Studies using alternative configurations for the KM3NeT-ARCA detector

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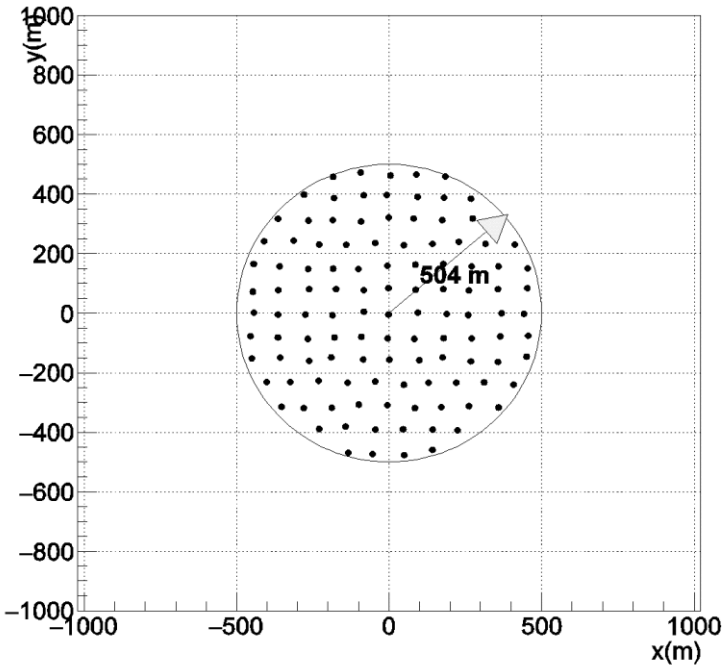
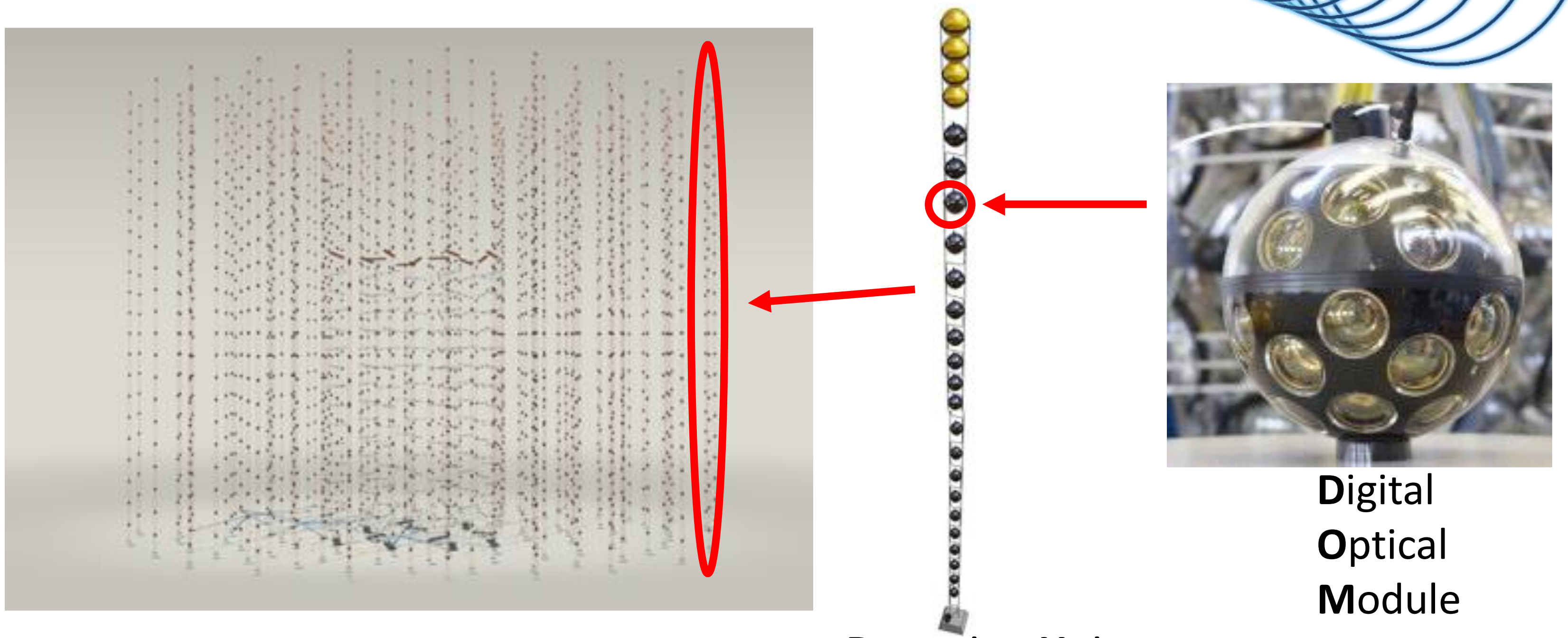
Outline

- The KM3NeT-ARCA detector for neutrino astronomy
- Alternative geometries
- Performance of the track reconstruction
- Sensitivity and Discovery Potential
- Conclusions

The KM3NeT-ARCA detector

KM3NeT is a research infrastructure in the Mediterranean Sea that will host neutrino detectors





The ARCA detector will consist of **2 blocks** with **115 Detection Units (DUs) each**, with **90 m** distance between them.

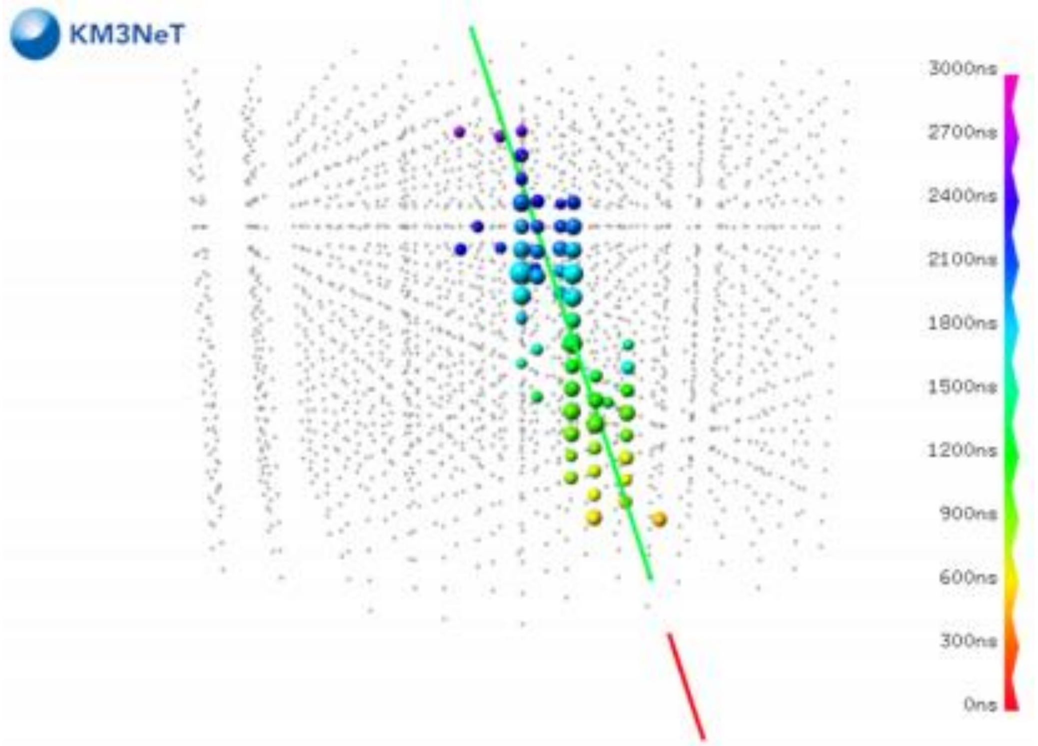
The DU is a vertical slender string equipped with **18 Digital Optical Modules (DOM) 36 m distant**.
Each DOM consists of **31 3'' PMTs**.

There is a sea network of submarine cables and Junction Boxes connected to shore via a main cable.

Event topology and detection

Track events

Mainly from ν_μ charged current interactions



- The detection of "upgoing" muons ensures their neutrino origin as no other known particle can pass through Earth without interacting.
- High energy muons can travel long distances through water without interacting, therefore we can detect muons produced very far from our detector and this leads to a very large effective volume.
- The accuracy of the muon reconstruction leads to high precision of the initial neutrino direction.

→ **ν_μ from charged current interactions is ideal for neutrino astronomy**

Objective

The recent results from the ICECUBE Collaboration on the unambiguous observation of neutrinos from extraterrestrial origin bring up the need of investigating, if a **gain in effective area** can be achieved by **enlarging the current detector configurations focusing on higher energies**.

Taking advantage of the excellent angular resolution of the KM3NeT reconstruction software, sparser detector configurations of the KM3NeT-ARCA detector can be studied.

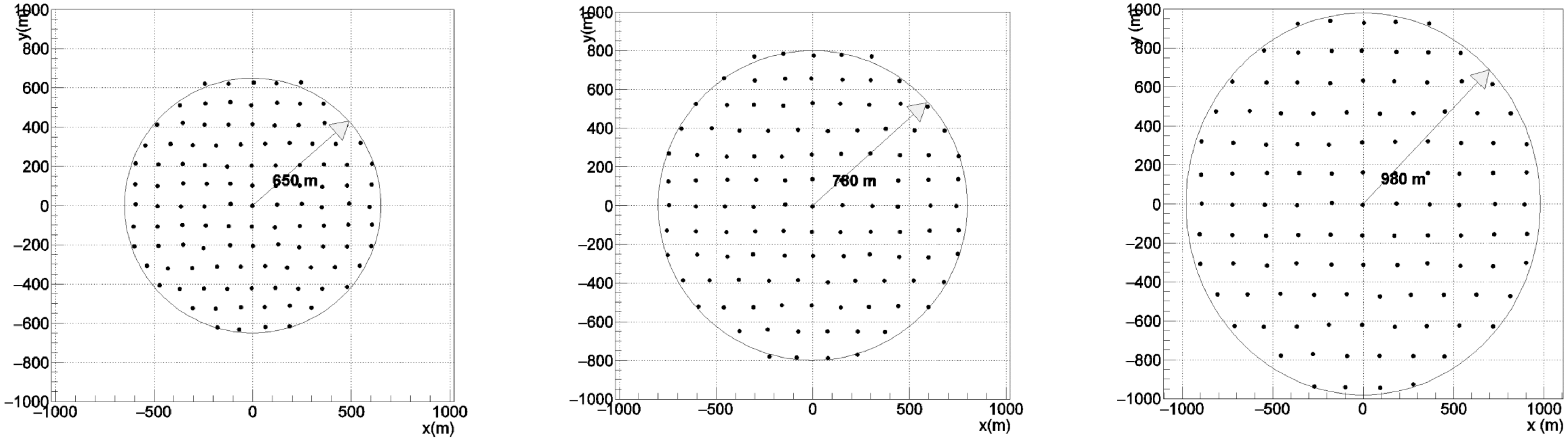
The objective of the study is to define the effect of sparser detector geometries on :

Angular resolution
Energy resolution
Sensitivity & Discovery Potential

Alternative geometries

3 **alternative KM3NeT- ARCA geometries** were made :

120 m – r: 650m | **150 m** – r: 760m | **180 m** – r: 980m

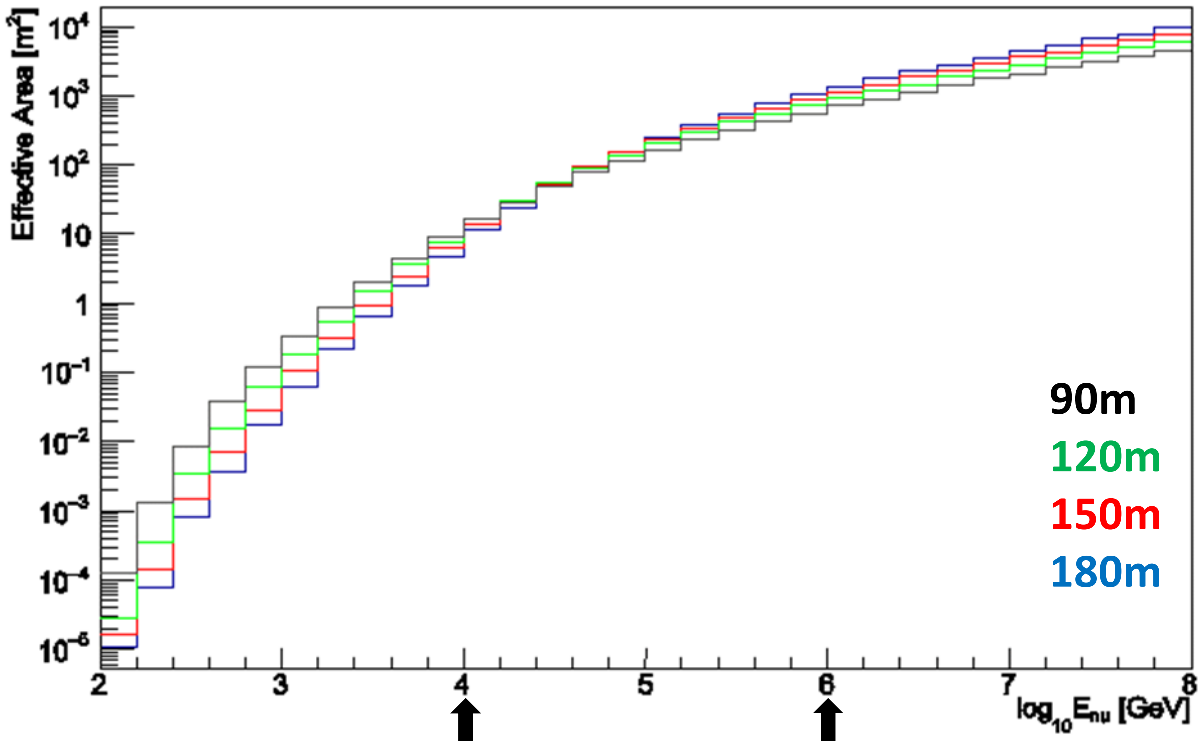


For each geometry, CC muon neutrino events have been generated, passed through the detector simulation including the trigger conditions and have been reconstructed using the official KM3NeT tools

Effective Areas

Differential rate in neutrino energy $= A_{eff}(E_\nu, \theta) \times \frac{dN_\nu(E_\nu,\theta)}{dE_\nu}$

We use the concept of the neutrino effective area to describe the response function of the detector with respect to energy and zenith angle.



Compared to standard KM3NeT-ARCA geometry

at **1 PeV** there is an increase of :

32%
69%
97%

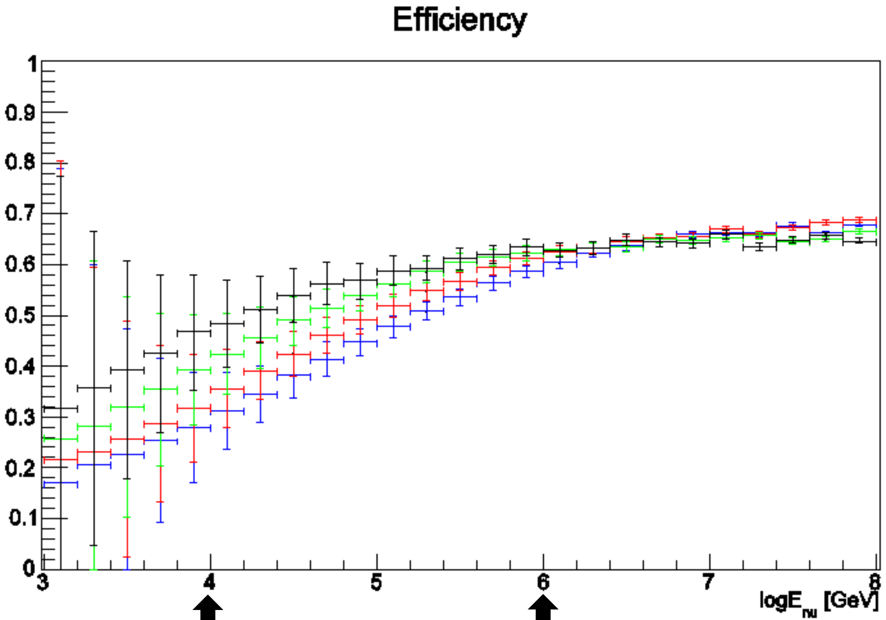
at **10 TeV** there is a loss of :

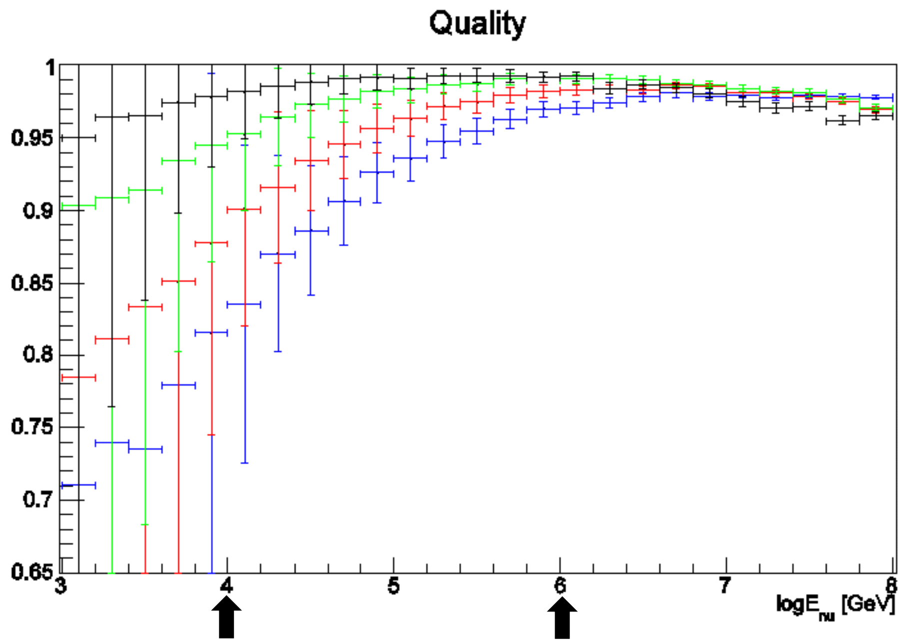
11%
12%
18%

Performance

All events satisfying the official reco quality cuts
All MC events

All well reco events (ΔΩ(μ_true, μ_reco) < 0.1°)
All reco events





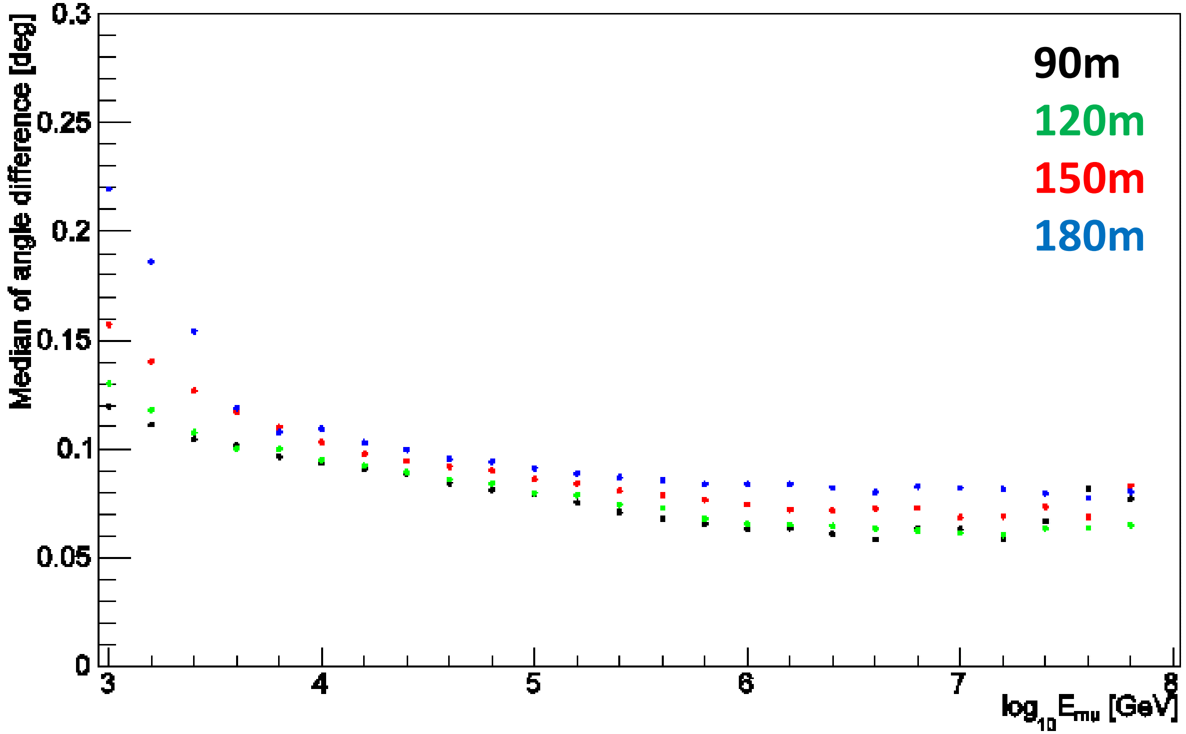
90m
120m
150m
180m

Efficiency	10 TeV	1 PeV
90m	48%	63%
120m	40%	63%
150m	34%	63%
180m	30%	60%

Quality	10 TeV	1 PeV
90m	98%	99%
120m	95%	99%
150m	90%	98%
180m	83%	96%

Reconstruction of the muon direction

KM3NeT aims for excellent reconstruction of the muon (and neutrino) direction
so events are considered **well reconstructed** if the angular resolution - **ΔΩ(μ_true, μ_reco) < 0.1°**

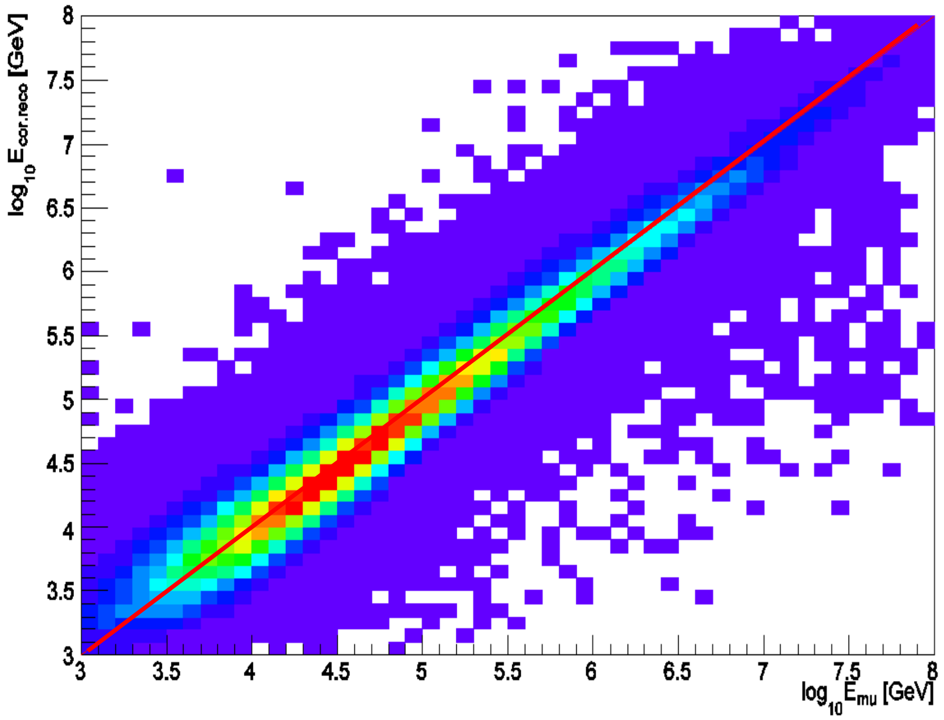


0.1°

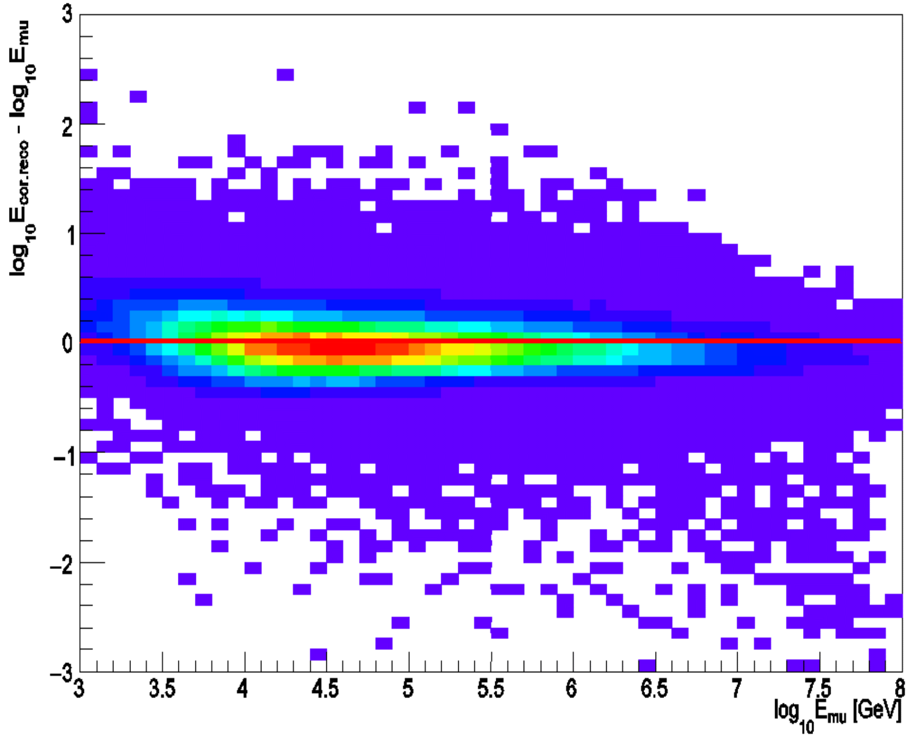
90 m	at 6 TeV
120 m	at 6 TeV
150 m	at 20 TeV
180 m	at 40 TeV

Reconstructed Energy
150 m alternative KM3NeT-ARCA geometry

Reconstructed energy vs MC muon energy

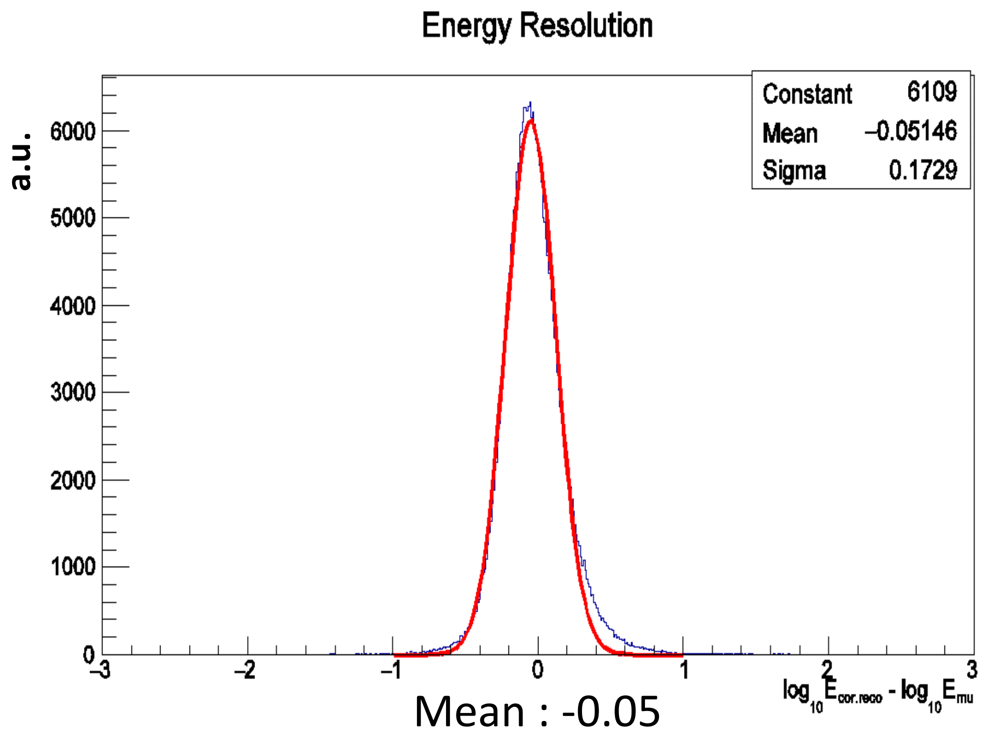


(Reconstructed energy – MC muon energy) vs MC muon energy



Energy Resolution
150 m alternative KM3NeT-ARCA geometry

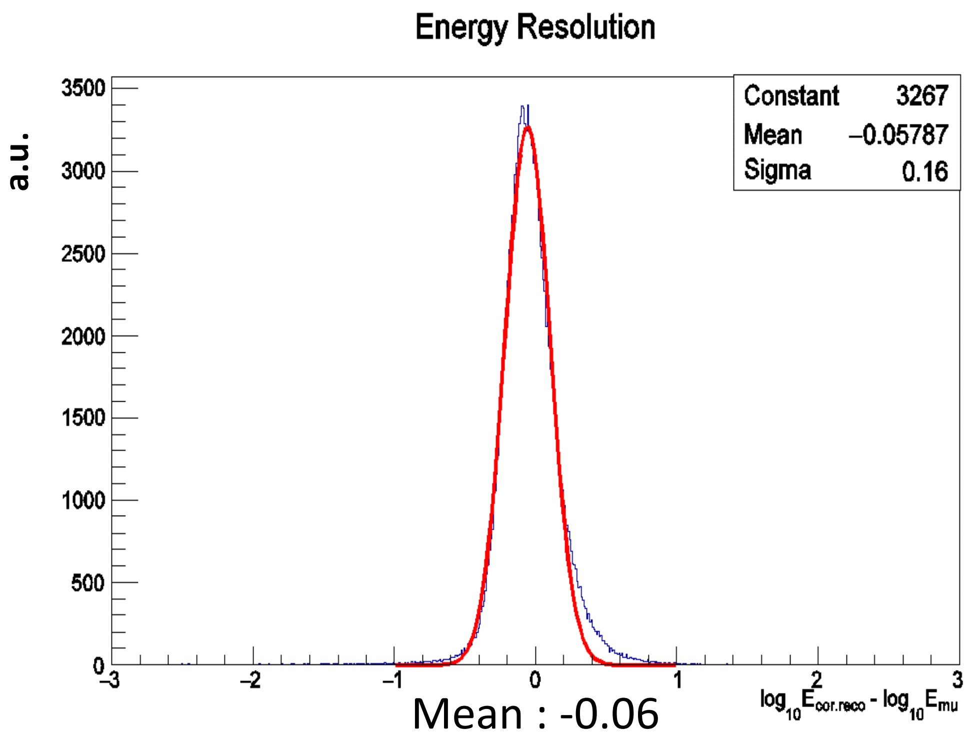
For E > 10TeV



Mean : -0.05

σ : 0.17

For E > 100TeV



Mean : -0.06

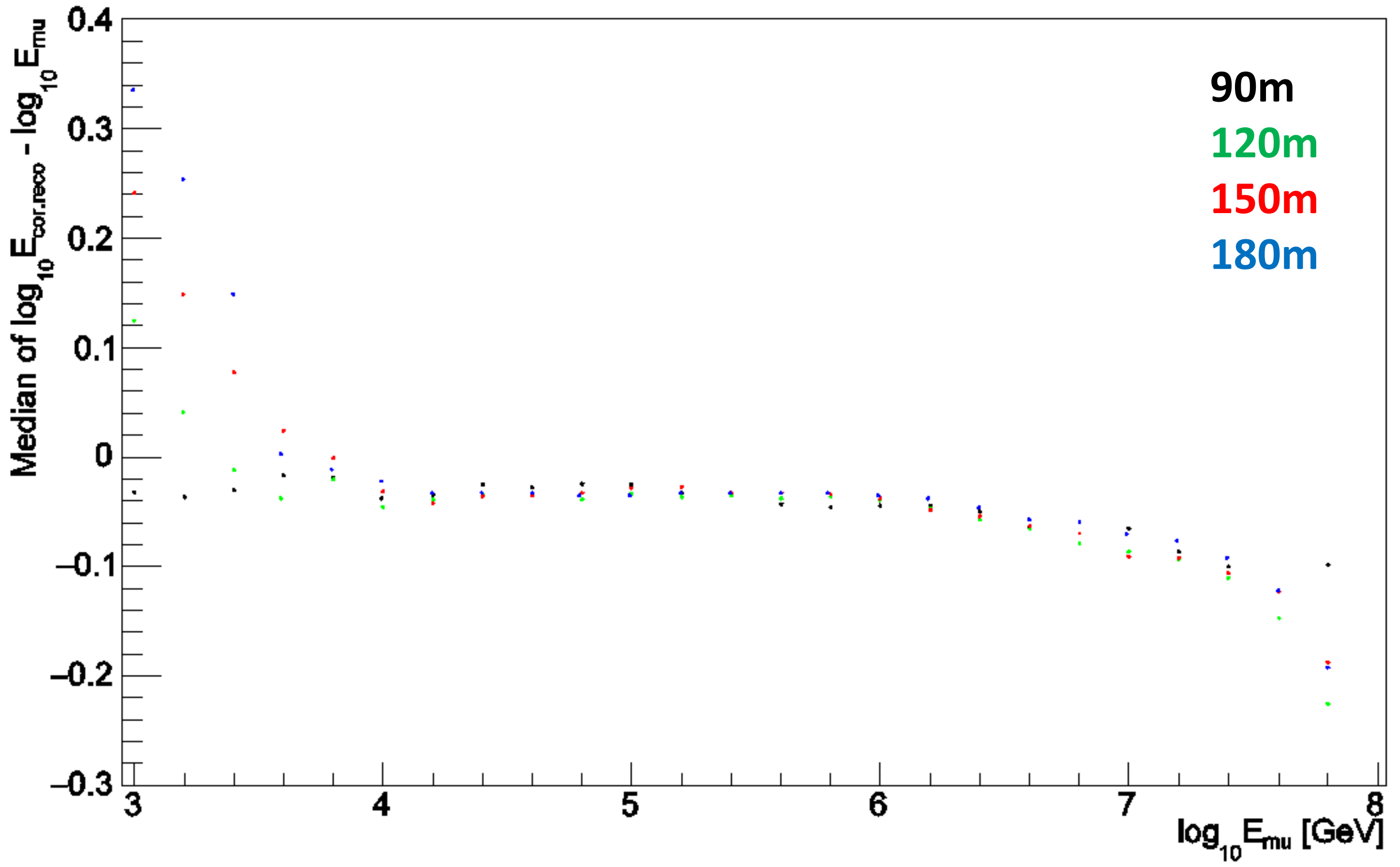
σ : 0.16

Compared to the standard geometry : **Mean** remains stable

σ gets from 0.18 to 0.17 for E > 10 TeV and from 0.17 to 0.16 for E > 100 TeV

i.e <u>there is no appreciable degradation</u>

Energy Resolution



Sensitivity and discovery potential studies

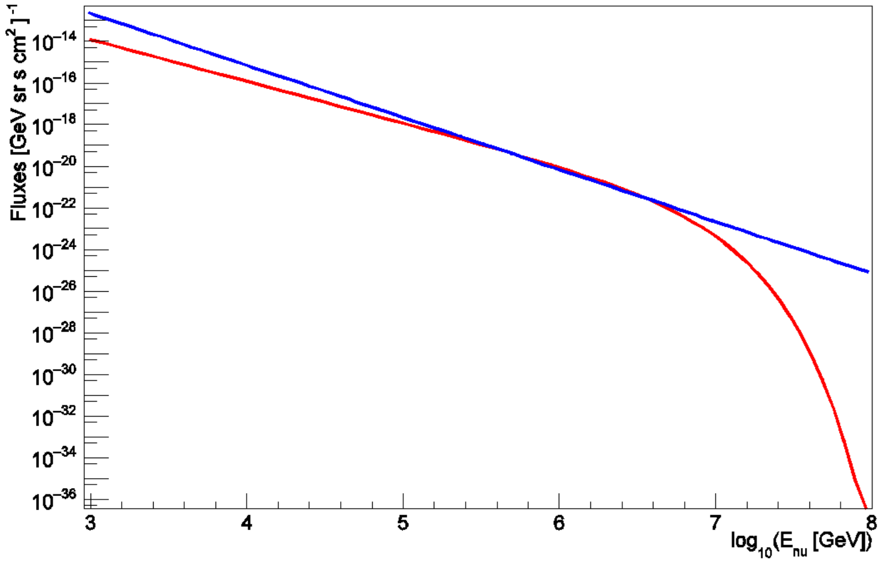
The **sensitivity** of the detector to a neutrino signal refers to the theoretical neutrino flux that can be excluded at a certain confidence level (for this study 90%) if no neutrino signal is detected.

The **discovery potential** refers to the minimum number of events needed to be observed with a very small probability ($\sim 10^{-7}$) that these events originate purely from background fluctuations (for this study 5σ significance and 50% confidence level).

For the sensitivity and discovery potential studies, 2 different fluxes have been used:

LoI flux : $1.2\cdot 10^{-8} \cdot (\frac{E}{1\ GeV})^{-2} \cdot e^{(\frac{-E}{3PeV})}\ [GeV^{-1} sr^{-1} s^{-1} cm^{-2}]$

IceCube flux : $2.2\cdot 10^{-18} \cdot \left(\frac{E}{100\ TeV}\right)^{-2.5}\ [GeV^{-1} sr^{-1} s^{-1} cm^{-2}]$



Sensitivity studies

LoI flux : $1.2\cdot 10^{-8}\cdot\left(\frac{E}{1\ GeV}\right)^{-2}\cdot e^{\left(\frac{-E}{3PeV}\right)}\ [GeV^{-1}sr^{-1}s^{-1}cm^{-2}]$

detector	θ_{reco}	# signal	# background	Φ_{90}
90m	[0°-180°]	17.96	13.18	**$0.502\cdot 10^{-8}$**
	[0°-100°)	9.49	12.70	**$0.934\cdot 10^{-8}$**
120m	[0°-180°]	20.38	10.64	**$0.406\cdot 10^{-8}$**
	[0°-100°)	12.84	16.31	**$0.770\cdot 10^{-8}$**
150m	[0°-180°]	26.79	15.97	**$0.366\cdot 10^{-8}$**
	[0°-100°)	14.01	16.25	**$0.702\cdot 10^{-8}$**
180m	[0°-180°]	27.11	13.96	**$0.341\cdot 10^{-8}$**
	[0°-100°)	13.93	13.96	**$0.664\cdot 10^{-8}$**

Discovery potential studies

LoI flux : $1.2 \cdot 10^{-8} \cdot (\frac{E}{1\ GeV})^{-2} \cdot e^{(\frac{-E}{3PeV})}\ [GeV^{-1}sr^{-1}s^{-1}cm^{-2}]$

detector	θ_{reco}	# signal	# background	$\Phi_{5\sigma}$
90m	[0°-180°]	14.96	8.36	**$1.469 \cdot 10^{-8}$**
	[0°-100°)	9.49	12.70	**$2.777 \cdot 10^{-8}$**
120m	[0°-180°]	20.38	10.64	**$1.238 \cdot 10^{-8}$**
	[0°-100°)	12.84	16.31	**$2.276 \cdot 10^{-8}$**
150m	[0°-180°]	32.10	25.17	**$1.103 \cdot 10^{-8}$**
	[0°-100°)	17.15	25.85	**$2.087 \cdot 10^{-8}$**
180m	[0°-180°]	27.11	13.96	**$1.004 \cdot 10^{-8}$**
	[0°-100°)	13.93	13.96	**$1.956 \cdot 10^{-8}$**

Sensitivity studies

IceCube flux : $2.2\cdot 10^{-18}\cdot\left(\frac{E}{100\ TeV}\right)^{-2.5}\ [GeV^{-1}sr^{-1}s^{-1}cm^{-2}]$

detector	θ_{reco}	# signal	# background	Φ_{90}
90m	[0°-180°]	39.92	52.41	$\mathbf{0.759\cdot 10^{-18}}$
	[0°-100°)	35.93	131.31	$\mathbf{1.291\cdot 10^{-18}}$
120m	[0°-180°]	43.48	41.93	$\mathbf{0.629\cdot 10^{-18}}$
	[0°-100°)	49.11	172.23	$\mathbf{1.071\cdot 10^{-18}}$
150m	[0°-180°]	46.21	41.12	$\mathbf{0.587\cdot 10^{-18}}$
	[0°-100°)	51.43	166.15	$\mathbf{1.005\cdot 10^{-18}}$
180m	[0°-180°]	22.16	36.45	$\mathbf{0.568\cdot 10^{-18}}$
	[0°-100°)	50.29	137.20	$\mathbf{0.942\cdot 10^{-18}}$

Discovery potential studies

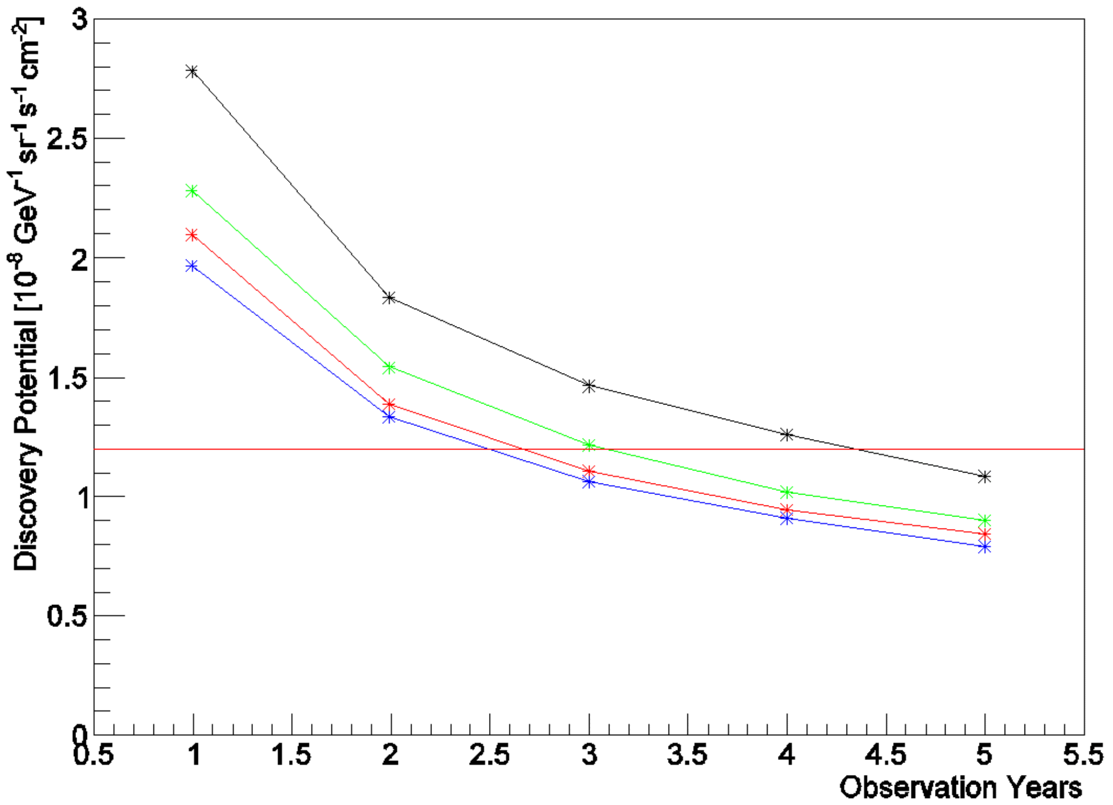
IceCube flux : $2.2 \cdot 10^{-18} \cdot \left(\frac{E}{100\ TeV}\right)^{-2.5} [GeV^{-1} sr^{-1} s^{-1} cm^{-2}]$

detector	θreco	# signal	# background	$\Phi_{5\sigma}$
90m	[0°-180°]	39.92	52.41	$\mathbf{2.220 \cdot 10^{-18}}$
	[0°-100°)	35.93	131.31	$\mathbf{3.758 \cdot 10^{-18}}$
120m	[0°-180°]	43.48	41.93	$\mathbf{1.859 \cdot 10^{-18}}$
	[0°-100°)	73.60	404.73	$\mathbf{3.137 \cdot 10^{-18}}$
150m	[0°-180°]	56.68	64.98	$\mathbf{1.736 \cdot 10^{-18}}$
	[0°-100°)	51.43	166.15	$\mathbf{2.930 \cdot 10^{-18}}$
180m	[0°-180°]	22.16	36.45	$\mathbf{1.661 \cdot 10^{-18}}$
	[0°-100°)	62.41	220.10	$\mathbf{2.770 \cdot 10^{-18}}$

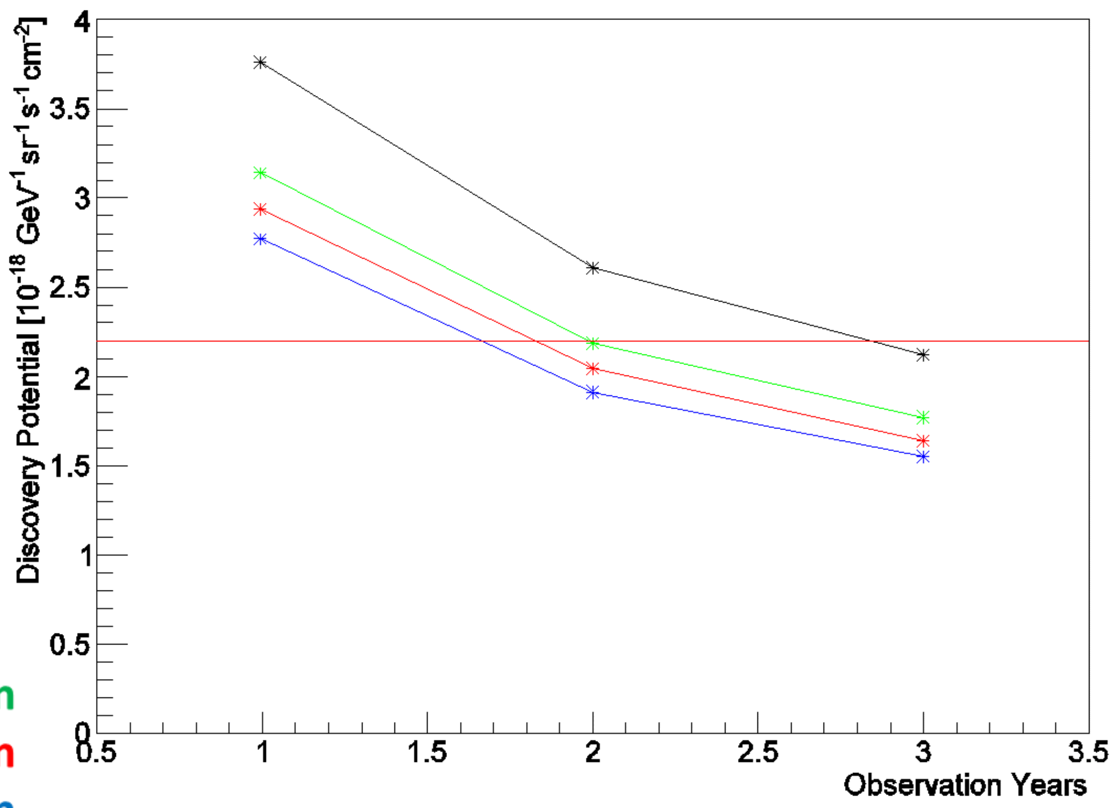
Discovery potential estimation

LoI flux : $1.2 \cdot 10^{-8} \cdot \left(\frac{E}{1\ GeV}\right)^{-2} \cdot e^{\left(\frac{-E}{3PeV}\right)}$ $[GeV^{-1} sr^{-1} s^{-1} cm^{-2}]$

IceCube flux : $2.2 \cdot 10^{-18} \cdot \left(\frac{E}{100\ TeV}\right)^{-2.5}$ $[GeV^{-1} sr^{-1} s^{-1} cm^{-2}]$



90m
120m
150m
180m



Conclusions

Alternative detector configurations with 120m, 150m and 180m distance between the strings have been studied.

Excellent **angular and energy resolution** were found for all the detector configurations.

The effect on the **sensitivity** was at the $\sim$40% level comparing at the 2 extremes (90m and 180m).

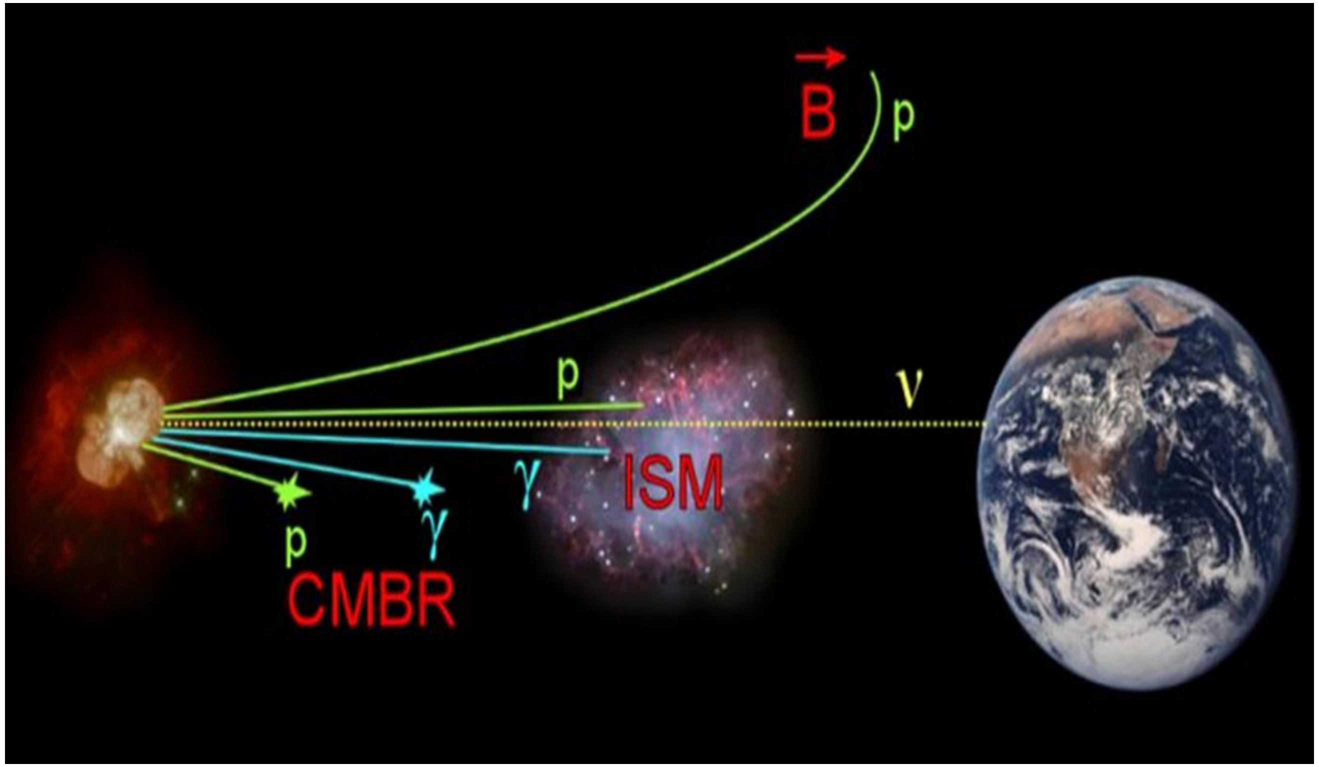
The effect on the **discovery potential** was at the $\sim$40% level comparing at the 2 extremes (90m and 180m) leading to a potential discovery in less time.

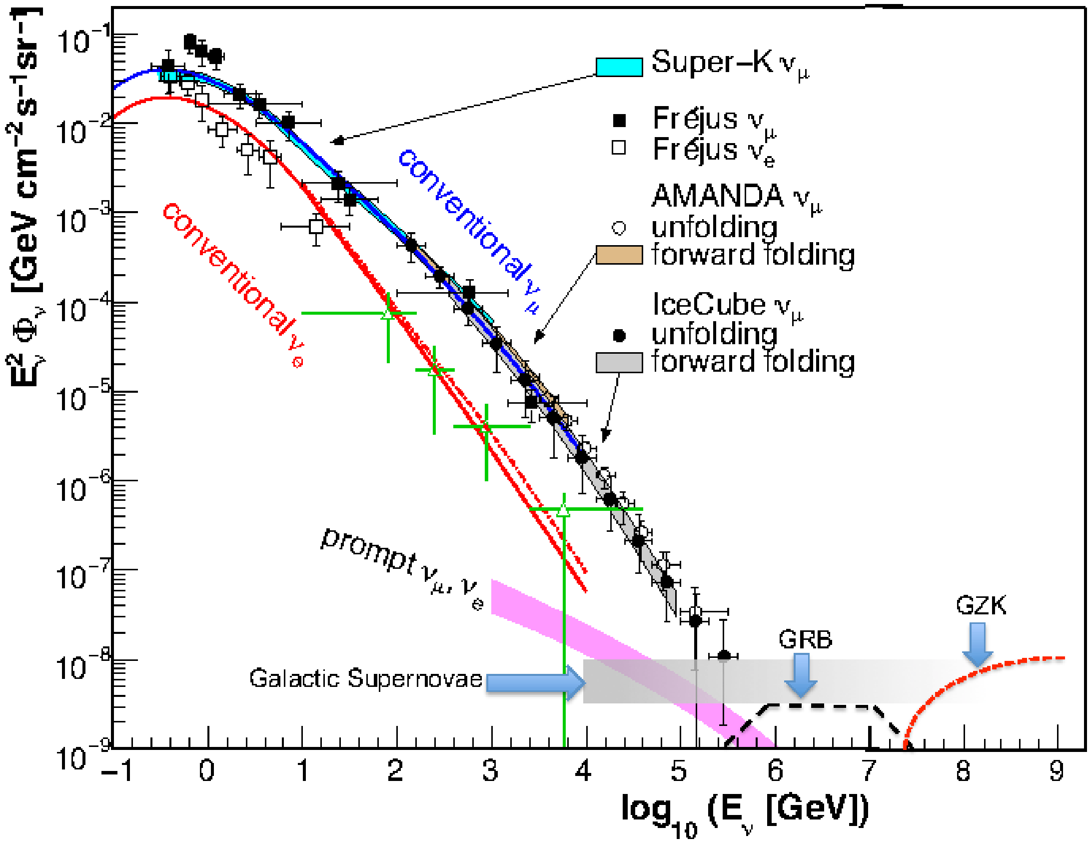
The **alternative geometry with 150m** distance between the strings seems to be **the best choice** as **it produces better results** from the standard and 120m alternative geometry and has a **better reconstruction quality and angular resolution** from the 180m alternative geometry.

Thank you for your attention

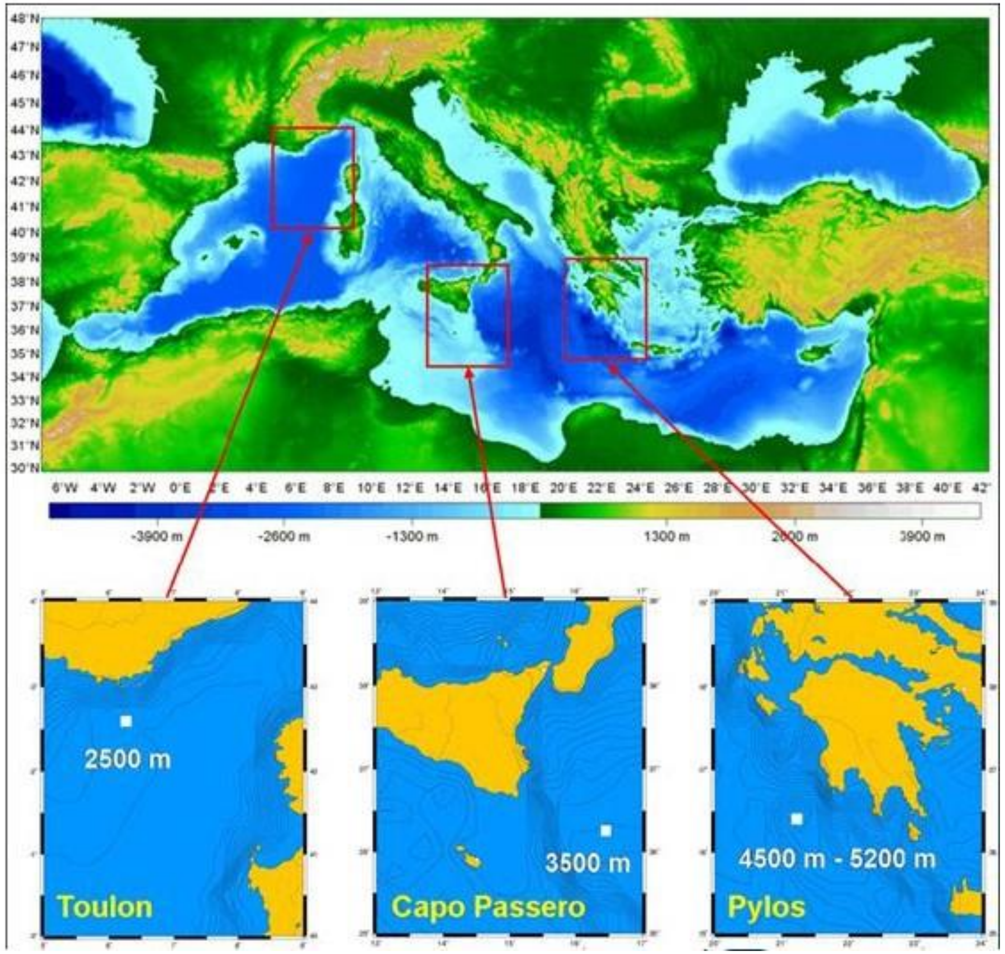
BACK UP SLIDES

Neutrino astronomy





The KM3NeT Project



KM3NeT is a research infrastructure in the Mediterranean Sea that will host neutrino detectors

Three deep-sea sites are selected for the optical properties of the water, distance to shore and local infrastructure,
namely off-shore Toulon (France), Capo Passero (Sicily, Italy) and Pylos (Peloponnese, Greece).

KM3NeT/ARCA (**A**stroparticle **R**esearch with **C**osmics in the **A**byss)

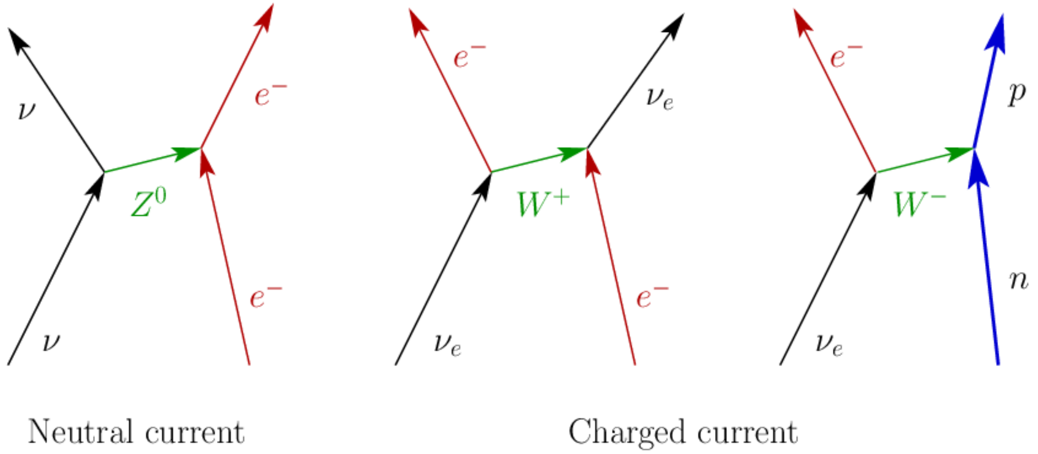
- discovery and observation of high energy (TeV - PeV) neutrino sources of cosmic origin

KM3NeT/ORCA (**O**scillation **R**esearch with **C**osmics in the **A**byss)

- determination of the neutrino mass hierarchy (atmospheric neutrinos with energies of O(~GeV))

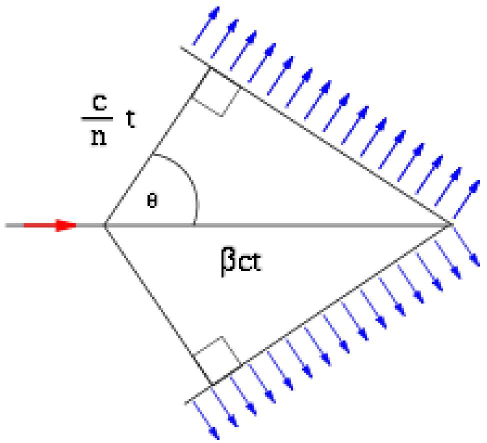
Detection Principle

Weak interactions

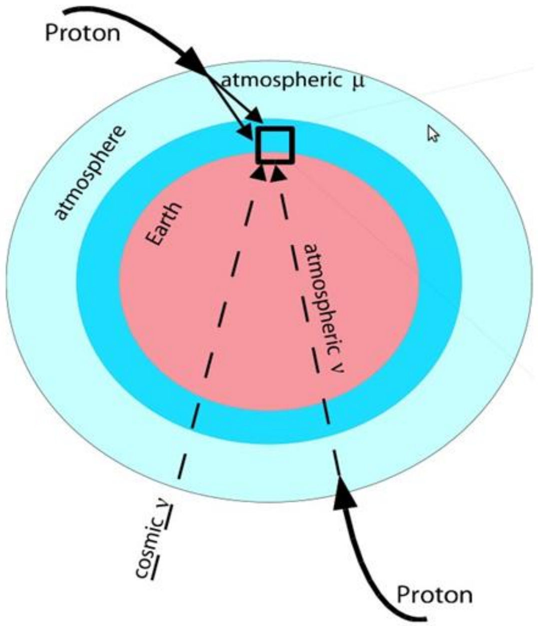


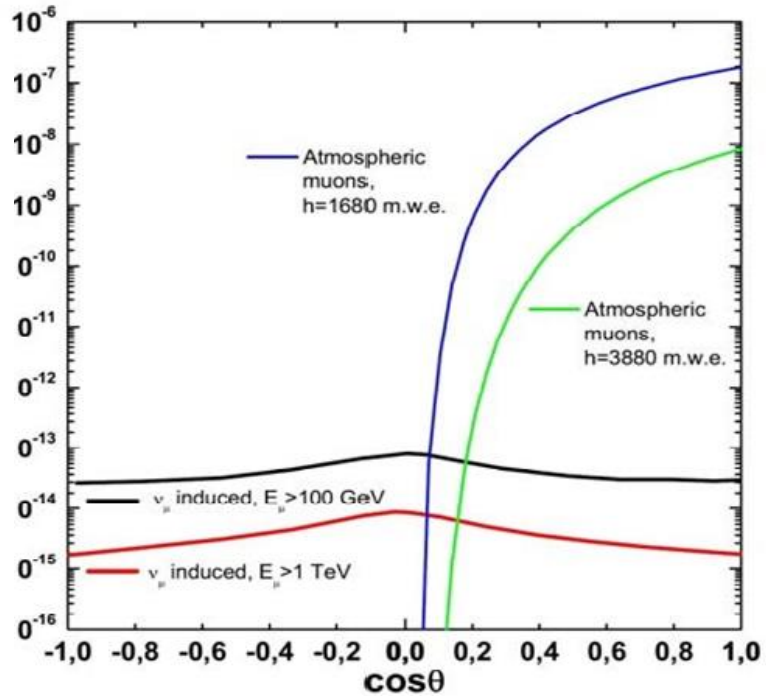
Cherenkov effect

$$\theta = \cos^{-1}\frac{1}{\beta n}$$



Background





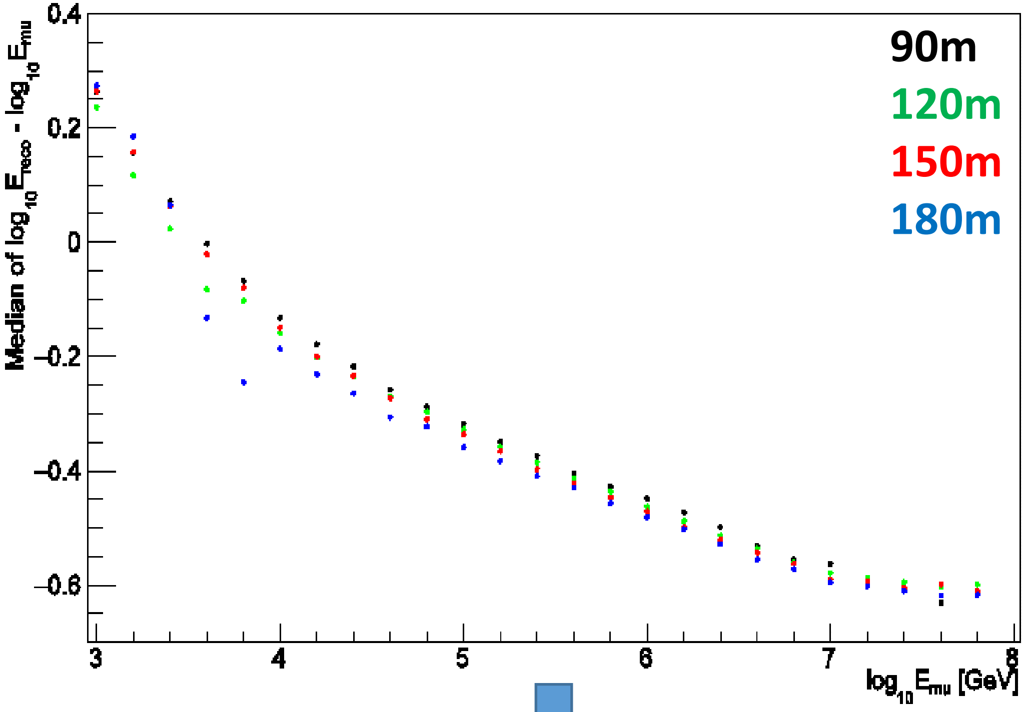
Reconstruction's quality cuts

The quality parameters for track selection are :

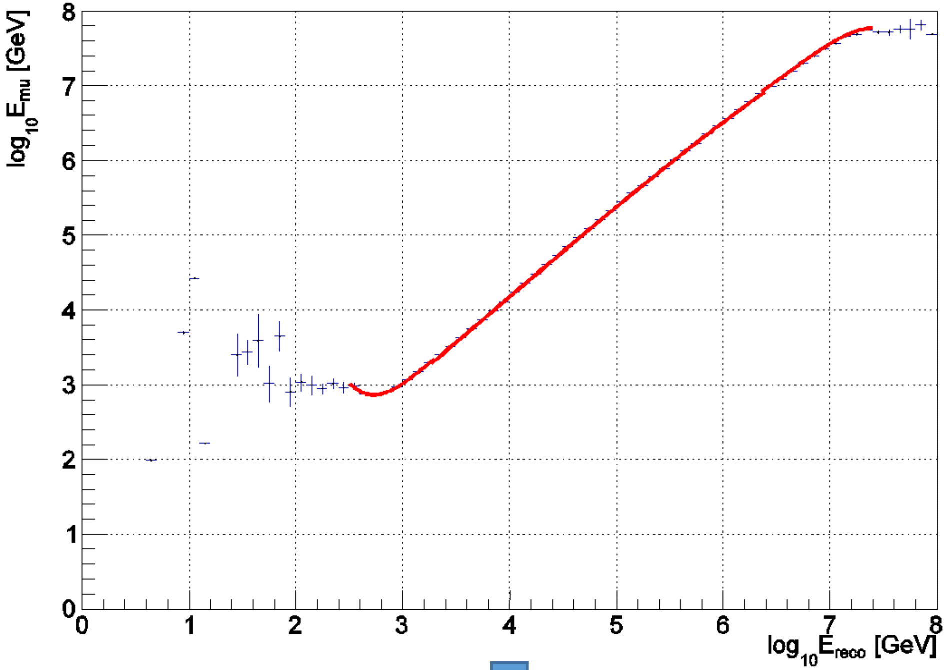
- the likelihood of the reconstructed tracks
- the likelihood divided by the number of hits related to the track
- the first error on the track parameters as : $Tx^2 + Ty^2$
- the second error on the track parameters as : Tx^2

Where Tx $and\ Ty$ are the estimated uncertainties in the x and y direction cosines.

Energy Reconstruction



Energy corrections should be made and applied

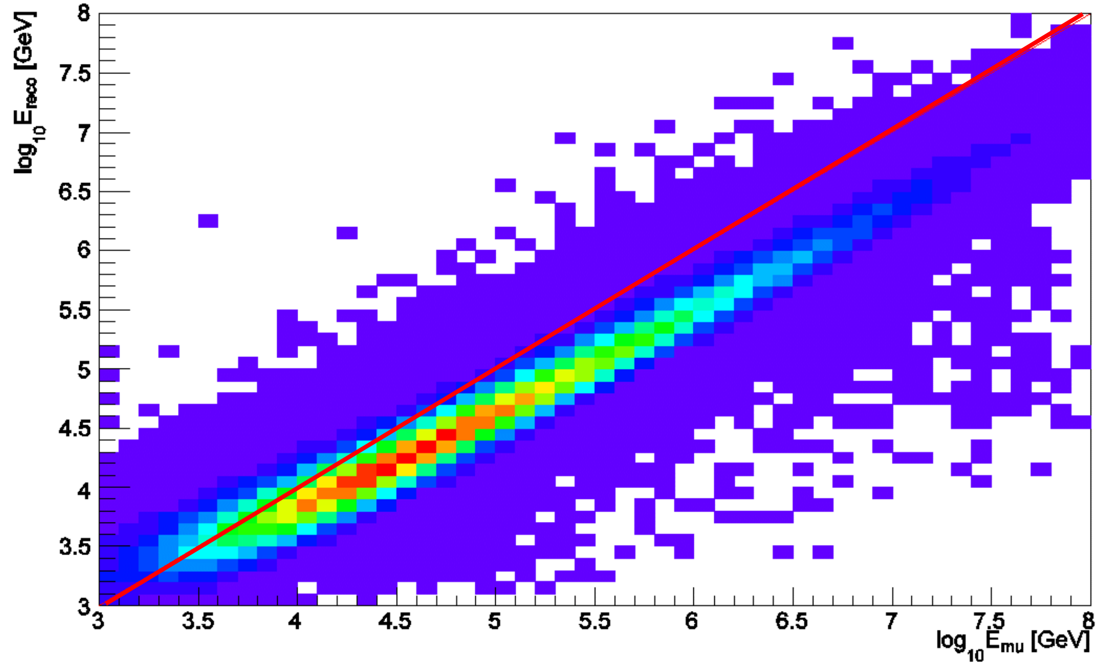


Energy corrections are made and applied for each alternative geometry

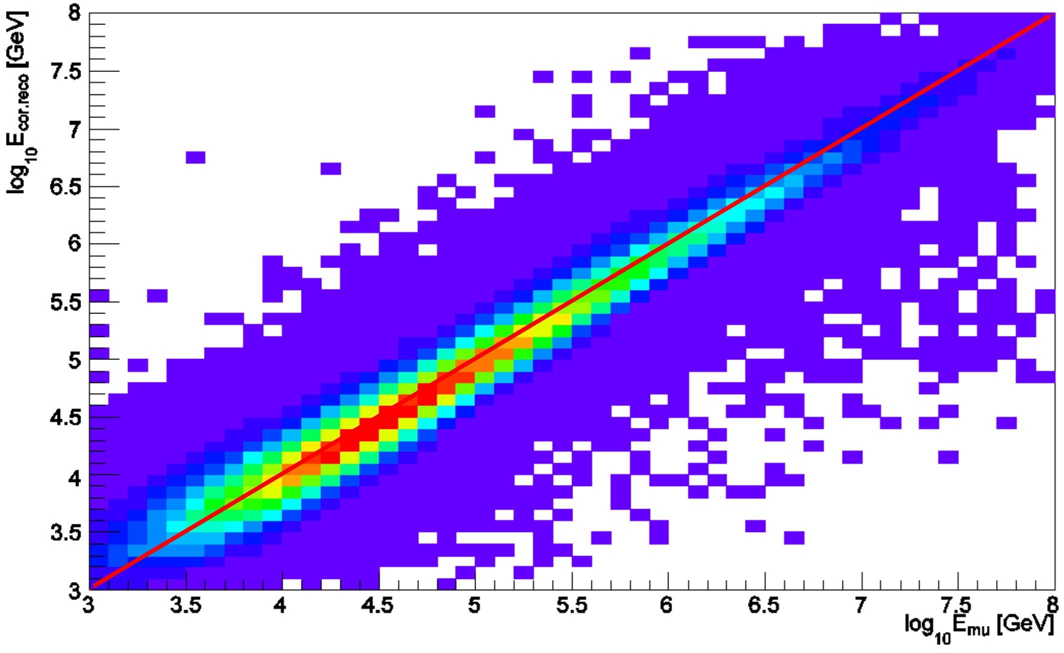
Reconstructed Energy 150 m alternative KM3NeT-ARCA geometry

Reconstructed energy vs MC muon energy

Before the energy correction



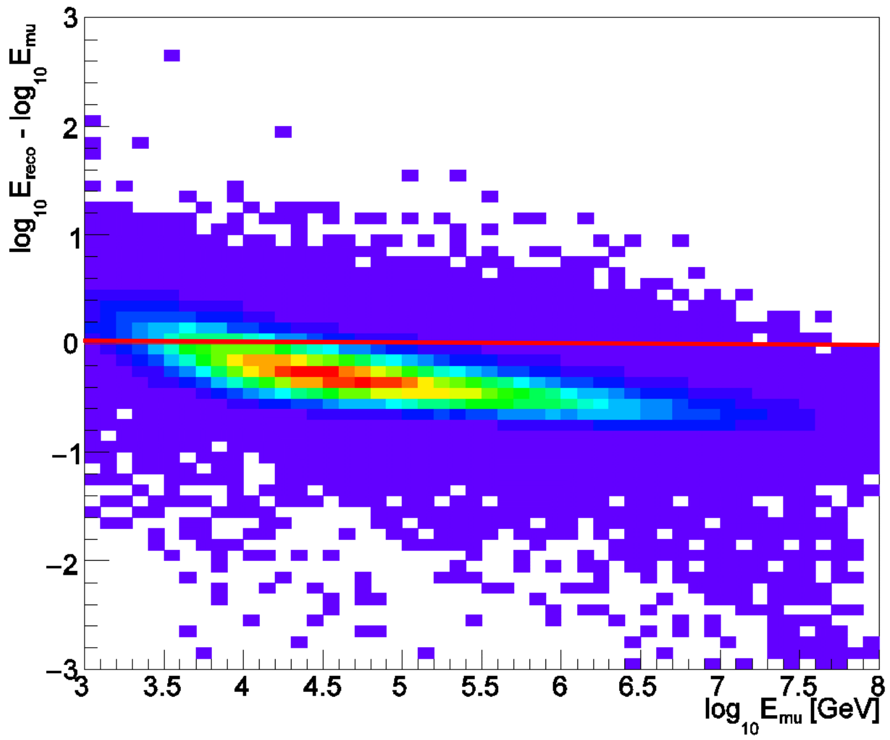
After the energy correction



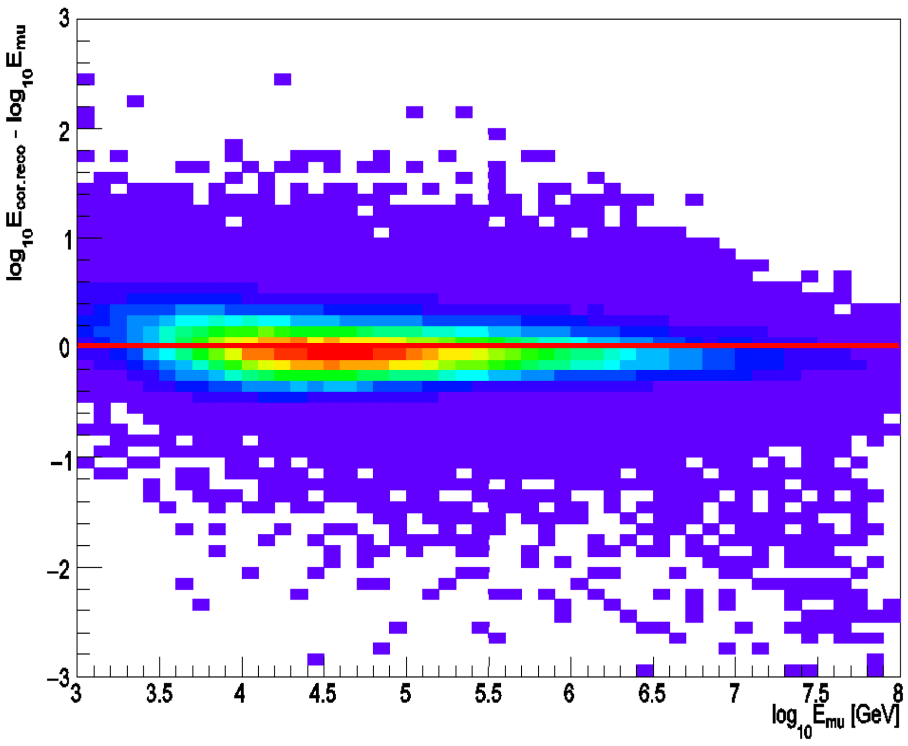
Reconstructed Energy
150 m alternative KM3NeT-ARCA geometry

(Reconstructed energy – MC muon energy) vs MC muon energy

Before the energy correction

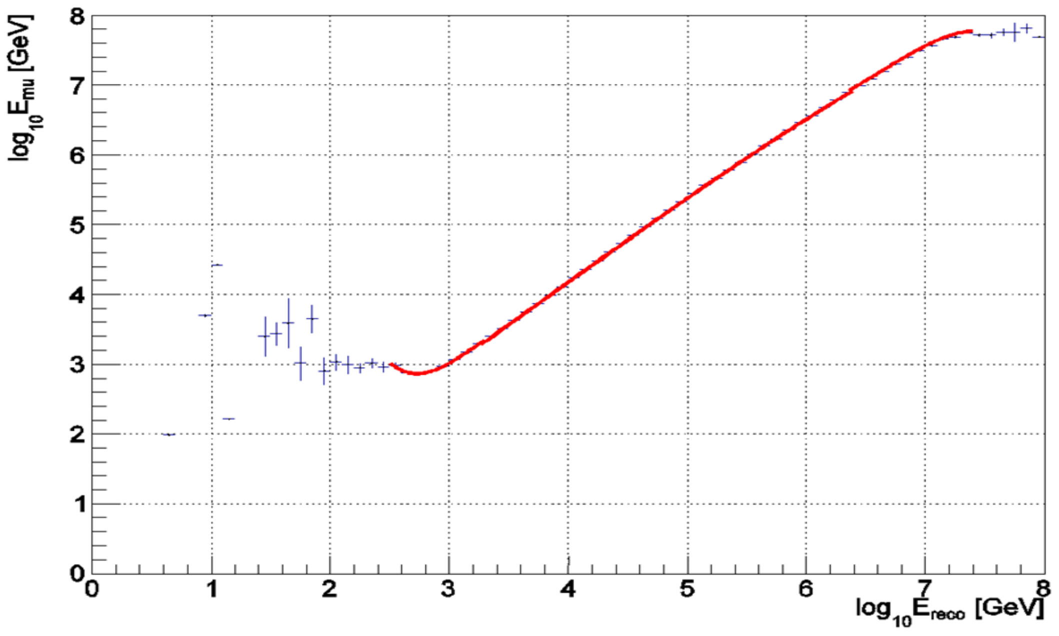


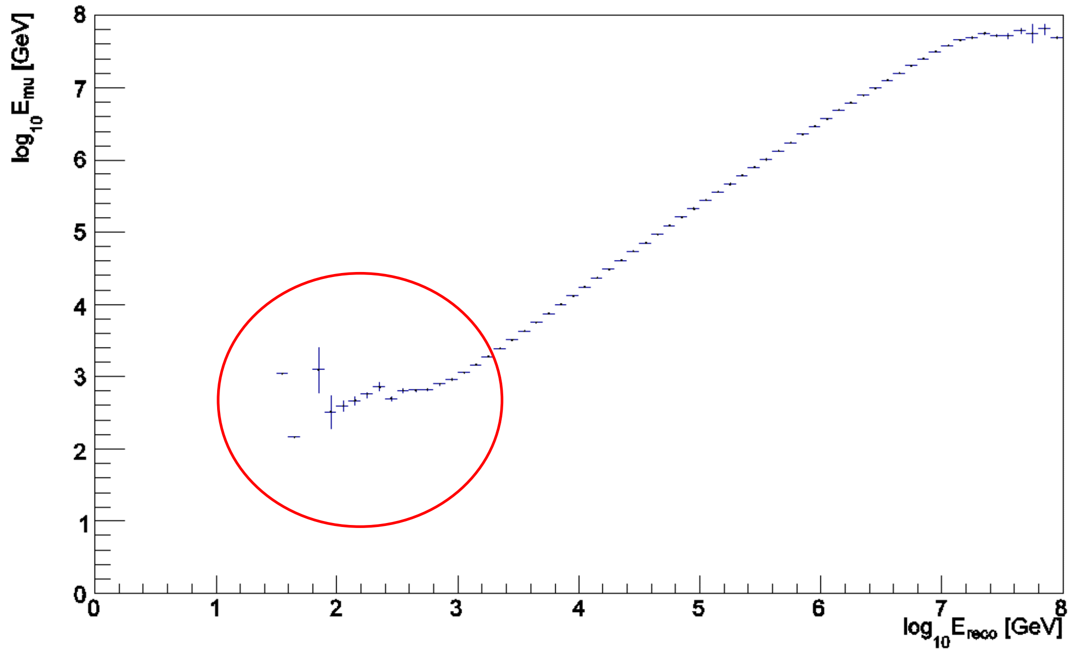
After the energy correction



Reconstructed Energy
150 m alternative KM3NeT-ARCA geometry

Events with ΔΩ < 1°





In low energies (E < 1 TeV) we have mostly badly reconstructed events

The binned method for statistical analysis

$$\Phi_{90} = k \times mrf = k \times \frac{\bar{\mu}_{90}(\langle n_b \rangle)}{\langle n_s \rangle}$$

90% confidence level average flux limit

Average maximum limit of background fluctuation at 90% of confidence level that would be observed after hypothetical repetition of an experiment with an expected background $<n_b>$ and no true signal

Average number of signal and background events estimated throught the Monte Carlo simulations

$$\Phi_{5\sigma}^{50\%CL} = k \times mdp = k \times \frac{\bar{n}_{5\sigma}^{50\%CL}(\langle n_b \rangle)}{\langle n_s \rangle}$$

50% confidence level and 5σ significance average flux limit

Average maximum limit of background fluctuation at 5σ significance and 50% of confidence level that would be observed after hypothetical repetition of an experiment with an expected background $<n_b>$ and no true signal