Dual-Readout Calorimetry
Simulation studies report

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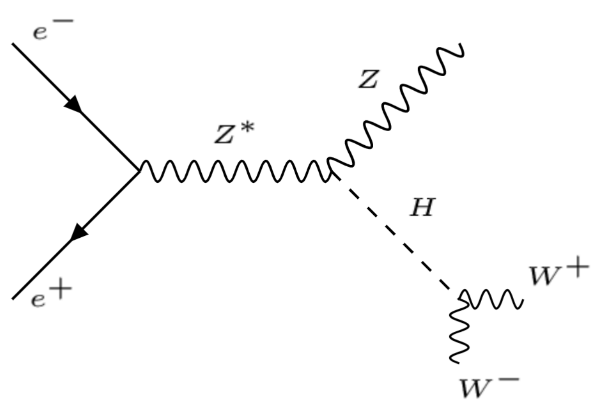
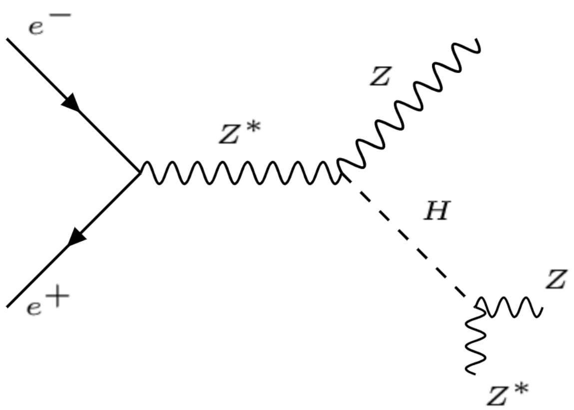
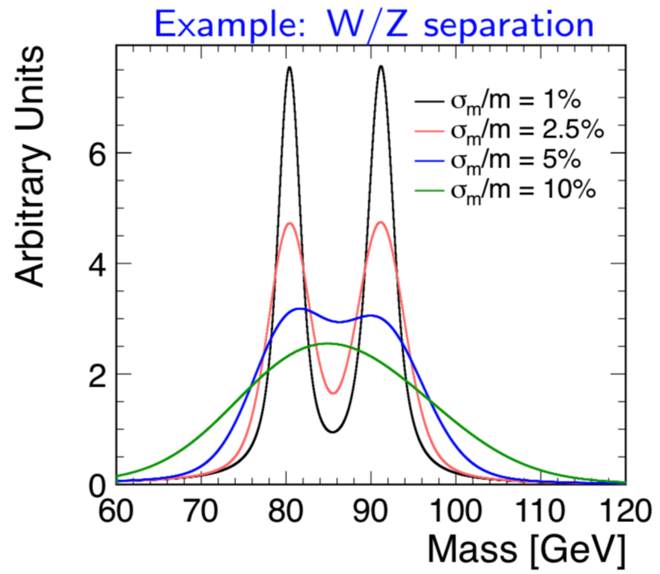
CERN - 10/01/2019

Calorimetry requirements





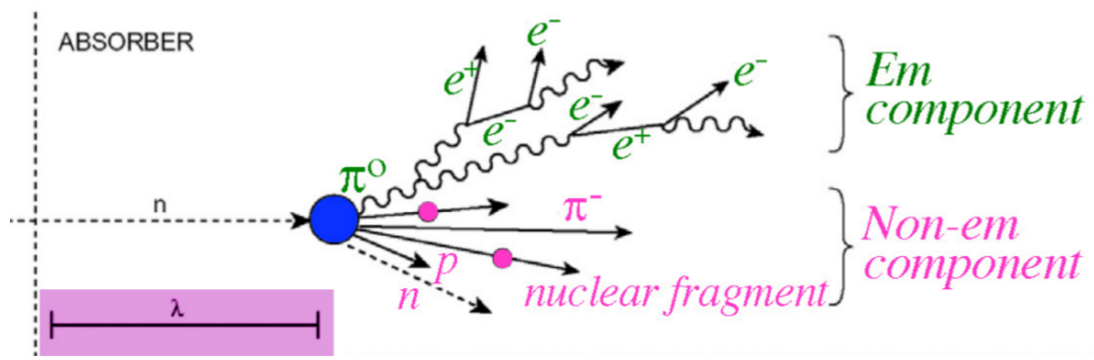


To statistically separate these two Higgs decay modes it is needed to reconstruct the Z and W invariant masses from jet decays with a resolution of ≃ 3 GeV.

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

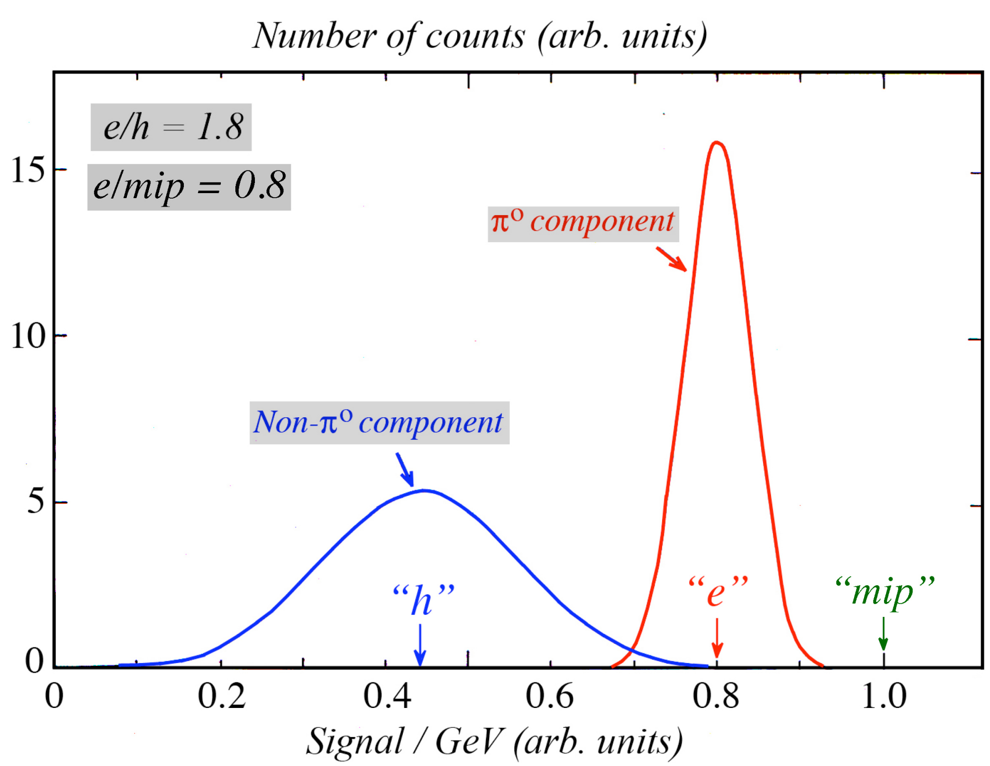
Such an energy resolution has been achieved for hadrons by calorimeters compensating by neutron boosting (e.g. SPACAL, ZEUS Calorimeter). But in future we could do better…

Non compensation



Electromagnetic component:
electrons, positrons and photons

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

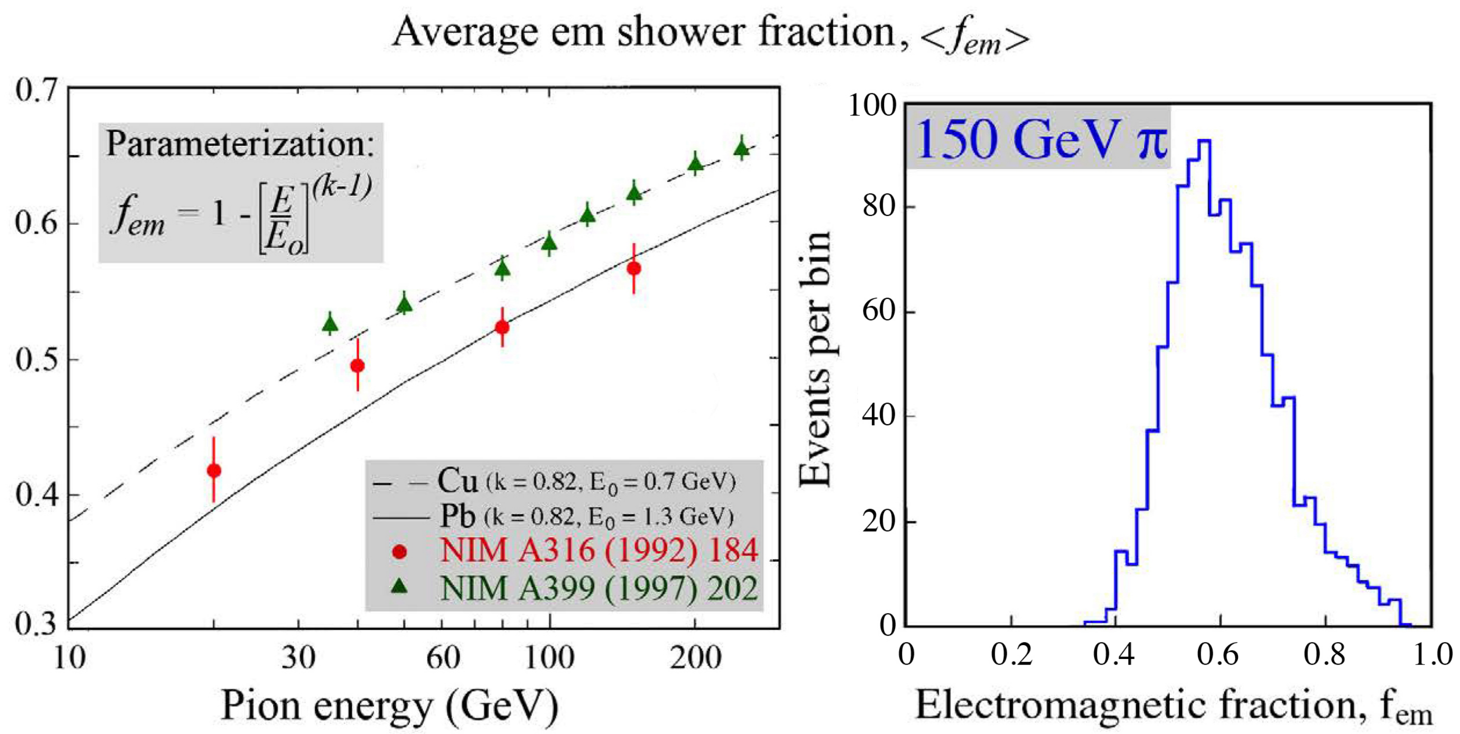


The calorimeter response is different for the two components:

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

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.

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

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

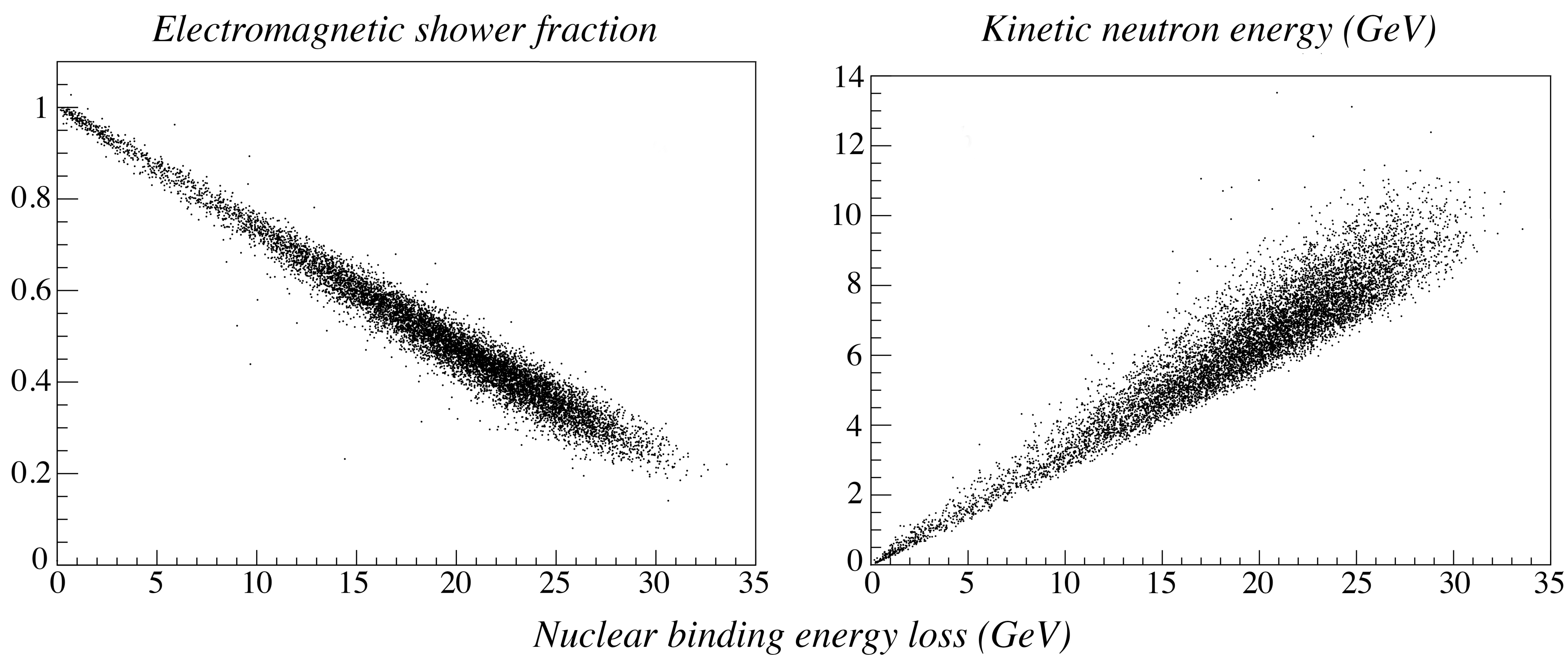
It is possible to estimate *fem* by measuring the ratio of the two signals event-by-event!

What are Geant4 predictions on its performance?

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.

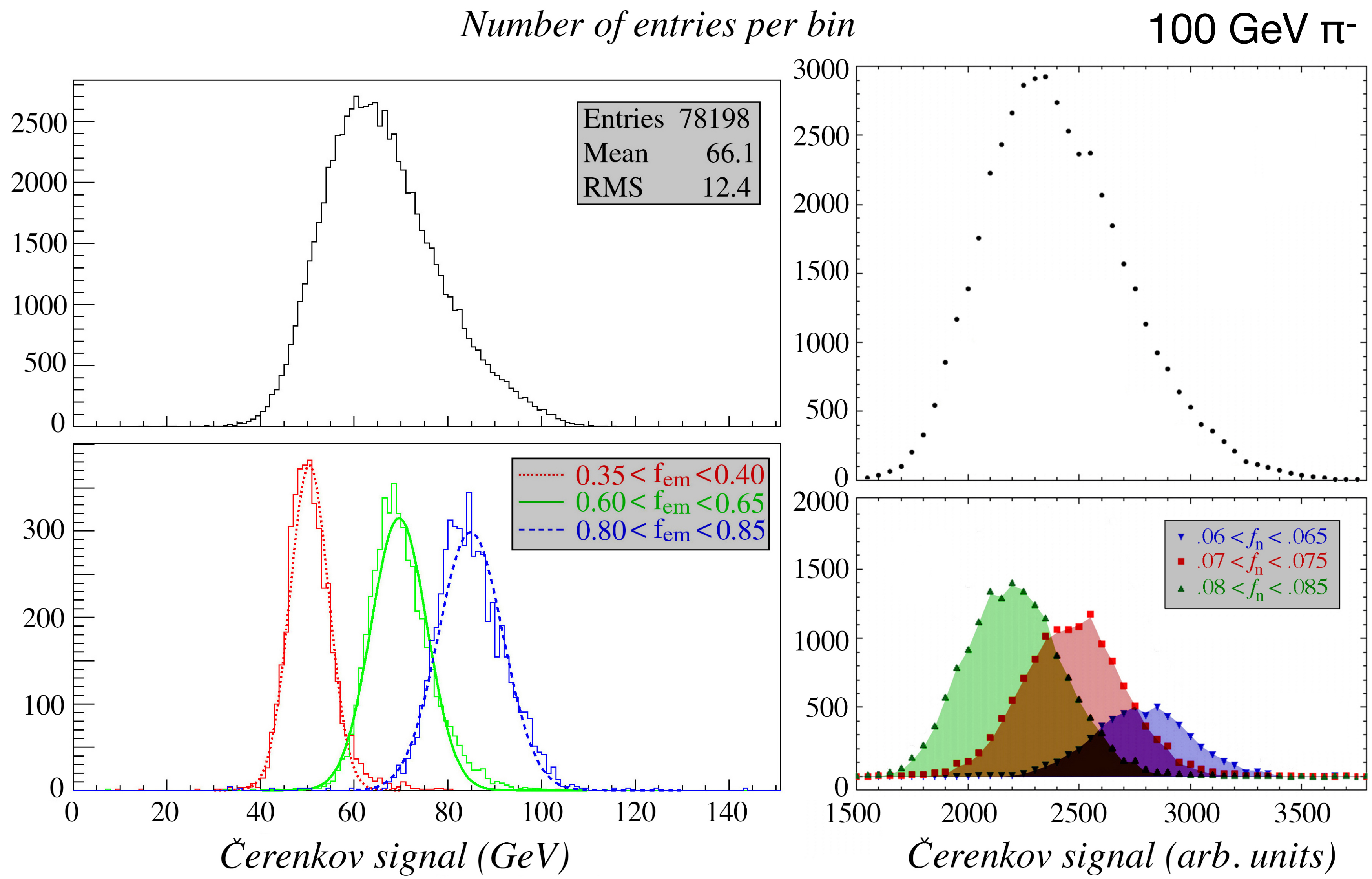


Geant4
π^-
100 GeV
in lead

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.

Does Geant4 reproduce the universality of the χ factor?

Universality of the χ factor

No dependence of the χ factor on the particle energy and type
is observed with simulations.

π- in brass

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
Test beam
prototypes
simulations
-
Preliminary

Absorber materials

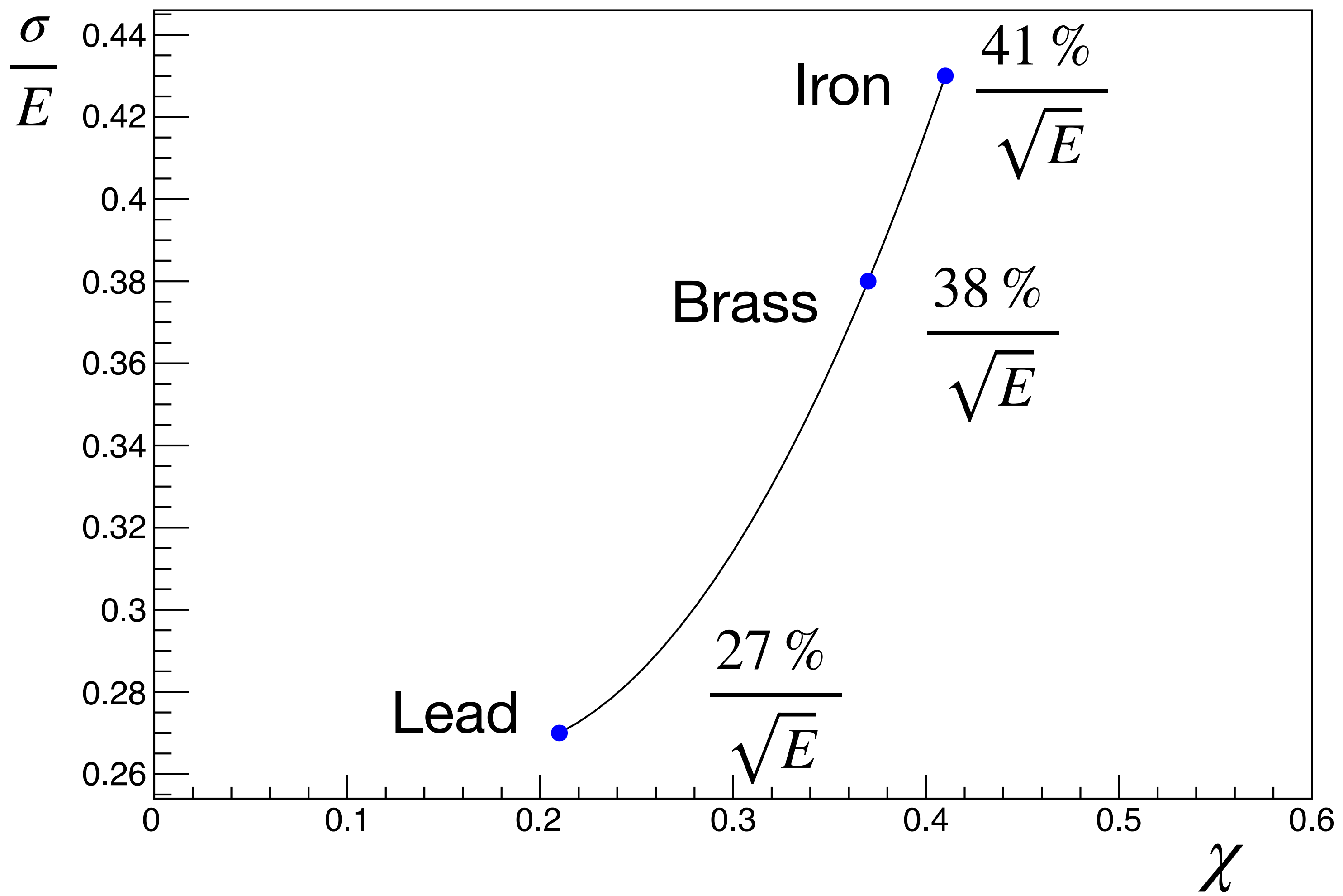
The material with the smaller χ factor will result in the better hadronic resolution.

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

$(h/e)_s$ → Keep it high

$(h/e)_c$ → Keep it low

Hadronic resolution at 1 GeV *vs.* χ

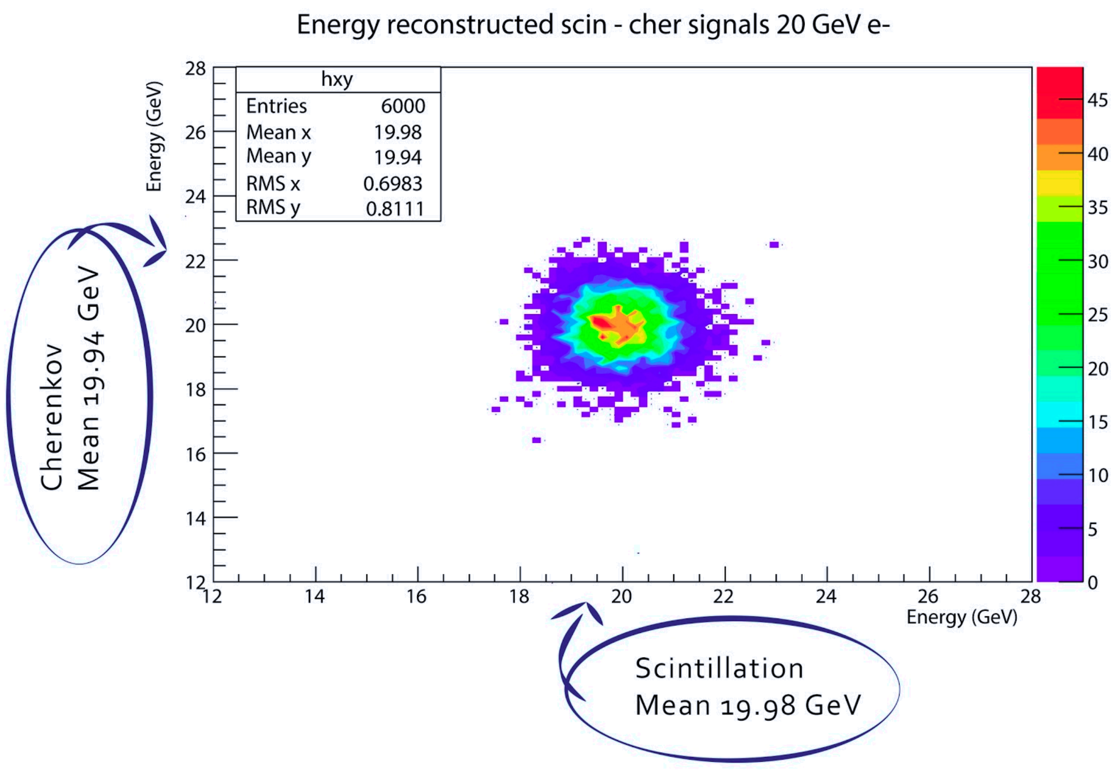


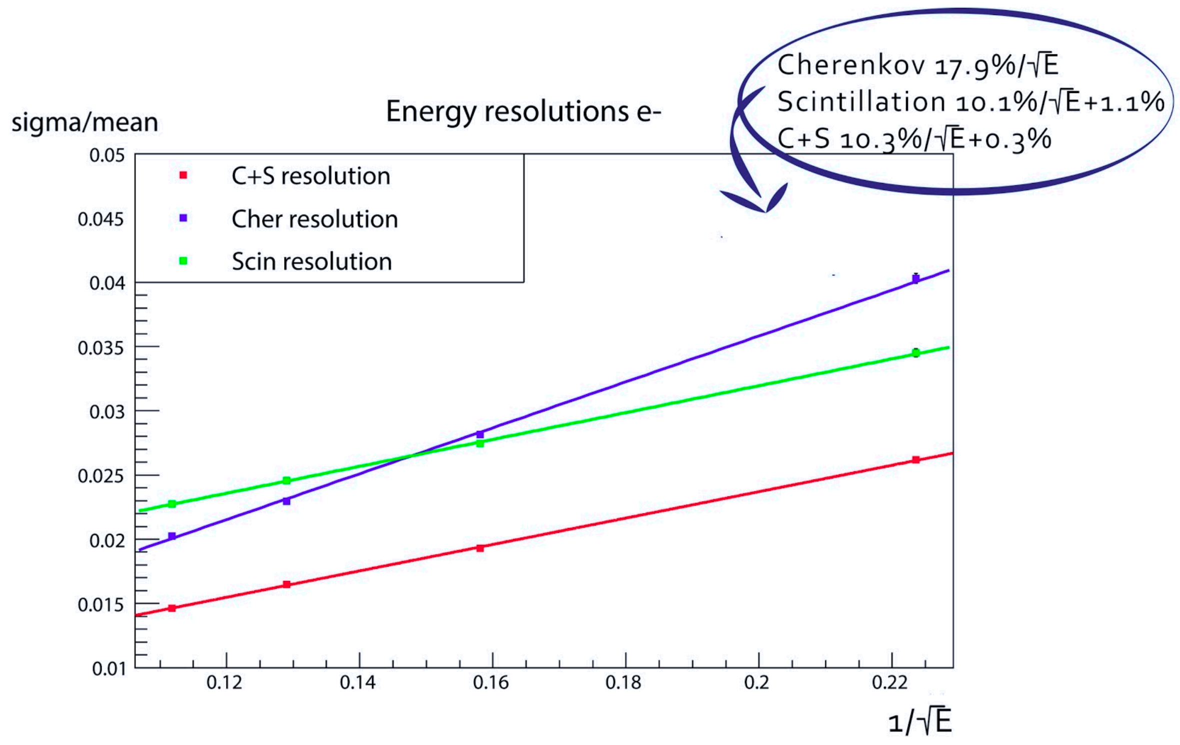
Geant4 - Preliminary
Test beam prototypes simulations

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 represents
for electrons two independent signals.



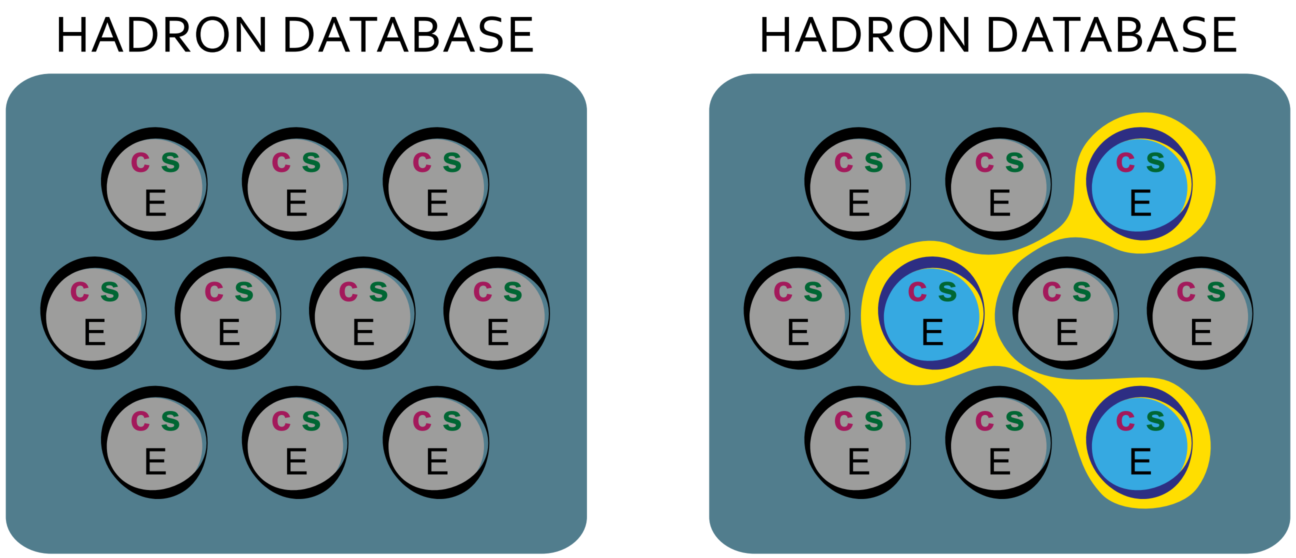


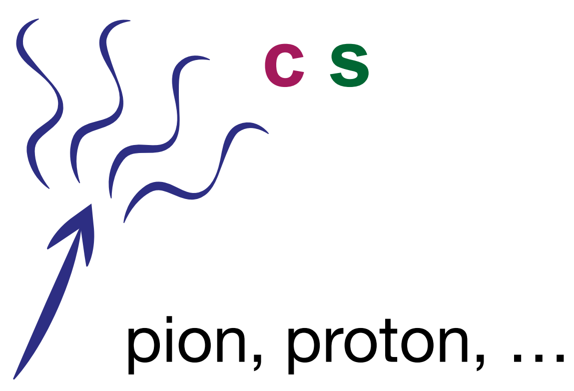
Geant4 - Preliminary

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.



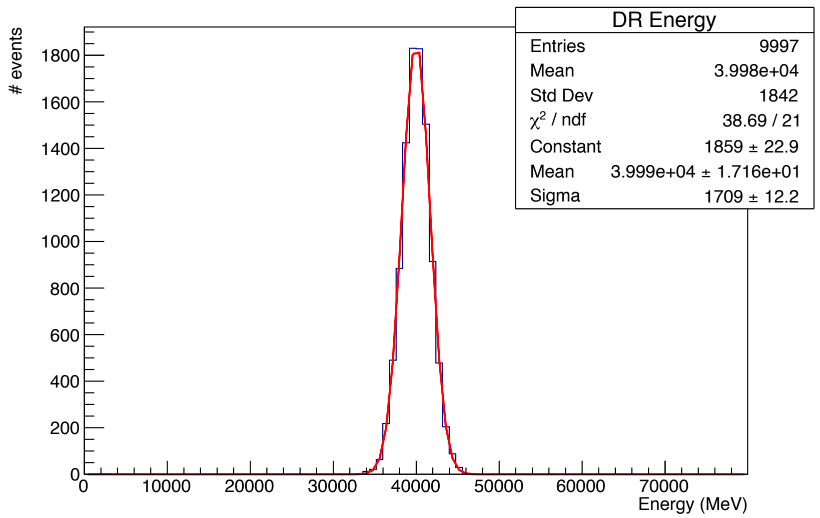


The correct hadron energy is then given by

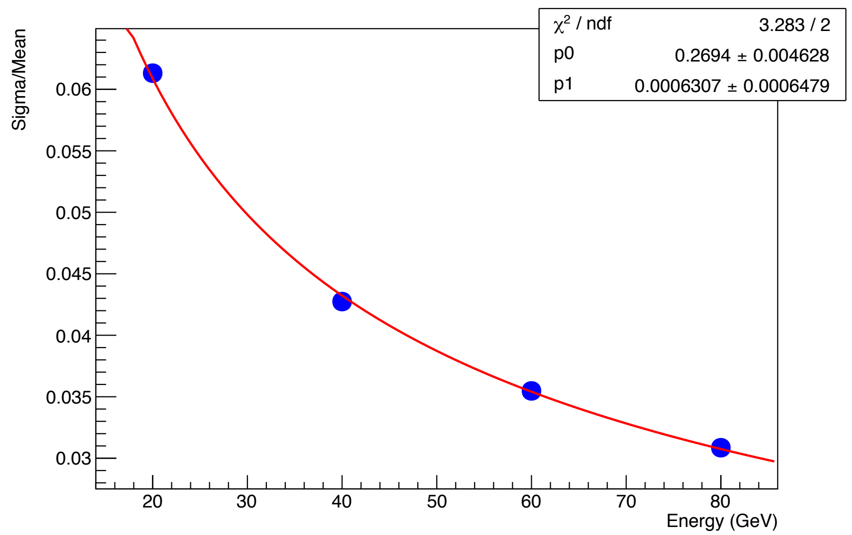
$$E = \frac{1}{2n}\sum_{i}^{n}\frac{E_i}{s_i}\times s + \frac{1}{2n}\sum_{i}^{n}\frac{E_i}{c_i}\times c$$

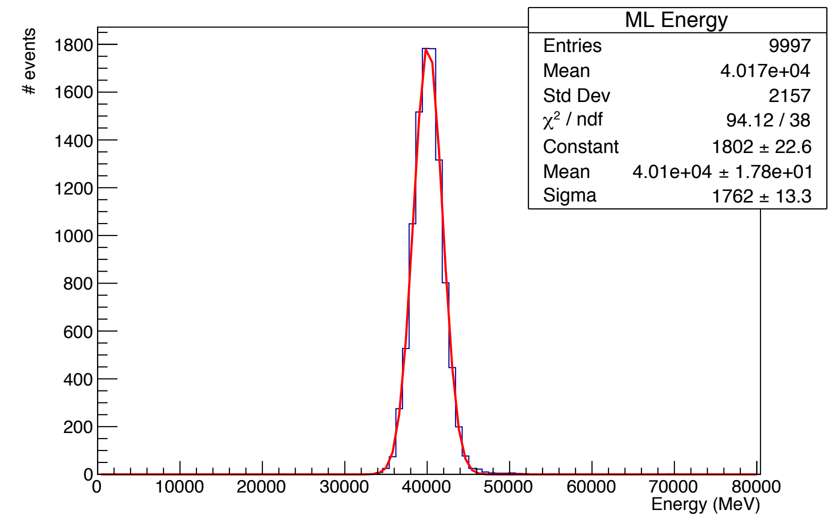
DR vs. ML

Lead

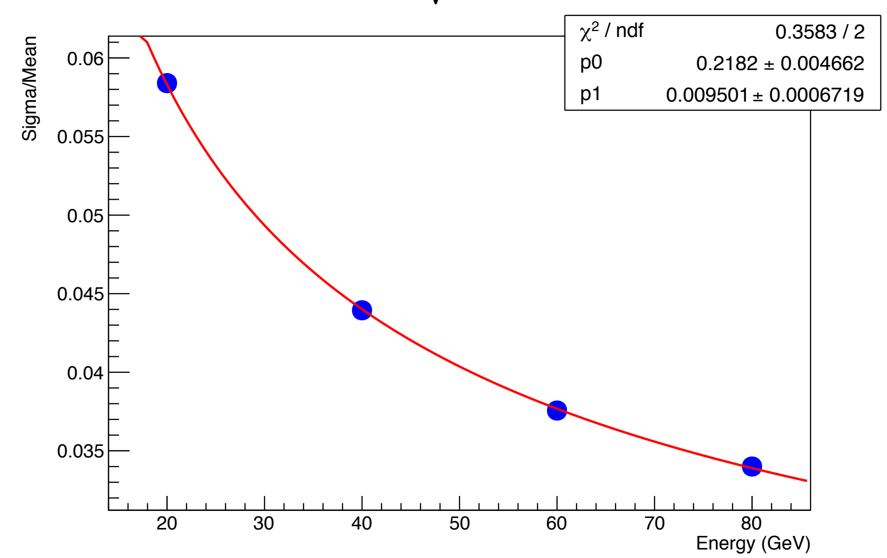


$$\frac{\sigma}{E} = \frac{27\ \%}{\sqrt{E}}$$





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

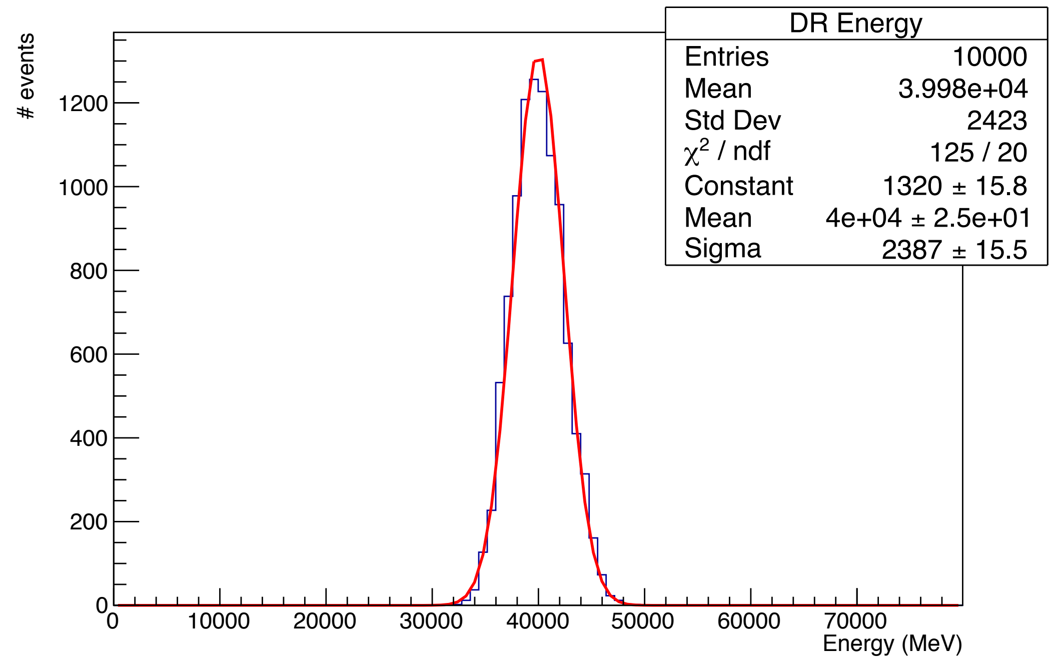


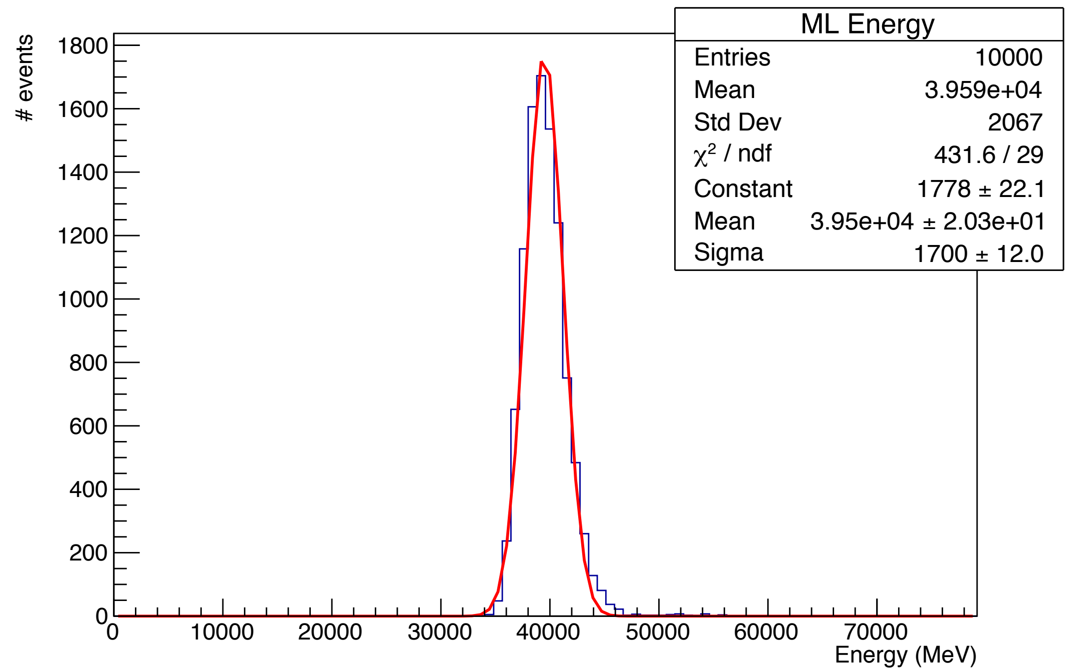
Geant4 - Preliminary

Two is better than one

It turns 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

Simplified jet study

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*

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

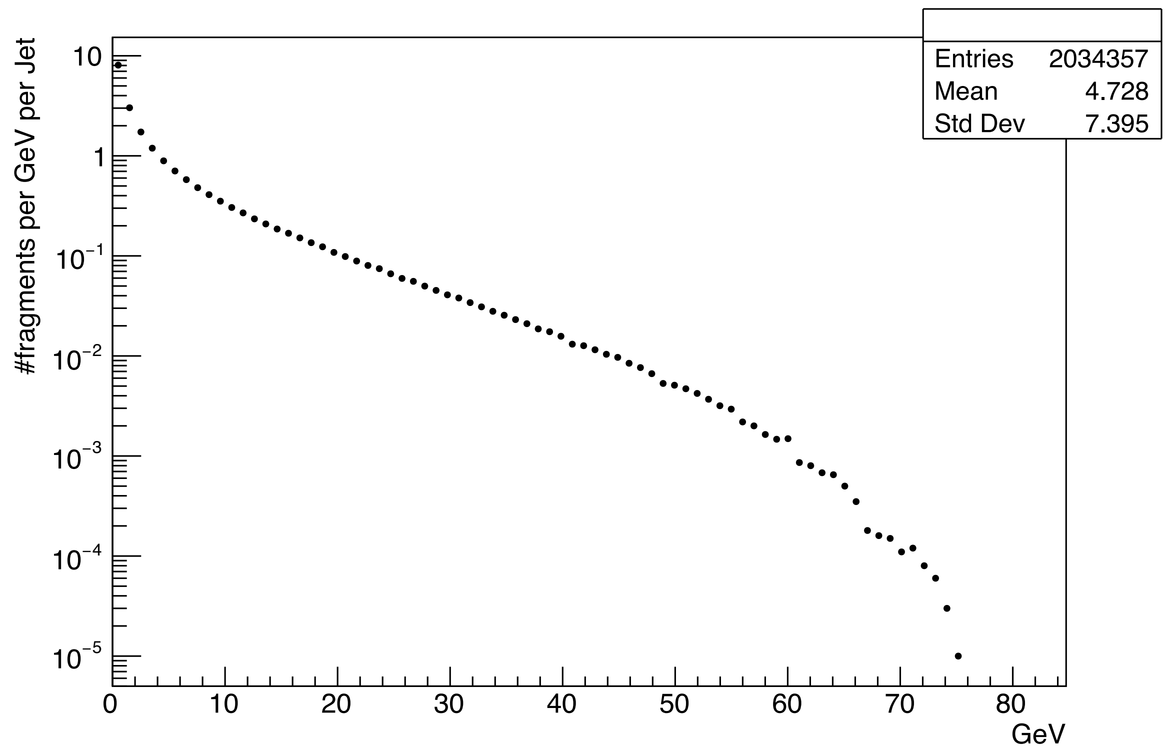
Electrons and gammas — **Yes**

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

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

Does it reconstruct the correct energy for all the particles?

Simplified jet structure



100 GeV jet

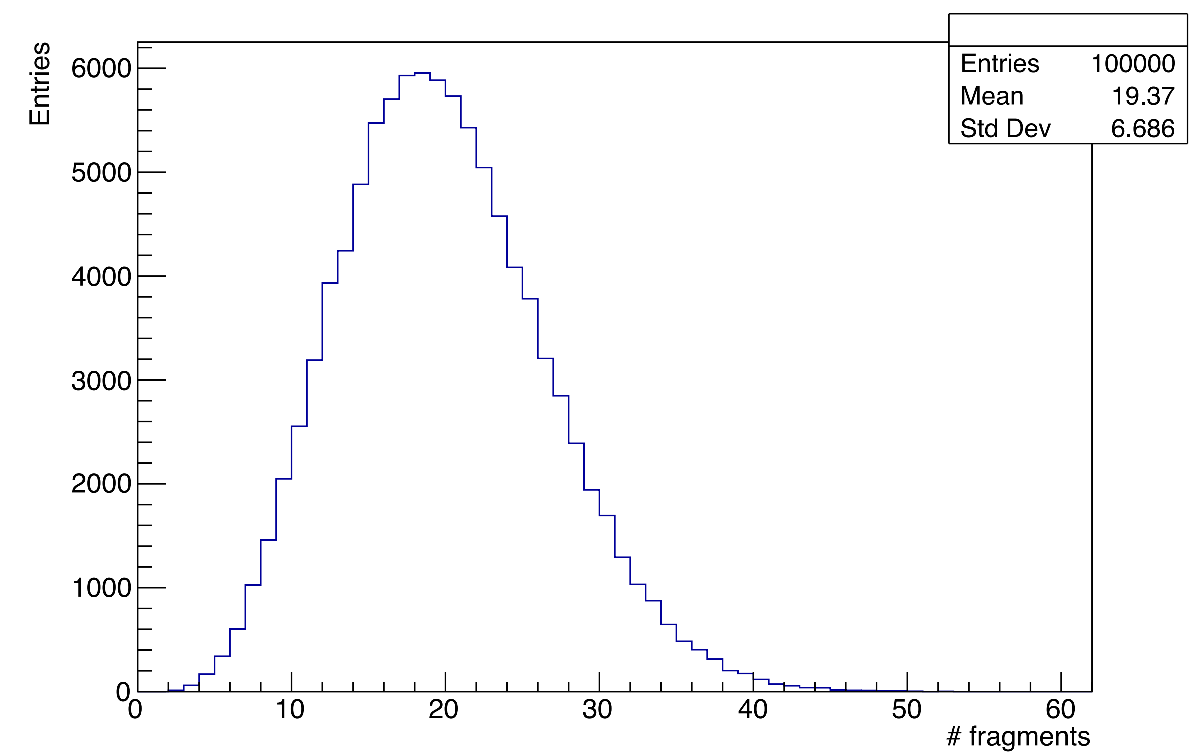
-

Average number of fragments per GeV per jet

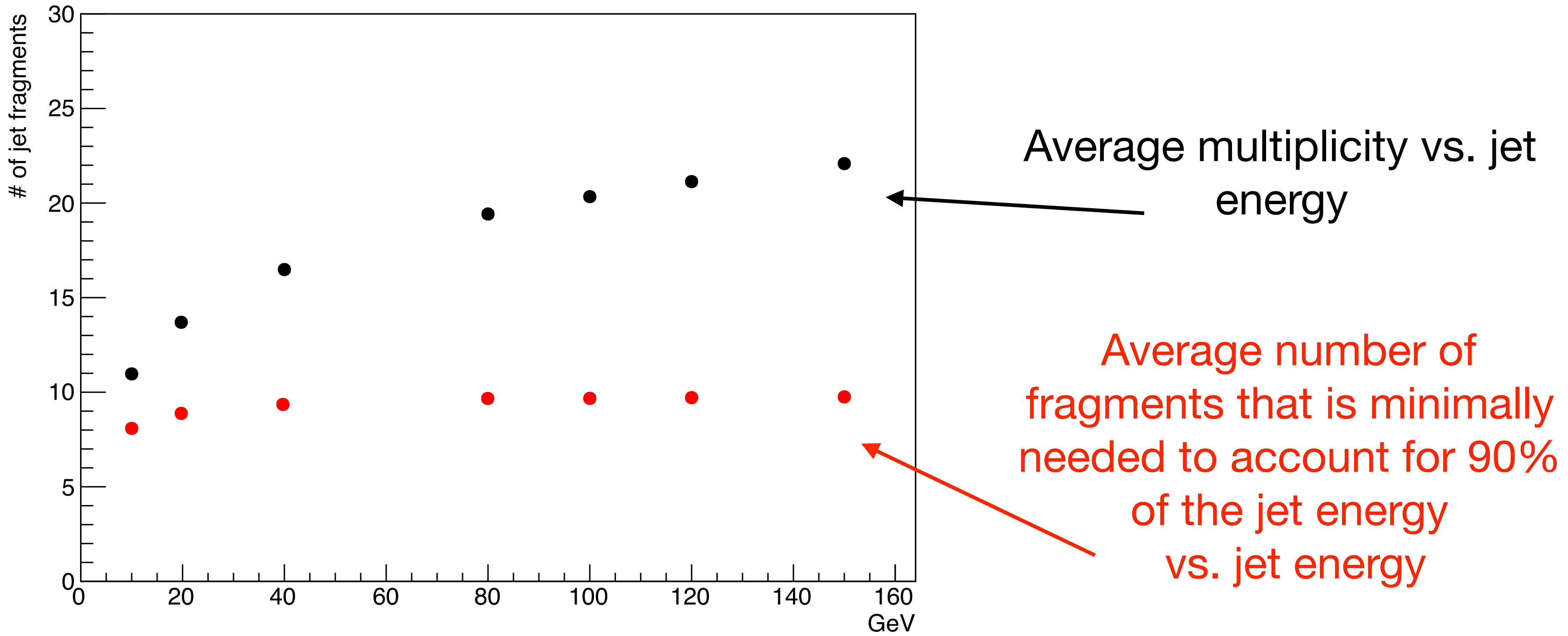
80 GeV jets

-

average jet multiplicity: ~20 jet fragments



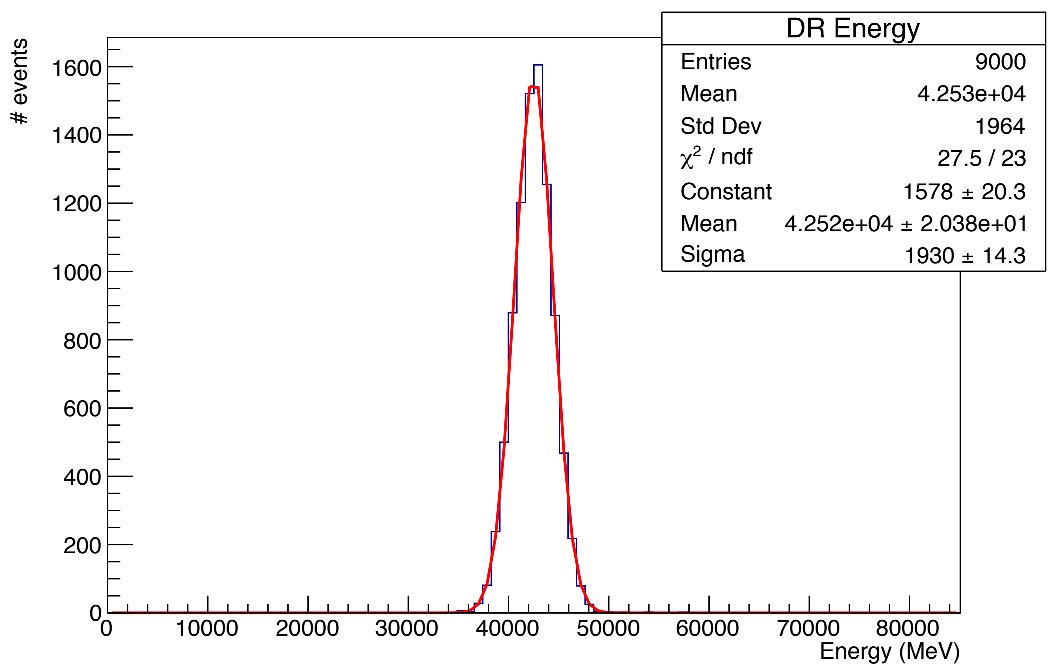
Simplified jet structure



The calorimeter has to deal with:
constant number of hard hadrons + increasing number of soft hadrons

Jet reconstructed energy

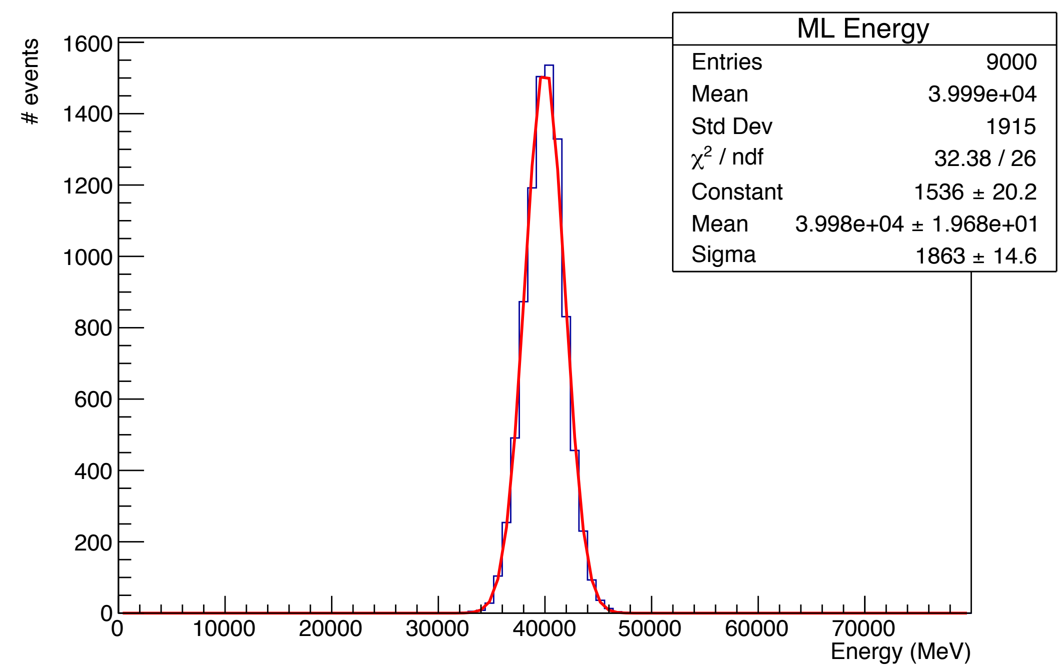
DR method



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

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

Machine Learning



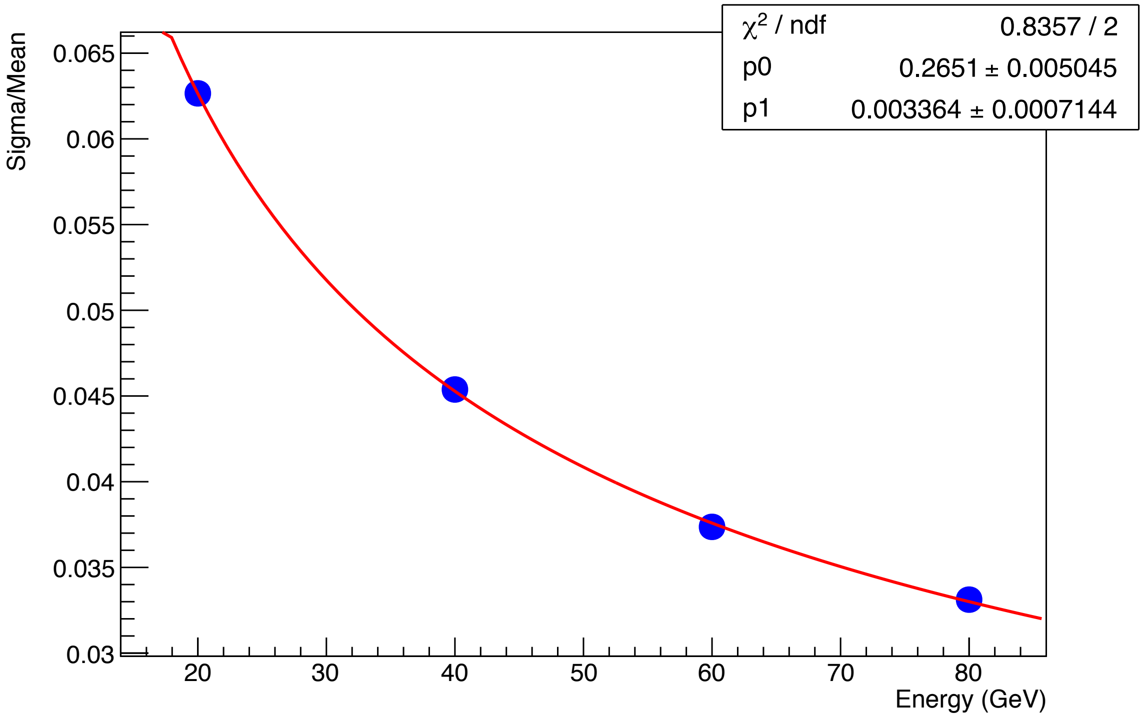
With machine learning
The energy is on average correctly reproduced:

Soft hadrons are present also in the trained database

Geant4 - Preliminary

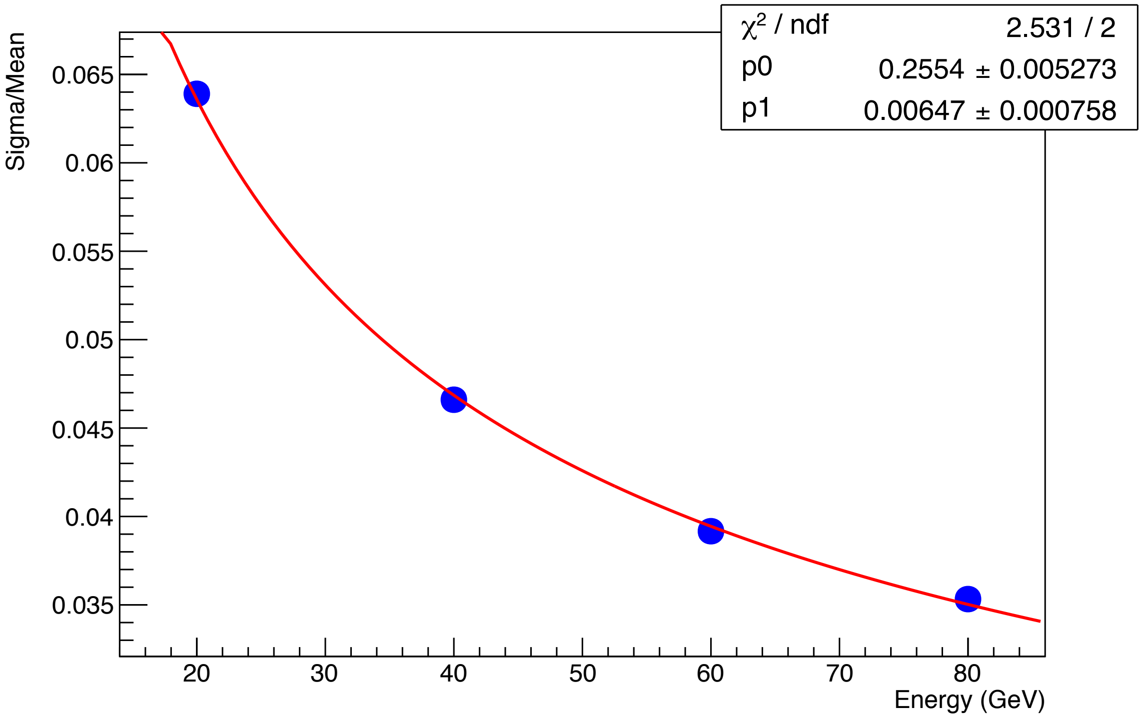
Jet energy resolution

DR method



$$\frac{\sigma}{E} = \frac{26.5\,\%}{\sqrt{E}} + 0.3\,\%$$

Machine Learning

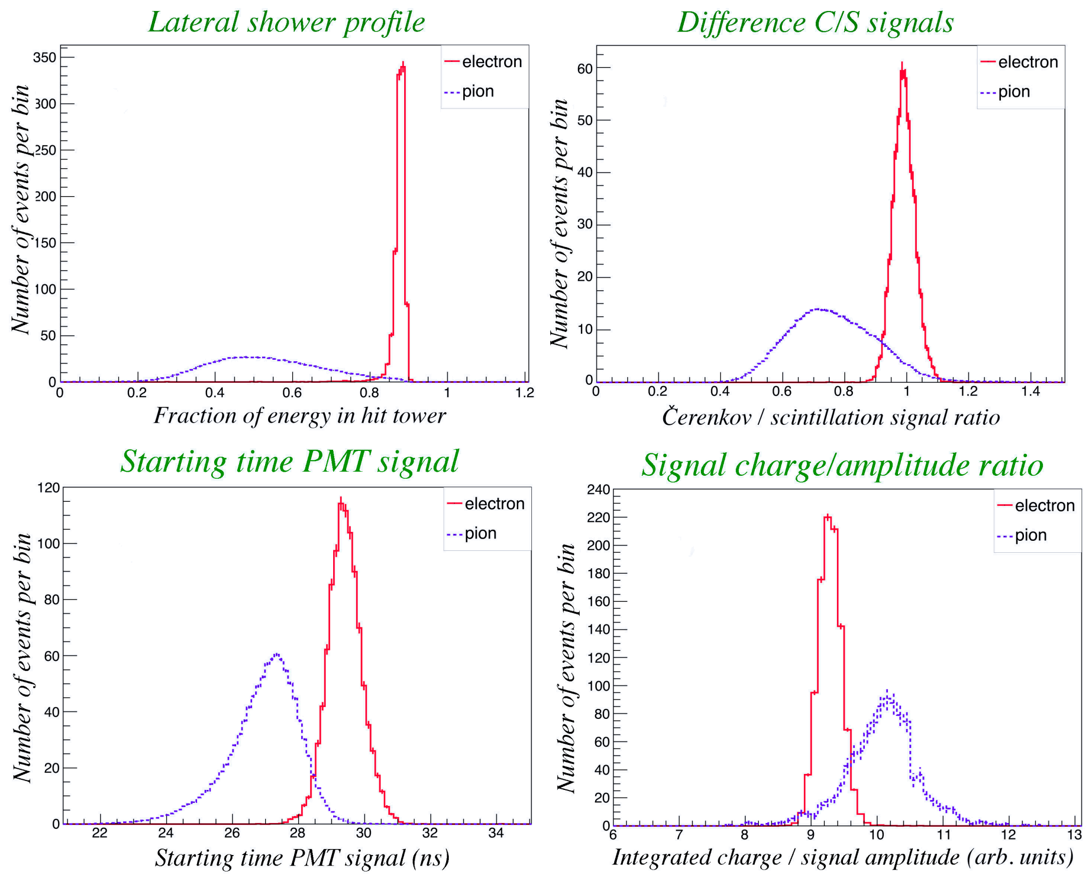


$$\frac{\sigma}{E} = \frac{25.5\,\%}{\sqrt{E}} + 0.6\,\%$$

Geant4 - Preliminary

Particle Identification

Four different particle identification techniques have been studied with data reaching a 99.8% electron/hadron identification efficiency.



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

Several particle identification techniques under implementation in simulations.

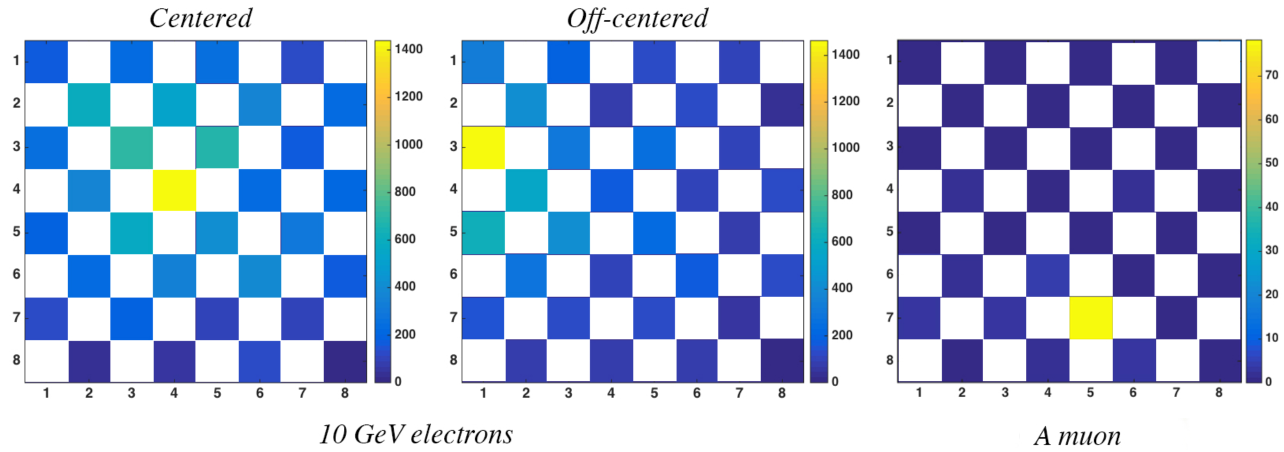
Tools:

C/S always available

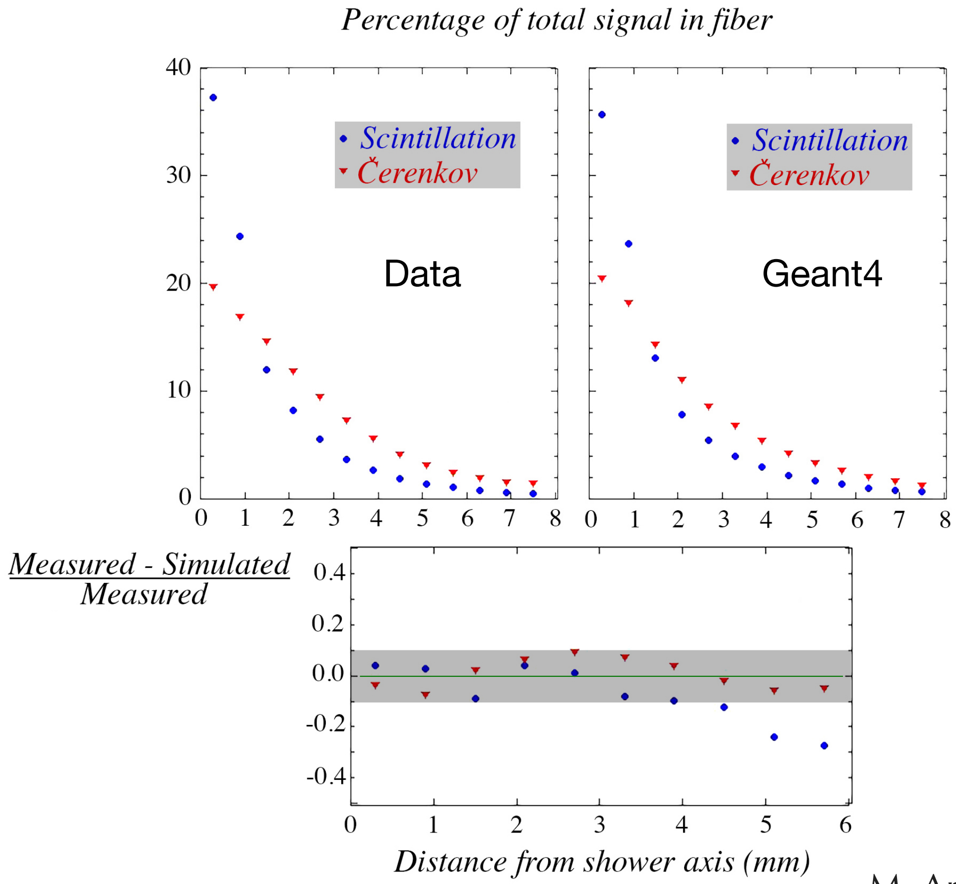
Different time structure (under development)

Granularity and clustering algorithms

SiPM based readout



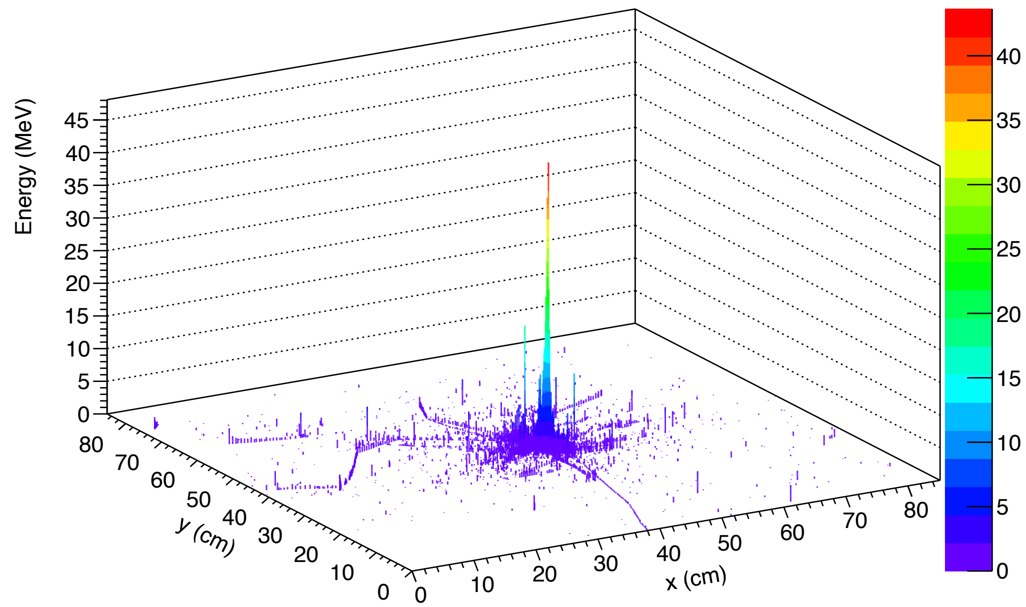
Event displays in a
1.2 x 1.2 cm^2
brass module.



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.

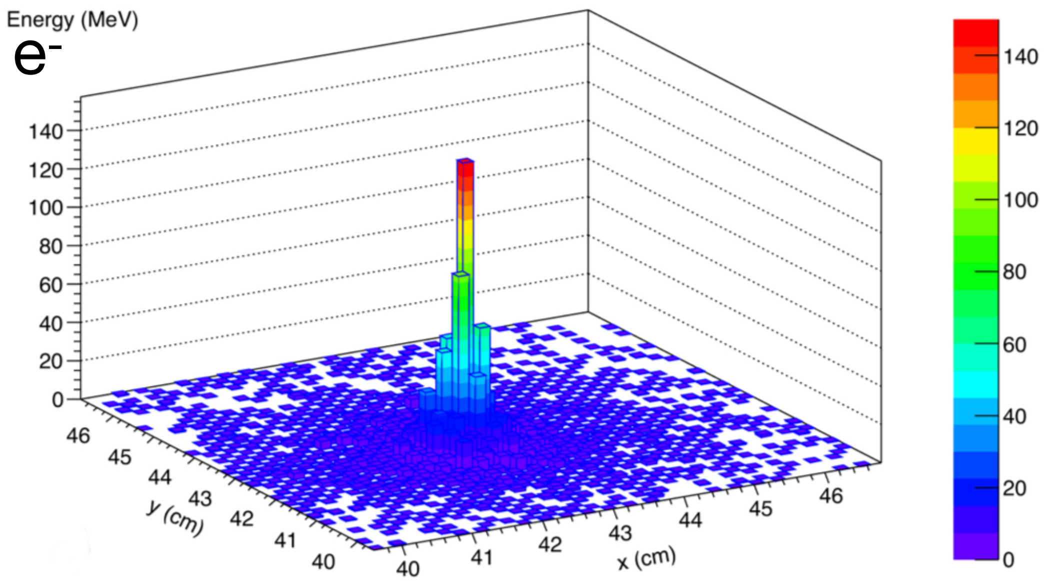
2D Granularity-SiPM Readout



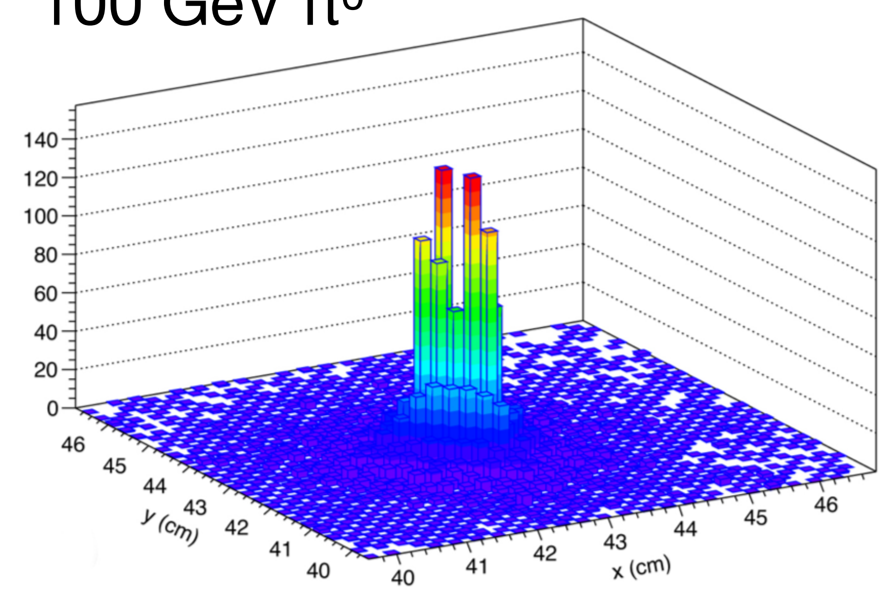
80 GeV π^-

Geant4

50 GeV e^-



100 GeV π^0



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

Multiple particles in DR - preliminary work

Separation using clustering algorithm in development

Molly Jensen, supervised by Mogens Dam, Niels Bohr Institute

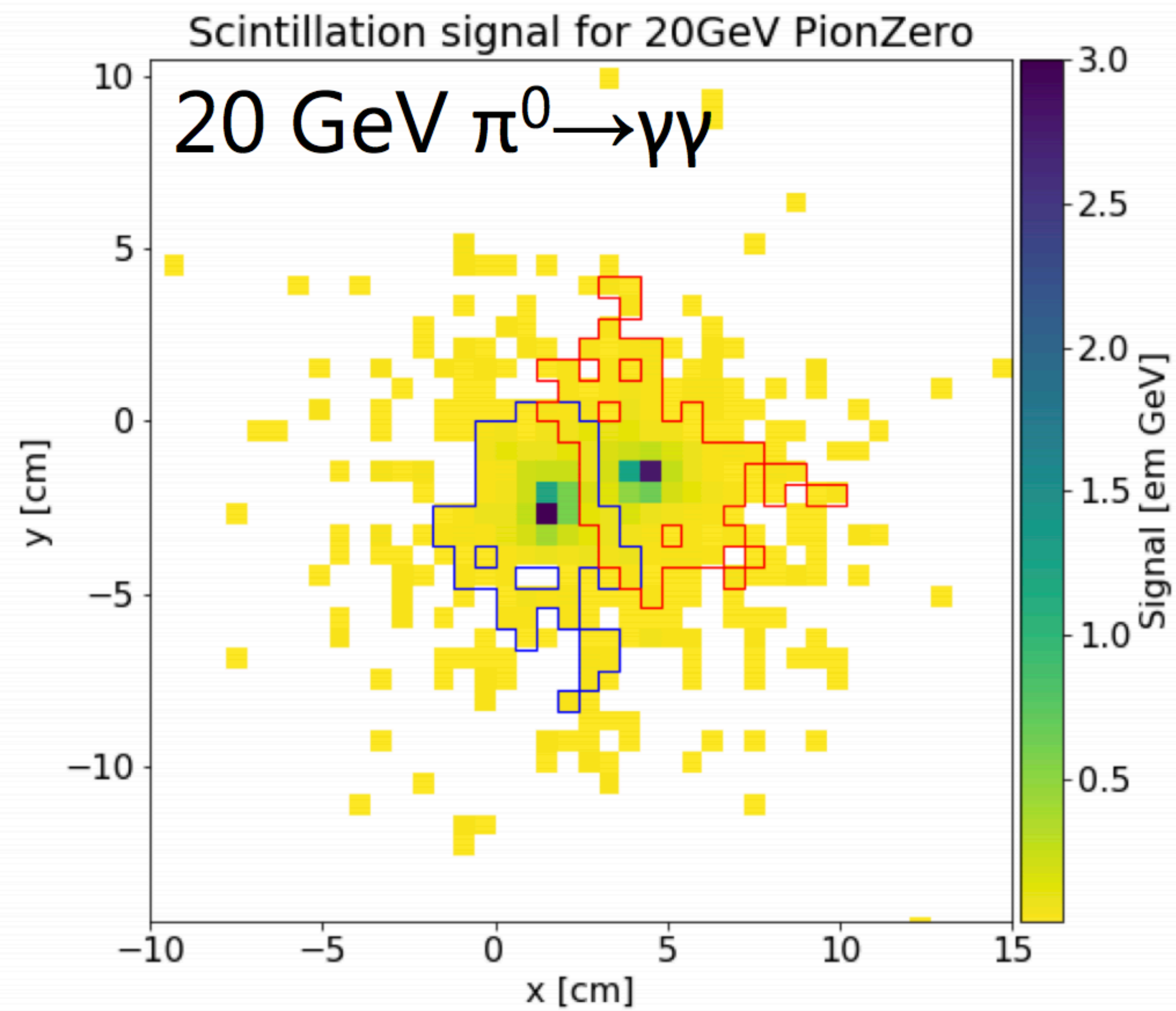
- Study tau physics:

$$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau \quad (17.39\,\%)$$
$$\tau^- \to e^- \overline{\nu}_e \nu_\tau \quad (17.82\,\%)$$
$$\tau^- \to \pi^- \nu_\tau \quad (10.82\,\%)$$
$$\tau^- \to \pi^- \pi^0 \nu_\tau \quad (25.49\,\%)$$

The goal is to separate decay channels and measure the energy of each decay product, to reconstruct the energy of the mother particle

- Easy to cluster EM showers in both scintillation and Cherenkov signal, e.g.

$$\pi^0 \to \gamma\gamma$$

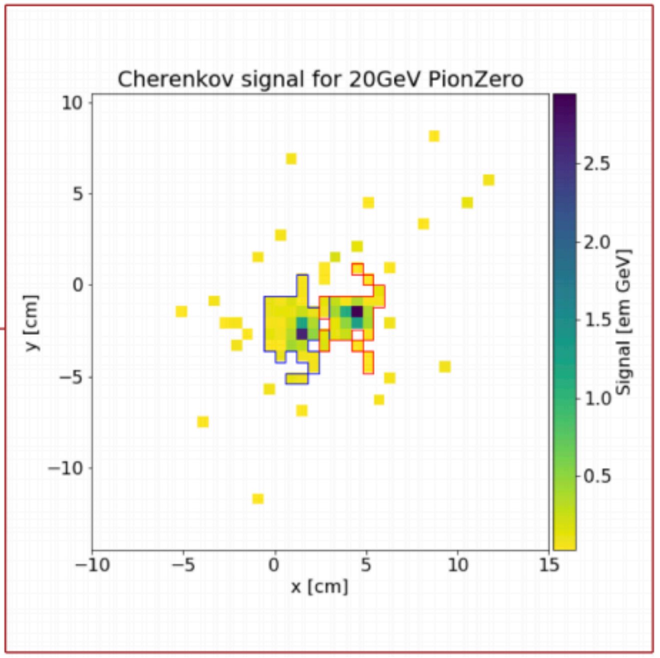


Geant4 simulation: https://github.com/lopezzot/DREAM.git
Plot shows two reconstructed clusters outlined by red and blue. Particle gun 2 m from calorimeter surface. Towers of 4x4 fibers: 8 Scintillating, 8 Cherenkov.

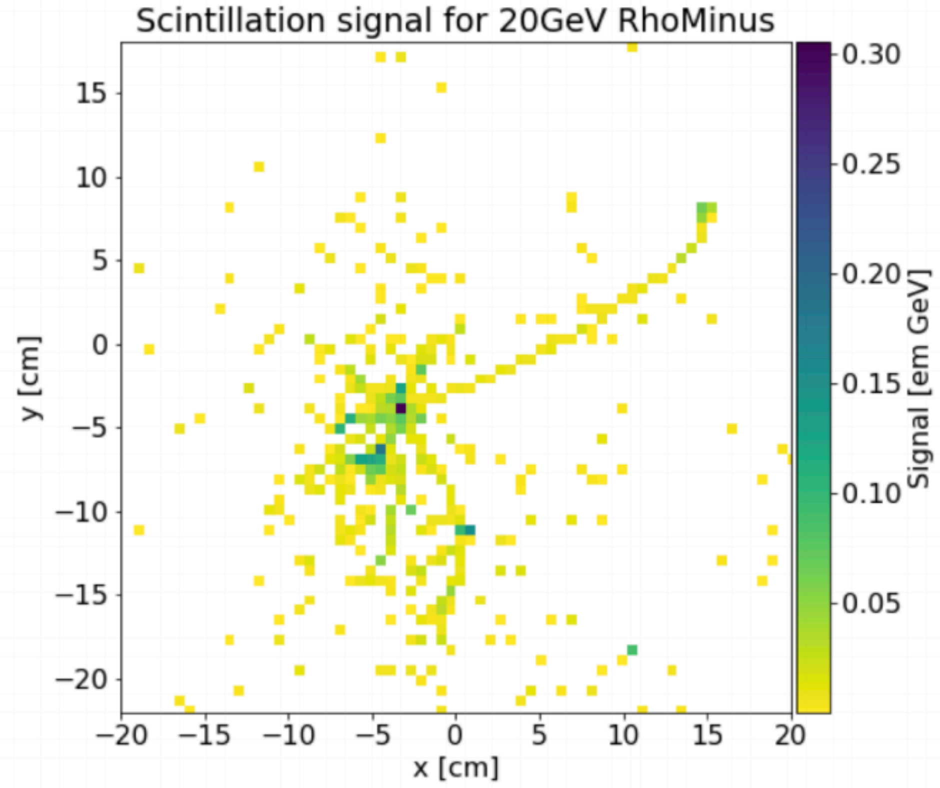
Continued

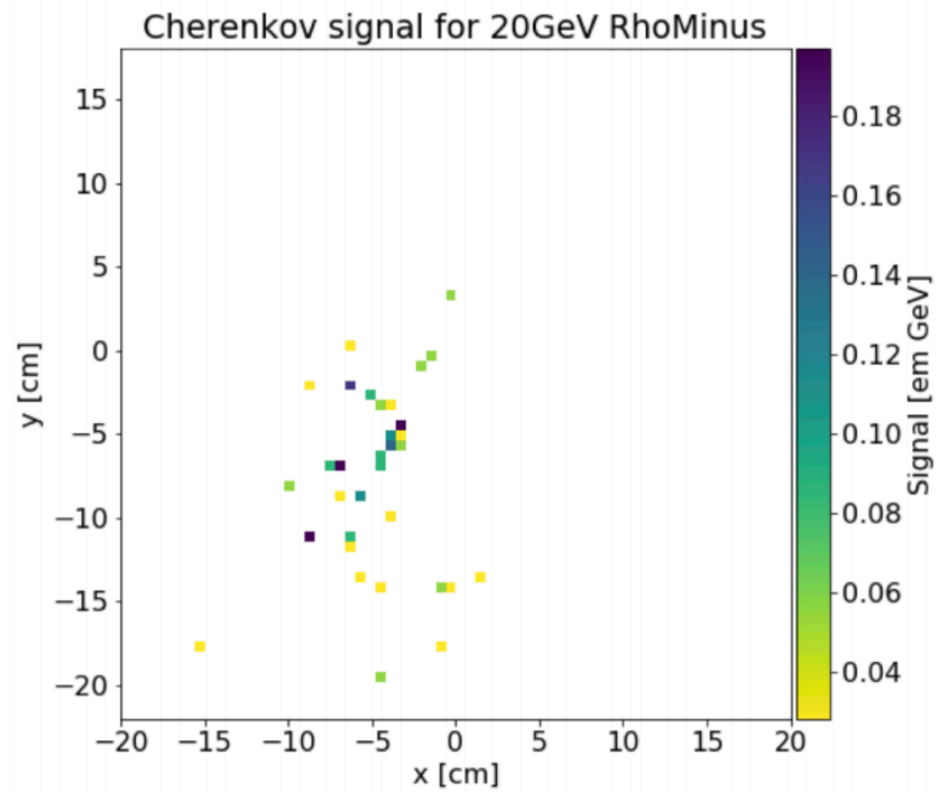
- Hadronic showers pose a bigger challenge
- Here study of superimposed hadronic and EM showers:

  E.g. it is more difficult to measure the π^- and π^0 energy, to reconstruct the ρ^- energy from $\rho^- \rightarrow \pi^- \pi^0$



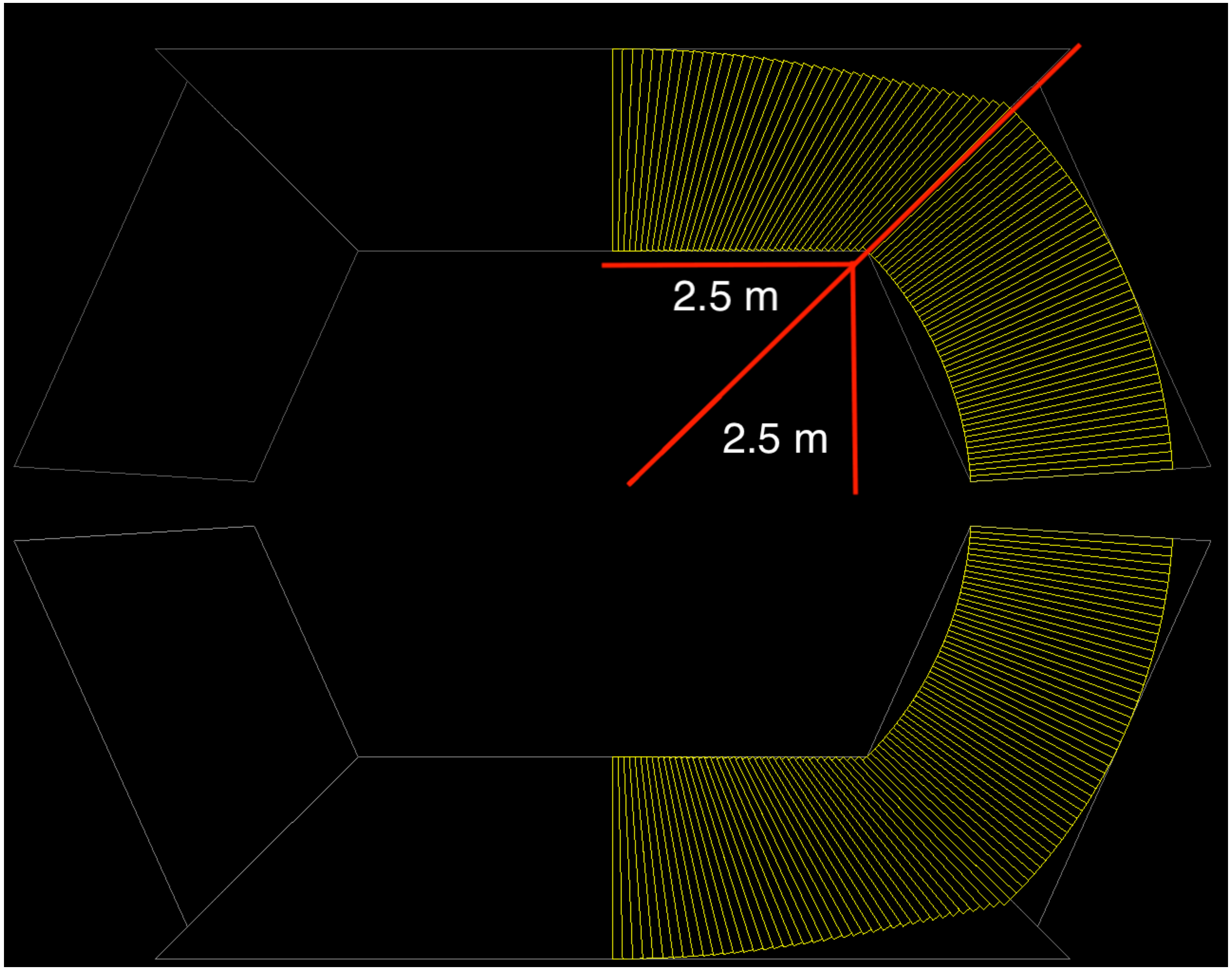
20 GeV $\rho^- \rightarrow \pi^- \pi^0$





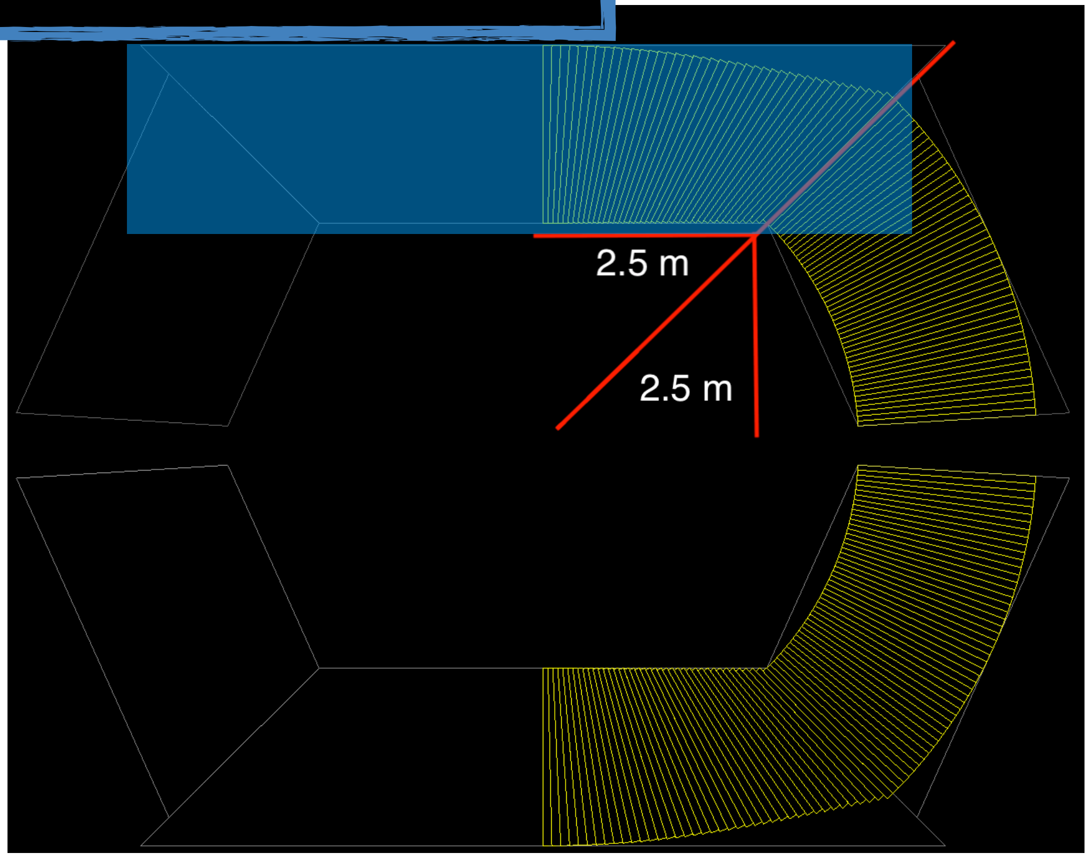
4th Concept like calorimeter

4π fully projective geometry

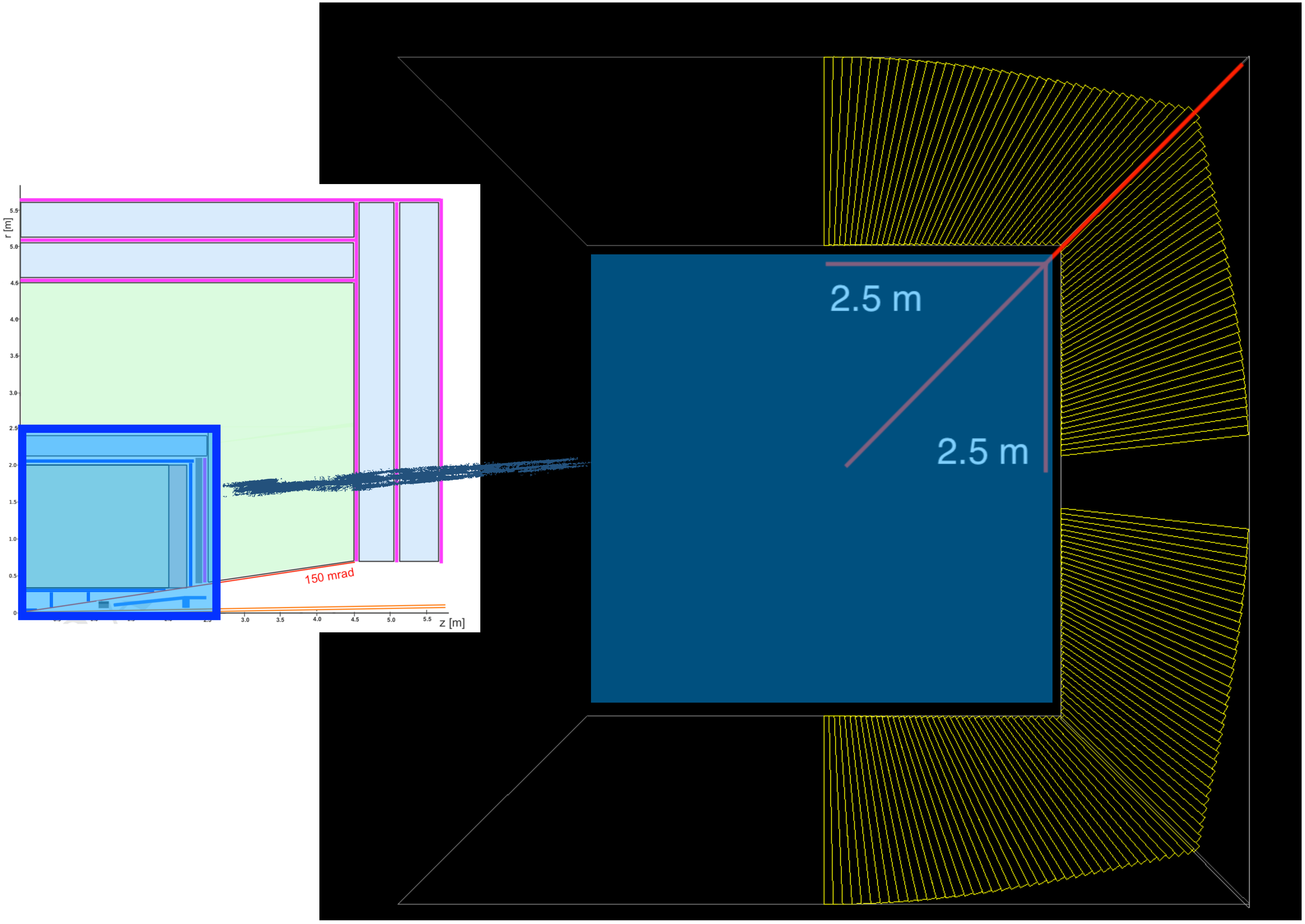


The barrel


40 towers right side
40 towers left side
45° between barrel
and endcap
2.5 m


2.5 m
2.5 m

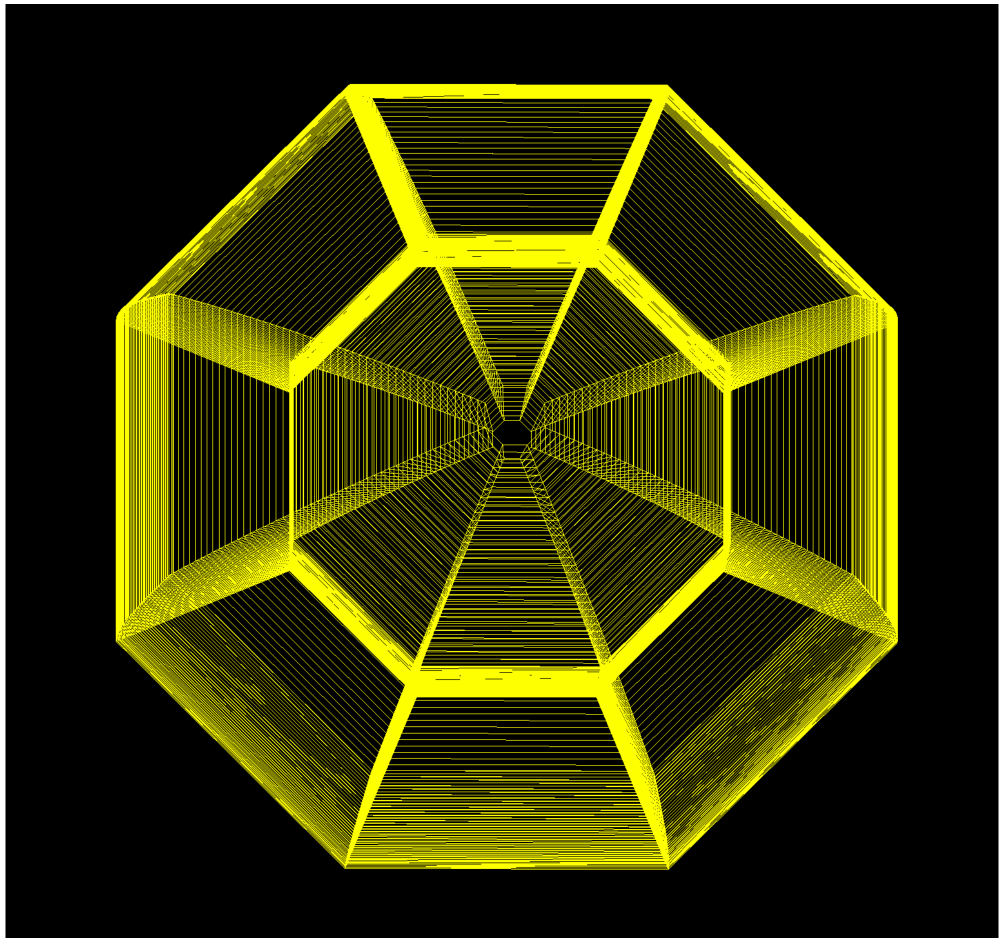
IDEA Calorimeter



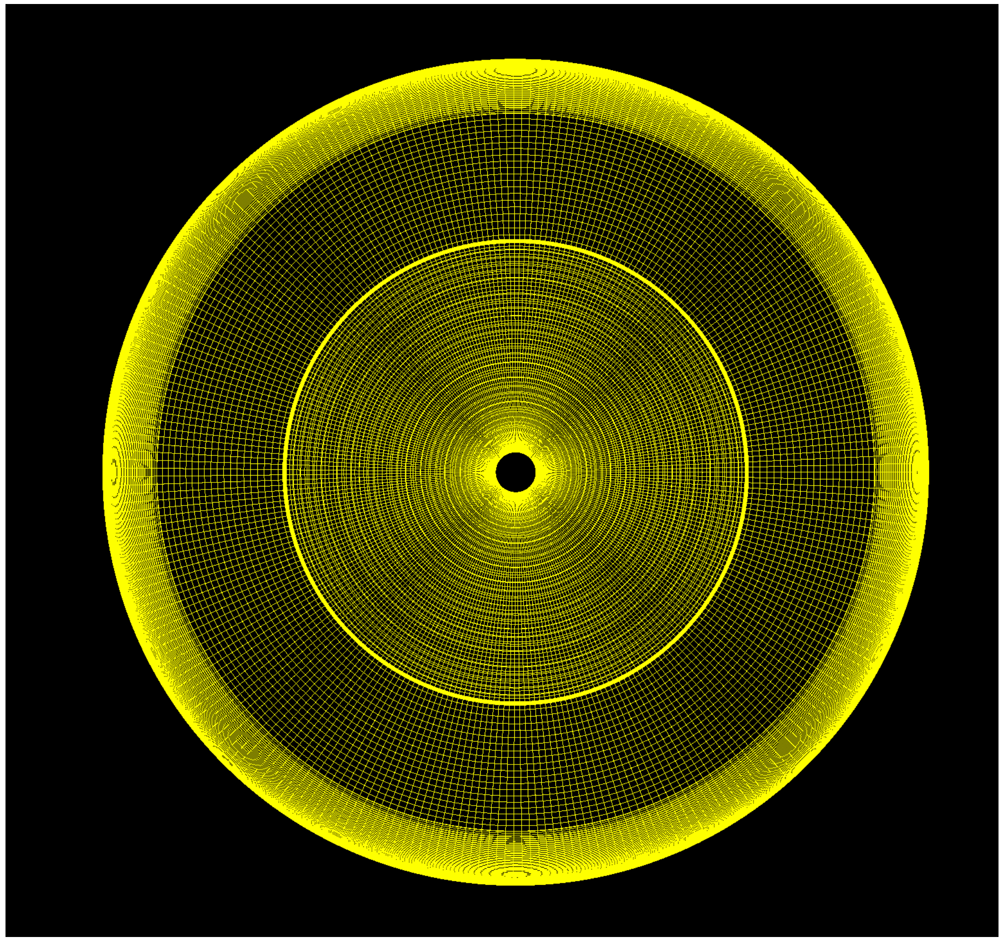
Wedge Geometry

The final number of wedges will be a balance
between the mechanical limitations and the expected performance.

8 wedges



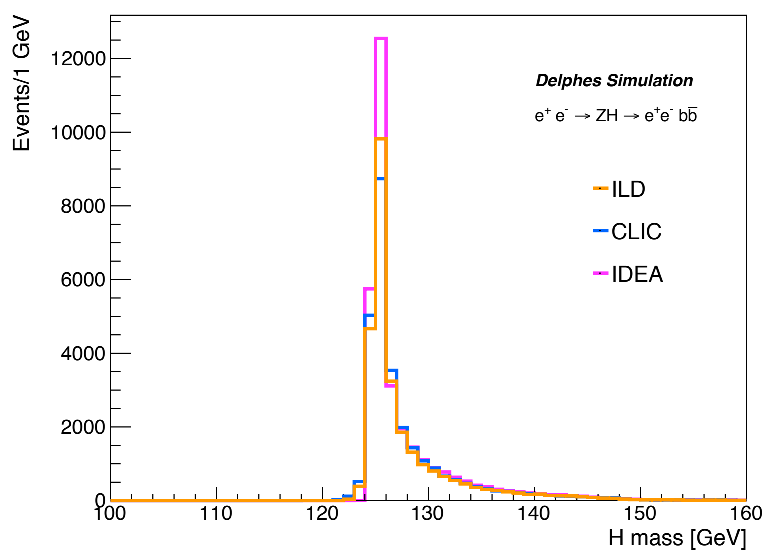
283 wedges

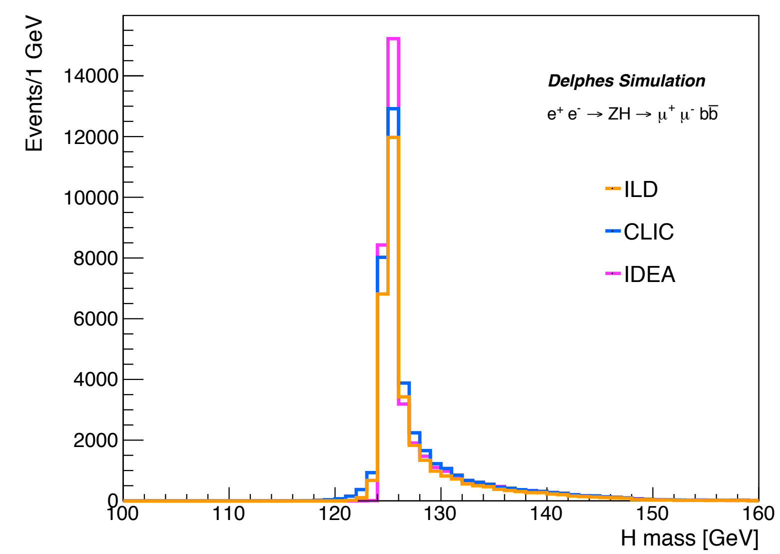


Currently under implementation within the FCCSW

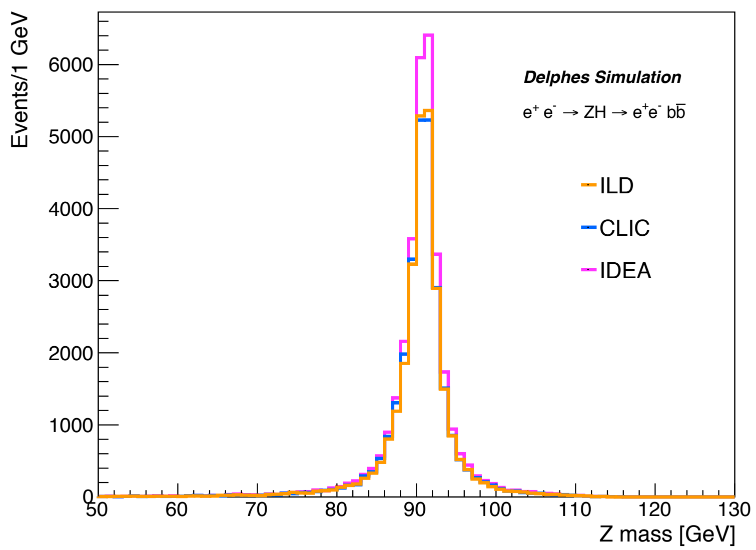
Delphes IDEA Fast Sim

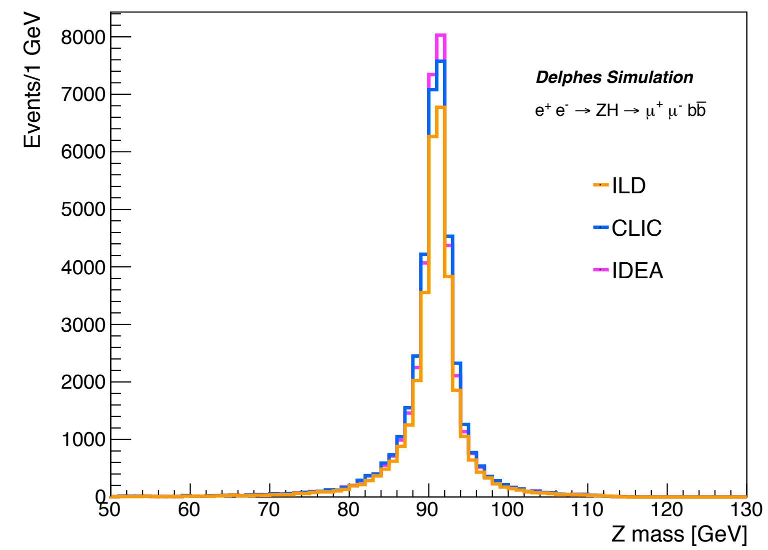
A first implementation of a fast simulation card with Delphes is based on single detector performances. See Elisa Fontanesi's talk.





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 on the software is certainly needed,
to complete the assessment

<u>we hope a strong collaboration will cluster around it.</u>