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The IDEA detector concept calorimeter system

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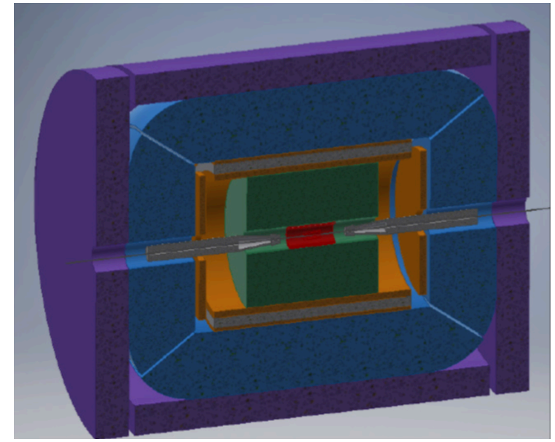
University of Sussex

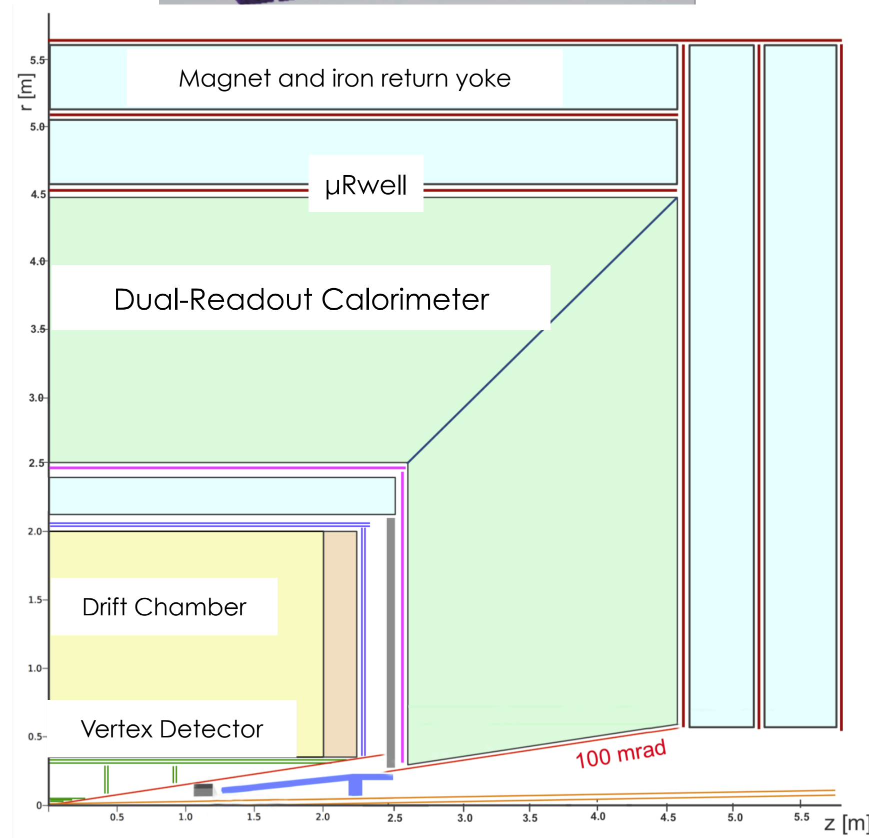
On behalf of the IDEA detector concept

IDEA (Innovative Detector for Electron-positron Accelerators)

- **Key points:**
  - **Silicon VTX detector plus ultra-low material drift chamber.**
    - Minimised multiple scattering for momentum range of interest.
  - Thin solenoid in front of the calorimeter.
  - **Single, dual-readout calorimeter** for **EM and HAD** calorimetry.
    - Option to have a **crystal, dual-readout** EM section.
  - **Pre-shower** and **muon spectrometer** based on μ-Rwell technology.

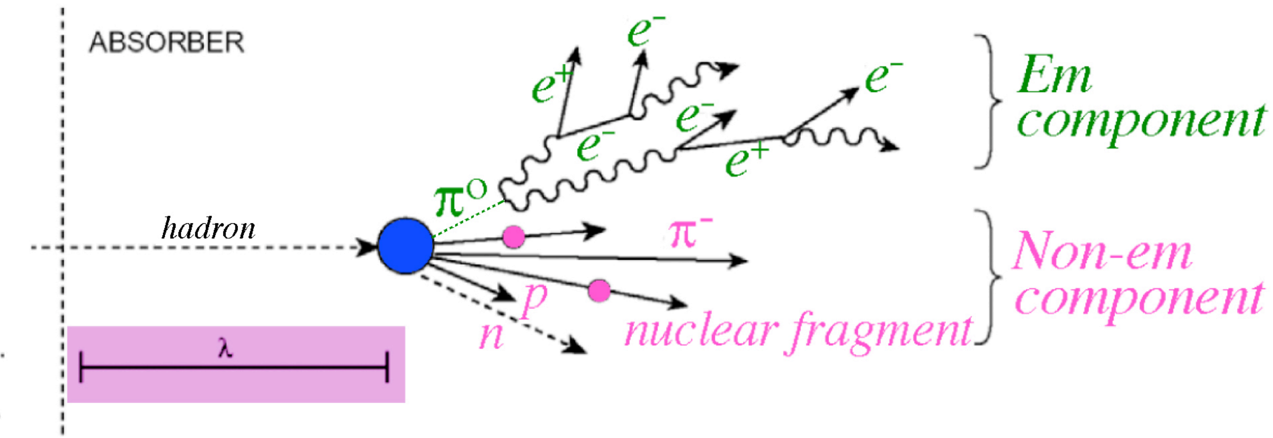
See overview talk from P. Azzi

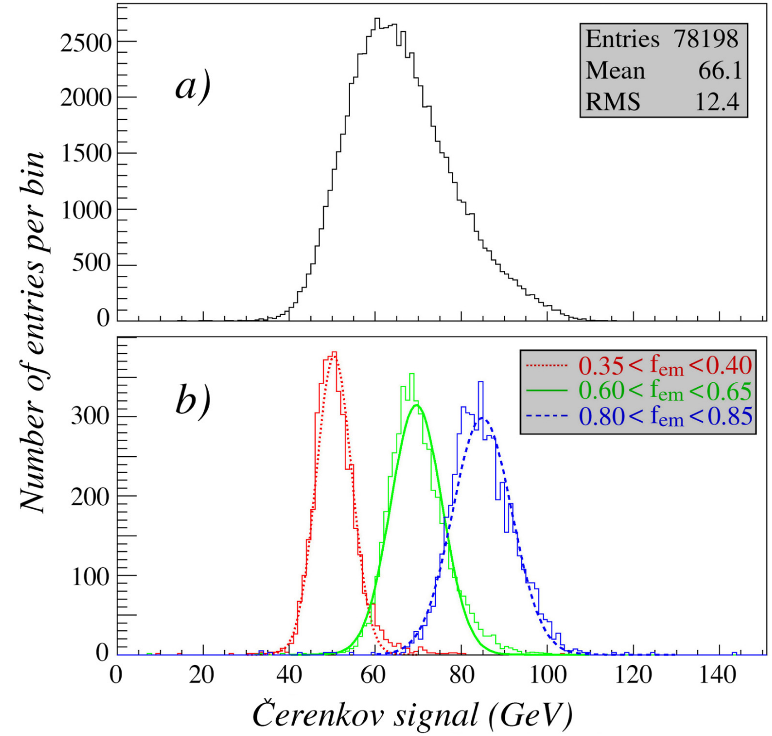




See also here for additional information

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.

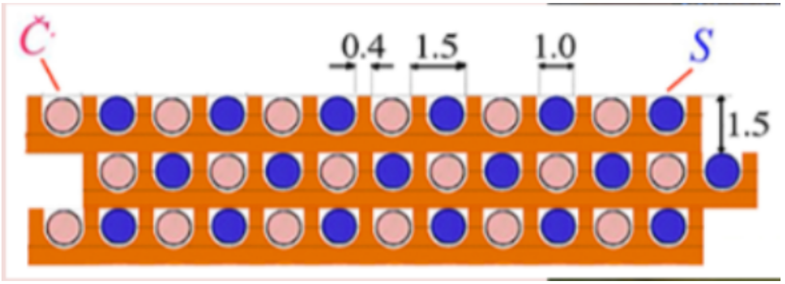
$$E_C = E\left(f_{em} + \left(\frac{h}{e}\right)_C (1 - f_{em})\right)$$

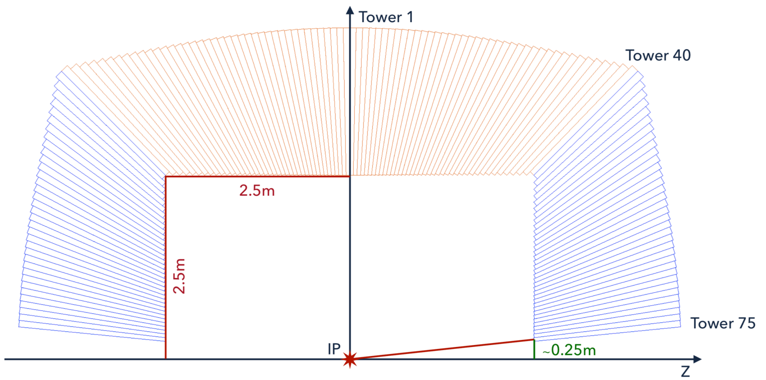
$$E_S = E\left(f_{em} + \left(\frac{h}{e}\right)_S (1 - f_{em})\right)$$

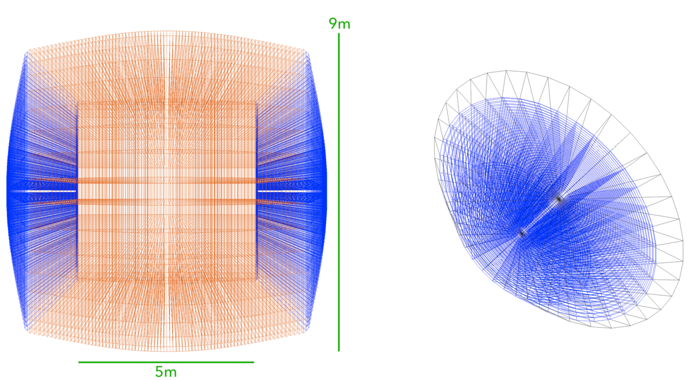
⇒

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

IDEA full simulation

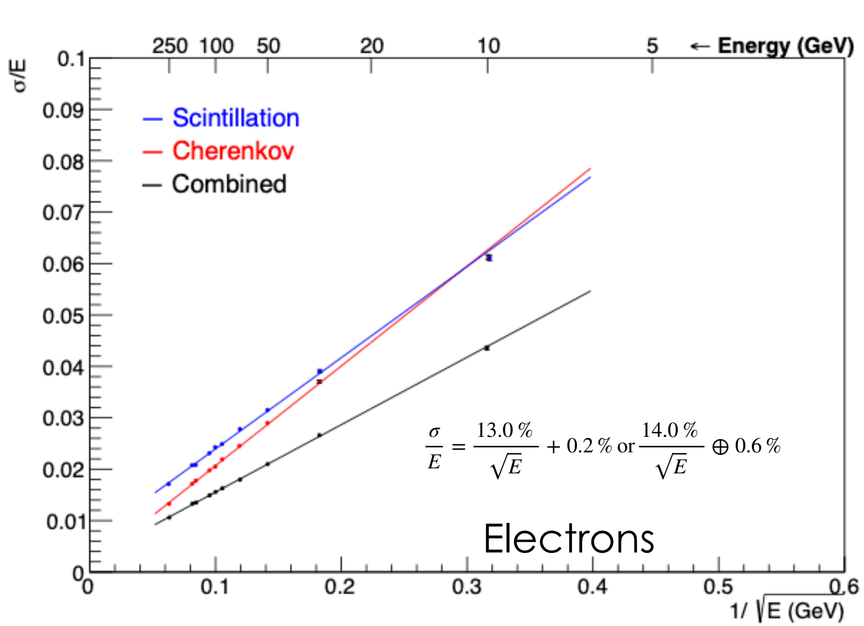


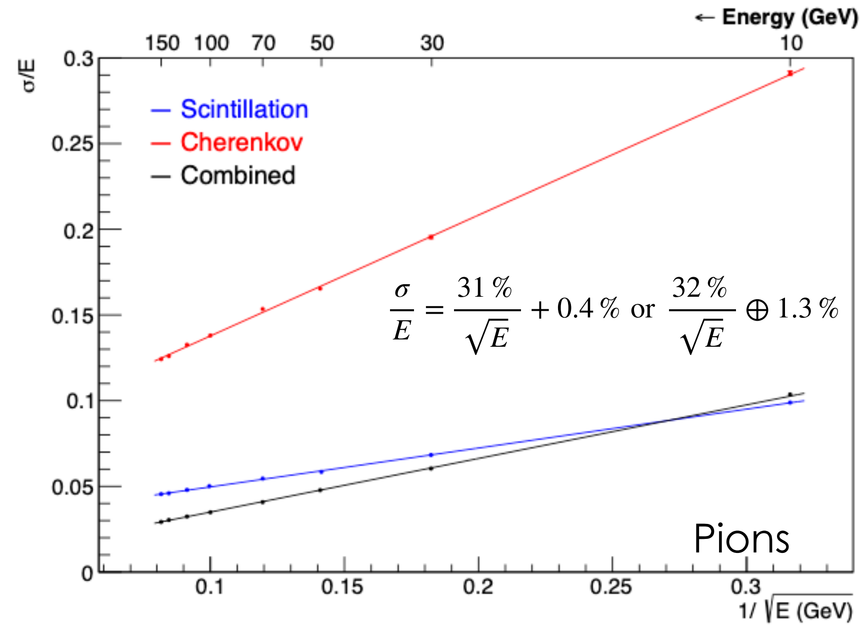


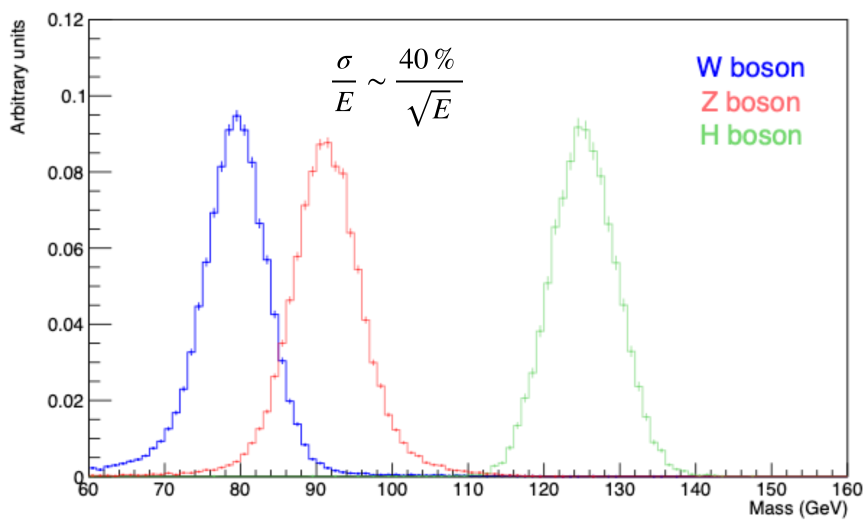


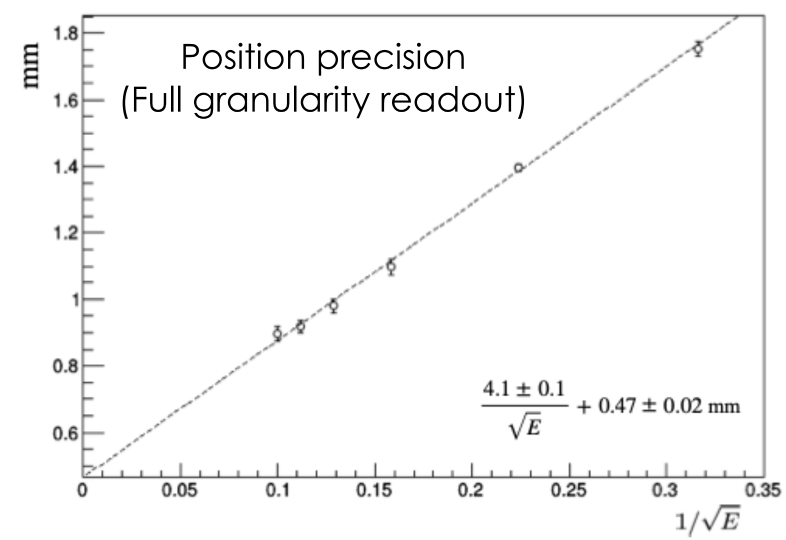
- **G4 simulation** of IDEA calorimeter:
  - For the calorimeter: Cu absorber, 1 mm fibers, 1.5 mm pitch.
- **130 M fibers channels:**
  - **Excellent angular resolution**, lateral shower shape sensitivity (if full granularity is retained).
  - **No longitudinal segmentation** out of the box.
- Full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

Full simulation performance in a nutshell









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

Longitudinal segmentation via timing

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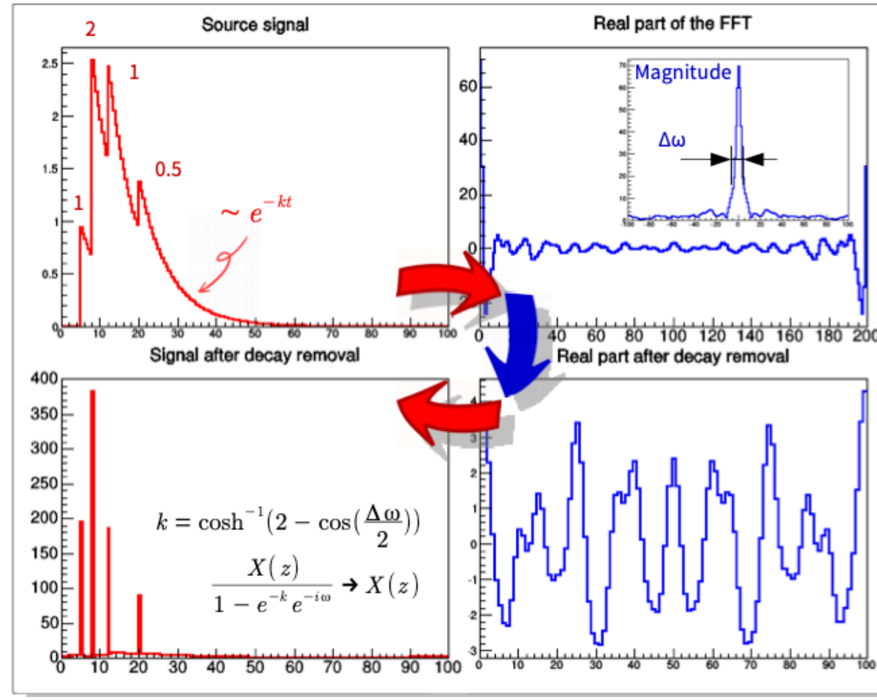
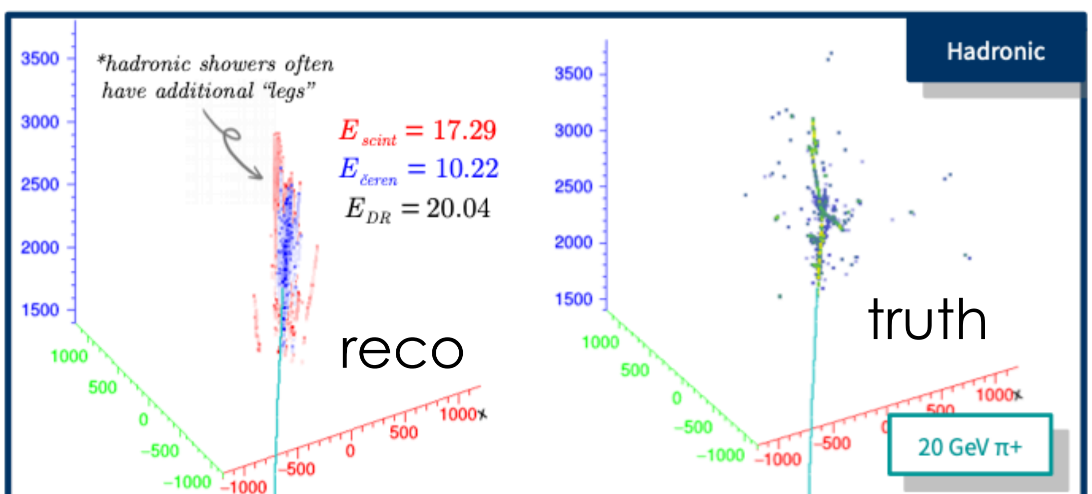
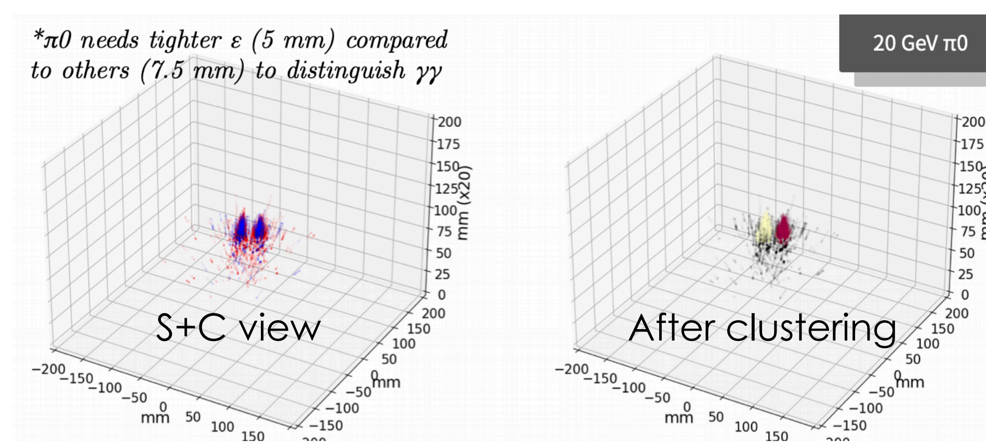
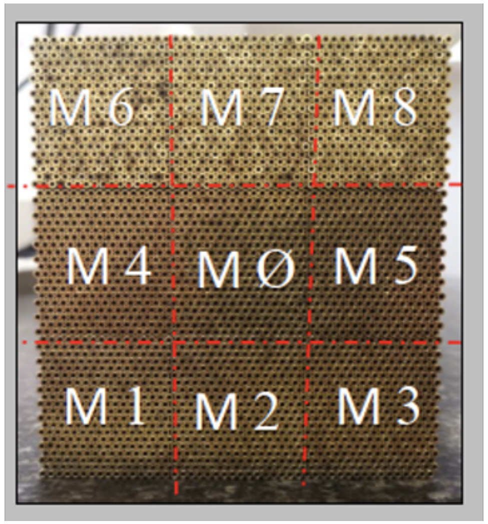
- Assume to read out **full signal from SiPM** sampled at 10 GHz.
    - Full SiPM response integrated in simulation/ digitization output.
- **FFT of signal** yields individual fiber hits and high-precision (< 100 ps) timing.
- Unlocks **full longitudinal information** about energy deposit.
- Combined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



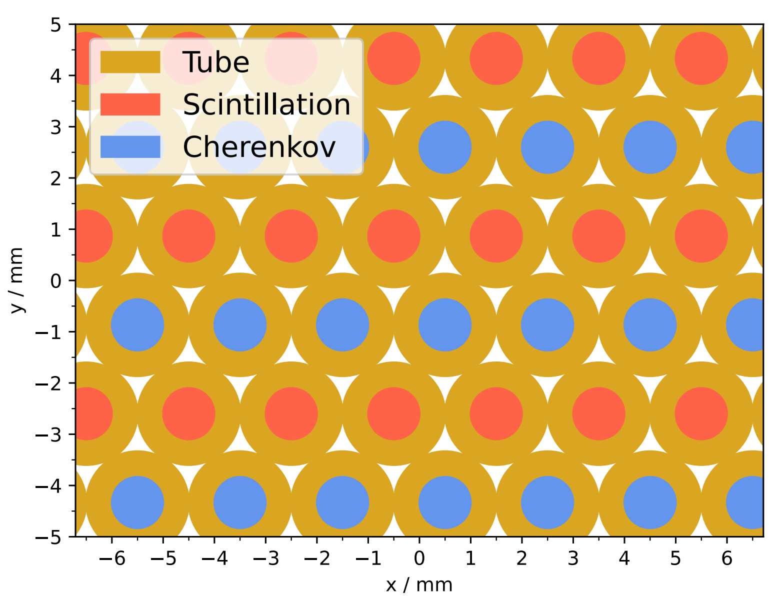


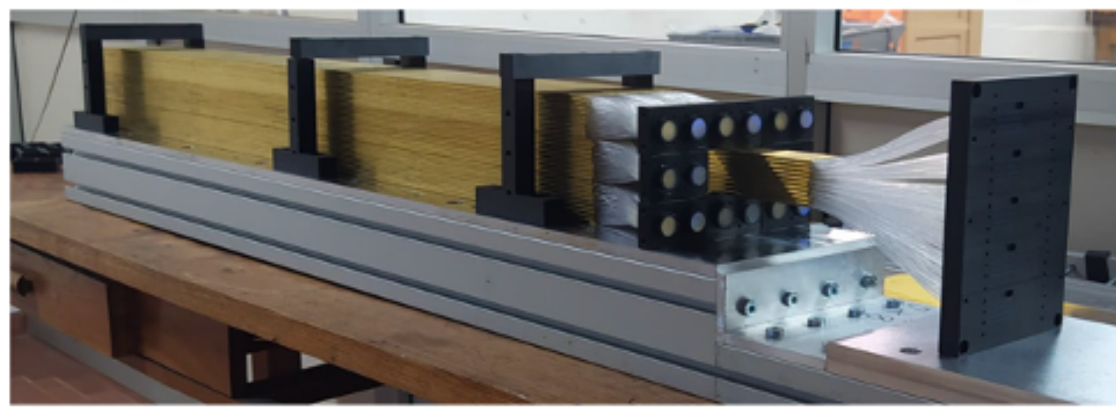


Bucatini calorimeter



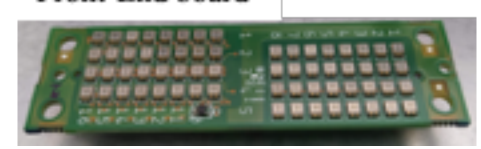
- Basic calorimeter unit: **one brass capillary tube** of 2 mm external diameter **hosting a fiber** (1 mm diameter).
- **EM-size prototype** (10x10x100 cm^3) put on beam (twice) in 2021.
  - 9 modules, each 16 x 20 capillary tubes.
- Readout:
  - M0 read with SiPM (one per fiber).
  - M1-8 read by 2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





FERS: readout boards

Front-End board



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

TB calibration procedure

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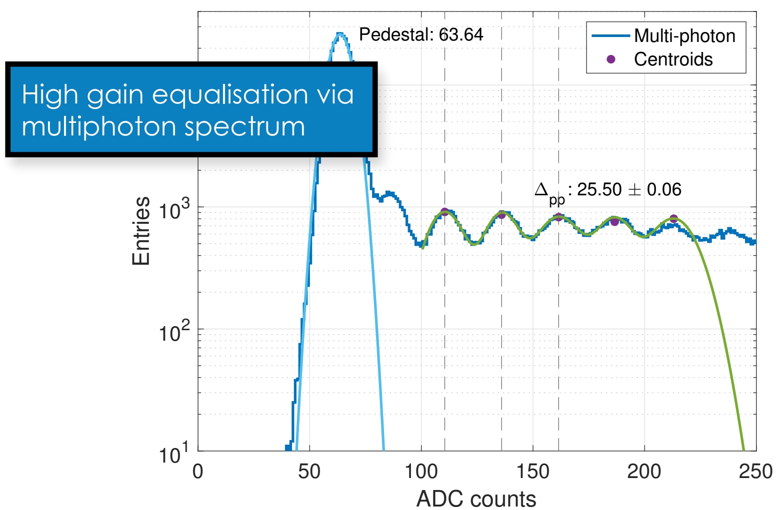
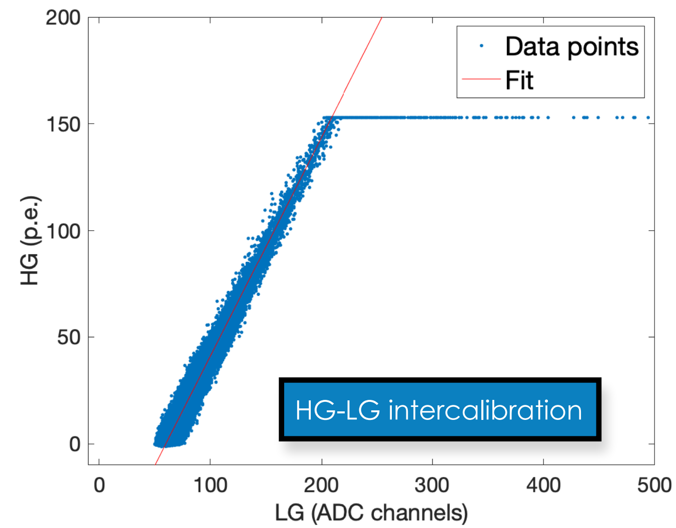
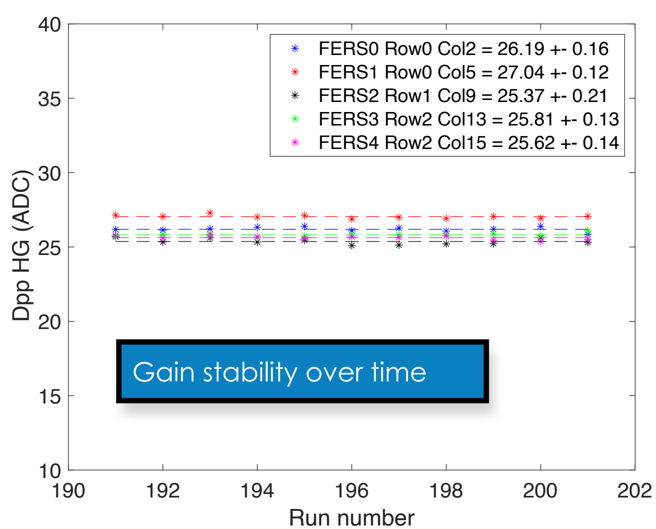
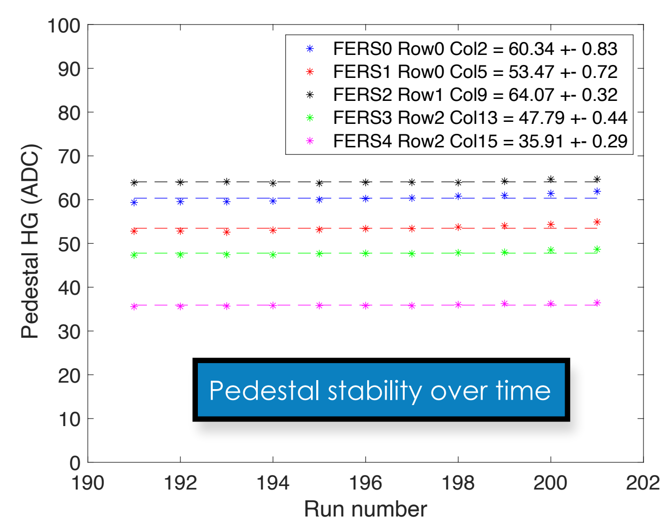
- SiPM equalisation obtained with **multiphoton spectrum** plus **intercalibration of high and low gain.**

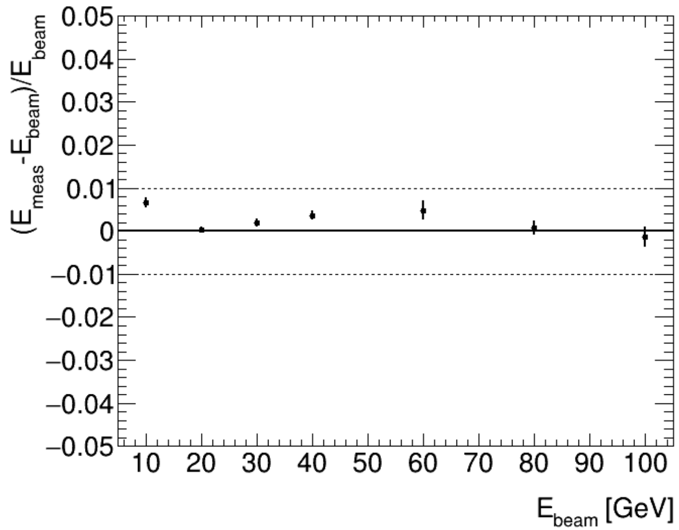




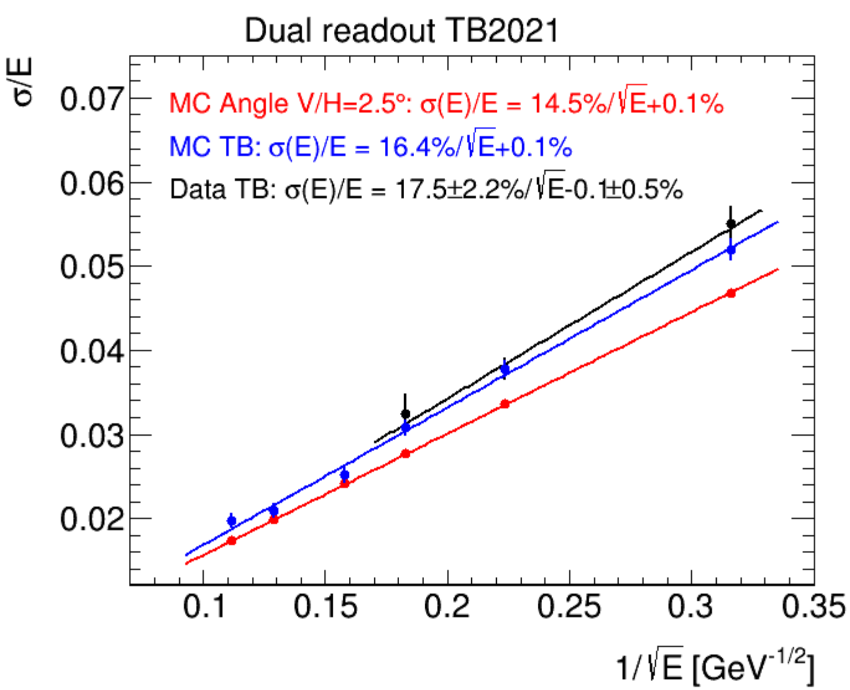


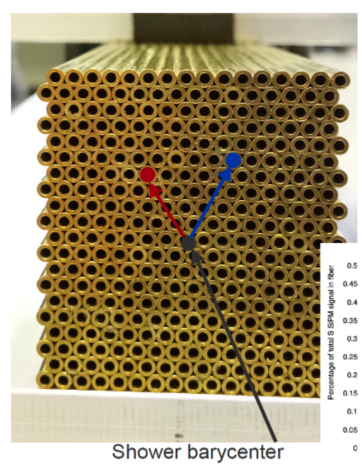


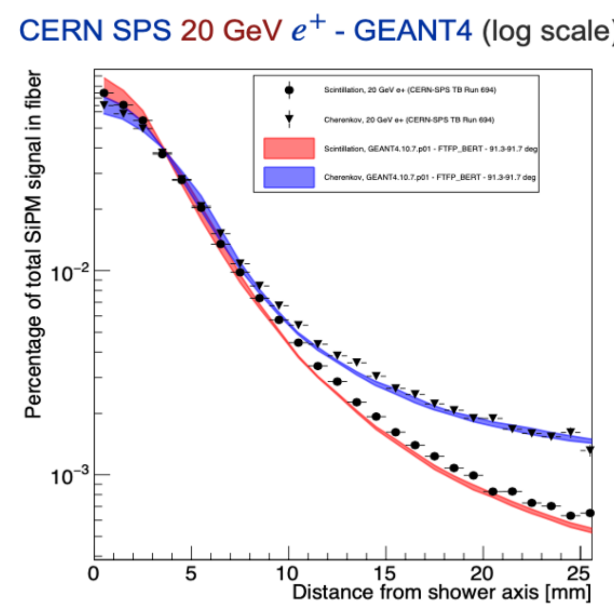
Results (bucatini calorimeter)



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

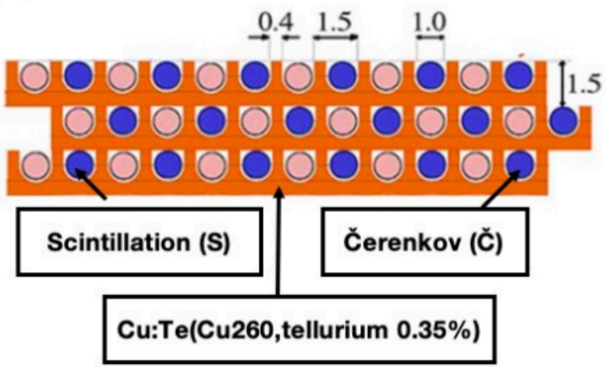






Not just bucatini

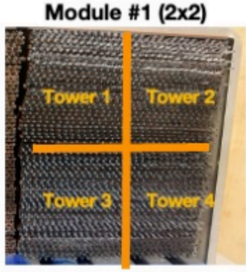
- **Copper Plate & Fibers**



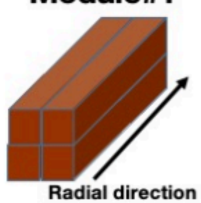
- **Copper plate (60)**
- Width : 10 cm
- Length : 2.5 m
- Thickness : ~1.6 mm
- Hole : 1 mm (diameter)
- Distance between hole : ~ 0.63 mm

- **Configuration of Fibers & Readout detector for Test Beam**

Module #1 (2x2)



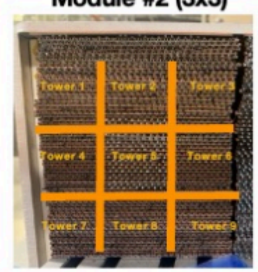
Module#1



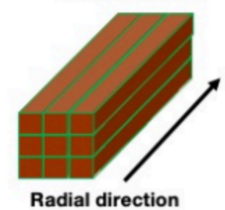
Module#1

Tower#1	Tower#2
Tower#3	Tower#4

Module #2 (3x3)



Module#2



Module#2

Tower#1	Tower#2	Tower#3
Tower#4	Tower#5	Tower#6
Tower#7	Tower#8	Tower#9

Combination of fibers for Module#1

	Tower #1	Tower #2	Tower #3	Tower #4
Scintillation fibers	Round / Single cladding	Round / Double cladding	Round / Single cladding	Square / Single cladding
Cherenkov fibers	Round / Single cladding	Round / Single cladding	Round / Single cladding	Round / Single cladding
Readout detector (2*4 ch)	2 PMTs	2 PMTs	2 MCP-PMTs	2 PMTs

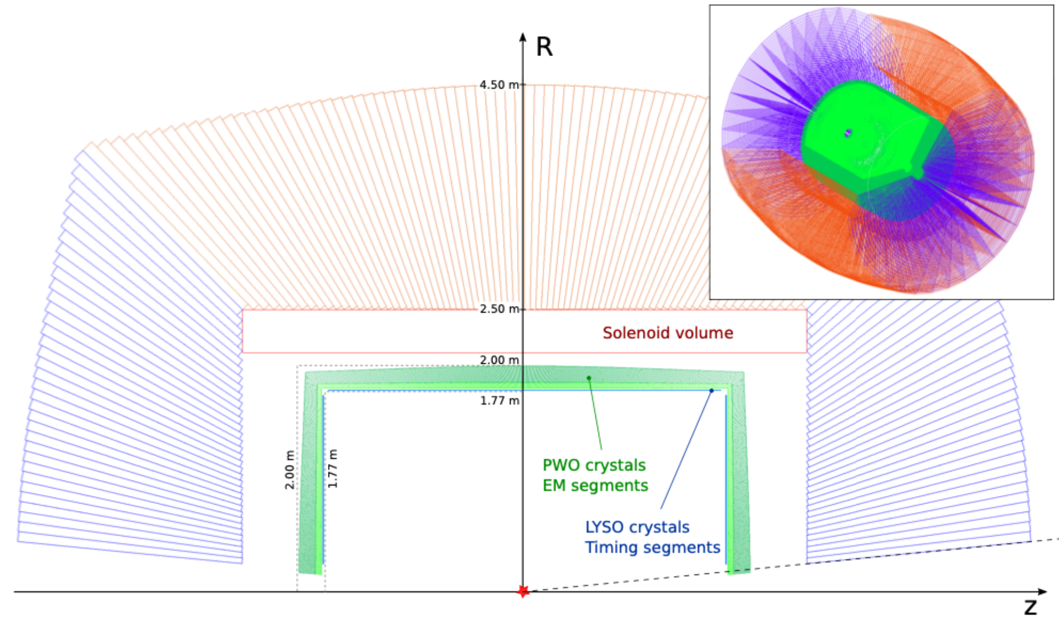
Combination of fibers for Module#2

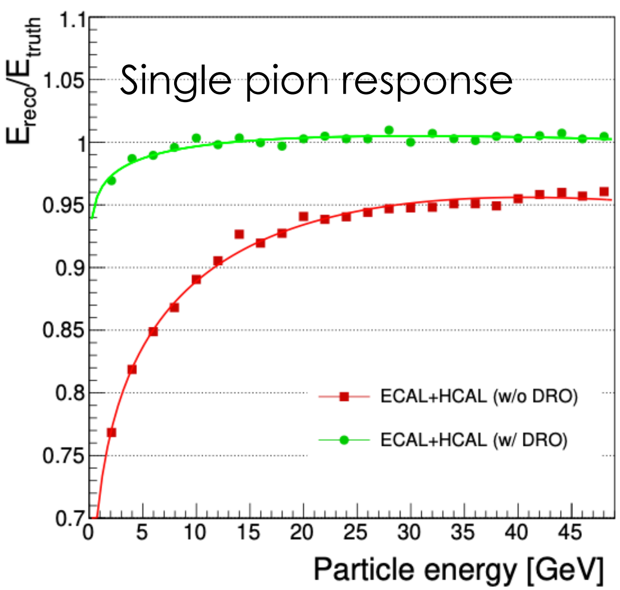
	Tower #1~4 and #6~9	Tower #5
Scintillation fibers	Round / Single cladding	Round / Single cladding
Cherenkov fibers	Round / Single cladding	Round / Single cladding
Readout detector (400+16 ch)	16 PMTs	400 SiPMs

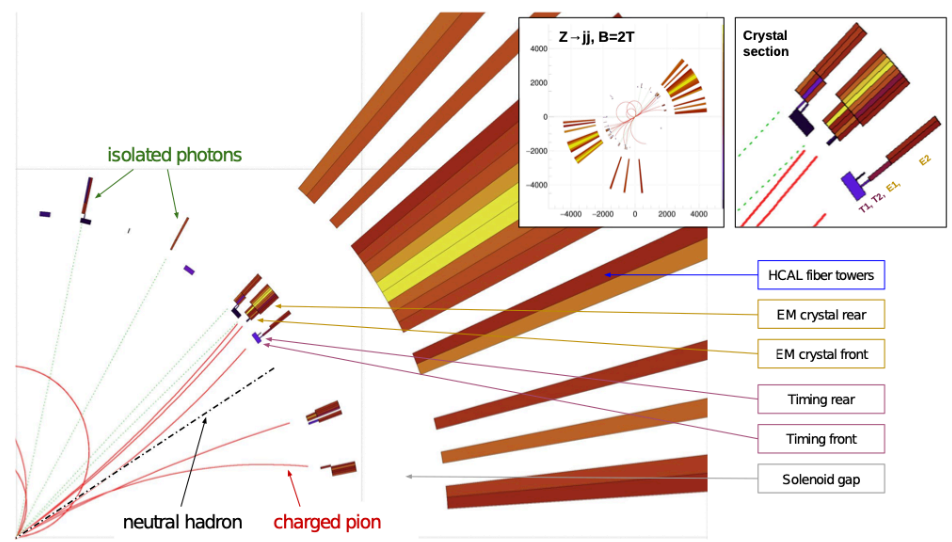
Dual readout with crystals

- LYSO (1 X_0 - timing layer) + 2 layers of PWO (1x1 cm^2) inside the IDEA solenoid.
- Crystals read out by SiPM:
  - Dual readout obtained **with separation in frequency** of Cherenkov light.
- **High energy resolution** for the EM section, adds **natural longitudinal segmentation**.
- Hadron calorimeter unchanged with respect to **fiber-only configuration**.

Taken from https://doi.org/10.1088/1748-0221/17/06/P06008







Crystal + fibre calorimeter - results

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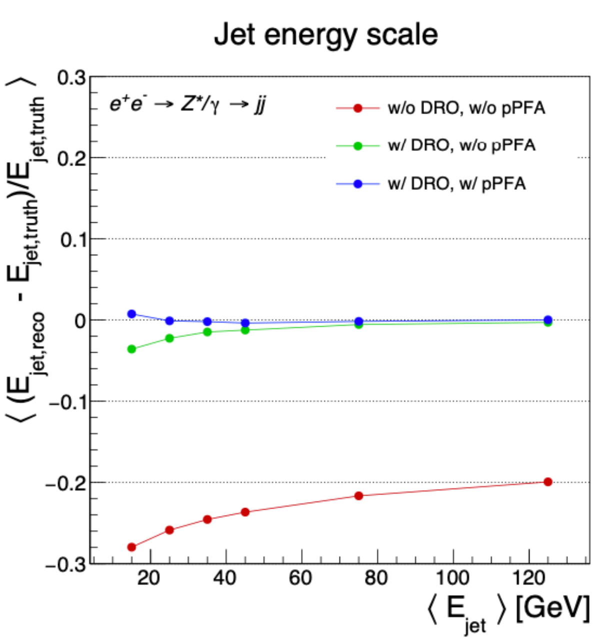
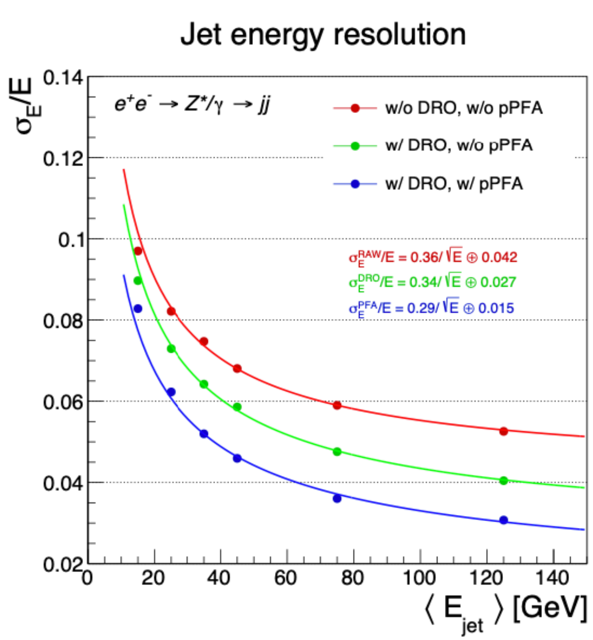
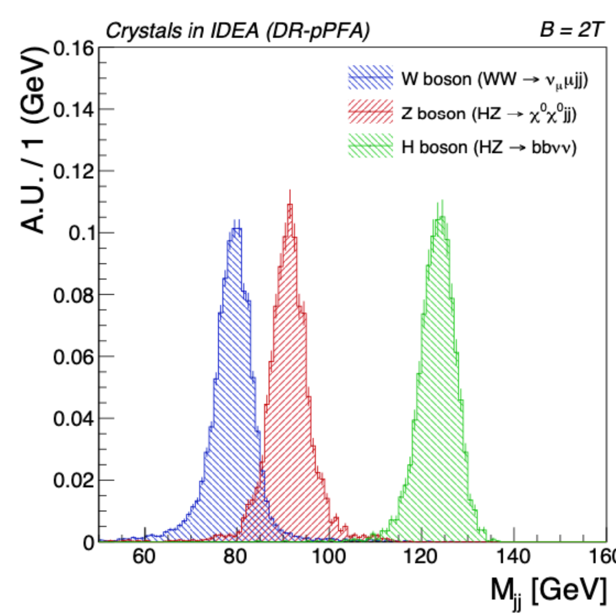
- Performance studies done on events with jets for a few different configurations:
  - No dual-readout (DRO) no Particle Flow Algorithm (PFA) applied.
  - With DRO but no PFA.
  - With DRO and PFA.
- **DRO recovers linearity** of the calorimeter response and improves resolution. PFA **further boosts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

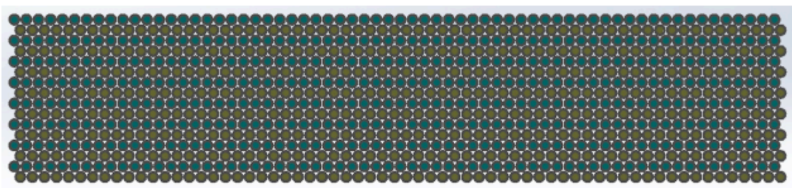






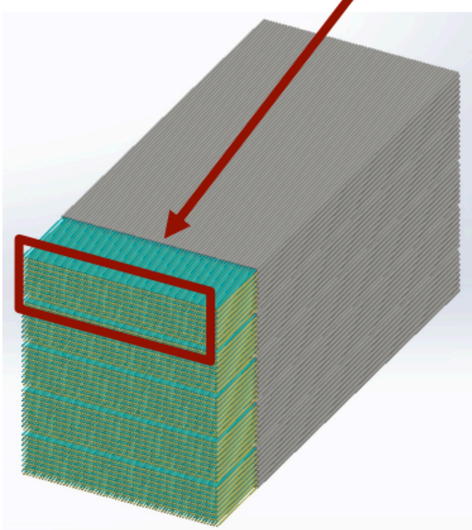
The future: prototype with hadronic containment

The Mini-Module



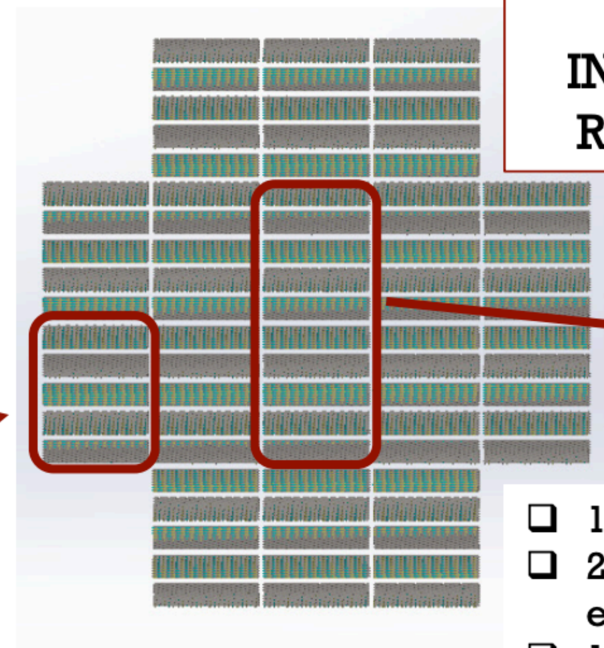
64 x 16 capillaries

The Module



5 Mini-modules
~ 13 x 13 x 250 cm^3

The hadronic prototype



HiDRa INFN-funded R&D project

The highly granular modules

- 16 modules in total
- 2 central modules equipped with SiPMs
- 14 modules equipped with PMTs
- ~ 65 x 65 x 250 cm^3

The challenge:

We have10240 SiPMs, fitting the back side of the detector

A truly international effort

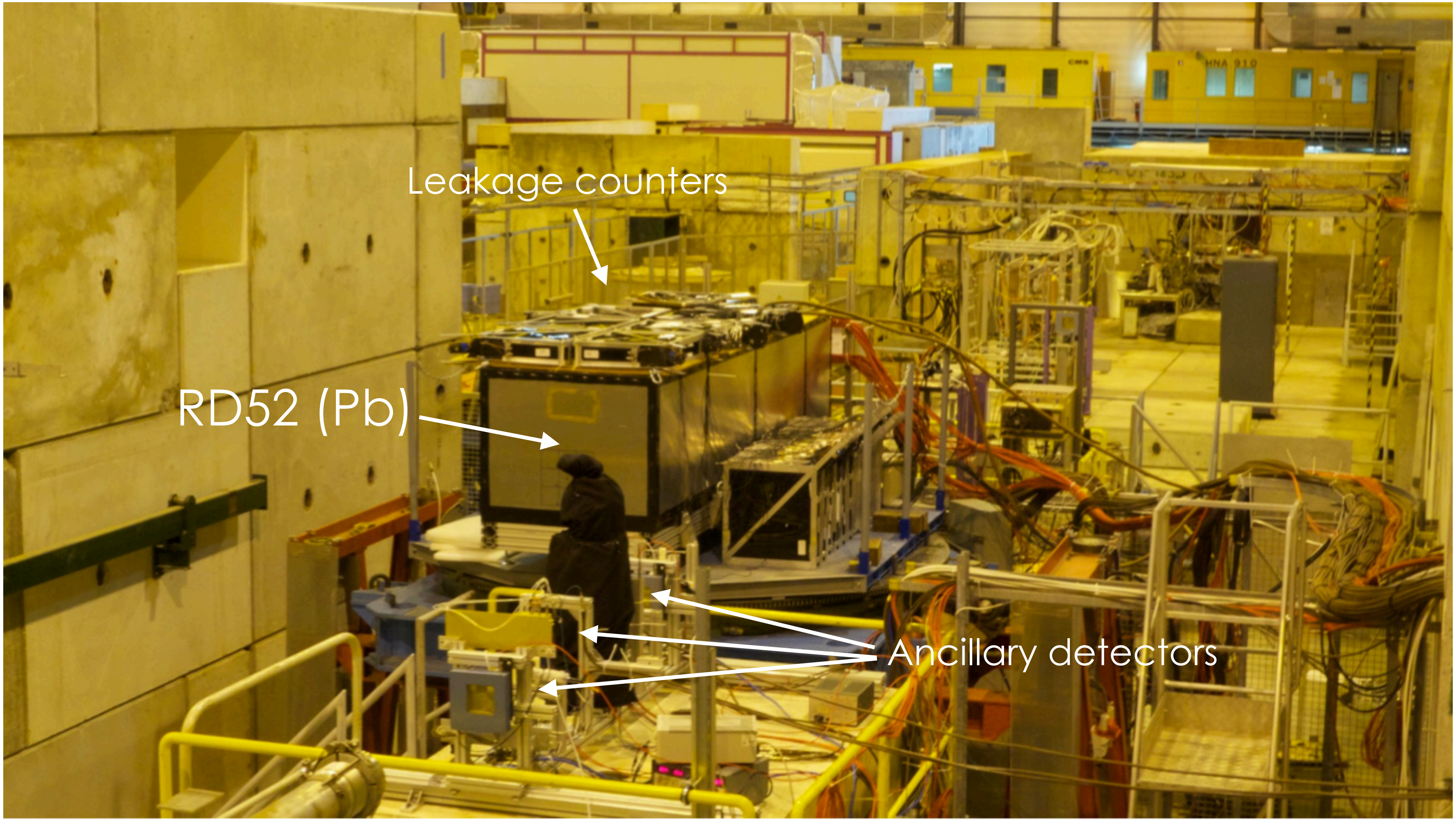
- Funding for Dual-readout-connected activities:
  - **AIDAinnova** partially supports activities related to **R&D for fiber/optics/SiPM + monitoring + simulation studies** for fibre calorimeter.
  - Significant (o(1 M) currency units each) from **DoE for crystal-DRO, Korea and INFN for fibre calorimeter** full containment efforts.

Summary

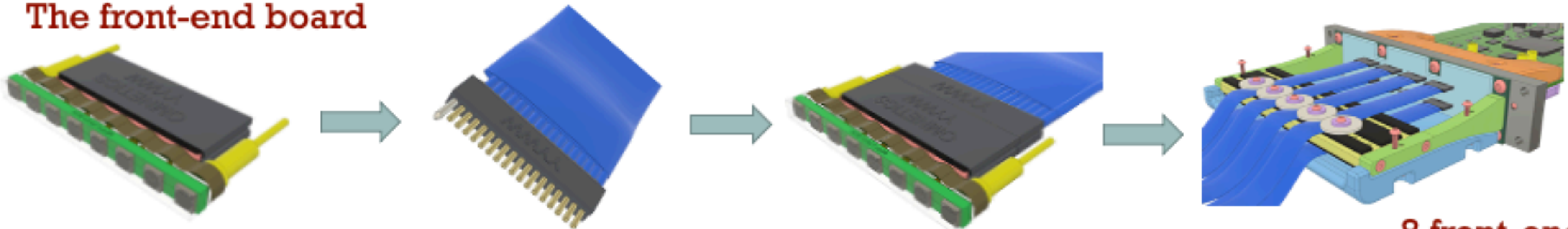
- **IDEA** implements a **fibre dual-readout calorimeter** as default option:
  - Good EM energy resolution, excellent lateral shower shape and position determination. Excellent hadronic energy resolution.
    - Proof of principle of **longitudinal shower shape** sensitivity through timing
  - EM-size **capillary tube (Bucatini) prototype** tested on beam in 2021. **Different mechanical options** + full extraction of SiPM signal tested on beam in 2022.
  - Toward the development of **a fully scalable - hadronic-size prototype** (mainly INFN and Korea).
- Crystal EM-section promises to deliver **excellent EM energy resolution** and performance **while boosting hadronic performance** (via intrinsic longitudinal segmentation and PF).
- The **international effort** for Dual Radout at e^+e^- colliders **is growing**:
  - Three large grants + AIDAinnova will support the R&D over the next future.
- Plenty of ideas and room for further collaboration:
  - If you are interested: Subscribe on egroups.cern.ch to idea-dualreadout@cern.ch.

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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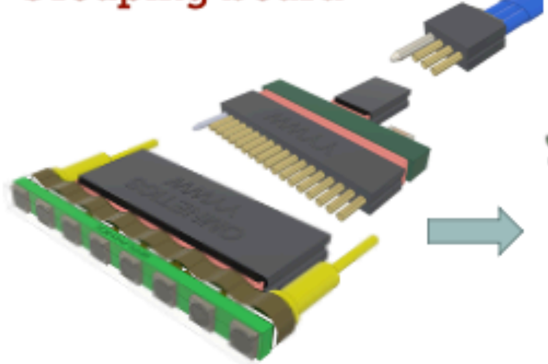
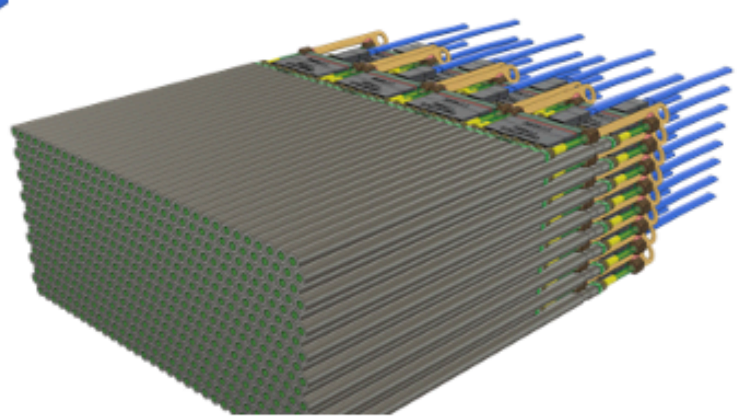
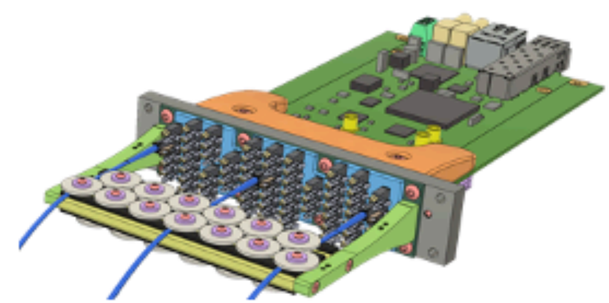
Grouping board



The Mini-Module



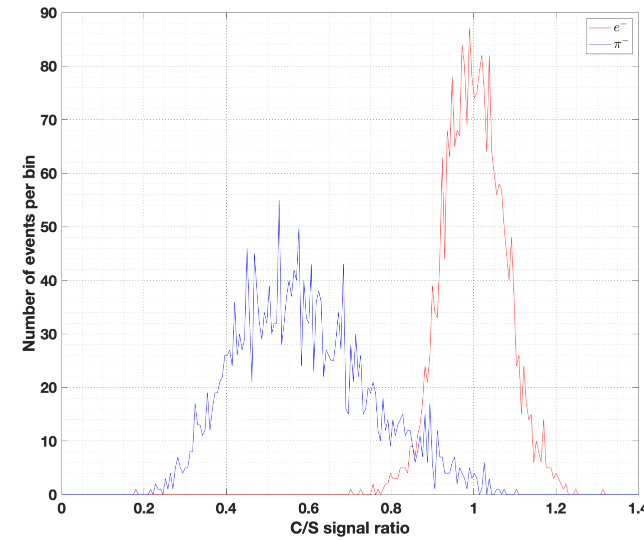


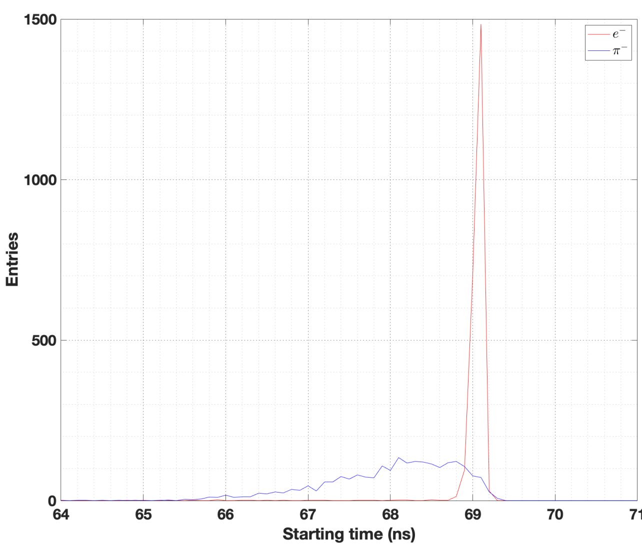
1 FERS serves 64 front-end boards with grouping

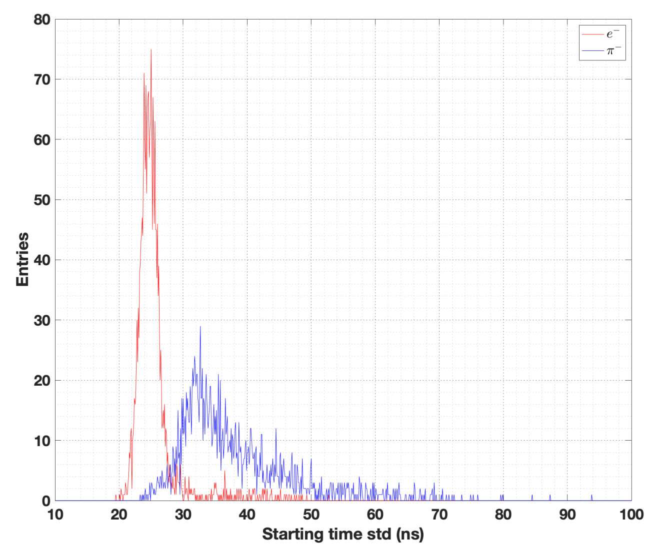
- Each bar of SiPMs will be operated at the same voltage (ΔV_{bd}<0.15V)
- The signals from 8 SiPMs are summed up in the grouping board

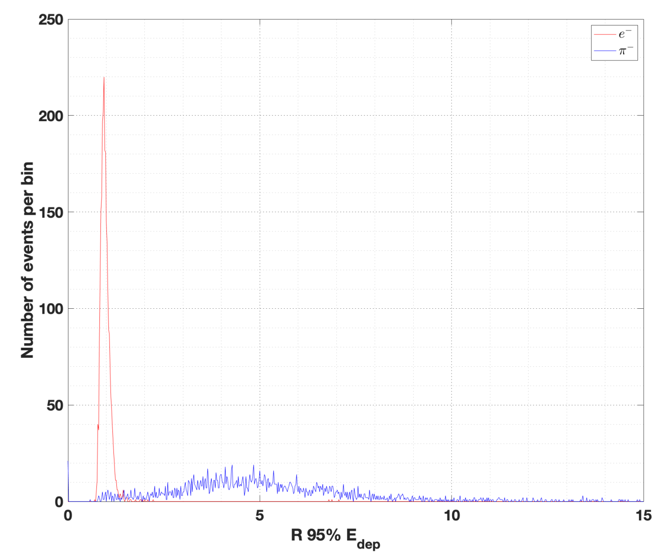
Particle identification

- 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

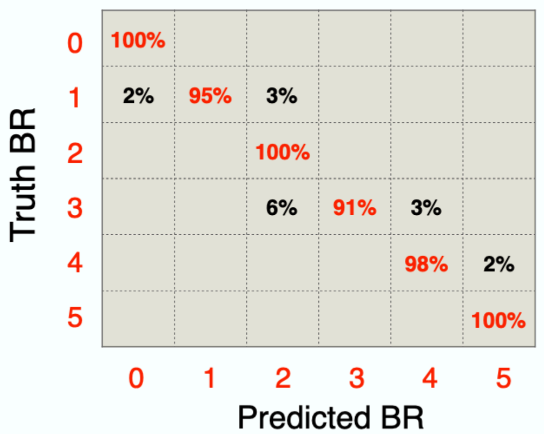
Advanced Machine Learning Applications

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

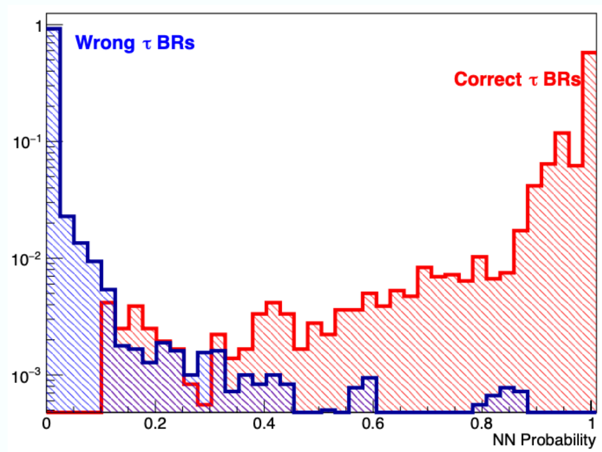
Data preprocessing needed to reduce data size and fit GPU memory

- 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:

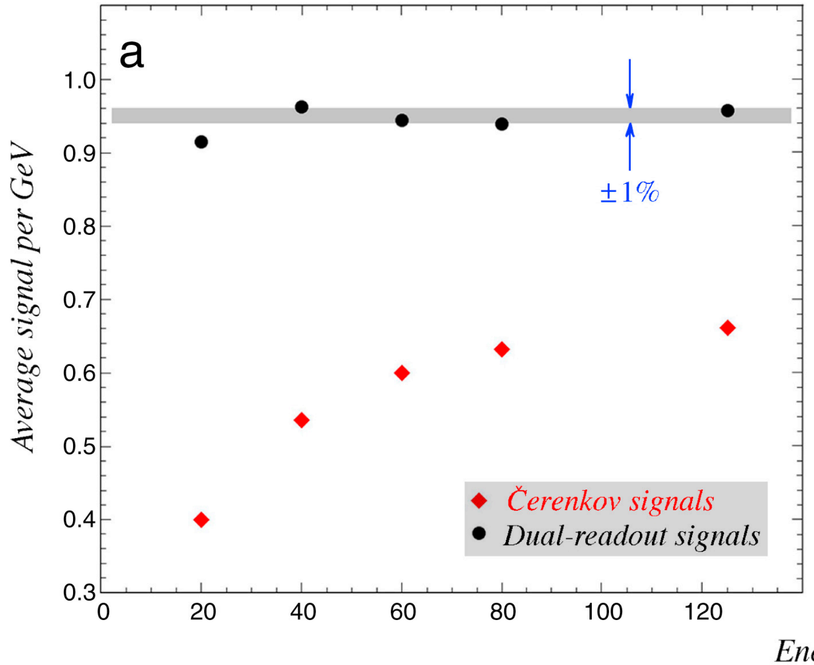


0	pi0 pi- nu_tau
1	e- anti_nu_e nu_tau
2	mu- anti_nu_mu nu_tau
3	pi- nu_tau
4	pi- pi- pi+ nu_tau
5	pi0 pi0 pi- nu_tau

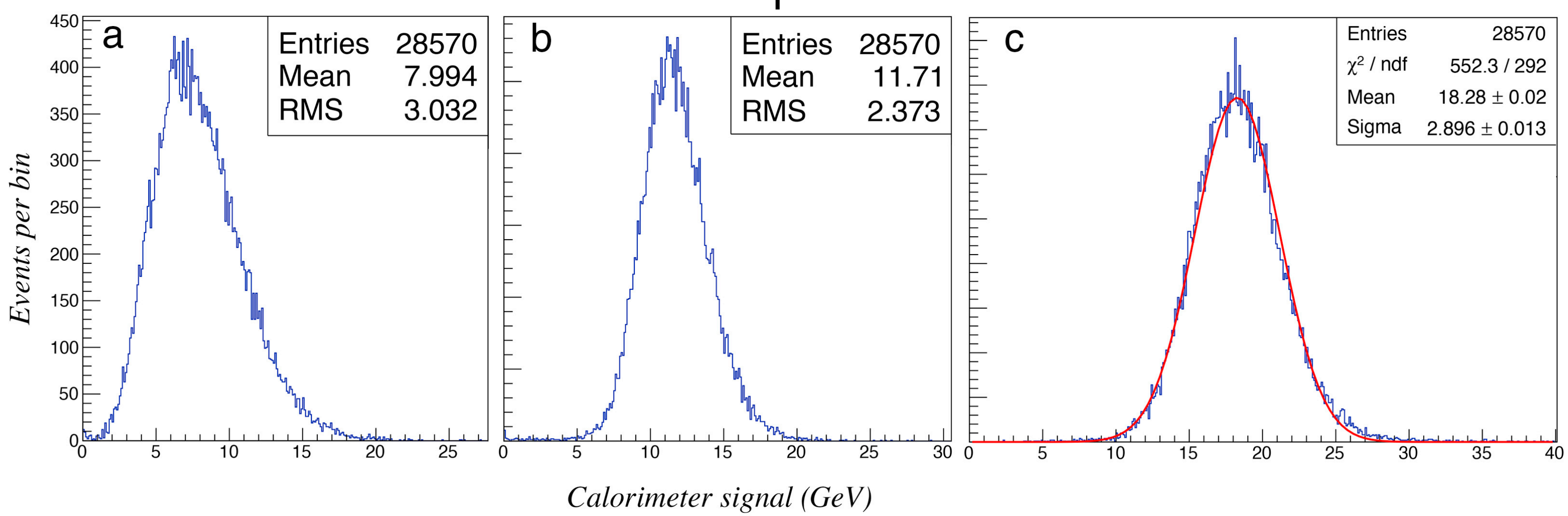
Single hadron response - linearity

NIM A 866 (2017) 76

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

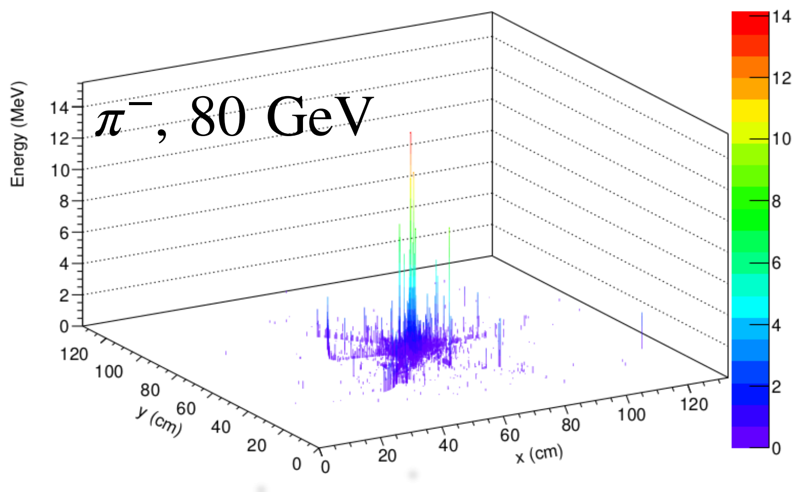


20 GeV pions

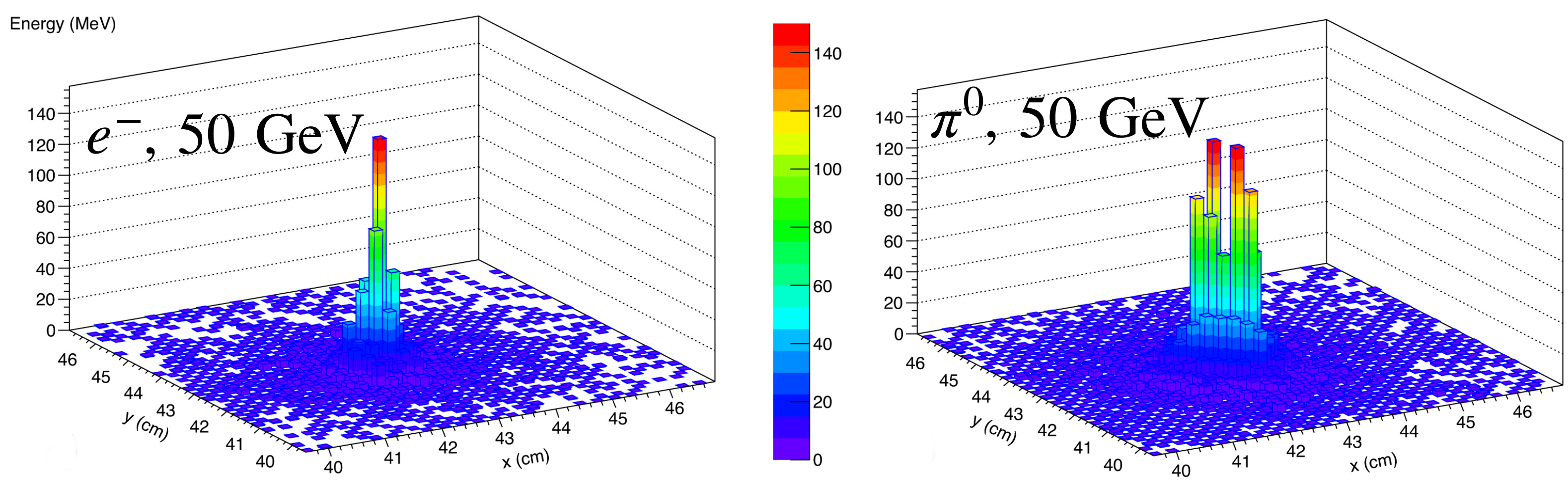


Shower shape

Work in progress

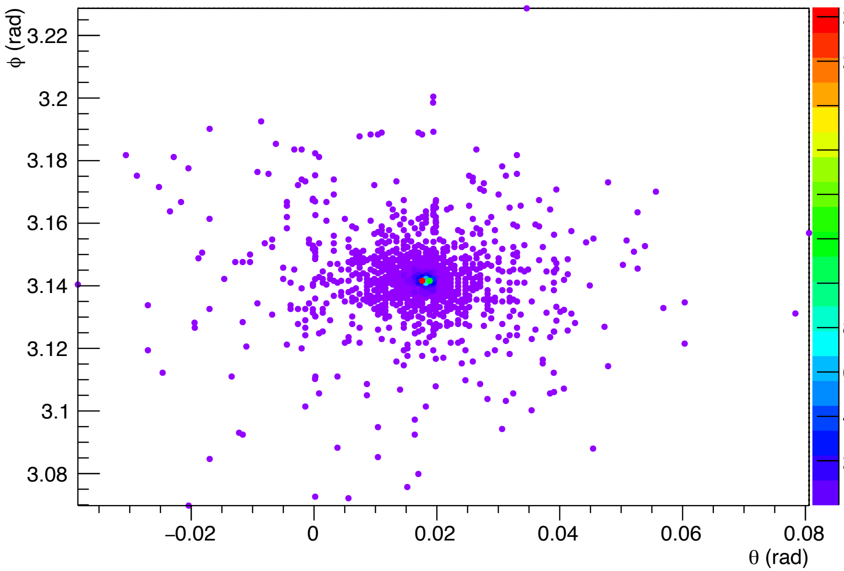


- Single particle shower shape
  - Using full implemented granularity

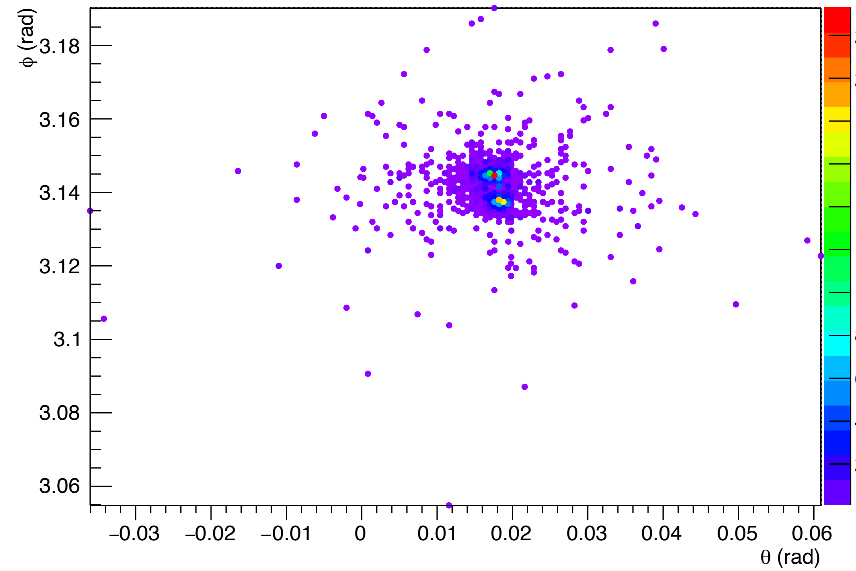


How events look like (full granularity)

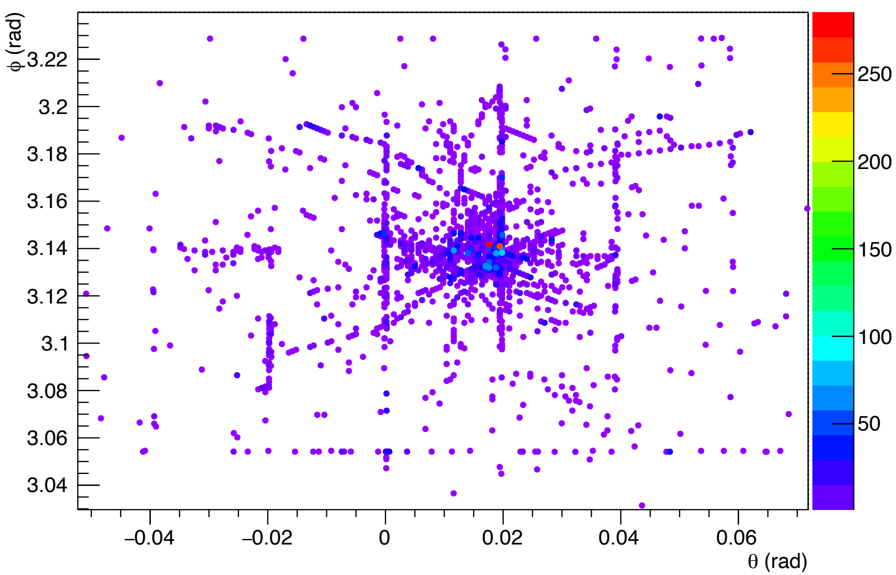
e- 40 GeV



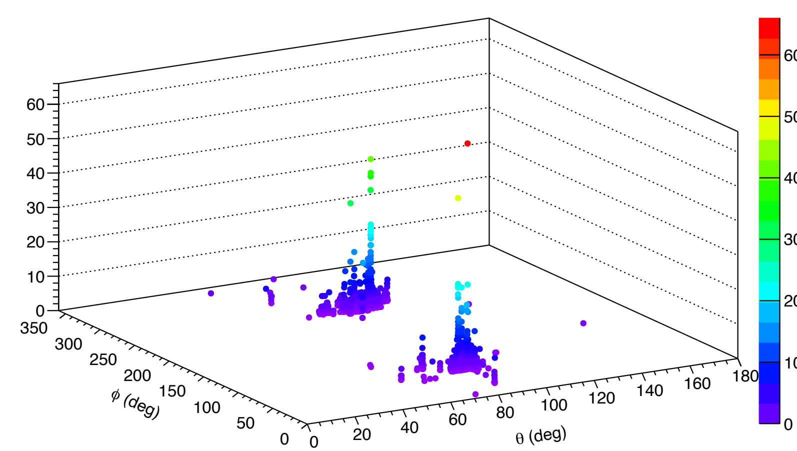
π^0 40 GeV



π^- 40 GeV



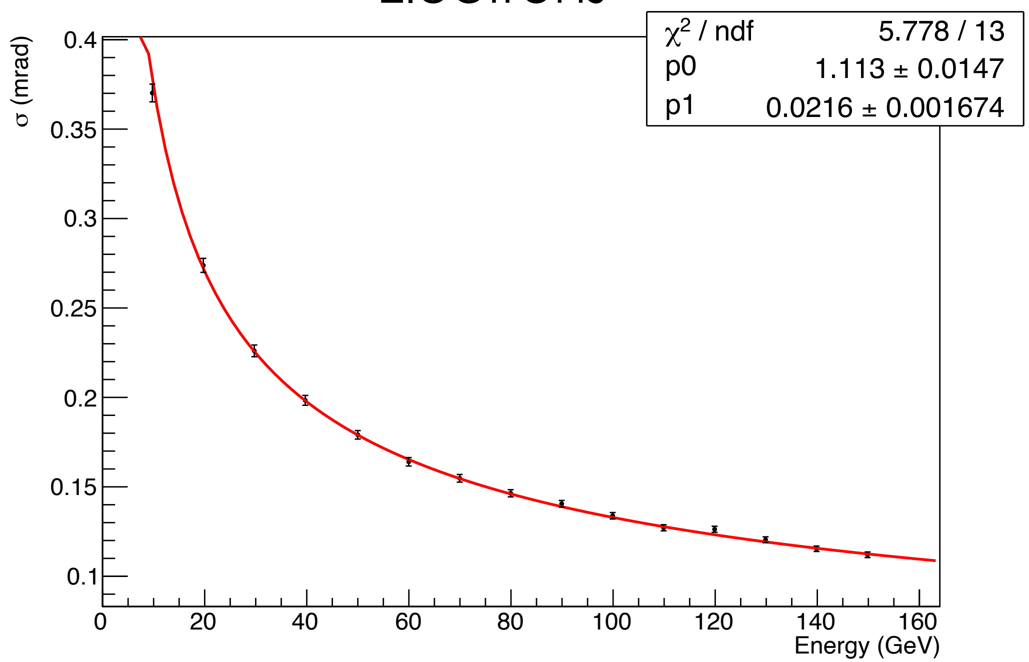
Di-jet



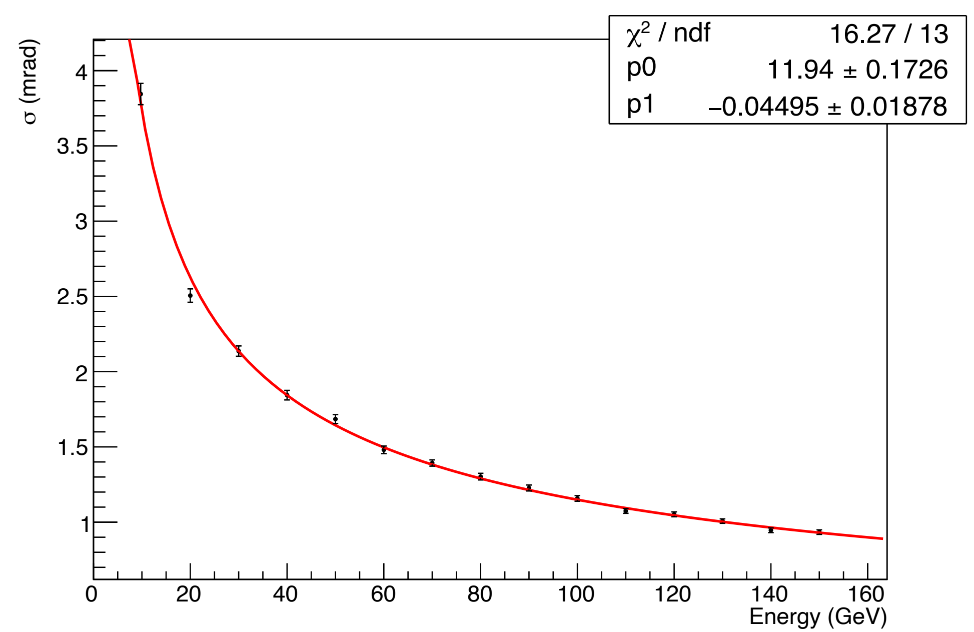
Angular resolutions

- The use of the **single fibre granularity** yields the ultimate angular resolution of the calorimeter.
- Position obtained as the **energy-weighted fibre mean**
- Fit with $\sigma(\text{rad}) = \frac{p_0}{\sqrt{E(GeV)}} + p_1$

Electrons



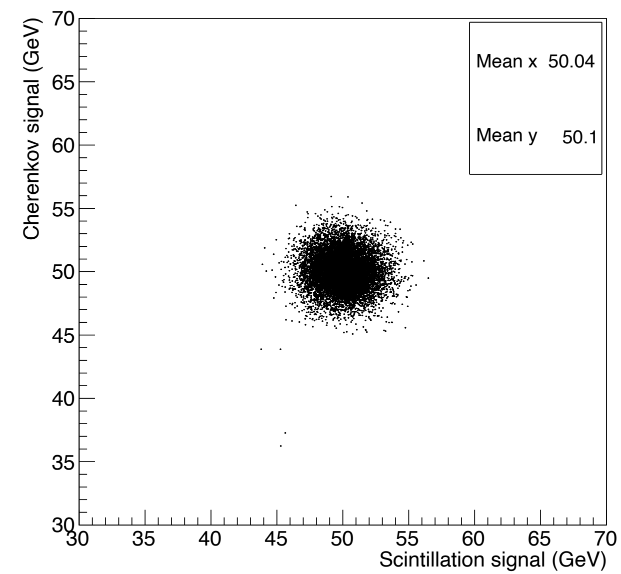
Pions



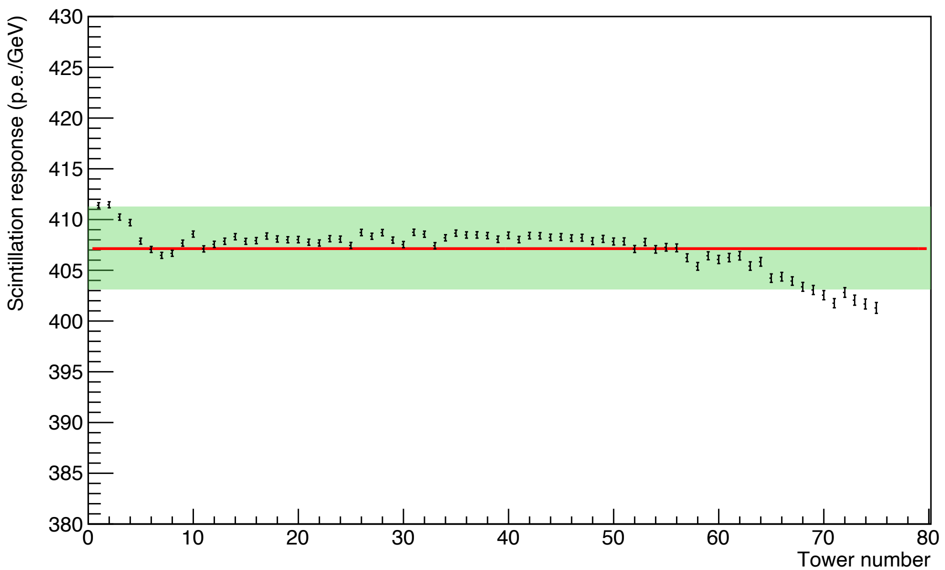
Calibration with electrons

- Light yield chosen **according to TB results**
- **After tower equalisation, e**nergy deposited by electrons used as pe/GeV calibration factor

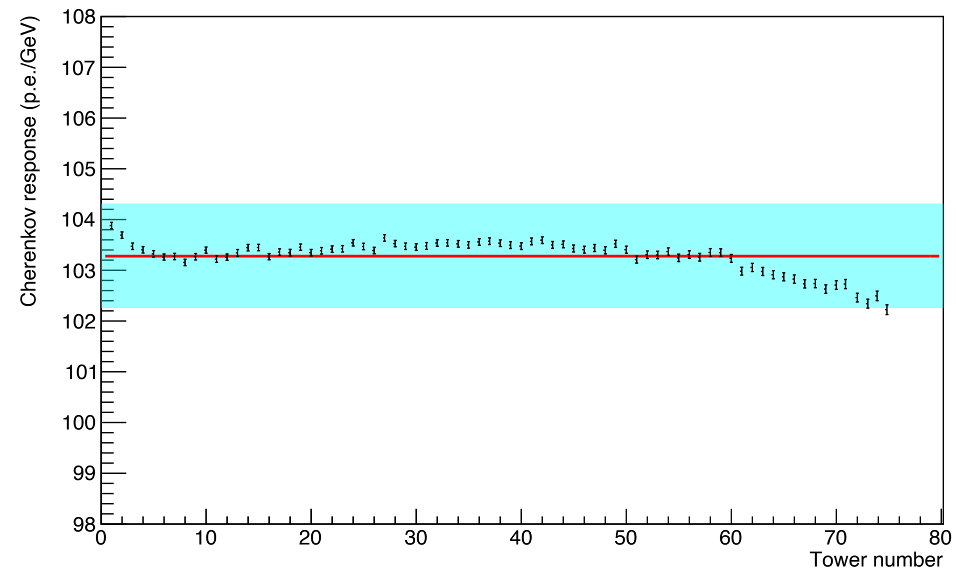
50 GeV electrons



40 GeV electrons - S channel



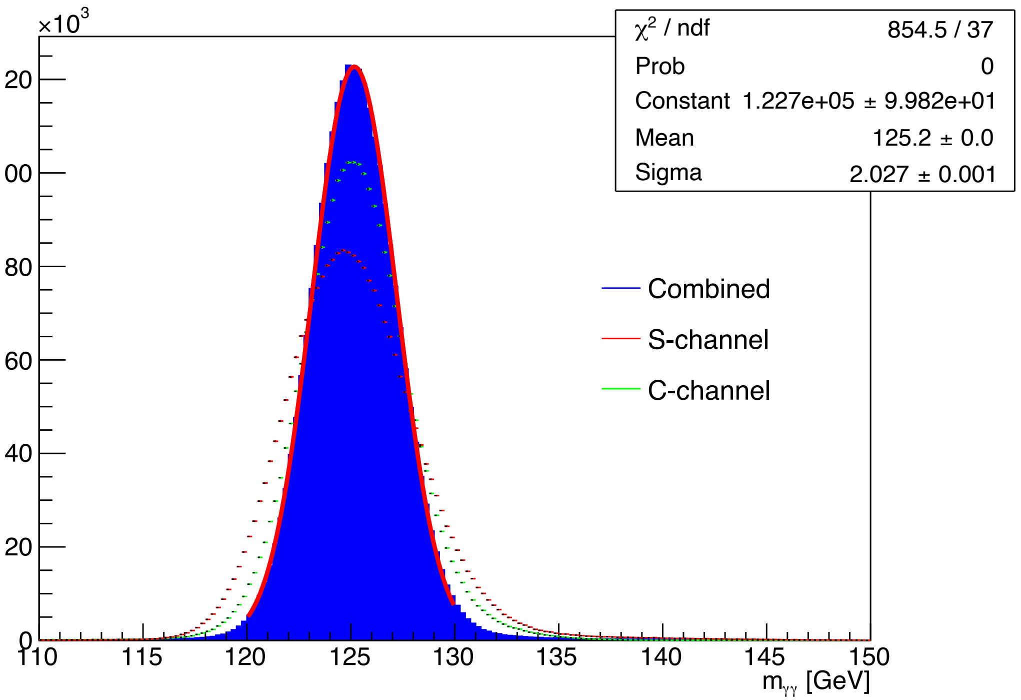
40 GeV electrons - C channel



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

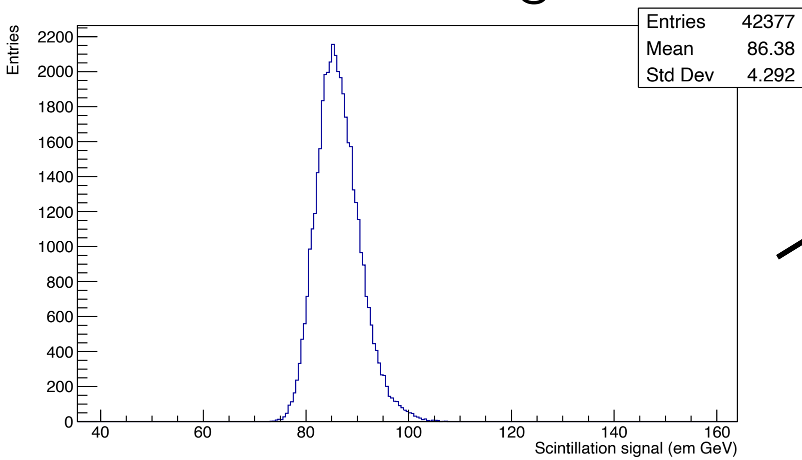
- Using 5M $e^+e^- \to ZH \to \nu\nu\gamma\gamma$ events and clustering opposite calorimeter hemispheres as photons.
- Dedicated calibration corrections for impact point on tower

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

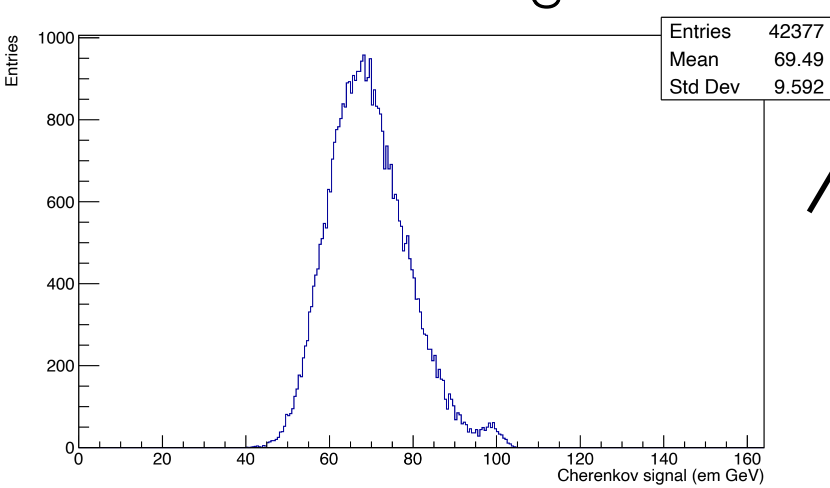


Single pion response

Scintillation signal

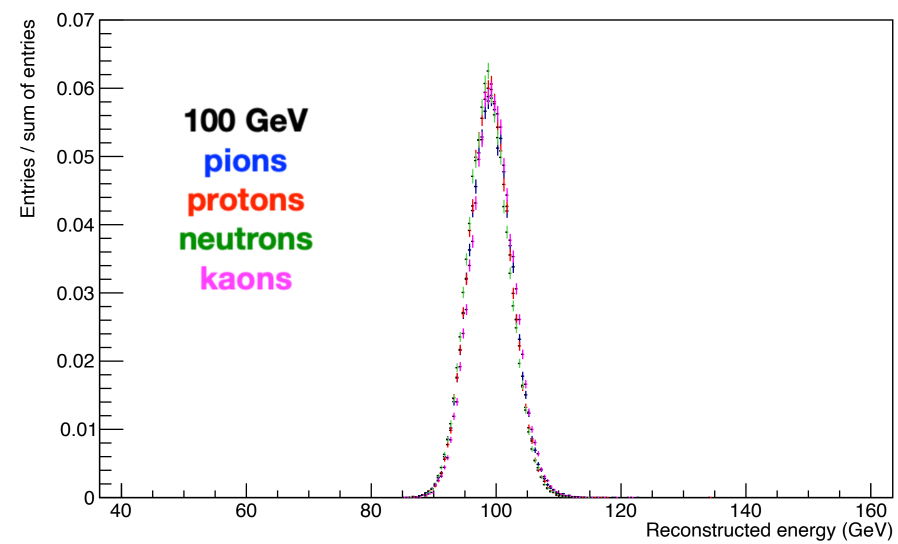


Cherenkov signal



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

Uniform response from different hadrons with a single χ



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

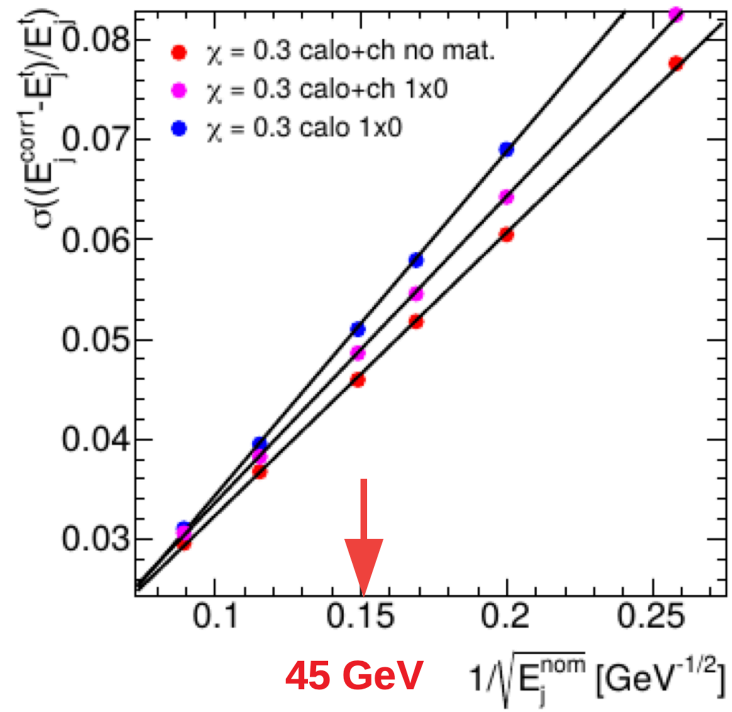
$$E_j^r = \frac{E_j^s + \chi E_j^c}{1-\chi}$$ + dedicated calibration

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



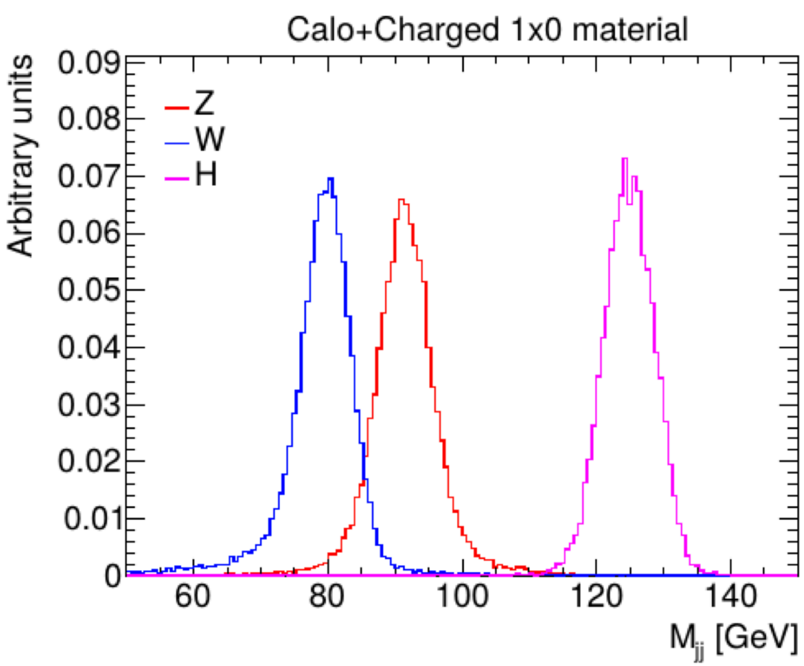
Dual readout achieves linearity with a resolution of **30%/√E with constant term ~ 0.5%**

Resonances studied with

$$e^+e^- \rightarrow ZH \rightarrow jj\tilde{\chi}_0^1\tilde{\chi}_0^1$$

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

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



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.