SUSY and Electric Dipole Moments

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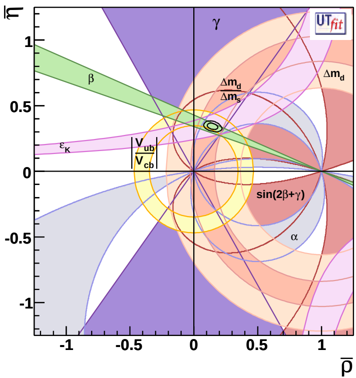
NP search strategies

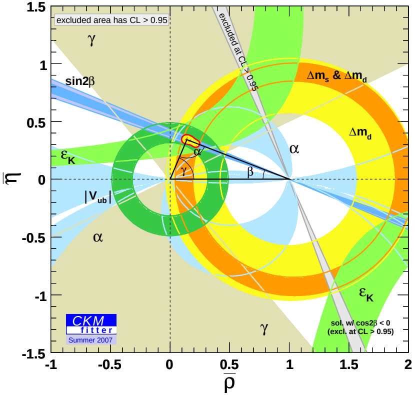
Where to look for New Physics?

- **Processes very suppressed or even forbidden in the SM**
  - FCNC processes ($\mu \to e\gamma$, $\tau \to \mu\gamma$, $B^0_{s,d} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$)
  - CPV effects (electron/neutron EDMs, $d_{e,n}$....)
  - CPV in $B_{s,d}$ decay/mixing amplitudes

- **Processes predicted with high precision in the SM**
  - EWPO as $\Delta\rho$, $(g-2)_\mu$....
  - LU in $R_M^{e/\mu} = \Gamma(K(\pi) \to e\nu)/\Gamma(K(\pi) \to \mu\nu)$

SM success





Impressive confirmation of the KM mechanism for CP violation

Minimal Flavor Violation

Model-independent fits

These general results are quite instructive if interpreted as bounds on the scale of new physics:

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(y_t V_{tb}^* V_{td})^2}{16\,\pi^2 M_W^2} + c_{NP}\frac{1}{\Lambda^2}$$

contrbution of the new heavy degrees of freedom

c_{NP}:

- ~ 1 — tree/strong + generic flavour → $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2)$ — loop + generic flavour → $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2$ — tree/strong + MFV → $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^* V_{tj})^2/(16\,\pi^2)$ — loop + MFV → $\Lambda \gtrsim 0.5$ TeV [K & B]

recent analysis: Bona *et al.* '07

If you don't think this is an accident of $\Delta F=2$... $\Rightarrow$ MFV

Minimal Flavour Violation

- SM without Yukawa interactions: $SU(3)^5$ global **flavour symmetry**

$$\mathbf{SU(3)_u \otimes SU(3)_d \otimes SU(3)_Q \otimes SU(3)_e \otimes SU(3)_L}$$

- Yukawa interactions break this symmetry
- Proposal for any New Physics model:

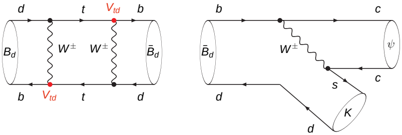
Yukawa structures as the only sources of flavour violation

$$\Downarrow$$

Minimal Flavour Violation
Notice that MFV allows for new CPV phases!

Hints for new sources of CP violation?

1. CP Asymmetry in $B \to \psi K_S$ and $\sin 2\beta$



- Tree level decay $\to$ sensitivity to the phase of the mixing amplitude without NP in the decay amplitude
- in SM: $\text{Arg}(M_{12}^d) = \text{Arg}(V_{td}^2) = 2\beta$

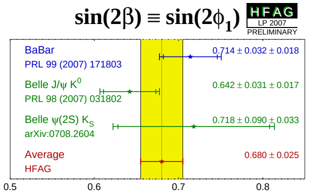
$$\sin 2\beta \overset{SM}{=} S^{exp.}_{\psi K_S} = 0.680 \pm 0.025$$

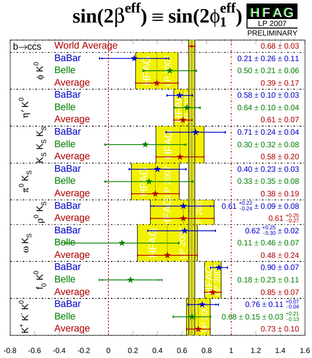
- In the SM also loop induced modes like $B \to \phi K_S$ and $B \to \eta' K_S$ give the same value

$$S^{SM}_{\phi K_S} = S^{SM}_{\eta' K_S} = S^{SM}_{\psi K_S} = \sin 2\beta$$

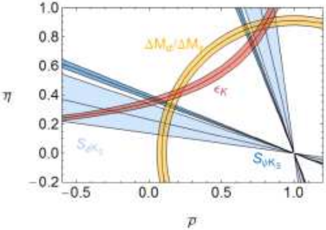
$$S^{exp.}_{\phi K_S} = 0.39 \pm 0.17 \qquad S^{exp.}_{\eta' K_S} = 0.61 \pm 0.07$$

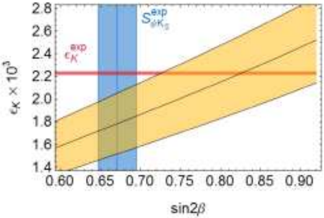
$\Rightarrow$ New Phases in decays?





Hints for New Sources of CP violation?





② Tensions in the Unitarity Triangle

Lunghi, Soni '08; Buras, Guadagnoli '08, '09

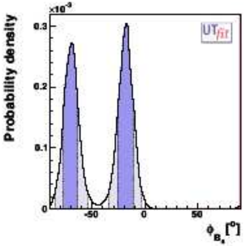
- Construct the UT using only $S_{\psi K_S}$ and $\Delta M_d/\Delta M_s$
- $\sin 2\beta$ as determinend from $B \to \psi K_S$ and R_t as determined from $\Delta M_d/\Delta M_s$ lead to a prediction for CP violation in the K system

$$\epsilon_K^{SM} = (1.78 \pm 0.25) \times 10^{-3} \quad \Leftrightarrow \quad \epsilon_K^{exp.} = (2.23 \pm 0.01) \times 10^{-3}$$

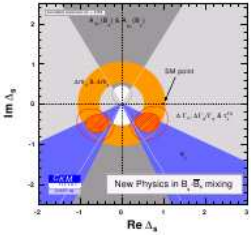
$\Rightarrow$ NP phase in B_d mixing?

$\Rightarrow$ Additional CP violation in K mixing?

Hints for New Sources of CP violation?

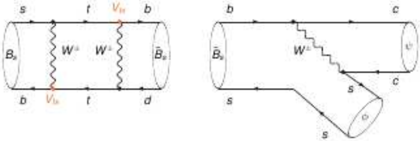


UTfit collaboration



CKM fitter collaboration

③ CP Asymmetry in $B_s \to \psi\phi$ and $\sin 2\beta_s$



- Tree level decay $\to$ sensitivity to the phase of the B_s mixing amplitude without NP in the decay amplitude
- in SM: $\mathrm{Arg}(M_{12}^s) = \mathrm{Arg}(V_{ts}^2) = 2\beta_s$ with $\beta_s \simeq 1^\circ$
- beyond the SM one has

$$S_{\psi\phi} = \sin 2(\beta_s + \Phi_{B_s}^{NP}) \ ,$$

- recent analyses seem to hint towards large NP effects

$$\Phi_{B_s}^{NP} = (19^\circ \pm 8^\circ) \cup (69^\circ \pm 7^\circ)$$

$\Rightarrow$ Large B_s mixing phase?

CP violation & EDMs

CP-violation and EDMs

Motivation:

- Baryogenesis requires extra $\not{CP}$
- SM also has an additional $\not{CP}$ source $\bar{\theta}$
- Most "UV completions" of SM (e.g. MSSM) provide additional sources of $\not{CP}$

Currently, all experimental data $\Rightarrow$ EDMs vanish to very high precision thus leading to very strong constraints on new physics.

NB: EDMs are observables accessible at the amplitude level, and so decouple more weakly than e.g. LFV observables

CP violation & EDMs

Constraints on TeV-Scale models

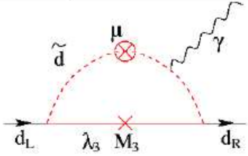
- E.G. MSSM: In general, the MSSM contains many new parameters, including multiple new CP-violating phases, e.g.

Complex ⇒ CP-odd phase

$$\Delta\mathcal{L} \sim -\mu \bar{\tilde{H}}_1 \tilde{H}_2 + B\mu\, H_1 H_2 + h.c. - \frac{1}{2}\left(M_3 \bar{\lambda}_3 \lambda_3 + M_2 \bar{\lambda}_2 \lambda_2 + M_1 \bar{\lambda}_1 \lambda_1\right) + h.c. - A^d_{ij} H_1 \tilde{q}_{Li} \tilde{q}_{Rj} + h.c + \cdots$$

With a universality assumption, 2 new physical CP-odd phases $\{\theta_\mu, \theta_A\}$

- EG:1-loop EDM contribution:



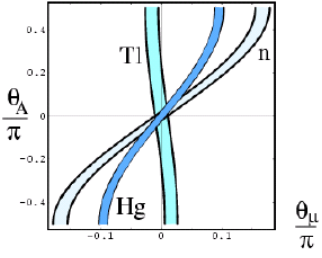
[Ellis, Ferrara & Nanopoulos '82]

$$\frac{d_d}{m_d} \sim \frac{1}{16\pi^2} \frac{\mu m_{\tilde{g}}}{M^4} \sin\theta_\mu$$

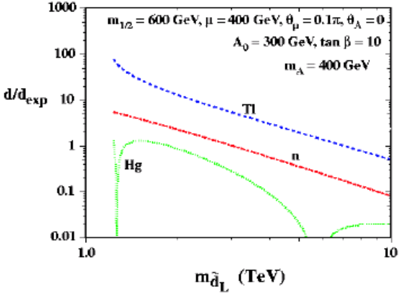
M ~ sfermion mass

CP violation & EDMs

SUSY CP Problem



$M_{soft} = 500\ GeV$



Generic Implications $\Rightarrow$ Soft CP-odd phases $O(10^{-2} - 10^{-3})$

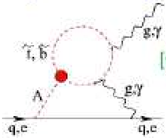
[Olive, Pospelov, AR, Santoso '05]

[Also: Barger et al. '01, Abel et al. '01, Pilaftsis '02]

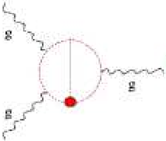
CP violation & EDMs

MSSM parameter space: $phases < O(10^{-3} - 1)$

Decoupling 1st/2nd generation

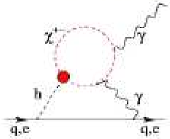


[Chang, Keung & Pilaftsis '98]



[Weinberg '89; Dai et al. 90]

Decoupling scalars (split SUSY, EW baryogenesis)

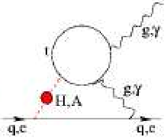


[Arkani-Hamed et al. '04]

Decoupling fermions

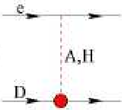
2 HDM

[Barr, Zee '92]



large tanβ

[Barr '92; Lebedev & Pospelov '02]



A Flavor Blind MSSM with CP Violating Phases

In a FBMSSM there are no additional flavor structures beyond the CKM but new flavor blind CP Violating Phases are allowed. We assume universal squark masses and diagonal trilinear couplings.

Parameters of a flavor blind MSSM

- Higgs sector: $\tan\beta$, $M_{H^\pm}$
- Higgsino mass: μ
- Gaugino masses: M_1, M_2, M_3
- squark masses: m_Q^2, m_U^2, m_D^2
- trilinear couplings: A_d, A_s, A_b, A_u, A_c, A_t

The Higgsino and Gaugino masses as well as the trilinear couplings can in general be complex.

Observables only depend on μM_i & μA_i.

W. Altmannshofer, A. J. Buras & P. P '08

Most important constraints: EDMs and $b \to s\gamma$

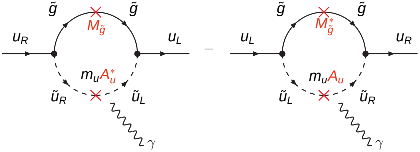
$d_e^{\text{exp.}} \lesssim 1.6 \times 10^{-27} e\text{cm}$

$d_n^{\text{exp.}} \lesssim 2.9 \times 10^{-26} e\text{cm}$

$d_e^{\text{SM}} \simeq 10^{-38} e\text{cm}$

$d_n^{\text{SM}} \simeq 10^{-32} e\text{cm}$

- In the MSSM, EDMs can be induced already at the 1loop level
  $\longrightarrow$ typically tight constraints on CP violating phases
- Example: Gluino contribution to the up-quark EDM



$$d_u \simeq \frac{e g_s^2}{16\pi^2} m_u \frac{\text{Im}(M_{\tilde g} A_u^*)}{\bar m_{\tilde u}^4} F\left(\frac{|M_{\tilde g}|^2}{\bar m_{\tilde u}^2}\right)$$

Constraints can be avoided by e.g.

- hierarchical trilinear couplings $A_{u,c} \ll A_t, A_{d,s} \ll A_b$
- heavy 1st and 2nd generation of squarks

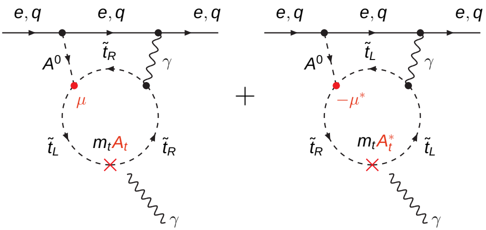
But: sizeable effects in flavor observables still possible, as 3rd generation squarks enter

Most important constraints: EDMs and $b \to s\gamma$

Chang, Keung, Pilaftsis '98

2-loop Barr-Zee type diagrams generating both lepton and quark EDMs

- sensitive to 3rd generation of squarks
- decouple with $1/\max(M_{A^0}^2, m_{\tilde{t}}^2)$



$d_f \propto \text{Im}(\mu A_t)$

$\longrightarrow$ Constraint on $\text{Im}(\mu A_t)$

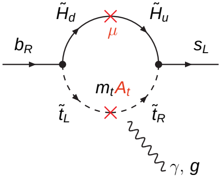
Most important constraints: EDMs and $b \to s\gamma$

$$\mathcal{BR}[B \to X_s\gamma]^{\text{exp.}} = (3.52 \pm 0.25) \times 10^{-4}$$ HFAG '08

$$\mathcal{BR}[B \to X_s\gamma]^{\text{SM}} = (3.15 \pm 0.23) \times 10^{-4}$$ Misiak et al. '06

- $b \to s\gamma$ amplitude is helicity suppressed
- typically large NP effects, even in a FBMSSM with low $\tan\beta$

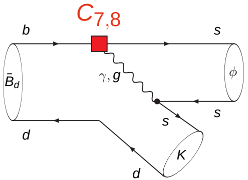
$$\mathcal{C}^{\tilde{\chi}^{\pm}}_{7,8}(\mu_{\text{SUSY}}) \simeq \frac{m_t^2}{\bar{m}_{\tilde{t}}^4} A_t \mu \tan\beta \times f_{7,8}\left(\frac{|\mu|^2}{\bar{m}_{\tilde{t}}^2}\right)$$



$$\mathcal{BR}[B \to X_s\gamma] \propto |\mathcal{C}_7^{\text{SM}}(m_b) + \mathcal{C}_7^{\text{NP}}(m_b)|^2 \simeq |\mathcal{C}_7^{\text{SM}}(m_b)|^2 + 2\text{Re}(\mathcal{C}_7^{\text{SM}}(m_b)\mathcal{C}_7^{\text{NP}}(m_b))$$

$\to$ Constraint on $\text{Re}(\mu A_t)$

CP Asymmetries in $B \to \phi K_S$ and $B \to \eta' K_S$



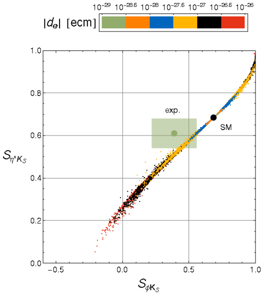
Time dependent CP Asymmetries in decays of neutral B mesons to final CP Eigenstates

$$A_{CP}(t, \phi K_S) = \frac{\Gamma(B(t) \to \phi K_S) - \Gamma(\bar{B}(t) \to \phi K_S)}{\Gamma(B(t) \to \phi K_S) + \Gamma(\bar{B}(t) \to \phi K_S)}$$
$$= C_{\phi K_S} \cos(\Delta M_d t) - S_{\phi K_S} \sin(\Delta M_d t)$$

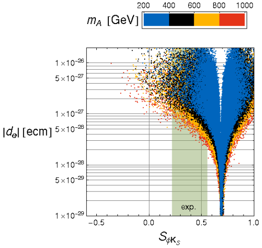
$$S_{\phi K_S} = -\frac{2\text{Im}(\xi_{\phi K_S})}{1 + |\xi_{\phi K_S}|^2} \quad , \quad \xi_{\phi K_S} = e^{-i\text{Arg}(M_{12}^d)} \frac{A(\bar{B} \to \phi K_S)}{A(B \to \phi K_S)}$$

- sizeable, correlated effects in $S_{\phi K_S}$ and $S_{\eta' K_S}$
- larger effects in $S_{\phi K_S}$ as indicated by the data
- for $S_{\phi K_S} \simeq 0.4$, lower bounds on the electron and neutron EDMs:

$$d_e \gtrsim 5 \times 10^{-28} \text{ecm} \quad , \quad d_n \gtrsim 8 \times 10^{-28} \text{ecm}$$



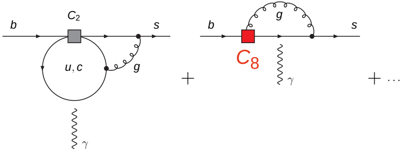
ABP'08



Direct CP Asymmetry in $b \to s\gamma$

Soares '91; Kagan, Neubert '98

$$A_{CP}^{bs\gamma} = \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)}$$

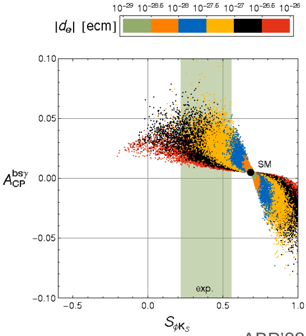


- arises first at order α_s
- doubly Cabibbo and GIM suppressed in the SM
- sizeable value would be clear signal for NP

$A_{CP}^{bs\gamma}(\text{SM}) \simeq (0.44^{+0.24}_{-0.14})\%$ Hurth, Lunghi, Porod '03

$A_{CP}^{bs\gamma}(\text{exp.}) \simeq (0.4 \pm 3.6)\%$ HFAG

- Sign of $A_{CP}^{bs\gamma}$ is correlated with sign of $S_{\phi K_S}$
- For $S_{\phi K_S} < S_{\phi K_S}^{\text{SM}} \Rightarrow 1\% \leq A_{CP}^{bs\gamma} \leq 6\%$



ABP'08

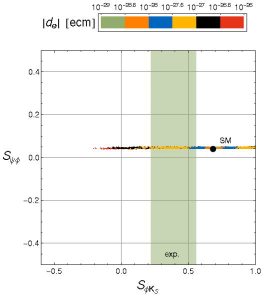
CP Violation in $\Delta F = 2$ transitions

1 Phases in the B_d and B_s mixing amplitudes

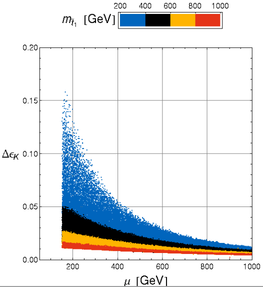
- Leading NP contributions to M_{12}^d and M_{12}^s turn out to be insensitive to the new phases of a flavor blind MSSM.

$$\text{Arg}(M_{12}^{d,s}) \simeq \text{Arg}(M_{12}^{d,s}(\text{SM}))$$

$\rightarrow S_{\psi K_S}$ and $S_{\psi\phi}$ are SM like



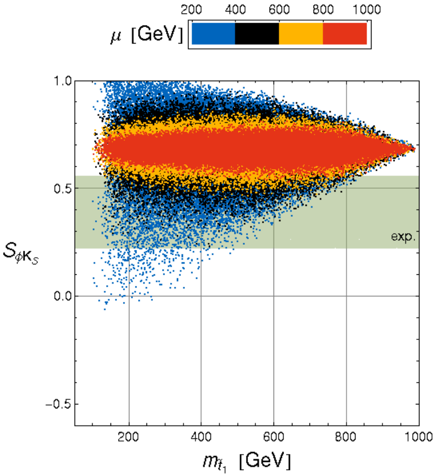
ABP'08

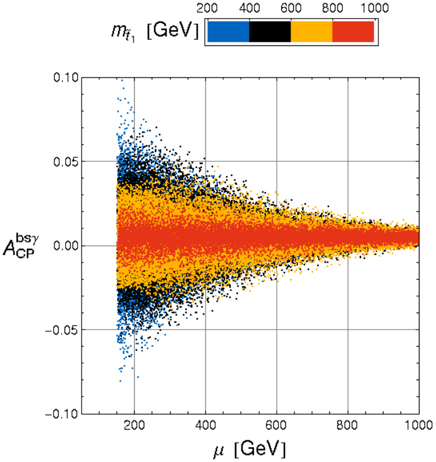


2 CP violation in K mixing

- Also M_{12}^K has no sensitivity to the new phases
- Still, $\epsilon_K \propto \text{Im}(M_{12}^K)$ can get a positive NP contribution up to 15%
- But only for a very light SUSY spectrum: $\mu, m_{\tilde{t}_1} \simeq 200\text{GeV}$

Implications for direct searches of SUSY particles





- $S_{\phi K_S} \simeq 0.4$ implies $\mu \lesssim 600$GeV and $m_{\tilde{t}_1} \lesssim 700$GeV
- $A_{CP}^{bs\gamma} \gtrsim 2\%$ implies $\mu \lesssim 600$GeV and $m_{\tilde{t}_1} \lesssim 800$GeV

The Anomalous Magnetic Moment of the Muon

$a_\mu^{\text{exp.}} = 1165920.80(63) \times 10^{-9}$ Muon (g-2) collaboration

$a_\mu^{\text{SM}} = 1165917.85(61) \times 10^{-9}$ Miller et al. '07

$$\Delta a_\mu = a_\mu^{\text{exp.}} - a_\mu^{\text{SM}} \simeq (3 \pm 1) \times 10^{-9}$$

$\simeq 3\sigma$ discrepancy

A very rough formula for SUSY contributions to a_μ

$$a_\mu^{\text{SUSY}} \simeq 1.5 \left(\frac{\tan\beta}{10}\right)\left(\frac{300\text{GeV}}{m_{\tilde{\ell}}}\right)^2 \text{sign}(\text{Re}(\mu)) \times 10^{-9}$$

with common SUSY mass $m_{\tilde{\ell}}$

$S_{\phi K_S} \simeq 0.4$ naturally leads to $a_\mu^{\text{SUSY}} \simeq$ few $\times 10^{-9}$

Flavored EDMs

Sfermion mass terms are also sources of ~~flavor~~ and/or ~~CP~~ .

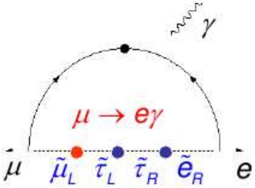
$$\delta_{ij}^{LL} \equiv \frac{\left(m^2_{\tilde{f}_L \tilde{f}_L}\right)_{ij}}{\bar{m}^2_{\tilde{f}}}, \ \delta_{ij}^{RR} \equiv \frac{\left(m^2_{\tilde{f}_R \tilde{f}_R}\right)_{ij}}{\bar{m}^2_{\tilde{f}}}, \ \delta_{ij}^{LR} \equiv \frac{\left(m^2_{\tilde{f}_L \tilde{f}_R}\right)_{ij}}{\bar{m}^2_{\tilde{f}}}$$

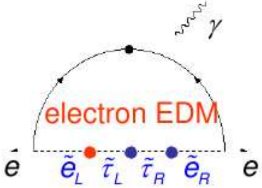
When left- and right-handed sfermions have mixing,

$$\delta_{ee}^{LR(\mathrm{eff})} \approx (m_\tau / m_e) \times \delta_{e\tau}^{LL} \delta_{e\tau}^{RR*} \delta_{ee}^{LR}, \qquad \delta_{dd}^{LR(\mathrm{eff})} \approx (m_b / m_d) \times \delta_{db}^{LL} \delta_{db}^{RR*} \delta_{dd}^{LR}.$$

And, if $\mathrm{Im}[\delta_{ij}^{LL} \delta_{ij}^{RR*}] \neq 0$, it contributes to EDMs even if $\phi_{B/A} = 0$.

FCNC processes and EDMs may be correlated to each others.





FCNC processes and EDMs probe flavor structure in ~~SUSY~~ terms.

Flavored EDMs

Supersymmetric SU(5) Ground Unification

Flavor-violating SUSY breaking mass terms for sfermion are induced by GUT interaction even if the flavor universality is imposed at the cutoff scale. (Hall, Kostelecky & Raby)

In MSSM with right-handed neutrinos,

CKM mixing ⇒ Left-handed sdown mixing
Neutrino mixing ⇒ Left-handed slepton mixing

In SUSY SU(5) GUT with right-handed neutrinos, quarks and leptons are unified, and then

CKM mixing ⇒ Right-handed slepton mixing
Neutrino mixing ⇒ Right-handed sdown mixing

We can check consistency among FCNCs and EDMs due to the GUT relation in flavor violation.

Flavored EDMs

RG induced Flavor Violating interactions in SUSY GUTs

- **SUSY SU(5)** [Barbieri & Hall, '95]

$$(\delta^{\tilde q}_{LL})_{ij} \sim h^u h^{u\dagger}{}_{ij} \sim h_t^2 V^{ik}_{CKM} V^{kj*}_{CKM} \rightarrow (\delta^{\tilde\ell}_{RR})_{ij} \simeq (\delta^{\tilde q}_{LL})_{ij}$$

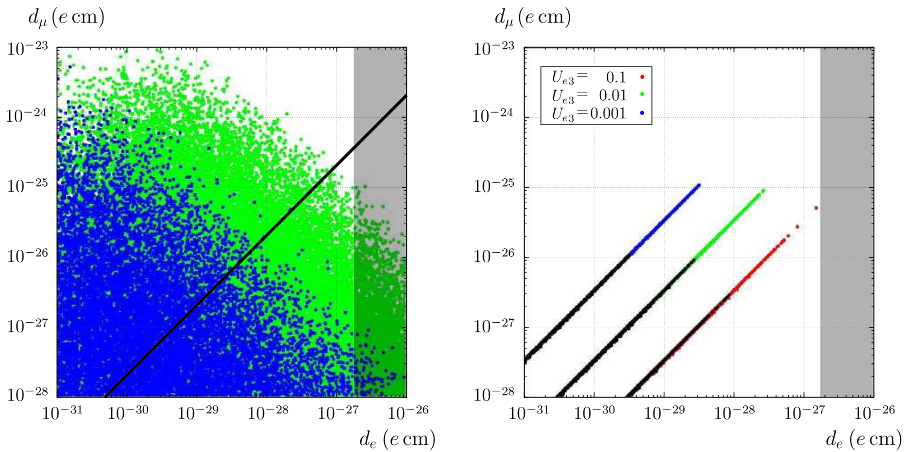
- **SUSY SU(5)+RN** [Yanagida et al., '95]

$$(\delta^{\tilde\ell}_{LL})_{ij} \sim (h^\nu h^{\nu\dagger})_{ij} \qquad \& \qquad (\delta^{\tilde\ell}_{RR})_{ij} \sim (h^u h^{u\dagger})_{ij}$$

- **SUSY SU(5)+RN** [Moroi, '00] **& SO(10)** [Chang et al., 02]

$$\sin\theta_{\mu\tau} \sim \frac{\sqrt{2}}{2} \Rightarrow (\delta^{\tilde\nu}_{LL})_{23} \sim 1 \Rightarrow (\delta^{\tilde q}_{RR})_{23} \sim 1$$

Electron vs muon EDMs and $\mathrm{BR}(\mu \to e\gamma)$



Green (blue) points $\to \mathrm{BR}(\mu \to e\gamma) < 10^{-11}(10^{-13})$

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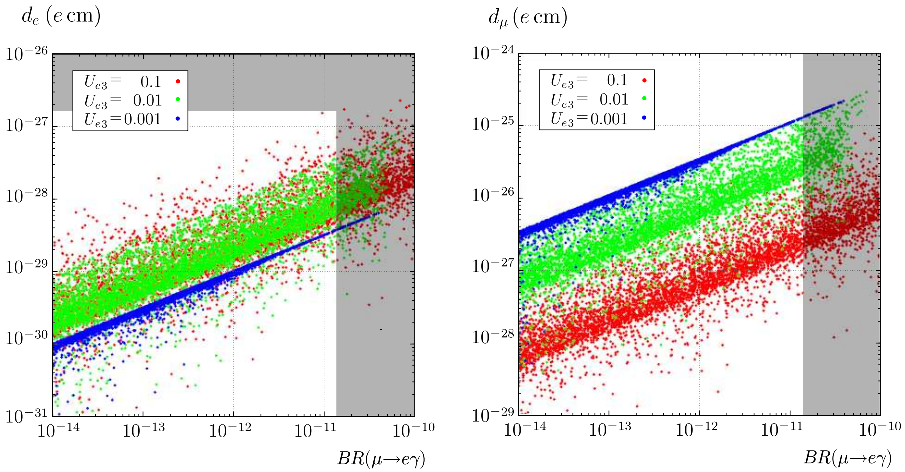
Electron & muon EDMs vs $\mathrm{BR}(\mu \to e\gamma)$ in $SU(5)_{RN}$



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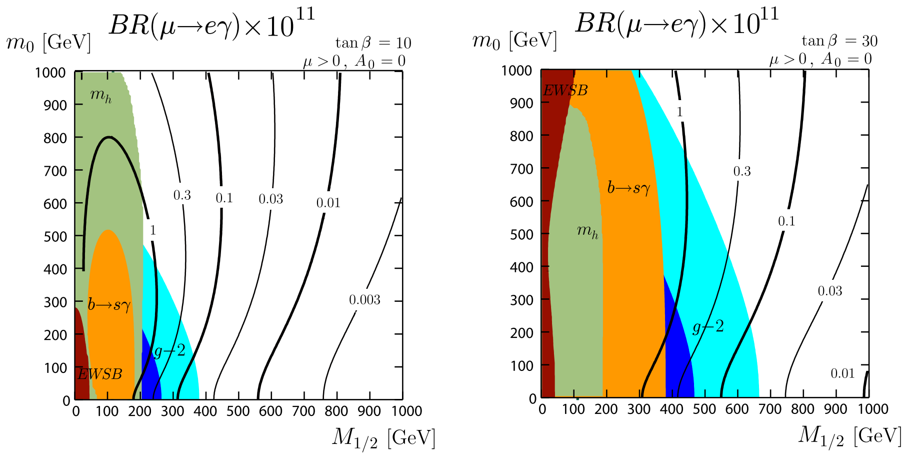
$\mathrm{BR}(\mu \to e\gamma)$ in $SU(5)_{RN}$ and the LHC reach



hierarchical ν_L and N_R, $U_{e3} = 0.1$, $M_{N_3} = 10^{-13}$ GeV

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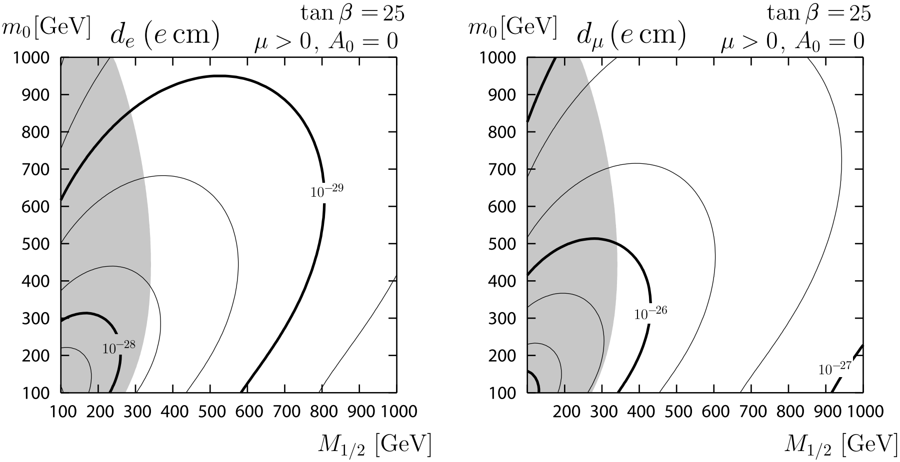
Leptonic EDMs in SUSY GUTs



Hisano, Nagai, P.P., 06',07',08'

The P-odd asymmetry in $\mu^+ \to e^+\gamma$

$$\frac{\mathrm{BR}(\ell_i \to \ell_j \gamma)}{\mathrm{BR}(\ell_i \to \ell_j \nu_i \bar{\nu}_j)} = \frac{48\pi^3 \alpha_{em}}{G_F^2} \left(|A_L^{\ell_i\ell_j}|^2 + |A_R^{\ell_i\ell_j}|^2 \right)$$

- **SUSY see-saw**

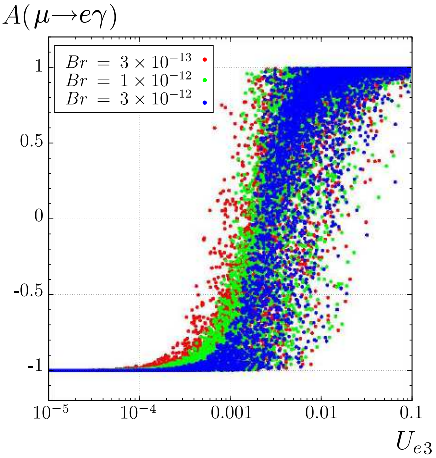
$$A_L^{\mu e} = \frac{\alpha_2}{4\pi} \frac{t_\beta}{\tilde{m}^2} \frac{\delta^L_{\mu e}}{15} \qquad A_R^{\mu e} \simeq \frac{m_e}{m_\mu} A_L^{\mu e}$$

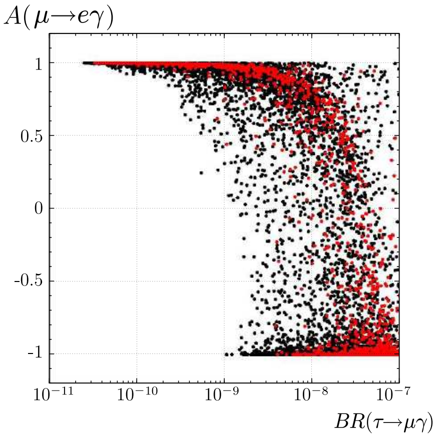
- **SUSY SU(5)+RN**

$$A_L^{\mu e} = \frac{\alpha_2}{4\pi} \frac{t_\beta}{\tilde{m}^2} \frac{\delta^L_{\mu e}}{15} \qquad A_R^{\mu e} = -\frac{\alpha_Y}{4\pi} \frac{t_\beta}{\tilde{m}^2} \frac{m_\tau}{m_\mu} \frac{\delta^L_{\mu\tau}\delta^R_{\tau e}}{30}$$

$$A(\mu^+ \to e^+\gamma) = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2}$$

$A(\mu \rightarrow e\gamma)$ in SUSY SU(5)+RN





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Conclusions

Where to look for New Physics?

- CPV in $b \to s$ transitions like $B \to \phi K_S, \eta' K_S, X_s \gamma$ & B_s mixing
- A correlated analysis among EDMs and FCNC-CPV observables could shed light on the underlying mechanism for CPV in NP.
- Evidence of leptonic EDMs and $\ell_i \to \ell_j \gamma$ would be a clear evidence of NP
- Leptonic EDMs and $\ell_i \to \ell_j \gamma$ can probe $\Lambda_{NP} > \mathrm{TeV}$, even beyond the LHC reach

$$\Downarrow$$

Flavor and/or CP violating observables, represent a complementary tool to the LHC to discover or constrain NP.