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Constraints on baryon number violation in supersymmetry from searches for neutron-antineutron oscillations and other observables

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Baryon number violation (BNV) in *R*-parity violating (RPV) supersymmetry is studied with a focus on $\Delta B = 2$ processes which allow neutron–anti-neutron ($n-\bar{n}$) oscillations. Simplified RPV-SUSY models, including only the relevant superpartners and couplings, are considered. Constraints from flavour physics, searches at the Large Hadron Collider and searches at dedicated BNV experiments are quantified for the various scenarios at the TeV scale. It is also shown that a proposed $n-\bar{n}$ experiment at the European Spallation Source has a sensitivity to a mass scale for new physics that goes beyond all other experiments and up to the PeV scale for certain regions of parameter space.

Fourth Annual Large Hadron Collider Physics
13-18 June 2016
Lund, Sweden

*Speaker.

PoS(LHCP2016)152

1. Introduction

The observation of baryon number violation (BNV) would be of fundamental significance and would address a number of open questions in modern physics. BNV is required to understand the matter-antimatter asymmetry of the universe [1]. Even within the Standard Model (SM) baryon number is subject only to an approximate conservation law. The SM predicts BNV to occur via rare non-perturbative electroweak instanton and sphaleron processes [2, 3] (the quantity $B-L$ is respected by the SM but not B and L separately). At the perturbative level baryon number conservation arises due to the specific matter content in the SM, and, like lepton number conservation, corresponds to an "accidental" symmetry of the SM. Furthermore, precision tests of the Equivalence Principle [4] offer no evidence for a long range force coupled to baryon number and thus a local gauge symmetry forbidding BNV. Given the above, it is unsurprising that BNV occurs as a generic feature of many proposed extensions to the SM, such as R-parity violating (RPV) supersymmetry [5].

A promising way to search for BNV is via the observation of the $|\Delta B| = 2$ process, neutron-antineutron ($n-\bar{n}$) oscillation [6, 7]. Setting aside the strong theoretical arguments for BNV, a strict experimentalist approach to testing conservation laws motivates $n-\bar{n}$ searches as they represent one of the few high precision channels in which baryon number would be the sole, hitherto respected, quantity which is violated. Conversely single proton decay searches require the simultaneous violation of both baryon and lepton number to conserve angular momentum.

Viewed in the broad perspective of the worldwide effort to look for violations of lepton number, baryon number and combinations thereof, searches for $n-\bar{n}$ ($|\Delta B| = 2$, $\Delta L = 0$, $\Delta|B-L| = 2$), single proton decays ($|\Delta B| = 1$, $|\Delta L| = 1$, $\Delta(B-L) = 0$), and neutrinoless double beta decays ($\Delta B = 0$, $|\Delta L| = 2$, $\Delta|B-L| = 2$) are complementary and, in some cases, symbiotic with each other. For example, neutrinoless double beta decay can be regarded as the leptonic equivalent of $n-\bar{n}$; both processes are in fact predicted in theories violating $B-L$ in which the $n-\bar{n}$ rate is connected to the neutrino mass sector [6]. While single proton decay and neutrinoless double beta decay searches are arguably of higher profile than $n-\bar{n}$ searches, taken together, all three types span a broad range of possible selection rules for possible ΔB, ΔL and $\Delta(B-L)$ transitions. Each plays an important role in the search for new physics, not least since they are sensitive to mass scales far in excess of that available at the Large Hadron Collider (LHC). A new $n-\bar{n}$ search with free neutrons at the European Spallation Source (ESS) has been recently proposed [8] which would be sensitive to oscillation probabilities up to three orders of magnitude lower than has previously been obtained. This paper is motivated in part by this new development.

In this work, constraints on BNV-only processes in RPV SUSY scenarios predicting $n-\bar{n}$ are quantified. Searches for new physics processes at the LHC, precision flavour measurements, and low energy BNV searches, including estimates for the proposed ESS search are considered. This paper is organised as follows. The six-quark $\Delta B = 2$ operators contributing to $n-\bar{n}$ or dinucleon decay in RPV models are given in Section 2. In Sections 3 and 4, RPV SUSY models and the experimental results used to set limits on these scenarios are described, respectively. The bounds on the models are given in Section 5 where it is shown that the proposed ESS search has a sensitivity up to the PeV mass scale. A summary is then given in Section 6. This paper is largely an abridged version of Ref. [9]; constraints are also studied here at higher mass scales than in that earlier work.

2. Operators contributing to $n-\bar{n}$ oscillation

The operators of interest for $n-\bar{n}$ oscillations and di-nucleon decay in the RPV context are the following:

$$\begin{aligned}
(u_R d_R d_R)^2 &\equiv \varepsilon_{abc} u^a_{R\dot{\alpha}} d^{\dot{\alpha}b}_R d^c_{R\dot{\gamma}}\, \varepsilon_{def} u^d_{R\dot{\beta}} d^{\dot{\beta}e}_R d^{\dot{\gamma}f}_R \\
(u_R d_R d_L)^2 &\equiv \varepsilon_{abc} u^a_{R\dot{\alpha}} d^{\dot{\alpha}b}_R d^{\gamma c}_L\, \varepsilon_{def} u^d_{R\dot{\beta}} d^{\dot{\beta}e}_R d^f_{L\gamma} \\
(u_L d_L d_R)^2 &\equiv \varepsilon_{abc} u^{\alpha a}_L d^b_{L\alpha} d^c_{R\dot{\gamma}}\, \varepsilon_{def} u^{\beta d}_L d^e_{L\beta} d^{\dot{\gamma}f}_R \\
(u_R d_R s_R)^2 &\equiv \varepsilon_{abc} u^a_{R\dot{\alpha}} d^{\dot{\alpha}b}_R s^c_{R\dot{\gamma}}\, \varepsilon_{def} u^d_{R\dot{\beta}} d^{\dot{\beta}e}_R s^{\dot{\gamma}f}_R .
\end{aligned} \tag{2.1}$$

Two component notation is used throughout the paper. $a,b,\ldots$ are colour indices, $\alpha,\beta,\ldots$ left-handed (LH) Weyl indices and $\dot{\alpha},\dot{\beta},\ldots$ right-handed (RH) ones. The second and third operator are Parity conjugate of each other. The last operator contributes only to di-nucleon decay $NN\to KK$ while the first three contribute to both $n-\bar{n}$ oscillation and di-nucleon decay $NN\to\pi\pi$.

The matrix elements for $n-\bar{n}$ and dinucleon declay can be seen, via dimensional reasoning, to be $\langle n|\mathscr{O}|\bar{n}\rangle = C\Lambda^6_{\rm QCD}$ and $\langle NN'|\mathscr{O}|KK'\rangle = C'\Lambda^5_{\rm QCD}$, respectively, for dimensionless coefficients C and C' depending on the operators and on the process at hand.

3. Baryon number violating supersymmetry

At the renormalizable level, the only additional BNV-only interaction, beyond the usual MSSM superpotential, is given by

$$W_{BRPV} = \lambda''_{ijk}\varepsilon_{abc}\bar{U}^a_i\bar{D}^b_j\bar{D}^c_k \tag{3.1}$$

where i,j,k and a,b,c are flavour and colour indices, respectively, and where the dimensionless coupling is antisymmetric in the last two indices, $\lambda''_{ijk} = -\lambda''_{ikj}$. This antisymmetry implies that there are 9 independent λ''_{ijk}-couplings: $\lambda''_{uds},\lambda''_{udb}\ldots$. This notation in terms of the quark/squark flavour is used in this paper when discussing explicit processes. The relevant couplings that can be probed at the $n-\bar{n}$ experiment under various assumptions are λ''_{uds}, λ''_{udb} and λ''_{tdb}. This work only considers renormalizable (dimension four) RPV operators. The possible relevance of non-renormalizable operator is briefly discussed in Ref. [9].

3.1 RPV SUSY scenarios predicting $n-\bar{n}$ oscillations

Because of the antisymmetric structure of the λ''_{ijk} couplings, non-vanishing RPV interactions of first generation quarks must involve second or third generation squarks, $\tilde{s}_R$ or $\tilde{b}_R$. This implies that $n-\bar{n}$ oscillations will arise only in presence of mixing among different squark flavours. The customary mass-insertion parameters are used to characterise squark mixing:

$$\left(\delta^d_{RR}\right)_{ij} \equiv \frac{(\tilde{m}^2_D)_{ij}}{\overline{m}^2_D}, \quad \left(\delta^d_{LL}\right)_{ij} \equiv \frac{(\tilde{m}^2_Q)_{ij}}{\overline{m}^2_Q}, \quad \left(\delta^d_{LR}\right)_{ij} \equiv \frac{m_j A^d_{ij}}{\overline{m}_D\overline{m}_Q}, \tag{3.2}$$

where $i\neq j$ and m_i are down quark masses; A^d_{ij}, $(\tilde{m}^2_D)_{ij}$, and $(\tilde{m}^2_Q)_{ij}$ are off-diagonal entries of the A-term matrix, and the squark mass matrices (RH and LH respectively), expressed in the flavour

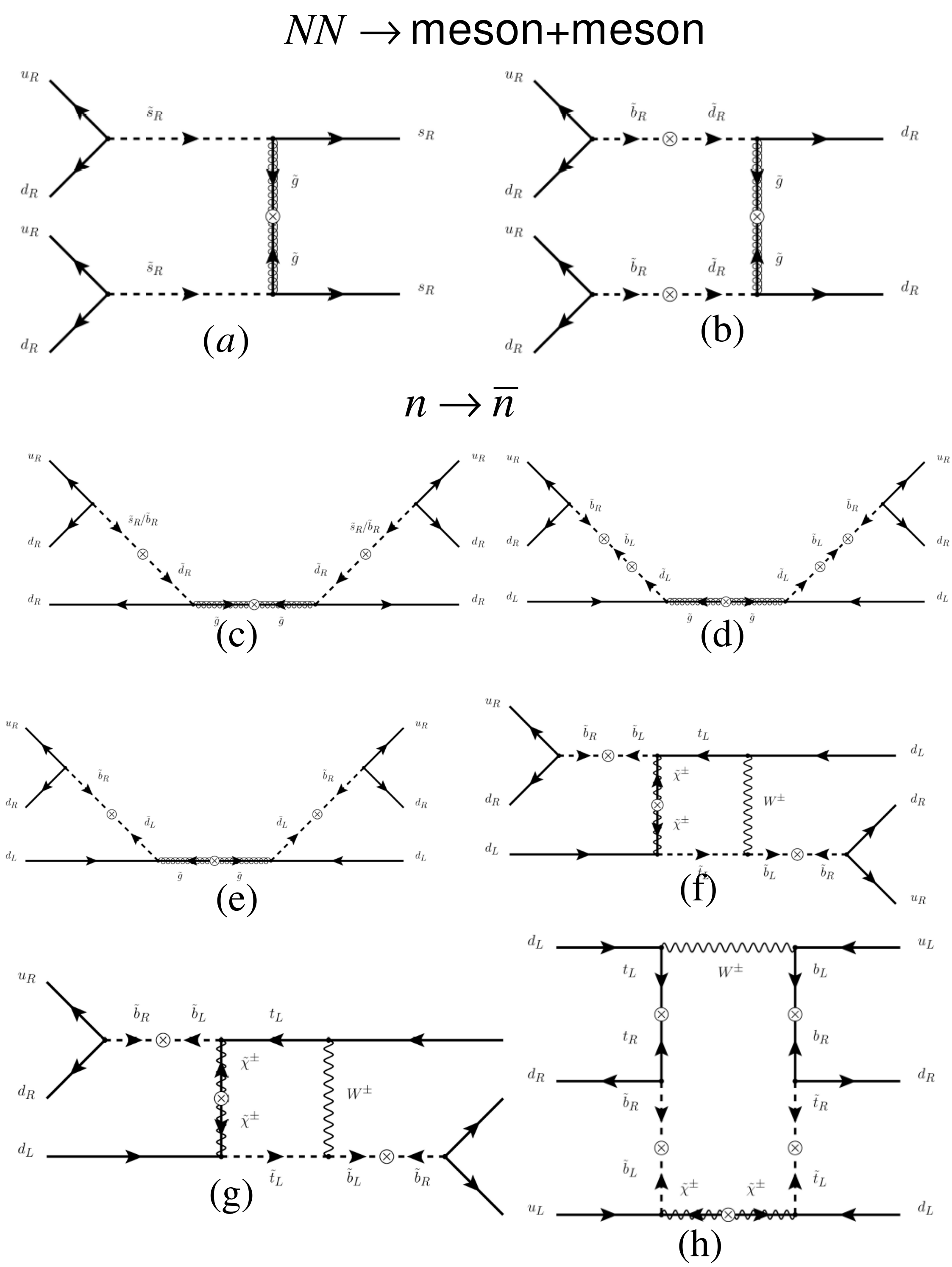

Figure 1: RPV processes giving $\Delta B = 2$ transitions. Dinucleon decay: (a) $NN \to KK$ and (b) $NN \to KK$. Neutron oscillations in various models considered in this paper: (c) Z_1 (d) Z_2, (e) BM_1 (f) BM_2, (g) GS and (h) CK .

basis where the down-quark mass matrix is diagonal. Finally, $\overline{m}_D$ and $\overline{m}_Q$ are average RH and LH down-squark masses.

A number of RPV scenarios for $n-\bar{n}$ are considered. Feynman diagrams of $n-\bar{n}$ corresponding to the various models are shown in Figure 1 along with Feynman diagrams of dinucleon decays ($NN \to KK$ and $NN \to \pi\pi$).

For each process, a simplified spectrum is assumed in which all the particles not contributing to the actual $n-\bar{n}$ diagram are assumed to be decoupled. The constraints from the other physical processes discussed in Section 4 will be applied to such models. The only important exception to the above rule arises when some superpartners belong to a multiplet of $SU(2)_L$. It is then necessary, because of $SU(2)_L$ gauge invariance, to assume the other member of the doublet to be present in the spectrum as well, and nearly degenerate in mass. Such sparticles do not contribute to the oscillation process and are given in parentheses when listed below. This case arises when LH squarks or a wino-like chargino are present in the diagrams. As far as the spectrum is concerned, all the relevant squarks as treated as being degenerate and their production cross-section are scaled accordingly.

- Models Z_1 and Z_2, based on Ref. [10] from Zwirner, require that flavour violation takes place in the 1-2 or in the 1-3 sector, respectively via RH squark mixing. The sparticle content comprises are $\tilde{g}, \tilde{d}_R$, $\tilde{s}_R$ (Z_1) and $\tilde{b}_R$ (Z_2) and the couplings are λ''_{uds} (Z_1), λ''_{udb} (Z_2), $(\delta^d_{RR})_{21}$ (Z_1) and $(\delta^d_{RR})_{31}$ (Z_2) .
- Models BM_1 is based on Ref. [11] from Barbieri and Masiero. This scenario contains no flavour mixing among RH squarks. The flavour transition necessary to generate a $\Delta B = 2$ operator via the λ'' couplings can then occur in the LH squark sector and be transmitted to the RH sector through LR squark mixing. The minimal particle content is $\tilde{g}, \tilde{b}_R, \tilde{b}_L, (\tilde{t}_L), \tilde{d}_L$ and $(\tilde{u}_L)$. The couplings are $\lambda''_{udb}, (\delta^d_{LL})_{31}$ and $(A_b - \mu \tan\beta)$.
- Model BM_2 is also based on Ref. [11] and similarly contains RH and LH quarks as part of its particle content: $\tilde{g}, \tilde{b}_R, \tilde{d}_L$ and $(\tilde{u}_L)$. A single mass insertion $(\delta^d_{LR})_{31}$ implements flavour violation and LR mixing.
- Model GS [12], from Goity and Sher, uses charginos to construct an electroweak SUSY process for neutron oscillations. A flavour changing box diagram is used, which is essentially the supersymmetric version of the GIM mechanism. The mechanism uses a wino-like chargino. The particle content is $\tilde{\chi}^{\pm}$, $(\tilde{\chi}^0)$, $\tilde{b}_R$,$\tilde{b}_L$, $\tilde{t}_R$ and $(\tilde{t}_L)$. The process is regulated with λ''_{udb} and $(A_b - \mu \tan\beta)$ couplings.
- Model CK [13], from Chang and Keung, is also based on an electroweak mechanism. Here, the RPV vertex occurs inside the loop. The particle content is $\tilde{\chi}^{\pm}$, $(\tilde{\chi}^0)$, $\tilde{b}_R$, $\tilde{t}_R$, $\tilde{b}_L$ and $(\tilde{t}_L)$. The couplings are λ''_{tds} and $(A_b - \mu \tan\beta)$ and $(A_b - \mu \cot\beta)$.

4. Constraints

Three different types of experimental measurements and searches are used to constrain the parameter space of the various RPV SUSY models. Searches and measurements of flavour and CP-violating physics are used together with results from the LHC and dedicated low energy BNV searches.

4.1 Flavour and CP-violation measurements.

If flavour violation occurs in the 1-2 sector, this gives rise to contributions to $K-\bar{K}$ mixing. The value of $\left|\left(\delta^d_{RR}\right)_{12}\right|$ can thus be constrained by the observed kaon mass splitting Δm_K and the CP violation parameter ε_K. For flavour violation in the 1-3 sector, constraints on $\left|\left(\delta^d_{RR}\right)_{13}\right|$ arise from $B-\bar{B}$ mixing.

Transitions of $b\to d\gamma$ strongly constrain models of $n-\bar{n}$ involving gluinos and down squarks of both RH and LH kinds which feature a LR squark chirality flip and flavour violation in the LH sector, or both the LR and the flavour mixing occuring at the same time. Bounds on $\left|\left(\delta^d_{LL}\right)_{13}\right|$ and $\left(\delta^d_{LR}\right)_{13}$ were obtained as in [14].

4.2 LHC searches

In the model considered here, the squarks and gluinos can become long-lived due to weak Yukawa couplings. If the lightest superpartner is a squark (gluino), it will necessarily decay into two (three) quarks via a RPV interaction. The gluino decay proceeds via an off-shell squark.

If either squarks or gluinos are long lived, they form so-called R-hadrons [15]. In the conservative approach adopted here, limits on squark and gluino production which are used correspond to detector interaction scenarios involving R-hadrons which provided the smallest efficiency. For lower $c\tau$ values, the R-hadrons can decay in the detector and leave a signature of a displaced vertex and decay products emerging from that vertex. Searches for non-decaying and decaying long-lived particles (LLPs) were made by the CMS experiment during Run 1, the results of which were converted into excluded regions of lifetime and mass for stops and gluinos in [16, 17] (see also [18]). Using these results, exclusion limits on coupling, mixing parameter and sparticle mass were quantified for the models considered in this work. In addition, CMS results recently obtained at a centre-of-mass energy of 13 TeV [19] were also taken into account to show the impact of the extension in mass exclusions for R-hadrons with long lifetimes $c\tau > 10^2$m.

For sufficiently large coupling values, the decays of squarks and gluinos will be prompt and result in a large number of jets in the final state. In order to extract bounds in the $(m_{\tilde{g}}-m_{\tilde{q}})$-plane from LHC results, a simulation for a simplified RPV SUSY model was done. This simulation uses `MadGraph5_aMC@NLO` [20] (version 2.3.3) and `Delphes` [21] (version 3.3.0) together with `PYTHIA8.212` [22]. For the detector simulation, the default `Delphes` ATLAS card is used, with the only change being that the jet radius parameter is set to 0.4 instead of 0.6.

A search for SUSY particles in final states with a large number of jets, which was conducted by the ATLAS collaboration on 20.3 fb^{-1} data collected at a centre-of-mass energy of 8 TeV [23], was considered. This analysis is aimed at signals which result in high jet multiplicities, i.e. it is mostly sensitive to $\tilde{g}\tilde{g}$- and $\tilde{g}\tilde{q}$-production and only to a lesser extent to $\tilde{q}\tilde{q}$- and $\tilde{q}\bar{\tilde{q}}$-production. Limits on the squark mass can be obtained from a CMS search using di-jet pairs [24].

4.3 Dedicated low energy BNV searches

Searches have been made for free neutron oscillations and anomalous nuclear decays, under the neutron oscillation or dinucleon-decay hypothesis [7]. The Super-Kamiokande experiment [25] has set a limit of 1.9×10^{32} years for oscillation of bound neutrons in ^{16}O, translating, after some assumptions on the nuclear suppression factor, to an indirect estimate of the free $n-\bar{n}$ oscillation time limit of 2.7×10^8 s. The currently best direct measurement of the free $n - \bar{n}$ oscillation time, done by ILL in Grenoble, sets a bound at 0.86×10^8 s [26]. Super-Kamiokande has also set the most stringent dinucleon decay limits of bound nucleons in ^{16}O corresponding to $pp \rightarrow K^+K^+$ and $nn \rightarrow \pi^0\pi^0$ of 1.7×10^{32}[27] and 4.04×10^{32} years [28], respectively .

5. Constraints on RPV-SUSY models

As described in Section 3.1, the model parameter space is based on the RPV Yukawa couplings, mixing paremeters and sparticle masses. Here the constraints are studied for representative values and ranges of the parameter space. A more comprehensive discussion of the model predictions can be found in Ref. [9]. Two mass regions are investigated: the TeV scale and the TeV-PeV region. The former is chosen to show the interplay of the collider and non-collider constraints whereas the latter illustrates the full sensitivity of the low energy BNV searches within the scenarios under study.

Figure 2 shows bounds on each of the SUSY RPV models for sparticle masses up to several TeV. Values of the Yukawa couplings and mixing parameters are given on the plots. Results for the strong scenarios (Z_1, Z_2, BM_1, and BM_2) are shown for low values of the Yukawa couplings chosen ($\lambda'' \sim 10^{-6} - 10^{-5}$) LHC searches for displaced jets and long-lived particles play a role in constraining the models up to gluino masses of around 1500 GeV. Dijet measurements give a sensitivity to squark masses up to around 400 GeV and the multijet measurement extends this to about 700 GeV.

For the Z_1 model, limits from the CP-violating kaon parameter ε_K are given for the conservative assumption of a maximal ($\frac{\pi}{4}$) CP-violating phase of $(\delta^d_{RR})_{12}$. This limit covers much of the region constrained by the aforementioned LHC measurements. A constraint is also given by the measurement of the kaon mass difference Δm_K though this excludes lower sparticle masses. Limits from $n - \bar{n}$ are weaker than the aforementioned bounds. Dinucleon searches for $NN \rightarrow KK$ provide limits for squark (gluino) masses below (above) around 1 TeV, a range covered by the other constraints. The proposed ESS search would give limits similar to those already obtained from the dinucleon search, for this scenario.

The limit from the B-mixing parameter Δm_B are shown for model Z_2 where it is seen to be weaker than those bounds from the jet measurements and long-lived and displaced particle searches. The BM_1 and BM_2 models are constrained by the same non-flavour LHC bounds as Z_1 and Z_2 which restrict similar sparticle mass regions. Limits from searches for $b \rightarrow d + \gamma$ are, however, important for BM_1 and BM_2. These typically extend to sparticle masses of 1000-1500 GeV. For the Z_2, BM_1 and BM_2 models the proposed $n - \bar{n}$ ESS search would extend the constrained sparticle mass region by 500-1000 GeV for sparticles in the mass region around the TeV scale.

Dijet results are shown to constrain the GS and CK EW scenarios for squark masses as for the earlier scenarios. The present body of limits from $n - \bar{n}$ and dinucleon searches is similar for to the dijet limits for the CK model, but extends the squark mass regime for the GS model by up to around 1 TeV for the CK scenario. The new ESS search would increase this sensitivity by several hundred GeV.

Moving from the somewhat congested TeV scale to higher mass scales ($> \mathcal{O}(10)$ TeV), the RPV Yukawa couplings and squark mixing parameters become increasingly unconstrained. Only

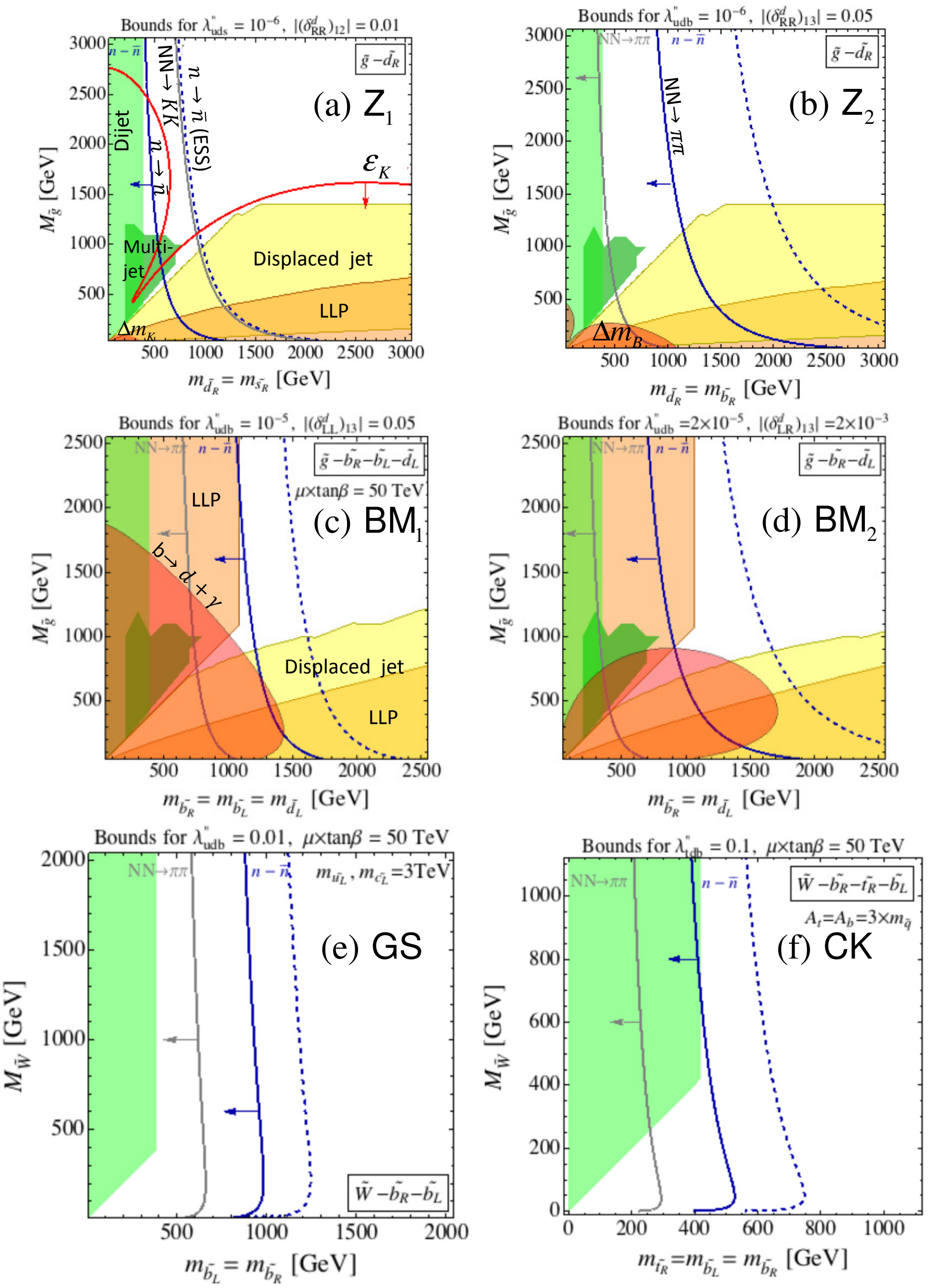

Figure 2: Bounds on RPV SUSY models predicting $n-\bar{n}$: (a) Z_1 (b) Z_2, (c) BM_1, (d) BM_2, (e) GS, (f) CK. Constraints from flavour and *CP*-violation measurements, LHC searches and dedicated low energy BNV searches are also shown. The sensitivity of the proposed search at the ESS is also given.

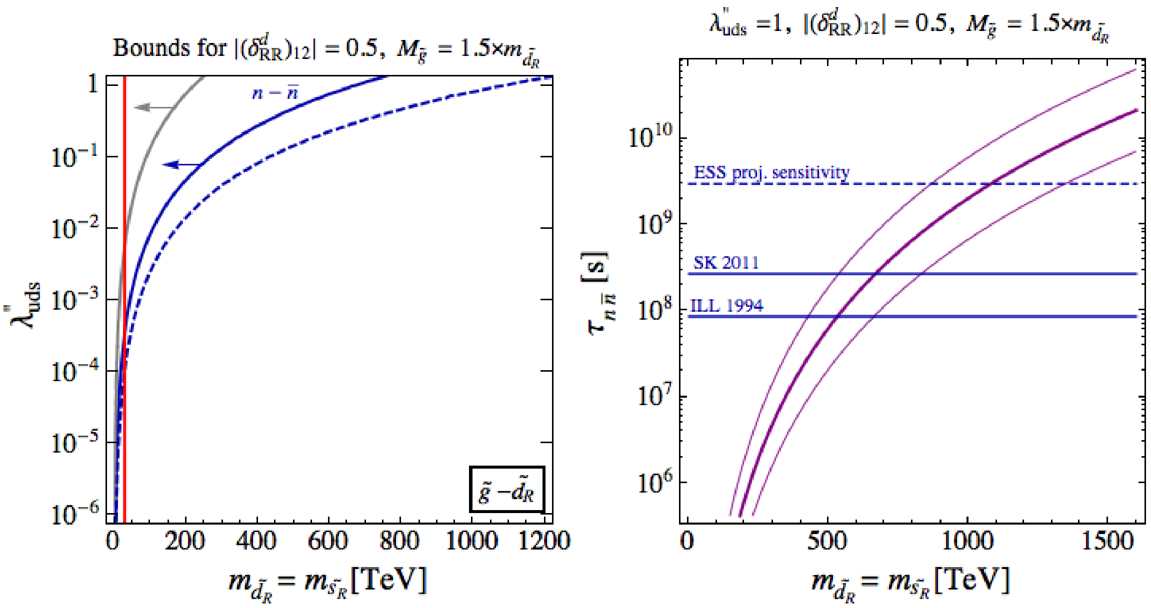

Figure 3: Left: excluded regions of λ''_{uds} versus squark mass. The red line represents the limit from LHC searches and precision flavour measurements. The gray (solid blue) line shows current dinucleon ($n-\bar{n}$) limits. The dashed blue line shows the sensitivity of the proposed ESS search. Right: $n-\bar{n}$ oscillation time versus squark mass. The thick purple line represents the best estimate and thin purple lines forming an envelope around the thick line show the uncertainty due to assumptions on the hadronic matrix element. Limits from ILL and SuperKamiokande are shown as solid blue lines; the sensitivity of the proposed ESS experiment is given by a dashed blue line. For both plots the Z_1 model is used.

the dedicated low energy BNV searches remain sensitive. To illustrate this, Figure 3 shows the bounds on squark mass and λ''_{uds} for the Z_1 model, large squark flavour mixing ($\left|\left(\delta^d_{RR}\right)_{12}\right| = 0.5$). The red line represents the present limits from the LHC and flavour data. The present low energy $n-\bar{n}$ corresponds to a squark mass limit around 700 TeV for a Yukawa coupling of unity. This is extended to 1100 TeV for the ESS search. These estimates are, however, affected by theoretical uncertainties on the hadronic matrix element. This is quantified in Figure 3 in which the oscillation time shown for the range $(1/3)\times(250\text{ MeV})^6 \leq \langle n|(u_R d_R d_R)^2|\bar{n}\rangle \leq 3\times(250\text{ MeV})^6$, shown as an envelope of thin curves around the central curve. The sensitivity of the ESS experiment can thus be said to lie in the range 800 – 1300 TeV in this scenario and thus explore up to the PeV scale.

6. Conclusions

Violation of baryon number is required to explain baryogenesis and plays an important role in many theories of physics beyond the SM, motivating searches for BNV-processes. The second run of the LHC is continuing to push the high energy frontier, searching for evidence for the correctness of such theories. However, as is well known in the context of flavour physics and *CP* violation, it is of utmost importance to also push the low energy frontier by means of precision experiments, since they can probe energy scales of the new physics that goes well beyond the reach the high energy colliders. In terms of BNV, the recently proposed $n-\bar{n}$ oscillation experiment at ESS provides a remarkable opportunity to make progress on this important issue.

In this paper constraints were quantified on simplied RPV-SUSY scenarios giving rise to processes in which baryon number is violated but lepton number remains conserved. The bounds imposed by flavour physics measurements, searches for dinucleon decays, $n-\bar{n}$ oscillations were calculated. Recast LHC searches were also used. The impact of the proposed ESS experiment was also estimated.

It was shown that, at the TeV scale complementary regions of the parameter space are covered by the various bounds. Beyond the TeV scale the low energy BNV searches remain sensitive. As well as exploring hitherto unexplored regions of parameter space at the TeV scale, the new proposed search at the ESS can open a discovery window up the PeV scale.

Acknowledgments

We thank our colleagues in the nnbar@ESS collaboration for discussions. D. M. is supported by the Swedish Research Council. C. P. is supported by the Swedish Research Council under the contract 637-2013-475, by IISN-Belgium (conventions 4.4511.06, 4.4505.86 and 4.4514.08) and by the “Communauté Française de Belgique" through the ARC program and by a “Mandat d’Impulsion Scientifique" of the F.R.S.-FNRS.

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