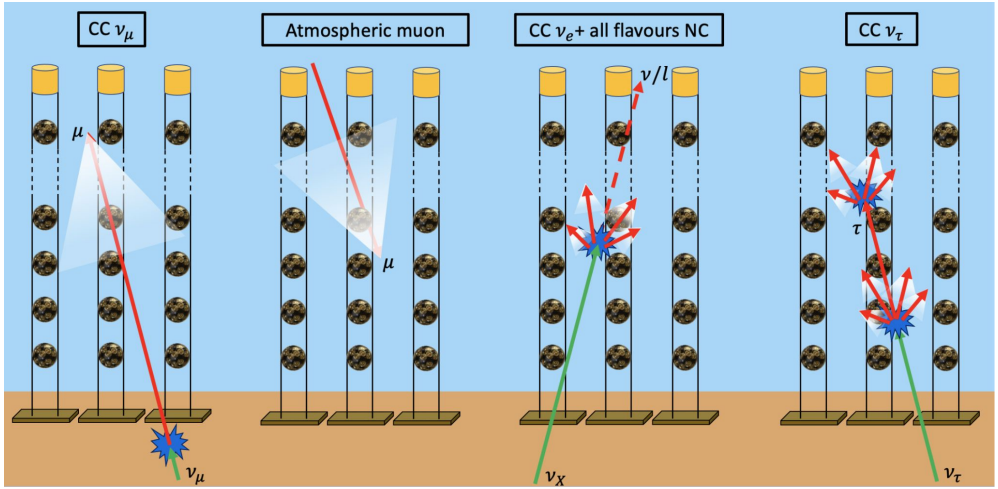
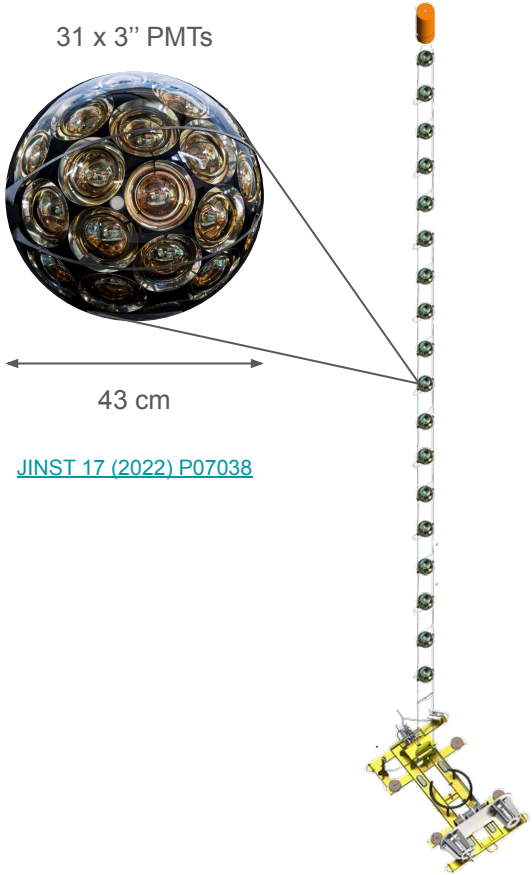
Overview of the Cosmic Ray studies with the KM3NeT detectors

Andrey Romanov on behalf of the KM3NeT Collaboration

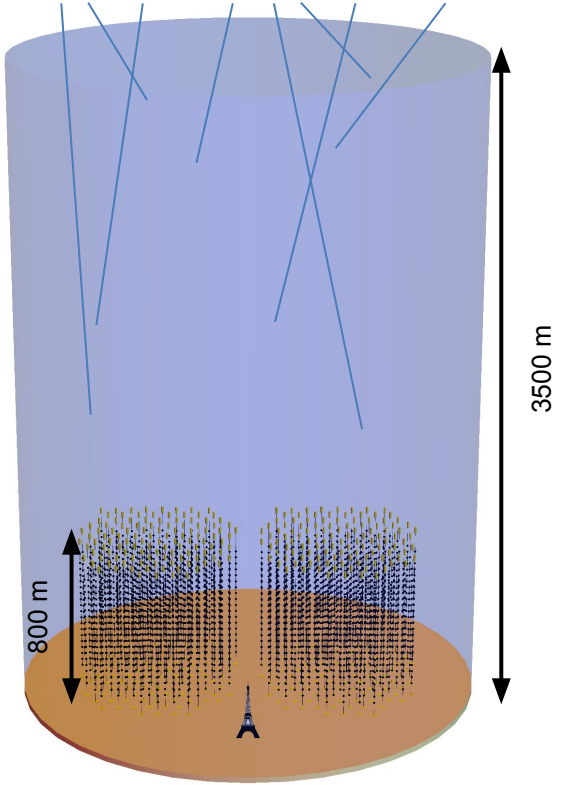
- Cherenkov light detection deep in the Mediterranean Sea
- 3D array of optical sensors - DOMs
- 31 PMTs in each DOM
- 18 DOMs on each vertical line - DU
- Two detectors, same technology





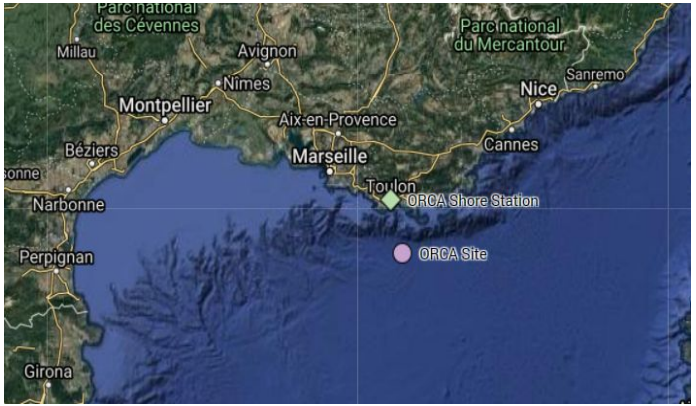
JINST 17 (2022) P07038

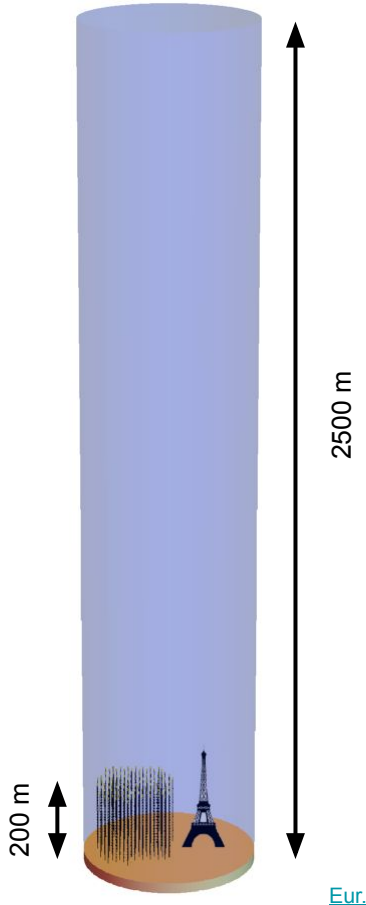
- KM3NeT/ARCA - high-energy neutrino astronomy
- Off-shore Sicily at ~3500m depth
- 2 x 115 DUs
- ~36 m vertically between DOMs
  ~90 m horizontally between DUs
- 1 Gton detector
- 33 DUs currently deployed



Nature 638, 376–382 (2025)

- KM3NeT/ORCA - neutrino oscillations and mass ordering
- Off-shore Toulon at ~2500m depth
- 1 x 115 DUs
- ~9 m vertically between DOMs
  ~20 m horizontally between DUs
- 8 Mton detector
- 28 DUs currently deployed





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- Leptons from EAS cascades initiated by the primary CRs:
  - Atmospheric neutrinos
  - Atmospheric muons

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  - Atmospheric neutrinos
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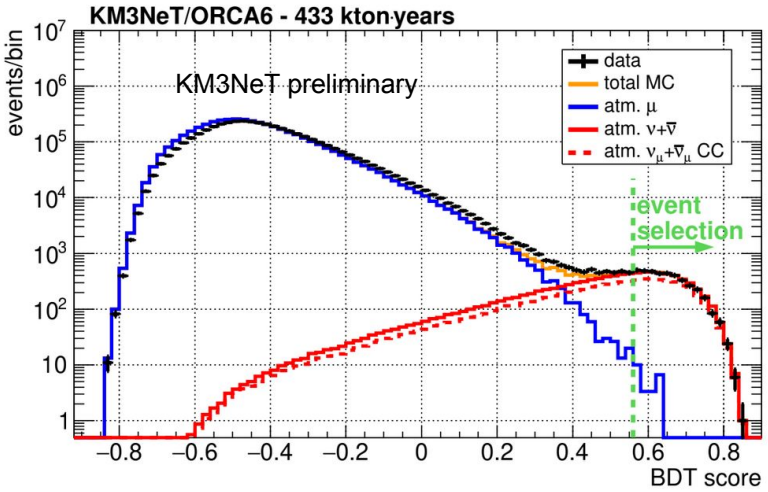
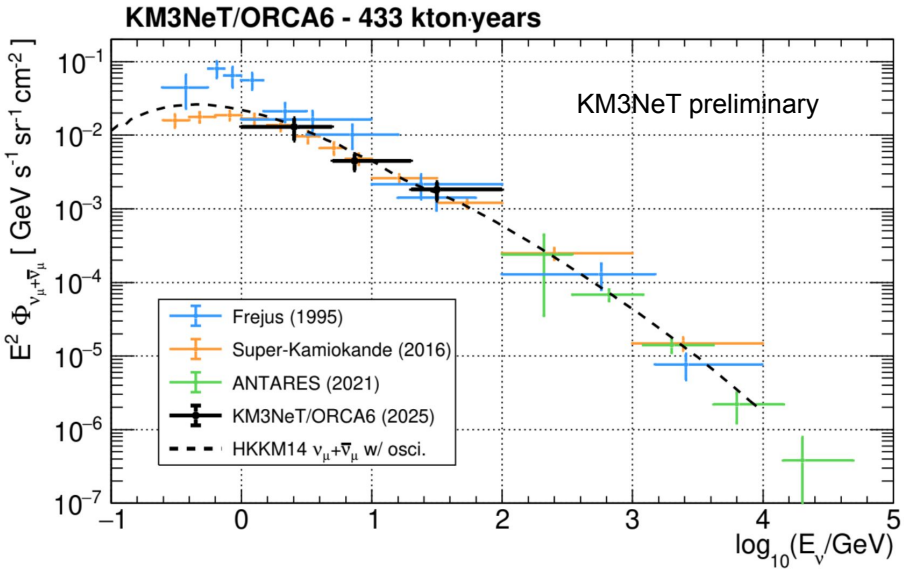
Atmospheric neutrino flux with KM3NeT/ORCA6

- First KM3NeT measurement of atmospheric muon neutrino flux
- 510 days of KM3NeT/ORCA6 (6-DUs) livetime
- 3894 neutrino candidate events
- Atmospheric muon contamination < 1%
- **Consistent with world data**

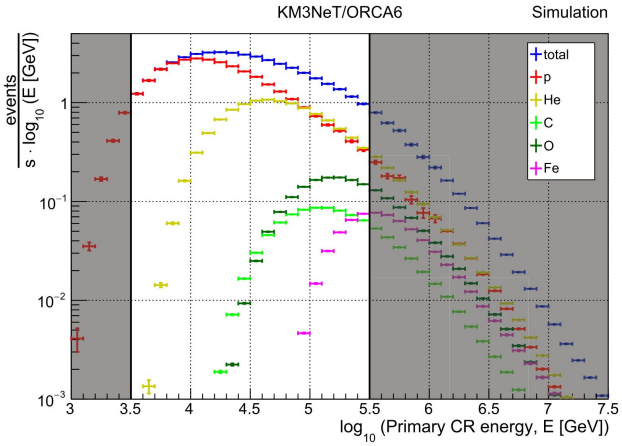


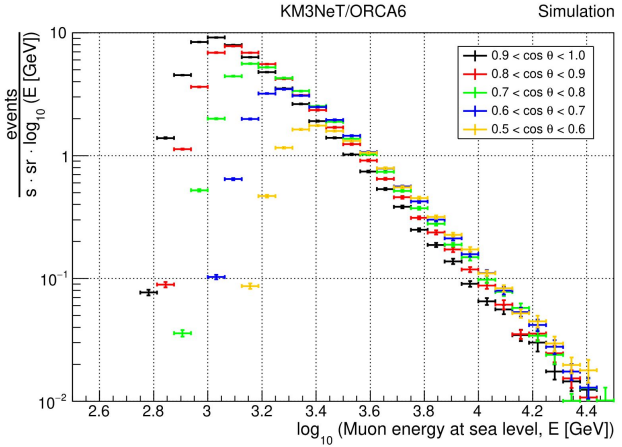


arXiv:2504.09119

- Leptons from EAS cascades initiated by the primary CRs:
  - Atmospheric neutrinos
  - Atmospheric muons

- Atmospheric muons - vast majority of reconstructed down-going events in KM3NeT
- Background for neutrino physics, **signal for CR studies**
- KM3NeT range (from simulation):
  - Primary CR energies:
    - ARCA6 -> 4 – 1000 TeV
    - ORCA6 -> 3 – 320 TeV
  - Sea level muon energies:
    - ARCA6 -> 1.1 – 34 TeV
    - ORCA6 -> 0.8 – 11 TeV
  - Pseudorapidities:
    - ARCA6 -> 8 – 11
    - ORCA6 -> 7.5 – 10.5





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Atmospheric muons with KM3NeT

- Measured muon rate compared to the model prediction
- Model:
  - Program - CORSIKA v7.7410
  - High-energy hadronic interactions - Sibyll 2.3d
  - Primary CR flux - Global Spline Fit
- **40% less muons in simulations** than in the data for ORCA6;
  The data/MC ratio is constant as a function of zenith angle
- **50 – 80% less muons in simulations** than in the data for ARCA6
  (systematic uncertainties are larger)
- The result is complementary to the *Muon Puzzle* observed with the ground-based CR observatories, e.g. Auger, TA, NEVOD …

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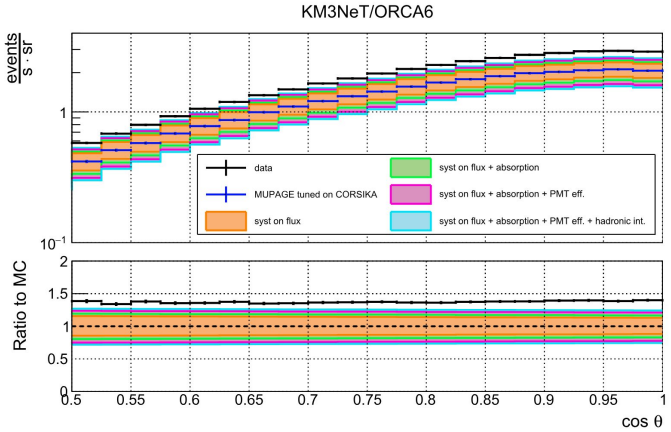

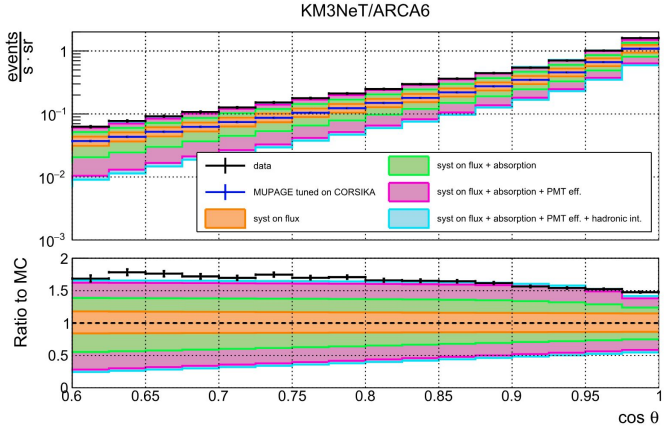

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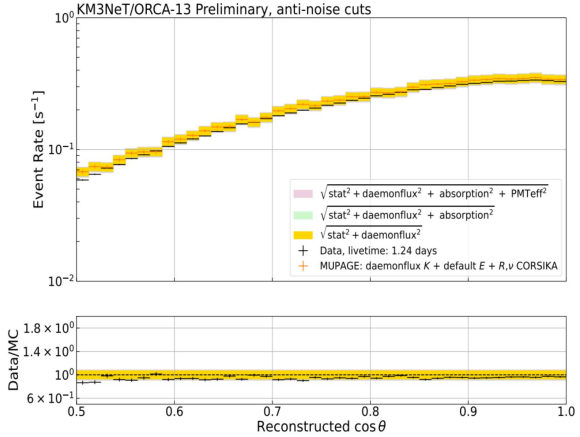
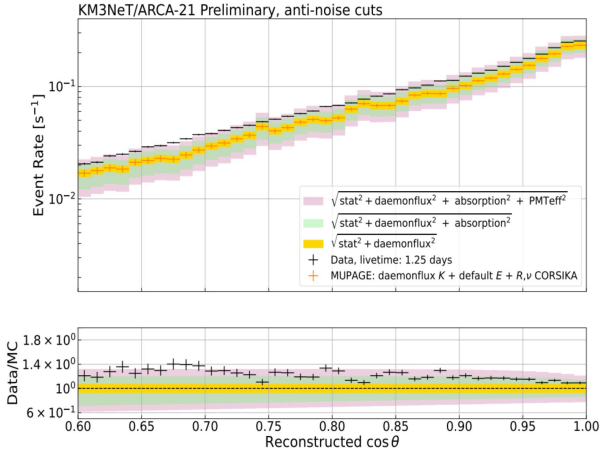
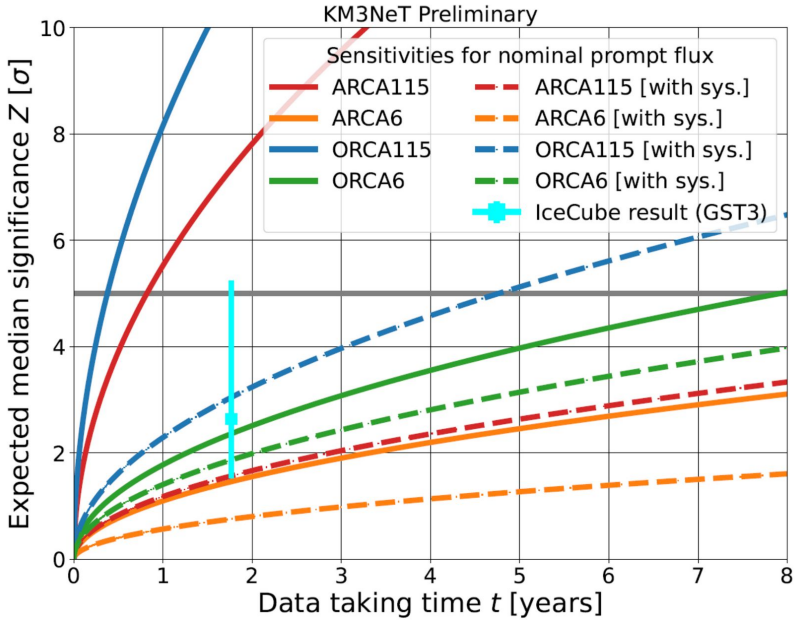
- Can daemonflux solve the discrepancy?
- Data-driven muon-calibrated neutrino flux:
  - Program - MCEq
  - High-energy hadronic interactions - calibrated DDM
  - Primary CR flux - calibrated GSF
- **data/MC discrepancy at <10%** level for ORCA13
- **data/MC discrepancy at <40%** level for ARCA21 (systematic uncertainties are larger)





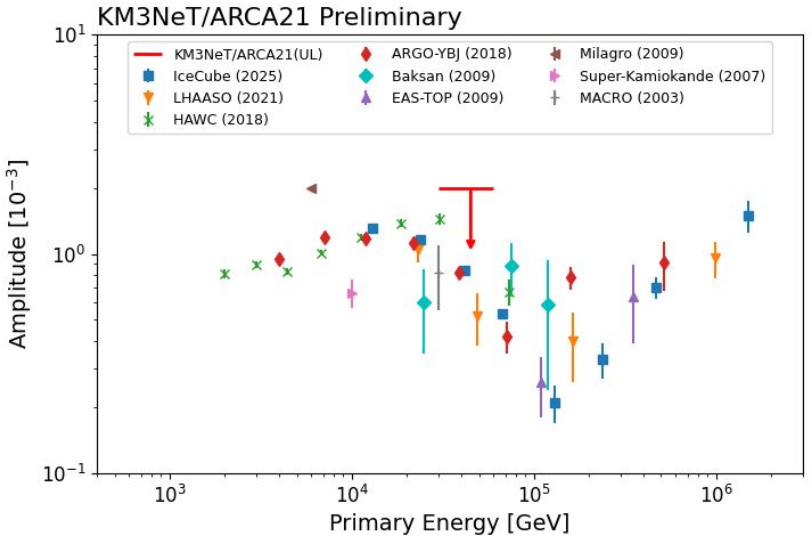
Sensitivity to prompt muon flux

- Prompt muon flux - muons from decays of heavy hadrons, *D*, ρ^0, ϕ, …
- Sensitivity of ARCA and ORCA detectors in 6 and 115 DU configuration estimated
- Simulation model:
  - Program - CORSIKA v7.7410
  - High-energy hadronic interactions - Sibyll 2.3d
  - Primary CR flux - GST3
- 5σ detection significance is expected after a few years of operation
- Currently, the sensitivity is limited by systematics



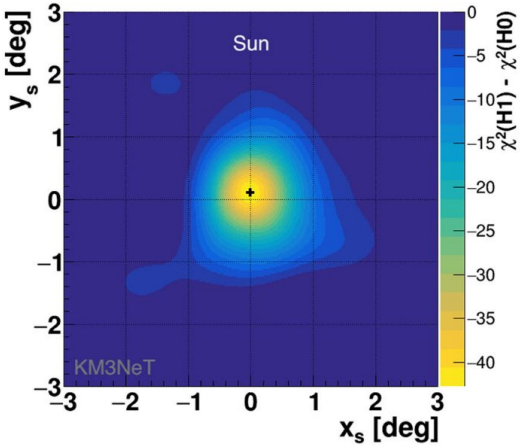
CR anisotropy with KM3NeT/ARCA

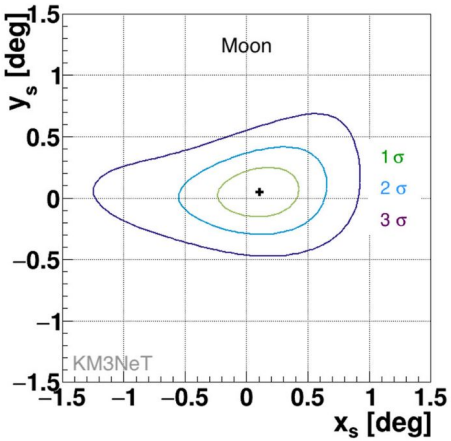
- First search for large-scale CR flux anisotropy with KM3NeT/ARCA21
- Observed signal for events with muons of E > 1 TeV
- Significance ~2σ
- Upper limit to the dipole amplitude at 99% CL is 2×10^{-3}
- Better sensitivity is expected with larger detectors and more data

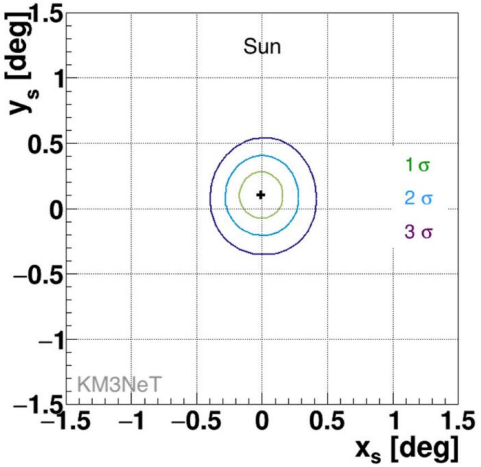


Observation of the Moon and Sun shadow with KM3NeT/ORCA6

- Deficit in atmospheric muon flux due to CR absorption by the Moon and Sun
- Measurement of the deficit allows for the estimation of the detector pointing accuracy and angular resolution
- Moon shadow - 4.2σ detection, σ_{res} = 0.49°;
  Sun shadow - 6.2σ detection, σ_{res} = 0.66°
- Pointing accuracy is within 1σ contour







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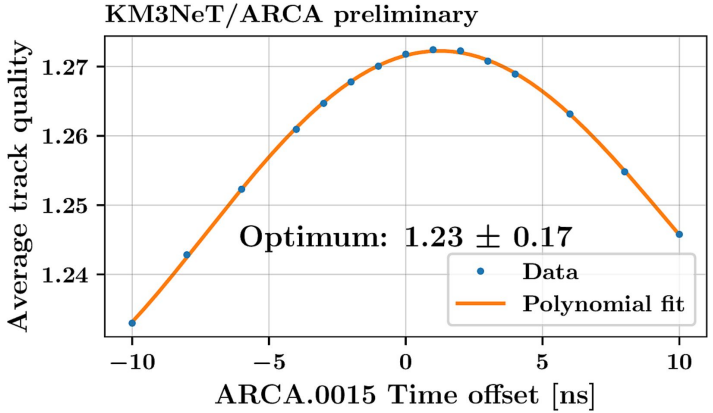
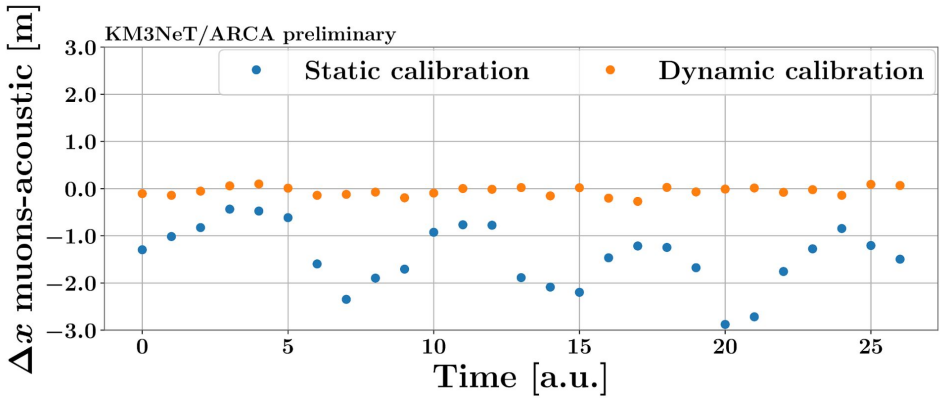
Time and position calibration using atmospheric muons

- Reconstructed muon tracks used for the inter-DU time calibration, synchronization of DUs
- Reconstruction “backwards”:
  - finding the maximum reconstruction likelihood by varying DU time reference, position, and orientation
- Time calibration: <ns accuracy for both detectors
- Cross-check goodness of acoustic-based time-dependent (“dynamic”) position calibration -> agree within ~10 cm





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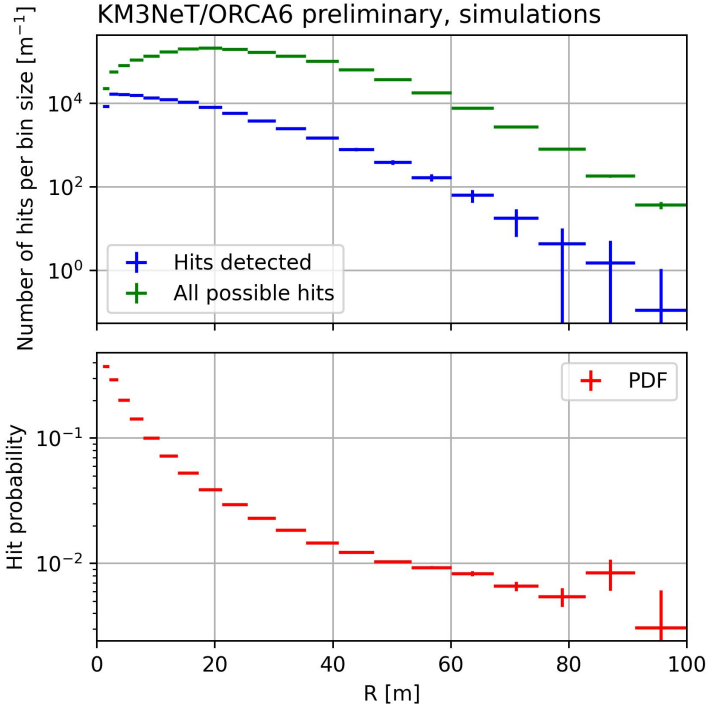
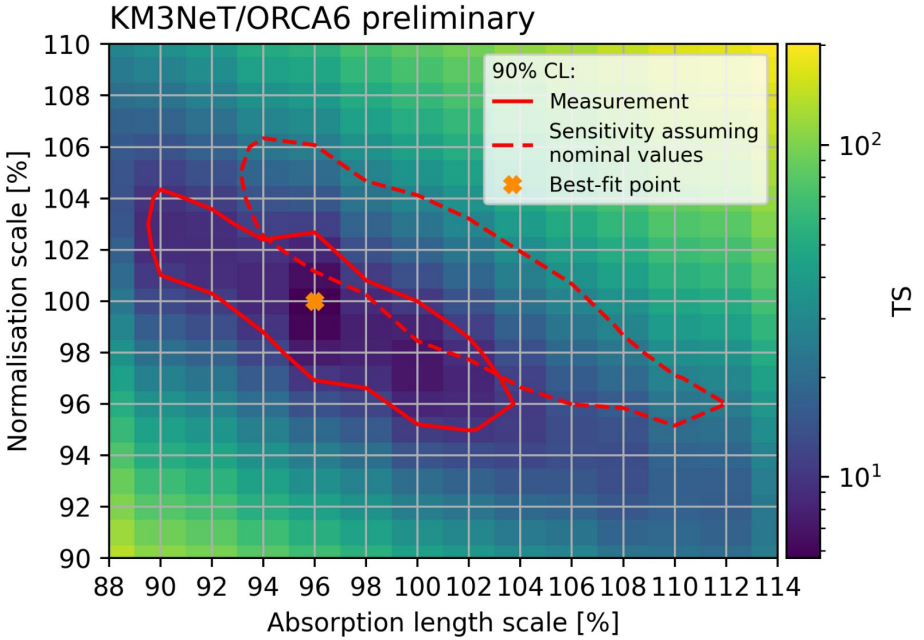
Water optical properties using stopping muons

- Measure water optical properties and light detection efficiency using in-situ data - light from stopping muons
- Stopping muons - MIPs (<100 GeV) ->
  well-defined light emission profile
- Purity of selection is ~97% (enlarged from 93% in the previous study)
- Stopping point resolution is ~4 m
  Direction reconstruction resolution is ~0.8 deg PoS(ICRC2023)203
- Obtain light detection PDF, number of detected hits divided by the number of PMTs capable of detecting hit(s)
- Compare MC PDFs with modified water properties to the data PDF to find best agreement



Water optical properties using stopping muons

- MC PDFs with L_{abs} and normalisation modified compared to the data PDF in terms of TS
- 10 days of KM3NeT/ORCA6 livetime used
- Best agreement for $0.96*L_{abs}$ and nominal normalisation
- Nominal properties within the 90% CL contour
- Uncertainties constrained well below the current limits, +-10% uncorrelated uncertainties



Conclusions

- First measurement of atmospheric muon neutrino flux is reported
- Several analyses using atmospheric muons in KM3NeT:
  - Comparison of the measured muon rate with model predictions;
    Additional input to the *Muon Puzzle*
  - Sensitivity to the prompt muon flux
  - Large scale CR anisotropy
- Muons are also used for calibrations:
  - Absolute pointing with the Moon/Sun shadow
  - Time calibration
  - Water optical properties and light detection efficiency
- **Stay tuned for the new results to be presented at the summer conferences, in particular ICRC 2025!**

Backup

- Air shower simulations with state-of-the-art QCD models show a significant deficit of GeV muons with respect to measurement
- The muon deficit has an onset at ~8 TeV in the nucleon-nucleon cms-system, followed by a linear increase with logarithm of the energy

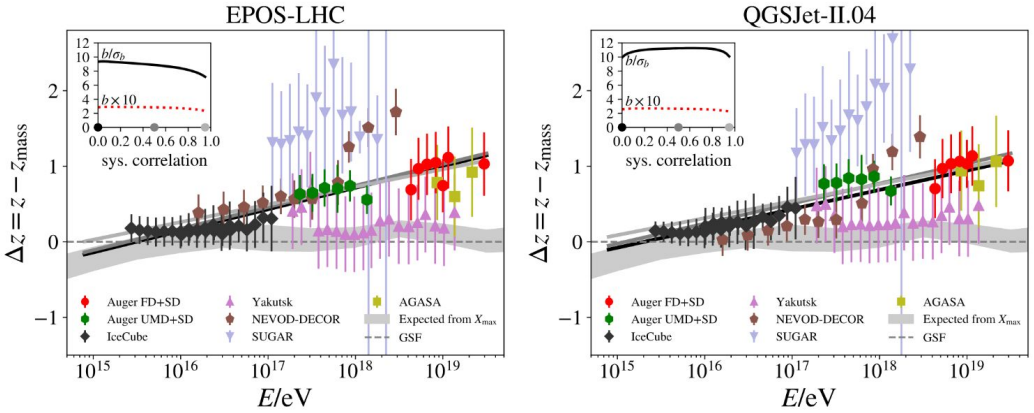


Fig. 8 Data from Fig. 3 after subtracting z_{mass}, the expected variation in z due to changes in the cosmic-ray composition (image from Soldin 2021). The expected variations are taken from the GSF model (dashed line), which in turn is derived primarily from X_{max} measurements (grey band). Solid lines represent fits that assume different levels of correlated experimental uncertainties. The deviation of the slope b from zero in standard deviations is shown in the inset as function of the assumed correlation. Also shown in the inset is the value of the slope, scaled by a factor of 10

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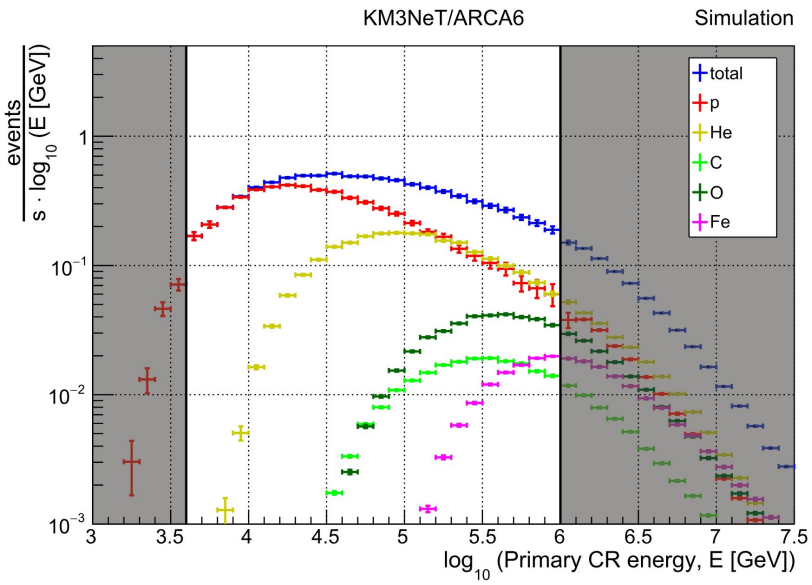
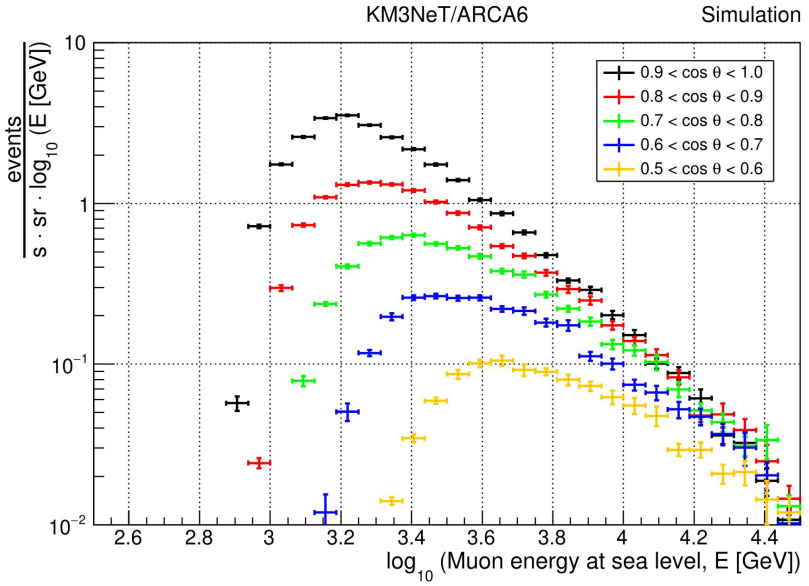
KM3NeT/ARCA6 muon energy range





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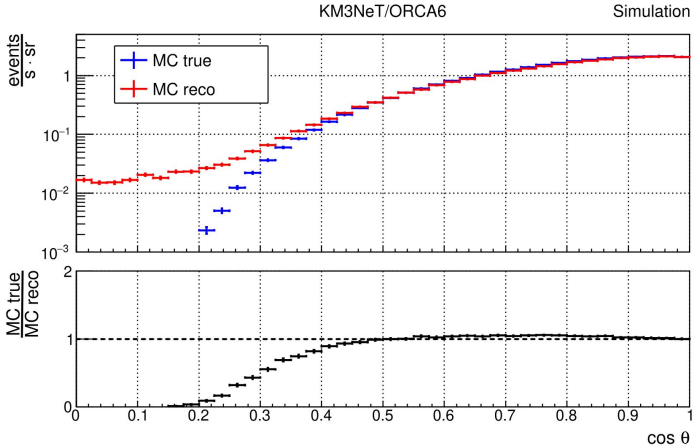
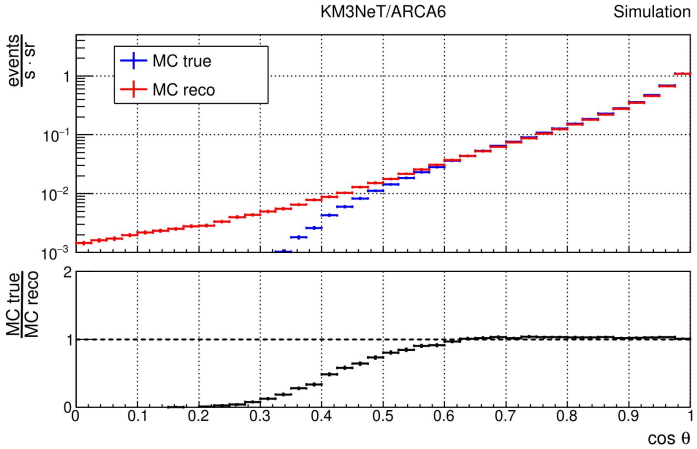
True vs reconstructed muon rate

- KM3NeT angular resolution is at the sub-degree level
- However, the very steep dependence of the muon flux on the true cosθ causes the few well-reconstructed inclined events to be hidden by a small fraction of mis-reconstructed more vertical muons





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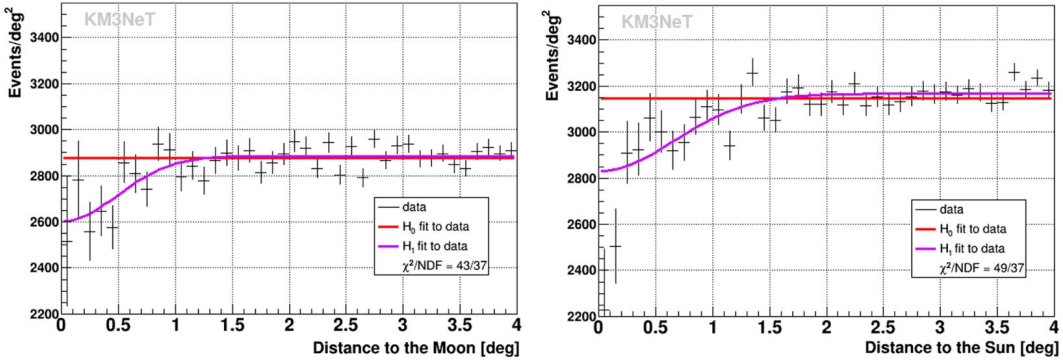

Fig. 5 Event density as a function of the distance to the Moon on the left and the Sun on the right. Data (black crosses) are compared to the H_0 fit (red) and the H_1 fit (magenta)

Table 1 Parameters from the fits at nominal position $(x_s, y_s) = (0, 0)$

Parameters	Moon 1D	Moon 2D	Sun 1D	Sun 2D
σ_{res}	$0.49° \pm 0.11°$	$0.49° \pm 0.15°$	$0.66° \pm 0.08°$	$0.65° \pm 0.13°$
A	0.69 ± 0.17	0.71 ± 0.27	1.38 ± 0.31	1.31 ± 0.34
$\Delta\chi^2_{H1/H0}$	-20.7	-21.3	-47.2	-43.0
Significance	4.2σ	4.2σ	6.5σ	6.2σ
Events/deg^2	2886	2892	3166	3161

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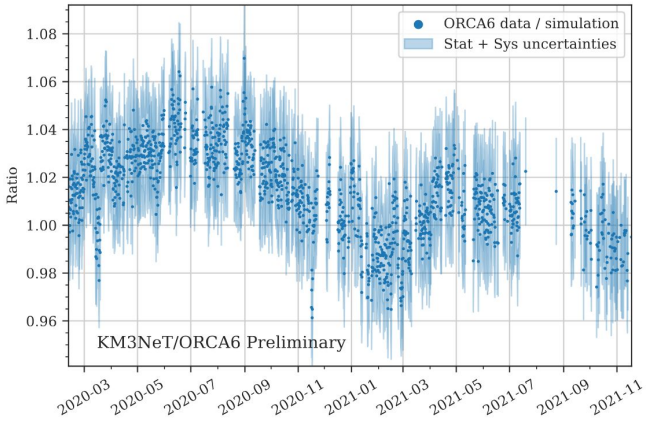
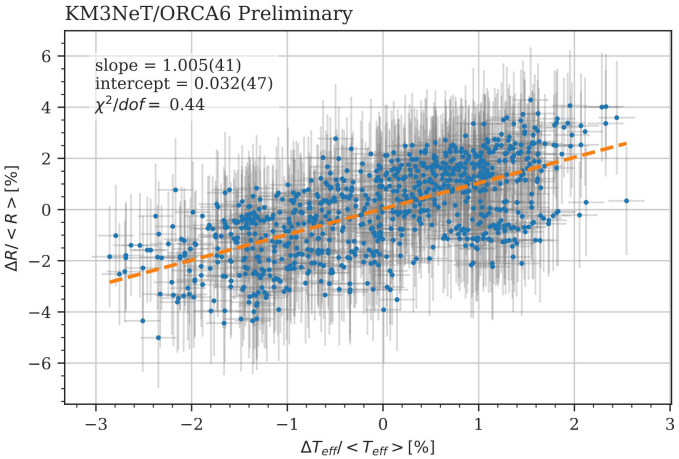
Seasonal variations in muon flux with KM3NeT/ORCA

- Muon flux varies with the atmospheric temperature
- Change in atm. T -> change in density ->
  change in interaction / decay probabilities -> change in muon flux
- KM3NeT simulations account for time-dependent detector response
- Variation in the observed data/MC ratio attributed to the seasonal variation in the muon flux
- 6% variation of muon rate (summer vs winter) observed





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