Theory Perspective on Flavour

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Flavour problem

flavour sector of the SM
[minimally extended to include
massive Majorana neutrinos]

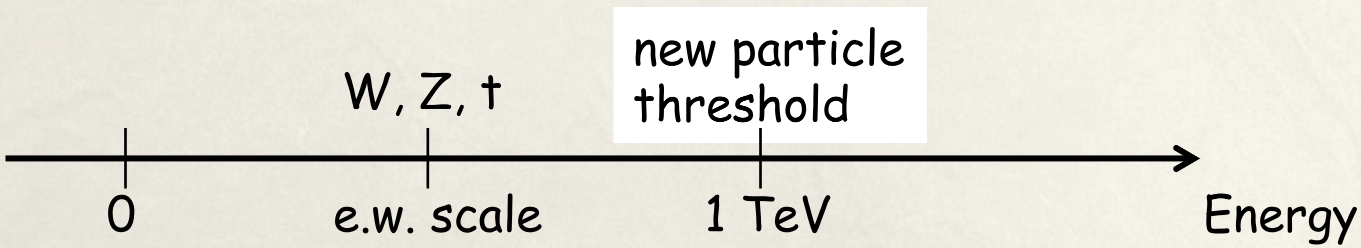
↔

22 parameters: $\mathcal{Y}$
18 measured
(+ 1 mass + 3 phases)

two aspects

1 origin of $\mathcal{Y}$

2



how to avoid large FCNC and CPV induced by the new particles?

less urgent? no evidence for a new threshold so far

this talk: main focus on 1, but also comments on 2

not a systematic review of models, rather a reappraisal of few well-known ideas as an introduction to the presentations of this Workshop

approaches

fundamental theory

[symmetry and/or dynamical principle]

$\mathcal{Y}$

1 $\mathcal{Y}$ should be deduced from first principles

most striking fact: nothing approaching a standard theory of $\mathcal{Y}$, despite decades of experimental progress and theoretical efforts

2 $\mathcal{Y}$ are due to chance

many variants
bottom-up: anarchy, FN models, fermions in ED, partial compositness
top-down: fundamental theory with a landscape of ground states

observed $\mathcal{Y}$ are environmental and cannot be fully predicted ⟷ relative sizes of solar planetary orbits

assumptions

knowledge of statistical distribution of $\mathcal{Y}$ in the fundamental theory

the observed $\mathcal{Y}$ are typical

[any anthropic selection?]

relevant questions

how typical are the $\mathcal{Y}$ we observe?

which is the statistical distribution of $\mathcal{Y}$ in the fundamental theory?

the quark sector

any empirical evidence for G_f from the quark sector?

G_f = $U(1)_{FN}$

[Froggatt, Nielsen 1979]

mass ratios and mixing angles are small, hierarchical parameters

$$\frac{m_u}{m_t} << \frac{m_c}{m_t} << 1 \qquad \frac{m_d}{m_b} << \frac{m_s}{m_b} << 1 \qquad |V_{ub}| << |V_{cb}| << |V_{us}| \equiv \lambda < 1$$

easily reproduced by $G_f=U(1)_{FN}$

mass ratios and mixing angles are powers of a small SB parameter λ

$U(1)_{FN}$ broken by

$$\lambda = \frac{<\varphi>}{\Lambda_f} \approx 0.2$$

flavon	Q_{FN}
φ	-1

$$y_u = F_{U^c} Y_u F_Q$$

$$y_d = F_{D^c} Y_d F_Q$$

call this map "hierarchy"

$$F_X = \begin{pmatrix} \lambda^{FN(X_1)} & 0 & 0 \\ 0 & \lambda^{FN(X_2)} & 0 \\ 0 & 0 & \lambda^{FN(X_3)} \end{pmatrix}$$

$Y_{u,d} \approx O(1)$

undetermined by $U(1)_{FN}$

$FN(X_i)$ are $U(1)_{FN}$ charges

$(X = Q, U^c, D^c)$

not a mere book-keeping

take $FN(Q_1) > FN(Q_2) > FN(Q_3) \geq 0$

$$\left(V_{u,d}\right)_{ij} \approx \frac{F_{Q_i}}{F_{Q_j}} < 1 \quad (i < j) \qquad V_{CKM} = V_u^+ V_d$$

$$V_{ud} \approx V_{cs} \approx V_{tb} \approx O(1)$$
$$V_{ub} \approx V_{td} \approx V_{us} \times V_{cb}$$

[O.K. within a factor of 2]

independently from the specific charge choice

correct orders of magnitude of V_{ij} reproduced by e.g. $FN(Q) = (3,2,0)$

correct orders of magnitude of quark/charged lepton mass ratios [up to a couple of moderate tunings] reproduced by e.g.

$FN(U^c) = FN(E^c) = FN(Q) = (3,2,0)$
$FN(D^c) = FN(L) = (2,0,0)$

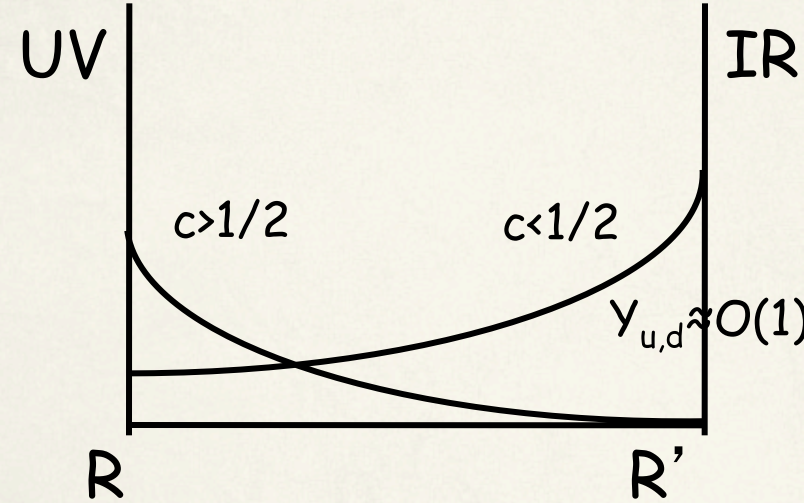
charge assignment compatible with SU(5) gauge unification

we have recently tested this scenario in the context of an SO(10) model
all FN charges <-> 4 parameters [F, Patel, Vicino to appear]

is a symmetry really needed ?

$$y_u = F_{U^c} Y_u F_Q$$

$$y_d = F_{D^c} Y_d F_Q$$



split fermions in an Extra Dimension

$$F_{X_i} = \sqrt{\frac{2\mu_i}{1-e^{-2\mu_i r}}}$$

ED	μ_i	r
Flat $[0,\pi R]$	M_i / Λ	$\Lambda\pi R$
Warped $[R,R']$	$1/2 - M_i R$	$\log R'/R$

M_i = bulk mass of fermion X_i
$Y_{u,d}$ = O(1) Yukawa couplings between bulk fermions and a Higgs localized at one brane

no symmetry:
hierarchy produced by geometry

partial compositness

$$F_{X_i} = \Delta_i M_i^{-1}$$

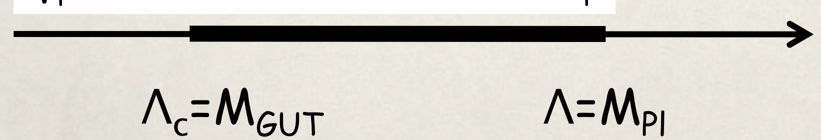
M_i = masses of composite fermions
Δ_i = elementary-composite mixing
$Y_{u,d}$ = O(1) Yukawa couplings in composite sector

chiral multiplets X_i of the MSSM coupled to a superconformal sector

[Nelson-Strassler 0006251]

$$F_{X_i} = \left(\frac{\Lambda_c}{\Lambda}\right)^{\frac{\gamma_i}{2}} < 1$$

γ_i anomalous dimension of X_i



dangerous FCNC

the "hierarchy" map can support a Maximal Flavour Symmetry similar to G_{MFV}

flavour group felt by quarks can be as large as G_{MFV}, but there are more spurions

$$F_Q, F_U{}^c, F_D{}^c, Y_u, Y_d$$

true flavour symmetry can be weaker, dep. on the way "hierarchy" is realized,
as e.g. in FN models [Dudas, von Gersdorff, Parmentier, Pokorski 1007.5208]
maximal symmetry applies to RS models [RS-GIM Agashe, Perez, Soni 0408134]

one concrete example

$$O_K^4 = (\bar{s}_L d_R)(\bar{s}_R d_L)$$

contributions to ε_K are both chiral and RG enhanced

arises from $\frac{1}{\Lambda_{NP}^2} (\bar{Q} F_Q^+ \gamma_\mu F_Q Q)\,(\bar{D}^c F_{D^c}^+ \gamma^\mu F_{D^c} D^c)$ ⇒ $C_K^4 \approx \frac{1}{\Lambda_{NP}^2} \frac{1}{\langle Y_d \rangle^2} \frac{2 m_d m_s}{v^2}$

$$\mathrm{Im}(C_K^4) < (160 \times 10^3\ TeV)^{-2}$$
$$\mathrm{Im}(C_K^4) \approx \mathrm{Re}(C_K^4)$$

⇒ $\langle Y_d \rangle \Lambda_{NP} > 20\ TeV$

confirmed by explicit computation in RS
$O_K{}^4$ from tree-level KK gluon exchange
[also neutron EDM -> M_{KK}>O(10) TeV]

$$M_{KK} > (22 \pm 6)\ TeV$$

[Csaki, Falkowski, Weiler 0804.1954
Von Gersdorff 1311.2078]

FCNC and/or CPV not sufficiently suppressed if there is New Physics at the TeV scale

some lessons from the quark sector

- Pattern of quark masses and mixing angles well-explained by a hierarchy map: underlying $Y_{u,d}$ are O(1)
  hierarchy realized in several different frameworks: FN, RS, NS,….
  symmetry is not a necessary ingredient

- correct order-of-magnitude predictions

- compatible with SU(5)/SO(10) GUTs

- compatible with/incorporated in known solutions to the hierarchy problem

- additional ingredients needed to control the new sources of FC/CPV arising from New Physics at the TeV scale

alignment
universality
…

$$F_Q \quad F_{D^c} \quad F_{U^c}$$
$$Y_d \quad Y_u$$

some symmetry ?

- large number of independent O(1) parameters: test of statistical distributions

additional constraints?

- present precision in quark mass/mixing parameters

testable predictions beyond order-of-magnitude accuracy ?

the lepton sector

small parameters

	$\sin^2\vartheta_{23}-1/2$	$\sin^2\vartheta_{13}$	$\Delta m^2_{21}/\lvert\Delta m^2_{31}\rvert$	$\Delta m_{21}/m_1$
NH	$0.067^{+0.032}_{-0.128}$	0.0234 ± 0.0020	0.0306 ± 0.0011	–
IH	$0.073^{+0.025}_{-0.043}$	0.0240 ± 0.0019	0.0319 ± 0.0009	≤ 0.016

1 accidental origin

[viable both for Majorana or Dirac neutrinos, here focus on Majorana]

$$F_{E_1^c} \gg F_{E_2^c} \gg F_{E_3^c}$$

$$F_{L_1} = F_{L_2} = F_{L_3}$$

Anarchy [Hall, Murayama, Weiner 1999 De Gouvea, Murayama 1204.1249]

$$m_\nu \propto \begin{pmatrix} O(1) & O(1) & O(1) \\ O(1) & O(1) & O(1) \\ O(1) & O(1) & O(1) \end{pmatrix}$$

mixing angles and mass ratios from random O(1) quantities

$$\lvert U_{PMNS}\rvert \approx \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.6 \\ 0.4 & 0.6 & 0.8 \end{pmatrix}$$

consistent with data

$\vartheta_{13} \approx 0.15$ rad and the hint for non maximal ϑ_{23} have strengthened the case for anarchy

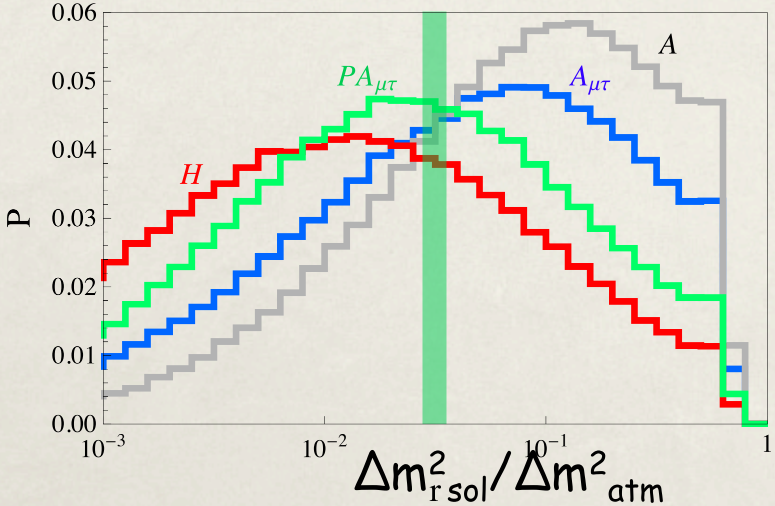
2 not entirely accidental

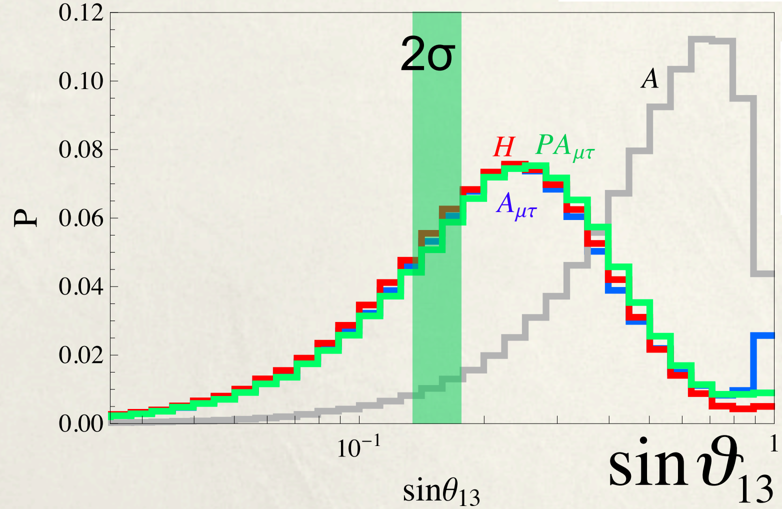
-- variants of Anarchy e.g. in $U(1)_{FN}$ models, quarks and leptons treated on equal foot
-- compatible with SU(5) unification

$$F(L_i) = \lambda^{FN(L_i)}$$

	$FN(L)$	λ
A	(0,0,0)	
$A_{\mu\tau}$	(1,0,0)	0.25
$PA_{\mu\tau}$	(2,0,0)	0.35
H	(2,1,0)	0.45

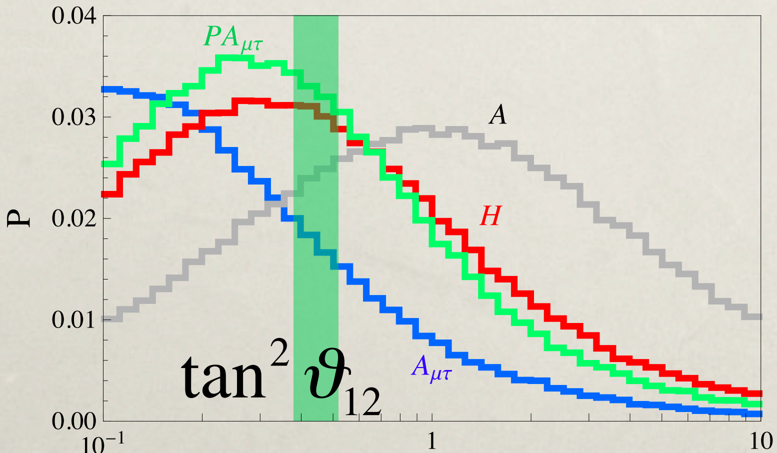
[Buchmuller, Domcke, Schmitz, 1111.387;
Altarelli,F,Masina, Merlo 1207.0587;
Bergstrom, Meloni, Merlo, 1403.4528]



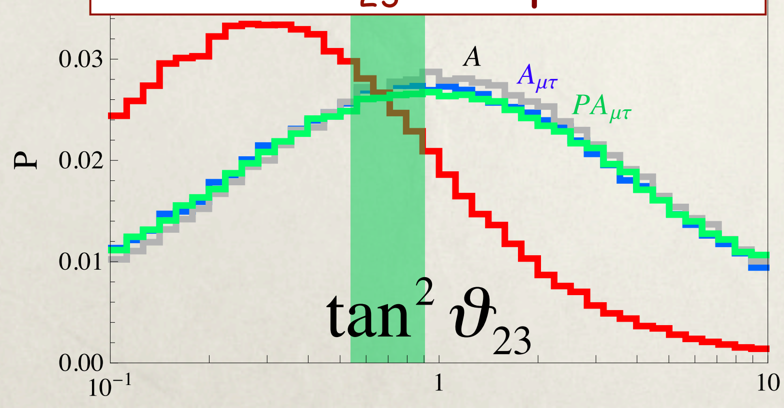


$$\sin^2\vartheta_{13} \approx \frac{\Delta m^2_{12}}{\Delta m^2_{13}}$$

NH favoured



maximal ϑ_{23} unexplained



difficult to go beyond order-of-magnitude predictions

constraints from lepton flavour violation

take the limit $m_\nu = 0$

if MFV applied, we would expect no LFV [y_e diagonal]

⟷

in our setup, in general F_{E^c}, F_L, Y_e do not commute [not even when F_L is universal] LFV expected at some level

dominant LFV dipole operator

$$L_{dip} = \frac{e}{\Lambda_{NP}^2} E^c (\sigma_{\mu\nu} F^{\mu\nu}) \underbrace{(F_{E^c} Y_e Y_e^+ Y_e F_L)}_{\text{not diagonal}} (H^+ L)$$

when $y_e = F_{E^c} Y_e F_L$ diagonal

Explicit computation in RS

[Agashe, Blechman, Petriello 0606021
Csaki, Grossman, Tanedo, Tsai 1004.2037]

comparable bounds from e EDM

[Keren-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi, 1205.5803]

$$BR(\mu \to e\gamma) < 5.7 \times 10^{-13}$$

➡ $$M_{KK} > O(10)\ TeV$$

➡ F_L universality is not enough

a sufficient condition for the absence of LFV:

$$F_{E^c}, Y_e, F_L$$ diagonal in the same basis

for instance:

$$F_L \propto 1 \qquad F_{E^c} \propto Y_e Y_e^+$$

[M.C. Chen and Yu, 08042503
Perez, Randall 0805.4652]

anything special from data, requiring a symmetry?

1 ϑ_{23} maximal ?

2 $\delta_{CP} = -\pi/2$?

3 U_{PMNS} close to TB (BM,...) ?

3 examples from a longer list...

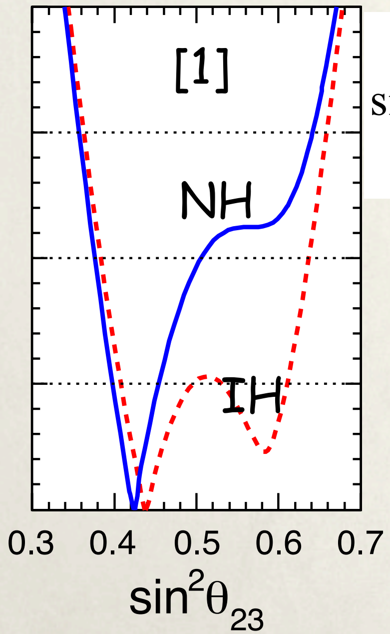
1 today most precise single determination of ϑ_{23} is from T2K ($P_{\mu\mu}$)

[1403.1532]

$$\sin^2\vartheta_{23} = \begin{cases} 0.514^{+0.055}_{-0.056} & \text{(NH)} \\ 0.511^{+0.055}_{-0.055} & \text{(IH)} \end{cases}$$

well compatible with ϑ_{23} maximal

global fits hint at ϑ_{23} non-maximal
main effect: interplay between SBL reactor experiments (P_{ee}) and LBL experiments searching ($P_{\mu e}$)



$$\sin^2\vartheta_{23} = \begin{cases} 0.567^{+0.032}_{-0.128} & \text{(NH)} \\ 0.573^{+0.025}_{-0.043} & \text{(IH)} \end{cases}$$

[2]

$$P_{ee} = 1 - \sin^2 2\vartheta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E} + \ldots$$

$$P_{\mu e} = \sin^2\vartheta_{23} \sin^2 2\vartheta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E} + \ldots$$

global fit:
[1] Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo 1312.2878
[2] Forero, Tortola, Valle 1405.7540

a small change of P_{ee} and/or $P_{\mu e}$ within about 1σ can bring back ϑ_{23} to maximal difficult to improve ϑ_{23} from $P_{\mu\mu}$

$$\delta\vartheta_{23} \approx \sqrt{\delta P_{\mu\mu}} / 2 \qquad \delta P_{\mu\mu} \approx 0.01 \quad \Rightarrow \quad \delta\vartheta_{23} \approx 0.05 \text{ rad } (2.9^0)$$

ϑ_{23} nearly maximal would be a crucial piece of information

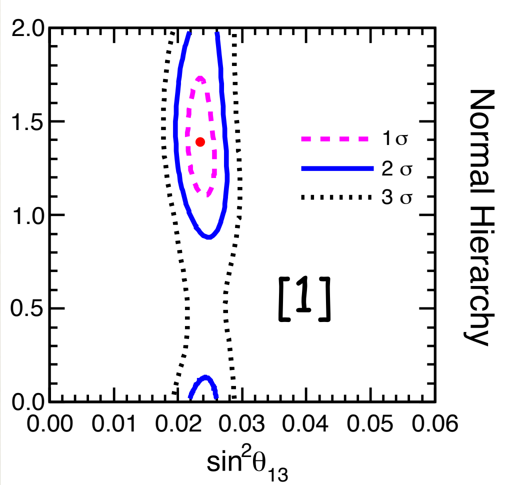
ϑ_{23} cannot be made maximal by RGE evolution
[barring tuning of b.c. and/or ad hoc thresold corrections]

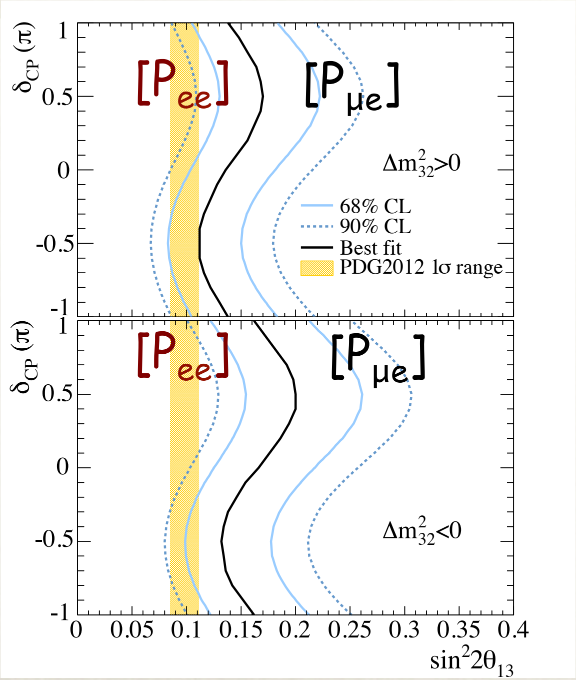
no maximal ϑ_{23} from an exact symmetry

broken abelian symmetries do not work
[not a theorem but no counterexamples]

⇒ we are left with broken non-abelian symmetries

2 $\delta_{CP} = -\pi/2$?





[T2K: 1311.4750 and 1311.4114]

3 U_{PMNS} close to TB (BM,…) ?

discrete flavor symmetries showed very efficient to reproduce U_{TB}, U_{BM},…

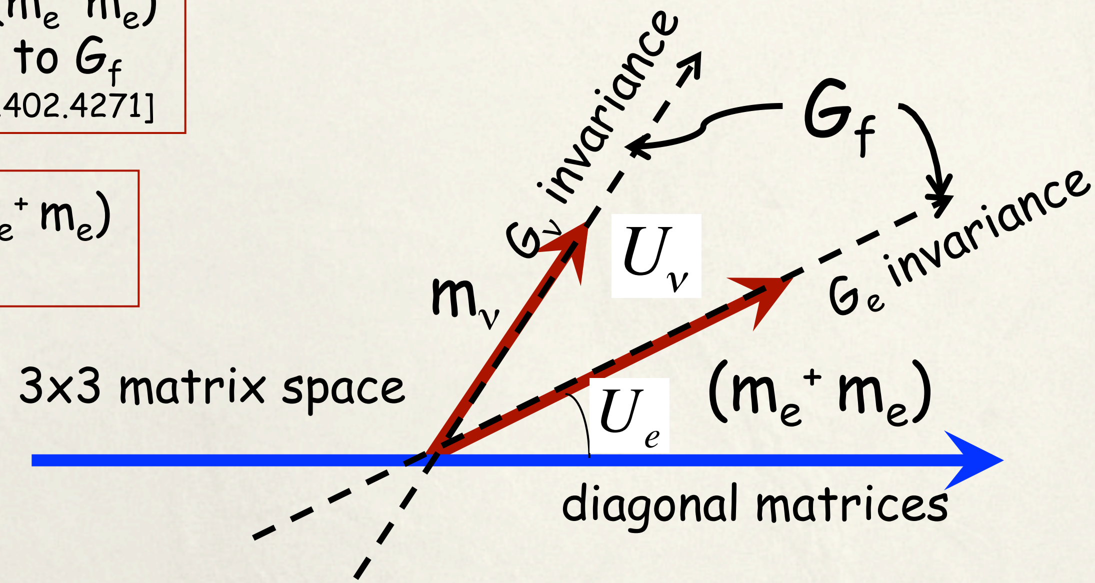
$$U_{PMNS} = U^0_{PMNS} + \text{corrections}$$

indirect: symmetries of m_ν and $(m_e^+ m_e)$ have no direct relation to G_f
[see King, Merle, Morisi, Shimizu and Tanimoto 1402.4271]

direct: symmetries of m_ν and $(m_e^+ m_e)$ are subgroups of G_f

4 predictions

$$\vartheta^0_{12} \quad \vartheta^0_{23} \quad \vartheta^0_{13} \quad \delta^0 (\text{mod } \pi)$$



Majorana neutrinos imply $G_\nu \leq Z_2 \times Z_2$

smallest group leading to TB: $S_4 \approx (A_4$+accidental symmetry)

neutrino masses fitted, not predicted.

expectation for $U^0_{PMNS} = U_{TB}$

$$\begin{cases} \vartheta^0_{13} = 0 \\ \vartheta^0_{23} = \dfrac{\pi}{4} \end{cases} \Rightarrow \begin{cases} \vartheta_{13} = \text{O(few degrees)} \\ \vartheta_{23} = \text{close to } \dfrac{\pi}{4} \end{cases}$$

not to spoil the agreement with ϑ_{12}

wrong!

1 add large corrections $O(\vartheta_{13}) \approx 0.2$

- predictability is lost since in general correction terms are many
- new dangerous sources of FC/CPV if NP is at the TeV scale

2 relax symmetry requirements

[Hernandez,Smirnov 1204.0445]

G_e as before
$G_\nu = Z_2$

2 predictions:
2 combinations of $\vartheta_{12}^0 \quad \vartheta_{23}^0 \quad \vartheta_{13}^0 \quad \delta_{CP}$

two deformations of TB, called Trimaximal [TM] mixing

TM_1

$$U^0 = U_{TB} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & e^{i\delta}\sin\alpha \\ 0 & -e^{-i\delta}\sin\alpha & \cos\alpha \end{pmatrix}$$

TM_2

$$U^0 = U_{TB} \times \begin{pmatrix} \cos\alpha & 0 & e^{i\delta}\sin\alpha \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\alpha & 0 & \cos\alpha \end{pmatrix}$$

leads to testable sum rules

TM_1:

$$\sin^2\vartheta_{12} = \frac{1}{3} - \frac{2}{3}\sin^2\vartheta_{13} + O(\sin^4\vartheta_{13})$$

$$\sin^2\vartheta_{23} = \frac{1}{2} - \sqrt{2}\sin\vartheta_{13}\cos\delta_{CP} + O(\sin^2\vartheta_{13})$$

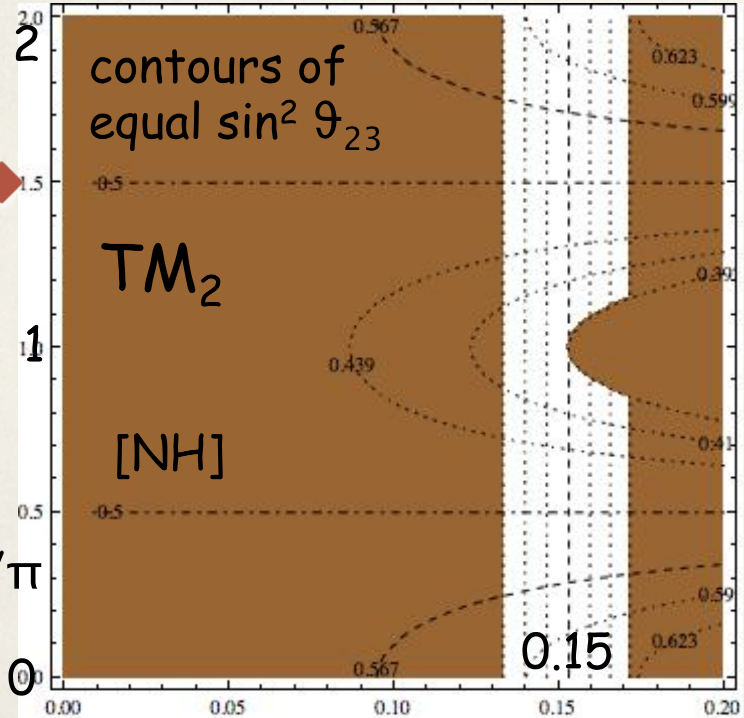
TM_2:

$$\sin^2\vartheta_{12} = \frac{1}{3} + \frac{1}{3}\sin^2\vartheta_{13} + O(\sin^4\vartheta_{13})$$

$$\sin^2\vartheta_{23} = \frac{1}{2} + \frac{1}{\sqrt{2}}\sin\vartheta_{13}\cos\delta_{CP} + O(\sin^2\vartheta_{13})$$

[He, Zee 2007 and 2011, Grimus, Lavoura 2008, Grimus, Lavoura, Singraber 2009, Albright, Rodejohann 2009, Antusch, King, Luhn, Spinrath 2011, King, Luhn 2011, G. Altarelli, F.F., L. Merlo and E. Stamou hep-ph/1205.4670] deviation from TB is linear in α for $\sin^2\theta_{23}$, whereas is quadratic for $\sin^2\theta_{12}$, the best measured angle

sum rules can be tested by measuring δ_{CP} and improving on $\sin^2\vartheta_{23}$



3 change discrete group G_f

- solutions exist
  special forms of TM$_2$

G_f	$\Delta(96)$	$\Delta(384)$	$\Delta(600)$
α	$\pm\pi/12$	$\pm\pi/24$	$\pm\pi/15$
$\sin^2\vartheta_{13}^0$	0.045	0.011	0.029

$$U^0 = U_{TB} \times \begin{pmatrix} \cos\alpha & 0 & e^{i\delta}\sin\alpha \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\alpha & 0 & \cos\alpha \end{pmatrix}$$

F.F., C. Hagedorn, R. de A.Toroop
hep-ph/1107.3486 and hep-ph/1112.1340
Lam 1208.5527 and 1301.1736
Holthausen1, Lim and Lindner 1212.2411
Neder, King, Stuart 1305.3200
Hagedorn, Meroni, Vitale 1307.5308]

$\delta^0 = 0,\pi$ (no CP violation) and
α "quantized" by group theory

complete classification of $|U_{PMNS}|$ from any finite group available now!

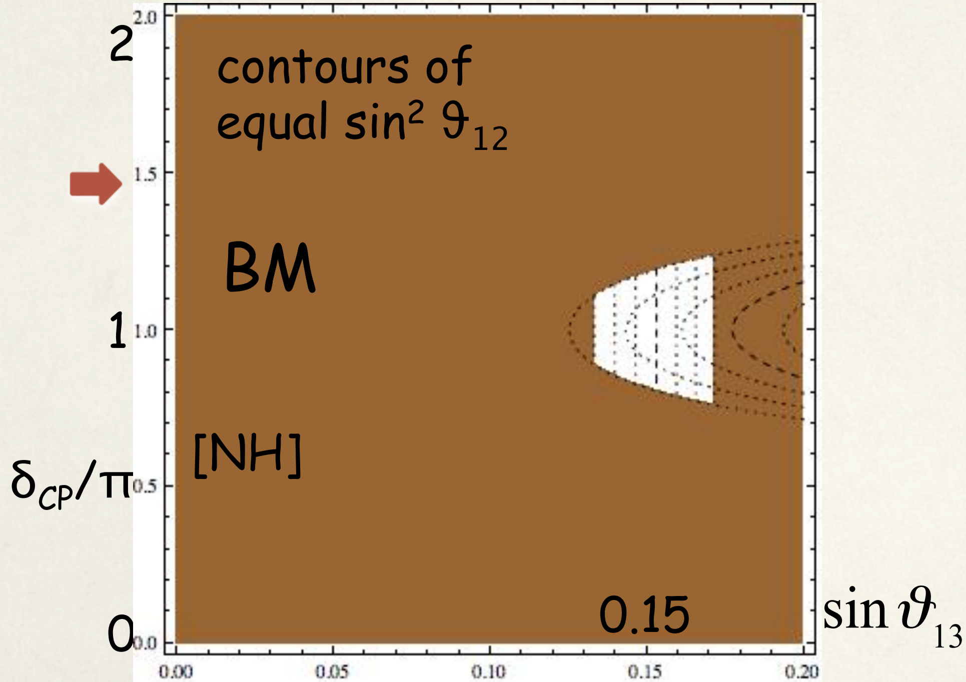
[Fonseca, Grimus 1405.3678]

4 change LO pattern

$$U^0_{PMNS} = U_{BM}$$

corrected by U^e_{12}

$$\sin^2\vartheta_{12} = \frac{1}{2} + \sin\vartheta_{13}\cos\delta_{CP} + O(\sin^2\vartheta_{13})$$



5 include CP in the SB pattern

$$G_{CP} = G_f \rtimes CP$$

$$G_e \qquad G_\nu = Z_2 \times CP$$

[F. F, C. Hagedorn and R. Ziegler 1211.5560, 1303.7178
Ding,King,Luhn,Stuart 1303.6180
Ding, King, Stuart 1307.4212]

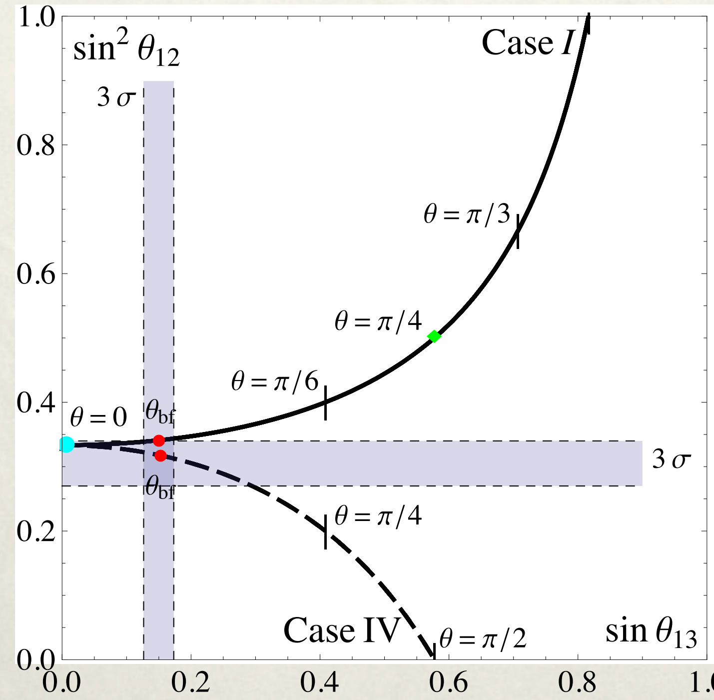
mixing angles and CP violating phases

$$(\vartheta^0_{12}, \vartheta^0_{23}, \vartheta^0_{13}, \delta^0, \alpha^0, \beta^0)$$

predicted in terms of a single real parameter $0 \le \vartheta \le \pi$

2 examples with $G_f = S_4$ $G_e = Z_3$

$$\sin^2\vartheta^0_{23} = \frac{1}{2} \qquad |\sin\delta^0| = 1 \qquad \sin\alpha^0 = 0 \qquad \sin\beta^0 = 0$$



no conclusions…

back up slides

Conclusions

- flavour symmetries are a useful tool in our quest of the origin of $\mathcal{Y}$ but no compelling and unique picture have emerged so far.
  Present data can be described within widely different frameworks
  [despite the constant, impressive progress on the experimental side]

- simple schemes with a minimal amount of structure can
  well reproduce the main features of $\mathcal{Y}$ in both quark and lepton sectors
  also in a GUT framework
  main drawbacks: -- no precise questions/no precision tests allowed
  [e.g. maximal ϑ_{23} unexplained]
  -- more structure needed to suppress FCNC and CPV
  if there is new physics at the TeV scale

- some special features [ϑ_{23} maximal, $\delta_{CP} = -\pi/2$, $U_{PMNS} \approx$ TB, BM,...]
  can survive experimental refinements and guide us in the search of
  a unifying principle for the flavour sector.

θ_{23} maximal from some flavour symmetries ?

a no-go theorem
[F. 2004]

$\vartheta_{23} = \pi/4$ can never arise in the limit of an exact realistic symmetry

charged lepton mass matrix:

$$m_l = m_l^0 + \delta m_l^0$$

symmetric limit

symmetry breaking effects: vanishing when flavour symmetry F is exact

realistic symmetry:

(1) $\left|\delta m_l^0\right| < \left|m_l^0\right|$

(2) m_l^0 has rank ≤1

$$m_l^0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

ϑ_{12}^e undetermined

$$U_{PMNS} = U_e^+ U_\nu$$

[omitting phases]

$$\tan\vartheta_{23}^0 = \tan\vartheta_{23}^\nu \cos\vartheta_{12}^e + \left(\frac{\tan\vartheta_{13}^\nu}{\cos\vartheta_{23}^\nu}\right)\sin\vartheta_{12}^e$$

undetermined

$$\vartheta_{23} = \frac{\pi}{4}$$

determined entirely by breaking effects
(different, in general, for ν and e sectors)

G_f = discrete flavor symmetry

$$U_{PMNS} = U^0_{PMNS} + \text{corrections}$$

some simple pattern, exactly reproduced by a flavor symmetry

- well motivated before 2012

$$U^0_{PMNS} = U_{TB} \equiv \begin{pmatrix} 2/\sqrt{6} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Tribimaximal Mixing

discrete flavor symmetries showed very efficient to reproduce U^0_{PMNS}

- still justified today?

$$U_{TB} \approx \begin{pmatrix} 0.82 & 0.58 & 0 \\ -0.41 & 0.58 & -0.71 \\ -0.41 & 0.58 & 0.71 \end{pmatrix}$$

$$|U_{PMNS}| = \begin{pmatrix} 0.80 \div 0.85 & 0.51 \div 0.59 & 0.13 \div 0.18 \\ 0.21 \div 0.54 & 0.42 \div 0.73 & 0.58 \div 0.81 \\ 0.22 \div 0.55 & 0.41 \div 0.73 & 0.57 \div 0.80 \end{pmatrix}$$

[3σ ranges from Gonzalez-Garcia, Maltoni, Salvado, Schwetz 1209.3023]

2011/2012 breakthrough

-- LBL experiments searching for $\nu_\mu \to \nu_e$ conversion [see Fogli's talk]

-- SBL reactor experiments searching for anti-ν_e disappearance

	Lisi [NeuTel 2013]	[1209.3023] [G-Garcia, Maltoni, Salvado, Schwetz]
$\sin^2\vartheta_{13}$	$0.0241^{+0.0025}_{-0.0025}$ (NO) $0.0244^{+0.0023}_{-0.0025}$ (IO)	$0.0227^{+0.0023}_{-0.0024}$
$\sin^2\vartheta_{23}$	$0.386^{+0.024}_{-0.021}$ (NO) $0.392^{+0.039}_{-0.022}$ (IO)	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$

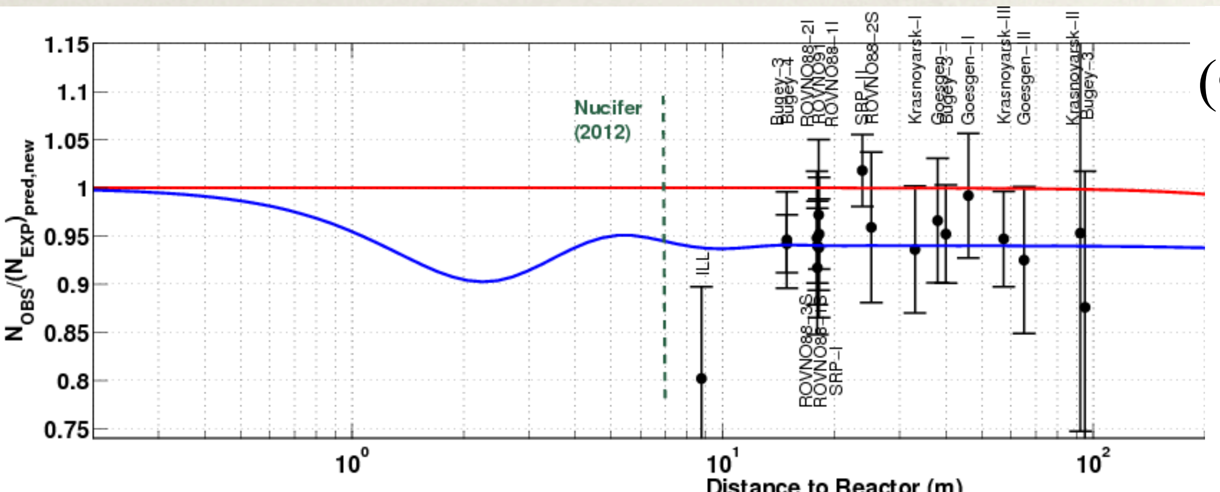
→ 10σ away from 0 — impact on flavor symmetry (part 3)

→ hint for non maximal ϑ_{23}

sterile neutrinos coming back

1 reactor anomaly (anti-ν_e disappearance)

re-evaluation of reactor anti-ν_e flux: new estimate 3.5% higher than old one



$$(\Phi_{exp} - \Phi_{th})/\Phi_{th} \approx -6\%$$

[th. uncertainty?]

very SBL L ≲ 100 m

$$\vartheta_{es} \approx 0.2$$

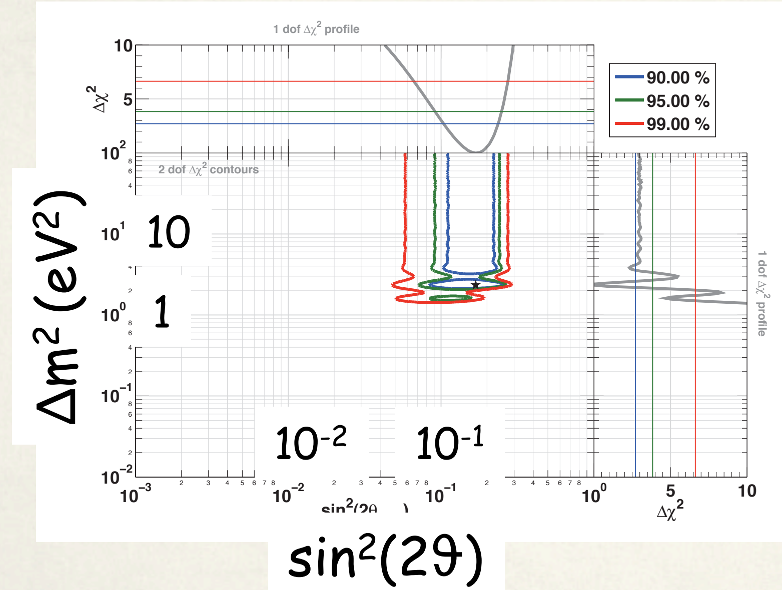
$$\Delta m^2 \approx m_s^2 \geq 1\, eV^2$$

supported by the Gallium anomaly

ν_e flux measured from high intensity radioactive sources in Gallex, Sage exp

$$\nu_e + {}^{71}Ga \to {}^{71}Ge + e^-$$

[error on σ or on Ge extraction efficiency]



most recent cosmological limits

[depending on assumed cosmological model, data set included,...]

relativistic degrees of freedom at recombination epoch

$$N_{eff} = 3.30 \pm 0.27$$

[Planck, WMAP, BAO, high multiple CMB data]

fully thermalized non relativistic ν

$$N_{eff} < 3.80 \quad (95\% \, CL)$$

$$m_s < 0.42 \, eV \quad (95\% \, CL)$$

2 long-standing claim

evidence for ν_μ -> ν_e appearance in accelerator experiments

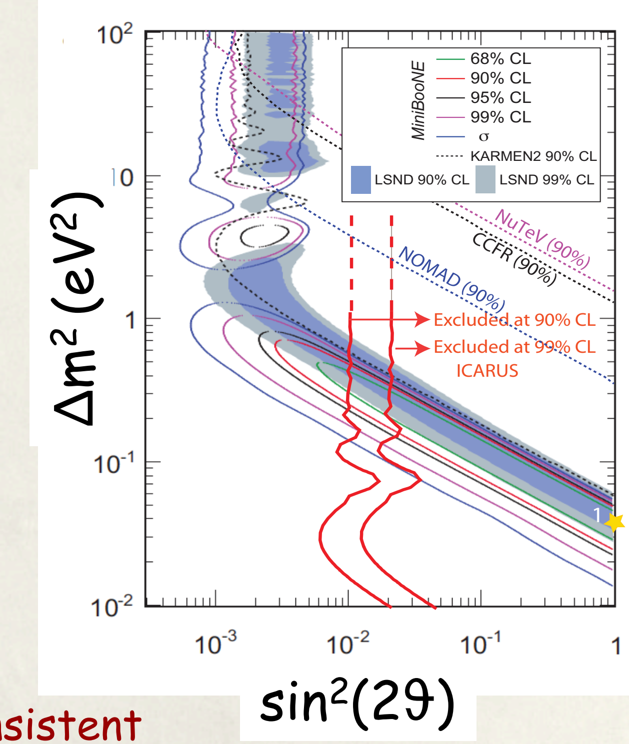
exp		$E(MeV)$	$L(m)$
LSND	$\bar{\nu}_\mu \to \bar{\nu}_e$	$10 \div 50$	30
MiniBoone	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	$300 \div 3000$	541

LSND: 3.8σ

MiniBoone: 3.8σ [signal from low-energy region] parameter space limited by negative results from Karmen and ICARUS

$$\vartheta_{e\mu} \approx 0.035$$

$$\Delta m^2 \approx 0.5\, eV^2$$

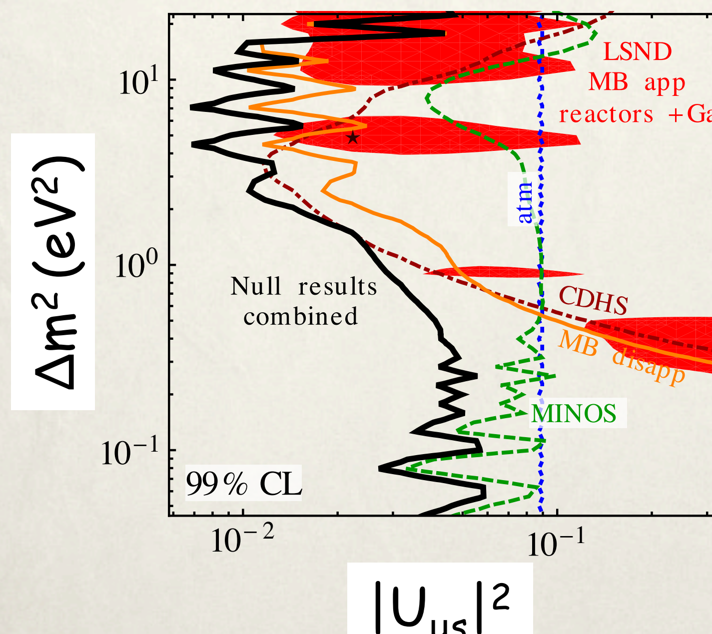


3 interpretation in 3+1 scheme: inconsistent (more than 1s disfavored by cosmology)

$$\underbrace{\vartheta_{e\mu}}_{0.035} \approx \underbrace{\vartheta_{es}}_{0.2} \times \vartheta_{\mu s} \Rightarrow \vartheta_{\mu s} \approx 0.2$$

predicted suppression in ν_μ disappearance experiments: undetected

by ignoring LSND/Miniboone data the reactor anomaly can be accommodated by $m_s \geq 1$ eV and $\vartheta_{es} \approx 0.2$
[not suitable for WDM, more on this later]

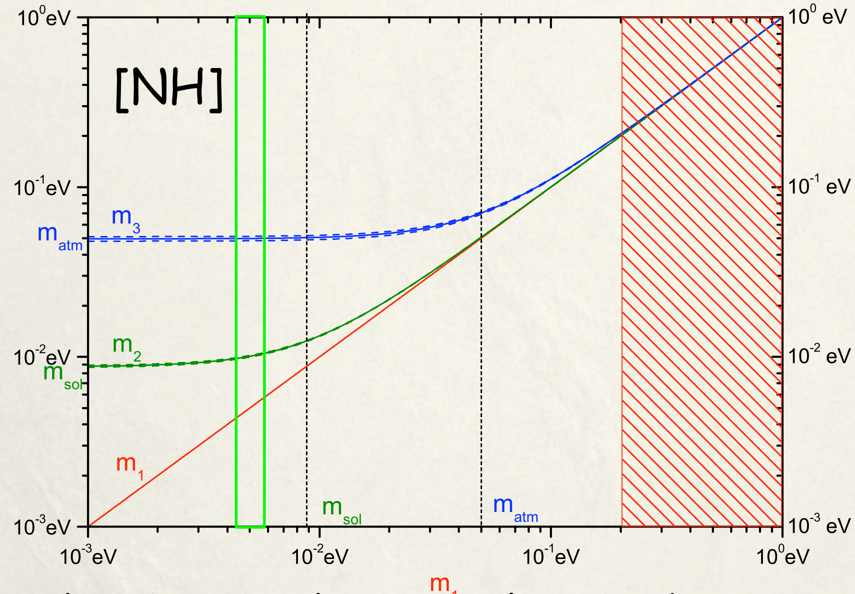


predictions based on $G_f = A_4 \times Z_3 \times U(1)_{FN}$ [+ SEE-SAW] [Altarelli, F 2005]

lepton mixing is TB, by construction, plus NLO corrections of order $0.005 < u < 0.05$
at the LO neutrino mass spectrum depends on two complex parameters
there is a sum rule among (complex) mass eigenvalues $m_{1,2,3}$

$$\frac{1}{m_3} = \frac{1}{m_1} - \frac{2}{m_2}$$

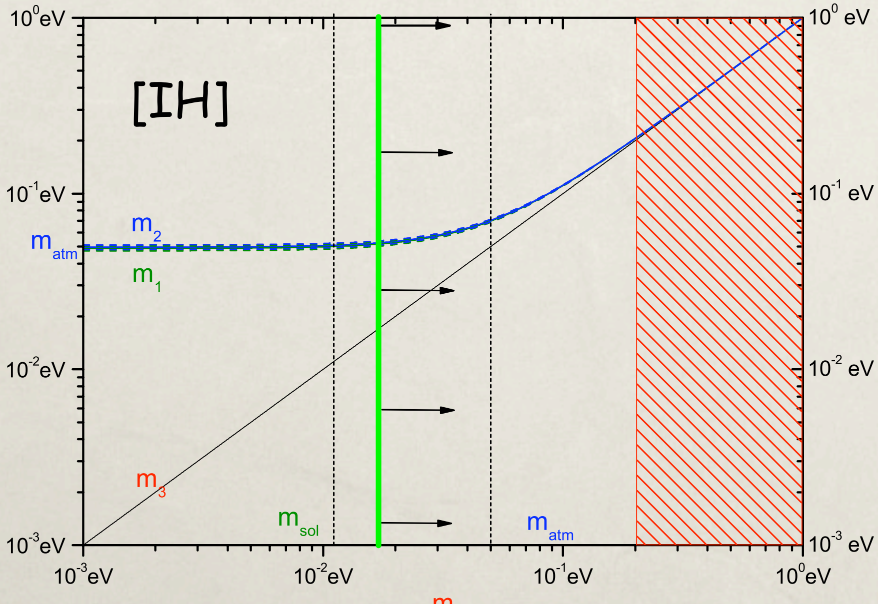
both normal [NH] and inverted [IH] hierarchy are allowed



in the NH case the sum rule
completely determines the spectrum

$$m_1 \approx 0.005\ eV \quad m_2 \approx 0.01\ eV \quad m_3 \approx 0.05\ eV$$

$$|m_{ee}| \approx 0.007\ eV$$



in the IH case the sum rule provides
a lower bound on m_3

$$m_3 \geq 0.017\ eV$$

$$|m_{ee}| \geq 0.017\ eV$$

NLO corrections are negligible for NH and for IH close to the lower bound