Dual Readout Calorimeter for Future Collider

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Calvision Collaboration

18-May-2023

LCWS2023 International Workshop on Future Linear Collider - SLAC

Dual Readout – DREAM module (2003)

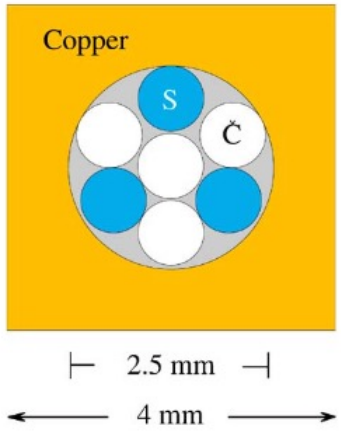
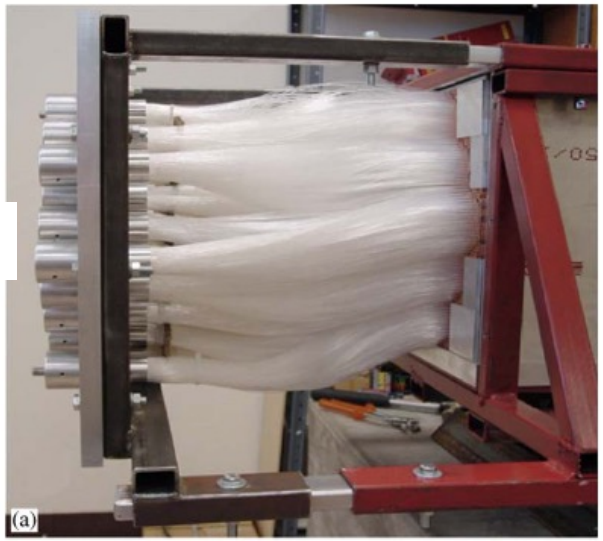


Fig. 1. The basic building block of the DREAM detector is a $4 \times 4\,mm^2$ extruded hollow copper rod of 2 meters length, with a 2.5 mm diameter central hole. Seven optical fibers (four Cherenkov and three scintillating fibers) with a diameter of 0.8 mm each are inserted in this hole.

Module at TTU 2003

36 x 32 x 200 cm^3



PMTs

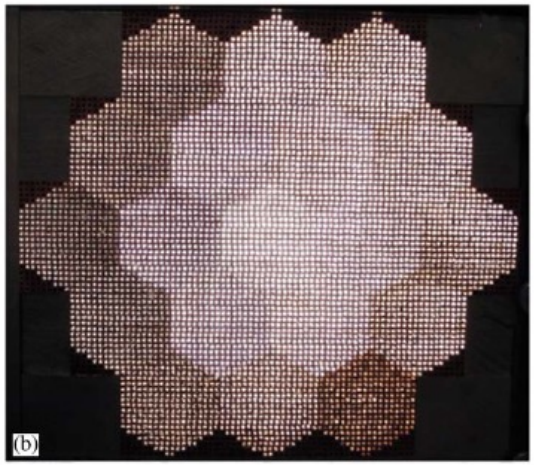
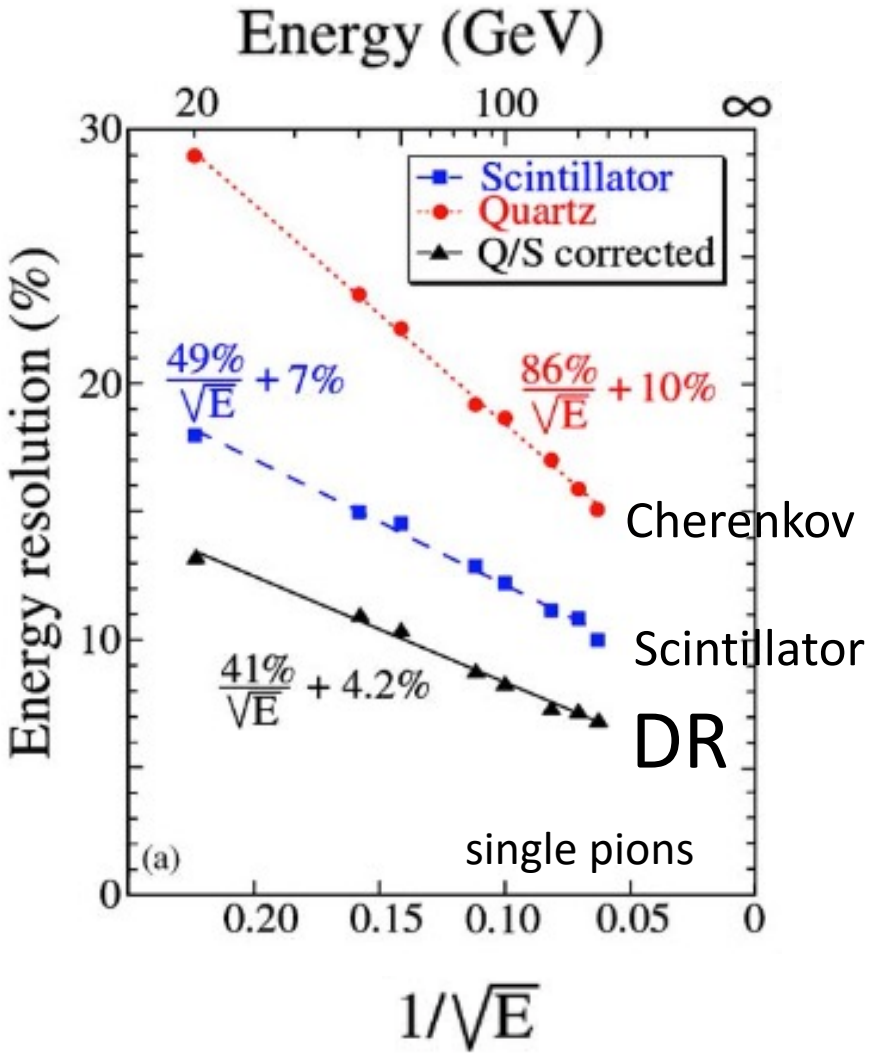


Fig. 3. The DREAM detector. Shown are the fiber bunches exiting from the rear face of the detector (a) and a picture taken from the front face while the rear end was illuminated (b).



Nucl. Instr. and Meth A537 (2005) 537

Dual Readout Method: Scintillation vs Cherenkov

In hadron-nuclei interactions, large fraction of hadron energy goes to nuclear dissociation and becomes invisible. We estimate the invisible energy from visible quantity.

Various methods have been developed.

- Compensation:

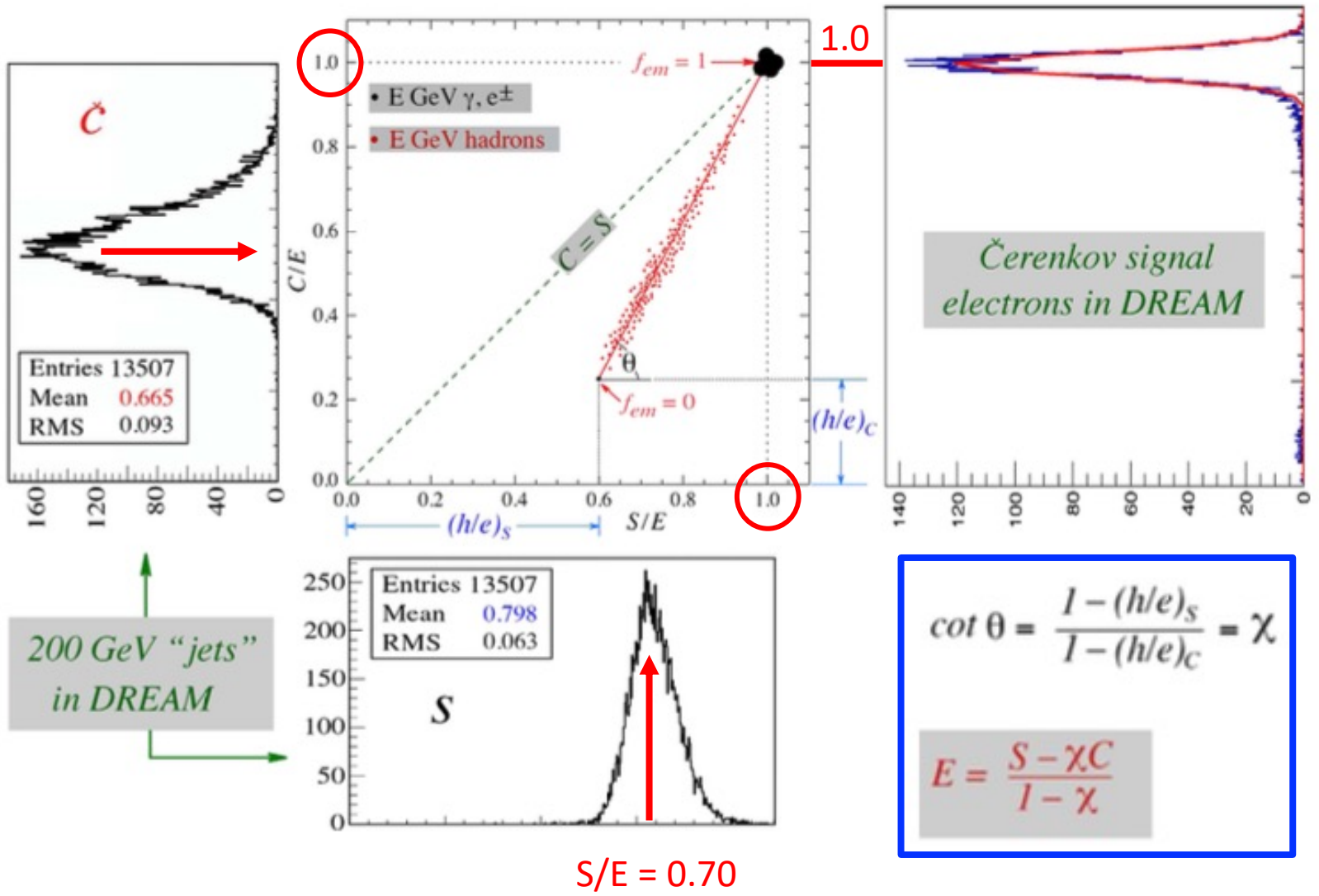
Using slow neutrons

- Dual Readout:

Using R= Scintillation/Cherenkov

- Neural Network

Using shower image in high granular calorimeter



Rev. Mod. Physics 90, 2018

IDEA (innovative Detector for Electron-positron Accelerators)

Micro Pattern Gas Detector
(micro Resistive Well)

Dual Readout Fiber Calorimeter
130 M C+S fibers
SiPM readout

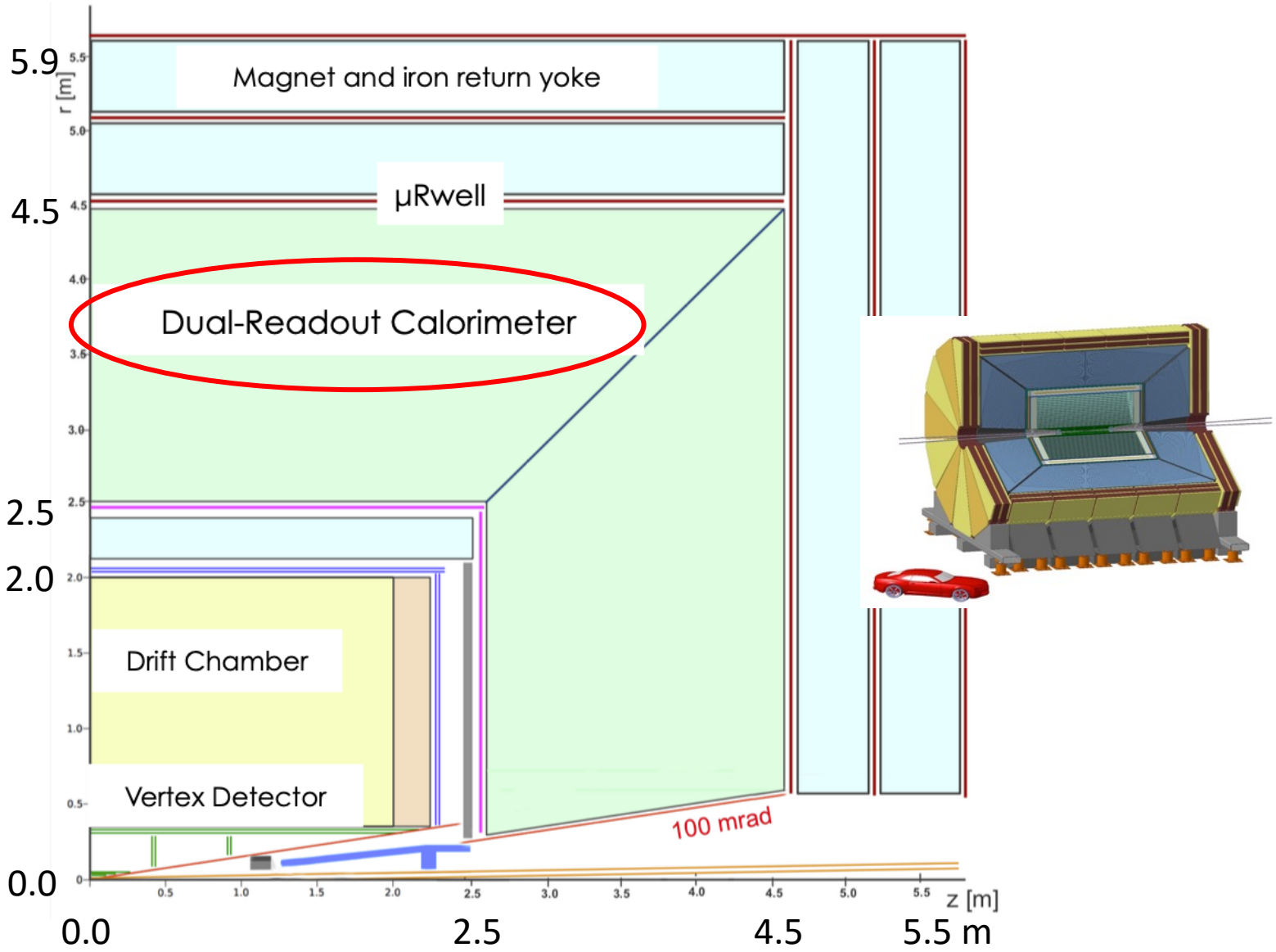
Pre-Shower:

Solenoid: 2T, 30 cm, 0.7 X_0

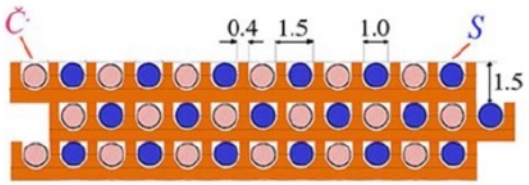
Drift Chamber: 1.6% X_0

low X_0 tracker

Si Pixels: 0.25% X_0 / layer
3/3 layers in barrel/outer



IDEA
Dual-Readout
Calorimeter



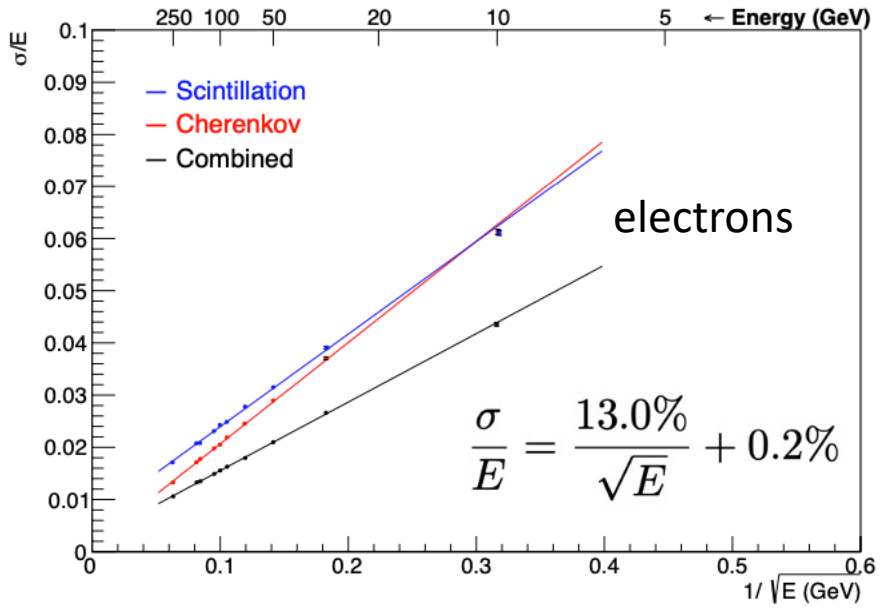
One SiPM per fiber
Very fine sampling

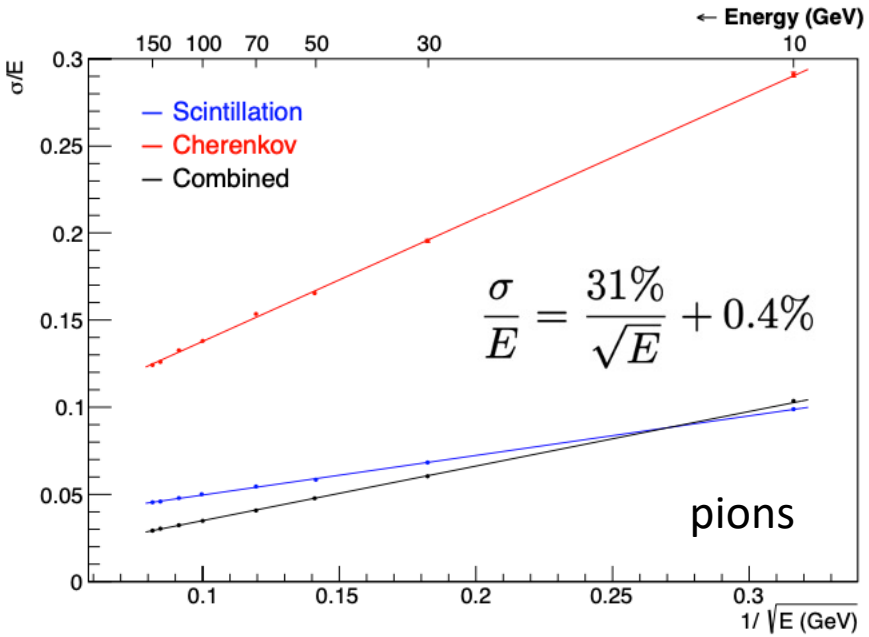
400 S-photons/GeV
100 C-photons/GeV

Tracker (in MC)
- Si pixels
- Si strips

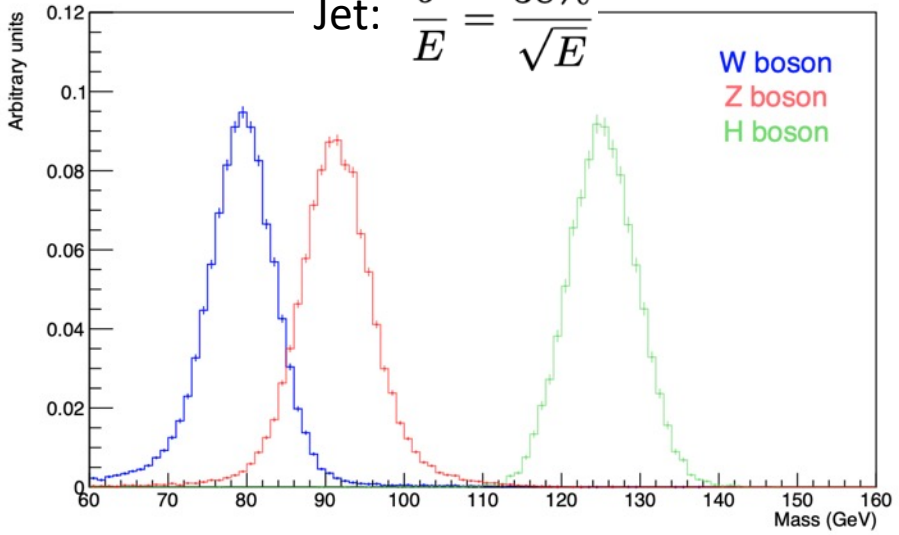
arXiv:2203.04312

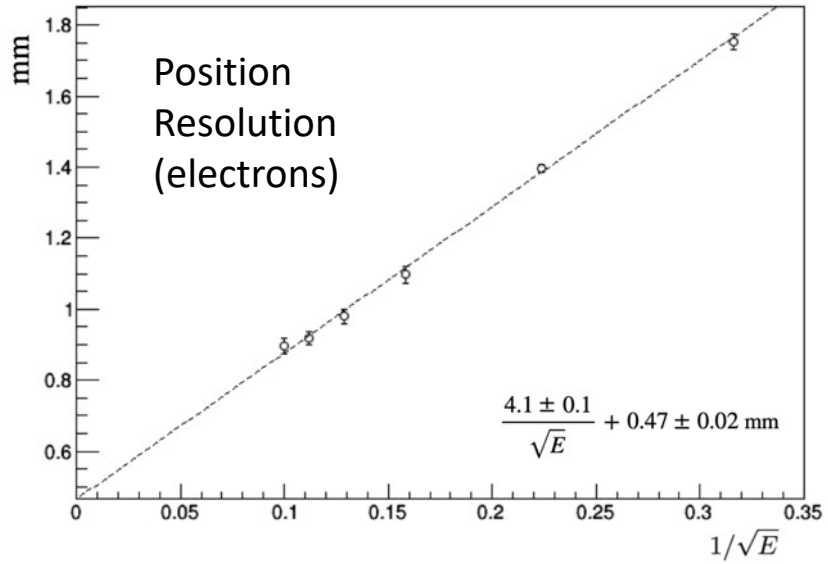
MC





Jet: $\frac{\sigma}{E} = \frac{38\%}{\sqrt{E}}$





Good separation for W/Z and Higgs.

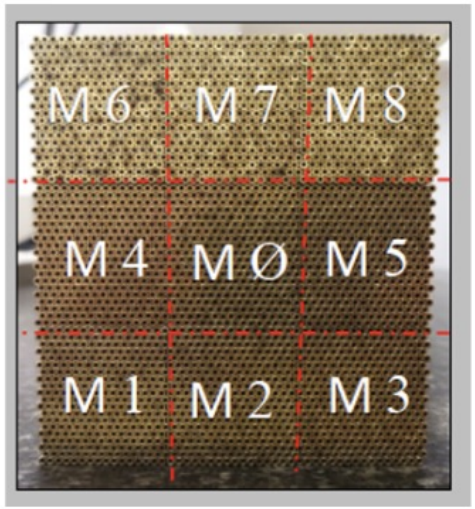
EM-size prototype module (10x10x100 cm^3) in IDEA TB 2021

Brass capillary tube: ϕ 2mm (1mm) outer (inner)

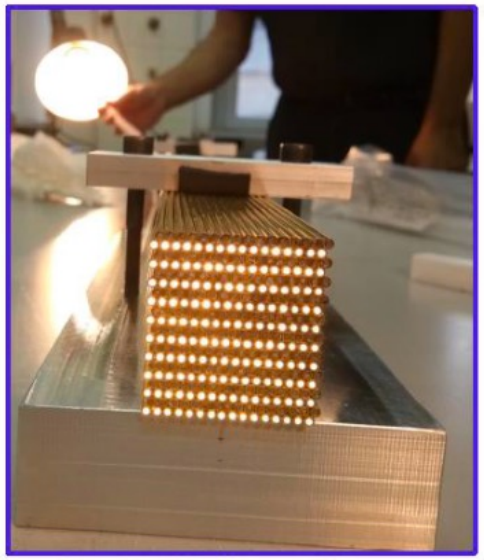
9 modules: 320 tubes / module

M0: SiPM (one per fiber) Hamamatsu S14160-1315 PS
M1-M9: PMT (one for S-fiber, one for C-fiber)

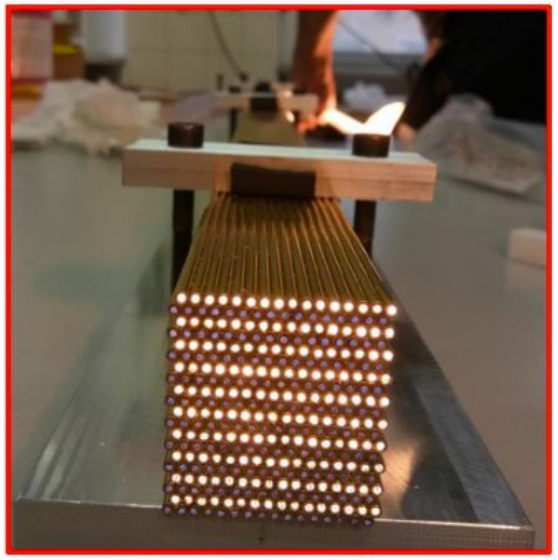
Readout: CAEN FERS A5202



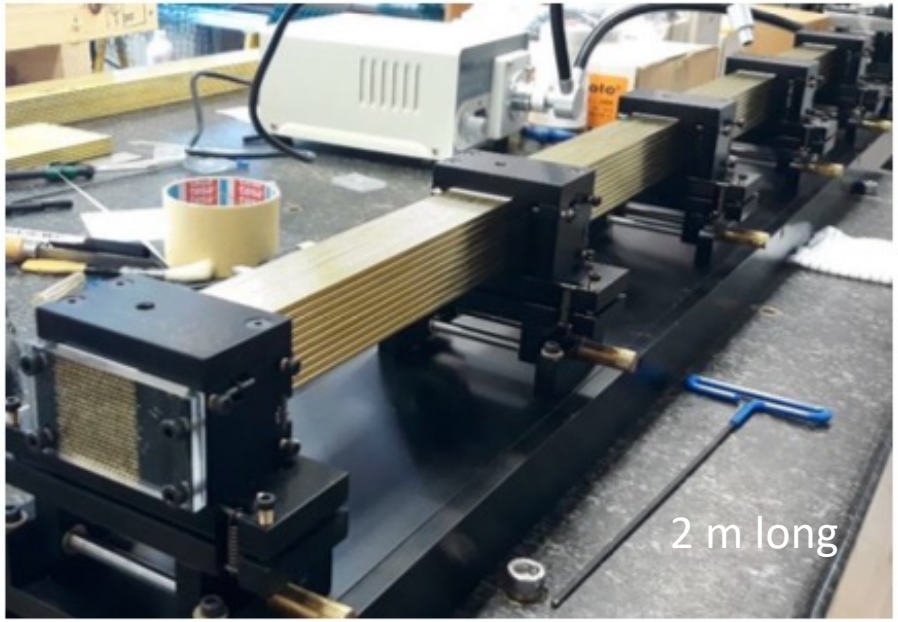
Bucatini calorimeter

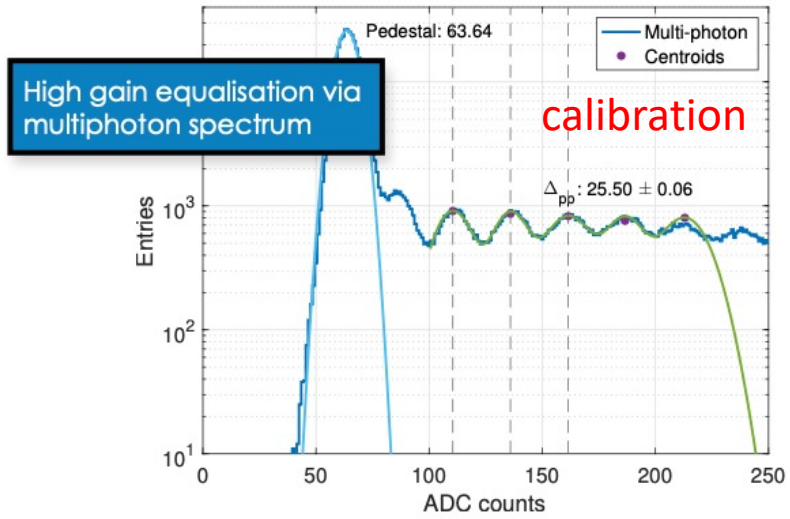


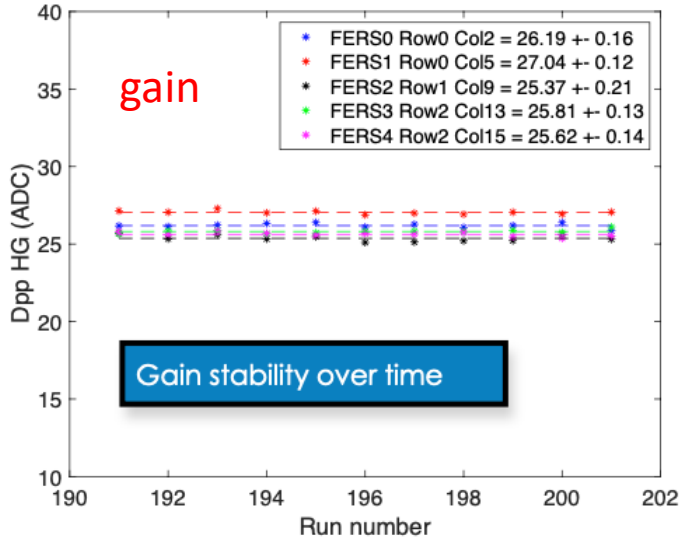
Scintillation fibers

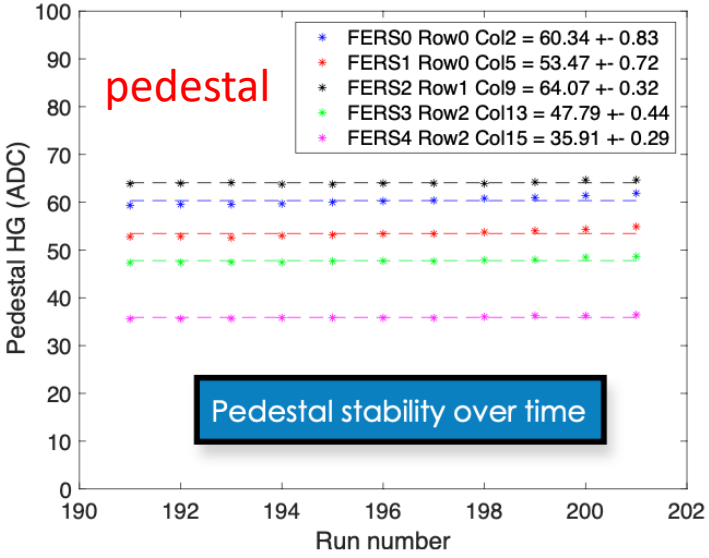


Cherenkov fibers



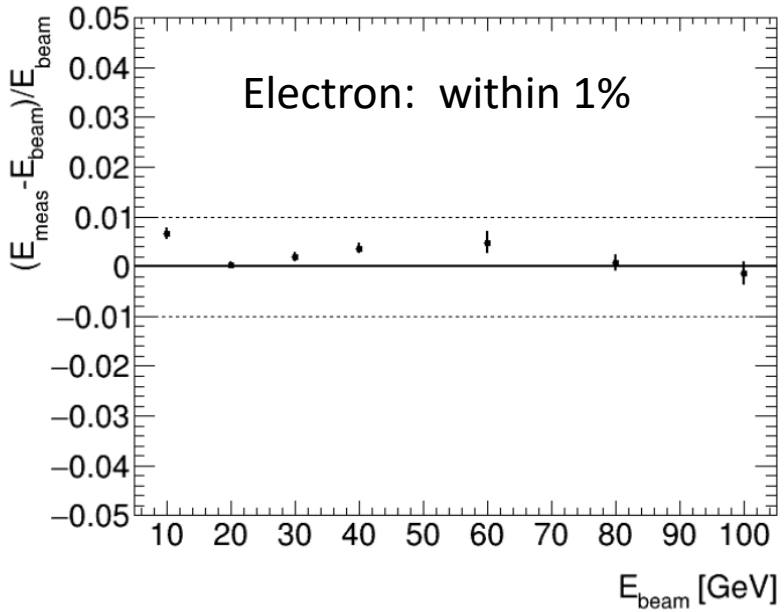




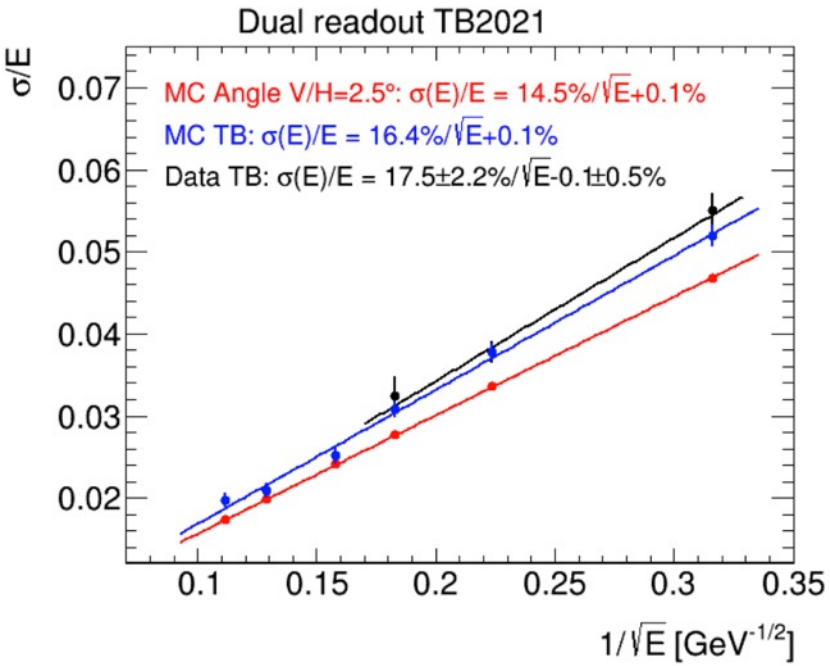


TB2021 e^- Results

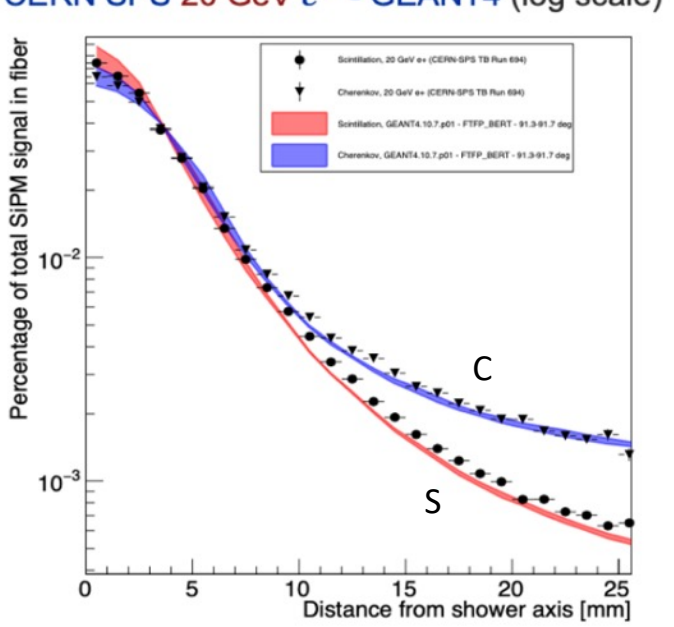
Linearity:



Resolution



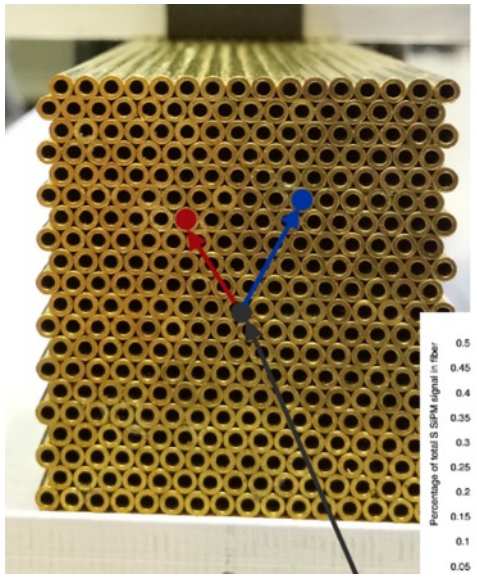
Lateral shower shape



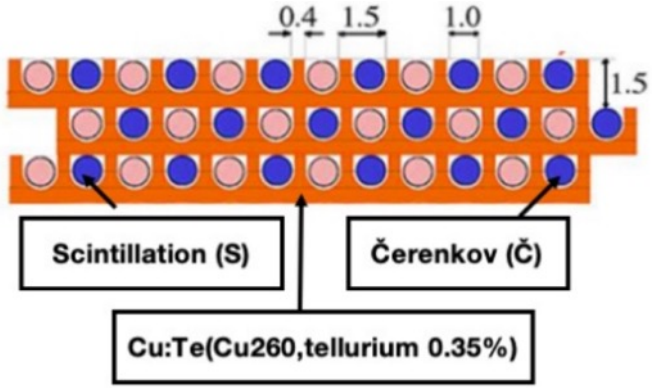
IDEA prototype modules

Challenges:
- Precision
- Projective geometry
- Mechanical rigidity

Brass capillary tube:

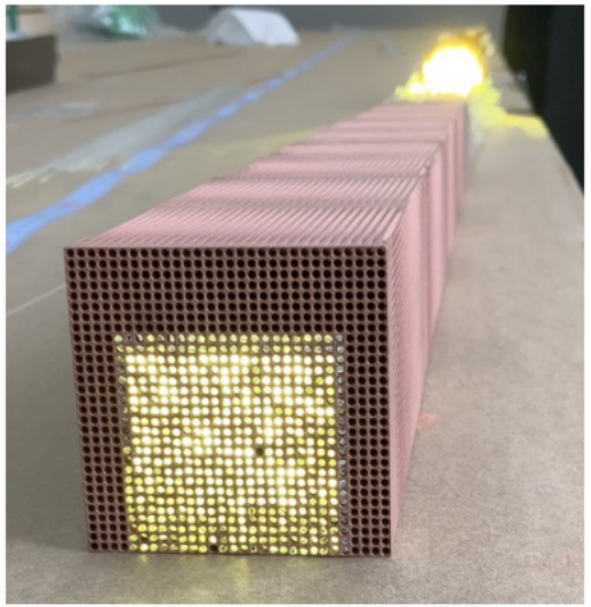


Cupper plate:

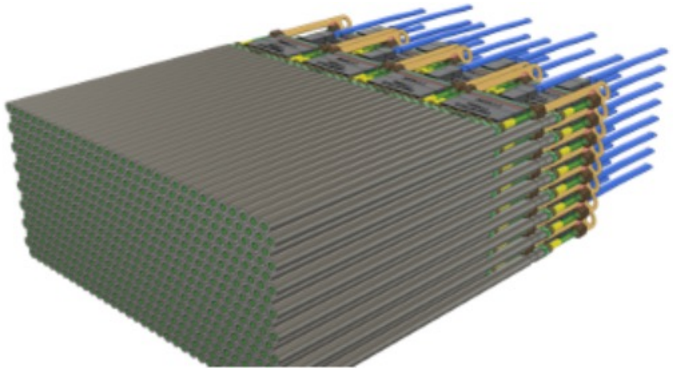


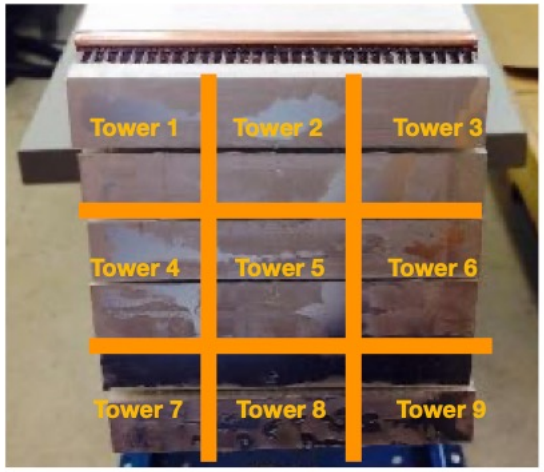
60 cm wide, 2.5 m long
61 plates to froma a module

3D print:



Challenge: SiPM on each fiber





3x3 modules in testbeam

Projective geometry

View from back:
Full length fibers lit at front.

Hybrid Segmented Calorimeter (Calvision Collaboration)

Timing LYSO (1 X_0)

+

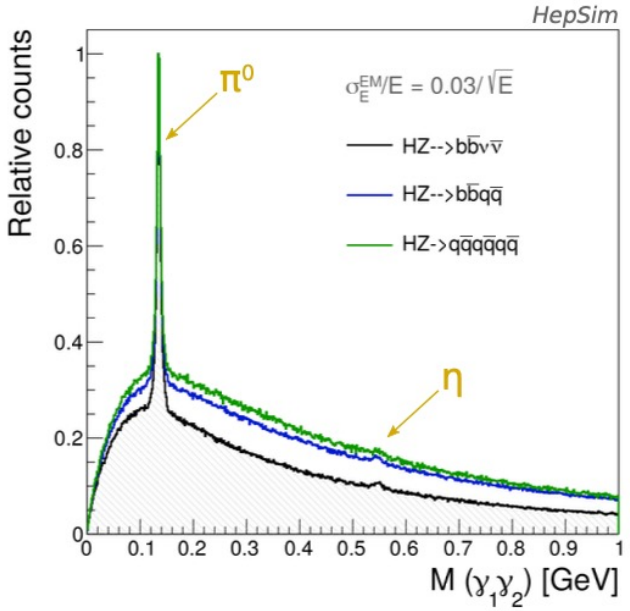
Dual Readout **Crystals** (ECAL)

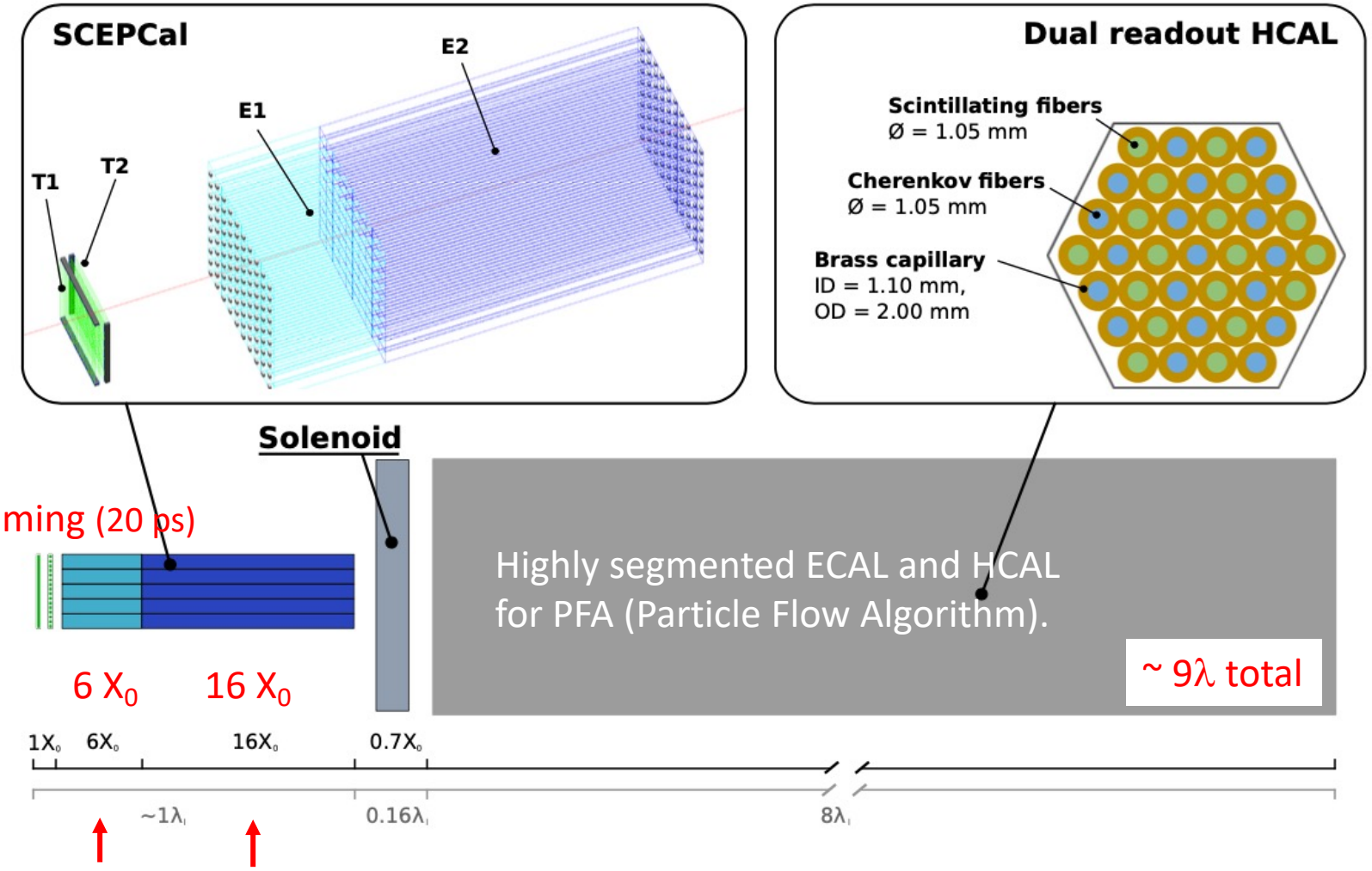
+

Dual Readout **Fibers** (HCAL)

EM resolution

$\sigma/E = 3.0\,\%/\sqrt{E} \oplus 0.5\,\%$

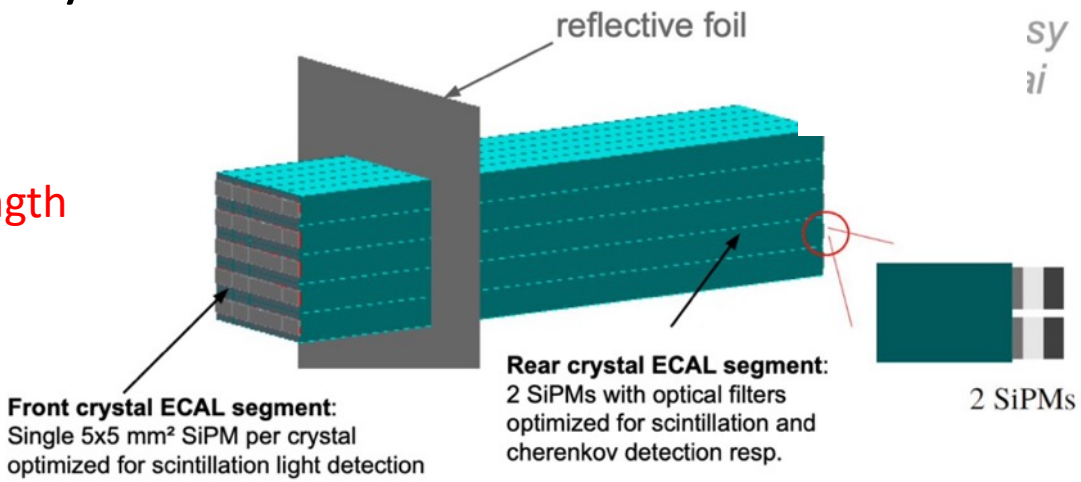




JINST 15 P11005

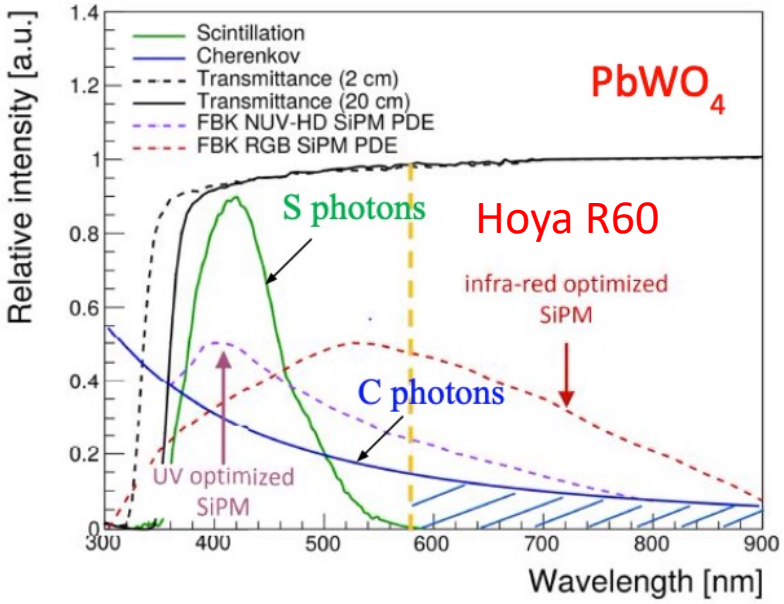
Separation of Scintillation light and Cherenkov light in crystal

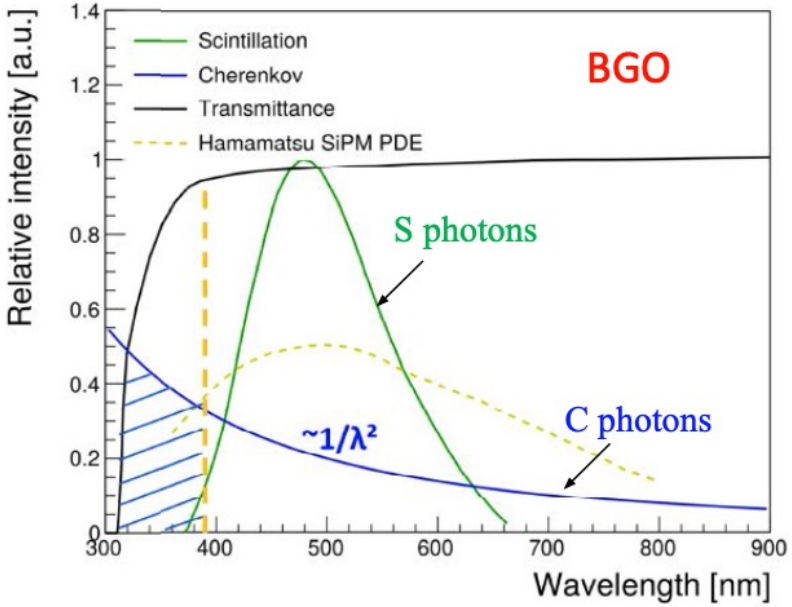
Timing
&
Wave length

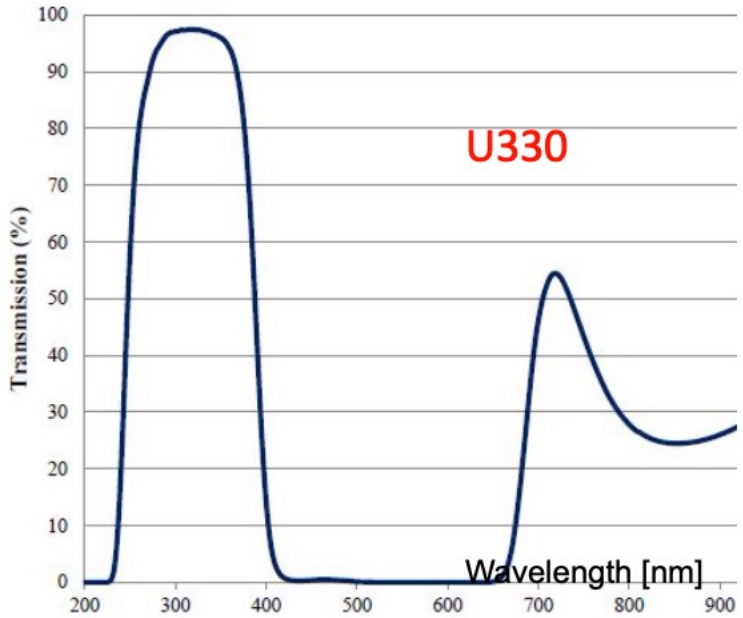


Optical filters

Filter	material	type	Density g/cm²	cut-on wavelength (nm)
U330	colored glass	band pass	2.78	-
#15-226	hard coated	long pass	-	600
R60	colored glass	long pass	2.69	600
UG11	colored glass	band pass	2.92	-
GG420	colored glass	long pass	2.55	420





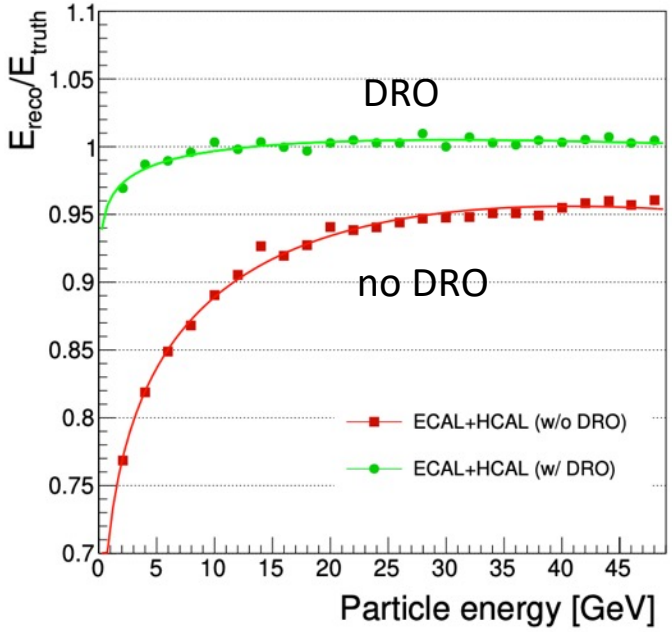


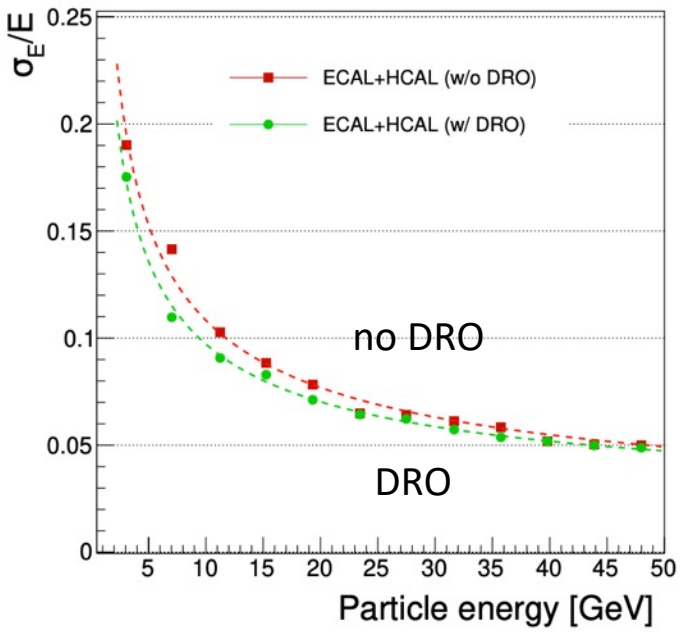
Tests with cosmic muons and beams are in progress.

ECAL (crystal) + HCAL (fiber) Performance

MC

Single pion ➔

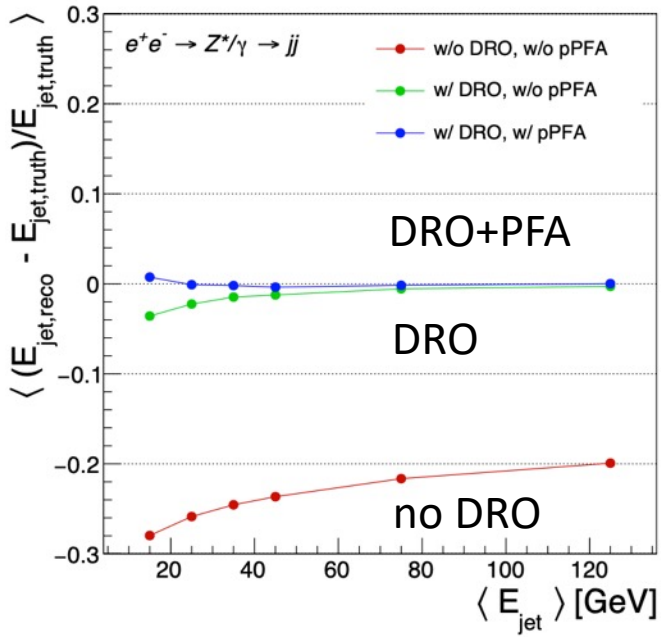


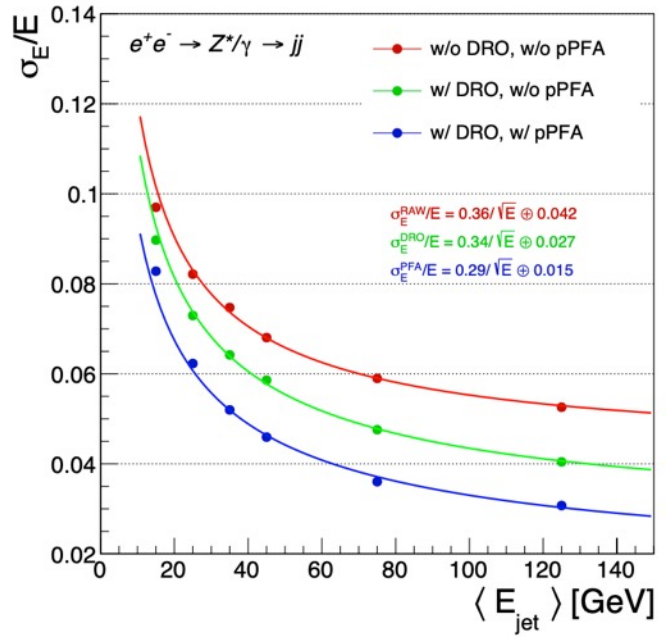


Jet energy scale

Jet energy resolution

Quark jet ➔





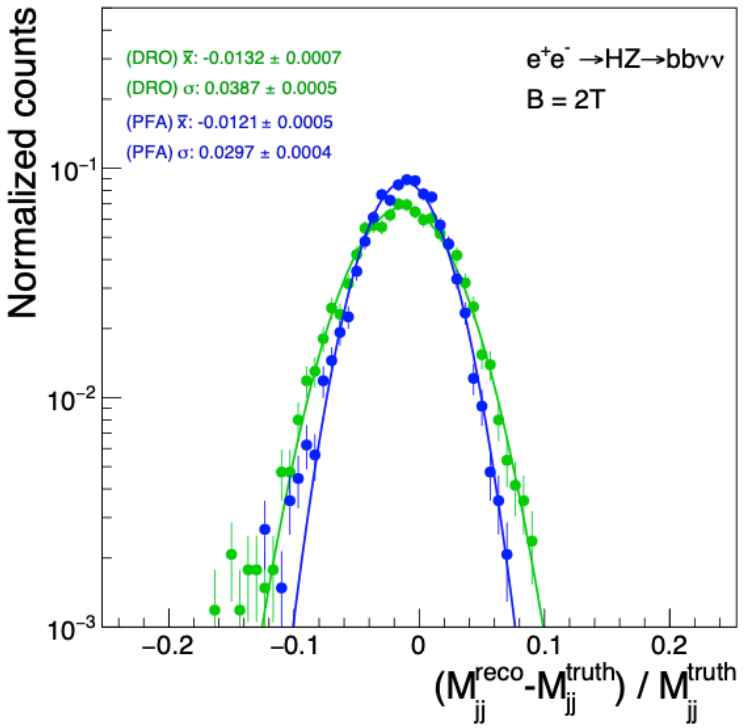
no DRO
DRO
DRO+PFA

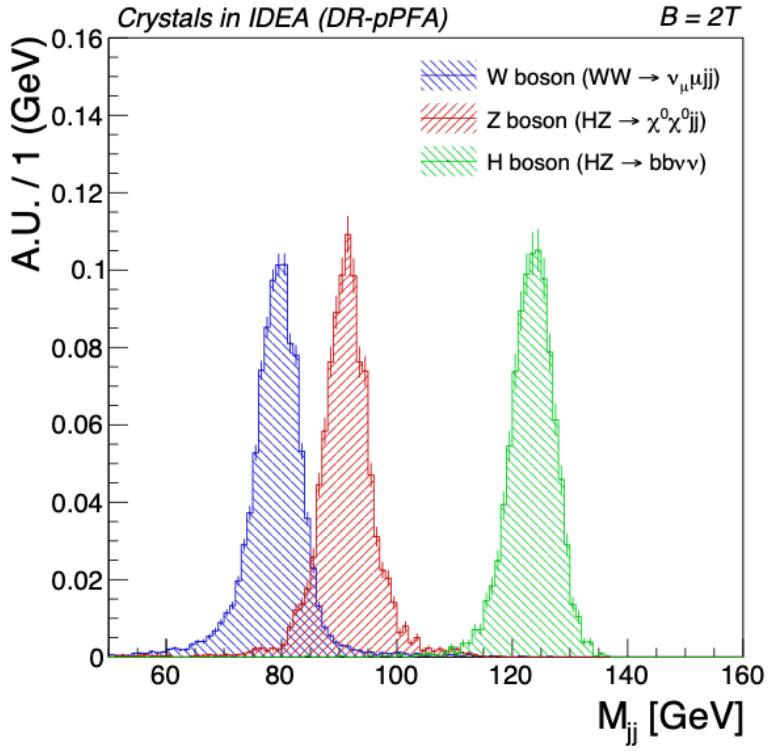
arXiv:2202.01474

ECAL (crystal) + HCAL (fiber) Performance

Table 3. Comparison of dijet invariant mass resolutions for the W, Z and H boson obtained using a 'calorimeter only' approach (with and without dual-readout correction) and using the DR-PFA.

	'Calo only' (w/o DRO)	'Calo only' (w/ DRO)	DR-PFA (w/ DRO)
W boson	5.6%	4.7%	3.8%
Z boson	4.7%	4.1%	3.3%
H boson	4.5%	3.9%	3.0%





arXiv:2202.01474

Precision ECAL - Crystal

TeraZ at FCC-ee
Detector Requirements

Flavour physics programme

- Formidable vertexing ability; b, c, s tagging
- Superb electromagnetic energy resolution
- Hadron identification covering the momentum range expected at the Z resonance

Tau physics programme

- Momentum resolution
  Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions
  Lifetime measurement
- Tracker and ECAL granularity and e/μ/π separation
  BR measurements, EWPOs, spectral functions

P. Janot, ECFA 19Nov2021
https://indico.cern.ch/event/1085137/

patrizia azzi - BNL April 25th 2023

$Bs^0 \rightarrow Ds^+K^- \rightarrow \phi\rho^+K^- \rightarrow K^+K^-\pi^+\pi^0K^-$

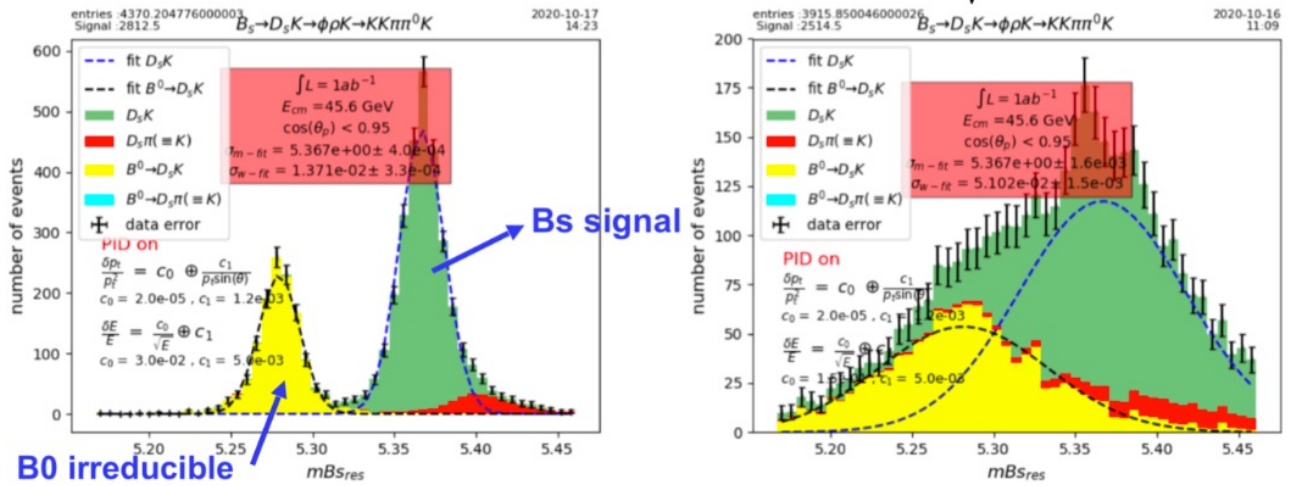
2107.02002

Assuming **state-of-the-art** calorimeter with

$$\frac{\delta E}{E} = \frac{0.03}{\sqrt{E}} \oplus 0.005$$

Assuming **HGCal like** calorimeter with

$$\frac{\delta E}{E} = \frac{0.15}{\sqrt{E}} \oplus 0.005$$



State-of-the-art Xtal-type to HGCal-type : $\sigma(D_s^{\pm}(\phi\rho^{\pm})K^{\mp}) \approx 14MeV \rightarrow 51MeV$

- **Improved EM energy resolution very important for jets and flavour/taus**
- **EM granularity also very important for flavor/taus and BSM physics to distinguish close-by photons**

https://indico.cern.ch/event/1244371/

Neural Network for Invisible Energy Estimation

DR with finely segmented crystal performs well for Higgs Factories. R&D for further improvement.

Invisible Energy
vs
# of Hadronic Vertices
in shower

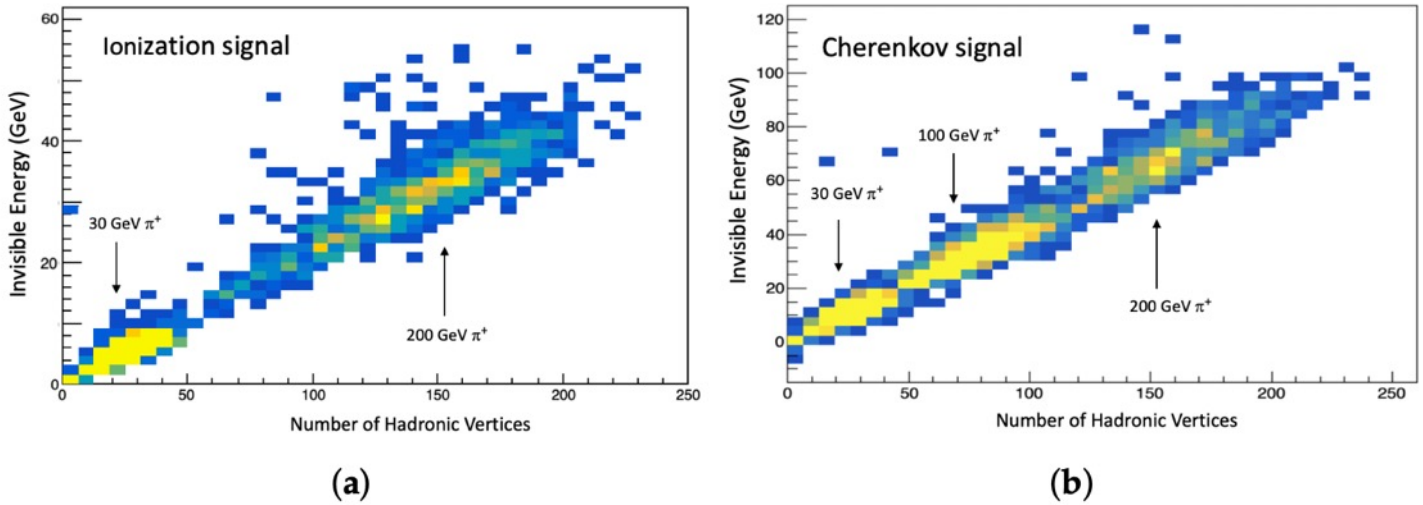


Figure 4. Invisible energy *vs* the number of hadronic vertices in a sampling calorimeter: (**a**) with ionization signal in Cu (17 mm) + Si (3 mm) and (**b**) with a Cherenkov signal in Cu (17 mm) + Quartz plate (3 mm) for 30 and 200 GeV π^+s. "Invisible energy" is defined as the difference between the beam energy and the simple sum of the ionization signal or Cherenkov signal. "Hadronic vertex" is defined as a vertex of hadron-nucleus inelastic interaction excluding neutron-nucleus interaction. The energy scale of the signals was calibrated with electrons.

Inv. E = E_{beam} - $E_{observed}$

➔ Neural Network to count and analyze vertices in hadronic shower (Vertex Imaging).

Instruments, 2022, 6, 43, https://doi.org/10.3390/instruments6040043

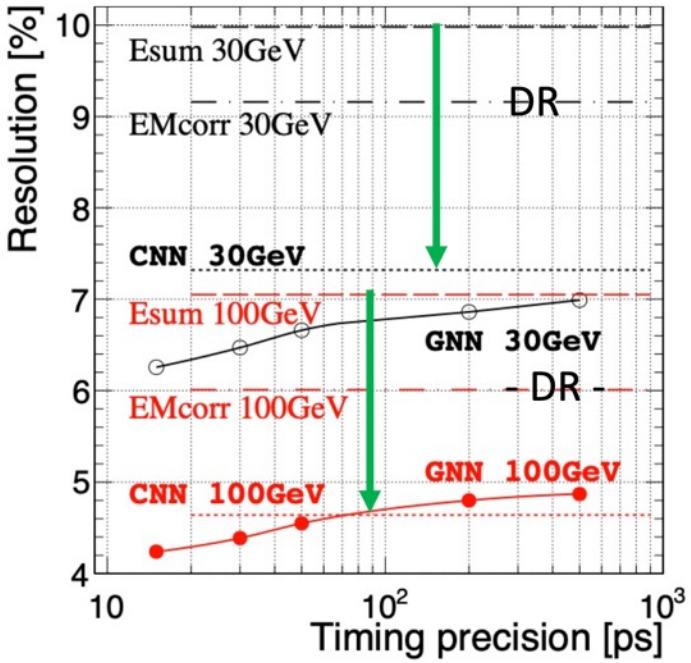
Neural Network on Fast Calorimeter / Fiber Calorimeter

MC studies

dE/dx (ionization) Calorimeter (*1)

20x20x20 mm^3 cube
Cu (17) +Si (3)

CNN: 0-5 ns 1 image/cube
GNN: 0-10 ns 8 images/cube (1st image: 15 ps)

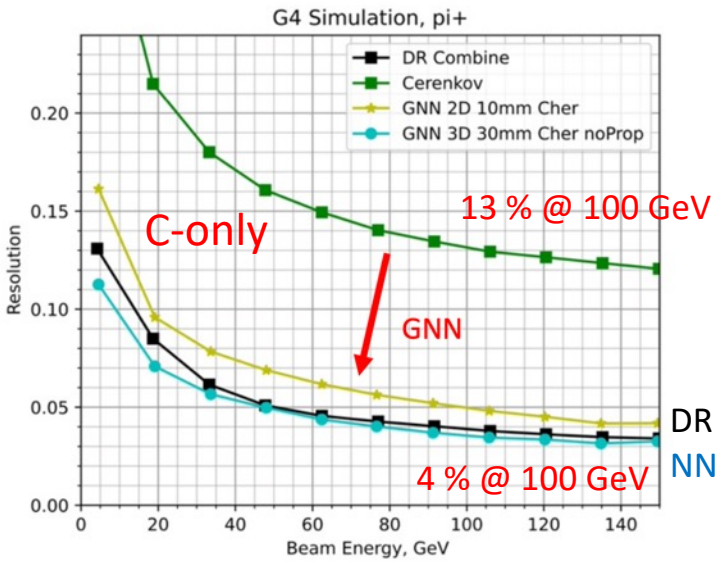


NN trained with pi+ works well for electrons/photons and jets.

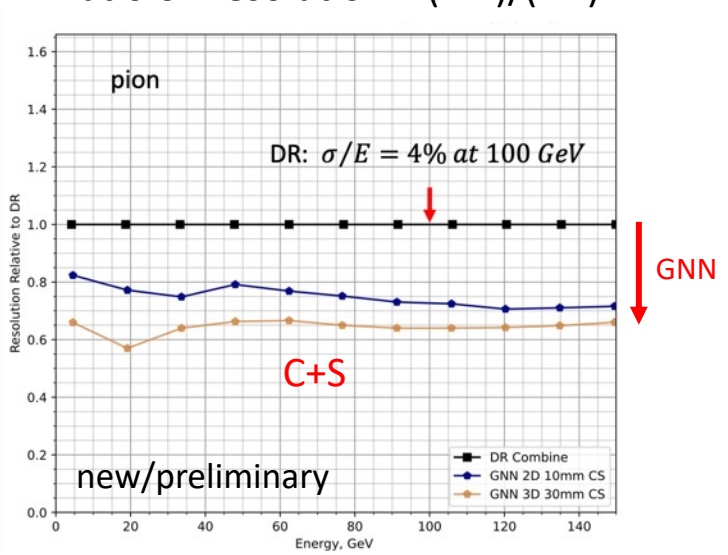
Dual Readout Fiber calorimeter (*2)

Cu absorber (2 m deep)
Fibers along beam direction:
1 mm ϕ fibers, 1.5 mm spacing, 34%
Transverse segmentation:
1x1 cm^2 for 2D analysis, 3x3 cm^2 for 3D analysis
Longitudinal segmentation: 2.5 cm with timing (50 ps)

Cherenkov

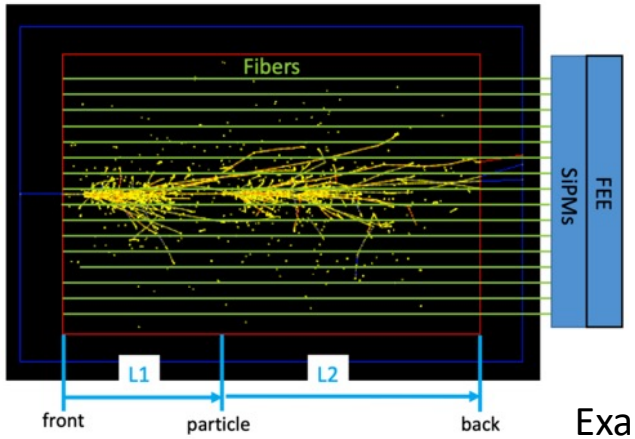


Ratio of Resolution = (NN)/(DR)



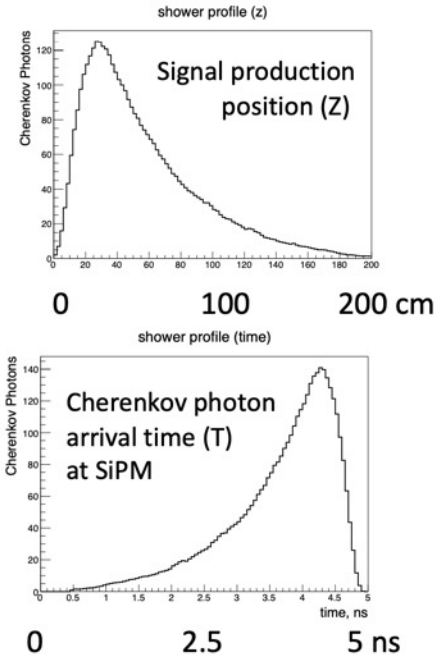
(*1) JINST 2021, 16, P12036, https://doi/10.48550.arXiv.2107.10207
(*2) Instruments, 2022, 6, 43, https://doi.org/10.3390/instruments6040043

Longitudinal Segmentation with Timing for NN and PFA

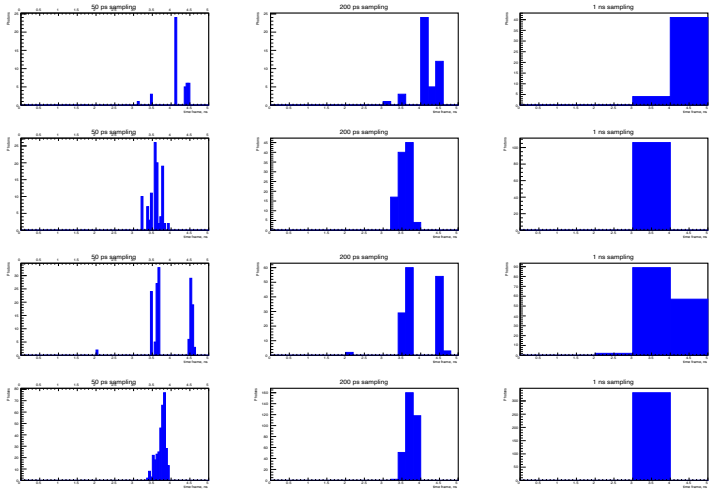


SPAD is fast (<10 ps) – faster than LGAD.

Need multi-hit capable SPAD array:
➔ digital-SiPM.



Example of Time structure of hadronic shower in a central tower (1.2 x 1.2 cm^2)



50 ps 200 ps 1.0 ns per bin

σ/E= 3.8 % 4.2% @ 100 GeV (13% simple sum)

Single hit timing (with laser)

Hamamatsu S14160-3015PS:

Crilin: A Semi-Homogeneous Calorimeter for a Future Muon Collider, Instruments 2022, 6,62

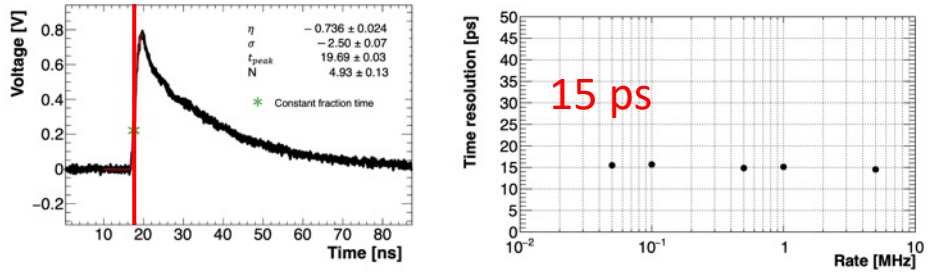
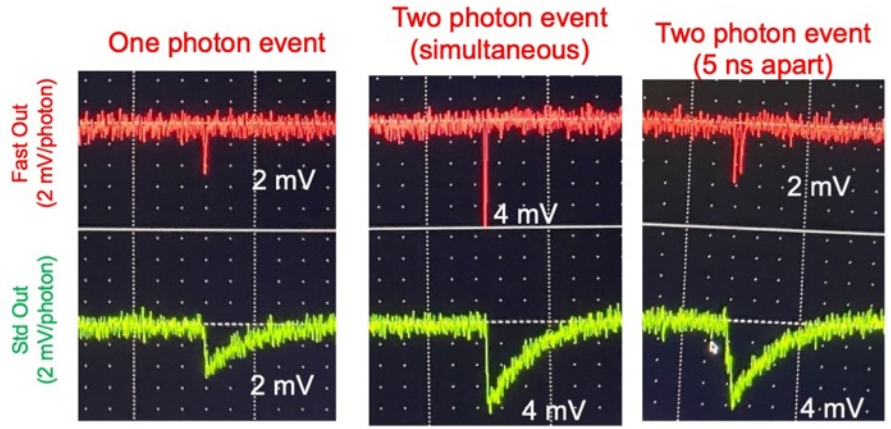


Figure 9. (**Left**): SiPM waveform in response to a laser pulse, sampled at 40 GS/s. Log-normal fit on the rising edge is overlaid. (**Right**): Effect of laser repetition rate on the time resolution.

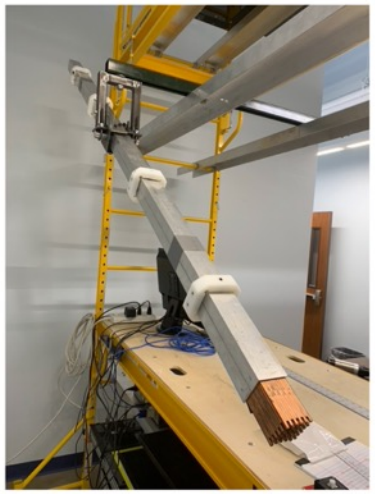
Multi-hit timing:

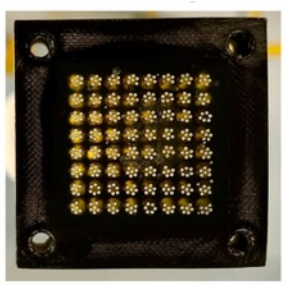
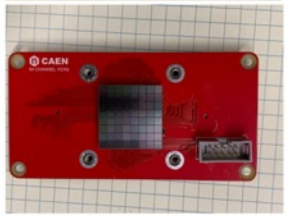
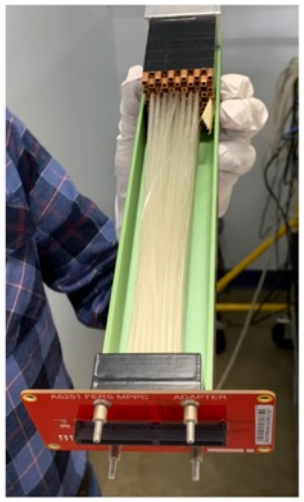
SensL MicroFC-SMA-30020-GEVB



(1) Cosmic Muon Test Stand at TTU

Hamamatsu S13361-30350AE08 (64 ch array)
CANE A5202 (64ch SiPM readout)

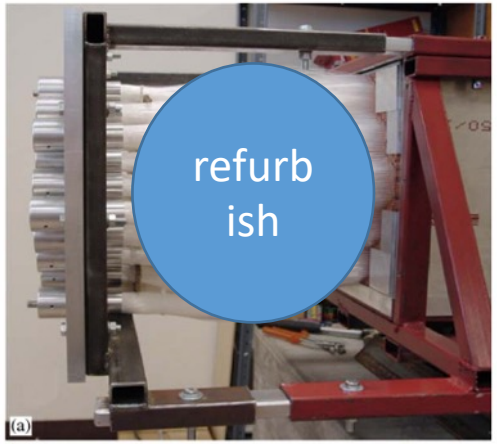


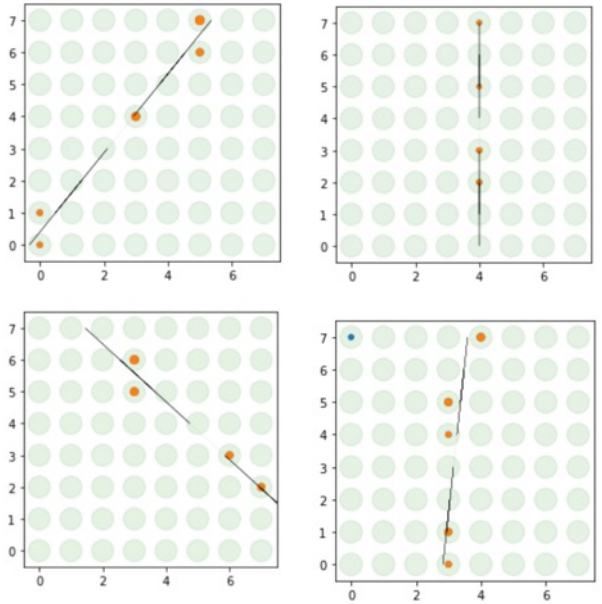




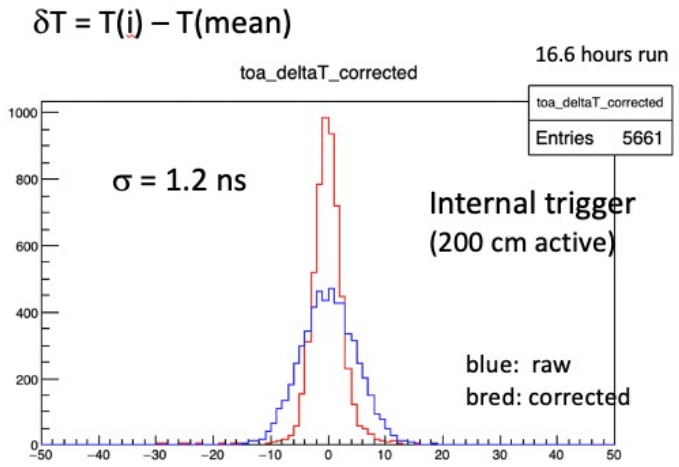
Platform for R&D of longitudinal segmentation with timing for fiber calorimeter.

(2) DREAM module

Refurbish with “new” SiPMs and FE/DAQ





Summary

- International Collaborations on Dual Readout Calorimeter for Future Colliders
  - Fibers: **IDEA** – INFN, Korea, …
  - Crystals+Fibers: **Calvision** – Caltech, **Maryland**, Michigan, MIT, Princeton, Purdue, TTU, Virginia + Argonne, Fermilab, Oak Ridge

  ❖Two collaborations have been working closely.

- Hybrid Highly Segmented Dual Readout Calorimeter will produce maximal information for Particle Flow Algorithm at future collider.

- R&D on both “hard” and “soft” are in progress for further improvement of the calorimeter.