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Development of the dual-readout calorimeter for future e+e- colliders

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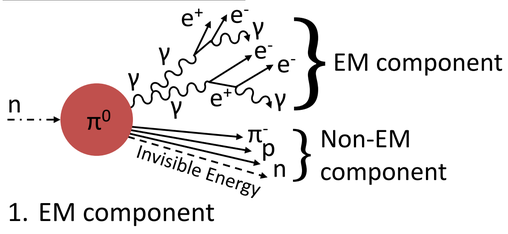
Supported by KiSTi

The Dual-readout Method

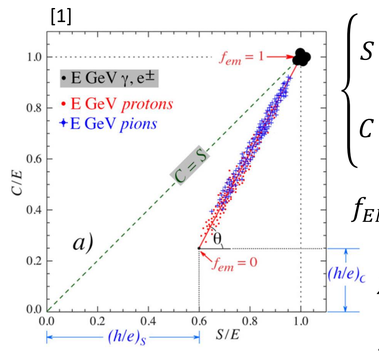
Hadronic shower



1. EM component
2. Invisible energy in non-EM component

→ Poor hadronic energy resolution!

[1]



$$\begin{cases} S = E\left[f_{EM} + \frac{1}{(e/h)_S}(1 - f_{EM})\right] \\ C = E\left[f_{EM} + \frac{1}{(e/h)_C}(1 - f_{EM})\right] \end{cases}$$

$$f_{EM} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1 - (h/e)_S] - [1 - (h/e)_C]}$$

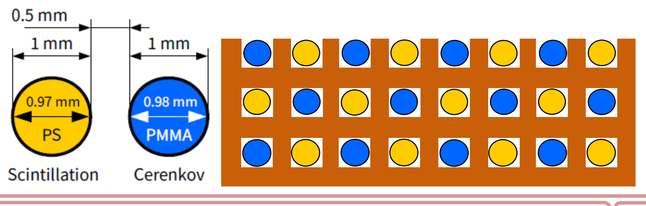
$$\chi \equiv \cot\theta = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

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

- Non-gaussian fluctuations of the EM shower component are a major factor that makes it difficult to measure energy of hadron shower
- Outstanding energy resolution can be achieved by measuring EM component and correcting hadron energy event by event

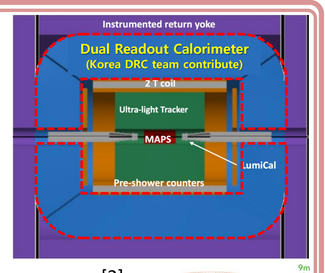
The Dual-readout Calorimeter

Fiber sampling calorimeter
- Absorber material: Cu
- Two active media: Scintillating and Cerenkov fibers



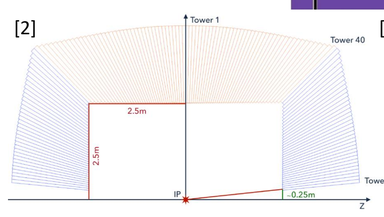
IDEA Detector

- IDEA detector is being discussed in conceptual design report of Both FCC-ee & CEPC.
- Dual-readout calorimeter is a **main calorimeter of IDEA detector** which detects **both EM & hadronic components**.
- Korean team led the design of the Dual-Readout Calorimeter for IDEA detector.

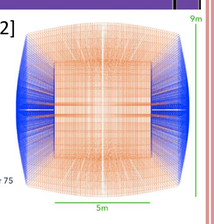


- Required Performance
  - For $H \rightarrow q\bar{q}, VV$ process
    ECAL, HCAL: $\sigma_E^{jet}/E \sim 3 - 4\%$
  - For $H \rightarrow q\bar{q}, VV$ process
    ECAL: $\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

[2]

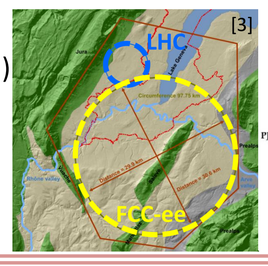


[2]

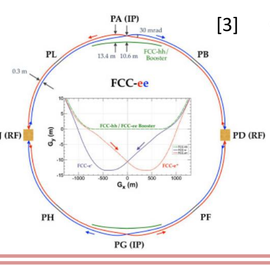


- FCC-ee (2040 ~)

[3]

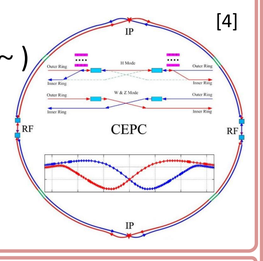


[3]



- CEPC (2030 ~)

[4]

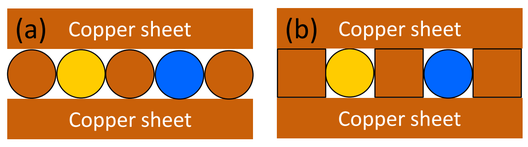


Prototype Module R&D

- Stacking

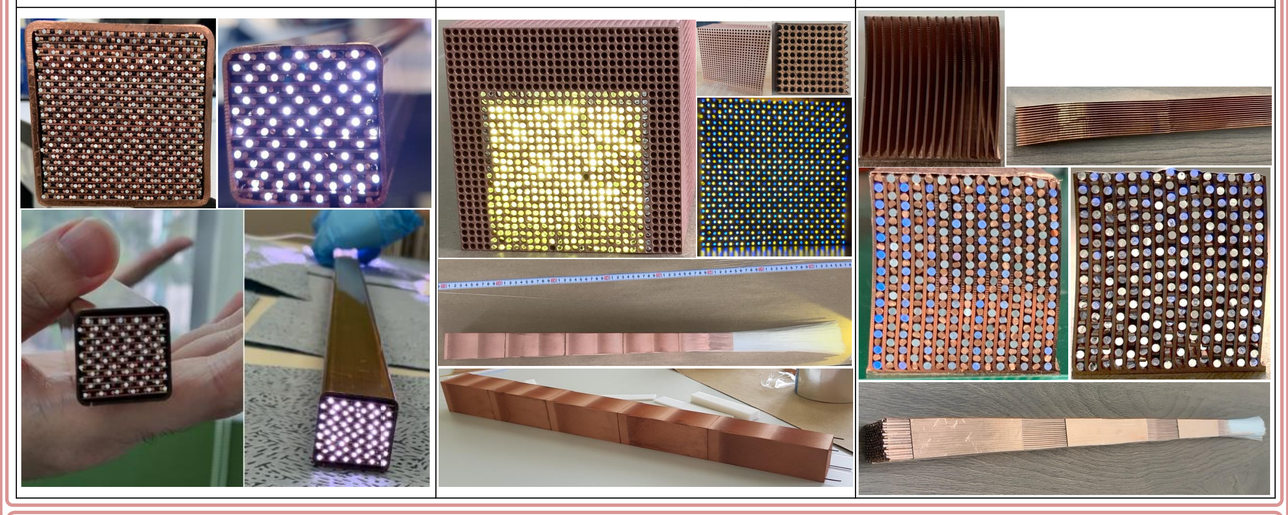
  (a) Copper wires and fibers

  (b) Copper shim and fibers



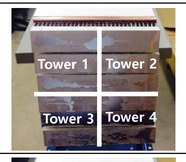
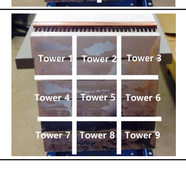
- Various Prototype Modules Based on Copper Forming Method.

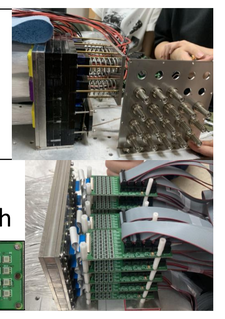
LEGO-like Module	3D Metal Printing	Skiving Fin Heatsink



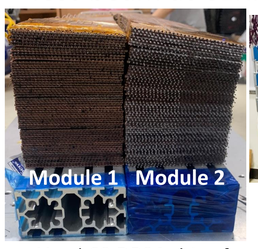
Test-beam experiment at 2022

- Measurement Goal

Module 1 (2x2)	- Shower depth - Time resolution (MCP-PMT) - Longitudinal shower profile - Light attenuation length		- Tower 1,2,4: 2 PMTs, each - Tower 3: 2 MCP-PMTs
Module 2 (3x3)	- Position resolution - Time resolution (SiPM) - EM energy resolution - Uniformity study		- Tower 1-4, 6-9: 16 PMTs, each - Tower 5: 400 SiPMs

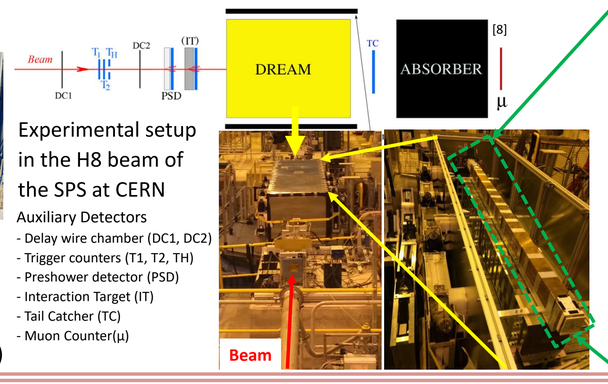


- R&D Goal
  - Readout system test (with MCP-PMT and SiPM)
  - Study of various type of optical fibers (Scintillation)
  - Time resolution (< 50 ps processing)
- Test-beam at CERN in Aug. 2022



1 TCB and 15 DAQ boards (made by Notice Korea)

- Used 60 DRS4 chips for 480 channels
- Sampling rate up to 5 GHz
- Save waveform(0.1 kHz) and pulse height(25 kHz)



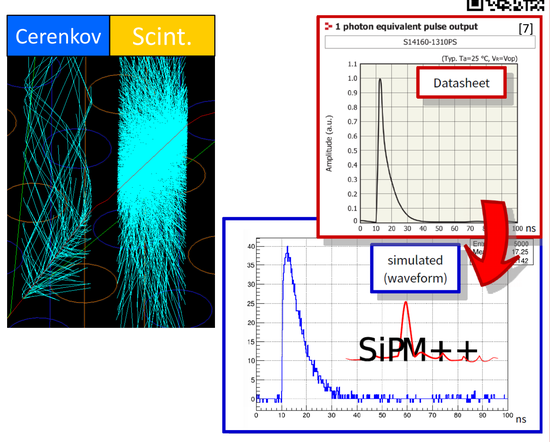
Experimental setup in the H8 beam of the SPS at CERN

Auxiliary Detectors
- Delay wire chamber (DC1, DC2)
- Trigger counters (T1, T2, TH)
- Preshower detector (PSD)
- Interaction Target (IT)
- Tail Catcher (TC)
- Muon Counter(μ)

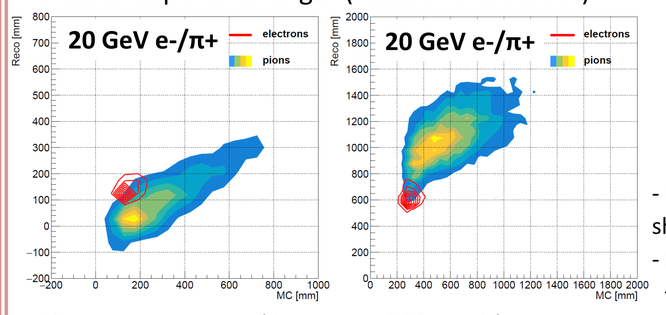
Software Development

- Reconstruction of 3D Shower Shape
  - Simulating optical photon in each fibers from calorimeter.
  - Simulating SiPM response with SimSiPM based on Hamamatsu SiPM datasheet.
  - With FFT, remove tail on waveform of SiPM then recover time of arrival of optical photon.

  → Detailed simulation of the time of arrival of optical photon.



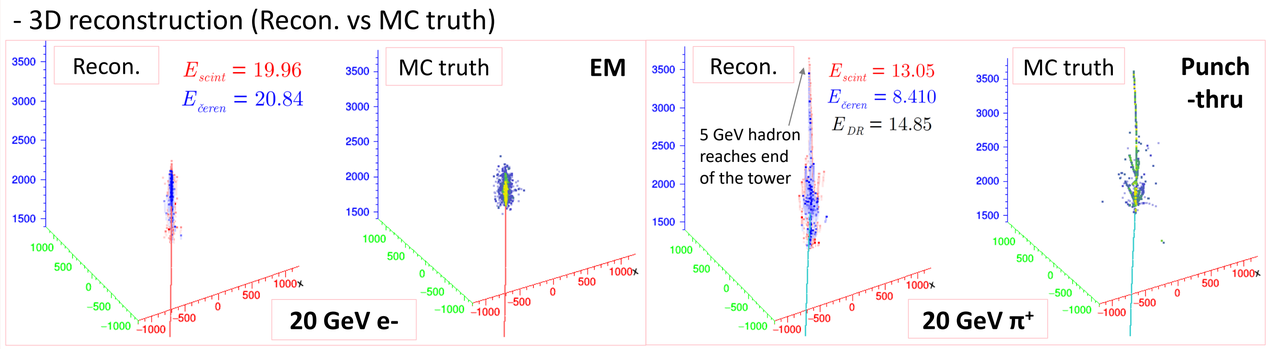
- Shower depth and length (Recon. vs MC truth)



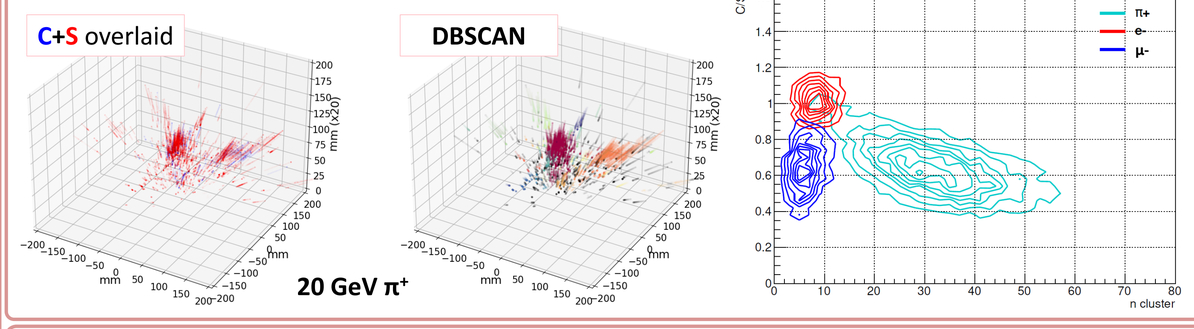
- Obtain linear correlation between MC vs Recon. of both shower depth & length simultaneously
- Longitudinal shape with excellent lateral granularity

→ 3D reconstruction!

- 3D reconstruction (Recon. vs MC truth)

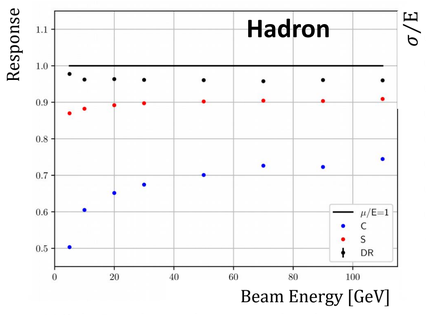


- Particle Id with substructure clustering

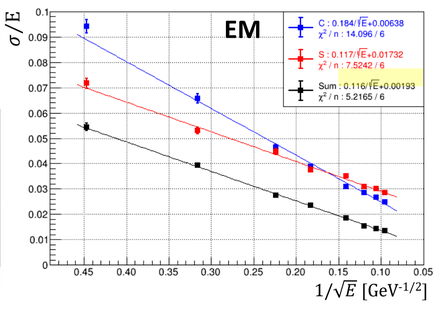


Simulation Performance Studies

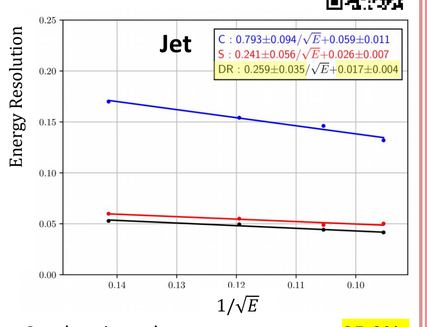
- Energy Resolution Study: Hadron, EM, jet



With Dual-readout method, linearity is closer to 1.



Stochastic and constant terms are 11.6%, 1.9%, respectively.



Stochastic and constant terms are 25.9%, 1.7%, respectively.

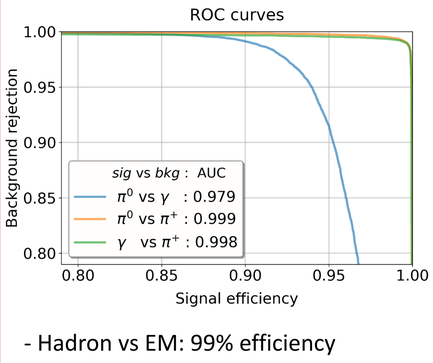
→ **3.1% E_{res} for 100 GeV jet**

***Satisfied the performance requirement!**

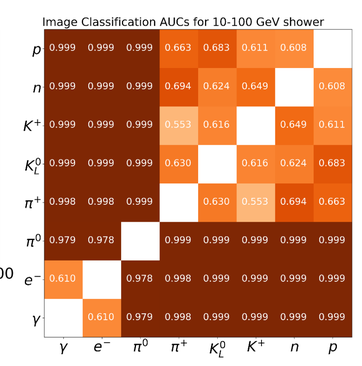
- Particle Identification using Deep Learning

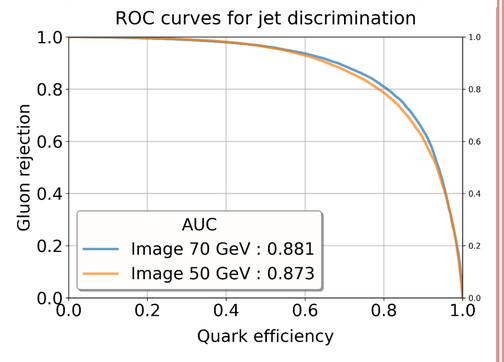
- Particle Shower Identification

- Quark and Gluon Jet Identification



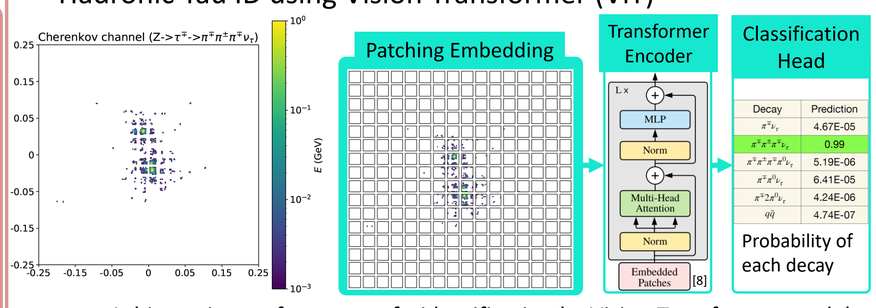
- Hadron vs EM: 99% efficiency
- π^0 vs other EM: 93% efficiency

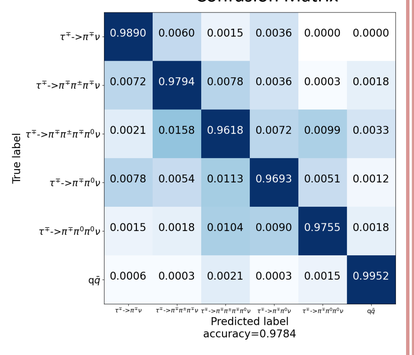




- Quark jet vs gluon jet: 79 ~ 80% efficiency

- Hadronic Tau ID using Vision Transformer (ViT)





Achieve nice performance of τ identification by Vision Transformer model.
- 97.8% total accuracy for the QCD jets and hadronic τ decays.
- Discriminate QCD jets with 99.5% accuracy.

Summary & Plan

- Dual-readout calorimeter has shown excellent performance with simulations through past years.
- Developing novel ideas to exploit timing information for longitudinal & 3D reconstruction.
  → first 3D reconstruction with fiber-sampling calorimeter.
- Simulation performance study shows dual-readout calorimeter satisfy the performance requirement.
- Implementing deep learning for various particle identification case and improving its performance.

- With the prototype modules, beam test at hospital will be performed.
- For test-beam experiment, commissioning and test are in progress then shipping to CERN within this month.

Reference

[1] S. Lee, M. Livan, R. Wigmans, "Dual-readout calorimetry", Rev. Modern Phys. 90(2018) 025002.
[2] "Expected performances of the IDEA Dual-Readout fully projective fiber calorimeter", L. Pezzotti, CHEF2019, Nov. 2019, Fukuoka, Japan
[3] "FCC-ee: The Lepton Collider Future Circular Collider Conceptual Design Report Volume 2", Eur. Phys. J. Special Topics 228, 261–623 (2019)
[4] "CEPC conceptual design report: Volume 2 - physics & detector", 2018, arXiv:1811.10545
[6] S. Lee, et al., "Hadron detection with a dual-readout fiber calorimeter", NIM A 866 (2017) 76-90
[7] "S14160-1310PS - MPPC - Hamamatsu Photonics", Hamamatsu, accessed Jul 1, 2022, https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s14160-1310ps_etc_kapd1070e.pdf
[8] "AN IMAGE IS WORTH 16X16 WORDS: TRANSFORMERS FOR IMAGE RECOGNITION AT SCALE", ICLR2021, Jun. 2021, arXiv:2010.11929