

Cosmic Muon Signature in LIGO

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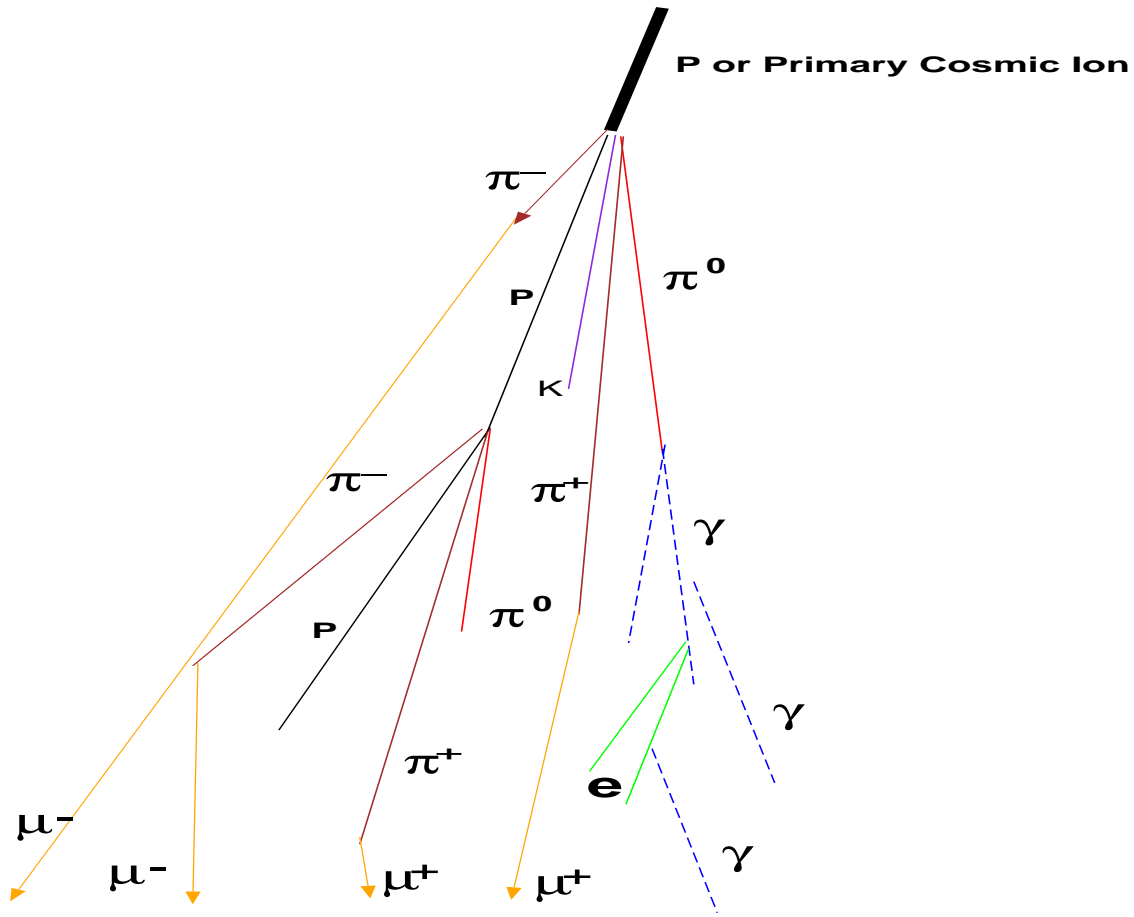
LIGO - MIT

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- Motivation
- Background Muon Effects on GW detectors
- Burst of Muon and GW detectors (data+MC)
- Catastrophic Muon interactions with TM
- Conclusions and Future Work



Why Muons?



›› p, some pi & K, fragments interaction ---> new particles

- 85% of produced particles are pions:
- Neutral Pi, K,. ---> E-M shower (few electrons), Cerenkov light
- Charged Pi, K ---> **muons** (75% of all part. = hard component)
- proton/muon ratio = 3.5% (1GeV/c) to 0.5% (10GeV/c)
- soft component/hard component = 30%

Background Muon at Sea Level⁽¹⁾

Important for search of periodic, steady or chirp GW sources

- Assumptions:

- Muon Flux: $N(\theta) = I_V \times (\cos\theta)^2 = \frac{0.8 \times 10^2}{m^2 \cdot \text{ster} \cdot s} \times (\cos\theta)^2$
- Energy Dependence: $N(E) \sim E^{-2}$
- Average Muon Energy at Sea Level $\sim 2\text{GeV}$ (i.e. MIP)
- Ionization Energy Loss only ($dE/dx \sim 2\text{MeV/g/cm}^2$)
- spherical TM, 10.8Kg (initial LIGO) or 30Kg (advanced LIGO)
- For one muon, the Average Momentum Loss in one TM:

$$\langle p_x \rangle^{1\mu} = \frac{\int p_x \cdot N(\theta) \cdot A d\Omega}{\int N(\theta) \cdot A d\Omega} = \frac{\rho \cdot D}{4c} \cdot \frac{dE}{dx}$$

- Displacement Spectral Density

- ›› for muon rate = dn/dt (Particle Data)

- ›› for muons Poison Distributed

$$x(f) = \frac{4 \cdot \langle p_x^{1\mu} \rangle \cdot \sqrt{\frac{dn}{dt}}}{m \cdot \omega^2} = \frac{5.97 \cdot 10^{-23}}{D \cdot f^2} [m / (\sqrt{\text{Hz}})]$$

- i.e does not depend on the mass material, but only on $1/D$

Background Muon at Sea Level⁽²⁾

- Strain due to background muons

›› for LIGO 4Km IFO

DETECTOR	TM Diameter	$h_{rms}^{\mu}(100\text{Hz})$	$h_{rms}^{LIGO}(100\text{Hz})$
Initial LIGO	21cm	$7.1 \cdot 10^{-29}$	$5 \cdot 10^{-22}$
Advanced LIGO	30cm	$2.2 \cdot 10^{-29}$	$5 \cdot 10^{-24}$

i.e the Background Muon flux has a *negligible* effect on LIGO in the “steady state search” mode.

Burst of Muons

Important for GW burst searches

›› Origin: VHE Primary Cosmic Rays

• Assumptions

›› TM = spherical mass, diameter D , $f_0 = 1 \text{ Hz} \ll f$

›› Momentum Deposited by a muon burst (density $\phi [\mu/m^2]$):

$$\langle p_x \rangle = \langle p_x \rangle^{1\mu} \cdot \left(\phi \cdot \frac{\pi D^2}{4} \right) = \frac{\rho \cdot D}{4c} \cdot \frac{dE}{dx} \times \left(\phi \cdot \frac{\pi D^2}{4} \right)$$

›› Displacement Spectral Density due to a muon burst:

$$x(f) = \frac{\langle p_x \rangle}{m\omega_0 f^2} = \frac{3\phi}{16\pi c f_0 f^2} \cdot \frac{dE}{dx} \cong 6.4 \cdot 10^{-24} \cdot \frac{\phi}{f^2} \left[\frac{m}{\sqrt{\text{Hz}}} \right]$$

— does not depend on mass characteristics (density, diameter)

• Muon Flux Calculation ($\phi [\mu/m^2]$)

›› GEANT Monte Carlo program (present work)

— Hadron - atmosphere interaction

— Study of Lateral Muon Density Distribution at detector level

— Muon Energy at Detector level

›› Experimental Data of VHE Muon Showers

— AGASA, Fly's Eye, Compilations, etc.



Summary of Muon Density

μ densities [μ/m^2] for various Primary Energies at 0 and 500m from the shower axis

Energy(eV)	Density at 0m	Density at 500m	Remarks
10^{12}	3×10^{-4}	2×10^{-5}	Present MC (Large errors)
10^{13}	10^{-2}	2×10^{-4}	Present MC
10^{14}	10^{-1}	10^{-3}	Present MC
0.5×10^{19}	$\sim 4 \times 10^3$	10^1	AGASA

- So Conservatively, at sea level, the Muon flux near the shower axis

$$\phi_{0m}(E) = E[eV] \times 10^{-15} [\mu/m^2]$$

›› As for example at 10^{20} eV the muon density near the shower axis is 10^5 muons per square meter

›› At 500m from the shower axis, the muon density is about 100 times smaller

Primary Energy Spectra

- Experimental data at VVHE

- AGASA + MOCCA MC
- FLY's EYE
- BACKSAN
- AKENO
- OLDER COMPILATIONS

- Primary Energy Density above $E_{sh} = 10^{15}$ eV

$$J(E_{sh}) \cong 6 \times 10^{18} E_{sh}^{-2.7} \left[\frac{1}{m^2 \text{ster} \cdot s \cdot eV} \right]$$

- Number of showers/year above an energy E [eV], in a disk of radius 100m:

$$N_{sh/yr}(E_{sh} > E) = \int \int \int_{A \Omega T} dA d\Omega dT \int_E^{\infty} J(E_{sh}) dE_{sh} \cong 1.9 \times 10^{31} E^{-1.7}$$

- It is assumed that: the muon distribution in this disk is uniform.

Burst of Muons and LIGO TM

- From previous calculations and data:

- ›› Displacement spectral density due to a burst of muons:

$$x(f) = \frac{3\phi}{16\pi c f_0 f^2} \cdot \frac{dE}{dx} \quad \text{where } \phi \text{ is the muon density}$$

- ›› Muon flux near the shower axis:

$$\phi_{0m}(E) = E[eV] \times 10^{-15} [\mu/m^2]$$

- ›› Number of showers/year above an energy E:

$$N_{sh/yr}(E_{sh} > E) = 1.9 \times 10^{31} E^{-1.7}$$

- Combining these relations;

- ›› The number of shower per year which may produce a TM displacement > detector noise:

$$N_{sh/yr}(x > x_N) = 3.7 \times 10^{-34} \cdot (x_N(f) \cdot f^2)^{-1.7}$$

- ›› At $f=100\text{Hz}$ and for **advanced LIGO (for 1 TM)**:

$$N_{sh/yr}(x > x_N) = 5.8 \times 10^{-41} \cdot x_N^{-1.7}(100\text{Hz}) = 0.6 \times 10^{-5}$$

A primary energy of about $2.3 \cdot 10^{21}$ eV is required to produce enough muons to excite one of the advanced LIGO Test Masses above the required sensitivity (due to muons ionization only).

Accidental Coincidences due to burst of muons

- Assumptions (Three IFO = LIGO)
 - ›› Rates in each TM = $N_{sh/yr}(x > x_N)$ as calculated above
 - ›› Rates in each IFO: $R = 4 \cdot N_{sh/yr}(x > x_N)$
 - ›› Correlated Coincidence rate between WA 2 & 4Km IFOs (simultaneous excitations of all ITMs): $R_{c(1,2)} = R/5$
 - ›› duration of the acceptance window is: $\tau_W = \tau_P + 2l/c$ where
 - τ_P is the duration of the pulse to be detected
 - $l = 4000\text{Km}$ is the distance between the WA and LA IFOs
 - c is the speed of light

- Accidental coincidence rate for all 3 IFOs:

$$R_{123} = (\tau_W \cdot \tau_P \cdot R^3) + \tau_W \cdot R_{c(1,2)} \cdot R < 0.1[\text{year}]$$

LIGO Accidental Coincidence Due to Burst of Muons in LIGO detector

τ_P [sec]	0.001	0.01	0.1	1
R_{123} [/year]	$2,7 \times 10^{-12}$	3.6×10^{-12}	1.2×10^{-11}	1×10^{-11}

Muon Catastrophic Interactions⁽¹⁾

Important for GW burst searches

- Displacement Spectral Density

$$\langle x(f) \rangle^{1\mu} = \frac{\langle p_x \rangle^{1\mu}}{m\omega_0 f^2}$$

›› for ionization loss only ($f_0 = 1\text{ Hz}$, spherical TM)

- initial LIGO: $\langle x(f) \rangle^{1\mu} = \frac{1.9 \times 10^{-22}}{f^2} [m/\sqrt{\text{Hz}}]$ (D=21cm)

- the average energy deposited by 1 muon (ionization only) in 21cm of quartz is ~100MeV.

- Catastrophic muon interaction

›› for initial LIGO: $x_{\text{LIGO}}(100\text{ Hz}) \cong 2 \times 10^{-19} [m/(\sqrt{\text{Hz}})]$

- To satisfy $\langle x(100) \rangle^{\mu} = x_{\text{LIGO}}(100\text{ Hz})$, the energy released in the TM (by the catastrophic muon(s) interaction) is ~ 1million GeV!

›› Similarly, for advanced LIGO, (m=30Kg, D=30cm)

- the required energy released in one TM ~ 21,600 GeV



Muon Catastrophic Interactions⁽²⁾

- GEANT MC#1 for muon energy at sea level:

- ›› for Proton Primary Energies $E > 1\text{TeV}$ (up to 100TeV),

- ~10% of muons have $E_\mu > 20\text{GeV}$; (20% above 10GeV)

- ›› number of muons in 1 year, with $E_\mu > 20\text{GeV}$ is:

$$N(E_\mu > 20\text{GeV}) = 0.1 \times N_{sh/yr}(E_{sh} > 1\text{TeV}) \cong 7 \times 10^9 [\mu/yr]$$

- GEANT MC#2 for energy deposited in TM:

- ›› for muons of energies between 20 to 100GeV

- only 8/1.5million muons ($\sim 5 \times 10^{-6}$) deposited more than 10GeV

- the average released energy/muon with catastrophic interaction ~ 15GeV -- **not enough to excite the LIGO TM** (we need $21,600\text{GeV}$ for advanced LIGO)

- Worst scenario: multiple simultaneous catastrophic muon interaction, in which case:

A primary energy of about 10^{26}eV is required to produce enough muons to excite the advanced LIGO above its sensitivity (due to multiple muon catastrophic interaction in one TM only).



Conclusions, Future Work

- GEANT Based MC --> good simulation of
 - ›› particle interactions with atmosphere up to 100TeV
 - ›› energy and angular/lateral distribution spectra
 - ›› secondary particles, showers, Cerenkov light production
 - ›› muon interaction including catastrophic energy losses
- Muon interaction with LIGO IFOs (MC+data):
 - ›› for Steady Source searches:
 - Background muons have a negligible effect on LIGO
 - ›› for Burst Sources searches (bursts of muons):
 - Accidental Coincidence analysis: negligible contribution
 - 10^{26} eV is required to produce enough muons, which by catastrophic loss of energy only may excite the advanced LIGO above its sensitivity: Negligible
- **Future Work:**
 - Altitude dependence of particle spectra and energies
 - Include hadrons: small flux, but large energy loss in material
 - study of electron fluxes and energy associated with large low altitude showers
 - simulations for other GW detectors