Optical and dual readout calorimeters

Conceptual designs and related R&D challenges

Iacopo Vivarelli
University of Sussex

UNIVERSITY OF SUSSEX

AIDA innova

Thanks to M. Lucchini, G. Gaudio, Y. Liu, H. Wilkens

Outline

- Generic overview of optical calorimeters.
- Examples of optical calorimeters:
  - HGC ECAL
  - Dual Readout
  - TileCal
- Summary

Introduction

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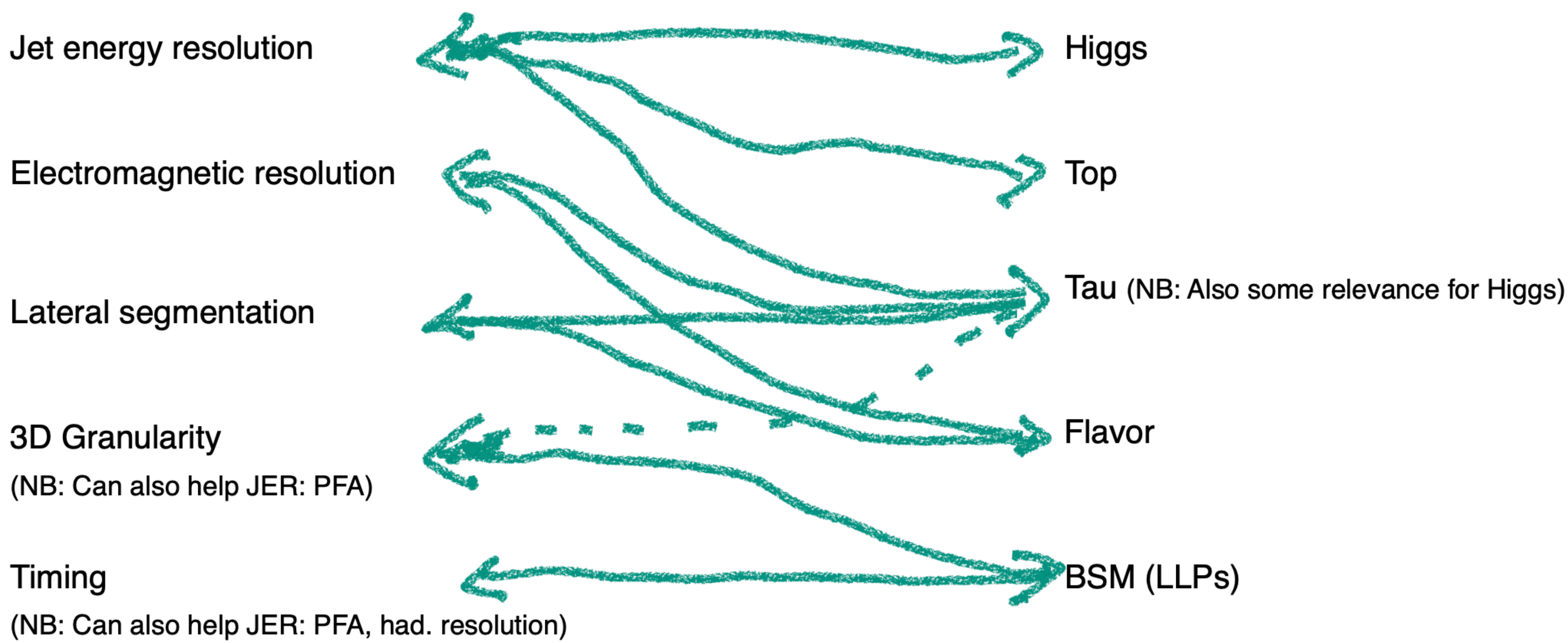
Main Observations

What do we need from Calorimetry?

Karlsruher Institut für Technologie

- The main performance criteria for a Higgs Factory calorimeter system:

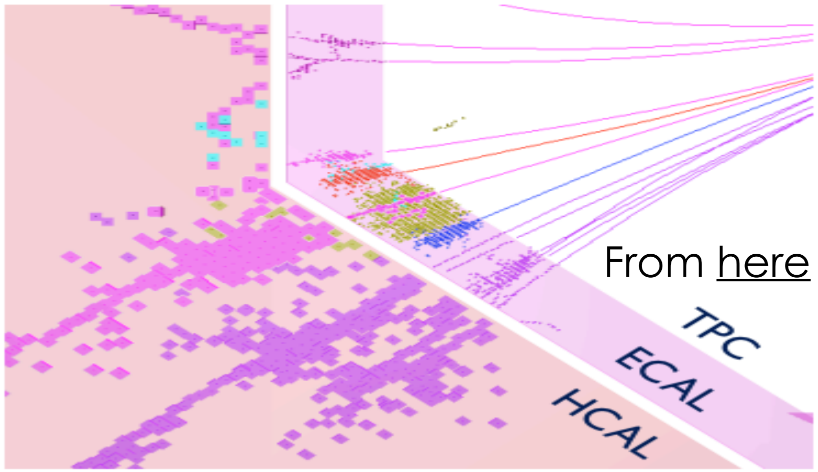


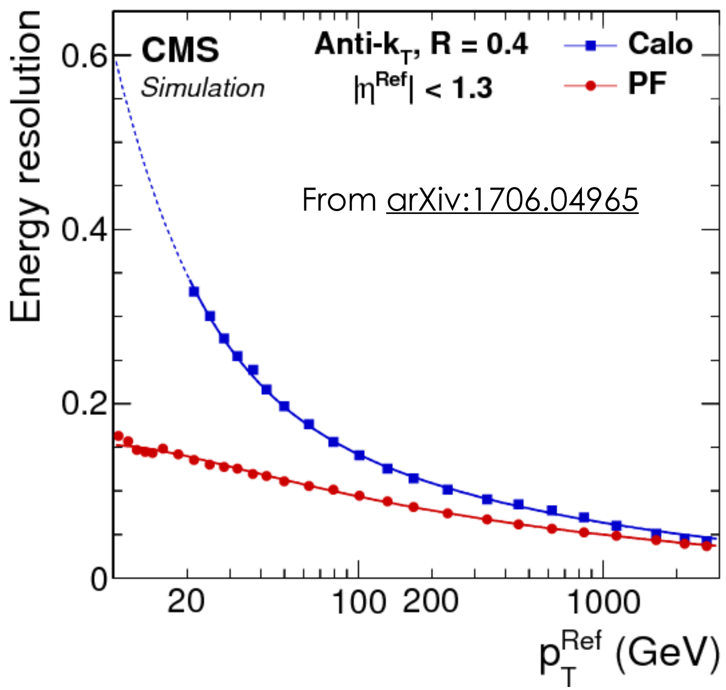
***Calorimeter R&D for Higgs Factories -** KSETA Workshop, March 2023*   Frank Simon (frank.simon@kit.edu)   Institute for Data Processing and Electronics   **19**

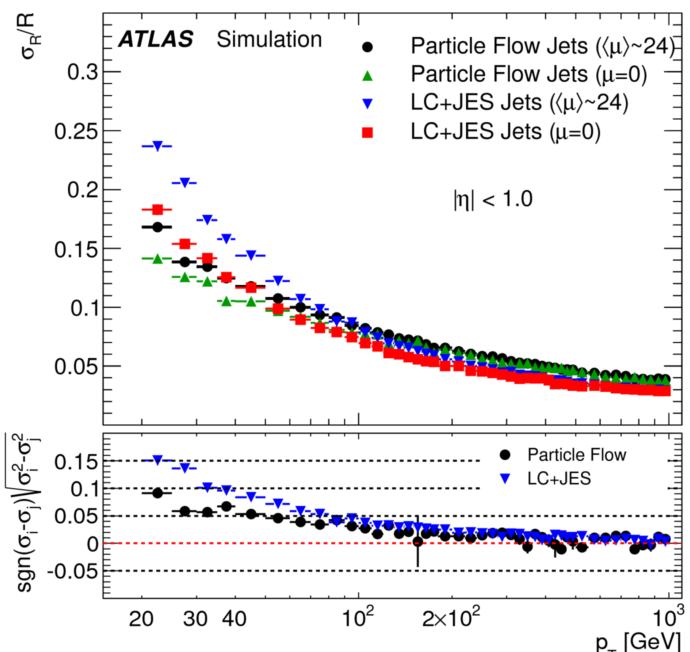
High-granularity PF-oriented calorimeters

- Particle-flow oriented calorimeters: optimised to yield the **best granularity and cluster separation**.
- Quality of energy measurement not the first priority.

Typical topologies of simulated 250GeV jets in ILD_o1_v05



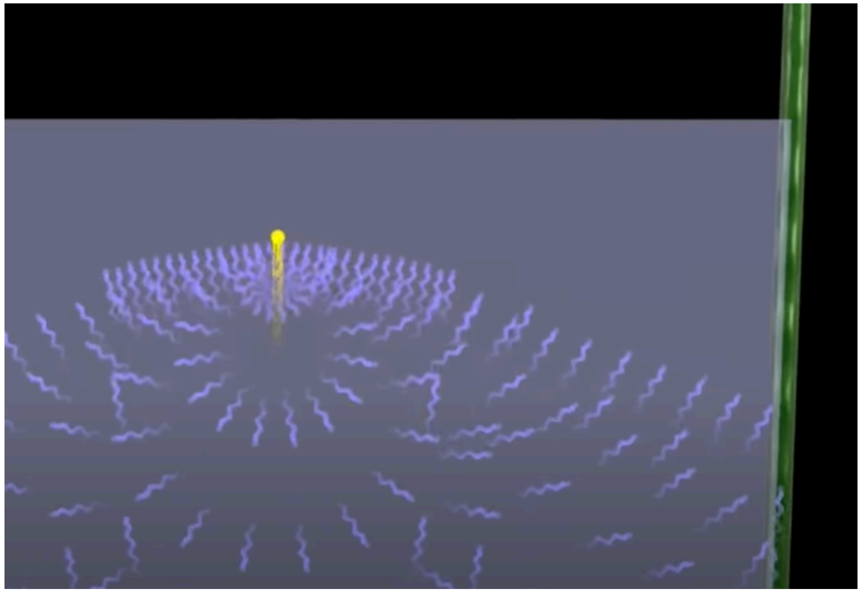


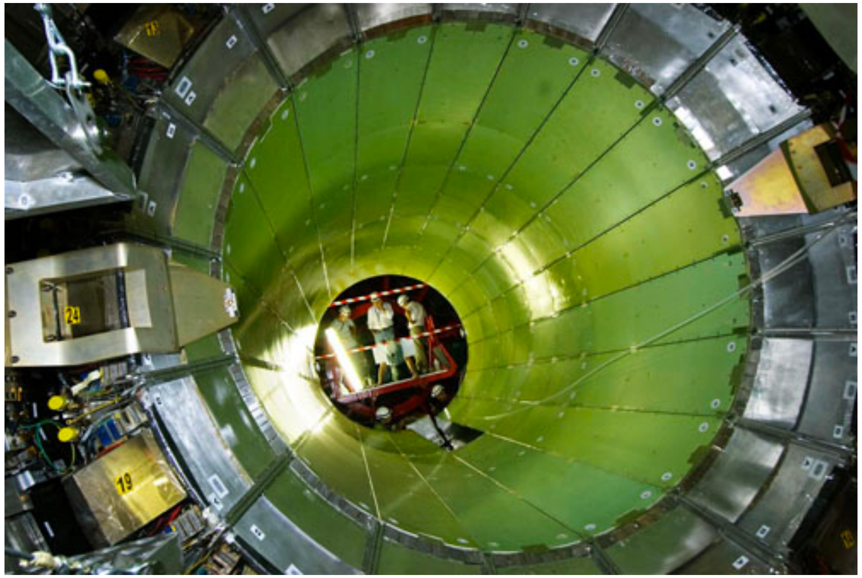


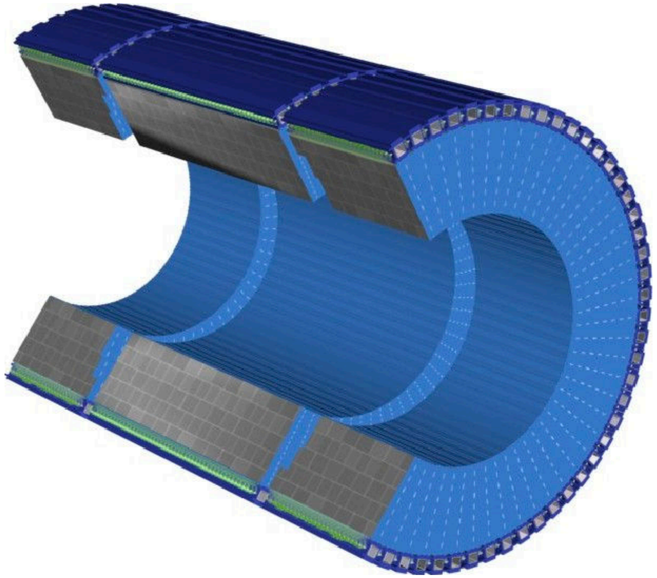
From Eur. Phys. J C77 (2017) 466

A different paradigm

- Optical calorimeters: estimate energy deposit **from amount of light** (scintillation, Cherenkov….) emitted because of the particle shower.
- Target a **high quality of the energy deposit measurement** (resolution, linearity, PID)
- Many variants used historically.
- …and many on the table for future experiments







How many different options?

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Scintillator based sampling calorimeters

- Dual Readout Fiber Calorimeter for Higgs Factories
- R&D on Spaghetti (EM) Calorimeter technologies for LHCb Upgrade II, Higgs factories, FCC-hh
- Fast-timing, ultracompact, radiation hard, EM calorimetry (*RADiCAL*) for FCC-hh
- High sampling fraction EM calorimeter with crystal grains (*GRAiNITA*) for FCC-ee
- Scintillating Tile HCAL for FCC-hh, FCC-ee

Homogeneous EM crystal calorimeters

- Maximum Information Crystal Calorimeter for Higgs Factories
- High Granularity Crystal Calorimeter for Higgs Factories
- Fast, segmented Crystal calorimeter for Muon Collider (*CRILIN*)

Homogeneous (EM+HAD) calorimeters

- Triple-readout sandwich calorimeter for DM and BSM low energy physics (*ADRIANO3*)
- Dual-readout Sandwich Calorimeter for future colliders

Large mass cryogenic calorimeters

- Large mass cryogenic calorimeters for neutrinoless double beta decay

Courtesy of M. Lucchini, P. Roloff

- Different technologies, different optimisations in mind.
  - And different targets, which implies different challenges.

Advantages and drawbacks

Advantages:

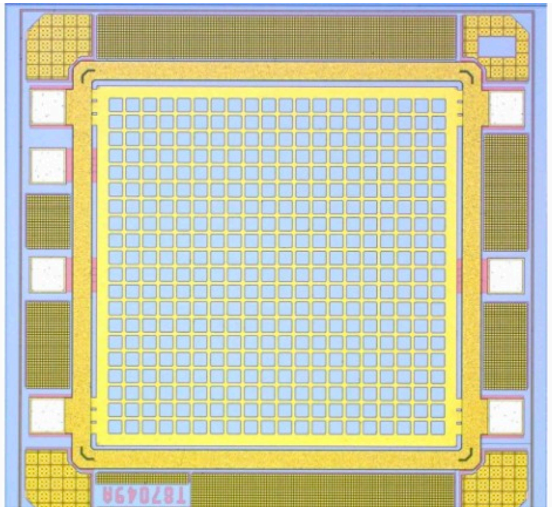
- Typically **trading off on position** precision in favour of **quality of energy measurement**.
- Typically leading to an easier optical **signal extraction:**
  - Less need for **cooling within the calorimeter volume** (with associated tecnical headaches)
  - Counterexample: High Granularity Crystal ECAL
- Number of channels (typically) **smaller**
  - Counterexample: IDEA fiber calorimeter

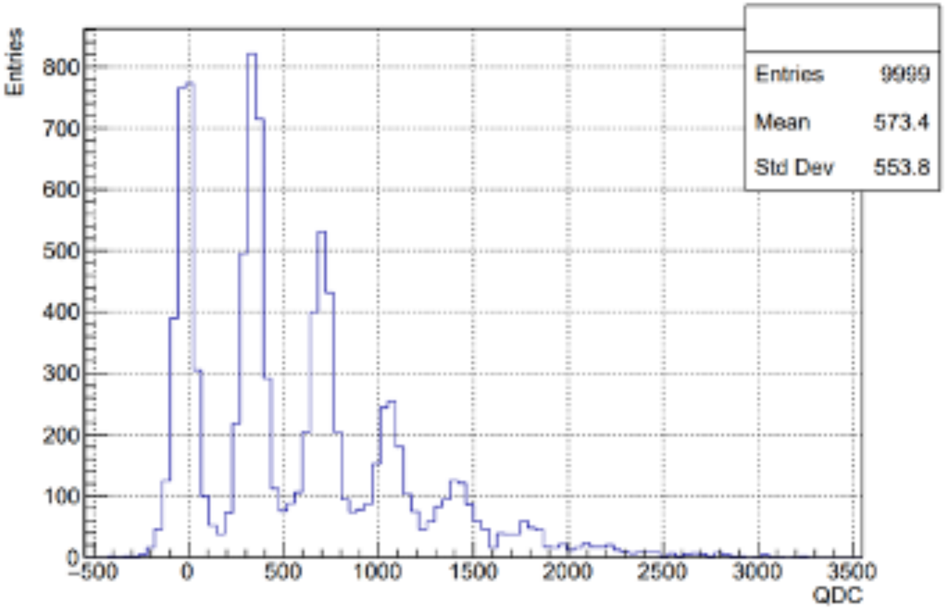
Potential drawbacks:

- The paradigm of **5D calorimeter** does not necessarily apply:
  - …although there are attempts to ditch limitations (HGC ECAL).
  - Position of energy deposit is determined with lower precision (example: IDEA dual readout calorimeter has no radial segmentation).
  - Response time of scintillators can limit precise timing information.

Sensors

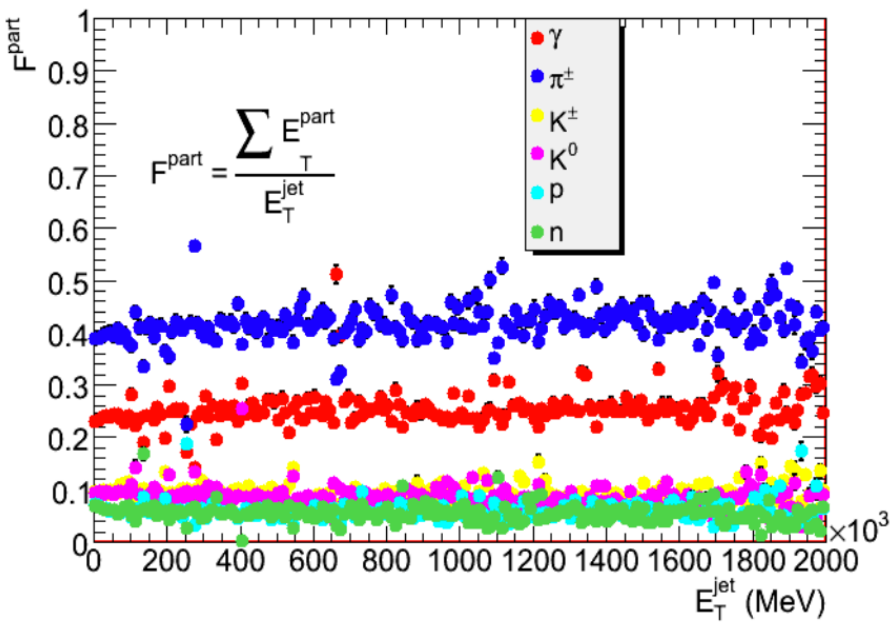
- Common challenges (and choices) for optical sensors.
  - SiPMs are a good candidate for many of the projects proposed
  - Easy to use, low bias voltage, stable, easy to monitor gain, dark count rate **not really an issue**.
- Optimised sensors desiderata:
  - More sensitivity to short wavelengths for Cherenkov light.
  - Packaged **CMOS SiPM units** for high granularity readout (Digital SiPM
  - (Not for e^+e^-) radiation hardness.

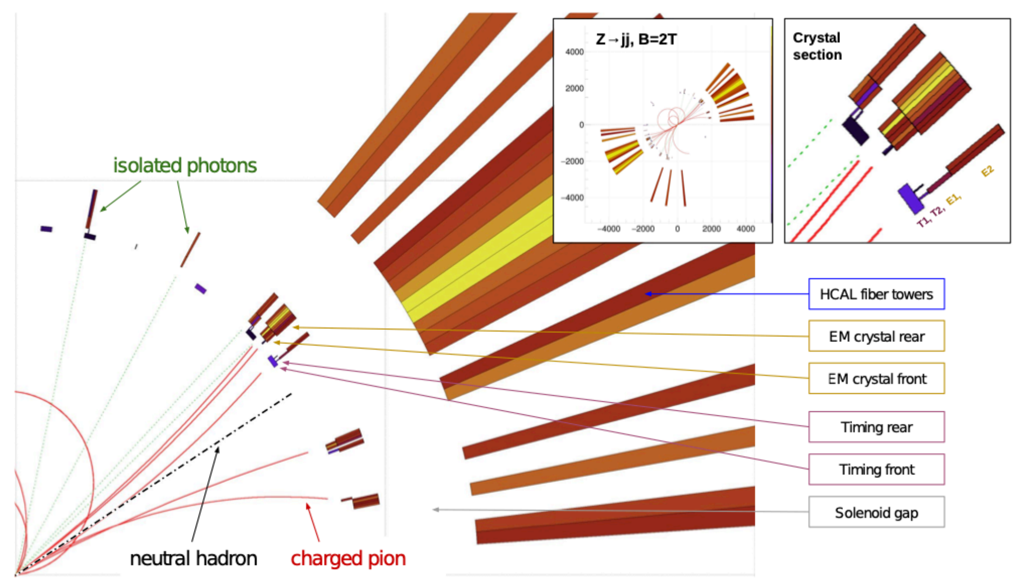




Optical calorimeters and PF

- Optical calorimeters **are not an alternative to PF.**
  - …although (with few exceptions) they are not **optimised** for PF.
- Very good measurement of the neutral part of the jet (mainly photons).
- Performance overall often competitive with those of the high-granularity counterparts.





Outline

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- **Examples of optical calorimeters:**
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  - Dual Readout
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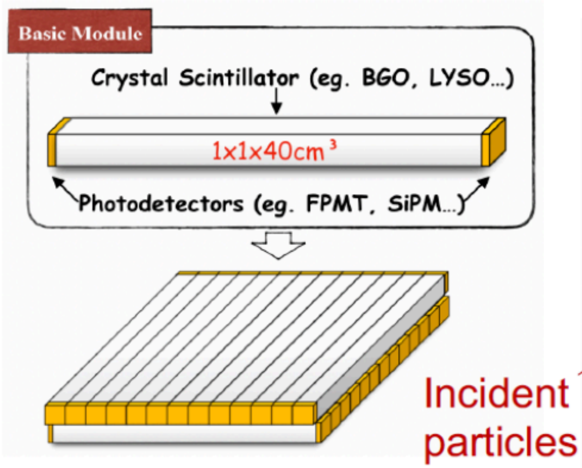
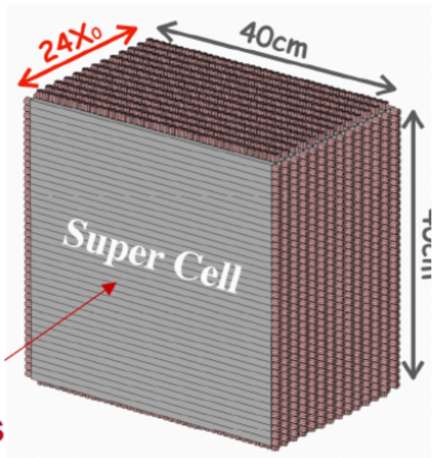
High-granularity Crystal ECAL

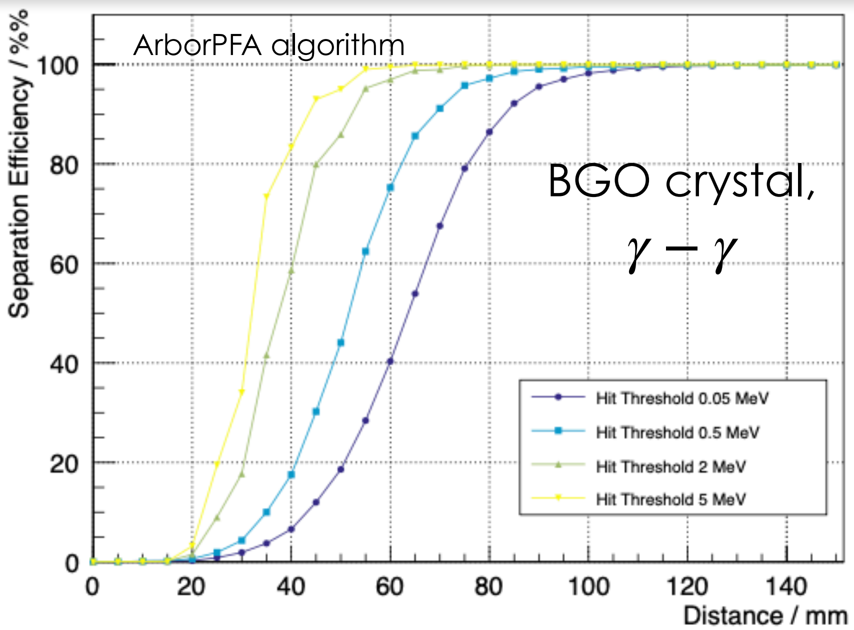
Taken from B. Qi's talk at Calor 2022

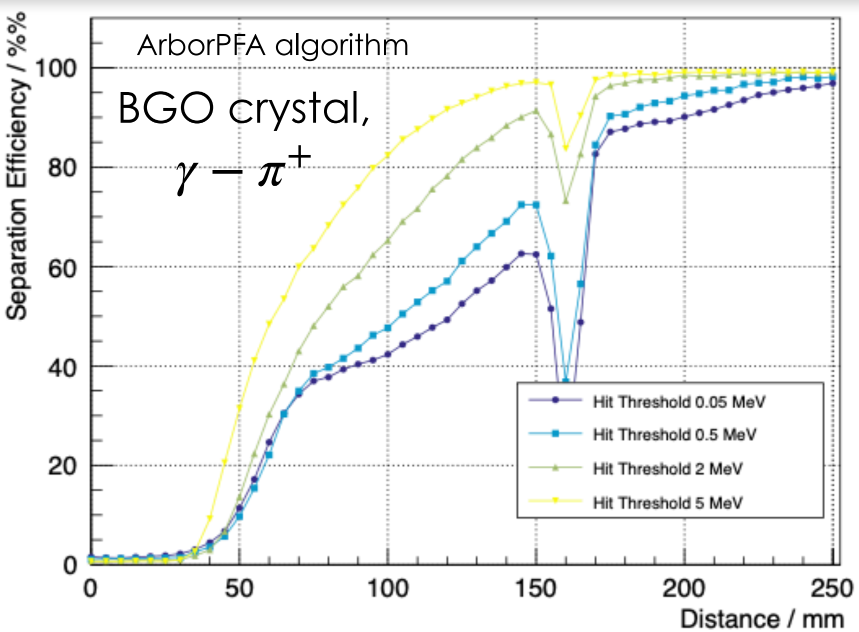
Homogeneous, highly granular geometry:
- **high resolution** for EM energy deposits
- Still suited for **PF applications**





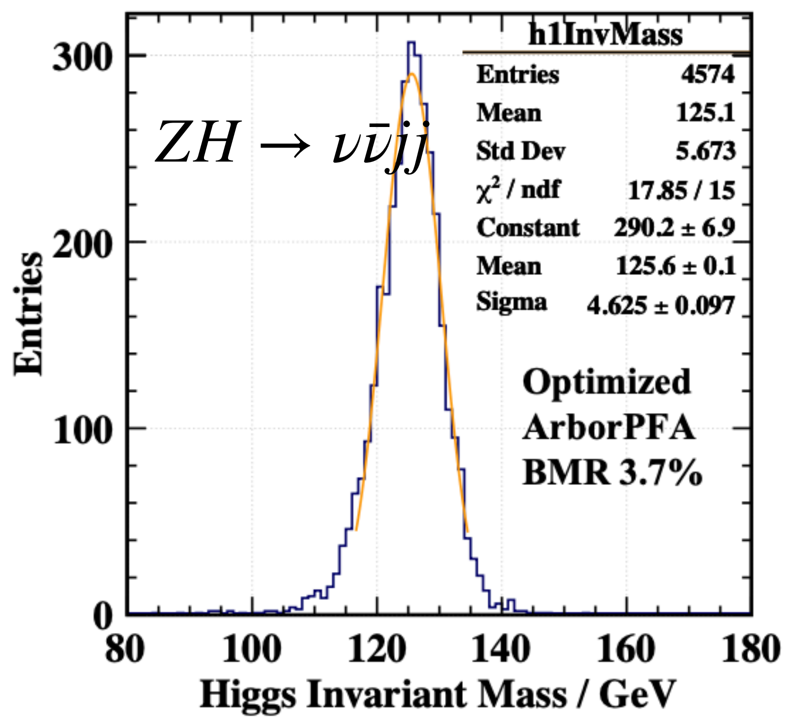
Particle separation as a function of the threshold and particle distance (assuming 1x1x2 cm³ granularity)

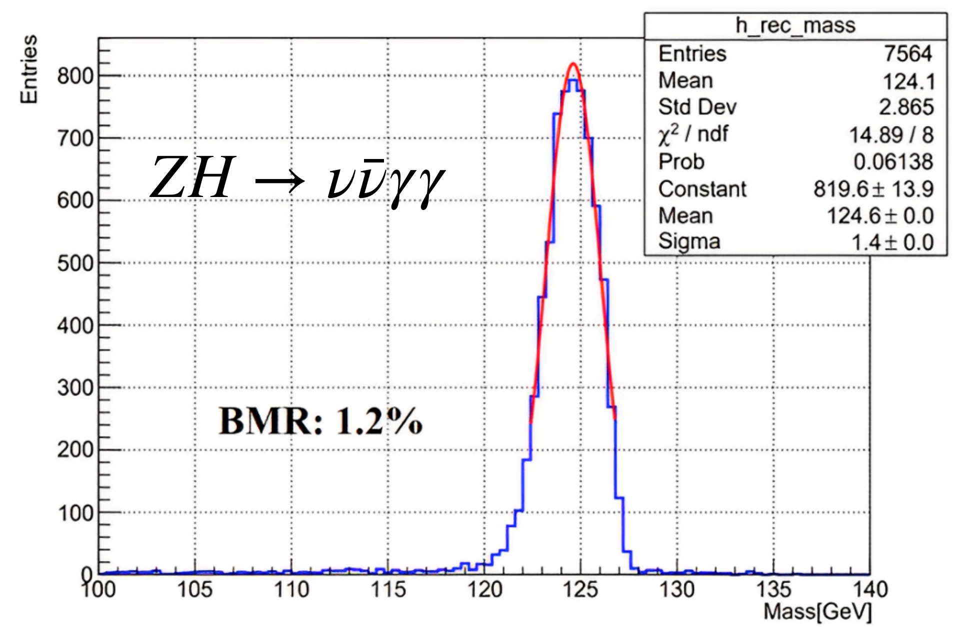




Particle flow performance

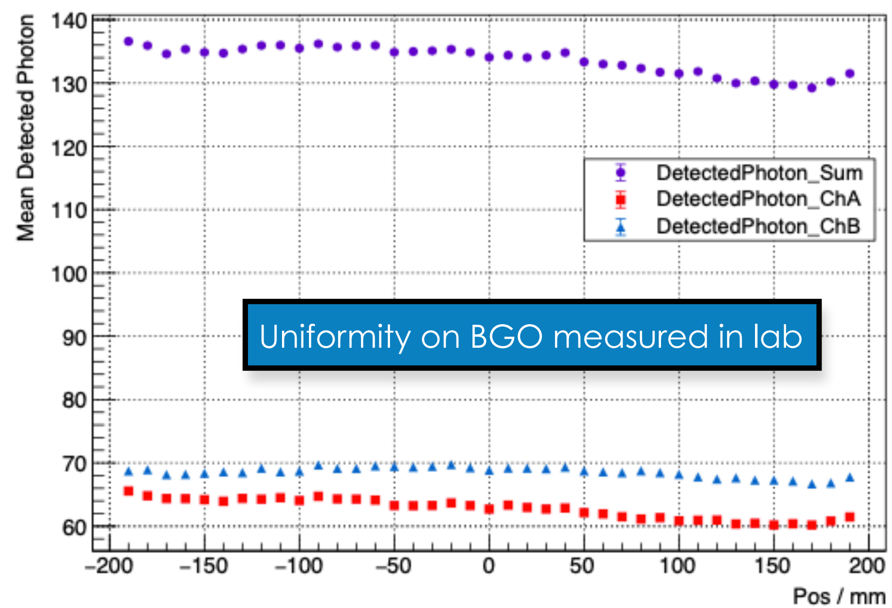
- HG Crystal ECAL used as EM section in the CEPC baseline detector.
- Re-optimised version of ArborPFA used
  - **Excellent resolution** for **di-photon resonances.** Competitive resolution for di-jet resonances.

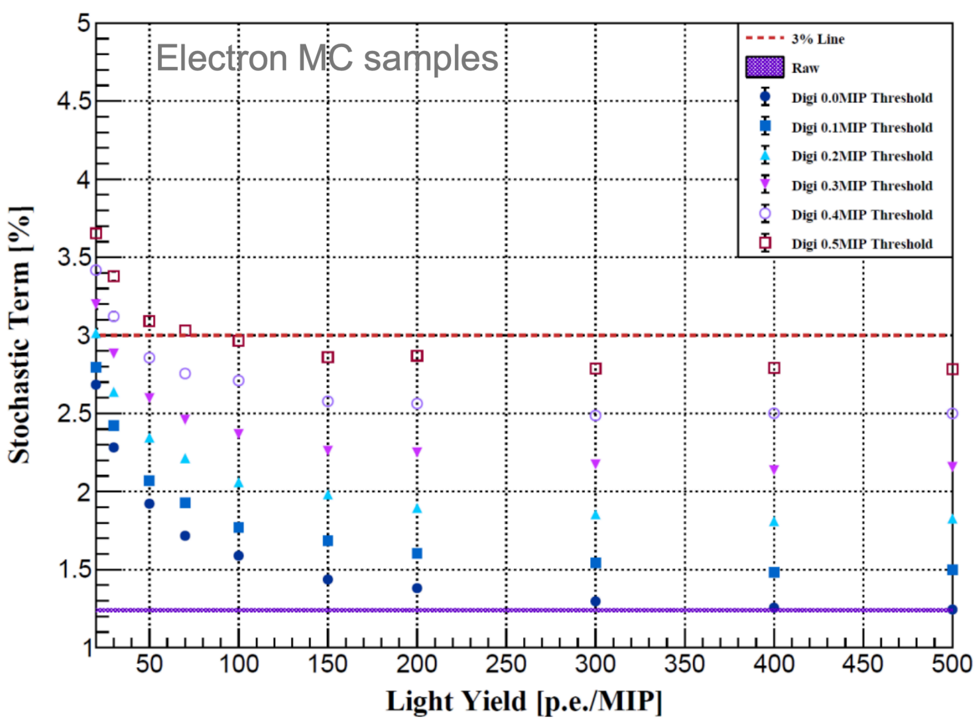


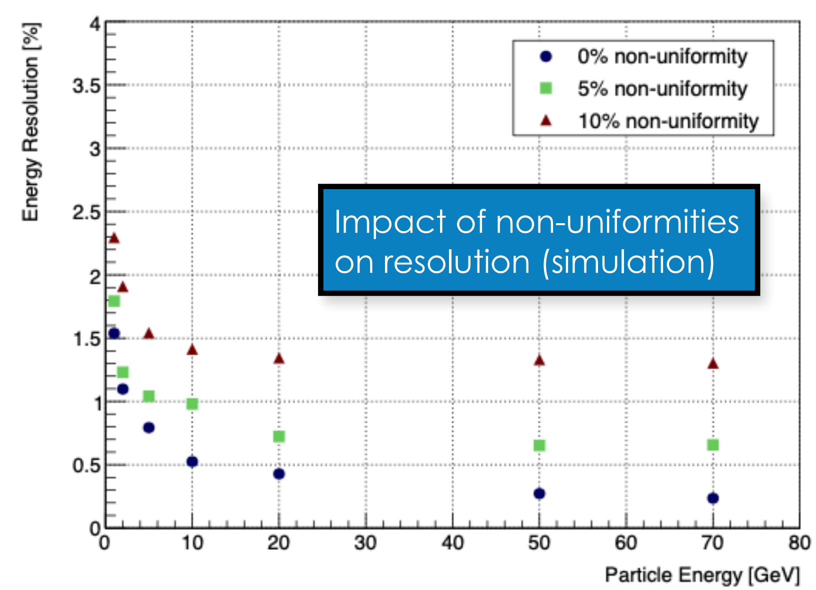


Light yield

- EM resolution target: 3% stochastic term
- A light-yield of **at least ~100 p.e./MIP needed** (while keeping thresholds small). Important critetium for crystal choice.
- Reasonable uniform response along crystal needed not to hamper resolution.



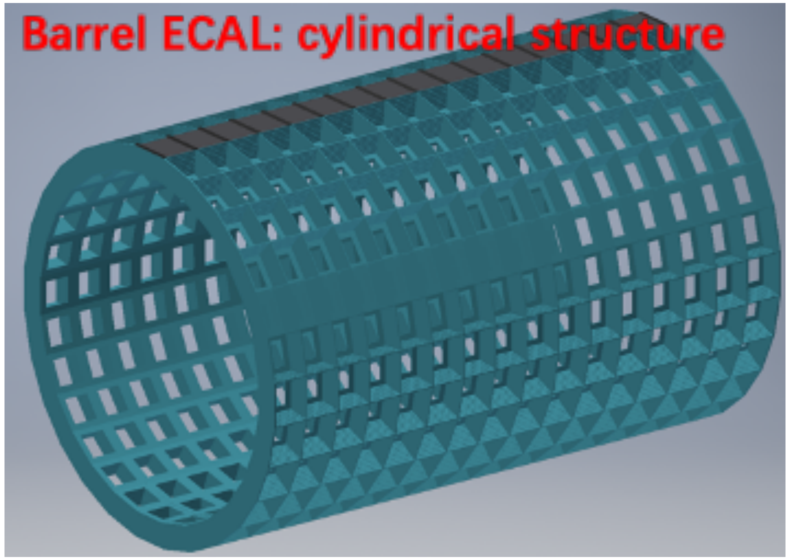




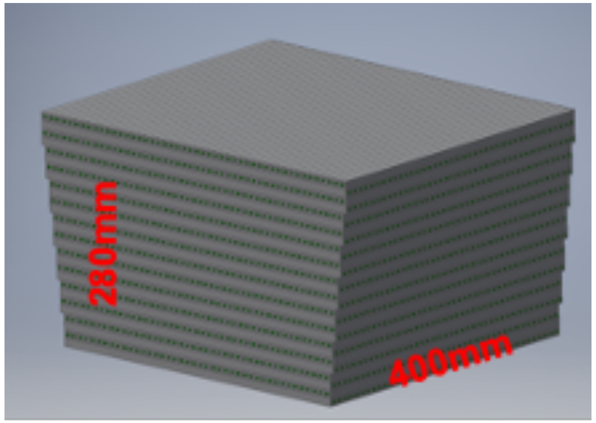
Full geometry in the making

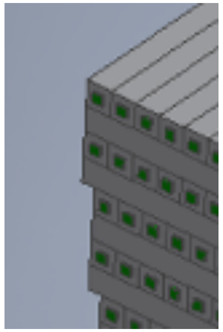
- CEPC crystal ECAL barrel geometry design
  - Finer segmentation of towers for better homogeneity
  - Decrease outer radius for lower cost of the outer detectors
  - 28 towers per ring, 17 rings along beam direction
  - ~25 radiation length: 28 layers

- Main challenges:
  - Mechanical structure (robust and light).
  - Cooling for fully integrated Front End + SiPM.
  - Dynamic range needed for SiPM (1-10^5 pe) while maintaining single pe capabilities.



Taken from B. Qi talk at CALICE meeting



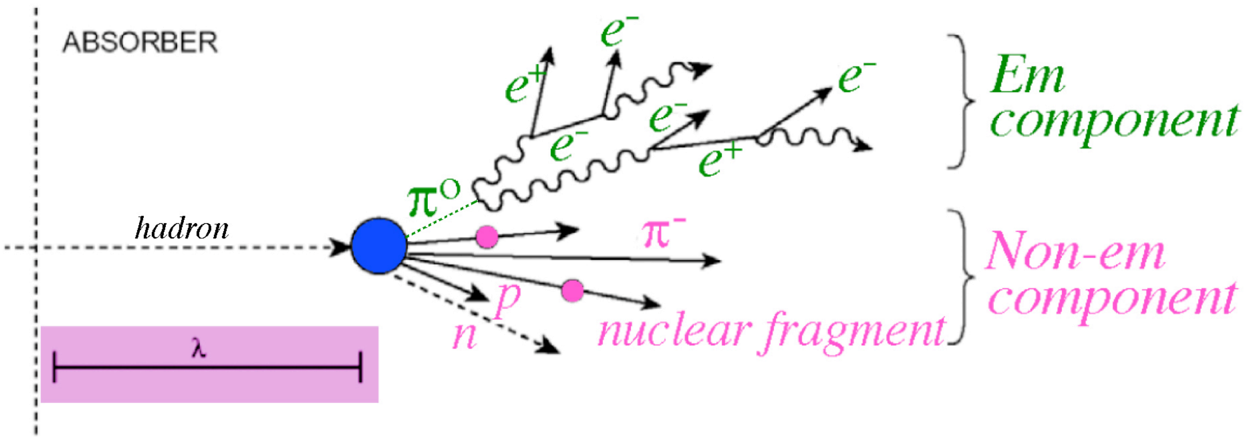


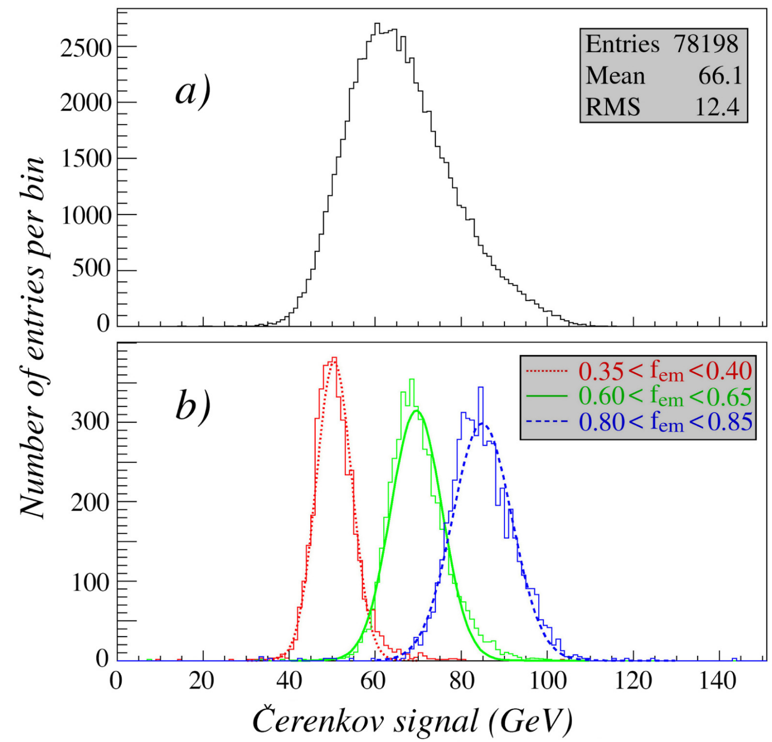
4 layers per "step" with the same transverse size

Outline

- ~~Generic overview of optical calorimeters.~~
- **Examples of optical calorimeters:**
  - ~~HGC ECAL~~
  - **Dual Readout**
  - TileCal
- Summary

Dual readout calorimetry





- **Non-compensating calorimeters**: response to em part different from that to non-em part. **h/e < 1.**
- $\langle f_{em} \rangle$ energy dependent ⇒ **Non-linear calorimeter response** to hadrons.
- $\langle f_{em} \rangle$ fluctuations **largely determine energy resolution** ⇒ sampling the hadronic shower with two calorimeters with different e/h **boosts energy resolution**.
- For a review about dual readout calorimetry, please see S. Lee, M. Livan, R. Wigmans, Rev. Mod. Phys. 90, 025002.

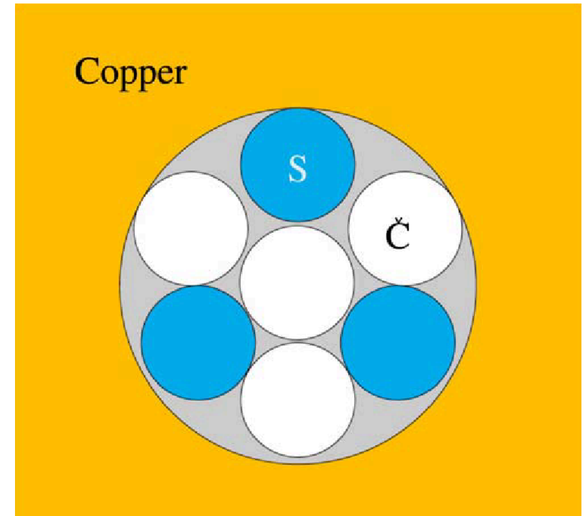
$$E_C = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_C (1 - f_{\mathrm{em}})\right)$$

$$E_S = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_S (1 - f_{\mathrm{em}})\right)$$

$$\Rightarrow \quad E = \frac{(E_S - \chi E_C)}{1 - \chi}$$

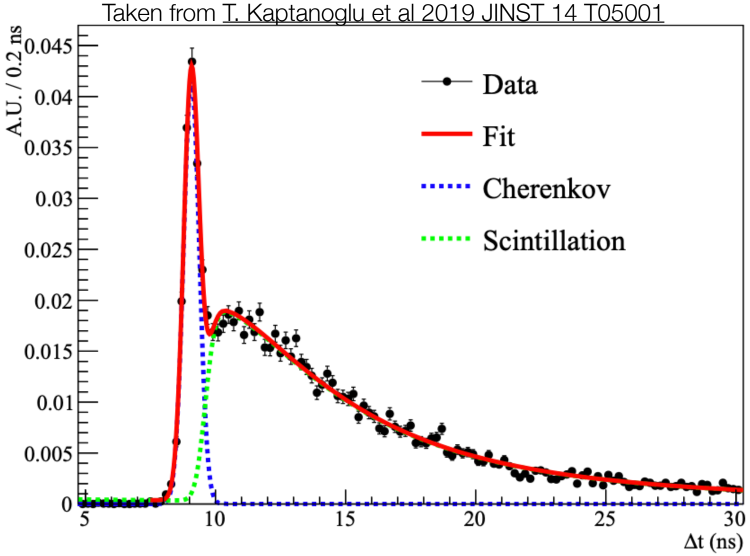
Dual readout - how?

- One needs two readouts with substantially different h/e.
- Normally done using Cherenkov and scintillation light.
- How to you separate them?



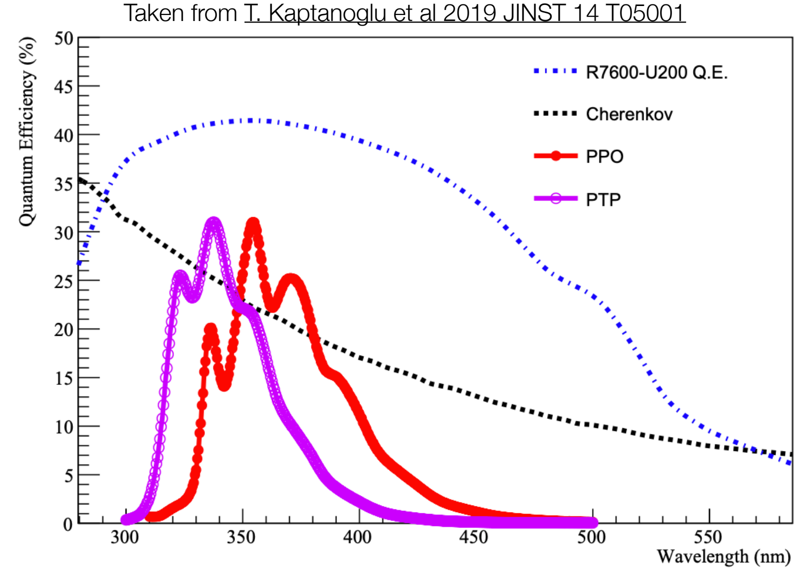
Physical separation of signals

Taken from T. Kaptanoglu et al 2019 JINST 14 T05001



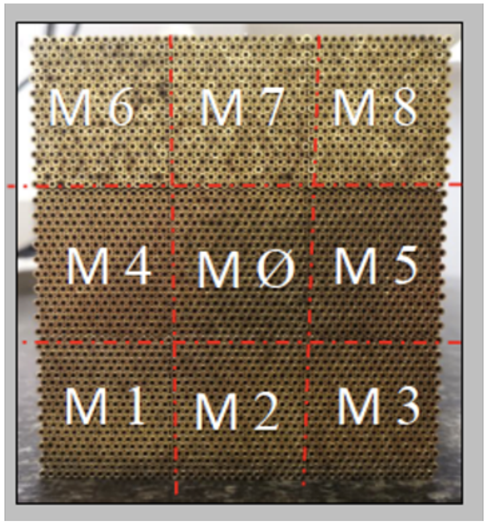
Separation in time

Taken from T. Kaptanoglu et al 2019 JINST 14 T05001

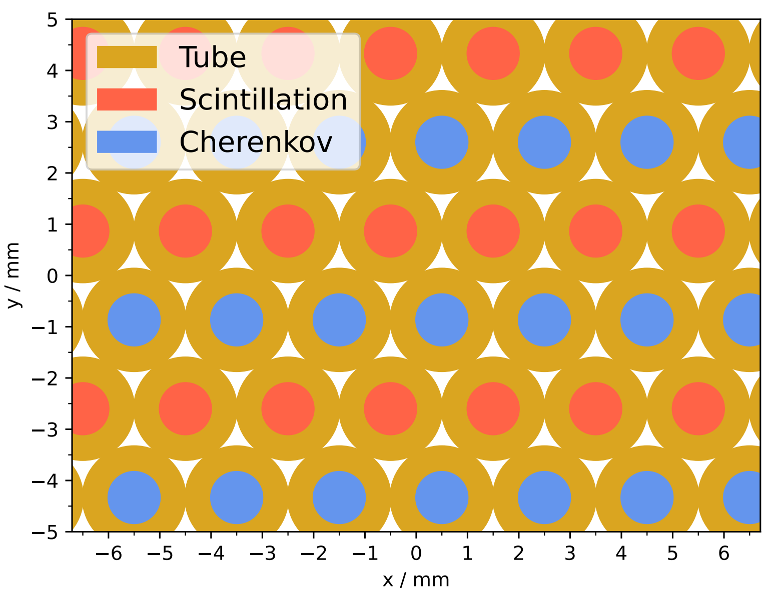


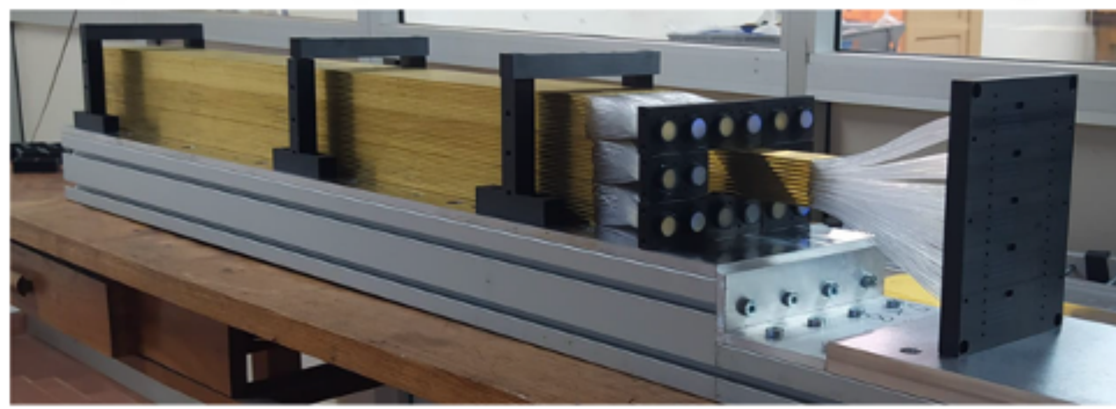
Separation in frequency

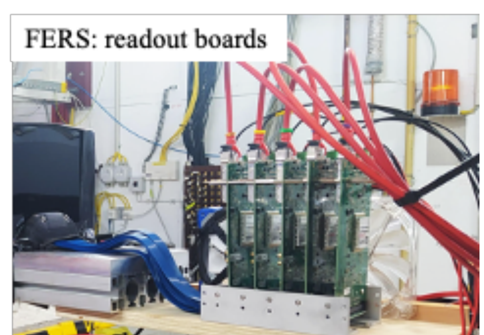
Physical separation

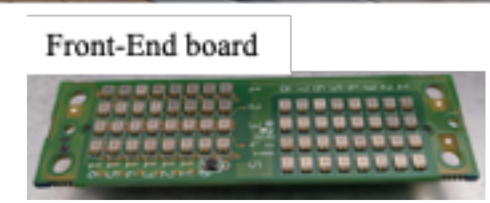


- Basic calorimeter unit: **one brass capillary tube** of 2 mm external diameter **hosting a fiber** (1 mm diameter).
- **EM-size prototype** (10x10x100 cm^3) put on beam (twice) in 2021.
  - 9 modules, each 16 x 20 capillary tubes.
- Readout:
  - M0 read with SiPM (one per fiber).
  - M1-8 read by 2 PMT each (one for Cherenkov, one for Scintillating fibers).



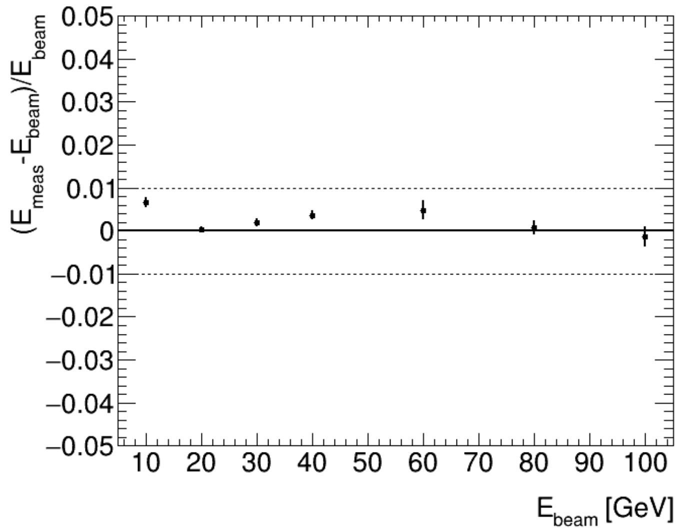




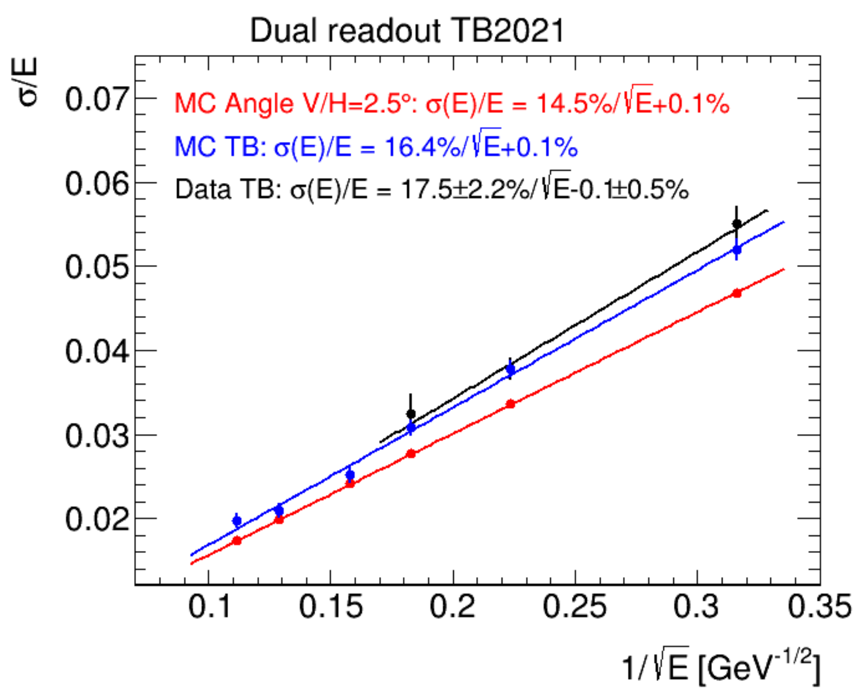


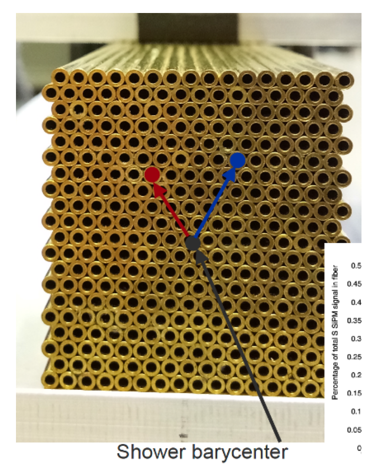
Hamamatsu SiPM:
S14160-1315 PS
Cell size: 15 μm

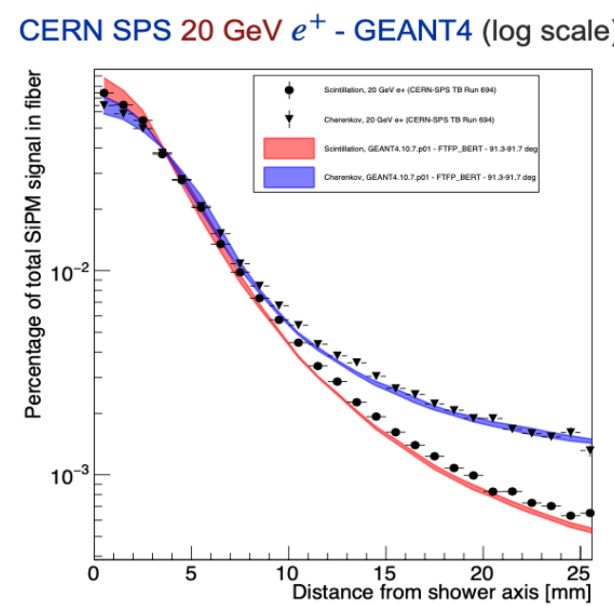
Results (bucatini calorimeter)



- After calibration with electrons, **linearity within 1%** over a wide range of enegies.
- Excellent **lateral shower shape development** measurements.

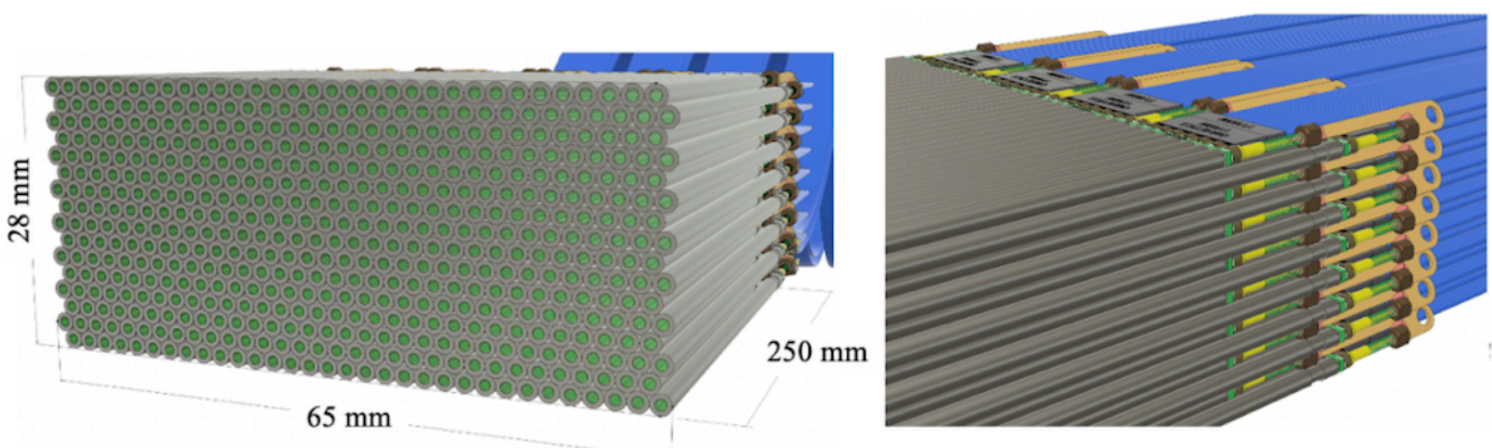




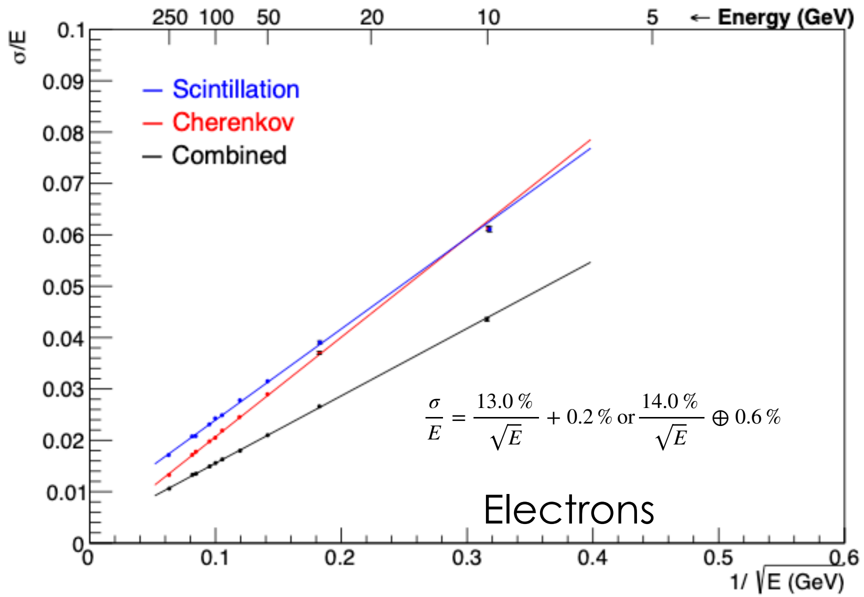


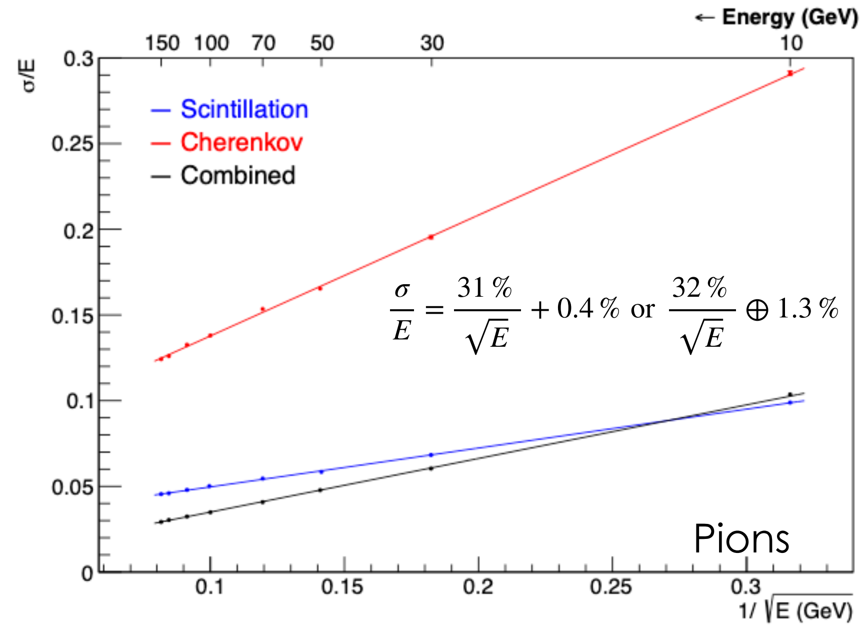
Challenges

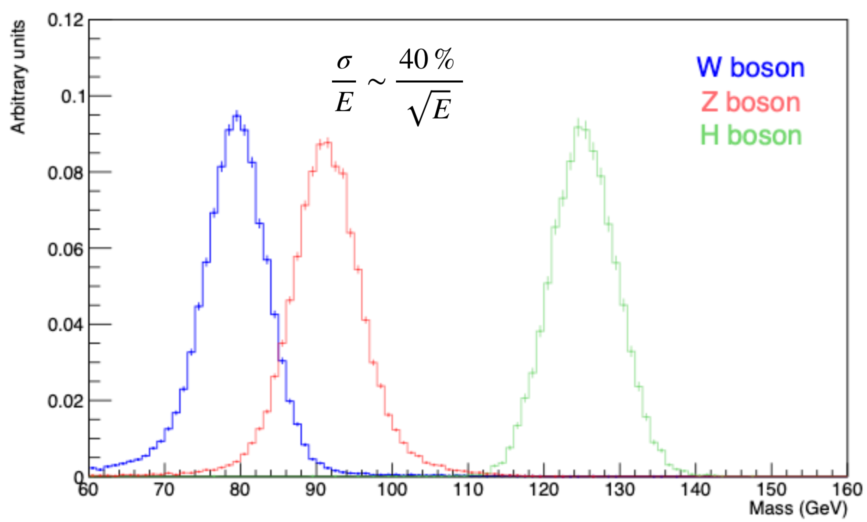
- Many channels if one wants **full granularity**
  - Development of a **scalable readout**; digital SiPM?
  - Channel grouping ⇒ loss of multiphoton spectrum ⇒ need for a calibration system.
- Lack of **longitufinal segmentation**
  - Exploit full waveform from SiPM? But this is going to cost, see backup.
- Low light yield from Cherenkov
  - Fiber/SiPM optimisation

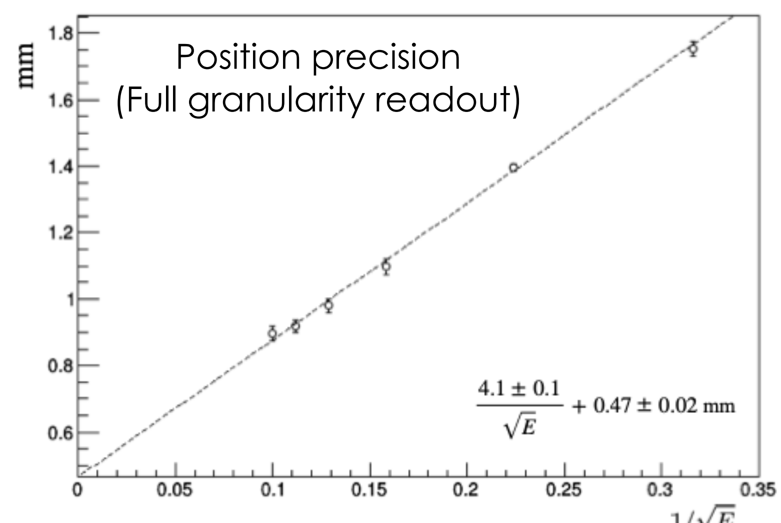


Full simulation performance in a nutshell





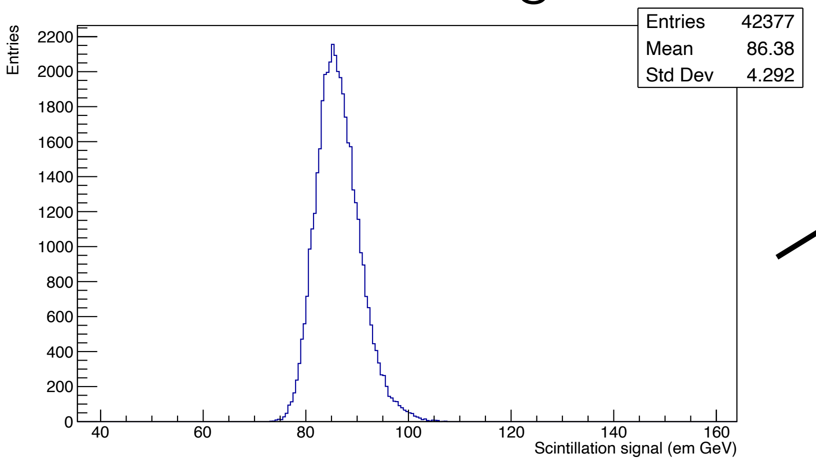




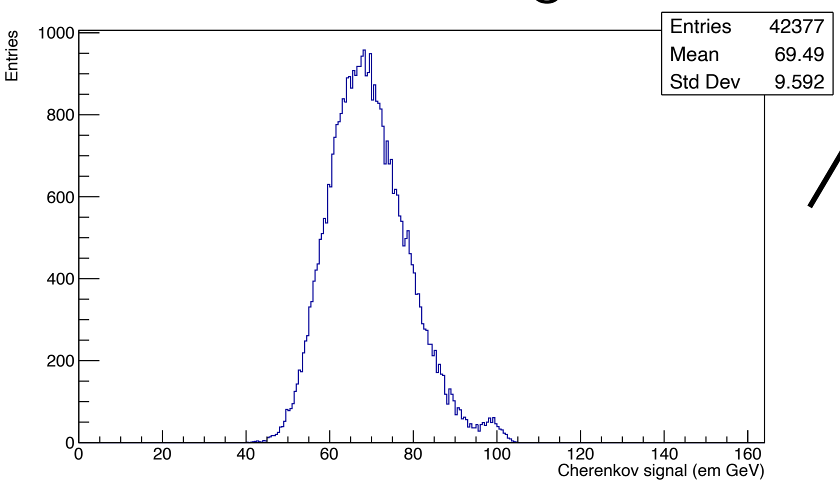
All plots taken from https://arxiv.org/pdf/2203.04312.pdf

Single pion response

Scintillation signal

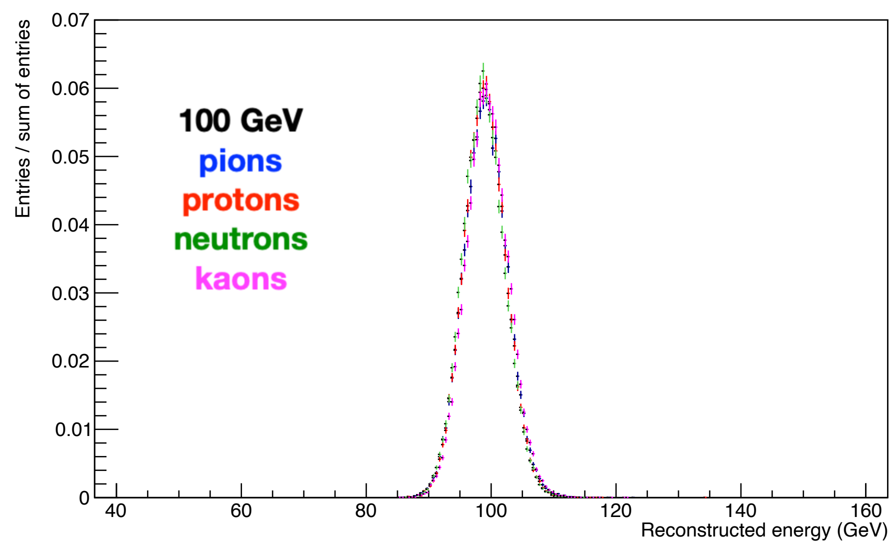


Cherenkov signal



$$E = \frac{E_S - \chi E_C}{1 - \chi}$$

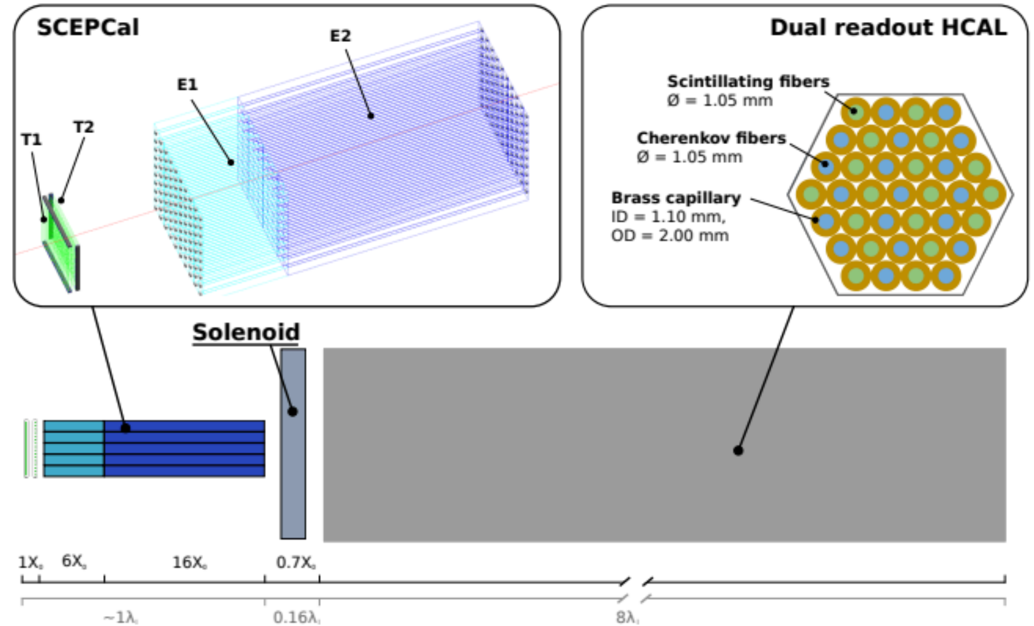
Uniform response from different hadrons with a single χ

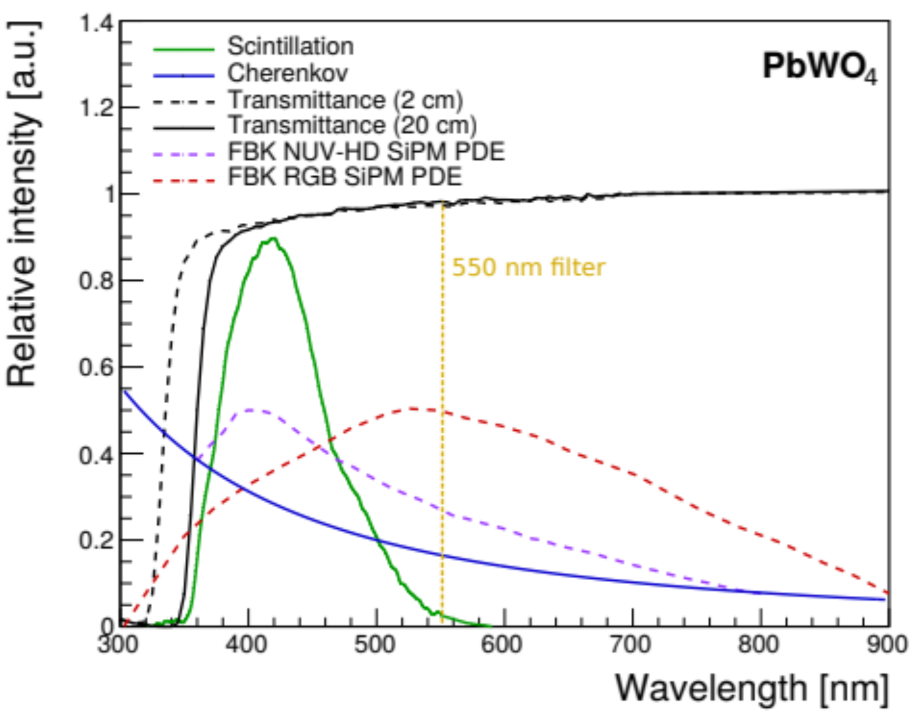


Separation in time/frequency

Taken from JINST 15 P11005 (2020)

- Dual readout with **homogeneous crystals**
  - As example: separating different light components with SiPM **sensitive to different regions of the spectrum.**
  - Interesting option for a **EM section** to be coupled to a (dual readout) **hadronic section**.



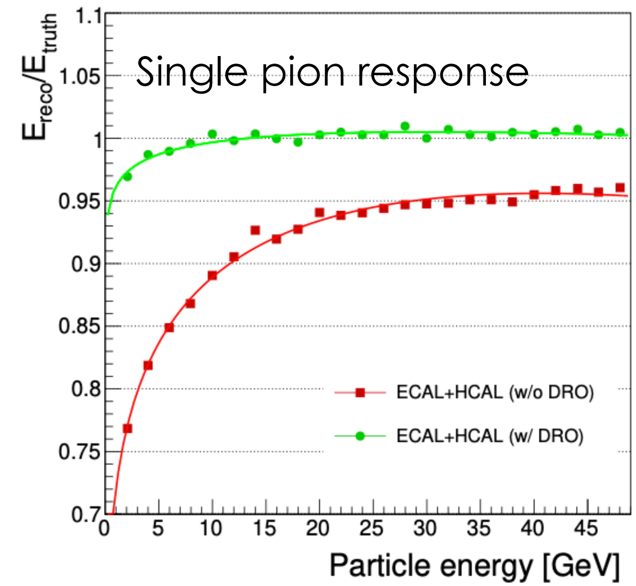


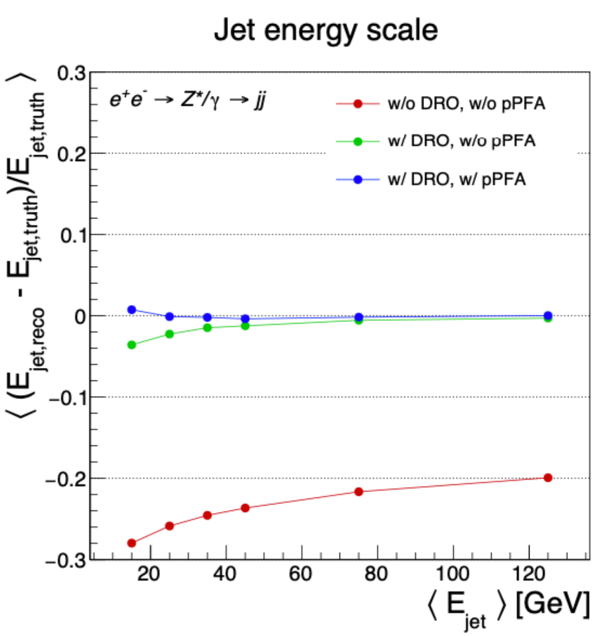
	S (ph/GeV)	Eff (S)	C (ph/GeV)	Eff (C)
Estimated detected (wavelength < 550 nm)	2000	1%	140	0.25%
Estimated detected (wavelength > 550 nm)	< 20	< 0.01%	160	0.3%

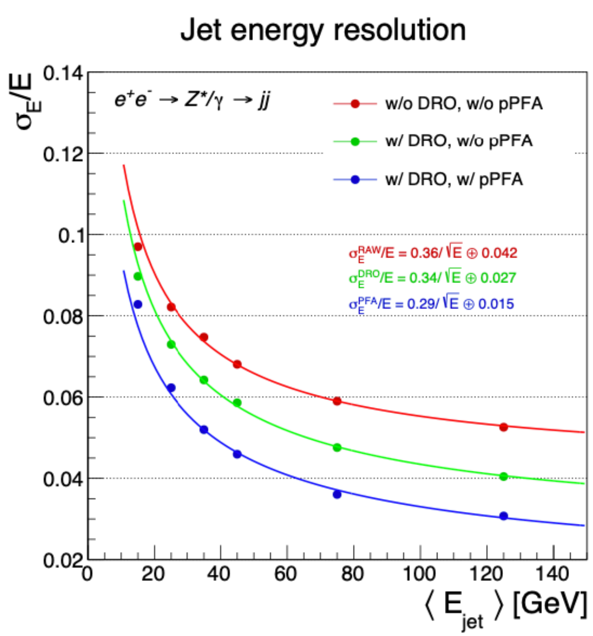
Performance

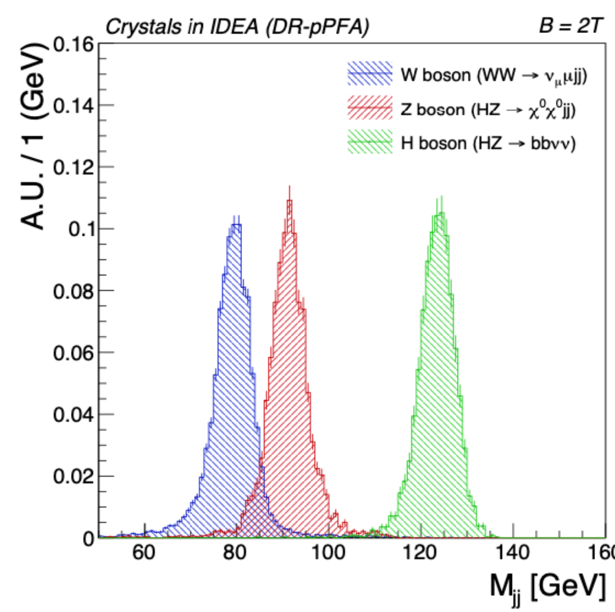
Taken from Arxiv:2202.01474

- **High energy resolution** for the EM section, adds **natural longitudinal segmentation**.
- Hadron calorimeter unchanged with respect to **fiber-only configuration**.









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- **Examples of optical calorimeters:**
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  - ~~Dual Readout~~
  - **TileCal**
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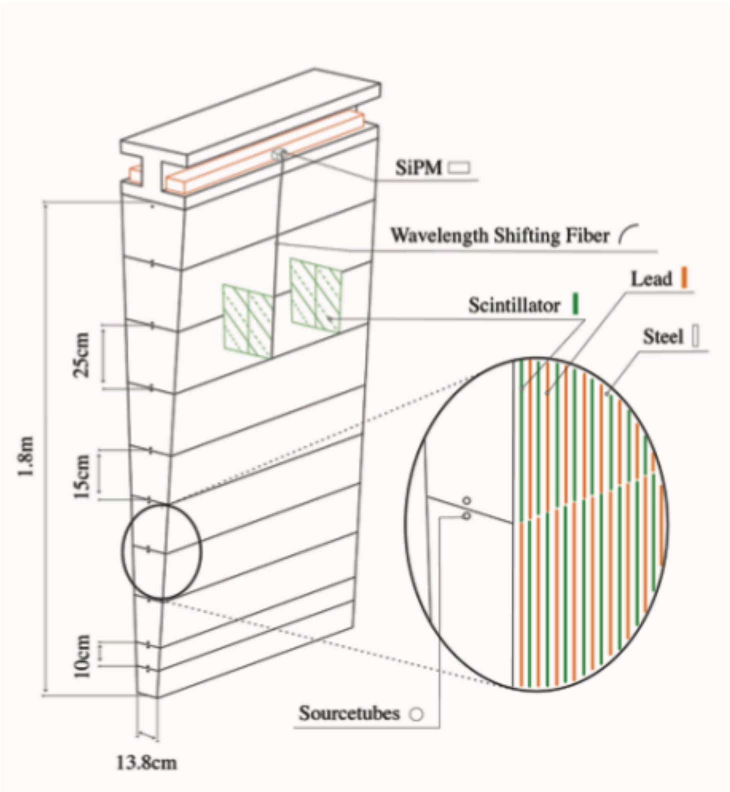
A very flexible and reliable option

- Strongly inspired by ATLAS central hadronic calorimeter.
- Designed for FCC-hh, but now being optimised for e^+e^-.



Specs:
5mm steel absorber plates,
alternating with 3mm Scint. and 4mm Pb tiles
128 modules in Φ, 2 tile/module
10 layers
$\Delta\eta=0.025$ (grouping 3-4 tiles), $\Delta\Phi=0.025$

- 4 times the tile density of ATLAS, 1 tile 1 channel.
- SiPM readout at outer radius (~10^{11} neq)
- Ongoing R&D on scintillator material and SiPMs (8kGy requirement).

Mechanical structure feasible.
Started testing Sci tile+WLS fibre+SiPM

See also DRD6 talk from H. Wilkens

Part of a full detector design

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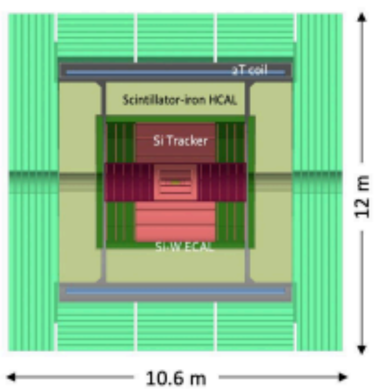
CDR

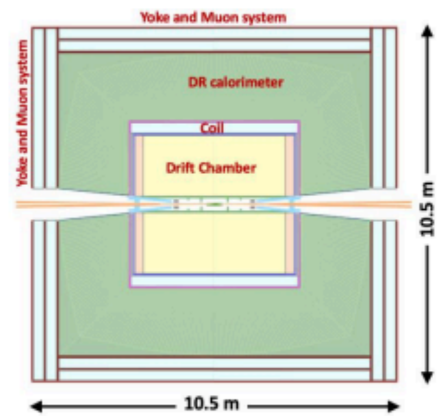
CLD



- Full Silicon vertex detector + tracker;
- Very high granularity, CALICE-like calorimetry;
- Muon system
- Large coil outside calorimeter system;

- Possible optimization for
  - Improved momentum and energy resolutions
  - PID capabilities

IDEA

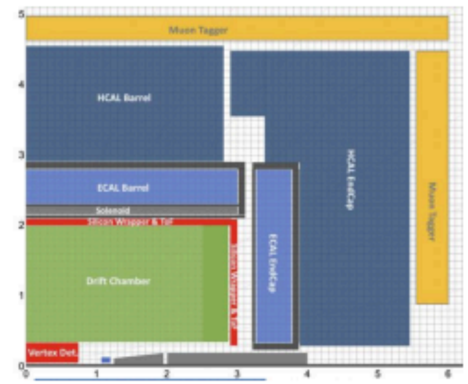


- Si vertex detector;
- Ultra light drift chamber w. powerfull PID;
- Monolitic dual readout calorimeter;
- Muon system;
- Compact, light coil inside calorimeter;

- Possibly augmented by crystal ECAL in front of coil;

Noble Liquid ECAL based

new

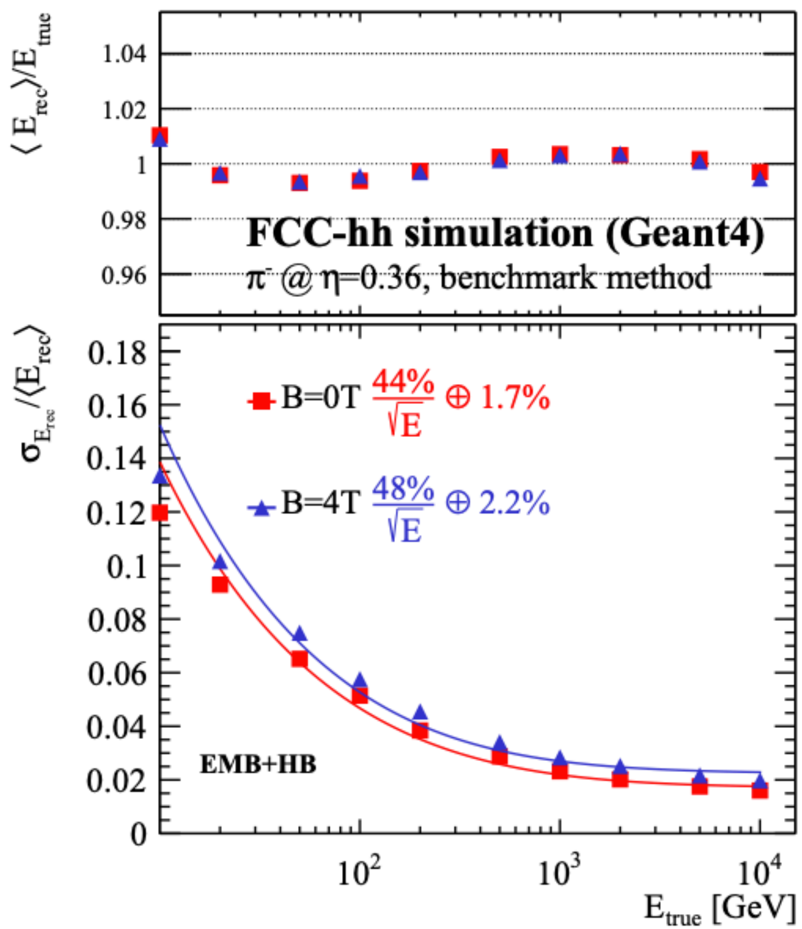


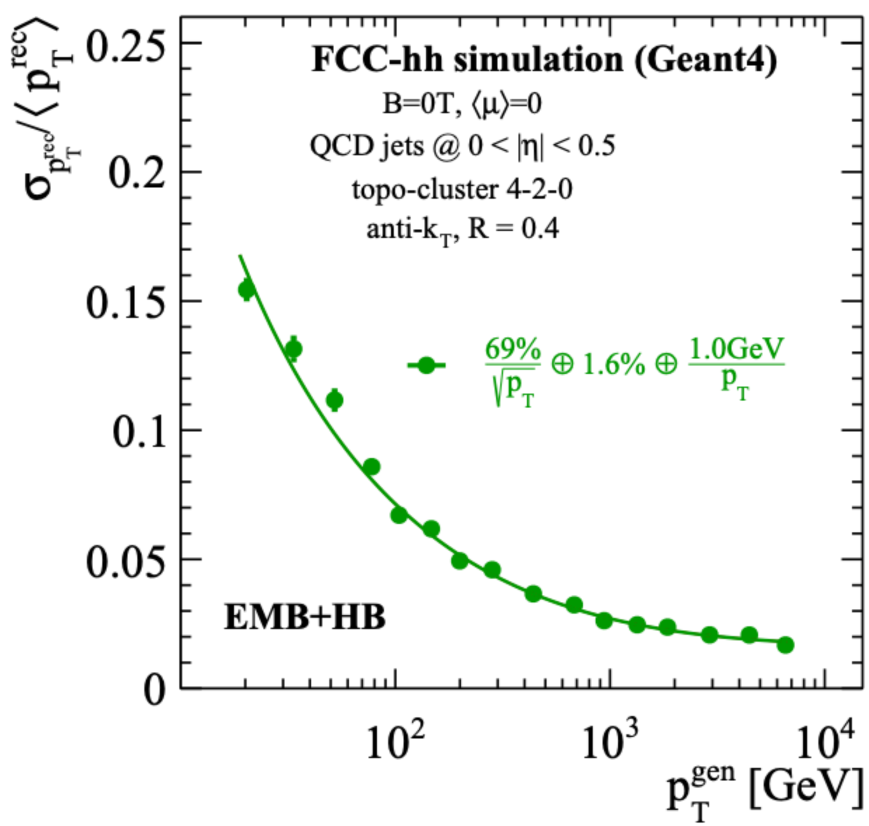
- High granularity Noble Liquid ECAL as core;
  - PB+LAr (or denser W+LCr)
- Drift chamber (or Si) tracking;
- CALICE-like HCAL;
- Muon system;
- Coil inside same cryostat as LAr, possibly outside ECAL.

M. Aleksa et. al.

Expected performance (hh)

- Hadron and jet response (for hh, being studied for ee)



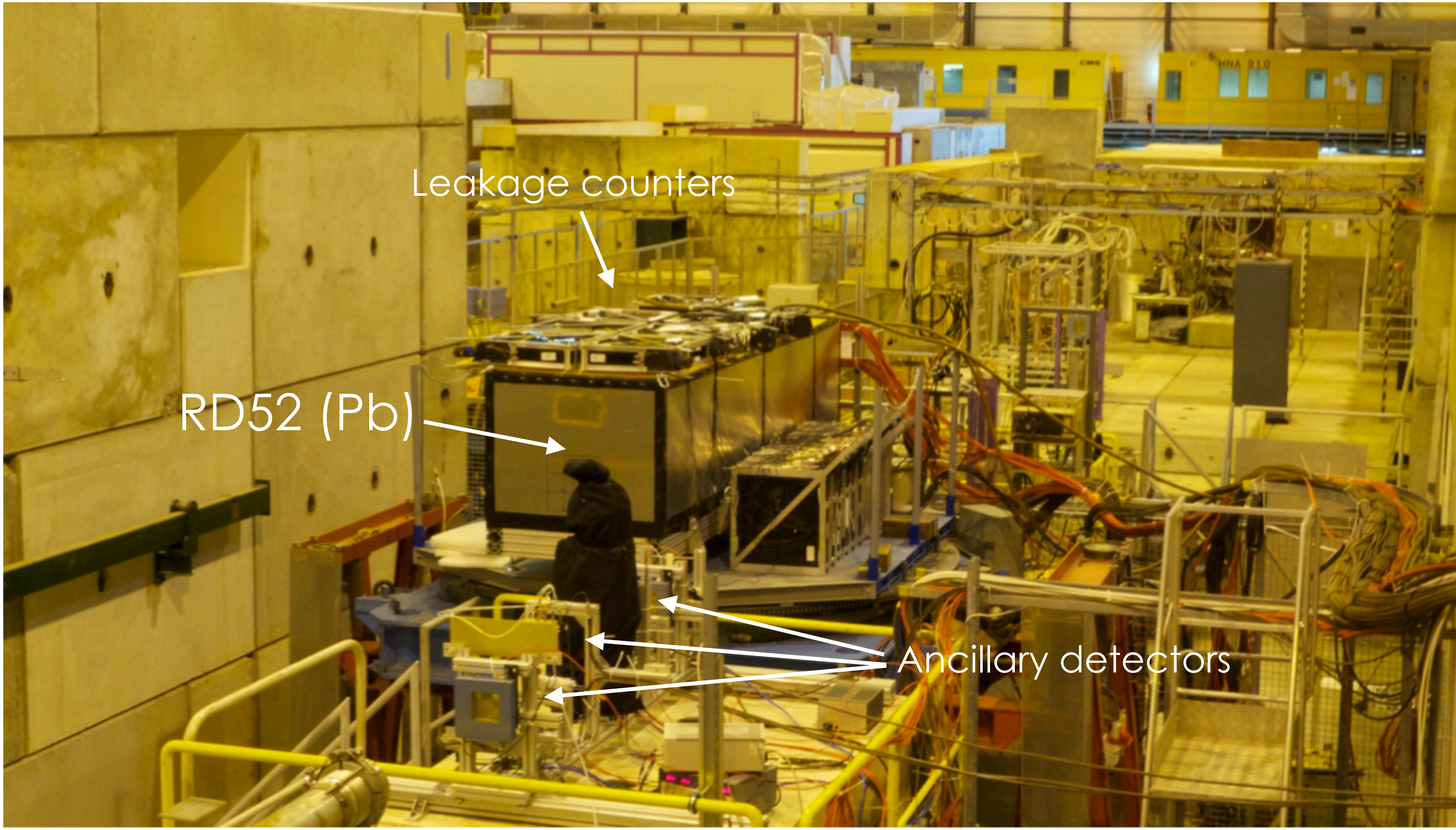


Summary

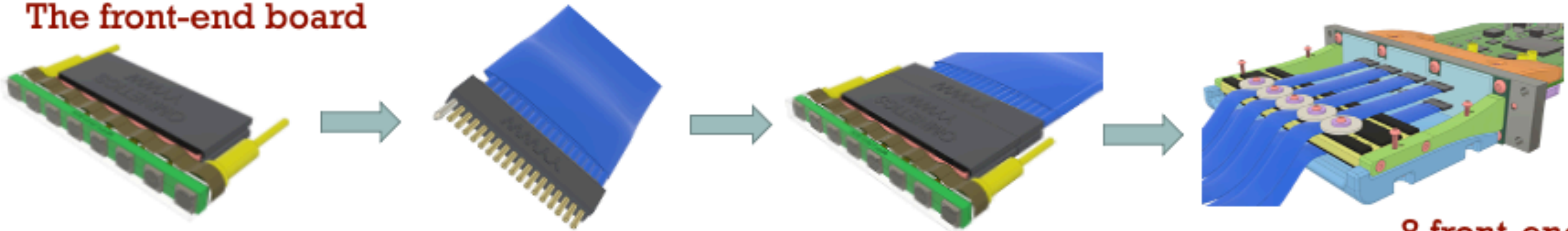
- Many options of **optical calorimeters** being developed for **future e^+e^- colliders**.
  - Single DRD6 track with **the most proposal submissions**.
- Many different paradigms being explored in parallel (homogeneus crystals, high granularity, dual readout, etc.)
- Each option comes with **its own challenges**. Some challenges are common:
  - **Sensor** sensitivity to short wavelengths, light yield struggle for Cherenkov, **readout granularity and scalability**.
- The field is healthy - big hopes for **ECFA DRD process**
  - A good framework to optimise **large-scale strategic R&D**, suppressing duplication.
  - And very **positive and constructive discussions** so far.
- A lot of work ahead (and behind) us. Everyone is **really opened to collaborating**, and happy to welcome new colleagues!

Backup

Dual readout calorimeter at work



The front-end board



8 front-end boards connected to 1 FERS

- Each SiPM is individually qualified: crucial for the system commissioning

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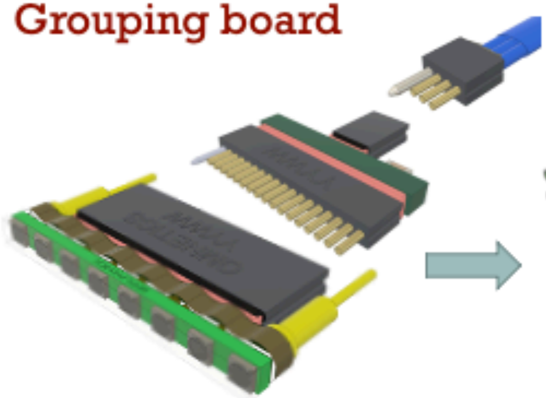
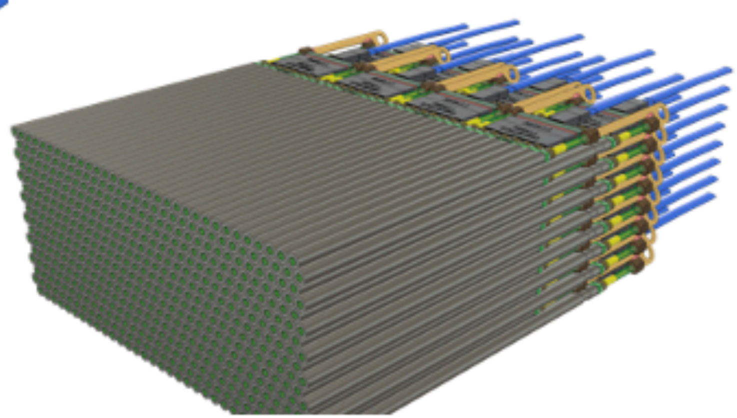
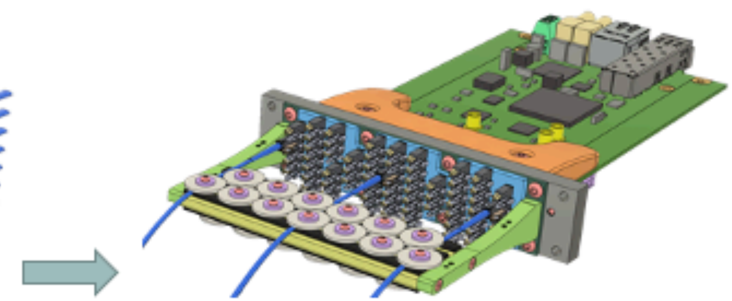
Grouping board



The Mini-Module



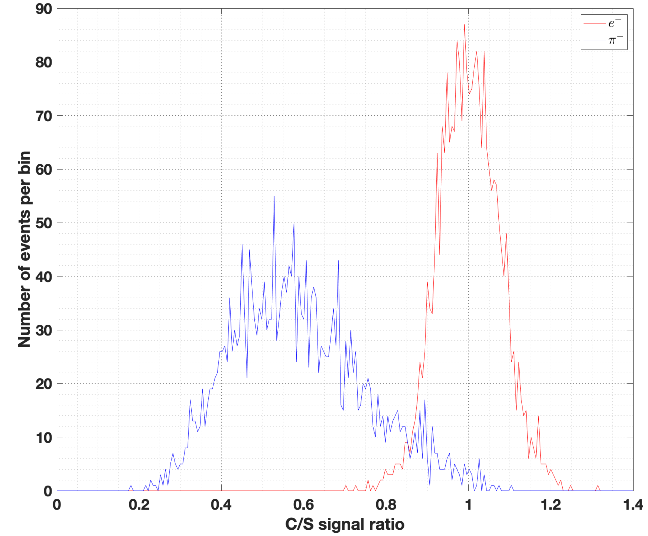


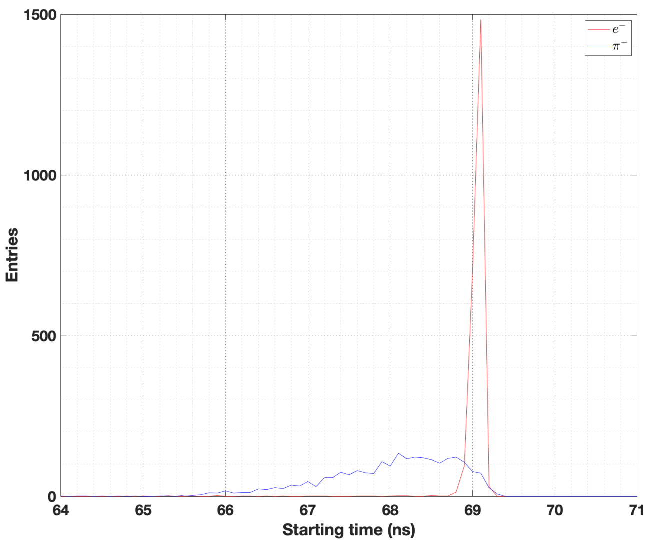
1 FERS serves 64 front-end boards with grouping

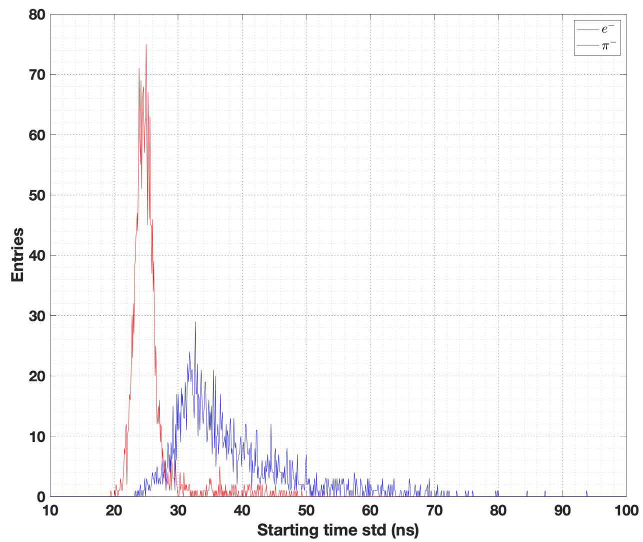
- Each bar of SiPMs will be operated at the same voltage (ΔV_{bd}<0.15V)
- The signals from 8 SiPMs are summed up in the grouping board

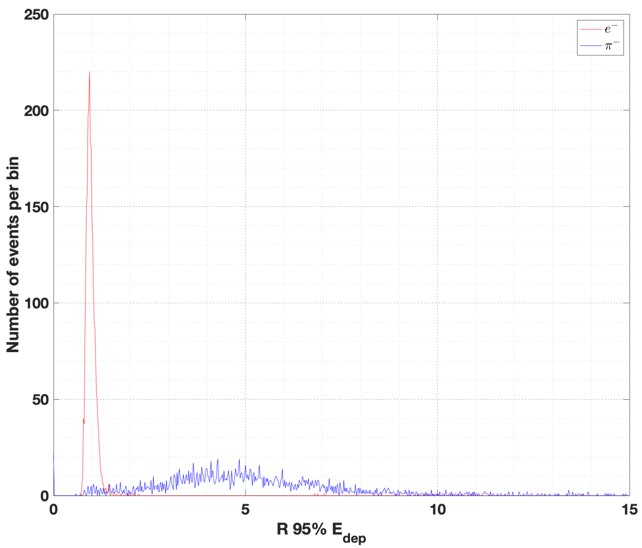
Particle identification

- Compare **electron and pion** shower shapes (20 GeV)
- Consider also **Time of arrival** of signal to SiPM (fiber propagation and SiPM + electronics time response parametrised in full sim)
- Combined performance: ε = 99.5%, fake ~1%









Tau decay identification

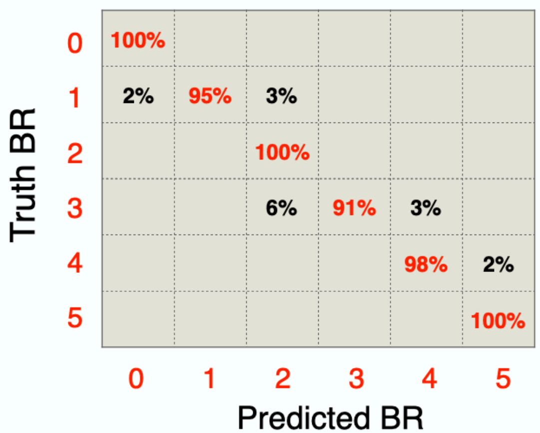
Advanced Machine Learning Applications

Some advanced applications on object reconstruction and identification are proceeding in parallel to the analytical approach. Some examples: tau lepton decays identification.

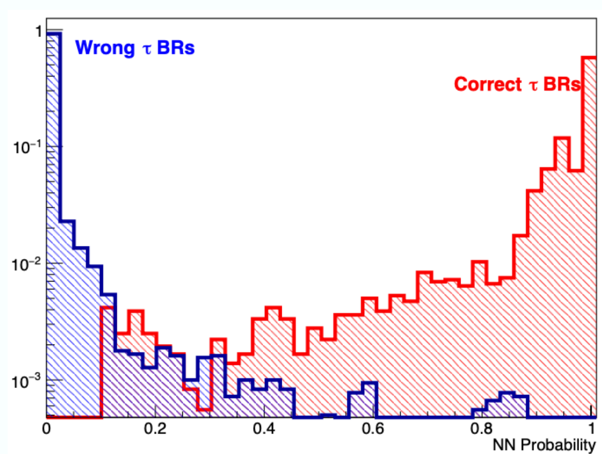
Data preprocessing needed to reduce data size and fit GPU memory

- Signals from fibers in each 1.2x1.2 cm^2 module are integrated to obtain a 111x111 matrix
- 5 information used for each matrix element: signal integral, signal height, peak position, time of crossing threshold and time-over-threshold
- Independently done for scintillation and Cherenkov fibers
- Each event is a 111x111x10 tensor

Confusion matrix shows a 97,3% average accuracy.



CNN output on test sample:

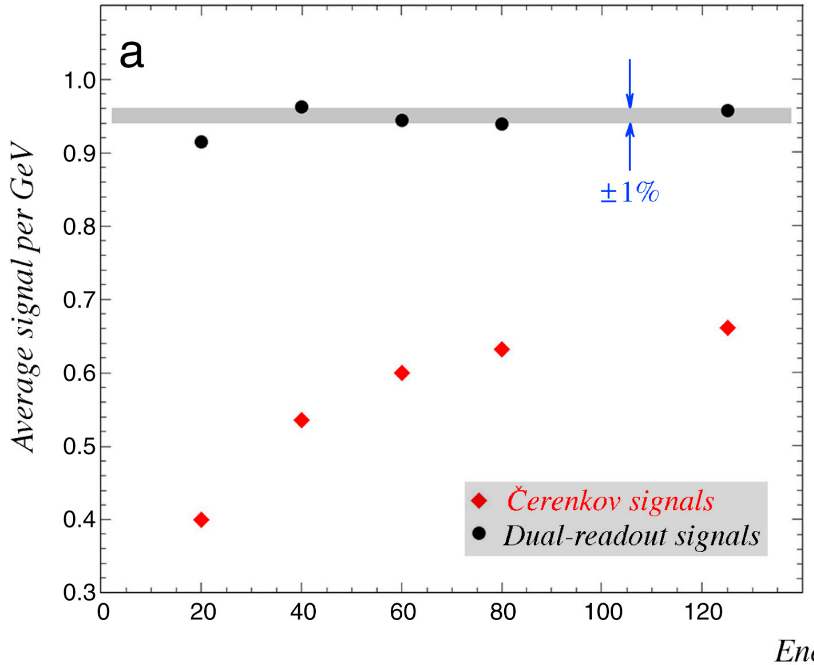


0	pi0 pi- nu_tau
1	e- anti_nu_e nu_tau
2	mu- anti_nu_mu nu_tau
3	pi- nu_tau
4	pi- pi- pi+ nu_tau
5	pi0 pi0 pi- nu_tau

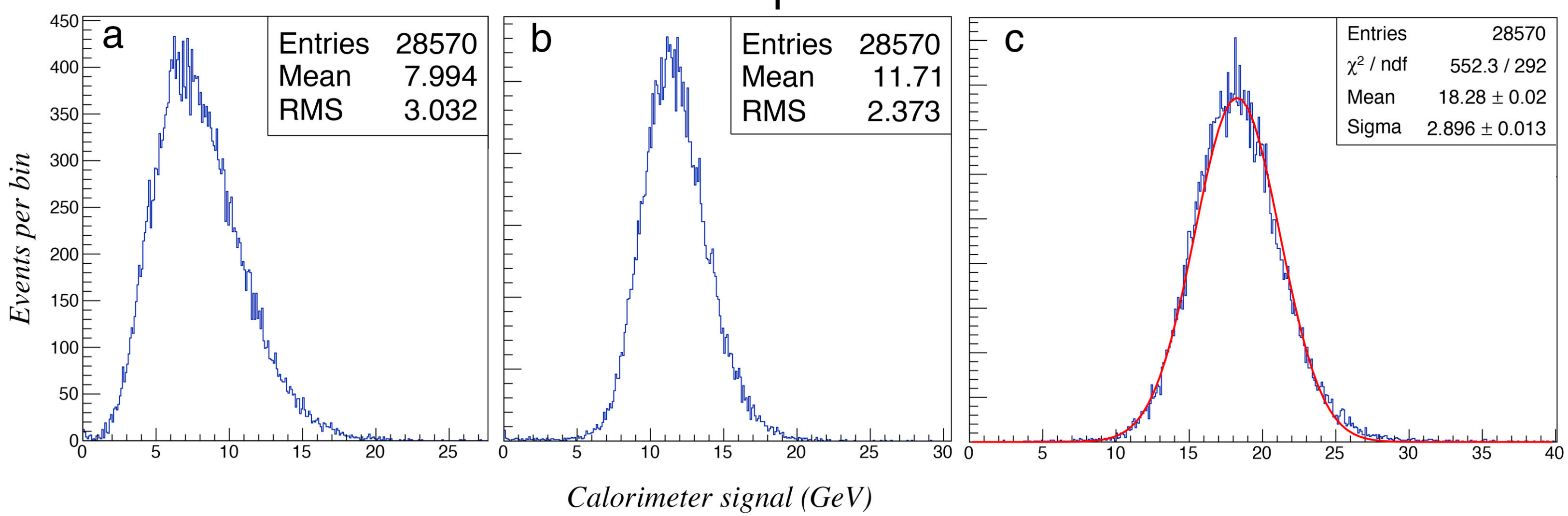
Single hadron response - linearity

NIM A 866 (2017) 76

- Dual readout signal **largely recovers linearity** while vastly improving resolution.



20 GeV pions



Shower shape

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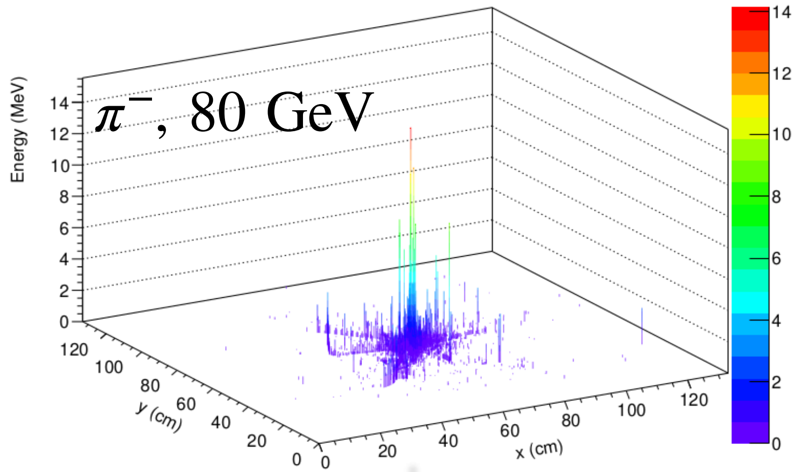
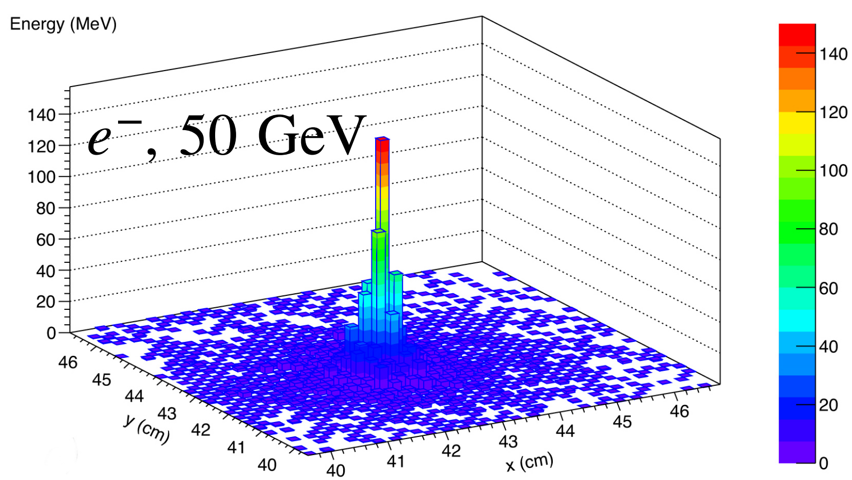
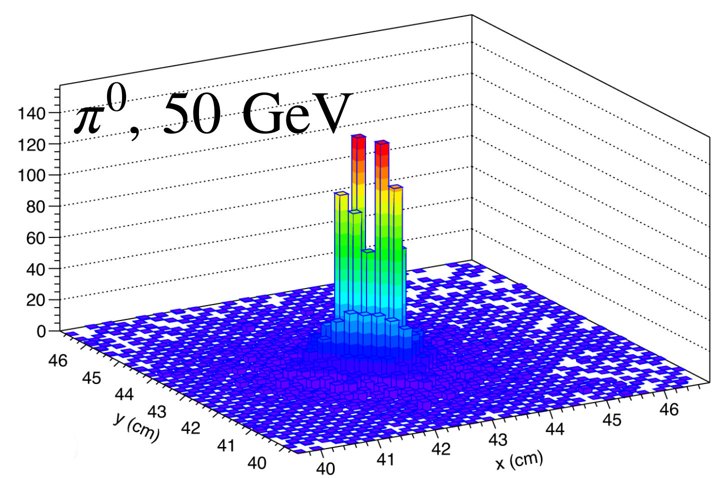
Work in progress

- Single particle shower shape
  - Using full implemented granularity

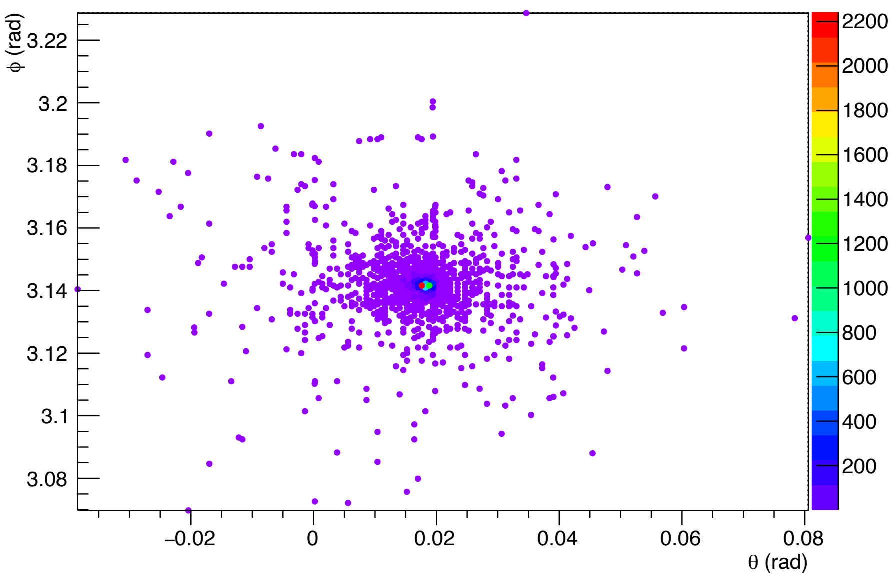




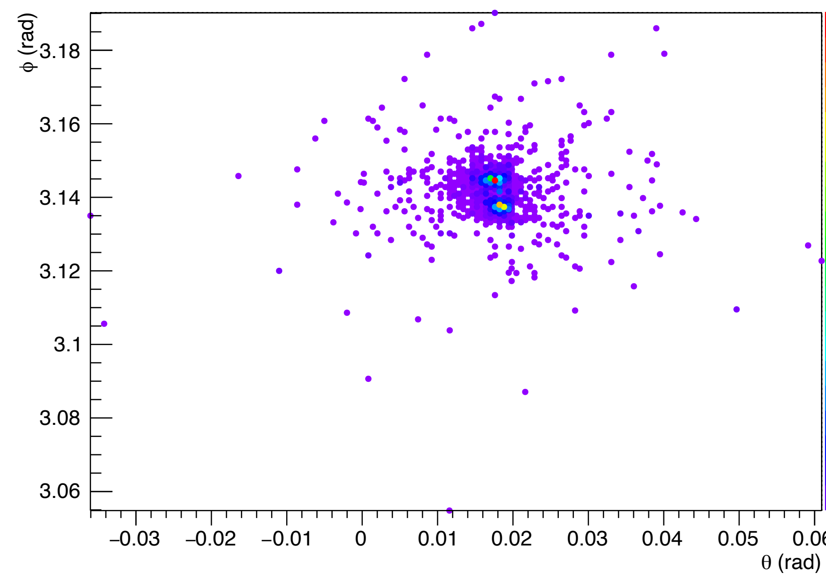


How events look like (full granularity)

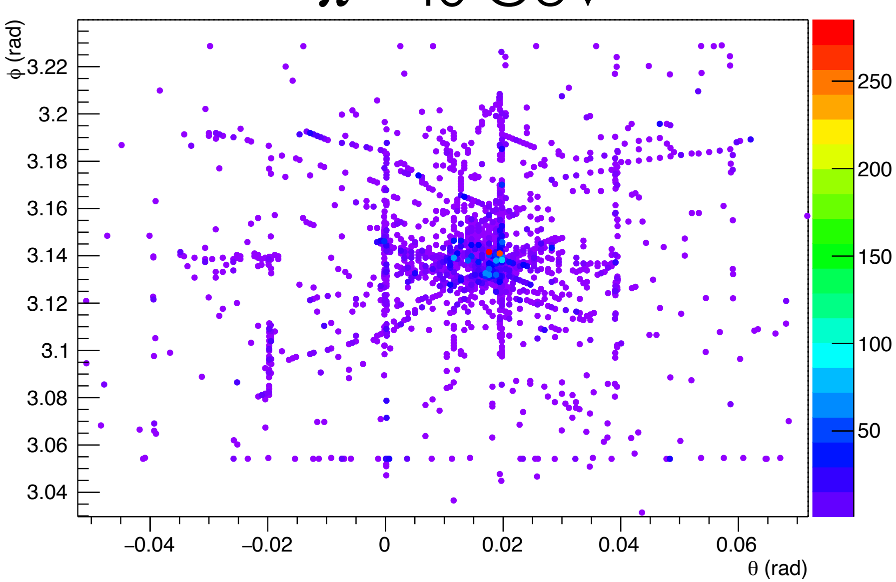
e- 40 GeV



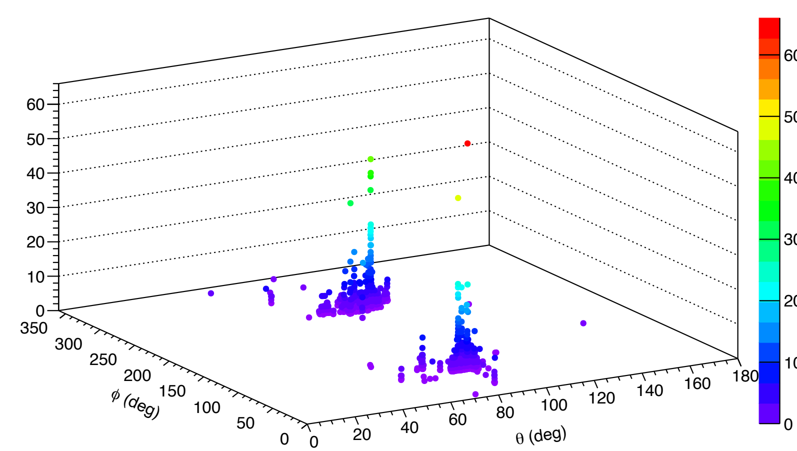
π^0 40 GeV



π^- 40 GeV



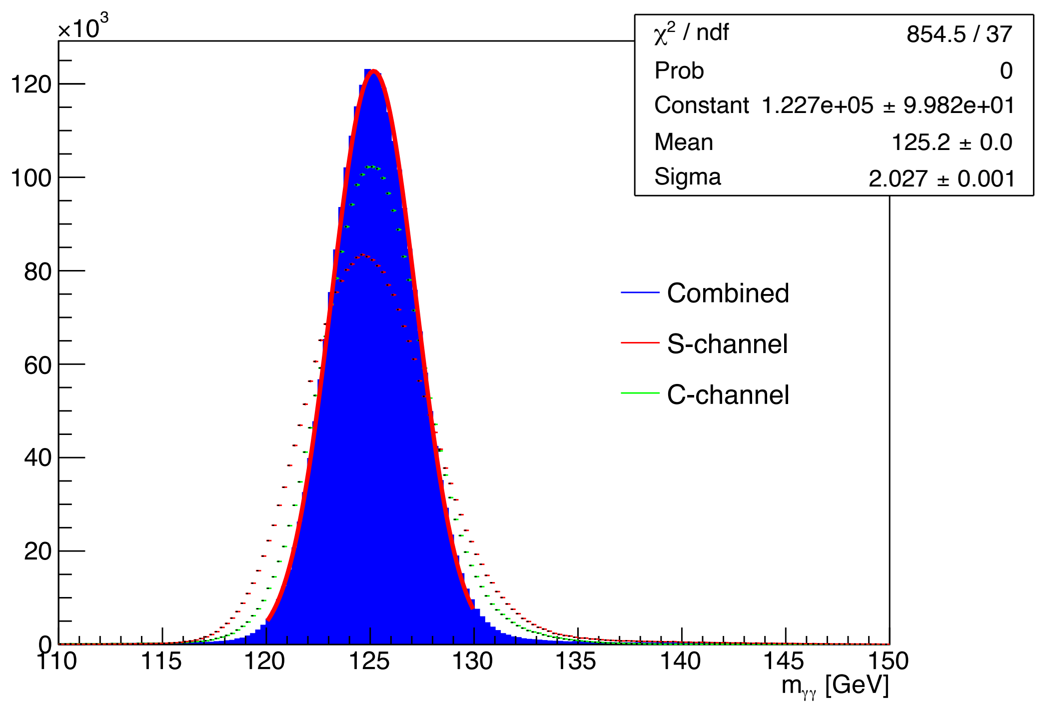
Di-jet



$H \to \gamma\gamma$ as a photon candle

- Using 5M $e^+e^- \to ZH \to \nu\nu\gamma\gamma$ events and clustering opposite calorimeter hemispheres as photons.
- Dedicated calibration corrections for impact point on tower

- Using tower granularity (estimated use of full granularity further improves mass resolution by 20%)
- Combined mass resolution ~ 2 GeV



Jet response

- Studied in **di-jet events so far** (reconstructed with ee_genkt algorithm in two exclusive jets)
- Separately reconstructing **S, C and truth-level jets**.
- Event cleaning: **central jets only** considered; reject events with **muons or neutrinos or poor containment**.
- Two options considered (with and without $1X_0$ of additional "tracker" material):

Calo only

$$E_j^r = \frac{E_j^s + \chi E_j^c}{1-\chi}$$ + dedicated calibration

Calo + charged

$$E_j^{r*} = E_j^{ch} + E_j^s - \frac{E_j^s E_j^{ch}}{E_j^r}$$ + dedicated calibration

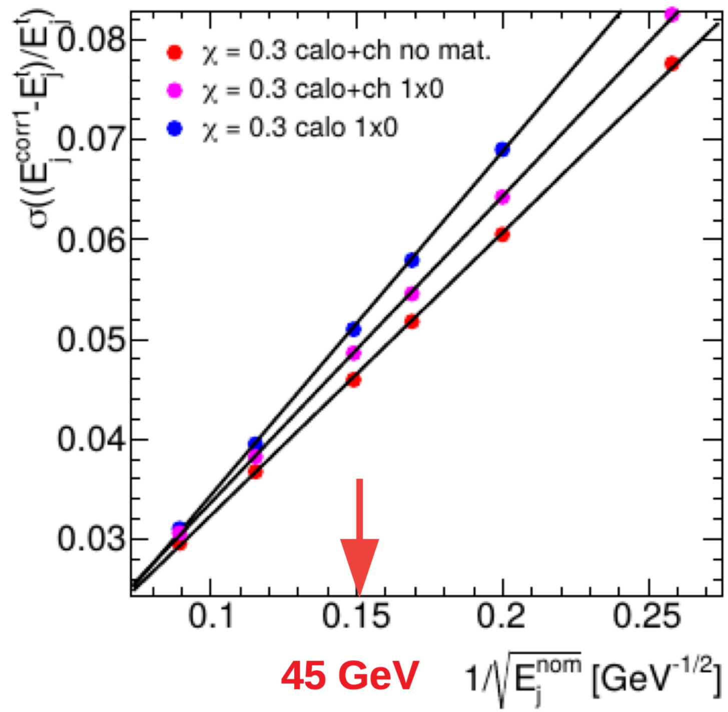
(Sum charged component and total energy, then correct for double counting)

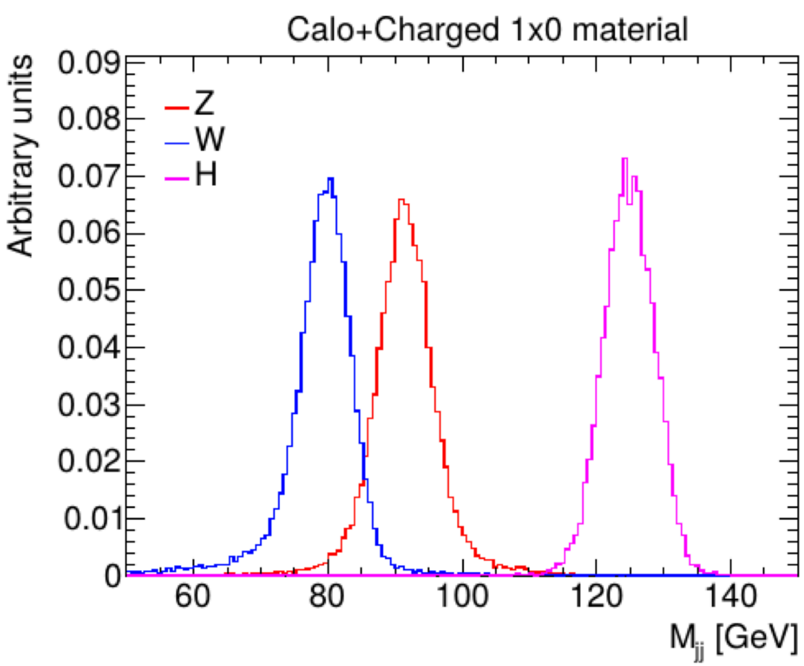
Jet response

Dual readout achieves linearity with a resolution of **30%/√E with constant term ~ 0.5%**

Resonances studied with

$$e^+e^- \to ZH \to jj\tilde{\chi}_0^1\tilde{\chi}_0^1$$
$$e^+e^- \to WW \to jj\mu\nu$$
$$e^+e^- \to ZH \to \nu\nu bb$$

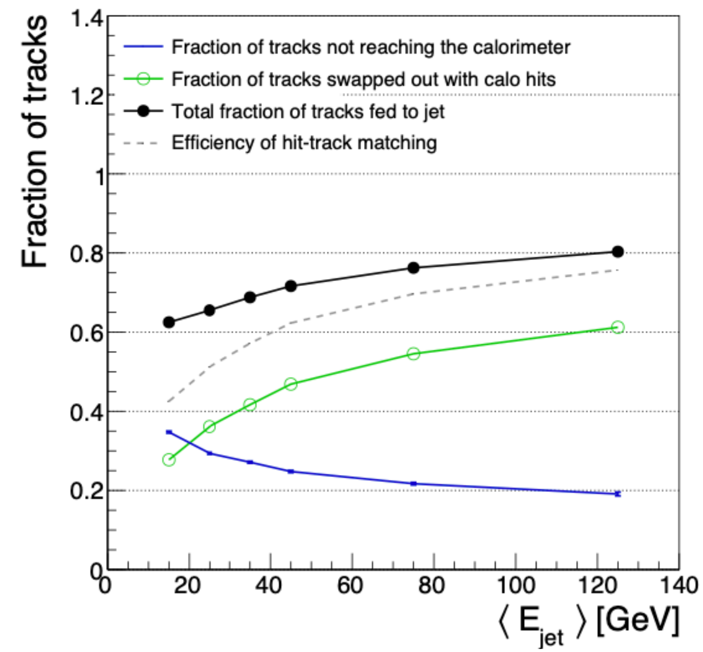


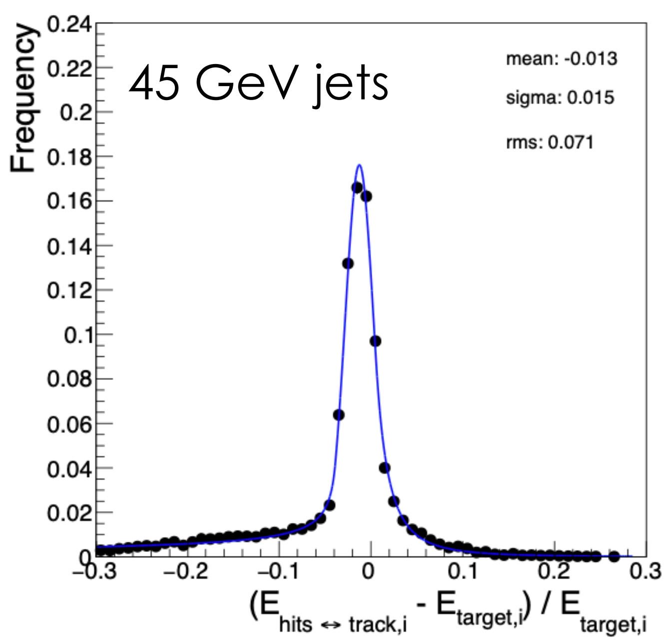


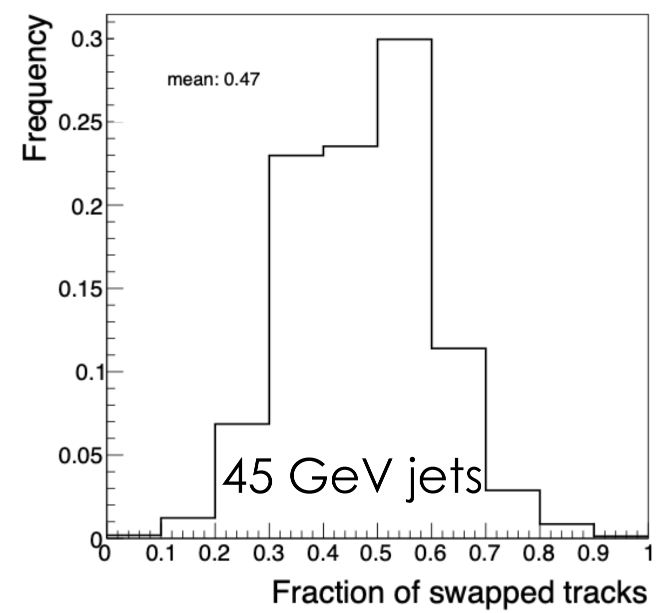
Configuration	W		Z		h	
	Δm	σ	Δm	σ	Δm	σ
Calo no material	-0.108	3.02	-0.009	3.14	-0.01	3.72
Calo+Ch no material	0.07	2.86	0.18	3.05	0.10	3.48
Calo 1X0	-0.08	3.14	-0.13	3.73	-0.18	3.95
Calo+Ch 1X0	0.08	3.01	0.21	3.26	-0.13	3.72

Particle flow

- A simple PF algorithm implemented for crystal + fibres calorimeter.
  - **Track-to-calo match** based on difference between expected response and track momentum.
  - Further refinement and enhancement possible, but implementation **good enough to see potential**.
  - More complex, machine-learning options for PF being explored as part of AIDAinnova for the fibre calorimeter.







Longitudinal segmentation via timing

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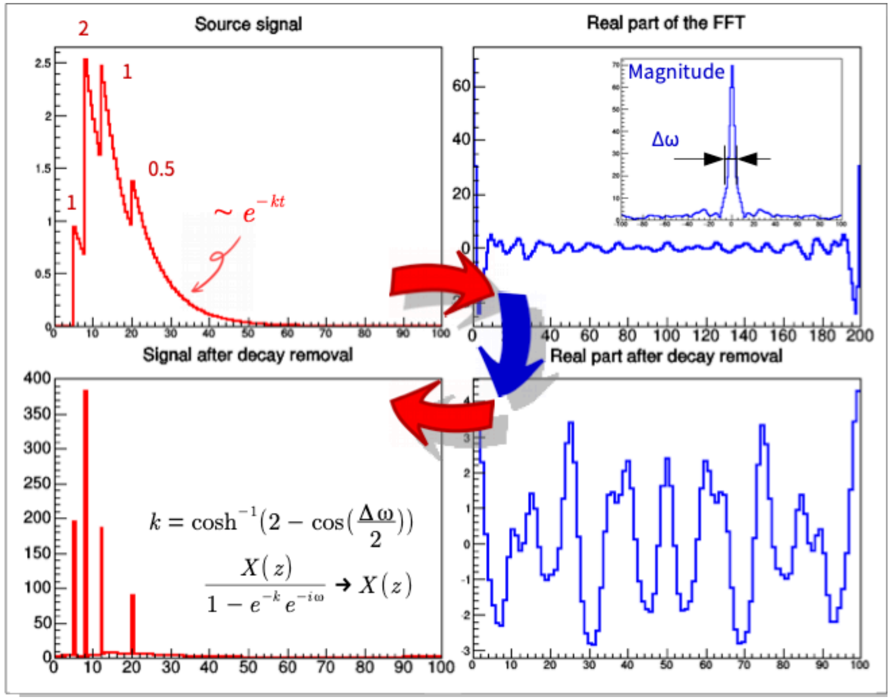
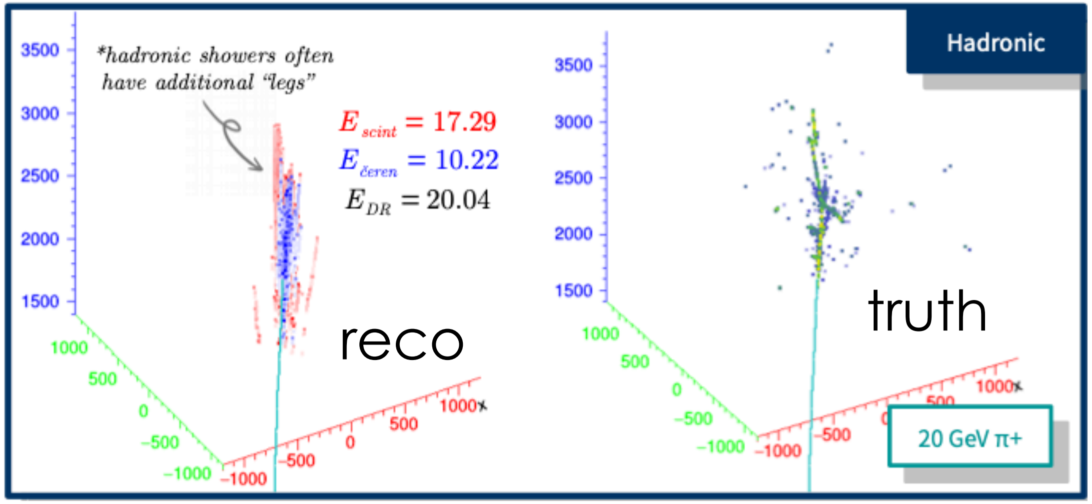
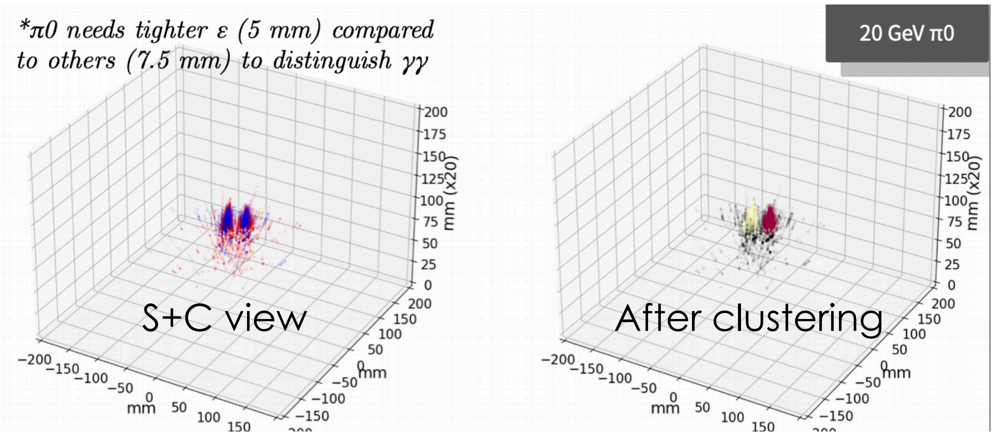
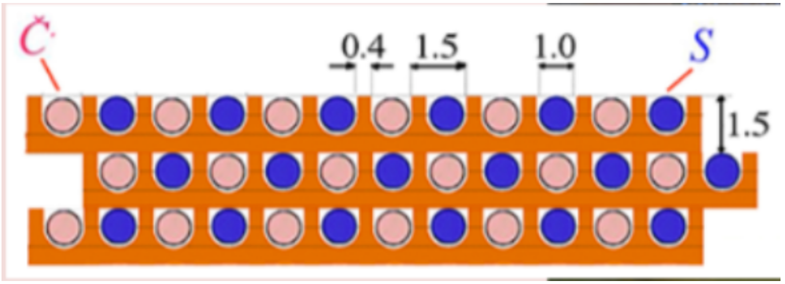
- Assume to read out **full signal from SiPM** sampled at 10 GHz.
  - Full SiPM response integrated in simulation/ digitization output.
- **FFT of signal** yields individual fiber hits and high-precision (< 100 ps) timing.
- Unlocks **full longitudinal information** about energy deposit.
- Combined with dual readout information allows **in-shower cluster identification.**
- See S. Kho's talk at Calor 2022.

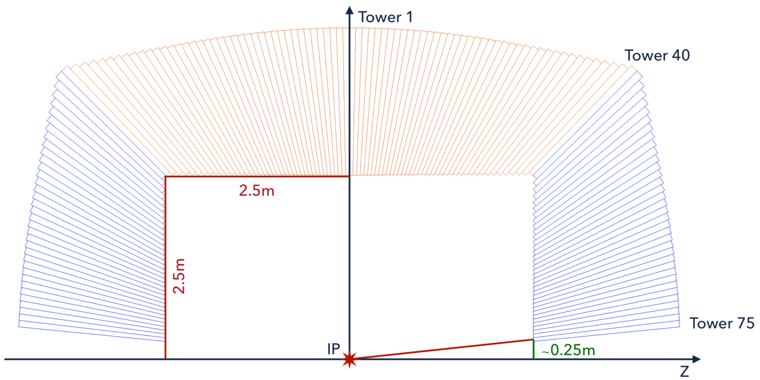


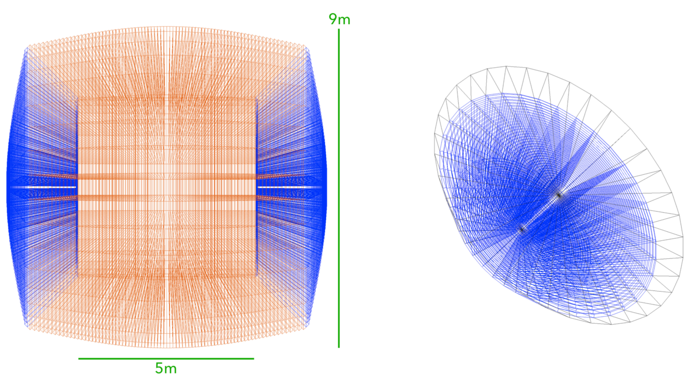




Physical separation



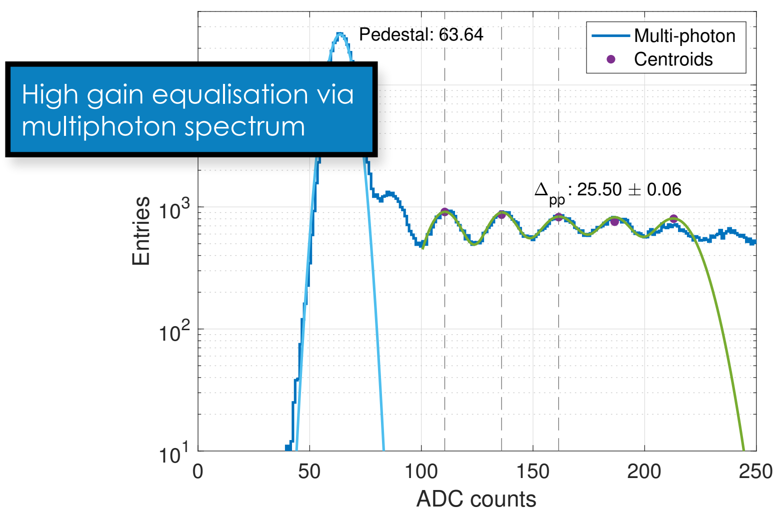


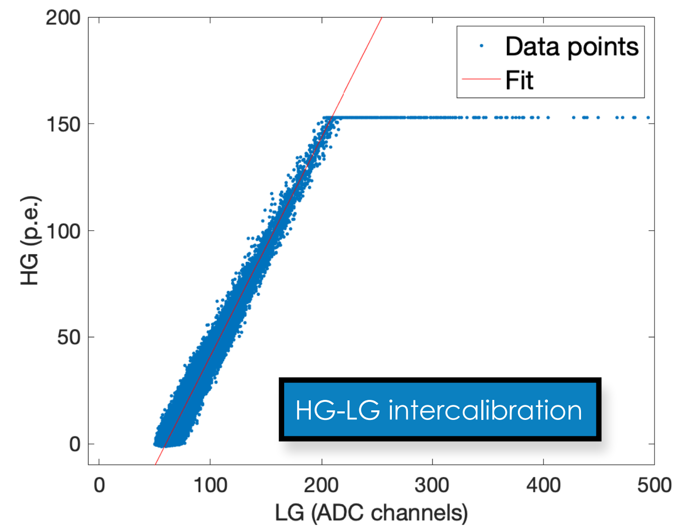


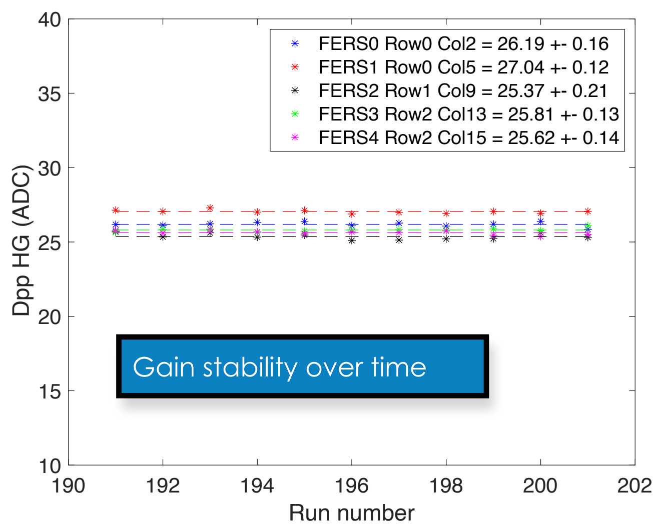
- **G4 simulation** of IDEA calorimeter:
  - For the calorimeter: Cu absorber, 1 mm fibers, 1.5 mm pitch.
- **130 M fibers channels:**
  - **Excellent angular resolution**, lateral shower shape sensitivity (if full granularity is retained).
  - **No longitudinal segmentation** out of the box.
- Full simulation **including drift chamber and solenoidal magnetic field** available
  - Already based on edm4hep. Integration with DD4hep ongoing.
  - See https://github.com/HEP-FCC/IDEADetectorSIM.

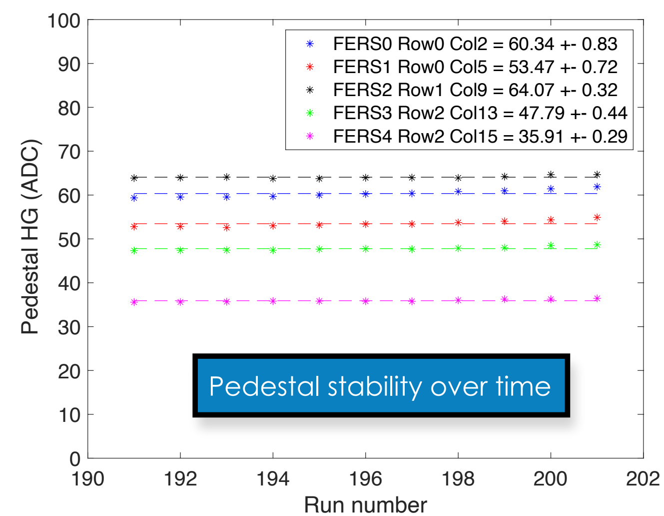
TB calibration procedure

- SiPM equalisation obtained with **multiphoton spectrum** plus **intercalibration of high and low gain.**



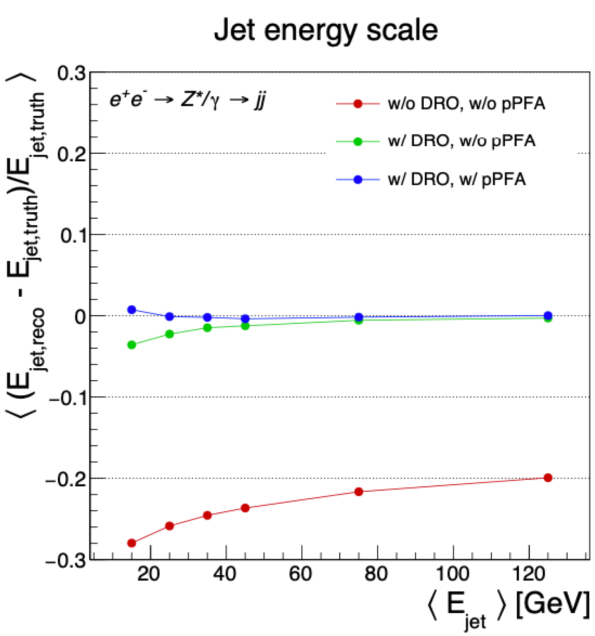


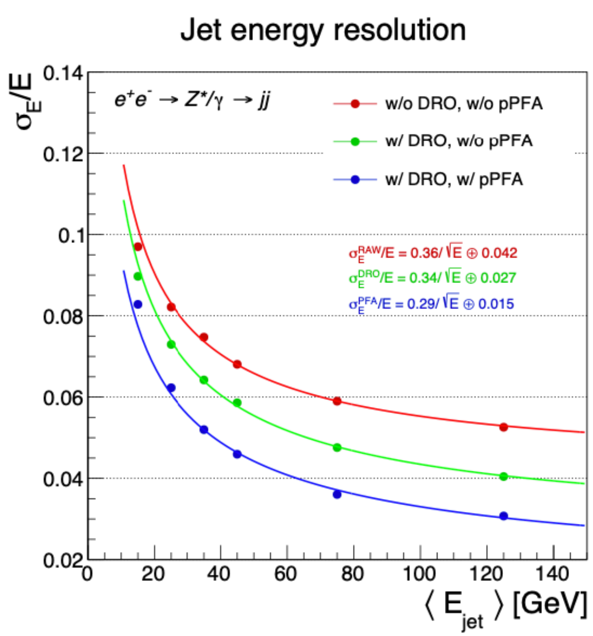


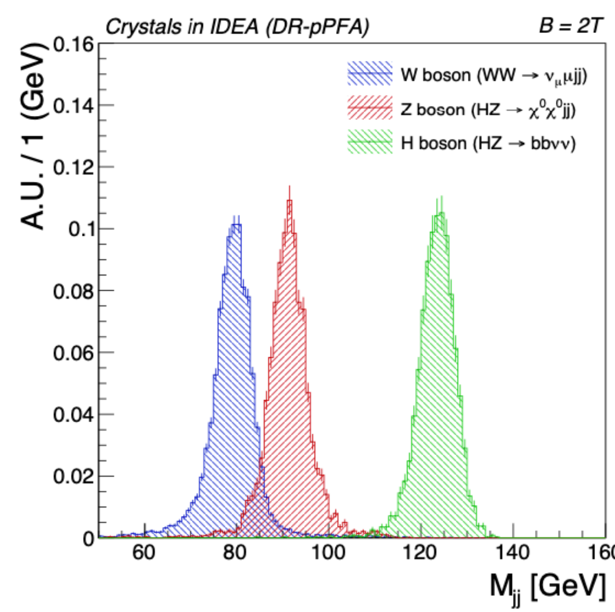


Crystal + fibre calorimeter - results

- Performance studies done on events with jets for a few different configurations:
  - No dual-readout (DRO) no Particle Flow Algorithm (PFA) applied.
  - With DRO but no PFA.
  - With DRO and PFA.
- **DRO recovers linearity** of the calorimeter response and improves resolution. PFA **further boosts resolution.**
  - **4.5**% at 50 GeV within reach.







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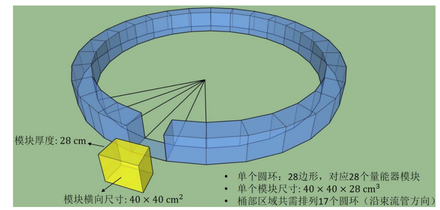
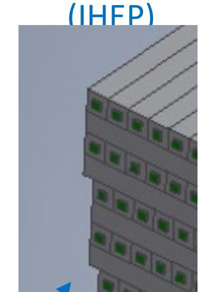
General geometry design of crystal ECAL

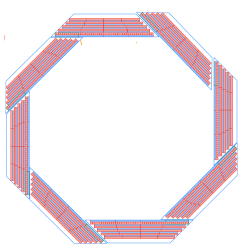
- CEPC crystal ECAL barrel geometry design
  - Finer segmentation of towers for better homogeneity
  - Decrease outer radius for lower cost of the outer detectors
  - 28 towers per ring, 17 rings along beam direction
  - ~25 radiation length: 28 layers



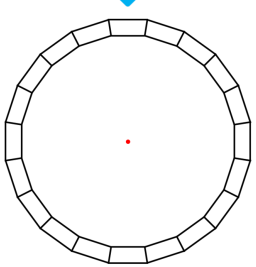
Quan Ji, Chang Shu (IHEP)



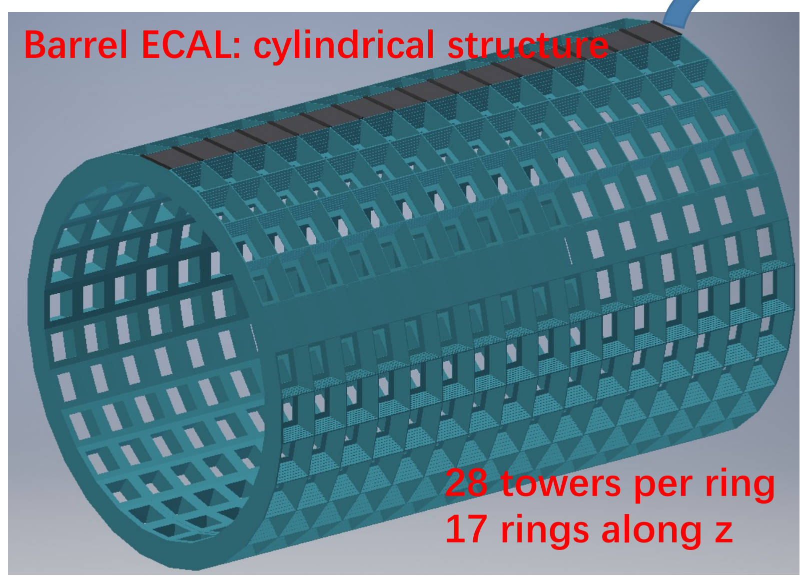
4 layers per "step" with the same transverse size

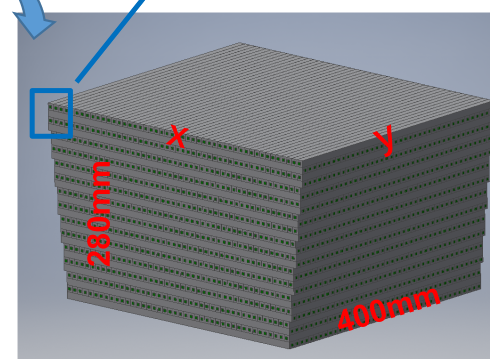


Previous design: octagonal detector



New design: cylindrical crystal ECAL





Key questions
- Space for electronics and cooling
- Assembly