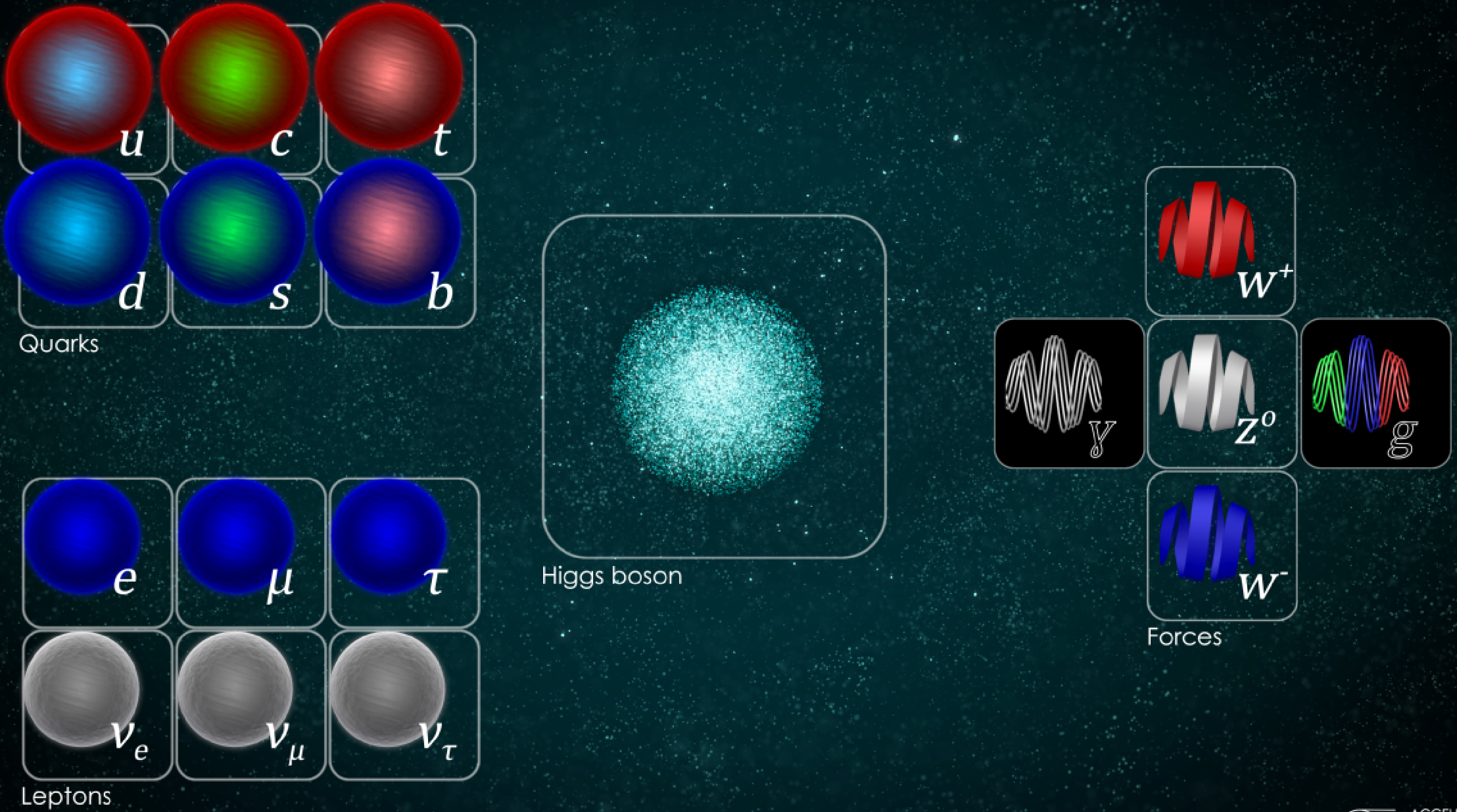
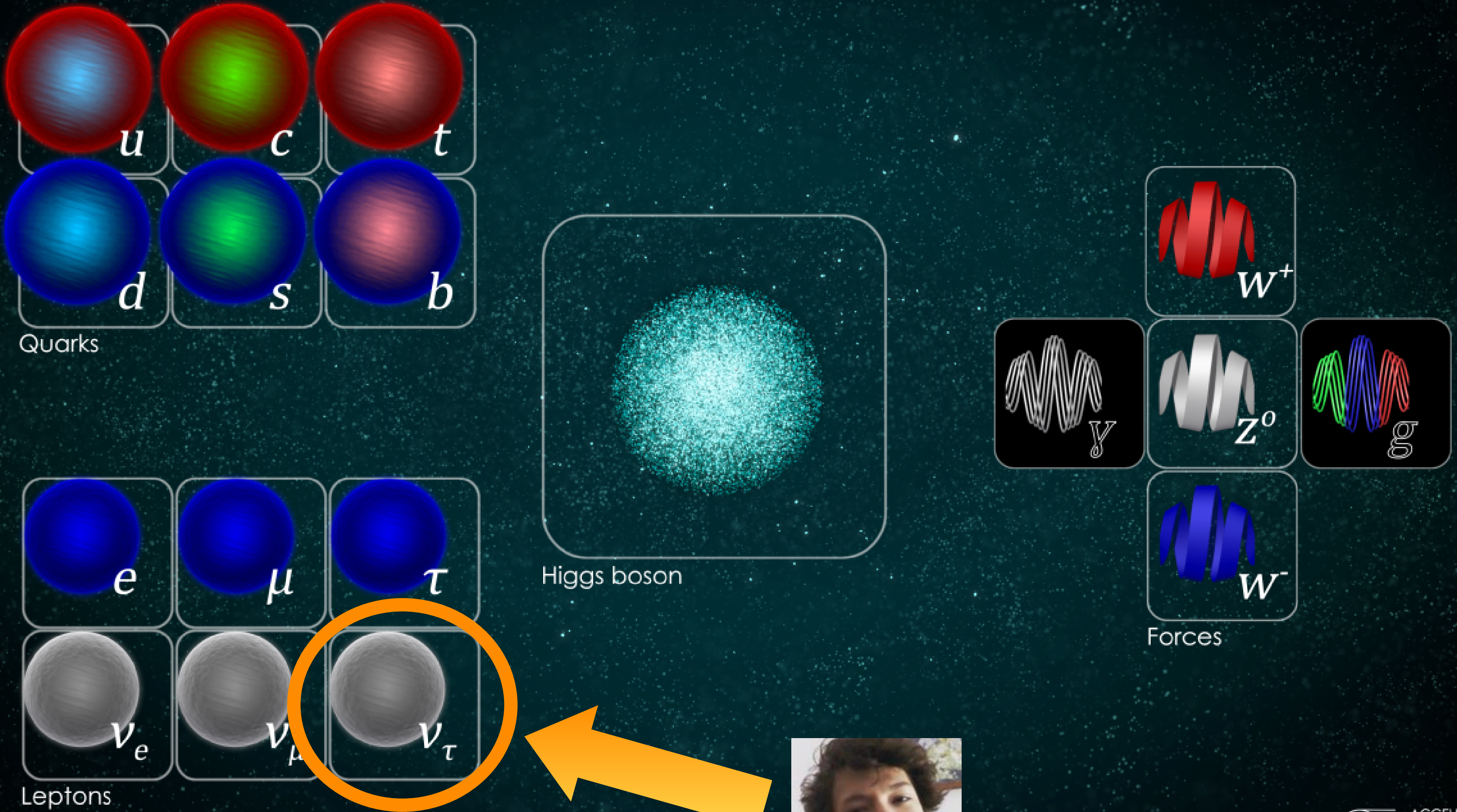
Measuring the atmospheric ν_τ-appearance with KM3NeT-ORCA

Bouke Jung

Choose your character!



Choose your character!



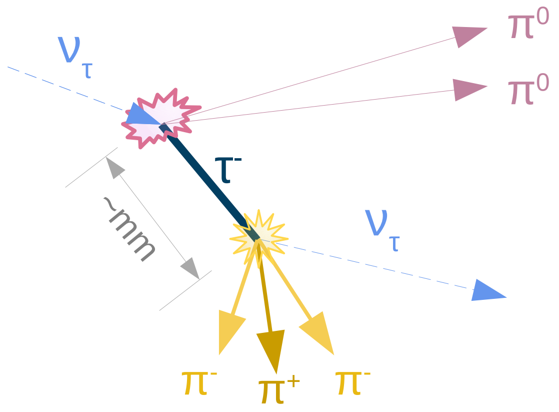
ACCELERATING SCIENCE

ν_τ-identification

- Only ~20 ν_τ identifications so far
  - 9 by DONuT (*arXiv:0711.0728*)
  - 10 by OPERA (*arXiv:1804.04912*)
  - 1-2 astrophysical ν_τ by IceCube (*arXiv:2011.03561*)

Identifying ν_τ is extremely hard!

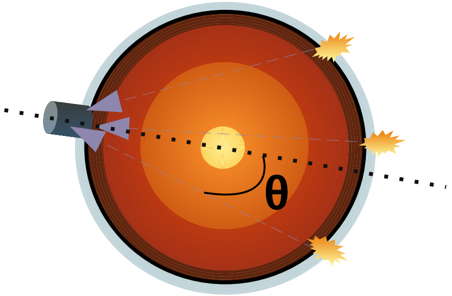
- Large τ-production threshold: $E_\nu > 3.5$ GeV
  - Oscillation maximum @ 2000-3000 km
    → requires very high ν-beam intensities
- Missing final-state energy
  - Challenging to reconstruct



Atmospheric ν_τ inference

Can also use statistical inference

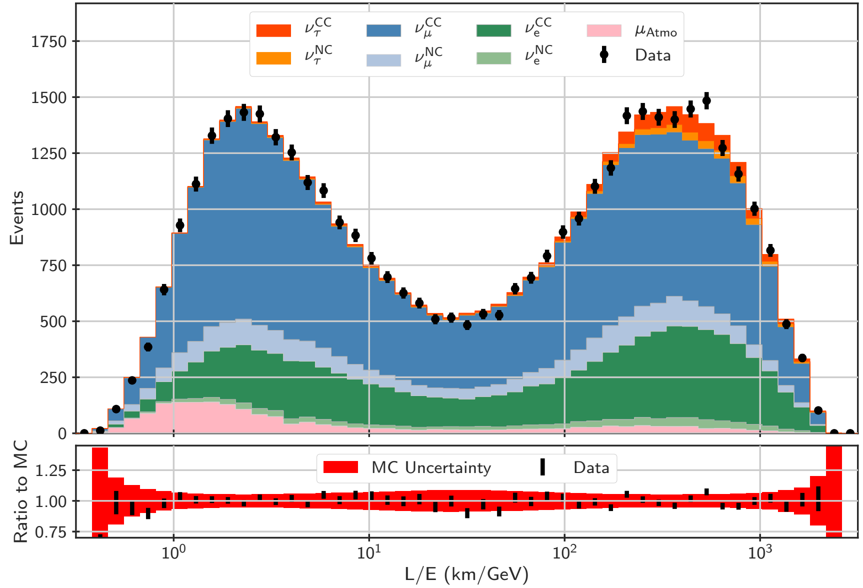
Exploit atm. flux + oscillations



Probe many oscillation baselines with one experiment

- Super-K (*arXiv:1711.09436*)
- IceCube (*arXiv:1901.05366*)
- KM3NeT (arXiv:soon…)

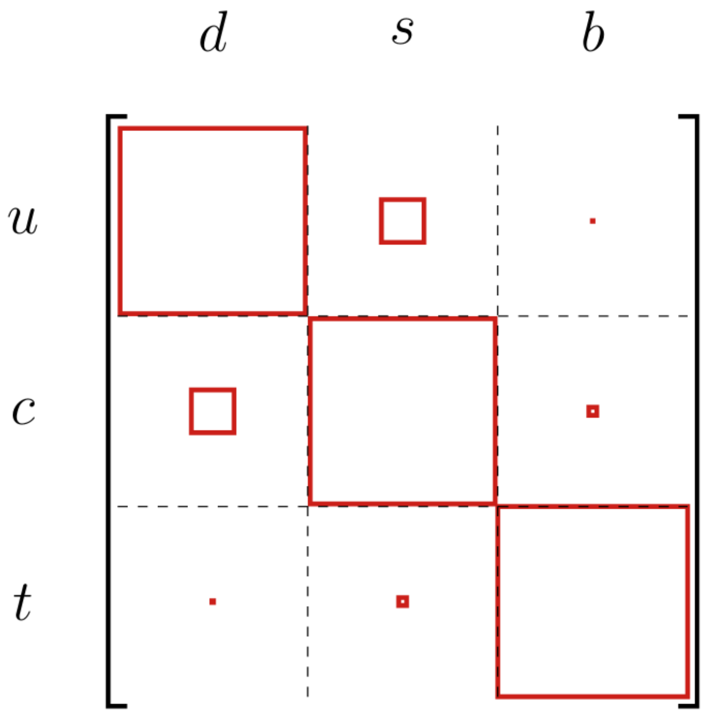
arXiv:1901.05366

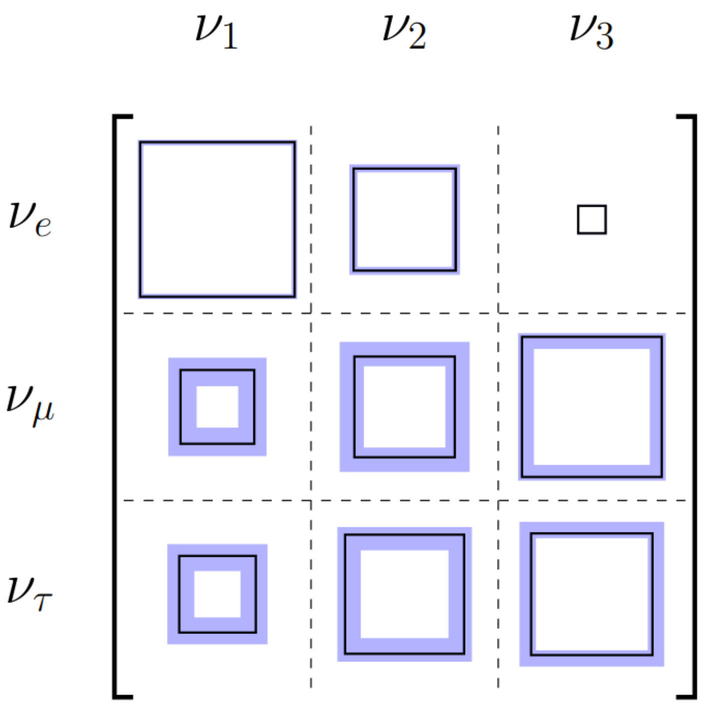


Separate challenges:

- Large cross-section uncertainties (~21%)
- Large uncertainties in unoscillated ν_τ-flux
  - depends on D_s production rate
    → hadronic interaction models

Why measure ν_τ?





Length = size
Band = 3σ unc.

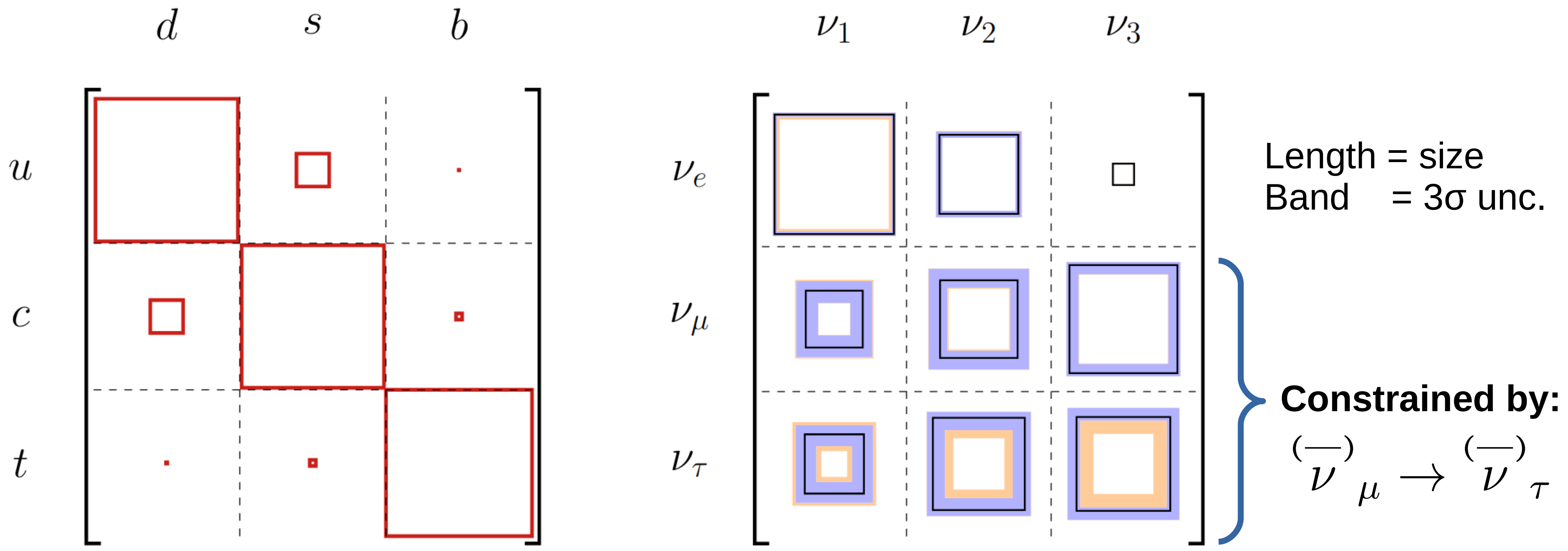
Constrained by:

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\tau$

Steffen Hallmann, Ph.D. dissertation (2021)

Why measure ν_τ?

If we let go of unitarity constraints...



Steffen Hallmann, Ph.D. dissertation (2021)

Non-unitarity: sterile neutrinos

Also theory-motivated reasons for testing this:

- Are there sterile neutrinos beyond the SM?

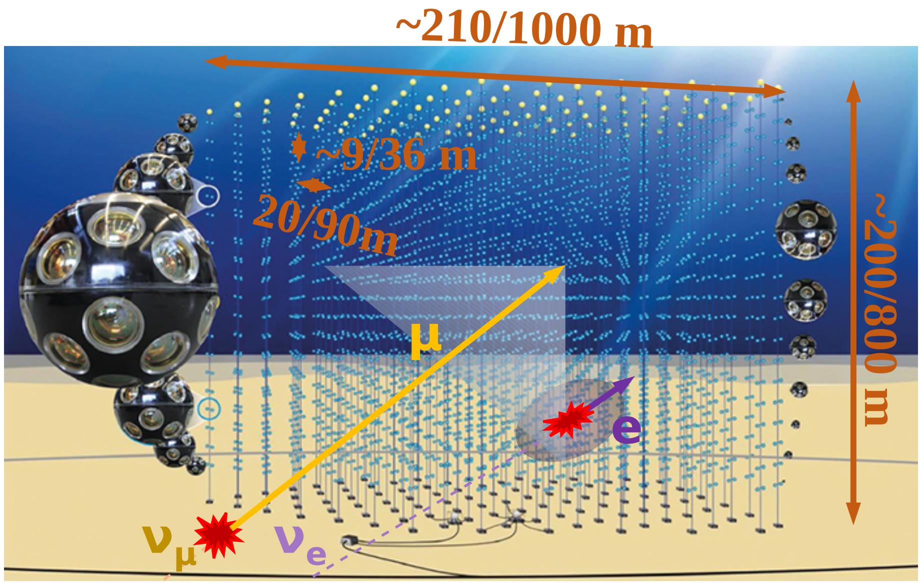
Standard PMNS

$$U_{\mathrm{PMNS}}^{\mathrm{Extended}} = \begin{pmatrix} \begin{pmatrix} \mathcal{U}_{e1} & \mathcal{U}_{e2} & \mathcal{U}_{e3} \\ \mathcal{U}_{\mu 1} & \mathcal{U}_{\mu 2} & \mathcal{U}_{\mu 3} \\ \mathcal{U}_{\tau 1} & \mathcal{U}_{\tau 2} & \mathcal{U}_{\tau 3} \end{pmatrix} & \begin{matrix} \cdots \\ \cdots \\ \cdots \end{matrix} & \begin{matrix} \mathcal{U}_{en} \\ \mathcal{U}_{\mu n} \\ \mathcal{U}_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \end{matrix} & \ddots & \vdots \\ \begin{matrix} \mathcal{U}_{s_n 1} & \mathcal{U}_{s_n 2} & \mathcal{U}_{s_n 3} \end{matrix} & \cdots & \mathcal{U}_{s_n n} \end{pmatrix}$$

The KM3NeT detector

University of Amsterdam Institute of Physics
Nikhef
KM3NeT

2 large-volume water cherenkov arrays



ARCA
- Focus: origin of cosmic neutrinos
- 3.5 km depth; 100 km off-shore from Capo Passero (Sicily)
- **Large, sparse grid → high energy (> TeV)**

ORCA
- Focus: atmospheric neutrino oscillations
- 2.5 km depth; 40 km off-shore from Toulon (France)
- **Small, dense grid → low energy (GeV)**

Detect Cherenkov photons induced by ν-interactions

Main infrastructure:
- 115 **D**etection **U**nits — per building block
- 18 **D**igital **O**ptical **M**odules — per DU
- 31 Hamamatsu R12199-02 **PMTs** — per DOM

} **64.170 PMTs** per block

Goal:
- 2 blocks for ARCA
- 1 block for ORCA

Measuring ν_τ @ KM3NeT

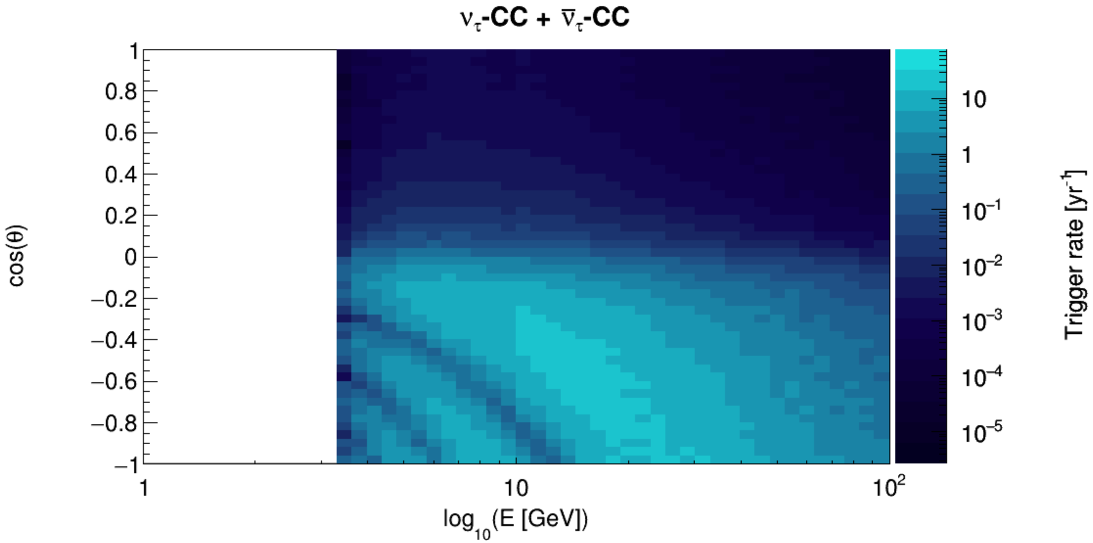
UNIVERSITY OF AMSTERDAM Institute of Physics

Nikhef

Numbers from arXiv:2203.05591

	DONuT (final)	OPERA (final)	Super-K (5326 d)	IceCube Deepcore (1006 d)	DUNE (TauOptimized)	KM3NeT
(anti-)ν_τ-CC	9	10	291	1804	O(100) / yr	>3000 / yr

KM3NeT will provide
largest ν_τ-sample to date!



KM3NeT ν_τ-sensitivity

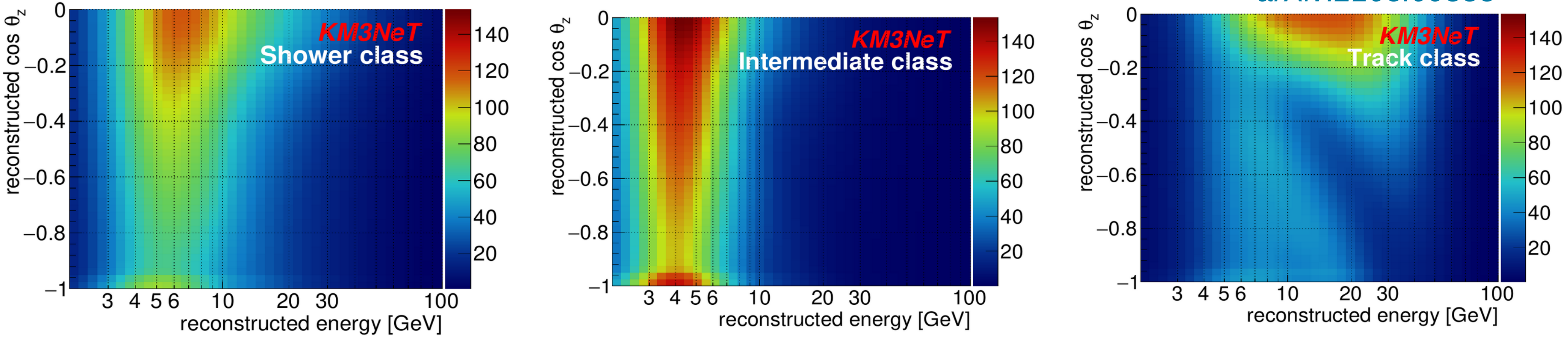
UNIVERSITY OF AMSTERDAM
Institute of Physics

Nikhef

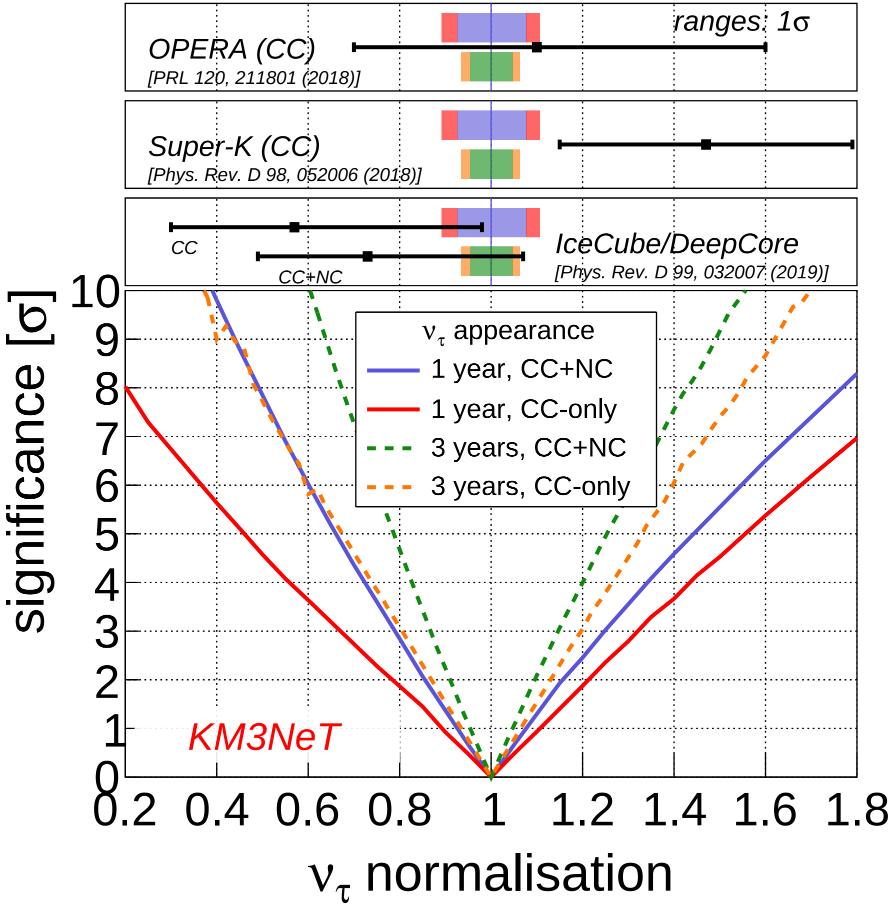
Based on log-likelihood ratio for the Poisson-statistics in each bin in reconstructed (E, cosθ)

- Compute Asimov dataset (bin statistics = expectation)
- Loop over fixed ν_τ-normalisations (= ratio alternative / expected ν_τ event-rate)
- Fit ν_τ-normalisation over assumed data by
  minimizing log-likelihood ratio as function of the nuisance parameters

arXiv:2103.09885

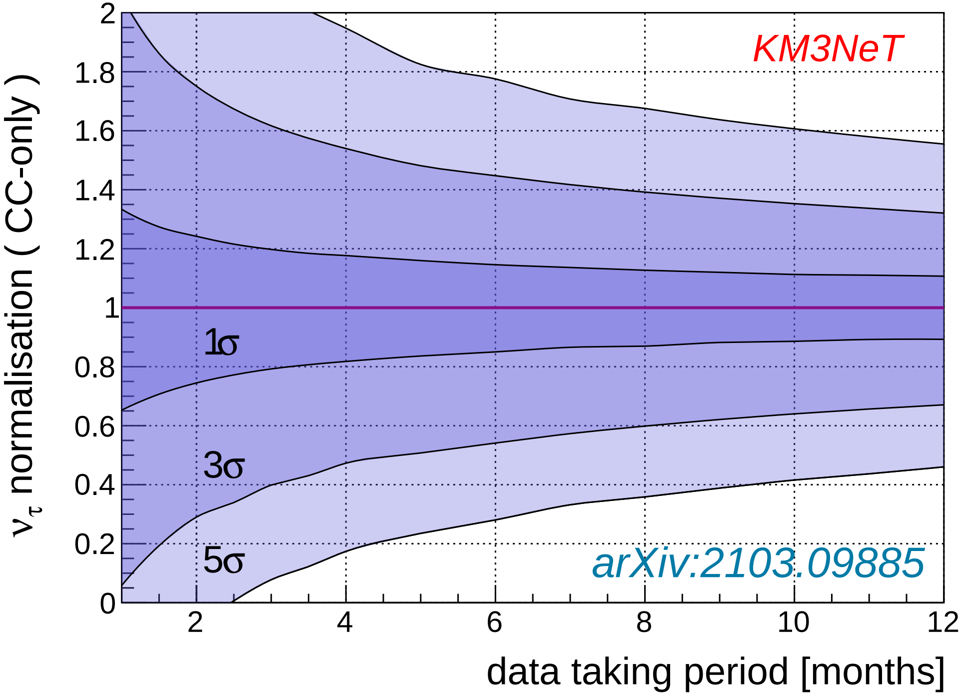


KM3NeT ν_τ-sensitivity



(anti-)ν_τ-event rate

variation >20% excluded @ 3σ
after 3 years of datataking



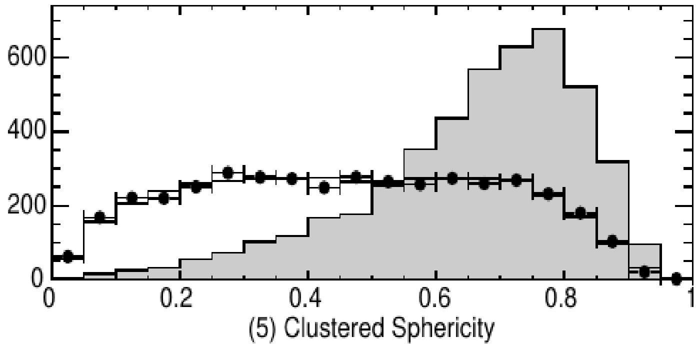
Potential improvements

Current fitting frameworks only allow for fits in terms of E and cosθ

But there are many other potentially interesting observables:

- Observed – expected hit times
- Hit distances
- Measures of isotropicness
  - Thrust
  - Hit sphericity
  - Fox-Wolfram moments

arXiv.1711.09436



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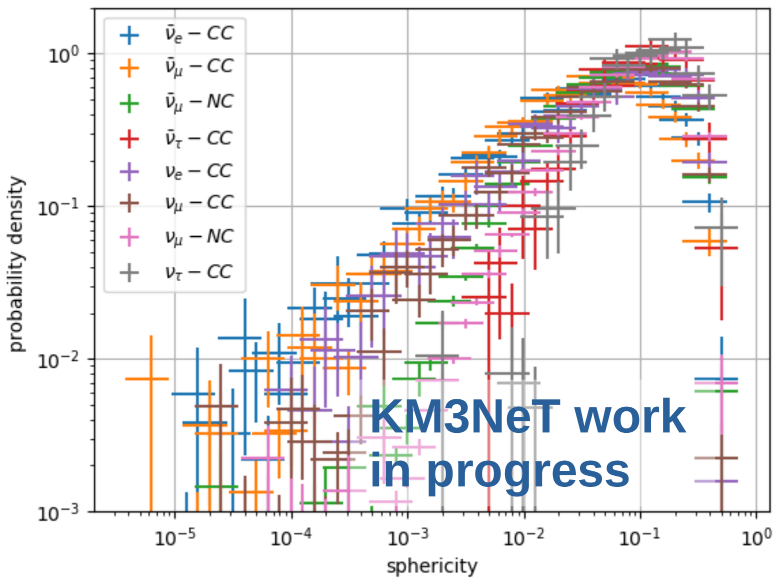


Template fitting

Template fits could offer a flexible way to expand the number of input variables

- Generate set of template histograms for given
  - Interaction cross-sections
  - Fluxes
  - Oscillation probabilities
  - …
- Determine chi-square
  - Plot landscapes
  - Fit best parameter settings

Template fitting

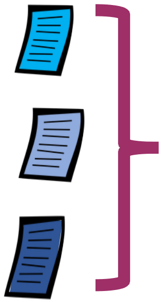
Template fits could offer a flexible way to expand the number of input variables

- Generate set of template histograms for given → **Computationally expensive!**
  - Interaction cross-sections
  - Fluxes
  - Oscillation probabilities
  - …

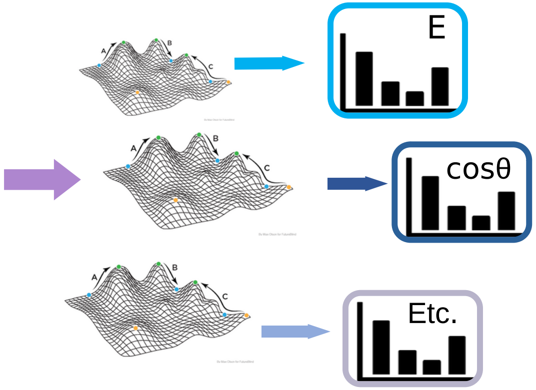
Reweighting offers solution

- Reuse existing MC
  (instead of generating from scratch)

- Determine chi-square
  - Plot landscapes
  - Fit best parameter settings



Index	p_1	...	T_{h1}	...
0	0.23	...	5.4	...
1	0.21	...	7.2	...
...	...	...	...	...



Summary

Measuring ν_τ-appearance is important!

- For constraining the bottom PMNS rows
- For testing unitarity → sterile neutrinos?

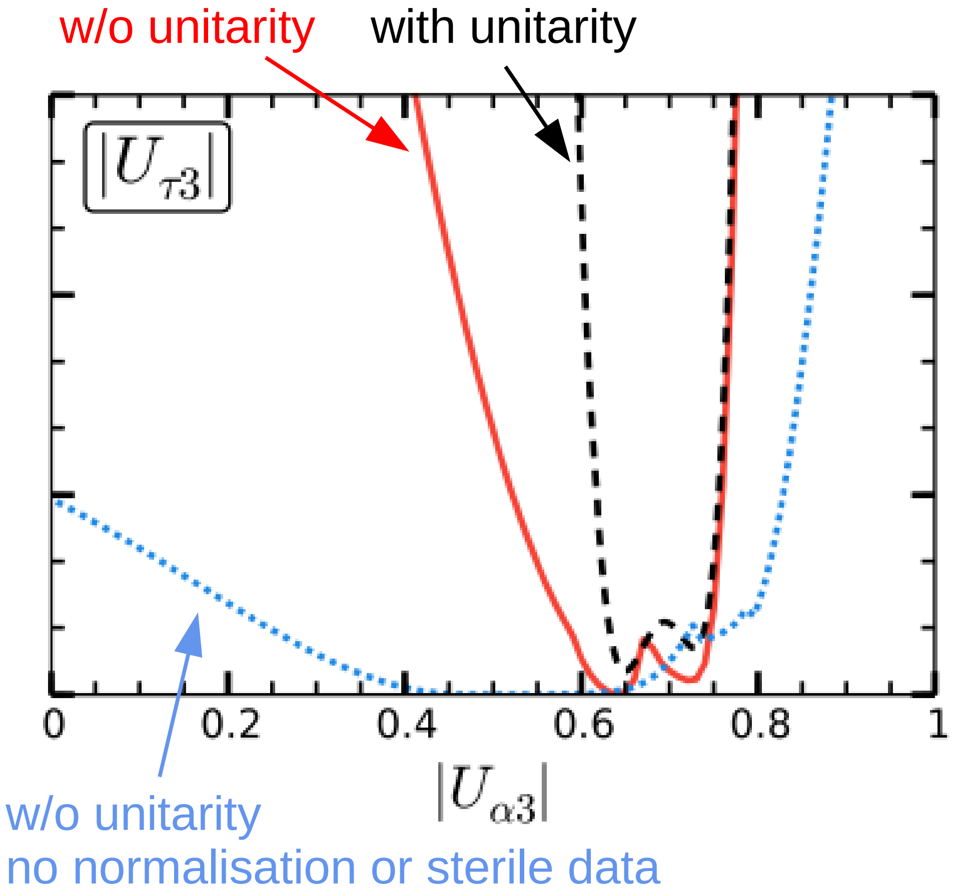
KM3NeT will measure the ν_τ-appearance with unprecendented precision

- > 3000 (anti-)ν_τ per year for ORCA-115 (more than any experiment before!)
- ν_τ-normalisation constrained to < 20% in 3 years!

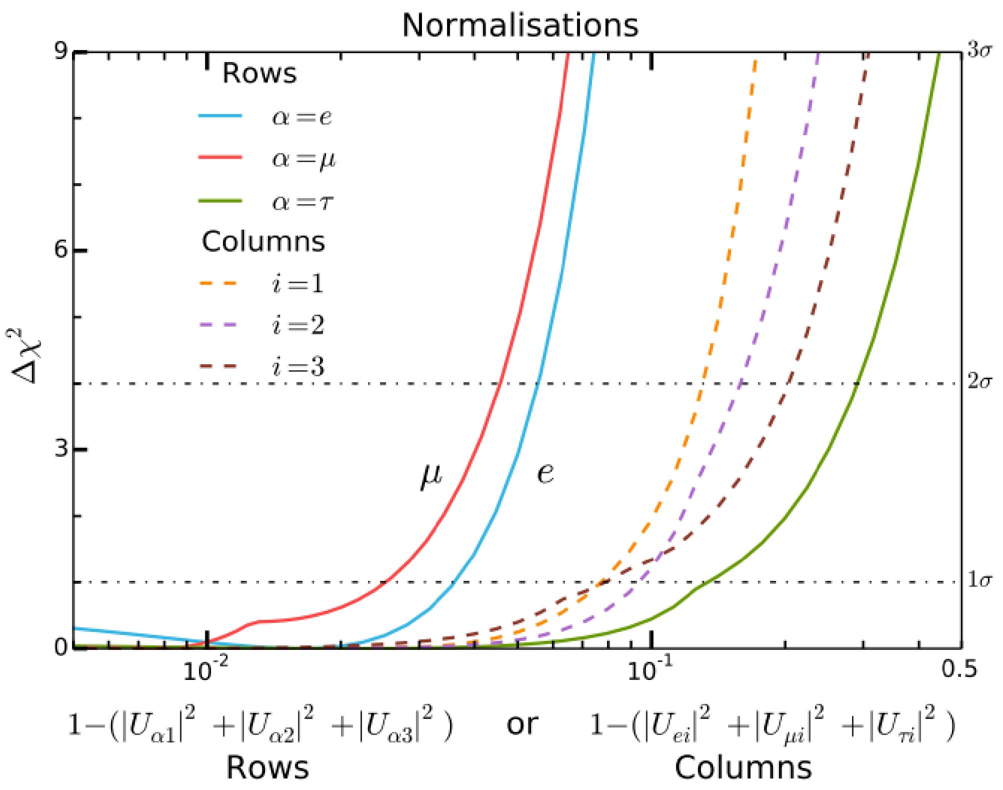
Template fitting procedure underway to further enhance sensitivity
and to facilitate some studies on systematics

EXTRA

Introduction: theory



arXiv:1508.05095



Reweighting example