Patterns of flavor signals in supersymmetric models and $a_{\rm sl}^{d,s}$

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CPV from B factories to Tevatron and LHCb,
Tohoku U, 02 September 2010

Introduction

The motivation of this meeting: "Evidence for an anomalous like-sign dimuon charge asymmetry" [D0, arXiv:1005.2757]

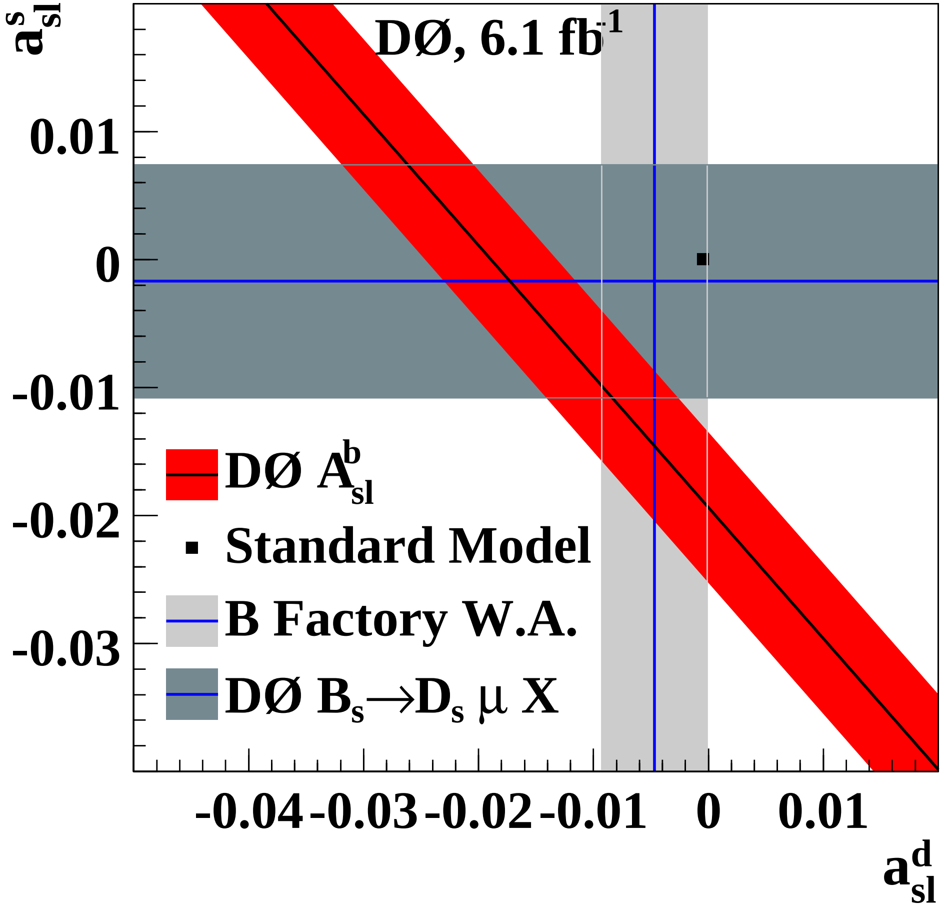
- $A^b_{\rm sl} = -0.00957 \pm 0.00251 \pm 0.00146$
- $A^b_{\rm sl}({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$
  $\Longrightarrow$ $3.2\,\sigma$ deviation.

$$A^b_{\rm sl} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}, \qquad N_b^{\pm\pm} = \#\text{ of } b\bar{b} \to \mu^\pm \mu^\pm X \text{ events}$$

$A^b_{\rm sl}$ is written by a linear combination of $a^d_{\rm sl}$ and $a^s_{\rm sl}$.

$$a^q_{\rm sl} = \frac{\Gamma(\overline{B}{}^0_q(t) \to \ell^+ X) - \Gamma(B^0_q(t) \to \ell^- X)}{\Gamma(\overline{B}{}^0_q(t) \to \ell^+ X) + \Gamma(B^0_q(t) \to \ell^- X)}, \qquad q = d,\, s.$$

$$B^0_q(t=0) = B^0_q\,[\bar{b}q], \qquad \overline{B}{}^0_q(t=0) = \overline{B}{}^0_q\,[b\bar{q}].$$



$1\,\sigma$ bands of a^d_{sl}, a^s_{sl} and A^b_{sl}.

- a^d_{sl} and a^s_{sl} are consistent with SM predictions within $1\,\sigma$.
- Three measurements are consistent with each other.
  - ▷ Overlapping region is away from the SM point.
- Theo. uncert. $\ll$ Exp. uncert.
  - ▷ $a^d_{\text{sl}} = (-4.8^{+1.0}_{-1.2}) \times 10^{-4}$
  - ▷ $a^s_{\text{sl}} = (2.06 \pm 0.57) \times 10^{-5}$ [Lenz & Nierste 2006]

[arXiv:1005.2757]

Good news, since people who are working on flavor physics frequently argue...

Flavor physics = probe for new physics beyond the SM.

- Heavy particles and their interactions contribute in various ways.

$\Rightarrow$ Plays a complementary role with direct measurements (@LHC).

  - ▷ SM: $b \to s, d$ (flavor) $\oplus$ m_t (direct) $\Rightarrow$ V_{td}, V_{ts}.
  - ▷ Similar case will occur in the study of physics beyond the SM.
    - $*$ $b \to s, d \oplus m_{\tilde{q}} \Rightarrow q_i - \tilde{q}_j - \tilde{g}$ coupling.

Experimental improvements expected.

- LHCb: $S_{\text{CP}}(B_s \to J/\psi\phi)$, $\cdots$.
- Super B factories with $\int \mathcal{L} = 50 - 75\text{ab}^{-1}$:

$\Rightarrow$ uncertainties reduced by $\sim \frac{1}{7}$ $(\int \mathcal{L}(\text{KEKB} + \text{PEPII}) \gtrsim 1.5\text{ab}^{-1})$.

- MEG: search for $\mu \to e\,\gamma$ with b.r. down to 10^{-13}.
  - ▷ current upper limit: $\text{B}(\mu \to e\,\gamma) < 1.1 \times 10^{-11}$ [MEGA].

Now that an "evidence" of BSM is given, its implication has to be studied ($\Longrightarrow$ talks in this meeting).

In PRD77(2008)095010 [arXiv:0711.2935], we (Goto, Okada, Shindou & Tanaka) studied quark/lepton flavor signals:

- LFV ($\mu \to e\,\gamma$, $\tau \to \mu\,\gamma$, $\tau \to e\,\gamma$),
- CP Asymmetries in B decays,
  - ▷ $S_{\mathrm{CP}}(B_d \to K^*\,\gamma)$, $S_{\mathrm{CP}}(B_d \to \rho\,\gamma)$
  - ▷ $S_{\mathrm{CP}}(B_d \to \phi\,K_S)$
  - ▷ $S_{\mathrm{CP}}(B_s \to J/\psi\,\phi)$

in SUSY models with various flavor structures:

- mSUGRA,
- MSSM with ν_R's,
- SU(5) SUSY GUT with ν_R's,
- U(2) Flavor Symmetry model.

We showed the pattern of flavor signals varies depending on the model.

$\Longrightarrow$ Flavor measurements are useful to distinguish models.

Although we did not study $a_{\rm sl}^{d,s}$ in the published paper, we computed SUSY corrections to $B^0-\overline{B}^0$ mixings matrix elements $M_{12}(B_{d,s})$ in order to evaluate:

- $B_{d,s}^0-\overline{B}_{d,s}^0$ mass splittings;
- Mixing-induced (time-dependent) CP asymmetries.

$\Longrightarrow$ $a_{\rm sl}^{d,s}$ can be calculated also.

Contents in the following:

- Models
- Numerical results ($\ni a_{\rm sl}^{d,s}$)
- Conclusion

Models

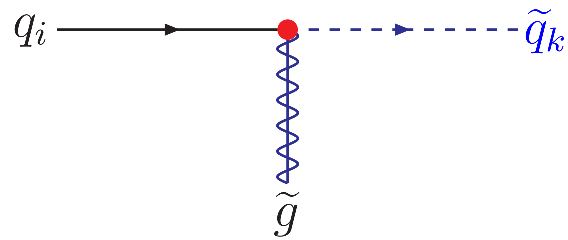
Minimal Supersymmetric Standard Model: a promising candidate for the physics beyond the SM.

MSSM = SM (gauge, Higgs, quarks/leptons, Yukawa)
+ extra Higgs doublet (type-II at tree level)
+ Supersymmetry (superpartners, interactions)
+ soft SUSY breaking ($>$ 100 parameters).

Sources of flavor mixing:

- Yukawa couplings $\rightarrow$ CKM (as in the SM).
- Soft SUSY breaking terms:
  - ▷ Squark/slepton mass matrices,
  - ▷ Trilinear scalar couplings ("A"-terms).

Mismatch between quark and squark mass bases
$\Rightarrow$ flavor mixing in quark–squark–"inos" couplings.



Mass matrices of down-type quarks and squarks:

$$\mathcal{M}_d = Y_D v_1,$$

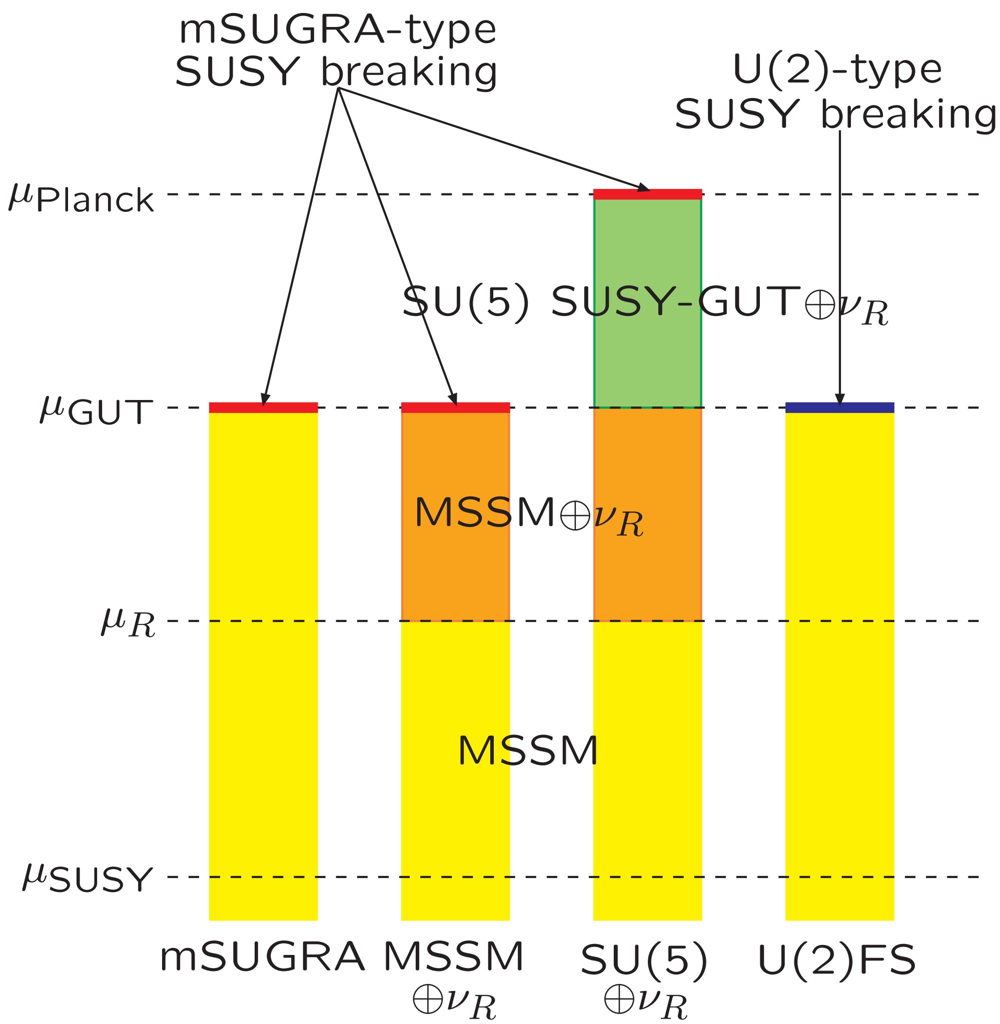
$$\mathcal{M}_{\tilde{d}}^2 = \begin{pmatrix} m_Q^2 + Y_D^\dagger Y_D v_1^2 + D_{d_L} & A_D^\dagger v_1 - \mu Y_D^\dagger v_2 \\ A_D v_1 - \mu^* Y_D v_2 & m_D^2 + Y_D Y_D^\dagger v_1^2 + D_{d_R} \end{pmatrix}, \quad \begin{matrix} \leftarrow \tilde{d}_L \\ \leftarrow \tilde{d}_R \end{matrix}$$

not simultaneously diagonalized *due to the soft SUSY breaking terms* m_Q^2, m_D^2 *and* A_D.

Studying flavor mixing in the MSSM $\Updownarrow$ Studying structure of soft SUSY breaking terms.

Models: Minimal Supersymmetric Standard Model $+\alpha$

"$+\alpha$": mechanism which controls flavor mixing in SUSY breaking.



- mSUGRA: $Y_{U,D}$ (V_{CKM}) only.
  - ▷ Flavor-blind SUSY breaking m_0, $m_{1/2}$, A_0.
- MSSM$\oplus\nu_R$: Y_ν affects running.
  - ▷ SUSY breaking = mSUGRA.
  - ▷ GUT: quark $\leftrightarrow$ lepton.
- U(2) flavor symmetry:
  - ▷ $Y_{U,D} \sim \begin{bmatrix} & \epsilon' & \\ \epsilon' & \epsilon & \epsilon \\ & \epsilon & 1 \end{bmatrix}$,
    ($\epsilon \sim V_{cb}$, $\epsilon'/\epsilon \sim V_{us}$).
  - ▷ $m^2_{Q,U,D} \sim m_0^2 \begin{bmatrix} 1 & & \\ & 1 & \epsilon \\ & \epsilon & O(1) \end{bmatrix}$,

Flavor mixing/CPV source

- V_{CKM} (all cases) $\Longrightarrow$ $\tilde{q}_L$ mixing (running).
  - ▷ Significant in $\mathrm{B}(b \to s\,\gamma)$; small in others.
  - ▷ GUT $\Longrightarrow$ $\tilde{\ell}_R$ mixing (Barbieri-Hall). $\mathbf{10} = \{q_L, (u_R)^c, (e_R)^c\}$.
- Y_ν (cases with ν_R's) $\Longrightarrow$ $\tilde{\ell}_L$ mixing (running above μ_R).
  - ▷ GUT $\Longrightarrow$ $\tilde{d}_R$ mixing (Moroi) $\bar{\mathbf{5}} = \{(d_R)^c, \ell_L\}$.
- $m^2_{Q,U,D}(\mu_{\text{GUT}})$ (U(2)FS).
  - ▷ U(2) structure neglected in (s)lepton sector.
- SUSY CPV phases (ϕ_A, ϕ_μ, $\cdots$).
  - ▷ Affect CP asymmetries in b decays, EDMs (e, n, Hg).

Structure of the neutrino mass matrices (MSSM$\oplus\nu_R$, SU(5)$\oplus\nu_R$)

Light: $|\Delta m^2_{32}|$(atm) $\gg \Delta m^2_{21}$(sol)

- Normal Hierarchy
  - ▷ $m_3 \gg m_2 \gg m_1 = 0.003\text{eV}$. ($\Delta m^2_{21} \gg m_1^2$)
- Inverted Hierarchy
  - ▷ $m_2 > m_1 \gg m_3$.
- Degenerate
  - ▷ $m_3 > m_2 > m_1$, $m_1^2 = (0.1\text{eV})^2 \gg |\Delta m^2_{32}|$.

Heavy (ν_R):

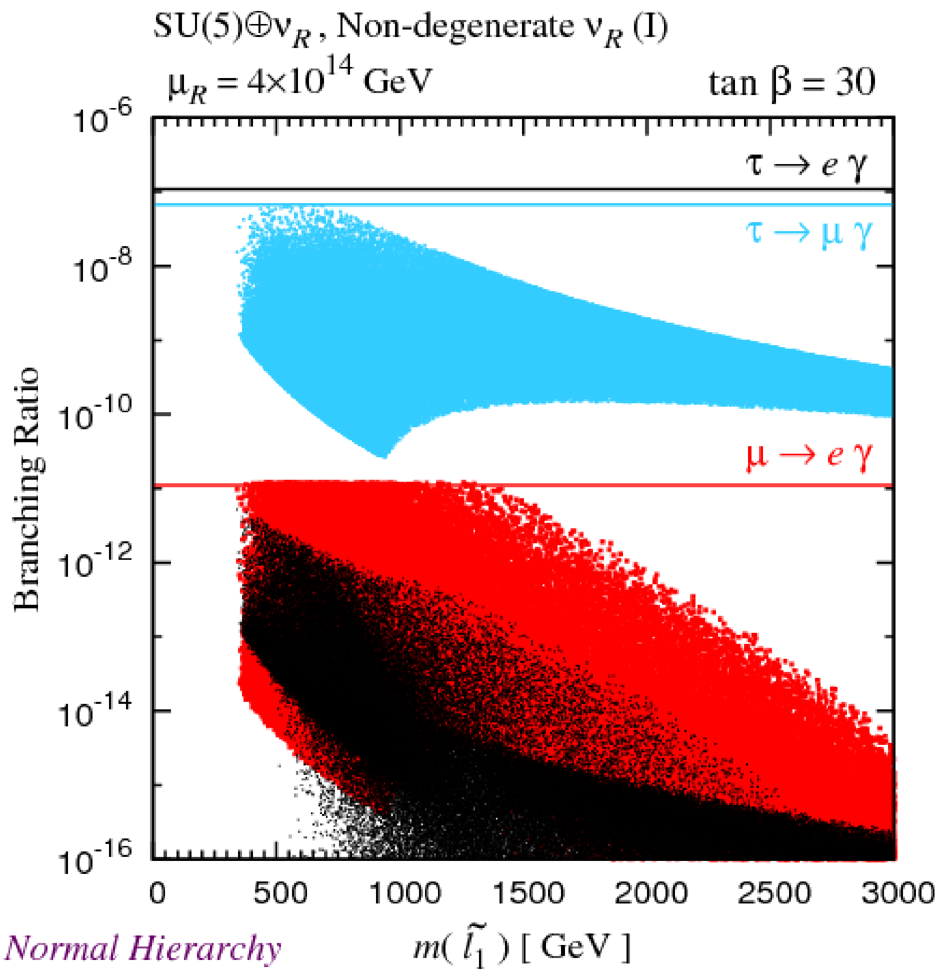
- Degenerate ν_R: $M_{\nu_R} \propto \mathbf{1}$.
  - ▷ $\mu \to e\,\gamma$ enhaced.
- Non-Degenerate ν_R: $M_{\nu_R} \not\propto \mathbf{1}$.
  - ▷ More free parameters in Y_ν.
  - ▷ $\mu \to e\,\gamma$ suppression possible.

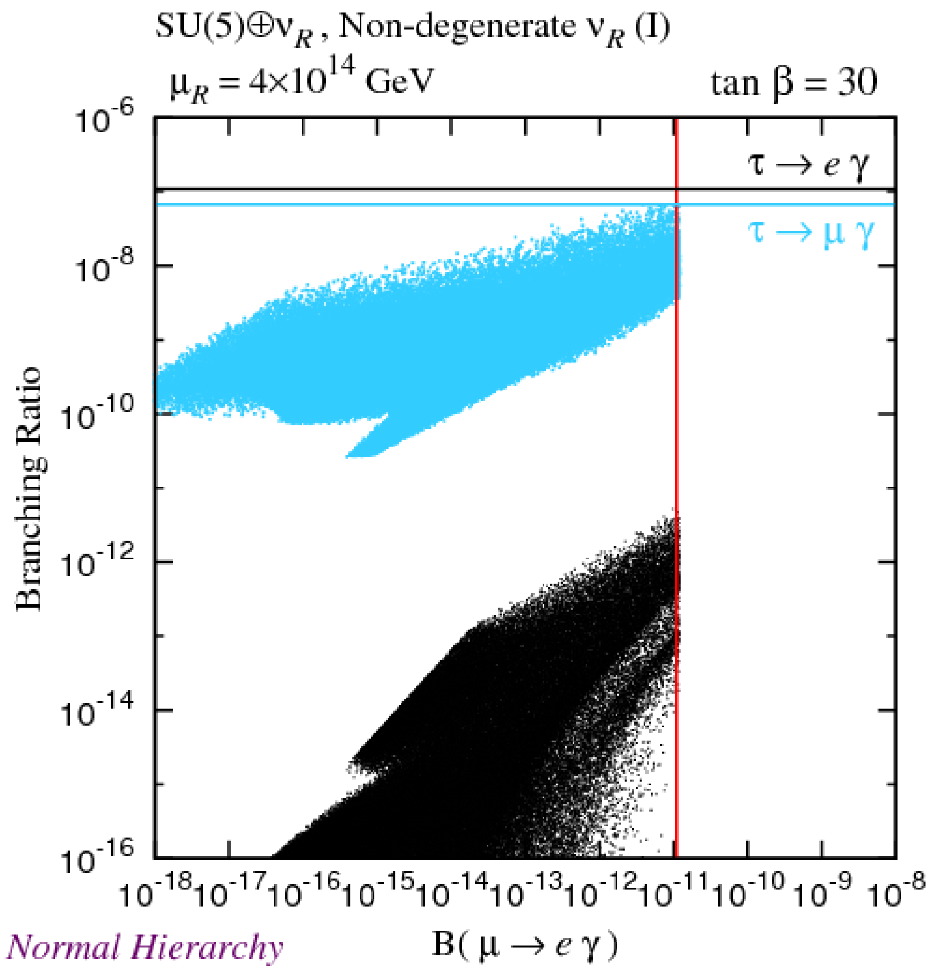
(I) $(Y_\nu)_{12} = (Y_\nu)_{21} = 0$, $(Y_\nu)_{13} = (Y_\nu)_{31} = 0$.

(II) $(Y_\nu)_{12} = (Y_\nu)_{21} = 0$, $(Y_\nu)_{23} = (Y_\nu)_{32} = 0$.

LFV: $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$

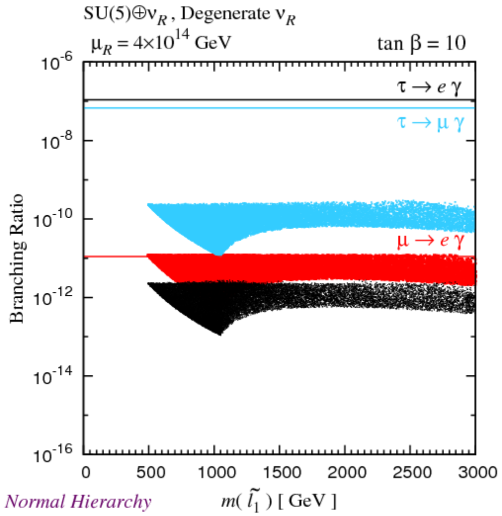
SU(5)$\oplus\nu_R$, Non-degenerate ν_R (I), Normal Hierarchy



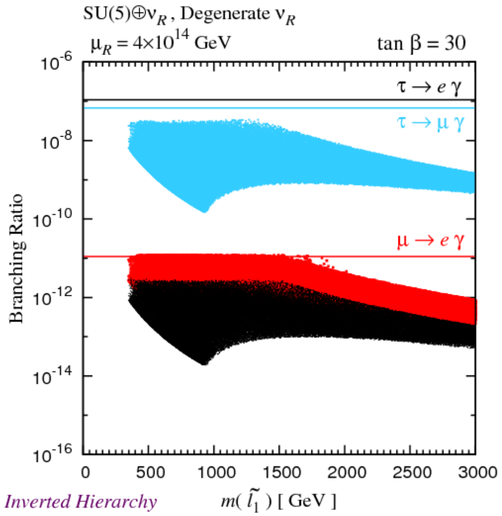


$m_{1/2}(\mu_G) \leq 1.5$TeV, $m_0(\mu_P) \leq 4$TeV scanned.

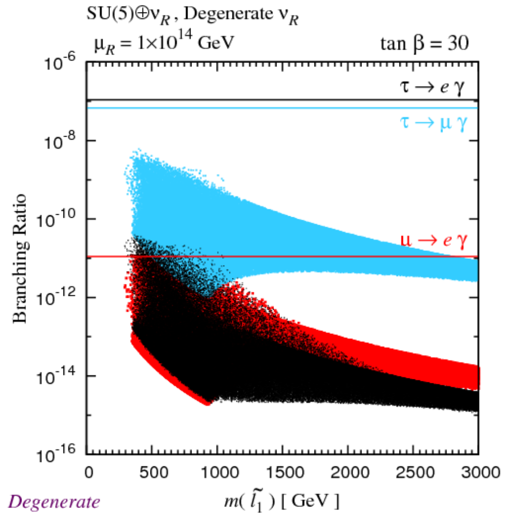
$\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$: SU(5)$\oplus\nu_R$ (Y_ν & $\mu_P \leftrightarrow \mu_G$ running)



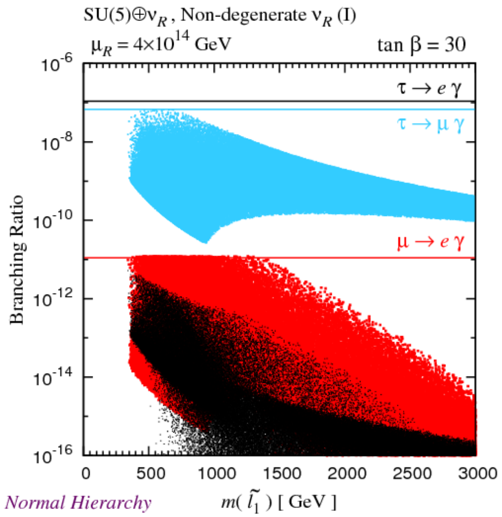
$D\nu_R$-NH



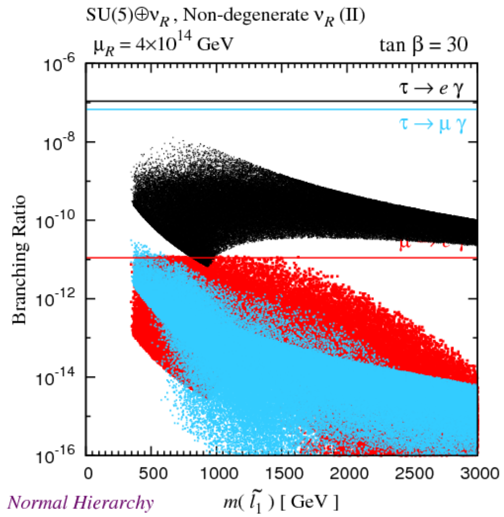
$D\nu_R$-IH



$D\nu_R$-D

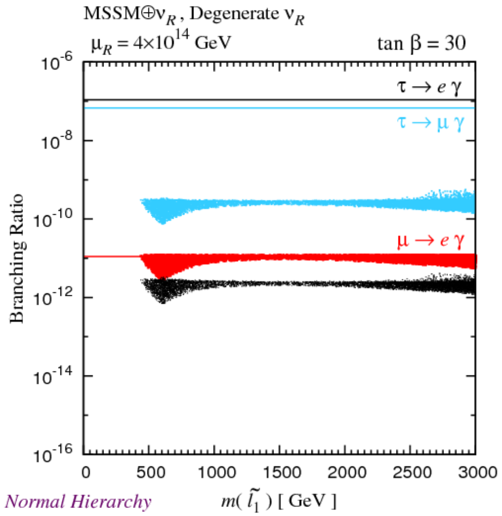


$ND\nu_R$(I)-NH

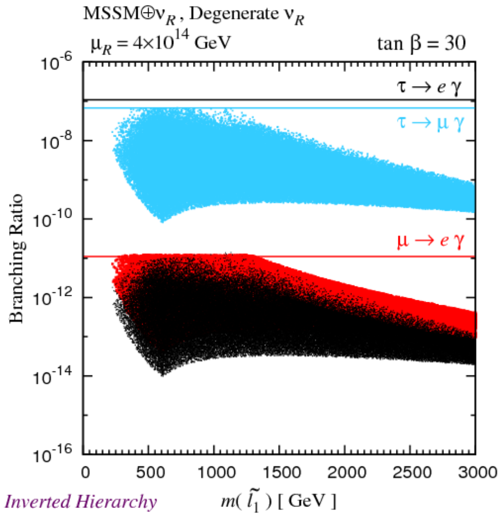


$ND\nu_R$(II)-NH

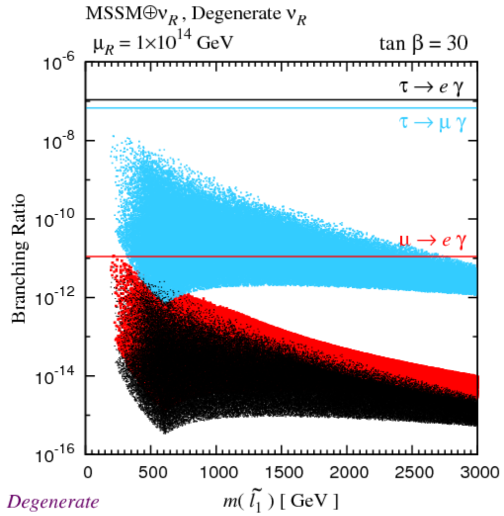
$\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$: MSSM$\oplus\nu_R$ (Y_ν only)



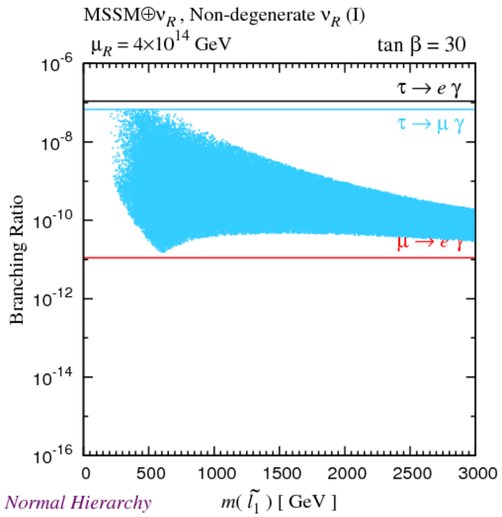
Dν_R-NH



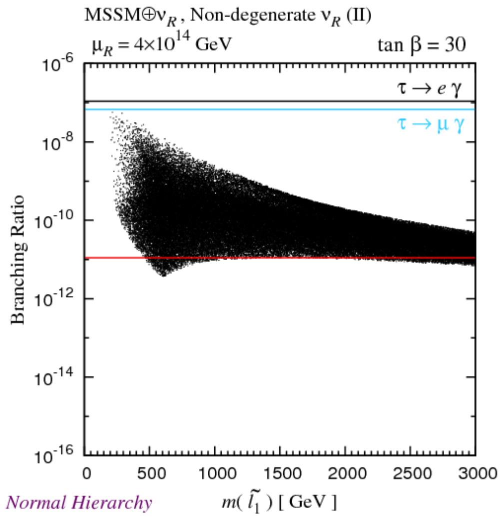
Dν_R-IH



Dν_R-D



NDν_R(I)-NH



NDν_R(II)-NH

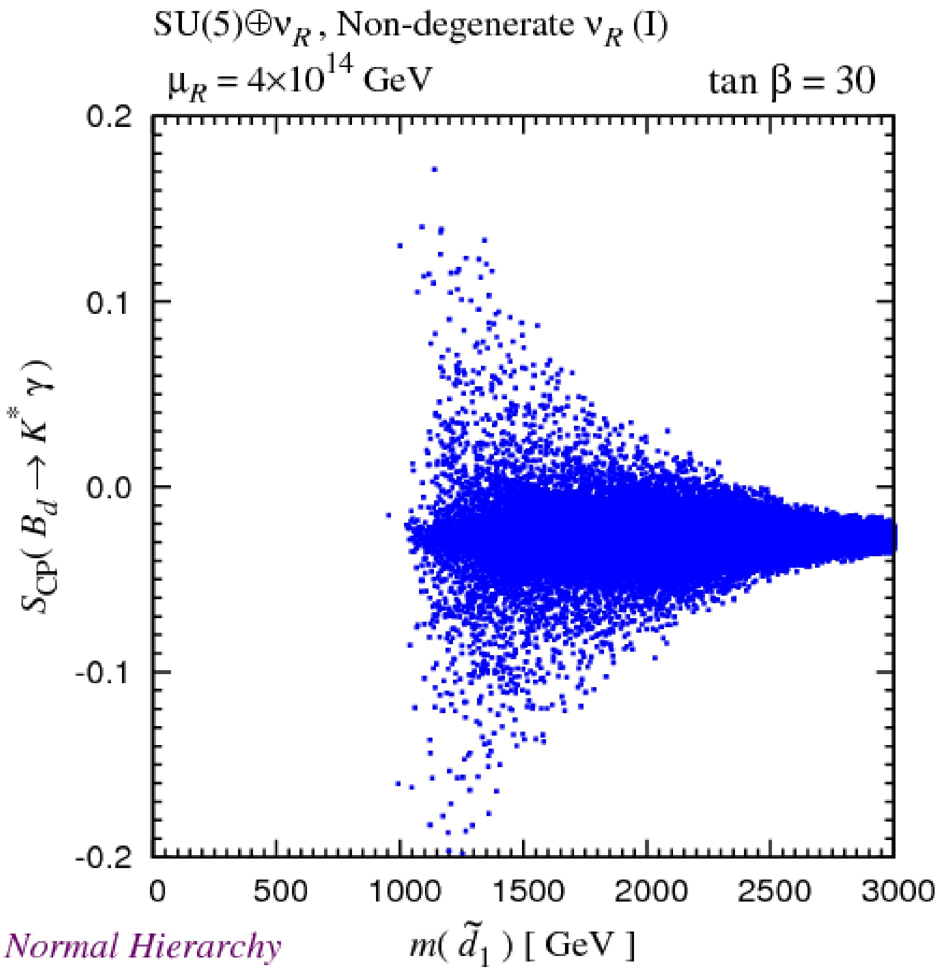
Time-dependent CP asymmetries in $b \to s/b \to d$ decays

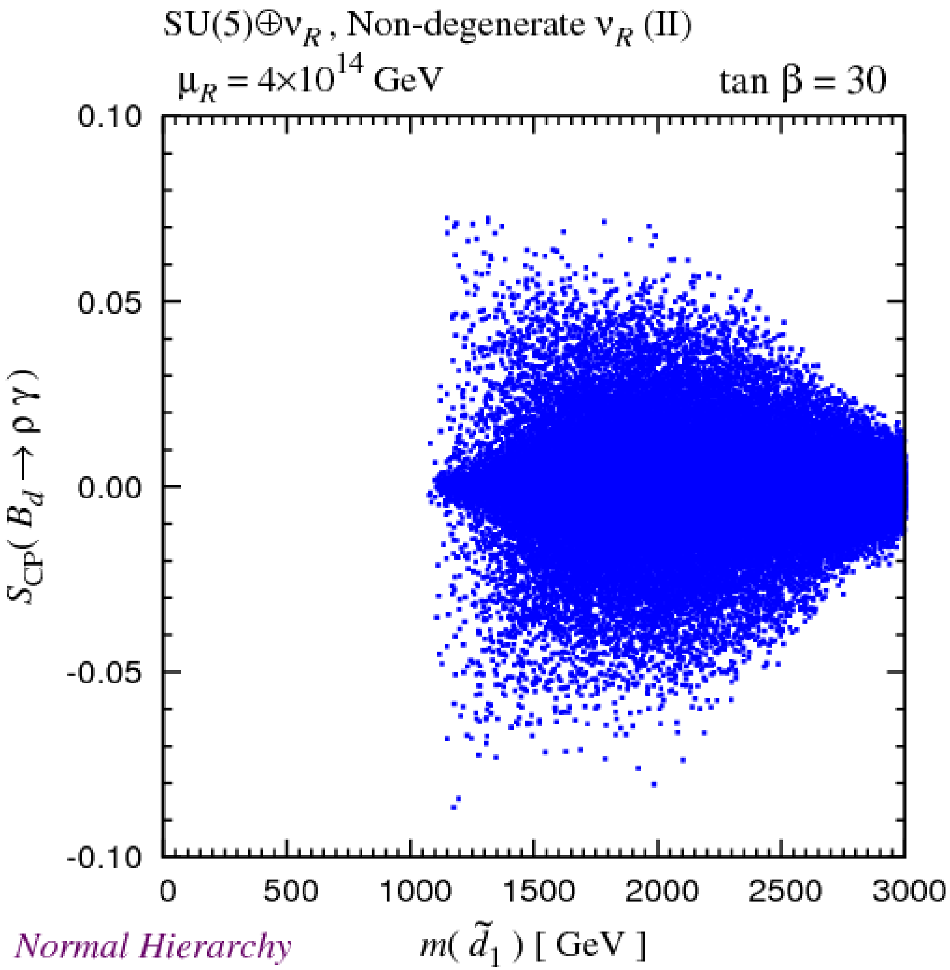
- $S_{CP}(B_d \to K^* \gamma)$, $S_{CP}(B_d \to \rho \gamma)$
  - ▷ $B_d - \overline{B}_d$ mixing $\otimes$ $b \to s(d)\gamma$ decay.
  - ▷ Interference between $b_R \to s(d)_L \gamma_L$ and $(\bar{b}_L) \to (s(\bar{d})_R)\gamma_L$; suppressed by $m_{s,d}/m_b$ in SM (Atwood-Gronau-Soni).
- $S_{CP}(B_d \to \phi K_S)$
  - ▷ $B_d - \overline{B}_d$ mixing $\otimes$ $b \to s s \bar{s}$ decay.
  - ▷ Differs from $S_{CP}(B_d \to J/\psi K_S)$ if new phase exists in $b \to s$ penguin amplitude.
- $S_{CP}(B_s \to J/\psi \phi)$
  - ▷ $B_s - \overline{B}_s$ mixing $\otimes$ $b \to s c \bar{c}$ decay.
  - ▷ Small in SM; enhanced if new phase exists in $B_s - \overline{B}_s$ mixing.

$\Longrightarrow$ $\tilde{d}_R$ mixing can contribute to all.

- Significant in SU(5) SUSY-GUT$\oplus\nu_R$ and U(2)FS.

$S_{\mathrm{CP}}(B_d \to K^*\gamma)$ [$b \to s$], $S_{\mathrm{CP}}(B_d \to \rho\gamma)$ [$b \to d$]

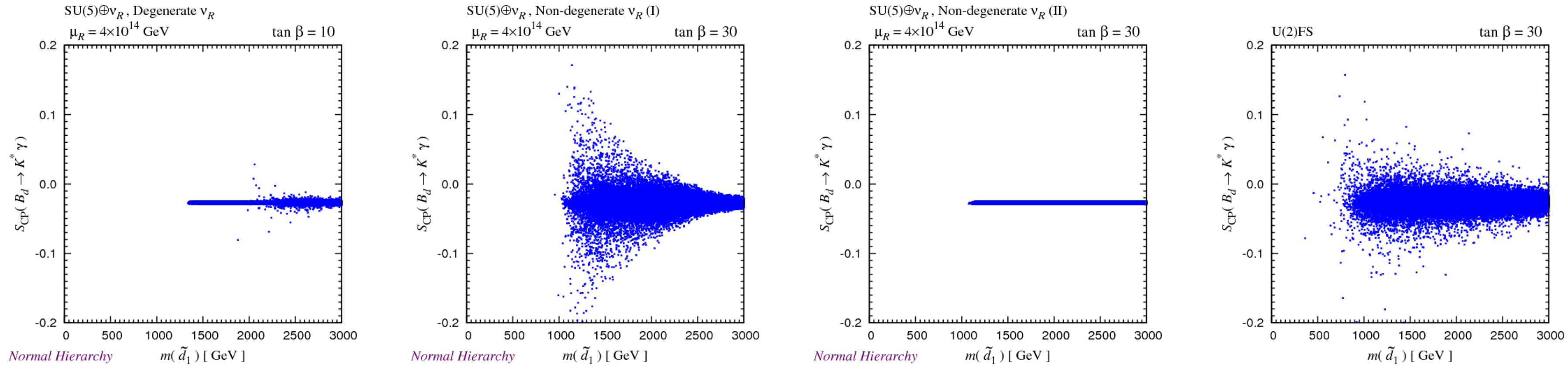




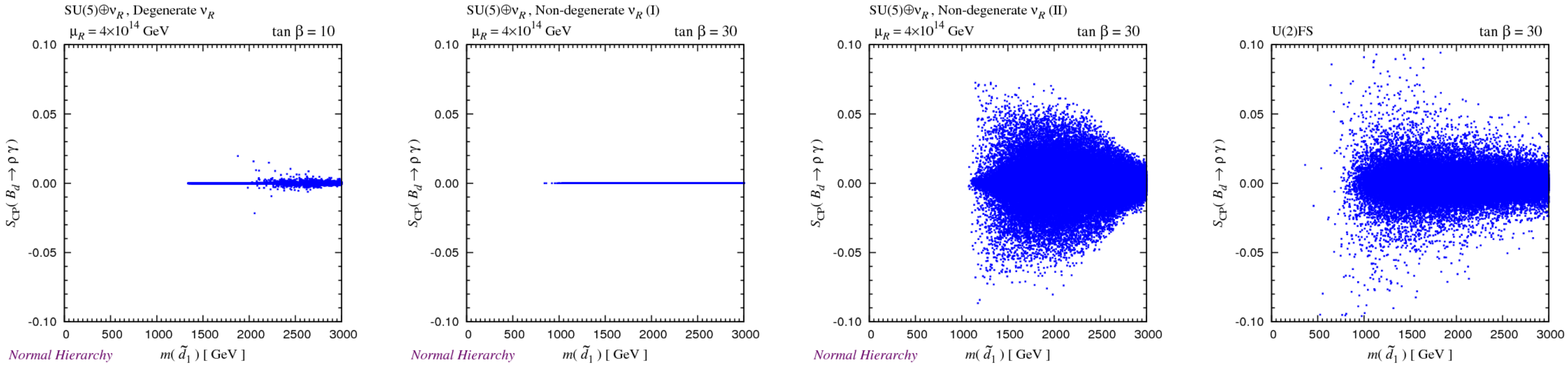
$S_{\mathrm{CP}}(B_d \to K^*\gamma)$ $[b \to s]$, $S_{\mathrm{CP}}(B_d \to \rho\gamma)$ $[b \to d]$

Significant in SU(5)$\oplus\nu_R$, U(2)FS; small in mSUGRA, MSSM$\oplus\nu_R$.

$S_{\mathrm{CP}}(B_d \to K^*\gamma)$ vs. $m(\tilde{d}_1)$



Dν_R-NH NDν_R(I)-NH NDν_R(II)-NH U(2)FS

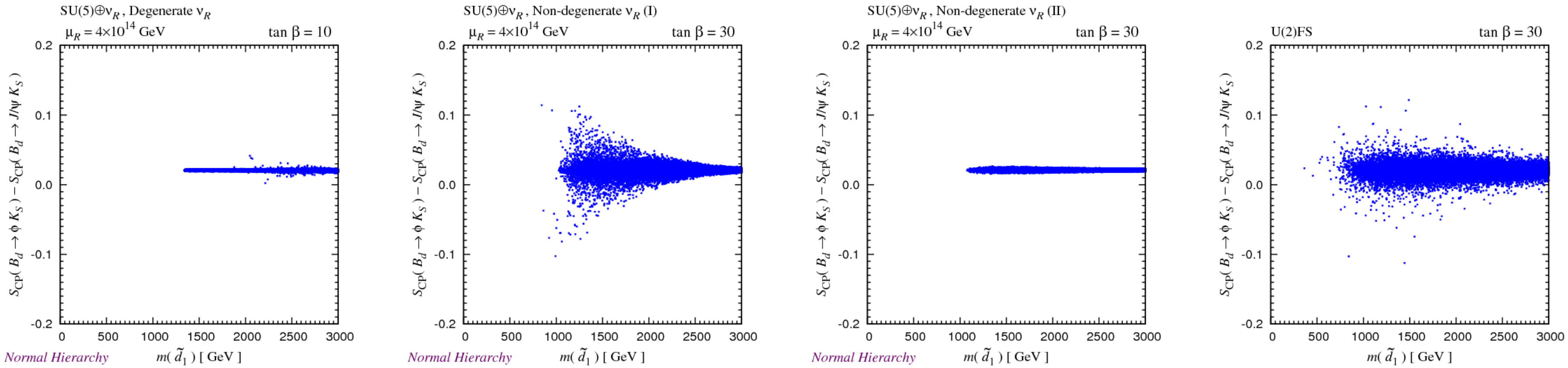


$S_{\mathrm{CP}}(B_d \to \rho\gamma)$ vs. $m(\tilde{d}_1)$

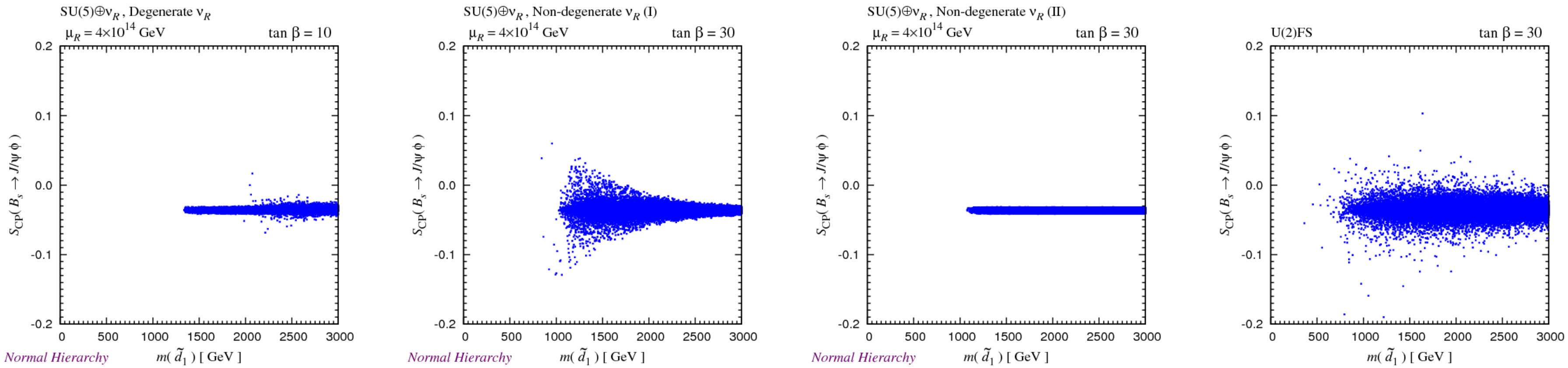
$S_{\rm CP}(B_d \to \phi K_S)$, $S_{\rm CP}(B_s \to J/\psi\phi)$ $[b \to s]$

Significant in SU(5)$\oplus\nu_R$, U(2)FS; small in mSUGRA, MSSM$\oplus\nu_R$.

$S_{\rm CP}(B_d \to \phi K_S) - S_{\rm CP}(B_d \to J/\psi K_S)$ vs. $m(\tilde{d}_1)$



Dν_R-NH | NDν_R(I)-NH | NDν_R(II)-NH | U(2)FS



$S_{\rm CP}(B_s \to J/\psi\phi)$ vs. $m(\tilde{d}_1)$

Summary: LFV

Model	$\mu \to e\gamma$	$\tau \to \mu\gamma$	$\tau \to e\gamma$
MSSM$\oplus\nu_R$			
Degenerate ν_R, NH	$\surd$		
Degenerate ν_R, IH	$\surd$	$\surd$	
Degenerate ν_R, D	$\surd$	$\surd$	
Non-degen. ν_R (I), NH		$\surd$	
Non-degen. ν_R (II), NH			$\surd$
SU(5)$\oplus\nu_R$			
Degenerate ν_R, NH	$\surd$		
Degenerate ν_R, IH	$\surd$	$\surd$	
Degenerate ν_R, D	$\surd$	$\surd$	
Non-degen. ν_R (I), NH	$\surd$	$\surd$	
Non-degen. ν_R (II), NH	$\surd$		$\surd$
Exp. sensitivity	10^{-13}	$2-8\times10^{-9}$	
	MEG	SuperB@$50-75$ab^{-1}	

$\surd$: B$(\mu \to e\,\gamma) \sim 10^{-11}$, B$(\tau \to \mu(e)\gamma) \sim 10^{-8}$ possible.

Summary: Time-dependent CPV in $b \to s(d)$

	$S_{\text{CP}}(K^*\gamma)$	$S_{\text{CP}}(\rho\gamma)$	$\Delta S_{\text{CP}}(\phi K_S)$	$S_{\text{CP}}(B_s \to J/\psi\phi)$
SU(5)$\oplus\nu_R$				
Dν_R, NH	~ 0.01	~ 0.01	~ 0.01	~ 0.01
Dν_R, IH	~ 0.2	~ 0.02	~ 0.2	~ 0.1
Dν_R, D	~ 0.01	~ 0.01	~ 0.01	~ 0.01
NDν_R(I), NH	~ 0.2		~ 0.1	~ 0.1
NDν_R(II), NH		~ 0.1		
U(2)FS	~ 0.2	~ 0.1	~ 0.1	~ 0.1
Exp. precision	$0.02-0.03$	$0.08-0.12$	$0.02-0.03$	~ 0.01
	SuperB@$50-75\text{ab}^{-1}$			LHCb@10fb^{-1}

- Small in mSUGRA, MSSM$\oplus\nu_R$.

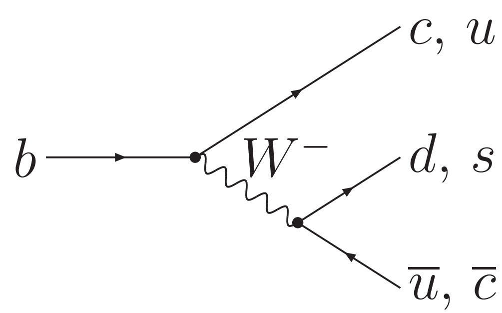
Semileptonic asymmetries

$$\boxed{a_{\mathrm{sl}}^{q} = \mathrm{Im}\,\frac{\Gamma_{12}}{M_{12}}} \qquad (|\Gamma_{12}| \ll |M_{12}| \text{ for } B^0 - \overline{B}^0).$$

$$|\Psi(t)\rangle = c(t)|B_q^0\rangle + \bar{c}(t)|\overline{B}_q^0\rangle$$

$$i\frac{d}{dt}\begin{pmatrix} c(t) \\ \bar{c}(t) \end{pmatrix} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^{*} - \frac{i}{2}\Gamma_{12}^{*} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}\begin{pmatrix} c(t) \\ \bar{c}(t) \end{pmatrix}$$

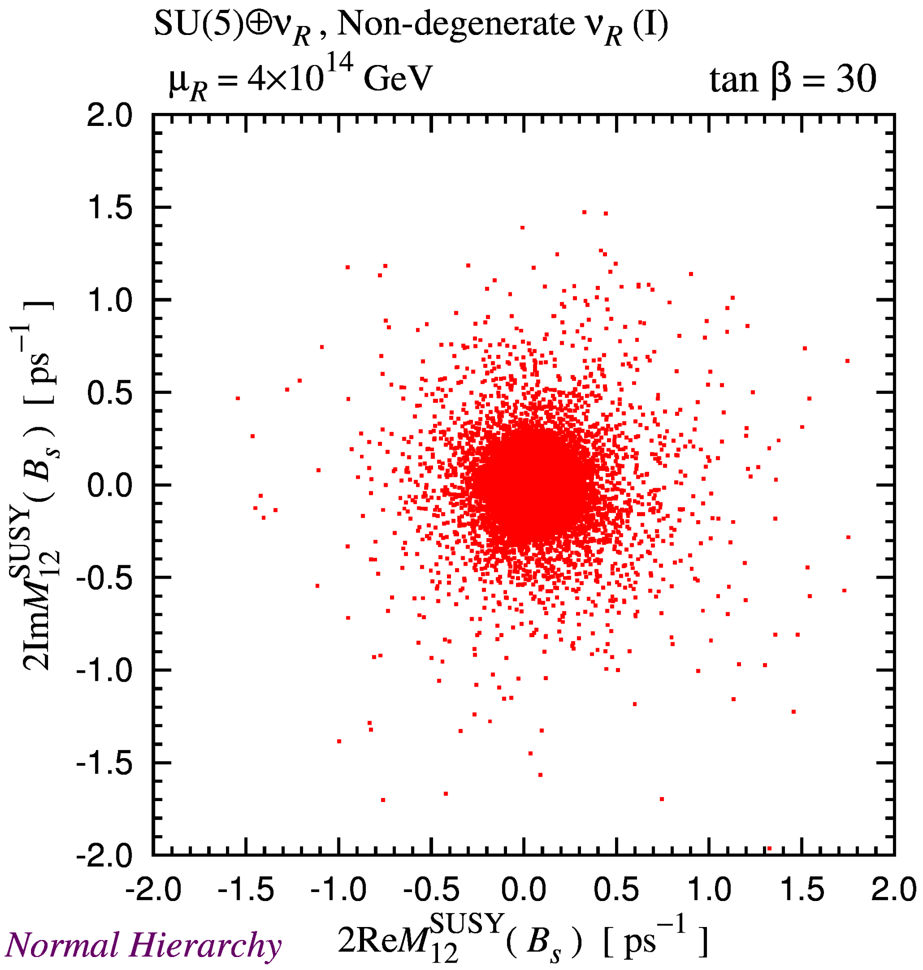
$$|B_q^0(t)\rangle \Longrightarrow c(0) = 1, \quad \bar{c}(0) = 0,$$
$$|\overline{B}_q^0(t)\rangle \Longrightarrow c(0) = 0, \quad \bar{c}(0) = 1.$$

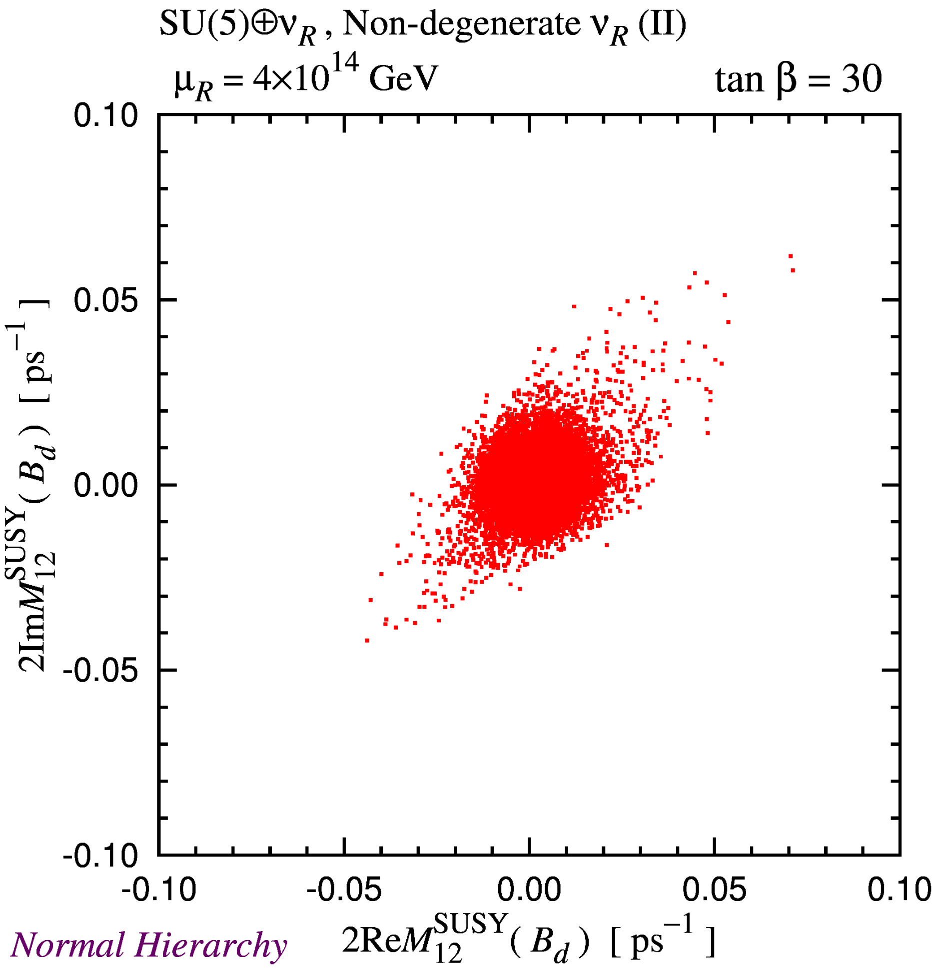


It is reasonable to assume $\Gamma_{12} = \Gamma_{12}^{\mathrm{SM}}$, since the decay process is dominated by tree-level W exchange.

$\Longrightarrow$ M_{12}^{SUSY} generates deviations in $a_{\mathrm{sl}}^{d,s}$.

SUSY contribution to M_{12}: $M_{12} = M_{12}^{\mathrm{SM}} + M_{12}^{\mathrm{SUSY}}$



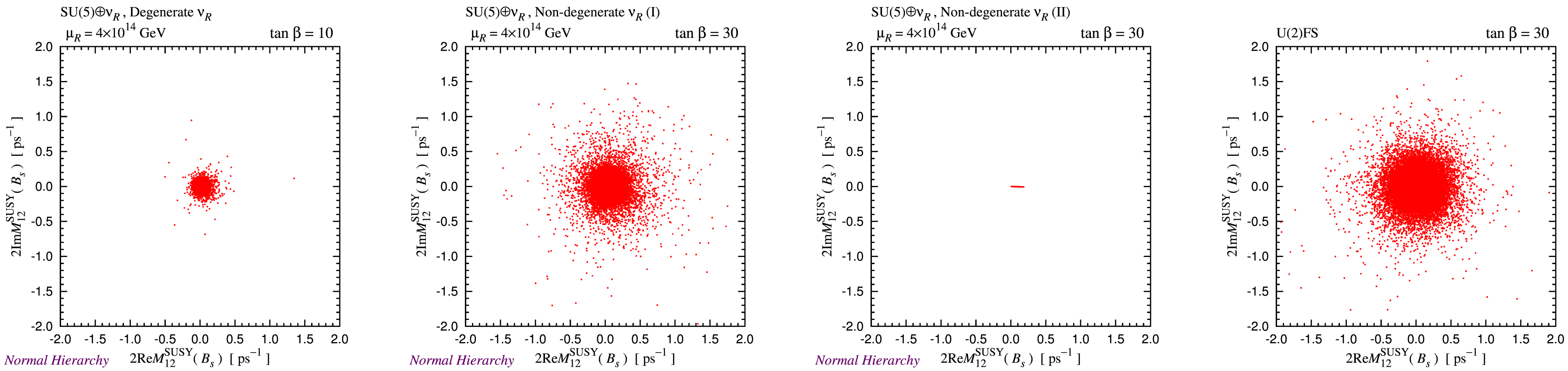


$\Delta M(B_s) = 17.77\,\mathrm{ps}^{-1}$ $\qquad$ $\Delta M(B_d) = 0.507\,\mathrm{ps}^{-1}$

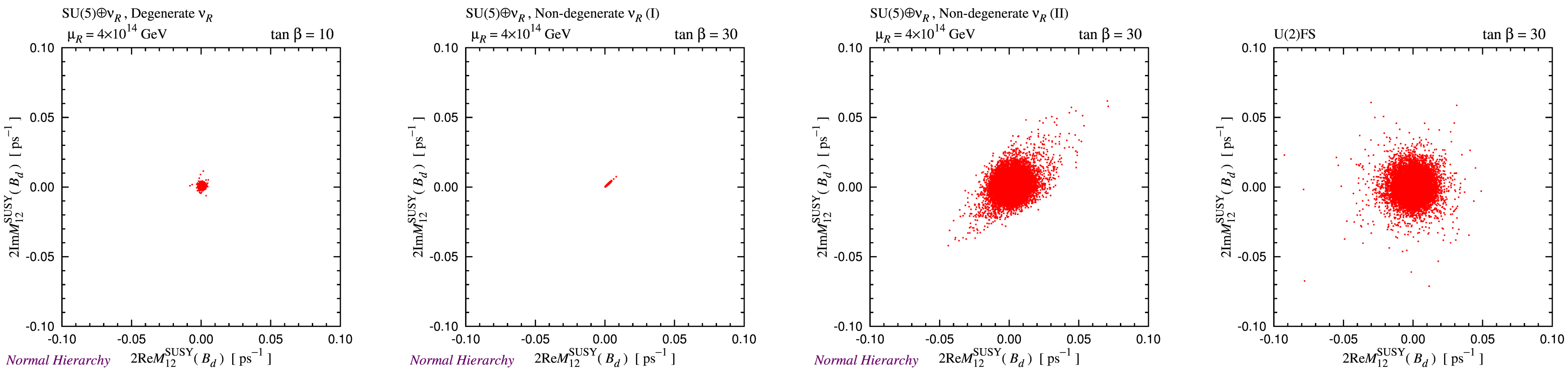
SUSY contribution to M_{12}

$$M_{12} = M_{12}^{\mathrm{SM}} + M_{12}^{\mathrm{SUSY}}.$$

$M_{12}^{\mathrm{SUSY}}(B_s)$

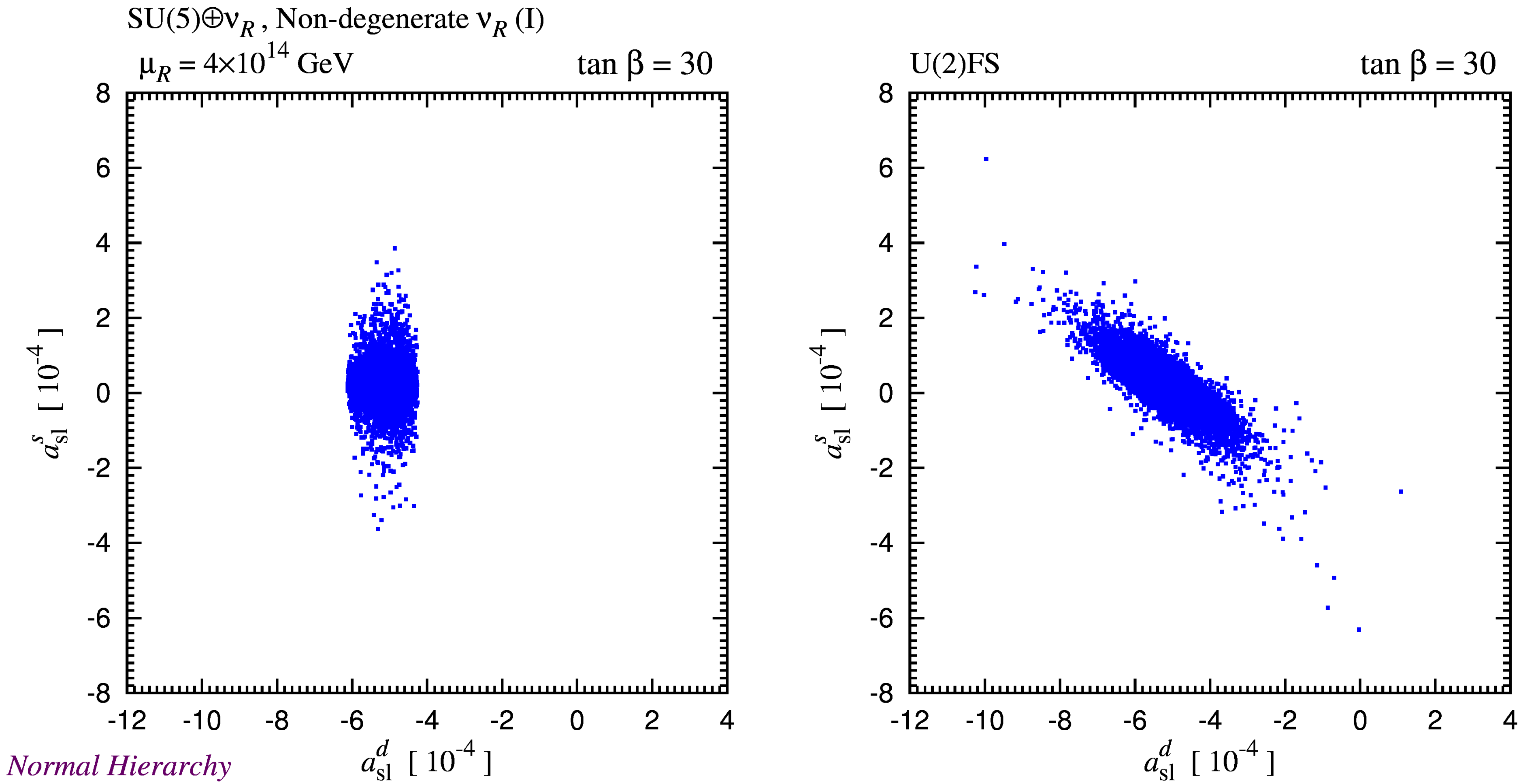


$\mathrm{D}\nu_R$-NH $\mathrm{ND}\nu_R(\mathrm{I})$-NH $\mathrm{ND}\nu_R(\mathrm{II})$-NH U(2)FS



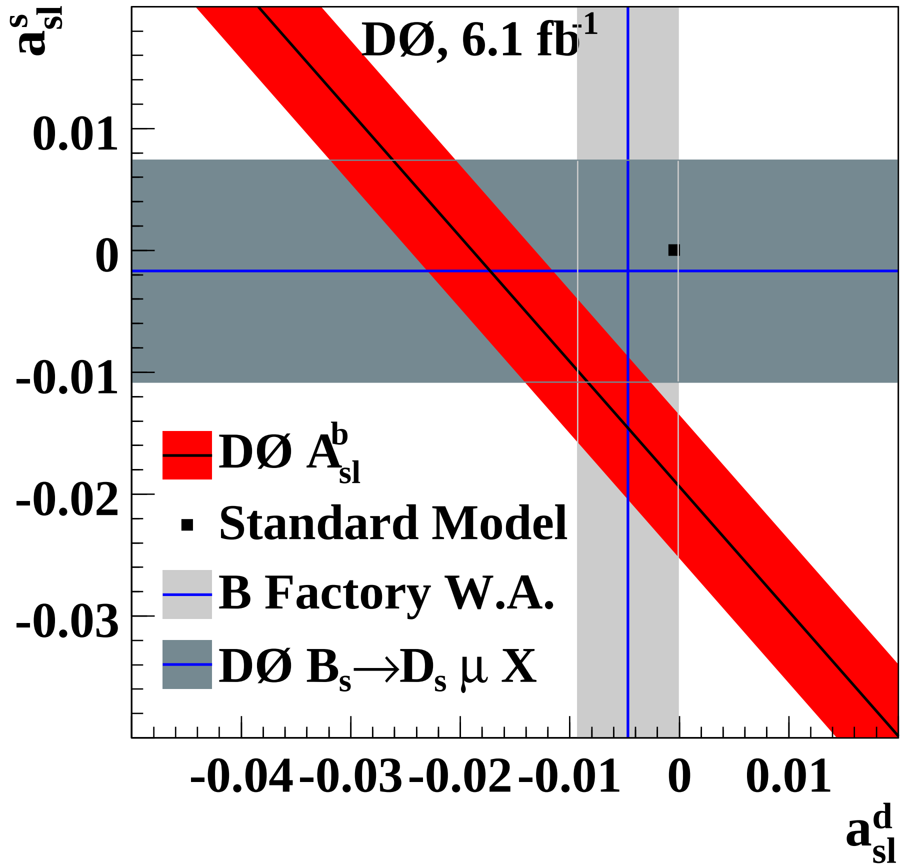
$M_{12}^{\mathrm{SUSY}}(B_d)$

$a_{\rm sl}^{d,s}$

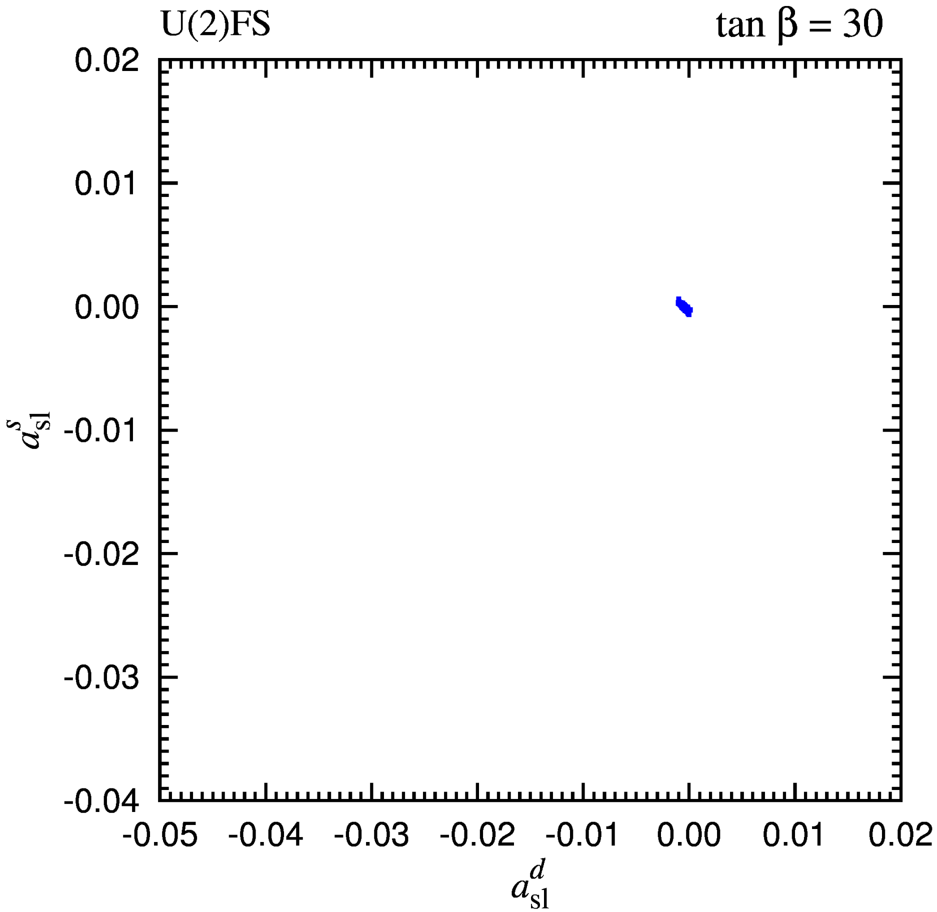


Deviations can be significantly larger than SM uncertainties, but...

$a_{\rm sl}^{d,s}$



DØ, 6.1 fb-1
0.01
0
-0.01
-0.02
-0.03
-0.04 -0.03 -0.02 -0.01 0 0.01
a_{sl}^{s}
a_{sl}^{d}
DØ A_{sl}^{b}
Standard Model
B Factory W.A.
DØ $B_s \to D_s \mu X$



U(2)FS
tan β = 30
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05 -0.04 -0.03 -0.02 -0.01 0.00 0.01 0.02
a_{sl}^{s}
a_{sl}^{d}

Conclusion

- Quark and lepton flavor signals are studied for SUSY models with various flavor structures.
- Each model gives different pattern of signals in $b \to s$, $b \to d$ and LFV processes.
- Measuring many processes is important to explore flavor structure of new physics beyond the SM.
- Reducing theoretical (hadronic) uncertainties in SM predictions to $O(\%)$ level is important.
- $a_{\rm sl}^{d,s}$ can be different from SM values, but insufficient to saturate the newly measured anomaly in the models studied here.