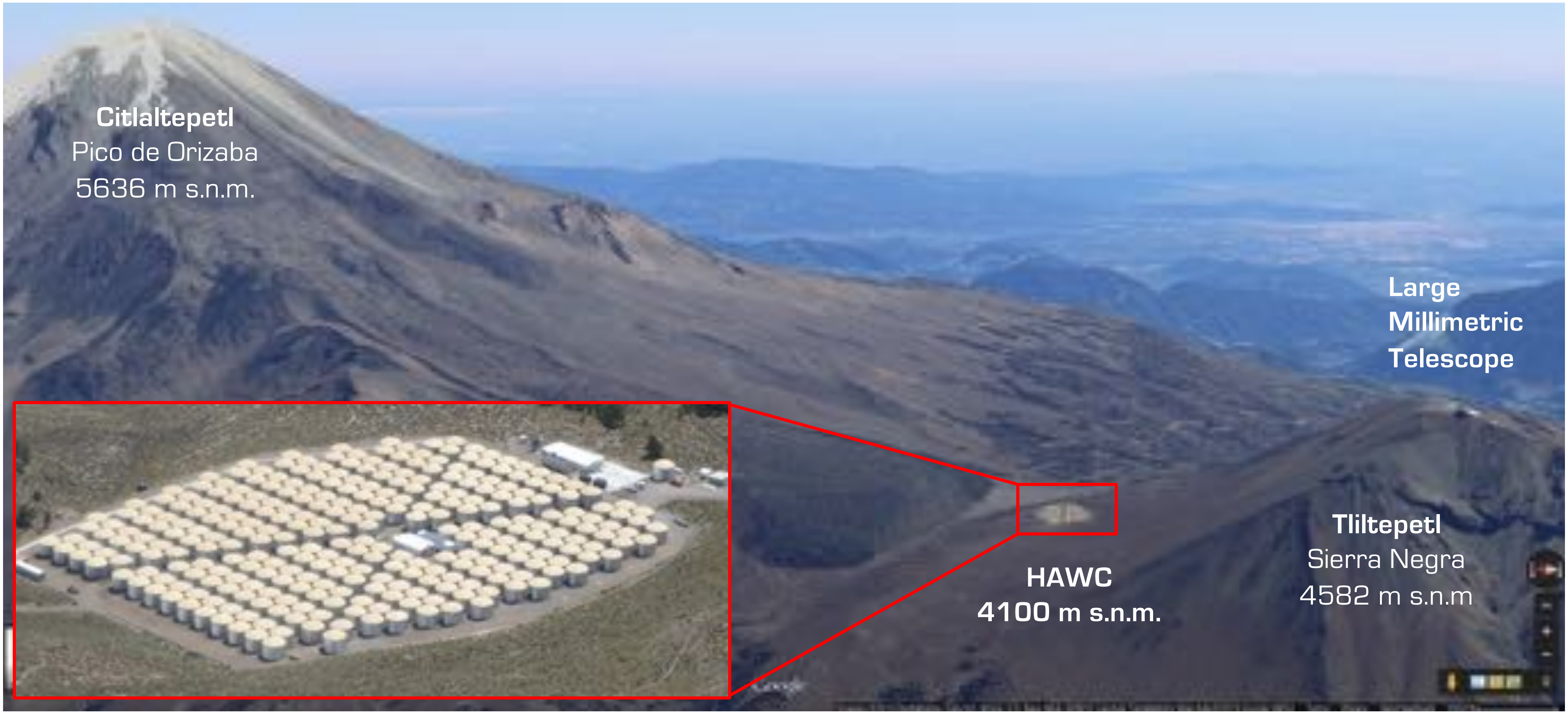
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

2019 Meeting of the Cosmic Ray Division
Puebla, Nov. 29.

Search of UHE neutrinos with HAWC

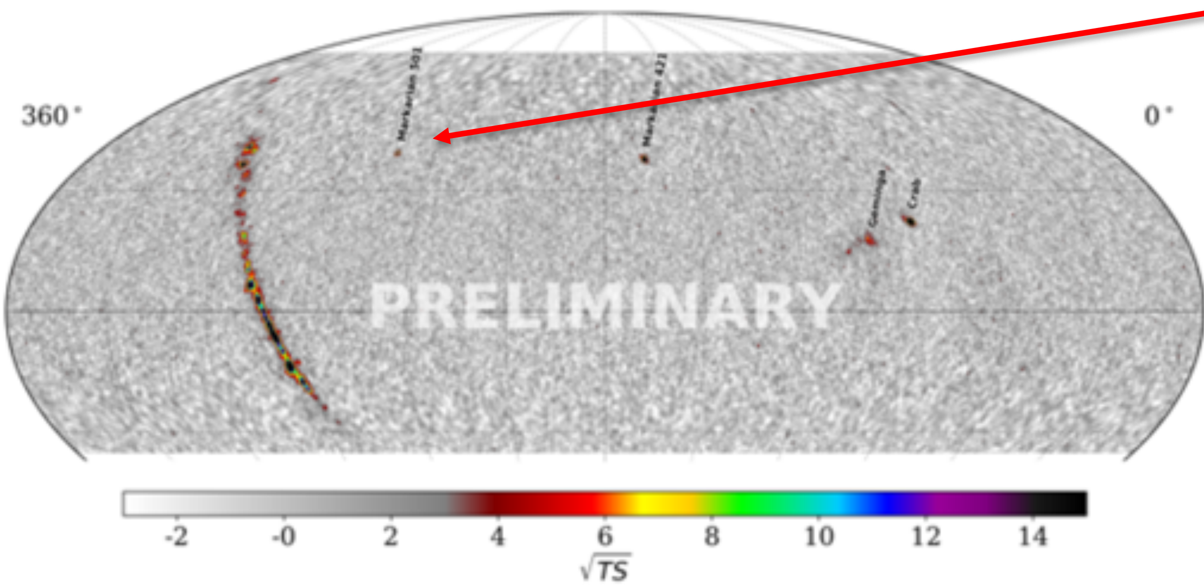
Hermes León Vargas
Instituto de Física, UNAM

Where is HAWC?



HAWC

Constraints on using photons as probes

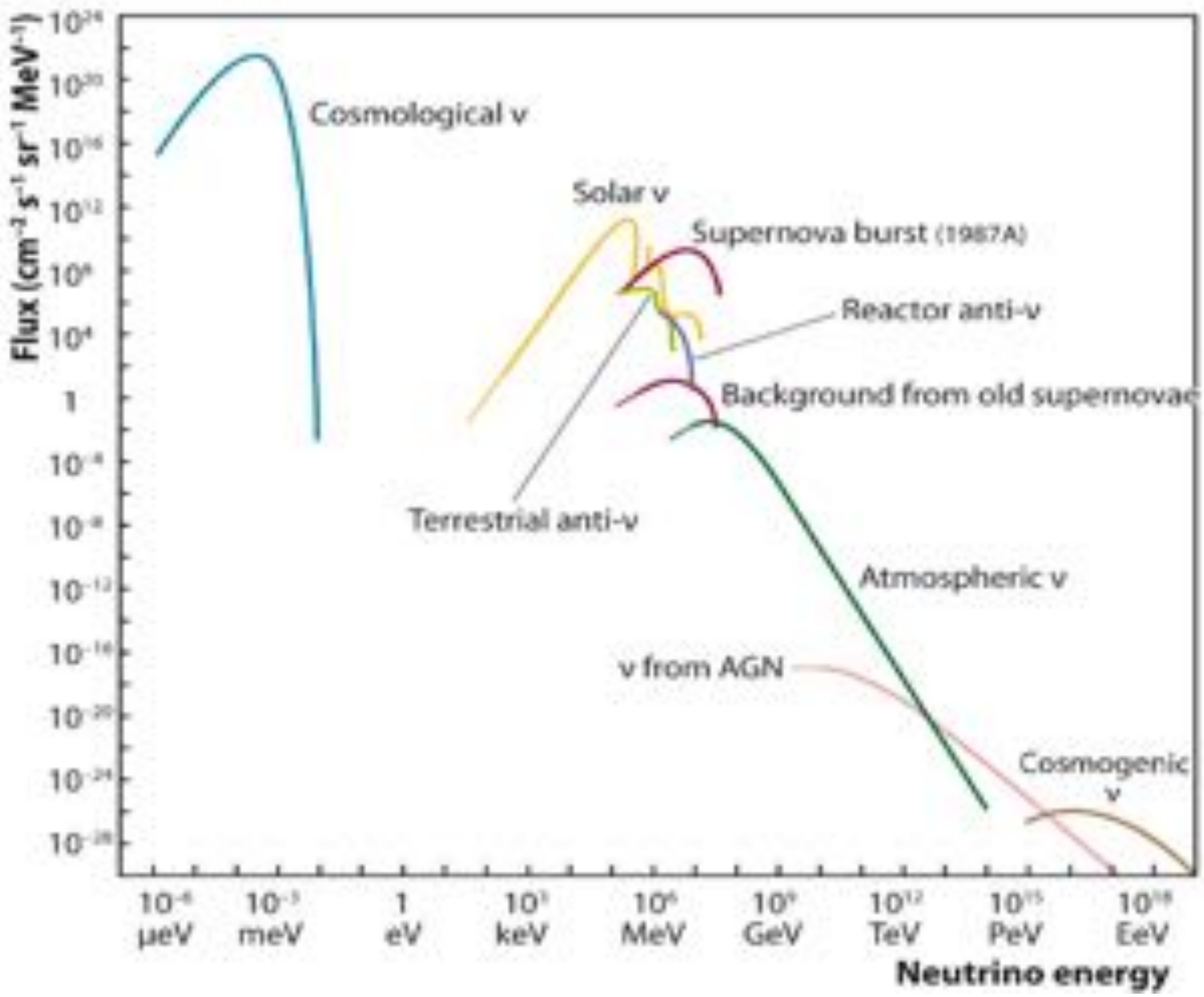


Markarian 501, farthest object observed by HAWC
Distance: ~ 140 Mpc

- Photons are excellent probes to locate astrophysical accelerators, but they are useful up to a maximum distance: the gamma-ray horizon
  - Sun – Galactic center: ~ 8 kpc, diameter ~ 50 kpc
  - Mean free path of 100 GeV's photons: ~ 1 Gpc
  - Mean free path of TeV photons : ~ 100 Mpc
  - Mean free path of PeV photons : ~ < 10 kpc

- To probe the highest energies (PeVs) we need something different…

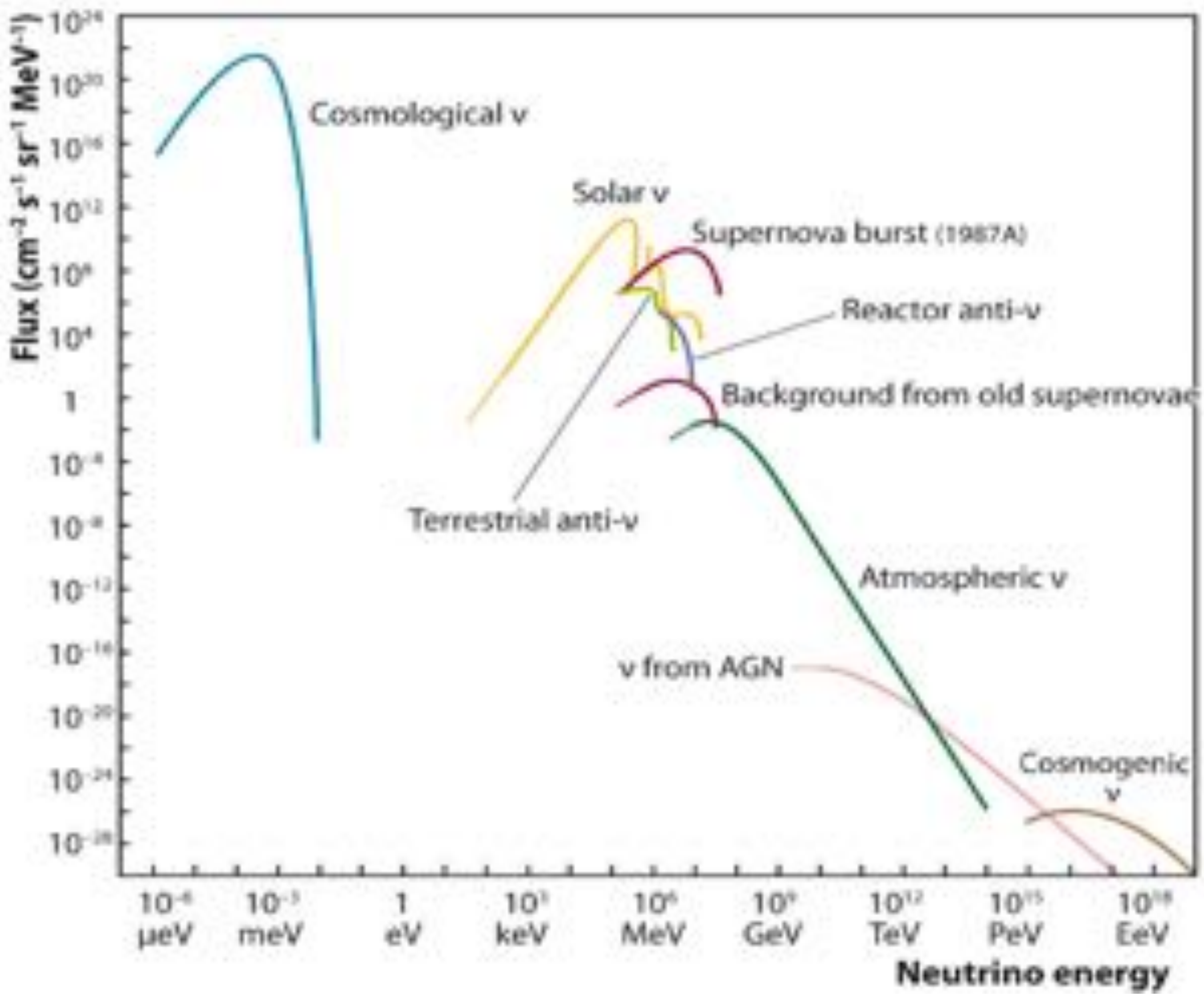
Neutrinos



Eur. Phys. J. H. 37 515-565 (2012) C. Spiering

The detection depends on:
- Flux
- Cross section

Neutrinos



Eur. Phys. J. H. 37 515-565 (2012) C. Spiering

The detection depends on:
- Flux
- Cross section

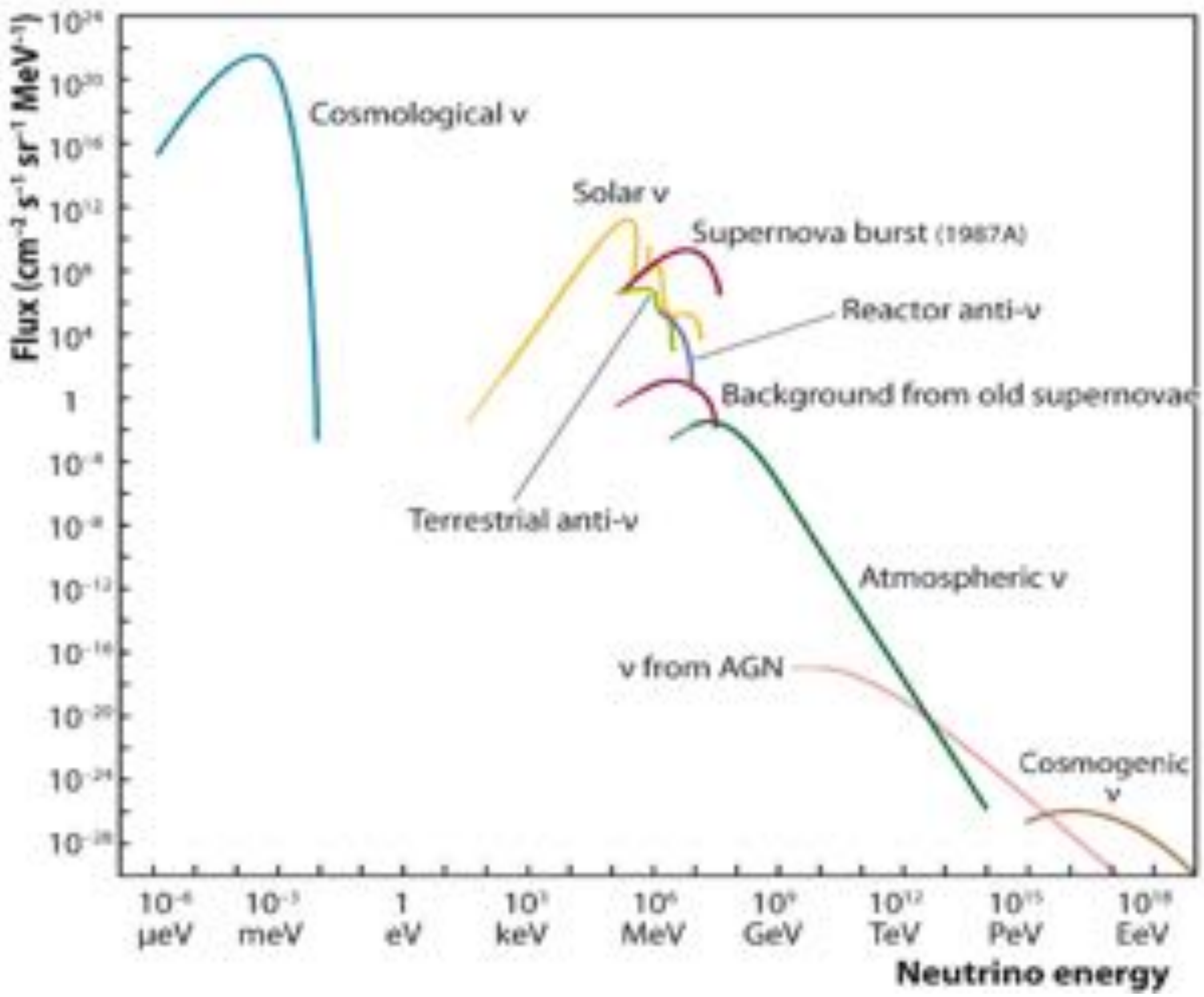
For solar neutrinos (pp)

$$^1H + ^1H \rightarrow ^2H + e^+ + \nu_e + 0.42\ MeV$$

The cross section for electron scattering:

$\sigma \sim 10^{-49}\ m^2$

Neutrinos



Eur. Phys. J. H. 37 515-565 (2012) C. Spiering

The detection depends on:
- Flux
- Cross section

Cosmogenic neutrinos
(100 PeV)

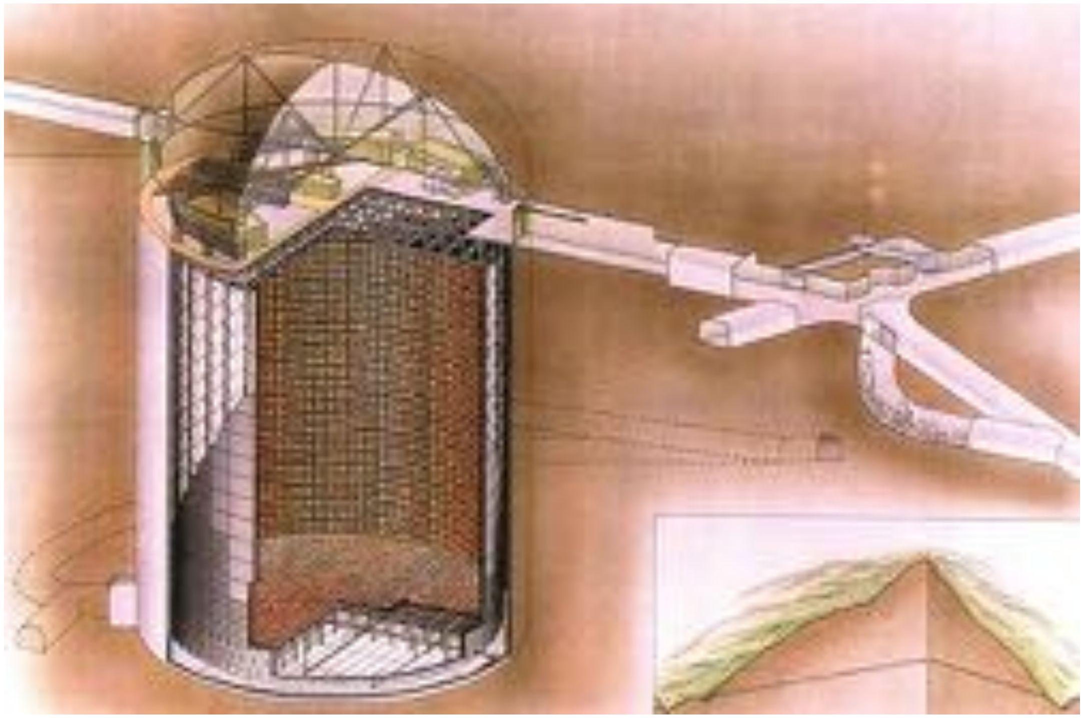
$$p + \gamma \rightarrow n + \pi^+$$

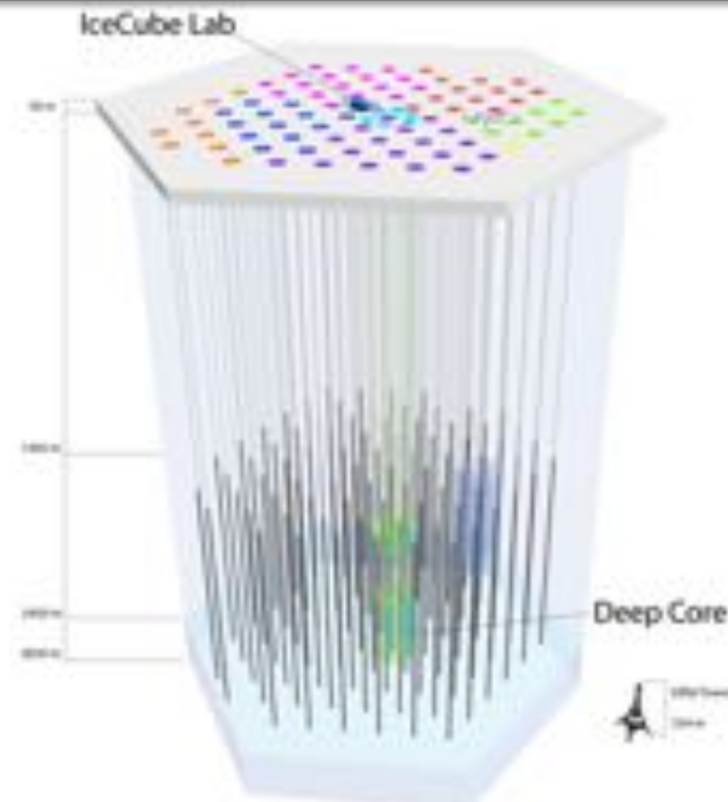
With the microwave bckg.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

σ ~ 10^{-37} m^2
But with a flux
(not very well constrained)
~10^{36} minor

Neutrino detection

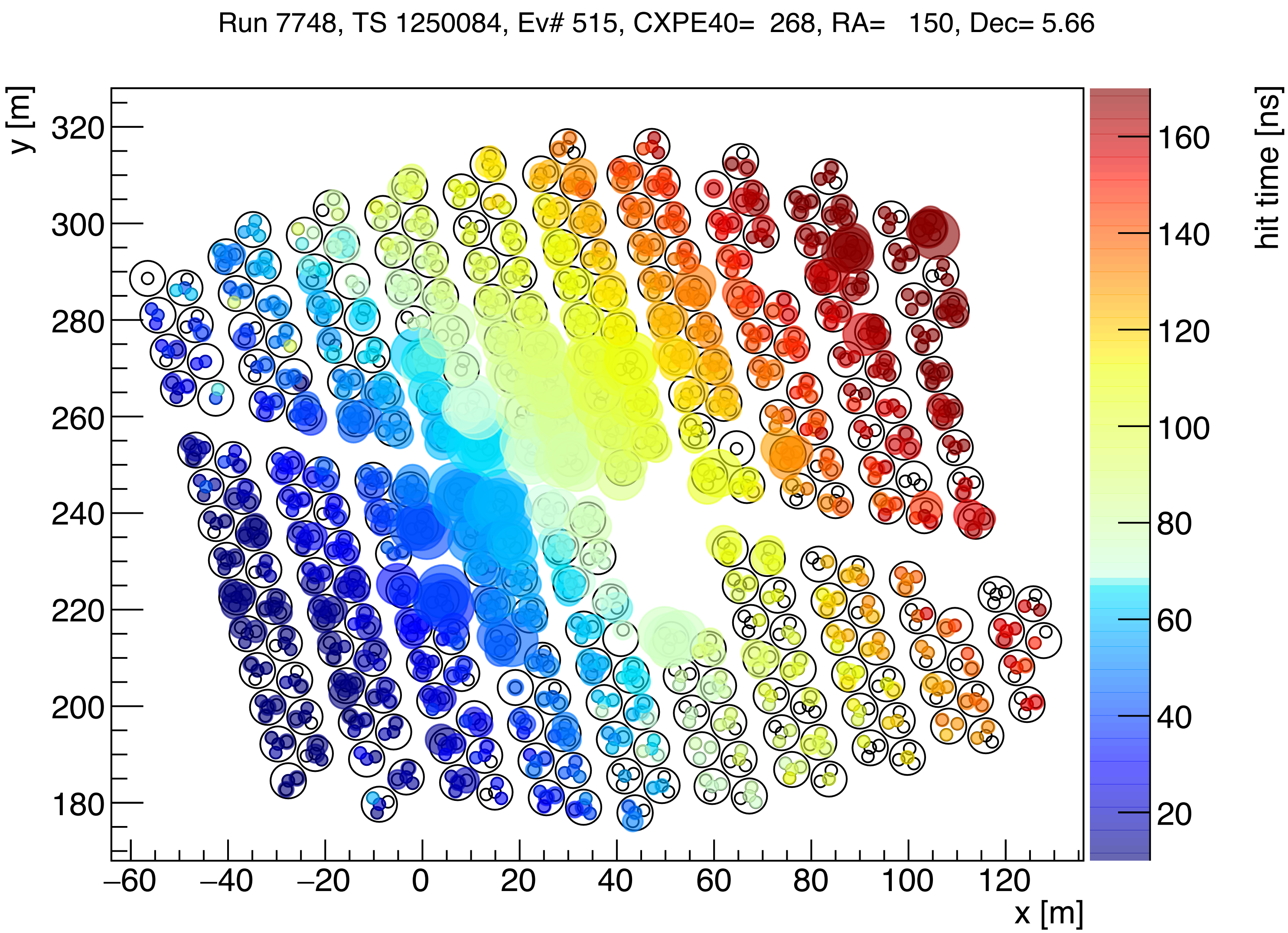




Super Kamiokande
1 km underground in Kamioka, Japan
50 million liters of water
Cost: 100 million USD

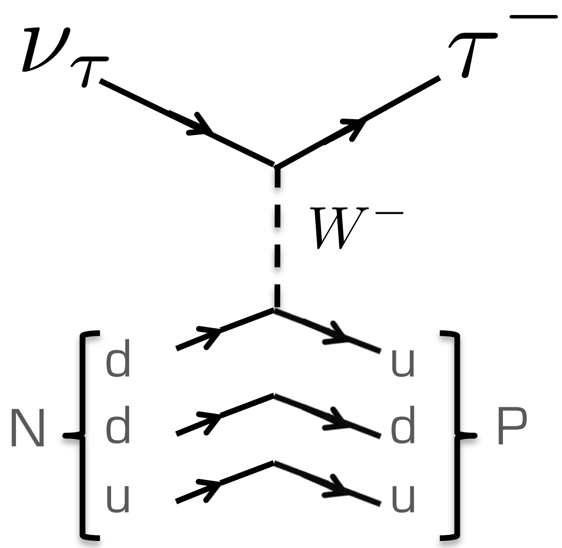
IceCube
Up to 2.8 km depth in the South Pole
1 km^3 of ice
Cost: 272 million USD

Atmospheric shower seen by HAWC



Indirect neutrino detection: Earth-skimming method

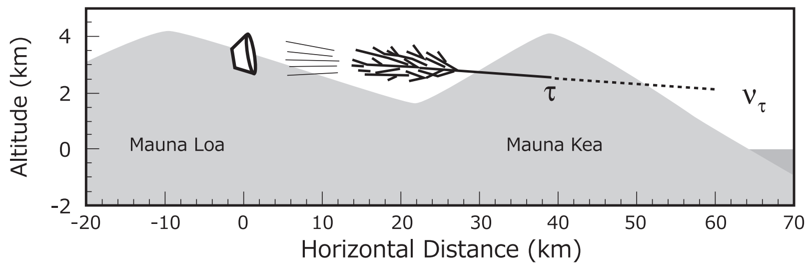
PRL 88, 161102 (2002)
J. Feng et al.

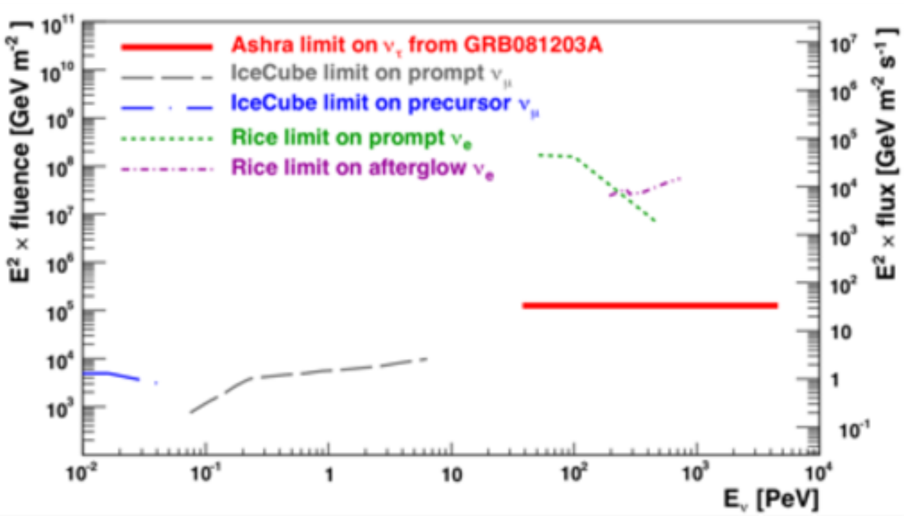


- The mountain is used as a shield for the atmospheric background
- Goal: Measure tracks produced by neutrino induced charged leptons

Examples from other experiments:

Ashra

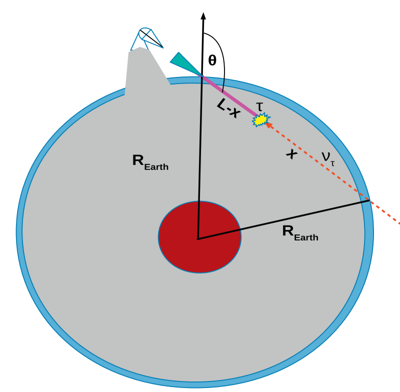




APJ 736:L12 (2011)

Observational search for PeV-EeV tau neutrino from GRB081203A

MAGIC

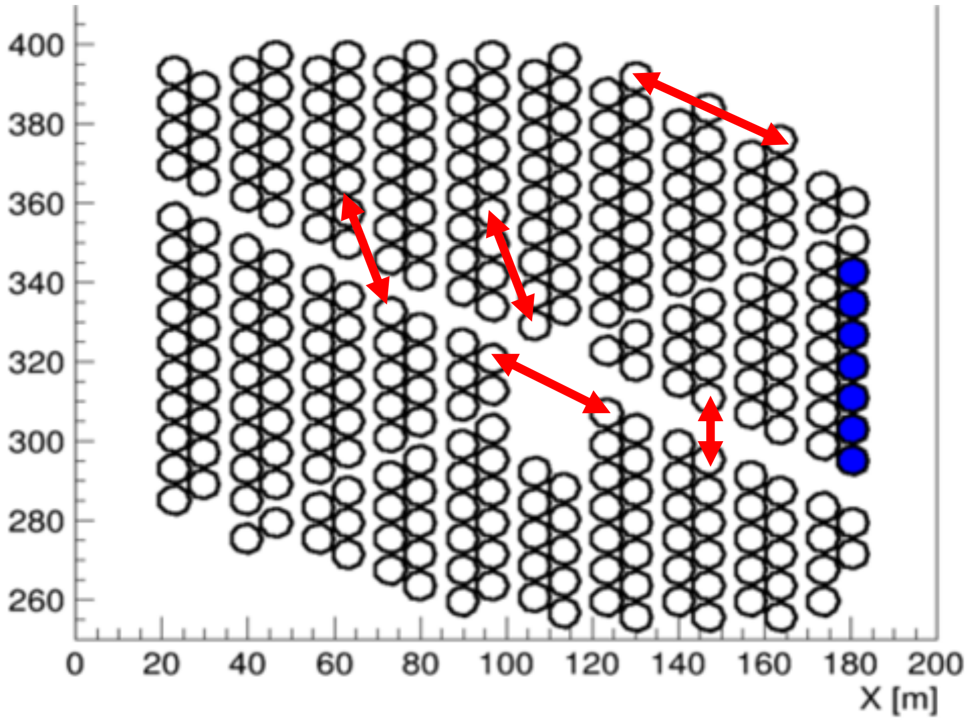


Astroparticle Physics 102 (2018) 77-88

Limits on the flux of tau neutrinos from 1 PeV to 3 EeV with the MAGIC telescopes

Using HAWC as a tracker

- Use each WCD as a pixel for track reconstruction
- Select groups of neighbor pixels with propagation between them consistent with the speed of light
- Store per pixel information (<T>, ΣPEs, NHits)



Data sample and selection cuts

Data from the shower trigger:

- 216 runs
- ~6 months of active time
- ~260 TB
- > 3.6×10^6 CPU hours

Pixel quality cuts:

- Minimum PMT charge: **4 PEs**
- Minimum PMT hits in each pixel: **2**
- Removal of pixels associated to atmospheric showers
- Isolated tracks

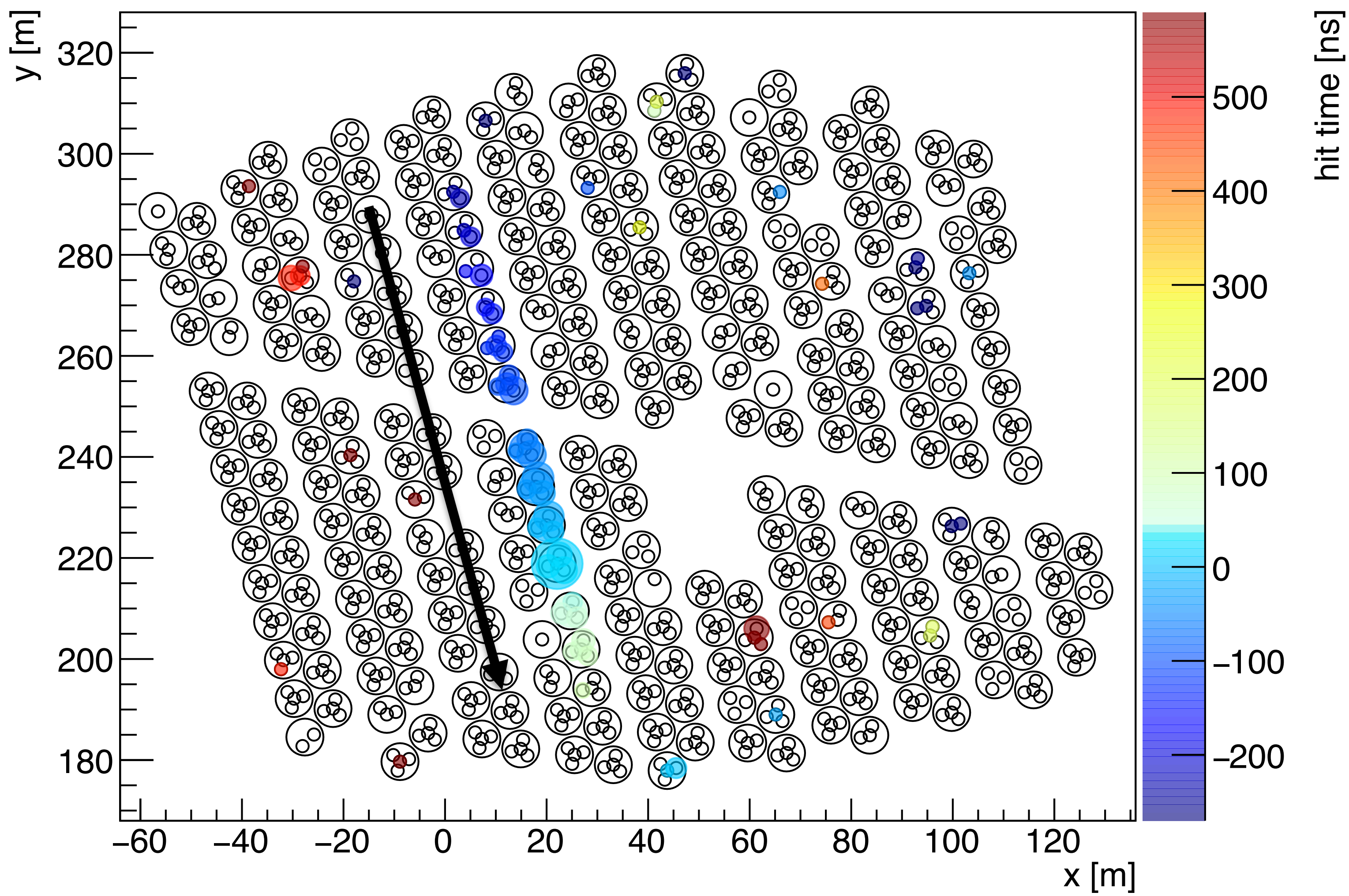
Data processing

For each two minutes (full field of view):

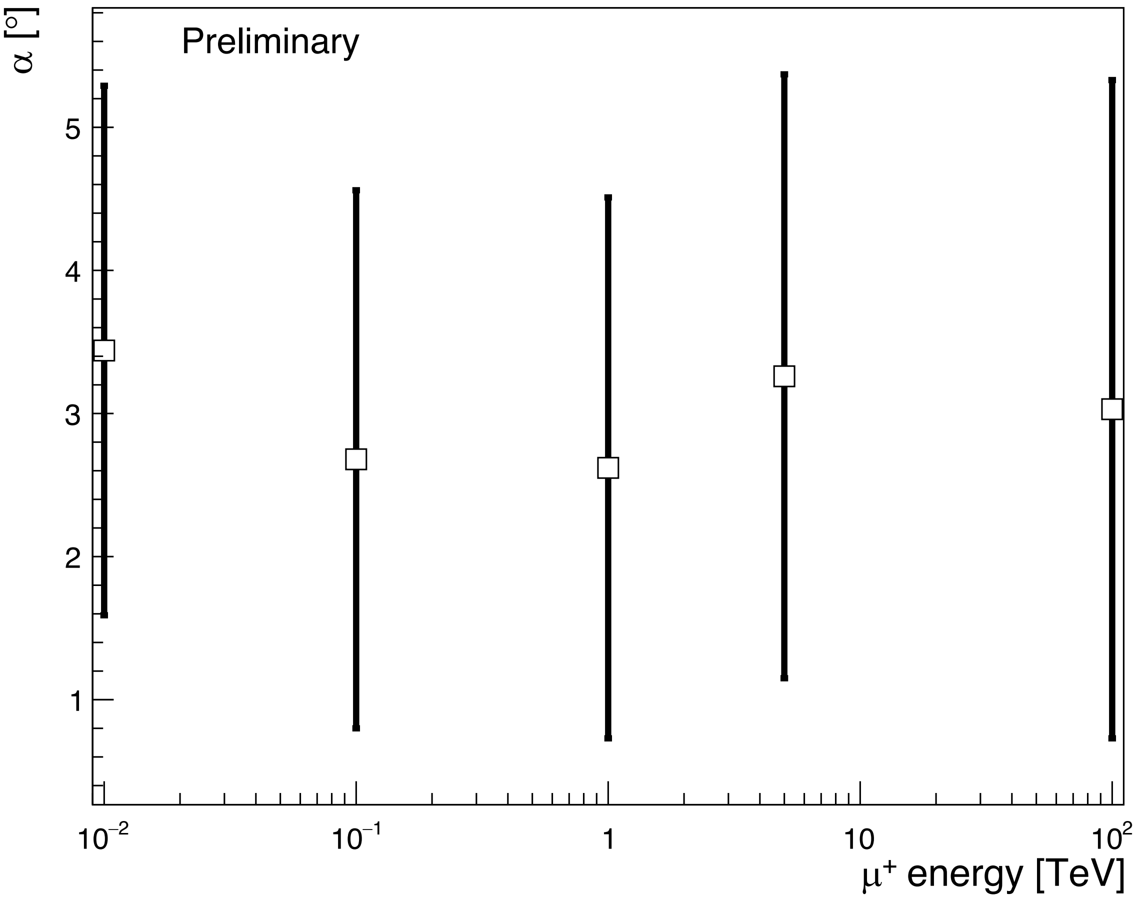
- ~2×10^6 triggers (2 neighbor pixels with signal)
- ~5×10^4 track candidates (3 neighbor pixels with propagation v ~ c)
  - Isolation cuts (reduce background)
  - Stricter relativistic propagation
- ~0.06 high quality tracks from Pico de Orizaba

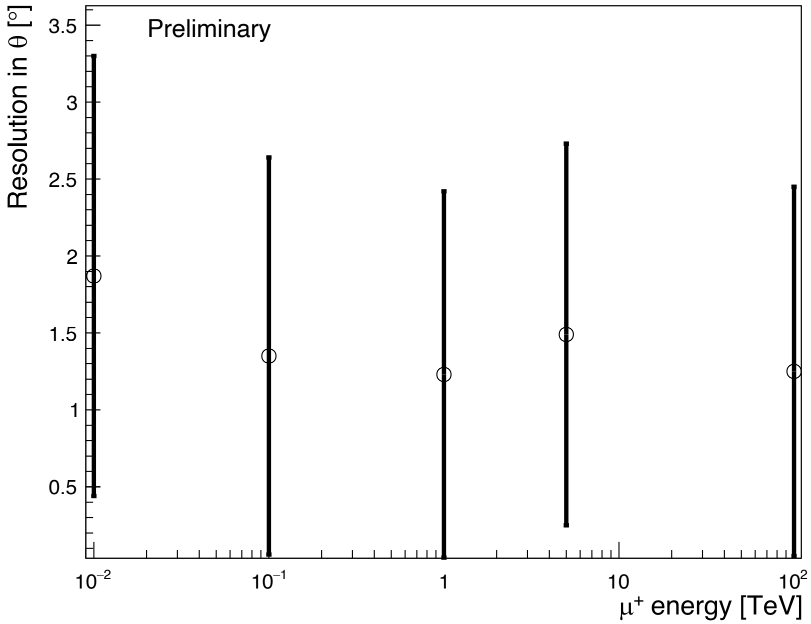
Example signals

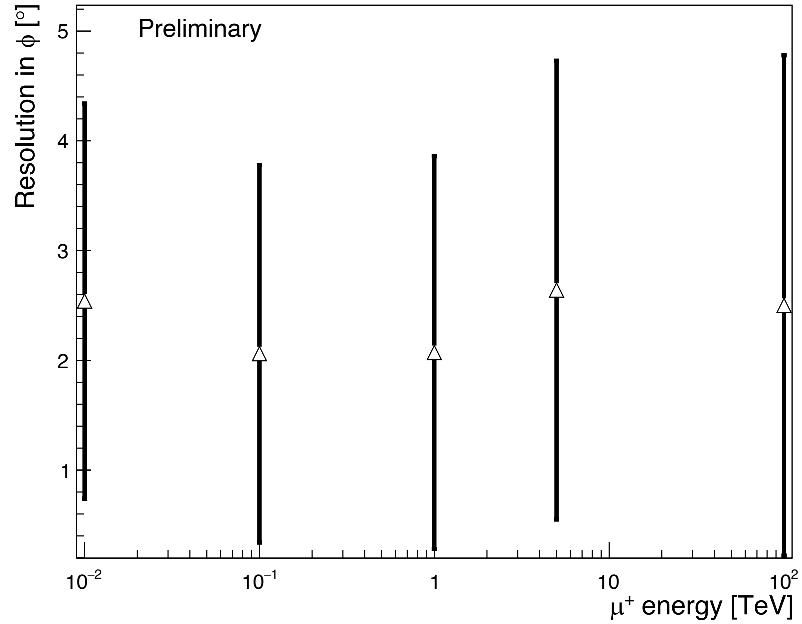
Real data: muon from northwest



Angular resolution







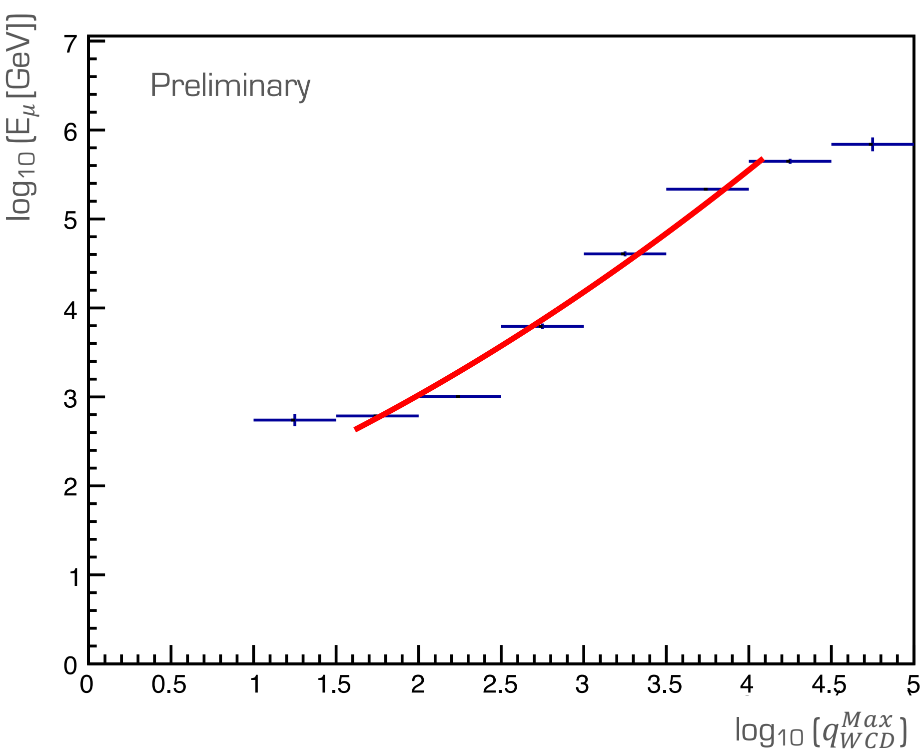
Stable angular resolution in the energy range [10 GeV – 100 TeV]

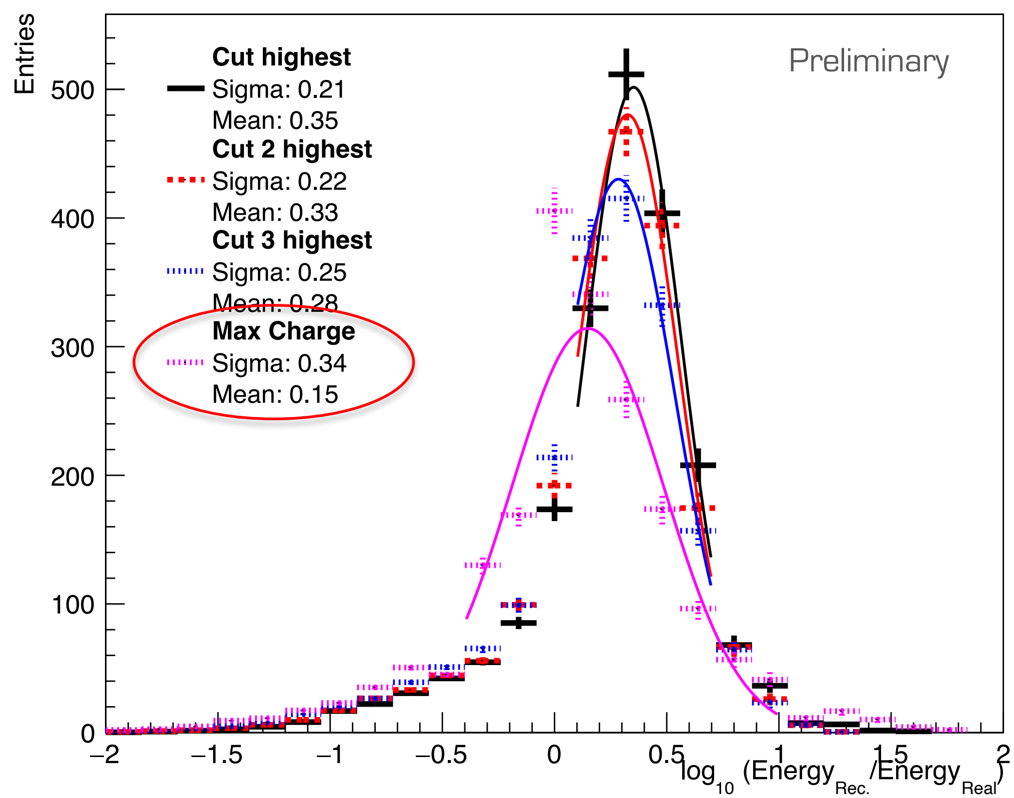
Developing an energy estimator

Adapt the method developed by IceCube[1]

$$\left(\frac{dE}{dx}\right) \approx f_{scale} \times q_{WCD} \qquad log(E_\mu) = A + B \times log(\frac{dE}{dx}) + C \times log^2(\frac{dE}{dx})$$

- Simpler to implement due to the opticall isolation of detector units and their dimensions
- q_{WCD} = the largest charge deposit in a 10 inch PMT

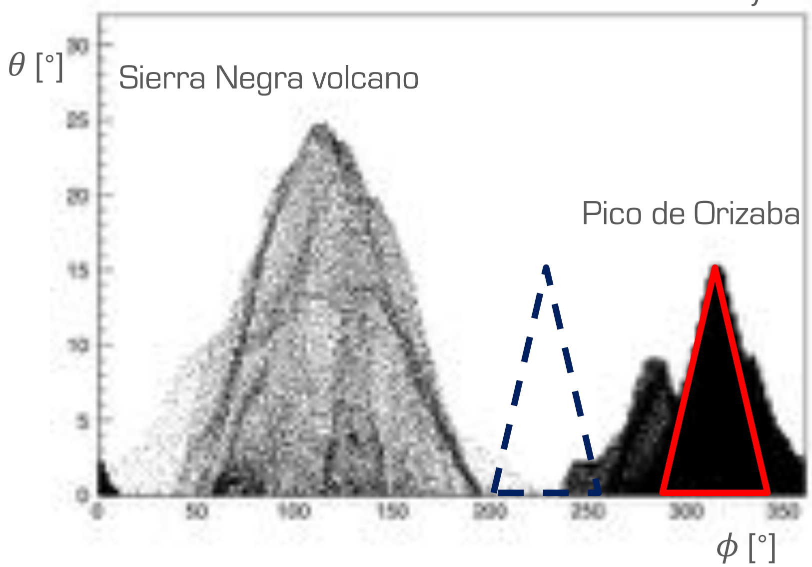


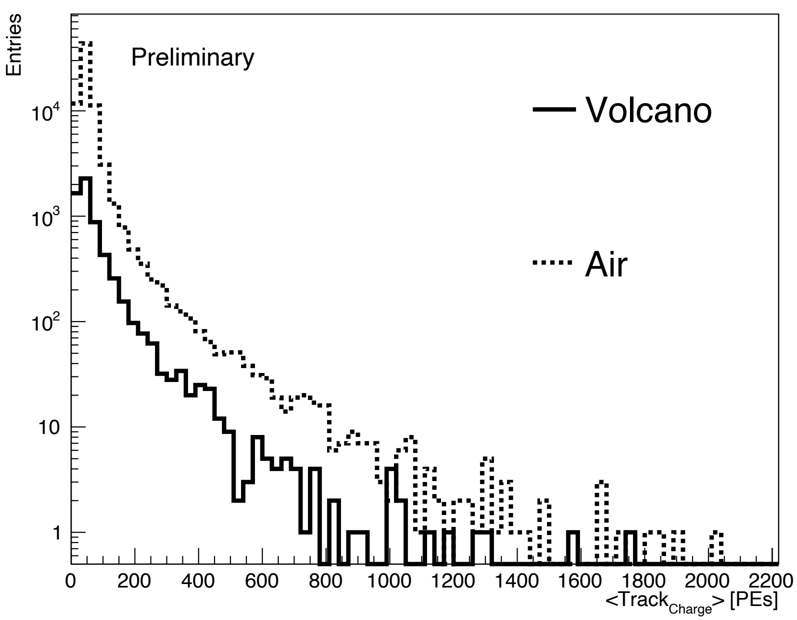


[1]An improved method for measuring muon energy using the truncated mean of dE/dx, NIM A 703 (2013)

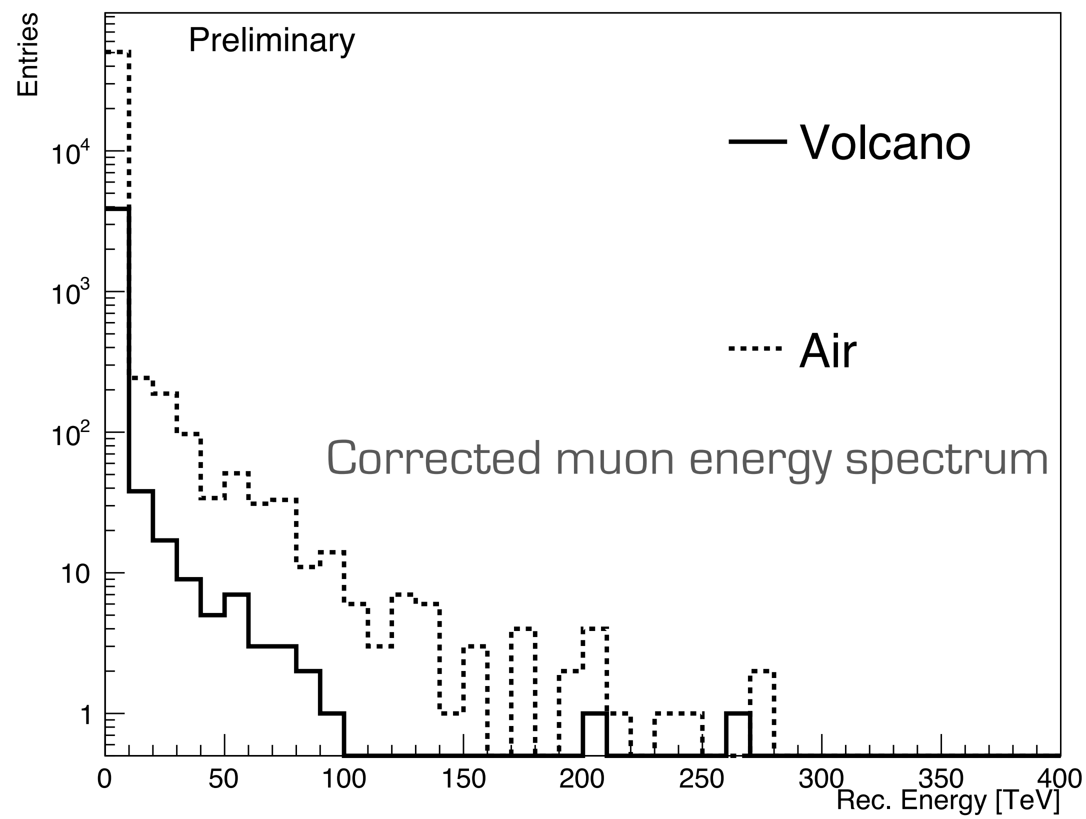
Calibration of the energy estimator

Horizon from the center of the detector array



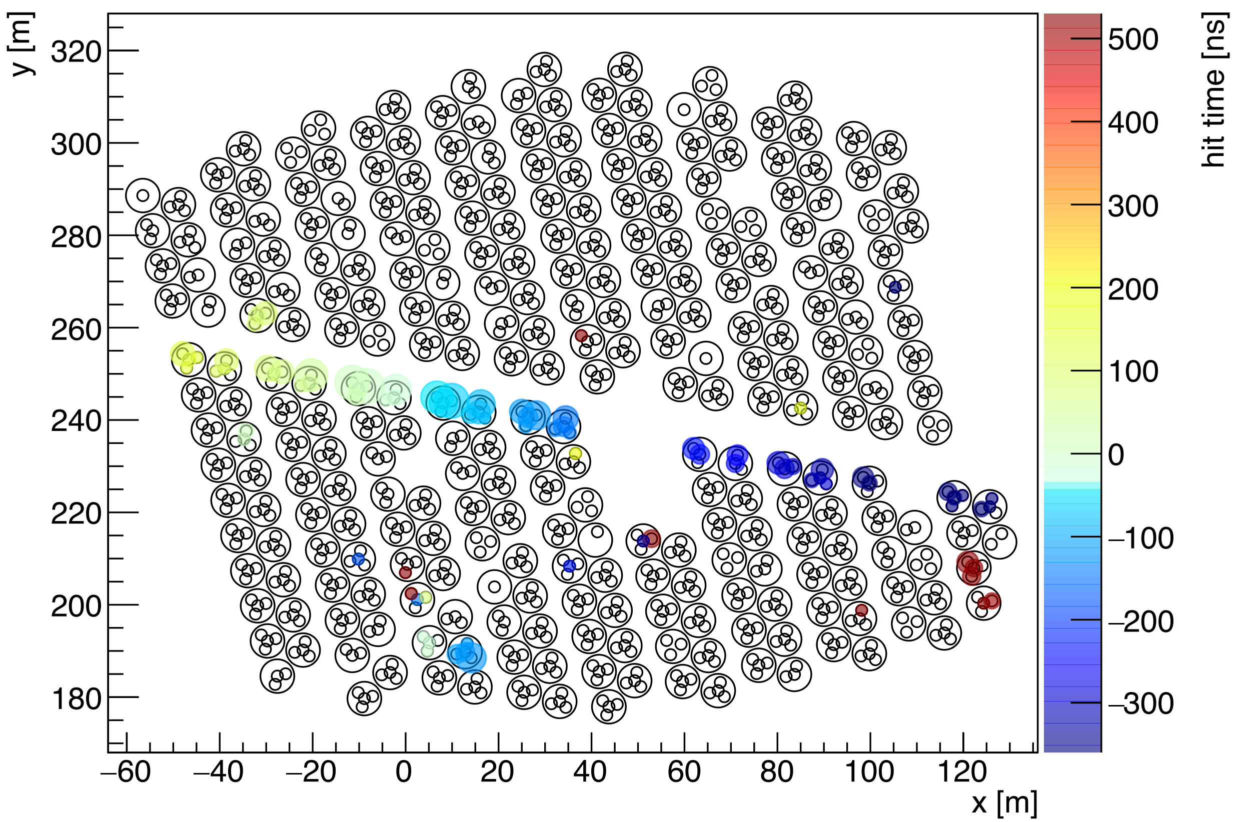


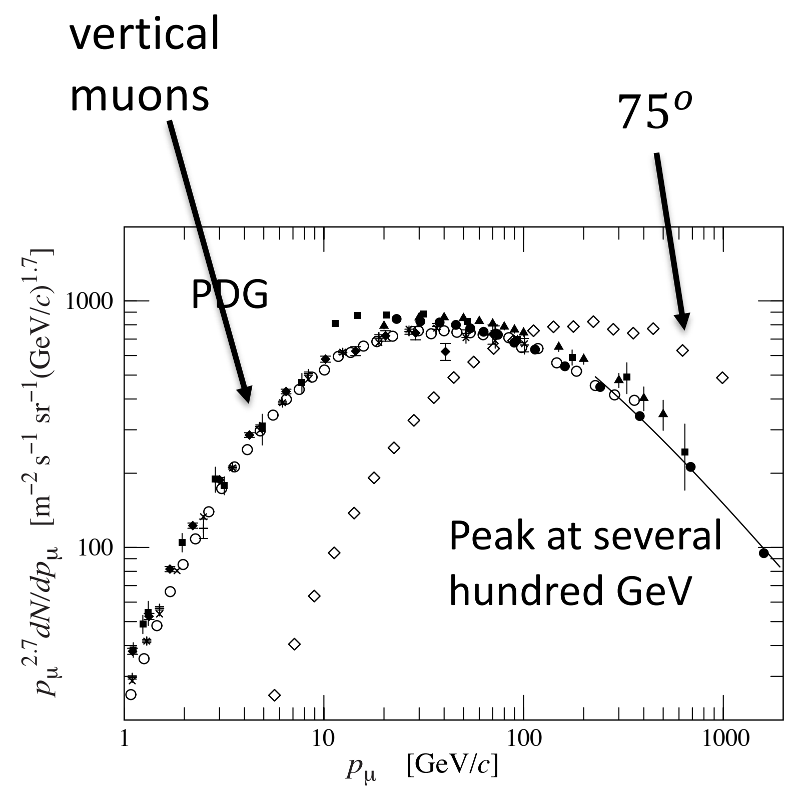
We use the measurements from a region without volcano to calibrate the signals, using the known spectral index[1,2,3]: ~3.7



[1] Atmospheric muon and neutrino fluxes at very high energy, Astroparticle Physics 34 (2011) 663-673
[2] PDG, Chin. Phys. C. 40 (2016) 100001
[3] Characterization of the atmospheric muon flux in IceCube, Astroparticle Physics 78 (2016) 1-27

Horizontal muon from East

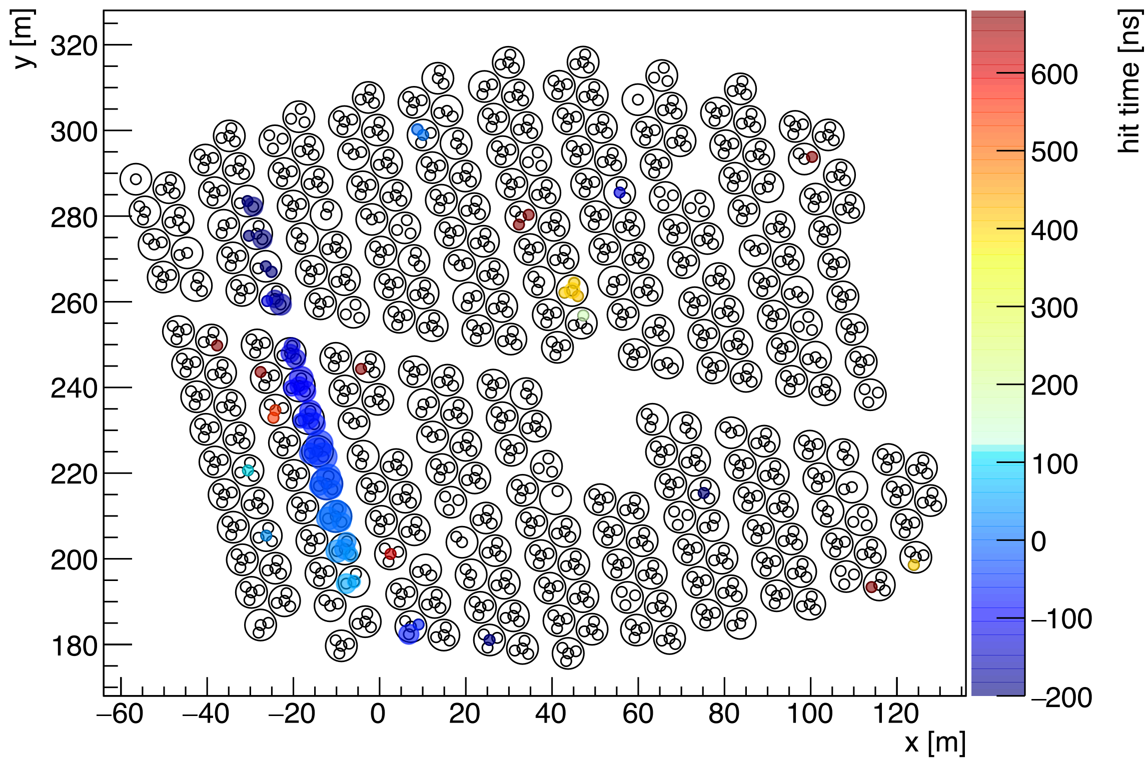


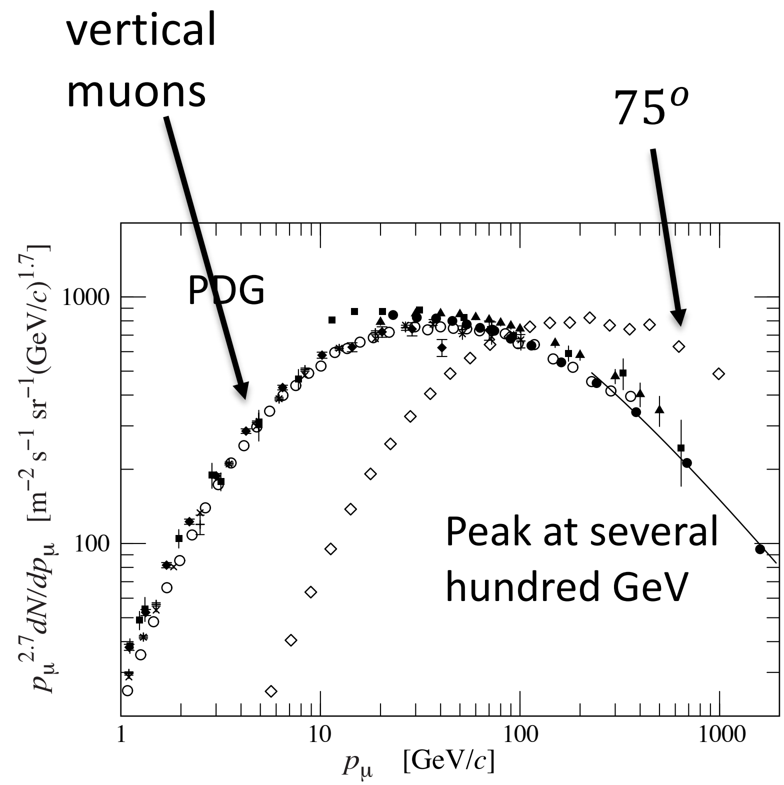


Estimated energy [TeV]
$0.4^{+0.4}_{-0.2}$

ϕ [°]	θ [°]
10.3 ± 2.3	0.5 ± 1.4

Long track from West

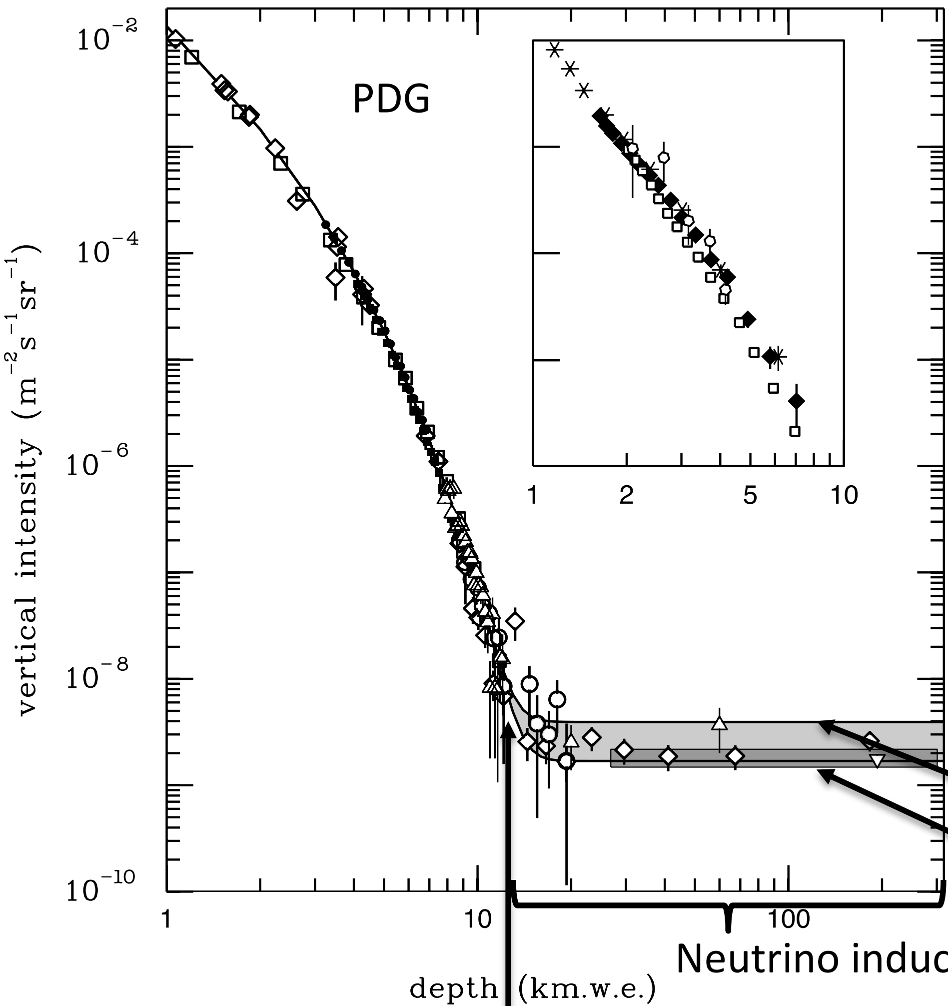


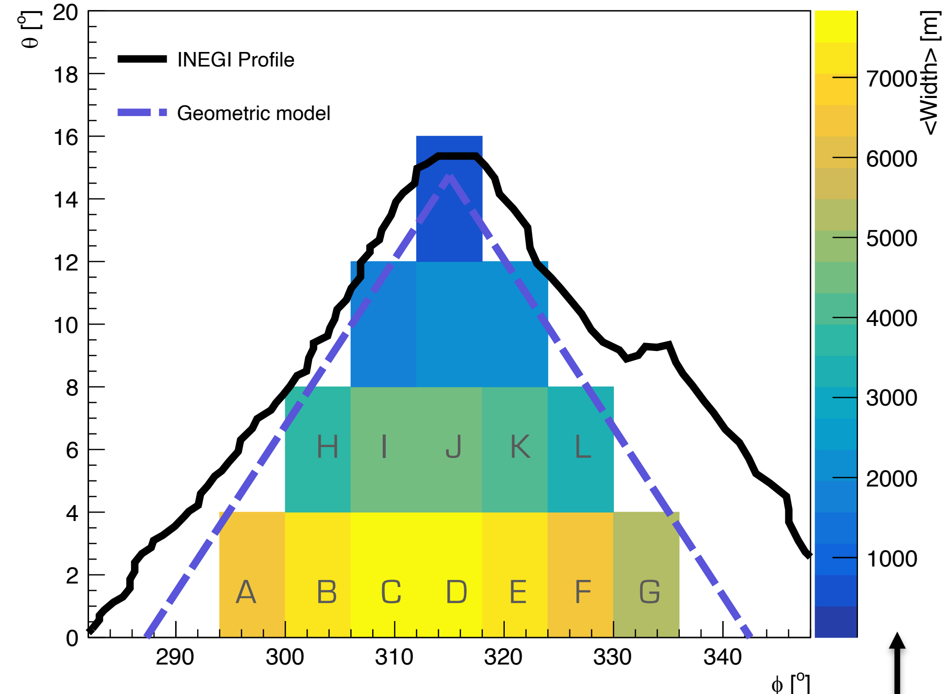


Estimated energy [TeV]
$0.7^{+0.8}_{-0.4}$

ϕ [°]	θ [°]
254.4 ± 2.3	1.3 ± 1.4

Muon intensity vs depth





Horizontal neutrino induced muons

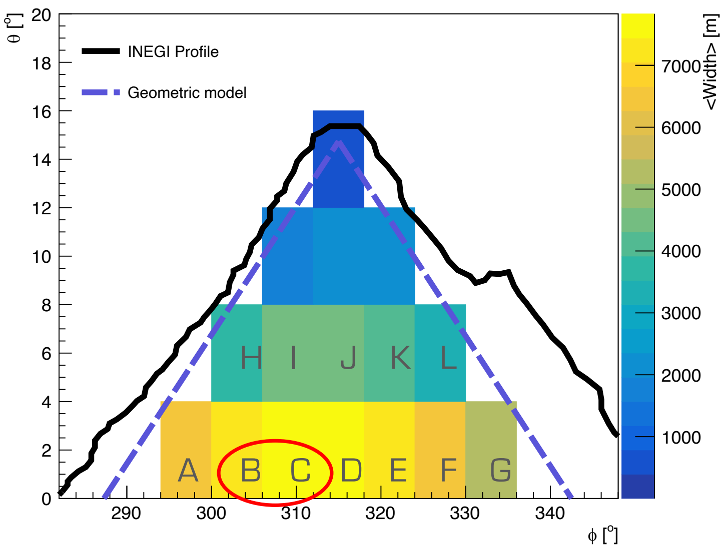
Vertically upward muons

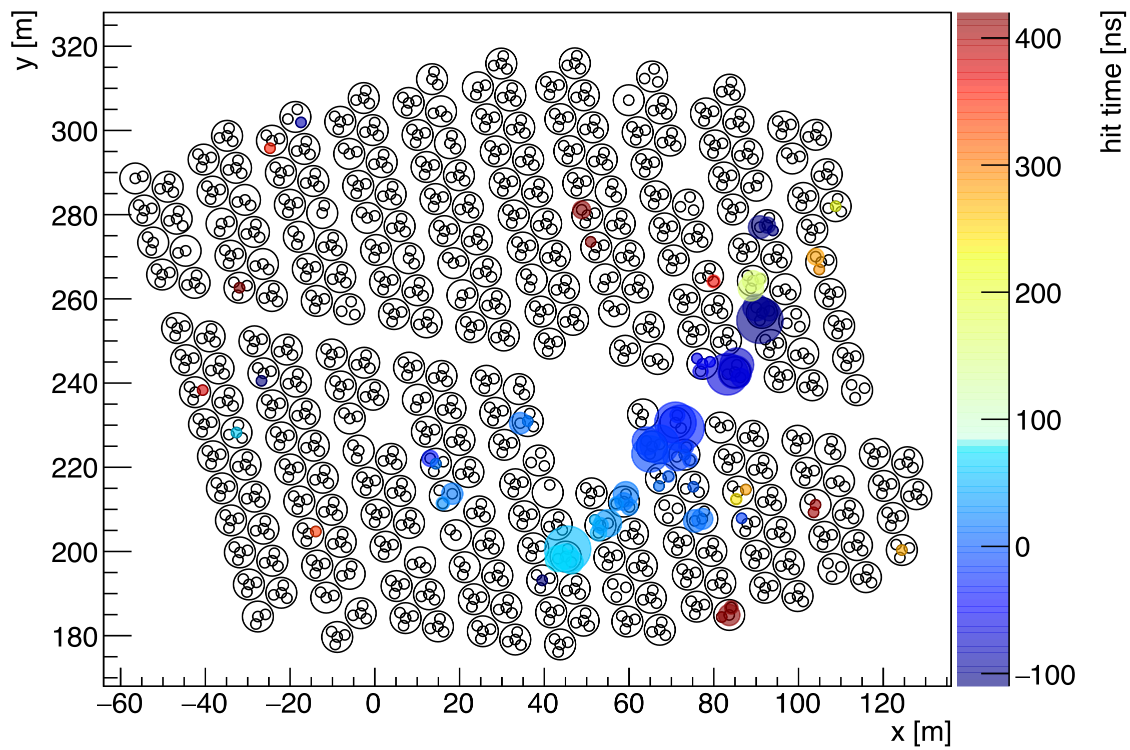
Neutrino induced muons above 2 GeV

Neutrino induced muons start just above 10 km.w.e.

Average distance traveled inside the volcano

Track from Citlaltepetl (I)





ϕ [°]	θ [°]
308.6 ± 2.3	1.1 ± 1.4

between the energy $E_{\mu,0}$ of a muon at production in the atmosphere and its average energy E_μ after traversing a thickness X of rock (or ice or water):

PDG

$$E_{\mu,0} = (E_\mu + \epsilon)\, e^{bX} - \epsilon \,. \tag{30.6}$$

<Overburden> [Km.w.e.]
~ 20

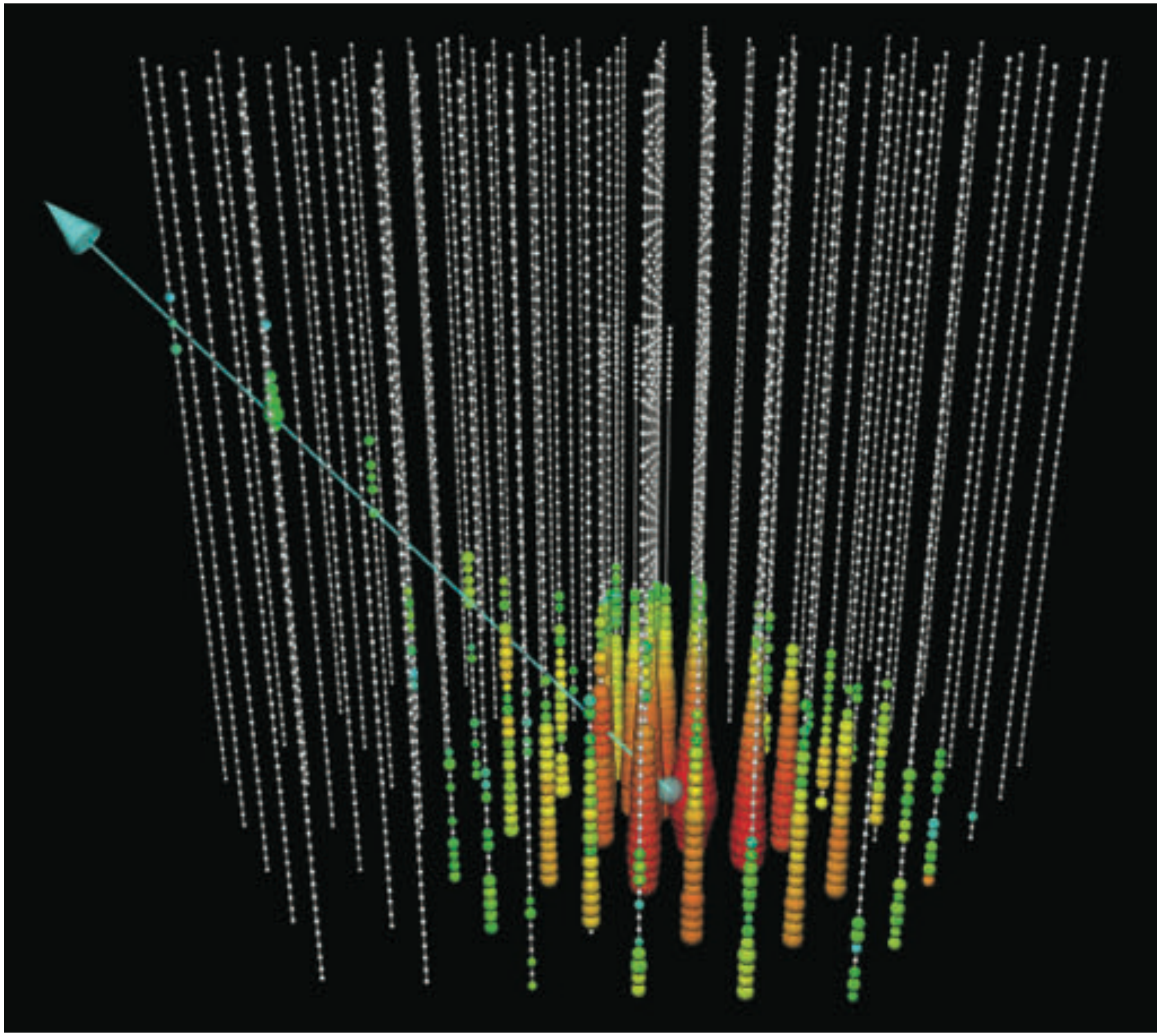
Estimated energy [TeV]
$1.7^{+2.0}_{-0.9}$

If using the minimum energy (800 GeV):

Initial muon energy: ~ 25 PeV

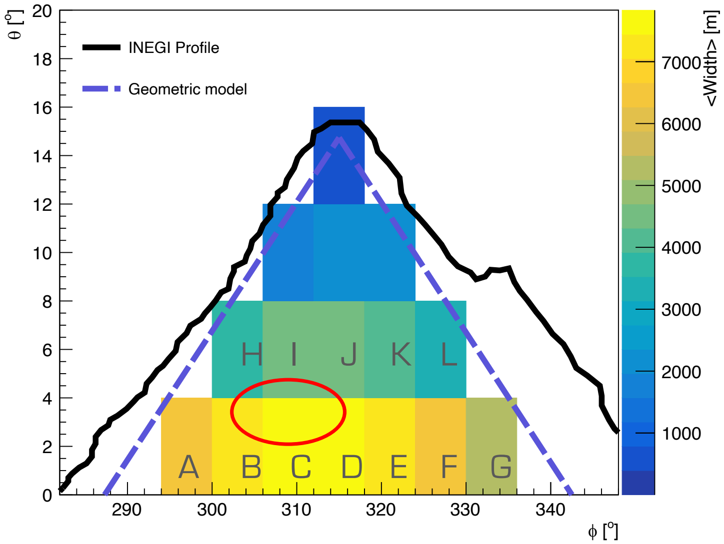
Expected signals above 5 PeV: < 0.00005

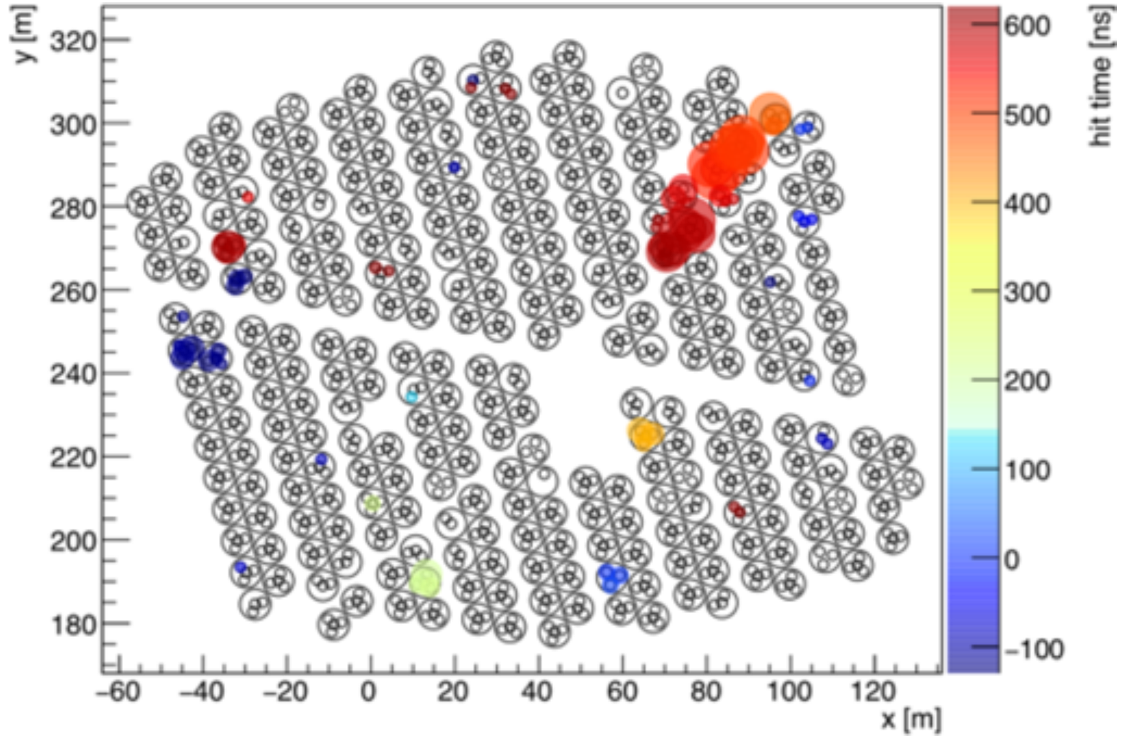
IceCube neutrino



250 TeV neutrino interaction with a muon

Track from Citlaltepetl (II)





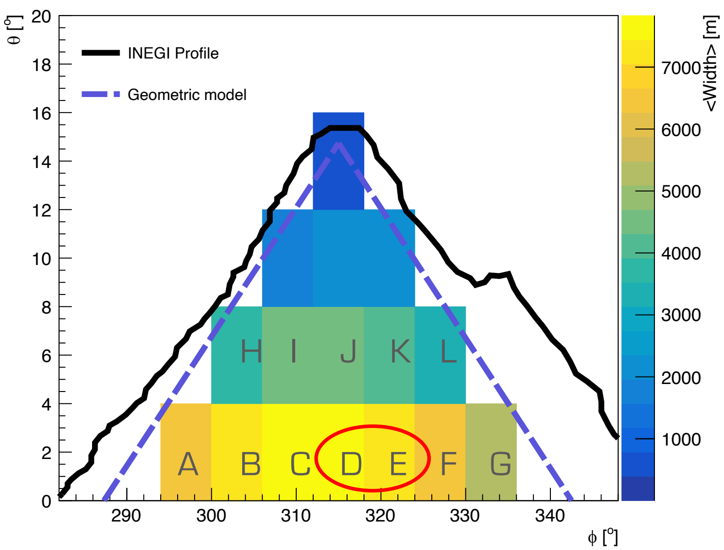
ϕ [°]	θ [°]
309.1 ± 2.3	3.5 ± 1.4

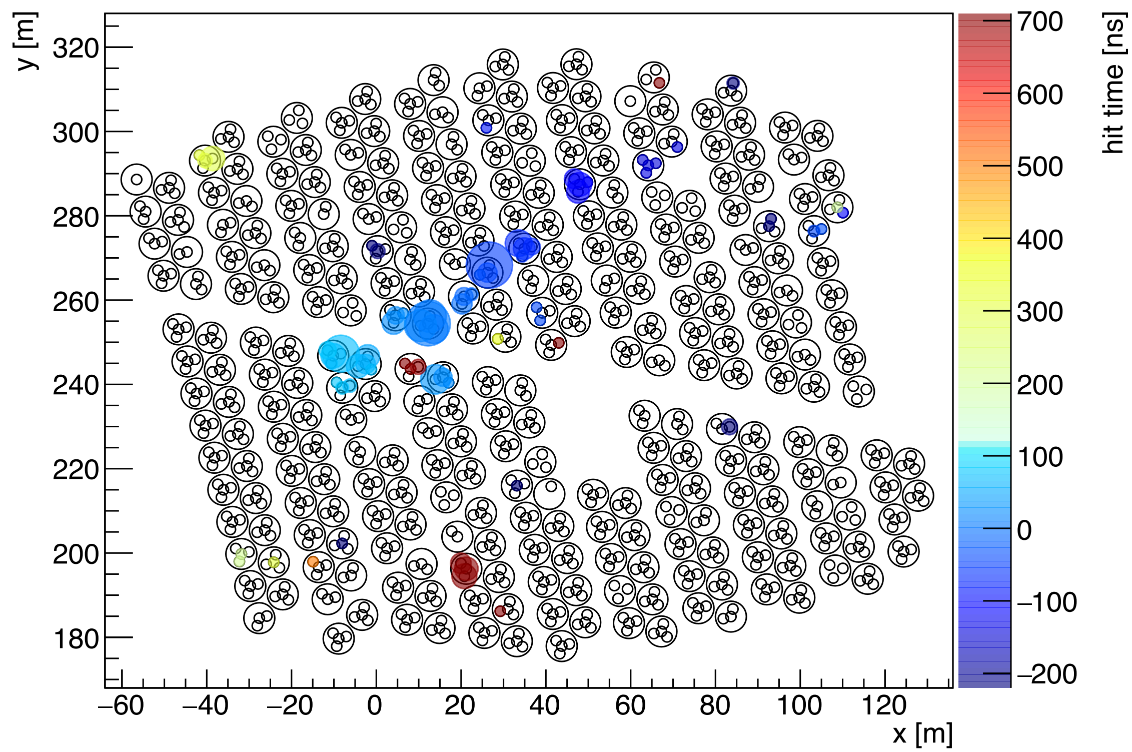
<Overburden> [Km.w.e.]
~ 20

Estimated energy [TeV]
$19.0^{+22.6}_{-10.3}$

If using the minimum energy (8.7 TeV):
Initial muon energy: ~ 176 PeV
Expected signals above 5 PeV: < 0.00005

Track from Citlaltepetl (III)





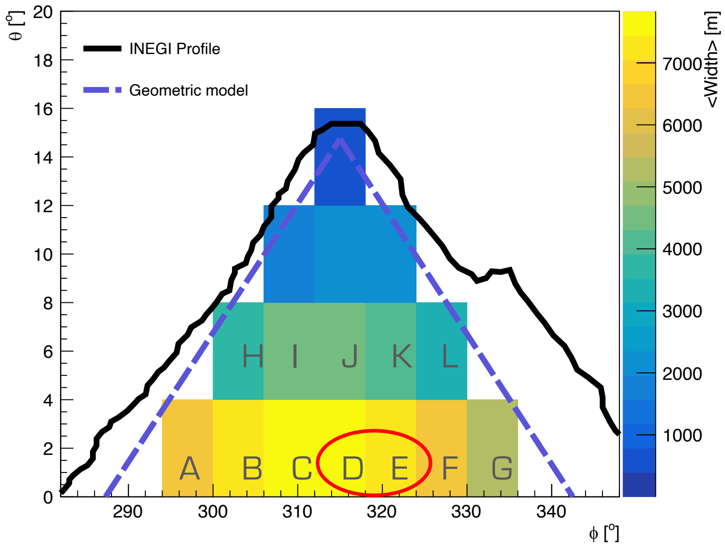
ϕ [°]	θ [°]
319.3 ± 2.3	1.2 ± 1.4

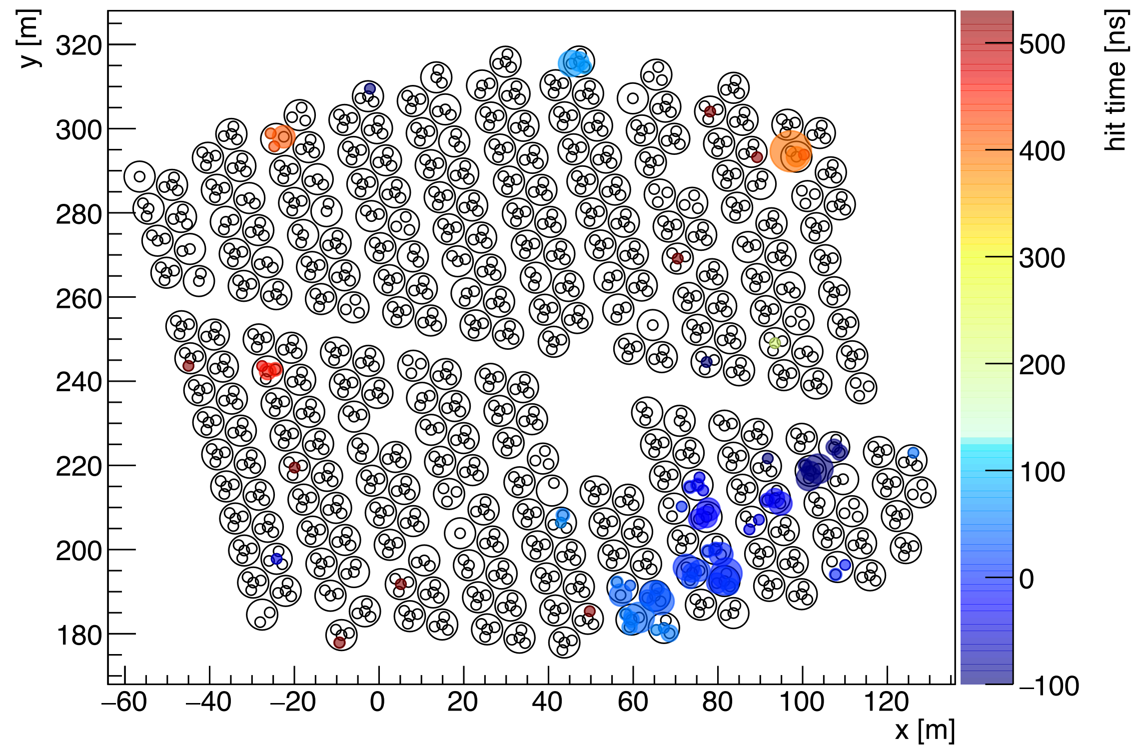
<Overburden> [Km.w.e.]
~ 18

Estimated energy [TeV]
$2.2^{+2.6}_{-1.2}$

If using the minimum energy (1.0 TeV):
Initial muon energy: ~ 15 PeV
Expected signals above 5 PeV: < 0.00005

Track from Citlaltepetl (IV)





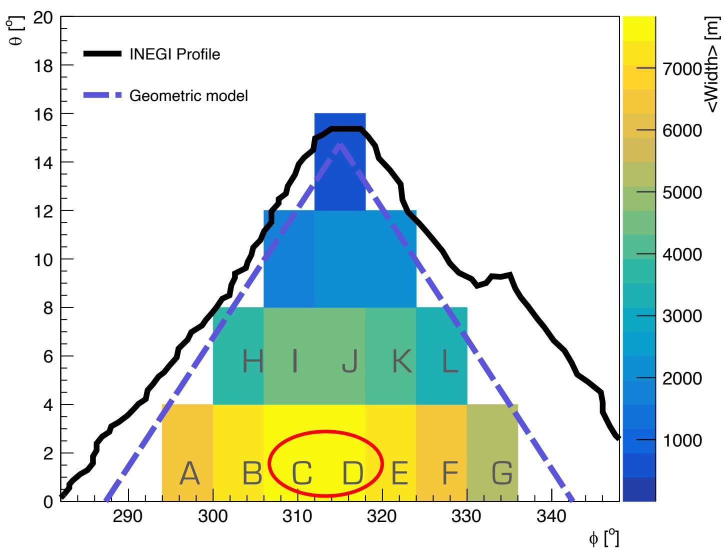
ϕ [°]	θ [°]
319.4 ± 2.3	1.3 ± 1.4

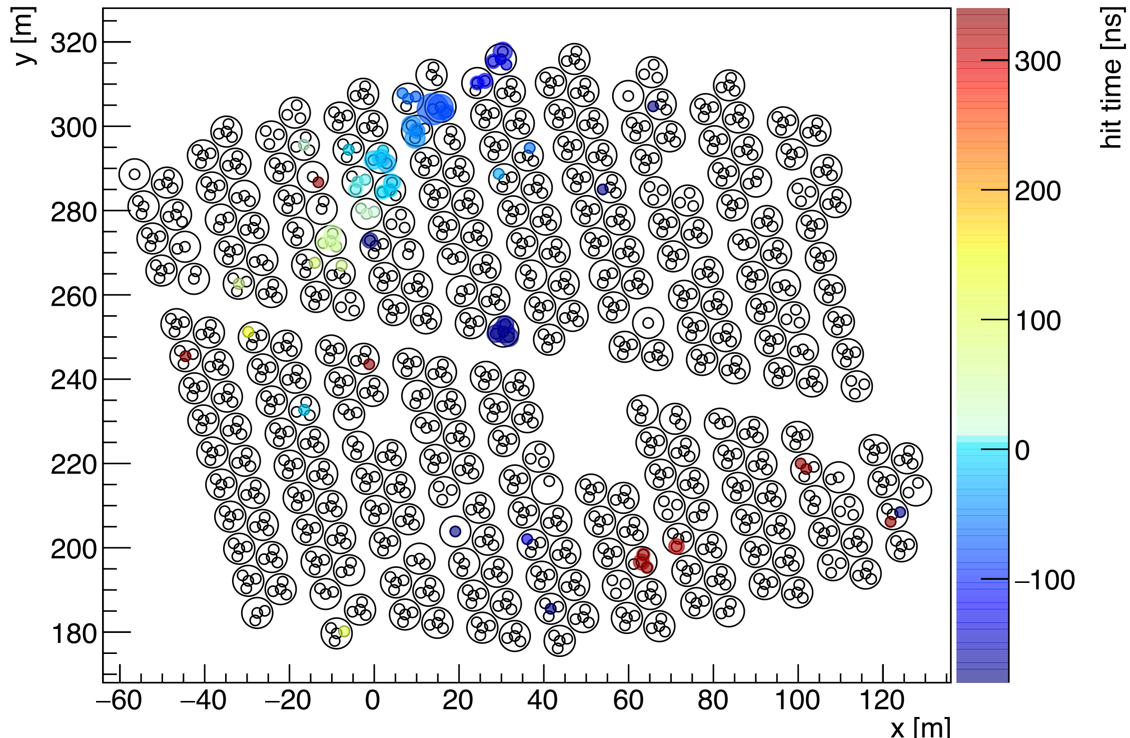
<Overburden> [Km.w.e.]
~ 18

Estimated energy [TeV]
$0.6^{+0.7}_{-0.3}$

If using the minimum energy (300 GeV):
Initial muon energy: ~ 8 PeV
Expected signals above 5 PeV: < 0.00005

Track from Citlaltepetl (V)





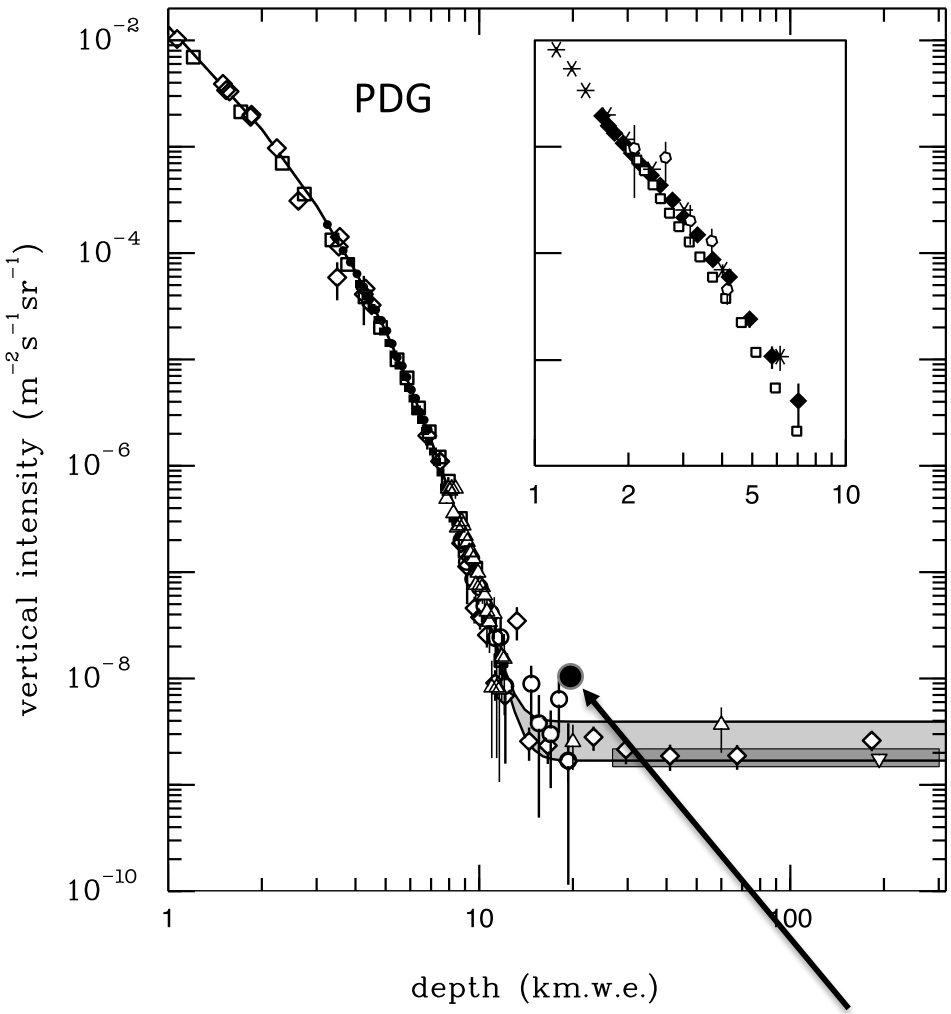
ϕ [°]	θ [°]
312.9 ± 2.3	1.5 ± 1.4

<Overburden> [Km.w.e.]
~ 20

Estimated energy [TeV]
$0.3^{+0.4}_{-0.2}$

If using the minimum energy (100 GeV):
Initial muon energy: ~ 11 PeV
Expected signals above 5 PeV: < 0.00005

Muon intensity vs depth



HAWC (preliminary)
approximate value: $\sim 3 \times 10^{-8}$

Conclusions

- We are working on a non conventional analysis with HAWC: the indirect search of very high energy neutrinos using the Earth-skimming method
- The method works and it was not necessary to implement a new trigger, the shower trigger is enough
- First candidate signals that could be associated to atmospheric neutrinos
- Plan to use transport codes of leptons through rock to improve the results
- New results coming soon