Muon Tagging Optical Modules for the IceCube Neutrino Observatory

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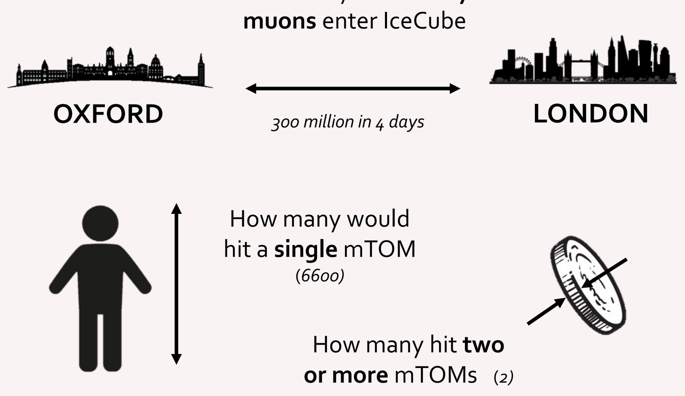
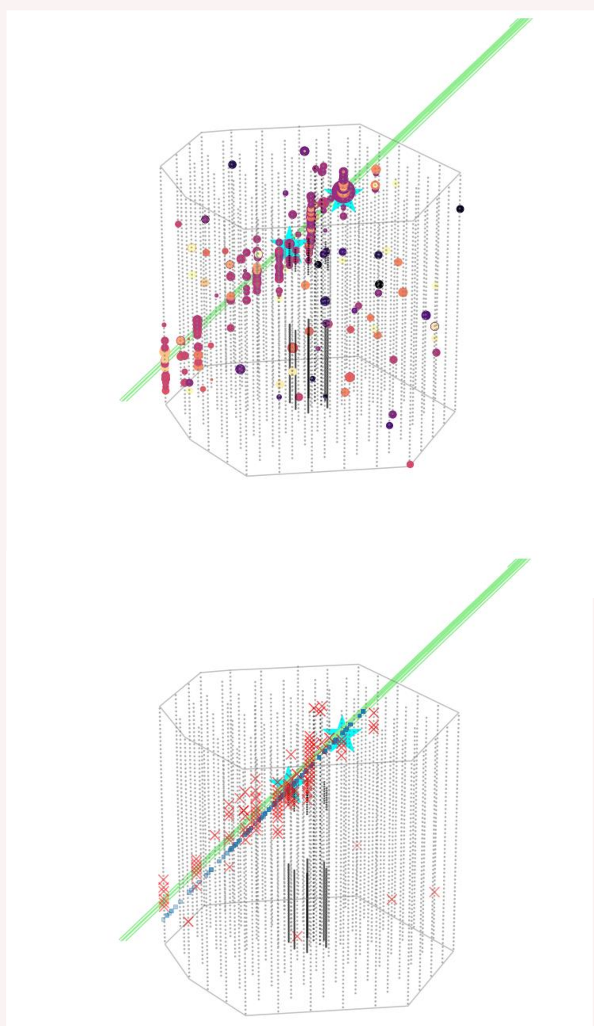
Feasibility study

Showers of cosmic ray muons result from a cascade of decays initiated when heavier particles hit the upper atmosphere. In my study, these were obtained from a CORSIKA computer model, and analysed in a custom Python simulation to assess how many particles would hit hypothetic mTOMs in the current IceCube array. An illustration of the quantitative results is given on the right.



The most useful kinds of events are when a single muon penetrates the array and hits multiple mTOMs far apart. The trajectory of the muon is then given to within the size of a single module (20 cm). My simulation shows that these would occur at a rate of order 1 per day.

Legend for custom event viewer:
- *the current IceCube and DeepCore*
- *a muon's trajectory*
- *charge deposited in a DOM*
- *DOMs used for reconstruction*
- *arrival time of the photon*
- *an mTOM hit*



Double hit event where the error in least-squares path reconstruction would be decreased from 3° w/o mTOMs (blue) to under 0.1°

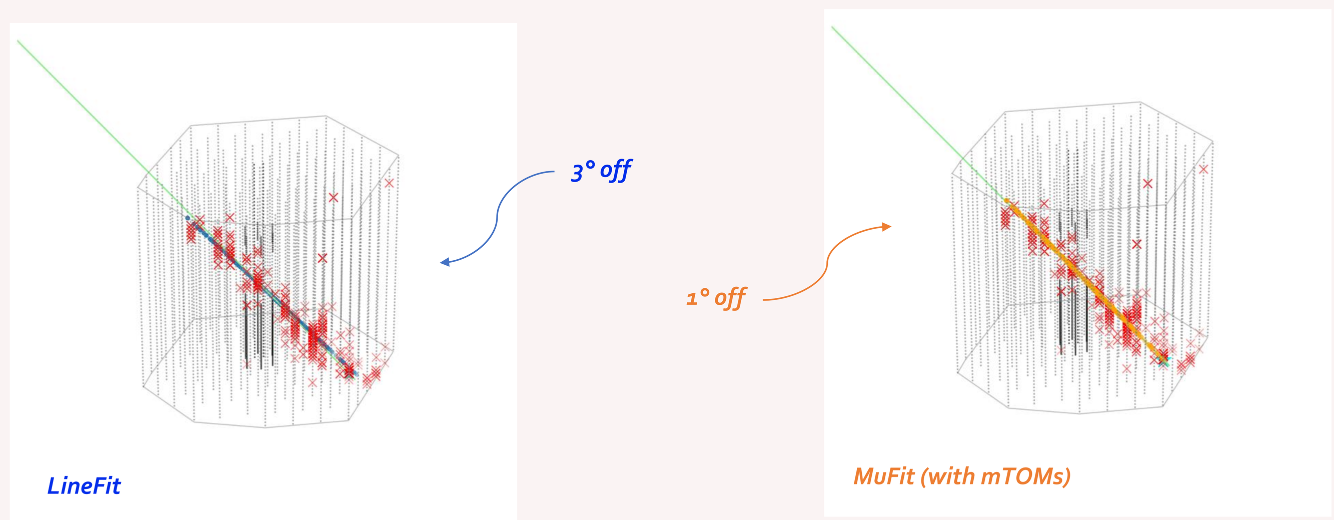
A second class of events occurs when only a single mTOM is hit. These are far more numerous but only fix one parameter in the line fitting process as described below, in the comparison of LineFit and an operational "MuFit". These events can still be used for training purposes but it is essential that those where real improvement is achieved through muon tagging be recognizable in quantities observed or simply reconstructed by IceCube.

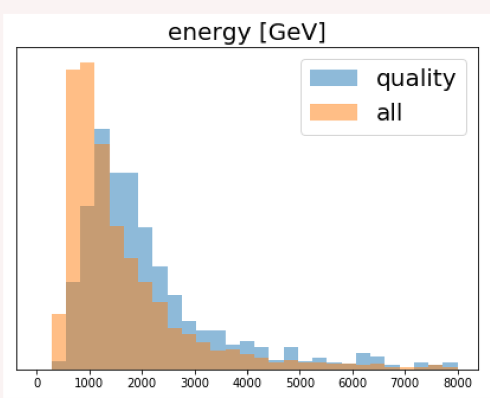
$$\chi^2 = \sum_j (x_{i,j} - m_i t_j - b_i)^2$$
$$m_i = \frac{\langle x_i\rangle \langle t\rangle - \langle x_i t\rangle}{\langle t\rangle^2 - \langle t^2\rangle}$$
$$b_i = \langle x_i\rangle - m_i \langle t\rangle$$

minimize

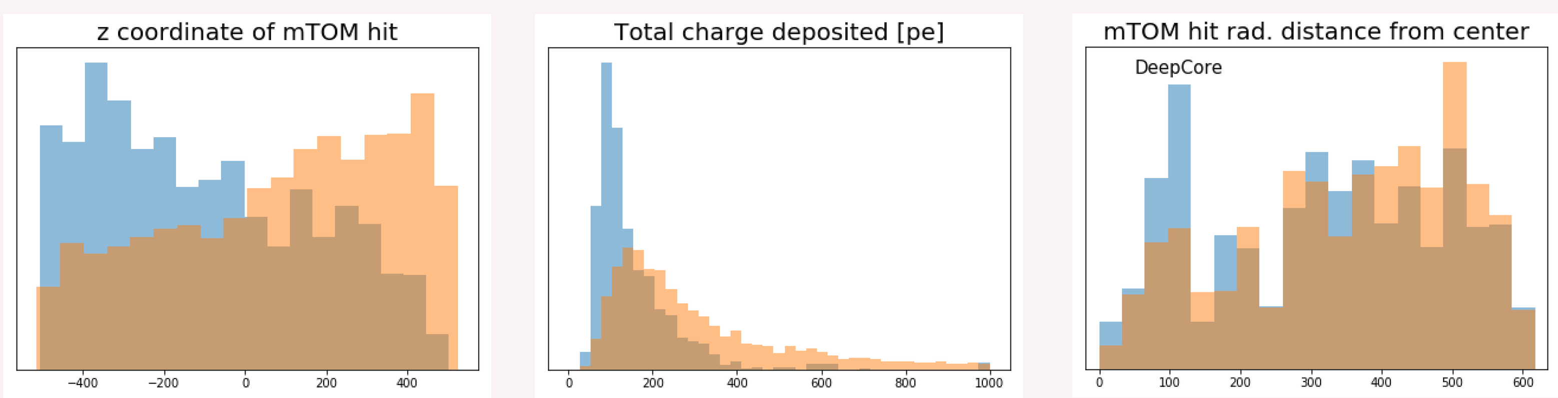
gradient/intercept given a "photon map" of the event

$$\chi^2 = \sum_j ((x_{i,0} - x_{i,j}) - m_i(t_0 - t_j))^2$$
$$m_i = \frac{\langle (x_{i,0} - x_{i,j})(t_0 - t_j)\rangle}{\langle (t_0 - t_j)^2\rangle}$$
$$b_i = x_{i,0} - m_i t_0$$



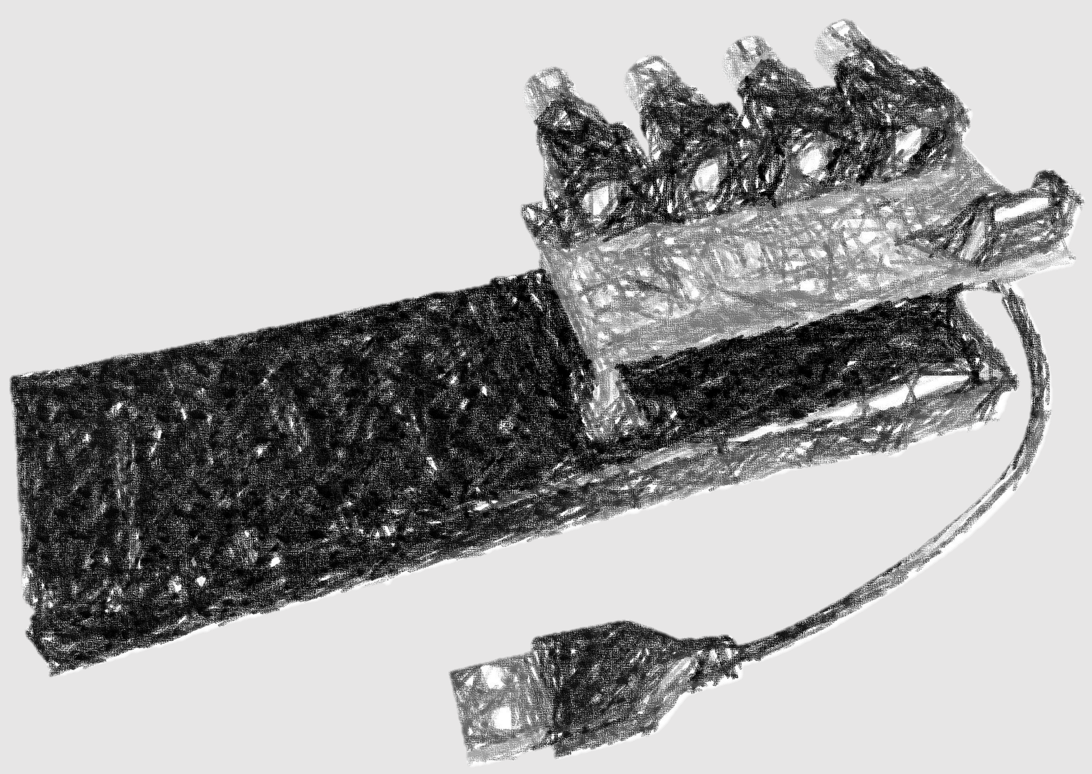


"Quality" events where reconstruction is significantly enhanced by the presence of single mTOM hits land predominantly in the bottom half of the detector, have low energy (survive longer) and deposit less charge into the array (fewer muons). They also come in from shallower angles from the horizon and fall onto the denser DeepCore strings. Individual histograms are normalized.



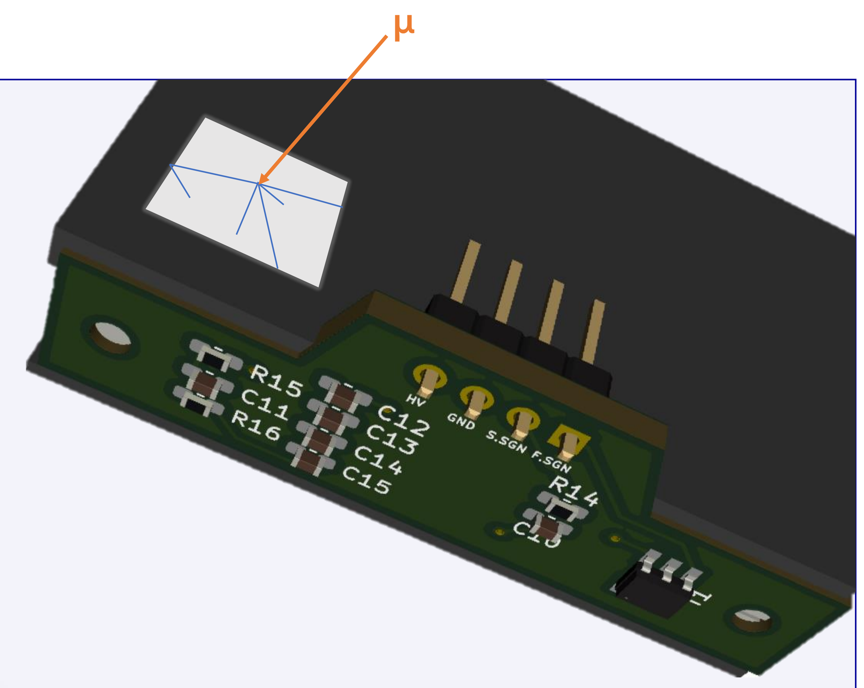
Cosmic rays: IceCube's unexpected hero?

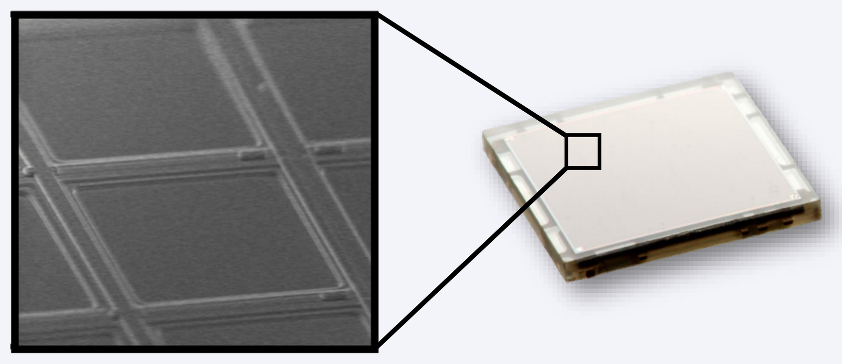
Every second, hundreds of cosmic ray muons enter the IceCube Neutrino Observatory located 1.5-2.5 km under the surface at South Pole. Most travel at a speed higher than the speed of light in ice and emit a cone of Cherenkov radiation. This light is detected by an array of about 5000 photomultipliers and can be processed to reconstruct the path of the muon. In a future upgrade, scientists are looking to equip new optical modules with affordable muon taggers (mTOMs). They will send out a binary signal when a muon passes directly through one of them and hence improve the observatory's reconstruction algorithms even for muons from genuine neutrino interactions. Cosmic ray muons which otherwise "pollute" the detector will thus be helping IceCube confirm its status as a pioneer of viable neutrino astronomy.



Instrumentation

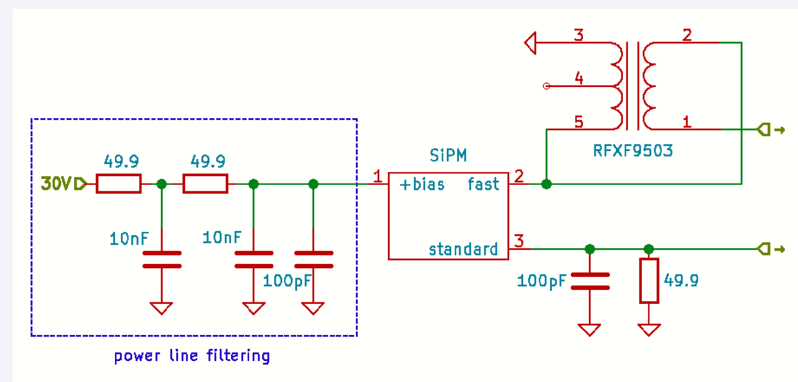
The mTOM is essentially a slab of plastic scintillator (polystyrene enriched with dopants), which re-emits the energy deposited by a charged particle like a muon in the form of light (at ~420nm). A silicon photomultiplier mounted to the slab's smallest side collects the light.

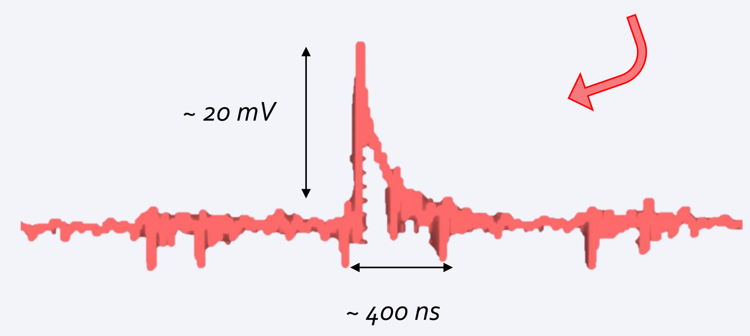




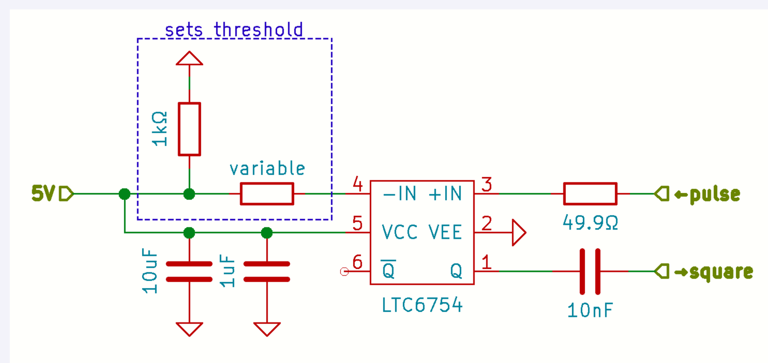
This comprises microcells, small P-N junctions which naturally form depletion regions. When a photon hits this region, it can produce an electron-hole pair and start a cascade through collisions with other electrons (provided sufficient potential difference). This lasts until a quenching resistor lowers the bias voltage and the result is a large peak in current which signifies the detection of single or multiple photons. We use the SenSL MicroFC 60035 C-Series.

SiPM read-out circuit

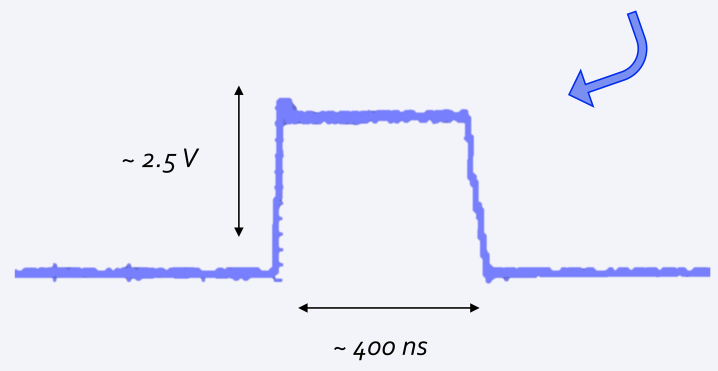


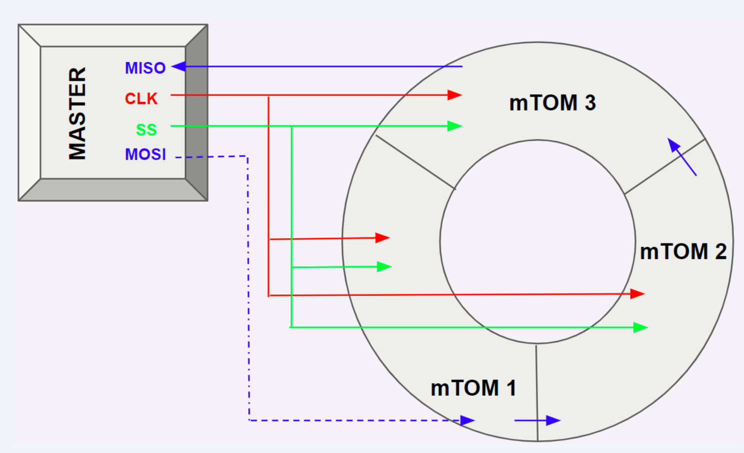


Comparator circuit



Going forward, the voltage threshold will have to be fine-tuned to prevent false positive detections. Working with the faster output (~2ns) of the SiPM presents challenges during amplification and would demand usage of a constant fraction discriminator (CFD), as the onset of peaks of different sizes varies.





A possible daisy-chained SPI connection of 3 mTOMs in one DOM is described on the left. This would require integrating simple microprocessors and memory as the Master cannot sample mTOMs at all times. An alternative is sending the square-wave above to the DOM for processing. That would require more adjustments to the main board.

CosmicWatch

mTOMs have inherited a lot of know-how from the Cosmic-Watch outreach programme. These pocket-sized detectors are cheap, easy to assemble and extremely low-power, which opens up a wide range of physics for enthusiasts and high school students to explore. Find out more about them by scanning the QR code!

SCAN ME

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Laidlaw Scholars
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