Lepton Flavour Violation after LHC

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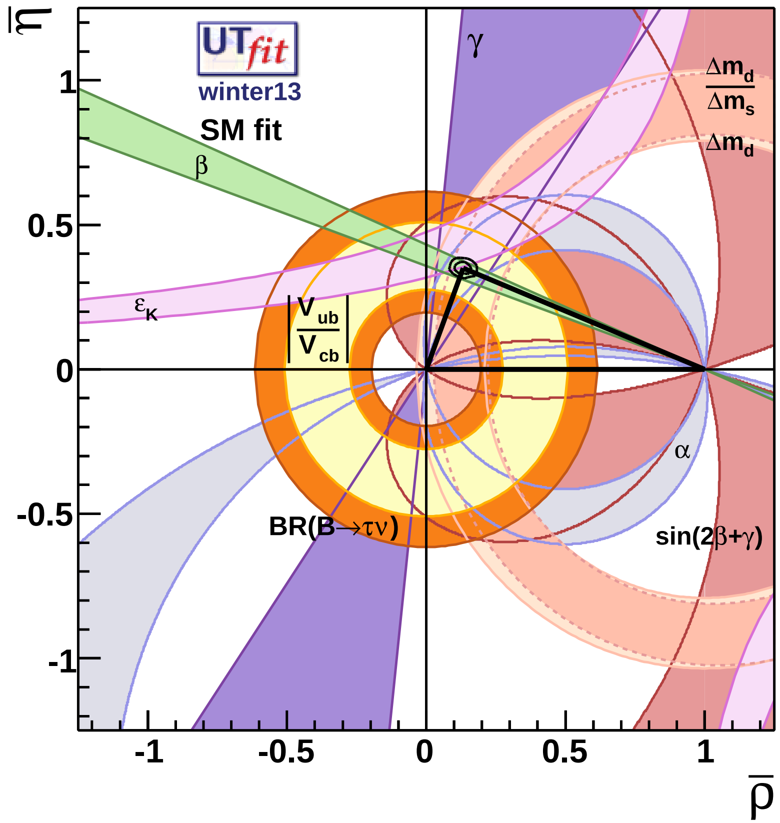

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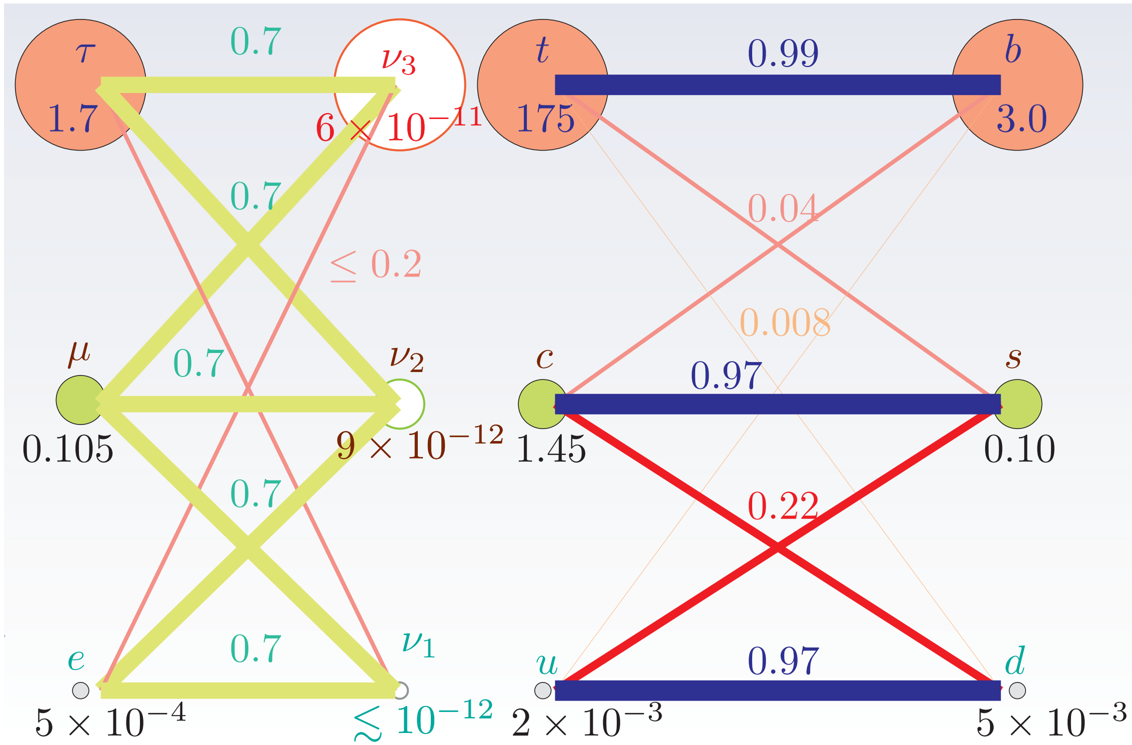

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$$\Downarrow$$

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 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 !!!**

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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

Ex. 1 **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.
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Ex. 2 **Supersymmetry**

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

Complementarity LHC-Flavour

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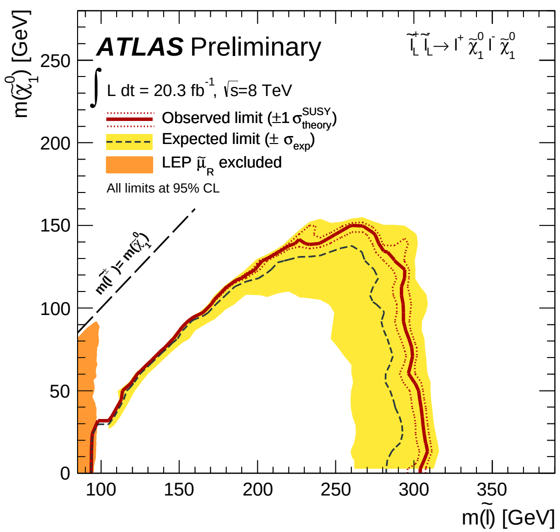
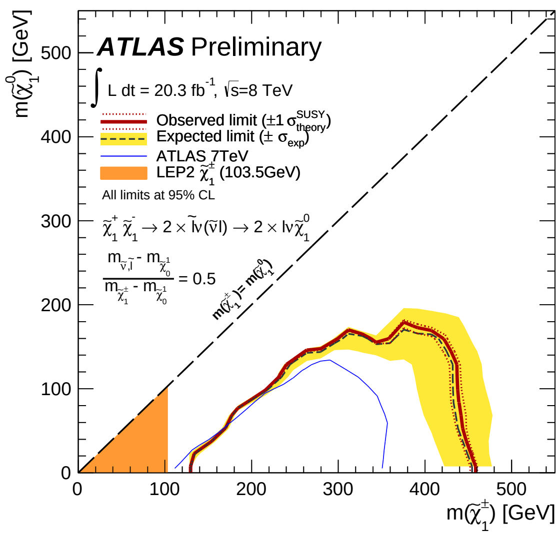
EW production: Direct limits on chargino and slepton masses $\longrightarrow$ EW production chargino/neutralino and 1st, 2nd gen. slepton. $M \gtrsim 300$ GeV. No signif. bounds on 3rd gen.

ATLAS-CONF-2013-049, CMS PAS SUS-12-022





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LHC–Flavour fact. Feedback:

1. LHC measures squark, gluino, neutralino mass scale
2. With this information Flavour factories determine $\tan\beta$ and mixings
3. These parameters help reanalyze LHC data
4. …

Experimental Results

mode	BR. upper limit (90%)	Experiment	Year
$\mu^+ \to e\gamma$	5.7×10^{-13}	MEG	2013
$\mu^+ \to e^+e^+e^-$	1.0×10^{-12}	SINDRUM I	1988
$\mu^-\,\mathrm{Ti} \to e^-\,\mathrm{Ti}$	5.7×10^{-13}	SINDRUM II	1998
$\mu^-\,\mathrm{Au} \to e^-\,\mathrm{Au}$	7×10^{-13}	SINDRUM II	2006
$\tau \to \mu\,\gamma$	4.4×10^{-8}	BaBar	2011
$\tau \to e\,\gamma$	3.3×10^{-8}	BaBar	2011
$\tau \to \mu\,\mu\,\mu$	4.0×10^{-8}	Belle	2011
$\tau \to \mu\,\rho$	1.2×10^{-8}	Belle	2012

Future prospects:

MEG $\Rightarrow \mathrm{B}(\mu \to e\gamma) < 5 \times 10^{-14}$, Mu3e $\Rightarrow \mathrm{B}(\mu \to eee) < O(10^{-16})$,
mu2e $\Rightarrow \mu \to e$ conv. $< O(10^{-16})$, LHCb $\Rightarrow \mathrm{B}(\tau \to \mu \ldots) < O(10^{-9})$

μ PHYSICS

- Very sensitive experiments in muon, $\Rightarrow$ Explore small couplings. . . or large NP scales for $O(1)$ couplings.

  $\Rightarrow$ LFV decays: $\mu \to e\gamma$, $\mu \to lll$, $\mu - e$ conv. in nuclei.

  $\Rightarrow$ CP violation. μ Electric Dipole Moment

τ PHYSICS

- 3rd generation (Yukawa) couplings larger, $\Rightarrow$ possible sizeable flavour effects.

  $\Rightarrow$ LFV decays: $\tau \to \mu\gamma$, $\tau \to lll$.

  $\Rightarrow$ CP violation. τ Electric Dipole Moment (and also AMM)

MI Constraints

$\tan\beta$ = 10, $m_{\tilde{l}}$ = 400 GeV, M_2 =150 GeV.

δ^l_{12}	$\mu \to e, \gamma$	$\mu \to e, e, e$
LL	2×10^{-4}	2×10^{-3}
RR	-	0.09
LR/RL	3×10^{-6}	3.5×10^{-5}

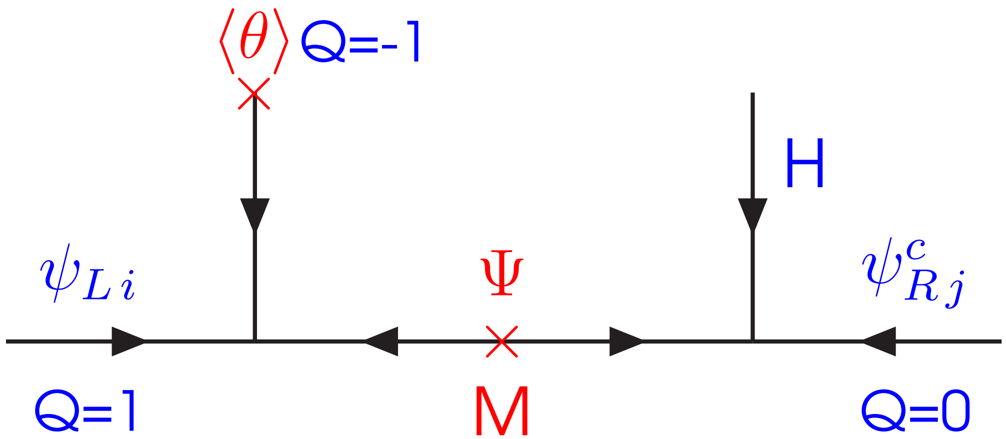
Ciuchini *et al.*, Nucl. Phys. B **783**, 112 (2007)

δ^l_{13}	$\tau \to e\gamma$	δ^l_{23}	$\tau \to \mu\gamma$
LL	0.12	LL	0.12
RR	-	RR	-
LR/RL	0.03	LR/RL	0.03

I. Masina, C.A. Savoy, Nucl. Phys. B **661**, 365 (2003)

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:

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

- 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:

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

Lepton Flavour violation

Off-diagonal entries in slepton masses generate LFV processes:

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

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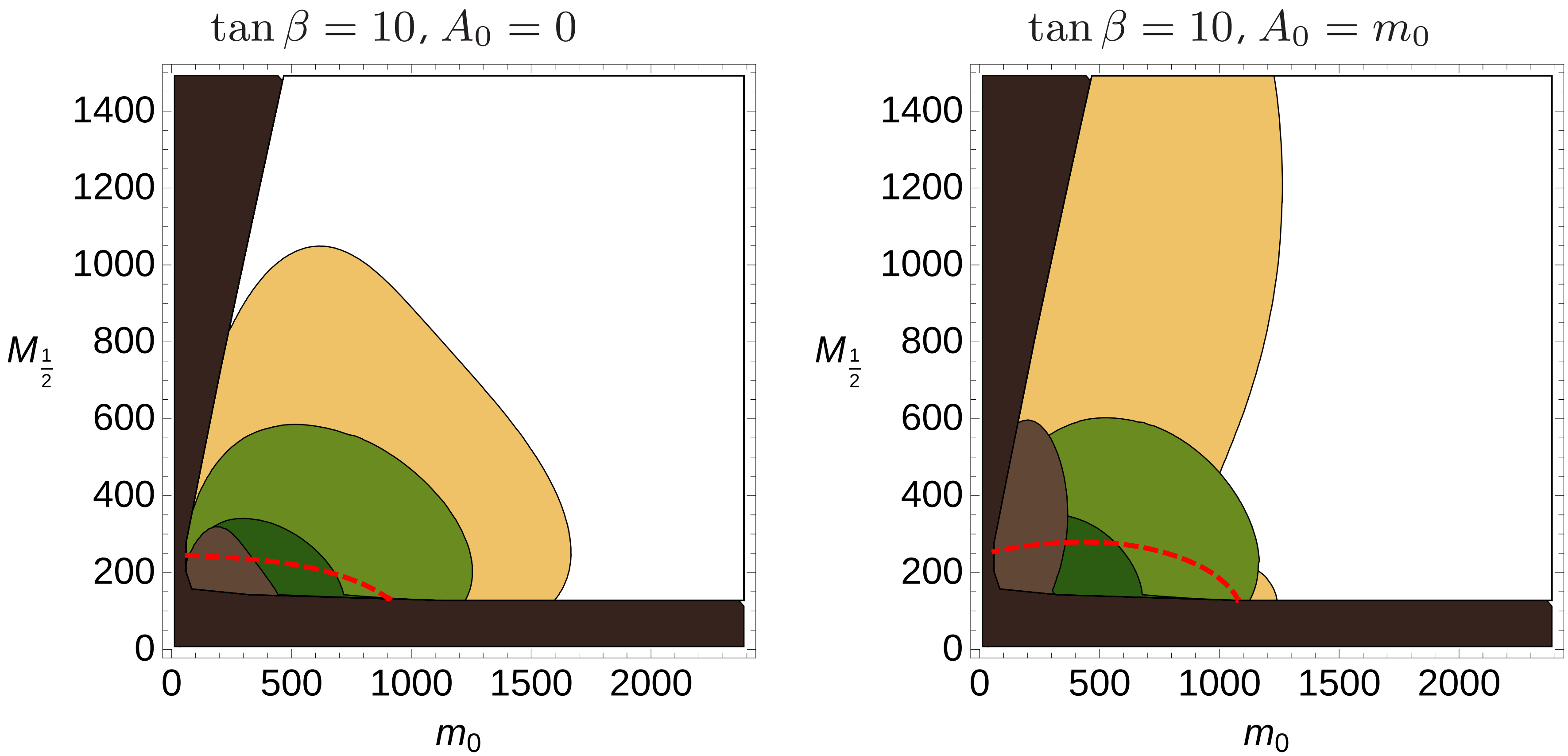
$SU(3)$ Flavour model

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

$$\Rightarrow \quad (\delta^e_{\mathrm{L}})_{12} = \tfrac{1}{3}\varepsilon^2\bar{\varepsilon} \simeq 10^{-4}.$$

$$\Rightarrow \quad (\delta^e_{\mathrm{L}})_{23} = 3y_t\bar{\varepsilon}^2 \simeq 10^{-2}.$$



Brown(light):10^{-11} (10^{-13}) $\mu \to e\gamma$, Green (light): 10^{-8} (10^{-9}) $\tau \to \mu\gamma$.

Flavoured EDMs

– SUSY EDMs in presence of flavour-blind phases (φ_μ, φ_A) directly proportional to lepton masses,

$$d^l_{\chi^+} \simeq \frac{-\alpha\, e\, m_l \tan\beta}{4\pi \sin^2\theta_W} \frac{\mathrm{Im}[M_2\, \mu]}{m^2_{\tilde{\nu}_e}} \frac{A(r_1) - A(r_2)}{m^2_{\chi^+_1} - m^2_{\chi^+_2}}$$

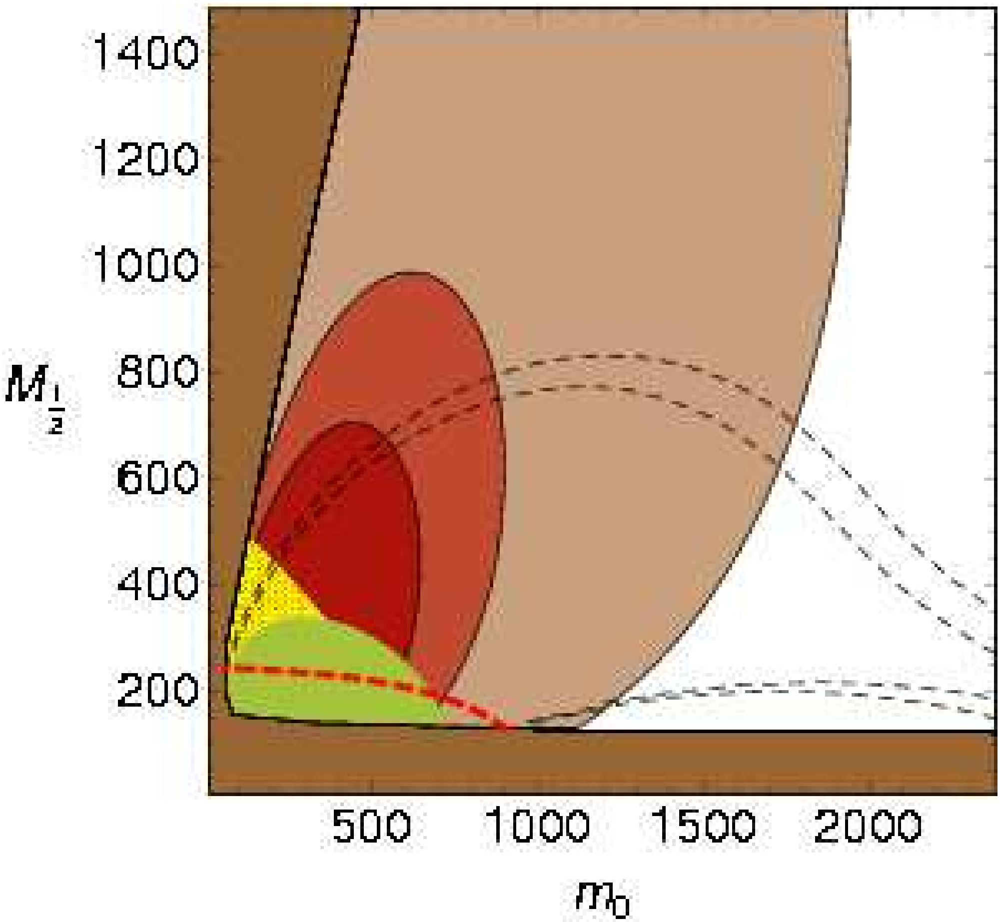
– Still, if $\varphi_\mu, \varphi_A = 0$, contributions to EDMs from offdiagonal elements in sfermion masses:

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

– 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

LFV experiments necessary
to solve the flavour problem.

$\Downarrow$

- New flavour structures provide valuable information on origin of flavour
- Rare muon decays, $\mu \to e\gamma$, very sensitive to LFV entries.
- LFV processes, $\tau \to \mu\gamma$, $\tau \to lll$, constrain 3rd generation couplings.
- Ratios of leptonic EDMs depend on flavour structures and new physics model.
- LFV and EDMs can explore large areas of flavour MSSM.