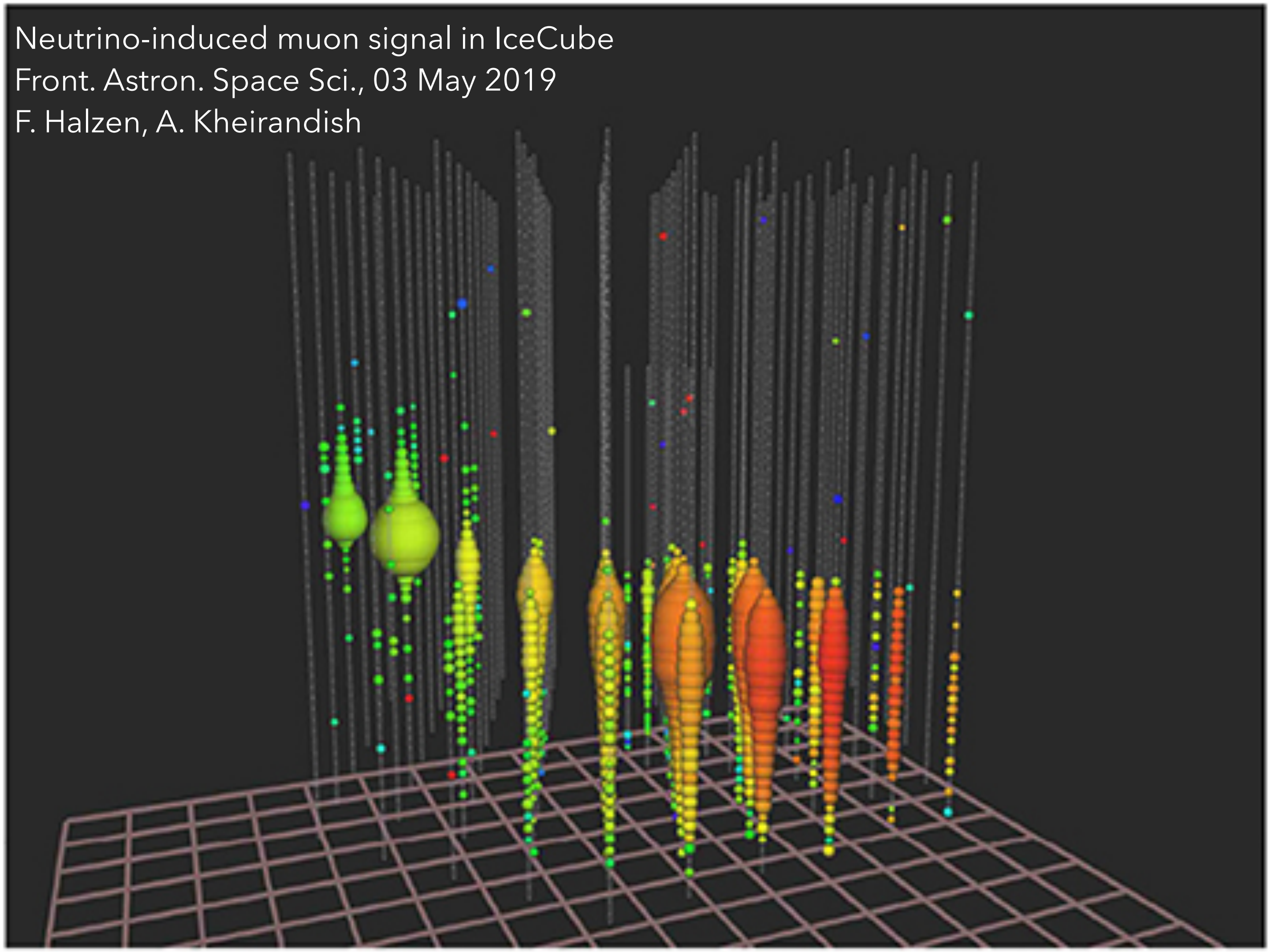
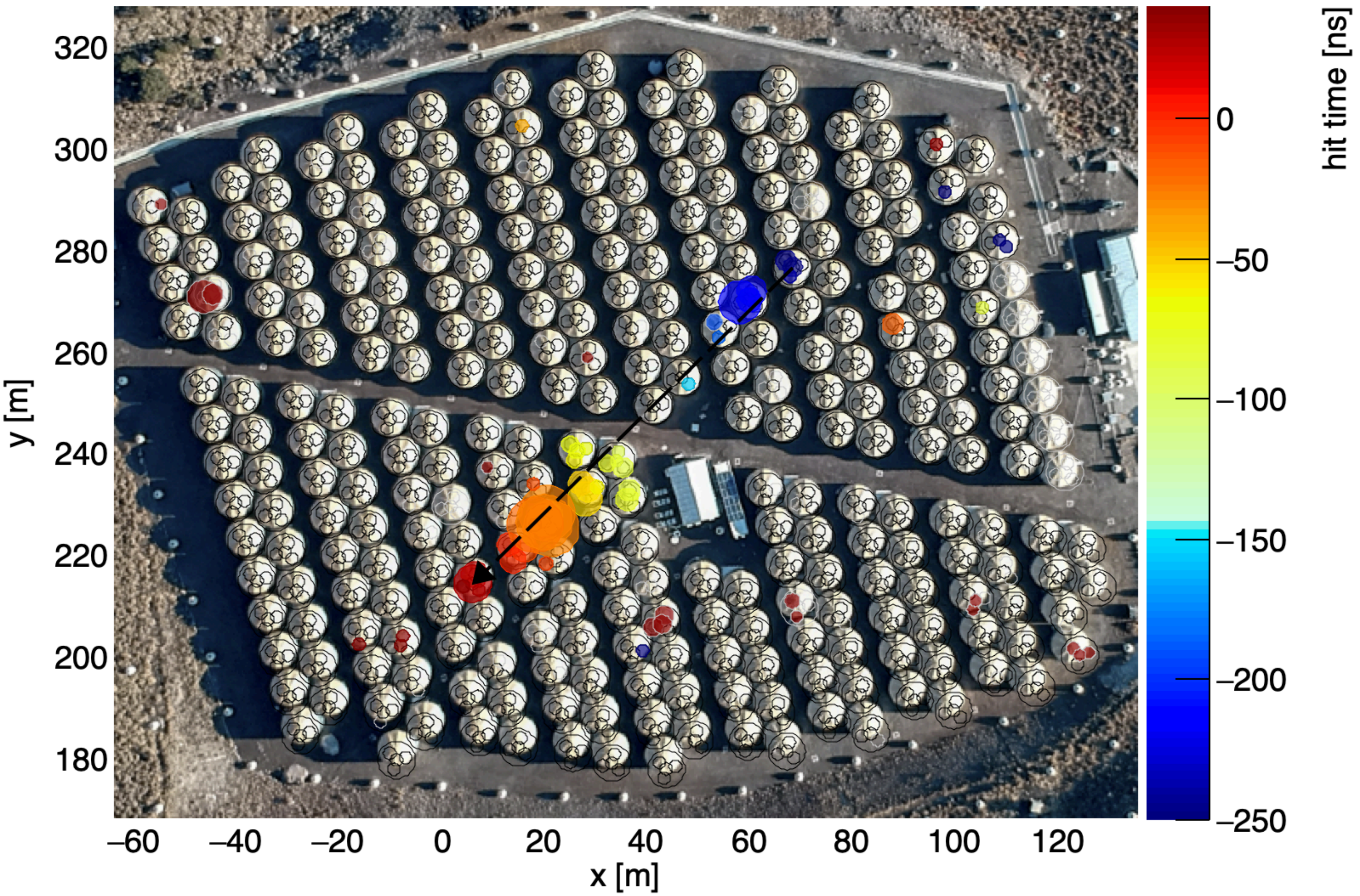

Neutrino-induced muon signal in IceCube
Front. Astron. Space Sci., 03 May 2019
F. Halzen, A. Kheirandish

Neutrino search with the HAWC observatory

Hermes León Vargas
XVIII Mexican Workshop on Particles and Fields
November 23, 2022

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory



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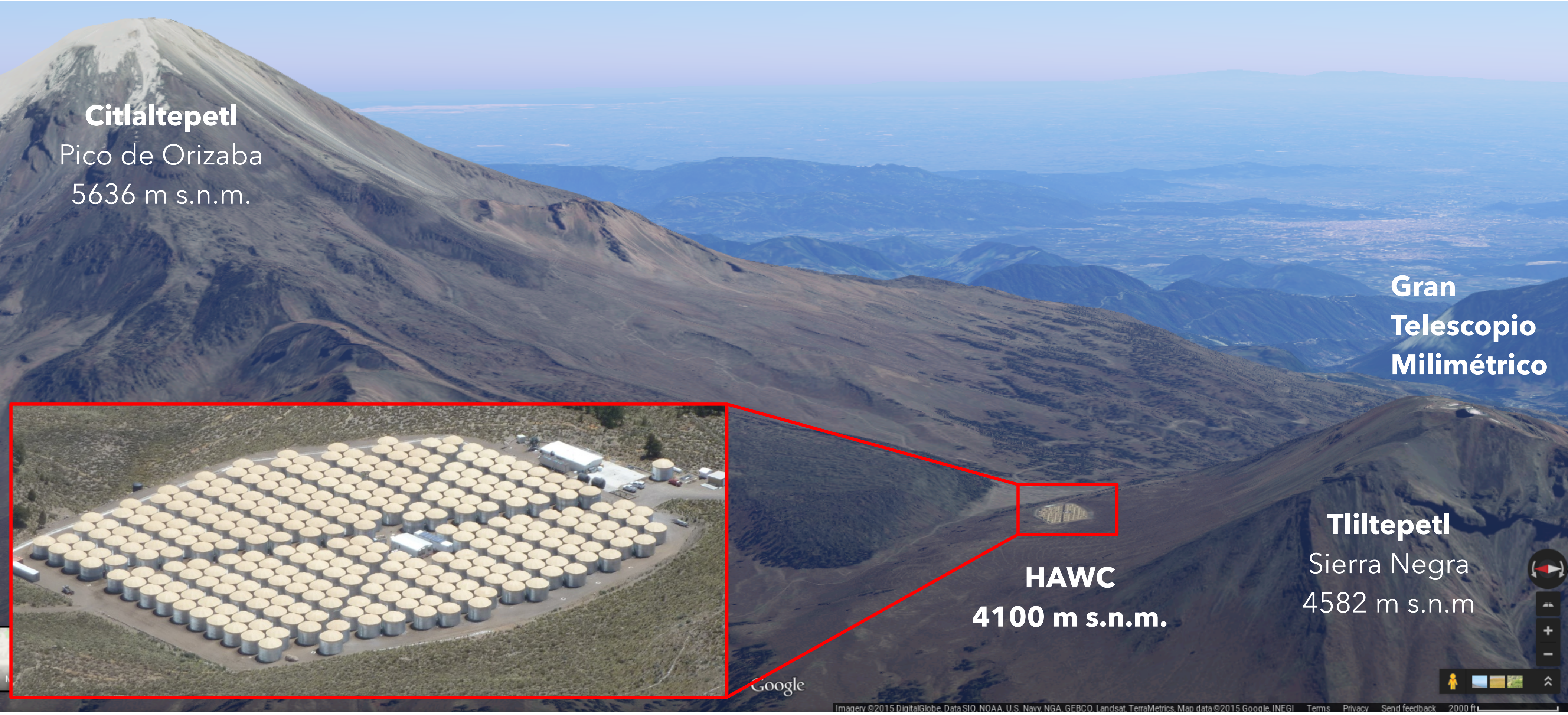
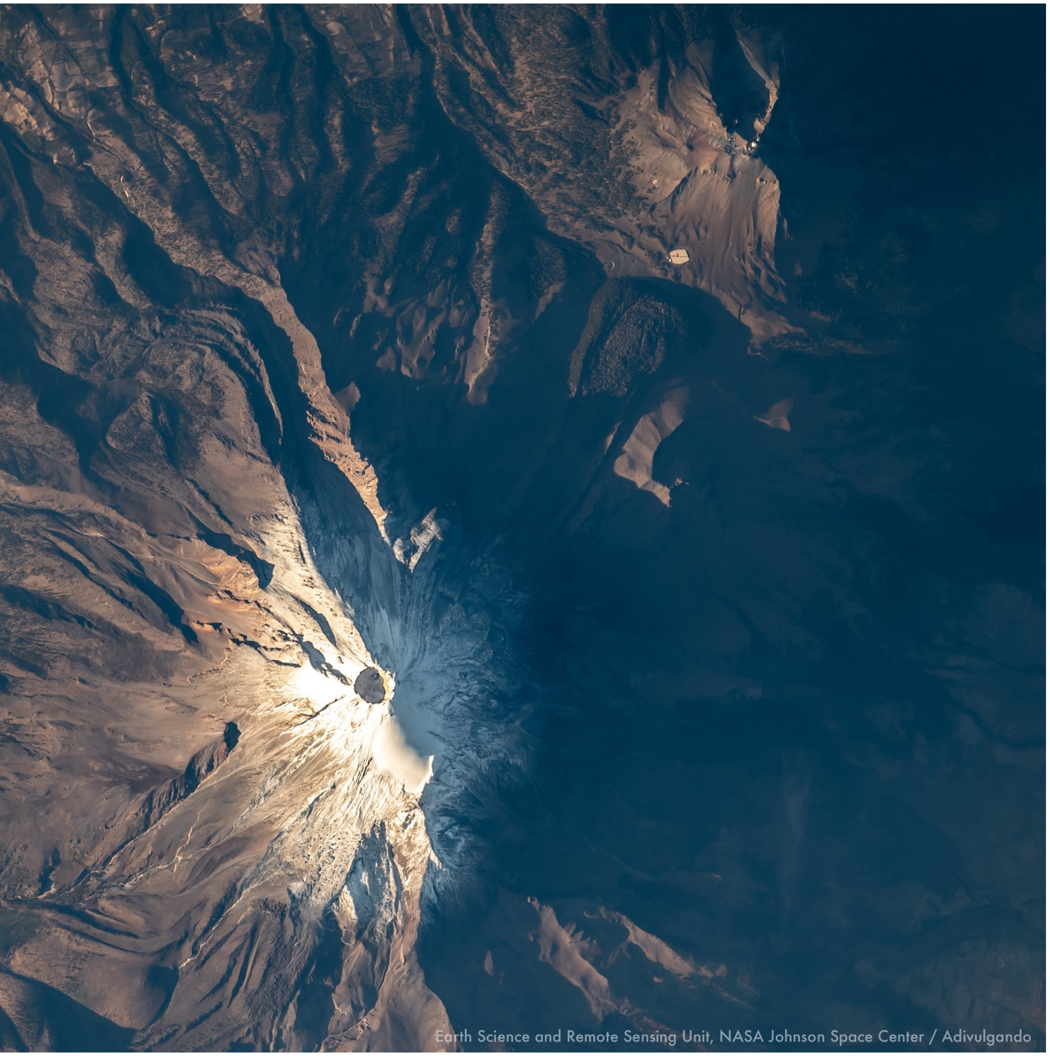


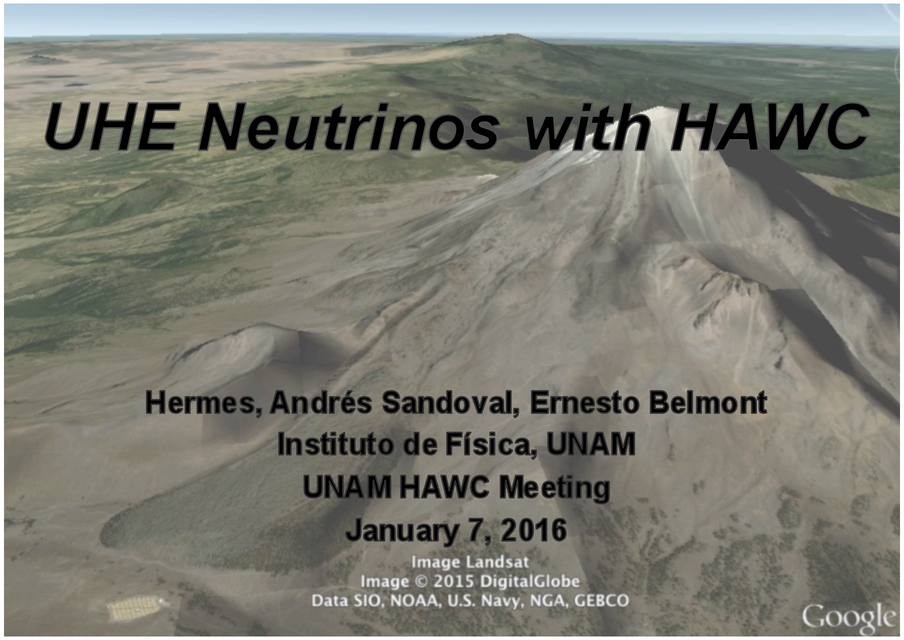
High Altitude Water Cherenkov



Earth Science and Remote Sensing Unit, NASA Johnson Space Center / Adivulgando

Earth Science and Remote Sensing Unit, NASA Johnson Space Center / Adivulgando

A long journey (~6 years)



UHE Neutrinos with HAWC

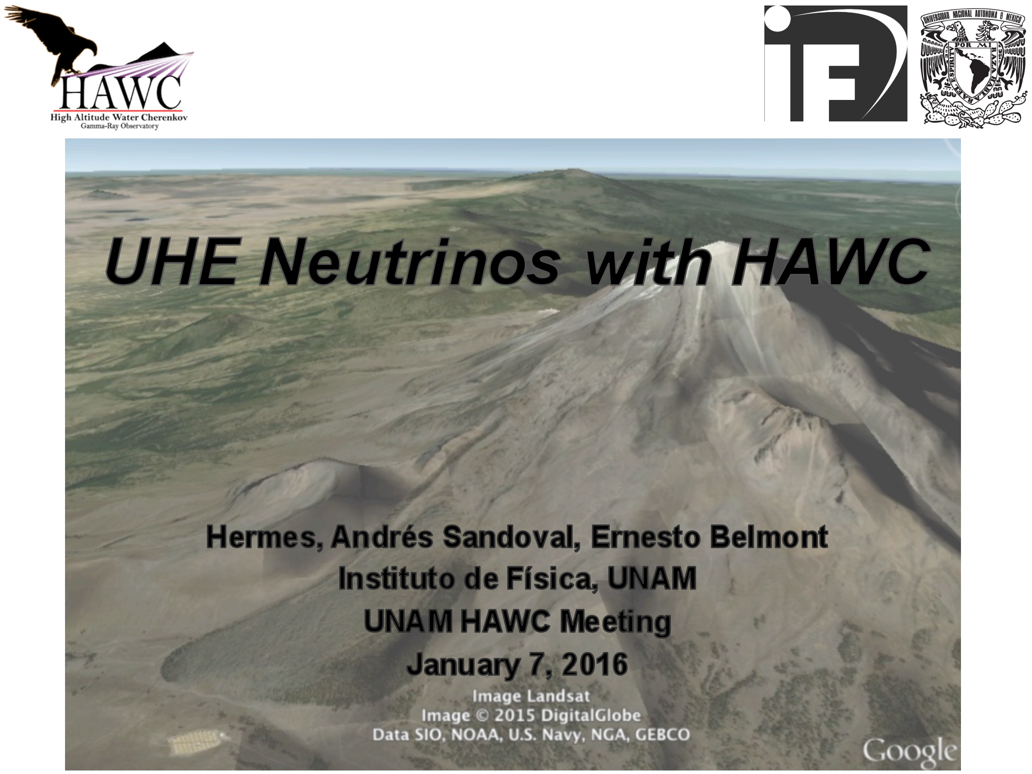
Hermes, Andrés Sandoval, Ernesto Belmont
Instituto de Física, UNAM
UNAM HAWC Meeting
January 7, 2016

Image Landsat
Image © 2015 DigitalGlobe
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

Google

First proposal to the
HAWC Collaboration
January, 2016

A long journey (~6 years)



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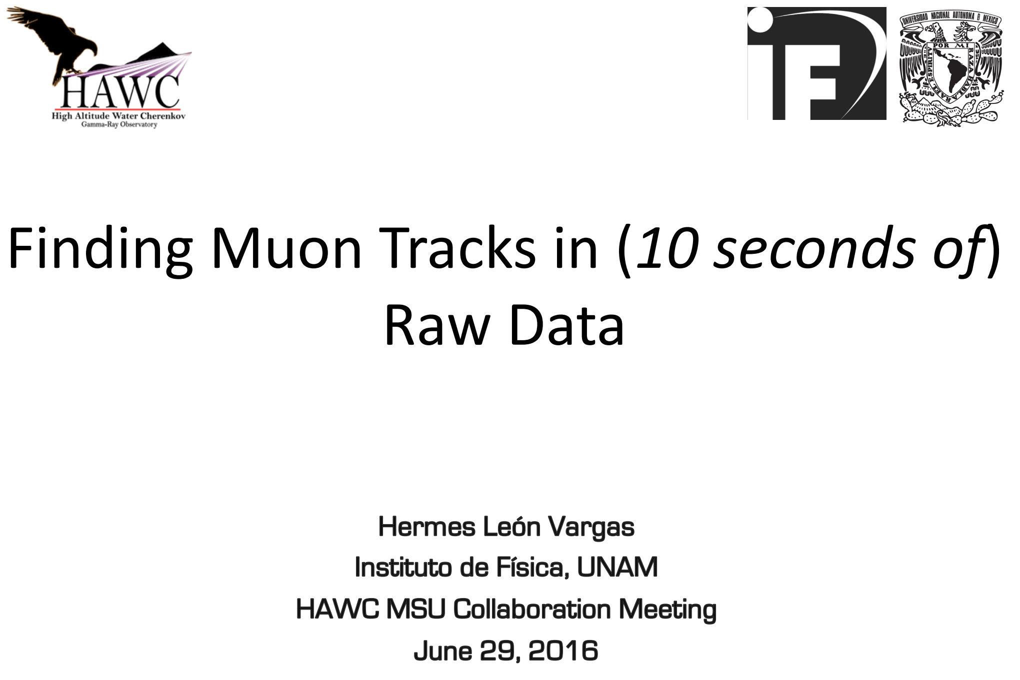

Finding Muon Tracks in (*10 seconds of*)
Raw Data

Hermes León Vargas
Instituto de Física, UNAM
HAWC MSU Collaboration Meeting
June 29, 2016

First proposal to the
HAWC Collaboration
January, 2016

First proof of principle with data
(10 seconds)
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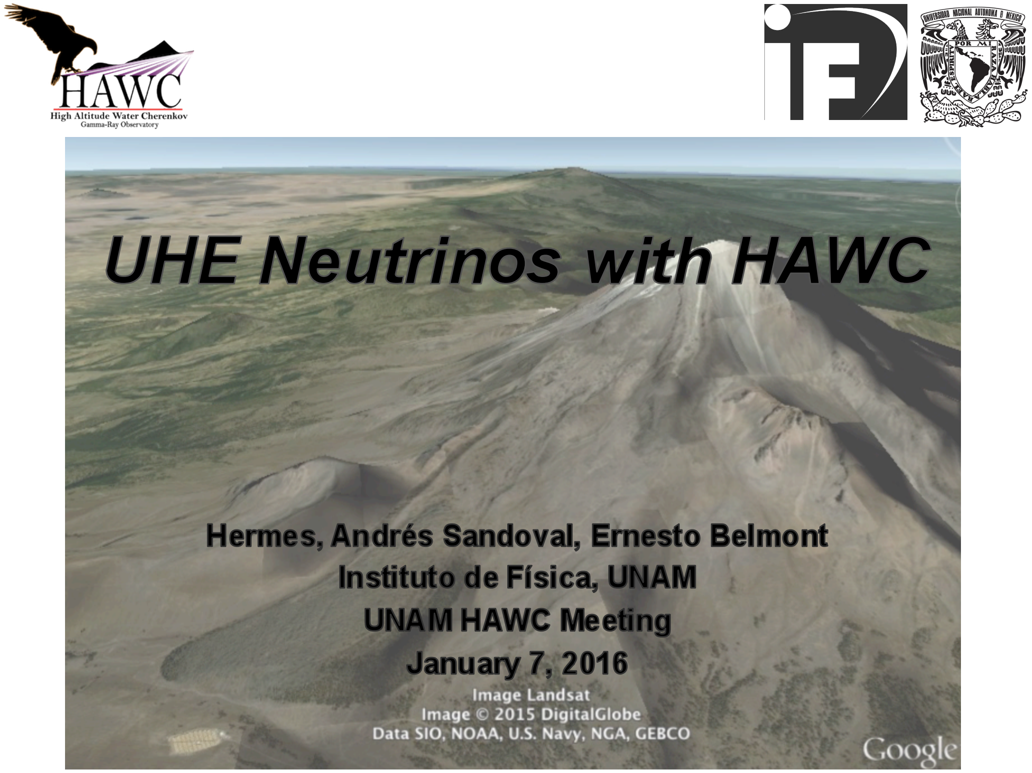
A long journey (~6 years)



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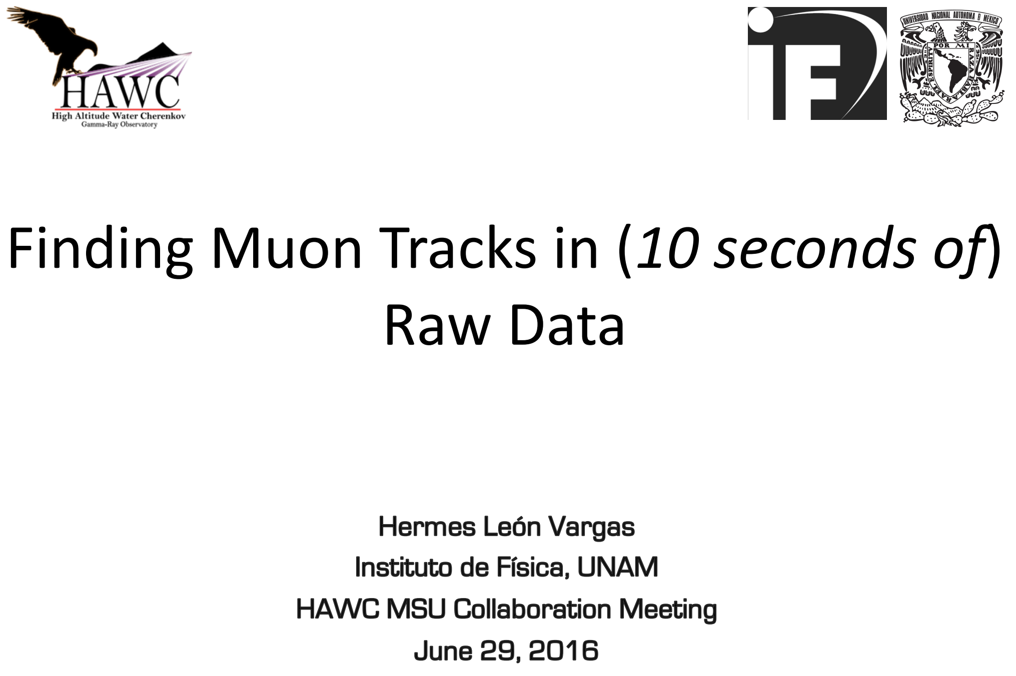

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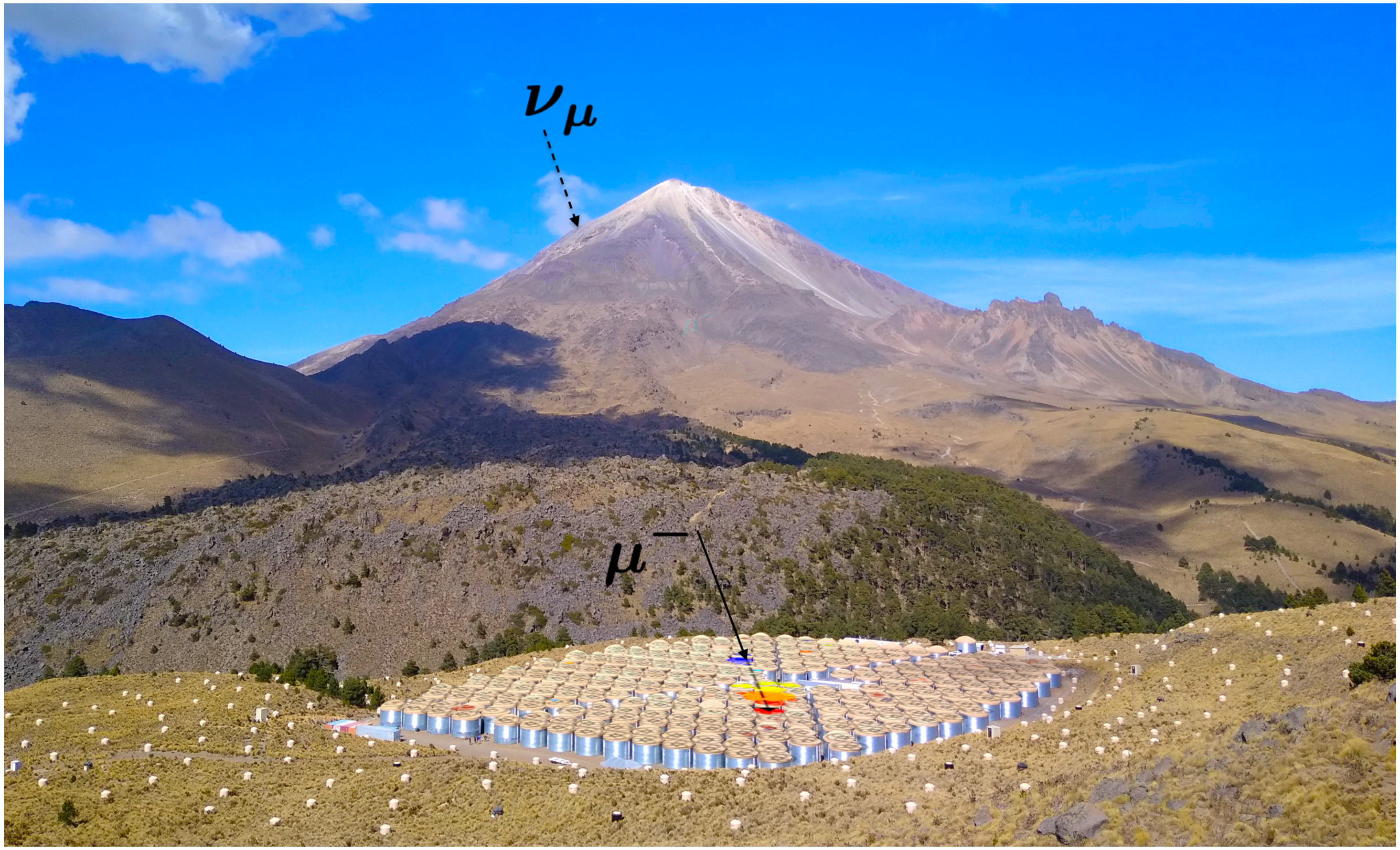
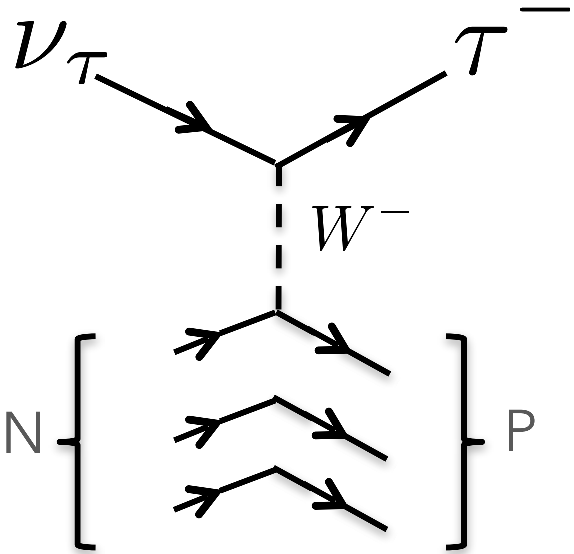
Publication: **April 2022**

Neutrino search with HAWC



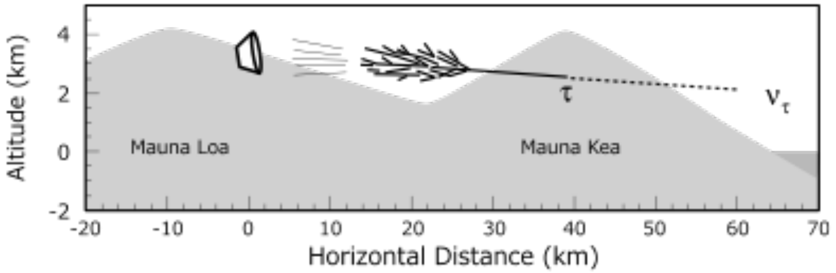
PRL 88, 161102 (2002)
J. Feng et al.

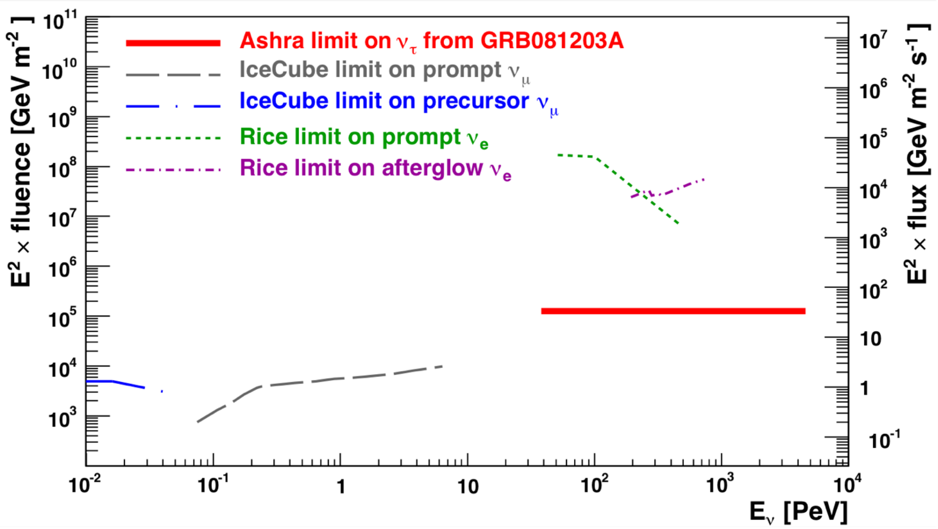


- The volcano also works as a background absorber (horizontal muons and air showers)
- Use HAWC to detect the charged lepton or its collimated decay products

Atmospheric Earth-skimming neutrino detection

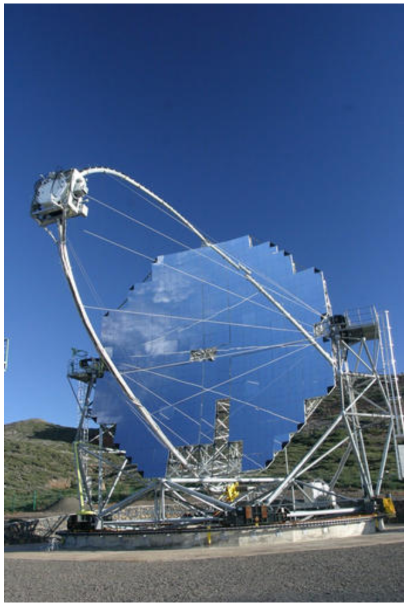
Ashra

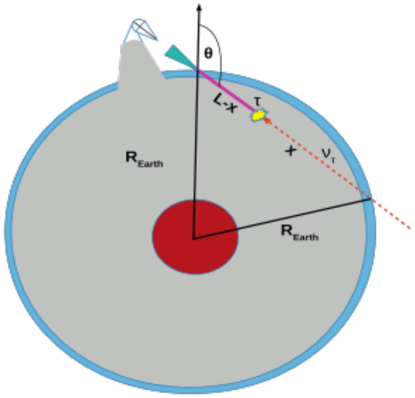




APJ 736:L12 (2011)
Observational search for PeV-EeV tau neutrino from GRB081203A

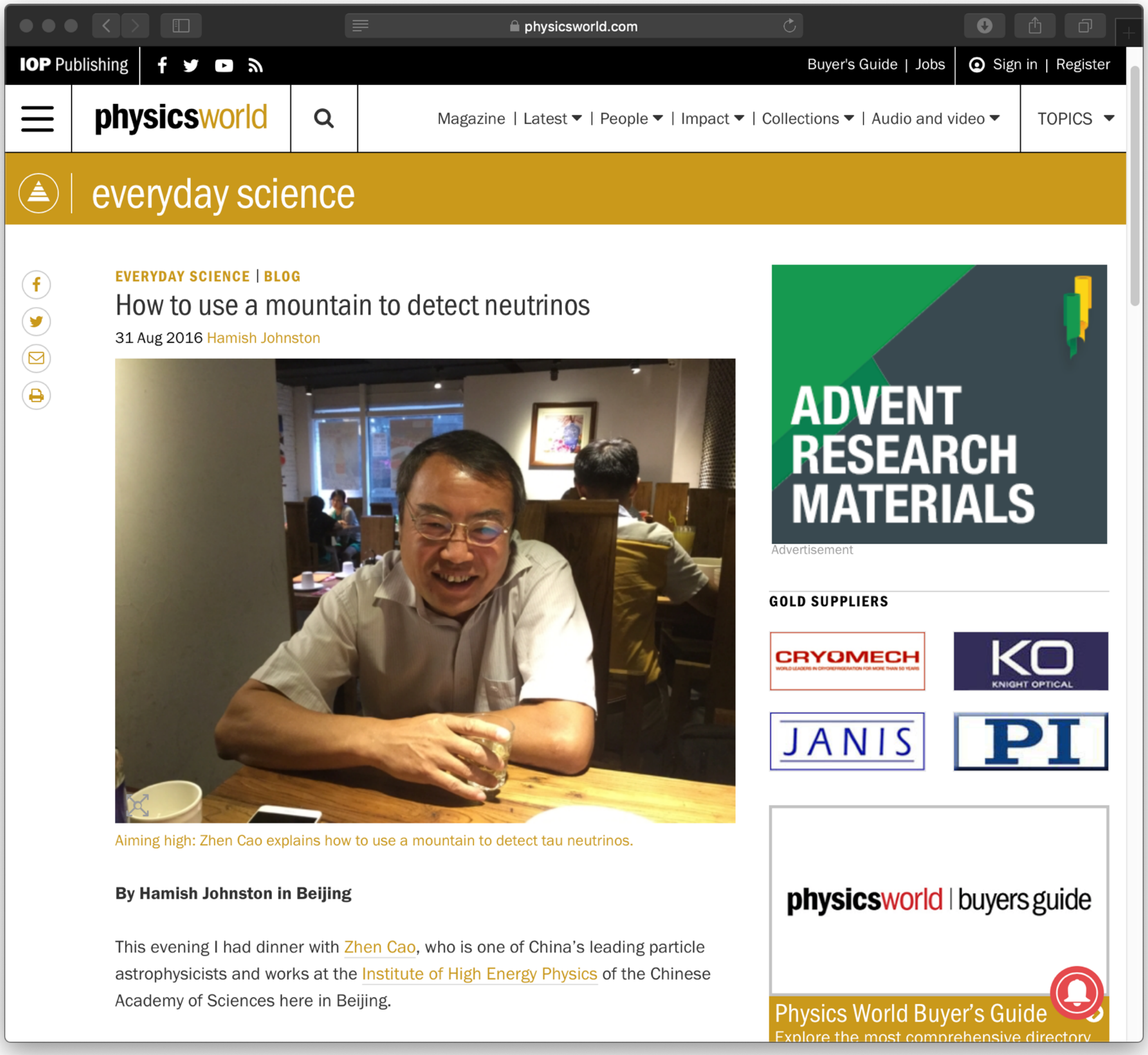
MAGIC





Astroparticle Physics 102 (2018) 77-88
Limits on the flux of tau neutrinos from 1 PeV to 3 EeV with the MAGIC telescopes

Atmospheric Earth-skimming neutrino detection



EVERYDAY SCIENCE | BLOG

How to use a mountain to detect neutrinos

31 Aug 2016 Hamish Johnston

Aiming high: Zhen Cao explains how to use a mountain to detect tau neutrinos.

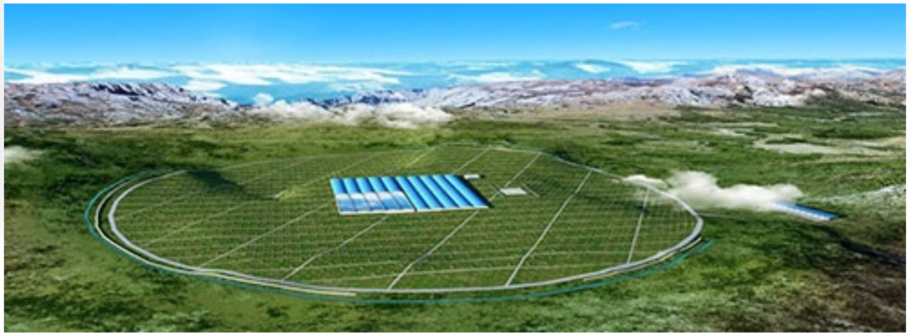
By Hamish Johnston in Beijing

This evening I had dinner with Zhen Cao, who is one of China's leading particle astrophysicists and works at the Institute of High Energy Physics of the Chinese Academy of Sciences here in Beijing.

Prof. Zhen Cao proposed to build the Cosmic Ray Tau Neutrino Telescope (CRTNT)

Similar to ASHRA, expectation of 1 neutrino per year

Instead appointed PI of LHAASO (180 M USD)



Not-underground astrophysical neutrino detectors

General opinion: Impossible, the background is too large

Some experimental proposals[1] (none was built):

- **GRANDE** (Gamma-Ray and Neutrino DEtector).
  Cherenkov detectors, 30,000 m^2 (1988)

- **LENA** (Lake Experiment on Neutrino Activities)
  Cherenkov detectors (1992)

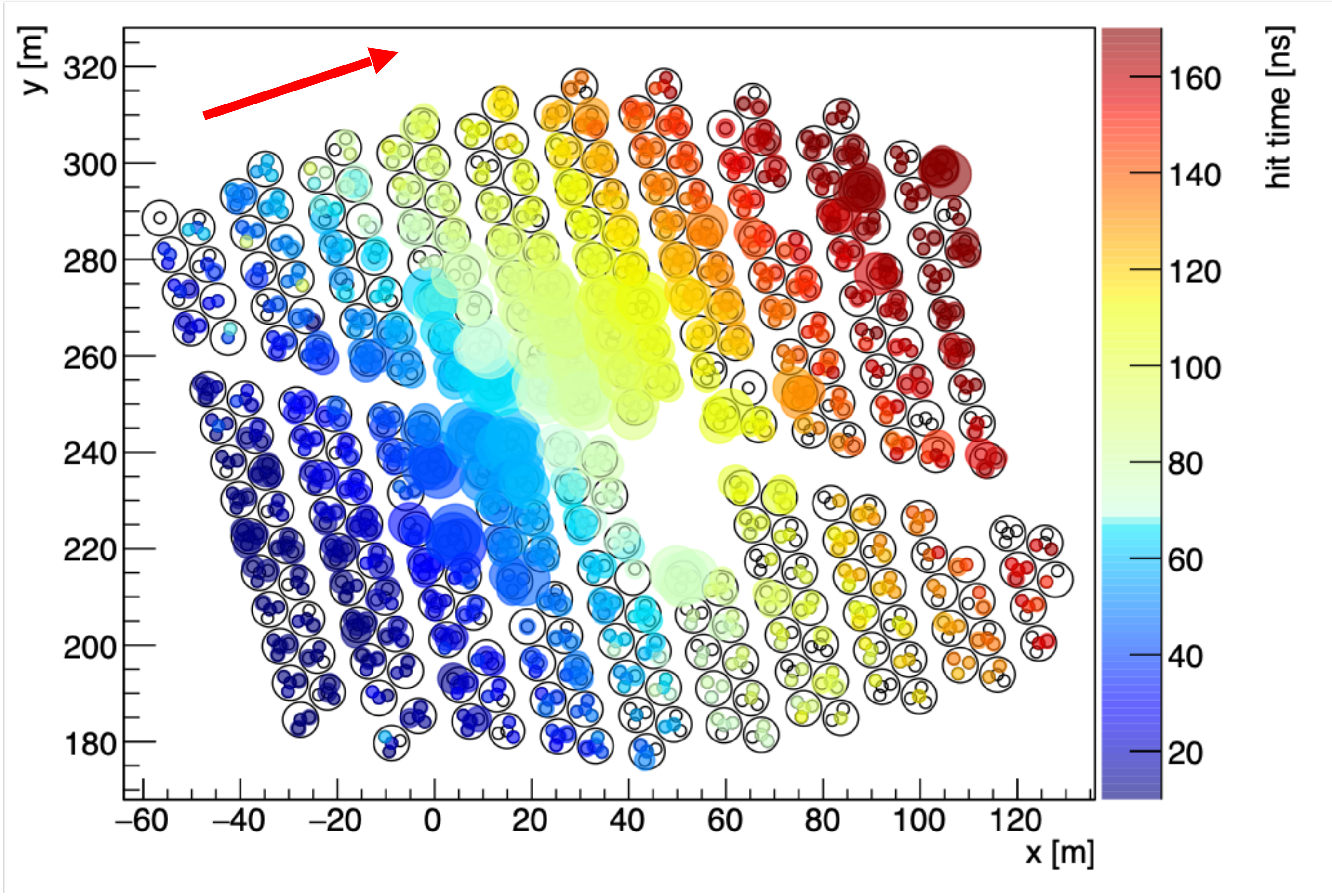
- **NET**
  3 layers of Cherenkov detectors at Gran Sasso (1991)

- **PAN** (Particle Astrophysics in Norrland)
  Detectors inside a lake in Sweden (1991)

- **SINGAO** (Southern Italy Neutrino and Gamma Astronomy Observatory)
  10 000 m^2 of RPCs (1988)

[1] C. Spiering. The European Physical Journal H 37 (2012) 515-565

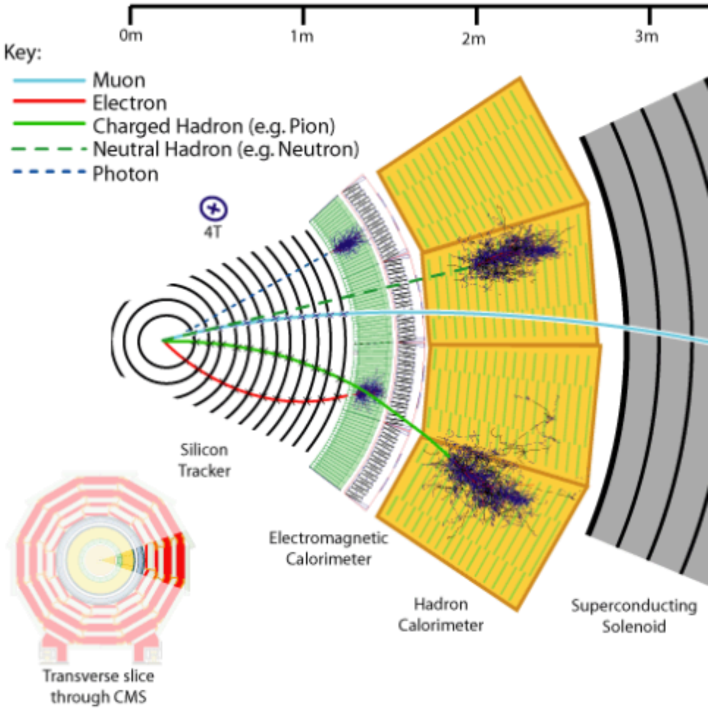
Data visualization in HAWC

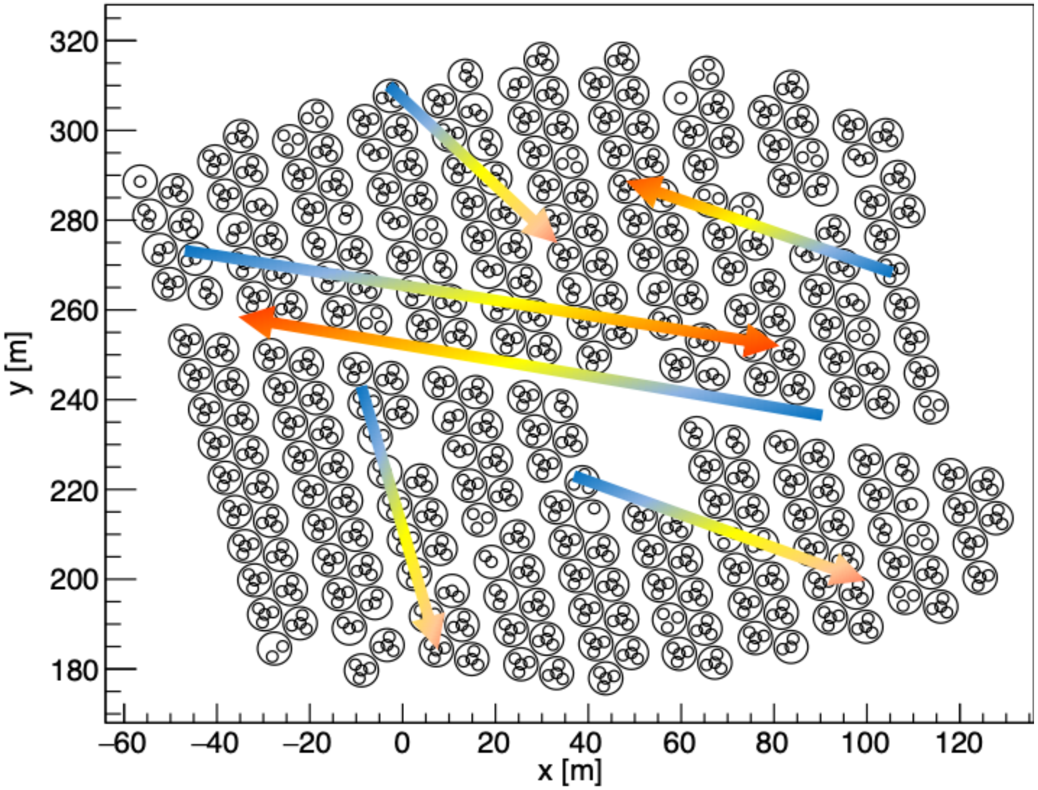


- Aerial view of the detector
- The display is that of a real data air shower.

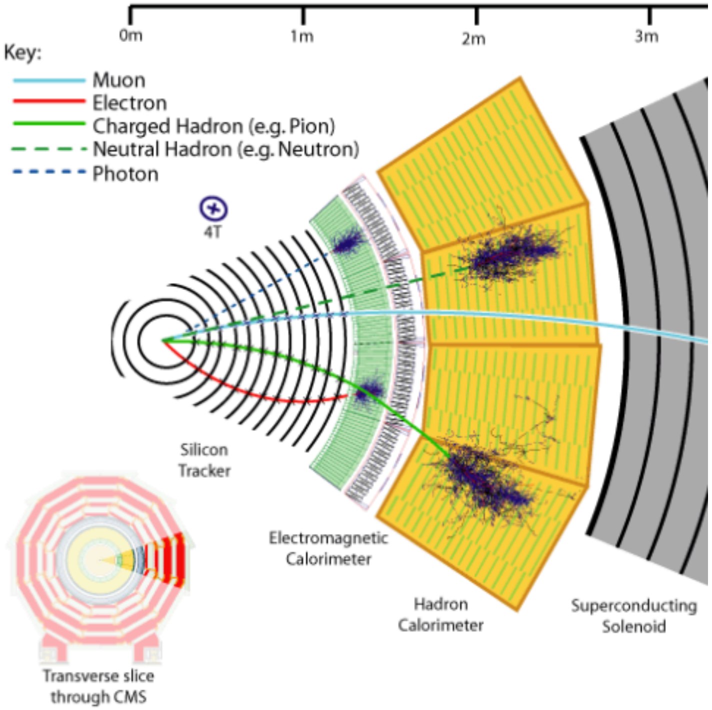
- The filled circle size is proportional to the charge detected by each PMT
- The color code represents the hit time [ns]

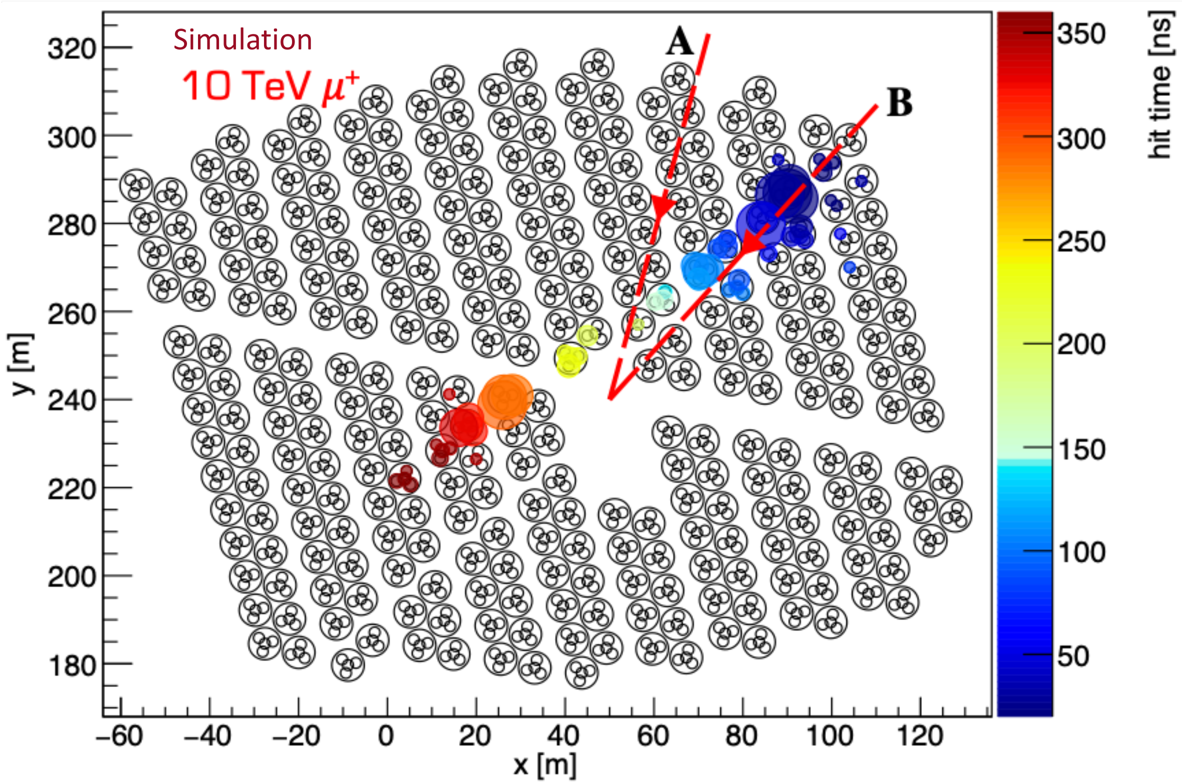
HAWC as a particle tracker





HAWC as a particle tracker

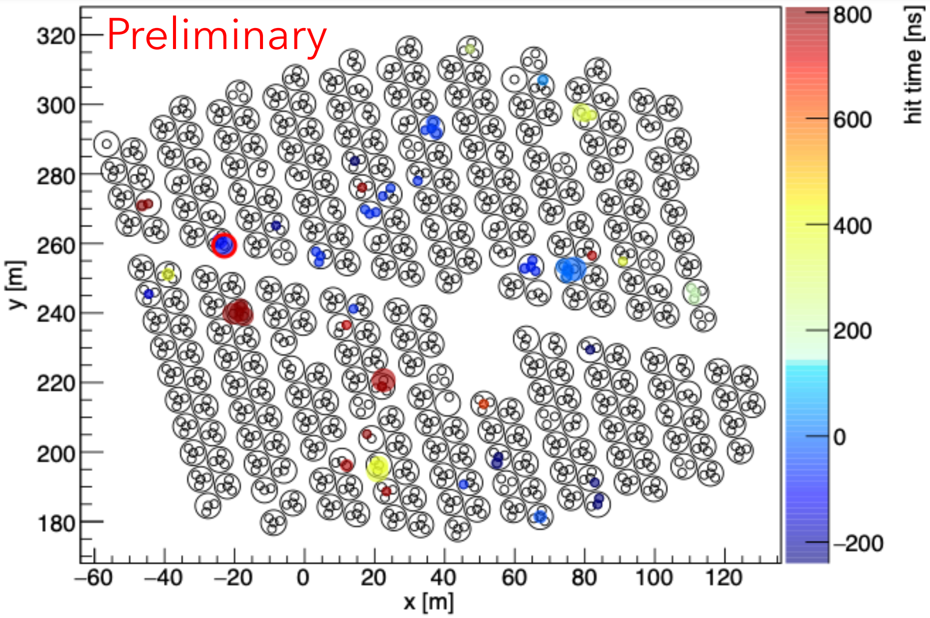


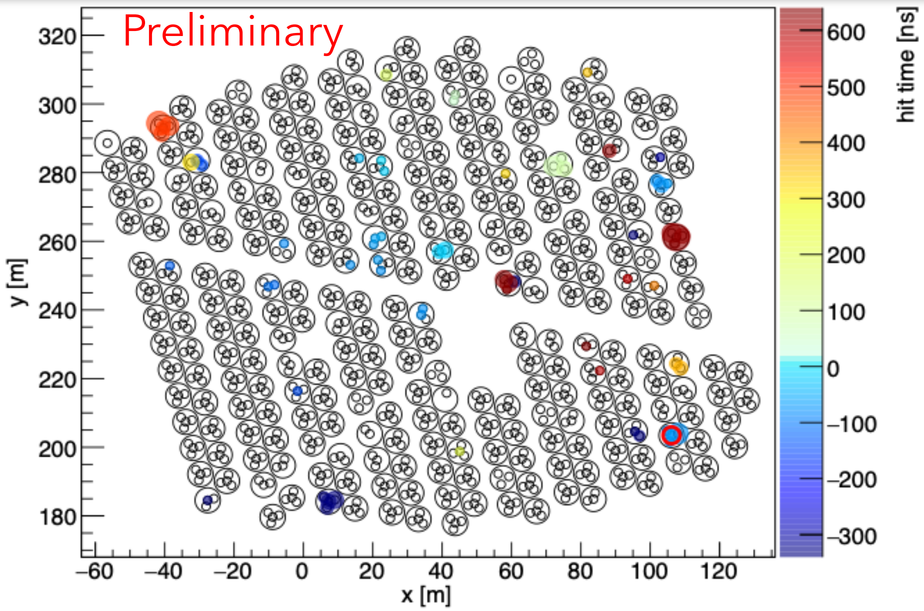


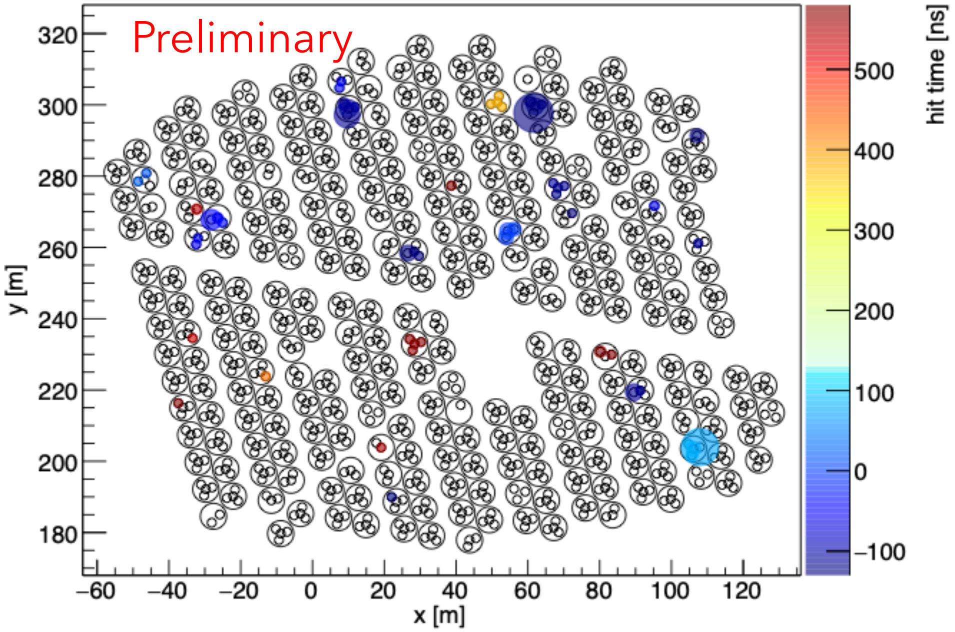
Selection criteria (software trigger) :

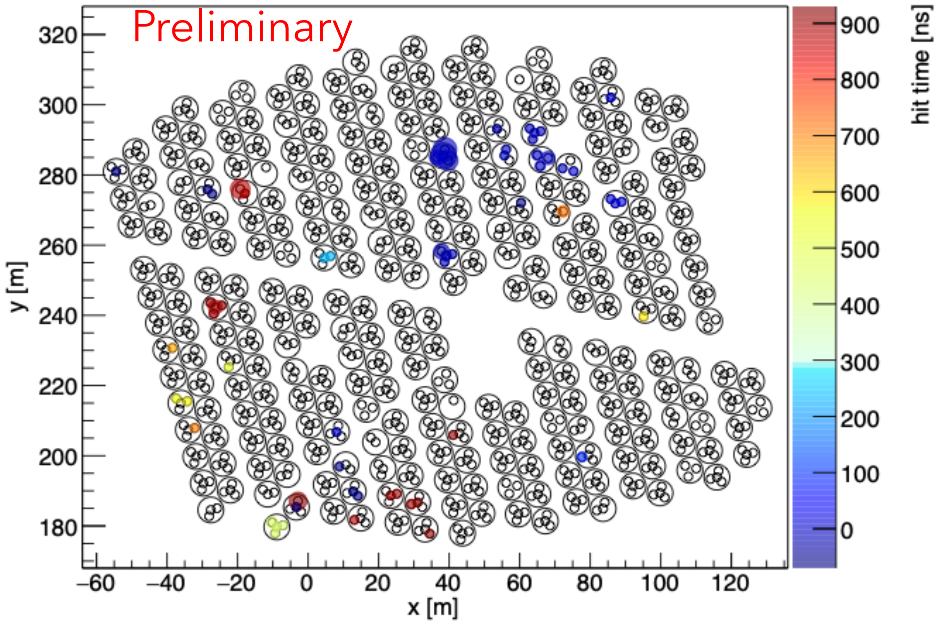
- Chain of hits in neighboring PMTs (same columns or closest columns), comprising at least 2 WCDs, with propagation consistent with speed of light
- Store WCD information (<T>, ΣPEs, NHits) ⟶ pixel for tracking

Real data "small" events









Data sample & selection

Data obtained using the air shower trigger:

- 216 runs
- **~6 months** of live time
- **~260 TB** processed ($> 7 \times 10^6$ CPU hours, using two clusters: UMD & UNAM)

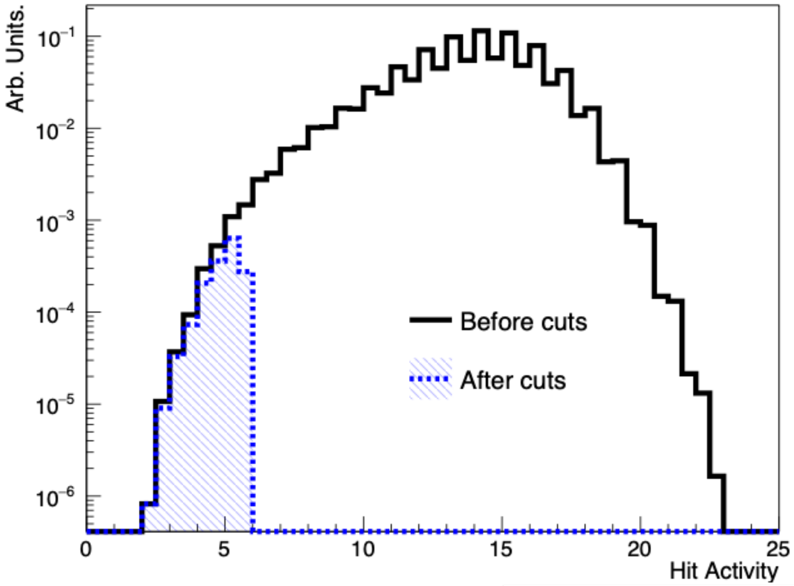
WCD selection cuts:

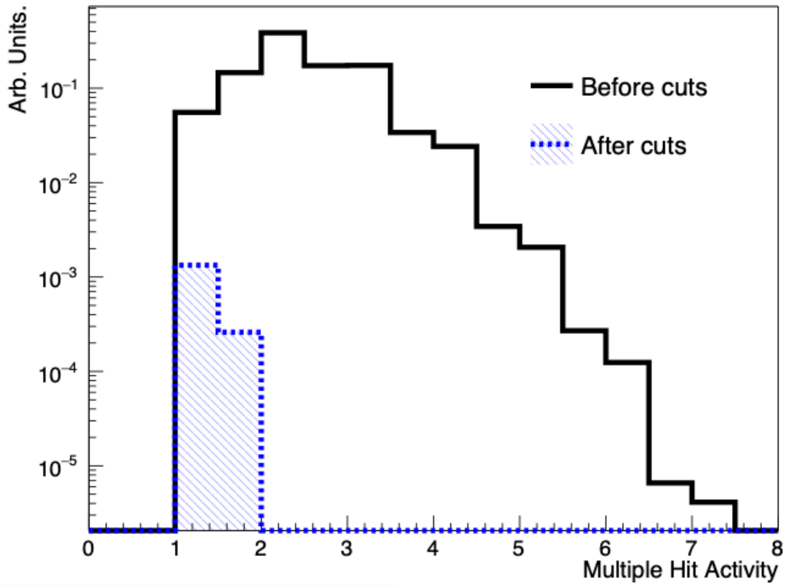
- Minimum PMT charge: **4 PEs**
- Minimum number of PMT with signal inside each WCD: **2/4**
  - Removal of hits identified as part of an air shower
- Isolation cuts on each track candidate

Background sources:

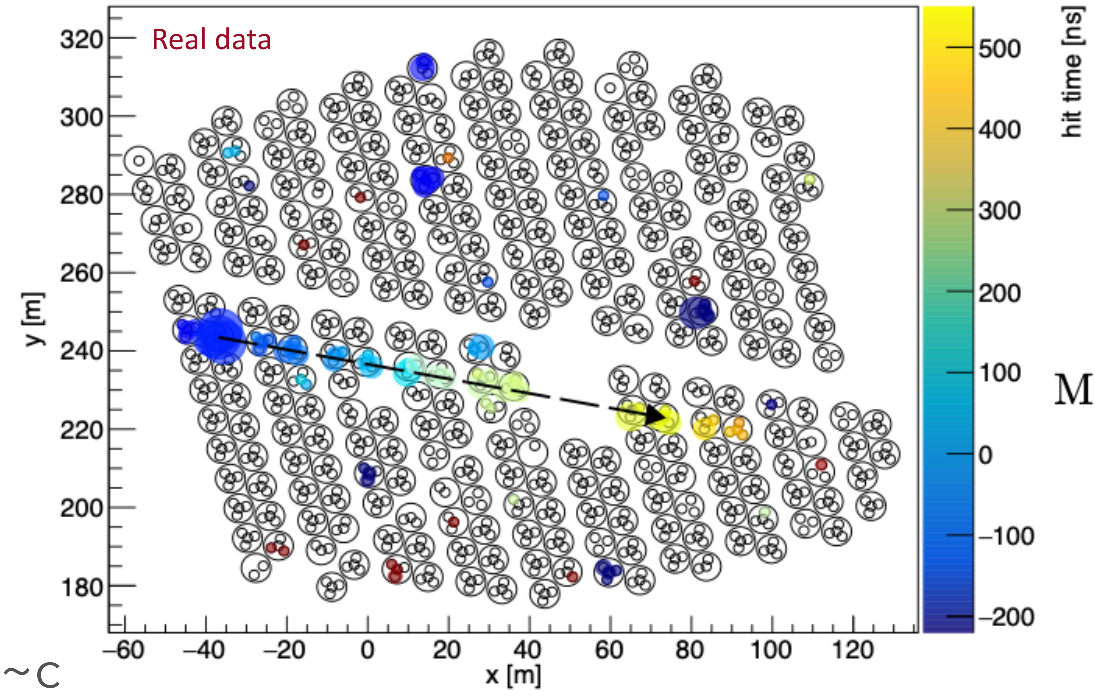
- Vertical muons hitting HAWC from above (~10^4 m^{-2} min^{-1})
  - Each HAWC WCD has a diameter of 7.3 m
  - The PMT rate is approximately 24 & 39 kHz
- Artificial tracks due to combinatorial background

Additional selection criteria





$$H_A = N_{WCDs}/N_{WCDs}^{Track},$$



$$M_{HA} = N_{WCDs}^{MHA}/N_{WCDs}^{Track},$$

Additional cut to
select propagation at ~c

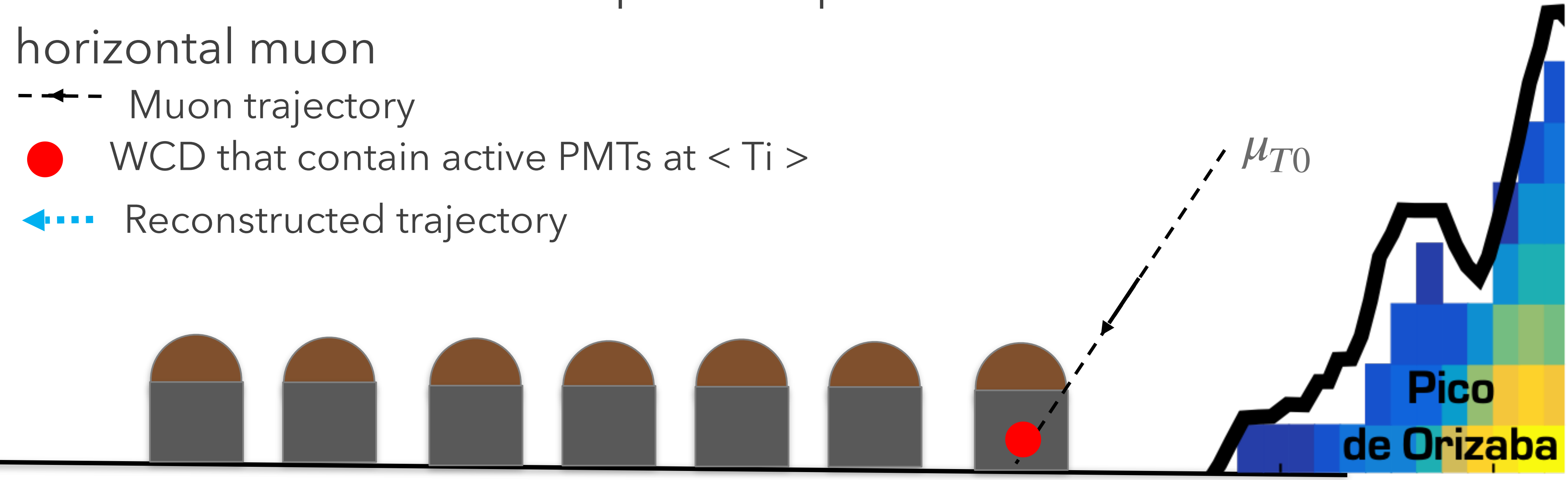
1) Combinatorial background

Several vertical muons can produce patterns that are similar to an horizontal muon

- - ← - - Muon trajectory

● WCD that contain active PMTs at < Ti >

◀··· Reconstructed trajectory



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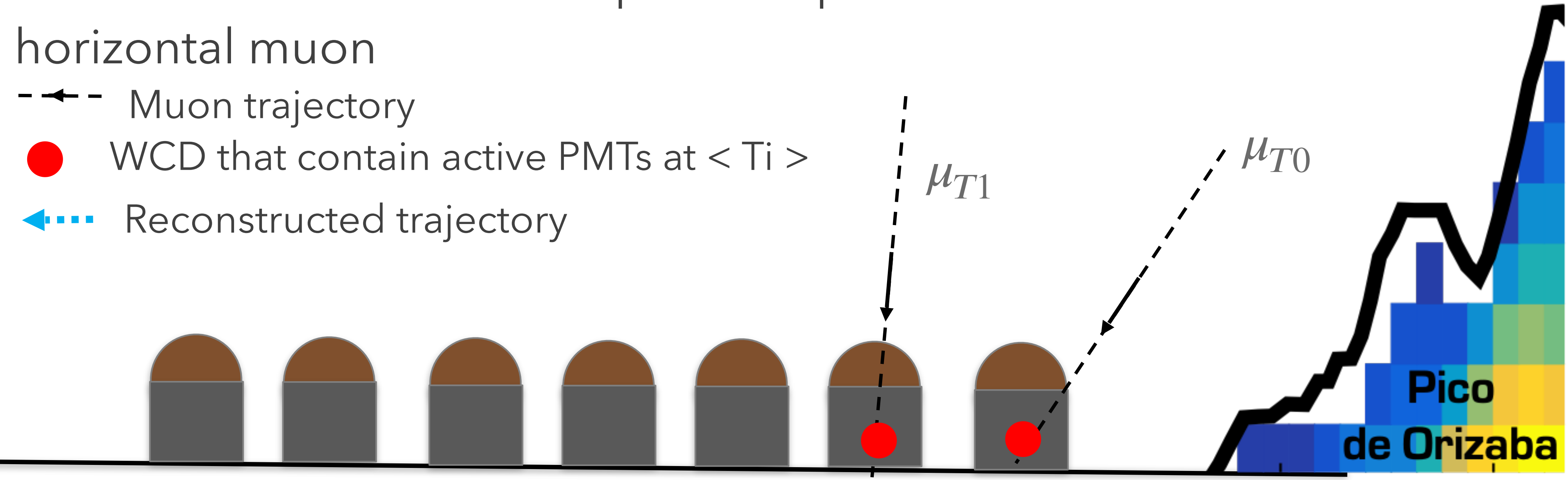

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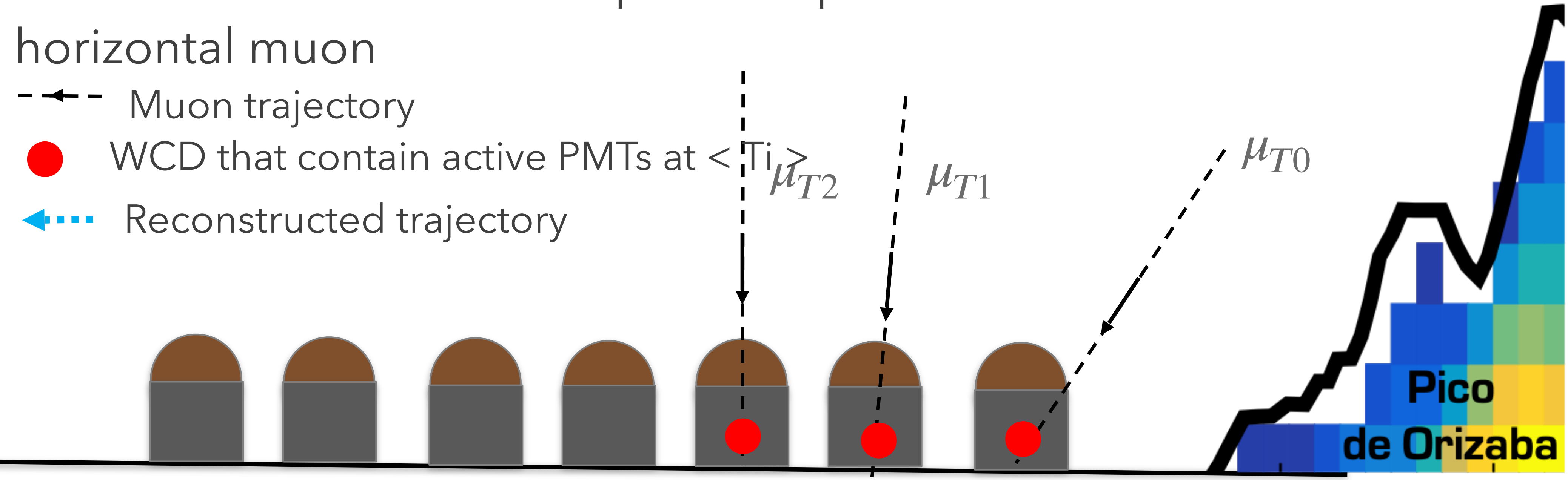

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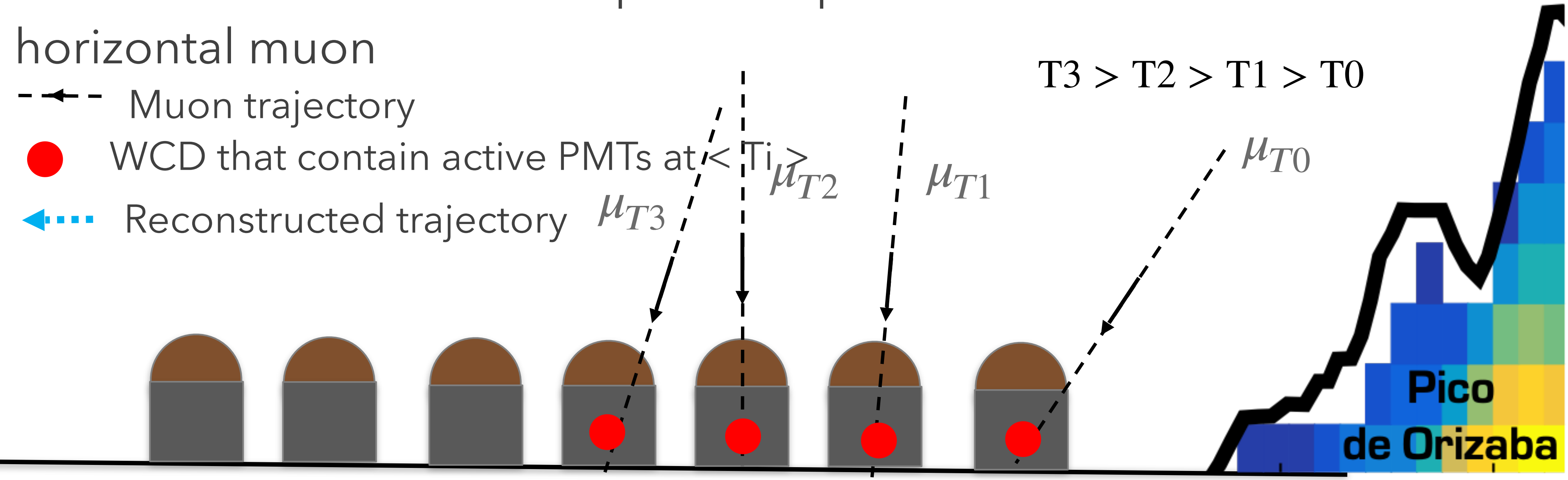
- - ◀ - - Muon trajectory

● WCD that contain active PMTs at < Ti >

◀···· Reconstructed trajectory



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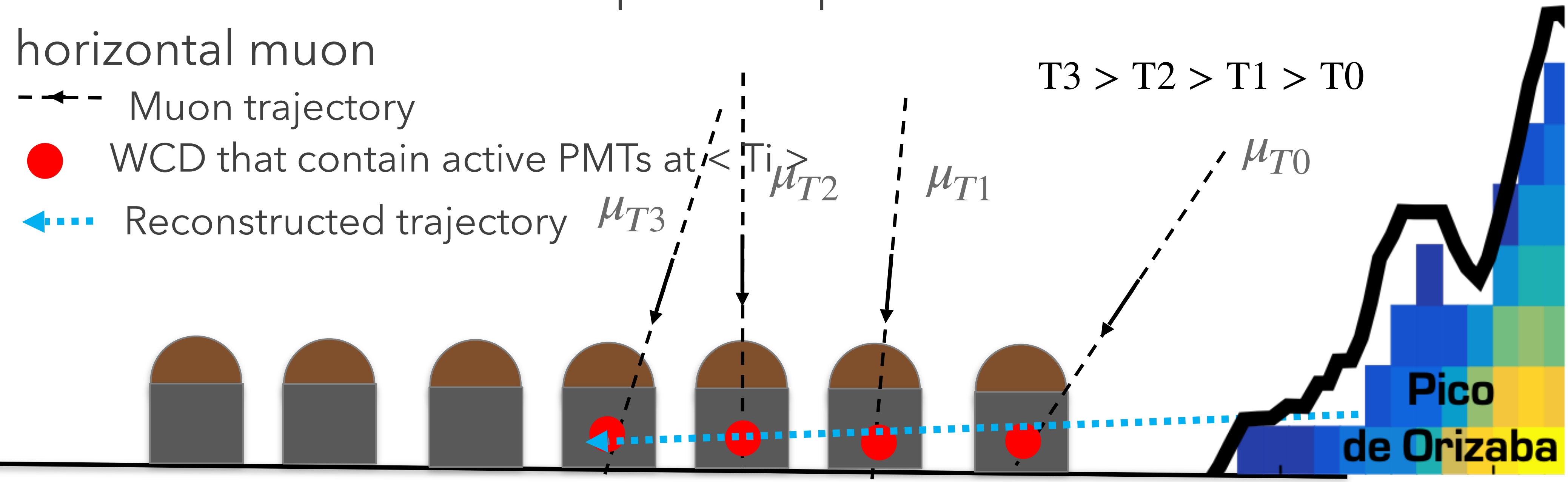

- - ◄ - - Muon trajectory

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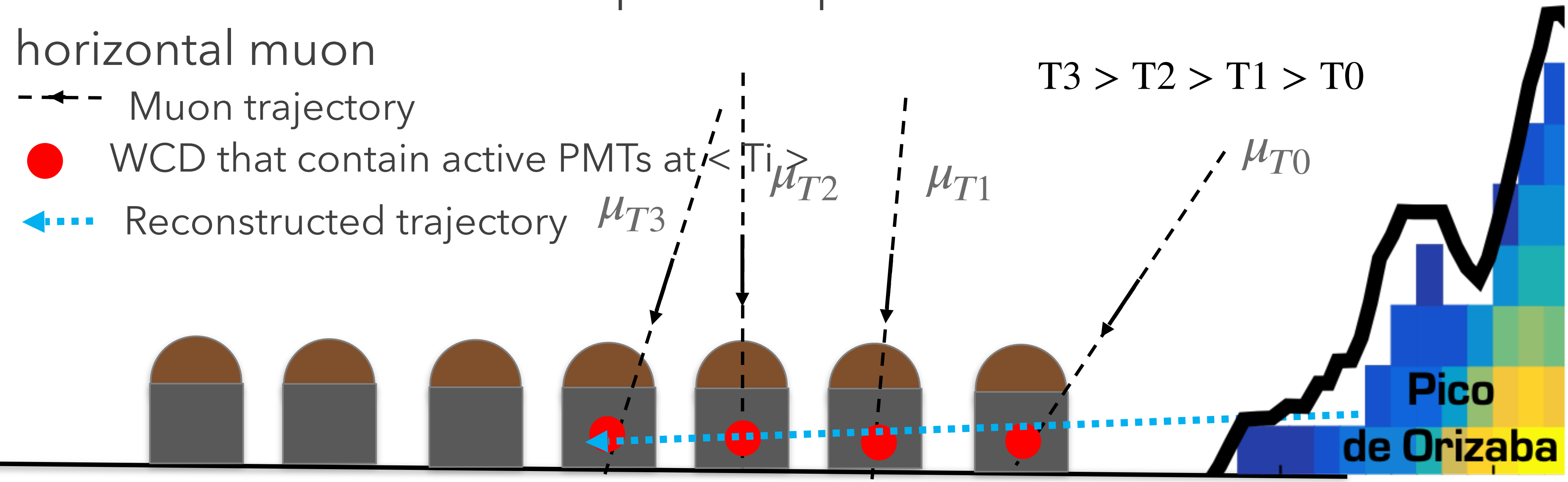

- - ◂ - - Muon trajectory

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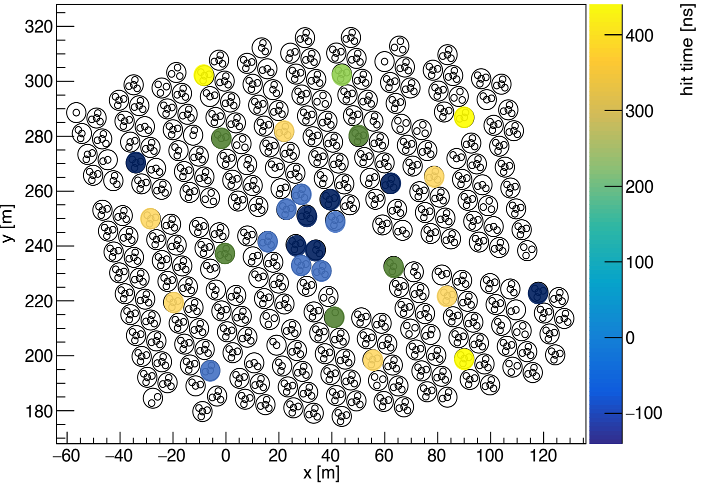
◂···· Reconstructed trajectory



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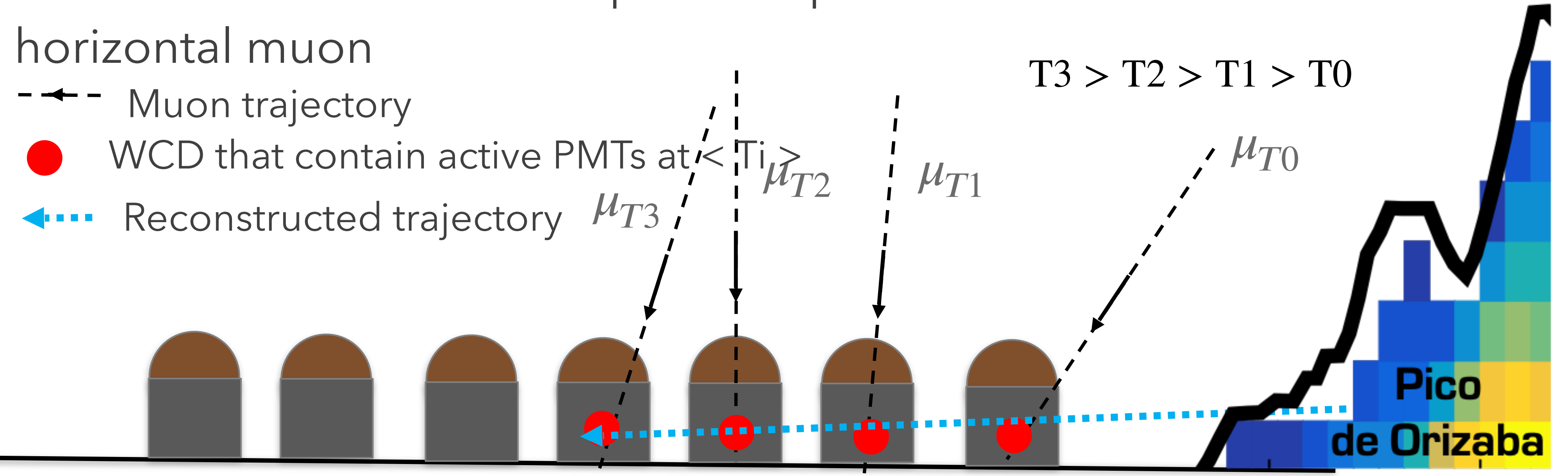

- - ← - - Muon trajectory

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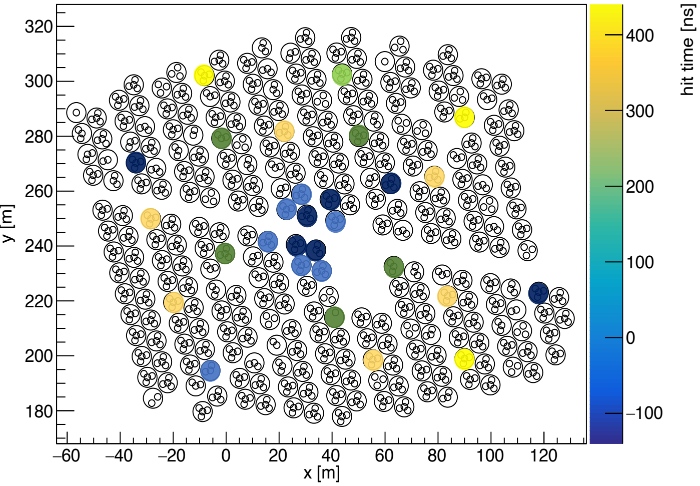
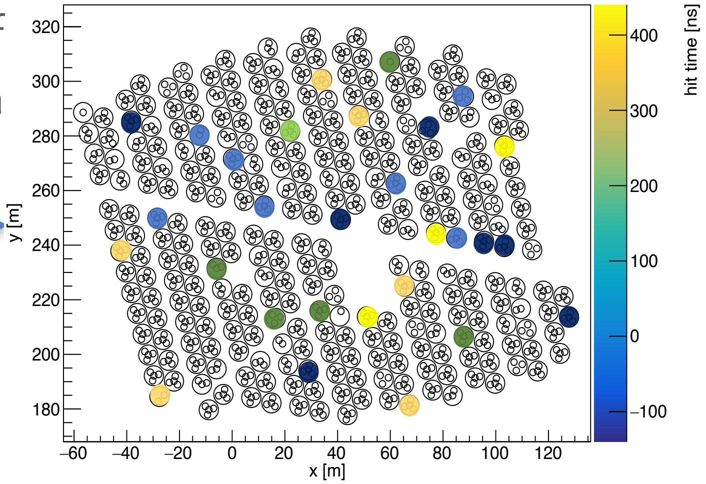


Randomly modify the position of PMTs with signal, for the full data set (6 months)



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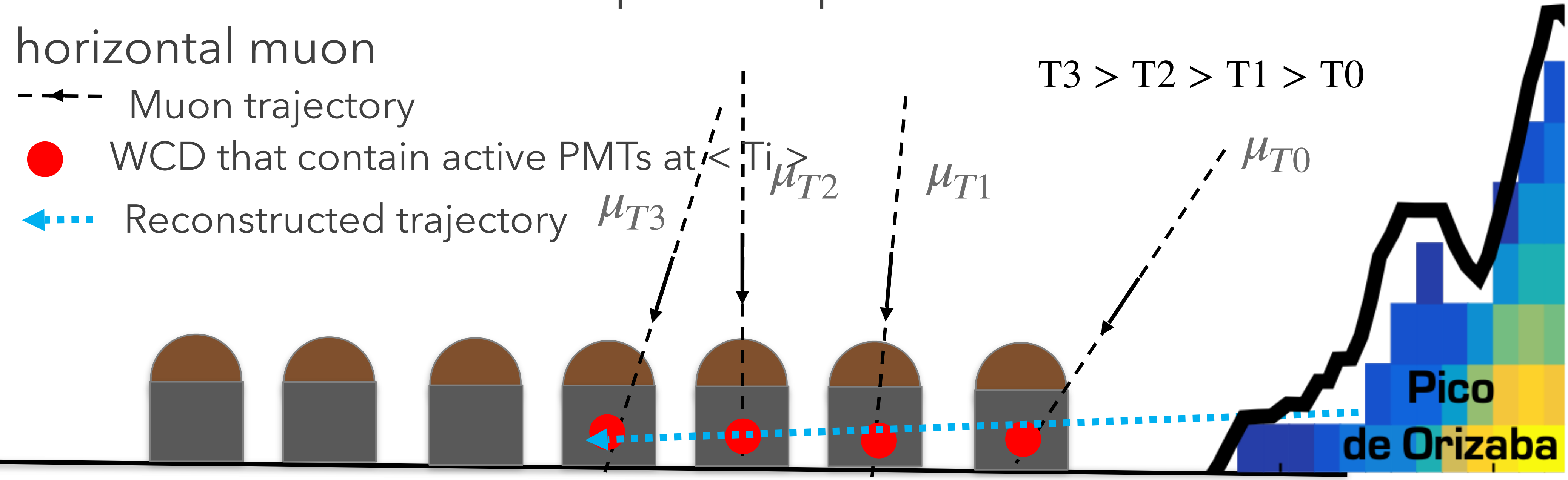
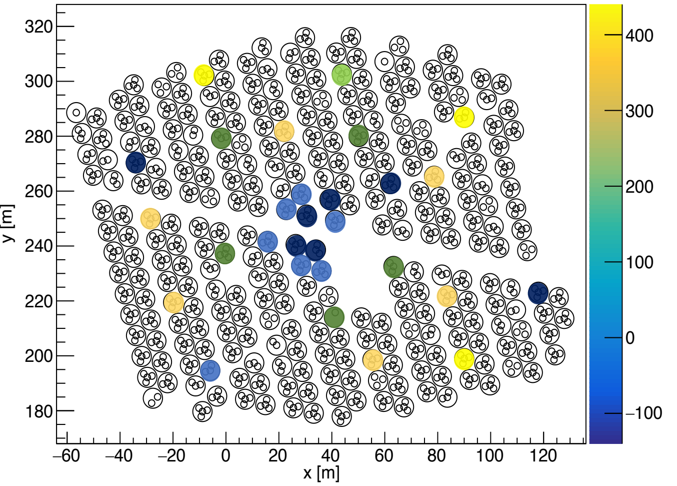
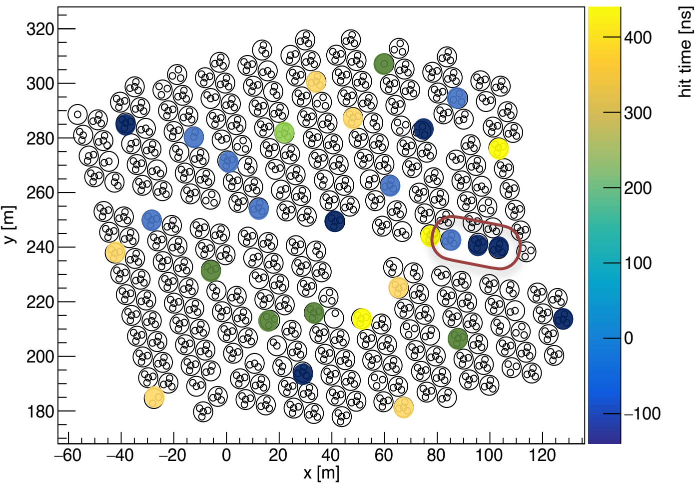




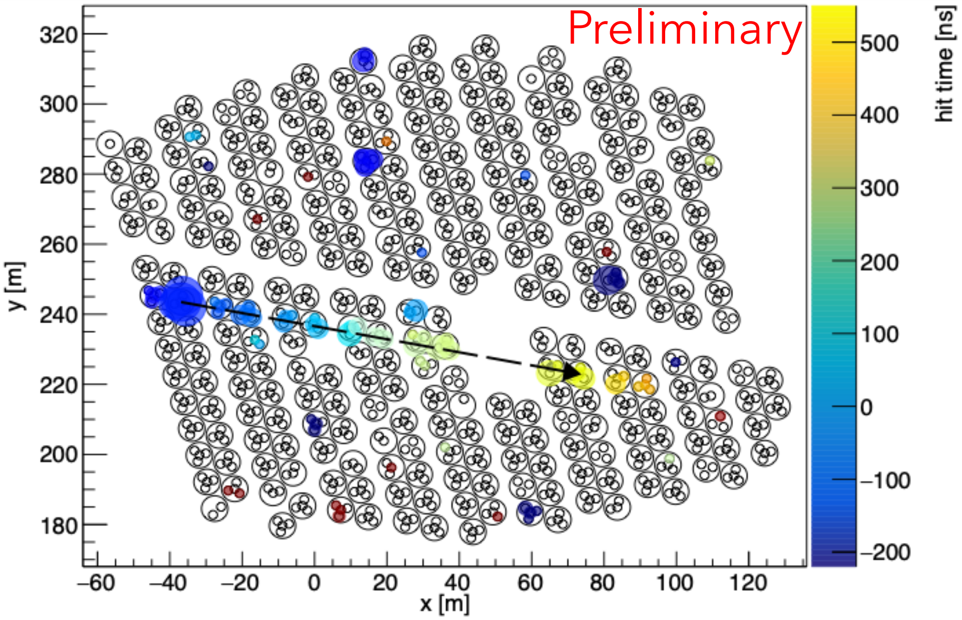
Randomly modify the position of PMTs with signal, for the full data set (6 months)

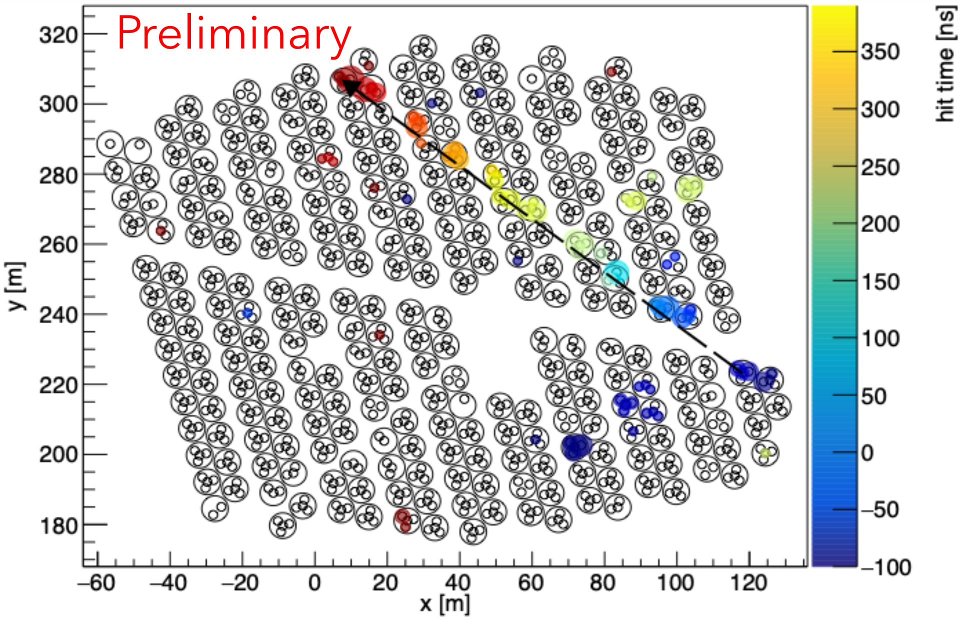
The longest random track consisted of 3 pixels

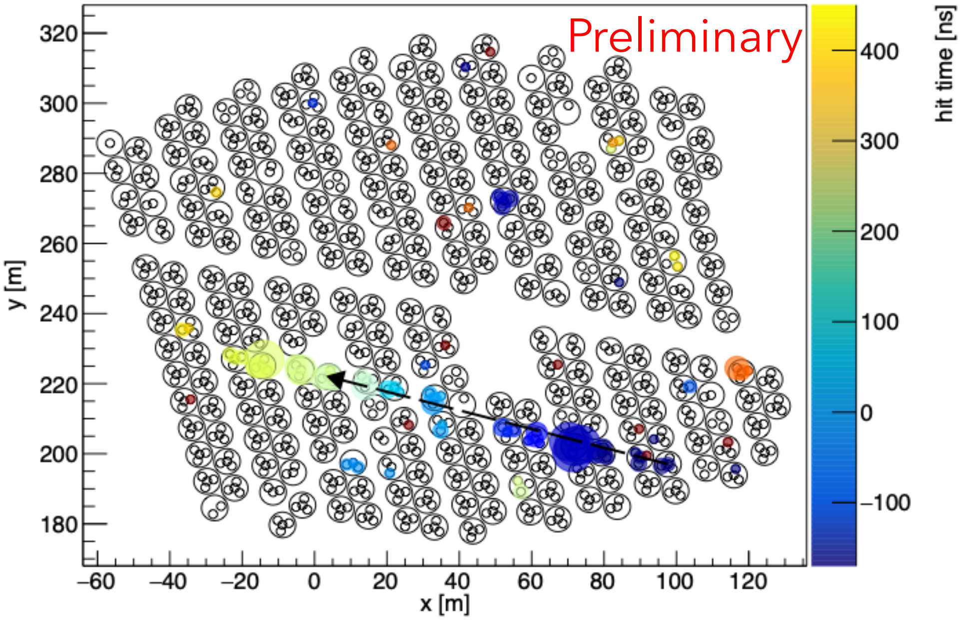


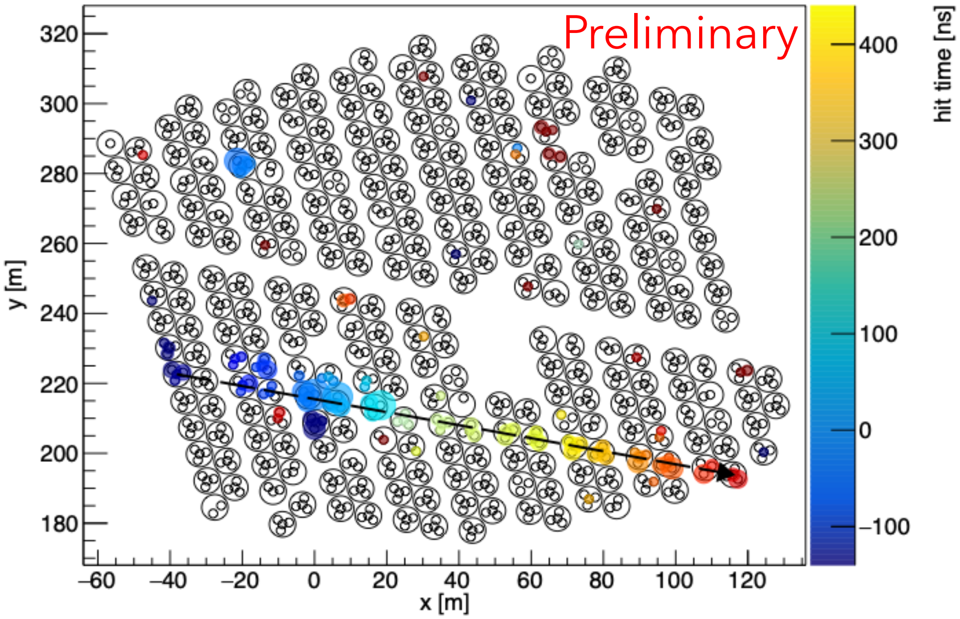
For the analysis we used only tracks with $N^{Track}_{Pixel} \geq 4$

Some examples of real data horizontal muons

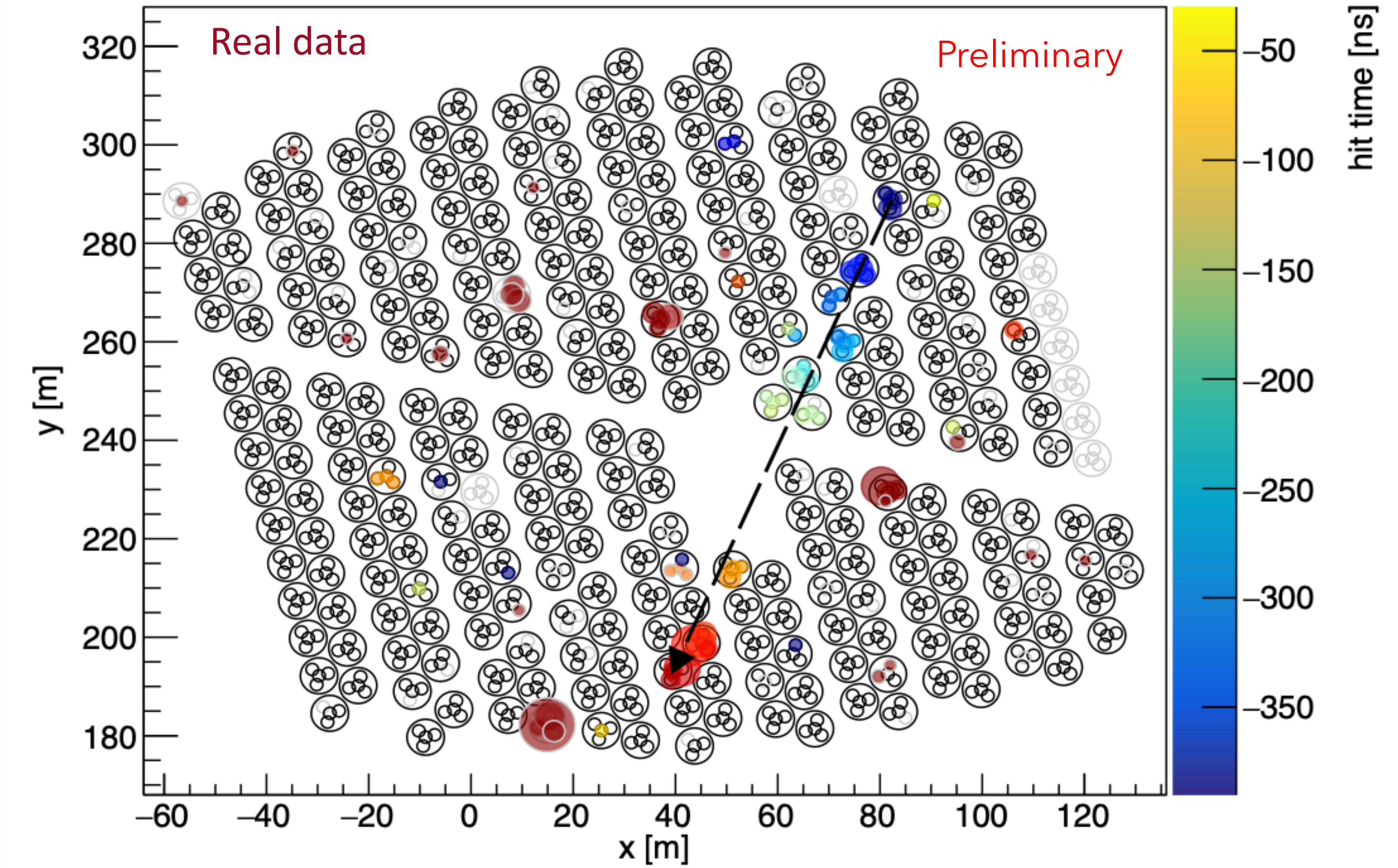






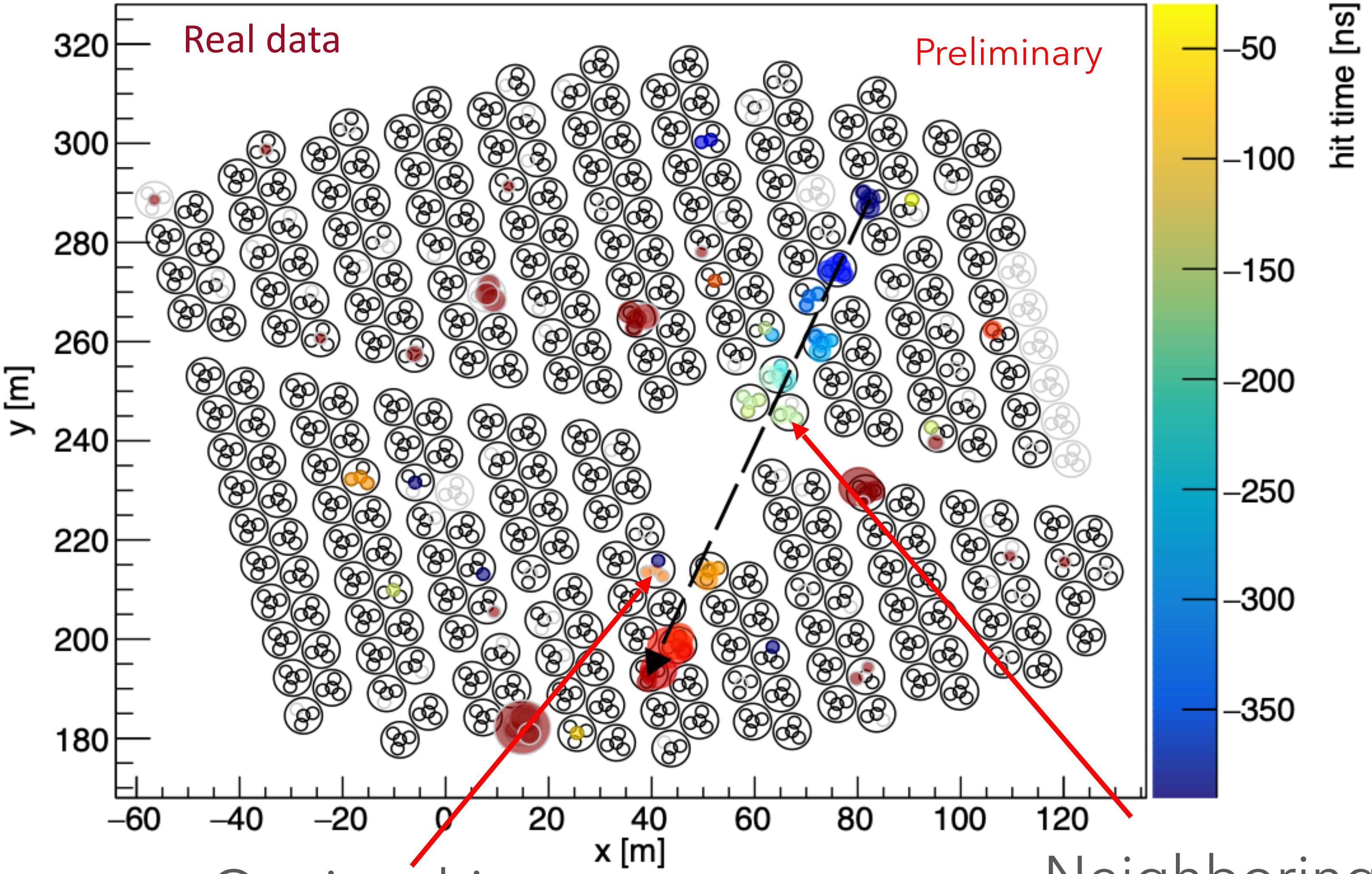


Hits outside a linear track



The tracks are not completely isolated, i.e. there are collinear hits

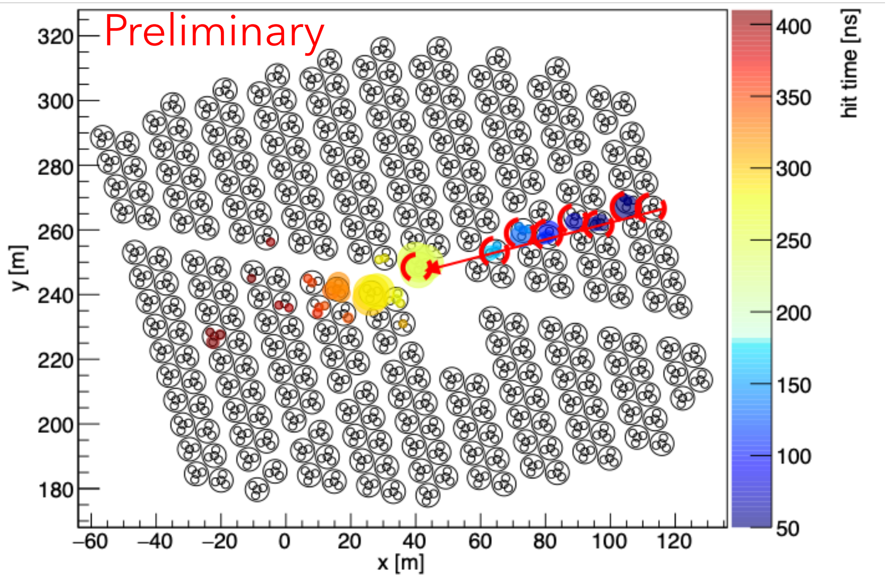
Hits outside a linear track

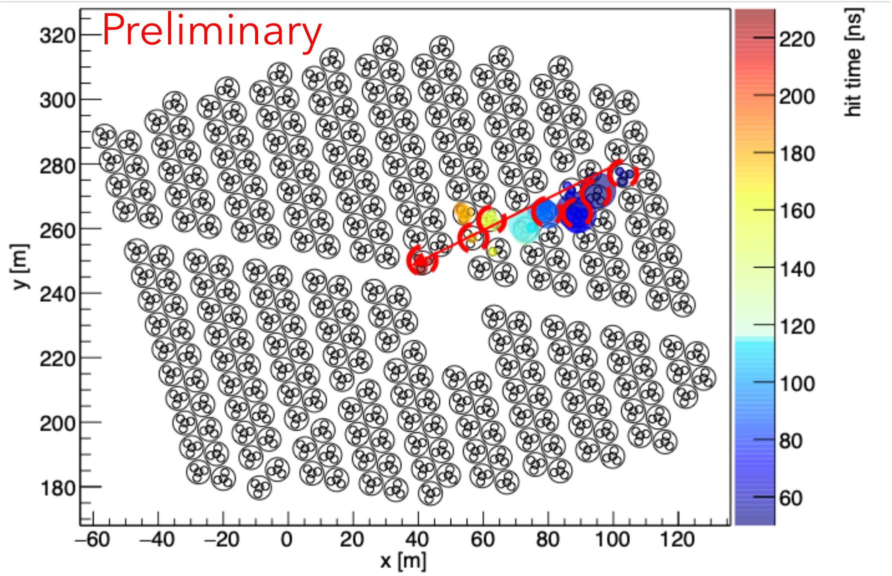


On time hits outside the track

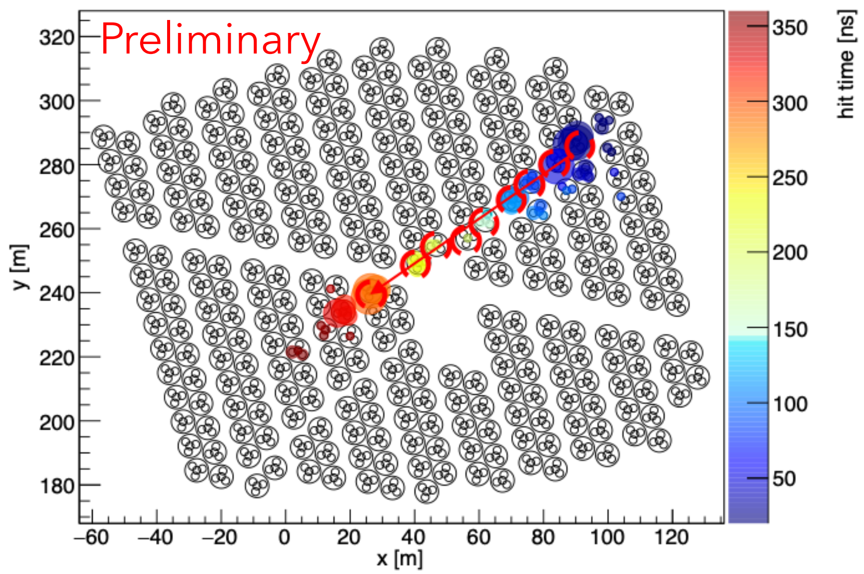
Neighboring WCDs with hits

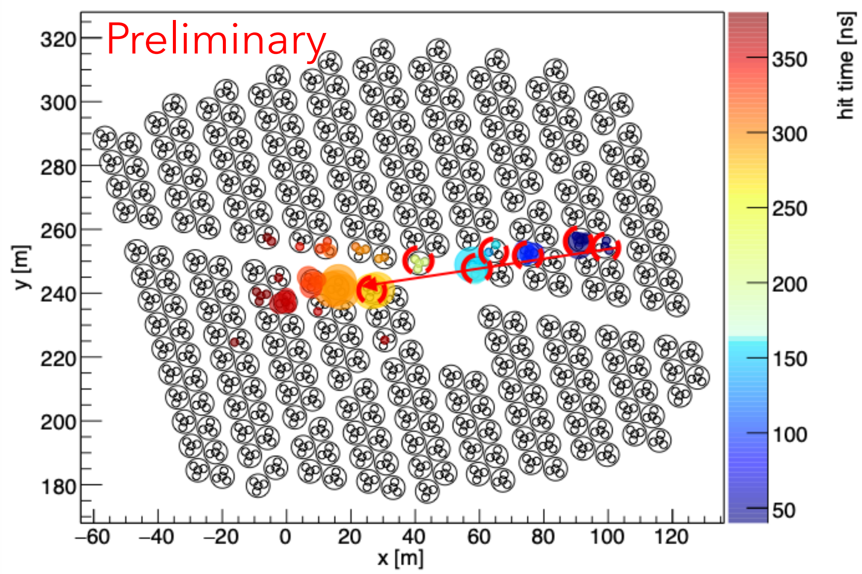
Does it happen in simulations?





The red circles indicate the path of the simulated muons





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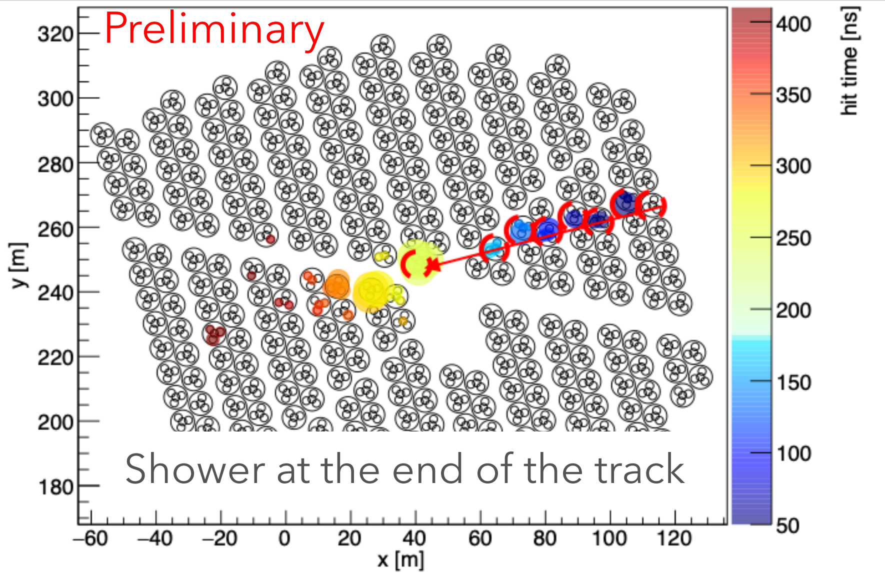
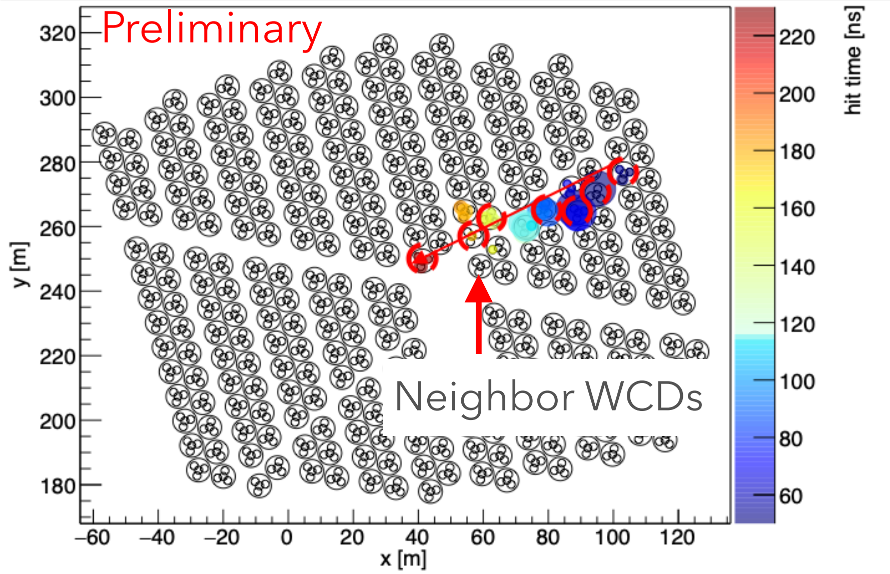
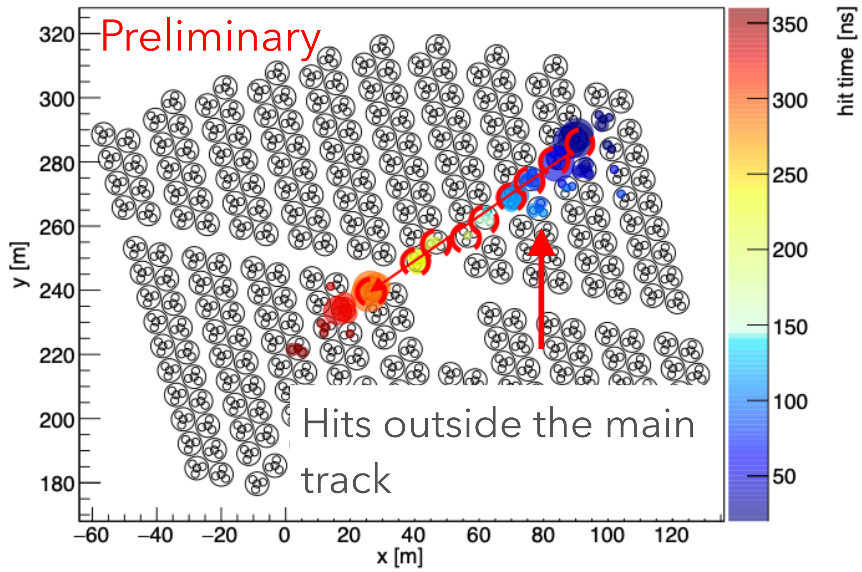


Shower at the end of the track

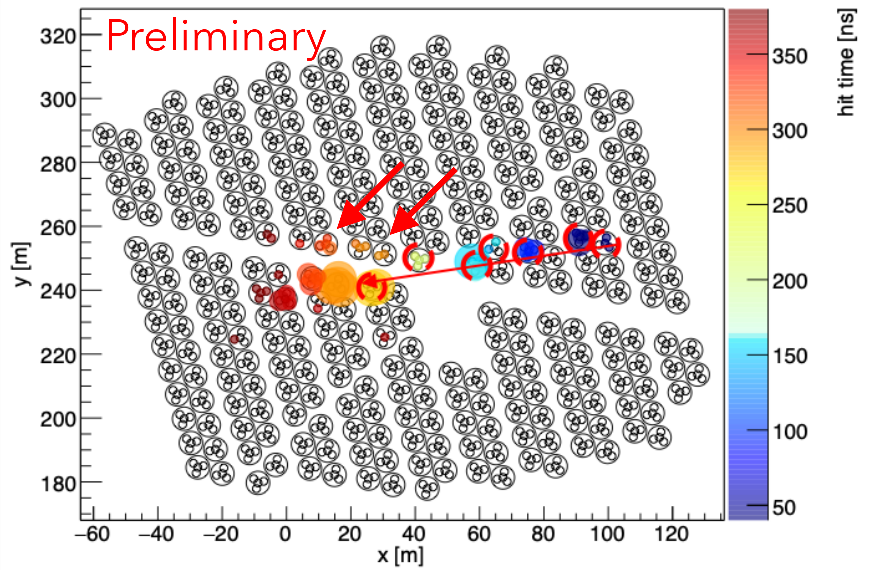


Neighbor WCDs

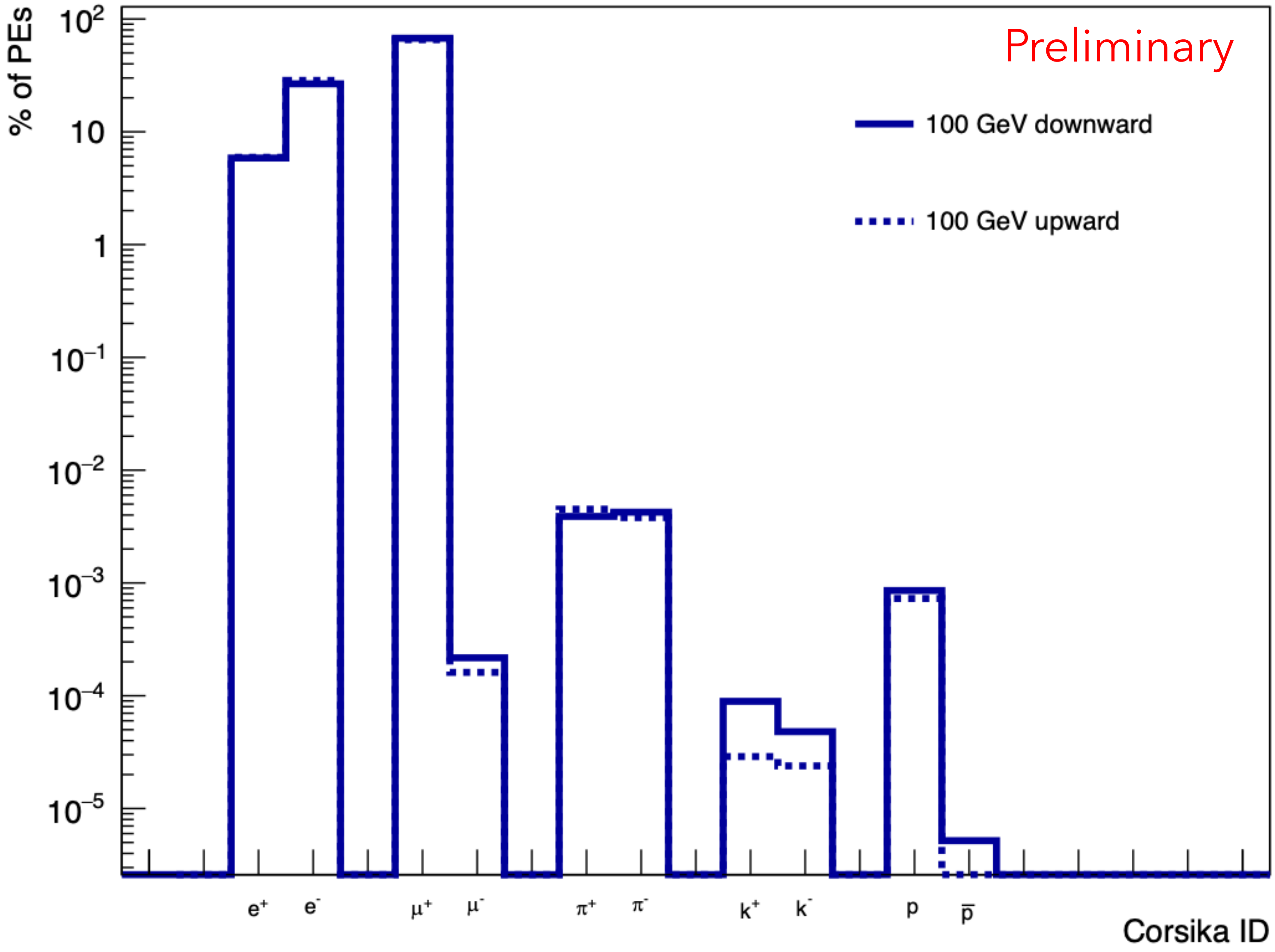
The red circles indicate the path of the simulated muons



Hits outside the main track

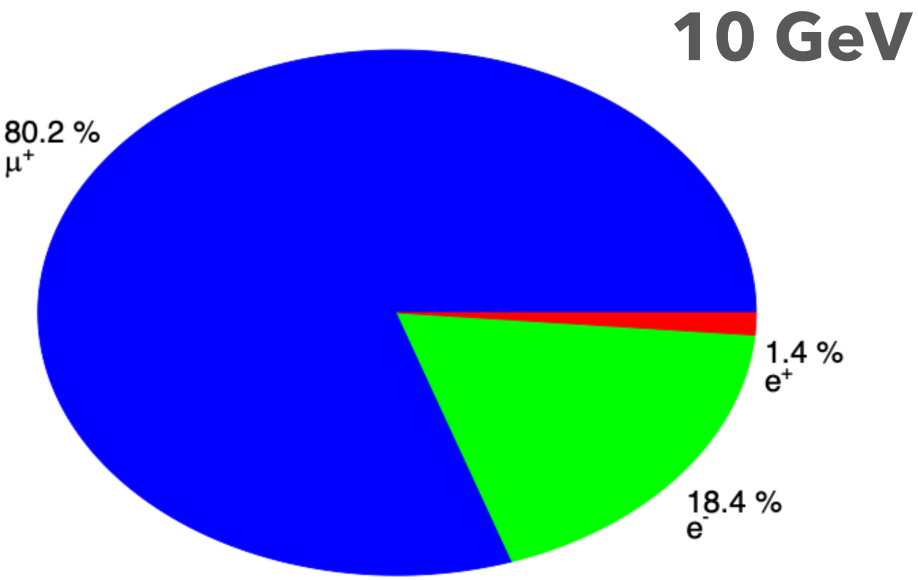


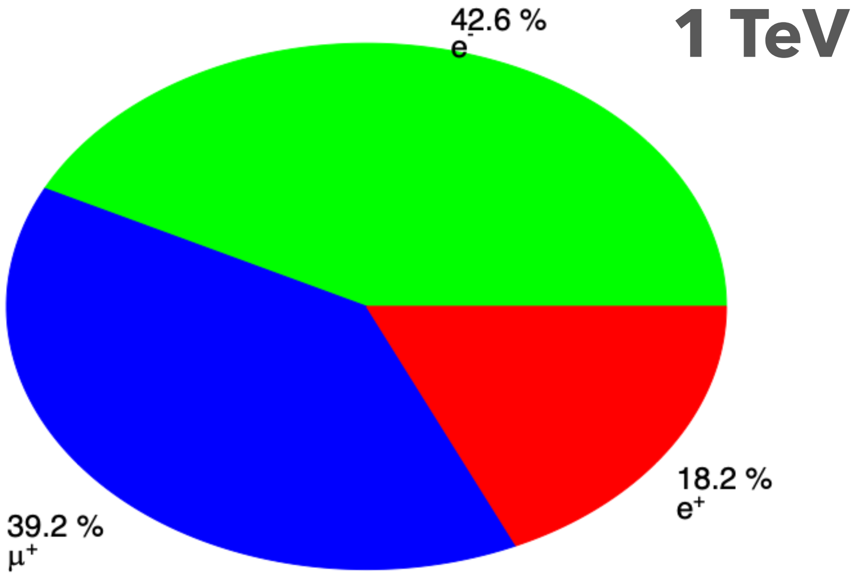
Cherenkov light sources



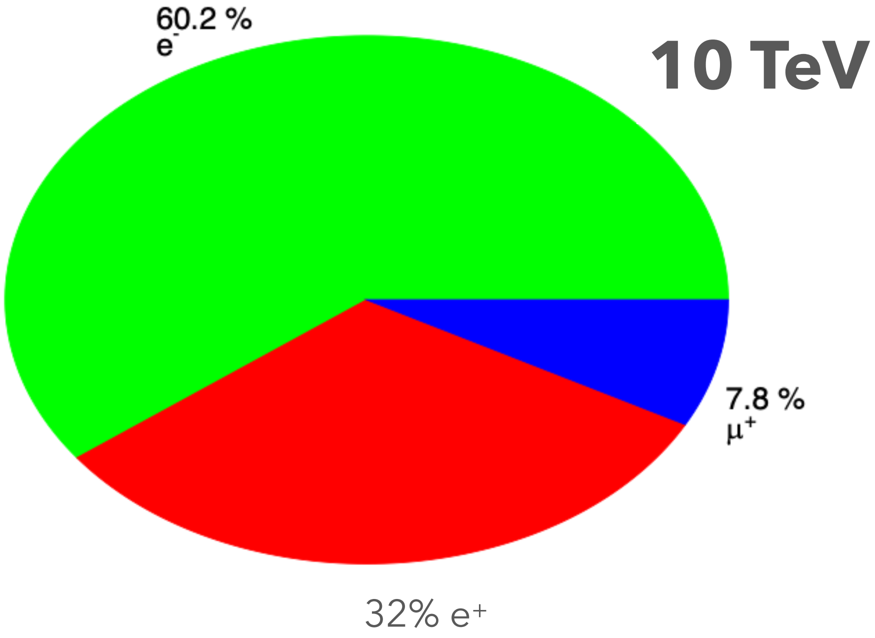
The injected particles are only positive muons

Cherenkov light sources

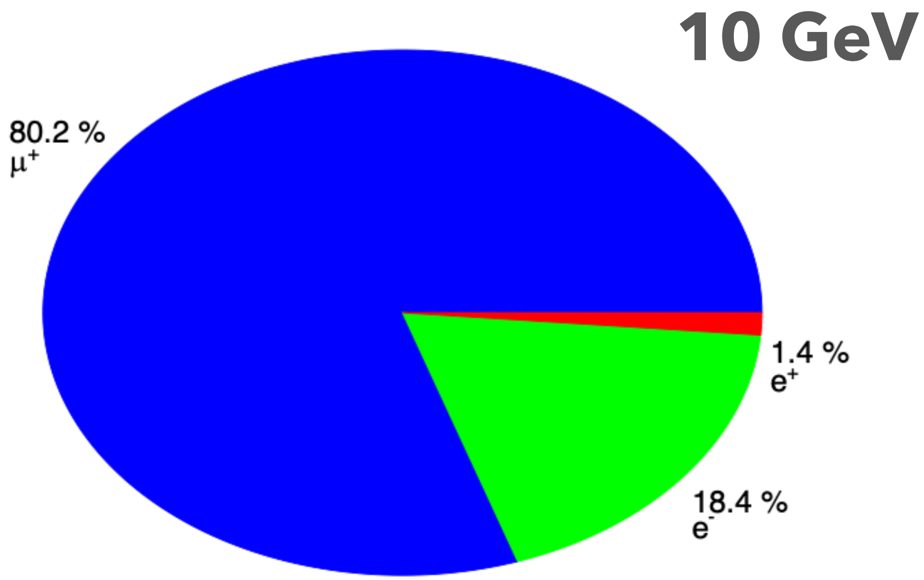


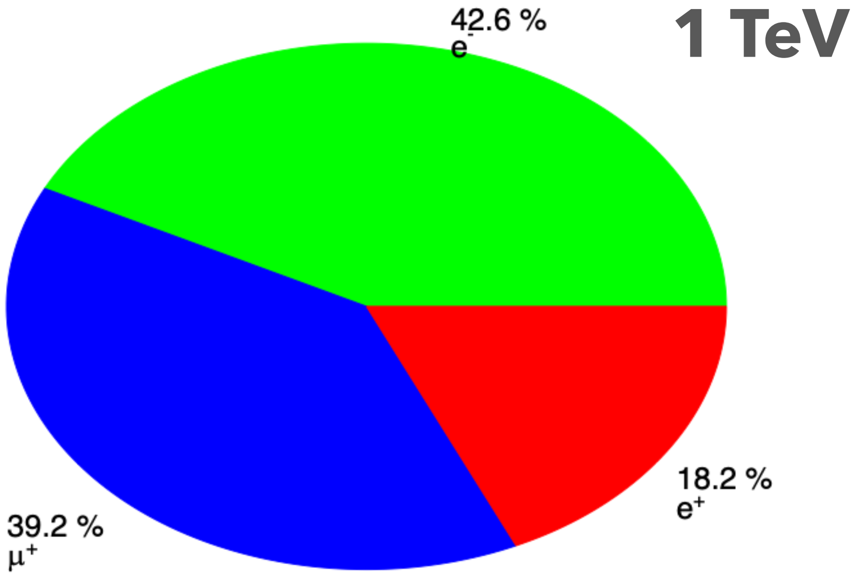


As the muon energy increases, it produces more secondary particles

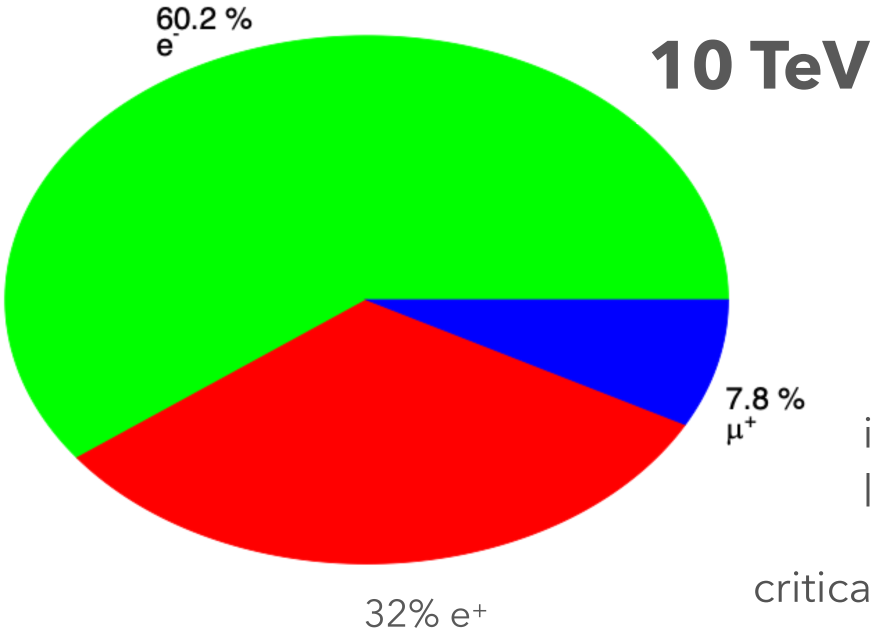


Cherenkov light sources


10 GeV


1 TeV

As the muon energy increases, it produces more secondary particles


10 TeV

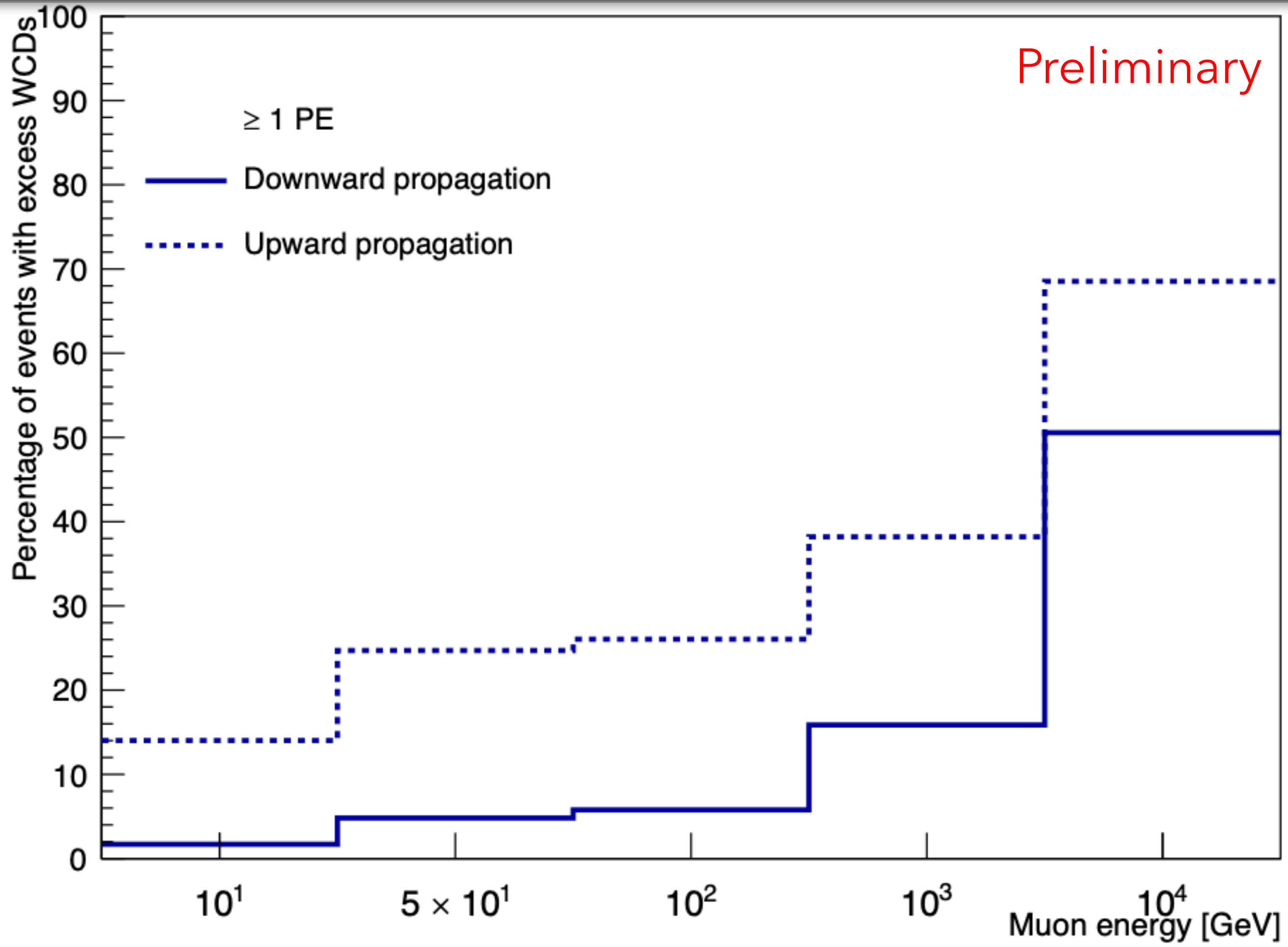
$$-\frac{dE_\mu}{dX} = a + bE_\mu$$

ionization loss

radiative loss (> 100 GeV)

critical energy ~ 500 GeV in rock

Hits outside a linear track



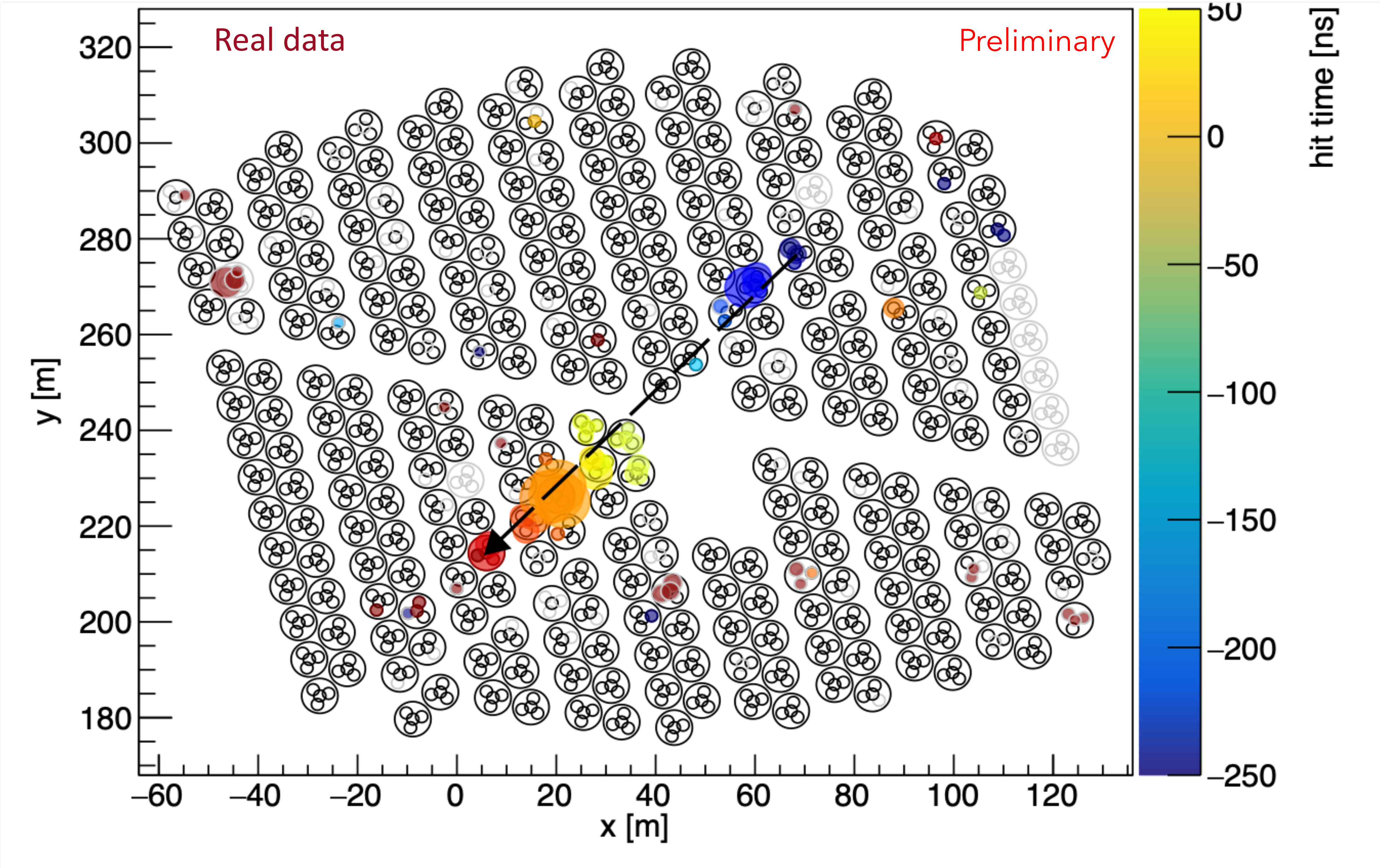
These simulations do not include noise from vertical muons

Excess WCDs: $WCDs^T$ - $WCDs^P$

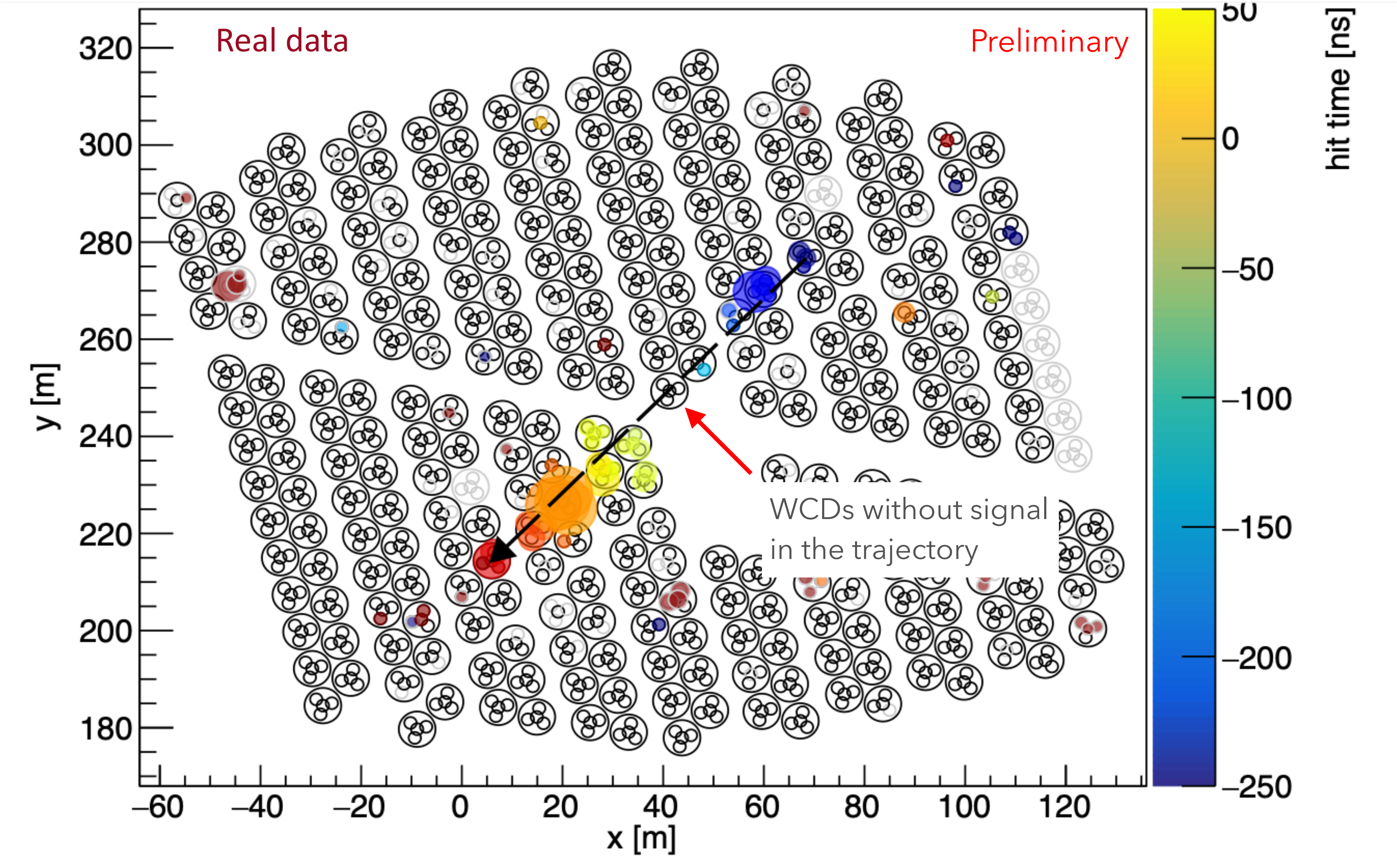
$WCDs^T$: Number of WCDs with at least 1 simulated PE

$WCDs^P$: Number of WCDs that intersect the path of the simulated muon

Tracks with discontinuities

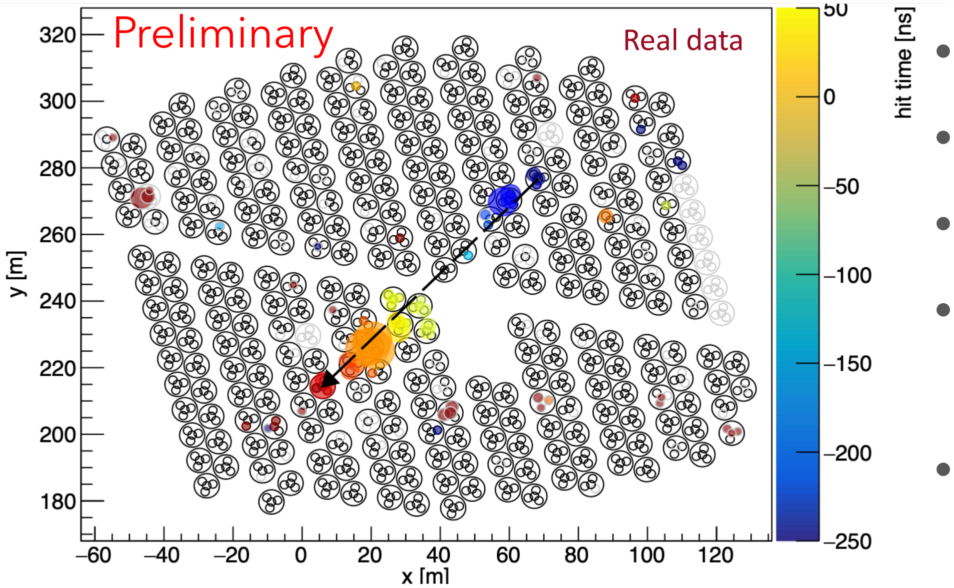


Tracks with discontinuities

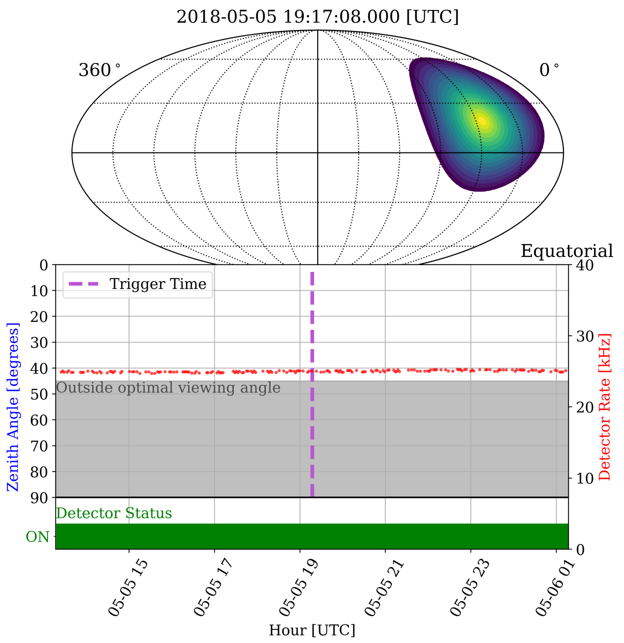


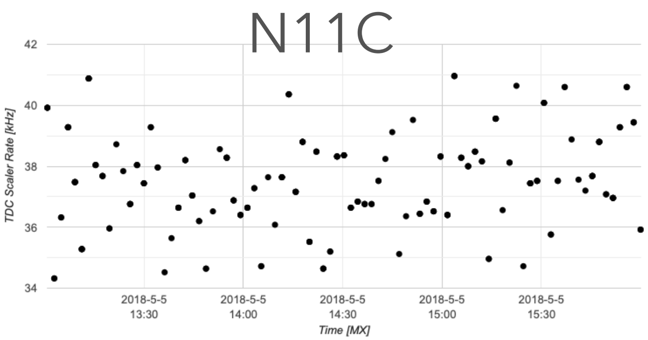
WCDs without signal in the trajectory

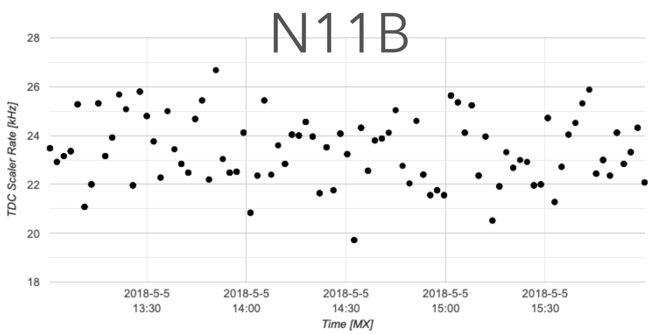
Tracks with discontinuities

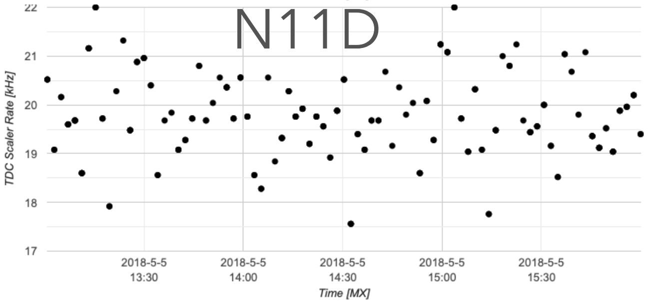


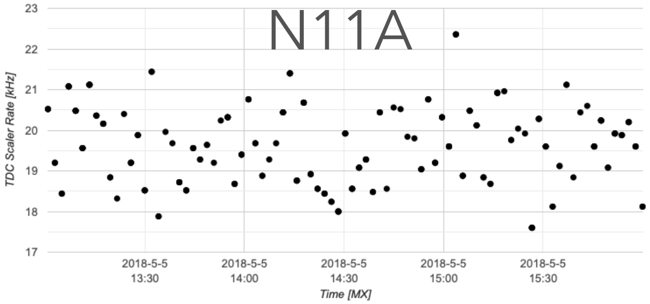
- Run: 7934
- May 5 2018, 19:17:08 UTC, 14:17:08 MX
- Discontinuity: hits in N11
- PMTs N11A-D taking good quality data in the current run
- No signals at the lowest level data (raw)



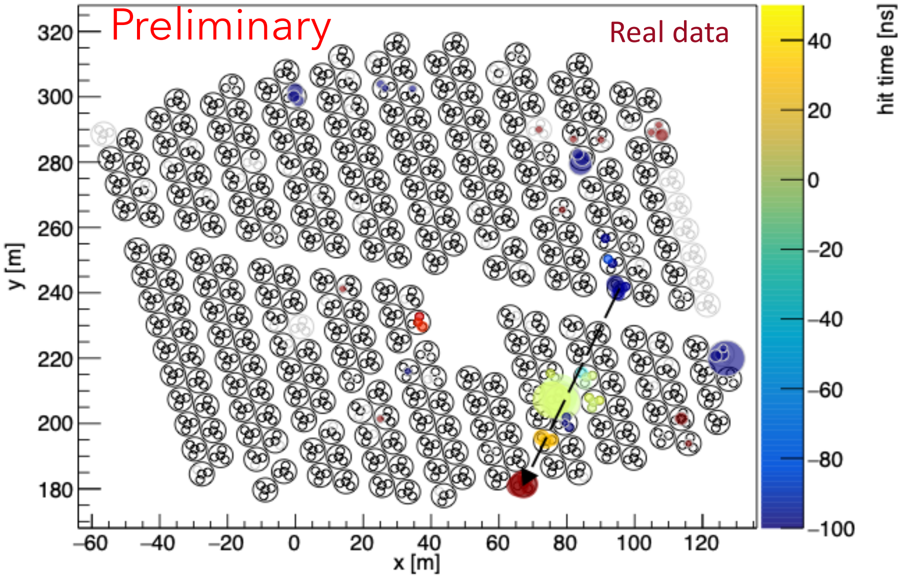




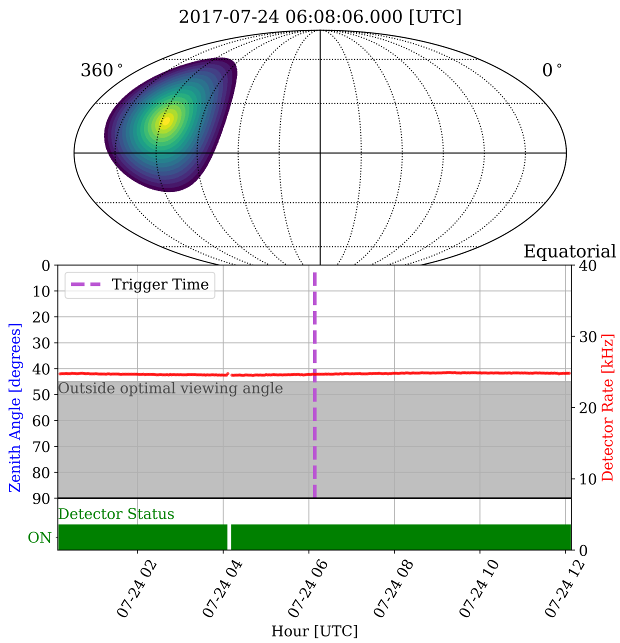


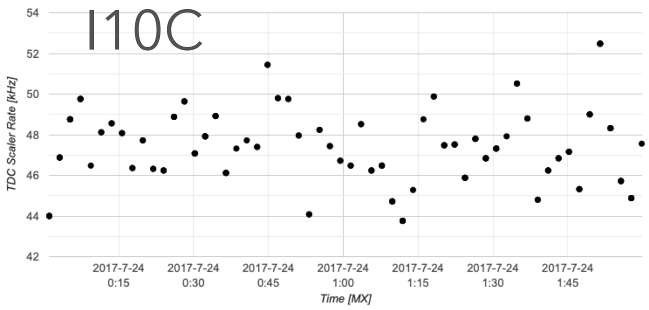


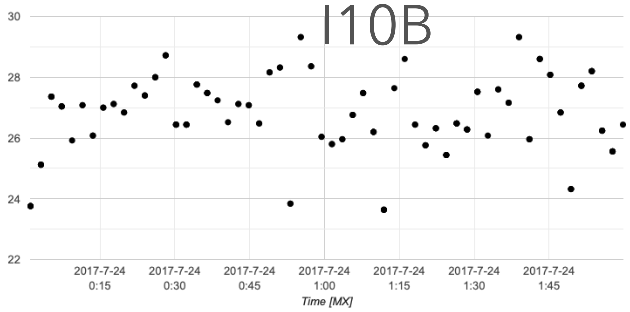
Tracks with discontinuities

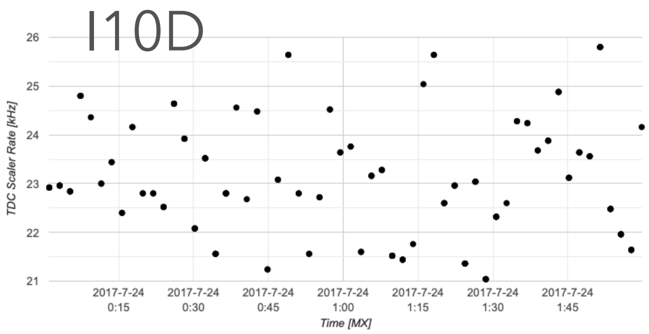


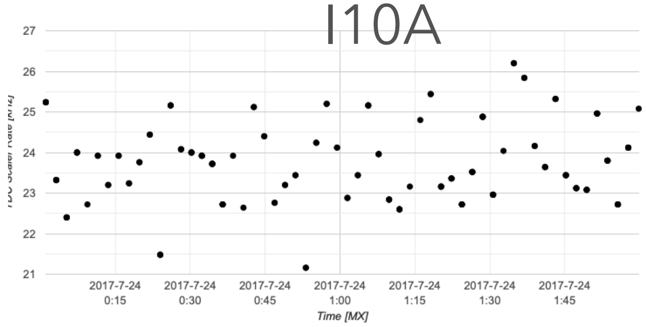
- Run: 6998
- July 24, 2017, 06:08:06 UTC, 01:08:06 MX
- Discontinuity: hits in I10
- PMTs I10A-D taking good quality data in the current run
- No signals at the lowest level data (raw)







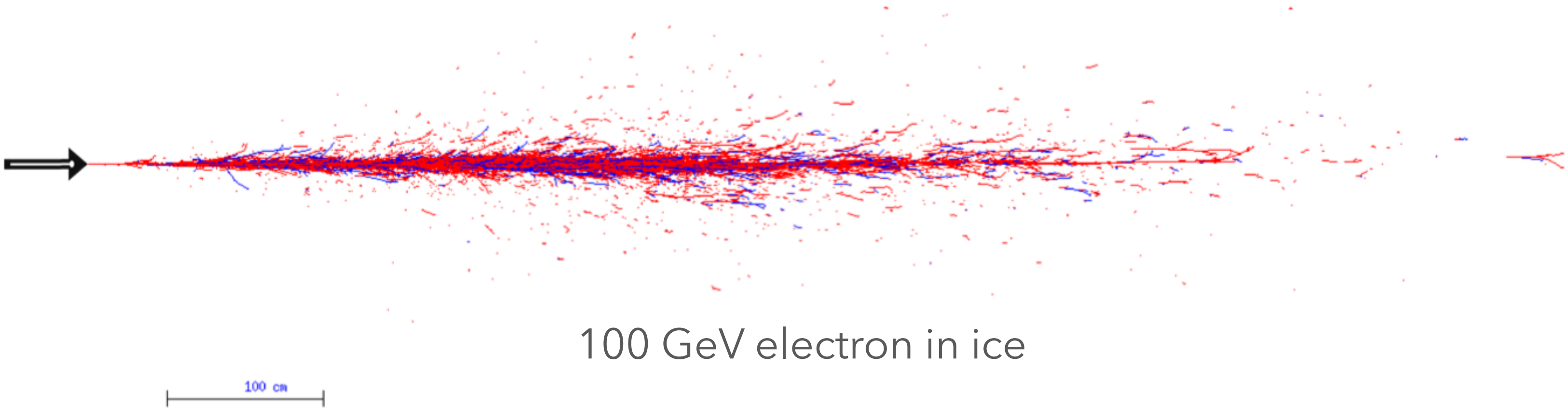




Light production fluctuations (muons)

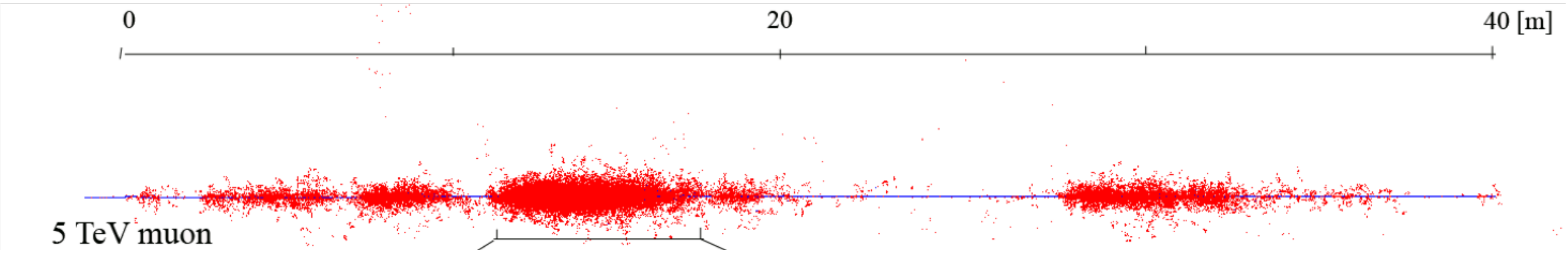
- The muon energy loss is not uniform
- Each HAWC WCD has a diameter of 7.3 m

Red = negative
Blue = positive



100 GeV electron in ice

L. Rädel, C. Wiebusch, Astroparticle Physics (2013) 102-113



Water

L. Rädel, C. Wiebusch, Astroparticle Physics (2012) 53-67

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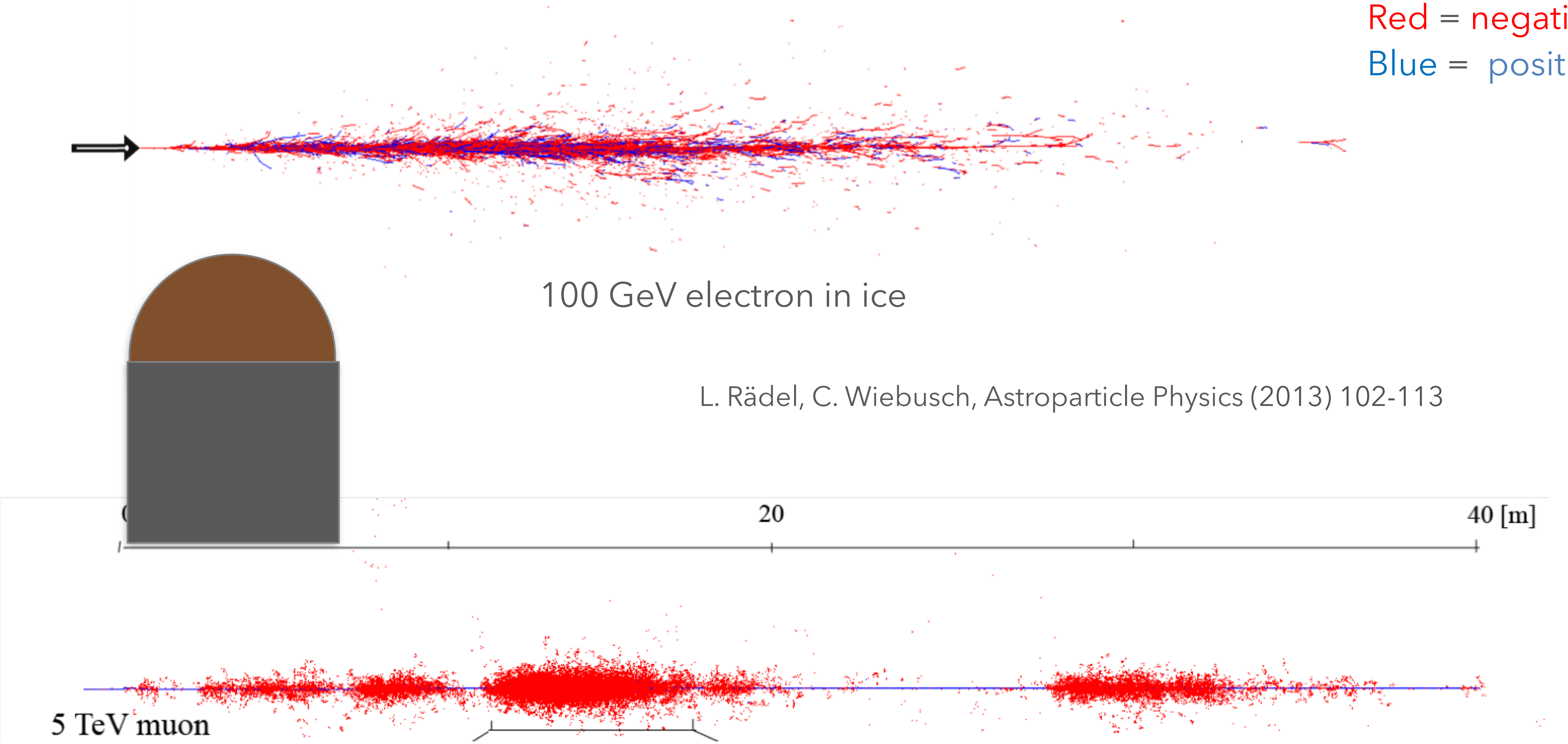


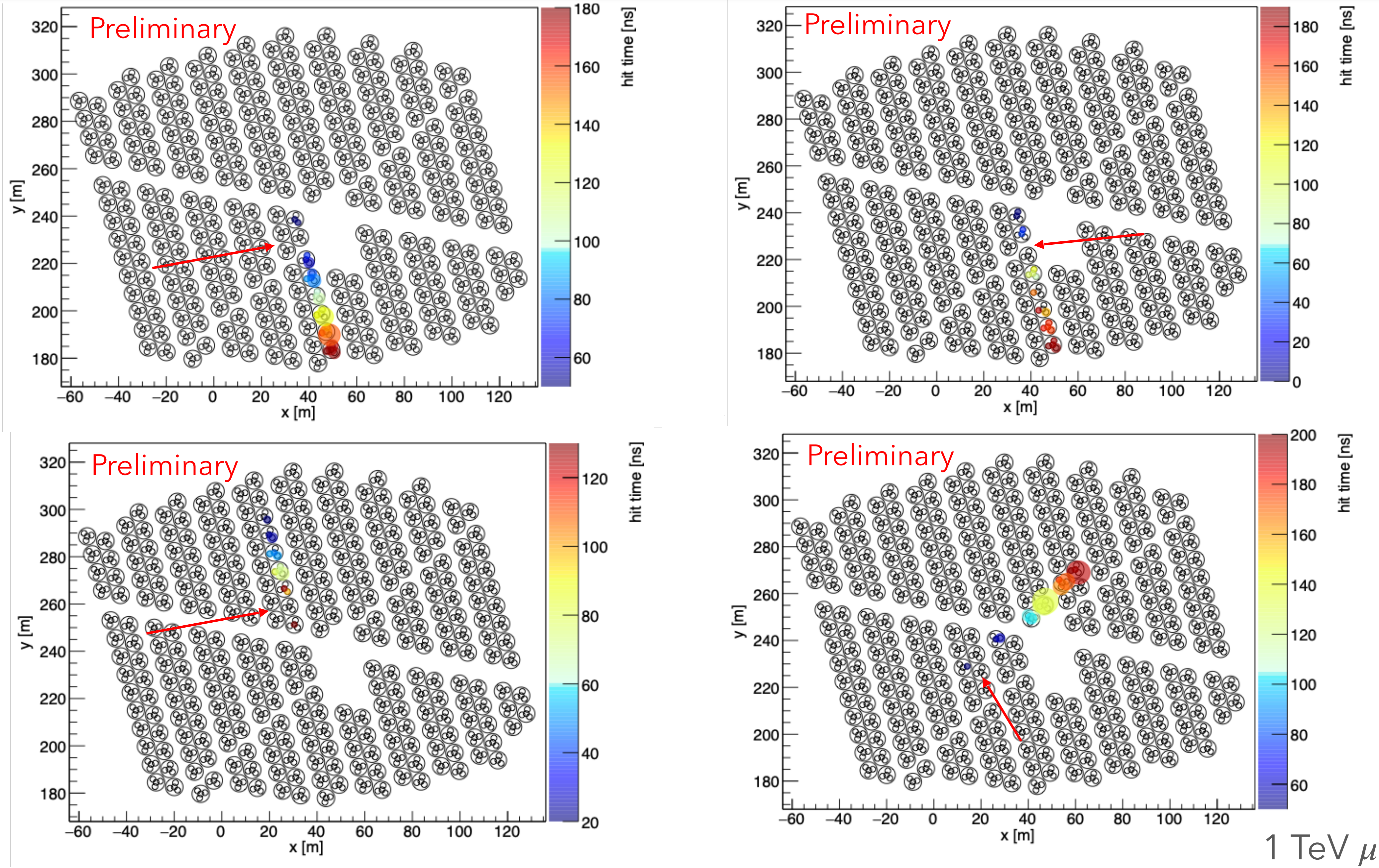
100 GeV electron in ice

L. Rädel, C. Wiebusch, Astroparticle Physics (2013) 102-113

Water

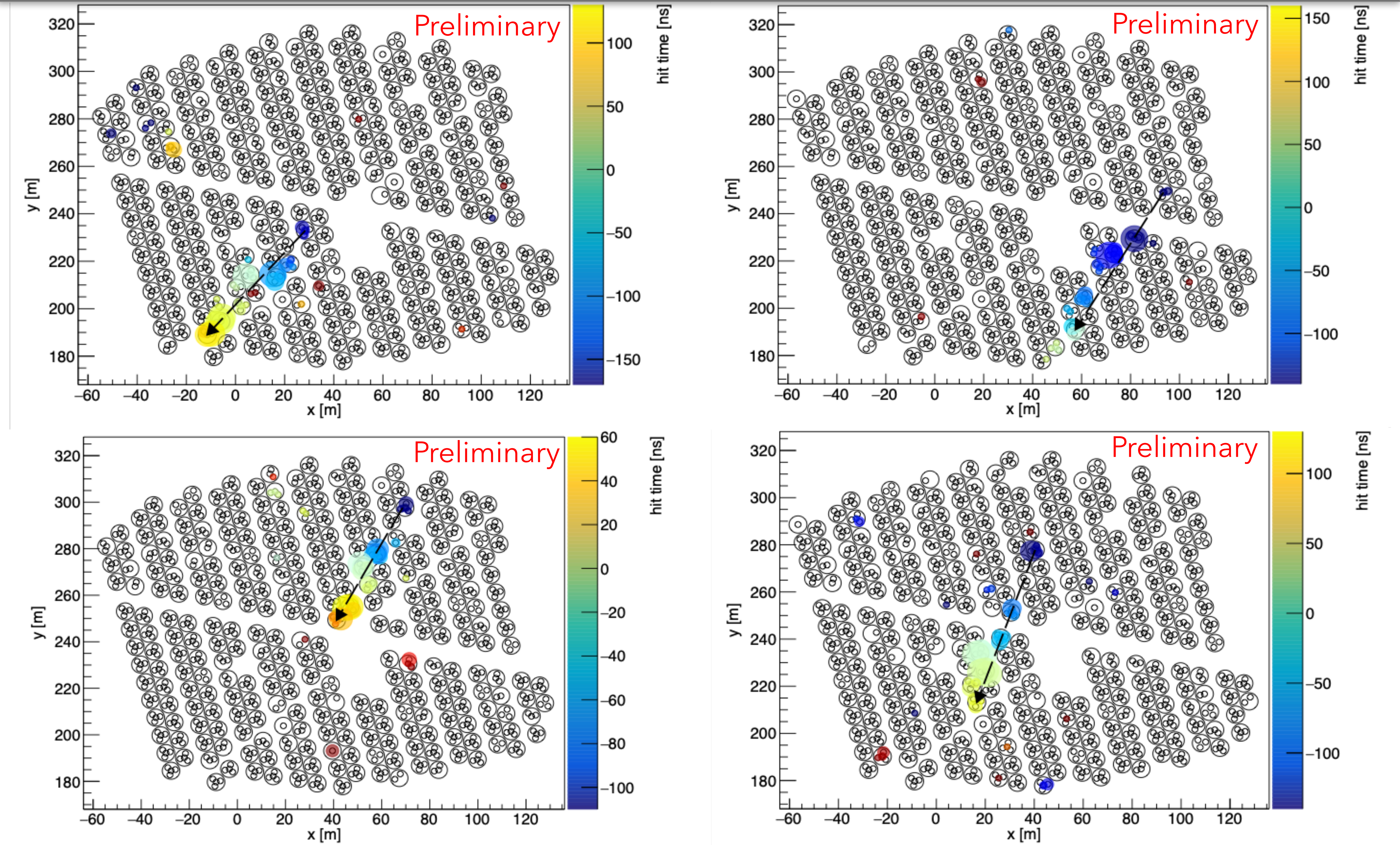
L. Rädel, C. Wiebusch, Astroparticle Physics (2012) 53-67

Does it happen in simulations?



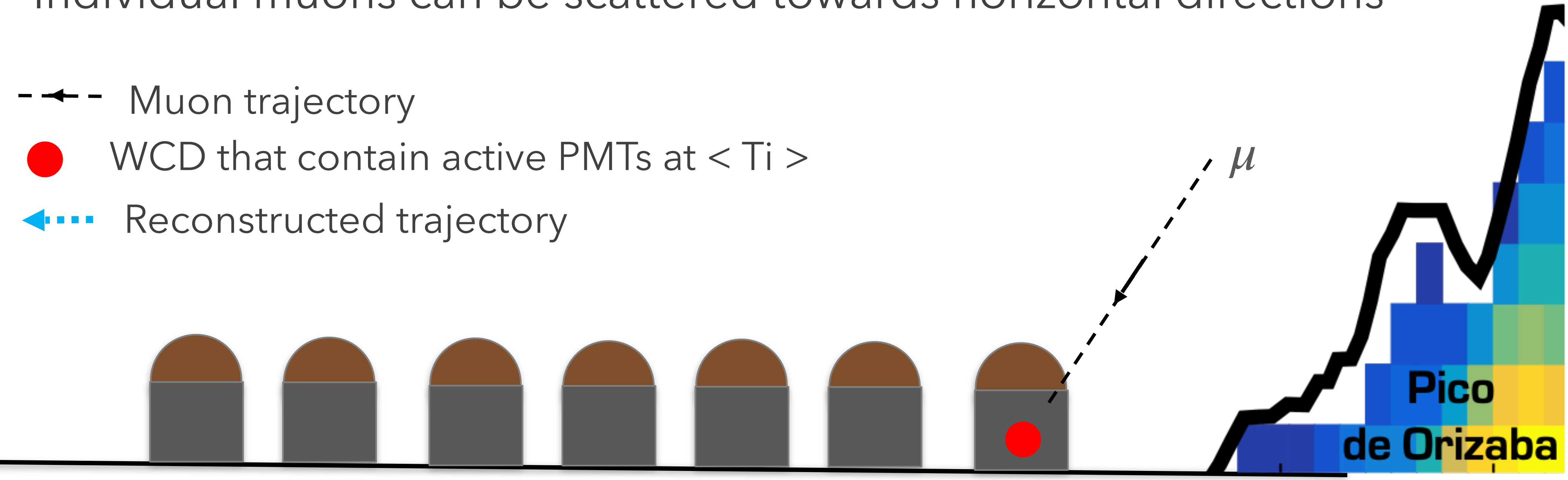
1 TeV μ

Real data tracks pointing to the mountain



2) Scattered muon background

Individual muons can be scattered towards horizontal directions



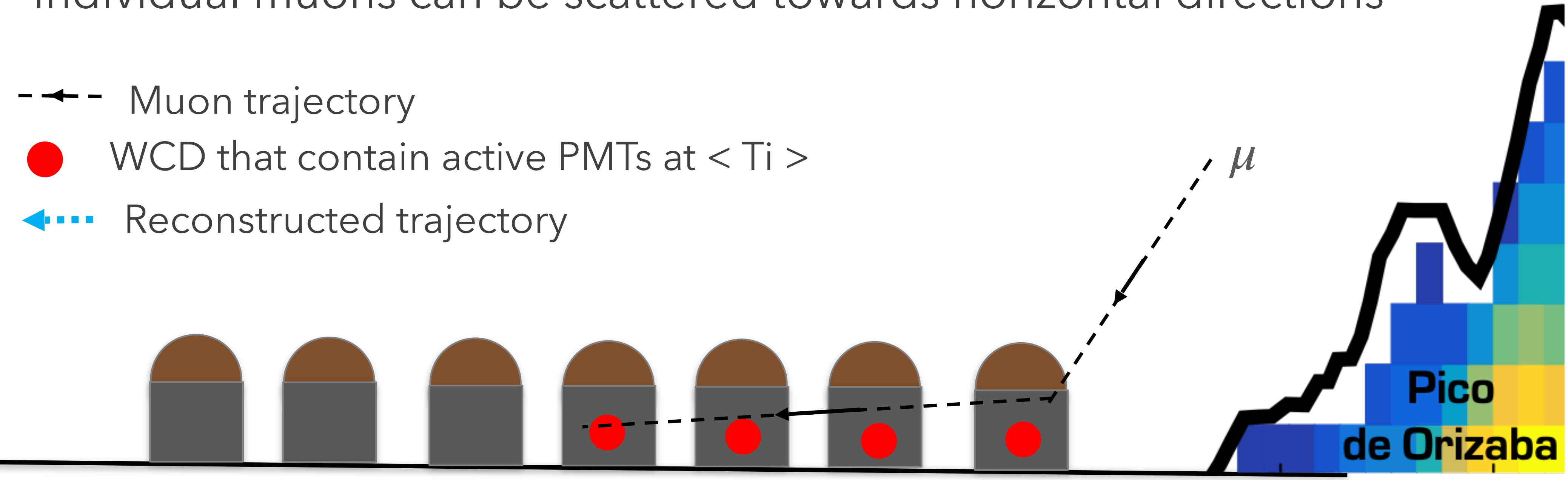
- - ◀ - - Muon trajectory

● WCD that contain active PMTs at < Ti >

◀····· Reconstructed trajectory

2) Scattered muon background

Individual muons can be scattered towards horizontal directions



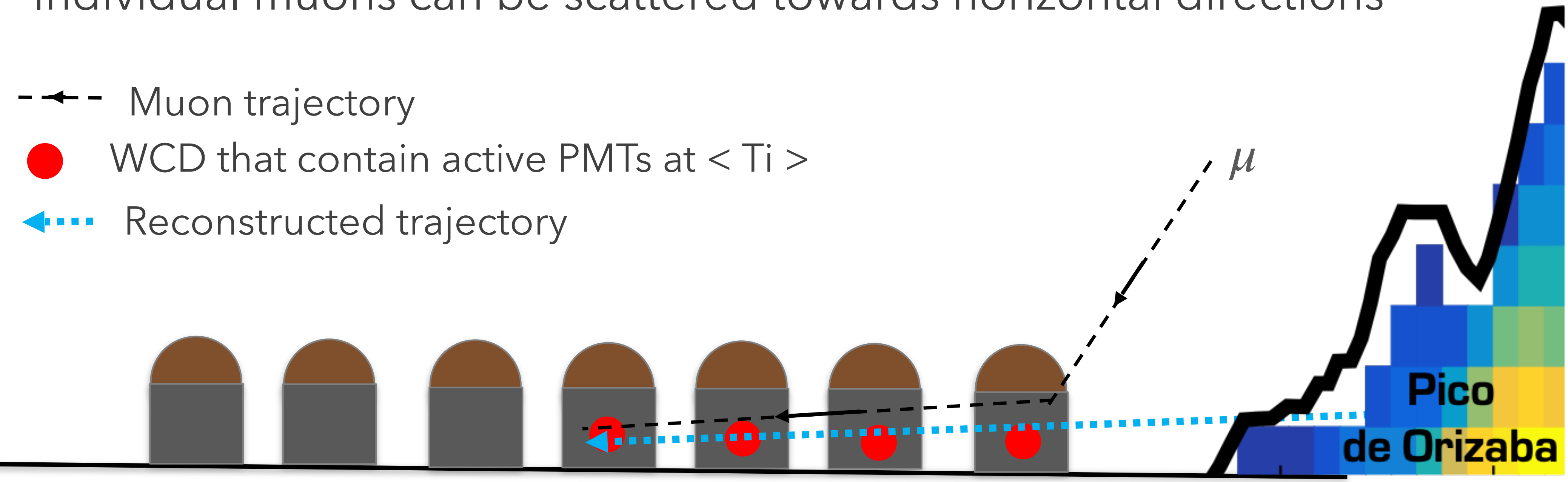
- - ← - - Muon trajectory

● WCD that contain active PMTs at < Ti >

◀∙∙∙ Reconstructed trajectory

2) Scattered muon background

Individual muons can be scattered towards horizontal directions



- - ◂ - - Muon trajectory

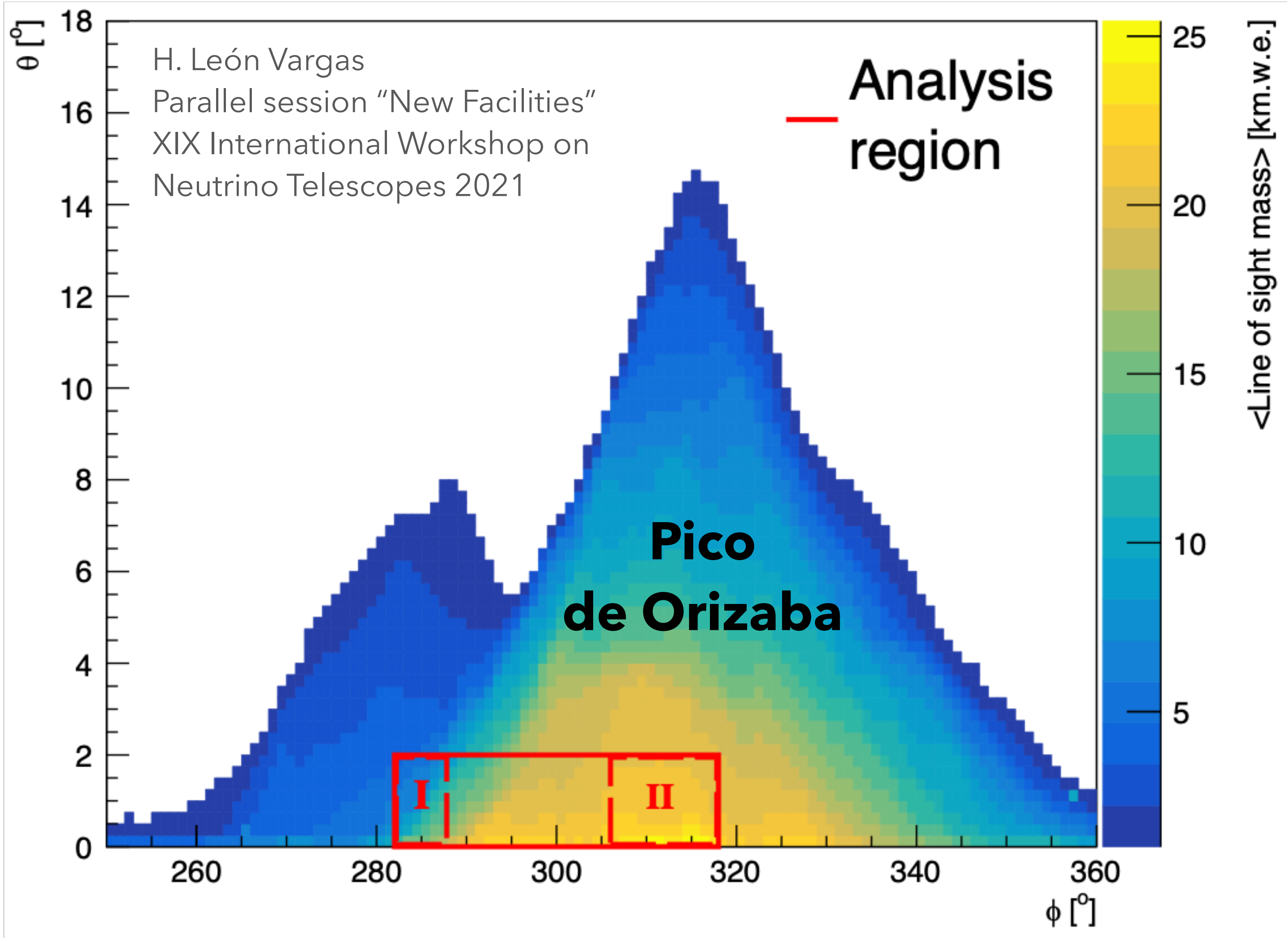
● WCD that contain active PMTs at < Ti >

◂ · · · Reconstructed trajectory

- This background is strongly energy dependent, i.e. < 20 GeV[1]
- The scattering probability depends on the initial propagation elevation, i.e. muons closer to the horizon are more easily scattered

[1] The muon background from backscattered cosmic-ray muon in a Surface Neutrino detector. Europhys. Lett. 14 (1991) 181-186

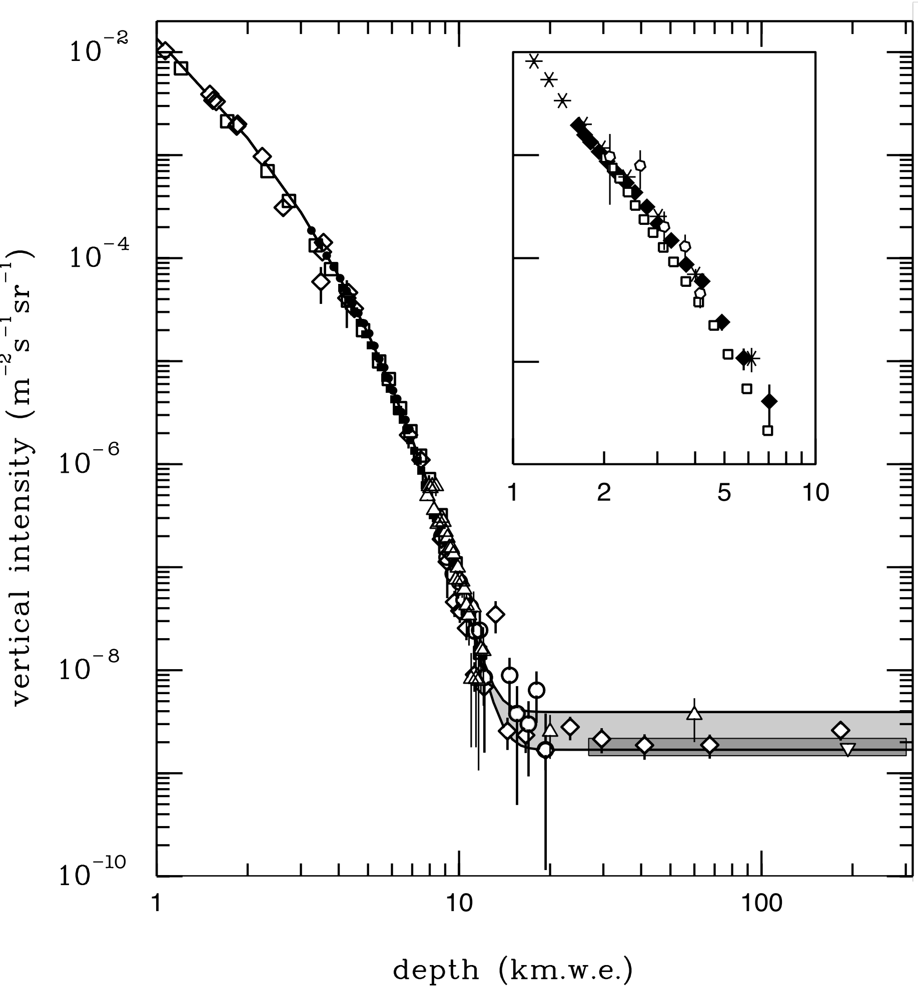
Scattering model



- ○ Profile of the volcano as seen from the center of HAWC
- ○ Conversion from geometry to LOSM using the average density of andesitic rocks ~ 2.6 g/cm^3

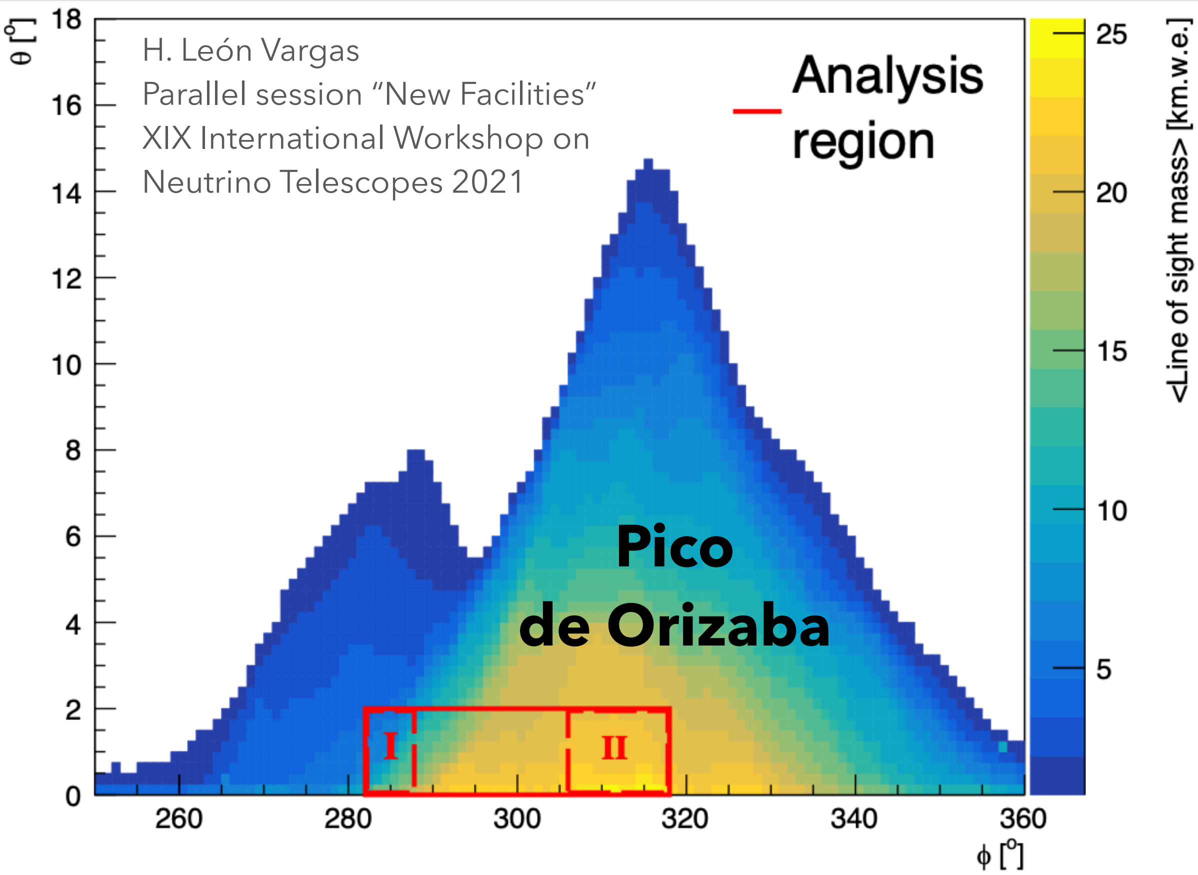
- The base of the volcano provides a region with very large LOSM
- The analysis is restricted to low elevations [0°, 2°]

Scattering model



Particle Data Group

Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

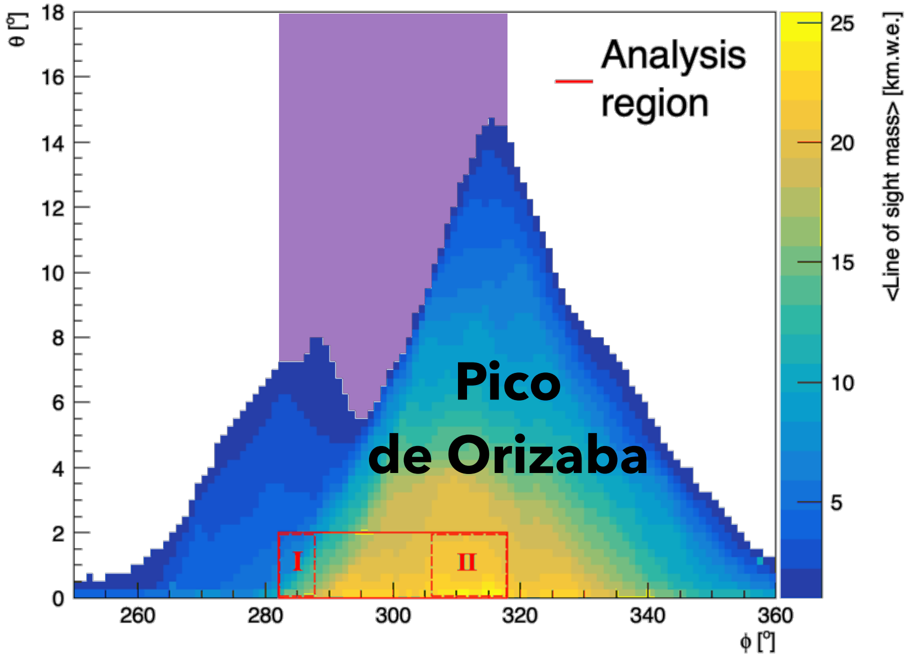


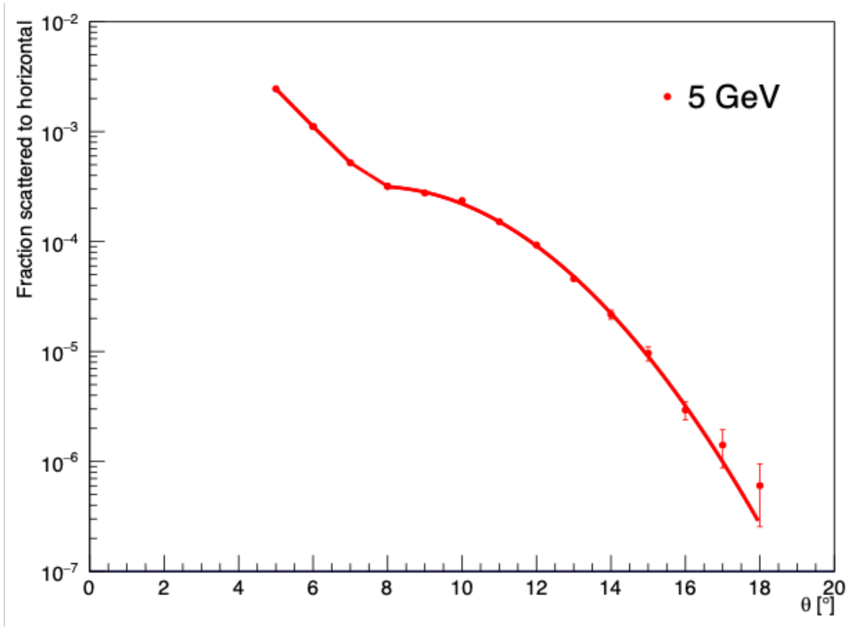
H. León Vargas

Parallel session "New Facilities"

XIX International Workshop on Neutrino Telescopes 2021

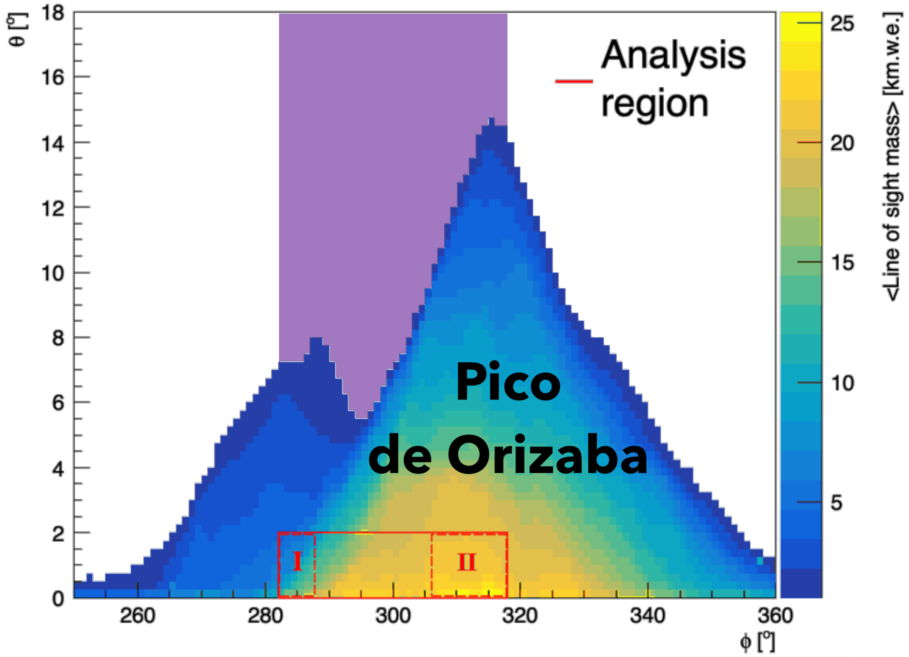
Scattering model

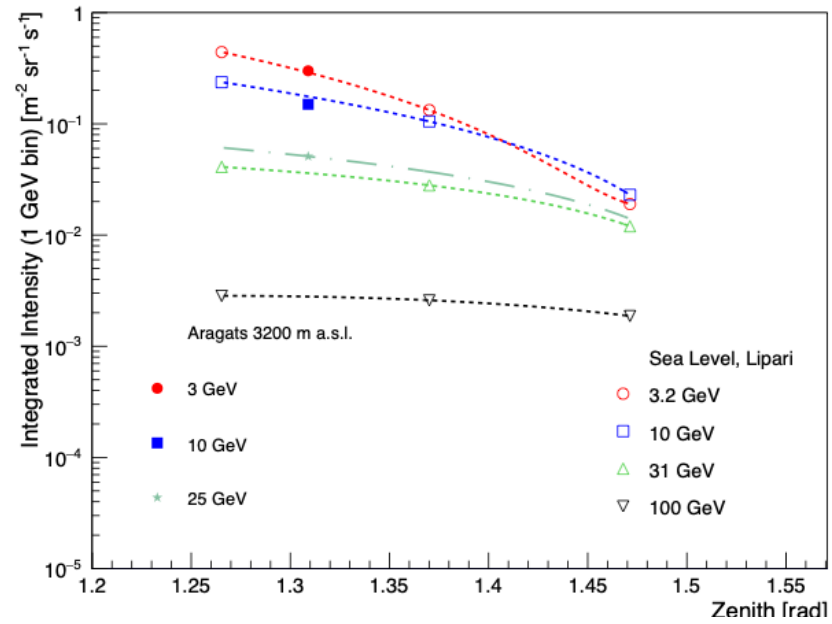




- The scattered muons that end in the analysis region come from the region not shielded by the volcano (purple shade).
- The scattering probability was evaluated using the GEANT4 simulation of HAWC.

Scattering model





- The scattered muons that end in the analysis region come from the region not shielded by the volcano (purple shade).
- The scattering probability was evaluated using the GEANT4 simulation of HAWC.
- Used data from Aragats[1] and the model from P. Lipari[2] to parametrize the zenith dependence of the muon intensity

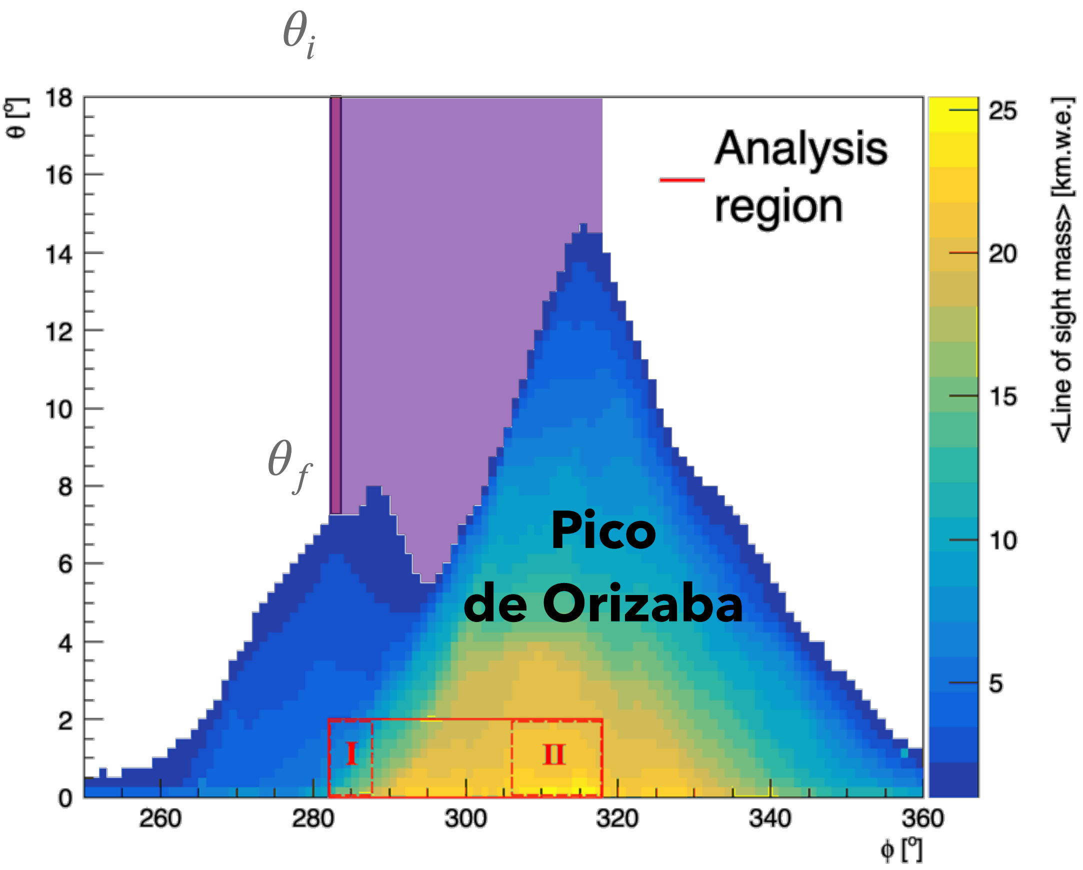
[1] Yerevan Physics Institute http://crd.yerphi.am/Muons

[2] Astropart. Phys. 1 (1993) 195-227

Scattering model

We calculate the scattered intensity in steps of 1^{o} in azimuth and integrate over the region not shielded by the volcano

$$\mathrm{F}^{\phi}_{\mathrm{Scatt}}(\mathrm{E} = \ 5\ \mathrm{GeV}) = \frac{\pi}{180}\int_{\theta_{\mathrm{i}}}^{\theta_{\mathrm{f}}} \mathrm{I}_{\mathrm{hor}}(\mathrm{E} = \ 5\ \mathrm{GeV}, \theta) \times \mathrm{P}_{\mathrm{scatt}}(\mathrm{E} = \ 5\ \mathrm{GeV}, \theta) \times \sin\theta \mathrm{d}\theta$$



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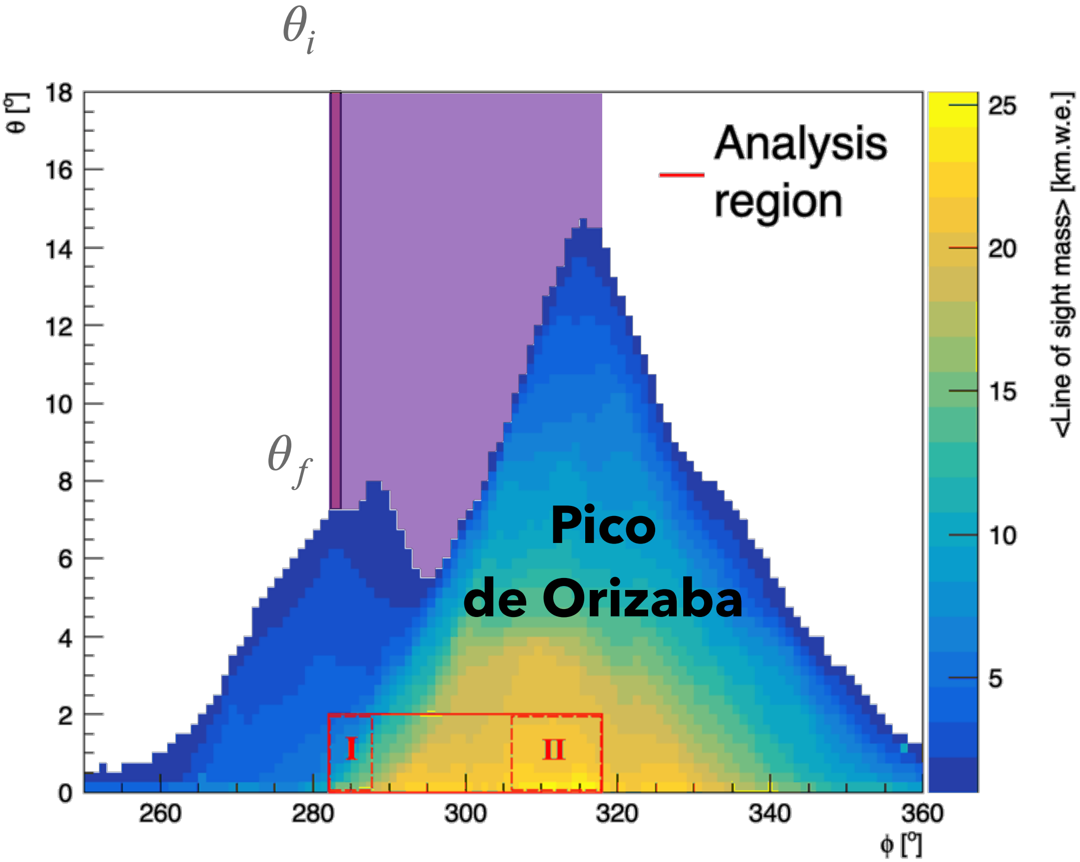


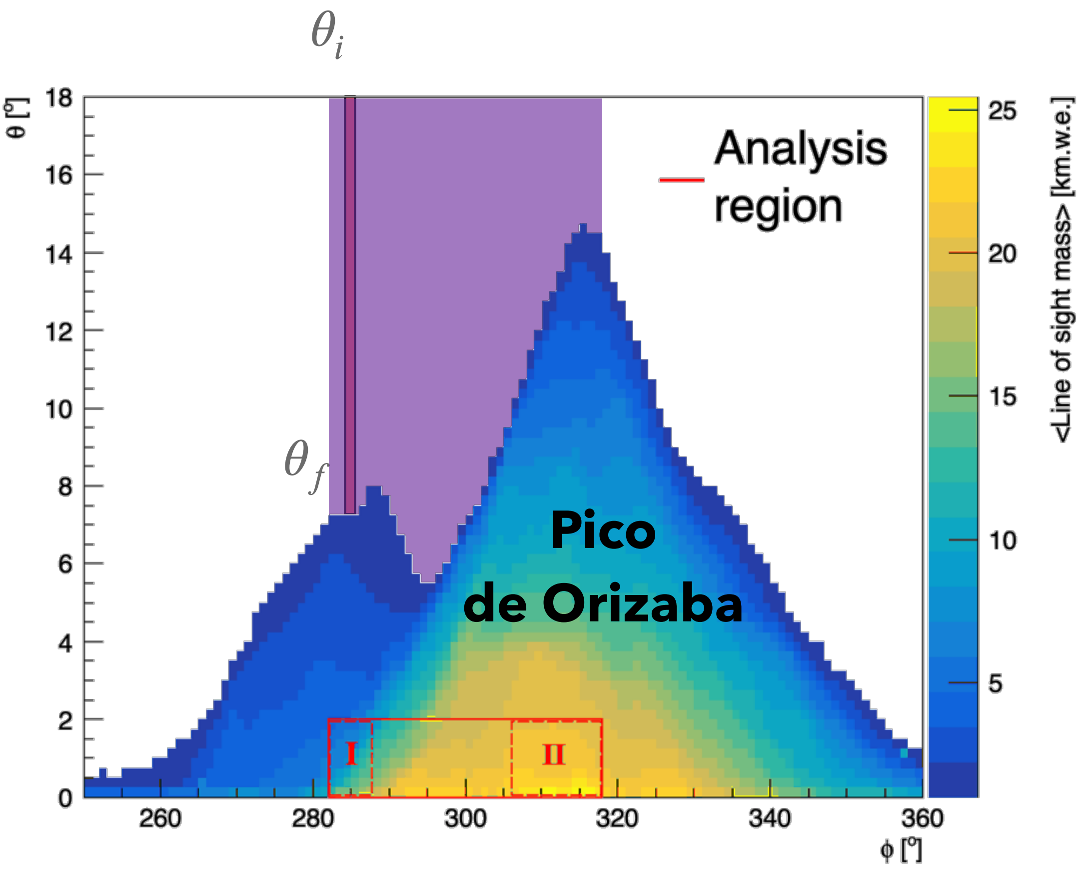
For region I (6^{o} in azimut):

$$\mathrm{F}^{\mathrm{I}}_{\mathrm{Scatt}}(\mathrm{E}= 5\ \mathrm{GeV}) = \sum_{\phi=1}^{\phi=6} \mathrm{F}^{\phi}_{\mathrm{Scatt}}(\mathrm{E}= 5\ \mathrm{GeV})$$

Scattering model

We calculate the scattered intensity in steps of 1^{o} in azimuth and integrate over the region not shielded by the volcano

$$\mathrm{F}^{\phi}_{\mathrm{Scatt}}(\mathrm{E}=\ 5\ \mathrm{GeV})=\frac{\pi}{180}\int_{\theta_{\mathrm{i}}}^{\theta_{\mathrm{f}}}\mathrm{I}_{\mathrm{hor}}(\mathrm{E}=\ 5\ \mathrm{GeV},\theta)\times\mathrm{P}_{\mathrm{scatt}}(\mathrm{E}=\ 5\ \mathrm{GeV},\theta)\times\sin\theta\mathrm{d}\theta$$



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Scattering model

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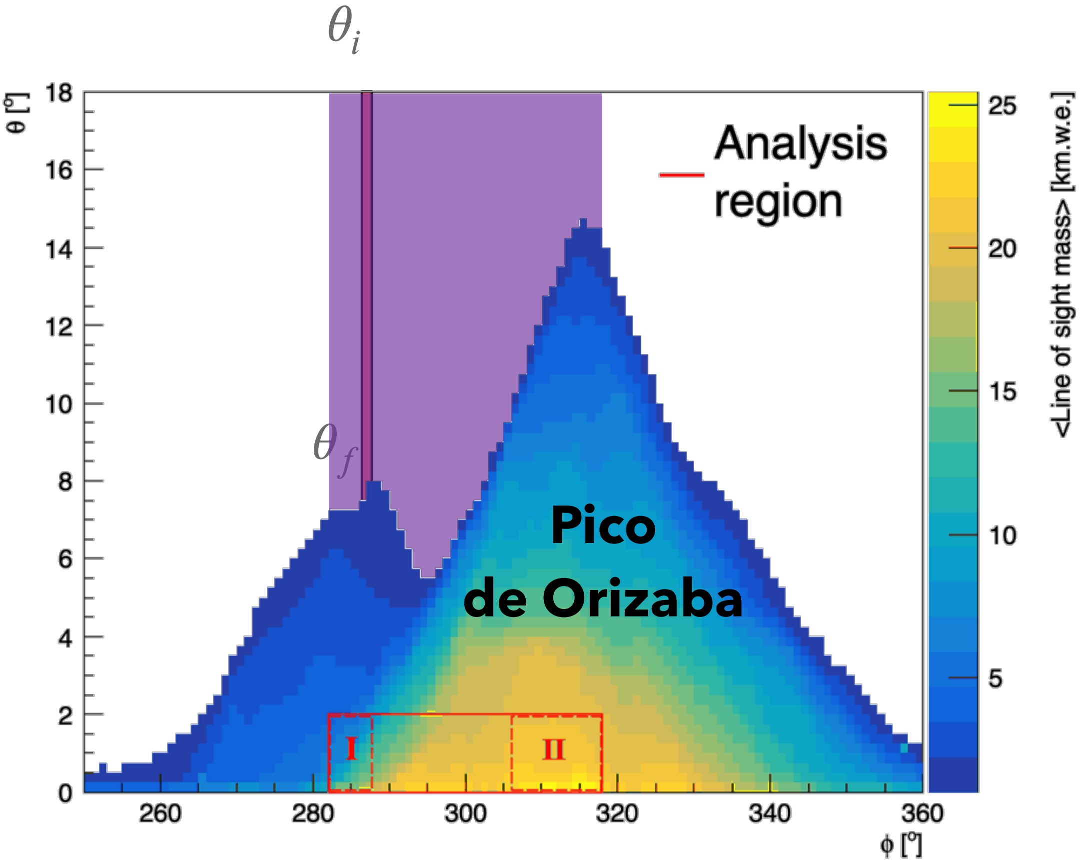
$$\mathrm{F}^{\phi}_{\mathrm{Scatt}}(\mathrm{E}=\ 5\ \mathrm{GeV})=\frac{\pi}{180}\int_{\theta_{\mathrm{i}}}^{\theta_{\mathrm{f}}}\mathrm{I}_{\mathrm{hor}}(\mathrm{E}=\ 5\ \mathrm{GeV},\theta)\times\mathrm{P}_{\mathrm{scatt}}(\mathrm{E}=\ 5\ \mathrm{GeV},\theta)\times\sin\theta\mathrm{d}\theta$$



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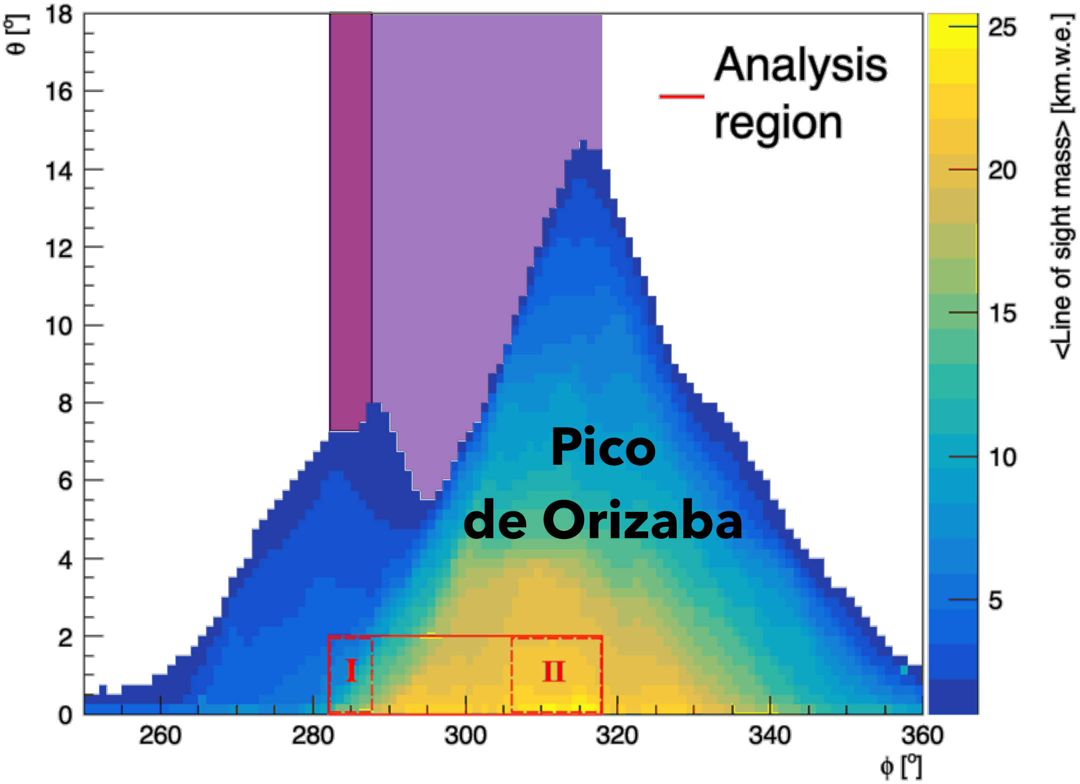

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Scattering model

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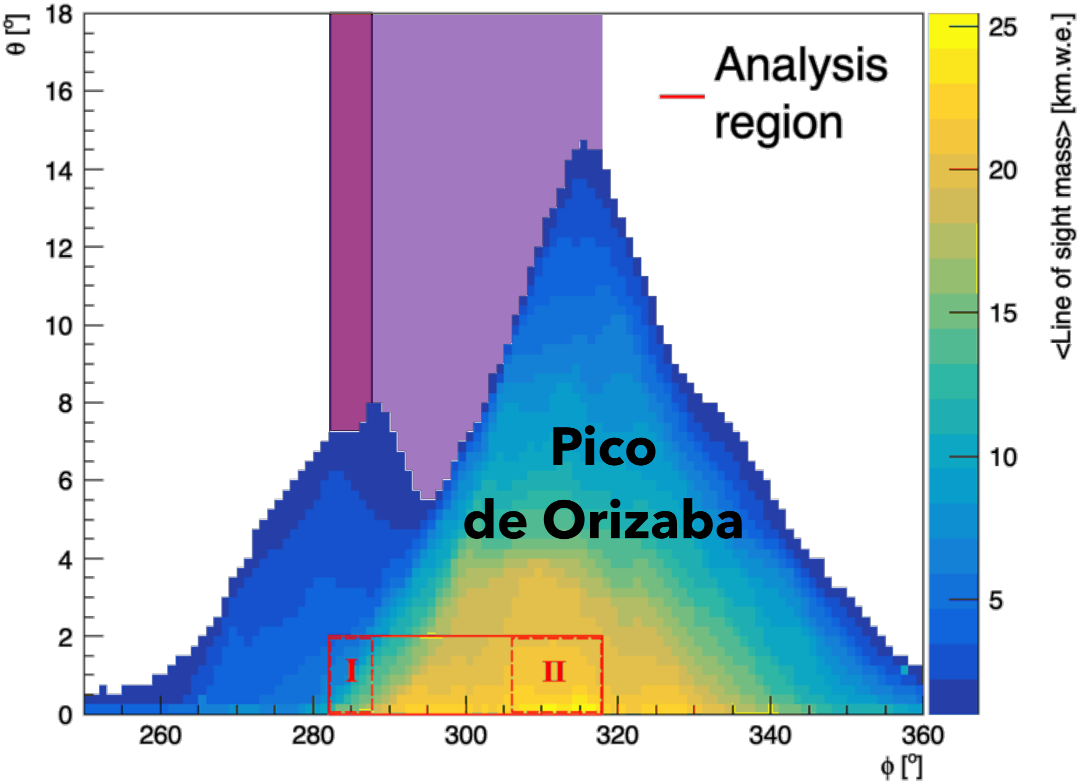
$$\mathrm{F}^{\phi}_{\mathrm{Scatt}}(\mathrm{E}=\ 5\ \mathrm{GeV}) = \frac{\pi}{180}\int_{\theta_{\mathrm{i}}}^{\theta_{\mathrm{f}}} \mathrm{I}_{\mathrm{hor}}(\mathrm{E}=\ 5\ \mathrm{GeV},\theta)\times \mathrm{P}_{\mathrm{scatt}}(\mathrm{E}=\ 5\ \mathrm{GeV},\theta)\times \sin\theta d\theta$$



For region I (6^{o} in azimut):

$$\mathrm{F}^{\mathrm{I}}_{\mathrm{Scatt}}(\mathrm{E}=\ 5\ \mathrm{GeV}) = \sum_{\phi=1}^{\phi=6} \mathrm{F}^{\phi}_{\mathrm{Scatt}}(\mathrm{E}=\ 5\ \mathrm{GeV})$$

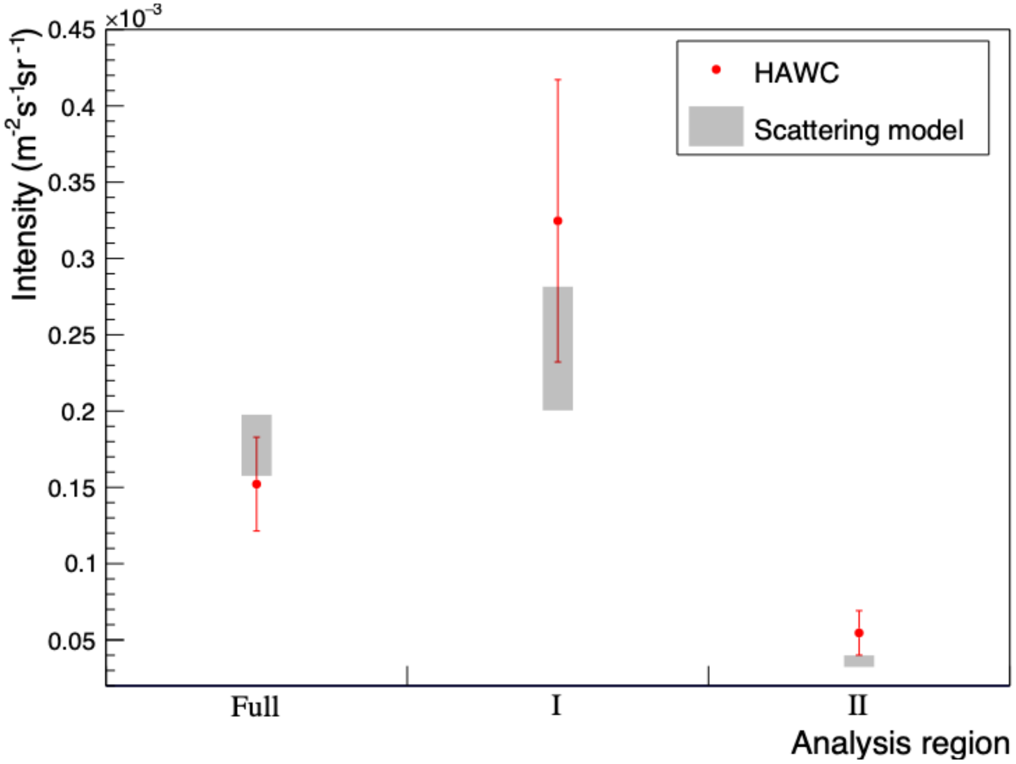
And adding the contributions for energies above the detection threshold:

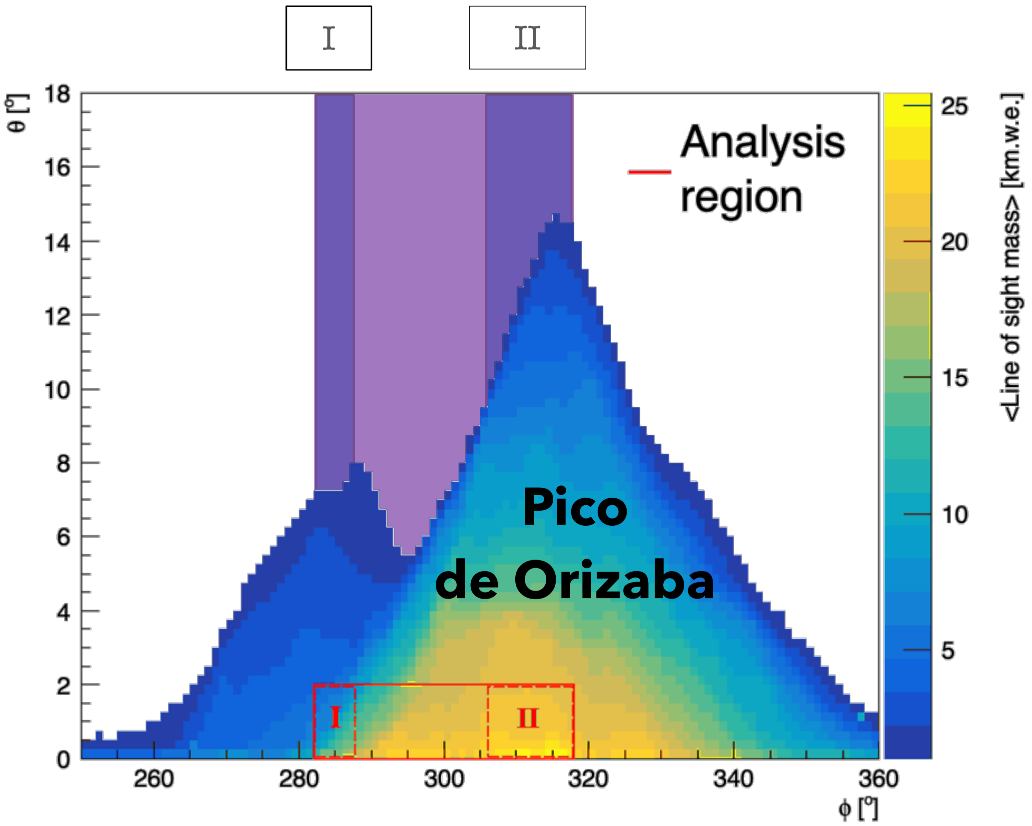
$$\mathrm{F}^{\mathrm{I}}_{\mathrm{Scatt}} = \sum_{\mathrm{E}=2,3,\ldots}^{\mathrm{E}=100\ \mathrm{GeV}} \mathrm{F}^{\mathrm{I}}_{\mathrm{Scatt}}(\mathrm{E})$$

$$\mathrm{Intensity}(\mathrm{i}) = \frac{\mathrm{F}^{\mathrm{i}}_{\mathrm{Scatt}}}{\Omega_{\mathrm{i}}}$$

Scattering model

The muon intensity is consistent with the scattering model in the 3 analysis regions

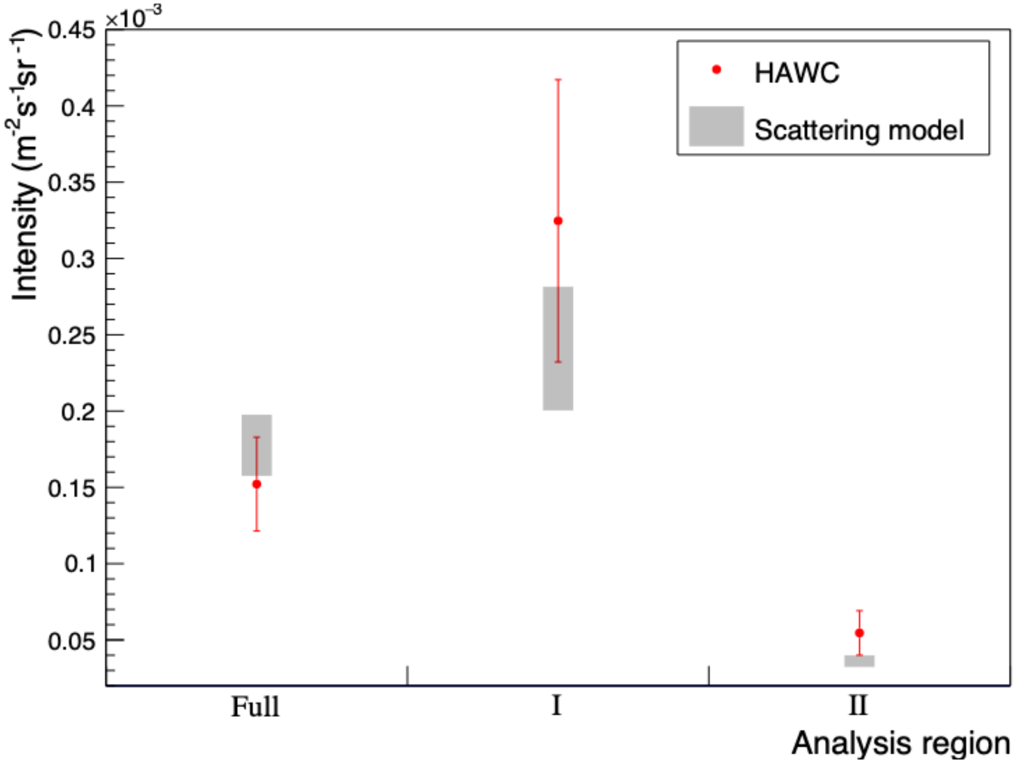




The signals are dominated by the background from scattered muons

How to find signals from neutrino interactions?

The strategy is to increase the detection threshold to remove the scattered background and keep neutrino-induced muons



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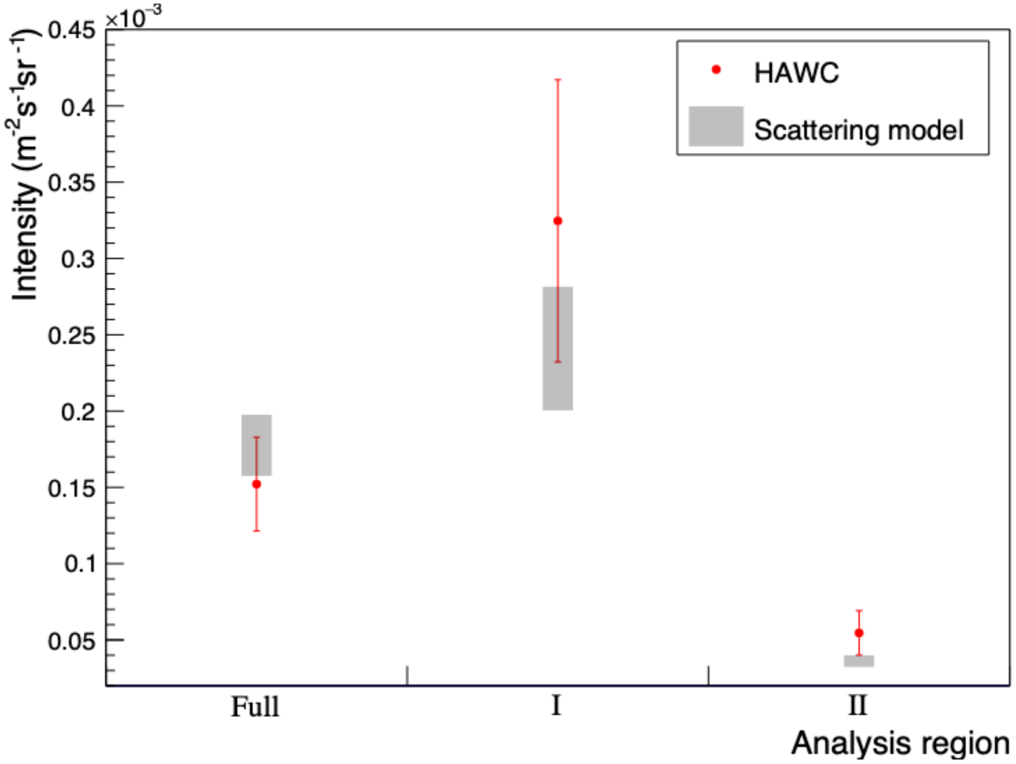
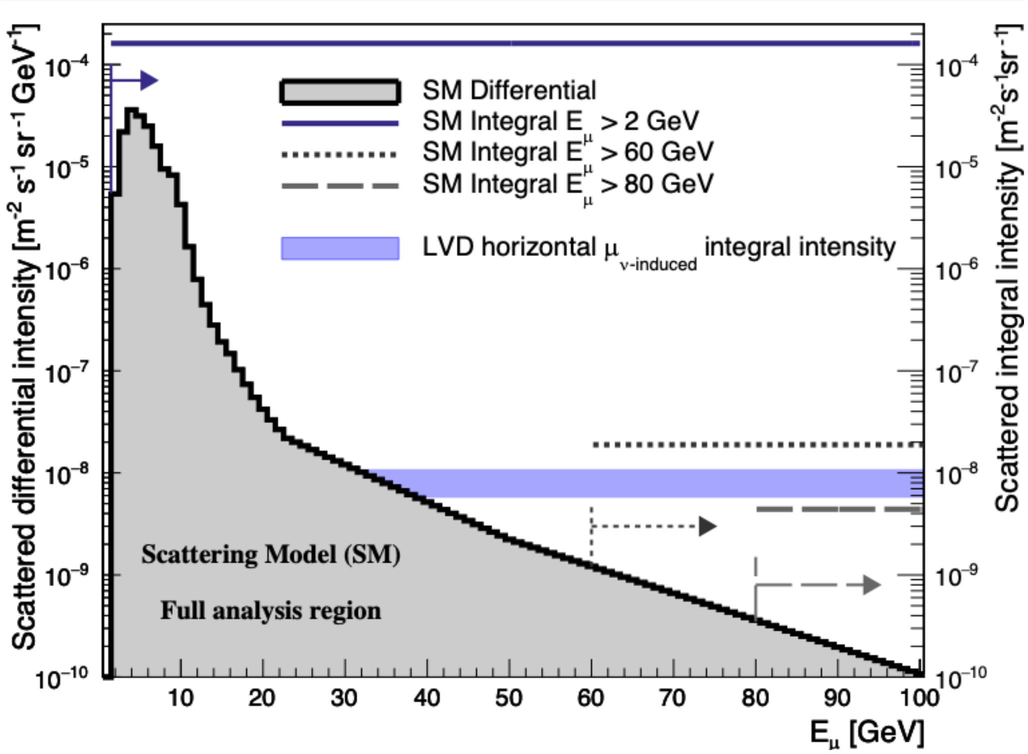




LVD: Large Volume Detector Astroparticle Physics 3 (1995)

Muons with energy > ~100 GeV will be free from the scattered background → neutrino-induced muons

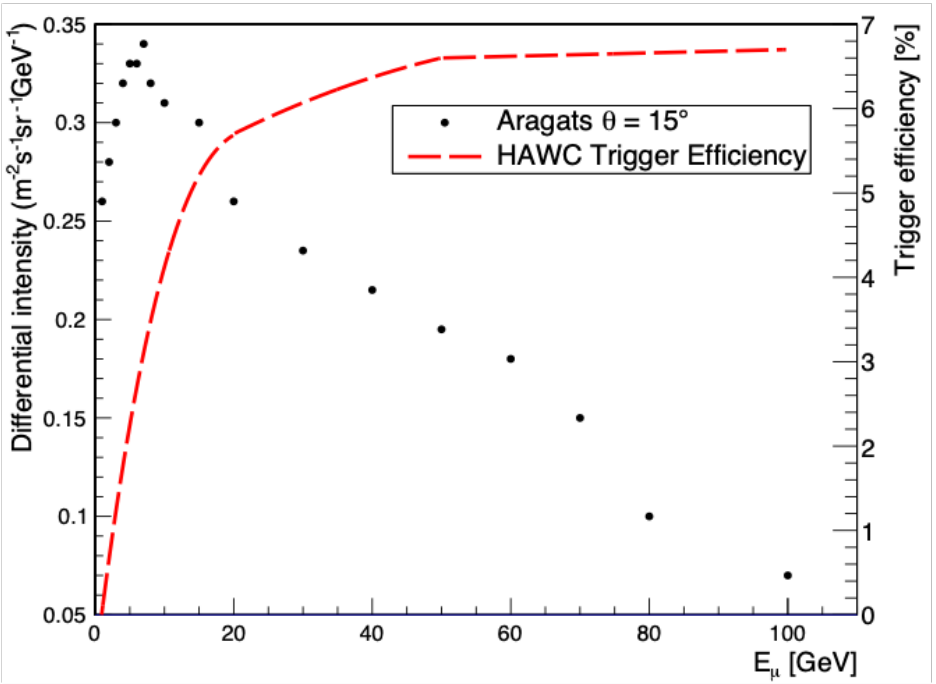
How to find signals from neutrino interactions?

Select muons with energy muons above that from those that are scattered (~100 GeV)

$$A_i = \frac{N_{\mathrm{Trigg}}}{\underset{\substack{\uparrow \\ (E_\mu)}}{N_{\mathrm{Gen}}}} \times A_{\mathrm{Gen}},$$

The detection probability is proportional to the effective area. This depends on the muon energy.

Bin	<LOSM> [km.w.e.]	$A\Omega$ [m^{2}sr]	Tracks
Full	$17.70^{+3.35}_{-9.23}$	$5.1\times10^{-2} \pm 9.2\times10^{-3}$	122
I	$9.54^{+1.95}_{-1.92}$	$4.1\times10^{-3} \pm 7.5\times10^{-4}$	21
II	$20.97^{+0.09}_{-0.13}$	$3.0\times10^{-2} \pm 5.4\times10^{-3}$	26



At higher energies, more PMTs are activated by the muons

How to find signals from neutrino interactions?

Compare the ratio $\frac{N_{Trigg}}{N_{Gen}}$ for muons at the most probable energy (~5 GeV) to those at 100 GeV.

$$\frac{\frac{N_{Trigg}}{N_{Gen}}\text{(100 GeV)}}{\frac{N_{Trigg}}{N_{Gen}}\text{(5 GeV)}} \sim 118$$

This gives a conservative estimate of the increase in the effective area if the detection threshold is 100 GeV

$A\Omega$ [$m^2 sr$]
$5.1\times10^{-2} \pm 9.2\times10^{-3}$

→ ≈ 6 m^2 sr

$N = I_\mu^\upsilon \times \Delta T \times A\Omega$ and using the neutrino-induced muon intensity from LVD

$I_\mu^\upsilon = 8.3\times10^{-9}\ m^{-2}s^{-1}sr^{-1}$

$\boxed{\text{N(1 year)} \approx 1.6}$

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This gives a conservative estimate of the increase in the effective area if the detection threshold is 100 GeV

$\mathrm{A\Omega\ [m^2 sr]}$
$5.1\times10^{-2} \pm 9.2\times10^{-3}$

$$\longrightarrow \approx 6\ \mathrm{m^2\ sr}$$

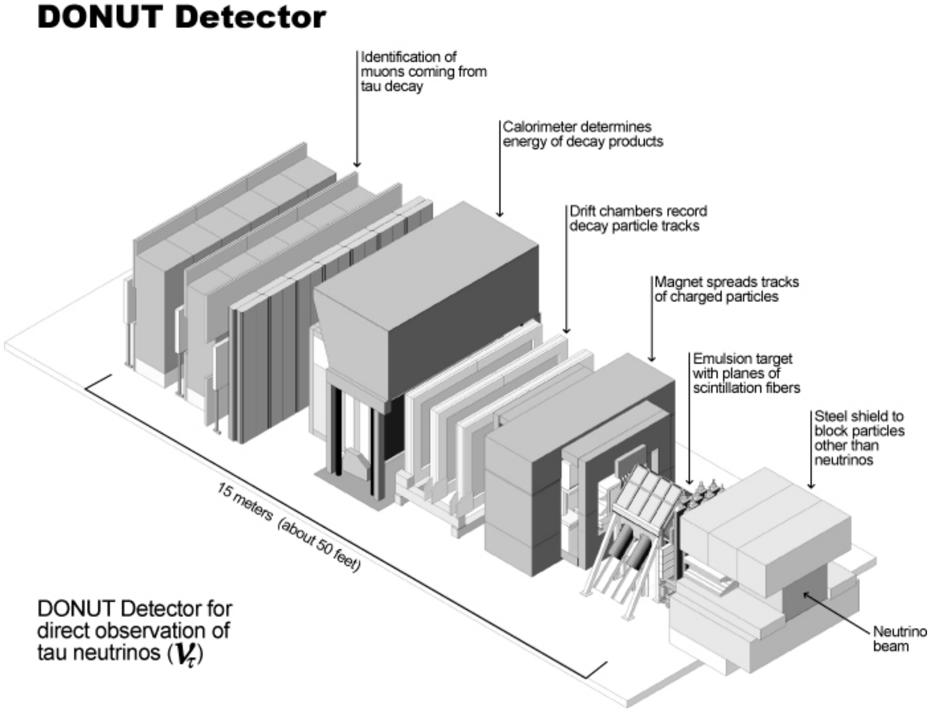
$N = I_\mu^v \times \Delta T \times A\Omega$ and using the neutrino-induced muon intensity from LVD

$$I_\mu^v = 8.3\times10^{-9}\, m^{-2} s^{-1} sr^{-1} \qquad \boxed{\mathrm{N(1\ year)} \approx 1.6}$$

This number may seem too low but:

- An above ground detector is much less expensive than those underground
- If we observe a very high energy signal, is more likely to be a tau lepton (due to the lepton energy loss)

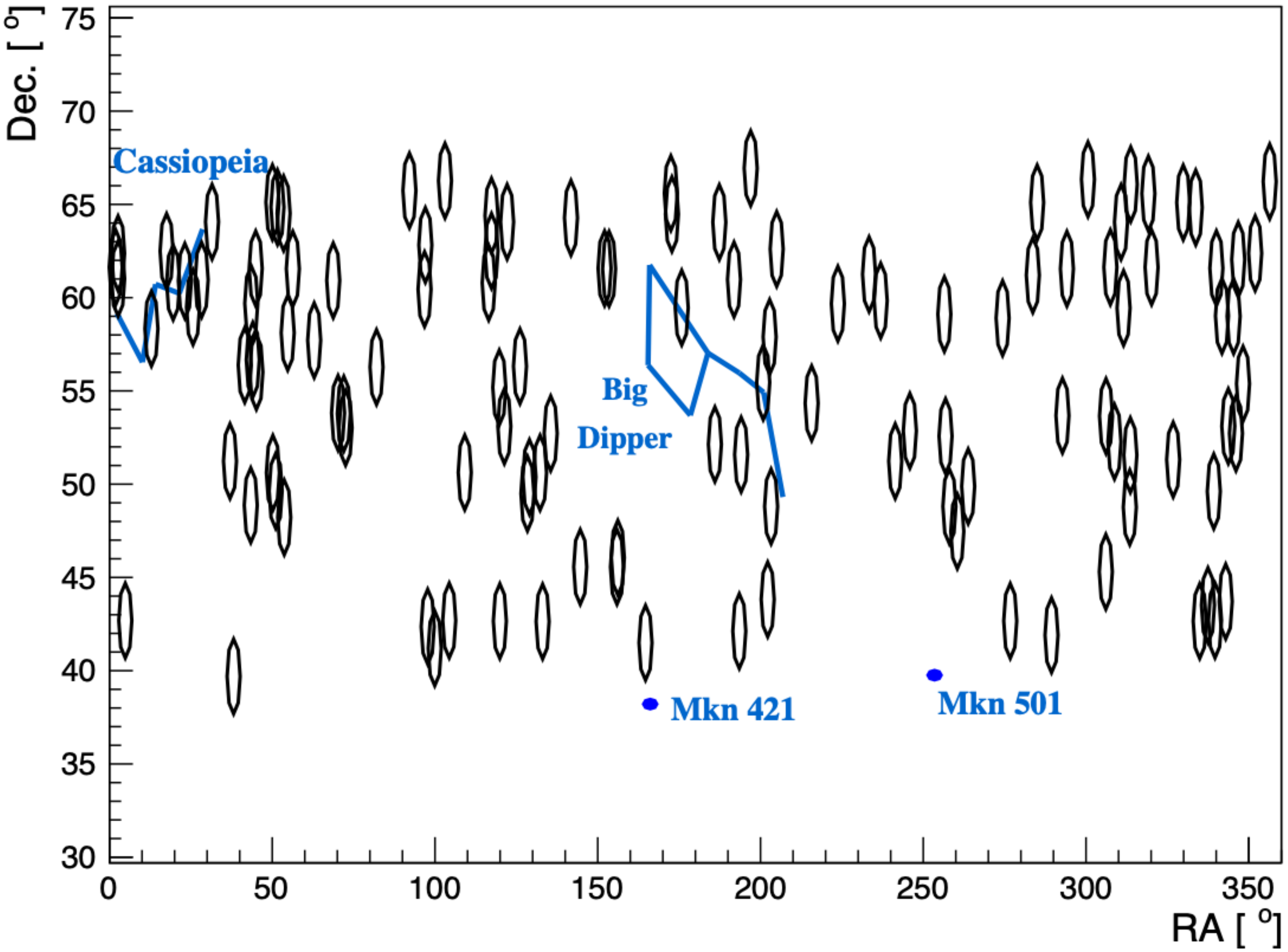
Tau neutrino direct detections



- Discovered in 2000 at FNAL
- Penultimate SM particle to be discovered
- 4 events, 3.5σ
- 2007: 9 tau neutrino candidates
- 2018: OPERA reports 10 candidates
- 2 more by IceCube (4 Nov, 2022)

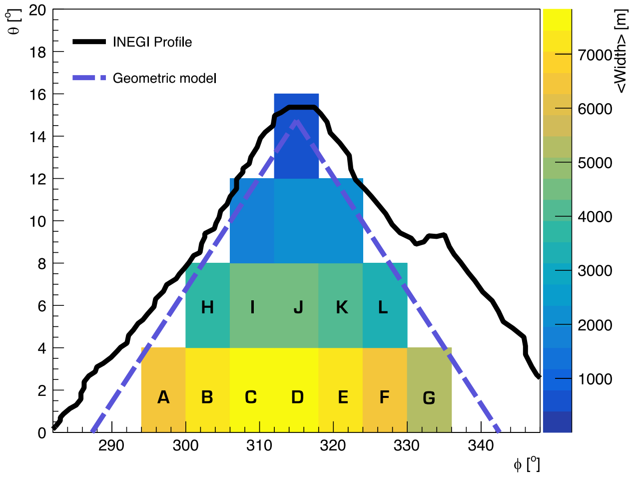
21 direct detections so far

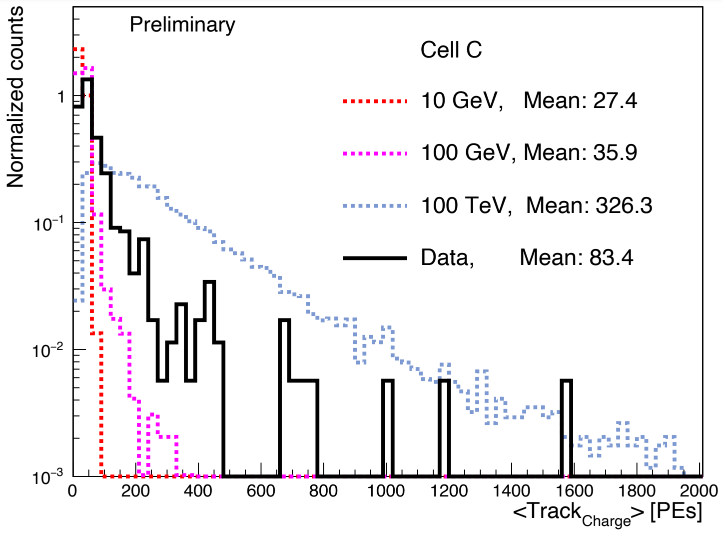
Field of view with HAWC

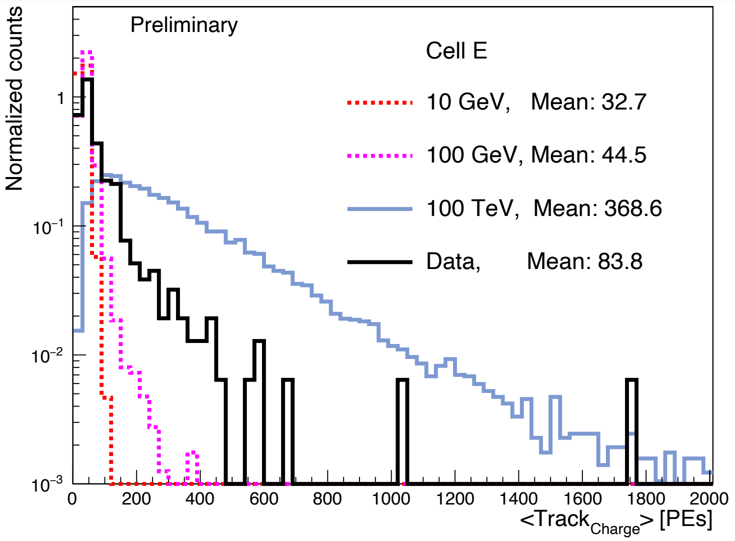


Arrival direction, in celestial coordinates, for the 122 detected events

Results from ICRC 2019







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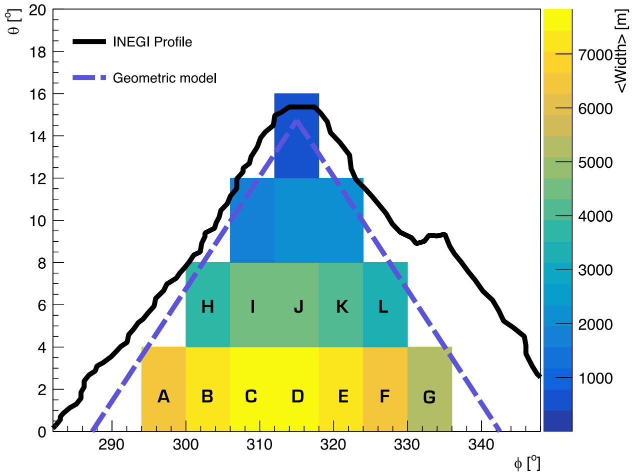
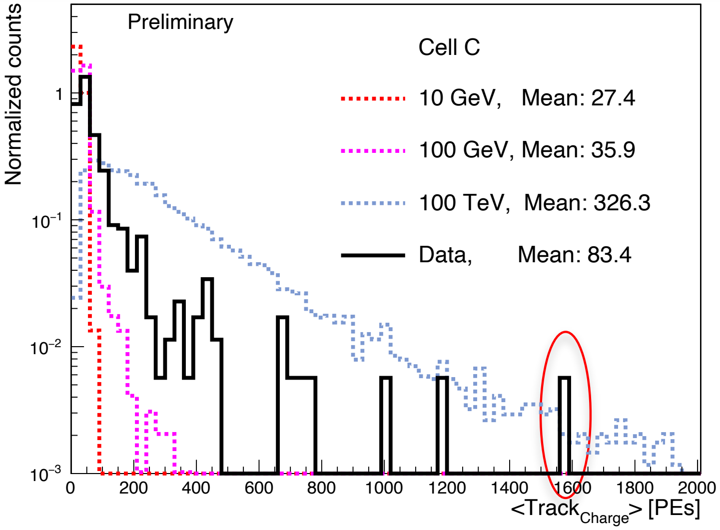
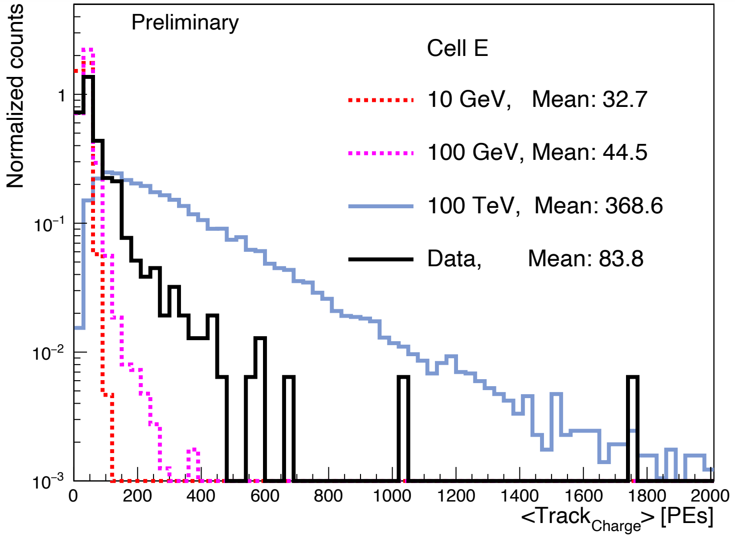
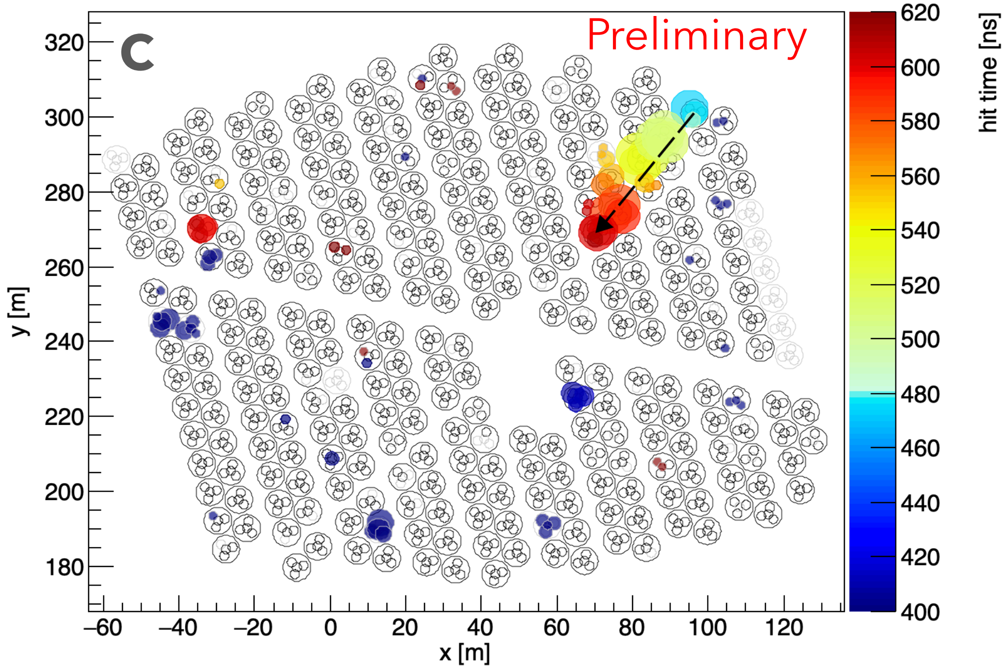
Results from ICRC 2019









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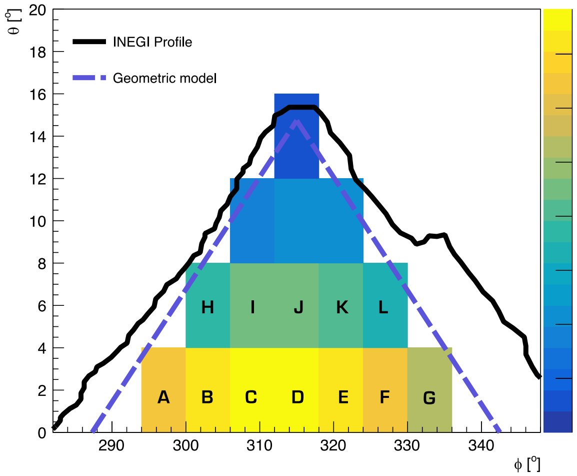

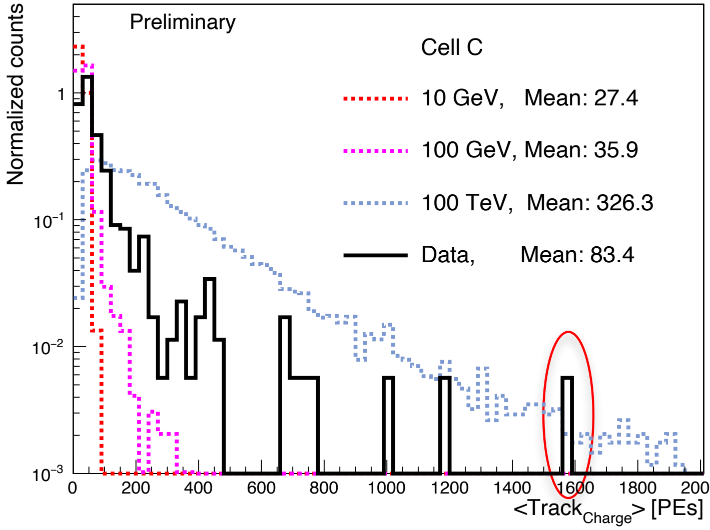

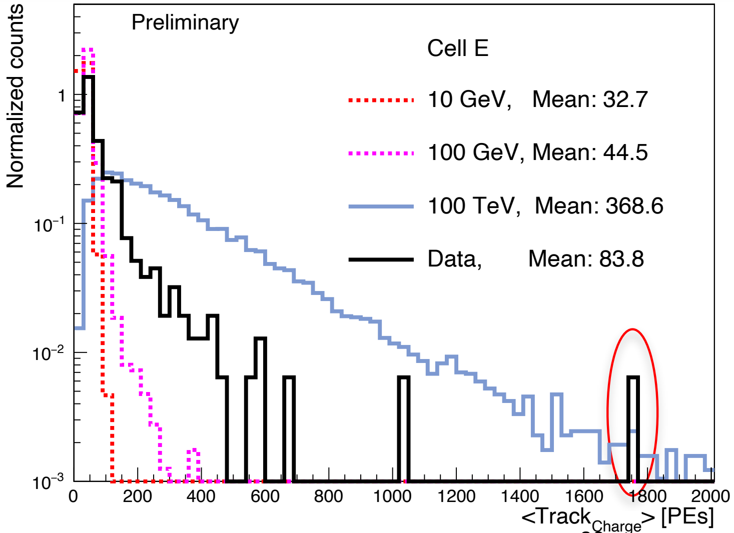

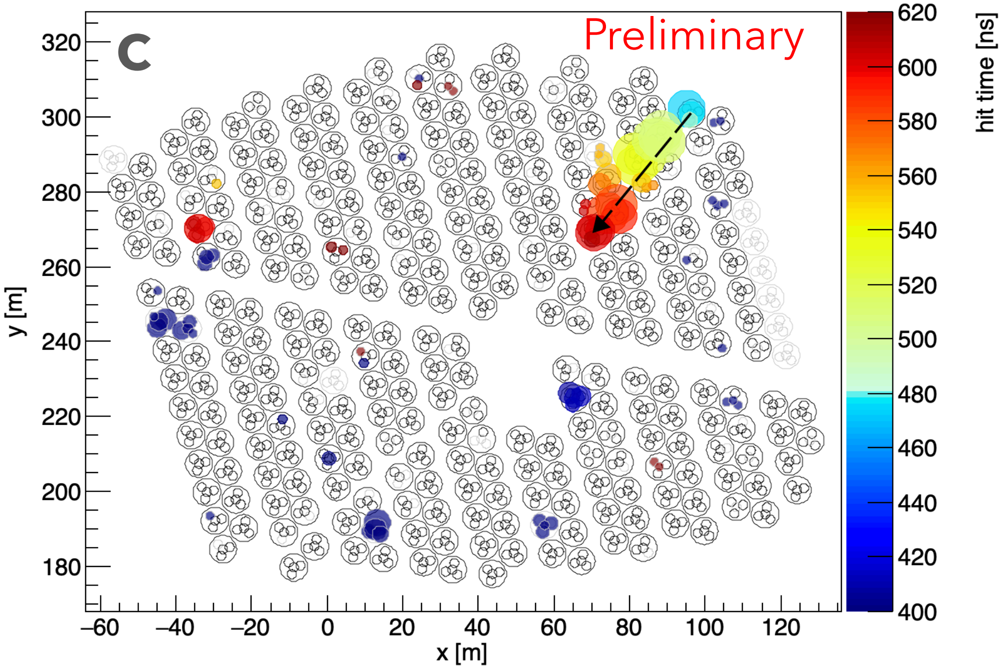

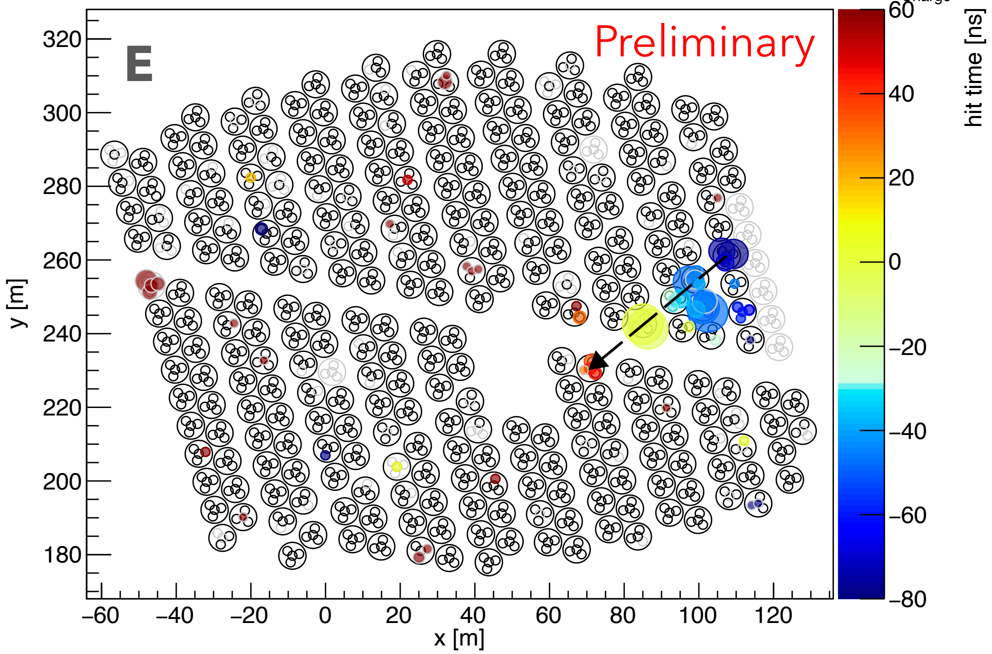

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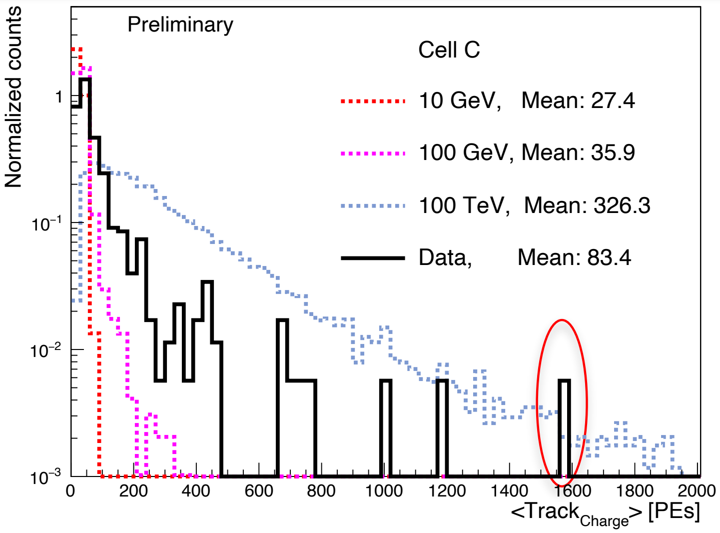
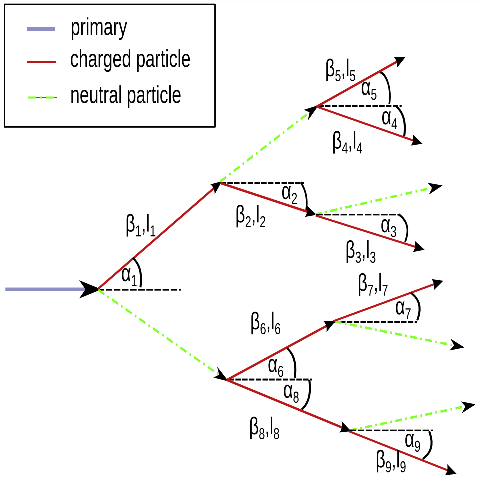
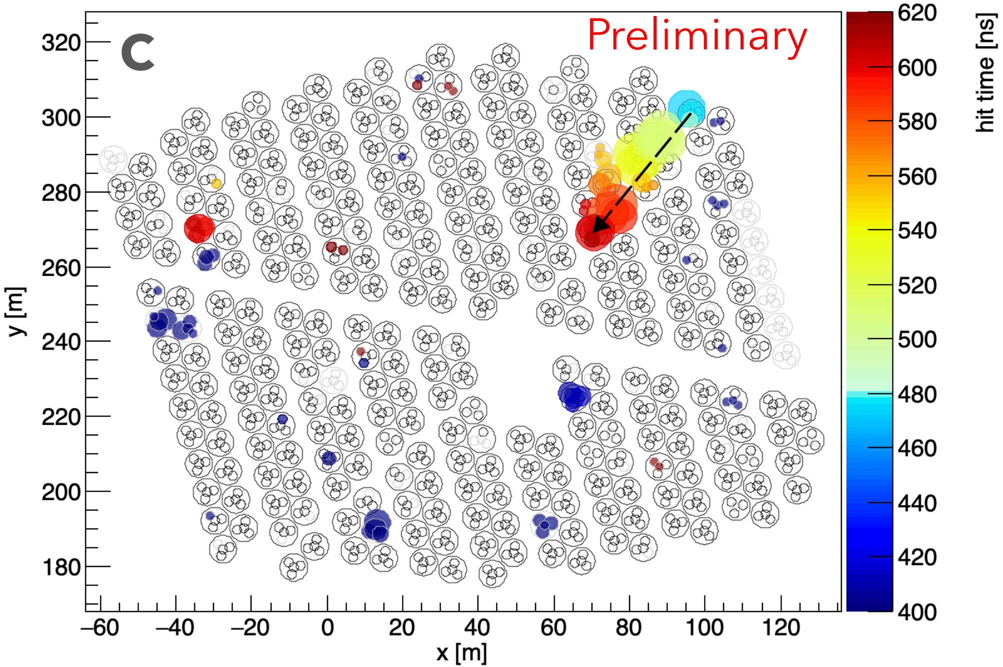
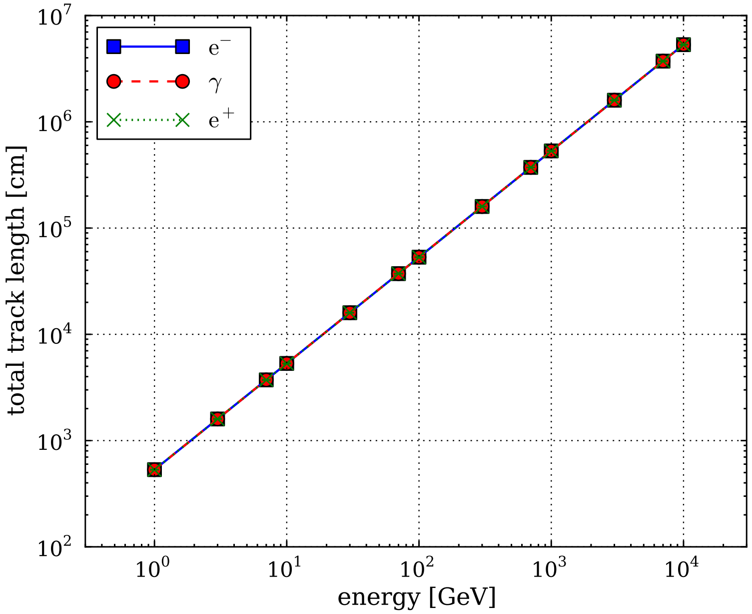
An average muon deposits < 30 PEs

Results from ICRC 2019









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[1] L. Rädel, C. Wiebusch, Astroparticle Physics (2013) 102-113

<u>This signal deposits ×50 the average energy loss</u>

Conclusions

- The HAWC observatory was designed to detect air showers produced by TeV gamma rays
- 8 years ago I started to investigate the possibility of using the "Earth-skimming" neutrino detection method using HAWC
- I developed all the tools needed for this study. The conclusion:

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[1] *Physics Division, Los Alamos National Laboratory, Los Alamos, NM, USA*
[2] *Instituto de Física, Universidad Nacional Autónoma de México, Ciudad de México, Mexico*
[3] *Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas, Mexico*
[4] *Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Mexico*
[5] *Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad de Mexico, Mexico*
[6] *Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de Mexico, Mexico*
[7] *Instituto Nacional de Astrofísica, Óptica y Electrónica, Puebla, Mexico*
[8] *Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 IFJ-PAN, Krakow, Poland*
[9] *Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, Puebla, Mexico*
[10] *Departamento de Física, Centro Universitario de Ciencias Exactas e Ingenierias, Universidad de Guadalajara, Guadalajara, Mexico*
[11] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Kashiwanoha, Japan*
[12] *Department of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin-Madison, Madison, WI, USA*
[13] *Department of Physics, University of Maryland, College Park, MD, USA*
[14] *Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Ave. Eugenio Garza Sada 2501, Monterrey, N.L., 64849, Mexico*
[15] *Department of Physics, Michigan Technological University, Houghton, MI, USA*
[16] *Max–Planck Institute for Nuclear Physics, 69117 Heidelberg, Germany*
[17] *Department of Physics, Faculty of Science, Chulalongkorn University, 254 Phayathai Road, Pathumwan, Bangkok 10330, Thailand*
[18] *National Astronomical Research Institute of Thailand (Public Organization), Don Kaeo, MaeRim, Chiang Mai 50180, Thailand*
[19] *Department of Physics and Astronomy, University of Utah, Salt Lake City, UT, USA*
[20] *Universidad Politecnica de Pachuca, Pachuca, Hgo, Mexico*
[21] *Centro de Investigación en Computación, Instituto Politécnico Nacional, México City, Mexico*
[22] *Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA*
[23] *Universidad Autónoma del Estado de Hidalgo, Pachuca, Mexico*
[24] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de Mexico, Ciudad de Mexico, Mexico*
[25] *Department of Physics, Stanford University, Stanford, CA 94305–4060, USA*
[26] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA*
[27] *University of Seoul, Seoul, Republic of Korea*
[28] *Tsung-Dao Lee Institute & School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, People's Republic of China*

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The close location of the HAWC observatory to the largest volcano in Mexico allows to perform a search for neutrino-induced horizontal muon and tau charged leptons. The section of the volcano located at the

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[*] Corresponding author.
E-mail address: hleonvar@fisica.unam.mx (H. León Vargas).

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Conclusions

- The HAWC observatory was designed to detect air showers produced by TeV gamma rays
- 8 years ago I started to investigate the possibility of using the “Earth-skimming” neutrino detection method using HAWC
- I developed all the tools needed for this study. The conclusion: <u>It is not impossible, just really hard</u>

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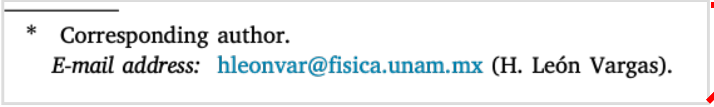
¡Thanks!



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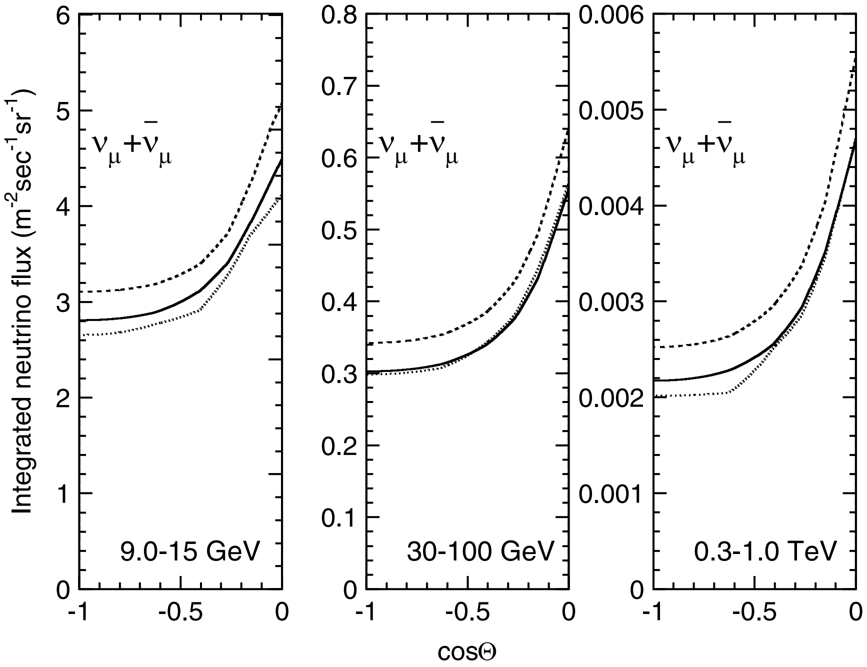
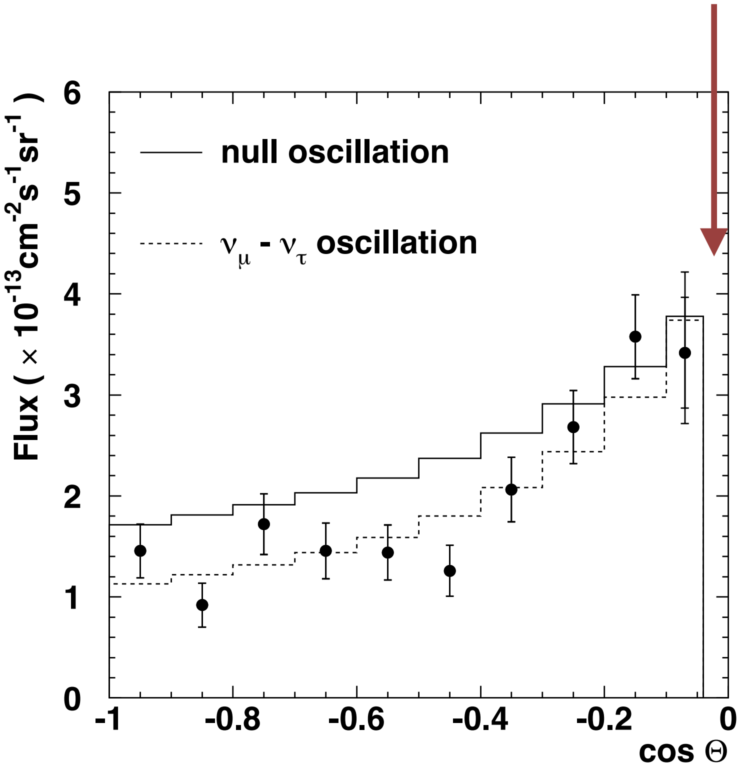
Horizontal signals

At the HAWC energy neutrinos come from pion and kaons. Vertical mesons interact before decay, this changes when the mesons propagate horizontally.



Super-Kamiokande. Phys. Rev. D 71 (2005) 112005



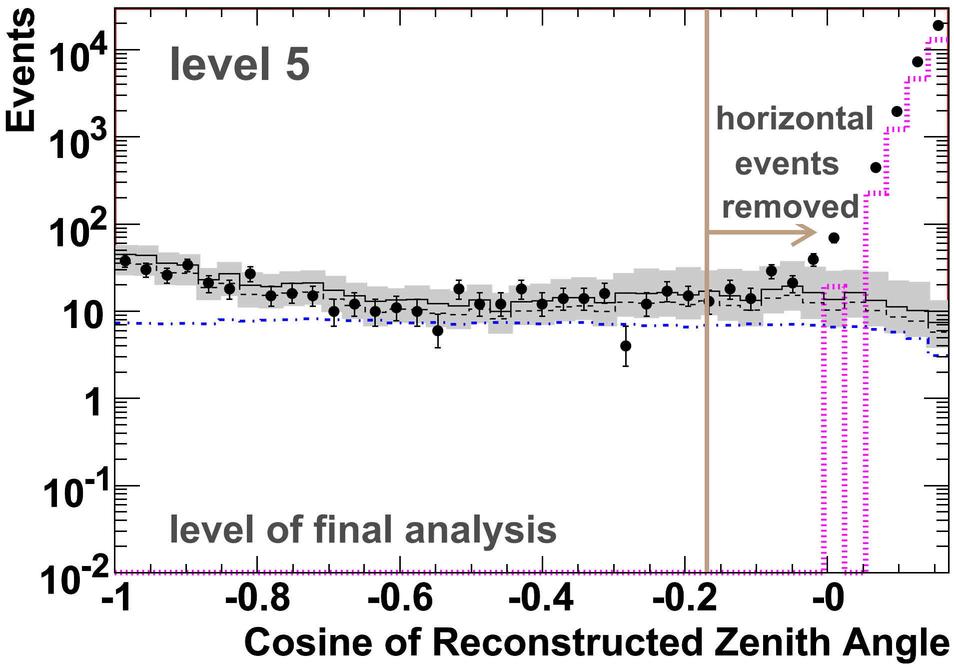
Kamiokande II+III.
Phys. Rev. Lett. 81 (1998) 10

The increase of the neutrino flux was predicted and observed. The factor of 2 is a rough approximation. LVD calculated a value of 2.3 ± 0.2.

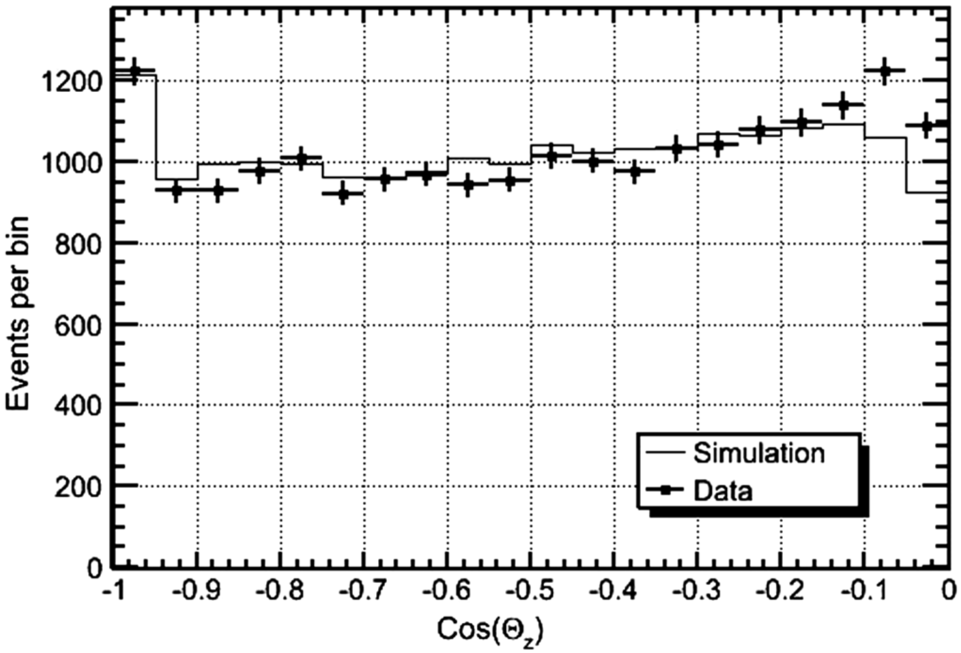
<u>Notice how the measurements do not go as horizontal as we do</u>

Horizontal signals

Other experiments have measured an excess of horizontal events



IceCube. Phys. Rev. D. 83 (2011) 012001.



Amanda-II. Phys. Rev. D. 76 (2007) 042008.