Flavor symmetries in the lepton sector (what changes with $\theta_{13} \neq 0$?)

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Program:

Discrete symmetries ✓

Continuous symmetries ✗

I'll try to give a general overview of virtues and problems.
Disclaimer: if your favorite model misses some problem...don't get angry, be happy!

What we know...

$$U_{PMNS} = R_{23} \; R_{13} \; R_{12} \; P_M$$

Atmospheric
$\theta_{23} \simeq 45^\circ$
maybe less??

Reactor
$\theta_{13} \simeq 9^\circ$

Solar
$\theta_{12} \simeq 35^\circ$

$$\Delta m_{12} \simeq 7.6 \times 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m_{13}| \simeq 2.4 \times 10^{-3}\ \mathrm{eV}^2$$

...and what we don't know

$$U_{PMNS} = R_{23} \; R_{13} \; R_{12} \; P_M$$

$\delta_{CP} = ?$

Majorana phases

- Absolute neutrino mass scale
- Normal or Inverted Hierarchy?
- Majorana or Dirac?

Is what we know enough

to infer

a fundamental theory?

A general observation

BASIS: when $m_{leptons}$ = diagonal:

- $\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry in ν sector
- $\mathbb{Z}_N$ symmetry in charged lepton sector

$\longrightarrow$ We want a larger symmetry broken down to these residual symmetries

The flavor symmetry program

- Choose a PMNS matrix (compatible with data)
- Infer $\mathbb{Z}_2 \times \mathbb{Z}_2$ generators (S,U), choose "N" of $\mathbb{Z}_N$, infer its generator (T)
- Construct the irreps of the group generated by $\langle S, U, T \rangle$
- Choose representations for matter fields (usually $L = \mathbf{3}$)

- Flavor symmetry breaking sector:

$$G \xrightarrow{\phi_{S,U}} G_{S,U}$$
$$G \xrightarrow{\phi_T} G_T$$

- Make sure that the vacuum alignment can be obtained in a reasonable way by minimizing a suitable potential for the flavons

Issues

- Usually masses fitted, not predicted
- Usually, additional symmetries needed to keep lepton and neutrino sector separated
- Usually, vacuum alignment requires additional fields to work
- Effective theory:

  $\rightarrow$ next-order terms play an important role, but <u>much more</u> parameters introduced in the theory

  $\rightarrow$ loss of the (already partial) predictivity

Two attitudes:

- Obtain from the very beginning a sizable θ_{13}
- After all, θ_{13} (quite?) small $\rightarrow$ maybe a correction to a simpler pattern?

A well known example

TBM Ansatz

$$s_{12} = \frac{1}{\sqrt{3}} \qquad \theta_{13} = 0 \qquad s_{23} = \frac{1}{\sqrt{2}}$$

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

Harrison, Perkins, Scott (2002)

The symmetry group zoo

A (partial) list:

A_4, S_4 ,$\mathbb{Z}_7 \rtimes \mathbb{Z}_3$, $\Delta(27)$, $\Delta(96)$, $\mathrm{PSL}_2(7)$

...

Common features:

- At leading order, TMB mixing
- At next-order, deviations from TBM

$A_4 \times \mathbb{Z}_3 \times U(1)_{FN}$ model by Altarelli-Feruglio

[hep-ph/0504165, hep-ph/0512103, ...]

$\theta_{13} = 0$ at leading order;
$\theta_{13} \neq 0$ at next-to-leading order, dependence on:

- neutrino masses
- 4 additional parameters coming from correction to neutrino mass matrix and vacuum alignment

Corrections expected also to the other angles, with dependence on a (partially) different list of parameters...

Not so difficult to have a sizable θ_{13} and (relatively) small corrections to θ_{12}, θ_{23} playing with parameters (although one would expect corrections of the same order)

Do we give up?

Of course not. Two possible solutions:

- we try to align the corrections into a specific direction (*i.e.* to enhance θ_{13}): DONE
- we try to obtain from the very beginning sizable θ_{13}: DONE

A suitable group to obtain $\theta_{13} \simeq \mathcal{O}(\lambda_c)$:

$$A_4 \times \mathbb{Z}_3 \times \mathbb{Z}_4$$

see Lin, 2009

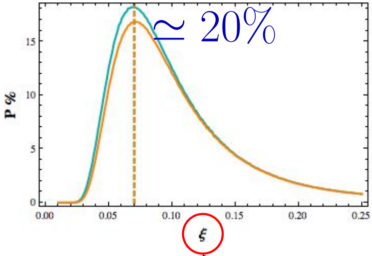
What changes?

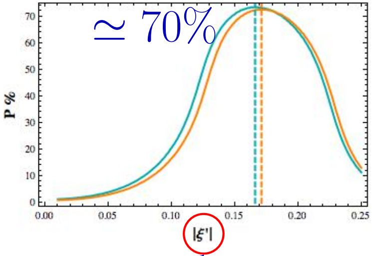
- vacuum alignment
- additional $\mathbb{Z}_4$ guarantees separation between neutrino and charged lepton sector also at NLO

Comparison

Altarelli-Feruglio-Merlo-Stamou, 1205.4670

typical A_4 "aligned" A_4





size
typical
corrections

(No) Conclusions

- After 10 years of effort, still a long way to go
- On the one hand, many symm groups suitable for description of neutrino physics: indication that we are on a correct way?
- On the other hand, extremely flexible, difficult to use data to discriminate
- Also simplest possibilities are not so simple, need for additional ingredients...