Quasi-Degenerate neutrinos and Tri-Bi-Maximal mixing

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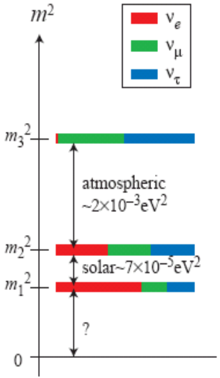
Outline

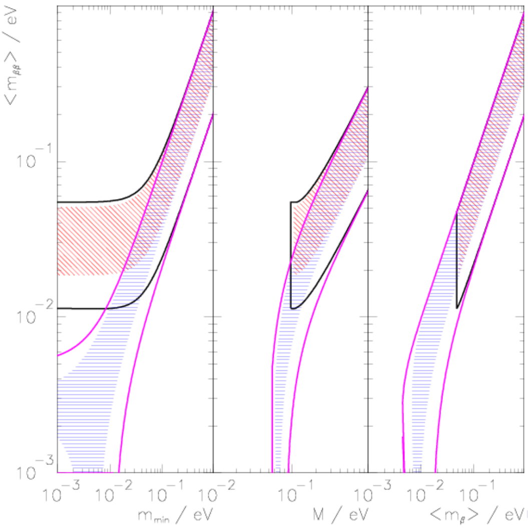
Summary of lepton mixing data

HPS / Tri-bi-maximal (TBM)

$$V_{PMNS} = \begin{pmatrix} -\sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \end{pmatrix}$$



Neutrinoless beta decay plot



Based on

arXiv 0811.2226

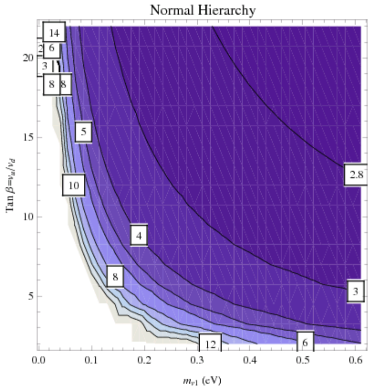
- Graham Ross (University of Oxford)
- Mario Serna (University of Oxford, now in the U.S.)

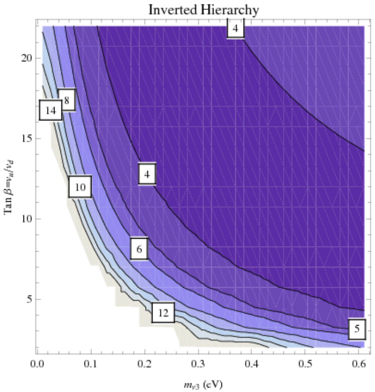
Limiting the high-energy scale

Emphasis on the energy scale

- Start at high-energy with exact TBM mixing
- Demand the low-energy angles to be viable
- Identify highest energy scales in m_ν / $\tan\beta$
- Useful for model building

Normal and Inverted Hierarchy contour plots





Family assignments

Underlying $SO(3)$ F.S.

- The familons ϕ^i_A are family triplets
- The doublet L^i is a family triplet
- e^c, μ^c, τ^c are family singlets

Desired vevs

$$\langle \phi_3 \rangle \propto (0, 0, 1)$$

$$\langle \phi_{23} \rangle \propto (0, 1, -1)$$

$$\langle \phi_{123} \rangle \propto (1, 1, 1)$$

Effective neutrino Lagrangian

Try to remember

$$\langle \phi_{23} \rangle \propto (0, 1, -1)$$

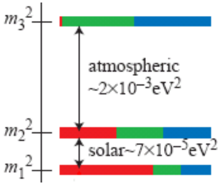
$$\langle \phi_{123} \rangle \propto (1, 1, 1)$$

Effective terms

$$W_\nu = y_0 (L^i L^i) H_u H_u$$

$$+ y_\odot (\phi^i_{123} L^i)^2 H_u H_u$$

$$+ y_@ (\phi^i_{23} L^i)^2 H_u H_u$$



Charged leptons

Charged leptons don't spoil TBM mixing

$$W_e = \lambda_e (L^i \phi^i_{123}) e^c H_d$$
$$+\lambda_\mu (L^i \phi^i_{23}) \mu^c H_d$$
$$+\lambda_\tau (L^i \phi^i_3) \tau^c H_d$$

Try to remember

Once again:

$$\langle \phi_3 \rangle \propto (0, 0, 1)$$
$$\langle \phi_{23} \rangle \propto (0, 1, -1)$$
$$\langle \phi_{123} \rangle \propto (1, 1, 1)$$

$\Delta(12)$ family symmetry

Why is it interesting?

- Small subgroup of $SO(3)_f$
- Added invariants useful for vacuum alignment
- Discrete family symmetries don't have associated D-terms

$\Delta(12)$ invariants

Transformation properties

Field (ϕ_i)	Z_2	Z_3
ϕ^1	ϕ^1	ϕ^3
ϕ^2	$-\phi^2$	ϕ^1
ϕ^3	$-\phi^3$	ϕ^2

- Allowed: all $SO(3)_f$ invariants (e.g. $L^i L^i$)
- Allowed: higher order discrete invariants (e.g. $\varphi^{i\dagger}\varphi^i\varphi^{i\dagger}\varphi^i$)

Soft radiative breaking

Continuous Breaks

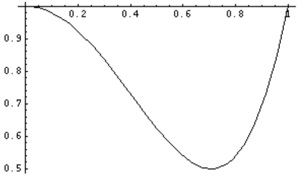
- $V_{cr} = -m^2(\varphi^i \varphi_i^\dagger)$
- Continuous symmetry, continuum of vacuum
- No specified $\langle \varphi \rangle$ direction

Soft alignment

2 generation case

- Discrete symmetry, discrete vacuum
- $V = V_{cr} \pm m^2_{3/2} (\varphi^{i\dagger} \varphi^i \varphi^{i\dagger} \varphi^i)$
- Extremise $|\varphi_1|^4 + |\varphi_2|^4$ (with set magnitude)
- + , VEV $\propto (1, 1) \rightarrow V \sim +2v^4/4$
- - , VEV $\propto (0, 1) \rightarrow V \sim -v^4$

Plot[{x^4 + (1 - x^2)^2}, {x, 0, 1}]



- Graphics -

Minimize[x^4 + (1 - x^2)^2, x]

$\{\frac{1}{2}, \{x \rightarrow \frac{1}{\sqrt{2}}\}\}$

ϕ_3 and ϕ_{123}

Quartic term minimisation

- $V = V_{cr} \pm m^2_{3/2} (\varphi^{i\dagger} \varphi^i \varphi^{i\dagger} \varphi^i)$
- For $\varphi = \phi_{123}, + \rightarrow \langle \phi_{123} \rangle \propto (1, 1, 1)$
- For $\varphi = \phi_3, - \rightarrow \langle \phi_3 \rangle \propto (0, 0, 1)$

RR: Old and New

ON

- Radiative corrections matter, particularly for QD neutrinos (Old)
- Highest energy scales that preserve hints of TBM at low scale (New)

QD: Older, Old and New

OON

- $SO(3)$ FS can give QD (Older)
- $\Delta(12)$ FS can give TBM (Old)
- $\Delta(12)$ FS can give QD TBM (New)