

Search for the diffuse astrophysical neutrino flux with KM3NeT/ARCA

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on behalf of the KM3NeT Collaboration

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Outline

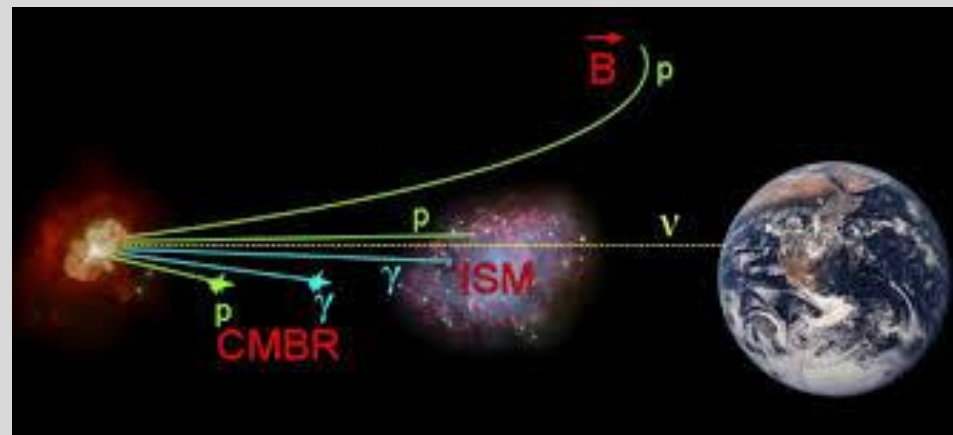
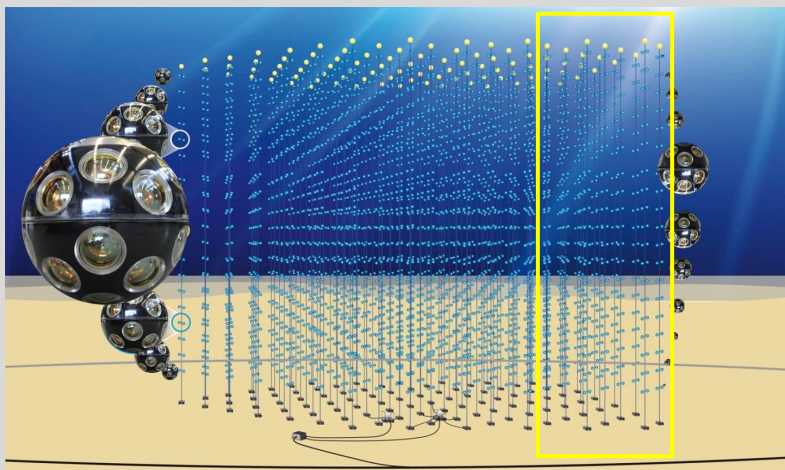
- The Diffuse Flux of Astrophysical Neutrinos with KM3NeT/ARCA
- Event Selection
- Statistical Analysis

The Diffuse Flux of Astrophysical Neutrinos with KM3NeT/ARCA

- ◆ Extreme cosmic accelerators produce high-energy neutrinos via proton-proton (pp) and proton-photon (p γ) collisions.
- ◆ Arriving from all directions, they form a diffuse flux of neutrinos from a collective of distant cosmic sources.

AGNs, GRBs,
Super/Hypernovae
etc.

ARCA (Astroparticle Research with Cosmics in the Abyss)



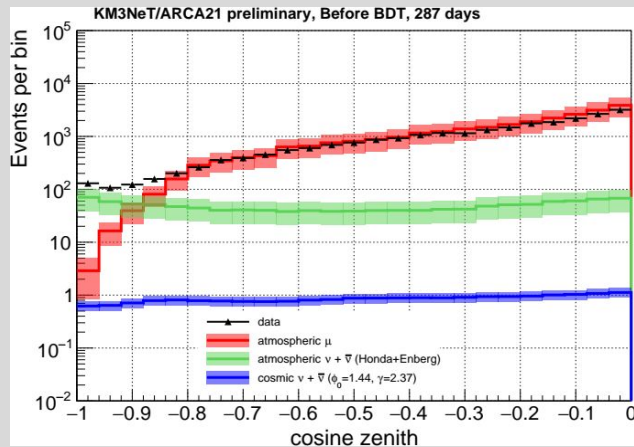
More on the [detector](#) and [astrophysical neutrinos](#) on tomorrow's talks by Dr. Ekaterini Tzamariudaki.

Event Selection

Need to yield a selection with high neutrino purity. Reduction of noise and physical background.

- Remove background noise from ^{40}K decays and bioluminescent activity in the sea by applying quality criteria to reconstruction variables.
- Atmospheric muons and neutrinos constitute the main physical sources of background in our analysis.
- Selecting events reconstructed as upgoing tracks effectively rejects the majority of atmospheric muons. Surviving muons are primarily misreconstructed events.
- Since the remaining background comprises poorly reconstructed events, applying additional cuts on key reconstruction variables isolates and removes these misidentified tracks.

**~ 1 billion atm. μ
are expected**



Still a contamination from atm. μ of 96% at this level.
Very faint neutrino signal.

atm. μ ~ 27000

atm. ν : 1208

astro. ν : 21

BDT Classification Scheme

Classification target

Class 1: Signal

Well Reconstructed (WR) ($\Delta\Omega < 5^\circ$)

Charged current (CC) ν_μ ($\bar{\nu}_\mu$) events

Class 0 — Background

Badly Reconstructed ($\Delta\Omega > 10^\circ$)

Atmospheric muon events

$\Delta\Omega$ is the angle between the Monte Carlo track and the reconstructed one

BDT: Boosted Decision Tree

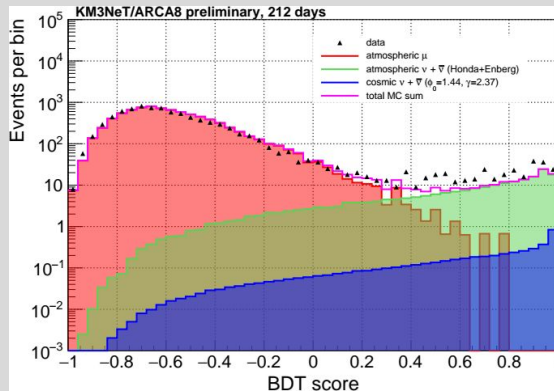
ANOVA: Analysis Of Variance

TMVA: Toolkit for MultiVariate data Analysis

ROC: Receiver Operating Characteristic curve

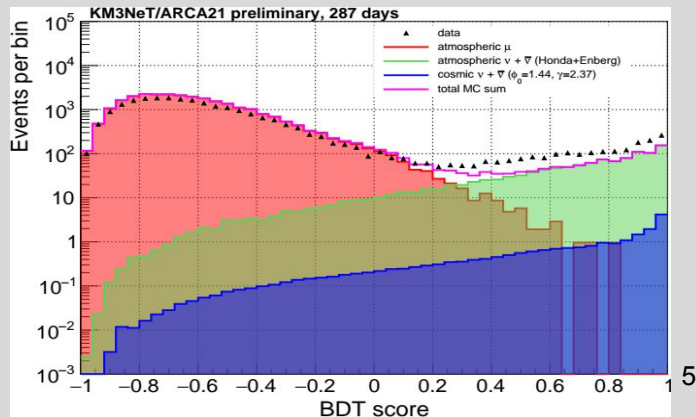
Feature Selection

- Quantities derived directly from the track reconstruction.
- Initial set of features selected & ranked by [ANOVA F-test score](#).
- Eliminate strongly correlated variables.
- Model-based feature selection using the variable importance as computed in [ROOT TMVA](#).



Hyper parameter tuning and model validation

- Hyper-parameters tuned via Grid Search.
- Evaluated on several metrics such as signal efficiency, ROC-integral, F1-score and data/MC agreement.
- Two models are trained and deployed: one for ARCA6/8 and one for ARCA19/21.
- Optimize a BDT cut for the different datasets to minimize atmospheric muon contamination.



- An all-flavour cosmic neutrino search (both CC+NC) is performed.
- As signal we consider cosmic (anti)neutrinos (3f) and the physics background are atmospheric (anti)neutrinos (3f) and muons.
- Atmospheric neutrinos are modeled using the Honda-Enberg flux.
- The diffuse flux of astrophysical neutrinos is commonly parameterised as:

$$\Phi_{\nu+\bar{\nu}}(E) = \frac{dN}{dE} = \phi_0 \cdot 10^{-18} \cdot \left(\frac{E}{100 \text{ TeV}} \right)^{-\gamma} [\text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$$

For ϕ_0 and γ use as baseline, [IceCube's](#) reported values.

- Use the Model Rejection Factor ([MRF](#)) technique to find the optimal cut on the reconstructed energy.
- Use a Bayesian and a frequentist statistical framework to perform a fit of these cosmic flux parameters using data of ARCA6+8+19+21.

Bayesian

Based on the Bayesian interpretation of probability, a posterior probability density function can be computed. The likelihood function is defined as a product of Poissonian PDFs over the energy bins:

$$L(N; S(\gamma), B, \phi_0) = \prod_i L_i = \prod_i \text{Poisson}(N_i, N_{\text{expected}}^{(i)} = B_i + \phi_0 S_i(\gamma))$$

Combination of the 4 data-taking periods:

$$L^{\text{total}}(N; S(\gamma), B, \phi_0) = L^{(6)} \cdot L^{(8)} \cdot L^{(19)} \cdot L^{(21)}$$

Marginalize probability:

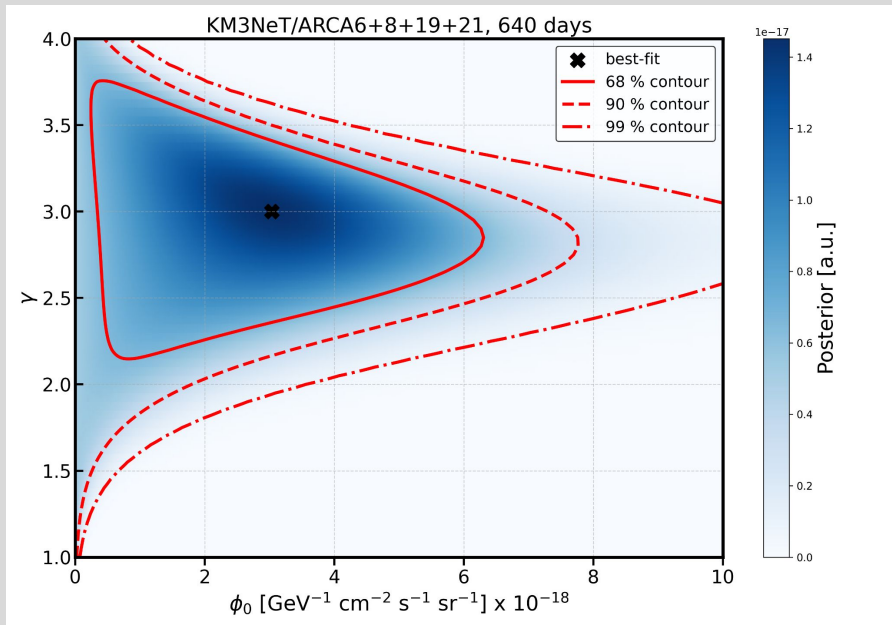
$$p(\phi_0, \gamma; N) = \int L(N; S(\gamma), B, \phi_0) \cdot \pi(B_i) \cdot \pi(S_i(\gamma)) \cdot \pi(\phi_0, \gamma) \cdot \prod_i dB_i dS_i(\gamma)$$

The prior distributions incorporate the uncertainty of the measurements. We use:

- $\pi(B_i) = \text{Gaussian}(\mu = B_i, \sigma = \sqrt{B_i})$
- $\pi(S_i(\gamma)) = \text{Gaussian}(\mu = 1, \sigma = 0.2)$, where 0.2 is the signal acceptance
- $\pi(\phi_0, \gamma) = 1$, since we assume no previous knowledge of ϕ_0 and γ

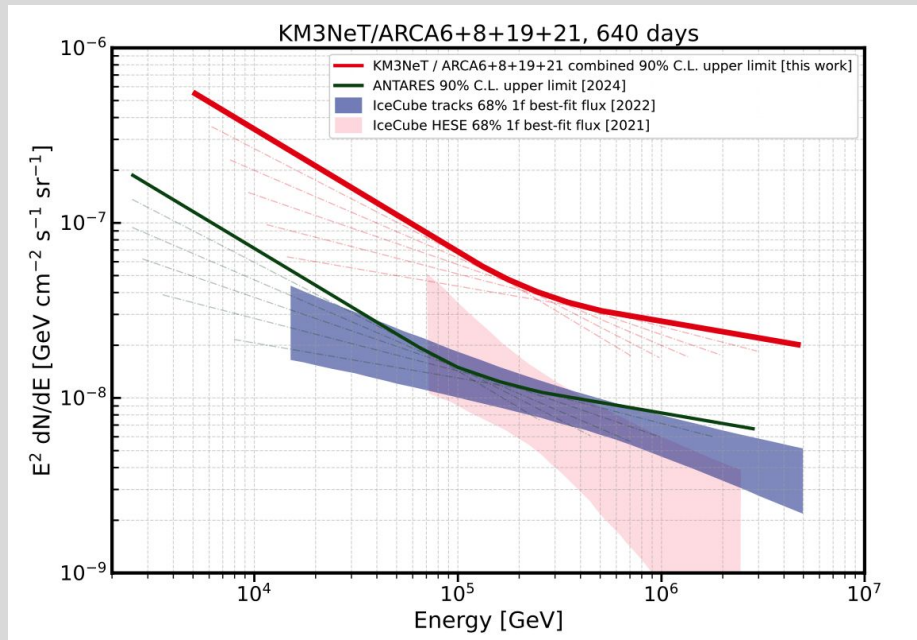
Bayesian - Results

The marginalized posterior probability density function is computed. An estimation of the maximum a posteriori (MAP) point for the neutrino flux parameters is possible.



$$\text{best } \phi_0 = 3.0^{+2.1}_{-2.0}$$

$$\text{best } \gamma = 3.00^{+0.30}_{-0.35}$$

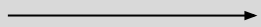


Upper limits on ϕ_0 for different values of the spectral index $\gamma=2.2-2.7$

Frequentist

A frequentist likelihood fit is also employed to estimate the flux parameters. A poissonian χ^2 is defined as follows:

$$\chi^2 = -2 \log L$$



d index denotes the different detector geometries and i runs over the energy bins.

$$\begin{aligned} \chi^2_{\alpha} = & \sum_d \sum_i 2 \left(P_i^{(d)} - D_i^{(d)} + D_i^{(d)} \ln \frac{D_i^{(d)}}{P_i^{(d)}} \right) \\ & + \sum_i \left(\frac{\alpha_{A,i}}{\sigma_A} \right)^2 + \left(\frac{\alpha_{M,i}}{\sigma_M} \right)^2 \\ & + \left(\frac{\alpha_S}{\sigma_S} \right)^2 . \\ P_i^{(d)} = & (1 + \alpha_S) S_i^{(d)} + (1 + \alpha_{A,i}) A_i^{(d)} + (1 + \alpha_{M,i}) M_i^{(d)} \end{aligned}$$

Systematic errors were incorporated as a combination of gaussian *nuisance parameters* and *pull-terms* using these α parameters shown above.

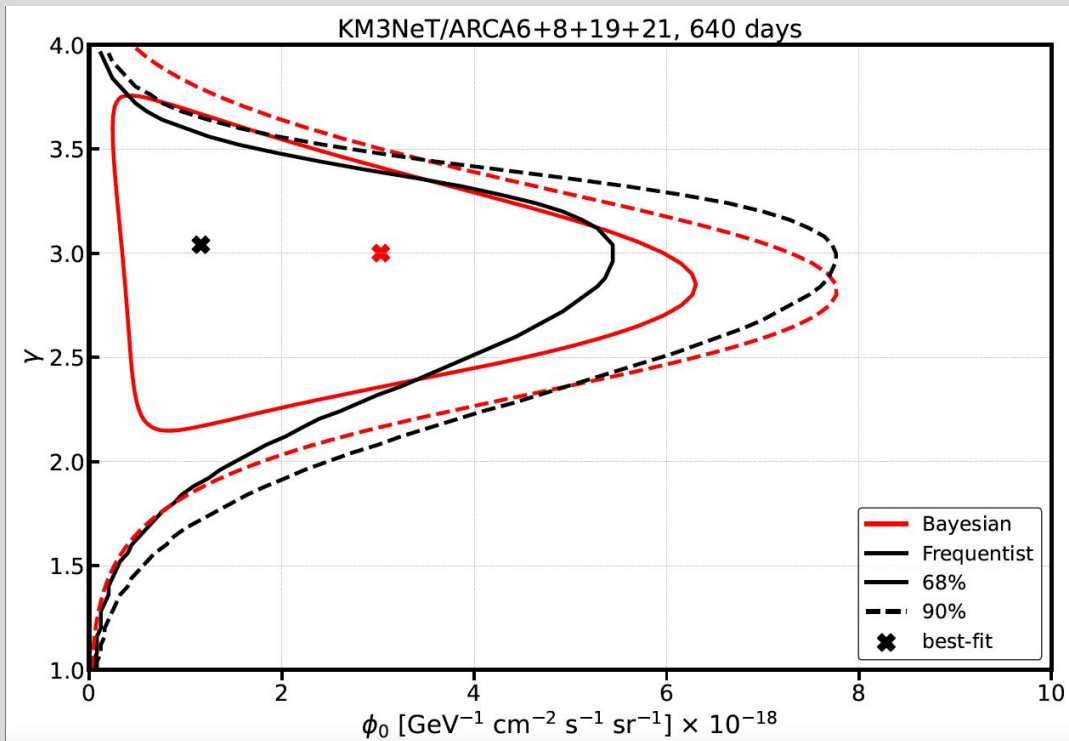
The χ^2 is minimized w.r.t. the nuisance parameters and the best-fit values is extracted for the parameters of interest.

Test statistic: $\lambda = \chi^2(\mu = 0) - \chi^2_{\min}$

Defining this test statistic we can also compute the detector sensitivity discovery potential.

Frequentist - Results

The best fit values and the corresponding 68% and 90% confidence/credible level contours can be compared with the Bayesian ones.



- Same event selection as for the Bayesian
- No reconstructed energy cut

No significant excess of cosmic neutrino signal is observed!

A [paper](#) has been prepared and submitted for publication by Vasilis Tsourapis and Leonidas Kalousis regarding details of this analysis!

Summary

- The analysis methodology for the search of the diffuse flux of astrophysical neutrinos using the first ~2 years of KM3NeT/ARCA data is presented.
- Fit results of all-sky cosmic flux parameters are reported and upper limits are set.
- No excess of cosmic neutrinos was observed within this time period.
- Inclusion of recent data in the analysis will approximately double the size of our statistical sample.
- As the ARCA detector is growing and our simulation and reconstruction is improving exciting times are coming!

Thank you for your attention!

Backup

Data taking periods

Data are collected while KM3NeT/ARCA is constructed. Data taking periods are named based on the number of deployed DUs at running time.

ARCA6

May 2021 – September 2021
92 days of analysed data

ARCA8

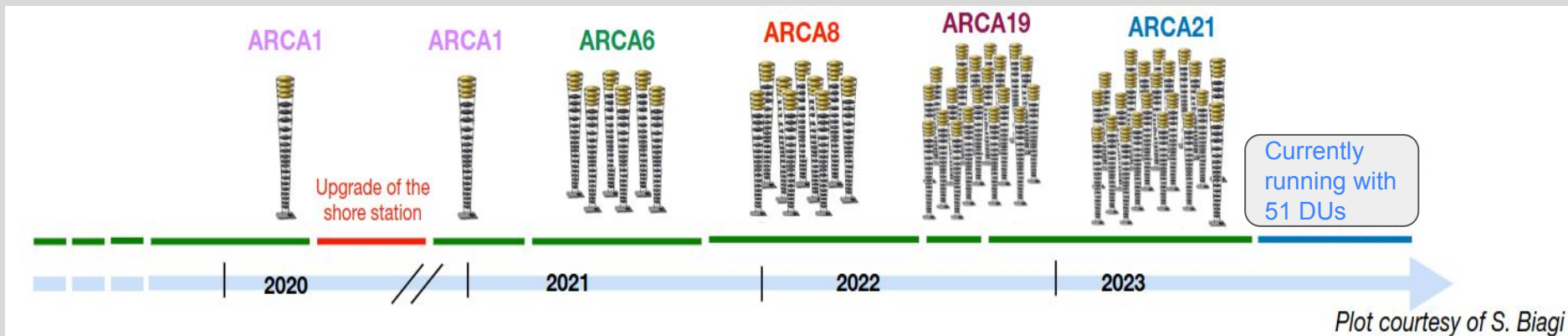
September 2021 – June 2022
212 days of analysed data

ARCA19

June 2022 – September 2022
48 days of analysed data

ARCA21

September 2022 – September 2023
287 days of analysed data



Since 2023, data have also been collected with 28, 30 and 51 deployed DUs of the ARCA detector! Analysis of those datasets is ongoing

pre-BDT cuts:

- Likelihood of the best reconstructed track > 50
- TrackLength (as given by the reconstruction) > 100.0
- $\log(\beta_0[\text{rad}]) < -1.5$ (β_0 : uncertainty on the reconstructed track direction from the error matrix)
- $\log(E_{\text{reco}} / \text{GeV}) > 2.7$
- TrackLength_2 (distance of the vertex and last emitted photon) > 100
- TrackLength_3 (distance of first and last emitted photons) > 100
- Number of DOMs with at least one triggered hit on a PMT ≥ 5

BDT hyper-parameters

- NTrees: Number of trees in the forest
- MinNodeSize: Minimum percentage of training events required in a leaf node
- AdaBoostBeta: Learning rate for AdaBoost algorithm
- NCuts: Number of grid points in variable range used in finding optimal cut in node splitting
- MaxDepth: Max depth of the decision tree allowed

Number of events after the BDT selection

	ARCA6 (BDT > 0.35)	ARCA8 (BDT > 0.27)	ARCA19 (BDT > 0.45)	ARCA21 (BDT > 0.40)
atm. $\nu + \bar{\nu}$	70.18	174.16	151.07	958.75
atm. μ	28.17 (32.72)	28.58 (31.71)	5.10 (6.33)	28.89 (29.94)
all atmospheric	98.35 (102.90)	202.74 (205.87)	156.17 (157.40)	987.64 (988.69)
cosmic $\nu + \bar{\nu}$	1.40	3.98	2.49	16.33
data	111	340	232	1780

Number of events after the BDT selection & energy cut

	ARCA6	ARCA8	ARCA19	ARCA21
atm. ν	11.03	16.95	7.40	24.48
atm. μ	18.74	13.31	1.22	4.87
cos. ν	0.85	1.97	0.91	4.53
data	14	34	11	48