Probing R-parity violation in B-meson decays to a baryon and a light neutralino

Zeren Simon Wang (NTHU)

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with C. O. Dib, JC Helo, V. E. Lyubovitskij, N. A. Neill, A. Soffer

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Mini-workshops in Theory & Experiment and Detector

Hong Kong University of Science and Technology

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Motivation

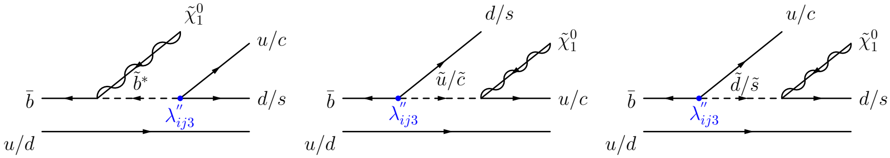
- Supersymmetry, R-parity-violation, rich phenomenology
- RPV-SUSY: light neutralinos allowed, naturally long-lived
- Belle II: $\Upsilon(4S)$, 50 ab^{-1}, 55×10^9 B-mesons, study rare B decays
- $B \to \mathcal{B}\tilde{\chi}_1^0$ via $\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$
- Constrain RPV-SUSY

RPV-MSSM

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

- RPV-MSSM allows light ($\mathcal{O}$(GeV)) neutralinos (binolike)
- $B \to \mathcal{B}\tilde{\chi}_1^0$ decays mediated by sfermions
- Assume $\tilde{\chi}_1^0$ LSP, degenerate sfermion masses, diagonal squarks
- Small RPV couplings & $m_{\tilde{\chi}_1^0}$ $\to$ a very long-lived $\tilde{\chi}_1^0$: $\not E$
- $\tilde{\chi}_1^0$ heavier than a proton, to prevent proton decays

$\tilde{\chi}_1^0$ production and RPV couplings (benchmark scenarios)

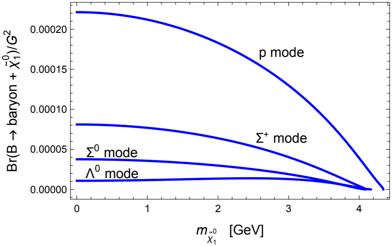


- λ''_{113}: $B^+ \to p\tilde{\chi}_1^0$
- λ''_{123}: $B^0 \to \Lambda^0\tilde{\chi}_1^0$, $B^+ \to \Sigma^+\tilde{\chi}_1^0$, $B^0 \to \Sigma^0\tilde{\chi}_1^0$
- λ''_{213}: $B^+ \to \Lambda_c^+\tilde{\chi}_1^0$, $B^+ \to \Sigma_c^+\tilde{\chi}_1^0$, $B^0 \to \Sigma_c^0\tilde{\chi}_1^0$
- λ''_{223}: $B^+ \to \Xi_c^+\tilde{\chi}_1^0$, $B^0 \to \Xi_c^0\tilde{\chi}_1^0$

$\tilde{\chi}_1^0$ production rate computation

$$\mathcal{M} = \bar{u}_p(p', s') \left[W_0^{LL}(q^2) + \frac{\not{q}}{m_{\tilde{\chi}_1^0}} W_1^{LL}(q^2) \right] P_L \, v_{\tilde{\chi}_1^0}(q, s)$$

- To compute W_0^{LL} and W_1^{LL}, use an SU(3) phenomenological Lagrangian for matrix elements involving a proton and light pseudoscalar mesons, and extend it to the bottom sector



$G^2 = \lambda''^2_{1j3} \times (1 \text{ TeV}/m_{\tilde{q}})^4$

The proton mode dominates

- Similarly for the other benchmark scenarios

$\tilde{\chi}_1^0$ decay in RPV

With

- small RPV couplings
- GeV-scale neutralino mass
- absence of squark mixing

the neutralino decay is kinematically suppressed by 3 off-shell propagators:

- a squark
- a bottom quark
- a W-boson

and also CKM suppressed
determining $\tilde{\chi}_1^0$ to appear as $\not{E}$ at the detector level

Analysis technique

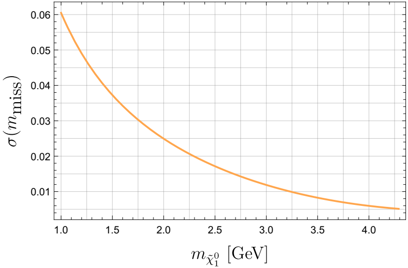
- Search strategy inspired by searches for $B^+ \to K^+\nu\bar{\nu}$&$B^+ \to \pi^+\nu\bar{\nu}$
- Reconstructing/tagging the decay of one of the B-mesons: tag B
- Tagging method: hadronic, semileptonic, inclusive
- hadronic: highest signal purity and lowest efficiency;
  inclusive: opposite
- All methods allow for obtaining distribution of m_{miss} peaking at $m_{\tilde{\chi}_1^0}$, distinct from background events
- Requirements:
  - Only one charged-particle track not associated with the tag B
  - Track identified as a proton for $B^+ \to p\tilde{\chi}_1^0$
  - The energy deposition in calorimeter clusters not associated with the proton or the tag-B decay products must be small in order to suppress background from neutrons and K_L^0 mesons.
- The three methods have similar sensitivities; we use hadronic

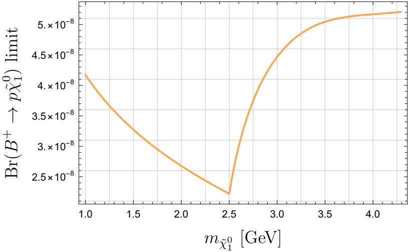
Background estimate

- Estimate the m_{miss}-dependent background in hadronic-tagging analysis of BABAR search for $B^+ \to K^+ \nu \bar{\nu}$
- Background numbers given in bins of width 100-MeV, then rescaled according to total number of $B\bar{B}$ events' ratio between BABAR and Belle II
- The estimated background is reduced relative to that in $B^+ \to K^+ \nu \bar{\nu}$ by the fact that the proton production rate in B^+ decays is about $R_{p/K} \approx 1/16$ of K^+ production
- Background from light-quark events is smaller and ignored
- Multiplication by $R_{p/K}$ gives N_b^{100}
- $N_b = N_b^{100} \frac{2\sigma(m_{\text{miss}})}{100\text{ MeV}}$
- $\sigma(m_{\text{miss}}) \sim \sigma(p_T^p) = \left(0.0019 \frac{pT}{\text{GeV}}\right)^2 + \left(0.003 \frac{1}{\beta}\right)^2$ at Belle, assumed the same at Belle II
- A smaller contribution to $\sigma(m_{\text{miss}})$ arises from the spread of the collider COM energy taken to be 5 MeV.

Sensitivities for $B^+ \to p\tilde{\chi}_1^0$

$$90\%\ \text{C.L. upper limits: } \mathcal{B}(B^0 \to p\tilde{\chi}_1^0) < \frac{1.64\sqrt{N_b}}{N_{BB}(\text{Belle II})\ \epsilon}$$





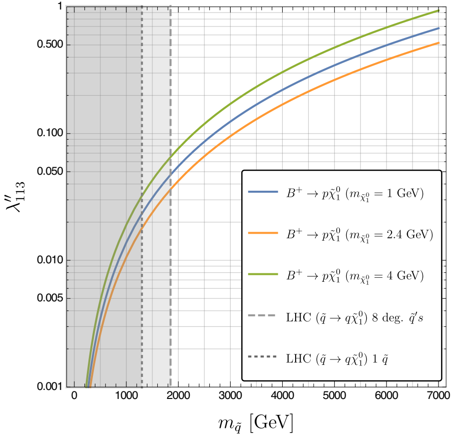
- $\epsilon \approx 95 \times 10^{-5}$: total reconstruction efficiency
- For the other benchmarks, similar strategies based on other searches

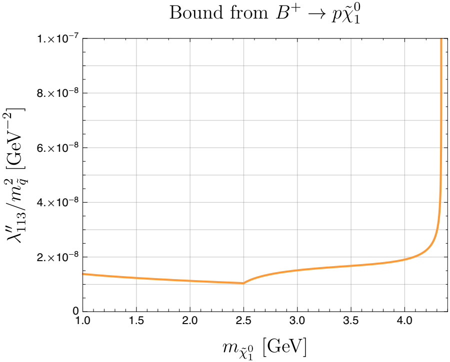
Current bounds

For a representative value of $m_{\tilde{\chi}_1^0} = 2.5$ GeV:

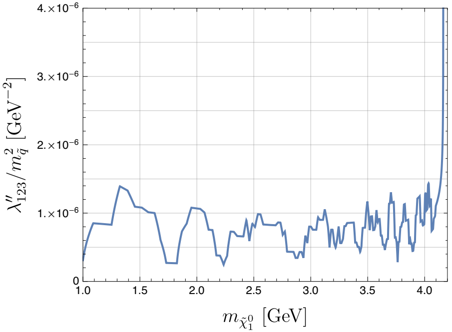
- from Ξ_b^0-$\bar{\Xi}_b^0$ oscillation:
  - $\lambda''_{123}/m_{\tilde{q}}^2 < 4 \times 10^{-4}$ GeV^{-2}
- di-nucleon decays:
  - $\lambda''_{113}/m_{\tilde{q}}^2 < 6 \times 10^{-4}$ GeV^{-2}
  - $\lambda''_{123}/m_{\tilde{q}}^2 < 2 \times 10^{-2}$ GeV^{-2}
  - $\lambda''_{213}/m_{\tilde{q}}^2 < 5 \times 10^{-6}$ GeV^{-2}
  - $\lambda''_{223}/m_{\tilde{q}}^2 < 2 \times 10^{-4}$ GeV^{-2}

Bounds on RPV parameter λ''_{113} at Belle II, 50 ab^{-1}





Bounds on RPV parameter λ''_{123}



Reinterpreted from preliminary BABAR limits on $B^0 \to \Lambda^0 \Psi_D$

Search for Baryogenesis and Dark Matter in B-meson Decays at BABAR, Poster presented at ICHEP 2022 (2022)

Summary

- RPV-SUSY with long-lived light neutralinos produced from rare B-decays at Belle II, for $m_{\tilde{\chi}_1^0}$ between 1 GeV and 4.5 GeV
- λ''_{113}, λ''_{123}, λ''_{213}, λ''_{223}, leading to $B \to \mathcal{B}\tilde{\chi}_1^0$
- Background estimates based on existing searches
- Belle II sensitivities are orders of magnitude stronger than current limits
- Further similar searches can be performed at B-factories

Thank You!

Back-up slides

R-parity and the RPV-MSSM

In general, the MSSM superpotential includes the following operators:

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

Lepton Number Violation & Baryon Number Violation
$\Rightarrow$ too fast proton decay rate!
$\Rightarrow$ An implicit ingredient of the MSSM: R_p conservation (RPC)

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

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

- SM fields: $R_p = +1$, superpartners: $R_p = -1$
- Forbids all the terms in $W_{\not{R}_p}$
- Renders the lightest supersymmetric particle (LSP) a stable cold DM candidate

RPV & long-lived $\tilde{\chi}_1^0$

However, RPC dim-5 operators could lead to proton decays

- Alternative: impose discrete symmetries allowing only LNV or BNV
- RPV $\rightarrow$ the LSP decays, no longer a DM candidate
- RPV-MSSM allows light ($\mathcal{O}$(GeV)) neutralinos (binolike)
- Assume $\tilde{\chi}_1^0$ LSP
- Small RPV couplings & $m_{\tilde{\chi}_1^0}$ $\rightarrow$ long-lived $\tilde{\chi}_1^0$'s