Adventures in IceCube Energy Reconstruction

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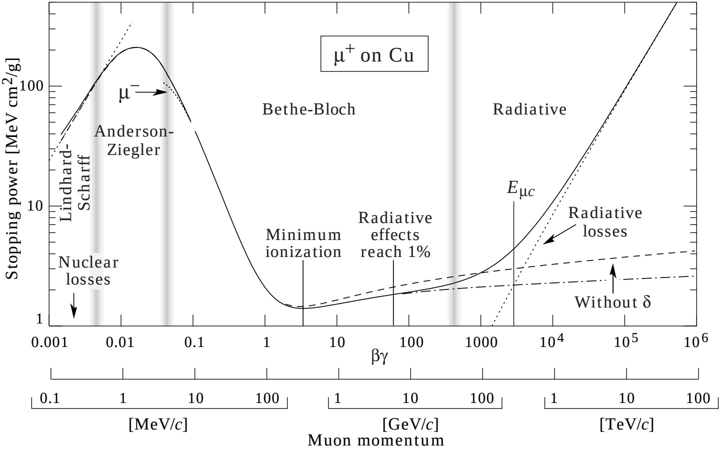
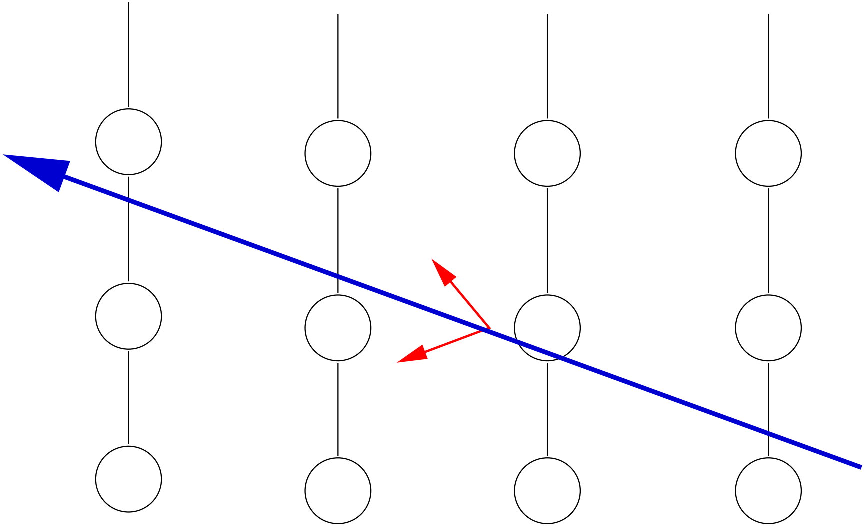
Muon Energy Loss



Particle Data Group

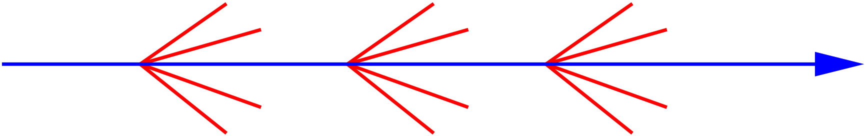
Photon Model

Model light from point sources or from finite extended sources (possibly stacking to an infinite muon), taking into account ice layering, etc.



Track Description

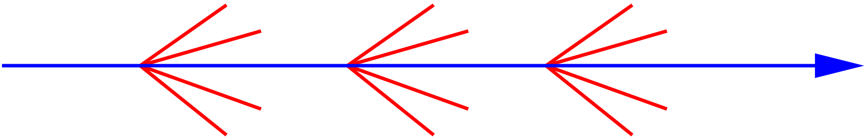
Muon loses energy by continuous ionization processes (steady Cerenkov emission) and by stochastic processes (bremsstrahlung, photonuclear processes etc. – pointlike emission)



Photorec

“Lightsaber” model: constant energy loss muon overlaid with cascades every meter. Calculate $\langle dE/dx \rangle$ by scaling up table to maximum likelihood fit to data

$\rightarrow$ constant energy loss and cascades scale with muons.



MuE

Most other IceCube energy reconstructions (e.g. MuE) work the same way, but with different ice parameterizations

Track segmentation

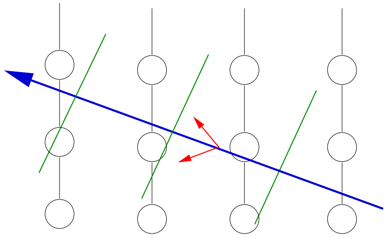
Losses from each cascade are stochastic, so they should scale independently. Muon-like losses are also not constant. So we break the track up into segments – every few meters place a cascade and muon segment.

Solving for all of these independently gets us:

- Starting/stopping/contained tracks
- Hybrid reconstruction
- Taus
- High-energy stochastics
- Better energy measurement
- Better particle ID
- Reconstruction quality cut
- Cascade detection
- Bundle multiplicities
- High-energy tests of QED
- ...

Simple Approach

- Divide detector into cylindrical segments centered on the track
- Apply Photorec/MuE algorithm in these sub-detectors
- Usually estimate muon energy by dropping large stochastics

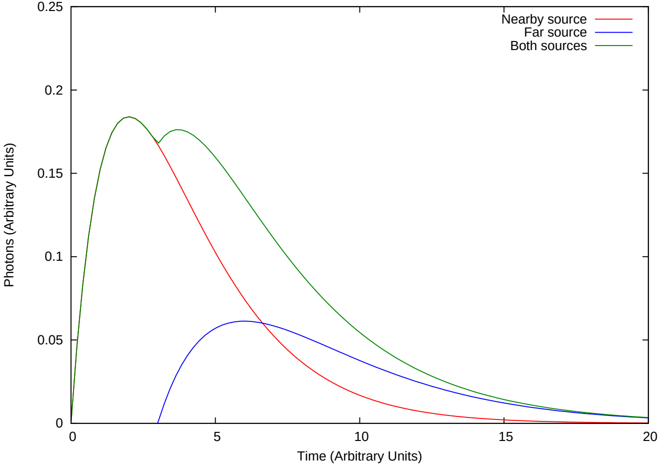


Implementations

IceCube: Truncated Energy, DDDDR

Complicated Approach (Millipede)

Observed photon distributions in each OM are a linear combination from all sources, with distributions from photon MC tables or parametrizations and normalizations from the energy loss at that source.



Unfolding Stochastics

We can deconvolve the stochastic losses by solving the linear system:

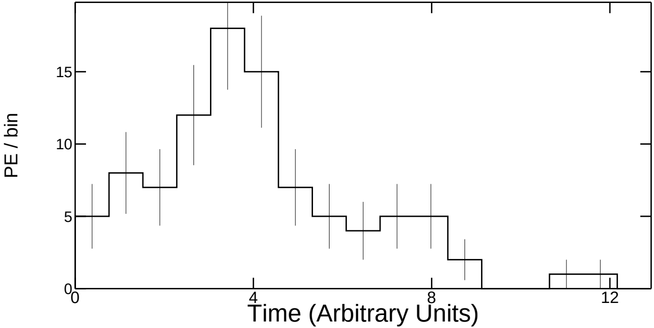
$$\begin{pmatrix} B_1(x_1) & B_2(x_1) & \cdots & B_n(x_1) \\ B_1(x_2) & B_2(x_2) & \cdots & B_n(x_2) \\ \vdots & & \ddots & \vdots \\ B_1(x_m) & B_2(x_m) & \cdots & B_n(x_m) \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \\ \vdots \\ E_m \end{pmatrix} = \begin{pmatrix} N_1 \\ N_2 \\ \vdots \\ N_m \end{pmatrix}$$

B_i: predicted photon distributions from each muon segment and shower
E_i: energy loss at each muon segment/shower
N_i: measured photon counts

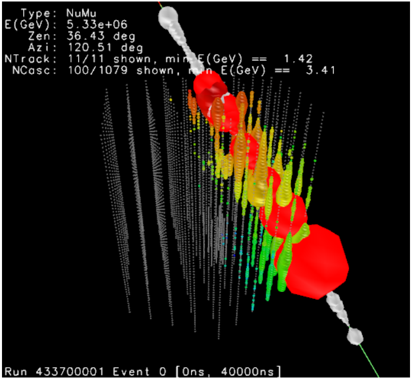
Defining the data vector

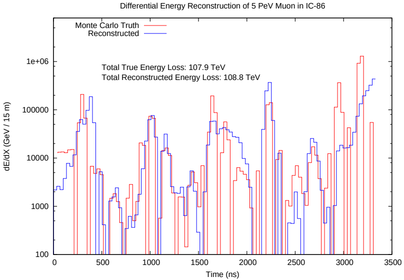
Simplest case: use absolute amplitudes in each OM (very fast)

Complicated case: make a charge histogram in time, fit amplitudes in each bin (somewhat slower)



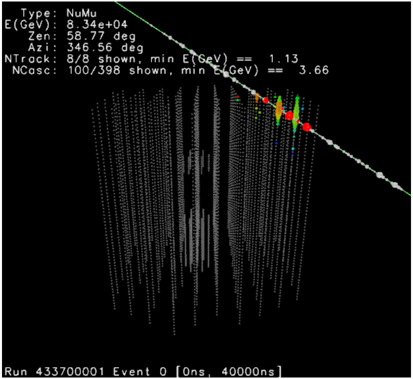
High Energy Performance

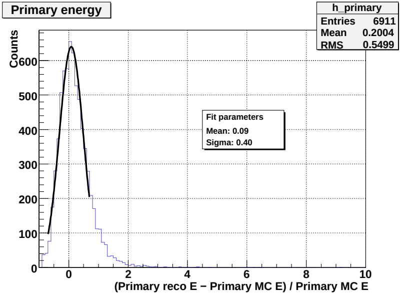




- ≈ 1% energy deposition resolution at 1 PeV
- Cascade position resolution ≈ a few meters
- Excellent event topology reconstruction

Low Energy Performance



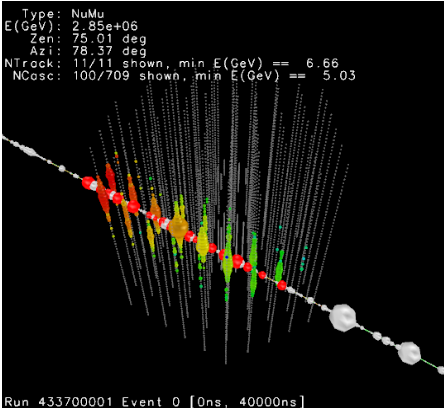


J. P. Yañez, DESY

- $\approx$ 40% energy deposition resolution at 20 GeV
- Track length to $\approx$ 10 meters

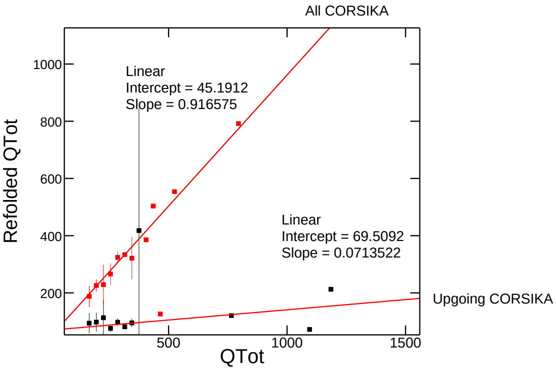
Estimating E_μ from topology

- High Energies (Uncontained)
  - Likelihood Fit to Event Topology ($P(E, E')$)
  - Provides much higher-quality fit to muon energy, since more information available
  - Work in Progress
- Low Energies (Contained)
  - Detector a calorimeter: Add energies
  - Excellent energy resolution ($\sim 10\%$), even approaching the detector threshold



Unconventional Uses

- Misreconstruction rejection (right)
- Cascade identification
- Muon Bundle Reconstruction by dE/dX profile



Overview

- Scalar Algorithms
  - Fast, simple, μ energy
  - MuE, Photorec
- Pseudo-Scalar Algorithms
  - Better μ energy
  - Truncated Energy, DDDDR
- Full Segmented Algorithms
  - High-precision event topology
  - MuE-X, Millipede