Introduction:

This document shows 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 the IC77 filter is to provide a sample of muons over the whole sky. To this end, the sky has been divided in different zenith regions and different cuts in track quality reconstruction and energy related parameter have been defined. Concerning the reconstruction strategies, this filter only maintains the reconstruction single-seeded log-likelihood fit (LLH) (Gulliver seeded with LineFit).

A minimum cut in \( N_{ch} \geq 8 \) is applied to the upgoing region of the sky and \( N_{ch} \geq 10 \) from the downgoing sky to contain CPU. This cut is used to cover all SMT-8 trigger events. For upgoing tracks, a cut in the quality of the track has shown to yield a better efficiency for neutrino signal (spectrum of \( E^{-2} \)) for the same muon trigger level than the equivalent cut in \( N_{ch} \). For that reason, a cut on \( \text{llh}/(N_{ch} - 2) \) has been applied for this upgoing region that goes from zenith angles of 180° to 78.5°. The reason why this log likelihood is been used instead of the standard RLogL is that, for the same level of efficiency it leads to a lower passing rates for atmospheric muons and lower bandwidth consume (see Figure 3).

On the other hand, in the upper hemisphere (zenith \( \leq 78.5^\circ \)), a cut in track quality becomes inefficient since the region is dominated by well reconstructed muons. But since this filter aims at selecting high energy muons, a cut on an energy related variable has been applied. Among them, in this proposal, we have selected the total integrated charge, \( \text{IntCharge} \) hereafter. Besides, a minimum requirement of \( N_{ch} \geq 10 \) is applied to the downgoing region since that will lessen use of CPU. The \( \text{IntCharge} \) has demonstrated to be more depth independent and sensitive to the total muon energy in the detector (See the studies by P. Berghaus). The computation of \( \text{IntCharge} \) 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.

Description of the filter:

a. **Definition:** This filter is intended for 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 provided by the SMT-8 trigger compared to all triggers in IC77 files:

Figure 1: Number of neutrino events, atmospheric (top) and signal events (bottom) for all triggered events compared to SMT triggered events.
Figure 2: Ratio of neutrino events for SMT-8 triggered events over all triggered events as a function of the primary energy of the neutrino (same for atmospheric and $E^2$ neutrinos).

b. **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 in 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.

Figure 3. Number of $N_{ch}$ for all triggered events in SMT-8.

The distinction between lower and upper hemisphere is done using the output provided by LineFit. Only those events
satisfying the base condition: \( Nch \geq 8 \land \land (Nch \geq 10 \lor \ LineFit\_zenith > 70 ) \) 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 \( \frac{\text{llh}}{(Nch - 2)} \) has shown to yield better signal efficiency to background rejection than the standard reduced log likelihood. The following plots show 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 new \( \text{llh}/(Nch -2) \) yields a better signal to background ratio.

![Figure 4 Curves of neutrino efficiencies for signal (left) and atmospheric (right) vs background efficiency for different variable cuts. ((Now upgoing on the left and downgoing on the right))](image)

For the downgoing region the dominant effect is well-reconstructed atmospheric muons from cosmic ray air showers and the most effective variable of separating \( E^{-2} \) spectrum neutrinos is an energy-based cut.
The filtering definition is the following:

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

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

**Lower hemisphere (180° - 80°):**

- \((\text{LLH}_\text{zenith} > 80 && \text{LLH}_\text{zenith} \leq 180) && \frac{\text{LLH}_\text{LogL}}{(Nch - 2)} \leq 8.1\)

**Upper hemisphere (80° - 0°):**

\[
\begin{align*}
(\text{LLH}_\text{zenith} > 60 && \text{LLH}_\text{zenith} \leq 80) && \log(\text{IntCharge}) \\
&\geq (3.9*(\cos(\text{LLH}_\text{zenith}) - 0.5) + 2.5) \\
(\text{LLH}_\text{zenith} > 0 && \text{LLH}_\text{zenith} \leq 60) && \log(\text{IntCharge}) \\
&\geq (0.6*(\cos(\text{LLH}_\text{zenith}) - 0.5) + 2.5)
\end{align*}
\]

Figure 5 The distribution of log10(IntCharge) versus -cos(LLH_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 \(-\cos(LLH\_Zenith)\) for the proposed cuts (left, the white line in figure 5) and a comparable box-like cut (right, the black lines in figure 5).

b. **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).

c. **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)

d. The fine-tuning of the passing rate can be done using the \(\text{llh}/(\text{Nch - 2})\) variable as a knob for the lower hemisphere as well as the \(\text{IntCharge}\) for the upper hemisphere. The following plot shows the effect of the \(\text{llh}/(\text{Nch-2})\) cut and \(\text{IntCharge}\) 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. As can be seen in Figure 7, the cut of \(\text{Nch} \geq 10\) for the upper hemisphere reduce the efficiencies for values of \(\log10(\text{IntCharge})\) below 1.5. Since
the charge cuts proposed here are tighter than this, the minimum Nch cut will have a negligible effect in the final efficiencies.

**Figure 7**: Signal efficiency (Purple) and atm. Neutrino rate as a function of the \( \text{l}l\text{h}/(N\text{ch} -2) \) cut for the lower hemisphere, zenith bin between 80-180°. The cut used in this proposal is 8.1.

**Passing rates:**

The following table shows the passing rates for atmospheric neutrinos and atmospheric muons using the proposed cuts and the base cut of: \( N\text{ch} \geq 8 \land (N\text{ch} \geq 10 \lor \text{LineFit}_\text{zenith} > 70^\circ) \). The atmospheric muon rates have been itemized by single muons, and double/triple coincident events. Nonetheless, due to the retriggering of IC80 files it is not possible to calculate actual individual rates for coincident events in IC56. The rates shown, however, are instructive to show how the new quality cut reduces the amount of coincident events compared to the old cut proposed (see Table A.2). 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>60 - 78.5</td>
<td>4.63 1.98 — 6.62</td>
<td>3.039e-4 (14.4)</td>
<td>54.7</td>
<td>3.42</td>
</tr>
<tr>
<td>Upper hemisphere</td>
<td>0 - 60</td>
<td>2.00 0.47 — 2.47</td>
<td>8.39e-6 (0.47)</td>
<td>26.4</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:**

The following plots show 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 related with a lack of statistics at those high energies.

**Figure 8** Signal efficiency for a $E^{-2}$ spectral index as a function of the primary neutrino energy (GeV) for zenith angles between 78.5-180°, 78.5-60° and 0-60°.

**CPU requirements:**

In order to compute the CPU loading, different unweighed 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"),
)