Improving pile-up handling in the Mu2e calorimeter MC

Fermilab Summer Internship

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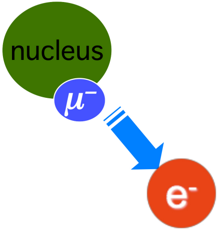
September 26, 2013

Outline

Mu2e experiment

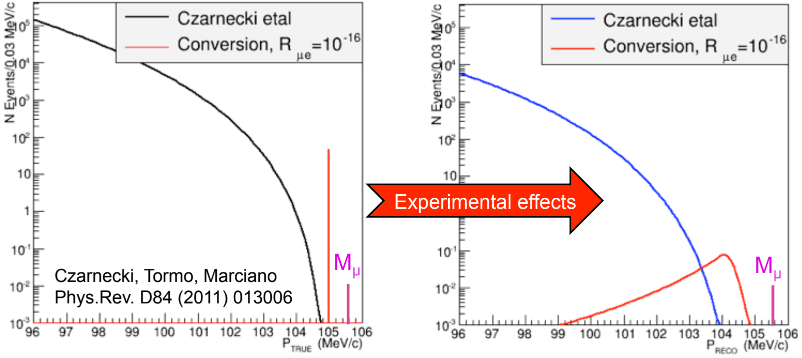
$$\mu^- N \longrightarrow e^- N$$



- Initial state: muonic atom
- Final state:
  - **Single mono-energetic electron** $\sim$ 105 MeV.
  - Recoiling nucleus (not measured).
  - Neutrino-less.
- Non-zero but negligible rate in the Standard Model.
- Observable rate in many New Physics scenarios (Charged Lepton Flavor Violation).

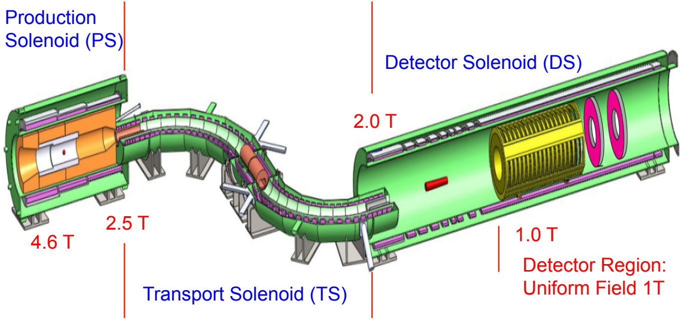
How the signal would look like

$$R_{\mu e} = \frac{\mu^- + N(A,Z) \to e^- + N(A,Z)}{\mu^- + N(A,Z) \to \nu_\mu + N(A,Z-1)}$$



Measure E_e spectrum $\rightarrow$ is there an excess at endpoint?

Mu2e experiment



1. μ is produced in the decay of π generated by a proton beam striking a production target.
2. μ are accompanied by e, π, anti-protons...
   - Wait for them to decay.
3. Pulse of low energy μ^- on thin Al foils (stopping target).
4. Momentum measurement by the tracker, energy measurement by the calorimeter.

Mu2e calorimeter

Role of the calorimeter

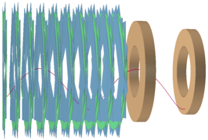
- Redundancy for the events reconstructed in the tracker.
- Trigger capability.
- Particle identification.

Requirements

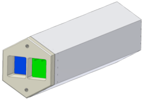
- Energy resolution of $\sigma_E < 2\%$ at 100 MeV to confirm tracker energy measurement.
- Time resolution less than 0.5 ns (energy deposits in time with tracker events).
- Work in a magnetic field of 1 T.

Current design

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



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



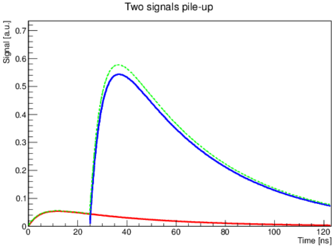
Objectives of the project

- Detector interaction simulation by GEANT4:
  - step-points along the particle path in the calorimeter.
- 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.
2. Crystal hits closer than 100 *ns* merged at crystal level.

- 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.

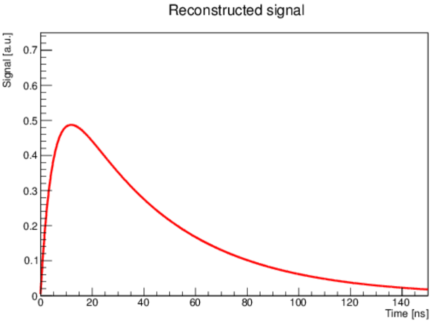


Current model: **event signal** at $t = 25$ *ns* merged with the **background one** at $t = 0$ *ns*.

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

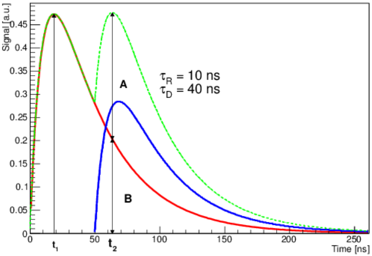
$$\textbf{Double signal:}\quad C_1 \cdot (e^{-\frac{t}{\tau_D}} - e^{-\frac{t}{\tau_R}}) + C_2 \cdot (e^{-\frac{t-\Delta t}{\tau_D}} - e^{-\frac{t-\Delta t}{\tau_R}})$$

Steps

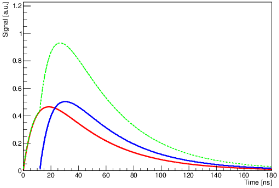
1. Merge all the signals within the leading edge time t_1.
2. If $A > k \cdot B$ at $t = t_2$ (see figure), the two signals are considered separately, otherwise merge them. Start from $k = 1$.

- 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.

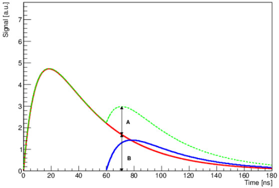
- $t_1 = \frac{\tau_D \cdot \tau_R}{\tau_D - \tau_R} \cdot \ln(\frac{\tau_D}{\tau_R}) \approx 18.48\, ns.$
- $t_2 = -\ln(\frac{\tau_D}{\tau_R} \cdot \frac{1+\frac{C_2}{C_1} e^{\frac{t_0}{\tau_R}}}{1+\frac{C_2}{C_1} e^{\frac{t_0}{\tau_D}}}) \frac{\tau_D \cdot \tau_R}{\tau_R - \tau_D}.$



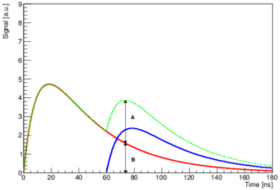
Examples



Merged
Second signal arrives within the leading edge time t_1.



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



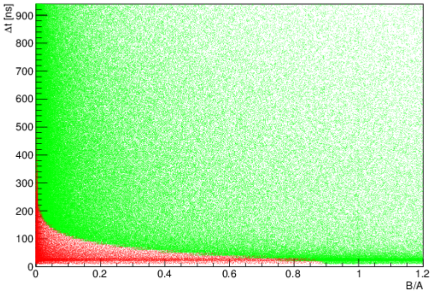
Not Merged
Second signal arrives after the leading edge time and $A > B$ (in this case $k = 1$).

Implementation and validation

Results

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

Δt vs $\frac{B}{A}$ for every signal

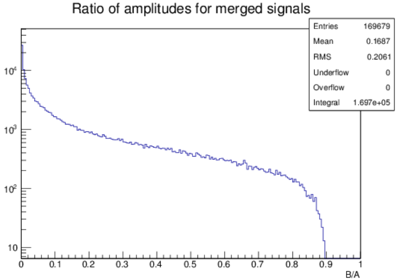


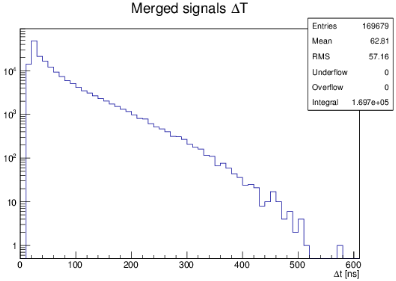
Three distinctly separated zones:

- $\Delta t \ll 100\, ns$ 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.

Results

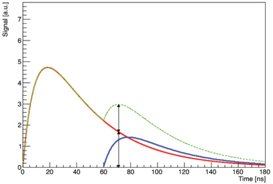
Merged signals



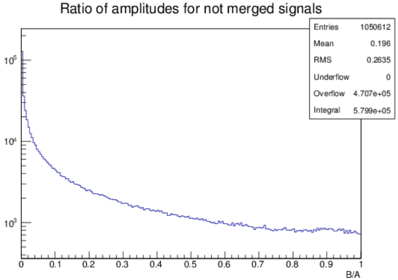


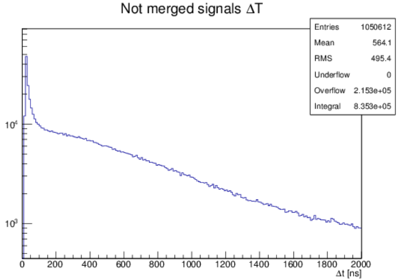
These are the projections for the ratio $\frac{B}{A}$ and for the Δt of the merged signals:

- 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*.



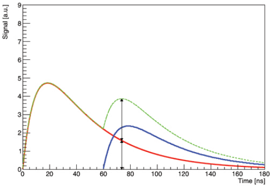
Not merged signals





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:

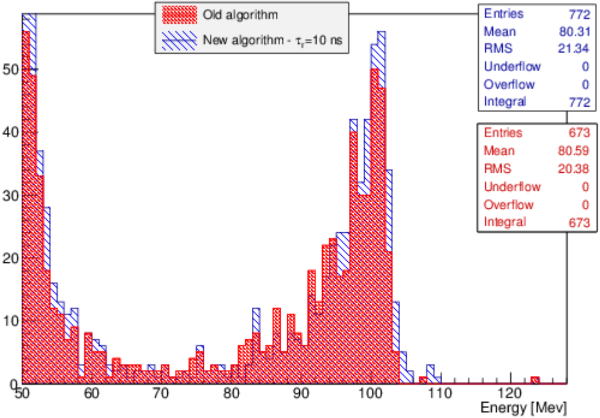
1. $\sim$ 6000 hits in the calorimeter per µbunch and $\sim$ 1000 crystals per disk.
2. $6/2 = 3$ hits per crystal per µbunch (same occupancy for the two disks).
3. For a µbunch time of 1700 *ns*, we have 1 hit every $\sim$ 550 *ns*.

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



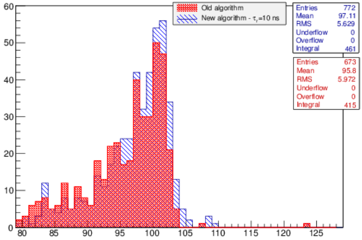
With the new algorithm we observe:

- 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).

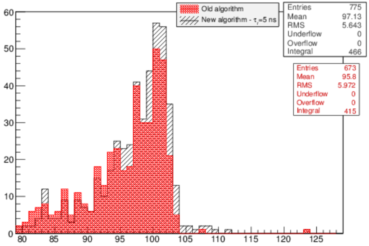
Energy of the CE clusters increases because there are less crystals “stolen” by the background: the clusters in [60 − 80] *MeV* interval move to the CE peak.

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.
- The constants used have now a direct physics meaning: τ_D and τ_R.
- Reducing the rising time constant τ_R by a factor of 2 (from $10\,ns$ to $5\,ns$) doesn't improve significantly the clustering.

Back-ups

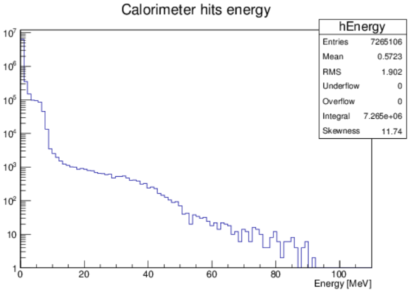
Modeling of the mixed events

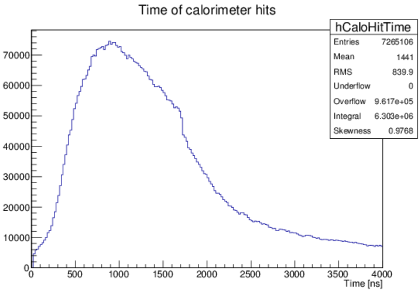
Background	Simulated e. (millions)
DIOs	20
Neutrons	38
Protons	3.2
Photons	63

- 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.