

Two Approaches for Flavour Models with Large θ_{13}

Martin Spinrath

FLASY 2012

Workshop on Flavour Symmetries



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?

Many opinions...

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...

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]

- Assume SU (5) relations:

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

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

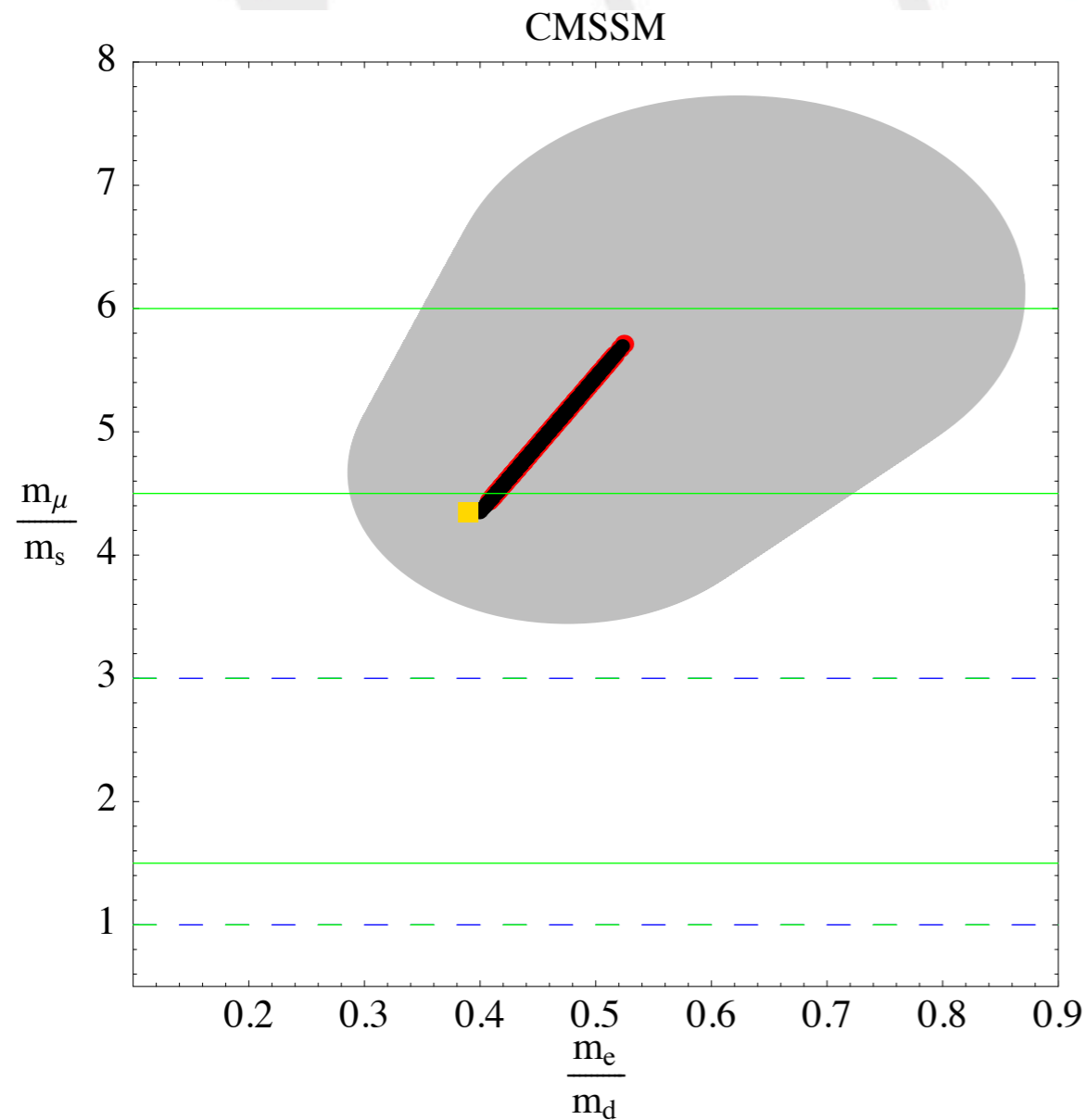
$$\sin \theta_{13} \approx \sin \theta_{12}^e \sin \theta_{23}^\nu \approx \frac{1}{\sqrt{2}} \frac{\beta' b'}{\gamma c}$$

- $\alpha, \beta, \beta', \gamma$ are SU(5) Clebsch-Gordan coefficients (1, -3/2, -3, 9/2, 6, ...)

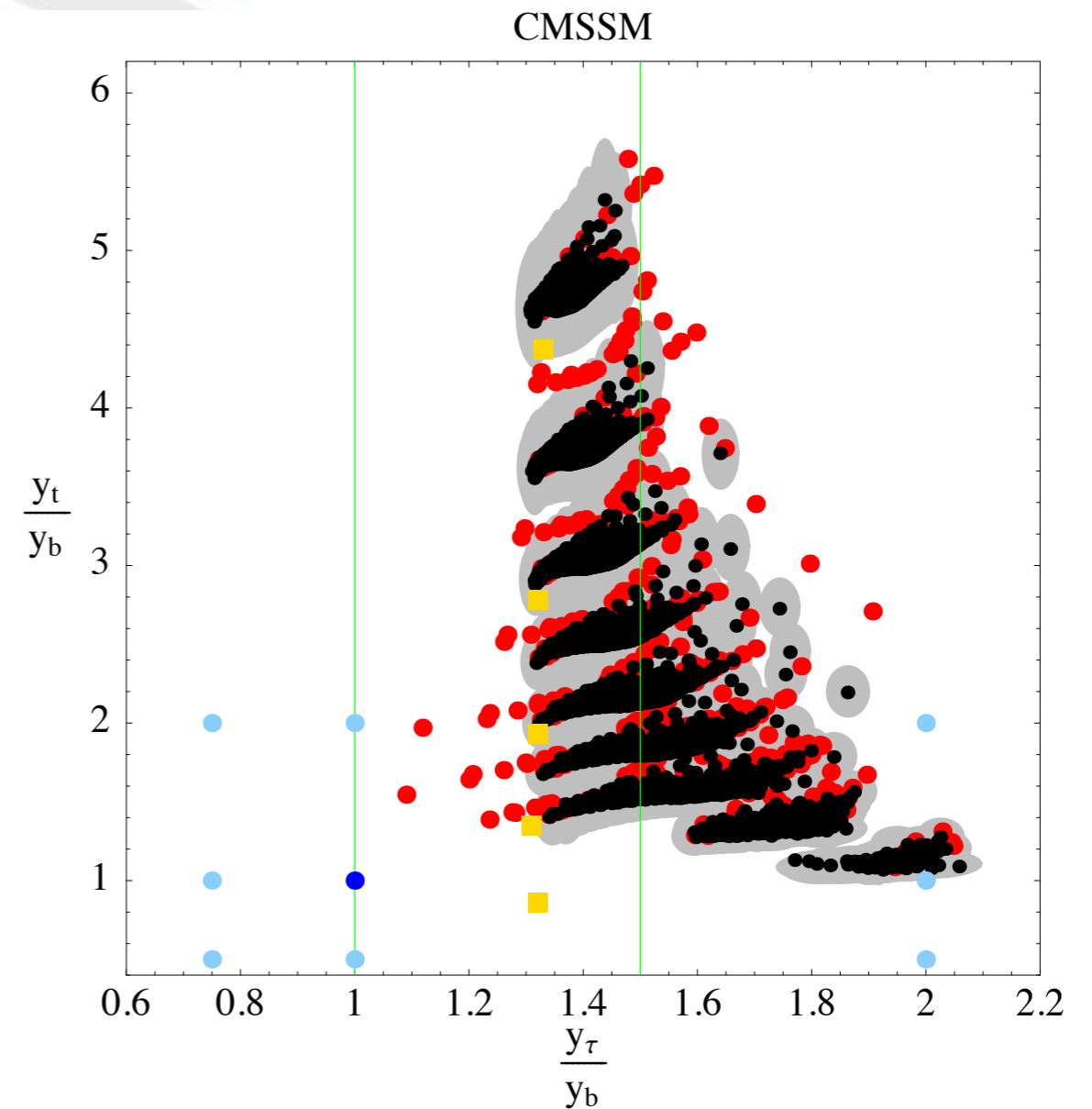
[for a list see Antusch, MS '09]

Intermezzo: GUT Relations

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



[Antusch, MS '09]



The Setup

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

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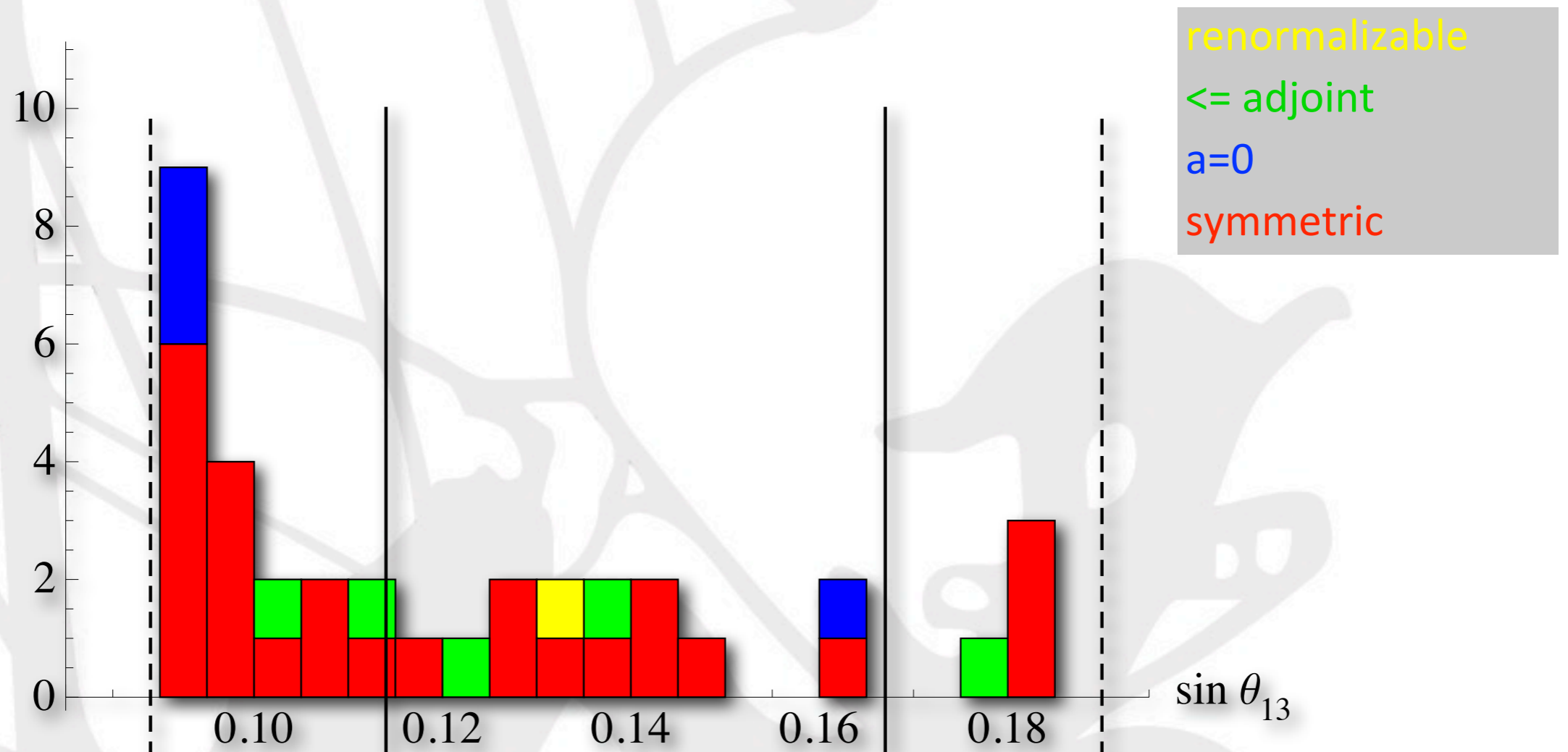
$$\sin \theta_{13} \approx \sin \theta_{12}^e \sin \theta_{23}^\nu \approx \frac{1}{\sqrt{2}} \frac{\beta' b'}{\gamma c}$$

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[for a list see Antusch, MS '09]

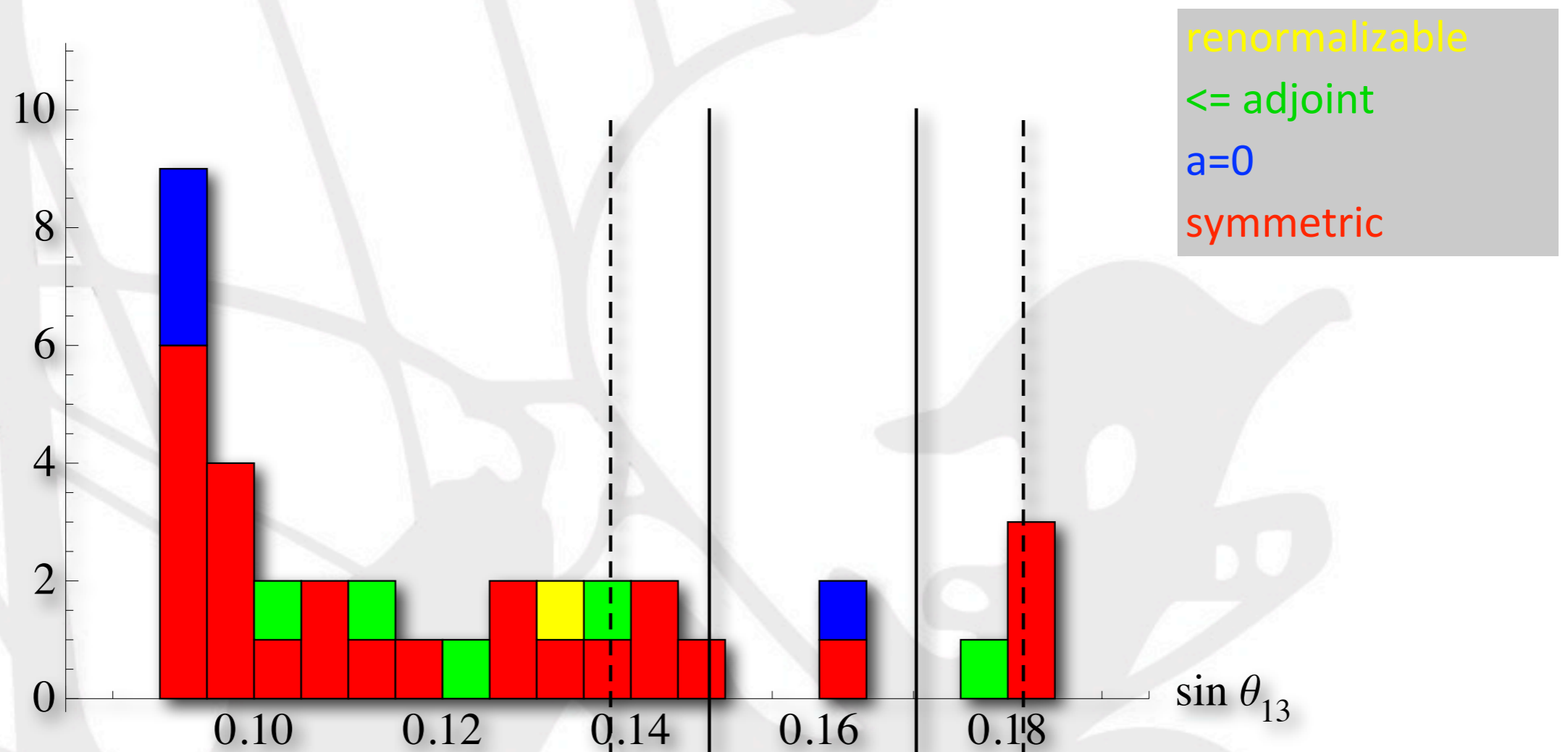
Scan results with free

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

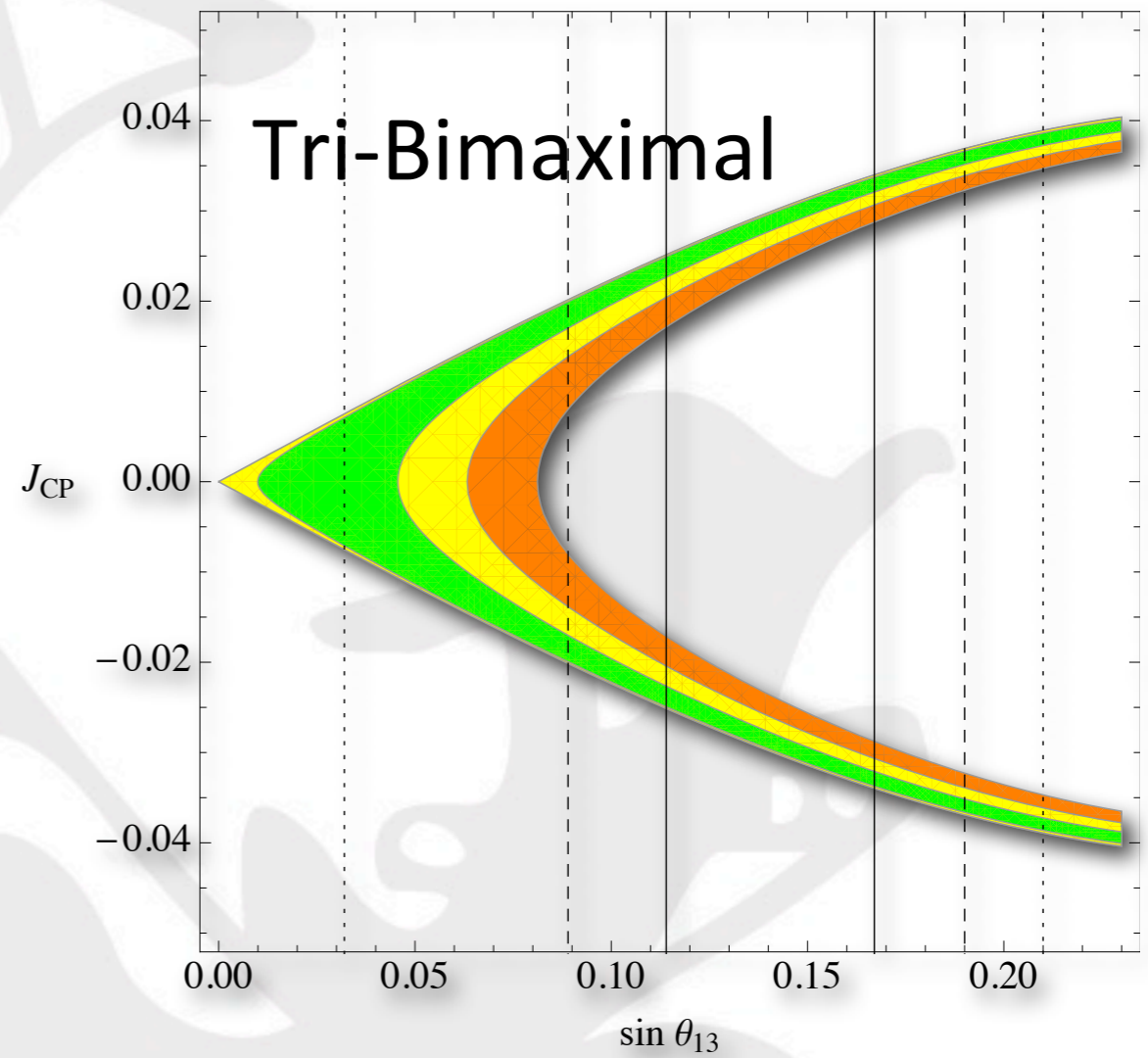
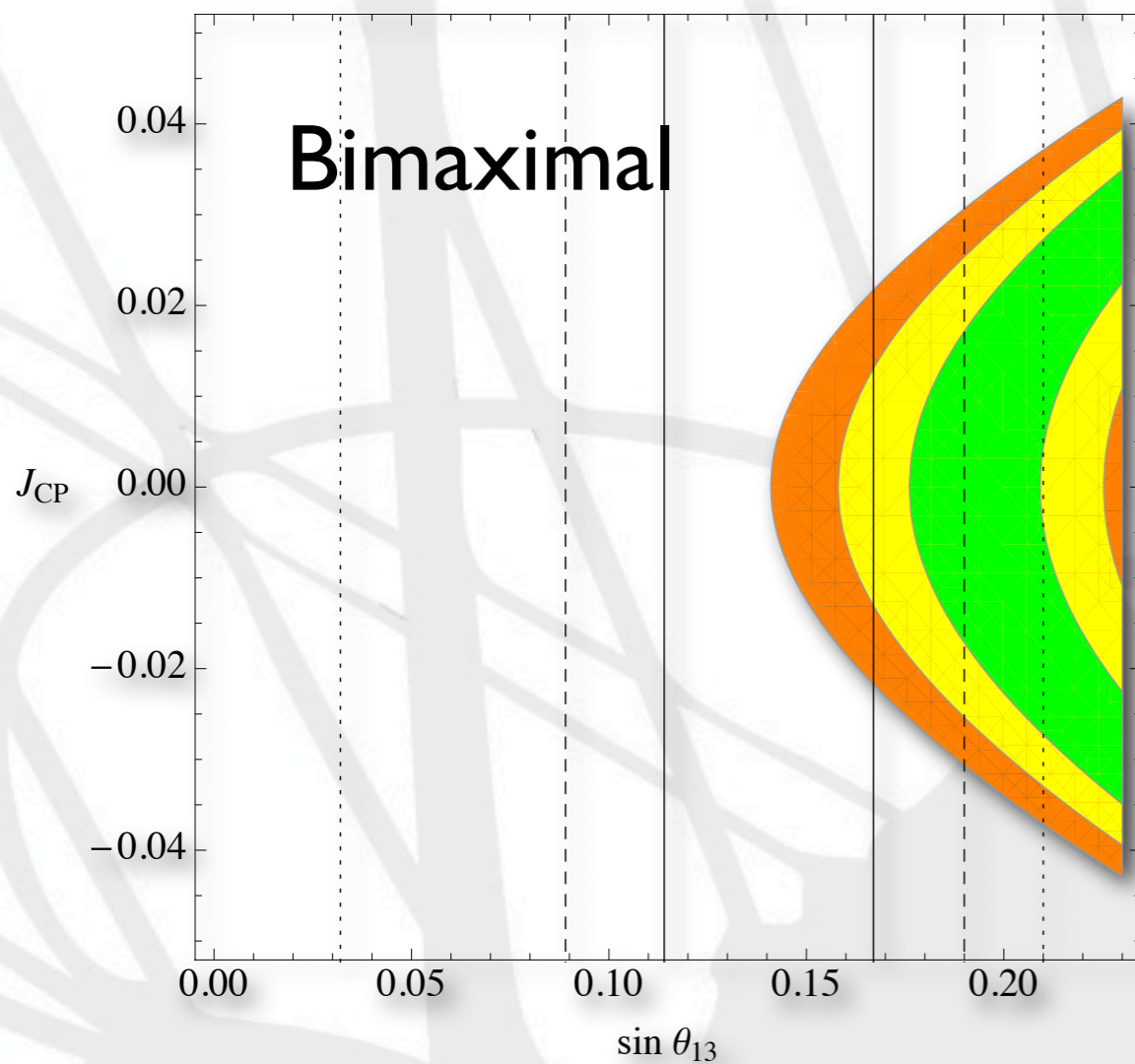
- For Bimaximal mixing:

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

- For Tri-Bimaximal mixing:

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

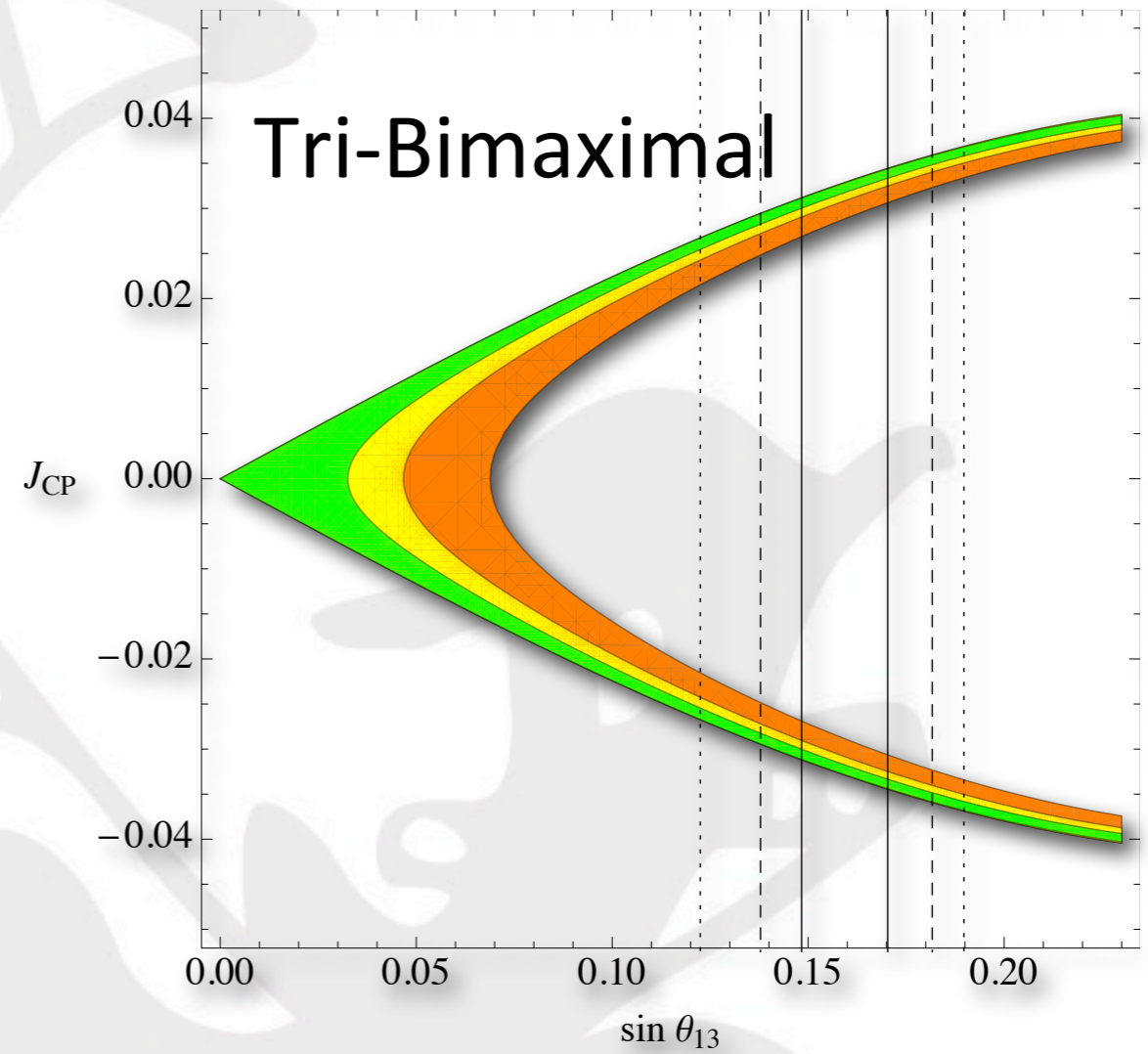
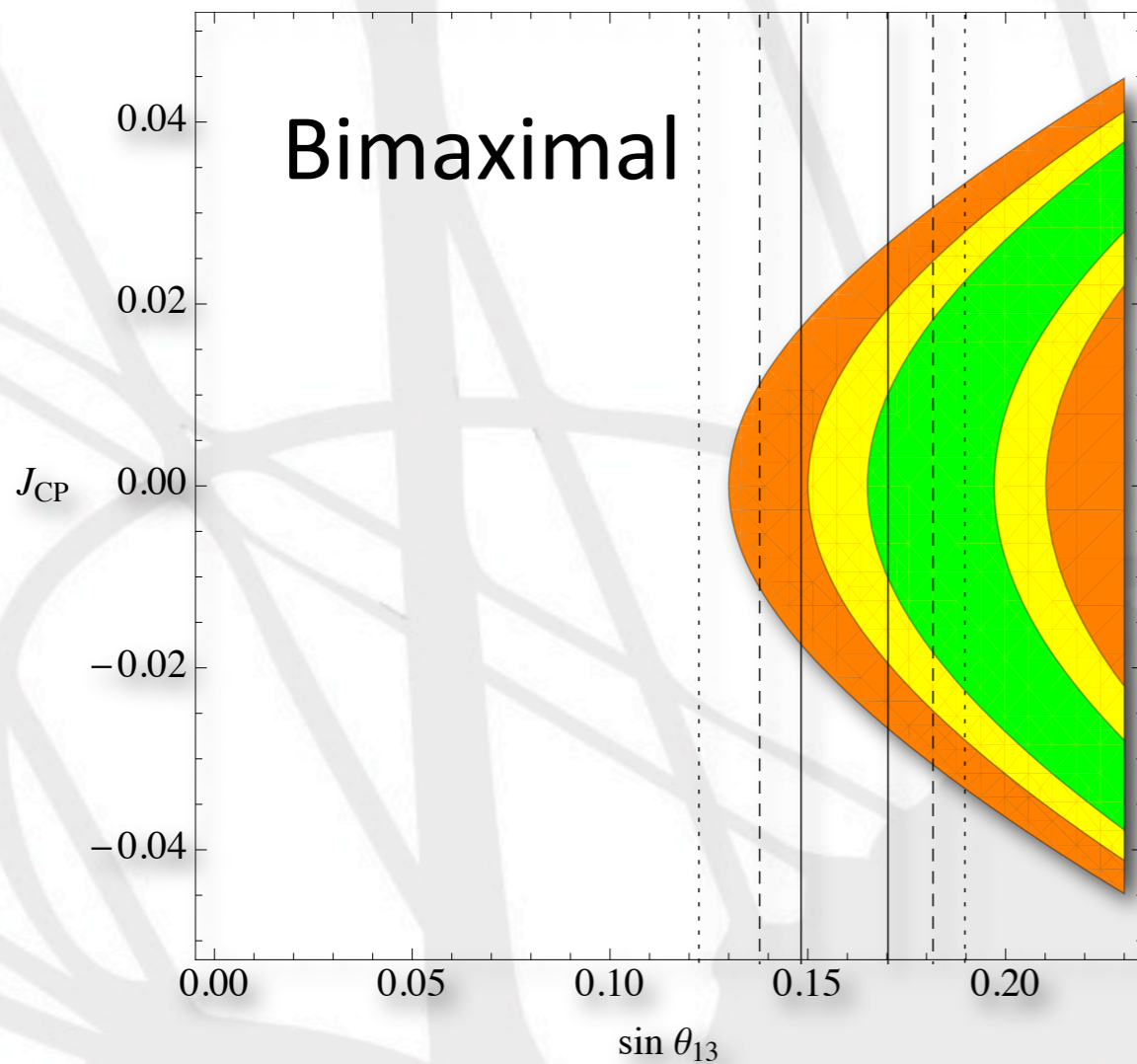
Implications for J_{CP} (June `11)



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

Implications for J_{CP}

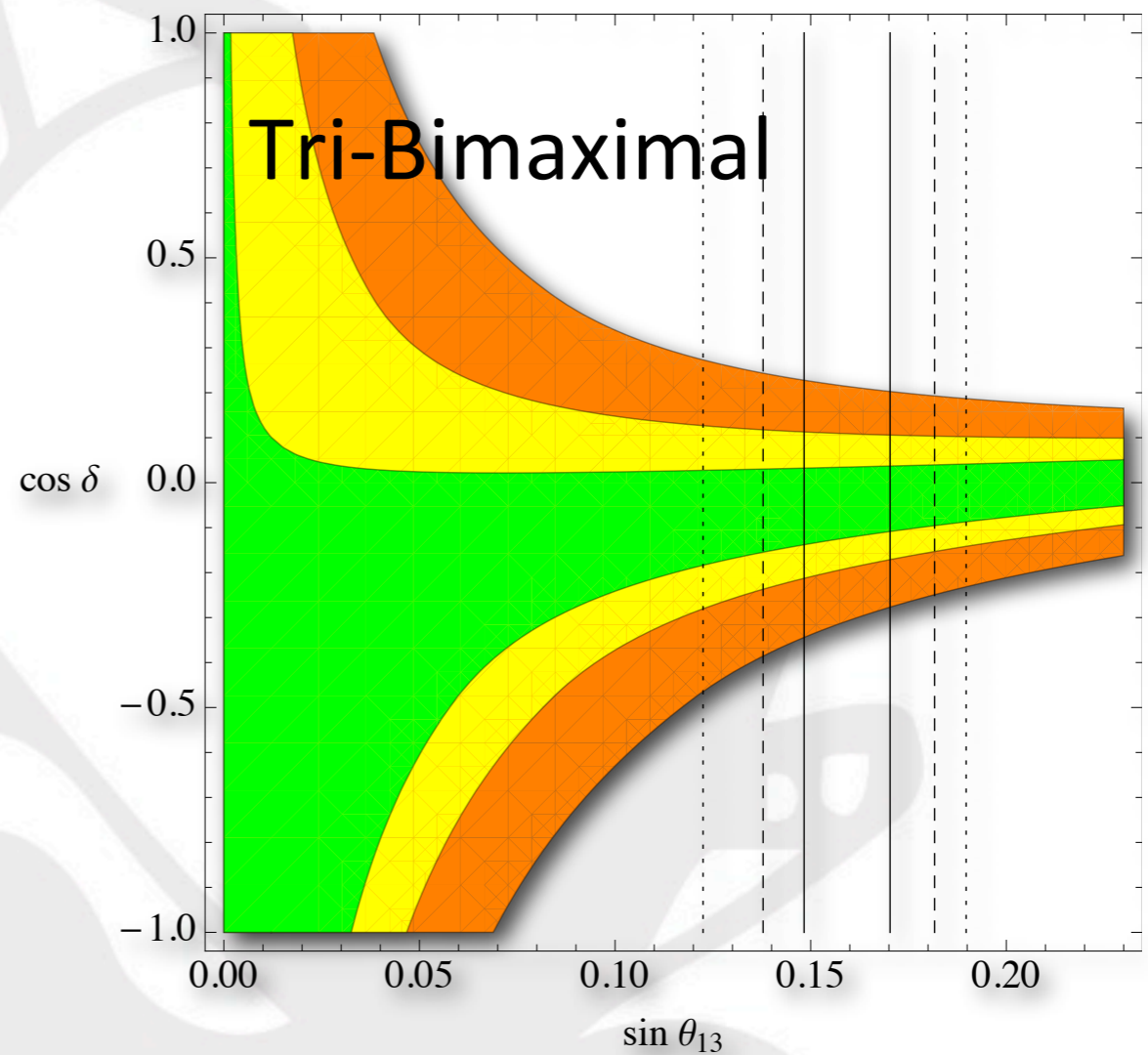
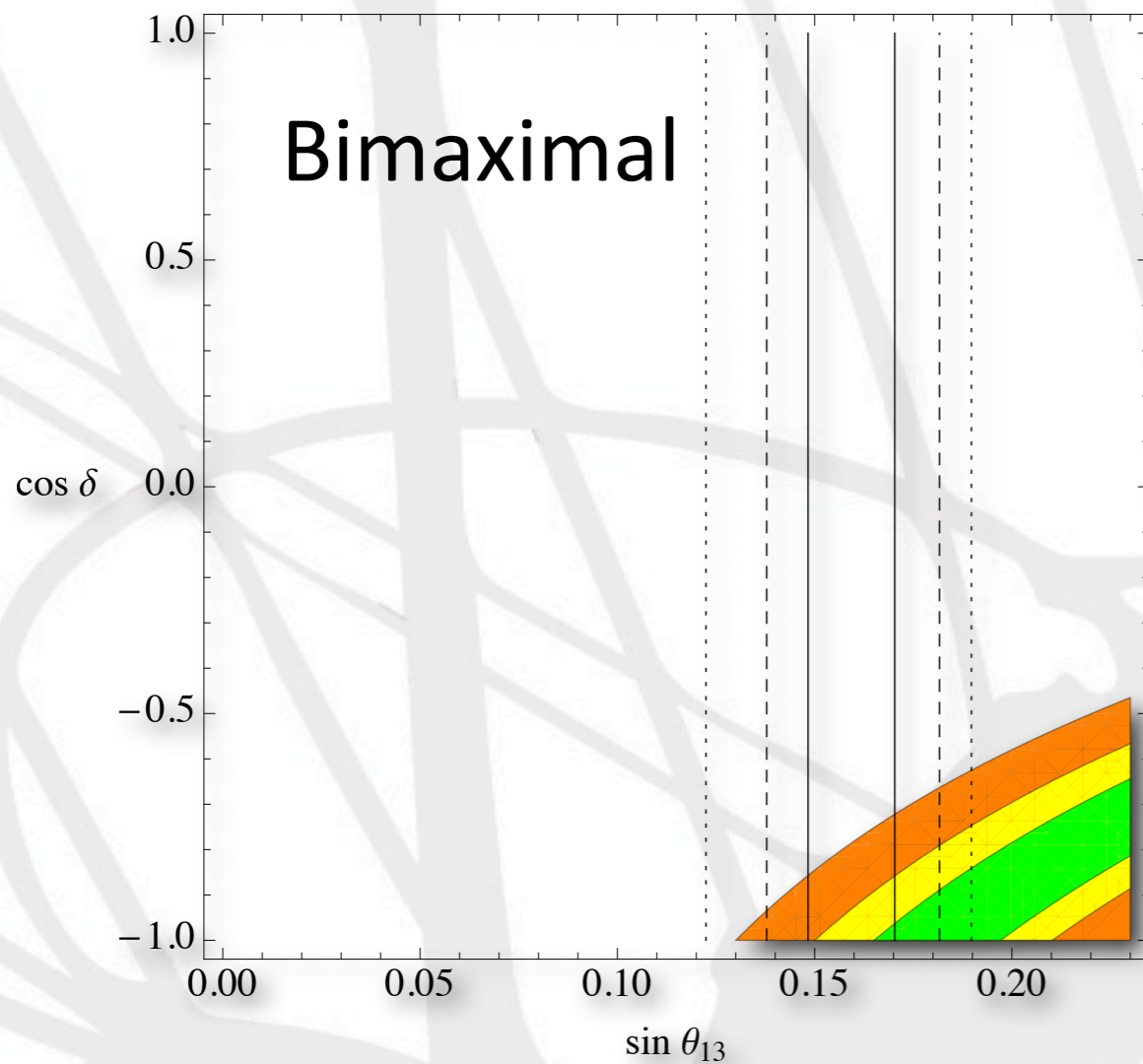
(May `12)



[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. Boudjema, 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

$$M_\nu = \frac{v^2 AA^T}{M_A} + \frac{v^2 BB^T}{M_B} + \frac{v^2 CC^T}{M_C}$$

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

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

Pattern for Mixing Schemes

- Minimalistic pattern for TBM (CSD):

[S.F. King '05]

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

- Pattern for trimaximal mixing (CSD2):

[Antusch, King, Luhn, MS '11]

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

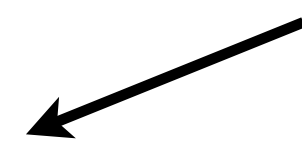
[Trimaximal variant we use based on C. S. Lam '06; C. H. Albright, W. Rodejohann '09; C. H. Albright, A. Dueck, W. Rodejohann '10]

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 ($F_0 = 0$):

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

Phenomenology I

[Antusch, King, Luhn, MS '11]

- The neutrino mass matrix:

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

- Approximate formulas:

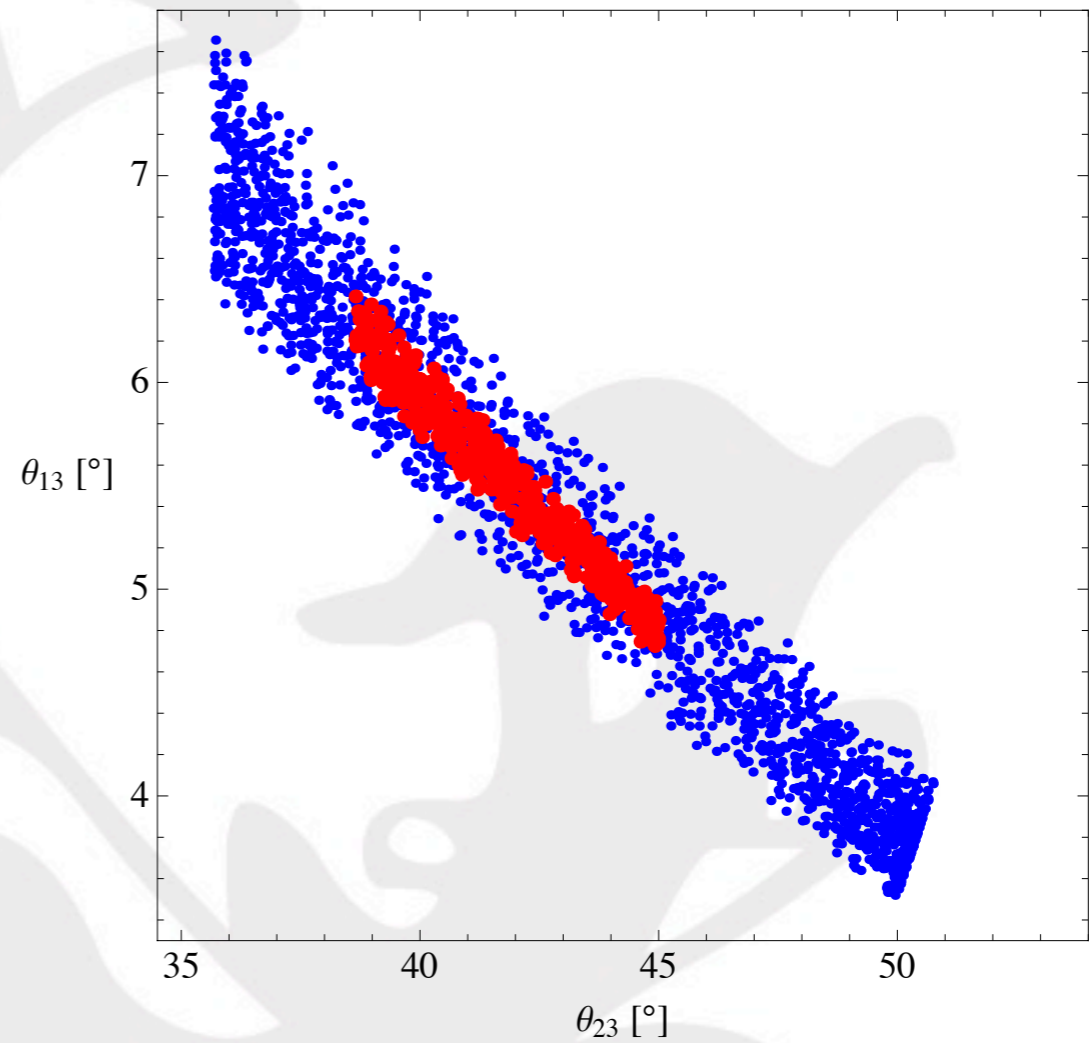
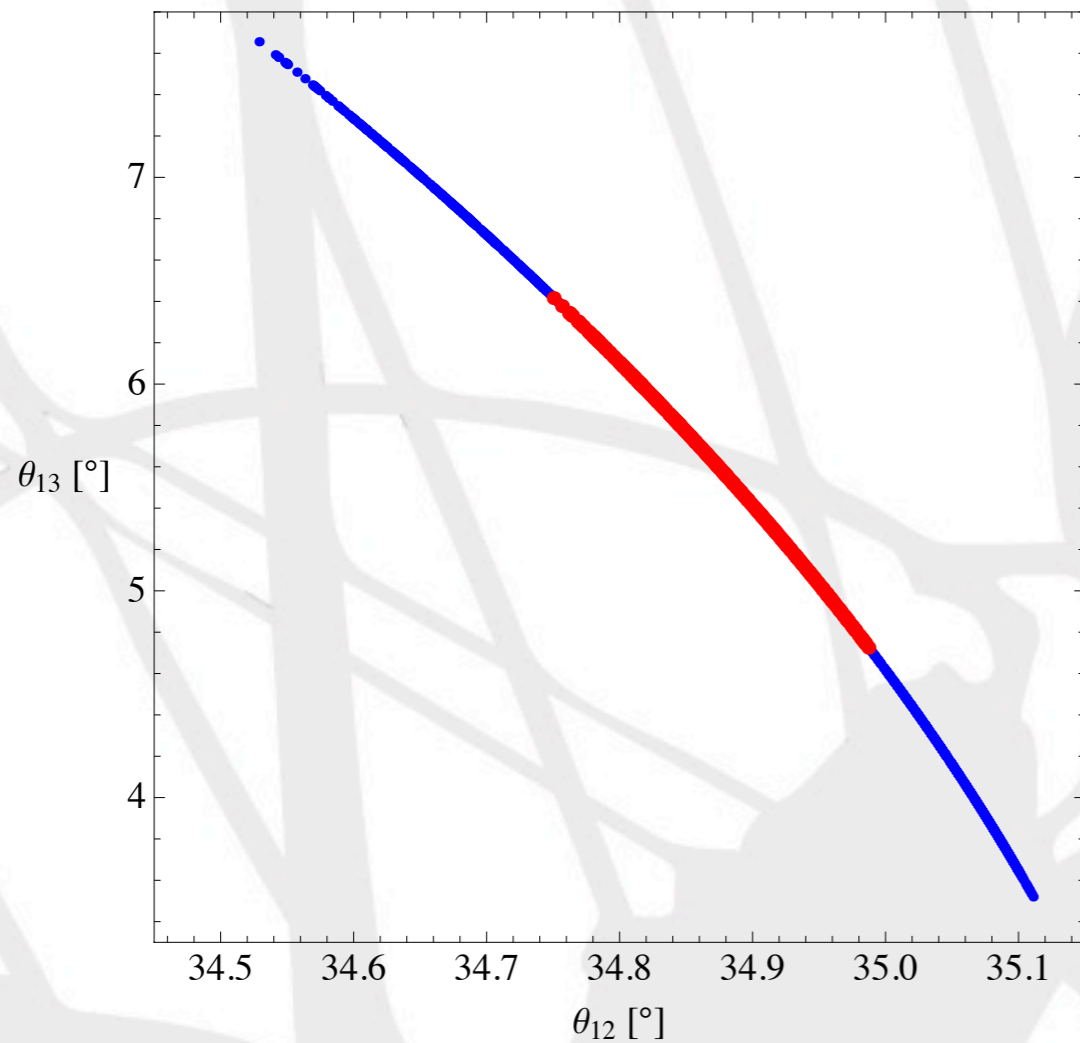
$$m_1^\nu = 0,$$

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

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

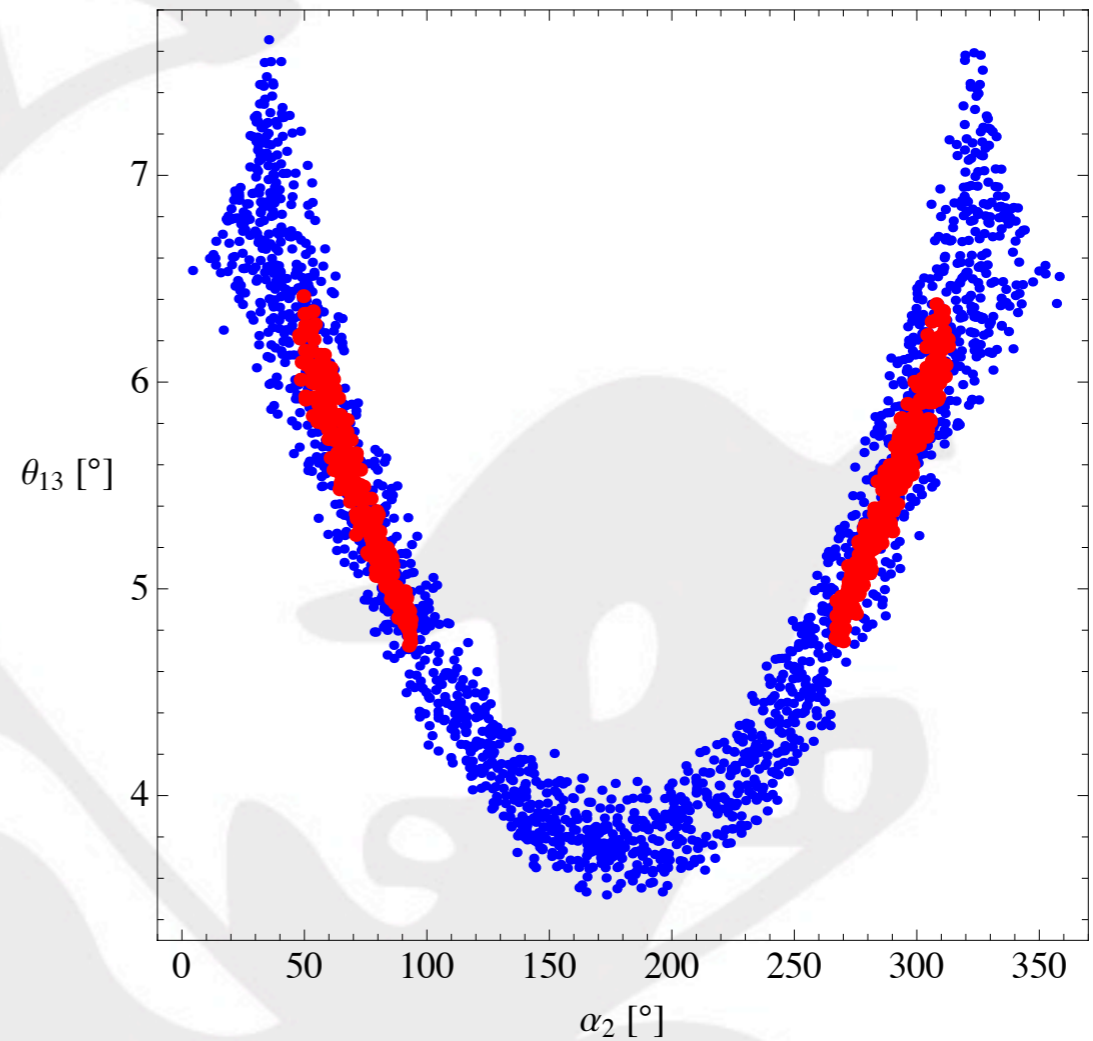
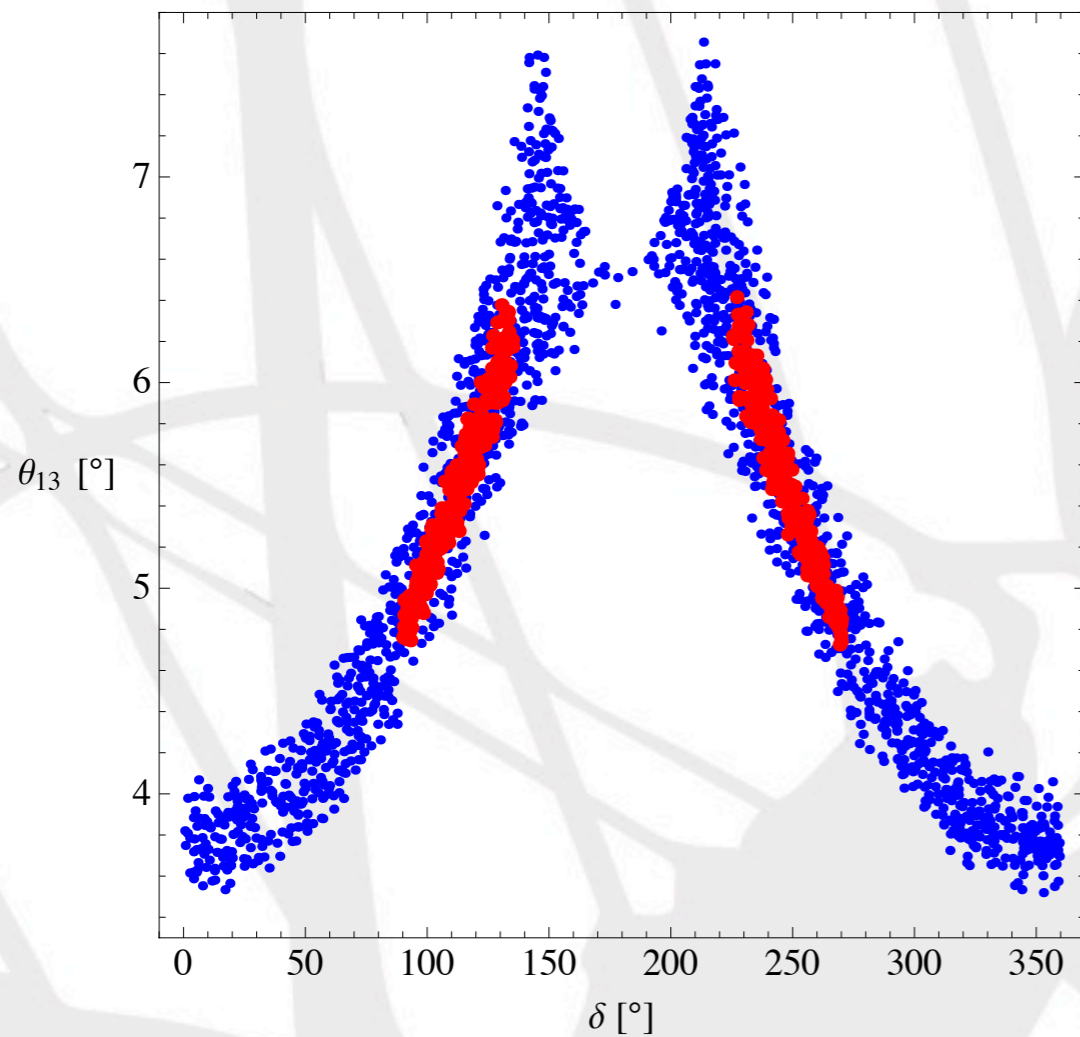
$$\theta_{13} = \frac{\sqrt{2}}{3} \frac{m_2^\nu}{m_3^\nu} \longleftarrow \text{Mass dependent!}$$

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 possibilities (out of many):
 - Charged Lepton Corrections
[Antusch, Maurer '11; Marzocca, Petcov, Romanino, MS '11]
 - Trimaximal Mixing
[Antusch, King, Luhn, MS '11]
- θ_{23} , mass hierarchy, CP violation?!

The background features a faint, light gray illustration. On the left, a globe is depicted with latitude and longitude lines. On the right, there is a classical bust of a man's head and shoulders, facing right. The text is centered over these elements.

**Thank you for your
attention!**