Master Thesis:

Testing and comparison of muon energy estimators for the IceCube neutrino observatory

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Fall semester 2008-2009
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Preface

This report summarizes the research work I did, within the framework of a "Master Project in Physics" of the Ecole Polytechnique Federale de Lausanne, under the academic supervision of Prof. Mathieu Ribordy. The research work presented here has been done in the group of Prof. Teresa Montaruli from September 15, 2008 to January 16, 2009 at the University of Wisconsin, Madison.

I would like to thanks Prof. Teresa Montaruli for having welcome me in the lab and for following my work so well and Prof. Mathieu Ribordy for giving me the opportunity to do my master thesis at the University of Wisconsin. Also thanks to all the IceCube group in UW and particulary Jon Dumm, Sean Grullon, Dmitry Chirkin and Chad Finley for their useful discussions and answering to all my questions and e-mails, Kim Krieger and Frances Culwell for helping me in all the administrative tasks and for making my stay in Wisconsin so nice and the IceCube team at EPFL: Levent Demirörs, Celine Terranova and Shirit Cohen for all their help. And of course thanks to my friend Sabrina, my Parents, Flora and Mickael.

Joel Bressieux
Abstract

Neutrino telescope will be able to detect neutrinos from galactic and extragalactic sources. To achieve this, precise track reconstructions are needed. But these telescopes are subject to large background that has to be separated from signal. The energy of the muons is a very important information to achieve this separation since background and signal don’t have the same energy spectra: atmospheric muons and neutrinos come from parents that undergo interactions and decay in the atmosphere, and the spectrum is softer than for astrophysical neutrinos coming directly from astrophysical sources. Implement a good energy reconstruction method in the point source search would improve the discovery potential [1]. At the moment, the IceCube collaboration uses mostly the number of hits DOMs (NChannel) as energy estimators. But recently, two energy estimators have been implemented that can achieve better performance: muE (one function) and Photorec (layered functions). These three energy estimators have been tested and compared in this work. Since the point source analysis for 22 strings of IceCube was using NChannel, we estimated the effect of changing it in a discovery potential study: since depth and zenith dependencies have been found, so a declination binning has been introduce in the point source code. The final sensitivity to a neutrino flux would improve by about a factor of 1.32.
Chapter 1

Introduction

1.1 Cosmic rays

1.1.1 Composition, origin, energy spectrum and interaction with Earth’s atmosphere.

Composition

Cosmic rays are charged particles originating from space impinging on Earth’s atmosphere. About 90% of all the incoming cosmic ray particles are protons, 9% are ionized helium nuclei (alpha particles), about 1% are electrons and less than 1% are heavy ions but they represent more than 50% of the total mass of the cosmic rays. These fractions should be considered indicative because they are energy dependent.

Origin and energy spectrum

Figure 1.1 shows the differential energy spectrum starting at 0.1 GeV. There is a large range of energies reflecting a variety of primary cosmic rays sources: Low energy cosmic rays ($E < 10^{10}\text{eV}$) are coming from the Sun. Mid range energy cosmic rays ($10^{10}\text{eV} < E < 10^{18}\text{eV}$) are dominantly from galactic sources (stars, supernovae...), cosmic rays with energies larger than $10^{18}\text{eV}$ are likely to be originating from extra galactic sources (AGN\(^1\), quasars, blazars...).

Unfortunately, cosmic rays do not point back to their sources unless they have very large energies (larger than $10^{18}\text{eV}$ [2]). The magnetic fields of the Earth, the Sun and the galaxy randomise the paths of charged particles. So for cosmic rays of galactic origin, the flux at Earth is isotropic.

Starting from 10 GeV the cosmic rays energy spectrum behaves as a power law function:

$$\frac{dN}{dE} \propto E^{-\alpha}$$

(1.1)

With parameter alpha equal to:

\(^1\)Active Galactic Nuclei
Figure 1.1: Cosmic rays energy spectrum

\[ \alpha = \begin{cases} 
2.7, & E < 10^{16}\text{eV} \\
3.0, & 10^{16} < E < 10^{18}\text{eV} \\
\sim 2.7, & E > 10^{18}\text{eV} 
\end{cases} \] (1.2)

Points where spectral indice changes are the knee (at 10^{16}\text{eV}) and the ankle (about 10^{18}\text{eV}).

Power law energy spectra can be explained if the energy gain is proportional to E (i.e. \( E' = E + \Delta E \); \( \Delta E = \xi E \)), as calculated in first and second order Fermi acceleration model.

**Second order Fermi acceleration**

In this model, plasma clouds are moving in the galaxy (with an isotropic speed velocity \( v \)). When particles go through a cloud, they are scattered in the magnetic field of the plasma. Particles’ speed become then isotropic in the cloud reference frame. The average energy gain is \( (v/c)^2 = \beta^2 \). Detailed calculation can be found in [3].

If a particle goes through \( n \) magnetic clouds, the energy of the particle will be:

\[ E^{(n)} = E^{(n-1)} + \xi E^{(n-1)} \] (1.3)

\[ E_n = E_0 (1 + \xi)^n \] (1.4)

where \( E_0 \) is the initial energy of the particle.
Galaxy escape probability increase with particle’s energy. But here, we consider that $P$ is energy independent. The probability the particle is still in the galaxy after $n$ shocks is $(1 - P_{\text{esc}})^n$.

From 1.3, we can find the number of necessary shocks to reach energy $E$:

$$n = \frac{\ln(E/E_0)}{\ln(1 + \xi)}$$ (1.5)

The number of particles accelerated to an energy bigger than $E$ (sum of probability to be in the galaxy at least $n$ shock) is:

$$N(\geq E) = \sum_{m \geq n} (1 - P_{\text{esc}})^m = \frac{(1 - P_{\text{esc}})^n}{P_{\text{esc}}}$$ (1.6)

inserting 1.5 in 1.6 we obtain:

$$N(\geq E) \approx \left(\frac{E/E_0}{P_{\text{esc}}}\right)^{-\gamma}$$ (1.7)

where $\gamma + 1$ is the spectral index:

$$\gamma = \frac{\ln \left(\frac{1}{1 - P_{\text{esc}}}\right)}{\ln(1 - \xi)}$$ (1.8)

The power law spectrum is a "qualitative" consequence from second order Fermi acceleration. A value of the spectral index $\gamma$ can be found using the first order Fermi acceleration model.

**First order Fermi acceleration**

In this model, cosmic rays acceleration is done in regions with ionized gas and supersonic shock waves (e.g Supernova explosion). Particles close to the shock wave can pass through it or be reflected several times and increase their kinetic energy. Figure 1.2 shows a supersonic shock wave moving in a gas with pressure $p$, temperature $T$, and density $\rho$. The gas is at rest in front of the shock wave. In the shock wave reference frame, the gas passes through the shock wave with velocity $v_1$ and has a velocity $v_2$ after. Using mass flow conservation [4]:

$$\rho_1 v_1 = \rho_2 v_2$$ (1.9)

Linear momentum flow conservation:

$$p_1 + \rho_1 v_1^2 = p_2 + \rho_2 v_2^2$$ (1.10)

is the linear momentum flow (the mass flow times the speed) plus a term of pressure. Energy conservation (Bernoulli equation):

$$w_1 + \frac{1}{2} v_1^2 = w_2 + \frac{1}{2} v_2^2$$ (1.11)

along a streamline with:

$$w = \epsilon + pV$$ (1.12)

$\epsilon$ is the free energy per mass units and $V$ is the specific volume.
For a supersonic wave, $Mach = U/c$, $c$ is the sound velocity in the gas at rest. For $M >> 1$:

$$\frac{p_1}{p_2} = \frac{2\gamma M^2}{\gamma + 1} \quad (1.13)$$

$$\frac{\rho_1}{\rho_2} = \frac{\gamma + 1}{\gamma - 1} \quad (1.14)$$

$$\frac{T_2}{T_1} = \frac{2\gamma(\gamma - 1)M^2}{(\gamma + 1)^2} \quad (1.15)$$

$\gamma = 5/3$ for a mono atomic gas. In this case, according to equation 1.14, $\rho_1/\rho_2 = 4$ and in the shock wave reference frame:

$$v_2 = \frac{1}{4}v_1 = \frac{1}{4}U \quad (1.16)$$

In the reference frame downstream of the shock wave, the upstream gas is moving at speed $V - \frac{3}{4}U$.

High energy particles in the gas at rest (downstream of the shock wave) are scattered and their velocity distribution becomes uniform. Some particles go through the shock wave. In the reference frame where the upstream gas is at rest, particles are also scattered and their speed velocity are uniform too. It is a symmetric case because the downstream gas is moving in our direction at $V - \frac{3}{4}U$ speed. If a particle goes through the shock wave, the process is the same. Particle’s energy variation is given by:
\[ \gamma^c = \left\langle \frac{\delta E}{E} \right\rangle = \frac{4V}{3c} = \frac{U}{c} \]  \hspace{1cm} (1.17)

This is a first order variation in \( U/c \). Here:

\[ \beta = 1 + \frac{U}{c} \]  \hspace{1cm} (1.18)

Now we have to compute the escape probability \( P \). For high energy particles going through the shock wave, flux per surface and time units is \( NC/4 \) (\( N \) is the particle density). For a particle, the probability to go through the shock wave is \( c \cos(\theta) \) in the interval \([0, \pi/2]\) and 0 anywhere else. There is \( N \sin \theta d\theta d\phi \) particles in the \([\theta, \theta + d\theta]\) interval and after integration over \( \phi \), the relative fraction to the solid angle is \( \sin \theta d\theta/2 \). The flux is:

\[ \frac{1}{2} NC \int_0^{\pi/2} \cos \theta \sin \theta d\theta = \frac{1}{4} NC \]  \hspace{1cm} (1.19)

After scattering processes, the upstream high energy particles population is isotropic and the gas has velocity \( v_2 = U/4 \). The lost flux will be \( NU/4 \). The fraction of lost particles after acceleration process is

\[ \frac{NU/4}{NC/4} - \frac{U}{c} \]  \hspace{1cm} (1.20)

The escape probability is then (for \( U/c >> 1 \))

\[ P = 1 - \frac{U}{c} \]  \hspace{1cm} (1.21)

\[ \ln(P) = \ln \left( 1 - \frac{U}{c} \right) \approx -\frac{U}{c} \]  \hspace{1cm} (1.22)

\[ \ln(\beta) = \ln \left( 1 + \frac{U}{c} \right) \approx \frac{U}{c} \]  \hspace{1cm} (1.23)

and using equation 1.8:

\[ N(E)dE = \text{const} \times E^{-2}dE \]  \hspace{1cm} (1.24)

This is a very important result: it means that the spectral index for the astrophysical neutrinos we want to observe is 2 whereas the spectral index of atmospheric neutrino is 3.7 (\( dN/dE \propto E^{-3.7} \) see 1.2). Neutrinos don’t interact from the source to the detector and keep the same energy (the \( E^{-2} \) spectra doesn’t change) while cosmic rays interact with the interstellar matter in the galaxy and loose energy.
Interaction with Earth’s atmosphere

When a cosmic ray particle interacts with the Earth’s atmosphere, it collides with molecules (oxygen or nitrogen), and produces an air shower (cf. Fig. 1.3 and [5]).

Millions of particles are created in an air shower (depending on the energy). Particles produced in such collisions are typically mesons (e.g. pions and kaons) which mainly decay into muons and neutrinos. For pions, e.g., one gets:

\[
\begin{align*}
\pi^0 & \rightarrow \gamma + \gamma \\
\pi^+ & \rightarrow \mu^+ + \nu_\mu \\
\pi^- & \rightarrow \mu^- + \bar{\nu}_\mu
\end{align*}
\] (1.25)

1.1.2 Neutrino physics

Neutrinos description

Neutrinos are uncharged leptons. There are three neutrino flavors: electron neutrino \( \nu_e \), muon neutrino \( \nu_\mu \) and tau neutrino \( \nu_\tau \). Neutrinos have a very small mass (smaller than 1eV) and interact only weakly.

Neutrino interaction in matter

The Earth is not transparent to high energy neutrino because of the scattering on nucleon’s quarks. For neutrinos with energies larger than \( 10^5 GeV \), the mean free path length becomes smaller than earth’s radius. Neutrinos interact with a nucleon in matter via the charged or neutral current:

- The neutral current interaction creates an hadronic shower \( X \) and another lower energy neutrino:

\[
\nu_l + N \rightarrow \nu_l + X,
\] (1.28)
where $N$ is a nucleus.

- The charged current interaction creates a charged lepton (electron, muon or tau) and an hadronic shower:

$$\nu_l + N \rightarrow l + X$$  \hspace{1cm} (1.29)

The cross section for the charged current reaction is a function of the neutrino energy $E_\nu$. For $10^{16} eV < E_\nu < 10^{21} eV$, it is given by [6]:

$$\sigma_{CC}(\nu N) = 5.53 \times 10^{-36} \text{cm}^2 \left(\frac{E_\nu}{1 \text{GeV}}\right)$$  \hspace{1cm} (1.30)

The $\nu_\mu N$ cross section as a function of the neutrino energy is shown in Figure 1.4.

![Figure 1.4: Cross sections for $\nu_l N$ interactions at high energies: dashed line, $\sigma(\nu_l N \rightarrow \nu_l + anything)$; thin line, $\sigma(\nu_l N \rightarrow l + anything)$; thick line, total (charged-current plus neutral-current) cross section. This Figure is taken from [6]](image)

1.2 Neutrino astronomy

There are several advantages to use neutrinos to study astrophysical sources:

- As shown by equation 1.30 and Figure 1.4, the neutrino interaction cross sections are very small, neutrinos can be detected on the Earth without having interacted from their creation point. Neutrinos can be absorbed by the Earth only at very high energies ($> 10^5$ GeV). Vertical neutrinos are absorbed at lower energies than more horizontal neutrinos. Whereas photons or cosmic rays interact strongly with matter or radiation.

- Neutrinos are stable particles and won’t decay during propagation, unlike neutrons (which have a mean free path of 1 kpc at $10^{18} eV$).
Since neutrino are not deflected by earth’s, galactic or extra galactic magnetic field, they point back to their source. Cosmic rays do not point back to their source unless they have very large energies (larger than $10^{18}$eV) [2]. However, all the above arguments make neutrinos very difficult to detect.

\[1.2.1 \text{ Neutrino observatory} \]

\textbf{Principle}

The detection principle for neutrinos is the following: hadrons X and leptons l from equation 1.29 generate Cherenkov photons (see 1.3), which are detected in the detector. A high energy $\nu_{\mu}$ creates a muon which is nearly colinear with the neutrino direction, having a mean deviation of $\langle \theta_{\mu_\nu}^2 \rangle = 0.7 \times (E_{\nu}/TeV)^{-0.7}$ [7] (which is in general smaller than the detector resolution). The direction of the muon is reconstructed from the time and amplitude information of the PMTs illuminated by the Cherenkov cone (Fig. 1.5). However, energy resolution is not good because a part of the track may be out of the detector and we can’t know how much of the energy of the neutrino was transferred to the charged lepton.

\textbf{Background}

The first source of background are down-going muons generated by meson decay in the atmosphere (eq.1.27) that reach the deep detector. The atmospheric muon flux is reduced by about a factor of $10^6$ by 2.5km of ice. The second source of background are up-going muons from atmospheric neutrinos (eq.1.27) which interact close to the detector.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.5.png}
\caption{Cherenkov light induced by a muon in a neutrino observatory.}
\end{figure}

\footnote{Photo-Multiplier Tubes}
1.2.2 The IceCube Neutrino Observatory

The IceCube detector is a large volume neutrino detector deployed in the deep ice below the surface of the geographic South Pole [8]. When completed in 2011, the detector will consist of 4800 digital optical modules. These will be arranged on 80 strings with 60 modules each between a depth of 1450m and 2450m. The detector is being deployed in stages during the austral summers from 2004 to 2011. After the 2007-2008 season, the detector consisted of 22 strings, termed IC22. Currently, 56 strings are installed and operational (IC56), instrumenting about two thirds of the final volume of $1\text{km}^3$ (see Fig. 1.6).

IceCube is optimized for the detection of muon neutrinos in the TeV to the PeV energy range. Neutrino induced muons are separated from air-shower induced muons by looking only to muons moving upward through the detector. Up-going muon events must be the product of a neutrino interactions near the detector since neutrinos are the only particles that can traverse the Earth without interacting up to above $10^5\text{GeV}$.

1.3 Muon energy loss

When a muon travels through matter, it loses energy due to ionization, bremsstrahlung, pair production and photonuclear interactions. All these energy losses have continuous and stochastic components ([9] and [10]).
1.3.1 Ionization

The ionization process is:

\[ \mu + \text{atom} \rightarrow \mu + \text{ion} + e^- \]  

(1.31)

The mean rate of energy loss through ionization is given by Bethe-Bloch equation [11] (Figure 1.7):

\[ -\frac{dE}{dx} = K z^2 Z \frac{1}{A \beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right] \]  

(1.32)

with \( K = 4\pi N_A r_e^2 m_e c^2 \) (\( r_e = e^2/4\pi\epsilon_0 m_e c^2 \) is the classical electron radius and \( N_A \) the Avogadro’s number), \( Z \) is the atomic number of absorber, \( A \) [g/mol] the atomic mass of absorber, \( m_e c^2 \) is the electron mass \( \times c^2 \), \( (m_e c^2 = 0.511 \text{MeV}) \), \( T_{\text{max}} \) is the maximum kinetic energy which can be imparted to a free electron in a single collision, \( \delta(\beta \gamma) \) is the density effect correction to ionization energy loss and \( I[\text{eV}] \) is the mean excitation energy. \( \gamma \) and \( \beta \) characterize particle energy and momentum.

![Figure 1.7: Stopping power (\( = -dE/dx \)) for positive muons in copper as a function of \( \beta \gamma = p/Mc \) over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power. This Figure is taken from [11].](image)

The Bethe-Bloch formula is a function of \( \beta \) only (independent on \( M \)) with a small dependence on the material.

1.3.2 Bremsstrahlung

This is the interaction of the particles with the electromagnetic field of the atomic nuclei which generate photons:

\[ \mu + \text{field} \rightarrow \mu + \gamma \]  

(1.33)
The energy loss is:

\[
\frac{dE}{dx} = -\frac{4NZ}{A} \alpha r_e^2 E \left[ \ln 191Z^{-1/3} + \frac{1}{18} \right]
\] (1.34)

The total bremsstrahlung cross section is proportional to \(Z(Z + 1)\). It is given by:

\[
\sigma_{\text{br}} = \frac{4Z^2 \alpha r_e^2}{k} F(E, k)
\] (1.35)

Where \(F(E, k)\) is a function depending of the screening of the nuclear field by the atomic electrons (see [9] for details).

The radiation length \(X_0\) is the characteristic length to describe bremsstrahlung. After traversing \(X_0\) of material, a high energy muon will have \(1/e\) of its initial energy:

\[
\frac{dE}{E} = -\frac{dX}{X_0}
\] (1.36)

and then:

\[
\langle E \rangle = E_0 e^{-X/X_0}
\] (1.37)

### 1.3.3 Photonuclear interaction

The process is:

\[
\mu + N \rightarrow \mu + N + \gamma \rightarrow \mu + N^*
\] (1.38)

It is negligible at low energies but becomes important for higher energies. Details and cross section can be found in [9] and [10].

### 1.3.4 Pair production

It is the bremsstrahlung inverse process:

\[
\mu + N \rightarrow \mu + N^* + e^+e^-
\] (1.39)

The cross section is [9]:

\[
\sigma_{\text{pair}} = \frac{A}{N_A} \frac{7}{9X_0}
\] (1.40)

### 1.3.5 Cherenkov light

A charged particle radiates if its velocity is greater than the speed of light in the medium. The high-energy muons emit a cone of Cherenkov light at a fixed angle \(\theta_c\) given by \(\cos \theta_c = (n\beta)^{-1}\). For relativistic particles in ice, \(\beta \approx 1\) and \(\theta_c \approx 41\) degree (with \(n = 1.32\) the index of refraction in the ice).

The intensity of the radiation per unit path length is proportional to the square of the particle charge and is:
\[
\frac{dN}{dL} = z^2 \frac{\alpha}{hc} \left[ 1 - \frac{1}{\beta^2 n^2} \right] \tag{1.41}
\]

where \(\alpha/(hc) = 370 eV^{-1} cm^{-1}\). The wavelength distribution of the emitted Cherenkov light is proportional to \(\lambda^{-2}\) and is distributed in the visible and UV range.

1.3.6 Average energy loss and critical energy \(E_{\mu c}\)

The average rate of muon energy loss is given by:

\[
-\frac{dE}{dx} = a(E) + b(E)E \tag{1.42}
\]

where \(a(E)\) is the ionization energy loss given by equation 1.32 and \(b(E)\) is the sum of \(e^+e^-\) pair production, bremsstrahlung and photonuclear contributions.

\(a(E)\) dominates at low energy i.e below the critical energy, whereas \(b(E)E\) dominates for high energies. For high energies, the muon energy loss is then directly related to the energy of the muon: we can find the energy of the muon just regarding at the energy loss. Above the critical energy, \(dE/dx\) is no more constant because stochastic energy loss (bremsstrahlung, pair production and photonuclear interaction) dominate over ionization, hence the energy loss is proportional to the muon energy and hence we can measure it even if the track is not fully contained in the detector.

The critical energy \(E_{\mu c}\) is the energy where \(b(E)E\) starts to dominate the average rate of muon energy loss. It is given by [10]:

\[
E_{\mu c} = \frac{a}{b} \tag{1.43}
\]

with \(a = 0.212/1.2 \frac{GeV}{mwe}\) and \(b = 0.251/1.2 \frac{1}{mwe}\). For muons in ice \(E_{\mu c} = 844 GeV\).
Chapter 2

Energy reconstruction testing

2.1 Likelihood description and quality parameters

2.1.1 Likelihood description

The reconstruction of a particle is a specific case of a more general problem of estimating a set of unknown parameters $\vec{a}$ given a set of experimentally measured values $\vec{x}$ [7]. The parameters, $\vec{a}$, (which for a muon for example can be a vertex position and its direction) are determined maximizing the likelihood $L(\vec{x}|\vec{a})$ which for independent measured values $x_i$ becomes:

$$L(\vec{x}|\vec{a}) = \prod_{i} p(x_i|\vec{a})$$ (2.1)

where $p(x_i|\vec{a})$ is the probability density function (PDF) of observing the measured value $x_i$ for a given value of the parameters $\vec{a}$. The reconstruction is done by minimizing $-\log L$ with respect to $\vec{a}$ seeded by a first guess of the parameter $\vec{a}$.

2.1.2 Likelihood method

In this section, some likelihood methods are described.

SPE32

It is the standard likelihood method (discussed in section 2.1.1) iterated 32 times after changing each time the initial seed and finding the minimum of the negative value of the logarithm of the likelihood again each time.

Bayesian likelihood

The bayesian likelihood is a down going zenith weighted technique useful to recognize misreconstructed up going muons. Real down going muons are reconstructed with a small (good) likelihood number whereas up going muons are reconstructed with a large (bad) likelihood number. Doing the difference between bayesian and regular likelihood, one can suppress down going events by cutting on negative and small values.
Paraboloid method

The paraboloid method uses the likelihood reconstruction to calculate errors. The likelihood function close to minimum is a paraboloid. The width of this paraboloid is estimated and represents an estimate of the angular resolution for the track (called $\sigma_{par}$ hereafter).

2.1.3 Quality parameters

For each reconstructed track, several parameters are calculated. These parameters are useful to estimate the quality of the reconstruction [7].

Likelihood parameter

The likelihood parameter $l$ is the absolute value of the maximum of the likelihood function. We can use the reduced log likelihood ($r \log l$) parameter which is defined as:

$$r \log l = -\frac{\log l}{N_{\text{free}}}$$

$N_{\text{free}}$ is the number of degrees of freedom. Smaller values of the reduced likelihood correspond to better track reconstruction.

Residual time

The geometrical time $t_{geo}$ is the theoretical time for a Cherenkov photon to travel from its emission point to the DOM without scattering. The time residual is defined as:

$$t_{res} = t_{hit} - t_{geo}$$

where $t_{hit}$ is the observed hit time. In the ideal case, $t_{res}$ should be equal to zero. The residual time gives information on the quality of the photons: if it is a prompt photon or a scattered one.

Number of direct hits

The number of direct hits ($N_{Dir}$) is the number of hits within a residual time window. Larger value of $N_{Dir}$ correspond to a more precise track reconstruction.

Error of the direction of the track

It is given by:

$$\sigma_{par} = \sqrt{\frac{\sigma_x^2 + \sigma_y^2}{2}}$$

It is the angular uncertainty of the events. $\sigma_x$ and $\sigma_y$ are computed in the paraboloid method.
2.2 Energy reconstruction

As explained in 1.1.1 atmospheric neutrinos (i.e. background) and astrophysical neutrinos (signal from point sources) have different energy spectra. For a good separation between signal and background, a good energy reconstruction is needed.

2.2.1 MuE

MuE returns the average number of photons emitted per unit length of a muon track \( \mu_0(d) \), where \( d \) is the distance to the track [12]. It is given by:

\[
\mu_0(d) = \left[ A_{eff} \cdot \frac{f(\eta) + 4g(d)\eta}{1 + g(d)} \right] \frac{1}{2\pi\sqrt{\lambda_\mu d} \tanh(d/\lambda_\mu)} e^{-\frac{d}{\lambda_a \sin \theta_c}}, \quad g(d) = \sinh \frac{d}{f d \lambda_e} \tag{2.5}
\]

Where \( A_{eff} \) is the effective PMT area, \( f(\eta) \) is the relative sensitivity of the OM for the photons arriving from an angle \( \eta \) relative to the PMT axis and \( \lambda_a \) is the absorption length. \( \lambda_\mu \) is given by:

\[
\sqrt{\lambda_\mu} = \frac{4\lambda_e}{3\sqrt{\pi\lambda_p}} e^{-d\left(\frac{1}{\lambda_a \sin \theta_c} - \frac{1}{\lambda_p}\right)} \tag{2.6}
\]

where \( \lambda_e \) is the effective scattering length and \( \lambda_p \) is the propagation length.

Above the muon critical energy (\( \sim 850 \) GeV) a muon and all secondaries it creates along its path produce a number of Cherenkov photons that is proportional to the muon energy (see 1.3.6).

2.2.2 Photorec

For photorec, the idea is to reconstruct quantities using the full waveform (fit a PDF which is assumed to describe the hypothesis reasonably well to the observed waveform)[13]. The likelihood formula is:

\[
\log P(t|\vec{x}, E) = \sum_{i=1}^{k} (n_i \log p(t_i|\vec{x})) + N_{pe} \log \mu_{tot} - \mu_{tot} \tag{2.7}
\]

The first sum is a sum over the waveform bins. \( n_i \) is the charge of a reconstructed pulse by an algorithm that extracts pulses given a waveform (called RecoPulse). The second and third terms are amplitude terms \( N_{pe} \) and \( \mu_{tot} \) are the total measured and expected charge. \( p(t_i|\vec{x}) \) is the normalized timing probability of a single photoelectron arriving at the DOM.

2.2.3 NChannel

NChannel is the number of hit DOMs. Since NChannel is proportional to the energy loss, it is used as an energy estimator. It is simple and fast but not very precise.
2.3 Data sample

Simulation dataset 651 (Nugen) is used. It is an IC22 simulation, with only $\nu_\mu$ with $E^{-1}$ neutrino spectrum. The $E^{-1}$ is used to get a reasonably high statistics at high energies and that then one can reweight events for any spectrum. In this section, plots are $E^{-2}$ weighted. Zenith is in the $0\,\text{deg}<\theta<180\,\text{deg}$ range (up-going), and energies are in the $10\,\text{GeV}<E<10^9\,\text{GeV}$ range. Tested Energy reconstruction are photorec, muE and NChannel.

IC22 PS Event Selection cuts are used:

- $FitStatus_{paraboloid} = 0$
- $\sigma_{par} < 3\,\text{deg}$
- $r \log l_{SPE32} < 9.5$
- $\log l_{Umbrella} - \log l_{SPE32} > 15$
- $\log l_{Bayes} - \log l_{SPE32} > 30$
- $zen_{1\,\text{iter}} > 70\,\text{deg}$ and $zen_{2\,\text{iter}} > 70\,\text{deg}$
- NOT ($r \log l_{SPE32} > 7.8$ and $NDirC < 7$)
- NOT ($r \log l_{SPE32} > 8.5$ and $NDirC < 8$)

where $FitStatus$ says if the fit succeed (0) or failed (1), $\log l_{Umbrella}$ is the likelihood value of the umbrella fit which is restricted to the opposite hemisphere (i.e. track parameters are constrained to the opposite hemisphere) and $NDirC$ is NDir for $-15\,\text{ns}<t_{\text{res}}<75\,\text{ns}$.

2.4 Energy scatter plots

In order to choose the best energy reconstruction to work with, muE, photorec and NChannel have been tested using simulations: simulated and reconstructed energy values have been compared regarding different parameters such as zenith, NChannel or angular resolution of the track.

2.4.1 Conversion function

Photorec returns $dE/dX$ while muE returns the photon density $n_0$ along the track and NChannel is the number of hit DOMs. For comparison purposes, NChannel, photorec and muE reconstructed quantities are converted into the same quantity $E_{\text{COG}}$ (the energy at the center of gravity of the hits). In Figure 2.1 a 7 parameters power law function is fitted on the most probable value for each bin on $\log(E_{\text{reco}})$ distribution.

The fitted function is a linear function on log-log scale with power-law cutoffs implemented on both sides of the energy scale [14]. The parameters include the slope $a$ and normalization $b$, 2 cutoff energies $x_{\text{min/ma}}x$ and 2 power-law indices $\alpha$ and $\beta$ (describing the behavior near cutoffs) and one more - how far to step back from cutoffs before using the slant extensions (that help avoid limiting the range of the function to values between cutoffs).
For converting \( \log(E_{\text{reco}}) = y \) as \( \log(E_{\text{COG}}) = x \), the fitted function is:

\[
\log(E_{\text{reco}}) = y = f(x) = a \log \left( \frac{b}{\left( \frac{1}{(10^x) + x_{\text{min}}^\alpha} + \frac{1}{x_{\text{max}}^\beta} \right)^{1/\beta}} \right)
\]  

(2.8)

Since we have \( x_{\text{min}} \ll x_{\text{max}} \):

\[
\lim_{x \to -\infty} f(x) = a \log \frac{b}{x_{\text{min}} + x_{\text{max}}} \approx a \log(b x_{\text{min}})
\]  

(2.9)

and

\[
\lim_{x \to \infty} = a \log(b x_{\text{max}})
\]  

(2.10)

Finally:

\[
\lim_{x_{\text{max}} \to \infty} x_{\text{min}} \to \infty = a \log b + ax
\]  

(2.11)

which is a log-log linear function.

Figure 2.1: \( E_{\text{COG}} \) vs \( E_{\text{reco}} \) plots: The 7 parameters power law function shown is used to convert \( \log(E_{\text{reco}}) \) to \( \log(E_{\text{COG}}) \). Crosses are the maximum of \( \log(E_{\text{reco}}) \) distribution of each twenty \( \log(E_{\text{COG}}) \) slices. Function 2.8 is fitted on these maxima.

2.4.2 Energy resolution

In the following, \( E_{\text{reco}} \) (muE, photorec and NChannel) are converted into COG muon energy using conversions functions found in 2.4.1.

Here, we define energy reconstruction as the difference between the log10 of the value returned by the reconstruction (\( \log(E_{\text{reco}}) \)) converted with equation 2.8 and the true value from the simulation (\( \log(E_{\text{COG}}) \)). Means are extracted for a fixed log10 \( E \) binning while \( \sigma \) of the energy resolutions plots
are extracted from gaussian fits on $\log(E_{\text{reco}}) - \log(E_{\text{COG}})$ distributions of $E_{\text{COG}}$ slices with same statistic (i.e. the same number of events) in each slices (gaussians fits are shown in appendix A).

In Figure 2.2, we can see that muE and photorec are better reconstructions than NChannel because means of the difference between the reconstructed energy and the true one are closer to zero and RMS and sigmas are smaller.

The $\sigma$ and RMS of the energy resolution are shown in Figure 2.3. $\sigma$ is bigger for energies in the ionization region below the critical energy $E_{\mu c}$. It is because the ionization term $a$ which dominates the energy loss (equation 1.42) is constant, so it is more difficult to find the muon energy with precision. For energies bigger than $E_{\mu c}$ (when $b(E)E$ dominates in equation 1.42), $\sigma$ becomes smaller because the energy loss depend directly of the energy of the muon. The energy resolution is then about $E_{\text{res}} \approx 10^{0.4} \approx 2.5\text{GeV}$ (0.4 is the sigma in $\log_{10} E$ and it is not for sure that E distributes as a gaussian so it is a first order calculation). For energies bigger than $10^7\text{GeV}$ the resolution becomes worse because we begin to have more contribution of far away events which are not fully contained in the detector. RMS errors are bigger than $\sigma$ errors because they are calculated for all the events in the slice (even the events far away from the mean) whereas $\sigma$ is extracted from a gaussian fit (see appendix A) close to the mean.

### 2.5 NChannel, zenith, angular resolution and energy likelihood ratio dependences

In this section, all $E_{\text{reco}}$ have been converted to $E_{\text{COG}}$ muon energy [GeV] using conversions functions found in 2.4.1. Means and $\sigma$ have been extracted from gaussian fits on the distributions of the energy resolution of X-axis bins.
2.5.1 Zenith dependence

For point source search, it is good to have the same sensibility all over the sky. We are interested on a uniform behavior of the energy reconstruction in zenith angle of the track $\cos(\theta)$. We study now the energy resolution as a function of $\cos(\theta)$ for SPE32 reconstruction. In Figure 2.4, the mean of the energy resolution for muE and photorec is close to zero and flat, without offset. This demonstrates the uniform sensitivity we want to have.

But the $\sigma$ of the gaussians plots in Fig. 2.5 are smaller for horizontal events ($\theta = \pi$) than for up-goings events ($\theta = \frac{\pi}{2}$). DOM’s distribution in the detector is more efficient for reconstructing horizontal tracks: along a vertical string there is a DOM each 17m while strings are horizontally spaced by 124m.

2.5.2 Angle resolution dependence

It is also interesting to look at the energy resolution as a function of the resolution angle: we want to check the hypothesis that if a track is better reconstructed, then also $E_{\text{reco}}$ will be more precise. Resolution angle $\psi$ is the angle between the direction of the true track and the reconstructed one.

In Figure 2.6, for $\psi < 1\text{deg}$, means are closer to zero for all the energy reconstructions. The $\sigma$ of the energy resolutions presented in Figure 2.7 show the same behavior: for $\psi < 1\text{deg}$, the energy resolution is better. This confirm our hypothesis that the energy reconstruction is more precise for well reconstructed tracks.
Figure 2.4: Converted $\log(E_{\text{reco}})$ - $\log(E_{\text{COG}})$ (i.e. energy resolution) vs. $\cos(\theta)$ reconstructed with SPE32. $\log(E_{\text{reco}})$ have been converted to $\log(E_{\text{COG}})$ using the function 2.8. The mean have been extracted from gaussians fitted on Converted $\log(E_{\text{reco}})$ - $\log(E_{\text{COG}})$ distribution of twenty $\cos(\theta)$ slices.

2.5.3 NChannel dependence

We now study the behavior of the energy resolution as a function of $\text{NChannel}$ that is a function of energy released in the detector. The ice properties are depth dependent: we have evidence from various calibration measurements that the ice is much more transparent below a dust layer that is located at around $z = -100m$ respect to the center of the detector at 2000m of depth compared to the upper part of the instrumented region. So the detector is divided in two parts: the upper part with $COGZ > -100m$ (Fig. 2.8 for distributions and 2.10 for the errors) and the lower part $COGZ < -100m$. (Fig. 2.9 for distributions and 2.10 for the errors).

We noticed that for photorec and mue results are more stable against the depth dependence of the ice respect to NChannel. This is a very good reason for considering them an improvement compared to NChannel. For NChannel and mue, there is also an offset between the means of the upper and the lower parts for high NChannel events (see Fig 2.9 and 2.8) whereas photorec is stable. We may have to calibrate NChannel and muE for both upper and lower part of the detector. In Figure 2.10, $\sigma$ are smaller for high NChannel events for the both two parts of the detector for all the energy estimators (for $NCh > 120$ $\sigma$ increase because of a lack of statistic).

Energy quality parameter

Since there is a likelihood value $r \log l_E$ for photorec, we want to look at the behavior of the energy resolution as a function of $r \log l_E$. $r \log l_E$ could be use as a quality parameter and we could cut on it to improve energy resolution. The mean in Figure 2.11 is closer to zero for $r \log l_E < 10$. In Figure 2.12 we can see that $\sigma$ is also smaller for $r \log l_E < 10$. It seems to confirm the hypothesis
Figure 2.5: $\sigma$ of energy resolution vs. $\cos(\theta)$ reconstructed with SPE32. Blue is for photorec, red is for muE and green is for NChannel. $\sigma$ have been extracted from gaussians fitted on Converted$[\log(E_{\text{reco}})] - \log(E_{\text{COG}})$ distribution of twenty $\cos(\theta)$ slices.

that $r \log l_E$ can be used as a quality parameter. Figure 2.13 shows the primary zenith distribution (zenith of the primary neutrino) for different cuts (PS analysis cuts, PS analysis cuts and $r \log l_E < 10$ and PS analysis cuts and $r \log l_E < 8$). We see that $r \log l_E$ cuts are zenith dependent: a cut in $r \log l_E$ suppress more events close to the horizon (where we have the best energy resolution according to 2.5.1) than up going events. So $r \log l_E$ can not be used as a cut parameter.
Figure 2.6: Converted $\log(E_{\text{reco}}) - \log(E_{\text{COG}})$ (i.e. energy resolution) vs. $\psi$. $\log(E_{\text{reco}})$ have been converted to $\log(E_{\text{COG}})$ using the function 2.8. The mean have been extracted from gaussians fitted on $\log(E_{\text{reco}}) - \log(E_{\text{COG}})$ distribution of twenty $\psi$ slices.

Figure 2.7: $\sigma$ of energy resolution vs. $\psi$. Blue is for photorec, red is for muE and green is for NChannel. $\sigma$ have been extracted from gaussians fitted on converted $\log(E_{\text{reco}}) - \log(E_{\text{COG}})$ distribution of twenty $\psi$ slices.
Figure 2.8: Converted $\log(E_{\text{reco}})$ - $\log(E_{\text{COG}})$ (i.e. energy resolution) vs. NChannel for COGZ $<-100\text{m}$. $\log(E_{\text{reco}})$ have been converted to $\log(E_{\text{COG}})$ using the function 2.8. The mean have been extracted from gaussians fitted on Converted $\log(E_{\text{reco}})$ - $\log(E_{\text{COG}})$ distribution of twenty NCh slices.

Figure 2.9: Converted $\log(E_{\text{reco}})$ - $\log(E_{\text{COG}})$ (i.e. energy resolution) vs. NChannel for COGZ $>-100\text{m}$. $\log(E_{\text{reco}})$ have been converted to $\log(E_{\text{COG}})$ using the function 2.8. The mean have been extracted from gaussians fitted on Converted $\log(E_{\text{reco}})$ - $\log(E_{\text{COG}})$ distribution of twenty NCh slices.
Figure 2.10: $\sigma$ of energy resolution vs. NChannel for COGZ > $-100m$ (left) and for COGZ < $-100m$ (right). Blue is for photorec, red is for muE and dark is for NChannel. $\sigma$ have been extracted from gaussians fitted on converted $[\log(E_{\text{reco}})] - \log(E_{\text{COG}})$ distribution of twenty NCh slices.

Figure 2.11: Converted $[\log(E_{\text{reco}})] - \log(E_{\text{COG}})$ (i.e. energy resolution) vs. $r\log l_E$. $\log(E_{\text{reco}})$ have been converted to $\log(E_{\text{COG}})$ using the function 2.8. The mean have been extracted from gaussians fitted on Converted $[\log(E_{\text{reco}})] - \log(E_{\text{COG}})$ distribution of twenty $r\log l_E$ slices.
Figure 2.12: $\sigma$ of energy resolution vs. $r \log l_E$. Blue is for photorec, red is for muE. $\sigma$ have been extracted from gaussians fitted on $\text{Converted}[\log(E_{\text{reco}})] - \log(E_{\text{COG}})$ distribution of twenty $r \log l_E$ slices.

Figure 2.13: Primary zenith distribution for different cuts on $r \log l_E$. The black line is IC22 point source cuts only, the blue line is IC22 point source cuts and $r \log l_E < 10$ and the red line is IC22 point source cuts and $r \log l_E < 8$. 

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Chapter 3

Discovery potential study

3.1 IC22 point source method

For a given source with location \( x = (r.a., \text{dec.}) \) and spectrum \( \gamma \), one needs to provide \[15\]

- \( S(x, E, \gamma) \): PDF describing spatial distribution of signal events and the distribution of an energy-correlated observable for signal events with the given spectrum \( \gamma \). NChannel is currently used as the energy observable \( E \).

- \( B(x, E) \): PDF describing spatial distribution and energy distribution of background events (atmospheric neutrinos + mis-reconstructed down-going muons which survive cuts).

The source PDF for each event \( S_i(x, E, \gamma) \) depends on the angular uncertainty \( \sigma_{\text{par}} \) (equation 2.4) of the event and the source location \( x_s \). The distributions of NChannel (the energy observable) for each possible source spectrum \( \gamma \) are calculated from neutrino-generator simulations weighted to the spectrum. The source PDF can be expressed as:

\[
S_i(|x_i - x_s|, E_i, \gamma) = \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{|x_i - x_s|^2}{2\sigma_i^2}\right) P_{\text{SigNch}}(E_i|\gamma) \tag{3.1}
\]

The background PDF also consists of a spatial PDF (now based on the declination distribution of the final data sample) and an energy PDF (based on the NChannel distribution of the final data sample):

\[
B(x_i, E_i) = P_{\text{BkgDec}}(x_i) P_{\text{BkgNch}}(E_i) \tag{3.2}
\]

3.2 \( E_{\text{reco}} \) distribution

For the future, we are particularly interested in understanding the dependency on the depth of the ice and on NChannel because the hotspot shown in Figure 3.1 is due to neutrino events like shown in Figure 3.2 that are deep in the ice and with very high NChannel. Hence we attempt to have a variable instead of NChannel (e.g \( \text{muE} \)) that is more stable in terms of energy reconstruction respect to ice depth and NCh. For the neutrino point source search, the most interesting region is the horizon because very high energy neutrinos are expected to come from the horizon since the earth begins to be opaque to very high energy neutrinos (see 1.2).
Moreover, in section 2.5, we pointed out depth and zenith dependencies of the energy resolution. To quantify it, distributions of the normalized energy reconstructions have been plotted for \( COGZ > -100 \text{m} \) and \( COGZ < -100 \text{m} \) in three declination bands (90 deg < \( \theta < 120 \) deg, 120 deg < \( \theta < 150 \) deg, 150 deg < \( \theta < 180 \) deg) in Figures 3.3 for NChannel, 3.4 for muE and 3.5 for photorec.

### 3.2.1 Ratio comparison

In Figures 3.6 (NChannel), 3.7 (MuE) and 3.8 (photorec) we represent the ratio up (higher part of the detector \( COGZ > -100 \text{m} \))/down (lower part \( COGZ < -100 \text{m} \)). Ideally we would choose for our analysis the variable that minimizes the differences between data and simulations for these ratios and the differences between upper and lower detector (ratios around 1) as well as differences between zenith regions (the 3 plots in each figure). We notice that energy estimators, and particularly muE, minimize differences between data and simulations respect to NChannel. Nonetheless photorec shows ratios in the vertical region that are much larger than one, compared to MuE and NChannel. MuE seems to be the best estimator concerning the agreement between data and simulations and the differences between bottom and top detector. Figures 3.6 to 3.8 nonetheless show some zenith dependence. The future analysis for IC40 could be improved if instead of taking the background PDF from all the sky we would bin it in these 3 regions shown in the figures or at least in 2 regions separating 150-180 from 90-150 degrees.

### 3.2.2 Discovery potential study

We are using NChannel to estimate the difference compared to the standard analysis that uses the background PDF in the entire sky respect to dividing it in declination regions. We estimated this for 2 sources at two different declinations. The background PDF is fitted using events from the declination band. Discovery potential fluxes (the flux needed from a source emitting \( E^{-2} \) neutrinos for a 5\( \sigma \) discovery and 50\% probability) found using the point source code are in Table 3.2.2.

The mean flux for 50\% probability detection is bigger for the source at 7 deg declination for horizontal declination band \( (2.35 \times 10^{-8}[\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}]) \) than for all sky \( (2.04 \times 10^{-8}[\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}]) \). We have an effect of 32\% due to the background PDF change. The effect is only 8\% for a 40 deg source. This is an important result: we could make a better NChannel background PDF by using different declination regions.
Figure 3.2: Neutrino event from the hot spot shown in Figure 3.1 in IceCube.

<table>
<thead>
<tr>
<th>Point Source declination [deg]</th>
<th>Declination bands [deg]</th>
<th>Mean Flux for 50% detection probability [GeV$^{-1}$cm$^{-2}$s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>90 &lt; zen &lt; 110</td>
<td>2.35 × 10$^{-8}$</td>
</tr>
<tr>
<td>7</td>
<td>80 &lt; zen (all sky)</td>
<td>2.04 × 10$^{-8}$</td>
</tr>
<tr>
<td>40</td>
<td>90 &lt; zen &lt; 110</td>
<td>3.84 × 10$^{-8}$</td>
</tr>
<tr>
<td>40</td>
<td>80 &lt; zen (all sky)</td>
<td>4.19 × 10$^{-8}$</td>
</tr>
</tbody>
</table>

Table 3.1: Discovery potential results: mean flux for 50% detection probability for two point sources declination on two declination bands
Figure 3.3: NChannel distribution for $COGZ > -100m$ and $COGZ < -100m$ for three declination bands: 90 deg $< \theta < 120$ deg (left), 120 deg $< \theta < 150$ deg (middle), 150 deg $< \theta < 180$ deg (right). IC22 data are in black, simulations with atmospheric weighting are in red and simulations with $E^{-2}$ weighting are in blue.
Figure 3.4: $\mu E$ distribution for $COGZ > -100m$ and $COGZ < -100m$ for three declination bands: $90 \text{ deg} < \theta < 120 \text{ deg}$ (left), $120 \text{ deg} < \theta < 150 \text{ deg}$ (middle), $150 \text{ deg} < \theta < 180 \text{ deg}$ (right). IC22 data are in black, simulations with atmospheric weighting are in red and simulations with $E^{-2}$ weighting are in blue.
Figure 3.5: Photorec distribution for \( COGZ > -100m \) and \( COGZ < -100m \) for three declination bands: 90 deg < \( \theta \) < 120 deg (left), 120 deg < \( \theta \) < 150 deg (middle), 150 deg < \( \theta \) < 180 deg (right). IC22 data are in black, simulations with atmospheric weighting are in red and simulations with \( E^{-2} \) weighting are in blue.

Figure 3.6: NChannel distributions' ratio up/down for three declination bands: 90 deg < \( \theta \) < 120 deg (left), 120 deg < \( \theta \) < 150 deg (middle), 150 deg < \( \theta \) < 180 deg (right). IC22 data are in black, simulations with atmospheric weighting are in red and simulations with \( E^{-2} \) weighting are in blue.
Figure 3.7: MuE distributions’ ratio up/down for three declination bands: 90 deg < θ < 120 deg (left), 120 deg < θ < 150 deg (middle), 150 deg < θ < 180 deg (right). IC22 data are in black, simulations with atmospheric weighting are in red and simulations with $E^{-2}$ weighting are in blue.

Figure 3.8: Photorec distributions’ ratio up/down for three declination bands: 90 deg < θ < 120 deg (left), 120 deg < θ < 150 deg (middle), 150 deg < θ < 180 deg (right). IC22 data are in black, simulations with atmospheric weighting are in red and simulations with $E^{-2}$ weighting are in blue.
Conclusion

The three energy estimator (muE, photorec and NChannel) have been tested and compared. The energy resolution is equivalent for muE and photorec, but both are better than NChannel (see section 2). The behavior is the same for all the energy estimator: The energy resolution is better for horizontal events, well reconstructed tracks and high NChannel events. The likelihood value of the energy reconstruction does not seem to be usable as a cut parameter.

In section 3 we demonstrated that muE is better, first because it is faster than photorec and second because it showed a lower dependence on the zenith of the up/down ratio of the detector. By doing a discovery potential study, we showed that implementing a binning to compute the background PDF with NChannel will improve the discovery potential by about a factor 1.32.
Figure A.1: Gaussians fit on energy resolution distribution for muE from figure 2.2. There is the same statistic in each $E_{COG}$ slice. Mean and sigma are plotted in Figure 2.2 and 2.3.
Figure A.2: Gaussians fit on energy resolution distribution for Photorec from figure 2.2. There is the same statistic in each $E_{COG}$ slice. Mean and sigma are plotted in Figure 2.2 and 2.3.
Figure A.3: Gaussians fit on energy resolution distribution for NChannel from figure 2.2. There is the same statistic in each $E_{COG}$ slice. Mean and sigma are plotted in Figure 2.2 and 2.3
Bibliography


