Lifetime Difference in $D^0 - \bar{D}^0$ Mixing within R-parity Violating Supersymmetry

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Based on

A. A. Petrov, G. K. Yeghiyan, Phys. Rev. D 77, 034018 (2008)

Outline

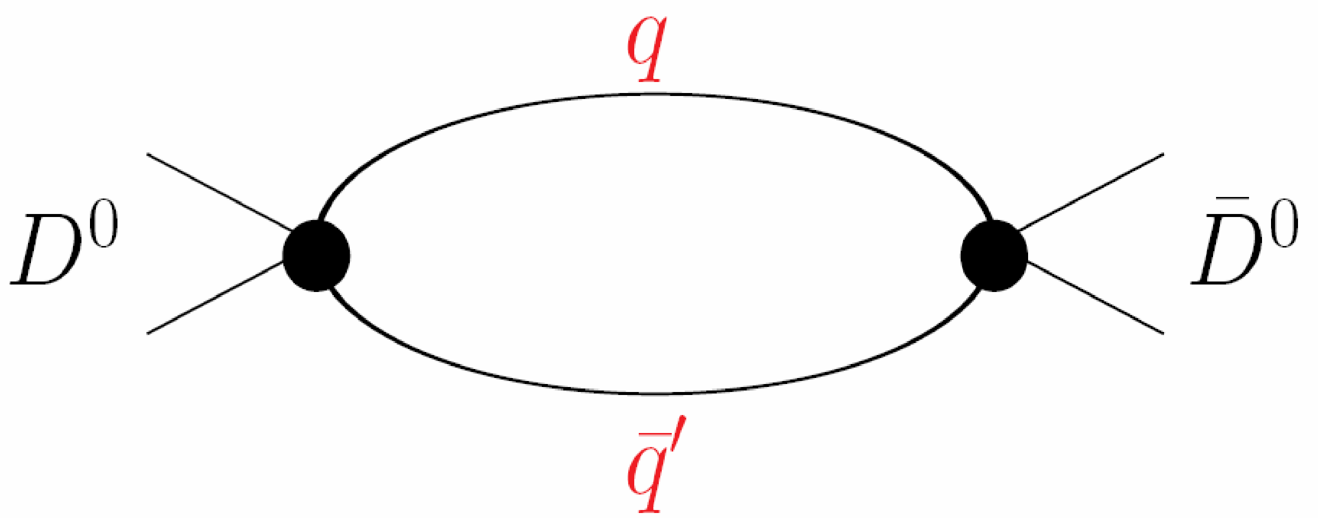
- We show that the contribution from RPV SUSY models with the leptonic number violation to $\Delta\Gamma_D$ is negative, i.e. opposite in sign to what is implied by the recent experimental evidence.

- It is possibly quite large in absolute value (may exceed the experimentally allowed values for $\Delta\Gamma_D$).

- We derive new constraints on the relevant RPV coupling pair products. Unlike those coming from the study of Δm_D, our bounds are insensitive or weakly sensitive to assumptions on R-parity conserving (pure MSSM) sector.

- We emphasize the necessity of taking into account of the transformation of RPV couplings from the weak eigenbasis to the quark mass eigenbasis.

It is known that $\Delta\Gamma_D$ is driven by the physics of $\Delta C=1$ sector both in the SM and beyond.



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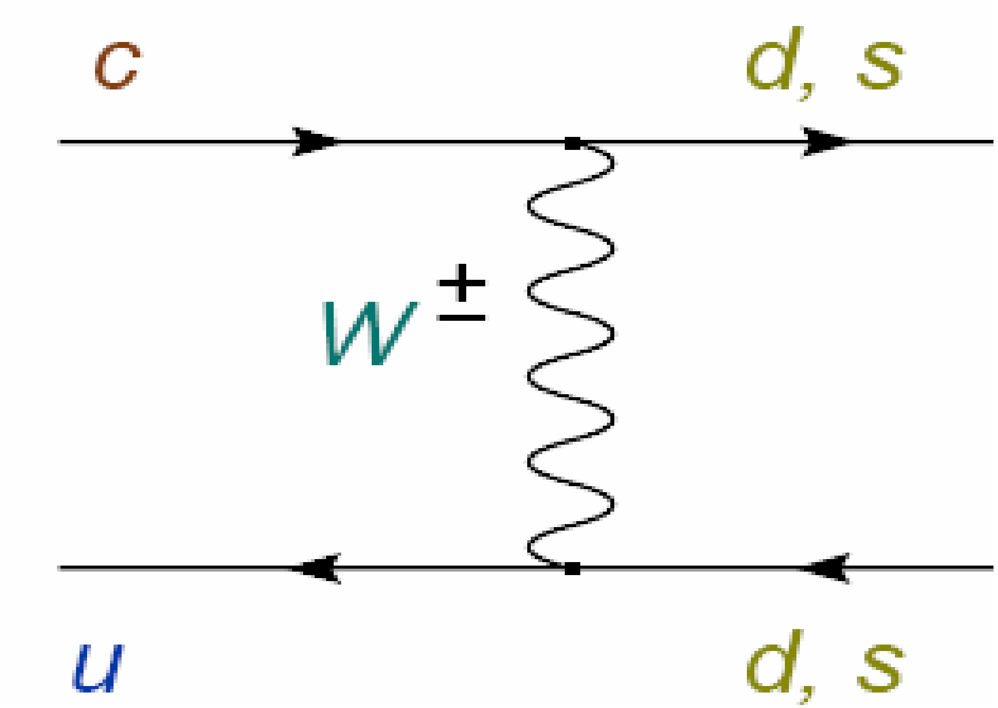
Let

$A[D^0 \to n] = A_n^{(SM)} + A_n^{(NP)}$, $|n>$ is a charmless state



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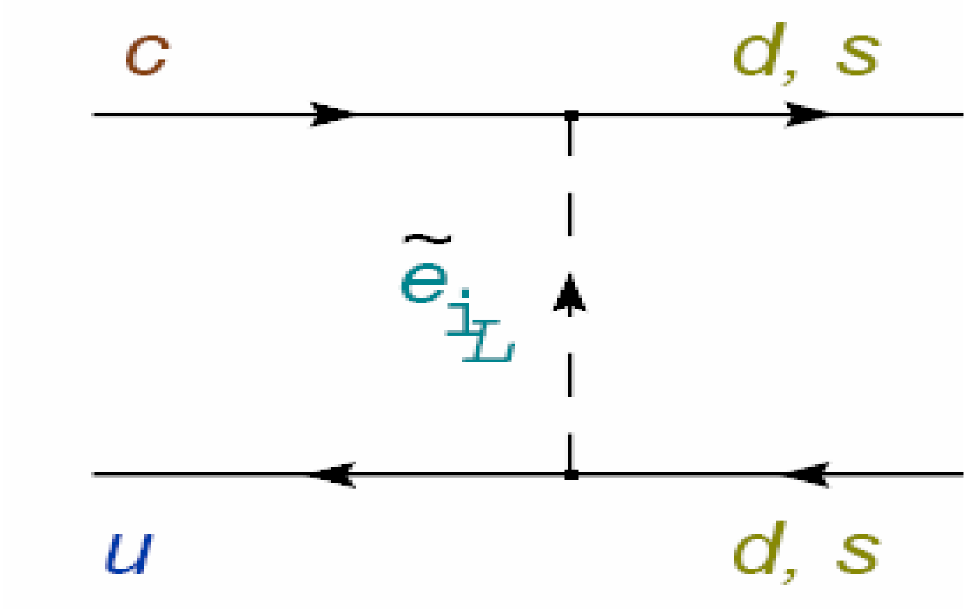

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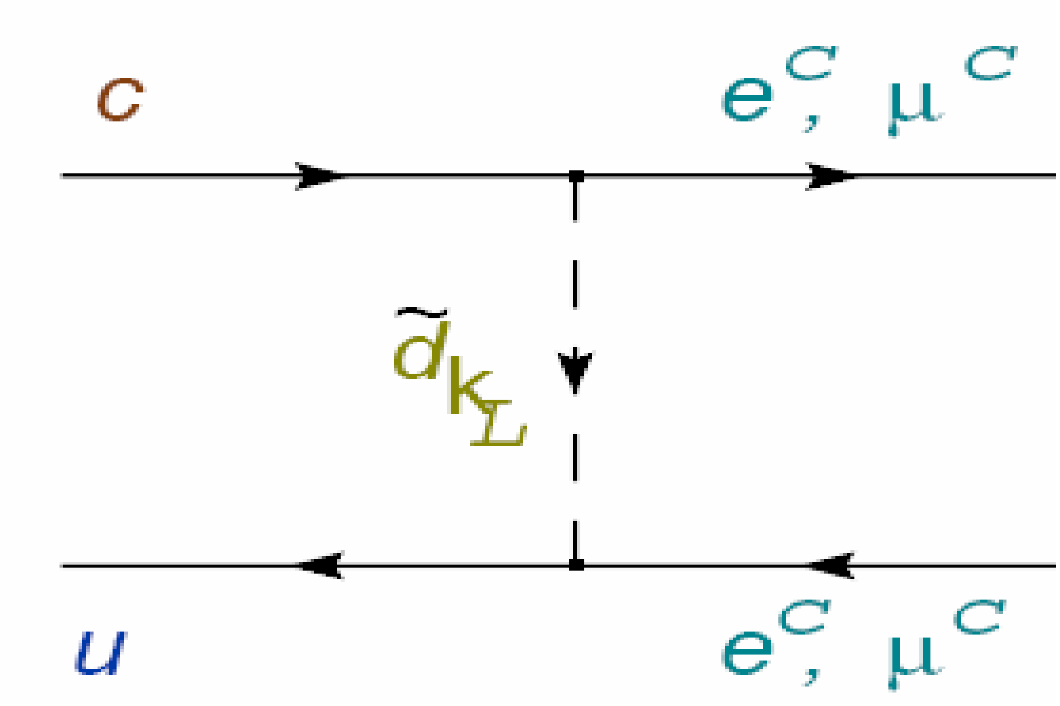

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Then for $y_D=\Delta\Gamma_D/(2\Gamma_D)$

$$y_D = \sum_n \frac{\rho_n}{\Gamma_{\rm D}} A_n^{\rm (SM)} \bar{A}_n^{\rm (SM)} + 2\sum_n \frac{\rho_n}{\Gamma_{\rm D}} A_n^{\rm (NP)} \bar{A}_n^{\rm (SM)} + \sum_n \frac{\rho_n}{\Gamma_{\rm D}} A_n^{\rm (NP)} \bar{A}_n^{\rm (NP)}$$

$$y_D = \sum_n \frac{\rho_n}{\Gamma_{\rm D}} A_n^{(\rm SM)} \bar{A}_n^{(\rm SM)} + 2\sum_n \frac{\rho_n}{\Gamma_{\rm D}} A_n^{(\rm NP)} \bar{A}_n^{(\rm SM)} + \sum_n \frac{\rho_n}{\Gamma_{\rm D}} A_n^{(\rm NP)} \bar{A}_n^{(\rm NP)}$$

The SM contribution is rather uncertain (due to long-distance effects): $y_{SM} \sim 10^{-4} \div 10^{-2}$

$y_D^{exp} = (6.6 \pm 2.1) \cdot 10^{-3}$ – is this due to the SM or NP or both of them?

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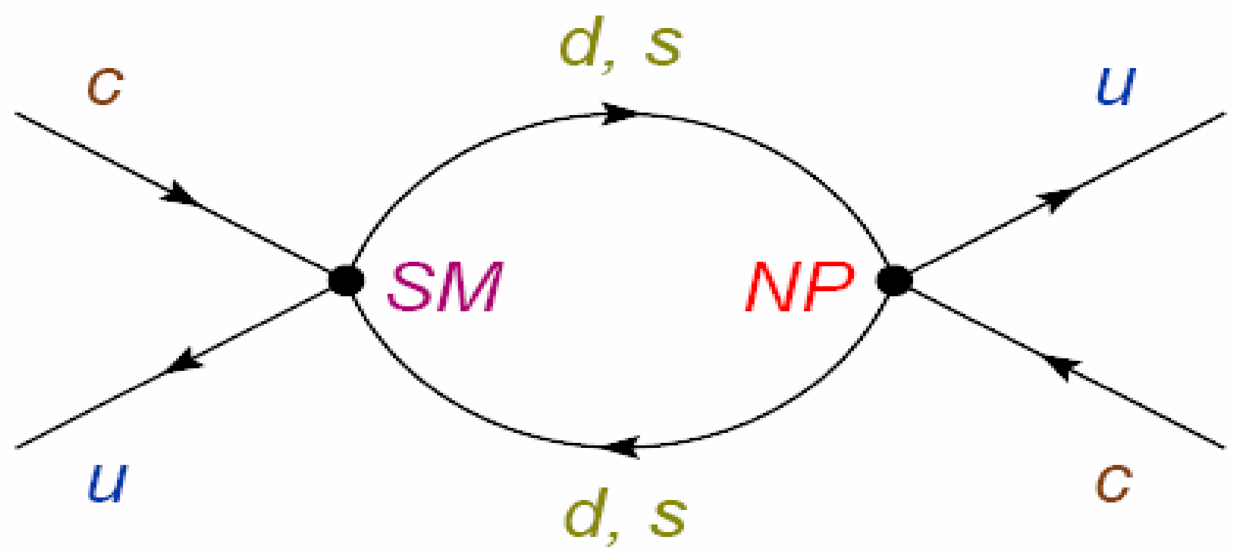
The second term (interference of the SM and NP ΔC=1 transitions) –

- yields $y_D \leq 10^{-4}$



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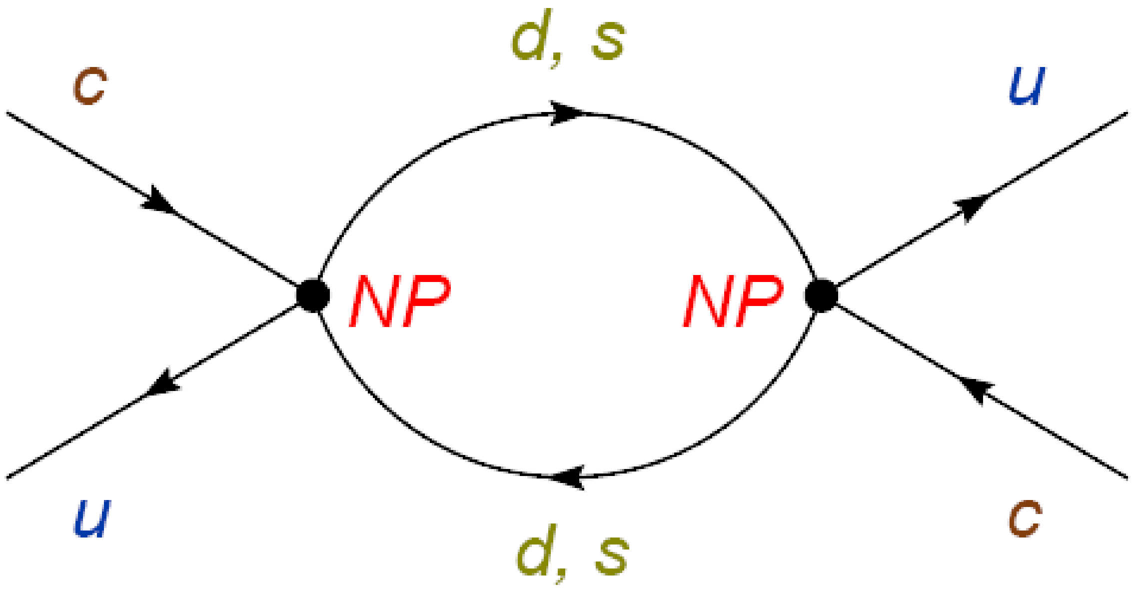

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It may seem unreasonable to consider this term, as it is suppressed as $(M_W^2/M_{NP}^2)^2$. On the other hand…

The SM contribution vanishes in the limit of the exact flavor SU(3) symmetry.

In many popular SM extensions and in particular within the RPV SUSY, the second term (interference of the SM and NP $\Delta C=1$ transitions) also vanishes in the limit of the exact flavor SU(3) symmetry.

Then the last term (pure NP contribution to $\Delta C=1$ transitions) if non-vanishing, dominates in the exact flavor SU(3) limit!

In the real world flavor SU(3) is of course broken, contributions of first two term are suppressed in powers m_s/m_c but they are not zero.

The last term may give numerically large contribution if

$M_W^2/M_{NP}^2 > m_s^2/m_c^2$.

Consider the diagrams with two NP generated $\Delta C=1$ transitions as well!

The purpose of our work was to revisit the problem of the NP contribution to y_D and provide constraints on RPV SUSY models as a primary example.

We considered a general low-energy SUSY scenario with no assumptions made on a SUSY breaking mechanism at unification scales.

Superpotential:

$$W_{\not R} = \sum_{i,j,k} \left[\frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c \right]$$

To avoid rapid proton decay, we put $\lambda'' = 0$. In the quark mass eigenbasis

$$\mathcal{L}_{\not R} = - \sum_{i,j,k} \widetilde{\lambda}'_{ijk} \left[\widetilde{e}_{i_L} \bar{d}_{k_R} u_{j_L} + \widetilde{u}_{j_L} \bar{d}_{k_R} e_{i_L} + \widetilde{d}^*_{k_R} \bar{e}^c_{i_R} u_{j_L} \right] +$$
$$+ \sum_{i,j,k} \lambda'_{ijk} \left[\widetilde{\nu}_{i_L} \bar{d}_{k_R} d_{j_L} + \widetilde{d}_{j_L} \bar{d}_{k_R} \nu_{i_L} + \widetilde{d}^*_{k_R} \bar{\nu}^c_{i_R} d_{j_L} \right] + h.c.$$

where

$$\widetilde{\lambda}'_{irm} = V^*_{rn} \lambda'_{inm}$$

Very often in the literature one neglects the difference between λ' and $\widetilde{\lambda}'$ based on

$$V_{jn} = \delta_{jn} + O(\lambda) \qquad \text{so} \qquad \widetilde{\lambda}_{ijk} \approx \lambda'_{ijk} + O(\lambda)$$

Subtlety: this is true if only there is no hierarchy in couplings λ' !

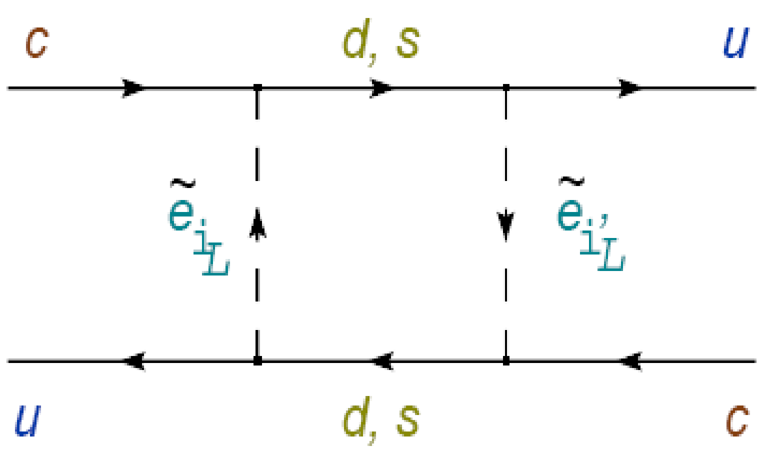
More generally, one can show that

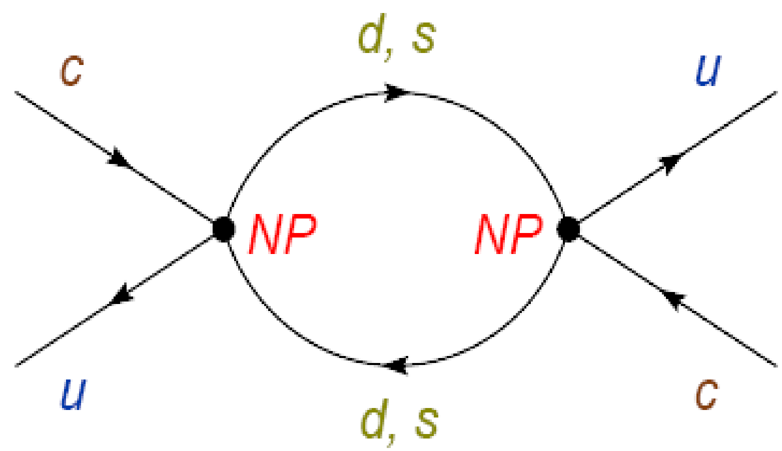
The above approximation is valid when studying or using constraints on individual couplings λ'

However, when considering bounds on RPV coupling pair products, one must specify if these bounds are for λ' x λ' or $\widetilde{\lambda}'$ x $\widetilde{\lambda}'$ pair products.

Otherwise: S. L. Chen, X. G. He, A. Hovhannissyan, H.S. Tsai - RPV SUSY contribution to y_D is rather small – but this is not true!

The dominant diagrams.





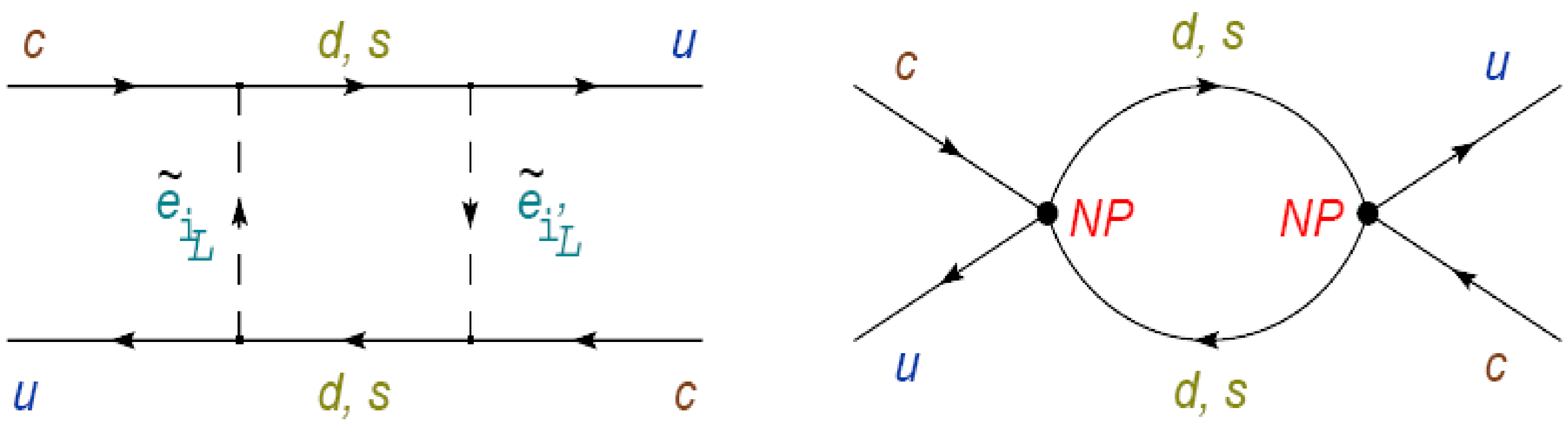
Neglecting numerically subdominant terms,

$$y_{\tilde{\ell}\tilde{\ell}} \approx \frac{-\, m_c^2 \; f_D^2 B_D m_D}{288\pi\Gamma_D \; m_{\tilde{\ell}}^4} \left[\frac{1}{2} + \frac{5}{8}\frac{\bar{B}_D^S}{B_D} \right] \left[\lambda_{ss}^2 + \lambda_{dd}^2 \right]$$

$$\lambda_{ss} \equiv \sum_i \widetilde{\lambda}'^*_{i12} \widetilde{\lambda}'_{i22} \gg \sum_i \lambda'^*_{i12} \lambda'_{i22}$$

$$\lambda_{dd} \equiv \sum_i \widetilde{\lambda}'^*_{i11} \widetilde{\lambda}'_{i21} \gg \sum_i \lambda'^*_{i11} \lambda'_{i21}$$

The dominant diagrams.



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$y_{\tilde{\ell}\tilde{\ell}} < 0.$ It is non-vanishing in the exact flavor SU(3) limit. Else, $|\lambda_{ss}| \leq 0.29$, $|\lambda_{dd}| \leq 0.29$ or $\lambda_{ss}^2 \leq 0.0841$ and $\lambda_{dd}^2 \leq 0.0841$, thus contribution of this type of diagrams is large.

Numerically

$$-0.12\left(\frac{100GeV}{m_{\tilde{\ell}}}\right)^4 \leq y_{\tilde{\ell}\tilde{\ell}} < 0$$

Within RPV SUSY models with the leptonic number violation, NP contribution to y_D is predominantly negative and may exceed in absolute value the experimentally allowed interval $y_D^{exp} = (6.6 \pm 2.1) \bullet 10^{-3}$

To avoid a contradiction with the experiment:

demand a large positive contribution from the SM (to have a destructive interference of two contributions) or

place severe constraint on λ_{ss} and λ_{dd}.

A. Falk et al., Phys. Rev. D 65, 054034 (2002): due do the long-distance effects, y_{SM} may be up to ~1/%.

Thus, RPV SUSY contribution to y_D should be ~1% or less as well.

Impose $-0.01 \le y_{new} \approx y_{\tilde{\ell}\tilde{\ell}}$ then either $m_{\tilde{\ell}} > 185\mathrm{GeV}$

or if $m_{\tilde{\ell}} \le 185\mathrm{GeV}$, then

$$|\lambda_{ss}| \le 0.082 \left(\frac{m_{\tilde{\ell}}}{100GeV}\right)^2 \qquad |\lambda_{dd}| \le 0.082 \left(\frac{m_{\tilde{\ell}}}{100GeV}\right)^2$$

Compare to constraints derived from the study of Δm_D. In our notations,

$$\lambda_{ss} \le 0.0037 \left(\frac{m_{\tilde{\ell}}}{100GeV}\right), \qquad \lambda_{dd} \le 0.0037 \left(\frac{m_{\tilde{\ell}}}{100GeV}\right)$$

About 20 times stronger than our ones?

Yes but in the limit when pure MSSM contribution to Δm_D is negligible.

The destructive interference between the pure MSSM and RPV sectors may distort bounds coming from Δm_D and make them inessential as compared to our ones.

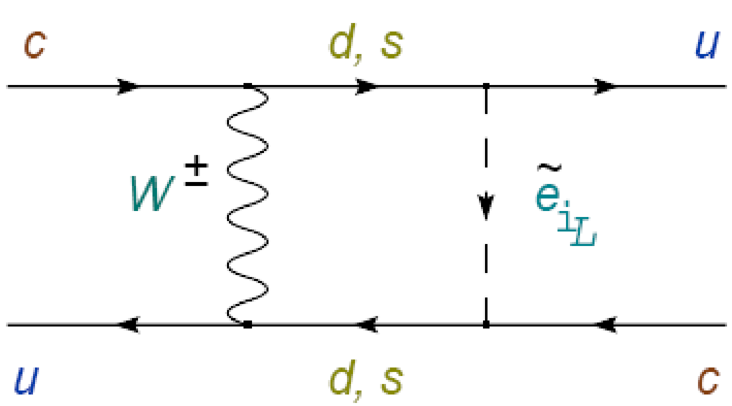
Contrary to this, pure MSSM contributes to $\Delta\Gamma_D$ only by NLO 2-loop dipenguin diagrams and naturally is expected to be small.

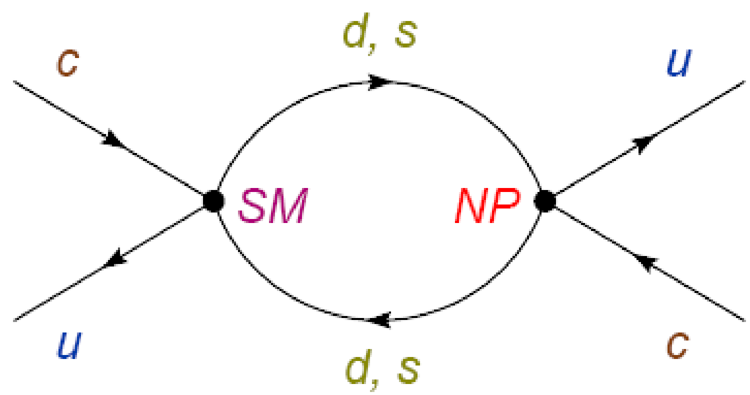
Our bounds coming from the study of $\Delta\Gamma_D$ are insensitive or weakly sensitive to the assumptions on the pure MSSM sector.

Summary of the main results:

- Within R-parity violating SUSY models, lifetime difference in $D^0 - \overline{D}^0$ mixing may be large: it may exceed in absolute value the experimentally allowed interval, $y_D^{exp} = \Delta\Gamma_D^{exp}/\Gamma_D = (6.6 \pm 2.1) \bullet 10^{-3}$, by an order of magnitude.
- When being large it is negative in sign. The existing experimental data may be the result of the destructive interference of the SM and RPV SUSY contributions.
- To derive this result it is very important to take into account transformation of RPV couplings from the weak eigenbasis to the quark mass eigenbasis.
- Using the existing experimental data on $y_D = \Delta\Gamma_D/(2\,\Gamma_D)$, we derive new bounds on the RPV coupling pair products and/or supersymmetric particle masses.
- Unlike those coming from studying of $x_D = \Delta m_D/\Gamma_D$, our bounds are insensitive or weakly sensitive to assumptions on the pure MSSM sector of the theory.

Supplementary slide N1



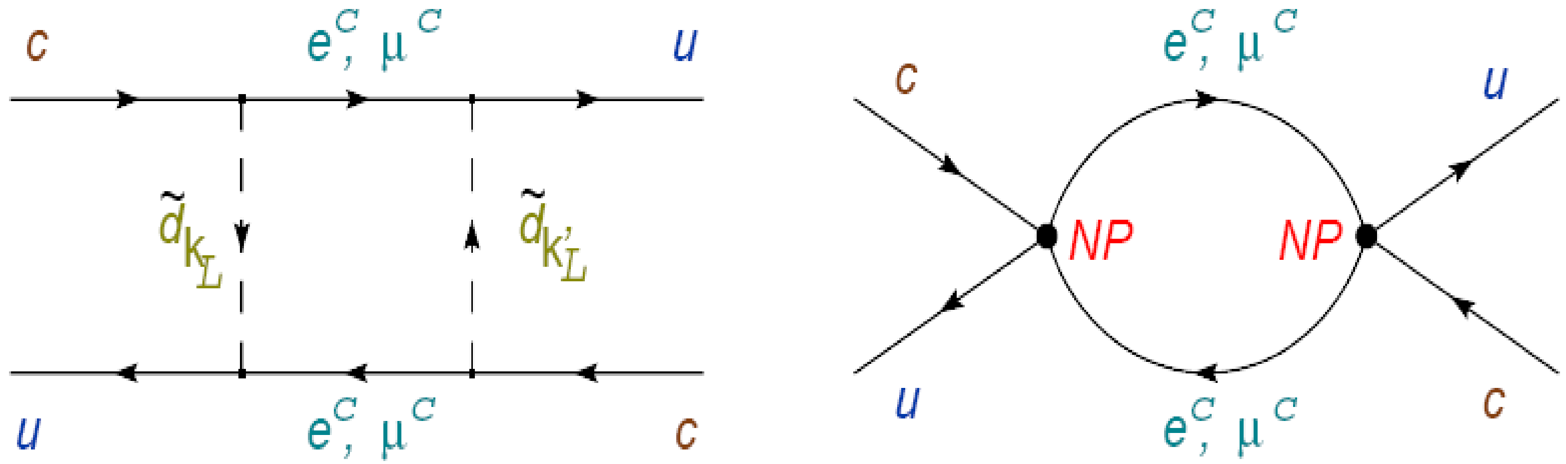


$$y_{SM,NP} = \frac{-G_F}{\sqrt{2}} \frac{f_D^2 B_D m_D}{6\pi\Gamma_D} \left(\frac{m_c^2}{m_{\tilde{\ell}}^2}\right) \left[C_1(m_c) + C_2(m_c)\right] \left[\lambda_{sd}\sqrt{x_s x_d} + \right.$$

$$\left. + \lambda\left(\lambda_{ss} x_s - \lambda_{dd} x_d\right) - \lambda^2 \lambda_{ds}\sqrt{x_s x_d}\ \right]$$

Contribution of this type of diagrams vanishes in the exact flavor SU(3) symmetry limit. As flavor SU(3) is broken $y_{SM,NP}$ is suppressed as $x_s = m_s^2/m_c^2$ or $x_d = m_d^2/m_c^2$. It is not hard to show that contribution of this type of diagrams is rather small.

Supplementary Slide N2



$$y_{\tilde{q}\tilde{q}} = \frac{m_c^2\ f_D^2 B_D m_D}{288\pi\Gamma_D\ m_{\tilde{q}}^4}\left[\frac{5}{8}\frac{\bar{B}_D^S}{B_D} - 1\right]\left[\ \lambda_{\mu\mu}^2 + \lambda_{ee}^2 + 2\ \lambda_{\mu e}\lambda_{e\mu}\ \right]$$

Contribution of this type of diagrams does not vanish in the exact flavor SU(3) limit, however it is numerically subdominant :

$$y_{\tilde{q}\tilde{q}} \leq 5.34 \cdot 10^{-5}$$

because of the stringent bounds on the RPV coupling products

Supplementary slide N3

$$\lambda_{ss} \equiv \sum_i \tilde{\lambda}'^*_{i12}\, \tilde{\lambda}'_{i22} = \sum_i \lambda'^*_{i12}\, \lambda'_{i22} + \lambda\Big[\sum_i |\lambda'_{i22}|^2 - \sum_i |\lambda'_{i12}|^2\Big]$$
$$+ A\lambda^2 \sum_i \lambda'^*_{i12}\, \lambda'_{i32} + A\lambda^3(1+\rho-i\eta)\sum_i \lambda'^*_{i32}\, \lambda'_{i22}$$
$$+A^2\lambda^5(\rho-i\eta)\sum_i |\lambda'_{i32}|^2$$

$$|\lambda'^*_{i12}\, \lambda'_{i22}| \leq 6.3\cdot 10^{-5}\left(\frac{m_{\tilde{q}}}{300GeV}\right)^2 \qquad |\sum_i \lambda'^*_{i12}\, \lambda'_{i22}| \leq 2.7\times 10^{-3}\left(\frac{m_{\tilde{\ell}}}{100GeV}\right)^2$$

For $m_{\tilde{q}} \geq 300\text{GeV}$, $|\lambda_{322}| \leq 1.12$ $\qquad |\lambda'_{312}| \leq 0.33(m_{\tilde{q}}/300GeV)$,

$$|\lambda_{312}| \leq 1.12$$

$$-0.025\left(\frac{m_{\tilde{q}}}{300GeV}\right)^2 \leq \lambda_{ss} \leq 0.29, \quad \text{if} \quad m_{\tilde{q}} \leq 1TeV,$$
$$-0.29 \leq \lambda_{ss} \leq 0.29, \quad \text{if} \quad m_{\tilde{q}} \geq 1TeV$$