Toward Physics Studies with Dual-Readout Calorimeter for Future e^+e^- Colliders

Hwidong Yoo (Yonsei Univ.)

On behalf of the Korea
Dual-Readout Calorimeter team

SM2021 EF01&EF02 meeting, Nov. 19, 2020

Dual-Readout Calorimeter (DRC)

The dual-readout calorimetry

- The major difficulty of measuring energy of hadronic shower comes from the fluctuation of EM fraction of a shower, f_em.
- f_em can be measured by implementing two different channels with different h/e response in a calorimeter.

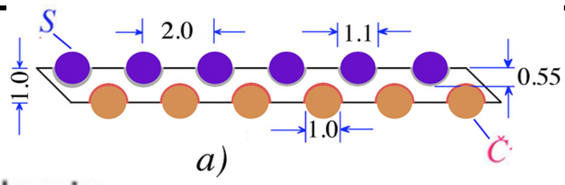
$$S = E[f_{em} + \frac{1}{(e/h)_S}(1-f_{em})],$$

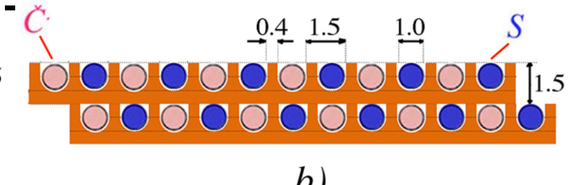
$$C = E[f_{em} + \frac{1}{(e/h)_C}(1-f_{em})].$$

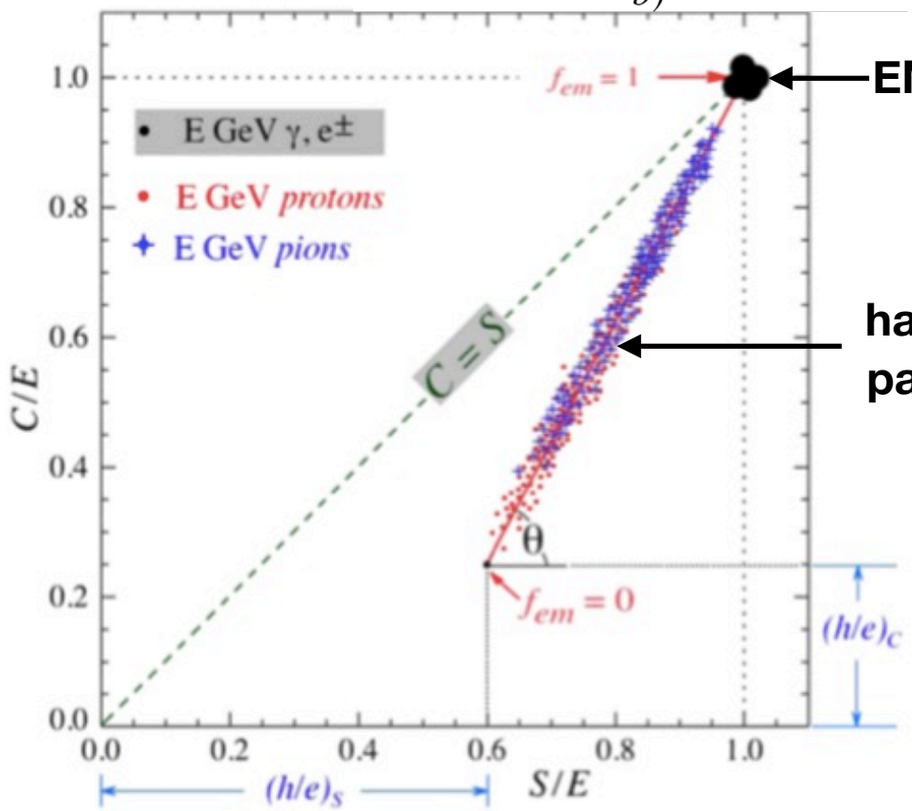
$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} \equiv \chi,$$

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

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







EM particles

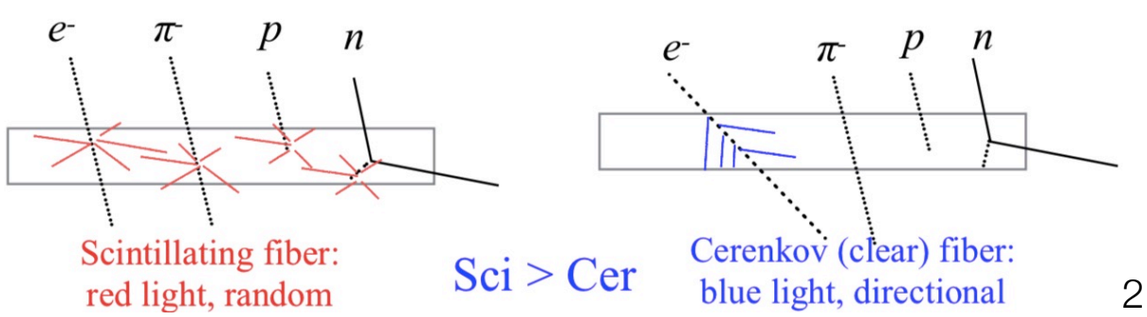
hadronic particles

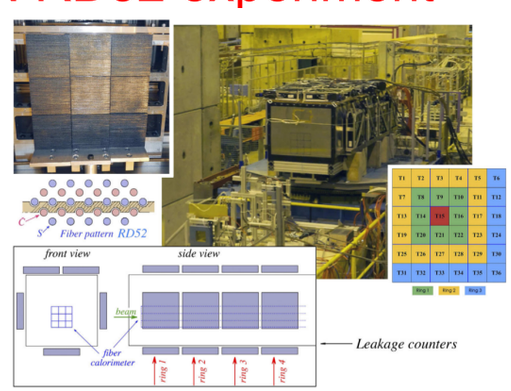
- Dual-readout calorimeter offers high-quality energy measurement for both EM particles and hadrons.
- Excellent energy resolution for hadrons can be achieved by measuring f_em and correcting the energy of hadron event-by-event.

Energy measured from scintillation channel vs Cerenkov channel for EM particle, π & p.

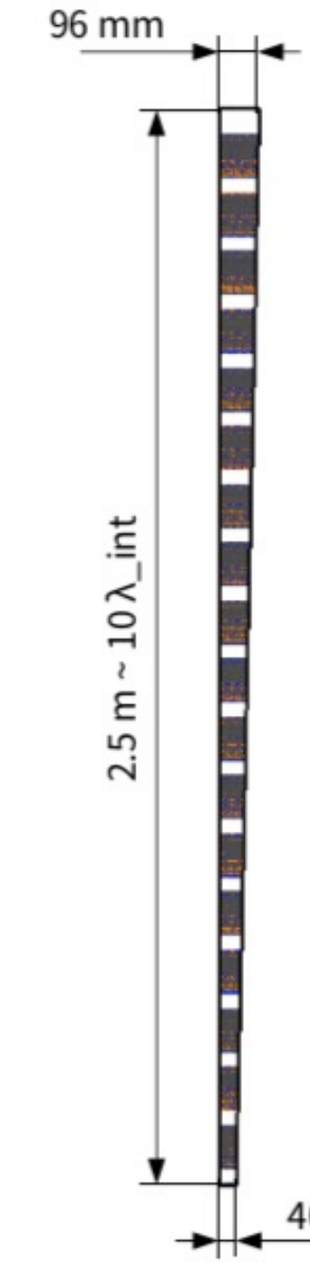
More than 20 years R&D: CERN RD52 experiment

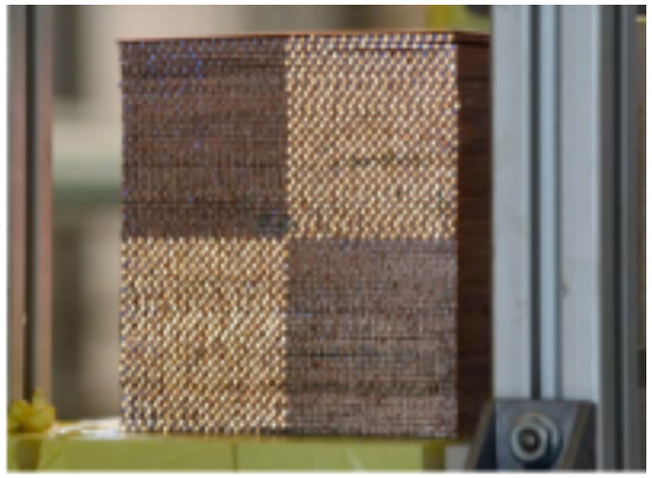
Signal generation: Scintillating & Cerenkov fibers

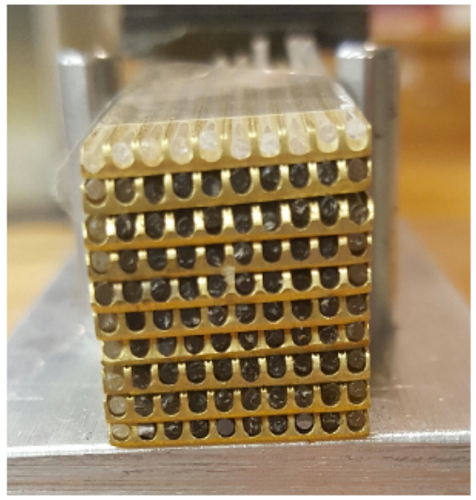




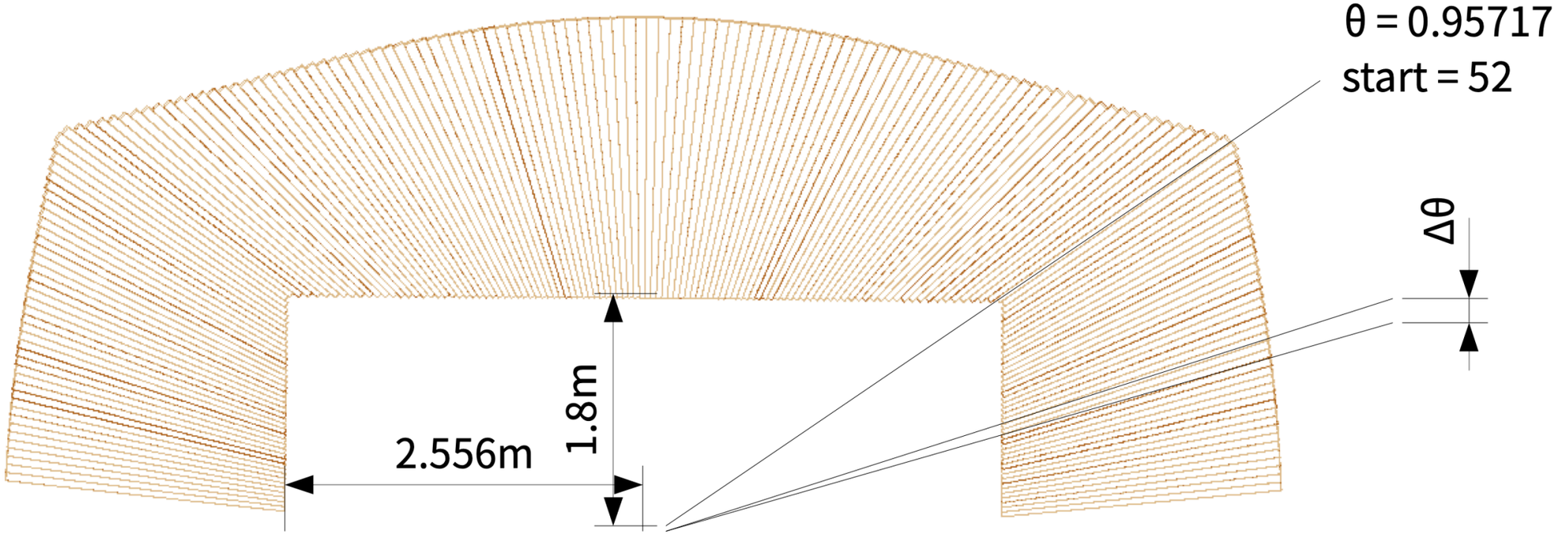
DRC Geometry and Module







IDEA



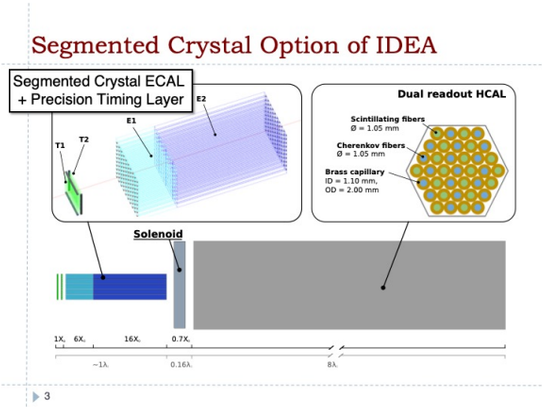
International Collaboration

Prof. Hyonsuk Jo (KNU)
Prof. Jason Lee (UoS)
Prof. Sehwook Lee (KNU)
Prof. Hwidong Yoo (YU)

Taiwan

Prof. Rong-Shyang Lu

Prof. Chia Ming Kuo



Prof. Richard Wigmans

Korea

full-size prototype detector

Japan

Prof. Yuji Enari

FCC hh ee he

DREAM FOR FUTURE

USA

Prof. John Hauptman

Prof. Sarah Eno

Prof. Chris Tully

Europe

Prof. Paolo Giacomelli (Bologna)
Prof. Romualdo Santoro (Insubria)
Prof. Roberto Ferrari (Pavia)
Prof. Franco Bedeschi (Pisa)

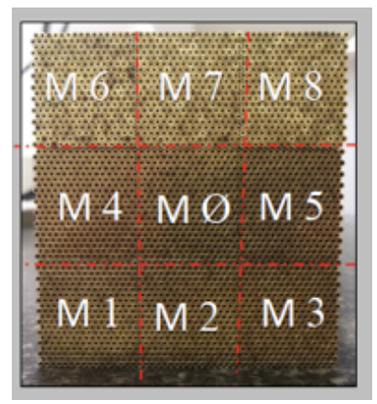
Prof. Iacopo Vivarelli

Prof. Valery Chmill

Big international collaboration for Dual-Readout Calorimeter is forming

- Regular meeting
- Compensated R&D options
- Combine efforts

Bucatini Project

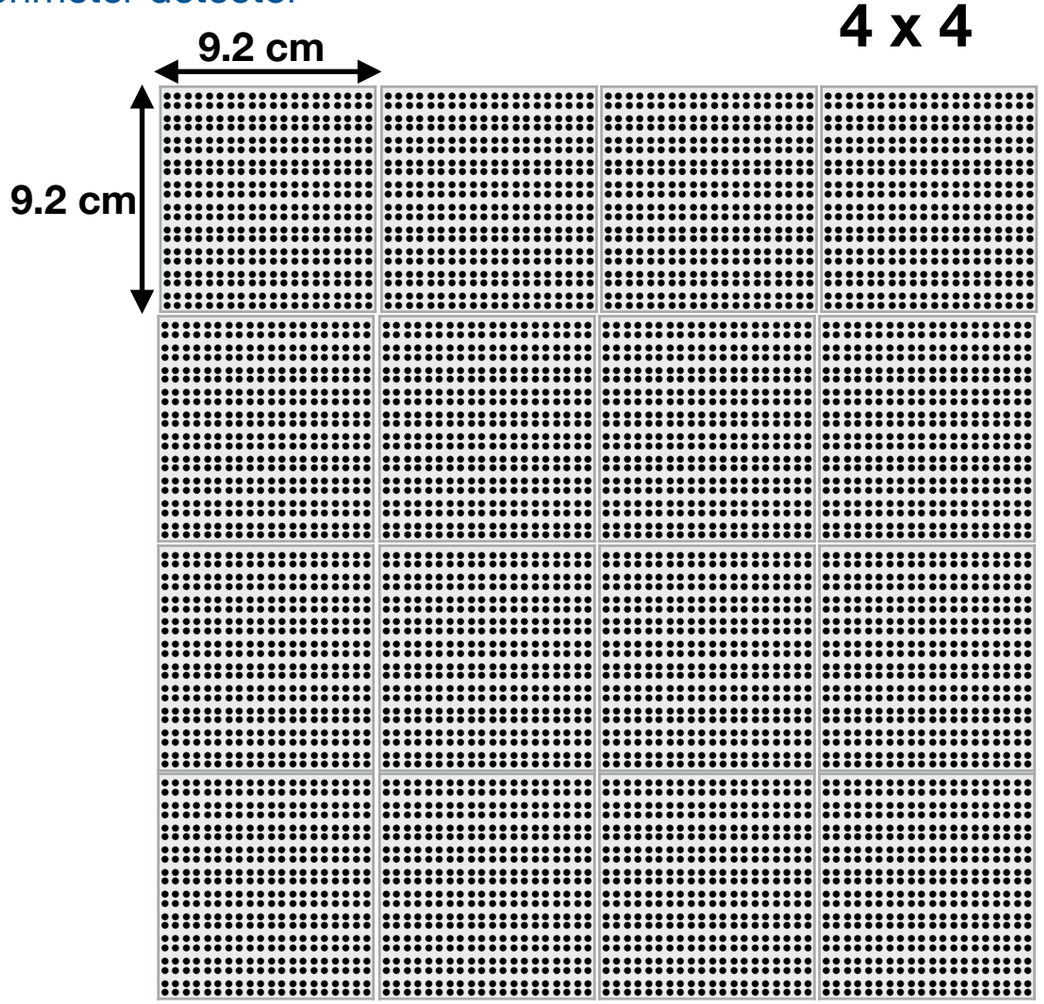


Goal of DRC R&D in Korea

- Primary goal: build a **prototype detector** for the detector design of FCC-ee experiment
  - 5 year R&D funding supported by Korea NRF: $2M for 5 years (2020 - 2025)
  - Consists of 16 modules (4 x 4): contain almost (97.5%) full hadronic shower energy
  - Demonstrate engineering aspects for full geometry detector
  - Optimize the performance of the detector
- Secondary goal: **train next generations** as an expert of (DRC) calorimeter detector

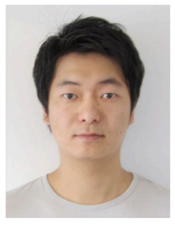
2017-9	2020-1	2022-5	TBD
Design	R&D	Prototype	Production

Stage	Topic
Design	Propose a design of Dual-Readout Calorimeter to IDEA detector concept
R&D	Perform R&D (including engineering aspects) based on HW & SW
Prototype	Build 4x4 detector and perform test beams
Production	TBD



Domestic Collaboration


H.S. Jo


S.H. Lee


S.W. Lee


H.D. Yoo

H.D. Yoo
DR Cal.

Steering Committee

Advisory Committee


J. Hauptman


R. Wigmans

S.K. Ha
Hardware

M.S. Ryu
Electronics

S. H. Ko
Software

ML

Cu forming
H.D. Yoo

Module
S.K. Ha

Fiber

Mechanical Support
S.W. Lee

SiPM
B.B. Kim

Readout
M.S. Ryu

Trigger/ DAQ
NOTICE Korea

Reco/pID
Y.J. Lee

GAN
J.S. Park
D.Y Kim

DD4HEP
S. H. Ko

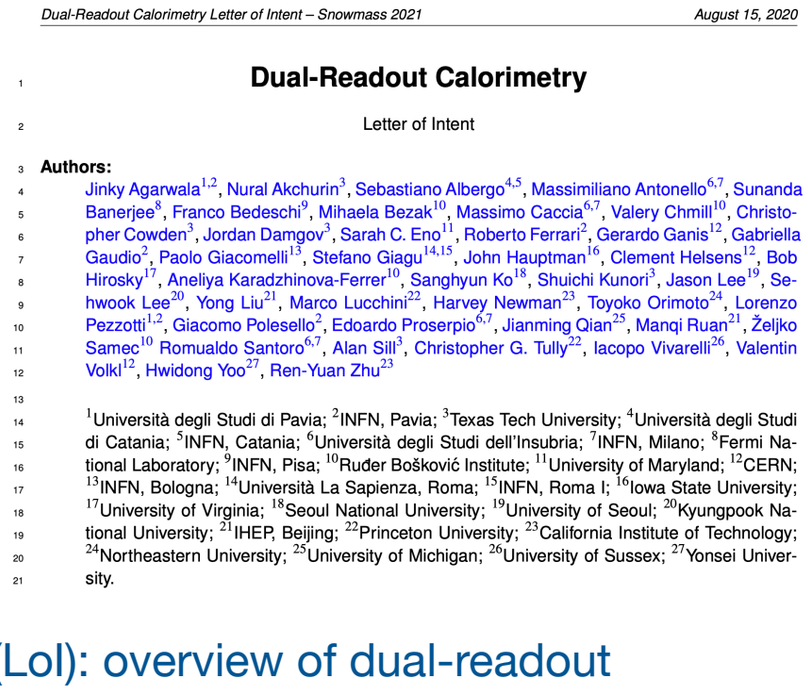
GEANT4
S. H. Ko

Performance
K.Y. Hwang
M.S. Kim

Magnetic Field
J.H. Lee

Snowmass21 (SM2021)

- Excellent opportunity to
  - Integrate US and world-wide research campaign
  - Collect new domestic members for DR Cal activity in Korea
  - Increase visibility our local activity to international colleagues



Dual-Readout Calorimetry Letter of Intent – Snowmass 2021 *August 15, 2020*

Dual-Readout Calorimetry

Letter of Intent

Authors:
Jinky Agarwala[1,2], Nural Akchurin[3], Sebastiano Albergo[4,5], Massimiliano Antonello[6,7], Sunanda Banerjee[8], Franco Bedeschi[9], Mihaela Bezak[10], Massimo Caccia[6,7], Valery Chmill[10], Christopher Cowden[3], Jordan Damgov[3], Sarah C. Eno[11], Roberto Ferrari[2], Gerardo Ganis[12], Gabriella Gaudio[2], Paolo Giacomelli[13], Stefano Giagu[14,15], John Hauptman[16], Clement Helsens[12], Bob Hirosky[17], Aneliya Karadzhinova-Ferrer[10], Sanghyun Ko[18], Shuichi Kunori[3], Jason Lee[19], Sehwook Lee[20], Yong Liu[21], Marco Lucchini[22], Harvey Newman[23], Toyoko Orimoto[24], Lorenzo Pezzotti[1,2], Giacomo Polesello[2], Edoardo Proserpio[6,7], Jianming Qian[25], Manqi Ruan[21], Željko Samec[10] Romualdo Santoro[6,7], Alan Sill[3], Christopher G. Tully[22], Iacopo Vivarelli[26], Valentin Volkl[12], Hwidong Yoo[27], Ren-Yuan Zhu[23]

[1]Università degli Studi di Pavia; [2]INFN, Pavia; [3]Texas Tech University; [4]Università degli Studi di Catania; [5]INFN, Catania; [6]Università degli Studi dell'Insubria; [7]INFN, Milano; [8]Fermi National Laboratory; [9]INFN, Pisa; [10]Ruđer Bošković Institute; [11]University of Maryland; [12]CERN; [13]INFN, Bologna; [14]Università La Sapienza, Roma; [15]INFN, Roma I; [16]Iowa State University; [17]University of Virginia; [18]Seoul National University; [19]University of Seoul; [20]Kyungpook National University; [21]IHEP, Beijing; [22]Princeton University; [23]California Institute of Technology; [24]Northeastern University; [25]University of Michigan; [26]University of Sussex; [27]Yonsei University.

- International dual-readout team prepared a single letter of interest (LoI): overview of dual-readout activities
  - https://www.snowmass21.org/docs/files/summaries/IF/SNOWMASS21-IF6-008.pdf
- Additional seven LoIs related to the dual-readout calorimeter R&D project have been submitted too!
- Various MC production such as multi-jets, Higgs and tau events are underway with GEANT4 + DD4hep infrastructure
  - Aim to deliver 1st set of MC samples during Nov.
  - If interest using our MC samples, please contact us! (hdyoo@cern.ch)

SM2021 with DRC in Korea

- Topic 1: Feasibility study of combining a MIP Timing Detector with the Dual-readout Calorimeter at future e+e- colliders (link)
  - Collaborators: D. Stuart (UCSB), C.S. Moon (KNU), J.H. Yoo (Korea Univ.)
- Topic 2: Heavy flavor tagging using machine learning technique with silicon vertex detector and Dual-Readout Calorimeter at future e+e- colliders (link)
  - Collaborators: J. Huang (BNL), Q. Hu (LLNL), S.H. Lim (PNU)
- Topic 3: tau reconstruction and identification using machine learning technique with Dual-Readout Calorimeter at future e+e- colliders (link)
  - Collaborators: M. Murray (U. of Kansas), Y.S. Kim (Sejong Univ.), Y.J. Kwon (Yonsei Univ.)
- Topic 4: Sensitivity study of H->Zγ with Dual-Readout Calorimeter at future e+e- colliders (link)
  - Collaborators: Y. Maravin (Kansas State Univ.), K.W. Nam (Kansas State Univ.)
- Topic 5: Multi-object identification with Dual-Readout Calorimeter at future e+e- colliders (link)
  - Collaborators: P. Chang (UCSD)
- Topic 6: Dual-Readout Calorimeter for the future Electron-Ion Collider (link)
  - Collaborators: S.H. Lim (PNU), H.S. Jo (KNU), Y.S. Kim (Sejong Univ.)
- Topic 7: Fast optical photon transport at GEANT4 with Dual-Readout Calorimeter at future e+e- colliders (link)

Feasibility study of combining a MIP Timing Detector with the Dual-Readout Calorimeter at future e^+e^- colliders

J.H. Yoo[1], S.W. Lee, C.S. Moon[2], S.H. Ko[3], D. Stuart[4], S.H. Lee[5], and J.W. Park, H.D. Yoo *[6]

[1]Korea University, Republic of Korea
[2]Kyungpook National University, Republic of Korea
[3]Seoul National University, Republic of Korea
[4]University of California, Santa Barbara, USA
[5]University of Seoul, Republic of Korea
[6]Yonsei University, Republic of Korea

August 30, 2020

Heavy flavour tagging using machine learning technique with silicon vertex detector and Dual-Readout Calorimeter at future e^+e^- colliders

J. Huang[1], Q. Hu[2], S.H. Lim[3], S.H. Lee, Y.J. Lee[4], and S.W. Kim, H.D. Yoo *[5]

[1]Brookhaven National Laboratory, USA
[2]Lawrence Livermore National Laboratory, USA
[3]Pusan National University, Republic of Korea
[4]University of Seoul, Republic of Korea
[5]Yonsei University, Republic of Korea

August 31, 2020

τ reconstruction and identification using machine learning technique with Dual-Readout Calorimeter at future e^+e^- colliders

Y.S. Kim[1], M. Murray[2], and K.H. Kim, Y.J. Kwon, H.D. Yoo *[3]

[1]Sejong University, Republic of Korea
[2]University of Kansas, USA
[3]Yonsei University, Republic of Korea

August 30, 2020

Sensitivity study of $H \to Z\gamma$ with Dual-Readout Calorimeter at future e^+e^- colliders

K.W. Nam, Y. Maravin[1] and H.D. Yoo *[2]

[1]Kansas State University, USA
[2]Yonsei University, Republic of Korea

August 30, 2020

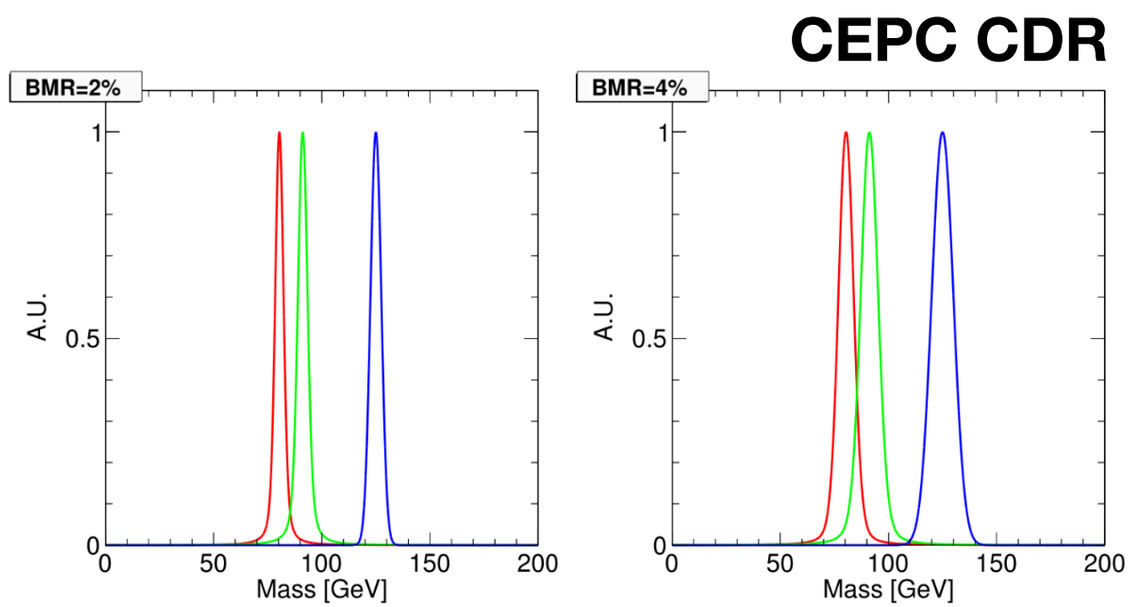
Multi-object identification with Dual-Readout Calorimeter at future e^+e^- colliders

P. Chang[a], S. K. Ha[b], K. Y. Hwang[b], H. D. Yoo[b]

[a]*University of California San Diego, USA*
[b]*Yonsei University, Republic of Korea*

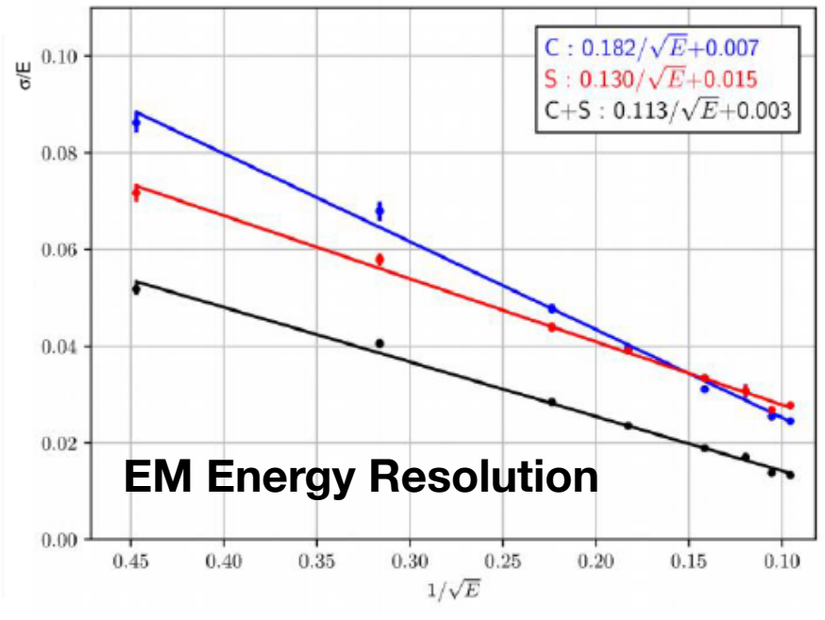
What Physics with DRC

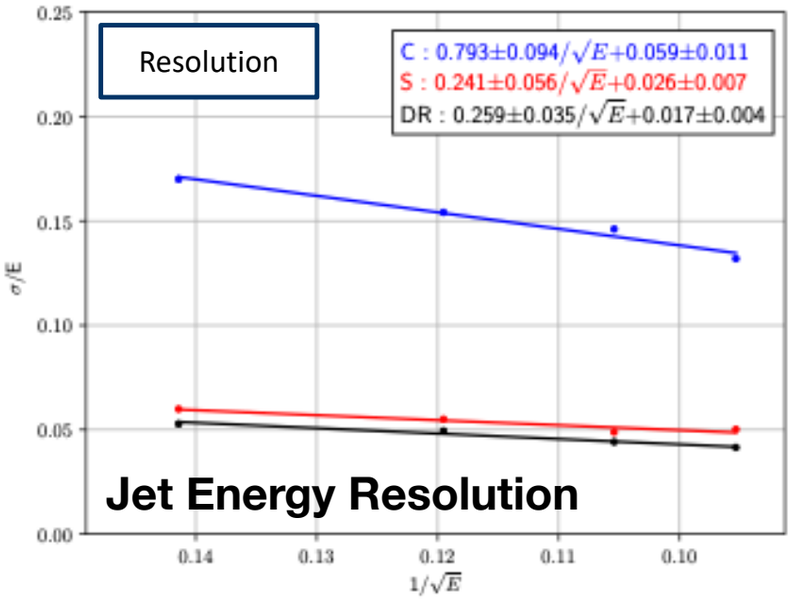
- Considerable physics objects with DR Cal: (for example) Higgs->gg, bb, cc, ττ, γγ, Zγ, ZZ, WW, invisible
- Physics object goals
  - Hadronic channel
    - W/Z/H mass separation: energy resolution 3-4% level
    - 5D information: energy + hit (3D) + timing
  - Excellent jet flavour tagging
    - Need a co-work with VTX (tracking) detector R&D group
    - Discriminate quark (u, b, c) and gluon jets with ML
  - Tau channel
    - Clear separation gamma and pi^0 reconstruction
    - Collimated topologies: separate gamma from close to hadronic showers
  - Related PID is quite important
- Need to check all necessary detector requirement for each physics topics (objects)

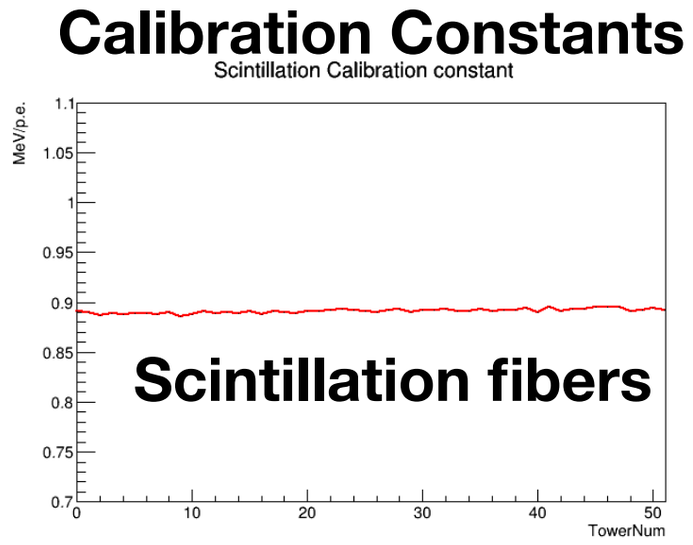


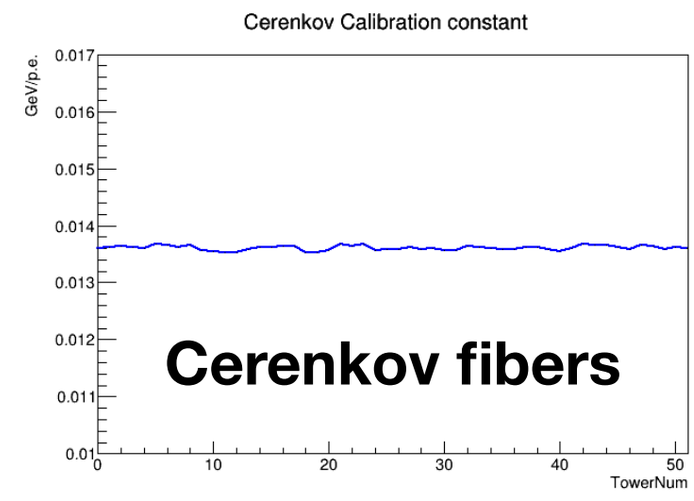
Energy Resolution

- Production of calibration constant with full GEANT4 simulation is on-going
  - Both barrel and endcap have been done
- Excellent EM and hadronic energy resolutions obtained by GEANT4 simulation
  - EM energy resolution: ~11%/sqrt(E)
  - Jet energy resolution: ~26%/sqrt(E)





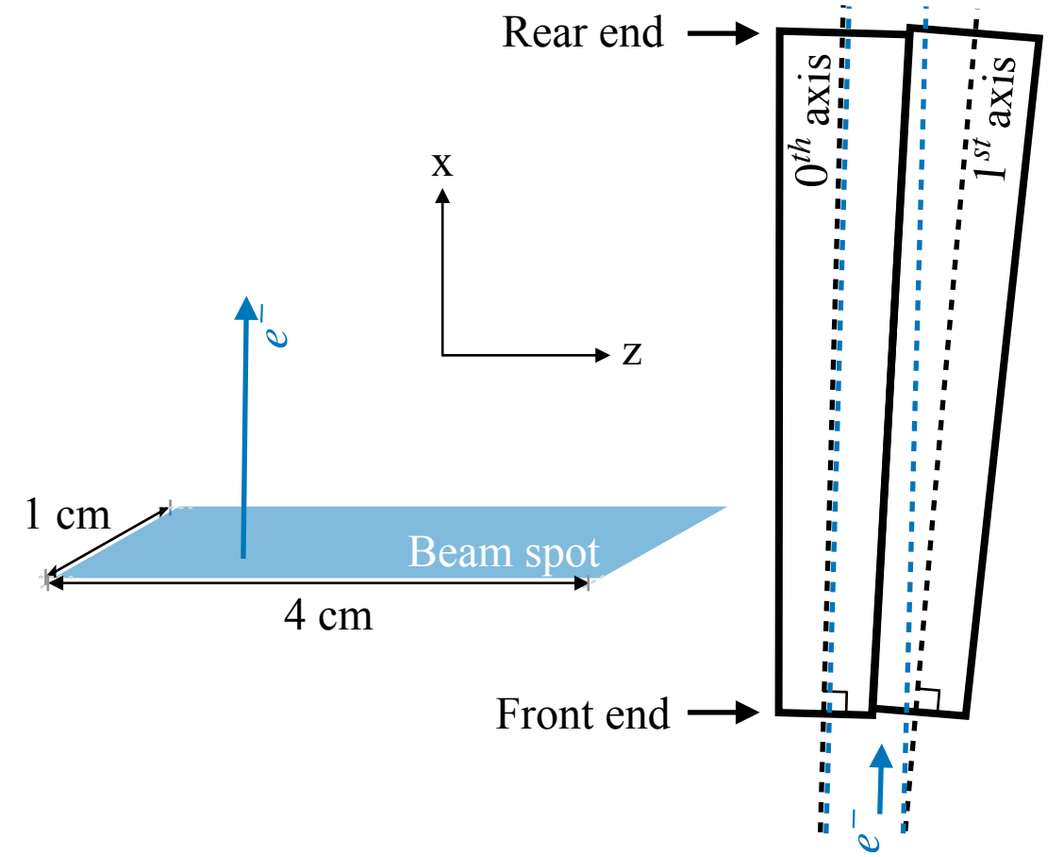


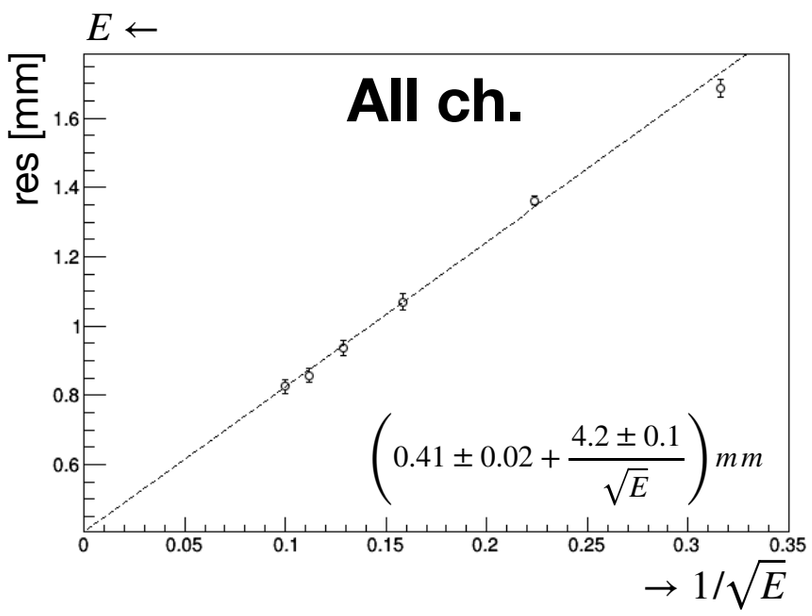


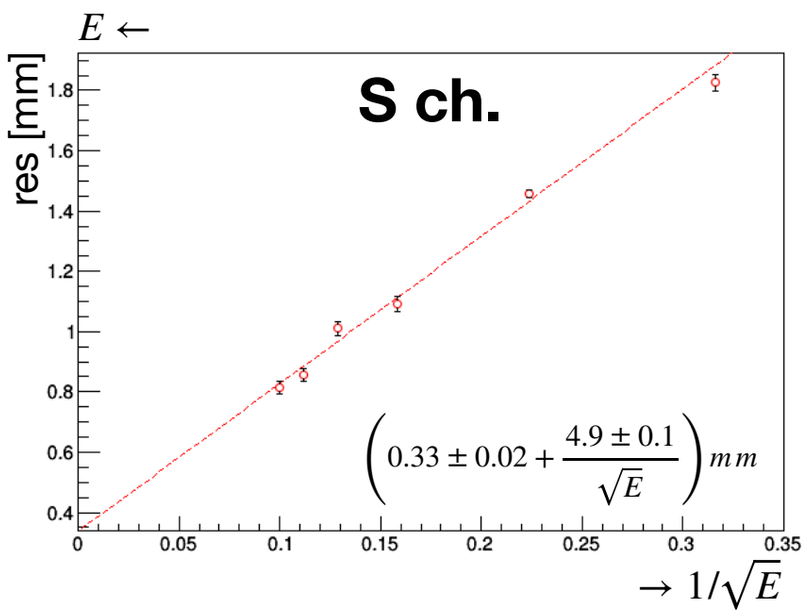
Tower #

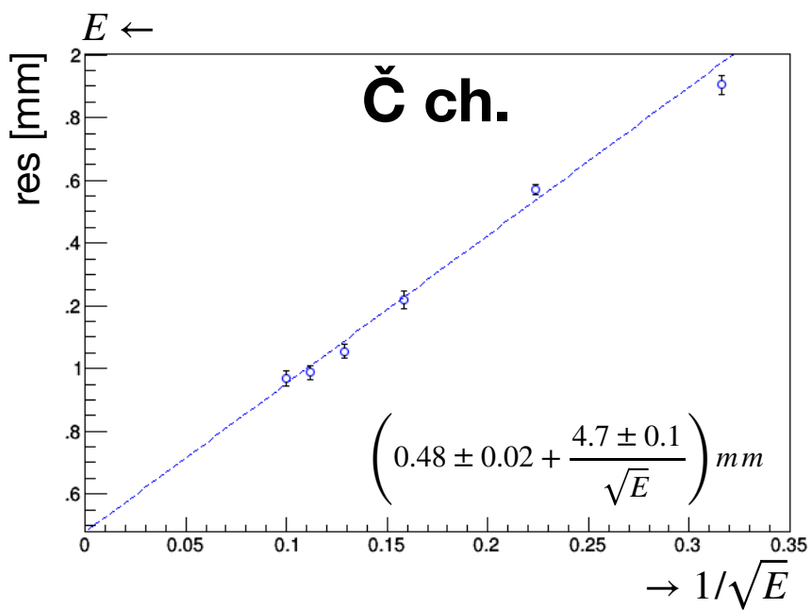
Position Resolution

- Tested by e^- beams of 6 different energies
  - 10, 20, 40, 60, 80 and100 GeV
- Position reconstructed by center of gravity of energies and compared with generated position
  - $\vec{x}_{reco} = \frac{\sum_i E_i \times \vec{x}_i}{\sum_i E_i}, i : \#\text{SiPM}$
- Preliminary position resolution:
  - $4.2\ \text{mm}/\sqrt{E} + 0.4\ \text{mm}$









DD4hep Migration

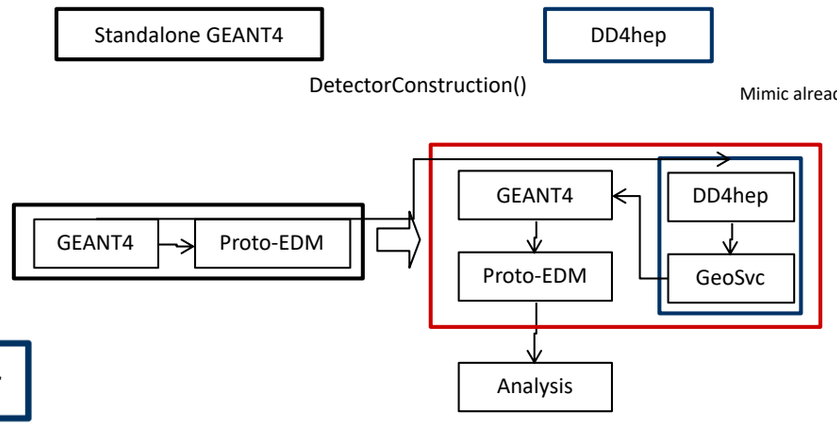
- Migrate dual-readout simulation framework to dd4hep

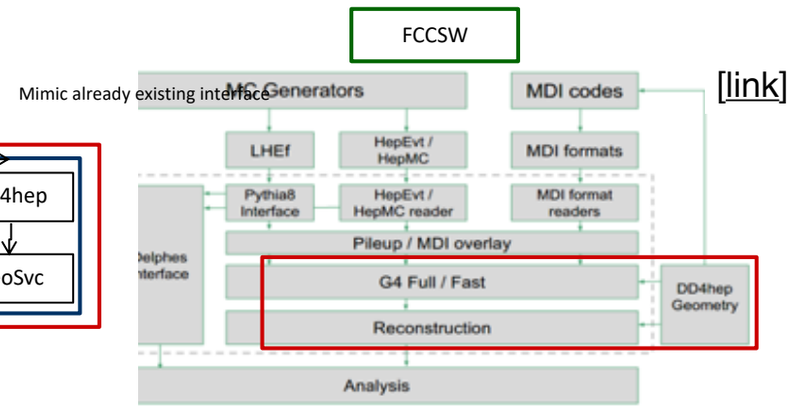
More details: S.H. Ko's talk in FCC workshop (link)

  - DD4hep is the next-generation standard of detector description

- Preliminary version is already provided to FCCSW team

  - Good agreement with GEANT4





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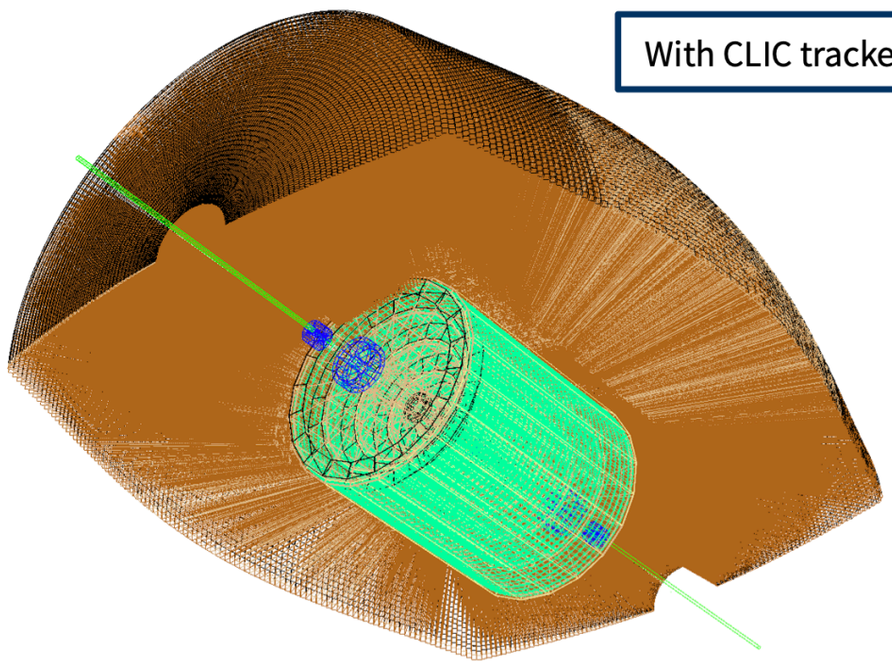
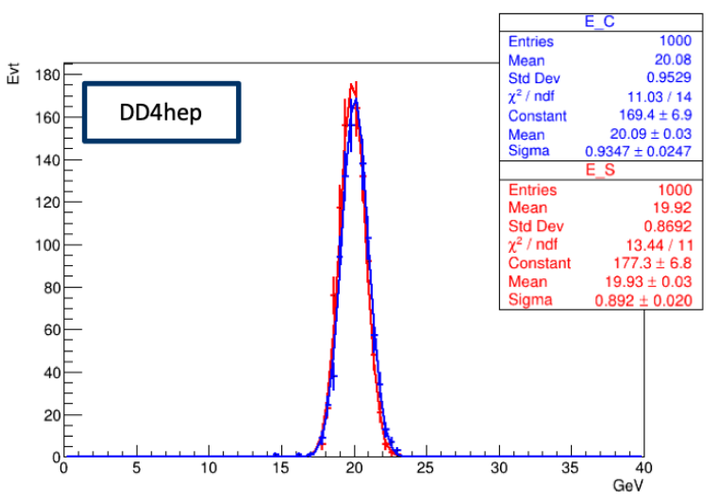
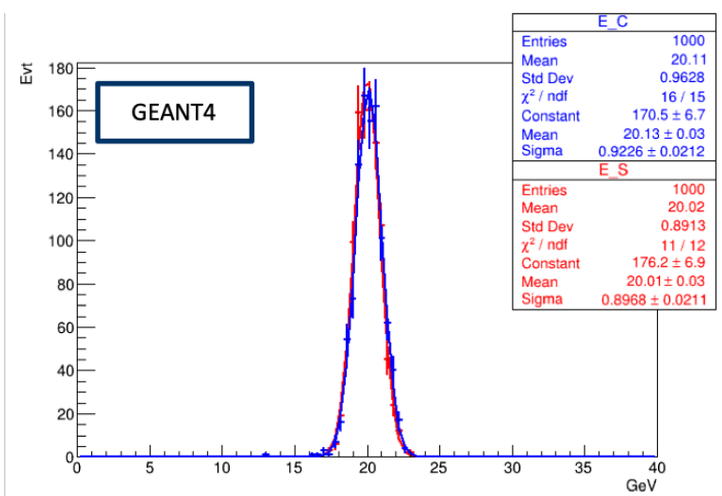






MC Taskforce in Korea-DRC

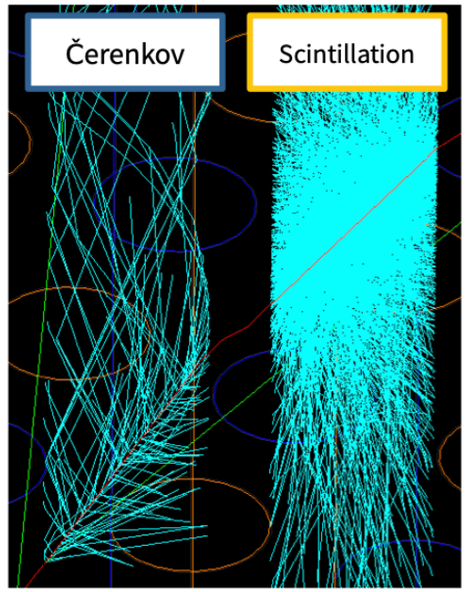
- Technical goal in our team: develop a proper MC sample infrastructure with the DRC R&D project
    - Practical goal for SM2021: provide physics MC samples with full GEANT4 simulation of the DRC detector (for the IDEA detector) to user groups
- We will help users can study the physics sensitivity under much more realistic experimental environment

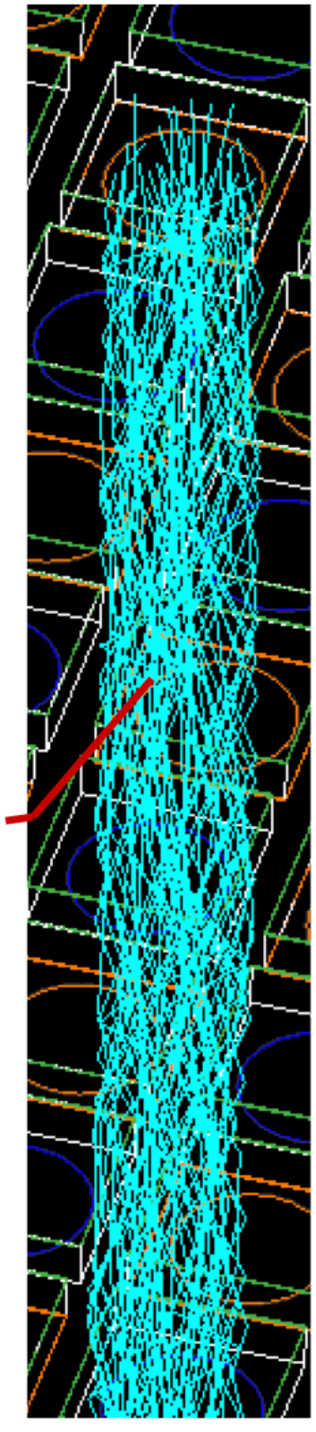
MC production checklist

	Mendatory	Multi-jet	H→Zγ	τ
GEN-lv	Matrix-element (H, Z, W, τ) kinematics (Pt, η, φ)	Parton kinematics	Fermion(Z→ff) & γ kinematics	τ decay particle kinematics
	Matrix-element particle mass	Mono-boson invariant mass, Pt	Z boson invariant mass, Pt	τ invariant mass, Pt
	MET kinematics	Di-boson invariant mass, Pt	H invariant mass, Pt	τ branching fraction
				Final state lepton kinematics (leptonic channel)
				Kinematics with Fastjet clustering (hadronic channel)
SIM-lv	Total energy deposit			Energy deposit with Fastjet clustering
	MET kinematics			
RECO-lv	S, C, DR energy			S, C energy with Fastjet clustering

(Semi-)Fast Simulation

- Full GEANT4 simulation of optical photon tracking explodes CPU cost: O(h)/evt
  - Developing fast simulation for optical photon tracking (7th LoI): O(few mins)/evt

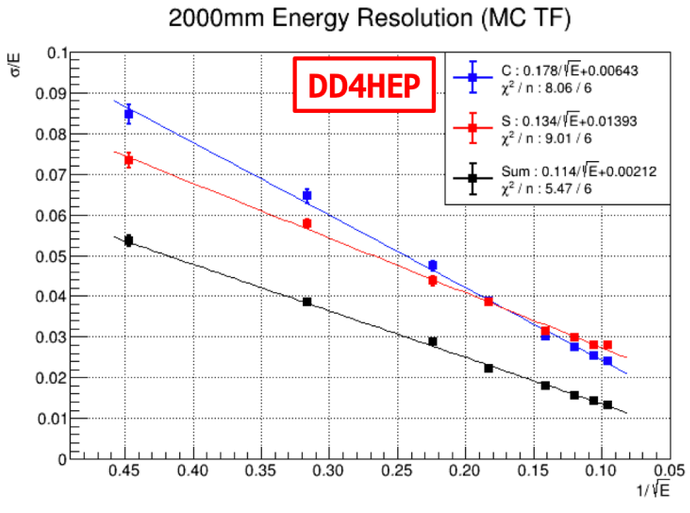


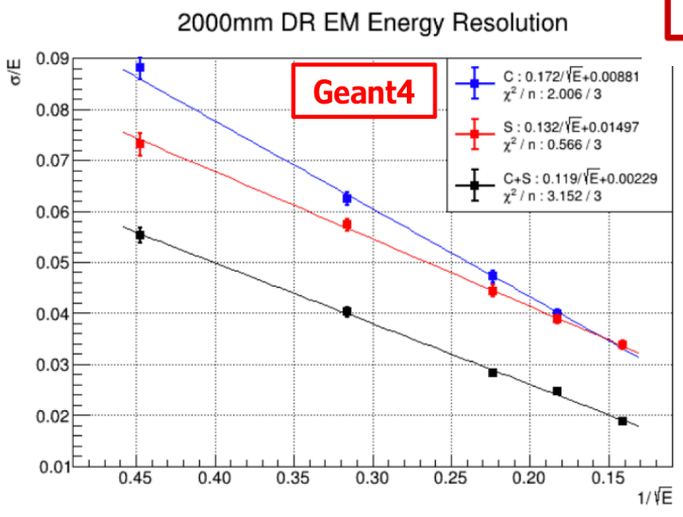


Important for a longitudinally unsegmented calorimeter

- Excellent consistencv of the detector

EM validation





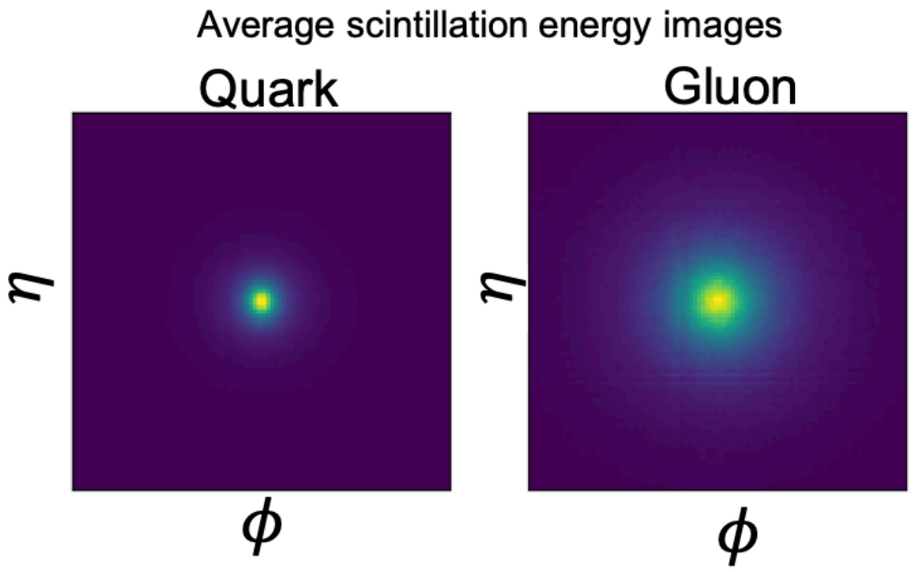
- 2000mm Wedge geometry EM energy resolution is measured with 5 different energy electron beams.
- Stochastic terms of energy resolutions are similar.

More details: S.H. Ko's talk in FCC workshop (link)

ML-based Application

- ML will be used widely in dual-readout calorimeter R&D

More details:
Y.J. Lee's talk
in CEPC workshop
(link)



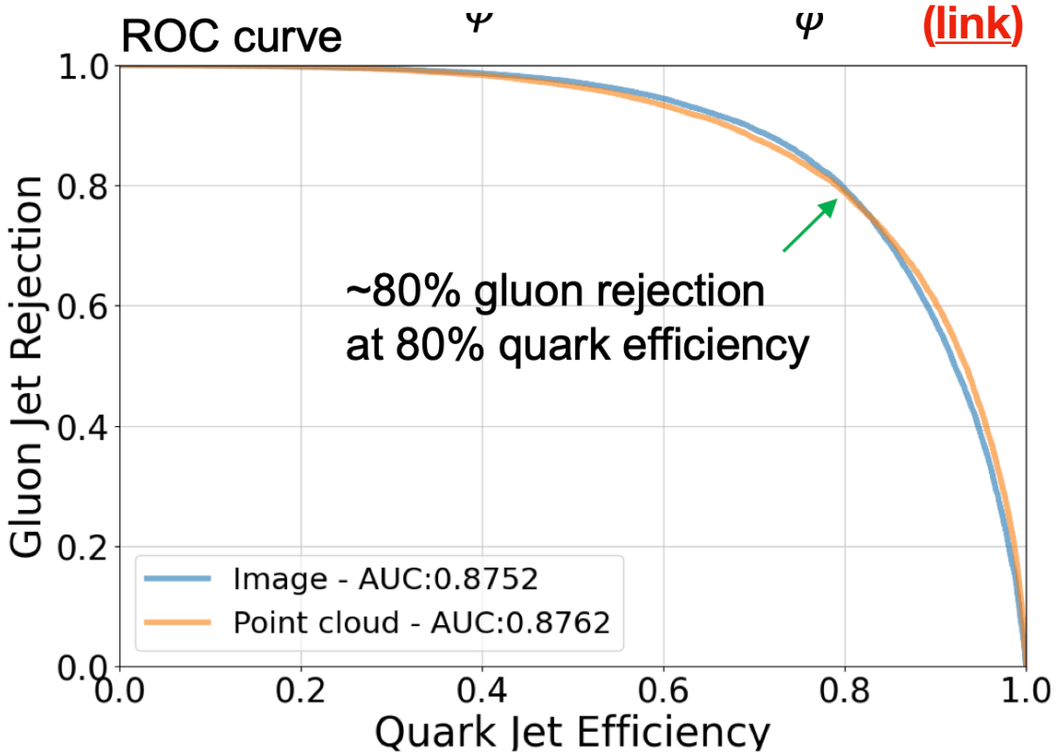
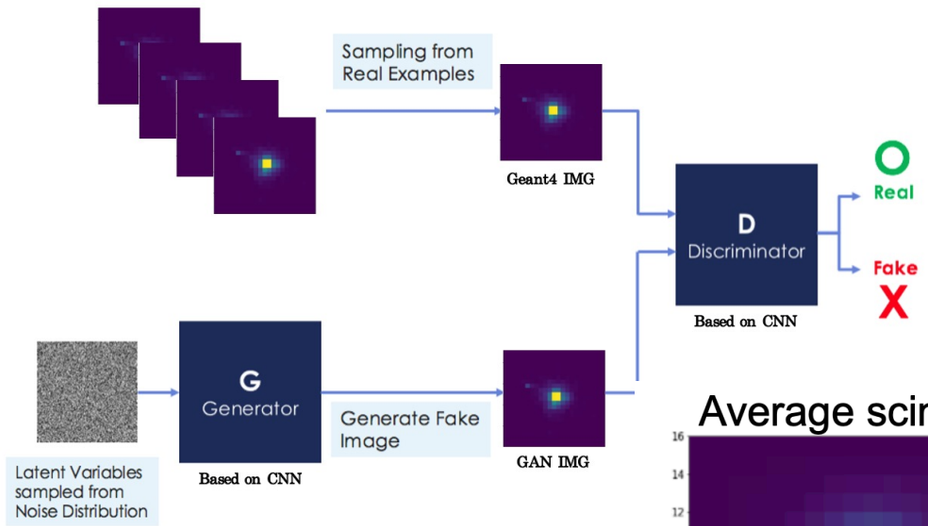
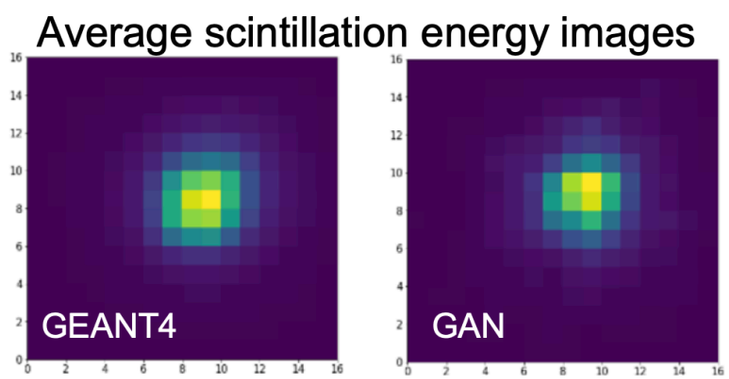
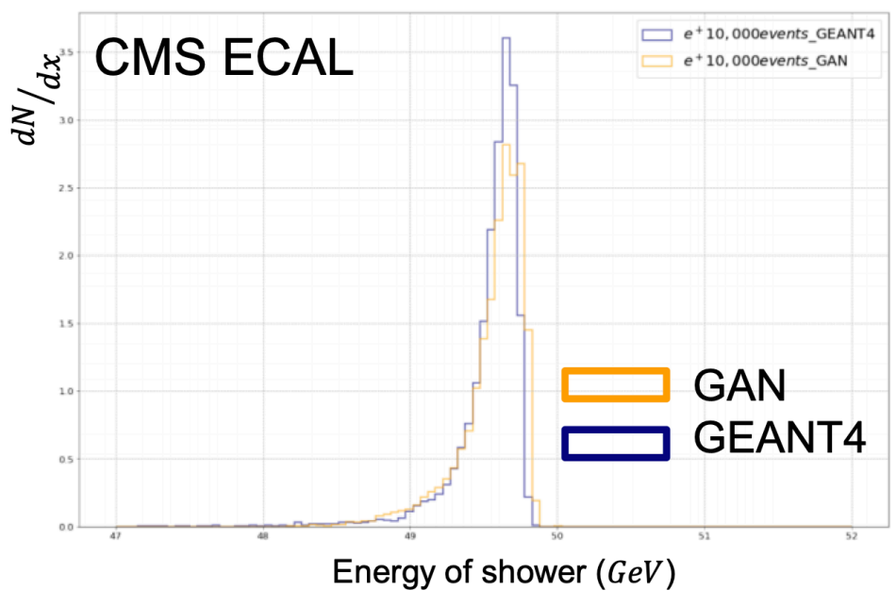


Image data format under development





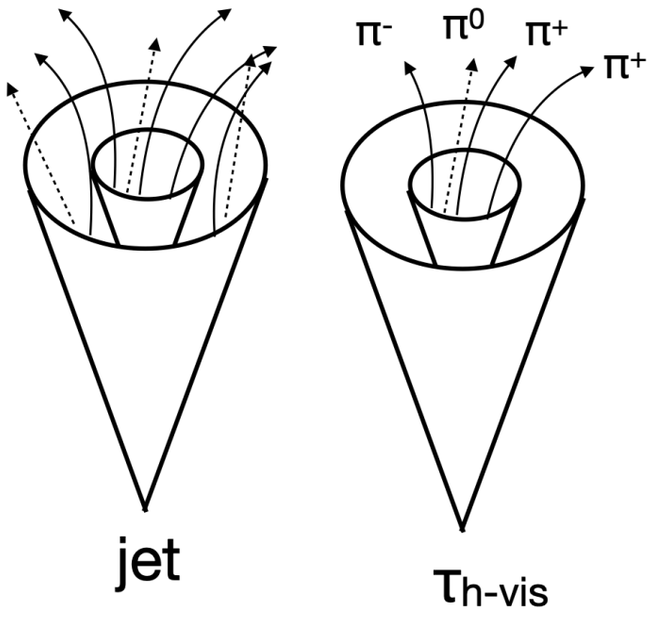


Tau Reconstruction

- Goal: build a baseline reconstruction algorithm for the tau for both leptonic and hadronic decays

  - Discriminant identification from major backgrounds such as quark or gluon jets, isolated electrons or muons

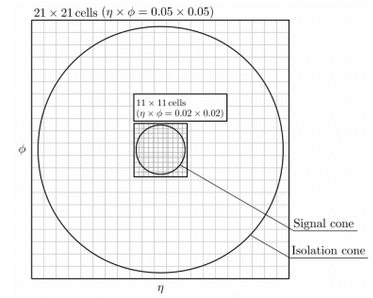
- Will apply deep ML technique such as multi class DNN for efficient identification

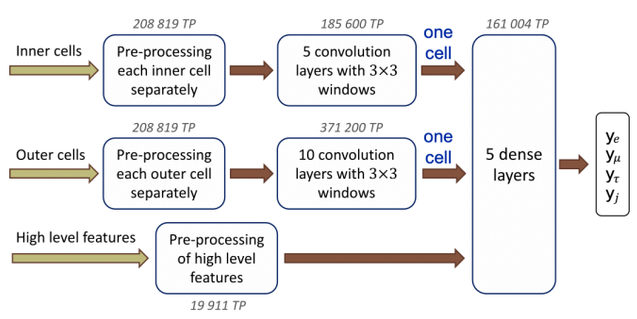


CMS τ_h identification: DeepTau

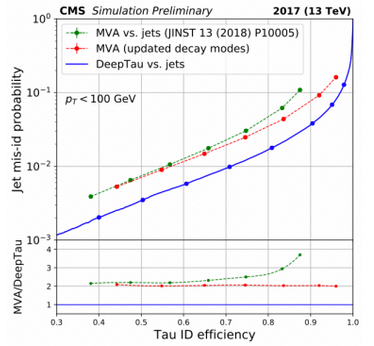
DeepTau algorithm

- deep neural network
- multiclassifier into τ_h, μ, e, or jet probabilities
- input:
  - high level variables similar to BDT
  - hadron/μ/e/γ information in $\eta\times\varphi$ cells of τ_h
- outperforms BDT



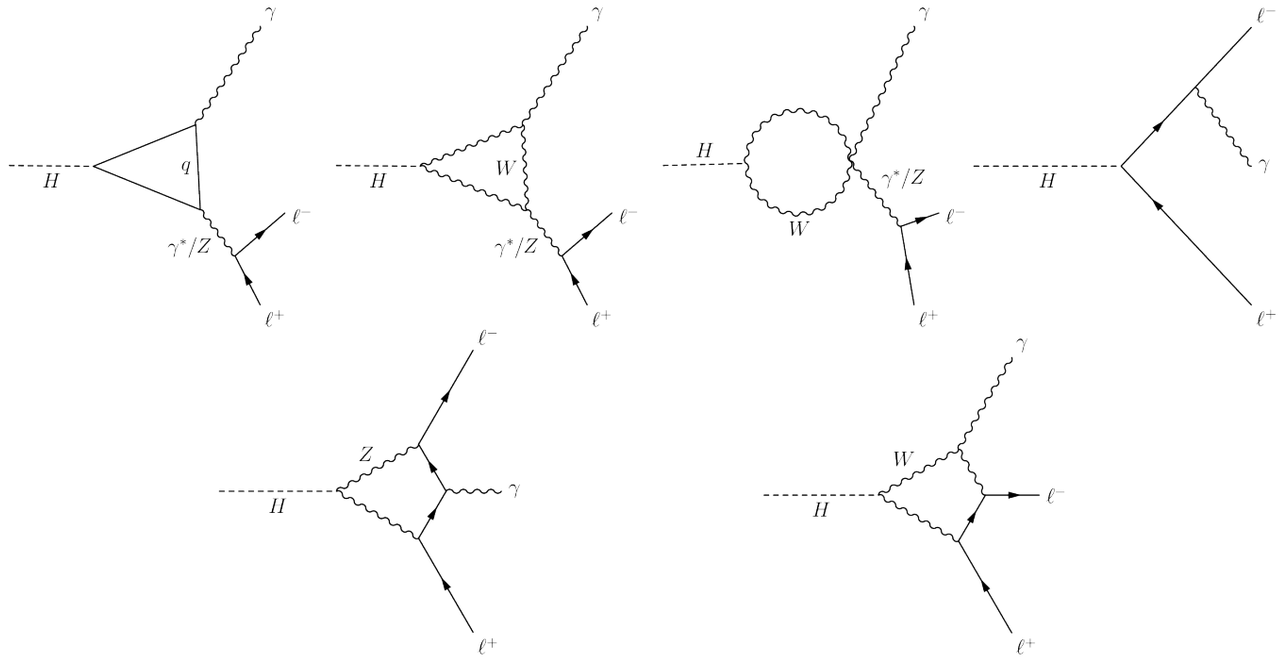


TP = trainable parameter



H→Zγ Study

- Goal: reconstruct the Higgs and Z bosons under the process of H→Zγ in hadronic channel
  - Excellent physics case to study the response of the DRC for both EM and hadronic particles
  - Multi-jet reconstruction & identification can be also studied



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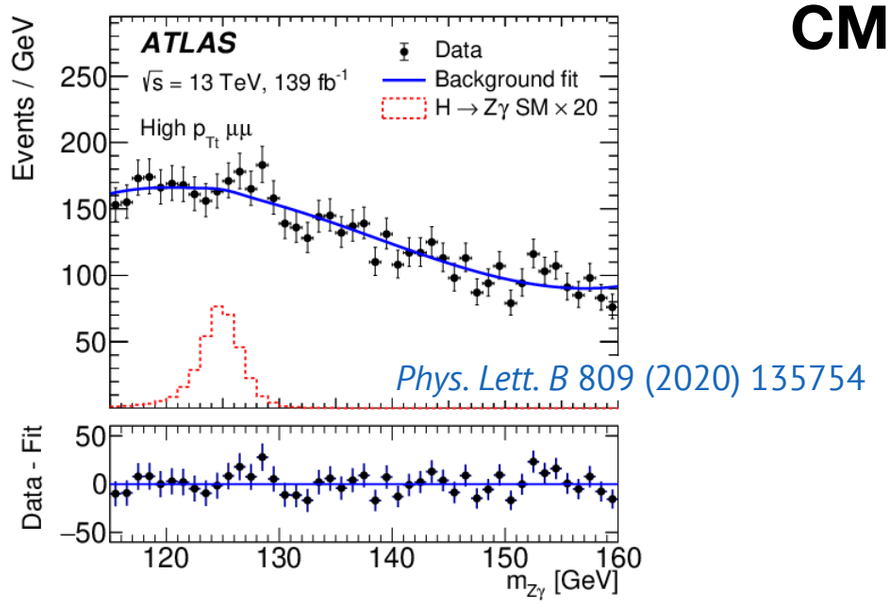

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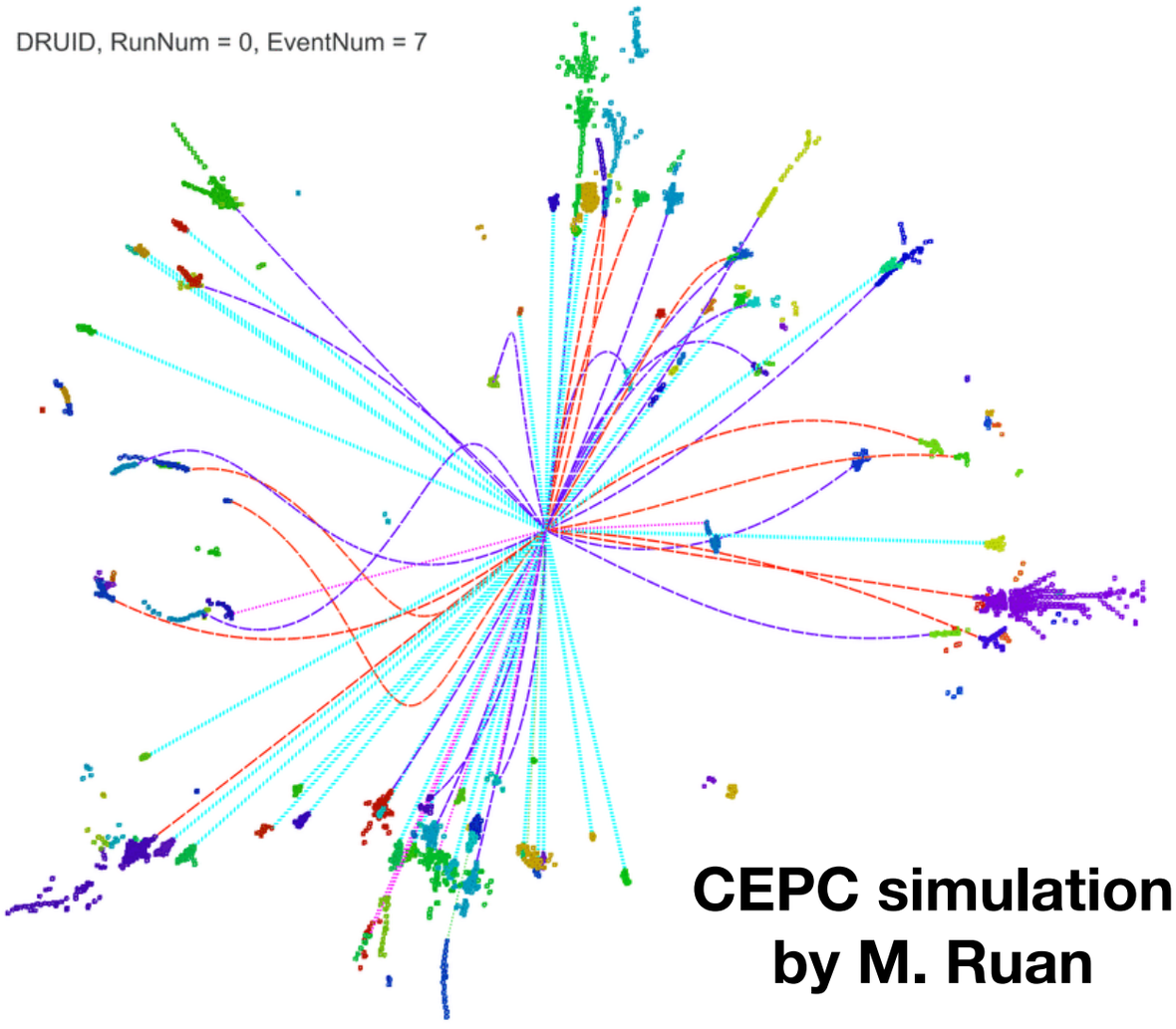
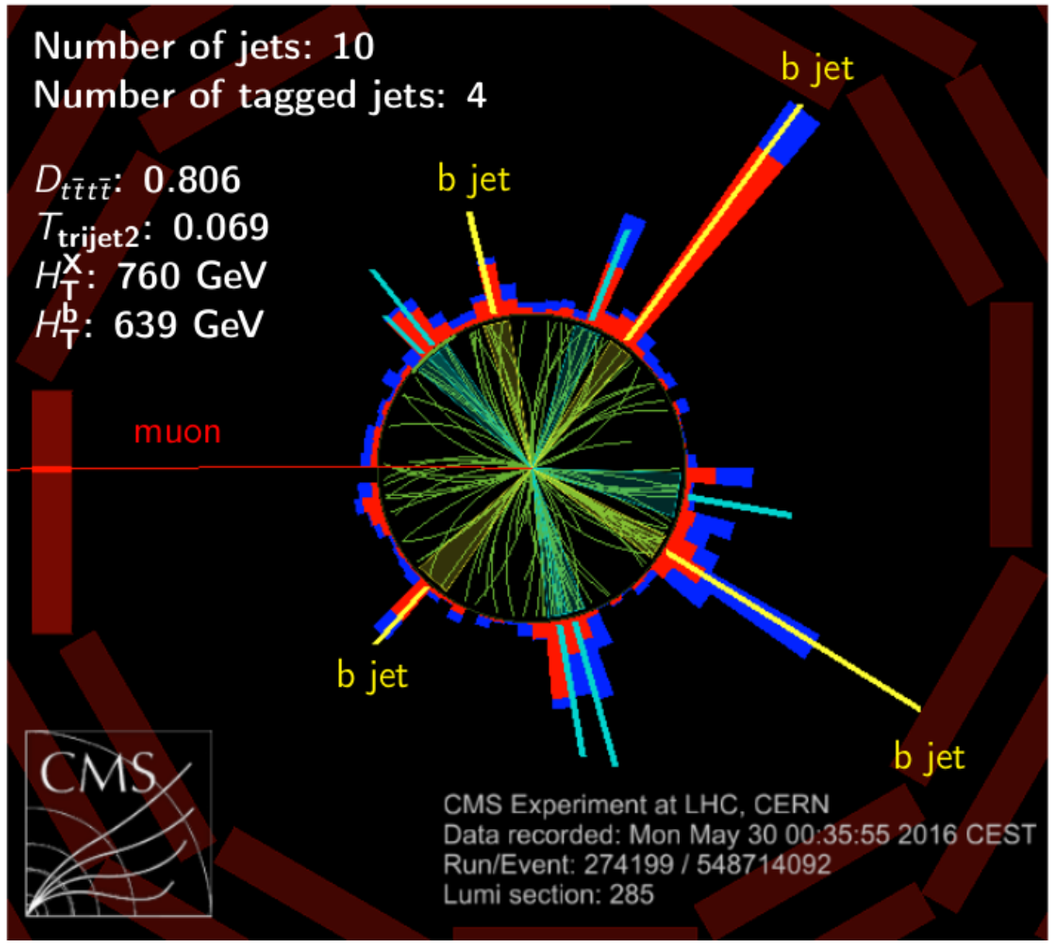
Multi-jet Reconstruction

- Goals
  - Reconstruct and identify multi-jet candidates from ZH, ttbar, diboson processes
  - Assess the impact of high-quality jet energy resolution from DRC with ML technique
  - Vary jet energy resolution and study the impact



CEPC simulation by M. Ruan



Computing Facilities

- Need huge resources for CPU and storage to perform full GEANT4 simulation
  - Due to full optical photon simulation for scintillation and Cerenkov fibers
- Current available resources: maximum 700 CPUs are available for our study!
  - KISTI: 150 cores under condor configuration
    - Additional 150 cores will be provided at Fall
  - KNU: 100-200 cores supported by supercomputing center
  - UoS: 100-200 cores supported by supercomputing center
  - SNU: ~150 cores available

Summary

- Dual-Readout Calorimeter R&D project for future e^+e^- collider in Korea is very active
  - 4x4 prototype detectors for next 5 years
  - Various simulation studies for performance and ML applications are on-going with huge computing facilities
- Various Snowmass21 studies are very active
  - Totally seven LoIs have been submitted with new domestic and US collaborators
  - Groups are formed with new domestic collaborators from ALICE, BELLE(II), and CMS members in Korea
- All members and colleagues are **very young group** (students, young postdocs, faculties)!
  - Very promising future of Korea HEP group

Pictures from our brilliant students… and many more people!

Doyoung Kim

Yun Eo

Kyuyoung Hwang

Sanghyun Ko

Yunjae Lee

Minsoo Kim

Back Up