

# YUKAWA UNIFICATIONS THROUGH SUSY THRESHOLDS AND THEIR EXPERIMENTAL IMPLICATIONS

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- Review of radiative corrections.
- Motivation for non universality in SU(5) GUT.
- SUSY spectrum and radiative corrections.
- FCNC constraints on the spectrum: strange and charm sector.
- Rare decays:  $K^+ \rightarrow \pi^+ \nu$ ,  $D^+ \rightarrow \pi^+ \nu$ .
- Summary and conclusions.

- Motivation for SUSY
  - 1 stabilize gauge hierarchy
  - 2 better unification
  - 3 dark matter
- SUSY breaking
  - 1 Over 100 new parameters beyond the SM
  - 2 new FCNC:  $K\bar{K}$  mixing,  $\mu \rightarrow e\gamma$
  - 3 new  $CP$  phases  $\rightarrow$  EDM.s for  $p$ ,  $n$  and  $e^-$
- To avoid the FCNC and CPV, SUSY breaking scenarios
  - 1 universal (mSUGRA, gauge mediation etc)
  - 2 decoupling (heavy sfermions)
  - 3 alignment (no off diagonal elements)

- RGE  $\rightarrow$  Gauge coupling &  $b$ - $\tau$  unifications :

$$\alpha_U = \alpha_i \text{ and } Y_b \simeq Y_\tau \text{ } (\sim 13 \div 24\%)$$

- For lighter generations  $\rightarrow$  Wrong GUT relations

$$Y_d/Y_s \simeq Y_e/Y_\mu \text{ instead observed } Y_d/Y_s \sim O(10)Y_e/Y_\mu$$

- Solutions

- 1 Extend Yukawa like interactions

[Georgi Jarlskog, 1979]

- 2 Radiative corrections from threshold of heavy fields: Superpartners provide finite SUSY corrections to fermion masses

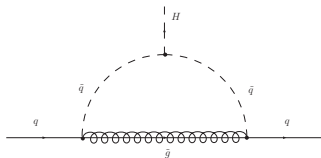
[Buchmuller and Wyler 1983, Hall, Kostelecky and Raby 1986].

# RADIATIVE SUSY CORRECTIONS

- SUSY corrections to MSSM spectrum is vital. Example:

$$m_h^2 \lesssim M_Z^2 + \frac{3G_F m_t^4}{2\sqrt{2}\pi^2} \log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

- Finite SUSY corrections to fermion masses: gluino, neutralino, chargino Example: Gluino squark loop



The induced correction (universal case) :

$$\begin{aligned} \delta m_d &\simeq -\frac{2}{3} \frac{\alpha_s}{\pi} (A_d - \mu Y_d \tan \beta) v_d m_{\tilde{g}} I(m_{\tilde{g}}^2, m_{\tilde{d}_1}^2, m_{\tilde{d}_2}^2) \\ &\simeq -\frac{\alpha_s}{3\pi} \frac{(a_0 - \mu \tan \beta) m_{\tilde{g}}}{\tilde{m}^2} m_d^0 \text{ for } A_f = Y_f a_0 \end{aligned}$$

where  $\tilde{m} = \text{Max}(m_{\tilde{g}}, m_{\tilde{d}_1}, m_{\tilde{d}_2})$

- Large  $\tan\beta$ :
  - ① motivated by  $SO(10)$  GUT
  - ② induce large threshold corrections to  $m_{d_i}$   
[Hall, Rattazzi and Sarid 1994].
  - ③ correct  $V_{CKM}$  [Blazek, Raby and Pokorsky 1995].
  - ④ large FC effects: Higgs mediated  $B_s \rightarrow \mu^+ \mu^-$ : [Babu and Kolda 1998].

$$Br(B_s \rightarrow \mu^+ \mu^-) \sim \tan^6 \beta$$

- For  $M_{SUSY} \sim$  all soft parameters and large  $\tan\beta \sim 50$

$$\frac{\delta m_d}{m_d^0} \simeq \frac{\alpha_s}{3\pi} \frac{\mu m_{\tilde{g}}}{\tilde{m}^2} \tan\beta \sim \text{sign}(\mu m_{\tilde{g}}) \frac{\alpha_s}{3\pi} \tan\beta \sim \pm O(1)$$

Soft mass universality  $\rightarrow$  the induced percentage is universal.

# NON UNIVERSALITY

- The SUSY thresholds are more prominent for quarks
- $SU(5)$  condition: at  $M_{GUT}$   $Y_{d_i}$  are set to  $Y_{l_i}$

- 1 The needed changes for light flavors (at  $M_{SUSY} = 500$  GeV)

$$\frac{m_d^{exp}}{m_d^0} \simeq 2.5 \rightarrow \delta m_d \sim 1.5 \text{ MeV}(-3.5 \text{ MeV}) \rightarrow \frac{\delta m_d}{m_d^0} \sim 1.5(-3.5)$$

$$\frac{m_s^{exp}}{m_s^0} \simeq 0.25 \rightarrow \delta m_s \sim -150 \text{ MeV} \rightarrow \frac{\delta m_s}{m_s^0} \sim -0.75$$

- 2 Correcting the wrong GUT ratios by SUSY thresholds requires non universality!

[Babu, Dutta and Mohapatra 1999]. , [Diaz Cruz, Murayama and Pierce 2001], [Antusch et al 2009].

- Two choices for non universality:

- 1 Using different soft masses  $\rightarrow$  large mass splitting in first two generation squarks. FCNC constraints may push the masses beyond the reach of LHC.
- 2 Choice in this talk: Large A-terms subject to local stability condition.

# LARGE A-TERMS, CHOICE FOR SOFT TERMS

- MSSM has many color/charge breaking vacua along D-flat directions.

- If the condition

$$A_{ij} \lesssim 1.75 \sqrt{\tilde{m}_i^2 + \tilde{m}_j^2 + \mu^2 + m_H^2} \text{ for interaction } A_{ij} \tilde{f}_i \tilde{f}_j H$$

satisfied, the lifetime of the vacuum is longer than the age of the universe.

[Kusenko, Langacker and Segre 1995], [Borzumatti et al 1999].

- GUT conditions

$$(Y_5)_{ji} \equiv (Y_d)_{ji} = (Y_l)_{ij},$$

$$(A_5)_{ij} \equiv (A_l)_{ji} = (A_d)_{ij}$$

$$(m_5^2)_{ij} \equiv (m_{\tilde{L}}^2)_{ij} = (m_{\tilde{d}c}^2)_{ij},$$

$$(m_{10}^2)_{ij} \equiv (m_{\tilde{e}c}^2)_{ij} = (m_{\tilde{u}c}^2)_{ij} = (m_{\tilde{Q}}^2)_{ij}$$

- In the basis  $Y_5$  diagonal we choose

- 1  $m_{10}^2$ ,  $m_5^2$  and  $A_5$  are diagonal.

- 2  $A_5 \neq a_0 Y_5$  to induce the needed threshold corrections



Parameter choice at GUT scale:

$\tan \beta$	5	10	15	25	35
$m_{1/2}$	-0.20	-0.21	-0.23	-0.23	-0.35
$m_{\tilde{Q}_{1,2}}^2, m_{\tilde{Q}_3}^2$	0.392	0.28	0.28	0.392	0.392, 2.69
$m_{\tilde{d}_{1,2}}^2, m_{\tilde{d}_3}^2$	0.448	0.32	0.32	0.448	0.448, 2.35

Parameter choice at  $M_{SUSY}$ :

$\tan \beta$	5	10	15	25	35
$\mu$	0.30	0.30	0.30	0.85	1.10
$A_d$	3.1	7.7	8.5	22.0	45.0
$A_s$	-0.34	-0.78	-0.76	-0.86	-1.2

- $A_s$  and soft masses are in TeV and  $\text{TeV}^2$ .,  $A_d$  is in  $GeV$
- We used publicly available SOFTSUSY, C++ code for our calculation.

- RGE to  $M_{EW}$   $\rightarrow$  Non universal soft masses:

$\tan \beta$	5	10	15	25	35
$m_{\tilde{Q}_1}^2$	0.807	0.466	0.506	0.613	0.882
$m_{\tilde{Q}_2}^2$	0.715	0.401	0.429	0.496	0.634
$m_{\tilde{Q}_3}^2$	0.520	0.270	0.294	3.27	1.44
$m_{\tilde{d}_1^c}^2$	0.795	0.487	0.525	0.650	0.894
$m_{\tilde{d}_2^c}^2$	0.610	0.357	0.349	0.414	0.396
$m_{\tilde{d}_2^c}^2$	0.777	0.474	0.493	0.542	2.27

The soft mass params are in  $\text{TeV}^2$

- Non-universal  $A$ -term for Unifications  $Y_{e_i} = Y_{d_i}$  split the soft masses

# MESON MASS SPLITTINGS

Results for mass splittings for different meson:

$\tan \beta$	5	10	15	25	35
$\Delta M_D \times 10^{-14}$ GeV	0.578	1.23	1.48	1.18	0.022
$\Delta M_K \times 10^{-15}$ GeV	0.027	0.199	-0.447	0.0342	0.0022
$\Delta M_B \times 10^{-16}$ GeV	1.9	1.46	1.07	1.37	46.4
$\Delta M_{B_s} \times 10^{-14}$ GeV	1.67	1.16	6.06	4.39	8.45

Experimental values:

$\Delta M_D$	$(1.57 \pm_{0.471}^{0.438}) \times 10^{-14}$ GeV
$\Delta M_K$	$(3.483 \pm 0.033) \times 10^{-15}$ GeV
$\Delta M_B$	$(3.337 \pm 0.006) \times 10^{-13}$ GeV
$\Delta M_{B_s}$	$(1.17 \pm 0.008) \times 10^{-11}$ GeV

The induced corrections to light down type quarks

$\tan \beta$	5	10	15	25	35
$\delta m_d$ MeV	1.48	1.61	1.32	1.61	1.59
$\delta m_s$ GeV	-0.157	-0.163	-0.157	-0.154	-0.161

$K, D, B$  mass splitting:

$\tan \beta$	5	10	15	25	35
$Br(D^+)$	0.34	0.90	1.03	0.161	0.001
$Br(K^+)$	0.018	1.77	5.94	0.134	0.386

Here

$$Br(D^+) \equiv B(D^+ \rightarrow \pi^+ \nu \bar{\nu}) \times 10^{11}$$

$$Br(K^+) \equiv B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \times 10^{11}$$

- The SM expectation for  $B(D^+ \rightarrow \pi^+ \nu \bar{\nu})$ :
  - ① short distance contribution  $\sim 10^{-16}$
  - ② long distance contribution  $\sim 10^{-15}$
- The SM expectation for
  - ①  $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{SM} \sim (8.22 \pm 0.84) \times 10^{-11}$
  - ② Experimental status [E787, E949 collaborations]  
 $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{Exp} = (15.7 \pm_{8.2}^{17.5}) 10^{-11}$

- Finite radiative corrections for fermion masses studied.
- Minimal SU(5) unifications for Yukawas of light charged leptons and down-type quarks can be achieved by finite SUSY corrections.
- To have unifications for lighter generations certain non universality is needed among soft parameters.
- For low and moderate  $\tan\beta$  we obtain the needed corrections for light down type quarks  $d$  and  $s$ .
- The non universality in  $A_5$  lead to rare charm decays.
- The branching fractions for  $D^+ \rightarrow \pi^+ \nu \bar{\nu}$  are found to be at the level of four order of magnitude larger than the SM expectation.