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Performance and analysis results of Dual-Readout simulated data

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On behalf of the IDEA detector concept

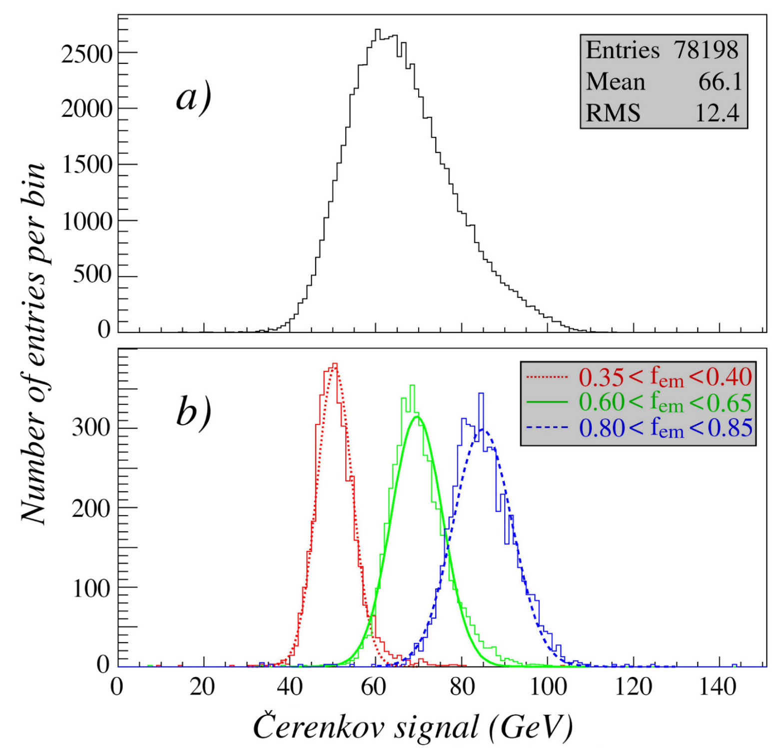
The dual-readout principle in a nutshell

- Sampling the **hadronic shower** with two readouts of **different e/h factor** allows to correct event by event for non-compensation.
- Cherenkov (C) channel mostly sensitive to the em shower component, Scintillation (S) sensitive to all.

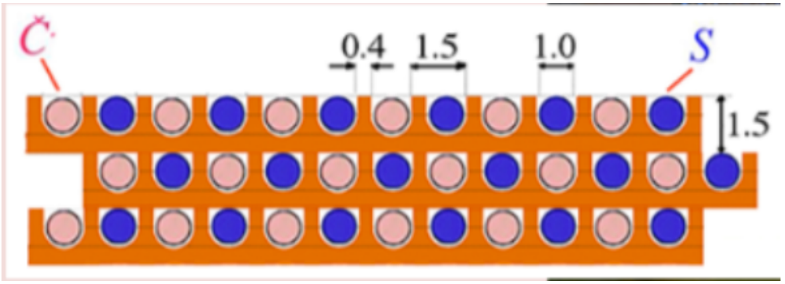
$$\begin{cases} E_S = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_S (1 - f_{\mathrm{em}})\right) \\ E_C = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_C (1 - f_{\mathrm{em}})\right) \end{cases}$$

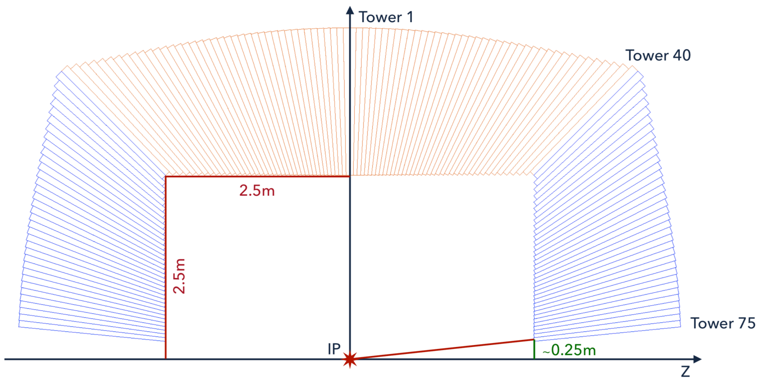
Two equations in two unkowns (f_{em} and E)

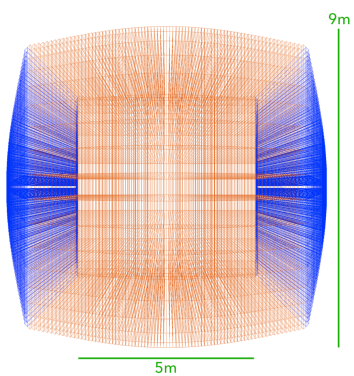
$$E = \frac{(E_S - \chi E_C)}{1 - \chi} \qquad \chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C}$$

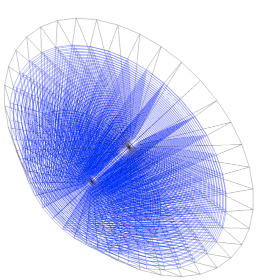


Simulation









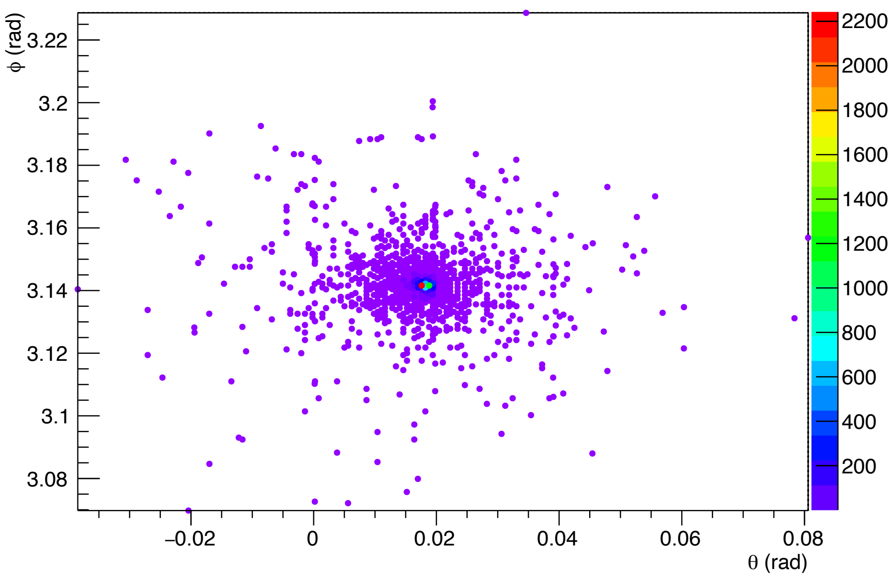
- Full G4 simulation of "final" geometry **is available**:
    - Cu absorber, 1 mm fibers, 1.5 mm pitch.
- Also existing parametrised simulation for physics studies.
- Different geometry also studied (see talk from Yunjae Lee).
- **Read out the single fibre: 130 M channels:**
    - Excellent angular resolution, lateral shower shape sensitivity
- In most studies, a coarser granularity is used:
    - **75 projective elements x 36 slices**

$$\Delta\theta = 1.125^\circ$$
$$\Delta\phi = 10^\circ$$

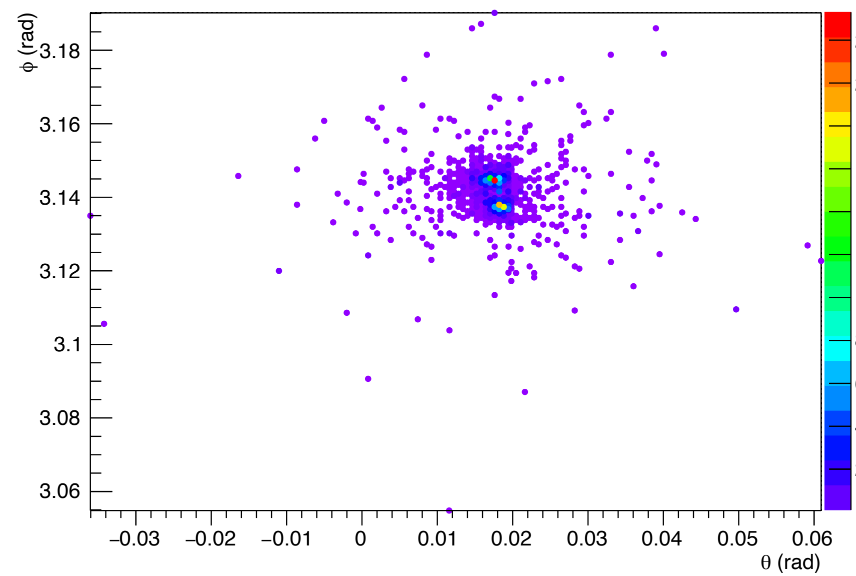
This is what I will refer to as "tower" in the following.

How events look like (full granularity)

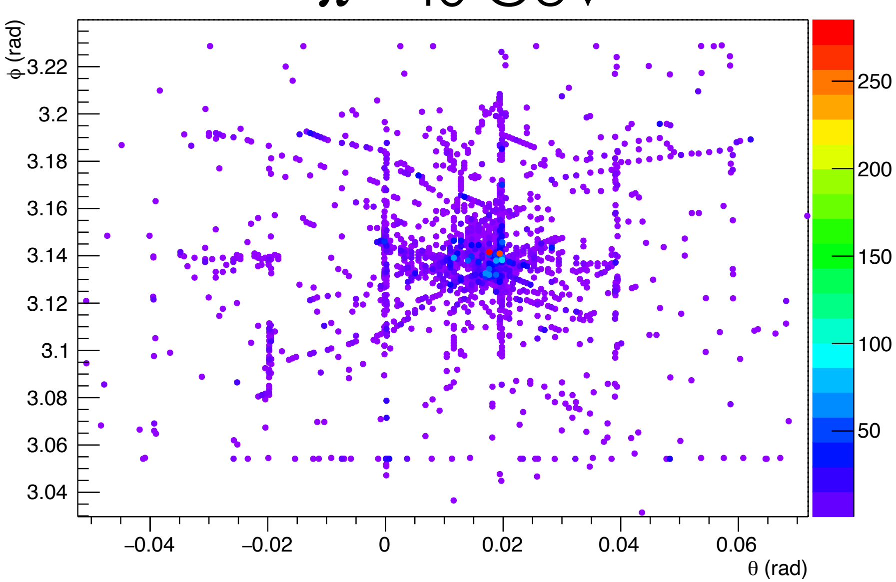
e- 40 GeV



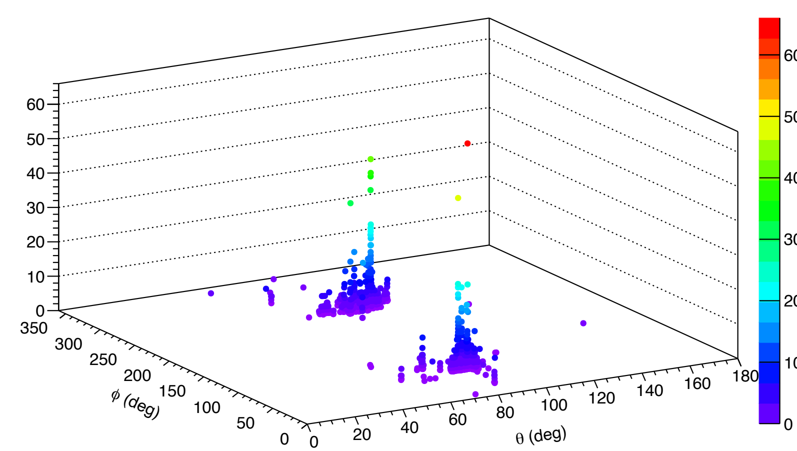
π^0 40 GeV



π^- 40 GeV



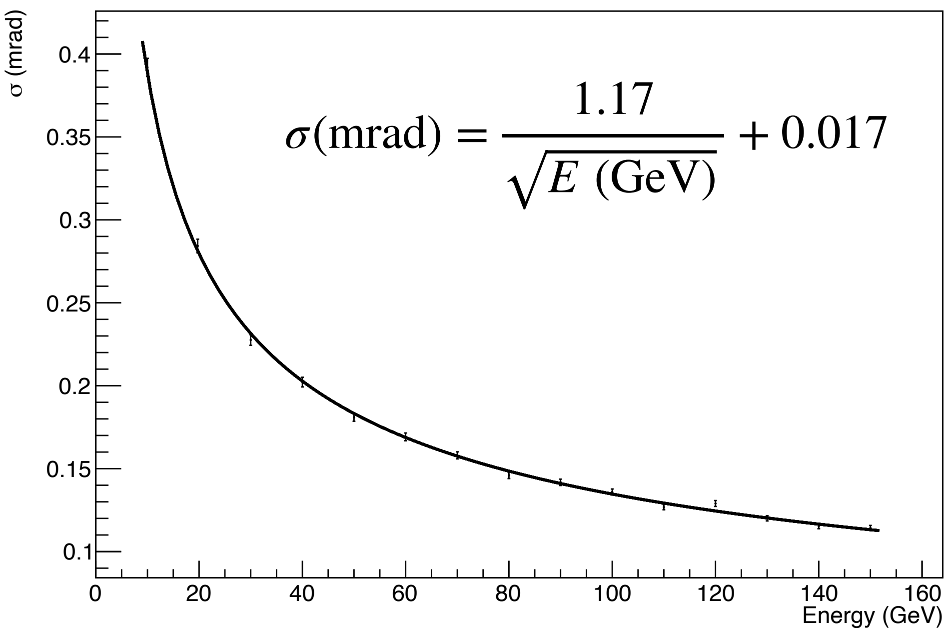
Di-jet



Angular resolutions

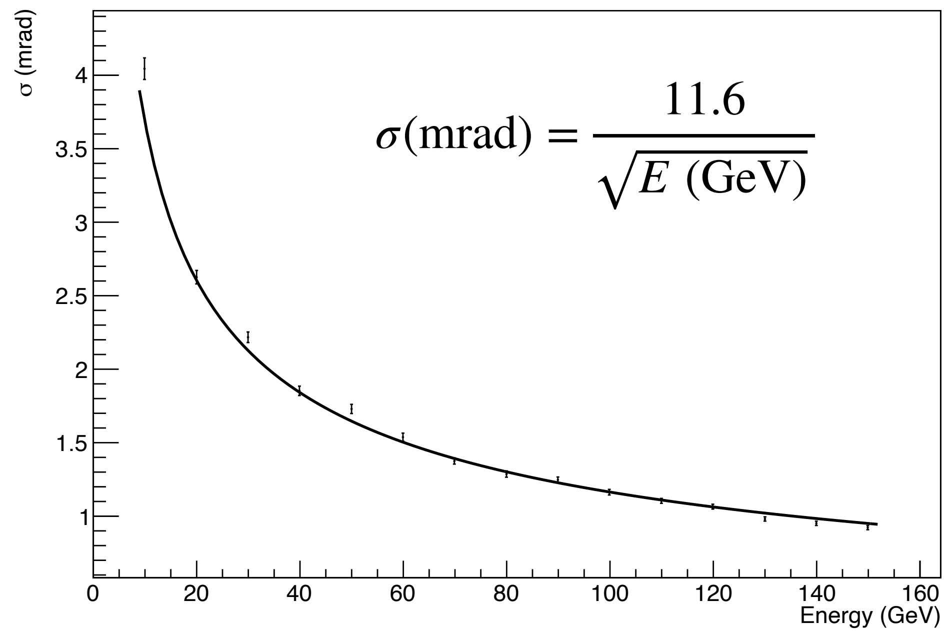
- The use of the **single-fibre granularity** yields the ultimate angular resolution of the calorimeter.
- Position obtained as the **energy-weighted fibre mean.**

Electrons



$$\sigma(\text{mrad}) = \frac{1.17}{\sqrt{E\ (\text{GeV})}} + 0.017$$

Pions

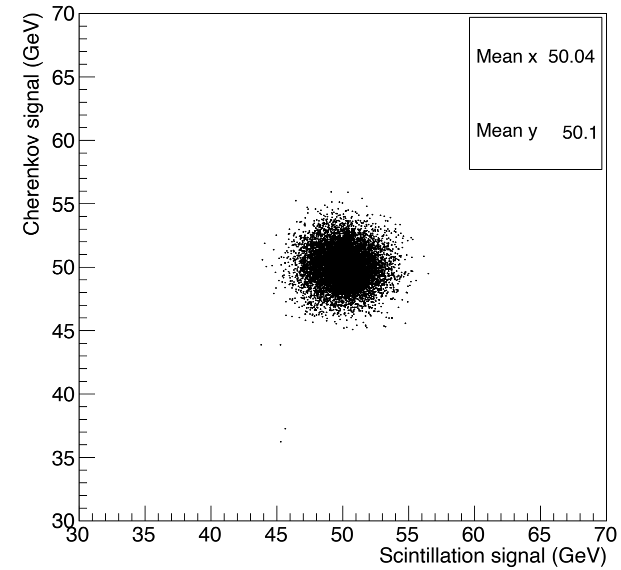


$$\sigma(\text{mrad}) = \frac{11.6}{\sqrt{E\ (\text{GeV})}}$$

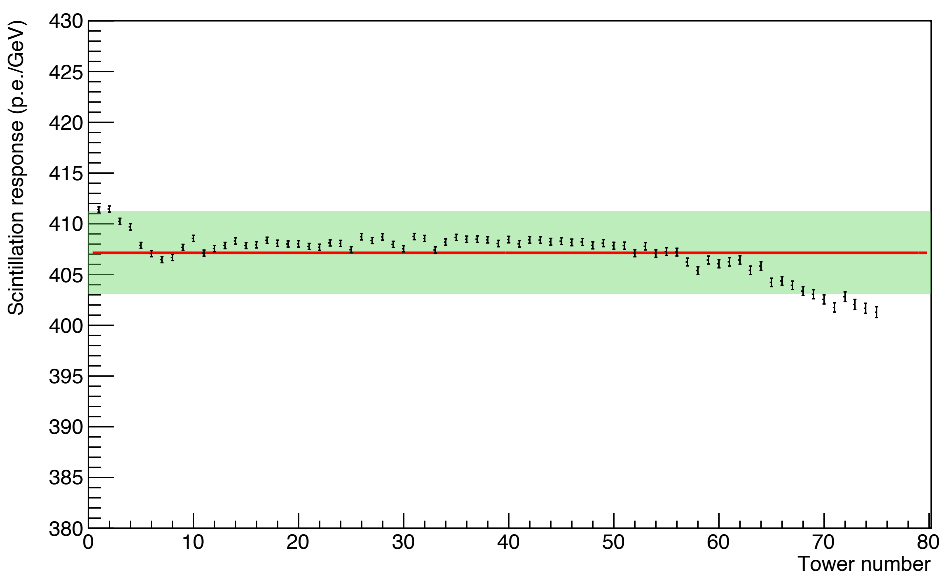
Calibration with electrons

- From now on using tower granularity.
- Light yield tuned **according to Test Beam results.**
- **After tower equalisation**, energy deposited by electrons used as pe/GeV calibration factor.

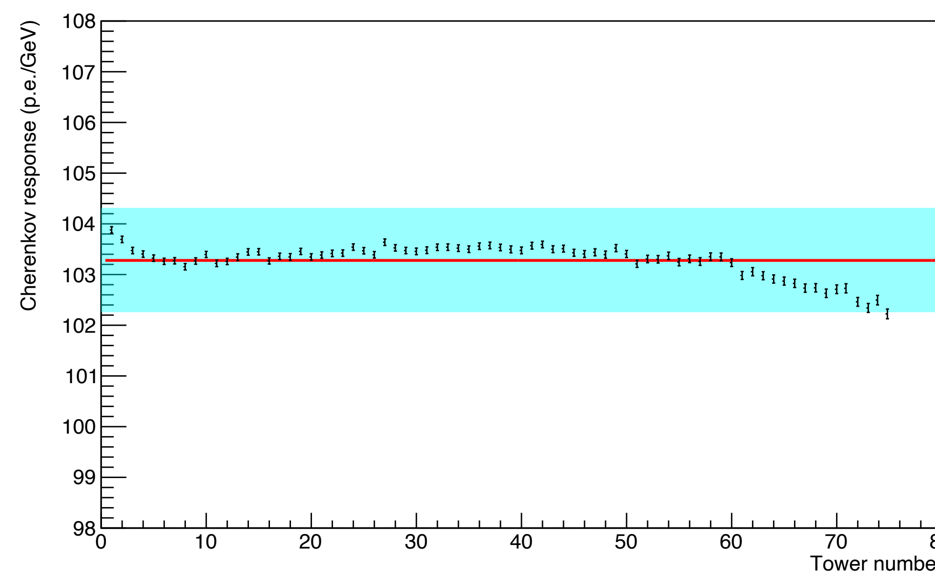
50 GeV electrons



40 GeV electrons - S channel



40 GeV electrons - C channel



Electromagnetic performance

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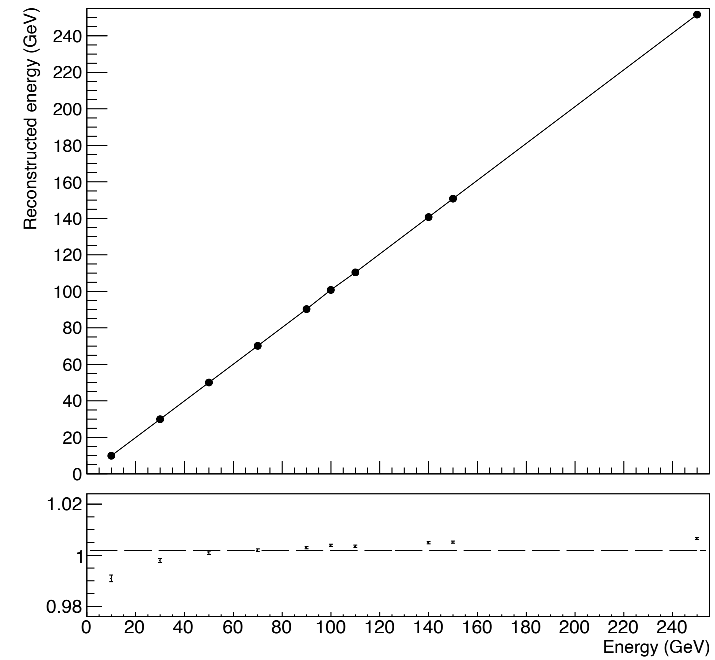
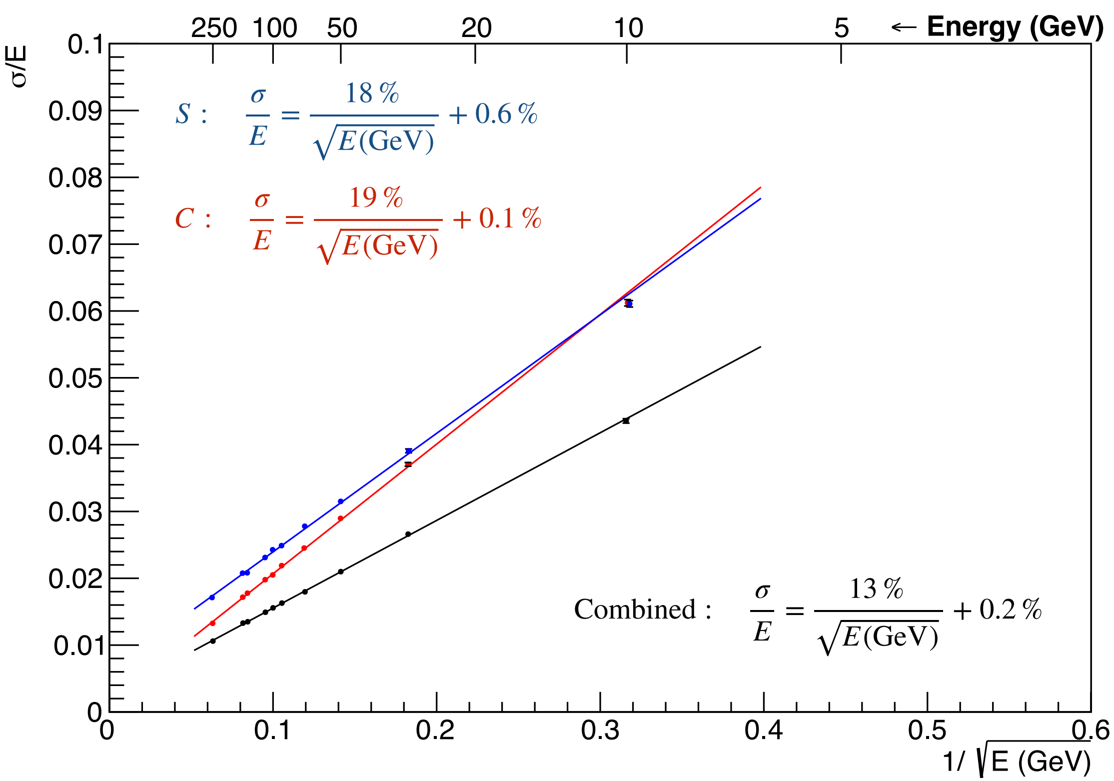
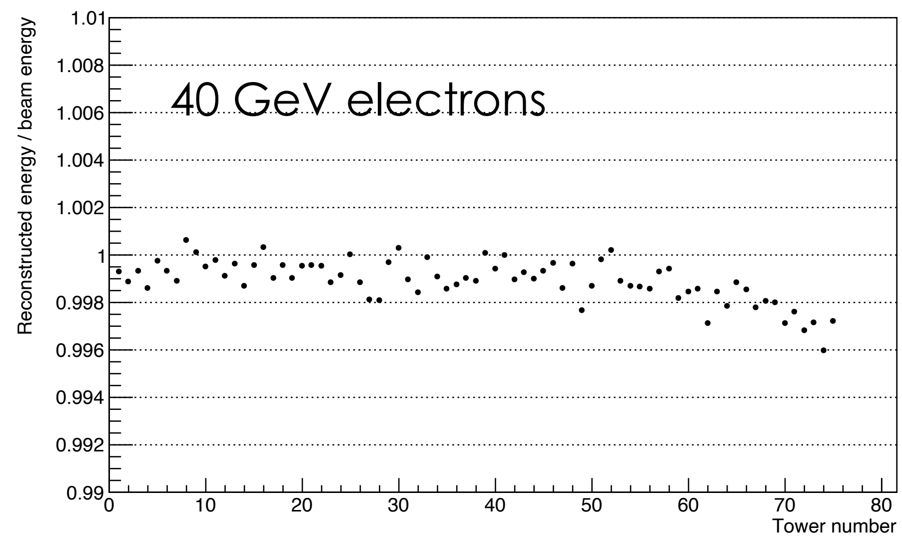
- Linearity Vs Energy within 1%, and uniform over towers.
- **Competitive electromagnetic resolution** for combined energy reconstruction.







Single pion response

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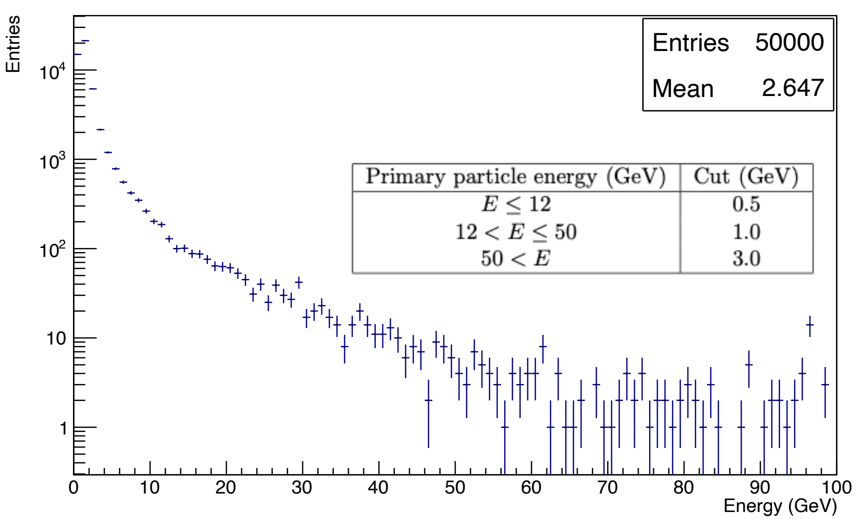
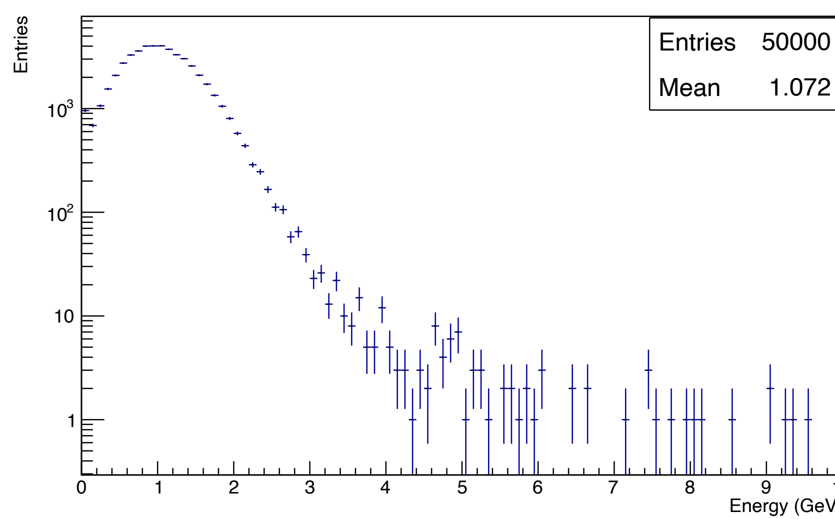
- Current IDEA calorimeter inner radius 2.5 m; outer radius 4.5.
  - **Reject events with poor containment** to focus on performance
- Evaluating performance using coarse granularity.

Kinetic energy escaped from calorimeter surface, 100 GeV pions



Primary particle energy (GeV)	Cut (GeV)
$E \leq 12$	0.5
$12 < E \leq 50$	1.0
$50 < E$	3.0

Energy carried away by neutrinos only, 100 GeV pions



Single pion response

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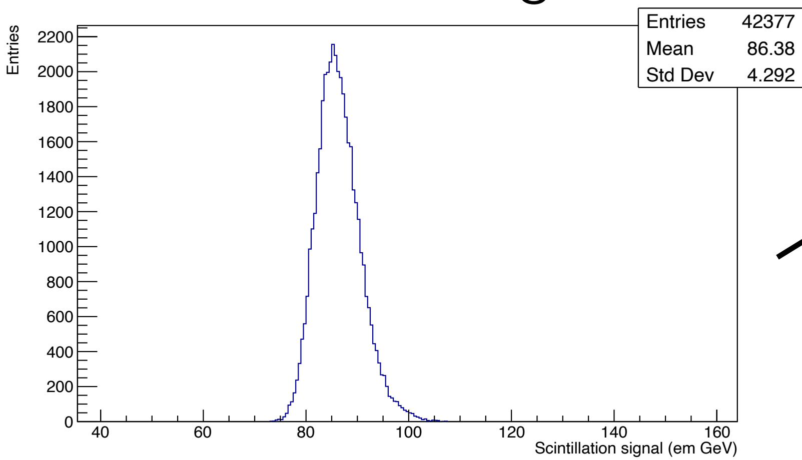
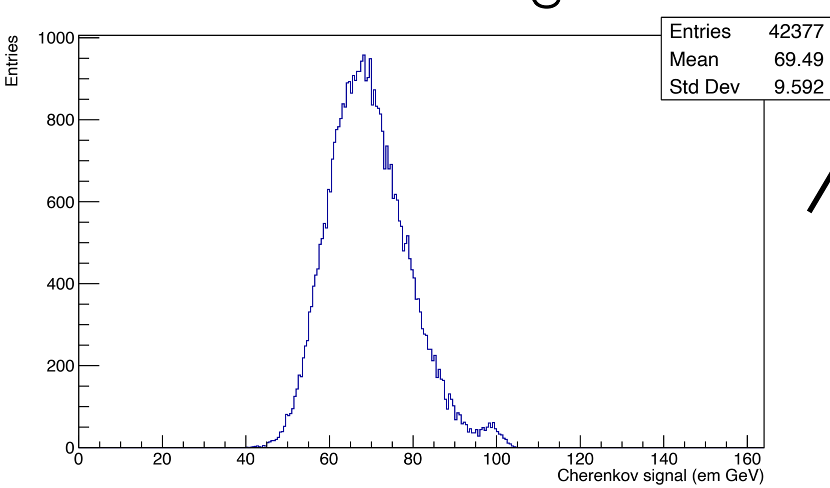
Scintillation signal

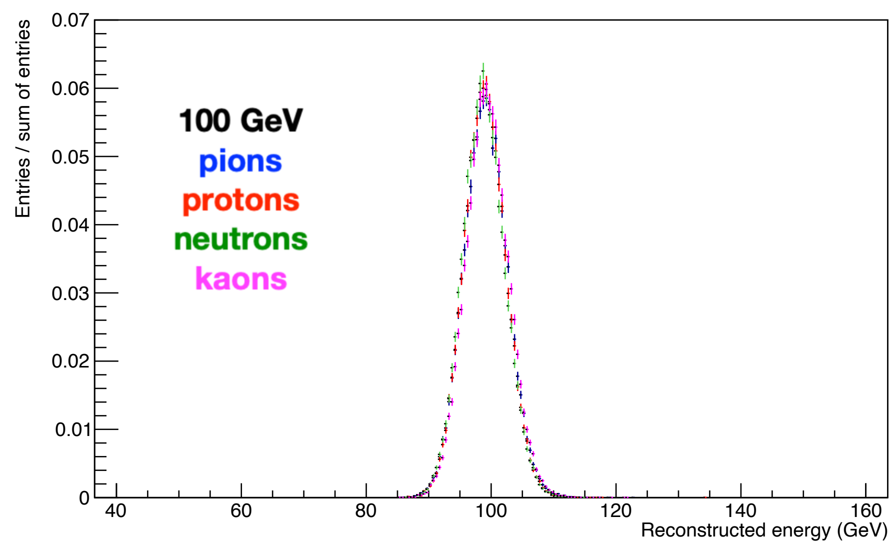


Cherenkov signal



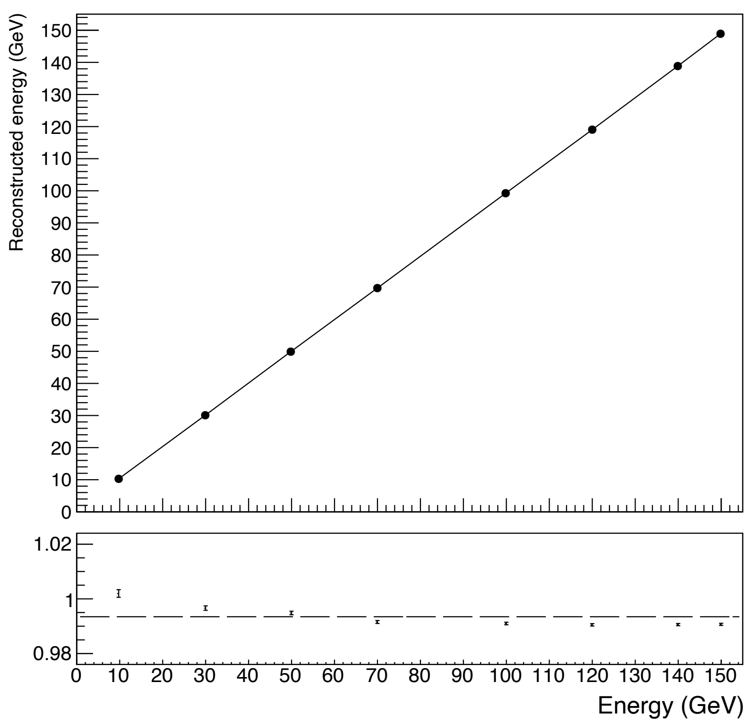
$$E = \frac{E_S - \chi E_C}{1 - \chi}$$

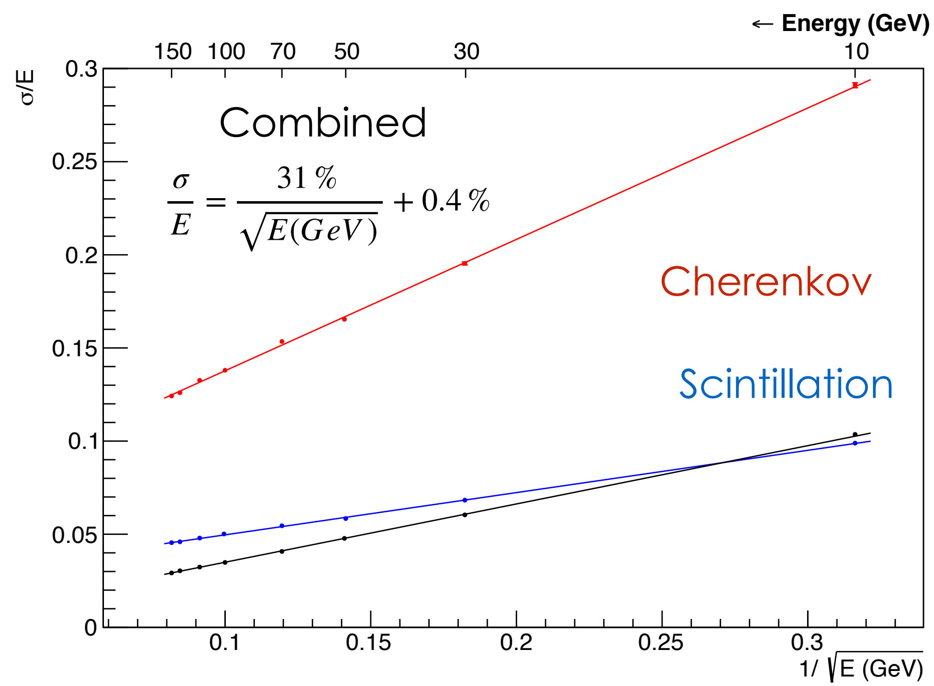
Uniform response from different hadrons with a single χ



Single pion response

- Linearity **within 1% "out of the box"**.
- Resolution **dominated by the S channel** and **clearly improved** by dual readout.





Jet response

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- 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

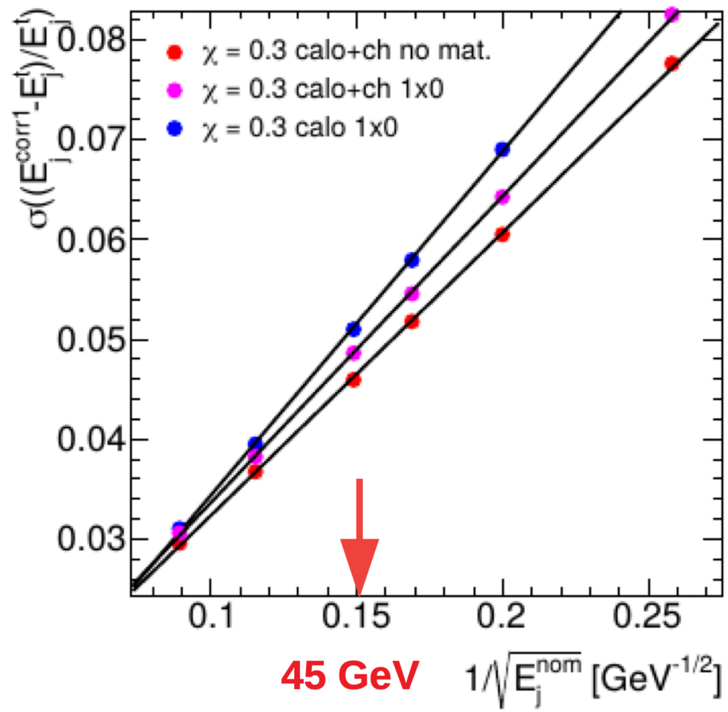
Calo + charged

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

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

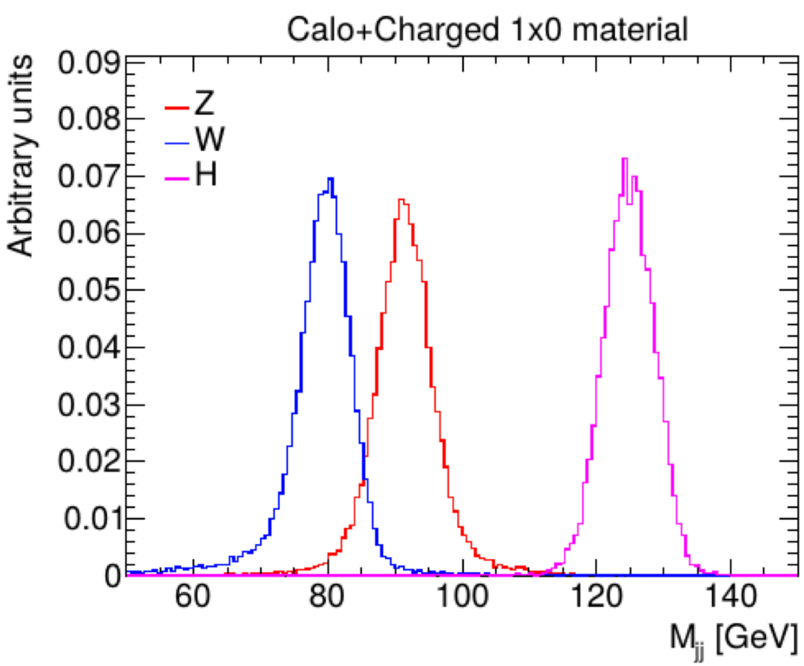
Jet response

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



Resonances studied with

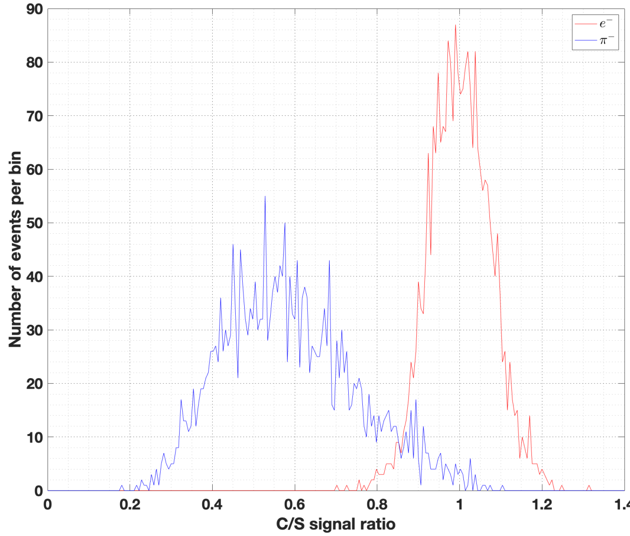
$$e^+e^- \to ZH \to jj\tilde{\chi}_0^1\tilde{\chi}_0^1$$
$$e^+e^- \to WW \to jj\mu\nu$$
$$e^+e^- \to ZH \to \nu\nu bb$$

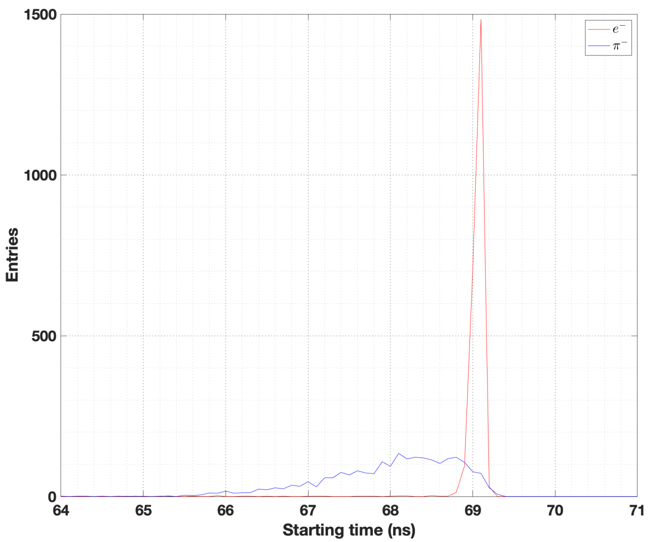


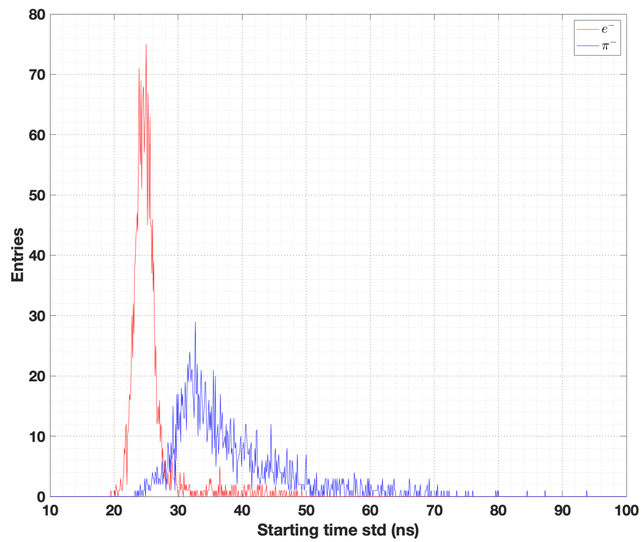
Configuration	W		Z		h	
	Δm	σ	Δm	σ	Δm	σ
Calo no material	-0.108	3.02	-0.009	3.14	-0.01	3.72
Calo+Ch no material	0.07	2.86	0.18	3.05	0.10	3.48
Calo 1X0	-0.08	3.14	-0.13	3.73	-0.18	3.95
Calo+Ch 1X0	0.08	3.01	0.21	3.26	-0.13	3.72

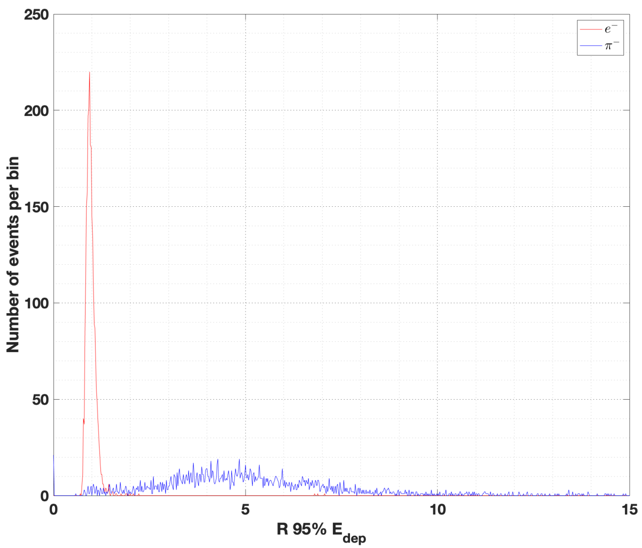
Particle identification

- 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%.









An outlook on ongoing activities

- Ongoing studies on **4- and 6-jet events**
  - requiring a more detailed final state reconstruction.
- Particle identification, energy reconstruction using machine learning, software integration with DD4hep detector description → see presentation from Yunjae Lee and backup.
- Preparation for **TB activities**:
  - 10x10x100 cm^3 module @DESY in February (COVID permitting - see talk from Romualdo Santoro).

Summary

- I presented the **simulated performance** (response linearity, energy and angular resolution) of the **IDEA dual-readout calorimeter** for:
  - Electrons (photons in backup).
  - Single hadrons.
  - Jets.
- Lots of **parallel efforts in many directions**: an exciting and lively collaboration!
- If you are interested:
  - Subscribe on egroups.cern.ch to idea-dualreadout@cern.ch

Backup

Dual readout - the principle

- Suppose I read out **two calorimeter signals, S and C, with different h/e**. Then:

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

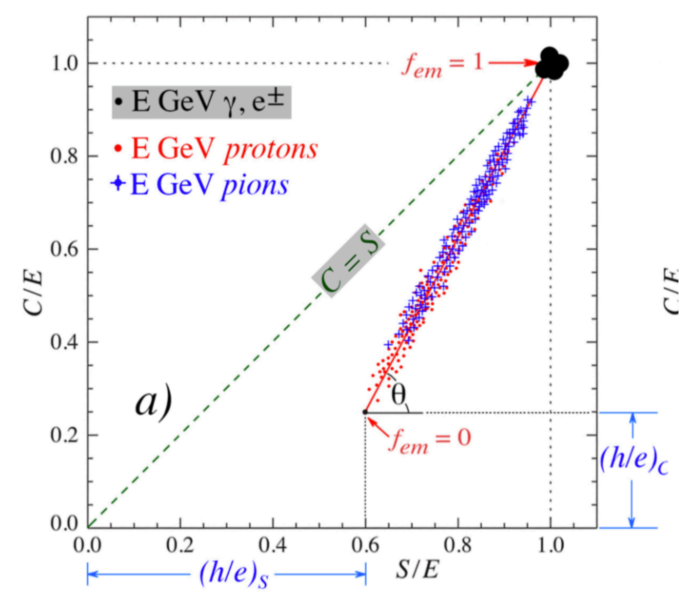
$$E_C = E\left(f_{\text{em}} + \left(\frac{h}{e}\right)_C (1 - f_{\text{em}})\right)$$

$$f_{\text{em}} = \frac{\left(\frac{h}{e}\right)_C - \left(\frac{h}{e}\right)_S \left(\frac{E_C}{E_S}\right)}{\left(\frac{E_C}{E_S}\right)\left(1 - \left(\frac{h}{e}\right)_S\right) - \left(1 - \left(\frac{h}{e}\right)_C\right)}$$

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

$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C}$$

Depends **only on the detector**, it can be determined in test beam, for example.



Tau decay identification

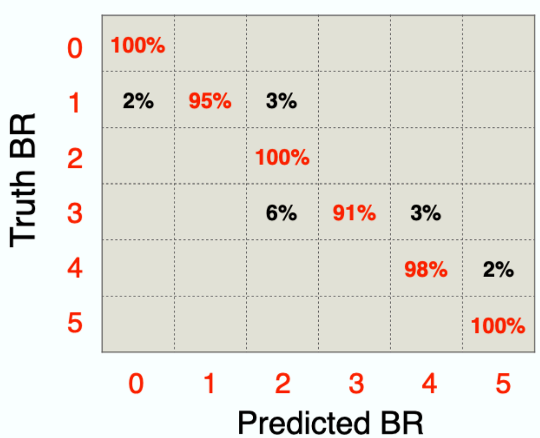
Advanced Machine Learning Applications

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

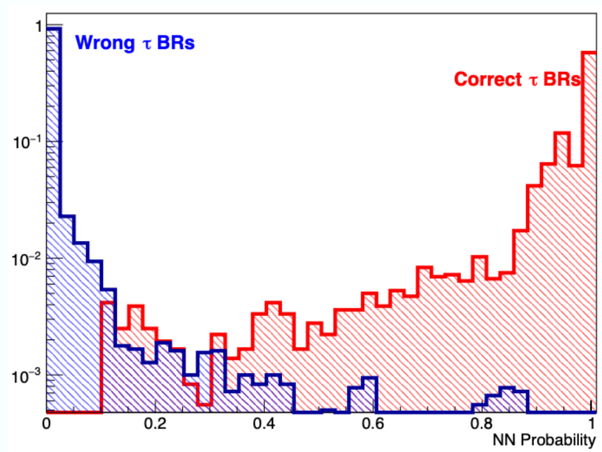
Data preprocessing needed to reduce data size and fit GPU memory

- 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

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

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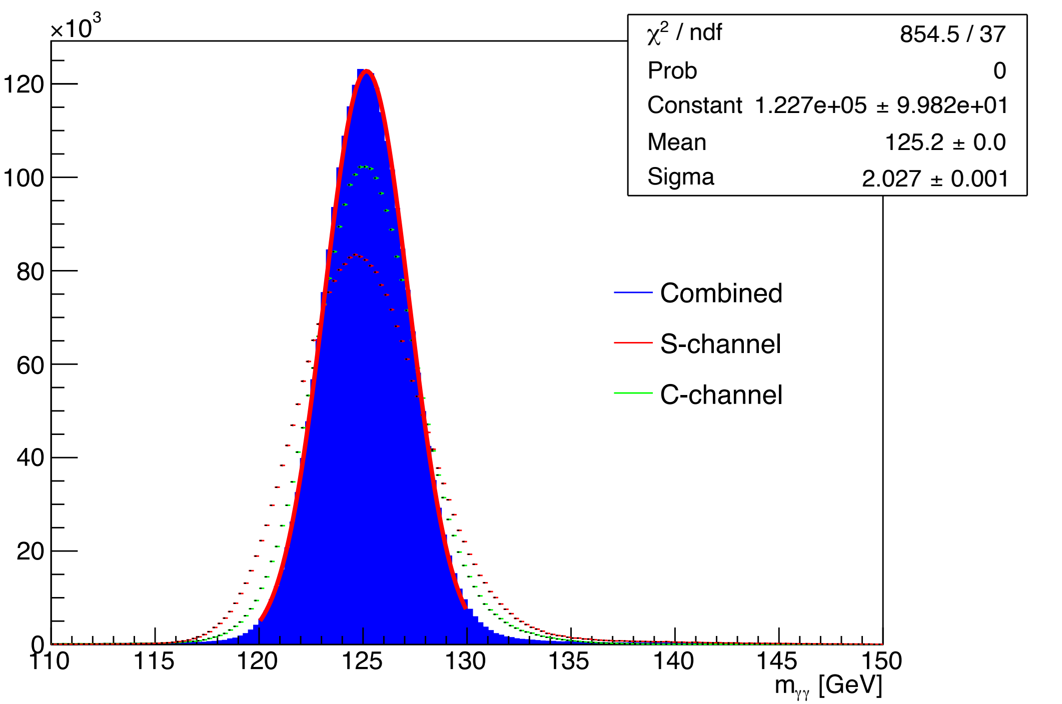
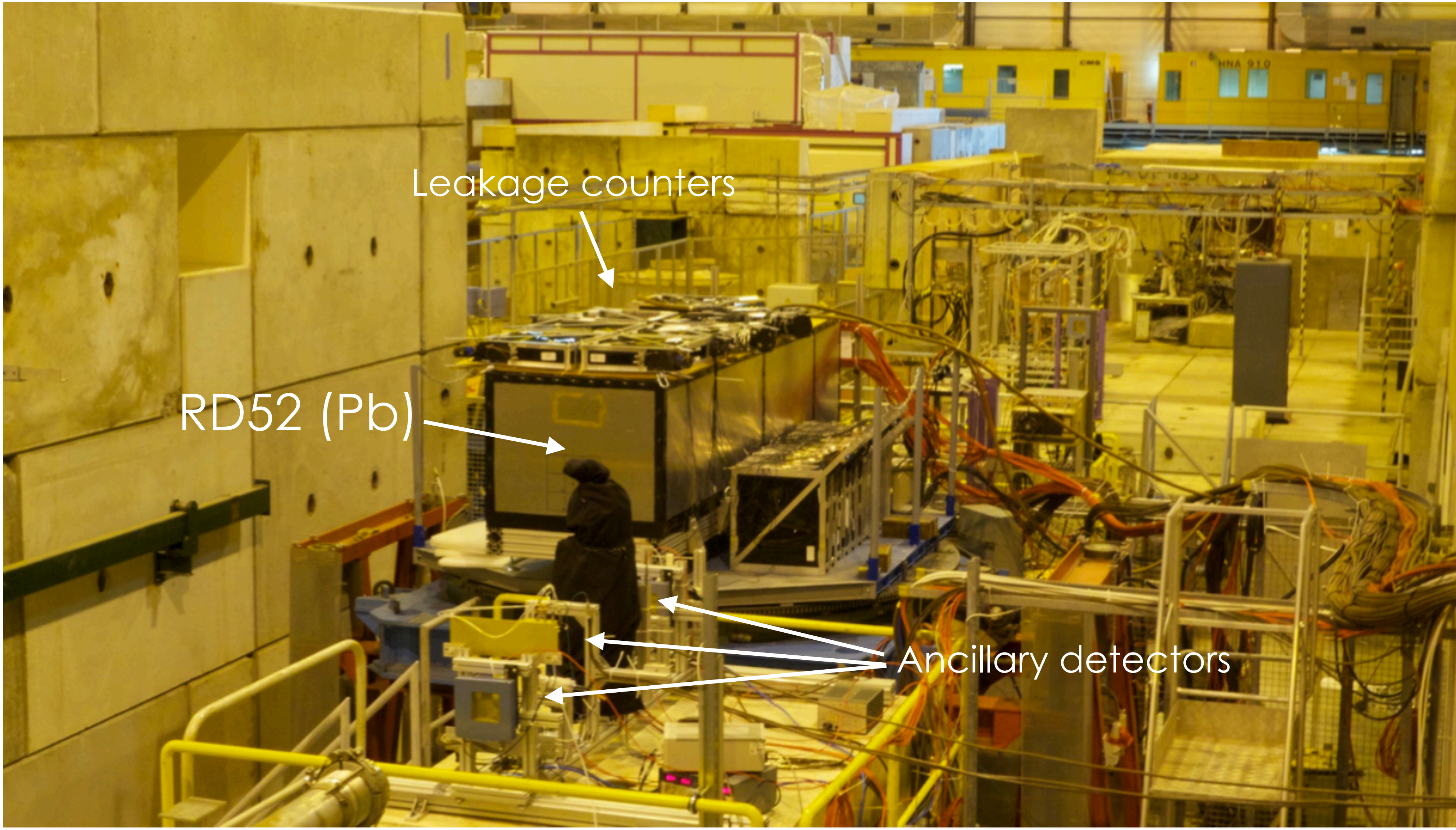
- Using 5M $e^+e^- \to ZH \to \nu\nu\gamma\gamma$ events and clustering opposite calorimeter hemispheres as photons.
- Dedicated calibration corrections for impact point on tower

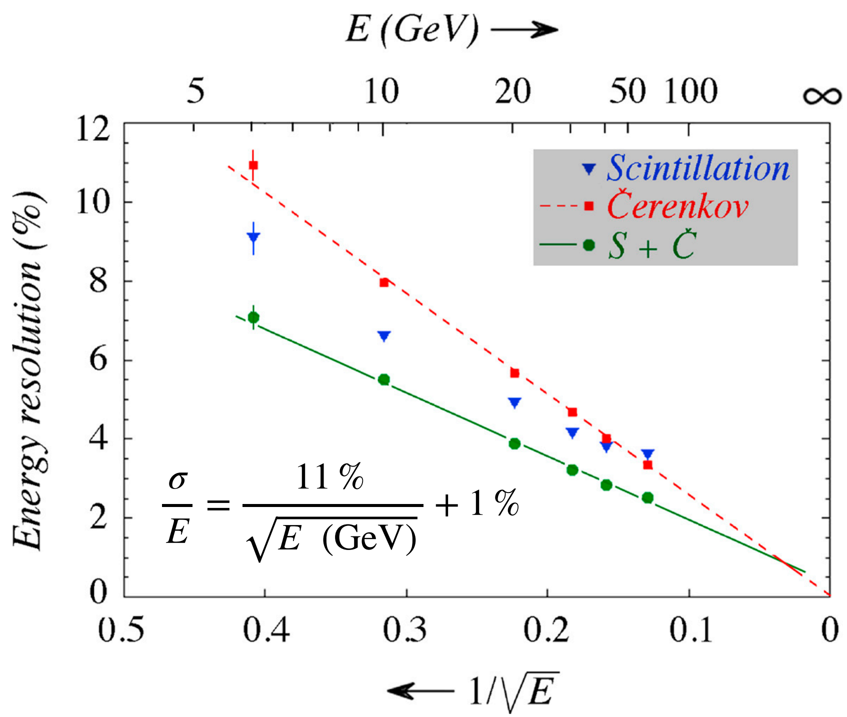
- Using tower granularity (estimated use of full granularity further improves mass resolution by 20%)
- Combined mass resolution ~ 2 GeV



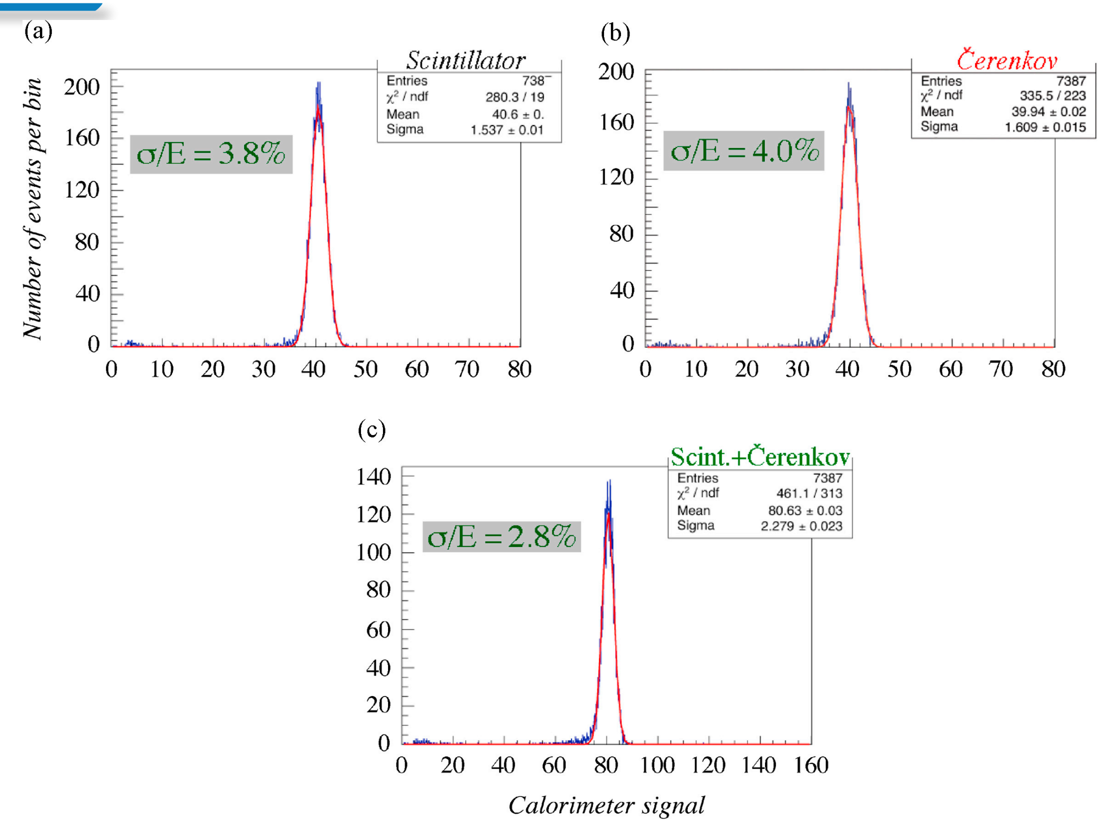
Dual readout calorimeter at work

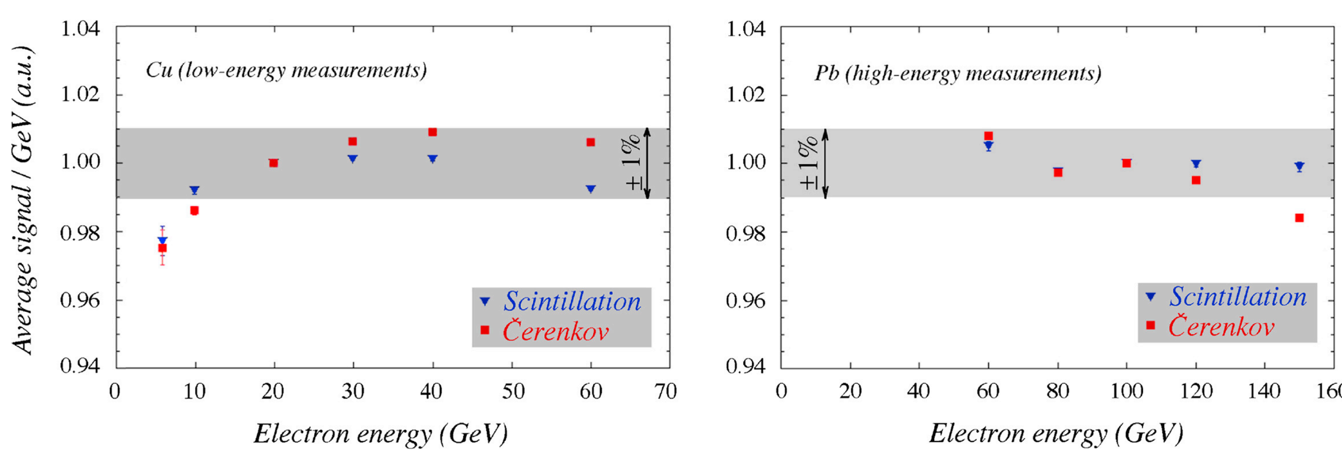


Electron response



40 GeV electrons





Single hadron response - linearity

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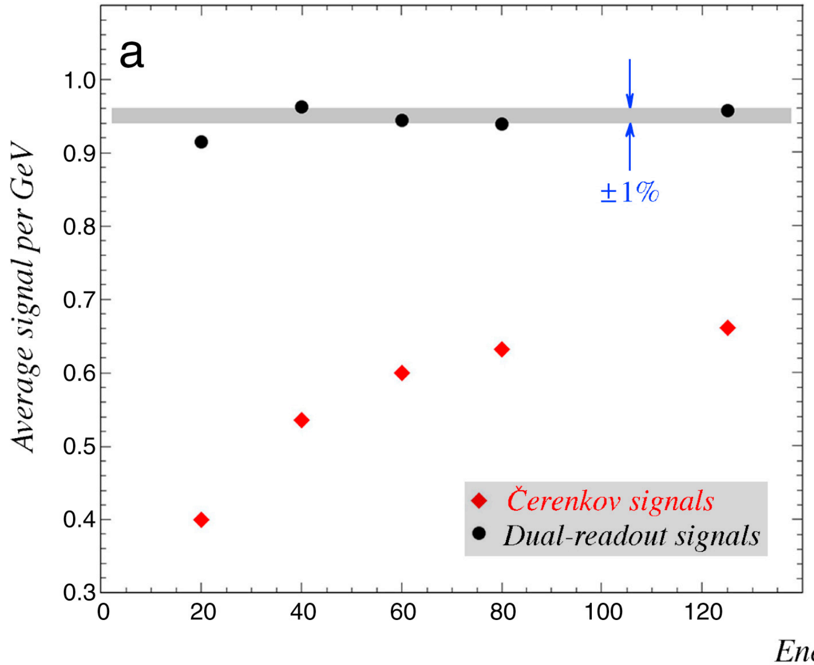
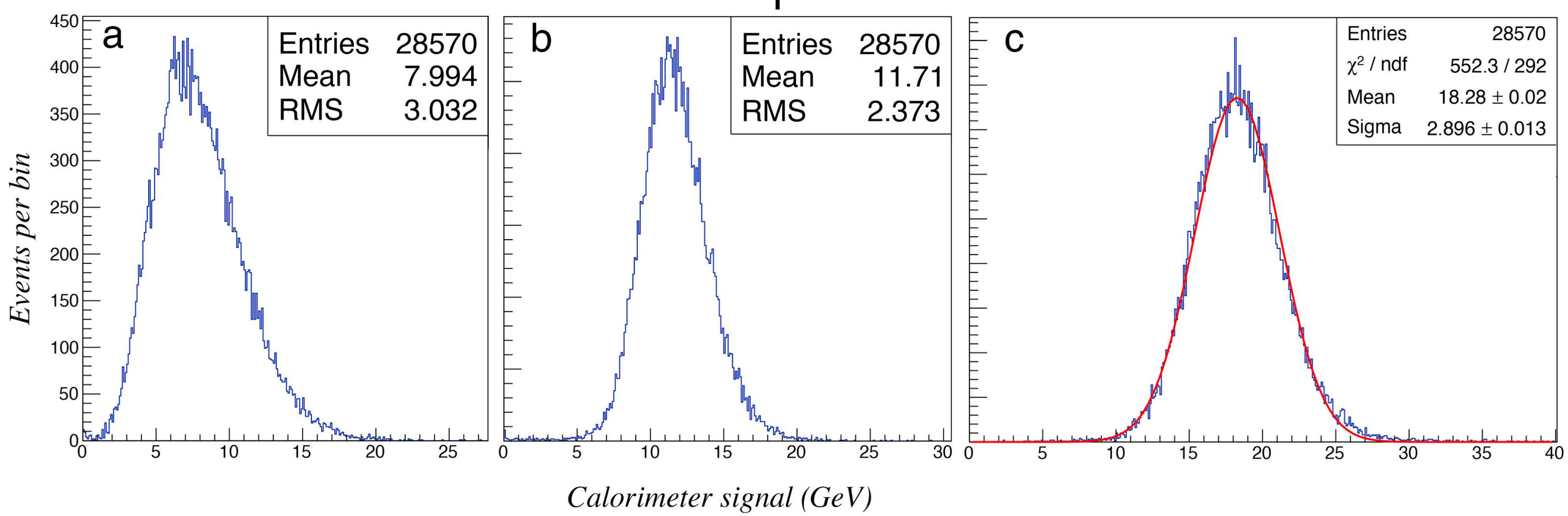
- Dual readout signal **largely recovers linearity** while vastly improving resolution.



20 GeV pions



Single hadron response - resolution

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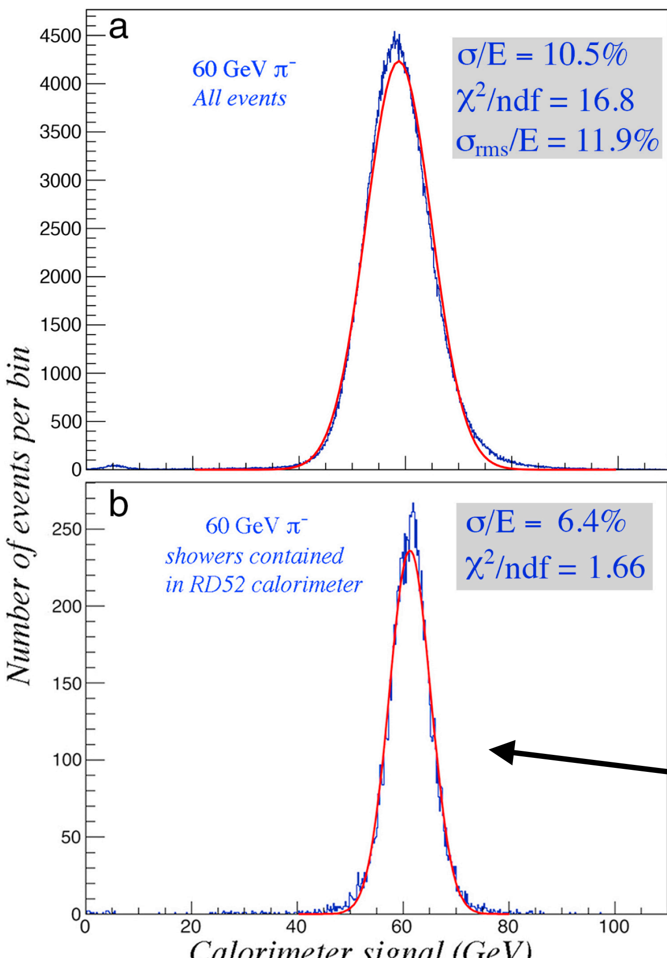
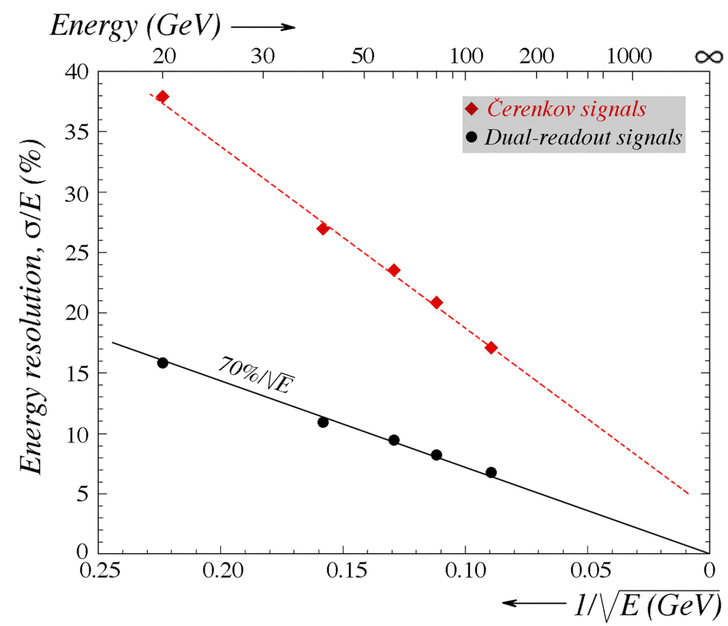
- Problem of calorimeter R&D: a **fully containing calorimeter** is **expensive.**

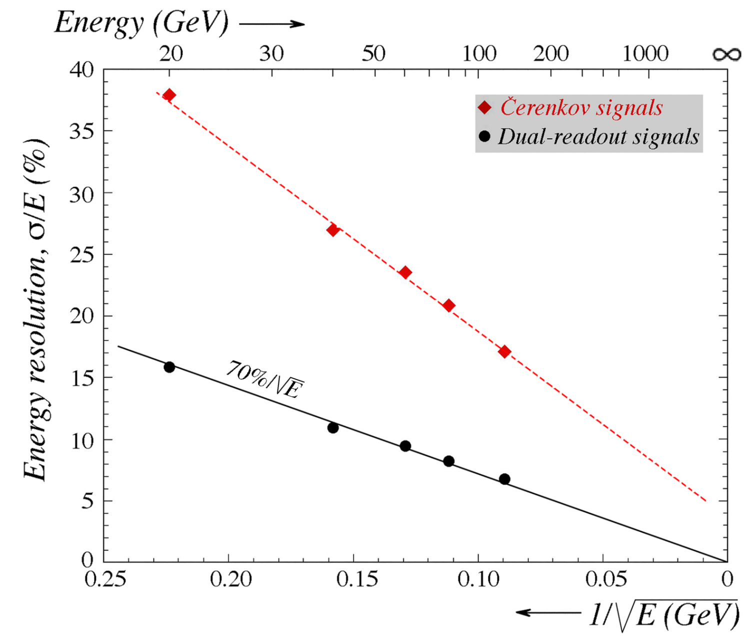




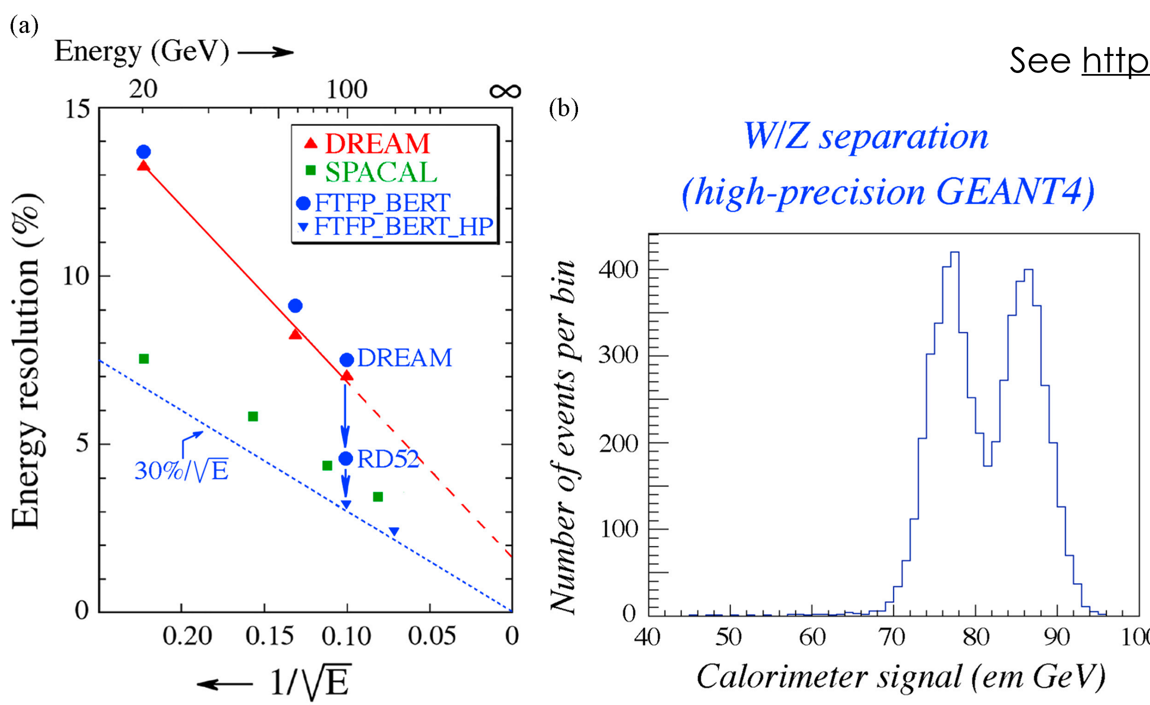
No signal in leakage counters

Performance of Dual Readout

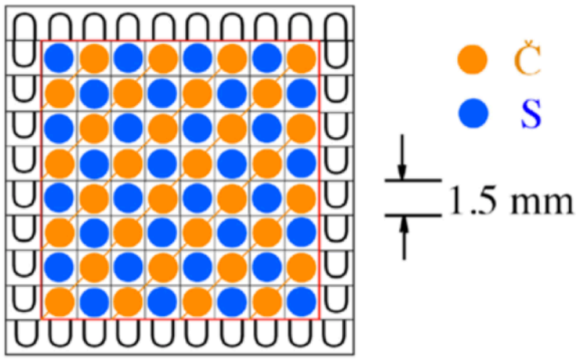
- **Hadronic resolution** comparable to **compensating calorimeters.**
  - Resolution at TB (dominated by leakage). G4 estimate **with full containment** $$\frac{\sigma}{E} = \frac{34\,\%}{\sqrt{E}}$$

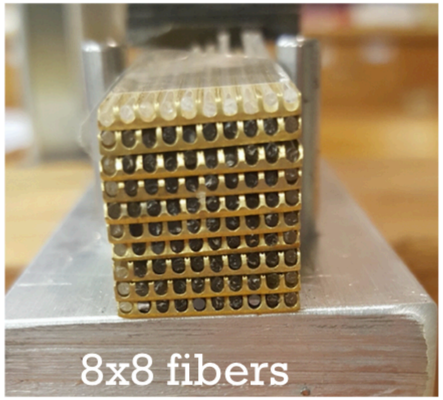


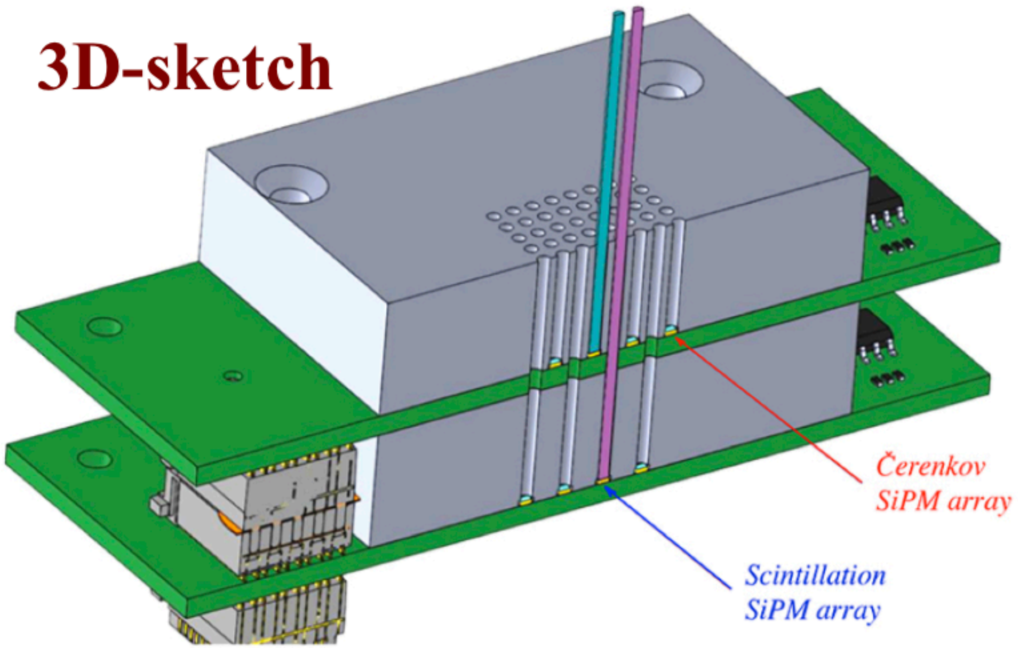
See https://doi.org/10.1016/j.ppnp.2018.07.003



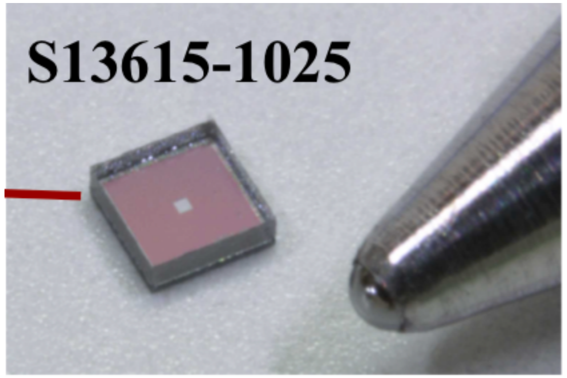
SiPM dual readout



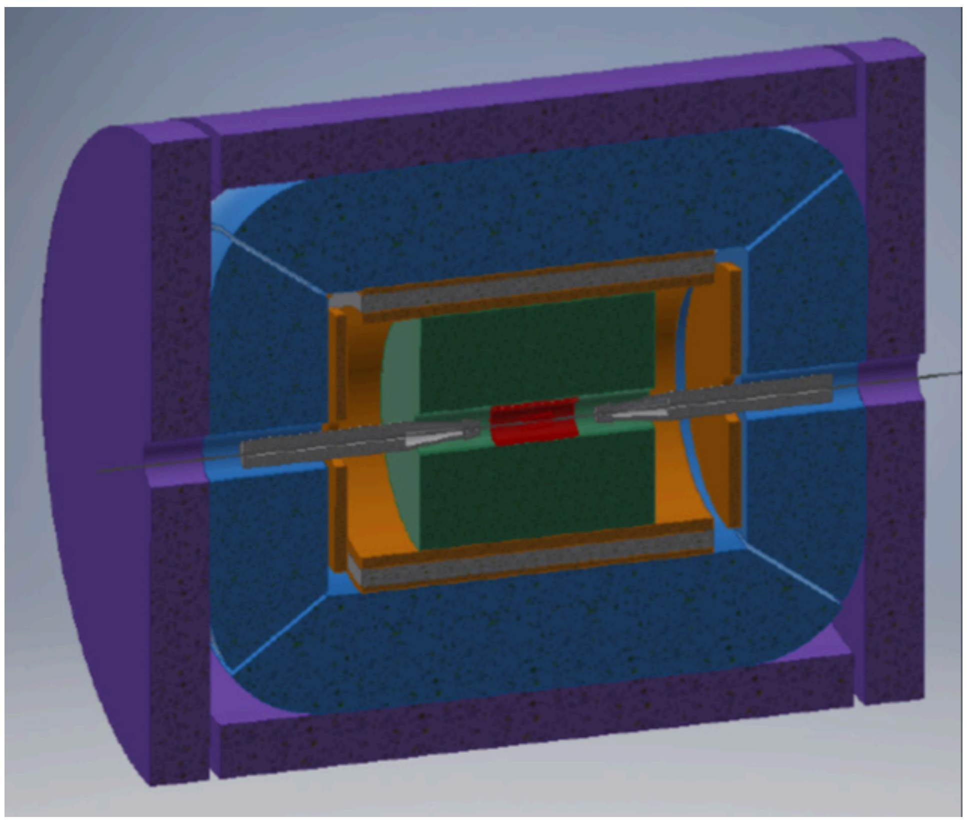


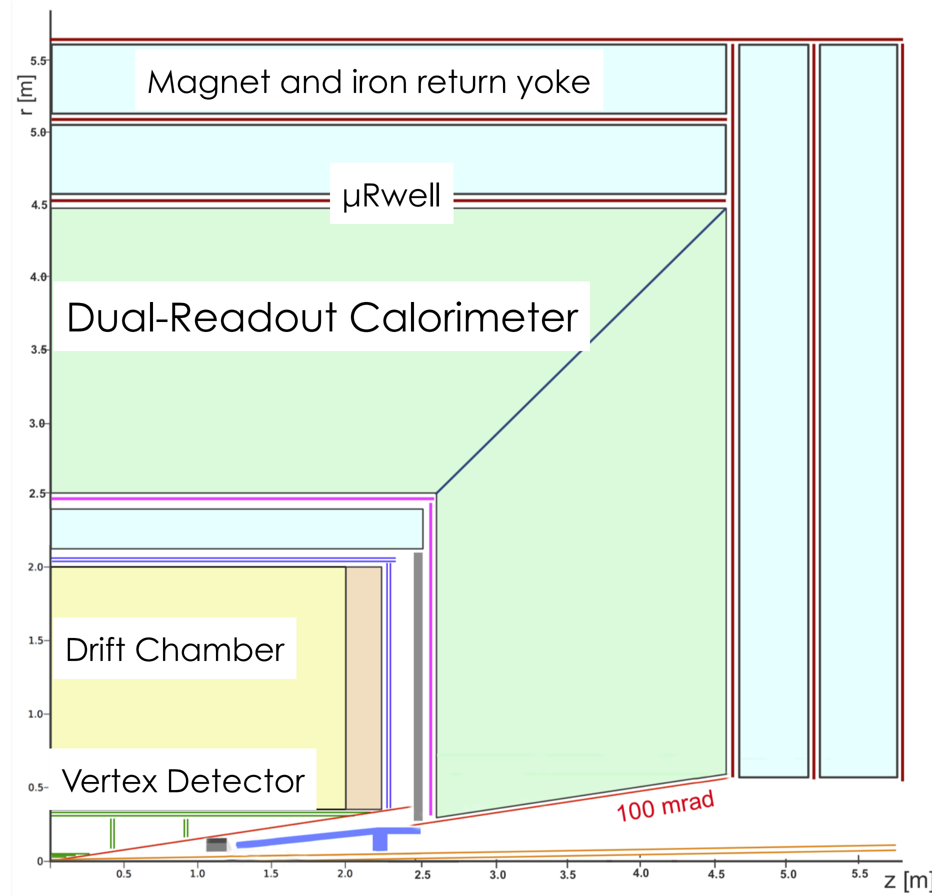


- Single fibre readout with **HAMAMATSU SiPM.**
- Readout for Cherenkov and Scintillation light **separated to minimise cross talk** (the latter expected to be ~ 50 times larger if not attenuated).



A practical implementation: IDEA

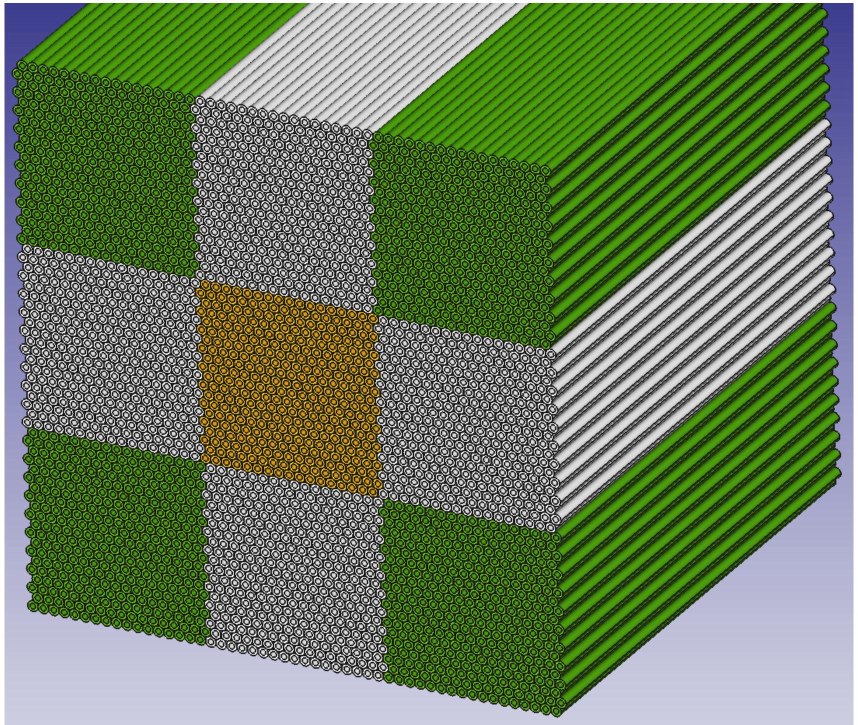


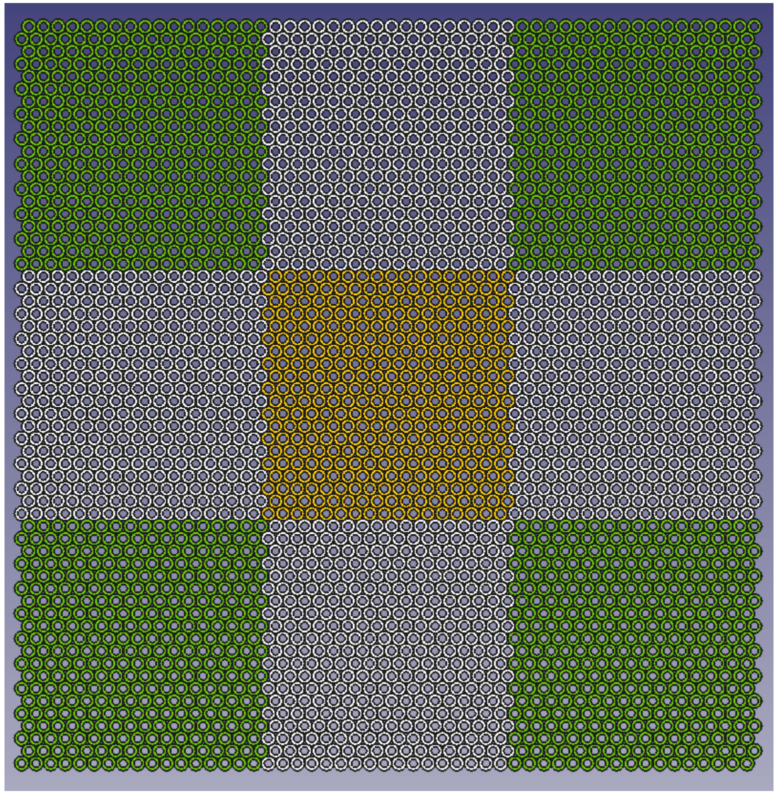


See here for additional information

2020 target

- Build a 10 x 10 x 100 cm^3 prototype:
  - Use **2 mm diameter** tubelets (CuZn37, glued with araldite)
    - 60 horizontal layers of 48 tubes
    - 9 readout towers of 16x20 tubes each
    - **SiPM** readout for the **central tower**, PMs (with reduced granularity) otherwise





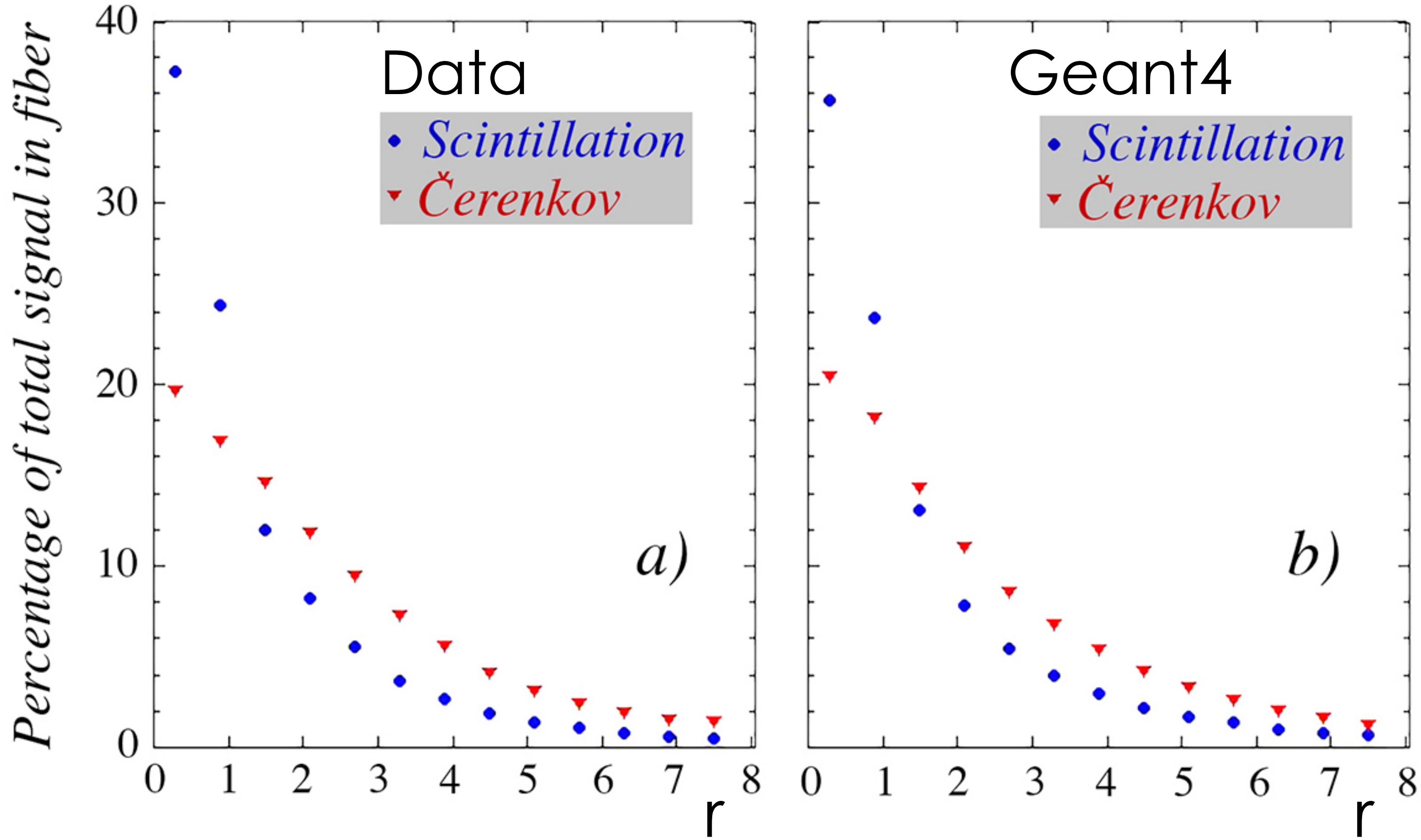
SiPM dual readout (shower shape)

- Readout of single fibre gives **unprecedented lateral segmentation.**
- Em lateral shower shape measured with **~ 1 mm precision**.

$$\bar{x} = \frac{\sum_i x_i E_i}{\sum_i E_i}; \bar{y} = \frac{\sum_i y_i E_i}{\sum_i E_i}$$

$$r = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2}$$

Doi:10.1016/j.nima.2018.05.016



Studies on χ values