Cosmic Muon Signature in LIGO

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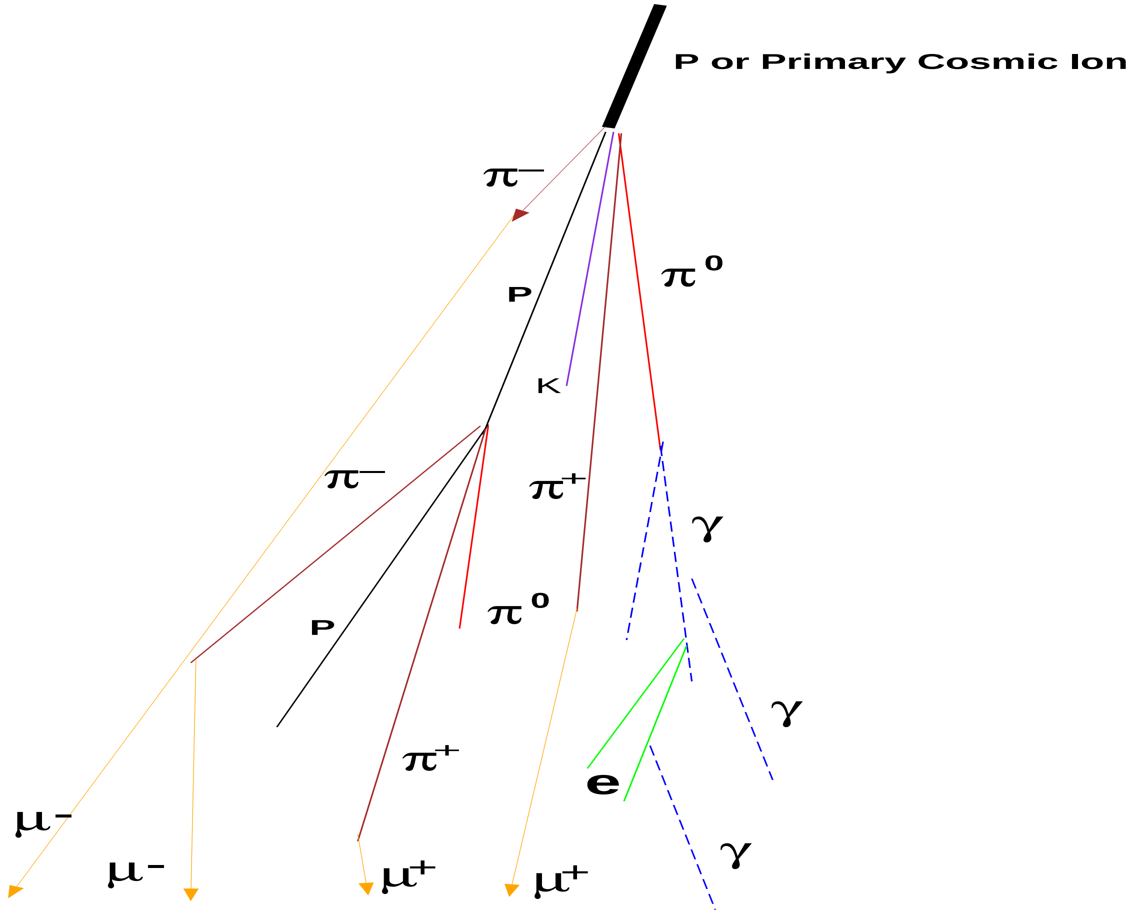
- Motivation
- Background Muon Effects on GW detectors
- Burst of Muon and GW detectors (data+MC)
- Catastrophic Muon interactions with TM
- Conclusions and Future Work

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: $N(\theta) = I_V \times (\cos\theta)^2 = \frac{0.8 \times 10^2}{m^2 \cdot ster \cdot s} \times (\cos\theta)^2$
  - Energy Dependence: $N(E) \sim E^{-2}$
  - Average Muon Energy at Sea Level ~ 2GeV (i.e. MIP)
  - Ionization Energy Loss only (dE/dx~2MeV/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

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

  - 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}^{μ}(100Hz)	h_{rms}^{LIGO}(100Hz)
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*, $f_0 = 1\,Hz << f$
  - 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:

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

    - 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 $[\mu/m^2]$ 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

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

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

$$N_{sh/yr}(E_{sh} > E) = \int_A \int_\Omega \int_T dA\, d\Omega\, dT \int_E^\infty J(E_{sh})\, dE_{sh} \cong 1.9\times10^{31} E^{-1.7}$$

  - 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:

$$x(f) = \frac{3\phi}{16\pi c f_0 f^2} \cdot \frac{dE}{dx}$$

where ϕ 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:

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

  - At f=100Hz and for advanced LIGO (for 1 TM):

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

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= 4000Km 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]	$2, 7\times10^{-12}$	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 ($\boldsymbol{f_0} = 1\,\boldsymbol{Hz}$, spherical TM)
    - – initial LIGO: $\langle x(f)\rangle^{1\mu} = \dfrac{1.9\times10^{-22}}{f^2}[m/\sqrt{Hz}]$ (D=21cm)
    - – the average energy deposited by 1 muon (ionization only) in 21cm of quartz is ~100MeV.

- Catastrophic muon interaction
  - ››for initial LIGO: $x_{\mathbf{LIGO}}(100\,Hz) \cong 2\times10^{\mathbf{-19}}[m/(\sqrt{Hz})]$
    - – To satisfy $\langle x(100)\rangle^{\mu} = x_{\mathbf{LIGO}}(100\,Hz)$, 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> 1TeV (up to 100TeV),
    - – ~10% of muons have $E_\mu > 20\,GeV$; (20% above 10GeV)
  - ›› number of muons in 1 year, with $E_\mu > 20\,GeV$ is:

$$N(\mathbf{E}_\mu > \mathbf{20\,GeV}) = 0.1 \times N_{sh/yr}(E_{sh} > 1\,TeV) \cong 7\times10^{9}\,[\mu/yr]$$

- GEANT MC#2 for energy deposited in TM:
  - ›› for muons of energies between 20 to 100GeV
    - – only 8/1.5million muons ($\sim 5\times10^{-6}$) deposited more than 10GeV
    - – the average released energy/muon with catastrophic interaction ~ 15GeV-- ***not enough to excite the LIGO TM*** (we need 21,600GeV 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