New results of R-parity-violating MSSM contributions to neutral mesons' mixing

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Motivation

- Softly-broken supersymmetric (SUSY) extensions of the Standard Model (SM) have long been regarded as a leading class of candidates for the resolution of the Hierarchy Problem, as well as a possible framework in view of understanding the nature of dark matter or the unification of gauge-couplings.
- R-parity-violating Minimal Supersymmetric Standard Model (RPV-MSSM) leads to a distinctive phenomenology related to LHC searches.
- Low-energy flavor observables can place stringent bounds on parameters that arise in New Physics (NP) theories.
- Existing studies in the literature are far from being comprehensive.

MSSM and R-parity

- Despite the fact that no predicted superpartner has been found in the LHC, the MSSM remains one of the leading candidates of NP theories
- It introduces for each Standard-Model (SM) field a superpartner field, thus solving the Hierarchy Problem in the SM
- R-parity for particles is usually implied to ensure proton stability and obtain automatically a lightest supersymmetric particle (LSP) as dark matter (DM) candidate if it is neutral

R-parity and RPV-MSSM

For each field, a discrete symmetry called R-parity is defined as follows:

R-parity

$R_P = (-1)^{3B+L+2S}$

B: baryon number, L: lepton number, S: spin.

- $R_P = +1$ for the SM fields and $R_P = -1$ for their superpartners.

RPV-MSSM superpotential

$$W_{\not{R}_p} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

Flavor violation! $\Rightarrow \Delta M_d, \Delta M_s, \Delta M_K$, experimentally well known.

Deficiencies in the literature studies

$\Delta M_d, \Delta M_s, \Delta M_K$ have been studied under RPV-MSSM in the past. However, deficiencies exist.

- Diagrams beyond the tree-level and box contributions have been ignored
- Sfermion mixings have been routinely ignored.
- RPV-induced mixings have also been routinely ignored.

RPV-induced mixings $\mu_i H_u L_i$:

- neutral Higgs-sneutrino
- charged Higgs-slepton
- neutralino-neutrino
- chargino-charged lepton

Computation procedure

- Framework: Effective Field Theory (EFT) where short-distance effects intervene via the Wilson coefficients of dimension-6 flavor-changing (ΔF$=2$) operators
- Amplitude: calculate Feynman diagrams using RPV-MSSM.
- Matching: match the full-theory amplitudes to the effective Lagrangian and obtain the corresponding Wilson coefficients.
- ΔM's: Use software to evaluate the effects of the Wilson coefficients on the ΔM's. Explicit formulas are also well known.

$$\Delta M = \frac{| < f|\mathcal{L}_{eff}|i > |}{M}$$

Low-energy EFT ΔF$=2$ operators

Effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \sum_i C_i O_i + h.c.$$

C_i: Wilson coefficients. O_i: dim-6 operators.

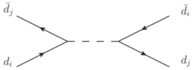
$$\begin{aligned}
O_1 &= (\bar{d}_j \gamma^\mu P_L d_i)(\bar{d}_j \gamma_\mu P_L d_i), & \tilde{O}_1 &= (\bar{d}_j \gamma^\mu P_R d_i)(\bar{d}_j \gamma_\mu P_R d_i),\\
O_2 &= (\bar{d}_j P_L d_i)(\bar{d}_j P_L d_i), & \tilde{O}_2 &= (\bar{d}_j P_R d_i)(\bar{d}_j P_R d_i),\\
O_3 &= (\bar{d}_j^a P_L d_i^b)(\bar{d}_j^b P_L d_i^a), & \tilde{O}_3 &= (\bar{d}_j^a P_R d_i^b)(\bar{d}_j^b P_R d_i^a),\\
O_4 &= (\bar{d}_j P_L d_i)(\bar{d}_j P_R d_i), & O_5 &= (\bar{d}_j^a P_L d_i^b)(\bar{d}_j^b P_R d_i^a).
\end{aligned}$$

$i, j = d, s, b$ down-type quarks, $a, b = 1, 2, 3$ three colors.

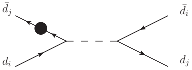
Compute the full-theory amplitudes

- Feynman t'Hooft gauge and dimensional regularization
- $\overline{DR}-$renormalization consistent with numerical tools
- Consider only short-distance effects: discarding QED and QCD loops. Photons and gluons are active fields in the EFT.
- Different topologies of Feynman diagrams: tree-level and its one-loop corrections, and one-loop box diagrams
- Crosscheck between four-component and two-component spinor formalisms

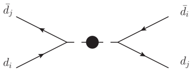
Topologies of Feynman diagrams I



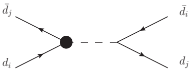
(a) Tree-level Feynman diagram



(b) Quark self-energy corrections



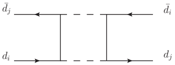
(c) Scalar self-energy



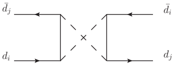
(d) Vertex corrections

The tree-level contribution is purely due to the λ' couplings of LQD operator.

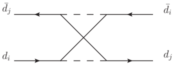
Topologies of Feynman diagrams II



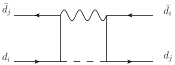
(a) S/F/S/F
"straight" box



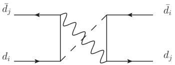
(b) S/F/S/F
"scalar-cross" box



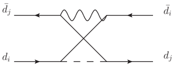
(c) S/F/S/F
"fermion-cross" box



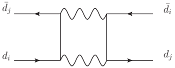
(d) V/F/S/F
"straight" box



(e) V/F/S/F
"cross" boxes



(f) V/F/S/F
"fermion-cross" box



(g) V/F/V/F
"straight" box

S: Scalar, F: Fermion, V: Vector

Different one-loop contributions

- SM-like: box diagrams with internal u, c, t quarks, W and Goldstone bosons
- 2-Higgs-doublet-model-like: box diagrams with internal u, c, t quarks, charged-Higgs bosons and possibly W or Goldstone bosons
- R-parity conserving: box diagrams with chargino/sup, neutralino/sdown or gluino/sdown particles in the loop
- RPV: self-energies and vertex corrections, box diagrams with sneutrino/quark, slepton/quark, lepton/squarks, neutrino/squark or quark/squark internal lines)
- RPV-driven mixing further mixes these contributions

Comparing analytic results with the literature

- Self-energy and vertex correcions were not considered before, but at least the scalar self-energy is consistent with Higgs self-energy calculation in the literature.
- R-parity conserving MSSM result is recovered.
- In no-mixing limit, comparing with the literature shows some difference:
  C_5 from $[\nu/\tilde{D}/\nu/\tilde{D}]$: difference in prefactor and in sfermion chiralities.
- Cross-check with amplitudes generated from public code `FlavorKit`

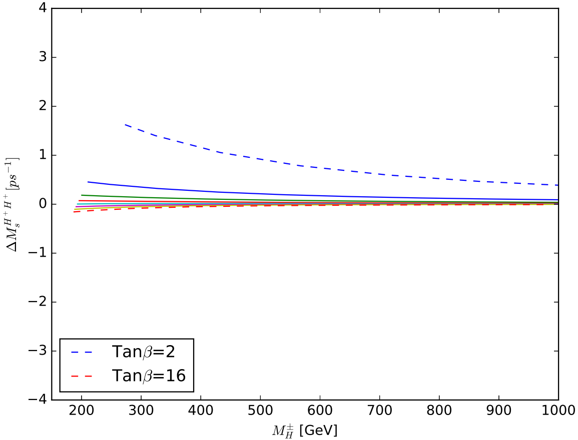
Software tools introduction

Tools: Mathematica packages `PreSARAH`, `SARAH`, `FlavorKit`, `SPheno` and Python3 software `Flavio`

- `PreSARAH`: incorporates quark self-energy and vertex corrections; scalar-self energy included by hand
- `SARAH`: uses *MSSM_TriRpV* model file modified by `PreSARAH`
- `FlavorKit`: generates all the amplitudes for general meson mixing $\bar{d}_j d_i \Leftrightarrow \bar{d}_i d_j$
- `SPheno`: spectrum generator, giving in particular Wilson coefficients and predictions for ΔM's.
- `Flavio`: Better handle with hadronic contributions for ΔM_d and ΔM_s.

Reproduction of plots in the literature I

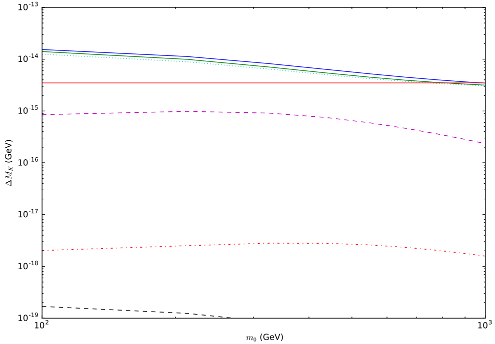
Figure 7 of Altmannshofer, Buras, Guadagnoli, 2007.
Using *MSSM* model file in `SARAH`.



Charged Higgs boxes contributions to ΔM_s.
$\mu > 0$, $A_0 = 0$,
$M_{1/2} = 120$ GeV.

Reproduction of plots in the literature II

Figure 4 of de Carlos, White, 1997.
Using *MSSMTriBpV* model file in SARAH.



$$\lambda''_{213}(GUT) = \lambda''_{223}(GUT) = 0.02$$
$$M_{1/2} = 100 \text{ GeV}$$
$$A_0 = 0, tan\beta = 10, \mu < 0.$$

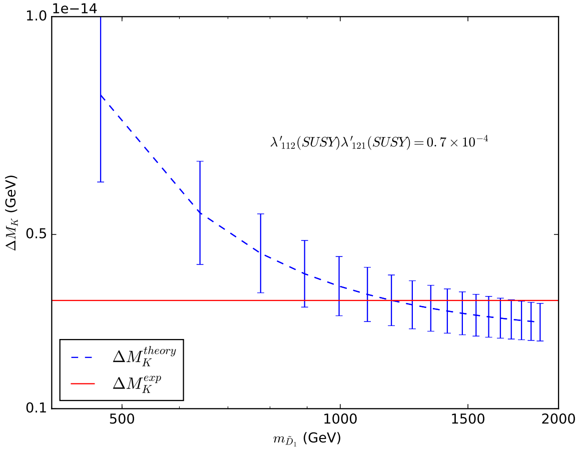
Different boxes contributions to ΔM_K.
black dashed: χ^0
red dot-dashed: $\chi^0 - \tilde{g}$
magenta dashed: $\tilde{g}$
red solid: experimental upper limit
blue solid: full
cyan dot: direct RPV boxes without W
green solid: direct RPV boxes with W

Numerics To-Do: Quark Flavor Violation (QFV)

Explore the size of and the interplay between different sources of QFV.

- λ' tree-level: $\lambda'_{i12} \cdot \lambda'_{i21}$, $\lambda'_{i13} \cdot \lambda'_{i31}$, $\lambda'_{i23} \cdot \lambda'_{i32}$, $(i = 1, 2, 3)$
- λ' boxes, unaligned with tree-level λ''s..
- λ'' boxes
- CKM (charged Higgs) v.s RPV
- RPC-MSSM v.s RPV

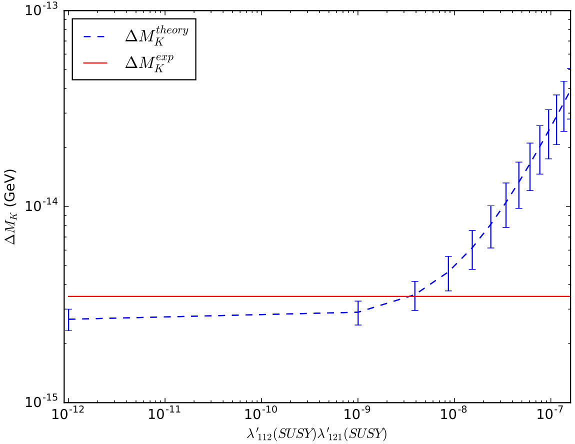
Plots of tree-level LQD couplings I



ΔM_K w.r.t. $m_{\tilde{D}_1}$
$M_1 = M_2 = M_3 = 500$ GeV
$\mu = 1000$ GeV,
$tan\beta = 10.$

Errorbar:
15% SM + 30% NP

Plots of tree-level LQD couplings II



ΔM_K w.r.t. $\lambda'_{112}\lambda'_{121}$ at SUSY scale

$M_1 = M_2 = M_3 = 500$ GeV

$\mu = 1000$ GeV,

$tan\beta = 10.$

Errorbar:

15% SM + 30% NP

Conclusion

- Studies on neutral mesons mixing from RPV-MSSM have huge room for improvement.
- Analytically, we obtained a comprehensive list of tree-level and one-loop contributioins to these processes excluding QED and QCD loops, and there is some difference w.r.t. some results in the literature
- Numerically, we are trying to compare the effects on Quark Flavor Violation from different sources: RPV-MSSM, RPC-MSSM, CKM, etc.

Thank You!
謝謝！

Matching amplitudes with Wilson coefficients

Procedure to determine the Wilson coefficients:

- calculate the scattering amplitude in the full theory;
- find the appropriate corresponding dim-6 operators;
- determine the Wilson coefficients of the operators by equating the amplitude calculated from the effective operators with that from the full theory.

Illustrate this by C_4^{tree}:

$$A_4^{\text{tree}} = \frac{\imath}{m_S^2}\left(\left[g_L^{Sd_jd_i}P_L\right]\otimes\left[g_R^{Sd_jd_i}P_R\right] + \left[g_R^{Sd_jd_i}P_R\right]\otimes\left[g_L^{Sd_jd_i}P_L\right]\right)$$

corresponding to O_4: $C_4^{\text{tree}} = \frac{\imath}{2m_S^2}(2g_L^{Sd_jd_i}g_R^{Sd_jd_i})$. Factor 2 in the denominator arises because O_4 is symmetrical:

$O_4 = (\bar{d}_jP_Ld_i)(\bar{d}_jP_Rd_i) = (\bar{d}_jP_Rd_i)(\bar{d}_jP_Ld_i)$