Testing discrete leptonic flavour symmetries at precision neutrino oscillation facilities

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Outline of talk

Oscillation physics present and future

Discrete leptonic flavour symmetries

Brief experimental interlude

Testing atmospheric sum-rules at next generation facilities

Conclusions

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Neutrino flavour and oscillations

- Contrary to the SM, neutrinos have mass and undergo flavour oscillations due to non-trivial mixing between the mass eigenstates and the flavour states.

- In the minimal scenario, the oscillation probability depends upon two mass squared splittings

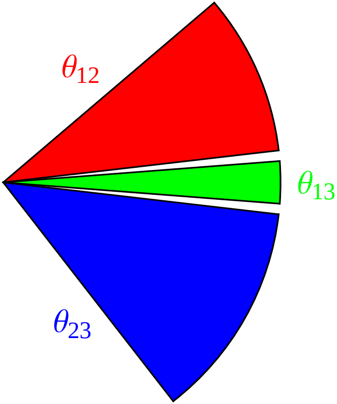
$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2 \qquad \text{and} \qquad \Delta m_{31}^2 \equiv m_3^2 - m_1^2 .$$

- The remaining parameters describe the mapping between bases, expressed as a 3×3 unitary matrix, such that $\nu_\alpha = (U_{\text{PMNS}})_{\alpha i}\, \nu_i$ where

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-\mathrm{i}\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{\mathrm{i}\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P .$$

What we know

- Thanks to decades of experimental work, including Daya Bay's discovery last year of θ_{13}, we now know all three of the angles which parameterize the PMNS matrix.



$$\begin{aligned}\sin^2\theta_{12} &\approx 0.31,\\ \sin^2\theta_{23} &\approx 0.52,\\ \sin^2\theta_{13} &\approx 0.02.\end{aligned}$$

- We also know the magnitudes of both mass squared differences and the sign of one.

$$\begin{aligned}\Delta m^2_{21} &\approx 7.59\times10^{-5}\\ \left|\Delta m^2_{32}\right| &\approx 2.50\times10^{-3}.\end{aligned}$$

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Does the leptonic sector exhibit CP-violation?

$$\theta_{12},\ \theta_{23},\ \theta_{13},$$
$$\Delta m^2_{12},\ \Delta m^2_{13},\ \delta_{CP}$$

Is that all there is? Do we need to extend the 3ν-mixing paradigm?

What next?

- In light of the measurement of θ_{13}, the mass hierarchy and δ are more easily measured than was widely expected. The next generation of long-baseline experiments (LBL) are expected to make significant progress on these issues.

- Now is the time to decide what else we would like to know about neutrino flavour. Fortunately, there are many BSM effects which may influence LBL physics:

$$\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

Non-Standard Interactions?

$$L \sim \underline{\mathbf{3}} \qquad \zeta' \sim \underline{\mathbf{1}}'$$

$$\mathcal{L}_{M_\nu} \supset y(LL)''\zeta'$$

Flavour symmetries?

$$\nu_S$$

Sterile neutrinos?

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Discrete leptonic flavour symmetries

- A popular topic amongst the model-building community, with many currently phenomenologically viable models.

- These models propose a discrete flavour symmetry, G_{F}, and all particles are assigned to representations of this symmetry. This shapes the Lagrangian in a characteristic way.

- This symmetry is then broken (often spontaneously by a set of *flavon* fields) which leads to distinct residual symmetries in the charged lepton and neutrino mass terms: this produces a non-trivial PMNS matrix.

$$\begin{tikzcd} & G_\nu \\ G_{\mathsf{F}} \arrow[ur] \arrow[dr] & \\ & G_\ell \end{tikzcd}$$

Hernandez-Smirnov approach (see 1204.0445 and 1212.2149)

- Attempts to constrain the PMNS from a bottom-up version of the symmetry breaking scenario. By specifying G_ν and G_ℓ, and making a few assumptions about G_F, we can derive constraints on U_PMNS.

- The subgroups G_ν and G_ℓ are chosen from the symmetries of the leptonic mass terms.

$$\mathcal{L}_\nu = \frac{1}{2}\overline{\nu^c}_L m_\nu \nu_L, \qquad \text{and} \qquad \mathcal{L}_\ell = \overline{E}_R m_\ell \ell_L.$$

- The symmetry of the neutrino mass term is $\mathbb{Z}_2 \times \mathbb{Z}_2$, whilst for the charged leptons it is $\mathrm{U}(1)^3$.

- It is *assumed* that the residual symmetries of these sectors are $G_\nu = \mathbb{Z}_2$ and $G_\ell = \mathbb{Z}_m$, and that the remaining symmetries are accidental.

Hernandez-Smirnov approach (cont.)

- Reversing the broken-symmetry scenario, these subgroups must be combined in some way to form the supergroup G_{F}. We assume that this group is defined by the relation $(G_\nu G_\ell)^p = 1$ for $p \in \mathbb{N}$.
- This assumption leads us to the von Dyck groups $D(2, m, p)$ given by the presentation

$$\langle S, T, W \mid S^2 = T^m = W^p = 1 \rangle.$$

- Assuming that our group G_{F} is *finite*, the only permissible groups turn out to be small order groups already popular in the literature

$$\mathrm{D}(2,2,3) = \mathrm{S}_3, \qquad \mathrm{D}(2,3,3) = \mathrm{A}_4,$$
$$\mathrm{D}(2,3,4) = \mathrm{S}_4, \qquad \mathrm{D}(2,3,5) = \mathrm{A}_5.$$

Constraints and correlations

- In the framework that I've discussed, the symmetries can be shown to fix a column of the PMNS matrix. This leads to two constraints on the PMNS matrix parameters

$$e.g. \qquad \begin{pmatrix} |U_{e1}|^2 \\ |U_{\mu 1}|^2 \\ |U_{\tau 1}|^2 \end{pmatrix} = \begin{pmatrix} \frac{1-\eta}{2} \\ \frac{1-\eta}{2} \\ \eta \end{pmatrix}.$$

- For the models that we are interested in, these constraints can be expressed as a definition of θ_{12} in terms of θ_{13}, called a *solar sum-rule*, and a correlation between θ_{23}, θ_{13} and $\cos\delta$, which is called the atmospheric sum-rule

$$e.g. \qquad |U_{e1}|^2 = \frac{1-\eta}{2} \quad \Longrightarrow \quad \cos^2\theta_{12} = \frac{1-\eta}{2\cos^2\theta_{13}}.$$

Atmospheric sum-rules

- To simplify our expressions we introduce the following parameters (King 2007)

$$\sin\theta_{12} \equiv \frac{1+s}{\sqrt{3}}, \qquad \sin\theta_{23} \equiv \frac{1+a}{\sqrt{2}}, \qquad \sin\theta_{13} = \frac{r}{\sqrt{2}},$$

  which have the following 1σ ranges (Fogli 2012)

$$-0.07 \leq s \leq -0.01, \qquad 0.21 \leq r \leq 0.23, \qquad -0.15 \leq a \leq -0.07.$$

- We then expand the atmospheric sum-rule to first order in r, this allows us to express *all phenomenologically interesting* models by the constraint

$$a = a_0 \pm \sqrt{\frac{\eta}{2(1-\eta)}}\, r\cos\delta + \mathcal{O}(r^2, a^2).$$

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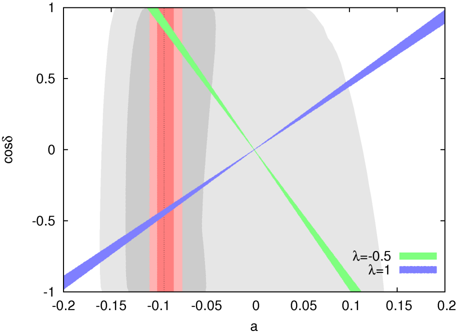
$$a = \lambda r \cos\delta + \mathcal{O}(r^2, a^2).$$

Sum-rules and current data

- The linearized sum-rule can be seen as a prediction of the model for the parameter $\cos\delta$.

$$\cos\delta = \frac{a}{\lambda r}$$

- The grey bands show the current global-fit data (NuFit 1.0 2012), whilst the pink bands show the projected sensitivity to a in 2025 with the current generation of experiments (Huber et al. 2009).



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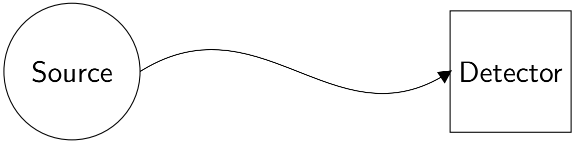
Long-baseline oscillation experiments

- Neutrino oscillation experiments all contain three elements: a source, a long distance over which to oscillate, and a very large detector.



- The source can be natural or man-made: the sun, mesons in the atmosphere, nuclear reactors *etc.*

- In our study, we have focused on two of the most promising precision next-generation experiments: superbeams and neutrino factories.

Superbeams and Neutrino Factories

- Both require very large $\mathcal{O}$(20 kton) underground detectors and long baselines $\mathcal{O}$(2000 km).
- Superbeams are more powerful versions of conventional neutrino beams, deriving their beams from meson decay. This has been shown to have a good physics reach for the mass hierarchy and measurements of δ. These could be in operation in the next 10 years.
- Neutrino factories instead study neutrinos produced from the decay of stored muons. This is technically more demanding, but offers a low background signal and has the best sensitivity to the oscillation parameters. These could be in operation in the next 20 years.

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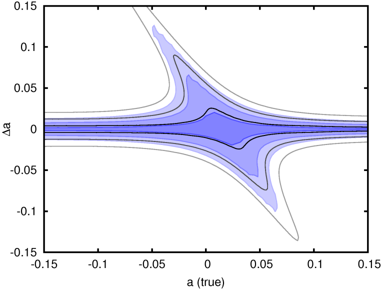
Testing atmospheric sum-rules

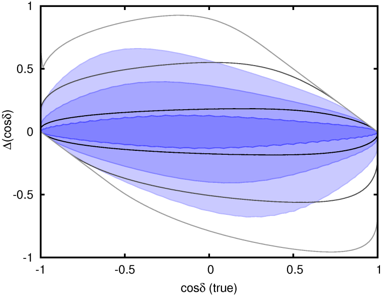
- We have simulated the measurement of sum-rules for two representative next-generation facilities, using the GLoBES package (see 0407333 and 0701187).
- A superbeam based on the LAGUNA-LBNO proposal of a beam from CERN to Pyhäsalmi (Finland). This has a baseline distance of 2300 km and a 20 kton liquid Argon detector (for more info. see CERN-SPSC-2012-021).
- We also consider a Low-Energy Neutrino Factory (LENF), similar to the International Design Study for a Neutrino Factory design. We assume a baseline of 2000 km and a stored-muon energy of 10 GeV. We use a Totally-Active Scintillator Detector (TASD) with a fiducial mass of 20 kton (see 1112.2853).

Precision in relevant parameters

- Precision on *a* at around 0.01 at 2σ at a LENF (for non-maximal θ_{23}). An improvement of about a factor of 3 on the projected values.

- The most difficult parameter to measure will be $\cos\delta$. We see that a superbeam from CERN to Pyhäsalmi has only a modest potential to constrain the parameter. However a LENF is especially good for the extremal values of $\cos\delta$.





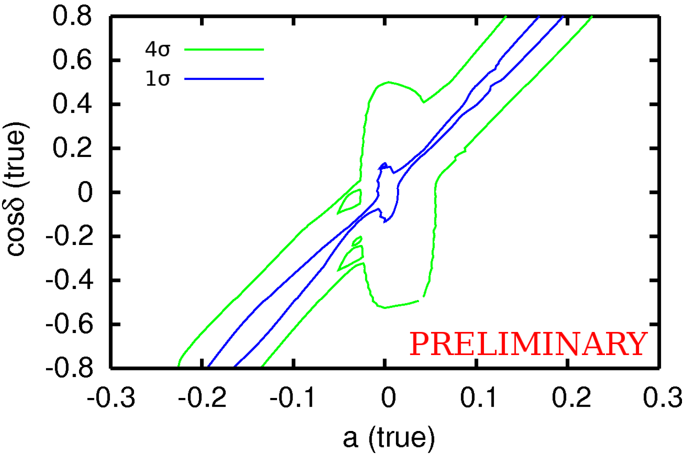
Excluding sum-rules directly

- Combining single parameter determinations (as in the previous slide) can only tell us so much about the ability to constrain parameter combinations.

- In general, parameter correlations can lead these sensitivities to change.

- We have considered all parameter sets which obey the relation $a = r\cos\delta$. We have then scanned over true values of a and $\cos\delta$ and produced pseudo-data. Then for each set of pseudo-data, we have plotted the $\Delta\chi^2$ value of the best-fitting solution obeying the sum-rule. When this becomes higher than a certain significance threshold, we can say that the sum-rule hypothesis is excluded.

Excluding sum-rules directly (cont.)



Simulation using GLoBES of the potential exclusion of $a = r\cos\delta$. This assumes a LENF with a 20kt TASD (Totally-Active Scintillator Detector), $L = 2000$ km and $E_\mu = 10$ GeV.

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- The next-generation of long-baseline experiments will make significant headway towards measuring CP violation and the mass hierarchy.
- Models with discrete flavour symmetries make predictions about the correlations amongst the parameters of the PMNS matrix. A large class of models can have these constraints expressed as atmospheric sum-rules.
- Next-generation oscillation experiments will be able to significantly constrain δ, and exclude specific atmospheric sum-rules for a large range of true parameter values. This can provide a concrete physical motivation for the search for precision.

Thank you.