LFV in SUSY-GUTs and SUSY at LHC

Sudhir Vempati

Centre for High Energy Physics
Indian Institute of Science, Bangalore

CERN Theory Institute

CERN, 9 May 2008

Outline

Outline

LHC will soon hopefully give us glimpses of physics beyond the Standard Electroweak Model...We dont know if it will be SUSY or something else.

Other Probes of SUSY

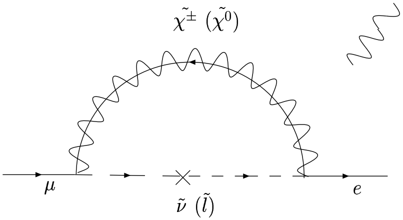
SUSY can also be probed indirectly by radiative effects

- Consider a rare process whose occurence (branching ratio) is highly suppressed in the Standard Model. In the presence of SUSY, the amplitude of this process can enhance by several orders of magnitude due to SUSY particles in the loop which can lead to observable effects in experiments.

Example

For me, a prototype is the process $\mu \rightarrow e + \gamma$.

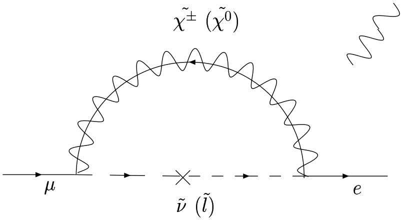
1. In the Standard Model, the branching ratio (BR) = 0.
2. If I add massive neutrinos, it becomes $\sim 10^{-50}$.
3. If I have SUSY, (seesaw + mSUGRA), BR $\sim 10^{-18}$ to10^{-6}.



Example

For me, a prototype is the process $\mu \to e + \gamma$.

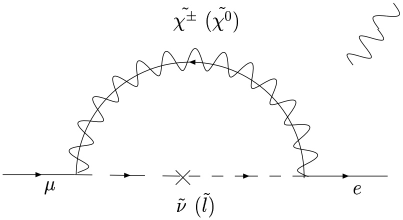
1. In the Standard Model, the branching ratio (BR) = 0.
2. If I add massive neutrinos, it becomes $\sim$ 10^{-50}.
3. If I have SUSY, (seesaw + mSUGRA), BR $\sim 10^{-18}$ to10^{-6}.



Example

For me, a prototype is the process $\mu \to e + \gamma$.

1. In the Standard Model, the branching ratio (BR) = 0.
2. If I add massive neutrinos, it becomes $\sim\ 10^{-50}$.
3. If I have SUSY, (seesaw + mSUGRA), BR $\sim 10^{-18}$ to10^{-6}.



In a Nut Shell...

Process	Present bound	Future sensitivity
BR($\mu \to e\gamma$)	1.2×10^{-11}	$\mathcal{O}(10^{-13} - 10^{-14})$
BR($\mu \to e\,e\,e$)	1.1×10^{-12}	$\mathcal{O}(10^{-13} - 10^{-14})$
CR($\mu \to e$ in Ti)	4.3×10^{-12}	$\mathcal{O}(10^{-18})^1$
BR($\tau \to e\gamma$)	3.1×10^{-7}	$\mathcal{O}(10^{-8}) - \mathcal{O}(10^{-9})^1$
BR($\tau \to e\,e\,e$)	2.7×10^{-7}	$\mathcal{O}(10^{-8}) - \mathcal{O}(10^{-9})^1$
BR($\tau \to \mu\gamma$)	6.8×10^{-8}	$\mathcal{O}(10^{-8}) - \mathcal{O}(10^{-9})^1$
BR($\tau \to \mu\,\mu\,\mu$)	2×10^{-7}	$\mathcal{O}(10^{-8}) - \mathcal{O}(10^{-9})^1$

In a Nut Shell...

If SUSY is the Physics Beyond Standard Electroweak Model

- Grand Unification (gauge coupling unification)
- Dark Matter Candidate (R-parity conservation)

and if

Case I SUSY breaking is flavour blind at the high scale

- Constraints coming from flavour violation through Seesaw mechanism in SO(10) models can become competitive to direct searches at LHC.
- Subtle role of unknown neutrino mixing angle U_{e3}
- Dark Matter regions are Dramatically different.

In a Nut Shell...

Case II SUSY breaking is flavour dependent at high scale

- Constraints coming from relations between leptonic and hadronic flavour violations can lead to significant understanding, SU(5) example.
- Dark Matter ?
- LHC ?

Outline

Seesaw induced flavour violation

Flavour blind SUSY breaking mSUGRA/cMSSM

Here, we will consider universal boundary conditions at the high scale, implying all the SUSY particles carry same SUSY breaking masses and couplings. All flavour violating mass terms, couplings are all set to zero.

$$m^2_{\tilde{f}} = m^2_0; \quad A_{ijk} = A_0; \quad M_i = M_{1/2} \tag{1}$$

To emphasize more, we have

$$m^2_{\tilde{e}\tilde{\mu}} \equiv 0 \tag{2}$$

at high scale where SUSY breaking is mediated to the visible sector. But, these terms are generated at the weak scale due to renormalisation group running in the presence of seesaw mechanism required for neutrino masses and mixing.

Seesaw mechanism in SUSY

The seesaw mechanism can be incorporated in the Minimal Supersymmetric Standard Model in a manner similar to what is done in the Standard Model, by adding right-handed neutrino superfields to the MSSM superpotential:

$$W = h^u_{ij} Q_i u^c_j H_2 + h^d_{ii} Q_i d^c_i H_1 + h^e_{ii} L_i e^c_i H_1 + h^\nu_{ij} L_i \nu^c_j H_2 + M_{R_{ii}} \nu^c_i \nu^c_i + \mu H_1 H_2, \quad (3)$$

$$M_R \gg h^\nu < v_2 >$$

implies

$$\mathcal{M}_\nu = -h^\nu M_R^{-1} h^{\nu\ T} v_2^2, \quad (4)$$

RG effects on soft parameters

We have $m^2_{\tilde{e}\tilde{\mu}} = 0$ at high scale, however at the weak scale :

RGE effects lead to

$$(\Delta^l_{ij})_{\rm LL} \approx -\frac{3m_0^2 + A_0^2}{8\pi^2} \sum_k (h^\nu_{ik} h^{\nu *}_{jk}) \ln \frac{M_X}{M_{R_k}}, \tag{5}$$

Any estimate of the amount of flavour violation at the weak scale would require information about neutrino Yukawa couplings h^ν and also the values of the right handed neutrino masses. Unfortunately, even after using all the information we have about neutrino masses and mixing angles, we cannot deduce this information. This is where GUTs come into the picture.

An SO(10) example

SO(10) models can shed some information on neutrino Yukawa couplings.

$$W_{SO(10)} = h_{ij}^{10} 16_i\, 16_j\, 10 + h_{ij}^{126} 16_i\, 16_j\, 126 + h_{ij}^{120} 16_i\, 16_j\, 120, \qquad (6)$$

Most General Mass matrices

$$M^u = M_{10}^{5} + M_{126}^{5} + M_{120}^{45}, \qquad (7)$$

$$M_{LR}^{\nu} = M_{10}^{5} - 3\, M_{126}^{5} + M_{120}^{5}, \qquad (8)$$

$$M^d = M_{10}^{\bar{5}} + M_{126}^{\bar{45}} + M_{120}^{\bar{5}} + M_{120}^{\bar{45}}, \qquad (9)$$

$$M^e = M_{10}^{\bar{5}} - 3M_{126}^{\bar{45}} + M_{120}^{\bar{5}} - 3M_{120}^{\bar{45}}, \qquad (10)$$

$$M_{LL}^{\nu} = M_{126}^{15} \quad , \quad M_R^{\nu} = M_{126}^{1}. \qquad (11)$$

Atleast one of the neutrino Yukawa couplings is as large as top Yukawa. Masiero,Vives,Vempati, NPB 649(2003)189 + old papers

What could be the neutrino mixing angles ?

Two benchmark cases :

- Following quarks, a small CKM like mixing angles
- Following neutrinos, large neutrino (PMNS) like mixing angles

Both these cases are possible within SO(10) seesaw. Possible to build flavour models.

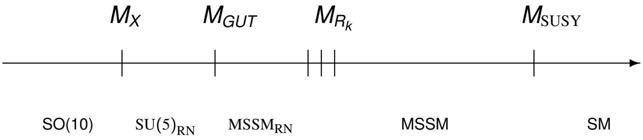


Figure: Schematic picture of the energy scales involved in the model.

Implications on the parameter space I

Two main effects due to addition of the GUT + seesaw effects :

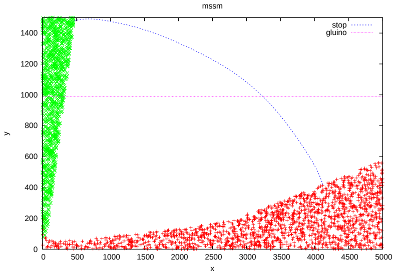
- $\tilde{\tau}_R$ sits in the 10 ; receives full $SU(5)$ gaugino contributions:

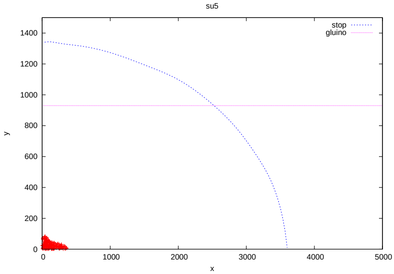
$$m^2_{\tilde{\tau}_R}(M_{GUT}) \approx \frac{144}{20\pi}\alpha_5 M^2_{1/2} \ln(\frac{M_X}{M_{GUT}}) \approx 0.25\, M^2_{1/2}, \quad (12)$$

- The neutrino Yukawa coupling taking part in the see-saw mechanism taken to be as large as the top Yukawa coupling, introduces an additional top-Yukawa like coupling to the up-type Higgs from the scales M_X down to M_R. Efficient REWSB.

Implications on the parameter space - II

The $(M_{1/2} - m_0)$ plane looks like :





Calibbi,Faccia, Masiero, Vempati, PRD 74 (2006) 116002

Minimal CKM-like Case

Model with two ten-plets (+ 126 for RH neutrinos)

inspired by Dimopolous, Hall '94, Buchmueller, Wyler '01

Several Sources of flavour violation

$$
\begin{aligned}
(\delta_{LL})_{\mu e} &= -\frac{3}{8\pi^2}\, Y_t^2 V_{td} V_{ts} \ln \frac{M_X}{M_{R_3}} \\
(\Delta_{RR})_{i\neq j} &= (m^2_{\tilde{10}})_{ij}(M_X \to M_{GUT}) \\
&= -3 \cdot \frac{3m_0^2 + a_0^2}{16\pi^2} V_{ti} V_{tj} \ln\left(\frac{M_X^2}{M_{GUT}^2}\right)
\end{aligned}
\qquad (13)
$$

A similar complicated formula for Δ_{LR}.

The Power of Prime

(1)MEG can probe only small regions of the parameter space for small tanβ.
(2) For large tan β significant amount can be probed by MEG.
However,

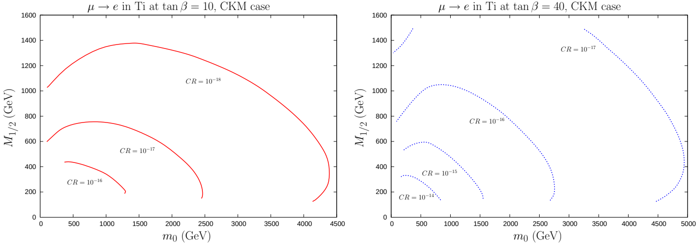


Figure 1: Contour plots at $A_0 = 0$ of the parameter space region within reach of different $\mu \to e$ in Ti CR sensitivities in the CKM case for low and high $\tan\beta$. We see that the PRIME experiment will be able to test the CKM $t_\beta = 10$ case for $(m_0, m_{\tilde{g}}) \lesssim 2800$ GeV and the $t_\beta = 40$ even beyond LHC reach.

Some Elements of Large mixing case

$$W_{SO(10)} = (Y_u)_{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}_u + (Y_d)_{ii}\mathbf{16}_i\mathbf{16}_i\frac{\mathbf{45}\ \mathbf{10}}{M_{\rm Planck}} + (Y_R)_{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{126} \quad (14)$$

inspired by Moroi '01, Chang, Masiero, Murayama '02

MNS

$$\begin{aligned}
(\delta_{LL})_{\mu e} &= -\frac{3}{8\pi^2}\, Y_t^2 U_{e3} U_{\mu 3} \ln\frac{M_X}{M_{R_3}} \\
(\delta_{LL})_{\tau \mu} &= -\frac{3}{8\pi^2}\, Y_t^2 U_{\mu 3} U_{\tau 3} \ln\frac{M_X}{M_{R_3}} \\
(\delta_{LL})_{\tau e} &= -\frac{3}{8\pi^2}\, Y_t^2 U_{e3} U_{\tau 3} \ln\frac{M_X}{M_{R_3}}
\end{aligned} \quad (15)$$

U_{e3} independent $\tau \rightarrow \mu + \gamma$

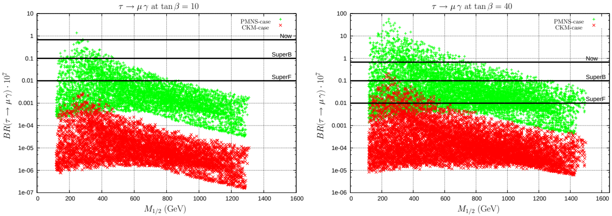


Figure 1: Scaled BR($\tau \rightarrow \mu\,\gamma$) vs. $M_{1/2}$. The plots are obtained by scanning the LHC accessible SUSY–GUT parameter space at fixed $\tan\beta$. The horizontal lines are the present (B factories), future (SuperKEKB) and planned (Super Flavour factory) experimental sensitivities.

The running of U_{e3} - I

Calibbi,Faccia,Masiero, Vempati, JHEP (2007) 0707:012

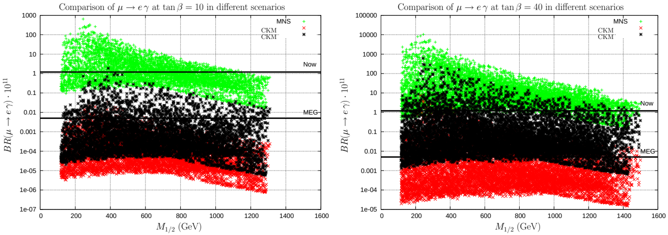


Figure 1: BR($\mu \to e\,\gamma$) as a probe of different SUSY–GUT scenarios. The plot are obtained by scanning the LHC accessible parameter space at fixed $\tan\beta$. The lines are the present (MEGA) and future (MEG) experimental sensitivities. We see that MEG will completely test the PMNS scenario for U_{e3} close to the CHOOZ bound and severely constrain it for $U_{e3} = 0$.

The running of U_{e3} - II

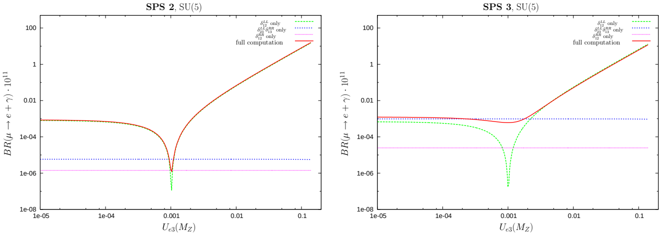


Figure 1: Different SU(5) contributions to BR($\mu \to e+\gamma$) for the benchmark points, as a function of low-energy U_{e3}.

Outline

For example : $\tan\beta$=10

Calibbi,Mambrini,Vempati, JHEP (2007) 0709:081 In the parameter space where LHC is likely to see SUSY.

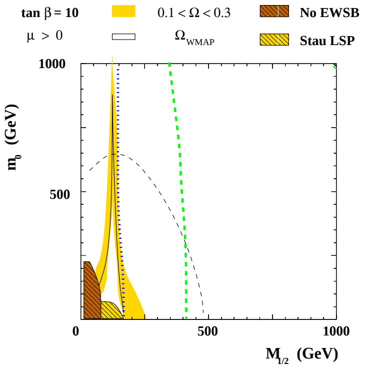


Figure 1: The $(m_0, M_{1/2})$ plane with all the low-energy constraints on the parameter space. While the color code is explained above, the green dashed line indicates the Higgs mass bound from the LEP, while the dark dashed

Is there any region..?

Infact, if one scans the entire parameter space

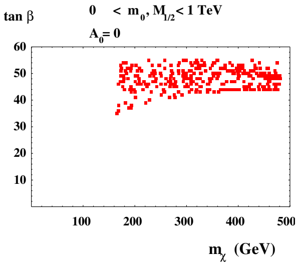
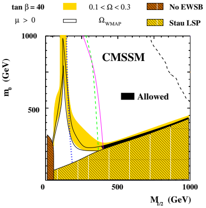
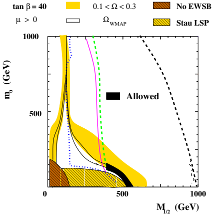


Figure 1: Points allowed by experimental and theoretical constrains after a scan on ($0 < m_0, M_{1/2} < 1$ TeV) and ($20 < \tan\beta < 55$)

A comparision between mSUGRA and SUSY-GUT

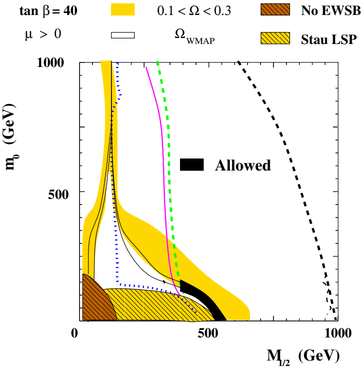
The coannihilation region for tan β=40 for the case of CMSSM and $SU(5)_{RN}$.





Zooming...the trunk region

Upper bound on neutralino mass (tan *beta* dependent).



Why ??...

At the weak scale, roughly the stau mass matrix is now given by:

$$\mathcal{M}^2_{\tilde{\tau}} = \begin{pmatrix} m^2_{\tilde{\tau}_{LL}} & m^2_{\tilde{\tau}_{LR}} \\ m^2_{\tilde{\tau}_{LR}} & m^2_{\tilde{\tau}_{RR}} \end{pmatrix}, \qquad (16)$$

where, including the pre-GUT effects,

$$m^2_{\tilde{\tau}_{RR}} \simeq (1-\rho)\, m_0^2 + 0.3\, M^2_{1/2} \qquad (17)$$

ρ is a positive coefficient dependent on $\tan\beta$. and

$$\begin{aligned} m^2_{\tilde{\tau}_{LR}} &= m_\tau\,(A_\tau - \mu \tan\beta) \\ &\approx -m_\tau\, \mu \tan\beta \end{aligned} \qquad (18)$$

Why ?? Contd...

In first approximation the lightest eigenvalue of Eq. (16) is given by:

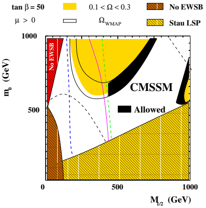
$$m^2_{\tilde{\tau}_1} \simeq m^2_{\tilde{\tau}_{RR}} - m_\tau\, \mu \tan\beta$$
$$\approx (1-\rho)\, m_0^2 + 0.3\, M^2_{1/2} - m_\tau\, \mu \tan\beta \qquad (19)$$

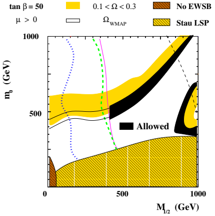
coannihilation condition

$m_{\tilde{\tau}_1} \approx M_1 \approx 0.47\, M_{1/2}$.
$\tan\beta \approx (1-\rho)(msusy/m_\tau)$, which leads to a lower limit on
$\tan\beta < 27$,

A comparision between mSUGRA and SUSY-GUT

We show the coannihilation region for tan β=50 for the case of CMSSM and $SU(5)_{RN}$.



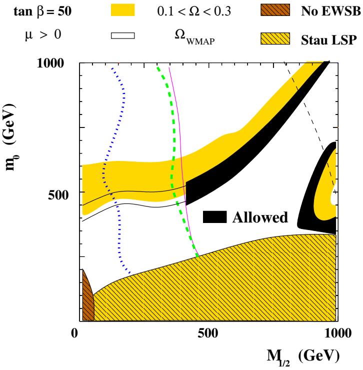


1

1

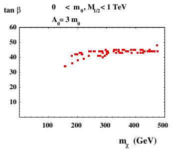
Zooming...

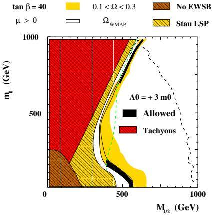
A large area opens up..corresponding to funnel region.



A-terms

$A_0 = 3\ \ m_0$ case. Left panel: points allowed by experimental and theoretical constrains after a scan on $(0 < m_0, M_{1/2} < 1$ TeV) and $(20 < \tan\beta < 55)$. Right panel: the $(m_0, M_{1/2})$ plane plot for $\tan\beta = 40$; the two branches of the stau coannihilation region.



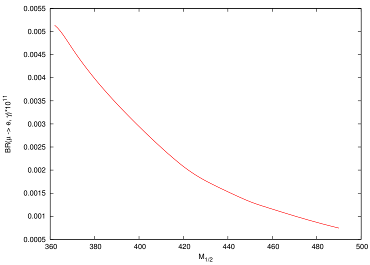


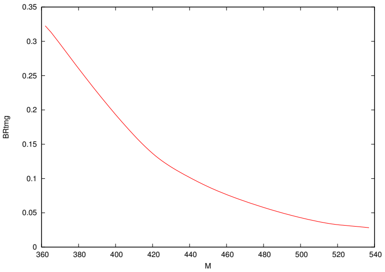
Putting together LFV and Dark Matter

Including DM requirements, we can compute the LFV for these regions: Calibbi,Godbole,Mambrini,Vempati

preliminary

For tan β =40



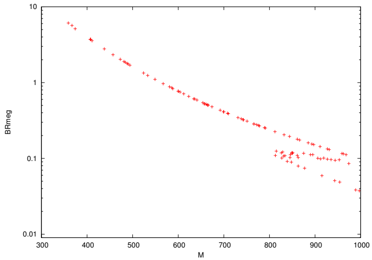


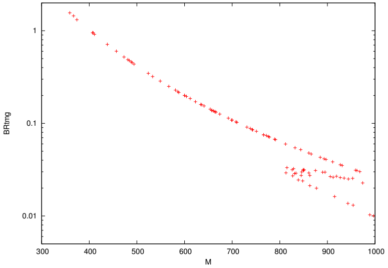
Putting together LFV and Dark Matter

Calibbi,Godbole,Mambrini,Vempati

preliminary

For tan β =50



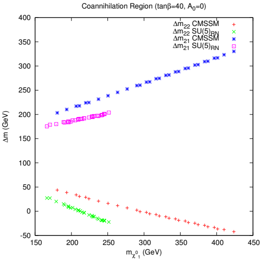


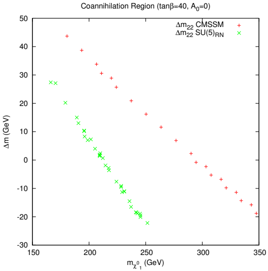
Putting together LFV and Dark Matter: LHC studies

Calibbi,Godbole,Mambrini,Vempati

preliminary

For tan β =40





Outline

Flavour Violating SUSY breaking

To empasize :

$$m^2_{\tilde{e}\tilde{\mu}} \neq 0 \qquad (20)$$

and similar terms at high scale where SUSY breaking is mediated to the visible sector. Most generic structure for SUSY breaking.
Reasons:

- In models of supersymmetry breaking based on supergravity or superstring theories, although it is possible to achieve universality or even no-scale boundary conditions under some assumptions on the Kähler potential, non-universal soft terms are generically present in the high scale effective lagrangian.
- In models with flavour symmetry imposed by a Froggatt–Nielsen mechanism, flavour violating corrections to the soft potential could be potentially large. More so, if the flavon fields contain SUSY breaking F-VEVs. Also D-terms.

SU(5) relations

Taking into account that matter is organized into the SU(5) representations $\mathbf{10} = (q, u^c, e^c)$ and $\bar{\mathbf{5}} = (l, d^c)$, one obtains the following relations

$$m^2_Q = m^2_{\tilde{e}^c} = m^2_{\tilde{u}^c} = m^2_{\mathbf{10}} \tag{21}$$

$$m^2_{\tilde{d}^c} = m^2_L = m^2_{\bar{\mathbf{5}}} \tag{22}$$

$$A^e_{ij} = A^d_{ji} \,. \tag{23}$$

SU (5) relations

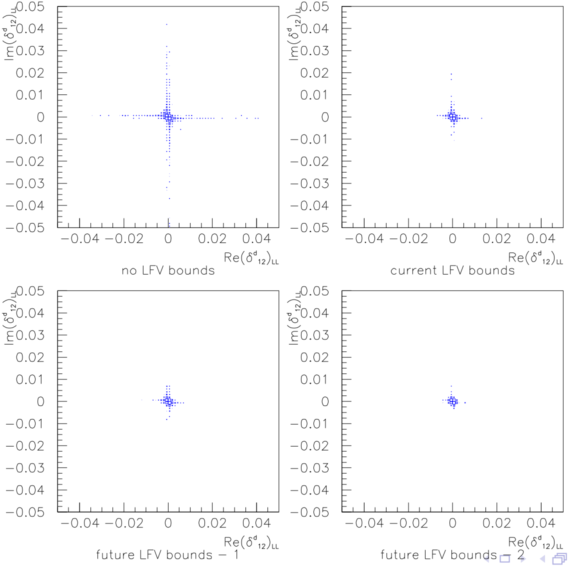
$$(\Delta^u_{ij})_{LL} = (\Delta^u_{ij})_{RR} = (\Delta^d_{ij})_{LL} = (\Delta^l_{ij})_{RR} \tag{24}$$

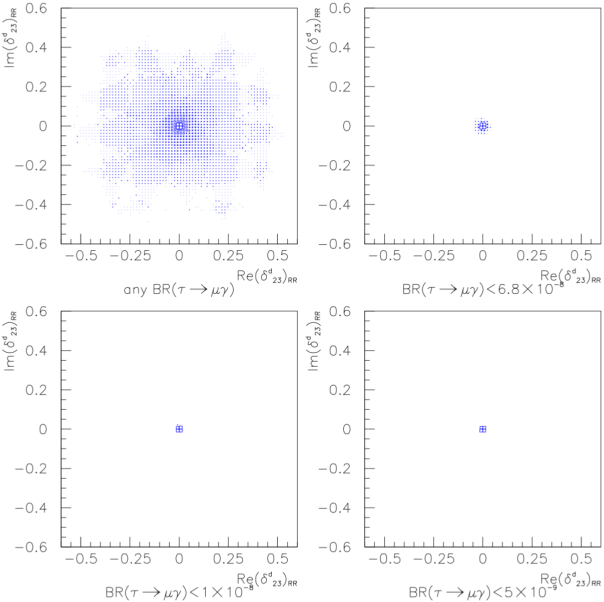
$$(\Delta^d_{ij})_{RR} = (\Delta^l_{ij})_{LL} \tag{25}$$

$$(\Delta^d_{ij})_{LR} = (\Delta^l_{ji})_{LR} = (\Delta^l_{ij})^\star_{RL} \tag{26}$$

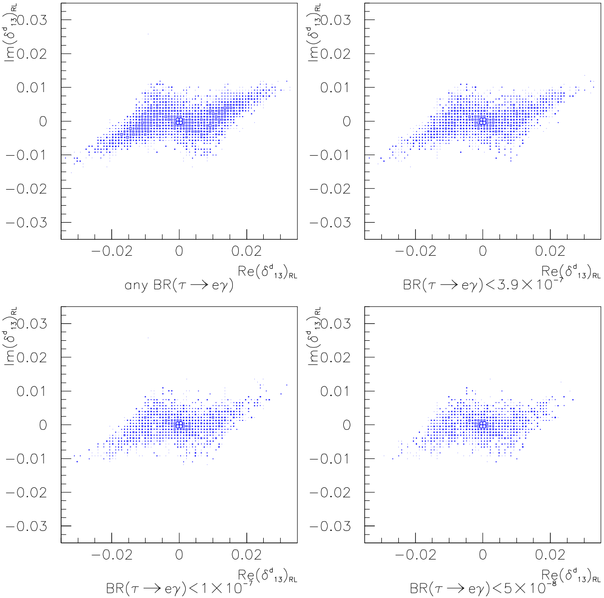
Some results

Ciuchini *et.al* NPB 783 (2007) 112





$Im(\delta^d_{23})_{RR}$
$Re(\delta^d_{23})_{RR}$
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.5
−0.25
0
0.25
0.5
any BR($\tau \to \mu\gamma$)
BR($\tau \to \mu\gamma$)<6.8×10^{-8}
BR($\tau \to \mu\gamma$)<1×10^{-8}
BR($\tau \to \mu\gamma$)<5×10^{-9}



$\mathrm{Im}(\delta^d_{13})_{RL}$
$\mathrm{Re}(\delta^d_{13})_{RL}$
any BR($\tau \to e\gamma$)
BR($\tau \to e\gamma$)$< 3.9 \times 10^{-7}$
BR($\tau \to e\gamma$)$< 1 \times 10^{-7}$
BR($\tau \to e\gamma$)$< 5 \times 10^{-8}$

Complementarity analysis in the generic case..

Dark Matter ?
LHC ?

Outline

Summary

- Even in the era of LHC, flavour physics has an important role to play.
- This is especially true if SUSY is discovered at LHC.
- Including DM requirements will play a big role in distinguishing various SUSY models.