



$U(2)^5$ Flavour Symmetries in SUSY for the Quark and Lepton Sector

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Barbieri, Isidori, JJP, Lodone, Straub: 1105.2296
Blankenburg, Isidori, JJP: 1204.0688
JJP: 1311.1837

Supersymmetry and the Hierarchy Problem

It seems SUSY particles are heavier than expected.

In addition, large Higgs mass hints towards a heavy spectrum, which compromises hierarchy problem.

“Is this the end of the SUSY story? Should we all go into dark matter? Or neutrino physics? Or finance?”



Supersymmetry and the Hierarchy Problem

Solution to hierarchy problem can be somewhat subjective.
Nevertheless, SUSY does minimise fine-tuning.

Examples:

- “Natural SUSY”: light stops, light Higgsinos, not too heavy gluinos.
Papucci, Ruderman, Weiler (1110.6926)
- “Focus Point SUSY”: light gauginos and Higgsinos, heavy scalars.
Feng, Matchev, Moroi (hep-ph/9908309)
- Non-Universal Gaugino Masses: light neutralino, heavy stops and heavy gluinos.
Antusch, Calibbi, Maurer, Monaco, Spinrath (1207.7236)

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How do we keep stops light?

Solution: Split-Family SUSY

Specially relevant in case first generation squarks are pushed to higher masses, and *gasp!* light stops are eventually observed.

Question: What do we do with flavour?

On the CMSSM, the MFV ansatz was used. On a split-family scenario, this can imply new fine-tuning.

We need an alternative ansatz: U(2)⁵

Outline

- Brief review of MFV
- The (s)quark sector and the flavour tension
- The (s)lepton sector and neutrino data

Review of MVF

Flavour in the CMSSM: Minimal Flavour Violation

- U(3)⁵ framework built in order to suppress New Physics contributions to flavoured processes.
- SUSY sfermion masses are forced to be nearly degenerate (although RGE effects can cause splitting).
- Flavour off-diagonal contributions are related to CKM and mass hierarchies: y_t, y_b .

Minimal Flavour Violation for (s)quarks

Assumption 1:

U(3)³ flavour symmetry is exact, and Yukawa couplings act as spurions breaking the symmetry.

$$Q^T \rightarrow Q^T U_Q^T$$

$$u_R^c \rightarrow U_u u_R^c$$

$$d_R^c \rightarrow U_d d_R^c$$

$$Y_u \rightarrow U_Q^* Y_u U_u^\dagger$$

$$Y_d \rightarrow U_Q^* Y_d U_d^\dagger$$

$$W = Q^T Y_u u_R^c H_u - Q^T Y_d d_R^c H_d + \dots$$

Minimal Flavour Violation for (s)quarks

Assumption 2:

Yukawa couplings are the only spurions available.

Example: $\tilde{Q}^\dagger m_{\tilde{Q}}^2 \tilde{Q}$

“Leading order”: $m_{\tilde{Q}}^2 \propto I$

“NLO”: $m_{\tilde{Q}}^2 \propto I + Y_u^* Y_u^T + Y_d^* Y_d^T$

Minimal Flavour Violation for (s)quarks

On the basis where Y_u is diagonal:

$$m_{\tilde{Q}}^2 \propto I + (Y_u^d)^* (Y_u^d)^T + V_{CKM} (Y_d^d)^* (Y_d^d)^T V_{CKM}^\dagger$$



$$(m_{\tilde{Q}}^2)_{ij} \propto \delta_{ij} + y_t^2 \delta_{ij} \delta_{i3} + y_b^2 (V_{CKM})_{i3} (V_{CKM}^\dagger)_{3j}$$

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Small mass splitting

Suppressed contribution
to flavour

U(2)³ in the (s)quark sector

Barbieri, Isidori, JJP, Lodone, Straub: 1105.2296

U(2)³ Ansatz: Symmetries

$$U(2)_Q \otimes U(2)_u \otimes U(2)_d$$

$$Q^{(2)} = (Q_1, \quad Q_2) \quad \sim \quad (\bar{2}, 1, 1)$$

$$u_R^{c(2)} = (u_{R,1}^c, \quad u_{R,2}^c)^T \quad \sim \quad (1, 2, 1)$$

$$d_R^{c(2)} = (d_{R,1}^c, \quad d_{R,2}^c)^T \quad \sim \quad (1, 1, 2)$$

$$W_q = y_t Q_3 t_R^c H_u + y_b Q_3 b_R^c H_d$$

$U(2)^3$ Ansatz: Symmetries

$$U(2)_Q \otimes U(2)_u \otimes U(2)_d$$

$$Q^{(2)} = (Q_1, Q_2) \sim (\bar{2}, 1, 1)$$

$$u_R^{c(2)} = (u_{R,1}^c, u_{R,2}^c)^T \sim (1, 2, 1)$$

$$d_R^{c(2)} = (d_{R,1}^c, d_{R,2}^c)^T \sim (1, 1, 2)$$

$$W_q = y_t Q_3 t_R^c H_u + y_b Q_3 b_R^c H_d$$

Large $\tan\beta$

U(2)³ Ansatz: Spurions

$$\Delta Y_u \sim (2, \bar{2}, 1)$$

$$\Delta Y_d \sim (2, 1, \bar{2})$$

$$Y_u = \left(\begin{array}{c|c} \Delta Y_u & 0 \\ \hline 0 & 1 \end{array} \right) y_t$$

$$Y_d = \left(\begin{array}{c|c} \Delta Y_d & 0 \\ \hline 0 & 1 \end{array} \right) y_b$$

U(2)³ Ansatz: Spurions

$$\Delta Y_u \sim (2, \bar{2}, 1)$$

$$\Delta Y_d \sim (2, 1, \bar{2})$$

$$V \sim (2, 1, 1)$$

$$Y_u = \left(\begin{array}{c|c} \Delta Y_u & x_t V \\ \hline 0 & 1 \end{array} \right) y_t$$

$$Y_d = \left(\begin{array}{c|c} \Delta Y_d & x_b V \\ \hline 0 & 1 \end{array} \right) y_b$$

U(2)³ Ansatz: Parametrisation

$$V \Rightarrow \begin{pmatrix} 0 \\ 1 \end{pmatrix} \epsilon$$

$$\Delta Y_f \Rightarrow U_{Q_f}^\dagger \Delta Y_f^d \quad U_{Q_f} = \begin{pmatrix} c_f & s_f e^{i\alpha_f} \\ -s_f e^{-i\alpha_f} & c_f \end{pmatrix}$$

We now need to determine ϵ , s_f and α_f .

U(2)³ Ansatz: CKM Matrix

$$V_{\text{CKM}} = \begin{pmatrix} c_u c_d + s_u s_d e^{i(\alpha_d - \alpha_u)} & -c_u s_d e^{-i\alpha_d} + s_u c_d e^{-i\alpha_u} & s_u s e^{-i(\alpha_u - \xi)} \\ c_u s_d e^{i\alpha_d} - s_u c_d e^{i\alpha_u} & c_u c_d + s_u s_d e^{i(\alpha_u - \alpha_d)} & c_u s e^{i\xi} \\ -s_d s e^{i(\alpha_d - \xi)} & -s c_d e^{-i\xi} & 1 \end{pmatrix}$$

U(2)³ Ansatz: CKM Matrix

$$V_{\text{CKM}} =$$

$$\begin{pmatrix} c_u c_d + s_u s_d e^{i(\alpha_d - \alpha_u)} & -c_u s_d e^{-i\alpha_d} + s_u c_d e^{-i\alpha_u} & s_u s e^{-i(\alpha_u - \xi)} \\ c_u s_d e^{i\alpha_d} - s_u c_d e^{i\alpha_u} & c_u c_d + s_u s_d e^{i(\alpha_u - \alpha_d)} & c_u s e^{i\xi} \\ -s_d s e^{i(\alpha_d - \xi)} & -s c_d e^{-i\xi} & 1 \end{pmatrix}$$

$$|s| = 0.0410 \pm 0.0004 \quad \Rightarrow \quad \epsilon \sim \lambda_{\text{CKM}}^2$$

$$s_u = 0.0916 \pm 0.005$$

$$s_d = -0.22 \pm 0.02$$

$$\cos(\alpha_u - \alpha_d) = -0.13 \pm 0.2$$

U(2)³ Ansatz: Squark sector

Soft masses in no-spurion limit:

$$m_{\tilde{f}}^2 = \begin{pmatrix} m_{f_h}^2 & 0 & 0 \\ 0 & m_{f_h}^2 & 0 \\ 0 & 0 & m_{f_l}^2 \end{pmatrix}$$

Same spurions that generated Yukawa structure shall generate soft mass structure.

U(2)³ Ansatz: Squark sector

$$m_{\tilde{u}}^2 = m_{u_h}^2 \left(\begin{array}{c|c} 1 + \Delta Y_u^T \Delta Y_u^* & x_u^* \Delta Y_u^T V^* \\ \hline x_u V^T \Delta Y_u^* & m_{u_l}^2 / m_{u_h}^2 \end{array} \right)$$

$$m_{\tilde{Q}}^2 = m_{Q_h}^2 \left(\begin{array}{c|c} 1 + V^* V^T + \Delta Y_u^* \Delta Y_u^T + \Delta Y_d^* \Delta Y_d^T & x_Q^* V^* \\ \hline x_Q V^T & m_{Q_l}^2 / m_{Q_h}^2 \end{array} \right)$$

U(2)³ Ansatz: Squark *LL* mixing matrix

$$W_L^{d\dagger} m_{\tilde{Q}}^2 W_L^d = (m_{\tilde{Q}}^2)^{\text{diag}}$$

$$W_L^d = \begin{pmatrix} c_d & \kappa^* & -\kappa^* s_L e^{i\gamma} \\ -\kappa & c_d & -c_d s_L e^{i\gamma} \\ 0 & s_L e^{-i\gamma} & 1 \end{pmatrix}$$

$$\kappa = c_d V_{td}/V_{ts}$$

No new phases on the (1-2) sector

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$$s_L e^{-i\gamma} = \epsilon e^{i\xi} (x_b + x_Q)$$

New phase on the (1-3) and (2-3) sectors!

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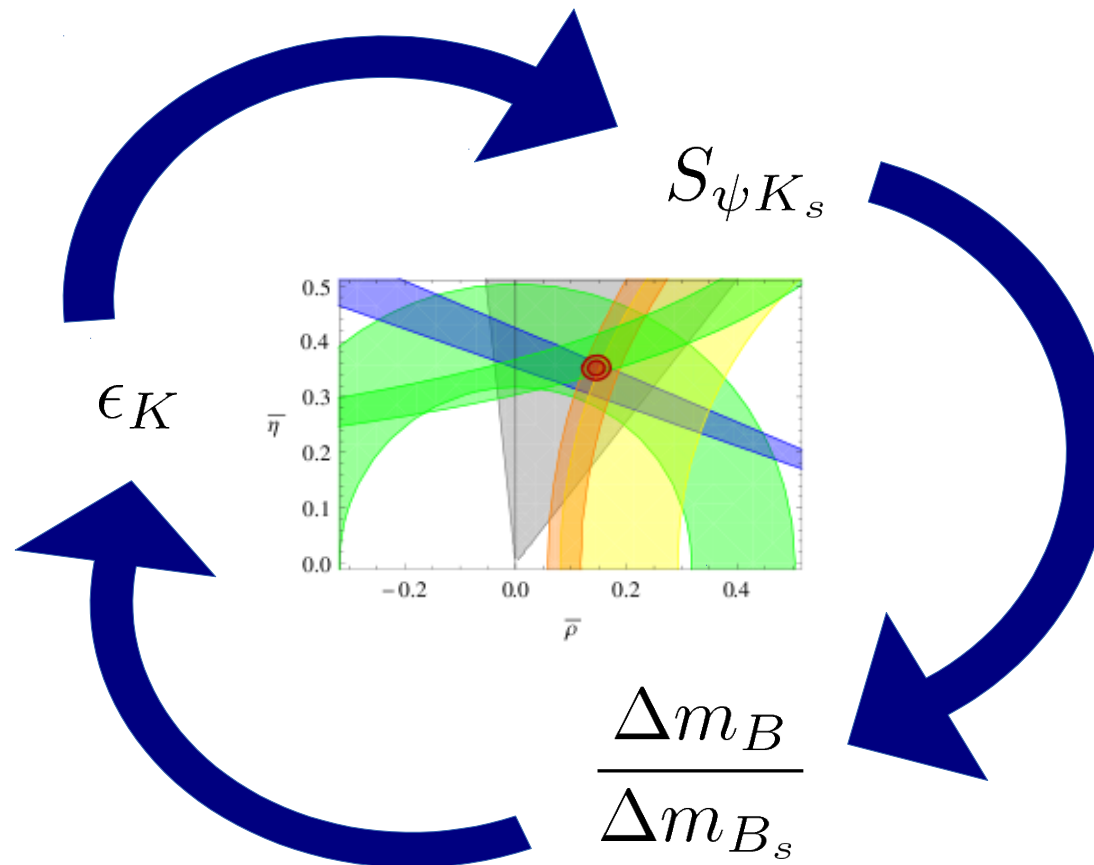
New CPV in (1-3)
sector is connected
to CPV in (2-3)
sector!

$$\kappa = c_d V_{td}/V_{ts} \quad \text{No new phases on the (1-2) sector}$$

$$s_L e^{-i\gamma} = \epsilon e^{i\xi} (x_b + x_Q)$$

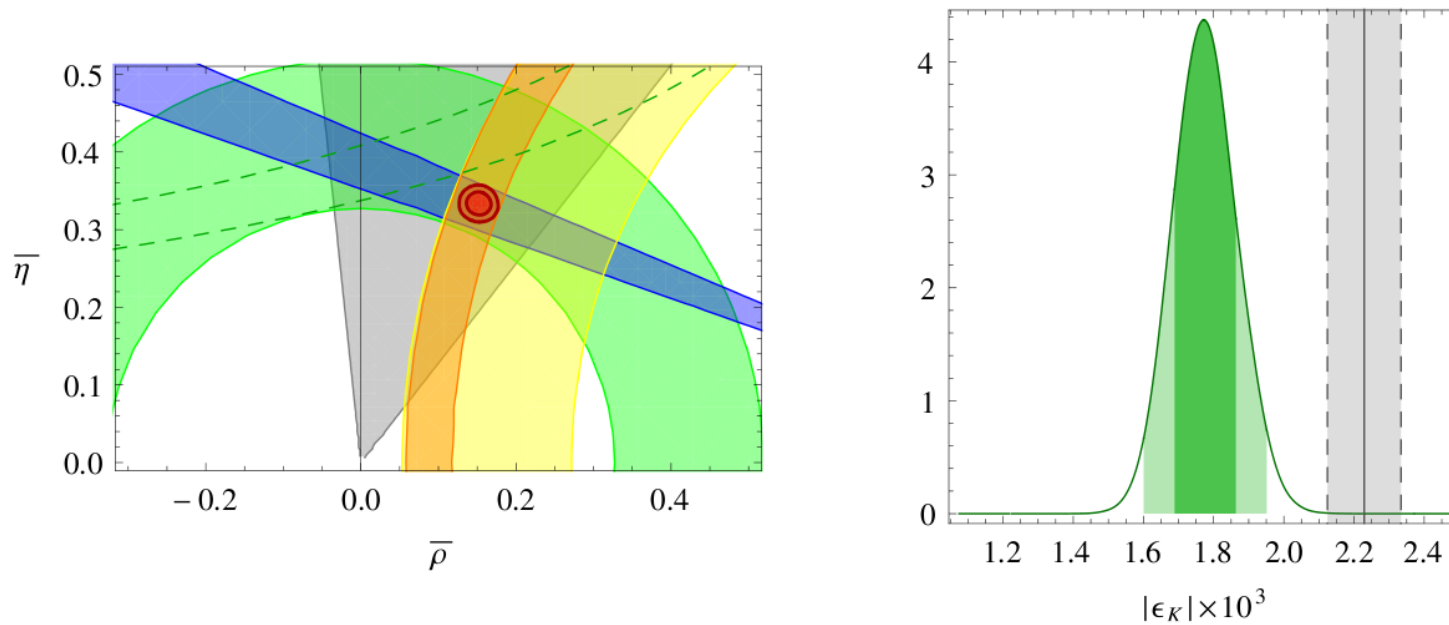
New phase on the (1-3) and (2-3) sectors!

U(2)³ and Flavour Tension?



Situation in 2011:

UT fit without ε_K :



Tension of more than 2σ

U(2)³ contribution to flavour

$$\epsilon_K = \epsilon_K^{\text{SM}(tt)} \times (1 + x^2 F_0) + \epsilon_K^{\text{SM}(tc+cc)}$$

$$x = \frac{c_d^2 s_L^2}{|V_{ts}|^2}$$

U(2)³ contribution to flavour

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$$S_{\psi K_S} = \sin (2\beta + \arg (1 + x F_0 e^{2i\gamma}))$$

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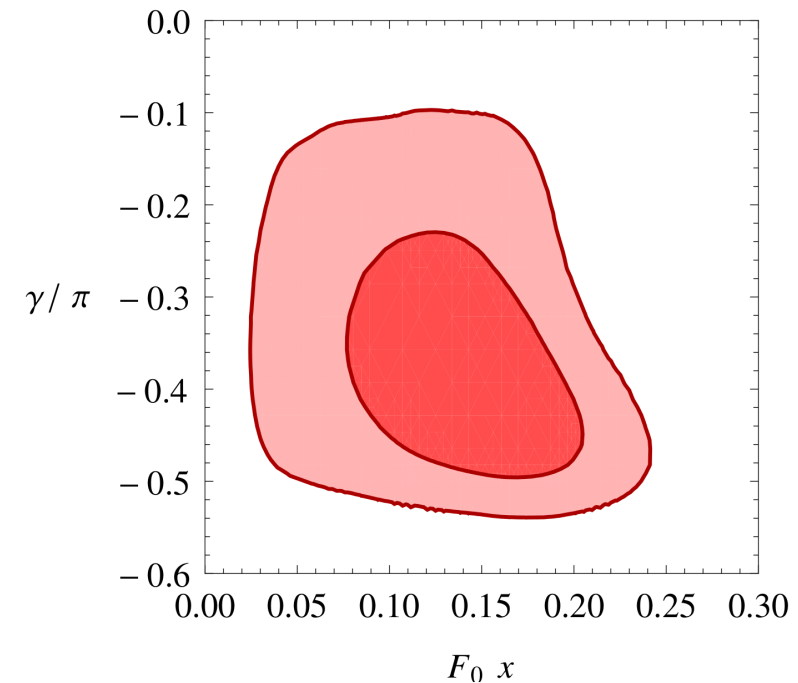
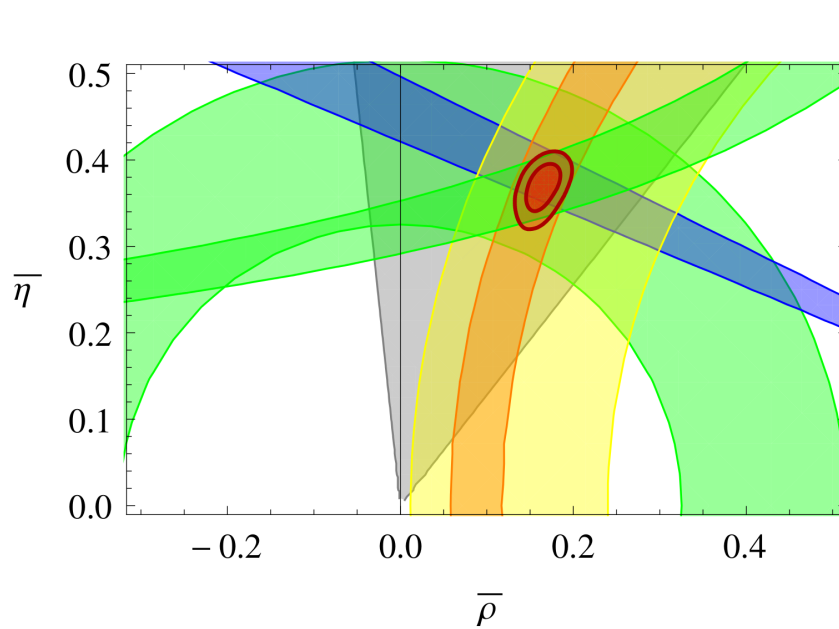
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$$\frac{\Delta M_d}{\Delta M_s} = \frac{\Delta M_d^{\text{SM}}}{\Delta M_s^{\text{SM}}}$$

$$x = \frac{c_d^2 s_L^2}{|V_{ts}|^2}$$

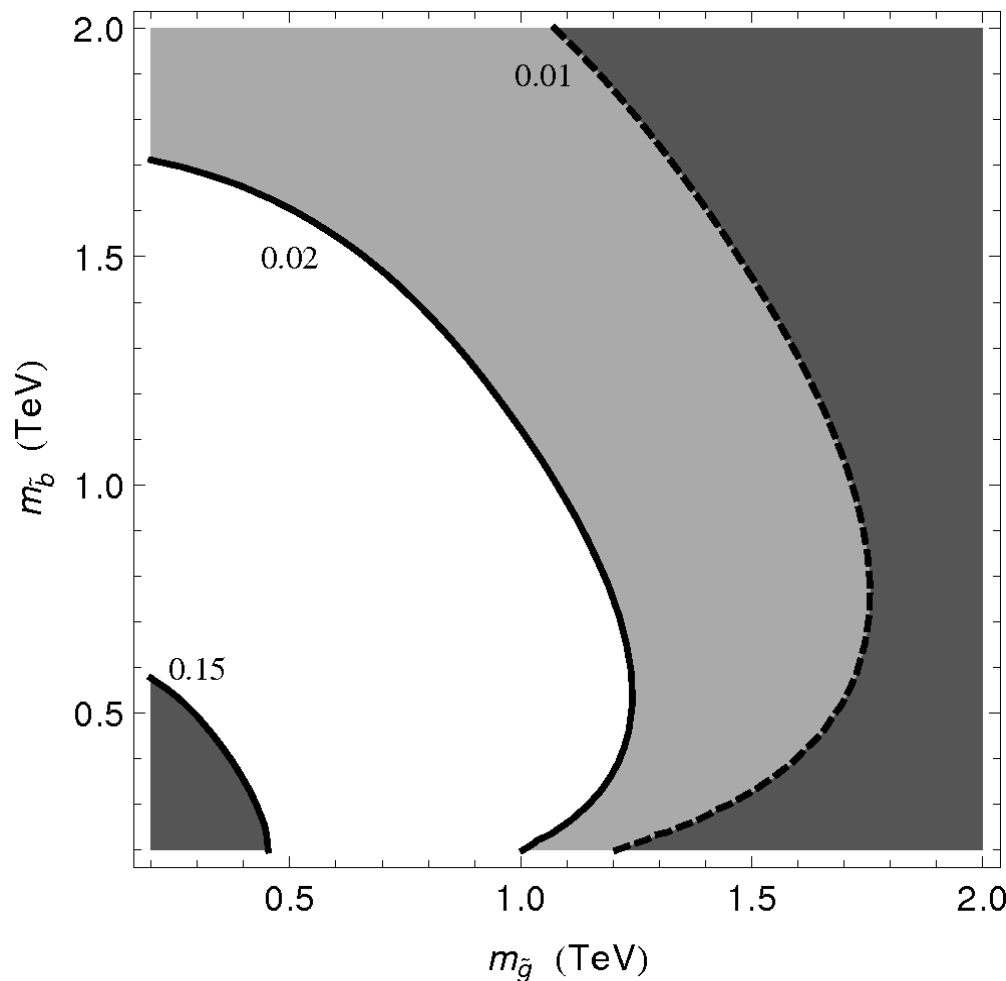
New fit with SUSY contribution



$$(\chi^2/N_{\text{d.o.f.}})_{\text{SM}} = 9.8/5$$

$$(\chi^2/N_{\text{d.o.f.}})_{\text{SUSY}} = 0.7/2$$

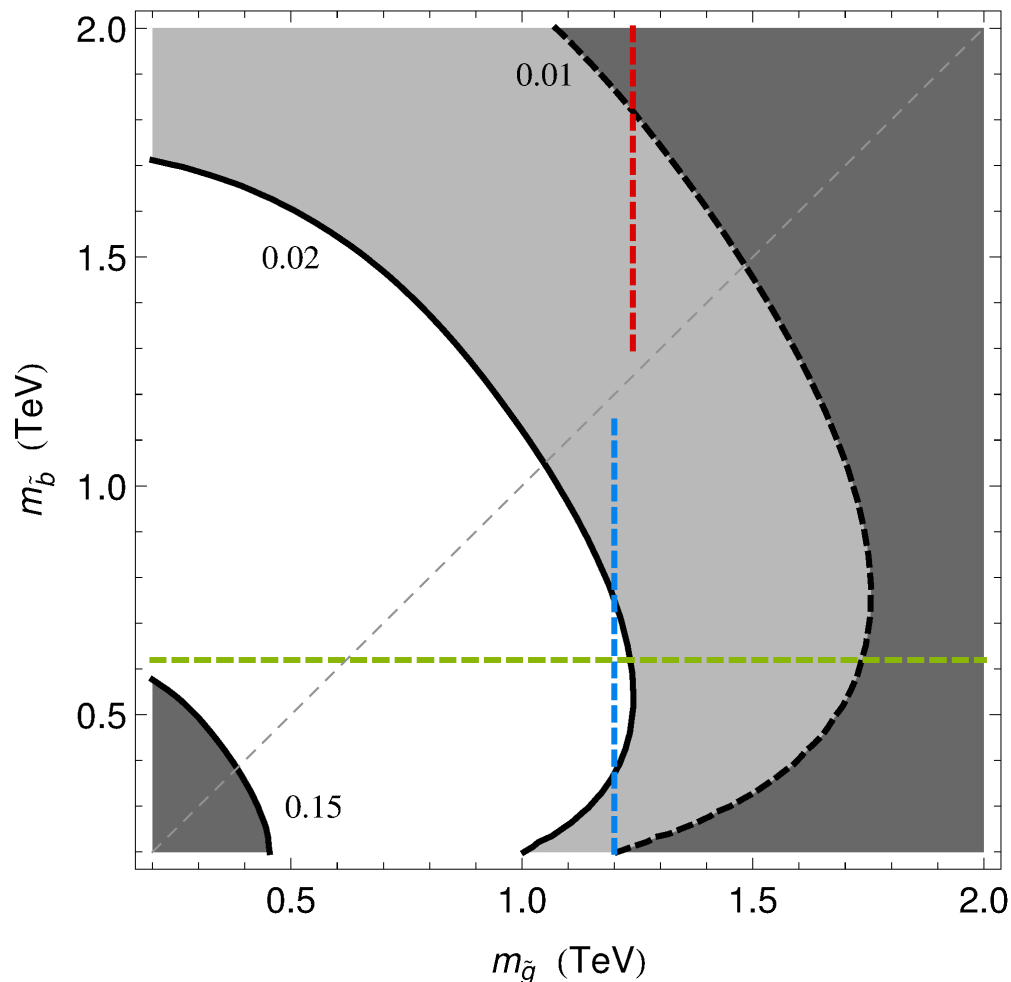
F_0 and superpartner masses



$$0.01 \lesssim F_0 < 0.15$$

Need light spectrum
for third generation
sfermions.

F₀ and superpartner masses



ATLAS: ATLAS-CONF-2013-061
CMS: CMS-PAS-SUS-13-004

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow b\bar{b}b\bar{b}\tilde{\chi}^0\tilde{\chi}^0$$

ATLAS: ATLAS-CONF-2013-061
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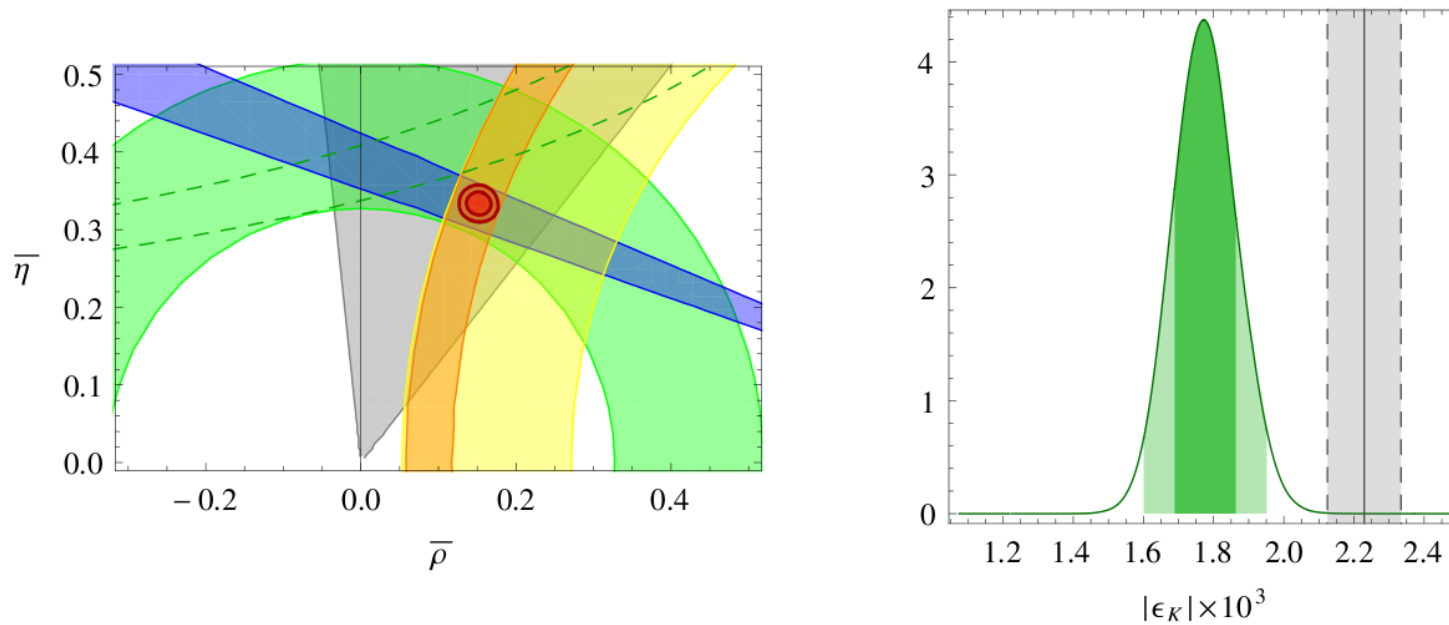
$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow \begin{aligned} &\tilde{b}\tilde{b}^*b\bar{b} \\ &b\bar{b}b\bar{b}\tilde{\chi}^0\tilde{\chi}^0 \end{aligned}$$

ATLAS: 1308.2631 [hep-ex]
CMS: 1303.2985 [hep-ex]

$$pp \rightarrow \tilde{b}\tilde{b}^* \rightarrow b\bar{b}\tilde{\chi}^0\tilde{\chi}^0$$

Situation in 2011:

UT fit without ε_K :



Tension of more than 2σ

Situation in 2014:

UT fit without ε_K : Tension of 1.1σ

Barbieri, Buttazzo, Sala, Straub (1402.6677 [hep-ph])

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Tension?

Barbieri, Buttazzo, Sala, Straub (1402.6677 [hep-ph])

Situation in 2014:

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Tension?

$$\eta_{cc} (2011) = 1.44 \pm 0.35$$

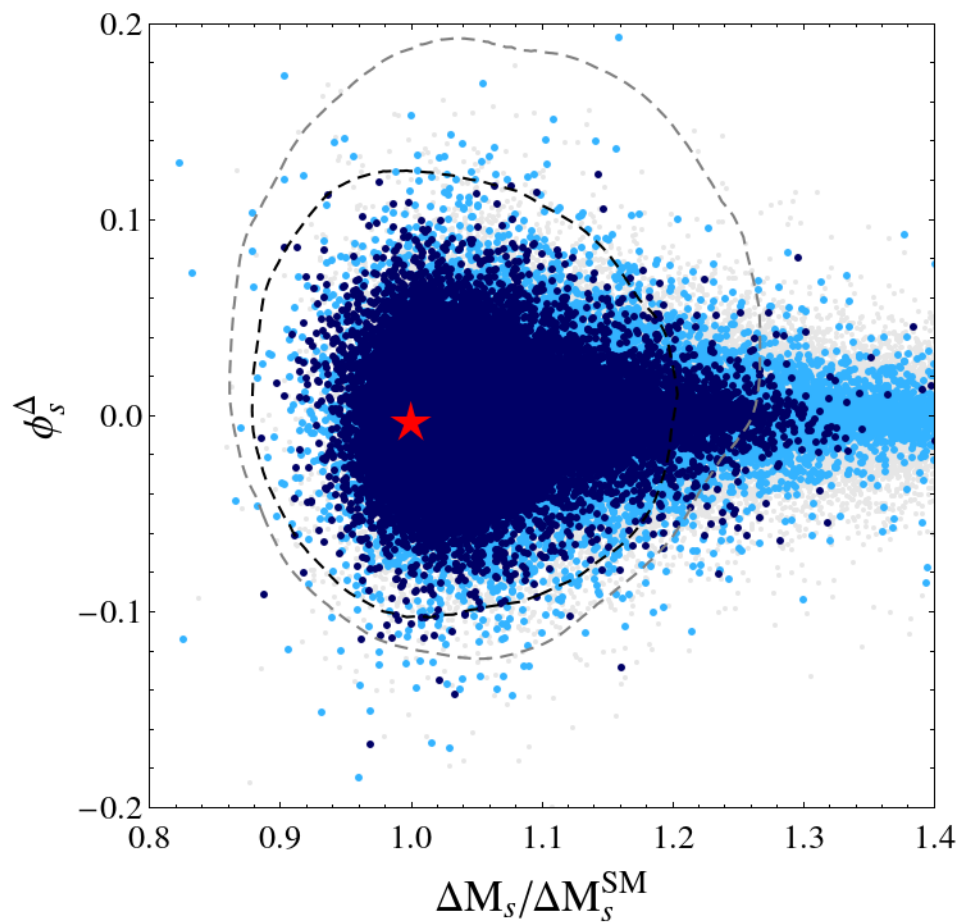
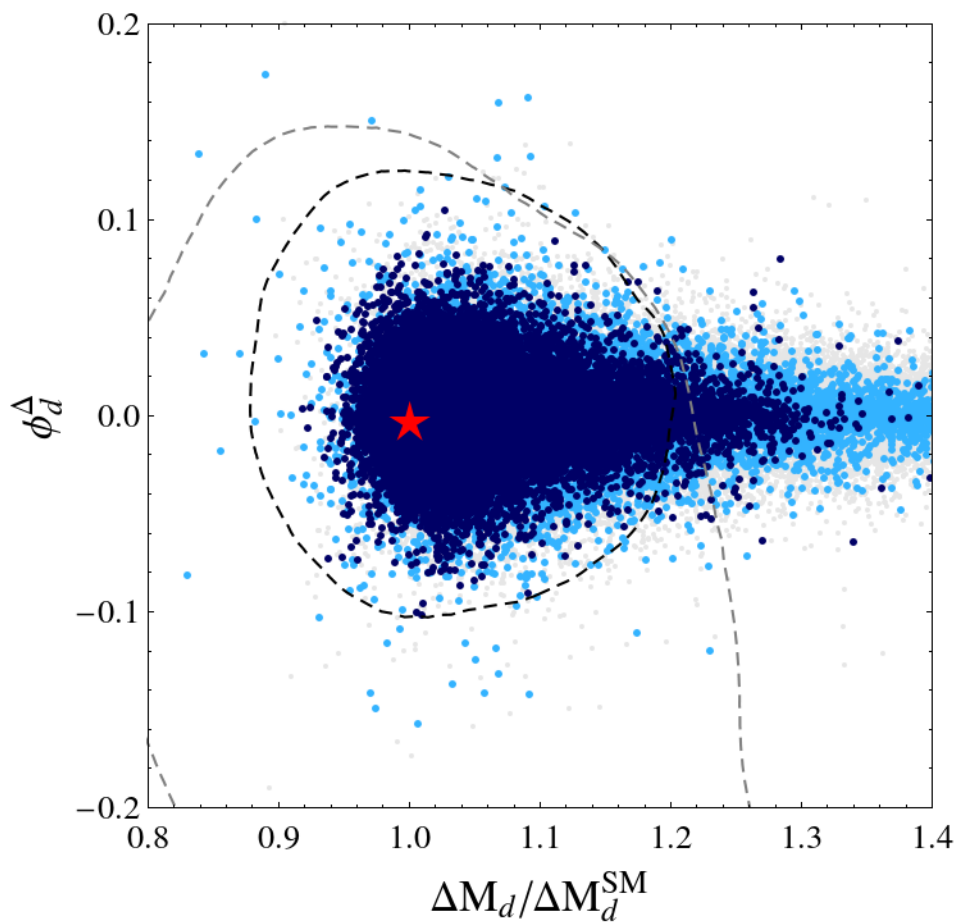
$$\eta_{cc} (2014) = 1.87 \pm 0.76$$

$$\hat{B}_K (2011) = 0.724 \pm 0.030$$

$$\hat{B}_K (2014) = 0.766 \pm 0.010$$

Barbieri, Buttazzo, Sala, Straub (1402.6677 [hep-ph])

Situation in 2014:



Barbieri, Buttazzo, Sala, Straub (1402.6677 [hep-ph])

U(2)³ in the (s)lepton sector

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Understanding Neutrinos

Mixing angles:

$$s_{12}^2 = 0.306_{-0.012}^{+0.012}$$

$$s_{13}^2 = 0.0229_{-0.0019}^{+0.0020}$$

$$s_{23}^2 = 0.446_{-0.007}^{+0.007} \oplus 0.587_{-0.037}^{+0.032}$$

Squared mass differences:

$$|\Delta m_{\text{atm}}^2| = (2.417_{-0.013}^{+0.013}) \times 10^{-3} \text{ eV}^2$$

$$\Delta m_{\text{sol}}^2 = (7.45_{-0.16}^{+0.19}) \times 10^{-5} \text{ eV}^2$$

Understanding Neutrinos

Majorana mass matrix:

$$\mathcal{L}^\nu = (m_\nu)_{ij} \bar{\nu}_L^{ci} \nu_L^j$$

Relation with angles:

$$M_\nu^2 = m_\nu^\dagger m_\nu = U_{\text{PMNS}} (m_\nu^2)^{\text{diag}} U_{\text{PMNS}}^\dagger$$

$$M_\nu^2 \approx m_{\text{light}}^2 \cdot I + \Delta m_{\text{atm}}^2 \cdot \eta$$

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If neutrinos are “heavy,” a mostly degenerate solution is preferred.

Understanding Neutrinos

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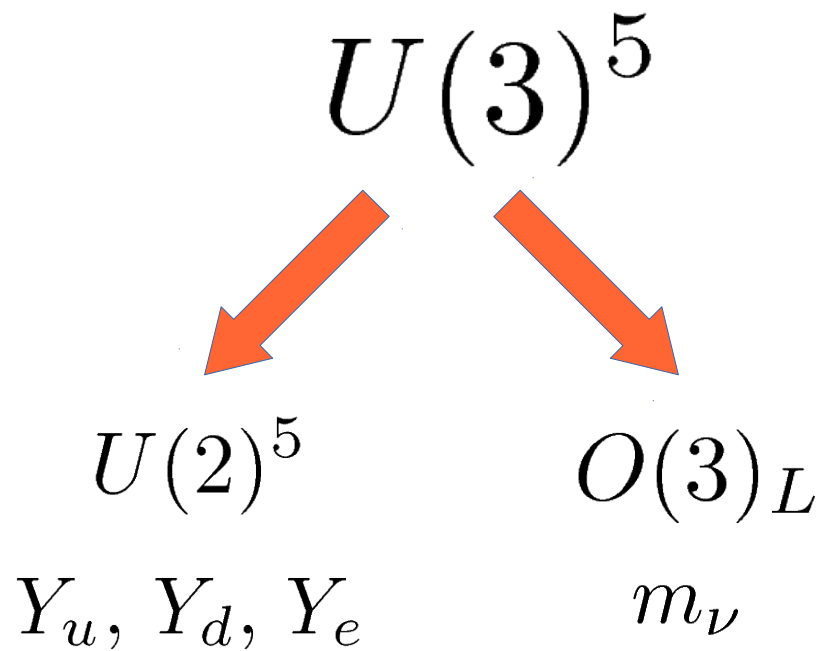
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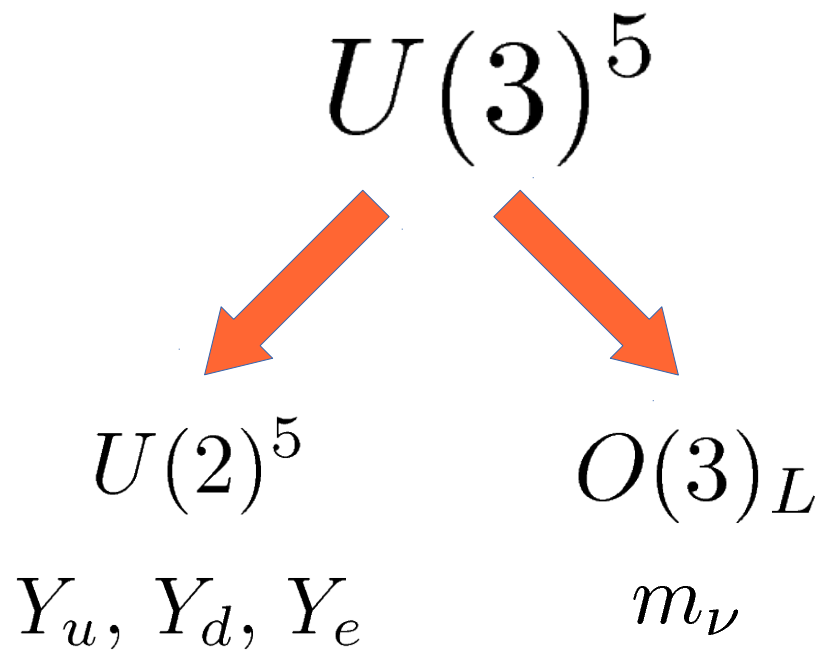
$$\eta_{[\text{n.h.}]} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s_{23}^2 & s_{23}c_{23} \\ 0 & s_{23}c_{23} & c_{23}^2 \end{pmatrix} \quad \eta_{[\text{i.h.}]} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23}^2 & -s_{23}c_{23} \\ 0 & -s_{23}c_{23} & s_{23}^2 \end{pmatrix}$$

Two alternatives

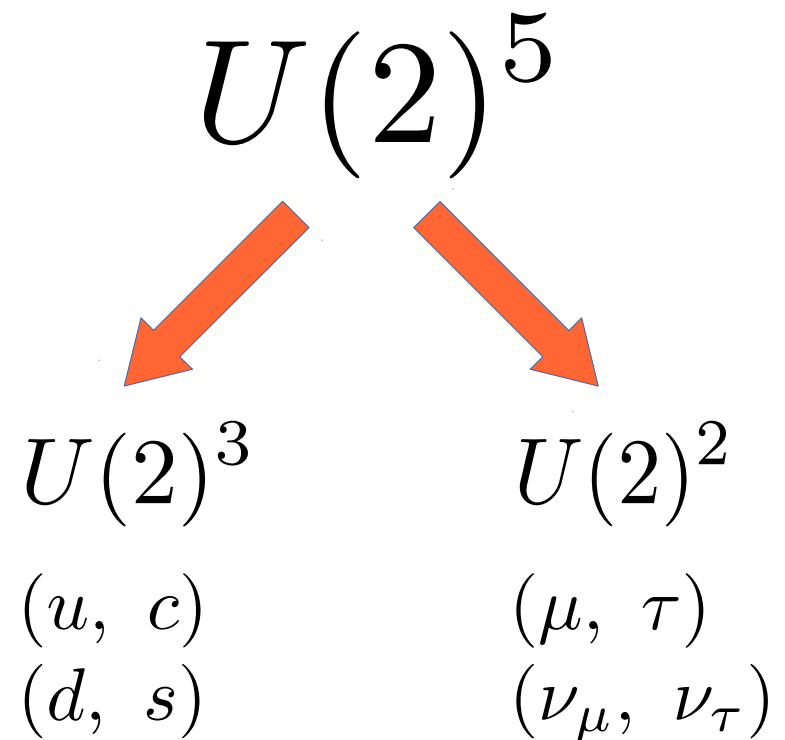


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Two alternatives



Blankenburg, Isidori, JJP: 1204.0688



JJP: 1311.1837

Shifted U(2)⁵: Quark Sector

$$U(2)_Q \otimes U(2)_u \otimes U(2)_d \otimes U(2)_L \otimes U(2)_e \\ \otimes U(1)_d \otimes U(1)_L \otimes U(1)_e$$

Shifted $U(2)^5$: Quark Sector

$$U(2)_Q \otimes U(2)_u \otimes U(2)_d \otimes U(2)_L \otimes U(2)_e \\ \otimes U(1)_d \otimes U(1)_L \otimes U(1)_e$$

$$\Delta Y_u \sim (2, \bar{2}, 1, 1, 1)_{(0,0,0)}$$

$$\Delta Y_d \sim (2, 1, \bar{2}, 1, 1)_{(0,0,0)}$$

$$V_q \sim (2, 1, 1, 1, 1)_{(0,0,0)}$$

$$y_b \sim (1, 1, 1, 1, 1)_{(q_d,0,0)}$$

$$Y_u = \left(\begin{array}{c|c} \Delta Y_u & x_t V_q \\ \hline 0 & 1 \end{array} \right) y_t \qquad Y_d = \left(\begin{array}{c|c} \Delta Y_d & x_b V_q y_b \\ \hline 0 & y_b \end{array} \right)$$

Shifted U(2)⁵: Charged Lepton Sector

$$U(2)_Q \otimes U(2)_u \otimes U(2)_d \otimes U(2)_L \otimes U(2)_e \\ \otimes U(1)_d \otimes U(1)_L \otimes U(1)_e$$

$$\Delta Y_e \sim (1, 1, 1, 2, \bar{2})_{(0,0,0)}$$

$$V_e \sim (1, 1, 1, 2, 1)_{(0,0,0)}$$

$$\lambda_L \sim (1, 1, 1, 1, 1)_{(0, q_L, 0)}$$

$$\lambda_e \sim (1, 1, 1, 1, 1)_{(0,0, q_e)}$$

Shifted $U(2)^5$: Charged Lepton Sector

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$$\lambda_L \lambda_e = y_e$$

Shifted $U(2)^5$: Charged Lepton Sector

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$$\lambda_L \sim (1, 1, 1, 1, 1)_{(0, q_L, 0)}$$

$$\lambda_e \sim (1, 1, 1, 1, 1)_{(0,0, q_e)}$$

$$\lambda_L \lambda_e = y_e$$

$$Y_e = \left(\begin{array}{c|c} y_e & 0 \\ \hline V_e \lambda_e & \Delta Y_e \end{array} \right)$$

Shifted $U(2)^5$: Neutrino Sector

$$U(2)_Q \otimes U(2)_u \otimes U(2)_d \otimes U(2)_L \otimes U(2)_e \\ \otimes U(1)_d \otimes U(1)_L \otimes U(1)_e$$

$$\Delta_L \sim (1, 1, 1, 3, 1)_{(0,0,0)}$$

$$V_e \sim (1, 1, 1, 2, 1)_{(0,0,0)}$$

$$\lambda_L \sim (1, 1, 1, 1, 1)_{(0, q_L, 0)}$$

$$m_\nu = \left(\begin{array}{c|c} r_1 \lambda_L^2 & r_2 \lambda_L V_e^T \\ \hline r_2 \lambda_L V_e & \Delta_L + V_e V_e^T \end{array} \right) \kappa_\nu .$$

Shifted U(2)⁵: Neutrino Sector

$$m_\nu = \begin{pmatrix} r_1 \lambda_L^2 & r_2 s_e \lambda_L \epsilon & r_2 c_e \lambda_L \epsilon \\ r_2 s_e \lambda_L \epsilon & U_\phi^T D U_\phi & \\ r_2 c_e \lambda_L \epsilon & & \end{pmatrix} \kappa_\nu$$


 $\Delta_L + V_e V_e^T$

$$D = \begin{pmatrix} d_1 e^{i\omega_1} & 0 \\ 0 & d_2 e^{i\omega_2} \end{pmatrix} \epsilon^2$$

$$U_\phi = \begin{pmatrix} c_\phi & s_\phi e^{i\omega_3} \\ -s_\phi e^{-i\omega_3} & c_\phi \end{pmatrix}$$

Shifted U(2)⁵: Neutrino Sector

$$s_{13}^2 \rightarrow 0, \quad (\Delta m_{\text{sol}}^2 / \Delta m_{\text{atm}}^2) \rightarrow 0$$

$$M_\nu^2 \approx m_{\text{light}}^2 \cdot I + \Delta m_{\text{atm}}^2 \cdot \begin{pmatrix} 0 & 0 & 0 \\ 0 & s_{23}^2 & s_{23}c_{23} \\ 0 & s_{23}c_{23} & c_{23}^2 \end{pmatrix}$$

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$$\lambda_L \rightarrow 0, \quad d_1 \rightarrow 0$$

$$M_\nu^2 \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & s_\phi^2 & s_\phi c_\phi \\ 0 & s_\phi c_\phi & c_\phi^2 \end{pmatrix} d_2^2 \epsilon^4 |\kappa_\nu|^2$$

Shifted U(2)⁵: Neutrino Sector

$$\lambda_L \rightarrow 0, \quad d_1 \neq 0$$

$$\zeta^2 \equiv \frac{\Delta m_{\text{sol}}^2}{\Delta m_{\text{atm}}^2} = \frac{d_1^2}{d_2^2}$$

$$s_{23}^2 = s_\phi^2$$

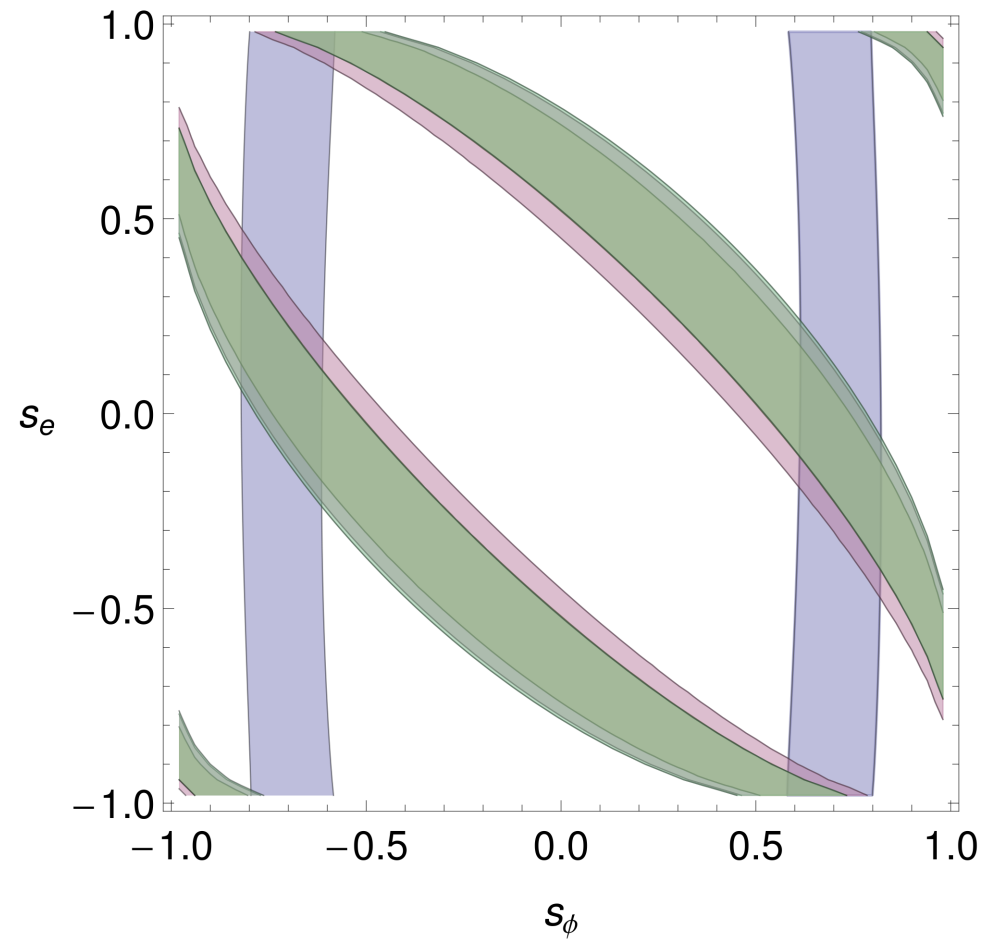
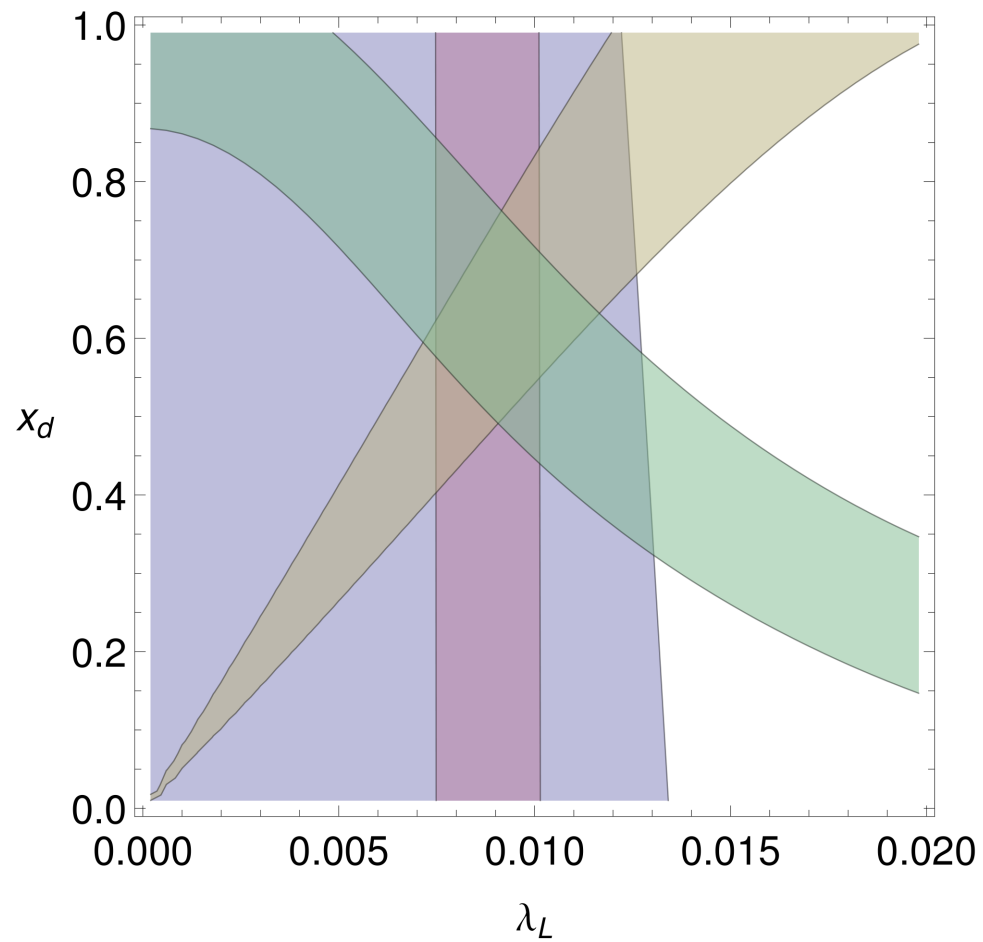
Shifted U(2)⁵: Neutrino Sector

$$\lambda_L \rightarrow 0, \quad d_1 \neq 0$$

$$\zeta^2 \equiv \frac{\Delta m_{\text{sol}}^2}{\Delta m_{\text{atm}}^2} = \frac{d_1^2}{d_2^2} \qquad s_{23}^2 = s_\phi^2$$

$$\lambda_L \neq 0, \quad d_1 \neq 0$$

$$d_1 = x_d \zeta_{\text{exp}} d_2$$



■ s_{23}^2
■ s_{12}^2

■ s_{13}^2
■ ζ^2

Shifted U(2)⁵: Neutrino Sector

Constraints from neutrino sector relevant for sleptons:

$$\begin{aligned}\lambda_L &\approx 10^{-2} \\ \lambda_e &\approx y_e 10^2 \\ \Delta_L &\approx \mathcal{O}(\epsilon^2)\end{aligned}$$

Shifted U(2)⁵: Slepton Sector

$$m_{\tilde{L}}^2 = \left(\begin{array}{c|c} m_l^2/m_h^2 & \lambda_L^* V_e^T \\ \hline \lambda_L V_e^* & I + \Delta Y_e^* \Delta Y_e^T + V_e^* V_e^T + \Delta_L^* \Delta_L \end{array} \right) m_h^2$$

$$m_{\tilde{e}_R^c}^2 = \left(\begin{array}{c|c} m_l^2/m_h^2 & \lambda_e^* V_e^\dagger \Delta Y_e \\ \hline \lambda_e \Delta Y_e^\dagger V_e & I + \Delta Y_e^\dagger \Delta Y_e \end{array} \right) m_h^2$$

Shifted U(2)⁵: Slepton Sector

$$\begin{aligned}
 m_{\tilde{L}}^2 &= \left(\begin{array}{c|c} m_l^2/m_h^2 & \lambda_L^* V_e^T \\ \hline \lambda_L V_e^* & I + \Delta Y_e^* \Delta Y_e^T + V_e^* V_e^T + \Delta_L^* \Delta_L \end{array} \right) m_h^2 \\
 m_{\tilde{e}_R^c}^2 &= \left(\begin{array}{c|c} m_l^2/m_h^2 & \lambda_e^* V_e^\dagger \Delta Y_e \\ \hline \lambda_e \Delta Y_e^\dagger V_e & I + \Delta Y_e^\dagger \Delta Y_e \end{array} \right) m_h^2
 \end{aligned}$$

Shifted U(2)⁵: Slepton Sector

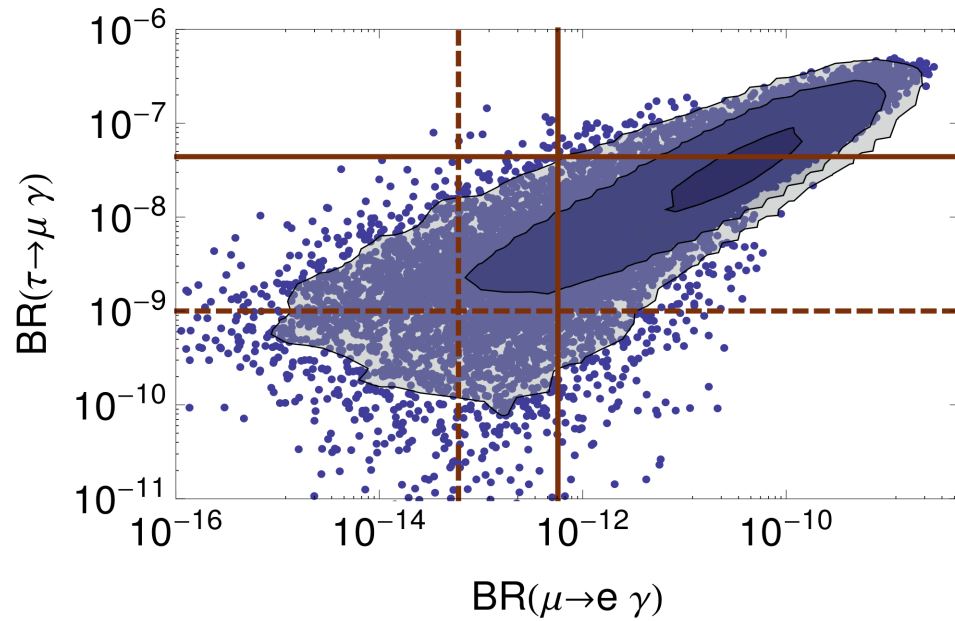
LL mixing matrix (coming from soft mass):

$$\mathcal{R}^L \sim \begin{pmatrix} 1 & s_e \lambda_L \epsilon & c_e \lambda_L \epsilon \\ -s_e \lambda_L \epsilon & 1 & s_e c_e \epsilon^2 / y_\tau^2 \\ -c_e \lambda_L \epsilon & -s_e c_e \epsilon^2 / y_\tau^2 & 1 \end{pmatrix}$$

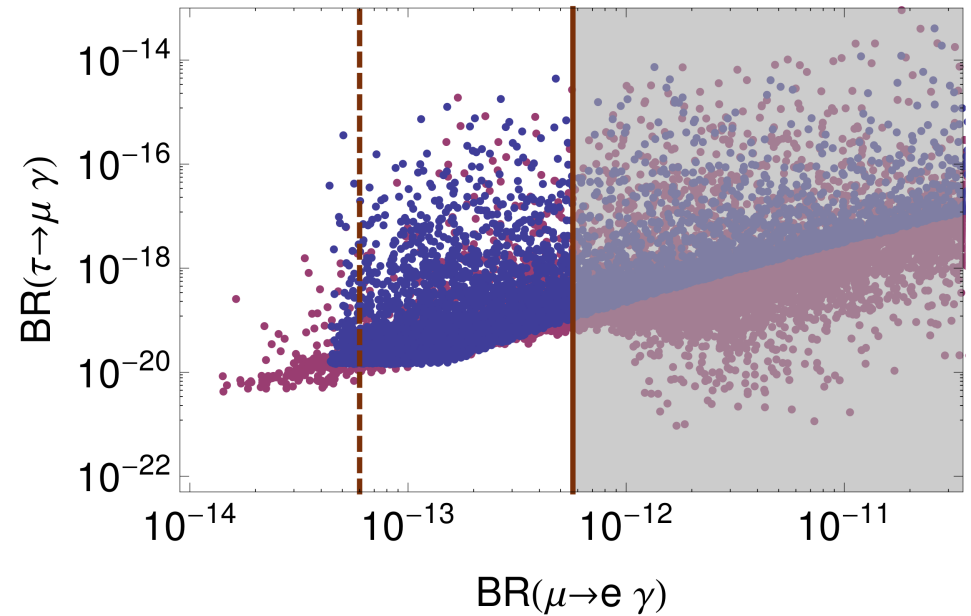
RR mixing matrix (coming from Yukawa):

$$\mathcal{R}^R \sim \begin{pmatrix} 1 & -s_e \lambda_e \epsilon / y_\mu & -c_e \lambda_e \epsilon / y_\tau \\ s_e \lambda_e \epsilon / y_\mu & 1 & 0 \\ c_e \lambda_e \epsilon / y_\tau & 0 & 1 \end{pmatrix}$$

Lepton Flavour Violation

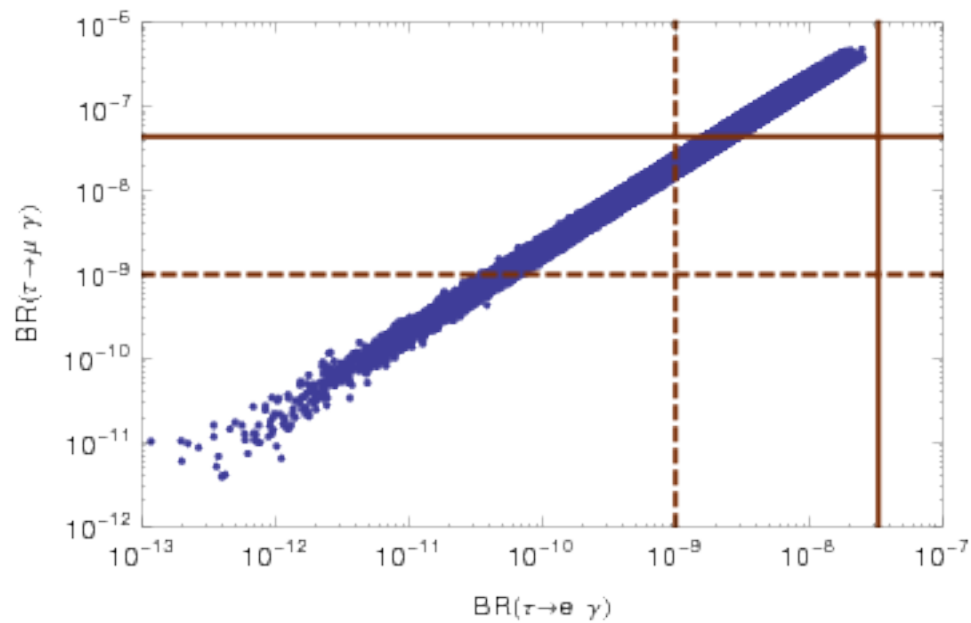


$$U(3)^5 \Rightarrow U(2)^5$$

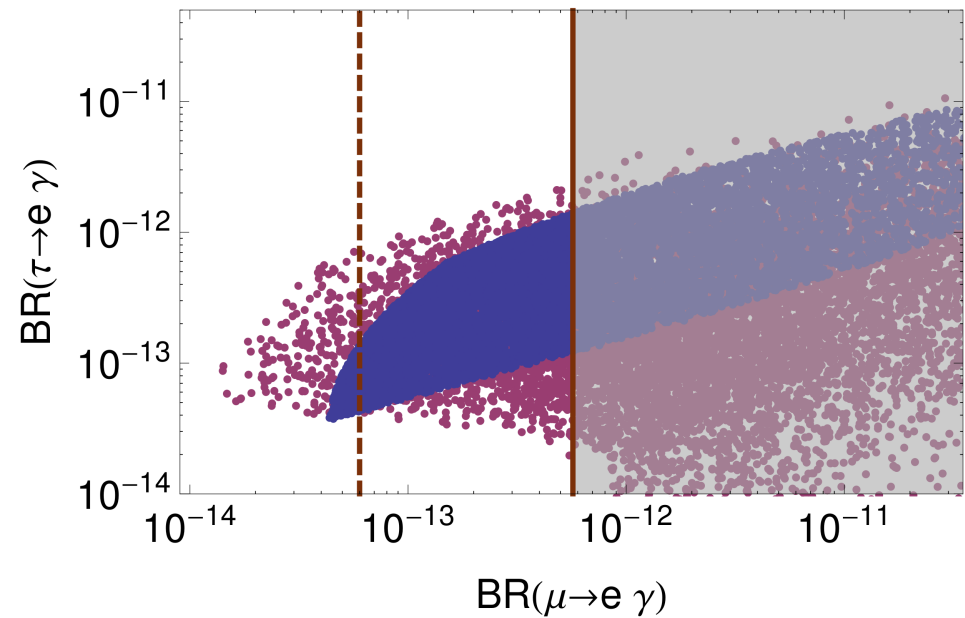


$$U(2)^5_{\text{shifted}}$$

Lepton Flavour Violation



$$U(3)^5 \Rightarrow U(2)^5$$



$$U(2)^5_{\text{shifted}}$$

Lightest Neutrino Mass

$$m_{\text{light}} \gtrsim 0.05 \text{ eV}$$

(can be probed by $m_{\beta\beta}$ and cosmology)

$$U(3)^5 \Rightarrow U(2)^5$$

$$m_{\text{light}} \lesssim 0.01 \text{ eV}$$

(cannot be probed by $m_{\beta\beta}$ nor cosmology)

$$U(2)_{\text{shifted}}^5$$

Conclusions

Conclusions

- U(2)³ ansatz in the quark sector accomodates split-family SUSY, and controls SUSY contributions to flavoured processes.
- Given LHC constraints, it is difficult to solve flavour tension, but hope is not lost yet.

Conclusions

- Neutrino sector requires a different approach: either going back to MFV and breaking it into U(2)⁵, or shifting U(2)² to second and third generations.
- Main predictions of shifted scheme are selectrons as lightest sleptons, vanishing lightest neutrino mass, and large $\mu \rightarrow e\gamma$ branching ratio.



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Neutrino Mixing, IH

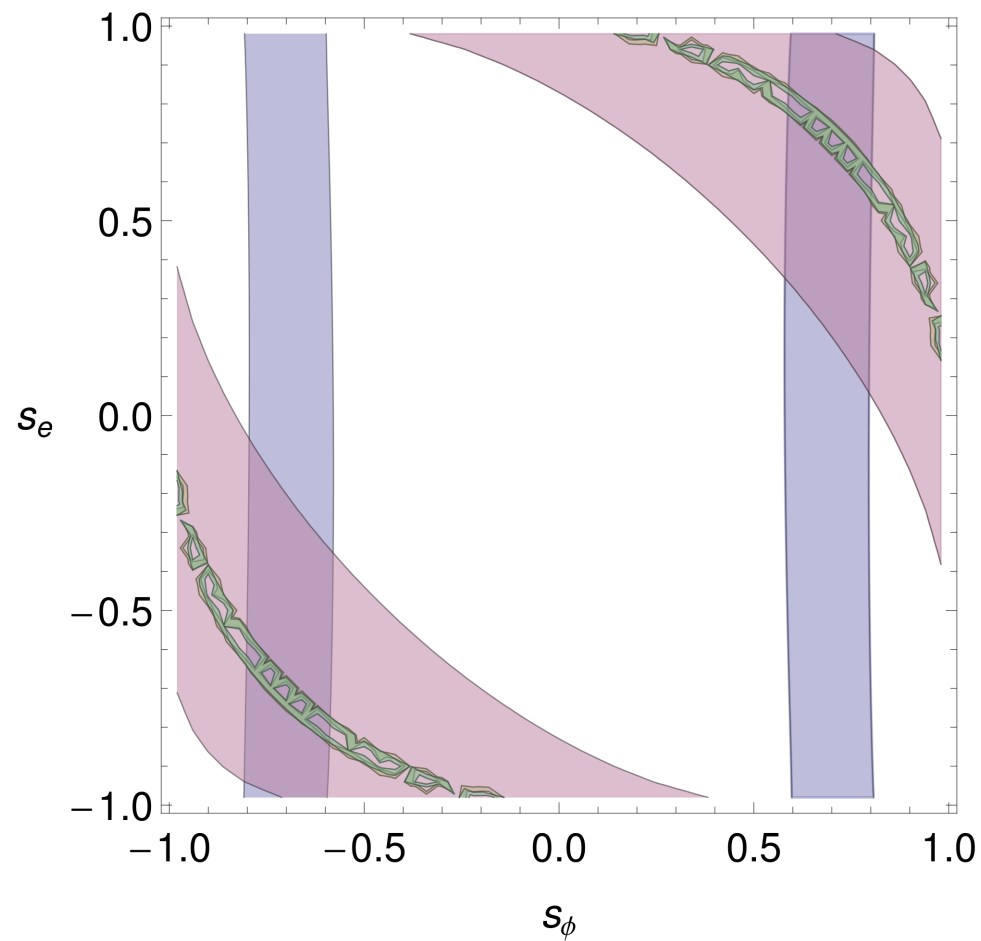
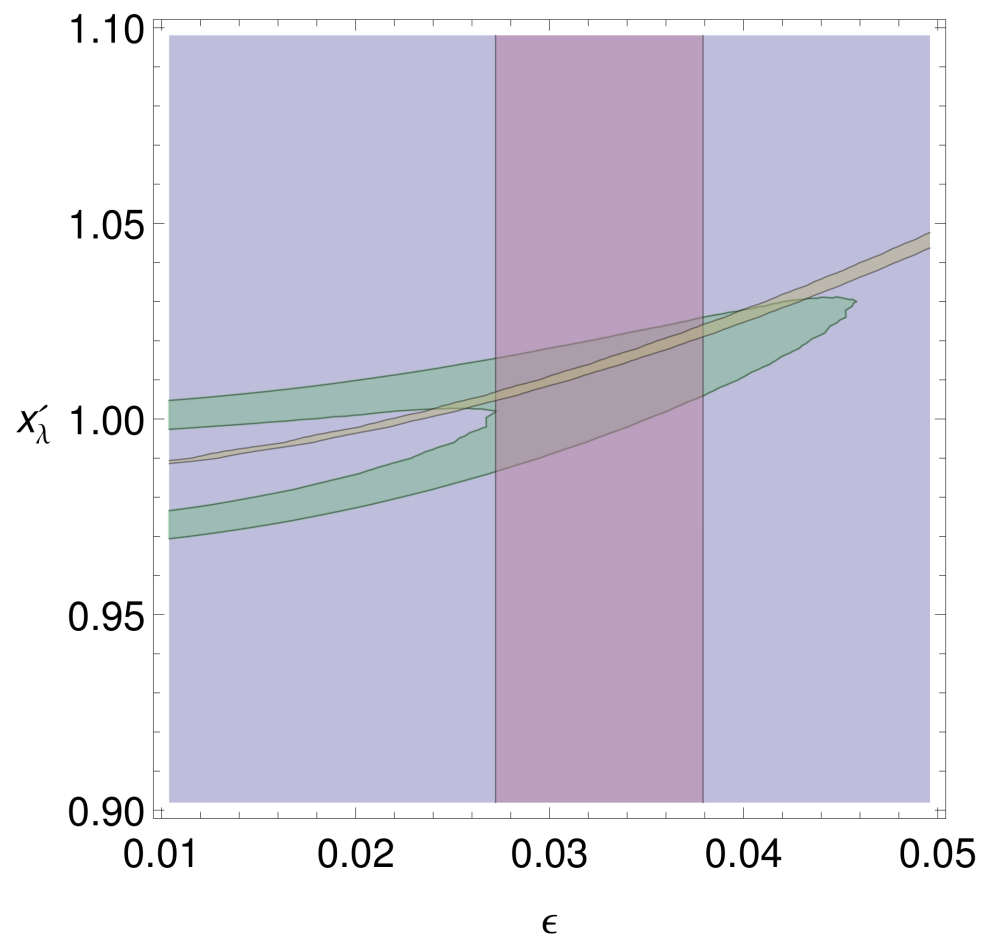
$$s_{13}^2 \rightarrow 0, \quad (\Delta m_{\text{sol}}^2 / \Delta m_{\text{atm}}^2) \rightarrow 0$$

$$M_\nu^2 \approx m_{\text{light}}^2 \cdot I + \Delta m_{\text{atm}}^2 \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23}^2 & -c_{23}s_{23} \\ 0 & -c_{23}s_{23} & s_{23}^2 \end{pmatrix}$$

$$d_1 \rightarrow 0, \quad d_2 \epsilon^2 \rightarrow \lambda_L^2, \quad \epsilon \rightarrow 0$$

$$M_\nu^2 \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & s_\phi^2 & s_\phi c_\phi \\ 0 & s_\phi c_\phi & c_\phi^2 \end{pmatrix} \lambda_L^4 |\kappa_\nu|^2$$

Neutrino Mixing, IH



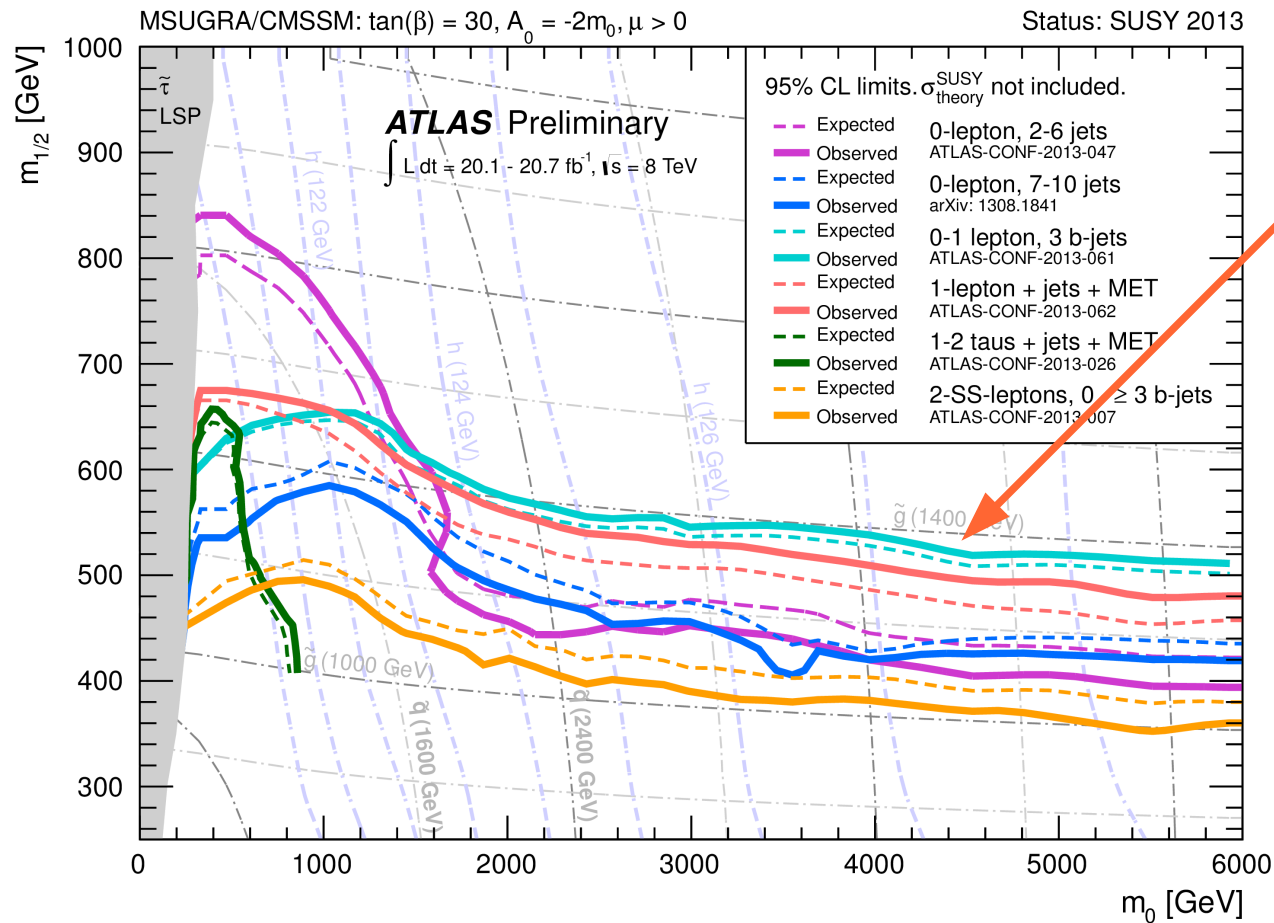
■ s_{23}^2

■ s_{12}^2

■ s_{13}^2

■ ζ^2

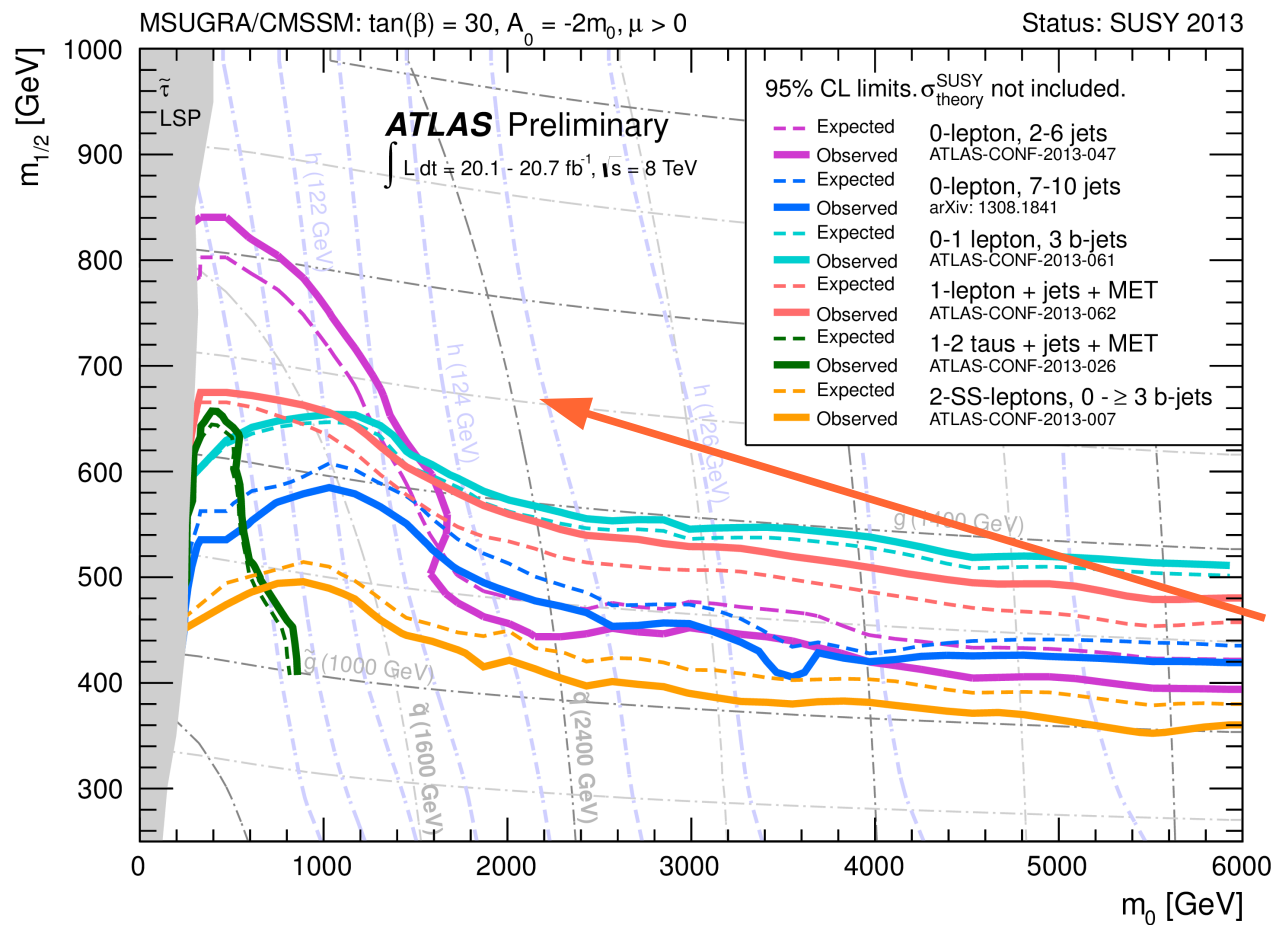
For Natural SUSY, the CMSSM might not be in such good shape



$$m_{\tilde{g}} \gtrsim 1400 \text{ GeV}$$

(Also for simplified models)

For Natural SUSY, the CMSSM might not be in such good shape



$$m_{\tilde{g}} \gtrsim 1400 \text{ GeV}$$

(Also for simplified models)

$$m_{\tilde{q}} \approx 2400 \text{ GeV}$$

$$\Rightarrow \begin{aligned} m_{\tilde{t}_1} &\approx 800 \text{ GeV} \\ m_{\tilde{t}_2} &\approx 1700 \text{ GeV} \\ \mu &\approx 1800 \text{ GeV} \end{aligned}$$

Input to CKM Fit

$ V_{ud} $	0.97425(22)	f_K	$(155.8 \pm 1.7) \text{ MeV}$
$ V_{us} $	0.2254(13)	$\hat{B}_K$	0.724 ± 0.030
$ V_{cb} $	$(40.89 \pm 0.70) \times 10^{-3}$	κ_ϵ	0.94 ± 0.02
$ V_{ub} $	$(3.97 \pm 0.45) \times 10^{-3}$	$f_{B_s} \sqrt{\hat{B}_s}$	$(291 \pm 16) \text{ MeV}$
γ_{CKM}	$(74 \pm 11)^\circ$	ξ	1.23 ± 0.04
$ \epsilon_K $	$(2.229 \pm 0.010) \times 10^{-3}$		
$S_{\psi K_S}$	0.673 ± 0.023		
ΔM_d	$(0.507 \pm 0.004) \text{ ps}^{-1}$		
ΔM_s	$(17.77 \pm 0.12) \text{ ps}^{-1}$		

New SUSY Contributions

$$\epsilon_K = \epsilon_K^{\text{SM}(\text{tt})} \times (1 + x^2 F_0) + \epsilon_K^{\text{SM}(\text{tc}+\text{cc})}$$

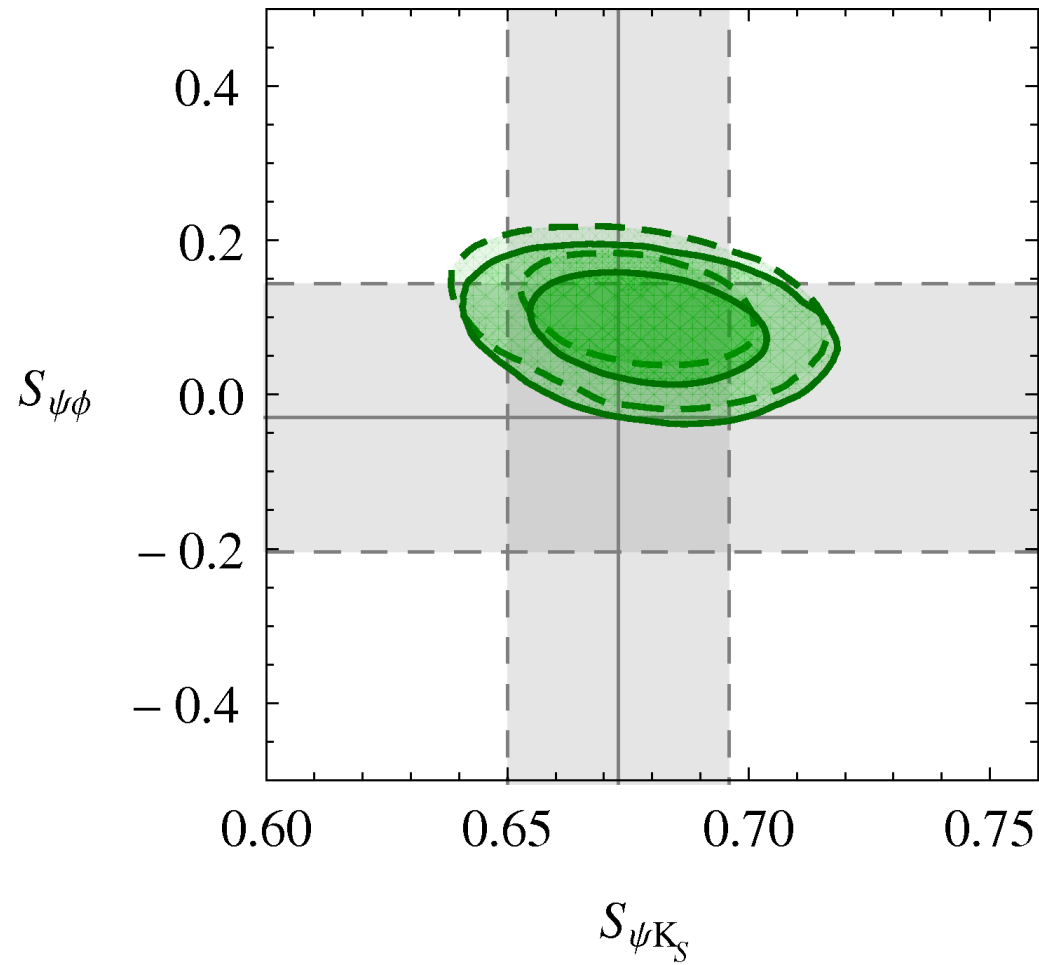
$$F_0 = \frac{2}{3} \left(\frac{g_s}{g} \right)^4 \frac{m_W^2}{m_{Q_3}^2} \frac{1}{S_0(x_t)} \left[f_0(x_g) + \mathcal{O} \left(\frac{m_{Q_l}^2}{m_{Q_h}^2} \right) \right]$$

$$f_0(x_g) = \frac{11 + 8x - 19x^2 + 26x \log(x) + 4x^2 \log(x)}{3(1-x)^3}$$

$$x = \frac{c_d^2 s_L^2}{|V_{ts}|^2}$$

$$x_g = \frac{m_{\tilde{g}}^2}{m_{Q_3}^2}$$

Predictions from Fit



Large $S_{\psi\phi}$!

$U(3)^5 \rightarrow U(2)^5$ Spurions

$$Y_e^{(0)} \sim (1, 1, 1, 3, \bar{3})$$

$$X \sim (1, 1, 1, 8, 1)$$

$$\Delta\hat{Y}_e \sim (1, 1, 1, 3, \bar{3})$$

$$\Delta\hat{Y}_e = \left(\begin{array}{c|c} \Delta Y_e & 0 \\ \hline 0 & 0 \end{array} \right)$$

$$Y_e = (1 + X)(Y_e^{(0)} + \Delta\hat{Y}_e) \rightarrow \left(\begin{array}{c|c} \Delta Y_e & V \\ \hline 0 & 1 \end{array} \right) y_\tau$$

$U(3)_L \rightarrow O(3)_L$ Spurion

We shall break $U(3)_L \rightarrow O(3)_L$ in neutrino sector.

One more spurion:

$$m_\nu^{(0)} \sim (1, 1, 1, 6, 1)$$

$$m_\nu = m_\nu^{(0)} + X m_\nu^{(0)} + m_\nu^{(0)} X^T$$

$$m_\nu = \bar{m}_{\nu_1} \left[I + e^{i\phi_\nu} \begin{pmatrix} -\sigma\epsilon & \gamma\epsilon^2 & 0 \\ \gamma\epsilon^2 & -\delta\epsilon & r\epsilon \\ 0 & r\epsilon & 0 \end{pmatrix} \right]$$

Neutrino Mixing: Δm^2

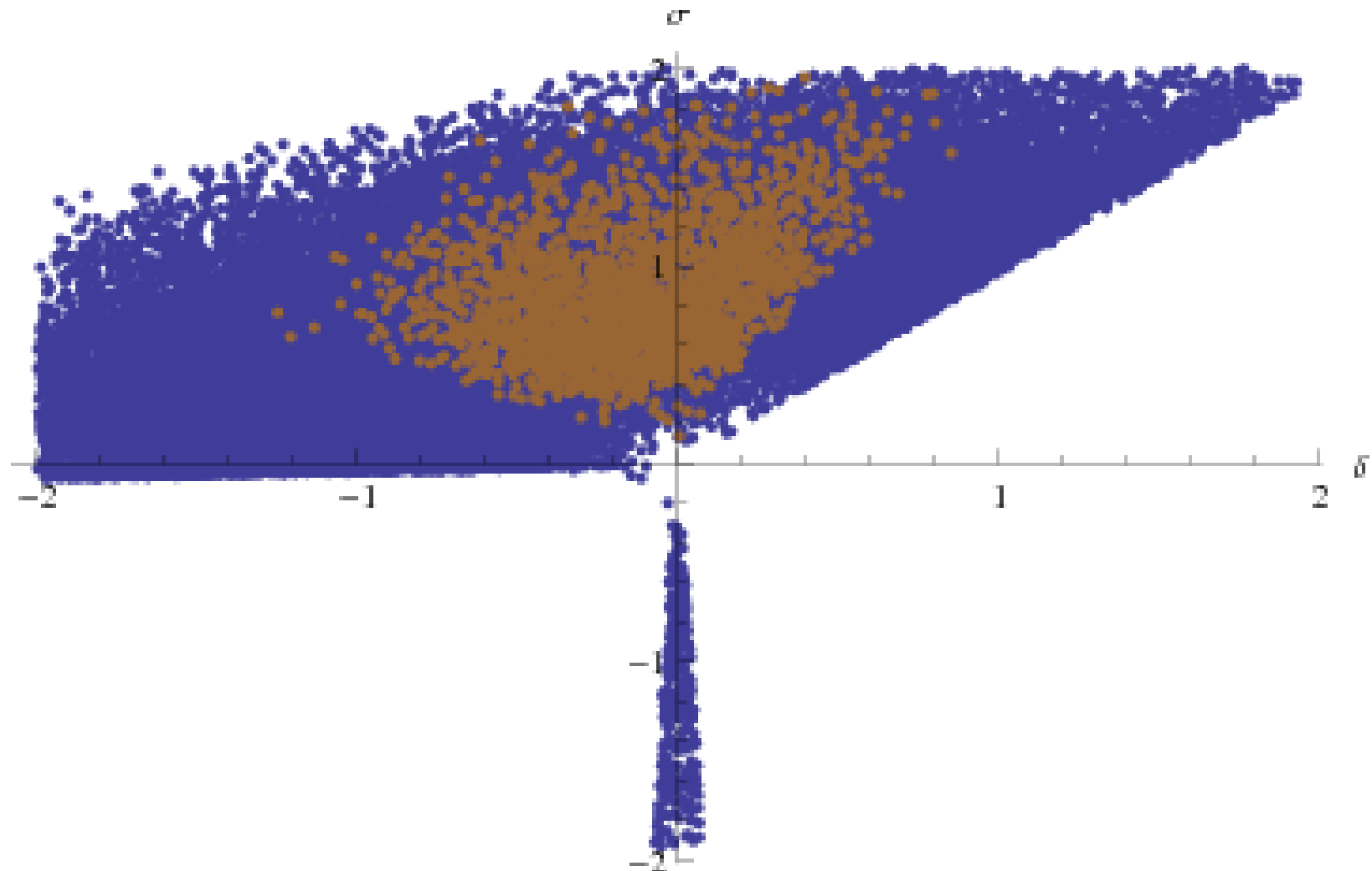
Mass Differences:

$$\Delta m_{\text{atm}}^2 = \tilde{m}_{\nu_1}^2 \left(2\sigma - \delta + [\delta^2 + 4r^2]^{1/2} \right) \epsilon$$

$$\zeta^2 = \frac{\Delta m_{\text{sol}}^2}{\Delta m_{\text{atm}}^2} = \frac{2\sigma - \delta - [\delta^2 + 4r^2]^{1/2}}{2\sigma - \delta + [\delta^2 + 4r^2]^{1/2}}$$

$$2\sigma - \delta - [\delta^2 + 4r^2]^{1/2} \sim \epsilon$$

Neutrino Mixing: Δm^2

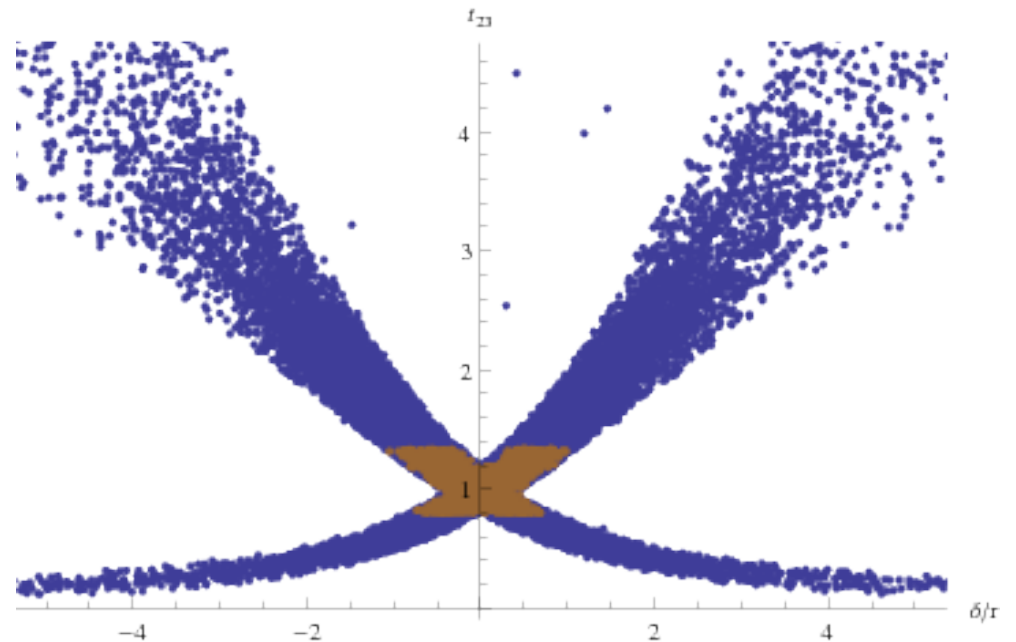


Neutrino Mixing: θ_{23}

Charged lepton mass basis:

$$M_\nu^2 = \bar{m}_{\nu_1}^2 \begin{pmatrix} 1 - 2\epsilon\sigma & -2s_e\epsilon(\sigma - \delta)e^{i\alpha_e} & 1 - 2\epsilon\delta \\ -2\epsilon s_e r e^{i\alpha_e} & 2\epsilon r & 1 \end{pmatrix} + O(\epsilon^2, s_e^2\epsilon)$$

$$\frac{s_{23}}{c_{23}} \approx \frac{\delta \pm [\delta^2 + 4r^2]^{1/2}}{2r}$$



Neutrino Mixing: θ_{13}

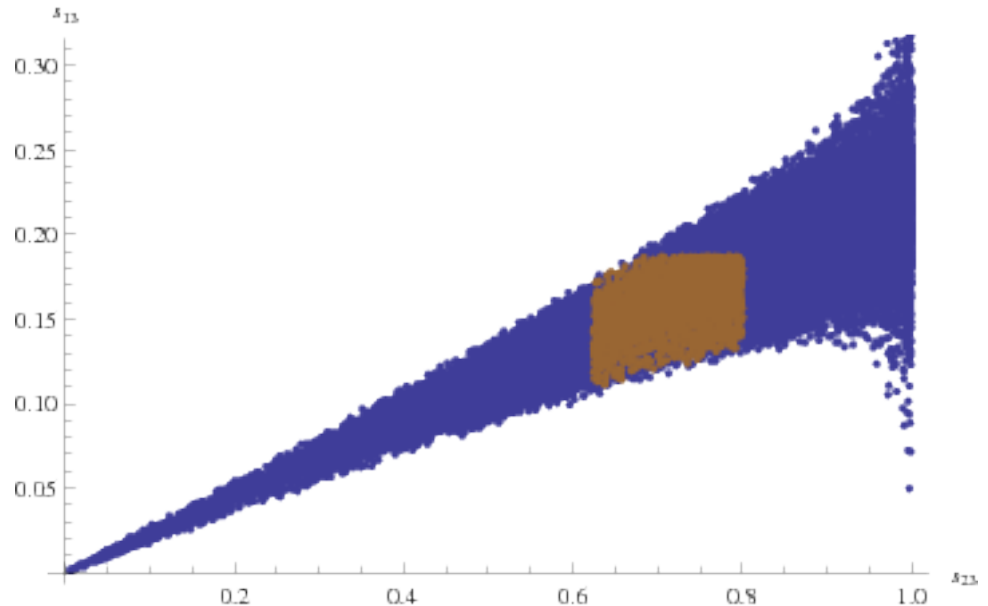
Charged lepton mass basis:

$$M_\nu^2 = \bar{m}_{\nu_1}^2 \begin{pmatrix} 1 - 2\epsilon\sigma & -2s_e\epsilon(\sigma - \delta)e^{i\alpha_e} & 1 - 2\epsilon\delta \\ -2\epsilon s_e r e^{i\alpha_e} & 2\epsilon r & 1 \end{pmatrix} + O(\epsilon^2, s_e^2\epsilon)$$

$$s_{13}e^{i\delta_P} = s_e s_{23}e^{\alpha_e + \pi}$$

$$s_e = s_d$$

$$\Rightarrow s_{13} = 0.16 \pm 0.02$$



Neutrino Mixing: θ_{12}

$$M_\nu^2 = m_\nu^\dagger m_\nu = U_{\text{PMNS}}(m_\nu^2)^{\text{diag}} U_{\text{PMNS}}^\dagger$$

$$\begin{aligned}(M_\nu^2)_{11} &= m_{\nu_1}^2 + \Delta m_{\text{atm}}^2 (s_{13}^2 + c_{13}^2 s_{12}^2 \zeta^2) \\(M_\nu^2)_{22} &= m_{\nu_1}^2 + \Delta m_{\text{atm}}^2 (c_{13}^2 s_{23}^2 + c_{23}^2 c_{12}^2 \zeta^2 - \mathcal{O}(s_{13} \zeta^2)) \\(M_\nu^2)_{33} &= m_{\nu_1}^2 + \Delta m_{\text{atm}}^2 (c_{13}^2 c_{23}^2 + s_{23}^2 c_{12}^2 \zeta^2 + \mathcal{O}(s_{13} \zeta^2))\end{aligned}$$

Neutrino Mixing: θ_{12}

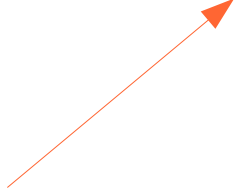
$$M_\nu^2 = m_\nu^\dagger m_\nu = U_{\text{PMNS}}(m_\nu^2)^{\text{diag}} U_{\text{PMNS}}^\dagger$$

$$\begin{aligned}(M_\nu^2)_{21} &= \Delta m_{\text{atm}}^2 \left[s_{13} c_{13} s_{23} e^{i\delta} + c_{13} c_{23} s_{12} c_{12} \zeta^2 - \mathcal{O}(s_{13} \zeta^2) \right] \\(M_\nu^2)_{31} &= \Delta m_{\text{atm}}^2 \left[s_{13} c_{13} c_{23} e^{i\delta} - c_{13} s_{23} s_{12} c_{12} \zeta^2 - \mathcal{O}(s_{13} \zeta^2) \right] \\(M_\nu^2)_{32} &= \Delta m_{\text{atm}}^2 \left[c_{13}^2 s_{23} c_{23} - s_{23} c_{23} c_{12}^2 \zeta^2 + \mathcal{O}(s_{13} \zeta^2) \right]\end{aligned}$$

Slepton Mass Matrix

$$\tilde{m}_{LL}^2 = \begin{pmatrix} 1 & c_3'' \epsilon^2 & 0 \\ c_3''^* \epsilon^2 & 1 + c_3 \epsilon & c_3' \epsilon \\ 0 & c_3'^* \epsilon & 1 + c_2 |y_\tau|^2 \end{pmatrix} \tilde{m}_L^2$$

We need a cancellation



Slepton Mixing

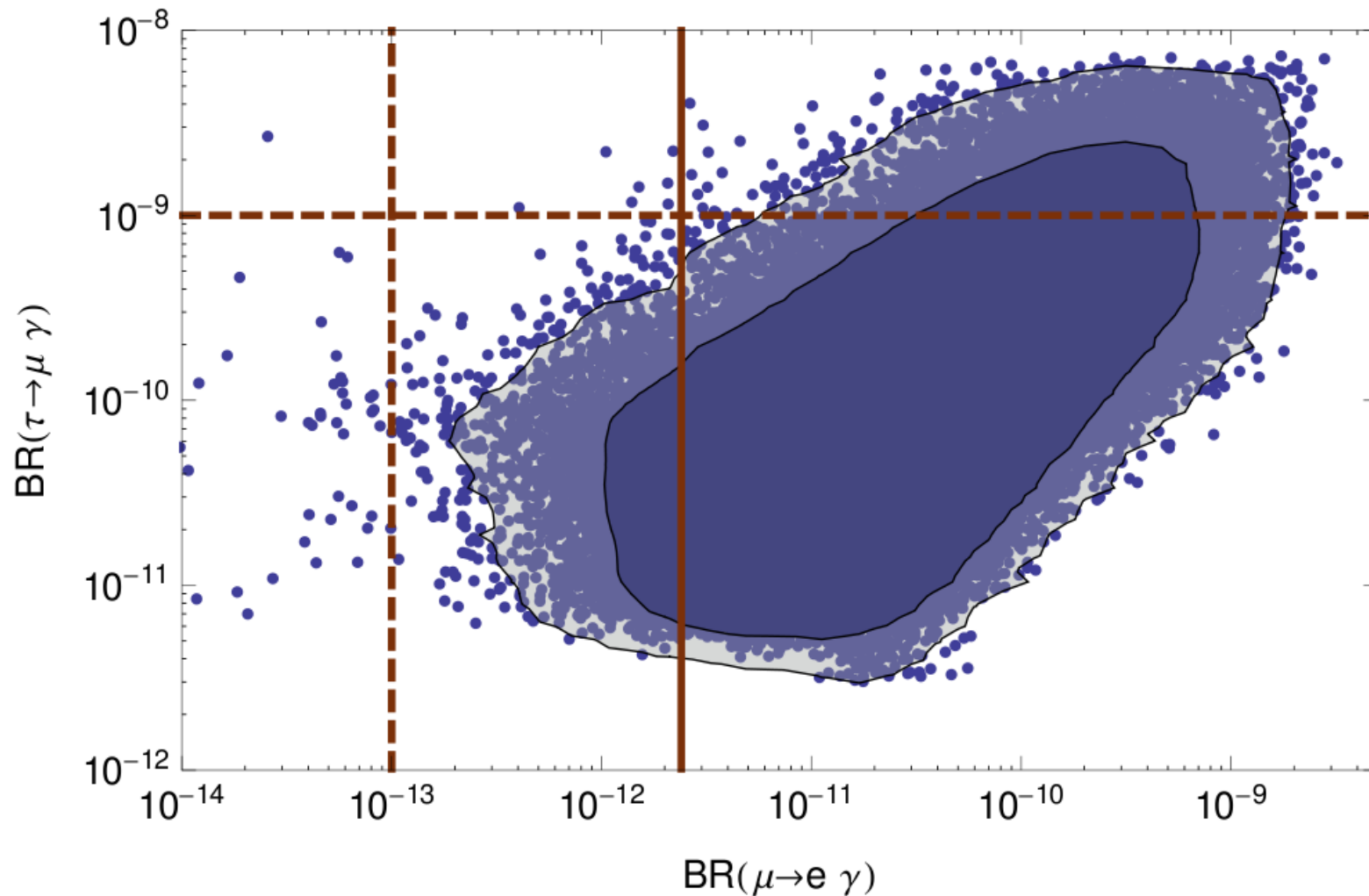
$$W_L^e = \begin{pmatrix} c_e & s_e e^{-i\alpha_e} & -s_e s_L^e e^{i\gamma} e^{-i\alpha_e} \\ -s_e e^{i\alpha_e} & c_e & -c_e s_L^e e^{i\gamma} \\ 0 & s_L^e e^{-i\gamma} & 1 \end{pmatrix}$$

$$\mathcal{R}_{13}^{\tilde{\nu}} = -s_e s_L^e e^{i(\gamma - \alpha_e)}$$

$$\mathcal{R}_{23}^{\tilde{\nu}} = -c_e s_L^e e^{i\gamma}$$

$$\mathcal{R}_{33}^{\tilde{\nu}} = 1$$

Lepton Flavour Violation



Neutrinoless Double Beta Decay

Bounds	
Experiment	Bound (eV), C.L.
KamLAND-Zen (^{136}Xe)	$< 0.3 - 0.6$, 90%
CUORICINO (^{130}Te)	$< 0.19 - 0.68$, 90%
GERDA (^{76}Ge)	$< 0.2 - 0.4$, 90%
EXO-200 (^{136}Xe)	$< 0.14 - 0.38$, 90%
Prospects	
Experiment	Reach (eV)
CUORE (^{130}Te)	$0.05 - 0.11$
NEXT (^{136}Xe)	$0.070 - 0.16$
S.NEMO (^{82}Se)	$0.055 - 0.14$
Lucifer (^{82}Se)	$0.033 - 0.085$

Parametrization

$$Y_e = \begin{pmatrix} y_e & 0 & 0 \\ -s_e \epsilon \lambda_e & y_\mu & 0 \\ c_e \epsilon \lambda_e & 0 & y_\tau \end{pmatrix}$$

- CP phases can be removed
- We need λ_e smaller than 0.01, to avoid fine-tuning in y_μ .
- For such values of λ_e , (LL) charged lepton mixing becomes negligible.

What if we start at M_{GUT} ?

- What sort of initial conditions should we look for?
- Is there any focusing effect?
- Are virtues of $U(2)^3$ preserved at all scales?

Initial Conditions

$$M_{1/2}$$

Universal gaugino mass

$$m_0$$

Universal Higgs mass

$$m_{heavy}$$

Universal heavy sfermion mass

$$\rho = \frac{m_{heavy}^2 - m_{light}^2}{m_{heavy}^2}$$

Universal light sfermion mass

$$A_0 \sim m_{heavy}$$

Universal trilinear coupling

Benchmarks

- Benchmark 1

$$m_{heavy} = 3 \text{ TeV}$$

$$M_{1/2} = 0.5 \text{ TeV}$$

$$\rho = 0.5$$

$$A_0 = -m_{heavy}$$

$$m_0 = 2.8 \text{ TeV}$$

- Benchmark 2

$$m_{heavy} = 8 \text{ TeV}$$

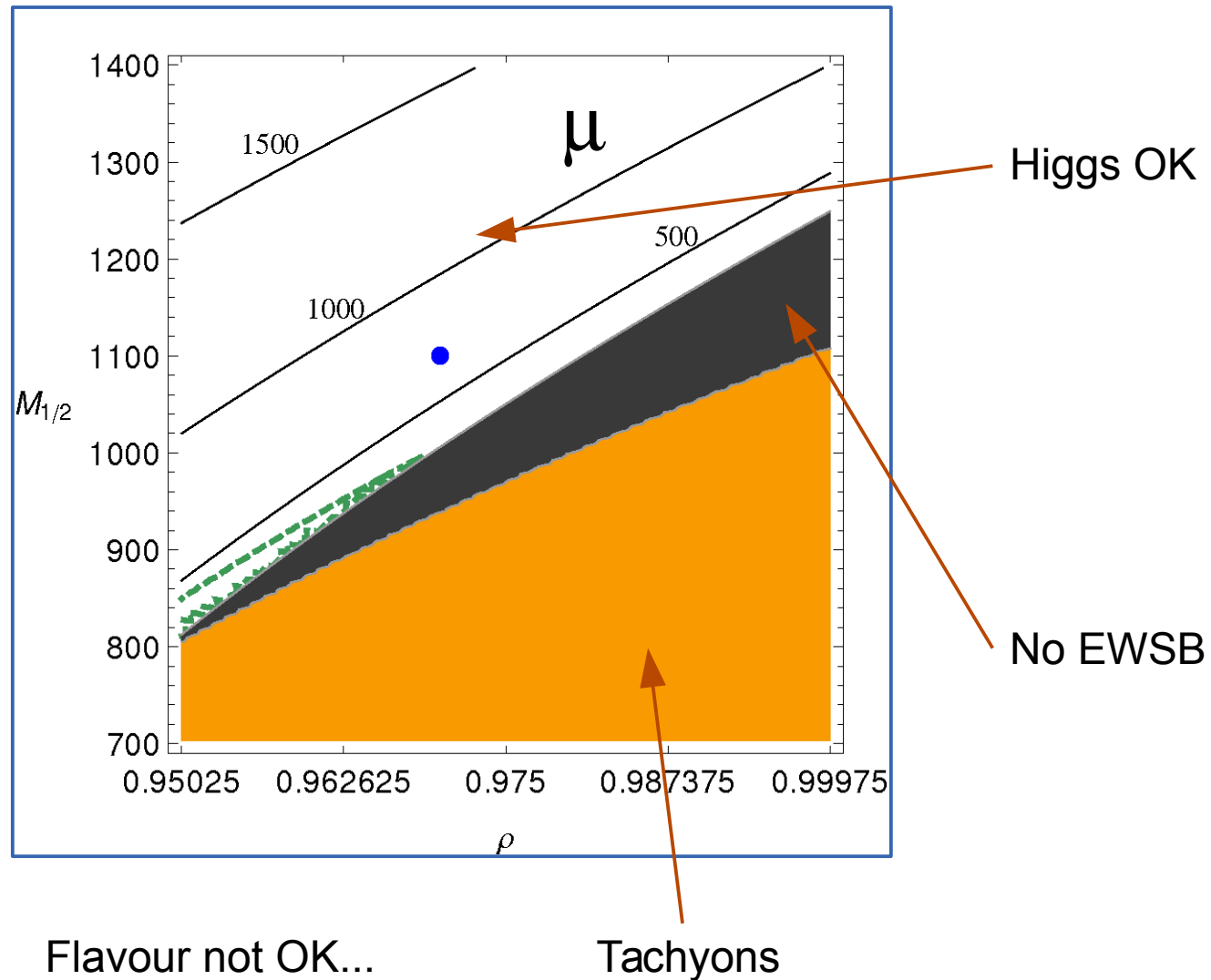
$$M_{1/2} = 1.1 \text{ TeV}$$

$$\rho = 0.97$$

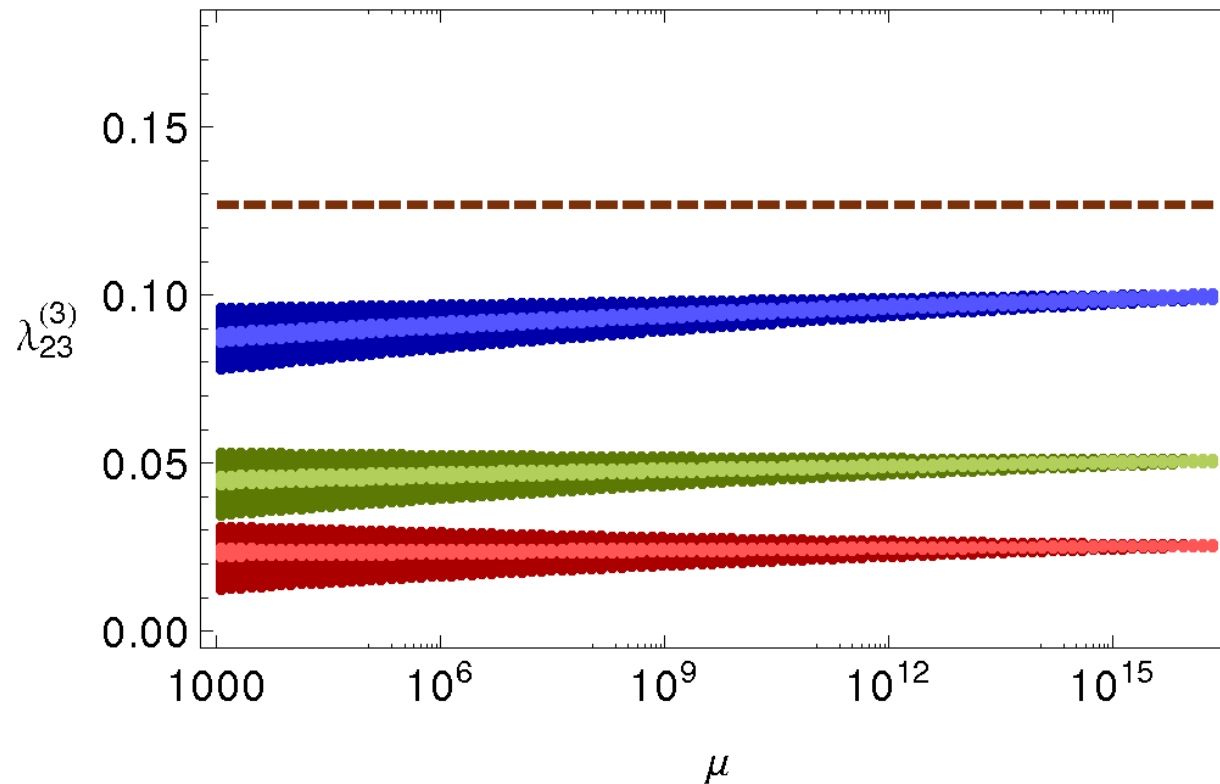
$$A_0 = -0.25m_{heavy}$$

$$m_0 = 2.5 \text{ TeV}$$

Benchmark 2



Mixing: Benchmark 2



$$\lambda_{23}^{(3)} = -c_d s_L e^{i\gamma_L}$$



$$|\lambda_{23}^{(3)}| = |V_{ts}| \sqrt{x}$$

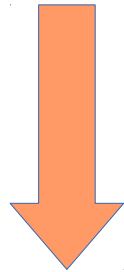
$$|\lambda_{23}^{(3)}| > 0.13$$

Structure

Main contribution to $\Delta F = 2$: $(LL)^2$

$$\lambda_{i \neq j}^{(a)} = (W_L^d)_{ia} (W_L^d)_{ja}^*$$

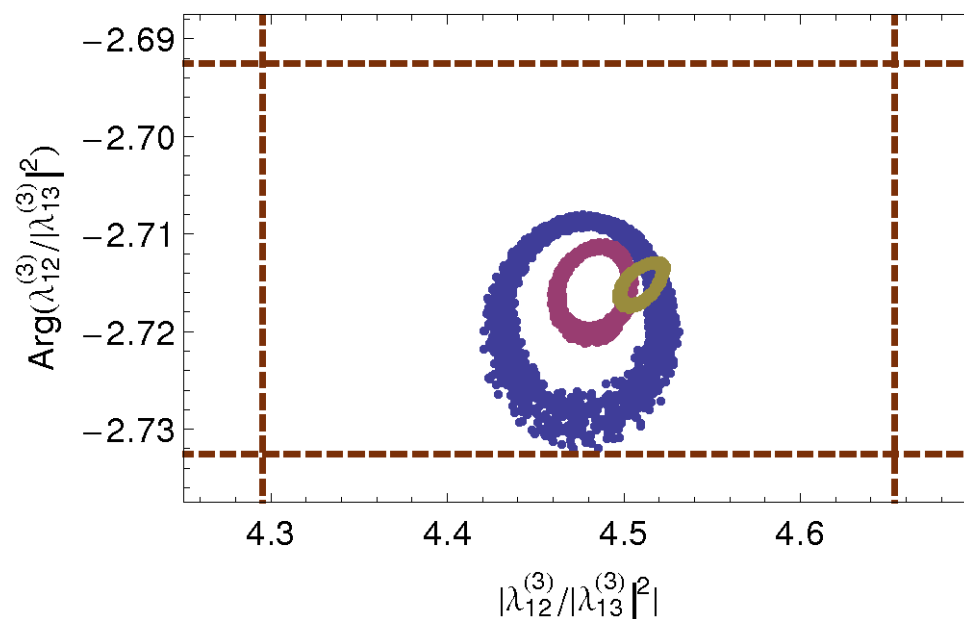
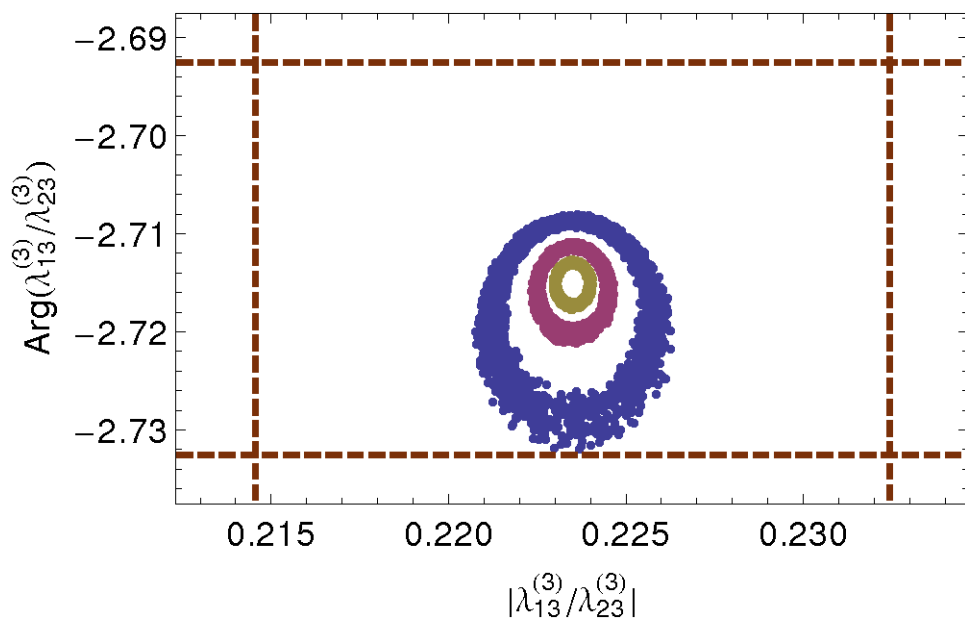
$$\lambda_{12}^{(3)} = c_d s_L^2 \kappa^* \quad \lambda_{13}^{(3)} = -s_L \kappa^* e^{i\gamma_L} \quad \lambda_{23}^{(3)} = -c_d s_L e^{i\gamma_L}$$



$$\frac{\lambda_{13}^{(3)}}{\lambda_{23}^{(3)}} = \frac{\kappa^*}{c_d}$$

$$\frac{\lambda_{12}^{(3)}}{|\lambda_{13}^{(3)}|^2} = \frac{c_d}{\kappa}$$

Structure: Benchmark 2



Structure is very stable.

More freedom in choice of $O(1)$ s.



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