A Large Reactor Mixing Angle from Flavour Models

Martin Spinrath

GGI/Invisibles workshop:
What is ν?

International School for Advanced Studies

How to revise this in 30 minutes?

A. Adulpravitchai, Y. H. Ahn, C. H. Albright, G. Altarelli, S. Antusch, A. Aranda, T. Araki, F. Bazzocchi, W. Buchmüller, P. S. Bhupal Dev, G. C. Branco, Q.-H. Cao, H.-Y. Cheng, I. K. Cooper, S. Dev, G. Blankenburg, C. Bonilla, F. Gonzalez Canales, W. Chao, J.-M. Chen, M.-C. Chen, X. Chu, A. Datta, K. N. Deepthi, M. Dhen, D. A. Dicus, G.-J. Ding, P. V. Dong, V. Domcke, L. Dorame, B. Dutta, D. A. Eby, L. Everett, R. P. Feger, F. Feruglio, P. Ferreira, P. H. Frampton, M. Fukugita, R. R. Gautam, S.-F. Ge, D. K. Ghosh, R. Gonzalez Felipe, S. Gollu, S. Gupta, W. Grimus,C. Gross, N. Haba, C. Hagedorn, T. Hambye, J. E. Kim, Y. Koide, K. Hashimoto, K. Harigaya, H. -J. He, X. -G. He, J. Heek, D. Hernandez, M. Holthausen, R. S. Hundi, M. Ibe, H. Ishimori, F. R. Joaquim, A. S. Joshipura, S. K. Kang, T. W. Kephart, S. Khalil, S. F. King, T. Kobayashi, S. Kumar, L. Lavoura, X.-Q. Li, H. N. Long, P. O. Ludl, C. Luhn, B. Q. Ma, E. Ma, S. K. Majee, K.T. Mahanthappa, D. Marzocca, V. Maurer, D. Meloni, A. Merle, A. Meroni, R. Mohanta, R. N. Mohapatra, E. Molinaro, A. Mondragon, M. Mondragon, S. Morisi, C. H. Nam, H. Nishiura, S. Oh, H. Okada, K. M. Patel, K. M. Parattu, E. Peinado, S. T. Petcov, N. Qin, A. Rashed, W. W. Repko, A. D. Rojas, W. Rodejohann, A. Romanino, G. G. Ross, S. Rigolin, M. A. Schmidt, K. Schmitz, M. Severson, M.-S. Seo, H. Serodio, Y. Shimizu, J. I. Silva-Marcos, L. Singh, K. Siyeon, C. Sluka, A. Yu. Smirnov, M. Spinrath, E. Stamou, A. J. Stuart, R. Takahashi, M. Tanimoto, R. d. A. Toorop, J. W. F. Valle, I. d. M. Varzielas, L. Velasco-Sevilla, V. V. Vien, B. Wang, Q. Wang, A. Watanabe, D. Wegman, A. Wingerter, Yue-Liang Wu, Z. -Z. Xing, T. T. Yanagida, W.-M. Yang, B. Zaldívar, F. -R. Yin, A. Zee, H. Zhang, Y.-j. Zheng, J.-J. Zhong, S. Zhou, R. Zwicky, …

Please let me know if I missed someone...

Two Approaches for Flavour Models with Large θ_{13}

Martin Spinrath

GGI/Invisibles workshop:
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International School for Advanced Studies

Outline

- Status
- Possibility I: Charged Lepton Corrections
- Possibility II: Trimaximal Mixing
- Summary and Conclusions

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One Year of Great Progress

	March 2011, NH	May 2012, NH
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	$0.320^{+0.015}_{-0.017}$
$\sin^2\theta_{23}$	0.51 ± 0.06	$0.49^{+0.08}_{-0.05}$
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$	$0.026^{+0.003}_{-0.004}$
δ	?	$(0.83^{+0.54}_{-0.64})\pi$
	[Schwetz, Tortola, Valle 2011]	**[Forero, Tortola, Valle 2012]**

So what?

- Very popular before: (Tri-)Bimaximal Mixing

$$\sin^2\theta_{12} = \left(\frac{1}{3}\right)\frac{1}{2}\,, \quad \sin^2\theta_{23} = \frac{1}{2}\,, \quad \sin^2\theta_{13} = 0$$

- Modifications? Alternatives? Plenty...
  - Solution I: Charged Lepton Sector Corrections

    [recently Antusch, Maurer `11; Marzocca, Petcov, Romanino, MS `11]
  - Solution II: Trimaximal Mixing

    [Antusch, King, Luhn, MS `11]

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The Setup

[Marzocca et al. `11, see also Antusch, Maurer `11]

- No 1-3 mixing in the neutrino and only 1-2 mixing in the charged lepton sector:

$$\sin\theta_{13} \approx \sin\theta_{12}^{e} \sin\theta_{23}^{\nu} \approx \frac{1}{\sqrt{2}} \frac{\beta'}{\gamma} \frac{b'}{c}$$

- Assume SU(5) relations:

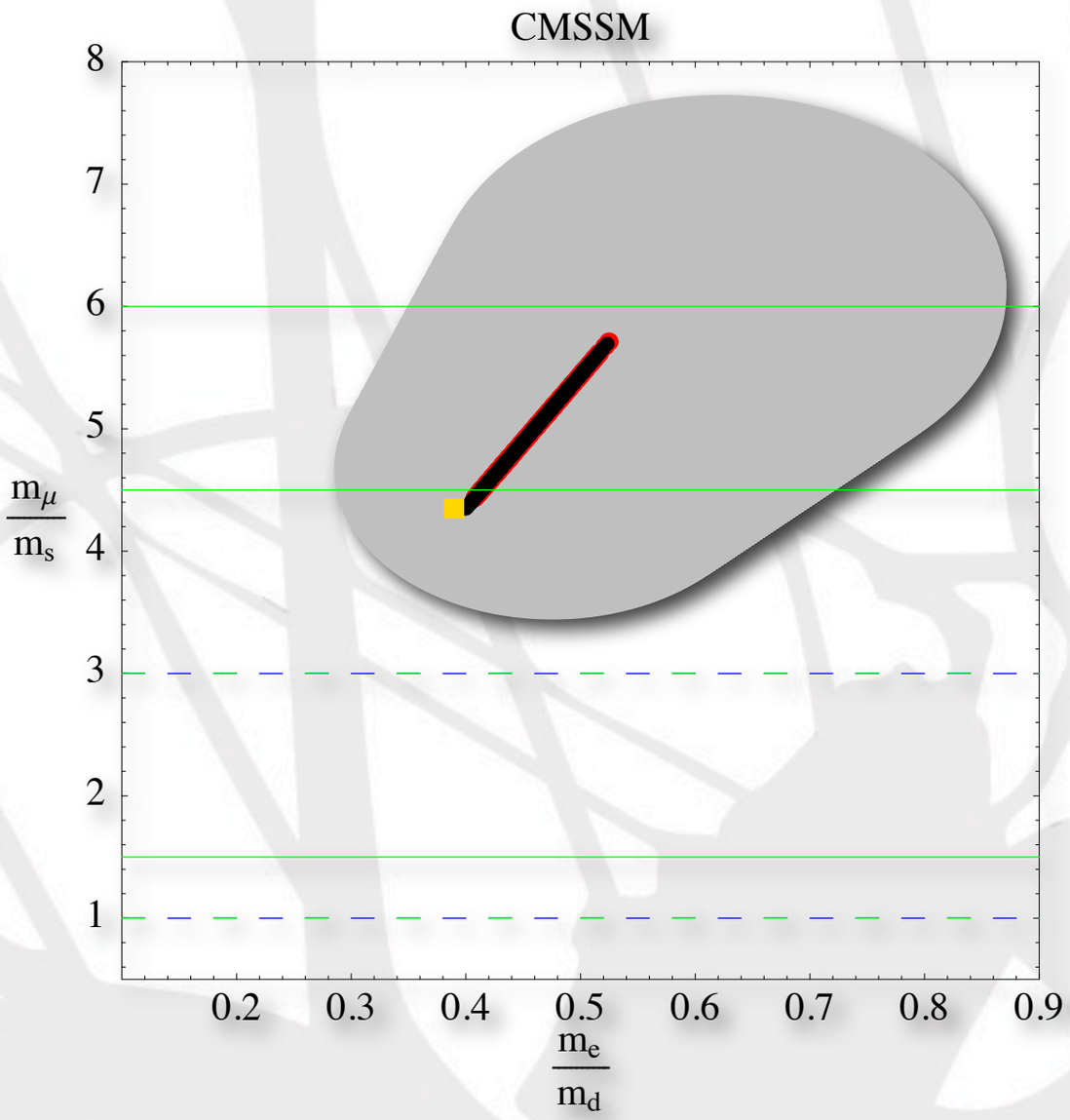
$$\hat{\lambda}^{D}_{[12]} = \begin{pmatrix} a & b' \\ b & c \end{pmatrix} \qquad \hat{\lambda}^{E}_{[12]} = \begin{pmatrix} \alpha a & \beta b \\ \beta' b' & \gamma c \end{pmatrix}$$

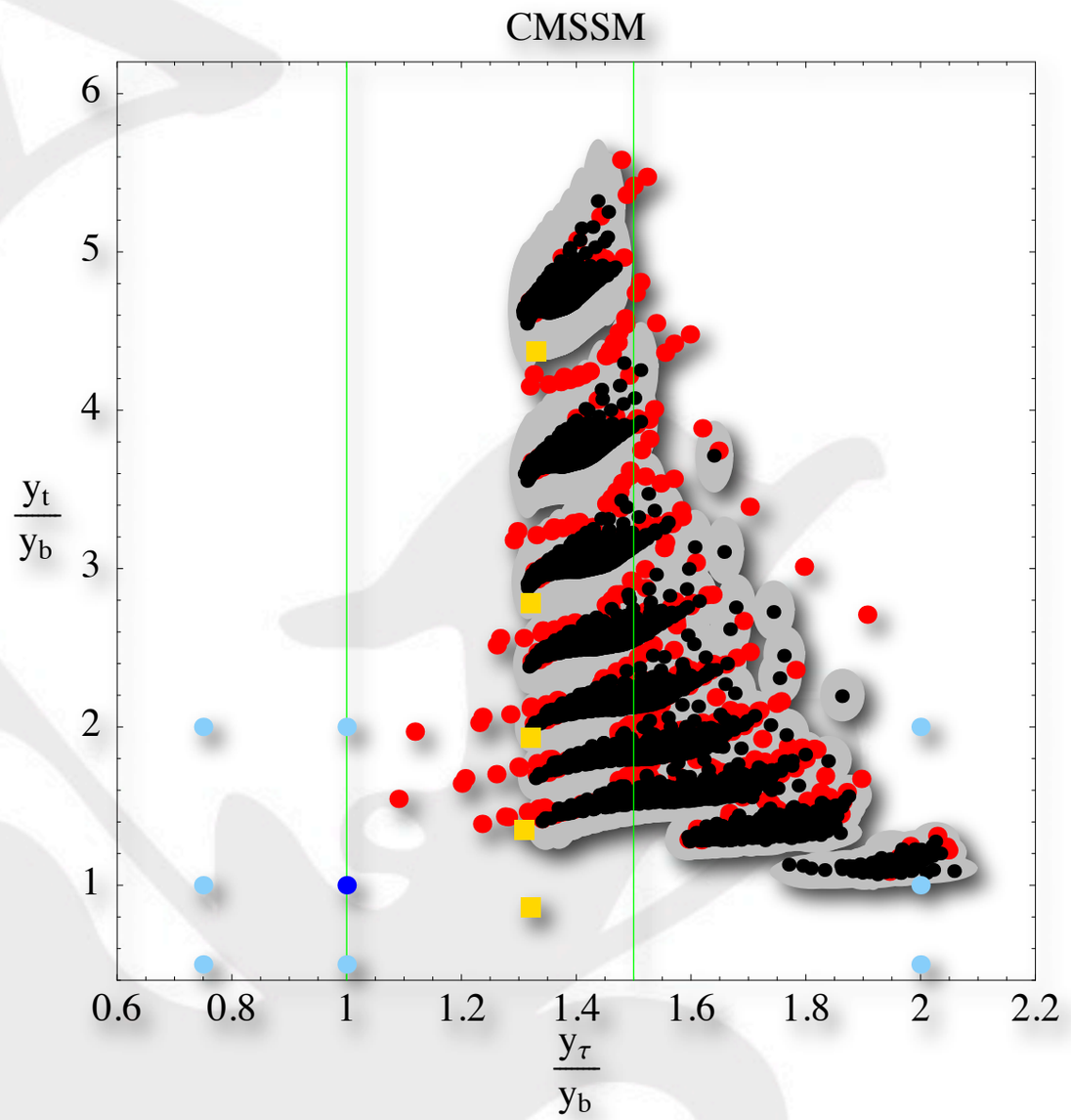
- α, β, β', γ are SU(5) Clebsch-Gordan coefficients (1, -3/2, -3 , 9/2, 6, ...)

[for a list see Antusch, MS `09]

Intermezzo: GUT Relations

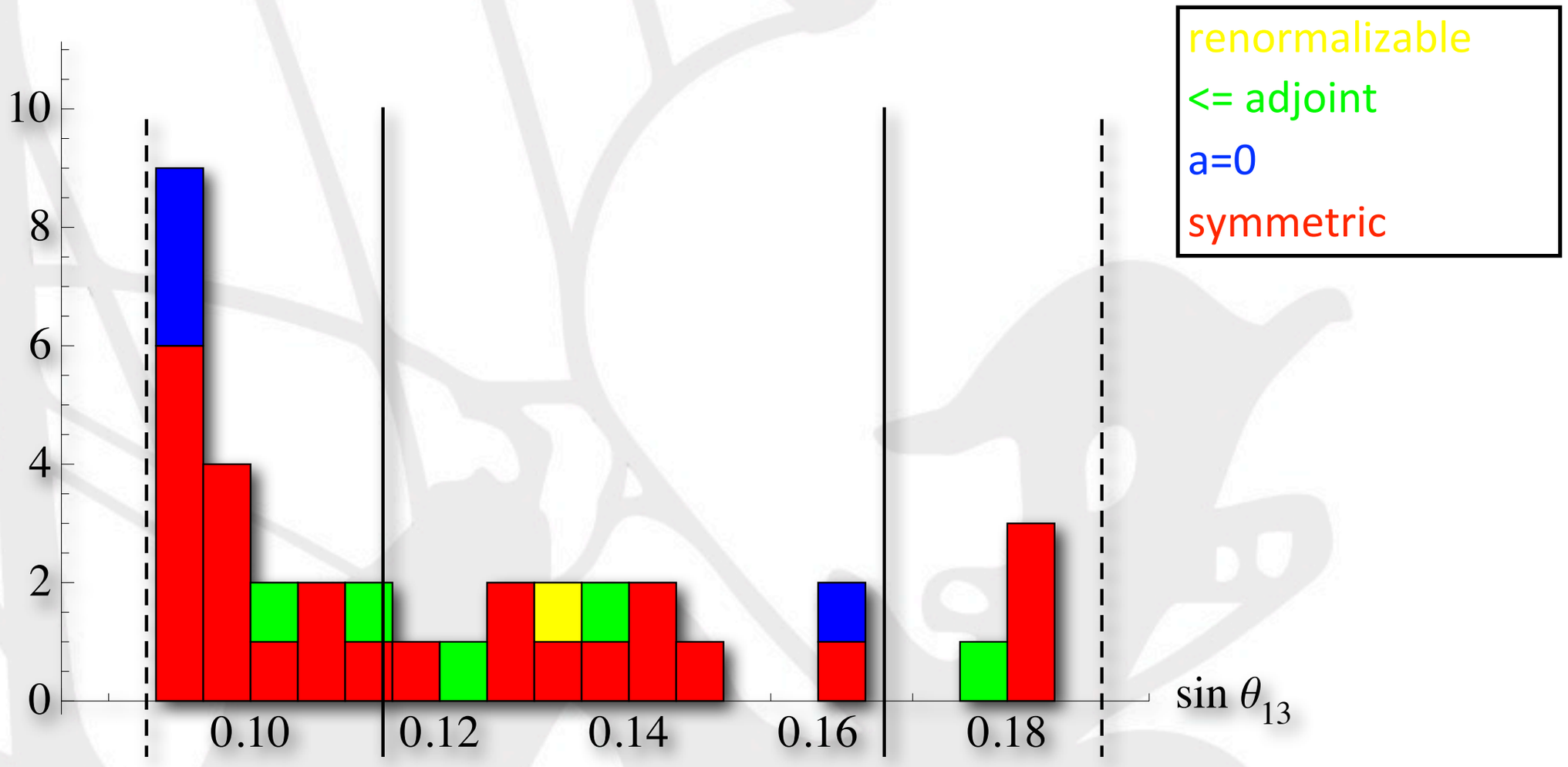
no SUSY thresholds	excluded
SU(5)	allowed
Pati-Salam	mass error





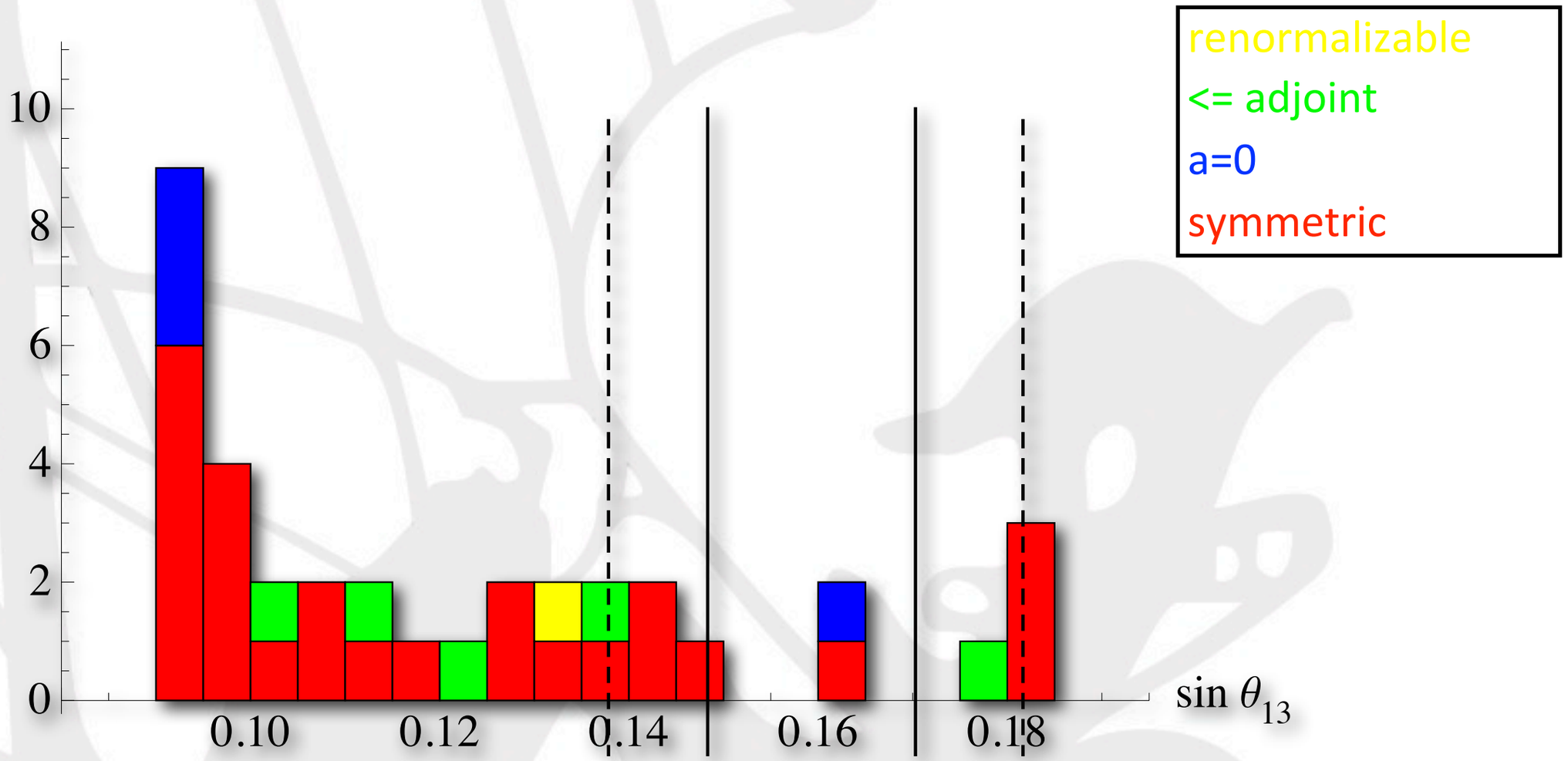
[Antusch, MS `09]

Scan results with free θ_{13} (June `11)



[Taken from Marzocca *et al.* `11, based on the global fit by Fogli *et al.* `11]

After Fitting to Exp. Data (May `12)



[Based on the global fit by Forero, Tortola, Valle `12, Thanks to D. Marzocca for providing this plot]

The Good Cases

$\{\alpha, \beta, \beta', \gamma\}$	$\sin\theta_{13}$
$\{-, -1/2, 6, 6\}$	0.164 ± 0.013
$\{-3/2, -3, -3, -3\}$	0.164 ± 0.007
$\{-18, 9/2, 9/2, 9/2\}$	0.149 ± 0.003

[Taken from Marzocca *et al.* `11]

For a model implementation see talk by A. Meroni

[A. Meroni, S. T. Petcov, MS `12]

Corrections to other Mixing Angles

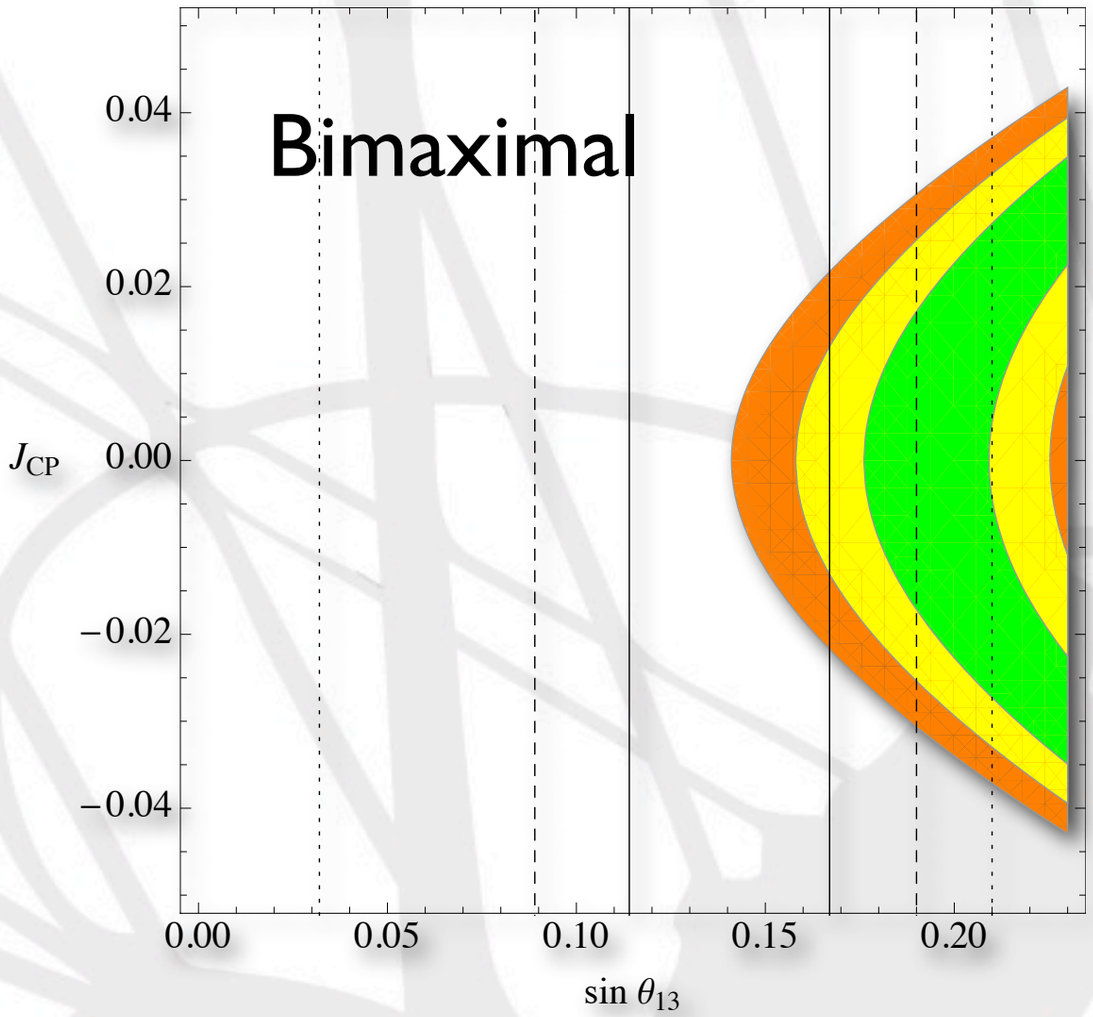
- For Bimaximal mixing:

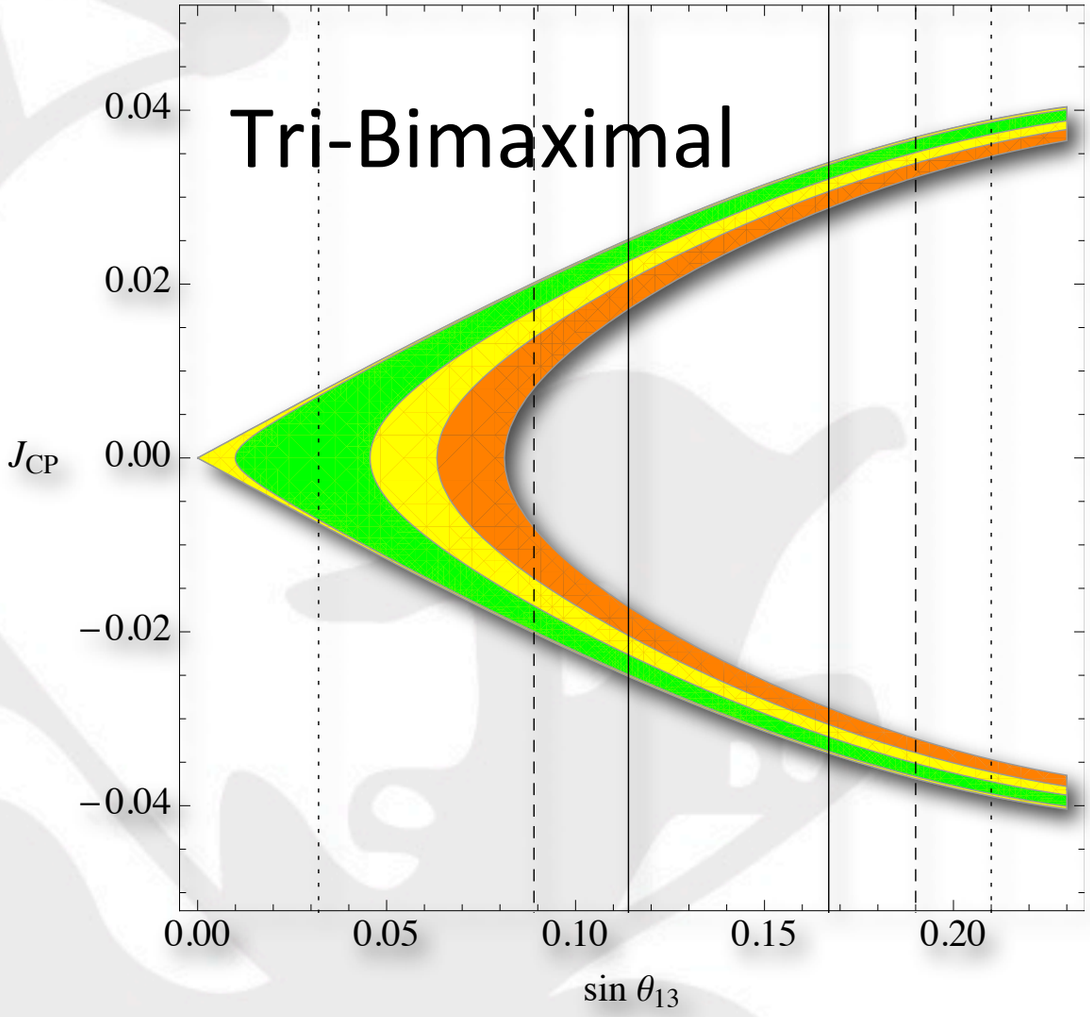
$$\sin^2\theta_{12} \approx \frac{1}{2} + \sin\theta_{13}\cos\delta$$

- For Tri-Bimaximal mixing:

$$\sin^2\theta_{12} \approx \frac{1}{3} + \frac{2\sqrt{2}}{3}\sin\theta_{13}\cos\delta$$

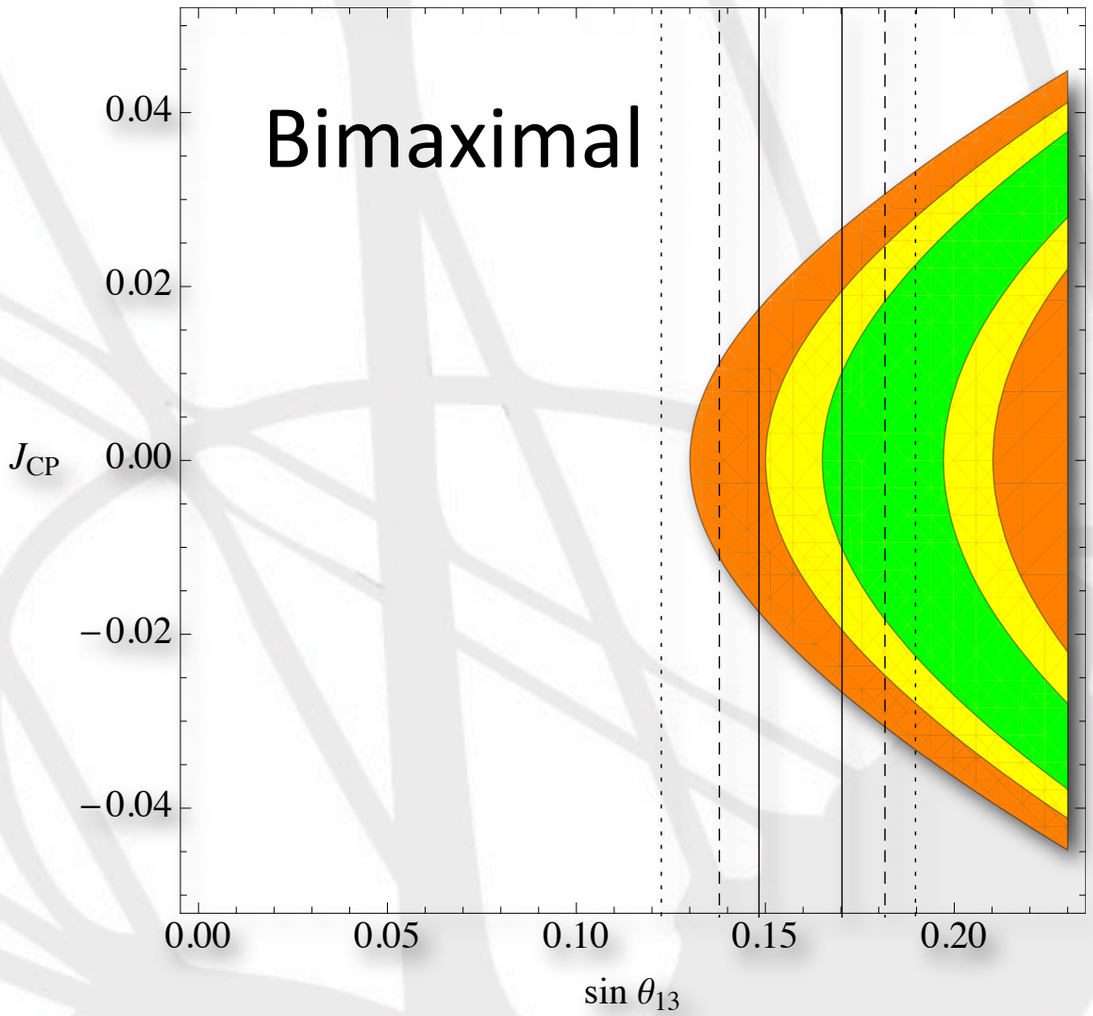
Implications for J_{CP} (June `11)

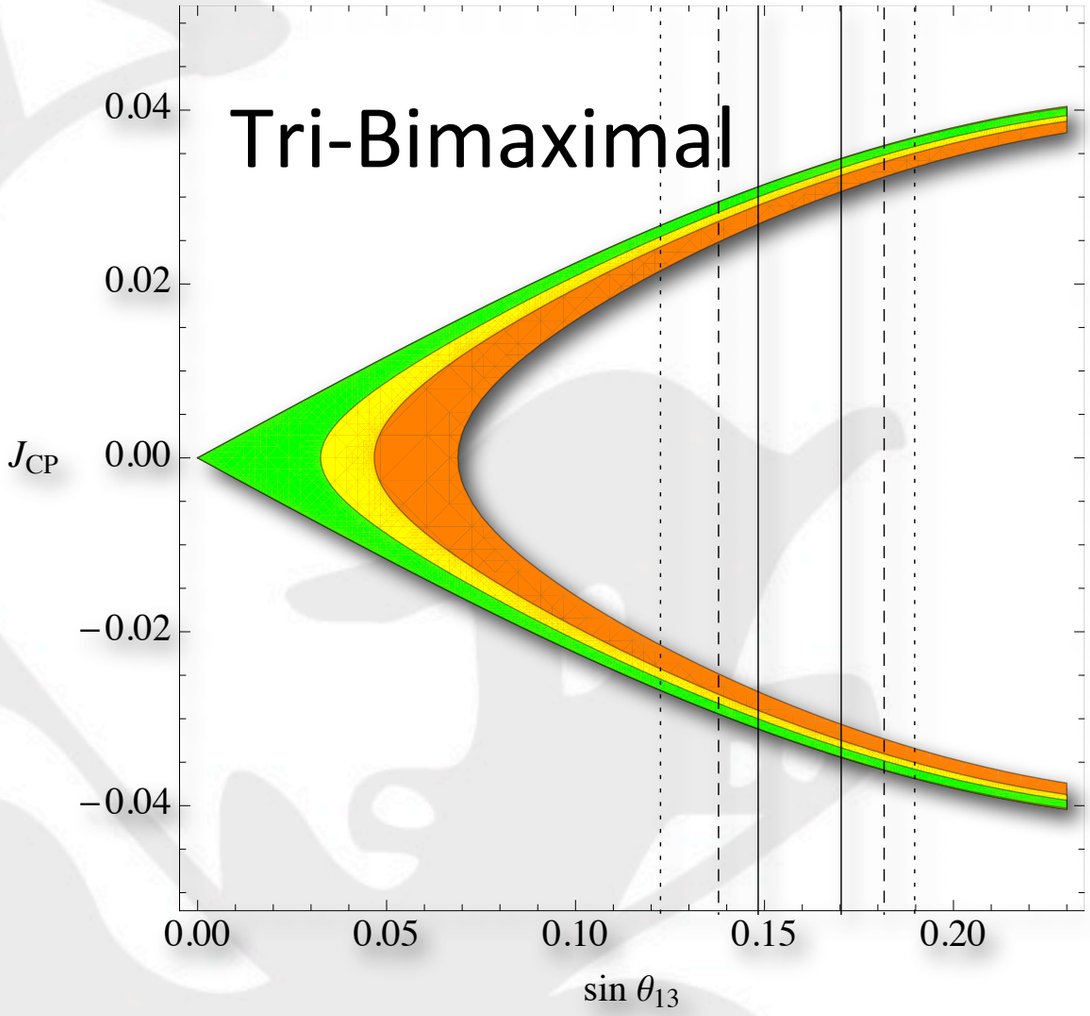




[Taken from Marzocca *et al.* `11, based on the global fit by Fogli *et al.* `11]

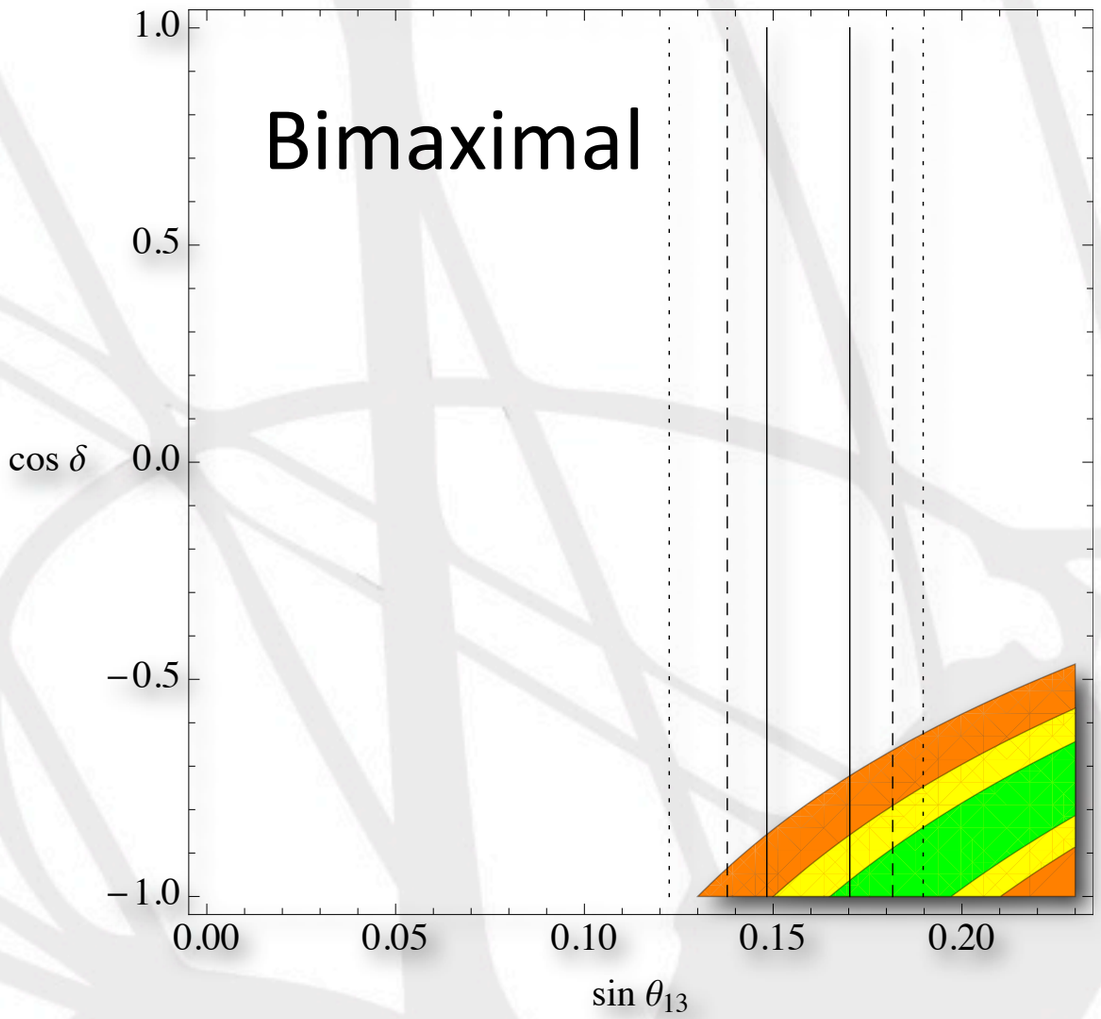
Implications for J_{CP} (May `12)

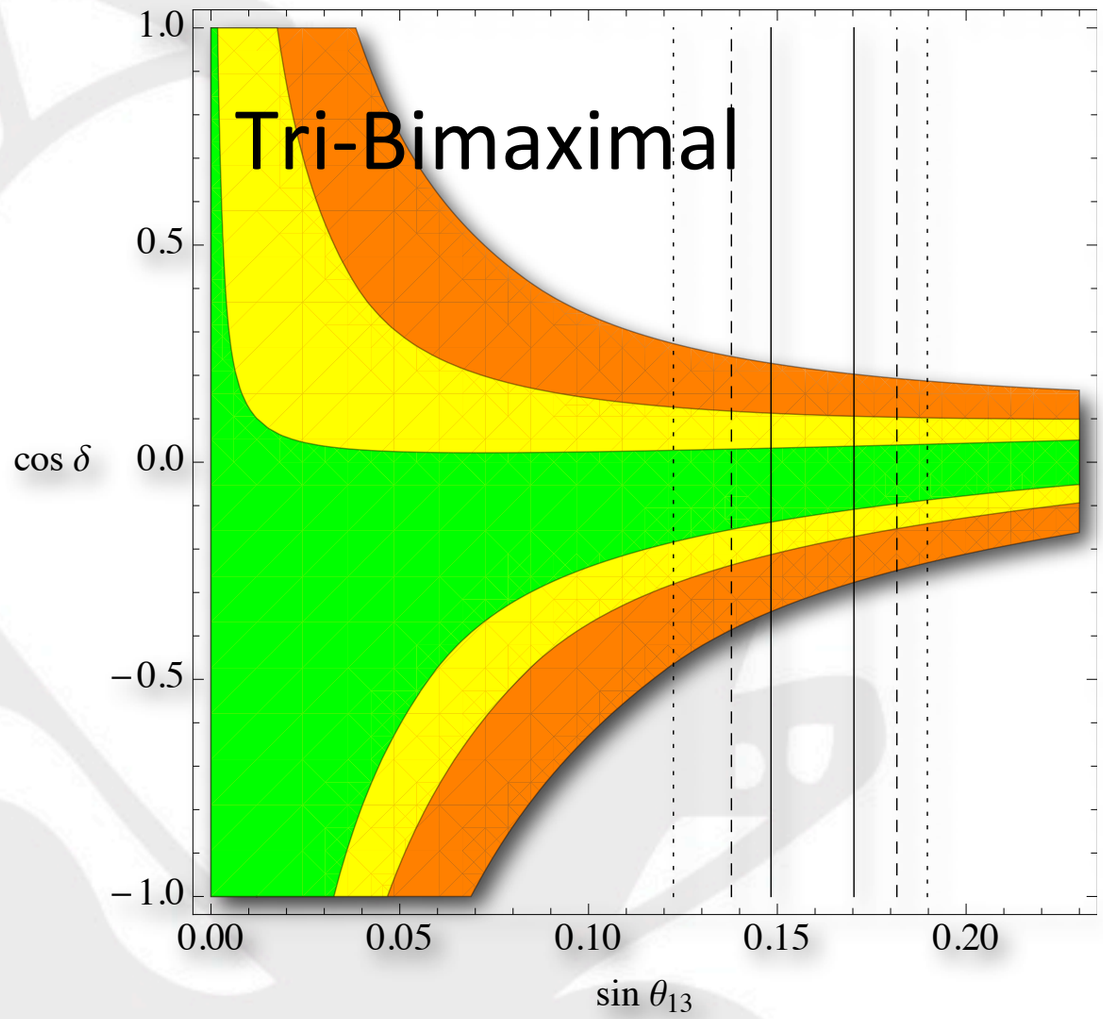




[Based on the global fit by Forero, Tortola, Valle `12, Thanks to D. Marzocca for providing this update]

Implications for δ (May `12)





[Based on the global fit by Forero, Tortola, Valle `12, Thanks to D. Marzocca for providing this update]

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Sequential Dominance

[S.F. King `98-`02, S. Antusch, S. Boudjemaa, S.F. King `10]

- We choose a basis

$$Y_\nu = (A, B, C) \quad \text{and} \quad M_R = \text{diag}(M_A, M_B, M_C)$$

- The neutrino mass matrix can be written as

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

- For a strong hierarchy $A^2/M_A >> B^2/M_B >> C^2/M_C$:

$$A \to \theta_{23} \ , \quad B \to \theta_{12} \ , \quad A, B \to \theta_{13}$$

Pattern for Mixing Schemes

- Minimalistic pattern for TBM (CSD):

[S.F. King `05]

$$Y_\nu = \begin{pmatrix} 0 & b \\ a & b \\ -a & b \end{pmatrix}, \qquad M_R = \begin{pmatrix} M_A & 0 \\ 0 & M_B \end{pmatrix}$$

- Pattern for trimaximal mixing (CSD2):

[Antusch, King, Luhn, MS `11]

$$Y_\nu = \begin{pmatrix} 0 & b \\ a & 0 \\ -a & 2b \end{pmatrix}, \qquad M_R = \begin{pmatrix} M_A & 0 \\ 0 & M_B \end{pmatrix}$$

[Trimaximal variant we use based on C. S. Lam `06; C. H. Albright, W. Rodejohann `09; C. H. Albright, A. Dueck, W. Rodejohann `10]

How to get these alignments?

[Antusch, King, Luhn, MS `11]

- Two sets of flavons:

1st column of U_{PMNS} (good θ_{12})

$$\langle \phi_1^\nu \rangle \propto \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix}, \quad \langle \phi_2^\nu \rangle \propto \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, \quad \langle \phi_3^\nu \rangle \propto \begin{pmatrix} -2 \\ 1 \\ 1 \end{pmatrix}$$

$$\langle \phi_1^e \rangle \propto \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad \langle \phi_2^e \rangle \propto \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \quad \langle \phi_3^e \rangle \propto \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

- Use orthogonality ($F_O = 0$):

$$\mathcal{W} = O_1(\phi_2^e \cdot \phi_{102}) + O_2(\phi_3^\nu \cdot \phi_{102})$$

Phenomenology I

[Antusch, King, Luhn, MS `11]

- The neutrino mass matrix:

$$M_\nu = m_a \begin{pmatrix} \eta & 0 & 2\eta \\ 0 & 1 & -1 \\ 2\eta & -1 & 1+4\eta \end{pmatrix} \ , \quad \eta = \epsilon \ \mathrm{e}^{\mathrm{i}\alpha} \ , \quad \epsilon \ll 1$$

- Approximate formulas:

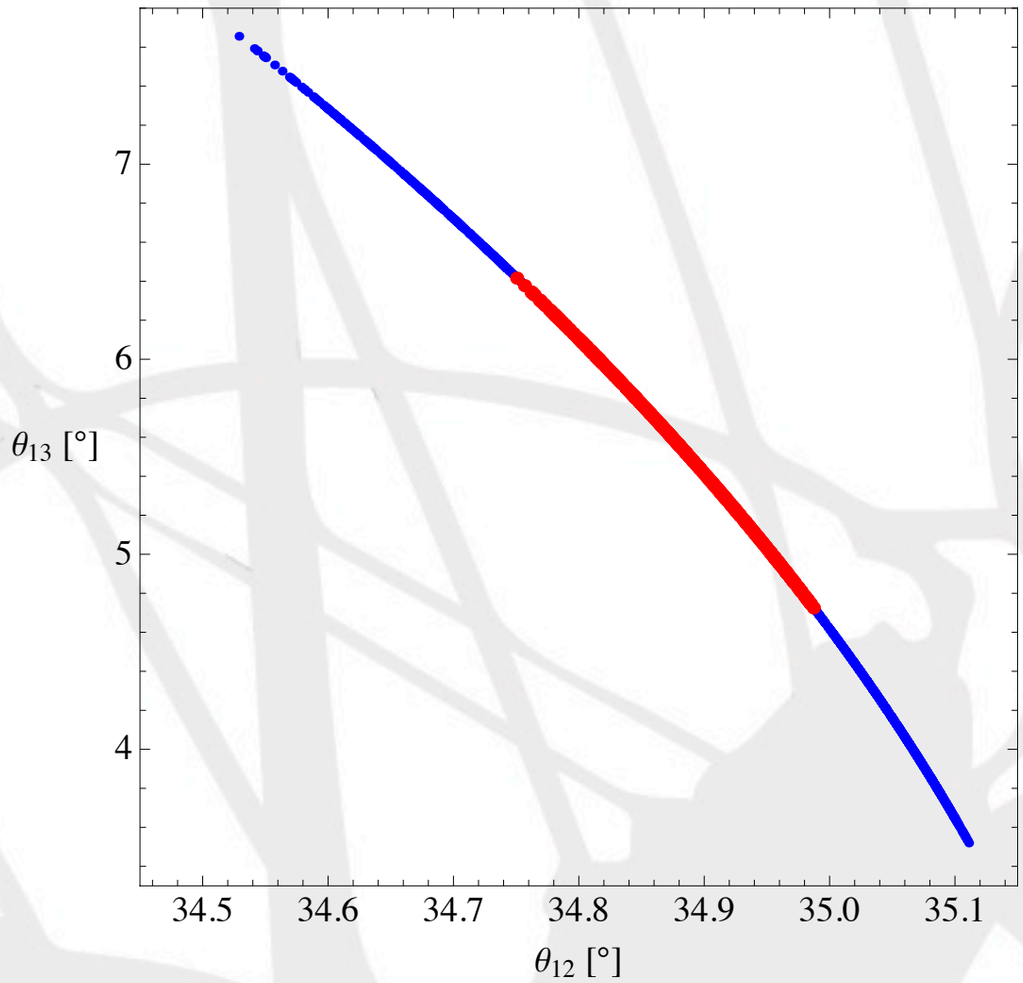
$$m_1^\nu = 0 \ ,$$

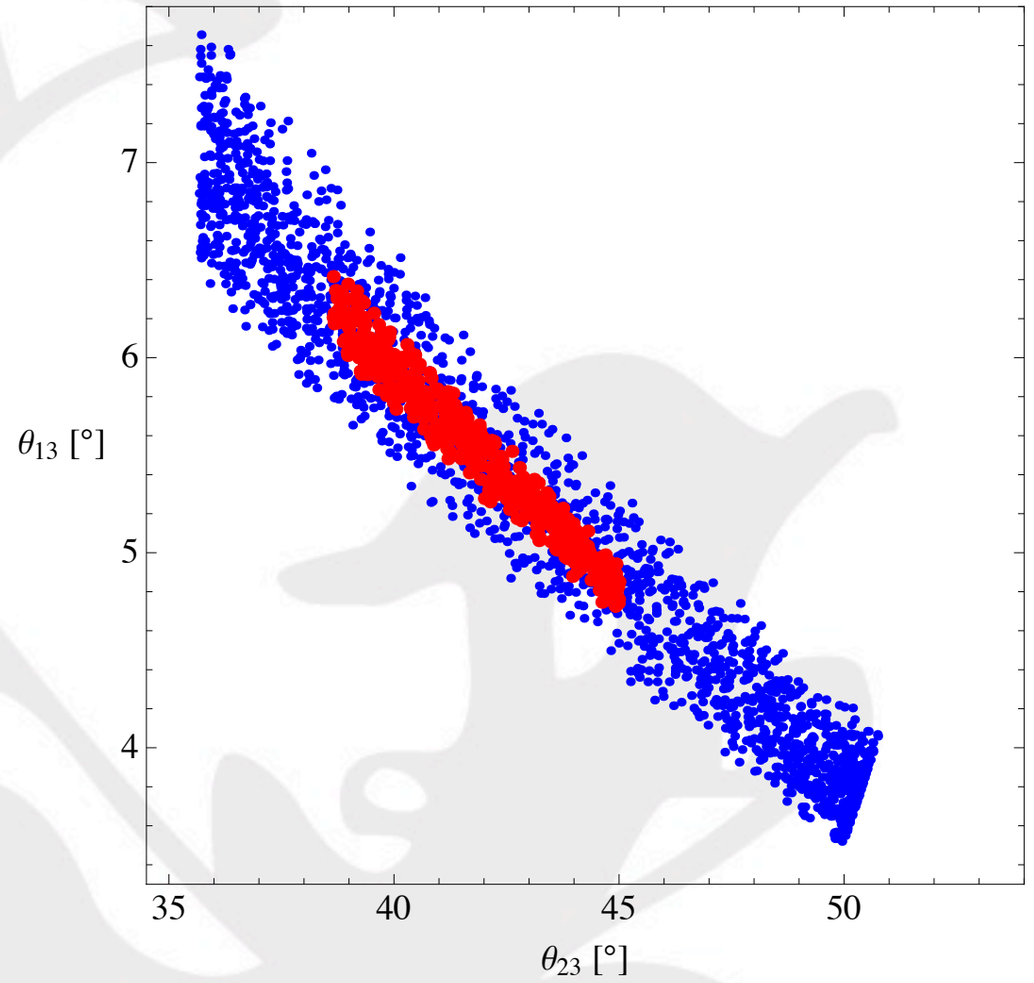
$$m_2^\nu = \left[3\,\epsilon \ - \ 3\,\epsilon^2 \cos\alpha \right] m_a \ ,$$

$$m_3^\nu = \left[2 \ + \ 2\,\epsilon \, \cos\alpha \ + \ \frac{\epsilon^2}{2} \left(7 - \cos 2\alpha\right) \right] m_a \ ,$$

$$\theta_{13} = \frac{\sqrt{2}}{3} \frac{m_2^\nu}{m_3^\nu}$$

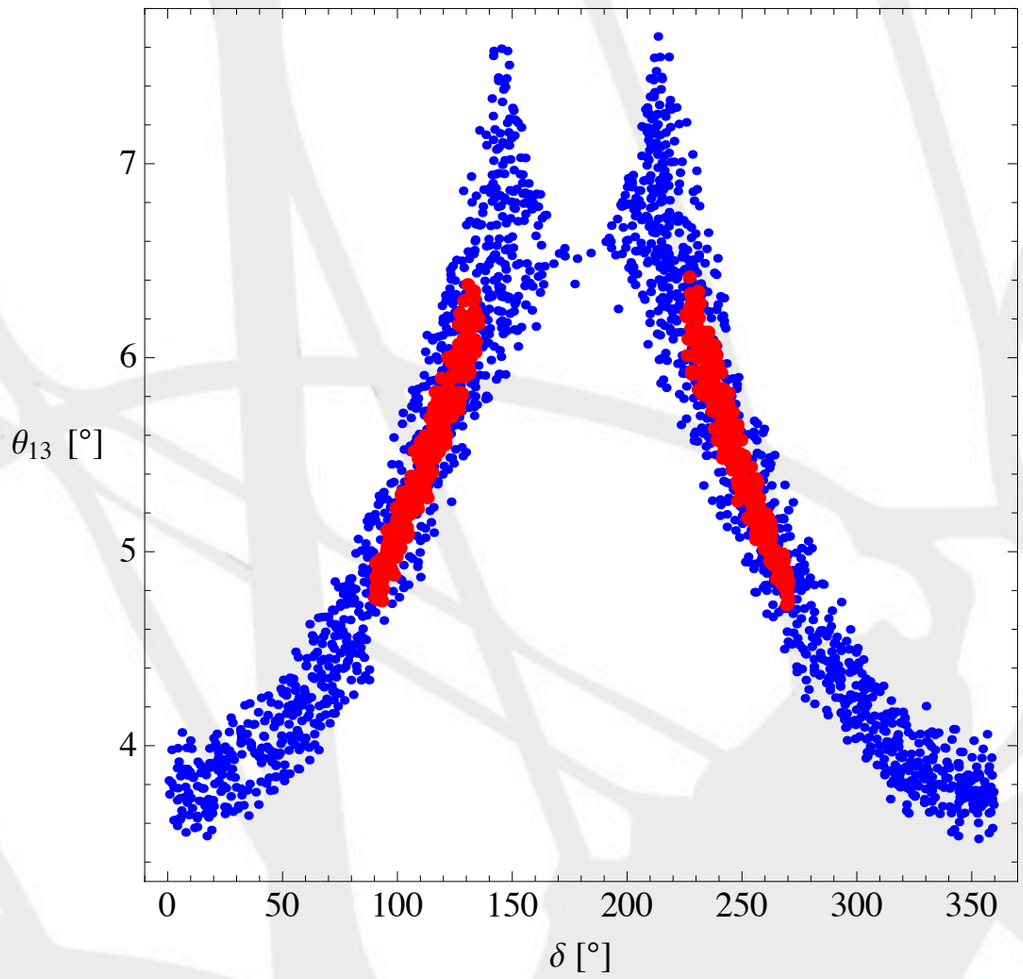
Phenomenology II

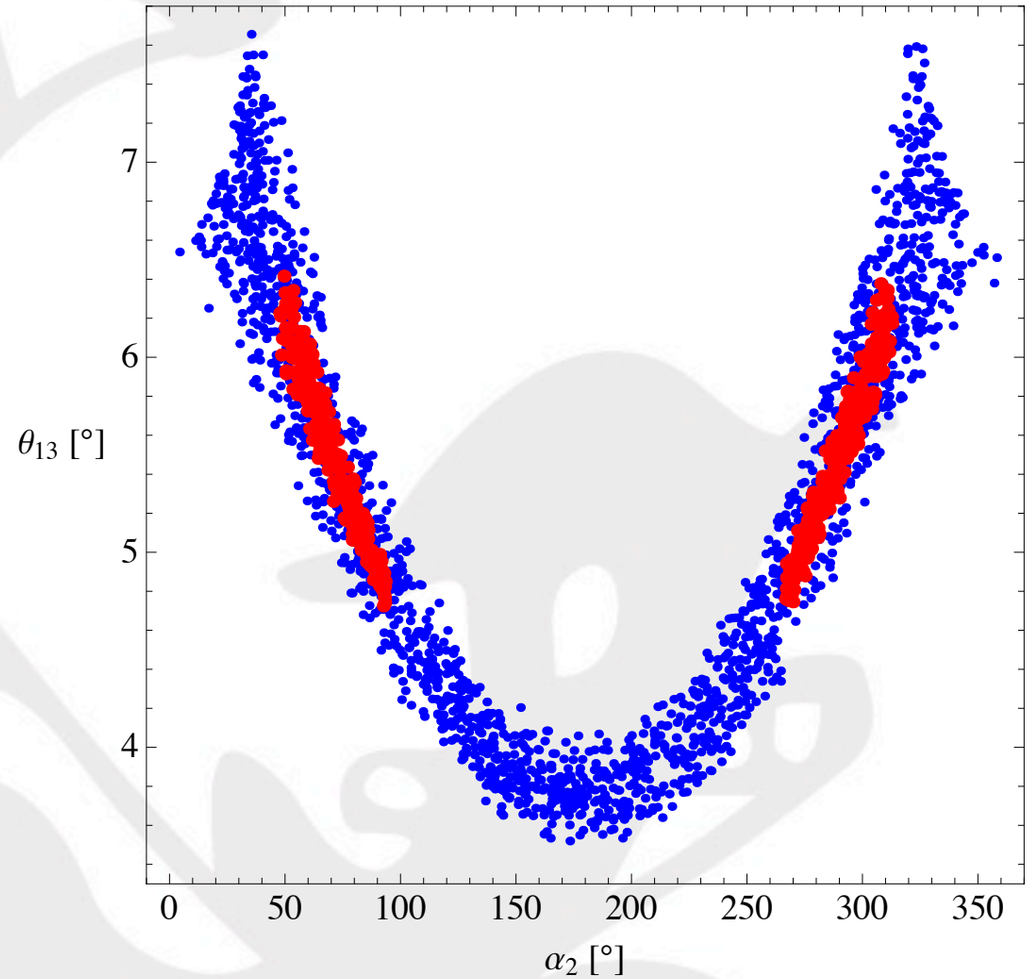




[Antusch, King, Luhn, MS `11; +3° from GUTs?! Work in progress...]

Phenomenology III





[Antusch, King, Luhn, MS `11; +3° from GUTs?! Work in progress...]

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Summary and Conclusions

- Many Flavour Models ruled out by new experimental data
- Where to go? 2 possibilites (out of many):
  - Charged Lepton Corrections

    [Antusch, Maurer `11; Marzocca, Petcov, Romanino, MS `11]
  - Trimaximal Mixing

    [Antusch, King, Luhn, MS `11]
- CP violation?!

Thanks for your attention!

Backup

[Antusch, King, Luhn, MS `11]

$$\theta_{23} = \frac{\pi}{4} + \epsilon \cos\alpha + \epsilon^2 \left(\frac{3}{2} - \cos 2\alpha \right) ,$$

$$\theta_{12} = \arcsin \frac{1}{\sqrt{3}} - \frac{\epsilon^2}{2\sqrt{2}} ,$$

$$\theta_{13} = \frac{\epsilon}{\sqrt{2}} + \frac{\epsilon^2}{2\sqrt{2}} \cos\alpha ,$$

$$\delta = \alpha - \epsilon \frac{5}{2} \sin\alpha \qquad (\text{only up to order } \epsilon) ,$$

$$\alpha_2 = -\alpha + 2\,\epsilon \sin\alpha - 3\,\epsilon^2 \sin 2\alpha ,$$

$$\alpha_3 = 0$$