$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and R-parity violating supersymmetry

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\(R_p\) violating SUSY

(R.Barbier *et al.*, R-parity violating supersymmetry [hep-ph/0406039])

R-parity:

\[ R_p = (-1)^{3(B-L)+2S} \]

-LSP, avoid too fast proton decay...but no strong theoretical motivation.

→ **New terms** allowing **R-parity violation** in the superpotential:

\[
W_{R_p} = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k
\]

→ 45 unknown complex couplings.

→ We focus on \(\lambda'_{ijk}\) couplings because they induce **tree level** contributions *via squark exchanges* to \(K^+ \rightarrow \pi^+ \nu \bar{\nu}\).

\[
\mathcal{L}_{L_i Q_j D^c_k} = -\lambda'_{ijk} \left( \tilde{d}^c_{kR} \tilde{\nu}^c_i d_{jL} + \tilde{d}_{jL} \nu_i \tilde{d}_{kR} \right) + h.c
\]
In the calculation of the branching ratio, we have:

- contributions from **SUSY with unbroken** $R_P$ (**neutralinos, charginos...in the loops**) which include **SM contributions**.

- contributions from **additional diagrams**:

![Diagrams](image.png)

**Figure 1**: *R-parity violating tree level diagrams contributing to the process $K^+ \rightarrow \pi^+ \nu\bar{\nu}$.*
• The Standard Model prediction is:

\[ BR(SM) = (8.18 \pm 1.22) \times 10^{-11} \]

→ No tree-level contribution. Prediction at 1-loop level.

• In the MSSM, the prediction changes by at most \( \sim \pm 50\% \)

→ No tree-level contribution too. Prediction at 1-loop level.

• The experimental value is (E787 and E949 collaborations):

\[ BR(exp) = (1.47 \pm 1.3) \times 10^{-10} \]

⇒ This is compatible with the Standard Model but there is enough place for new physics. We can deduce constraints on \( \lambda'_{ijk} \) s.
The RPV couplings $\lambda'_{ijk}$'s appear in the BR formula as products.

⇒ The constraints are on $\epsilon_{ij}$:

$$\epsilon_{ij} = \sum_n \left( \frac{\lambda'_{i2n} \lambda'_{j1n}}{m_{\tilde{d}n_R}^2} - \frac{\lambda'_{in1} \lambda'_{jn2}}{m_{\tilde{d}n_L}^2} \right) (200 \text{ GeV})^2$$

→ The branching ratio can be written as:

$$BR \propto \left( \sum_i |A_i^{\text{MSSM}} + \frac{\epsilon_{ii}}{4k (200 \text{ GeV})^2} |^2 + \sum_{i \neq j} \frac{|\epsilon_{ij}|^2}{16k^2 (200 \text{ GeV})^4} \right)$$

(the sum is over $\nu$'s and $\bar{\nu}$'s flavours), $k$ is a numerical factor.
The possibility of **interferences** makes the extraction of **upper-bounds** harder. They occur if the final neutrino and antineutrino are of the same flavour, \( i = j \).

The general branching ratio formula compared with the experimental value gives:

\[
\sum_{i=e,\mu,\tau} \left( \text{Re}(\epsilon_{ii}) + \frac{\alpha_i}{2} \right)^2 + \sum_{i=e,\mu,\tau} \left( \text{Im}(\epsilon_{ii}) + \frac{\beta}{2} \right)^2 = R^2
\]

- \( \alpha \) and \( \beta \) contains CKM inputs and loop functions (originally in \( A_i^{\text{MSSM}} \)).
- \( R \) is proportional to \( (BR^{exp} - BR^{MSSM}|_{min}) \) and contains the shifts \( \alpha \) and \( \beta \).

⇒ For only one non-zero \( \epsilon_{ii} \), this equation describes a **circle in the complex plane**.
The resulting constraint for $\epsilon_{11}$ is the following circle:

Figure 2: Allowed region for $Re(\epsilon_{11})$ and $Im(\epsilon_{11})$ in units of $10^{-5}$. We take 200 GeV as reference value for the mass of the squarks.
If we choose the point \((Re(\epsilon_{11}) = -2 \times 10^{-5}, Im(\epsilon_{11}) = -2 \times 10^{-5})\) to have an **numerical idea of the constraint**, we have:

\[ |\epsilon_{11}| = 2.8 \times 10^{-5} \]

Then, if we naively set all the couplings to zero except one product (single product dominance hypothesis)

\[ |\frac{\lambda'_{i2n} \lambda'_{i1n}}{m_2^2 \tilde{d}n_R} | < 2.8 \times 10^{-5} \]

\[ |\frac{\lambda'_{in1} \lambda'_{in2}}{m_2^2 \tilde{d}n_L} | < 2.8 \times 10^{-5} \]
Summary and conclusions

We have investigated the decay $K^+ \to \pi^+ \nu \bar{\nu}$ to obtain stringent limits on the R-parity violating couplings.

- We updated the SM and MSSM values of the branching ratio of $K^+ \to \pi^+ \nu \bar{\nu}$

- We obtained more realistic upper-bounds on the products of the RPV couplings $\lambda'$ by including for the first time in the analysis:
  - one loop SM contribution,
  - one loop MSSM contribution,
  - Interferences between MSSM and "pure" RPV part.