QNP 2024

QNP 2024 – The 10th International Conference on Quarks and Nuclear Physics

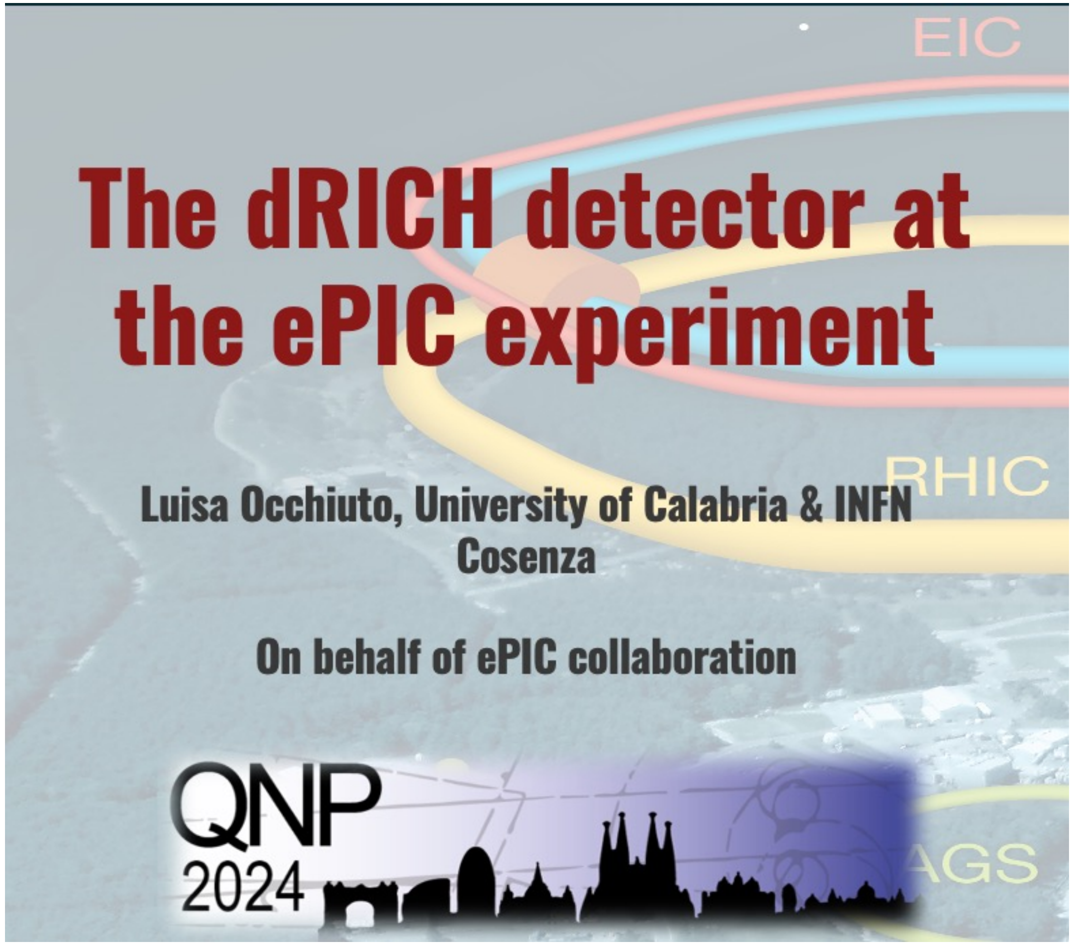
The SIPM-based optical readout of the ePIC-dRICH detector at the EIC

INFN BOLOGNA Istituto Nazionale di Fisica Nucleare

P. Antonioli – INFN Bologna

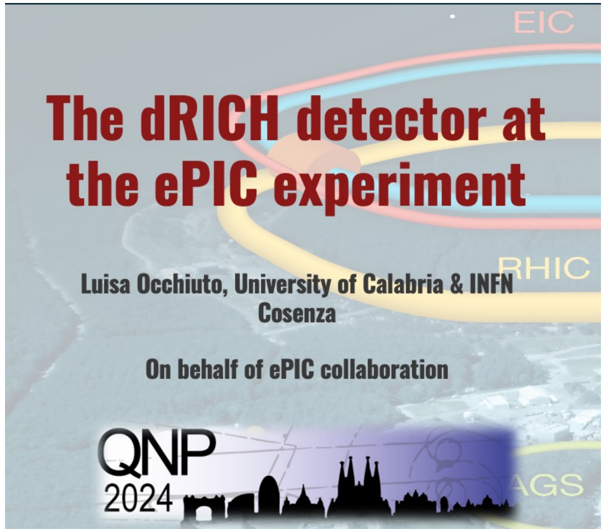
on behalf of the ePIC dRICH Collaboration

No need of an introduction thanks to...



Have a look at Luisa's talk (Monday session)

No need of an introduction thanks to...



MY TALK WILL MAINLY COVER THIS

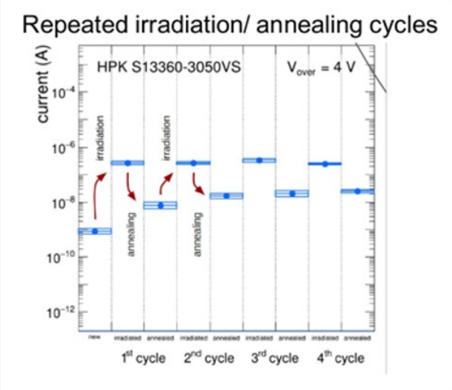
SiPM SENSORS

PRO
- ✓ Single photon detection;
- ✓ High Photon Detection Efficiency;
- ✓ Good time resolution;
- ✓ Insensitive to magnetic field.
- ✓ Cheap
- ✓ Low voltage operation

CONS:
- ✓ Large Dark Count Rate
- ✓ Prone to radiation damage

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

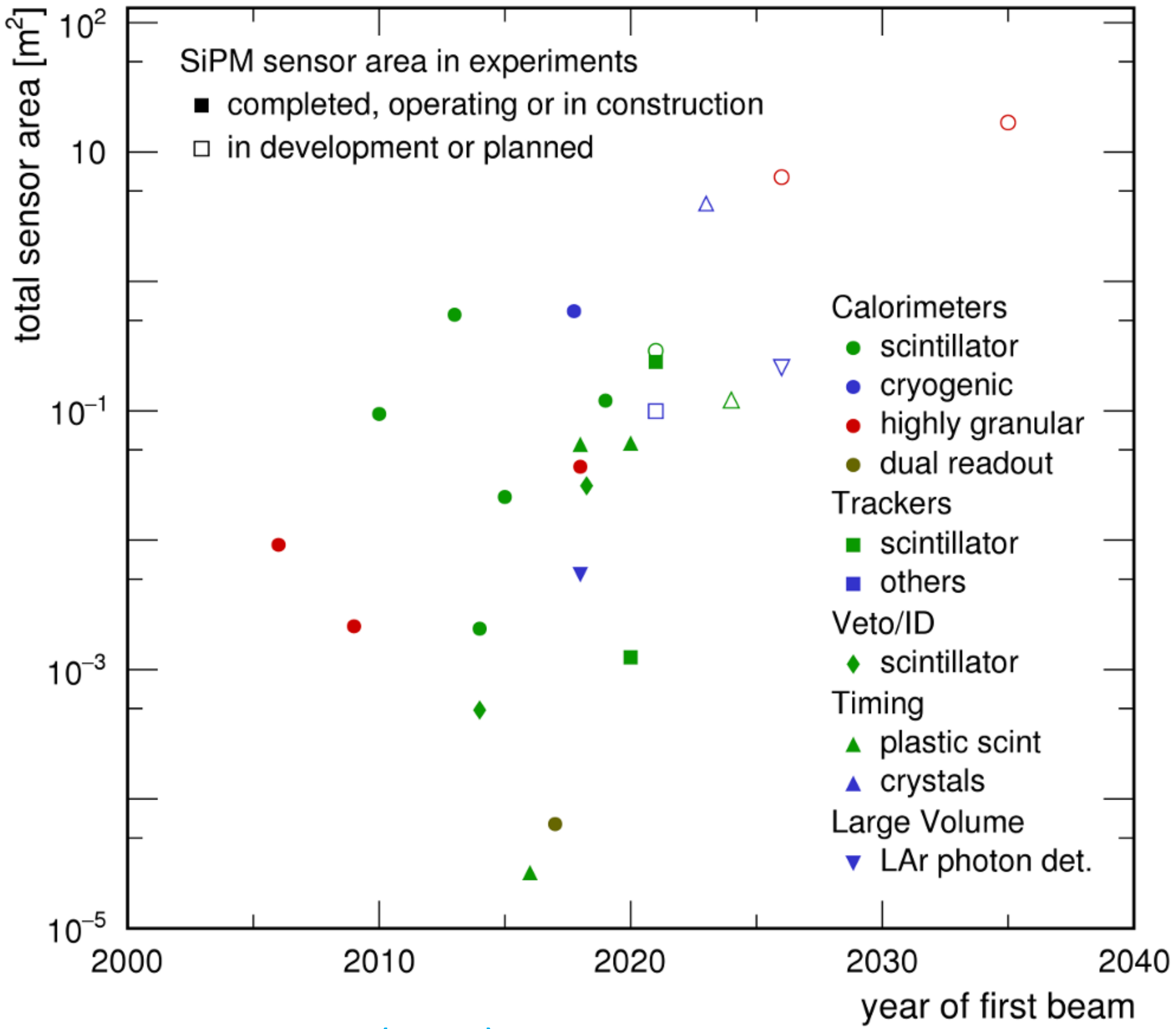
- ➢ Expected **DCR 300 kHz** for each SiPM channel.
- ➢ **Time window** of **1 ns** → $3 \cdot 10^{-4}$ probability of hit noise per 1ns.
- ➢ Expected **noise hits** → ~ **100 per event** in $3 \cdot 10^{5}$ SiPMs system



For further details pay attention at Pietro Antonioli's talk! ☺

luisa.occhiuto@cern.ch QNP2024 15

SIPMs are now ubiquitous in HEP/NP/Astropart



F. Simon, NIMA 926 (2019) 85-100

SiPM are naturally attractive for HEP/NP

- Small size
- High Photon-detection efficiency
- Cheap
- Insensitive to magnetic field
- No high signal with MIP
- High Gain

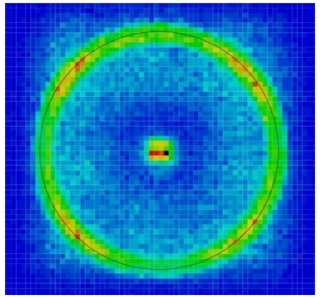
- ➢ Radiation tolerance
- ➢ Finite dynamic range (depending on cells)
- ➢ Temperature dependence of V_{bd}
- ➢ Dark Count Rate

Next generation: SiPM O(1-10 m^2) area/detector

Review of recent SiPM for HEP applications
M. Bonesini et al.,
Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167903

but... no RICH with a SIPM-based readout so far!

Pioneering work during Belle II Upgrade studies
P. Križan et al. NIM A594 (2008) 13
https://doi.org/10.1016/j.nima.2008.05.040
https://doi.org/10.1016/j.nima.2008.07.013



CAVEAT:
BelleII studies were done with (now obsolete, noisy and out-of-market)
Hamamatsu MPPC S10362-11-100P

Main reference: a relatively recent (2020) review exactly on this topic:
https://doi.org/10.1016/j.nima.2020.163804
S. Korpar, P. Križan. "Solid state single photon sensors for the RICH application"

As potential detectors were listed here:

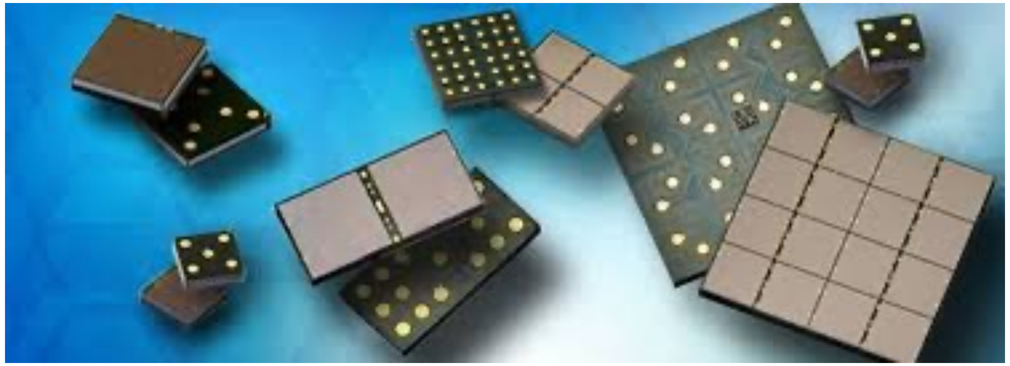
- HELIX
- LHCb RICH1 Upgrade 2
- RICH for a SuperCharm-Tau factory (21 m^2)
- BELLE II ARICH
- EIC RICH

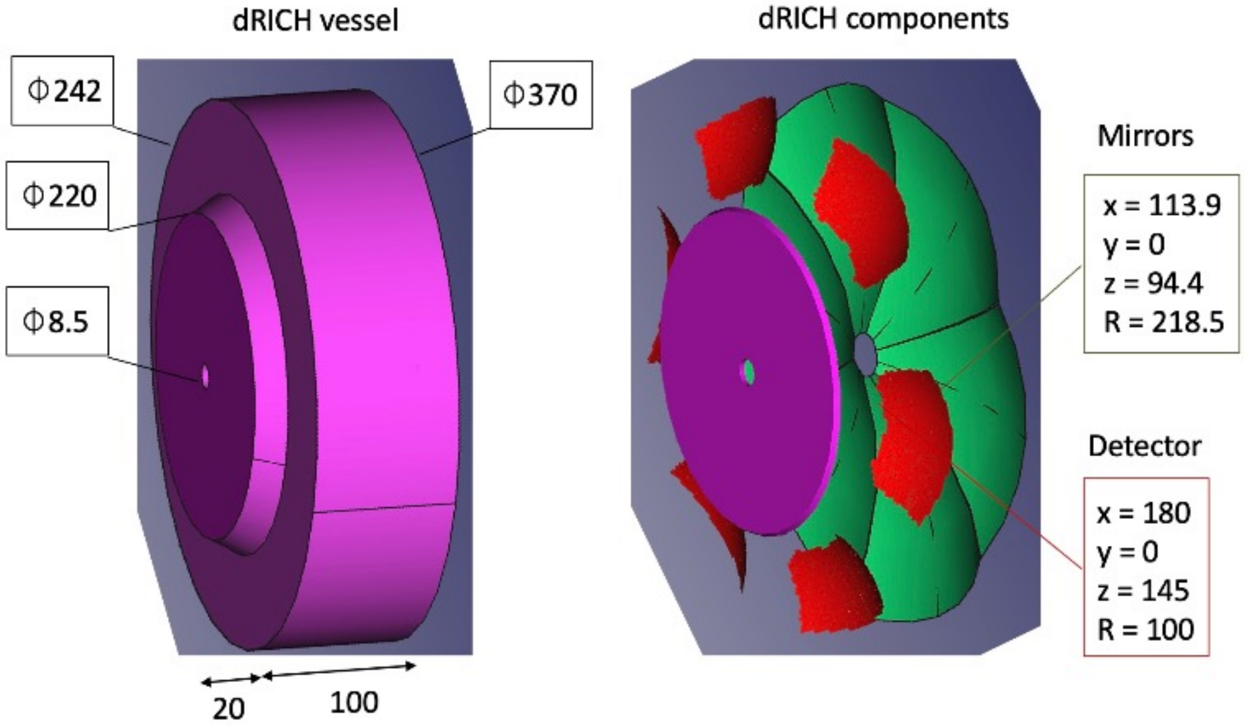
dRICH will be now world first RICH with SIPM

7. Summary

Semiconductor sensors for single photons, in particular SiPMs, are a novel device for RICH. Their advantages, operation in the magnetic field, high quantum efficiency, low supply voltage, fast response, flexible granularity, make them an almost ideal sensor for ring imaging Cherenkov detectors. The main challenge, a high occupancy due to dark counts, can be overcome by a narrow time window and by using light collecting elements to increase the ratio of the light collection area and the SiPM sensor area. The remaining issue for operation in experimental environments with high radiation exposure, in particular by neutrons, is under intense study for the next generation of experiments.

A SiPM readout for a RICH detector?





Silicon photomultipliers

✓ Insensitive to magnetic field

✓ Cheap / Integrated arrays

✓ Time resolution within requirements (< 200 ps RMS)

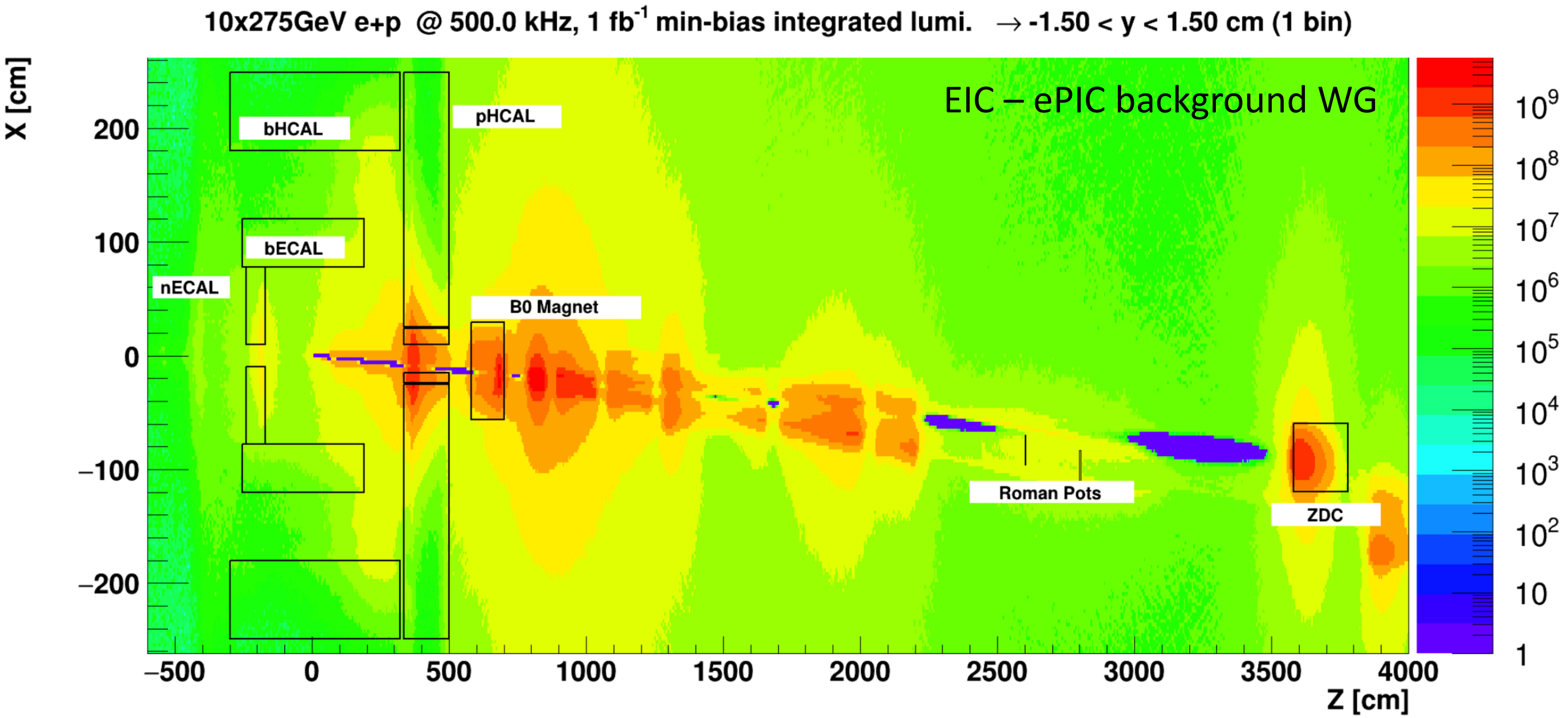
✓ Commercially available

? Single Photon resolution needed!

? DCR vs temperature → cooling

? Not radiation tolerant: DCR increases!

How much radiation?

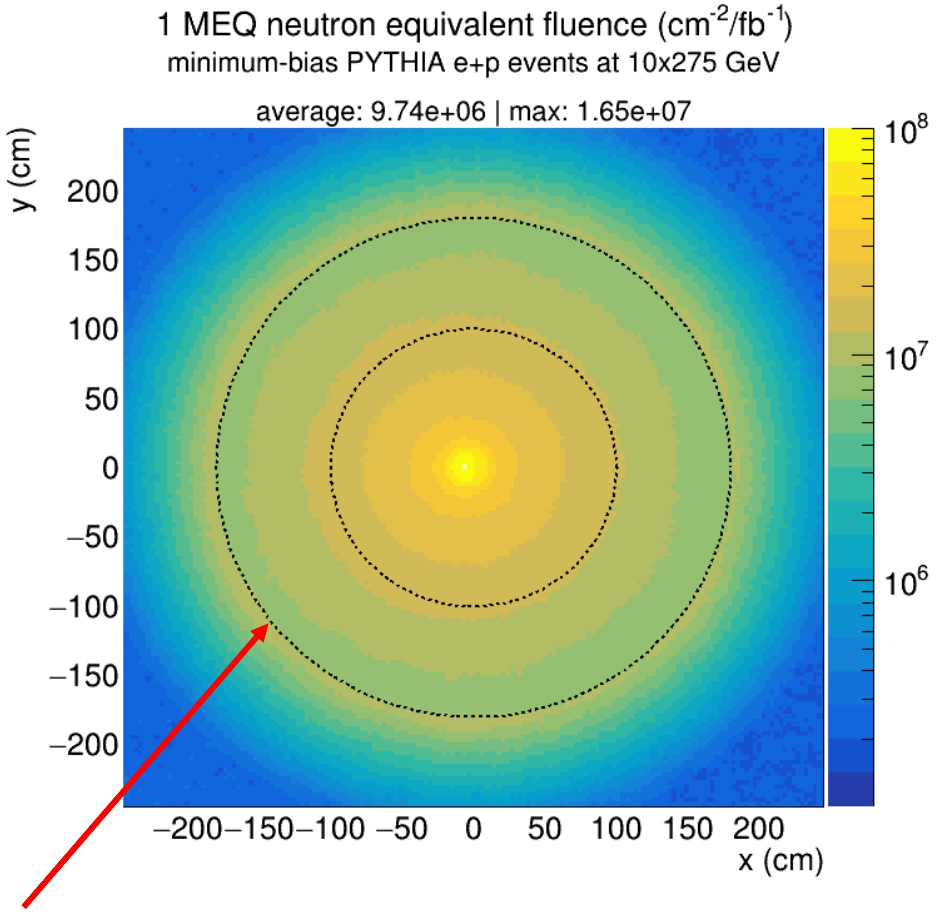


1-MeV n_{eq}/cm^2 fluence fb^{-1}

Detailed simulation of the whole radiation load (including here ePIC far forward detectors)
Generally speaking an ep collider is moderately hostile (with respect to LHC!!)

[from now on for fluences: n_{eq}/cm^2 = 1-MeV n_{eq}/cm^2]

How much radiation?

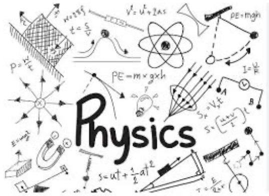


location of dRICH ohotosensors at given Z interval

location of dRICH photosensors:

mean ≈ **9.7 10^6 n_{eq}/cm^2 every 1 fb^{-1}**

max ≈ **1.7 10^7 n_{eq}/cm^2 every 1 fb^{-1}**



10^9 n_{eq}/cm^2 → most of the key physics topics (10 fb^{-1})

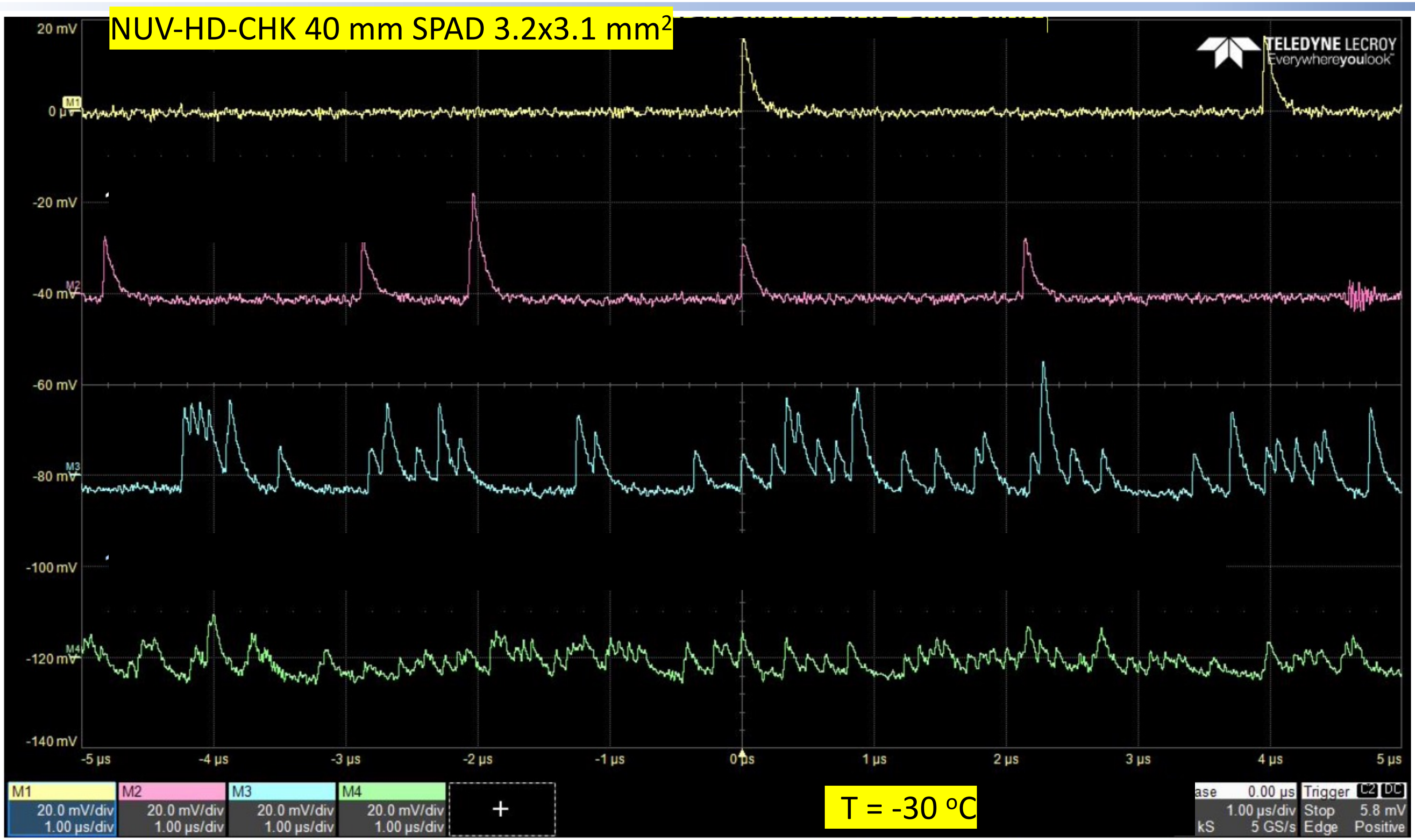
10^{10} n_{eq}/cm^2 → GPD and more statistically eager topics (100 fb^{-1})

10^{11} n_{eq}/cm^2 → may be we will never go here… (1000 fb^{-1})

10^{11} n_{eq}/cm^2 is a ”true maximum”

Can we use SiPM for a Cherenkov detector up to 10^{11} n_{eq} $/cm^2$ fluence?

A reality check on the scope....



10^8 n_{eq} ok

10^9 n_{eq} still ok

10^{10} n_{eq} challenging

10^{11} n_{eq} baseline lost

A compact summary of this R&D program

R&D conceived in 2020 (during lockdown!)

What we wrote in a first meeting in Apirl 2020 (all@home)

A SiPM R&D program towards a forward RICH proposal for EIC

R&D needed for SiPM:

1. Proof of "feasibility": DCR & operating conditions, single photon detection etc.
2. Radiation tolerance (& annealing)
3. Readout electronics: ASIC (+ streaming readout)

Note these three R&D items deeply interlinked!

2

selection of different sensors (SPAD cell, integration)/ manufacturers (HPK, OnSemi, FBK, Broadcom, ...)
check effects of irradiation at different fluences $10^8 – 10^{11}$ neq/cm^2
test annealing with different procedures (oven and electrically induced)
test effects of repeated annealing cycles
develop annealing in situ procedure
elaborate an ageing model

3x3 mm sensors
4 x 8 "format"

3

develop readout with a devoted ASIC (ALCOR)
develop integrated electronics (Photo Detetor Units)
plan dRICH readout

1

proof of feasibility/intergation (incl cooling) → test beam operations (2021, 2022, 2023, 2024)

A compact summary of this R&D program

R&D conceived in 2020 (during lockdown!)

How it is organized this talk

A SiPM R&D program towards a forward RICH proposal for EIC

INFN Istituto Nazionale di Fisica Nucleare

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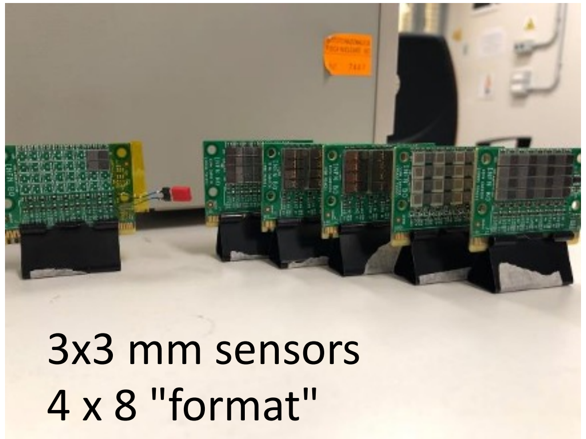
1

selection of different sensors (SPAD cell, integration)/ manufacturers (HPK, OnSemi, FBK, Broadcom, ...)
check effects of irradiation at different fluences 108 – 1011 neq
test annealing with different procedures (oven and electrically induced)
test effects of repeated annealing cycles
develop annealing in situ procedure
elaborate an ageing model



2

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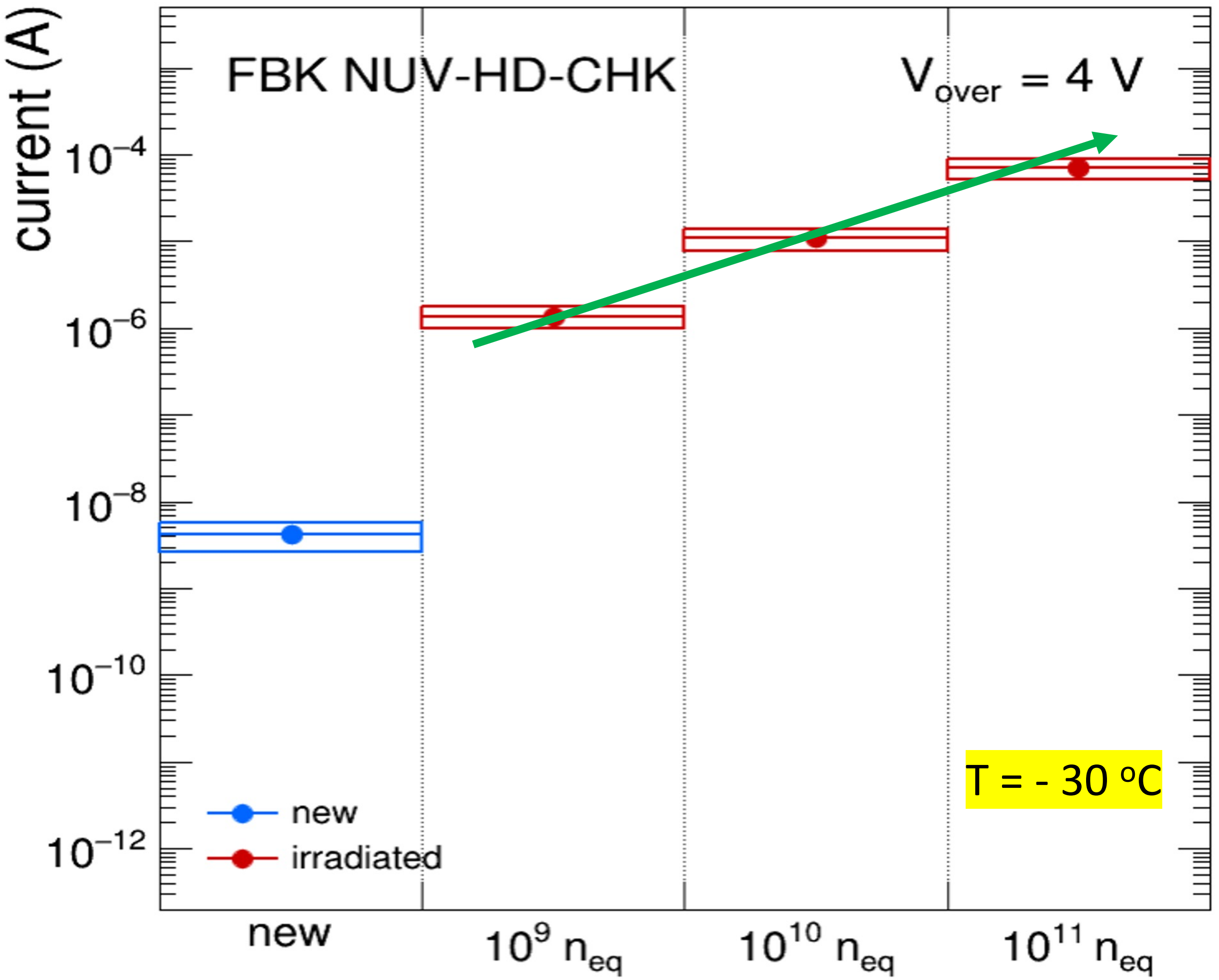
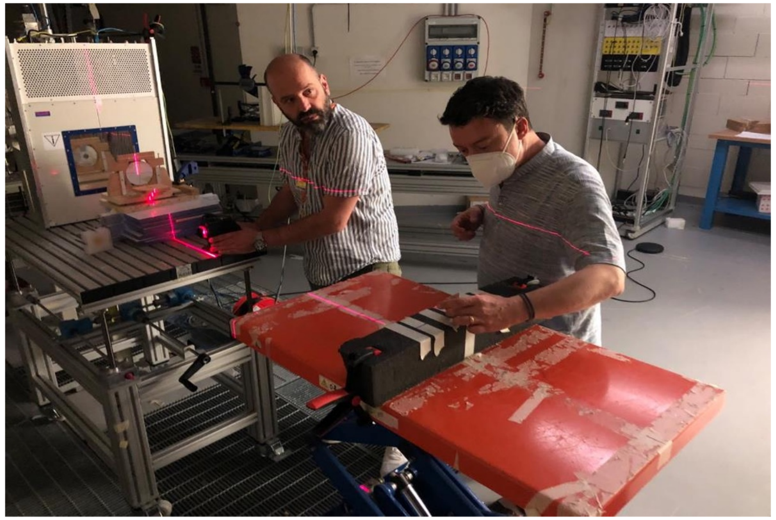
Irradiation tests



Irradiation facilities used:

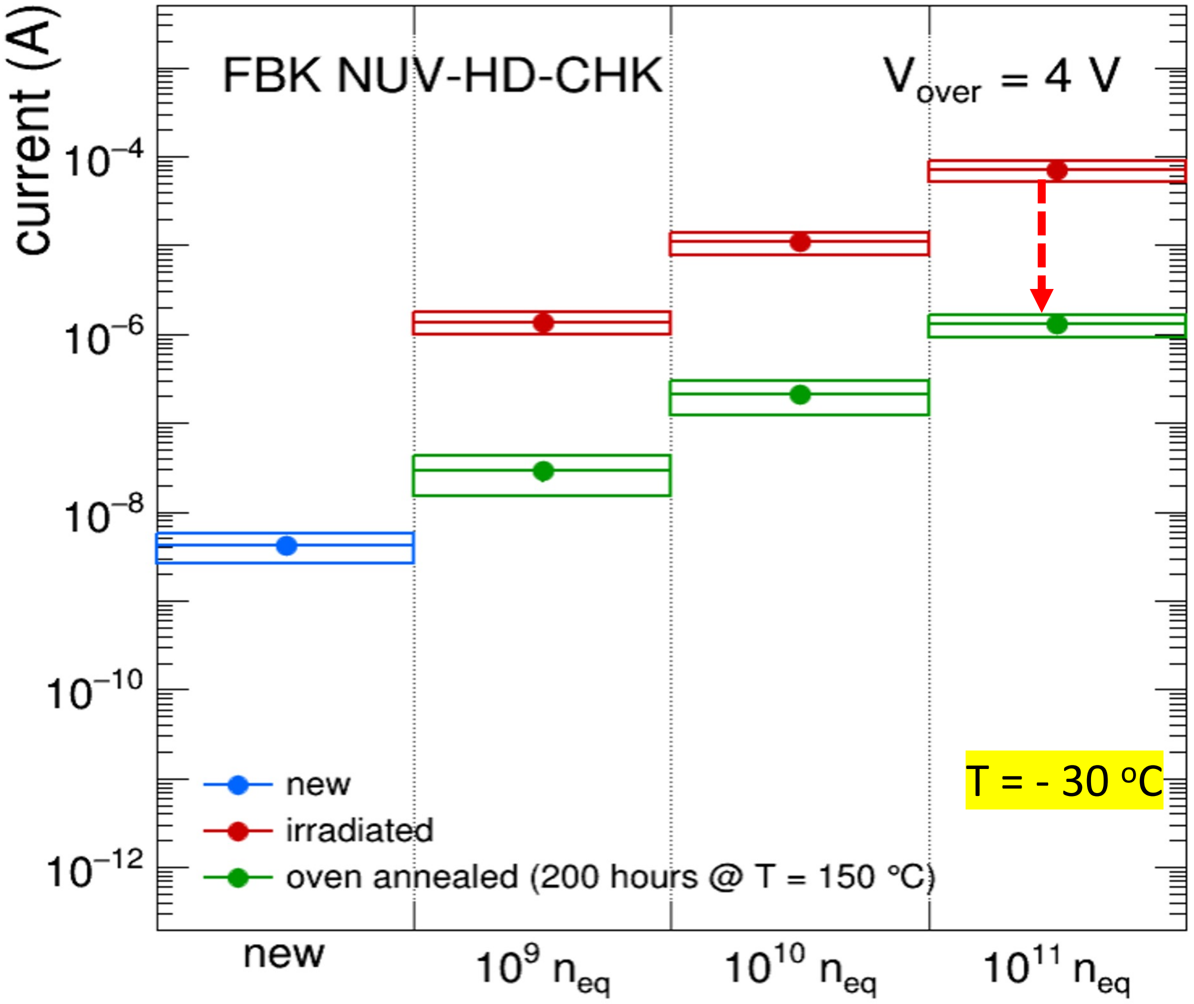
- Hadrontherapy Center in Trento (protons)
- INFN Legnaro National Laboratories (neutrons)
- CHARM facility @ CERN (2024)
- next: GIF @ CERN (γ) (2024)

linear increase with fluence



First wave of results reported for example at RICH2022 (R. Preghenella)
Results on neutron irradiation at TREDI2024 (N. Rubini)

Annealing (oven) at high temperature

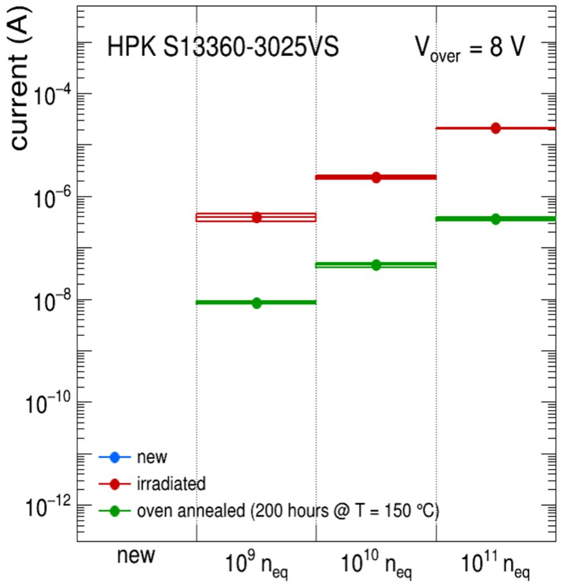


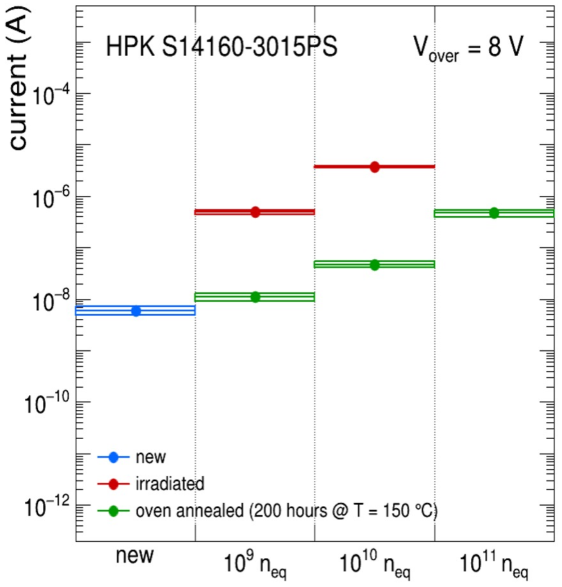
R. Preghenella et al., *Nucl.Instrum.Meth.A* 1056 (2023) 168578

SiPM in oven for 160 hours at 150 °C
a factor 100 of damage reduction

the **annealed sensor** works as it would have received 100 less fluence!

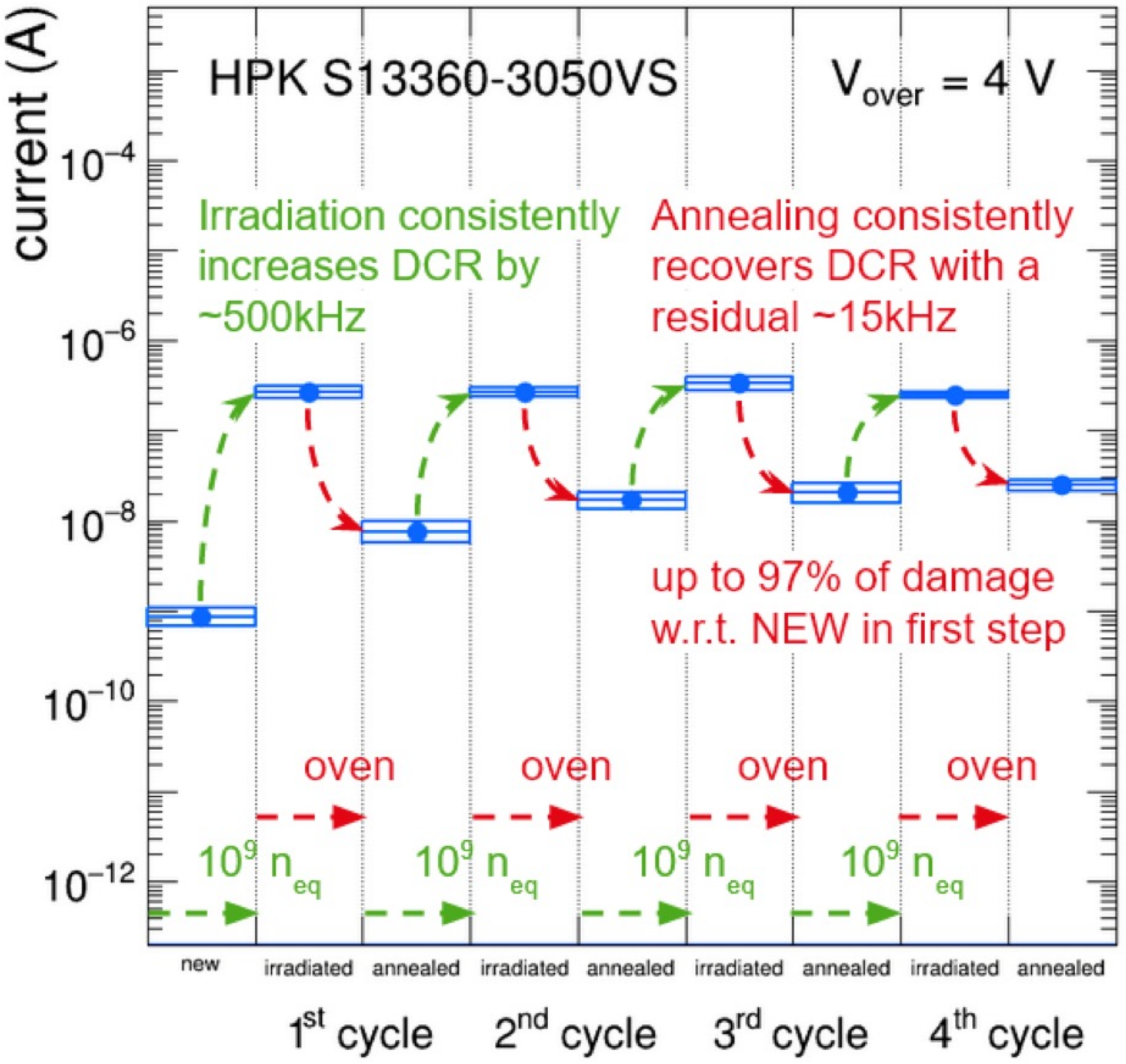
results consistent with existing literature
[M. Calvi et al., NIMA 922 (2019) 243]





similar results on various HPK sensors

2022 campaign: irradiation-annealing cycles



"getting closer to the experimental setup"

- ✓ test **reproducibility** of repeated irradiated/annealing cycles on the same sensors.
- ✓ each shot is 10^9 n_{eq}
- ✓ extract parameters (sensor and V_{over} specific!) to shape annealing cycles in the experiment:
  - ➢ f_d : every 10^9 n_{eq} increases by 500 kHz DCR pixel rate (3x3 mm^2)
  - ➢ f_a : each annealing leaves 15 kHz of additional DCR rate

$$DCR_r\,(k) = DCR_0 + f_d + (k-1)f_a$$

DCR after k irradiation and k-1 annealing cycles

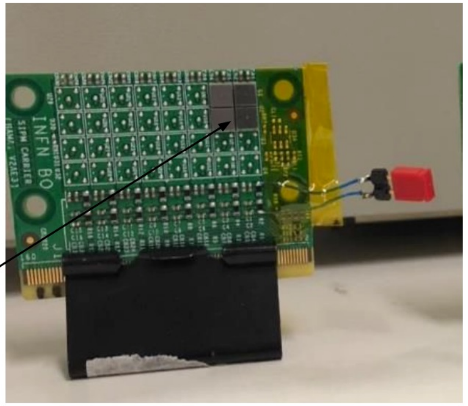
*Take home message

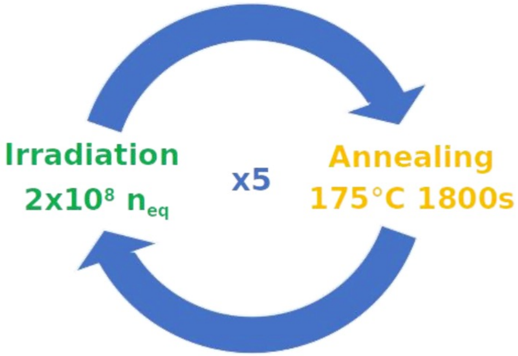
annealing repairs f_a/f_d of newly produced damage on a given sensor (97% for HPK)

O(100) sensors under test

2022-2023 Investigating different annealing methods

testing online annealing solutions ("in situ")

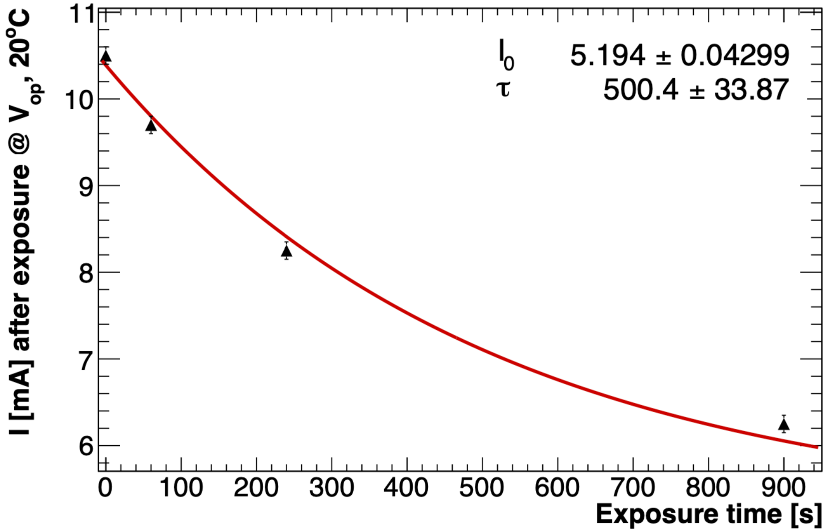




Electrically induced annealing techniques

- forward bias + Joule effect: ~ 1 W / sensor → T = 175 °C
- could pave the way to more frequent and *in situ* (without dismounting sensors) annealing cycles

→ irradiation fluence (10^9 n_{eq}/cm^2) split in five shots, interleaved by 30 minutes annealing



M. Cordelli *et al* 2021 *JINST* **16** T12012 results on HPK and SensL (OnSemi) sensors, both forward and inverse bias

2022: Electrically induced annealing techniques

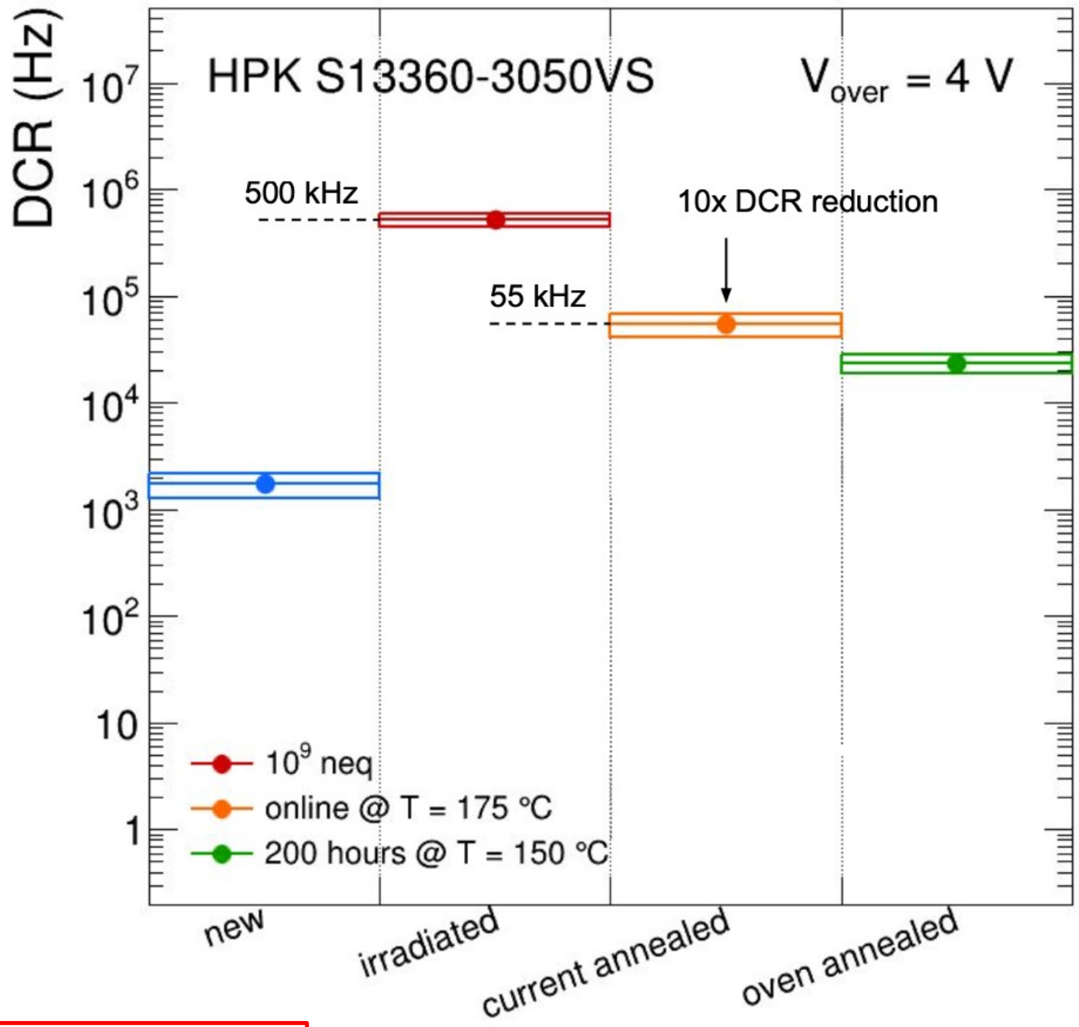
The sensors current-annealed found at 55 kHz

Residual DCR not good as in oven (15 kHz) but:

- 100 times faster!! (2.5 hours vs 200 hours!)
- can be done in-situ
- can be done more frequently

It looks very promising!

Specific R&D planned for 2023 on this item

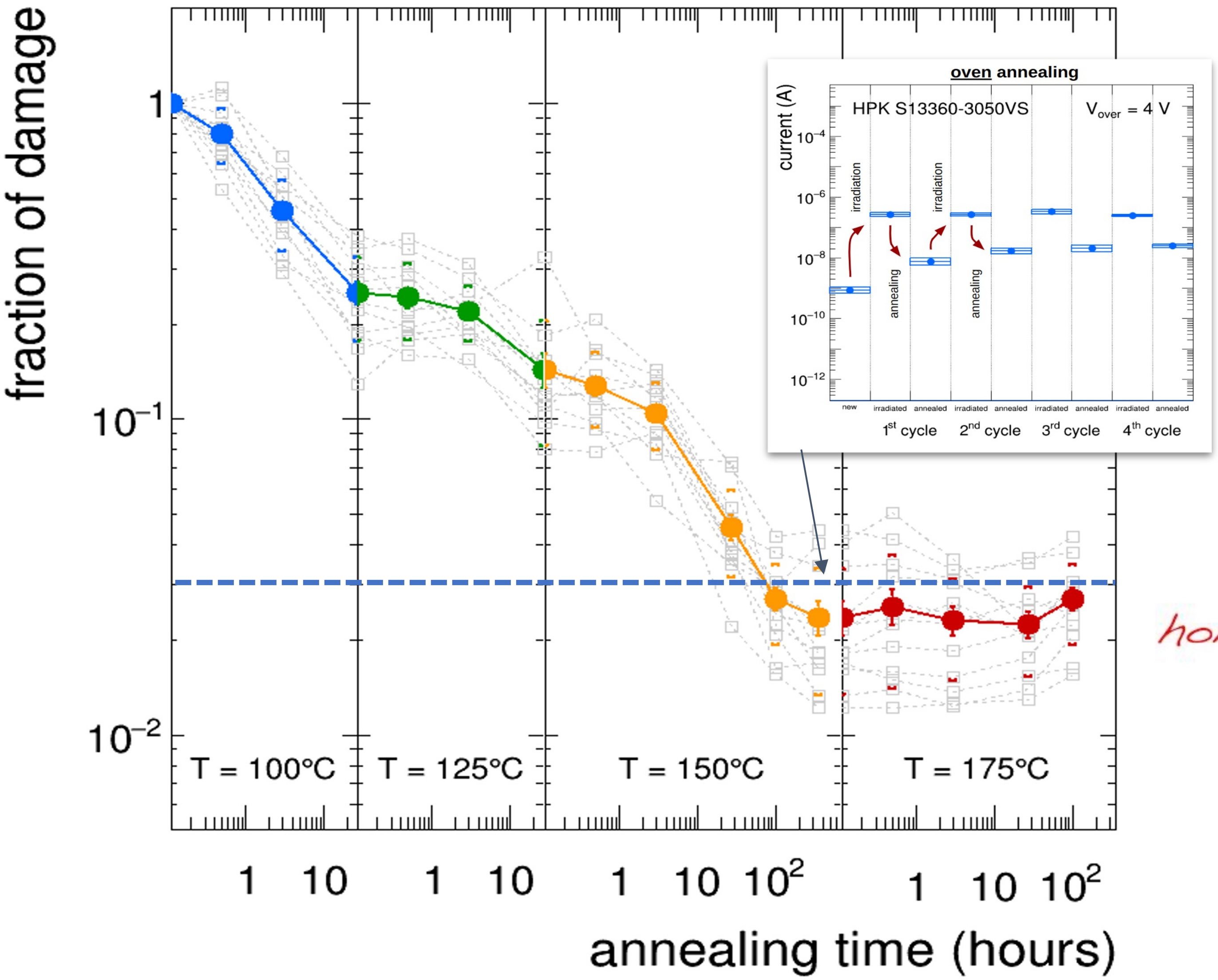


orkshop

Slide ftaken from talk at CPAD2022 (PA)

2023-2024: detailed annealing studies

electrically induced annealing: forward bias



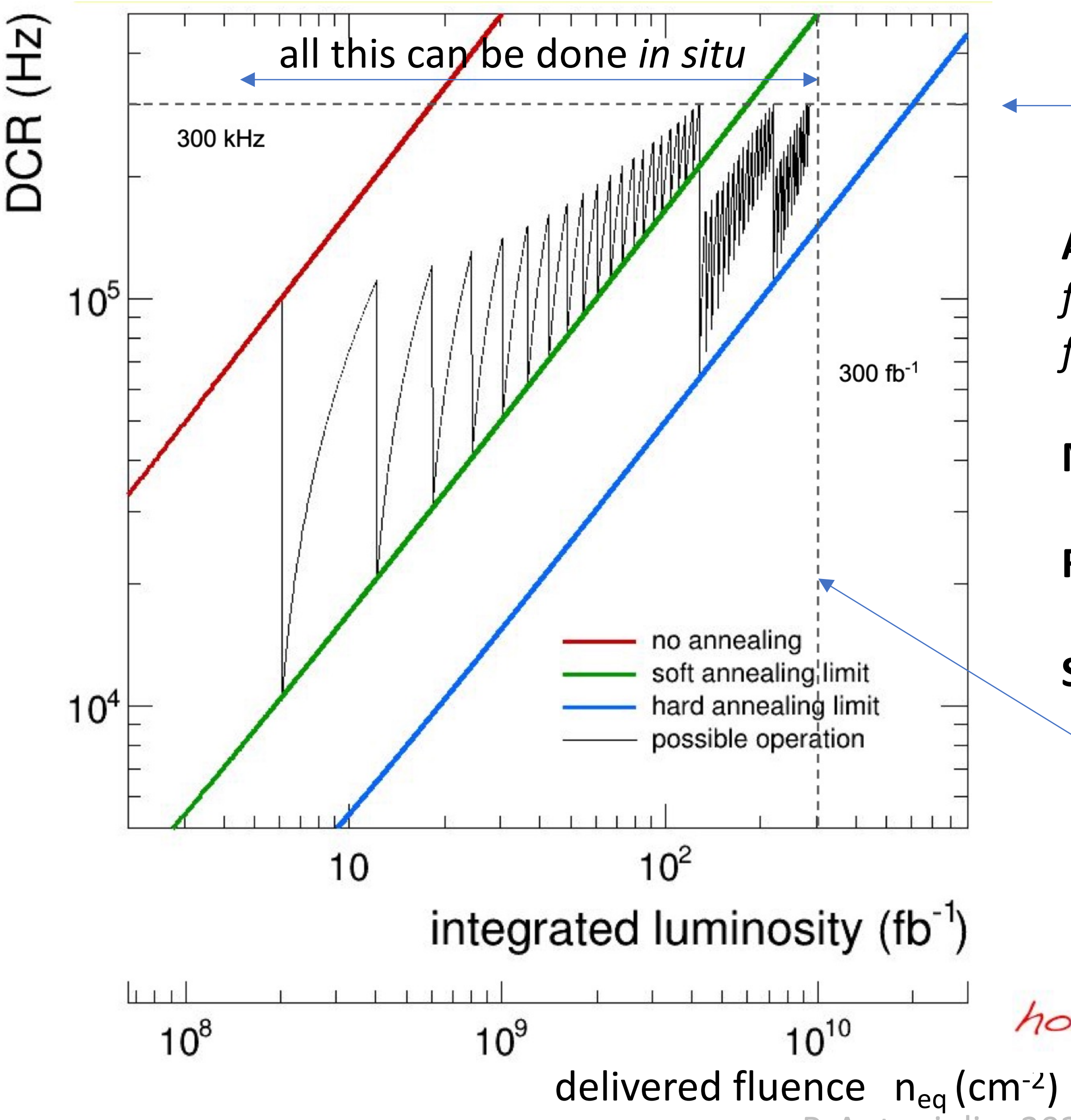
- large number of sensors (gray-points): average and RMS
- how we cure the damage as a function of time?
- how we cure the damage as a function of T?

T=100, 125, 150, 175 °C

*Take home message

2-3% of residual damage (in DCR)
175 °C doesn't make a difference
oven is not necessary

Putting pieces together: ageing model



this is a DCR limit per sensor we don't want to pass to curb throughput / keep safe SNR → **keep safe physics**

Ageing/annealing parameters from 2022 campaign
f_d = 500 kHz/10^9 neq (damage additive on top of DCR)
f_a = 15 kHz (residual damage)

Model is sensor specific: here HPK S13360-50 @VOV=4 V/T=-30 °C

Radiation load: 1.75 10^7 $n_{eq}/cm^2 \cdot fb^{-1}$

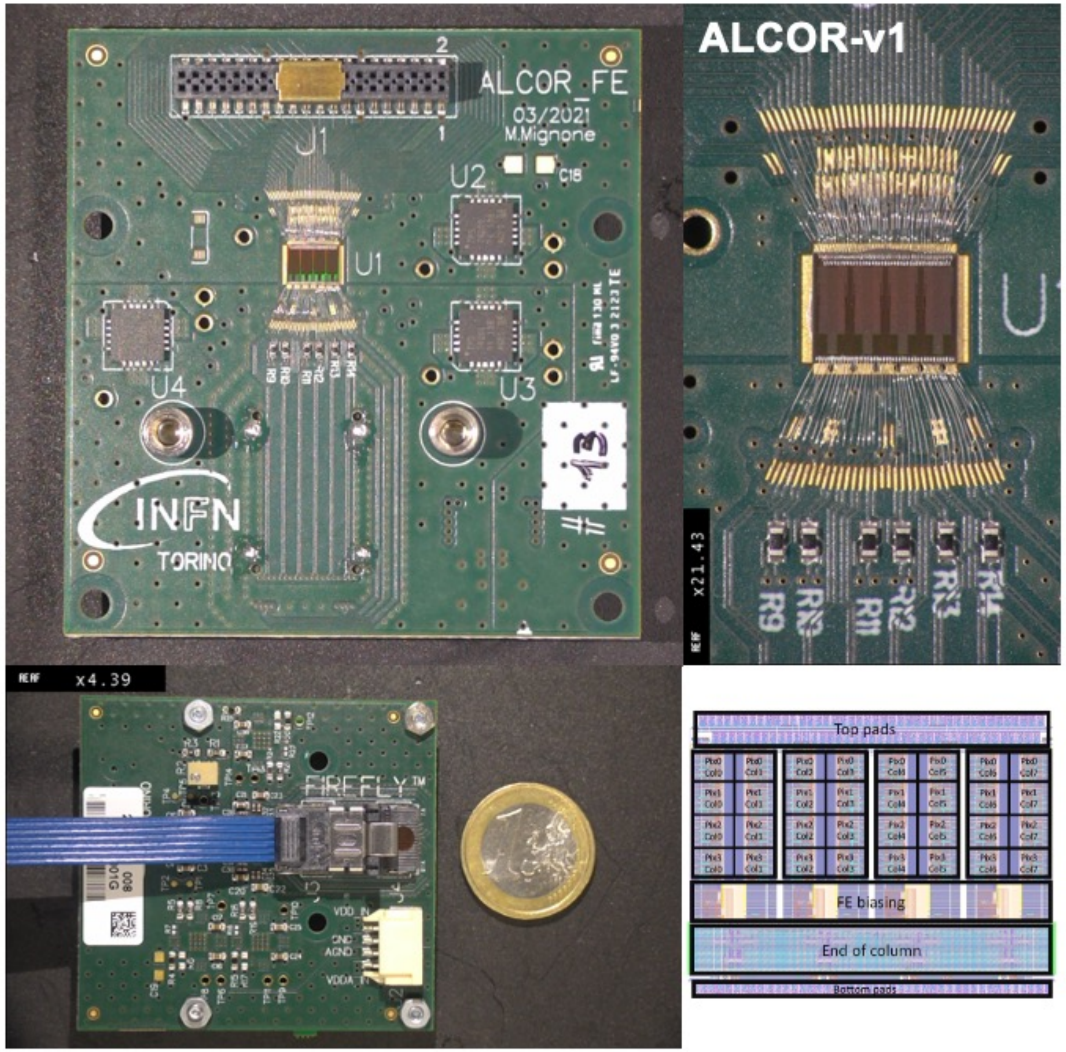
Safety factor: 2x included in the plot

Here we might want to dismount (replace sensors or... further optimize)

*Take home message

- radiation damage is under control
- more handles available (decrease VOV, decrease T)

Electronics and detector integration: ASIC



ALCOR R. Kugathasan, *PoS* TWEPP2019 (2020) 011.

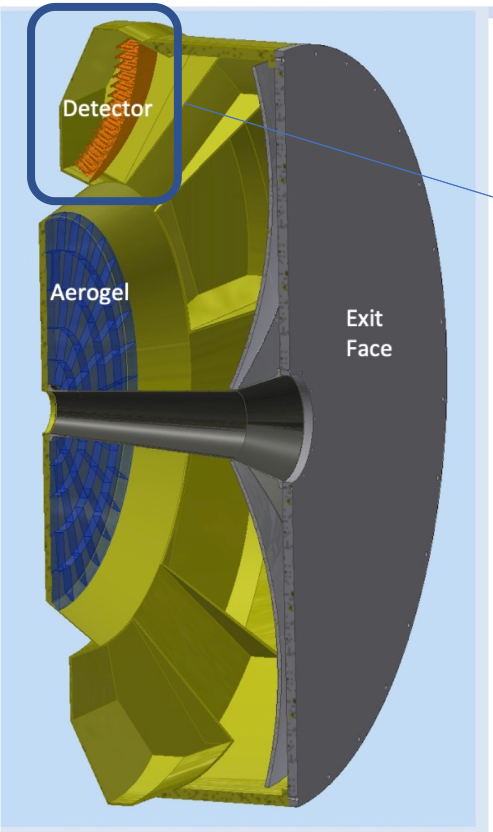
the dRICH ASIC: ALCOR mixed-signal ASIC

Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

- v1, 2.0, 2.1: 32 channels, wirebonded, 320 MHz
- v3 64 channels, BGA package, 394.08 MHz clock (multiple of EIC Clock)

✓ v1 originally developed for cryogenic applications (DARKSIDE)
✓ **high integration**: amplifier – discriminator -- TDC
✓ 20 or 40 ps LSB @394.08 MHz
✓ **digital shutter to suppress DCR off-gate** (1-2 ns sync with bunch crossing)
✓ serialized high-speed digital output (8 lanes/chip)
✓ SPI interface

Electronics and detector integration: the PDU



dRICH PDUs… are **here** inside sector "detector box"

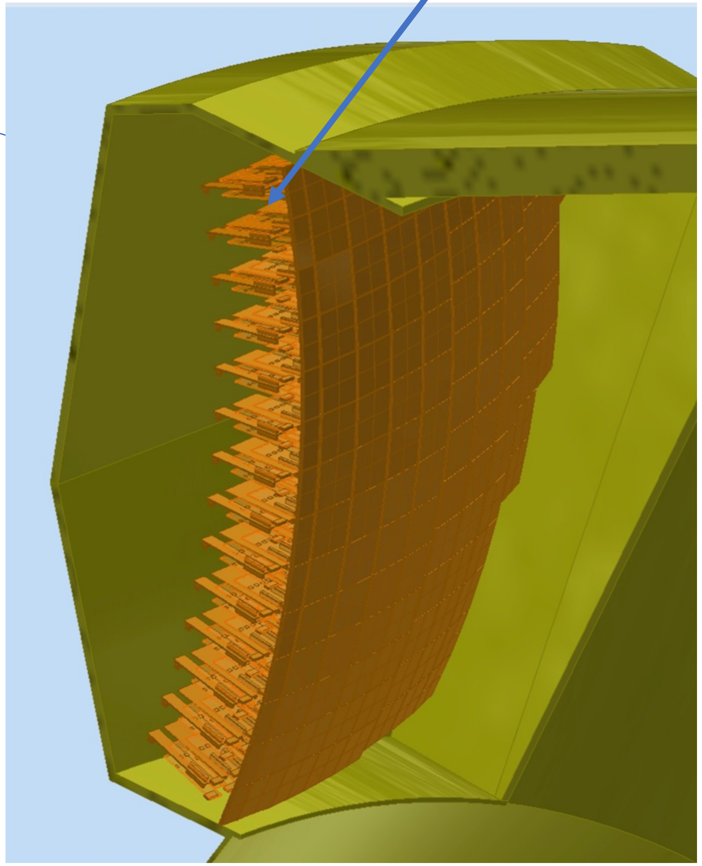
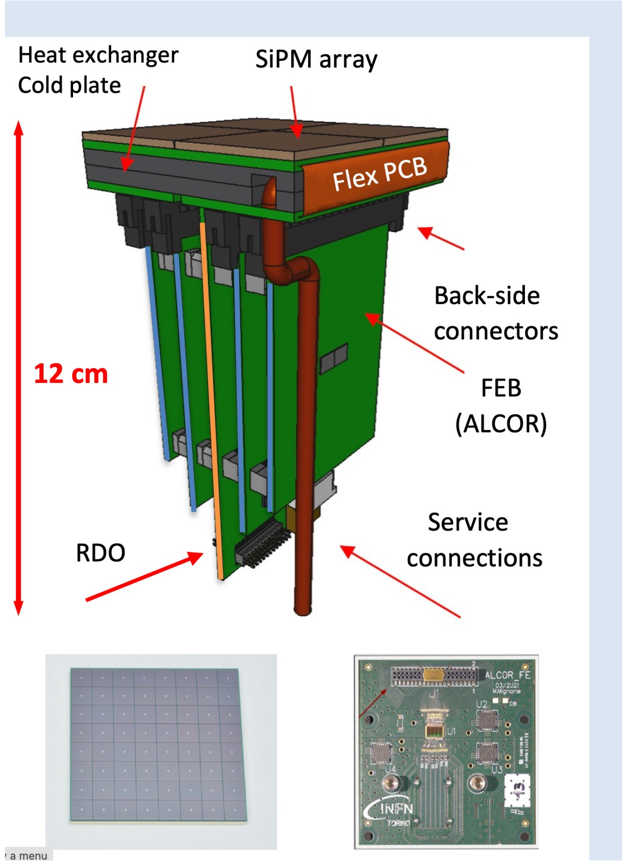


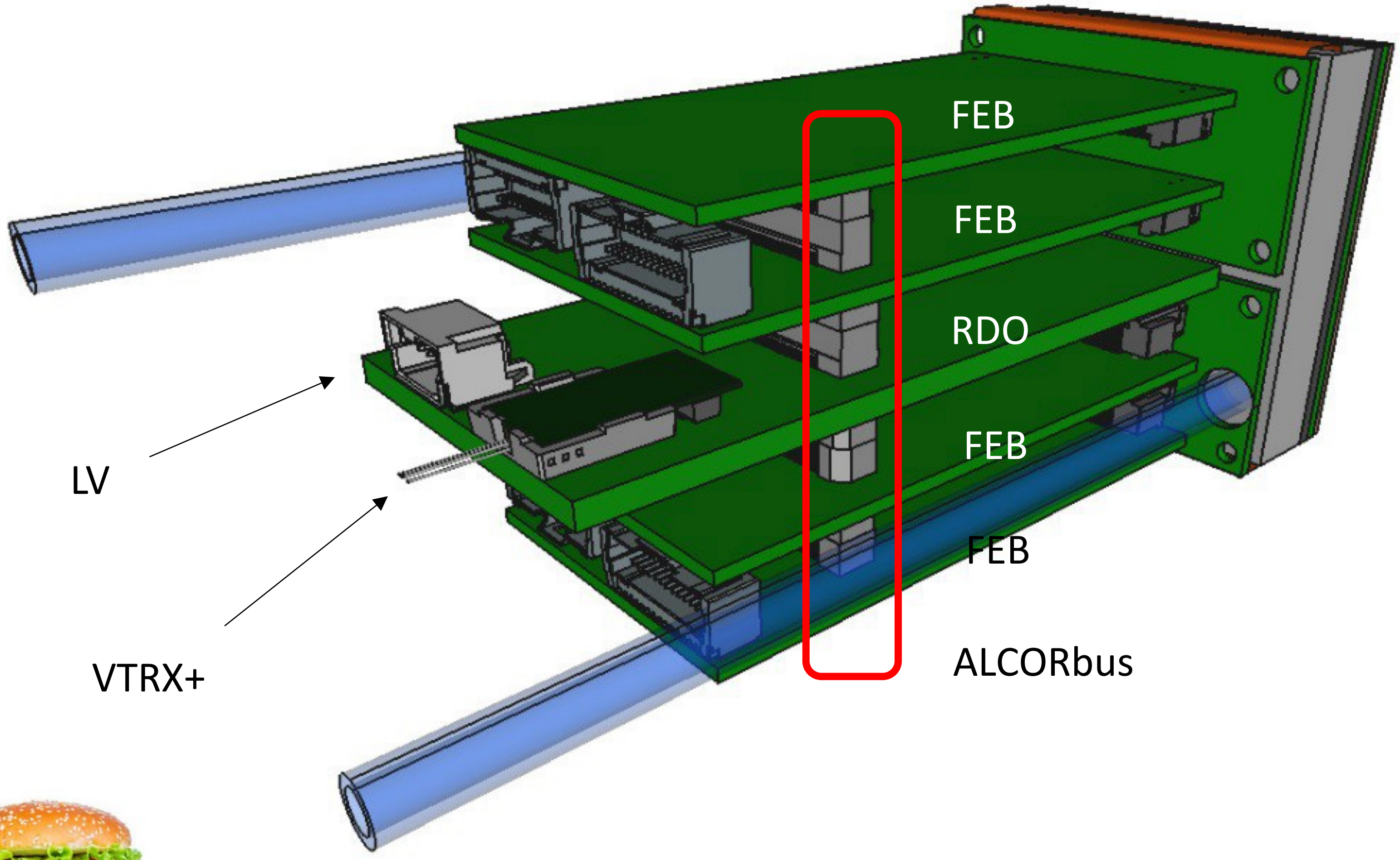
PHOTO DETECTOR UNIT (PDU)



More on electronics and PDU integration: TWEPP 2023 (L. Rignanese), iWorID 2024 (R. Preghenella)

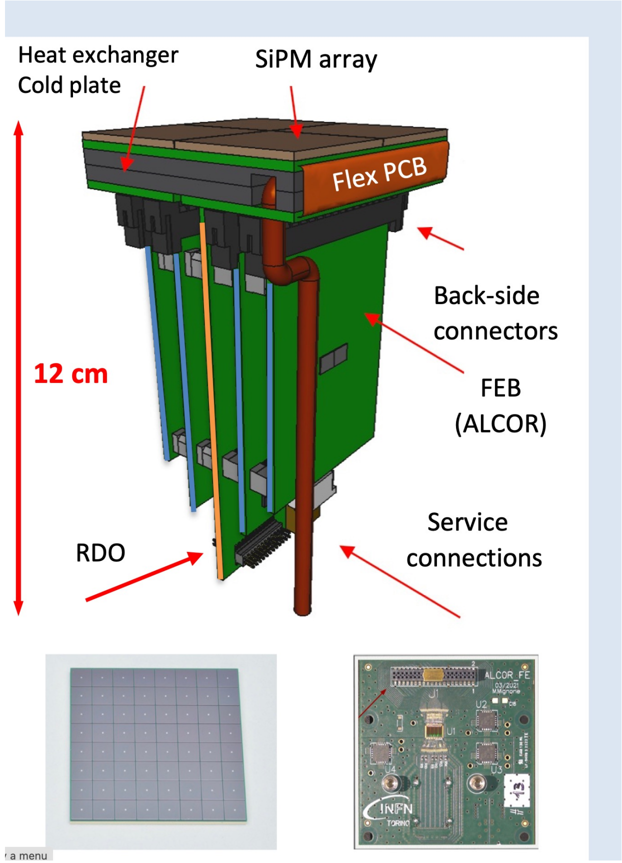
More on PDU

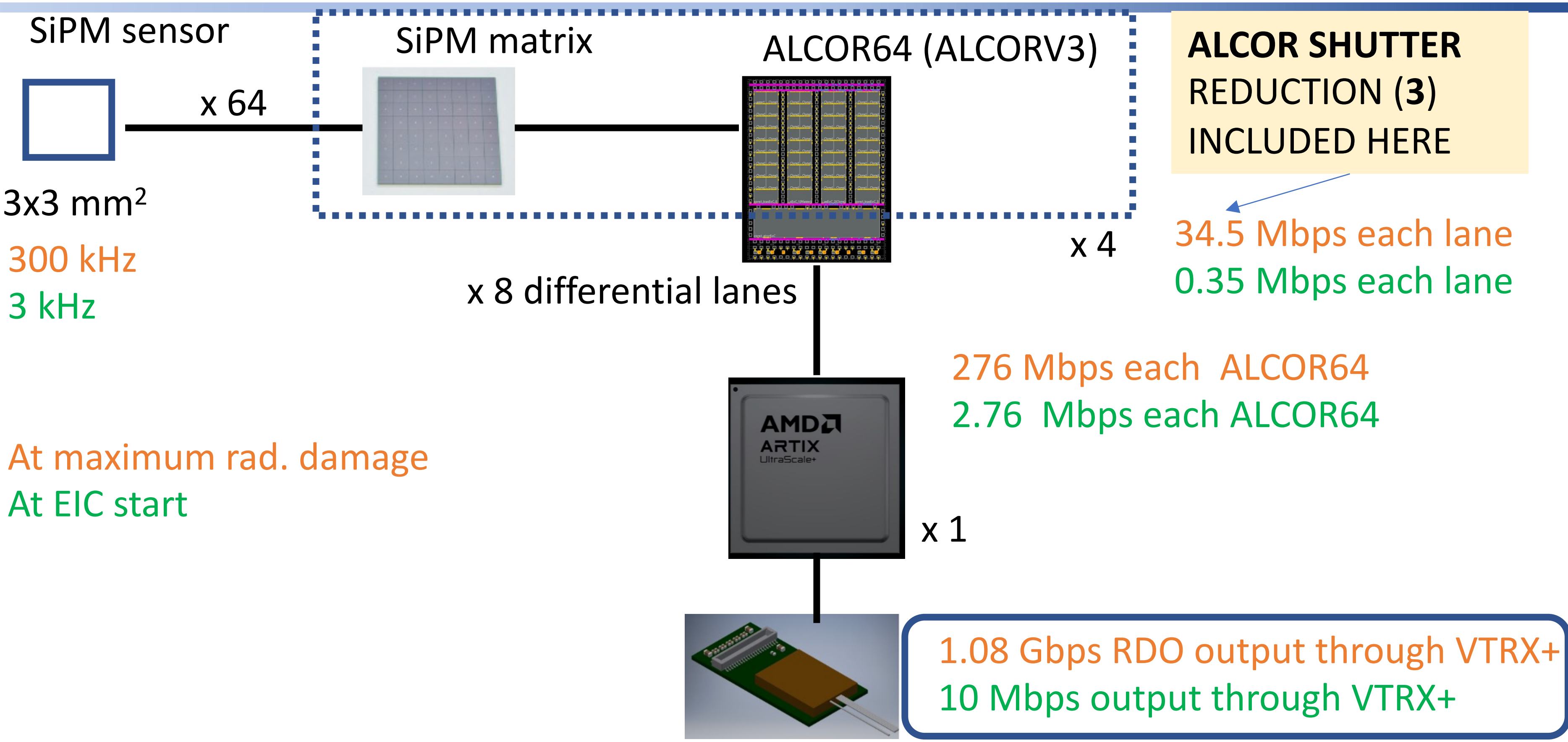
Each PDU via RDO must:
- provide interface with ePIC DAQ
- provide readout of 4 ALCOR v3
  (64 channel each)



- The dRICH electronic - burger :

dRICH DAQ readout (and DCR… again)

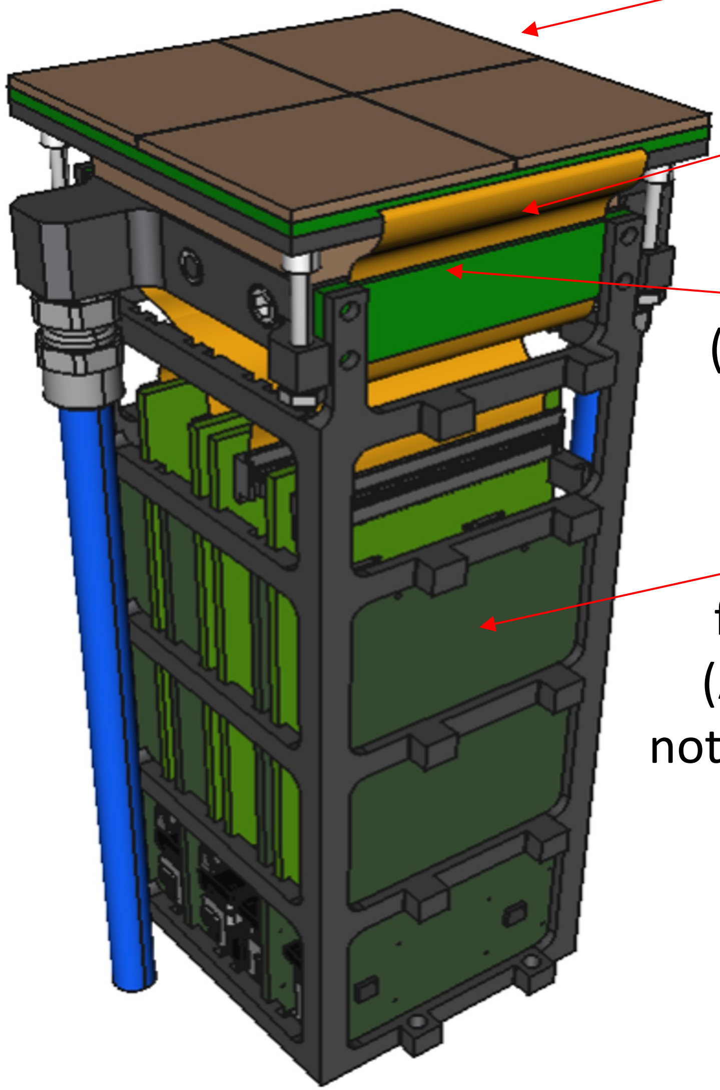


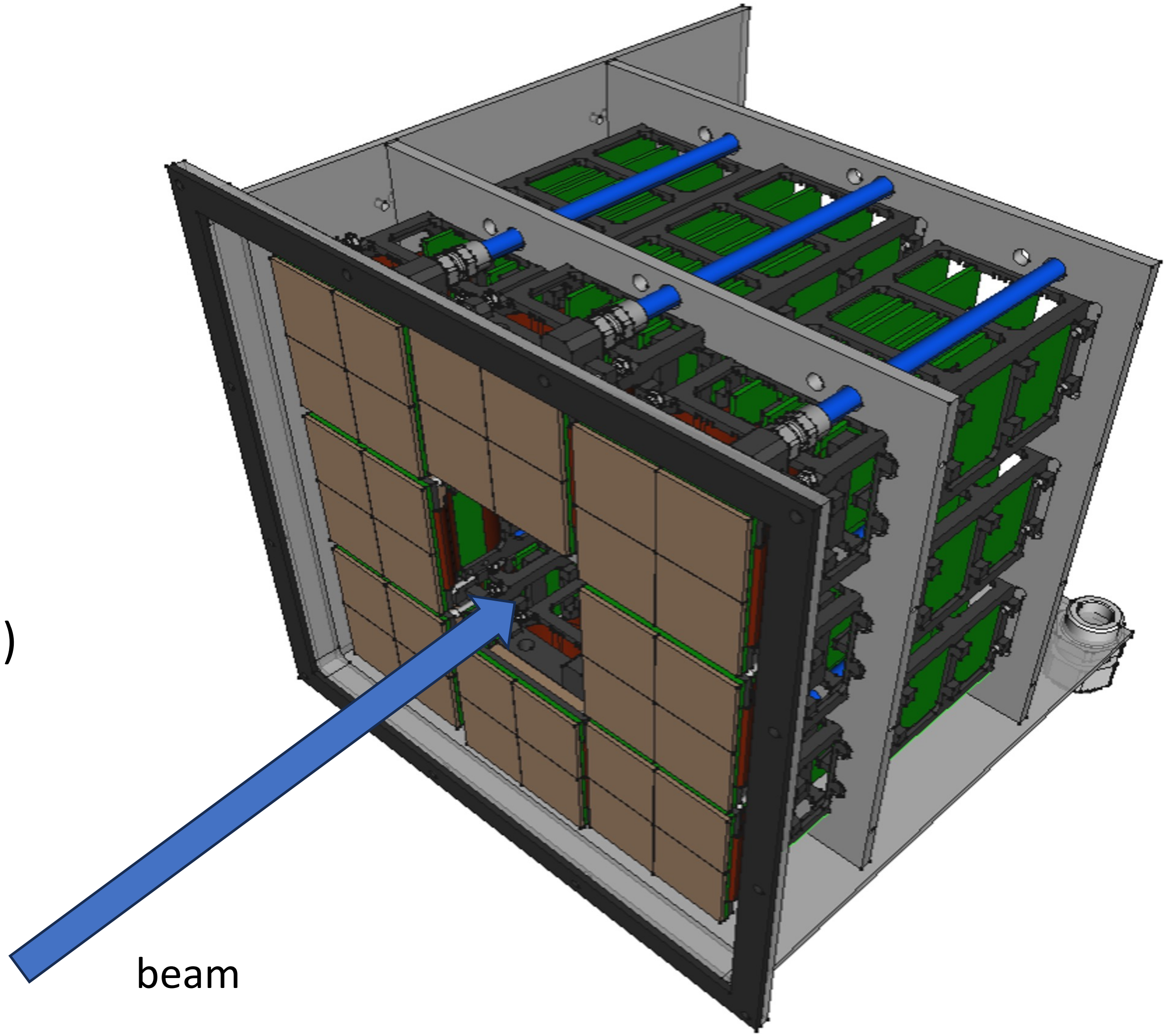


- dRICH DAQ modelled to cope with DCR at maximum radiation damage
- dRICH output at start of EIC operation will be small
- further data reduction in Data Aggregator Modules (48 links – PCI card)

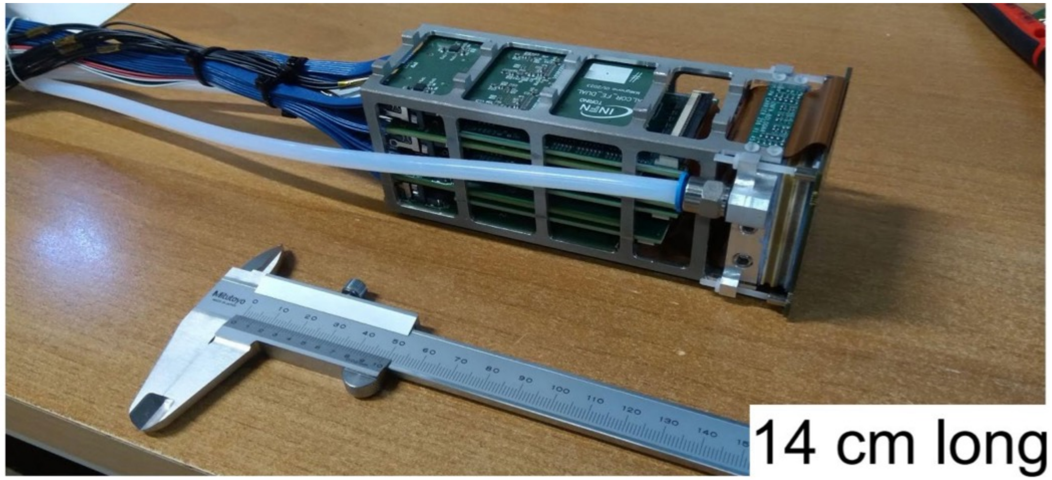
Global dRICH throughput out of RDO:
1.4 Tbps (14 Gbps)

Prototyping dRICH PDU and dRICH "camera"

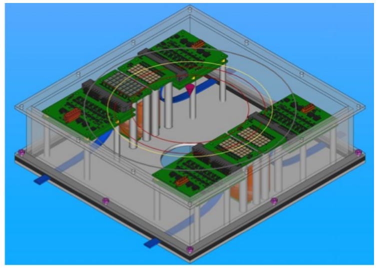


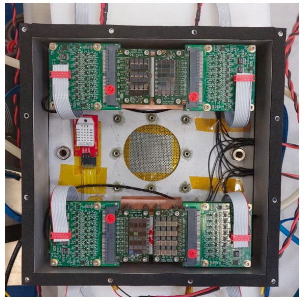


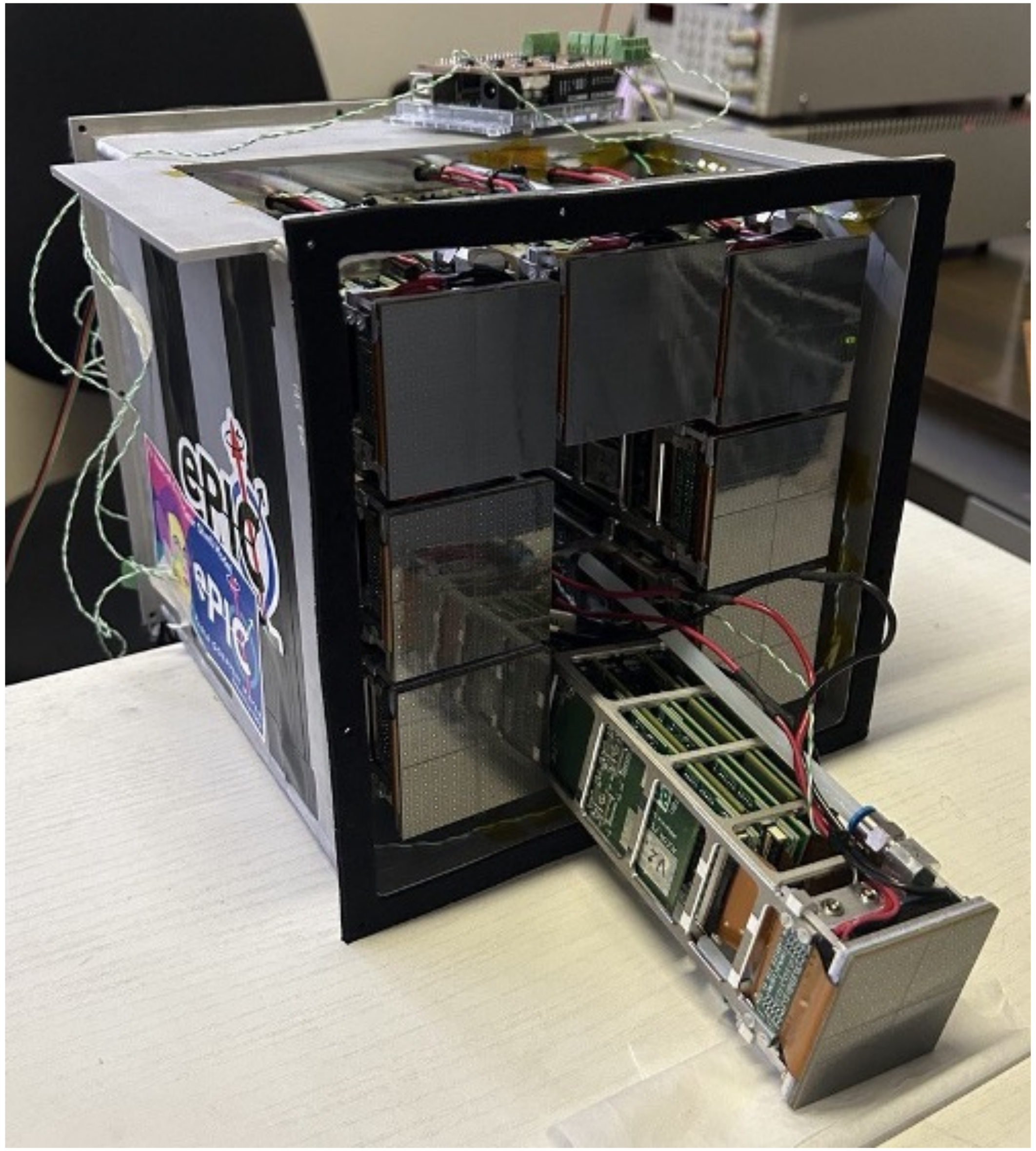
Prototyping dRICH PDU and dRICH "camera"



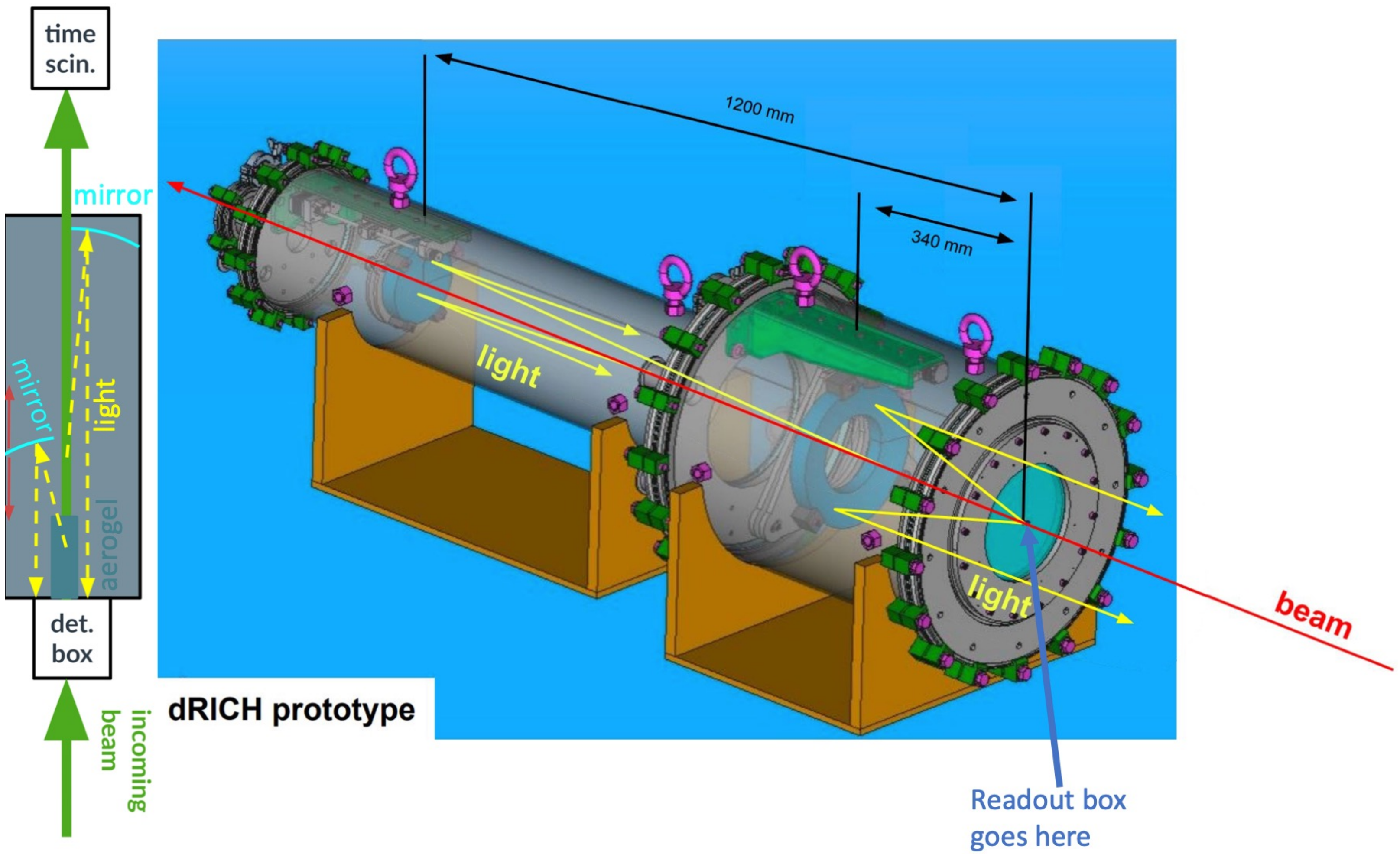
equipped with HPK S13360-50/S13360-75
2024: 2k channels
2023: 1.2 k channels
2021-2022: minimal "detector box" 128 channels

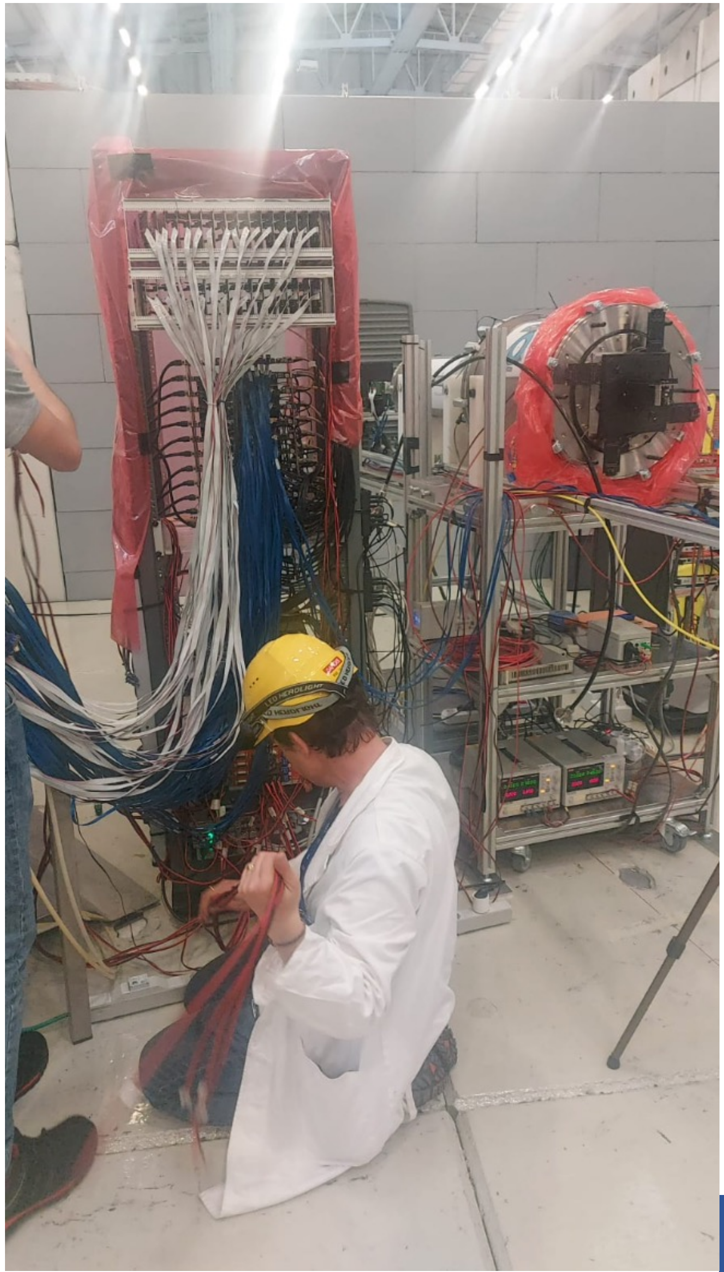




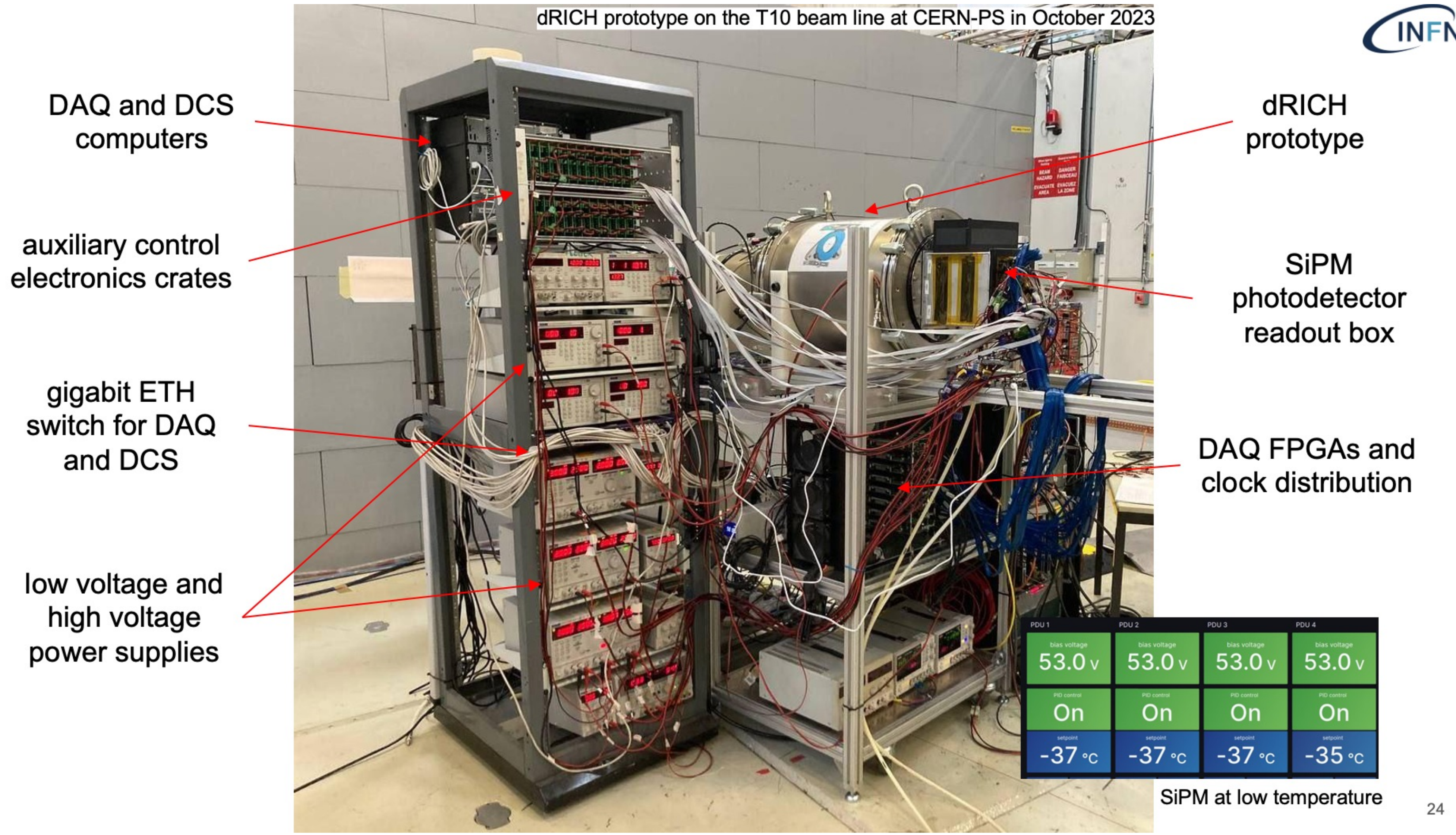


Test beams: putting pieces together on the floor





More on dRICH test beam setup at BTTB24 (M. Giacalone)
dRICH prototype: S. Vallarino et al., *Nucl.Instrum.Meth.A* 1058 (2024) 168834



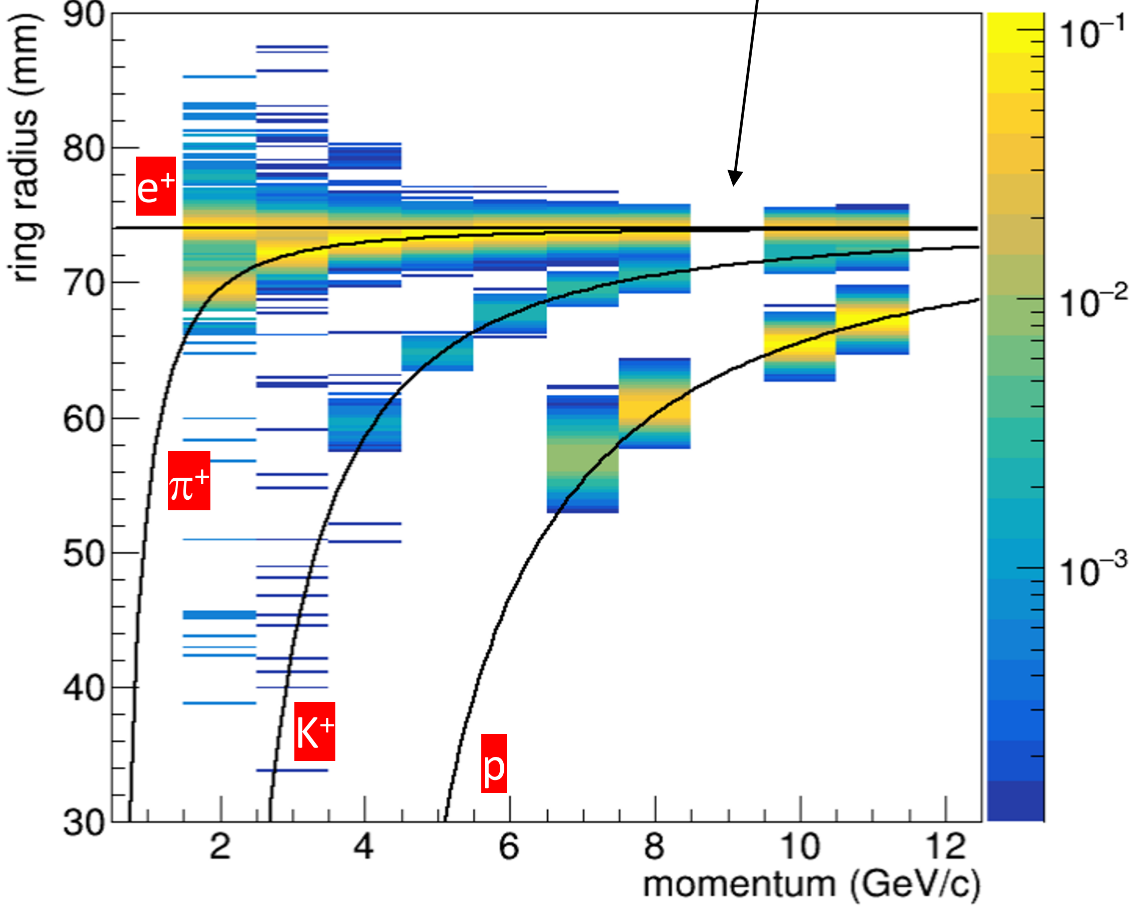
dRICH readout @ test beam: L. Rignanese et al, *JINST* 19 (2024) 02, C02062

credits: R. Preghenella@iWoRiD24

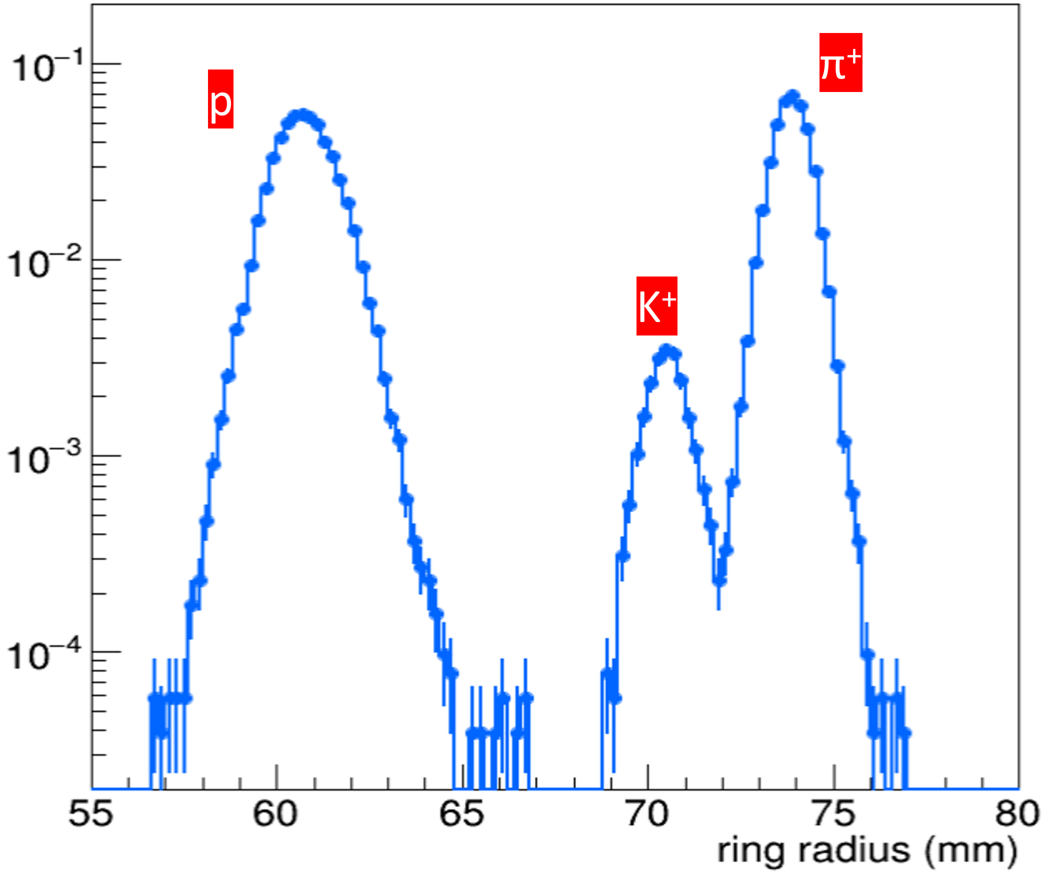
Test beams results (2024)

Beam momentum scan
Aerogel radiator only
Positive beam

Murphy law holds:
something wrong in beam setup at 9 GeV/c

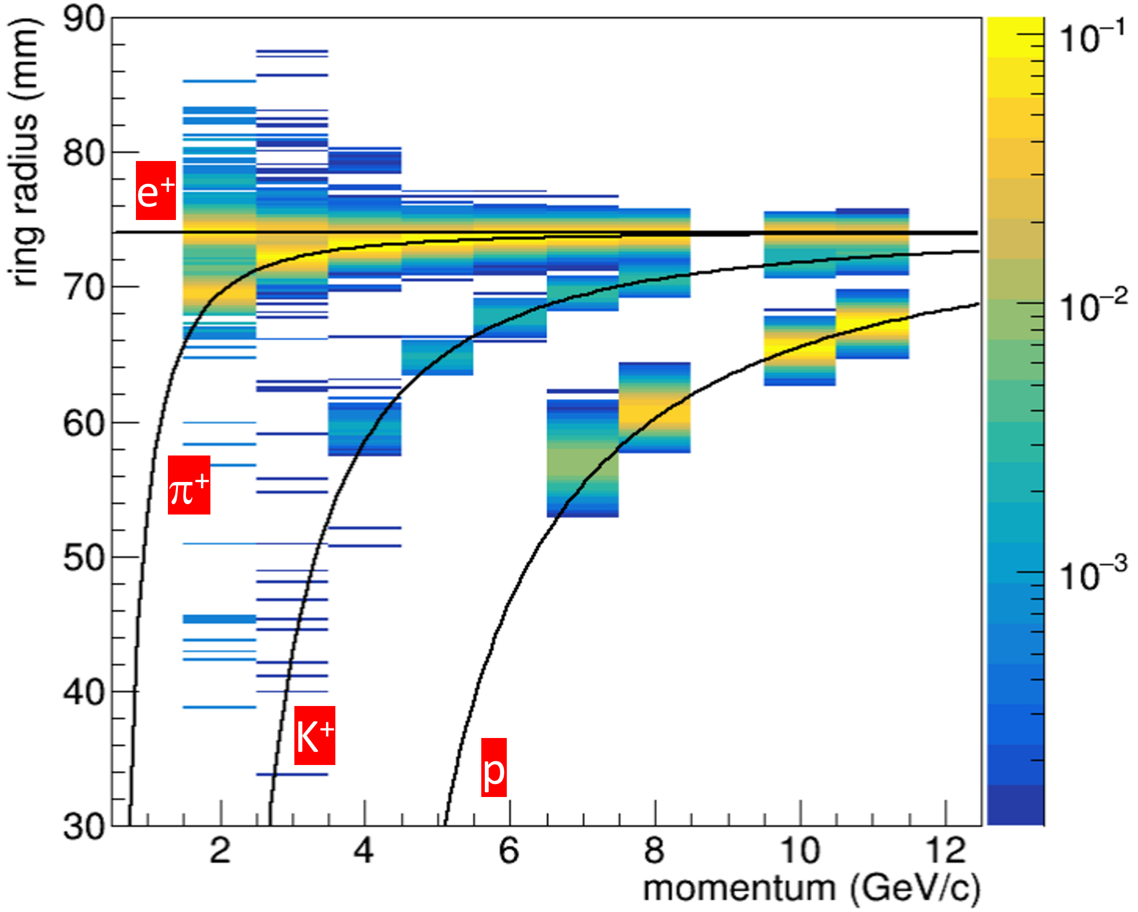


reconstructed ring radius at 8 GeV/c beam momentum

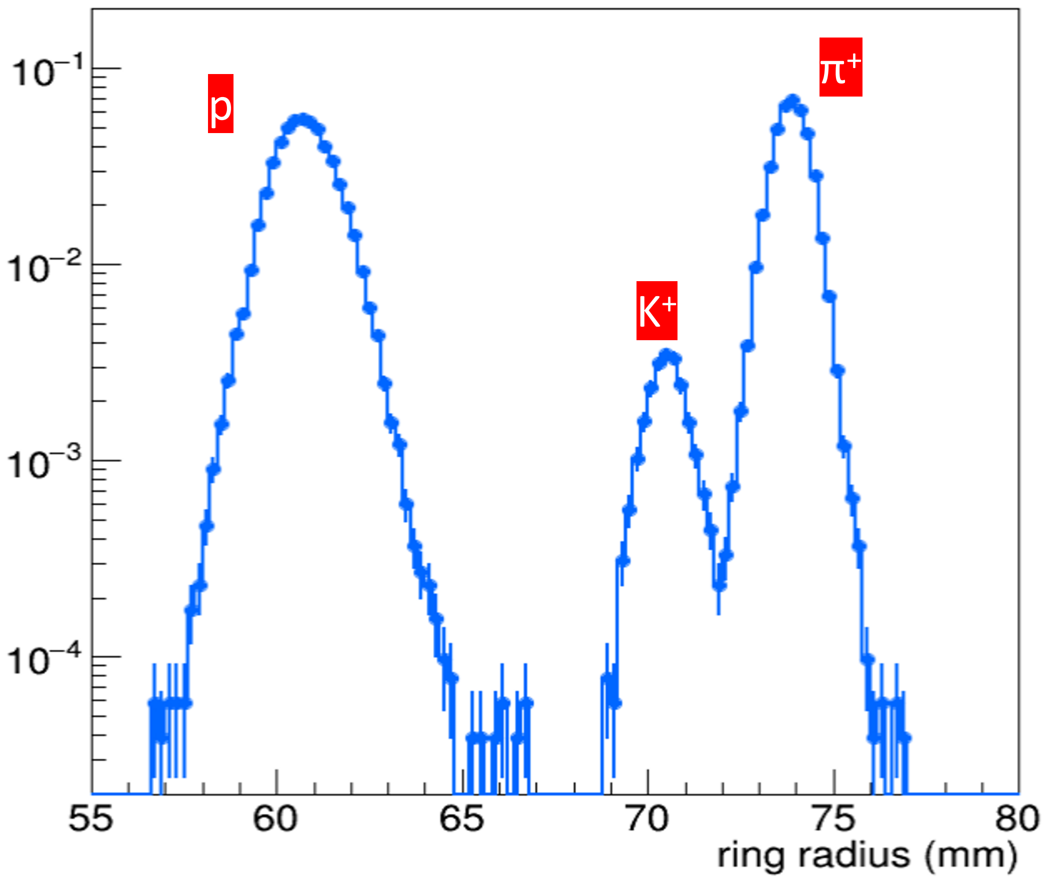


Test beams results (2024)

Beam momentum scan
Aerogel radiator only
Positive beam

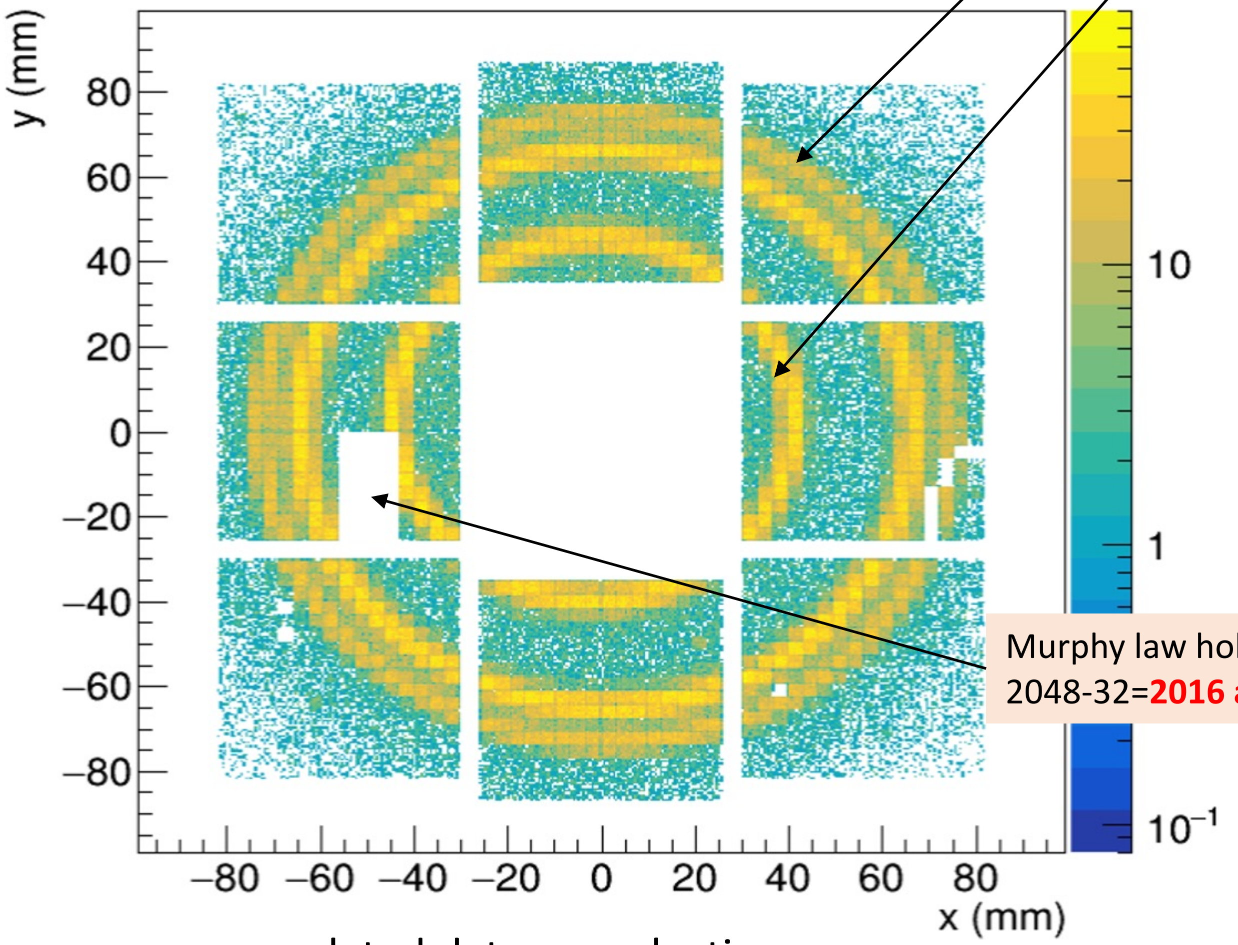


reconstructed ring radius at 8 GeV/c beam momentum



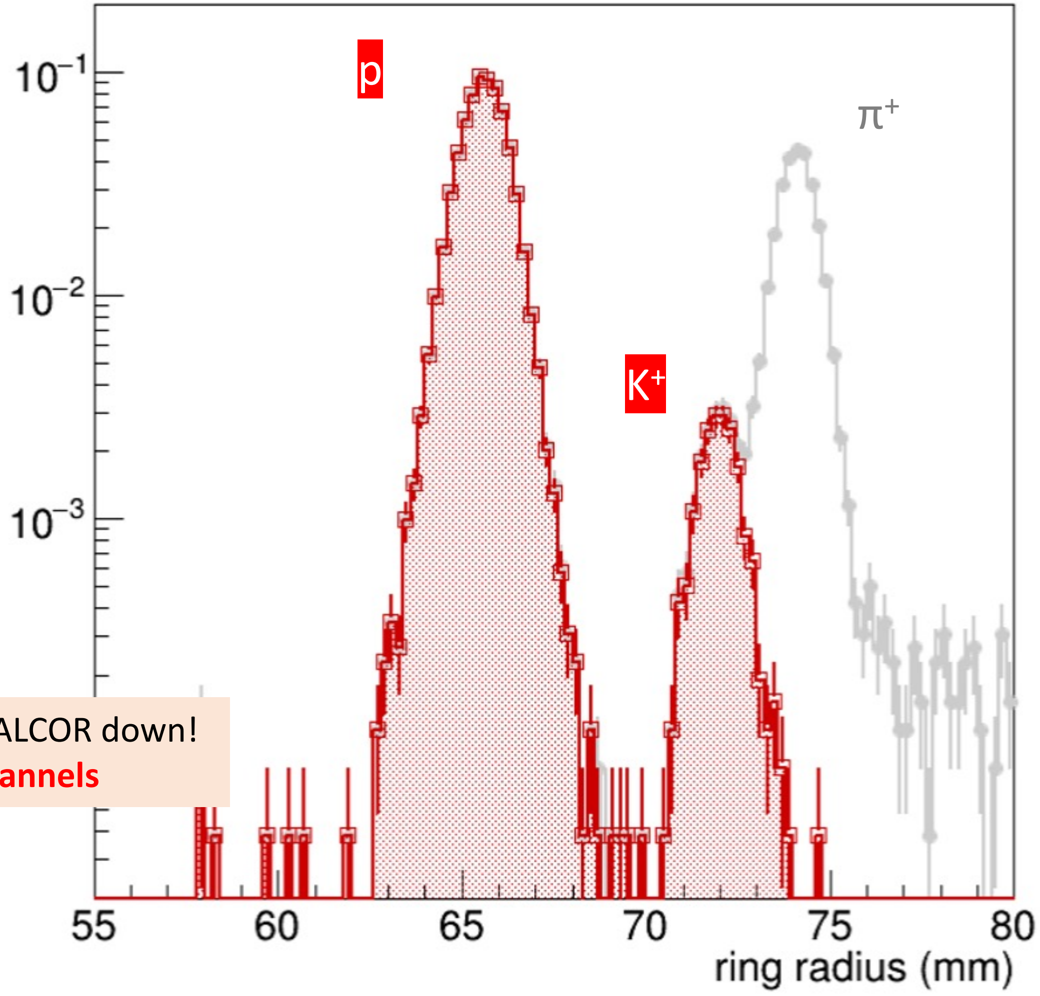
Test beam results: exploiting a **dual** RICH

At 10 GeV/c kaons and protons are below C_2F_6 gas threshold
If you have a gas ring... you have a pion!



accumulated data, no selection

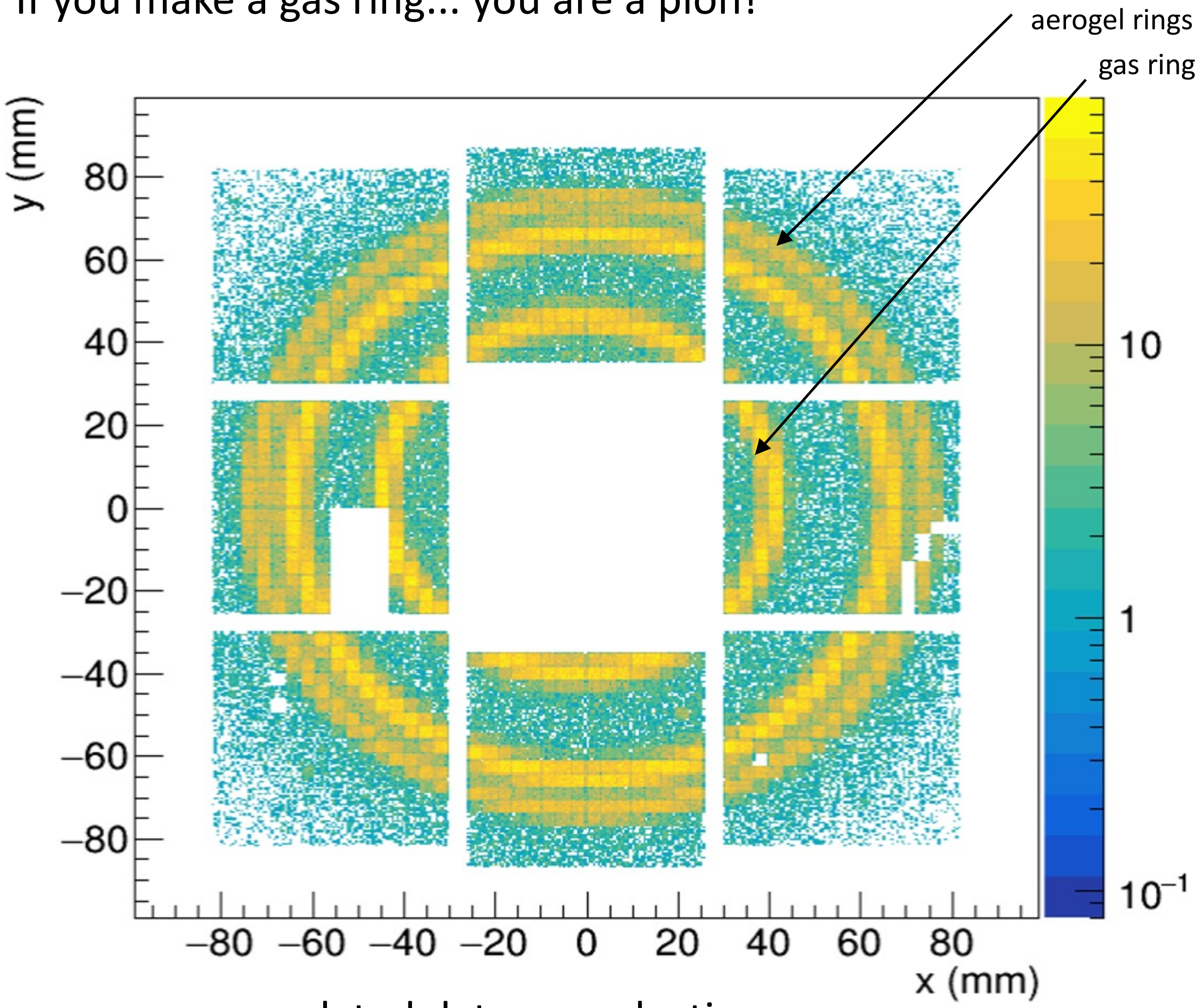
Murphy law holds: one ALCOR down!
2048-32=**2016 active channels**



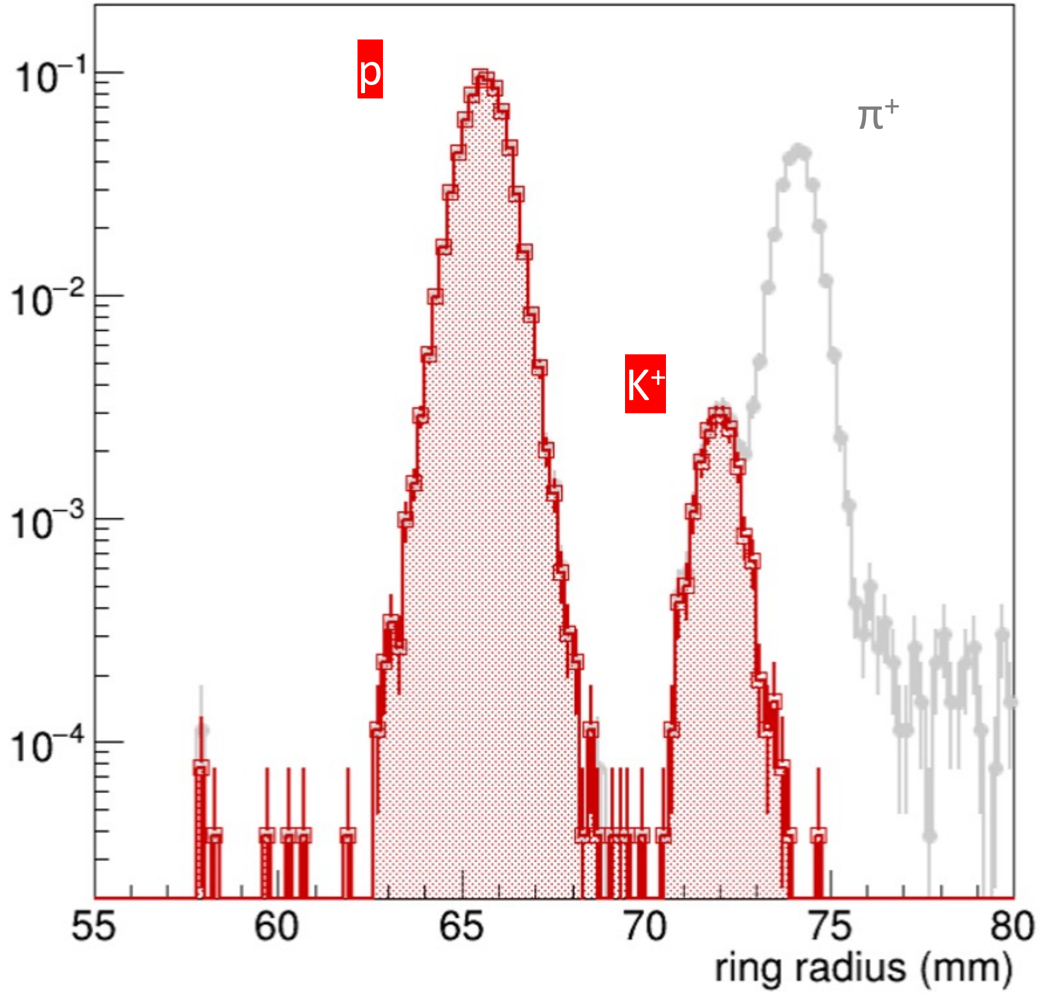
gas ring removes pions → K selection at 10 GeV/c

Test beam results: exploiting a **dual** RICH

At 10 GeV/c kaons and protons are below C_2F_6 gas threshold
If you make a gas ring... you are a pion!



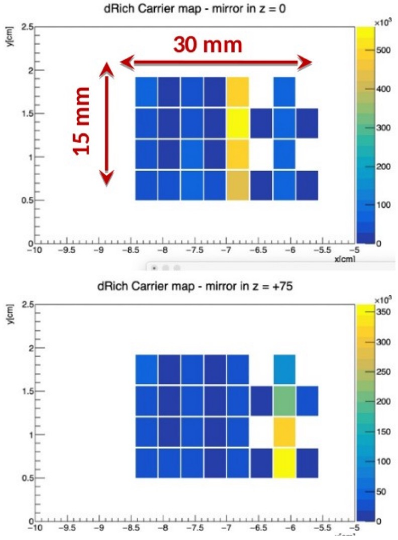
accumulated data, no selection



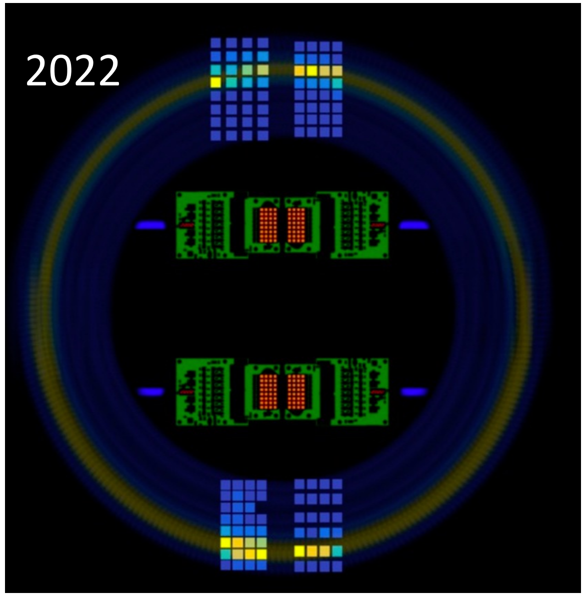
gas ring removes pions → K selection at 10 GeV/c

Test beams results: we get more Cerenkov photons every year ;-)

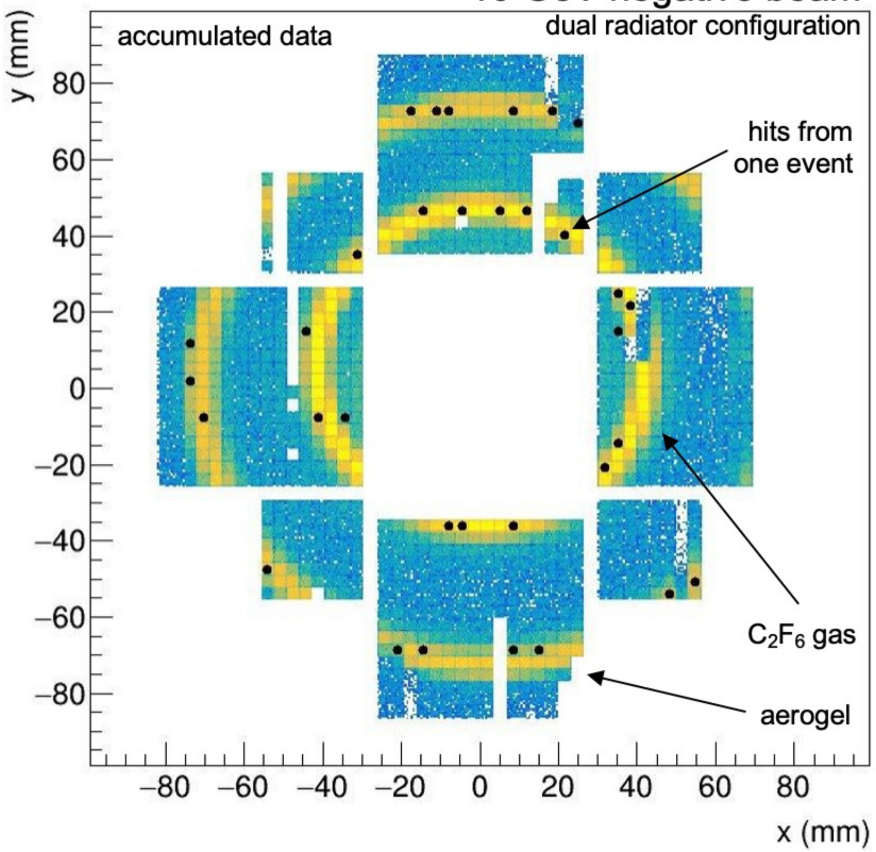
2021 (!)



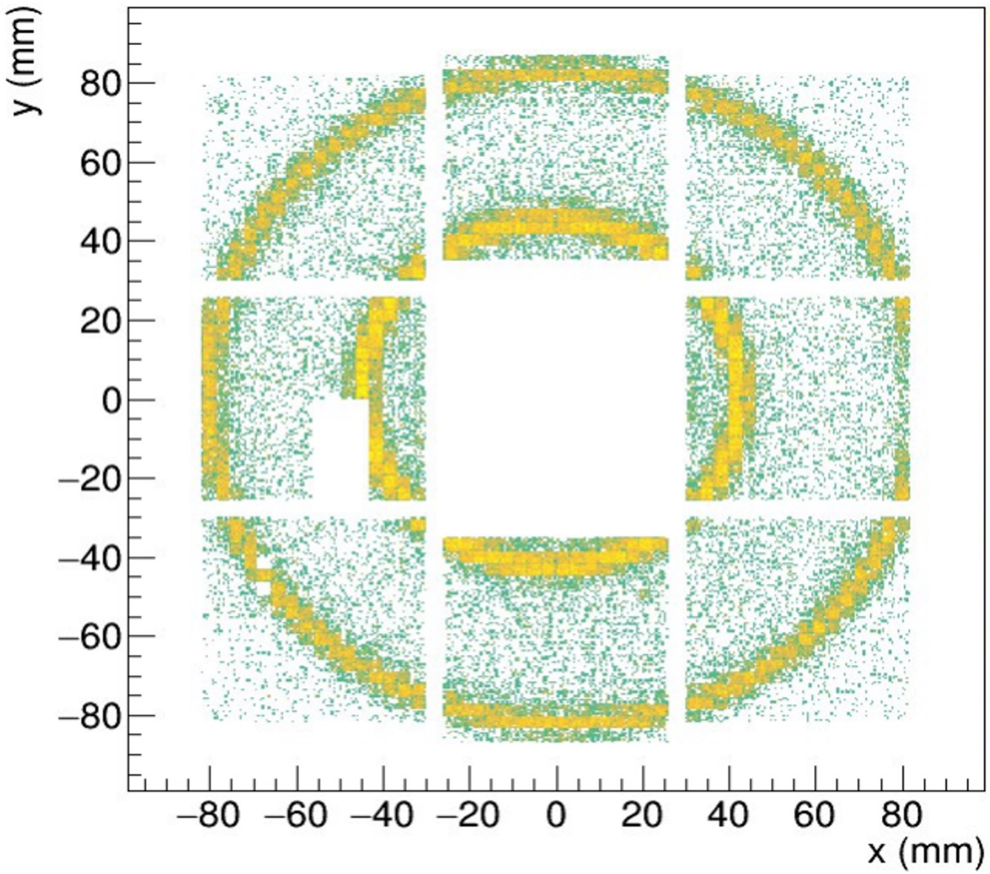
2022



2023



2024



Conclusions and outlook

- successfull R&D program / journey to prove we can operate a RICH with SIPM photosensors at the EIC
  - SIPM option fullfill requirements (time resolution + PDE + no magnetic field)
  - Mitigation strategies to reduce radiation damage in place
  - Electronics (ASIC + readout) tested / under advanced design
  - Test beam results remain best proof

- several integration/engineering challenges ahead of us → ePIC TDR will be our next step!

Pteparing to look inside the nucleon with a pair of SiPM glasses

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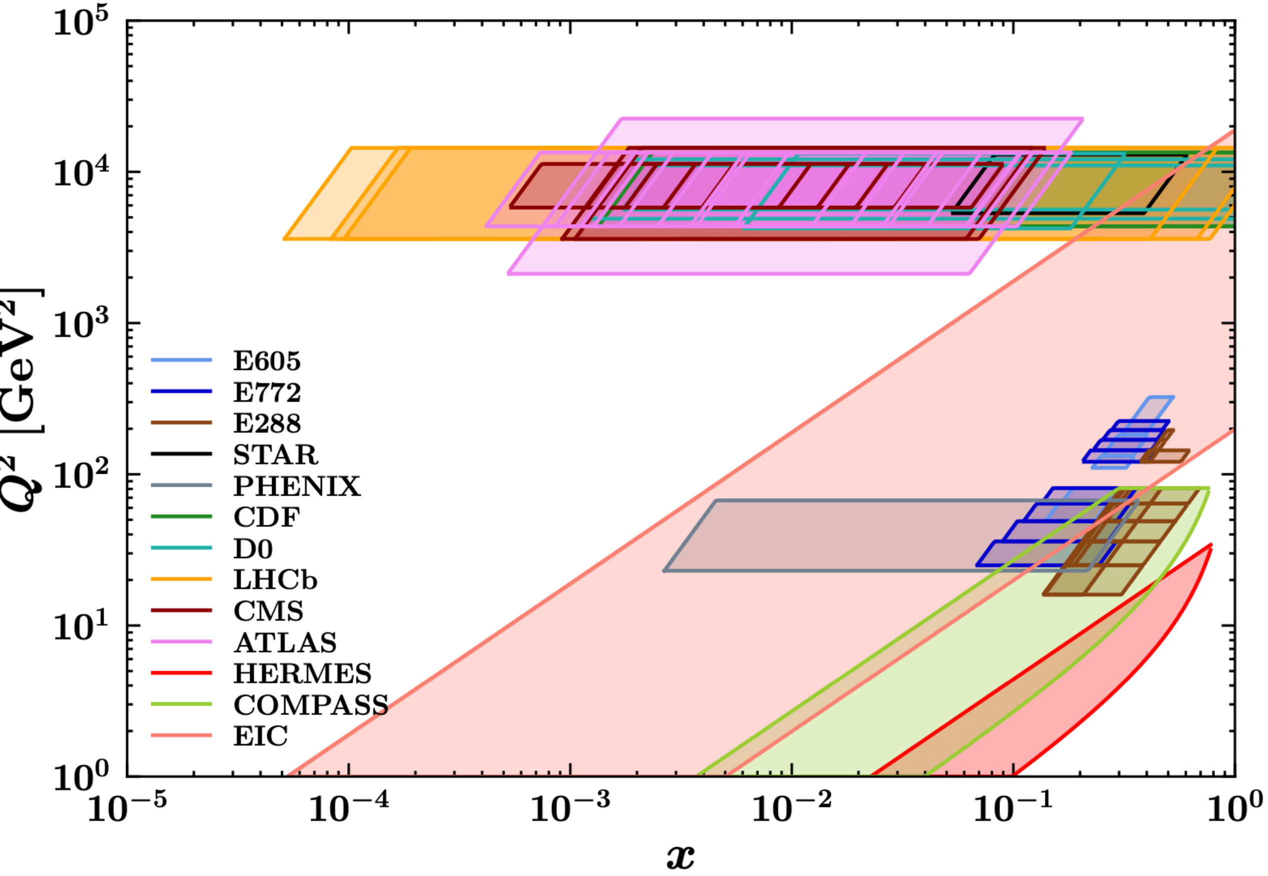
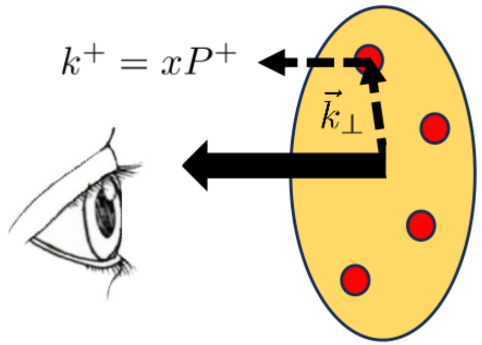
dRICH is key for hadron PID

→ key for SIDIS studies

→ key for TMD measurements





EIC impact will be huge

MAPTMD22 global fit of 2031 SIDIS + Drell Yan

Bacchetta et al. (MAP Coll.) JHEP 10 (22) 127