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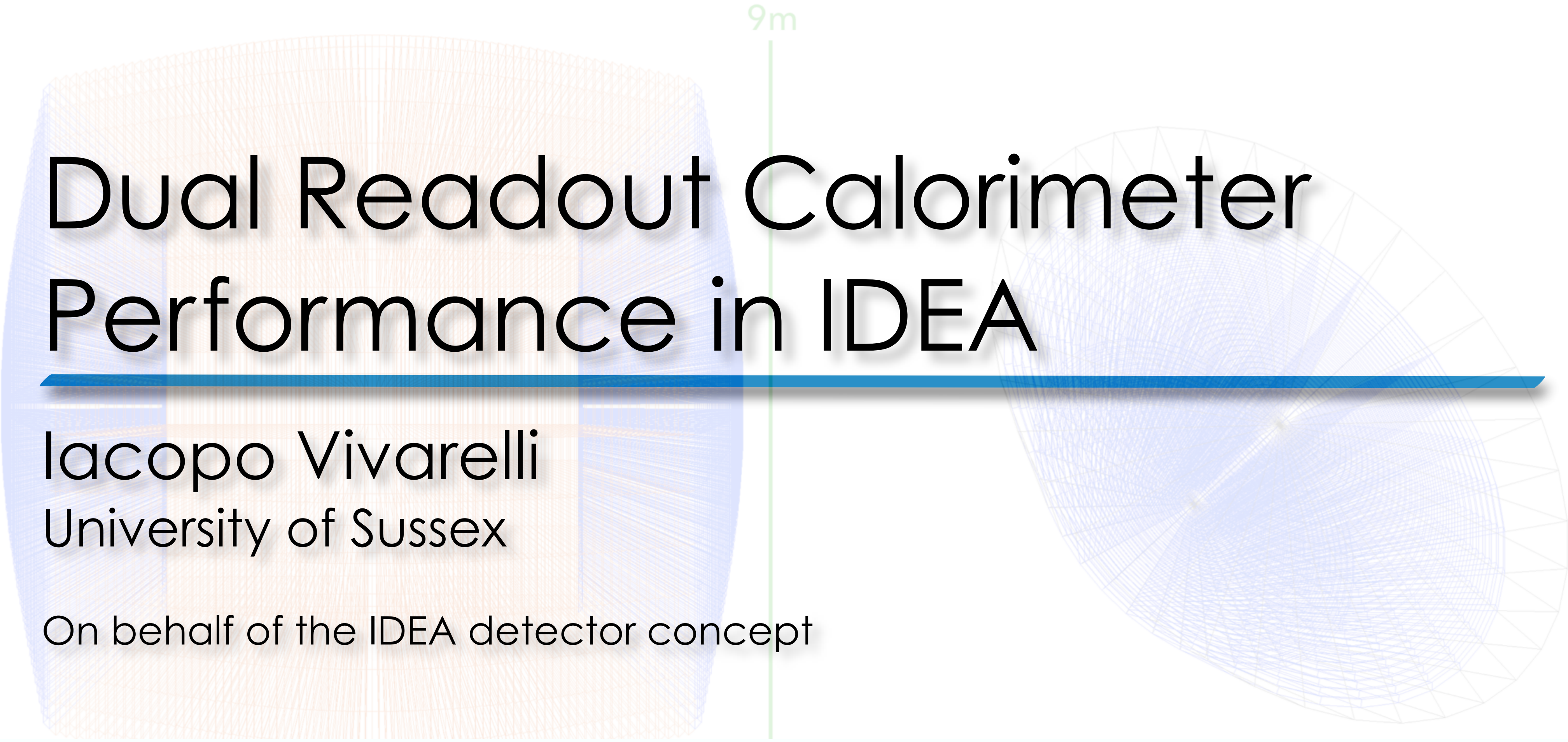
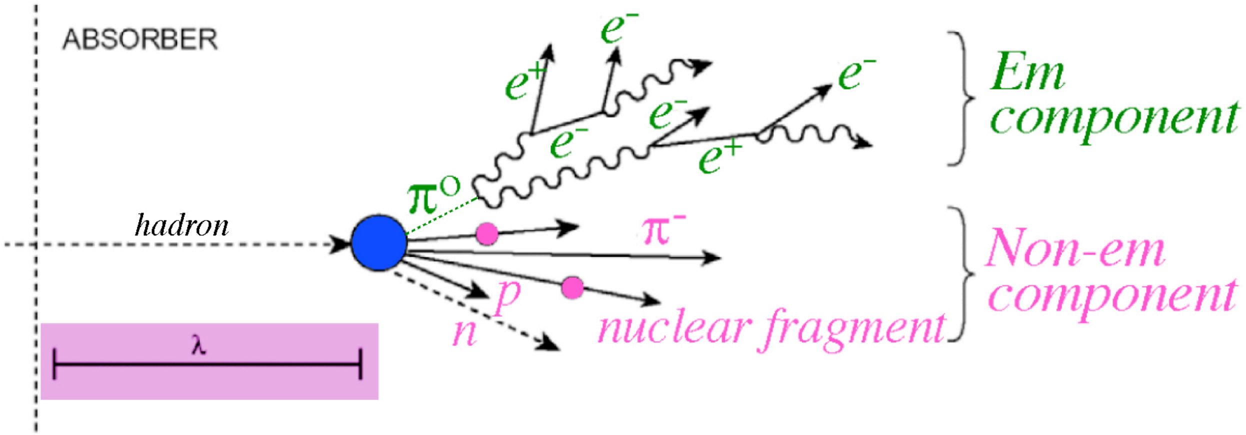


Dual Readout Calorimeter Performance in IDEA

Iacopo Vivarelli
University of Sussex

On behalf of the IDEA detector concept

The curse of hadronic calorimetry



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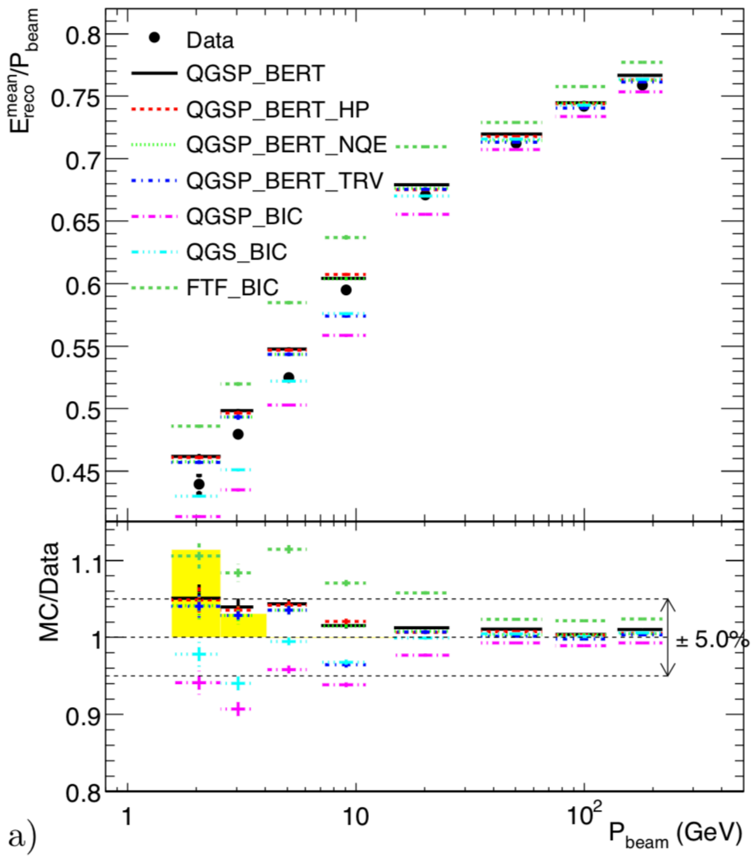


- **Non-compensating calorimeters**: response to em part different from that to non-em part. **h/e < 1**
- $\langle f_{em} \rangle$ energy dependent ⇒ **Non-linear calorimeter response** to hadrons (and large fluctuations)

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

Dual readout - the principle

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

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

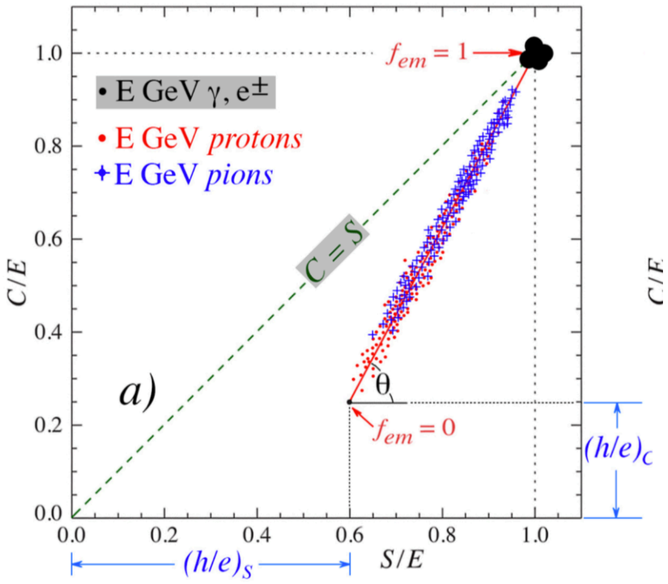
$$E_C = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_C (1 - f_{\mathrm{em}})\right)$$

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

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

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

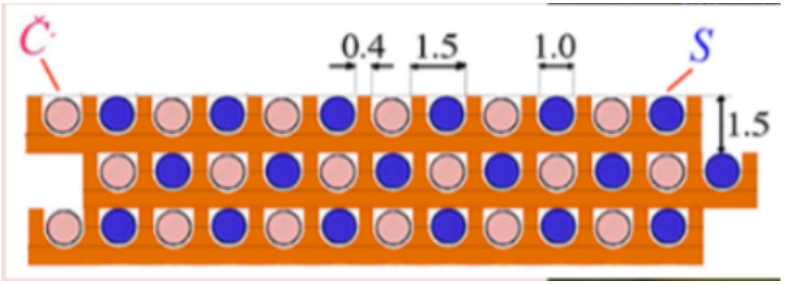
Depends **only on the detector**, it can be determined in test beam, for example.

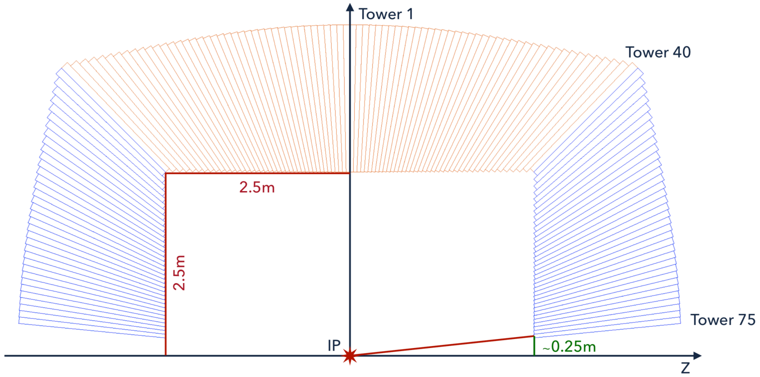


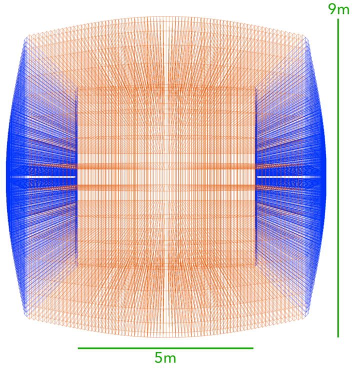
In this talk

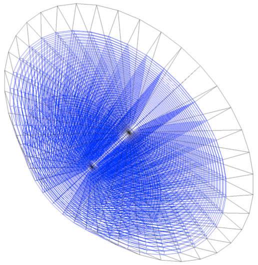
- **Single electron** and **single pion** performance using the **IDEA calorimeter simulation**
  - Another DR calorimeter Geant4 simulation using the ILC 4th concept geometry developed within the collaboration, see here
- Di-jet event performance
- Using $H \to \gamma\gamma$ as a candle for photons.
- Other ongoing DR activities

Simulation









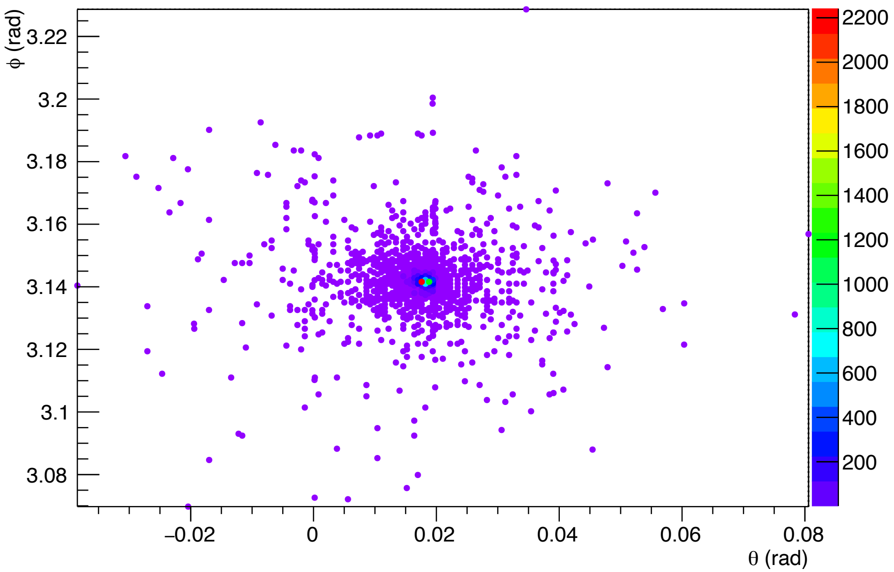
- Full G4 simulation of “final” geometry **is available**:
  - Cu absorber, 1 mm fibers, 1.5 mm pitch
- Also existing parametrised simulation for physics studies
- **Read out the single fibre: 130 M channels:**
  - Excellent angular resolution, lateral shower shape sensitivity
- In most studies, a coarser granularity is used
  - **75 projective elements x 36 slices**

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

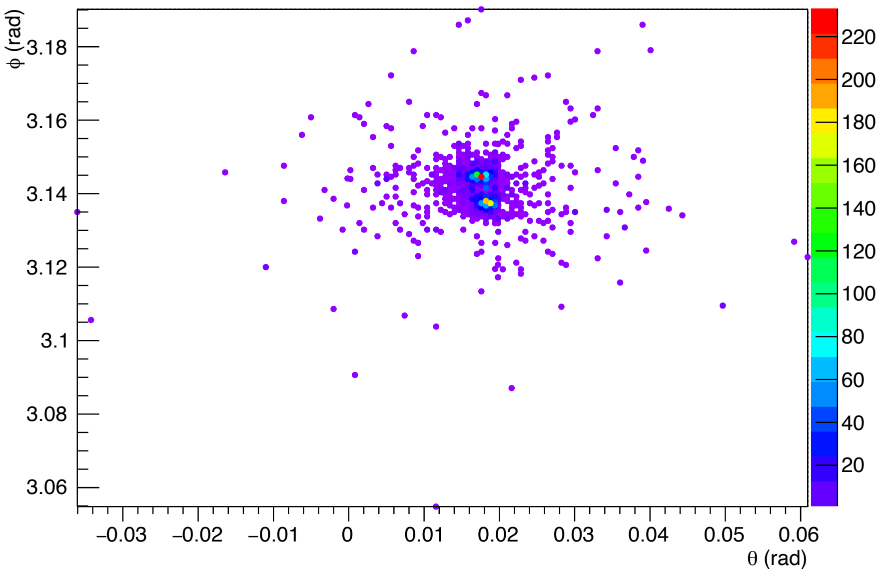
This is what I will refer to as “tower” in the following

How events look like (full granularity)

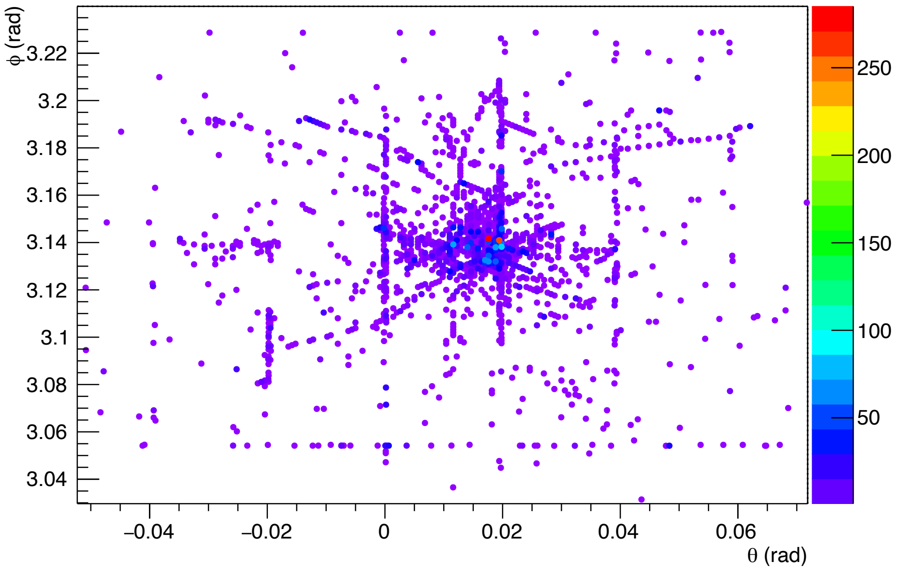
e^- 40 GeV



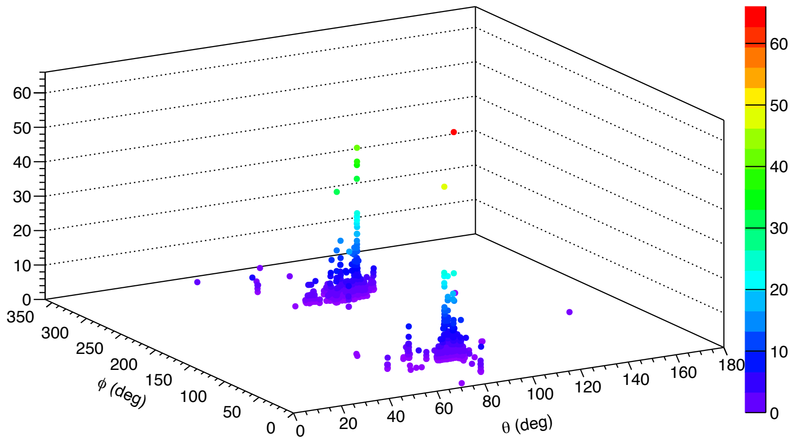
π^0 40 GeV



π^- 40 GeV



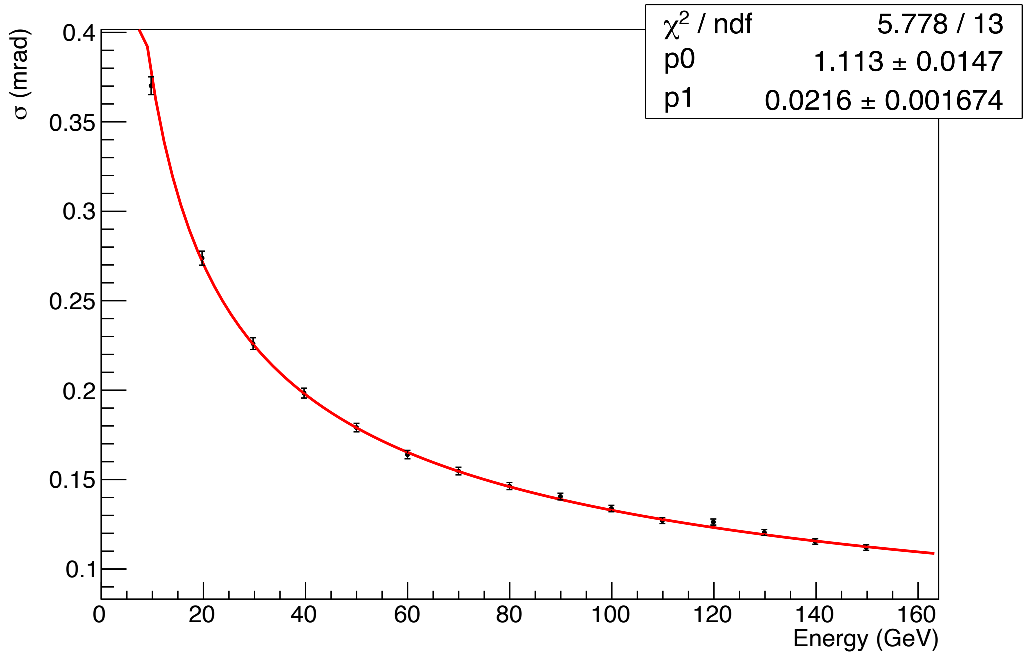
Di-jet



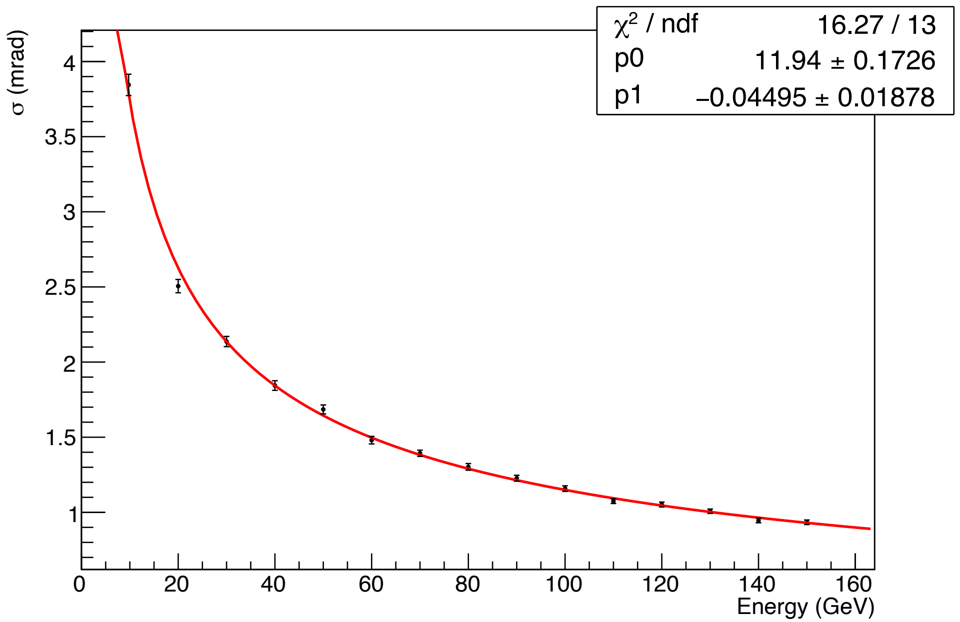
Angular resolutions

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

Electrons



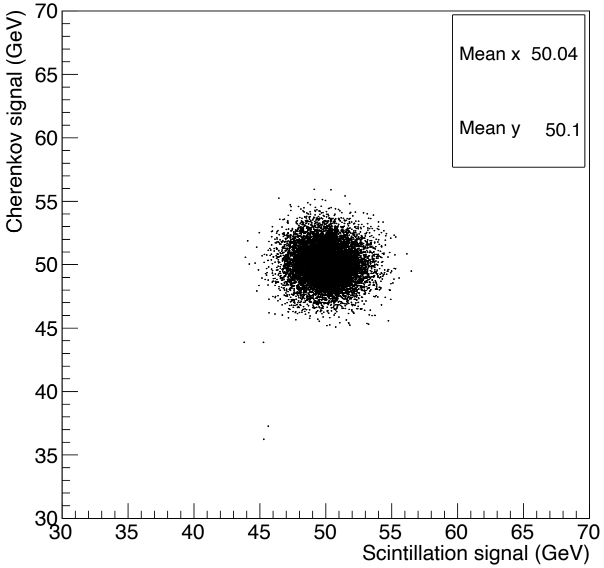
Pions



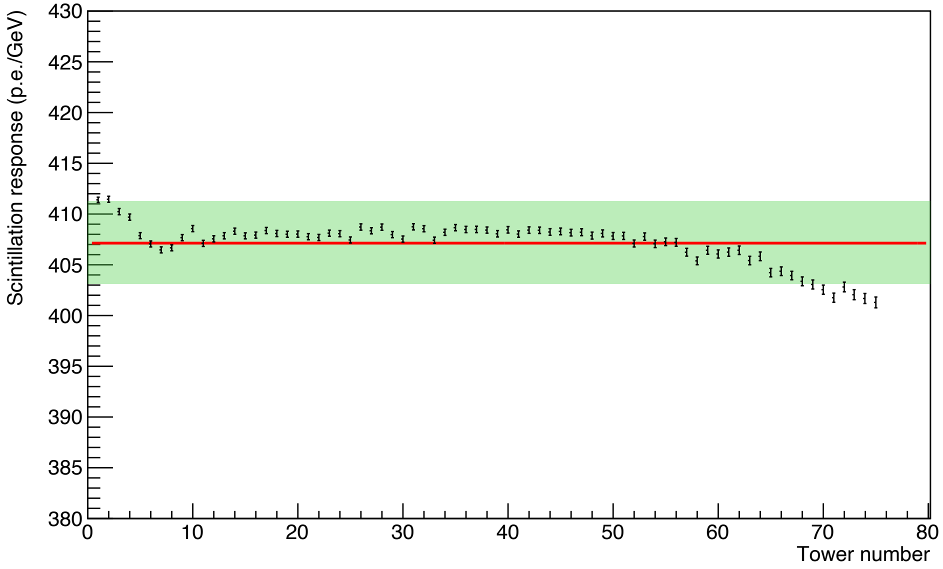
Calibration with electrons

- Light yield chosen **according to TB results**
- Energy deposited by electrons in a tower (90% containment) used as pe/GeV calibration factor

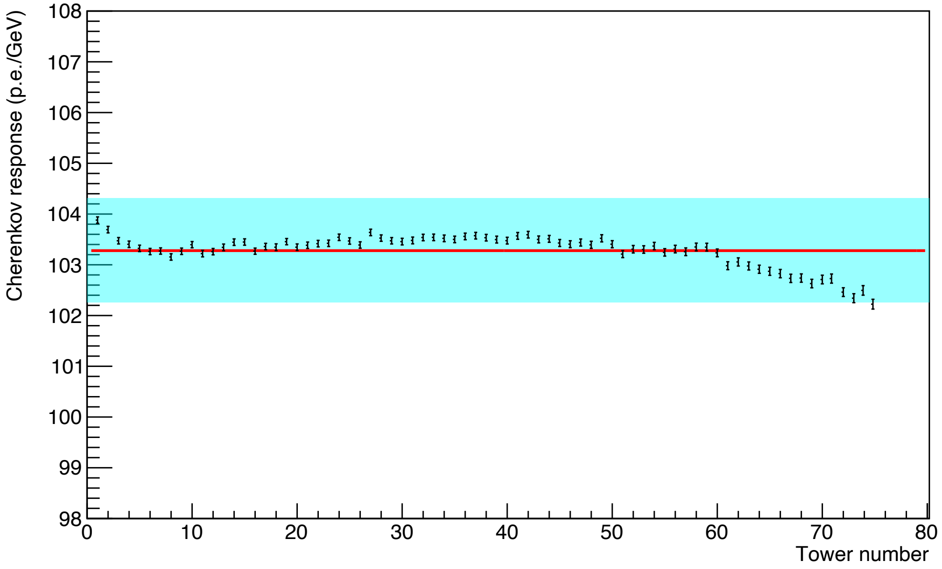
50 GeV electrons



40 GeV electrons - S channel

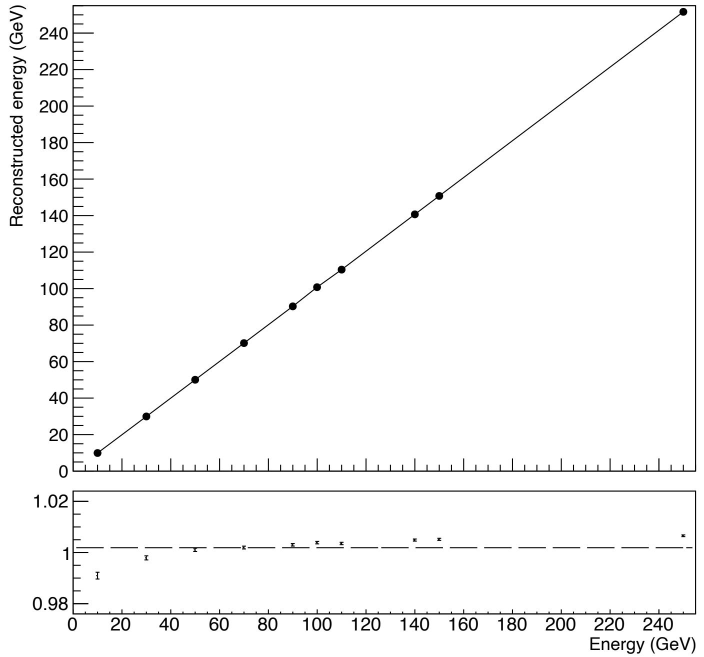


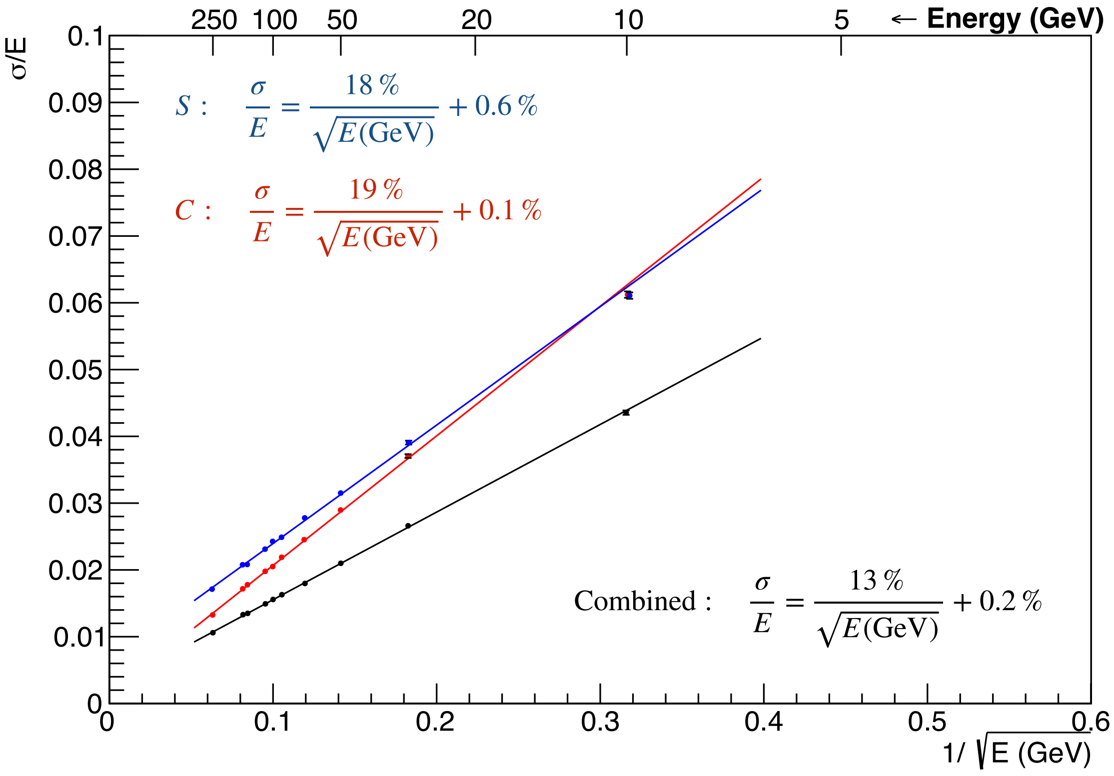
40 GeV electrons - C channel

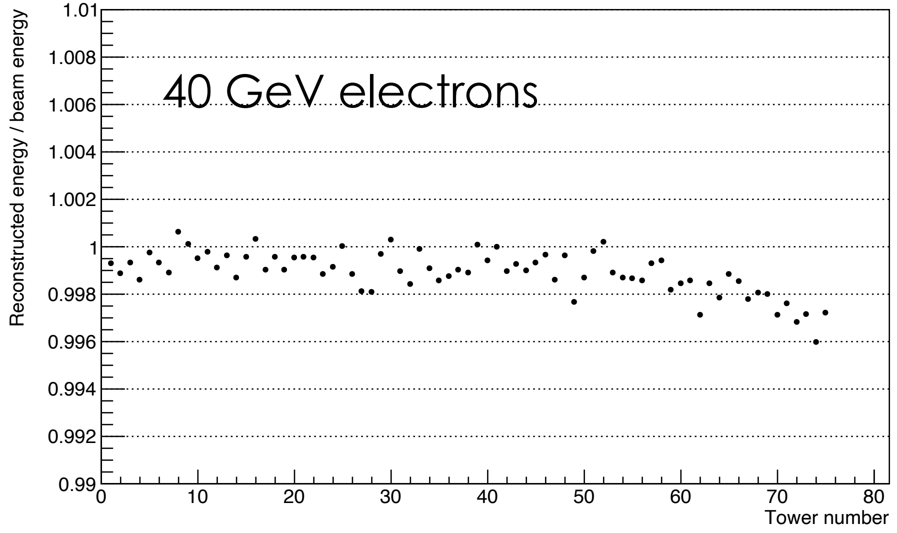


Electromagnetic performance

- From now on using tower granularity
- Linearity Vs Energy within 1%, and uniform over towers
- **Competitive electromagnetic resolution** for combined energy reconstruction

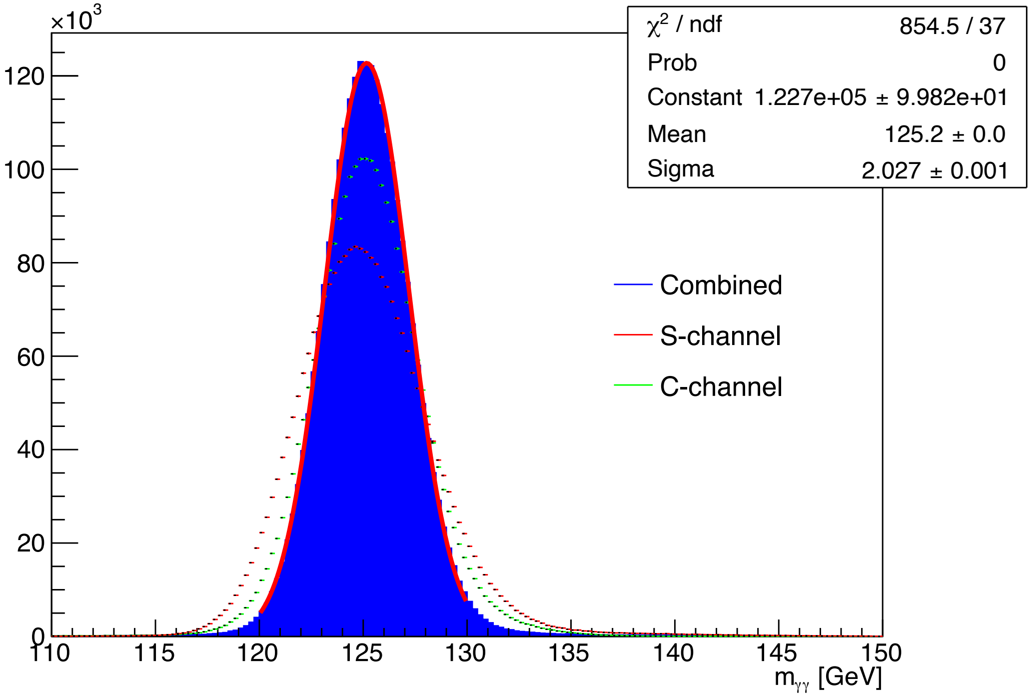






$H \rightarrow \gamma\gamma$ as a photon candle

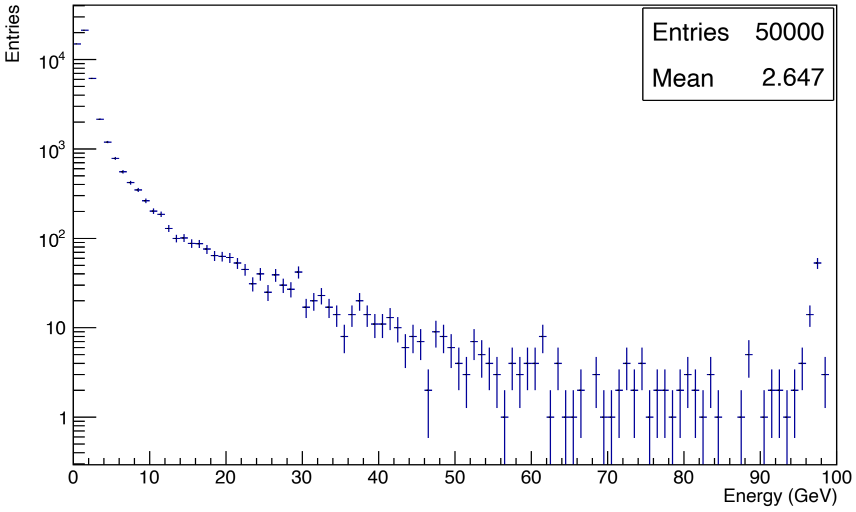
- Using 5M $e^+e^- \rightarrow ZH \rightarrow \nu\nu\gamma\gamma$ events and clustering opposite calorimeter hemispheres as photons.
- Dedicated calibration corrections for impact point on tower
- Using tower granularity (estimated use of full granularity further improves mass resolution by 20%)
- Combined mass resolution ~ 2 GeV



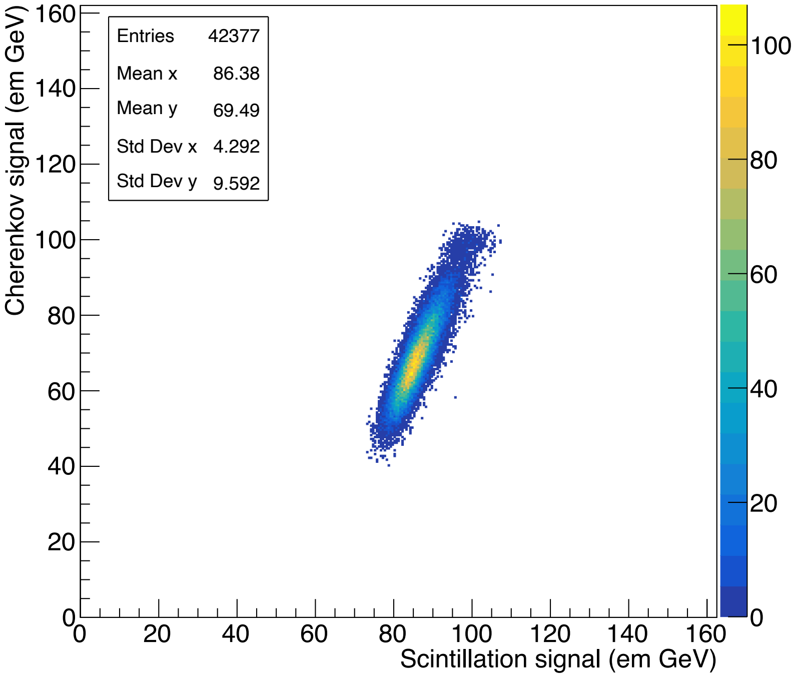
Single pion response

- Current IDEA calorimeter inner radius 2.5 m; outer radius 4.5.
  - **Reject events with poor containment** to focus on performance
- Correlation between S and C in agreement with what seen at the test beam with RD52

Kinetic energy escaped from calorimeter surface, 100 GeV pions

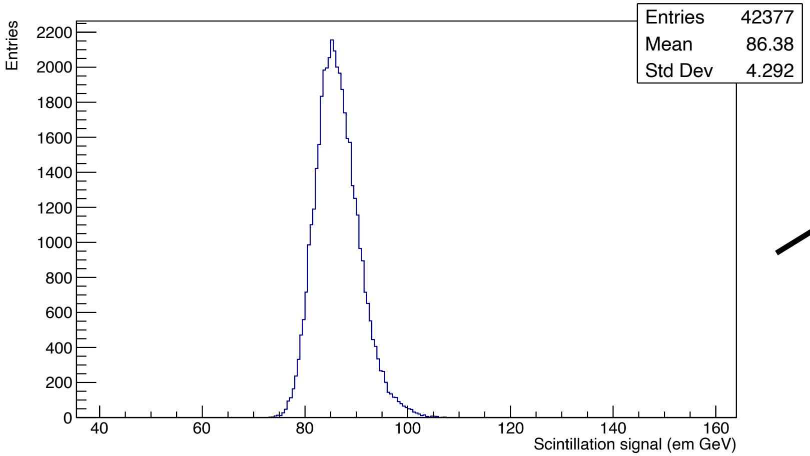


Kinetic energy escaped from calorimeter surface, 100 GeV pions

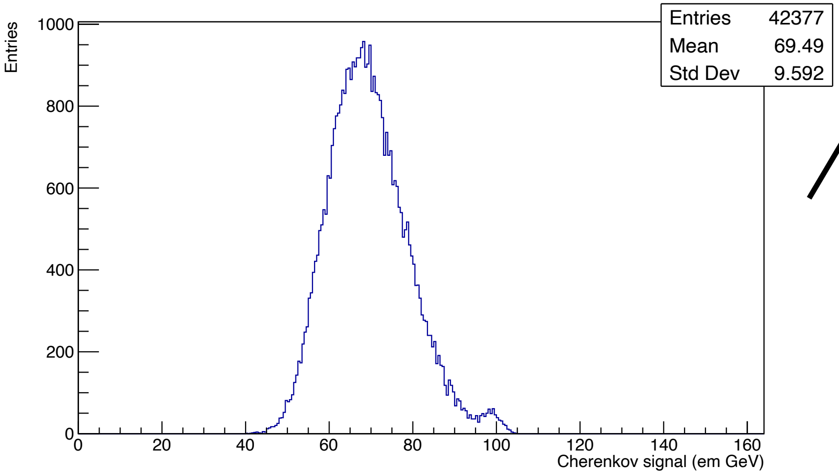


Single pion response

Scintillation signal

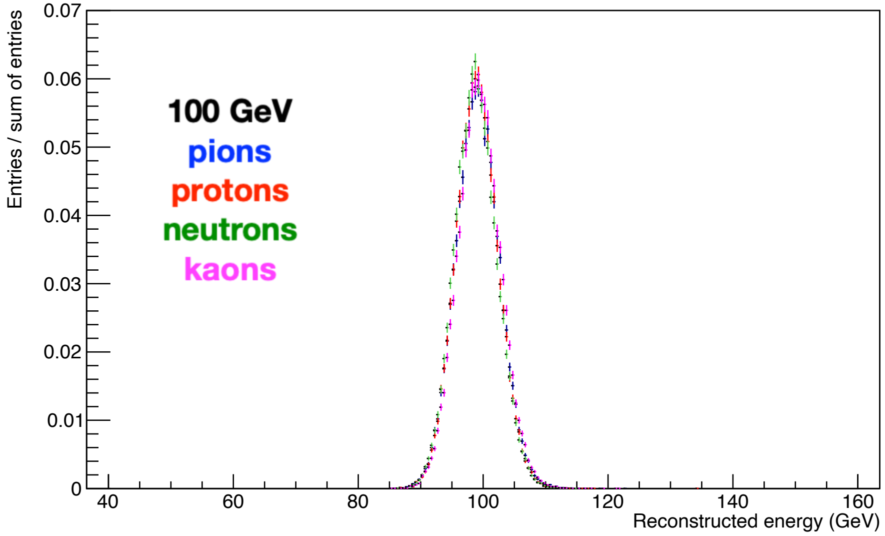


Cherenkov signal



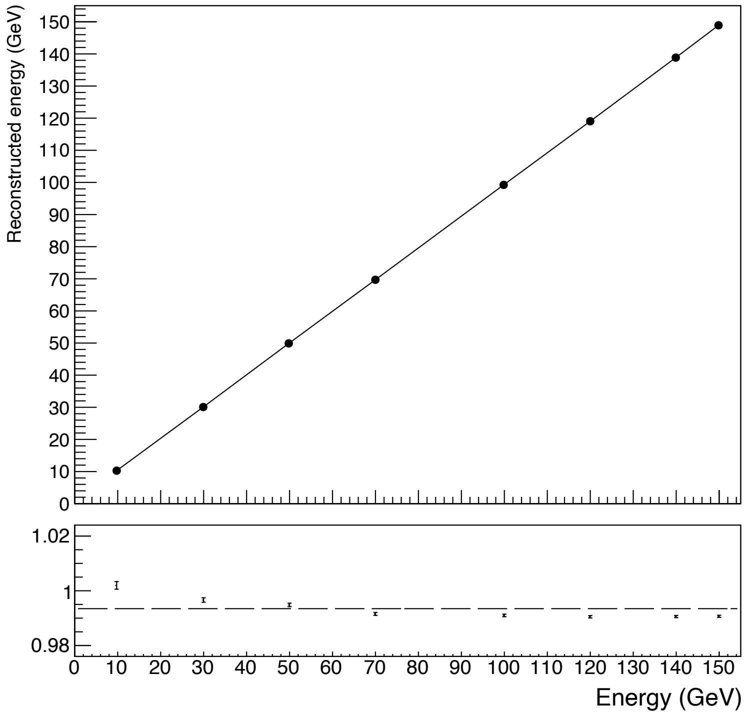
$$E = \frac{E_S - \chi E_C}{1 - \chi}$$

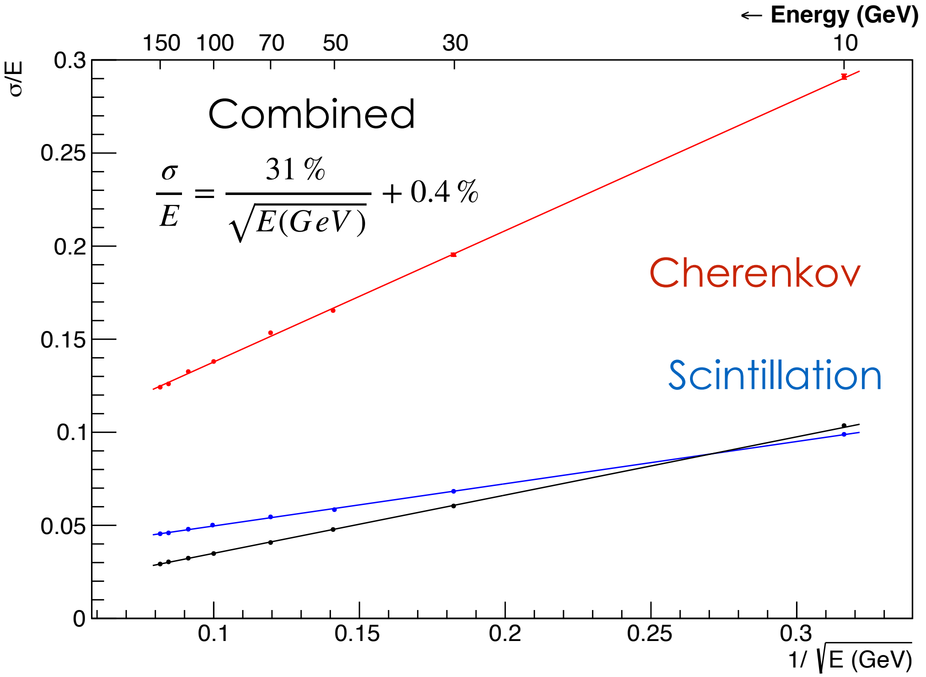
Uniform response from different hadrons with a single χ



Single pion response

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





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

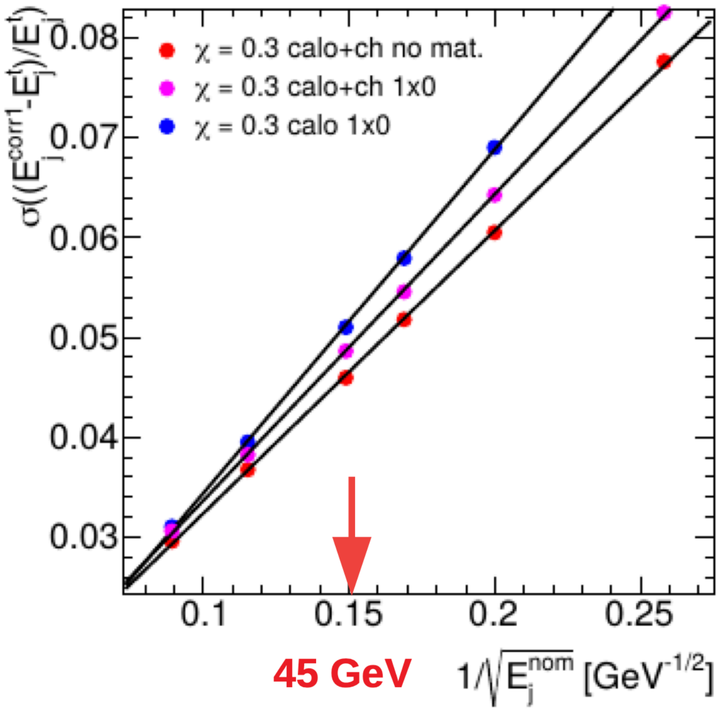
Calo + charged

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

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

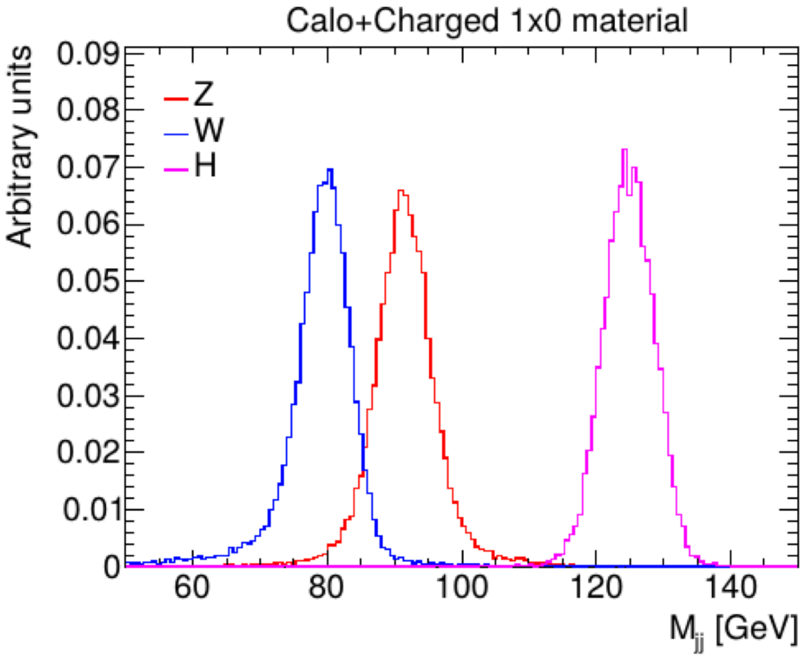
Jet response

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



Resonances studied with

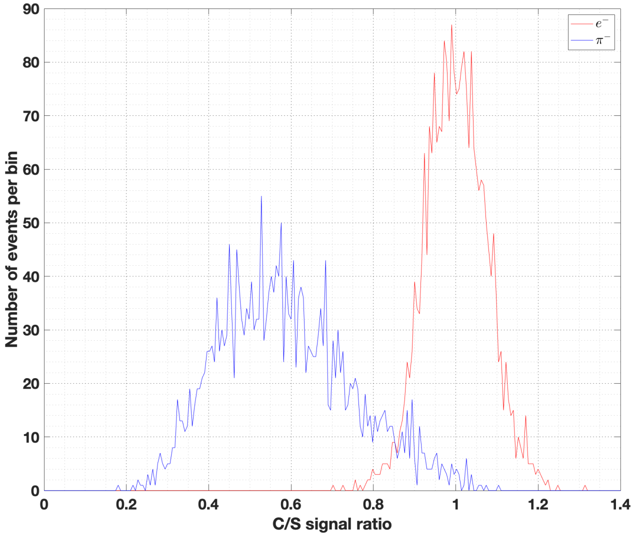
$$e^+e^- \to ZH \to jj\tilde{\chi}_0^1\tilde{\chi}_0^1$$
$$e^+e^- \to WH \to jj\tilde{\chi}_0^1\tilde{\chi}_0^1$$
$$e^+e^- \to ZH \to \nu\nu bb$$

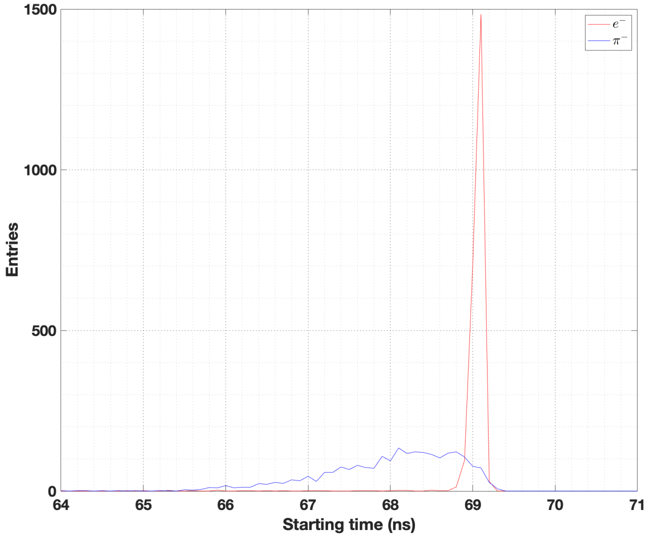


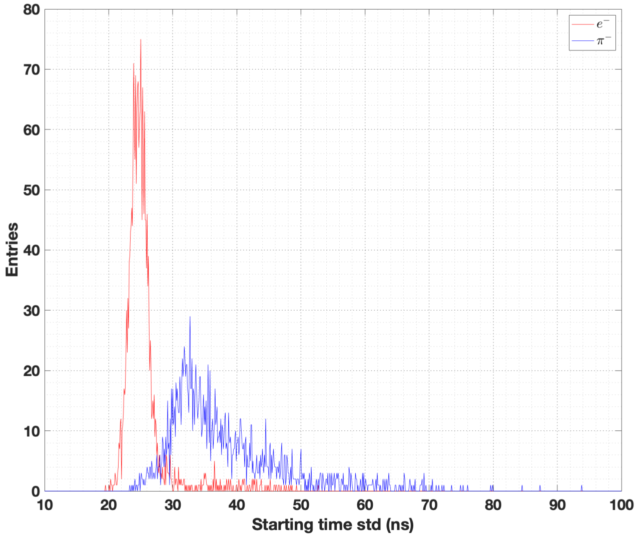
Configuration	W		Z		h	
	Δm	σ	Δm	σ	Δm	σ
Calo no material	-0.108	3.02	-0.009	3.14	-0.01	3.72
Calo+Ch no material	0.07	2.86	0.18	3.05	0.10	3.48
Calo 1X0	-0.08	3.14	-0.13	3.73	-0.18	3.95
Calo+Ch 1X0	0.08	3.01	0.21	3.26	-0.13	3.72

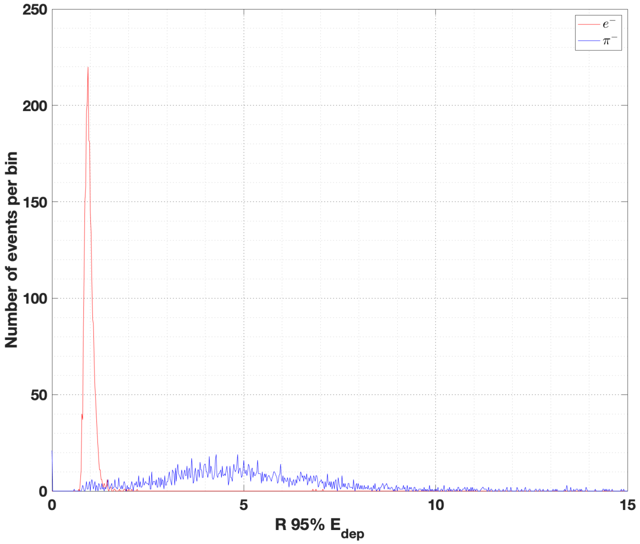
Particle identification

- 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%

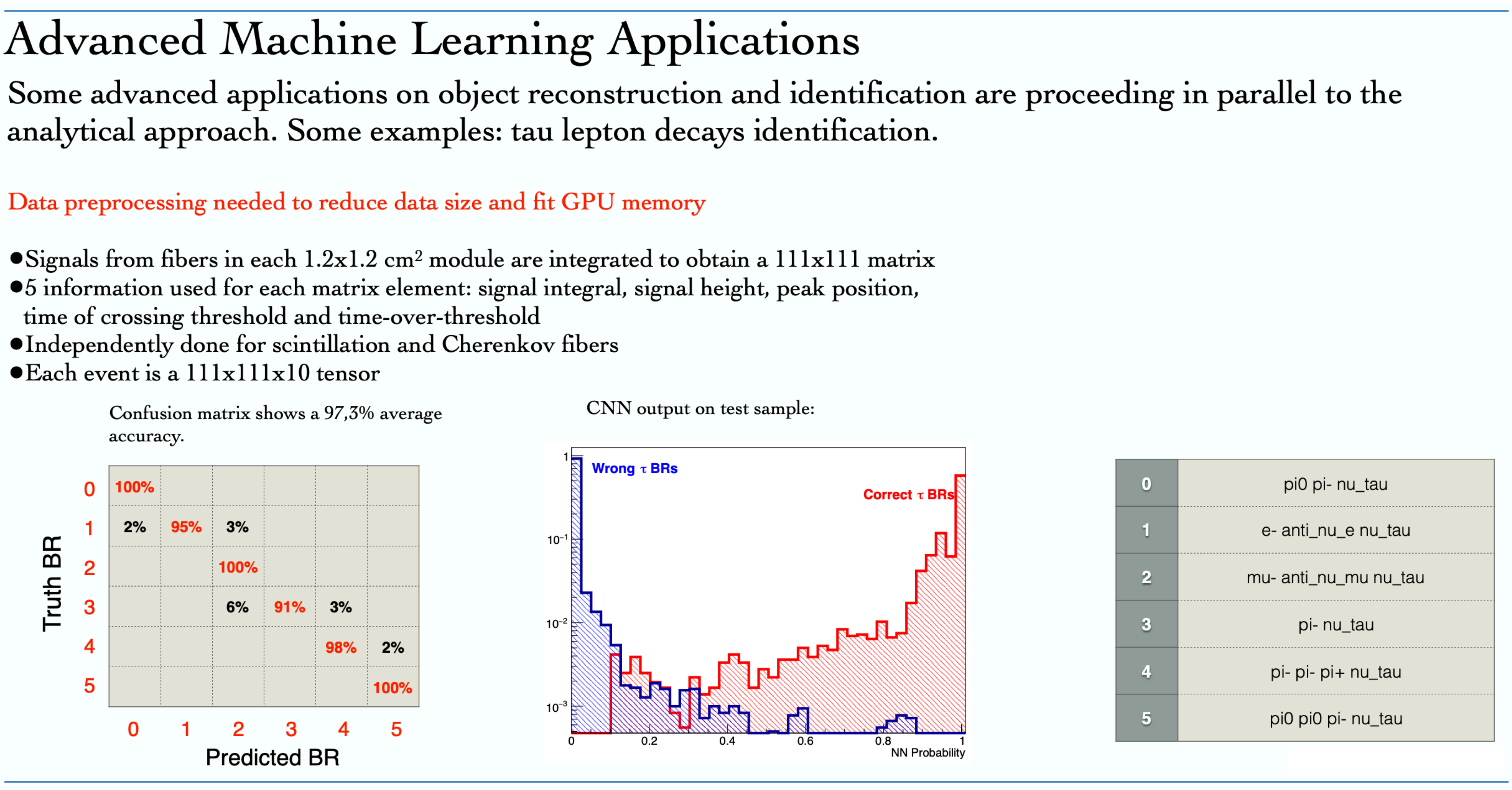








Tau decay identification



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.

Truth BR

	0	1	2	3	4	5
0	100%					
1	2%	95%	3%			
2			100%			
3			6%	91%	3%	
4					98%	2%
5						100%

Predicted BR

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

An outlook on ongoing activities

- Ongoing studies on **4- and 6-jet events**
  - requiring a more detailed final state reconstruction.
- Preparation for **TB activities**:
  - 10x10x100 cm^3 module @DESY dates to be confirmed.
- Software:
  - Using Gan for simulations
  - Simulation integration in DD4Hep
  - Speed up of optical photon transportation in G4
  - Simulation of SiPM/digitization

Summary

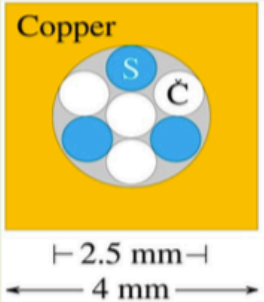
- I presented the **simulated performance** (response linearity, energy and angular resolution) of the **IDEA Dual Readout calorimeter** for:
  - Electrons and photons
  - Single hadrons
  - Jets
- Discussed **particle identification** for e/π and τ decay identification.
- Lots of **parallel efforts 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 calorimeters (PMT readouts)

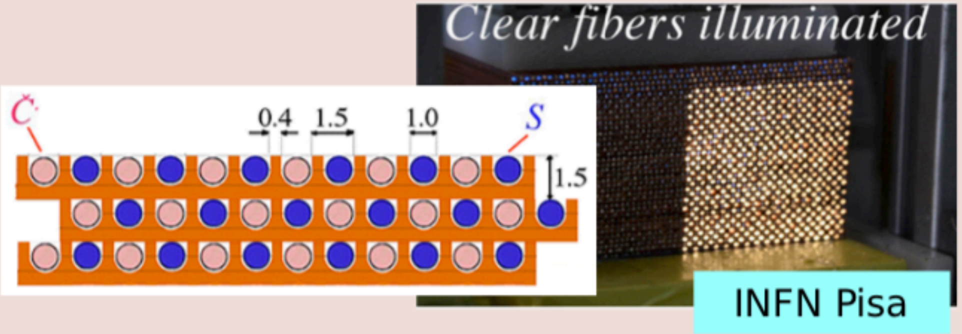
2003
DREAM

Cu: 19 towers, 2 PMT each
2m long, 16.2 cm wide
Sampling fraction: 2%



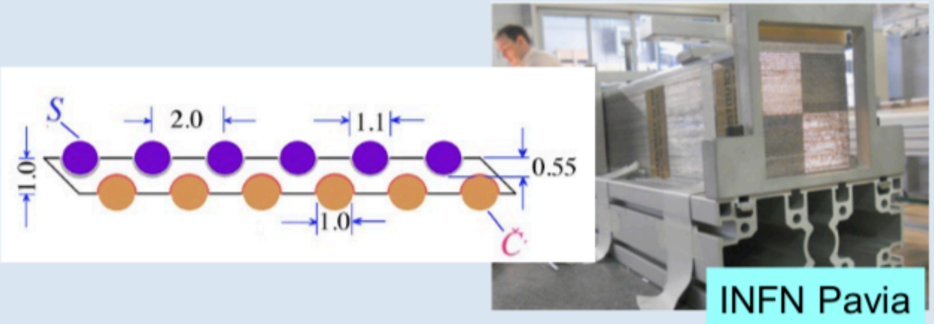
2012
RD52

Cu, 2 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}

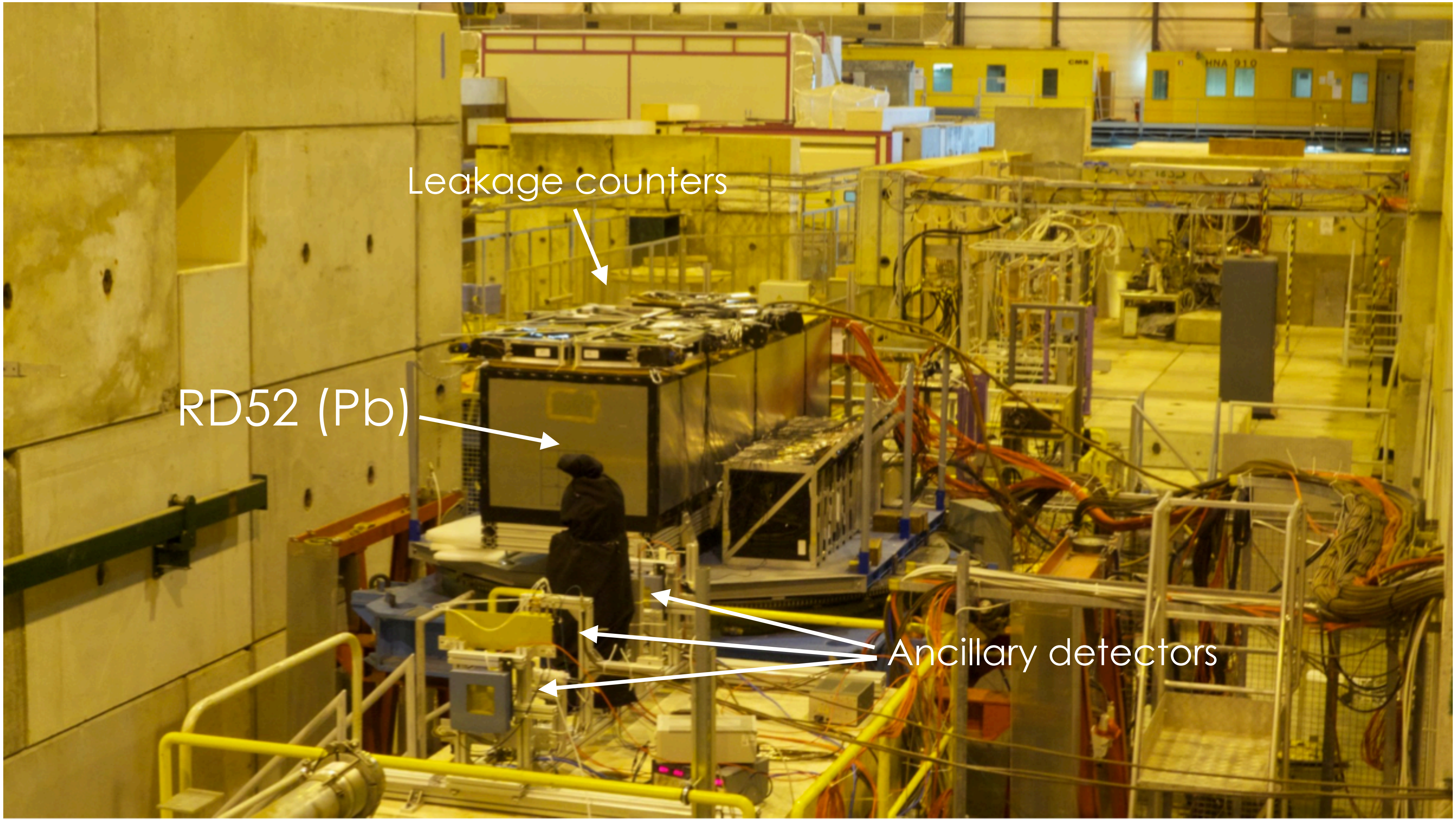


2012
RD52

Pb, 9 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}

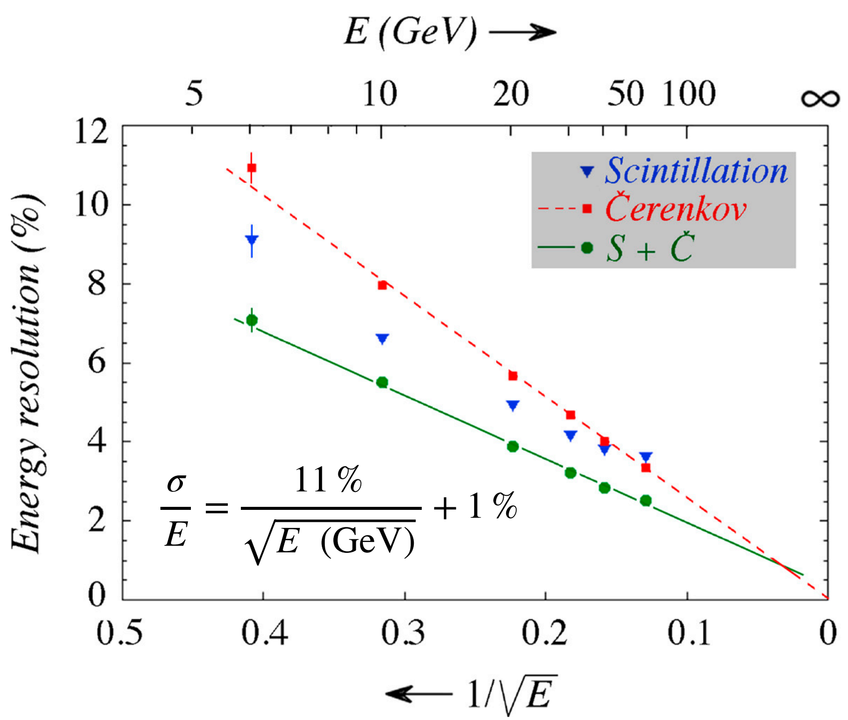


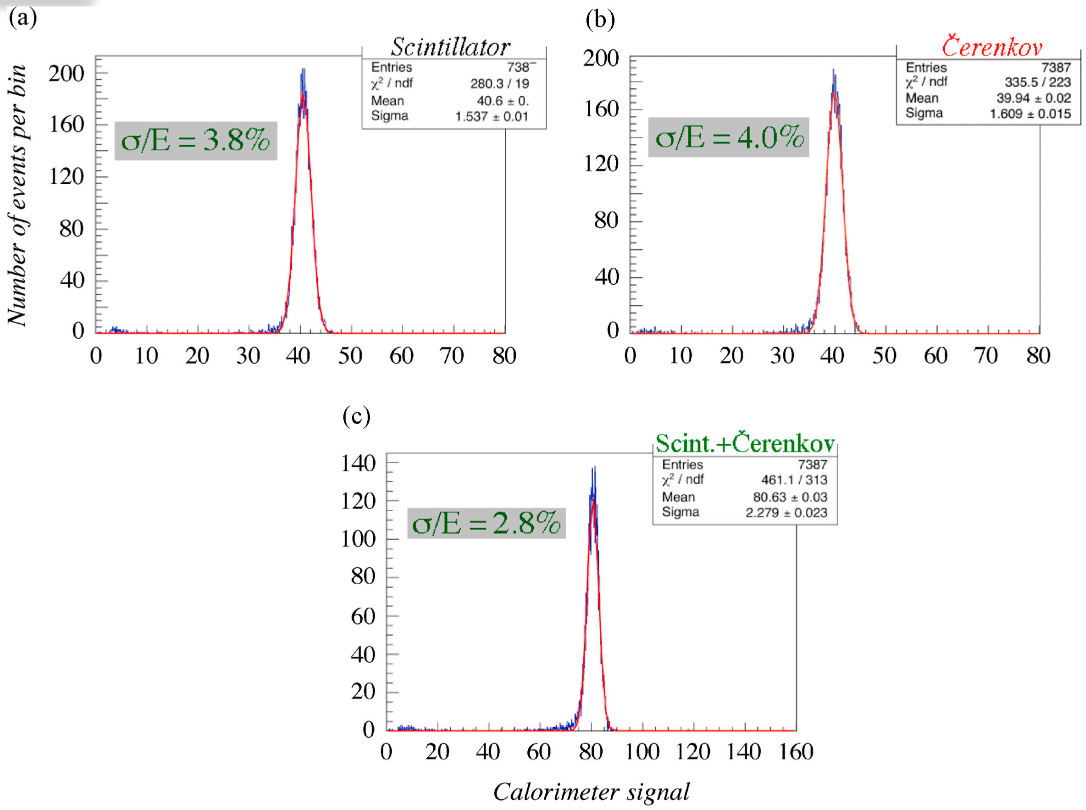
Dual readout calorimeter at work

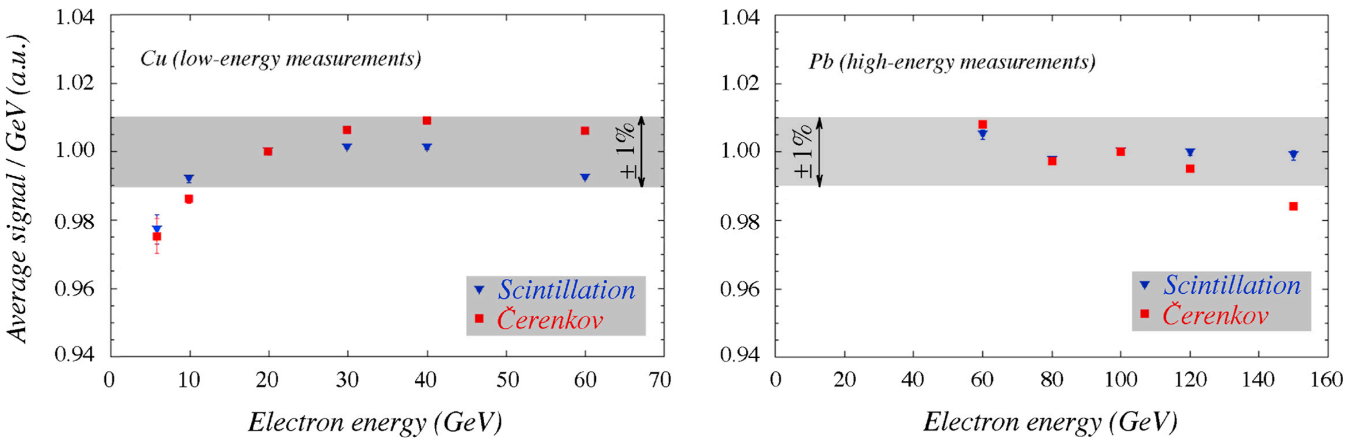


Electron response

40 GeV electrons



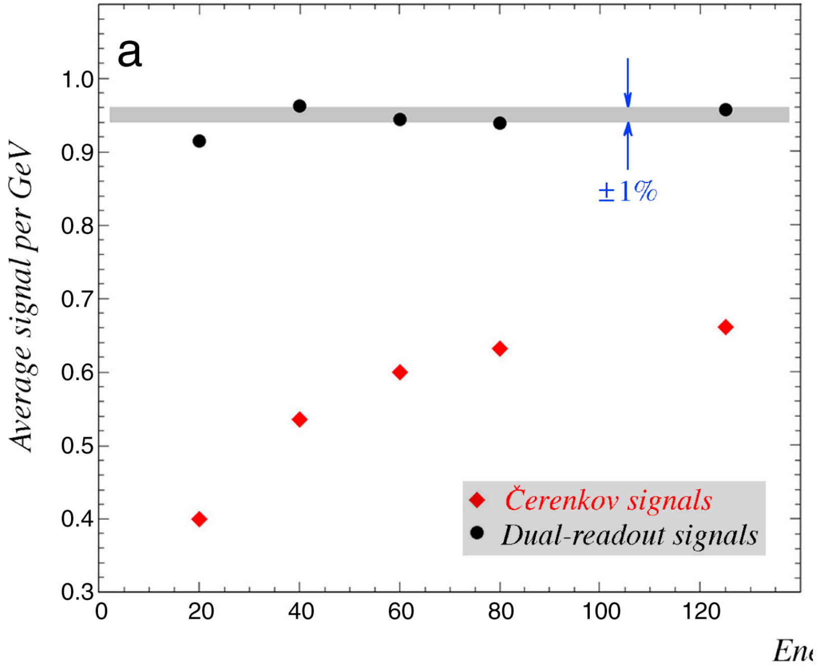




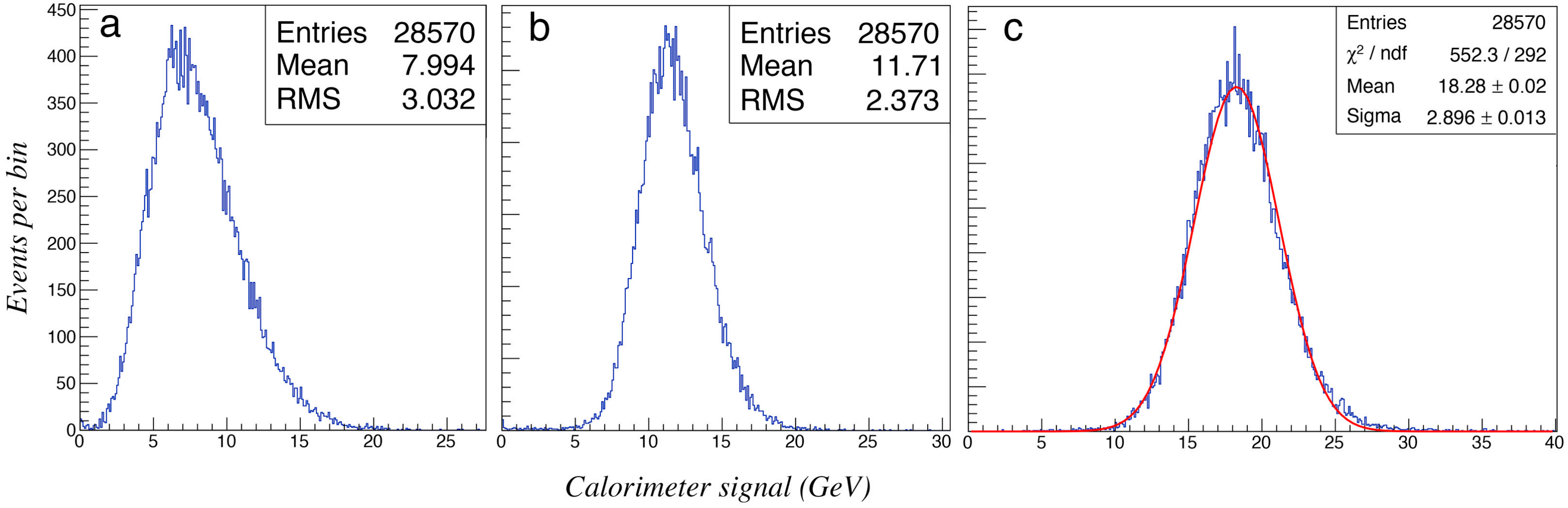
Single hadron response - linearity

NIM A 866 (2017) 76

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

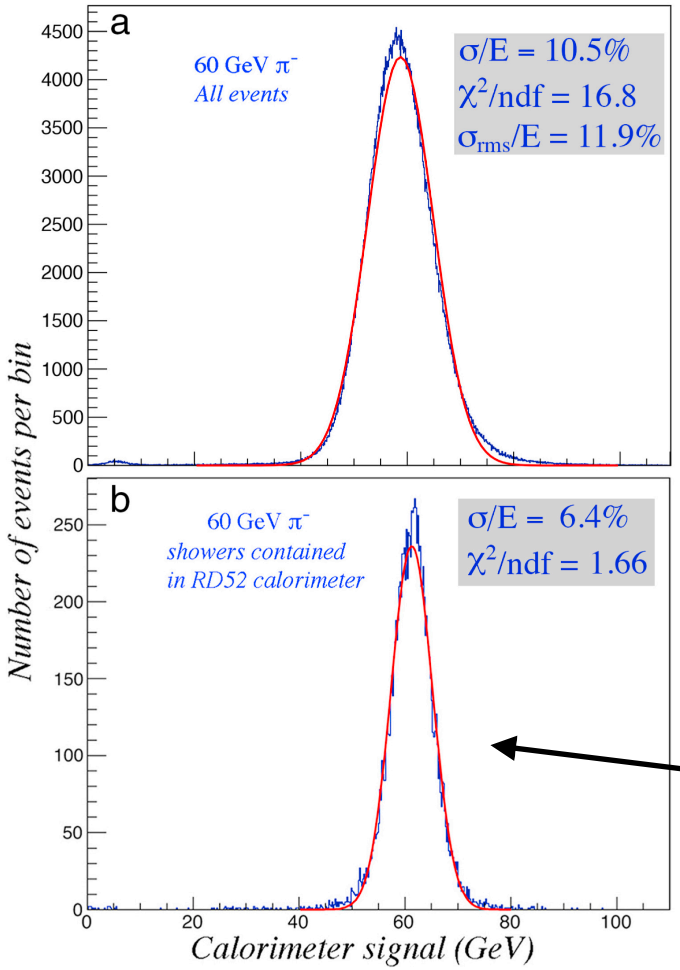


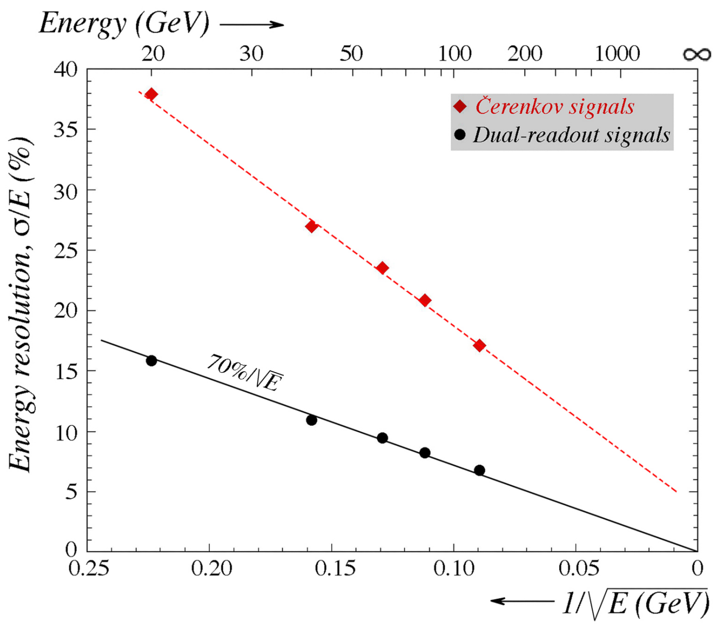
20 GeV pions



Single hadron response - resolution

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



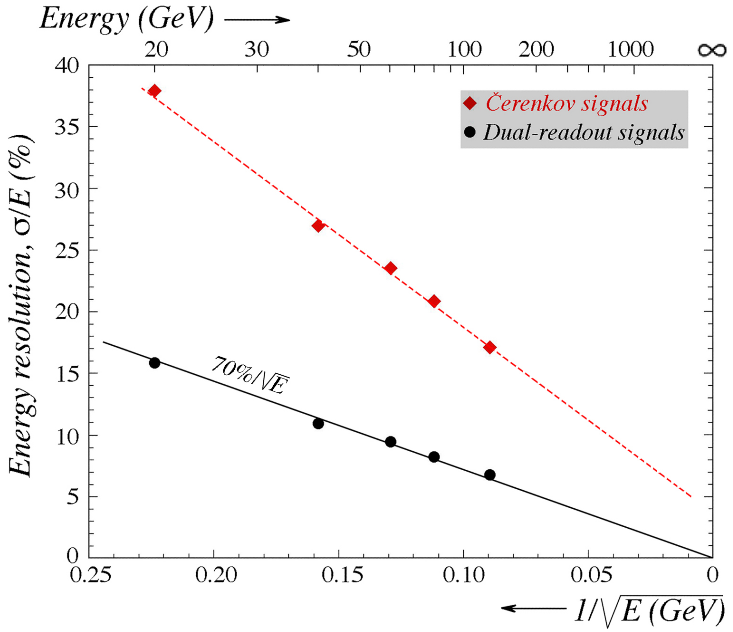


No signal in leakage counters

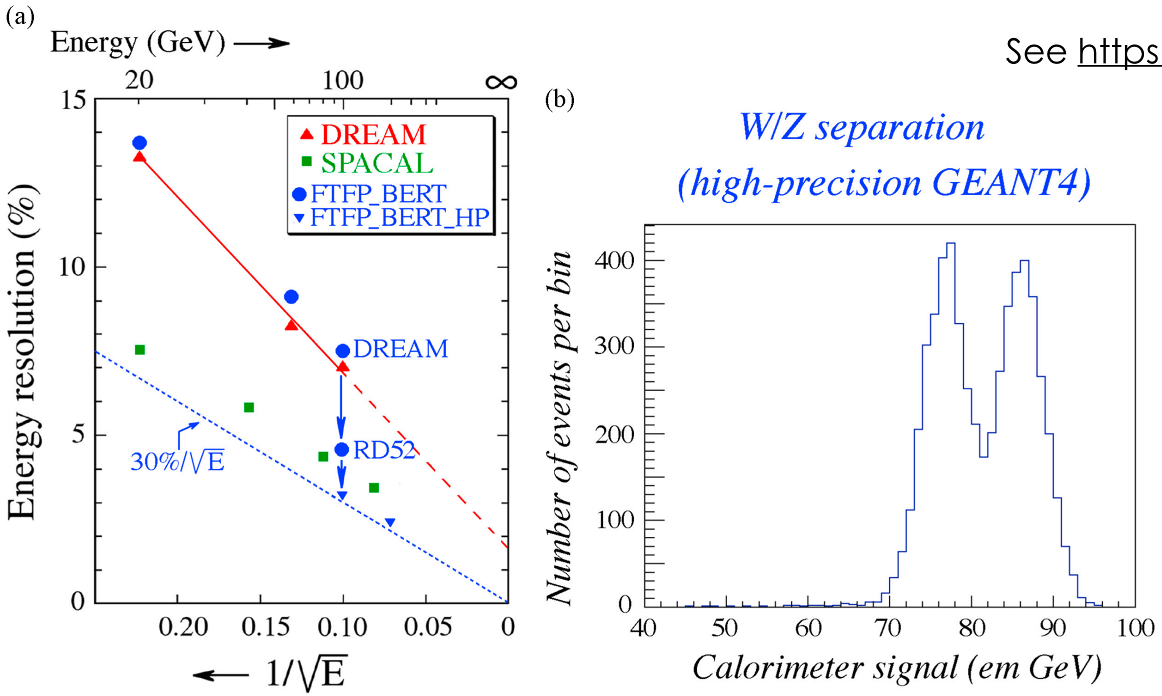
Performance of Dual Readout

- **Hadronic resolution** comparable to **compensating calorimeters**.
  - Resolution at TB (dominated by leakage). G4 estimate **with full containment**

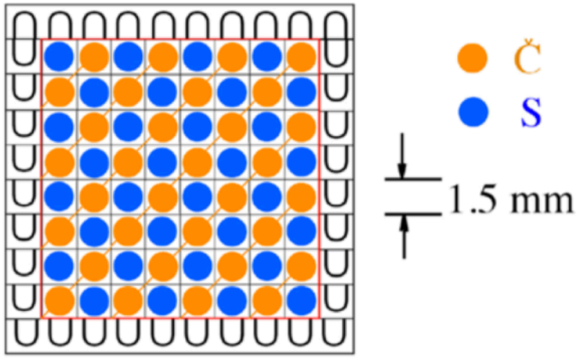
$$\frac{\sigma}{E} = \frac{34\,\%}{\sqrt{E}}$$

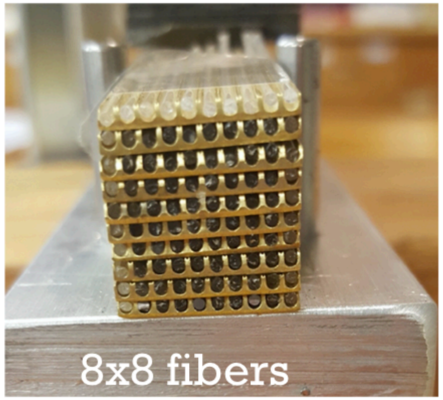


See https://doi.org/10.1016/j.ppnp.2018.07.003

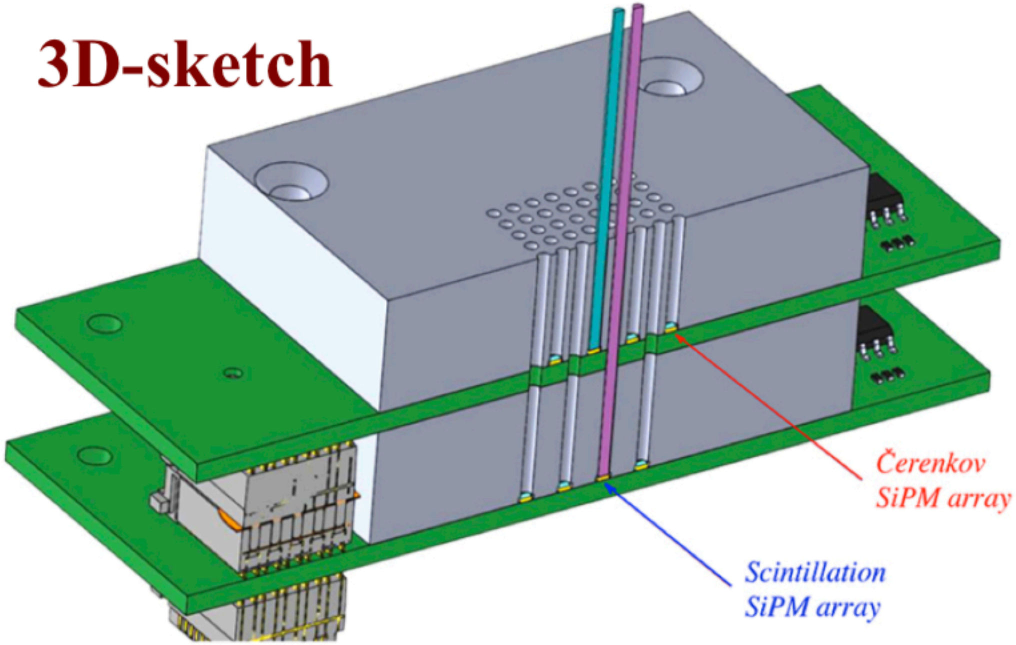


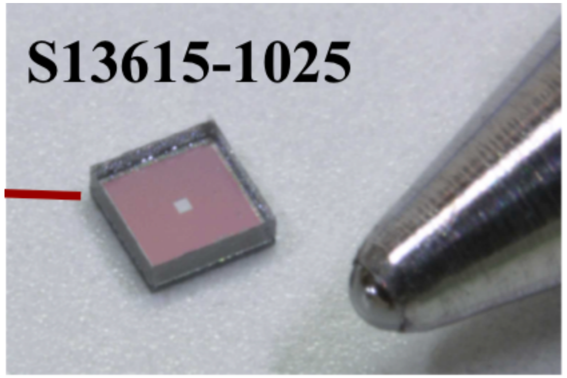
SiPM dual readout



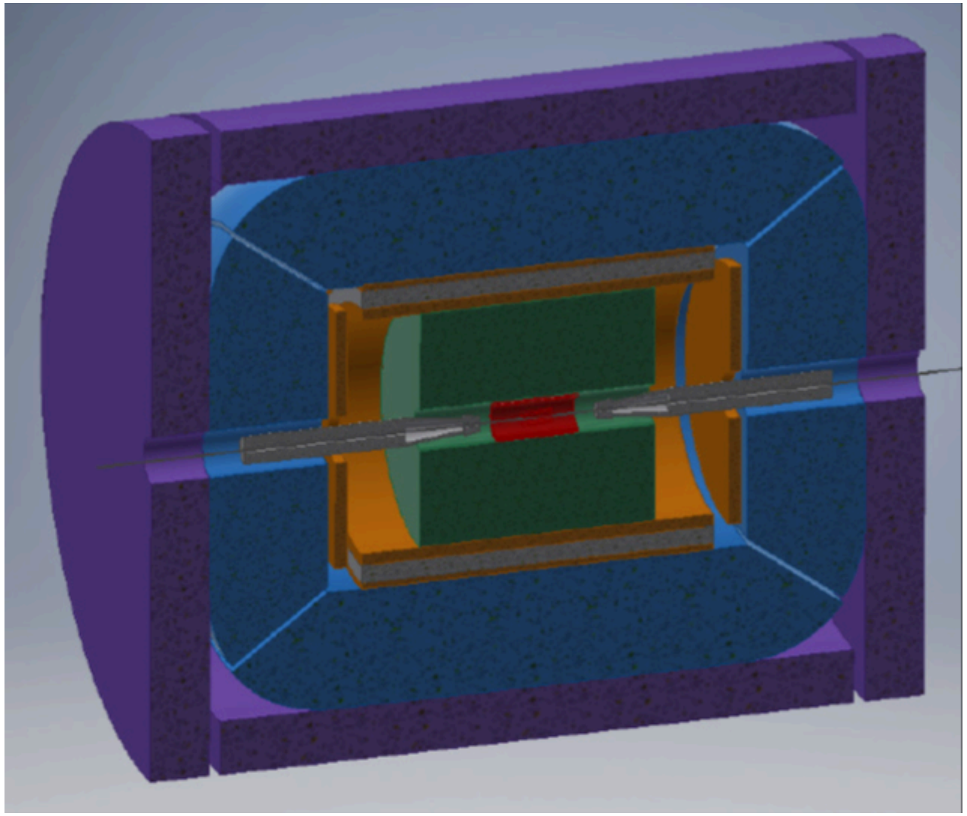


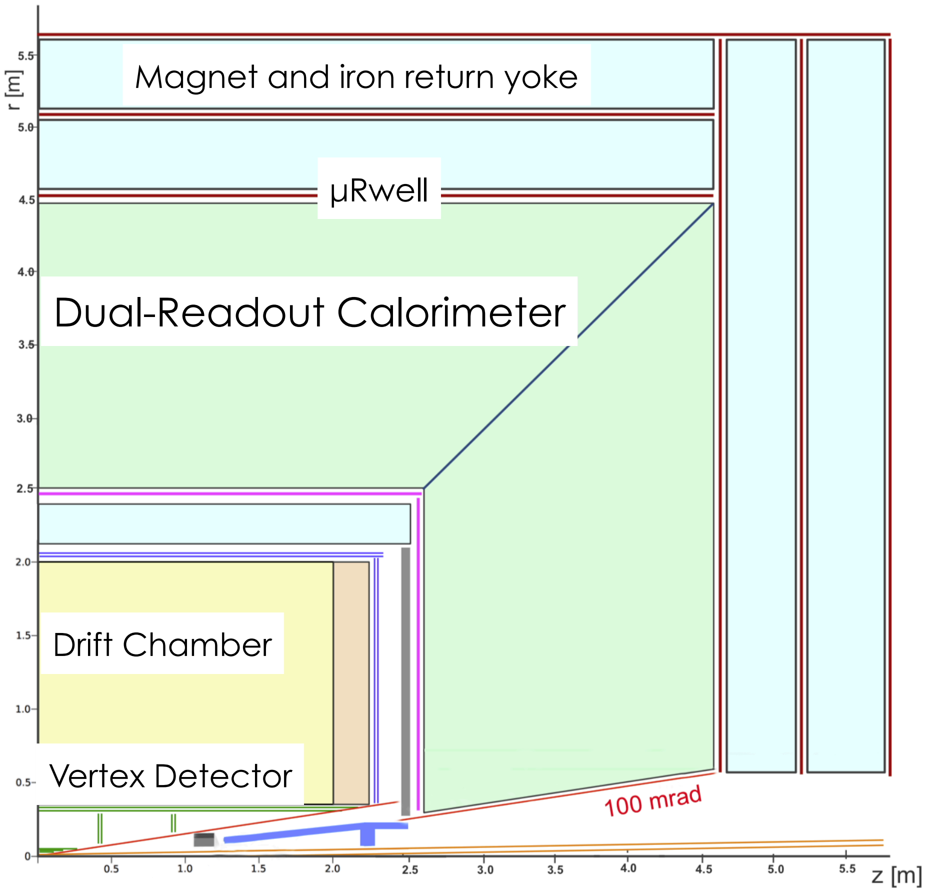
- Single fibre readout with **HAMAMATSU SiPM.**
- Readout for Cherenkov and Scintillation light **separated to minimise cross talk** (the latter expected to be ~ 50 times larger if not attenuated).





A practical implementation: IDEA

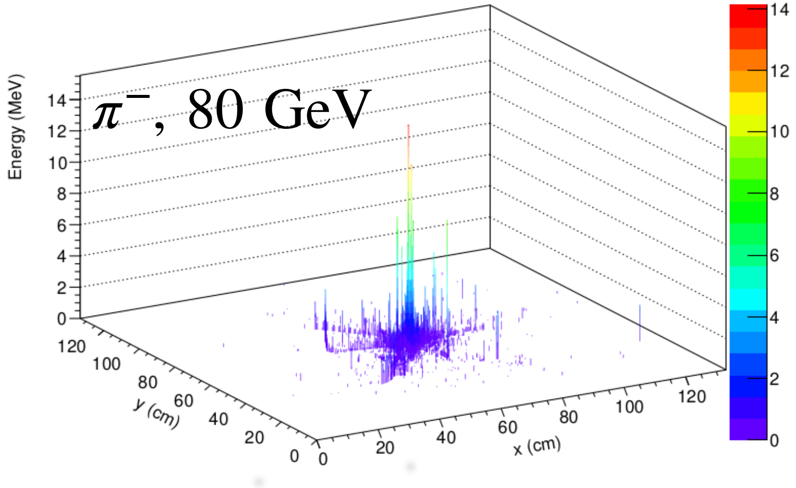


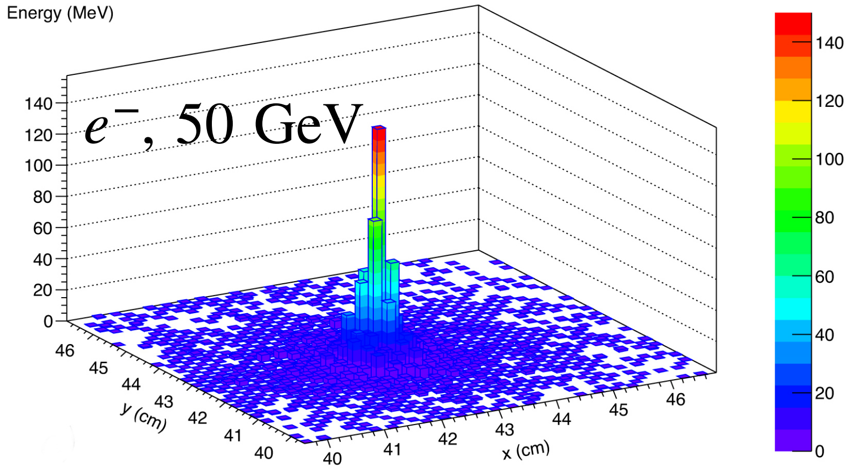


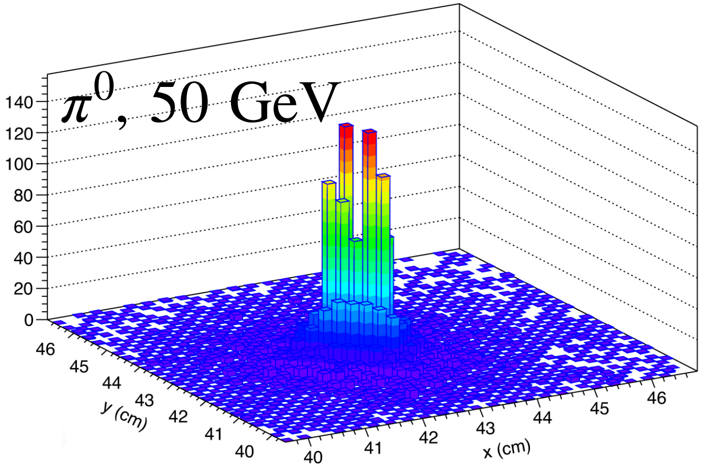
See here for additional information

Shower shape

- Single particle shower shape
  - Using full implemented granularity

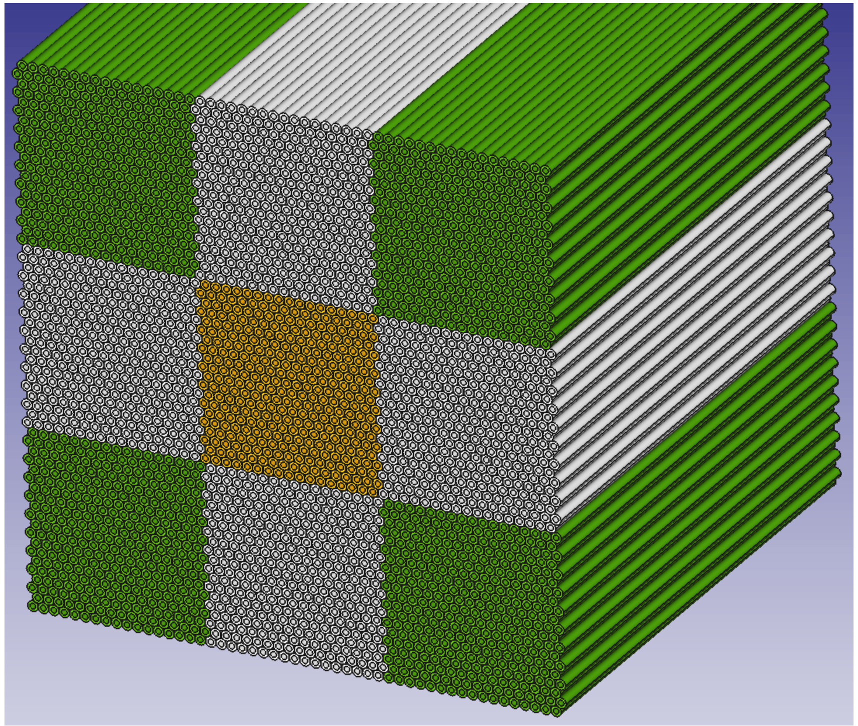


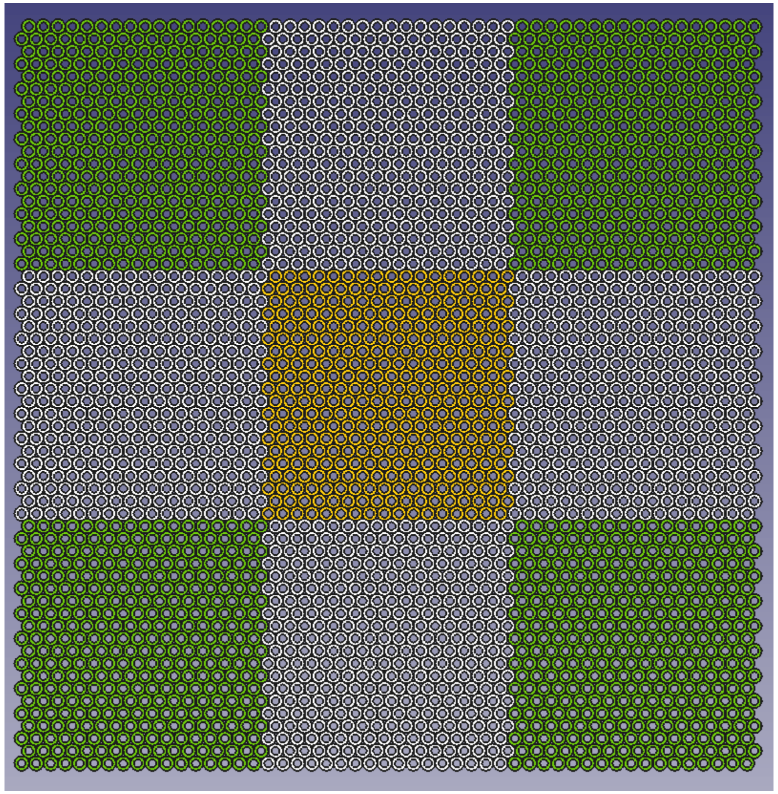




2020 target

- Build a 10 x 10 x 100 cm³ prototype:
  - Use **2 mm diameter** tubelets (CuZn37, glued with araldite)
    - 60 horizontal layers of 51 tubes
    - 9 readout towers of 17x20 tubes each
    - **SiPM** readout for the **central tower**, PMs (with reduced granularity) otherwise





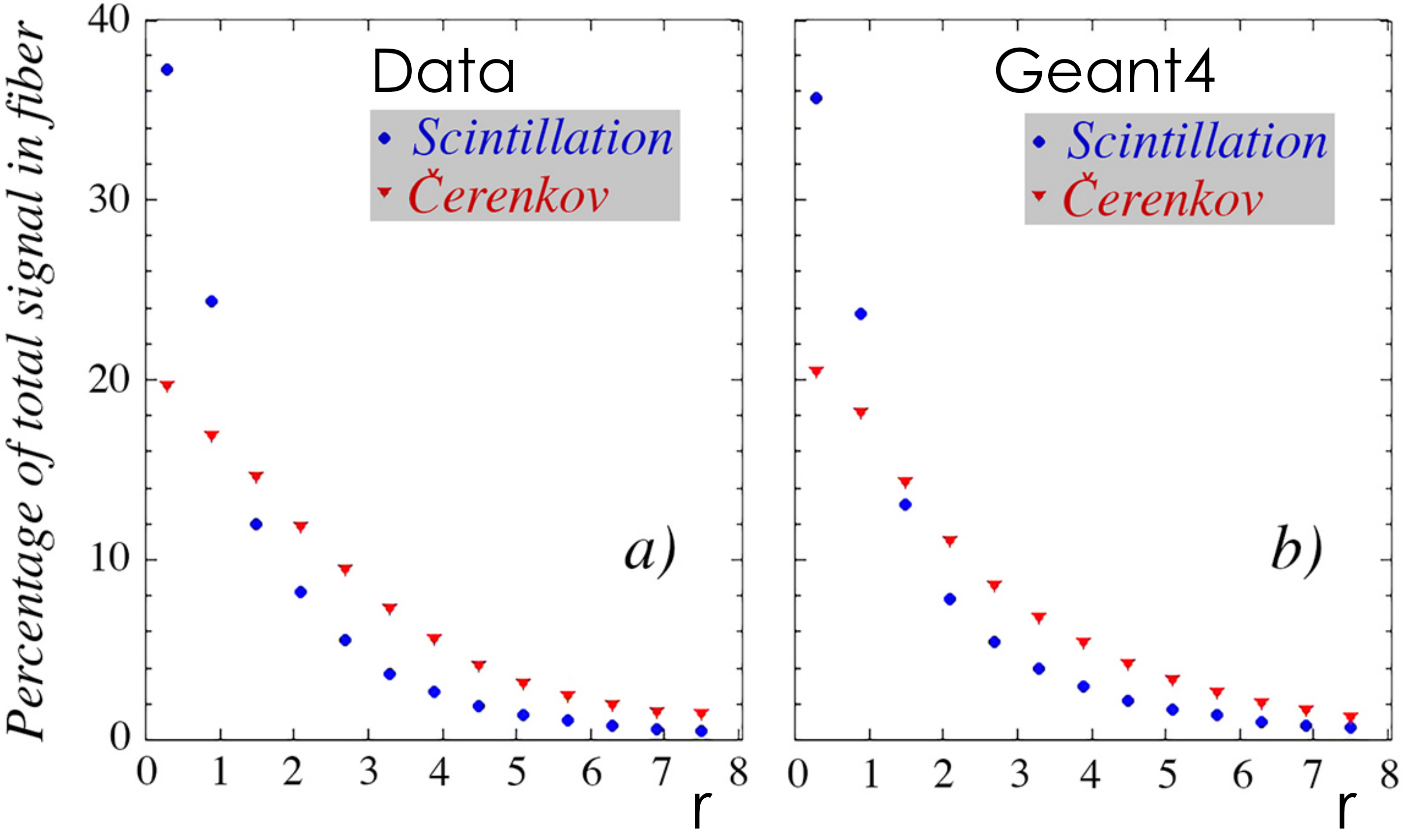
SiPM dual readout (shower shape)

- 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