IceCube Muon Filter for 2010 Pole Season

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Version: 1.0 Dec 6 2009

Introduction:

This document outlines the IC77 muon filter proposal. As the number of deployed strings increases in the 2009 season (from 59 to 77) so are expected the trigger rates. This muon filter proposal has been developed with the aim of providing a sample of muons useful for analyses over the whole sky. We follow the same philosophy of the IC59 muon filter. The sky has been divided in different zenith regions and different cuts in track quality reconstruction and total charge (that is related to energy). Concerning the reconstruction strategies, this online filter uses the single-seeded likelihood (LLH) (Gulliver seeded with LineFit) reconstruction.

A minimum cut $N_{ch} \geq 8$ is applied to the upgoing region of the sky and $N_{ch} \geq 10$ to the downgoing events to contain CPU. The $N_{ch}$ distribution from simulation of the triggered events (SMT-8) is shown in figure 1. For upgoing tracks, a cut in the quality of the track has shown to yield a better efficiency for the neutrino signal (spectrum of $E^{-2}$) with respect to the trigger level than cuts in $N_{ch}$. For this reason, a cut on $\log{(N_{ch} - 2)}$ has been applied in the upgoing region (we refer to as 'upgoing' the region between zenith angles of $180^\circ$ to $78.5^\circ$, or $\arccos(-1)$ to $\arccos(0.2)$). The reason why this log likelihood is been used instead of the standard RLogL is that, for the same of signal efficiency it leads to lower passing rates for atmospheric muons and hence lower bandwidth consumption (see Figure 4).

On the other hand, in the upper hemisphere (zenith $\leq 78.5^\circ$), a cut on the track quality becomes inefficient since the region is dominated by well reconstructed muons. But since this filter aims at selecting high energy muons, aside from the $N_{ch} \geq 10$ applied for CPU reasons, a cut on an energy related variable (total integrated charge, IntCharge hereafter) has been applied. The IntCharge has demonstrated to be less depth dependent and sensitive to the total muon energy in the detector than other variables, such as $N_{ch}$ (See the studies by P. Berghaus). The computation of IntCharge comes from the I3RecoPulseSeries and the sum is performed within the I3MuonFilter module:
intChage_ = 0;
I3RecoPulseSeriesMap::const_iterator miter;

for(miter=iniceChannels.begin(); miter!=iniceChannels.end(); miter++) {
    const I3RecoPulseSeries &thishitinfo = miter->second;
    for (I3RecoPulseSeries::const_iterator iseries =
         thishitinfo.begin();
        iseries != thishitinfo.end(); iseries++)
        intCharge_ += iseries->GetCharge();
}

It is also important to mention that the zenith region that ranges from 0 to 50° will overlap with the EHE filter so it should be considered that the rates for that region are inclusive rates (not exclusive with respect to other filters), and not much additional bandwidth will be required.

![Figure 1. Number of Nch for all triggered events in SMT-8.](image)

**Description of the filter:**

**Definition:** This filter applies to SMT-8 events. Other filters are supposed to cover the lower energy region (WIMP, up and down contained filters, ULEE, DeepCore...). Figure 1 show the event rate of the SMT-8 trigger compared to all triggers for IC77.
Figure 2: Number of neutrino events, atmospheric (top) and signal events (bottom) for all triggered events compared to SMT triggered events.

Figure 3: Ratio SMT-8 triggered events over all triggered events for neutrino signal as a function of the neutrino energy.
**Cuts:** As mentioned before, this filter proposal aims at the extension of the muon filter range to whole sky coverage. Therefore, the filter can be divided into two main regions in the sky. A minimum base requirement of $N_{ch} \geq 8$ is applied to the lower hemisphere, while this cut is increased to 10 for the upper hemisphere. On the other hand, the efficiency of this base cut over SMT-8 triggers is of about 67% for atmospheric neutrinos and about 95% for signal neutrinos with a spectral index of 2. Figure 3 shows the $N_{ch}$ distribution of SMT-8 triggered events.

The distinction between lower and upper hemisphere is done using the output provided by LineFit. Only those events satisfying the base condition: $N_{ch} \geq 8 \land (N_{ch} \geq 10 \lor \text{LineFit\_zenith > 70})$ will be processed by the filtering. This base requirement will reduce a considerable amount of CPU loading.

The filtering cuts have been defined separately for each zenith regions. For the region below the horizon (zenith \( \geq 80^\circ \)), the quality variable in the LLH fit $\text{llh} / (N_{ch} - 2)$ has shown to yield better signal efficiency to background rejection than the standard reduced log likelihood. Figure 4 shows the signal and atmospheric neutrino efficiencies versus the background rate in percentage for a set of quality variables for the upgoing region. As can be seen the $\text{llh}/(N_{ch} - 2)$ variable yields a better signal to background ratio in the upgoing region while the charge is the best variable for the downgoing region.

![Figure 4](image)

*Figure 4 Curves of signal neutrino efficiencies versus background efficiency (best variables are on the bottom and right in these plots). (left) upgoing region (right) downgoing region.*
As already observed, for the downgoing region the most effective variable for separating $E^{-2}$ spectrum neutrinos is an energy-based cut rather than the quality of the reconstruction, since events are mostly well-reconstructed downgoing muons.

The filtering definition is the following:

**Base cut (prior LLH fit):**

- $Nch \geq 8 \&\& (Nch \geq 10 \text{ } || \text{ } LineFit\text{ }_\text{zenith} > 70)$

**Lower hemisphere (180° - 78.5°):**

- $(LLH\text{ }_\text{zenith} > 78.5 \&\& LLH\text{ }_\text{zenith} \leq 180) \&\& LLH\text{ }_\text{LogL} / (Nch - 2) \leq 8.1$

**Upper hemisphere (78.5° - 0°):**

- $(LLH\text{ }_\text{zenith} > 60 \&\& LLH\text{ }_\text{zenith} \leq 78.5) \&\& log(\text{IntCharge}) \geq (3.9 \times (cos(LLH\text{ }_\text{zenith}) - 0.5) + 2.5)$

- $(LLH\text{ }_\text{zenith} > 0 \&\& LLH\text{ }_\text{zenith} \leq 60) \&\& log(\text{IntCharge}) \geq (0.6 \times (cos(LLH\text{ }_\text{zenith}) - 0.5) + 2.5)$

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**Figure 5** The distribution of log10(IntCharge) versus -cos(LL_H_Zenith) for a sample of single CORSIKA events. The white line is the proposed cut, comparing to a box-like cut in black which yields similar rates and atmospheric and signal neutrino efficiencies.
Figure 6: The rate as a function of $-\cos(\text{LLH}\_\text{Zenith})$ for the proposed cuts (left, the white line in figure 5) and a comparable box-like cut (right, the black lines in figure 5).

**Required modules:** The version V01-04-00 of Gulliver, Gulliver-modules, and Lilliput are needed. The trunk of jeb-filter-IC77 is needed for the new filter (I3MuonFilter).

**Settings:** A sample python script, showing the settings and parameters required by the Gulliver services, I3DOMCalibrator, Feature Extractor, Time Window Cleaning, icepick modules, reconstruction modules, and the new filter module, is included in the following pages. Specially, the Feature Extractor settings have changed since last operation, new settings are:

- UseNewDiscThreshold = F
- ADCThreshold = 1.8
- FastFirstPeak = 7
- Single Pulse only extraction (FastPeakUnfolding = -1)

The fine-tuning of the passing rate can be done using the llh/(Nch - 2) variable as a knob for the lower hemisphere as well as the IntCharge for the upper hemisphere. Figure 7 shows the effect of the llh/(Nch-2) cut and IntCharge in the passing rates for atmospheric muons and efficiency to an $E^2$ signal. The 100% is defined at trigger level, that is, all events triggered by the SMT-8 in the same zenith region.
Figure 7: Signal efficiency (Purple) and atm. Neutrino rate as a function of the $l lh/ (Nch -2)$ cut for the lower hemisphere, zenith bin between $78.5-180^\circ$. The cut used in this proposal is 8.1.

**Passing rates:**

Table 1 shows the passing rates for atmospheric neutrinos and atmospheric muons using the proposed cuts and the base cut of: $Nch \geq 8$ $\&\& (Nch \geq 10 \text{ } \| \text{ LineFit}_\text{zenith} > 70^\circ)$. The atmospheric muon rates have been itemized by single muons, and double coincident events. The total bandwidth and the neutrino efficiency for a signal of $E^{-2}$ are also shown. Trigger rates are defined by all SMT-8 triggered events in each zenith region.
<table>
<thead>
<tr>
<th>Zenith (°)</th>
<th>Atm. Muons (Hz): single double total</th>
<th>Atm neutrinos in Hz (%)</th>
<th>Signal efficiency (%)</th>
<th>Bandwidth (GB/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower hemisphere</td>
<td>78.5 - 180</td>
<td>15.3 15.1 — 30.4</td>
<td>1.04e-2 (85.9)</td>
<td>93.2</td>
</tr>
<tr>
<td>Upper hemisphere</td>
<td>60 - 78.5</td>
<td>4.63 1.98 — 6.62</td>
<td>3.039e-4 (14.4)</td>
<td>54.7</td>
</tr>
<tr>
<td>0 - 60</td>
<td>2.00 0.47 — 2.47</td>
<td>8.39e-6 (0.47)</td>
<td>26.4</td>
<td>4.1</td>
</tr>
<tr>
<td>Total</td>
<td>21.9 17.5 — 39.5</td>
<td>1.07e-2 (66.9)</td>
<td>79.9</td>
<td>15.01</td>
</tr>
</tbody>
</table>

Table 1: Atmospheric muon/neutrino rates, signal efficiency and consumed bandwidth for different regions of the sky according to the proposed filter with Nch ≥ 8 for the LineFit_zenith > 70° and Nch ≥ 10 for LineFit_zenith ≤ 70°. The rates for the whole sky are also shown.

Simulation:

Files processed correspond to Corsika production 1509 for single muons, 1511 for coincident muons and 1550 for triple coincident muons. In order to compute the efficiency the neutrino production, dataset 1542 has been used. Reprocessed files can be found in:

/net/user/mfbaker/std-processing/branch/IC59/build/IC77/PFFilt/

Filter Efficiency:
Figure 8 shows the signal efficiency (for a $E^{-2}$ spectrum) at trigger level (all SMT-8 events), for different zenith bands as a function of the energy of the neutrino. The peaky structure at high-energy bins is due to poor statistics at those high energies.

### CPU requirements:

In order to compute the CPU loading, different unweighted CORSIKA production were used. In particular, for single muons the production 2267 was processed to estimate the CPU time needed to perform the filter. As in the last year filtering, the main load will be due to the LLH fit. The expected number is about 34 CPUs for the IC77 configuration. The FeatureExtractor module for the Gulliver fit will take approximately an additional 6 CPUs.
tray.AddModule("I3FilterModule<I3MuonFilter>"","muonfilter_2010")(
    #("TriggerEvalList",["InIceSMTTriggered"]),
    ("TriggerEvalList",["SMT8TriggerBool"]),
    ("DecisionName","ICMuonFilter_10"),
    ("DiscardEvents",False),
    ("IceCubeResponseKey","TWCleanPulses"),
    ("CosZenithZone1",[-1.0, 0.2]),
    ("CosZenithZone2",[ 0.2, 0.5]),
    ("CosZenithZone3",[ 0.5, 1.0]),
    ("LogLZone1",8.1),
    ("SlopeZone2",3.9),
    ("InterceptZone2",0.55),
    ("SlopeZone3",0.6),
    ("InterceptZone3",2.2),
    ("IceCubeTriggers","SMT8I3Trigger"),
    #("IceCubeTriggers","I3TriggerHierarchy"),
    ("PriParticleKey","PoleTrackLlhFit"),
    ("LLHFitParamsKey","PoleTrackLlhFitFitParams"),
)