Metastability bounds on flavor-violating A-terms in the MSSM

Jae-hyeon Park

INFN Padova

Work in progress
Results are **preliminary**

KIAS-KAIST-YITP joint workshop, KIAS, 2009-09-04

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(or Age of the universe and flavor physics)

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FCNC signatures of supersymmetry

- Sfermion mass term:

$$-\mathscr{L}_{\text{soft}} \ni \widetilde{f}^*_{Ai}\,(M^2_{f,AB})_{ij}\,\widetilde{f}_{Bj}$$

$f = u,d,l;\ A,B = L,R;\ i,j = 1,2,3$

- may lead to an interaction

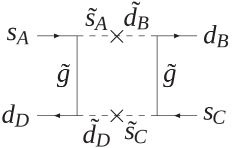
$$\tilde{f}_{B\,j} \text{ - - - }\times\text{ - - - } \tilde{f}_{A\,i} \qquad = -i\,(M^2_{f,AB})_{ij}$$

if M^2_f is non-diagonal in the basis where m_f is diagonal

- For almost diagonal $M^2_{\tilde{f}}$, use a mass insertion parameter

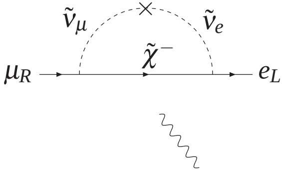
$$(\delta^f_{ij})_{AB} \equiv (\Delta^f_{ij})_{AB}/m^2_{\tilde{f}}$$
$$(M^2_{f,AB})_{ij} = m^2_{\tilde{f}}\,\delta_{AB}\delta_{ij} + (\Delta^f_{ij})_{AB}$$

- K^0–$\overline{K^0}$ mixing



$$\propto\ (\delta^d_{12})_{BA} \times (\delta^d_{12})_{DC}$$

- $\mu \to e\gamma$



$$\propto\ (\delta^l_{12})_{LL}$$

My question

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- Suppose sparticles are heavier than LHC reach, e.g.

$$m_{\tilde{g}}, m_{\tilde{q}}, m_{\tilde{l}} \gtrsim 3\ \mathrm{TeV}$$

How much can we hope from indirect searches in flavor physics?

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- Suppose sparticles are heavier than LHC reach, e.g.

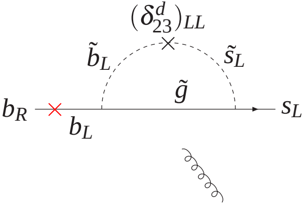
$$m_{\tilde{g}}, m_{\tilde{q}}, m_{\tilde{l}} \gtrsim 3\ \mathrm{TeV}$$

How much can we hope from indirect searches in flavor physics?

- Focus on $(\delta^f_{ij})_{LR}$

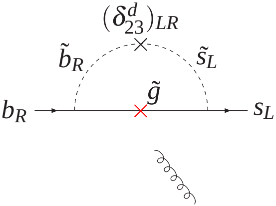
Scaling of supersymmetric effects

- $(\delta^d_{23})_{LL}$



$$\propto \quad (\delta^d_{23})_{LL} \, \frac{m_b}{m^2_{\tilde{q}}} \quad \propto \quad \frac{1}{M^2_{\text{SUSY}}}$$

- $(\delta^d_{23})_{LR}$

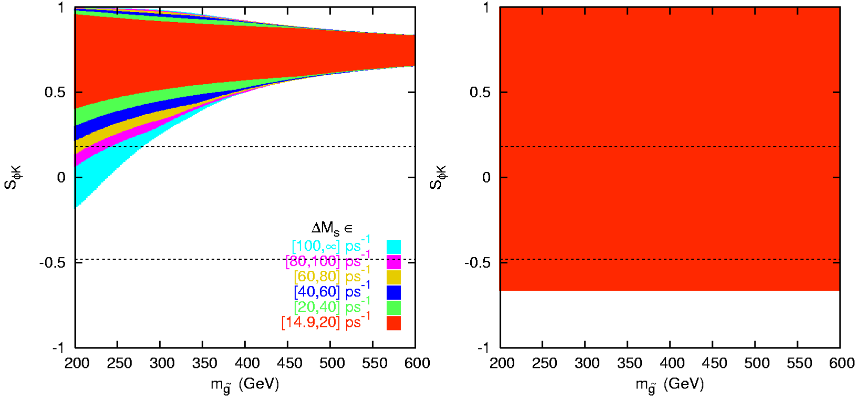


$$\propto \quad (\delta^d_{23})_{LR} \, \frac{m_{\tilde{g}}}{m^2_{\tilde{q}}} \quad \propto \quad \frac{1}{M_{\text{SUSY}}}$$

δ_{LR}'s decouple slower than $\delta_{LL,RR}$

- Allow $|\delta^d_{23}| < 1$ consistent with $B(B \to X_s \gamma)$ fixing $m^2_{\tilde{g}}/m^2_{\tilde{q}} = 1$

Kane, Ko, Kolda, JhP, Wang×2, PRD(2004)



$(\delta^d_{23})_{LL}$ $(\delta^d_{23})_{LR}$

My question: how large flavor-violating A can be?

- In terms of soft supersymmetry breaking terms

$$(\delta^u_{ij})_{LR} = \frac{A^u_{ij}\langle H^0_u\rangle}{m^2_{\tilde{q}}}, \quad (\delta^d_{ij})_{LR} = \frac{A^d_{ij}\langle H^0_d\rangle}{m^2_{\tilde{q}}}, \quad (\delta^l_{ij})_{LR} = \frac{A^l_{ij}\langle H^0_d\rangle}{m^2_{\tilde{l}}}$$

- Conceivable approaches
  - using ansatz
  - using flavor models
  - model-independent

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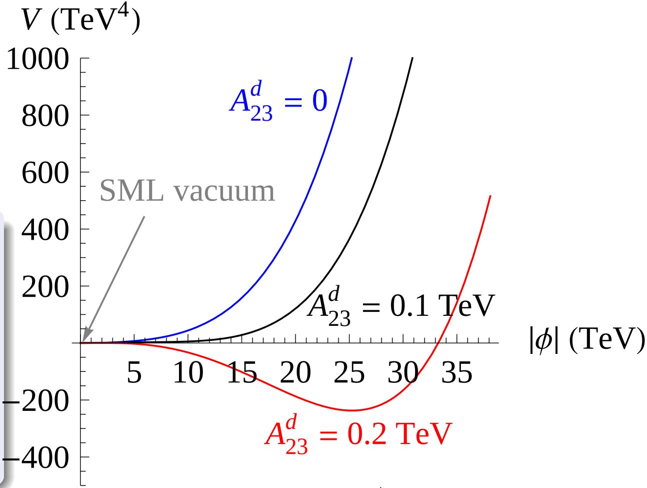
- Conceivable approaches
  - using ansatz
  - using flavor models
  - model-independent $\longleftarrow$ this work

Large A-terms cause vacuum instability

- Scalar potential for SPS1a
- Vacua deeper than the SML vacuum appear for large A
- $\langle\widetilde{l}\rangle \neq 0$ breaks charge
  $\langle\widetilde{q}\rangle \neq 0$ breaks charge & color



$$|\phi| \equiv \left(\sum_\alpha |\phi_\alpha|^2\right)^{1/2}$$

$$\phi_\alpha = H_u, H_d, \widetilde{Q}, \widetilde{u}^c, \widetilde{d}^c, \widetilde{L}, \widetilde{e}^c$$

Outline

Scalar potential of MSSM

$$
\begin{aligned}
W &= H_u\, Q_i\, (\lambda_u)_{ij}\, u^c_j + H_d\, Q_i\, (\lambda_d)_{ij}\, d^c_j + H_d\, L_i\, (\lambda_l)_{ij}\, e^c_j \\
V &= V_D + V_F + V_{\text{soft}} \\
V_D &= \frac{1}{2}\sum_a g_a^2 \Big(\sum_\alpha \phi^\dagger_\alpha T^a \phi_\alpha \Big)^2 \\
V_F &= \sum_\alpha \left| \frac{\partial W}{\partial \phi_\alpha} \right|^2 \\
V_{\text{soft}} &= \widetilde{Q}^*_i (M^2_Q)_{ij} \widetilde{Q}_j + \widetilde{u^c_i}^* (M^2_{u^c})_{ij} \widetilde{u^c_j} + \widetilde{d^c_i}^* (M^2_{d^c})_{ij} \widetilde{d^c_j} \\
&\quad + 2\mathrm{Re}\big[H_u\, \widetilde{Q}_i\, A^u_{ij}\, \widetilde{u^c_j} + H_d\, \widetilde{Q}_i\, A^d_{ij}\, \widetilde{d^c_j} \big] \\
&\quad + \text{lepton sector} \\
&\quad + 2\mathrm{Re}\big[b H_u H_d \big]
\end{aligned}
$$

Vacuum stability bounds

Frere, Jones, Raby, NPB(1983)

- Take a D-flat direction, $|H_u^0| = |\widetilde{t}| = |\widetilde{t^c}| = a \quad \rightsquigarrow \quad V_D = 0$

$$V_{\text{L.E.}} = [(M_Q^2)_3 + (M_{u^c}^2)_3 + m_{H_u}^2 + |\mu|^2]\, a^2 - 2|A_t|\, a^3 + 3\lambda_t^2 a^4$$

- A charge- and color-breaking (CCB) minimum deeper than the SML vacuum appears unless

$$|A_t|^2 < 3\lambda_t^2 [(M_Q^2)_3 + (M_{u^c}^2)_3 + M_{H_u}^2 + |\mu|^2]$$

- More directions have been found although they are not related to flavor-conserving A

Casas, Lleyda, Munoz, NPB(1996)

CCB bounds on flavor-violating A

Casas, Dimopoulos, PLB(1996)

- Take a D-flat direction, $|H_d^0| = |\widetilde{d}_2| = |\widetilde{d}_3^c| = a \quad \rightsquigarrow \quad V_D = 0$

$$V_{\text{L.E.}} = [(M_Q^2)_2 + (M_{d^c}^2)_3 + m_{H_d}^2 + |\mu|^2]\, a^2 - 2|A_{23}^d|\, a^3 + (\lambda_s^2 + \lambda_b^2) a^4$$

- A CCB minimum appears unless

$$|A_{23}^d|^2 < \lambda_b^2 [(M_Q^2)_2 + (M_{d^c}^2)_3 + m_{H_d}^2 + |\mu|^2]$$

$$|A_{ij}^u|^2 < \lambda_{u_k}^2 [(M_Q^2)_i + (M_{u^c}^2)_j + m_{H_u}^2 + |\mu|^2], \quad k = \max(i,j)$$
$$|A_{ij}^d|^2 < \lambda_{d_k}^2 [(M_Q^2)_i + (M_{d^c}^2)_j + m_{H_d}^2 + |\mu|^2], \quad k = \max(i,j)$$
$$|A_{ij}^l|^2 < \lambda_{e_k}^2 [(M_L^2)_i + (M_{e^c}^2)_j + m_{H_d}^2 + |\mu|^2], \quad k = \max(i,j)$$

- Do not decouple even for heavy sfermions

$$(\delta_{ij}^d)_{LR} < m_{d_k} \frac{[2M_{\text{av}}^2 + m_{H_d}^2 + |\mu|^2]^{1/2}}{M_{\text{av}}^2} \sim \frac{m_{d_k}}{m_{\widetilde{q}}}, \quad k = \max(i,j)$$

UFB bounds on flavor-violating A

Casas, Dimopoulos, PLB(1996)

- Take direction $|\widetilde{d}_2|^2 = |\widetilde{d}_3^c|^2 = |H_d^0|^2 + |\widetilde{\nu}_1|^2 = a^2$ with $H_d^0 = a^2 A_{23}^d / [\lambda_b^2 a^2 + m_{H_d}^2 + |\mu|^2 - (M_L^2)_1]$
- If $\boxed{|H_d^0| < a}$ then $V_D = 0$

$$V_{\rm L.E} = a^2 \left[(M_Q^2)_2 + (M_{d^c}^2)_3 + (M_L^2)_1 - |A_{23}^d|^2 \frac{a^2}{a^2(\lambda_b^2 + \lambda_s^2) + m_{H_d}^2 + |\mu|^2 - (M_L^2)_1} \right]$$

- An unbounded-from-below (UFB) direction appears unless

$$|A_{23}^d|^2 < \lambda_b^2 [(M_Q^2)_2 + (M_{d^c}^2)_3 + (M_L^2)_1]$$

$$|A_{ij}^u|^2 < \lambda_{u_k}^2 [(M_Q^2)_i + (M_{u^c}^2)_j + (M_L^2)_p + (M_{e^c}^2)_q], \quad k = \max(i,j), p \neq q$$
$$|A_{ij}^d|^2 < \lambda_{d_k}^2 [(M_Q^2)_i + (M_{d^c}^2)_j + (M_L^2)_m], \quad k = \max(i,j)$$
$$|A_{ij}^l|^2 < \lambda_{e_k}^2 [(M_L^2)_i + (M_{e^c}^2)_j + (M_L^2)_m], \quad k = \max(i,j), m \neq i,j$$

- Do not decouple either

Vacuum **meta**stability bounds

- (Absolute) vacuum stability is a sufficient condition but not necessary
- It might be overkill to exclude every point in parameter space that leads to CCB or UFB direction
- A more reasonable view on vacuum stability would be

> Do not exclude a parameter set if the false vacuum lifetime is longer than the age of the universe

- There have been studies on (flavor-conserving) A_t in this approach

  Claudson, Hall, Hinchliffe, NPB(1983)

  Kusenko, Langacker, Segre, PRD(1996)

- This work is on flavor-violating A-terms

Outline

False vacuum decay rate

Callan, Coleman, PRD(1977)

- Decay rate per unit volume in the semiclassical approximation

$$\Gamma/V = A \exp(-S_E[\overline{\phi}])$$

- Euclidean action

$$S_E[\phi(x_E)] = \int d^4x_E \left[\left| \frac{d\phi}{dx_E} \right|^2 + V(\phi) \right]$$

- "Bounce" $\overline{\phi}$ is an $O(4)$-symmetric solution of

$$\delta S_E[\phi] = 0 \quad \rightsquigarrow \quad 2\frac{d^2\phi}{d\rho^2} + \frac{6}{\rho}\frac{d\phi}{d\rho} = \nabla V(\phi)$$

with boundary conditions

$$\overline{\phi}(\rho = \infty) = \phi^f, \quad (d\overline{\phi}/d\rho)(\rho = 0) = 0$$

- With guesstimate $A \sim (100\ \mathrm{GeV})^4$,

$$(\Gamma/V)\, t_0^4 \lesssim 1, \quad t_0 \simeq 10\ \mathrm{Gyr} \quad \rightsquigarrow \quad \boxed{S_E[\overline{\phi}] \gtrsim 400}$$

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Two-step method

Konstandin, Huber, JCAP(2006)

- Analytic solution unknown $\rightsquigarrow$ Use computers
- Bounce is not a minimum of $S_E[\phi]$ but a saddle point
  $\rightsquigarrow$ Cannot use numerical minimization
- But, a solution of $\delta \widetilde{S}_E^{(1)}[\phi] = 0$ is a minimum of $\widetilde{S}_E^{(1)}[\phi]$ with Euclidean action in α dimensions

$$\widetilde{S}_E^{(\alpha)}[\phi(\rho)] = 2\pi^2 \int_0^\infty d\rho\, \rho^{(\alpha-1)} \left[\left| \frac{d\phi}{d\rho} \right|^2 + V(\phi) \right]$$

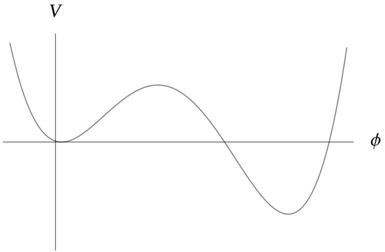
- $\widetilde{S}_E^{(4)}[\phi] = S_E[\phi]$

The method

1. Minimization of $\widetilde{S}_E^{(\alpha)}[\phi]$ for $\alpha = 1$
2. Continuation to $\alpha = 4$ by iteration

- Boundary conditions are always $\overline{\phi}(\infty) = \phi^f,\ (d\overline{\phi}/d\rho)(0) = 0$

Solving the equation of motion



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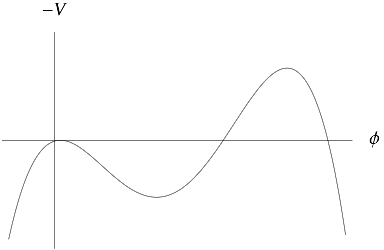
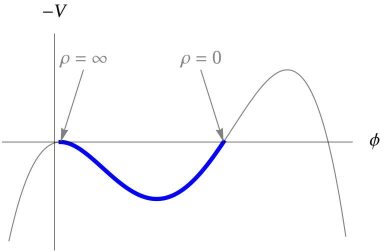


Solving the equation of motion

1. Solve the undamped equation ($\alpha = 1$) by minimizing $\widetilde{S}_E^{(1)}[\phi]$

$$2\frac{d^2\phi}{d\rho^2} = \nabla V(\phi)$$

$$\phi(\infty) = \phi^f, \quad (d\phi/d\rho)(0) = 0$$



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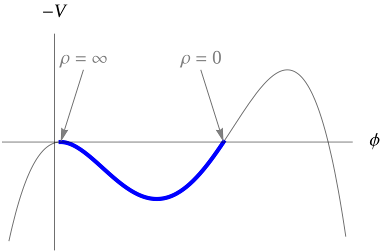
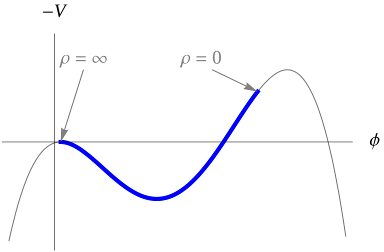


$\downarrow$

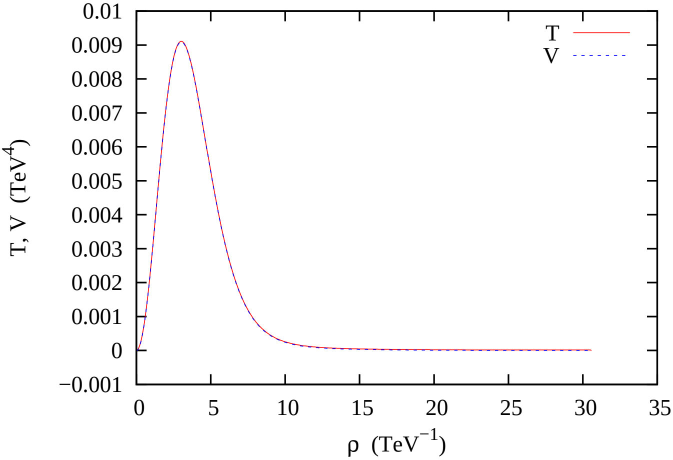
2. Deform to damped equation by increasing α to 4

$$2\frac{d^2\phi}{d\rho^2} + 2\frac{\alpha - 1}{\rho}\frac{d\phi}{d\rho} = \nabla V(\phi)$$
$$\phi(\infty) = \phi^f, \quad (d\phi/d\rho)(0) = 0$$



Conservation of energy

- After minimizing $\widetilde{S}_E^{(1)}[\phi]$ (the undamped case) for $m_{\widetilde{q}} = 0.5$ TeV, $A_{23}^d = 0.9$ TeV



- $T - V$ well conserved with $T \equiv |d\phi/d\rho|^2$

Numerical analysis

- Assume flavor violation only in A-terms

$$M^2_{Q,u^c,d^c} = \begin{bmatrix} m^2_{\tilde{q}} & 0 & 0 \\ 0 & m^2_{\tilde{q}} & 0 \\ 0 & 0 & m^2_{\tilde{q}} \end{bmatrix}, \quad A^d = \begin{bmatrix} A_d\lambda_d & A^d_{12} & A^d_{13} \\ A^d_{21} & A_s\lambda_s & A^d_{23} \\ A^d_{31} & A^d_{32} & A_b\lambda_b \end{bmatrix}$$

- Turn on one A^d_{ij} at a time and set the others to zero
- Higgs mass parameters $m^2_{H_u},\ m^2_{H_d},\ b,\ \mu$ from SPS1a
  $\rightsquigarrow\ \tan\beta = 10$
- Choose A^d_{ij} bigger than stability bound but not so big that SML vacuum becomes tachyonic
- Exclude A^d_{ij} such that $S_E[\overline{\phi}] < 400$
- Similarly for sleptons

Limits from FCNC

- Constraints on δ^d's

Sector	Inputs
1–2	$\varepsilon'/\varepsilon_K$, ε_K, ΔM_K
1–3	$B(B \to \rho/\omega\gamma)$[1] ΔM_{B_d}, $\sin 2\beta$, $\cos 2\beta$
2–3	$b \to s\gamma$, $b \to s l^+ l^-$, ΔM_{B_s}

Ciuchini et al, NPB(2007)
[1]Ko, Kramer, JhP, EPJC(2002)

- Constraints on δ^l's

Process	Present upper bound		Future upper bound	
$B(\mu \to e\gamma)$	$1.2 \cdot 10^{-11}$	MEGA	$1 \cdot 10^{-13}$	MEG
$B(\tau \to e\gamma)$	$1.1 \cdot 10^{-7}$	BABAR	$2 \cdot 10^{-9}$	SuperB
$B(\tau \to \mu\gamma)$	$6.8 \cdot 10^{-8}$	Belle	$2 \cdot 10^{-9}$	SuperB

Outline

Results on A^d

- Take $\tan\beta = 10$, $m_{A^0} = 0.4$ TeV
- Take $m_{\tilde{q}} = 0.5$ TeV for all bounds, $m_{\tilde{g}} = m_{\tilde{q}}$ for FCNC

MI	Stability	Metastability	Present FCNC	Future FCNC
$\lvert(\delta^d_{12})_{LR}\rvert$	$2\cdot10^{-4}$	$5\cdot10^{-2}$	$9\cdot10^{-5}$ [1]	
$\lvert(\delta^d_{13})_{LR}\rvert$	$1\cdot10^{-2}$	$6\cdot10^{-2}$	$1\cdot10^{-2}$ [2]	$2\cdot10^{-3}$ [3]
$\lvert(\delta^d_{23})_{LR}\rvert$	$1\cdot10^{-2}$	$6\cdot10^{-2}$	$5\cdot10^{-3}$ [3]	$5\cdot10^{-3}$ [3]

[1] Ciuchini et al (2007); [2] Ko, Kramer, JhP (2002); [3] CDR of SuperB, 0709.0451

- Take $m_{\tilde{q}} = 3.0$ TeV for all bounds, $m_{\tilde{g}} = m_{\tilde{q}}$ for FCNC

MI	Stability	Metastability	Present FCNC	Future FCNC
$\lvert(\delta^d_{12})_{LR}\rvert$	$3\cdot10^{-5}$	$7\cdot10^{-3}$	$5\cdot10^{-4}$	
$\lvert(\delta^d_{13})_{LR}\rvert$	$2\cdot10^{-3}$	$8\cdot10^{-3}$	$6\cdot10^{-2}$	$1\cdot10^{-2}$
$\lvert(\delta^d_{23})_{LR}\rvert$	$2\cdot10^{-3}$	$8\cdot10^{-3}$	$3\cdot10^{-2}$	$3\cdot10^{-2}$

Results on A^l

- Take $\tan\beta = 10$, $m_{A^0} = 0.4$ TeV
- Take $m_{\tilde{l}} = 0.5$ TeV for all bounds, $M_1 \propto m_{\tilde{l}}$ for FCNC

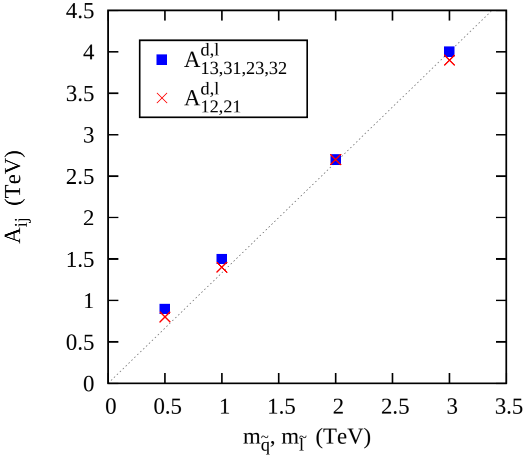
MI	Stability	Metastability	present FCNC	future FCNC
$\lvert(\delta^l_{12})_{LR}\rvert$	$4 \cdot 10^{-4}$	$5 \cdot 10^{-2}$	$1 \cdot 10^{-5}$ [1]	$1 \cdot 10^{-6}$
$\lvert(\delta^l_{13})_{LR}\rvert$	$6 \cdot 10^{-3}$	$6 \cdot 10^{-2}$	$5 \cdot 10^{-2}$ [1]	$7 \cdot 10^{-3}$
$\lvert(\delta^l_{23})_{LR}\rvert$	$6 \cdot 10^{-3}$	$6 \cdot 10^{-2}$	$4 \cdot 10^{-2}$ [1]	$7 \cdot 10^{-3}$

[1] Ciuchini et al, NPB(2007)

- Take $m_{\tilde{l}} = 3.0$ TeV for all bounds, $M_1 \propto m_{\tilde{l}}$ for FCNC

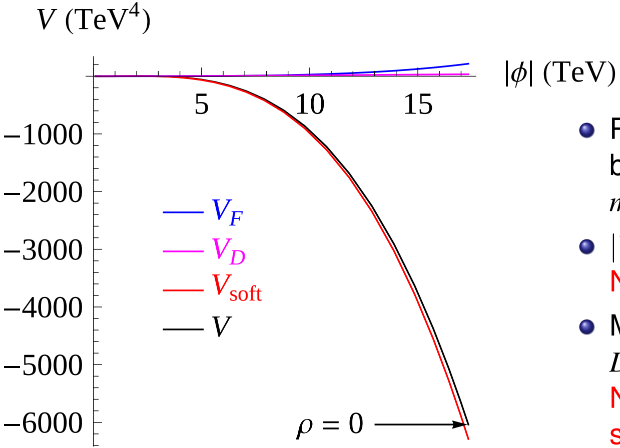
MI	Stability	Metastability	present FCNC	future FCNC
$\lvert(\delta^l_{12})_{LR}\rvert$	$6 \cdot 10^{-5}$	$7 \cdot 10^{-3}$	$8 \cdot 10^{-5}$	$7 \cdot 10^{-6}$
$\lvert(\delta^l_{13})_{LR}\rvert$	$1 \cdot 10^{-3}$	$7 \cdot 10^{-3}$	$3 \cdot 10^{-1}$	$4 \cdot 10^{-2}$
$\lvert(\delta^l_{23})_{LR}\rvert$	$1 \cdot 10^{-3}$	$7 \cdot 10^{-3}$	$2 \cdot 10^{-1}$	$4 \cdot 10^{-2}$

Universal dependence on sfermion mass



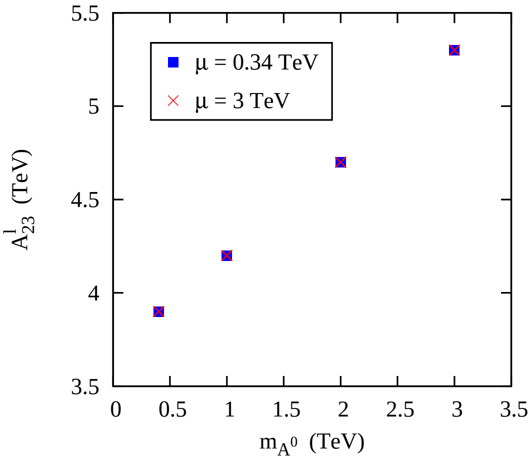
- Upper bound on A^f_{ij} for $i \neq j$
- Independent of family indices
- Same for squarks and sleptons
- Bound on $A^f_{ij} \propto m_{\tilde{f}}$

Why universal?



- Potential profile of bounce for $m_{\tilde{q}} = 3$ TeV, $A^d_{23} = 4$ TeV
- $|V_F| \ll |V_{\text{soft}}| \quad \rightsquigarrow$ No Yukawa dependence
- Moves almost along D-flat direction $\rightsquigarrow$ No difference between squarks and sleptons
- $\rho = 0$ not at true vacuum

Dependence on Higgs mass parameters



$$m_{H_u}^2,\ m_{H_d}^2,\ b,\ \mu$$

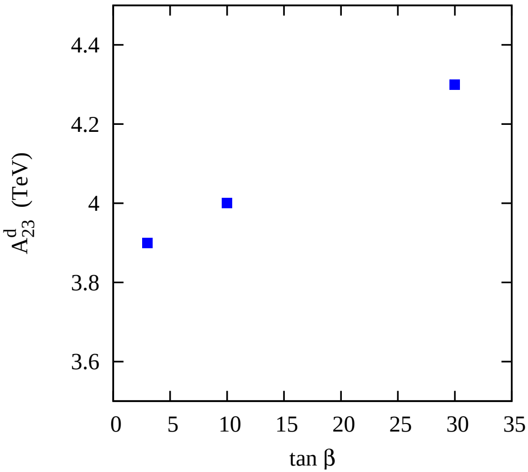
$$\Updownarrow$$

$$m_Z,\ \tan\beta,\ m_{A^0},\ \mu$$

- Bound on A^l_{23} for $m_{\tilde{q}} = 3$ TeV

- Bound on A^f_{ij} increases as m_{A^0} grows
- Independent of μ

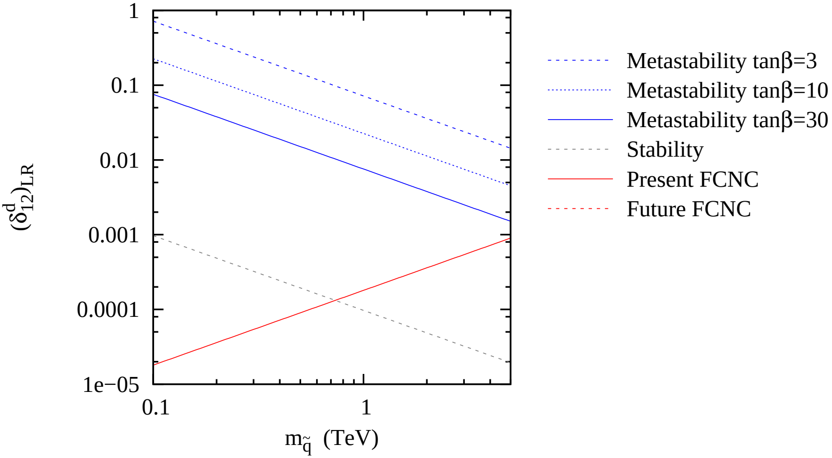
Dependence on $\tan\beta$



- Bound on A^f_{ij} insensitive to $\tan\beta$
- Bound on δ roughly $\propto \cos\beta$

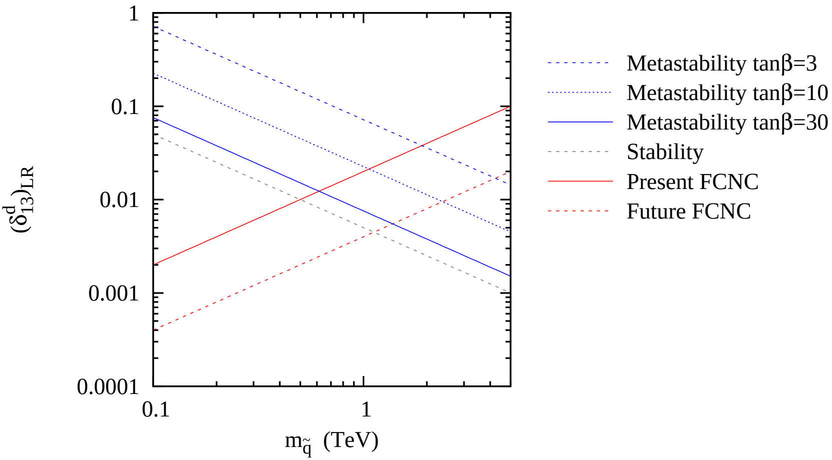
Comparison with other bounds

- For $m_{A^0} = 0.4$ TeV



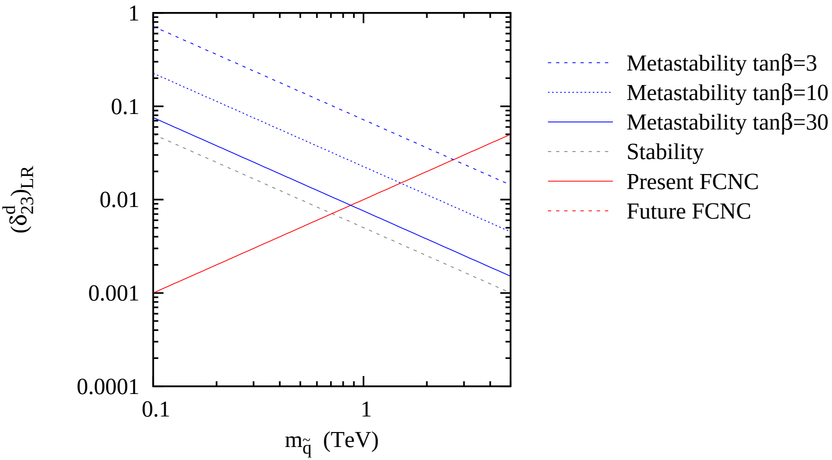
Comparison with other bounds

- For $m_{A^0} = 0.4$ TeV



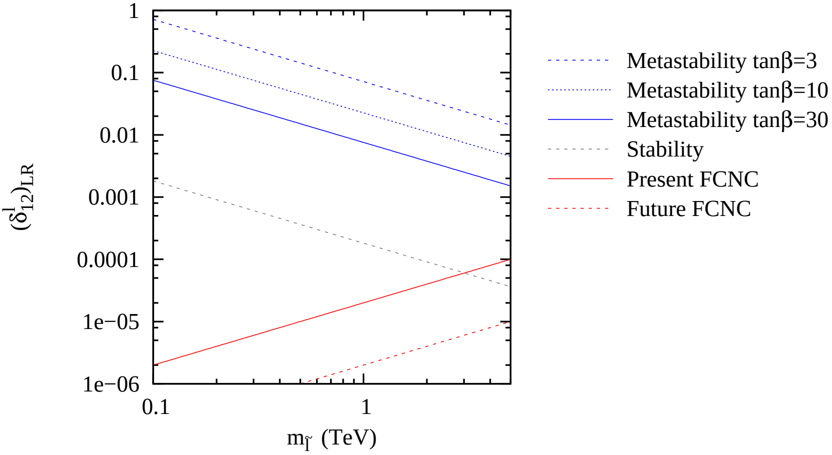
Comparison with other bounds

- For $m_{A^0} = 0.4$ TeV



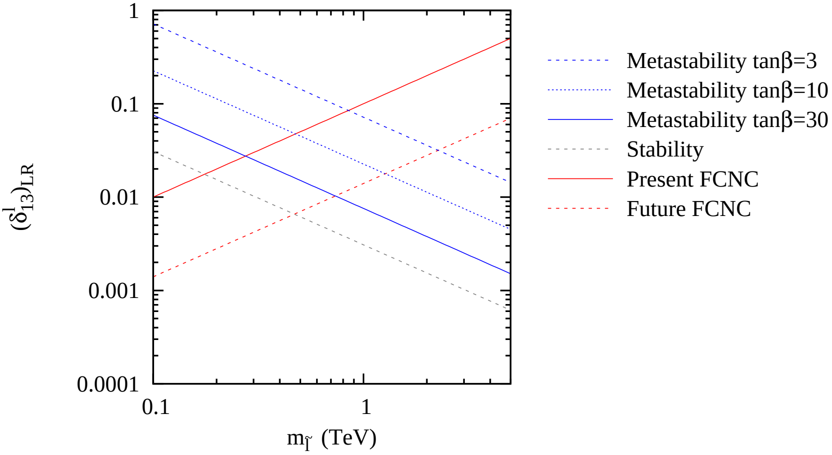
Comparison with other bounds

- For $m_{A^0} = 0.4\ \text{TeV}$



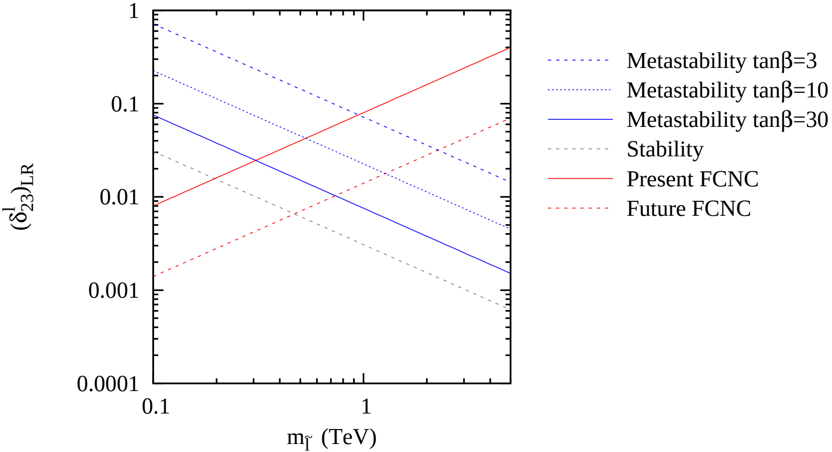
Comparison with other bounds

- For $m_{A^0} = 0.4$ TeV

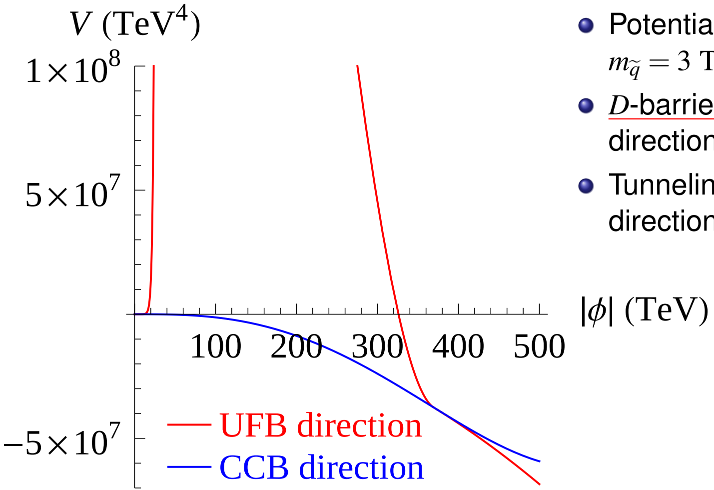


Comparison with other bounds

- For $m_{A^0} = 0.4$ TeV



CCB & UFB directions



- Potential for $m_{\tilde{q}} = 3$ TeV, $A^d_{23} = 4$ TeV
- D-barrier in UFB direction
- Tunneling occurs to CCB direction

New physics searches in B decays

- Rough estimate of supersymmetric effects on $S_{CP}^{\phi K}$

$$\Delta S_{CP}^{\phi K} \sim 10 \times \left|(\delta_{23}^d)_{LR} + (\delta_{23}^d)_{RL}\right| \times \left(\frac{3\ \mathrm{TeV}}{m_{\tilde{q}}}\right)$$

Khalil, Kou, PRD(2003)

- Metastability bound allows $(\delta_{23}^d)_{LR} \sim 8 \cdot 10^{-3}$ for $m_{\tilde{q}} = 3\ \mathrm{TeV}$

$\rightsquigarrow$ $\Delta S_{CP}^{\phi K} \sim 8 \cdot 10^{-2}$ maximally

- Sensitivity of a super B factory at $75\ \mathrm{ab}^{-1}$ is $\Delta S_{CP}^{\phi K} = 2 \cdot 10^{-2}$

CDR of SuperB, 0709.0451

- Could find an evidence for new physics

LFV searches

- For $m_{\tilde{l}} = 3$ TeV, $\tan\beta = 10$, $m_{A^0} = 0.4$ TeV, metastability bounds suppress $\tau \to \mu\gamma$ and $\tau \to e\gamma$ (from LR insertions) below the sensitivities at a super B factory
- Lowering $\tan\beta$ and increasing m_{A^0} may loosen the bounds
- $\Gamma(\mu \to e\gamma)$ is allowed to be much higher than the sensitivity of MEG

Summary

- Obtained more sensible (at least in my view) bounds on flavor-violating A-terms from vacuum structure of the MSSM
- Bounds on A^f_{ij} are (almost) flavor universal and the same for squarks and sleptons
- Bounds on A^f_{ij} become weaker for higher m_{A^0} but are independent of μ and insensitive to $\tan\beta$
- For squark and gluino masses around $3\ \mathrm{TeV}$, a super B factory still has a chance to find a discrepancy in $S^{\phi K}_{CP}$
- For slepton and gaugino masses around $3\ \mathrm{TeV}$, sleptonic LR insertions would be hard to probe via τ LFV at a super B factory
- Metastability bound allows for discovery of $\mu \to e\gamma$ at MEG

Wish list

- Consider up-type squark sector
- Study implications on flavor/CP violating processes
- Revisit constraints on flavor-conserving A-terms, in particular A_t
- Radiative corrections
- Find nicer interpretations of results