A Flavour Framework for Natural SUSY with Neutrino Mixing

Joel Jones-Pérez
Universitat de València

Based on:
R. Barbieri, G. Isidori, JJP, P. Lodone, D. Straub (arXiv:1105.2296 [hep-ph])
G. Blankenburg, G. Isidori, JJP (arXiv: 1204.0688 [hep-ph])
C. Hagedorn, JJP (In preparation)

SUSY 2013 – Trieste

Natural SUSY, anyone?

- It seems SUSY particles are heavier than expected.
- Large Higgs mass hints towards a heavy spectrum, which compromises hierarchy problem.
- How do we minimize the fine-tuning?

Natural SUSY, anyone?

- Light higgsinos
- Light-ish stops (maybe sbottoms, staus?)
- Not too heavy gluinos
- First two generation squarks: over 2 TeV.
- Everything else: ???

Papucci, Ruderman, Weiler (1110.6926)

Natural SUSY, anyone?

- Light higgsinos
- Light-ish stops (maybe sbottoms, staus?)
- Not too heavy gluinos
- First two generation squarks: over 2 TeV.
- Everything else: ???

What about flavour?

Papucci, Ruderman, Weiler (1110.6926)

Good ol' MFV

- $U(3)^5$ framework built in order to suppress New Physics contributions to flavoured processes.
- Sfermion masses are forced to be nearly degenerate.
- Flavour off-diagonal contributions are related to CKM and mass hierarchies: y_t, y_b.

Maybe not so suitable for natural SUSY...

D'Ambrosio, Giudice, Isidori, Strumia (hep-ph/0207036)

Open Questions

- Can we build an MFV-like framework that can suppress flavour effects in SUSY, while allowing large mass differences?
- Can this framework reproduce the observed quark hierarchy and mixing?
- Can this framework reproduce the observed neutrino hierarchy and mixing?

Open Questions

- Can we build an MFV-like framework that can suppress flavour effects in SUSY, while allowing large mass differences?
- Can this framework reproduce the observed quark hierarchy and mixing?
- Can this framework reproduce the observed neutrino hierarchy and mixing?

Yes!

Replace U(3) by U(2)

Outline

- $U(2)^3$ framework in the quark sector.
- $U(3)^5$ -> $U(2)^5$ framework in the lepton sector.
- New, shifted $U(2)^5$ framework with light stops, sbottoms and selectrons.

$U(2)^3$ in the Quark Sector

arXiv:1105.2296 [hep-ph]

U(2)^3 Framework

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

$$\begin{aligned} Q^{(2)} &= (Q_1, \quad Q_2) &\sim& \quad (\bar{2}, 1, 1) \\ u_R^{c(2)} &= (u_{R,1}^c, \quad u_{R,2}^c)^T &\sim& \quad (1, 2, 1) \\ d_R^{c(2)} &= (d_{R,1}^c, \quad d_{R,2}^c)^T &\sim& \quad (1, 1, 2) \end{aligned}$$

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

$U(2)^3$ Spurions

$$\begin{aligned} \Delta Y_u &\sim (2, \bar{2}, 1) \\ \Delta Y_d &\sim (2, 1, \bar{2}) \\ V &\sim (2, 1, 1) \end{aligned}$$

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

Hierarchy between y_{f2} and y_{f3} should be related to suppression in ΔY_f.

Hierarchy between V_{cb} and V_{tb} should be related to suppression in V.

Soft SUSY Masses

Unbroken 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 the Yukawa structure shall generate the soft mass structure.

Soft SUSY Masses

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

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

$U(2)^5$ in the Quark + Lepton Sector

First Try

arXiv:1204.0688 [hep-ph]

Neutrino Data

Neutrino oscillation data:

$$s_{12}^2 = 0.306 \pm 0.012 \qquad s_{23}^2 = 0.437^{+0.061}_{-0.031}$$

$$s_{13}^2 = 0.0231 \pm 0.0023$$

$$\begin{aligned} \Delta m^2_{\rm sol} &= (7.45^{+0.19}_{-0.16}) \times 10^{-5}\ {\rm eV}^2 \\ |\Delta m^2_{\rm atm}| &= (2.421 \pm 0.022) \times 10^{-3}\ {\rm eV}^2 \end{aligned}$$

http://www.nu-fit.org

Incompatibility of U(2)^5

Neutrino mass matrix:

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

Relation with angles:

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

Incompatibility of U(2)^5

Neutrino mass matrix:

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

Relation with angles:

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

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

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

Back to MFV

$$U(3)^5$$

$$U(2)^5$$

$$Y_u,\ Y_d,\ Y_e$$

$$O(3)_L$$

$$m_\nu$$

Spurions and Yukawa Sector

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

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

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

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

Spurions and Neutrino Sector

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

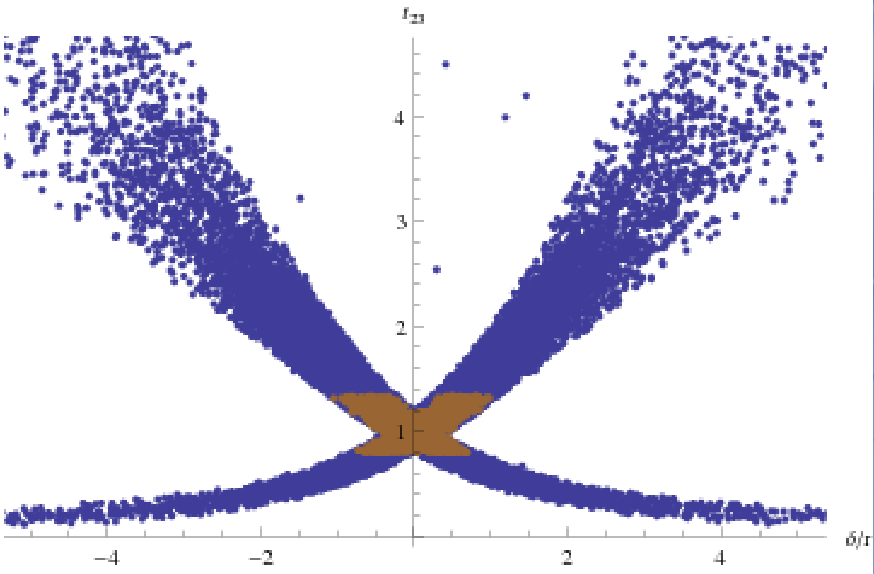
$$m_\nu^{(0)} \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

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

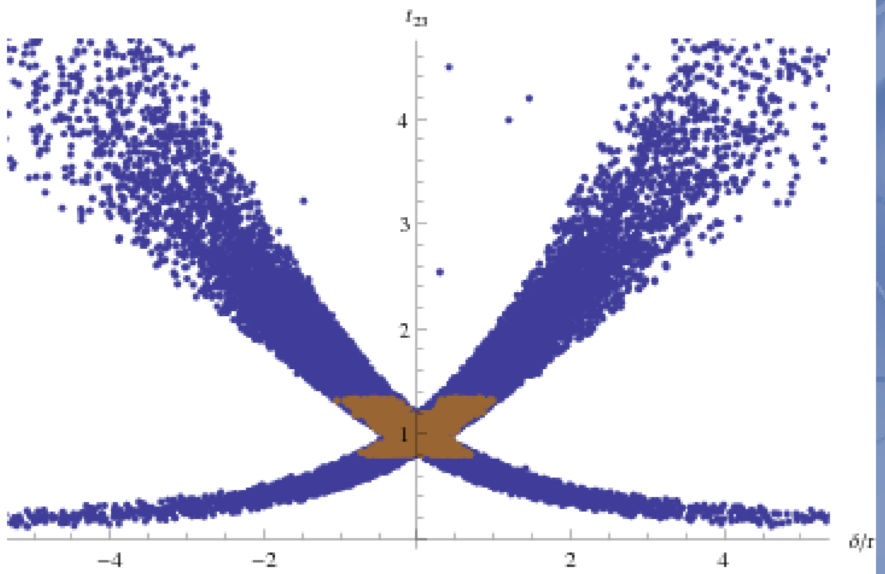
Neutrino Mixing

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



Neutrino Mixing

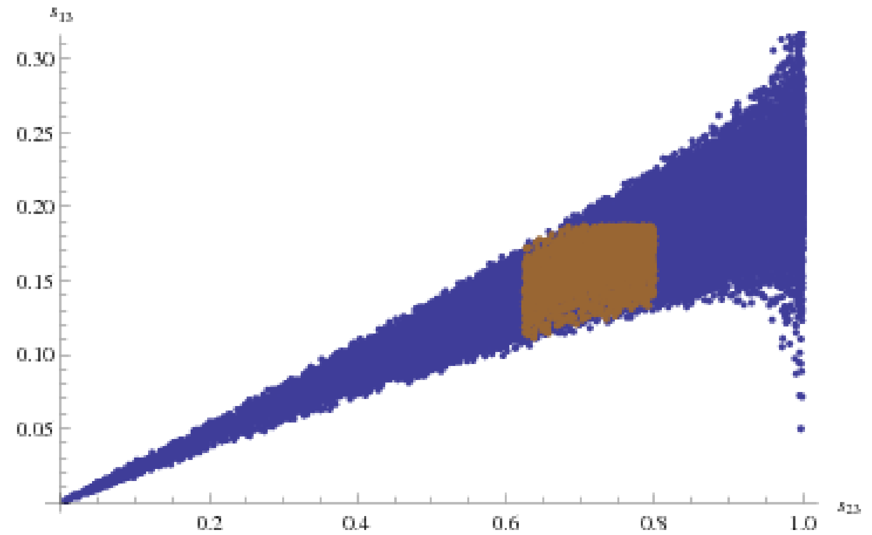
$$\frac{s_{23}}{c_{23}} \approx \frac{\delta \pm [\delta^2 + 4r^2]^{1/2}}{2r}$$



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

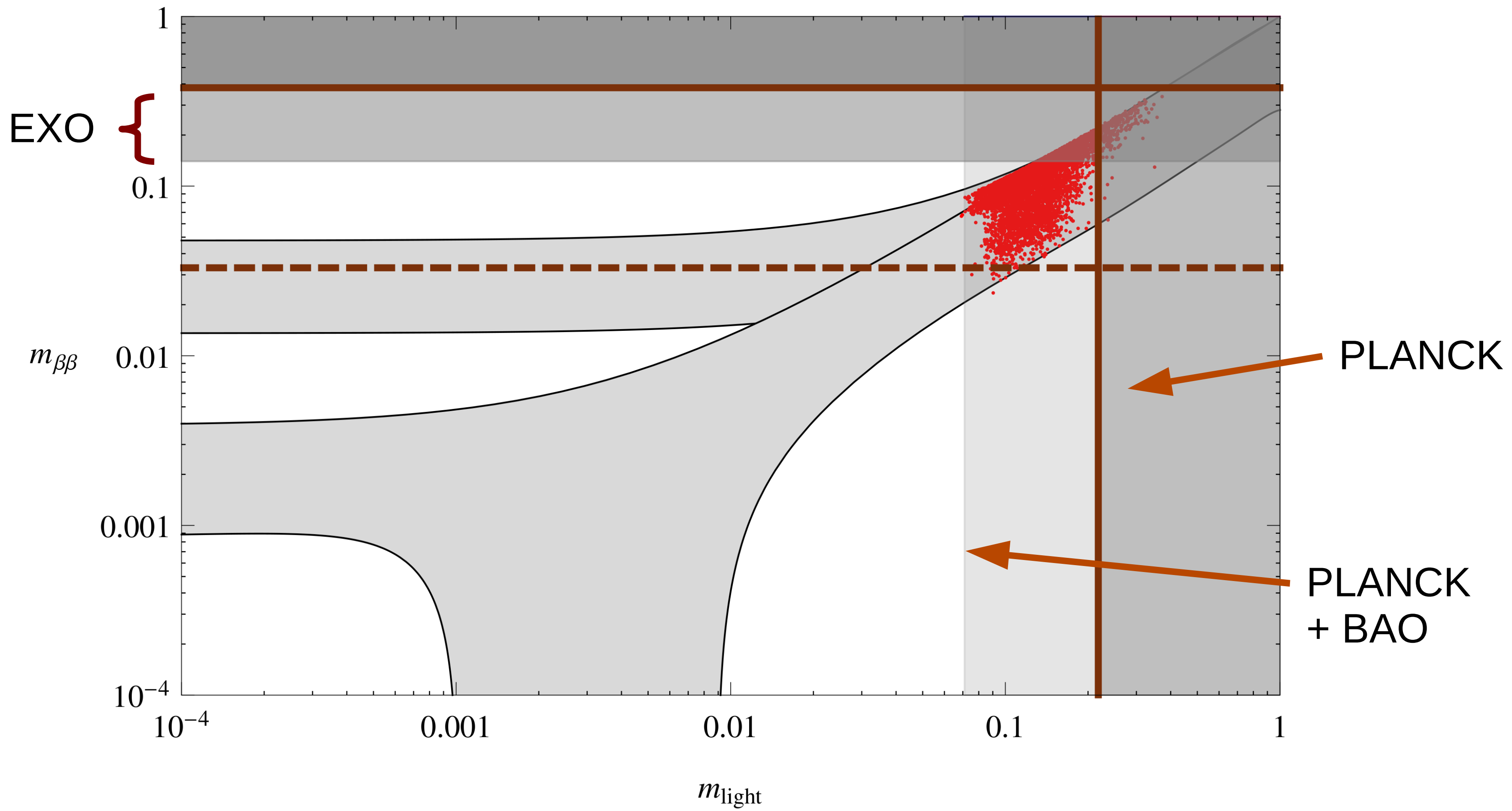
$$s_e = s_d \sim 0.2$$

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



Neutrinoless Double Beta Decay

Large values for m_{light} and $m_{\beta\beta}$.

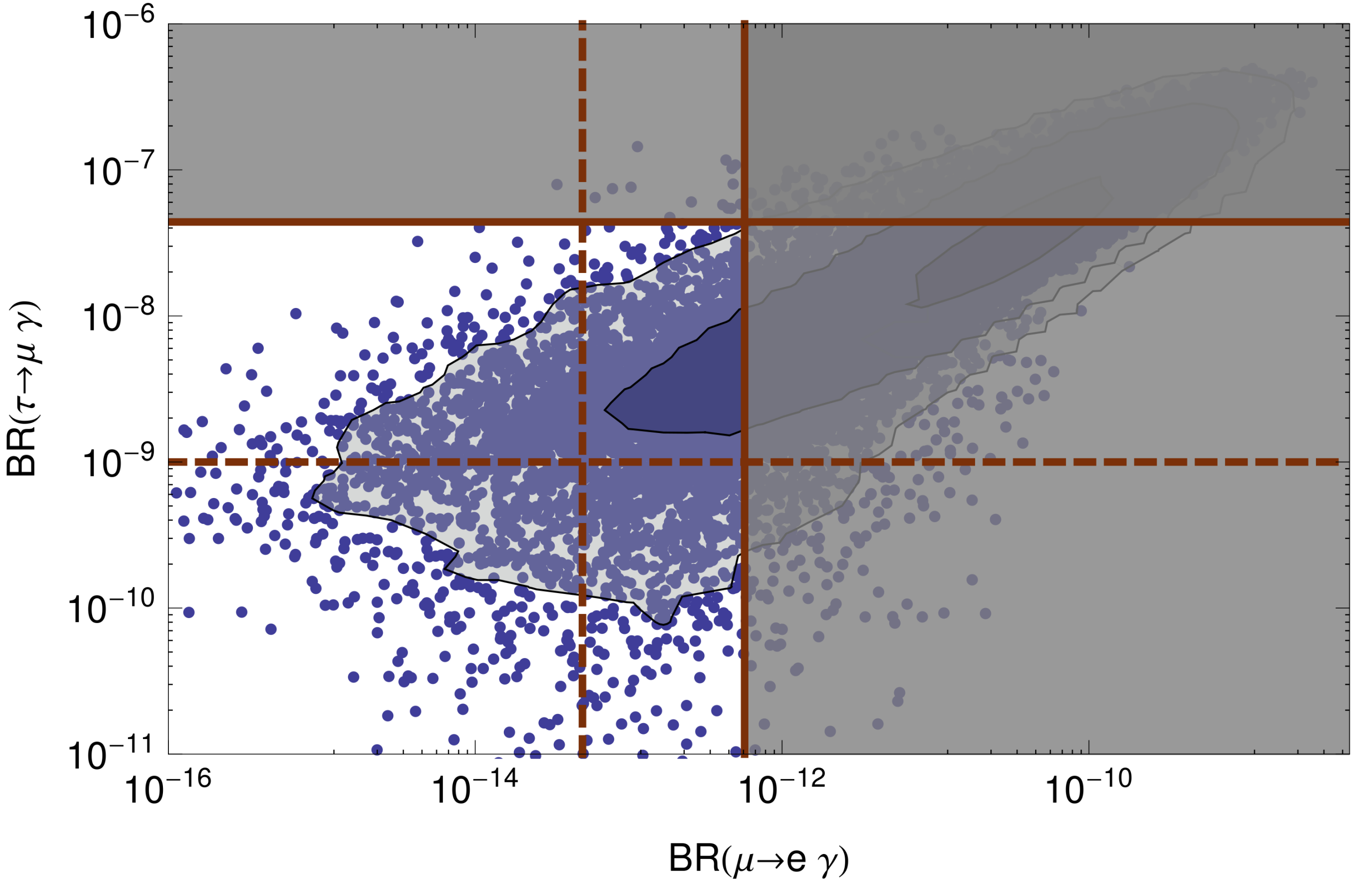


Soft SUSY Masses

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

We need a cancellation
Similar to MFV

Lepton Flavour Violation



$\tan\beta = 10$

$M_2 = 500$ GeV

$M_1 = 250$ GeV

$\mu = 600$ GeV

$$\tilde{m}_{\rm light} \lesssim 1 \text{ TeV}$$

$U(2)^5$ in the Quark + Lepton Sector

Second Try

New Idea: Shifted Flavour Symmetry

New U(1) transformation for three U(2) singlets:

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

$$W_q = y_t \, Q_3 \, t_R^c \, H_u$$

New Idea: Shifted Flavour Symmetry

New U(1) transformation for three U(2) singlets:

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

$$W_q = y_t \, Q_3 \, t^c_R \, H_u$$

One new spurion for quark sector: y_b

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

New Idea: Shifted Flavour Symmetry

New U(1) transformation for three U(2) singlets:

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

Two new spurions for lepton sector: $\lambda_L, \quad \lambda_e$

New Idea: Shifted Flavour Symmetry

Difference with quark sector: the singlets represent the first generation, not the third!

$$\lambda_L \lambda_e \approx y_e$$

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

$U(2)^2$ symmetry in lepton sector gets shifted towards second and third generation.

Neutrino Sector

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

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

$$m_\nu \sim \begin{pmatrix} \lambda_L^2 & -s_e\,\lambda_L\,\epsilon & c_e\,\lambda_L\,\epsilon \\ -s_e\,\lambda_L\,\epsilon & s_e^2\epsilon^2 + \epsilon'_{22} & -s_e c_e \epsilon^2 + \epsilon'_{23} \\ c_e\,\lambda_L\,\epsilon & -s_e c_e \epsilon^2 + \epsilon'_{23} & c_e^2\epsilon^2 + \epsilon'_{33} \end{pmatrix}\kappa_\nu$$

Neutrino Sector

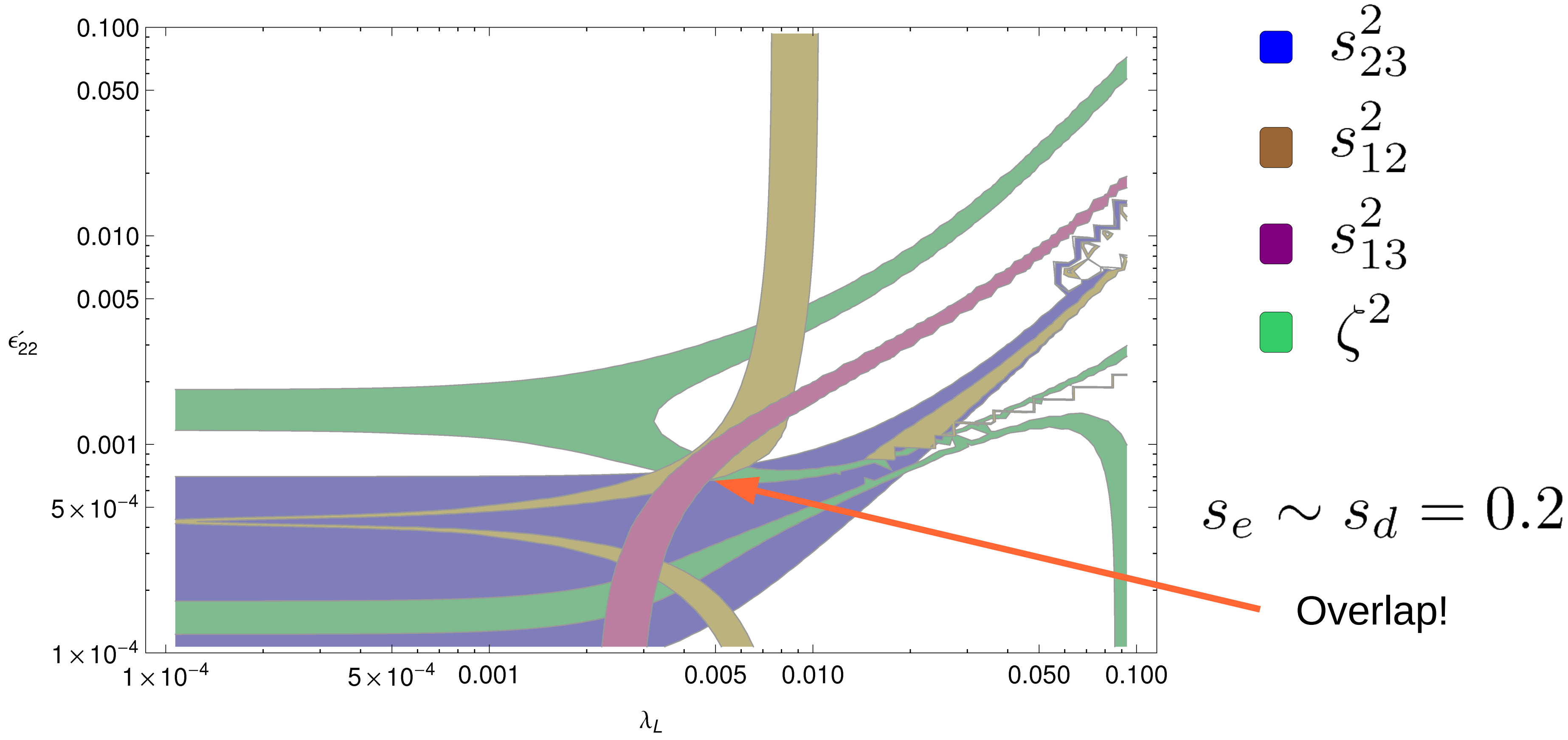
- Limit $\lambda_L = 0, \text{ and } \epsilon'_{22} = \epsilon'_{33}, \text{ and } \epsilon'_{23} = 0$

$$\zeta^2 = \frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}} = \frac{(\epsilon^2 + \epsilon'_{33})^2}{\epsilon'^2_{33}}$$

We need negative $\epsilon'_{33} \sim -2 \times 10^{-3}$

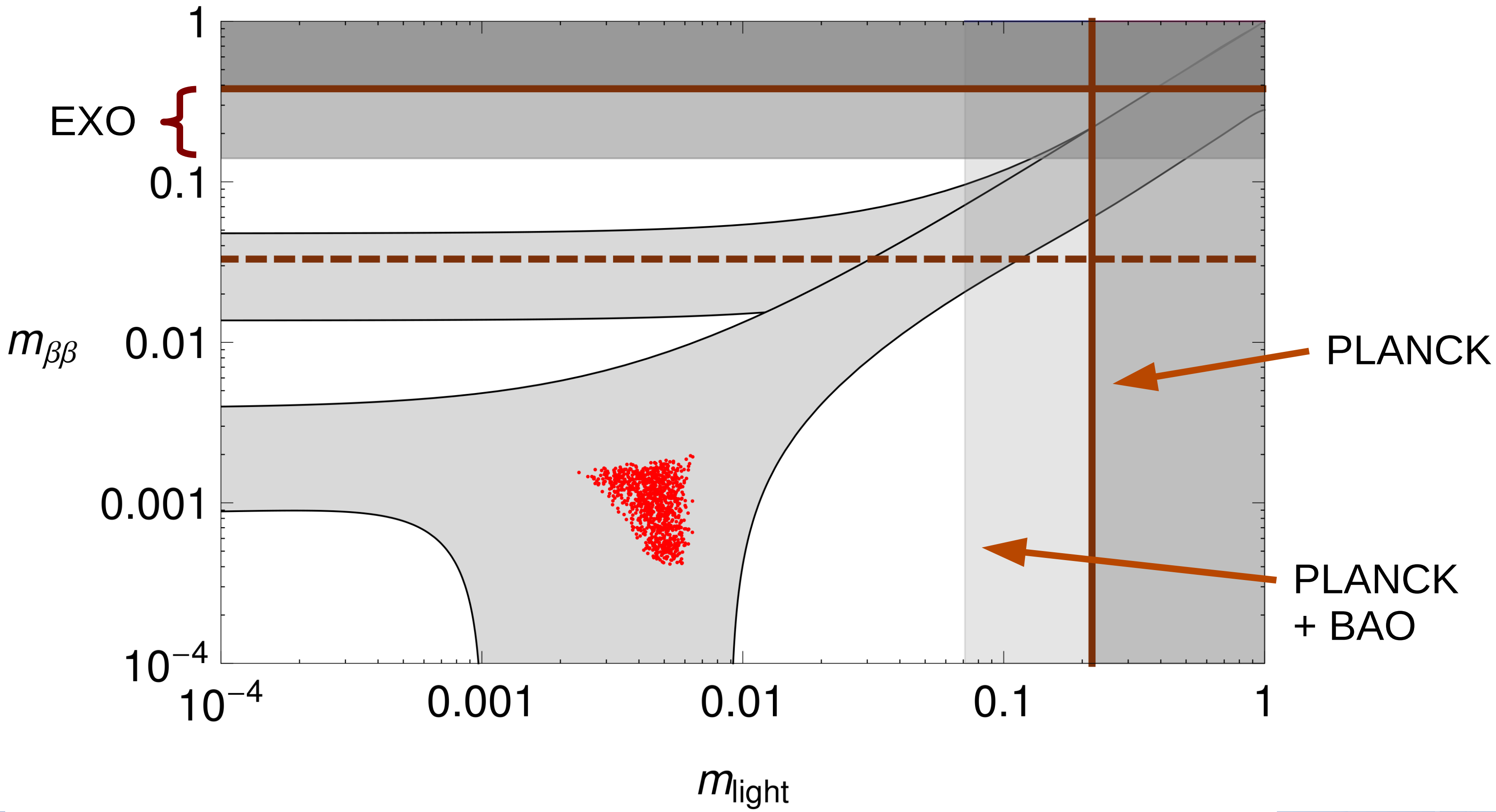
Neutrino Sector

- To generate non-vanishing θ_{13}, we need to break μ-τ symmetry: $\epsilon'_{22} \neq \epsilon'_{33}$



Neutrinoless Double Beta Decay

Large values for m_{light} and $m_{\beta\beta}$.



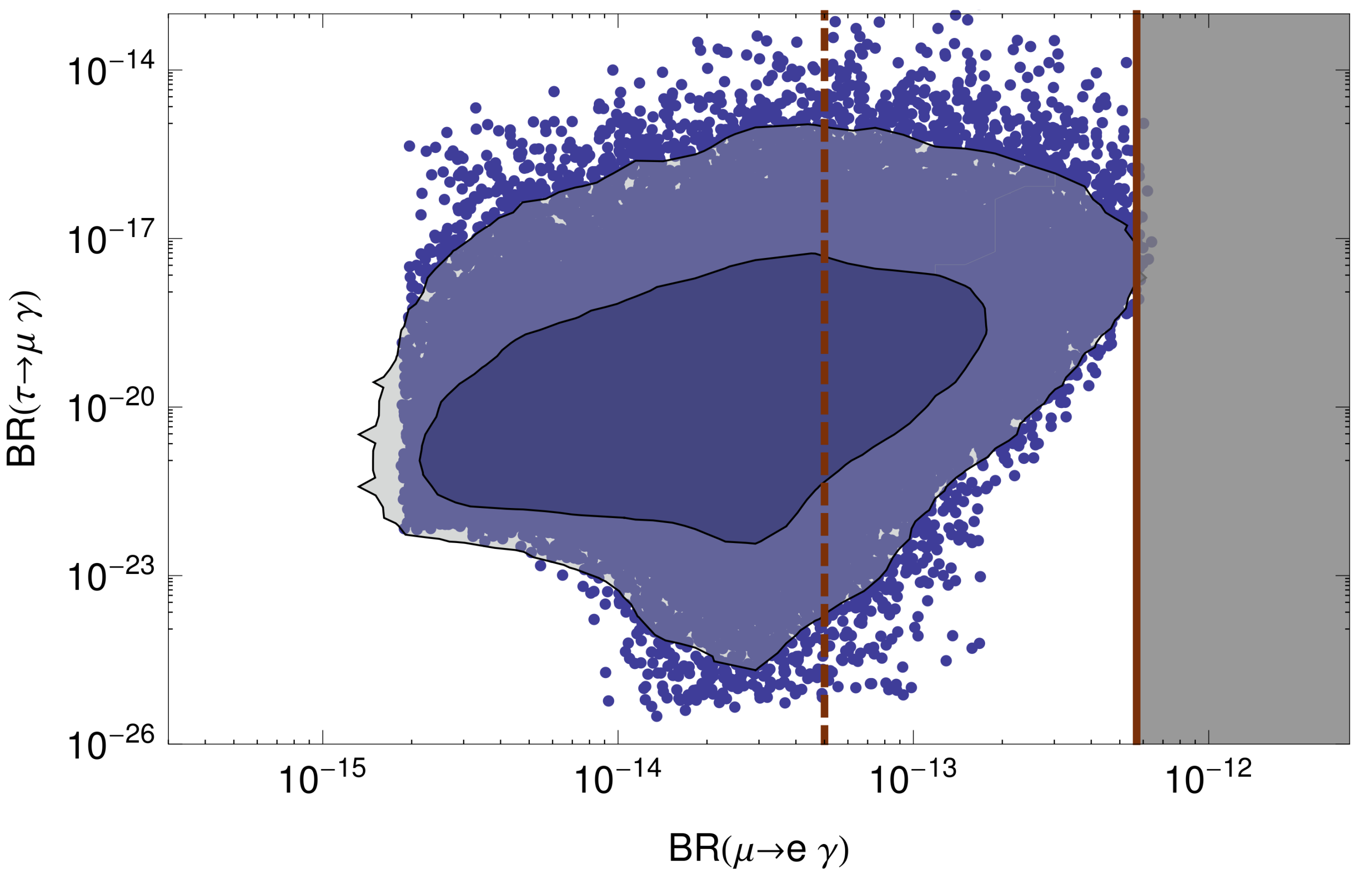
Slepton Sector

$$\frac{m^2_{\tilde{L}}}{m^2_h} = \left(\begin{array}{c|c} m^2_l/m^2_h & \lambda^*_L\, V_e^T \\ \hline \lambda_L\, V_e^* & I + \Delta Y_e^* \Delta Y_e^T + V_e^* V_e^T + 2\Delta^*_L \Delta_L \end{array}\right)$$

$$\frac{m^2_{\tilde{e}^c_R}}{m^2_h} = \left(\begin{array}{c|c} m^2_l/m^2_h & \lambda^*_e\, V_e^\dagger \Delta Y_e \\ \hline \lambda_e\, \Delta Y_e^\dagger\, V_e & I + \Delta Y_e^\dagger \Delta Y_e \end{array}\right)$$

Main feature: light selectrons, heavy smuons and staus.

Lepton Flavour Violation



$\tan\beta = 10$
$M_2 = 500$ GeV
$M_1 = 250$ GeV
$\mu = 600$ GeV

$$\tilde{m}_{\mathrm{light}} \lesssim 1\ \mathrm{TeV}$$

Conclusions

Conclusions

- $U(2)^3$ framework in the quark sector is compatible with effective SUSY.
- An analogous $U(2)^2$ framework in the lepton sector does not work, as neutrino mixing implies that second and third generation are connected.

Conclusions

- We have explored two options:
- $U(3)^5$ -> $U(2)^5$ + O(3)
  - Degenerate neutrino masses, observation of $0\nu\beta\beta$ decay soon.
  - Large LFV rates.
  - Some fine-tuning.
- Shifted $U(2)^5$, with light selectrons.
  - Normal hierarchy, too small $0\nu\beta\beta$.
  - Very small LFV rates.

Backup

Parametrization

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

$$\Delta Y_f = \begin{pmatrix} c_f & s_f \, e^{i\alpha_f} \\ -s_f \, e^{-i\alpha_f} & c_f \end{pmatrix} \Delta Y_f^{\mathrm{diag}}$$

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

Notice there is no loss of generality within parametrization.

CKM

$$V_{\rm CKM} =$$

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

$$\begin{aligned} |s| &= 0.0410 \pm 0.0004 \qquad \Rightarrow \epsilon \sim \lambda^2_{\rm CKM} \\ s_u &= 0.0916 \pm 0.005 \\ s_d &= -0.22 \pm 0.02 \\ \cos(\alpha_u - \alpha_d) &= -0.13 \pm 0.2 \end{aligned}$$

$U(2)^3$ Framework for Small *tan*β

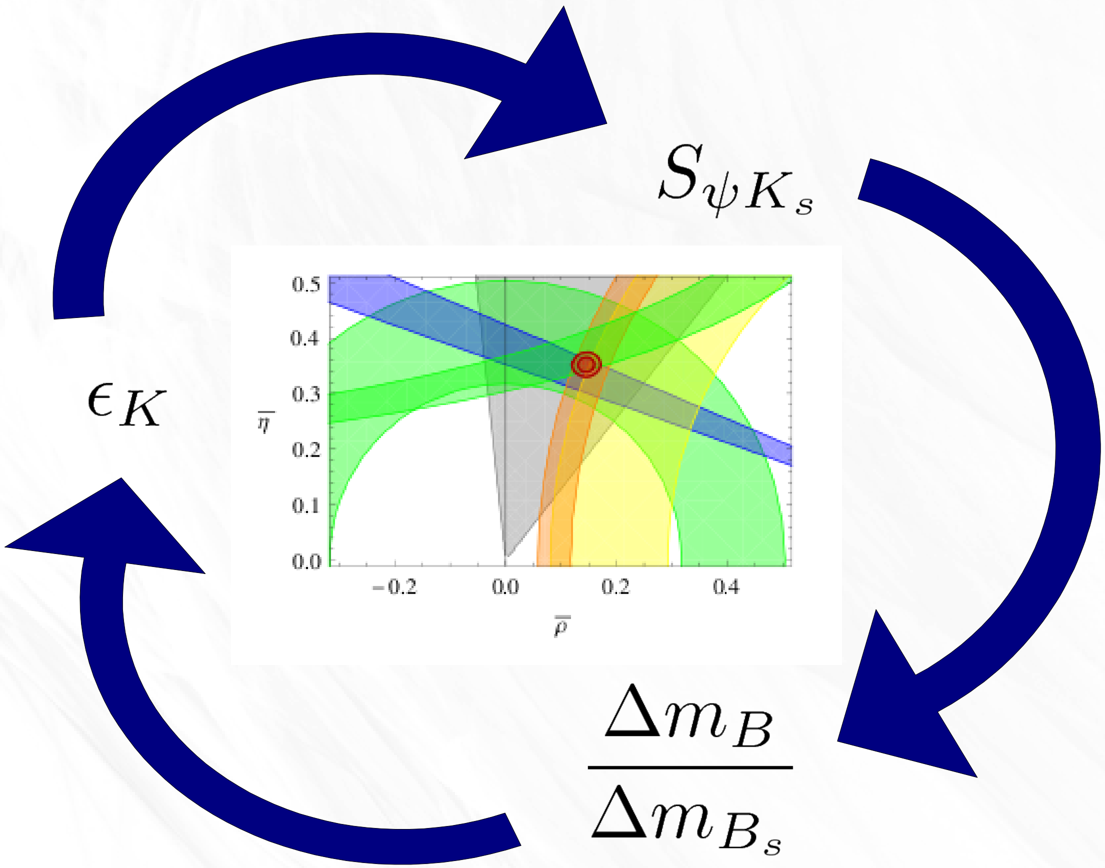
$$U(2)_Q \otimes U(2)_u \otimes U(2)_d \otimes U(1)_b$$

$$\begin{aligned} d_R^{c(2)} &\rightarrow e^{i\beta}\, d_R^{c(2)} \\ b_R^c &\rightarrow e^{i\beta}\, b_R^c \end{aligned}$$

$$y_b \rightarrow e^{-i\beta}\, y_b$$

Small Spurion

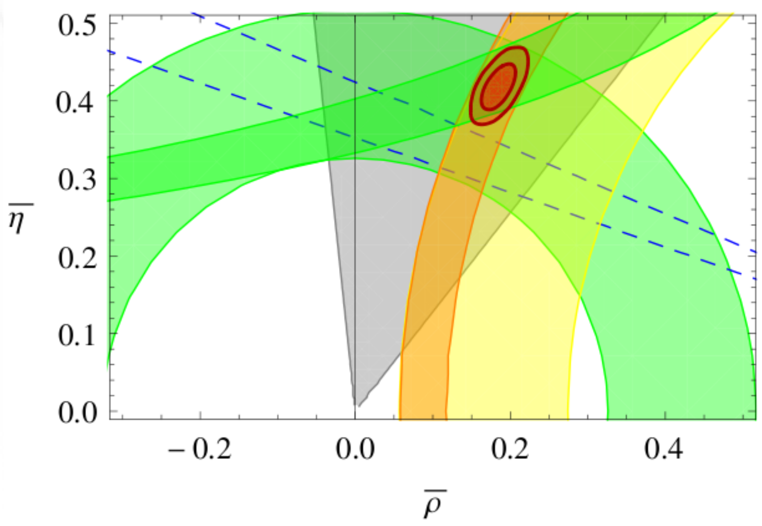
Flavour Tension in the SM

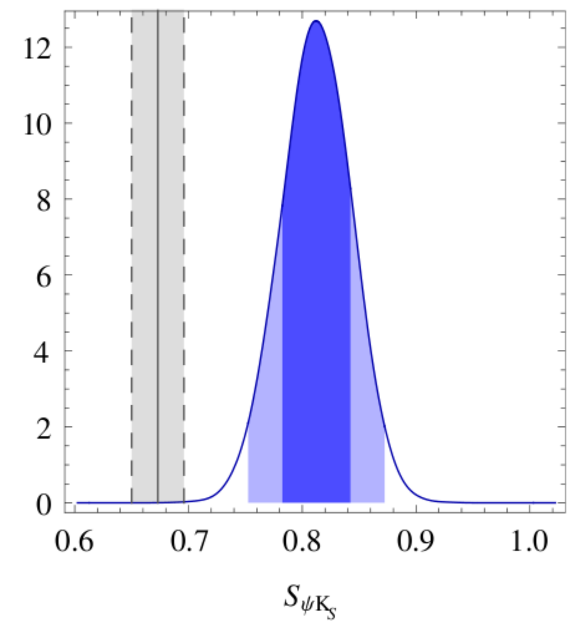


Buras, Guadagnoli (0901.2056 [hep-ph])
Altmannshofer *et al* (0909.1333 [hep-ph])

Flavour Tension in the SM

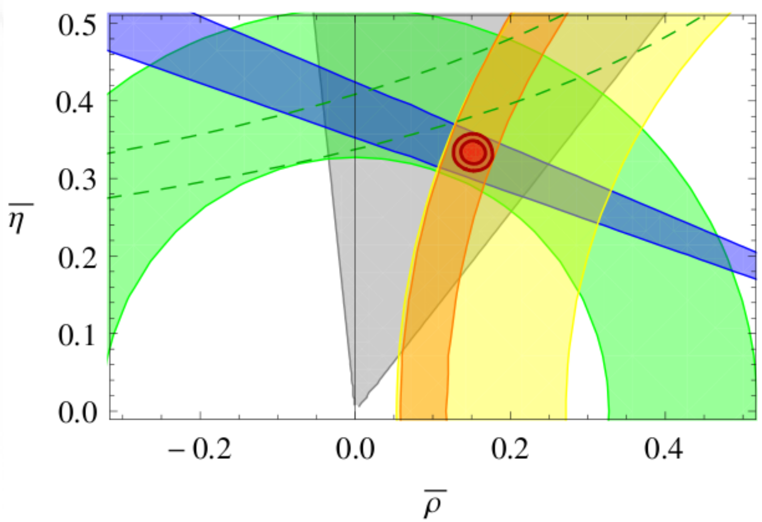
UT fit without $S_{\psi Ks}$:

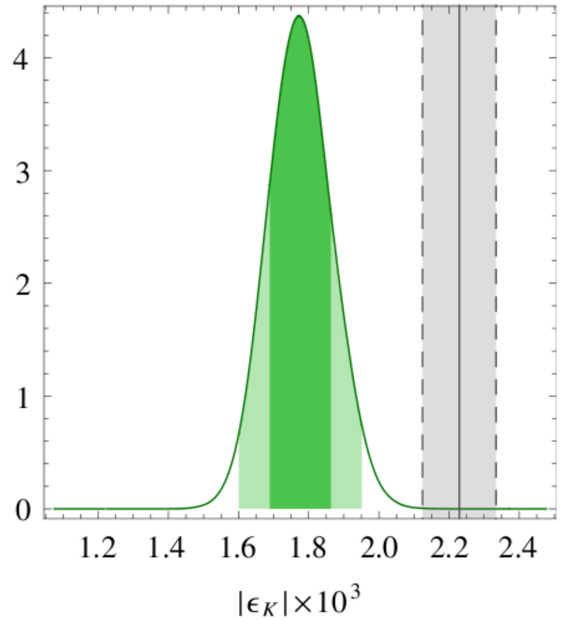




Flavour Tension in the SM

UT fit without ε_K:





Squark Mixing Matrices

$$W_L^{d\dagger}\ m^2_{\tilde{Q}}\ W_L^d = (m^2_{\tilde{Q}})^{\rm diag}$$

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

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

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

No new phases on the (1-2) sector!

$$s_L e^{i\gamma} \quad = \quad e^{-i\xi}(s_{x_b} e^{-i\phi_b} + s_Q e^{-i\phi_Q})$$

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

New SUSY Contributions

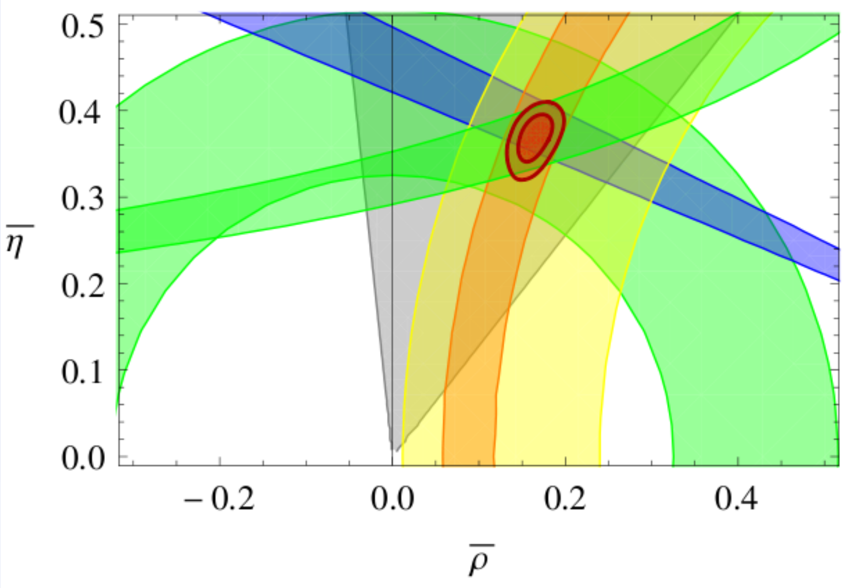
$(LL)^2$ contributions on K, B and B_s sectors all depend on:

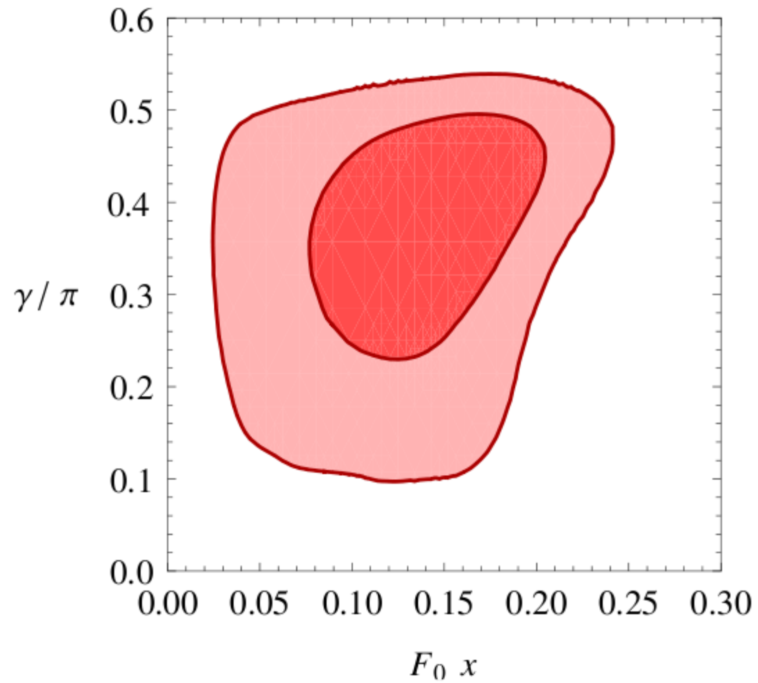
The same loop function: $$F_0 = F_0(m_{\tilde{g}}^2/m_{\tilde{b}}^2)$$

The same mixing parameter: $$x = \frac{c_d^2 s_L^2}{|V_{ts}|^2}$$

The same phase: $$\gamma_L$$

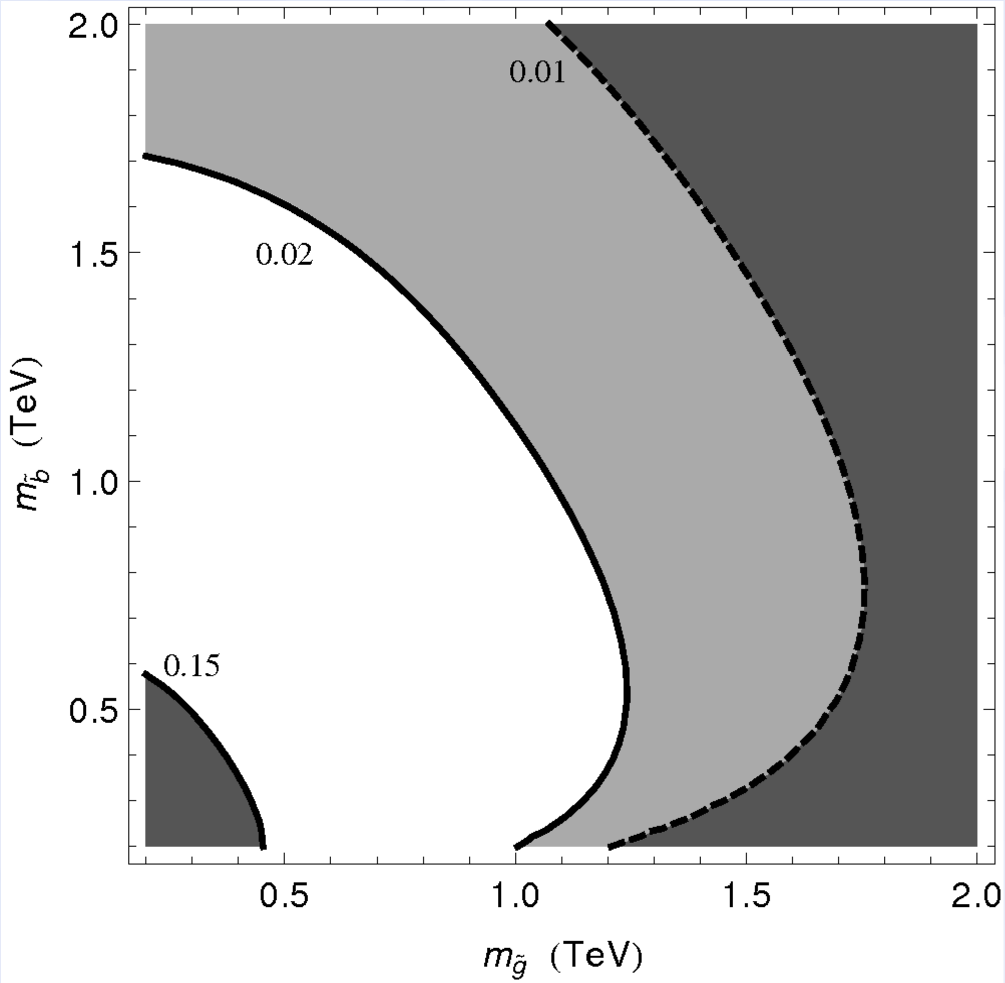
Fit with SUSY Contribution





$$(\chi^2/N_{\rm d.o.f.})_{\rm SM} = 9.8/5 \qquad (\chi^2/N_{\rm d.o.f.})_{\rm SUSY} = 0.7/2$$

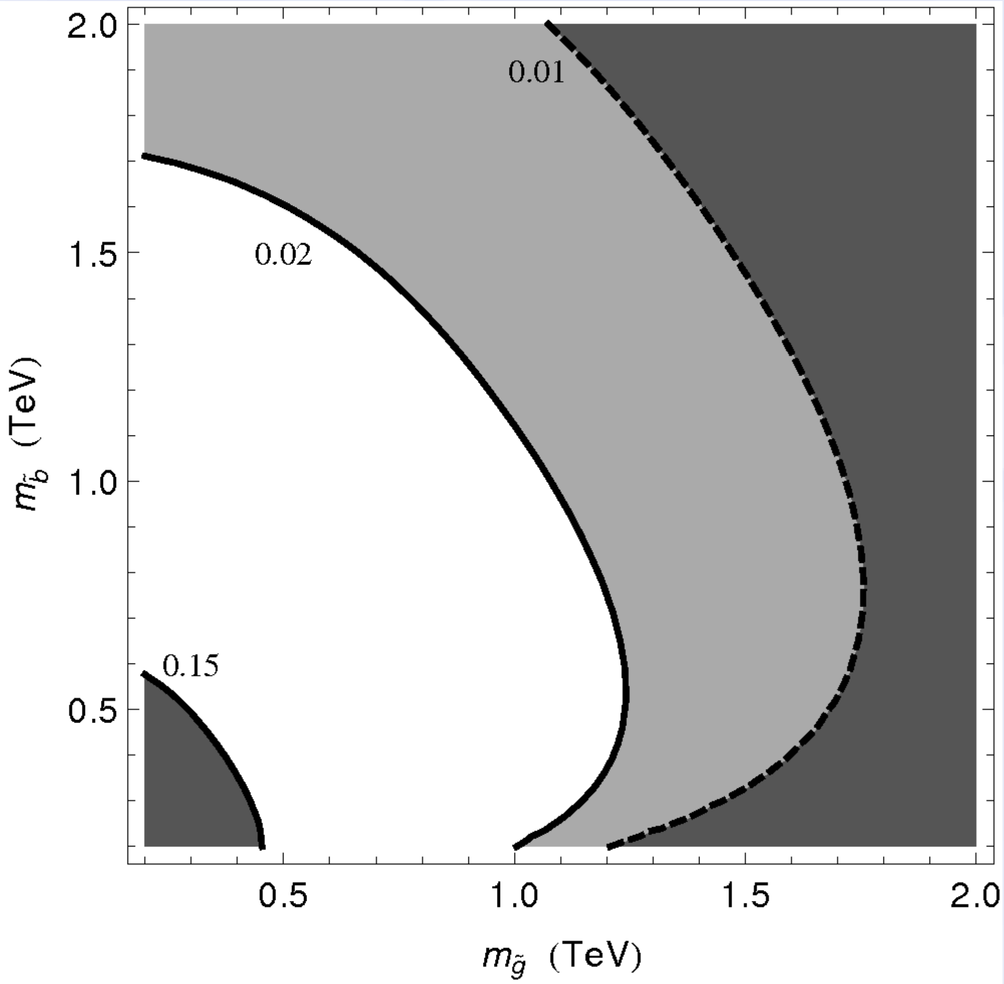
Where does F_0 have the right size?



$$0.02 \lesssim F_0 < 0.15$$

Need light spectrum for third generation sfermions.

Where does F_0 have the right size?

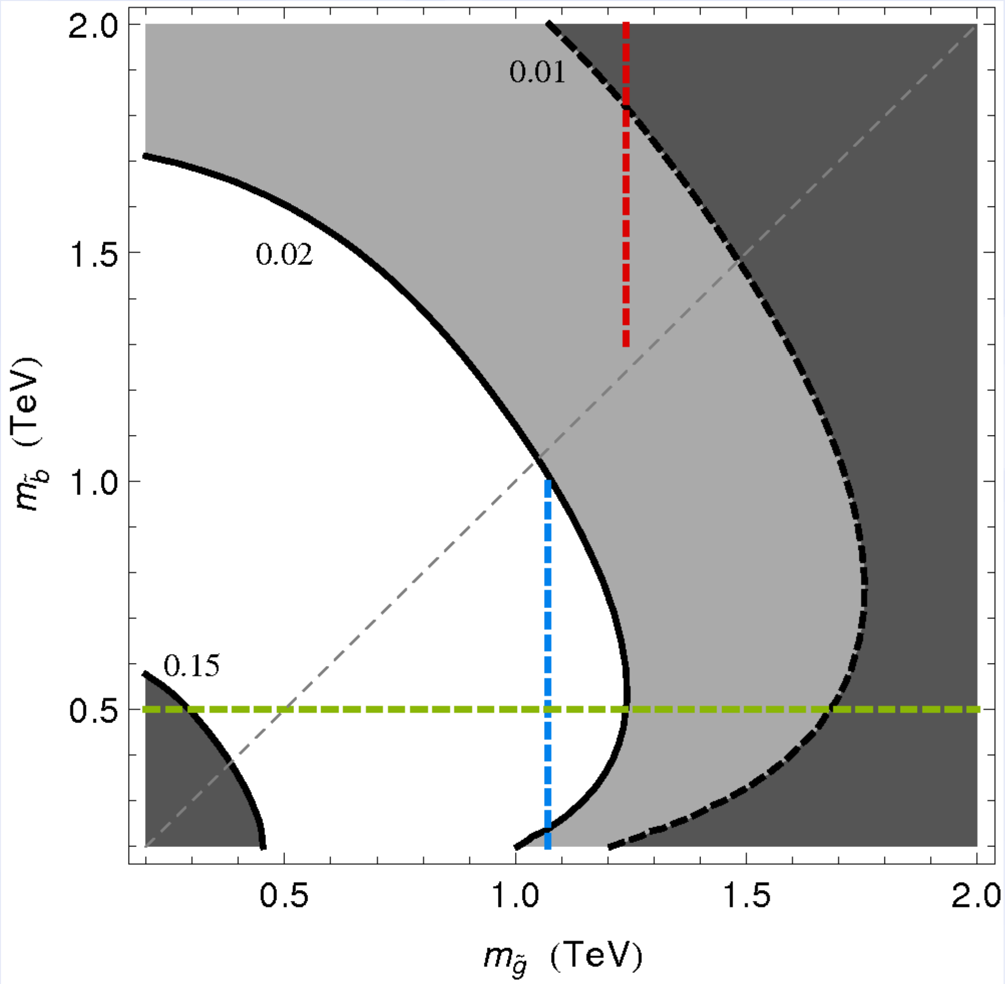


$$0.02 \lesssim F_0 < 0.15$$

$$x \gtrsim 1.5 \qquad x \gtrsim 0.2$$

Need light spectrum for third generation sfermions.

Where does F_0 have the right size?



ATLAS: ATLAS-CONF-2012-145

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

ATLAS: 1207.4686 [hep-ex]

$$pp \longrightarrow \tilde{g}\tilde{g} \quad \longrightarrow \quad \tilde{b}\tilde{b}^* b\bar{b}$$

$$\longrightarrow \quad b\bar{b}b\bar{b}\tilde{\chi}^0\tilde{\chi}^0$$

CMS: CMS-SUS-11-022

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

Spurions and Yukawa Sector

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

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

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

$$Y_e^{(0)} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} y_\tau^{(0)}$$

$$X = \left(\begin{array}{c|c} \Delta_L & V \\ \hline V^\dagger & x \end{array}\right) \qquad \Delta\hat{Y}_e = \left(\begin{array}{c|c} \Delta Y_e & 0 \\ \hline 0 & 0 \end{array}\right)$$

$U(3)_L$ -> $O(3)_L$ Spurion

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

Rotation to basis where Y_e is diagonal:

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

Neutrino Mixing (U(3)-O(3)): Δm^2

Mass Differences:

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

ε determines scale of neutrino masses

Neutrino Mixing (U(3)-O(3)): Δm^2

Mass Differences:

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

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

Neutrino Mixing (U(3)-O(3)): Δm^2

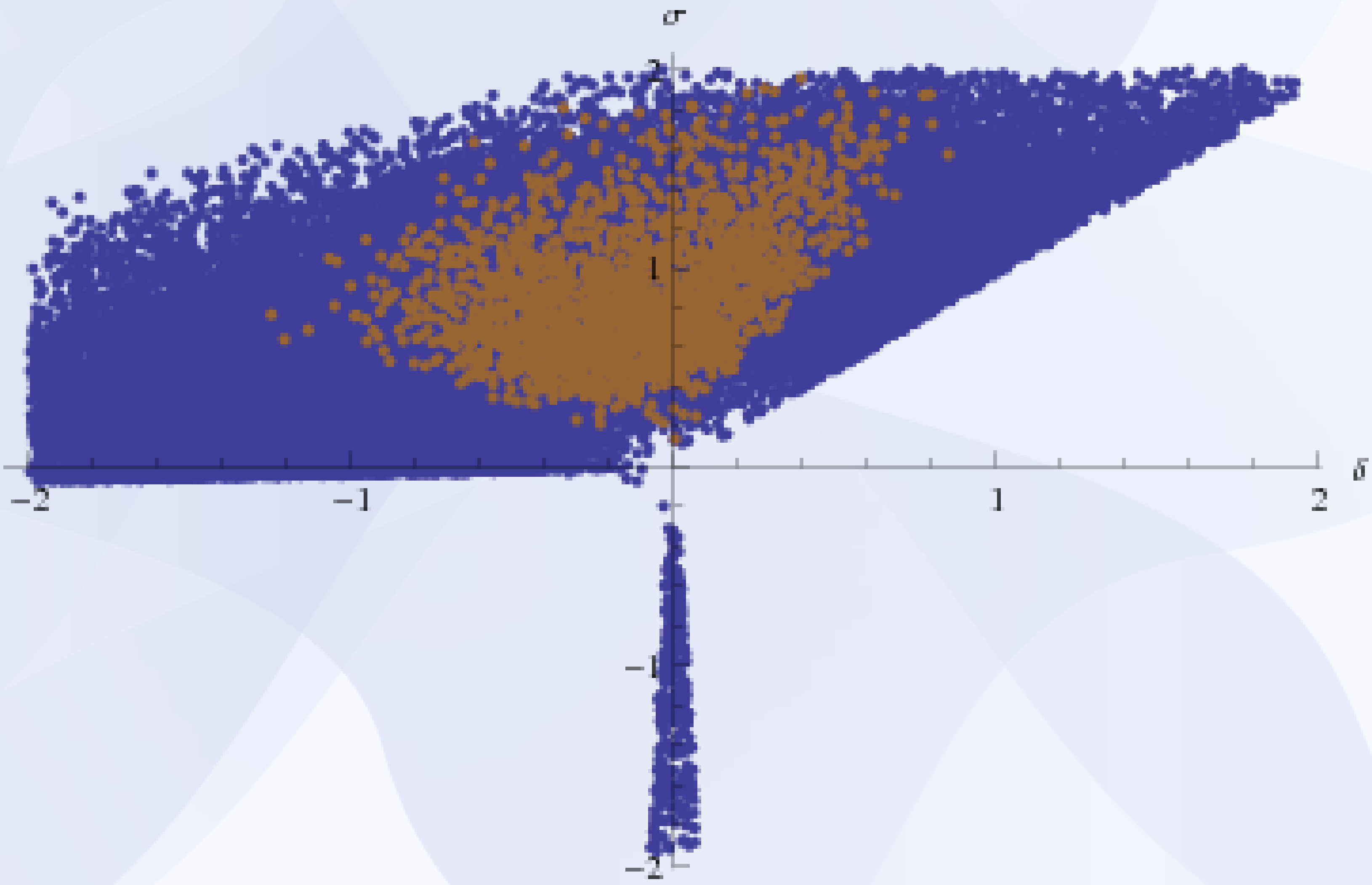
Mass Differences:

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

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

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

Neutrino Mixing (U(3)-O(3)): Δm^2



Neutrino Mixing: θ_{12}

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

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

Neutrino Mixing: θ_{12}

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

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

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)	$0.033 - 0.085$

Schwingenheuer, 1210.7432

U(3)-U(2): Slepton Mixing

$$\mathcal{R}_L^{\tilde{\nu}\dagger} = \begin{pmatrix} c_e & s_e e^{-i\alpha_e} & -s_e s_L^e e^{i\gamma} e^{-i\alpha_e} \\ -s_e e^{i\alpha_e} & c_e & -c_e s_L^e e^{i\gamma} \\ 0 & s_L^e e^{-i\gamma} & 1 \end{pmatrix}$$

$$\begin{aligned} \mathcal{R}_{13}^{\tilde{\nu}} &= -s_e\, s_L^e\, e^{i(\gamma-\alpha_e)} \\ \mathcal{R}_{23}^{\tilde{\nu}} &= -c_e\, s_L^e\, e^{i\gamma} \\ \mathcal{R}_{33}^{\tilde{\nu}} &= 1 \end{aligned}$$

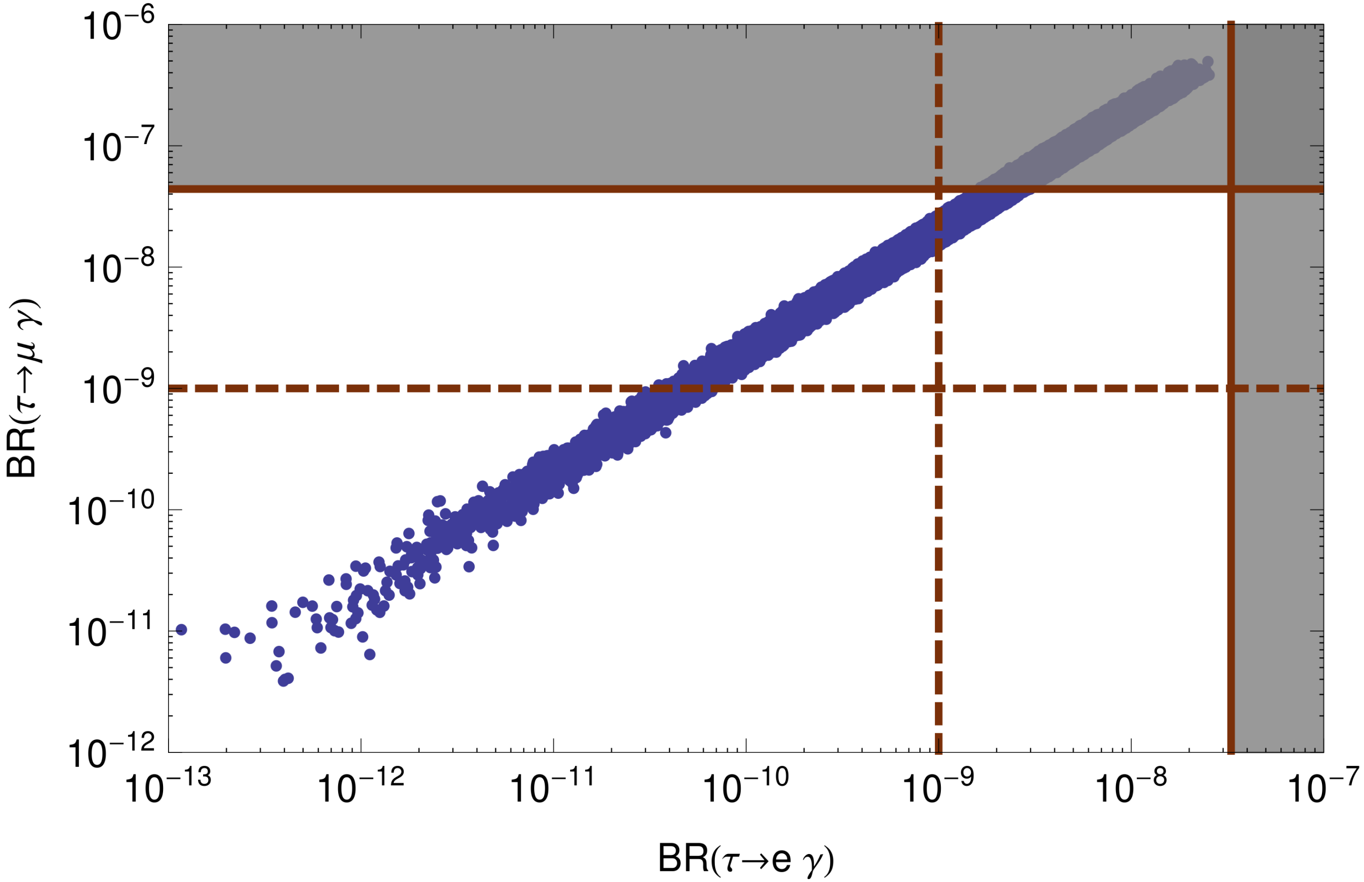
U(3)-U(2): LFV

$$\left(\frac{\mathcal{B}(\mu \to e\gamma)}{\mathcal{B}(\tau \to \mu\gamma)}\right)^{\chi^\pm} \approx \left(\frac{m_\mu}{m_\tau}\right)^5 \frac{\Gamma_\tau}{\Gamma_\mu} \left|\frac{\mathcal{R}^{\tilde{\nu}}_{23}\mathcal{R}^{\tilde{\nu}*}_{13}}{\mathcal{R}^{\tilde{\nu}}_{33}\mathcal{R}^{\tilde{\nu}*}_{23}}\right|^2$$

$$\approx 5.1\, s_e^2\, {s_L^e}^2$$

$$\left(\frac{\mathcal{B}(\tau \to e\gamma)}{\mathcal{B}(\tau \to \mu\gamma)}\right)^{\chi^\pm} \approx \left|\frac{\mathcal{R}^{\tilde{\nu}}_{33}\mathcal{R}^{\tilde{\nu}*}_{13}}{\mathcal{R}^{\tilde{\nu}}_{33}\mathcal{R}^{\tilde{\nu}*}_{23}}\right|^2 \approx s_e^2$$

Lepton Flavour Violation



$\tan\beta = 10$
$M_2 = 500$ GeV
$M_1 = 250$ GeV
$\mu = 600$ GeV

$$\tilde{m}_{\rm light} \lesssim 1 \text{ TeV}$$

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, charged lepton mixing becomes negligible.

Neutrino Sector

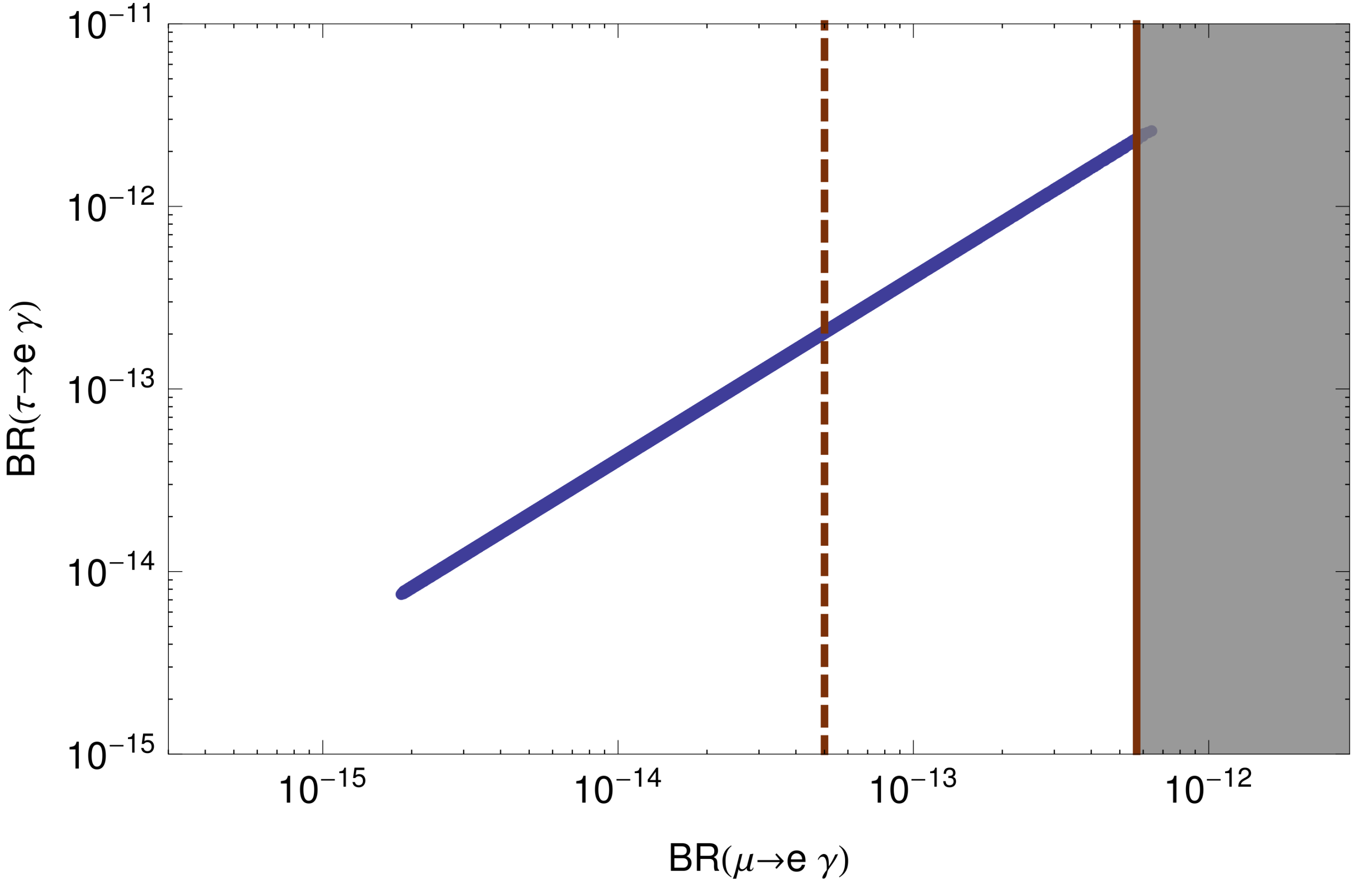
- Requirement from NH:

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

- Our framework, when $\lambda_L = 0$, $\varepsilon_{ij} = 0$:

$$M_\nu^2 \to \begin{pmatrix} 0 & 0 & 0 \\ 0 & s_e^2 & -s_e c_e \\ 0 & -s_e c_e & c_e^2 \end{pmatrix} \epsilon^4 \kappa_\nu^2$$

Lepton Flavour Violation



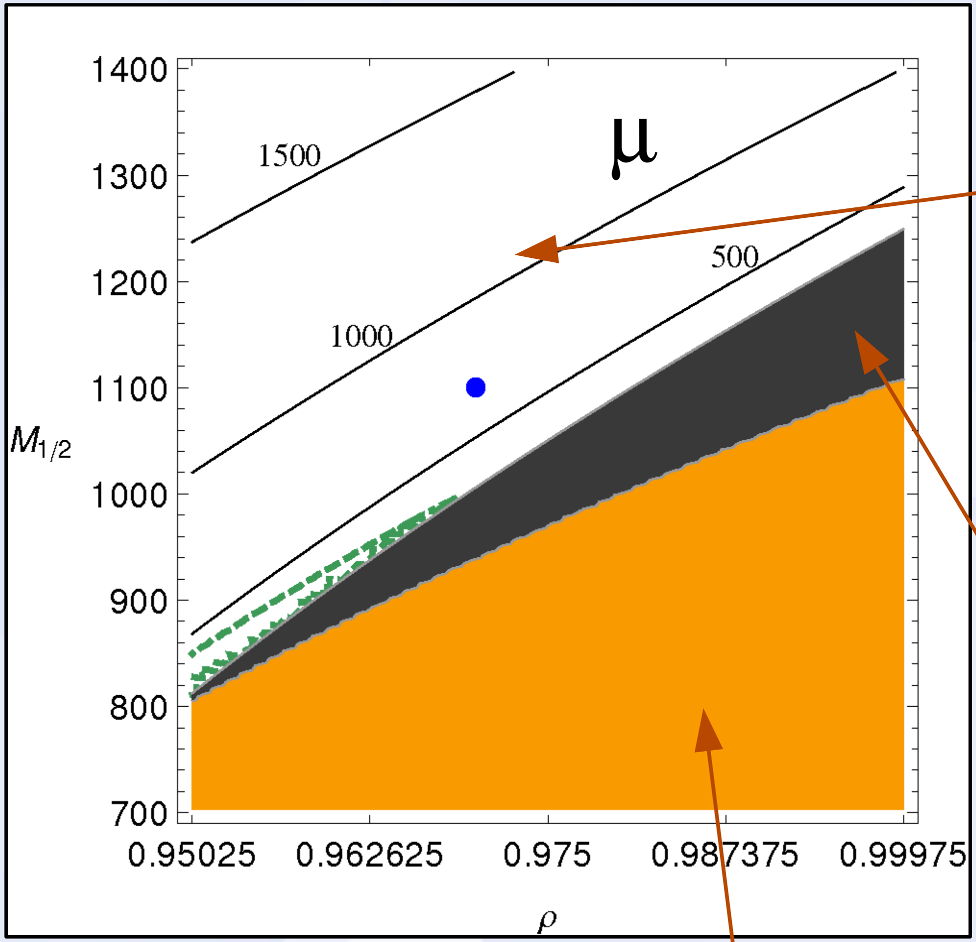
tanβ = 10
M_2 = 500 GeV
M_1 = 250 GeV
μ = 600 GeV

$$\tilde{m}_{\rm light} \lesssim 1 \text{ TeV}$$

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?

Benchmark 2



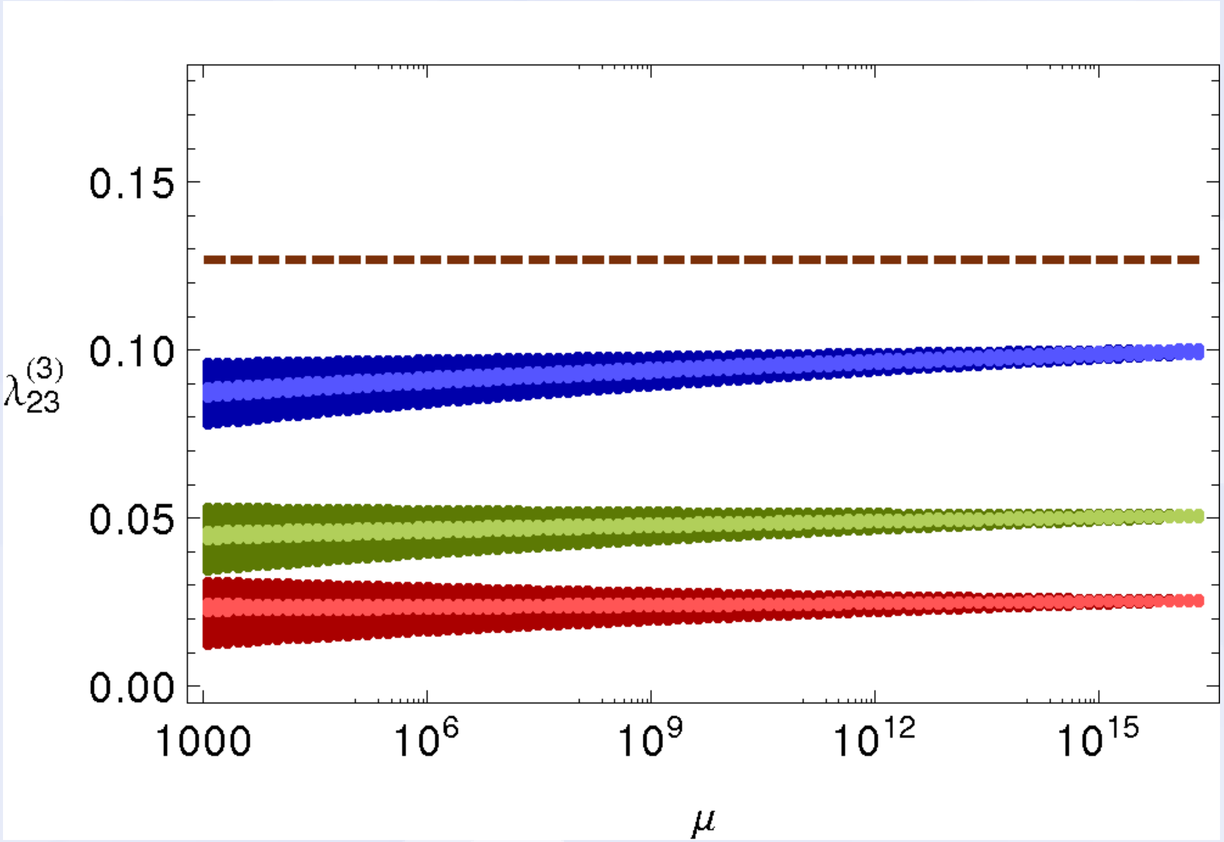
Higgs OK

No EWSB

Flavour not OK...

Tachyons

Mixing: Benchmark 2



Even less modifications

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

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

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

Structure

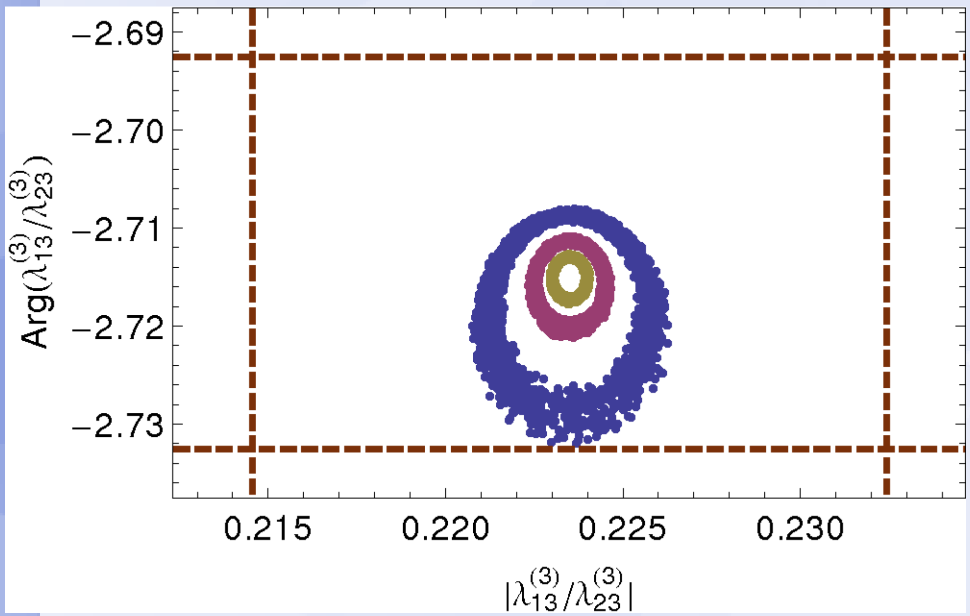
Main contribution to ΔF = 2: (LL)^2

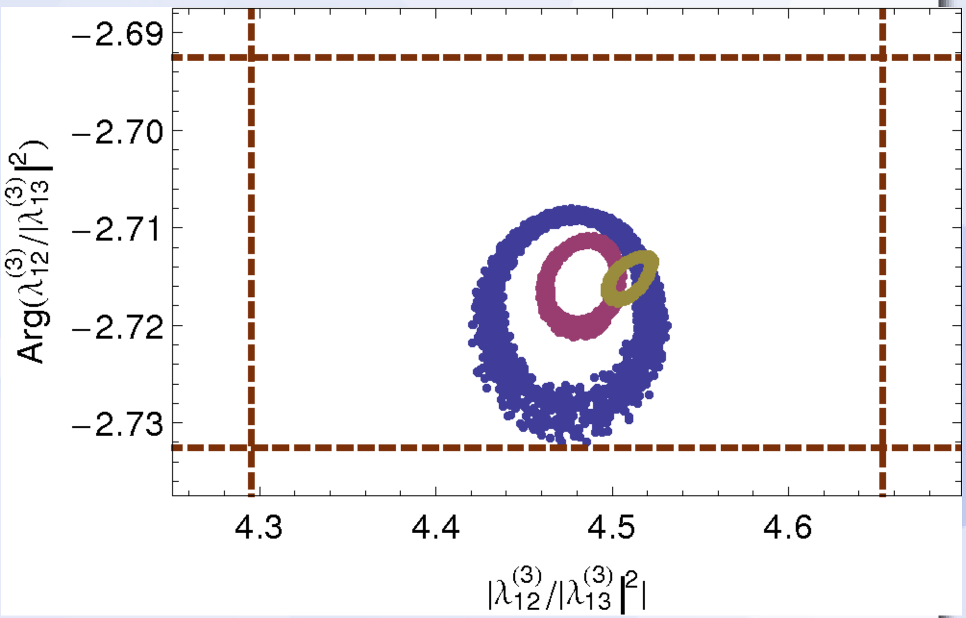
$$\lambda^{(a)}_{i\neq j} = (W^d_L)_{ia}(W^d_L)^*_{ja}$$

$$\lambda^{(3)}_{12} = c_d\, s^2_L\, \kappa^* \qquad \lambda^{(3)}_{13} = -s_L \kappa^* e^{i\gamma_L} \qquad \lambda^{(3)}_{23} = -c_d s_L e^{i\gamma_L}$$

$$\frac{\lambda^{(3)}_{13}}{\lambda^{(3)}_{23}} = \frac{\kappa^*}{c_d} \qquad \frac{\lambda^{(3)}_{12}}{|\lambda^{(3)}_{13}|^2} = \frac{c_d}{\kappa}$$

Structure: Benchmark 2





Structure is very stable.

More freedom in choice of O(1)s.

Dynamical Two-Site Model

$$G_1^{SM} \otimes G_2^{SM}$$

Third generation
Higgs

First + second generation

↓

U(2) symmetry

Dynamical Two-Site Model

Chiral field	$G_1^{\rm SM}$	$G_2^{\rm SM}$
χ_h	$(3, 2, \frac{1}{6})$	$(\bar{3}, 2, -\frac{1}{6})$
$\tilde{\chi}_h$	$(\bar{3}, 2, -\frac{1}{6})$	$(3, 2, \frac{1}{6})$
χ_ℓ	$(1, 2, \frac{1}{2})$	$(1, 2, -\frac{1}{2})$
$\tilde{\chi}_\ell$	$(1, 2, -\frac{1}{2})$	$(1, 2, \frac{1}{2})$

$$Y_u,\, Y_d \sim \begin{pmatrix} \epsilon_\ell & \epsilon_\ell & \epsilon_h \\ \epsilon_\ell & \epsilon_\ell & \epsilon_h \\ \epsilon_\ell\epsilon_h & \epsilon_\ell\epsilon_h & 1 \end{pmatrix}$$