Search for TeV electron neutrinos from high-energy transients with LHAASO

Gou Quanbu[1] , Li Zhuo[2], *Giuseppe Di Sciascio*[3], Hou Chao[1], Liu Jiangtao[1], Chang Xiaochuan[1], Lv Hongkui[1], Huang Tianqi[2], Wang Yaping[1], Wang Zheng[1]

[1] Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, P.O. Box 918, 100049 Beijing, China
[2] Department of Astronomy, School of Physics, Peking University, Beijing 100871, China
[3] INFN - Sezione Roma Tor Vergata, I-00133 Roma, Italy

LHAASO Scientific Observation and Multi-messenger Astronomy Workshop

April 24 - 28, 2019

A NSFC proposal to study HAS

Abstract:

High-energy transients, including gamma-ray bursts (GRBs), supernovae, and blazars, are potential sources of high-energy cosmic rays. Neutrinos are penetrating neutral particles, and among the four traditional messengers, they may be the best probe of the origin of cosmic rays.

Horizontal air showers (HAS) are initiated by deeply penetrating high energy particles such as muons and neutrinos. Indeed, at large zenith angles the electromagnetic component of ordinary air showers is attenuated by the atmosphere well before reaching the ground level. The showers with significant muon component could be further rejected by underground muon detector. This provides a method to search neutrinos from HAS. ARGO-YBJ experiment, with electromagnetic particle detectors only, has ever tried to search neutrinos associated with GRBs from HAS events.

The LHAASO experiment has a large array of both electromagnetic particle detectors and underground muon detectors. In 100 TeV energy region it will become the most sensitive experiment for detecting gamma rays.

The goal of this work is to establish and develop a method for searching TeV electronic neutrinos associated with astrophysical transients with LHAASO experiment, by looking at HAS induced by the charged current (CC) interaction of these neutrinos with the air nuclei.

This study can be crucial to constrain the physics of the related objects, and to identify the sources of the high-energy cosmic rays. In particular, this technique could represent a complementary methodology to search with large area arrays for electronic neutrinos associated to buried GRB jets which are predicted to generate a soft neutrino spectrum with a fluence at TeV energies a few orders of magnitude greater than that characterizing the GRBs observed in gamma-rays.

Follow-up of a previous ARGO-YBJ analysis

33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

ICRC 2013

Search for TeV electron neutrinos from Gamma Ray Bursts with the ARGO−YBJ experiment

B. D'ETTORRE PIAZZOLI[1,2], T. DI GIROLAMO[1,2], R. IUPPA[3,4], B. PANICO[3,4] FOR THE ARGO−YBJ COLLABORATION.

"We report here on a search for ν_e-induced HAS ($73° \leq \theta \leq 77°$) in temporal coincidence with the prompt phase of Gamma Ray Bursts."

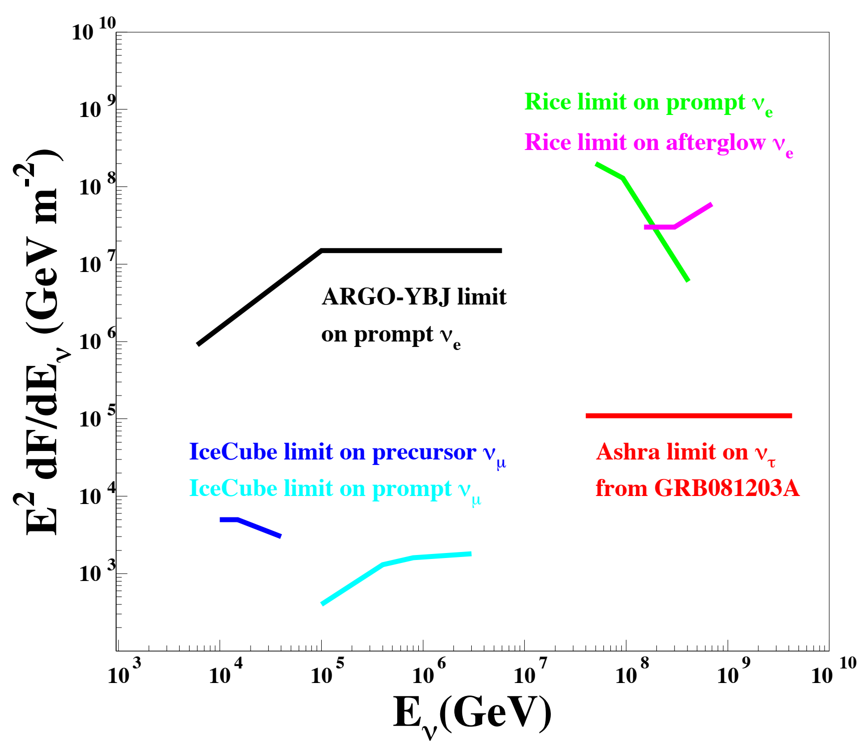


Fig. 4: 90% c.l. upper limits on the ν fluence for different experiments and GRB phases.

GRB	T_0 (UT)	T90 (s)	θ (deg)	z	IC
080205	07:55:51	106.5	73.4	–	n
080413	02:54:19	46	74.1	2.43	y
080613	09:35:21	30	76.0	–	y
080625	12:28:31	80	73.8	–	y
080925	18:35:55	29	73.9	–	y
081221	16:21:11	34	73.1	2.26	y
090112B	17:30:15	12	76.9	–	y
090113	18:40:39	9.1	75.5	1.75	y
090227	07:25:57	50	73.3	–	y
090323	00:02:43	150	74.1	3.57	y
090427	23:26:27	15	74.1	–	y
090610B	17:21:32	202.5	76.0	–	y
090625	05:37:00	51	74.6	–	y
090701	05:23:56	12	75.5	–	y
090915	15:35:36	8	74.8	–	y
100213B	22:58:34	48.0	73.0	–	y
100331B	21:08:38	30	75.7	–	y
100425A	02:50:45	37.0	72.3	1.76	y
100906A	13:49:27	114.4	73.4	1.73	n
100915B	05:49:38	4	75.0	–	n
110529A	00:48:43	0.41	75.0	–	n
110708A	04:43:22	50	75.2	–	n
120602A	05:00:01	54	75.3	–	n
120712A	13:42:27	14.7	74.6	4.17	n
120803B	11:06:06	37.5	74.3	–	n
121201A	12:25:42	85	76.8	3.39	n

Table 1: List of GRBs with zenith angle $73° \leq \theta \leq 77°$ (November 2007 - January 2013) in the ARGO−YBJ field of view.

Detection of cosmic neutrinos

COSMIC NEUTRINOS OF ULTRA-HIGH ENERGIES AND DETECTION POSSIBILITY

V. S. BEREZINSKY and A. YU. SMIRNOV
Institute for Nuclear Study, U.S.S.R. Academy of Sciences, Moscow, U.S.S.R.

(Received 24 June, 1974)

The neutrino spectrum is represented by curve 2 in Figure 1. The neutrinos with $E \geqslant 10^{17}$ eV can be detected by the produced extensive air showers at large zenith angle. Due to their small cross-section, the neutrinos can traverse the large mass of the atmosphere and cause the showers at the depth optimal for their development. The arrival frequency of neutrino-produced showers does not depend on the zenith angle and, hence, the transition from proton-produced showers to neutrino showers should be characterized by transition from exponentially falling angular dependence to angular independent distribution (plateau). The neutrino-produced showers can have small radius curvature. On Haverah Park and Sydney arrays there were the showers

Horizontal Air showers

At large zenith angles there are also 3 other kinds of showers being the background events (they are analysed in Section 4):

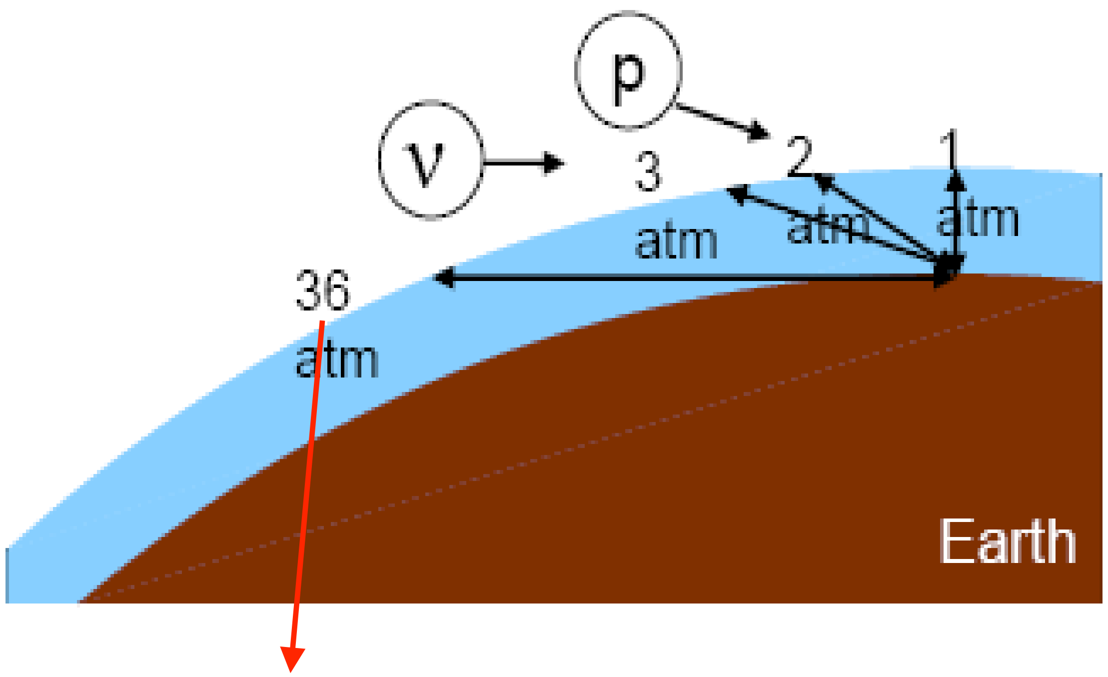
(1) The showers caused by the protons penetrating without collisions to the large depth of the atmosphere. The arrival frequency of these 'proton showers' quickly decreases with increase of zenith angle θ. The background due to these showers determines the lower bound of the zenith angles at which 'neutrino showers' can be observed.

(2) The showers caused by the nuclear interactions of muons with $E > 10^{17}$ eV at large atmospheric depth. The flux of the muons is small due to the large decay path length of the parent K and π-mesons. These 'muon showers' determine the upper bound of the zenith angles accessible for the observation of the neutrino showers.

(3) The showers of muons surviving from the extensive air showers originated at the top of the atmosphere. These muon 'remnant showers' acquire a small electron escort when crossing the atmosphere. The remnant shower with the total number of particles $N \sim 10^8$ corresponds to the primary proton energy $E_p > 10^{20}$ eV and, hence, the intensity of these showers is small. The remnant showers can be easily discriminated experimentally from the 'neutrino showers'. The remnant showers cause the bulk of the background events in zenith angle band limited at small angles by proton showers and at large angles by muon showers.

EAS by neutrino interactions

The observation of HAS provides a *"well shielded laboratory"* for the detection of penetrating particles: high energy muons, cosmic neutrinos, possible weakly interacting particles produced in the decays of cosmological superheavy particles, will leave a clear signature in this dump.



36,000 g/cm² !!!

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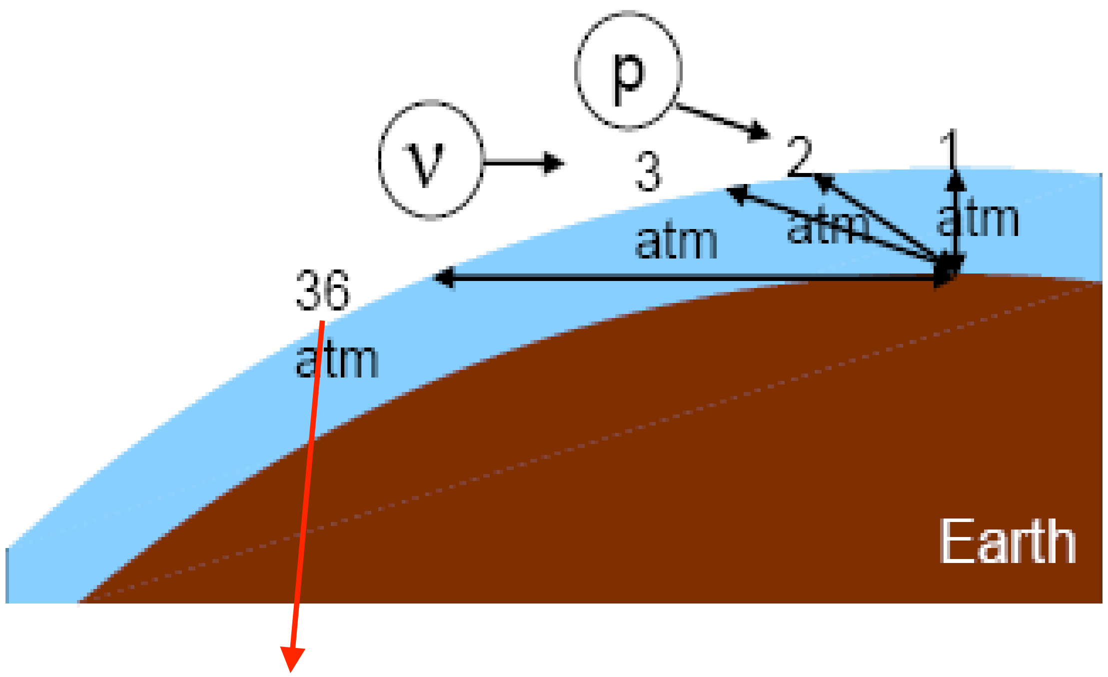

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Electron neutrinos are more effective for the generation of showers since in the process (1) the total neutrino energy is transferred to the cascade, while for muon neutrinos with $E_\nu \approx 10 - 100$ TeV the fraction of energy transferred amounts to only ~ 30%.

Neutrinos produce showers through:

CC-interactions:

(1) $$(\bar{\nu}_l)\nu_l + N => l^{\pm} + hadrons$$

NC-interactions:

(2) $$(\bar{\nu}_l)\nu_l + N => (\bar{\nu}_l)\nu_l + hadrons$$

where l = e, μ or τ;

and resonance production [17,18]:

(3) $$\bar{\nu}_e + e^- => W^- => hadrons$$

where the resonant neutrino energy is:

$$E_0[GeV] = m_W^2/2m_e = 6.410^6$$

Horizontal Air Showers

a) High energy ***single muons*** can interact through ***bremsstrahlung*** (which dominate 10:1) or deep inelastic scattering and initiate showers at appropriate depth for detection. Such ***showers*** are essentially ***electromagnetic***, since the remnant muons from the initial showers are dispersed over a very large area.

b) UHE CRs interacting at very large zenith angles produce a 'large' amount of muons (pion decay favoured due to the low atm density). ***EAS composed only by muons*** (e.m. component fully absorbed)

c) ***Neutrinos*** induced showers have some intermediate typology, being more ***similar to conventional CR EAS or to events a)***, when a large amount of energy is transferred to the ***electromagnetic*** cascade.

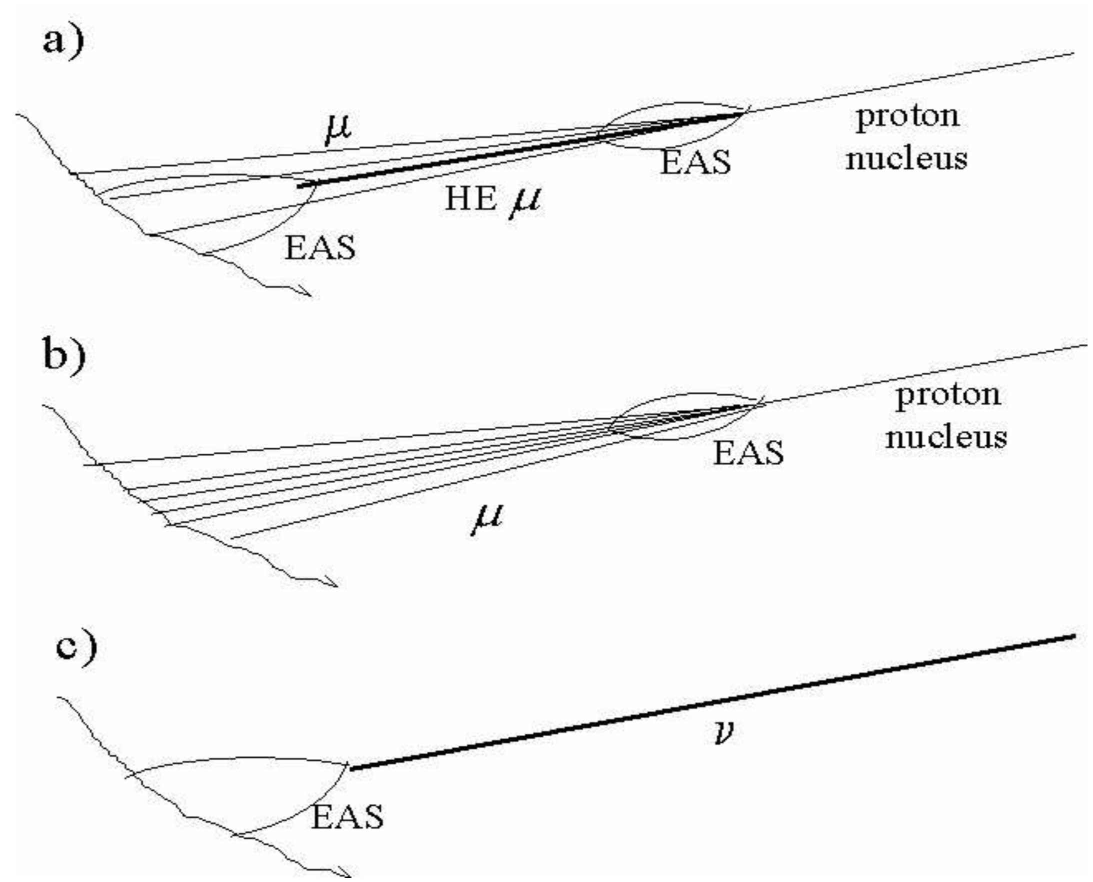

Figure 1. Possible sources of Horizontal Air Showers: a) "local" high energy muon interactions, b) muon dominated showers, residuals from an UHE c.r. interaction at very large distance, c) neutrino events.

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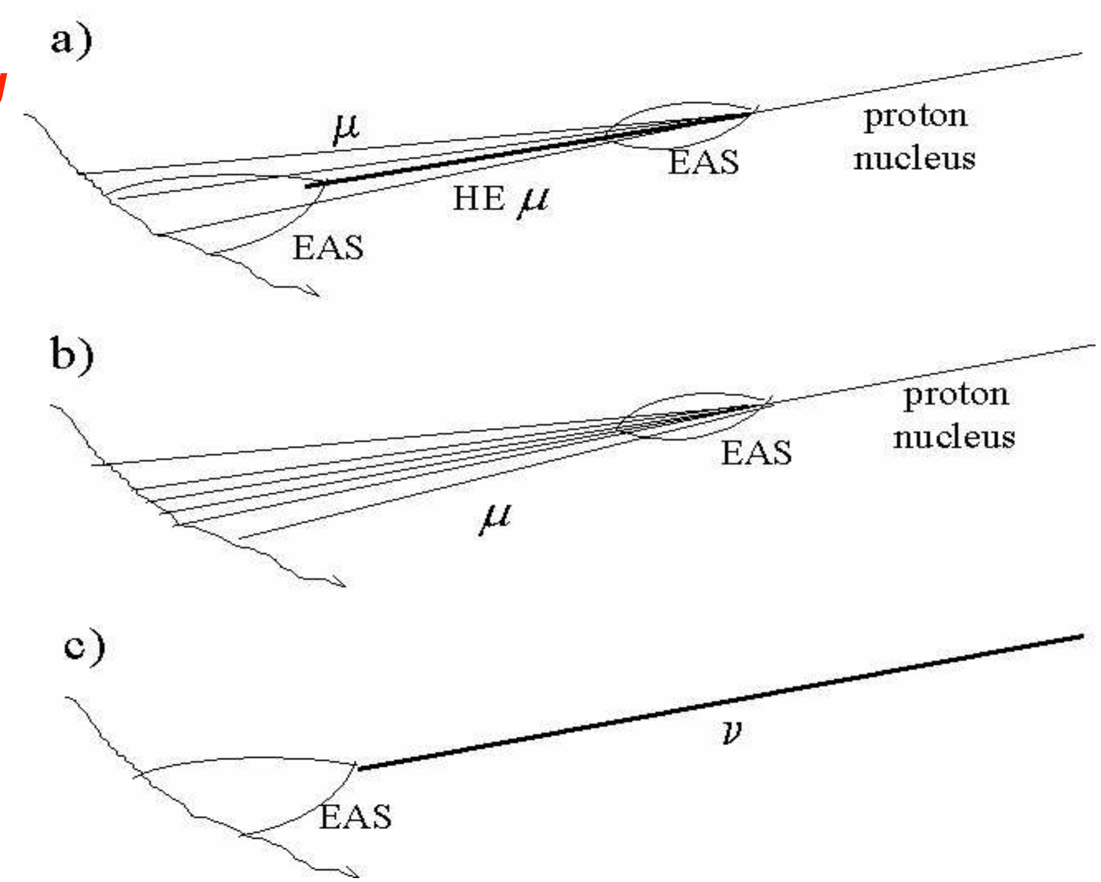
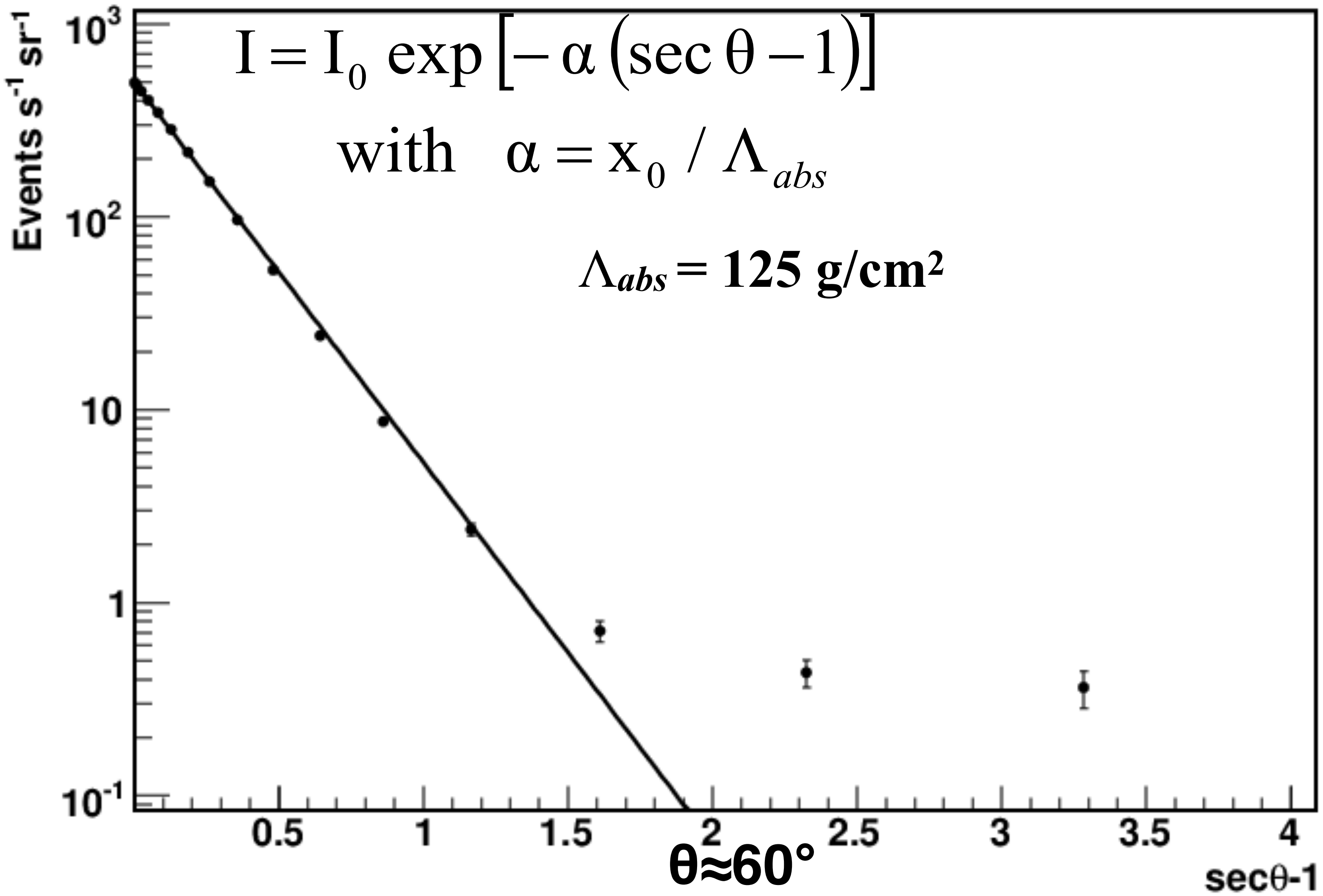


Figure 1. Possible sources of Horizontal Air Showers: a) "local" high energy muon interactions, b) muon dominated showers, residuals from an UHE c.r. interaction at very large distance, c) neutrino events.

Arrays must have the possibility of discriminating between the different topologies of events through ***μ/e identification***

LHAASO: > 40,000 m^2 μ-detector

Rate as a function of the zenith angle



YBJ altitude – 606 g/cm²
θ>70° - 1248 g/cm²
θ>80° - 2458 g/cm²

The *attenuation length* Λ_{N_e} describes the average decrease of the electron number N_e with increasing atmospheric depth X in showers selected to be similar in primary energy:

$$\langle N_e(X) \rangle \propto \exp\left(-X/\Lambda_{N_e}\right)$$

The *absorption length* Λ_{rate} is defined to parameterize the decrease of the integral flux $j(>N_e)$ of showers with electron numbers greater than N_e at a given atmospheric depth X (*decrease of the counting rate*):

$$j(>N_e, X) \propto \exp\left(-X/\Lambda_{rate}\right)$$

$$\gamma = \Lambda_{att} / \Lambda_{abs} \qquad \Lambda_{att} \approx 220 \text{ g/cm}^2, \; \Lambda_{abs} \approx 130 \text{ g/cm}^2$$

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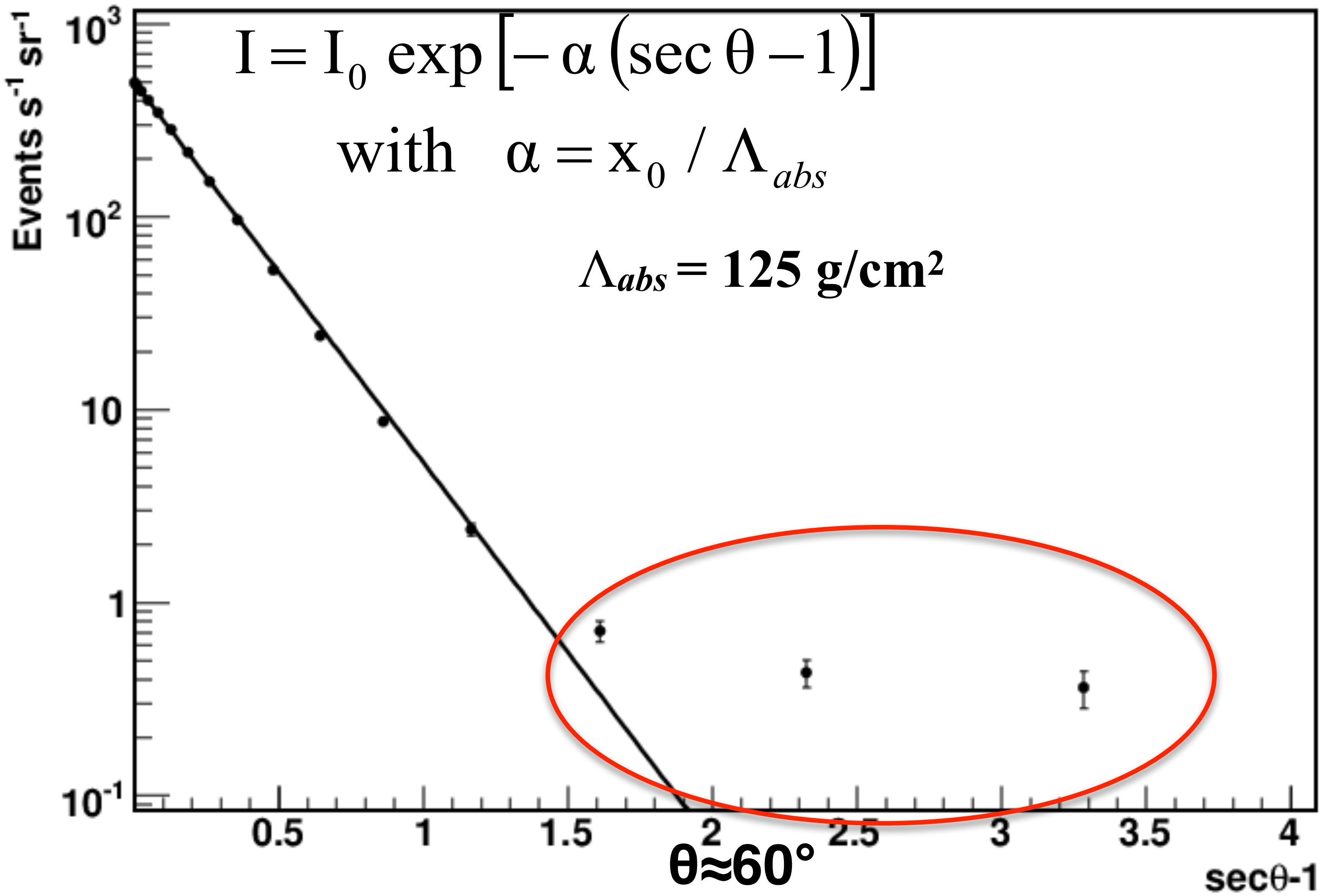

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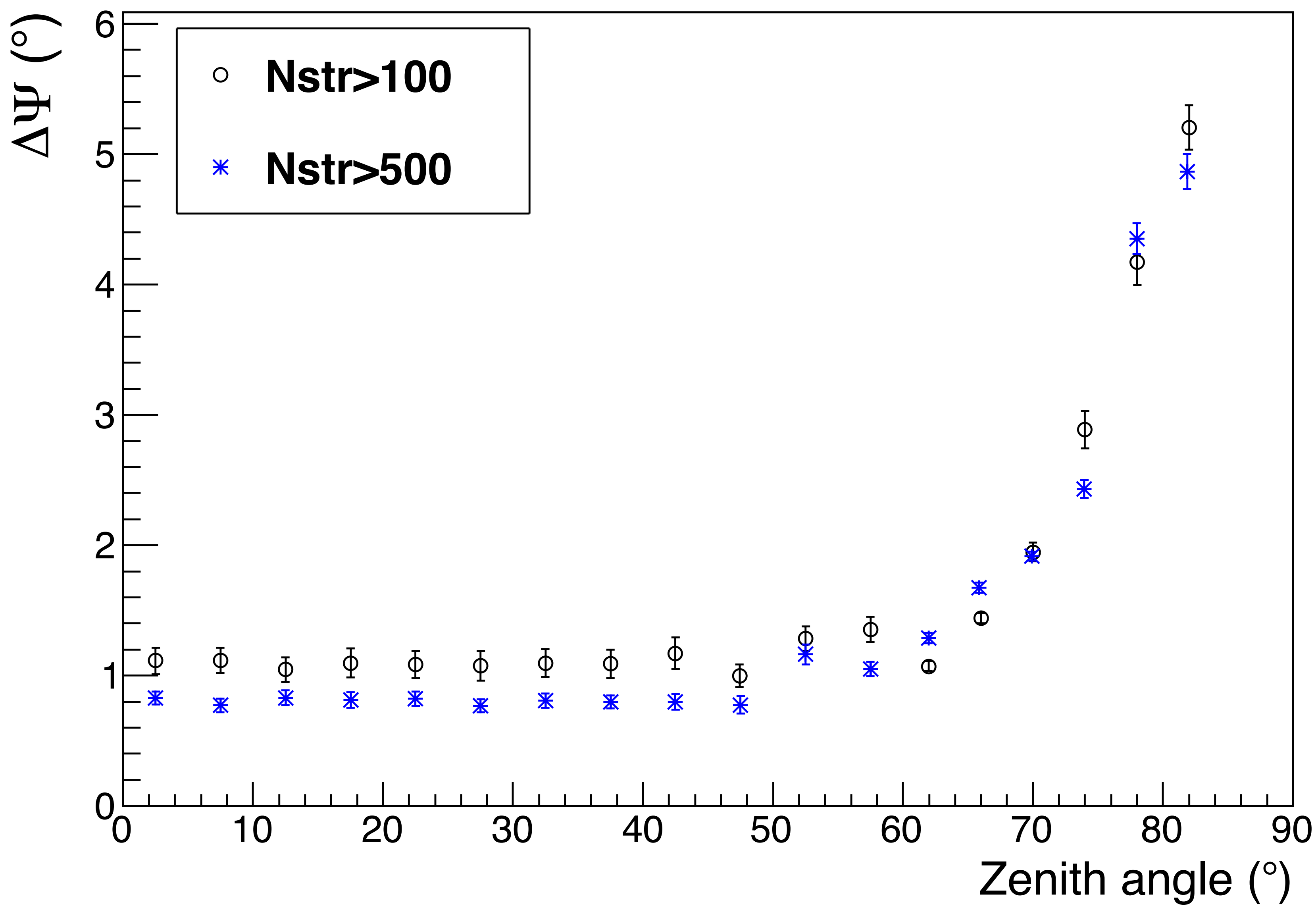
$$\Lambda_{att} \approx 220 \text{ g/cm}^2, \ \Lambda_{abs} \approx 130 \text{ g/cm}^2$$

From the experimental point of view only *accurate measurements of arrival directions* can allow to extract the neutrino-produced showers from the large background due to primary protons and nuclei.

Angular resolution vs zenith angle

Angular resolution worsens with increasing zenith angle: 2.3° for $73° \leq \theta \leq 77°$



Analysis of HAS by ARGO-YBJ

33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

ICRC 2013

Observation of Horizontal Air Showers with ARGO-YBJ

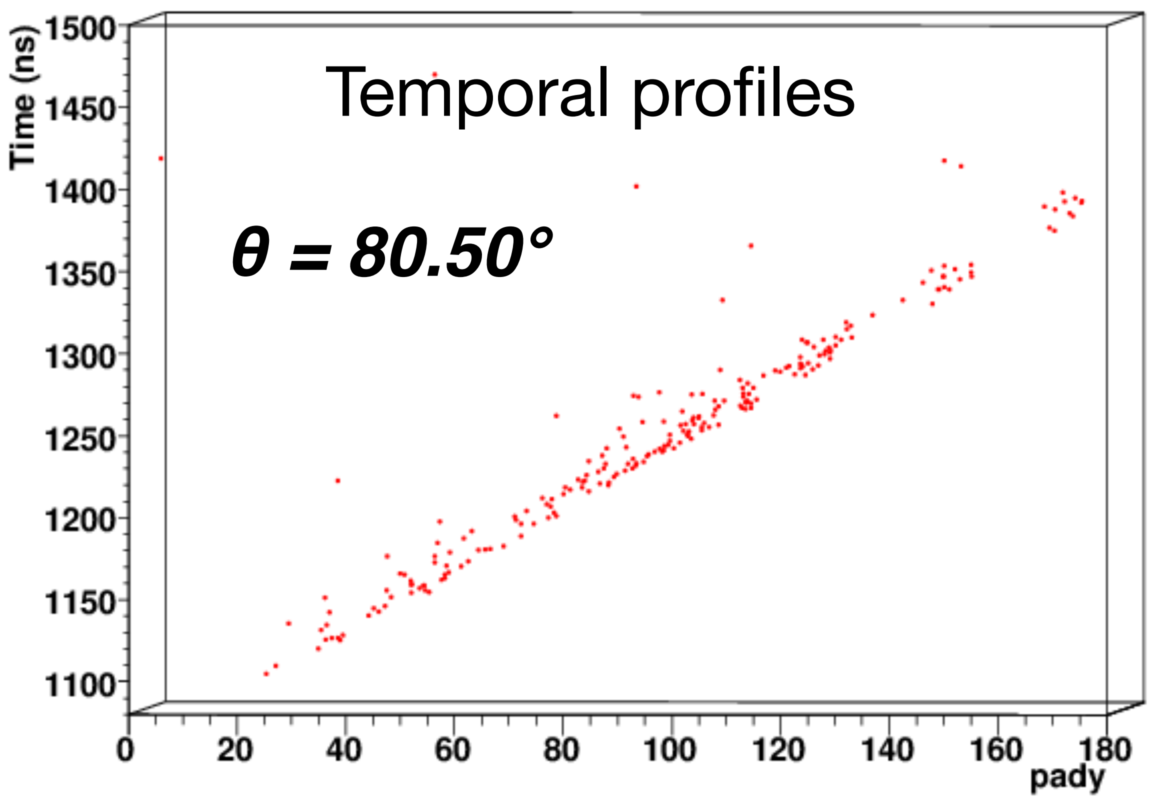
G. DI SCIASCIO[1], B. PANICO[1] FOR THE ARGO-YBJ COLLABORATION.

[1] *INFN, Sezione di Roma Tor Vergata, Viale della Ricerca Scientifica 1, Roma*

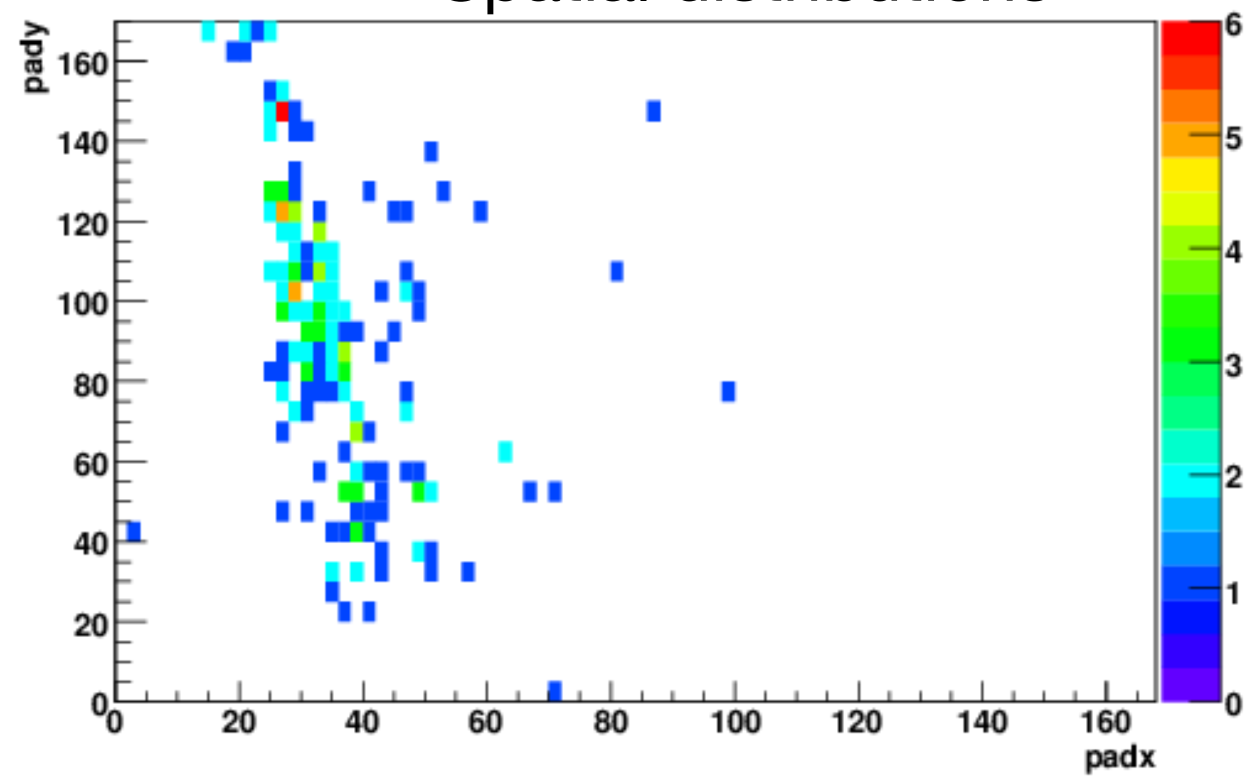
disciascio@roma2.infn.it

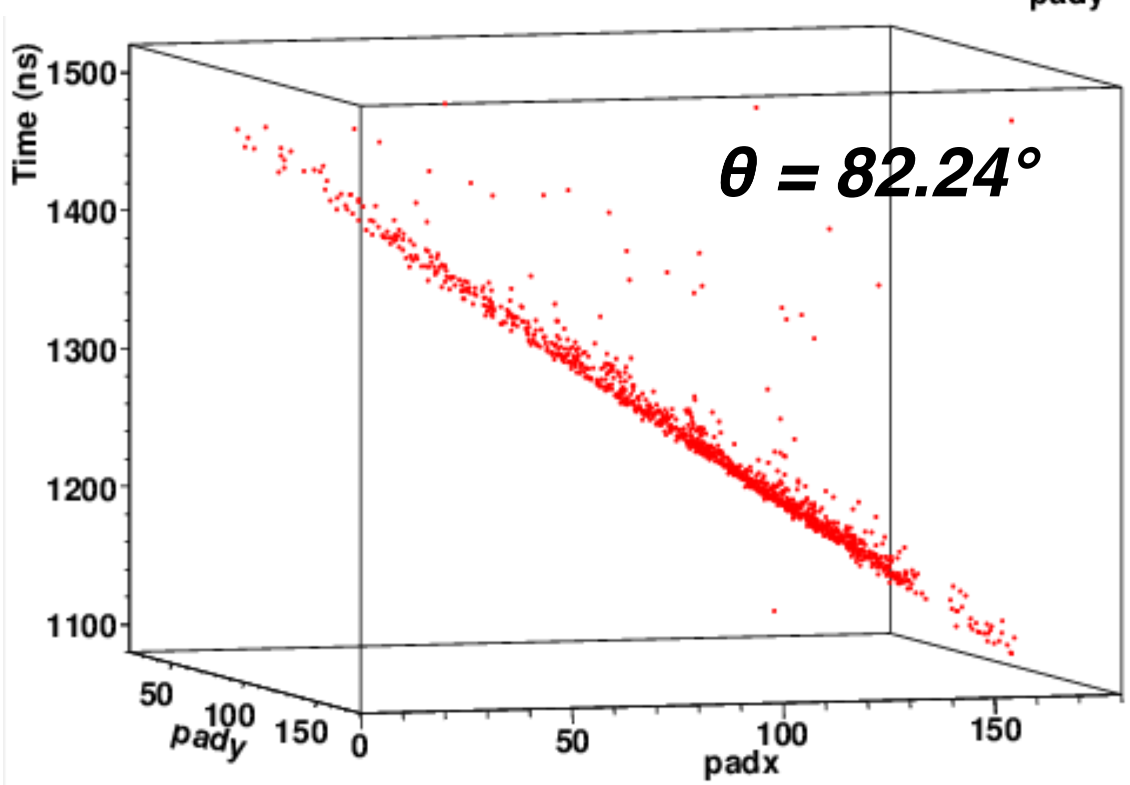
Abstract: The understanding of Cosmic Rays (CRs) origin at any energy is made difficult by the poor knowledge of the elemental composition of the radiation. Inclined showers ($\theta > 60^\circ$) induced by very high-energy CRs are mainly produced by secondary muons, in contrast to the vertical ones dominated by photons and electrons stemming from π^0 decays. Measurements of the CRs rate at different zenith angles give information on the relative number of muons in a shower, which is dependent on the CR elemental composition, thus providing an important tool to probe the CR mass distribution but also the hadronic interaction models. In this paper a study of the non-attenuated shower component at a zenith angle $\theta > 60^\circ$, through the observation of the so-called horizontal air showers by the ARGO-YBJ experiment, is presented. More than 10^7 well-contained horizontal events have been analyzed to study the production and interaction of high energy CR muons and neutrinos.

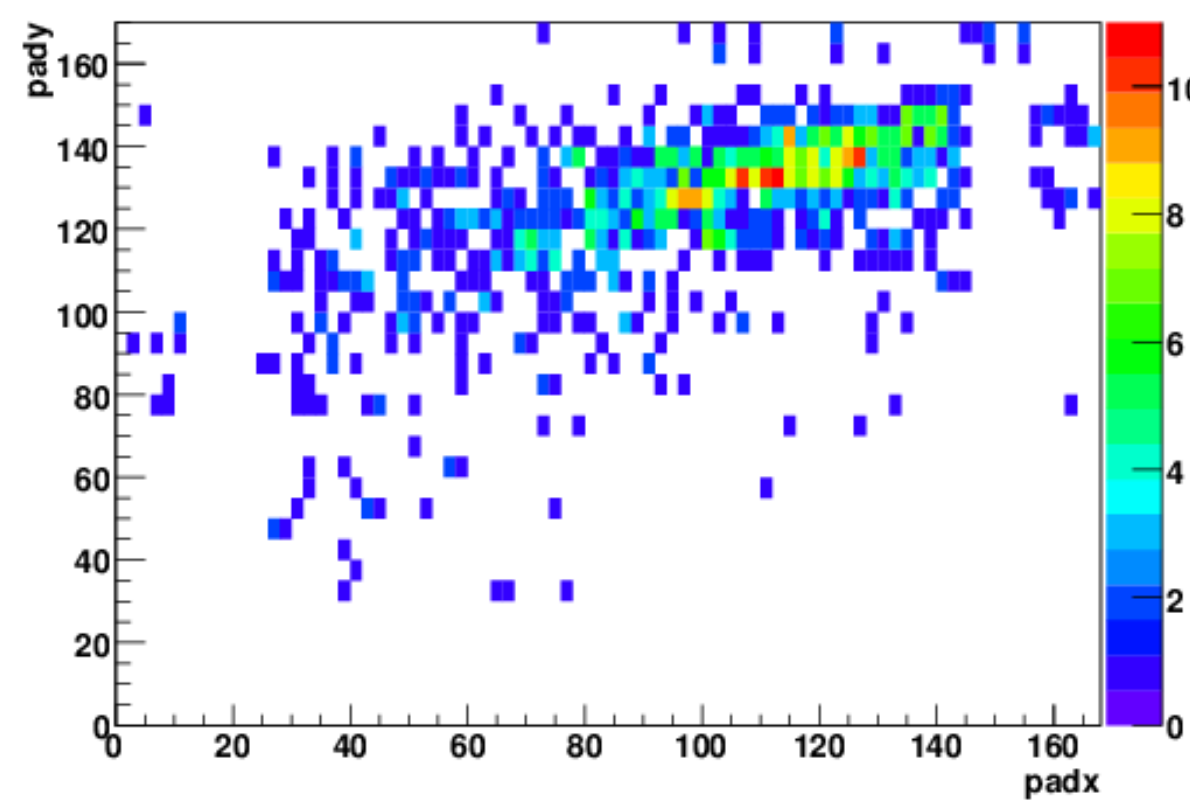
Horizontal Air Showers by ARGO-YBJ



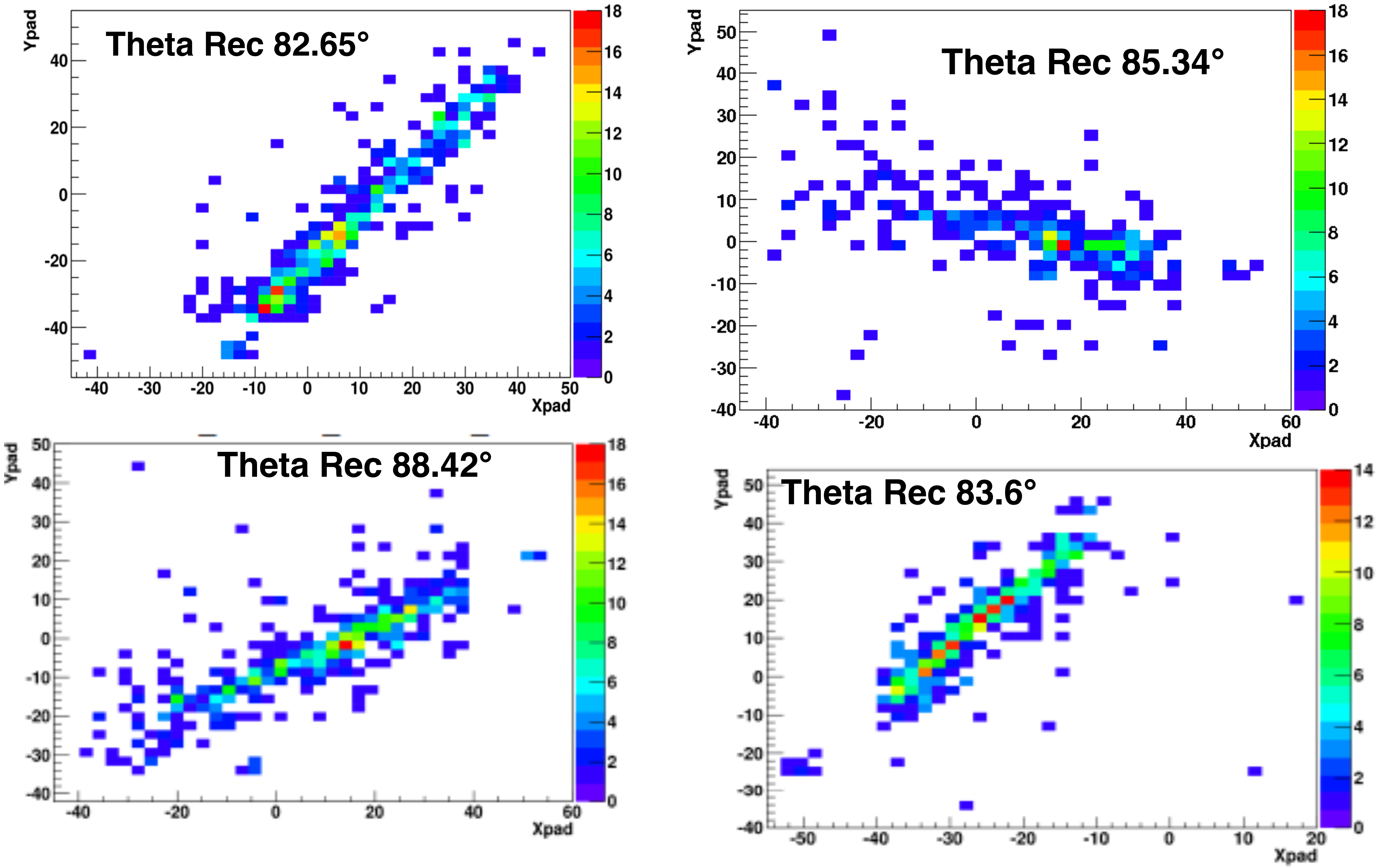
Spatial distributions





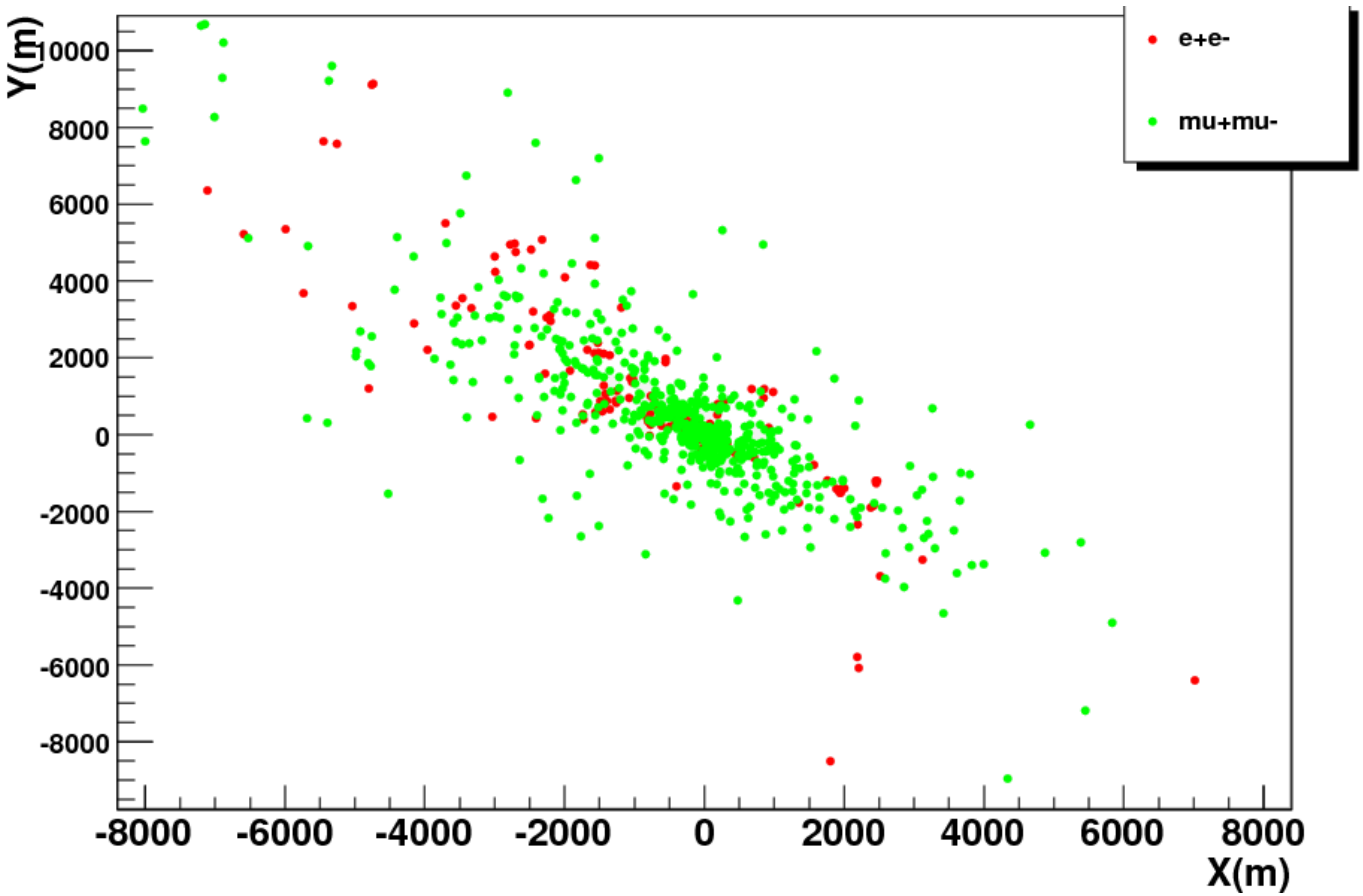


Horizontal Air Showers by ARGO-YBJ

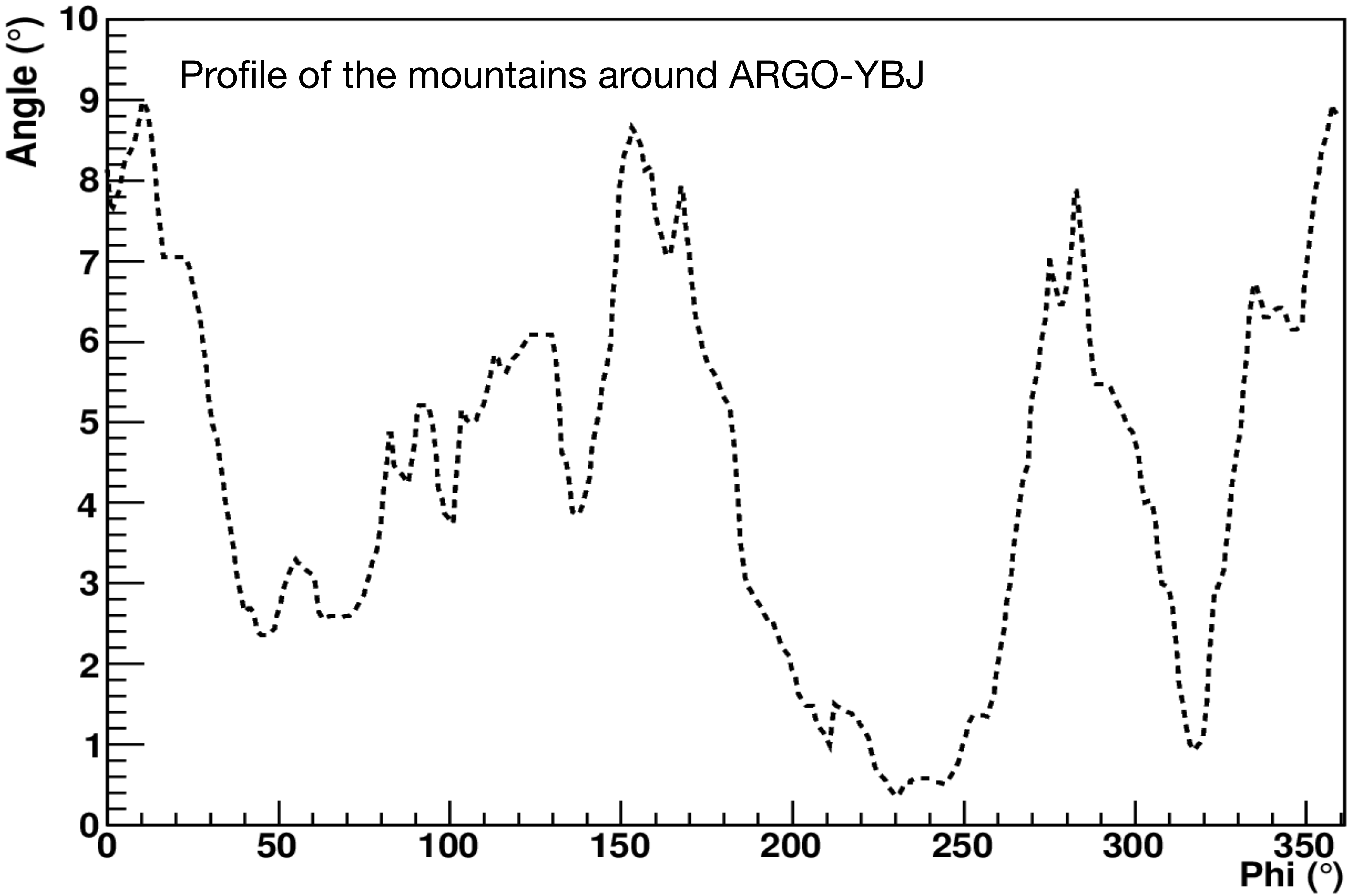


Simulated HAS

MonteCarlo simulation proton = 80° - 3367 g/cm²



Azimuthal distribution EAS > 80 deg



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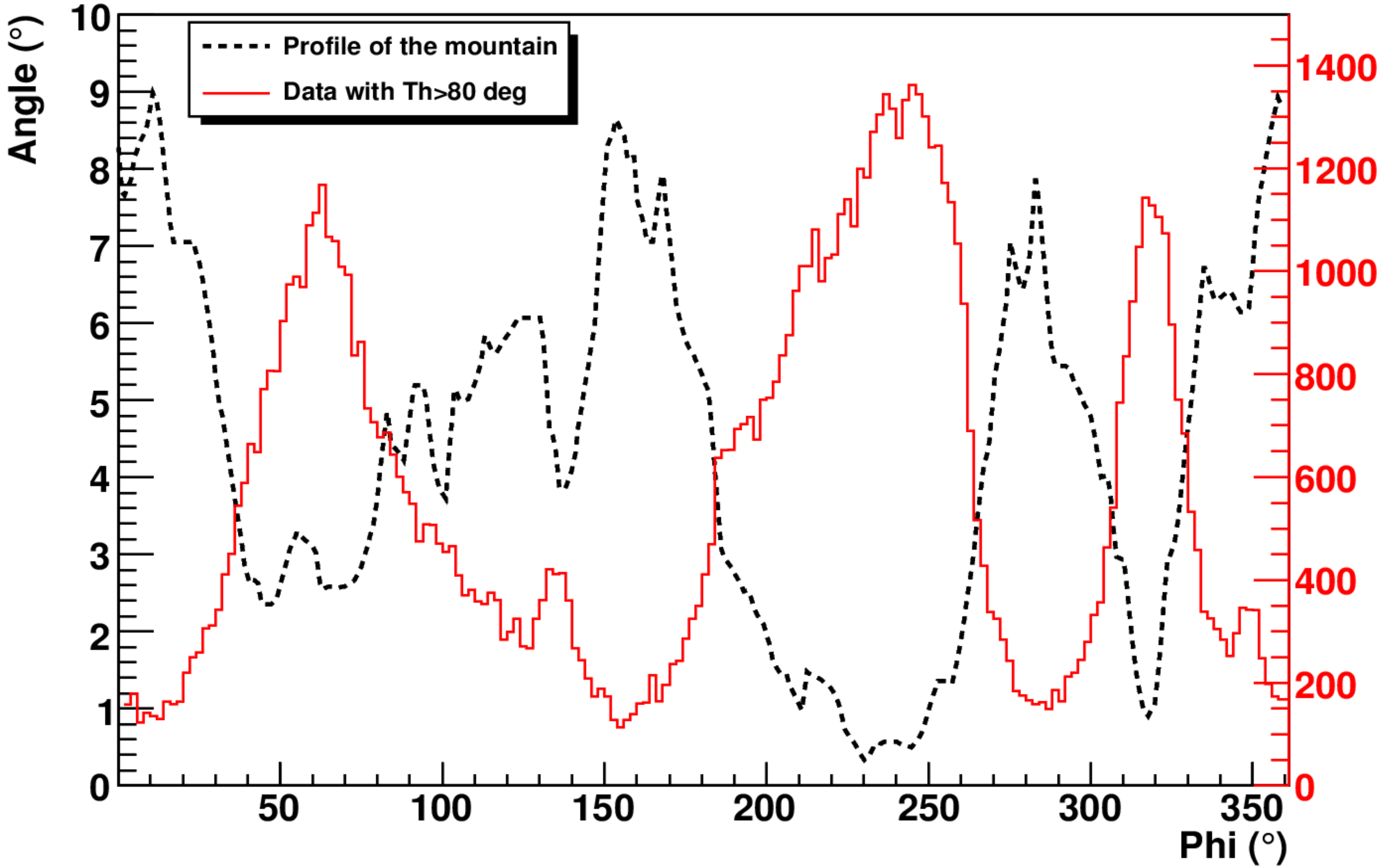
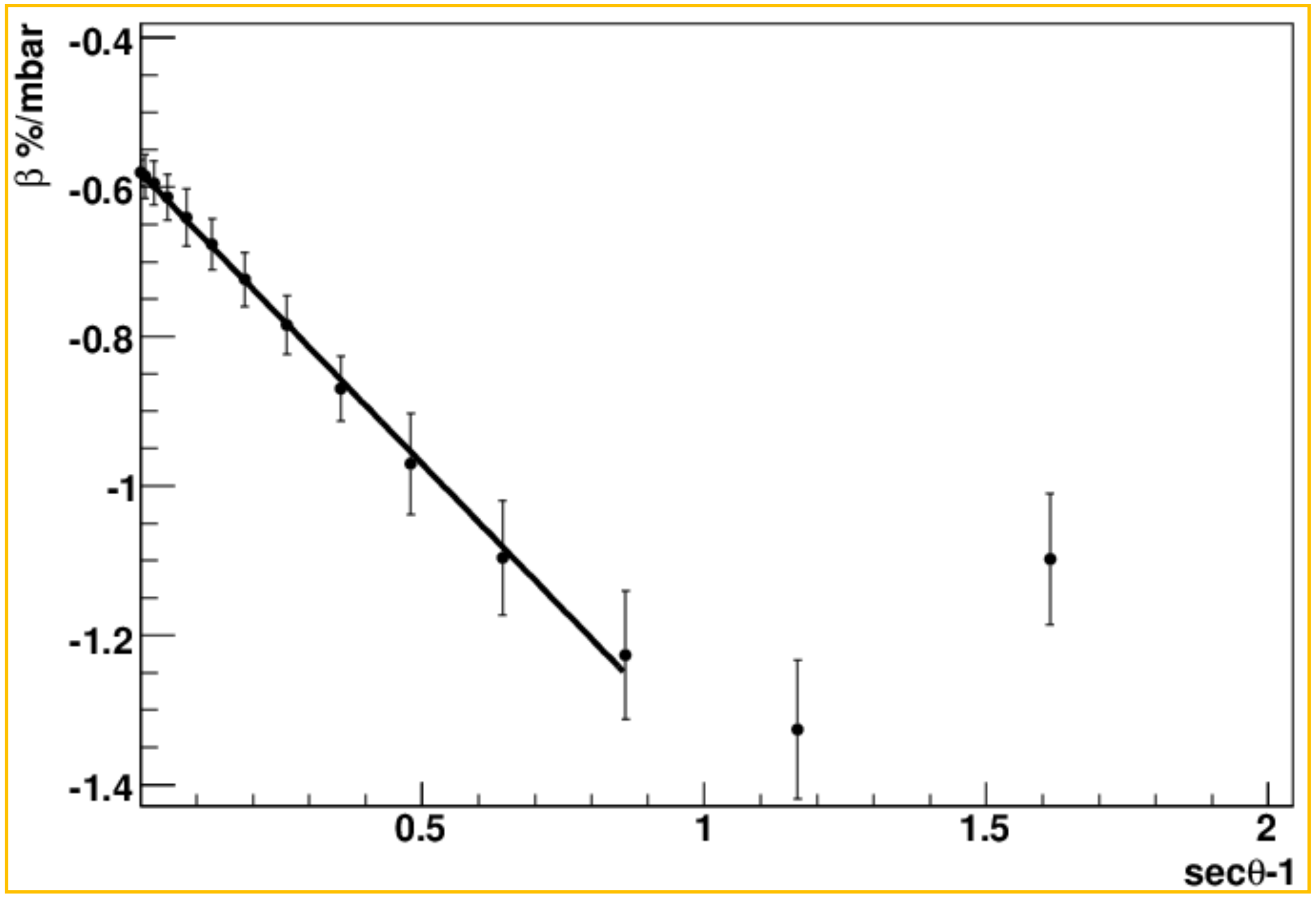


The barometric coefficient

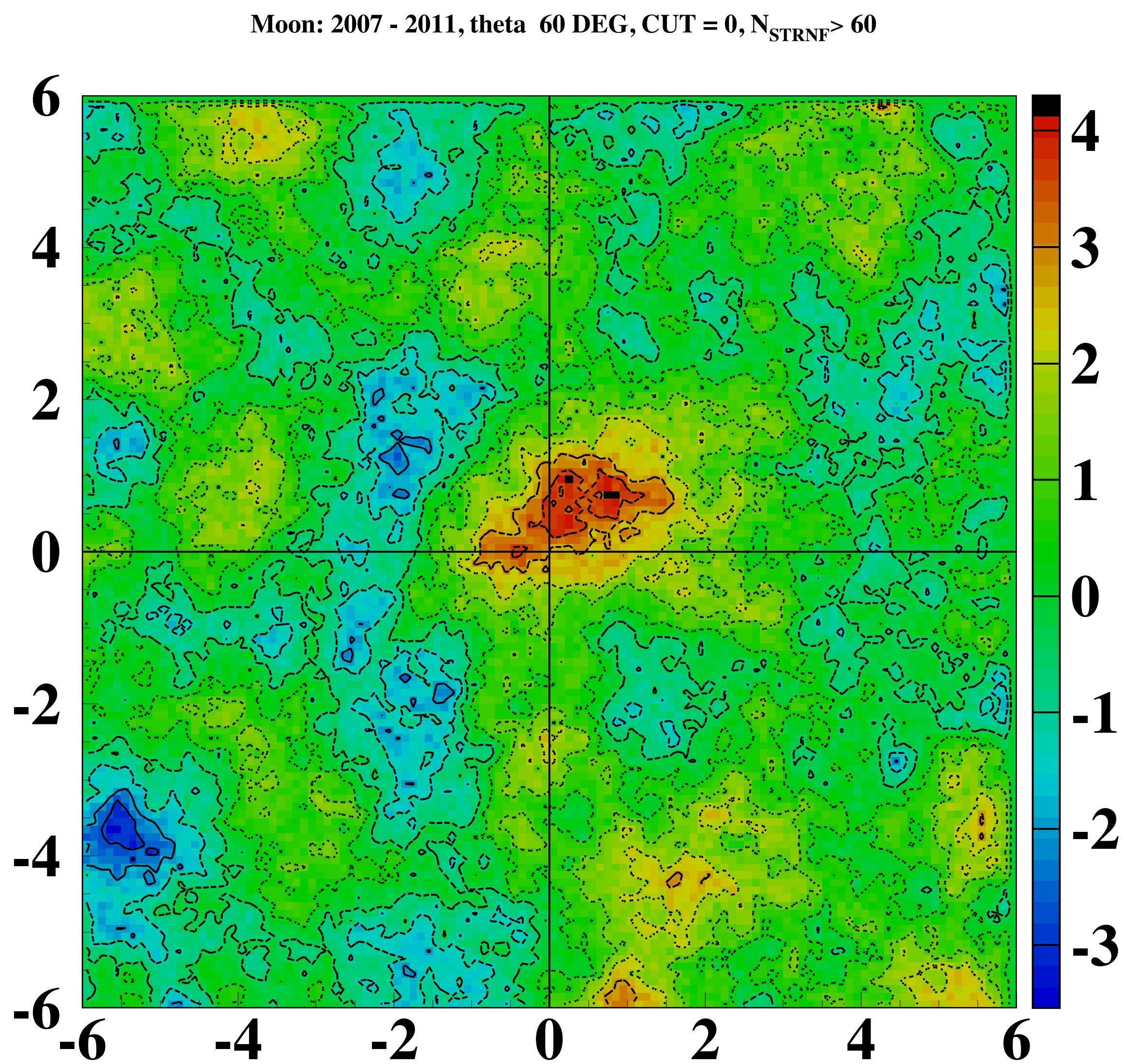


The dependence of the barometric effect on the zenith angle clearly shows a deviation from the *secθ* behaviour for *secθ* > 2.

In fact, the barometric coefficient $\beta = \frac{1}{n}\frac{dn}{dx}$

where *n* = counting rate and *x* = atmospheric pressure, is related to zenith angle as: β(θ) = β(0°) *secθ*. This can be explained by the presence of a *"non-attenuated"* EAS component that dominates for angles larger than 70°.

Moon Shadow > 60 deg



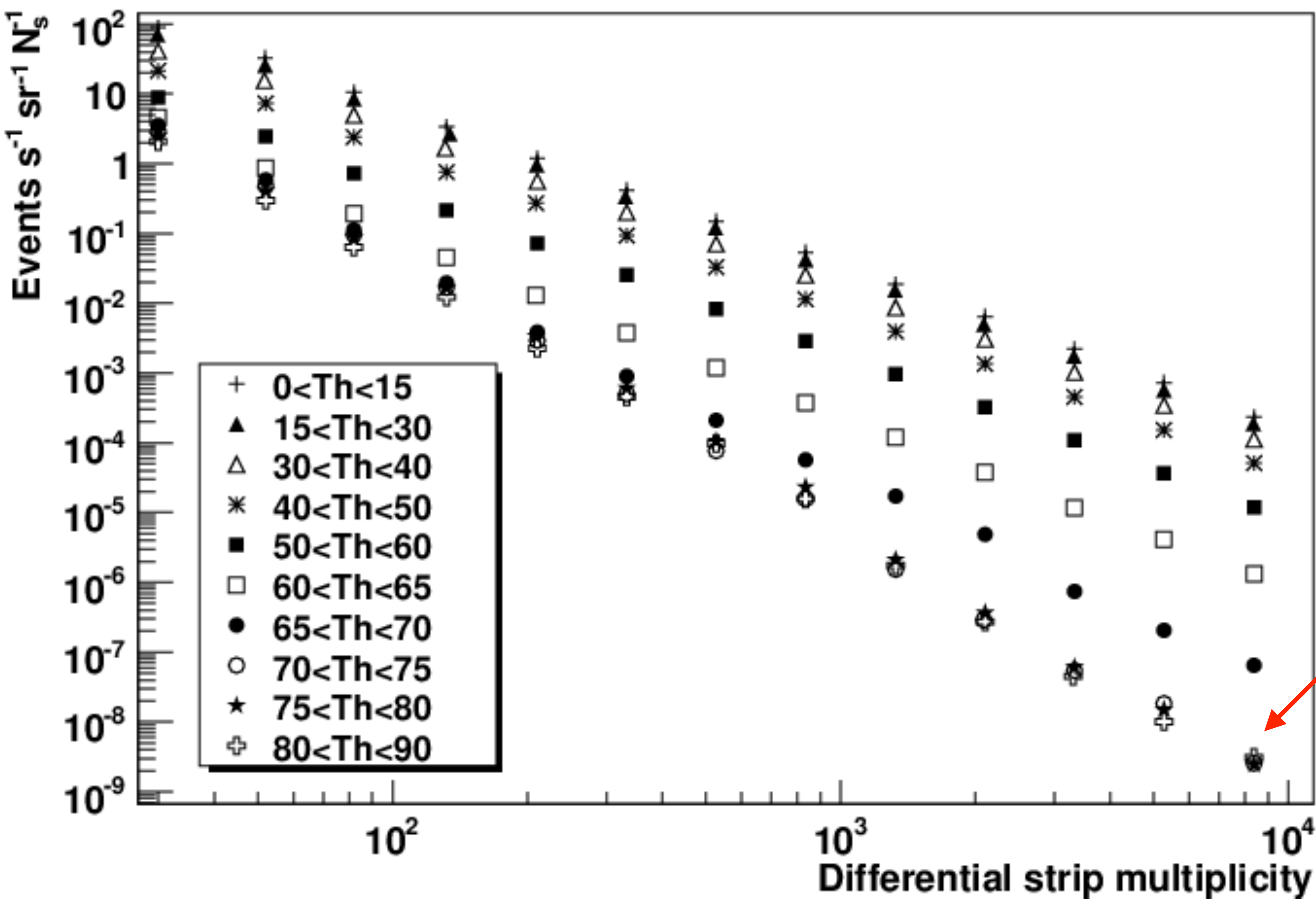
The significance map of the Moon region observed at a zenith angle θ > 60° It contains all the events collected by ARGO-YBJ in 5-years data taking with bin N> 60 fired strips on the central carpet. The significance of the maximum deficit is about 5 s.d.

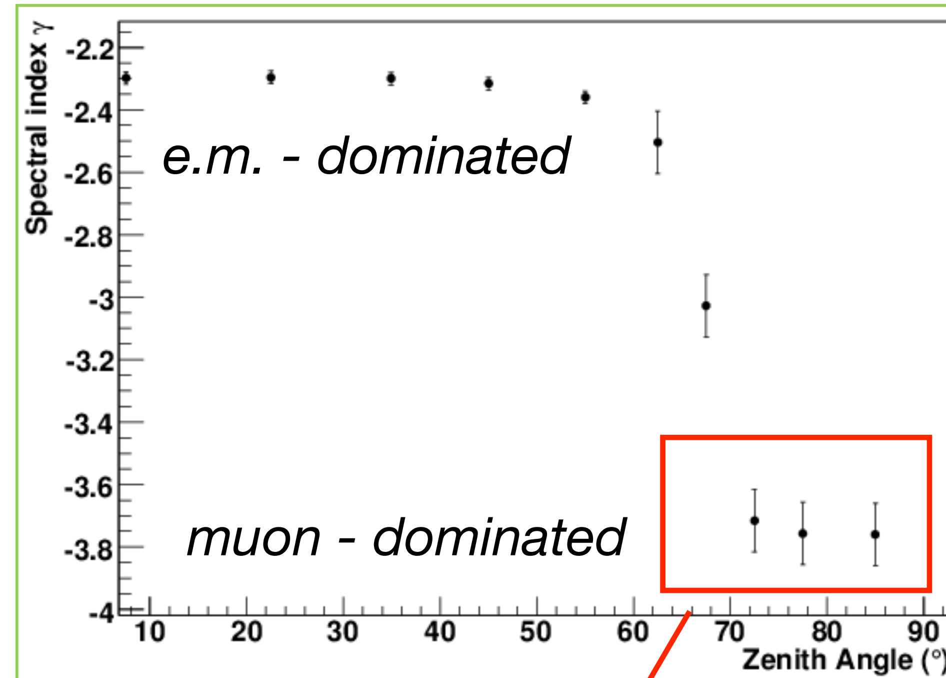
We stress that this is ***the first time*** that an air shower array detected the Moon shadow mainly due to ***muon-induced showers in horizontal events***.

This result makes us confident about the angular resolution and the selection procedure of inclined showers.

Measured Rate of HAS

Strip multiplicity for different zenith angles

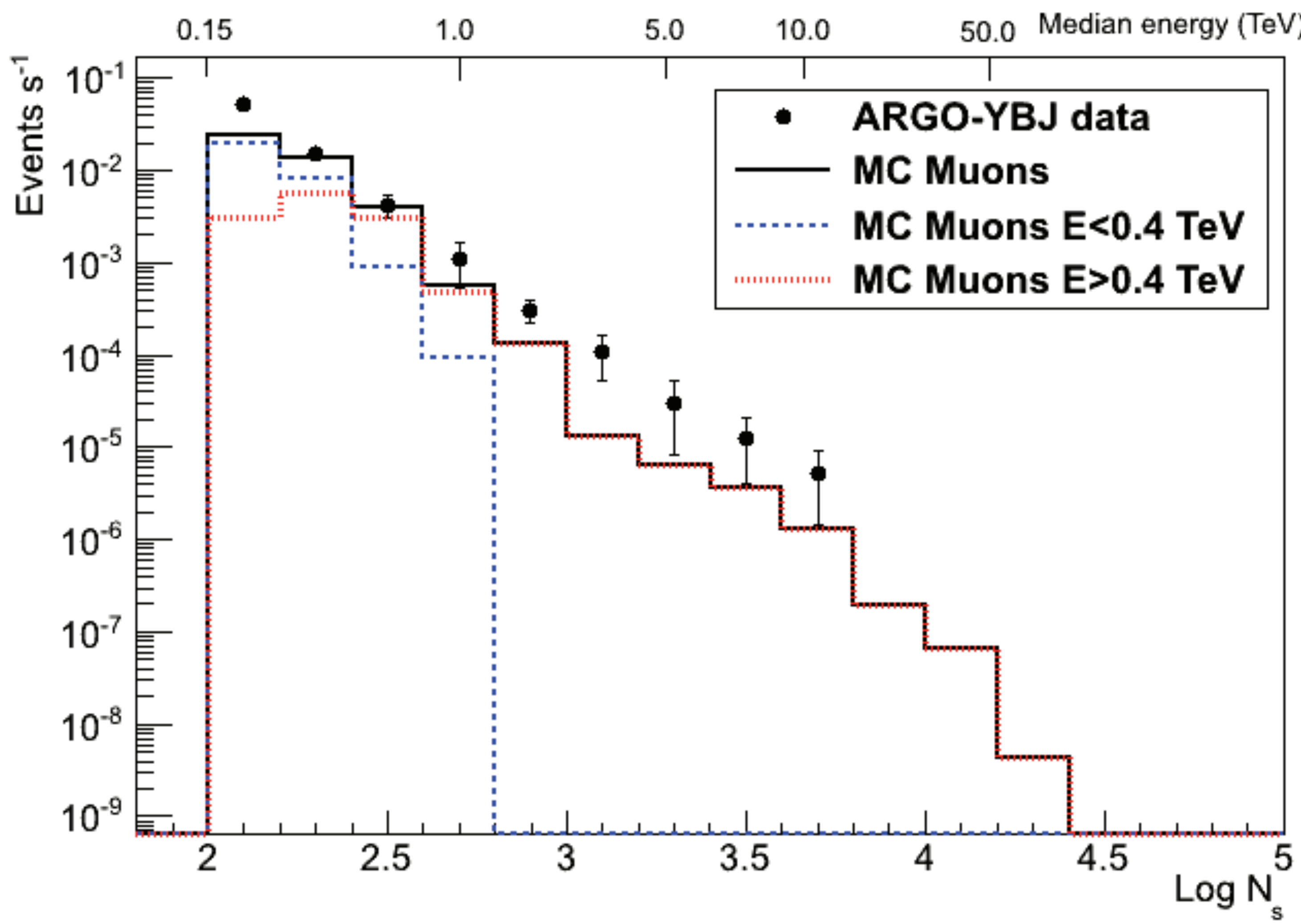




γ ≈ -3.70
spectral index muons in EAS

HAS size spectrum

Comparison (only shape) between HAS rate measured by ARGO-YBJ and MC expectations for 70° < θ <75°. The upper scale shows the corresponding muon median energy.



We have simulated showers induced by muons with the energy spectrum measured by Allkofer and collaborators in 1979 at 75°

Limits on prompt electron neutrinos

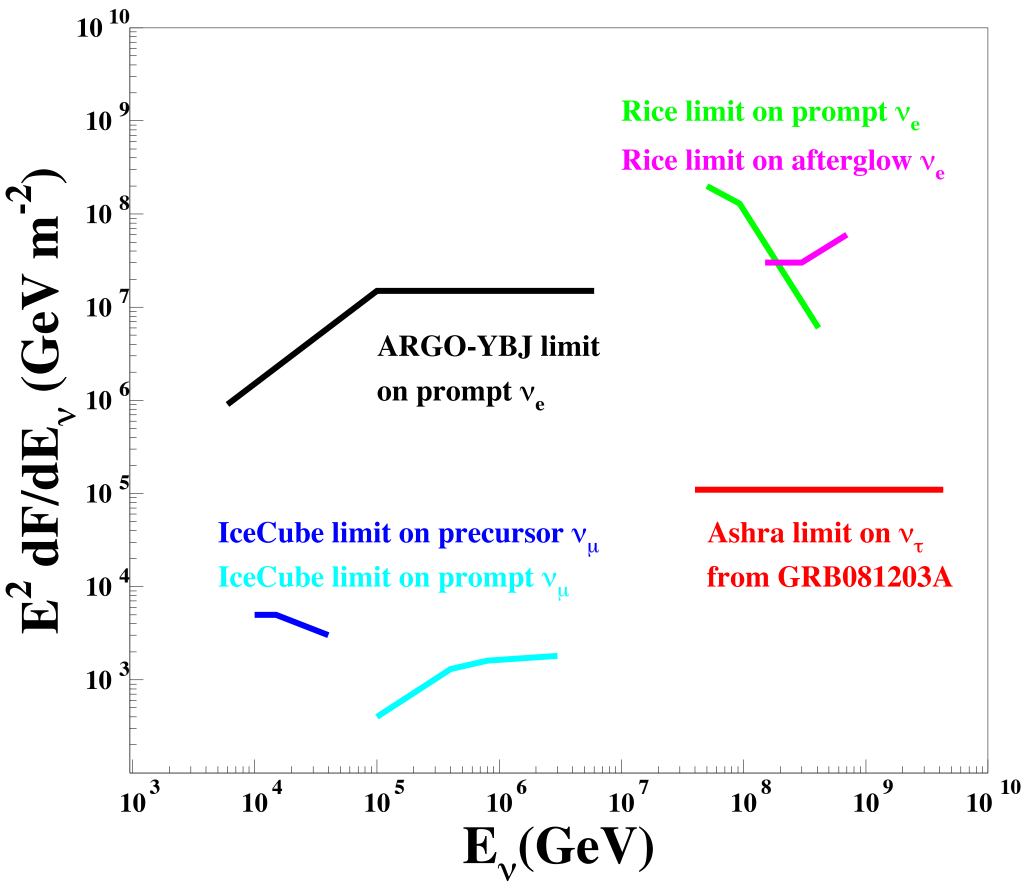


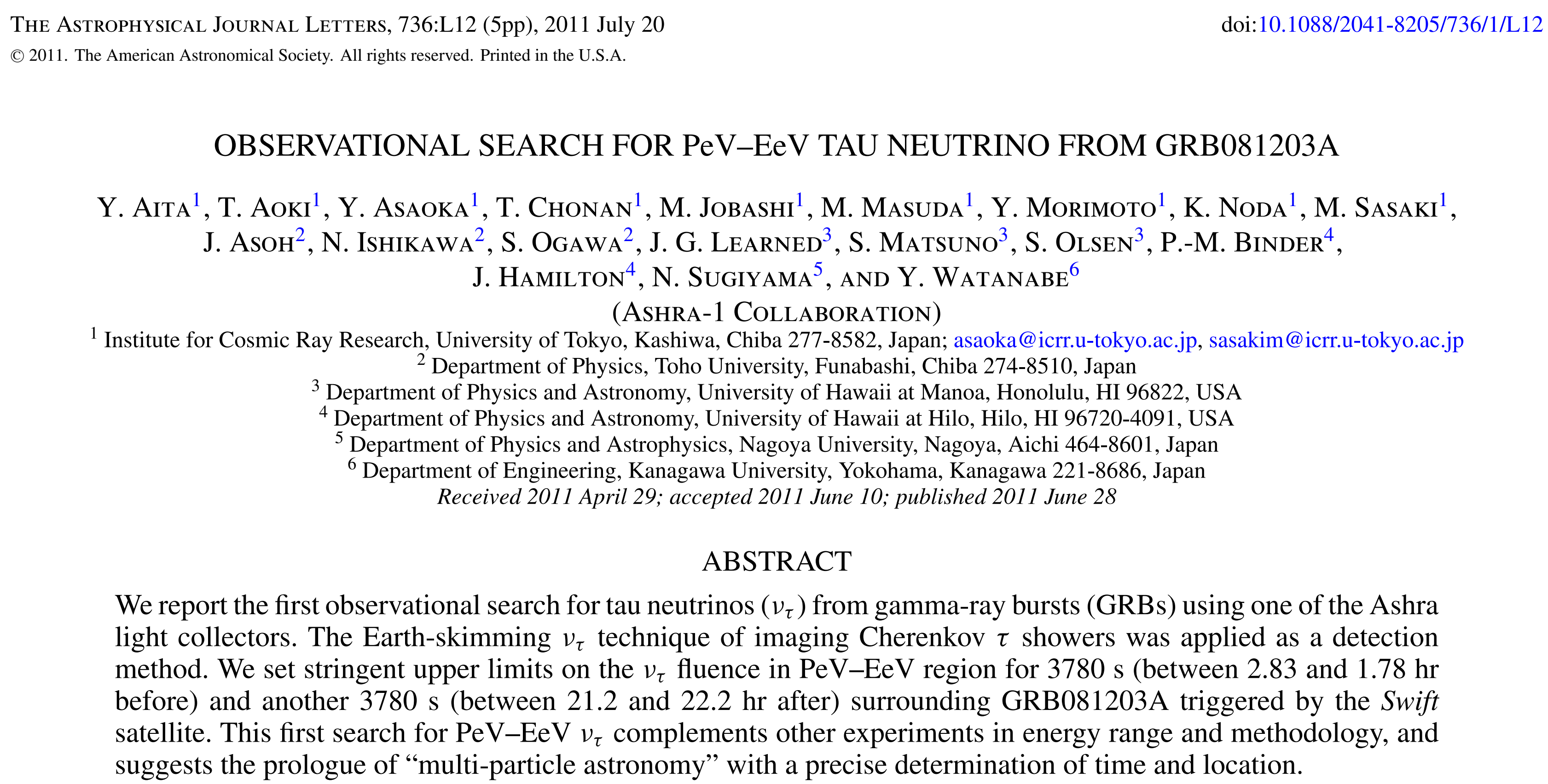
Fig. 4: 90% c.l. upper limits on the ν fluence for different experiments and GRB phases.

ciently reconstructed [10]. The number of ν-induced showers with more than N_0 strips is given by:

$$N_{ev}(>N_0) = A_f \cdot \cos\theta \int dE_\nu \frac{dF(E_\nu)}{dE_\nu} P(E_\nu; > N_0) \quad (1)$$

where $dF(E_\nu)/dE_\nu$ is the ν energy spectrum and $P(E_\nu; > N_0)$ is the probability that a ν of energy E_ν can generate a shower with core inside the area A_f and a number of charged particles firing more than N_0 strips. The ν-shower conversion probability $P(E_\nu; > N_0)$ is obtained by a full simulation in which we use the cross section for the CC ν interaction given in [1] with the CTEQ4-DIS parton distribution, while the shower development is handled by the CORSIKA code and the detector response is simulated with the ARGOG package based on the GEANT3 code.

Not only low energy: the role of WFCTA


The Astrophysical Journal Letters, 736:L12 (5pp), 2011 July 20 doi:10.1088/2041-8205/736/1/L12

OBSERVATIONAL SEARCH FOR PeV–EeV TAU NEUTRINO FROM GRB081203A

Y. Aita[1], T. Aoki[1], Y. Asaoka[1], T. Chonan[1], M. Jobashi[1], M. Masuda[1], Y. Morimoto[1], K. Noda[1], M. Sasaki[1], J. Asoh[2], N. Ishikawa[2], S. Ogawa[2], J. G. Learned[3], S. Matsuno[3], S. Olsen[3], P.-M. Binder[4], J. Hamilton[4], N. Sugiyama[5], and Y. Watanabe[6]
(Ashra-1 Collaboration)
[1] Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan; asaoka@icrr.u-tokyo.ac.jp, sasakim@icrr.u-tokyo.ac.jp
[2] Department of Physics, Toho University, Funabashi, Chiba 274-8510, Japan
[3] Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822, USA
[4] Department of Physics and Astronomy, University of Hawaii at Hilo, Hilo, HI 96720-4091, USA
[5] Department of Physics and Astrophysics, Nagoya University, Nagoya, Aichi 464-8601, Japan
[6] Department of Engineering, Kanagawa University, Yokohama, Kanagawa 221-8686, Japan
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ABSTRACT

We report the first observational search for tau neutrinos (ν_τ) from gamma-ray bursts (GRBs) using one of the Ashra light collectors. The Earth-skimming ν_τ technique of imaging Cherenkov τ showers was applied as a detection method. We set stringent upper limits on the ν_τ fluence in PeV–EeV region for 3780 s (between 2.83 and 1.78 hr before) and another 3780 s (between 21.2 and 22.2 hr after) surrounding GRB081203A triggered by the *Swift* satellite. This first search for PeV–EeV ν_τ complements other experiments in energy range and methodology, and suggests the prologue of "multi-particle astronomy" with a precise determination of time and location.

The all-sky survey high-resolution air-shower detector (ASHRA) is a complex of ***unconventional optical collectors to detect UV, Cherenkov and fluorescence light*** that image VHE air showers in a 42° diameter field of view covering 77% of the entire night sky with a resolution of a few arcminutes.

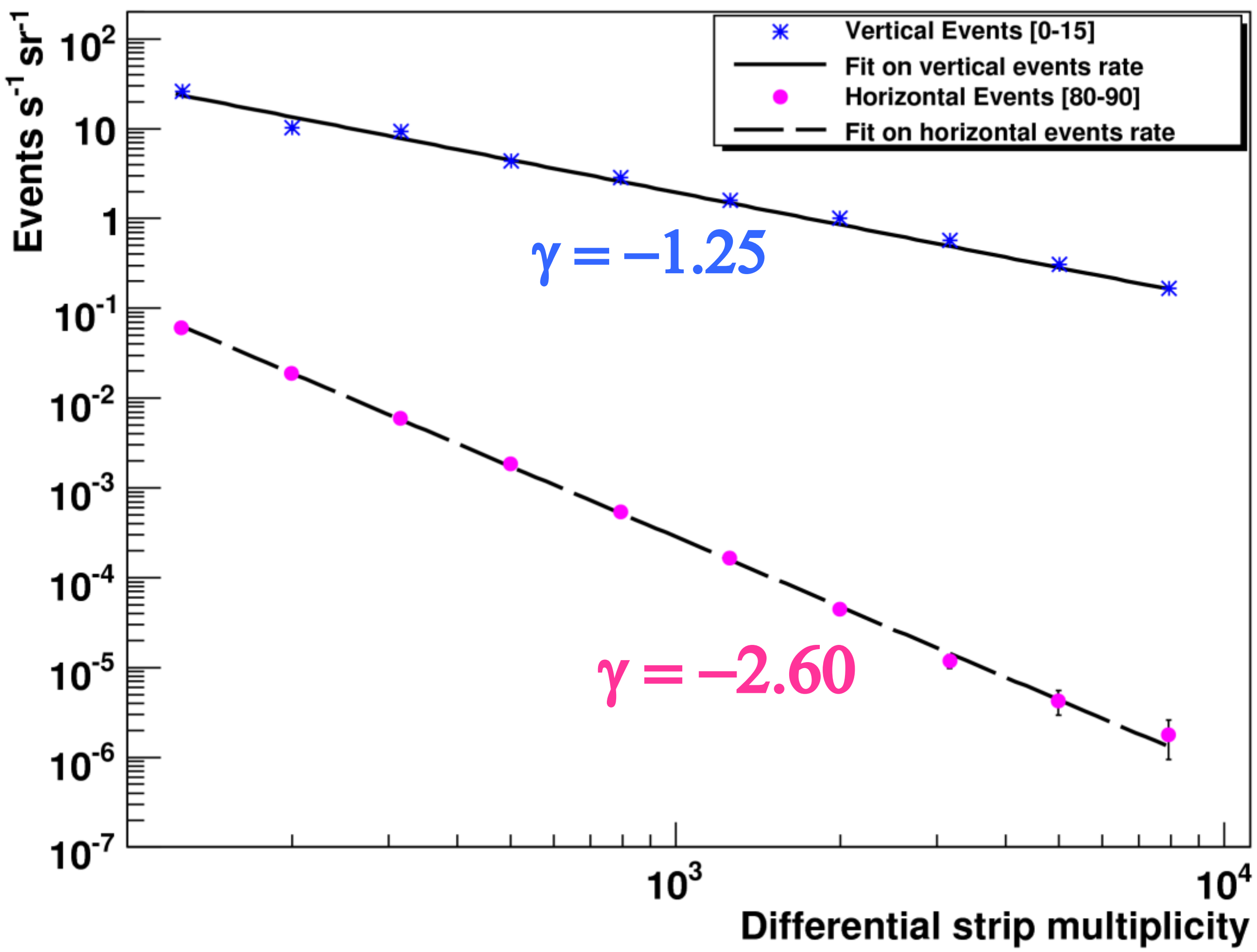
Proposal to study the sensitivity of WFCTA at PeV energies

Conclusions

- In the multi-messenger era observation of neutrino events from flaring/explosive phenomena crucial.
- Due to the lack of detailed knowledge of the evolution of the accelerated proton spectrum in the forward shocks, there is huge ambiguity in calculation of neutrino fluxes. It is important to set observational limit especially on each burst due to much different environment burst by burst.
- Observation of HAS important for a number of reasons (increase effective area, study of hadronic interactions, neutrinos, …).
- Good opportunity for LHAASO with unprecedented muon detector area and array of Cherenkov telescopes.
- With WFCTA, LHAASO could complement the IceCube results for the sub-PeV energy region.

Size (strip) spectrum

YBJ altitude: 606 g/cm²
Showers with zenith angle >80° - 3367 g/cm²



MonteCarlo simulation
proton = 80° - 3367 g/cm²