Dual readout calorimetry developments towards FCC

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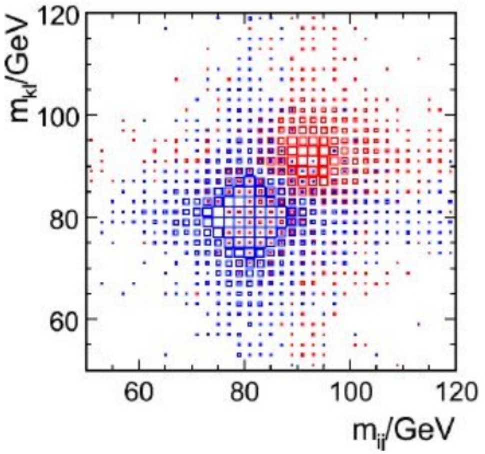
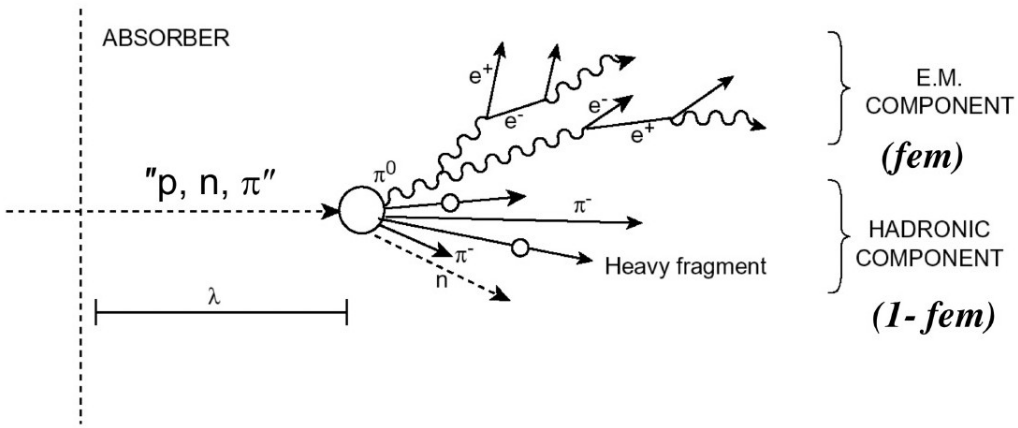
On behalf of the

IDEA Dual-Readout Calorimeter Collaboration

Hadronic calorimetry at FCC-ee

- Higgs factories: measure with high precision Higgs couplings
- Want to distinguish H→WW from H→ ZZ in their hadronic decays: separate hadronic peak of W from Z:
  - Required~3% resolution on peak at 80-90 GeV
  - Very difficult:





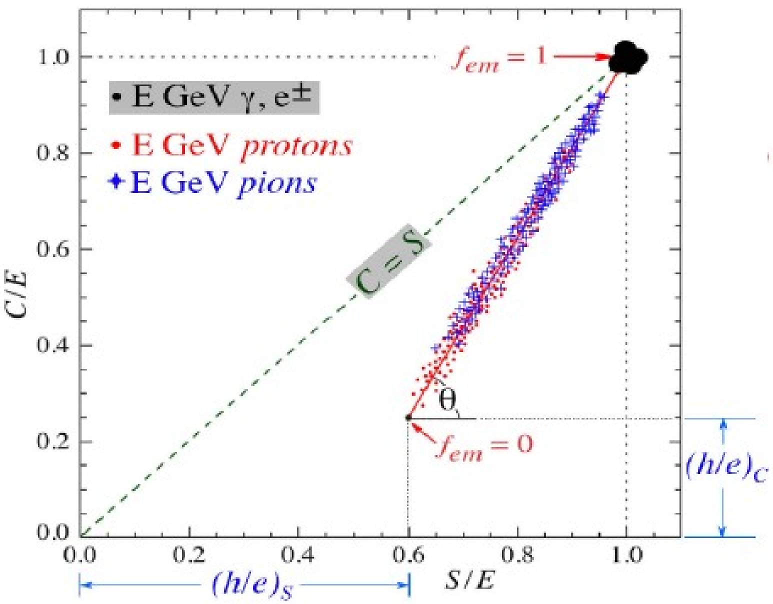
Calorimeters have different reponse to Hadronic and E.M. components
Ratio of two components varies event by event and average depends on energy:

- Non-gaussian shape of signal
- Non-linear response

Dual readout calorimetry

Fluctuations in energy measurement of hadronic showers: correct event by event through measurement of EM fraction of shower using simultaneously two sampling processes

- Cherenkov light (mainly EM shower component)
- Scintillation light (total deposited energy)



$$C = E\left[f_{em} + \frac{1}{(e/h)_C}(1-f_{em})\right]$$

$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1-f_{em})\right]$$

e.g. if: (e/h) = 1.3(S) vs 4.7(C)

$$\frac{C}{S} = \frac{f_{em} + 0.21(1-f_{em})}{f_{em} + 0.77(1-f_{em})}$$

$$E = \frac{S - \chi C}{1-\chi}$$

Universally valid!

with: $\chi = \dfrac{1-(h/e)_S}{1-(h/e)_C}$

Independent of energy and particle type

Implement in the IDEA detector as a highly granular fibre-based calorimeter

IDEA baseline concept

Muon chambers

μ-RWELL in return yoke

Dual-readout calorimetry 2 m / 7 λ_{int}

μ-RWELL preshower

Thin superconducting solenoid

2 T, 30 cm, ~ 0.7 X_0 , 0.16 λ_{int} @ 90°

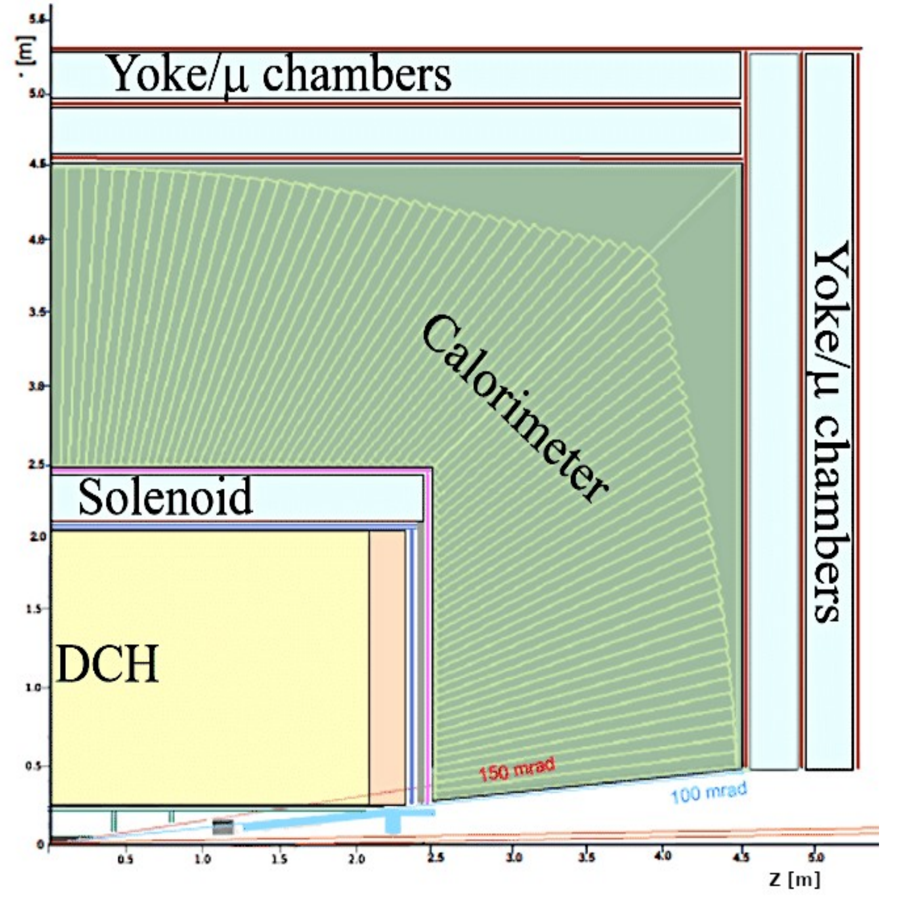
Highly transparent for tracking

Si pixel vertex detector

Drift Chamber

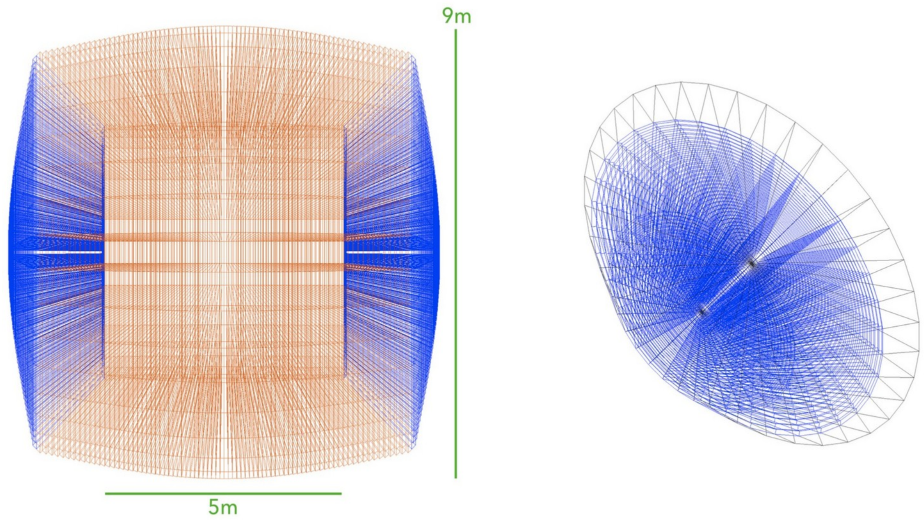
Si wrappers (strips)

Beam pipe: r ~ 1.5 cm

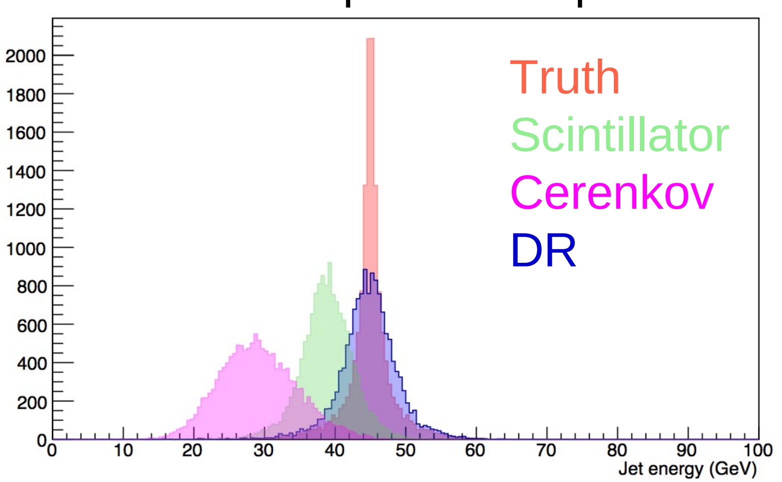


Expected Performance of DR calorimeter

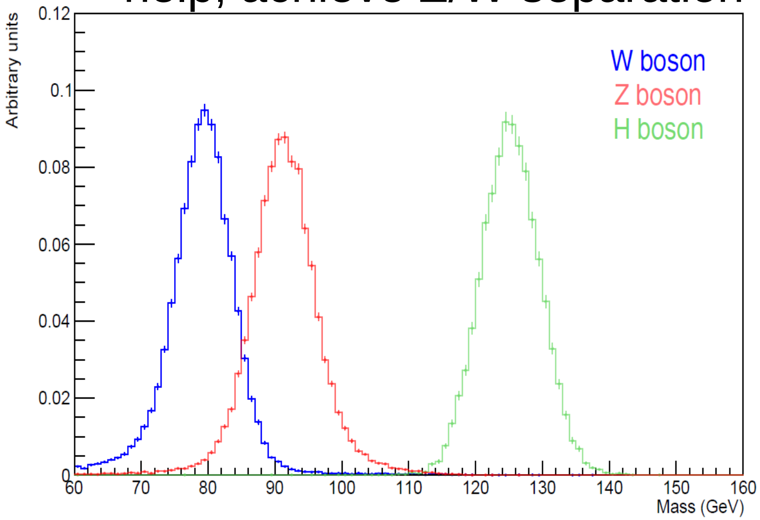
- DR fibre calorimeter
  - ~ 130 M fibres
    - 1 mm ⌀, 1.5 mm pitch
  - copper absorber
  - 75 projective towers × 36 slices
    - $\Delta\vartheta$ = 1.125°, $\Delta\phi$ = 10.0°
    - ϑ coverage: down to ~100 mrad
- G4 simulation available
  - tuned to RD52 TB data
  - DD4HEP in development
- Outdated layout, being updated



With DR recover gaussian shape and correct position of peak



With DR, even without PFA help, achieve Z/W separation



DR development activities

Three main activities

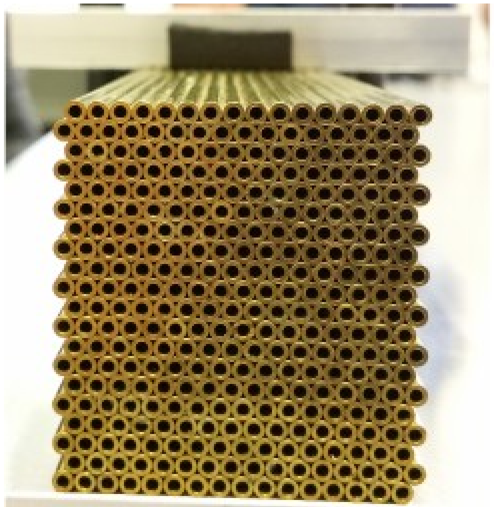
1) South Korea → projective fibre-sampling calorimeter

2) INFN, Sussex University → fibre-sampling calorimeter

3) Calvision project: INFN+US → development of crystal EM calorimeter

Concentrate today on European developments

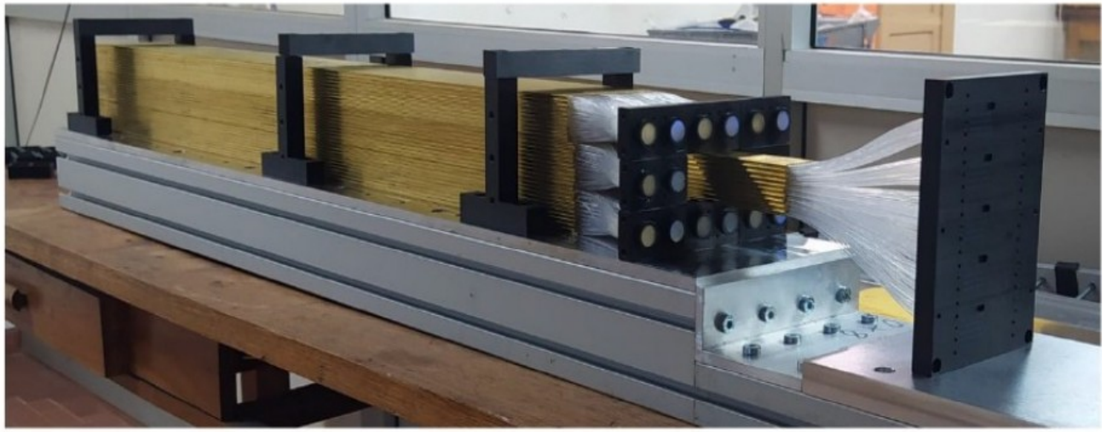
Dual-readout module development



- Geometry based on metal capillaries acting as absorber with inserted fibres → easy modular assembly
- Read out ideally every single fibre with a SiPM: achieve unprecedented granularity allowing detailed shower reconstruction and particle ID

Built and tested in beam small EM module (10x10x100 cm^3) to test assembly procedure, integration of SiPMs and to tune GEANT4 simulation

Testbeam

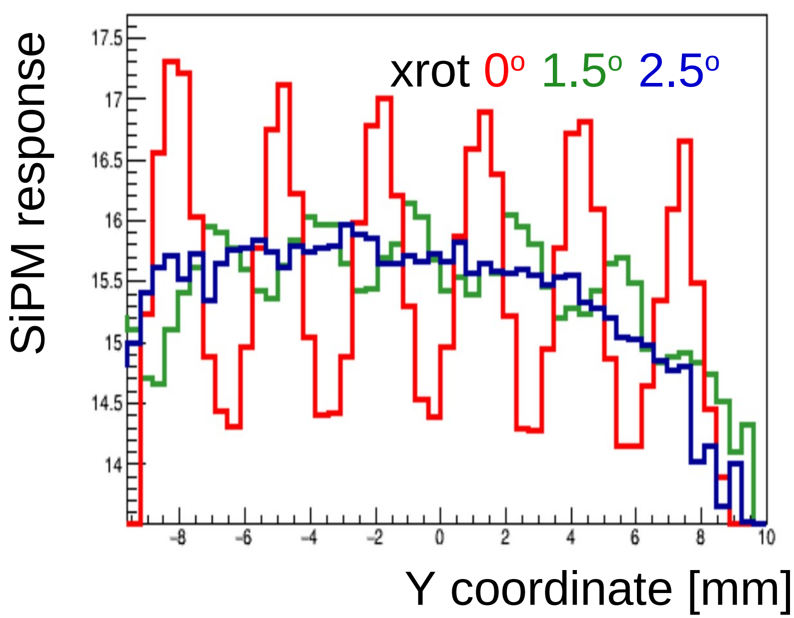


Only central part of module ($3x3\ cm^2$) equipped with SiPM

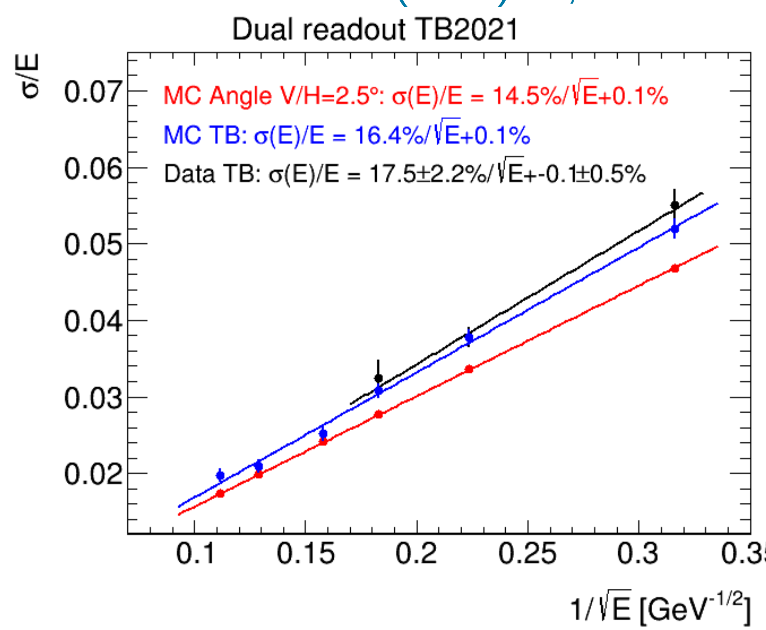
Test 2021 (CERN+DESY):

- Verified strong dependence of response on impact angle
- Low electron statistics in SPS beam only allowed limited testing

Angular dependence (simulation)



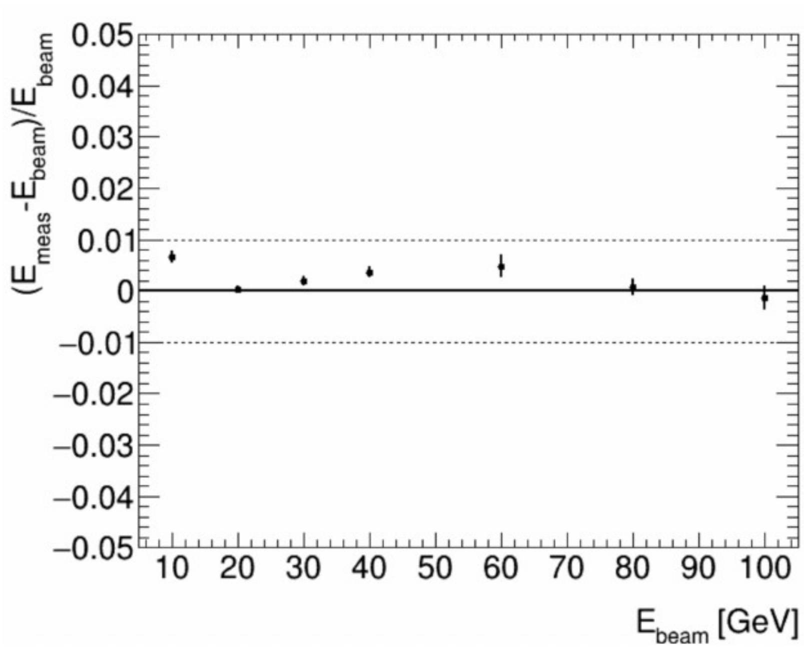
Electron resolution from
JINST 18 (2023) 09, P09021



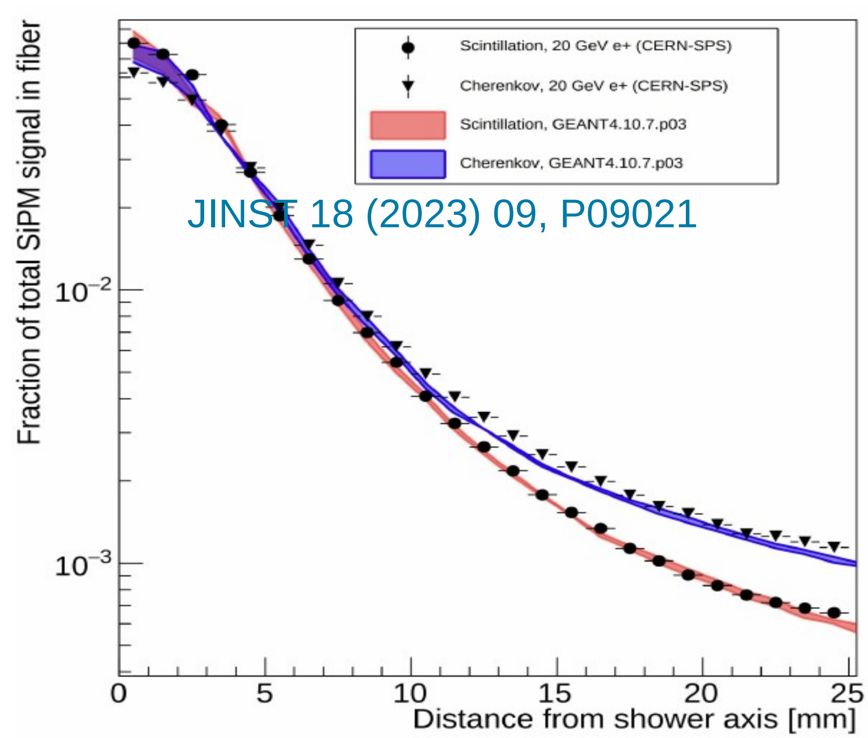
TB2021 results

JINST 18 (2023) 09, P09021

Energy well reconstructed within 1%



Lateral shower profile measured through high granular SiPM information and compared to G4 simulation

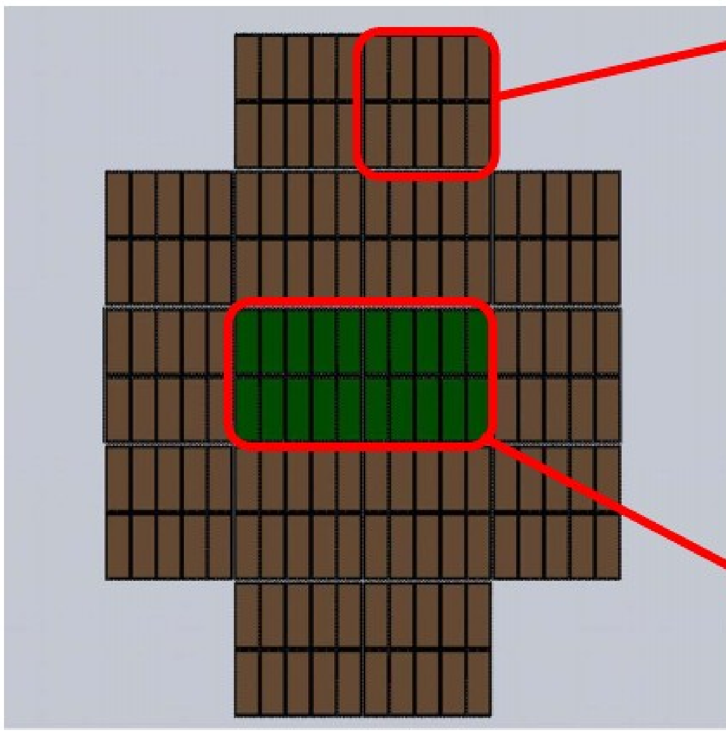


Additional data taken with same module
In 2023: analysis ongoing

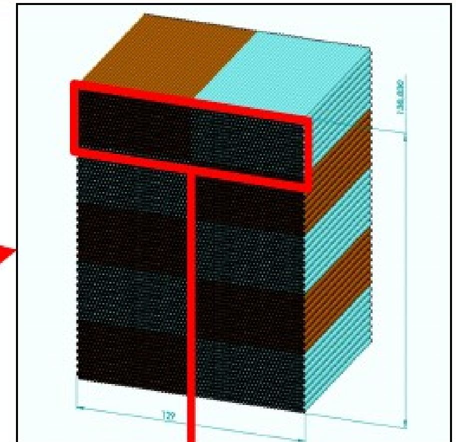
HyDRa project

Hadronic-size prototype:

16 modules w/ highly granular core



HiDRa

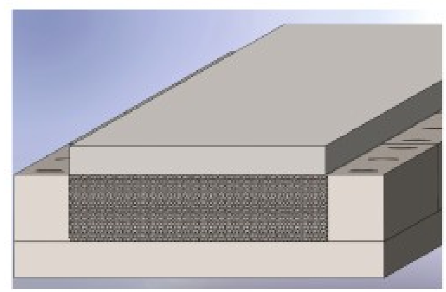


1 Module:
5 MMs
~ 13 × 13 cm^2

1 MiniModule:

64 × 16 =
1024 fibres in total

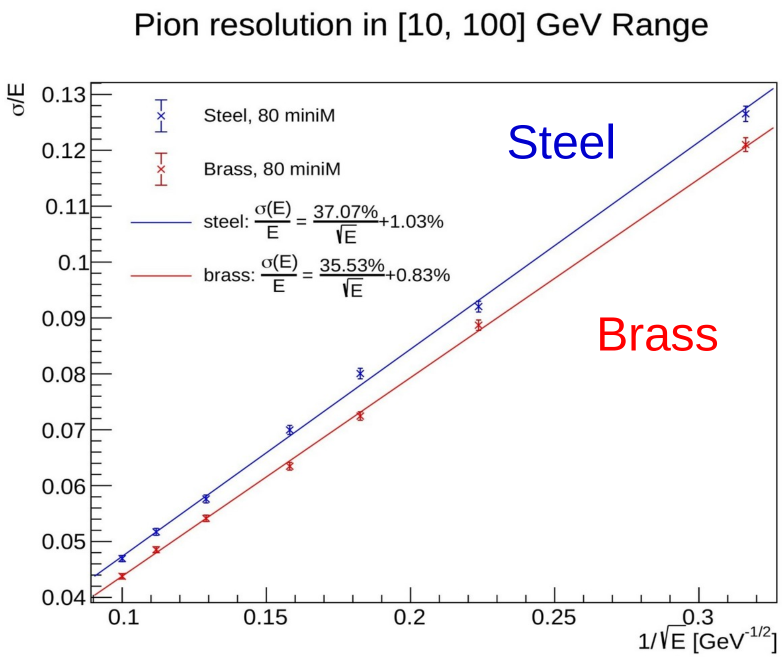
512 S + 512 C

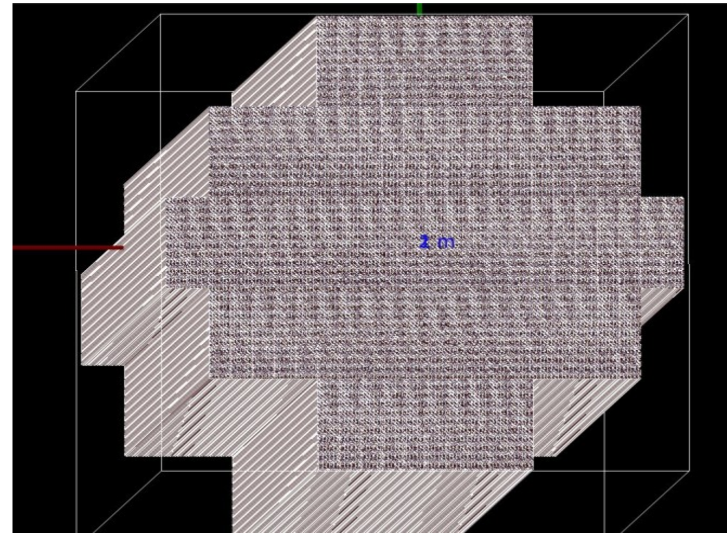


highly granular core:

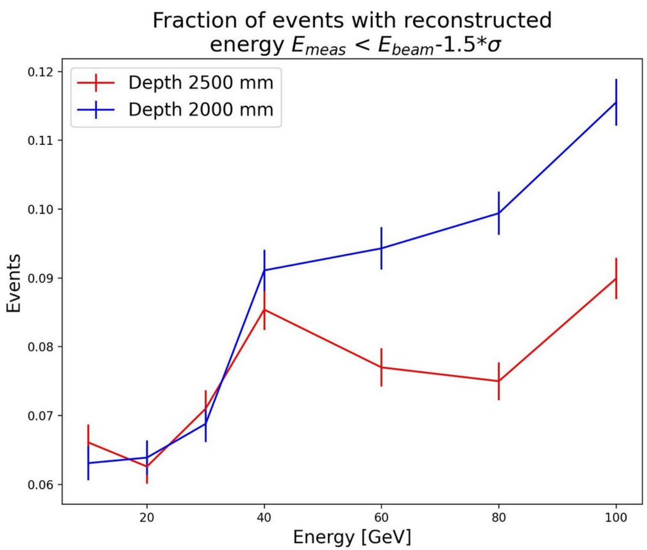
10240 fibres to be read out with SiPMs

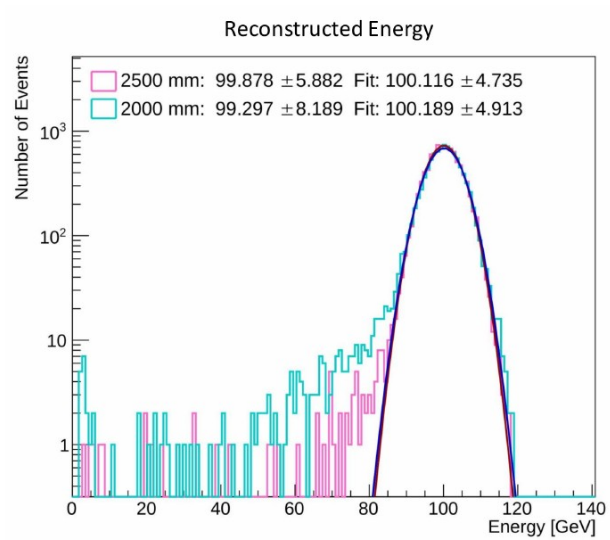
Fullsim studies for geometry definition





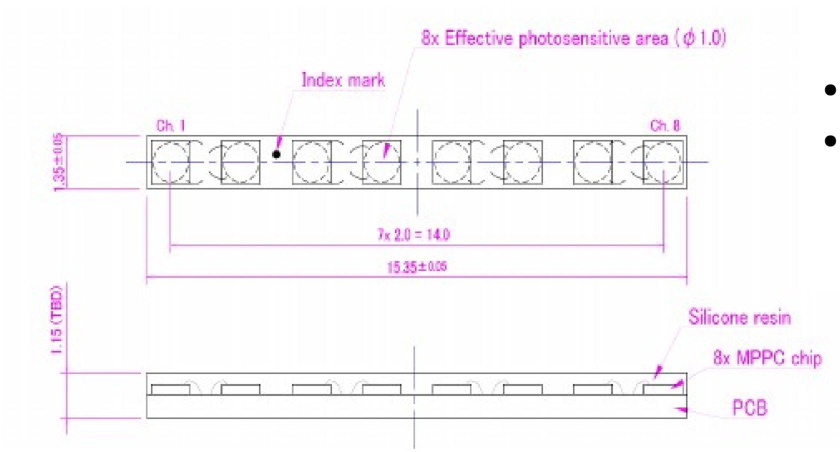
Study impact of absorber material on pion resolution: steel slightly worse but cheaper than brass



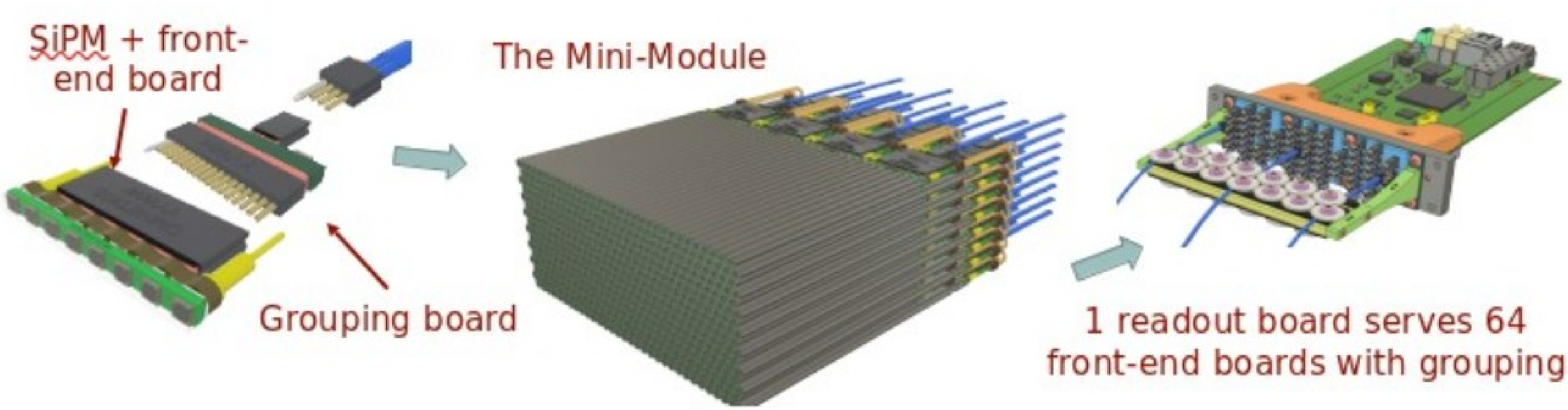


Study tails in response to pions to define calorimeter length

SiPM integration



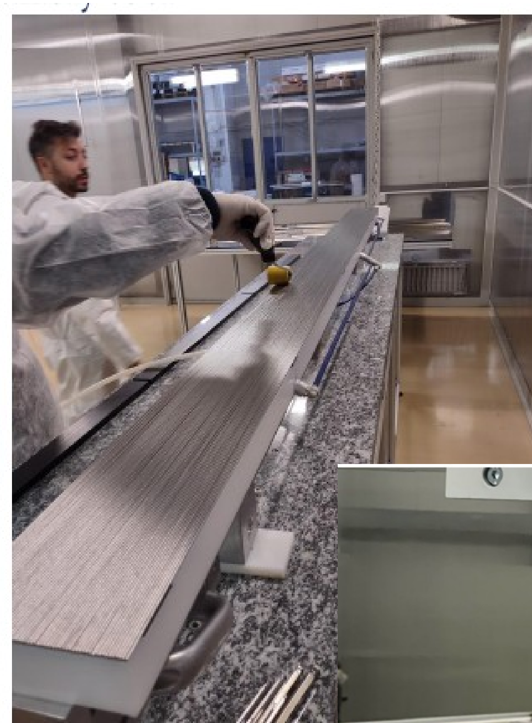
- Custom designed module with 8 SiPMs (1x1 mm^2) from Hamamatsu
- 2 mm SiPM interspace
- Pitch: 10 µm for S fibres, 15 µm for C fibres (optimize dynamic range/photon detection efficiency)

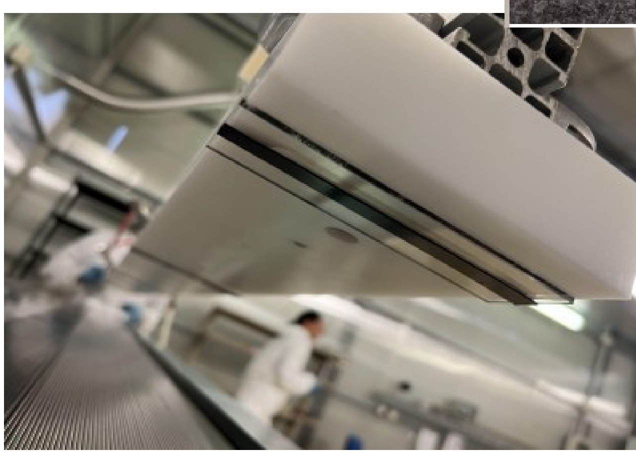


- Each SiPM bar operated at same voltage (V_{bd}<0.15V)
- Signals from 8 SiPMs summed up in grouping board

Construction

Tube aligned in a reference tool





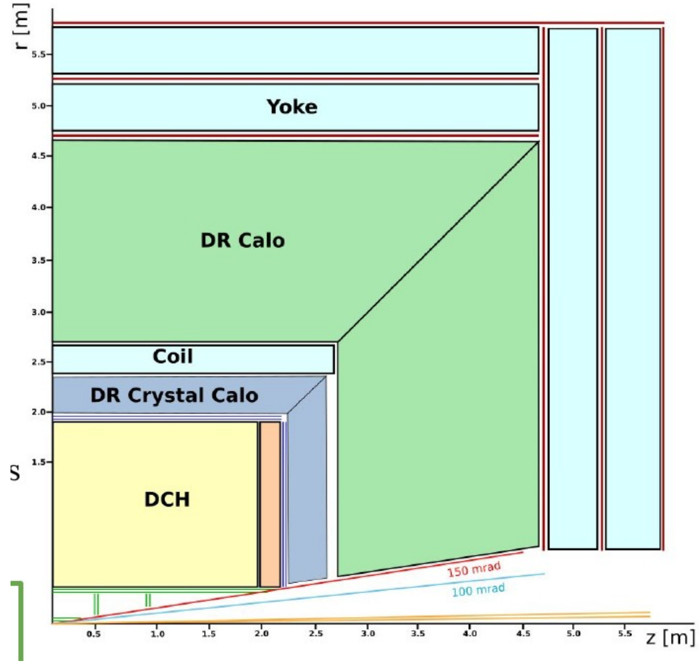
Stiffback-like technique for tube handling, gluing and positioning in the assemby tool

Semi-automatic system for planarity QAQC

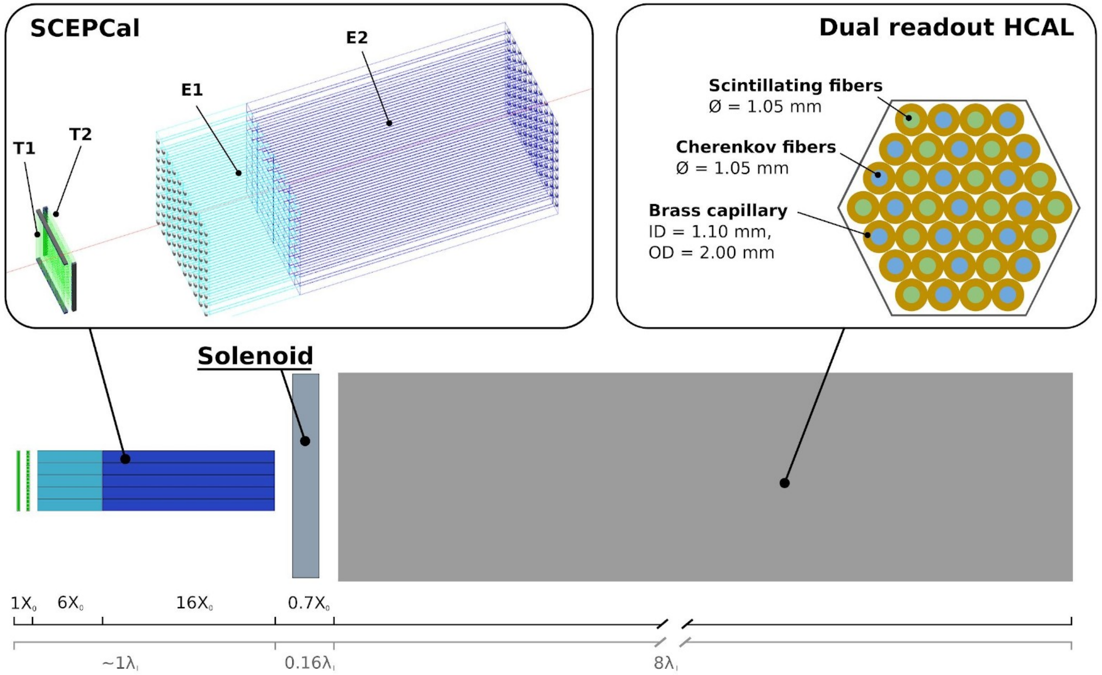
Vacuum+double-sided tape for tube handling

IDEA++

- Homogeneous high-resolution EM crystal calorimeter with dual readout inside solenoid
- Longitudinal and lateral segmentation
- Timing layer in front of calo

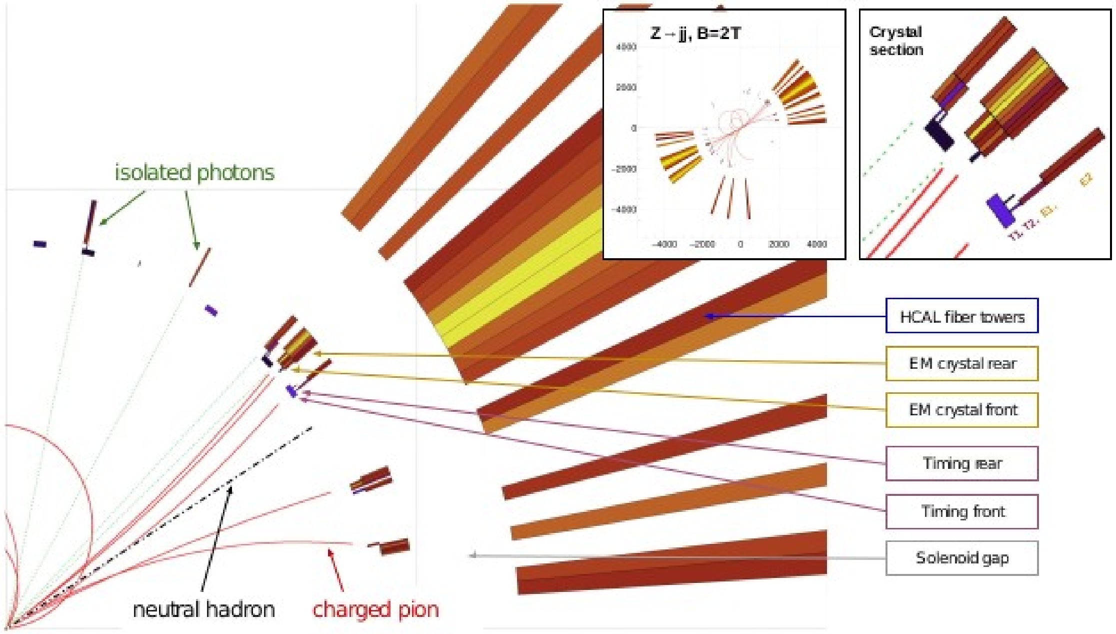


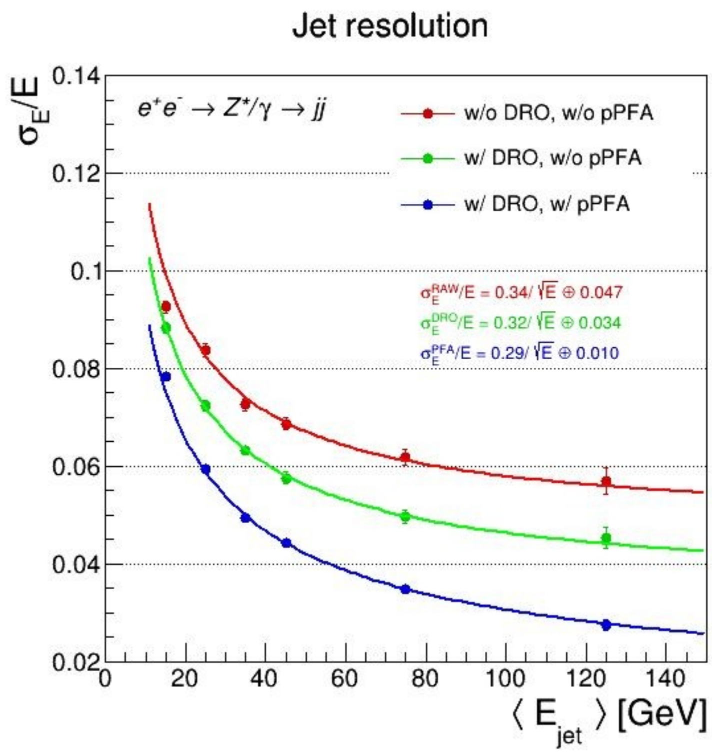
- ECAL ~20 cm $PbWO_4$
  - 2 layers: 6+16 X_0
  - DR with filters
  - $\sigma_{EM} \approx 3\% /\sqrt{E}$
- timing layer
  - LYSO:Ce crystals
  - $\sigma_t \sim 20$ ps
- HCAL layer
  - $\sigma_{HAD}/E \sim 26\%/\sqrt{E}$



Expected performance

JINST 17 (2022) 06, P06008





Geant4 simulation of Z→jj events:

- magnetic field ON but NO tracker
- Gaussian smearings of MC tracks according to expected IDEA tracker performance
- for each track extrapolate impact point
- remove and store tracks not reaching calo

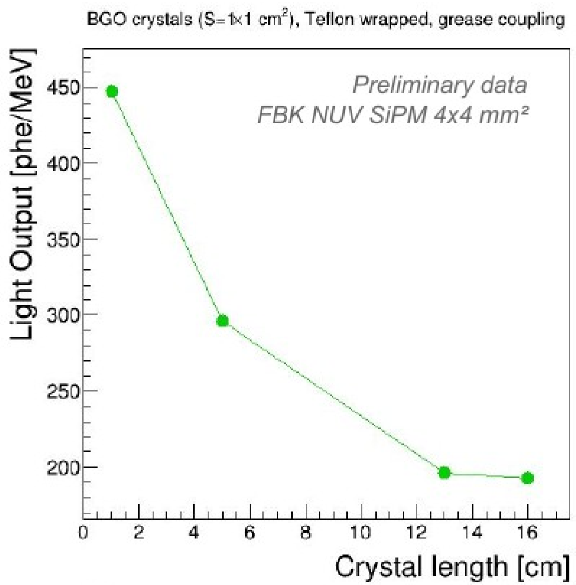
Develop PFA algorithm using parametrised tracker and fully simulated high granularity response for DR crystal+sampling geometry

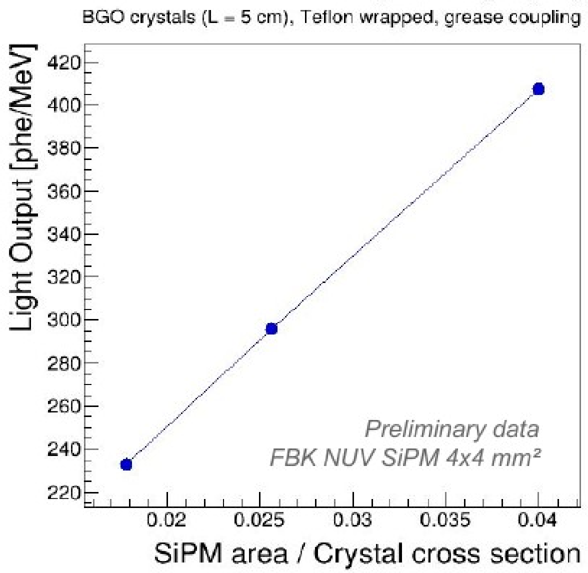
Ongoing developments

Read out from same active material (scintillating crystal) scintillation (S) and Cherenkov (C) components

R&D activities:

- Crystals:
  - Optimisation of crystal cross section and longitudinal segmentation
  - Choice of materials → prominent candidates are BGO, BSO, PWO due to high density, small R_M and X_0, high refractive index (Cherenkov yield)
- Filters:
  - Development/identification of custom thin wavelength filters to separate S & C components with sufficient light yield and purity
- SiPM readout:
  - Dynamic range, linearity, etc
  - Explore very small cell size SiPMs (<10 um)



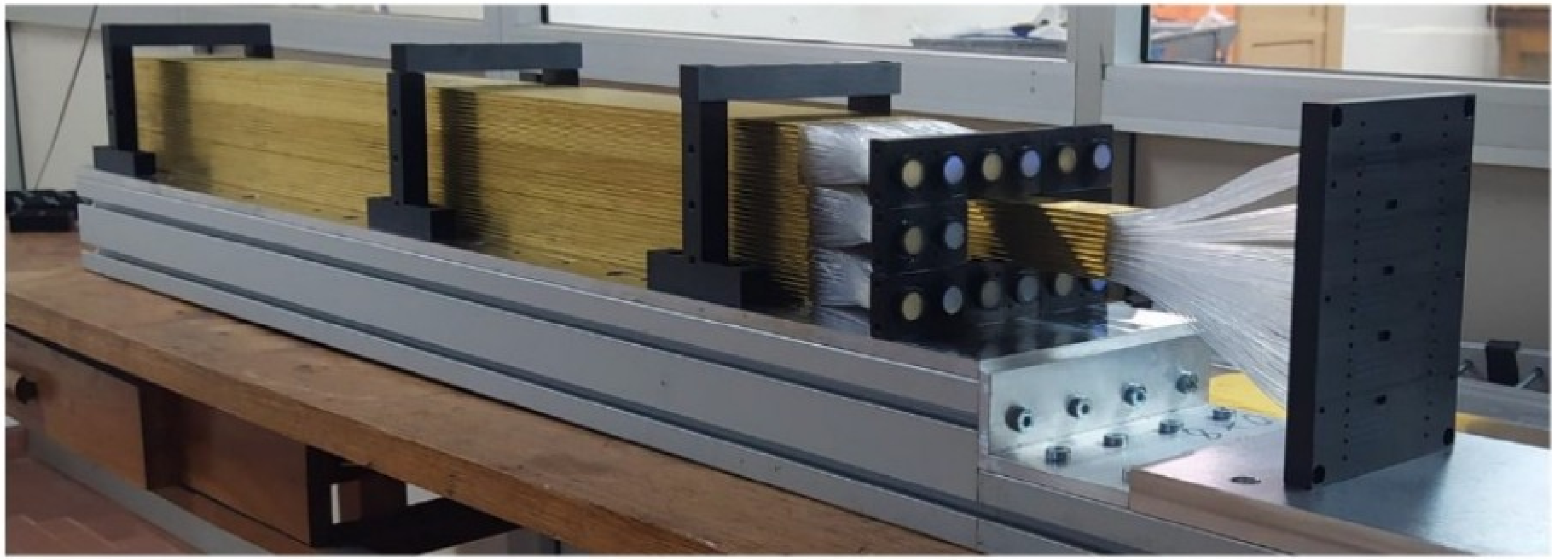


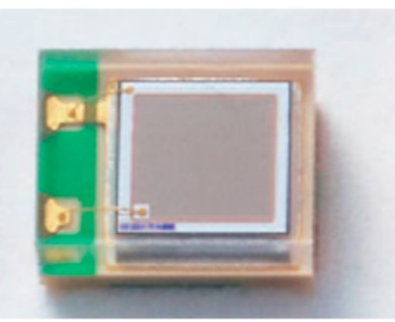
Light yield measurements in Mi-Bicocca

Conclusions

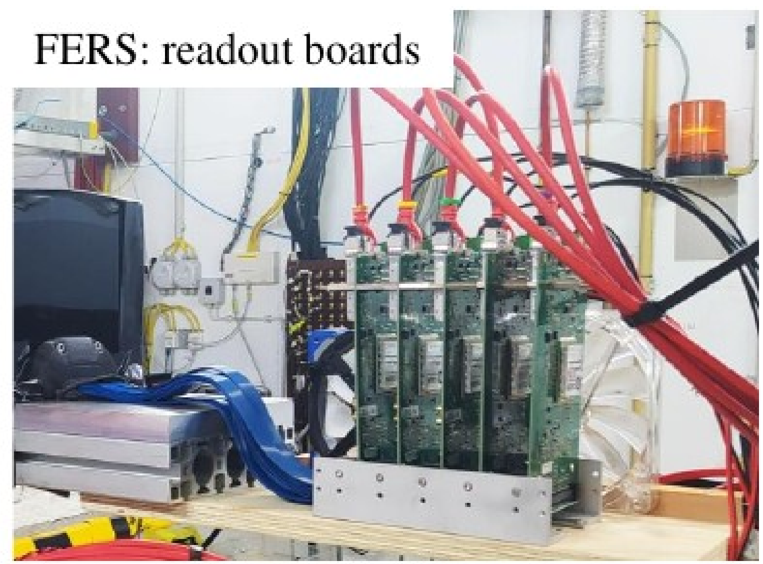
- Dual-readout calorimetry is a viable approach for achieving the strict performance goals on hadronic measurement of future Higgs factories
- Baseline approach: full DR calorimeter
  - High granularity through readout of (ideally) each fibre with SiPMs
  - Construction based on fibres inserted in metal capillaries
  - Tested small EM-size module to understand construction issues and integration with SiPMs
  - Hadronic-size module funded by INFN and under construction
- Alternate approach: Crystal EM calorimeter+sampling HAD calorimeter
  - Excellent E.M. resolution
  - Transverse and longitudinal segmentation for use in particle flow algorithms
  - Vigorous R&D activity with strong INFN and US participation

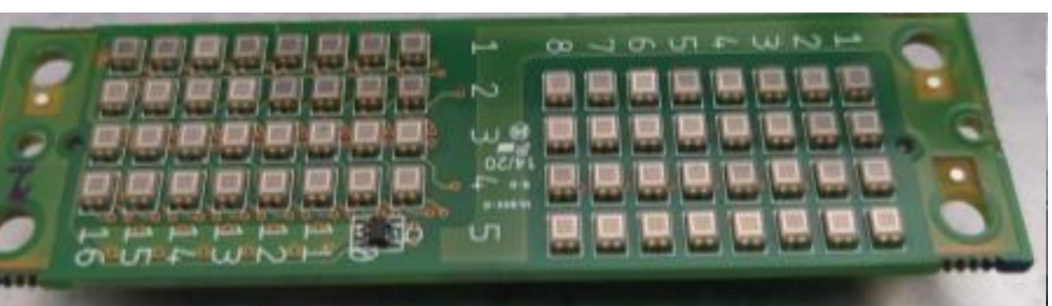
Backup



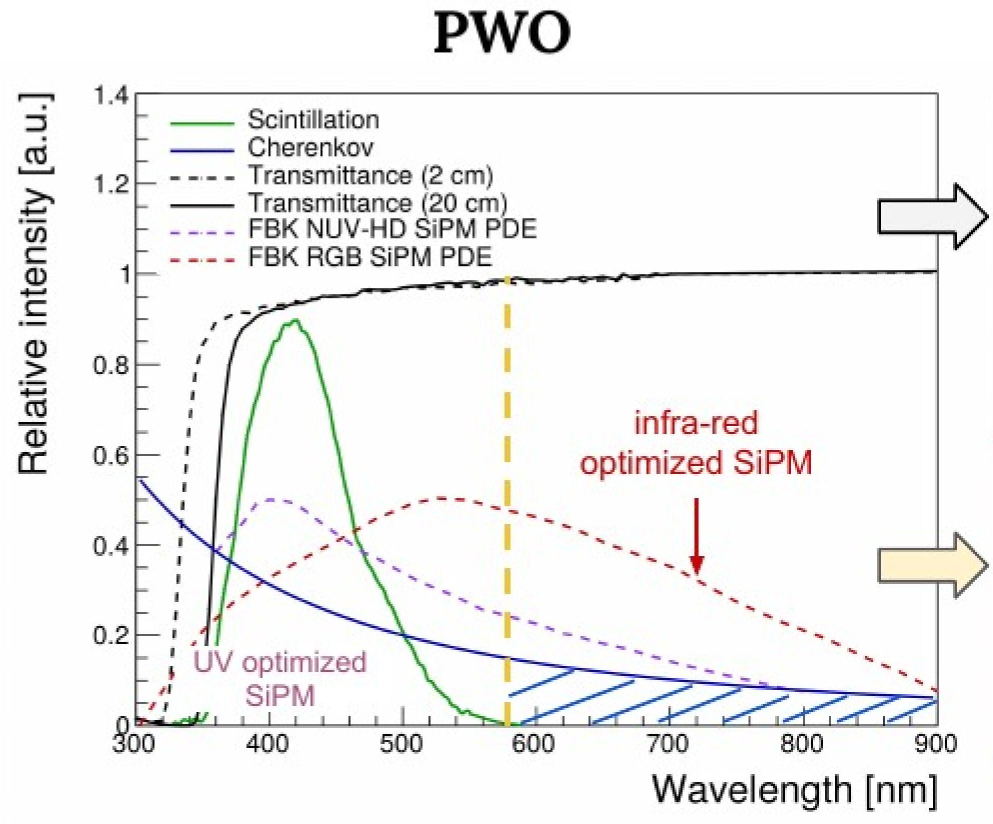


FERS: readout boards





Dual Readout for crystals



Estimated:

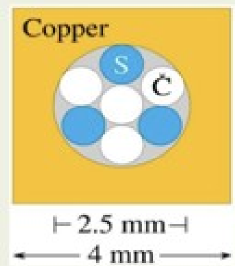
- >**2000 phe/GeV** for scintillation photons
- >**100 phe/GeV** for Cherenkov photons

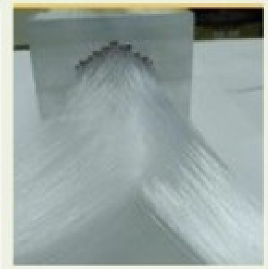
Cherenkov photons above scintillation peak are much less affected by self-absorption

Past Dual readout R&D

2003
DREAM

Copper
2m long, 16.2 cm wide
19 towers, 2 PMT each
Sampling fraction: 2%

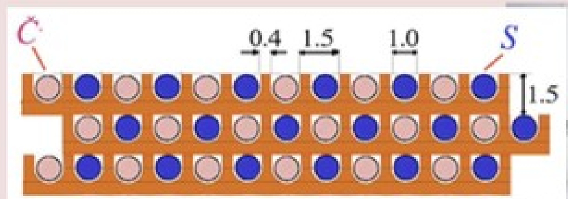




2012
RD52

Copper, 2 modules

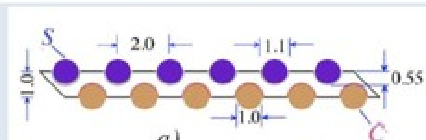
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 4.5%, 10 λ_{int}

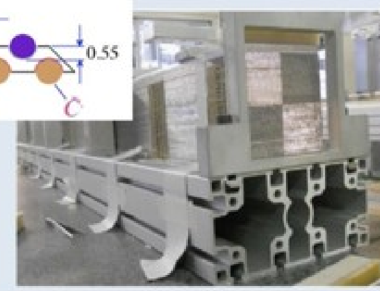


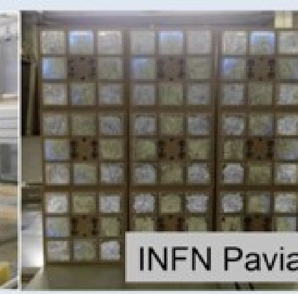
2012
RD52

Lead, 9 modules

Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 5%, 10 λ_{int}

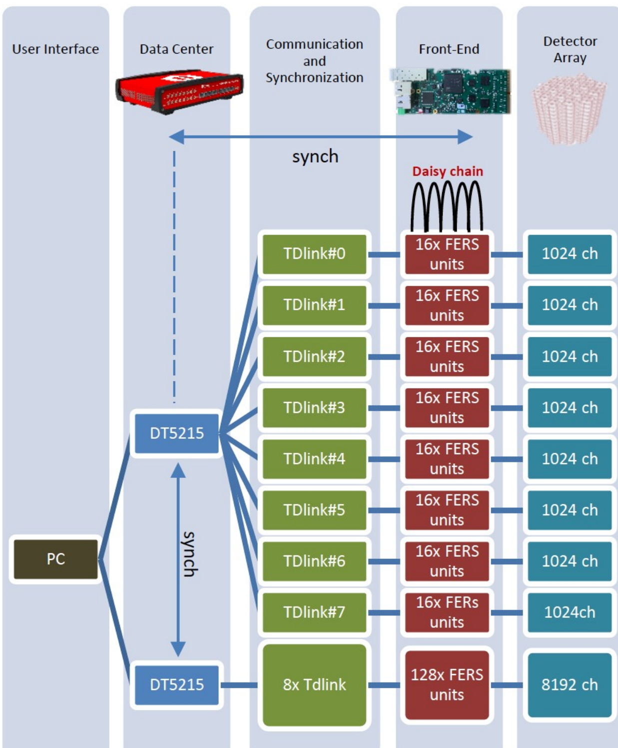




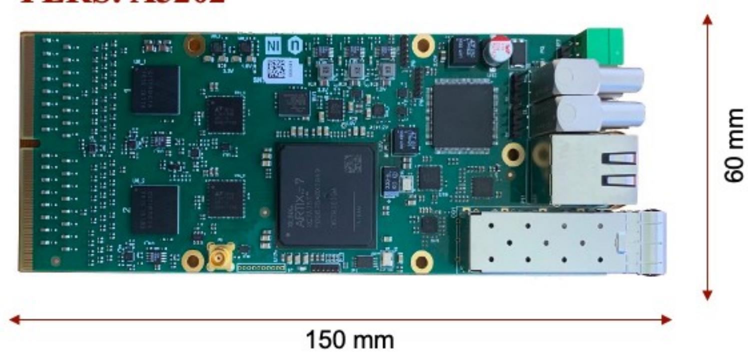


EM-size prototype readout

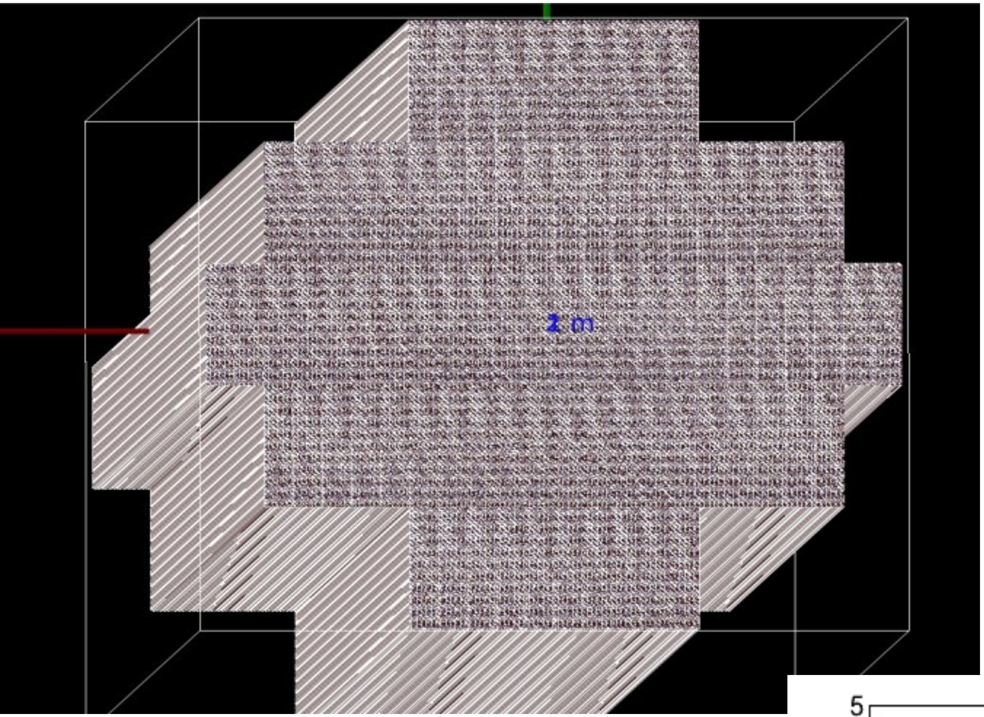
- PMTs read out with QDC (V792AC) and TDC (V775N) modules from Caen
- The highly granular module (320 SiPMs) read out with the Caen FERS system (5200) using 5 readout boards (A5202)



FERS: A5202



- 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)

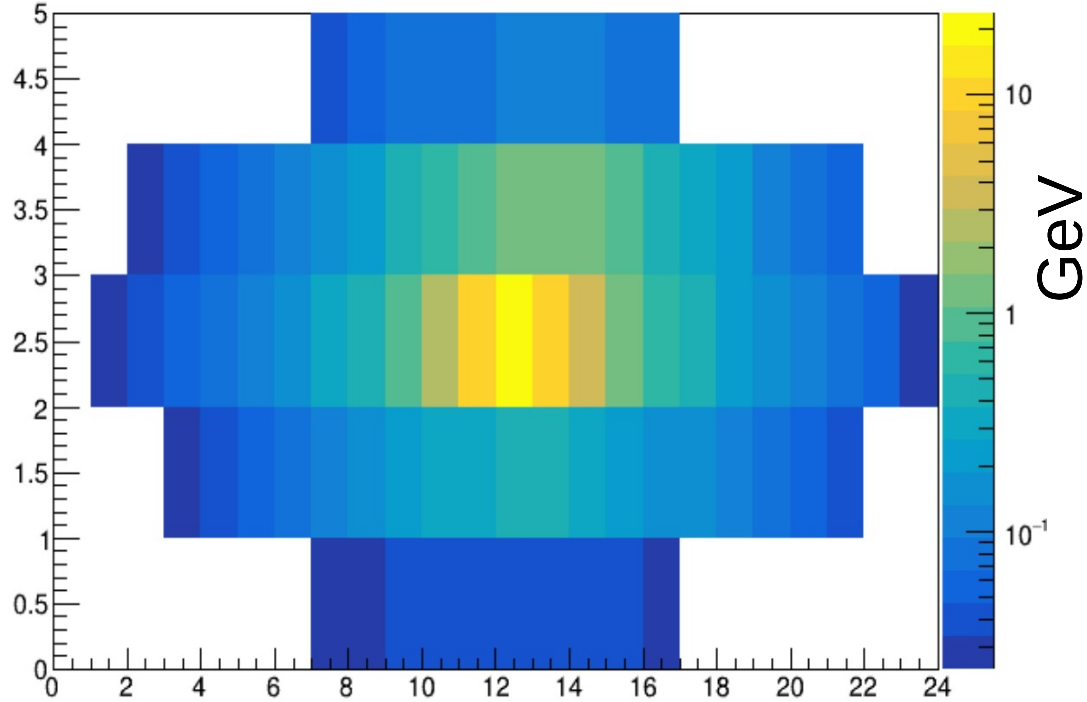


Hidra simulation

Based on simulation validated on TB2021 result implement HiDRa geometry

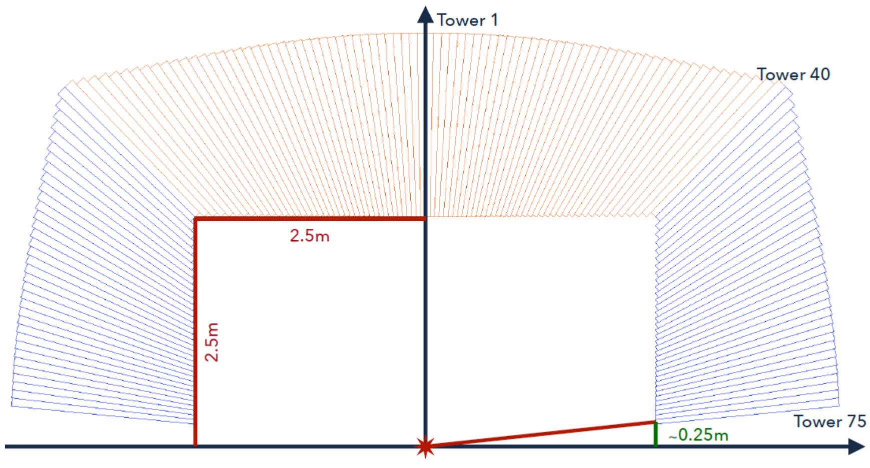
80 GeV π^+ impact angles 2.5 deg, 2.5 deg: calo map
Brass absorber

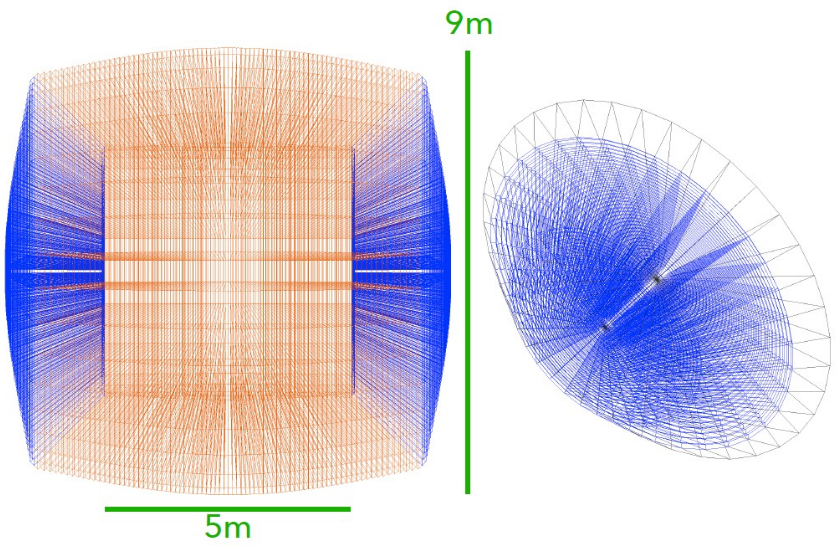
~97% containment



Baseline geometry IDEA

- 2m long copper based towers
- 36 towers around the beam axis
- Inner diameter: 5 m
- Outer diameter: 9m @ 90°





Expected performances

- 10% - 15% / EM energy resolution
- 25% - 30% / Energy resolution for single hadron
- 5% energy resolution for jets @ 50 GeV
- Less than the percent linearity in the FCC-ee energy ranges for e-/, hadrons and jets

Longitudinal segmentation with timing (US)

Dual-readout fibre calorimeter → signal sampled at 20 GHz

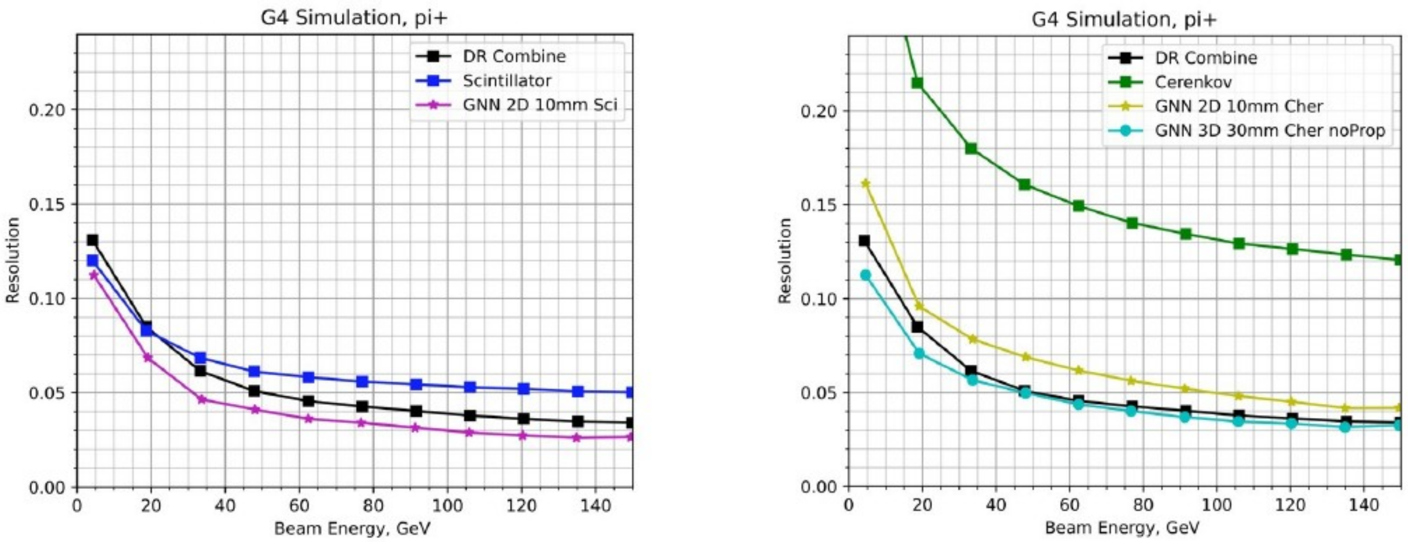
Preliminary results
No optimisation

Cu absorber (2 m deep)

Fibre axis aligned w/ beam direction: 1 mm Φ fibres, 1.5 mm spacing

Transverse segmentation: 1×1 cm^2 for 2D analysis, 3×3 cm^2 for 3D analysis

3D imaging fibre DR calorimeter coupled to Graph DNN



Slide by R. Ferrari

Longitudinal segmentation with timing (US)

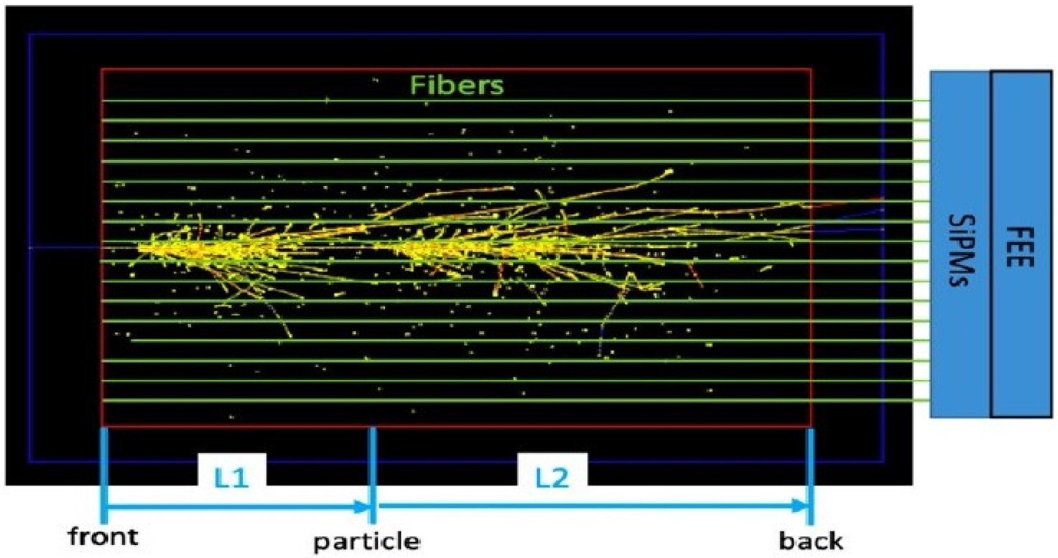


Table 1. The energy resolution of the 3D GNN reconstruction with various timing resolutions for longitudinal segmentation.

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

@ 100 GeV

only cherenkov fibres

Slide by R. Ferrari

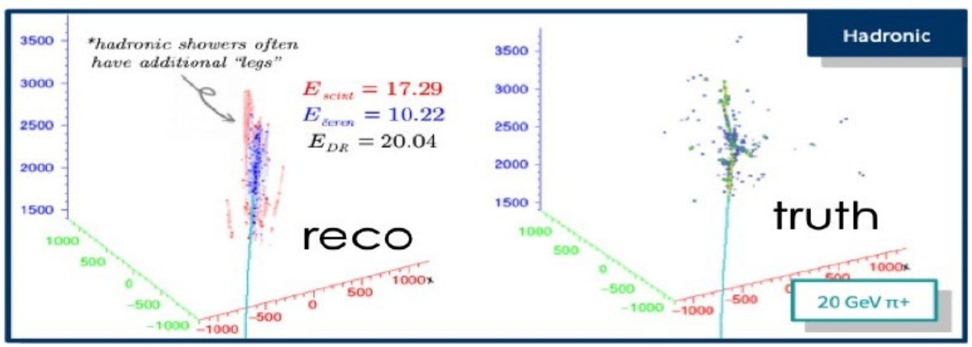
Longitudinal segmentation with timing (S. Korea)

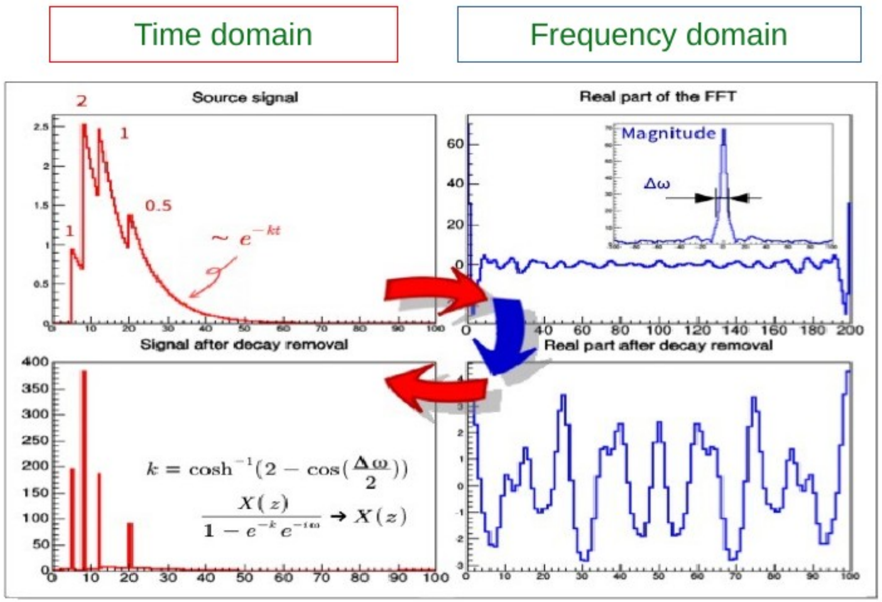
Full SiPM signal sampled at 10 GHz

FFT used to mitigate exponential tail

Unlocks full longitudinal information about energy deposit

Combined with DR information
allows in-shower cluster identification





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