# Flavour beyond the Standard Model

Oscar Vives

**Flavour Physics & SuperB.**

Benasque, *19–21/01/2011*

# The flavour problem

# THE FLAVOUR PROBLEM

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*The universe is simple;*
*it is the explanation that is complex ...*

**Woody Allen**

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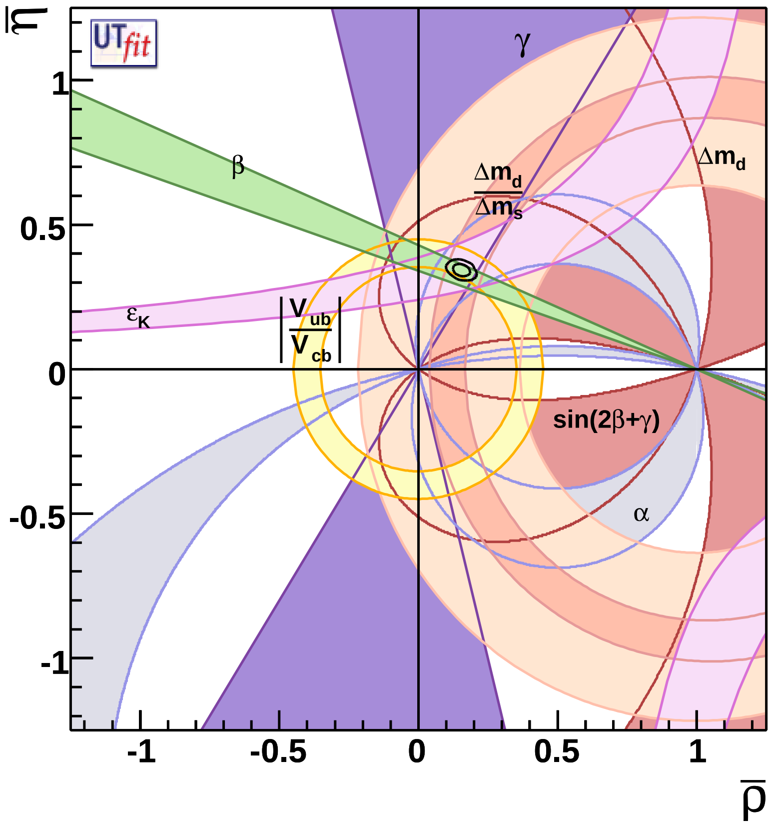

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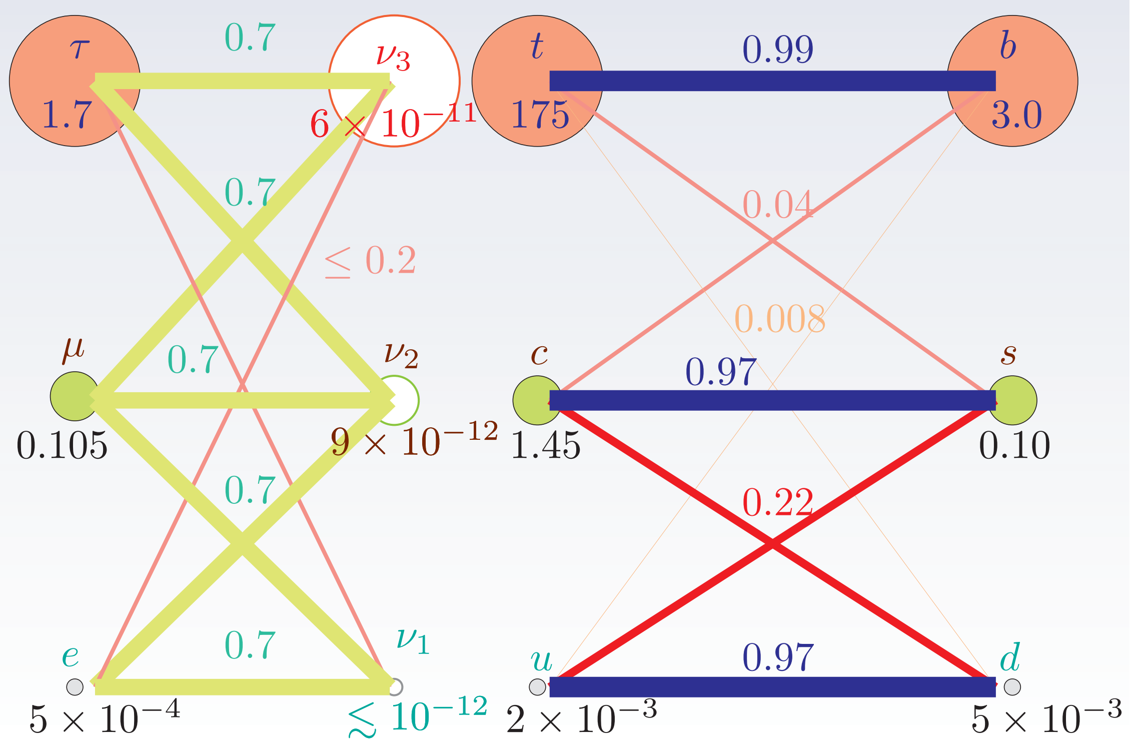

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$$\Downarrow$$

Still, lots of work needed!!

## Standard Model

All Observed *Flavour Changing Neutral Currents* can be accomodated in Yukawa couplings:

$$\mathcal{L}_Y \;=\; H\,\bar{Q}_i\,Y^d_{ij}\,d_j \;+\; H^*\,\bar{Q}_i\,Y^u_{ij}\,u_j$$

Only masses and CKM mixings, $V_{\rm CKM}$, observable...

$\Longrightarrow$ a) what is the origin of the Yukawa structures??

b) why is there a CP-violating phase in CKM??

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**New flavour observables needed !!**

## New Physics

New flavour structures generically present $\Longrightarrow$ measure of new observables provides new information on flavour origin...

## SUSY Flavour (and CP) problems

Soft masses fixed by $m_{3/2}$. $O(m_{3/2})$ elements in soft matrices.

$\Rightarrow$ **Severe FCNC problem !!!**

CP broken, we can expect all complex paramaters have $O(1)$ phases. $\Rightarrow$ **Too large EDMs !!!**

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SM Flavour and CP

Fermion masses fixed by $M_W$. If $O(1)$ elements in Yukawa matrices and $O(1)$ phases

$\Longrightarrow$ **Impossible reproduce masses, mixings and CP observables !!!**

# Flavoured New Physics

## 2 Higgs Doublet Models

- Four possible Yukawa matrices. $\Longrightarrow$ Large FCNC.
- Discrete symmetry (type I, type II) to forbid FCNC. $\Longrightarrow$ No connection with structure of flavour matrices.
- Alignment of Yukawa matrices $\Longrightarrow$ *ad hoc* requirement, no connection with struct. of flavour matrices.
- Flavour symmetry fixes Yukawa structures $\Longrightarrow$ Yukawa couplings to the same quark quasi-aligned.

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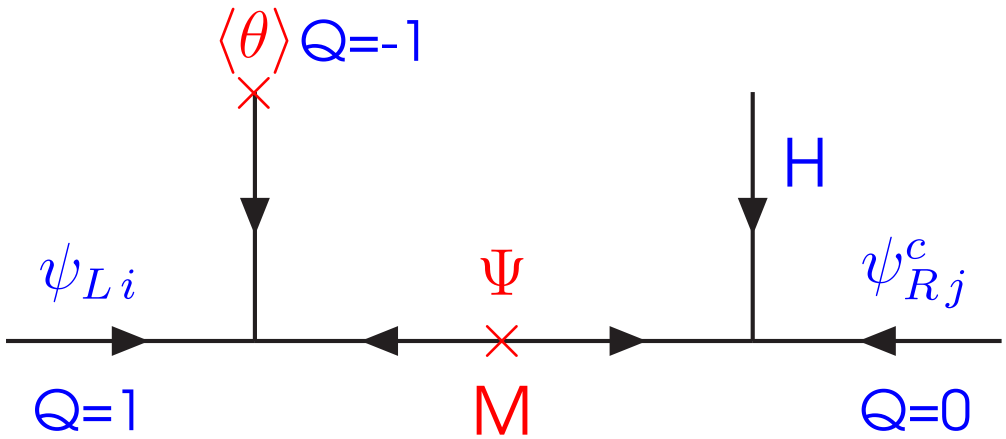
## Supersymmetry

- Five sfermion mass matrices and Three trilinear matrices $\Rightarrow$ Lots of new observables to understand flavour.

# Flavour symmetries in SUSY

- Very different elements in Yukawas: $y_t \simeq 1,\, y_u \simeq 10^{-5}$
- Expect couplings in a "fundamental" theory $\mathcal{O}(1)$
- Small couplings generated at higher order or function of small vevs.
- Froggatt-Nielsen mechanism and flavour symmetry to understand small Yukawa elements. Example: $U(1)_{fl}$




$$\Rightarrow Y_{ij} = \left(\frac{\langle\theta\rangle}{M}\right) \ll 1$$

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$\Downarrow$

**We can relate the structure in Yukawa matrices to the nonuniversality in Soft Breaking masses !!!**

## Symmetric texture

- Non-Abelian flavour symmetries.

$$Y^{d,e} = \begin{pmatrix} 0 & 1.5\ \varepsilon^3 & 0.4\ \varepsilon^3 \\ 1.5\ \varepsilon^3 & \Sigma\ \varepsilon^2 & 1.3\ \Sigma\ \varepsilon^2 \\ 0.4\ \varepsilon^3 & 1.3\ \Sigma\ \varepsilon^2 & 1 \end{pmatrix} y_b$$

- Universal sfermion masses in in unbroken limit:

$$\mathcal{L}_{m^2} = m_0^2 \Phi^\dagger \Phi = m_0^2 \,(\phi_1\ \phi_2\ \phi_3)^* \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}$$

- After symmetry breaking:

$$M^2_{\tilde{D}_R, \tilde{E}_L} \simeq \begin{pmatrix} 1 + \bar{\varepsilon}^3 & \bar{\varepsilon}^3 & 0 \\ \bar{\varepsilon}^3 & 1 + \bar{\varepsilon}^2 & \bar{\varepsilon}^2 \\ 0 & \bar{\varepsilon}^2 & 1 + \bar{\varepsilon} \end{pmatrix} m_0^2$$

## Asymmetric texture

- Abelian flavour symmetries.

$$Y^{d,e} = \begin{pmatrix} \varepsilon^4 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon & 1 & 1 \end{pmatrix} y_b$$

- In principle nonuniversal masses in unbroken symmetry:

$$\mathcal{L}_{m^2} = m_1^2\ \phi_1^* \phi_1 + m_2^2\ \phi_2^* \phi_2 + m_3^2\ \phi_3^* \phi_3$$

- After symmetry breaking:

$$M^2_{\tilde{D}_R, \tilde{E}_L} \simeq \begin{pmatrix} 1 & \bar{\varepsilon} & \bar{\varepsilon} \\ \bar{\varepsilon} & c & b \\ \bar{\varepsilon} & b & a \end{pmatrix} m_0^2$$

# Abelian Flavour symmetry

- "Realistic" model with two Abelian groups $U(1)_1 \times U(1)_2$

- Charges under $(U(1)_1, U(1)_2)$:

$Q_1 \sim (0,1)$, $Q_2 \sim (1,0)$, $Q_3 \sim (0,0)$, $\phi_1 \sim (-1,0)$ with $\langle\phi_1\rangle/M = \lambda_c^2$

$d_1^c \sim (3,-1)$, $d_2^c \sim (1,0)$, $d_3^c \sim (1,0)$, (flavons)

$u_1^c \sim (0,1)$, $u_2^c \sim (-1,1)$, $u_3^c \sim (0,0)$ $\phi_2 \sim (0,-1)$ with $\langle\phi_2\rangle/M = \lambda_c^3$

- Yukawa couplings proportional to: $Y_{ij} = \left(\frac{\langle\phi_1\rangle}{M}\right)^{(q_1^i + q_1^j)} \left(\frac{\langle\phi_2\rangle}{M}\right)^{(q_2^i + q_2^j)}$

$$M^{d,e} = \langle H_1\rangle\, \lambda^2 \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ 0 & \lambda^2 & \lambda^2 \\ 0 & 1 & 1 \end{pmatrix}, \qquad M^u = \langle H_2\rangle \begin{pmatrix} \lambda^6 & 0 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & 0 & 1 \end{pmatrix}.$$

- Soft mass coupling $\phi_i^\dagger \phi_i$ invariant under all symmetries

$\Longrightarrow$ flavour diagonal soft masses allowed by flavour symmetry

- Diagonal masses required to be equal by phenomenology

- After symmetry breaking offdiagonal entries proportional to flavon vevs

$$M_{ij}^2 = m_0^2 \left(\frac{\langle\phi_1\rangle}{M}\right)^{|q_1^i - q_1^j|} \left(\frac{\langle\phi_2\rangle}{M}\right)^{|q_2^i - q_2^j|}$$

$$M^2_{\tilde{D}_R,\tilde{E}_L} \sim m_0^2 \begin{pmatrix} 1 & \lambda^7 & \lambda^7 \\ \lambda^7 & 1 & 1 \\ \lambda^7 & 1 & 1 \end{pmatrix}, \qquad M^2_{\tilde{U}_R} \sim m_0^2 \begin{pmatrix} 1 & \lambda^2 & \lambda^3 \\ \lambda^2 & 1 & \lambda^5 \\ \lambda^3 & \lambda^5 & 1 \end{pmatrix},$$

$$M^2_{\tilde{D}_L} = M^2_{\tilde{U}_L} \sim m_0^2 \begin{pmatrix} 1 & \lambda^5 & \lambda^3 \\ \lambda^5 & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}.$$

# $SU(3)$ Flavour model

- $Q, L, d^c, u^c, e^c \sim \mathbf{3}$; flavon fields: $\theta_3, \theta_{23} \sim \overline{\mathbf{3}}, \overline{\theta}_3, \overline{\theta}_{23} \sim \mathbf{3}$
- Family Symmetry breaking: $SU(3) \xrightarrow{\langle\theta_3\rangle} SU(2) \xrightarrow{\langle\theta_{23}\rangle} \emptyset$

$$\langle\theta_3\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} a_3^u & 0 \\ 0 & a_3^d\ e^{i\chi} \end{pmatrix}, \langle\bar{\theta}_3\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} a_3^u\ e^{i\alpha_u} & 0 \\ 0 & a_3^d\ e^{i\alpha_d} \end{pmatrix},$$

$$\langle\theta_{23}\rangle = \begin{pmatrix} 0 \\ b_{23} \\ b_{23}\ e^{i\beta_3} \end{pmatrix}, \quad \langle\bar{\theta}_{23}\rangle = \begin{pmatrix} 0 \\ b_{23}\ e^{i\beta_2'} \\ b_{23}\ e^{i(\beta_2'-\beta_3)} \end{pmatrix}.$$

with $\left(\frac{a_3}{M}\right) \sim \mathcal{O}(1), \left(\frac{b}{M_u}\right) \simeq \left(\frac{b}{M_d}\right)^2 = \varepsilon \sim 0.05$

- Yukawa superpotential:

$$W_Y = H\psi_i\psi_j^c\left[\theta_3^i\theta_3^j + \theta_{23}^i\theta_{23}^j\left(\theta_3\overline{\theta_3}\right) + \epsilon^{ikl}\overline{\theta}_{23,k}\overline{\theta}_{3,l}\theta_{23}^j\left(\theta_{23}\overline{\theta_3}\right)\right]$$

$$Y^f = \begin{pmatrix} 0 & a\,\varepsilon^3 e^{i\delta_f} & b\,\varepsilon^3 e^{i(\delta_f+\beta_3)} \\ a\,\varepsilon^3 e^{i\delta_f} & \varepsilon^2 & c\,\varepsilon^2 e^{i\beta_3} \\ b\,\varepsilon^3 e^{i(\delta_f+\beta_3)} & c\,\varepsilon^2 e^{i\beta_3} & 1 \end{pmatrix} \frac{|a_3|^2}{M^2}$$

- Soft mass coupling $\Phi^\dagger\Phi$ invariant $\Rightarrow$ common soft mass for the triplet

- Universality guaranteed in the exact symmetry limit.

- After symmetry breaking offdiagonal entries proportional to (complex) flavon vevs

$$M^2_{ij} = m_0^2 \Big(\delta^{ij} + \frac{1}{M^2}[\theta_3^{i\dagger}\theta_3^j + \overline{\theta}_3^{i\dagger}\overline{\theta}_3^j + \theta_{23}^{i\dagger}\theta_{23}^j + \overline{\theta}_{23}^{i\dagger}\overline{\theta}_{23}^j] + \frac{1}{M^4}[(\epsilon^{ikl}\overline{\theta}_{3,k}\overline{\theta}_{23,l})^\dagger(\epsilon^{jmn}\overline{\theta}_{3,m}\overline{\theta}_{23,n}) + (\epsilon_{ikl}\theta_3^k\theta_{23}^l)^\dagger(\epsilon_{jmn}\theta_3^m\theta_{23}^n)] + \ldots\Big)$$

$$M^2_{\tilde{F}_R}(M^2_{\tilde{F}_L}) \propto \begin{pmatrix} 1+\bar{\varepsilon}^3 & \frac{\bar{\varepsilon}^3}{3} & \bar{\varepsilon}^3 e^{-i(\beta_3-\chi)} \\ \frac{\bar{\varepsilon}^3}{3} & 1+\bar{\varepsilon}^2 & \bar{\varepsilon}^2 e^{-i(\beta_3-\chi)} \\ \bar{\varepsilon}^3 e^{-i(\beta_3-\chi)} & \bar{\varepsilon}^2 e^{-i(\beta_3-\chi)} & 1+\bar{\varepsilon} \end{pmatrix} m_0^2$$

$$M^2_{\tilde{D}_R}{}^{\rm SCKM} \simeq 6\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1+\bar{\varepsilon}^3 & \bar{\varepsilon}^3 & \bar{\varepsilon}^3 \\ \bar{\varepsilon}^3 & 1+\bar{\varepsilon}^2 & \bar{\varepsilon}^2 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & 1+\bar{\varepsilon} \end{pmatrix} m_0^2$$

(with $\bar{\varepsilon} \simeq 0.15$,$\varepsilon \simeq 0.05$ )

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$$M^2_{\tilde{D}_R}{}^{\mathrm{SCKM}} \simeq 6\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1 & 0.003 & 0.003 \\ 0.003 & 1 & 0.02 \\ 0.003 & 0.02 & 1 \end{pmatrix} m_0^2$$

(with $\bar{\varepsilon} \simeq 0.15$, $\varepsilon \simeq 0.05$ )

## At $M_W$ in the SCKM basis:

$$M^2_{\tilde{D}_L} \simeq 6\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1+\varepsilon^3 & \varepsilon^2\bar{\varepsilon} & \varepsilon^2\bar{\varepsilon} + c_{\rm run}\ \bar{\varepsilon}^3 \\ \varepsilon^2\bar{\varepsilon} & 1+\varepsilon^2 & \varepsilon^2 + c_{\rm run}\ \bar{\varepsilon}^2 \\ \varepsilon^2\bar{\varepsilon} + c_{\rm run}\ \bar{\varepsilon}^3 & \varepsilon^2 + c_{\rm run}\ \bar{\varepsilon}^2 & 1+\bar{\varepsilon} \end{pmatrix} m_0^2$$

$$M^2_{\tilde{E}_R} \simeq 0.15\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1+\bar{\varepsilon}^3 & \frac{\bar{\varepsilon}^3}{3} & \bar{\varepsilon}^3 \\ \frac{\bar{\varepsilon}^3}{3} & 1+\bar{\varepsilon}^2 & \bar{\varepsilon}^2 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & 1+\bar{\varepsilon} \end{pmatrix} m_0^2$$

$$M^2_{\tilde{E}_L} \simeq 0.5\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1+\varepsilon^3 & \frac{\varepsilon^2\bar{\varepsilon}}{3} & \varepsilon^2\bar{\varepsilon} + c_{\rm run}\ \bar{\varepsilon}^3 \\ \frac{\varepsilon^2\bar{\varepsilon}}{3} & 1+\varepsilon^2 & \varepsilon^2 + 3\ c_{\rm run}\ \bar{\varepsilon}^2 \\ \varepsilon^2\bar{\varepsilon} + c_{\rm run}\ \bar{\varepsilon}^3 & \varepsilon^2 + 3\ c_{\rm run}\ \bar{\varepsilon}^2 & 1+\varepsilon \end{pmatrix} m_0^2$$

## At $M_W$ in the SCKM basis:

$$M^2_{\tilde{D}_L} \simeq 6\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1 & 4\times 10^{-4} & 7\times 10^{-4} \\ 4\times 10^{-4} & 1 & 4\times 10^{-3} \\ 7\times 10^{-4} & 4\times 10^{-3} & 1 \end{pmatrix} m_0^2$$

$$M^2_{\tilde{E}_R} \simeq 0.15\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1 & 0.001 & 0.003 \\ 0.001 & 1 & 0.02 \\ 0.003 & 0.02 & 1 \end{pmatrix} m_0^2$$

$$M^2_{\tilde{E}_L} \simeq 0.5\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1 & 1\times 10^{-4} & 7\times 10^{-4} \\ 1\times 10^{-4} & 1 & 1\times 10^{-2} \\ 7\times 10^{-4} & 1\times 10^{-2} & 1 \end{pmatrix} m_0^2$$

# Lepton Flavour violation

Off-diagonal entries in slepton masses generate *LFV* processes:

$$\mathrm{BR}(l_i \to l_j \gamma) \;\simeq\; \frac{3\pi\alpha_2^3}{G_F^2} \left| \frac{(\delta^e_{\mathrm{L}})_{ij}}{m^2_{\tilde{l}}} \; \frac{\mu M_2 \tan\beta}{(M_2^2 - \mu^2)} \; F_{2L}(a_2, b) \right|^2$$

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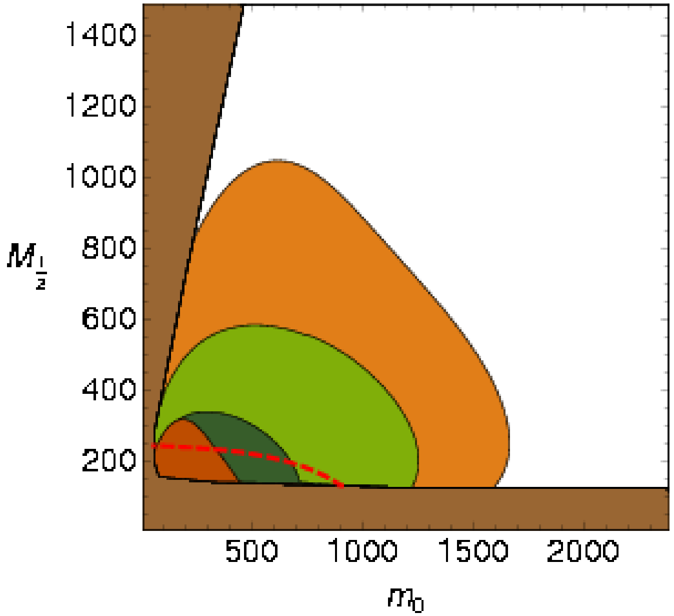
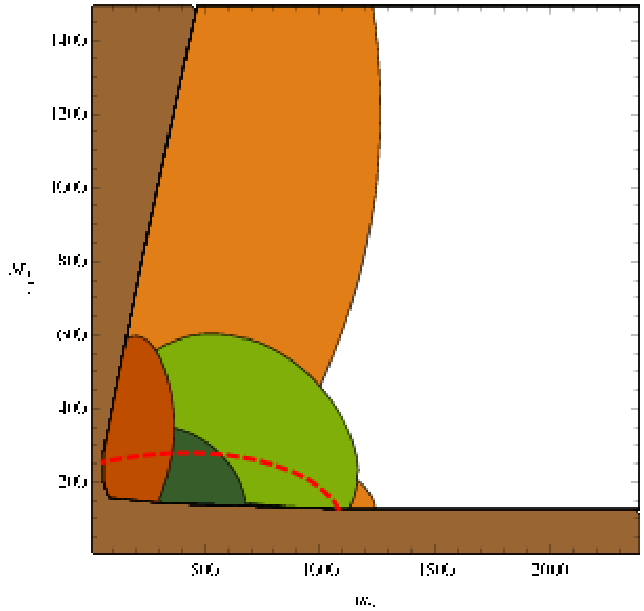
$\tan\beta = 10,\ A_0 = 0$




$\tan\beta = 10,\ A_0 = m_0$



Brown(light):Present (fut.) $\mu \to e\gamma$, Green (light): Present (fut.) $\tau \to \mu\gamma$.

# FLAVOURED EDMS

– SUSY EDMs in presence of flavour-blind phases ($\varphi_\mu, \varphi_A$) directly proportional to lepton masses,

$$d^l_{\chi^+} \simeq \frac{-\alpha\, e\, m_l \tan\beta}{4\pi \sin^2\theta_W} \frac{\text{Im}[M_2\ \mu]}{m^2_{\tilde{\nu}_e}} \frac{A(r_1) - A(r_2)}{m^2_{\chi_1^+} - m^2_{\chi_2^+}}$$

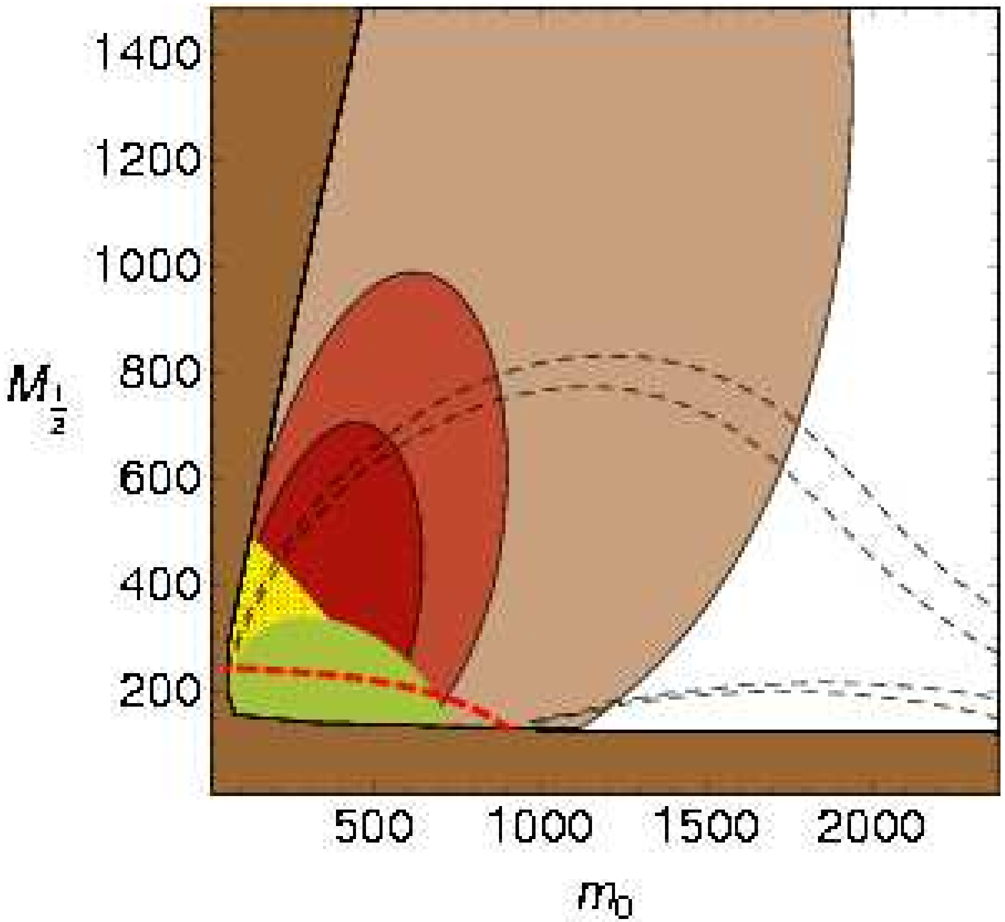
– Still, if $\varphi_\mu, \varphi_A = 0$, contributions to EDMs from offdiagonal elements in sfermion masses:

$$d_e \propto (\delta^e_{LL})_{1i}(\delta^e_{LR})_{i1}\, f_1 + (\delta^e_{LR})_{1i}(\delta^e_{RR})_{i1}\, f_2 + (\delta^e_{LL})_{1i}(\delta^e_{LR})_{ij}(\delta^e_{RR})_{j1} f_3$$

– In 2HdM $d_l$ proportional to three masses and mixings

$$d_l \propto m_l\, m_i^2\, |K_{li}|^2\, f$$

$\Rightarrow$ Three leptonic EDMs must be measured independently to discriminate the source!!!




From light to dark: $d_e = 1 \times 10^{-30}, 5 \times 10^{-29}, 1 \times 10^{-29}$ e cm

# Conclusions

Flavour symmetries solve the CP and flavour problems both in New Physics (SUSY) and in the SM!

$\Downarrow$

- New flavour structures will provide valuable information on the origin of flavour
- LFV processes ($\mu \to e\gamma$) close to present exp. limits.
- Ratios of leptonic EDMs depend on flavour structures and new physics model.
- Sizeable contribution in the Kaon sector natural.
- LFV and EDMs can explore large areas of flavour MSSM in near future.