Neutrino Quantum Decoherence with KM3NeT/ARCA

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on behalf of the KM3NeT Collaboration

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Neutrino Quantum Decoherence

- **Decoherence**: loss of coherence of the neutrino mass eigenstates due to the coupling of the neutrino quantum system to a larger environment.
- Effect envisaged by theories of **quantum gravity**.
- The time evolution of the neutrino density matrix ρ(t) is given by:

$$\rho \propto e^{-\left(\Gamma + i\frac{\Delta m^2_{ij}}{2E}\right)t}$$

$$\Gamma(E) = \Gamma(E_0)\left(\frac{E}{E_0}\right)^n$$

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Decoherence parameter

Standard Oscillations

Power-law index

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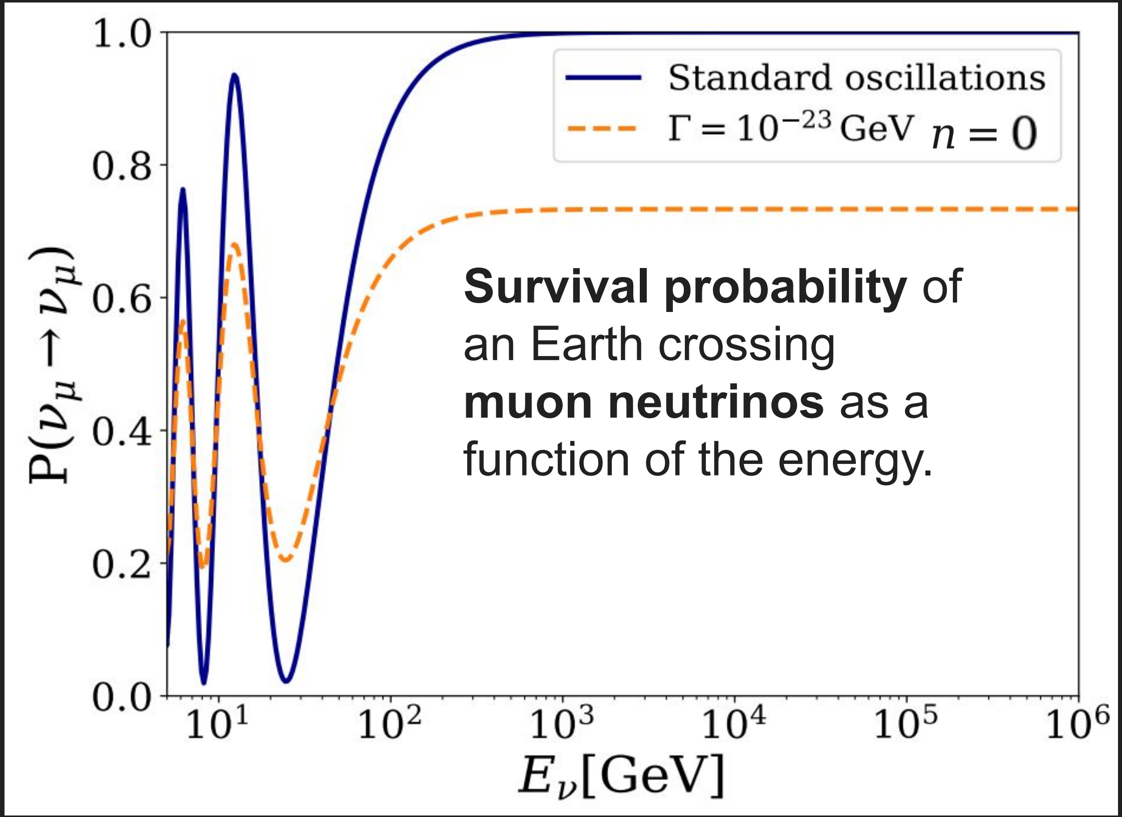
→ Decoherence leads to a damping of the neutrino oscillation amplitude.

Neutrino oscillations with decoherence



How to detect decoherence with KM3NeT:

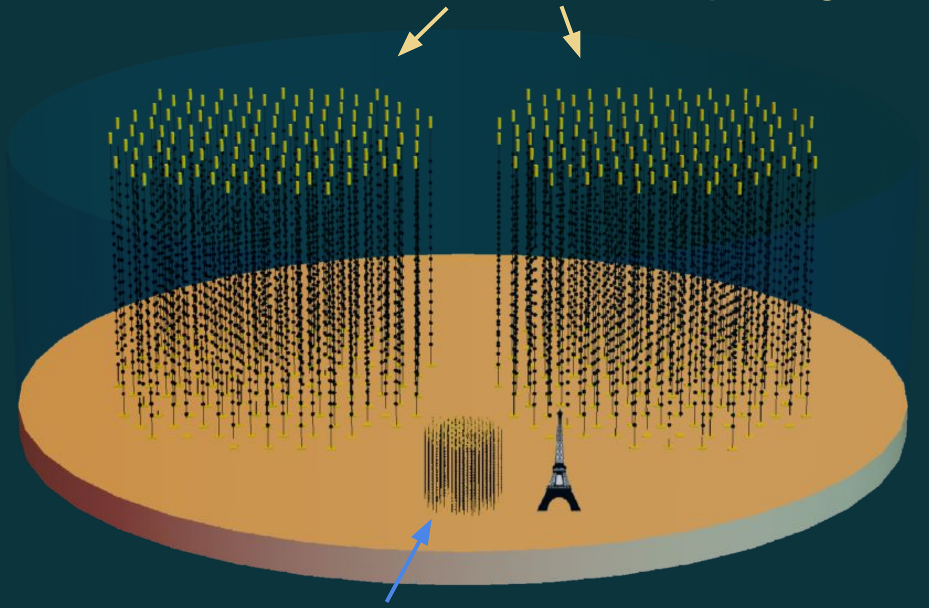
- Modified oscillation probabilities lead to a modified expected event rate.

→ Observe **atmospheric** neutrinos and decide whether the data is better described by standard oscillations or by decoherence.

KM3NeT analysis methods

KM3NeT - two water Cherenkov detectors in the Mediterranean Sea

ARCA
36m vert. x 90m horiz. spacing



ORCA
9m vert. x 20m horiz. spacing

KM3NeT/ARCA (astrophysics):
Capo Passero, Sicily, Italy

- Search for astrophysical neutrinos.
- Sub-TeV to PeV energies.
- Final configuration: 2 x 115 detection units,1 Gton intrumented volume.
- **This work:** sensitivities for 1 year with 115 detection units.

KM3NeT/ORCA (oscillations):
La Seyne-sur-Mer, France

- Study of atmospheric ν oscillations.
- Few GeV to～100 GeV energies.

Decoherence analysis workflow

1. **Predict initial flux:**

   - Atmospheric neutrino flux

   from cosmic ray interactions predicted solving cascade equations.

   mceq (Phys.Rev.D 108 (2023) 10, 103040), *daemonflux* (Phys.Rev.D 107 (2023) 12, 123037)

   ⟶ *daemonflux*, a data-driven neutrino flux calibrated on atmospheric muons, allows to propagate flux uncertainties related to hadronic yields and the cosmic ray spectrum.

   - Astrophysical neutrino flux

   modelled as a single power-law based on IceCube results (*PoS-ICRC2023-1064*).

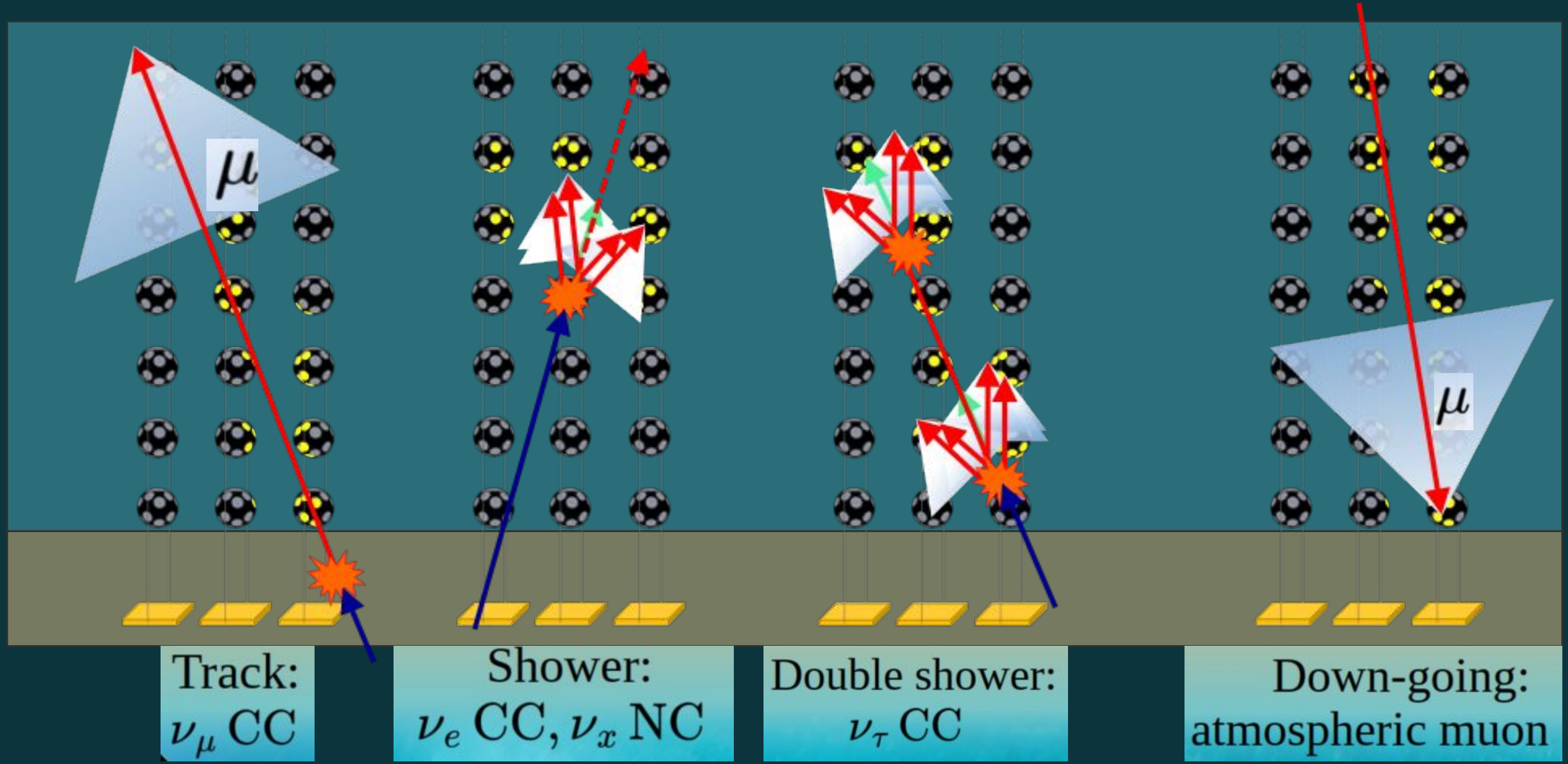
2. **Propagate neutrino flux to the detector:**

   Compute evolution for standard oscillations (H0) and decoherence (H1).

   nuSQuIDS (Comput.Phys.Commun. 277 (2022) 108346).

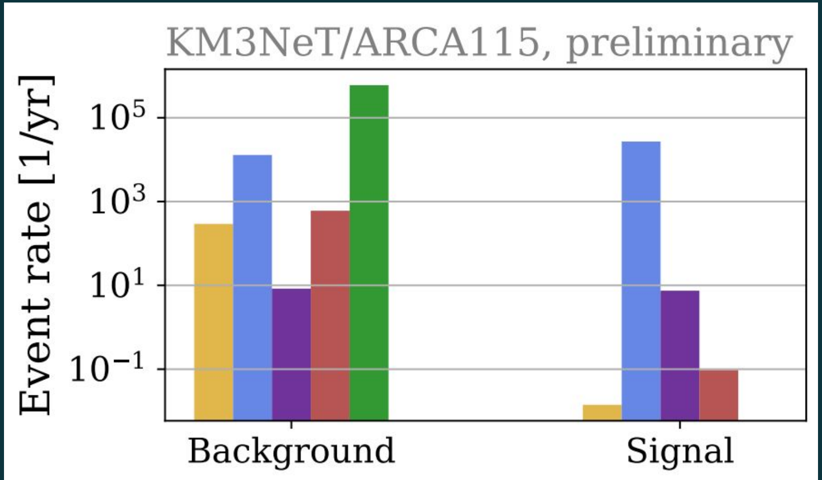
3. Reconstruct events:

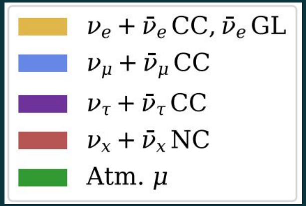
Based on the detected light pattern, classify events as track-like or shower-like.



4. Remove background events:

- Only use up-going events.
- Employ Boosted Decision Tree (BDT) to remove remaining, misrecontructed atmospheric muons.





Signal: very well reconstructed track-like events.

	Before BDT	After BDT
$\nu_\mu + \bar{\nu}_\mu$ CC	33534	22350
Atm. μ	149433	5

Expected event rate per year, ARCA115, Selection for this analysis.

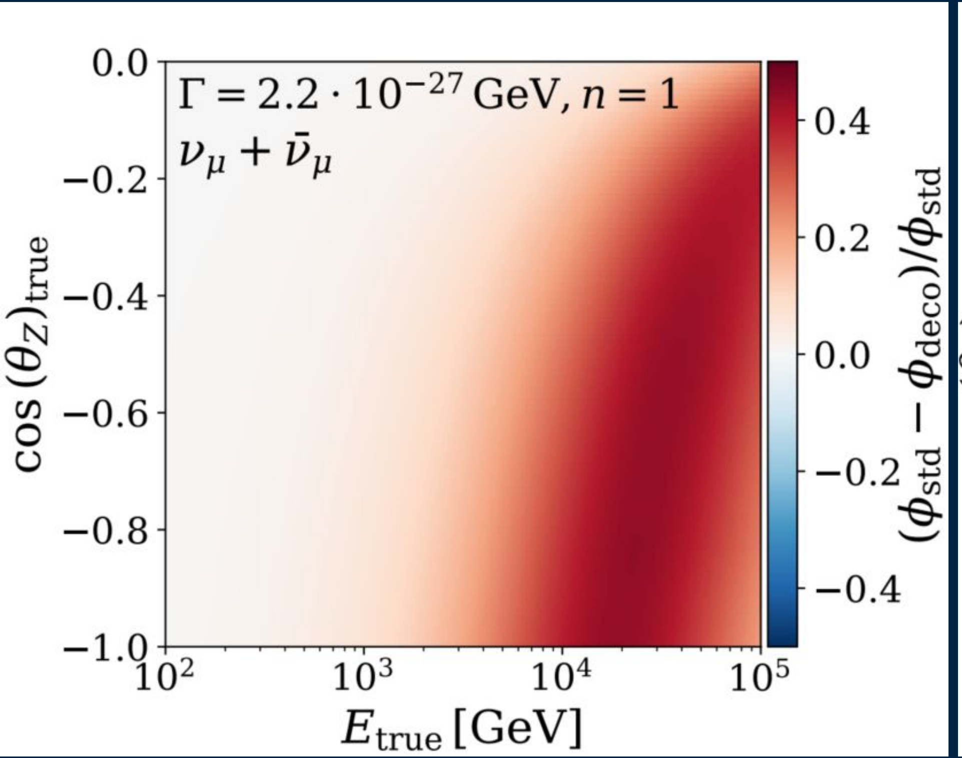
5. **Obtain sensitivities:**

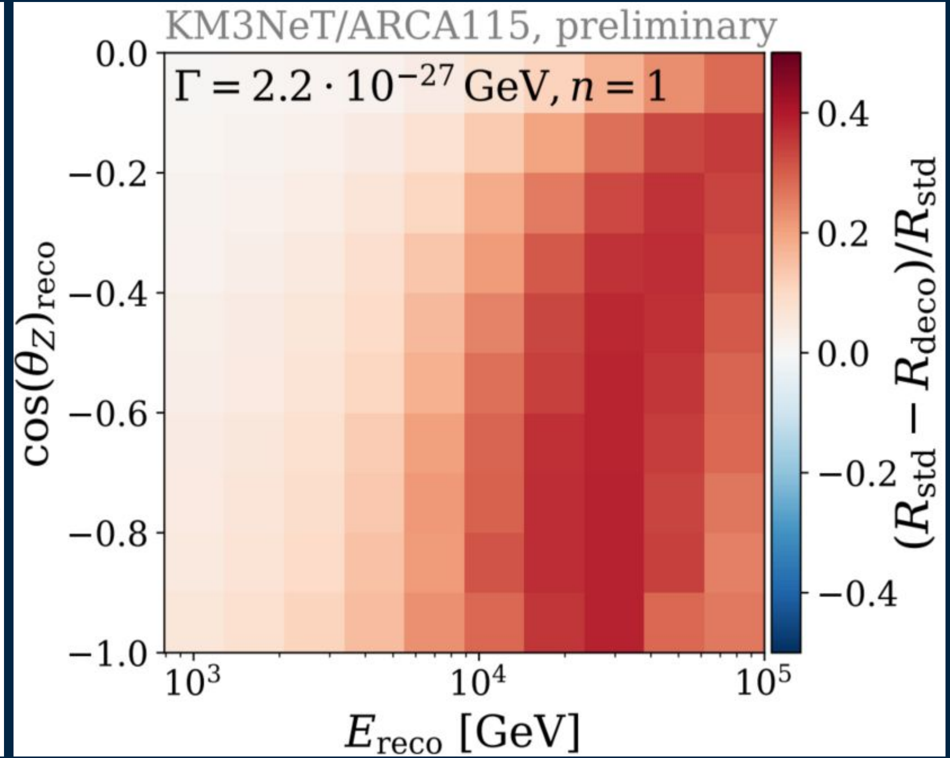
Compute ratio of probabilities between standard oscillation hypothesis (H0), and decoherence hypothesis (H1).

GollumFit (arXiv:2506.04491):

- An open-source framework for binned-likelihood neutrino telescope analyses.
- Maximizes an **effective likelihood** that is based on a poisson likelihood and takes MC statistical uncertainties into account (JHEP 06 (2019) 030).
- Implements several **systematic uncertainties** that are common to all neutrino telescopes.

Event distributions and sensitivities

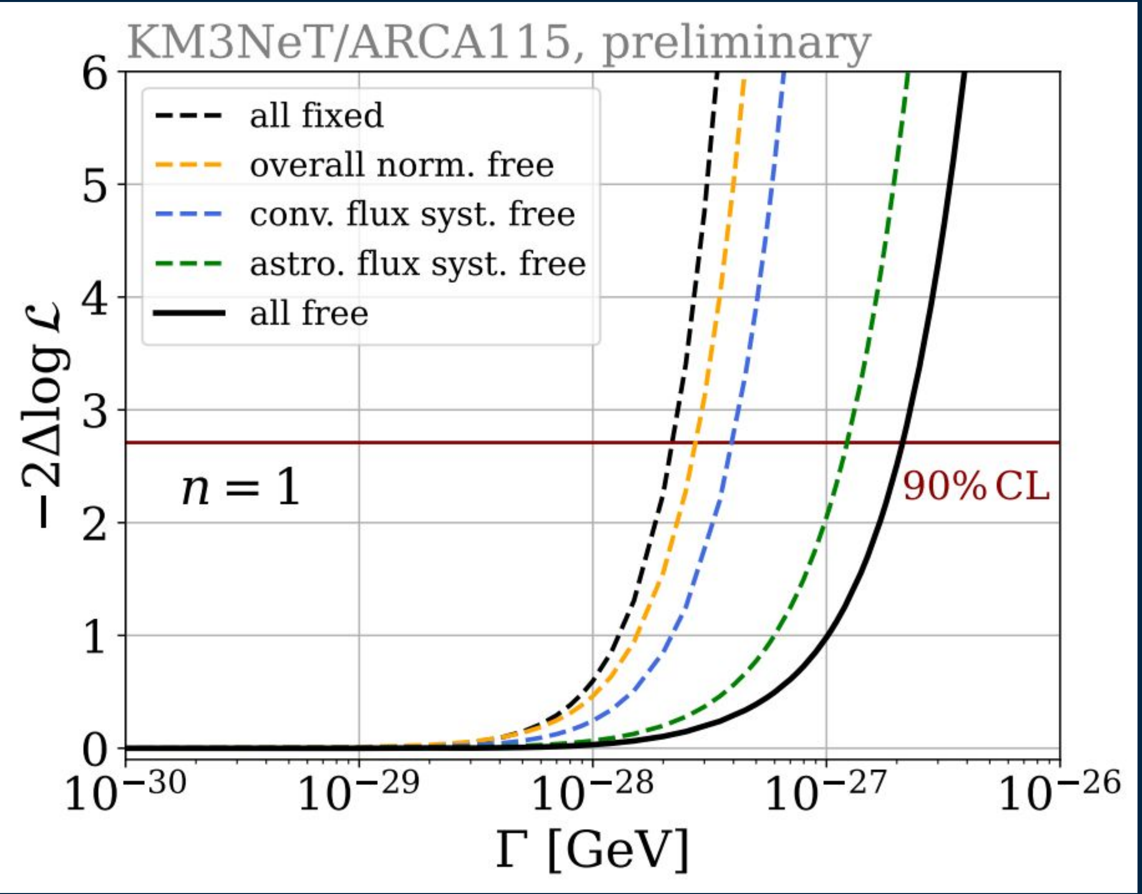




Theory: difference in the propagated neutrino flux for standard oscillations and decoherence over the **true** energy and zenith angle.

Difference in the expected event rates for standard oscillations and decoherence over the **reconstructed** energy and zenith angle.

Log-likelihood ratio as a function of the decoherence parameter



Orange:
Only absolute normalization fitted.

Blue:
Conventional atmospheric flux parameters fitted.

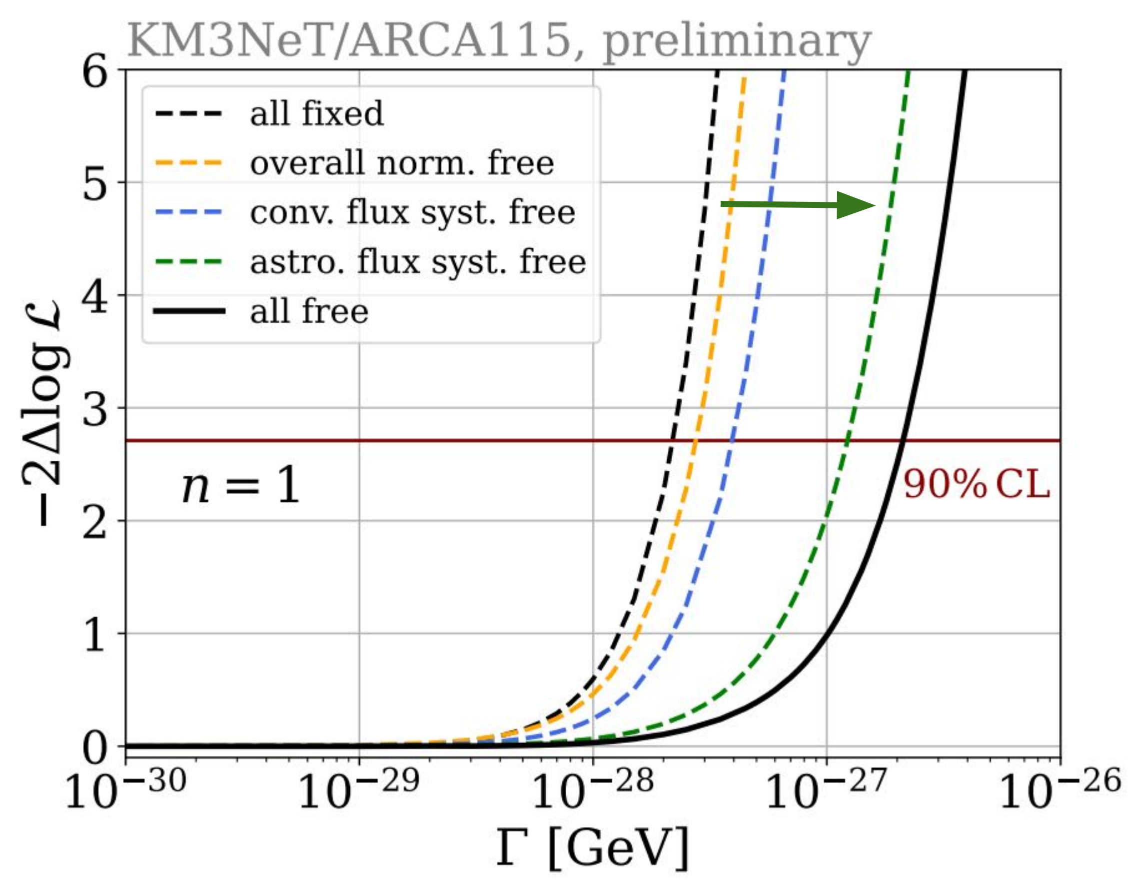
Green:
Astrophysical flux parameters fitted.

Systematic uncertainties

- **Conventional atmospheric flux uncertainties:**
  - Parameters from *daemonflux*:
    10 parameters related to the hadronic yield in the atmosphere and
    6 parameters describing main features of the cosmic ray spectrum.
  - Uncertainty in the atmospheric density.
  - Uncertainty in kaon energy losses due to interactions in the atmosphere.

- **Astrophysical flux uncertainties:**
  (Parameters meant to cover current measurements by IceCube)
  - 2 spectral indices and the location of the breaking point of the spectrum.
  - Neutrino to antineutrino ratio (nominal 1:1).
  - Normalization of the astrophysical flux.

Log-likelihood ratio as a function of the decoherence parameter



Green:
Astrophysical flux parameters fitted.
Largest impact on sensitivity!

Reducing uncertainties in the astrophysical neutrino flux is relevant for any analysis looking for beyond Standard Model effects at high energies.

Comparison to upper limits by IceCube

Nature Phys. 20 (2024) 6, 913-920

Values in GeV	ARCA115, 1 year, sensitivities	IceCube, 8 years, upper limits
$n = 1$	$2.12 \cdot 10^{-27}$	$6.89 \cdot 10^{-28}$
$n = 2$	$4.45 \cdot 10^{-32}$	$9.80 \cdot 10^{-33}$

- Sensitivities are close to the current upper limits by IceCube:
  - IceCube analysis describes astrophysical flux in terms of a single spectral index and a normalization parameter.
  - This analysis is more conservative in terms of our knowledge about the astrophysical flux and allows to fit a broken power-law.
  - However, this analysis does not consider detector systematics yet.

Summary and outlook

- **KM3NeT/ORCA** has already probed several new physics effects at few GeV to 100 GeV energies:
    - Decoherence (JCAP 03 (2025) 039), Non-standard-interactions (JCAP 02 (2025) 073), Sterile neutrinos (*2510.07360*), Non-unitary mixing (*JHEP 07 (2025) 213*)
- This is the first analysis addressing searches beyond the Standard Model in neutrino oscillations with **KM3NeT/ARCA**.
- First decoherence sensitivities indicate that atmospheric neutrino studies are feasible with ARCA.

→ In the future, **KM3NeT** will be able to study beyond Standard Models effects at GeV energies with **ORCA**, and at TeV to PeV energies with **ARCA**.

Thank you very much
for your attention!

Questions?

Backup

Decoherence Theory

Time evolution:

$$\frac{d\rho(t)}{dt} = -i[H, \rho(t)] + \mathcal{D}[\rho(t)]$$

$$\mathcal{D}[\rho] = \frac{1}{2}\sum_{k=1}^{N^2-1}\left(\left[V_k, \rho(t)V_k^\dagger\right] + \left[V_k\rho(t), V_k^\dagger\right]\right)$$

Conditions:

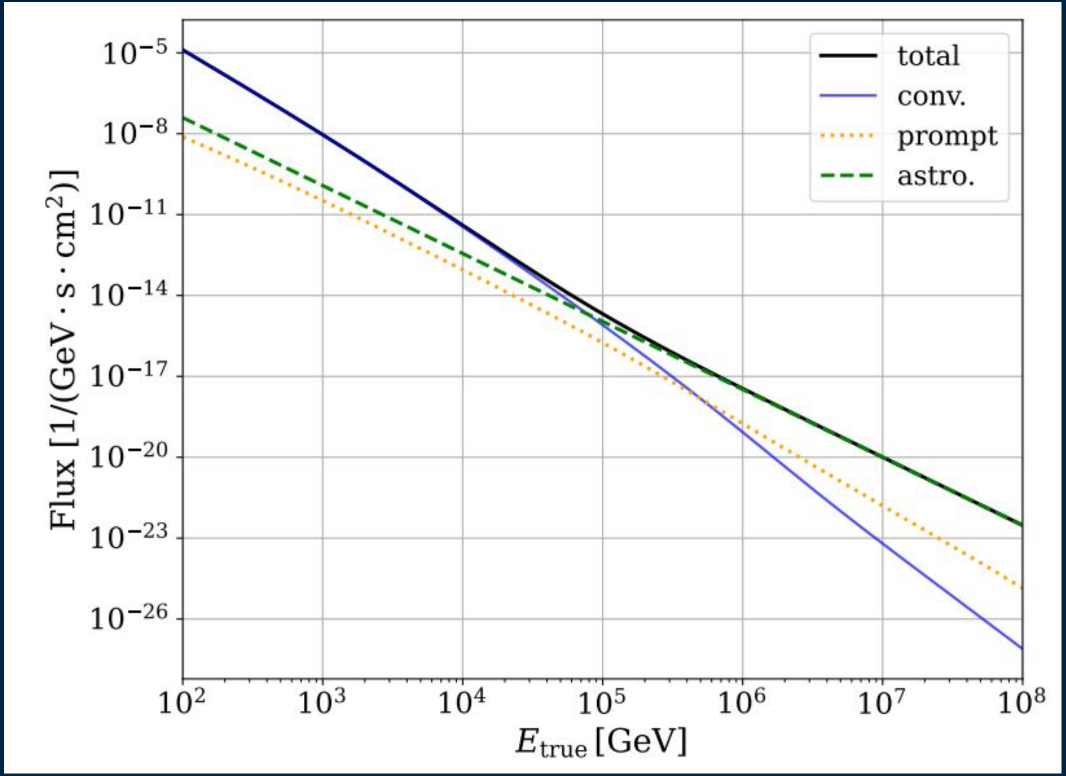
- Energy conservation
- Probability conservation
- Complete positivity

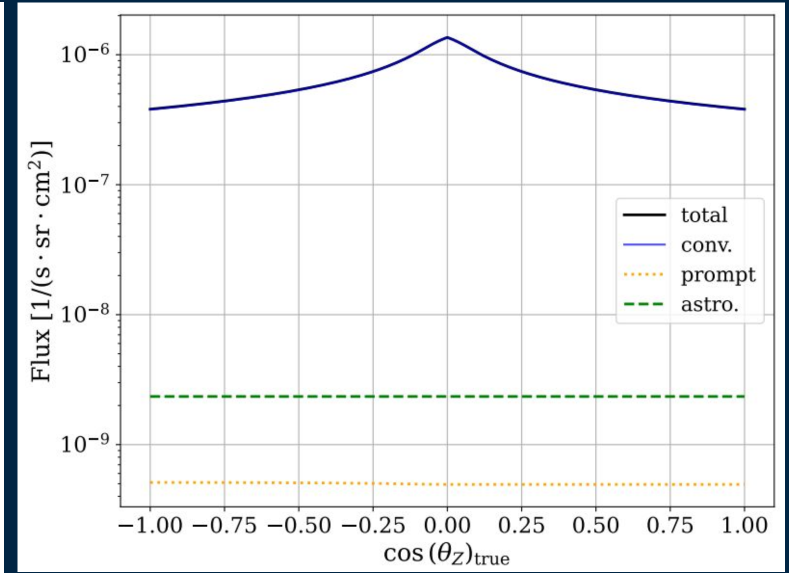
$$\rho \propto e^{-\left(\Gamma + i\frac{\Delta m_{ij}^2}{2E}\right)t}$$

Expansion in SU(3):

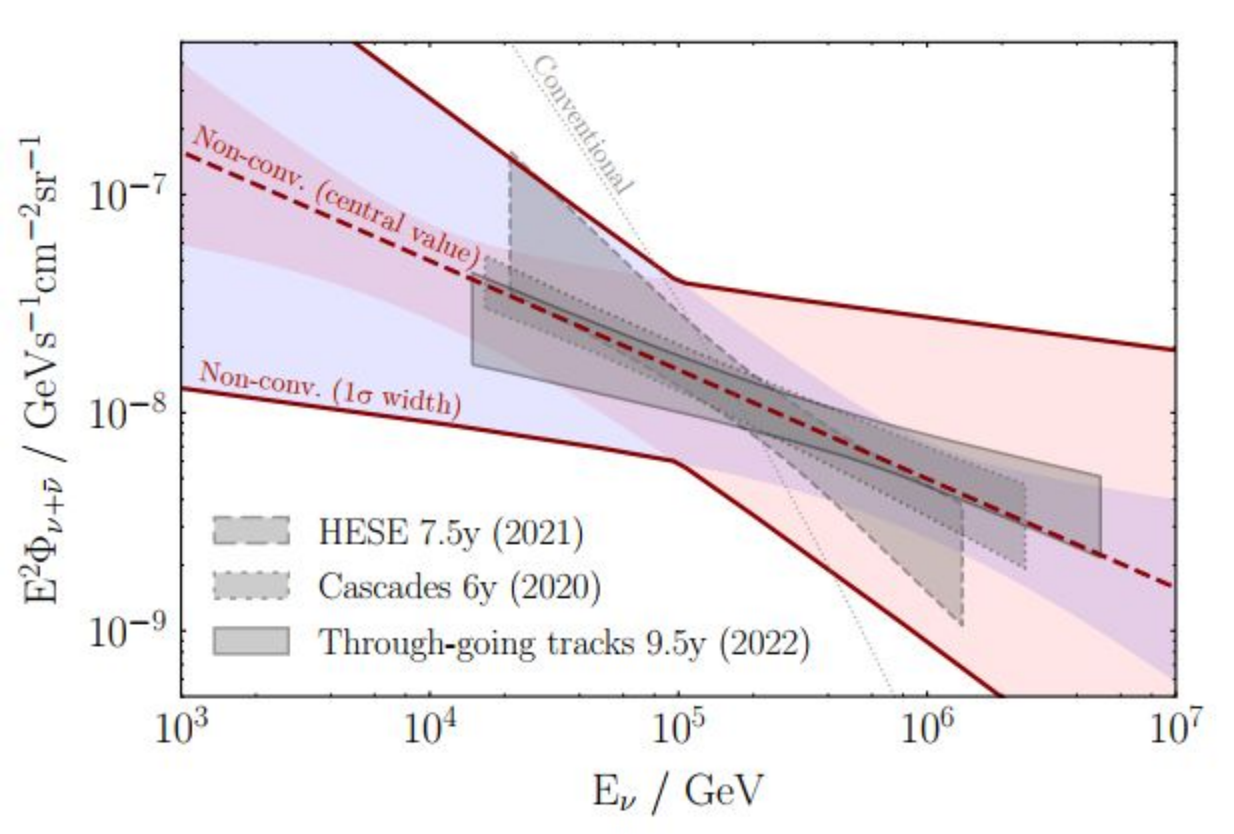
$$\mathcal{D}[\rho(t)] = (D_{\mu\nu}\rho^\nu)\lambda^\mu \longrightarrow D_{\text{phase perturbation}} = \text{diag}(0, \Gamma, \Gamma, 0, \Gamma, \Gamma, \Gamma, \Gamma, 0)$$

Input fluxes as a function of true energy and zenith angle





Astrophysical flux uncertainties and IceCube data



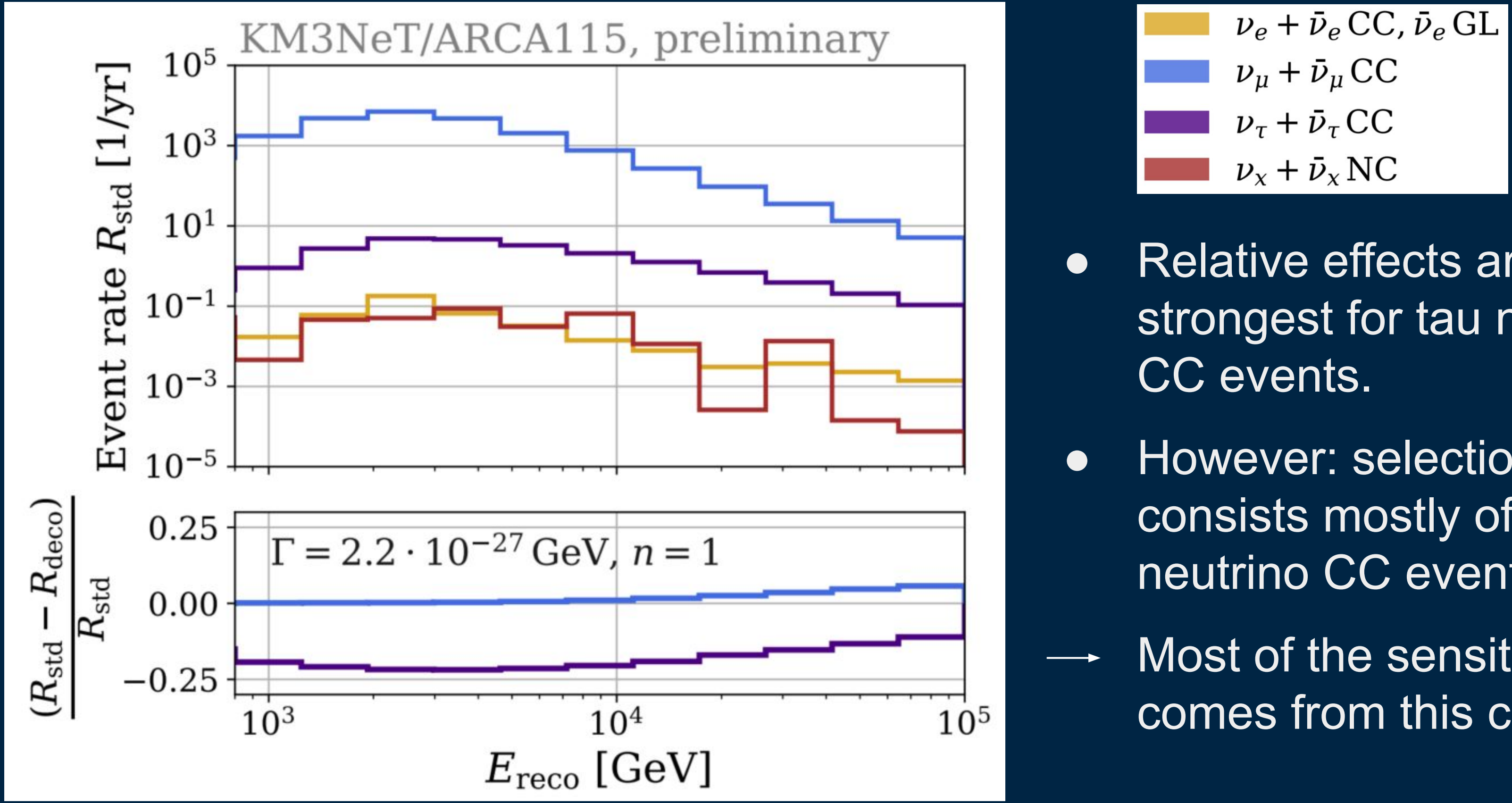
Astrophysical neutrino flux measured by IceCube with different datasets (grey).

Area covered by astrophysical systematic uncertainty parameters in GollumFit (red).

Taken from

Phys.Rev.D 110 (2024) 9, 092009

Event rate as a function of the reconstructed energy



- Relative effects are strongest for tau neutrino CC events.
- However: selection consists mostly of muon neutrino CC events.

→ Most of the sensitivity comes from this channel.

GollumFit likelihood maximization

Phys.Rev.D 110 (2024) 9, 092009

- Binned likelihood maximization

$$\mathcal{L}(\vec{\theta},\vec{\eta}) = \prod_{i\in\{\text{bins}\}} \mathcal{L}_{\text{eff}}(\mu_i(\vec{\theta},\vec{\eta}), x_i),$$

$$\mathcal{L}_{\text{BF}} = \max_{\vec{\theta},\vec{\eta}} \mathcal{L}(\vec{\theta},\vec{\eta})\Pi(\vec{\theta},\vec{\eta}),$$

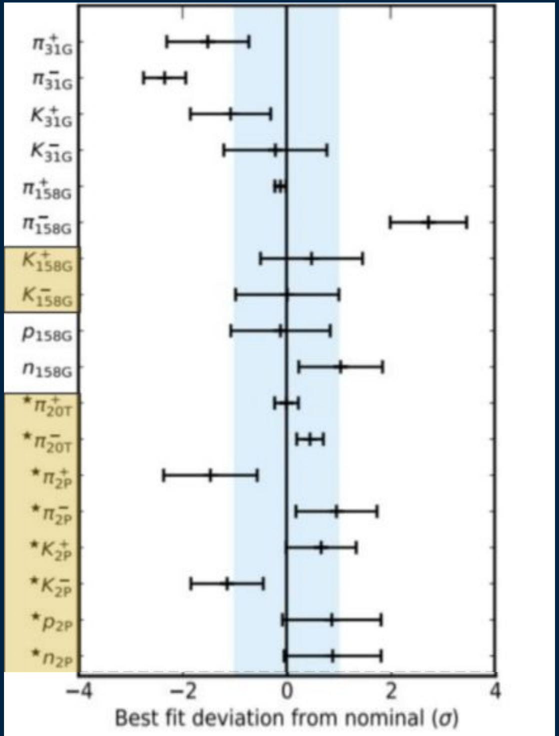
Physics parameters

Systematic parameters

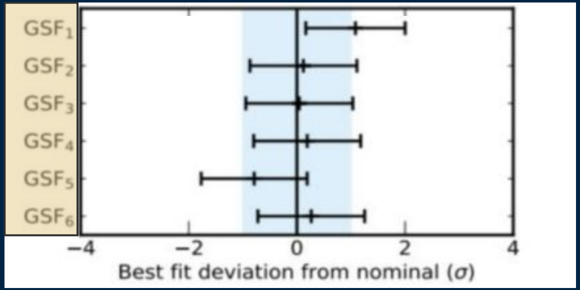
Penalty term for priors on parameters

- Effective likelihood is a modified poisson likelihood that takes into account MC statistical uncertainties in weighted samples.
- Only systematic parameters are fitted in GollumFit.
- Event rates depend on systematic parameters through gradient, splines, or analytic formulae.

Conventional systematic parameters from daemonflux

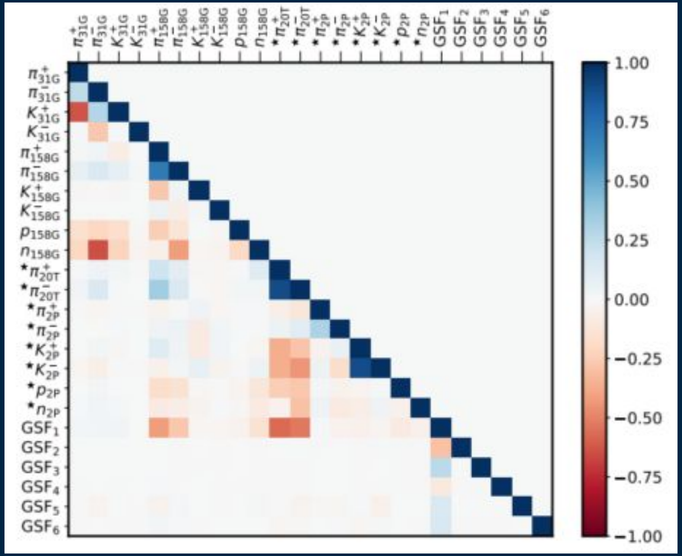


Hadronic yield in the atmosphere.



Cosmic ray spectrum parameters.

Parameters identified as relevant to describe flux uncertainties in KM3NeT/ARCA are marked in yellow.



Correlations.

Taken from [Phys.Rev.D 107 (2023) 12, 123037]