A tau scenario application to a search for upward-going showers with the Fluorescence Detector of the Pierre Auger Observatory

I. Caracas[1] for the Pierre Auger collaboration*

[1]University of Wuppertal, 42119 Wuppertal, Germany

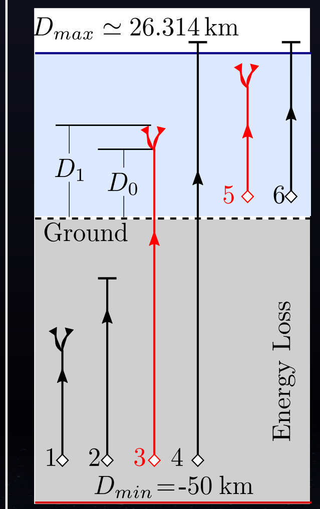
*Full author list at http://www.auger.org/archive/authors_icrc_2021.html

Introduction

Recent observations of two coherent radio pulses with the ANITA detector are consistent with steeply upward-going cosmic ray showers with energies of few tenths of an EeV and remain unexplained. The Pierre Auger Observatory has a large exposure to upward-propagating shower-like events, and we have used 14 years of its Fluorescence Detector (FD) data to perform a generic search for such events. The general search for up-going cosmic ray air showers is recast here in terms of a general τ-lepton model.

The goal of this study is accomplished by generating τ-leptons within the Earth and its atmosphere with an intensity dependent on the media density. The zenith angle, location and calorimetric energy of any resulting τ induced air shower are further used to calculate the exposure and upper flux limits. For maximal flexibility, the results are independent of the τ-production scenario, allowing for a straightforward application of these results to the wide range of BSM model which aim to describe the anomalous ANITA events.

Tau Simulations - based on NuTauSim [2]



Taus generated inside and above Earth up to D_{max} (cases 1 - 6)

- generated flux (prop to media density): used for exposure and upper flux limits calculation
  - Energy spectrum: γ = -1
  - $\lg E_{0,\tau}/\mathrm{eV} \in [16.5, 20]$

Taus decaying in the FD - FoV (cases 3 and 5):

- used to calculate the expected trigger rate of τ induced air showers

FD - FoV $\begin{cases} \lg E_{sh}/\mathrm{eV} \in [16.5, 18.5] \\ H_1 \in [0, 9\,\mathrm{km}] \end{cases}$

Tau Decays

Tau decays are simulated with TAUOLA [4]: all decay branches are considered. Secondary particles which contribute to air shower energy: $i = e^{+/-}, \pi^{+/-}, \pi^0, K^{+/-}, K^0$

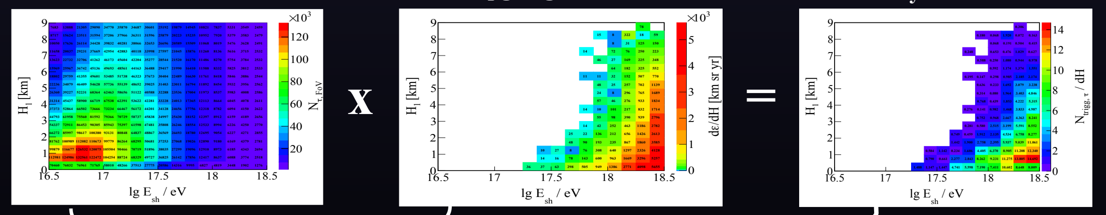
$$E_{sh} = \sum_i E_i(E_{\tau,decay})$$

Height of the first interaction is calculated using the zenith angle, average first interaction depth of each secondary, shower injection distance and atmospheric profile

$$\left.\begin{array}{l} X_1 = \sum_i X_1^i \cdot \frac{E_i}{E_{sh}} \\ \theta \in [110^\circ - 180^\circ] \\ H_0 = D_0 \cdot \cos\theta \end{array}\right\} H_1$$

Double Differential Results

τ- decay induced showers in the FD-Fov × **Exposure of the FD to upgoing showers[3]** = **τ - decays measured by the FD**



$$N_{\rm fov}(E_{\rm sh}, H_1) \times \frac{Ex(E_{\rm sh}, H_1)}{2\pi S_{gen}\Delta T} = N_{\rm trig}(E_{sh}, H_1) \rightarrow^{\text{back-tracked to primary energy}} \rightarrow N_{\rm trig}(E_0|E_{sh}, H_1)$$

The exposure of the FD and upper flux limits to τ-induced air showers relative to τ primary energy, E_0, are calculated using the distribution of triggering events

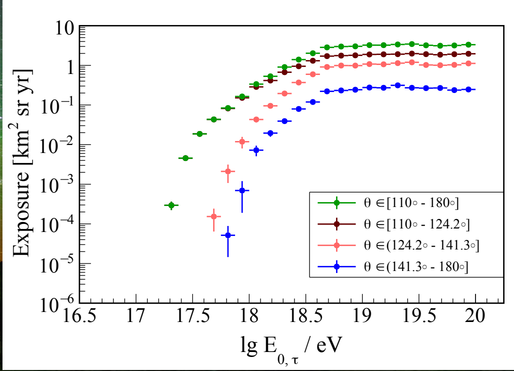
$$N_{\rm trig}(E_0) = \sum_{E_{sh}} \sum_{H_1} N_{\rm trig}(E_0|E_{sh}, H_1)$$

Results: Exposure and Upper flux limits to up-going τ showers

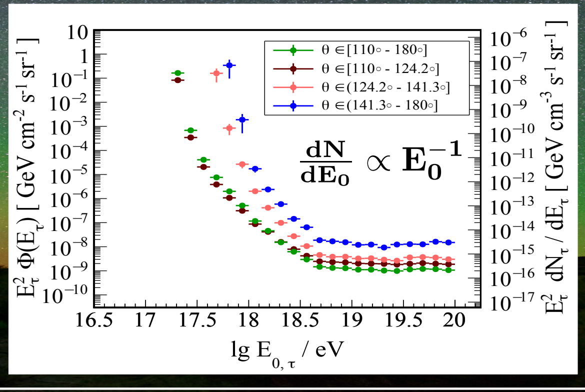
$$\mathcal{E}_\tau(\mathbf{E_0}) = \frac{\mathbf{N_{trig}(E_0)}}{\mathbf{N_{gen}(E_0)}} \cdot \mathbf{2\pi S_{gen}\Delta T}$$

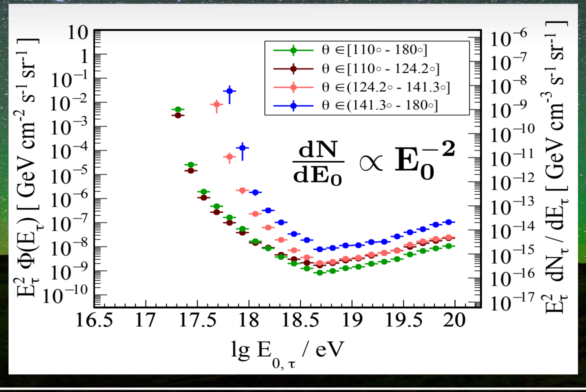
$$\left.\begin{array}{c} N_{\rm obs} = 1 \rightarrow N_{\rm FC,cand}(\mathrm{CL} = 95\%) = 4.05 \\ \text{background consistent: } N_{bkg} = 0.5 \\ N_{\rm FC,cand}(E_{bin}) = \frac{N_{\rm FC,cand}}{nEbins} \cdot \frac{\sum_{nEbins} N_{{\rm cand},\tau}(E_{bin})}{N_{{\rm cand},\tau}(E_{bin})} \end{array}\right\} \mathbf{\Phi_\tau^{95\%}(E_{bin})} = \frac{\mathbf{N_{FC,cand}(E_{bin})}}{\mathcal{E}_\tau\mathbf{(E_{bin})}}$$

Exposure to τ-induced showers vs. τ primary energy: $E_{0,\tau}$



Upper Flux Limits (CI = 95%) for τ-induced showers vs. τ primary energy $E_{0,\tau}$





Conclusions

The response of the FD of the Pierre Auger Observatory to up-going τ-induced air showers has been studied. This has been accomplished by simulating τ-leptons with zenith angles in a range of 110°-180° generated both below and above Earth. The τ-leptons generation is agnostic to the production mechanism. The τ-leptons are propagatated through the Earth and followed through the atmosphere until they reach a maximum height of 9 km defined in [3]. All recorded τ-decays in the FD-FoV are then used to estimate the exposure to up-going τ-induced air showers using the double differential exposure of the FD from the general study. This is then translated to upper flux limits to up-going τ showers for two different primary τ energy spectra.

Bibliography

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