Status report on cosmic muon event tagging with light signal

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**Introduction**

- **WA105 SB Meeting, 14 April 2017:**
  - ~30% of cosmic muons *can't be detected* (S1 photons don't reach the PMT array)
  - A peak search algorithm has been developed: tagging of ~65% of detectable muons

- **Outline:**
  - Undetectable muons characteristics
  - Algorithm efficiency for $\lambda_{\text{Abs}} = 30\text{m}$
  - Algorithm efficiency for $\lambda_{\text{Abs}} = 4\text{m}$
  - Use of the S1 peak exponential shapes to improve the efficiency *(very preliminary)*

**Study done with:**
- PMT quantum efficiency: 0.20
- Electroluminescence gain $G=300$
- PMT and electronics response not taken into account
- Sum of the 36 PMT signals
- 400ns sampling
- PMTs non-uniformly spaced
Fraction of muons depositing photons on PMT array

**Detectable muon**: muon inducing S1 signal  
**Undetectable muon**: muon which doesn't induce a S1 signal

- A lot of photons don't reach the PMT array (mostly due to the absorption in LAr and absorption on stainless-steel components)
- If all the photons produced by a muon are absorbed, this muon can't be detected using the light signal

Study done with 55 cosmic events:
- $\lambda_{\text{Abs}}=30\,\text{m}$  
  $\rightarrow$ 75.1% of muons are detectable
- $\lambda_{\text{Abs}}=4\,\text{m}$  
  $\rightarrow$ 70.4% of muons are detectable

$\rightarrow$ The difference between the two $\lambda_{\text{Abs}}$ is small: most of the photons impacted by the LAr absorption are already lost at $\lambda_{\text{Abs}}=30\,\text{m}$
Undetectable muon trajectories

Cosmic muon trajectories for 1 event

All comic muons entering the fiducial volume within the (-4ms, +4ms) time window

Undetectable muons
Undetectable muon trajectories

Trajectories of undetectable muon for 55 events

Undetectable muons:
- Muons traveling at the top of the detector, especially in the corners
- Muons with short track length

→ It amounts to about 25% of all cosmic muons
The aim is to tag the S1 peaks

1. Look for **bins** with a number of photons **above** a given **threshold**

2. Does **not** search a new peak until finding at least $N_{\text{bin\_below}}$ **consecutive** bins **below** the threshold

**2 parameters:**
- Threshold
- $N_{\text{bin\_below}}$

**Note:** At last talk, use of a **temporary cut** on the **ratio** between the **peak maximum** and the **peak width**

→ An **improvement** of this cut is **under study** (see end of the talk)
Peak search algorithm efficiency ($\lambda_{\text{Abs}} = 30\text{m}$)

Efficiency = $\# \text{peaks matching a muon} / \# \text{detectable muons}$

Fraction of false peaks = $\# \text{peaks that don't match a muon} / \# \text{found peaks}$

For Thresholds > 100 ph/bins:
- Fraction of false peaks < 15%
- Maximum efficiency $\sim 68\%$ for $N_{\text{bin\_below}} < 12$
Peak search algorithm efficiency ($\lambda_{Abs} = 4m$)

**Efficiency** = \#peaks matching a muon / \#detectable muons

**Fraction of false peaks** = \#peaks that don't match a muon / \#found peaks

For Thresholds > 6ph/bins: Very low fraction of false peaks with a maximum efficiency $\sim 78\%$
Peak search algorithm efficiency

Efficiency = \# peaks matching a muon / \#detectable muons

Fraction of false peaks = \# peaks that don't match a muon / \#found peaks

→ \textbf{S2 signal} is more affected by the LAr absorption: \textbf{S1 signal} is more visible

→ The tagging is \textbf{more efficient} for \(\lambda_{\text{Abs}}=4\text{m}\) (but \textbf{important reduction} of the light signal)
S1 peak exponential shapes

Preliminary study

Most of false peaks = S2 fluctuations tagged as S1 peaks

→ Can we use the S1 peak exponential shapes to reject false peaks?

Computation of a “theoretical” peak width:

$$\Delta t_{\text{Threshold}} = \text{time to go back below the threshold}$$

$$N(\Delta t_{\text{Threshold}}) = N_{\text{max}} \exp\left(\frac{-\Delta t_{\text{Threshold}}}{\tau_{\text{slow}}}\right) = \text{Threshold}$$

$$\Delta t_{\text{Threshold}} = \tau_{\text{slow}} \left(\ln(N_{\text{max}}) - \ln(\text{Threshold})\right)$$

1600ns

The exponential shape is modified by the photon travel in LAr:

→ We can’t directly use $\Delta t_{\text{Threshold}}$ to reject false peaks.

→ We look at the ratio between the width found by the algorithm and $\Delta t_{\text{Threshold}}$:

$$\frac{\text{peak width}}{\Delta t_{\text{Threshold}}}$$
S1 peak exponential shapes

Distribution of \(\text{peak width} / \Delta t_{\text{Threshold}}\) for all the found peaks

\[ \lambda_{\text{Abs}} = 30 \text{m} \]

\[ \text{Threshold} = 70 \text{ph/bins} \]
\[ N_{\text{bin below}} = 10 \text{bins} \]
\[ 55 \text{ events} \]

Most of the S2 background fluctuations correspond to peaks with only one bin above the threshold

- 1 bin with 4 photons above threshold:
  \[ \frac{\text{peak width}}{\Delta t_{\text{Threshold}}} = \frac{11 \cdot 400}{1600 (\ln(74) - \ln(70))} = 49.5 \]
- 1 bin with 5 photons above threshold: 39.9
- 1 bin with 6 photons above threshold: 33.4

Note: for the time being, peak_width takes \(N_{\text{bin below}}\) into account

→ Can be a good criteria to reject S2 fluctuations tagged as S1 peaks
S1 peak exponential shapes

Efficiency = \# peaks matching a muon / \#detectable muons

Fraction of false peaks = \# peaks that don't match a muon / \#found peaks

Efficiency and fraction of false peaks for different Threshold (50→150ph/bins)

only peaks with \( \frac{\text{peak width}}{\Delta t_{\text{Threshold}}} < 15 \) are tagged as S1 peaks

- **Reduction** of the fraction of false peaks
  → **Maximum** fraction of false peaks of 18% instead of 80% (for Threshold=50ph/bins)

- **Maximum efficiency** of 68% with ~4% of false peaks
  → **Without the cut**: for the same efficiency, 12% of the found peaks are false

→ **Ongoing study**
Conclusion and next steps

- ~25% of cosmic muons can't be detected with the light signal
  → Muons traveling at the top of the detector and/or with short tracks

- Work on the peak search algorithm:
  - Using 2 parameters: Threshold and $N_{\text{bin below}}$
    - For 400ns sampling, tagging of
      - 68% of detectable muons ($\lambda_{\text{Abs}} = 30m$)
      - 80% of detectable muons ($\lambda_{\text{Abs}} = 4m$)
  - Adding a 3rd parameter based on the peak width estimation: significant reduction of S2 background
    - Example: reduction of a factor 3 for $\lambda_{\text{Abs}} = 30m$

- Next steps:
  - Take into account the PMT and electronics responses
  - Impact of the binning on the algorithm efficiency (400ns and 25ns sampling)
  - Use of the S1 peak shapes to reject false peaks
  - Impact of the LAr absorption length on the algorithm efficiency ($\lambda_{\text{Abs}} = 30m, 4m$ and $\lambda_{\text{Abs}} = 89m$)

Used in ProtoDUNE-SP simulations