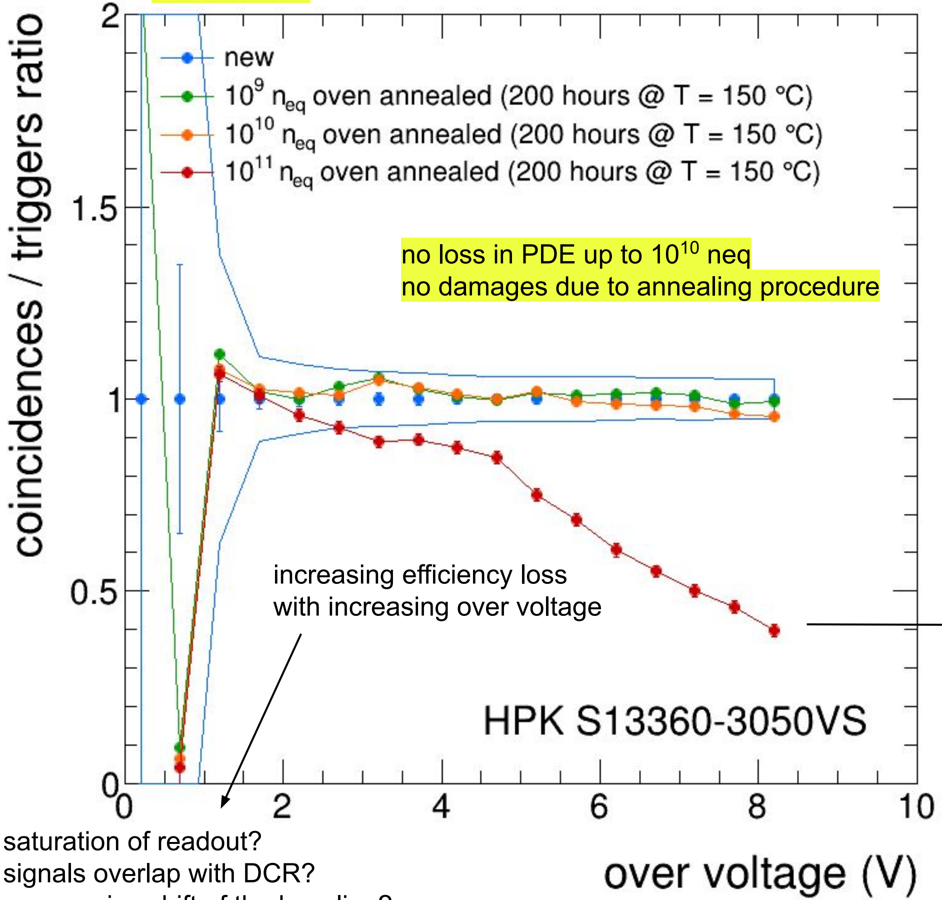
sensor functions as if it received ~ 100x less fluence



similar observation with different types of Hamamatsu sensors

Light response after irradiation and annealing

ratio wrt. new

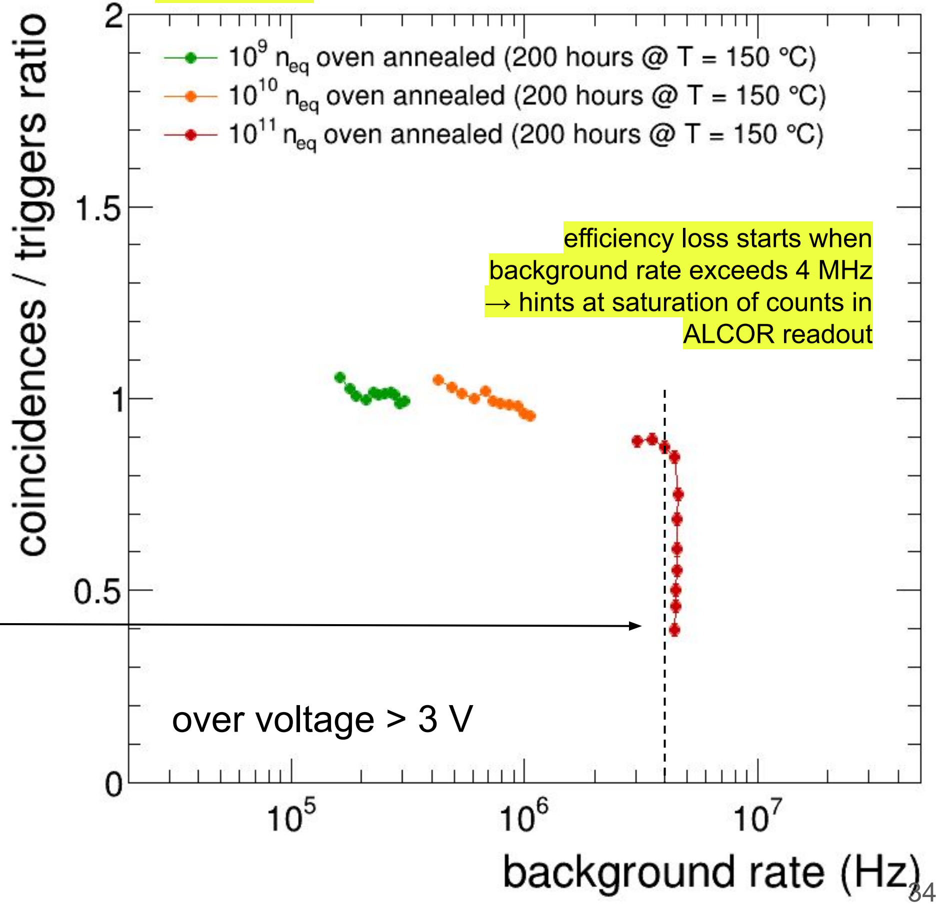


no loss in PDE up to 10^{10} neq
no damages due to annealing procedure

increasing efficiency loss
with increasing over voltage

saturation of readout?
signals overlap with DCR?
progressive shift of the baseline?

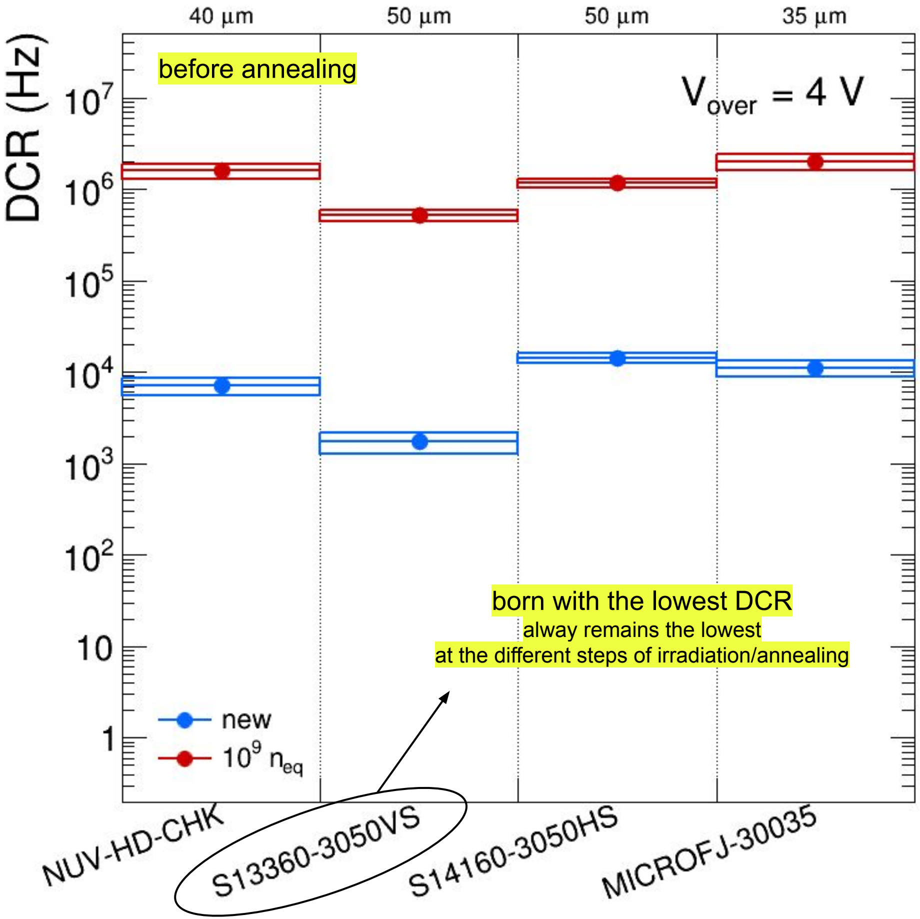
ratio wrt. new



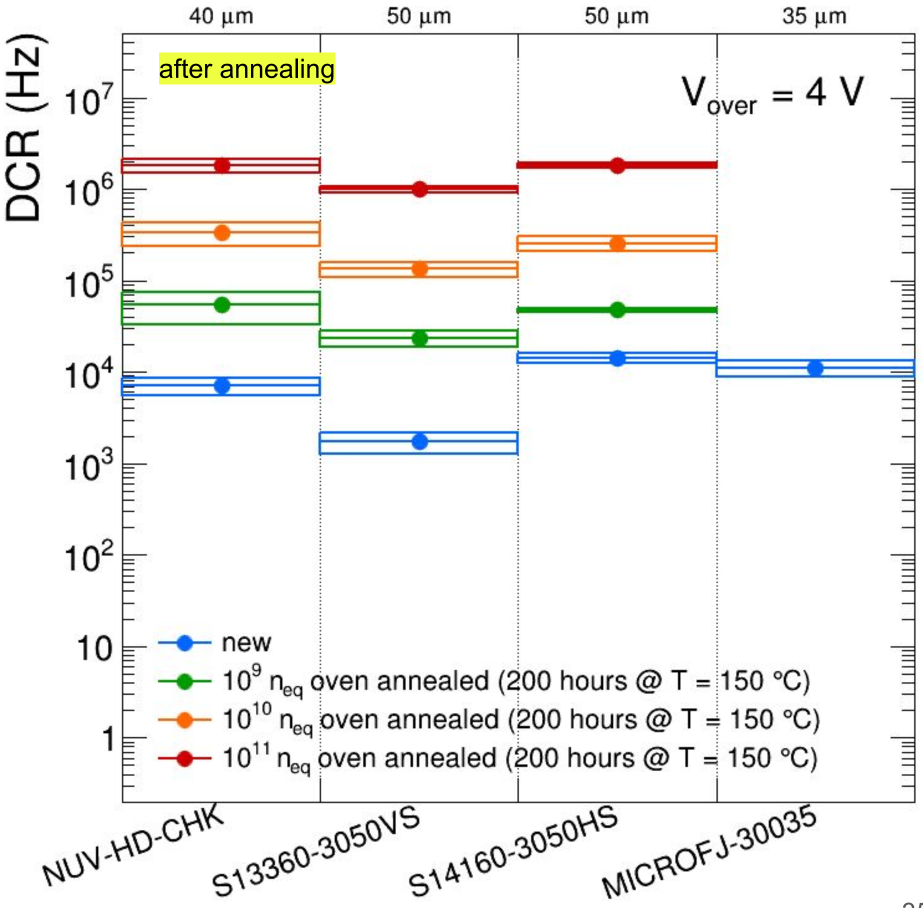
efficiency loss starts when
background rate exceeds 4 MHz
→ hints at saturation of counts in
ALCOR readout

over voltage > 3 V

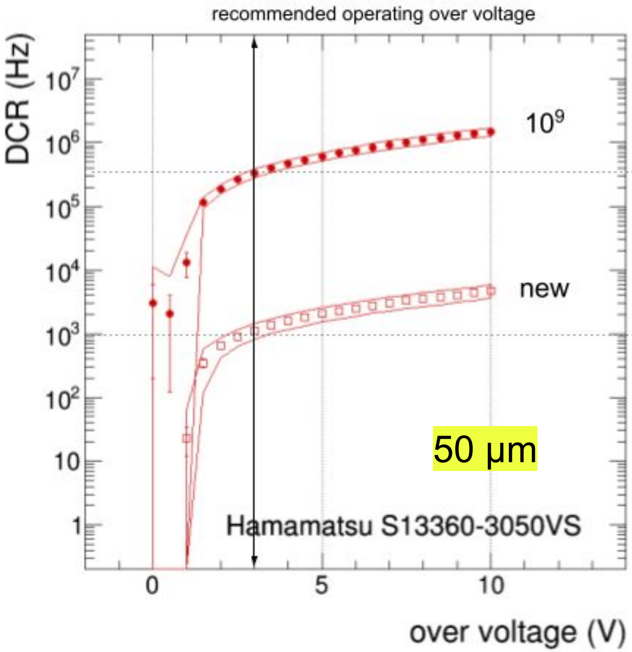
DCR after irradiation and annealing

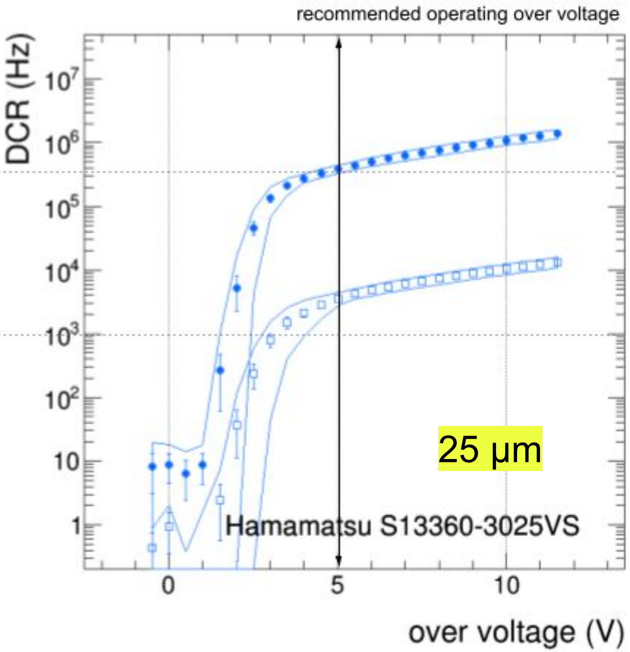


born with the lowest DCR
alway remains the lowest
at the different steps of irradiation/annealing



Small vs. large SPAD sensors





sensors with small SPADs have lower SNR

also after irradiation

not radiation harder for what concerns DCR increase

- **sensors operated at Hamamatsu recommended over-voltage**
  - [datasheet] 50 µm sensors have 40% PDE, 25 µm have 25%
  - [measured] 50 µm sensors have lower DCR than 25 µm when new
  - [measured] both sensors have similar DCR after irradiation

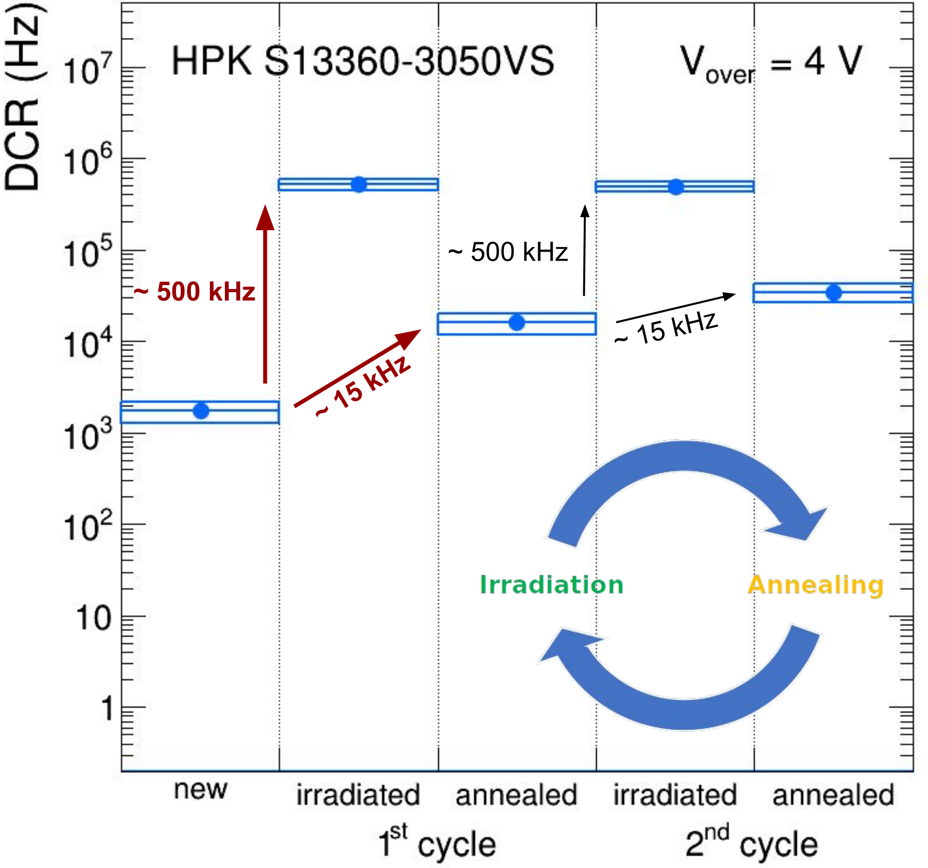
similar results obtained on SENSL sensors

SiPM custom boards for ongoing R&D

our results point towards large SPADs for RICH applications → must test 75 um

- **new SiPM carriers**
  - keep same boards designed in 2020
  - populate 3 rows
    - 4 sensors / row
  - sensors from Hamamatsu
    - 4x S13360-3050
    - 4x S14160-3050
    - 4x S13360-3075
- **perform different type of irradiation/annealing studies**
  - one carrier board for each study
- **keep a minimal statistical sample for each study**
  - 4 sensors / type

Repeated irradiation-annealing cycles



test reproducibility of repeated irradiation-annealing cycles

simulate a realistic experimental situation

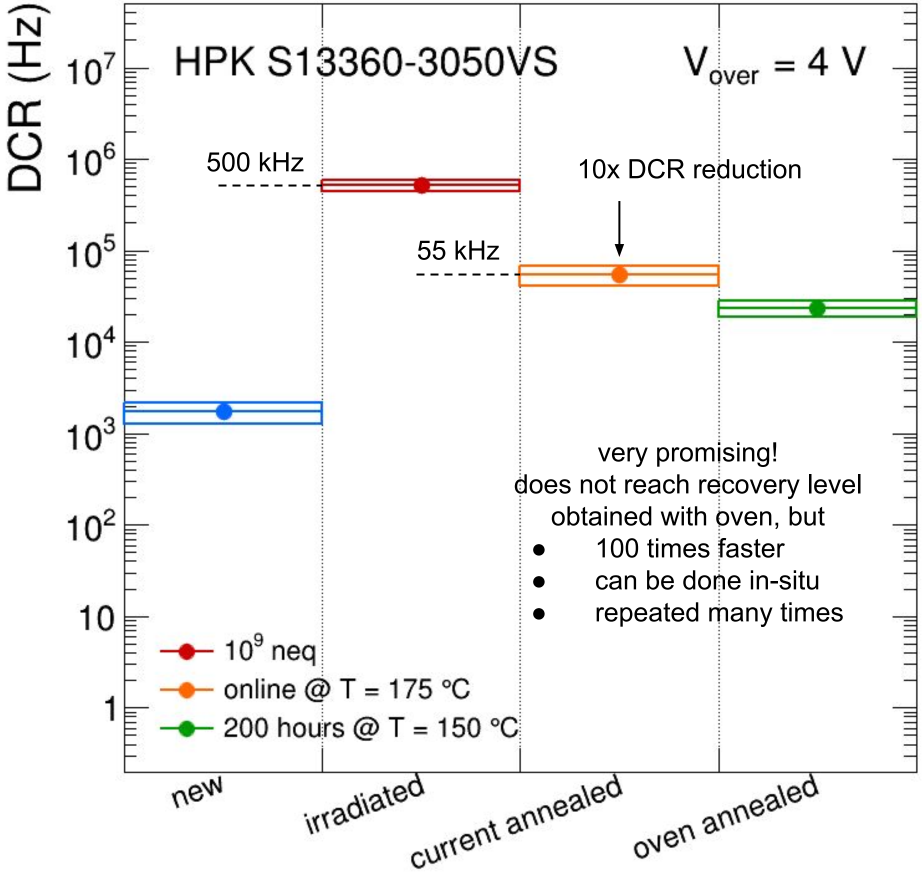
- consistent irradiation damage
  - DCR increases by ~ 500 kHz (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- consistent residual damage
  - ~ 15 kHz (@ Vover = 4) of residual DCR
  - builds up after each irradiation-annealing

annealing cures same fraction of newly-produced damage

~ 97% for HPK S13360-3050 sensors

Online annealing

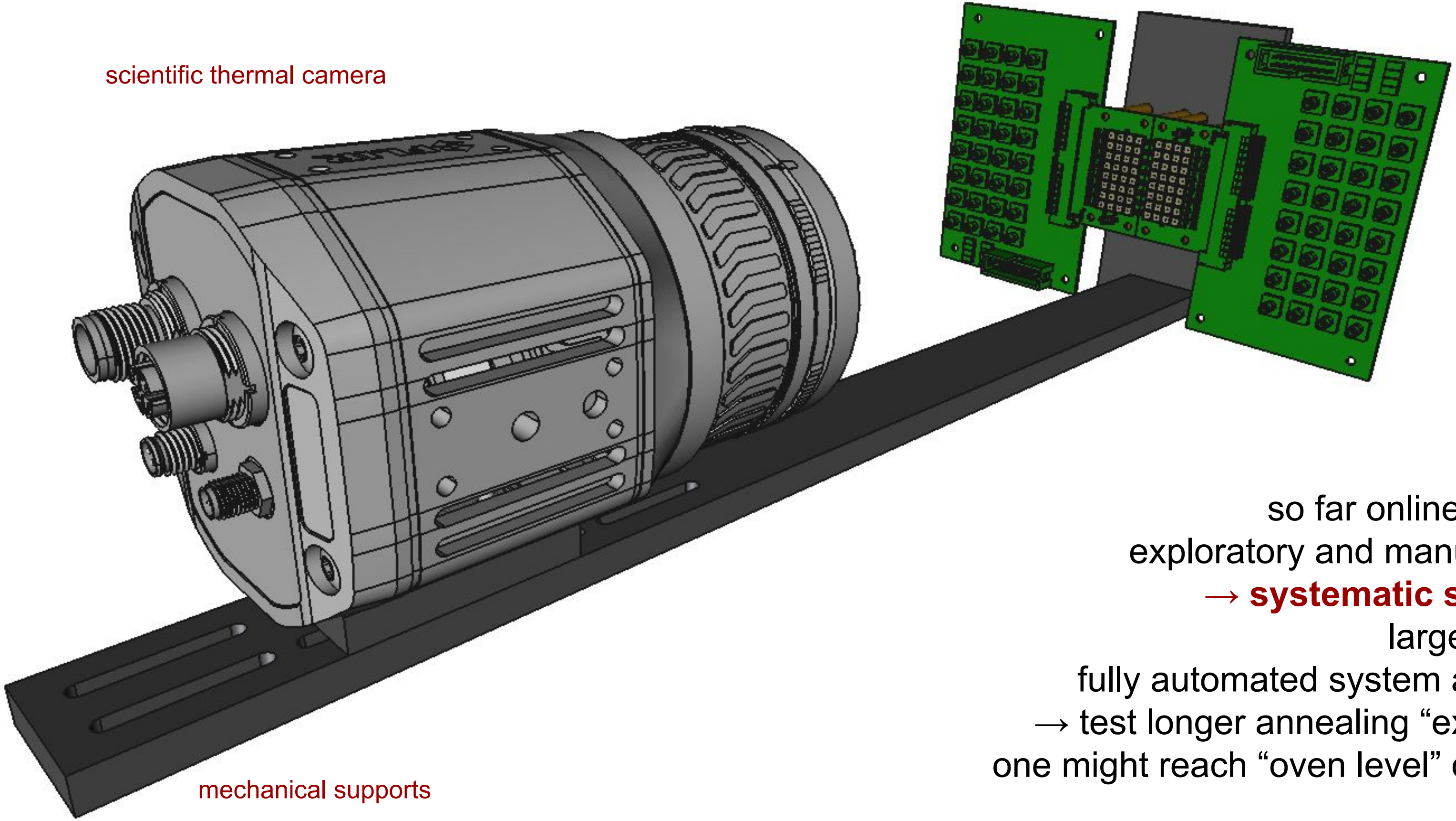
explore solutions for in-situ annealing



very promising!
does not reach recovery level obtained with oven, but

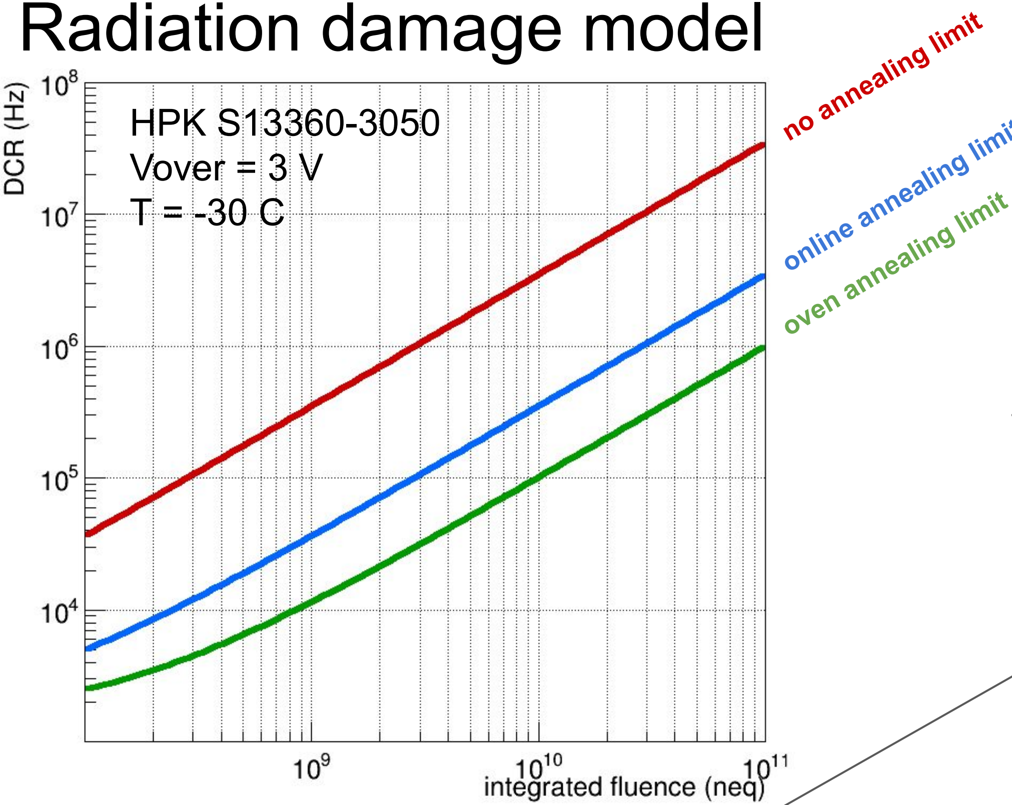
- 100 times faster
- can be done in-situ
- repeated many times

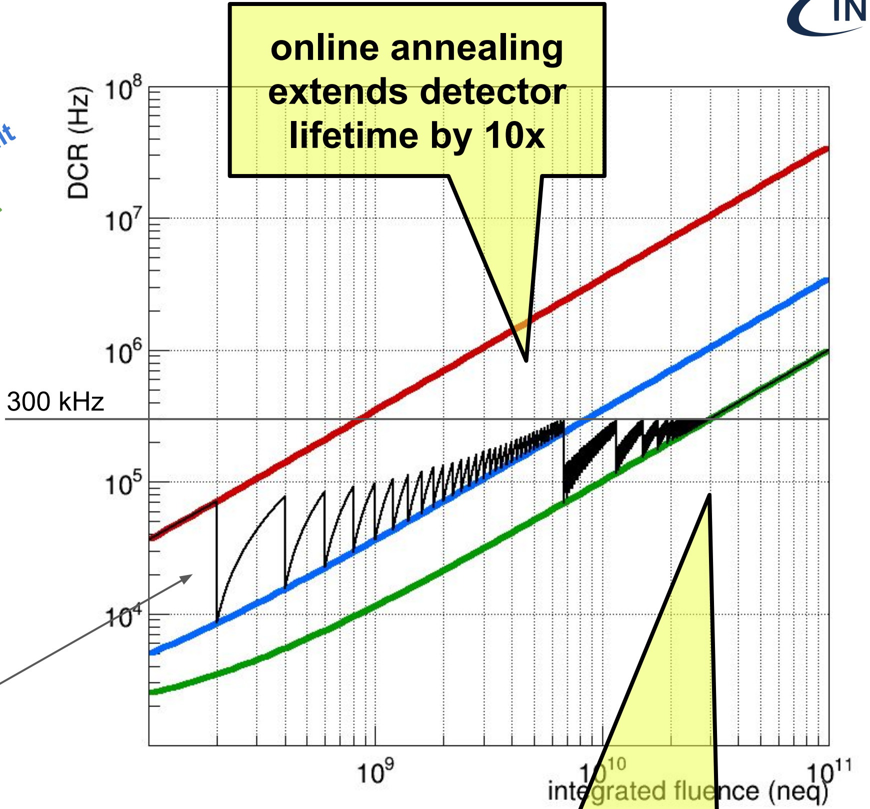
Automated multiple SiPM online annealing



so far online annealing was
exploratory and manually performed
→ **systematic studies in 2023**
larger SiPM sample
fully automated system and procedures
→ test longer annealing “exposition” times
one might reach “oven level” cure of damage

Radiation damage model





online annealing extends detector lifetime by 10x

after several years of operation one might need/want to upgrade with new SiPM technology

online annealing every 2 10^8 neq (many times)
oven annealing when DCR > 300 kHz (few times)

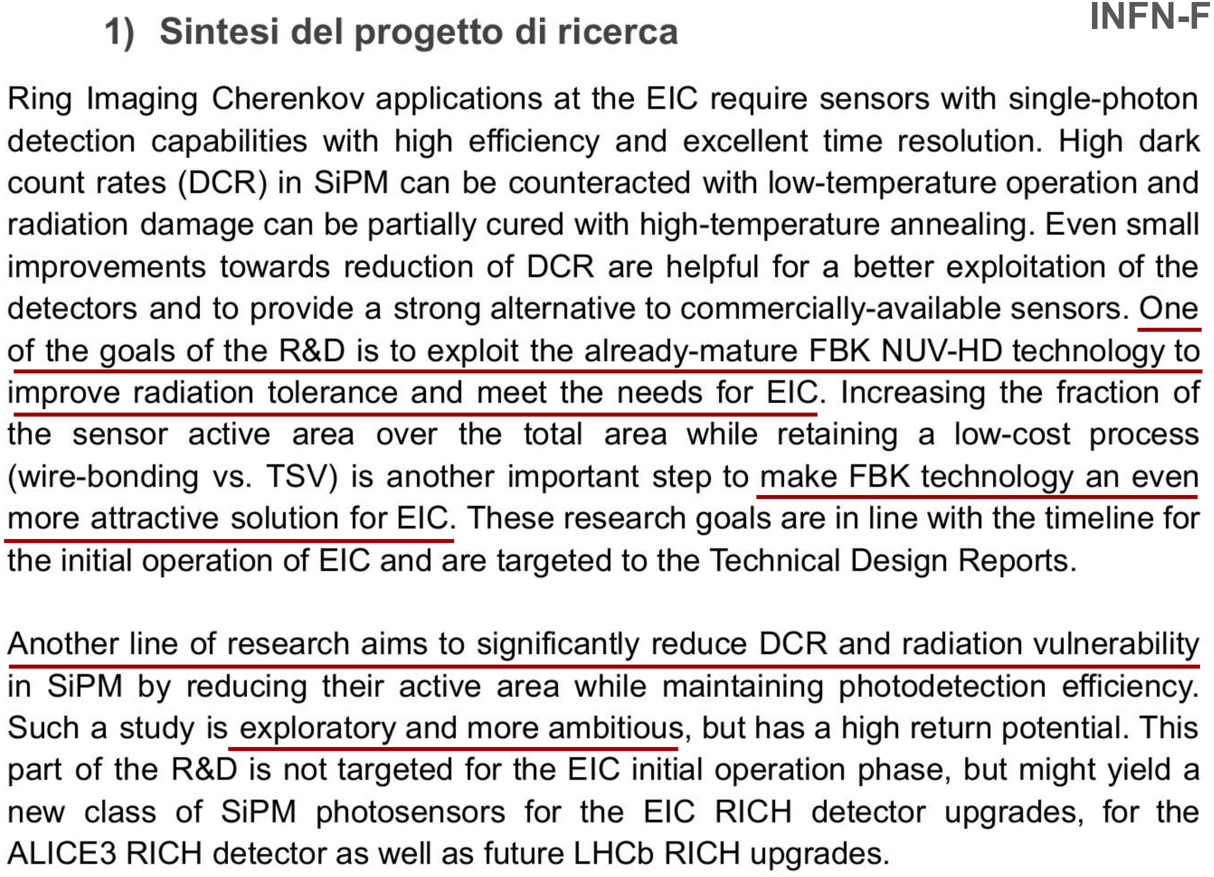
this is a potential scenario, R&D studies and data collection is ongoing

SiPM run with FBK

sipm4eic project

funded and approved within
INFN-FBK Collaboration agreement

start of run October 2023



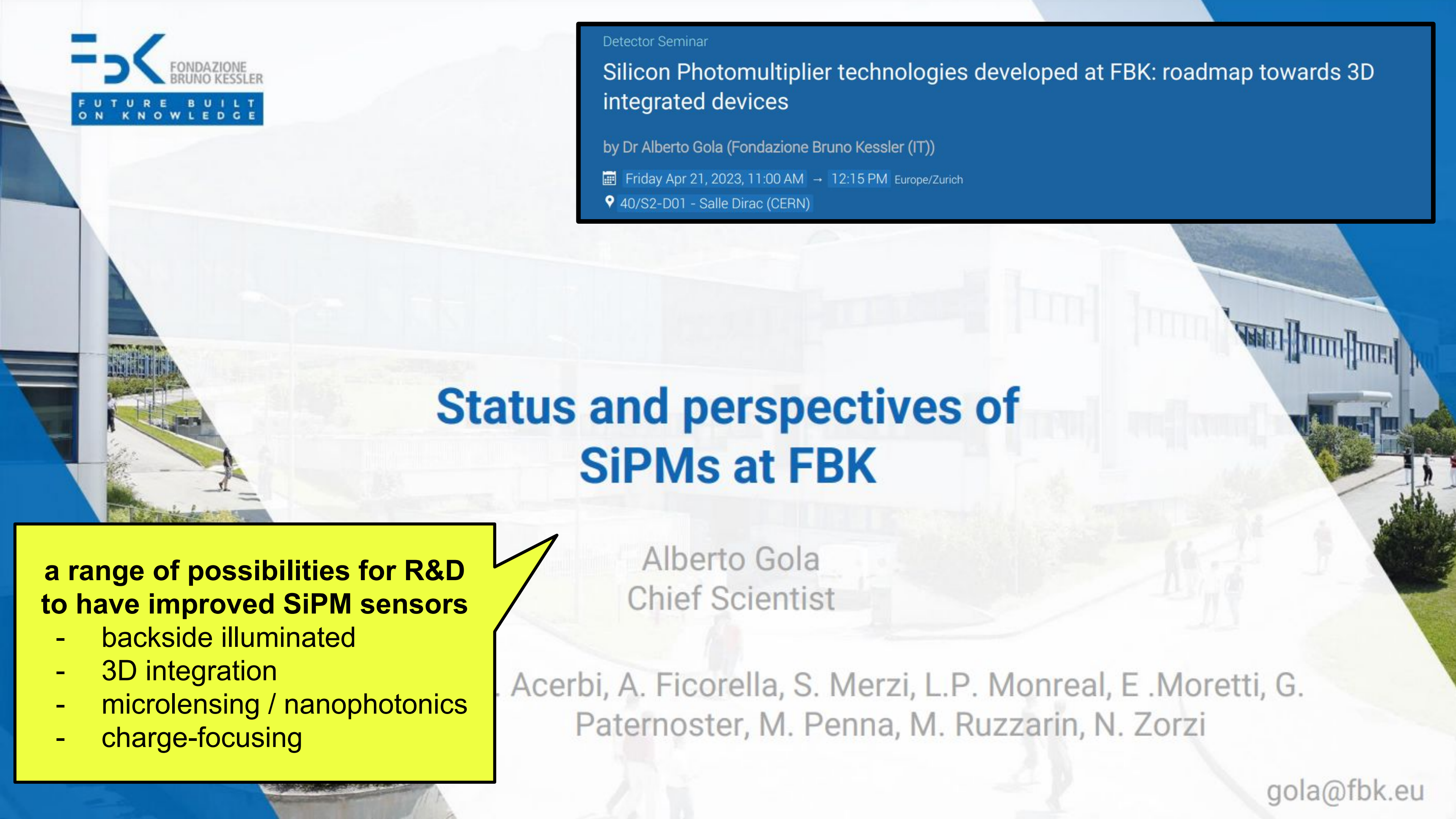
1) Sintesi del progetto di ricerca

Ring Imaging Cherenkov applications at the EIC require sensors with single-photon detection capabilities with high efficiency and excellent time resolution. High dark count rates (DCR) in SiPM can be counteracted with low-temperature operation and radiation damage can be partially cured with high-temperature annealing. Even small improvements towards reduction of DCR are helpful for a better exploitation of the detectors and to provide a strong alternative to commercially-available sensors. One of the goals of the R&D is to exploit the already-mature FBK NUV-HD technology to improve radiation tolerance and meet the needs for EIC. Increasing the fraction of the sensor active area over the total area while retaining a low-cost process (wire-bonding vs. TSV) is another important step to make FBK technology an even more attractive solution for EIC. These research goals are in line with the timeline for the initial operation of EIC and are targeted to the Technical Design Reports.

Another line of research aims to significantly reduce DCR and radiation vulnerability in SiPM by reducing their active area while maintaining photodetection efficiency. Such a study is exploratory and more ambitious, but has a high return potential. This part of the R&D is not targeted for the EIC initial operation phase, but might yield a new class of SiPM photosensors for the EIC RICH detector upgrades, for the ALICE3 RICH detector as well as future LHCb RICH upgrades.

in line with
initial operation
of EIC

might yield sensors for
EIC RICH upgrades
and for ALICE3 RICH



Detector Seminar

Silicon Photomultiplier technologies developed at FBK: roadmap towards 3D integrated devices

by Dr Alberto Gola (Fondazione Bruno Kessler (IT))

Friday Apr 21, 2023, 11:00 AM → 12:15 PM Europe/Zurich

40/S2-D01 - Salle Dirac (CERN)

FONDAZIONE BRUNO KESSLER

FUTURE BUILT ON KNOWLEDGE

Status and perspectives of SiPMs at FBK

Alberto Gola
Chief Scientist

Acerbi, A. Ficorella, S. Merzi, L.P. Monreal, E .Moretti, G. Paternoster, M. Penna, M. Ruzzarin, N. Zorzi

gola@fbk.eu

a range of possibilities for R&D to have improved SiPM sensors

- backside illuminated
- 3D integration
- microlensing / nanophotonics
- charge-focusing

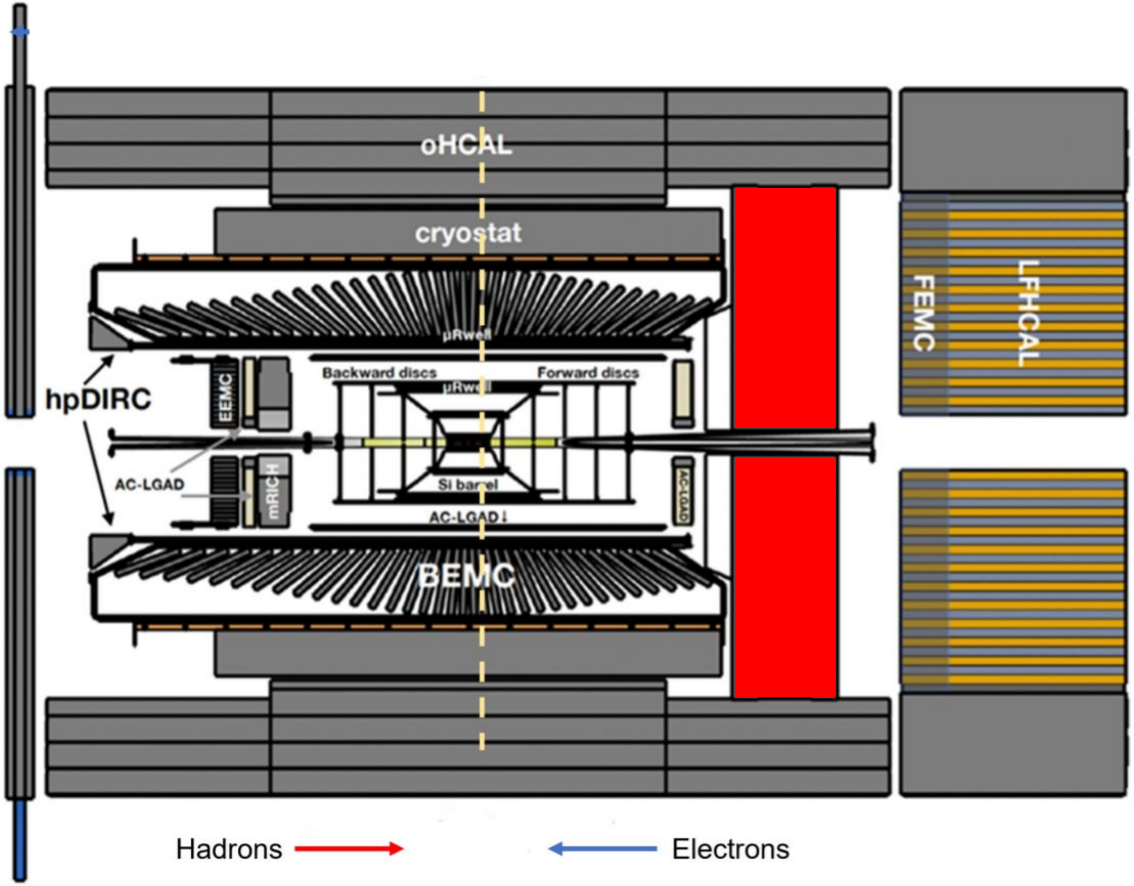
SiPM plans for FY 2023

Milestones FY 2023

critical results for pre-TDR

- Timing measurement of irradiated (and annealed) sensors (6/2023)
- Comparison of the results achieved with proton and neutron irradiation sources (8/2023)
- Study of annealing in-situ technique with a proposed model selected as baseline for the pre-TDR (9/2023)

- **single-photon time resolution**
  - of full SiPM-ALCOR readout chain
    - no capacity to measure it so far
  - critical to set performance simulation
- **alternative annealing solutions**
  - so far done with industrial oven (days)
  - address ideas for faster / in-situ recovery
    - exploration started, promising
    - critical to become structured R&D
- **irradiation campaigns**
  - so far only with 150 MeV protons
  - critical to collect data on neutron damage
    - might be topologically different
    - effectiveness of annealing
    - test NIEL damage hypothesis
  - irradiation needed to test new annealings
- **operation at low temperature**
  - so far characterisation in climatic chamber
    - compare results with TEC (Peltier) cooling
  - explore alternative solution to TEC
    - liquid, hybrid (liquid + TEC) approaches
- **development of new sensors**
  - within INFN-FBK collaboration agreement
    - critical for procurement risk mitigation
  - reduction of DCR
    - field / thickness optimisation
    - exploration of advanced microlensing
  - development of “monolithic” SiPM sensor array
    - wire bonded, cost reduction



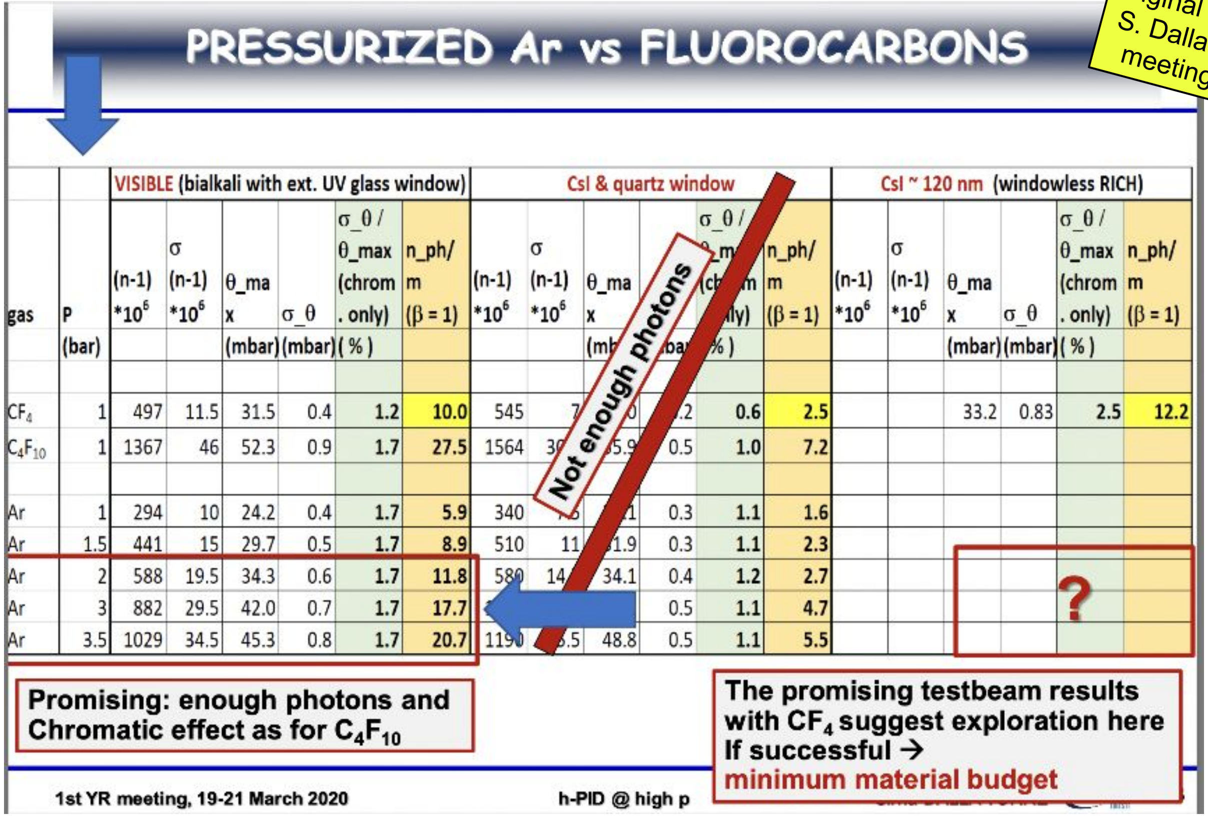
gas radiator

dRICH gas radiator and vessel

R&D to build an eco-friendly dRICH: replace C_2F_6 with pressurized Argon

Original idea discussed by S. Dalla Torre at first YR meeting (March 2020)

Increase Ar pressure to increase number of photons



PRESSURIZED Ar vs FLUOROCARBONS

gas	P	VISIBLE (bialkali with ext. UV glass window)						CsI & quartz window						CsI ~ 120 nm (windowless RICH)					
	(bar)	(n-1) $*10^6$	σ (n-1) $*10^6$	θ_max (mbar)	σ_θ (mbar)	σ_θ / θ_max (chrom. only) (%)	n_ph/m (β = 1)	(n-1) $*10^6$	σ (n-1) $*10^6$	θ_max (mbar)	σ_θ (mbar)	σ_θ / θ_max (chrom. only) (%)	n_ph/m (β = 1)	(n-1) $*10^6$	σ (n-1) $*10^6$	θ_max (mbar)	σ_θ (mbar)	σ_θ / θ_max (chrom. only) (%)	n_ph/m (β = 1)
CF_4	1	497	11.5	31.5	0.4	1.2	10.0	545	[illegible]	[illegible]	[illegible]	0.6	2.5			33.2	0.83	2.5	12.2
C_4F_{10}	1	1367	46	52.3	0.9	1.7	27.5	1564	[illegible]	[illegible]	0.5	1.0	7.2						
Ar	1	294	10	24.2	0.4	1.7	5.9	340	[illegible]	[illegible]	0.3	1.1	1.6						
Ar	1.5	441	15	29.7	0.5	1.7	8.9	510	11	[illegible]	0.3	1.1	2.3						
Ar	2	588	19.5	34.3	0.6	1.7	11.8	580	14	34.1	0.4	1.2	2.7						
Ar	3	882	29.5	42.0	0.7	1.7	17.7	[illegible]	[illegible]	[illegible]	0.5	1.1	4.7					?	
Ar	3.5	1029	34.5	45.3	0.8	1.7	20.7	1190	[illegible]	48.8	0.5	1.1	5.5						

Not enough photons

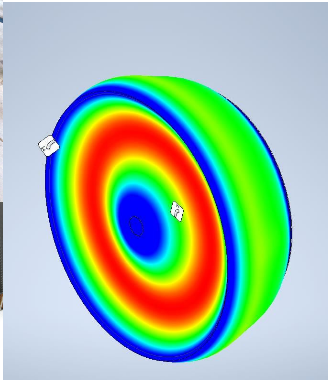
Promising: enough photons and Chromatic effect as for C_4F_{10}

The promising testbeam results with CF_4 suggest exploration here
If successful →
minimum material budget

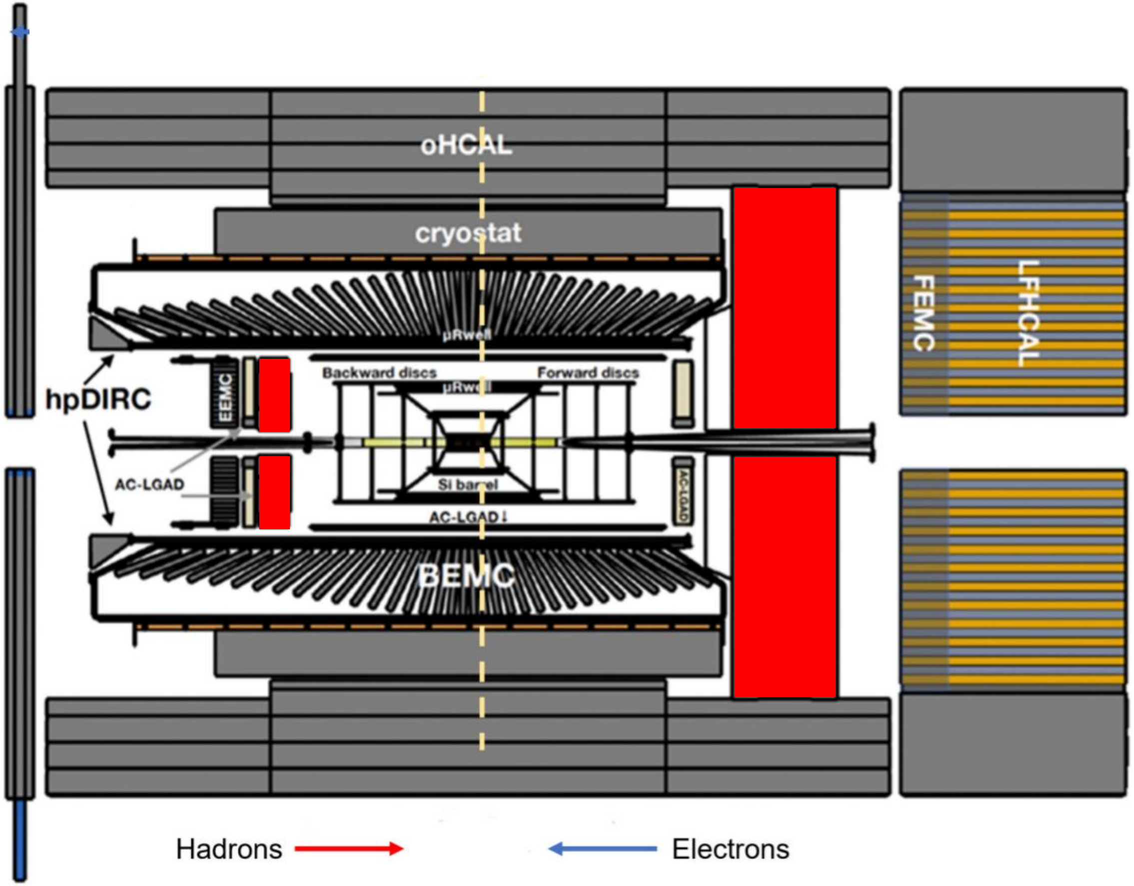
1st YR meeting, 19-21 March 2020

h-PID @ high p

promising solution **needs**
a well advanced vessel design
to work with pressurised (3 bar) Argon
(material studies with scaled vessel prototype)



aerogel


oHCAL
cryostat
μRwell
Backward discs
Forward discs
μRwell
hpDIRC
EEMC
AC-LGAD
Si barrel
AC-LGAD
AC-LGAD
BEMC
FEMC
LFHCAL
Hadrons
Electrons

Aerogel type and characterisation

EIC project meeting with Aerogel Factory (Tabata) in December 2022
R&D specifications being defined with Project and detector subsystems (pfRICH, dRICH)
characterisation of test samples is a strong synergy with ALICE3 RICH efforts

Measurements performed on **20 silica aerogel tiles** at CERN in July-August 2022.

Tiles manufactured at Aerogel Factory Co., Ltd. and delivered in March 2021.

TILES CHARACTERISTICS

Tile	Refractive index @405 nm	Expected t [mm]
1	1.03	20.7
2		20.8
3		20.1
4		20.5
5		20.4
6		10.0
7		10.0
8	1.04	20.3
9		20.5
10		20.3
11		20.4
12		20.5
13	1.05	20.5
14		20.7
15		20.6
16		20.6
17		20.8
18	1.005	20.0
19		20.0
20		20.0

Tile specifications provided by the producer

$$T(\lambda) = e^{-\frac{t}{\Lambda_{trasm}}} = e^{-t\left(\frac{1}{\Lambda_A}+\frac{1}{\Lambda_S}\right)} = A\cdot e^{-\frac{B\,t}{\lambda^8}}\cdot e^{-\frac{C\,t}{\lambda^4}}$$

TRANSMISSION LENGTH:

$$T(\lambda) = e^{-\frac{t}{\Lambda_{trasm}}}$$

$$\Lambda_{trasm} = -\frac{t}{\ln(T)}$$

SCATTERING LENGTH:

$$e^{-\left(\frac{t}{\Lambda_S}\right)} = e^{-\frac{C\,t}{\lambda^4}}$$

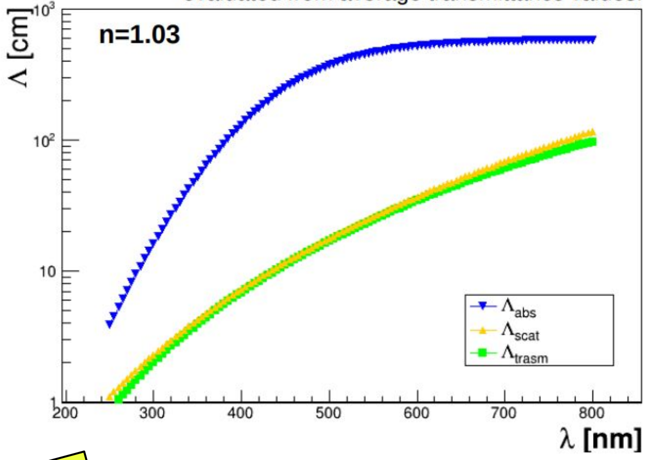
$$\Lambda_{scat} = \frac{\lambda^4}{C}$$

ABSORPTION LENGTH:

$$e^{-\left(\frac{t}{\Lambda_A}\right)} = A\cdot e^{-\frac{B\,t}{\lambda^8}}$$

$$\Lambda_{abs} = \frac{\lambda^8\cdot t}{B\,t - \lambda^8\cdot\ln(A)}$$

Average transmission length, evaluated from average transmittance values.



MALL IMPACT OF THE ABSORPTION ON THE TRANSMISSION LENGTH

measurements performed within ALICE3 RICH reported at dRICH meeting

Summary

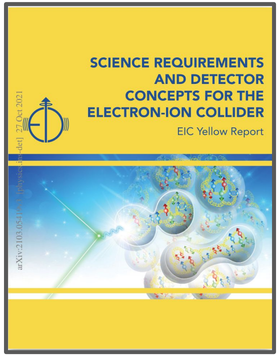
ePIC meets EIC PID needs with advanced detector technology

- **PID is one of the major challenges for the ePIC detector at the EIC**
  - physics requires high-purity π K p over large phase-space
  - multiple techniques needed
    - time-of-flight, ring imaging Cherenkov
    - calorimetry for e (μ) identification
- **selected detector technologies meet the requirements**
  - AC-LGAD TOF
  - high-performance DIRC
  - dual-radiator RICH
  - proximity-focusing RICH
- **ongoing R&D activities**
  - risk reduction
  - optimisation of technologies
- **synergies with CERN and LHC upgrades**
  - over a broad spectrum

END

Detector requirements for PID

definition of requirements in the Yellow Report

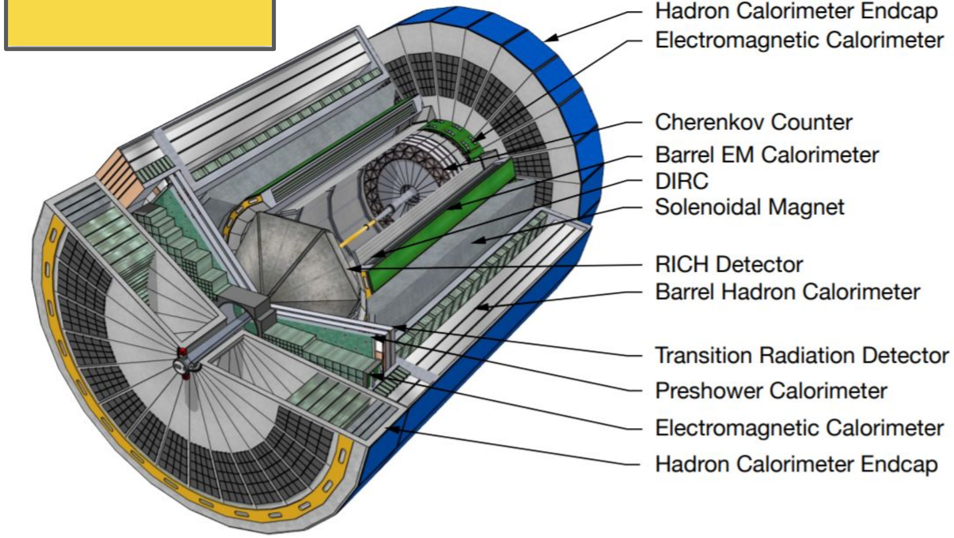


SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER

EIC Yellow Report

arXiv:2103.05419v3 [physics.ins-det] 27 Oct 2021

- **generic all-purpose detector and performance matrix**
  - summarises the detector requirements for the diverse physics program at EIC
  - focus on the PID-relevant subset of the detector matrix



η	θ	Nomenclature			Electrons and Photons			π/K/p	
	(mrad)				Resolution σ_E/E	PID	min E photon	p-Range (GeV/c)	Separation
-4.0 to -3.5				Backward Detector	not accessible				
-3.5 to -3.0			Central Detector		$1\%/E \oplus 2.5\%/\sqrt{E} \oplus 1\%$ (for 40 cm space)	π suppression up to 1:1E-4	20 MeV	≤ 10 GeV/c	≥ 3 σ
-3.0 to -2.5									
-2.5 to -2.0									
-2.0 to -1.5					$2\%/E \oplus (4\text{-}8)\%/\sqrt{E} \oplus 2\%$ (Upper limit achievable with 50 cm space *Better resolution requires ~65 cm space allocated)	π suppression up to 1:(1E-3 - 1E-2)	50 MeV		
-1.5 to -1.0									
-1.0 to -0.5				Barrel	$2\%/E \oplus (12\text{-}14)\%/\sqrt{E} \oplus (2\text{-}3)\%$ for 30 cm space A better stochastic term can be achieved with more space: 2.5% with crystals 35cm 10% sampling 40cm 4% SciGlass 65cm *Better resolution requires ~65 cm space allocated)	π suppression up to 1:1E-2	100 MeV (50 MeV if higher resolution)	≤ 6 GeV/c	
-0.5 to 0.0									
0.0 to 0.5									
0.5 to 1.0								≤ 6 GeV/c	
1.0 to 1.5				Forward Detectors	$2\%/E \oplus (4^{*}\text{-}12)\%/\sqrt{E} \oplus 2\%$ Upper limit achievable with 40cm space *Better resolution requires ~65 cm space allocated	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c (worse approaching 3.5)	
1.5 to 2.0									
2.0 to 2.5									
2.5 to 3.0									
3.0 to 3.5									

arXiv:2103.05419 [physics.ins-det]

Generic R&D projects since 2014

PID

Project	Topic
eRD1	EIC Calorimeter Development
eRD2	A Compact Magnetic Field Cloaking Device
eRD3	Design and assembly of fast and lightweight forward tracking prototype systems
eRD6	**Tracking and PID detector R&D towards an EIC detector**
eRD10	**(Sub) 10 Picosecond Timing Detectors at the EIC**
eRD11	**RICH detector for the EIC’S forward region particle identification - Simulations**
eRD12	Polarimeter, Luminosity Monitor and Low Q2-Tagger for Electron Beam
eRD14	**An integrated program for particle identification (PID)**
eRD15	R&D for a Compton Electron Detector
eRD16	Forward/Backward Tracking at EIC using MAPS Detectors
eRD17	BeAGLE: A Tool to Refine Detector Requirements for eA Collisions in the Nuclear Shadowing/Saturation Regime
eRD18	Precision Central Silicon Tracking & Vertexing
eRD19	Detailed Simulations of Machine Background Sources and the Impact to Detector Operations
eRD20	Developing Simulation and Analysis Tools for the EIC
eRD21	EIC Background Studies and the Impact on the IR and Detector design
eRD22	**GEM based Transition Radiation Tracker R&D**
eRD23	Streaming Readout for EIC Detectors
eRD24	Silicon Detectors with high Position and Timing Resolution as Roman Pots at EIC
eRD25	Si-Tracking
eRD26	Pulsed Laser System for Compton Polarimetry
eRD27	High Resolution ZDC
eRD28	Superconducting Nanowire Detectors
eRD29	**Precision Timing Silicon Detectors for for combined PID and Tracking System**

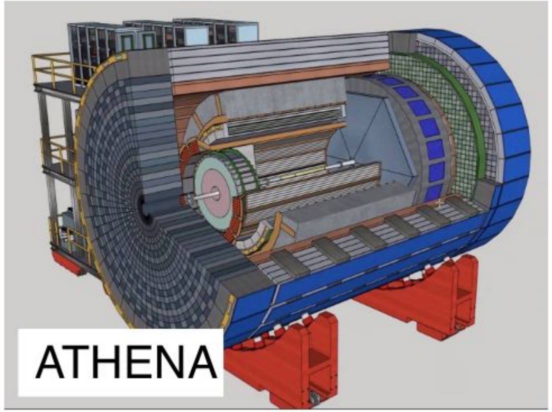
Project R&D

Generic R&D program ended in September 2021
focus on projects targeted for the EIC detector

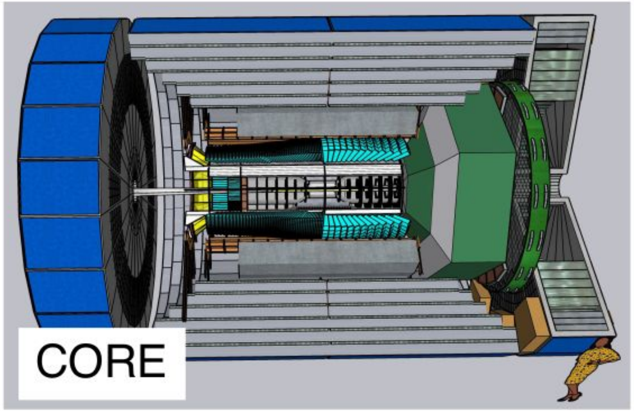
- **Project driven R&D scope**
    - reflects reference detector as defined in CD-1
    - encapsulate Project and detector systems
    - reduce risk, ensure feasibility, optimisation

Project	Topic
eRD101	**Modular RICH / aerogel RICH**
eRD102	**Dual-radiator RICH**
eRD103	**High-performance DIRC**
eRD104	Silicon service reduction
eRD105	SciGlass
eRD106	Forward EMCAL
eRD107	Forward HCAL
eRD108	Cylindrical / planar MPGD
eRD109	ASICs / electronics
eRD110	**Photosensors**
eRD111	Silicon tracked (excluding electronics)
eRD112	**AC-LGAD (including ASIC)**

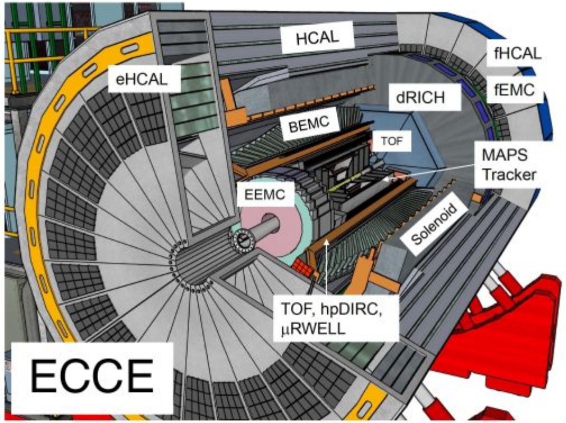
PID in detector proposals



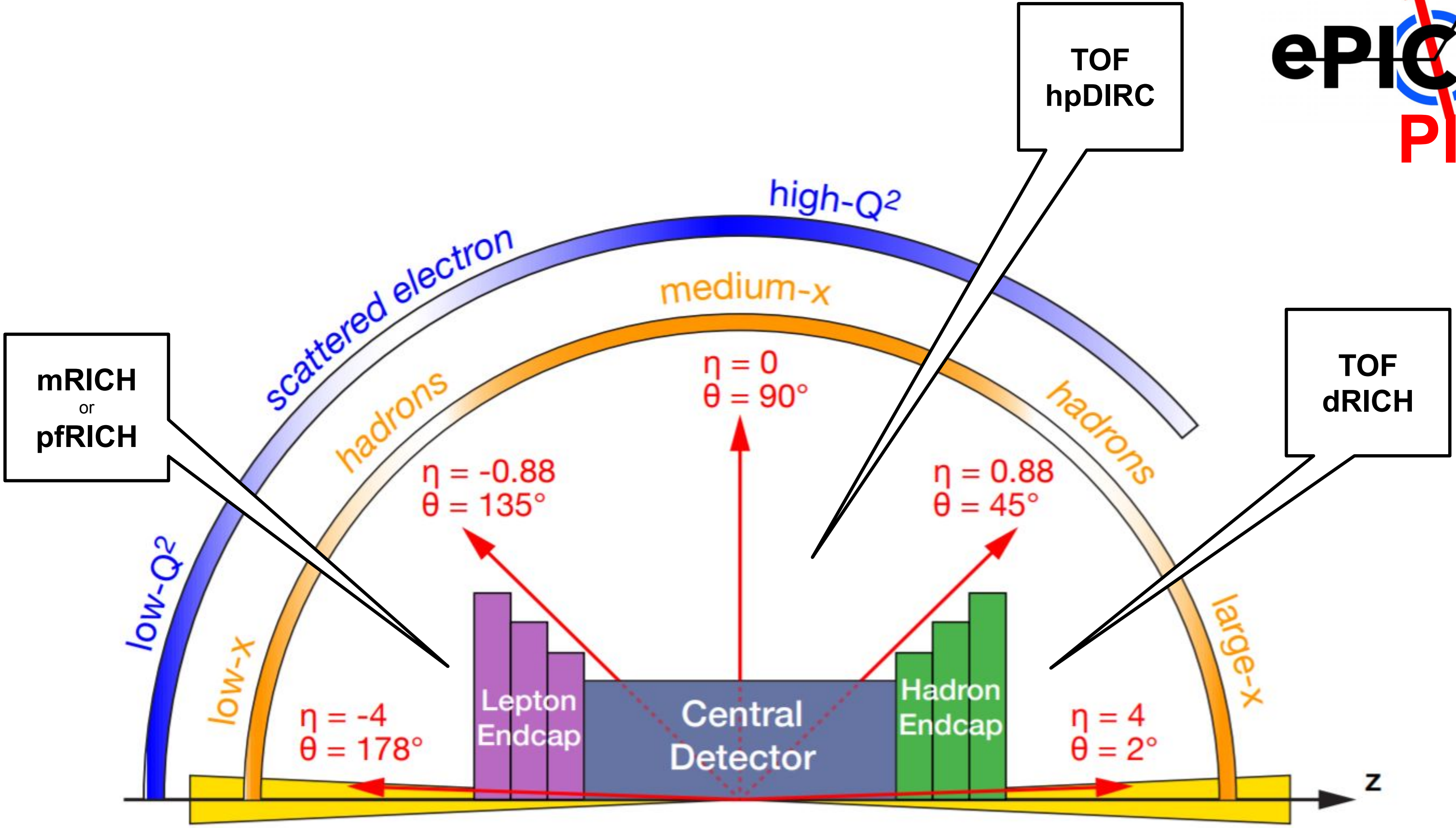
- **backward**
  proximity-focus RICH
- **central**
  high-performance DIRC
  AC-LGAD TOF
- **forward**
  dual-radiator RICH



- **backward**
  AC-LGAD TOF
- **central**
  high-performance DIRC
- **forward**
  dual-radiator RICH



- **backward**
  modular RICH
  AC-LGAD TOF
- **central**
  high-performance DIRC
  AC-LGAD TOF
- **forward**
  dual-radiator RICH
  AC-LGAD TOF



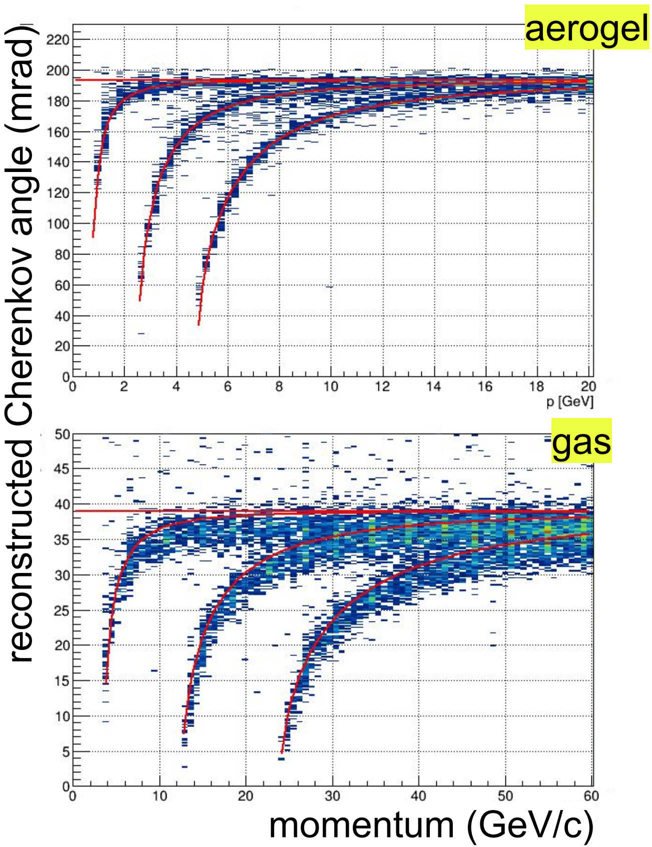
TOF
hpDIRC

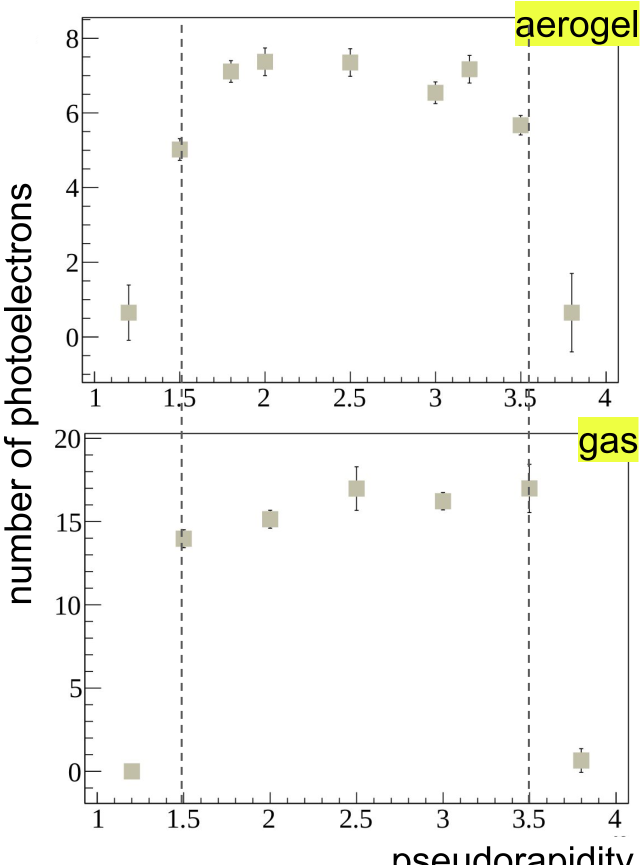
mRICH
or
pfRICH

TOF
dRICH

dRICH performance simulation

inverse ray-tracing reconstruction algorithm shared with pfRICH

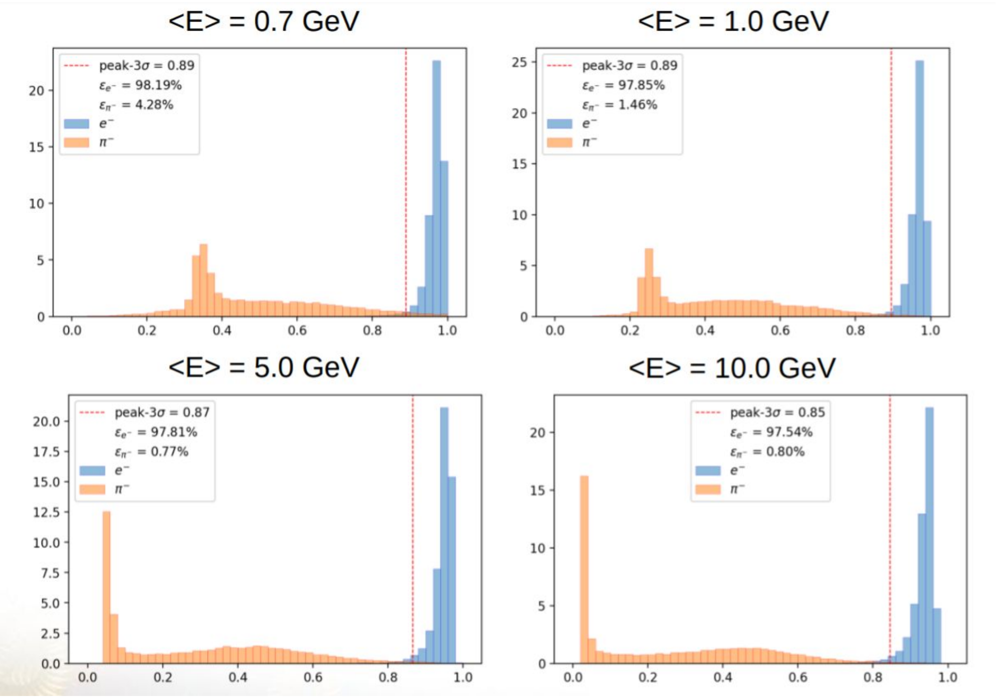


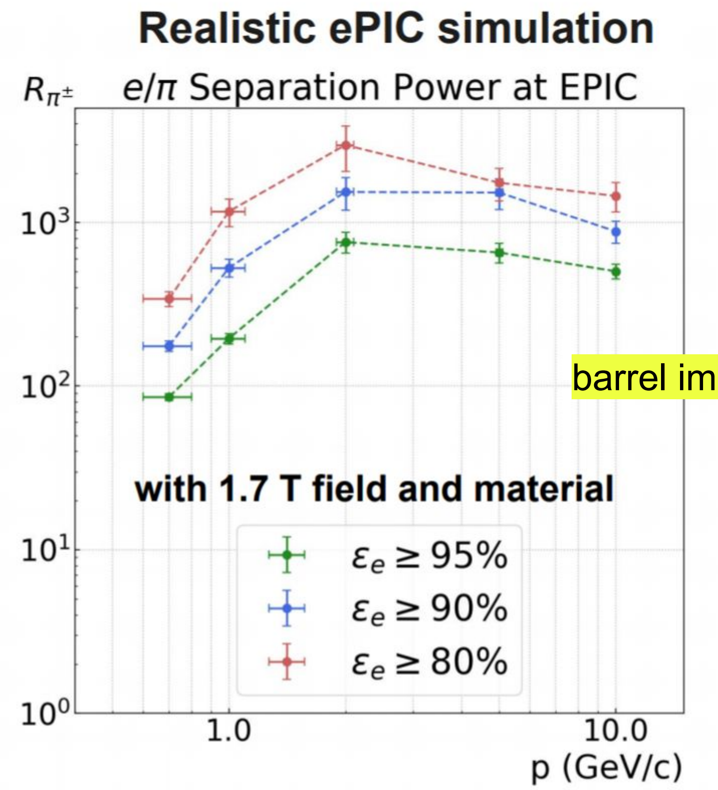


EMCal e/π separation power

excellent, up to 10^4 pion suppression

barrel SciGlass





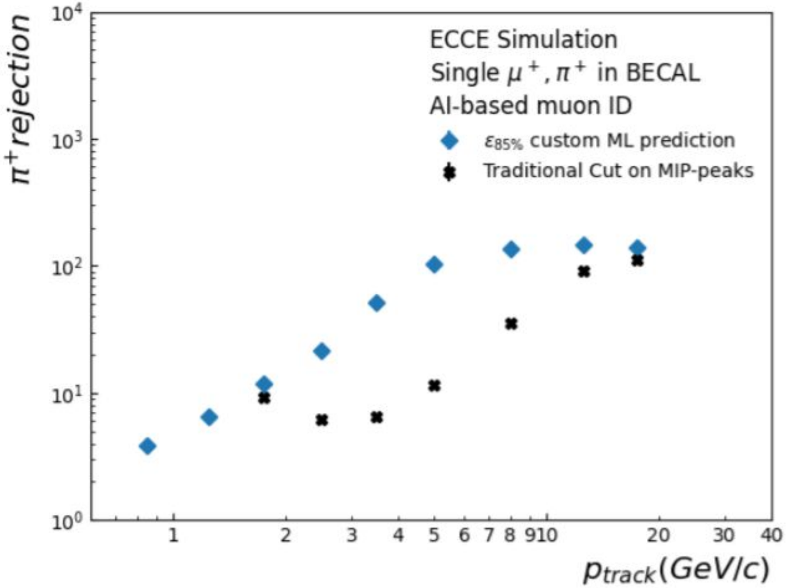
barrel imaging

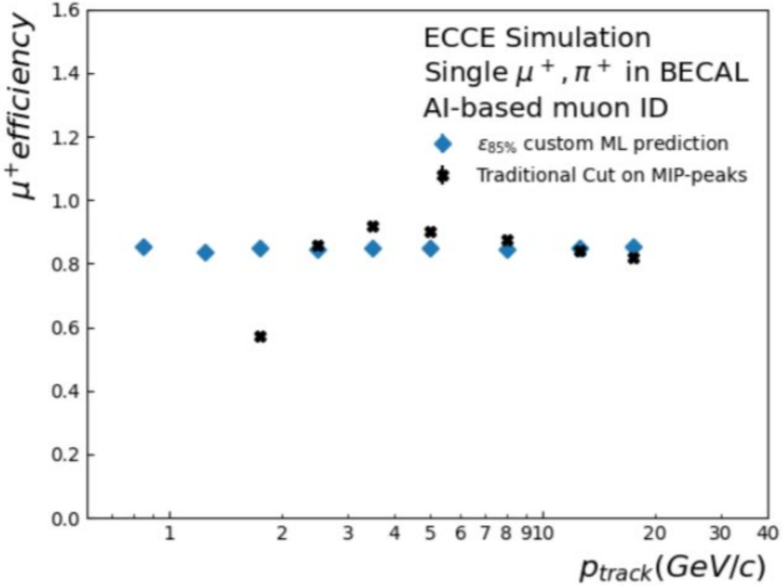
Muon identification

muon ID using a combination of EM and Hadron calorimetry

Total hadron interaction length:
6-7 λ_0 for central and 7-8 λ_0 for forward
Pion punch through probability: 10^{-2} to 10^{-3} level

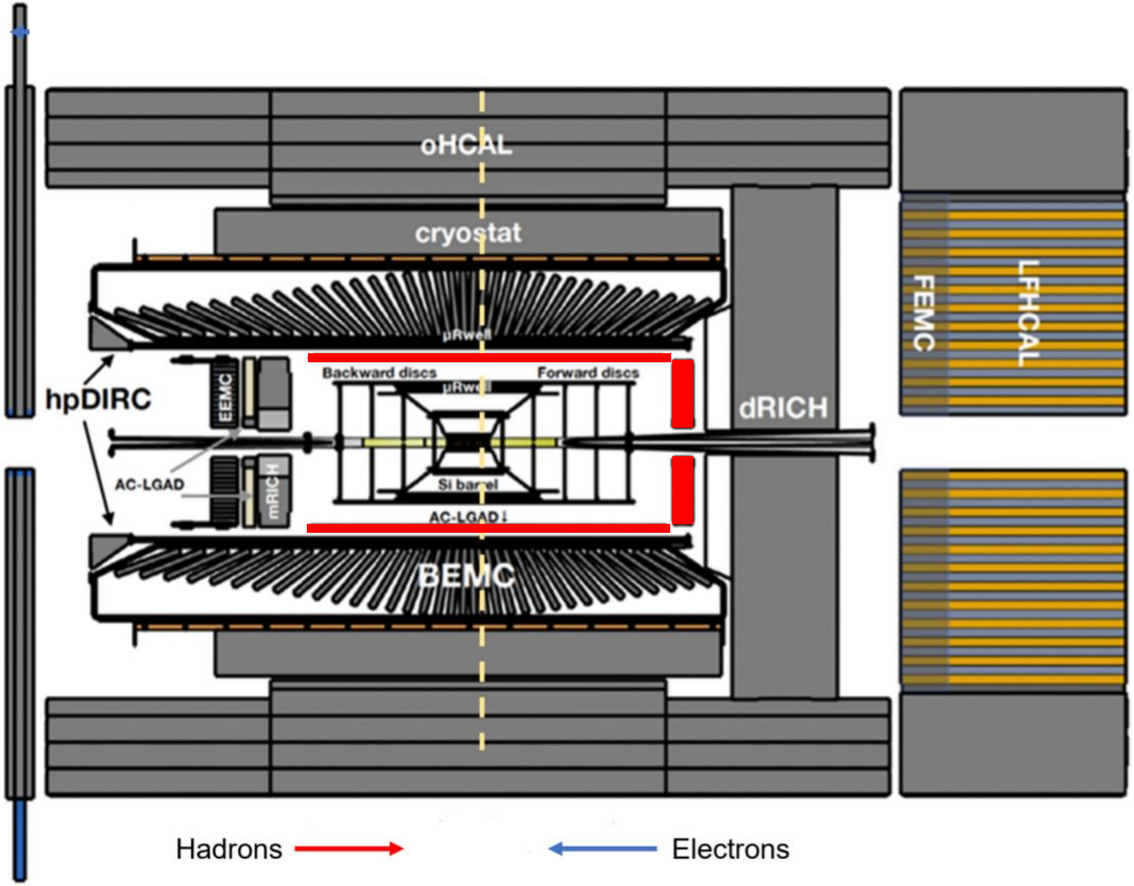
- Utilizing central track, barrel EMCal, EMCal active support and barrel HCal
- Pion rejection starting at 10^{-1} at low p and saturate above 100:1 above a few GeV/c





ePIC

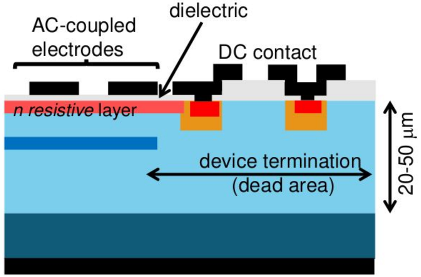
Time of Flight

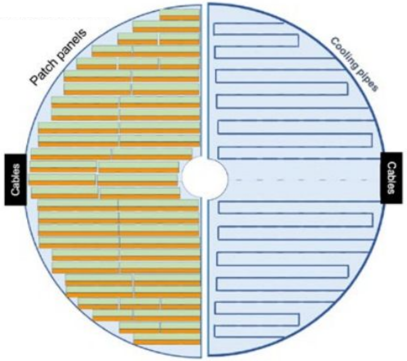


TOF – Time of Flight

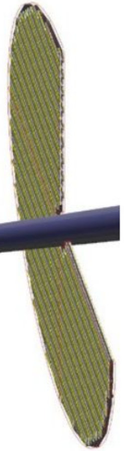
based on AC-LGAD technology, also used in far forward ePIC instrumentation

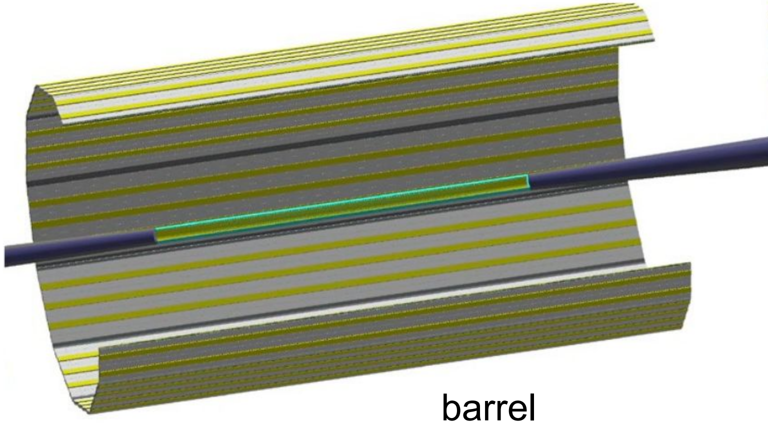
- **two AC-LGAD layers**
  - barrel, |η| < 1.4
  - forward, 1.5 < η < 3.5
- **barrel**
  - 500 μm x 1 cm strips
  - 1% X_0
- **forward**
  - 500 μm x 500 μm pixels
  - 8% X_0
- **performance**
  - space resolution: 30 μm
  - time resolution: σ ~ 25 ps





forward

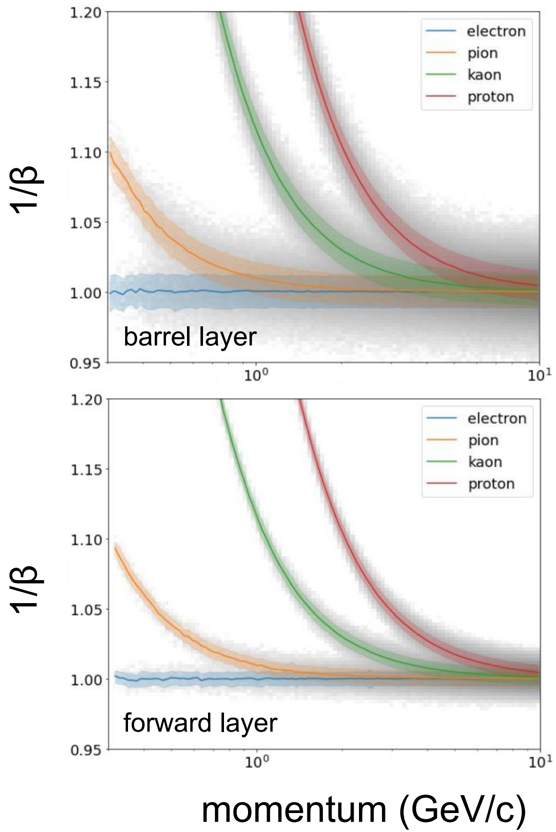




barrel

TOF performance simulation

detector geometry implemented in Geant, digitisation and integration in tracking software

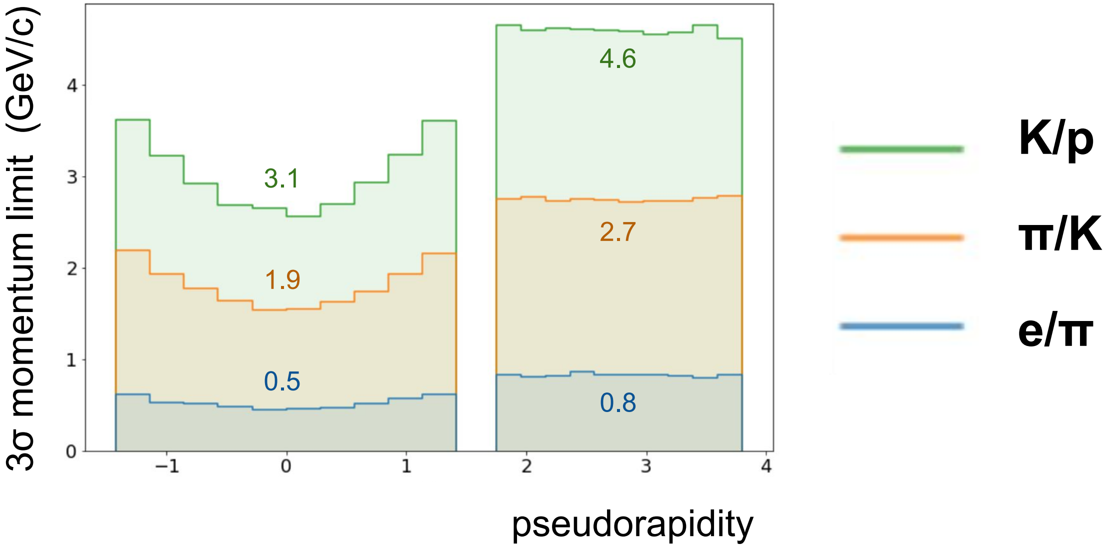


barrel layer

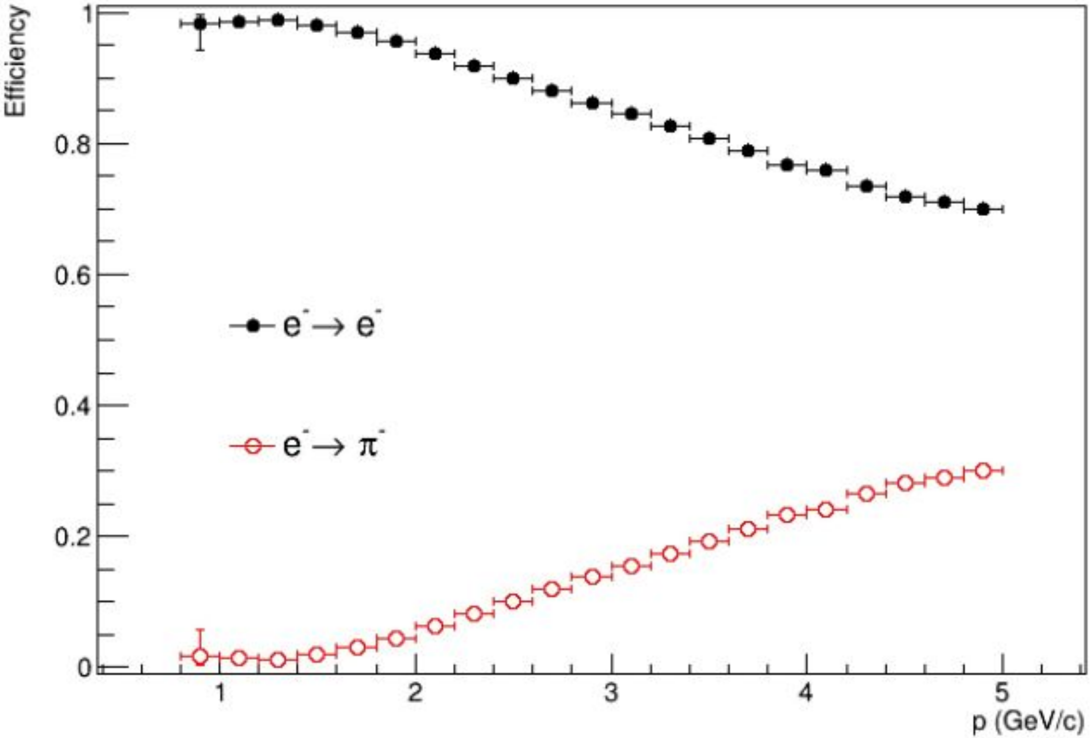
- e/pi up to 0.5 GeV/c
- pi/K up to 1.9 GeV/c
- K/p up to 3.1 GeV/c

forward layer

- e/pi up to 0.8 GeV/c
- pi/K up to 2.7 GeV/c
- K/p up to 4.6 GeV/c



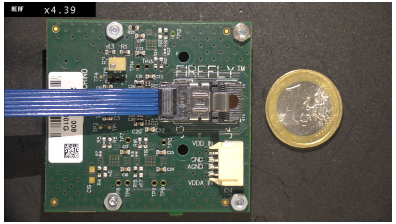
mRICH electron-ID

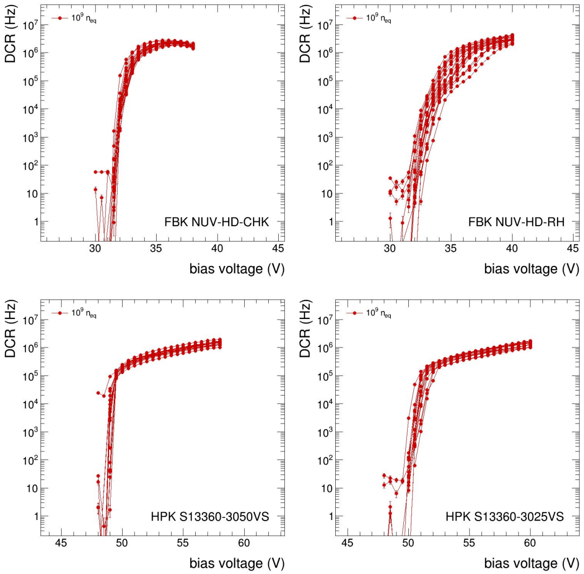


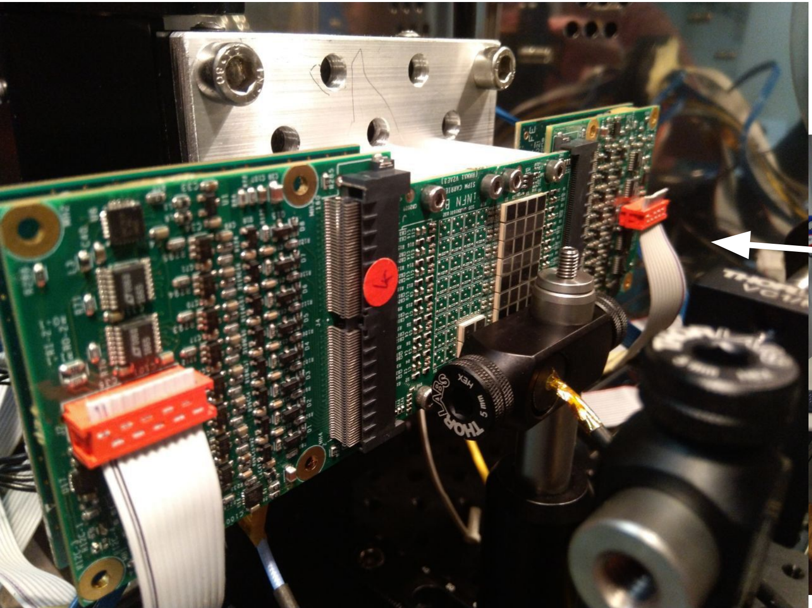
Murad Sarsour

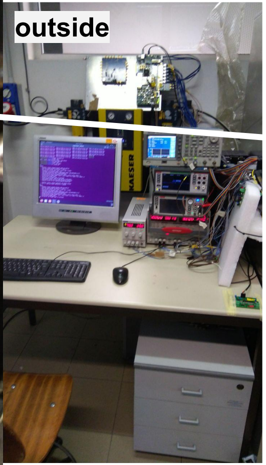
LED measurements

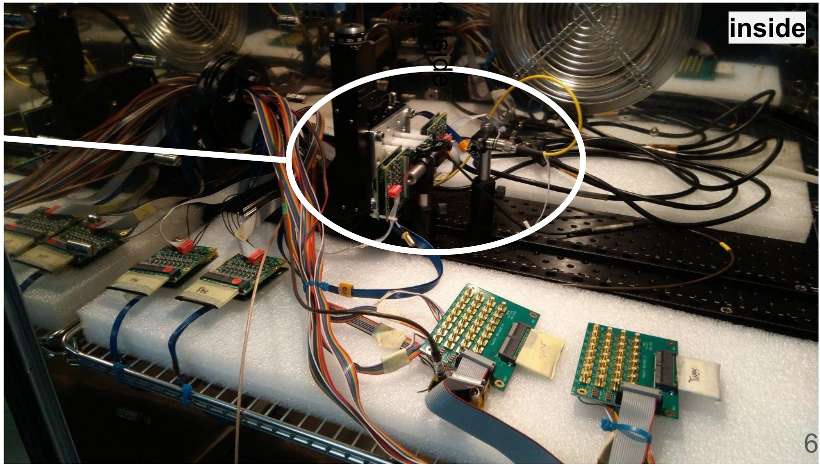
- **climatic chamber**
  low-temperature operation
  all reported measurements at T = -30 °C
- **arbitrary function generator**
  pulse to LED and readout (trigger)
- **2x ALCOR-based front-end chain**
  automatic measurement of 2x SiPM boards (64 channels)
- **FPGA (Xilinx) readout**



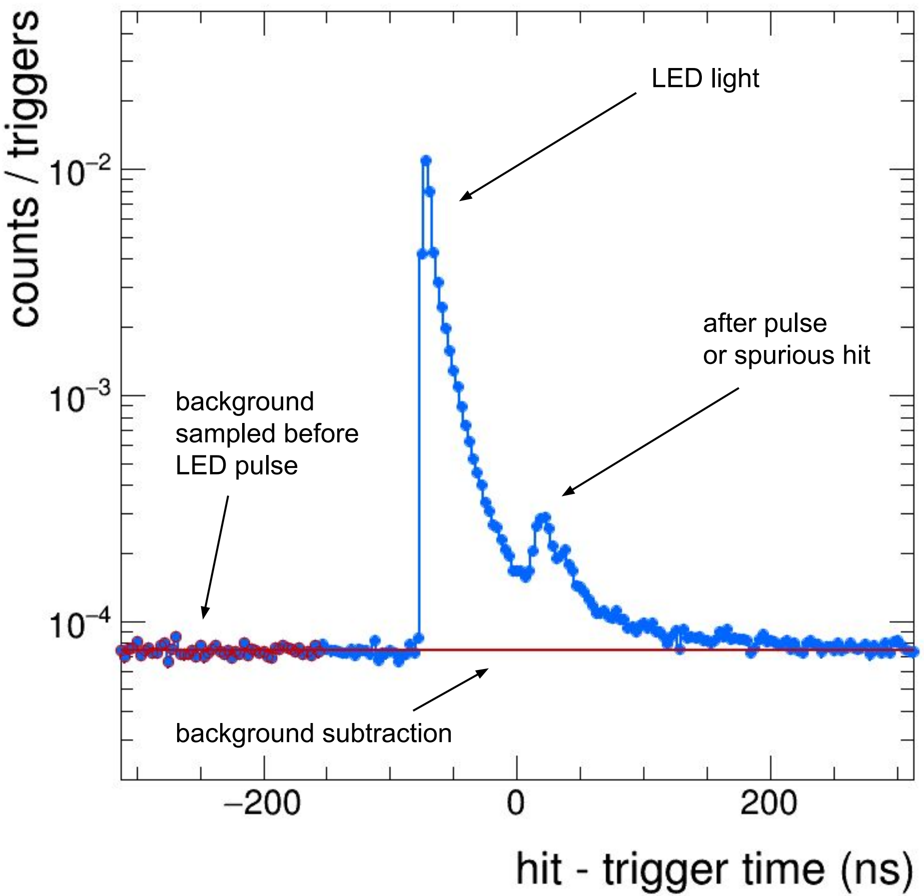








Light response with pulsed LED



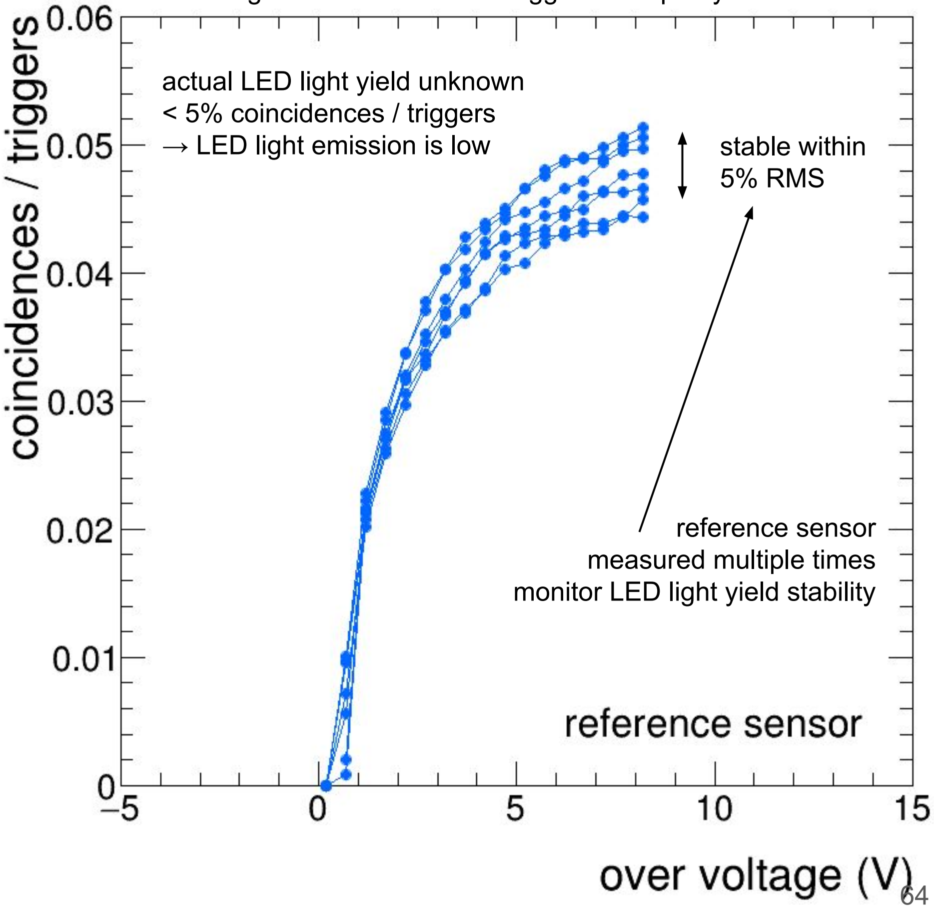
LED light

after pulse
or spurious hit

background
sampled before
LED pulse

background subtraction

integrated coincidences / triggers as a proxy for PDE

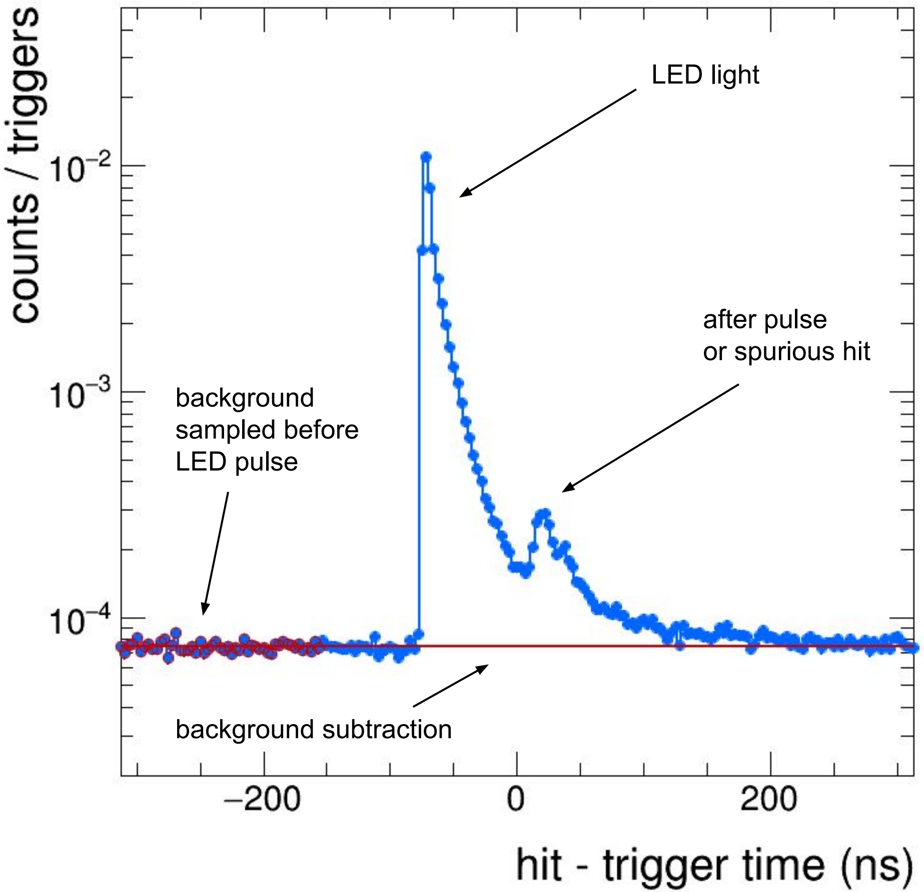


actual LED light yield unknown
< 5% coincidences / triggers
→ LED light emission is low

stable within
5% RMS

reference sensor
measured multiple times
monitor LED light yield stability

Light response with pulsed LED

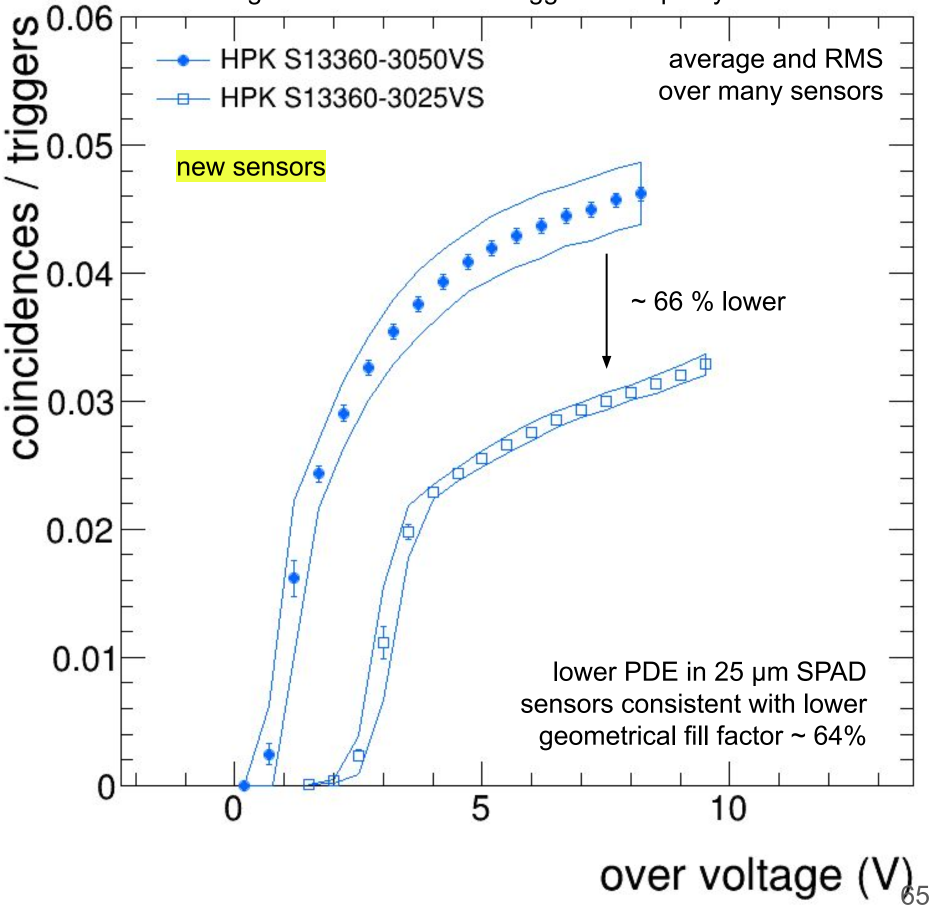

LED light

after pulse
or spurious hit

background
sampled before
LED pulse

background subtraction

integrated coincidences / triggers as a proxy for PDE


new sensors

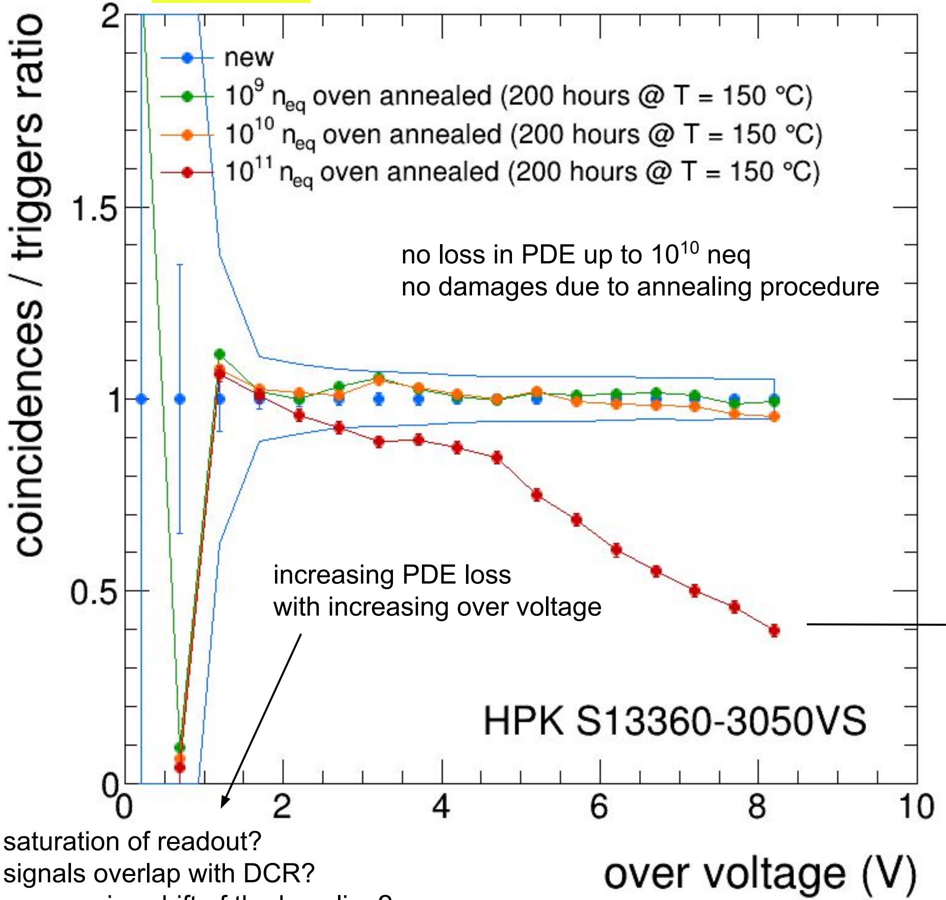
average and RMS
over many sensors

~ 66 % lower

lower PDE in 25 µm SPAD
sensors consistent with lower
geometrical fill factor ~ 64%

Light response after irradiation and annealing

ratio wrt. new

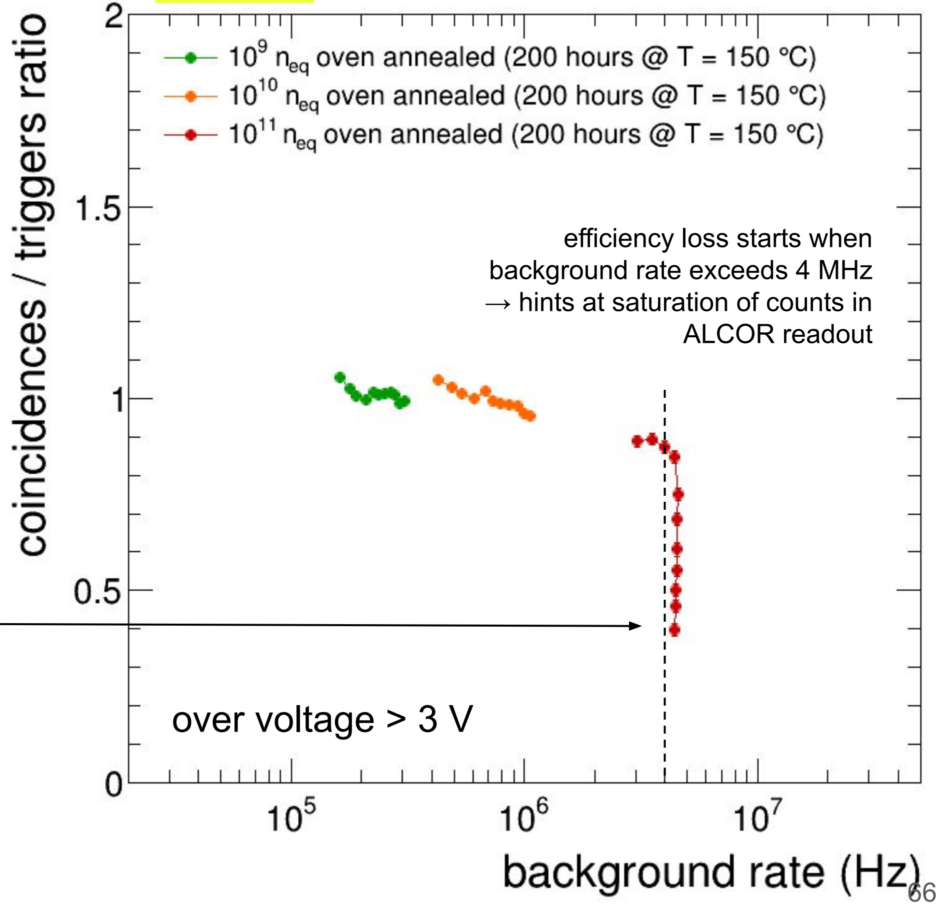


no loss in PDE up to 10^{10} neq
no damages due to annealing procedure

increasing PDE loss
with increasing over voltage

saturation of readout?
signals overlap with DCR?
progressive shift of the baseline?

ratio wrt. new

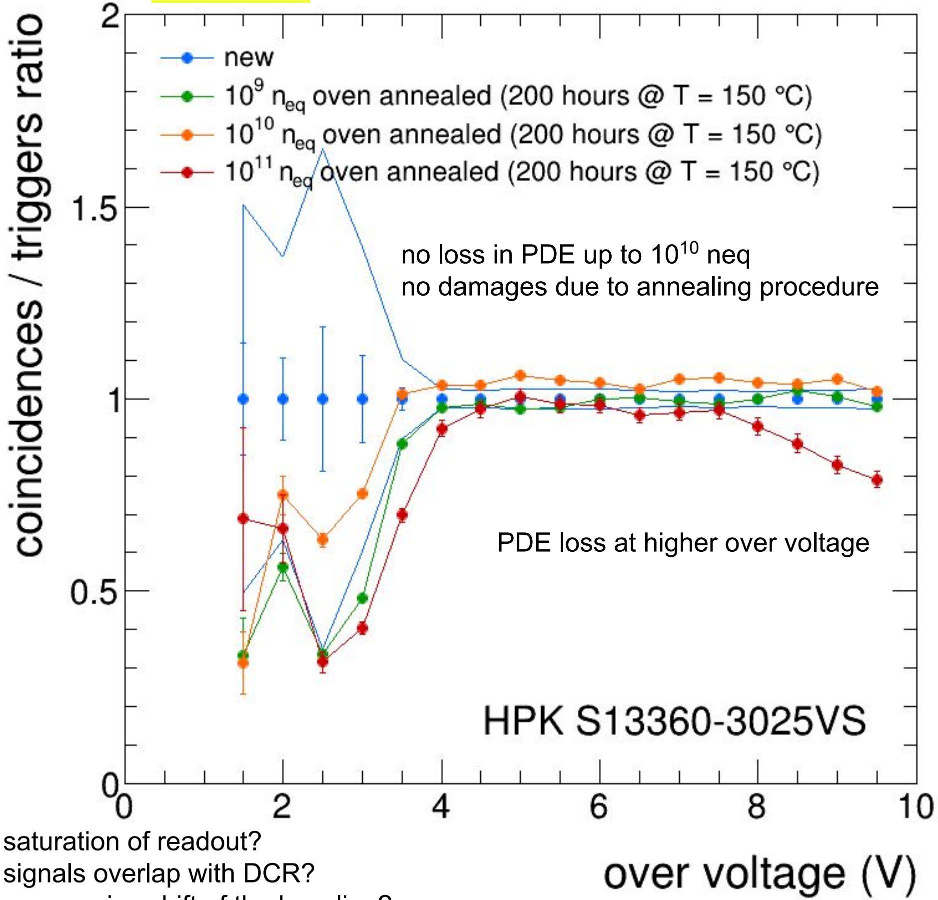


efficiency loss starts when
background rate exceeds 4 MHz
→ hints at saturation of counts in
ALCOR readout

over voltage > 3 V

Light response after irradiation and annealing

ratio wrt. new

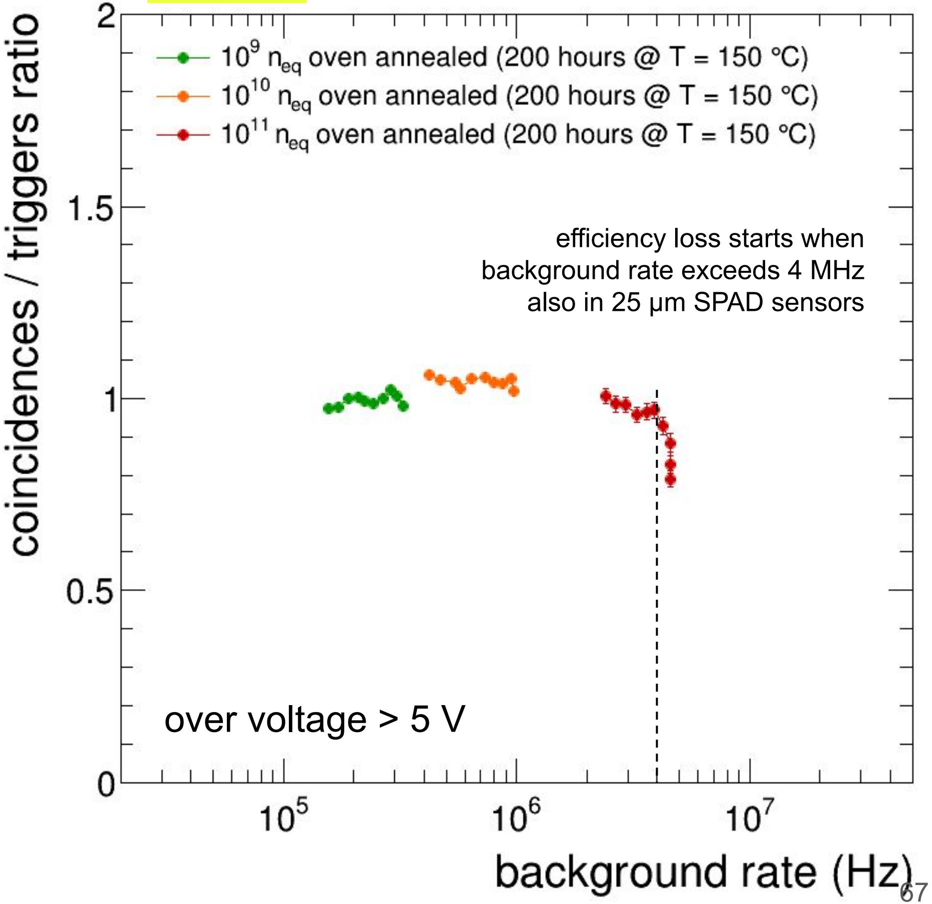


no loss in PDE up to 10^{10} neq
no damages due to annealing procedure

PDE loss at higher over voltage

saturation of readout?
signals overlap with DCR?
progressive shift of the baseline?

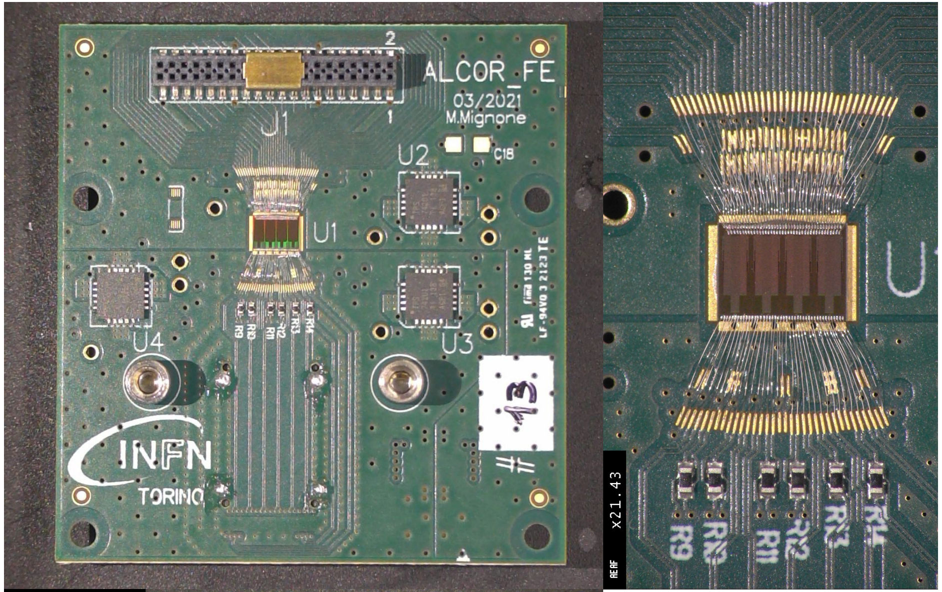
ratio wrt. new

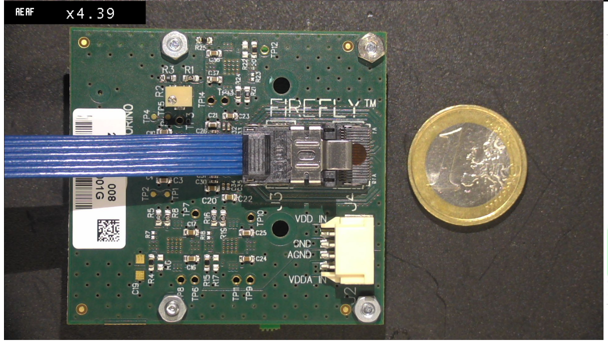


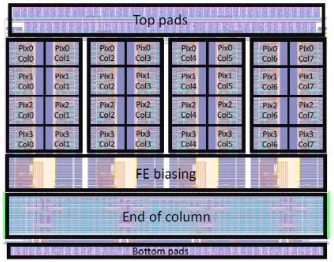
efficiency loss starts when
background rate exceeds 4 MHz
also in 25 µm SPAD sensors

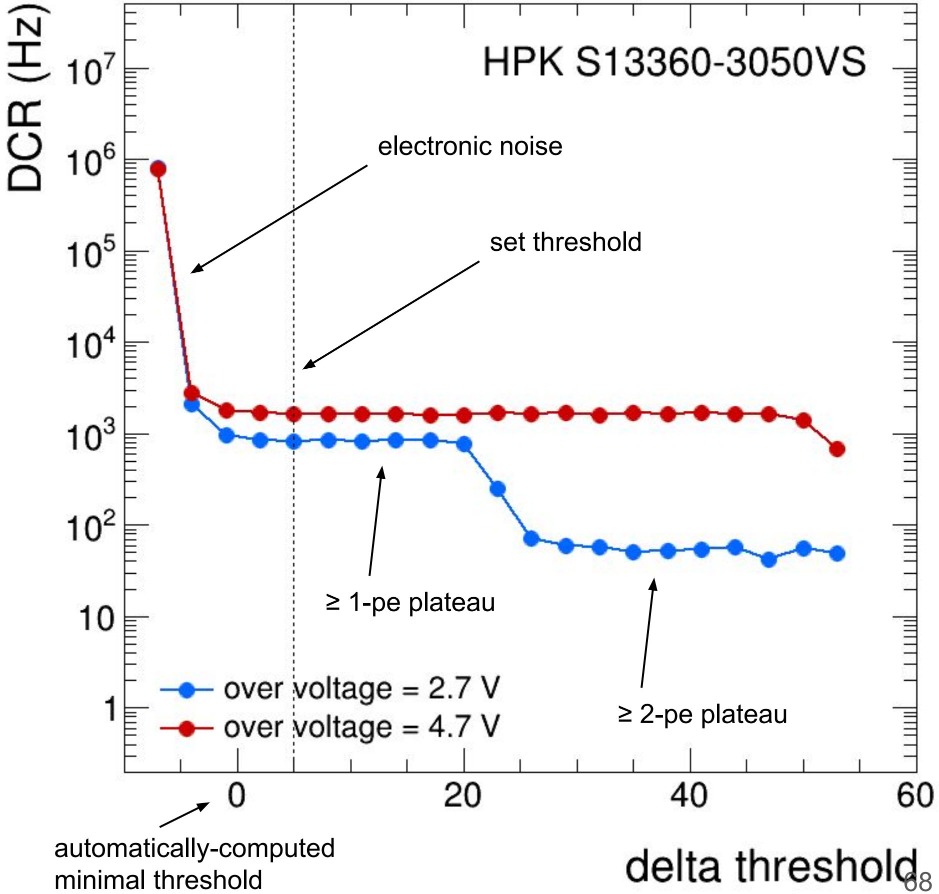
over voltage > 5 V

Photon counting with ALCOR









electronic noise

set threshold

≥ 1-pe plateau

≥ 2-pe plateau

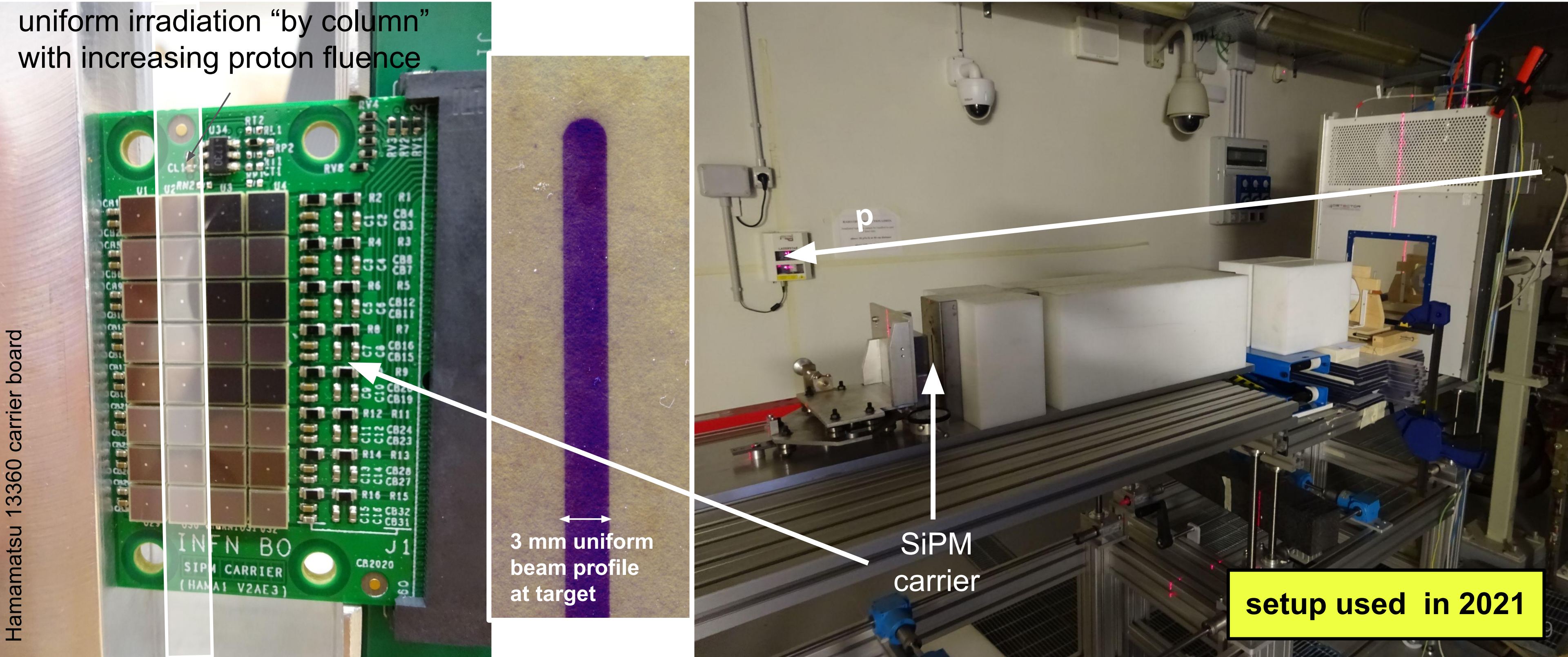
automatically-computed minimal threshold

Irradiation at Trento Proton-Therapy hall (TIFPA)

3x3 mm^2 SiPM sensors
4x8 “matrix” (carrier board)

multiple types of SiPM: **Hamamatsu** commercial (13360 and 14160)
FBK prototypes (rad.hard and timing optimised)

148 MeV protons → scattering system → collimation system → carrier board



uniform irradiation “by column” with increasing proton fluence

3 mm uniform beam profile at target

setup used in 2021

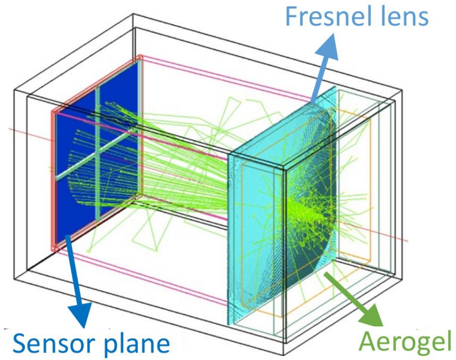
mRICH – modular RICH

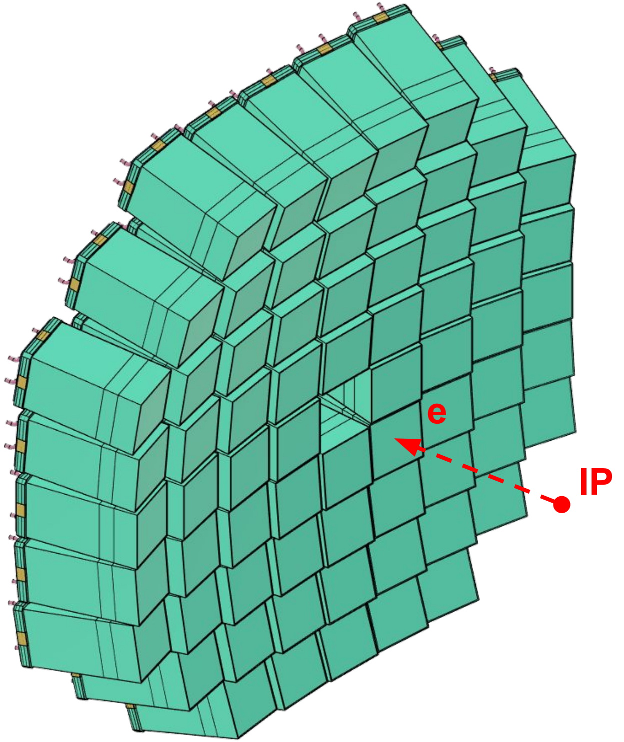
a compact, projective and modular RICH detector

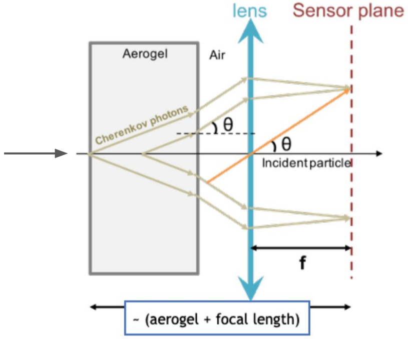
- **key components of a module**
  - 3-cm aerogel radiator (n = 1.03)
  - 6’’ acrylic Fresnel lens
  - mirror wall set
  - photosensor surface
- **smaller and sharper rings**

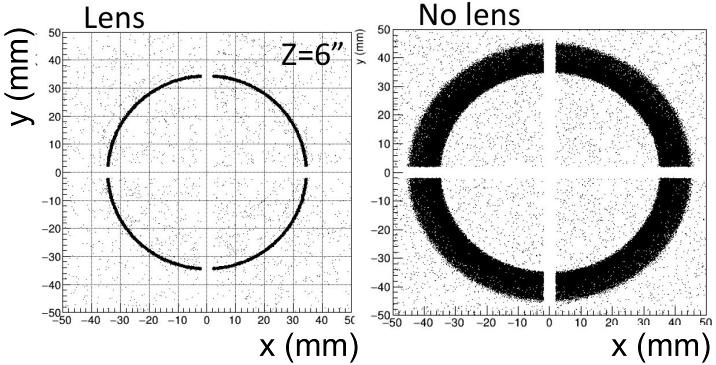
wrt proximity focusing

  - better resolution, less sensor area





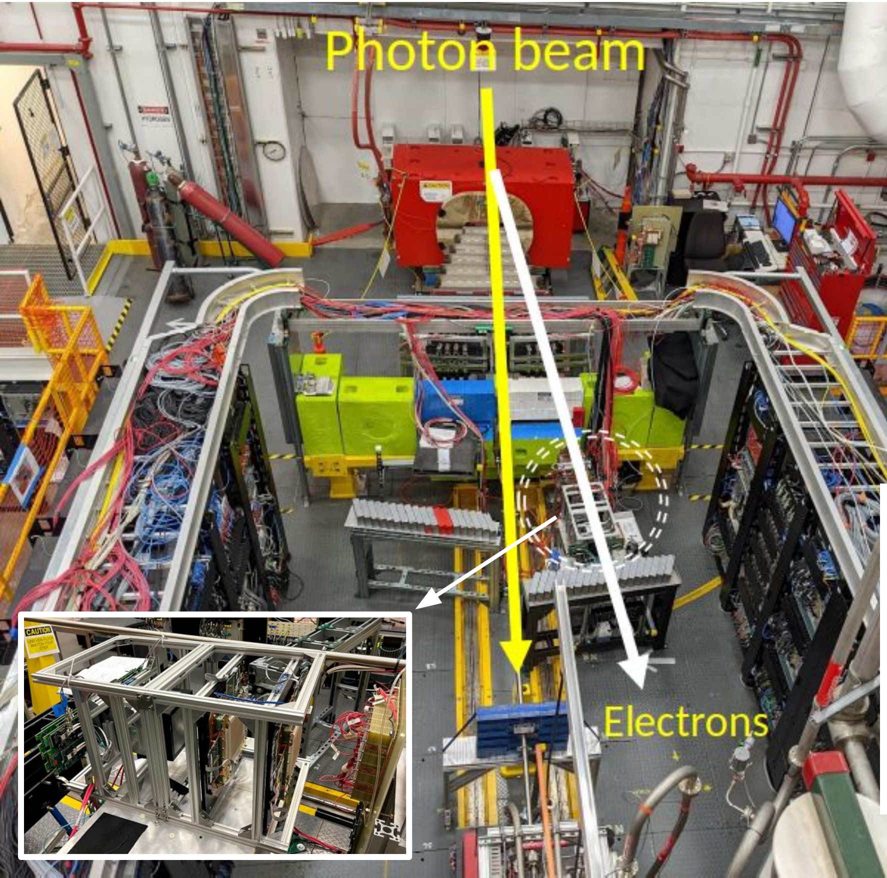


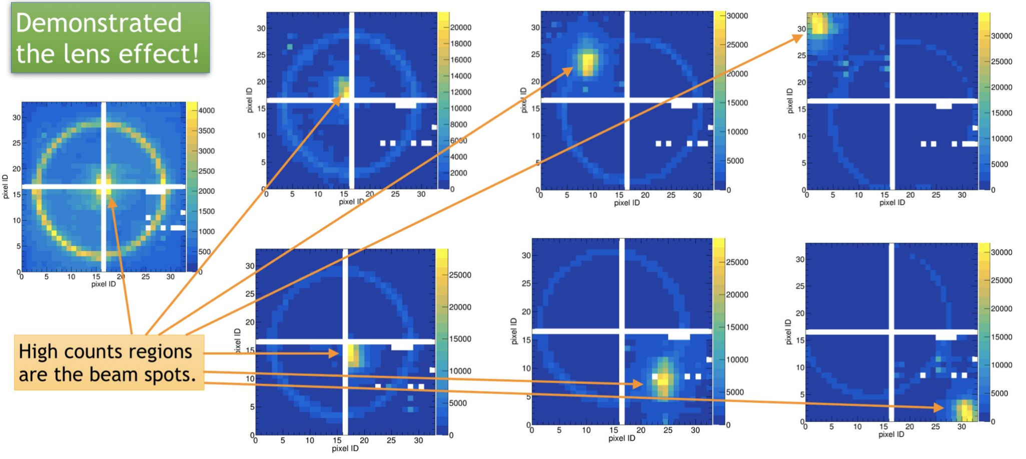


mRICH beam tests

verified working principle and validated simulation

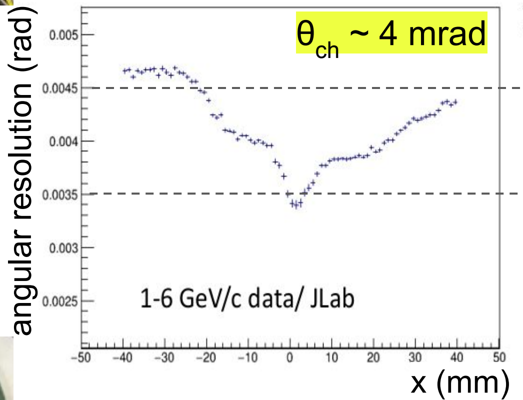
JLab Hall D





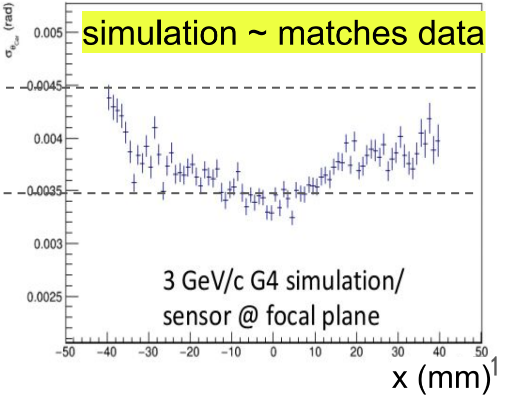
Demonstrated the lens effect!

High counts regions are the beam spots.



θ_{ch} ~ 4 mrad

1-6 GeV/c data/ JLab

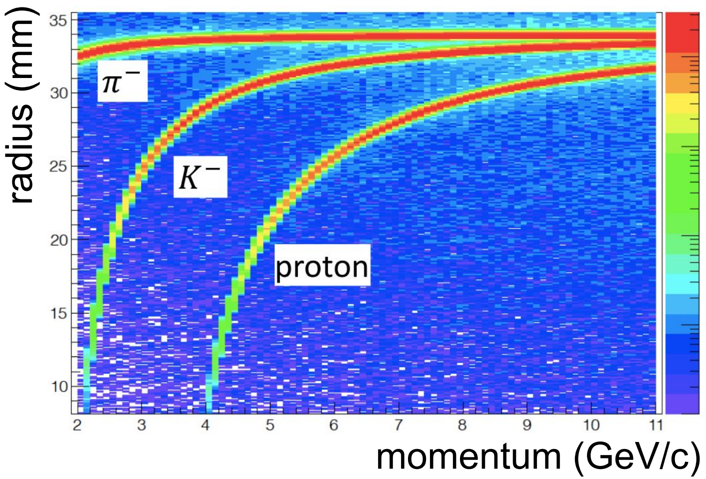


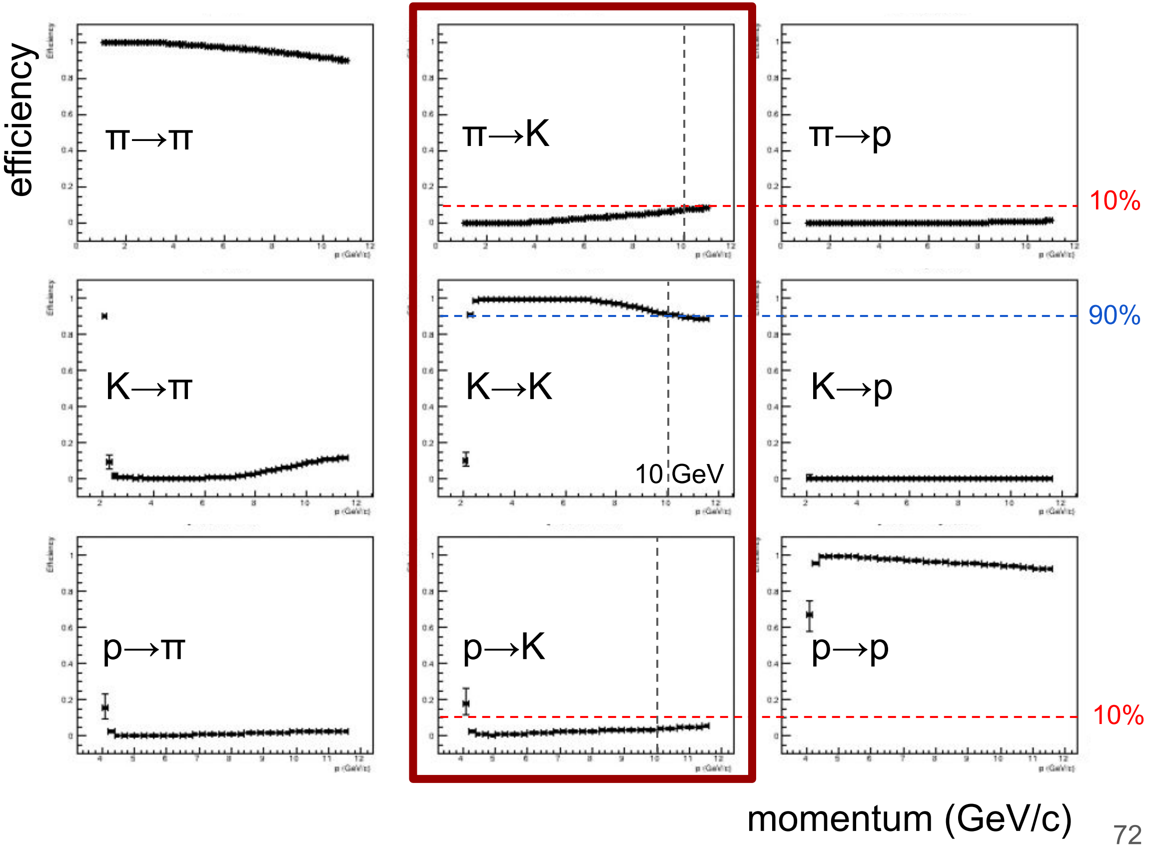
simulation ~ matches data

3 GeV/c G4 simulation/ sensor @ focal plane

mRICH performance simulation

full Geant4 simulation and reconstruction (single particle events)

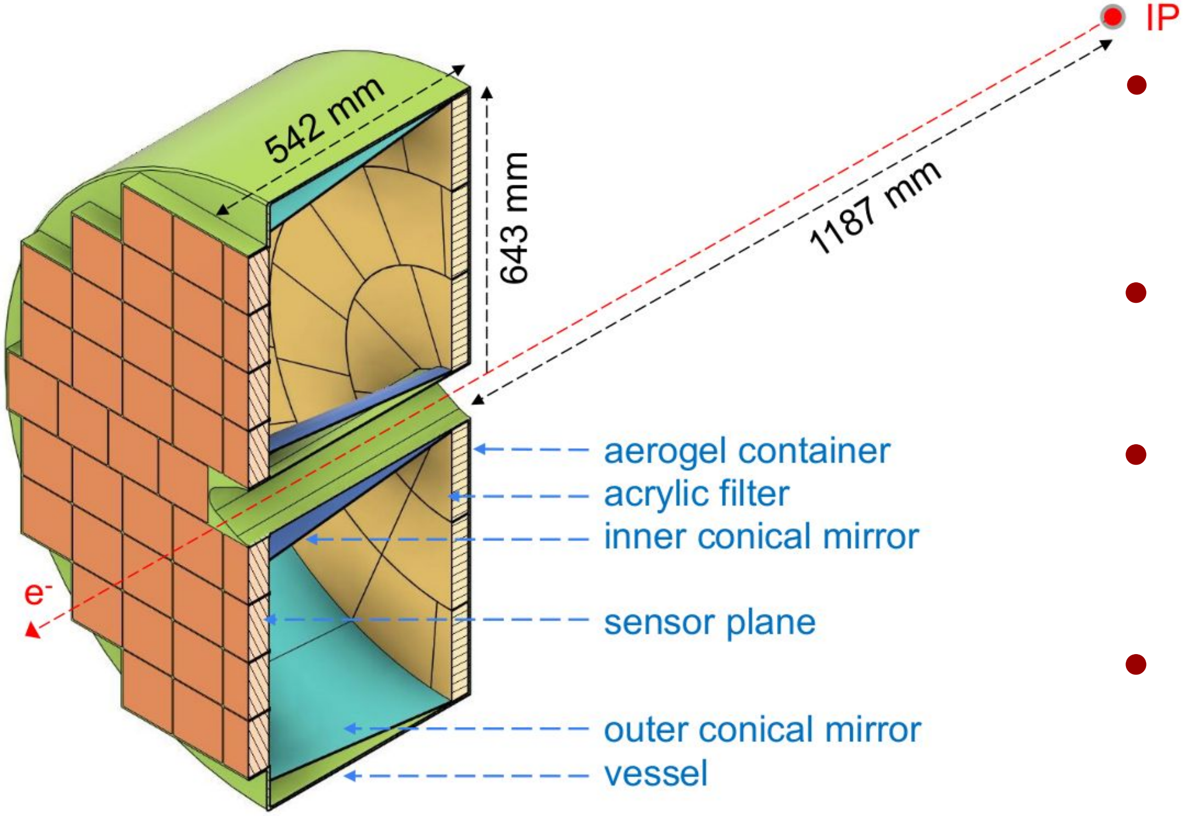




- **kaon-ID efficiency**
  - ○ K→K
  - ○ better than 90% up to 10 GeV/c
- **kaon mis-ID probability**
  - ○ π→K
  - ○ lower than 10% up to 10 GeV/c

pfRICH – proximity focusing RICH

a classical proximity focusing RICH with timing capability for MIPs

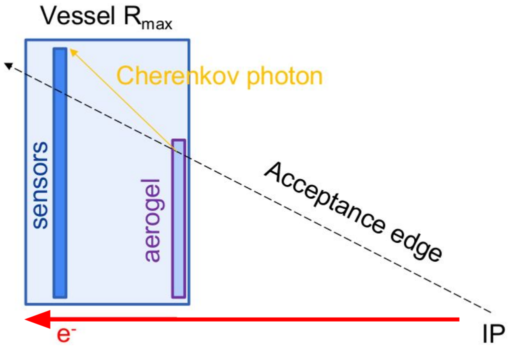


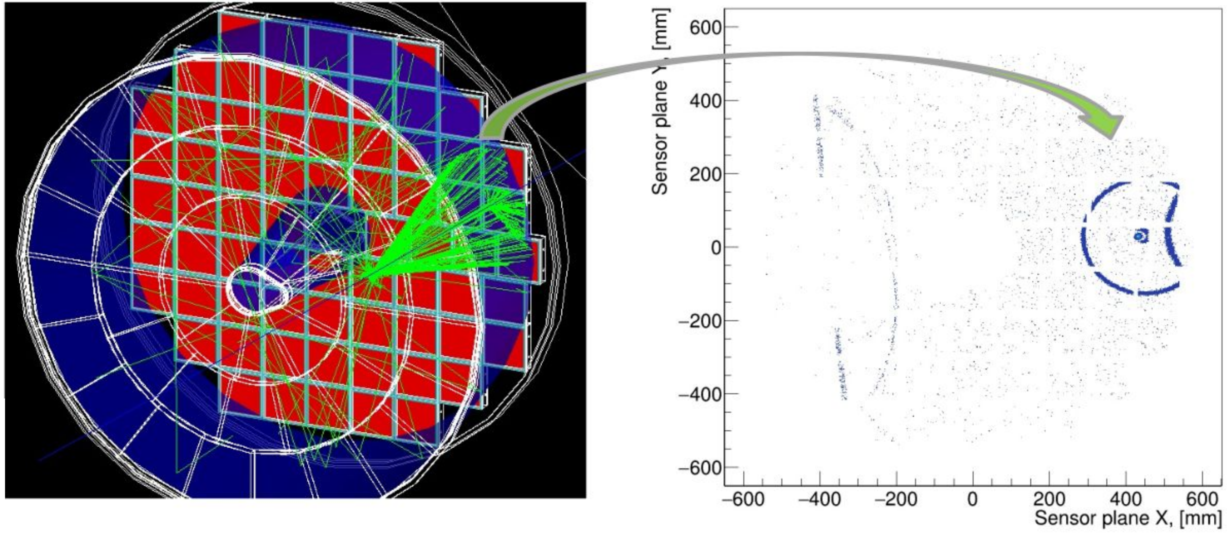
- **Cherenkov radiator**
  - 2.5 cm thick aerogel (n = 1.04-1.05)
  - with 300 nm acrylic filter
  - $\langle N_{pe} \rangle \sim 11\text{-}12$
- **proximity gap**
  - 45 cm long
  - nitrogen filled
- **HRPPD photosensors**
  - 120 x 120 mm tiles
  - pixelation: 32 x 32 pads
  - DC-coupled
- **timing capability**
  - MIP produces UV light (dozens of pe) in the HRPPD window
  - provide time with $\sigma < 20$ ps

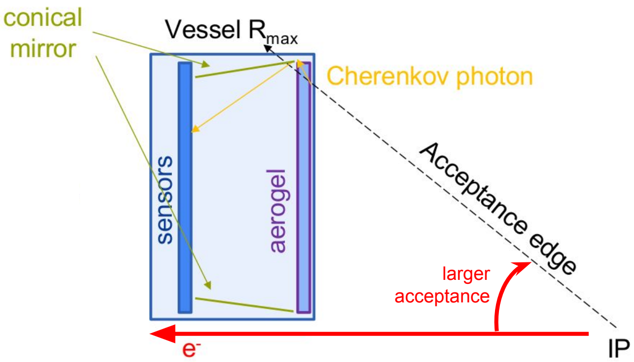
pfRICH acceptance optimisation

use side wall mirrors to increase pseudorapidity acceptance

without wall mirrors



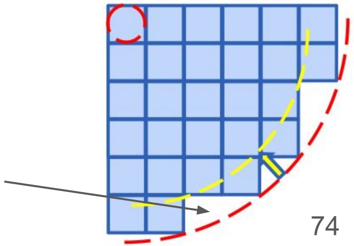




with wall mirrors

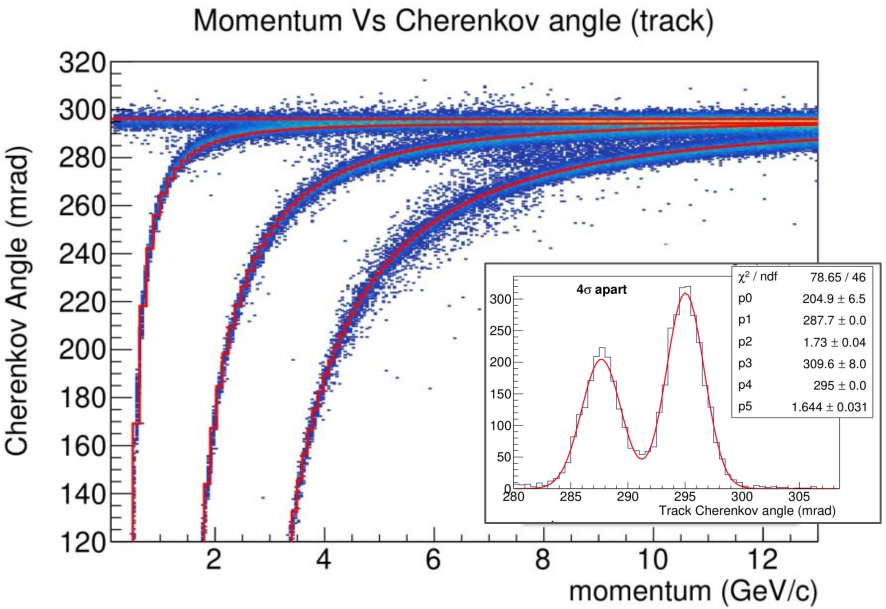
achieve -3.5 < η < -1.5 acceptance

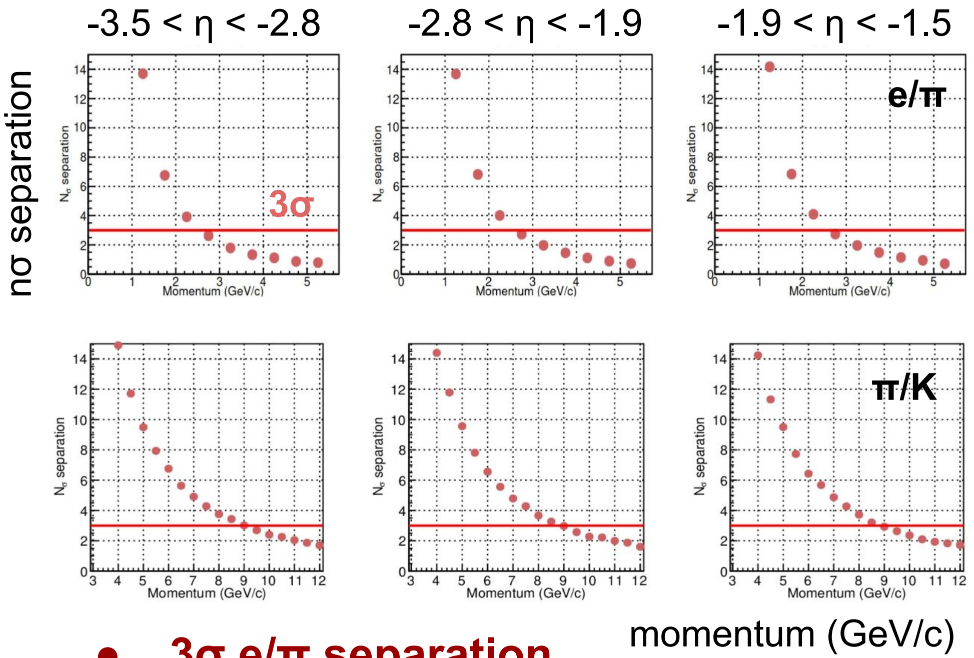
conical mirrors to avoid inefficiency of the sensor plane



pfRICH performance simulation

complete Geant4 simulation, event-level digitisation and reconstruction





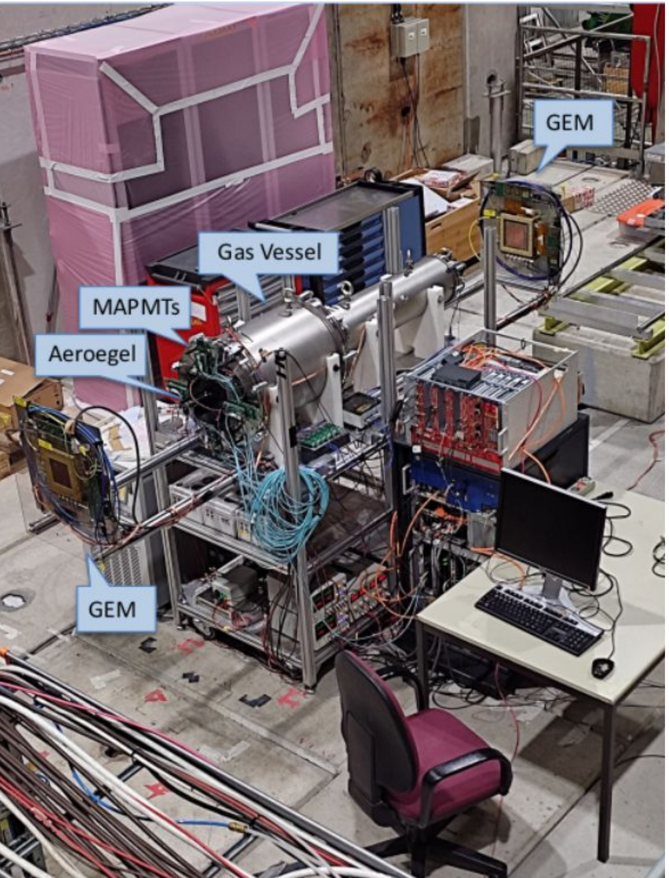
- **direct and reflected photon hits**
  - reconstruction algorithm capable of handling complex categories
  - angles in agreement with expectations

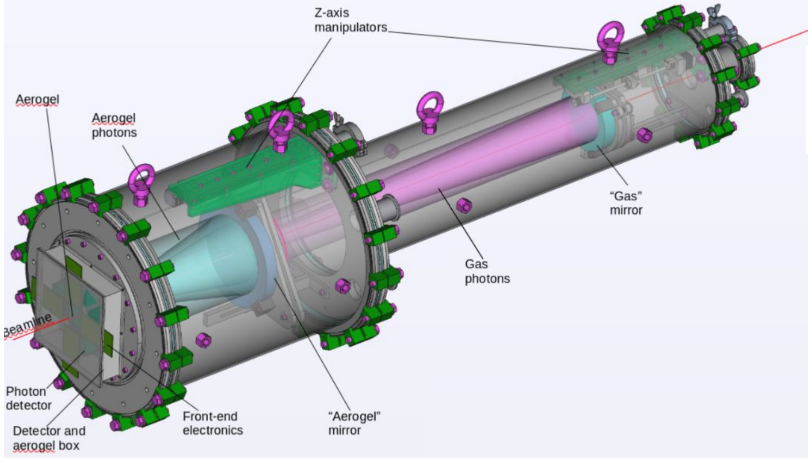
- **3σ e/π separation**
  - up to ~ 2.5 GeV/c
- **3σ π/K separation**
  - up to ~ 9.0 GeV/c

dRICH beam tests

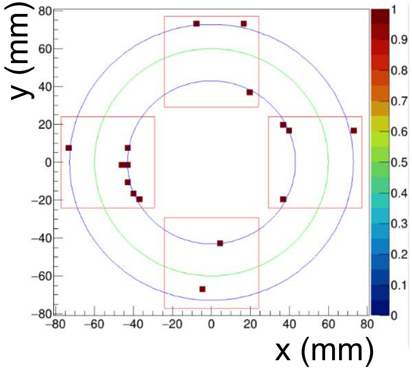
CERN SPS

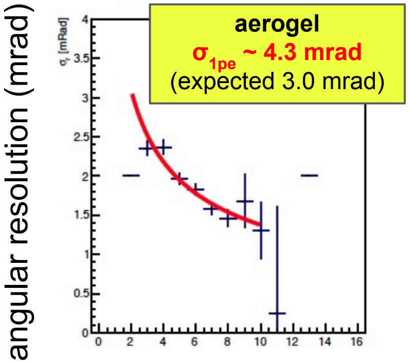
detector prototype to study dual radiator performance and interplay

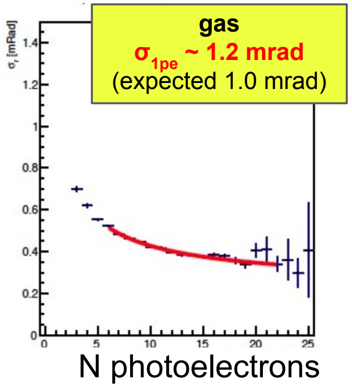




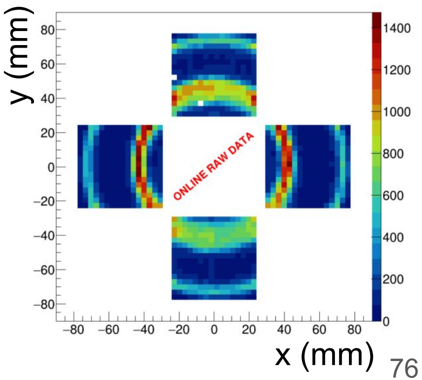
single event





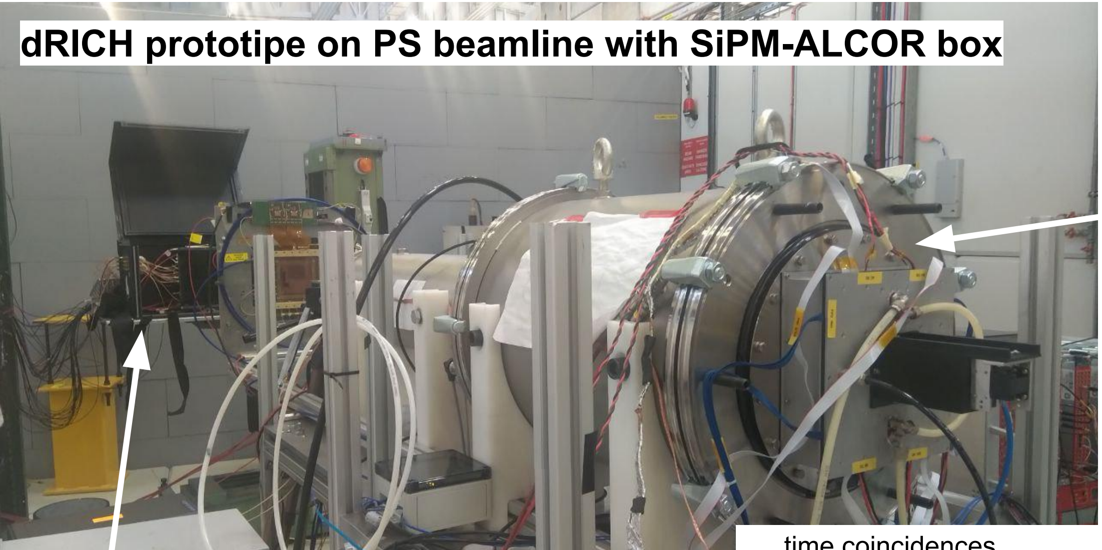


accumulated data



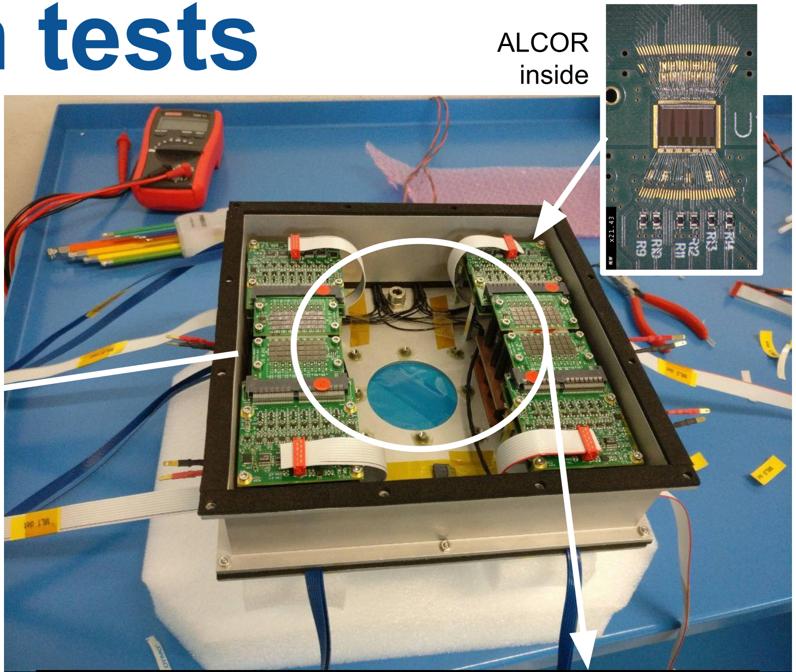
dRICH beam tests

successful operation of SiPM with complete readout chain



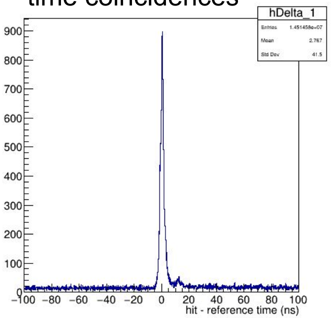
dRICH prototipe on PS beamline with SiPM-ALCOR box

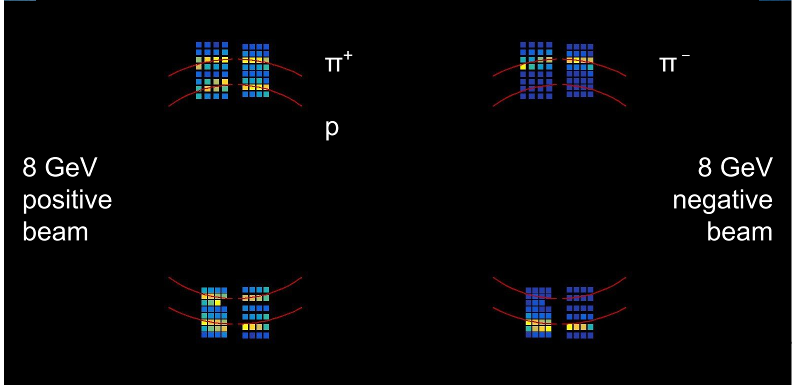
beamline shared with LAPPD test



ALCOR
inside

time coincidences





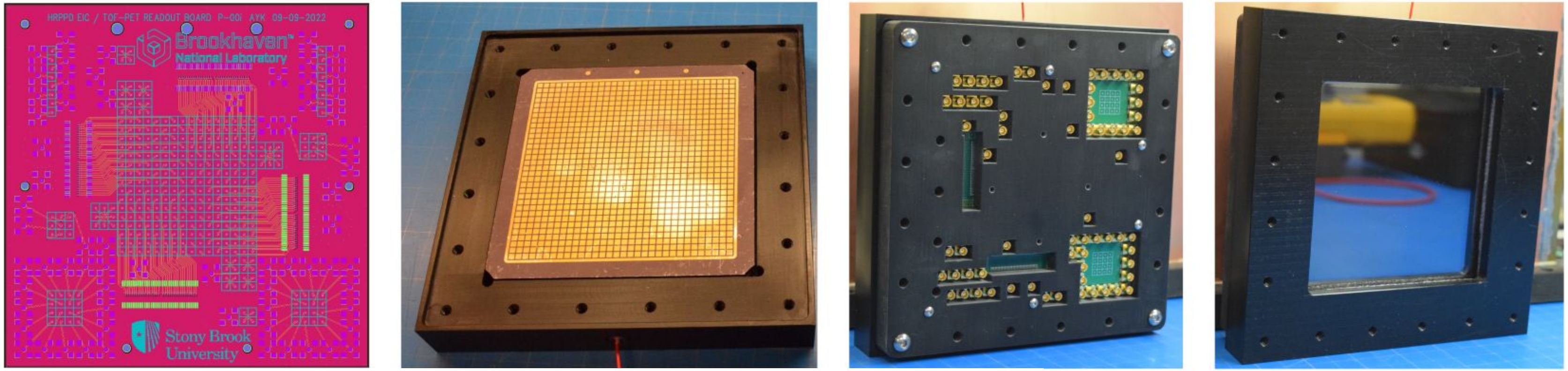
8 GeV
positive
beam

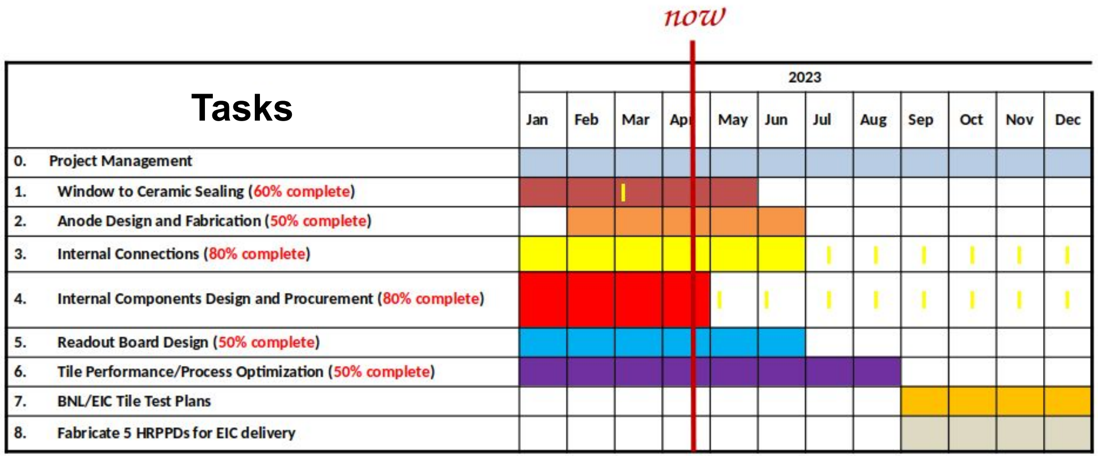
8 GeV
negative
beam

SiPM sensors were **irradiated** (up to 10^{10}) and **annealed** (150 hours at T = 150 C)

Status of photosensor development

developing HRPPD with Incom Inc. as part of the eRD110 (photosensors) consortium activities



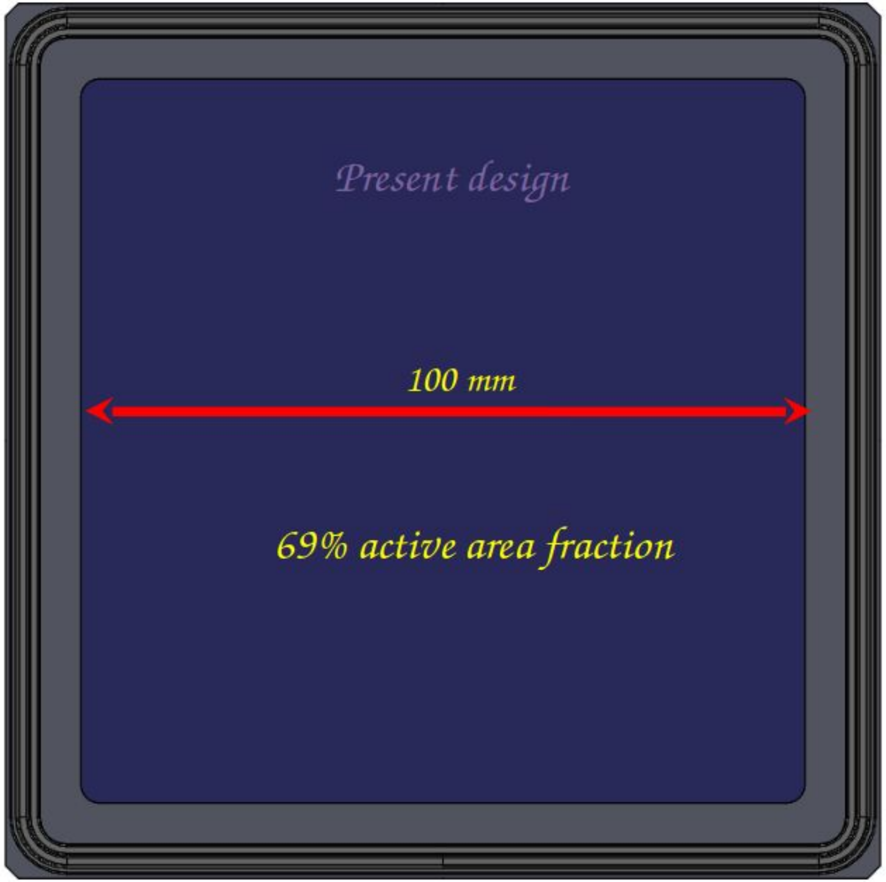


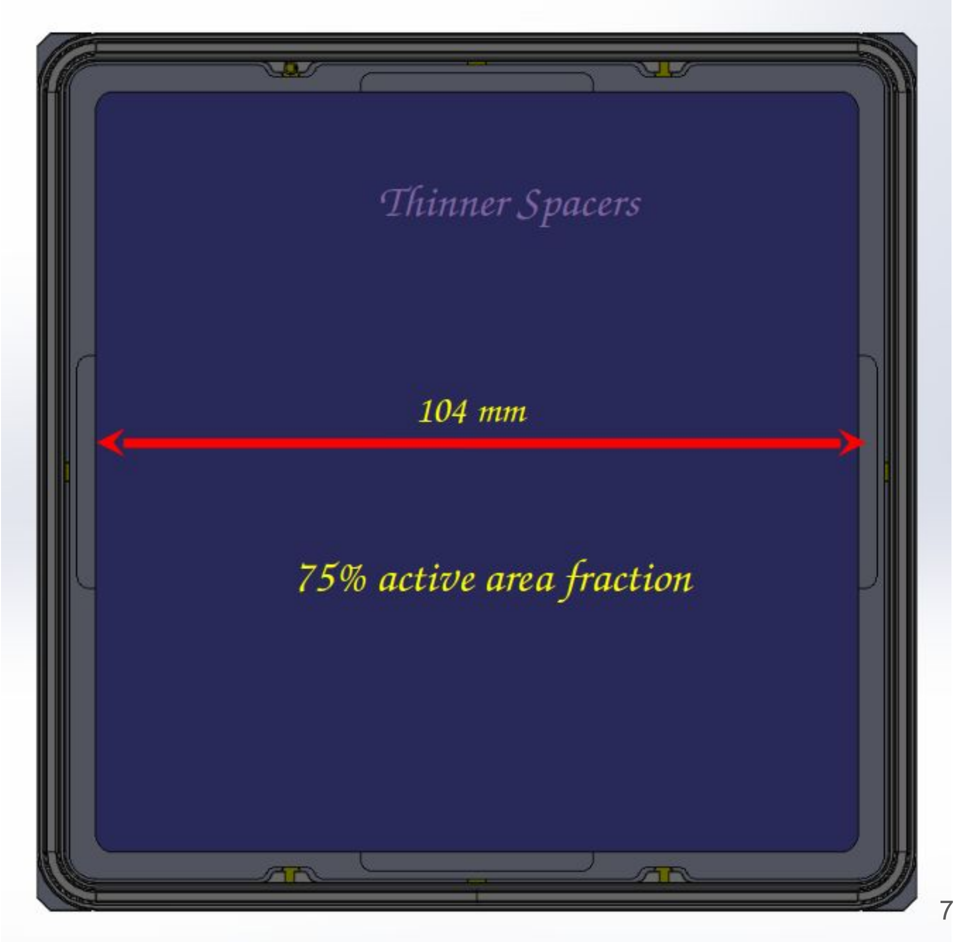
Tasks	2023											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0. Project Management	■	■	■	■	■	■	■	■	■	■	■	■
1. Window to Ceramic Sealing (60% complete)	■	■	■ |	■	■							
2. Anode Design and Fabrication (50% complete)		■	■	■	■	■						
3. Internal Connections (80% complete)	■	■	■	■	■	■	|	|	|	|	|	|
4. Internal Components Design and Procurement (80% complete)	■	■	■	■	|	|	|	|	|	|	|	|
5. Readout Board Design (50% complete)	■	■	■	■	■	■						
6. Tile Performance/Process Optimization (50% complete)	■	■	■	■	■	■	■	■				
7. BNL/EIC Tile Test Plans									■	■	■	■
8. Fabricate 5 HRPPDs for EIC delivery									■	■	■	■

first five HRPPD tiles for the EIC to be produced by Incom in 2023

after the final round of design modifications
manufacturing expected to start in August

HRPPD active area

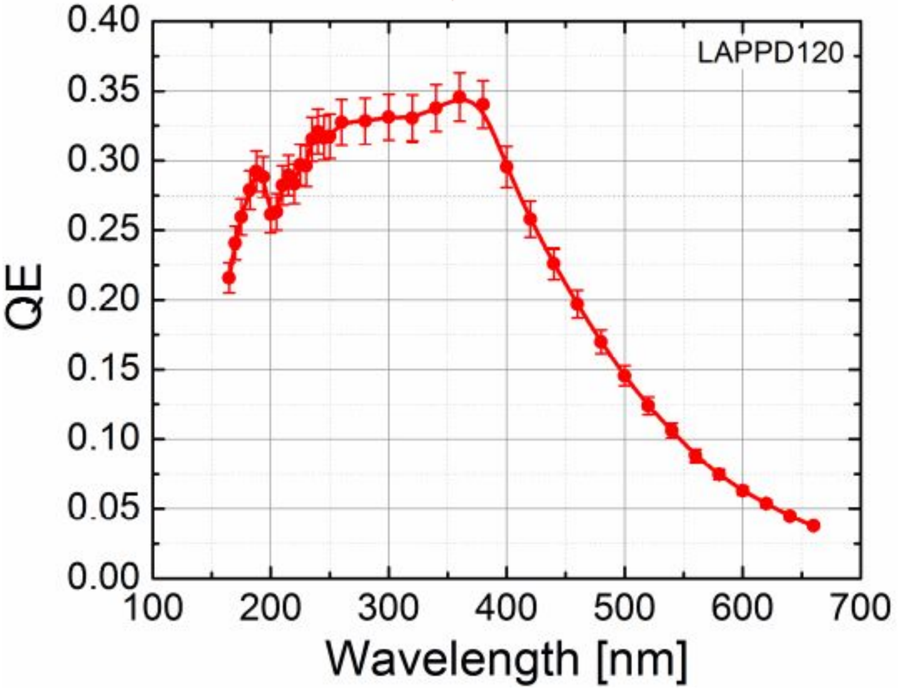


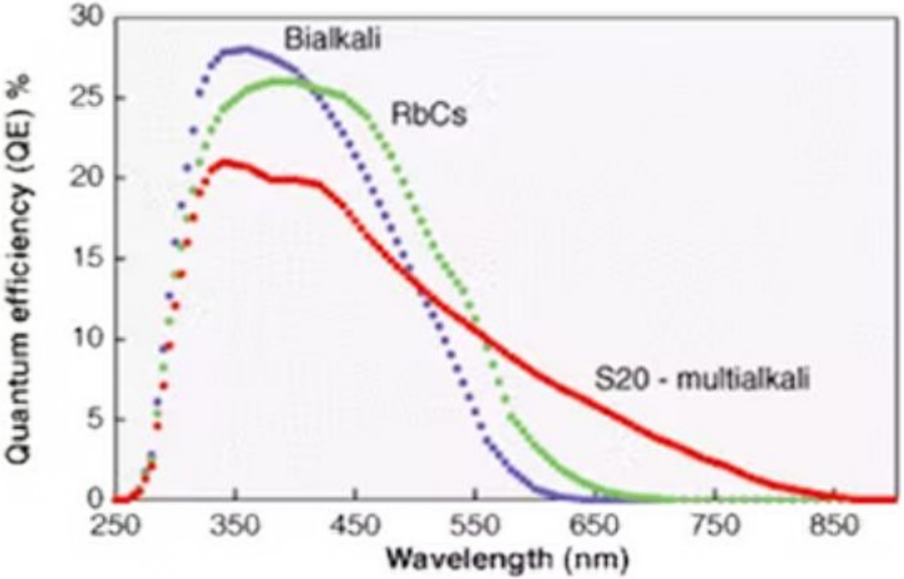


Photocathode optimisation

Goal: Shift QE max to longer wavelengths

Na_2KSb

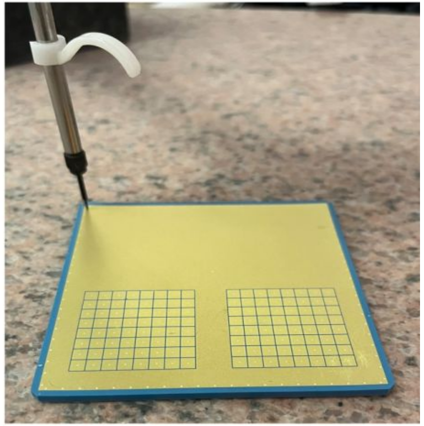


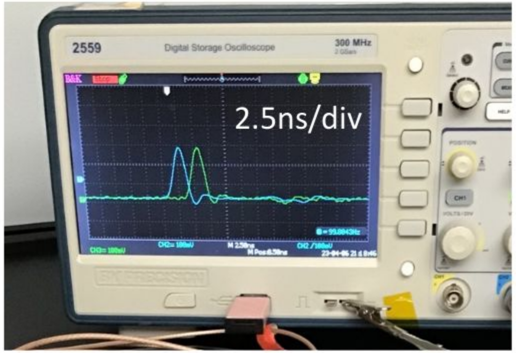


Test anodes: small size multi-layer ceramic prototype

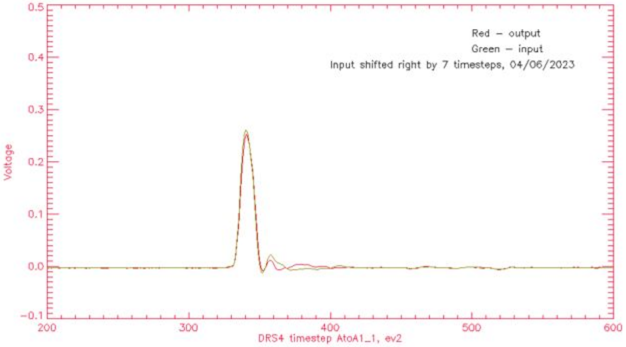
- First two 3” LTCC anode plates by Techtra (Poland) were examined at Incom
  - Flatness is tolerable on a 3.0mm thick plate, less so on a 2.5mm thick one
  - Vacuum tightness of the 3.0 mm plate confirmed
  - No measurable cross-talk introduced in the ceramic stack
    - 50 Ohm impedance matched isolated coplanar waveguide trace configuration
  - Small trace capacitance (few pF) confirmed

  - Certain signal degradation observed on the long (5 cm) traces





2.5ns/div

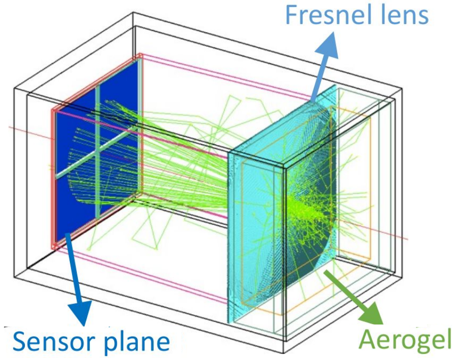


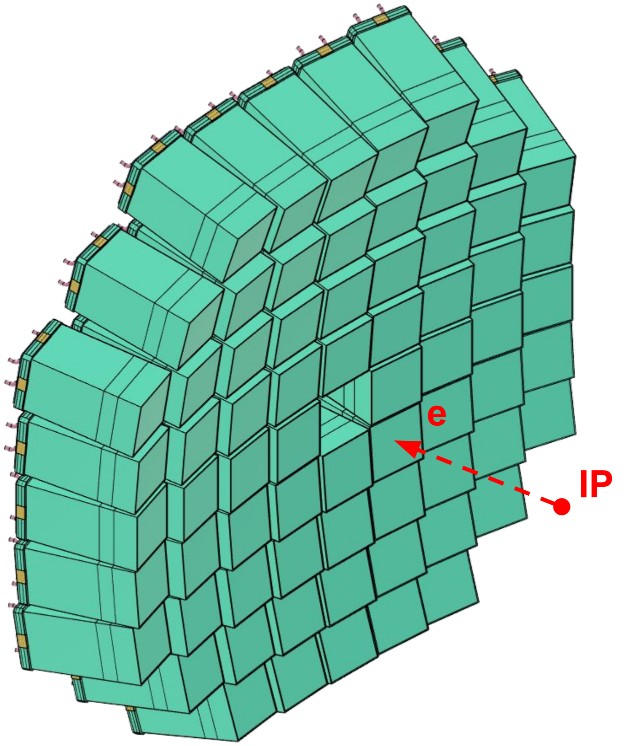
mRICH – modular RICH

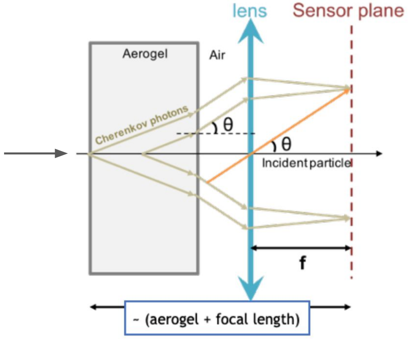
a compact, projective and modular RICH detector

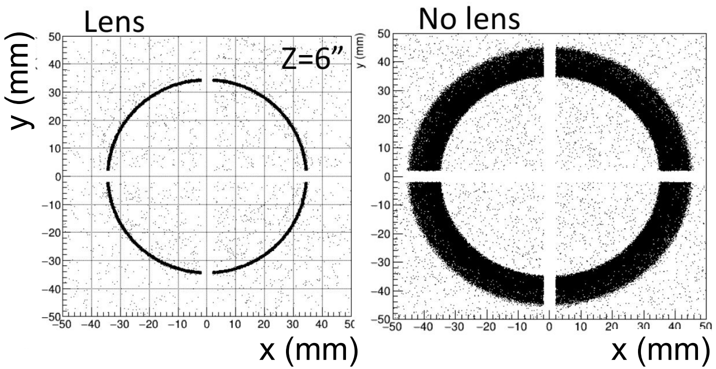
- **key components of a module**
  - 3-cm aerogel radiator (n = 1.03)
  - 6'' acrylic Fresnel lens
  - mirror wall set
  - photosensor surface
- **smaller and sharper rings**

  wrt proximity focusing
  - better resolution, less sensor area







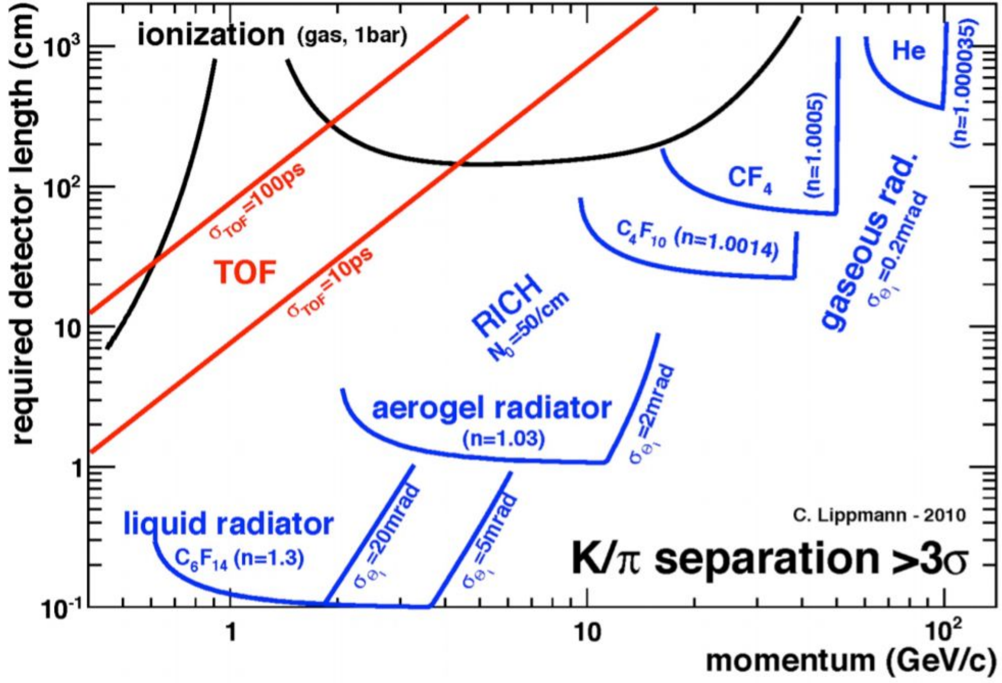


Particle identification techniques

EIC detector need more than one technique to cover the entire momentum ranges

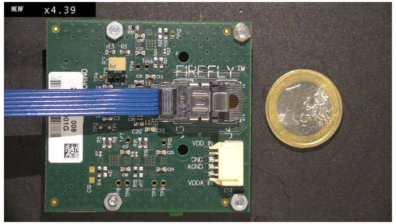
- **central (< 6 GeV/c)**
  - TPC, TOF, DIRC
- **backward (< 10 GeV/c)**
  - aerogel RICH
- **forward (< 50 GeV/c)**
  - gaseous RICH

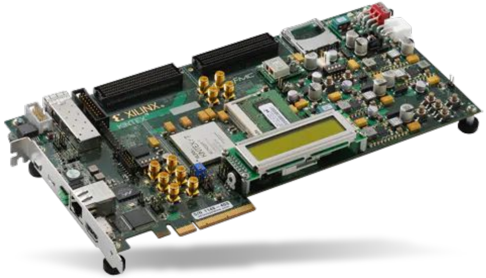
C.Lippmann, NIMA 666 (2012) 148



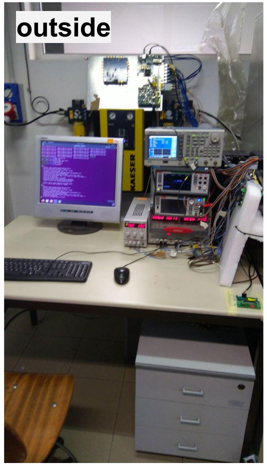
Characterisation setup

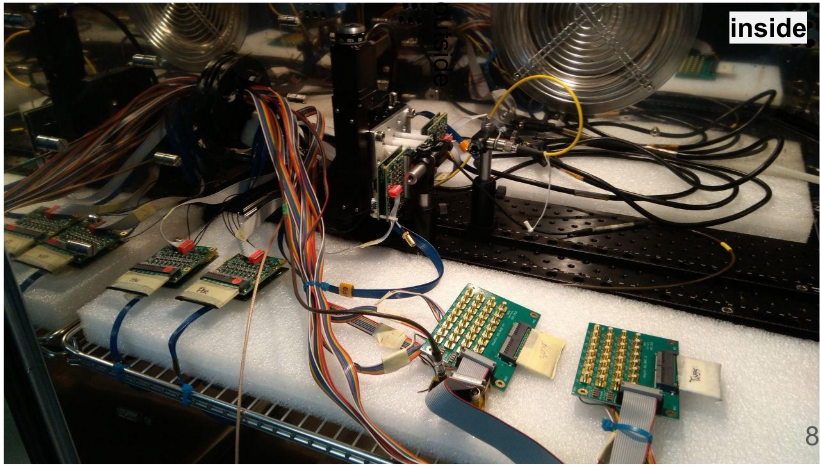
- **climatic chamber**
  low-temperature operation (T = -30 C)
- **2x 40-channel multiplexers**
  source meter
- **ALCOR-based front-end chain**
  FPGA (Xilinx) readout
  automatic measurement of 4x SiPM boards (128 channels)



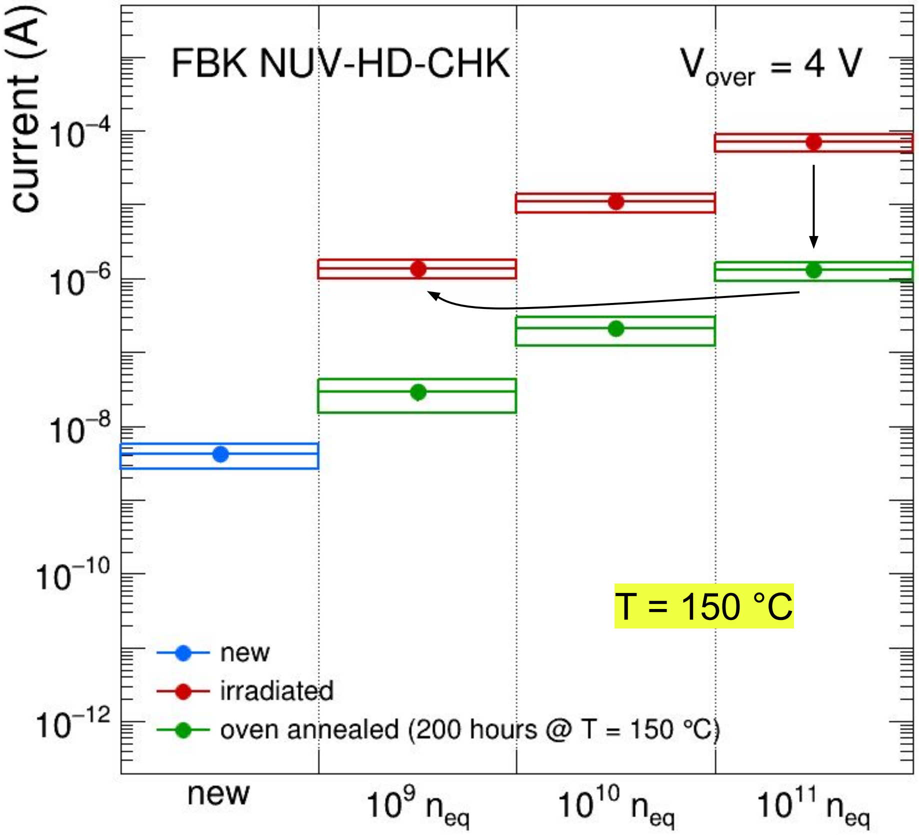


@BO



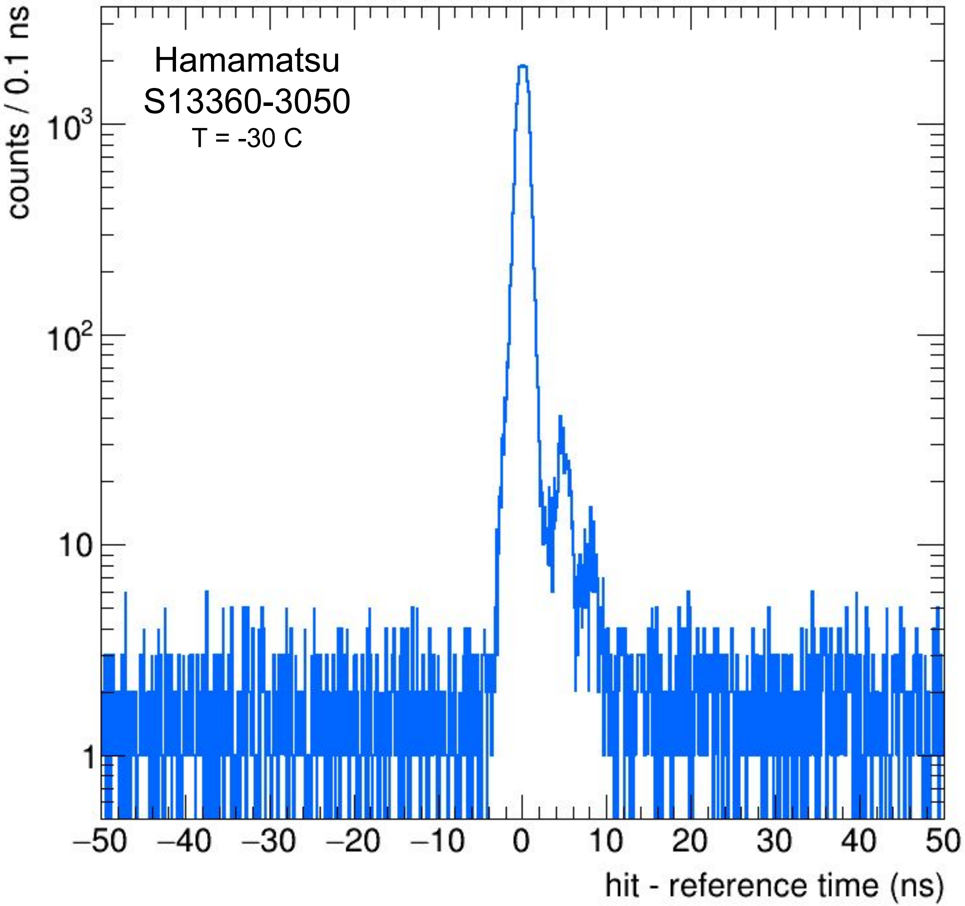


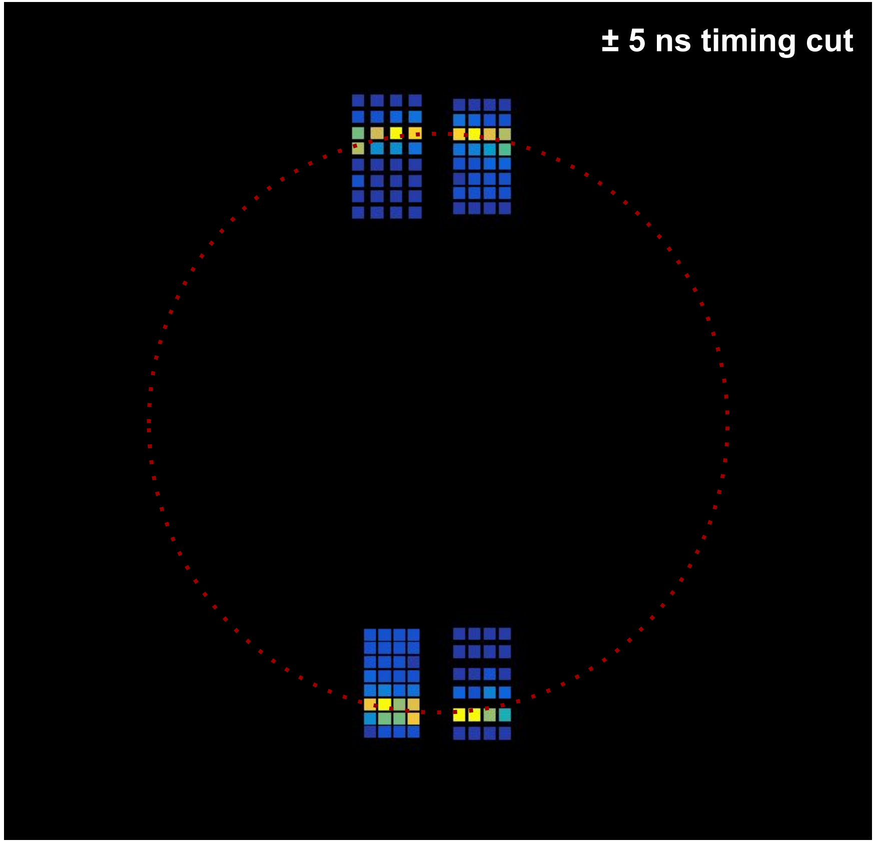
High-temperature annealing recovery



<u>~ 100x current reduction</u>
sensor functions as if it
received ~ 100x less fluence

after irradiation with $2 \cdot 10^9$ n_{eq}/cm^2 fluence (protons) and oven annealing at T = 150 C for 150 hours





after irradiation with $2 \cdot 10^9\ n_{eq}/cm^2$ fluence (protons)
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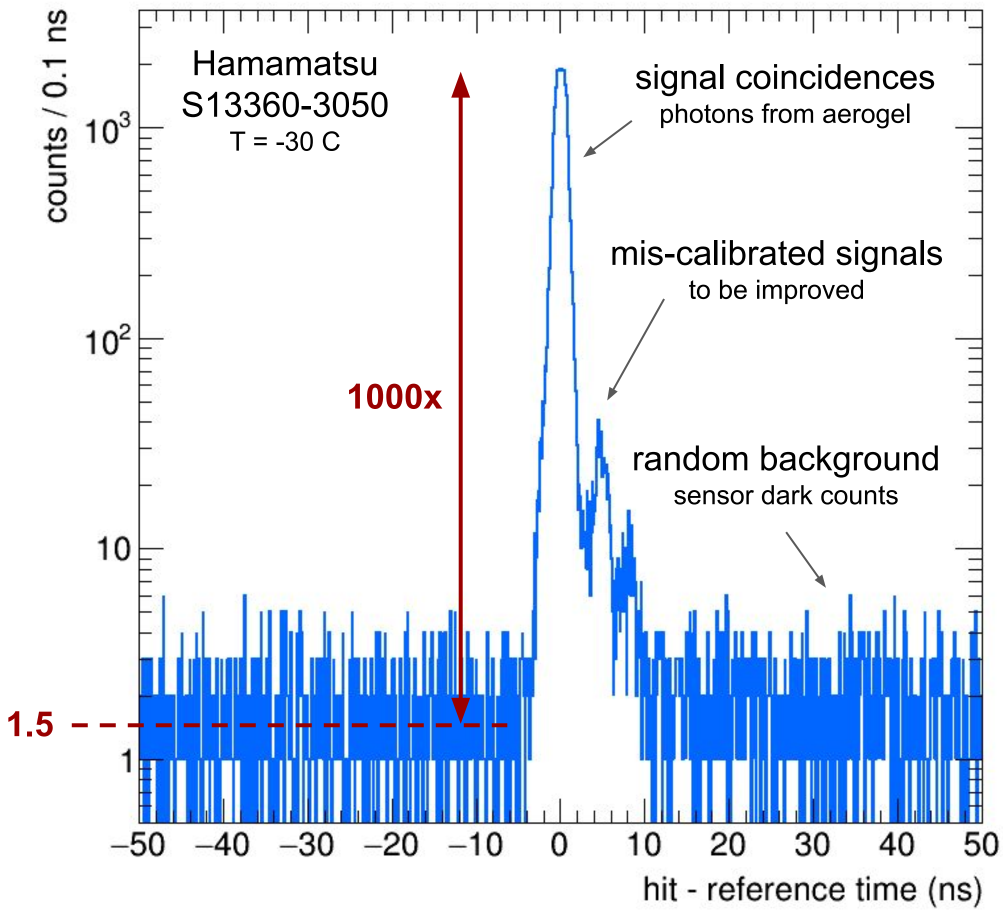
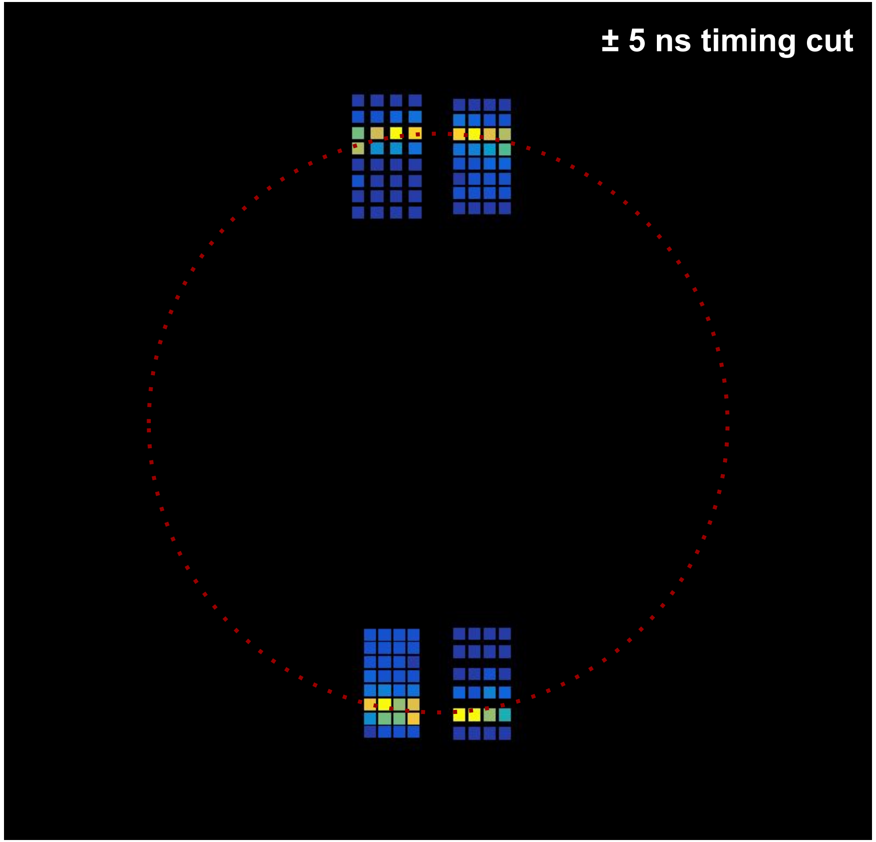
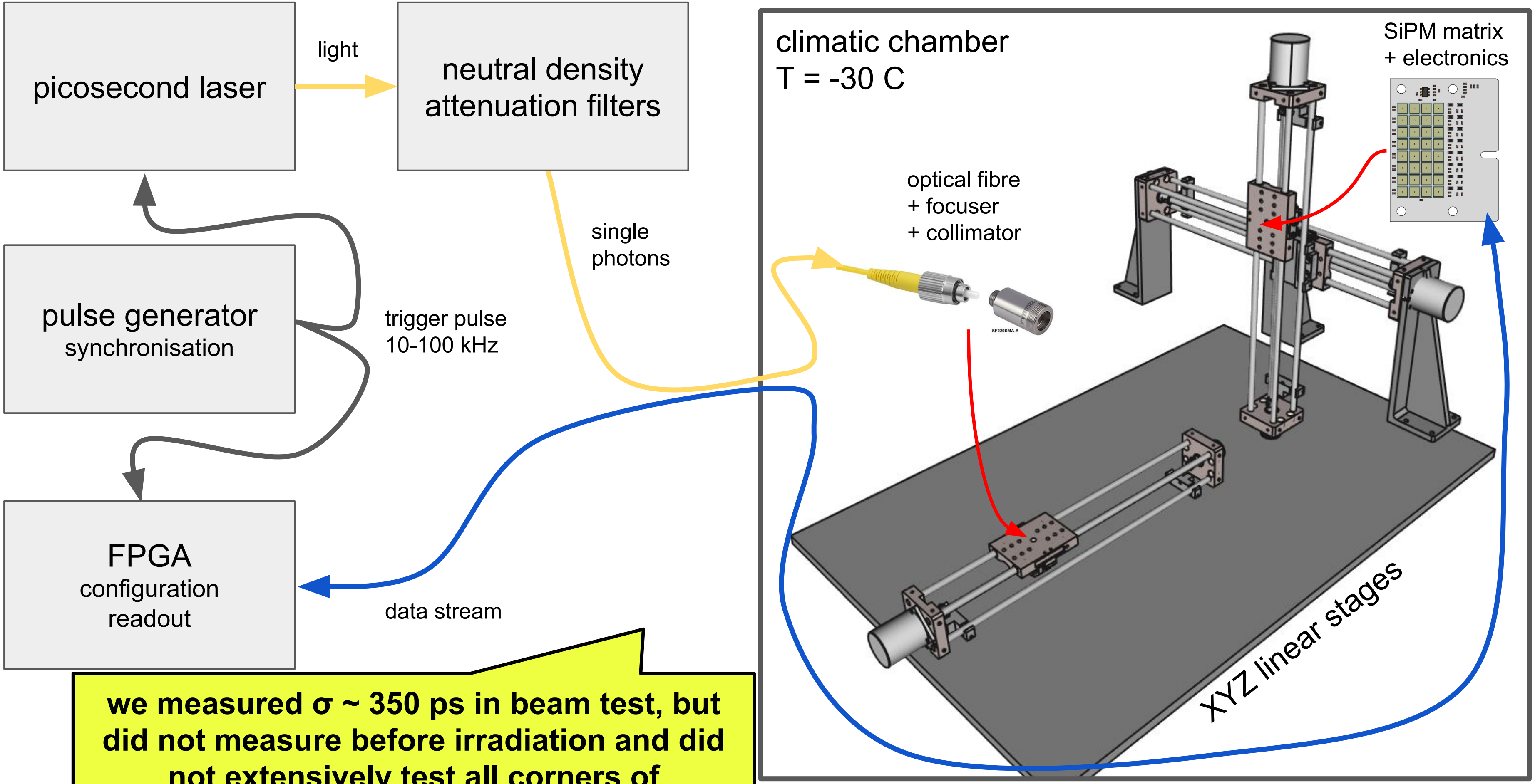




sensor DCR ~ 15 kHz

new laser setup for detailed characterisation of SiPM before/after irradiation/annealing



picosecond laser

light

neutral density attenuation filters

pulse generator
synchronisation

trigger pulse
10-100 kHz

single
photons

FPGA
configuration
readout

data stream

climatic chamber
T = -30 C

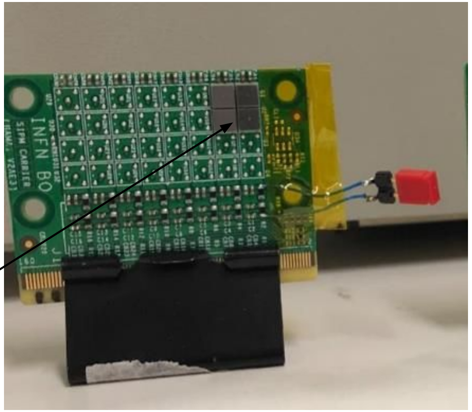
optical fibre
+ focuser
+ collimator

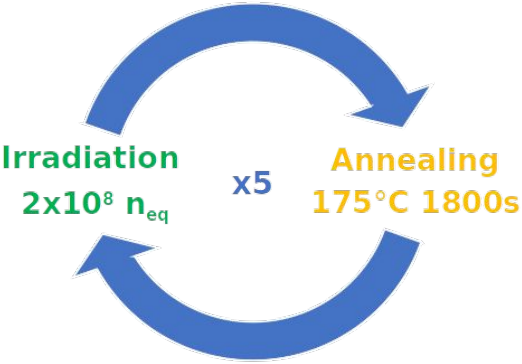
SiPM matrix
+ electronics

XYZ linear stages

we measured σ ~ 350 ps in beam test, but did not measure before irradiation and did not extensively test all corners of SiPM+electronics phase-space, do it in lab

Online annealing




Irradiation
$2\mathrm{x}10^8$ n_{eq}

x5

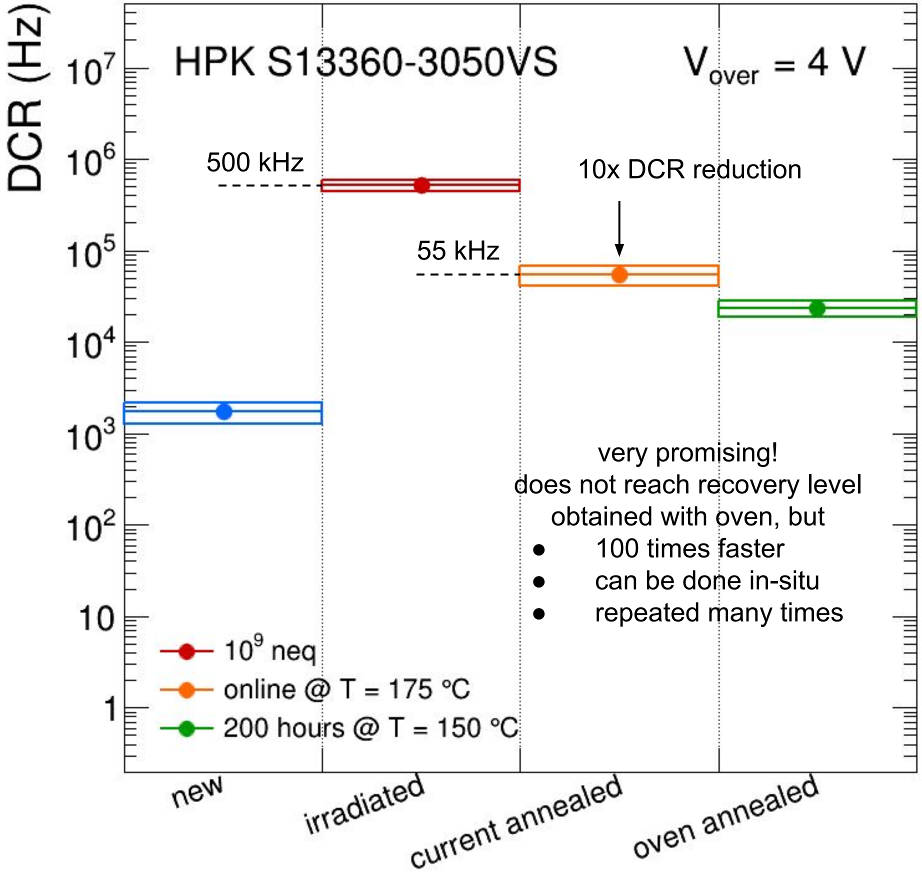
Annealing
175°C 1800s

explore solutions for in-situ annealing

- total fluence of 10^9 n_{eq}
  - delivered in 5 chunks
  - each of 2 10^8 n_{eq}
- interleave by annealing
  - forward bias, ~ 1 W / sensor
  - T = 175 °C, thermal camera
  - 30 minutes
- preliminary tests
  - Hamamatsu S13360-3050

Online annealing

explore solutions for in-situ annealing

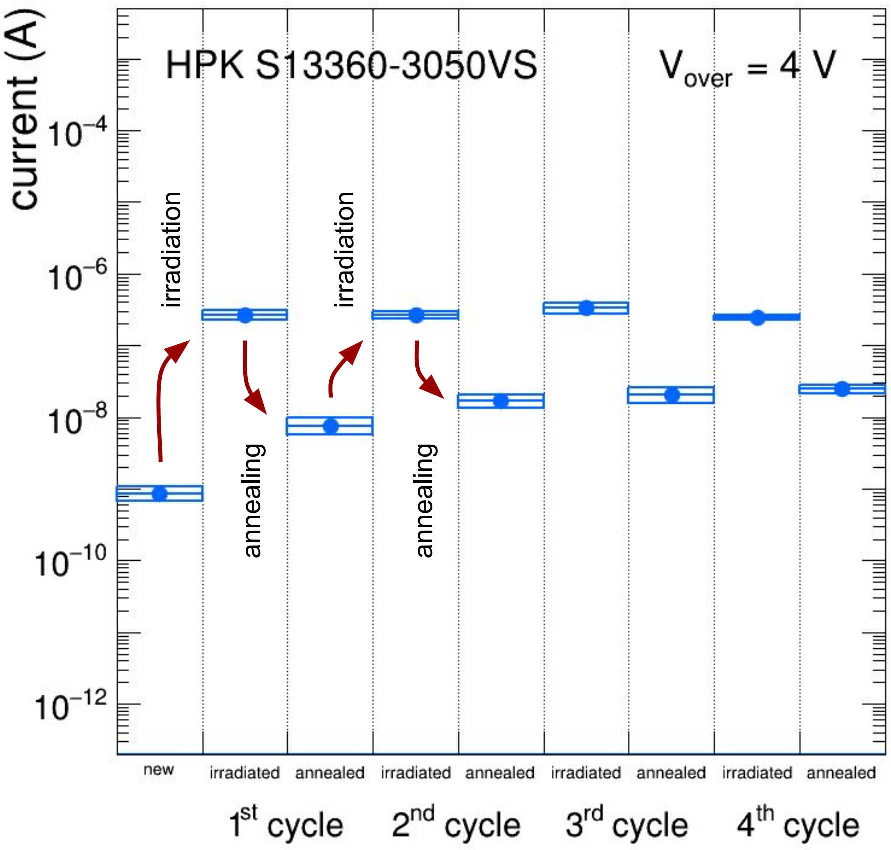


very promising!
does not reach recovery level obtained with oven, but

- 100 times faster
- can be done in-situ
- repeated many times

Repeated irradiation-annealing cycles

oven annealing

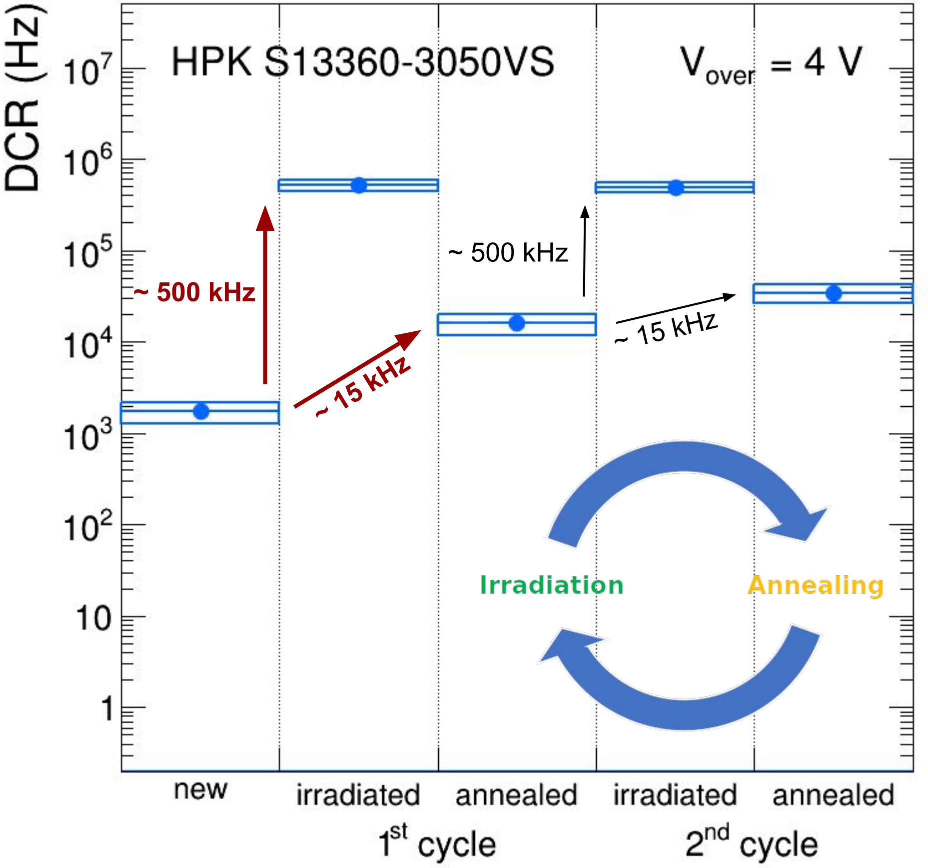


test reproducibility of repeated irradiation-annealing cycles

simulate a realistic experimental situation

- campaign is concluded
  - partial results reported here
  - all measurements in following slides
- 4 cycles performed in 2022
  - irradiation fluence/cycle of 10^9 n_{eq}
  - annealing in oven for 150 hours at 150 °C
- interleaved with full characterisation
  - new
  - after each irradiation
  - after each annealing

Repeated irradiation-annealing cycles



test reproducibility of repeated irradiation-annealing cycles

simulate a realistic experimental situation

- consistent irradiation damage
  - DCR increases by ~ 500 kHz (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- consistent residual damage
  - ~ 15 kHz (@ Vover = 4) of residual DCR
  - builds up after each irradiation-annealing

annealing cures same fraction of newly-produced damage

~ 97% for HPK S13360-3050 sensors

SiPM option for RICH optical readout

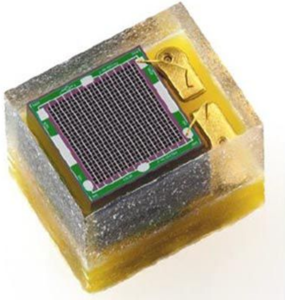
- **pros**
  - cheap
  - high photon efficiency
  - excellent time resolution
  - insensitive to magnetic field

- **cons**

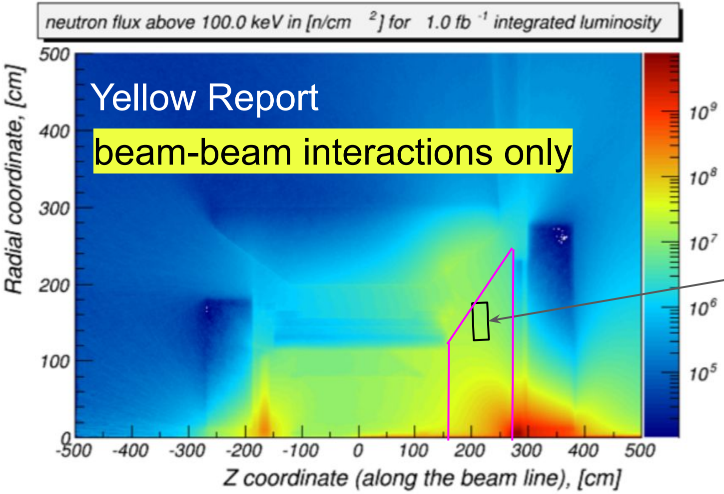
large dark count rates

not radiation tolerant

R&D focus on risk-mitigation strategies

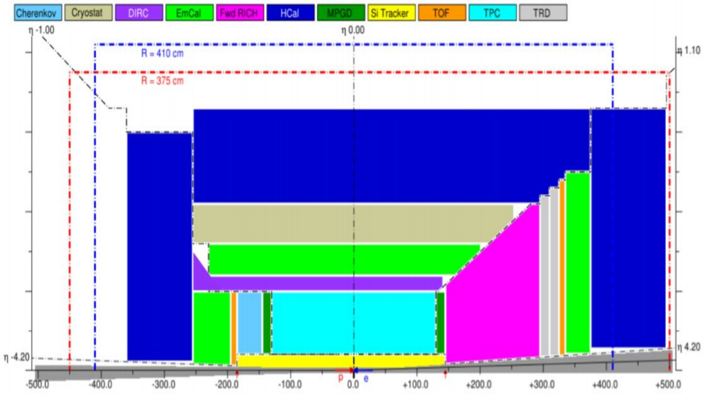


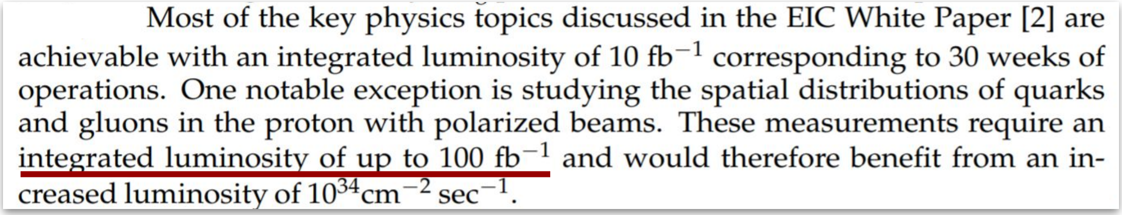
Neutron fluxes and SiPM radiation damage



Yellow Report

beam-beam interactions only





Most of the key physics topics discussed in the EIC White Paper [2] are achievable with an integrated luminosity of 10 fb^{-1} corresponding to 30 weeks of operations. One notable exception is studying the spatial distributions of quarks and gluons in the proton with polarized beams. These measurements require an integrated luminosity of up to 100 fb^{-1} and would therefore benefit from an increased luminosity of $10^{34}\text{cm}^{-2}\ \text{sec}^{-1}$.

possible location of dRICH photosensors
neutron fluence for 1 fb^{-1} → 1-5 10^7 n/cm^2 (> 100 keV ~ 1 MeV n_{eq})

- radiation level is moderate
- magnetic field is high(ish)

R&D on SiPM as potential photodetector for dRICH, main goal
study SiPM usability for Cherenkov up to 10^{11} 1-MeV n_{eq}/cm^2

notice that 10^{11} n_{eq}/cm^2 would correspond to 2000-10000 fb^{-1} integrated $\mathscr{L}$
quite a long time of EIC running before we reach there, if ever
it would be between 6-30 years of continuous running at $\mathscr{L} = 10^{34}\ s^{-1}\ cm^{-2}$

→ better do study in smaller steps of radiation load

10^9 1-MeV n_{eq}/cm^2	*most of the key physics topics*
10^{10} 1-MeV n_{eq}/cm^2	*should cover most demanding measurements*
10^{11} 1-MeV n_{eq}/cm^2	*possibly never reached*

SiPM radiation damage and mitigation strategies

Radiation damages increase currents, affects V_{bd} and increase DCR
With very high radiation loads can bring to baseline loss, but…
does not seem to be a problem up to 10^{11} n_{eq}/cm^2 (if cooled, T = -30 C)

If the baseline is healthy, single-photon signals can be be detected
one can work on reducing the DCR with following mitigation strategies:

- Reduce operating temperatures (**cooling**)
- Use **timing**
- High-temperature **annealing** cycles

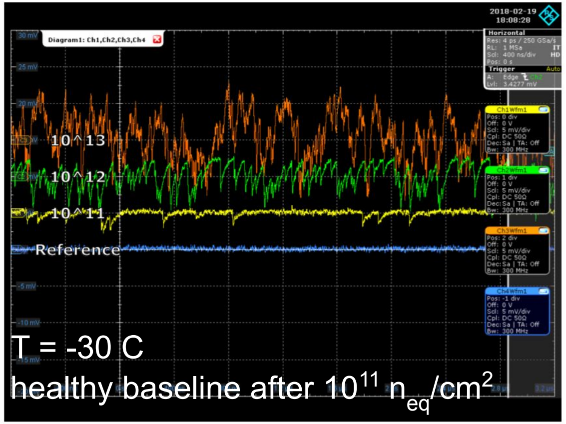
Key point for R&D on RICH optical readout with SiPM:

- demonstrate capability to measure Single Photon
- keep DCR under control (ring imaging background)

despite radiation damages

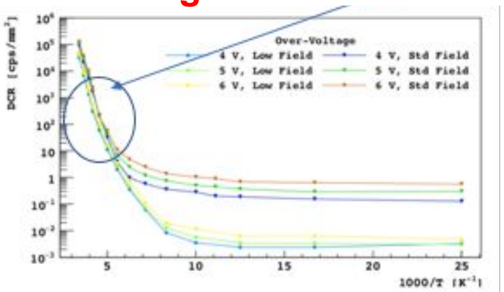
Calvi, NIM A 922 (2019) 243

10^{11}

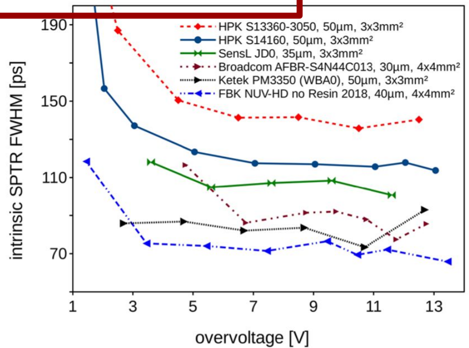


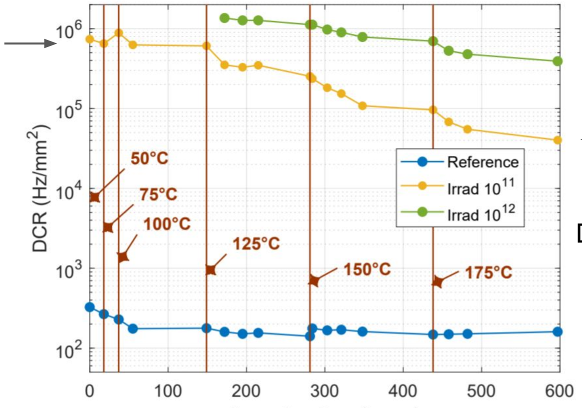
T = -30 C
healthy baseline after 10^{11} n_{eq}/cm^2

cooling



timing



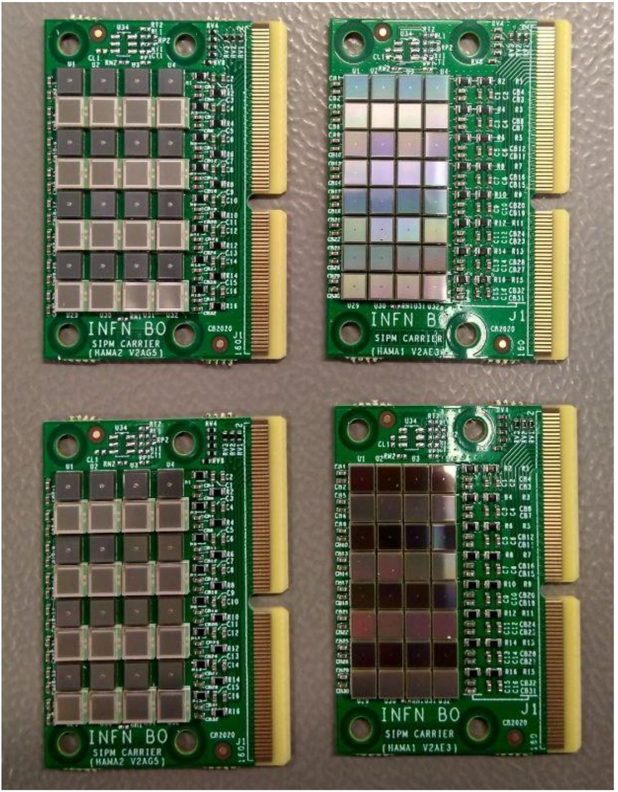


20x less DCR

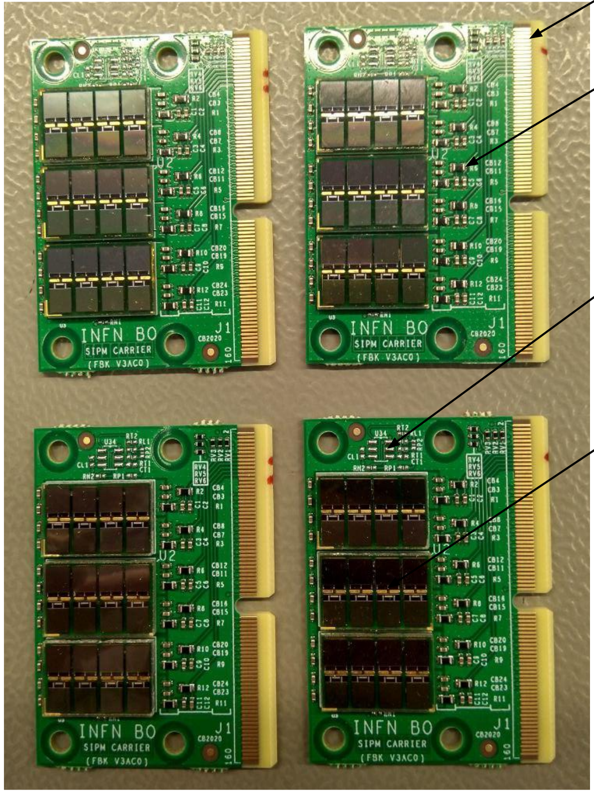
annealing

SiPM custom carrier boards

8x4 matrices with commercial Hamamatsu



6x4 matrices with prototype FBK sensors



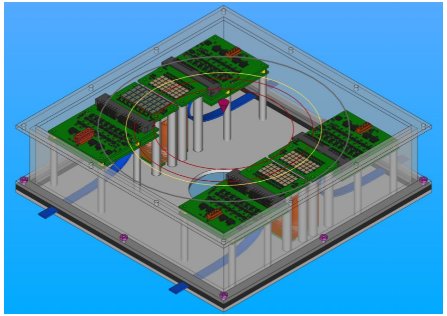
high-density edge connector

high-T grade FR4 for annealing up to 180 °C

temperature sensor for
operation with Peltier cooling

many metallic vias for heat conductivity
(Peltier cooling from the back)

prototype SiPM readout box

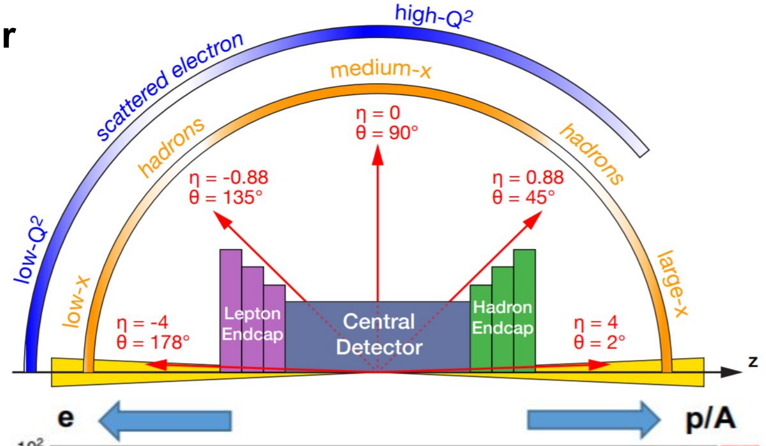


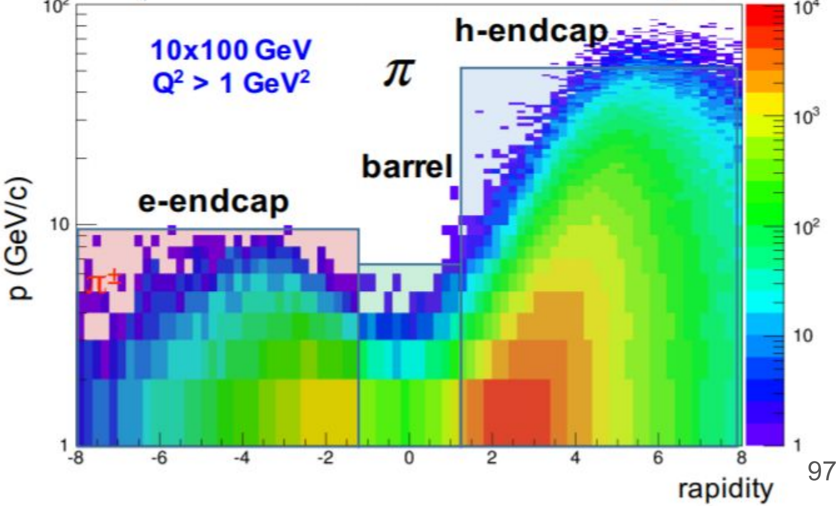
withstand irradiation, high-T annealing and low-T operation in form-factor usable in beam tests

Particle identification at EIC

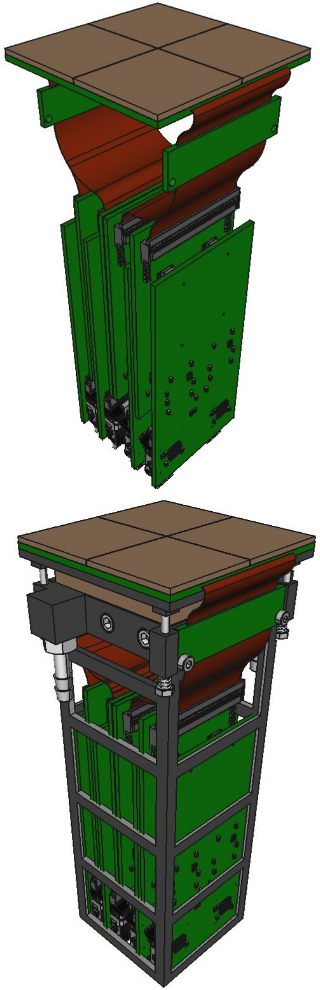
one of the major challenges for the detector

- **physics requirements**
  - pion, kaon and proton ID
  - over a wide range $|\eta| \leq 3.5$
  - with better than 3σ separation
  - significant pion/electron suppression
- **momentum-rapidity coverage**
  - forward: up to 50 GeV/c
  - central: up to 6 GeV/c
  - backward: up to 10 GeV/c
- **demands different technologies**





developing mechanical layout, readout electronics for SiPM-ALCOR-based dRICH prototype

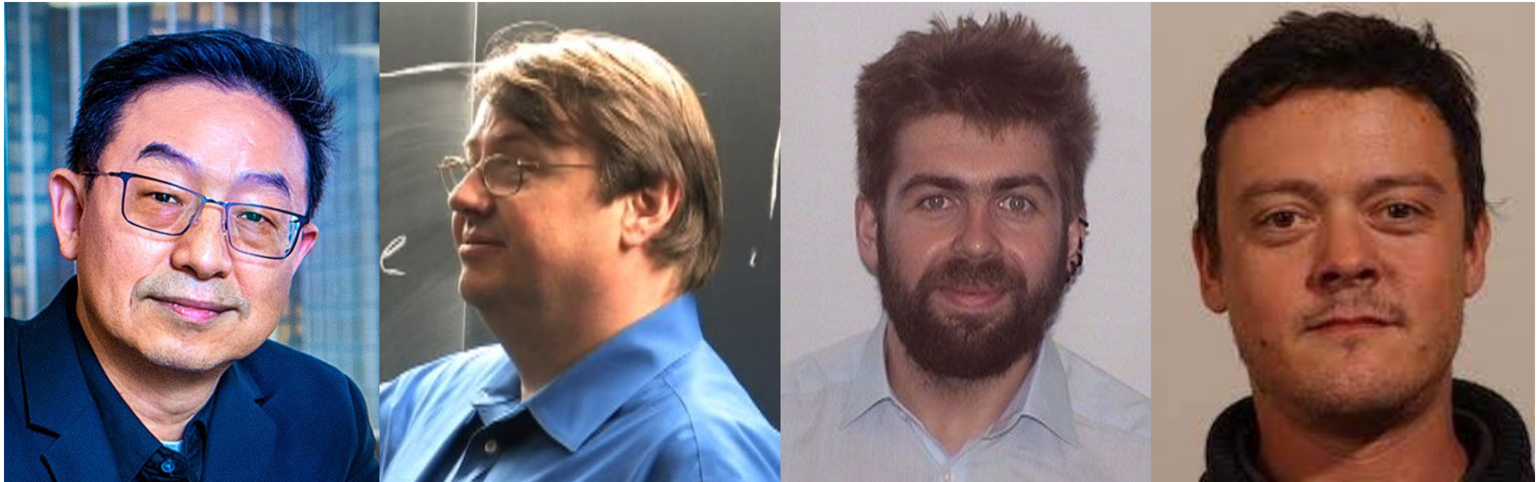


dRICH beam tests in August and October (with ALICE RICH) at CERN

Cherenkov PID WG

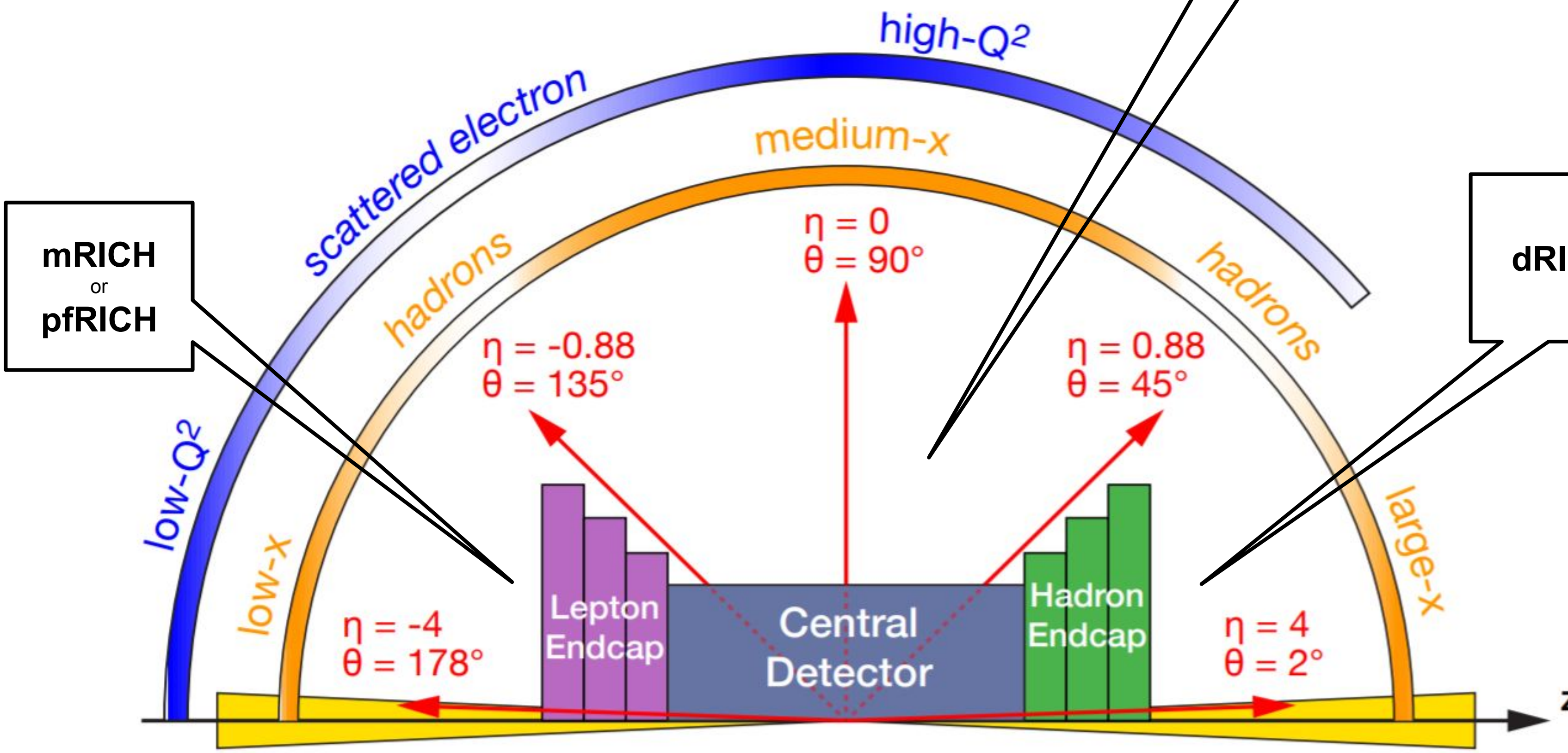
Xiaochun He
Thomas Hemmick
Grzegorz Kalicy
Roberto Preghenella

Cherenkov PID WG activities now replaced
Detector Subsistem Collaborations
new cross-cutting PID WG (including TOF)



ePIC

Cherenkov PID



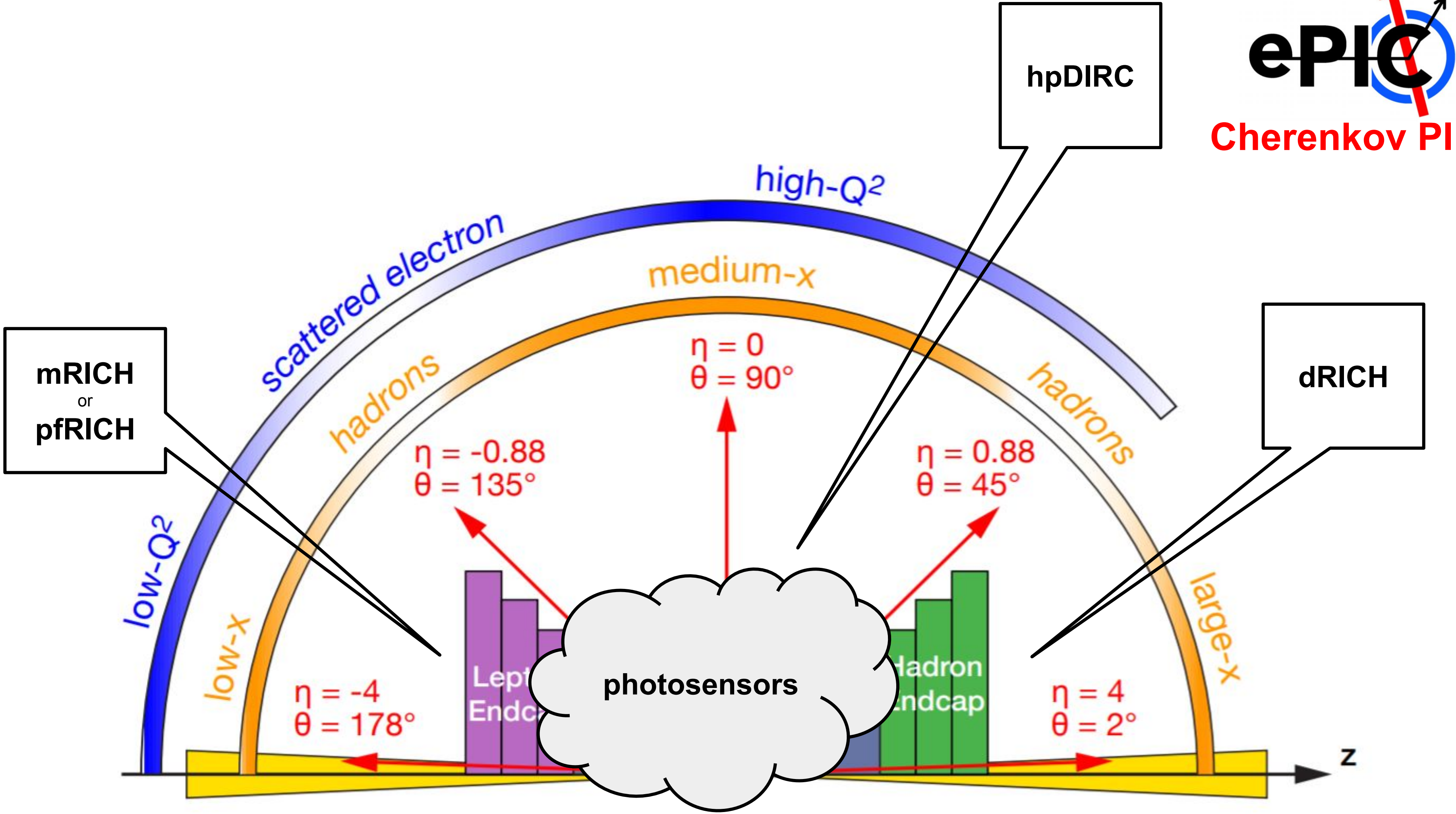
hpDIRC

mRICH
or
pfRICH

dRICH

ePIC

Cherenkov PID



hpDIRC

mRICH
or
pfRICH

dRICH

photosensors