Using a precise time measurement in a highly granular calorimeter

how much?

Mastering time, a dream?

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Study done with the simulation of the ILD detector in its version "large" with
SiW ECal cells of 5mm side and
semidigital HCal with a very experimental cell size of 1mm.
The time precision is that of Geant4.

More than twenty years ago calorimeters for Tesla, then ILC have been devised with a huge 2d pixellisation,
Orders of magnitude more than in previous colliders LHC or LEP.
The sampling, designed to achieve a given resolution, induces a longitudinal grain forming a 3d voxel
which matches the 2d pixel size.

But the time which articulates the shower development was completely left aside.

The current developments in electronics have opened (CMS HGCAL)
the possibility to record the time of the calorimeters energy deposits with accuracies similar to the pixel size (1cm=30ps)
or better if the position in the pixel can be known or if pixels can be combined.
and the showers can be accurately described in the Minkowski space, embedding the ideas of succession and causality.

The purpose of this paper, is just to present a heuristic approach
toward figuring out the potentialities of describing accurately the events and singularly the calorimeter showers
in space-time for reconstructing appropriately the events.

A simple exploratory work.

Remark for fun: the energies involved in these deposits are typically the MIPs left by particles crossing the detecting layers, dE/dx
in layers of silicon of few 100 µm, that is not a numerical match to the energy corresponding to the pixel size (10^{-4}eV= 1 cm).

The first part will be on time-of-flight and the diverse possibilities brought by measuring time between specific points

- PID, or rather m, measuring the β by timing and the momentum by curvature.
- Separating the contributions from neutrals
- Measuring the momentum through the β

Then the direct impact on calorimetric objects reconstruction will be discussed,

- cleaning of the detector by time dispersion,
- use of the time development of showers and causality to properly reconstruct calorimetric objects, their positions and energies, but also the presence of decays.

Out of calorimetry, how a good timing along a track may reveal decays or inconsistencies?

- To measure a duration a reference is needed, the natural global one is the clock of the accelerator, but what is its accuracy?
  How well can we define the particular collision time? Length of the bunches, design of the interaction zone.
- Then how is measured the time of a particle passing through a detector piece?
  Plenty of technological details are to be considered but are eluded in this paper where we focus on what could be possible results.
- Relative calibration between collision and detection: flying particles with a well defined β, photons.

Charged PID: Measuring the time-of-flight and the trajectory length, speed of the particle, what info to draw from the β?
The perspective of time-of-flight for PID as a complement to or an ersatz of dE/dx has already been largely studied. A tool for non TPC.
For hadron or muon tracks it is mostly done using one or more timing layers
for electrons/photons a number of calorimeter layers, for hadrons?
here the number of hits measured brings statistical improvement

Is there something else?

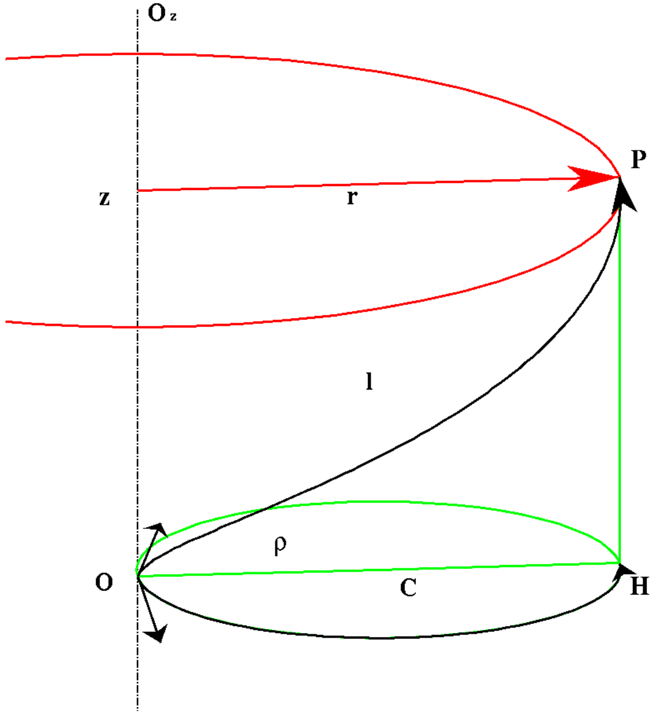
Yes

It provides also information on neutrals,
A shower time-stamped can be checked as being prompt by time as well as by direction.
Two close by showers can be separated. Neutrals or
A shower close to a track can be identified as prompt and not linked to the track, for example for rather low energy charged tracks taus.

neutrals PID

One step further, if we know the β of a particle, we have information on its momentum.
Considering that the nature of a particle is known its momentum can be inferred from its β rather than from the curvature of its trajectory.
This looks quite funny being much less precise except if
there is no information from the curvature: neutrals or tracks along the field: A very forward time tracker
What can be expected? Identifying photon, neutral kaon or neutron, measuring the momenta at a 10% level.

Another application but to a tracker with accurate time measurement:
The cleaning out of all the hits which can not have been created by tracks in their first half turn, improving performance and time.



Without combinatorics

But measuring the time is not necessarily between interaction and detection points

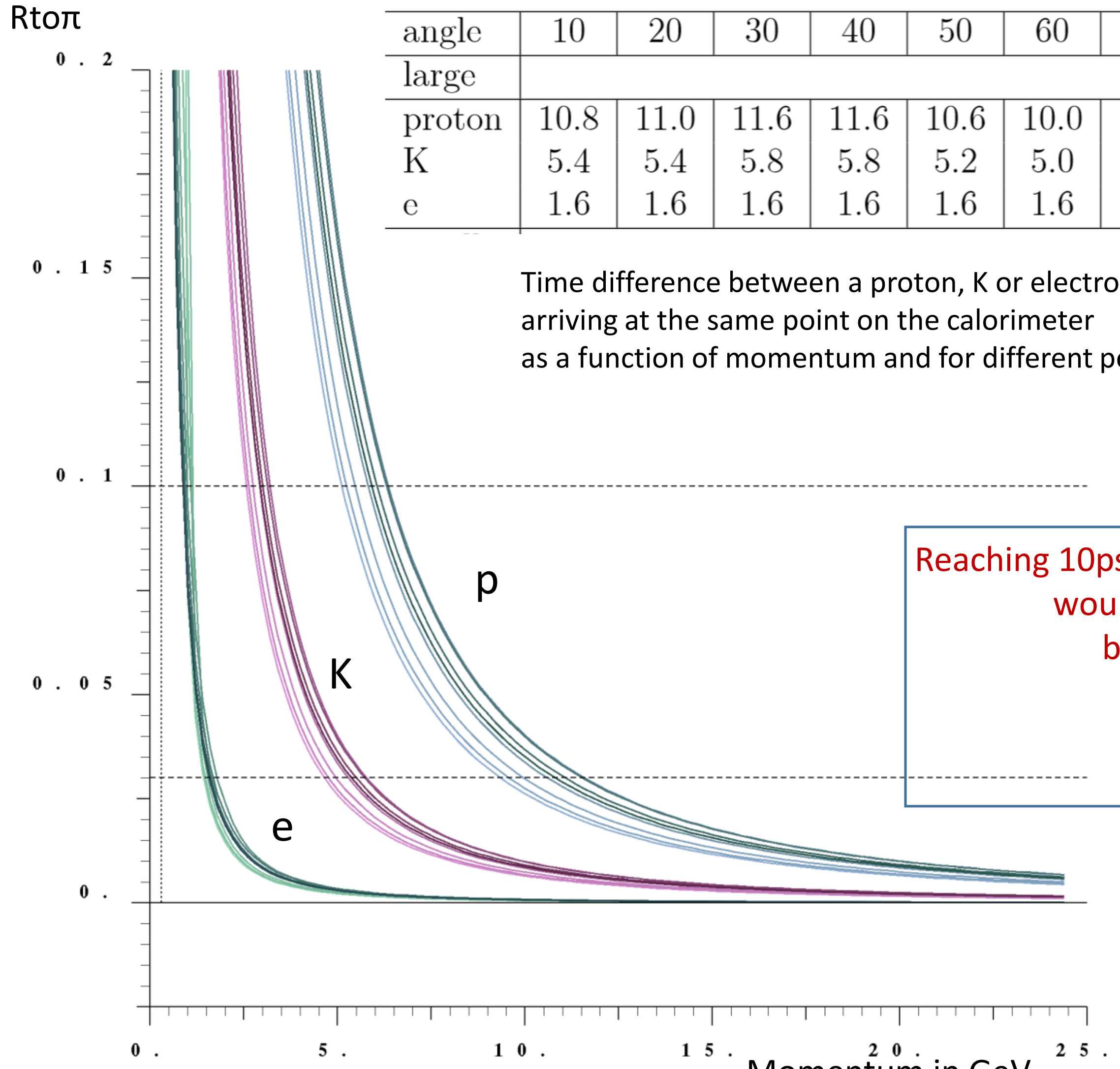
Measuring the change in β along a track brings also information, see later for calorimetry application:
If you have more than two points on a track, you can estimate the β on each segment.
The δβ, if out of errors can track a pattern error,
but also a decay, an information on top of a spatial kink?
Space-time kink.

PID

Momenta (GeV) of intercept with 30ps

angle	10	20	30	40	50	60	70	80
large								
proton	10.8	11.0	11.6	11.6	10.6	10.0	9.6	9.4
K	5.4	5.4	5.8	5.8	5.2	5.0	4.8	4.6
e	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.4

Time difference between a proton, K or electron and a pion arriving at the same point on the calorimeter as a function of momentum and for different polar angles



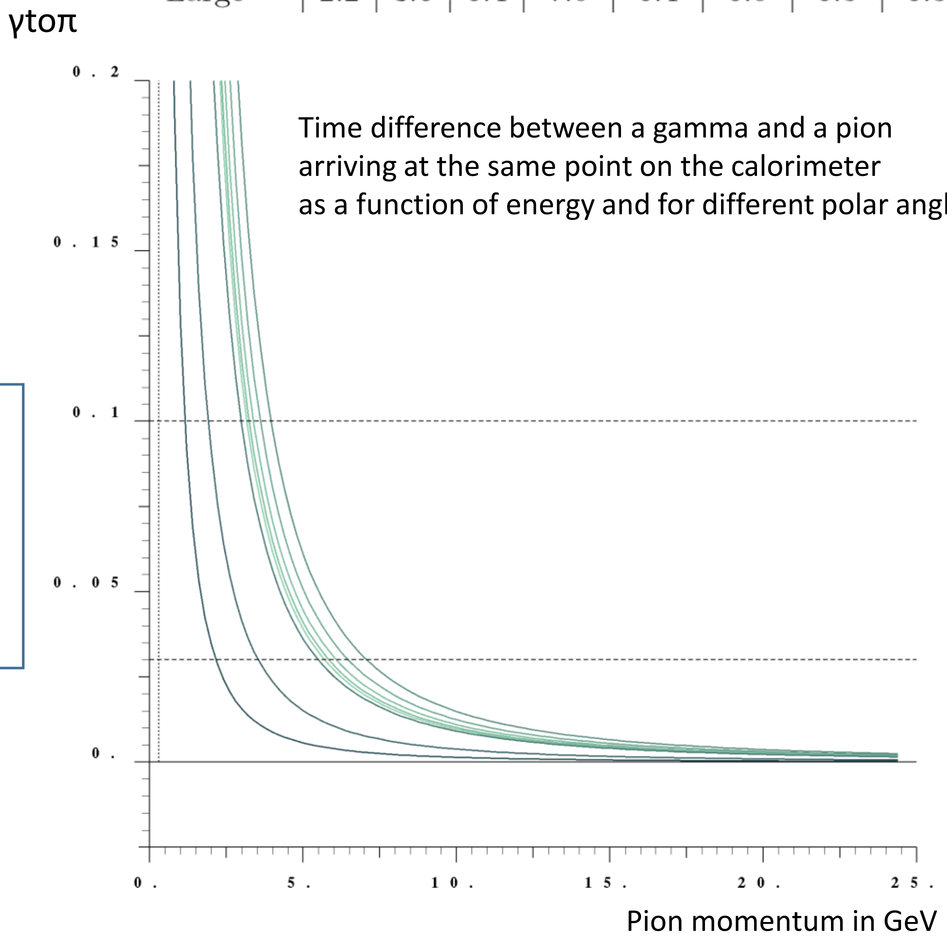
Reaching 10ps (3mm) rather than 30 would dramatically improve but that is the limit from the pixel size but for showers or position tricks

Gamma identification close to a π

Momenta (GeV) of intercept with 30ps

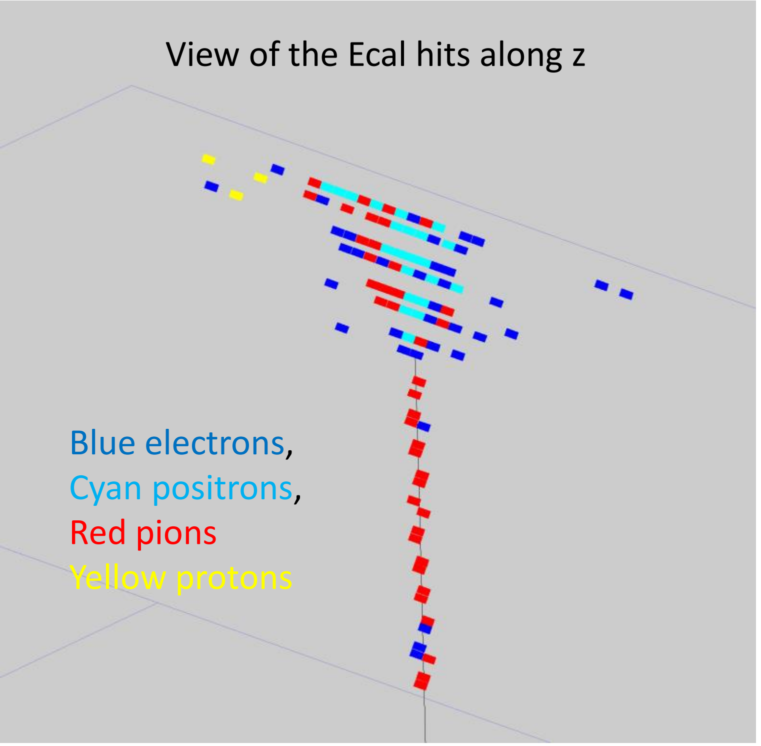
angle (°)	10	20	30	40	50	60	70	80
Large	2.2	3.6	5.4	7.0	6.4	6.0	5.8	5.8

Time difference between a gamma and a pion arriving at the same point on the calorimeter as a function of energy and for different polar angles

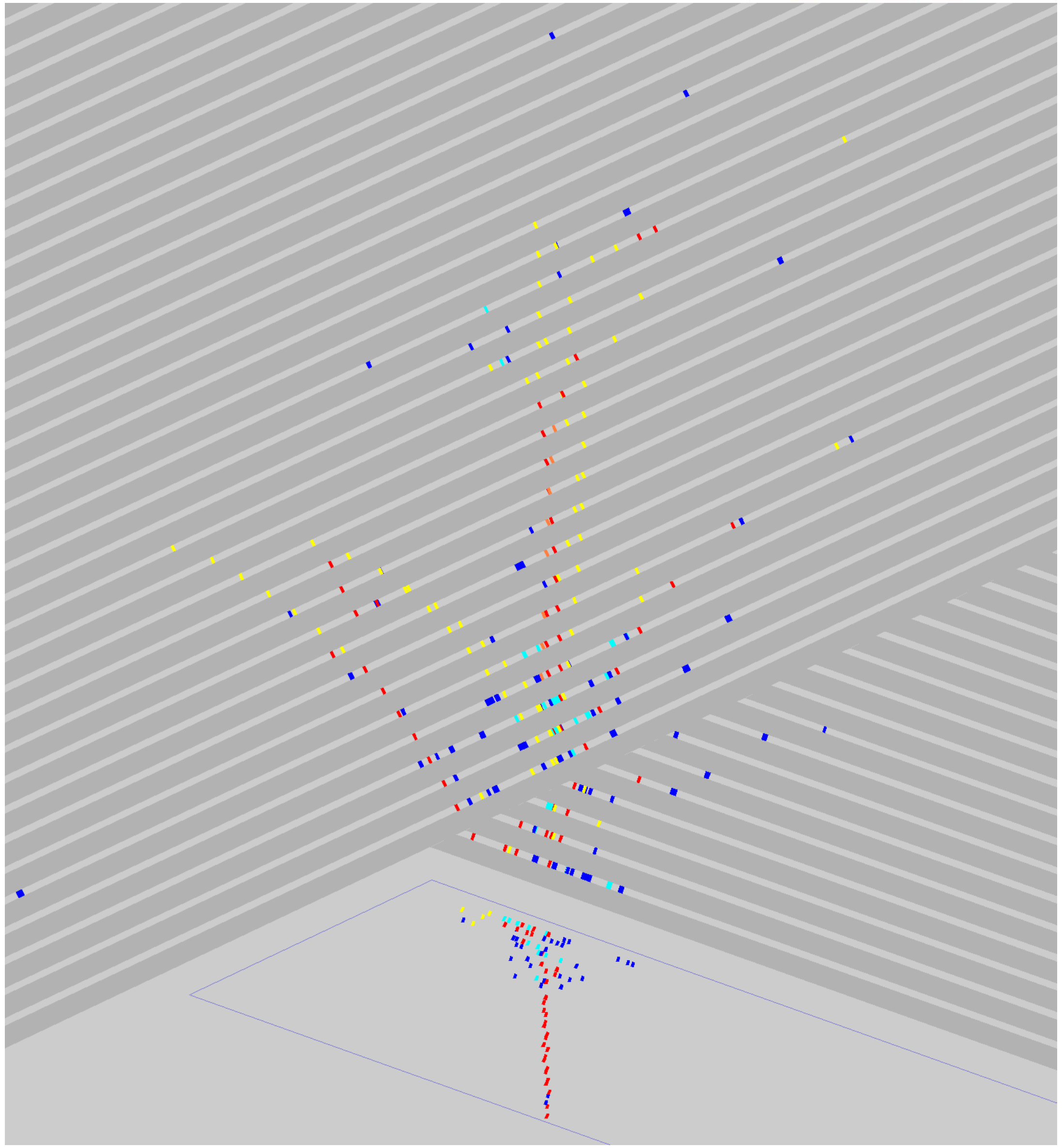


Source of observation

Most of the remarks which will follow have been inspired by observing a number of 40 GeV pion interactions.



The colour code is linked to the nature of the particle which deposited energy
On the right picture you observe pion and proton tracks .
The structure of the Ecal and of the HCal are shown.



Ecal time distributions once a cut in energy at a 1/3 of a MIP applied.

Cleaning and pollution

The time distribution of hits and the collision repetition rate. 554ns (166000 mm) between bunches,

looking at the time distribution of 40 GeV pion+

How many hits get into the integration time of the collision, of the next, etc?

Source of these late hits?

Look at previous slide

from the 244 hits 192 are in time (2000-2454) : β high enough

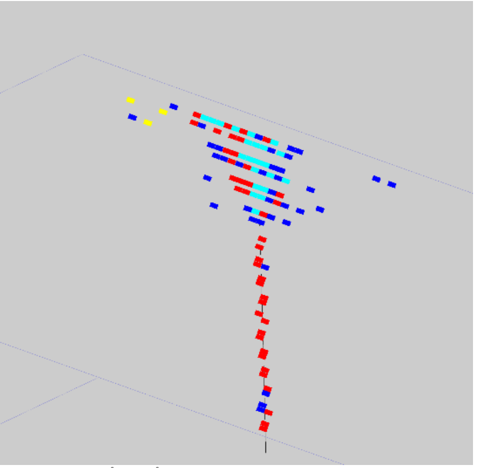
$75e^{+}$ $32pi^{+}$ $77e^{-}$ $8pi^{-}$ hits

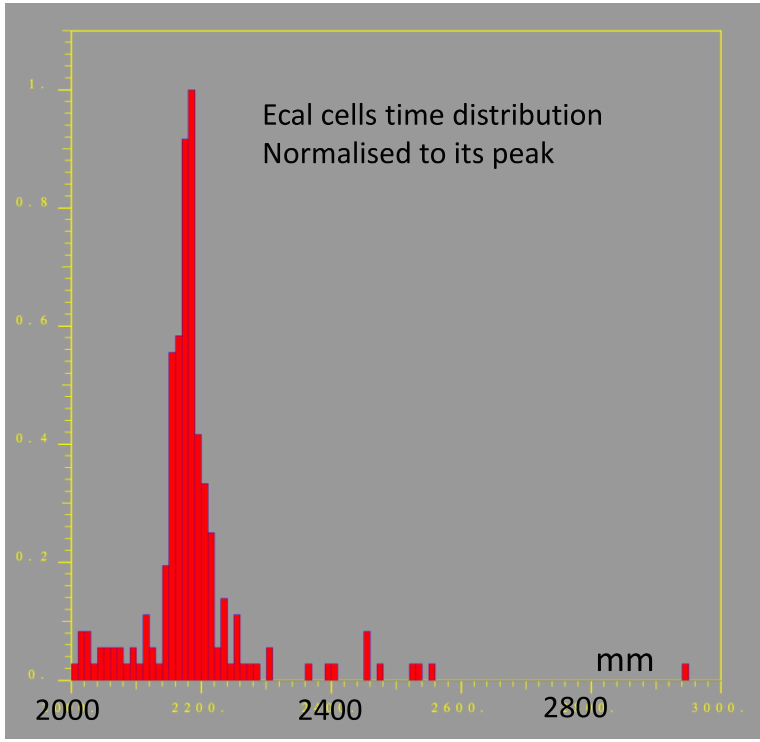
52 are out of time

only 4 protons, mostly e- and few silicon isotopes, no pion.

9 after next crossing, 8 e- , 1 e+

3 after next to next, maximum time about 1km.





HCal time distributions once a cut in energy at a 1/3 of a MIP applied.

Time cut at 3500mm.

In view of their small size the cells are first clustered

Evt 14, 20 out of 236 are out of time, there are few (3) protons, and massively (15) electrons

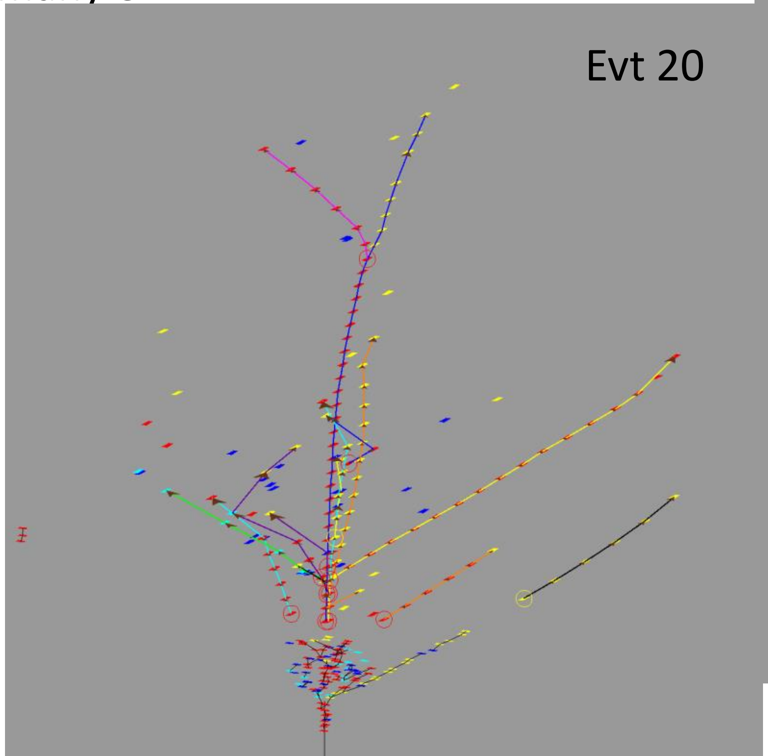
216 clusters in time including 84 e^+ or e^-, kaons, protons, pions

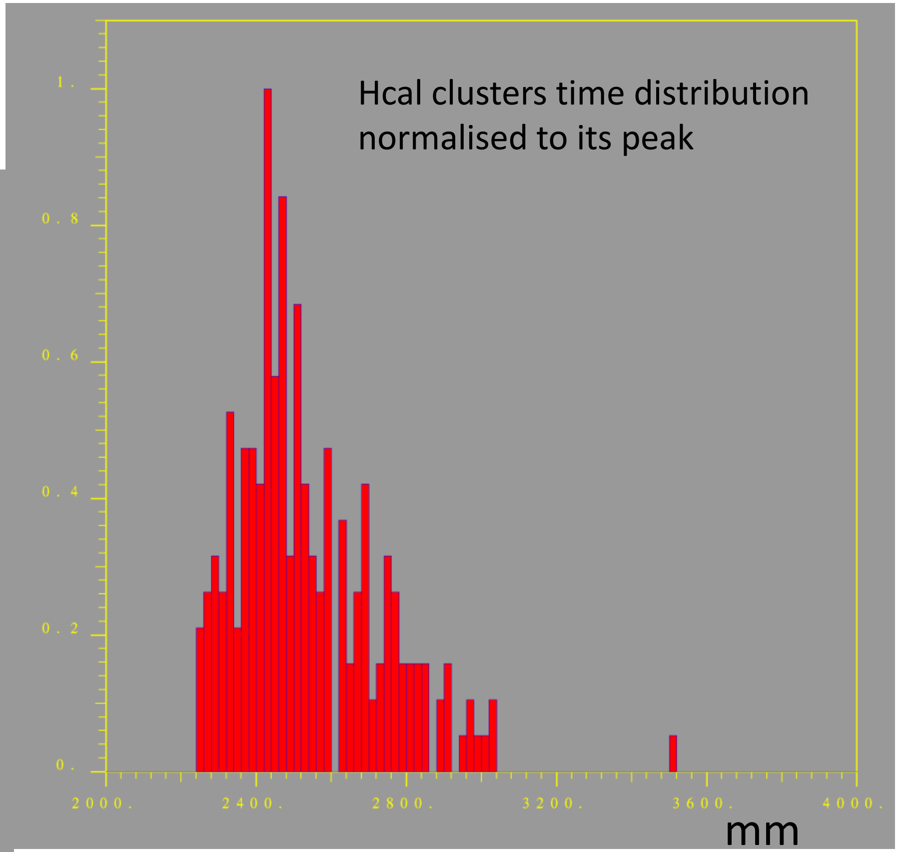
12 after next collision, electrons.

Evt 20, 29 out of 204 are out of time, almost all electrons, 2 C12

175 clusters in time p, pions, many e-

The hadrons are building tracks.





not much is out of time

Not many trailing hits

Conclusions on the shower cleaning   Ecal
- The intrinsic cut in energy plus a cut in time cleans very effectively,
  impacts the reconstruction time and efficiency (for event 14 from 353 to 190, & few others).
- It seems that the ones rejected as out of time result from nuclear reactions or Compton.
- They look rather incoherent with the main structure
- The hits appearing after next collision are limited,
- The probability to be on a good event is low and the location of the remnants more or less predictable.

For the gaseous Hcal
Time does not bring much cleaning

First go to an appropriate 4d space-time

Time measurement:

to insure the homogeneity between space (mm) and time, the time unit is taken as being also the mm (~0.3ps)
The origin of time is taken at the origin of space, the interaction point (or the earliest hit in the Ecal, rather uniquely defined).

Choice of axes:

A shower has a more or less well defined space axis, we will call it ζ,
which coincides with the flight direction or the track direction at the entrance of the calorimeter.
As the shower develops with time it is largely along this axis when the two other space axes are
rather uncorrelated with time.

The figures on slide 12 display the views ηζ, ηt, ξζ, ξt
The figures on slide 13 display the ζt view for an event (40 GeV positive pion) in the right system.
The correlation is obvious and we see tracks developing with different and evolving speeds.

For completeness we could show also ξη.
or a little rotating movie in 4d

Shower reconstruction

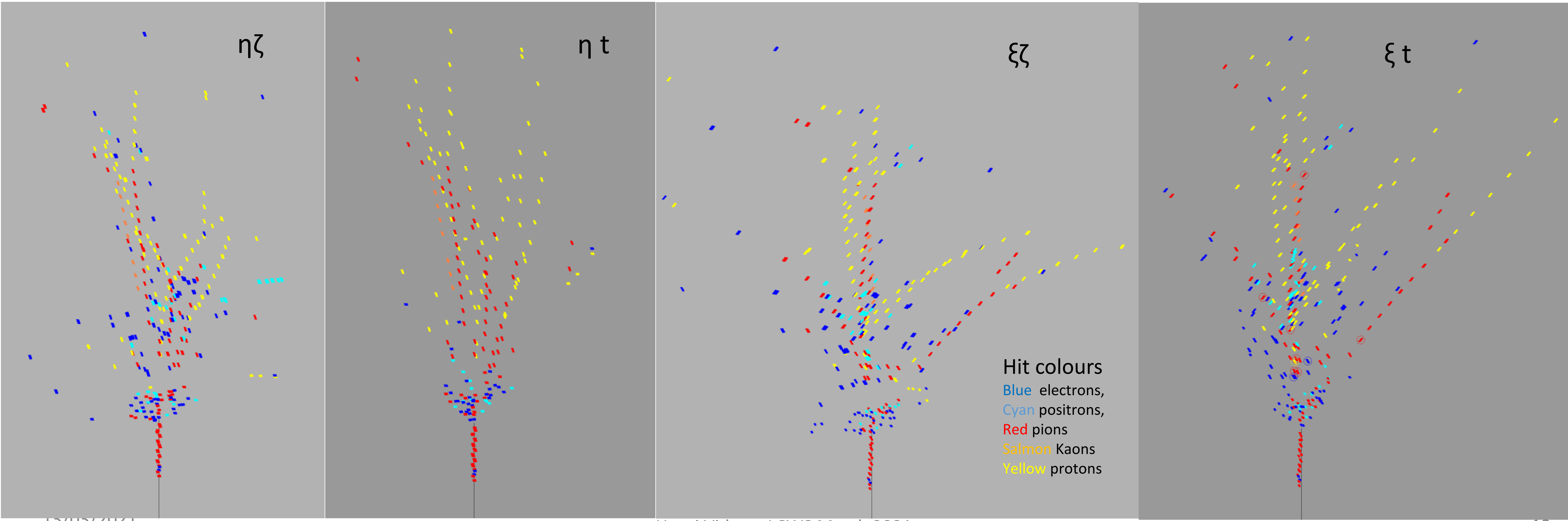
It is known that the more dimensions, the easiest to reconstruct patterns

Using the time-space

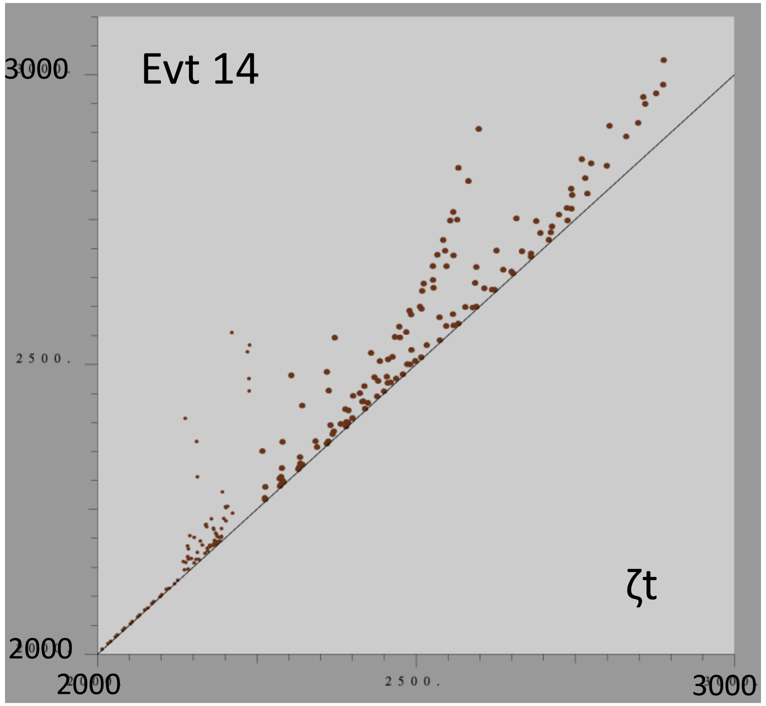
To figure out the pattern of a shower developed by a charged track or a neutral
We assume that the main direction of the shower, called ζ, is
- along the flight line from interaction to the earliest hit in the Ecal (or globally) for a neutral
- along the track direction at the position of the earliest hit for a charged track

Two perpendicular coordinates, ξ and η, are chosen to optimise the match with the detector axes, mostly for visualisation.
Then t which is much correlated to ζ.

You see immediately
the role of the β
and how the protons slow down
when the pions do not



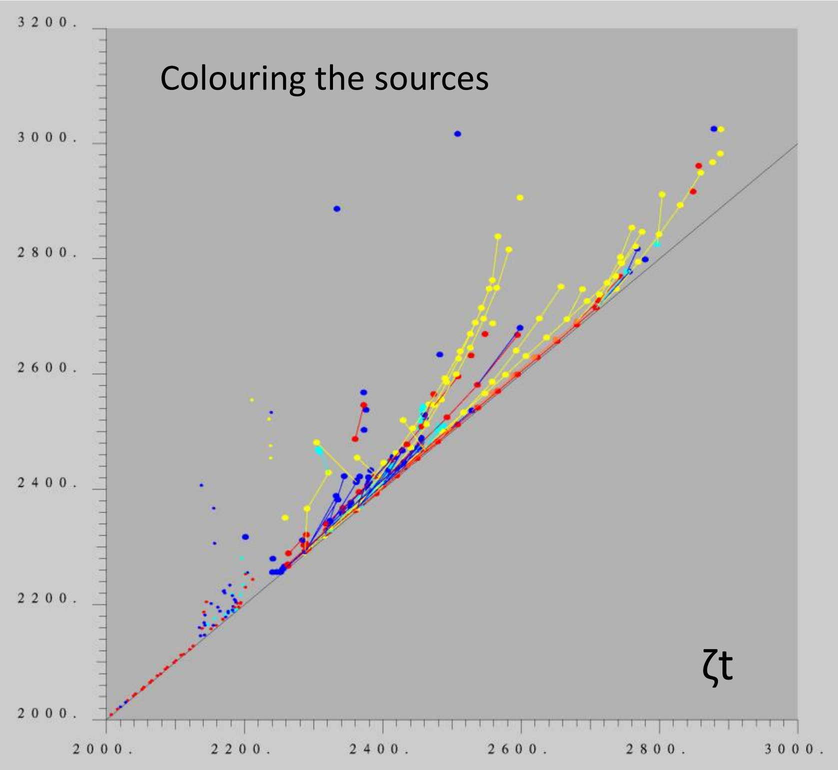
t in mm



ζ in mm

t versus ζ for the Ecal cells, small circles and for the Hcal cells, large ones.
No t is smaller than ζ,
the hadronic tracks are clearly visible corresponding to different sets of β with energy loss.

Even though the pattern seems easier in ξηt than ξηζ it has to be done in 4d.



For the reconstruction we can use quite naturally a method like Arbor (ref. HV, Manqi Ruan, Rémi Eté)

Method: Getting the shower as a tree developing from a root, the point where the particle penetrates the Ecal.
But the root is now trivial to define as a local time minimum compatible with flying from the interaction.

The shower develops surely with growing time and never comes back (backscattering in ζ, not in t)

The main constraint in connecting hits in the pattern is that any hit connection
has to be causal

which works also between sub-showers generated by neutrals,

and most of the time smooth.

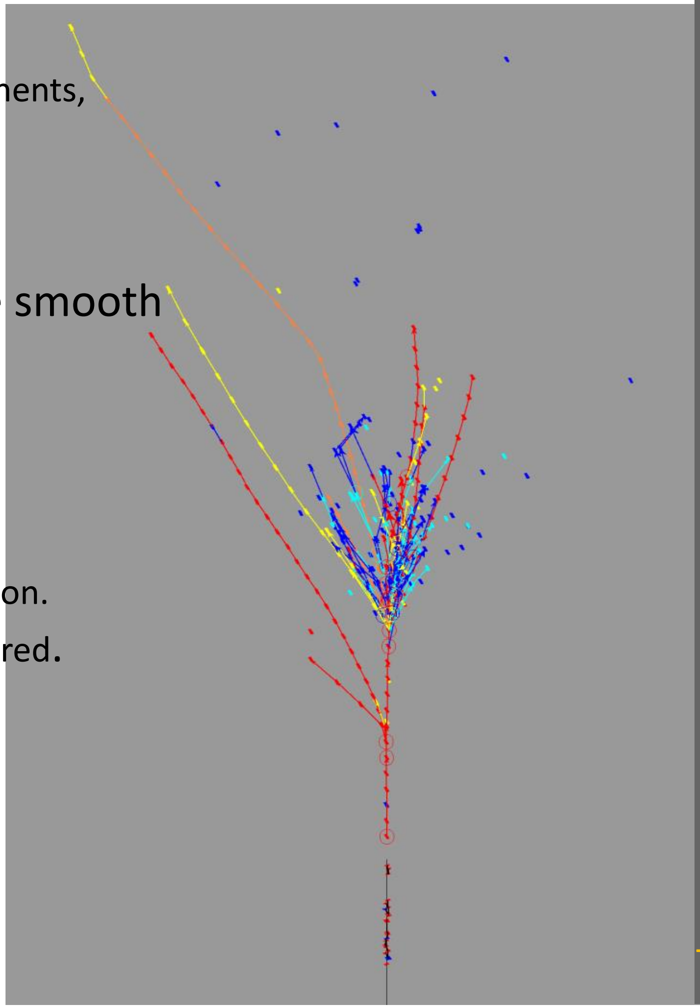
To be fully useful
The time measurement precision between interconnected hits has to be matched to distances:
- in the Ecal the sampling pitch is around 6.5mm, rather hard to match
- in the Hcal it is around 30mm which seems well possible.
where a measurement with a precision of 3mm induces a δβ of 10%.

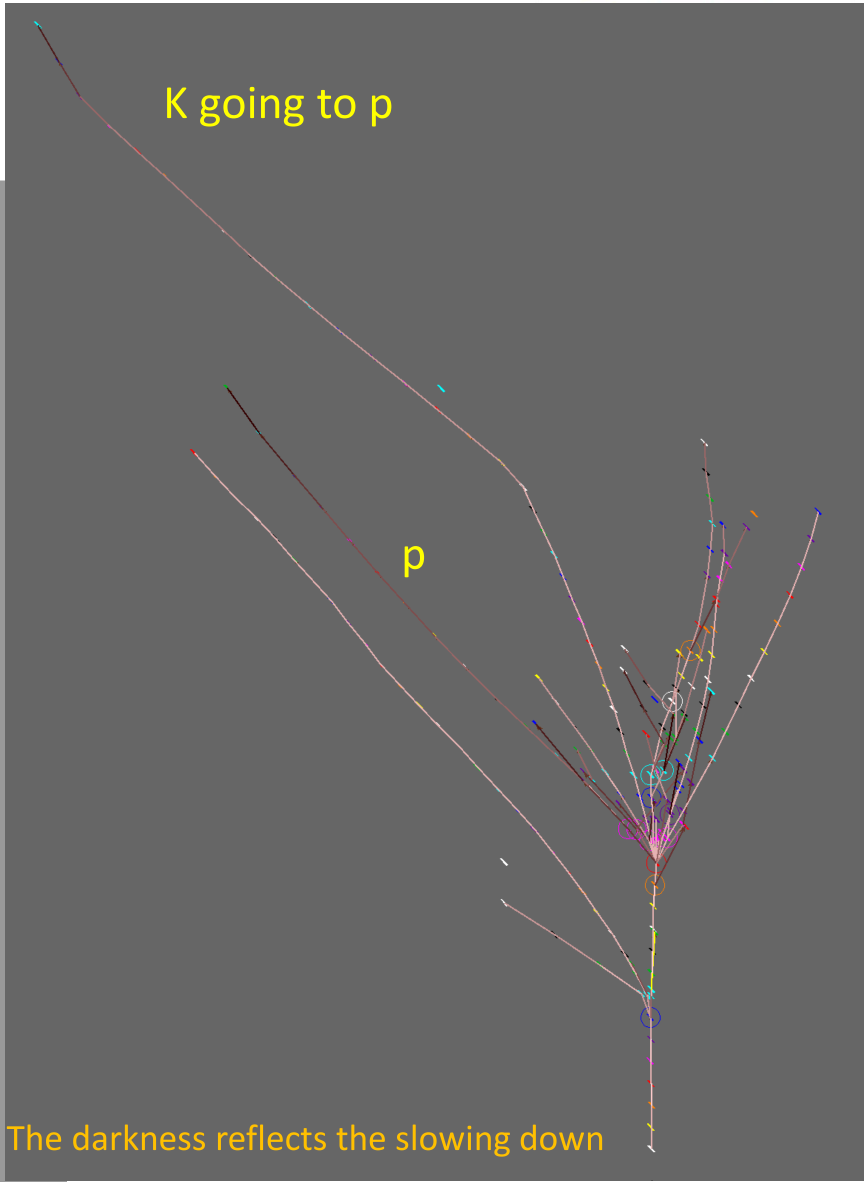
In quo tractatur de natura et virbus arborum
Adam Lonicer 1551

The constraint from a smooth β, within the errors, and the identification of decays
β can more or less be measured on each connector joigning two successive hits,
a change of β along a track.

A hadronic shower as seen in previous figures shows two components,
the hadronic tracks, the electromagnetic parts,
the hadrons fly a measurable time&distance
with a β uncertainty of 10% per step.
Successive βs measured along the track have to be smooth
and the energy loss on a certain length provides
an ID and an estimate of the momentum,
watch protons versus pions
Better, if the track comes to a stop,
its ID and energy are then measured by range with good precision.
The energy of a track sailing through the calorimeter can be inferred.

A precise measurement of the time provides
a strong tool to reconstruct tracks in a shower,
to identify them,
to measure their energy, to identify a decay
as a spatial kink and a β step (space-time kink).





But impact of measuring the time:

- the added functionality may need cooling,
- adding matter in front of calorimetry
- adding cost

Nevertheless we can hope for a nice evolution on the electronic side.

Rethinking the design?

It appeared that often the precision we can reach on time is marginally sufficient.

For making a good job, is there a better global design to explore? for example
an ECal not that dense inducing certainly a wider Moliere radius
but compensating thanks to a more efficient reconstruction
still with a material like W separating properly electrons and hadrons??

Trying to be open minded

Redesigning the calorimeter alone?

The end

Quite a work to make it real !

Have a good time

Back up

First a discussion of the energy readout cut:

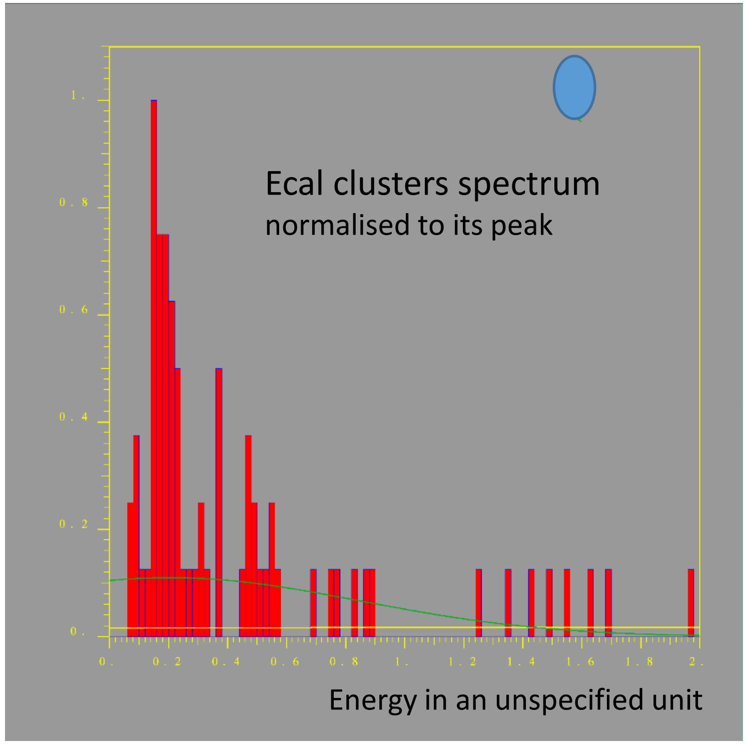
In the energy distribution of the ECal cells, we see the MIP with a distribution at lower energies, there is a tail from the Landau but also deposits shared between adjacent cells.

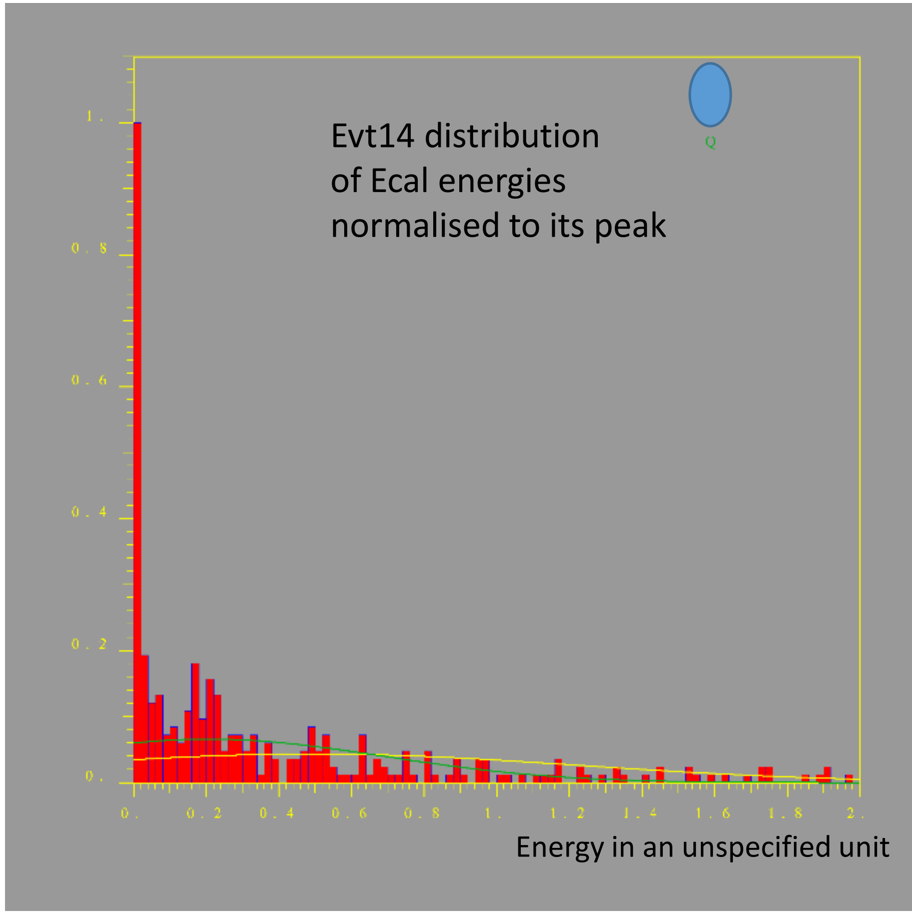
Can be seen by looking at the energy distribution of clusters rather than hits.

To reduce the inefficiencies due to cell borders, the threshold to keep a signal should be less than half a MIP for a border between two cells going to a quarter of a MIP.

Such a cut exists in the read-out and is to be applied before anything else.

Cut between 1/3 & 1/4 MIP 170 keV 0.18 10^{-3} GeV

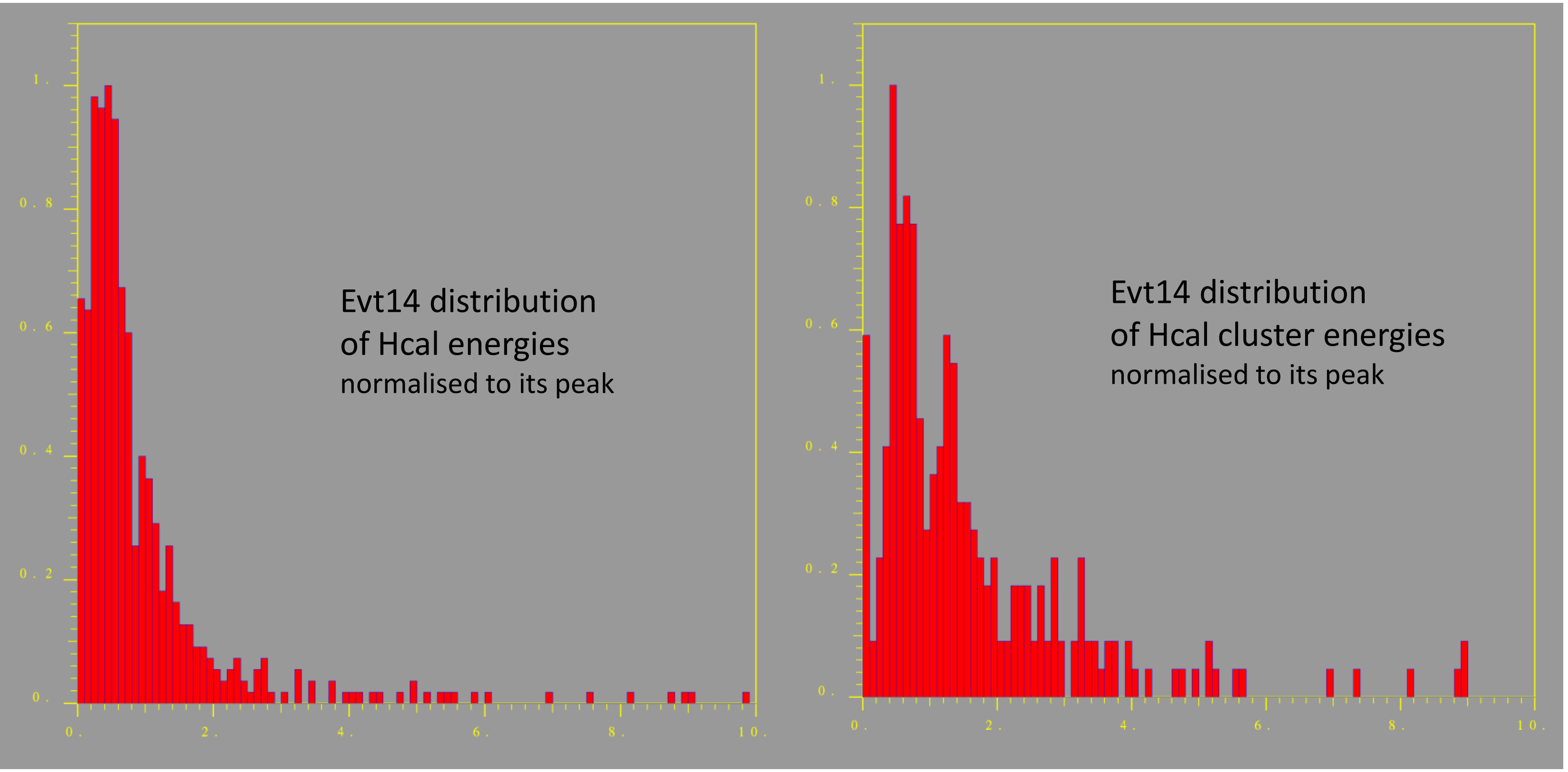




In the energy units used here the cut will be set at 0.06 for ECal and 0.2 for Hcal.

for event 14, 109 Ecal hits out of 353 are below energy threshold

Are those at the cell borders? Where?



Cut at 0.2 Air: 67 MeV in 300 m then in 3mm 67 MeV 10^{-5} = 670 eV
Its multiplied by 10^{6} when for Ecal multiplied by 10^{3}
MIP observed at 0.6 10^{-6} GeV . OK