A Dual Readout Calorimeter for FCC-ee ?

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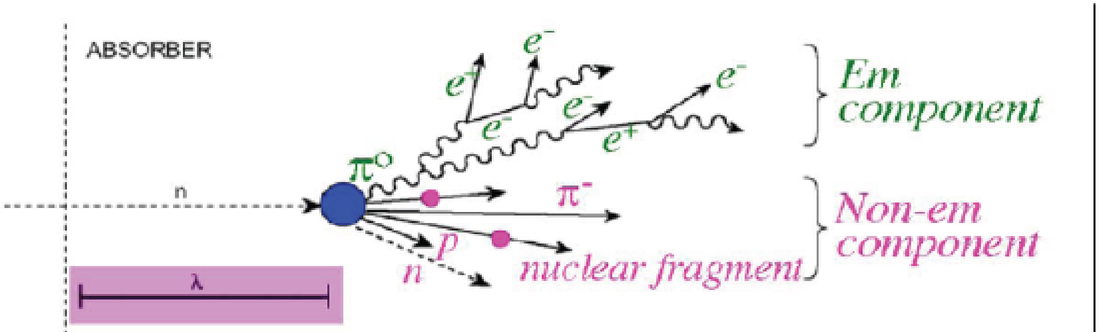
on behalf of the IDEA Dual-Readout Calorimeter Collaboration
January, 21st 2021

Dual-readout in a nutshell

electrons positrons, photons, π^0



Charged hadrons (π,k…), nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

Cherenkov light (C)	only produced by relativistic particles, dominated by electromagnetic shower component
Scintillation light (S)	measure dE/dx

Measure the electromagnetic fraction event by event to equalize the response off-line

- **Compensation** achieved without construction constraints
- **Calibration** of a hadron calorimeter just with electrons
- **High resolution** EM and HAD calorimetry

$$S = [\, f_{em} + (h/e)_s \times (1 - f_{em}) \,] \times E$$
$$C = [\, f_{em} + (h/e)_c \times (1 - f_{em}) \,] \times E$$

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

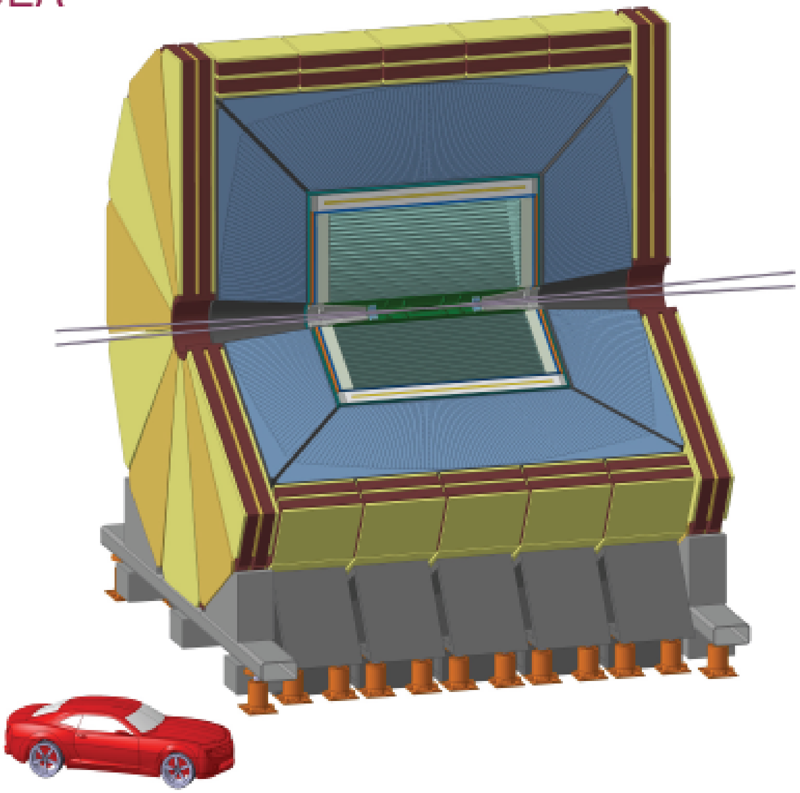
e/h ratios (c = $(h/e)_c$ and s = $(h/e)_s$ for either Cherenkov or scintillation structure) can be measured

Θ and χ are independent of both energy and particle type

It is possible to evaluate $f = \dfrac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$ and $E = \dfrac{S - \chi C}{1 - \chi}$

Dual-readout calorimeter: international collaboration

IDEA



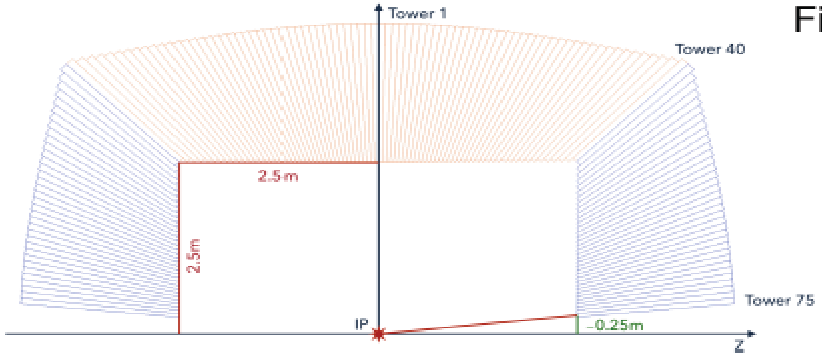
Innovative Detector for Electron-positron Accelerators

- Included in FCC and CepC CDRs
- Growing international collaboration in
  - **Europe**: **Croatia** (RBI), **UK** (Univ. of Sussex), **Italy** (INFN-BO, INFN-CT, INFN-PI, INFN-PV, Univ. of Insubria)
  - **Asia: Korea** (Kyungpook Univ., Seoul Univ., Univ.of Seoul, Yonsei Univ.)
  - **USA:** Iowa State Univ., Texas Tech Univ., Univ. of Meryland, Univ. of Princeton

idea-dualreadout@cern.ch

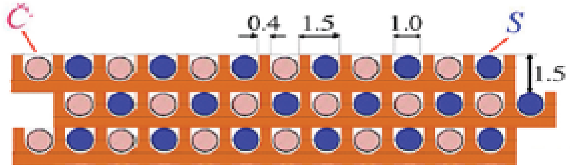
https://indico.cern.ch/category/10684/

Simulations for performance studies



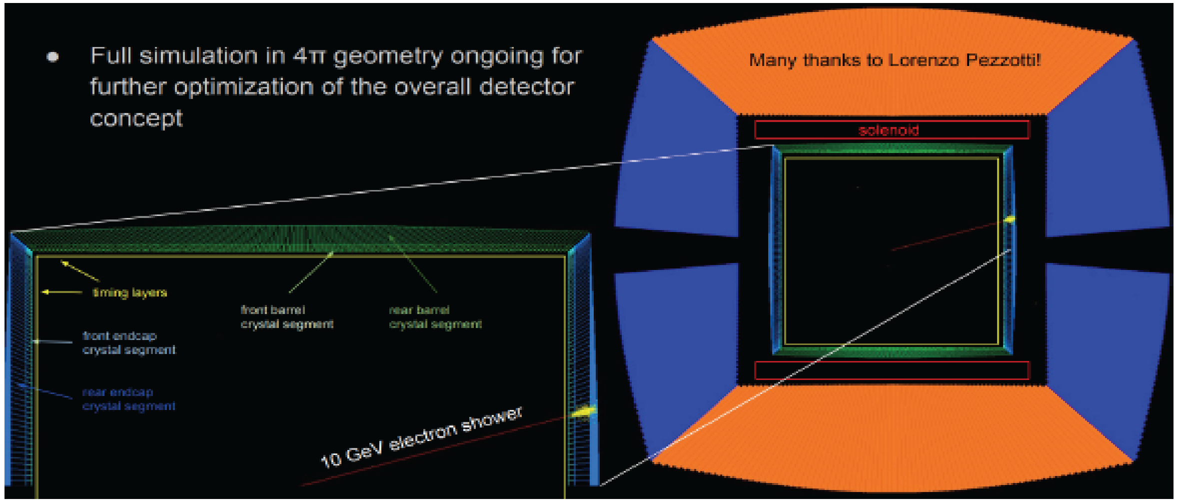
Fiber DR calorimeter

G4 standalone simulation



75 projective elements x 36 slices
Copper + scintillating and Cherenkov fibers

Fiber+crystal options



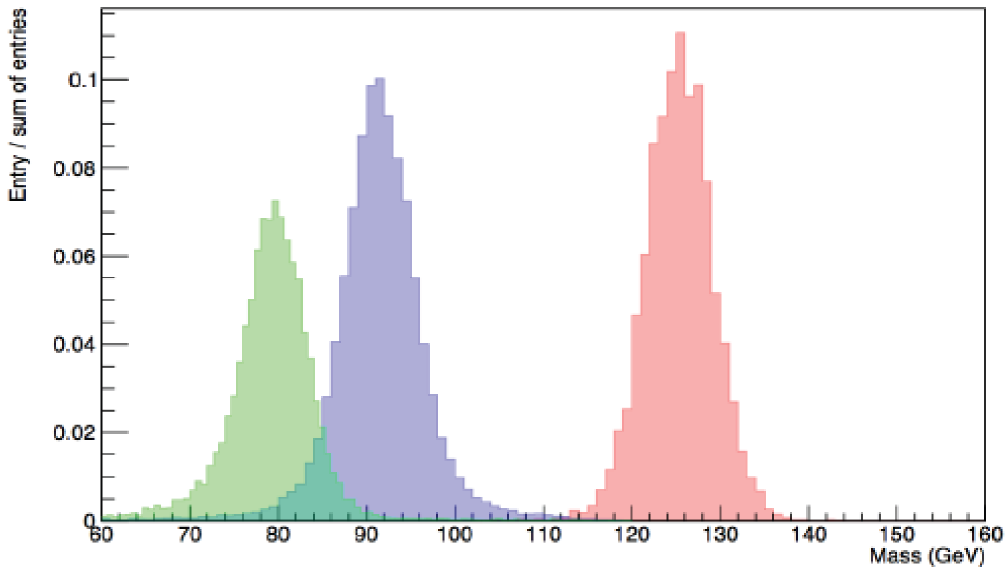
Jet generated with PYTHIA8, tuned to LEP measurement
Propagated in GEANT4 calorimeter
Obtain C and S response + (θ,ϕ) of the tower
Get jet 4-momenta
Clustering with FASTJET (Duhram kt algorithm)

$$e^+e^- \rightarrow HZ \rightarrow \tilde{\chi}^0\tilde{\chi}^0 jj$$

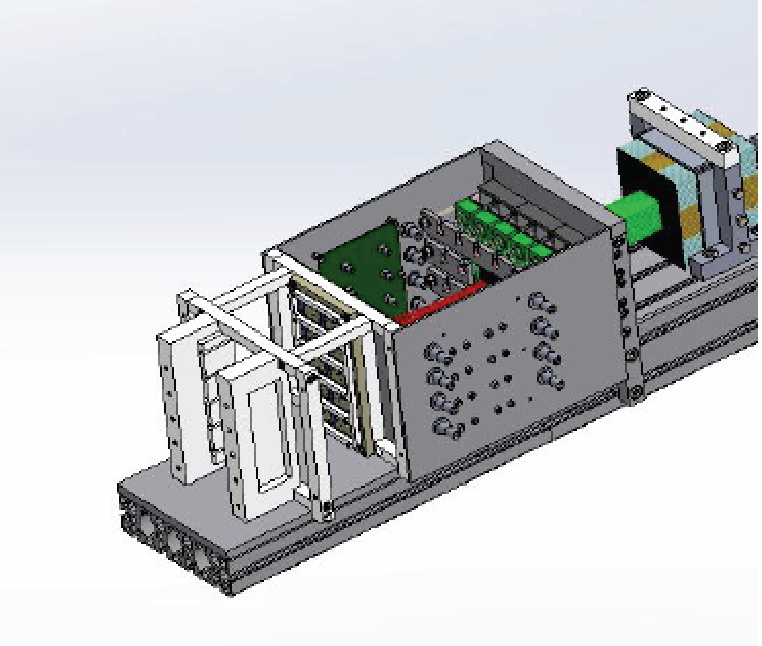
$$e^+e^- \rightarrow WW \rightarrow \nu_\mu \mu jj$$

$$e^+e^- \rightarrow HZ \rightarrow bb\nu\nu$$

PYTHIA8 + GEANT4 + FASTJET

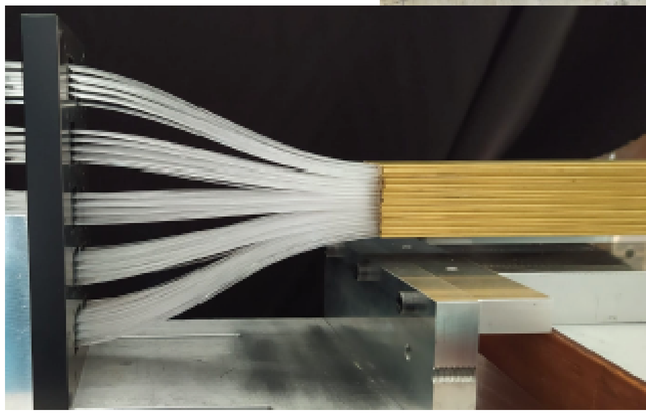


Capillary-tubes based prototype

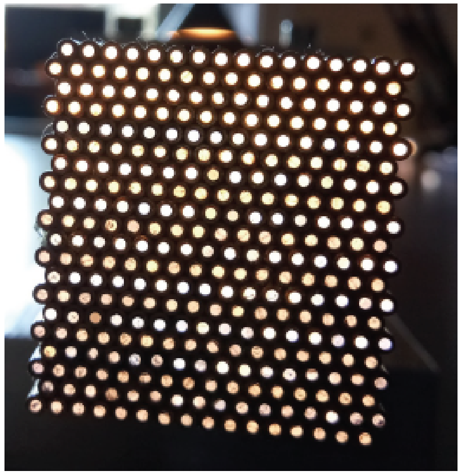


10x10 cm^2 divided in 9 towers, 1m long
16x20 capillary each (160 C + 160 S)

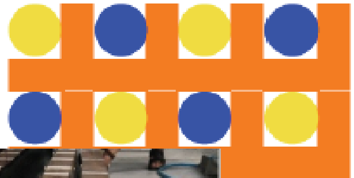
Capillary:
2mm outer diameter, 1mm inner diameter
Material: brass CuZn37



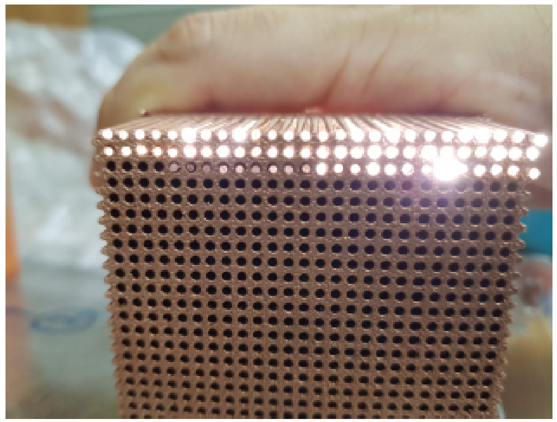
Readout:
- 1 central tower readout by SiPMs
- 8 surrounding towers readout by PMTs (à la RD_52)



Capillary-tubes calorimeter

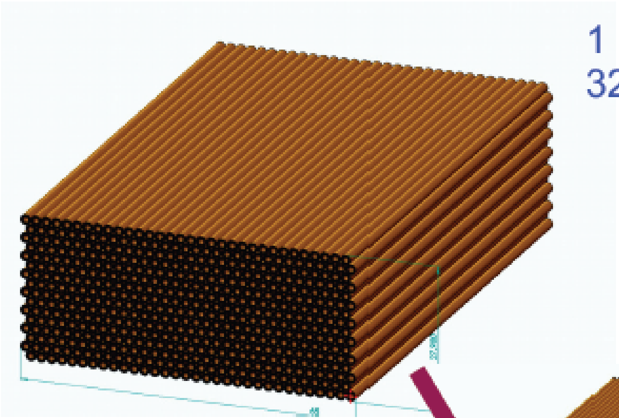


Plates-absorber calorimeter

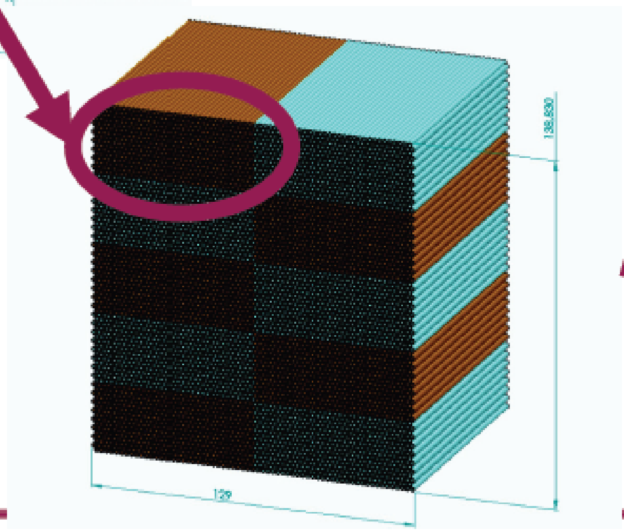


3D-printing matrix calorimeter

Capillary-tubes based calo



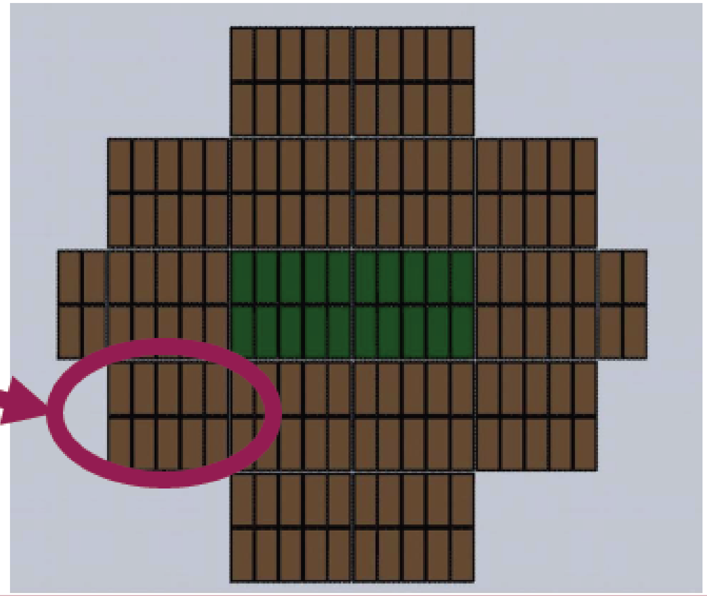
1 Mini-Module (MM):
32 x 16 channel (512 ch)



1 Module:
2 x 5 MMs
→ 10 FEE boards
(8-channel grouping)
~ 13 x13 x 200 cm³

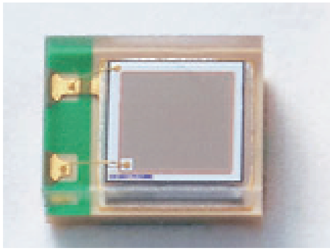
17 modules, ~ 65 x 65 x 200 cm³

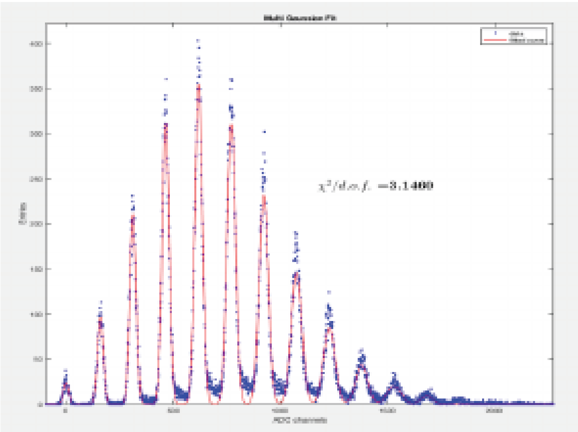
- 2 central modules with SiPMs
  → ~ 10 k SiPMs, ~ 20 FEE boards
- all others with PMTs
  → ~ 150 PMTs



SiPM - FEE-boards

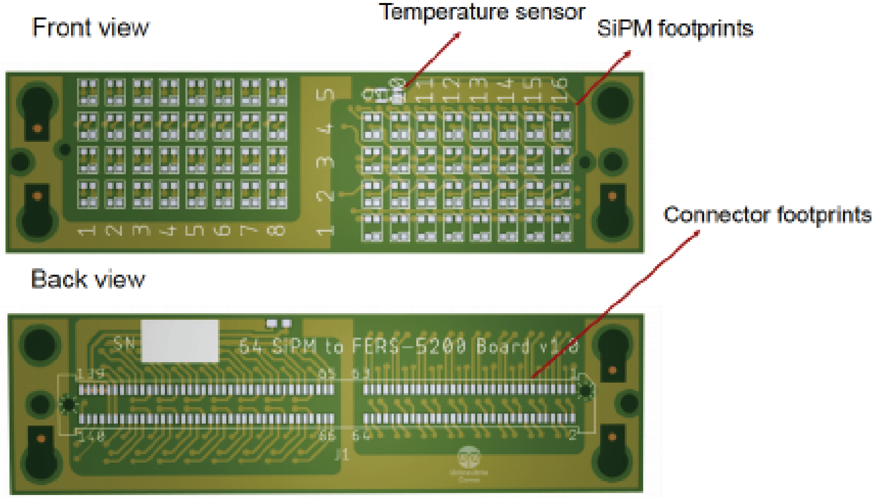
Sensor: S14160-1315PS
Cell size =15μm
Vbias = 42 (≈ 4 V over breakdown)
Signal amplification: 40dB
Measured Xtalk = 2%

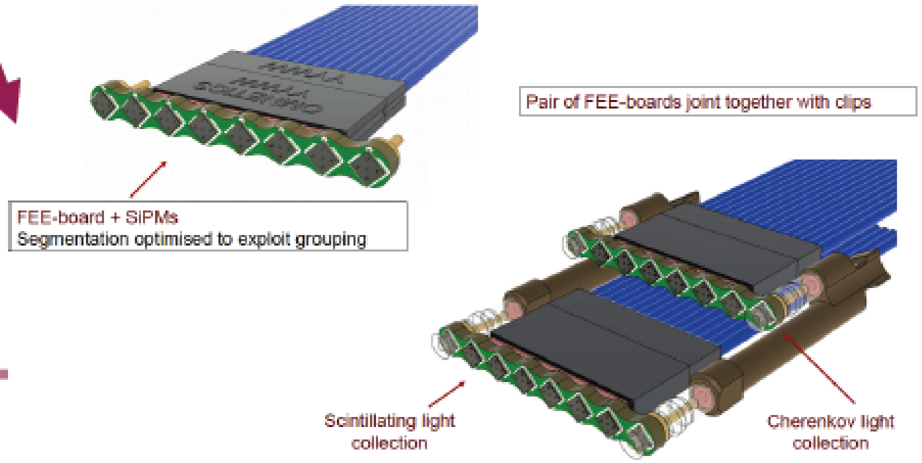




TB like

Toward experiment



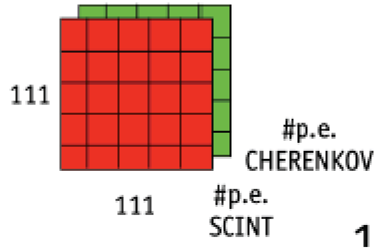


SiPM cell size is one of the crucial parameter to cope with saturation (linearity) in Scintillation channel

Machine-Learning approach

Reconstruct and identify particle is under development with promising results.

3-class label	8-class label	
0	0	$\tau \to \mu\nu\nu$
0	1	$\tau \to e\nu\nu$
1	2	$\tau \to \pi\nu$
1	3	$\tau \to \pi\pi^0\nu$
1	4	$\tau \to \pi\pi^0\pi^0\nu$
1	5	$\tau \to \pi\pi\pi\nu$
1	6	$\tau \to \pi\pi\pi\pi^0\nu$
2	7	$Z \to qq$ jets



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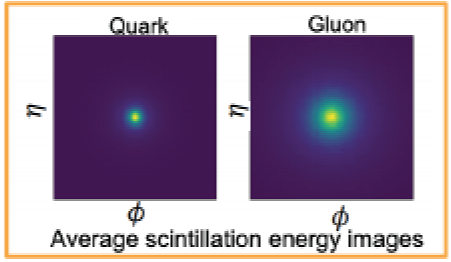
DNN models:

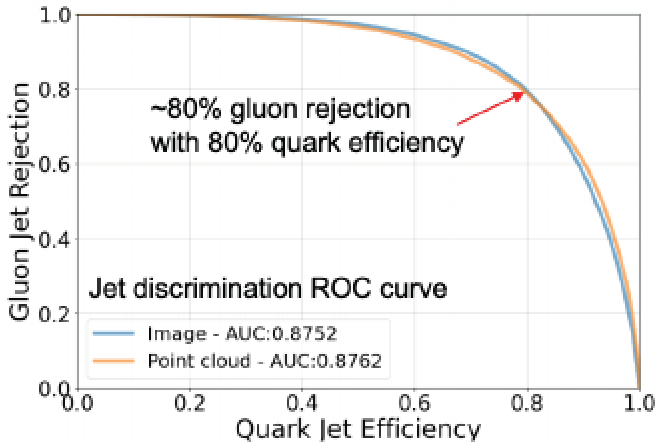
- VGG-like CNN with 3D and 2D convolutions: jet/tau representation 2-channel 111x111 mesh
- DGCNN: jet/tau representation: 2D point-cloud of fbres coordinates + #p.e. as features

Truth BR \ Predicted BR	$\tau \to \mu\nu\nu$	$\tau \to e\nu\nu$	$\tau \to \pi\nu$	$\tau \to \pi\pi^0\nu$	$\tau \to \pi\pi^0\pi^0\nu$	$\tau \to \pi\pi\pi\nu$	$\tau \to \pi\pi\pi\pi^0\nu$	$Z \to qq$ jets
$\tau \to \mu\nu\nu$	97%	2%	1%					
$\tau \to e\nu\nu$	1%	97%	1%	1%				
$\tau \to \pi\nu$	1%	3%	87%	4%	1%	2%		1%
$\tau \to \pi\pi^0\nu$		1%	5%	76%	13%	1%	3%	1%
$\tau \to \pi\pi^0\pi^0\nu$				7%	88%		4%	1%
$\tau \to \pi\pi\pi\nu$			5%	2%		75%	15%	2%
$\tau \to \pi\pi\pi\pi^0\nu$			1%	1%	4%	8%	81%	5%
$Z \to qq$ jets					1%	1%	2%	96%

Predicted BR
(B field and material)
average accuracy: **87%**

CNN model





Outlook

- Many funding requests ongoing
  - S. Korea: large founding over ~5 years (APPROVED)
  - AIDA innova: mainly Post-doc positions (APPROVED)
  - Submitting PRIN at Italian MUR
  - Submitting INFN call CSN5: ~ 900k€ over three years (next summer)

- SNOWMASS Process
  - https://snowmass21.org/instrumentation/calorimetry#submitted_loi
  - Large number of LoI submitted

- ✦ Very wide range of activities ongoing
  - ✦ Simulation, ML approach for reco, performance studies, physics studies …
  - ✦ Development in both the calorimeter construction technique and readout…
    - ✦ These activities mostly affected by covid-19 spread.
    - ✦ Foreseen TB @Desy postponed from Nov. 2020 to Feb. 2021, to be understood
- ✦ Collaboration is open to new groups interested in this detector technology

CLD, IDEA and LAr calorimeter concepts

Representative of the 3 major sampling calorimeter concepts now all targeting:

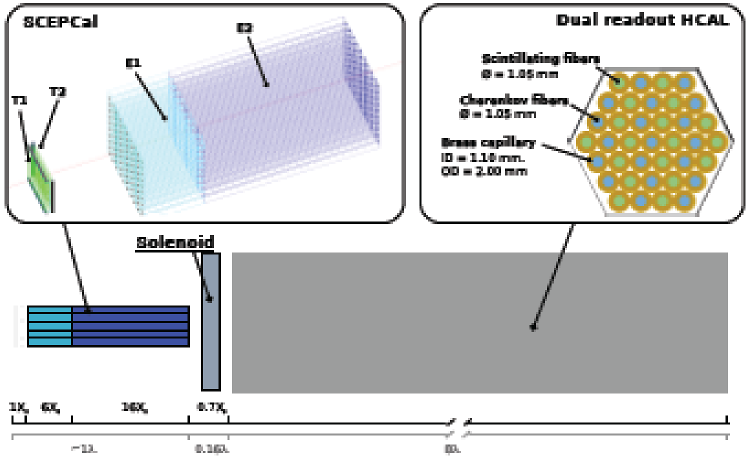
- PFlow reconstruction, originally proposed and specific optimization of CALICE design
- A certain level of compensation in EM-Had. energy components of hadron showers
- ➢ Technologies differ in ⊥ and // segmentation, sampling fraction, timing capability…

- CLD CALICE-like design, Si-W EM + Scint. Tiles+SiPM/RPC-Steel AHCAL/DHCAL (see V. Boudry)
  - High transverse granularity (25 mm^2 pads in EM section followed by 9(1) cm^2 pads AHCAL/DHCAL
  - High longitudinal 23/48 sampling in EM/HCAL for event by event energy corrections including compensation and leakage
  - Timing capability $\lesssim$ 50 ps per cell (ex. CMS HGC)
- IDEA Dual Readout calorimeter, Cerenkov & Scint. fibers + SiPM (see G. Gaudio)
  - Concept for intrinsic EM/Had compensation
  - High transverse segmentation 7 mm^2
  - Timing can provide some equivalent to longitudinal segmentation
- LAr sampling calorimeter (proposal with similar concept as for FCC-hh)
  - High transverse granularity $\Delta\eta \times \Delta\varphi \approx 0.01 \times 0.01$; first layer $\Delta\eta \times \Delta\varphi \approx 0.0025 \times 0.02$ and 8 (or more) depths segmentation, good sampling fraction, uniformity and linearity
  - Timing capability 60(100) ps for 50(100) GeV showers

CLD, IDEA and LAr calorimeter performance

- Primary goal for Z-W separation of 3% resolution for 50 GeV jets appears well-fulfilled; with PFlow reconstruction techniques it should require $\sigma E(\gamma)/\sqrt{E} \lesssim 20\%$ and $\sigma E(K_0)/\sqrt{E} \lesssim 45\%$*
  - $\sigma E(EM)/\sqrt{E} \simeq 16\%/\sqrt{E} \oplus 1\%$** - $11\%/\sqrt{E} \oplus 0.8\%$*** - $\lesssim 10\%/\sqrt{E}$****
  - $\sigma E(had)/\sqrt{E} \simeq 44\%/\sqrt{E} \oplus 2\%$** - $30\text{-}40\%/\sqrt{E} \oplus 1\%$*** - $37\%/\sqrt{E} \oplus 1\%$****
  - $\sigma E/E$ Jets ≃ 3.5 % (50 GeV) jets w/ PFlow - 5.4(5.2)% 45 GeV jets w/(w/o) 1 X/X_0, w/o PFlow
- Other performance variables e/π ID, π_0/γ ID, angular resolution can vary with technology
  - ➢ Thorough studies are needed to assess impact of variables & relatively small performance differences with physics benchmarks
  - Performance is likely going to further improve with R&D and reconstruction techniques progress
    - Example of new technical options
      - ➢ Si-W ECAL with MAPS (digital calorimetry including timing)
      - ➢ Dual readout with single fibers for Cerenkov and Scintillation with pulse shape analyses from front and rear readout (see E. Auffray)
    - Further exploitation of multivariate and deep learning reconstruction technics
      - ➢ Including timing measurement

- SCEPCal homogenous crystal*
  - 2 timing layers 3 x 3 mm^2 followed by 2 depths 1 x 1 cm^2 (½ R_M) ⊥ granularity
  - New concept of dual readout for neutral hadrons pre-showering EM/Had. Compensation
  - $\sigma E(EM)/\sqrt{E} \simeq 3\%/\sqrt{E} \oplus 0.5\%$
  - $\sigma E(had)/\sqrt{E} \simeq 27\%/\sqrt{E} \oplus 2\%$
  - ➢ Ongoing implementation in simulation with IDEA dual readout HCAL after solenoid



- Technical alternatives
  - ➢ Crystal fibers for higher ⊥ granularity (see E. Auffray)

Tour de Table / Case studies / R&D / Stages

IRFU	Saclay
APC	Paris
CPPM	Marseille
IJCLab	Orsay
IPHC	Strasbourg
IP2I	Lyon
LAPP	Annecy
LPC	Clermont
LLR	Palaiseau
LPNHE	Paris
LPSC	Grenoble
L2IT	Toulouse

Next meeting: Vendredi 23 Avril 15h30