# Dual-Readout Fibre Calorimeter

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on behalf of the Dual Readout group

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# Dual-Readout Collaboration

- South Korea → projective fibre-sampling calorimeter
- Europa: INFN, Sussex University → fibre-sampling calorimeter
- U.S. (Calvision project): mainly (but not only) on crystal em calorimeter

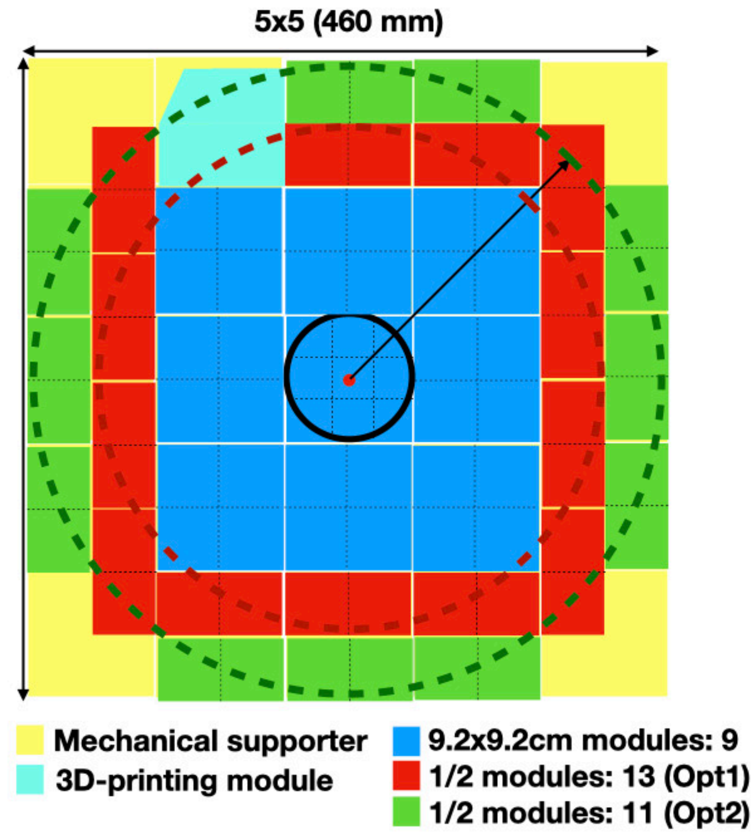
- Other Synergies:
  - Crystal Clear Collaboration: R&D on scintillating crystals (mainly, but not only, on crystal em calorimeter )

# Dual-Readout Calorimeter R&D in South Korea

- Different options under study:
  - Absorber production and assembly procedure
  - Fibre types (round, square, single/double cladding)
  - Light sensors (PMT, MCP-PMT, SiPM )

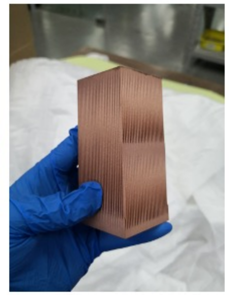
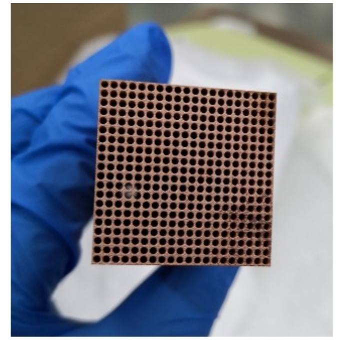
More details on the project are available here

Goal by 2025 for
the full-size prototype



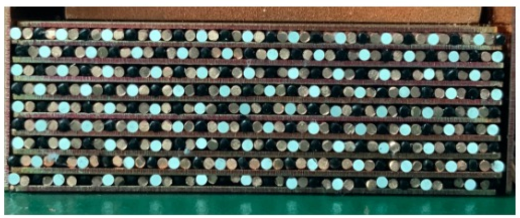
# R&D for module production

- 3D-printing

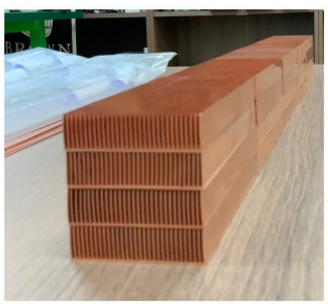
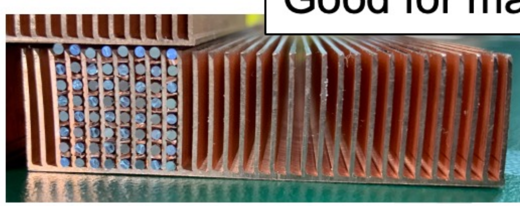
Excellent accuracy but quite expensive

- Stacking (LEGO-like)



Good accuracy and quite cheap

- Skiving Fin Heatsink

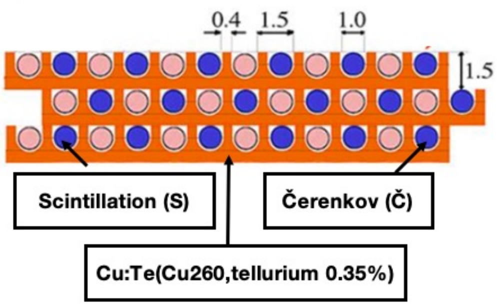



Good for mass production!

high accuracy and low cost

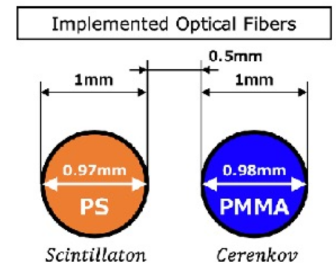
# The 2 modules tested on beam in 2022

- **Copper Plate & Fibers**



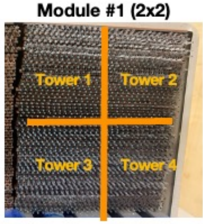

- **Copper plate (60)**
- Width : 10 cm
- Length : 2.5 m
- Thickness : ~1.6 mm
- Hole : 1 mm (diameter)
- Distance between hole : ~ 0.63 mm

- **Optical fibers**
  - Scintillation fibers & Cerenkov fibers
    **(Kuraray SCSF-78)** **(Mitsubishi SK-40)**

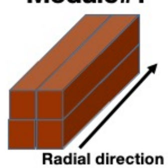



- **Configuration of Fibers & Readout detector for Test Beam**

**Module #1 (2x2)**



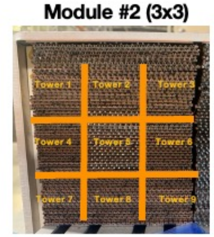

**Module#1**



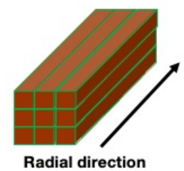

**Module#1**

| | |
|---|---|
| Tower#1 | Tower#2 |
| Tower#3 | Tower#4 |

**Module #2 (3x3)**



**Module#2**




**Module#2**

| | | |
|---|---|---|
| Tower#1 | Tower#2 | Tower#3 |
| Tower#4 | Tower#5 | Tower#6 |
| Tower#7 | Tower#8 | Tower#9 |

Combination of fibers for Module#1

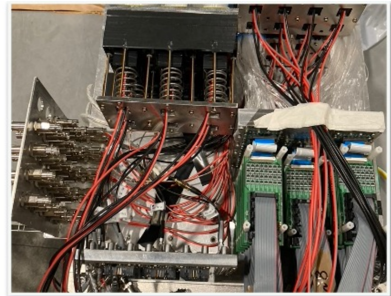
| | Tower #1 | Tower #2 | Tower #3 | Tower #4 |
|---|---|---|---|---|
| Scintillation fibers | Round / Single cladding | Round / Double cladding | Round / Single cladding | Square / Single cladding |
| Cherenkov fibers | Round / Single cladding | Round / Single cladding | Round / Single cladding | Round / Single cladding |
| Readout detector (2*4 ch) | 2 PMTs | 2 PMTs | 2 MCP-PMTs | 2 PMTs |

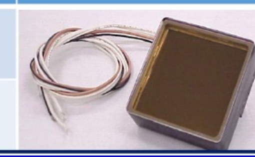
Combination of fibers for Module#2

| | Tower #1~4 and #6~9 | Tower #5 |
|---|---|---|
| Scintillation fibers | Round / Single cladding | Round / Single cladding |
| Cherenkov fibers | Round / Single cladding | Round / Single cladding |
| Readout detector (400+16 ch) | 16 PMTs | 400 SiPMs |

# The 2 modules tested on beam in 2022

- Module 1
  - Read out information
    PMT (6ch) + MCP-PMT (2ch)
- Module 2
  - Read out information
    PMT (16ch) + SiPM (416ch, T.5)



| MCP-PMT | Window size | light | Quantum Efficinecy (Q.E.) | max. HV (V) | Rise time (ns) | Pulse width (ns) | photo |
|---|---|---|---|---|---|---|---|
| PLANACON XP85012 | 53x53 mm$^2$ | scintillation | ~7% at 550 nm | 2400 | 0.6 | 1.8 |  |
| PLANACON XP85112 | | Cerenkov | ~21% at 400 nm | 2800 | 0.5 | 0.7 | |

| PMT | Window size | Q.E. for Ck. | Q.E. for Sc. | max. HV (V) | Time response (ns) | | | photo |
|---|---|---|---|---|---|---|---|---|
| | | | | | anode pulse rise time | electron transit time | Transit time spread (FWHM) |  |
| R8900 series (old) | 23.5x23.5 mm$^2$ | 35% at 420 nm | ~7% at 550 nm | 1000 | 2.2 | 11.9 | 0.75 | |
| **R11265-100 (new)** | **23x23 mm$^2$** | **~35% at 400 nm** | **~7% at 550 nm** | | **1.3** | **5.8** | **0.27** | |

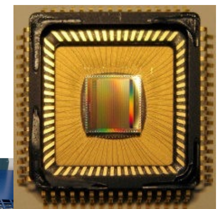
| SiPM | photosensitive area | photo detection efficiency (PDE) | | operating voltage | Gain at $V_{BD}$+5V | Linearity of Q.E. | number of pixels | geo. Fill factor |
|---|---|---|---|---|---|---|---|---|
| S14160-1310PS | 1.3x1.3 (1.69 mm$^2$) | ~15% at 400 nm | ~17% at 550 nm | $V_{breaking\ Down}$ + 5 V | ~1.75x10$^5$ | ~2x10$^{10}$/sec as incident photons | 16675 | 31 % (0.524 mm$^2$) |
| fiber (Φ1 mm) | 0.785 mm$^2$ | | | | | | ~7745 (effectively) | |

# DAQ system used on beam in 2022

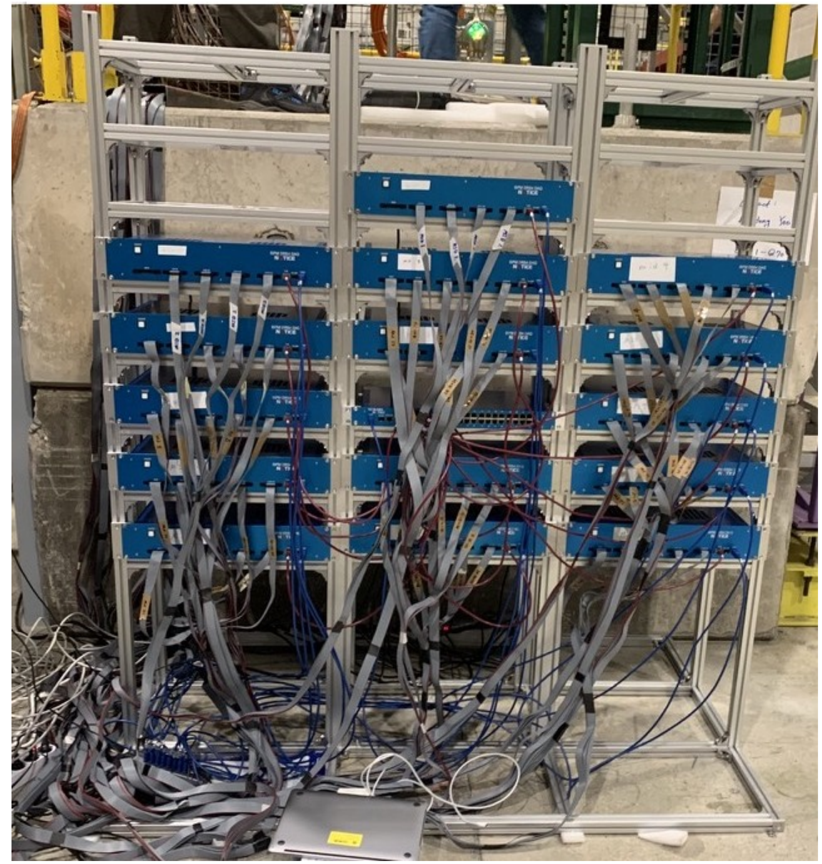
- System made of 15 DAQ Boards + 1 TCB Board

- DAQ Board:
  - One board covers 32 channels
  - DRS4 chip (from 0.7 Gsps to 5 Gsps with 1024 sampling points)
  - 16 pin Ribbon cable

DRS4 chip



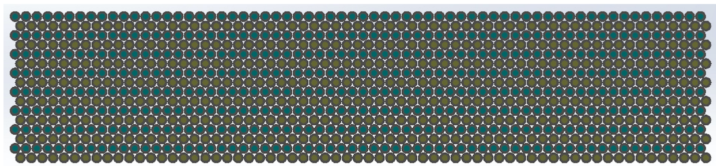
- TCB Board
  - Control the setting value of DAQ boards and the trigger system
  - Connect DAQ boards with TCP/IP cable, cover 40 ch DAQ



- All boards connected with PC using USB3 line

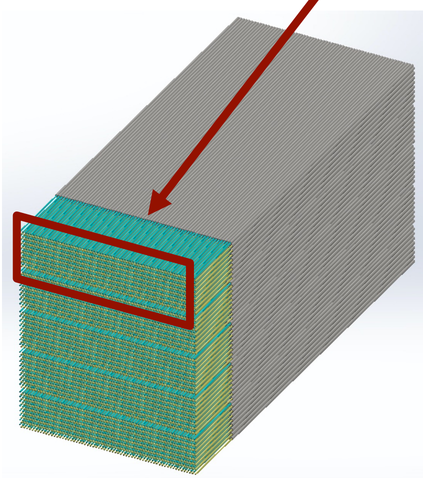
# Dual-Readout Calorimeter R&D in Europe

## The Mini-Module



64 x 16 capillaries

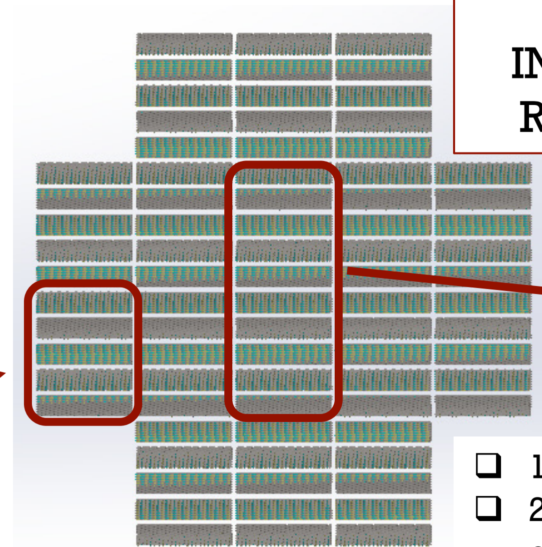
## The Module



5 Mini-modules
~ 13 x 13 x 250 cm$^3$

## The hadronic prototype

HiDRa
INFN-funded
R&D project



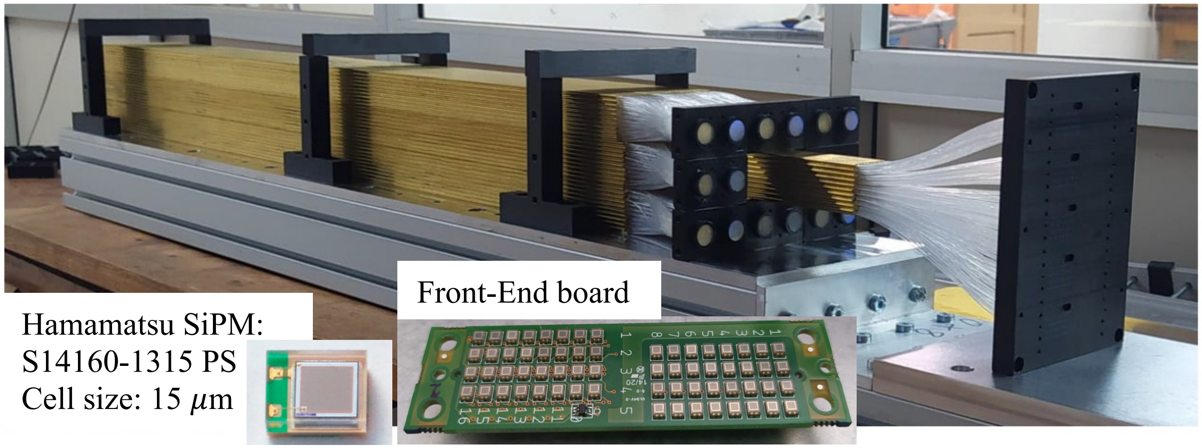
The highly granular modules

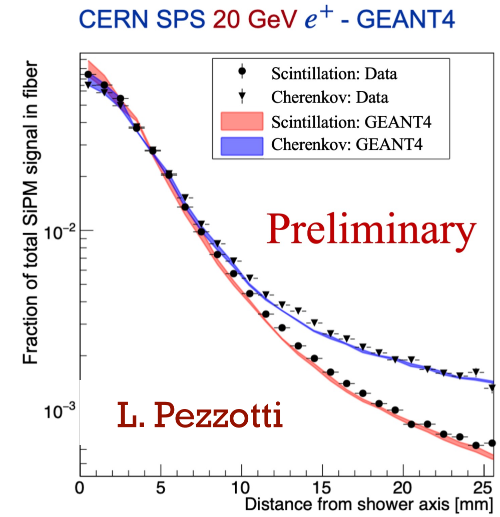
- 16 modules in total
- 2 central modules equipped with SiPMs
- 14 modules equipped with PMTs
- ~ 65 x 65 x 250 cm$^3$

**The challenge:**

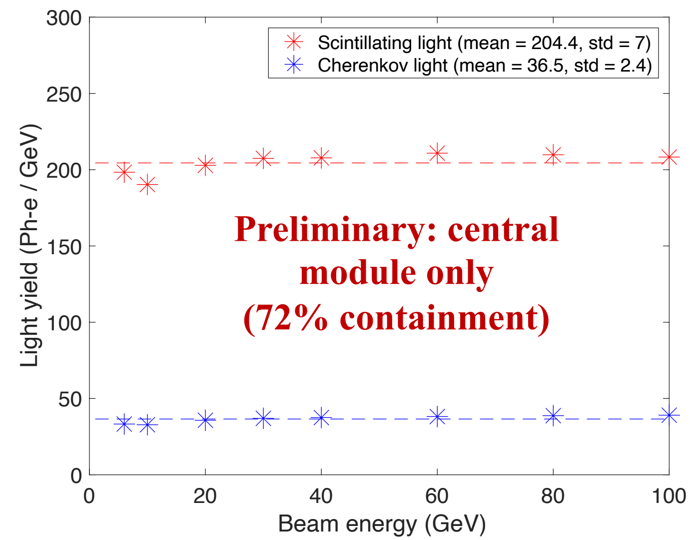
We have10240 SiPMs, fitting the back side of the detector

# Few results from the 2021 test beam




- A small prototype has been tested on beam in 2021 (@DESY and @CERN) with electrons ranging from 1 to 100 GeV
- The prototype was made of brass capillary tubes (2 mm outer diameter) each hosting a fibre of 1 mm diameter: : (10x10x100 cm³)
- There are 9 towers containing 16x20 capillaries with alternating scintillating and clear fibres
- The central tower is equipped with SiPMs while the surrounding towers are connected to PMTs (costs saving reason)



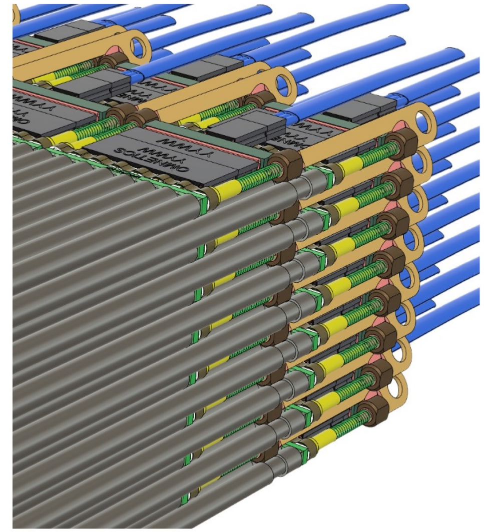



Calor2022 – DOI: 10.3390/instruments6040059

# The design of a scalable solution

Quite challenging integration that requires:

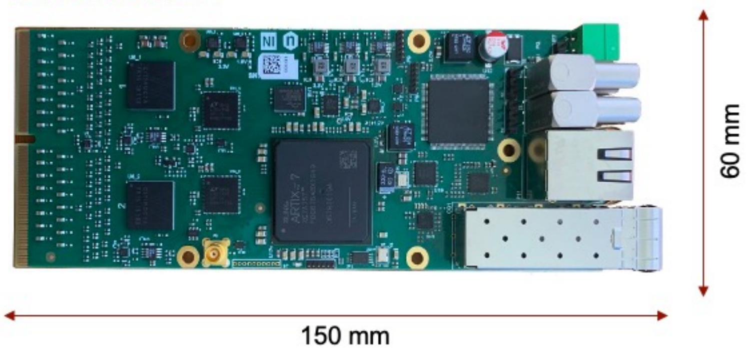
- Precise assembly procedure
- Compact components: there is almost no space in the rear part of the calorimeter
  - SiPMs
  - Mechanical support
  - Cabling and readout to serve all channels



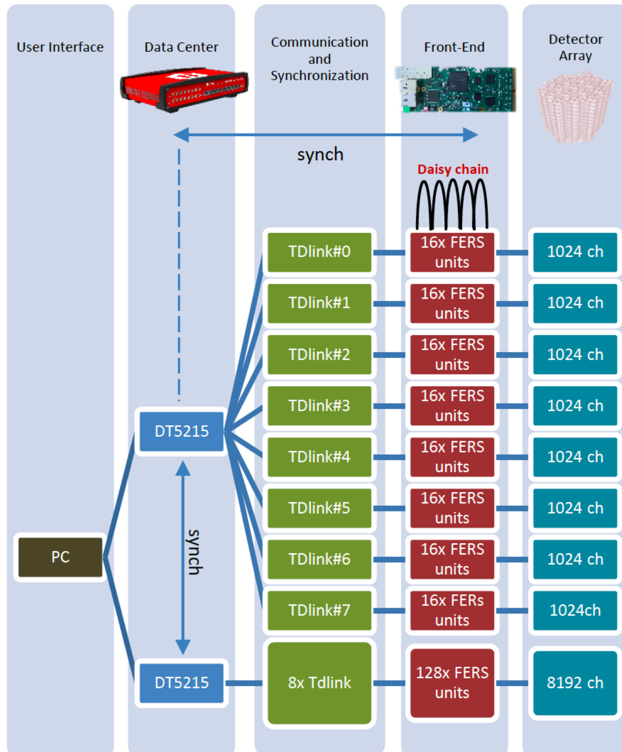
More details are available here

# SiPM integration and readout

- The highly granular module is operated with the Caen FERS system (5200) and the A5202 readout boards

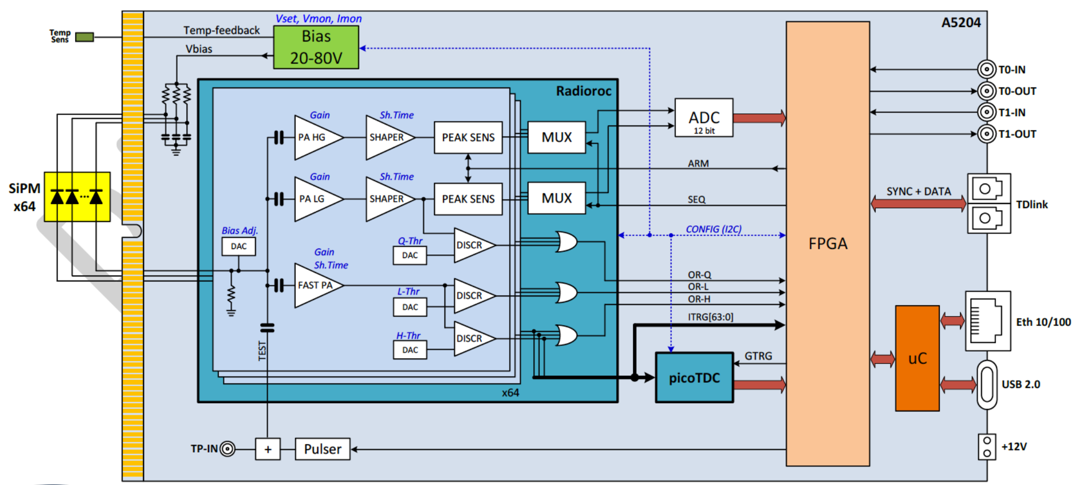


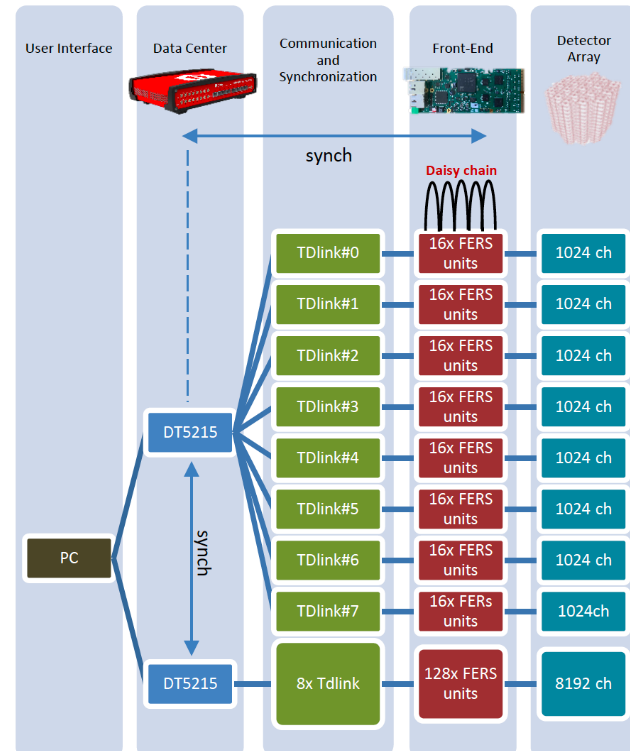

- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout (6.25 Gbit/s)



# SiPM integration and readout

- An alternative for the highly granular modules could be the A5204 readout board, equipped with the RadioROC (not yet available)
- similar performance as the CITIROC in spectroscopy
- better timing performances
  - 64 individual digital signal with jitter at level of 55ps (FWHM) on single photoelectron
  - Digital signals connected to a picoTDC (ASIC produced by CERN) with LSB ~ 3ps



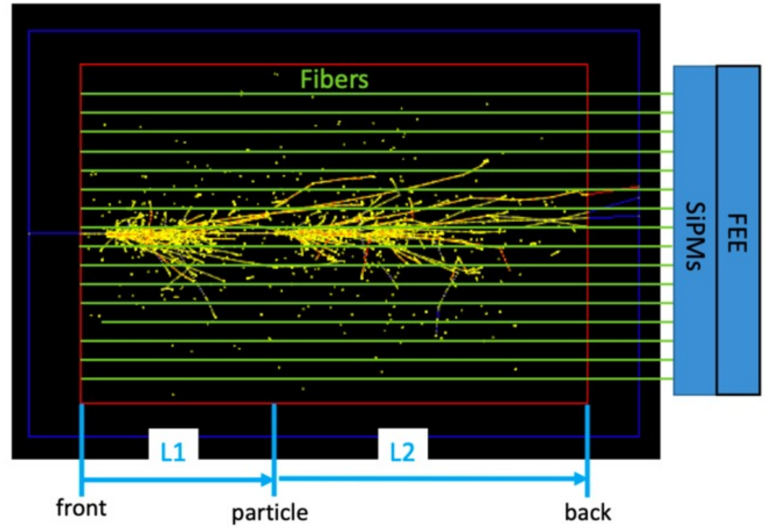
# Alternative readout schema could be considered

* high performance waveform digitizer

* Digital Silicon Photomultiplier

# Longitudinal segmentation with timing

- Time information may provide longitudinal segmentation (3D-detector)
- Main advantages:
  - Less channels than a true 3D segmented detector
  - Less radiation for the readout electronics
  - No services in the calorimeter volume
- A recent Monte Carlo study indicates a good potential of 3D Imaging Fiber Calorimeter when used with ML technology



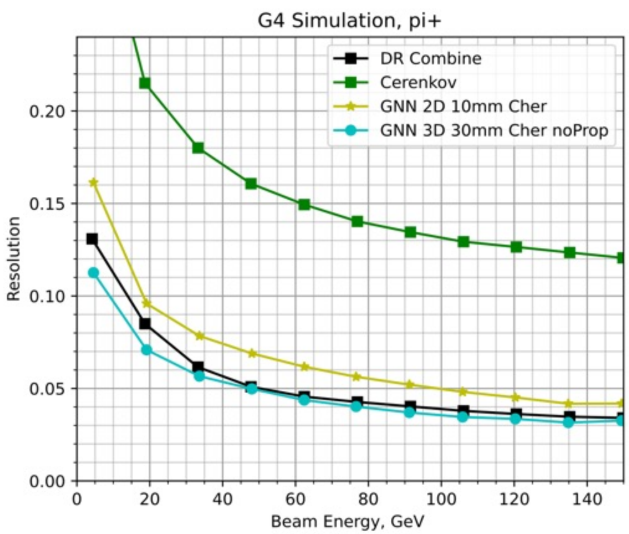



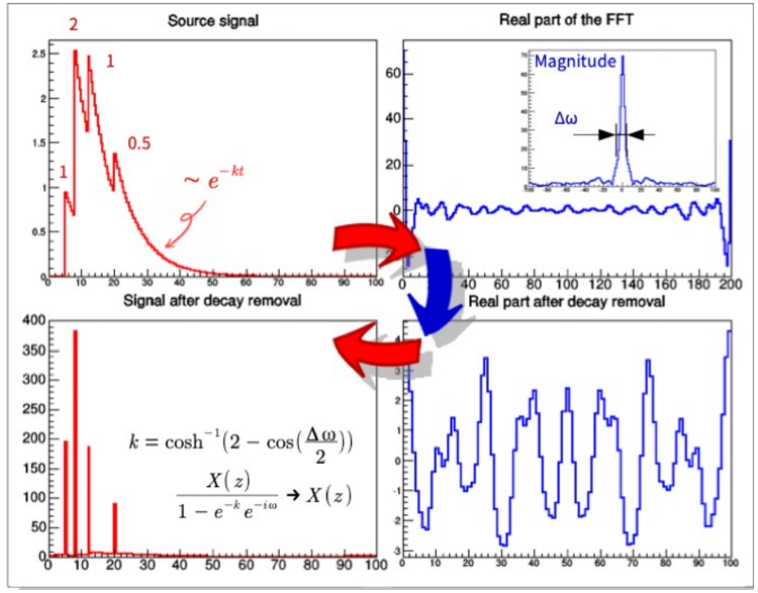

**Table 1.** The energy resolution of the 3D GNN reconstruction with various timing resolutions for longitudinal segmentation.

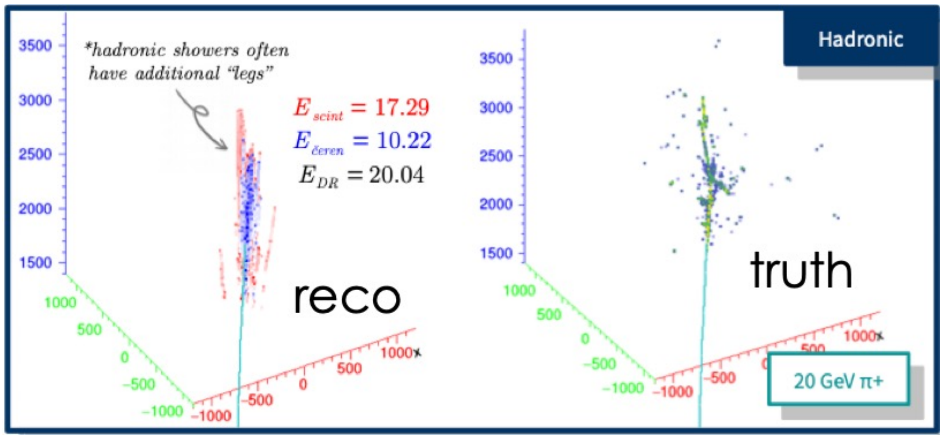
| Timing Resolution $\Delta(t)$, ps | Position Resolution $\Delta(z)$, cm | Energy Resolution $\sigma$/E, % |
|---|---|---|
| 0 | 0.0 | 3.6 |
| 100 | 5.0 | 3.9 |
| 150 | 7.5 | 4.0 |
| 200 | 10.0 | 4.2 |

https://doi.org/10.3390/instruments6040043

# Longitudinal segmentation with timing

- Assume to read out full signal from SiPM sampled at 10 GHz.
- FFT of signal yields individual fiber hits and high-precision (< 100 ps) timing.
- Unlocks full longitudinal information about energy deposit.
- Combined with dual readout information allows in-shower cluster identification.

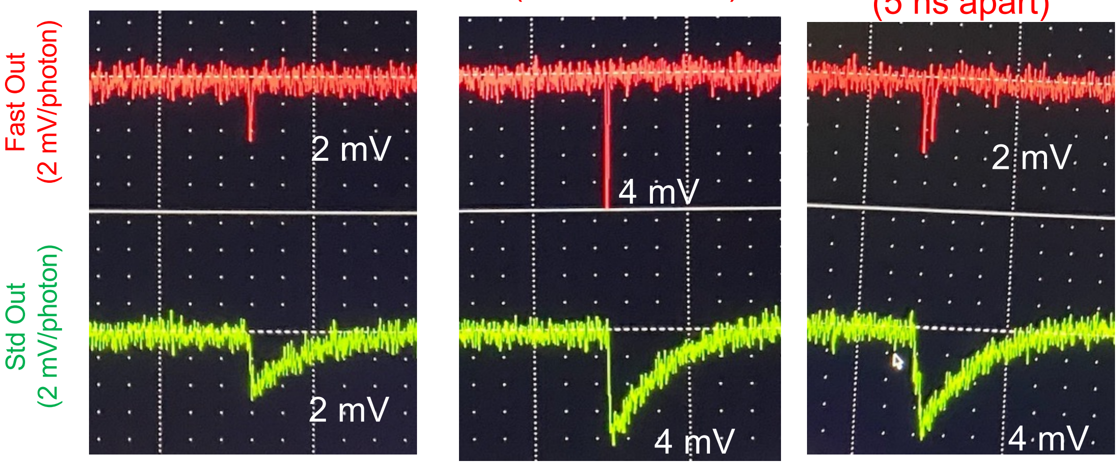


# Waveform digitizer (AARDVARC v3)

SiPMs are excellent photon counting devices and have potential to map time structure of showers in calorimeter when used with high performance waveform digitizer.

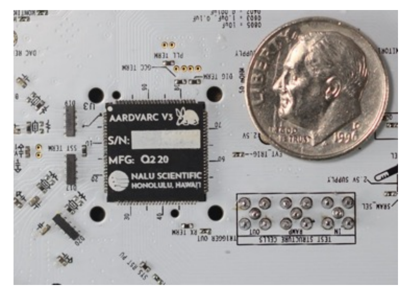
Results with SensL (MicroFC-30020SMT):
SiPM with fast and standard outputs.




CPAD 2021, https://indico.fnal.gov/event/46746/contributions/210063/

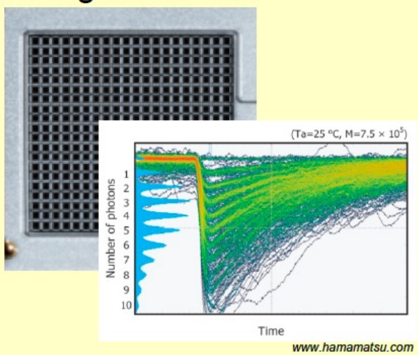
NALU Scientific AARDVARC v3

- Sampling rate 10-14 GSa/s,
- 12 bits ADC,
- 4-8 ps timing resolution,
- 32 k sampling buffer,
- bandwidth 2 GHz,
- System-on-Chip (CPU)



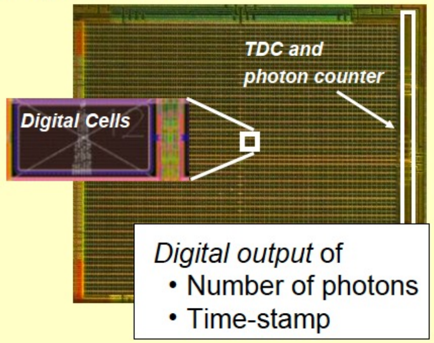
# Alternative readout: dSiPM

Analog SiPM




- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

Digital SiPM




- Each diode is a digital switch
- Digital sum of detected photons
- Digital data output

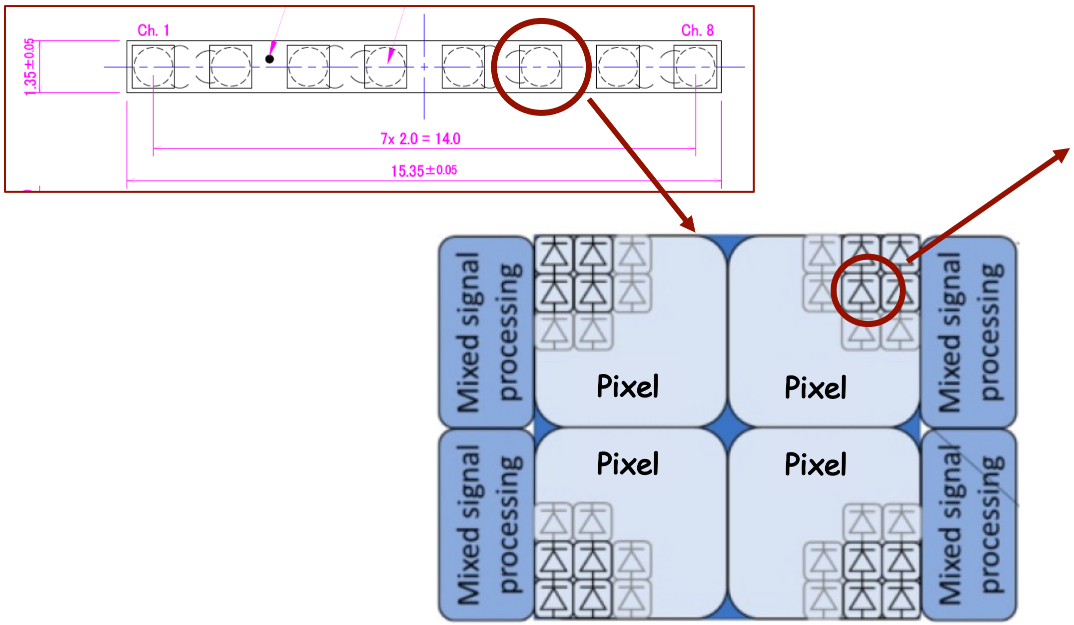
**With dSiPM there is no need for analogue signal post-processing**

- SPAD array in CMOS technologies may offer the following benefits:
  - To embed complex functions in the same substrate (e.g. SPAD masking, counting, TDCs)
  - The design of the front-end electronics can be optimized to preserve signal integrity (especially useful for timing)
  - The monolithic structure simplifies the assembly for large area detectors
  - Development costs can be kept relatively low if the design is based on standard process

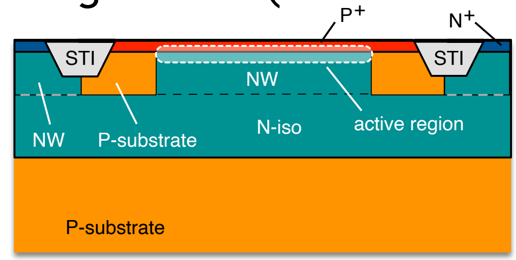
# Sensor requirements for DR-Calorimetry

| | Scintillating (Cherenkov) |
|---|---|
| Unit Area ($mm^2$) | 1 x 1 |
| Micro-cell pitch ($\mu m$) | 10 or 15 |
| Macro-pixel ($\mu m^2$) | 500 x 500 (or less) |
| PDE (%) | (20 - 50) |
| DCR (kHz) | Not crucial |
| AP (%) | As low as possible (≈ 1) |
| Xtalk (%) | As low as possible (few %) |
| Trigger | External |
| Data: light intensity | Number of fired cells in 1 or 2 time windows (tenths ns long) |
| Data: time | Time of Arrival in the time window (< 100 ps) possibly TOT |
| Final - Package | Strip with 8 units |
| Connection | BGA |

# A possible floorplan and readout architecture




Single SPAD (150 nm CMOS technology )




- p+/n-well junction, isolated from substrate by deep n-well
- Readout electronics integrated in a monolithic structure with the sensor

- The building block consists of 8 dSiPM, 1x1mm$^2$, based on SPAD arrays with 15$\mu$m pitch or less
- The local electronic circuits will be kept to a minimum to guarantee high fill-factor
- The inter-dSiPM spacing is used to accommodate the processing electronics
- The 1 mm$^2$ dSiPM will be subdivided in quadrants (Pixel), each served by dedicated, mixed analogue and digital electronics

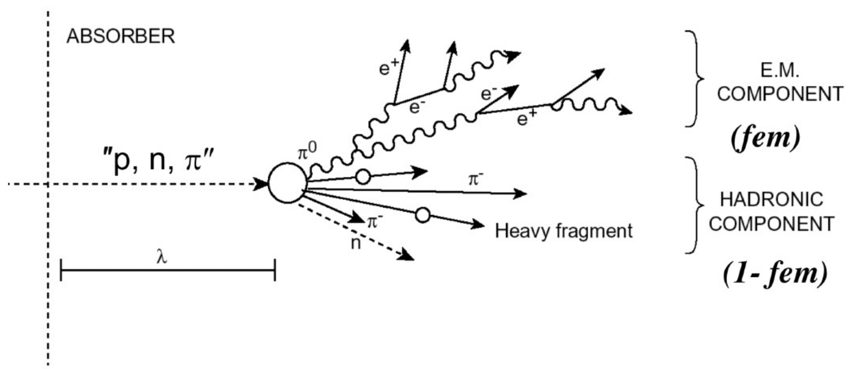
# Outlook

- R&D on dual-readout calorimetry follows all possible directions
  - Innovative absorber production to guarantee good quality and affordable cost
  - Assembly solutions that could be considered for large scale production
  - Fibres and light sensors
- Readout architecture: two baseline solutions but space for other ways
  - Timing information improvements (AARDVARC v3, RADIOROC and dSiPM)
  - High-performance waveform digitizer with feature extraction (AARDVARC v3)
  - Cost reduction and reduced system complexity (dSiPM)
- Detector performance
  - Assess performance for single physics objects (energy resolutions and PID)
  - Validate the G4 simulation
  - Optimization of transverse and longitudinal segmentation
  - Exploit DNN method
  - PFA performance assessment

To follow up the R&D, subscribe on egroups.cern.ch to idea.dualreadout@cern.ch

# Backup

# Dual Readout: the principle




- Non compensating calorimeter (h/e<1): has a different response to electromagnetic (fem) and hadronic component (1-fem)
- The fem is energy dependent: it induces a non-linear calorimetric response to hadrons and large fluctuations

- By reading two calorimetric signals (S and C) with different h/e, the fem can be measured event by event and the compensation can be achieved off-line

$$E_S = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_S (1 - f_{\mathrm{em}})\right)$$

$$E_C = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_C (1 - f_{\mathrm{em}})\right)$$

$$f_{\mathrm{em}} = \frac{\left(\frac{h}{e}\right)_C - \left(\frac{h}{e}\right)_S \left(\frac{E_C}{E_S}\right)}{\left(\frac{E_C}{E_S}\right)\left(1 - \left(\frac{h}{e}\right)_S\right) - \left(1 - \left(\frac{h}{e}\right)_C\right)}$$

$$E = \frac{(E_S - \chi E_C)}{1 - \chi}$$

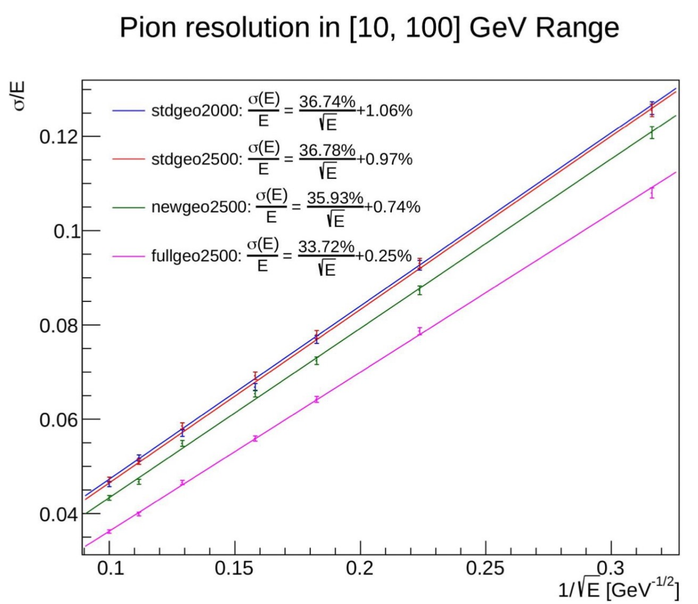
$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C}$$

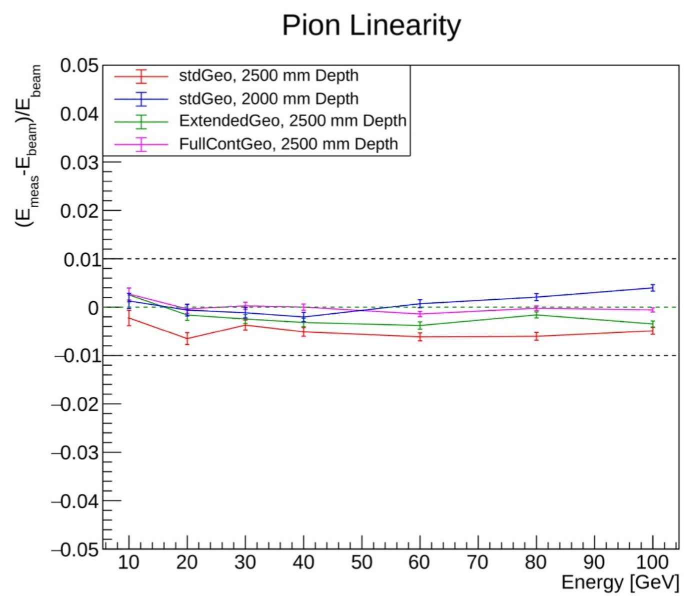
$\chi$ does not depend from energy and particle type. It is detector dependent: it can be measured on beam tests

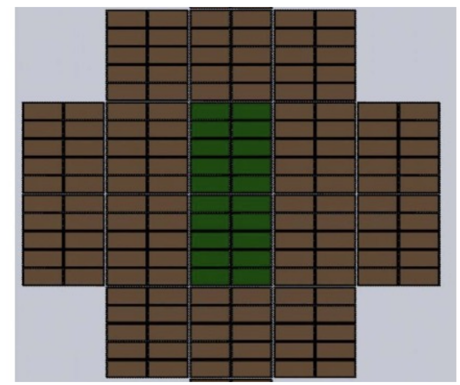
S. Lee et al, RevModPhys, 90, 025002 (2018)
*DOI: 10.1103/RevModPhys.90.025002*

# HiDRa: the expected performances

- Resolution studies performed with the HiDRa geometry based on a full simulation tuned on recent test beam results (2021)
  - Beam tilted by 2.5° in both X and Y directions
  - Capillary outer diameter = 2mm and fibre diameter =1mm
- Resolution and linearity with single pions (different geometries)



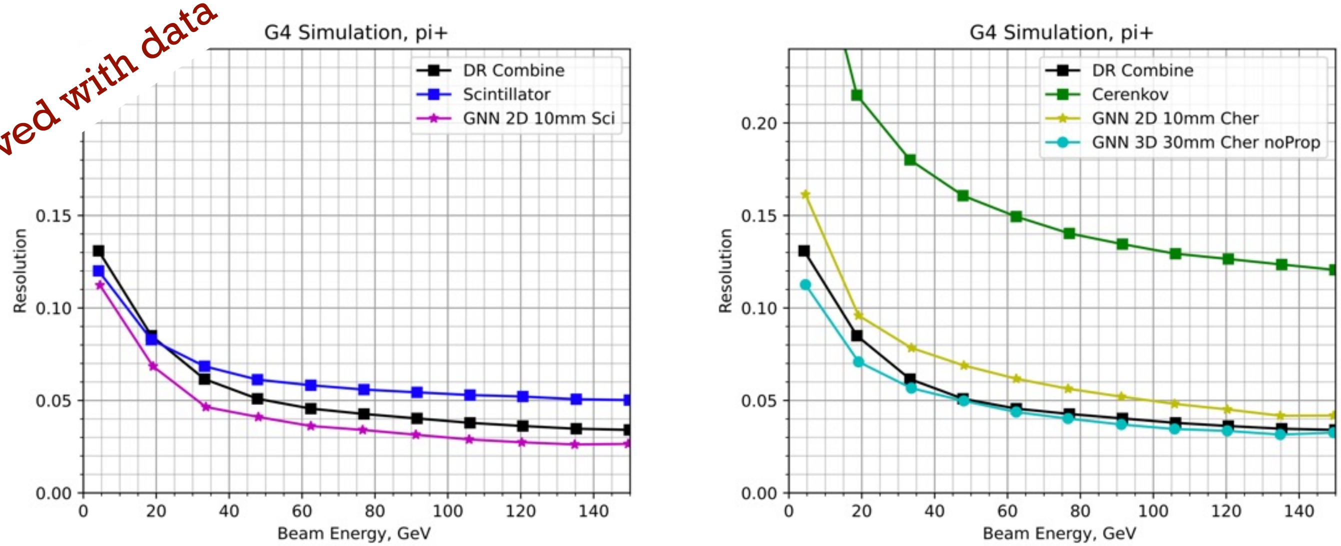



# Breaking news: do we still need dual-readout method?

- A recent Monte Carlo study indicates a good potential of 3D Imaging Fiber Calorimeter when used with ML technology
- The resolution by the DR method is compared with the GNN-technique
  - GNN 2D 10mm sci (Sci-signal is summed in box 10x10mm$^2$)
  - GNN 3D 30mm Ch (Ch-signal is summed in box 30x30mm$^2$ + timing info)

To be proved with data




(a) (b)

https://doi.org/10.3390/instruments6040043