Patterns of flavour signals in SUSY models

T. Goto, Y. Okada, T. S. and M. Tanaka,
arXiv:0711.2935

Tetsuo SHINDOU

DESY

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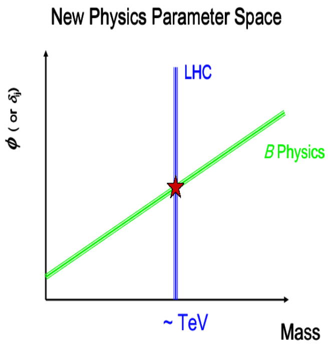
Talk at SuperB Workshop VI, Valencia

Outline

Flavour physics in the LHC era

- A powerful discovery machine, the LHC, is starting in a year.
- Flavour experiments will become very significant in the LHC era
  - Past and present flavour experiments (Belle, Babar, Tevatron, MEGA, etc) have already give strong constraints on models beyond the SM
  - Several new experiments are under construction (MEG, LHCb, BESIII, etc)
  - There are future plans of Super B factory

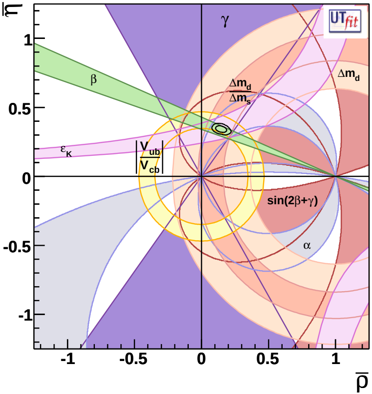


J.Hewett and D. G. Hitlin (ed.), hep-ph/050326

CKM in the SM

The CKM matrix seems to work perfectly !
All the data are consistent with CKM

- Semileptonic decay $\Rightarrow |V_{ub}/V_{cb}|$
- K–$\bar{K}$ mixing $\Rightarrow \epsilon_K$
- B_d–$\bar{B}_d$ mixing $\Rightarrow \Delta m_{B_d}$
- B_s–$\bar{B}_s$ mixing $\Rightarrow \Delta m_{B_d}/\Delta m_{B_s}$
- CPV in $B \to J/\psi K_S \Rightarrow \phi_1$
- CPV in $B \to \pi^+\pi^-$ and $B \to \rho^+\rho^- \Rightarrow \phi_2$
- CPV in $B \to D^{(*)}K \Rightarrow \phi_3$
- $B \to \tau\nu$
- $\ldots$



CKM determination by tree level process

However we should determine CKM parameters by Tree-Level processes in order to study new physics effect

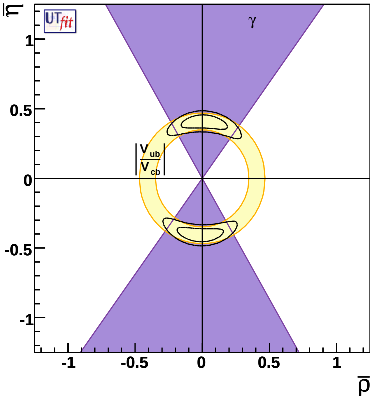
$|V_{ub}|$, ϕ_3

$+B_d$ mixing and CP asymmetries

$+B_s$ mixing and CP asymmetries

$+\epsilon_K$

New Physics

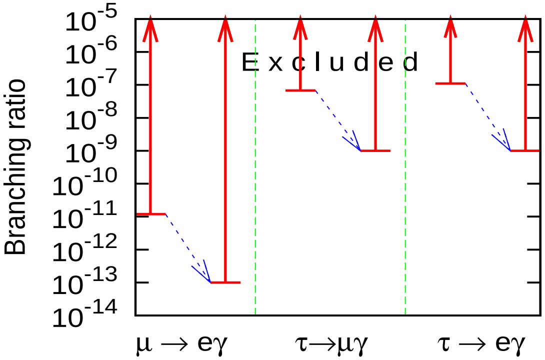


Which sector is affected by NP depends on a detail of a model

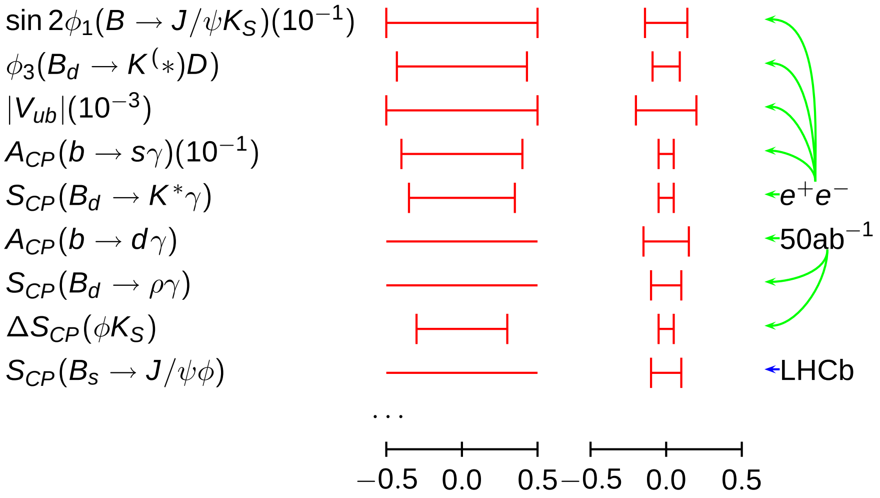
Improvement of ϕ_3 is important

Sensitivity at present and future LFV exp.

- MEG (starting soon) $\Rightarrow$ B$(\mu \to e\gamma) < \mathcal{O}(10^{-13})$
- superB factory $\Rightarrow$ B$(\tau \to \mu(e)\gamma) < \mathcal{O}(10^{-9})$



Sensitivity at present and future B exp.



Flavour physics in various SUSY models

T. Goto, Y. Okada, Y. Shimizu, T.S., and M. Tanaka, PRD66,035009, PRD70,035012
T. Goto, Y. Okada, T.S., and M. Tanaka, arXiv:0711.2935

- In order to see how flavour signals can distinguish different models, we study various quark and lepton flavour observables in several SUSY models.
- Models
  - mSUGRA (CMSSM)
  - MSSM with Right-handed Neutrinos
  - SU(5) SUSY GUT with RN
  - MSSM with U(2) flavour symmetry
- Processes
  - LFV
  - $A_{CP}(b \to s(d)\gamma)$, $S_{CP}(B \to K^*\gamma)$, $S_{CP}(B \to \rho\gamma)$
  - $S_{CP}(B \to \phi K_S)$
  - $S_{CP}(B_s \to J/\psi\phi)$
  - Check of unitarity triangle

SUSY and flavour physics

- There are SUSY partners of the SM particles

SM particles		SUSY partners
W, Z, γ, H gluon quark lepton	↔	Neutralino & Chargino gluino squark slepton

New flavour mixing → squark, slepton

- $m_{\tilde{f}}^2 = (Y^\dagger Y)_{ij} v^2 + m_{ij}^2$

Origin of SUSY breaking (universal, FS, etc)

↓

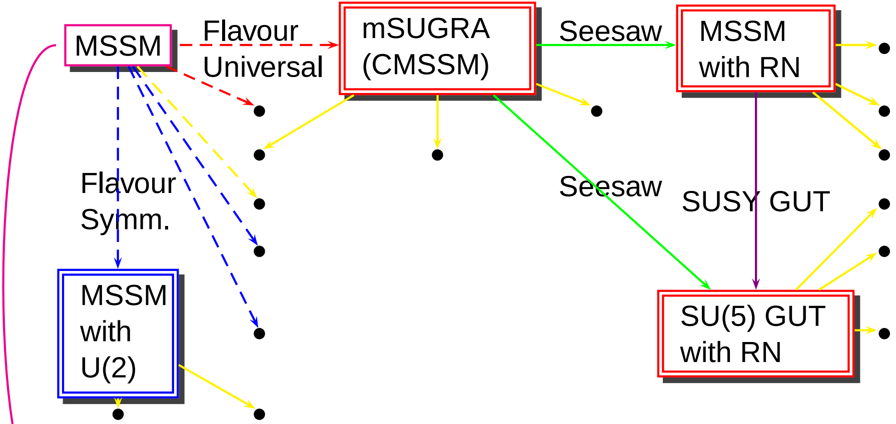
RG running (SUSY GUT, Y_ν, etc)

↓

SUSY breaking terms at ∼TeV → m_{ij}^2

Outline

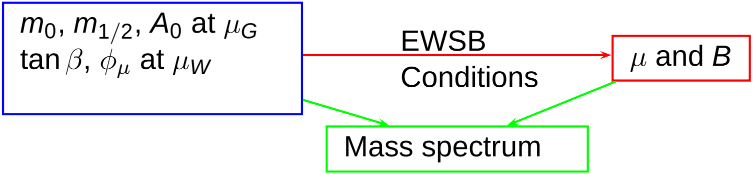
Classifications of models



- (General) MSSM includes very many parameters
- Dangerous FCNC (Flavour problem)

mSUGRA (CMSSM)

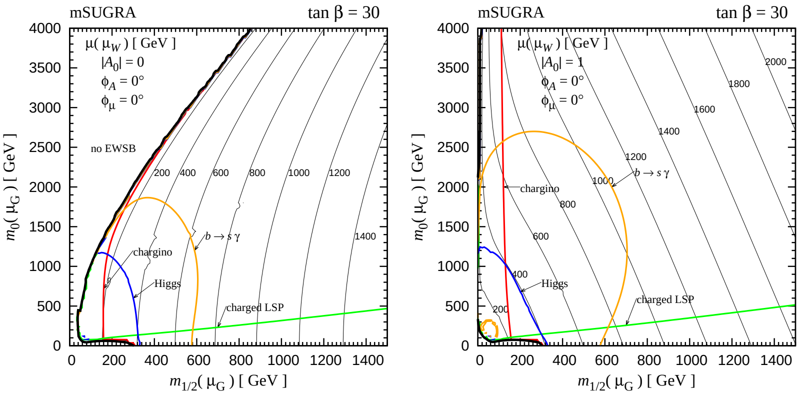
- Supersymmetry-breaking parameters at μ_G:
  - Universal soft scalar masses:
    $m_Q^2 = m_U^2 = m_D^2 = m_L^2 = m_E^2 = m_0^2\mathbf{1}$, $m_{H_1}^2 = m_{H_2}^2 = m_0^2$
  - GUT relation on the gaugino masses
    $M_1(\mu_G) = M_2(\mu_G) = M_3(\mu_G) = m_{1/2}$
  - A-terms:
    $A_U = A_0 m_0 Y_U$, $A_D = A_0 m_0 Y_D$, $A_E = A_0 m_0 Y_E$
- $\tan\beta = \langle H_2\rangle / \langle H_1\rangle$ is also a model parameter
- The model is characterized by 4(5) free parameters



mSUGRA (CMSSM)

- Mass spectrums:
  - Gauginos: $M_i = (\alpha_i/\alpha_G) m_{1/2}$
    $\Rightarrow M_1 \sim 0.4 m_{1/2}$, $M_2 \sim 0.8 m_{1/2}$, $M_3 \sim 3 m_{1/2}$
  - Squarks : $m_Q^2 \sim m_0^2 + 7 m_{1/2}^2$, $m_U^2 \sim m_D^2 \sim m_0^2 + 6 m_{1/2}^2$
    M_{Q_3} and M_{U_3} get a large contribution from Y_t
  - Sleptons: $m_L^2 \sim m_0^2 + 0.5 m_{1/2}^2$, $m_E^2 \sim m_0^2 + 0.2 m_{1/2}^2$
- Flavour violation is MFV at μ_G
  - Only Yukawa couplings break flavour symmetry of $SU(3)^5$
  - Flavour violation in sfermion sectors is induced by running
    $\Rightarrow$ Flavour mixings in $\tilde{Q}$ sector
  - Negligible non-standard contribution in the CKM fit
  - Significant contribution to $b \to s\gamma$
- EDM experiments constrain CP phases in A- and μ- terms
  In our analysis, $\phi_\mu = \phi_A = 0$ is used

The value of μ (mSUGRA)



Introducing seesaw mechanism to CMSSM

- Seesaw mechanism is an attractive candidate to generate small but finite neutrino masses
  - Introducing heavy right-handed neutrinos, N^c

    $\mathcal{W} = Y_E E^c L \cdot H_1 + Y_N E^c L \cdot H_2 + \frac{1}{2} M_N N^c N^c$

    N^c are decoupled

    $\mathcal{W} = Y_E E^c L \cdot H_1 - \frac{1}{2}\kappa_\nu (L \cdot H_2)(L \cdot H_2)$
  - Y_N and M_N are related to U and m_i

    $$(m_\nu) = U^* \mathrm{diag}(m_1, m_2, m_3) U^\dagger = \langle H_2 \rangle^2 Y_N^T M_N^{-1} Y_N$$
  - There are additional 3+6 real parameters at μ_R:
    Taking diagonal Y_E and M_N basis, Y_N can be written as

    $Y_N = \frac{1}{\langle H_2 \rangle} \mathrm{diag}(\sqrt{M_{N1}}, \sqrt{M_{N2}}, \sqrt{M_{N3}}) R\, \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}) U^\dagger$

    J. A. Casas and A. Ibarra, NPB618,171

    Eigenvalues of M_N $\quad R^T R = \mathbf{1} \Rightarrow$ 6 parameters
  - Mixing in $\tilde{L}$ sector is induced through the running

MSSM with RN

We consider three structures of Y_N

- Degenerate (and real R) RN: $M_N \propto \mathbf{1}$
  - Solar-ν mixing $\Rightarrow \tilde{\mu}_L \to \tilde{e}_L$
  - Atmospheric-ν mixing $\Rightarrow \tilde{\tau}_L \to \tilde{\mu}_L$
- Non-Degenerate (I): $M_N \not\propto \mathbf{1}$

J. Ellis *et al*, PRD66, 115013

$$Y_N = \begin{pmatrix} * & & \\ & * & * \\ & * & * \end{pmatrix} \Rightarrow$$

$\tilde{\mu}_L \to \tilde{e}_L$ & $\tilde{\tau}_L \to \tilde{e}_L$: suppressed
$\tilde{\tau}_L \to \tilde{\mu}_L$: unsuppressed

- Non-Degenerate (II): $M_N \not\propto \mathbf{1}$

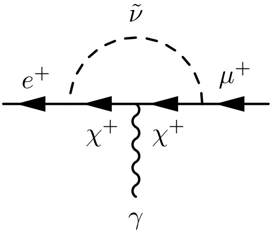
J. Ellis *et al*, PRD66, 115013

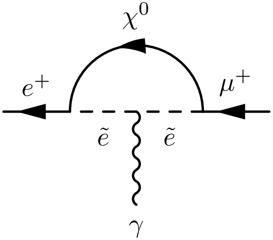
$$Y_N = \begin{pmatrix} * & & * \\ & * & \\ * & & * \end{pmatrix} \Rightarrow$$

$\tilde{\mu}_L \to \tilde{e}_L$ & $\tilde{\tau}_L \to \tilde{\mu}_L$: suppressed
$\tilde{\tau}_L \to \tilde{e}_L$: unsuppressed

MSSM with RN

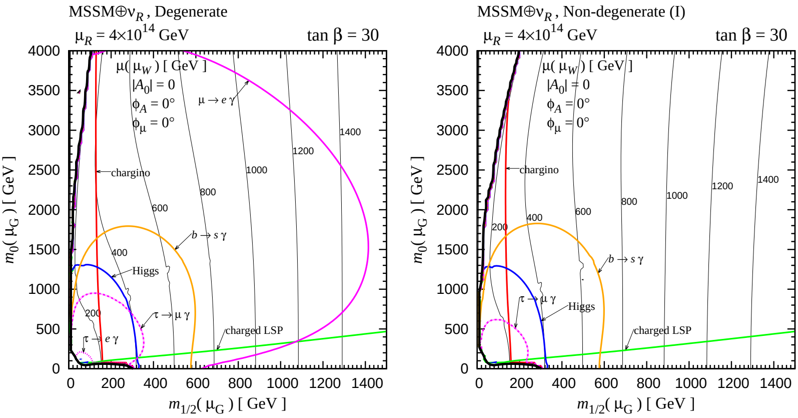
- Large contribution to LFV is expected for large Y_N
  $\Rightarrow \mu \to e\gamma$ constraint can be very strong for heavy M_N





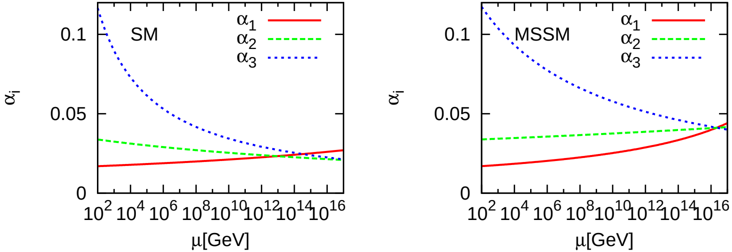
- Quark sector is almost same as mSUGRA (CMSSM) case
- Y_N affects also the running of m^2_{H2}

μ in MSSM with RN



SU(5) SUSY GUT with RN

- SUSY seems to support a grand unification



- Quarks and leptons are embedded in
  $\mathbf{10} = \{Q, U^c, E^c\}$ $\bar{\mathbf{5}} = \{D^c, L\}$ $\mathbf{1} = \{N^c\}$
  - mixing in Q (CKM) $\Rightarrow$ mixing in $\tilde{E}^c$ above μ_G
  - mixing in L (Y_N) $\Rightarrow$ mixing in $\tilde{D}^c$ above μ_G
  - $Y_N \Rightarrow$ mixing in $\tilde{L}$ (same as MSSM with RN)

SU(5) SUSY GUT with RN

Again we consider three structures of Y_N

- Degenerate: $M_N \propto \mathbf{1}$
  - Solar-ν mixing $\Rightarrow \tilde{\mu}_L \to \tilde{e}_L$ & $\tilde{s}_R \to \tilde{d}_R$
  - Atmospheric-ν mixing $\Rightarrow \tilde{\tau}_L \to \tilde{\mu}_L$ & $\tilde{b}_R \to \tilde{s}_R$
- Non-Degenerate (I):

$$Y_N = \begin{pmatrix} * & & \\ & * & * \\ & * & * \end{pmatrix} \Rightarrow$$

$\tilde{\mu}_L \to \tilde{e}_L$ & $\tilde{\tau}_L \to \tilde{e}_L$: suppressed
$\tilde{\tau}_L \to \tilde{\mu}_L$ & $\tilde{b}_R \to \tilde{s}_R$: unsuppressed

- Non-Degenerate (II):

$$Y_N = \begin{pmatrix} * & & * \\ & * & \\ * & & * \end{pmatrix} \Rightarrow$$

$\tilde{\mu}_L \to \tilde{e}_L$ & $\tilde{\tau}_L \to \tilde{\mu}_L$: suppressed
$\tilde{\tau}_L \to \tilde{e}_L$ & $\tilde{b}_R \to \tilde{d}_R$: unsuppressed

MSSM with U(2) FS

A. Pomarol, D. Tommasini, NPB466,3; R. Barbieri, G. Dvarli, L. Hall, PLB377, 76;
R. Barbieri, L. Hall, NCA110, 1; R. Barbieri, L. Hall, S. Raby, A. Romanino, NPB493, 3;
R. Barbier, L. Hall, A. Romanino, PLB401,47;
A. Masiero, M. Piai, A. Romanino,L. Silverstrini, PRD64, 075005 ...

- $Y_{U,D}$ and $m^2_{Q,U,D}$ are controlled by the same flavour symmetry, U(2)
  - 1st and 2nd generation $\rightarrow$ U(2) doublet
  - 3rd generation $\rightarrow$ U(2) singlet
  - Symmetry is broken as

$$\mathrm{U(2)} \xrightarrow{\epsilon} \mathrm{U(1)} \xrightarrow{\epsilon'} \text{no symmetry}, \ \epsilon \gg \epsilon'$$

- We ignore the lepton sector in this analysis
  Lepton sector depends on details of the model
  (How to generate neutrino masses, etc)

SUSY breaking at μ_G

- Yukawa couplings

$$Y_Q \simeq y_Q \begin{pmatrix} 0 & a_Q\epsilon' & 0 \\ -a_Q\epsilon' & b_Q\epsilon & c_Q\epsilon \\ 0 & d_Q\epsilon & 1 \end{pmatrix} \quad Q = U, D$$

$\Rightarrow \epsilon \sim \lambda^2,\ \epsilon' \sim \lambda^3$

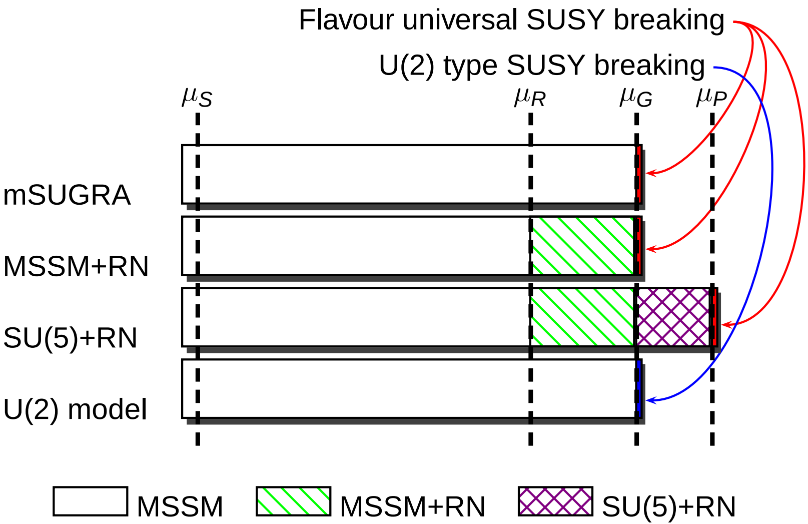
- Sfermion mass matrix

$$m_X^2 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 + r_{22}^X\epsilon^2 & r_{23}^X\epsilon \\ 0 & r_{23}^{X*}\epsilon & r_{33}^X \end{pmatrix} \quad X = Q, U, D$$

Rightarrow possible large 2-3 mixing

- We set $A_Q = a_0 Y_Q$ for simplicity
- GUT relation on gaugino masses are assumed

Cut-off and models



Outline

Processes

We consider the following processes

- LFV in MSSM with RN and SU(5) with RN
- CP asymmetry of $b \to s(d)\gamma$
  - Direct CP asymmetries
  - Time-dependent CP asymmetries:

    $S_{CP}(B_d \to K^*\gamma)$ & $S_{CP}(B_d \to \rho\gamma) \Leftarrow \boxed{B_d\text{–}\bar{B}_d} \times \boxed{b \to s(d)\gamma}$

    $m_{s,d}/m_b$ suppression in the SM ($S_{CP} = \frac{2\mathrm{Im}(e^{-i\phi_M} C_{7L} C_{7R}))}{|C_{7L}^2|+|C_{7R}^2|}$)

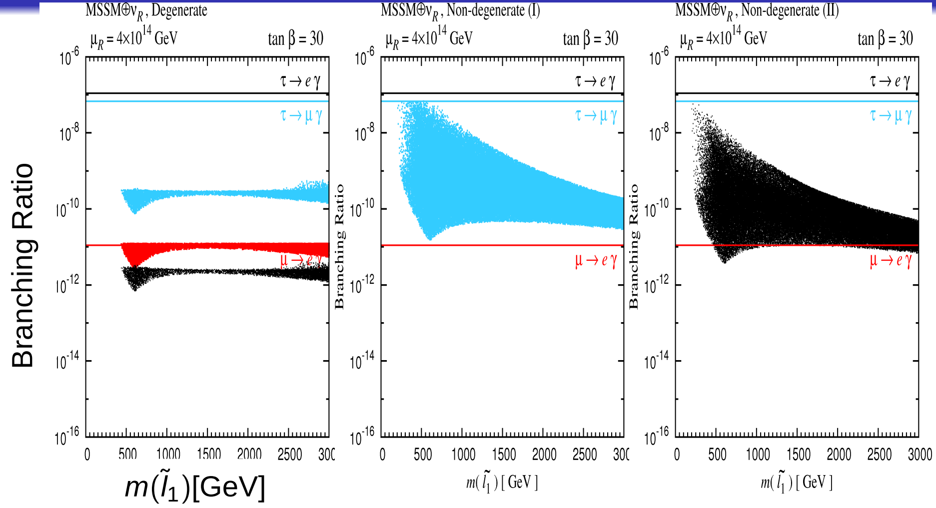
    D. Atwood, M. Gronau, and A. Soni, PRL79,185
- $S_{CP}(B_d \to \phi K_S) \Leftarrow \boxed{B_d\text{–}\bar{B}_d} \times \boxed{b \to s s \bar{s}}$

  new CP phase in $b \to s$ penguin

  $\Rightarrow$ deviation from $S_{CP}(B_d \to J/\psi K_S)$
- $S_{CP}(B_s \to J/\psi\phi) \Leftarrow \boxed{B_s\text{–}\bar{B}_s} \times \boxed{b \to s c \bar{c}}$

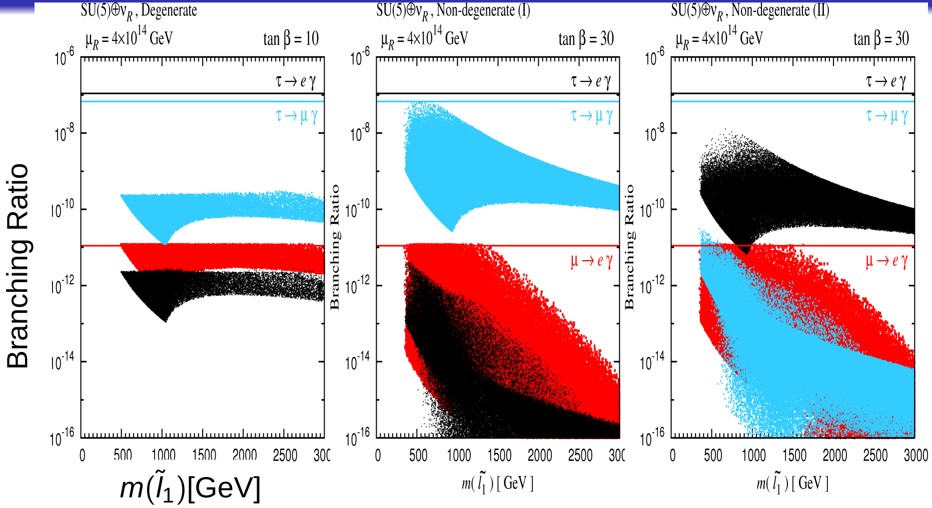
  Sensitive to new phase in B_s–$\bar{B}_s$
- Correlation between ϕ_3 and $\Delta m_{B_s}/\Delta m_{B_d}$

LFV in MSSM+RN



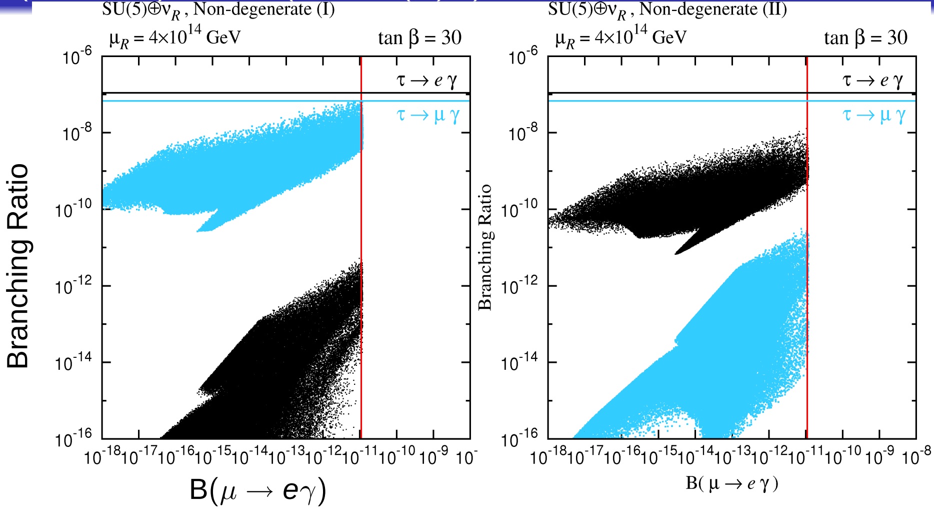
Degenerate Non-degen. (I) Non-degen. (II)

LFV in SU(5)+RN



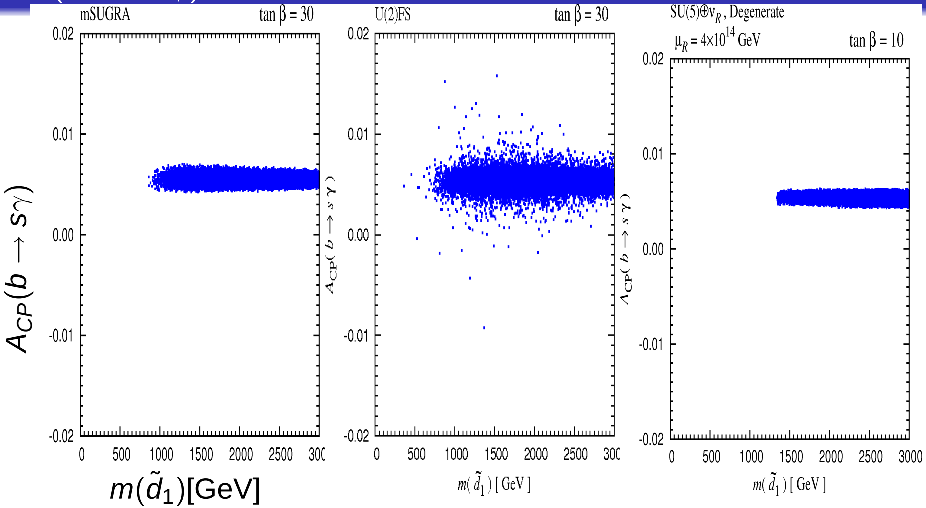
Degenerate Non-degen. (I) Non-degen. (II)

$B(\mu \to e\gamma)$ and $B(\tau \to \mu(e)\gamma)$



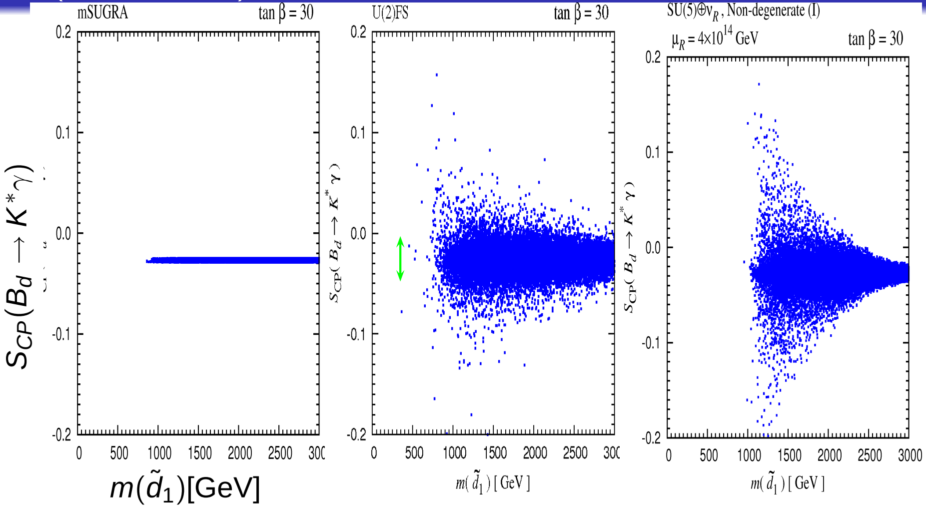
SU(5)+RN Non-degen. (I) SU(5)+RN Non-degen. (II)

$A_{CP}(b \to s\gamma)$



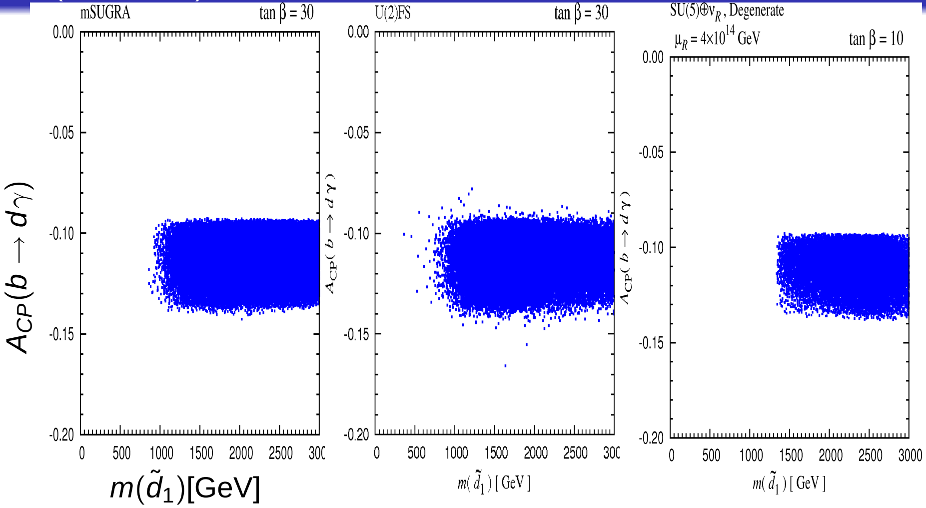
mSUGRA U(2) SU(5) Degen.

$S_{CP}(B_d \to K^*\gamma)$



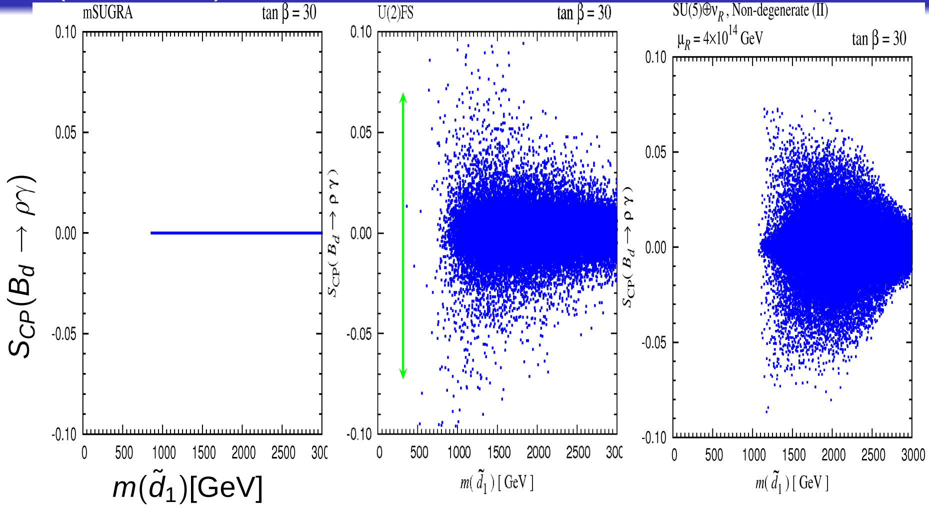
mSUGRA U(2) SU(5) Non-Degen. (I)

$A_{CP}(b \to d\gamma)$



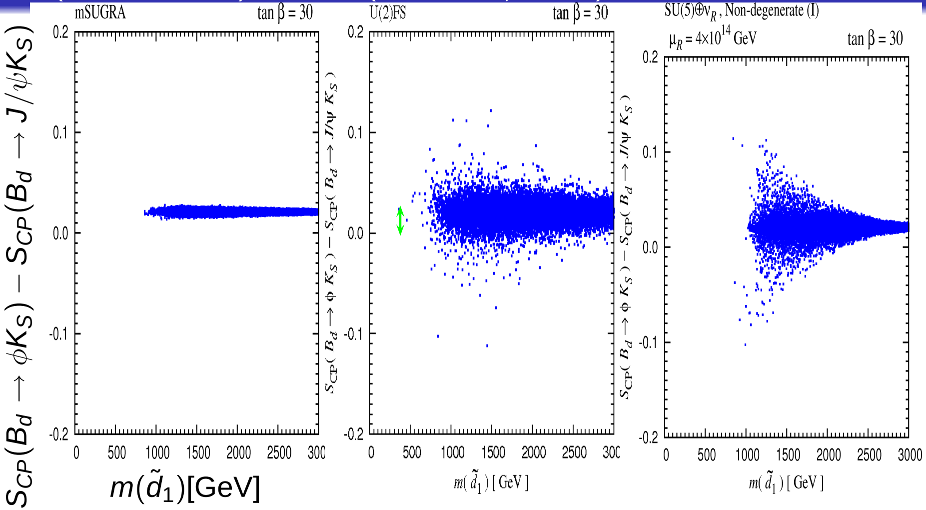
mSUGRA U(2) SU(5) Degen.

$S_{CP}(B_d \to \rho\gamma)$



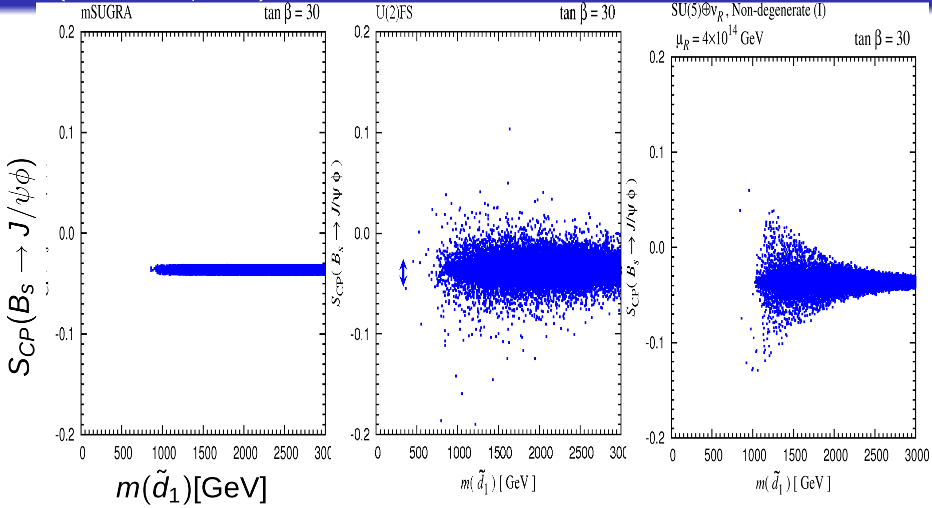
mSUGRA U(2) SU(5) Non-Degen. (II)

$S_{CP}(B_d \to \phi K_S) - S_{CP}(B_d \to J/\psi K_S)$



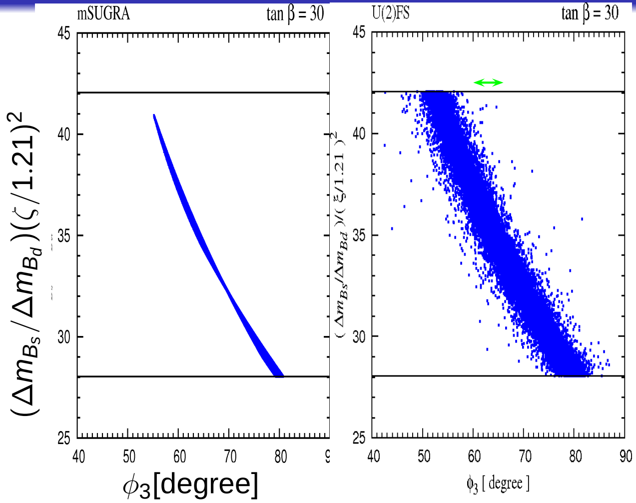
mSUGRA U(2) SU(5) Non-Degen. (I)

$S_{CP}(B_s \to J/\psi\phi)$



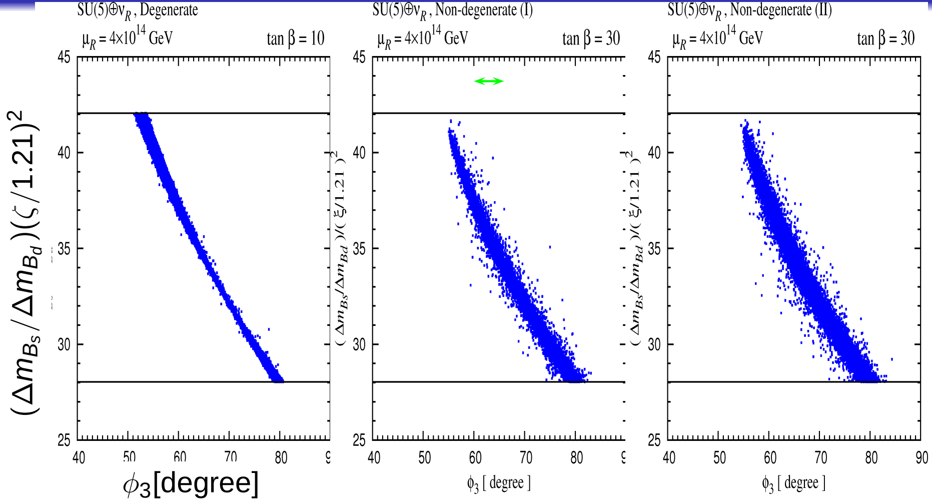
mSUGRA U(2) SU(5) Non-Degen. (I)

Correlation between ϕ_3 and $\Delta m_{B_s}/\Delta m_{B_d}$



mSUGRA U(2)

Correlation between ϕ_3 and $\Delta m_{B_s}/\Delta m_{B_d}$



SU(5) Degen SU(5) Non-Degen. (I) SU(5) Non-Degen. (II)

Outline

LFV

	$\mu \to e\gamma$	$\tau \to \mu\gamma$	$\tau \to e\gamma$
mSUGRA	–	–	–
MSSM+RN			
degenerate	$\surd$		
non-degen. I		$\surd$	
non-degen. II			$\surd$
SU(5)+RN			
degenerate	$\surd$		
non-degen. I	$\surd$	$\surd$	
non-degen. II	$\surd$		$\surd$
U(2) FS	–	–	–

CPV in $b \to s(d)$ — (I)

	$A_{CP}(s\gamma)$	$S_{CP}(K^*\gamma)$	$A_{CP}(d\gamma)$	$S_{CP}(\rho\gamma)$
mSUGRA				
MSSM+RN				
degenerate				
non-degen. I				
non-degen. II				
SU(5)+RN				
degenerate		•		•
non-degen. I		$\surd$		
non-degen. II				$\surd$
U(2) FS	$\surd$	$\surd$		$\surd$

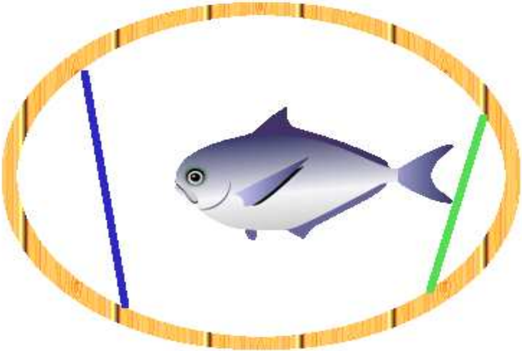
CPV in $b \to s(d)$ — (II)

	$\Delta S_{CP}(\phi K_S)$	$S_{CP}(B_s \to J/\psi\phi)$	$\Delta\phi_3$
mSUGRA			
MSSM+RN			
degenerate			
non-degen. I			
non-degen. II			
SU(5)+RN			
degenerate	•	•	
non-degen. I	$\surd$	$\surd$	•
non-degen. II			•
U(2) FS	$\surd$	$\surd$	•

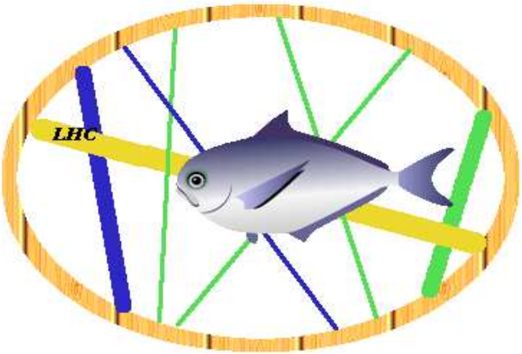
Conclusions

- We have studied on various quark and lepton flavour signals for several typical SUSY models, mSUGRA, MSSM with RN, SU(5) SUSY GUT with RN, and MSSM with U(2) FS.
- Each model gives different pattern of the predictions on $b \to s$, $b \to d$ processes and LFV.
- It is very important to see as many processes as possible for exploring flavour structure of new physics in the LHC era.

How to catch a “NP” fish

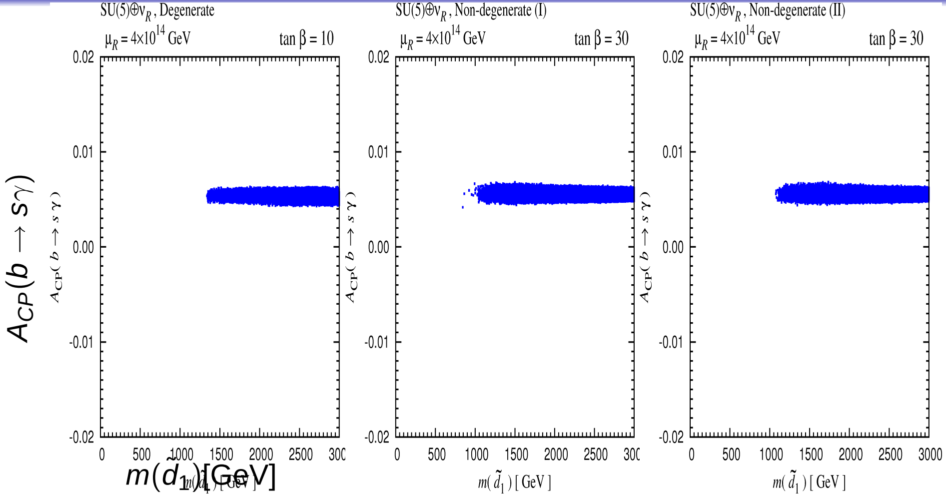


How to catch a “NP” fish



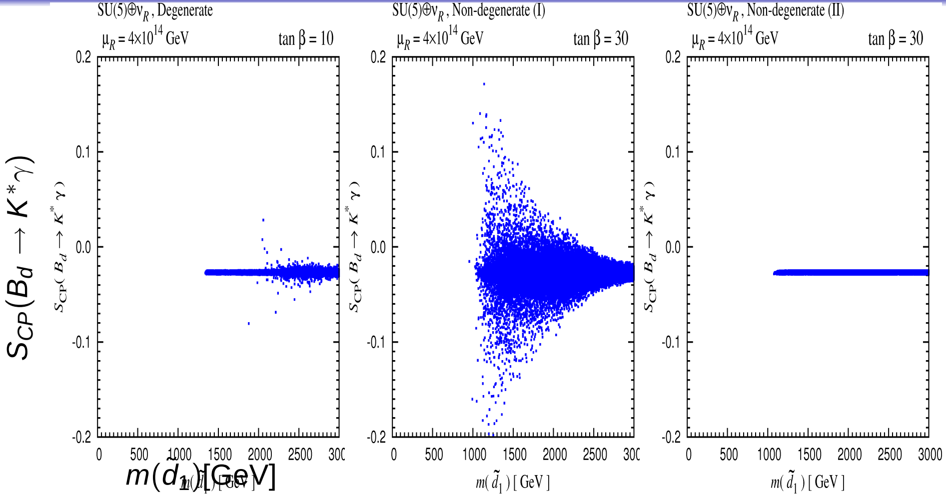
End of talk

$A_{CP}(b \to s\gamma)$



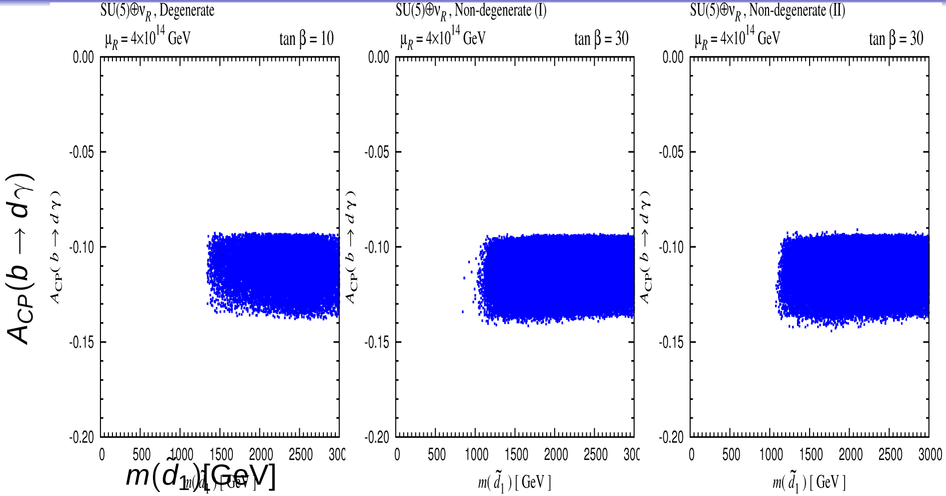
SU(5) Degen SU(5) Non-Degen. (I) SU(5) Non-Degen. (II)

$S_{CP}(B_d \to K^*\gamma)$



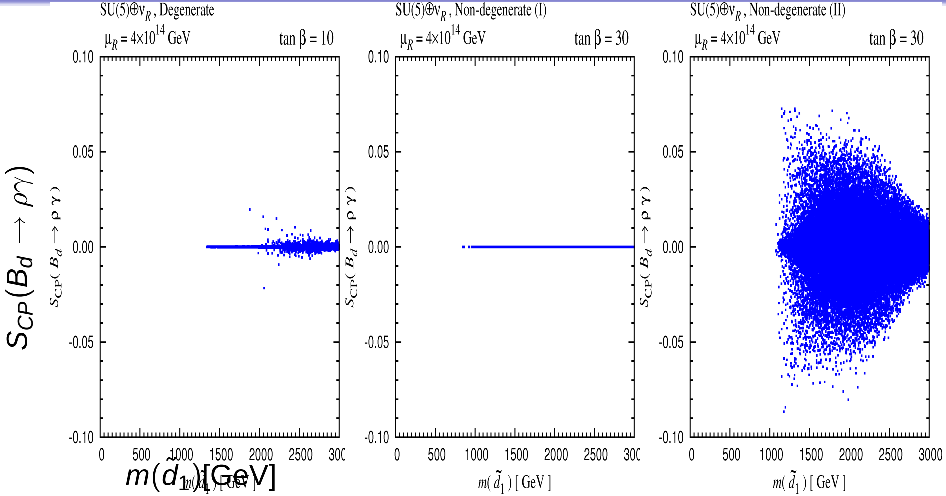
SU(5) Degen SU(5) Non-Degen. (I) SU(5) Non-Degen. (II)

$A_{CP}(b \to d\gamma)$



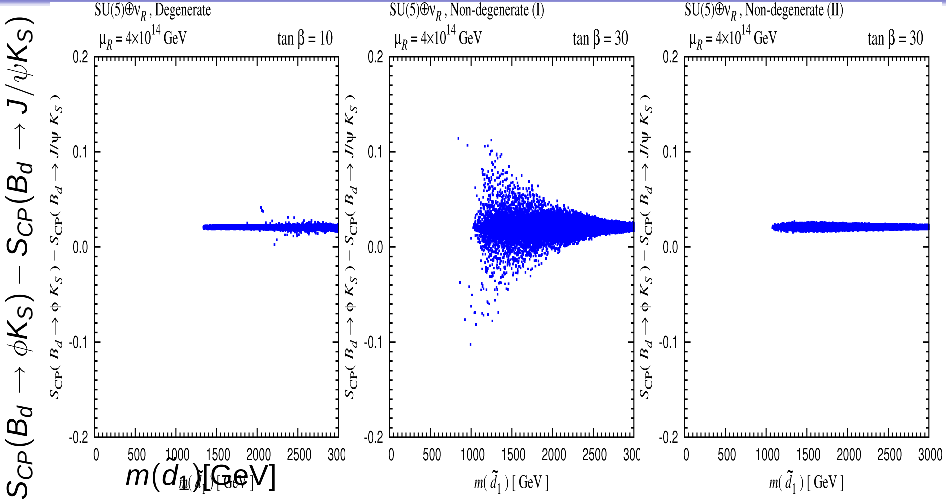
SU(5) Degen SU(5) Non-Degen. (I) SU(5) Non-Degen. (II)

$S_{CP}(B_d \to \rho\gamma)$



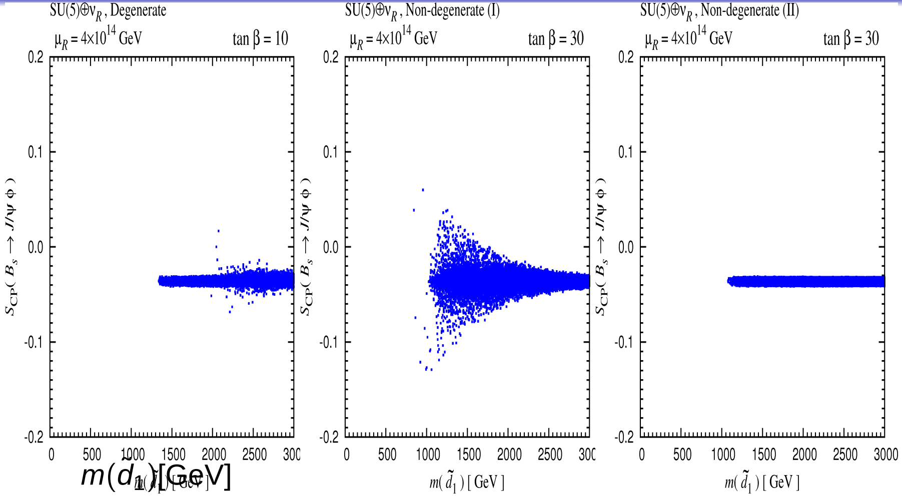
SU(5) Degen SU(5) Non-Degen. (I) SU(5) Non-Degen. (II)

$S_{CP}(B_d \to \phi K_S) - S_{CP}(B_d \to J/\psi K_S)$



SU(5) Degen SU(5) Non-Degen. (I) SU(5) Non-Degen. (II)

$S_{CP}(B_s \to J/\psi\phi)$



$S_{CP}(B_s \to J/\psi\phi)$

$m(\tilde{d}_1)$[GeV]

SU(5) Degen SU(5) Non-Degen. (I) SU(5) Non-Degen. (II)