Sensitivity of ICAL to TeV-PeV Gamma-rays at INO

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ADNHEAP 2017, Bose Institute
February 16, 2017
Motivation

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- Muons from Gamma-ray induced showers
- ICAL at INO
- Energy loss of HE muons in rock
- Spectrum of muons from Gamma-ray
- Muon charge ratio
- Expected signal to noise ratio
- Summary
Introduction

- The detection of TeV-PeV $\gamma$-rays gives evidence of **galactic & extragalactic sources**.
- These sources mainly include pulsars, supernova, hypernova & blazars.

**Detection**:
- **Direct detection**:
  - **Space based expts** – EGRET, Large Area Telescope of Fermi Gamma-ray space Telescope (GLAST)
- **Indirect detection**:
  - **Ground based expts** – VERITAS, HESS-I & II, Milagro, HAWC, Cherenkov Telescope Array (CTA) etc…
  - **Underground based expts** – ICE CUBE, AMANDA, ANTARES etc…

- The **Iron Calorimeter detector** [1] at India-based Neutrino Observatory can detect **muons from $\gamma$-rays** and can also measure their **charge**.
Muons from Gamma-ray induced showers

Gamma-ray \( (\gamma(E_\gamma) \propto E_\gamma^{-(b+1)}) \)

(Most dominant production channels \(^\text{[2]}\))

- Photo production
  \[ \gamma + N \rightarrow N' + \pi^\pm \]
  \[ \pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \]
  - GeV region
  - \( E_\mu \sim 0.25 E_\gamma \)

- Muon pair production
  \[ \gamma + N \rightarrow N' + \mu^+ + \mu^- \]

- TeV region
  \[ E_\mu \sim 0.5 E_\gamma \]

- At high energy photo production is suppressed by muon pair production channel due to the decrease and increase in production cross-section with energy.

\( b \) – spectral index
\( N \) – nucleus of the atmosphere
\( N' \) – scattered nucleus
ICAL at INO

- **ICAL**: Sampling Calorimeter, Rectangular in shape, Modular in structure, 3 modules (51 kt).
- B field ~ 1.3 Tesla
- Optimized for the detection of atmospheric $\nu^{'\mu}s$ and $\bar{\nu}^{'\mu}s$.
- It is proposed to built under rock cover ~ 1Km.

*Flux of cosmic ray muons vs depth*
Energy loss of high energy muons in rock

- The energy loss rate $\frac{dE}{dx} = -\alpha - \beta E$
- The average muon energy $[3]$ at depth $X$ is
  \[ E^X = \left( E^S + \frac{\alpha}{\beta} \right) e^{-\beta x} - \frac{\alpha}{\beta} \]
- The minimum energy required for $\mu$ to reach a depth $X$,
  \[ E_{\text{min}} = \frac{\alpha}{\beta} (e^{\beta x} - 1) \]
  \[ \frac{\alpha}{\beta} = 500 \text{ GeV}, \beta \sim 4 \times 10^{-6} \text{ gm/cm}^2, \rho_{\text{rock}} = 2.89 \text{ gm/cm}^3 \]
- $E_{\text{min}} \geq 1 \text{ TeV (00)} - 4.5 \text{ TeV (600)}$
- **Backgrounds**:
  - Cosmic ray muons
  - Flux $\sim 10^{-4} \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ for 3.8 Km water equivalent at INO site
  - They can be identified by looking events from a fixed direction where the number is large compared to the cosmic ray muons.
The muon spectrum for observed non-transient Galactic sources (pulsars & supernova remnant) from “The 2nd Catalog of Hard Fermi-LAT Sources (2FHL)” [4] with photon energy flux in the energy range of 50 GeV to 2 TeV.

- **b = 0.3**
  - J0048.0+5449

- **b = 0.7**
  - J0310.4-5019

- **b = 0.5**
  - J2321.1+5910

- **b = 0.9**
  - J0138.2+5811
Muon charge ratio

- ICAL will use magnetic field ~1.3 T, which can identify the charge of μs.

- Muons from cosmic ray \(^{[5]}\):

\[
r_\mu \equiv \frac{N_{\mu^+}}{N_{\mu^-}} = \frac{f_\pi}{1 + 1.1E_\mu \cos\theta/115 \text{ GeV}} + \frac{\eta f_\kappa}{1 - f_\pi} \frac{1 + 1.1E_\mu \cos\theta/850 \text{ GeV}}{1 + 1.1E_\mu \cos\theta/115 \text{ GeV}} + \frac{\eta (1 - f_\kappa)}{1 - f_\pi} \frac{1 + 1.1E_\mu \cos\theta/850 \text{ GeV}}{1 + 1.1E_\mu \cos\theta/115 \text{ GeV}}
\]

- Gamma-rays :-
  1. Photo production –

\[
r_\mu \equiv \frac{N_{\mu^+}}{N_{\mu^-}} = \frac{f_\pi}{1 + 1.1E_\mu \cos\theta/115 \text{ GeV}} = 1.24
\]
  2. Muon pair production –

\[
r_\mu \equiv \frac{N_{\mu^+}}{N_{\mu^-}} = 1
\]

- Using GEANT4 simulation \(^{[6]}\) for ICAL μ the CID efficiency is 98% for energy of 4 – 20 GeV ( \(\theta = 0^0\) to \(70^0\))

- If CID efficiency is 80-90%, for 50 GeV muon using ICAL, then it can also identify the charge of muons from \(\gamma\) -ray.

The ratio between the flux of \(\mu^+\) to \(\mu^-\) vs \(E_\mu\) from photon shower with any index and any influence, in case of both pion decay & muon pair production, and cosmic ray muons.
Expected signal to noise ratio

- In order to suppress the bg over signal it is very important to see their ratio.
- The ratio has been calculated for non-transient galactic sources observed by LAT.
- Number of events $^7$ $N = I_\mu(\theta). A. T. \delta \theta$
  
  $A = 768 \text{ m}^2$, ICAL Transverse Area
  
  $T = 5 \text{ years}$, ICAL running period
  
  $\delta \theta = 10^\circ$, ICAL angular resolution

- Photon energy flux in the energy range of 50 GeV to 2 TeV.
- Signal to noise ratio for muon energy of 1 TeV.

<table>
<thead>
<tr>
<th>Source 2FHL</th>
<th>Spectral index</th>
<th>TeV Km$^{-2}$ S$^{-1}$</th>
<th>$S/\sqrt{N}$ ($\mu^+$)</th>
<th>$S/\sqrt{N}$ ($\mu^-$)</th>
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<tbody>
<tr>
<td>J0537.4-6908</td>
<td>0.15</td>
<td>0.126078</td>
<td>$9.46361 \times 10^6$</td>
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<td>J1745.1-3035</td>
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<td>0.167896</td>
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<td>J0048.0+5449</td>
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<td>J0316.6+4120</td>
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<td>0.45</td>
<td>0.075522</td>
<td>0.473365</td>
<td>0.560093</td>
</tr>
</tbody>
</table>
Summary

- We have investigated the sensitivity of ICAL detector for the detection of HE µs from observed non-transient Galactic γ-ray sources from “The 2nd Catalog of Hard Fermi-LAT Sources”.

- From the analysis it is found that, γ-ray sources with spectral index of < 0.45 are more sensitive.

- Because their flux is larger than the muons from cosmic rays which act as background to these signals.

- In order to summarize the neutrino detector like Iron Calorimeter at India-based Neutrino Observatory can be used as γ-ray telescope.
THANK YOU
11) M. Guan, J. Cao, C. Yang, Y. Sun, K.-B. Luk, Muon simulation at the Daya Bay site.
Muon flux from gamma-rays:

- Muon flux from pion decay $^{[8,9]}$:

$$\frac{dN_\mu}{dE_\mu} = \int_0^{t_{\text{max}}} dt B_{\mu \pi} \int_{E_\mu}^{E_{\mu}/r} \frac{dE'}{(1-r)E'} \frac{\pi(E', t)}{d\pi(t)}.$$ 

$$\pi(E, t) = \gamma_0 \lambda_{\gamma A} \frac{(\sigma_0 + \lambda_1)(\sigma_0 + \lambda_2)}{\lambda_2 - \lambda_1} \times \text{Min} \left( \left[ \frac{1}{\sigma_0 + \lambda_1} \sum_{j=1}^{100} \frac{\lambda_i^{j-1} t^j}{(j-1)!(\delta+j)} \right] \left[ \frac{e^{\lambda_1 t} - e^{t/\Lambda_\pi}}{(\sigma_0 + \lambda_1)(\lambda_1 + \frac{1}{\Lambda_\pi})} - \frac{e^{\lambda_2 t} - e^{t/\Lambda_\pi}}{(\sigma_0 + \lambda_2)(\lambda_2 + \frac{1}{\Lambda_\pi})} \right] \right)$$

- Muon flux from direct muon-pair production $^{[8,10]}$:

$$\frac{dN_\mu}{d\epsilon_\mu} = 2\lambda_{\text{rad}} \frac{N_A}{A} \gamma_0 (\epsilon_\mu) \int_0^1 dx x^b \frac{d\sigma}{dx} (x, \frac{\epsilon_\mu}{x}) \int_0^{t_{\text{max}}} dt \gamma_2 (t, b).$$

$$\frac{d\sigma}{dx} (x, \epsilon_\gamma) = 4\alpha Z^2 \left( r_0 \frac{m_e}{m_\mu} \right)^2 \left[ 1 - \frac{4}{3} x(1-x) \right] \left[ \Phi_{\text{el}}(\delta) + \frac{1}{Z} \Phi_{\text{in}}(\delta) \right]$$

Muon flux from cosmic ray $^{[11]}$:

$$\frac{dN}{dE_\mu d\cos \theta} = 0.14 \left( \frac{E_\mu}{\text{GeV}} \left( 1 + \frac{3.64 \text{GeV}}{E_\mu (\cos \theta \times 1.29)} \right)^{-2.7} \left[ 1 + \frac{1}{1 + \frac{1.1 E_\mu \cos \theta}{1.25 \text{GeV}}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos \theta}{5.5 \text{GeV}}} \right] \right) \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$