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

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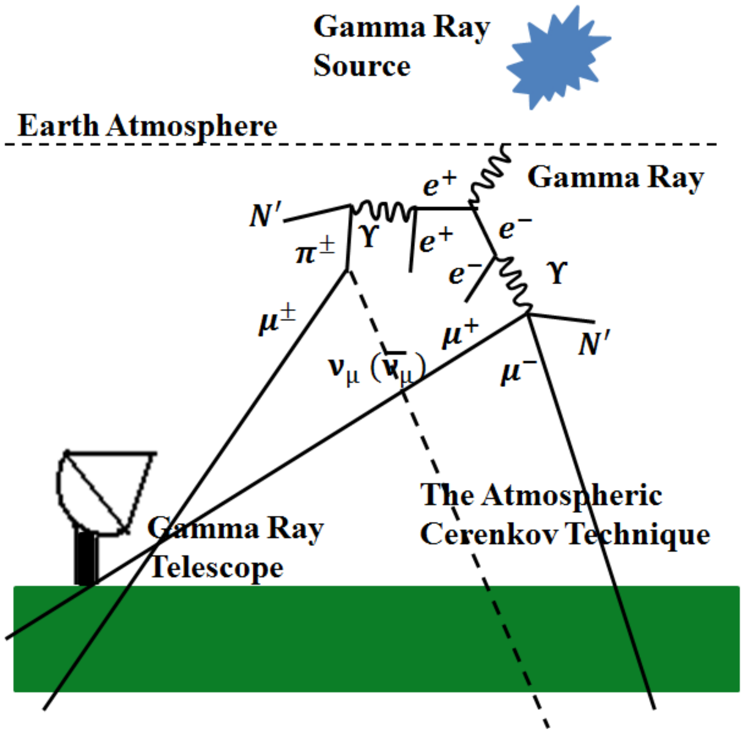
Motivation

- Introduction
- 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 γ-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 γ-rays** and can also measure their **charge**.



Schematic diagram of Υ-ray induced shower.

Muons from Gamma-ray induced showers

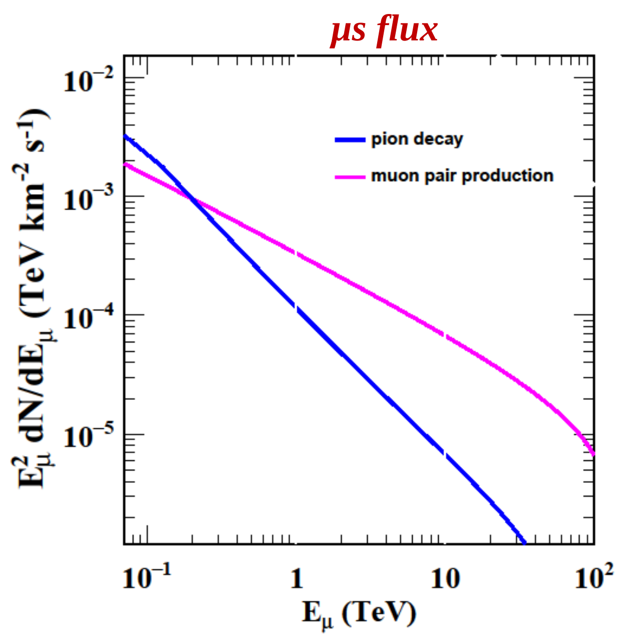
Gamma-ray $(\gamma(E_\gamma) \propto E_\gamma^{-(b+1)})$

(Most dominant production channels [2])

- photo production

$$\gamma + N \rightarrow N' + \pi^{\pm}$$
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu \, (\overline{\nu}_\mu)$$

- GeV region
- $E_\mu \sim 0.25\, E_\gamma$



- μ pair production

$$\gamma + N \rightarrow N' + \mu^{+} + \mu^{-}$$

- TeV region
- $E_\mu \sim 0.5\, E_\gamma$

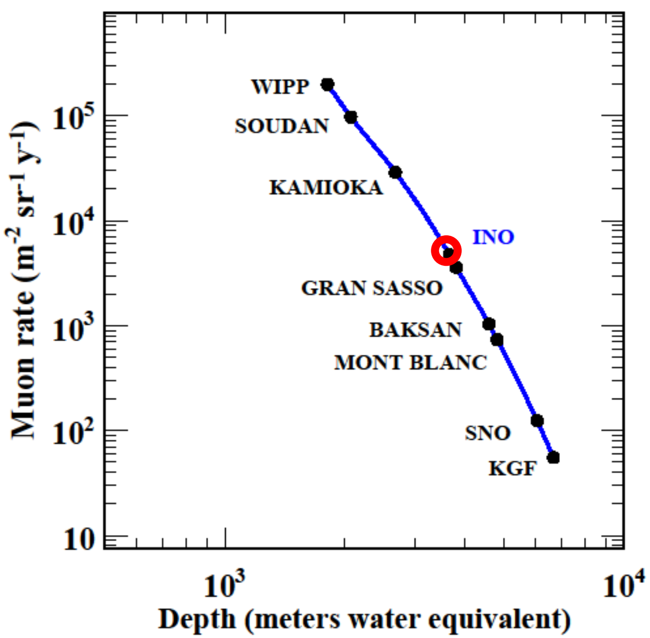
b – spectral index
N – nucleus of the atmosphere
N′ – scattered nucleus

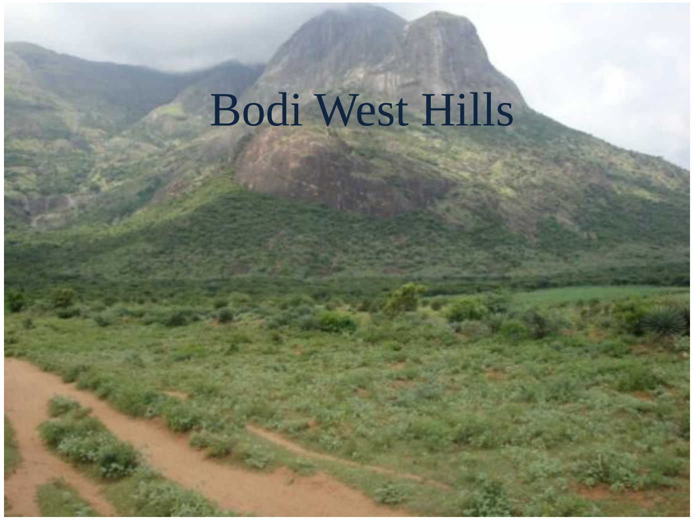
- At high energy photo production is suppressed by muon pair production channel due to the decrease and increase in production cross-section with energy.

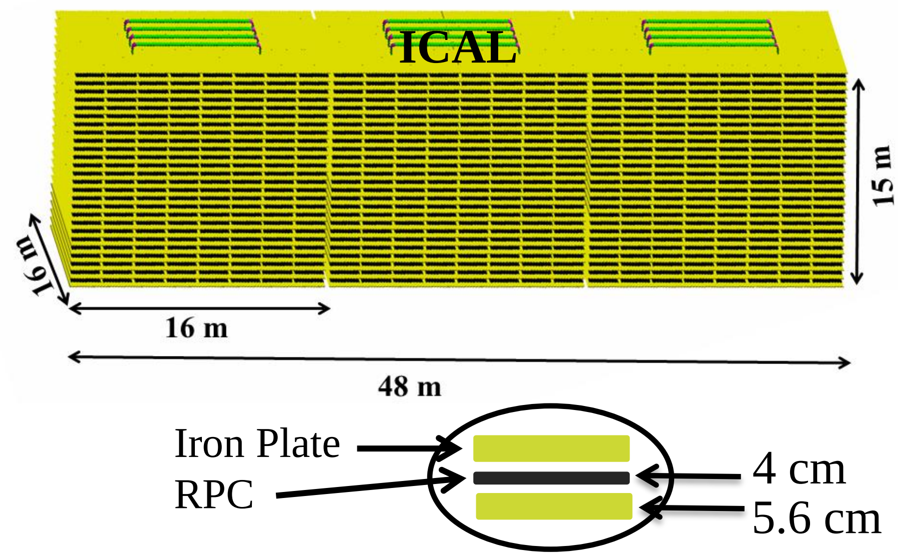
ICAL at INO

- **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

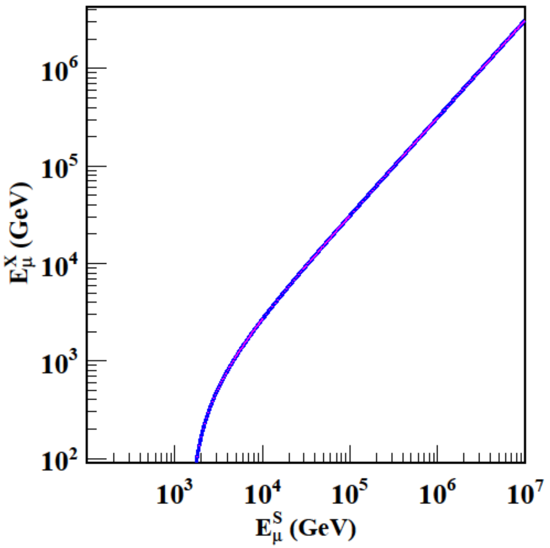
$$E^X = \left(E^S + \frac{\alpha}{\beta}\right) e^{-\beta X} - \frac{\alpha}{\beta}$$

- The minimum energy required for μ to reach a depth X,

$$E_{min} = \frac{\alpha}{\beta}(e^{\beta X} - 1)$$

$\frac{\alpha}{\beta}$= 500 GeV, $\beta \sim 4 \times 10^{-6}$ gm/cm^2, ρ_{rock} = 2.89 gm/cm^3

- **$E_{min} \geq$ 1 TeV (0^0) – 4.5 TeV (60^0)**
- **<u>Backgrounds :</u>**
  - Cosmic ray muons
  - Flux ~ **10^{-4} m^{-2} sr^{-1} 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.



Surface energy vs energy at a depth of 1 Km for muon.

Spectrum of muons from Υ-ray

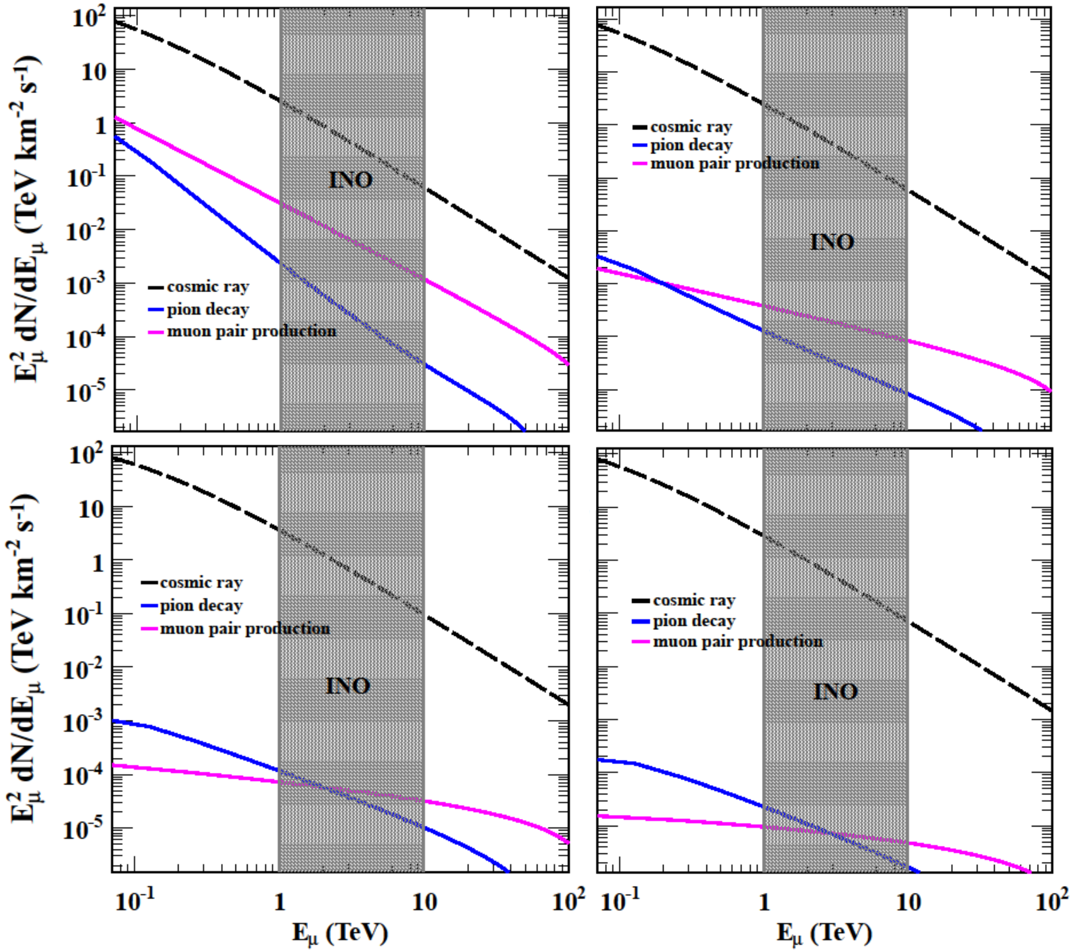
- The muon spectrum for observed **non-transient Galactic sources** (pulsars & supernova remnant) from **"The 2^{nd} Catalog of Hard Fermi-LAT Sources (2FHL)"** [4] with photon energy flux in the energy range of **50 GeV** to **2 TeV**.

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] :-

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

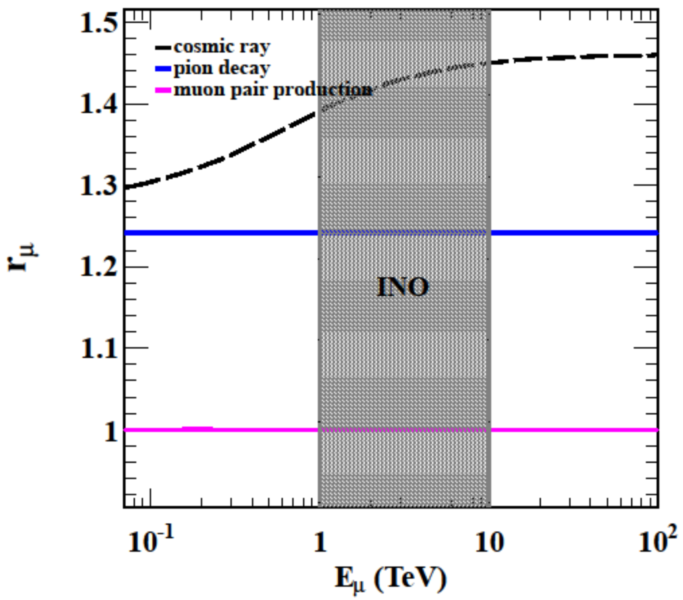
- **Gamma-rays :-**
  1. **Photo production –**

$$r_\mu \equiv \frac{N_{\mu^+}}{N_{\mu^-}} = \frac{\frac{f_\pi}{1+1.1E_\mu \cos\vartheta/115\ GeV}}{\frac{1-f_\pi}{1+1.1E_\mu \cos\vartheta/115\ GeV}} = 1.24$$

  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 γ -ray.



The ratio between the flux of μ^+ to μ^- vs E_μ 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 $= I_{\mu}(\theta).A.T.\delta\theta$

$A = 768\ m^2$, ICAL Transverse Area

$T = 5$ years, ICAL running period

$\delta\theta = 1^0$, 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.

Source 2FHL	**Spectral index**	**TeV $Km^{-2}\ S^{-1}$**	**$S/\sqrt{N}$ (μ^+)**	**$S/\sqrt{N}$ (μ^-)**
J0537.4-6908	0.15	0.126078	9.46361×10^{6}	1.11975×10^{7}
J1703.4-4145	0.24	0.180379	1126.38	1332.75
J1745.1-3035	0.25	0.167896	1035.74	1225.5
J0048.0+5449	0.30	0.047685	4.39481	5.20001
J0316.6+4120	0.34	0.083012	7.2855	8.62032
J0319.7+1849	0.45	0.075522	0.473365	0.560093

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

References

1) S. Ahmed, et al., Physics Potential of the ICAL detector at the India-based Neutrino Observatory (INO), arXiv:1505.07380.
2) M. Drees, F. Halzen, K. Hikasa, Muons in ϒ showers, Phys. Rev. D39 (1989) 1310.
3) T. K. Gaisser, R. Engel, E. Resconi, Cosmic Rays and Particle Physics, Cambridge University Press.
4) M. Ackermann, et al., 2FHL: The Second Catalog of Hard Fermi-LAT Sources, Astrophys. J. Suppl. 222 (1) (2016) 5. arXiv:1508.04449, doi:10.3847/0067-0049/222/1/5.
5) P. A. Schreiner, J. Reichenbacher, M. C. Goodman, Interpretation of the Underground Muon Charge Ratio, Astropart. Phys. 32 (2009) 61 - 71.
6) A. Chatterjee et al., A Simulations Study of the Muon Response of the Iron Calorimeter Detector at the India-based Neutrino Observatory, JINST 9 (2014) P07001.
7) N. Gupta, P. Bhattacharjee, Detecting TeV gamma-rays from gamma-ray bursts by ground based muon detectors, arXiv:astro-ph/0108311.
8) T. L. Astraatmadja, On the detection of TeV gamma-rays from GRB with Km-cube neutrino telescopes-I. Muon event rate from single GRBs, Mon. Not. Roy. Astron. Soc. 418 (2011) 1774-1786.
9) F. Halzen, A. Kappes, A. O Murchadha, Gamma-ray Astronomy with Muons: Sensitivity of IceCube to PeVatrons in the Southern Sky, Phys. Rev. D80 (2009) 083009.
10) H. Bethe, W. Heitler, On the Stopping of fast particles and on the creation of positive electrons, Proc. Roy. Soc. Lond. A146 (1934) 83 - 112.
11) M. Guan, J. Cao, C. Yang, Y. Sun, K.-B. Luk, Muon simulation at the Daya Bay site.

BACKUP

- Muon flux from gamma-rays :
  - Muon flux from pion decay [8,9] :-

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

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

  - Muon flux from direct muon-pair production [8,10] :-

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

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

- Muon flux from cosmic ray [11] :-

$$\frac{dN}{dE_\mu d\cos\theta} = 0.14\left(\frac{E_\mu}{\rm GeV}\left(1+\frac{3.64{\rm GeV}}{E_\mu[\cos\theta^\star]^{1.29}}\right)\right)^{-2.7}\left[\frac{1}{1+\frac{1.1E_\mu\cos\theta^\star}{115{\rm GeV}}}+\frac{0.054}{1+\frac{1.1E_\mu\cos\theta^\star}{850{\rm GeV}}}\right]{\rm GeV}^{-1}{\rm cm}^{-2}{\rm s}^{-1}{\rm sr}^{-1}$$