Improving pile-up handling in the Mu2e calorimeter MC

Fermilab Summer Internship

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September 11, 2013

Outline

Mu2e calorimeter

Role of the calorimeter

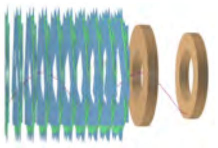
- Redundancy for the events reconstructed in the tracker.
- Trigger capability.
- Particle identification.

Requirements

- Energy resolution of $\sigma_E < 2\%$ at 100 MeV to confirm tracker energy measurement.
- Time resolution less than 0.5 ns (energy deposits in time with tracker events).
- Work in a magnetic field of 1 T.

Current design

- Two-disks of $\sim$ 1000 hexagonal LYSO crystals each.



- Two $1 \times 1\,cm^2$ APDs for each crystal.

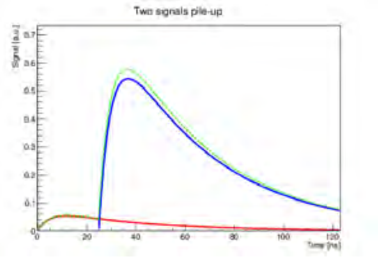
Objectives of the project

- Detector interaction simulation by GEANT4:
  - step-points along the particle path in the calorimeter.
- V. Stomacchi is studying the reconstruction of piled-up signals.
- We want to implement a parametrized readout simulation + signal reconstruction in presence of a pile-up.
- Easily tunable algorithm.

Current model of digitization

1. G4 step-points closer than 30 *ns* merged at readout level (`MakeCaloReadoutHits`).
2. Crystal hits closer than 100 *ns* merged at crystal level (`MakeCaloCrystalHits`).

- For merged signals: energy is the sum of the energies and time is the time of the first signal.
- Limited ways of handling pile-up.
- Constants haven't a direct physics meaning, are correlated which complicates tuning.

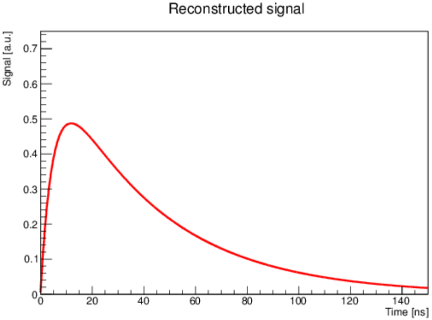


Current model: **event signal** at $t = 25\,ns$ merged with the **background one** at $t = 0\,ns$.

Parametrization of the signal

Standard signal shape parametrization

$$A \cdot (e^{-\frac{t}{\tau_D}} - e^{-\frac{t}{\tau_R}}) = A \cdot e^{-\frac{t}{\tau_D}} (1 - e^{\frac{t}{\tau_D} - \frac{t}{\tau_R}})$$



Parameters

- Decay constant time $\tau_D = 40\,ns$ ($\sim$ decay time of LYSO);
- Rise time $\tau_R = 10\,ns$ ($\sim$ electronic rise time);
- Amplitude $A \propto \frac{E}{\tau_D - \tau_R}$ in $\int S(t)\,dt \propto E$ approximation, where E is the energy of the hit.

New algorithm

Double signal: $C_1 \cdot (e^{-\frac{t}{\tau_D}} - e^{-\frac{t}{\tau_R}}) + C_2 \cdot (e^{-\frac{t-t_0}{\tau_D}} - e^{-\frac{t-t_0}{\tau_R}})$

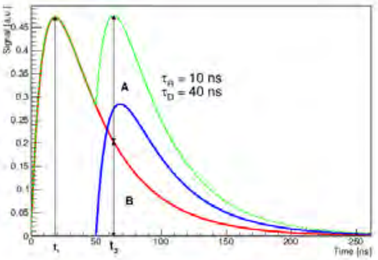
Steps

In `MakeCaloCrystalHitsNew` module:

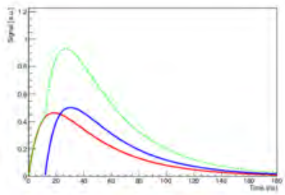
1. Merge all the signals within the leading edge time t_1.
2. If $A > k \cdot B$ at $t = t_2$ (see figure), the two signals are considered separately, otherwise merge them. Start from $k = 1$.

- $t_1 = \frac{\tau_D \cdot \tau_R}{\tau_D - \tau_R} \cdot \ln(\frac{\tau_D}{\tau_R}) \approx 18.48\,ns.$
- $t_2 = -\ln(\frac{\tau_D}{\tau_R} \cdot \frac{1+\frac{C_2}{C_1} e^{\frac{t_0}{\tau_R}}}{1+\frac{C_2}{C_1} e^{\frac{t_0}{\tau_D}}}) \frac{\tau_D \cdot \tau_R}{\tau_R - \tau_D}.$

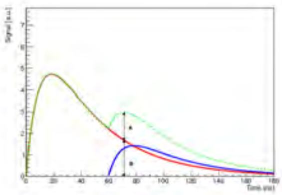
- Signals simulated as combination of two exponentials: quite close to reality.
- Analytical solution.
- Tunable constants for the signal shape (τ_D, τ_R).
- Tunable constant for signal merging (k).
- Issues related to timing resolution are outside the scope of this talk.



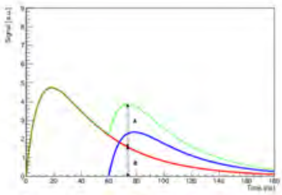
Examples



Merged
Second signal arrives within the leading edge time t_1.



Merged
Second signal arrives after the leading edge time, but $A < B$.



Not Merged
Second signal arrives after the leading edge time and $A > B$ (in this case $k = 1$).

Implementation and validation

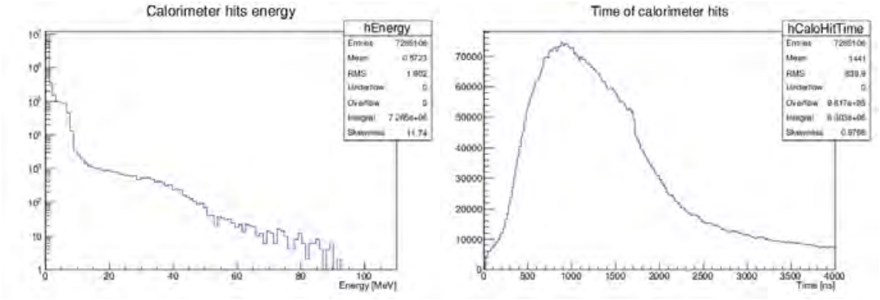
Modeling of the mixed events

Background	Simulated e. (millions)
DIOs	20
Neutrons	38
Protons	3.2
Photons	63

- These events are needed for 1000 μbunches.
- The numbers of events per μbunch are taken from [1].
- The events are filtered by the `MinimumHits` module in `trackerOrCalorimeter` mode, in order the reduce the size of output files.

[1] Mu2e Doc 2297-v2.

Distributions of the calorimeter hits



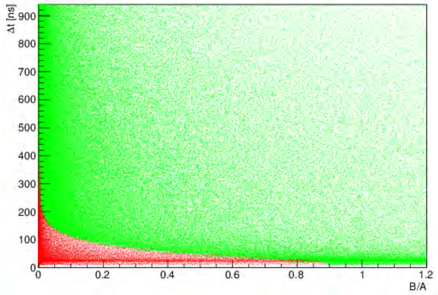
- We generated 1000 conversion electrons with a standard mix of backgrounds [2].
- These are the distributions of the energy and of the time of the hits in the crystals.

[2] Mu2e Doc 2351-v1.

Results

$$A \cdot (e^{-\frac{t}{\tau_D}} - e^{-\frac{t}{\tau_R}}) + B \cdot (e^{-\frac{t-t_0}{\tau_D}} - e^{-\frac{t-t_0}{\tau_R}})$$

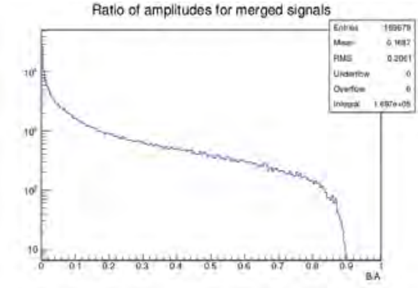
Δt vs $\frac{B}{A}$ for every signal

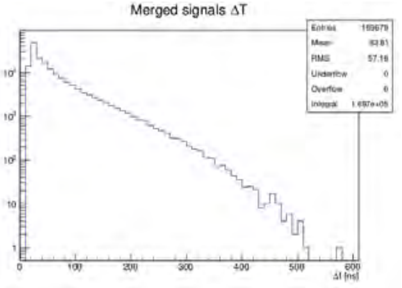


Three distinctly separated zones:

- $\Delta t \ll 100\, ns$ and $\frac{B}{A} \ll 1$. Two signals very close in time and the second one much smaller than the first one: always merged.
- $\Delta t \gg 100\, ns$ and $\frac{B}{A} \gg 0.1$. Two signals quite far in time and the second one not so smaller than the first one: never merged.
- $\Delta t < t_1 \approx 18\, ns$. Two signals within leading edge time t_1: always merged.

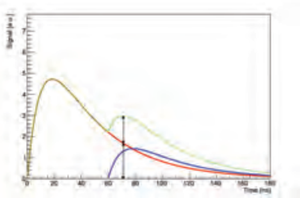
Merged signals





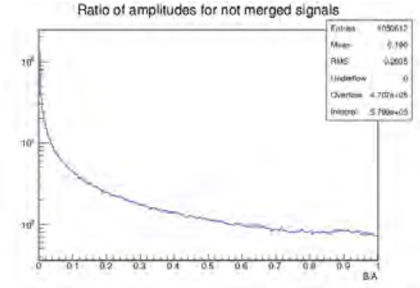
These are the projections for the ratio $\frac{B}{A}$ and for the Δt of the merged signals:

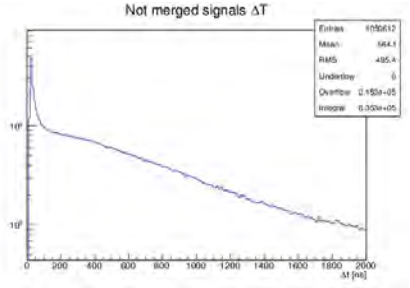
- when the second signal is sufficiently large (~ 0.9 the first signal) merging does not occur;
- in the Δt distributions we observe a long tail up to 600 *ns*.



Results

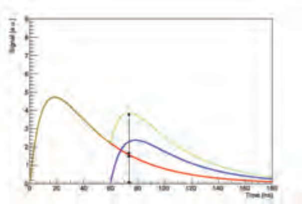
Not merged signals





These are the projections for the ratio $\frac{B}{A}$ and for the Δt of the not merged signals:

- the second signal is not merged when its amplitude is greater than the one of the first signal ($\frac{B}{A} > 1$);
- there is a significant number of signals separated by less than 100 *ns* which get resolved.



Validation

Default pile-up handling algorithm (`MakeCaloCrystalHits`):

- A background hit 100 *ns* before the CE hit could "steal" a crystal from the cluster.
- A background hit within 100 *ns* after the CE one is always merged.
- A background hit more than 100 *ns* later is always considered a separate hit.

Expected improvement:

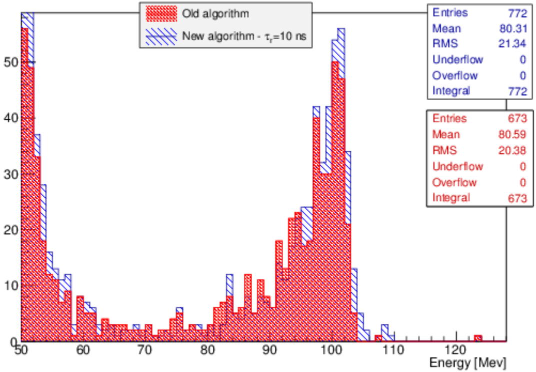
1. ~ 6000 hits in the calorimeter per μbunch and ~ 1000 crystals per disk.
2. $6/2 = 3$ hits per crystal per μbunch (same occupancy for the two disks).
3. For a μbunch time of 1700 *ns*, we have 1 hit every $\sim 550\,ns$.

Probability to lose the seed of the cluster because of the background

Previous algorithm: $\frac{100\,ns}{550\,ns} \sim 18\,\%$ New algorithm: $\frac{18\,ns}{550\,ns} \sim 3.3\,\%$

Improvement of the number of events in the CE peak of $O(10)\,\%$

Cluster energy



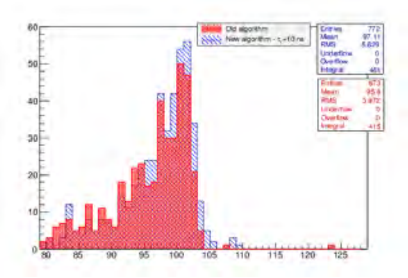
With the new algorithm we observe:

- more entries in the [50 : 60] *MeV* interval (DIOs tail);
- less entries in the [60 : 80] *MeV* interval;
- more entries in the [80 : 110] *MeV* interval (CEs).

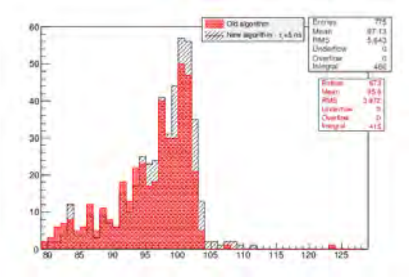
Energy of the CE clusters increases because there are less crystals "stolen" by the background: the clusters in [60 − 80] *MeV* interval move to the CE peak.

Cluster energy

$\tau_R = 10\, ns$



$\tau_R = 5\, ns$



Assuming as the CE peak the interval $[95 - 105]\, MeV$ we obtain:

- $\sim 24\%$ **increase** in the number of events in the peak with $\tau_R = 10\, ns$.
- $\sim 25\%$ **increase** in the number of events in the peak with $\tau_R = 5\, ns$.

The improvement obtained halving the rising time constant τ_R is quite small.

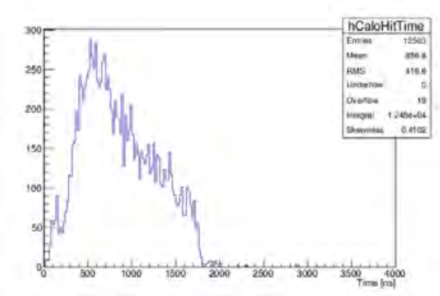
Summary and plans

- With this new algorithm we observe a $O(20)\,\%$ increase in the number of events in the CE peak.
- `MakeCaloCrystalHitsNew_module` committed into the CVS repository (`HitMakers`).
- The constants used have now a direct physics meaning: τ_D and τ_R.
- Halving the rising time constant τ_R doesn't improve significantly the clustering.
- Discuss results at the Mu2e calorimeter meeting, switch to new default.
- Write a note describing the algorithm.

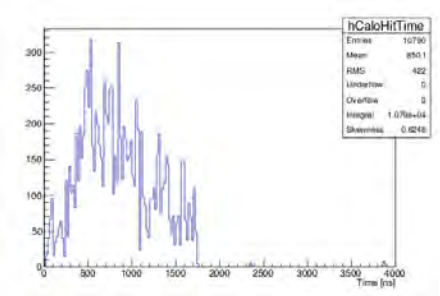
Backups

Calorimeter hit time distribution for every component

DIOs



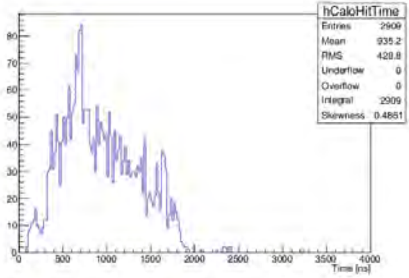
Conversion electrons



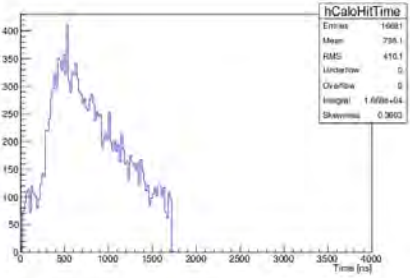
Backups

Calorimeter hit time distribution for every component

Protons



Photons



Calorimeter hit time distribution for every component

Neutrons