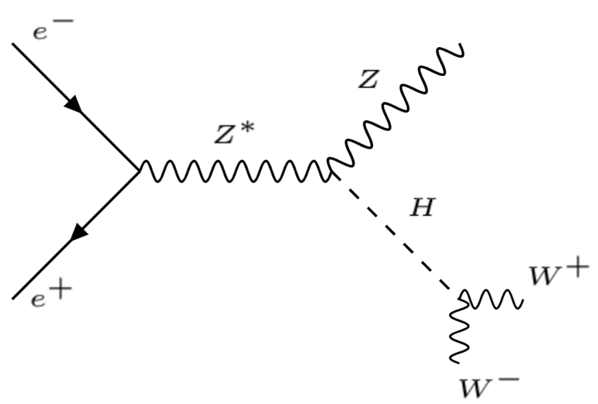
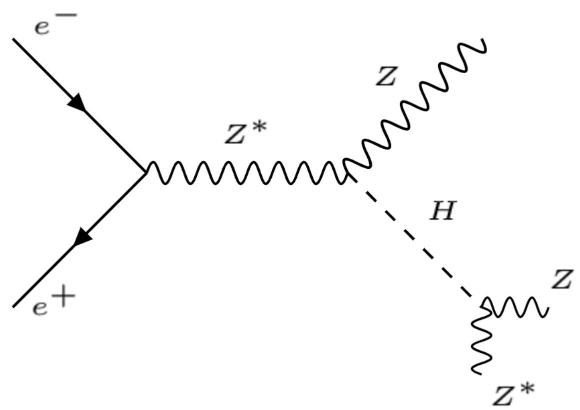
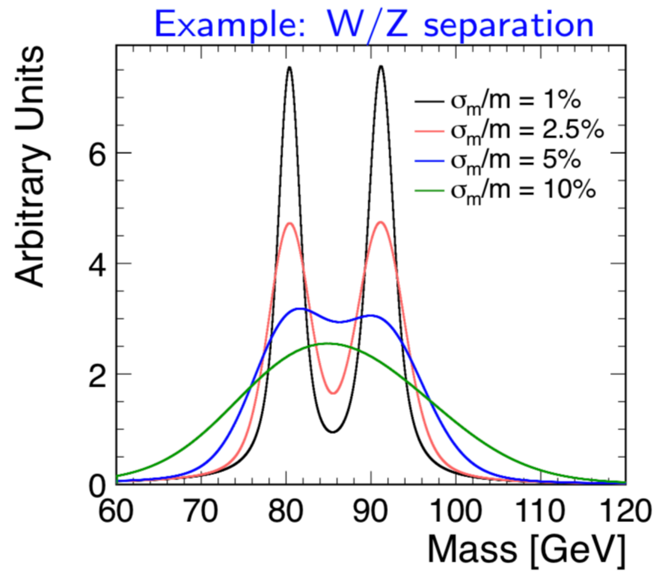
Dual-Readout Calorimetry

Lorenzo Pezzotti
University of Pavia, INFN Pavia
2018 CEPC Workshop
Institute of High Energy Physics

Calorimetry requirements





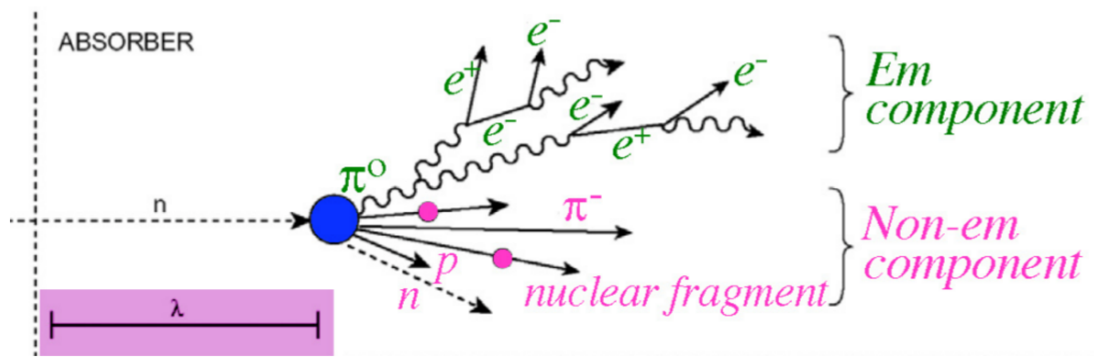


To statistically separate these two Higgs decay modes it is needed to reconstruct the Z and W invariant masses from jet decays with a resolution of ≃ 3 GeV.

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

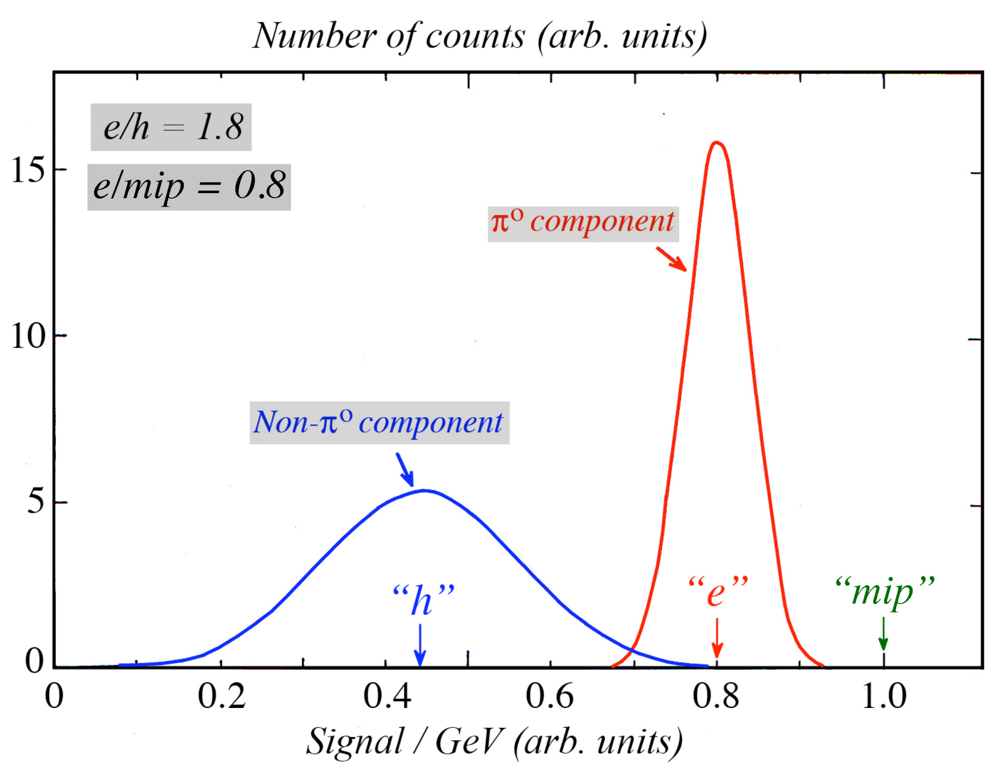
Such an energy resolution has been achieved for hadrons by calorimeters compensating by neutron boosting (e.g. SPACAL, ZEUS Calorimeter). But in future we could do better…

Non compensation



Electromagnetic component:
electrons, positrons and photons

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

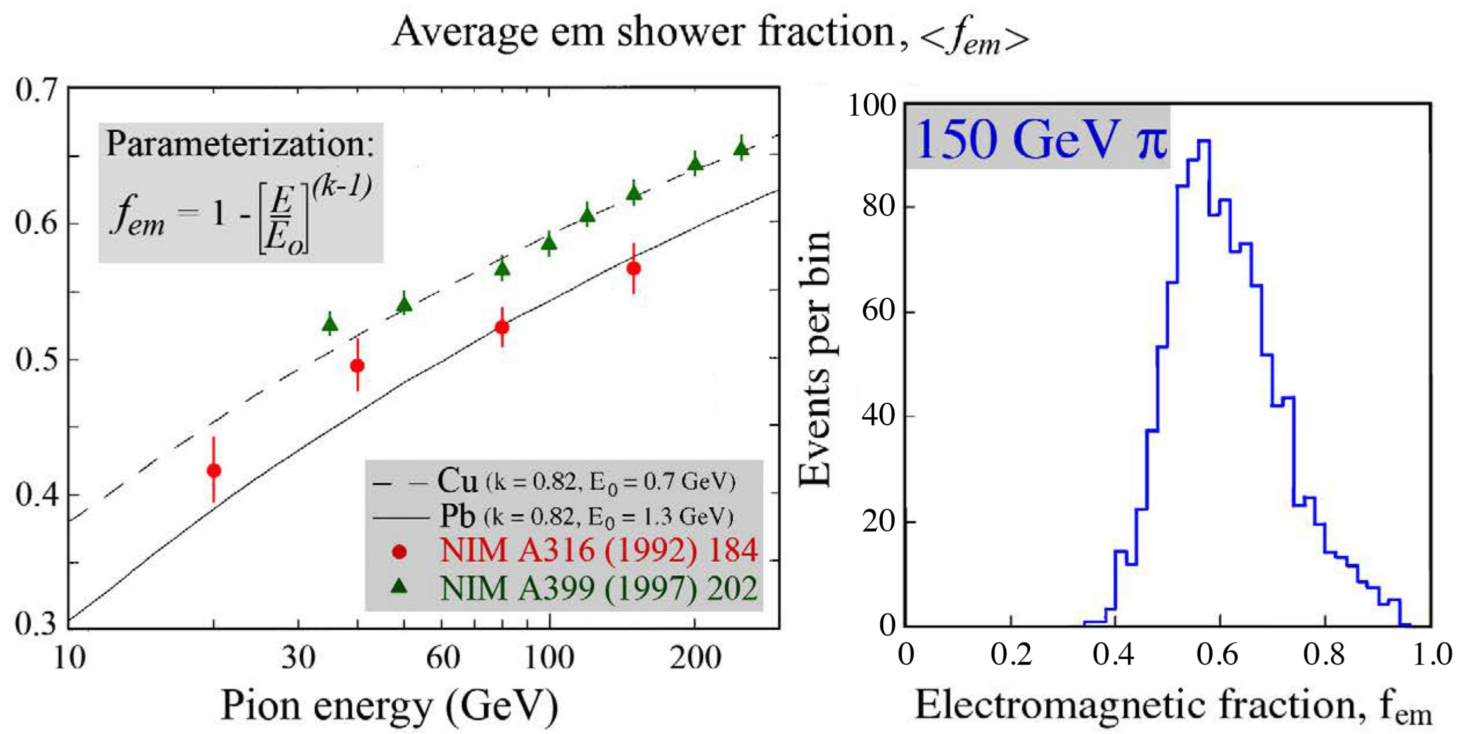


The calorimeter response is different for the two components:

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

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:

A non symmetrical 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 *non compensation* limits 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 release a light signal.

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

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

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

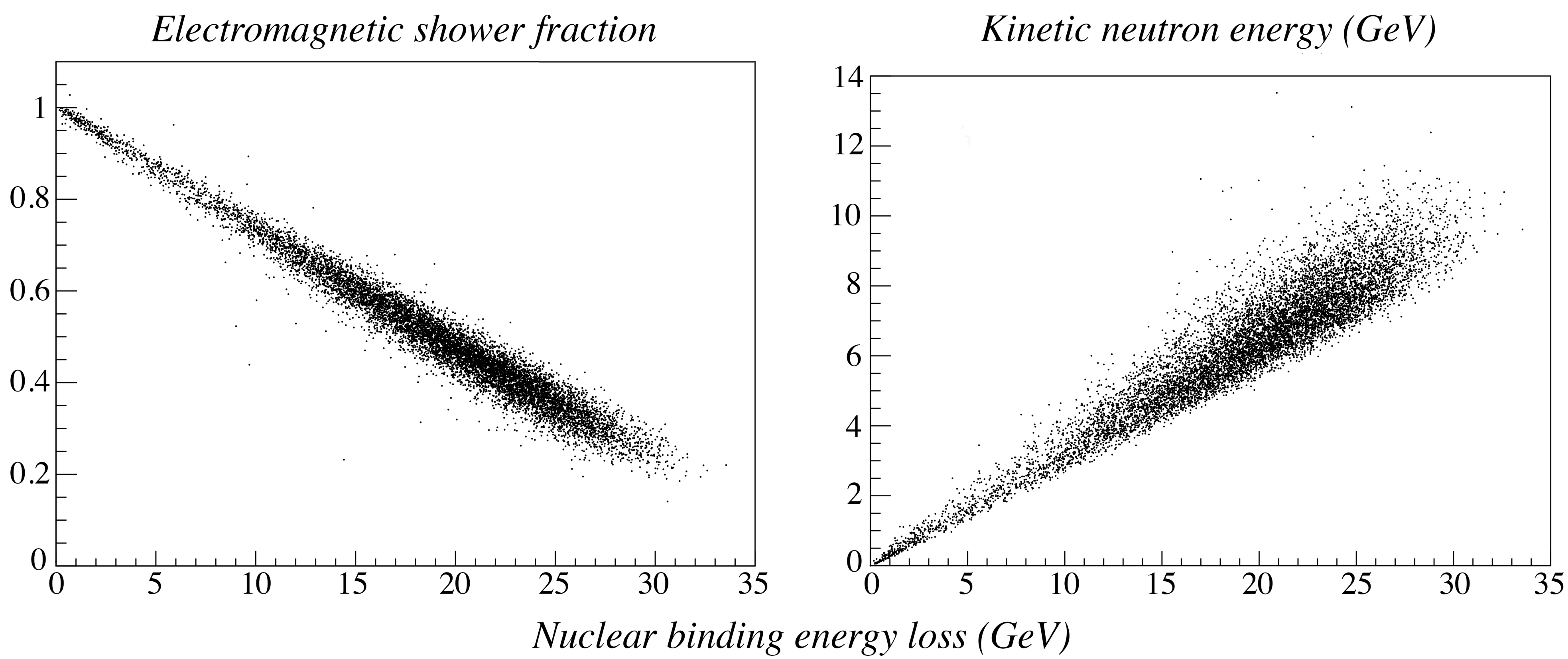
$$\frac{S}{C} = \frac{fem + \left(\frac{h}{e}\right)_s (1 - fem)}{fem + \left(\frac{h}{e}\right)_c (1 - fem)} \longrightarrow$$

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 that is the *invisible energy* affecting only the non-electromagnetic component.

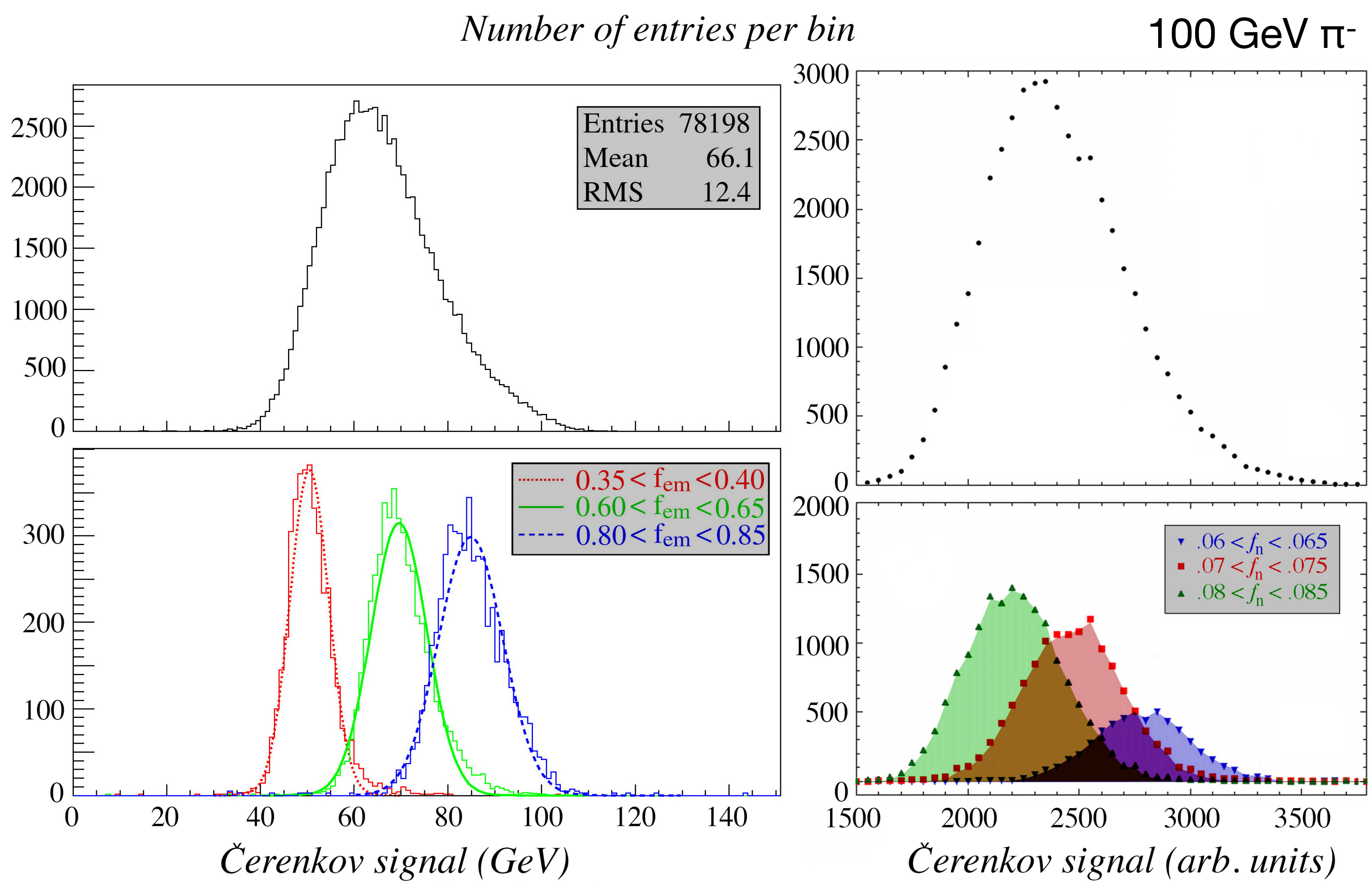
The **most precise calorimeter** is likely the one that exploits the quantity **better correlated** to the invisible energy.



S. Lee, M. Livan, R. Wigmans, Nucl. Instr. and Meth. in Phys. Res. A 882 (2018) 148.

Why is it better than the past?

Hints of this better correlation were already present in data!



S. Lee, M. Livan, R. Wigmans, Nucl. Instr. and Meth. in Phys. Res. A 882 (2018) 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.*

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

Universality of the χ factor

No dependence of the χ factor is observed with simulations.

Brass

π^- GeV	h/e_s	h/e_c	χ
20	0.77	0.37	0.37
40	0.77	0.37	0.37
60	0.77	0.38	0.37
80	0.77	0.38	0.37

Geant4 - Preliminary

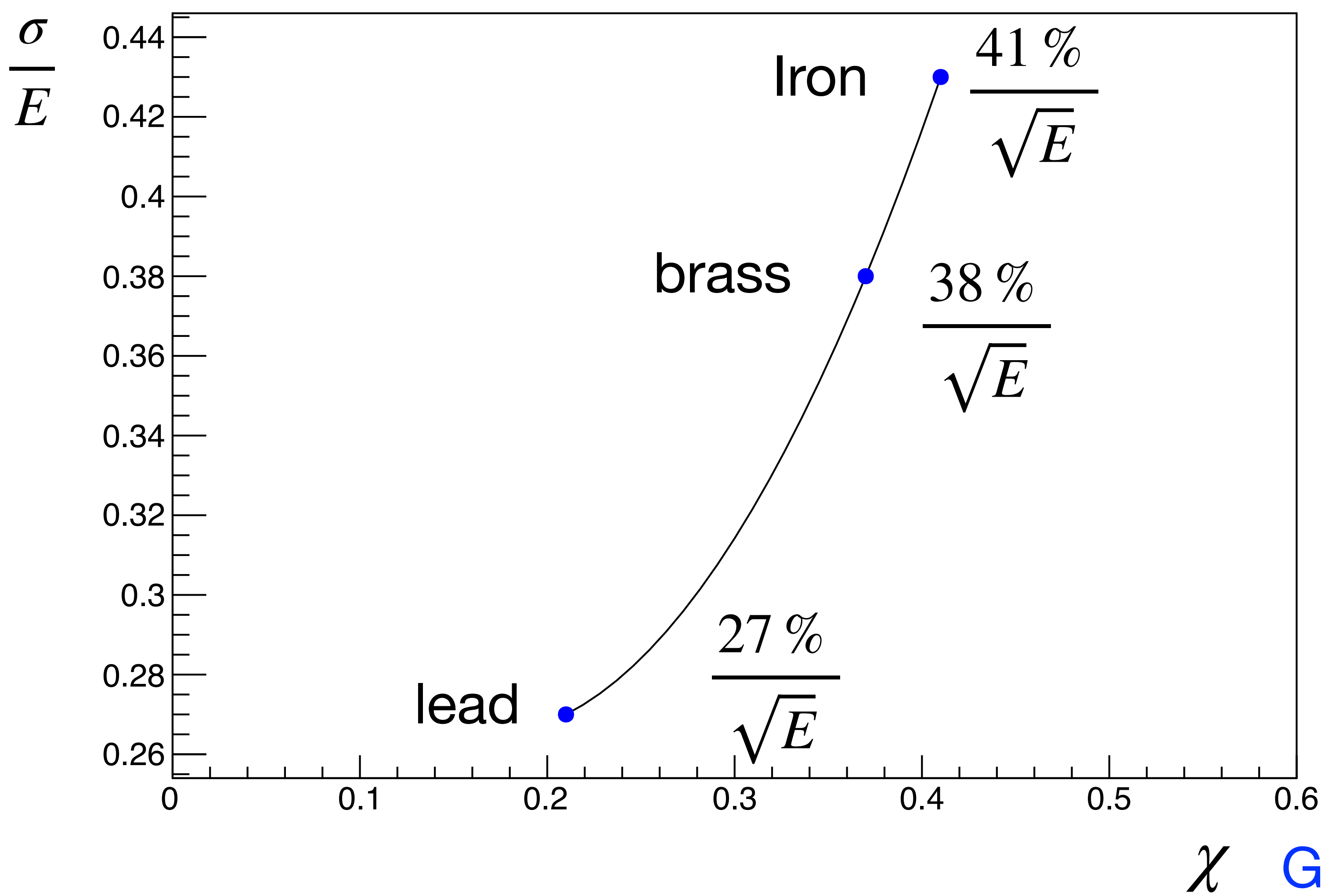
Absorber materials

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

$(h/e)_s$ → Keep it high

$(h/e)_c$ → Keep it low

Hadronic resolution at 1 GeV *vs.* χ



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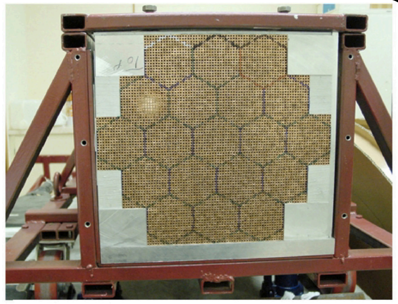
Dual-readout prototypes

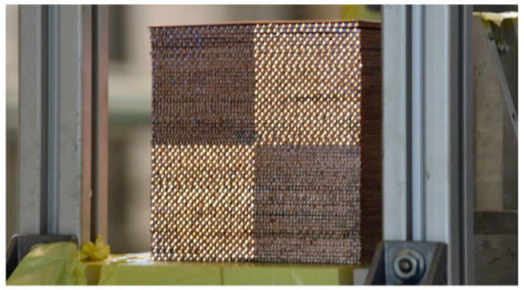
DREAM
2003

Copper
2 m long, 16.2 cm wide
19 towers, sampling fraction 2%



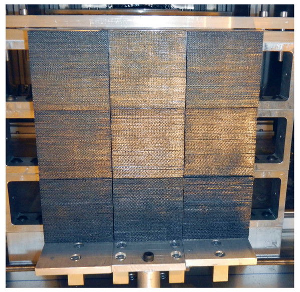
RD52
2012

Copper
module 9.3 x 9.3 x 250 cm^3
2 modules, sampling fraction 4.5%



RD52
2012

Lead
module 9.3 x 9.3 x 250 cm^3
9 modules, sampling fraction 5.0%



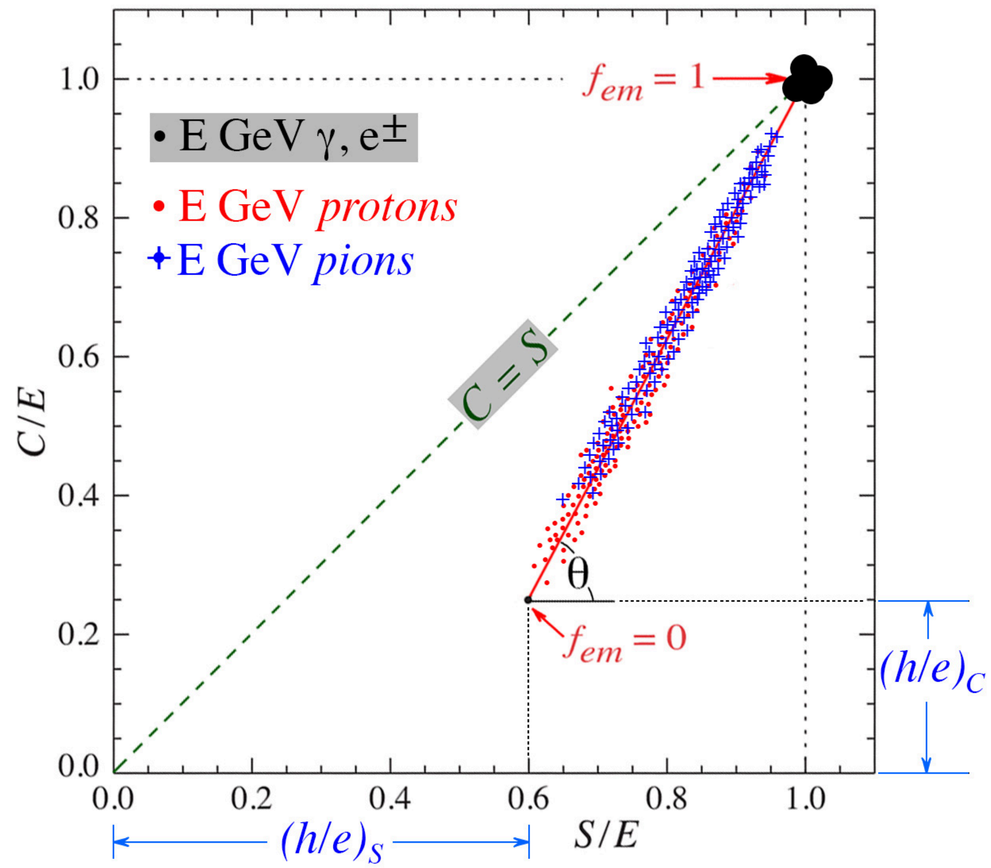
"… study of performance with full simulation of a full containment prototype would be a big advantage at this stage."

CEPC CDR Referee

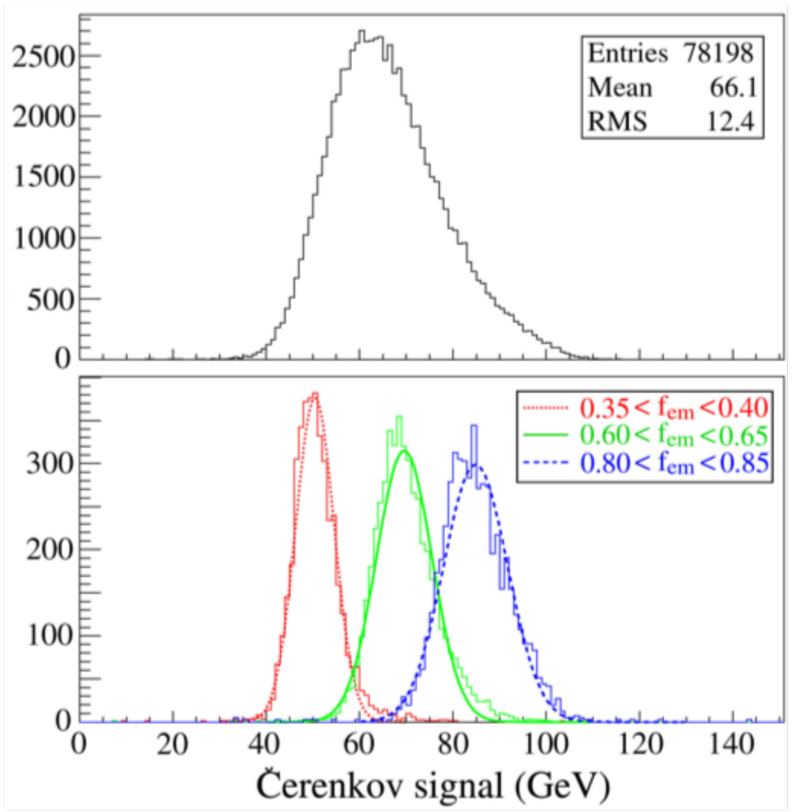
RD52 Results

The heritage of the RD52 Collaboration is the demonstration of the feasibility of this method by proving that:

The non compensation problems are fixed
The χ factor is energy and particle type independent



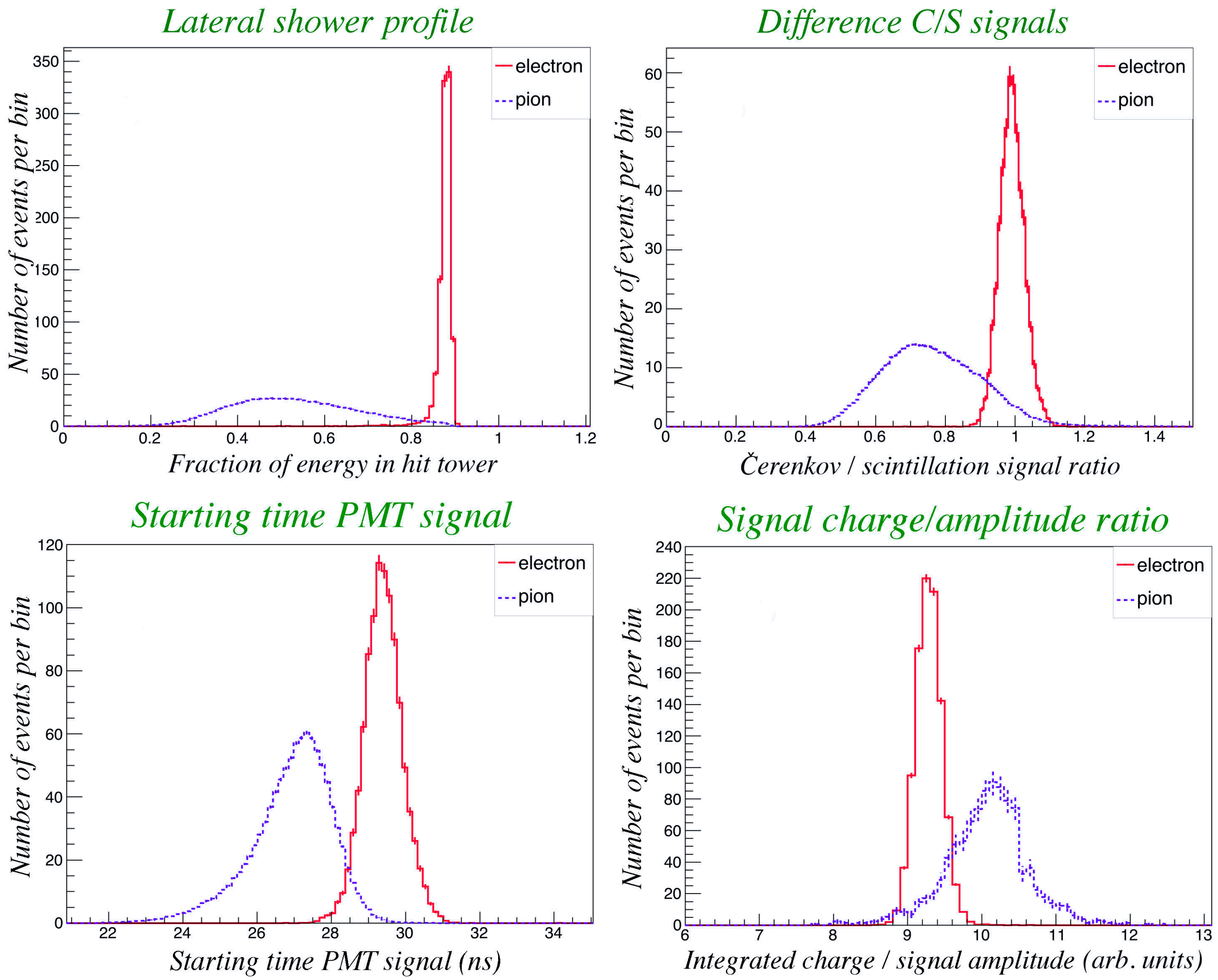
100 GeV π^-



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

Particle Identification

Also, four different particle identification techniques have been studied reaching a 99.8% electron/hadron identification efficiency.

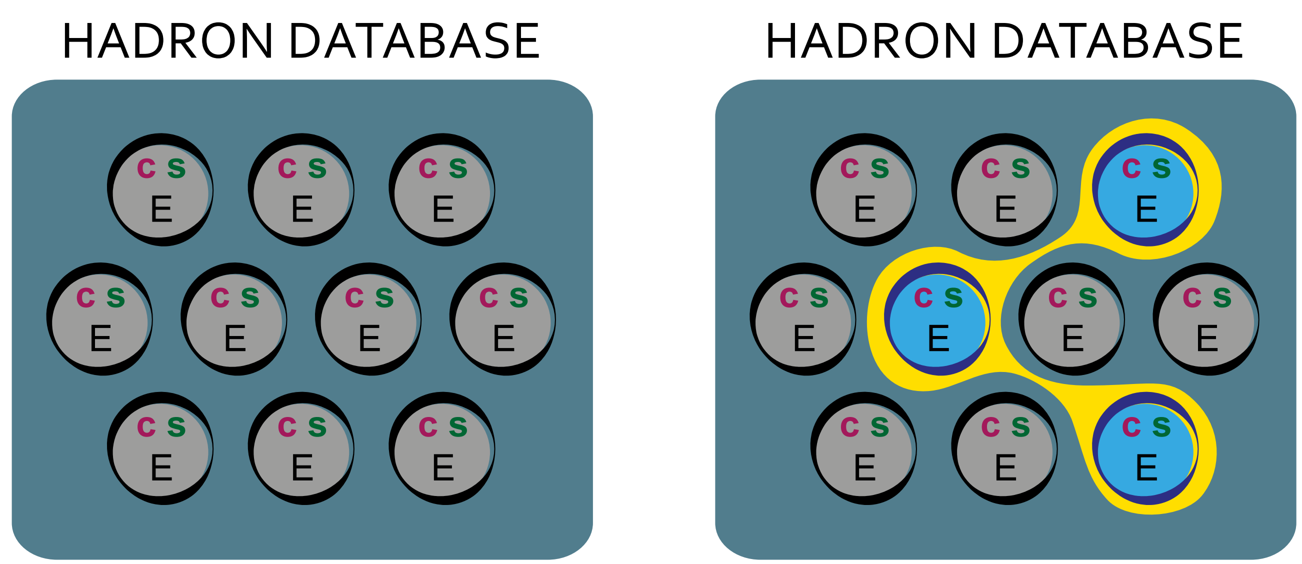


N. Akchurin, et al., Nucl. Instr. and Meth. in Phys. Res. A 735 (2014) 120.

Machine Learning

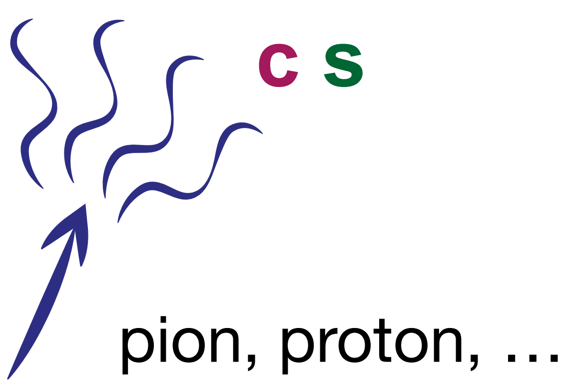
A new machine learning inspired technique is a promising solution to *also* exploit calibrations with hadrons.

The single event under reconstruction is compared to only pre stored events with approximately the same electromagnetic fraction.



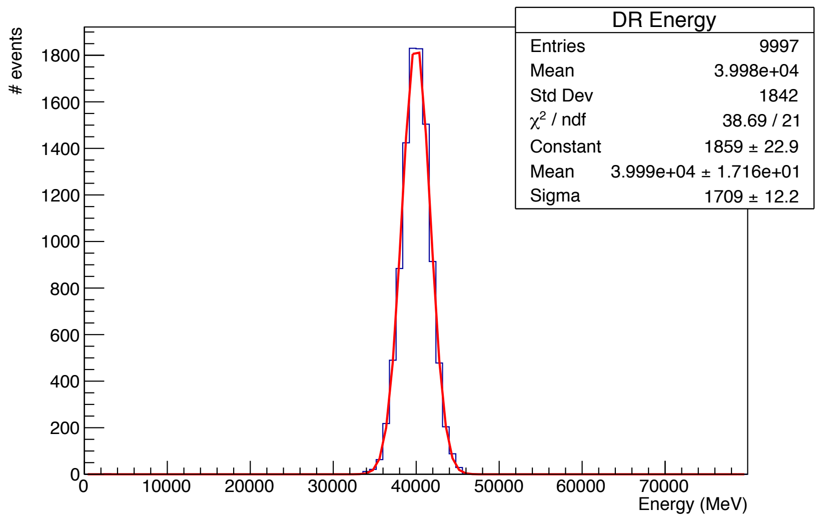
The correct hadron energy is then given by

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

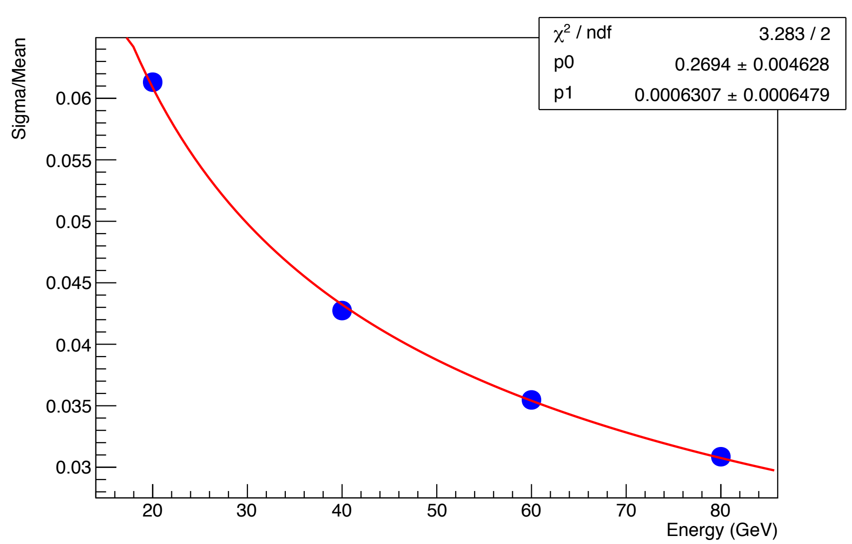


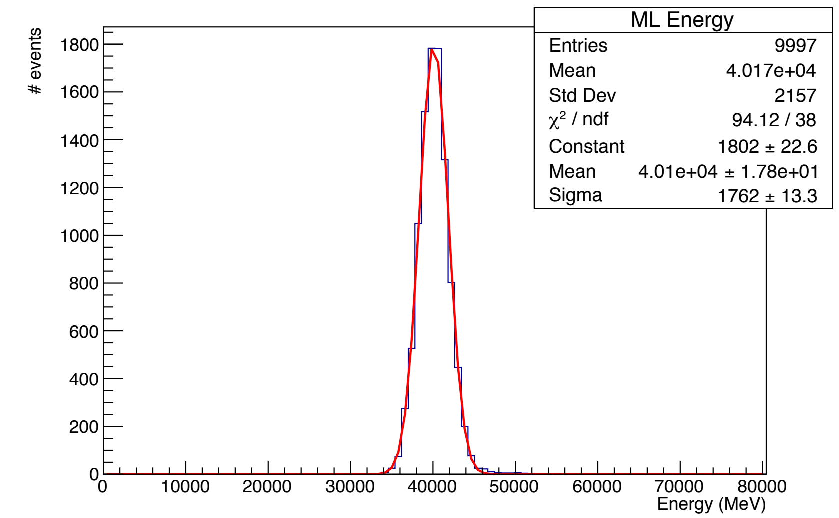
DR vs. ML

Lead

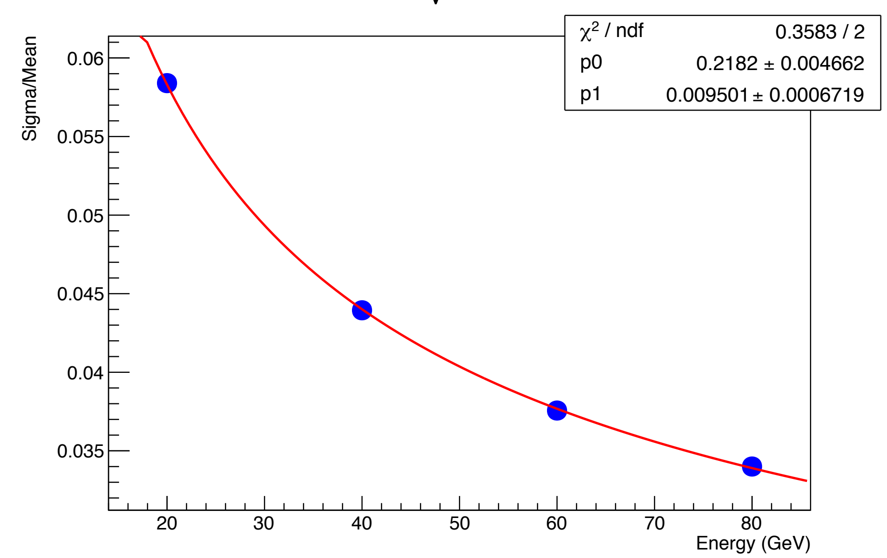


$$\frac{\sigma}{E} = \frac{27\ \%}{\sqrt{E}}$$





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

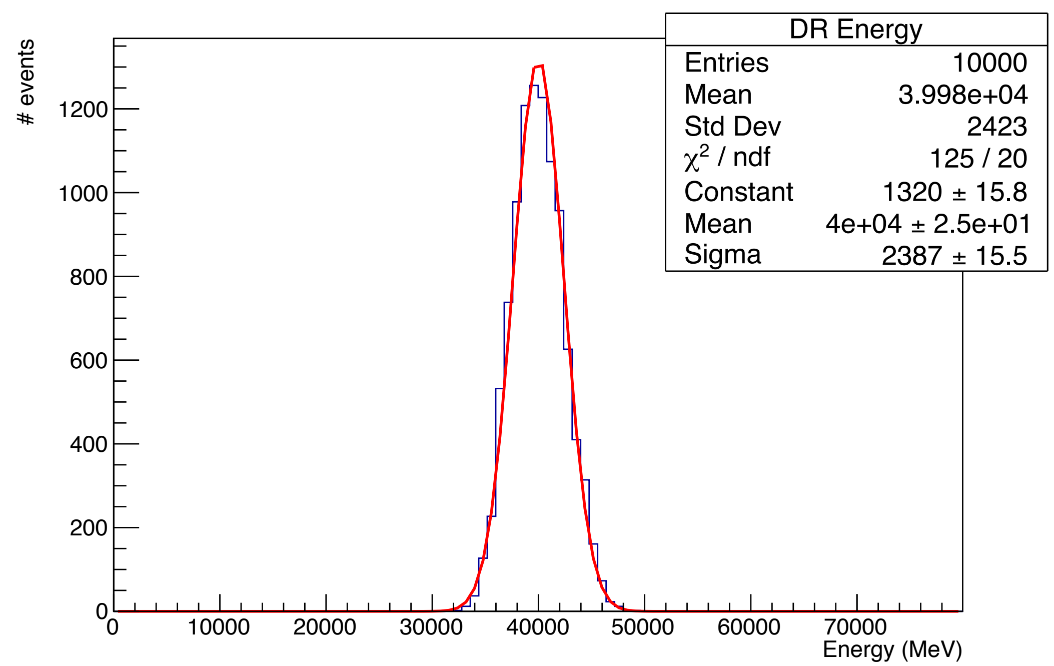


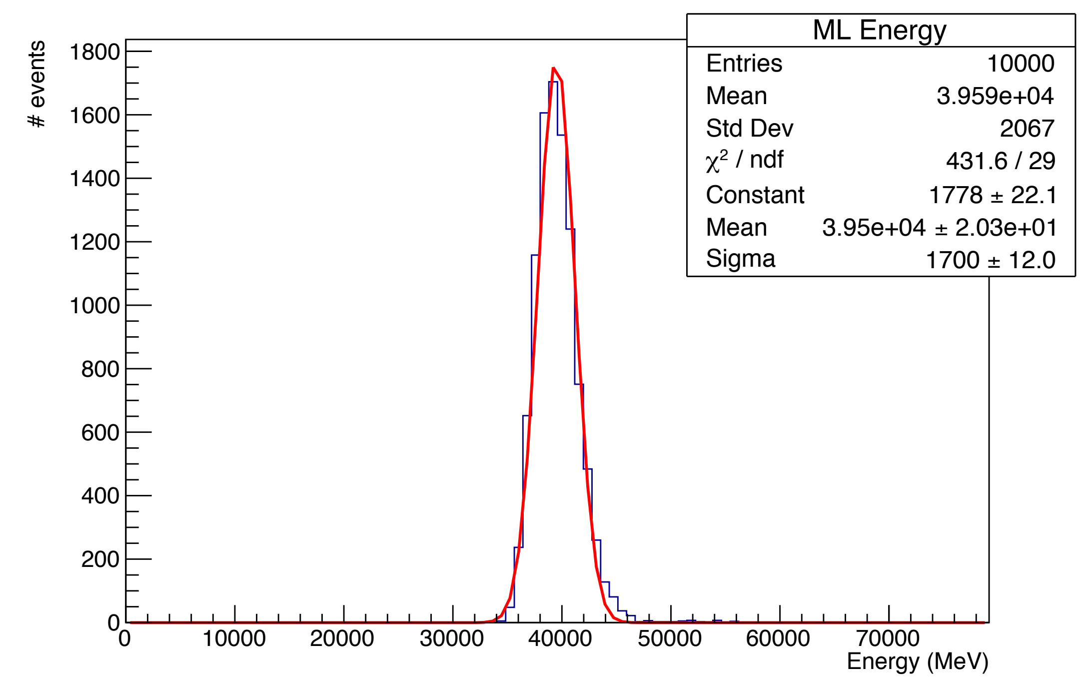
Geant4 - Preliminary

Two is better than one

It turned out that with this calibration with hadrons it is possible to reconstruct also the energy of electrons.

40 GeV e^- reconstructed with the DR method and the ML method





Calibration: electrons

↓

Reconstruct: electrons and hadrons

Calibration: hadrons

↓

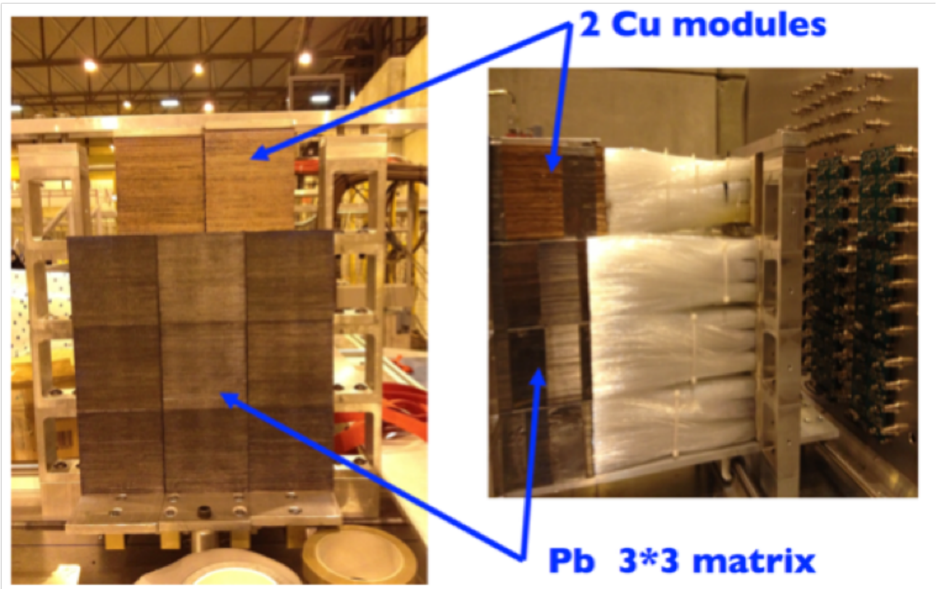
Reconstruct: electrons and hadrons

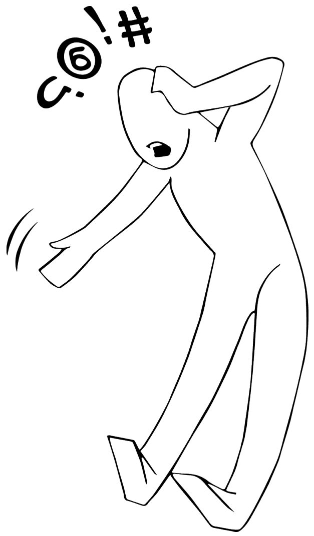
Geant4 - Preliminary

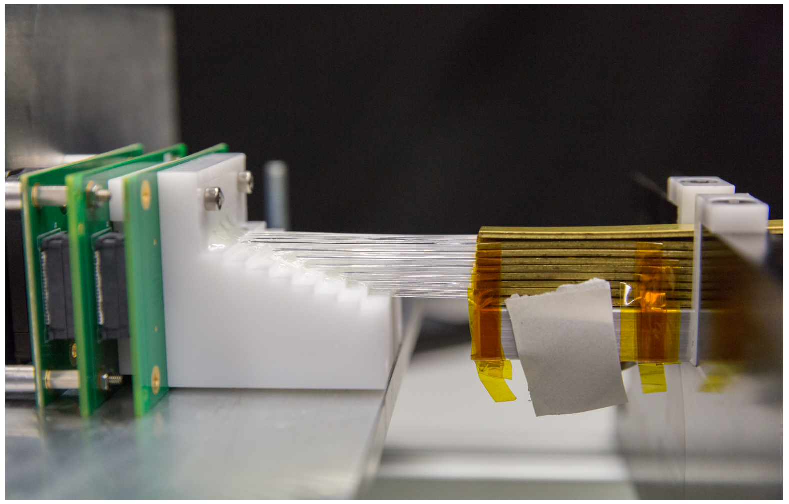
SiPM based readout

Advantages of Silicon Photomultipliers wrt PMTs:

- Compact readout: a single SiPM directly coupled to each fiber
- Magnetic field insensitive
- Higher photon detection efficiency (Cherenkov p.e. are a limiting factor for both hadronic and electromagnetic resolution)
- Unprecedented 2-dimensional shower spatial sampling





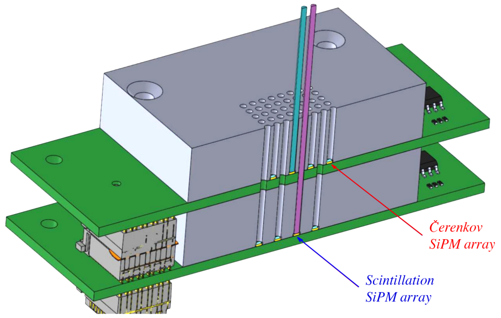


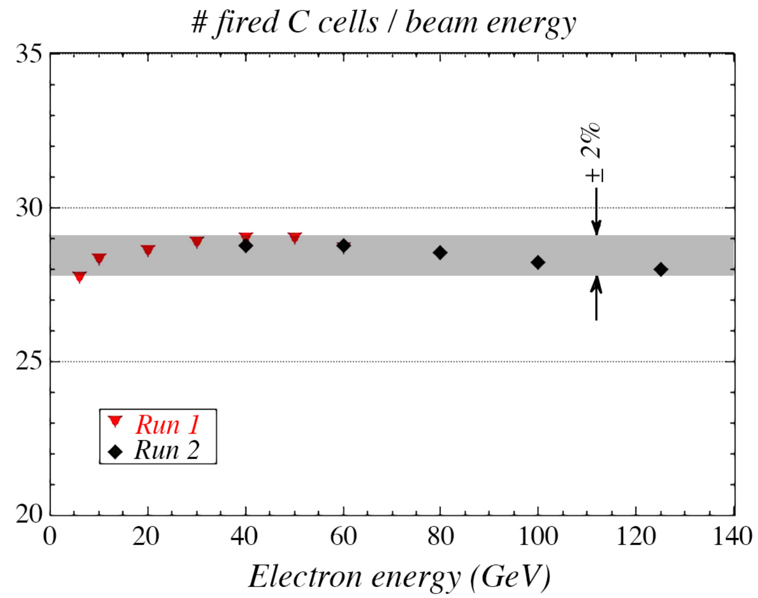
Signal linearity & Crosstalk

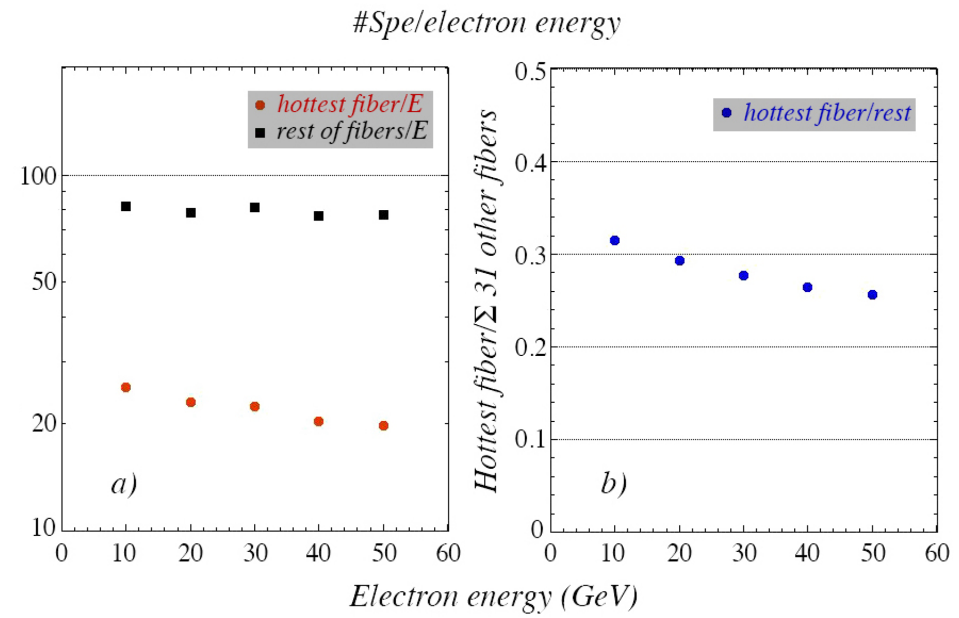
Cherenkov light yield: 28.6 Cpe/GeV, 2% linear from 10 to 125 GeV. Correcting for 45% em energy containment: ~ 54 Cpe/GeV

Scintillation light yield: Correcting for 45% em energy containment and occupancy effects: ~ 3200 Spe/GeV, 50 times greater than the Cherenkov one.

Cross talk: With a two tier structure the two kind of fibers were readout on two spaced boards and the optical crosstalk was kept below 0.3%

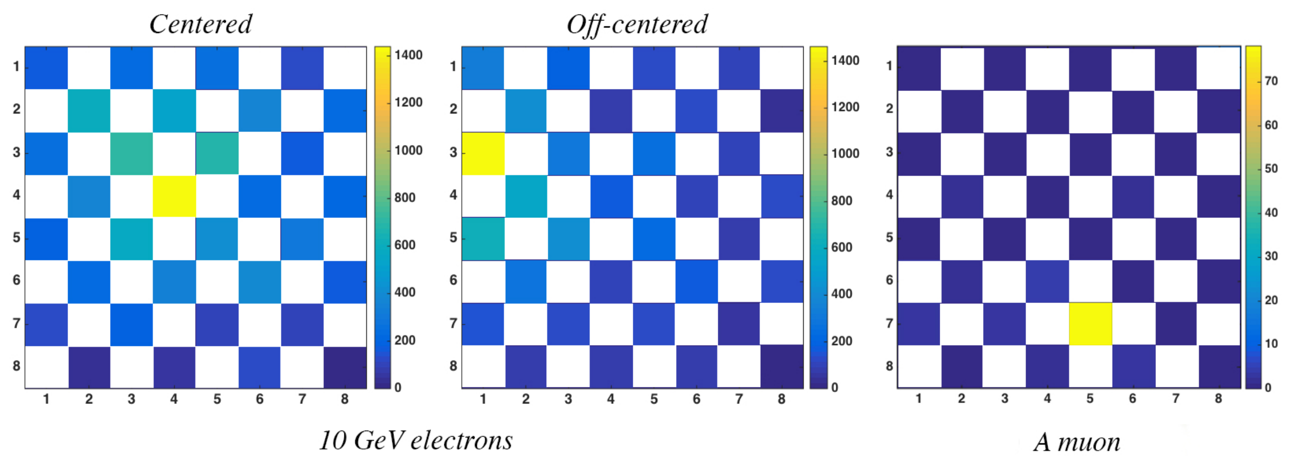




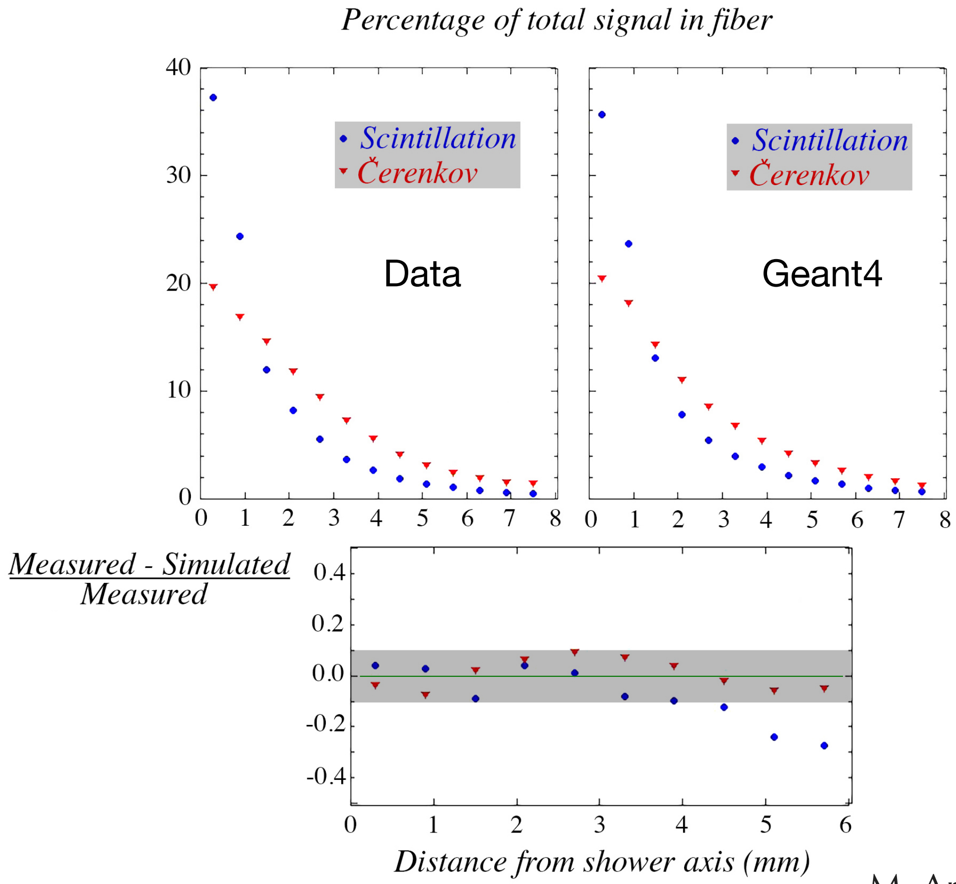


M. Antonello, et al, Nucl. Instr. and Meth. in Phys. Res. A 899 (2018) 52.

Is it a plus?



Event displays in a
1.2 x 1.2 cm^2
brass module.



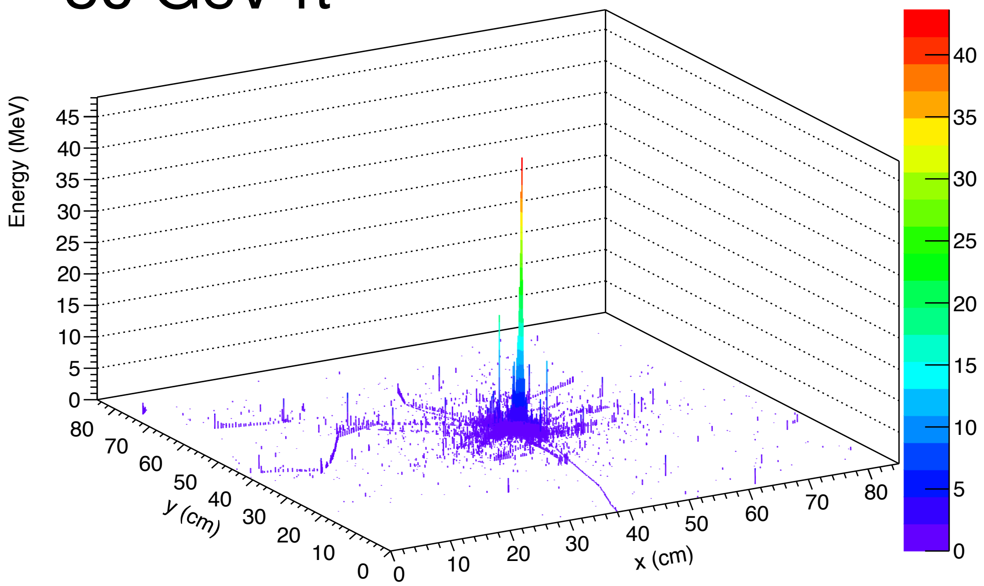
Most precise measurement
of the electromagnetic
radial profile
close to the shower axis.

M. Antonello, et al, Nucl. Instr. and Meth. in Phys. Res. A 899 (2018) 52.

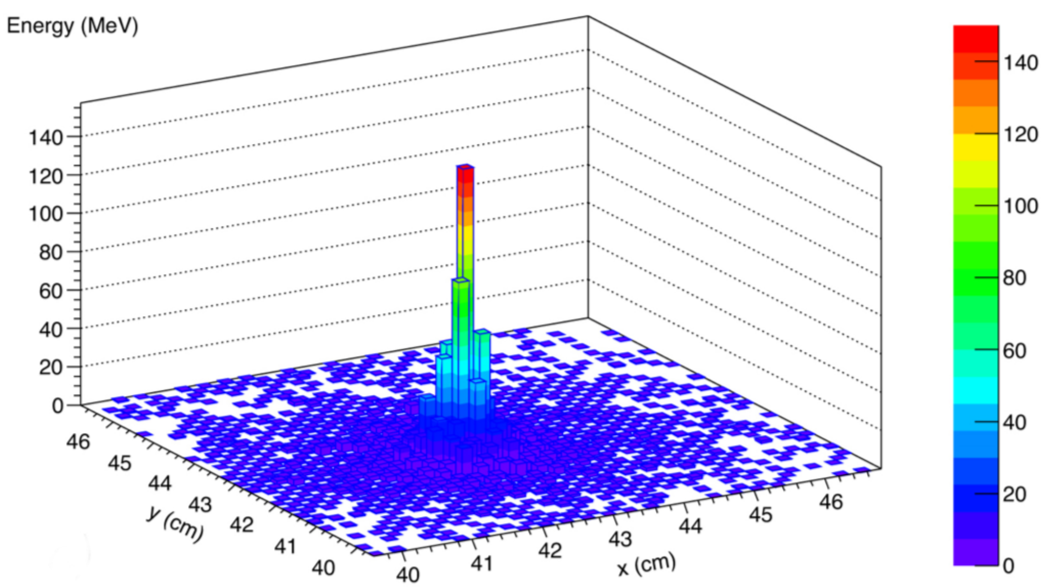
Is it a plus?

Geant4

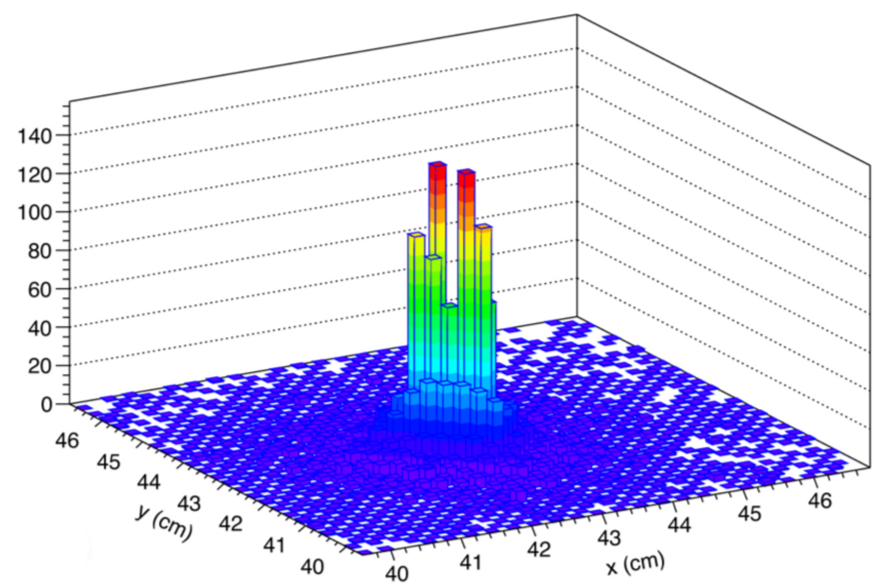
80 GeV π⁻



50 GeV e⁻

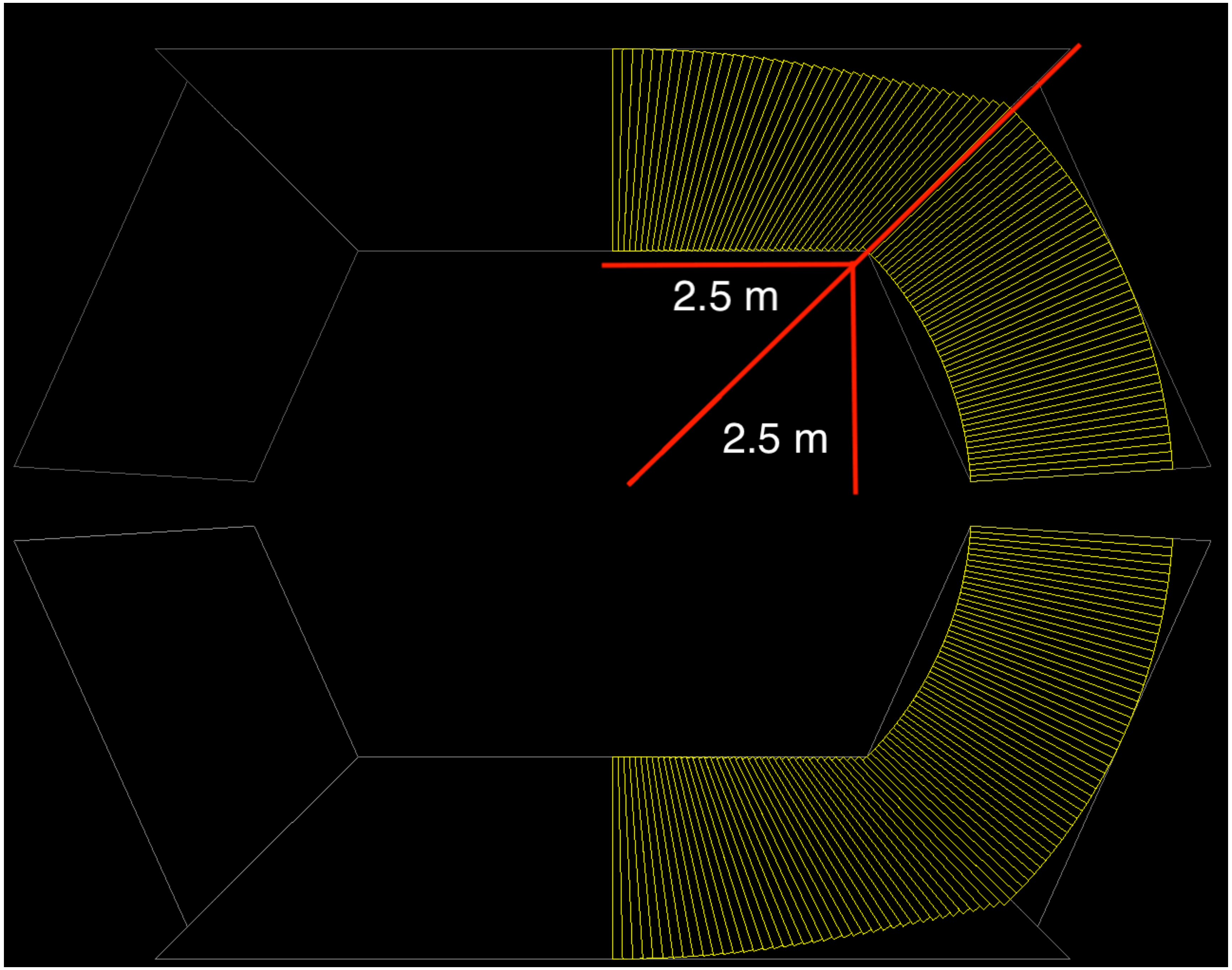


100 GeV π⁰

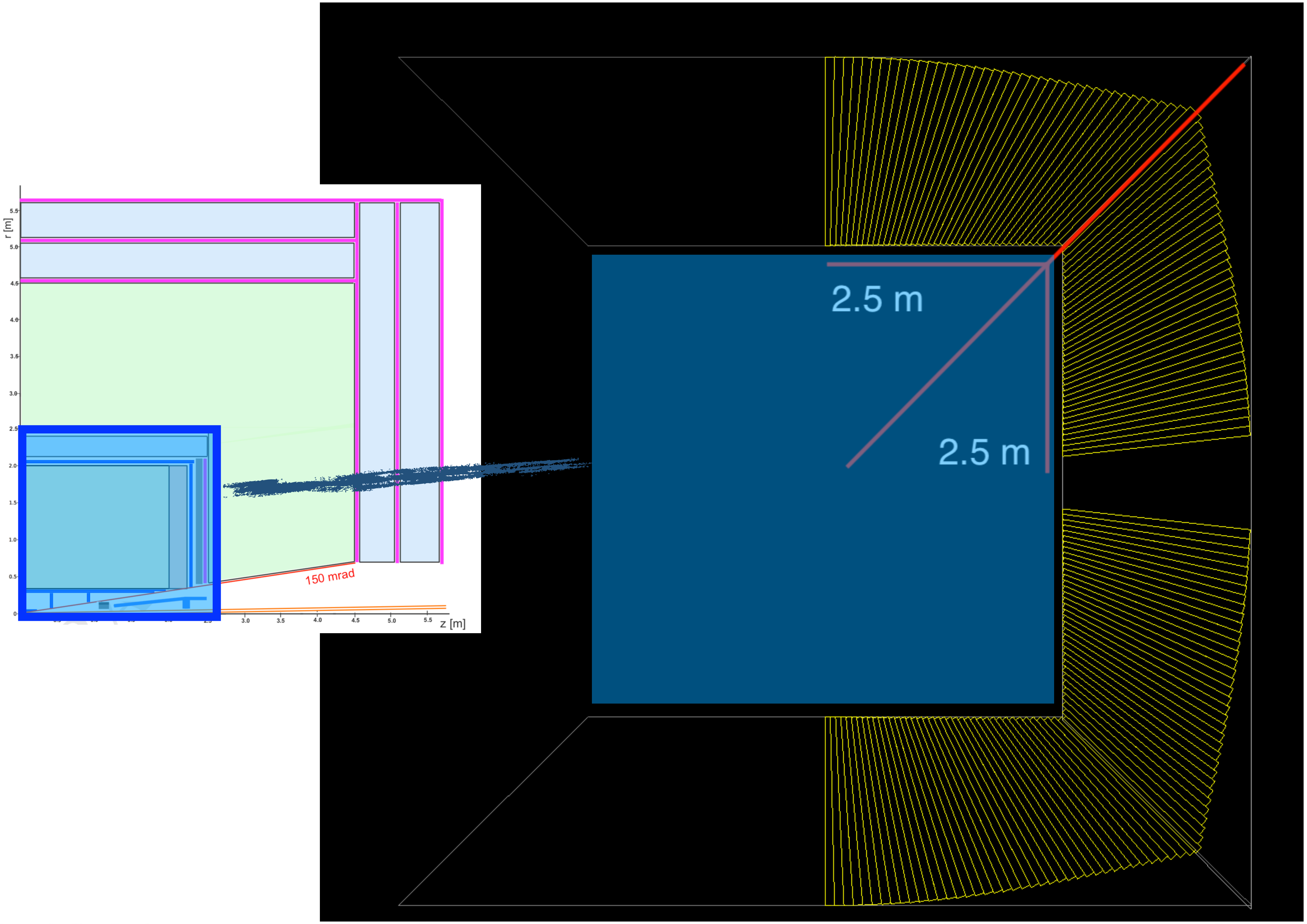


A 100 GeV π^0 decaying 2 m before the calorimeter is identified as two electromagnetic showers.

4th Concept like calorimeter

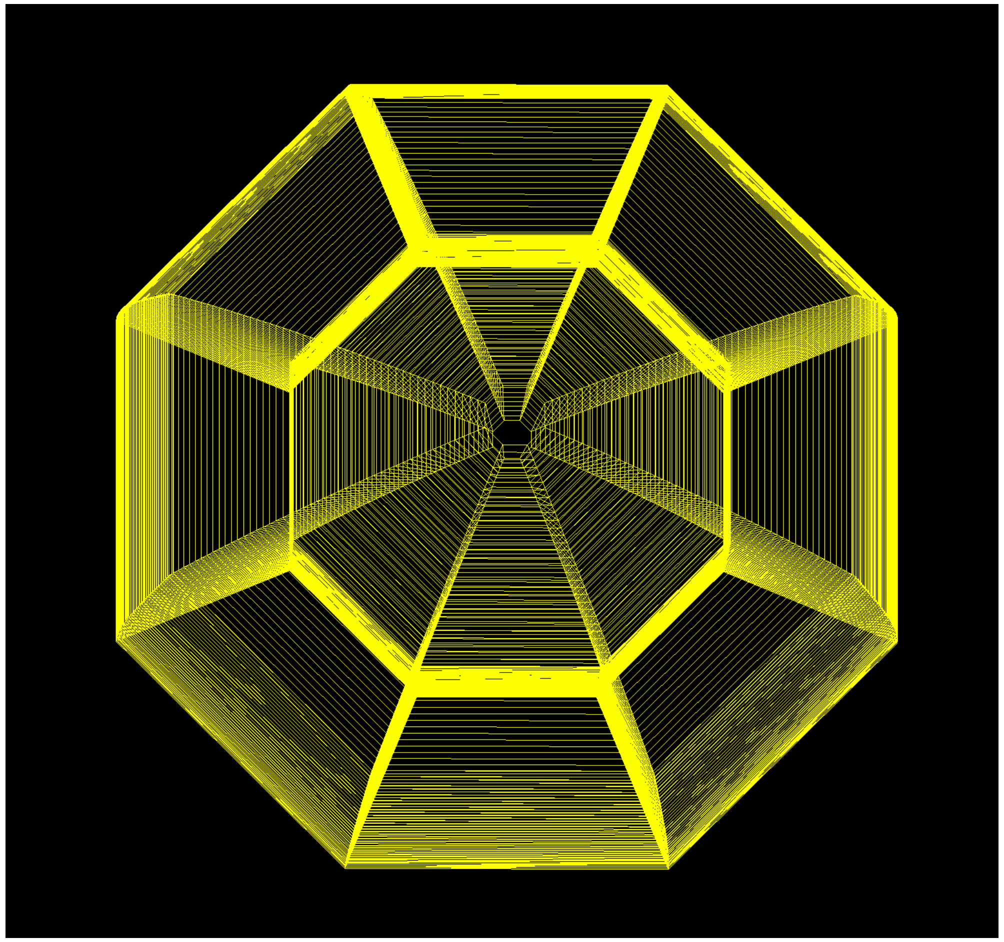


IDEA Calorimeter

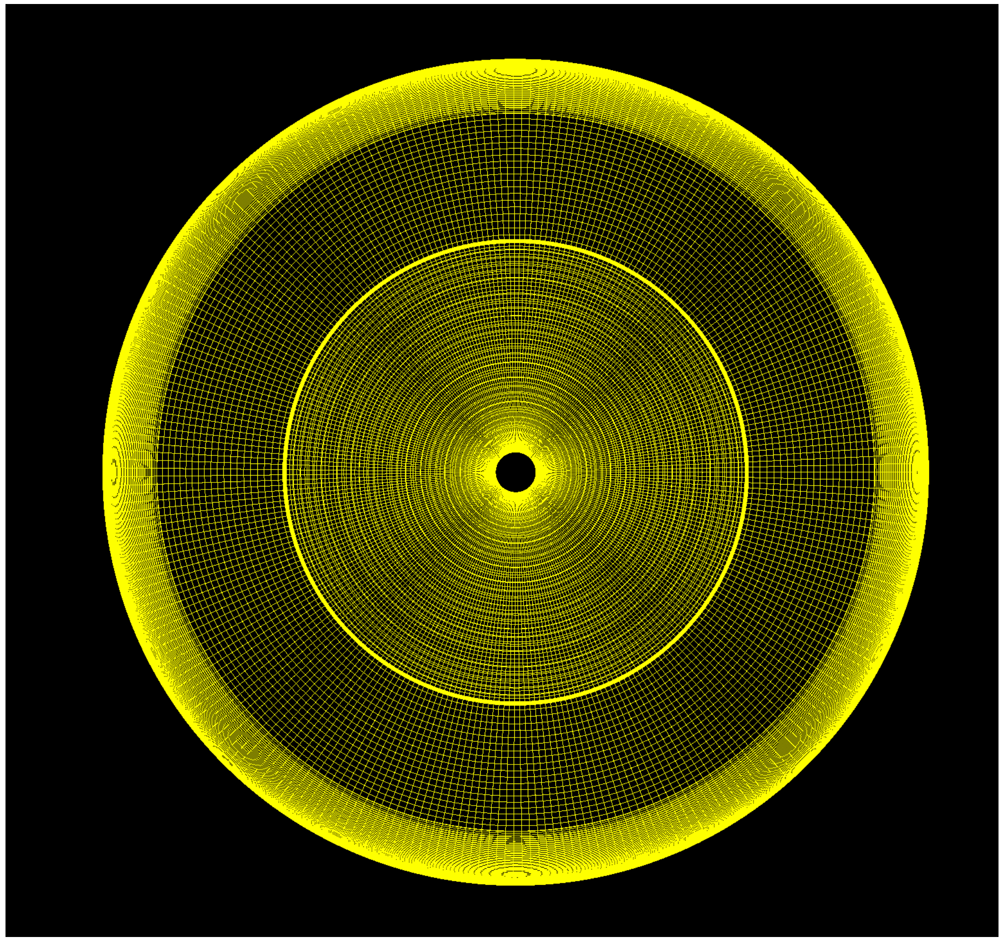


Wedge Geometry

8 wedges

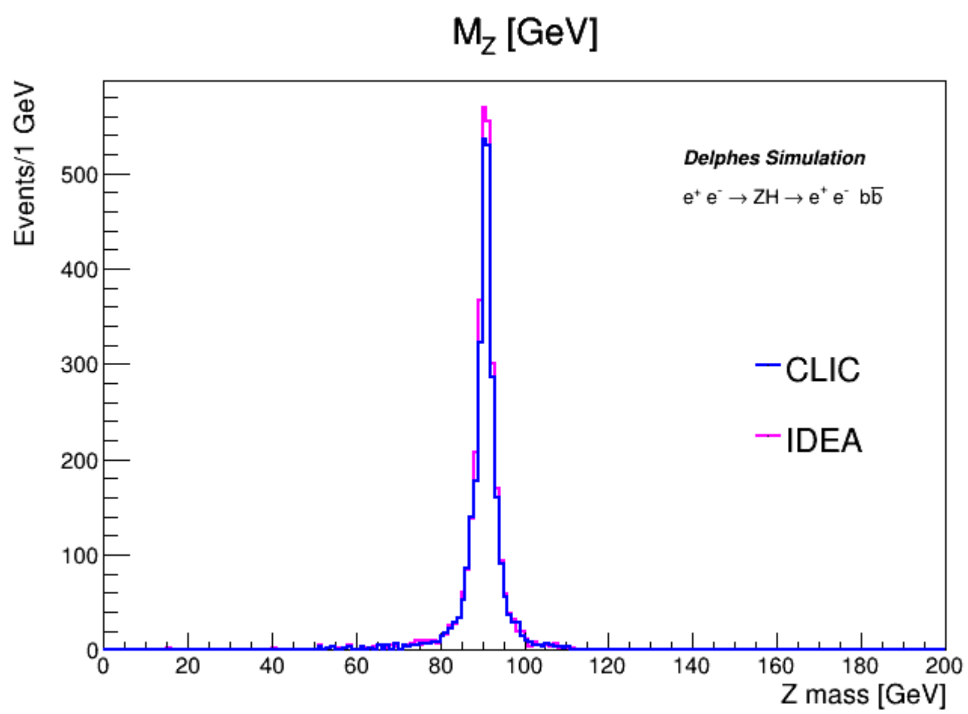


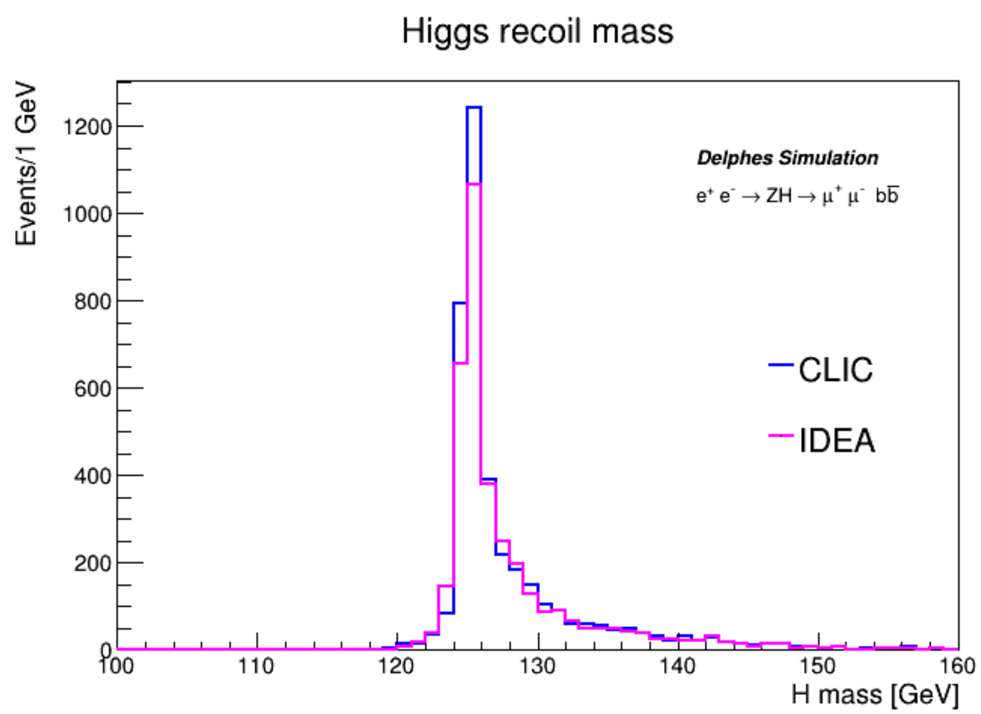
283 wedges



Delphes IDEA Fast Sim

A first implementation of a fast simulation card with Delphes
is based on single detector performances.





Delphes - Preliminary

Conclusion

There are indications to believe a dual-readout calorimeter to be the fundamentally most precise calorimeter for hadron detection ever.

A significant effort is certainly needed both on software and hardware, to complete the assessment

we hope a strong collaboration will cluster around it.