Neutrinos and Symmetries

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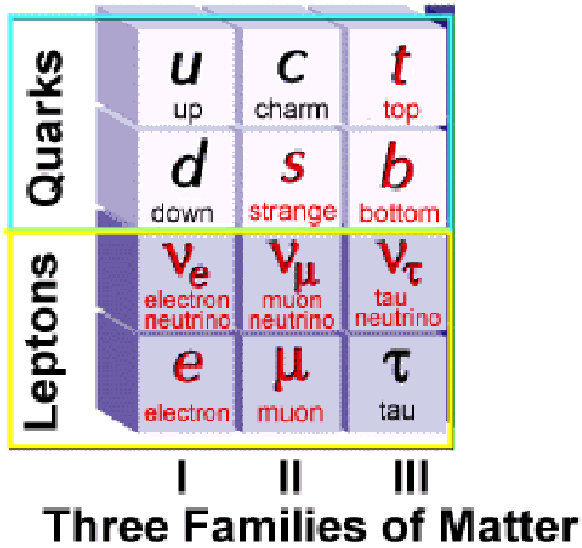
Flavor symmetry: reasons from experiment

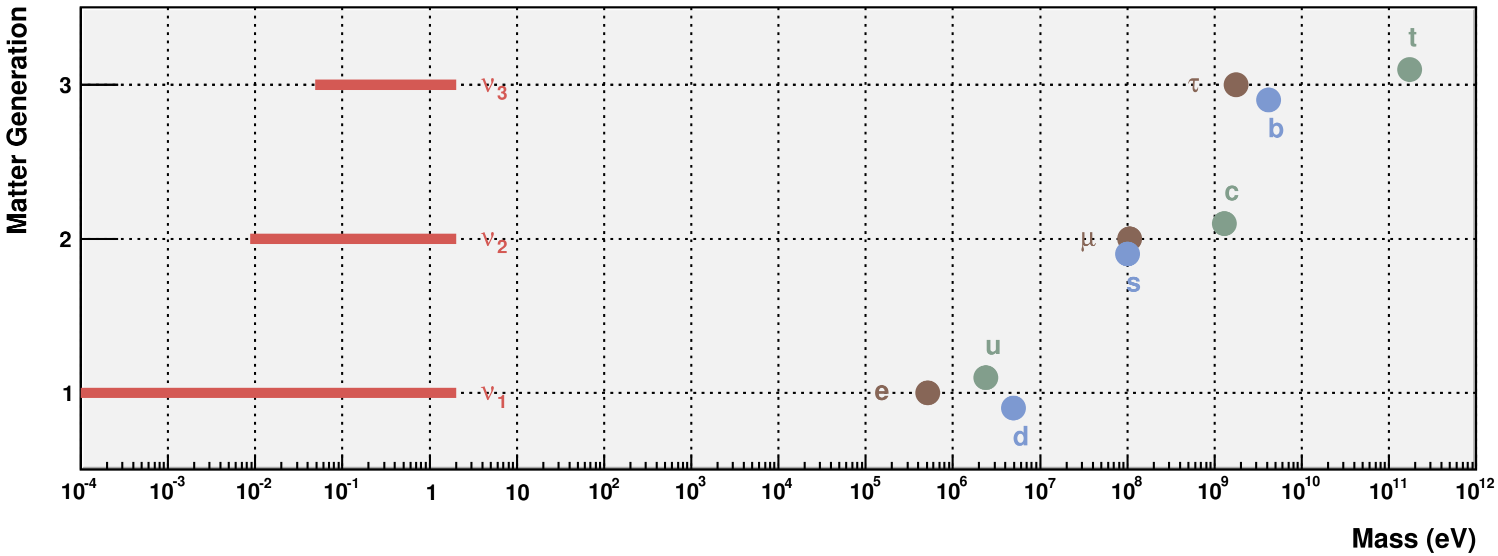
- observation of three generations of elementary particles



non-abelian flavor symmetry as reason for three generations

Flavor symmetry: reasons from experiment

- observation of three generations of elementary particles
- strong mass hierarchy among charged fermions



log scale

Froggatt-Nielsen symmetry $U(1)_{FN}$ parametrizes mass hierarchy

Flavor symmetry: reasons from experiment

- observation of three generations of elementary particles
- strong mass hierarchy among charged fermions
- solar (much) smaller than atmospheric mass splitting

$$\frac{\Delta m^2_{21}}{\Delta m^2_{31}} \approx 0.03 \ \ [\mathrm{NO}]$$

(NuFIT ('18))

$SO(2)$ can explain partially degenerate neutrino masses

(Hernandez/Smirnov ('13))

Flavor symmetry: reasons from experiment

- observation of three generations of elementary particles
- strong mass hierarchy among charged fermions
- solar (much) smaller than atmospheric mass splitting
- very different mixing among quarks and leptons

$$||V_{CKM}|| = \begin{pmatrix} 0.97 & 0.23 & 3.6 \cdot 10^{-3} \\ 0.22 & 0.97 & 0.041 \\ 8.8 \cdot 10^{-3} & 0.040 & 0.999 \end{pmatrix}$$

(PDG ('17 update))

[NO]

$$||U_{PMNS}|| = \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.33 & 0.60 & 0.73 \\ 0.46 & 0.58 & 0.67 \end{pmatrix}$$

(NuFIT ('18))

different (residual) flavor symmetries for quarks and leptons

Flavor symmetry: reasons from experiment

- observation of three generations of elementary particles
- strong mass hierarchy among charged fermions
- solar (much) smaller than atmospheric mass splitting
- very different mixing among quarks and leptons
- $\theta_{13} \ll \theta_{12}, \theta_{23}$ in the lepton sector

$$\sin^2\theta_{13} = 0.02206\ , \quad \sin^2\theta_{12} = 0.307\ , \quad \sin^2\theta_{23} = 0.538 \quad [\mathrm{NO}]$$

(NuFIT ('18))

certain values of θ_{ij} from discrete flavor symmetries
well-known: tri-bi-maximal mixing *(Harrison et al. ('02), Xing ('02))*

Flavor symmetry: reasons from experiment

- observation of three generations of elementary particles
- strong mass hierarchy among charged fermions
- solar (much) smaller than atmospheric mass splitting
- very different mixing among quarks and leptons
- $\theta_{13} \ll \theta_{12},\, \theta_{23}$ in the lepton sector
- non-observation of e.g. charged lepton flavor violation

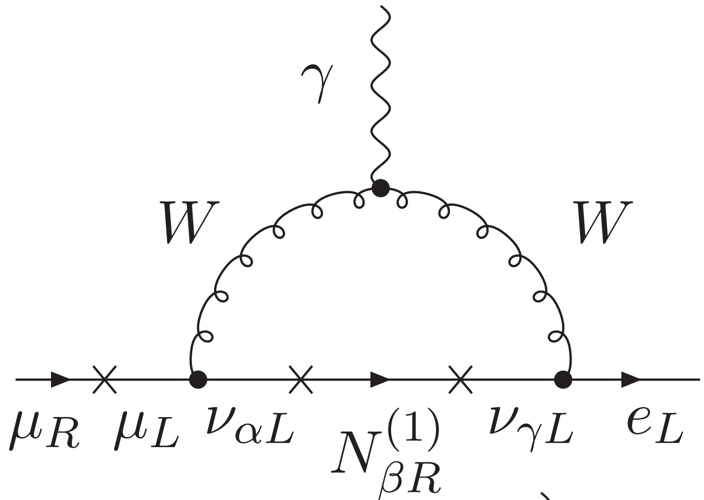
$$\mathrm{BR}\left(\mu^+ \to e^+\gamma\right) < 2.55 \times 10^{-13}$$

(MEG ('16))

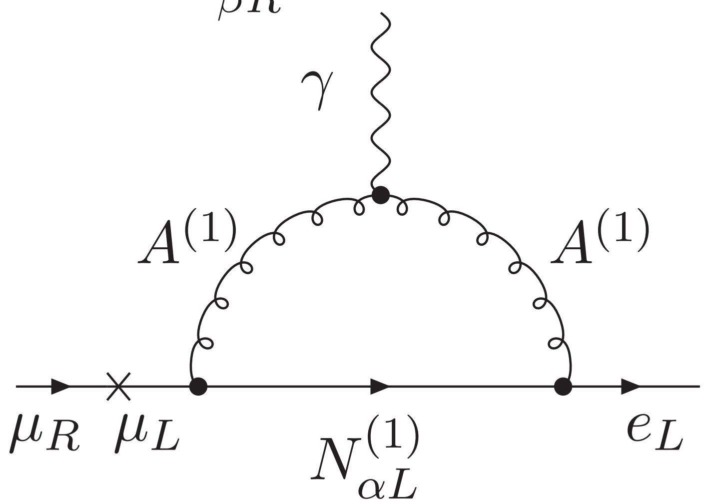
protection of flavor sector in BSM theories needed

Flavor symmetry: reasons from experiment

KK excitation in loop

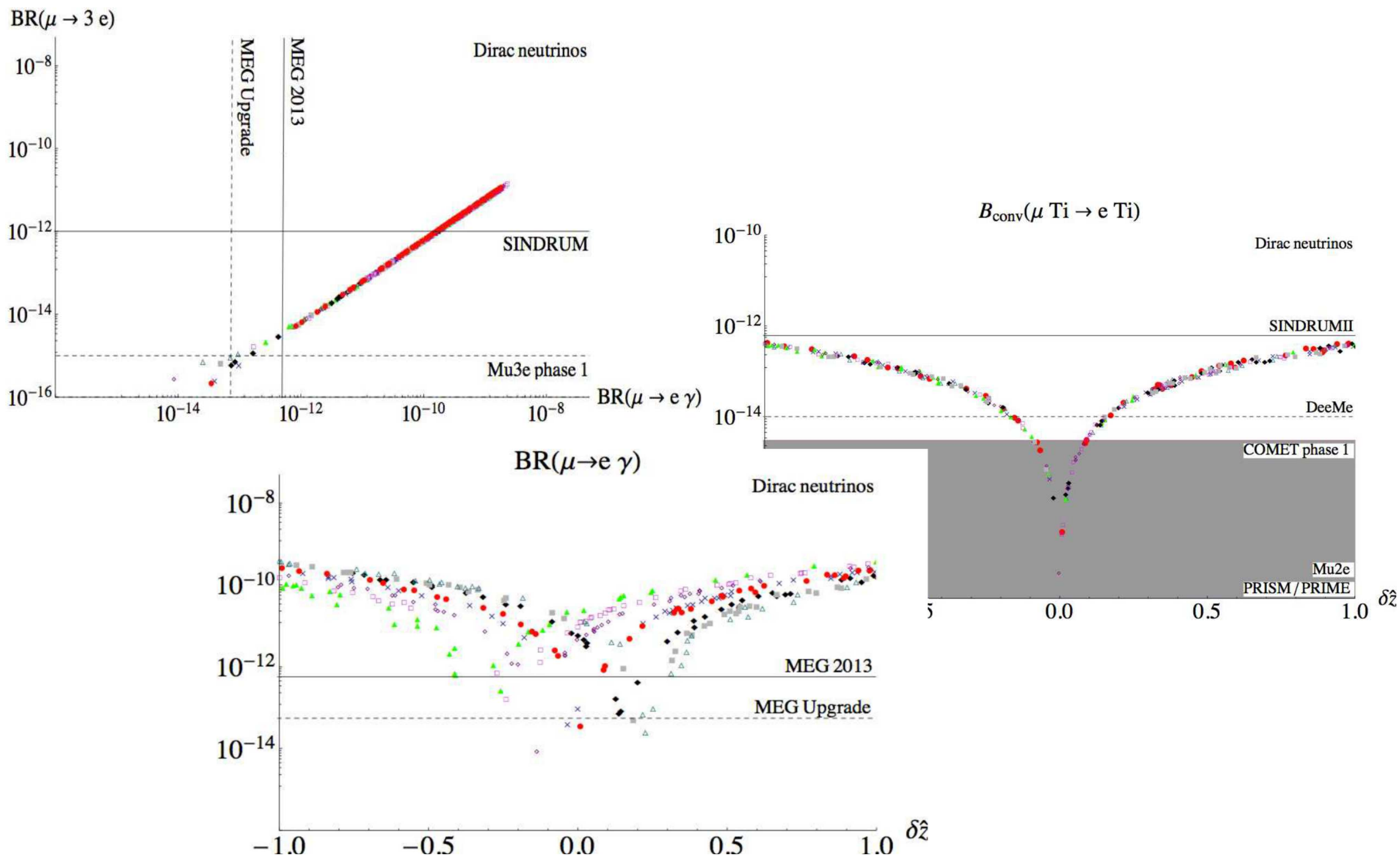


Exotic gauge boson in loop



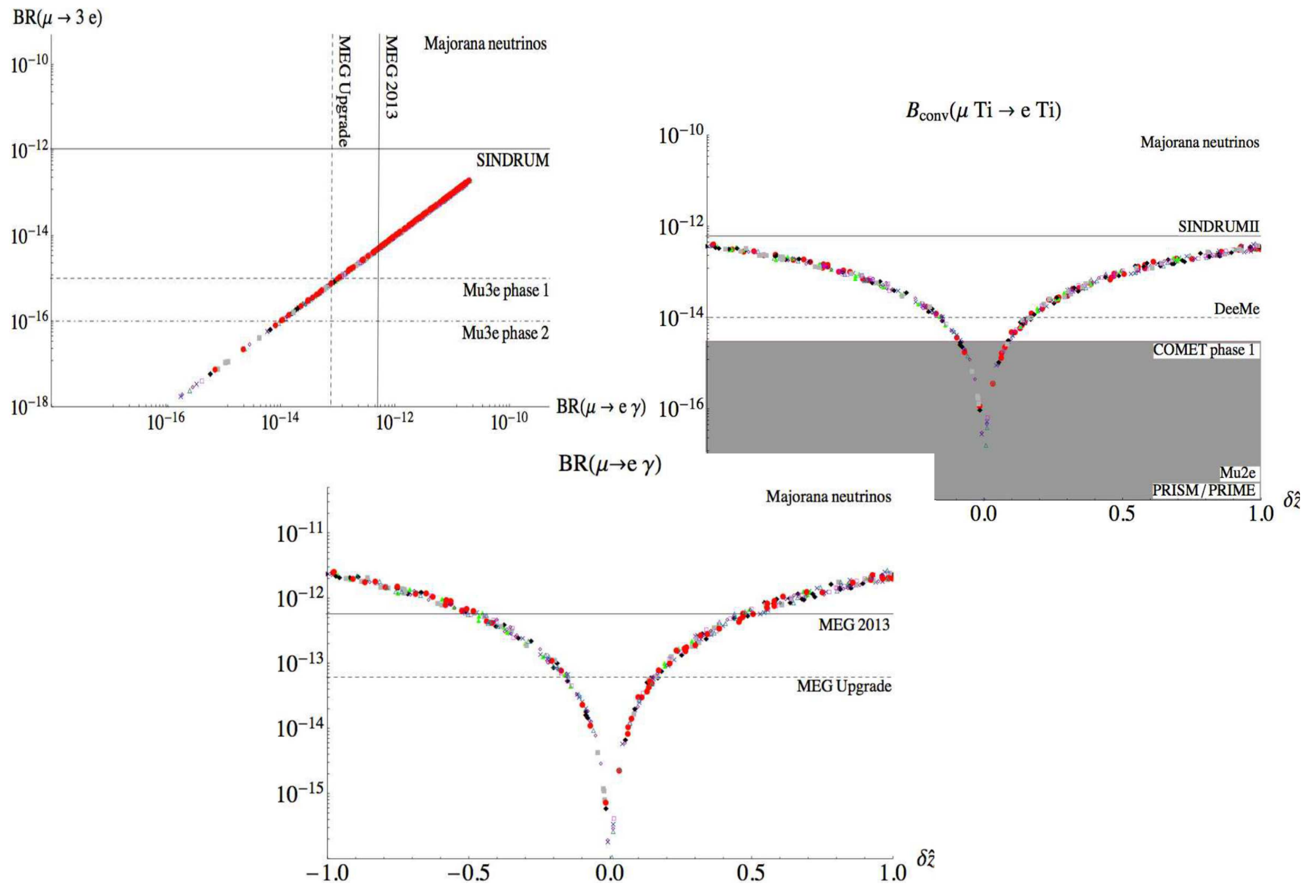
Flavor symmetry: reasons from experiment

$\delta\hat{z}$ parametrizes boundary kinetic terms *(H/Serone ('11))*



Flavor symmetry: reasons from experiment

$\delta\hat{z}$ parametrizes boundary kinetic terms ***(H/Serone ('11))***



Flavor symmetry: guesses from experiment

- relation between strong quark mass hierarchy and small quark mixing?

$$|V_{us}| = |V_{cd}| = \sqrt{\frac{m_d}{m_s}}$$

(Gatto/Sartori/Tonin ('68))

Flavor symmetry: guesses from experiment

- relation between strong quark mass hierarchy and small quark mixing?
- relation between origin of neutrino masses and large lepton mixing? Possibly mass hierarchy?
  Majorana nature of neutrinos

Flavor symmetry: guesses from experiment

- relation between strong quark mass hierarchy and small quark mixing?
- relation between origin of neutrino masses and large lepton mixing? Possibly mass hierarchy?
- maximal atmospheric mixing, $\theta_{23} = \frac{\pi}{4}$?

$$\sin^2\theta_{23} = 0.538^{+0.033}_{-0.069} \;\; [\mathrm{NO}]$$

(NuFIT ('18))

discrete flavor symmetries usually predict certain value of θ_{23}

Flavor symmetry: guesses from experiment

- relation between strong quark mass hierarchy and small quark mixing?
- relation between origin of neutrino masses and large lepton mixing? Possibly mass hierarchy?
- maximal atmospheric mixing, $\theta_{23} = \frac{\pi}{4}$?
- maximal CP violation in neutrino oscillations, $\delta = 90^\circ$ or $\delta = 270^\circ$?

$$\delta = \left(234^{+43}_{-31}\right)^\circ \quad [\mathrm{NO}]$$

(NuFIT ('18))

flavor and CP symmetries combined predict non-trivial δ
$\mu - \tau$ exchange symmetry which predicts θ_{23} and δ maximal

(Harrison/Scott ('02,'04), Grimus/Lavoura ('03))

Flavor symmetry: guesses from experiment

- relation between strong quark mass hierarchy and small quark mixing?
- relation between origin of neutrino masses and large lepton mixing? Possibly mass hierarchy?
- maximal atmospheric mixing, $\theta_{23} = \frac{\pi}{4}$?
- maximal CP violation in neutrino oscillations?
- correlation among lepton mixing angles?

  e.g. *(Di Iura/H/Meloni ('15), Li/Ding ('15), Ballett/Pascoli/Turner ('15))*

  flavor and CP symmetries combined can lead to sum rules

$$\sin^2\theta_{12} = \frac{\sin^2\varphi}{1-\sin^2\theta_{13}} \approx \frac{0.276}{1-\sin^2\theta_{13}} \gtrsim 0.276$$

$$\sin^2\theta_{23} \approx \frac{1}{2}\left(1 \pm (1-\sqrt{5})\,\sin\theta_{13}\right) \approx 0.5 \mp 0.618\,\sin\theta_{13} \approx \begin{cases} 0.409 \\ 0.591 \end{cases}$$

Flavor symmetry: guesses from experiment

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- relation between origin of neutrino masses and large lepton mixing? Possibly mass hierarchy?
- maximal atmospheric mixing, $\theta_{23} = \frac{\pi}{4}$?
- maximal CP violation in neutrino oscillations?
- correlation among lepton mixing angles?
  e.g.
  complementarity between mixing angles has been proposed

$$\theta_{13} + \theta_{12} \approx 45^\circ \text{ or } \theta_{23}$$

(Zhang/Ma ('12), Zheng/Ma ('12))

Flavor symmetry: guesses from experiment

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- relation between origin of neutrino masses and large lepton mixing? Possibly mass hierarchy?
- maximal atmospheric mixing, $\theta_{23} = \frac{\pi}{4}$?
- maximal CP violation in neutrino oscillations?
- correlation among lepton mixing angles?
- complementarity between lepton and quark mixing angles?

$$\theta^q_{12} + \theta_{12} \approx 45^\circ \quad \text{and} \quad \theta^q_{23} + \theta_{23} \approx 45^\circ$$

(Minakata/Smirnov ('04), Raidal ('04), ...)

points towards (grand) unified theory where
charged leptons have mixing like down-type quarks and
neutrinos a certain mixing pattern e.g. ***Antusch/King/Mohapatra ('05)***

Flavor symmetry: guesses from experiment

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- complementarity between lepton and quark mixing angles?
- correlation between low and high energy CP violation?

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Flavor symmetry: guesses from experiment

- correlation between low and high energy CP violation?
  can we correlate low energy CP phases δ, α, β and baryon asymmetry of the Universe?
  yes, if leptogenesis is responsible for baryon asymmetry
  several interesting studies in the literature
  e.g.

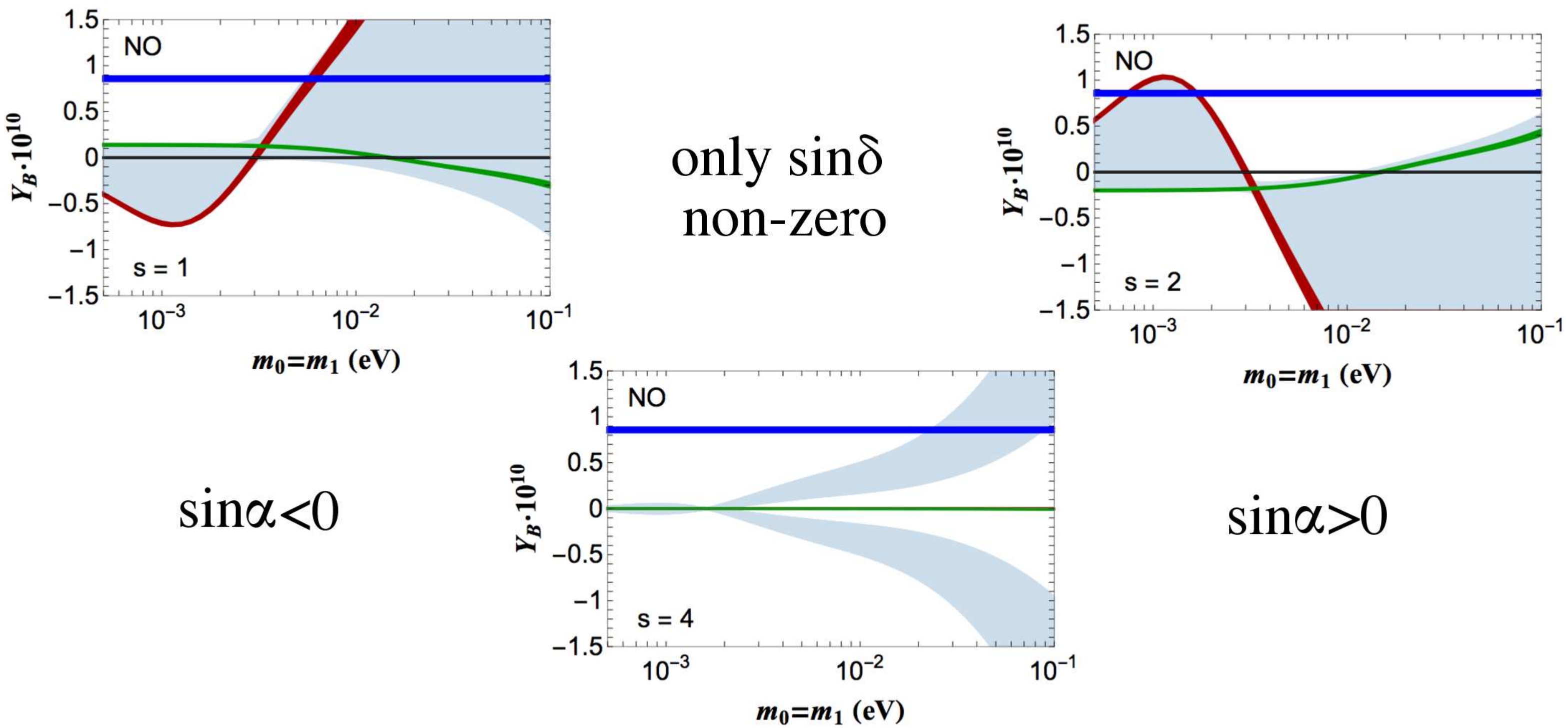
$$|\sin\delta\,\sin\theta_{13}| \gtrsim 0.11$$

  if only δ non-trivial and flavor effects relevant

(Pascoli/Petcov/Riotto ('06))

Flavor symmetry: guesses from experiment

- correlation between low and high energy CP violation? unflavored leptogenesis in scenario with flavor and CP symmetries



(H/Molinaro ('16))

Flavor symmetry: future experiment

- (nearly) massless lightest neutrino?
  protection of lightest neutrino mass from symmetry,
  e.g. Majorana neutrinos and Z_N symmetry with $N > 2$

(Joshipura/Patel ('14))

Flavor symmetry: future experiment

- (nearly) massless lightest neutrino?
  “economic" approach (Occam’s razor):
  type I seesaw with only two right-handed neutrinos

  e.g. ***Harigaya/Ibe/Yanagida (’12)***

Flavor symmetry: future experiment

- (nearly) massless lightest neutrino?
- quasi-degenerate neutrino masses?
  underlying symmetry $[S]O(3)$

(Hernandez/Smirnov ('13), Alonso et al. ('13))

Flavor symmetry: future experiment

- (nearly) massless lightest neutrino?
- quasi-degenerate neutrino masses?
- correlations among lepton mixing angles and CP phase δ?
  e.g.
  certain mixing for neutrinos and certain correction from charged leptons

$U_{PMNS} = U_e^\dagger \, \Psi \, U_\nu(\theta_{12}^\nu)$ with $U_e = R_{23}(\theta_{23}^e) \, R_{12}(\theta_{12}^e)$ and Ψ phases

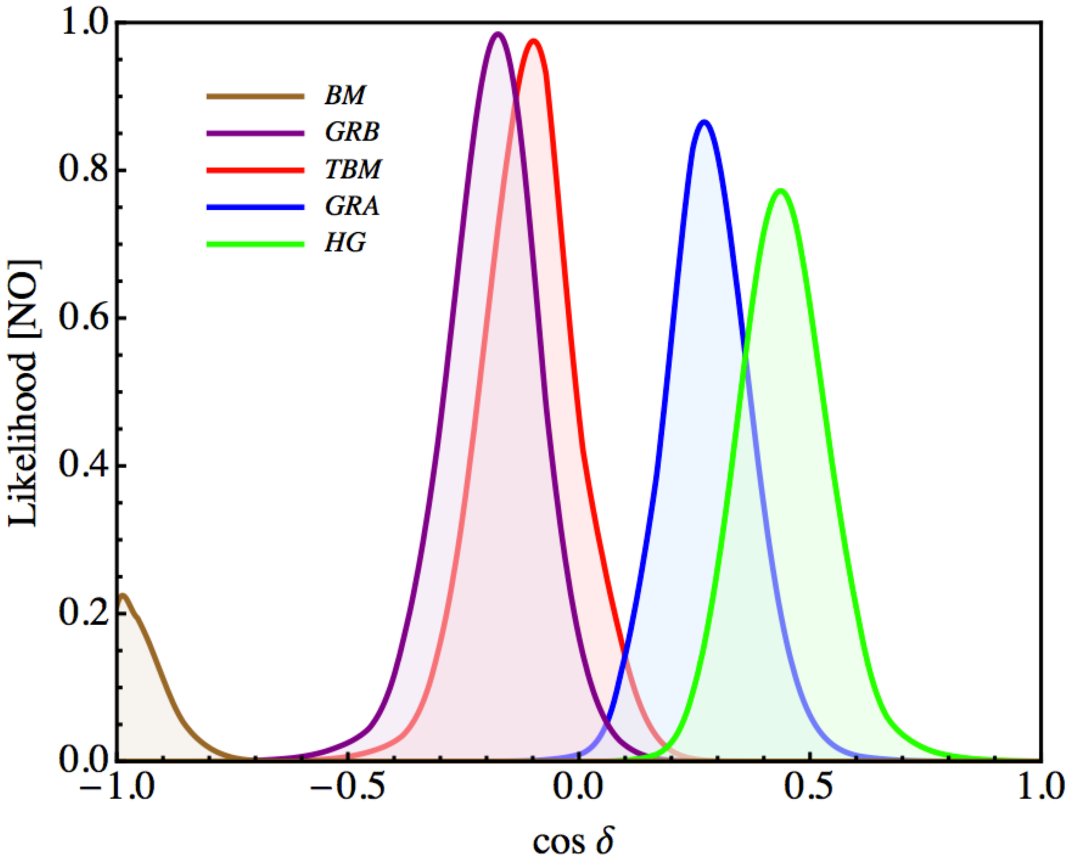
which leads to

$$\cos\delta = \frac{\tan\theta_{23}\sin^2\theta_{12} + \frac{\sin^2\theta_{13}\cos^2\theta_{12}}{\tan\theta_{23}} - \sin^2\theta_{12}^\nu \left(\tan\theta_{23} + \frac{\sin^2\theta_{13}}{\tan\theta_{23}}\right)}{\sin 2\theta_{12}\sin\theta_{13}}$$

(Petcov ('14), Ballett et al. ('14), Girardi et al. ('14))

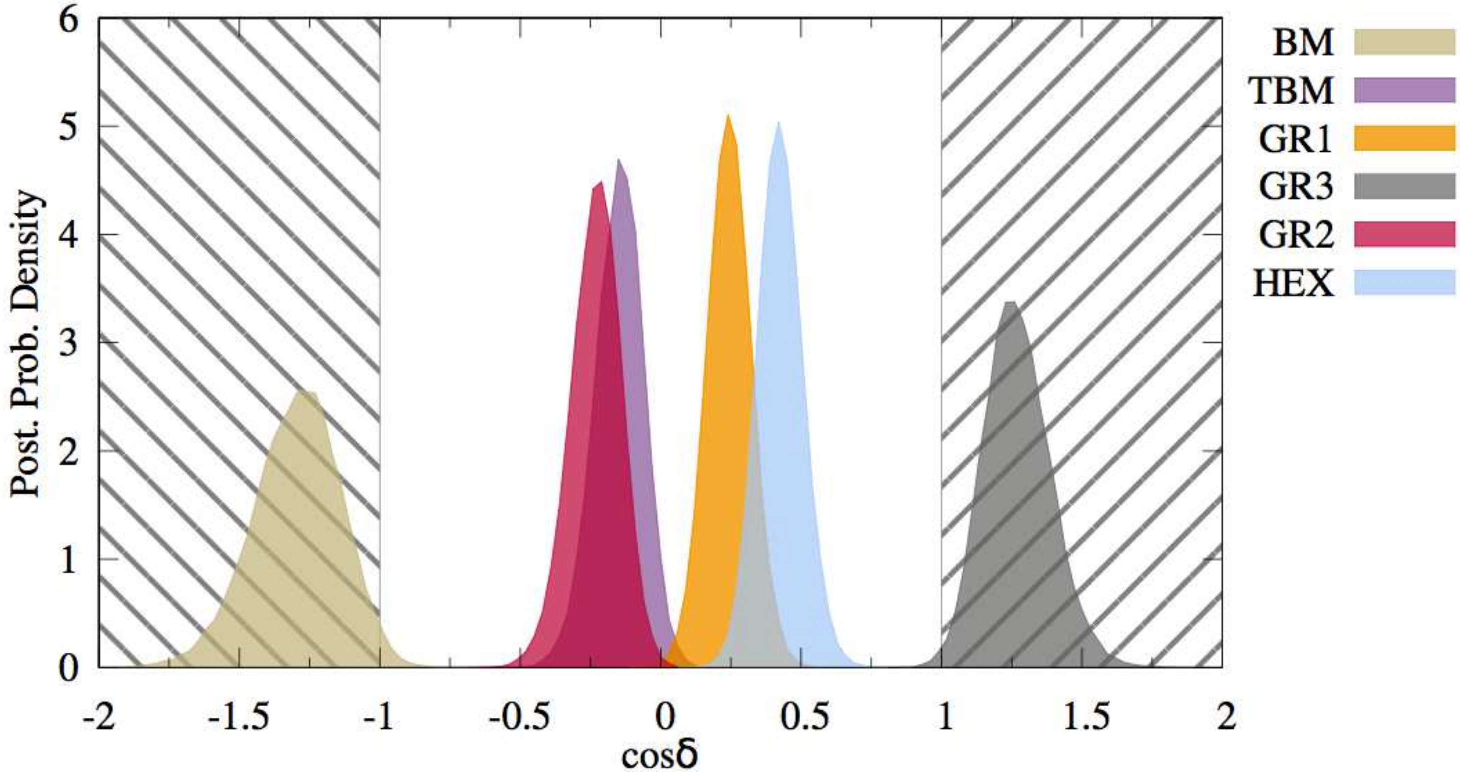
Flavor symmetry: future experiment

(Girardi et al. ('14))



Flavor symmetry: future experiment

(Ballett et al. ('14))



Flavor symmetry: future experiment

- correlations among lepton mixing angles and CP phase δ?
  flavor and CP symmetries combined predict mixing patterns with only one real free parameter
  example:
  adjusting mixing angles to experimental data leads to

$$|\sin\delta| \gtrsim 0.71$$

and both Majorana phases α, β depend on CP symmetry $X(s)$ only

$$|\sin\alpha| = |\sin\beta| = |\sin 6\,\phi_s| \quad \text{with} \quad \phi_s = \frac{\pi s}{n} \quad \text{and} \quad s = 0, ..., n-1$$

(H/Meroni/Molinaro ('14))

Flavor symmetry: future experiment

(H/Meroni/Molinaro ('14))

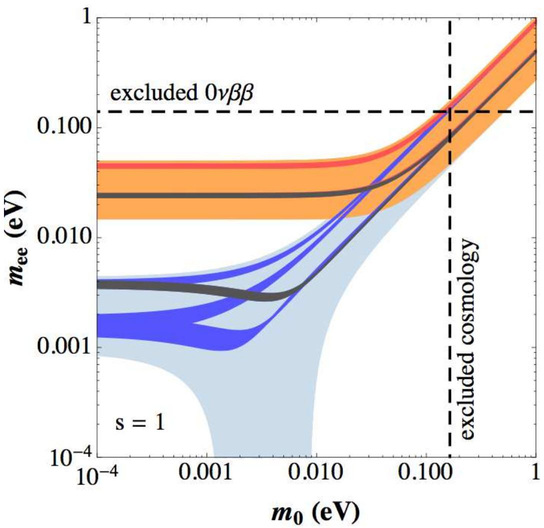
s	$\sin^2\theta_{13}$	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin\delta$	$\sin\alpha = \sin\beta$
$s=1$	0.0220	0.318	0.579	0.936	$-1/\sqrt{2}$
	0.0220	0.318	0.421	-0.936	$-1/\sqrt{2}$
$s=2$	0.0216	0.319	0.645	-0.739	1
$s=4$	0.0220	0.318	0.5	∓ 1	0

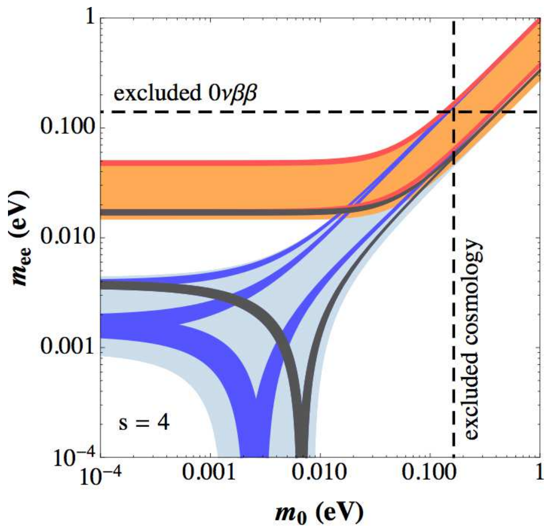
Flavor symmetry: future experiment

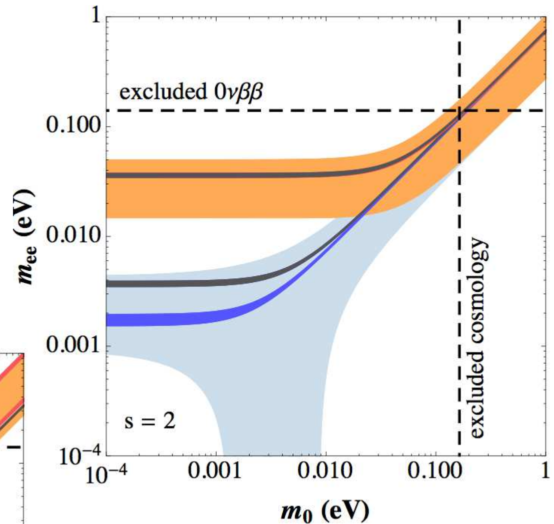
- (nearly) massless lightest neutrino?
- quasi-degenerate neutrino masses?
- correlations among lepton mixing angles and CP phase δ?
- Majorana phases from neutrinoless double beta decay?
  e.g. flavor and CP symmetries combined can predict them

Flavor symmetry: future experiment

(H/Molinaro ('16))







Flavor symmetry: future experiment

- (nearly) massless lightest neutrino?
- quasi-degenerate neutrino masses?
- correlations among lepton mixing angles and CP phase δ?
- Majorana phases from neutrinoless double beta decay?
  caveats:
  only one combination of phases can be determined,
  maybe unlucky to suffer from cancellation,
  there might well be more than one mechanism

Flavor symmetry: future experiment

- (nearly) massless lightest neutrino?
- quasi-degenerate neutrino masses?
- correlations among lepton mixing angles and CP phase δ?
- Majorana phases from neutrinoless double beta decay?
- lepton number violation at LHC?

Flavor symmetry: future experiment

- (nearly) massless lightest neutrino?
- quasi-degenerate neutrino masses?
- correlations among lepton mixing angles and CP phase δ?
- Majorana phases from neutrinoless double beta decay?
- lepton number violation at LHC?
- possibility to rule out classes of theories?

Flavor symmetry: reasons from theory

- symmetries are an efficient tool for reducing number of free parameters

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Flavor symmetry: reasons from theory

- symmetries are an efficient tool for reducing number of free parameters
- symmetries have proven very useful to describe gauge interactions
- symmetries can protect certain features
- possibility to combine gauge and flavor symmetry in more fundamental theory?
- in BSM theories new particles also carry flavor
  e.g. supersymmetric theories, extra-dimensional theories with fermions in the bulk, extended dark sector

Flavor symmetry: scope?

- understanding of features of leptons and/or quarks?
  lepton mixing seems to prefer unification of generations in $\mathbf{3}$
  quarks seem to prefer to decouple third generation: $\mathbf{2}+\mathbf{1}$

Flavor symmetry: scope?

- understanding of features of leptons and/or quarks?
  refining questions:
  are leptons and quarks governed by the same flavor symmetry?
  if not, what about grand unification?

Flavor symmetry: scope?

- understanding of features of leptons and/or quarks?
- understanding of masses and/or mixing patterns?
  often uncorrelated for leptons
  charged lepton mass hierarchy from Froggatt-Nielsen symmetry
  lepton mixing from discrete non-abelian symmetry

Flavor symmetry: scope?

- understanding of features of leptons and/or quarks?
- understanding of masses and/or mixing patterns?
- what shall the symmetry describe at all?
  current best fit values for lepton mixing angles?
  or “simple" mixing pattern at leading order like
  tri-bi-maximal mixing?

Flavor symmetry: scope?

- understanding of features of leptons and/or quarks?
- understanding of masses and/or mixing patterns?
- what shall the symmetry describe at all?
  actually, this question entails further ones like:
  at which scale shall the symmetry predict masses and mixing parameters?
  what corrects “simple" mixing pattern?
  and how model-dependent are such corrections?

Flavor symmetry: choice

- non-abelian vs abelian
  $SU(3)$, discrete subgroups of $SU(3)$ vs Z_N, $U(1)$

Flavor symmetry: choice

- non-abelian vs abelian
  or in other words: mixing vs masses
  or in other words: predicted values vs orders of magnitude

Flavor symmetry: choice

- non-abelian vs abelian
- continuous vs discrete
  $SU(3)$ vs discrete subgroups of $SU(3)$

Flavor symmetry: choice

- non-abelian vs abelian
- continuous vs discrete
  or in other words: a few vs many symmetries
  or in other words: gross structures vs predicted values

Flavor symmetry: choice

- non-abelian vs abelian
- continuous vs discrete
  - if continuous, should it be gauged?
  - if discrete, what about gauging it?

Flavor symmetry: choice

- non-abelian vs abelian
- continuous vs discrete
- choice of residual symmetries
  are there any?

Features of models: choice

- framework
  - supersymmetric or not
  - with extra dimension or not/composite theories
  - grand unified theories
  - string theory

Features of models: choice

- framework
- flavor symmetry breaking
  - spontaneous
    - with which type of fields?
    - at which scale?
    - to residual symmetries?
  - soft (arbitrary?)
  - explicit (arbitrary?)

Features of models: choice

- framework
- flavor symmetry breaking
- neutrino masses
  - Dirac vs Majorana
  - tree level vs loop level

these choices also influence choice of flavor symmetry

Challenges

- uniqueness of flavor symmetry?
  - many symmetries lead to very similar results
  - how to find the “correct" symmetry?

Challenges

- uniqueness of flavor symmetry?
  - many symmetries lead to very similar results
  - how to find the “correct" symmetry?
    - be “economical" and use smallest symmetry ? there are very many models with A_4 or S_4 as flavor symmetry

Challenges

- uniqueness of flavor symmetry?
  - many symmetries lead to very similar results
  - how to find the “correct" symmetry?
    - be “economical" and use smallest symmetry ?
    - use further input on symmetries from theory?
      - gauge (discrete/continuous) flavor symmetry

        e.g. ***Araki et al. (’08)***
      - try to derive flavor symmetry

        e.g. ***Altarelli/Feruglio (’06)***

Challenges

- uniqueness of flavor symmetry?
  - many symmetries lead to very similar results
  - how to find the “correct" symmetry?
    - be “economical" and use smallest symmetry ?
    - use further input on symmetries from theory?
    - shall we rely on further data (in BSM theory)?
      - suppression of charged lepton flavor violation

        e.g. ***Antusch/King/Malinsky, Feruglio et al. (’08)***
      - include Dark Matter, when choosing flavor symmetry

        e.g. ***Hirsch et al. (’10)***

Challenges

- uniqueness of flavor symmetry?
- corrections
  - do always exist, are always model-dependent
  - enter usually in several places:
    corrections to vacuum alignment, mixing of symmetry breaking sectors, ...
  - might be highly relevant and/or need to be strongly suppressed
  - arise from RG running and can be large

Challenges

- uniqueness of flavor symmetry?
- corrections
- “technical" problems, like vacuum alignment

Arguments against flavor symmetry

- fermion masses are stable under quantum corrections

Arguments against flavor symmetry

- fermion masses are stable under quantum corrections
- no clear pattern visible:
  is θ_{13} really much smaller than $\theta_{12,23}$ in the lepton sector?
  (semi-)anarchy for neutrinos OK

  (Buchmüller/Domcke/Schmitz ('11), de Gouvea/Murayama ('12), Ding/Morisi/Valle ('12), Altarelli et al. ('12), Bergström/Meloni/Merlo ('14), Brdar/König/Kopp ('15), ...)

Arguments against flavor symmetry

- fermion masses are stable under quantum corrections
- no clear pattern visible
- we only have few data:
  fermion masses, mixing angles, two CP phases

Arguments against flavor symmetry

- fermion masses are stable under quantum corrections
- no clear pattern visible
- we only have few data
- interpretation of data is too difficult:
  hard to decide what indicates symmetry, what not

Arguments against flavor symmetry

- fermion masses are stable under quantum corrections
- no clear pattern visible
- we only have few data
- interpretation of data is too difficult
- CP phase in quark sector is large, no good explanation yet
  one reason: all quark mixing angles are small
  for recent attempt see ***Li/Lu/Ding ('17)***

Arguments against flavor symmetry

- fermion masses are stable under quantum corrections
- no clear pattern visible
- we only have few data
- interpretation of data is too difficult
- CP phase in quark sector is large, no good explanation yet
- models are sophisticated, yet incomplete

What happens, if something new shows up?

- confirmation of light sterile neutrino?

  e.g. ***Merle/Morisi/Winter ('14)***

- NSIs found?

  e.g. ***Wang/Zhou ('18)***

- charged lepton flavor violation detected?

  for $h \to \mu\tau$ e.g. ***Heeck et al. ('14)***

- a new particle directly detected?

In the end
something beyond flavor symmetry

- can one get correct lepton mixing from RG flow?

(Casas/Espinosa/Ibarra/Navarro ('99), Chankowski/Krolikowski/Pokorski ('00), Feruglio ('16))

- could asymptotically safe theories be the solution?

first steps, see *Pelaggi et al. ('17)*

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- could asymptotically safe theories be the solution?

first steps, see ***Pelaggi et al. ('17)***

I hope this presentation triggers some discussion.

Thank you for your attention.