A heuristic description of

Possible uses of time in calorimeter objects reconstruction,

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A development of the 3d algorithm « arbor » (« april » as an offspring)
What brings the introduction of time in the calorimeter objects reconstruction?
Does the time approach dictate modifying the ILD detector concept?
Does it dictate specific modifications?

Study based on the ILD design, its Monte Carlo simulation, an adequate digitisation.
Original algorithm coded in Fanal (quite specific), it is being adapted in C++ and ILD software environment at LLR by Hao Liang.

A description of some performances
specifically those used by JCB in his analyses of flavour physics.

The approach: *What could be the ultimate performances? How do they degrade when degrading the time accuracy*.
Use directly sub-hits?

Measuring the 4d space-time imprint of the events produced in the ILD detector, singularly the calorimetric system:
a 3d space paved with sensitive cells, recording particle energy deposits and the time at which they deposit.

The sensitive cells, square Si diodes few hundreds of µm thick with an area of 5.5x5.5mm²
define the space measurement precision when the time recording precision, of the order of tens of ps (e.g. 30ps), is to be studied.
As most of the particles considered propagate at about c we opt for measuring time and space in the same unit chosen to be mm, about 3ps.
The ps being about 300µm, the ≈6mm cell size appears close to the time precision
and the measure on the 4d space is rather homogeneous and isotropic. Consider the sampling distance.

This space has then an underlying Minkowsky structure, hence has a non definite positive norm which introduces the notions of past and future, then causality.

All the event hit cells are in the future of the beam-beam collision and
when and where a particle penetrates the calorimeter, through a cell referred to as « start »,
all the hit cells are in the future of this start.

The time space correlation

By handling an event in full 4d instead of projecting on the 3d space we could expect the pattern analysis to be tremendously easier

except if the time dimension is strongly correlated to one space direction,

which is the case:

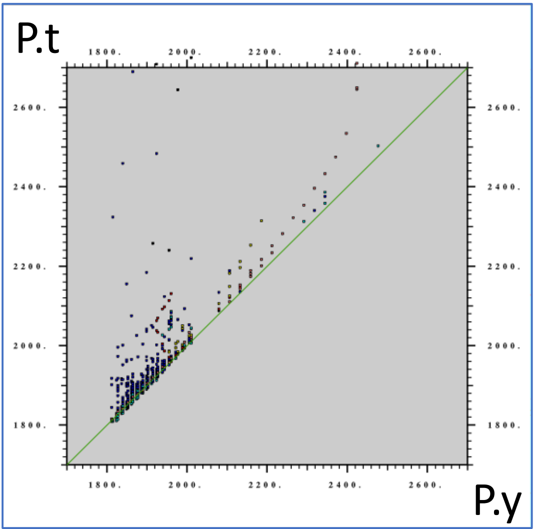
When a shower develops in the calorimeter, the time is strongly correlated to the shower direction.

This point was the cornerstone of the arbor-3d algorithm.

The time in Géant4

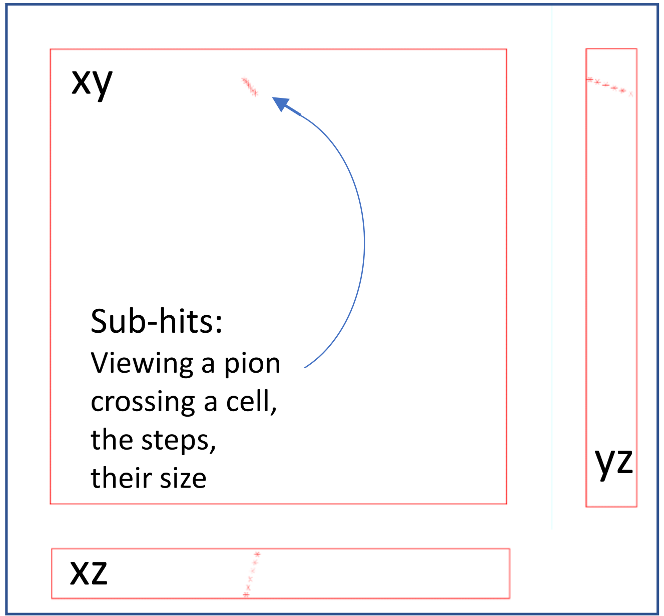
Particles are propagated by steps,
a step ends
at an interaction,
when crossing a bound,
when it gets too long. About free parameter

When the step is in a sensitive medium
its central point is recorded
together with its length
the energy lost along
and its time at the middle
to build a so-called « sub-hit ».



Time versus longitudinal distance to the start for the cells.

Some cells have a time smaller than the distance, this is due here to the introduced time smearing.

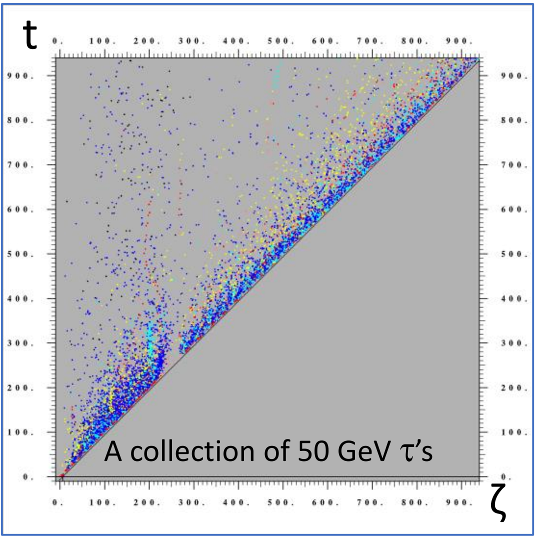


The hit cell time is defined:

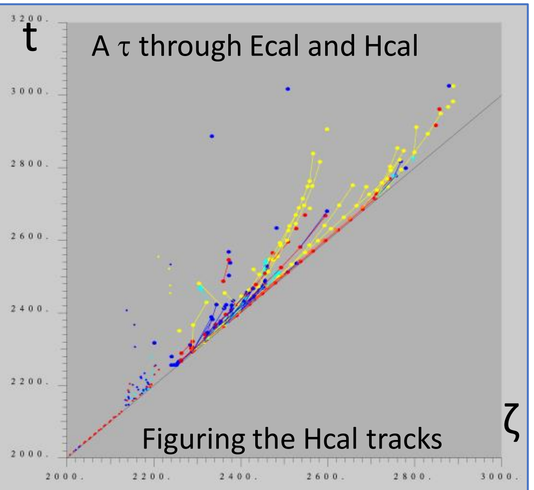
as the earliest sub-hit time
above an energy threshold,
transferred to the step start at c
then corrected by adding the
signal propagation time in the pad.

It may also be smeared by a given gaussian fluctuation.

The space time correlation a pain and a blessing



Time versus longitudinal distance for the cells.
A tolerance of 6mm has been introduced
The high level of correlation is obvious.
There exists also a slight correlation between time and transverse dimensions.



To illustrate the space-time correlation we make a change of coordinates system putting the system origin at the start of the shower, taking the ζ direction along the shower and ξ and η directions to form an orthonormal system.

Then (left) we plot the cell time versus the ζ coordinate.

Plots on the right:
We can also provide ξ η t views of the event (right) compared to ξ η ζ views(left).
There you can observe a π^+ going back spatially but "forward" in time, and the cleaning of Comptons.

Colours from the hit particle species:
Rose pi-
Red pi+
Yellow proton
Black ions
Green photon
Blue electron
Cyan positron

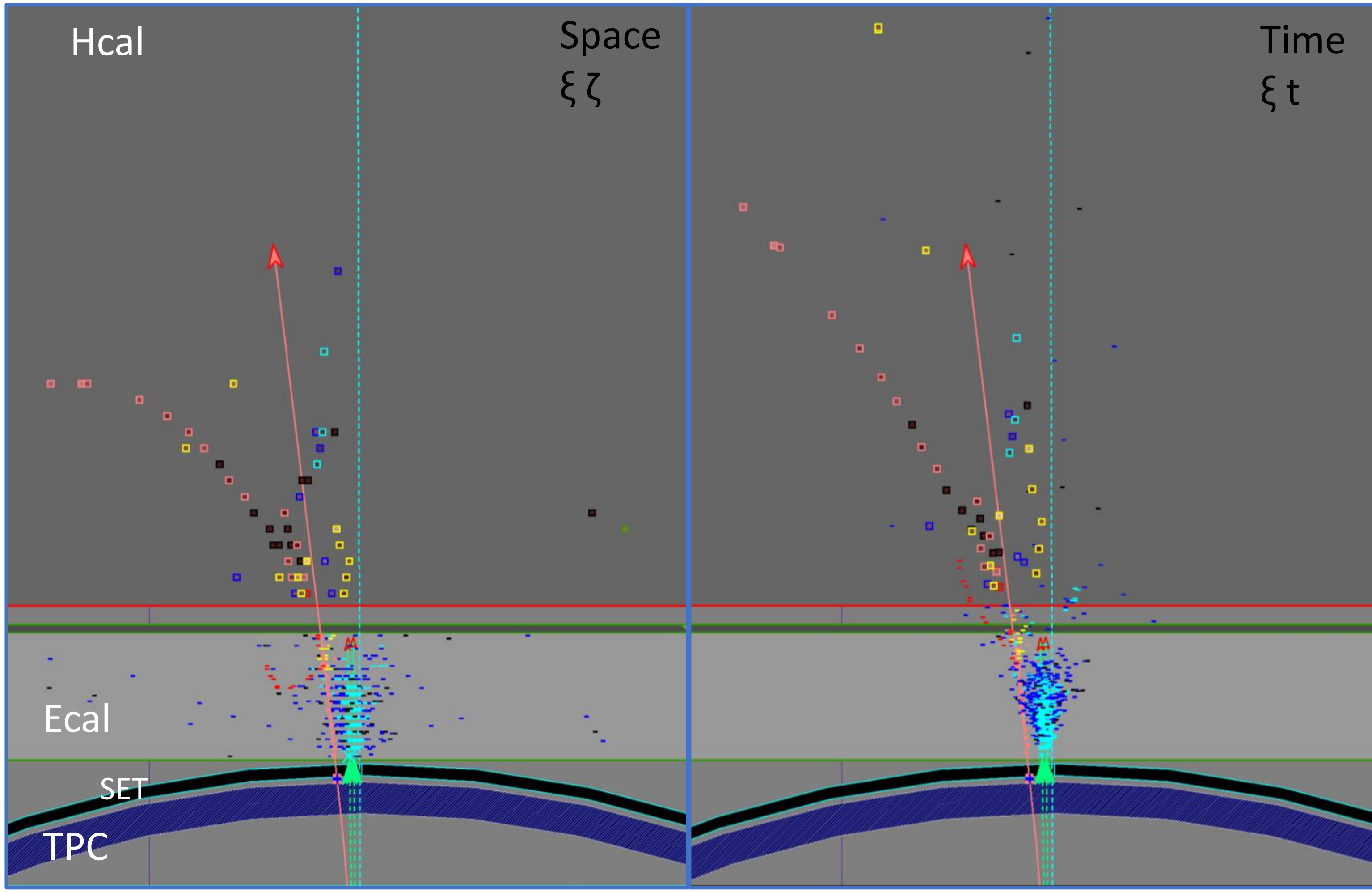


Figure 1: 50 GeV $\tau^- \to \rho^- \nu_\tau$ event

Viewing a shower as a history of interactions
recorded in a sampling calorimeter sensitive medium.

A shower can be seen as the tree formed by the successive interactions of the shower particles with the calorimeter.
In the electromagnetic component the particles are almost only electrons, positrons and photons

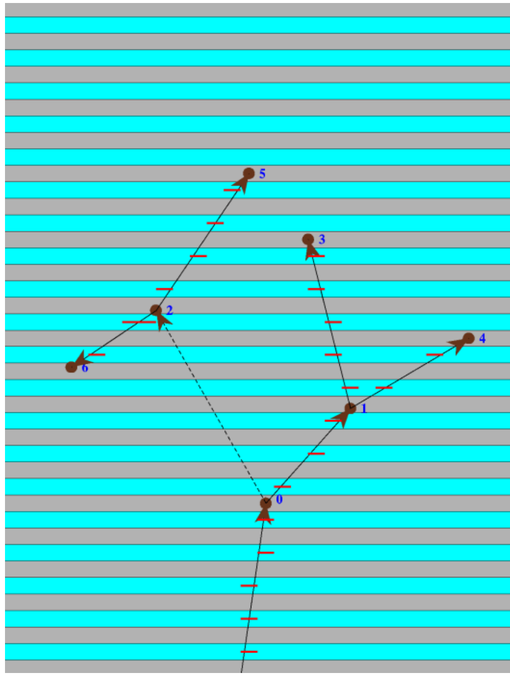
The photons interact mostly by creating pairs
but also, in the shower halo, by Compton diffusion (see previous slide) or nuclear excitation
The result of the interaction is then a collection of electrons, electron-positron pairs, sometimes ions.
The electrons and positrons produce photons by Bremsstrahlung or annihilation.

These particles trajectories connect the interactions.
The interactions occur mostly in the W layers but are detected when particles pass through Si.
Then the reconstructed tree joining Si hit cells will be distorted with respect to the interaction points tree, would it be wise to keep the radiator close to the sensors?
but time oriented tree connectors may nevertheless be built and drawn.

On top of this distortion our Si cells record suffers from some defects:
energy deposits below threshold, electronic inefficiencies or mechanical dead zones between sub-detectors.

If the first two have a random character, the mechanics side is well identified.
The technic of causal connections can adapt readily to these zones identifying where are the ends.

Handling the sub-detectors together helps getting through the dead zones,
for example between Hcal and Ecal, as done in some later examples, or SET and Ecal.



Space scheme of a shower induced by a charged particle

It could be good to have the sensitive medium
close after the radiator

If you start with what is reasonable today, will you ever reach what is mandatory tomorrow?

For making a sampling calorimeter you play with few geometrical entangled parameters, in order
to achieve an energy resolution linked to the energy,
to achieve a position precision
to achieve a time precision:
⇒ the sampling pitch linked to the energy resolution, hence the sampling distance
the cell size linked to the position the angular precision the time precision
the time uncertainty anti-linked to the cell size and the sampling distance, linked to the energy
and an optimum may come from those being similar, *a sampling distance rather larger that the time uncertainty itself commensurable to the cell size*.

But these 3 parameters are strongly physics and hardware dominated
In the ILD design, the Ecal Si-W version has odd and even sampling distances* (!? I know) 3 or 9mm
5.5x5.5mm² cells for a time uncertainty hoped for at 30ps (10mm) including the signal propagation time
The RPC Hcal has sampling distance of about 25mm, cells 1x1 cm² and time uncertainty about 150ps (50mm)
The scintillator version has 26.5mm, cells 3x3 cm² and time uncertainty about 80ps (for 2x2cm²) including the signal propagation time

Specific to the detector parts Ecal, Hcal depending on the detecting medium and to be matched to their structure.

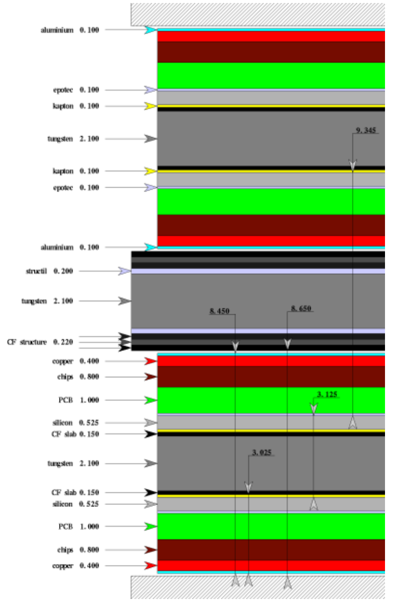
Clearly revisiting would be welcome

* A slight change in design makes it much better: 5 and 7mm

Constructing a shower as a start cell followed by a causal time oriented tree,

- finding the starts of the present showers,
- collecting the future (domain) of each start,
- handling the overlaps.

Structure of the ILD sampling
the distance between adjacent layers is alternatively 3 or 9 mm.



Getting the start

- If the time uncertainty is clearly smaller than the shortest distance between layers, the solution is trivial:

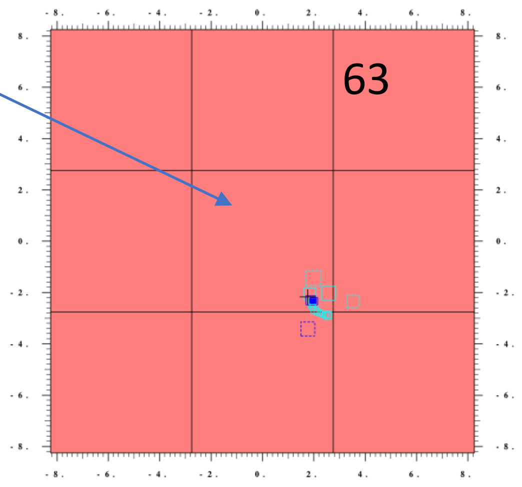
The start hit is the earliest hit. *And that works*!

- But there may be more hits close to the start, remember that the interaction is somewhat before with a short time distance, shorter than space *in the same layer*, then the start point is taken as the 4d barycentre, pink figure.

Problem when the shower develops "along" the sampling

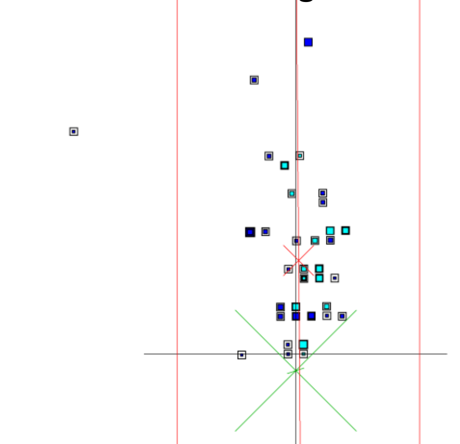
A tolerance on the causal constraint handles the time measurement smearing due to the space granularity and time uncertainty.

Improving the start definition
The central cell is the start hit cell,
the sub-hits are drawn as squares,
there are sub-hits in two cells adjacent to the start by an edge,
the black cross shows the final start,
barycentre of the three cells.

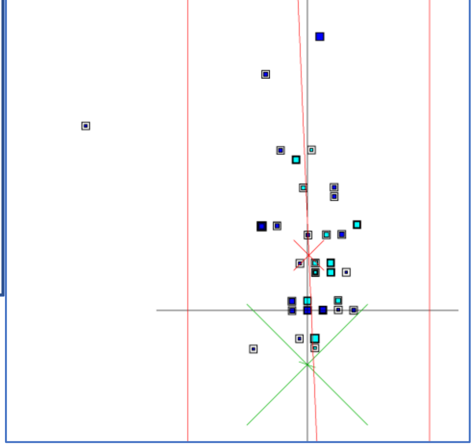


Same 1 GeV photon xz views, with different time smearings the introduction of a time fluctuation moves the start

Time smearing = 1mm



Time smearing = 10mm



With this tolerance, are all the hits still in the future of the start? If large enough

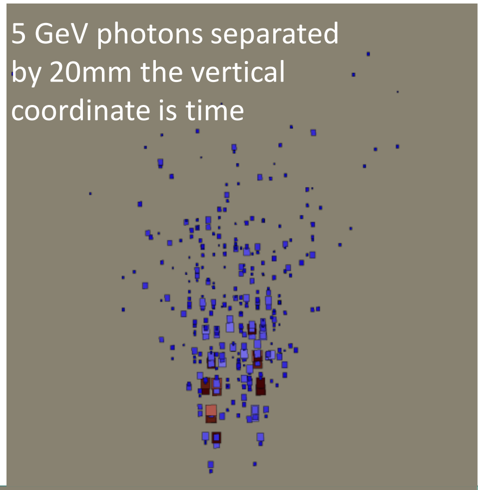
Second trick

- If sampling too sparse but commensurable (e.g. 10mm) to the tolerance we can use the space coordinate along the shower or the layer number to find the true start, because the causal constraint still eliminates the bad possibility of a backscattering.

(Anyway do work on the layers spacing)

Collecting the domain of a start

Having found a start we can collect all the hits which are in its future by testing the causality from the start. We call it the domain of that start:
All the shower hits are inside this domain but it can contain also hits from other showers.



Different forms of the causality constraint:
calling Δt the time difference between actual cell and start and Δd their distance
we have to introduce a tolerance ε in the constraint according
to the way the space and time measurements are affected by uncertainties:

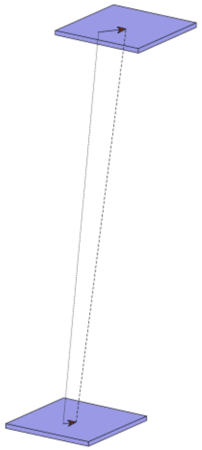
- $\Delta t / \Delta d > 1 + \varepsilon$ does not work, goes bad very soon with Δd
- $\Delta t - \Delta d > \varepsilon$ but the cell geometry induces a strong dependence of Δt – Δd on Δd.

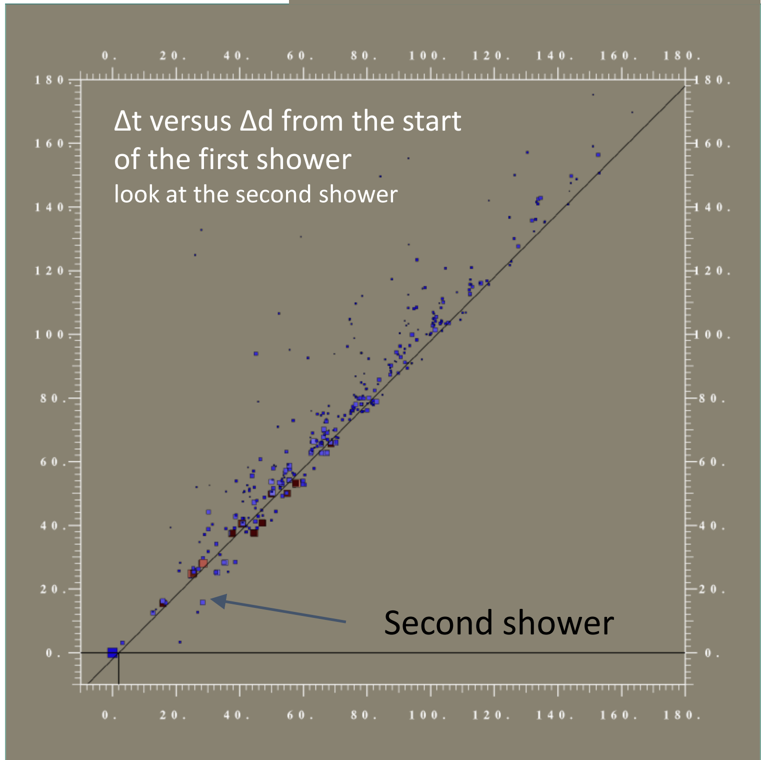
  I have used this most of the time with a dependence of ε on Δd, a step for example.
- $\sqrt{\Delta t^2 - \Delta d^2} > \varepsilon$ which looks nicely relativistic and introduces a dependence on Δt + Δs.

To be worked on.

ε contains a geometrical part linked to the cell size,
hence from about 6mm when the connection spans few layers to much less at large distance,
it contains also the time uncertainty which, for our tests, ranges between 0 and 10mm.

For time uncertainty smaller than the interlayer distance it works beautifully. It is manageable at 10mm.





Efficiency for low energy isolated photons

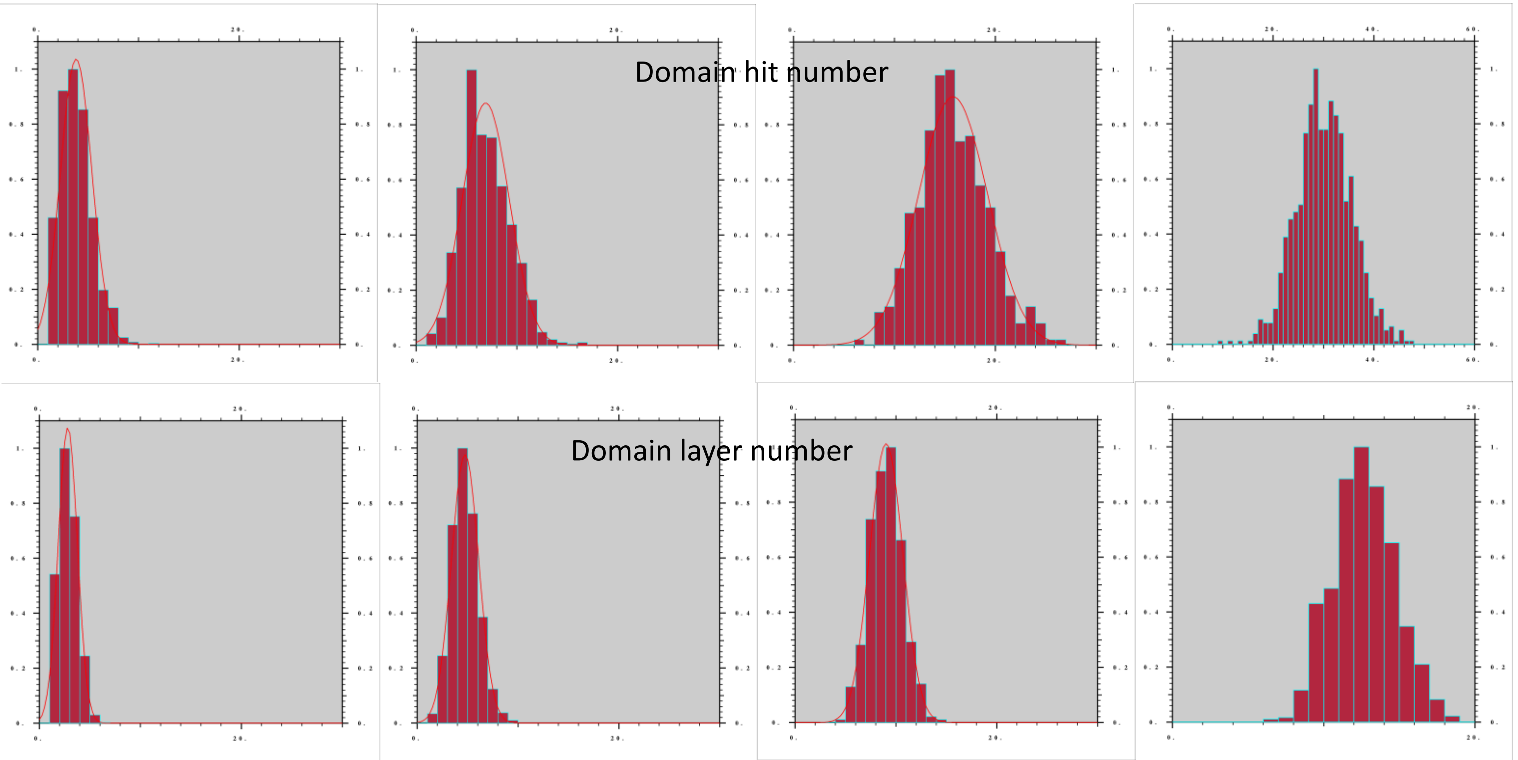
An important contribution :finding low energy photons (Most of those isolated).

Looking at isolated starts, looking at their domains, counting the hits and the layers of the domain.

Recipe: *We require the number of hits and the number of layers in the domain to be > 1*
To compute the efficiencies we apply first fiducial cuts on the photon MC tracks.

This study is done with a time fluctuation at 10mm (30ps).

50 MeV | 100 MeV | 250 MeV | 500 MeV



Collect showers starts:
Identify their domains,
Look if they are associated to a track .
If none is found it is declared neutral,
hadrons are separated by depth of conversion and shape (see later)

Photon efficiencies
We apply first some fiducial cuts to reject events where the photon interacts before reaching the calorimeter

Energy	event number	≥ 2 hits	≥ 2 layers
50 MeV	944	81%	76%
		for 3 hits and 2 layers 59%	
100 MeV	942	98.9	98.5%
250 MeV	379 all have > 5 hits	100%	100%

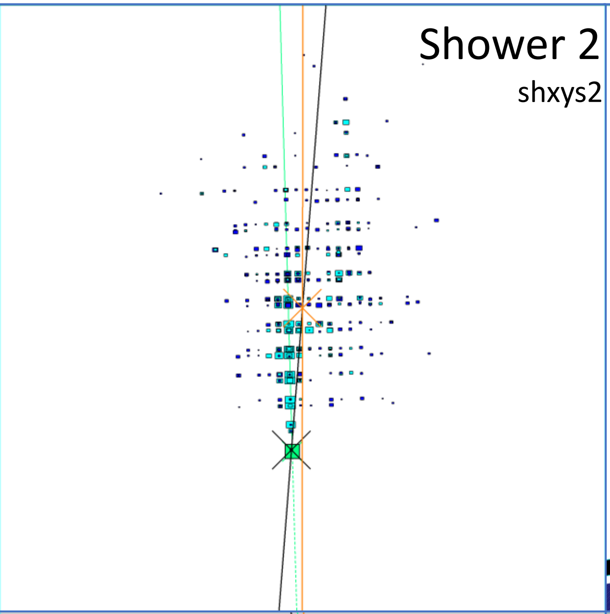
But can they come from noise, be fakes?
The S/N ratio has been measured above 10.
The cell number is about 10^9.
We look for at least 2 hits synchronised together and with beam at about 30ps.
⇒ Beam photon halo, not fakes

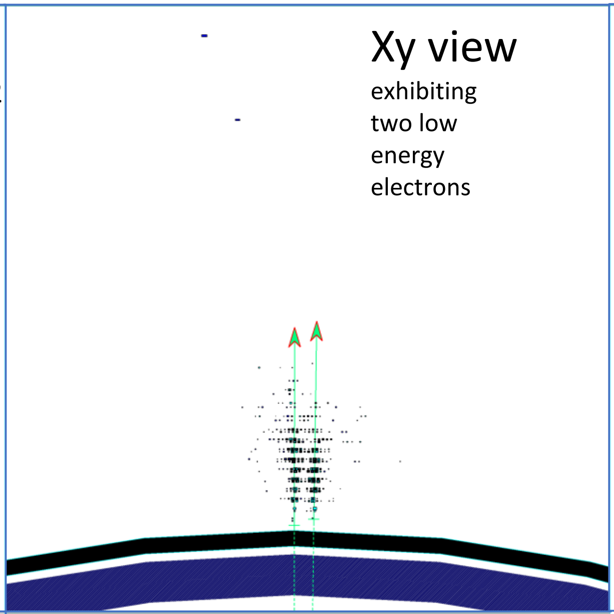
What if close to another shower? See later

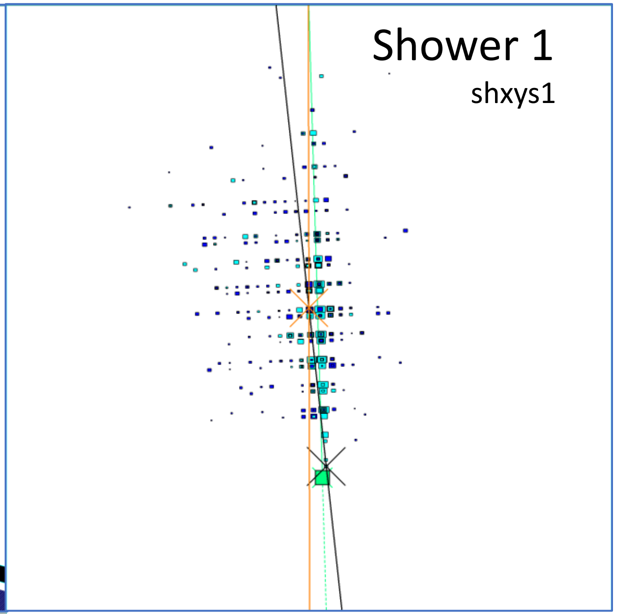
Example of close by photons

Evt 6

Trying to figure out more elaborate examples

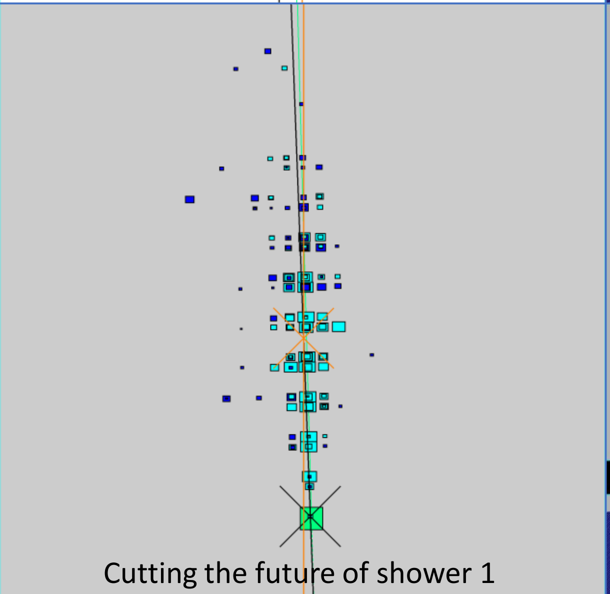


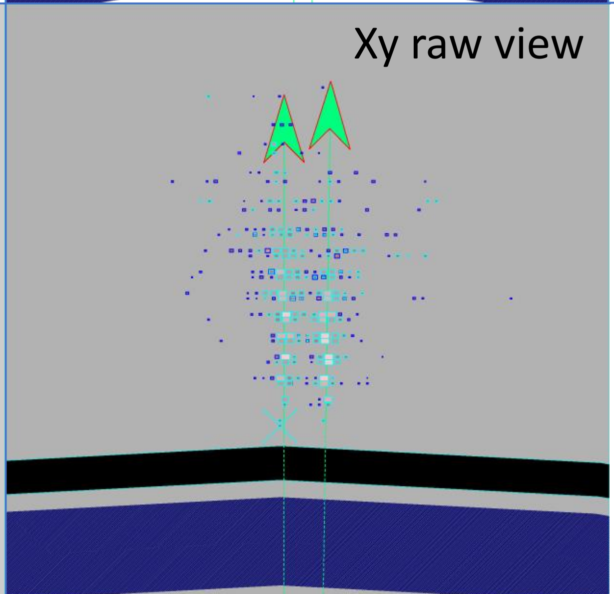




2 10 GeV photons
at 37mm transverse distance

Total 618 hits for E = 461
The shower 1 contains 451 hits 73% , E=280 61%
the other 493, E= 309
with an overlap of 326 53% , E=129 28%



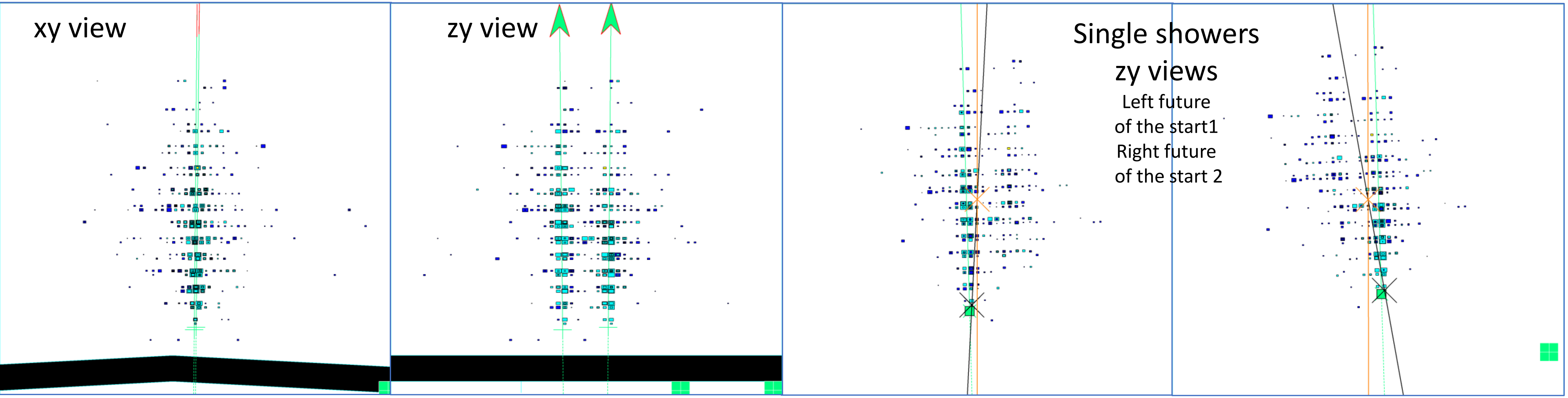


Cutting the future of shower 2

The size of the cells
depends on the energy
The cyan are positron drawn
on top of the electron blue

Example of double photons

Evt 5



The two 10 GeV photon impacts are at a distance of 35mm transverse to the line of flight
the contamination of each shower by the other is obvious but no confusion at the level of the starts.
The shower 1 contains 515 hits, the other 508 with an overlap of 362 and a total of 660 for 687
above energy threshold and in energy.

The size of the cells depends on the energy
The blue cells are electrons
the cyan are positrons
The green crosses or squares are the photos endpoints.
The black X are the starts
The orange X are the barycentres
The orange line is the main axis of the ellipsoid of inertia

The strategy of analysis

How to analyse a complete event in the calorimeter:

Find in the calorimeter the earliest hit: the first start

Collect its domain, consider the domain complement

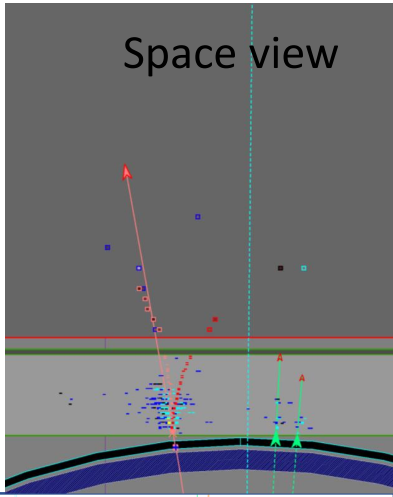
Find the earliest hit: the second start, collect its domain

which may well overlap with the first one

Consider the complement of the two domains union,

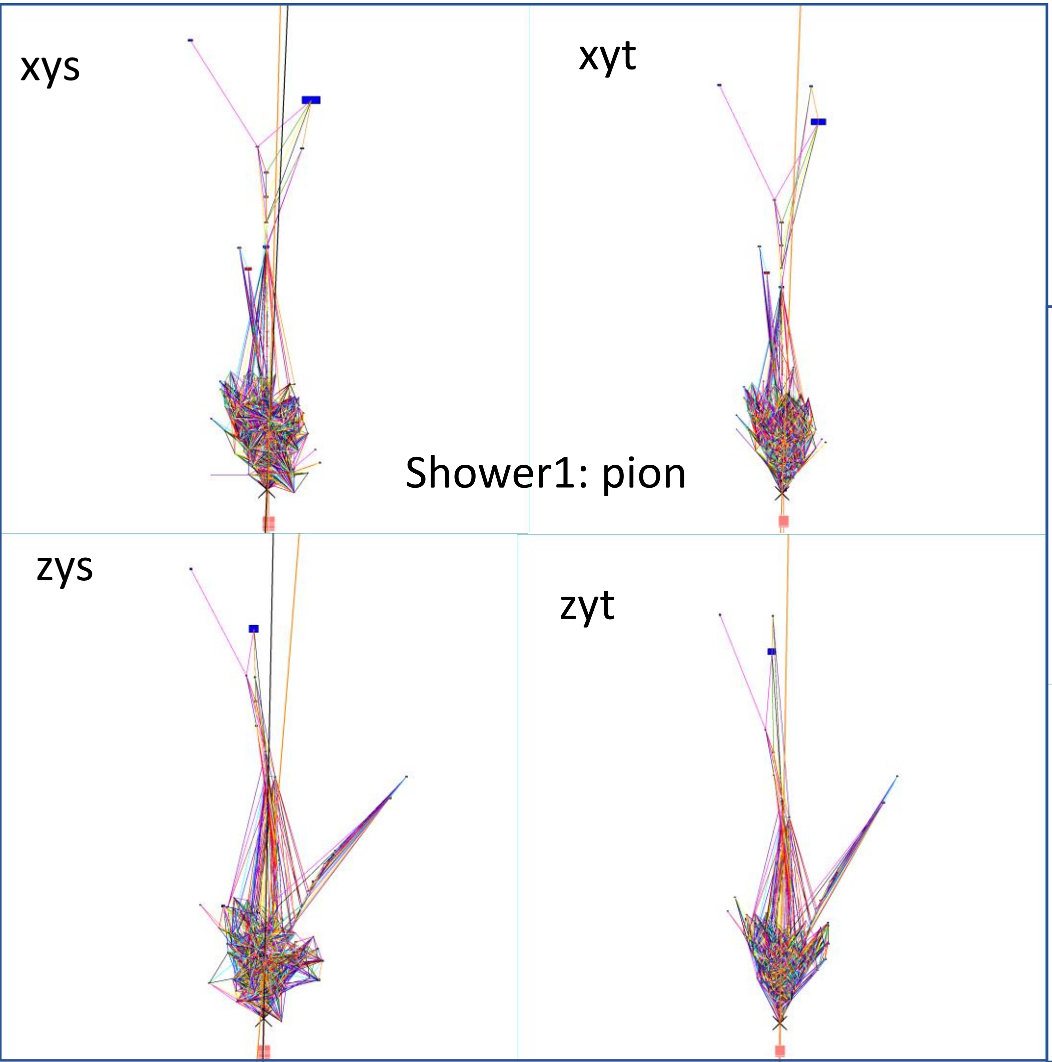
and so and so

Then we can work separately on each domain

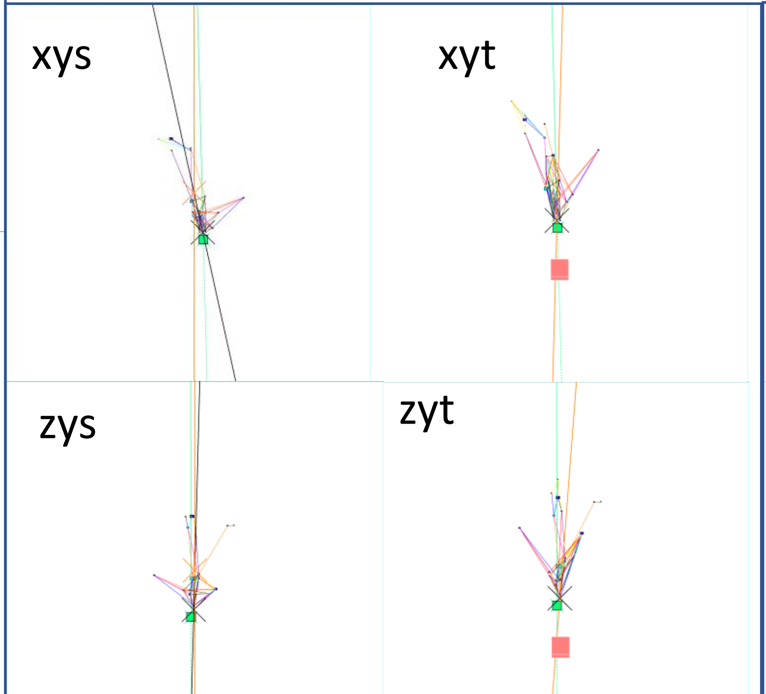


event 4 a simple and clean

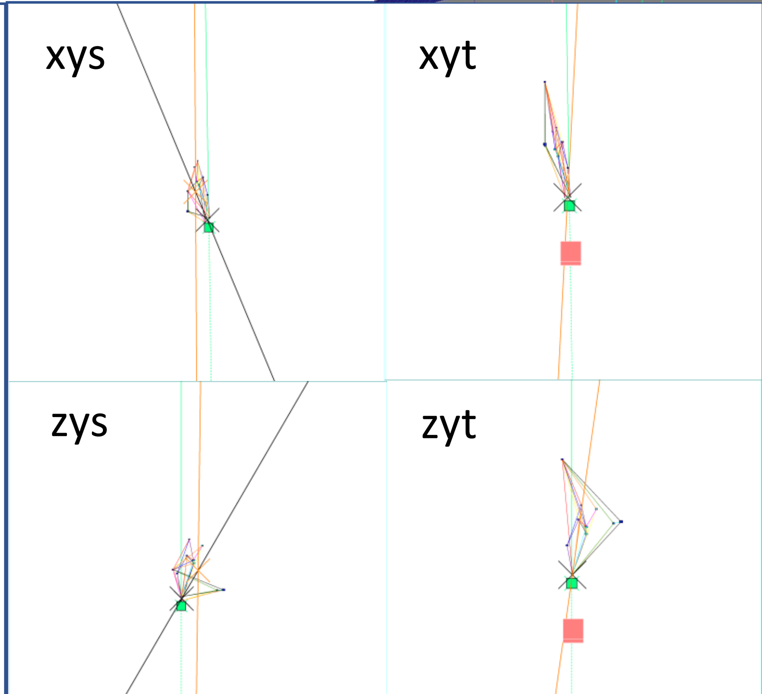
50 GeV τ decaying into $\rho^- \nu_\tau$



Shower1: pion



Shower2: 340 MeV γ



Shower3: 120 MeV γ

I showed you things on hadrons and Hcal
through the taus
But I have not the leisure to expand on interesting subjects like K^0_l or neutrons, especially at low energies

Some other time

Having identified a shower with its start and its domain what can we say about the photon position?
and, under the condition of knowing the origin, the photon direction

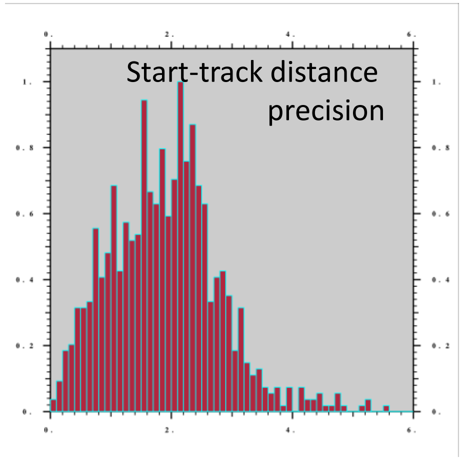
The first tool is the start

When the start is found, we know that the position is within the start cell, our approximation is the centre of the cell or better if the start has more cells. The precision can be studied by looking at the distance track-cell centre, top-left figure

This is *independent of the energy*, then useful at low energy. The distribution peaks at 2mm as expected.

This induces an angle uncertainty < 1 mrad under the assumption that the origin is the collision point

unsensitive to the neighbouring



Another way is to compute the barycentre of the shower,

this is energy dependent and sensitive to isolation.

But the transverse fluctuation of the shower can be reduced *by a cut on "causality"*

: then the track-barycentre distribution

peaks at 1.5mm at 2 GeV.

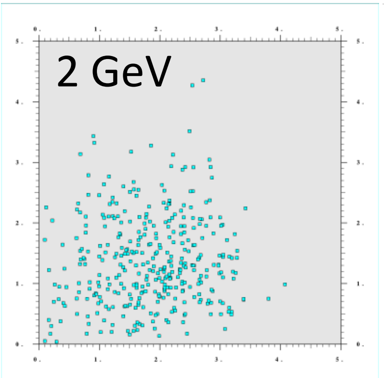
Subtle cut on the long times, sources of fluctuations

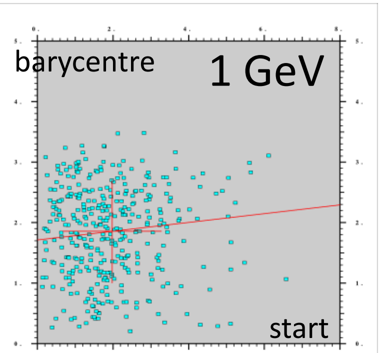
The adjacent (below) figures show that there is no correlation between the two methods.

They can be combined and the median goes to 1.04 at 2 GeV. About half a mrad.

To be compared with the minimum opening angle of a 10 GeV π^0: 10mrad.

Notice that in the case of a π^0 the origin is the same for both photons.





Correl coeff 0.063 θ = 0.072

Measuring the directions

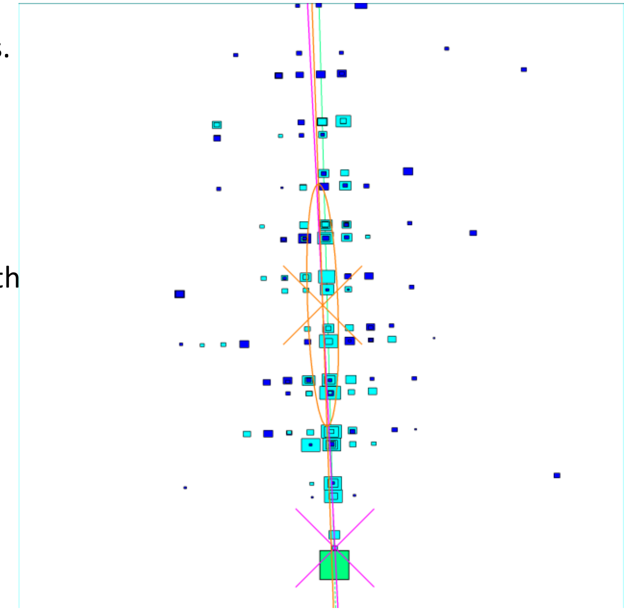
An other method is to look for the direction as provided by the shape of the shower and specifically by the shower moments. These being sensitive to outliers, the thrust may be more adequate.

$$M = \frac{1}{E}\sum_{i=1}^{n} E^i \begin{pmatrix} P_x^i P_x^i & P_x^i P_y^i & P_x^i P_z^i \\ P_y^i P_x^i & P_y^i P_y^i & P_y^i P_z^i \\ P_z^i P_x^i & P_z^i P_y^i & P_z^i P_z^i \end{pmatrix}$$

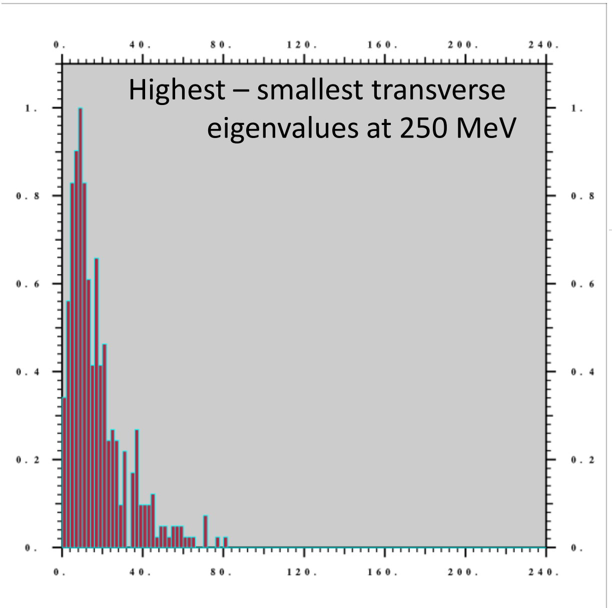
where $E = \sum_i E^i = E_1 + E_2$
if the shower contains 2 particles

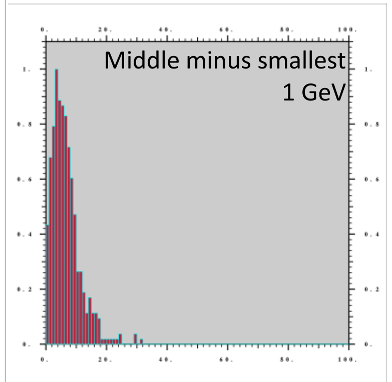
$$m^2 = E^2 \frac{(\lambda_2 - \lambda_3)}{L^2}$$

The P^i are the cells coordinates, M is the shower moments matrix.
The eigenvectors provide the axes of the ellipsoid of moments (orange),
the eigenvalues which have the dimension of [L²], measure the square of the axes.
One value is expected to be large, the associated eigenvector
providing the shower direction axis (orange),
which may be compared to the directions provided by other methods:
the line barycentre-start (magenta), (the green line is the line of flight)
the line of flight passing by the barycentre or the start or a combination of both



The two other eigenvalues measure the transverse shape,
hence the revolution symmetry of the shower and provide a way to check
that the shower corresponds to a photon alone and not to a π^0.
The square of the mass of a system of two particles is linked
to the difference of the second and third eigenvalues.





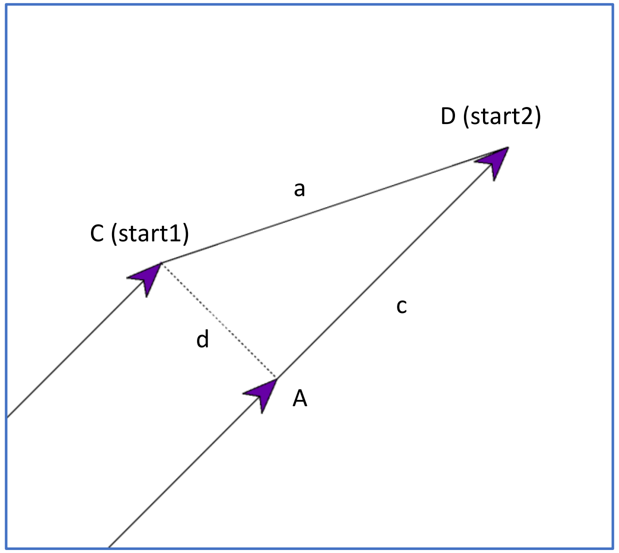
The probability that there are two particles in a shower can be assessed from the difference of these eigenvalues (introduced by Bulos), see slide
We can plot this for one photon distributions at different energies

At 1 GeV the error on the angle of the ellipsoid axis is 59 mrad
It corresponds to missing the main vertex by 12 cm. Redo

Probability to pick a photon close to another shower

Specific performances used by JC

Consider a photon shower with its start,
at what distance from this start can we dream to see a later photon start?
There are other ways to notice a close by photon, like moments.

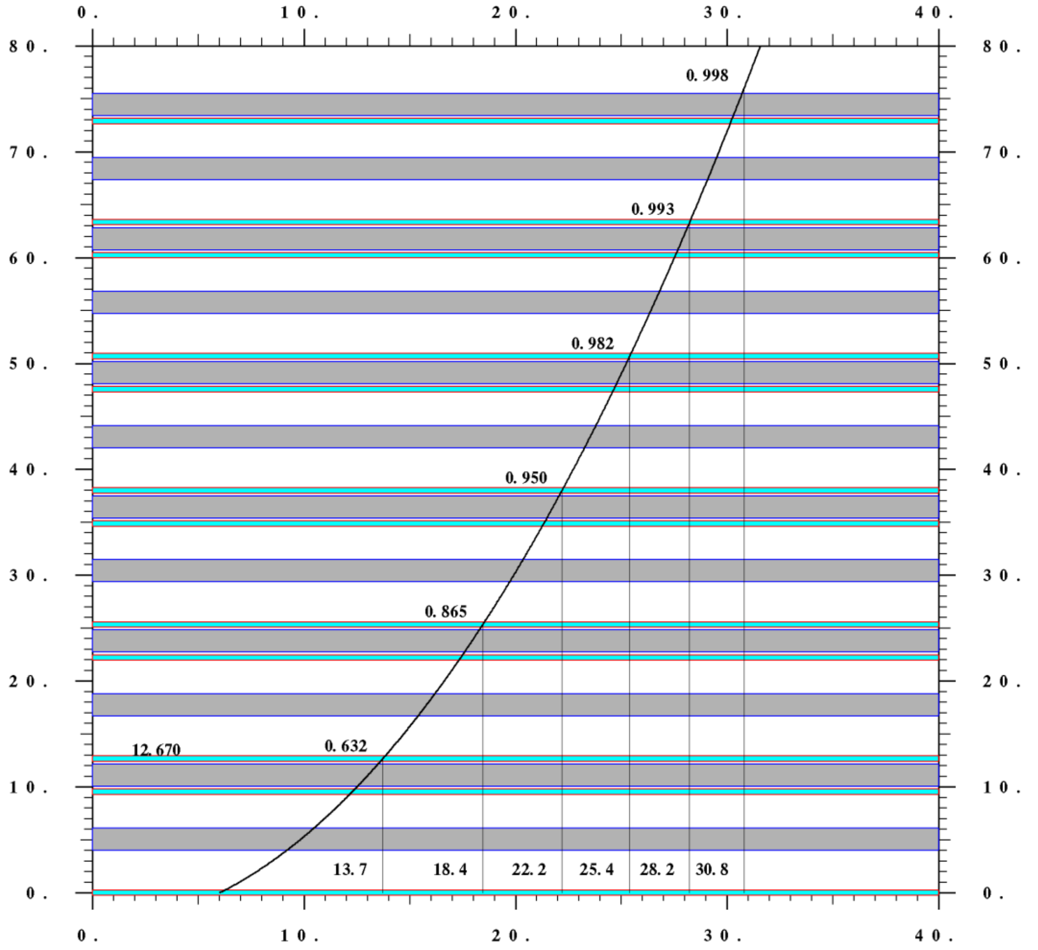


Calling k the time tolerance, the condition is
a-c > k
at the limit a-c = k
$d^2 = a^2 - c^2 = (a-c)(a+c) = k\,(a+c)$.
$c = \frac{1}{2}\left(\frac{d^2}{k} - k\right)$, curve on the right plot

Example from the right diagram:
At a distance of 18.4 mm
the probability to see a new later photon start is 86%

For a time uncertainty of 20 ps

In grey the W layers, in cyan the Si layers



In this drawing the start happens in an odd layer the first physical layer being numbered 0.

Few words on the statistical approach of the dense electromagnetic showers:
moments ...
It appears more difficult with rather sparse hadronic showers

From moments we can know that you have at least 2 overlapping showers
If two γs from a π^0 overlap but with distinct starts we can compute their energies from the sum of the energies and the angle given by the sole starts or the shower beginnings

$$E_1 + E_2 = E \qquad\qquad E_1\, E_2 = \frac{m_{\pi^0}^2}{2(1 - cos\theta)}$$

The mass can be inferred from the transverse moments, once known, the two energies can be computed
Do we need them? Or the individual directions?
Having a good approximation of the energy sharing, the photon energies can be fitted

But why am I staying with a purely 3d statistical approach, what if I would mix with time?
Would I keep a euclidean view or not, what would become important? What can I learn?

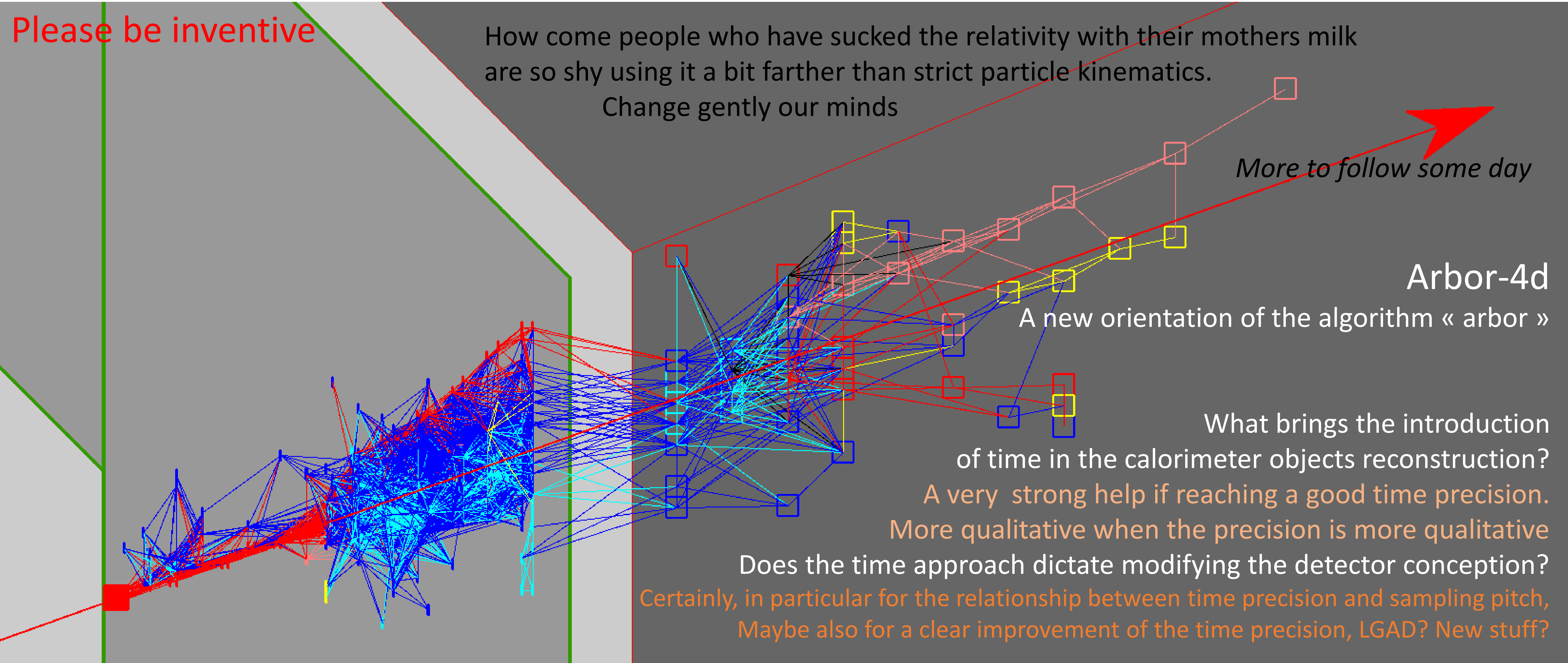
Next day?

Back to arbor_4D

That has been largely done, more can be. Structure the results

Next time

Please, be inventive



Please be inventive

How come people who have sucked the relativity with their mothers milk are so shy using it a bit farther than strict particle kinematics.

Change gently our minds

More to follow some day

Arbor-4d

A new orientation of the algorithm « arbor »

What brings the introduction of time in the calorimeter objects reconstruction?

A very strong help if reaching a good time precision.

More qualitative when the precision is more qualitative

Does the time approach dictate modifying the detector conception?

Certainly, in particular for the relationship between time precision and sampling pitch,

Maybe also for a clear improvement of the time precision, LGAD? New stuff?

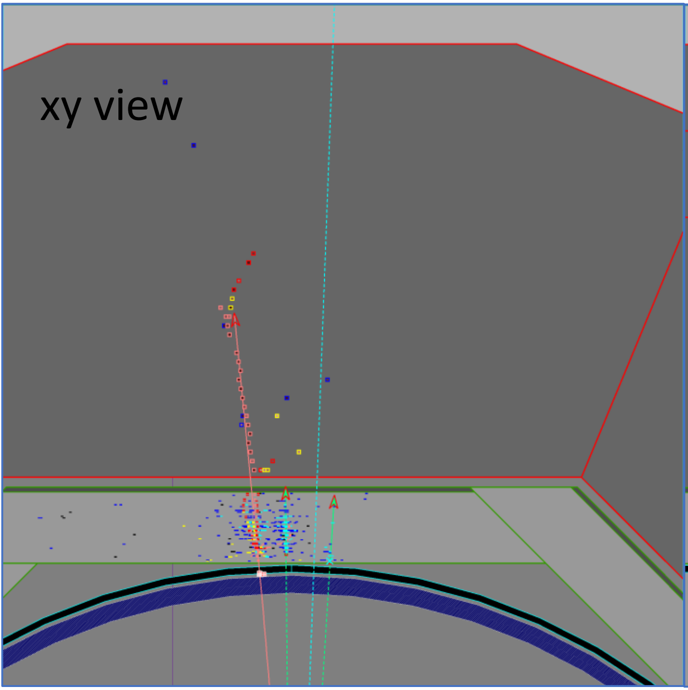
The end

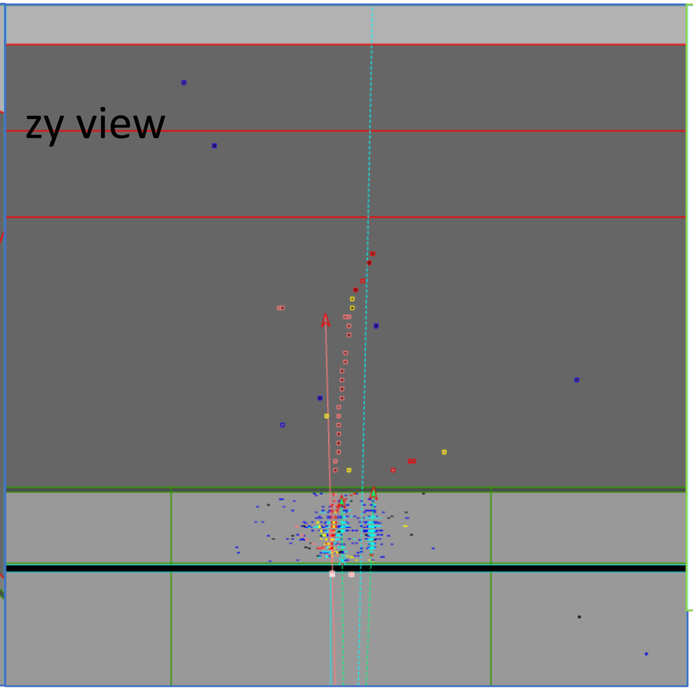
Backup

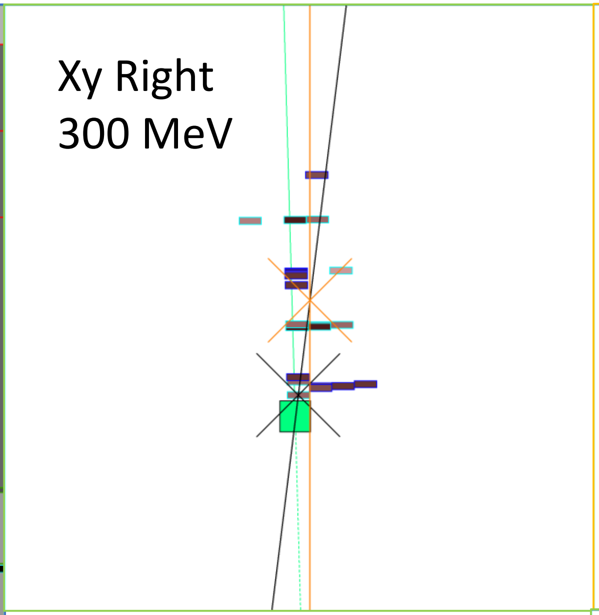
50 GeV $\tau^- \to \rho^- \nu_\tau$ event 14

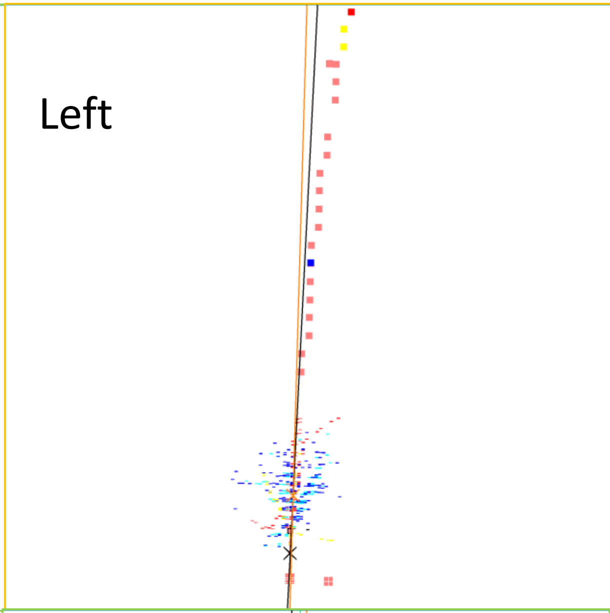
Raw views

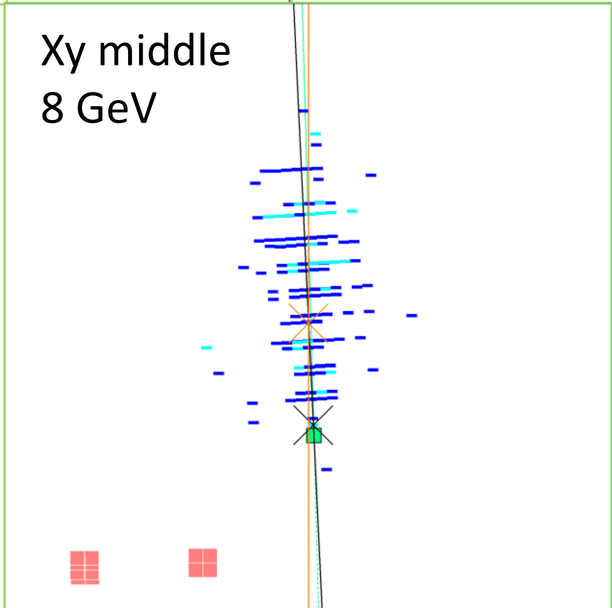
After reconstruction











The three showers are reconstructed:

1 a 300 MeV photon

2 a 23 GeV charged pion

3 a 8 GeV photon

The 2 pink squares are the SET hits

The black X is the start, the orange cross is the barycentre,
the squares are the track endpoints

The black line is the direction given by the start and the barycentre,
the orange line is the main axis of the shower.

How to analyse a complete event in the calorimeter:

Find in the calorimeter the earliest hit: the first start

Collect its domain, consider the domain complement

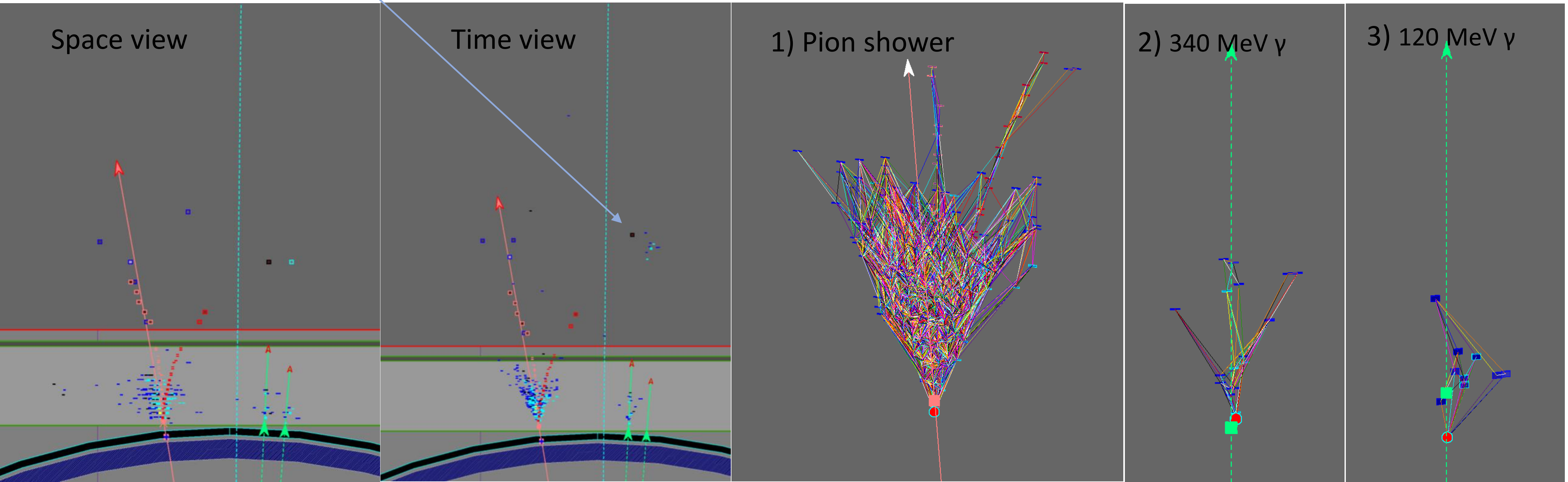
Find the earliest hit: the second start, collect its domain which may well overlap with the first one

Consider the complement of the two domains union, and so and so

Then we can work separately on each domain

This is illustrated with event 4 a simple and clean 50 GeV τ decaying into $\rho^- \nu_\tau$

A slow photon??



Plan of the presentation

- Measuring the 4d space-time of the events produced in the ILD detector
- This space-time as a Minkowsky space with its norm
  - A pattern search always helped by one more dimension
  - But correlation between time and space
  - The norm and the notion of causality, an event in the future of the beam-beam interaction
- Understanding a shower as a history of interactions recorded in a sampling calorimeter
  - the defects of the record
  - The cells interconnections along the time line
  - Handling the sub-detectors together, getting through the dead zones
- Building the shower as a start (particle calorimeter interaction) followed by a time oriented tree, finding start, overlaps
- What provides the knowledge of the start? collecting the domain
- Measuring the positions, measuring the directions, measuring the energies
- Getting the substructures, signing the nature of shower linked particles (e.g. taus), improving the energy estimate
- Collecting the neutrals and their origins
  - Efficiency for low energy photons
  - Probability to pick a photon close to another shower
  - Specific performances used by JC: low energy photon detection efficiency, close by showers
- Statistical approach of the electromagnetic shower, moments or .. Mass splitting of energies

photon_energy_GeV	resolution	resolution_error
0.1	0.3221310495020391	0.0053461502044693
0.25	0.2387350152561416	0.0017936968537283
0.5	0.1738651171497932	0.0017771026822713
1.0	0.1305642204862711	0.0021805689824668
2.0	0.0973891462562992	0.0011217663133953
5.0	0.0647859071818347	0.0008843576720853
10.0	0.0484589049364831	0.0007004587247311
20.0	0.0343086511699615	0.000591922833012
30.0	0.0292544499087485	0.0005919391487021
40.0	0.0248494936907954	0.0003222100305896
50.0	0.0226852542660961	0.0003105113197298
60.0	0.0209953992462071	0.0003096261975146

les données sont bien ajustées (pdf attaché) avec la fonction
[a]*x+[b]+[c]/x+[d]*x^2 ou x=1/$\sqrt{E}$
où j'ai fixé c à 0

χ^2 / ndf 19.55 / 8
a 14.29 ± 0.22
b 0.2872 ± 0.0378
c 0 ± 0.0
d -1.312 ± 0.121

Linearity corrected resolutions with the optimised parametrisation:

Energy	cor-resol	raw H_reso	factor	en_res
0.05	0.564	0.48	1.18	0.76
0.1	0.407	0.37	1.10	0.52
0.25	0.252	0.235	1.07	0.31
0.5	0.201	0.1840	1.09	0.25
1.	0.163	0.143	1.14	0.18
2.	0.122	0.099	1.22	0.12
5.	0.156	0.115	1.35	0.13

Up to now we considered the causality solely between the start and the shower cells ,
which ignores any shower scale, radiation or interaction length, shower opening or mechanical sizes.

This can come in when reconstructing the causal detail of the shower tree.
We introduce then a spatial length cut in the connections, (rather than time)
depending on the location of the beginning and the end.

We construct the valid connectors, causal and limited, between cells.
This operation may help discovering substructures in the domains reflecting for example
neutral hadron production,
A shower cleaning by requesting a more local consistency .

Evading charged tracks and in Hcal momenta measurements (Calor 2010 already)
These substructures shed light on the nature of the particles involved
Improving energy estimate
The calorimeter as a tracker
In calorimeter beta measurement, energy by range
Identification of the electromagnetic zones, compensation?