# Atmospheric muon background rejection for an underwater Neutrino Telescope

HEP

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Athens

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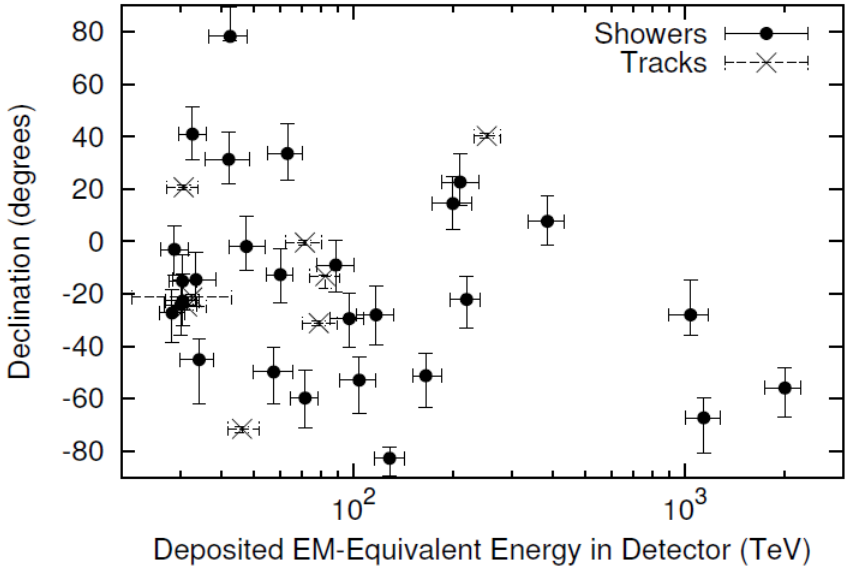
# Introduction - Motivation

Recently the IceCube collaboration has published the results of three years of data taking.

From Phys. Rev. Lett. **113**, 101101

They reported the discovery of 37 high energy ν events with energies 30 TeV to 2 PeV, 3 of which having energy more than 1 PeV.




Based on this study they published the astrophysical neutrino diffuse flux.

All these events have their interaction vertices inside a volume slightly smaller than the instrumented volume of the detector. This was done to reject atmospheric muon events (background).

# Background for neutrino telescopes

- Background:
  1. Atmospheric muons:
     - Created in the atmosphere.
     - Only downgoing.
  2. Atmospheric neutrinos:
     - Also created in the atmosphere.
     - Reach the detector from all directions.
     - Only difference from astrophysical neutrinos (signal) is their energy spectrum.
     - Irreducible background.

- Noise (for underwater ν telescopes):
  - The decay of $^{40}K$ produces photons which can de detected by the Photo Multiplier Tubes (PMTs).

# Background for KM3NeT

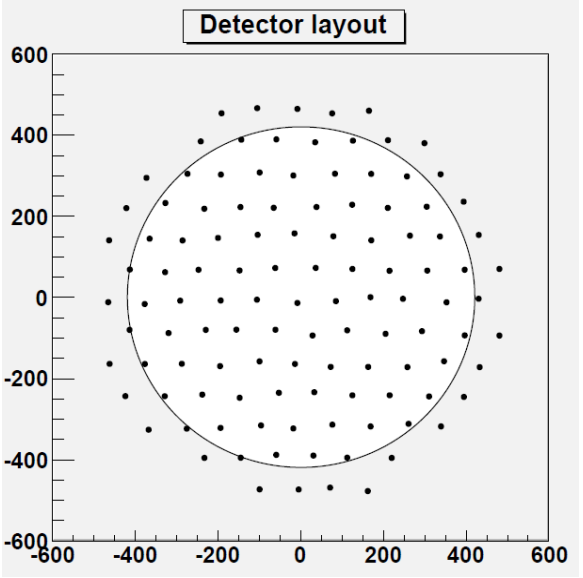
- KM3NeT is a future European deep-sea research infrastructure that will host a neutrino telescope with a volume of several cubic kilometers at the bottom of the Mediterranean Sea.

- Background or KM3NeT is the same as all other neutrino Telescopes:
  - Atmospheric muons can be rejected using different techniques
  - Atmospheric neutrinos cannot be rejected (unless they are a part of an airshower and are accompanied by muons).

- For this study:
  - Use events generated/simulated with the latest tools of KM3NeT
  - Signal: $\nu_\mu \longrightarrow \mu$ via CC interactions, interacting inside a fiducial volume.
  - Background: atmospheric muons
    - 1 sample with $E_{bundle} > 10$ TeV $\longrightarrow$ livetime of ~ 26 days
    - 1 sample with $E_{bundle} > 50$ TeV $\longrightarrow$ livetime of ~ 3 years
  - Background: $\nu_\mu \longrightarrow \mu$ via CC interactions, interacting outside the fiducial volume
  - Focus on events that their energy can be reliably reconstructed.
  - **Focus on high energy events with $E_\nu > 30$ TeV**

# Vertex containment

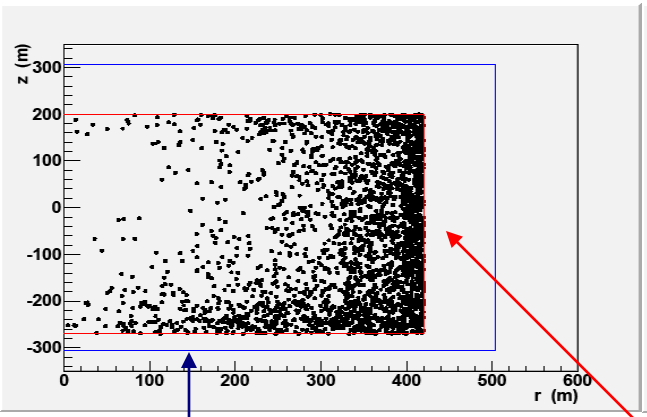
- A first step to reduce the atmospheric muon background is to accept only those events with interaction vertex inside a volume smaller than the instrumented volume (fiducial volume).
  - Cylinder with r = 420m $z_{max}$ = 200m $z_{min}$ = -270m
- This containment requirement alone is NOT enough.

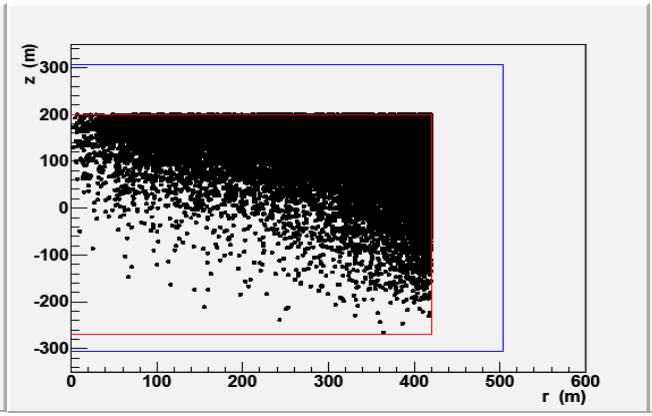


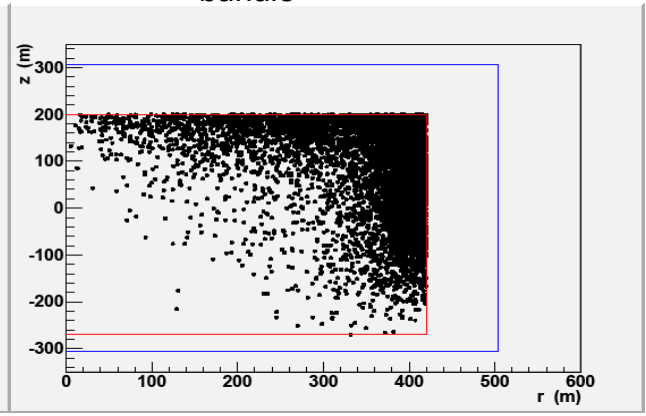

CC Events with their true vertex out of the fiducial volume

Atmospheric muons with $E_{bundle}$ > 10TeV

Atmospheric muons with $E_{bundle}$ > 50TeV



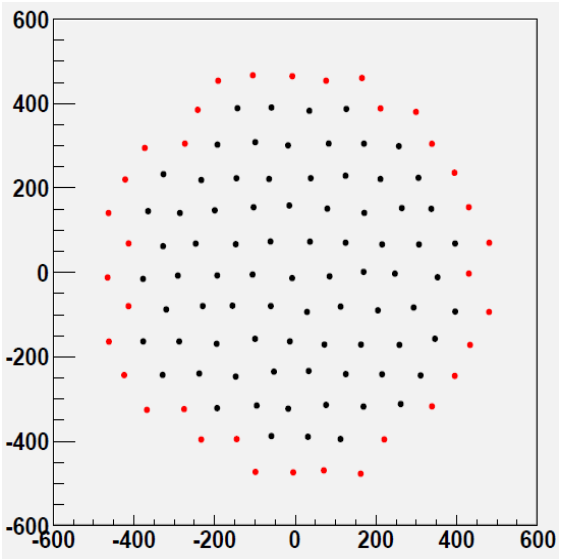




Detector volume

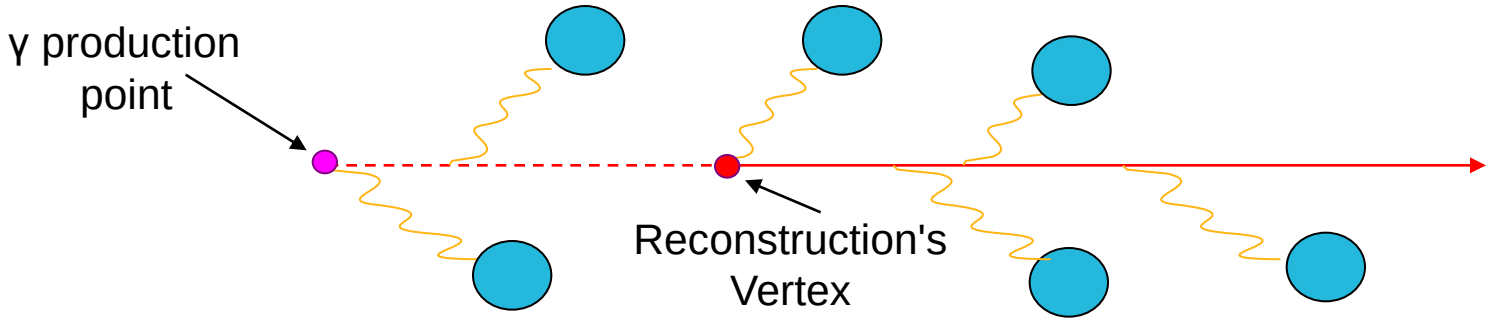
Fiducial volume

# Background suppression

- Discard events that have “high” activity in border areas:
  - Border areas = border Strings + highest 2 Oms
  - First in time OM used by the reconstruction in border areas
  - Largest energy deposition in border areas BEHIND vertex.




- Checking for hits behind the vertex in coincidence with the track.
  - Check for OMs with HIGH activity if they can be correlated to the track.
  - Check for OMs with low activity if they can be correlated to the track using VERY strict criteria.
  - Assuming Cherenkov photons, check if the production point is contained



# Background suppression

- Separate events with at least 1 coincidence in boarder areas
  - Either from muons entering the detector or from CC events with large hadronic activity.
  - For these events we require some activity consistent with the track hypothesis behind the reconstructed vertex.
- Use the fact that a CC interaction can be accompanied by hadronic activity (that looks like a shower).
  - Found quantities that have a discriminating power on $\nu_\mu \rightarrow \mu$ interacting inside the fiducial volume, against (atmospheric) muons entering the detector.
  - Take 3 intervals of the reconstructed zenith ($0^o$ – $30^o$ , $30^o$ – $60^o$, more than $60^o$).
  - For each zenith interval apply cuts on these quantities.
- Since we focus on $E_\nu$ > 30TeV we require a large number of OMs to be used by the reconstruction and/or to have relatively high activity (3 pulses in time coincidence).

# Results

| | CC events Vtx in fid.vol. | CC events Vtx in fid.vol. $E_\nu > 30$TeV | CC events Vtx out fid.vol. | Atm muons $E_{bundle} > 10$TeV Livetime~26 days | Atm muons $E_{bundle} > 50$TeV Livetime~3 yrs |
|---|---|---|---|---|---|
| Reco vtx in the fid.vol. | 4,792 | 2,714 | 2,646 | 28,183 | 9,923 |
| Cuts for Energy reconstruction | 3,124 | 1,981 | 2,120 | 20,105 | 3,192 |
| Before dividing the sample depending on the border activity | 2,886 | 1,825 | 384 | 1,124 | 68 |
| border activity and zenith dependent cuts | 2,625 | 1,753 | 82 | 52 | 1 |
| All cuts | 1,954 | 1,666 | 26 | 0 | 0 |

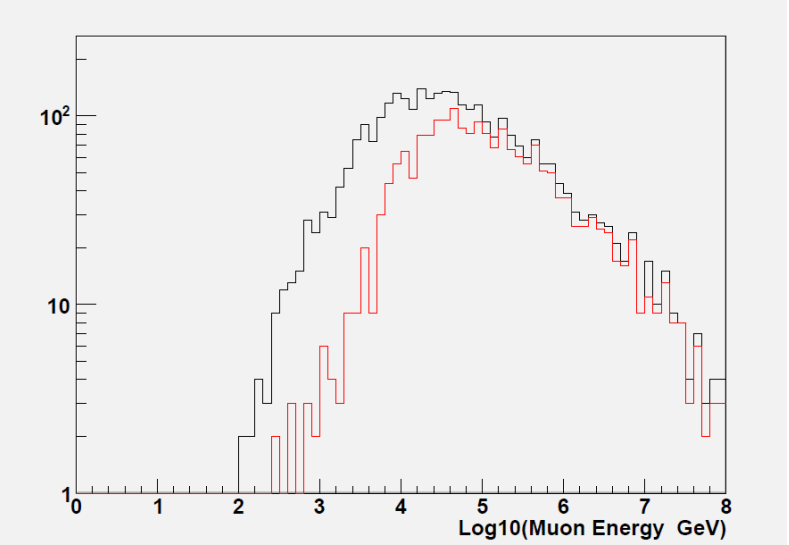
# Results

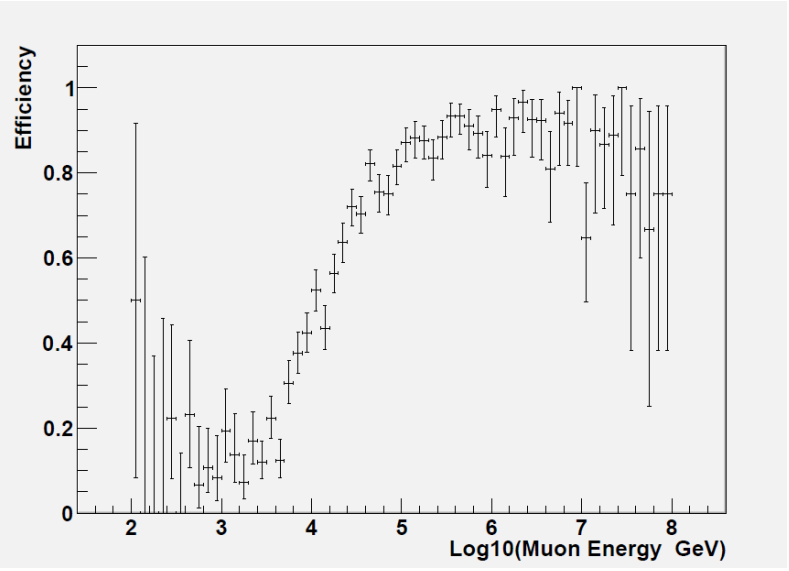
- **No atmospheric muon event left!**

All CC events:

**All events reconstructed as in the fiducial volume after Energy Reconstruction Cuts.**

**Events after all cuts.**




**Efficiency ~ 62%**

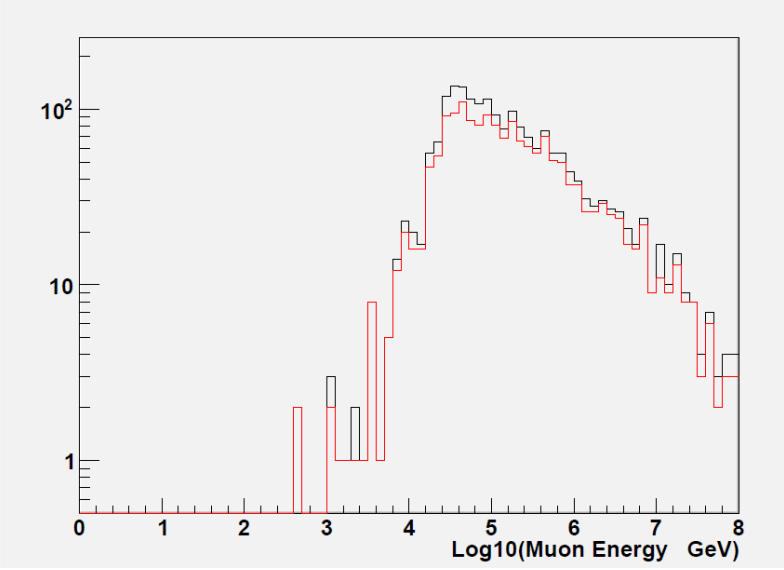
# Results

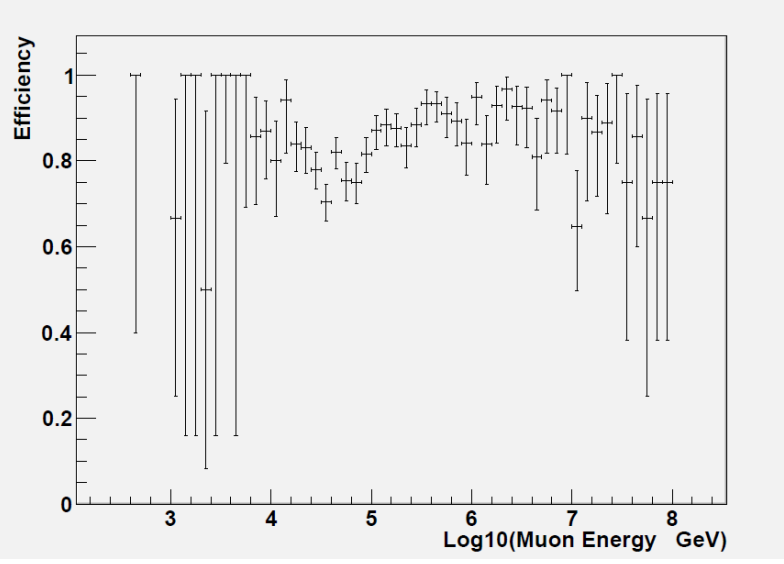
- **No atmospheric muon event left!**

CC events $\mathbf{E_\nu > 30TeV}$:

**All events reconstructed as in the fiducial volume after Energy Reconstruction Cuts.**

**Events after all cuts.**




**Efficiency ~ 84%**

# Results

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| Before dividing the sample depending on the border activity | 2,886 | 1,825 | 384 | 1,124 | 68 |
| border activity and zenith dependent cuts | 2,625 | 1,753 | 82 | 52 | 1 |
| All cuts | 1,954 | 1,666 | **26** | 0 | 0 |

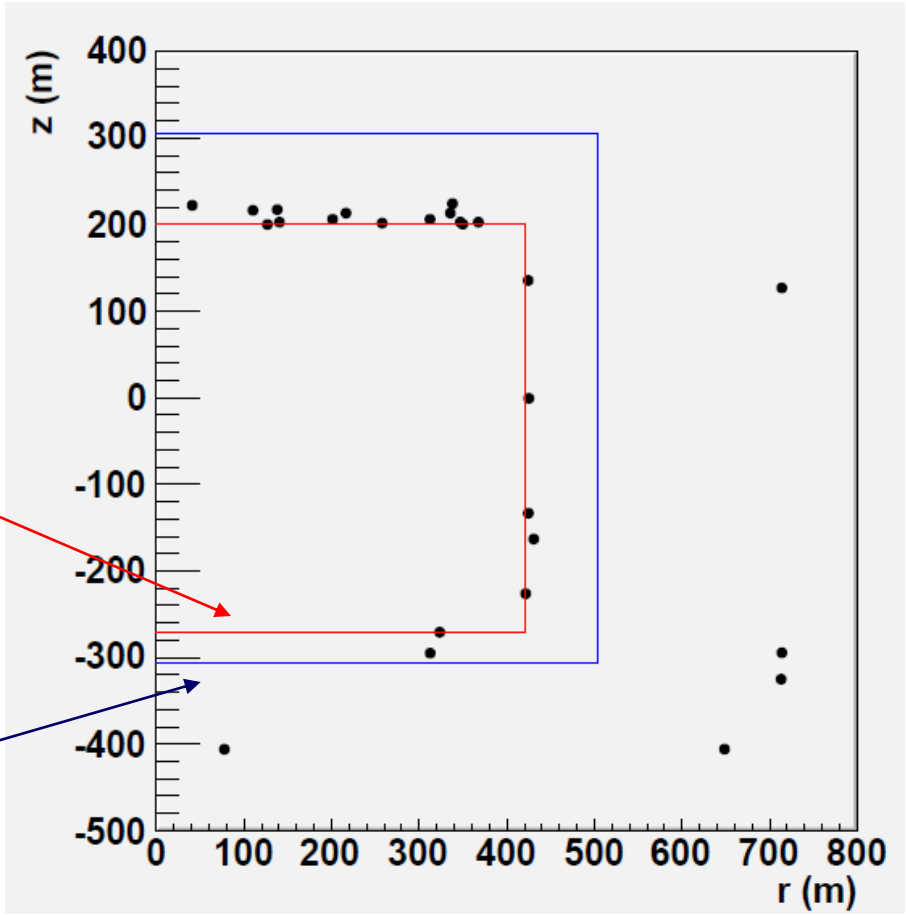
# Results

For the 26 events that are left after all cuts and have their true Vertex outside the fiducial volume:

Most of them have their Vertices **Inside** the detector's volume and at the edge of the fiducial volume

**Red lines**: **Fiducial volume**

**Blue lines**: **Detector's volume**



# Conclusion

- No atmospheric muon event left

  (for $E_{bundle}$>10TeV ~ 26 days and $E_{bundle}$>50TeV ~ 3 years)
- Very high suppression of the contribution of events with the true vertex outside the fiducial volume but reconstructed as inside.
  (per mille level of these events survive).
- For CC events with Ev > 30TeV **efficiency ~ 84%** compared to events reconstructed as in the fiducial and passing the energy reconstruction cuts.
- This method was also applied to a different reconstruction used for point sources (TeV range) with similar results.

| events reconstructed as inside the fiducial volume | **signal events** efficiency 81% | v interacting outside the fiducial vol | atmospheric muon events $E_{bundle}$ > 10 TeV | atmospheric muon events $E_{bundle}$ > 50 TeV |
|---|---|---|---|---|
| before our selection | 1852 | 5756 | 41421 | 2860 |
| after our selection | 1502 | 17 | 1 | 0 |

# Thank you!

# Back up – coincidences in border areas

A coincidence in border areas is when there are at least 2 hits (in the same or in neighboring border OMs / strings) that the difference of their time differences between the measured time and the expected time from the track hypothesis is less than 20 ns.

For events with at least 1coincidence in border areas:

- Keep those events with at least 1 OM with high activity behind the reco vertex consistent with the track hypothesis.
- By this we ensure that we discard mostly atmospheric muons and not CC events with hadronic activity close to the edge of the fiducial volume.

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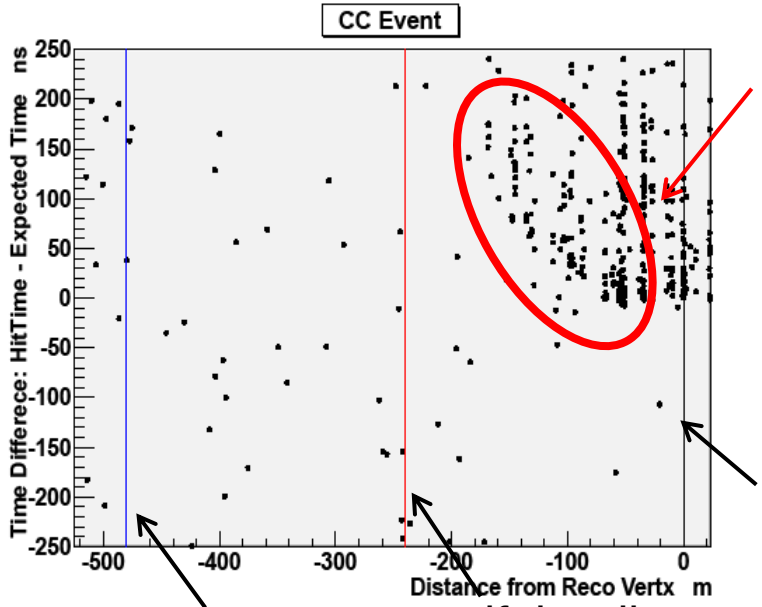
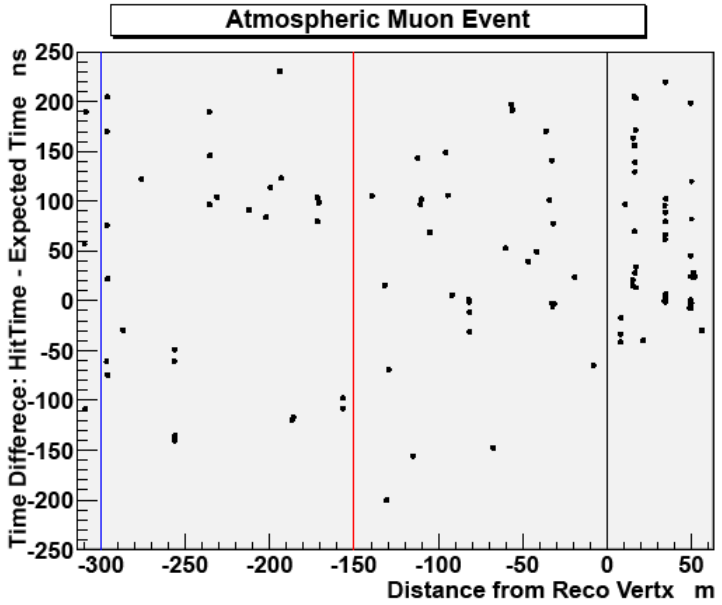
# Back up - Background Suppression

The quantities mentioned in slide 7 that have a discriminating power between CC events and incoming muon

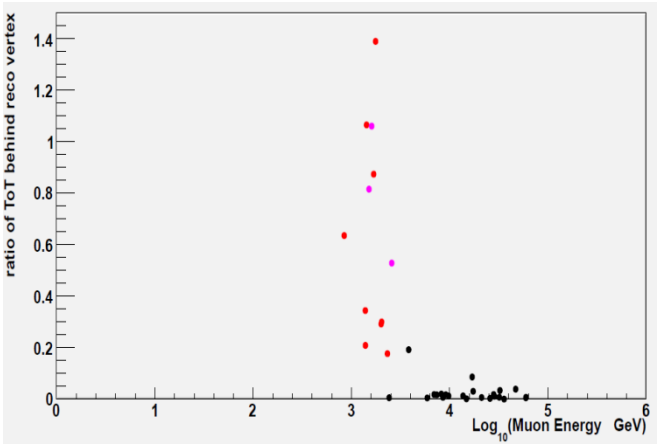
- Total ToT behind reconstructed vertex (equivalent to energy deposited behind the reconstructed vertex) → tends to be large for CC events
- Ratio of ToT: second half (far from vertex) over first half (near vertex) → tends to be smaller for CC events due to the hadronic activity.



# Back up - Background Suppression

For each sample (2 samples depending on boarder activity with 3 zenith intervals each) we investigate the ratio of TOT as a function of the activity behind the reconstructed vertex and apply a cut.




**All CC events**

Black dots: CC events

Red dots: atm muons with $E_{bundle} > 10TeV$

Magenta dots: atm muon with $E_{bundle} > 50TeV$

**CC events with $E_{\nu} > 30TeV$**