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

Jae-hyeon Park

DESY Hamburg

Work in progress

SUSY 2010
24.08.10, Physikalisches Institut, Bonn

My question

- Assume MSSM

My question

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

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

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

My question

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

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

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

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

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

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

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

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

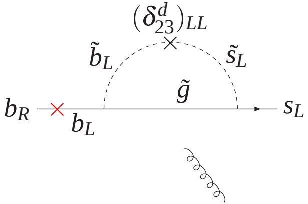
How much can we hope from indirect searches in flavor physics?

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

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

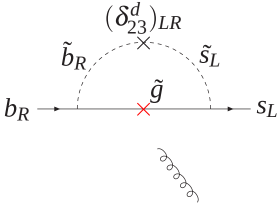
Scaling of supersymmetric effects

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



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

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

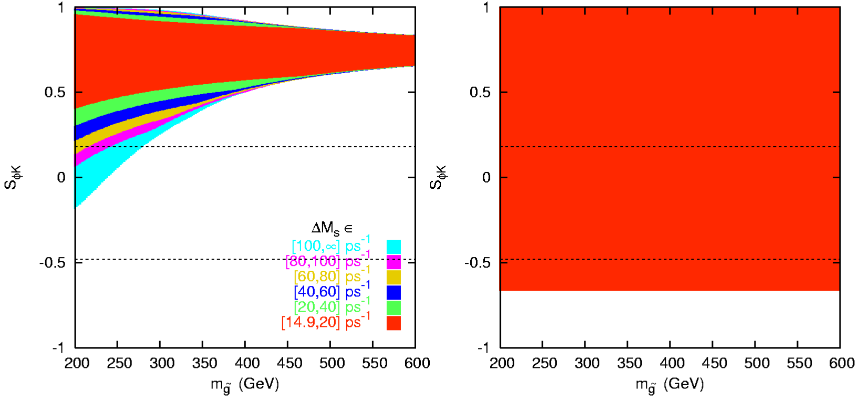


$$\propto \quad (\delta^d_{23})_{LR} \, \frac{m_{\tilde{g}}}{m^2_{\tilde{q}}} \quad \propto \quad \frac{1}{M_{\mathrm{SUSY}}}$$

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

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

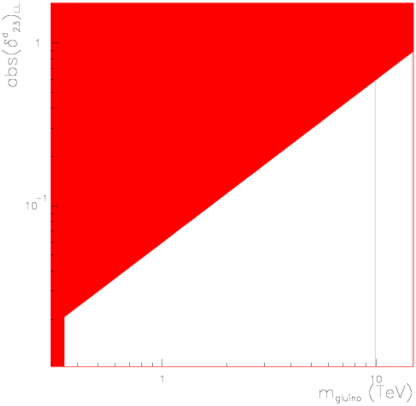
Kane, Ko, Kolda, JhP, Wang×2, PRD(2004)

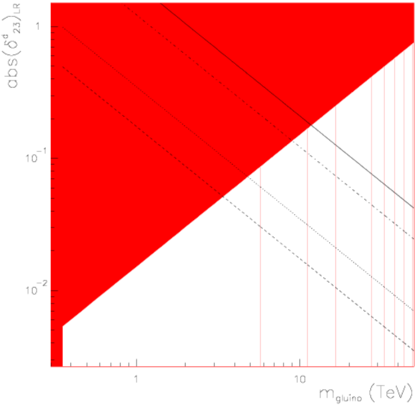


$(\delta^d_{23})_{LL}$ $(\delta^d_{23})_{LR}$

Sensitivity of SuperB

CDR of SuperB, 0709.0451

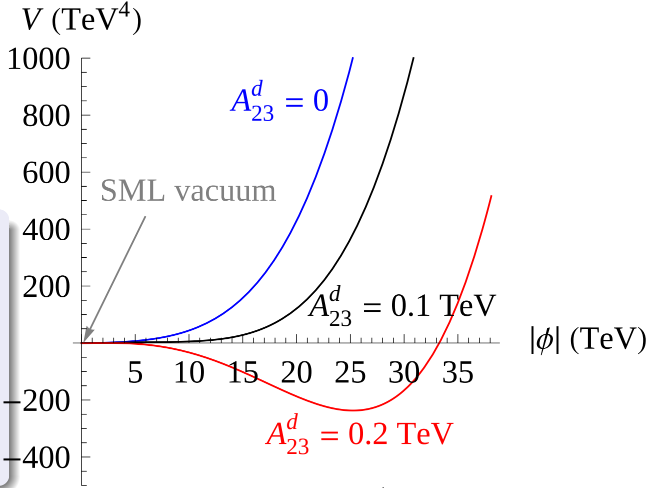




Dashed, dotted, dot-dashed, solid lines: CCB bounds for $\tan\beta = 5, 10, 35, 60$ (?)

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



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

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

Scalar potential of MSSM

$$W = H_u\, Q_i\, (\lambda_u)_{ij}\, u_j^c + H_d\, Q_i\, (\lambda_d)_{ij}\, d_j^c + H_d\, L_i\, (\lambda_l)_{ij}\, e_j^c + \mu\, H_u H_d$$

$$V = V_D + V_F + V_{\text{soft}}$$

$$V_D = \frac{1}{2}\sum_a g_a^2 \Big(\sum_\alpha \phi_\alpha^\dagger T^a \phi_\alpha\Big)^2$$

$$V_F = \sum_\alpha \left|\frac{\partial W}{\partial \phi_\alpha}\right|^2$$

$$\begin{aligned} V_{\text{soft}} = {} & \widetilde{Q}_i^*\, (M_Q^2)_{ij}\, \widetilde{Q}_j + \widetilde{u_i^c}^*\, (M_{u^c}^2)_{ij}\, \widetilde{u_j^c} + \widetilde{d_i^c}^*\, (M_{d^c}^2)_{ij}\, \widetilde{d_j^c} \\ & + 2\mathrm{Re}\big[H_u\, \widetilde{Q}_i\, A_{ij}^u\, \widetilde{u_j^c} + H_d\, \widetilde{Q}_i\, A_{ij}^d\, \widetilde{d_j^c}\big] \\ & + \text{lepton sector} \\ & + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + 2\mathrm{Re}\big[b\, H_u H_d\big] \end{aligned}$$

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

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

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

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

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

- Do not decouple even for heavy sfermions

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

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

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

$$S_E[\phi(\rho)] = 2\pi^2 \int_0^\infty d\rho\,\rho^3 \left[\left| \frac{d\phi}{d\rho} \right|^2 + V(\phi) \right]$$

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

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

Numerical analysis

- Assume flavor violation only in A-terms

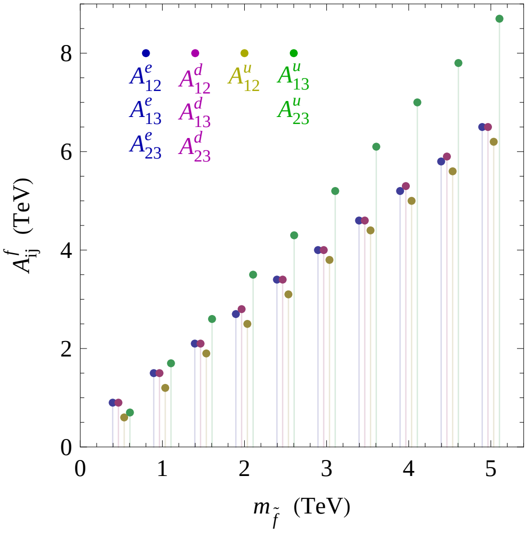
$$M^2_{Q,u^c,d^c} = \begin{bmatrix} m^2_{\tilde{q}} & 0 & 0 \\ 0 & m^2_{\tilde{q}} & 0 \\ 0 & 0 & m^2_{\tilde{q}} \end{bmatrix}, \quad A^d = \begin{bmatrix} A_d\lambda_d & A^d_{12} & A^d_{13} \\ A^d_{21} & A_s\lambda_s & A^d_{23} \\ A^d_{31} & A^d_{32} & A_b\lambda_b \end{bmatrix}$$

- Turn on one A^d_{ij} at a time and set the others to zero
- Numerically compute $\overline{\phi}(\rho)$ using a method derived from

Konstandin, Huber, JCAP(2006)

- Exclude A^d_{ij} such that $S_E[\overline{\phi}] < 400$
- Similarly for A^l_{ij}, A^u_{ij}

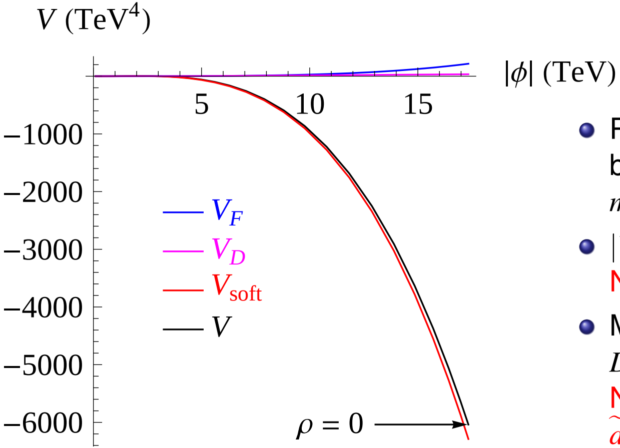
Dependence on sfermion mass



- Upper bound on A^f_{ij} for $i \neq j$
- $\max A^f_{ij} = \max A^f_{ji} \propto m_{\tilde{f}}$

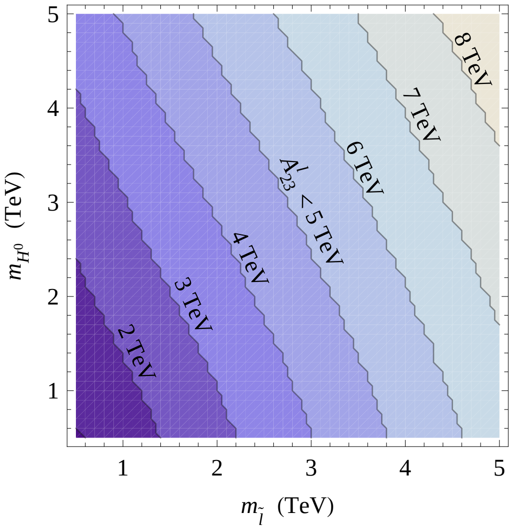
- Independent of family indices except $A^u_{13}, A^u_{31}, A^u_{23}, A^u_{32}$
- $\max A^d_{ij} \simeq \max A^l_{ij} > \max A^u_{12}$

Decomposition of potential



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

Dependence on Higgs mass parameters



$m^2_{H_u},\ m^2_{H_d},\ b,\ \mu$

$\Updownarrow$

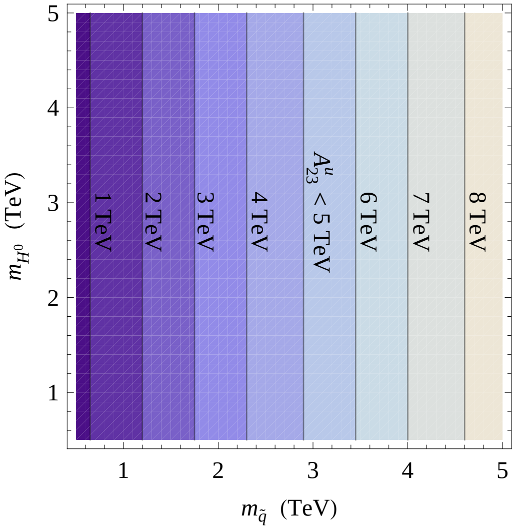
$m_Z,\ \tan\beta,\ m_{H^0},\ \mu$

- Contours of $\max A^l_{23}$ for $\tan\beta = 10$

$$H_d \sim v_d + \cos\beta h^0 + \sin\beta H^0$$

- Independent of μ

Dependence on Higgs mass parameters



$m^2_{H_u},\ m^2_{H_d},\ b,\ \mu$

$\Updownarrow$

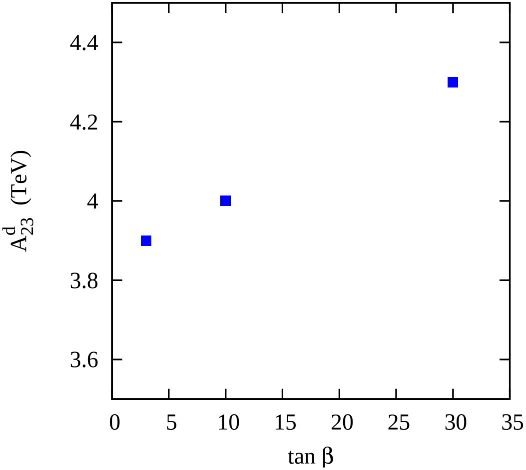
$m_Z,\ \tan\beta,\ m_{H^0},\ \mu$

- Contours of $\max A^u_{23}$ for $\tan\beta = 10$

$$H_u \sim v_u + \sin\beta h^0 - \cos\beta H^0$$

- Independent of μ

Dependence on $\tan\beta$



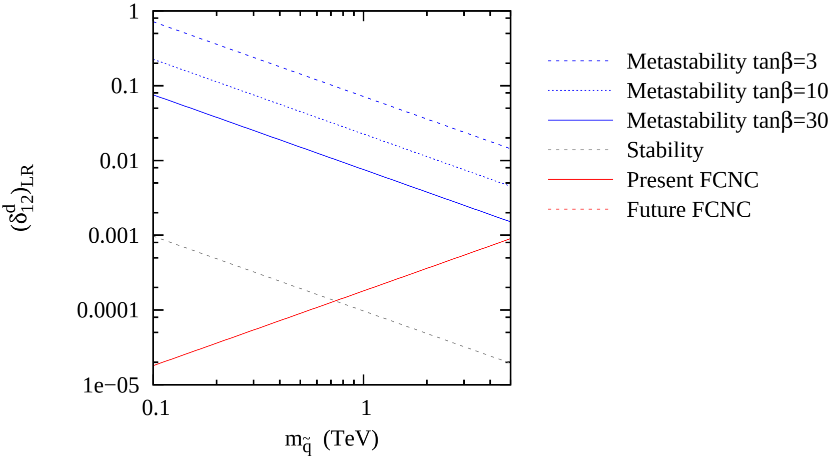
- Bound on A^f_{ij} insensitive to $\tan\beta$
- Roughly

$$\max(\delta^{d,l})_{LR} \propto \cos\beta$$

$$\max(\delta^{u}_{ij})_{LR} \propto \sin\beta$$

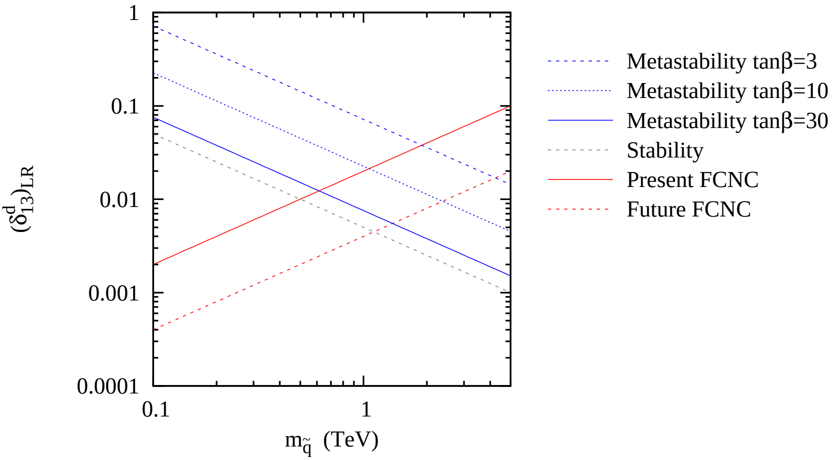
Comparison with other bounds

- For $m_{H^0} = 0.5$ TeV



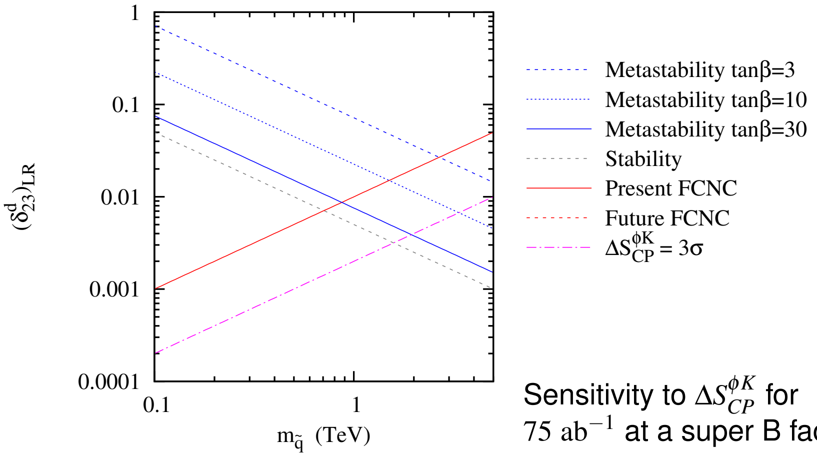
Comparison with other bounds

- For $m_{H^0} = 0.5$ TeV



Comparison with other bounds

- For $m_{H^0} = 0.5$ TeV

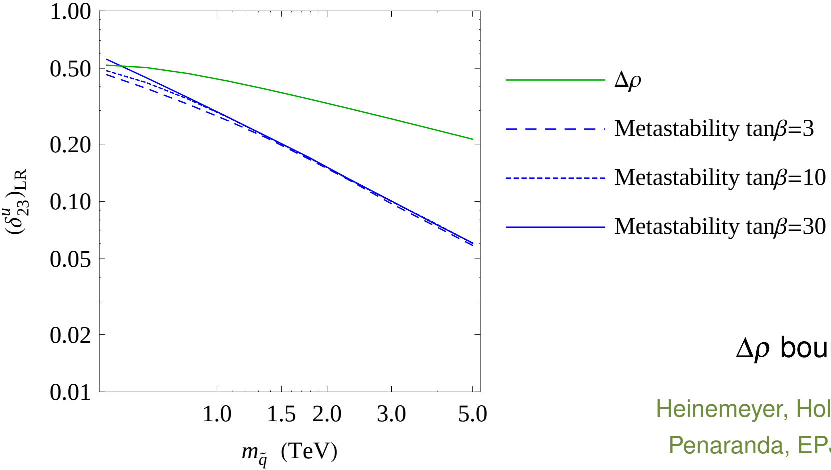


Sensitivity to $\Delta S^{\phi K}_{CP}$ for $75\ \mathrm{ab}^{-1}$ at a super B factory

CDR of SuperB, 0709.0451

Comparison with other bounds

- For $m_{H^0} = 0.5$ TeV

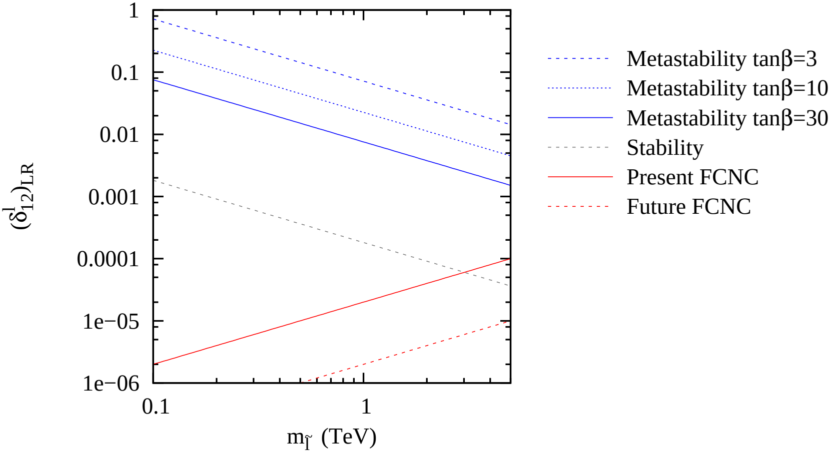


$\Delta\rho$ bound from

Heinemeyer, Hollik, Merz, Penaranda, EPJC(2004)

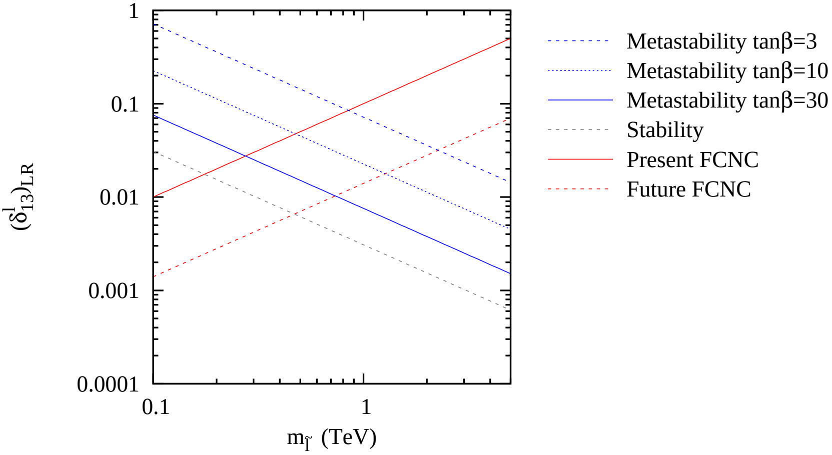
Comparison with other bounds

- For $m_{H^0} = 0.5$ TeV



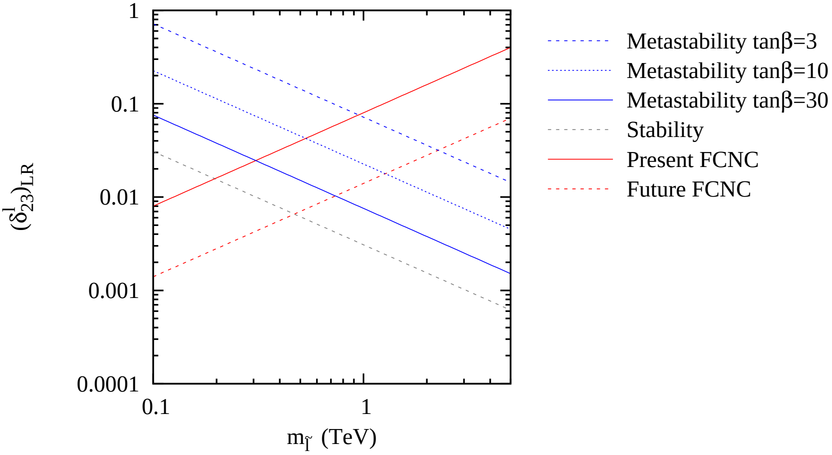
Comparison with other bounds

- For $m_{H^0} = 0.5$ TeV



Comparison with other bounds

- For $m_{H^0} = 0.5$ TeV



Summary

- Obtained more sensible (at least in my view) bounds on flavor-violating A-terms from vacuum structure of the MSSM
- Can understand properties of bounds qualitatively from D-flat directions
- Bounds on A^u_{13}, A^u_{23} are stronger than those from $\Delta\rho$ for $m_{\tilde{q}} \gtrsim 1$ TeV
- For squark and gluino masses around 3 TeV, a super B factory still has a chance to find a discrepancy in $S_{CP}^{\phi K}$
- For slepton and gaugino masses around 3 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

Dependence on S_E