UNIVERSITY OF Southampton
School of Physics and Astronomy

SUSY and Neutrinos

Steve King

19th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2011)

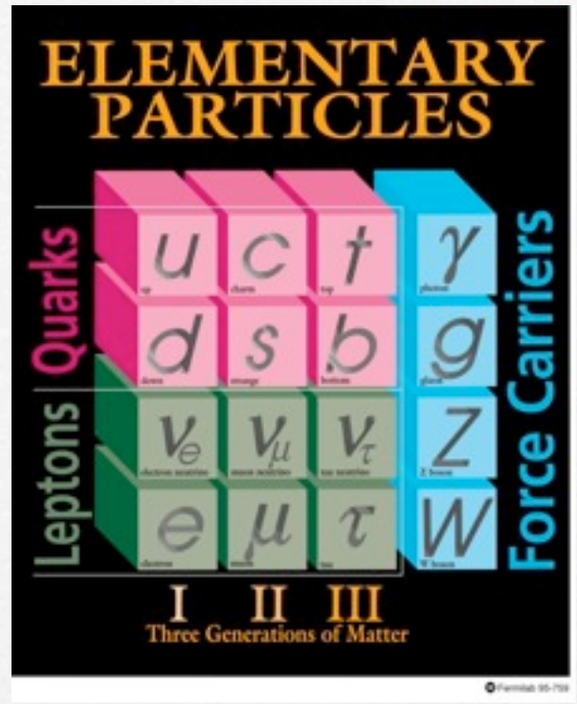
Fermilab, 1st September 2011

Neutrinos at a glance

- Neutrinos have tiny masses, not very hierarchical
- Neutrinos mix a lot (unlike the quarks)
- 7 (or 9) new parameters for SM
- Lepton Flavor is not conserved
- Of all fermions, neutrinos are least understood
- First new physics beyond the SM...because...

In the Standard Model...

1. There are no right-handed neutrinos
2. There are only Higgs doublets of $SU(2)_L$
3. There are only renormalizable terms



- So neutrinos are massless, with ν_e, ν_μ, ν_τ distinguished by separate lepton numbers L_e, L_μ, L_τ
- Neutrinos and anti-neutrinos are distinguished by the total conserved lepton number $L = L_e + L_\mu + L_\tau$
- To generate neutrino mass we must relax 1 and/or 2 and/or 3 e.g. type I see-saw adds right-handed neutrinos

Implications for PP and Cosmology

- Origin of tiny neutrino mass

  Extra dimensions, See-saw mechanism, RPV SUSY

- Unification of matter, forces and flavour

  SUSY, GUTs, Family Symmetry,...

Particle Physics

- Did neutrinos play a role in our existence?

  Leptogenesis

- Did neutrinos play a role in forming galaxies?

  Hot/Warm Dark matter component

- Did neutrinos play a role in birth of the universe?

  Sneutrino inflation

- Can neutrinos shed light on dark energy? $\Lambda \sim m_\nu^4$

Cosmology

Neutrino mass from see-saw

P.Minkowski, PLB67(1977)421

Possible type II contribution

Dirac matrix

Diagonalise to give effective mass

$M^{\nu}\overline{\nu_L}\nu_L^c$

$$\begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_{LR} \\ m_{LR}^T & M_{RR} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

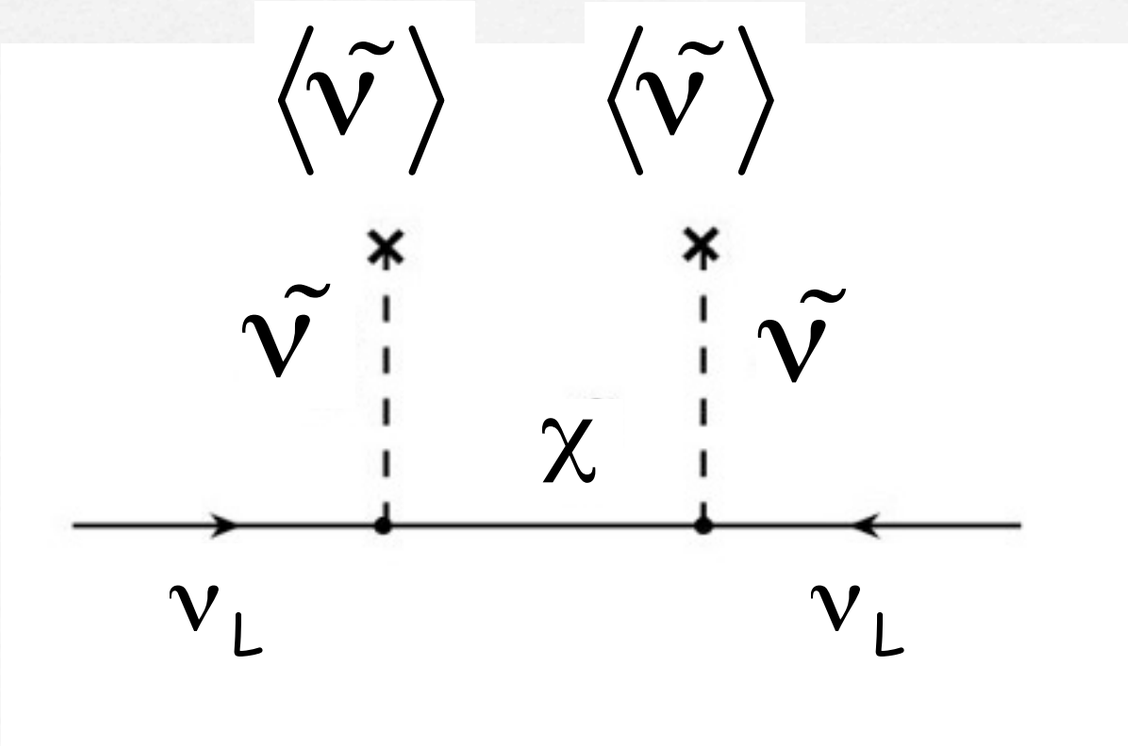
Heavy Majorana matrix

Light Majorana matrix $\longrightarrow$ $M^{\nu} = m_{LR} M_{RR}^{-1} m_{LR}^T \sim \frac{m_D^2}{M_R}$

- A very natural and appealing mechanism!
- Neutrinos are so light because RH neutrino get heavy Majorana masses (L number violated at HE)
- Neutrinos are a probe of physics at high energy scales up to M_{GUT}
- Large scales imply a new hierarchy problem $\longrightarrow$ SUSY!

Neutrino mass from SUSY

- Majorana masses can be generated via RPV SUSY
- Scalar partners of lepton doublets (slepton doublets) have same quantum numbers as Higgs doublets
- If R-parity is violated then sneutrinos may get (small) VEVs inducing a mixing between neutrinos and neutralinos χ



$$m^{\nu}_{LL} \approx \frac{\langle\tilde{\nu}\rangle^2}{M_{\chi}} \approx \frac{MeV^2}{TeV} \approx eV$$

LHC prediction from mSUGRA:

$$\tan^2\theta_{\rm atm} \simeq \frac{BR(\tilde{\chi}_1^0 \to \mu^{\pm} W^{\mp})}{BR(\tilde{\chi}_1^0 \to \tau^{\pm} W^{\mp})}$$

Drees, Diaz, Hirsch, Porod, Romao, Valle,...

De Campos, Eboli, Hirsch, Magro, Porod, Restrepo, Valle

Three Neutrino Mixing

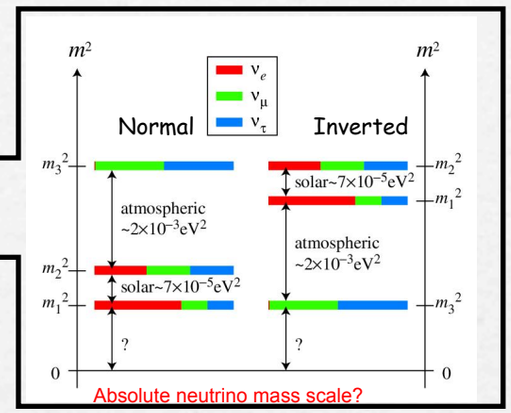
Standard Model states

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Pontecorvo
Maki
Nakagawa
Sakata

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino mass states



$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij}$
$c_{ij} = \cos\theta_{ij}$

Atmospheric | Reactor | Solar | Majorana

Oscillation phase δ

Majorana phases α_1, α_2

3 masses + 3 angles + 1 (or 3) phase(s)
= 7 (or 9) new parameters for SM

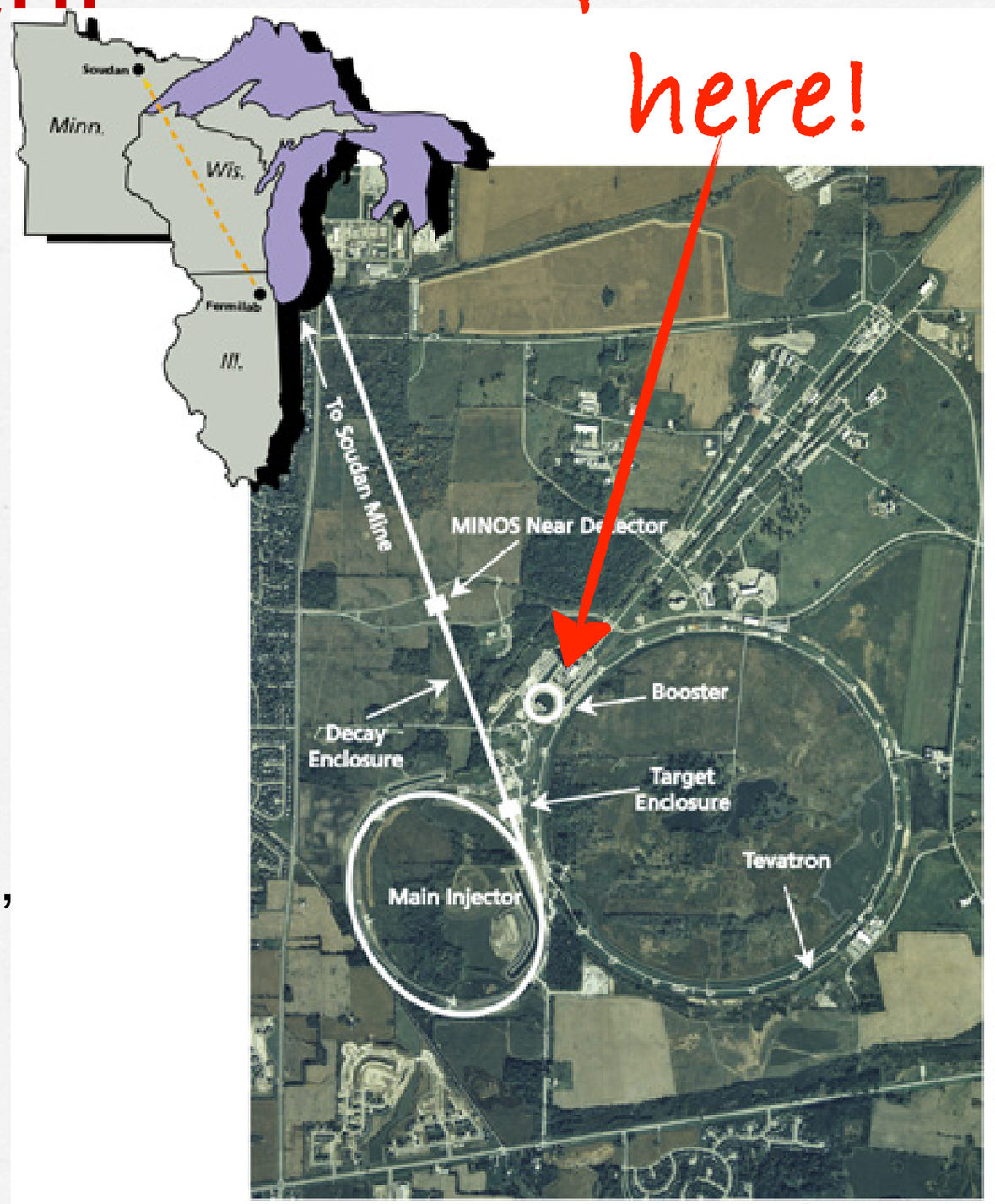
History of Neutrino Mixing

- ☑ Atmospheric ν_μ disappear, large θ_{23} (SK) (98)
- ☑ Solar ν_e disappear, large θ_{12} (H/S,Ga,SK) (02)
- ☑ Solar ν_e are converted to $\nu_\mu + \nu_\tau$ (SNO) (02)
- ☑ Reactor anti-ν_e disappear/reappear (KamLAND) (04)
- ☑ Accelerator ν_μ disappear (K2K 04 , MINOS 06)
- ☑ Accelerator ν_μ converted to ν_τ (OPERA 10)
- ☑ Accelerator ν_μ converted to ν_e , θ_{13} (T2K, MINOS) (11)

MINOS Experiment

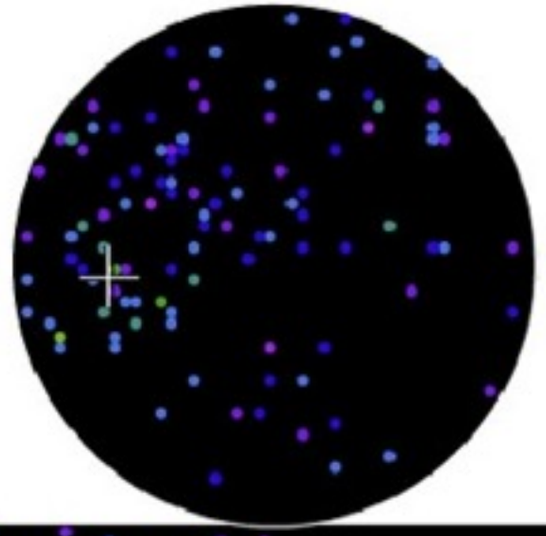
Chris Smith

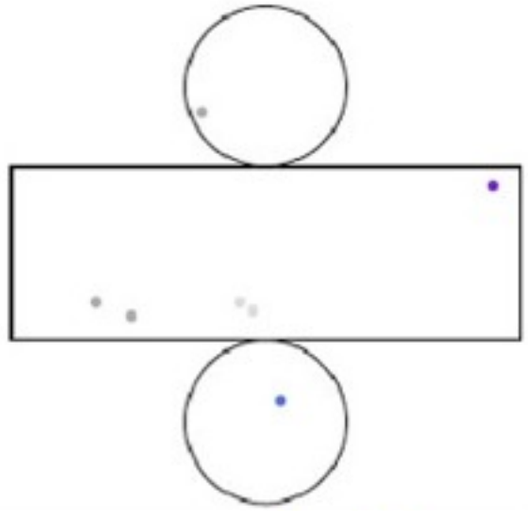
- Main Injector Neutrino Oscillation Search
- High power ν_μ beam produced by 120 GeV protons from the Main Injector at FNAL
- Two functionally identical detectors:
- Near detector (ND) at Fermilab to measure the beam composition and energy spectrum
- Far detector (FD), 735km away, in the Soudan Mine, Minnesota to search for evidence of oscillations



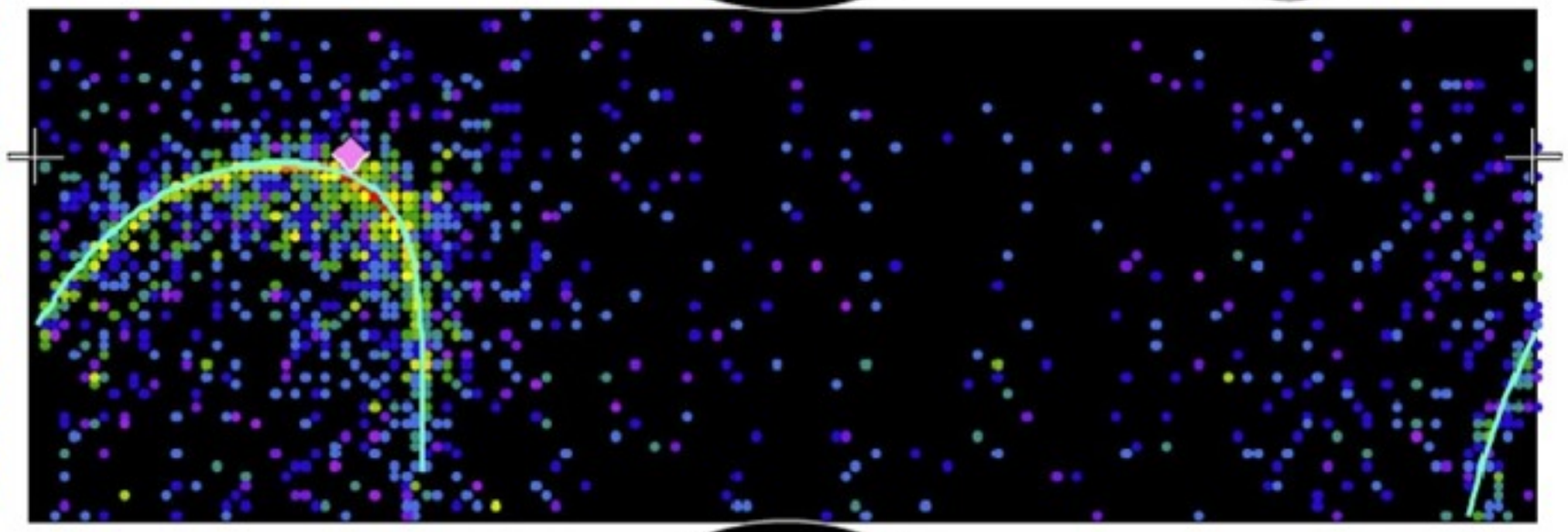
Super-Kamiokande IV

T2K Beam Run 33 Spill 822275
Run 66778 Sub 585 Event 134229437
10-05-12:21:03:22
T2K beam dt = 1902.2 ns
Inner: 1600 hits, 3681 pe
Outer: 2 hits, 2 pe
Trigger: 0x80000007
D_wall: 614.4 cm
e-like, p = 381.8 MeV/c



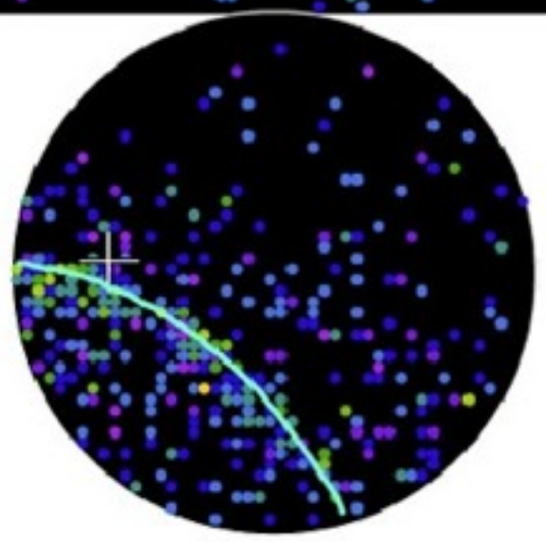


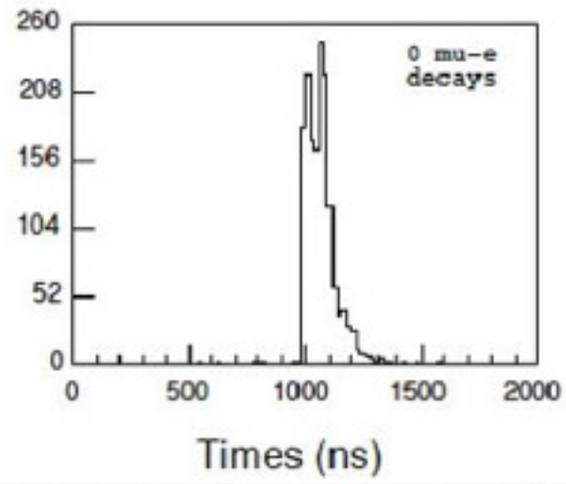
Charge(pe)
- >26.7
- 23.3-26.7
- 20.2-23.3
- 17.3-20.2
- 14.7-17.3
- 12.2-14.7
- 10.0-12.2
- 8.0-10.0
- 6.2- 8.0
- 4.7- 6.2
- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- < 0.2



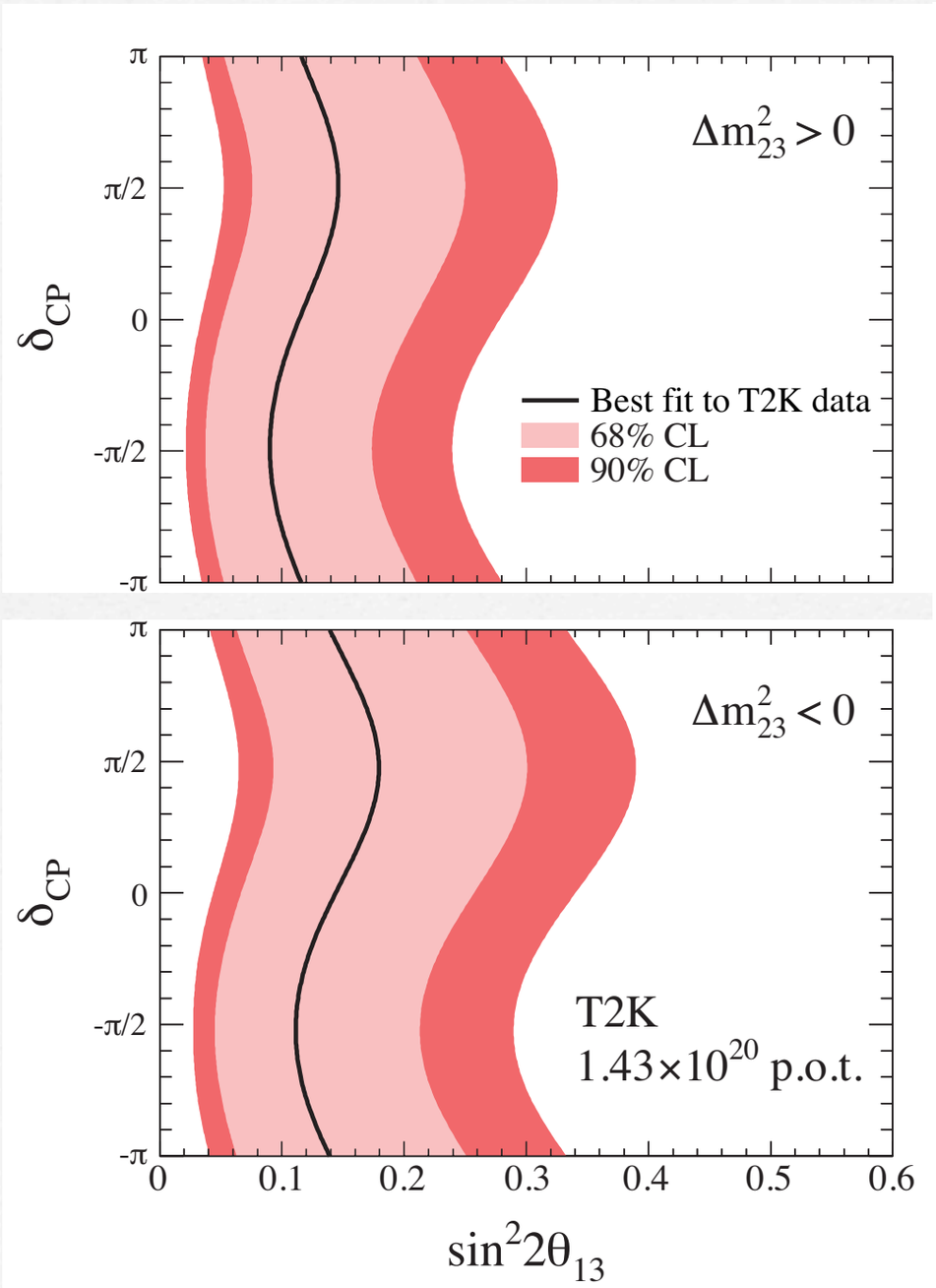
T2K

$\nu_\mu \rightarrow \nu_e$

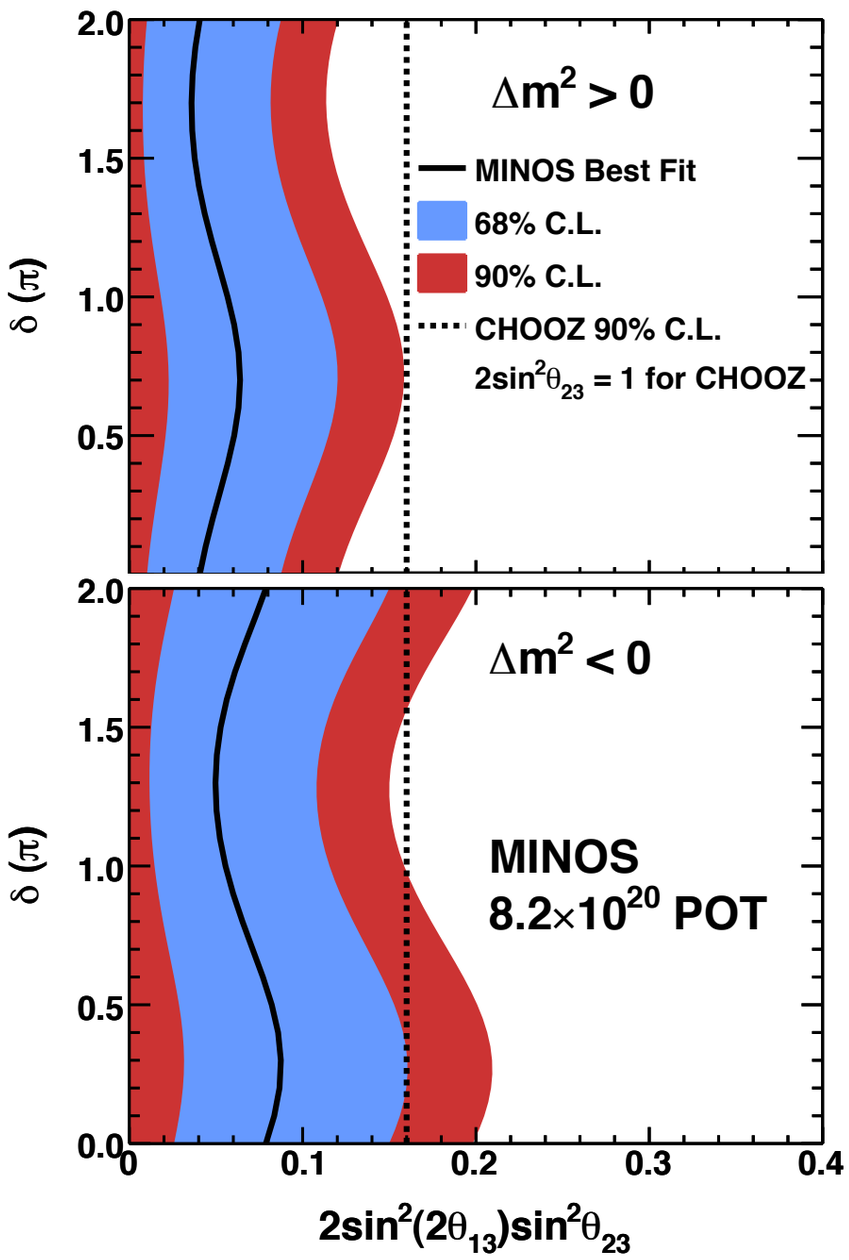




T2K


$\Delta m^2_{23} > 0$
Best fit to T2K data
68% CL
90% CL
$\Delta m^2_{23} < 0$
T2K
1.43×10^{20} p.o.t.
δ_{CP}
π
π/2
0
-π/2
-π
0
0.1
0.2
0.3
0.4
0.5
0.6
$\sin^2 2\theta_{13}$

MINOS


$\Delta m^2 > 0$
MINOS Best Fit
68% C.L.
90% C.L.
CHOOZ 90% C.L.
$2\sin^2\theta_{23}$ = 1 for CHOOZ
$\Delta m^2 < 0$
MINOS
8.2×10^{20} POT
δ (π)
2.0
1.5
1.0
0.5
0.0
0
0.1
0.2
0.3
0.4
$2\sin^2(2\theta_{13})\sin^2\theta_{23}$

Papers since T2K/MINOS

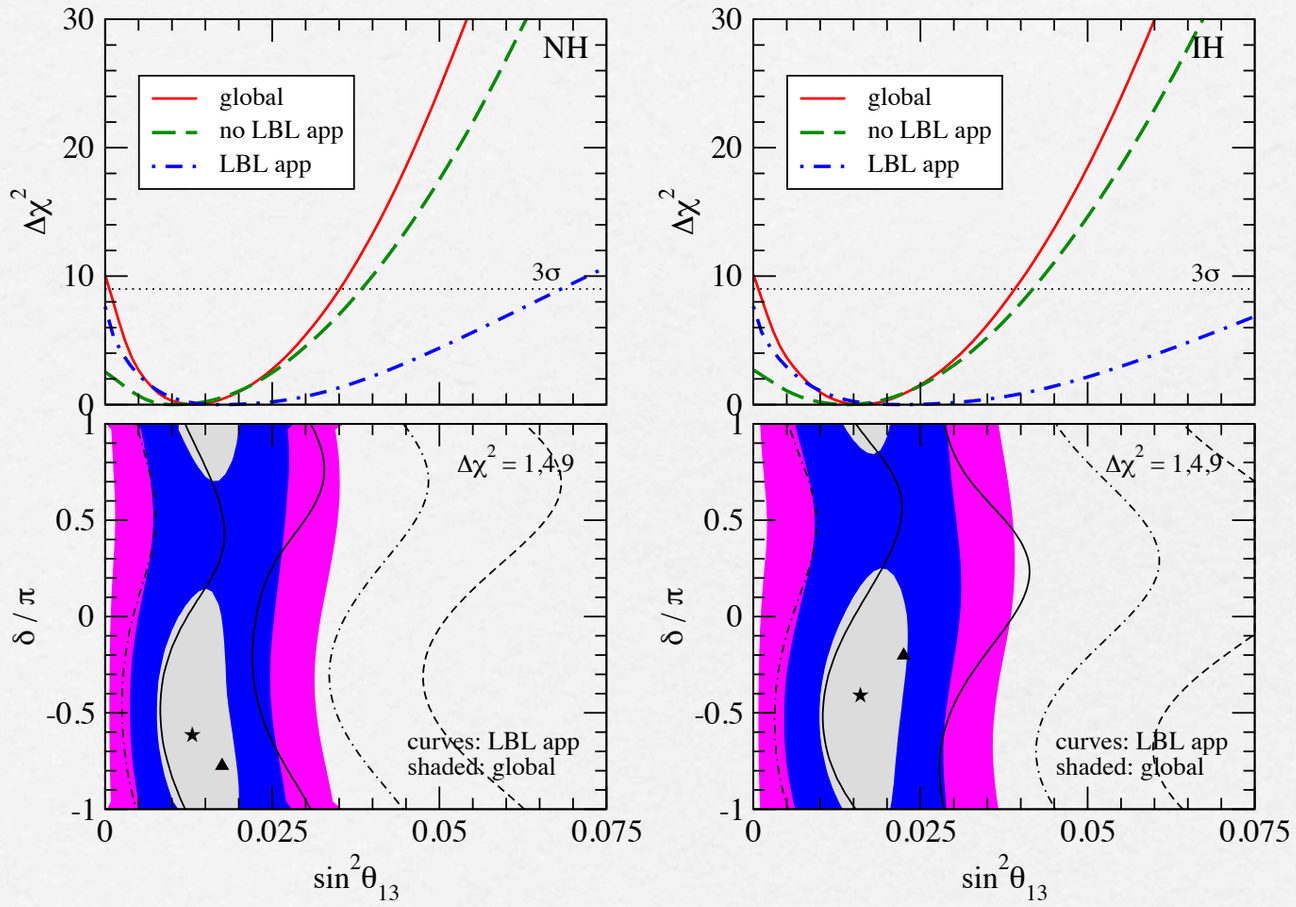
- H.-J. He, F.-R. Yin, arXiv:1104.2654; Z.-Z. Xing, arXiv:1106.3244; N. Qin and B. Q. Ma, Phys. Lett. B **702** (2011) 143 [arXiv: 1106.3284]; Y. j. Zheng and B. Q. Ma, arXiv:1106.4040; S. Zhou, arXiv:1106.4808; T. Araki, arXiv:1106.5211; N. Haba, R. Taka- hashi, arXiv:1106.5926; D. Meloni, arXiv: 1107.0221; S. Morisi, K. M. Patel and E. Peinado, arXiv:1107.0696; W. Chao, Y.-J. Zheng, arXiv:1107.0738; H. Zhang, S. Zhou, arXiv: 1107.1097; X. Chu, M. Dhen, T. Hambye, arXiv:1107.1589; P. S. B. Dev, R. N. Mohapatra, M. Severson, arXiv:1107.2378; R. d. A. Toorop, F. Feruglio, C. Hagedorn, arXiv:1107.3486; S. Antusch, V. Maurer, arXiv:1107.3728; Q. H. Cao, S. Khalil, E. Ma and H. Okada, arXiv:1108.0570; D. Marzocca, S. T. Petcov, A. Romanino and M. Spinrath, arXiv:1108.0614; S. F. Ge, D. A. Dicus and W. W. Repko, arXiv:1108.0964; F. Bazzocchi, arXiv:1108.2497; Y. Shimizu, M. Tanimoto and A. Watanabe, arXiv:1105.2929; X. G. He and A. Zee, arXiv:1106.4359; S. F. King and C. Luhn, arXiv:1107.5332

Plus many more

Global Fits

Schwetz, Tortola, Valle '11

parameter	best fit $\pm 1\sigma$
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	$2.50^{+0.09}_{-0.16}$ $-(2.40^{+0.08}_{-0.09})$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$
$\sin^2\theta_{23}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06
$\sin^2\theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$ $\left(-0.41^{+0.65}_{-0.70}\right)\pi$



c.f.Fogli, Lisi, Marrone,Palazzo, Rotunno'11

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.58	0.306	0.021	0.42	2.35

King 0710.0530

Model Independent Parametrisation

$$U_{\rm PMNS} \approx \begin{pmatrix} \frac{2}{\sqrt{6}}(1-\frac{1}{2}s) & \frac{1}{\sqrt{3}}(1+s) & \frac{1}{\sqrt{2}}re^{-i\delta} \\ -\frac{1}{\sqrt{6}}(1+s-a+re^{i\delta}) & \frac{1}{\sqrt{3}}(1-\frac{1}{2}s-a-\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}}(1+a) \\ \frac{1}{\sqrt{6}}(1+s+a-re^{i\delta}) & -\frac{1}{\sqrt{3}}(1-\frac{1}{2}s+a+\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}}(1-a) \end{pmatrix} P$$

$$\sin\theta_{12} = \frac{1}{\sqrt{3}}(1+s)\ , \qquad \sin\theta_{23} = \frac{1}{\sqrt{2}}(1+a)\ , \qquad \sin\theta_{13} = \frac{r}{\sqrt{2}}$$

$$\theta_{12} = 34^o \pm 1^o \qquad \theta_{23} = 46^o \pm 4^o \qquad \theta_{13} = 7.5^o \pm 1.5^o$$

$$s = -0.03 \pm 0.03 \qquad a = 0.015 \pm 0.07 \qquad r = 0.18 \pm 0.04$$

s = solar a = atmospheric r = reactor

related parametrisations by Pakvasa, Rodejohann, Weiler; Parke; ...

Harrison, Perkins, Scott; Xing

Tri-bimaximal

Excluded by T2K $r \neq 0$

$$s = a = r = 0$$

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

$$M_\nu = \frac{v^2 A A^T}{M_A} + \frac{v^2 B B^T}{M_B}$$

$$A \propto \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \quad B \propto \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$$\frac{A A^T}{M_A} \gg \frac{B B^T}{M_B}$$

hep-ph/0506297

CSD

King; Antusch,Boudjemaa,K; Morisi,Patel,Peinado

Tri-bimaximal-reactor

OK

$$s = a = 0, \; r \neq 0$$

$$U_{TBR} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} r e^{-i\delta} \\ -\frac{1}{\sqrt{6}}(1 + r e^{i\delta}) & \frac{1}{\sqrt{3}}(1 - \frac{1}{2} r e^{i\delta}) & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}}(1 - r e^{i\delta}) & -\frac{1}{\sqrt{3}}(1 + \frac{1}{2} r e^{i\delta}) & \frac{1}{\sqrt{2}} \end{pmatrix} P$$

$$M_\nu = \frac{v^2 A A^T}{M_A} + \frac{v^2 B B^T}{M_B}$$

$$A \propto \begin{pmatrix} r e^{-i\delta} \\ 1 \\ -1 \end{pmatrix} \quad B \propto \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$$\frac{A A^T}{M_A} \gg \frac{B B^T}{M_B}$$

0903.3199

PCSD

Lam; Albright,Rodejohann

Trimaximal1

OK for range of δ

$$a = r\cos\delta \qquad s = 0$$

$$U_{\mathrm{TM}_1} = P'\begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}}re^{-i\delta} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}}(1-\frac{3}{2}re^{i\delta}) & \frac{1}{\sqrt{2}}(1+re^{-i\delta}) \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}}(1+\frac{3}{2}re^{i\delta}) & -\frac{1}{\sqrt{2}}(1-re^{-i\delta}) \end{pmatrix} P$$

$$M_\nu = \frac{v^2 A A^T}{M_A} + \frac{v^2 B B^T}{M_B}$$

$$A \propto \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \quad B \propto \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} \text{ or } B \propto \begin{pmatrix} 1 \\ 0 \\ 2 \end{pmatrix}$$

$$\frac{AA^T}{M_A} \gg \frac{BB^T}{M_B}$$

CSD2 1108.4278

Haba,Watanabe,Yoshioka; He,Zee; Grimus,Lavoura; Albright,Rodejohann

Trimaximal2

OK for larger range of δ

$$a = -\frac{1}{2}r\cos\delta \qquad s = 0$$

$$U_{\mathrm{TM}_2} = P'\begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}}re^{-i\delta} \\ -\frac{1}{\sqrt{6}}(1+\frac{3}{2}re^{i\delta}) & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}}(1-\frac{1}{2}re^{-i\delta}) \\ -\frac{1}{\sqrt{6}}(1-\frac{3}{2}re^{i\delta}) & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}}(1+\frac{1}{2}re^{-i\delta}) \end{pmatrix} P$$

$$M_\nu = \frac{v^2 A A^T}{M_A} + \frac{v^2 B B^T}{M_B}$$

$$A \propto \begin{pmatrix} re^{-i\delta} \\ 1-re^{-i\delta} \\ -1 \end{pmatrix} \quad B \propto \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$$\frac{AA^T}{M_A} \gg \frac{BB^T}{M_B}$$

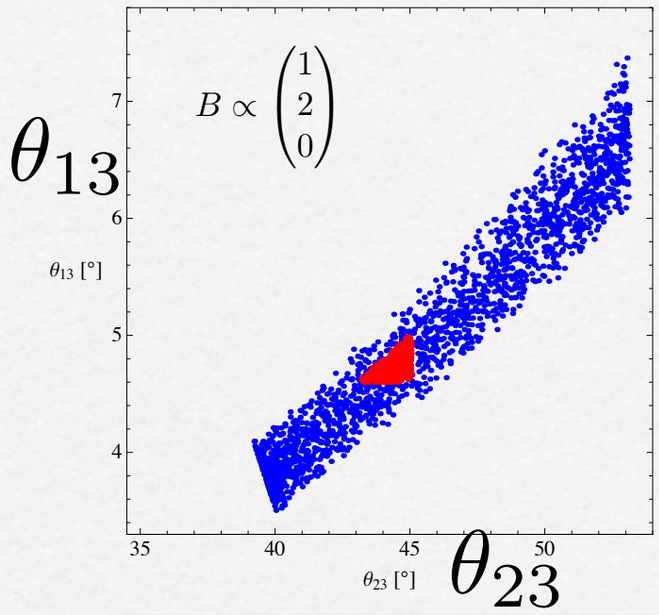
PCSD2 1011.6167

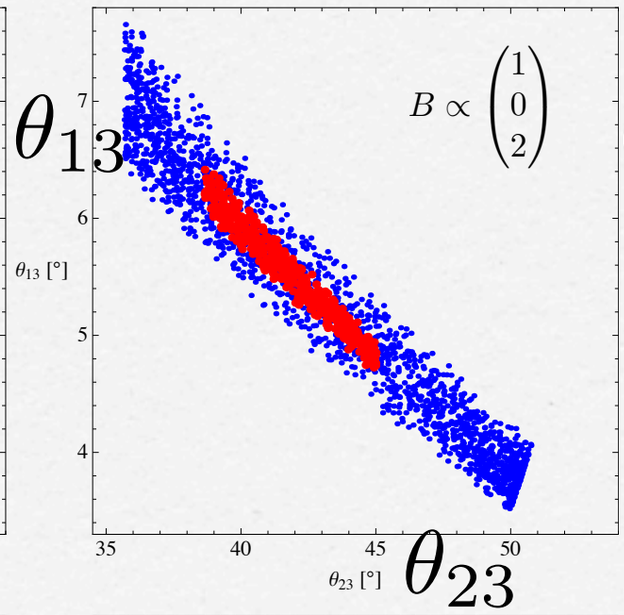
CSD2→TM1

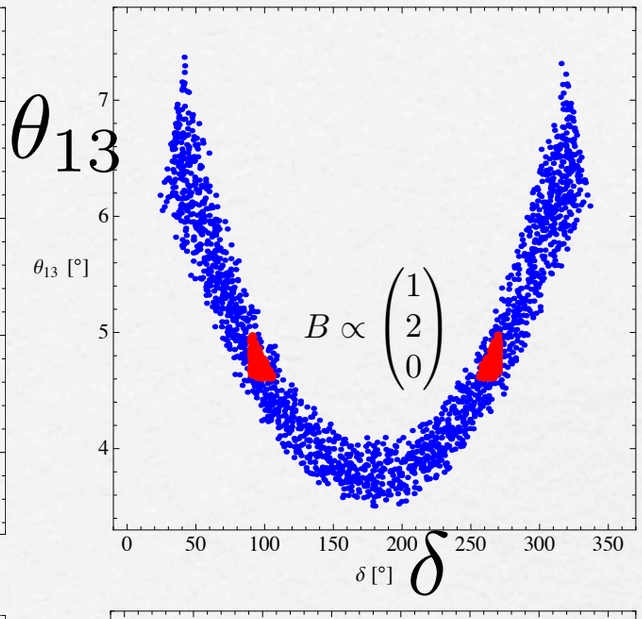
$$r = \frac{2}{3}\frac{m_2^\nu}{m_3^\nu} \sim \frac{2}{15} \quad \rightarrow \quad \theta_{13} \sim 5^\circ - 6^\circ$$

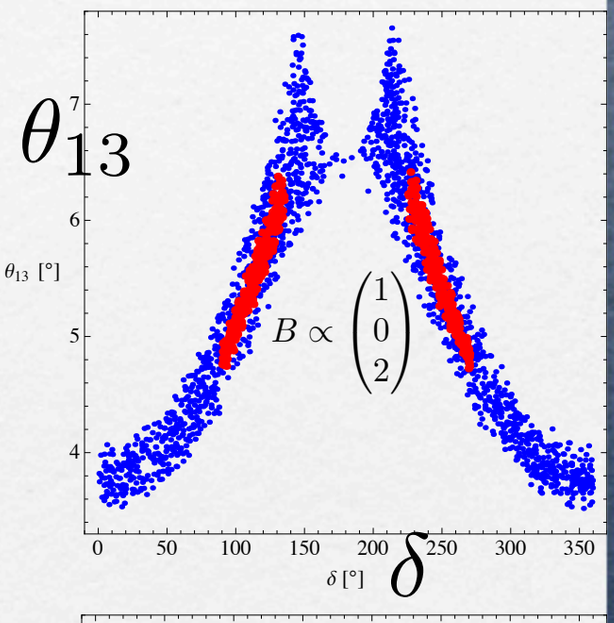
Antusch,King,Luhn,Spinrath **1108.4278**

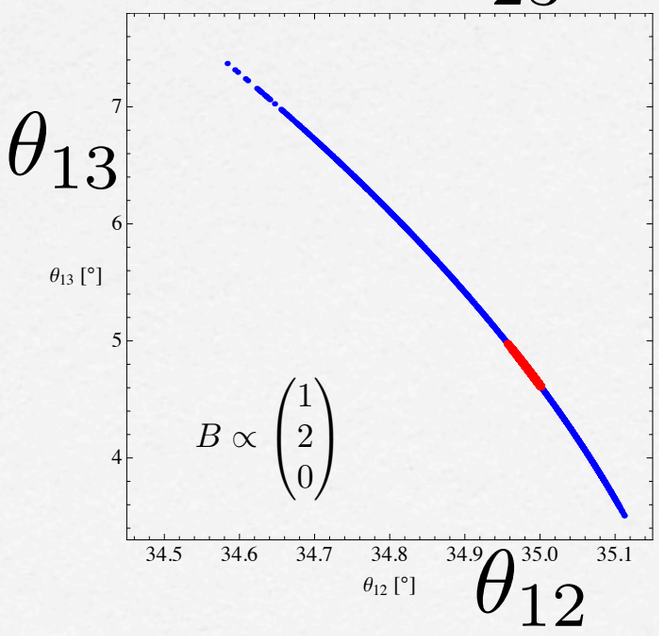
- Leptogenesis phase = Oscillation phase $Y_B \propto \pm \sin\delta$

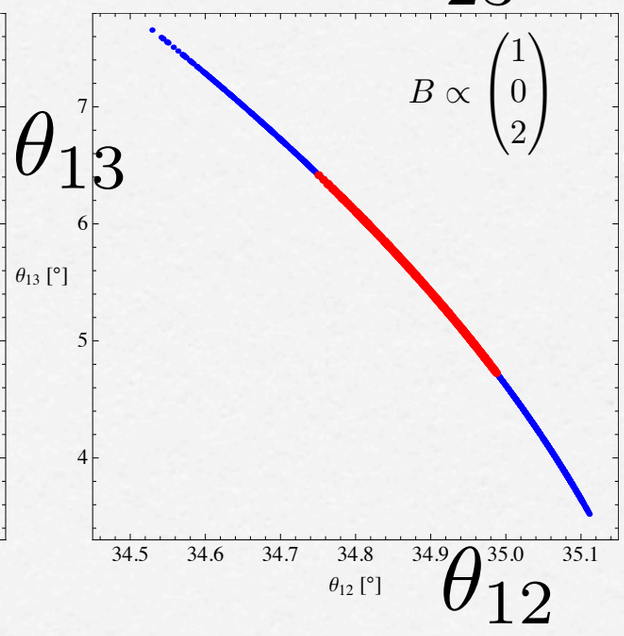


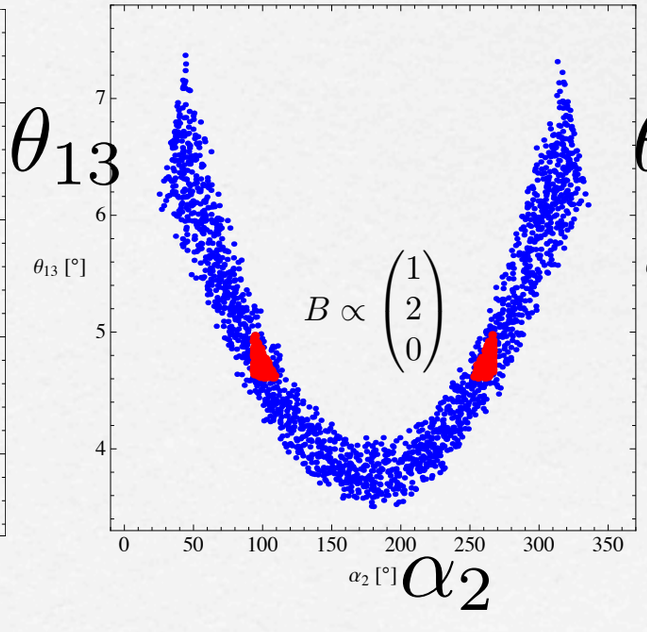


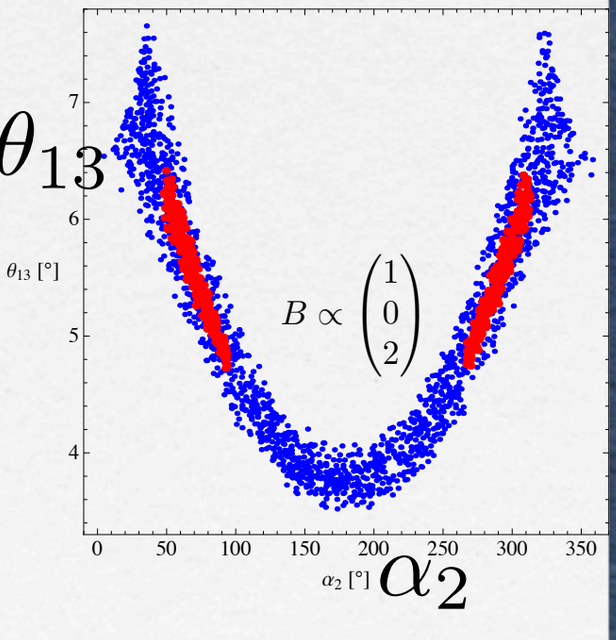












Family Symmetry

$$\frac{1}{3}\begin{pmatrix}-1 & 2 & 2\\ 2 & -1 & 2\\ 2 & 2 & -1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \omega^2 & 0\\ 0 & 0 & \omega\end{pmatrix}\mp\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 1\\ 0 & 1 & 0\end{pmatrix}$$

- TB mixing respects discrete symmetry $S, T, U \in S_4$

$$SM^\nu S = M^\nu \quad TM^E T = M^E \quad UM^\nu U = M^\nu$$ Lam

- TM2 mixing respects discrete sym $S, T \in A_4$

$$SM^\nu S = M^\nu \quad TM^E T = M^E$$

- Since TB mixing is a good approximation, this suggests an S4 family symmetry broken to A4

$$S_4 \to A_4$$ King, Luhn **1107.5332 JHEP**

A4 Model

Altarelli, Ferguglio

$L=3,\ N^c=3$

King, Luhn; Shimizu, Tanimoto, Watanabe

$$W^{\nu}_{A_4} = yLH_uN^c + (y_1\varphi_S + y_2\xi + y'_3\xi' + y''_3\xi'')N^cN^c$$

$$m_D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} y\,v_u \qquad \langle\varphi_S\rangle = v_S \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

TB violation $\Delta = \frac{1}{2}(\gamma'' - \gamma')$

$$M_R = \left[\alpha \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} + \beta \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} + \gamma' \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix} + \gamma'' \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}\right]$$

$$\alpha = y_1 v_S,\ \beta = y_2\langle\xi\rangle,\ \gamma' = y'_3\langle\xi'\rangle,\ \gamma'' = y''_3\langle\xi''\rangle$$

without ξ', ξ'' m_D, M_R respect S and U invariance → TB mixing

with ξ', ξ'' M_R respects S but not U invariance → TM2 mixing

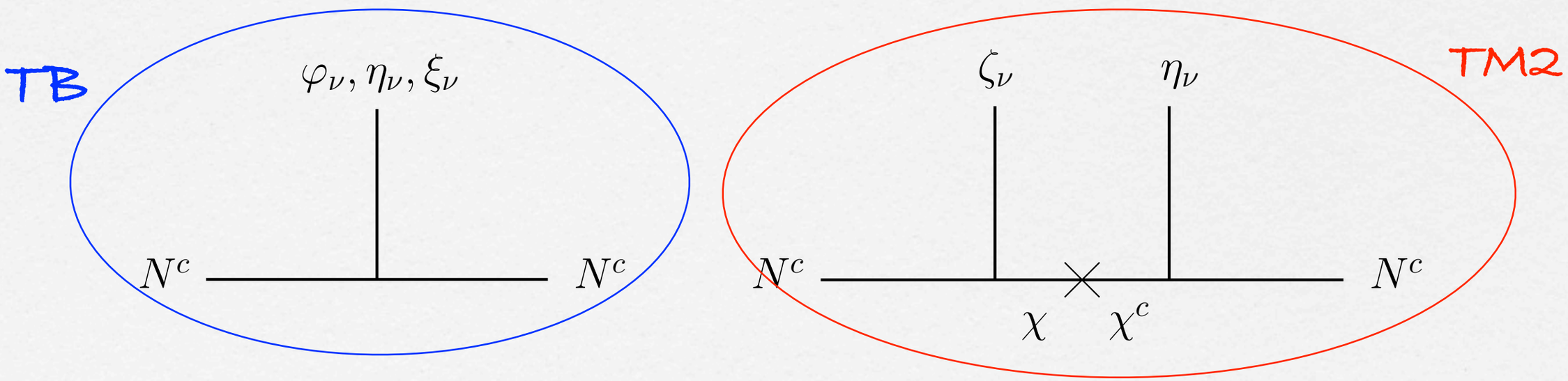
S4 Model

King, Luhn **1107.5332 JHEP**

$$W_{S_4}^{\nu,\text{eff}} \sim LH_uN^c + (\varphi_\nu + \xi_\nu + \eta_\nu)N^cN^c + \frac{\zeta_\nu}{M_\chi}\eta_\nu N^cN^c$$

unifies ξ′, ξ″ into a doublet η, restores TB

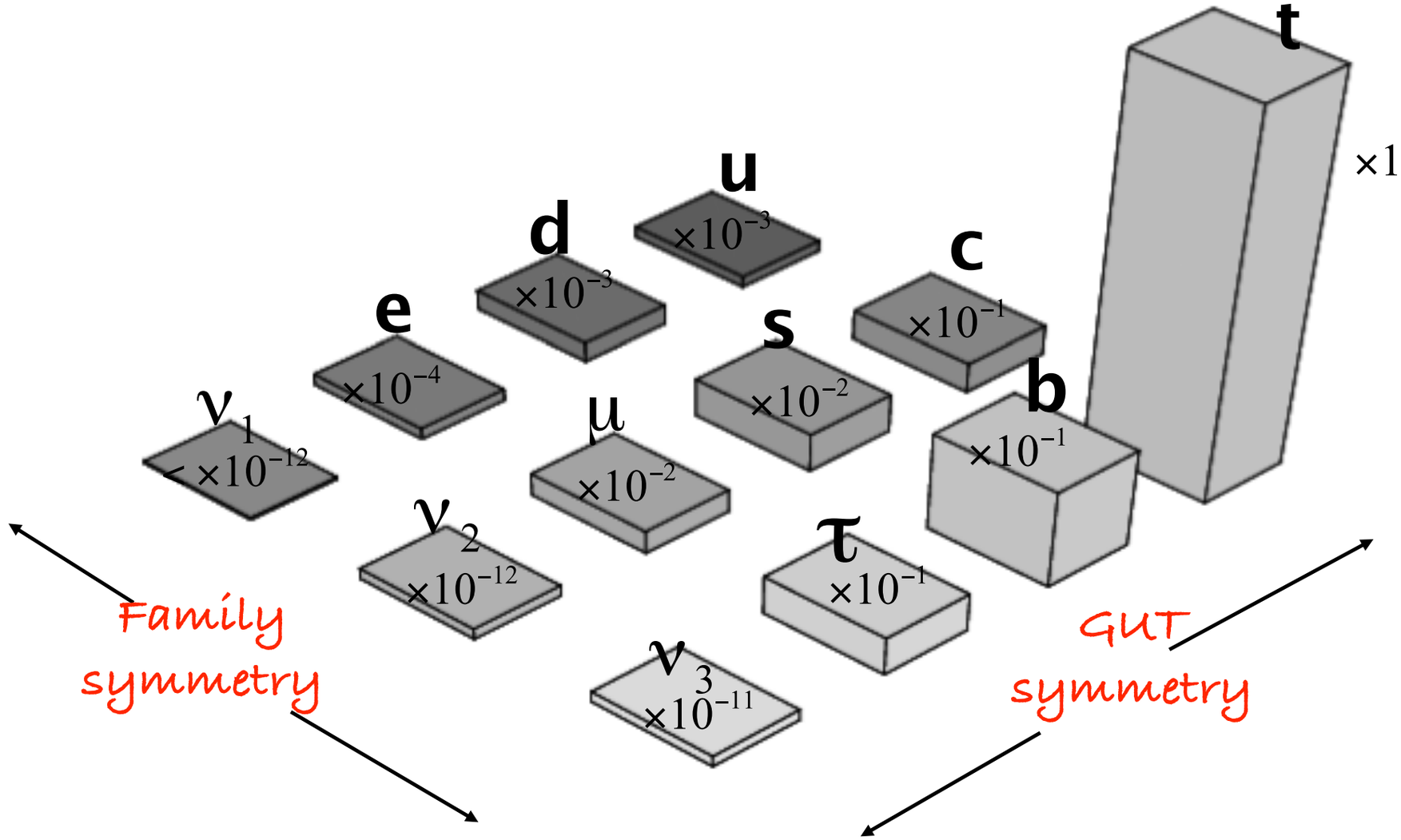
$<\zeta_\nu>$ breaks S4→A4 and TB→TM2



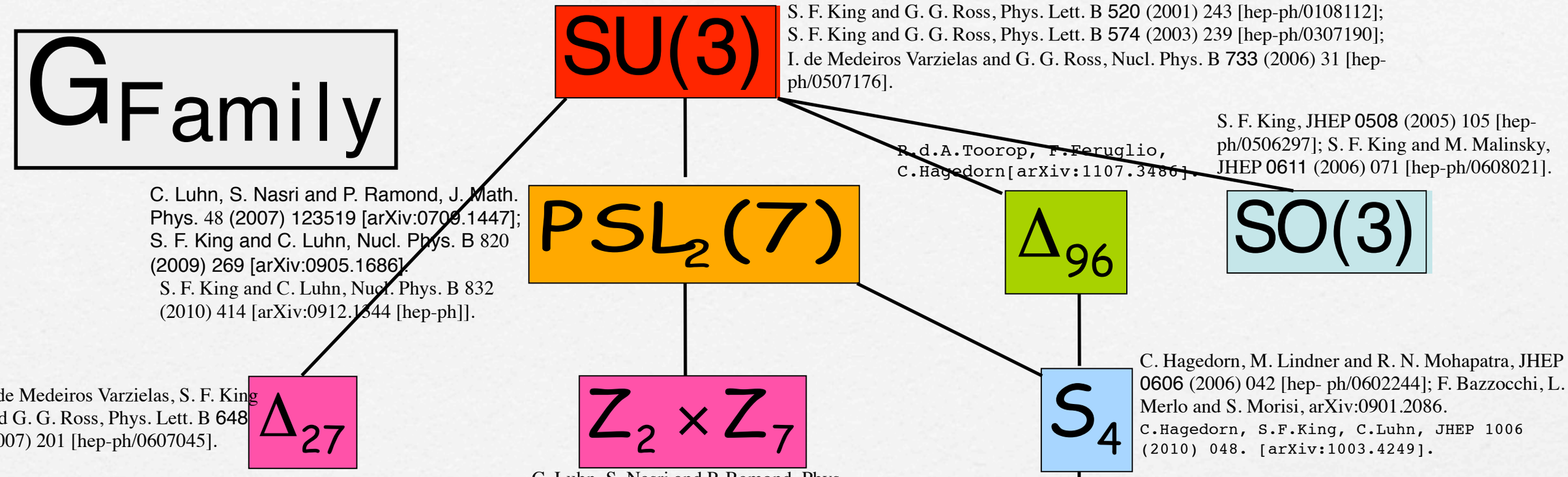
S4 model has TB at LO with TM2 corrections at HO

Explains why $\theta_{13} < \theta_{12}, \theta_{23}$

Family Symmetry × GUTs



G_F Family



S. F. King and G. G. Ross, Phys. Lett. B **520** (2001) 243 [hep-ph/0108112]; S. F. King and G. G. Ross, Phys. Lett. B **574** (2003) 239 [hep-ph/0307190]; I. de Medeiros Varzielas and G. G. Ross, Nucl. Phys. B **733** (2006) 31 [hep-ph/0507176].

S. F. King, JHEP **0508** (2005) 105 [hep-ph/0506297]; S. F. King and M. Malinsky, JHEP **0611** (2006) 071 [hep-ph/0608021].

R.d.A.Toorop, F.Feruglio, C.Hagedorn[arXiv:1107.3486].

C. Luhn, S. Nasri and P. Ramond, J. Math. Phys. 48 (2007) 123519 [arXiv:0709.1447]; S. F. King and C. Luhn, Nucl. Phys. B 820 (2009) 269 [arXiv:0905.1686].
S. F. King and C. Luhn, Nucl. Phys. B 832 (2010) 414 [arXiv:0912.1344 [hep-ph]].

I. de Medeiros Varzielas, S. F. King and G. G. Ross, Phys. Lett. B **648** (2007) 201 [hep-ph/0607045].

C. Luhn, S. Nasri and P. Ramond, Phys. Lett. B **652** (2007) 27 [arXiv:0706.2341].

C. Hagedorn, M. Lindner and R. N. Mohapatra, JHEP **0606** (2006) 042 [hep- ph/0602244]; F. Bazzocchi, L. Merlo and S. Morisi, arXiv:0901.2086.
C.Hagedorn, S.F.King, C.Luhn, JHEP 1006 (2010) 048. [arXiv:1003.4249].

E. Ma and G. Rajasekaran, Phys. Rev. D **64** (2001) 113012 [hep-ph/0106291]; E. Ma, Phys. Rev. D **73** (2006) 057304 [hep-ph/0511133]; G. Altarelli and F. Feruglio, Nucl. Phys. B **720** (2005) 64 [hep-ph/0504165]; K. S. Babu and X. G. He, hep- ph/0507217; G. Altarelli and F. Feruglio, Nucl. Phys. B **741** (2006) 215 [hep- ph/0512103]; M. Hirsch, A. S. Joshipura, S. Kaneko and J. W. F. Valle, Phys. Rev. Lett. **99** (2007) 151802 [hep-ph/0703046]; Y. Lin, Nucl. Phys. B **813** (2009) 91 [arXiv:0804.2867]; G. Altarelli and D. Meloni, arXiv:0905.0620.
T. J. Burrows and S. F. King, Nucl. Phys. B 835 (2010) 174 [arXiv:0909.1433 [hep-ph]].
K. S. Babu, E. Ma and J. W. F. Valle, Phys. Lett. B **552** (2003) 207 [hep- ph/0206292]; F. Bazzocchi, S. Morisi and M. Picariello, Phys. Lett. B **659** (2008) 628 [arXiv:0710.2928]; M. Honda and M. Tanimoto, Prog. Theor. Phys. **119** (2008) 583 [arXiv:0801.0181]; G. Altarelli, F. Feruglio and C. Hagedorn, JHEP **0803** (2008) 052 [arXiv: 0802.0090]; P. Ciafaloni, M. Picariello, E. Torrente-Lujan and A. Urbano, arXiv:0901.2236.
S. F. King and M. Malinsky, Phys. Lett. B **645** (2007) 351 [hep-ph/0610250].

Other symmetries:

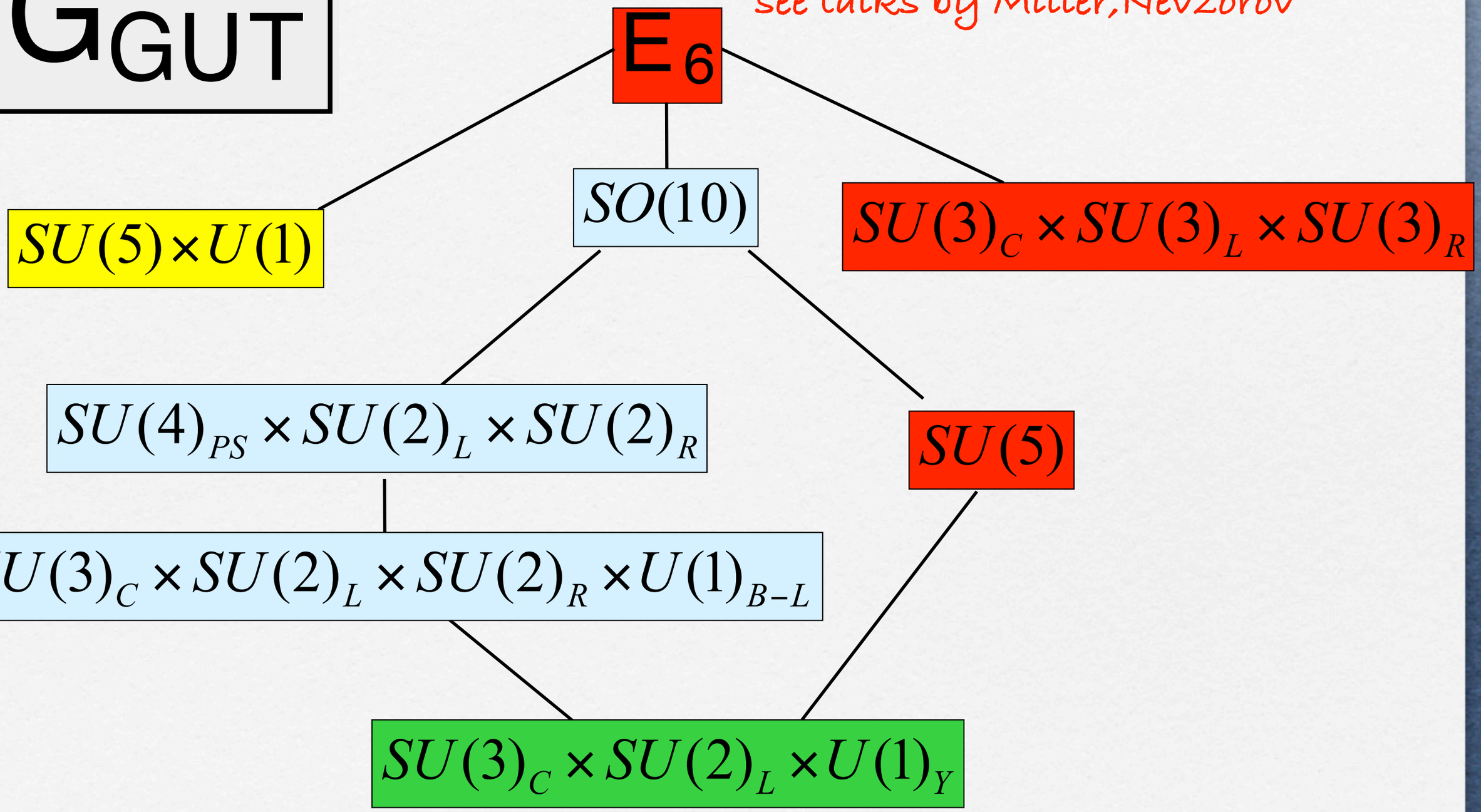
A. Aranda, C. D. Carone and R. F. Lebed, Phys. Rev. D **62** (2000) 016009 [hep- ph/0002044]; F. Feruglio, C. Hagedorn, Y. Lin and L. Merlo, Nucl. Phys. B **775** (2007) 120 [hep-ph/0702194]; M. C. Chen and K. T. Mahanthappa, Phys. Lett. B **652** (2007) 34 [arXiv:0705.0714]; P. H. Frampton and T. W. Kephart, JHEP **0709** (2007) 110 [arXiv:0706.1186]; A. Aranda, Phys. Rev. D **76** (2007) 111301 [arXiv:0707.3661]; P. H. Frampton and S. Matsuzaki, arXiv:0902.1140.
W. Grimus and L. Lavoura, JHEP **0508** (2005) 013 [hep-ph/0504153]; W. Grimus and L. Lavoura, JHEP **0601** (2006) 018 [hep-ph/0509239]; N. Haba, A. Watanabe and K. Yoshioka, Phys. Rev. Lett. **97** (2006) 041601 [hep-ph/0603116]; R. N. Mohap- atra, S. Nasri and H. B. Yu, Phys. Lett. B **639** (2006) 318 [hep-ph/0605020]; Y. Koide, Eur. Phys. J. C **50** (2007) 809 [hep-ph/0612058]; M. Mitra and S. Choubey, Phys. Rev. D **78** (2008) 115014 [arXiv:0806.3254].

M. Frigerio, S. Kaneko, E. Ma and M. Tanimoto, Phys. Rev. D **71** (2005) 011901 [hep-ph/0409187]; K. S. Babu and J. Kubo, Phys. Rev. D **71** (2005) 056006 [hep- ph/0411226]; Y. Kajiyama, E. Itou and J. Kubo, Nucl. Phys. B **743** (2006) 74 [hep- ph/0511268]. L.L.Everett, A.J.Stuart, Phys.Rev.D79 (2009)085005.[arXiv:0812.1057]

see talks by Chen, Stuart

G_{GUT}

see talks by Miller, Nevzorov



Example Models: S4×SU(5)

Hagedorn, King, Luhn;

Antusch, King, Luhn, Spinrath

$$F = \begin{pmatrix} F_1 \\ F_2 \\ F_3 \end{pmatrix} \sim \mathbf{3}\,, \qquad T = \begin{pmatrix} T_1 \\ T_2 \end{pmatrix} \sim \mathbf{2}\,, \quad T_3 \sim \mathbf{1}\,.$$

Purely real or imaginary vacuum alignments

Fritzsch type quark mass matrices

$$M_u \sim \begin{pmatrix} \lambda^8 & \lambda^6 & 0 \\ \lambda^6 & \lambda^4 & 0 \\ 0 & 0 & 1 \end{pmatrix} v_u\,, \qquad M_d \sim \begin{pmatrix} 0 & i\lambda^5 & 0 \\ i\lambda^5 & \lambda^4 & 2\lambda^4 \\ 0 & 0 & \lambda^2 \end{pmatrix} v_d\,,$$

GUT relation

Charged lepton mass matrix

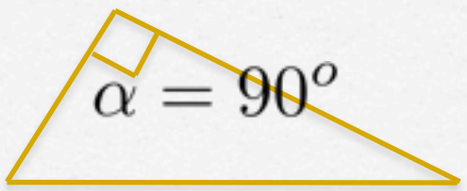
$$M_e \sim \begin{pmatrix} 0 & i\lambda^5 & 0 \\ i\lambda^5 & -3\lambda^4 & 0 \\ 0 & -6\lambda^4 & \lambda^2 \end{pmatrix} v_d$$

Neutrino mass matrices

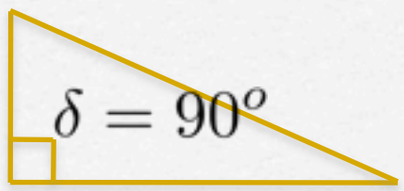
$$M_D \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} v_u\,, \qquad M_R \sim \begin{pmatrix} \alpha+2\gamma & \beta-\gamma & \beta-\gamma \\ \beta-\gamma & \beta+2\gamma & \alpha-\gamma \\ \beta-\gamma & \alpha-\gamma & \beta+2\gamma \end{pmatrix} \lambda^4 M$$

Phase sum rule $\alpha \approx \delta^d_{12} - \delta^u_{12}$

Quark unitarity triangle



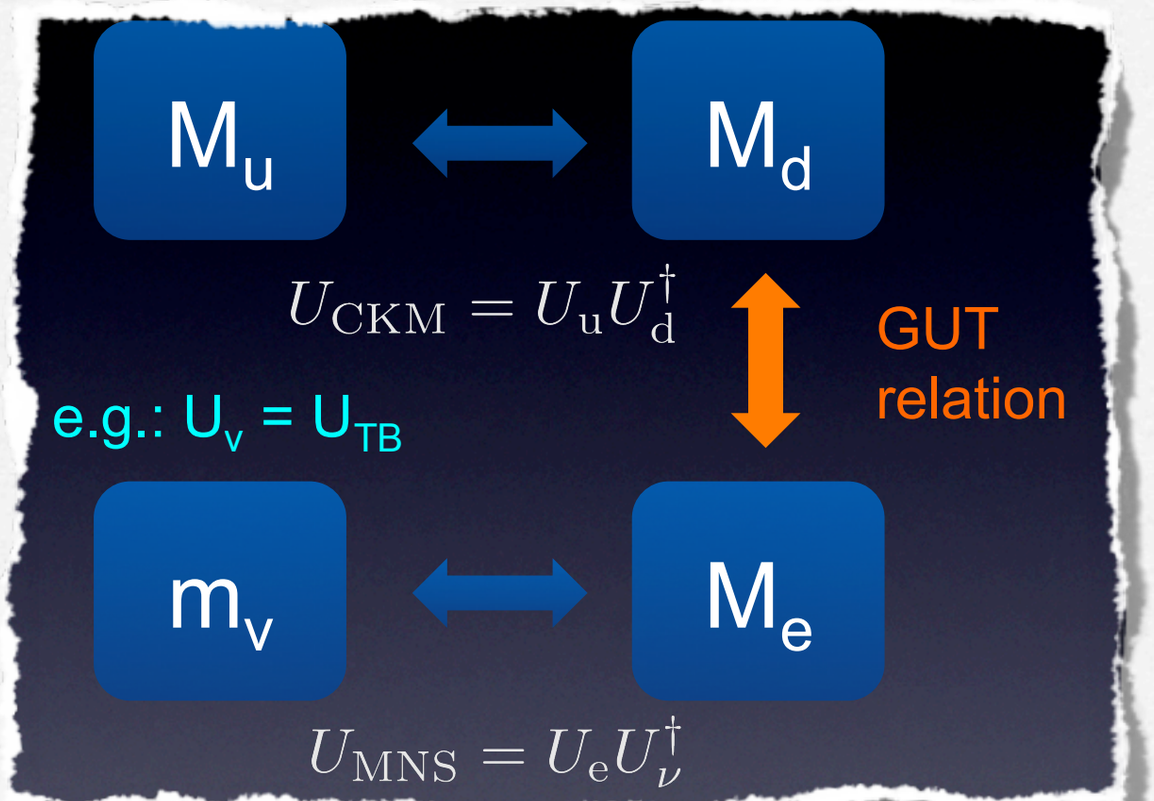
Lepton unitarity triangle



TB neutrino mixing

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

Family Symmetry × GUT predictions



$$\theta_{12}^d \approx \theta_C \approx 13^\circ$$ in a class of models

$$\theta_{12}^e \approx \frac{\theta_{12}^d}{3}$$ Georgi-Jarlskog GUT relation

(c.f. alternative GUT relations: Antusch, Maurer; Marzocca, Petcov, Romanino, Spinrath)

$$\theta_{12}^e s_{23}^\nu \approx \frac{1}{3\sqrt{2}}\theta_C \approx 3^o$$

0810.3863 Antusch, King, Malinsky

η = RG correction

$$s_{23} e^{-i\delta_{23}} \approx s_{23}^\nu \left(1 + \frac{\eta}{2} {c_{23}^\nu}^2\right) e^{-i\delta_{23}^\nu} - \theta_{23}^e c_{23}^\nu e^{-i\delta_{23}^e} ,$$

T2K $$s_{13} e^{-i\delta_{13}} \approx \theta_{13}^\nu e^{-i\delta_{13}^\nu} - \theta_{12}^e s_{23}^\nu e^{-i(\delta_{23}^\nu + \delta_{12}^e)} + \frac{m_2^\nu}{m_3^\nu} \eta c_{12}^\nu s_{12}^\nu c_{23}^\nu s_{23}^\nu e^{-i(\delta_{12}^\nu - \delta_{23}^\nu)} ,$$

$$s_{12} e^{-i\delta_{12}} \approx s_{12}^\nu \left(1 + \frac{\eta}{2} {c_{12}^\nu}^2 {s_{23}^\nu}^2\right) e^{-i\delta_{12}^\nu} - \theta_{12}^e c_{23}^\nu c_{12}^\nu e^{-i\delta_{12}^e} .$$

CSD2 $\theta_{13}^\nu \sim 5^o - 6^o$

SUSY and Family Symmetry

Family symmetry does two things for the price of one

- Explain flavour structure in the SM, e.g.:

$$M_d \sim \begin{pmatrix} 0 & \varepsilon_1\varepsilon_2 & \varepsilon_1\varepsilon_2 \\ \varepsilon_1\varepsilon_2 & \varepsilon_2^2 & \varepsilon_2^2 \\ \varepsilon_1\varepsilon_2 & \varepsilon_2^2 & \varepsilon_3^2 \end{pmatrix} v_{\rm d}$$

- Generate flavour stucture of the SUSY particles:

0708.1282
Antusch, King, Malinksy

$$\widetilde{M}_{d_R} \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} m_0 + \begin{pmatrix} \varepsilon_1^2 & \varepsilon_1^2 & \varepsilon_1^2 \\ \varepsilon_1^2 & \varepsilon_2^2 & \varepsilon_2^2 \\ \varepsilon_1^2 & \varepsilon_2^2 & \varepsilon_3^2 \end{pmatrix} m_0$$

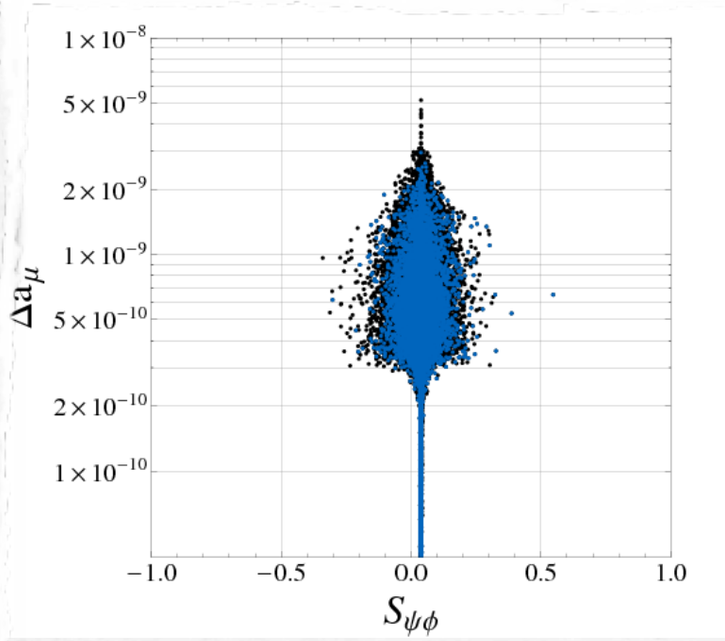
Ameliorates SUSY CP

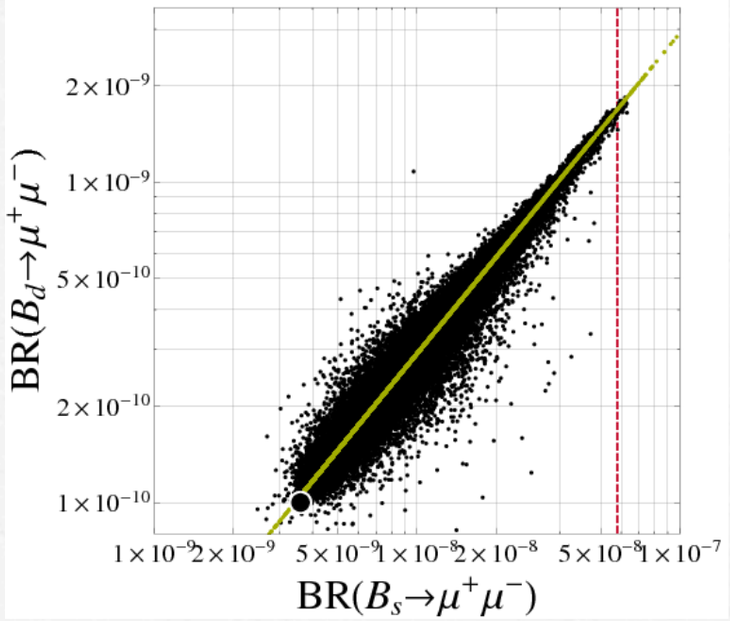
Family symmetry!

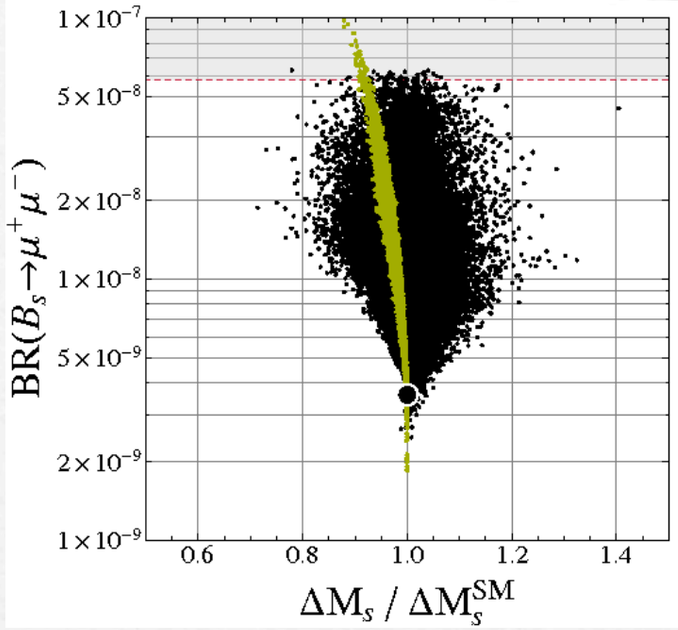
$$A_d \sim \begin{pmatrix} 0 & \varepsilon_1\varepsilon_2 & \varepsilon_1\varepsilon_2 \\ \varepsilon_1\varepsilon_2 & \varepsilon_2^2 & \varepsilon_2^2 \\ \varepsilon_1\varepsilon_2 & \varepsilon_2^2 & \varepsilon_3^2 \end{pmatrix} A_0$$

SUSY flavour structure related to the one of the SM

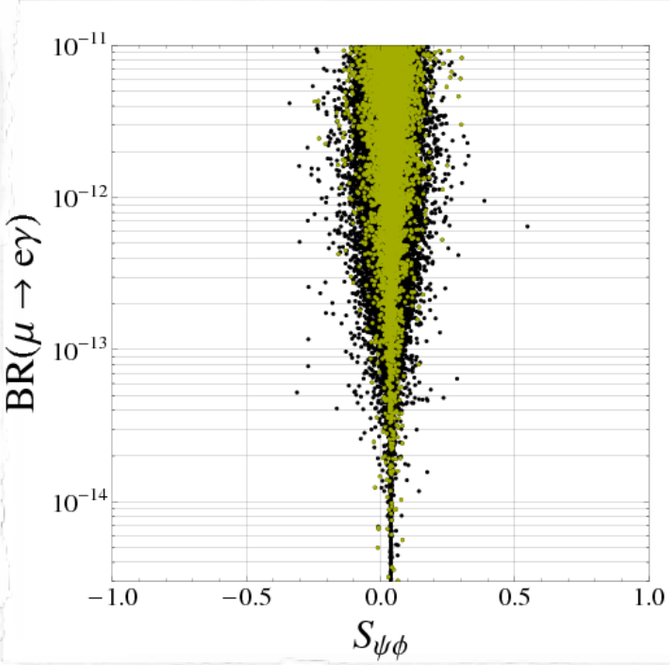
Flavour changing in AKM model

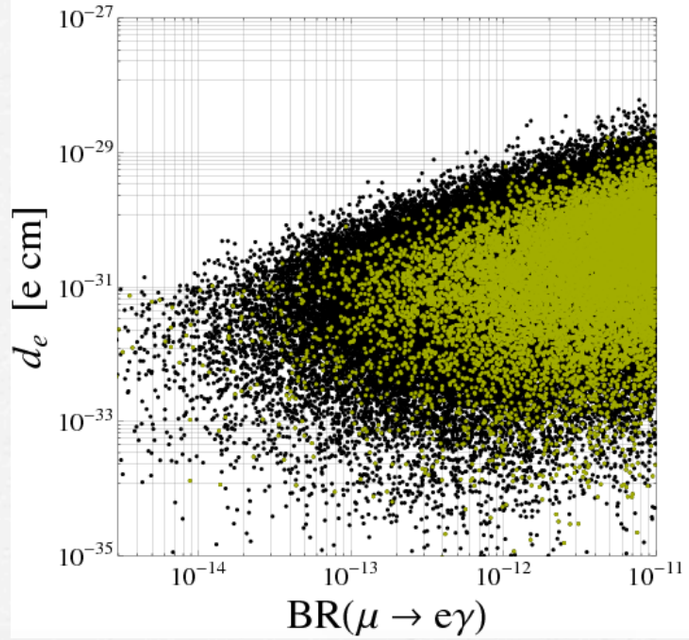


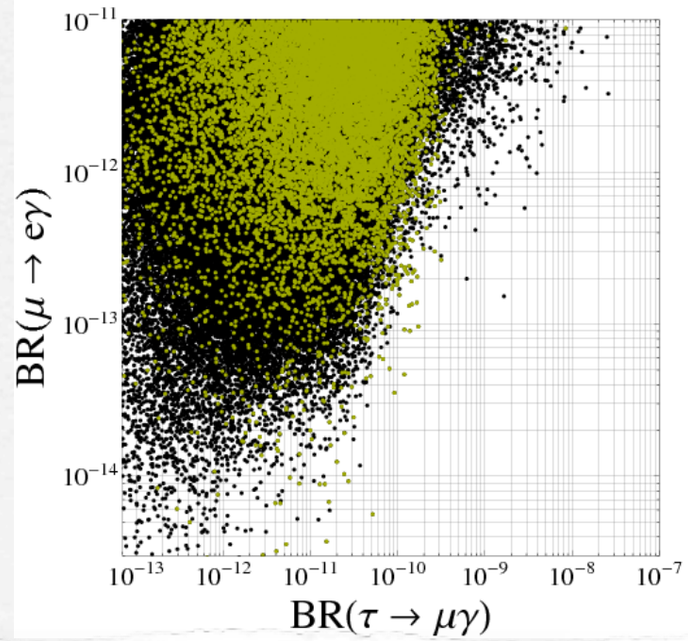




Altmannshofer, Buras, Gori, Paradisi, Straub







DNA Profiles

Altmannshofer, Buras, Gori, Paradisi, Straub

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}\,(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Conclusion

- Neutrino mass and mixing is possibly the most important discovery in particle physics since the top quark at Fermilab in 1995 but is BSM with implications for PP/Cosmo
- Since 1998 there have been major breakthroughs every couple of years, latest is θ_{13} at T2K/MINOS (non-zero in global fits at 3σ)
- Non-zero θ_{13} excludes TB lepton mixing but new possibilities remain: TBR, TM1, TM2,...
- Family symmetry approach remains viable, with θ_{13} providing additional refinements to the picture, e.g. S4→A4 giving TB→TM2 at HO
- Combination of Family symmetry and SUSY GUTs is very powerful and leads to corrections to lepton mixing from quark mixing and ameliorates the SUSY Flavour and CP problems with characteristic DNA profiles

Vacuum Alignment

With Driving fields (SUSY F-terms)

Altarelli, Feruglio

$$M(\varphi_T\varphi_0^T) + g(\varphi_0^T\varphi_T\varphi_T) + g_1(\varphi_0^S\varphi_S\varphi_S)$$

$$\phi_S \sim \begin{pmatrix}1\\1\\1\end{pmatrix} \quad \phi_T \sim \begin{pmatrix}1\\0\\0\end{pmatrix}$$

Without Driving fields (SUSY D-terms)

SFK, Malinsky

$$\Delta V = \kappa \sum \phi^{i\dagger}\phi^i\phi^{i\dagger}\phi^i + \lambda|\phi_2^\dagger.\overset{i}{\phi}_3|^2$$

$$\phi_2 \sim \begin{pmatrix}1\\1\\1\end{pmatrix} \quad \phi_3 \sim \begin{pmatrix}0\\1\\-1\end{pmatrix}$$

Orbifold boundary conditions

Kobayashi, Omura, Yoshioka; Burrows, SFK

$$\varphi_S(-z_1) = P_2\varphi_S(z_1)$$

$$\varphi_T(\omega z_2) = P_3\varphi_T(z_2)$$

$$\phi_S \sim \begin{pmatrix}1\\1\\1\end{pmatrix} \quad \phi_T \sim \begin{pmatrix}1\\0\\0\end{pmatrix}$$