Background at Daya Bay

MAND-sim Workshop, KSU, Manhattan, KS (June 2005)

Alfred Tang
Chinese University of Hong Kong
Location of Daya Bay

Beijing

Daya Bay

Hong Kong
Landing in Hong Kong
Daya Bay Nuclear Power Plant
Goals of Simulations

- Use MUSIC to calculate integrated muon intensity and energy at any underground site for any arbitrary hill profile.
- Use FLUKA to calculate the spallated neutron flux and energy.
- Use GEANT4 and GLG4sim to study detector physics.
The Heart of MUSIC

Energy Loss = ?

depth $X$

MUSIC

final muon energy $E_\mu$

initial muon energy $E_{\mu_0}$
Solving Integrals

Vertical Muon Intensity

\[ I^{\nu}_{\mu} = \int_{0}^{\infty} dE_{\mu 0} P(E_{\mu}, E_{\mu 0}, h, \theta^{*} = 0) \frac{dN_{\mu 0}(E_{\mu 0}, \cos \theta^{*} = 1)}{dE_{\mu 0} \, d\Omega} \]

Integrated Muon Intensity

\[ J_{\mu} = \int_{S} d\Omega \int_{0}^{\infty} dE_{\mu 0} P(E_{\mu}, E_{\mu 0}, X, \theta^{*}, \phi) \frac{dN_{\mu 0}(E_{\mu 0}, \cos \theta^{*})}{dE_{\mu 0} \, d\Omega} \]
Traditional Gaisser Parameterization

\[
\frac{dN_\mu}{dE_\mu} \approx \frac{0.14 \; E_\mu^{-2.7}}{\text{cm}^2 \; \text{s sr GeV}} \left\{ \frac{1}{1 + \frac{1.1 E_\mu \cos \theta}{115}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos \theta}{850}} \right\}
\]

\[E_\mu > \frac{100}{\cos \theta}\]

\[\theta < 70^\circ\]
A False Start

Fits from traditional Gaisser Parameterization
Angular Correction

\[
\cos \theta^* = \frac{\sqrt{x^2 + p_1^2 + p_2 x^{p_3} + p_4 x^{p_5}}}{1 + p_1^2 + p_2 + p_4}
\]

\[x \equiv \cos \theta\]

\[p_1 = 0.102573\]

\[p_2 = -0.068287\]

\[p_3 = 0.958633\]

\[p_4 = 0.0407253\]

\[p_5 = 0.817285\]
Further Modification

Based on a parameterization of V. Kudryavtsev modified by the author

\[
\frac{dN_\mu}{dE_\mu} \approx A \frac{0.14 E_\mu^{-2.7}}{\text{cm}^2 \text{s sr GeV}} \left\{ \frac{1}{1 + \frac{1.1 E_\mu \cos\theta^*}{115}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos\theta^*}{850}} + r_c \right\}
\]

\[A = 1, \quad \tilde{E}_\mu = E_\mu, \quad r_c = 0\]

**If** \(E_\mu < \frac{100}{\cos \theta}\), **then**

\[r_c = 10^{-4}\]

\[\Delta = 2.06 \times 10^{-3} \left( \frac{950}{\cos \theta^*} - 90 \right)\]

\[
\tilde{E}_\mu = E_\mu + \Delta
\]

\[A = 1.1 \left( \frac{9 \sqrt{\cos \theta + 0.001}}{103} \right)^{4.5} \tilde{E}_\mu \cos \theta^*\]
Back on Track: Modified Gaisser

![Graph showing modified Gaisser](image)
Uniform Generation without Binning

A simple example with 30 events:

\[
I = \frac{2}{10} \frac{dN_1}{dE} \Delta E + \frac{4}{10} \frac{dN_2}{dE} \Delta E + \frac{7}{10} \frac{dN_3}{dE} \Delta E
\]

\[= \frac{3 \Delta E}{30} \left( 2 \frac{dN_1}{dE} + 4 \frac{dN_2}{dE} + 7 \frac{dN_3}{dE} \right) \]

- Binning or no binning gives the same answer.
- Uniform generation is faster, simpler and uses less memory.
- Uniform generation does not require the generation of correlated pairs of \( E \) and \( \cos \theta \) as in the generation according to the distribution.
- This algorithm is based on a MUSIC code written by J. Formaggio.
Ground Level Integrated Angular Distribution

\[ \frac{dI}{d\Omega} \text{ (cm}^{-2}\text{ sr}^{-1}\text{ s}^{-1}) \]

- Monte Carlo (Present)
- Gaussian Quadrature
- Flint (1972)
- Wilson (1959)

\[ \cos(\theta) \]
The commonly accepted value for vertical muon energy on ground level is 4 GeV. The simulated value is 4.19 GeV.
Vertical Muon Intensity

![Graph showing vertical muon intensity versus height in km.w.e.]

- Crouch (EX)
- Bakun (EX)
- LVD (EX)
- MARCO (EX)
- Frøyn (EX)
- Crookes and Rastia (EX)
- Bergmannas et al. (EX)
- Stockel (EX)
- Castagnoli et al (EX)
- Avan and Avan (EX)
- Randell and Hazen (EX)
- Clay and Van Gemert (EX)
- Wilson (EX)
- Kudryavtsev (MC)
- Present work (MC)
Ratio of MC over EX Vertical Intensities

- Crouch (EX)
- Crookes and Rustin (EX)
- Bergamasco et al. (EX)
- Stockel (EX)
- Castagnoli et al. (EX)
- Avan and Avan (EX)
- Clay and Vaa Gernert (EX)
- Wilson (EX)
Flat Surface Integrated Muon Intensity

<table>
<thead>
<tr>
<th>$h$ (mwe)</th>
<th>Sheffield (MUSIC)</th>
<th>CUHK (MUSIC)</th>
<th>Braidwood$^1$ (MUSIC)</th>
<th>Braidwood$^2$ (GEANT4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>$1.70 \times 10^{-5}$</td>
<td>$6.11 \times 10^{-5}$</td>
<td>$6.23 \times 10^{-5}$</td>
<td>$4.63 \times 10^{-5}$</td>
</tr>
<tr>
<td>500</td>
<td>$2.20 \times 10^{-6}$</td>
<td>$1.71 \times 10^{-5}$</td>
<td>$1.64 \times 10^{-5}$</td>
<td>$1.45 \times 10^{-5}$</td>
</tr>
<tr>
<td>700</td>
<td>$6.54 \times 10^{-6}$</td>
<td>$6.54 \times 10^{-6}$</td>
<td>$6.31 \times 10^{-6}$</td>
<td>$6.57 \times 10^{-6}$</td>
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<tr>
<td>1000</td>
<td>$2.20 \times 10^{-6}$</td>
<td>$2.21 \times 10^{-6}$</td>
<td>$2.23 \times 10^{-6}$</td>
<td>$2.32 \times 10^{-6}$</td>
</tr>
</tbody>
</table>
Flat Surface Average Muon Energy

\[ E_p (\text{GeV}) \]

<table>
<thead>
<tr>
<th>( h ) (mwe)</th>
<th>Sheffield (MUSIC)</th>
<th>CUHK (MUSIC)</th>
<th>Braidwood (GEANT4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td></td>
<td>68.2</td>
<td>60.9</td>
</tr>
<tr>
<td>500</td>
<td>97</td>
<td>97.1</td>
<td>91.2</td>
</tr>
<tr>
<td>700</td>
<td></td>
<td>124</td>
<td>120</td>
</tr>
<tr>
<td>1000</td>
<td>157</td>
<td>158</td>
<td>154</td>
</tr>
</tbody>
</table>
Latticization Algorithm for Arbitrary Hill Profiles
The Pyramid Test

<table>
<thead>
<tr>
<th>Method</th>
<th>( E_\mu ) (GeV)</th>
<th>( R_\mu ) (Hz)</th>
<th>Cuts</th>
<th>( E_\mu ) (GeV)</th>
<th>( R_\mu ) (Hz)</th>
<th>Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exact</td>
<td>57</td>
<td>676</td>
<td>((45 - 5000)) GeV ((0 - 70)^\circ)</td>
<td>156</td>
<td>14</td>
<td>((230 - 5000)) GeV ((0 - 70)^\circ)</td>
</tr>
<tr>
<td></td>
<td>61</td>
<td>748</td>
<td>((45 - 5000)) GeV ((0 - 87.7)^\circ)</td>
<td>161</td>
<td>15</td>
<td>((230 - 5000)) GeV ((0 - 90)^\circ)</td>
</tr>
<tr>
<td></td>
<td>61</td>
<td>747</td>
<td>((0.106 - 5000)) GeV ((0 - 87.7)^\circ)</td>
<td>162</td>
<td>15</td>
<td>((0.106 - 5000)) GeV ((0 - 90)^\circ)</td>
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<tr>
<td></td>
<td>61</td>
<td>748</td>
<td>((0.106 - 10^6)) GeV ((0 - 87.7)^\circ)</td>
<td>174</td>
<td>15</td>
<td>((0.106 - 10^6)) GeV ((0 - 90)^\circ)</td>
</tr>
<tr>
<td>Lattice</td>
<td>57</td>
<td>679</td>
<td>((45 - 5000)) GeV ((0 - 70)^\circ)</td>
<td>157</td>
<td>14</td>
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Comparison with Boulby Mine

- The Boulby Mine lies beneath a flat surface of 2800mwe overburden.
- The measured average muon energy is 260 GeV.
- The simulated average muon energy is 271 GeV.
Arbitrary Hill Profile

3D topographic map generated by 3DField
Far Detector
\[ J_\mu = (2.03 \pm 0.07) \times 10^{-9} \text{ cm}^{-2} \text{s}^{-1} \]
\[ E_\mu = 172 \pm 2 \text{ GeV} \]
\[ h = 440.2 \text{ m} \]

Mid Detector
\[ J_\mu = (7.70 \pm 0.25) \times 10^{-9} \text{ cm}^{-2} \text{s}^{-1} \]
\[ E_\mu = 134 \pm 1 \text{ GeV} \]
\[ h = 279.1 \text{ m} \]

Daya Bay Detector
\[ J_\mu = (8.78 \pm 0.48) \times 10^{-5} \text{ cm}^{-2} \text{s}^{-1} \]
\[ E_\mu = 63 \pm 2 \text{ GeV} \]
\[ h = 141.5 \text{ m} \]

Ling’ao Detector
\[ J_\mu = (3.60 \pm 0.20) \times 10^{-5} \text{ cm}^{-2} \text{s}^{-1} \]
\[ E_\mu = 82 \pm 3 \text{ GeV} \]
\[ h = 145.7 \text{ m} \]
Final Muon Energy Distribution
Final Muon Angular Distribution

Daya Bay

Mid

Far

Ling’ao
FLUKA Simulation for Neutron Shield (Preliminary Results)

PE = polyethylene
Summary of Simulation Results

- The present MUSIC calculation has passed all the self-consistency checks.
- It agrees with all the published experimental and simulated results.
- The FLUKA simulation is on track but needs more work.
- Detector simulations using GEANT4 and GLG4sim are currently on the way.