Theory Perspective on Flavour

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Approaches to the flavour puzzle

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?

any empirical evidence for a symmetry 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

$$y_u = F_{U^c} Y_u F_Q$$
$$y_d = F_{D^c} Y_d F_Q$$

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

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

$FN(Q) = (3,2,0)$

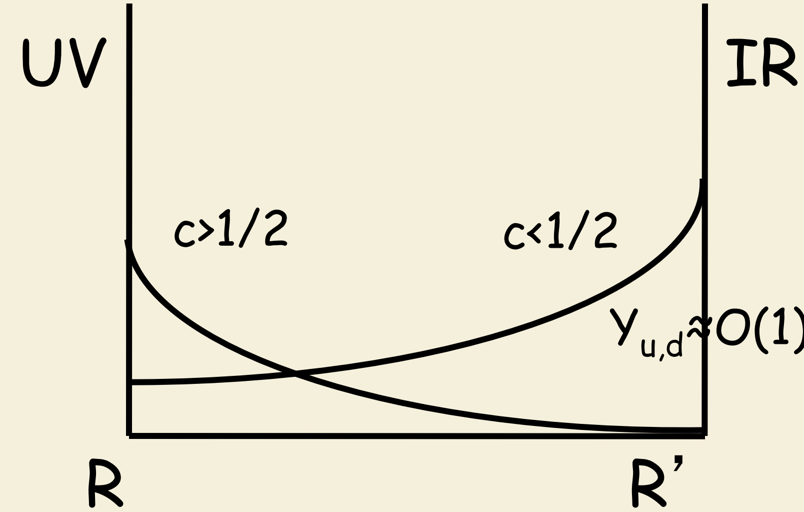
correct orders of magnitude of quark/charged lepton mass ratios [up to a couple of moderate tunings] reproduced by e.g.

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

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

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

ED	μ_i	ρ
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

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

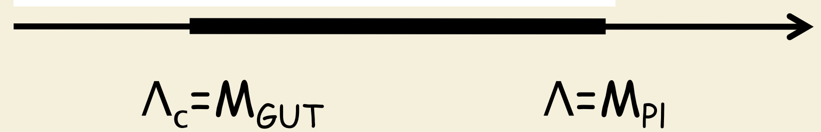
M_i = masses of composite fermions
Δ_i = elementary-composite mixing
$Y_{u,d}$ = O(1) Yukawa couplings in composite sector

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



can be extended to the lepton sector

no evidence for big hierarchies in neutrino mixing angles
clear hierarchy only in the charged lepton masses

$$F_{E_1^c} << F_{E_2^c} << F_{E_3^c}$$
$$F_{L_1} \approx F_{L_2} \approx F_{L_3}$$

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

1 an extreme possibility

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

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

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

consistent with data

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

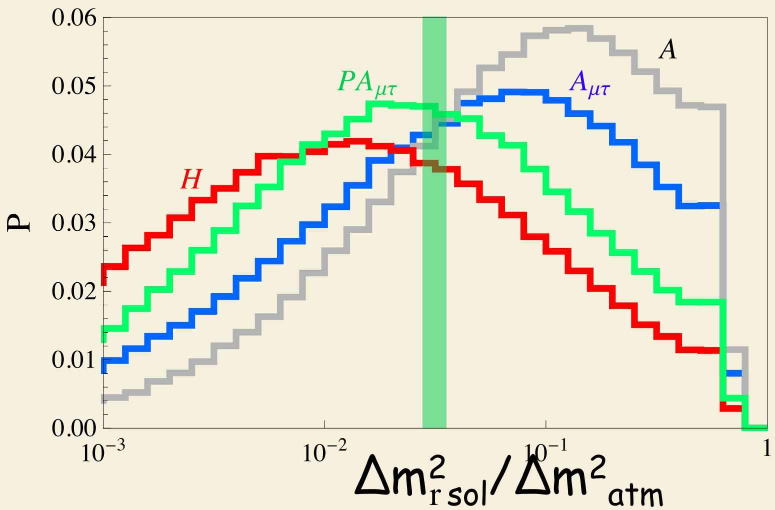
2 with many variants…

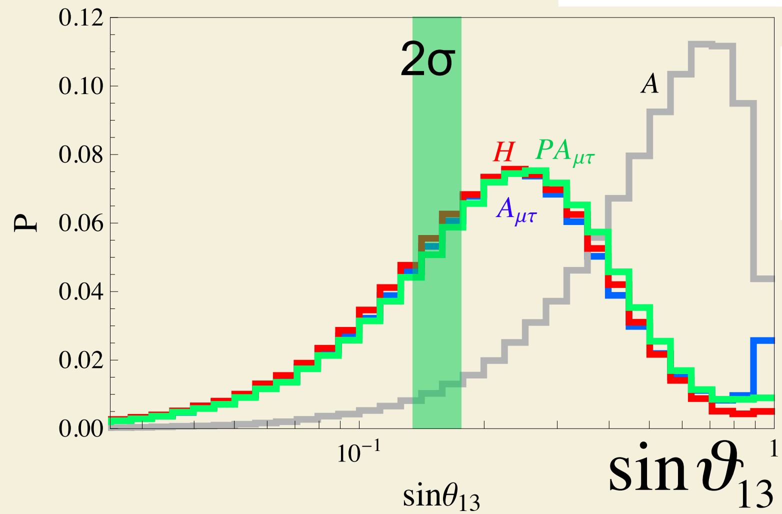
-- variants of Anarchy e.g. in $U(1)_{FN}$ models, quarks and leptons treated on equal foot
-- compatible with SU(5) unification

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

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

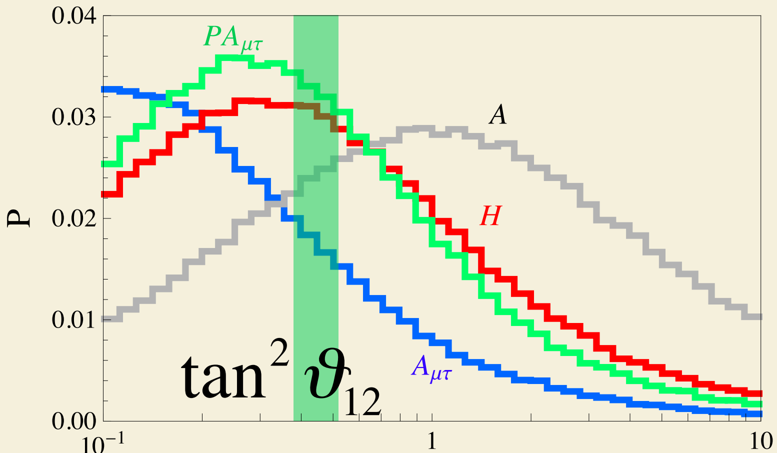
	$FN(L)$	λ
A	(0,0,0)	
$A_{\mu\tau}$	(1,0,0)	0.25
$PA_{\mu\tau}$	(2,0,0)	0.35
H	(2,1,0)	0.45



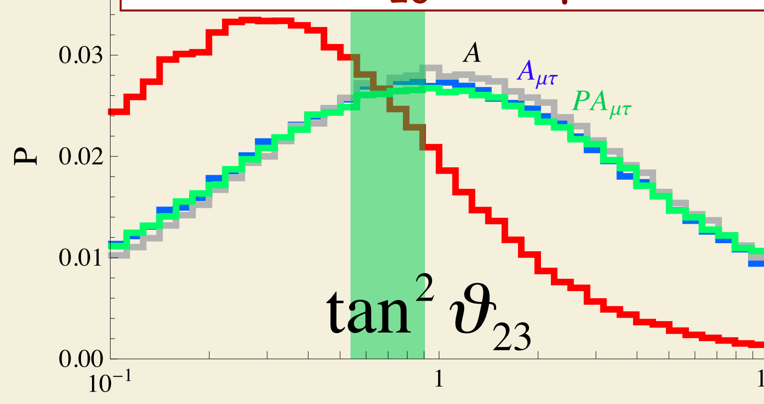


$$\sin^2\vartheta_{13} \approx \frac{\Delta m^2_{12}}{\Delta m^2_{13}}$$

NH favoured



maximal ϑ_{23} unexplained



difficult to go beyond order-of-magnitude predictions

flavor puzzle made simpler in SU(5) ?

$\bar{5} = (l, d^c)$ $\quad 10 = (q, u^c, e^c)$ $\quad 1 = \nu^c$

$5_H = (D, T)$ Higgs

$$L_Y = -y_u^{ij} 10_i 10_j 5_H - y_d^{ij} \bar{5}_i 10_j \bar{5}_H - y_\nu^{ij} 1_i \bar{5}_j 5_H - \frac{1}{2} M_{ij} 1_i 1_j + h.c.$$

$y_d = y_e^T$

not a bad first-order approximations
only corrections of O(1) needed
remedies well-known

$y_\nu = F_1 Y_\nu F_{\bar{5}} \qquad M = F_1 \mu F_1$

only three matrices $F_{10}, F_{\bar{5}}, F_1$

$$y_u = F_{10} Y_u F_{10} \quad y_d = F_{\bar{5}} Y_d F_{10} \quad y_e = F_{10} Y_d^T F_{\bar{5}}$$

$$m_\nu \propto F_{\bar{5}} Y_\nu^T \mu^{-1} Y_\nu F_{\bar{5}}$$

adopt anarchy anzatz

F_1 dependence cancels in m_ν

$F_{\bar{5}} \approx \mathrm{diag}(1,1,1)$

large l mixing corresponds to a large d^c mixing: unobservable in weak int. of quarks

hierarchy mostly due to F_{10}

$$m_u : m_c : m_t \approx m_d^2 : m_s^2 : m_b^2 \approx m_e^2 : m_\mu^2 : m_\tau^2$$

$$F_{10} \approx \begin{pmatrix} \lambda^{3\div4} & 0 & 0 \\ 0 & \lambda^2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

realistic picture after correcting $y_d = y_e^T$

and SO(10) ?

previous picture seems incompatible with SO(10) at first sight

a whole SM generation in a 16

$$L_Y = -y_{10}^{ij} 16_i 16_j 10_H + h.c.$$

only one matrix F_{16}

O(1)

$$y_{10} = F_{16} Y_{10} F_{16}$$

affects all members of the 16 in the same way: no distinction between quarks and leptons

adding more Yukawa couplings does not help, if Y are all O(1)

$$L_Y = -16_i \left[y_{10}^{ij} 10_H + y_{120}^{ij} 120_H + y_{126}^{ij} 126_H \right] 16_j + h.c.$$

$$\frac{m_{d_i}}{m_{d_j}} \approx \frac{m_{u_i}}{m_{u_j}} \approx \frac{m_{e_i}}{m_{e_j}}$$

extension to SO(10) made possible by Kitano-Li

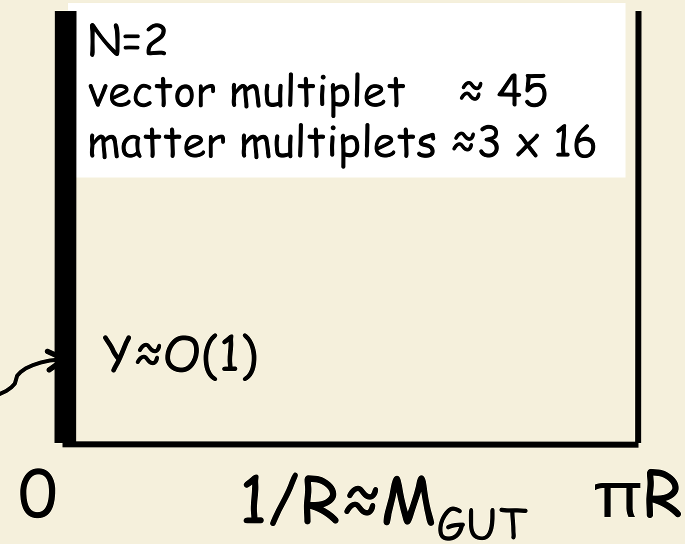
[Phys.Rev. D67 (2003) 116004]

SUSY SO(10) model in (flat) 5D

5D N=1 SUSY is
4D N=2 SUSY

5D = S^1/Z_2
breaks N=2 SUSY
down to N=1

Higgs and Yukawa
interactions on y=0
brane



0^{th} order approximation

$$F_{16_i} = \sqrt{\frac{2\mu_i}{1-e^{-2\mu_i\rho}}}$$

$\mu_i = \frac{M_i}{\Lambda}$ bulk mass of 16_i in units of Λ

$\rho = \Lambda \pi R$ length of ED in units 1/Λ

zero-mode wave-function of 16_i evaluated at y=0
no distinction between quarks and leptons within the same family

1^{st} key ingredient

bulk gauge interaction between 16_i and vector multiplet = universal Yukawa interaction

$$16_i^c\left[M_i-\sqrt{2}g_5 45_\Phi\right]16_i$$

N=1 chiral multiplet being part of N=2 vector multiplet

$$SO(10)\rightarrow SU(5)\times U(1)_X\rightarrow SU(5)\rightarrow G_{SM}$$

$$\langle 45_\Phi\rangle = v_\Phi^{3/2}$$

$$\mu_i\rightarrow\mu_i^r=\mu_i-Q_X^r k$$

r	10	$\bar{5}$	1
Q_X^r	-1	3	-5

$$k=\sqrt{2}g_5\frac{v_\Phi^{3/2}}{\Lambda}$$

we are back to the SU(5) case

$$y_u=F_{10}Y_uF_{10}\qquad y_d=F_{\bar{5}}Y_dF_{10}\qquad y_e=F_{10}Y_eF_{\bar{5}}\qquad m_\nu\propto F_{\bar{5}}Y_\nu^T\mu^{-1}Y_\nu F_{\bar{5}}$$

$$r=(10,\bar{5},1)\qquad F_{r_i}=\sqrt{\frac{2\mu_i^r}{1-e^{-2\mu_i^r\rho}}}$$

profiles F controlled by only 4 free parameters: μ_i and k

2^{nd} key ingredient

multiple contributions to O(1) Yukawa couplings at y=0 such that Y_u, Y_d, Y_e, Y_ν can be treated as independent [otherwise incorrect mass relations]

$$\frac{\delta(y)}{\Lambda}\left[Y_{ij}16_i 16_j 10_H + Y'_{ij}16_i 16_j 10_H \frac{45_H}{\Lambda} + \ldots\right]$$

more details in poster session by Denise Vicino

we have reconsidered the KL model [F, Patel, Vicino 1407.2913]

1 modified Yukawa couplings at y=0 such that Y_u, Y_d, Y_e, Y_ν arise from operators of the same dimensionality

$$\frac{\delta(y)}{\Lambda}\left[Y_{10}^{ij}16_i 16_j 10_H + Y_{120}^{ij}16_i 16_j 120_H + Y_{126}^{ij}16_i 16_j 126_H + \right]$$

cut-off scale Λ can be > M_{GUT}

27 O(1) free parameters ⟷ chance

2 explicit solution to the doublet-triplet splitting problem through the missing partner mechanism

light sector: 10_H and 120_H [3 pairs of D and 3 pairs of T]

heavy sector: 126_H, $\overline{126}_H$, 45_H 120_H [2 pairs of D and 3 pairs of T]

8 O(1) free parameters define the light Higgs combinations

3 fit to an idealized set of 17 data

Observable	Normal ordering Fitted value	Pull	Inverted ordering Fitted value	Pull
y_t	0.51	0	0.54	1.00
y_b	0.37	0	0.37	0
y_τ	0.51	0	0.47	-1.00
m_u/m_c	0.0027	0	0.0031	0.67
m_d/m_s	0.051	0	0.045	-0.86
m_e/m_μ	0.0048	0	0.0048	0
m_c/m_t	0.0023	0	0.0023	0
m_s/m_b	0.016	0	0.015	-0.50
m_μ/m_τ	0.050	0	0.049	-0.50
$\|V_{us}\|$	0.227	0	0.227	0
$\|V_{cb}\|$	0.037	0	0.038	1.00
$\|V_{ub}\|$	0.0033	0	0.0030	-0.50
J_{CP}	0.000023	0	0.000021	-0.51
Δ_S/Δ_A	0.0309	0	0.0320	0.73
$\sin^2\theta_{12}$	0.308	0	0.309	0.06
$\sin^2\theta_{23}$	0.425	0	0.435	-0.07
$\sin^2\theta_{13}$	0.0234	0	0.0237	-0.10
$\chi^2_{\min}$		≈ 0		≈ 5.75
	Predicted value		**Predicted value**	
$m_{\nu_{\text{lightest}}}$ [meV]	0.08		2.15	
$\|m_{\beta\beta}\|$ [meV]	1.63		30.4	
$\sin\delta^l_{CP}$	0.265		0.510	
M_{N_1} [GeV]	3.85×10^6		1.13×10^4	
M_{N_2} [GeV]	9.31×10^7		3.06×10^6	
M_{N_3} [GeV]	2.19×10^{14}		2.02×10^{13}	
υ_R [GeV]	0.05×10^{16}		0.18×10^{16}	

TABLE II. Results from numerical fit corresponding to minimized χ^2 for normal (NO) and inverted ordering (IO) in neutrino masses. The fit is carried out for the GUT scale extrapolated data given in Table I for $\tan\beta = 50$. The input parameters are collected in Appendix.

35 O(1) + 4 profile parameters

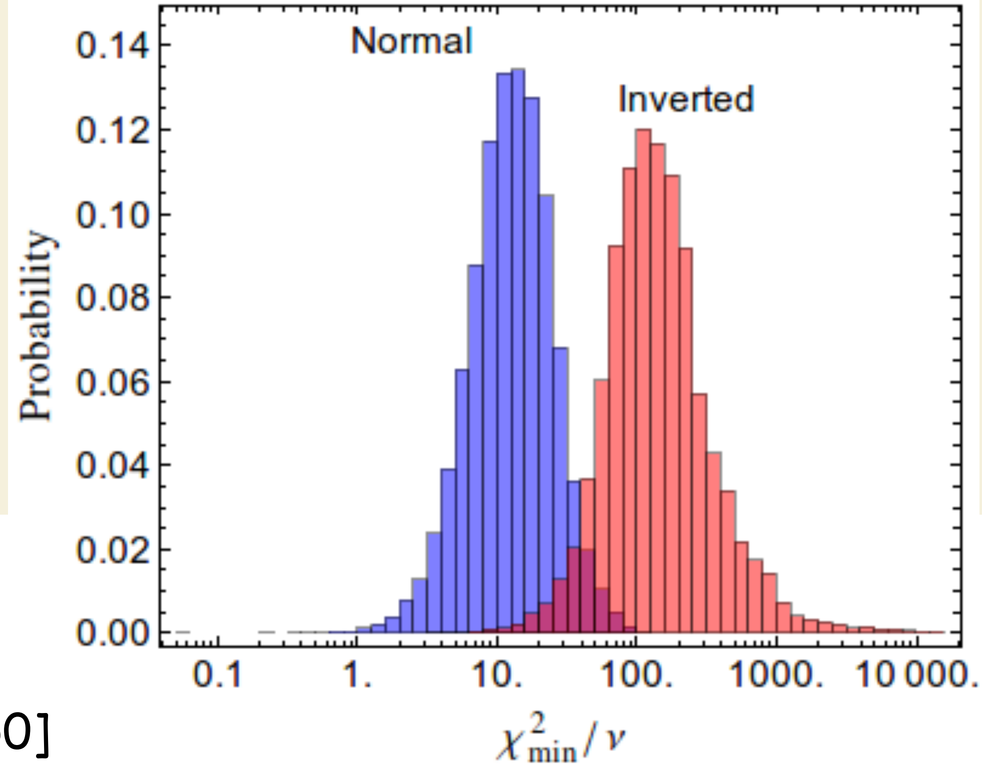
agreement not completely trivial: indeed only large tanβ is allowed [here tanβ=50]

both NO and IO neutrino spectrum lead to a decent fit

are the 27 O(1) Yukawa coupling fine-tuned?

we reiterate the fit by first generating a random sample of Yukawas
for every such fit 27 parameters are now fixed: 8+4=12 free parameters
ν=(17-12)=5 dof

flat distributions
$|Y_{ij}| \in [0.5, 1.5]$
$\arg(Y_{ij}) \in [0, 2\pi]$
or
$Y_{ij} \in (1+i, -1+i, -1-i, 1-i)$



[tanβ=50]

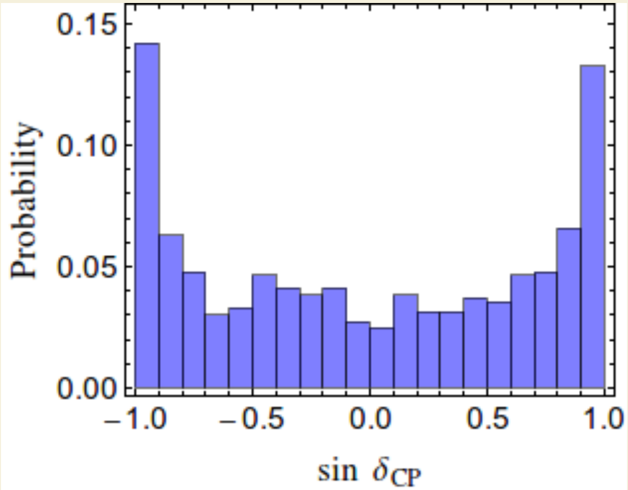
IO is fine-tuned: no anarchy

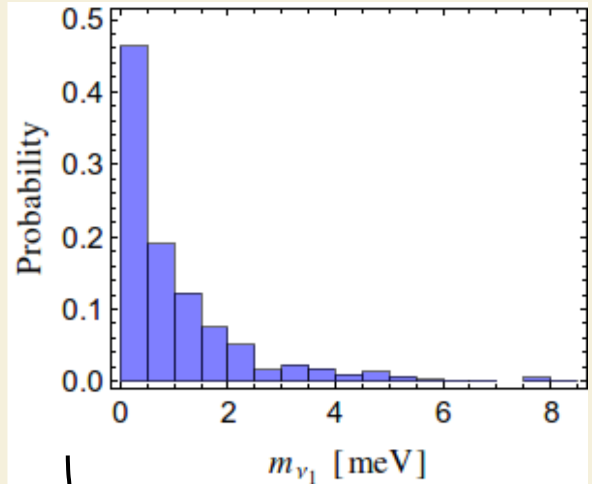
for NO fine-tuning acceptable

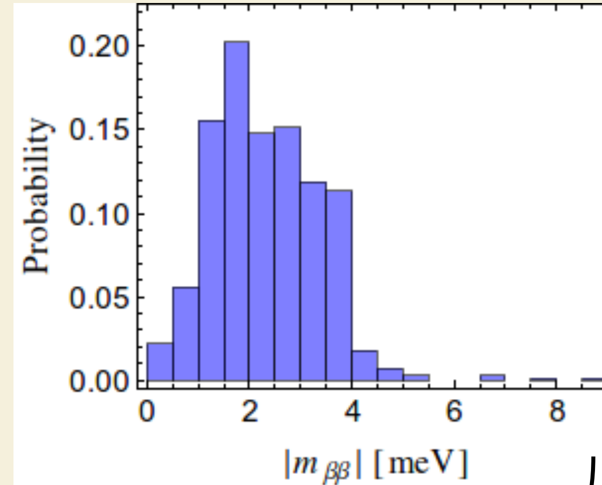
$p-$value	0.50	0.10	**0.05**	0.001
χ^2_{min}/ν (for $\nu = 5$)	≤ 0.87	≤ 1.85	$\leq \mathbf{2.21}$	≤ 4.10
successful cases (NO)	0.1%	0.7%	**1.2%**	5.6%
successful cases (IO)	$< 10^{-3}$%	$< 10^{-3}$%	$\mathbf{10^{-3}}$**%**	0.01%

TABLE III. The fraction of successful events obtained for different $p-$values from random samples of $\mathcal{O}(1)$ Yukawa couplings in case of normal and inverted ordering in the neutrino masses.

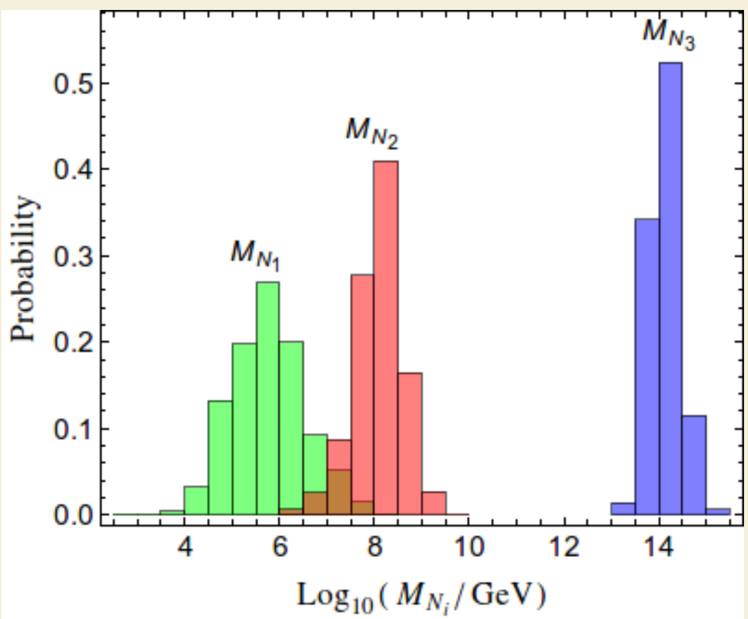
our predictions for NO [tanβ=50]







beyond the reach of current experiments:
the model can be easily falsified



RH neutrinos too-light:
leptogenesis from Lightest or NTL
reutrino decay does not work

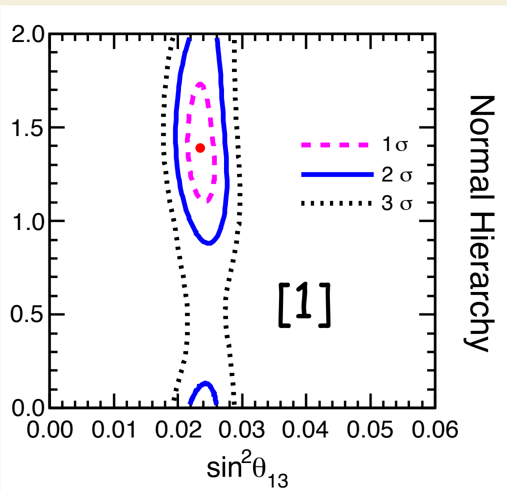
special features of data should be considered accidental in previous picture

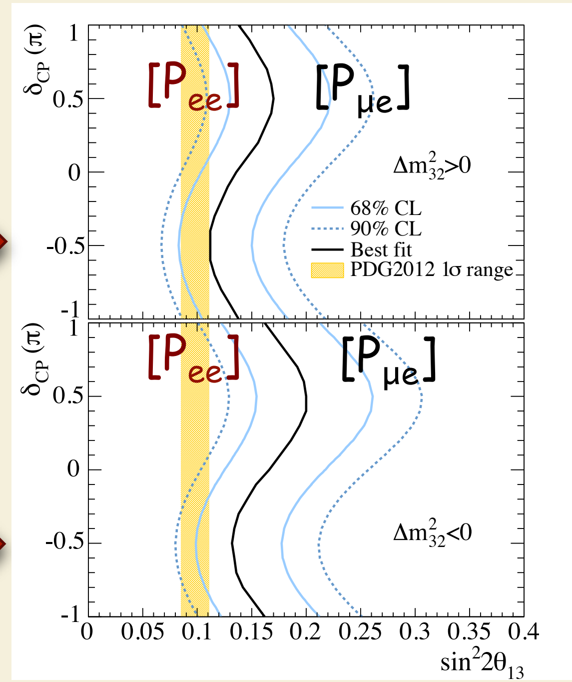
1 today most precise single determination of ϑ_{23} is from T2K ($P_{\mu\mu}$) [1403.1532]

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

well compatible with ϑ_{23} maximal

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





[T2K: 1311.4750 and 1311.4114]

global fit:
G.-Garcia, Maltoni, Salvado, Schwetz 1209.3023
[1] Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo 1312.2878
Forero, Tortola, Valle 1405.7540

both ϑ_{23} maximal and $\delta_{CP} = -\pi/2$ can be explained by flavour symmetries [-> next talks]

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
first principles

back up slides

Observables	$\tan\beta = 10$	$\tan\beta = 50$
y_t	0.48 ± 0.02	0.51 ± 0.03
y_b	0.051 ± 0.002	0.37 ± 0.02
y_τ	0.070 ± 0.003	0.51 ± 0.04
m_u/m_c	0.0027 ± 0.0006	0.0027 ± 0.0006
m_d/m_s	0.051 ± 0.007	0.051 ± 0.007
m_e/m_μ	0.0048 ± 0.0002	0.0048 ± 0.0002
m_c/m_t	0.0025 ± 0.0002	0.0023 ± 0.0002
m_s/m_b	0.019 ± 0.002	0.016 ± 0.002
m_μ/m_τ	0.059 ± 0.002	0.050 ± 0.002
$\lvert V_{us}\rvert$	0.227 ± 0.001	
$\lvert V_{cb}\rvert$	0.037 ± 0.001	
$\lvert V_{ub}\rvert$	0.0033 ± 0.0006	
J_{CP}	0.000023 ± 0.000004	
$\Delta_S/10^{-5}$ eV^2	7.54 ± 0.26 (NO or IO)	
$\Delta_A/10^{-3}$ eV^2	2.44 ± 0.08 (NO)	2.40 ± 0.07 (IO)
$\sin^2\theta_{12}$	0.308 ± 0.017 (NO or IO)	
$\sin^2\theta_{23}$	0.425 ± 0.029 (NO)	0.437 ± 0.029 (IO)
$\sin^2\theta_{13}$	0.0234 ± 0.0022 (NO)	0.0239 ± 0.0021 (IO)

TABLE I. The GUT scale values of the charged fermion masses and quark mixing parameters from [30] that we use in our analysis. The lepton mixing angles and solar and atmospheric mass differences are taken from a global fit analysis [34] ignoring the running effects. NO (IO) stands for the normal (inverted) ordering in the neutrino masses.

$$F_{16_i} = \sqrt{\frac{2\mu_i}{1-e^{-2\mu_i\rho}}} = \begin{cases} \sqrt{2\mu_i} & (\mu_i > 0 \quad \mu_i\rho \geq 1) \\ \sqrt{2\left|\mu_i\right|}e^{-\left|\mu_i\right|\rho} & (\mu_i < 0 \quad \left|\mu_i\right|\rho \geq 1) \\ 1/\sqrt{\rho} & (\left|\mu_i\right|\rho < 1) \end{cases}$$

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

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

when $y_e = F_{E^c}Y_eF_L$ diagonal

Explicit computation in RS

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

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

$$M_{KK} > O(10)\ TeV$$

comparable bounds from e EDM

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

➡ 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:

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

[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]

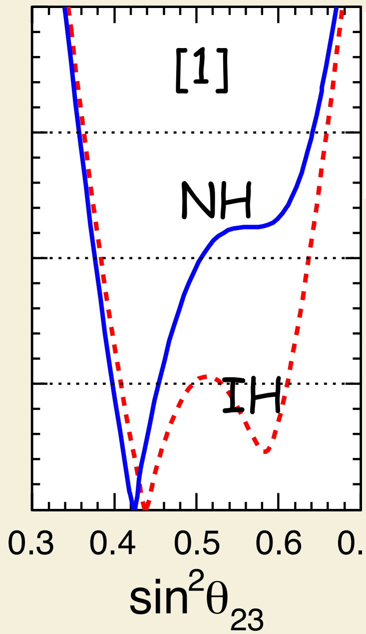
$$\sin^2\vartheta_{23} = \begin{cases} 0.514^{+0.055}_{-0.056} & \text{(NH)} \\ 0.511^{+0.055}_{-0.055} & \text{(IH)} \end{cases}$$

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 ($P_{\mu e}$)

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

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



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

[2]

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 $P_{\mu\mu}$

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

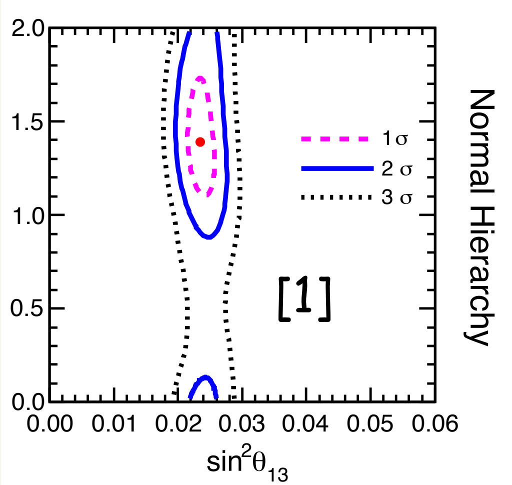
ϑ_{23} nearly maximal would be a crucial piece of information

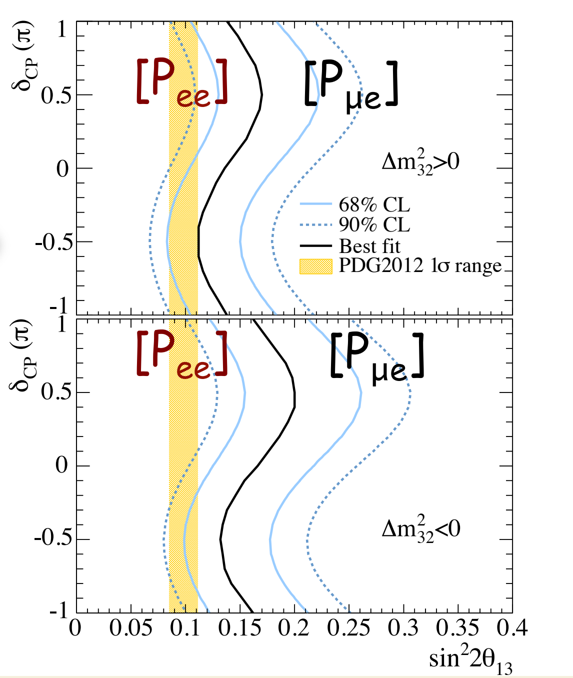
ϑ_{23} cannot be made maximal by RGE evolution
[barring tuning of b.c. and/or thresold corrections]

when a flavour symmetry is present, ϑ_{23} is determined entirely by breaking effects [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},...

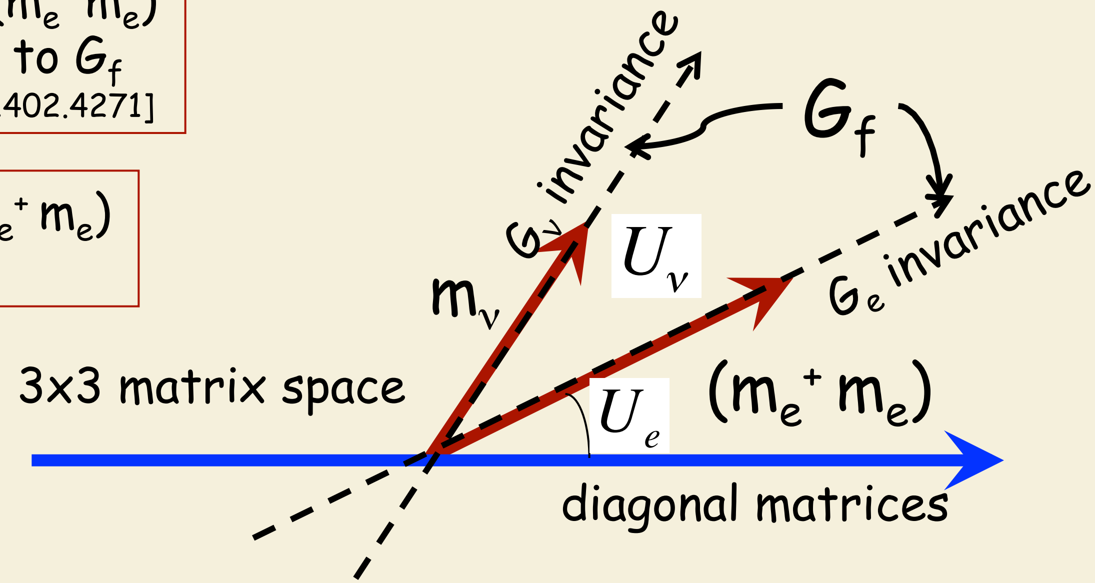
$U_{PMNS} = U^0_{PMNS}$ + corrections

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

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



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

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

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 $\vartheta^0_{12} \quad \vartheta^0_{23} \quad \vartheta^0_{13} \quad \delta_{CP}$

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$_1$:

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

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

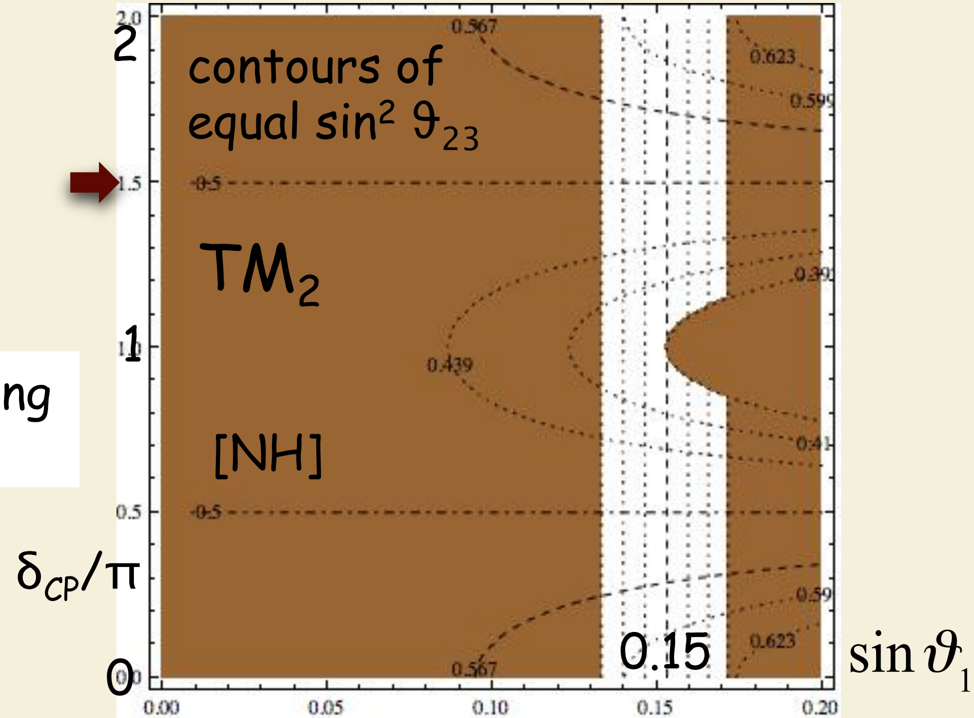
TM$_2$:

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

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

[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!

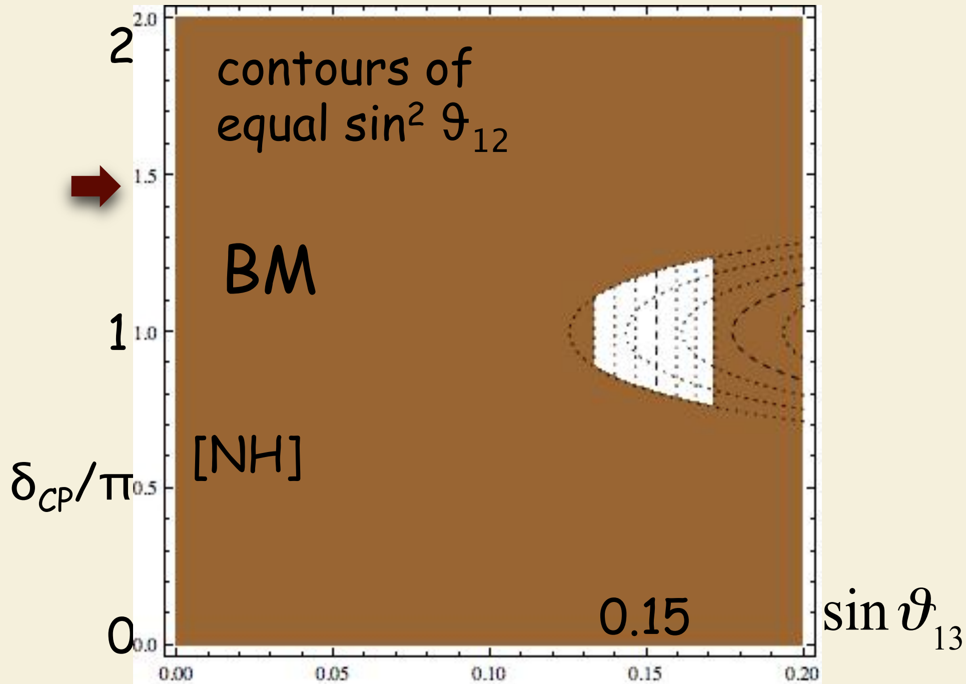
[Fonseca, Grimus 1405.3678]

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

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

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

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

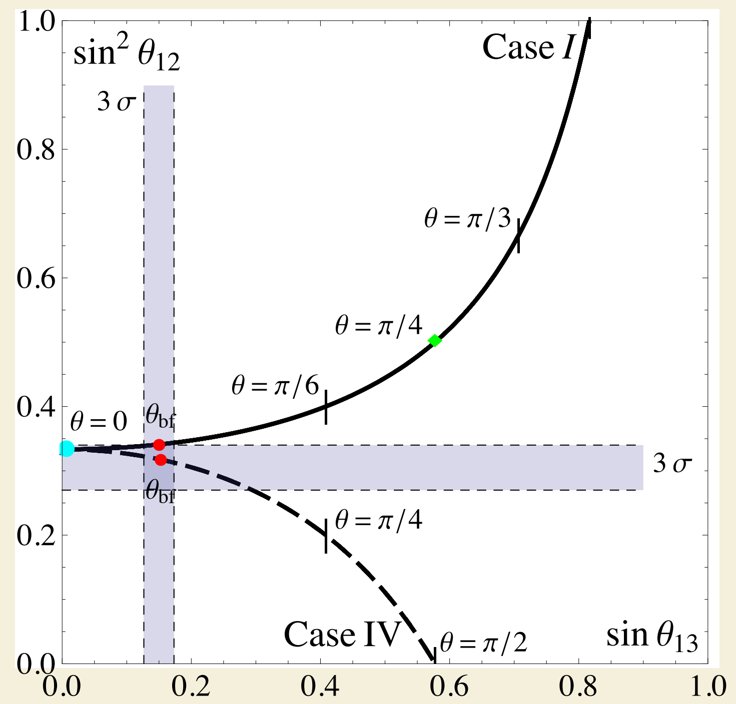
mixing angles and CP violating phases

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

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

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

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



back up slides

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

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

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)

2011/2012 breakthrough

-- LBL experiments searching for $\nu_\mu \to \nu_e$ conversion

-- SBL reactor experiments searching for anti-ν_e disappearance

[see Fogli's talk]

	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

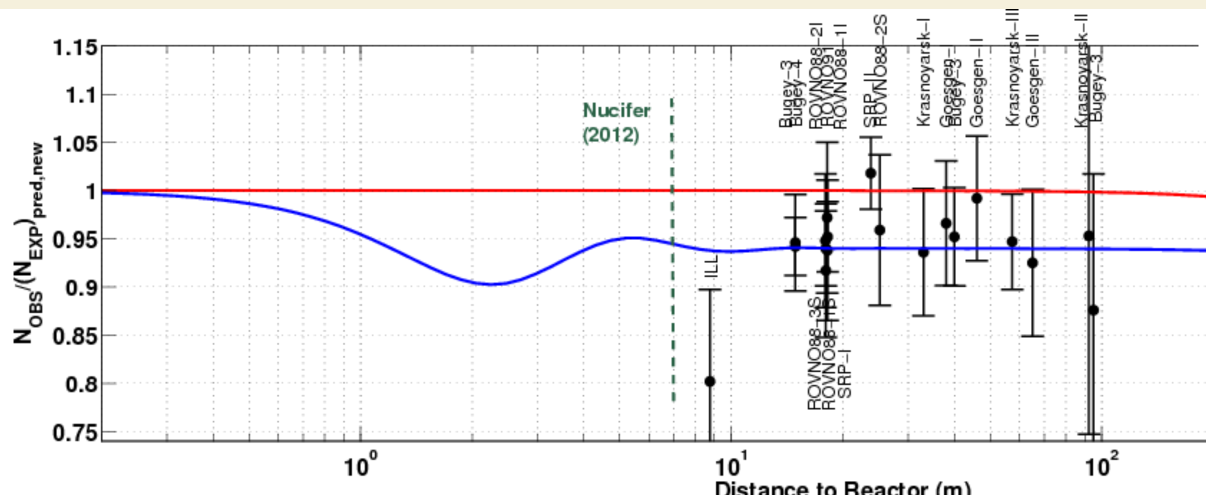
impact on flavor symmetry (part 3)

→ 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

$\vartheta_{es} \approx 0.2$

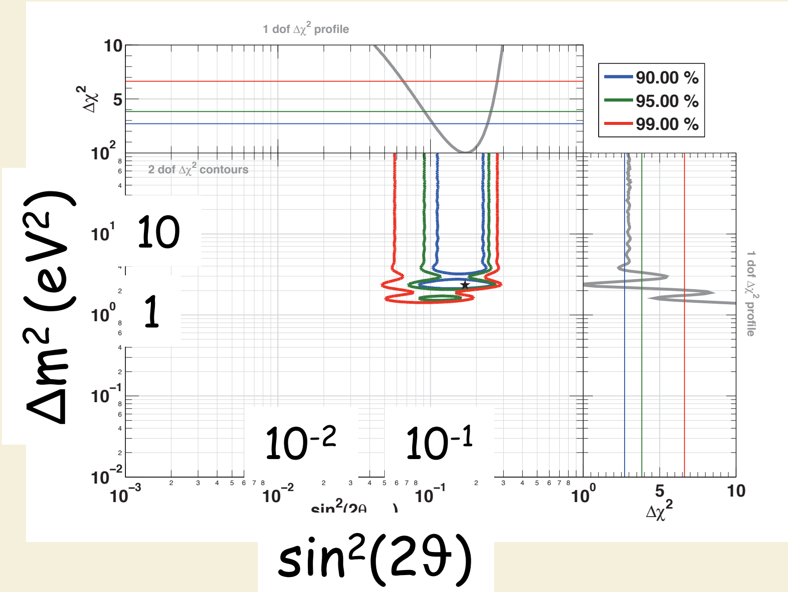
$\Delta m^2 \approx m_s^2 \geq 1\, eV^2$

supported by the Gallium anomaly

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

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

[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

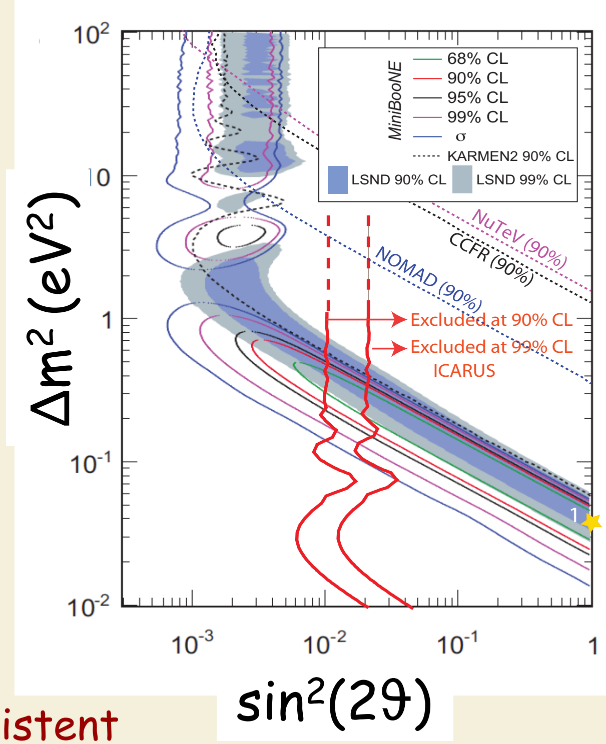
evidence for $\nu_\mu \rightarrow \nu_e$ appearance in accelerator experiments

exp		$E(MeV)$	$L(m)$	
$LSND$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$10 \div 50$	30	3.8σ
$MiniBoone$	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$300 \div 3000$	541	3.8σ [signal from low-energy region]

parameter space limited by negative results from Karmen and ICARUS

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

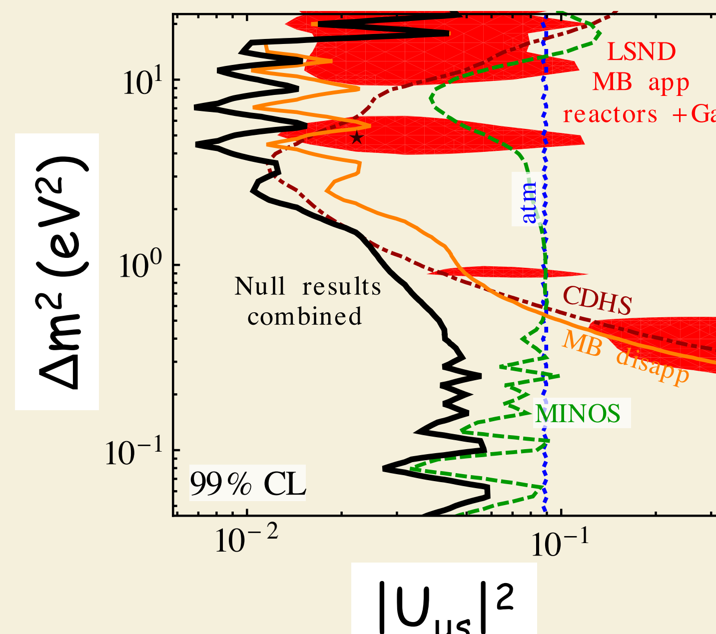
$$\Delta m^2 \approx 0.5\, eV^2$$



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



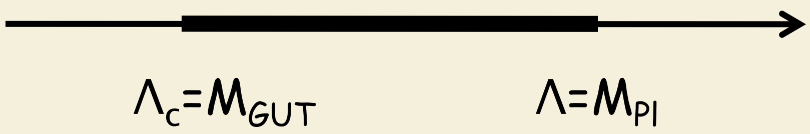
by ignoring LSND/Miniboone data the reactor anomaly can be accommodated by $m_s \geq 1$ eV and $\vartheta_{es} \approx 0.2$
[not suitable for WDM, more on this later]

other realizations of Anarchy (II)

Nelson-Strassler [0006251 "Suppressing Flavor Anarchy"]

Anarchy can arise when matter chiral supermultiplets X_i of the MSSM are coupled to a superconformal sector in some finite energy range

e.g.



large positive anomalous dimensions for X_i: $\qquad \frac{\gamma_i}{2} \equiv d(X_i) - 1 > 0$

$$K = \sum_i Z_i X_i^+ X_i + \ldots \qquad Z_i(\Lambda_c) = \underbrace{Z_i(\Lambda)}_{1} \left(\frac{\Lambda_c}{\Lambda}\right)^{-\gamma_i}$$

Anarchy through wave function renormalization: $X_i \to F_{X_i} X_i$

$$w = Y_{ij} X_i X_j H + \ldots \to (F_{X_i} Y_{ij} F_{X_j}) X_i X_j H + \ldots \qquad F_{X_i} = \left(\frac{\Lambda_c}{\Lambda}\right)^{\frac{\gamma_i}{2}} < 1$$

[as in FN with a single flavon and positive FN charges]

no underlying flavour symmetry

[an anomaly free R symmetry is generated dynamically at the IR stable fixed point: $\dim(X_i) = 2/3\, R(X_i)$]

anomalous dimensions γ_i calculable when gauge group and field content are known

[Polland, Simmons-Duffin 0910.4585]