Dual-readout calorimetry

An integrated high-resolution solution
for energy measurements
at future electron-positron colliders

VCI
2019

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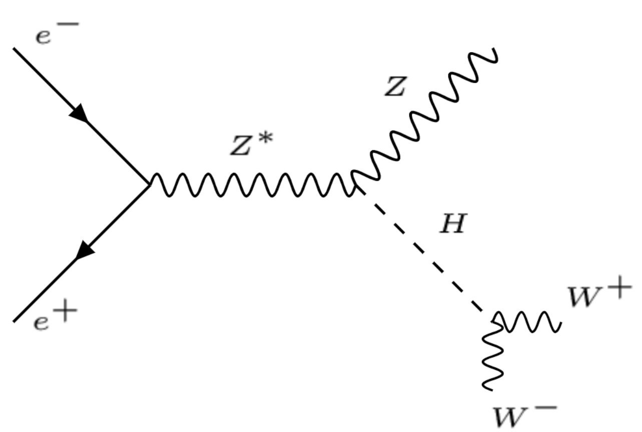
Wien, 18-22 February 2019

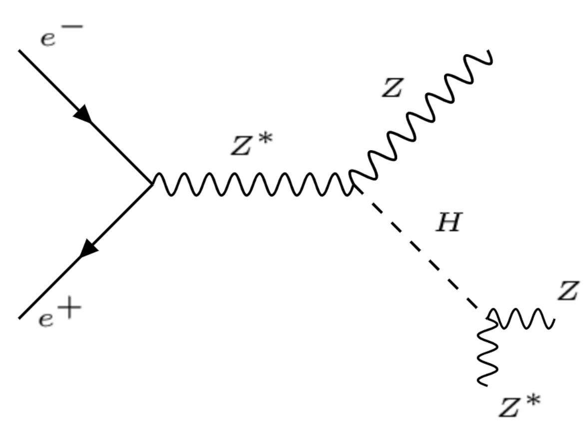
Calorimetry Requirements

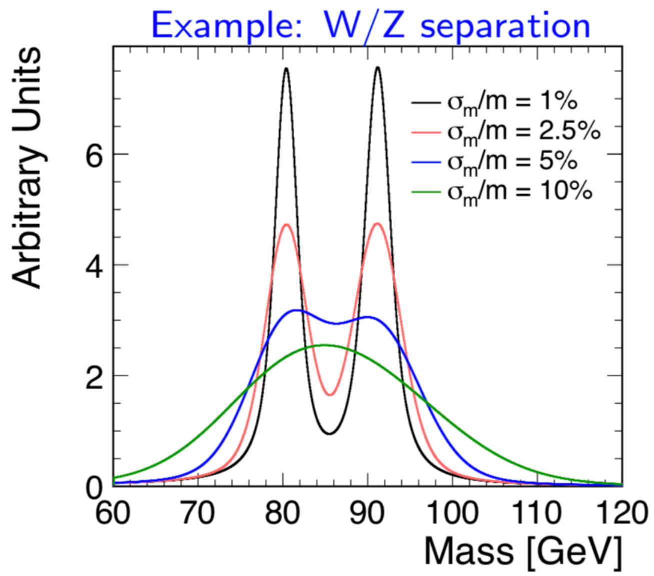
at future leptonic colliders

The jet energy resolution is the fundamental quantity for event reconstruction and tagging in multi-jet final states.

Example: HZ → 4jet







At an energy resolution of:

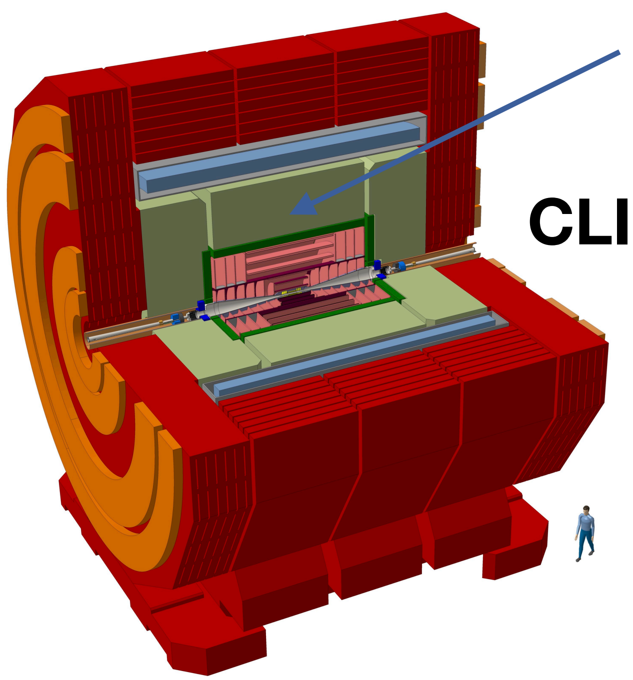
$$\frac{\sigma}{E} \simeq \frac{30\,\%}{\sqrt{E}}$$

the detector resolution is comparable to the natural widths of W and Z bosons.

Two Proposed Solutions:

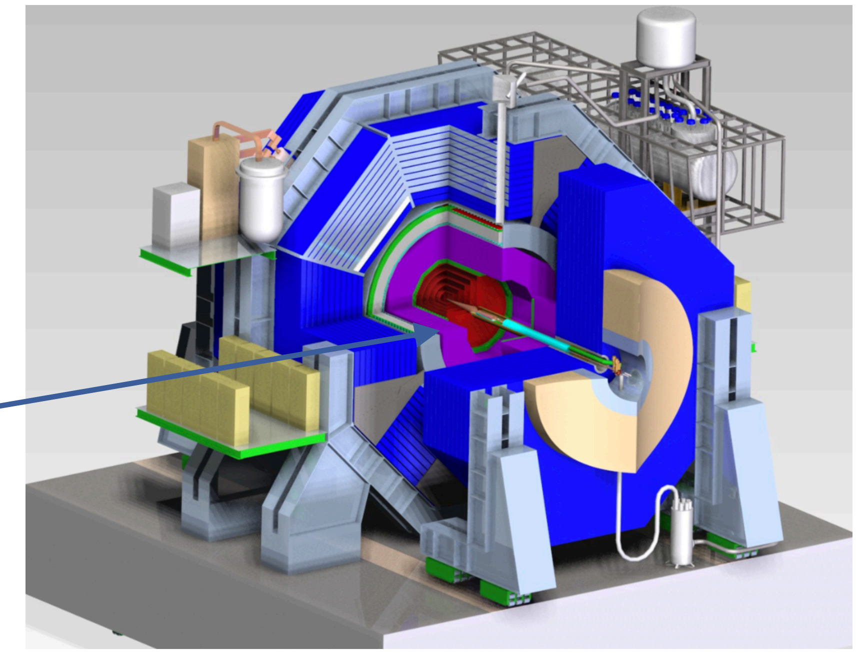
Dual-readout calorimetry and Particle Flow with Highly granular calorimeters.

Calorimetry at future leptonic colliders



Highly granular calorimeters

CLIC detector

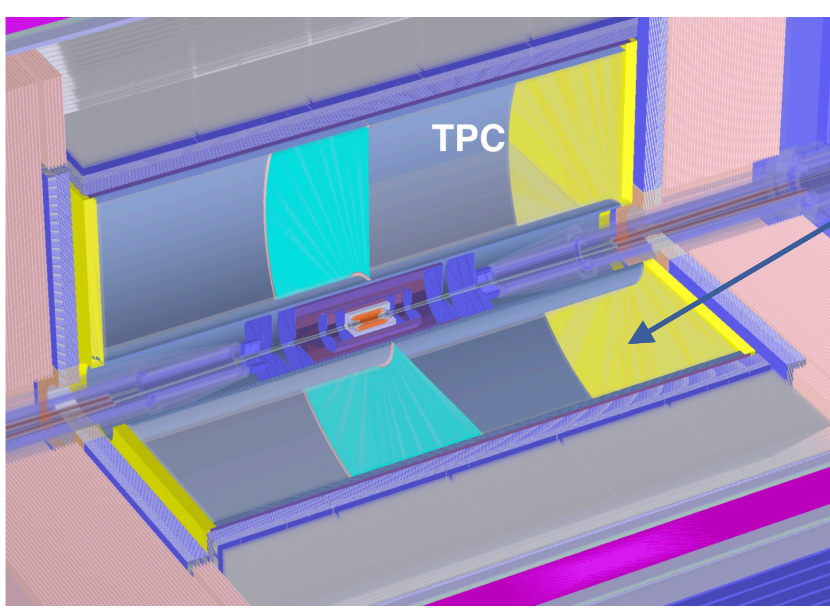


Highly granular calorimeters

ILC SiD detector

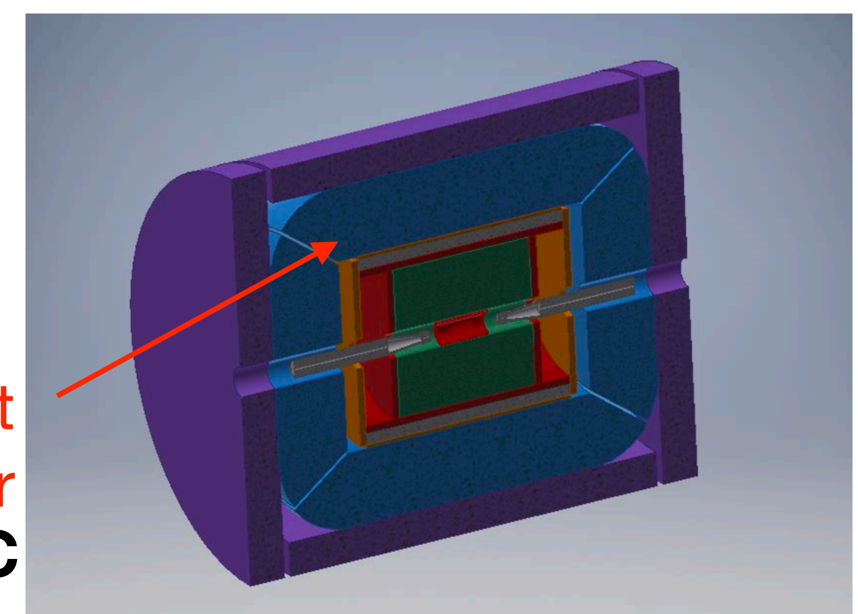
CepC detector

Highly granular calorimeters



Dual-readout calorimeter

FCCee & CepC IDEA detector

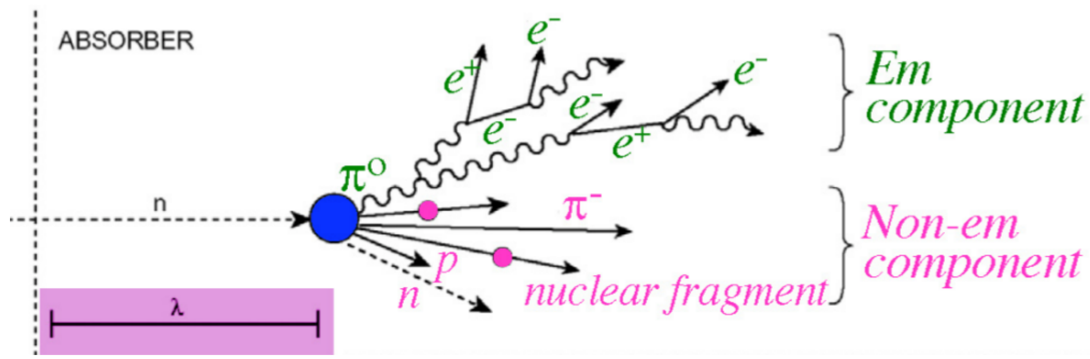


FCC CDR: https://cds.cern.ch/record/2653669

CEPC CDR: https://arxiv.org/abs/1811.10545

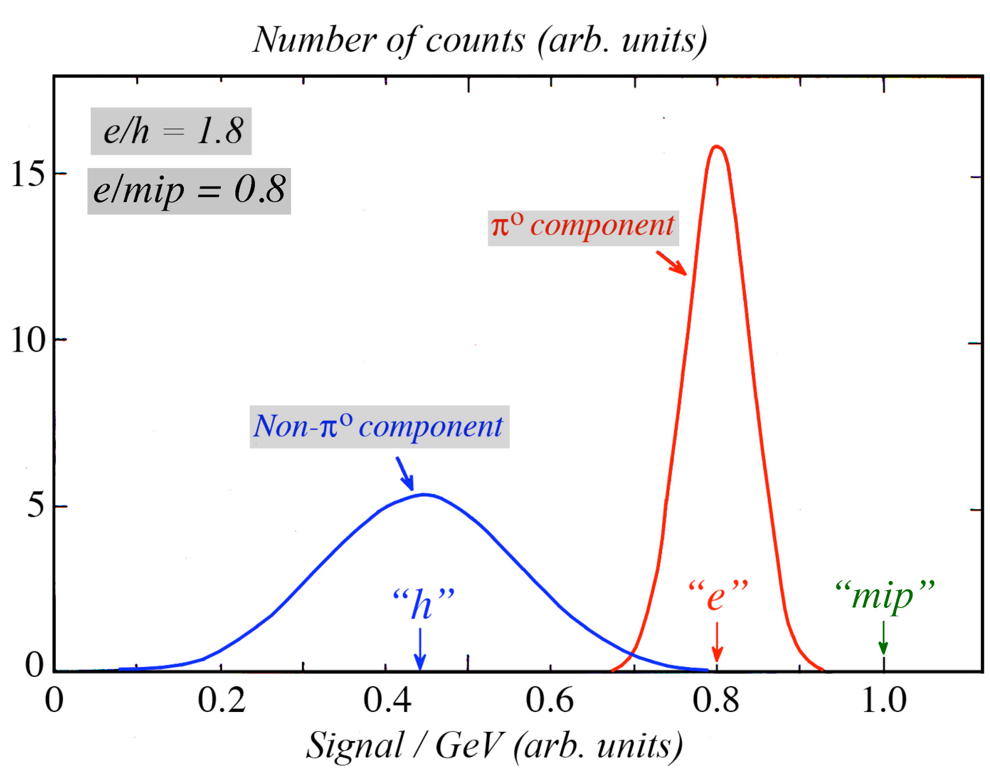
Non compensation

or why hadronic calorimetry is so hard…



Electromagnetic component: electrons, positrons and photons

Non-electromagnetic component: charged hadrons, nuclear fragments, neutrons, *invisible energy*

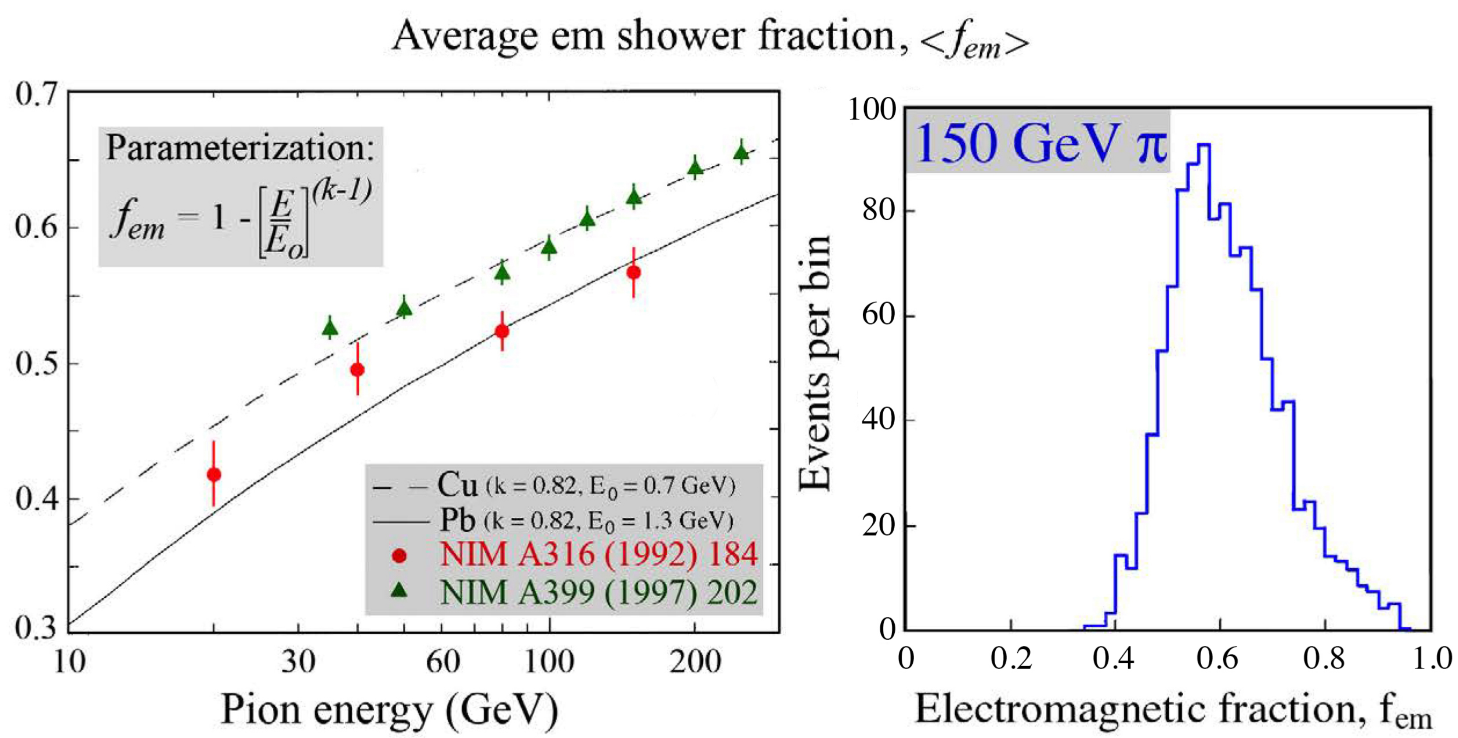


The calorimeter response is different for the two components:

$$\frac{h}{e} \neq 1$$

Non compensation problems

Event-by-event fluctuations of the electromagnetic component are non symmetrical, with an average value increasing with the energy.



All non compensating calorimeters, in hadron detection, exhibit:

An asymmetrical reconstructed energy
A non linear reconstructed energy
An energy resolution much broader than 30%/√E

D. Acosta, et al., Nucl. Instrum. Methods A316 (1992) 184.
N. Akchurin, et al., Nucl. Instrum. Methods A399 (1997) 202.

Dual-readout method

The only way to overcome the limits due to lack of compensation is to measure the electromagnetic fraction event-by-event and correcting for its value.

Scintillation signal from scintillating fibers: every ionizing particle passing through them releases a light signal.

$$S = E\left[fem + \left(\frac{h}{e}\right)_s (1 - fem)\right]$$

Cherenkov signal from clear-plastic fibers: every relativistic charged particle (almost exclusively electrons) passing through them releases a light signal.

$$C = E\left[fem + \left(\frac{h}{e}\right)_c (1 - fem)\right]$$

$$\frac{S}{C} = \frac{fem + \left(\frac{h}{e}\right)_s (1 - fem)}{fem + \left(\frac{h}{e}\right)_c (1 - fem)}$$

It is possible to estimate *fem* by measuring the ratio of the two signals event-by-event

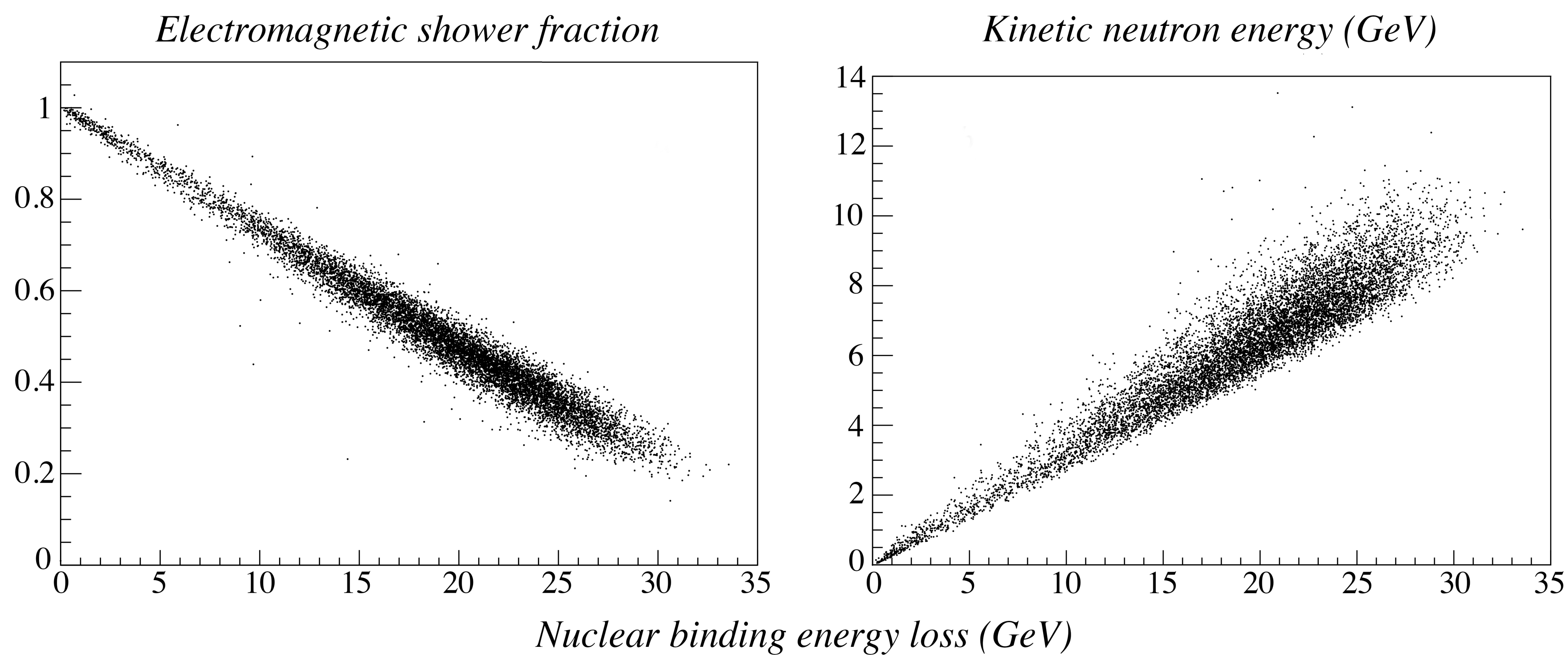
Why is it better than the past?

Usually, h/e < 1:
the main source of this is the *invisible energy* affecting only the non-electromagnetic component.

The most precise calorimeter is likely the one that exploits the quantity better correlated to the invisible energy.

Dual-readout calorimeters

Neutron boosting calorimeters: SPACAL, ZEUS Calorimeter, …



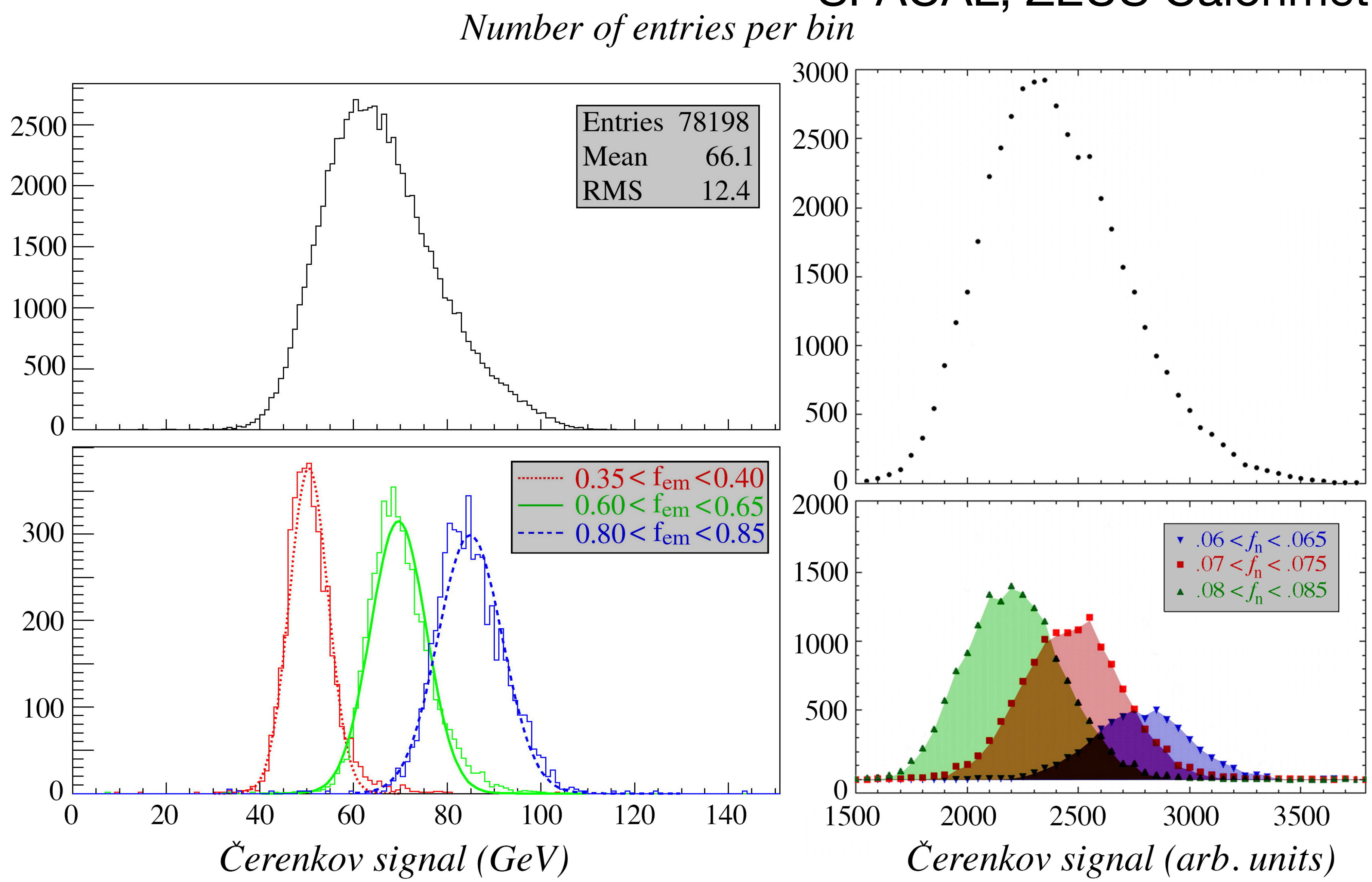
S. Lee, M. Livan, R. Wigmans, Nucl. Instr. and Meth. in Phys. Res. A 882 148.

Why is it better than the past?

Hints of this better correlation were already present in data!

Dual-readout calorimeters

Neutron boosting calorimeters: SPACAL, ZEUS Calorimeter, …



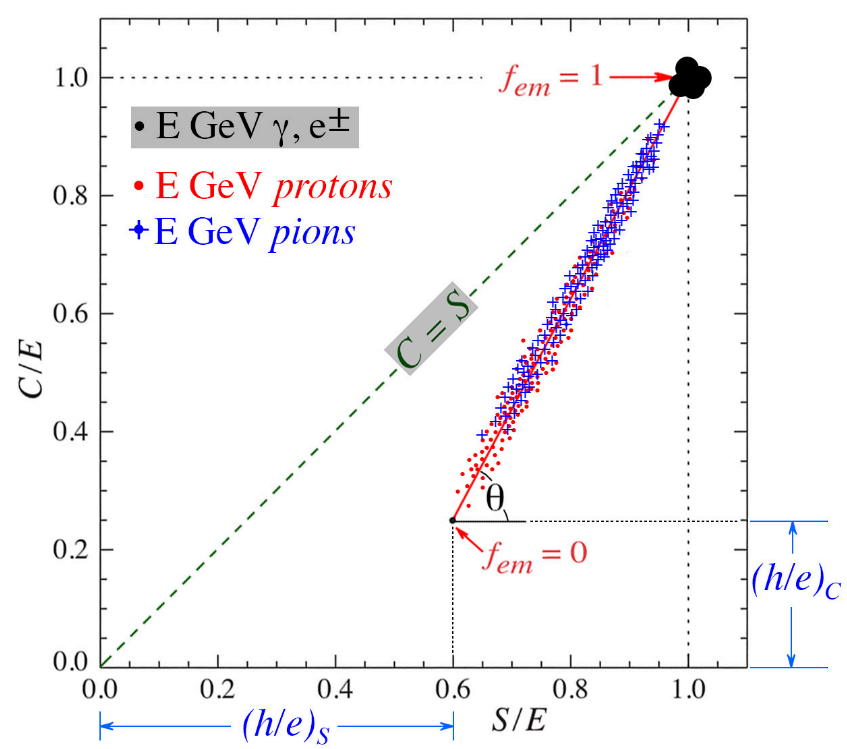
S. Lee, M. Livan, R. Wigmans, Nucl. Instr. and Meth. in Phys. Res. A 882 148.

How to apply it?

After a calibration with electrons, the S and C reconstructed energy must be combined with:

$$E = \frac{S - \chi C}{1 - \chi} \qquad \chi = \frac{1 - (h/e)_s}{1 - (h/e)_c}$$

This equation correctly reproduces both the electron and the hadron energies:
everything is calibrated at the electromagnetic scale, i.e. with electrons.



From the RD52 lead calorimeter

S. Lee, M. Livan, R. Wigmans, Rev. Mod. Phys. 90 (2018) 025002.

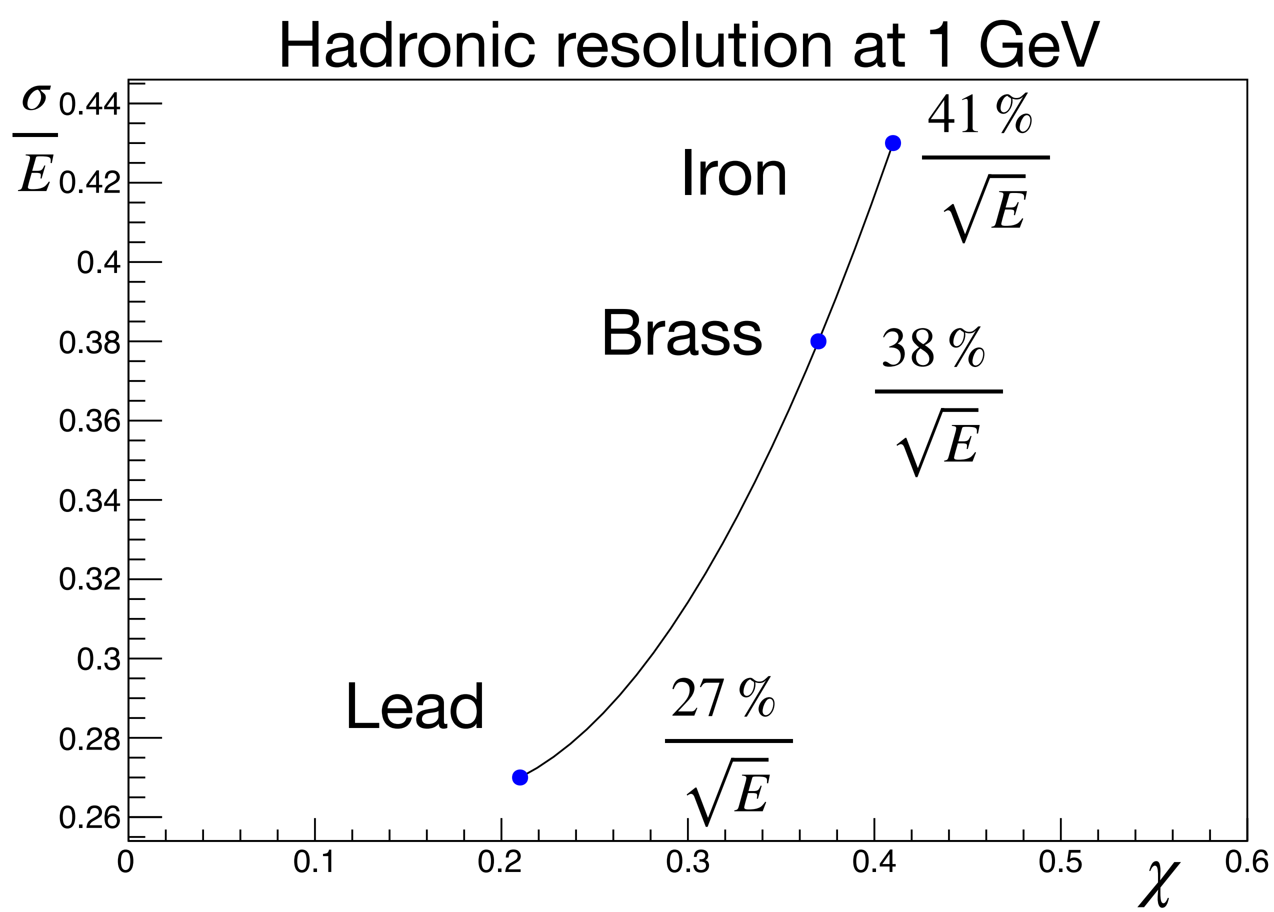
Absorber Materials

The χ factor is universal: it does not depend on energy or particle type!
It does only depend on the materials and geometry.

$$\chi = \frac{1 - (h/e)_s}{1 - (h/e)_c}$$

$(h/e)_s$ → Keep it high

$(h/e)_c$ → Keep it low



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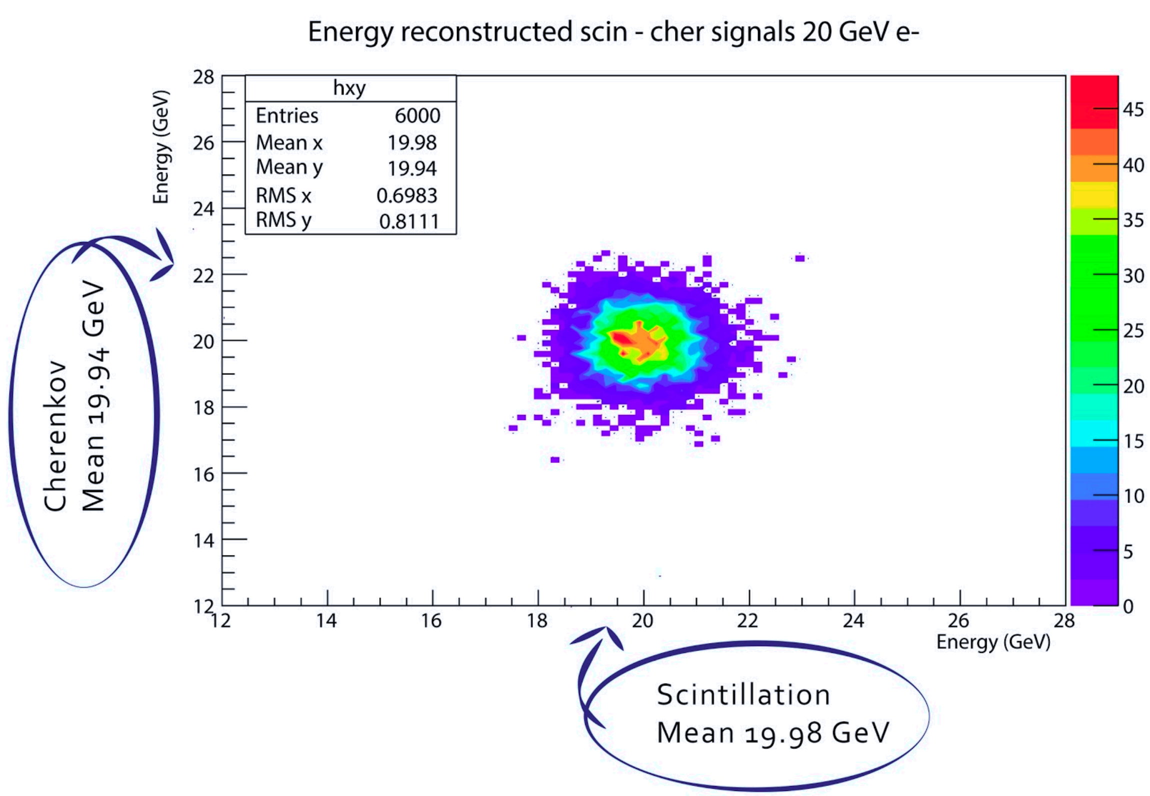
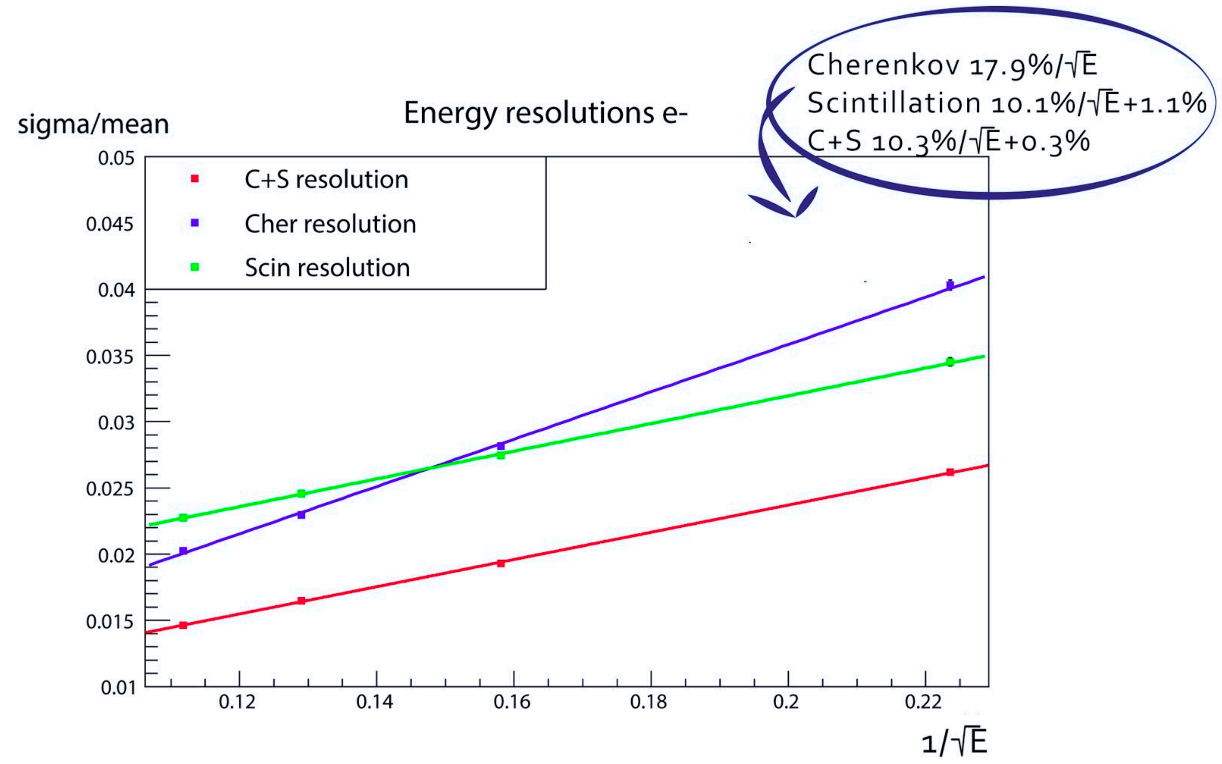
Em performance

The sampling fraction can be raised up as much as possible
(not possible with calorimeters compensating by neutron boosting).

The scintillation and Cherenkov signals represent
for electrons two independent signals.

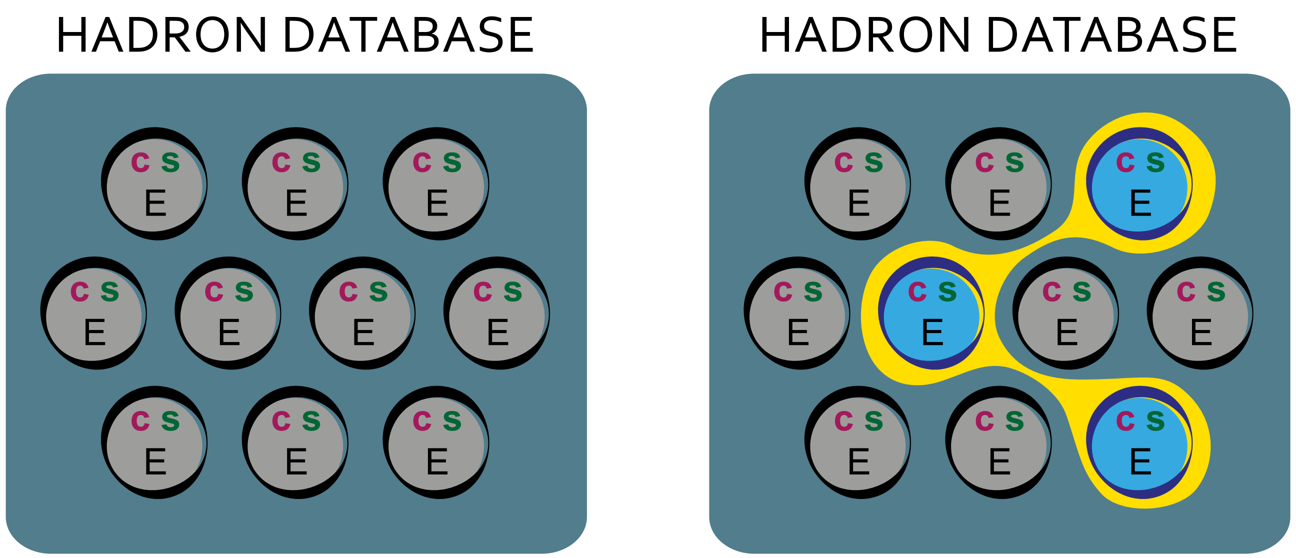


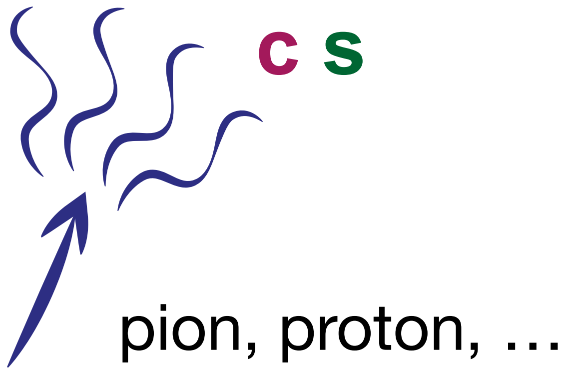


A dual-readout calorimeter can reach an excellent electromagnetic and hadronic performance in a single package.

Machine Learning

A new machine learning inspired technique is a promising solution to *also* exploit calibrations with hadrons.
The single event under reconstruction is compared to only pre stored events with approximately the same electromagnetic fraction.

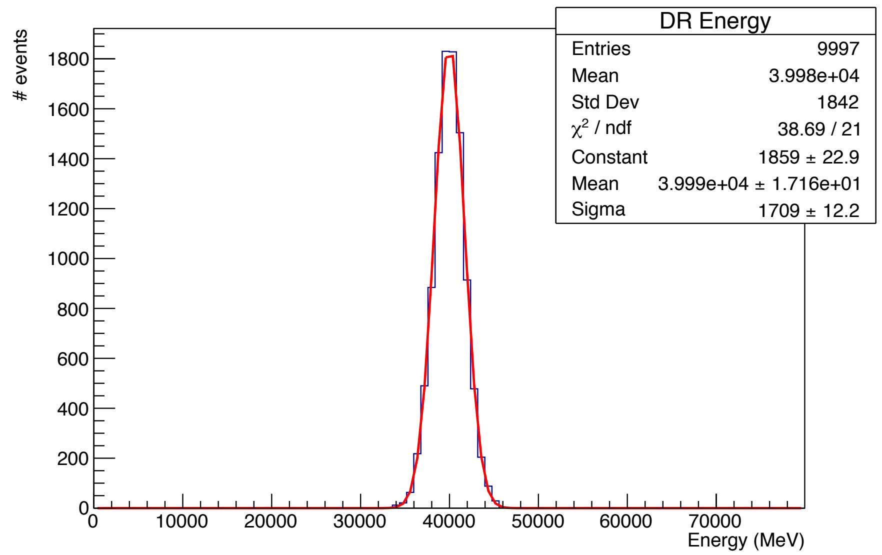




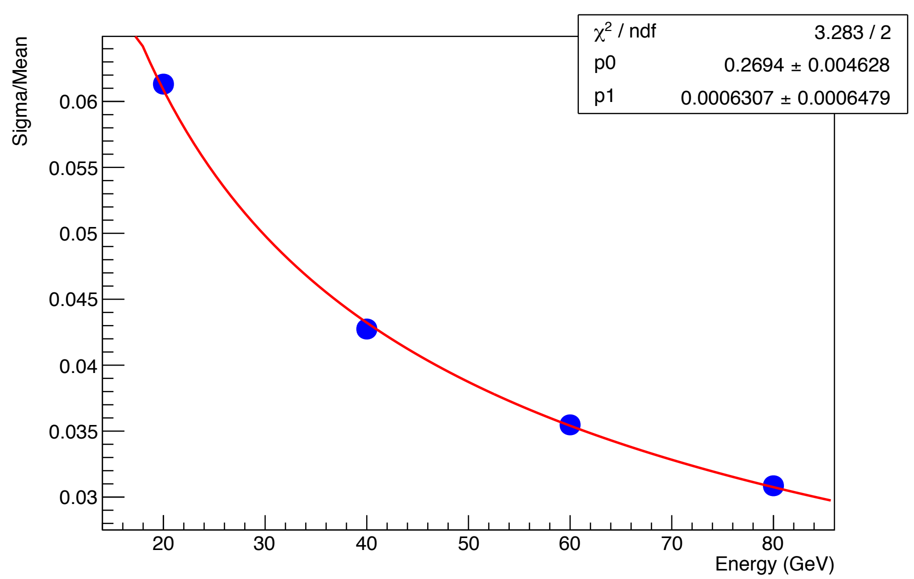
The correct hadron energy is then given by

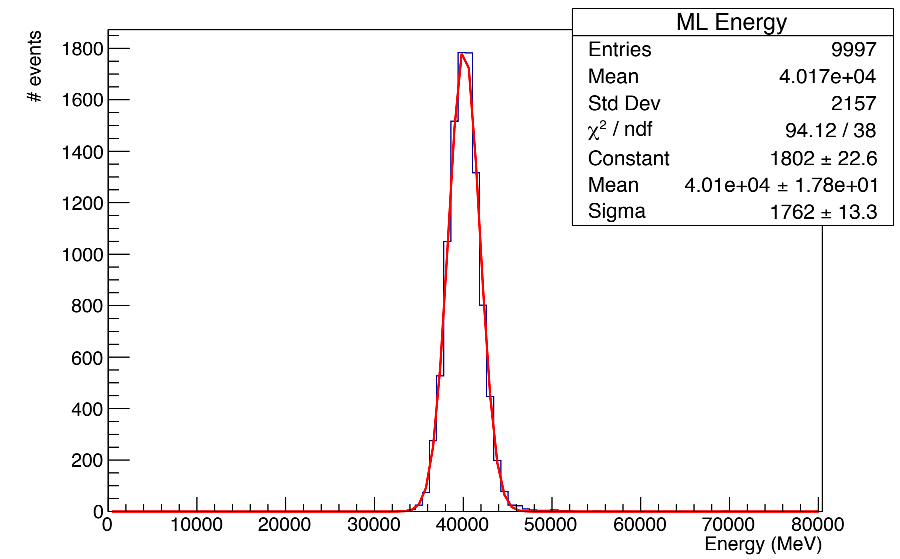
$$E = \frac{1}{2n}\sum_{i}^{n}\frac{E_i}{s_i}\times s + \frac{1}{2n}\sum_{i}^{n}\frac{E_i}{c_i}\times c$$

Dual Readout method vs. Machine Learning

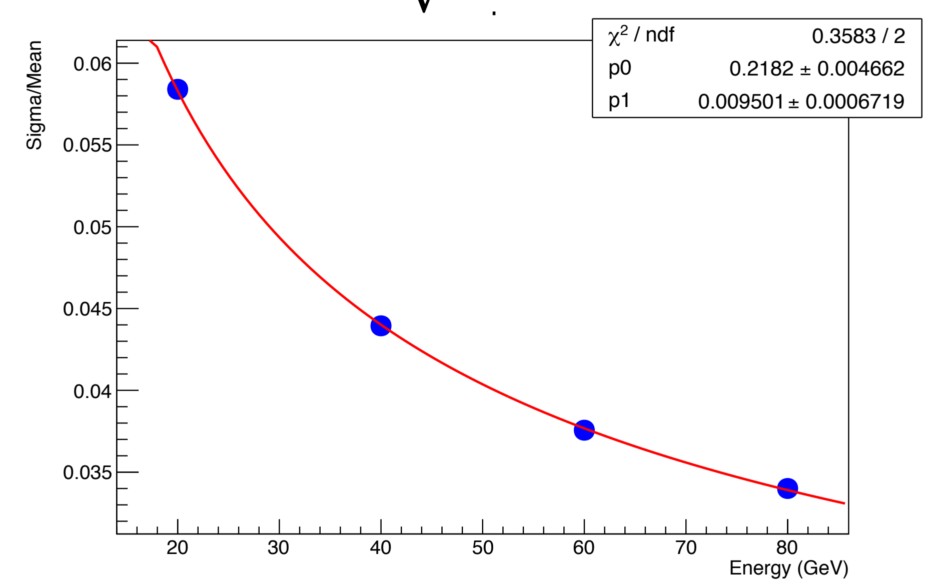


$$\frac{\sigma}{E} = \frac{27\,\%}{\sqrt{E}}$$





$$\frac{\sigma}{E} = \frac{22\,\%}{\sqrt{E}} \pm 0.9\,\%$$



Lead based calorimeter - 40 GeV π^-

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Simplified jet structure

The same machine learning algorithm could be calibrated and used to reconstruct energy of jets.

Simplified jet model assuming:

fragmentation function

$$D(z) = (\alpha + 1)\frac{(1-z)^{\alpha}}{z}$$

$$\alpha = 3$$

$z =$ *jet energy fraction*

jet composition

$90\,\%$ *pion* $10\,\%$ *kaon*

$30\,\%$ *neutral* $70\,\%$ *charged*

Does it reconstruct the correct energy for all the particles?

$$E = \frac{S - \chi C}{1 - \chi}$$

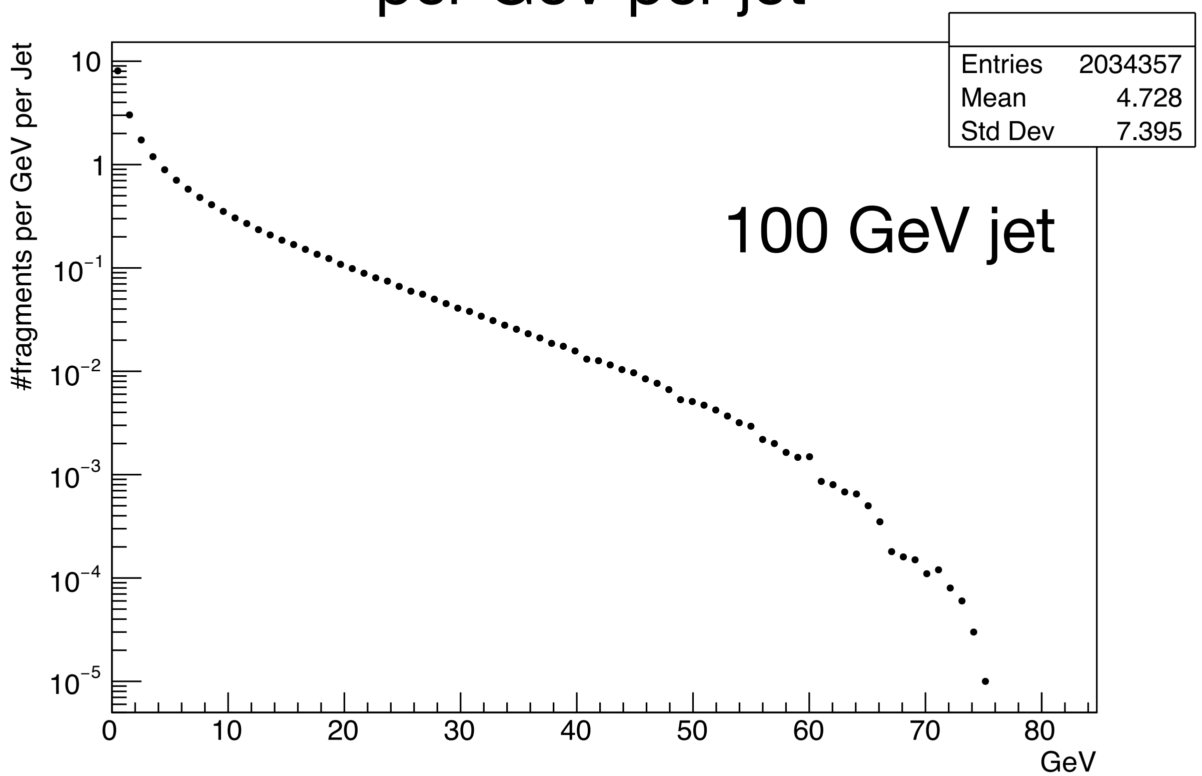
Electrons and gammas **Yes**

Hard hadrons (undergoing nuclear interactions) **Yes**

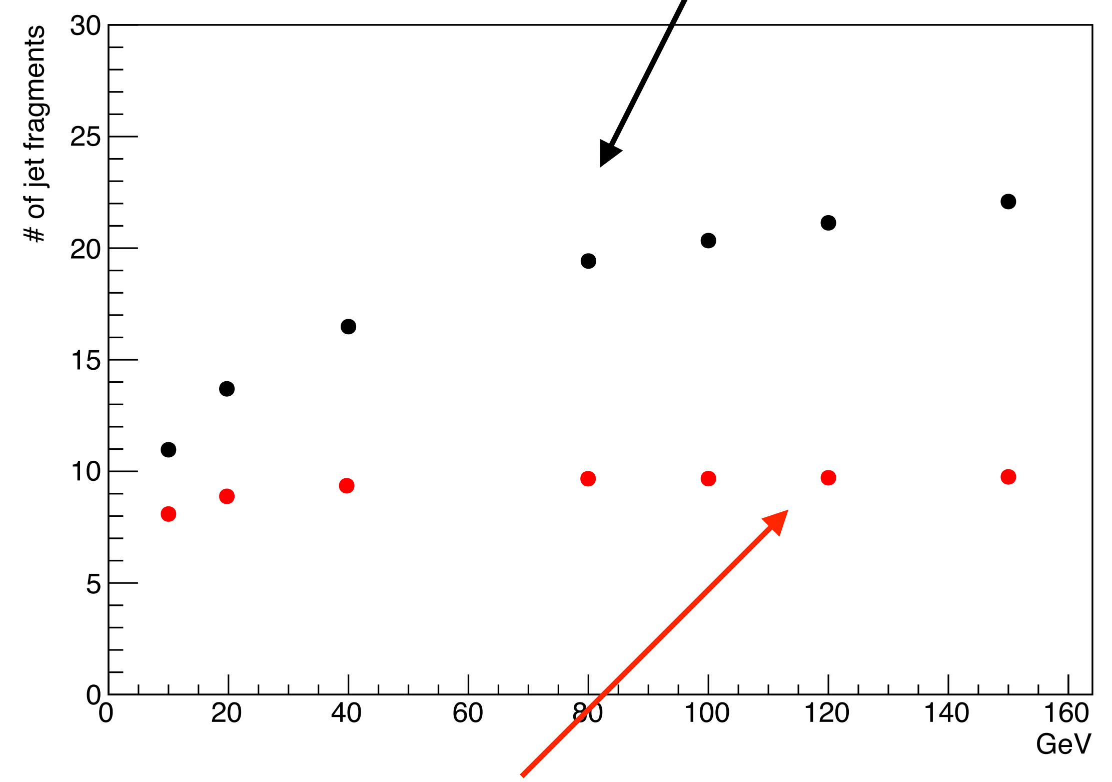
Soft hadrons (behaving like *mips*) **? usually** $\frac{e}{mip} \neq 1$

Simplified jet structure

Average number of fragments per GeV per jet



Average multiplicity vs. jet energy

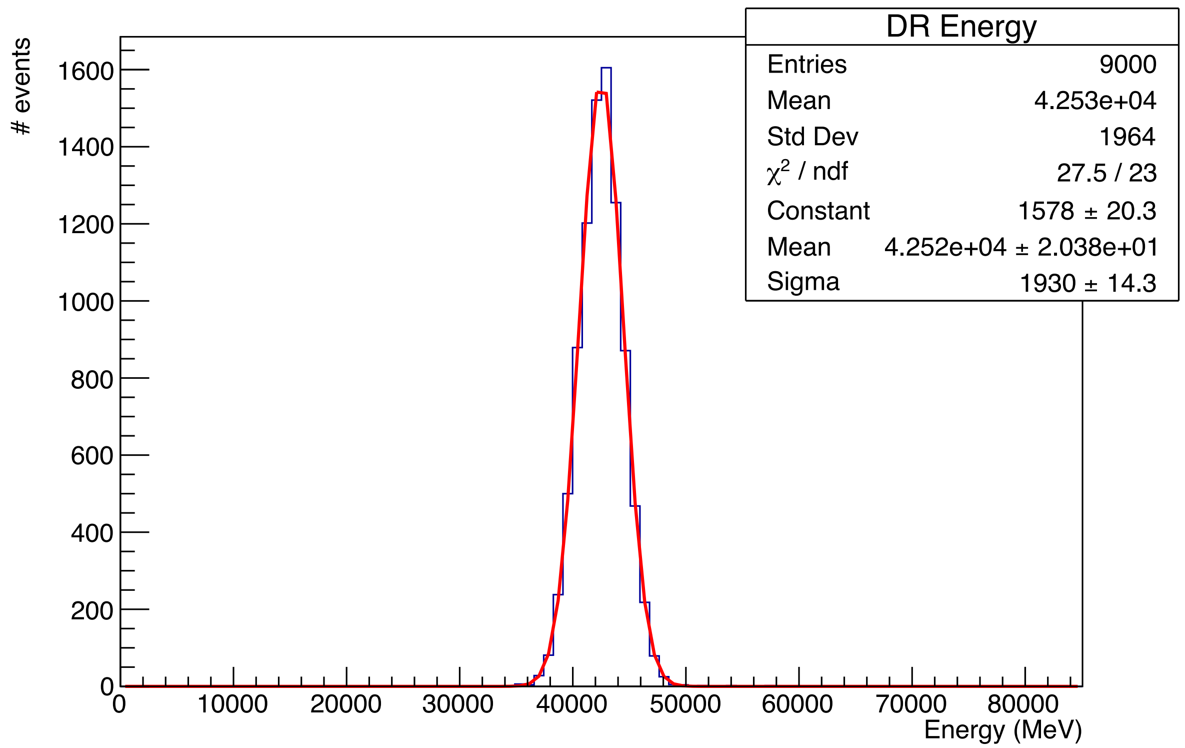


Average number of fragments that is minimally needed to account for 90% of the jet energy vs. jet energy

When detecting hadrons the calorimeter deals with a constant number of hard hadrons plus an increasing number of soft hadrons.

Jet energy reconstruction

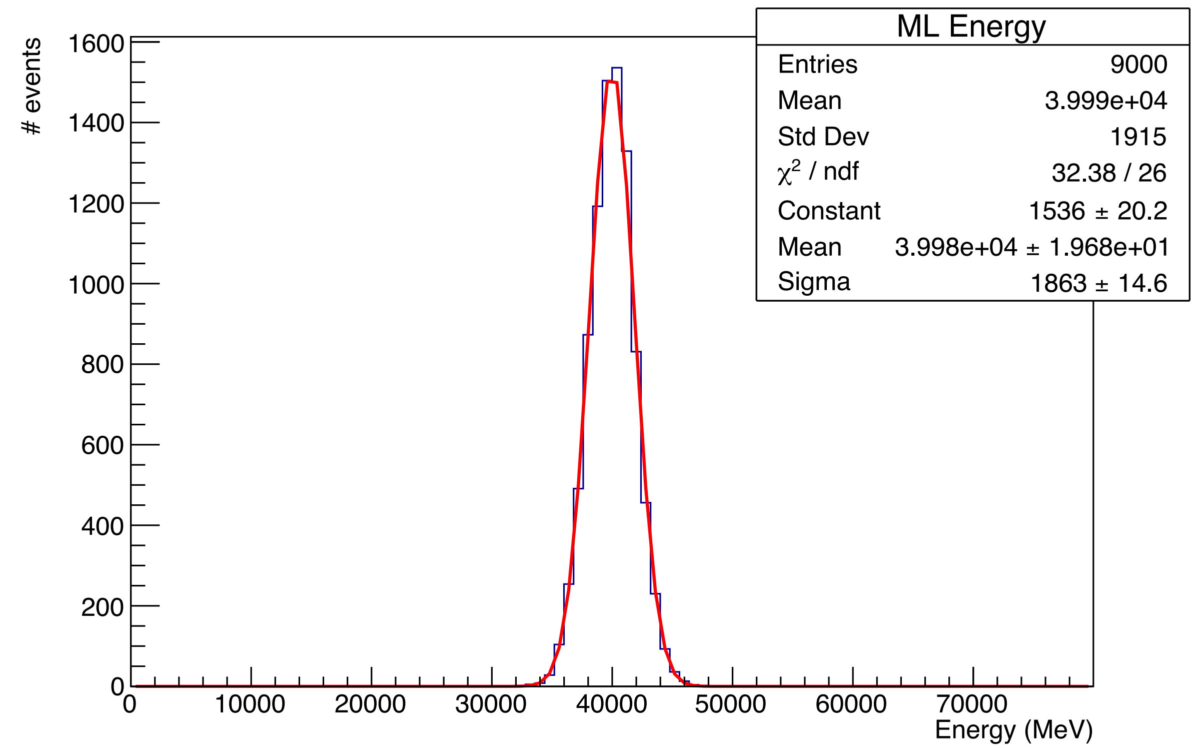
DR method



With the classical approach
the average reconstructed energy
is slightly overestimated due to:

$$\frac{e}{mip} < 1$$

Machine Learning



With machine learning
the energy is on average correctly
reproduced:

Soft hadrons are present also in the trained database

A dual-readout calorimeter can reach an excellent electromagnetic, hadronic and jet performance in a single package.

Lead based calorimeter - 40 GeV jet

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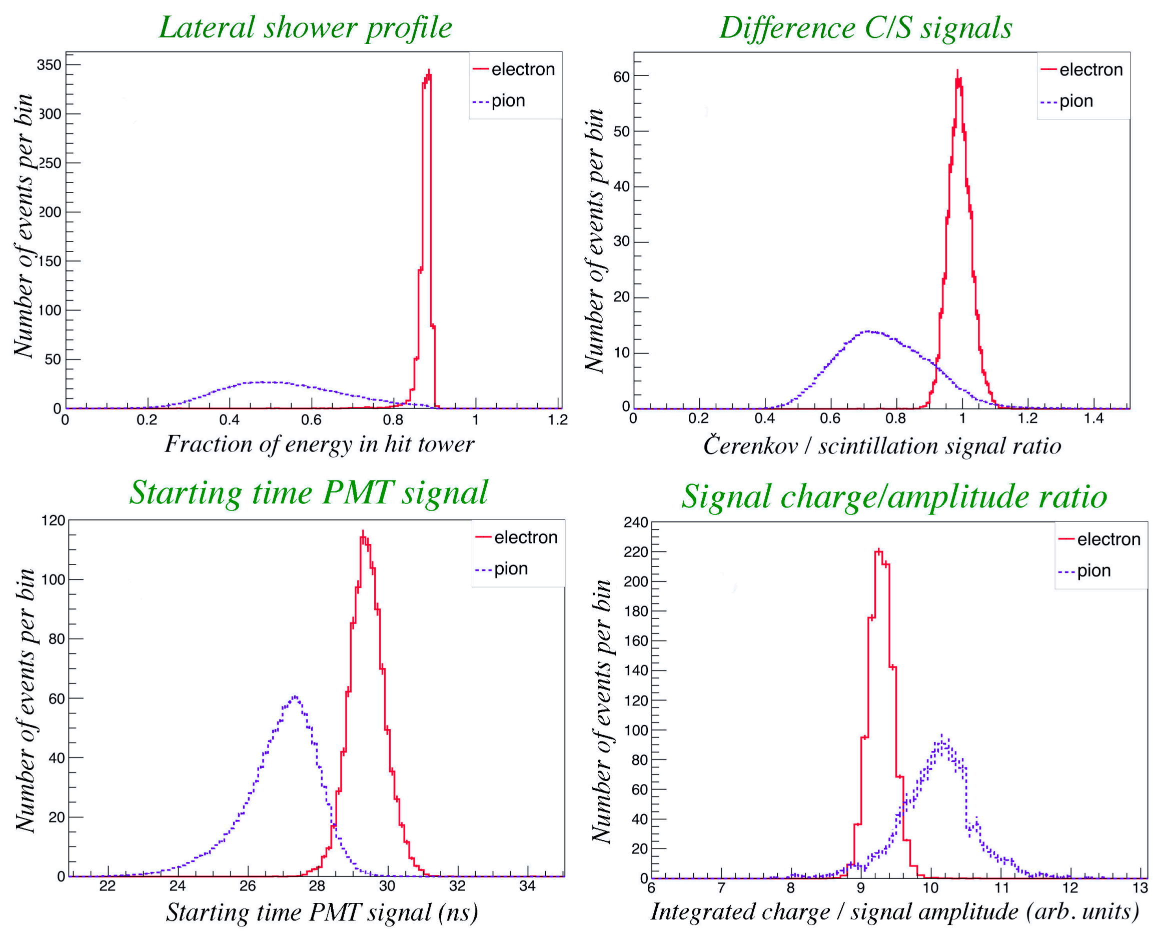
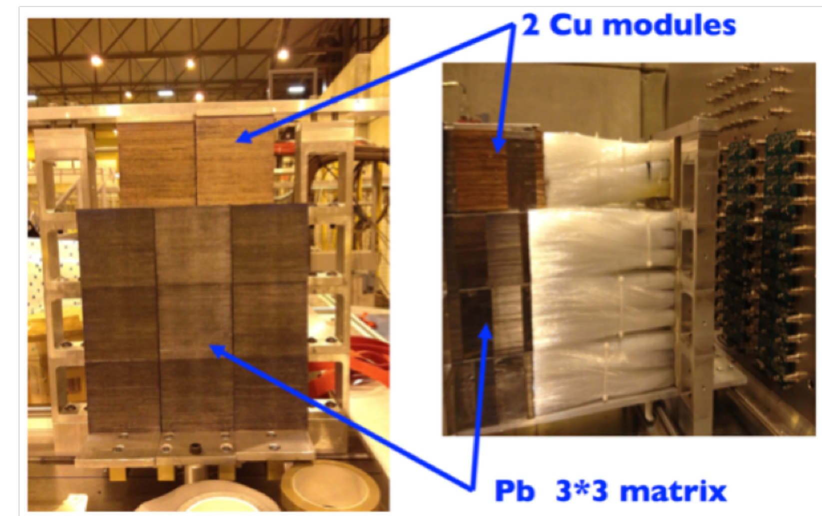
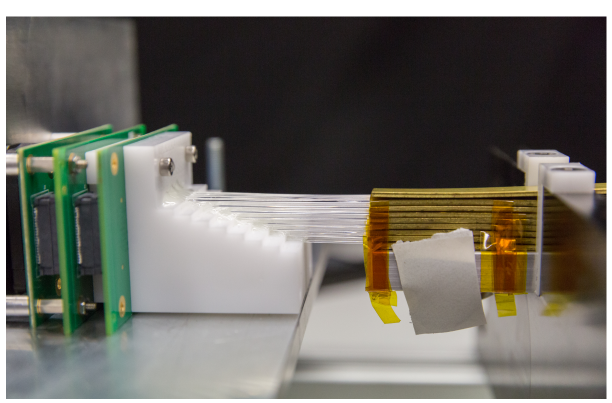
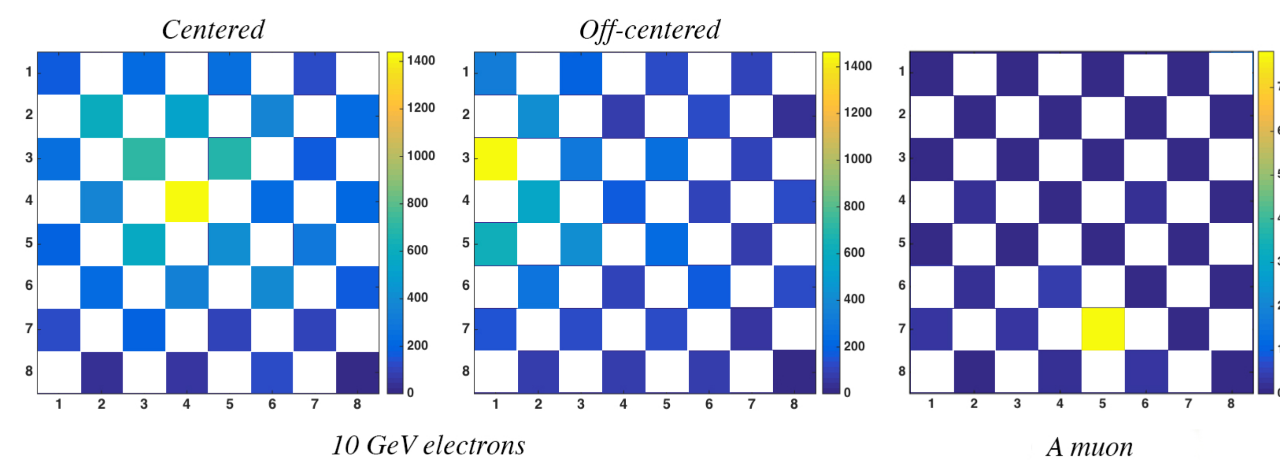
Particle Identification





Four different particle identification techniques have been studied with data reaching, for isolated particles, a 99.8% electron identification efficiency with a rejection factor of 500 for pions.





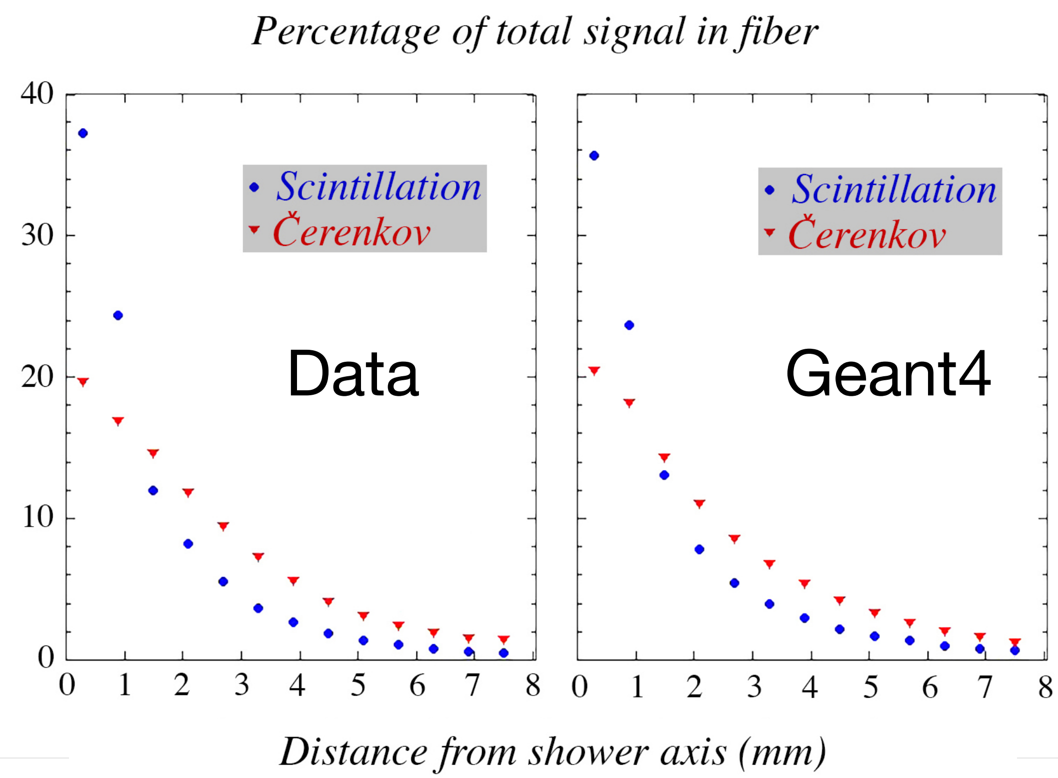
At VCI 2019: A SiPM-based dual-readout calorimeter for future leptonic colliders

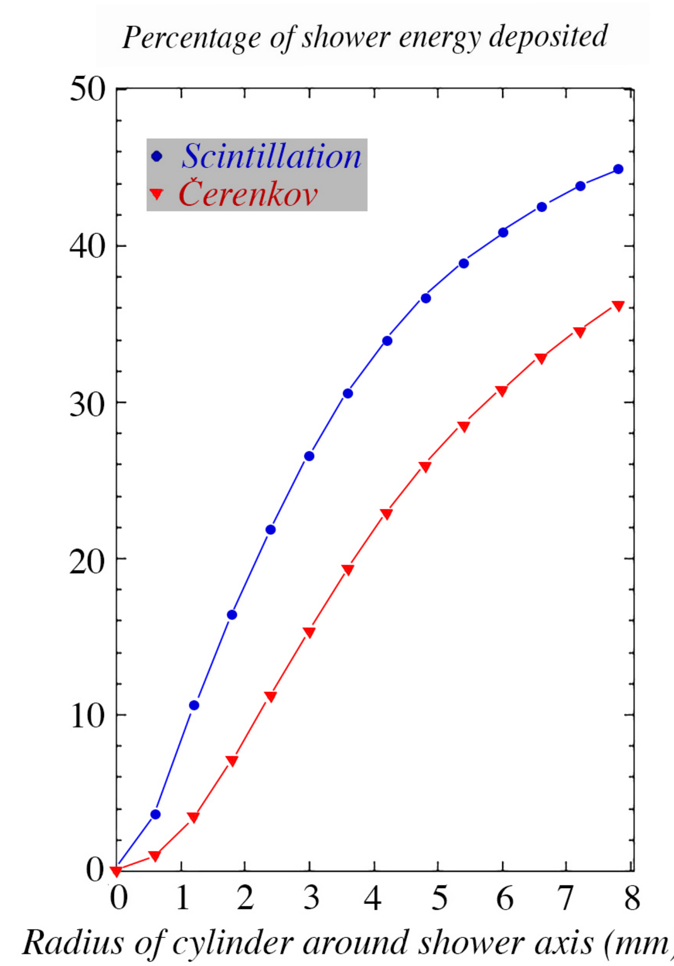
N. Akchurin, et al., Nucl. Instr. and Meth. in Phys. Res. A 735 (2014) 120.

M. Antonello, et al, Nucl. Instr. and Meth. in Phys. Res. A 899 52.

Particle Identification

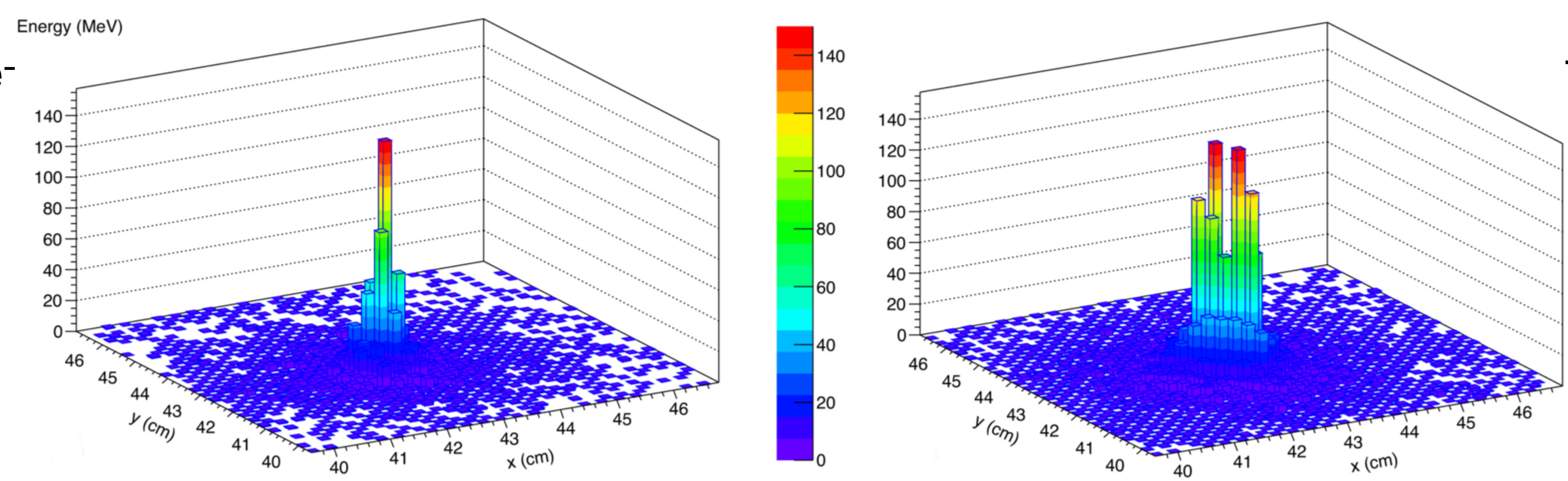
granularity helps





50 GeV e^-

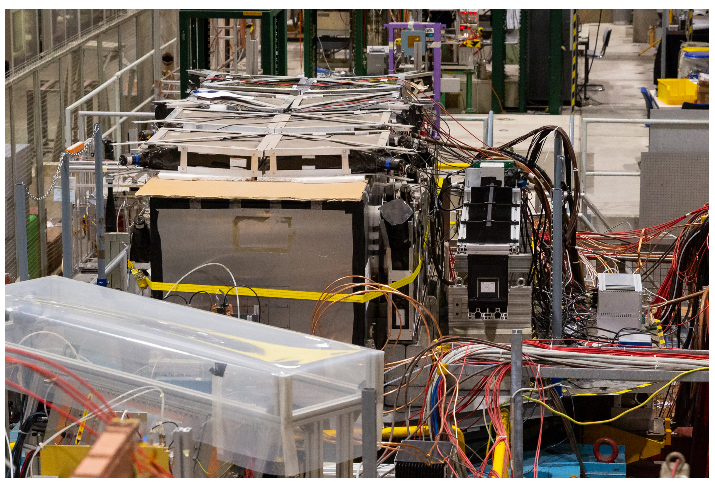
100 GeV π^0



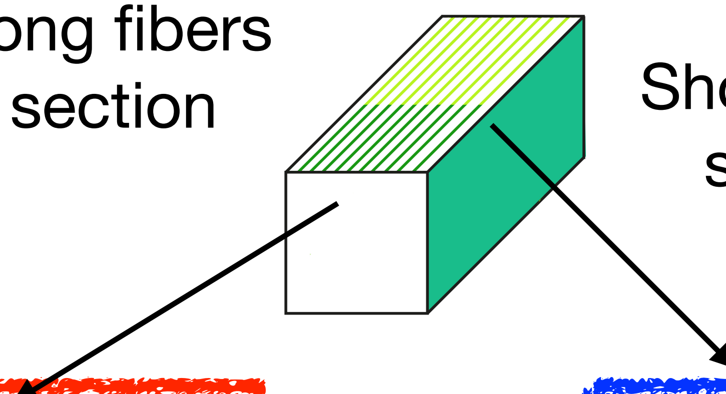
The IDEA 2019 Test Beam

To deal with particle identification with multi particle environment a longitudinal segmentation given by an electromagnetic and a hadronic section might be needed.

A possible solution is investigated with a 9x9x250 cm^3 lead module with half fibers staggered of 25 cm from the front face.

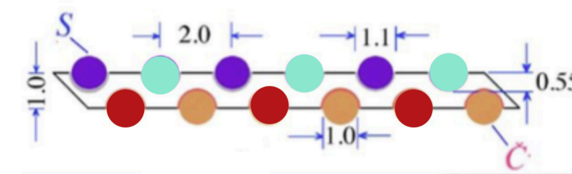


Long fibers section

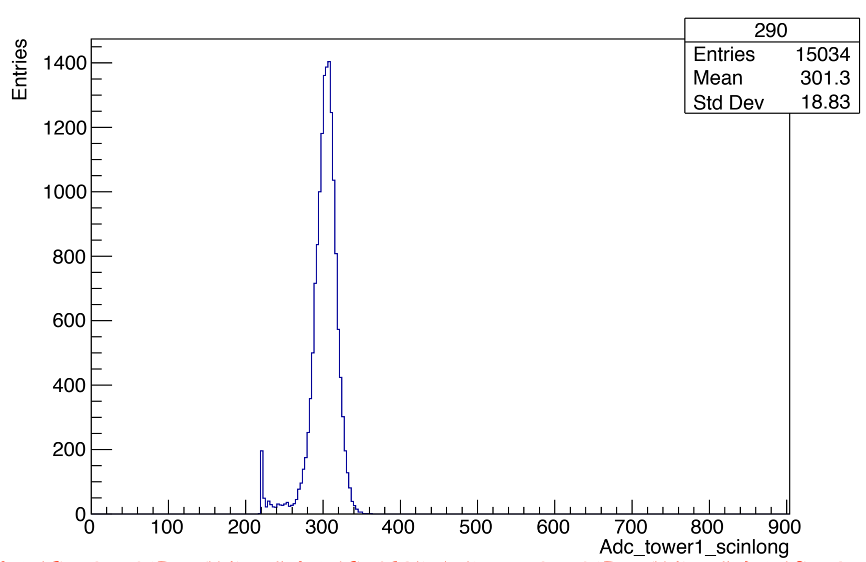


Short fibers section

"*Staggered*" module: 4 kind of fibres
S-short S-long C-short C-long



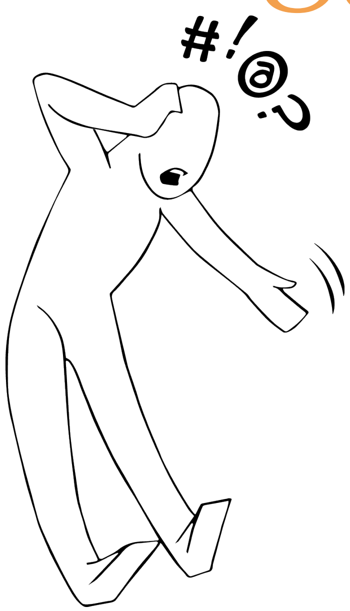
20 GeV e^- in long fibers



20 GeV e^- in short fibers

Signal
Compatible with pedestal

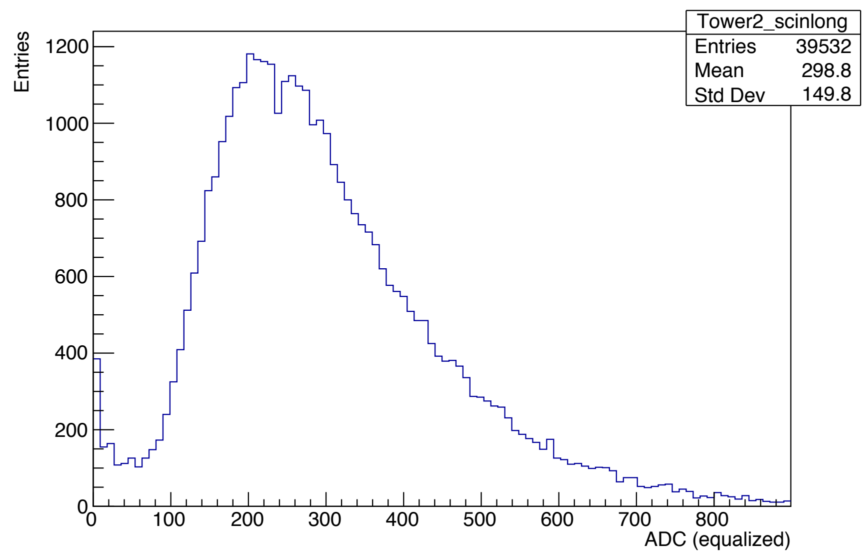
Staggered module results



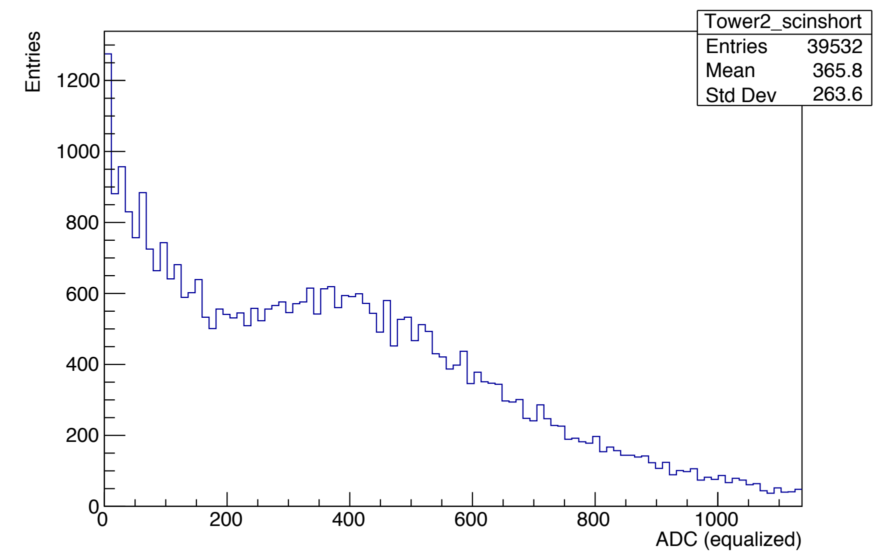
But… how is it possible to calibrate the short fibers with electrons if electrons do not reach short fibers?

Scintillating fibers

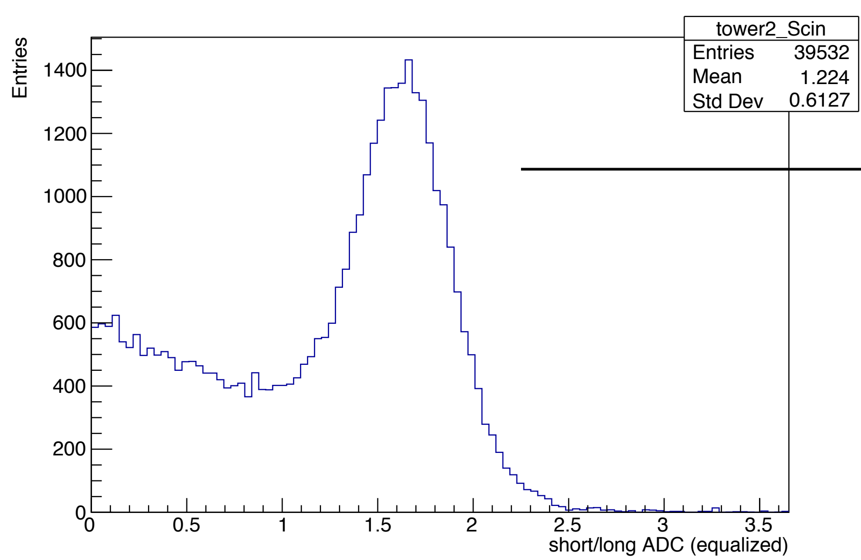
60 GeV π⁻ long fibers



60 GeV π⁻ short fibers

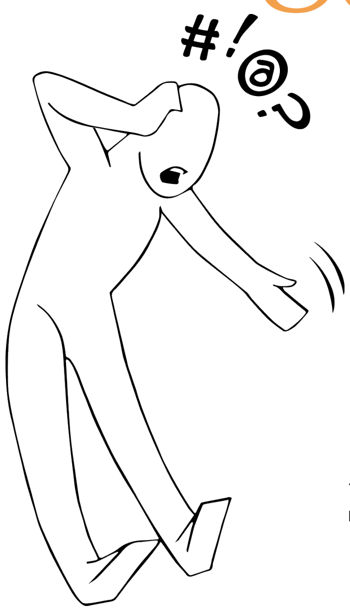


60 GeV π⁻ short/long fibers



Peak induced by hadrons that start showering late in the short section:
<u>mean value can be used to scale calibration constants of long fibers to obtain the short fiber ones.</u>

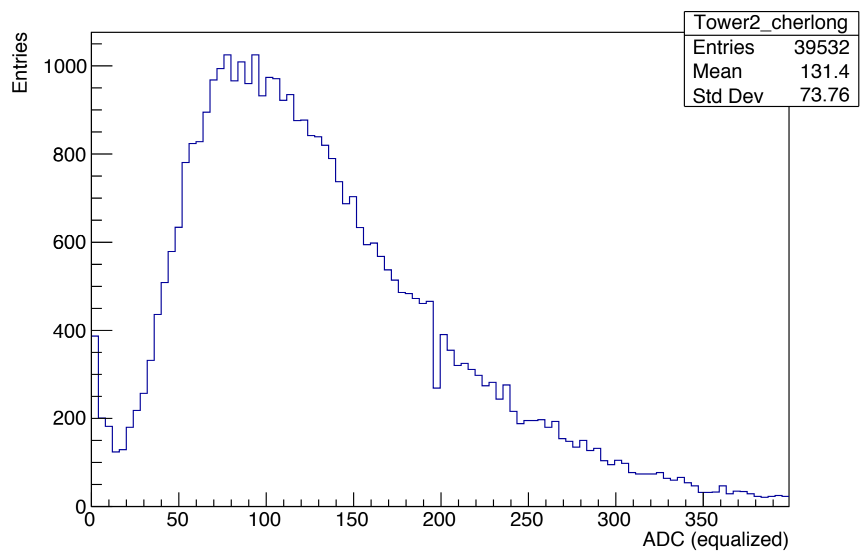
Staggered module results



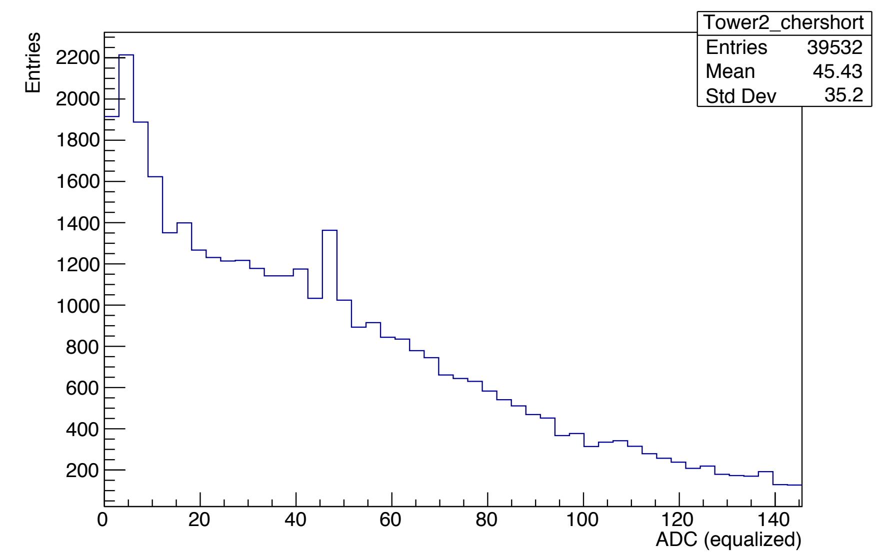
And for the Cherenkov signal?

Cherenkov fibers

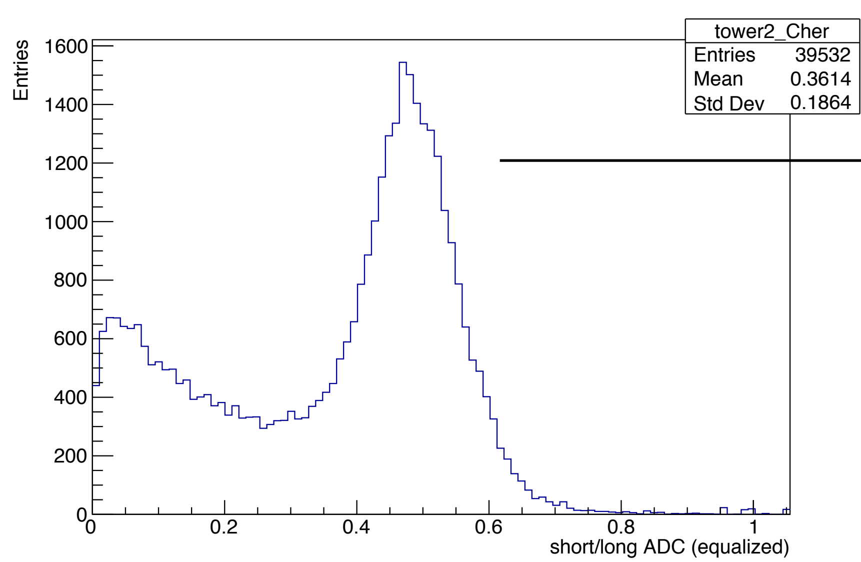
60 GeV π⁻ long fibers



60 GeV π⁻ short fibers

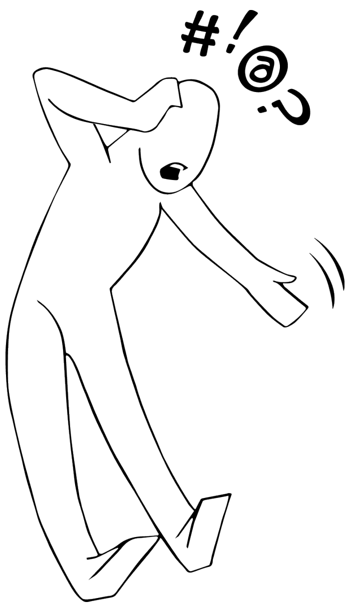


60 GeV π⁻ short/long fibers



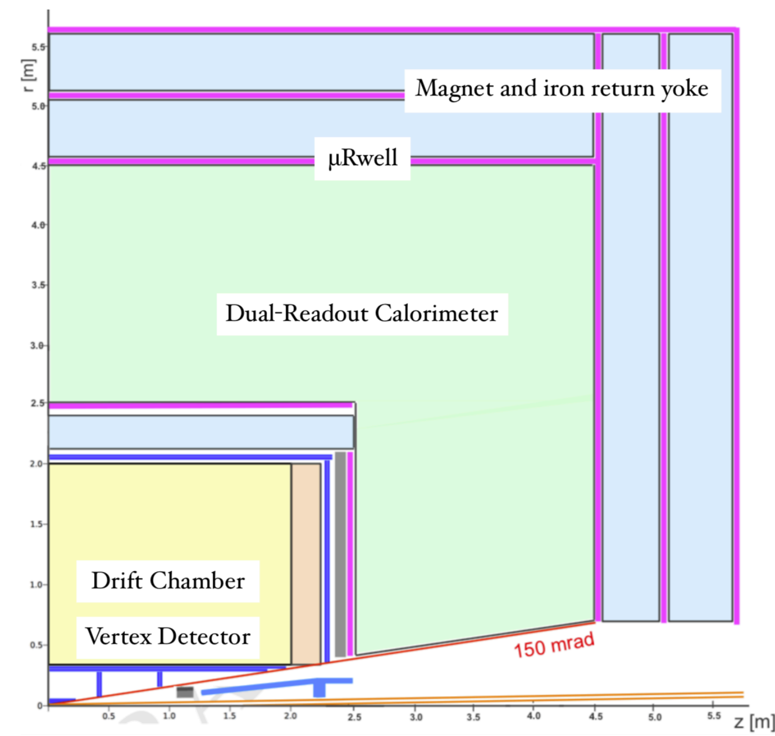
Peak mean value can be used to scale calibration constants of long fibers to obtain the short fiber ones, even for the Cherenkov signal.

Effect of budget material in front of calorimeter



The IDEA calorimeter is placed after the magnet. What is the effect of the budget material on the electromagnetic performance?

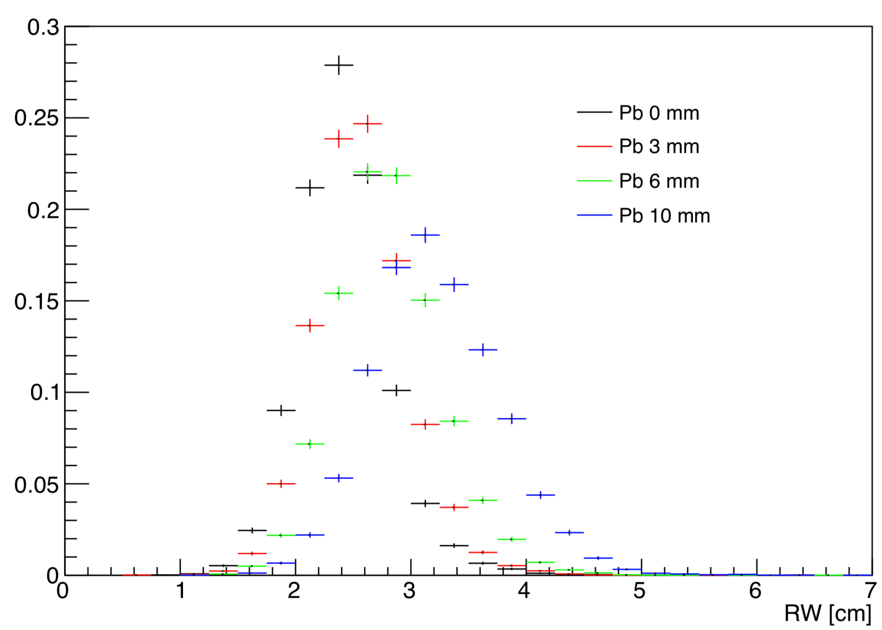
RD52 lead calorimeter with lead absorbers in front and a GEM Detector as preshower



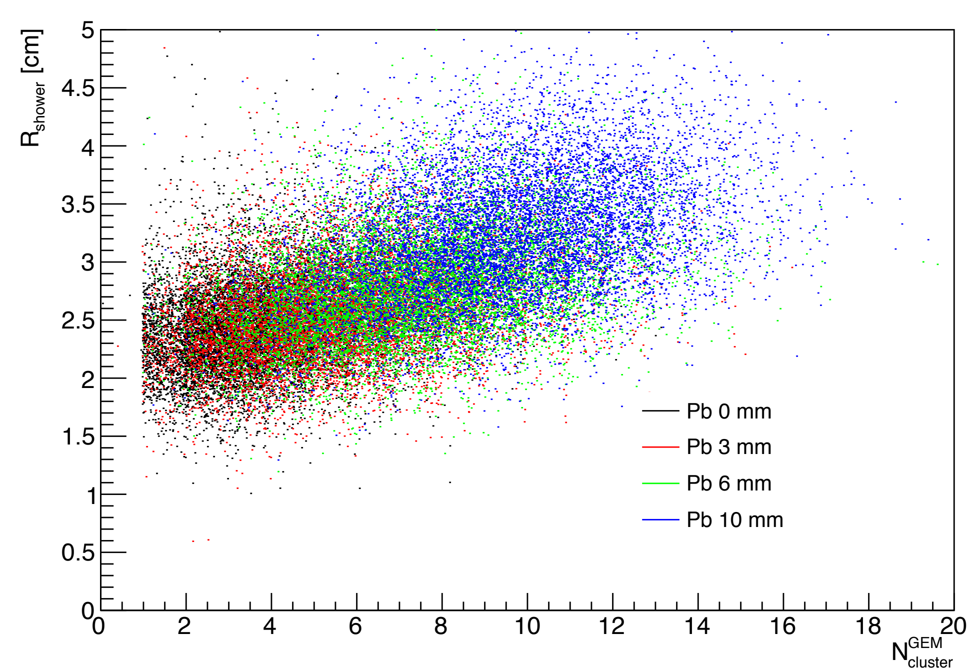
The structure of the IDEA detector and its overall dimensions

Weighted radius of the em showers given by

$$R_w = \frac{\Sigma_{ch} E_{ch} \sqrt{x_{ch}^2 + y_{ch}^2}}{\Sigma_{ch} E_{ch}}$$



Correlation between radius of shower and number of cluster in GEM preshower



Conclusions

- The excellent electromagnetic and hadronic resolution of a dual readout calorimeter, as well as its high transverse granularity, make it a great candidate for a detector at future e^+e^- colliders.

- The RD_FA Collaboration is developing a SiPM based readout, a machine learning based energy calibration/reconstruction and is studying some longitudinal segmentation options. As alternative to the longitudinal segmentation, the extraction of timing information will also be addressed.

More at VCI 2019:
A SiPM-based dual-readout calorimeter for future leptonic colliders,
M. Antonello, 19/02 El9
IDEA Test Beam Results,
L. Borgonovi, Poster Session A