YUKAWA UNIFICATIONS THROUGH SUSY THRESHOLDS AND THEIR EXPERIMENTAL IMPLICATIONS

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OVERVIEW

- 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: $K^+ \to \pi^+\nu$, $D^+ \to \pi^+\nu$.
- Summary and conclusions.

SUSY CORRECTIONS

- 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, $\mu \to e\gamma$
    3. new CP phases → 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 daigonal elements)

SUSY SU(5) GUT

- RGE → Gauge coupling & b–τ unifications :

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

- For lighter generations → Wrong GUT relations

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

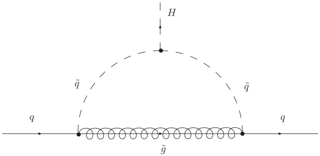
- Solutions
  1. Extend Yukawa like interactions
     [Georgi Jarlskog, 1979]
  2. Radiative corrections from threshold of heavy fields: Superpartners provide finite SUSY corrections to fermion masses
     [Buchmuller and Wyler 1983, Hall, Kostelecky and Raby 1986].

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) :

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

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

RADIATIVE SUSY CORRECTIONS CNTD

- 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 $B_s \to \mu^+\mu^-$: [Babu and Kolda 1998].

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

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

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

Soft mass universality → 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)

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

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

  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 → 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

$$\begin{aligned}
&(Y_5)_{ji} \equiv (Y_d)_{ji} = (Y_l)_{ij},\\
&(A_5)_{ij} \equiv (A_l)_{ji} = (A_d)_{ij}\\
&(m^2_{\tilde{5}})_{ij} \equiv (m^2_{\tilde{L}})_{ij} = (m^2_{\tilde{d}^c})_{ij},\\
&(m^2_{\tilde{10}})_{ij} \equiv (m^2_{\tilde{e}^c})_{ij} = (m^2_{\tilde{u}^c})_{ij} = (m^2_{\tilde{Q}})_{ij}
\end{aligned}$$

- In the basis Y_5 diagonal we choose
  1. $m^2_{\tilde{10}}$, $m^2_{\tilde{5}}$ and A_5 are diagonal.
  2. $A_5 \neq a_0 Y_5$ to induce the needed threshold corrections

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PARAMETERS

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
$m^2_{\tilde{Q}_{1,2}}$,$m^2_{\tilde{Q}_3}$	0.392	0.28	0.28	0.392	0.392, 2.69
$m^2_{\tilde{d}_{1,2}}$, $m^2_{\tilde{d}_3}$	0.448	0.32	0.32	0.448	0.448, 2.35

Parameter choice at M_{SUSY}:

$\tan\beta$	5	10	15	25	35
μ	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 TeV^2., A_d is in GeV
- We used publicly available SOFTSUSY, C++ code for our calculation.

SPECTRUM

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

$\tan\beta$	5	10	15	25	35
$m^2_{\tilde{Q}_1}$	0.807	0.466	0.506	0.613	0.882
$m^2_{\tilde{Q}_2}$	0.715	0.401	0.429	0.496	0.634
$m^2_{\tilde{Q}_3}$	0.520	0.270	0.294	3.27	1.44
$m^2_{\tilde{d}^c_1}$	0.795	0.487	0.525	0.650	0.894
$m^2_{\tilde{d}^c_2}$	0.610	0.357	0.349	0.414	0.396
$m^2_{\tilde{d}^c_2}$	0.777	0.474	0.493	0.542	2.27

The soft mass params are in 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:

ΔM_D	$(1.57\pm^{0.438}_{0.471}) \times 10^{-14}$ GeV
ΔM_K	$(3.483 \pm 0.033) \times 10^{-15}$ GeV
ΔM_B	$(3.337 \pm 0.006) \times 10^{-13}$ GeV
ΔM_{B_s}	$(1.17 \pm 0.008) \times 10^{-11}$ GeV

The induced corrections to light doawn type quarks

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

RARE DECAYS

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

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

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

CONCLUSIONS

- Finite radiative corrections for fermmion 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 rear 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.

SYSTEMATICS IN X-SEC MEASUREMENT

- Initial state/final state radiation (ISR/FSR) uncertainties.
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    1. More ISR/FSR increases the number of jets and has effects on P_Ts of objects.
    2. Study by varying parameters in PYTHIA such as λ_{QCD} and the the ISR/FSR cutoffs.
- PDF uncertainties.

  Both CTEQ6M and MRST2002 error sets at NLO have been used to evaluate these.
- Jet energy scale (JES).
    1. The principal source of systematic uncertainties for most LHC (and hadron collider in general) measurements.
    2. Many factors influencing JES: dead material, underlying event, energy lost outside jet cones...
    3. Data driven methods to determine JES: P_T balance in Z+jets, γ+jets.
    4. Light jet scale and b-jet scale different. b-jet scale difficult to measure, need to use $Z \to b\bar{b}$.
    5. Can also use $t\bar{t}$ itself to measure light jet scale, via M_W.
    6. Ultimate goal is to reduce JES uncertainty to 1%.