Work in Progress

Search for New Physics in Astrophysical Flavor at IceCube

IceCube Lab (ICL)
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Queen Mary • MIT

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Why Flavour Ratio

Relates directly to the **source flavour composition**

Source Composition

$$f_{\alpha,\oplus} = \sum_{i\beta} |\, U_{i\alpha}\, |^2 |\, U_{i\beta}\, |^2 \, f_{\beta,S}$$

Measured Composition

SM Case

Example **source** flavour ratio scenarios:

$$[\, f_{e,S} \; : f_{\mu,S} \; : f_{\tau,S} \,]$$

➔ [1 : 2 : 0] charged pion-decay decay

➔ [1 : 0 : 0] neutron decay dominant

➔ [0 : 1 : 0] rapid muon energy loss

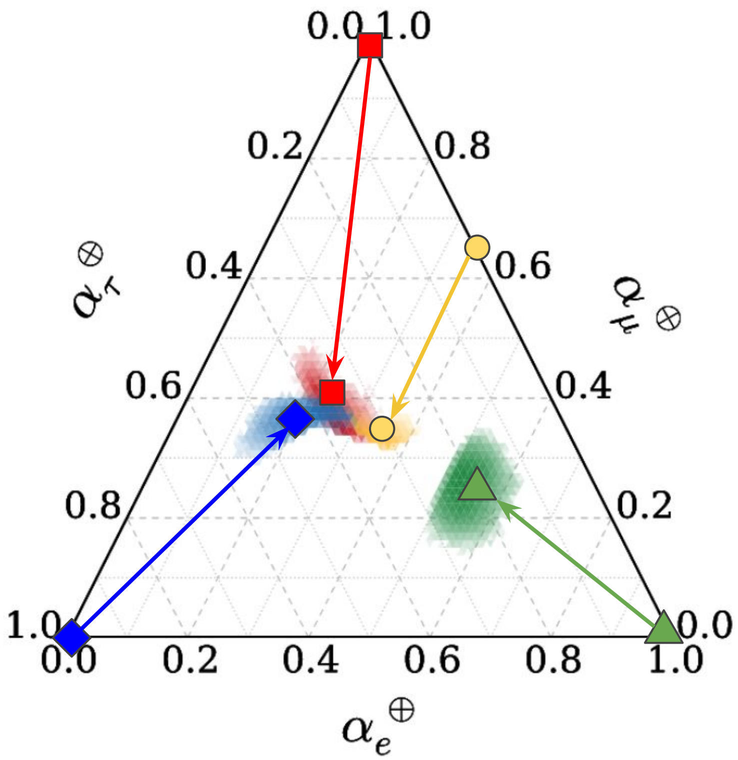
➔ [0 : 0 : 1] exotic tau (BSM)

NuFIT 3.0 (2016)

$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

3x3 complex unitary matrix

Why Flavour Ratio



Example **source** flavour ratio scenarios:

$$[\, f_{e,S} \;:\; f_{\mu,S} \;:\; f_{\tau,S} \,]$$

- ➔ [1 : 2 : 0] charged pion-decay decay
- ➔ [1 : 0 : 0] neutron decay dominant
- ➔ [0 : 1 : 0] rapid muon energy loss
- ➔ [0 : 0 : 1] exotic tau (BSM)

Source flavour ratio is modified on the way to Earth due to neutrino mixing

Why Flavour Ratio - BSM

Relates directly to the **source flavour composition** and the **new physics mixing matrix elements**

New Physics Mixing Matrix

Source Composition

$$f_{\alpha,\oplus,d} = \frac{1}{\Delta E}\int_{\Delta E}\sum_{i\beta} |V_{i\alpha,d}(E)|^2 |V_{i\beta,d}(E)|^2 f(E)_{\beta,S}\, dE$$

Measured Composition

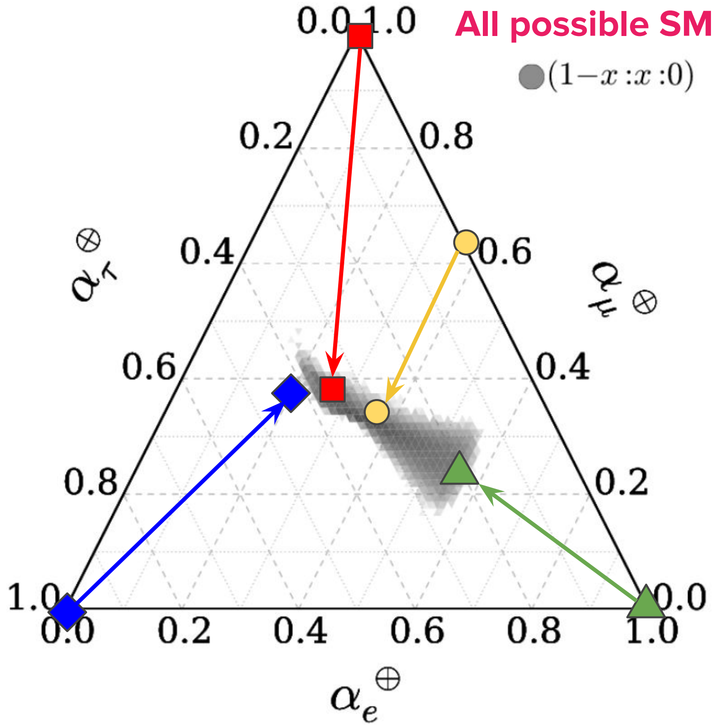
Constrain BSM elements through V_d

Unitary Mixing Matrix

$$|V_{i\alpha,d}(E)|^2 |V_{i\beta,d}(E)|^2$$

3x3 complex unitary matrix

Why Flavour Ratio - BSM



Example **source** flavour ratio scenarios:

$$[\, f_{e,S} \;:\; f_{\mu,S} \;:\; f_{\tau,S} \,]$$

- → [1 : 2 : 0] charged pion-decay decay
- → [1 : 0 : 0] neutron decay dominant
- → [0 : 1 : 0] rapid muon energy loss
- → [0 : 0 : 1] exotic tau (BSM)

Discovery -> Significant measurement outside this contour

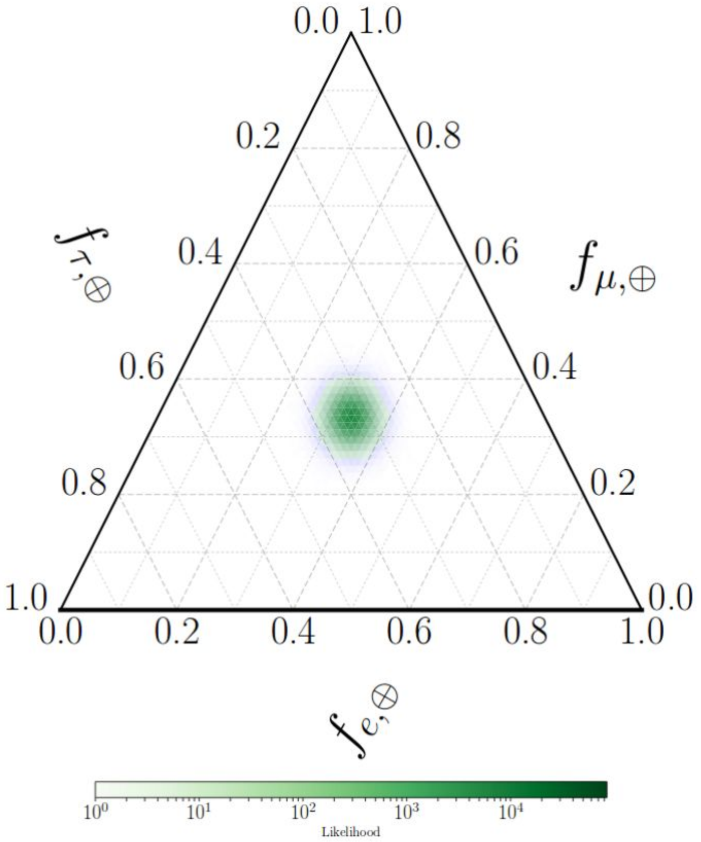
Sensitivity -> Can set a sensitivity on the **scale of new physics**

Toy Study

For the **likelihood**, we used a multidimensional **normal** distribution around a chosen (measured) central value e.g. (1, 1, 1) with a set deviation (sigma) e.g. 0.001

In this toy model, we **assume this is the flavour ratio measurement**, then we try to **fit** for the new physics elements, $\tilde{U}_d$ and the scale O_d/Λ_d through V_d.

Note: Region in **blue** is outside the 1 sigma band.



Fake Likelihood for Toy Study

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Bayesian Analysis

$$p\left(D\right) = \int p\left(D \mid \Theta, \alpha\right) \cdot p\left(\Theta, \alpha\right)\, d\Theta\, d\alpha$$

The goal is to obtain the posterior distribution marginalised over your nuisance parameters

Joint Posterior / **Likelihood** / **Prior**

$$p\left(\Theta, \alpha \mid D\right) = \frac{p\left(D \mid \Theta, \alpha\right) \cdot p\left(\Theta, \alpha\right)}{p\left(D\right)}$$

Marginal Likelihood

$$p\left(\Theta \mid D\right) = \int p\left(\Theta, \alpha \mid D\right) d\alpha$$

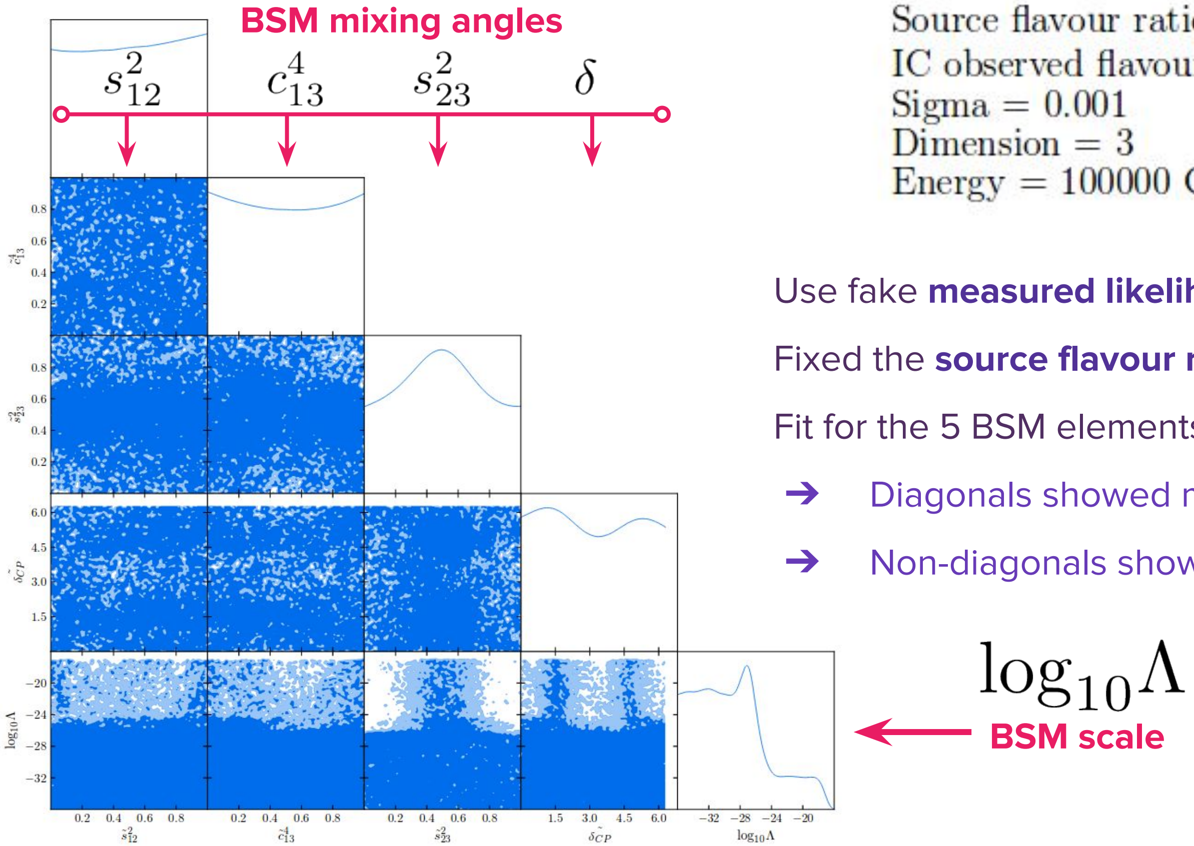
Marginalised Posterior

Problem: In a multidimensional space, the integral over the nuisance parameters is difficult to perform directly

Instead: Use an MCMC to sample over the joint posterior, after which the sampled points can be integrated over in a more straightforward way to obtain the marginalised posterior

emcee The MCMC Hammer

Toy Study



Source flavour ratio = [0.33, 0.67, 0.00]
IC observed flavour ratio = [0.33, 0.33, 0.33]
Sigma = 0.001
Dimension = 3
Energy = 100000 GeV

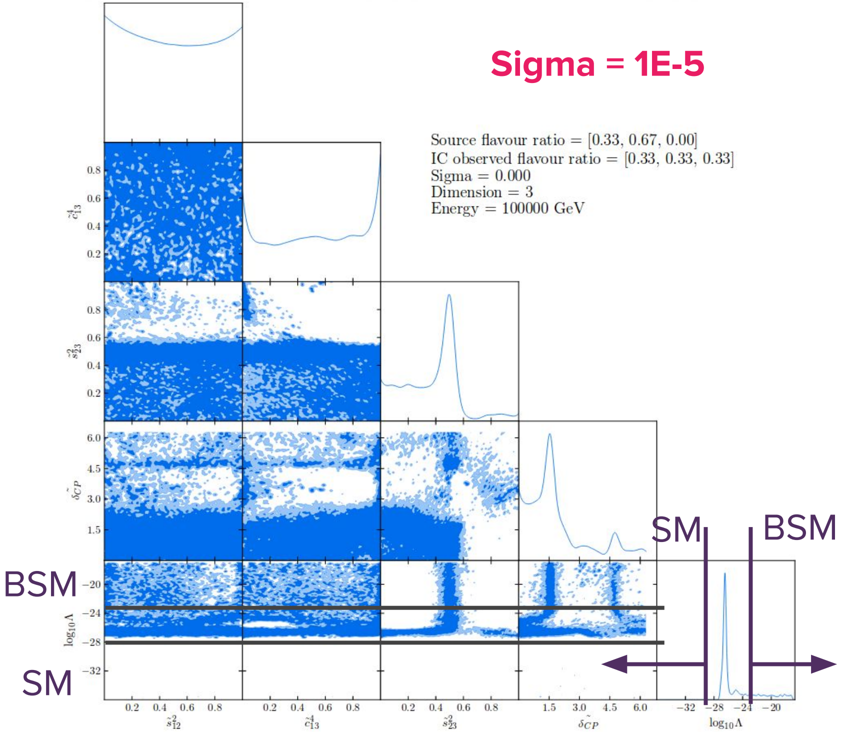
Use fake **measured likelihood** centred on [1 : 1 : 1]

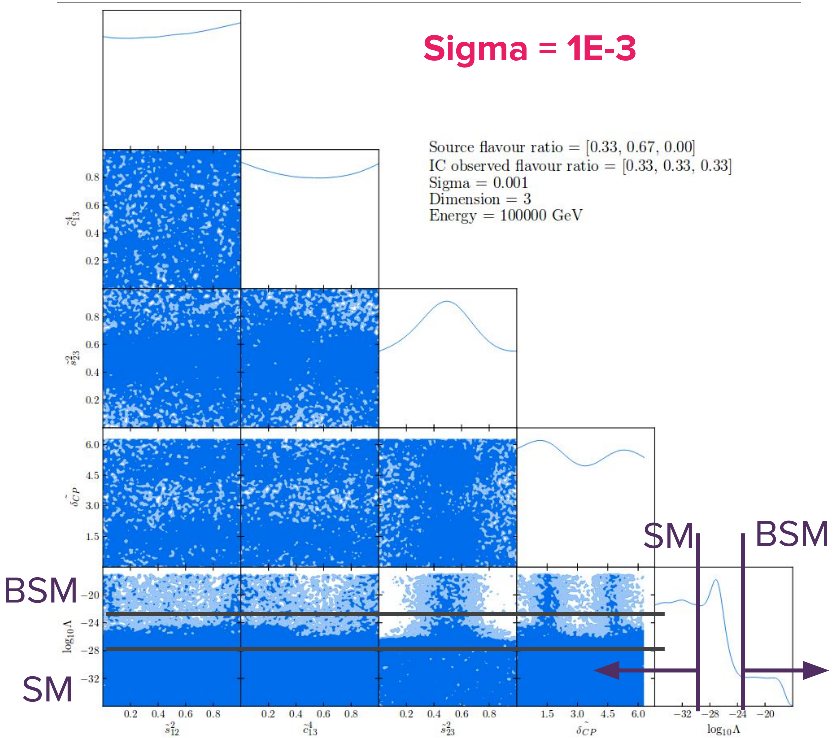
Fixed the **source flavour ratio** to the [1 : 2 : 0] scenario

Fit for the 5 BSM elements contained in V_d

- ➔ Diagonals showed marginalised posteriors
- ➔ Non-diagonals show the joint posteriors

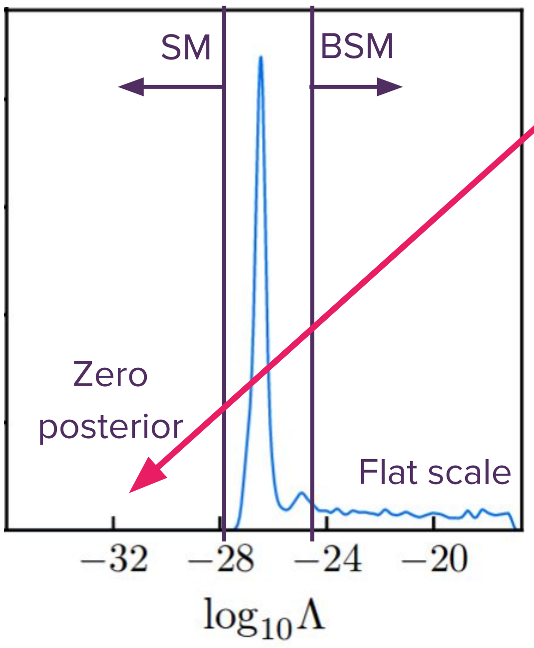
Toy Study


Sigma = 1E-5
Source flavour ratio = [0.33, 0.67, 0.00]
IC observed flavour ratio = [0.33, 0.33, 0.33]
Sigma = 0.000
Dimension = 3
Energy = 100000 GeV
SM
BSM
BSM
SM
$\tilde{s}_{12}^2$
$\tilde{c}_{13}^4$
$\tilde{s}_{23}^2$
$\tilde{\delta}_{CP}$
$\log_{10}\Lambda$


Sigma = 1E-3
Source flavour ratio = [0.33, 0.67, 0.00]
IC observed flavour ratio = [0.33, 0.33, 0.33]
Sigma = 0.001
Dimension = 3
Energy = 100000 GeV
SM
BSM
BSM
SM
$\tilde{s}_{12}^2$
$\tilde{c}_{13}^4$
$\tilde{s}_{23}^2$
$\tilde{\delta}_{CP}$
$\log_{10}\Lambda$

Toy Study - Results

Sigma = 1E-5

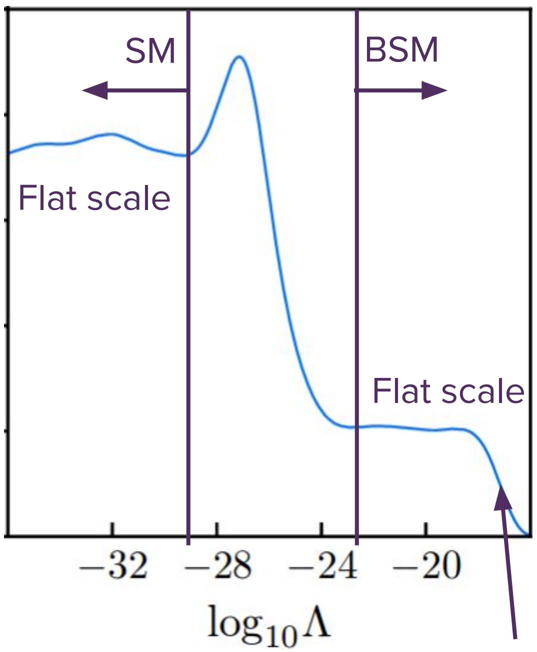


A pure SM NuFIT mixing is not accurate enough to be consistent with a source flavor ratio of (1:2:0).

We need either:

- Introduction of BSM component
- A less accurate measurement of the flavour ratio

Sigma = 1E-3



Artificial boundary dip

[1] Argüelles, Katori, Salvado, PRL115(2015)161303
[2] IceCube, Science 342 (2013) 1242856

Future

Relates directly to the **source flavour composition** and the **new physics mixing matrix elements**

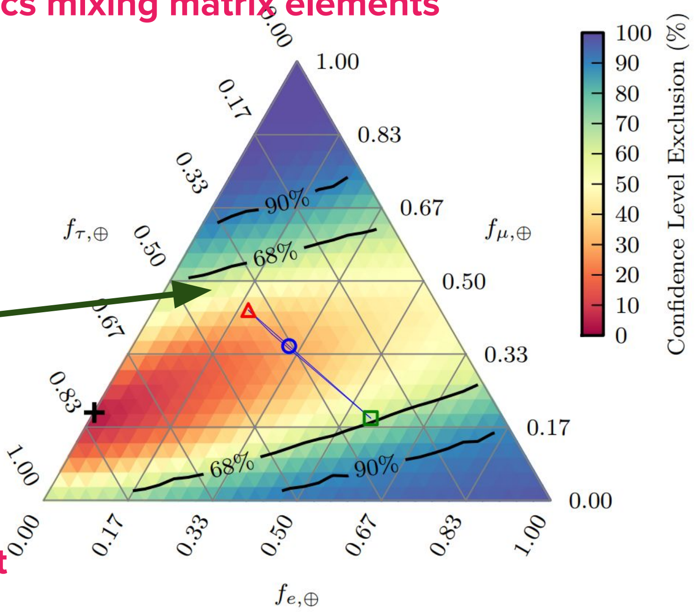
New Physics Mixing Matrix

Source Composition

$$f_{\alpha,\oplus,d} = \frac{1}{\Delta E} \int_{\Delta E} \sum_{i\beta} |V_{i\alpha,d}(E)|^2 |V_{i\beta,d}(E)|^2 f(E)_{\beta,S} dE$$ [1]

Measured Composition

Constrain BSM elements through V_d



Likelihood contour of the flavour ratio measurement will be our input

- Relevant systematic errors will be folded into this likelihood

This analysis is an interpretation of this flavour ratio measurement

- In the space of the **Mixing Matrix Elements with New Physics**

Will be using HESE selection[2] with an updated 7 years of data

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Thanks for listening!
Sven Lidstrom, NSF

Past IceCube Measurement

"Flavor Ratio of Astrophysical Neutrinos above 35 TeV in IceCube"

➔ Extended HESE event selection down to 1500 PE

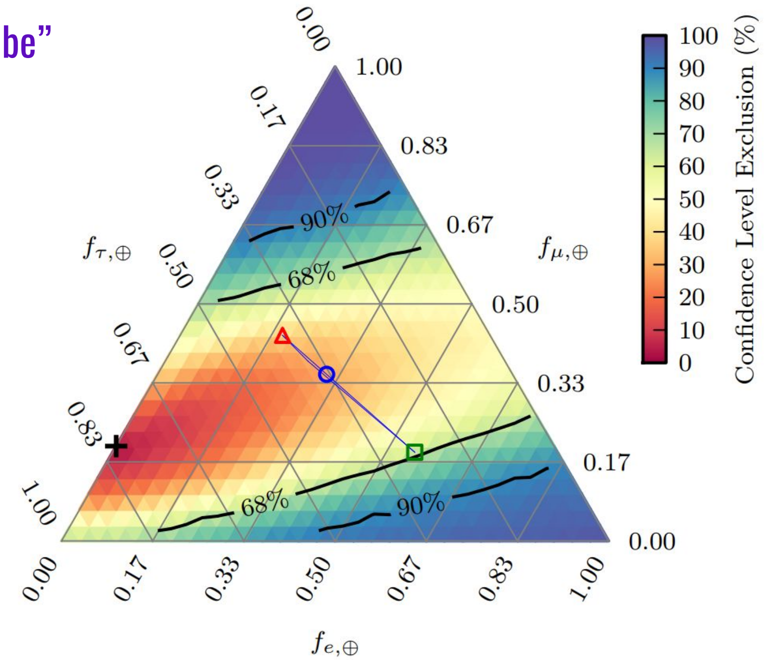
➔ 129 showers and 8 tracks collected in three years from 2010 to 2013

➔ Tracks correspond to numu and muonic decay nutau

- ◆ Muonic decay nutau ~ 17.4% branching ratio

➔ Cascades correspond to nue and nutau

➔ Consistent with source flavour ratio of (1 : 1 : 1)



New Physics in Effective Hamiltonian

Introducing new physics in the **mixing matrix elements**

$$H_d = \frac{1}{2E} U M^2 U^\dagger + \frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger = V_d(E) \Delta V_d^\dagger(E)$$

Dimension

Standard Mixing

New Physics Terms

Mixing Matrix with New Physics

Same as the approach taken for the IC86LV analysis (https://wiki.icecube.wisc.edu/index.php/IC86LV_atmo)

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \ldots$$

Standard Mixing Term

$$\frac{1}{2E} U M^2 U^\dagger$$

Energy

Mass eigenvalues

Standard Unitary 3x3 mixing matrix

➔ Set to NuFIT values

NuFIT 3.0 (2016)

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New Physics Terms

New operators can be interpreted in different new physics contexts

- ➔ Lorentz and CPT Violation
- ➔ Non-standard Interactions
- ➔ Dark Energy Interaction
- ➔ Equivalence Principle Violation

$$\frac{E^{d-3}}{\Lambda_d}\tilde{U}_d O_d \tilde{U}_d^{\dagger}$$

- **Energy Dependence** (E)
- **Dimension** (d)
- **Scale of new physics** (Λ_d)
- **New Physics Elements for dimension d** ($\tilde{U}_d$, $\tilde{U}_d^{\dagger}$) → **3x3 complex unitary matrix**

Goal is to set limits on these elements

➔ **For each d**

New Physics Mixing Matrix

Diagonalise Standard Mixing + New Physics Terms

Dimension

Energy Dependent

$$V_d(E)\Delta V_d^\dagger(E)$$

New Physics Mixing Matrix for dimension d

3x3 complex unitary matrix

➔ Form in which the new physics enters the oscillation formula

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New Physics Mixing Matrix

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Measured Composition

Constrain BSM elements through V_d

Unitary Mixing Matrix

$$\mid V_{i\alpha,d}(E)\mid^2 \mid V_{i\beta,d}(E)\mid^2$$

3x3 complex unitary matrix

Likelihood contour of the flavour ratio measurement will be our input

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Sampling

How do we select exactly which parameters to scan over?

$$\tilde{U}_d = e^{i\eta} e^{i\phi_1\lambda_3 + i\phi_2\lambda_8} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{12} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} e^{i\chi_1\lambda_3 + i\chi_2\lambda_8}$$

➔ In this case the Haar measure is given by (ignoring Majorana and unphysical phases):

$$dU = ds_{12}^2 \wedge dc_{13}^4 \wedge ds_{23}^2 \wedge d\delta$$

Volume Elements

Therefore, we will sample uniformly in $s_{12}^2, c_{13}^4, s_{23}^2, \delta$

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Sampling

How do we select exactly which parameters to scan over?

$$f_{\beta,S} = \begin{pmatrix} f_{e,S} \\ f_{\mu,S} \\ f_{\tau,S} \end{pmatrix} = \begin{pmatrix} sin^2\phi_S \ cos^2\psi_S \\ sin^2\phi_S \ sin^2\psi_S \\ cos^2\phi_S \end{pmatrix}$$

$$\sum_\beta f(E)_{\beta,S} = 1$$

➔ In this case the Haar measure is given by

$$df = dsin^4\phi \wedge dcos(2\psi)$$

Therefore, we will sample uniformly in $sin^4\phi$, $cos(2\psi)$

Sampling

How do we select exactly which parameters to scan over?

$$\mathcal{O}_d/\Lambda_d \longrightarrow \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Lambda_{1,d} & 0 \\ 0 & 0 & \Lambda_{2,d} \end{bmatrix}$$

Therefore, we will sample uniformly in $\Lambda_{1,d}$, $\Lambda_{2,d}$

In total the 8 parameters we scan over:

$s_{12}^2 \quad c_{13}^4 \quad s_{23}^2 \quad \delta$

$\tilde{U}_d$

$\Lambda_{1,d} \quad \Lambda_{2,d}$

$\mathcal{O}_d/\Lambda_d$

nuisance parameters

$sin^4\phi \quad cos(2\psi)$

$f(E)_{\beta,S}$

MCMC Scan

➔ **Use MCMC to scan over $\tilde{U}_d$, O_d/Λ_d, $f(E)_{\beta,S}$**

How many parameters do we scan over?

$\tilde{U}_d \longrightarrow$ 3x3 Unitary Matrix => **4 degrees of freedom**

$$O_d/\Lambda_d \longrightarrow \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Lambda_{1,d} & 0 \\ 0 & 0 & \Lambda_{2,d} \end{bmatrix}$$

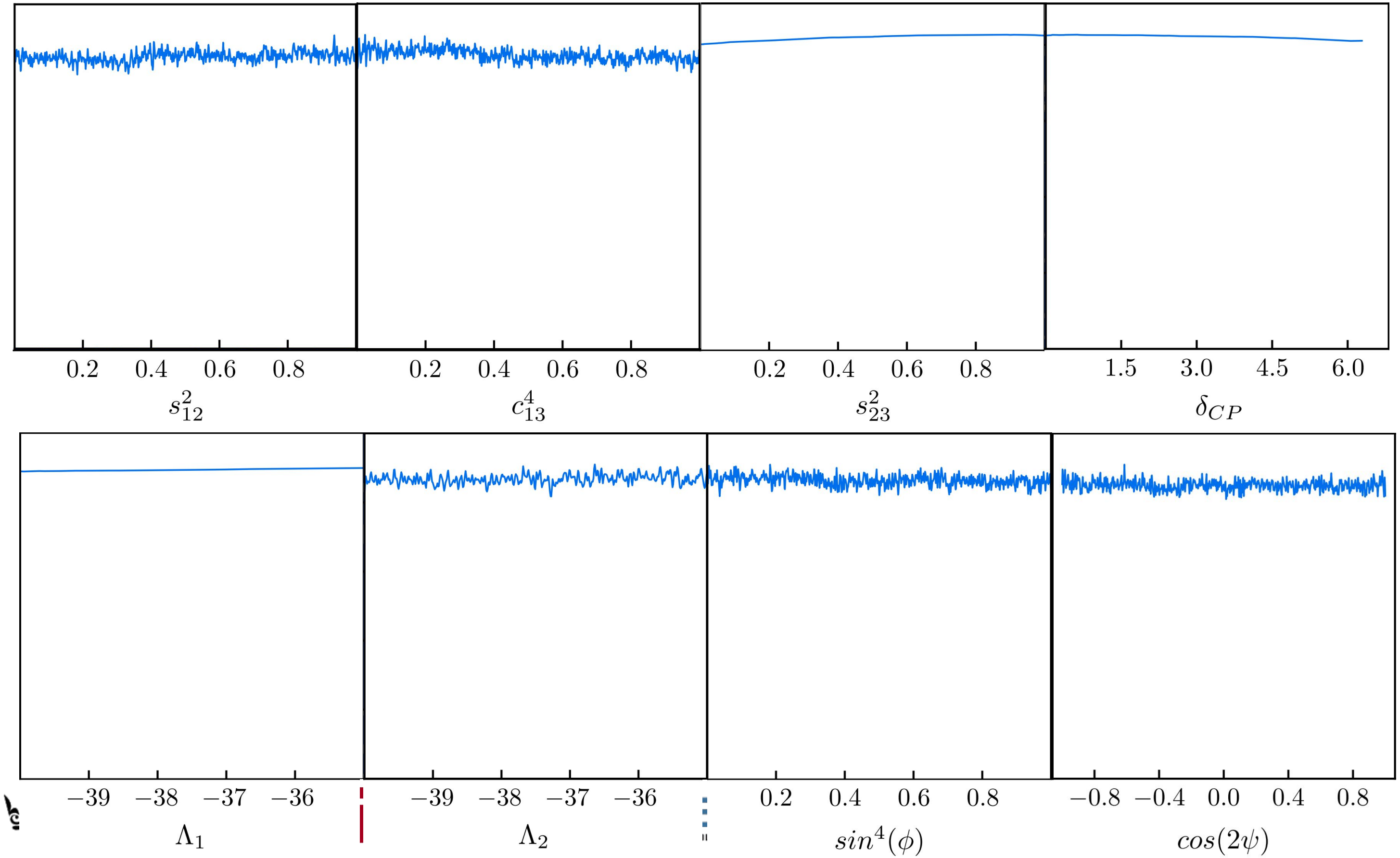
3x3 Diagonal Matrix with 2 non-zero components => **2 degrees of freedom**

$f(E)_{\beta,S} \longrightarrow$ 3 Initial flavour ratios, with the condition $\sum_\beta f(E)_{\beta,S} = 1$ => **2 degrees of freedom**

➔ **Therefore we have 8 degrees of freedom which we are scanning over**

Toy Study

Flat Likelihood



Marginalized posteriors

EXPLORING HIGH DIMENSIONAL SPACES without introducing artificial biases : very hard! But DONE