Long-lived light neutralinos at Belle II

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arXiv:2012.00438

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December 10th, 2020
FSP Workshop (online): Long-lived particles at Belle II

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Motivation

- In the RPV-SUSY, light neutralinos are still allowed by different constraints and can be long-lived
- Belle II: e^- beam of 7 GeV collides with e^+ beam of 4 GeV
- A large number of $\tau^+\tau^-$ events $\Rightarrow$ study rare τ decays
- *Long-lived* $\tilde{\chi}_1^0$'s from τ decays at Belle II

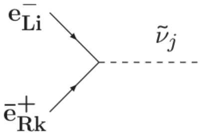
RPV-MSSM

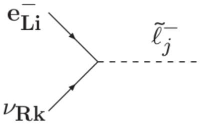
$$W_{\not{R}_p} = \mu_i H_u \cdot L_i + \frac{1}{2}\lambda_{ijk} L_i \cdot L_j \bar{E}_k + \lambda'_{ijk} L_i \cdot Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

- RPV-MSSM allows light ($\mathcal{O}$(GeV)) neutralinos (binolike)
- $\tau \to \tilde{\chi}_1^0 + X$ and $\tilde{\chi}_1^0 \to \nu_\tau + Y$ decays mediated by sfermions
- Assume $\tilde{\chi}_1^0$ LSP and degenerate sfermion masses
- *Small RPV couplings & $m_{\tilde{\chi}_1^0}$* $\to$ long-lived $\tilde{\chi}_1^0$'s

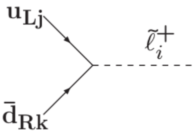
(Partly) New Yukawa-like couplings

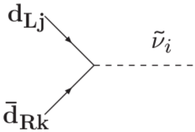
- $L_i L_j E_k$



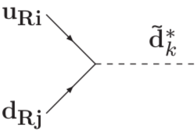


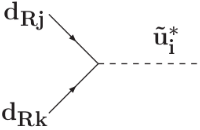
- $L_i Q_j D_k$





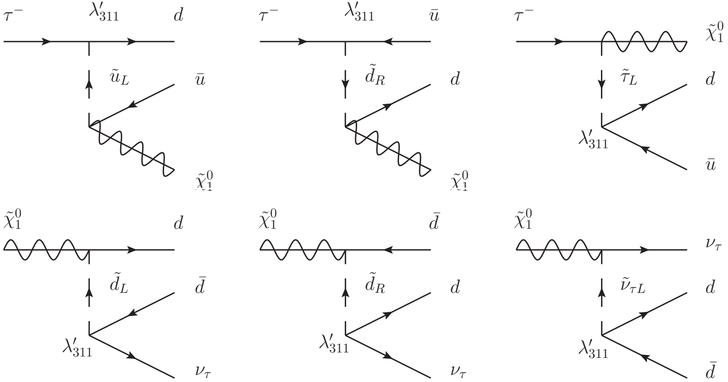
- $U_i D_j D_k$





Benchmark scenarios and Feynman diagrams

- Focus on λ'_{311} and λ'_{312} (but not both simultaneously)



- Both $\Gamma(\tau^- \to \tilde{\chi}_1^0 d\bar{u})$ and $\Gamma(\tilde{\chi}_1^0 \to \nu_\tau d\bar{d})$ proportional to $(\lambda'_{31k}/m^2_{\tilde{f}})^2$

Detail of benchmark scenarios

$\tau \to \tilde{\chi}_1^0\ M_1^{(*)},\ \tilde{\chi}_1^0 \to M_2^{(*)}\ \nu_\tau$		
	Scenario 1	Scenario 2
λ' (production & decay)	λ'_{311}	λ'_{312}
Mesons in $\tilde{\chi}_1^0$ production (M_1)	$\pi^\pm$, $\rho^\pm$	$K^\pm\ K^{*\pm}$
Mesons in $\tilde{\chi}_1^0$ decay (M_2)	π^0, ρ, ω, η, η'	K^0, K^{*0}
M_2 decays with charged particles	$\eta \to \pi^+\pi^-\gamma$, $\eta \to \pi^+\pi^-\pi^0$, $\eta' \to \pi^+\pi^-(\eta \to 3\pi^0)$, $\eta' \to \pi^0\pi^0(\eta \to \pi^+\pi^-\pi^0)$, $\eta' \to \pi^+\pi^-(\eta \to \gamma\gamma)$, $\eta' \to \pi^0\pi^0(\eta \to \pi^+\pi^-\gamma)$ $\eta' \to \gamma(\omega \to \pi^+\pi^-\pi^0)$, $\eta' \to \gamma(\rho \to \pi^+\pi^-)$ $\eta' \to \gamma(\omega \to \pi^+\pi^-)$, $\eta' \to \pi^+\pi^-(\eta \to \pi^+\pi^-\gamma)$ $\eta' \to \pi^+\pi^-(\eta \to \pi^+\pi^-\pi^0)$	$K_S \to \pi^+\pi^-$, $K^{*0} \to \pi^\pm K^\mp$

Present bounds

- RPV coupling bounds:

$$|\lambda'_{31k}| < 0.20 \, \frac{m_{\tilde{d}_R}}{1 \text{ TeV}} + 0.046$$

Recast of an ATLAS search with 36.1 fb^{-1} [Bansal et al. 2019]

- Experimental and theoretical uncertainties in $\tau \to P\nu_\tau$ $(P = \pi, K)$

$$\mathcal{B}(\tau \to \pi\nu_\tau)_{EXP} = (10.82 \pm 0.05)\%, \quad \mathcal{B}(\tau \to K\nu_\tau)_{EXP} = (0.696 \pm 0.01)\%$$
$$\mathcal{B}(\tau \to \pi\nu_\tau)_{SM} = (10.90 \pm 0.027)\%, \quad \mathcal{B}(\tau \to K\nu_\tau)_{SM} = (0.722 \pm 0.004)\%$$

$$\Rightarrow \sigma_{\mathcal{B}(\tau \to \pi\nu_\tau)} = 0.057 \times 10^{-2}, \quad \sigma_{\mathcal{B}(\tau \to K\nu_\tau)} = 0.011 \times 10^{-2}$$

$$\Rightarrow \mathcal{B}(\tau \to P\tilde{\chi}^0_1) \lesssim 2\sigma_{\mathcal{B}(\tau \to P\nu_\tau)}$$

Event selection

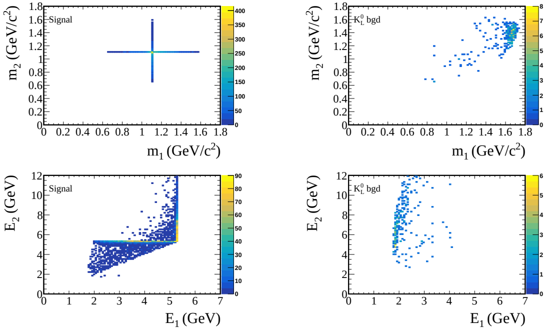
- $e^+e^- \to \tau^+\tau^-$ event selection:
  - A single track that recoils against the rest of the event in the opposite hemisphere, accompanied by large missing energy and transverse momentum
  - It leaves the backgrounds from $e^+e^- \to \tau^+\tau^-$ events as the dominant source, efficiently rejecting all other sources of background
- Require two identified charged pions to form a DV

Background estimate: I

- Focus on displaced η and η', effective at suppressing background
- Main signal process for background consideration:
  $\tau^- \to \pi^- \tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to \eta \nu_\tau$, $\eta \to \pi^+\pi^-\pi^0$
- The main background: $\tau^- \to \pi^- \pi_p^0 K_L \nu_\tau$ with $K_L \xrightarrow{disp.} \pi^+\pi^-\pi_d^0$
  - $\pi_{p/d}^0 \to \gamma_{p/d}^1 \gamma_{p/d}^2$, and $\gamma_p^i \gamma_d^j$ can form a fake π^0
  - The fake π^0 or π_p^0, with $\pi^+\pi^-$, can give a fake η candidate
  - The two remaining photons can escape via endcap of calorimeter or go undetected for being too soft
- Estimate no. of bgd by *EvtGen* MC simulation
- K_L decay in fiducial volume: $10 < r < 80$ cm and $-40 < z < 120$ cm
- Require two photons other than $\gamma_d^1 \gamma_d^2$ form a π^0, energy of each photon > 100 MeV, their inv. mass within 15 MeV of m_{π^0}
- Require inv. mass of the η candidate within 15 MeV of m_η
- The remaining photons escape the cal. or have energy < 100 MeV
- 300 background events at the end in the Belle II dataset

Background estimate: II

- Apply the constraints of the signal decay chain to determine the neutrino 4-momentum up to a 2-fold ambiguity because of a quadratic equation
- Distributions of the two calculated neutralino masses m_1 and m_2, and the τ energies E_1 and E_2 for signal ($\tau^- \to \pi^- \tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to \eta\nu$ with $m_{\tilde{\chi}_1^0} = 1.1$ GeV) & bgd ($\tau^- \to \pi^- \pi_p^0 K_L \nu_\tau$)



- Background and signal distributions are distinct $\to$ background-free
- Other signatures have even smaller background

Visible final states, signal acceptance, and efficiency

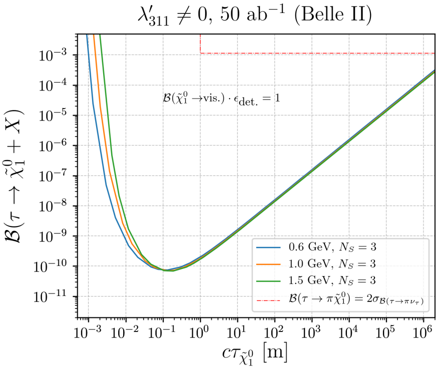
- Visible final states: $\tilde{\chi}_1^0$ decay into at least two charged pions
- Signal acceptance: $10 < r < 80$ cm, $-40 < z < 120$ cm
- Reconstruction efficiency:
  - $\pi^+\pi^-$: 12%
  - Any additional π^0 or γ: 70%
  - Any additional $\pi^+\pi^-$: 85%
  - $M_2 = K_S$ susceptible to $\tau^- \to \pi^- K_S \nu_\tau$ background because $c\tau_{K_S} = 2.7$ cm. This background will be suppressed by requiring that the K_S momentum does not point back to the IP: 90%

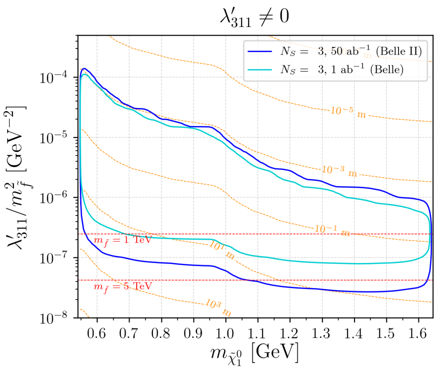
Signal number estimate

$$N_S = 2N_{\tau^-\tau^+} \cdot \mathcal{B}(\tau \to \text{ 1 prong}) \cdot \mathcal{B}(\tau \to \tilde{\chi}_1^0 M_1^{(*)}) \cdot \mathcal{B}(\tilde{\chi}_1^0 \to \text{ visibles}) \cdot \epsilon_{\text{acc.}} \cdot \epsilon_{\text{det.}}$$

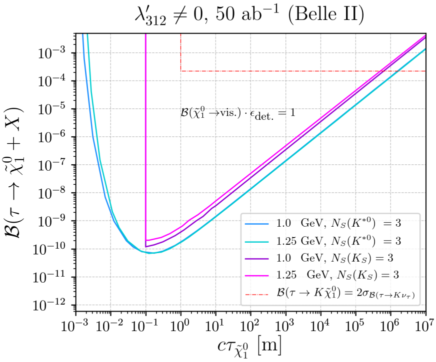
- $N_{\tau^-\tau^+} = 4.6 \times 10^{10}$ with 50 ab^{-1}
- $\mathcal{B}(\tau \to \text{ 1 prong}) \approx 85\%$, a single track
- $\mathcal{B}(\tilde{\chi}_1^0 \to \text{ visibles})$: ≥ 2 charged pions
- $\epsilon_{\text{acc.}}$: detector acceptance, estimated with Pythia 8 simulation using exponential decay distribution
- $\epsilon_{\text{det.}}$: detector reconstruction efficiency
- Model parameters: $m_{\tilde{\chi}_1^0}$ and $\lambda'_{31k}/m^2_{\tilde{f}}$

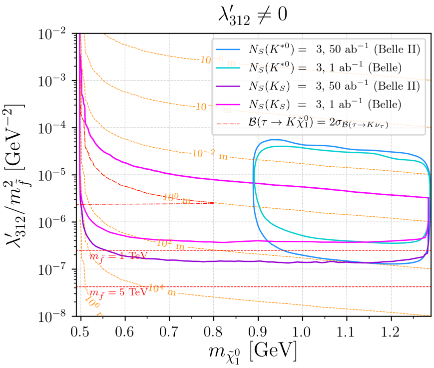
Numerical results: $\lambda'_{311} \neq 0$





Numerical results: $\lambda'_{312} \neq 0$





Summary

- RPV-SUSY with long-lived light neutralinos produced from rare tau decays at Belle II, for $m_{\tilde{\chi}_1^0}$ between 0.5 GeV and $m_\tau - m_\pi$
- Two scenarios: λ'_{311} and λ'_{312}
- Background found to be negligible
- Belle II sensitivities are orders of magnitude stronger than the current limits
- Further scenarios of LLPs from τ decays can be pursued at Belle II

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

⇒ too fast proton decay rate!

⇒ 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*

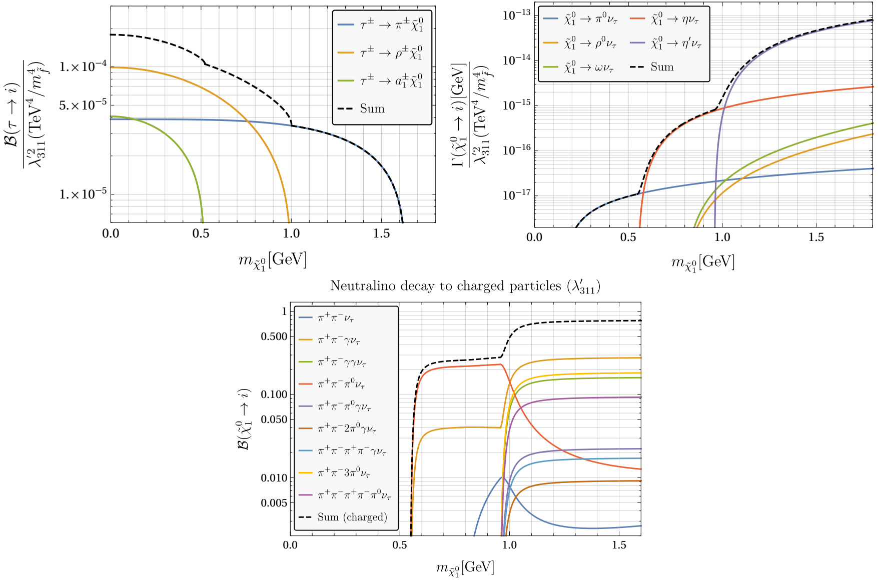
- SM fields: $R_p = +1$, superpartners: $R_p = -1$
- Forbids all the terms in $W_{\not{R}_p}$
- Renders the lightest supersymmetric particle (LSP) a stable cold DM candidate

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

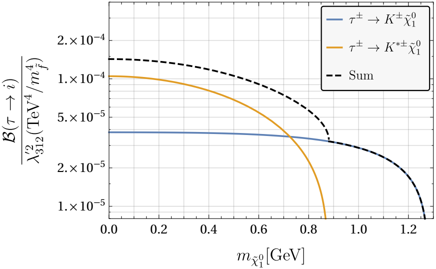
However, *RPC dim-5* operators could lead to proton decays

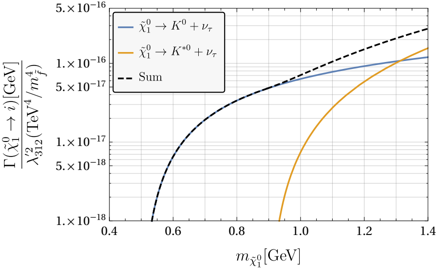
- *Alternative*: impose discrete symmetries allowing only LNV or BNV
- RPV $\rightarrow$ the LSP decays, no longer a DM candidate
- RPV-MSSM allows light ($\mathcal{O}$(GeV)) neutralinos (binolike)
- Assume $\tilde{\chi}_1^0$ LSP
- Small RPV couplings & $m_{\tilde{\chi}_1^0}$ $\rightarrow$ long-lived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

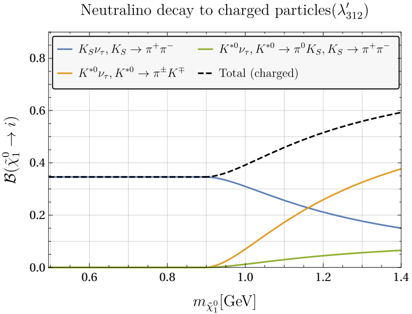
Neutralino production and decay: $\lambda'_{311} \neq 0$



Neutralino production and decay: $\lambda'_{312} \neq 0$







Visible branching fractions of the neutralino: $\lambda'_{311} \neq 0$

$\mathcal{B}(\tilde{\chi}_1^0 \to \text{ visibles}) =$

$$
\begin{aligned}
&\mathcal{B}(\tilde{\chi}_1^0 \to \nu_\tau \pi^0) \cdot \mathcal{B}(\pi^0 \to \text{ visibles}) + \mathcal{B}(\tilde{\chi}_1^0 \to \nu_\tau \rho^0) \cdot \mathcal{B}(\rho^0 \to \text{ visibles}) \\
&+\mathcal{B}(\tilde{\chi}_1^0 \to \nu_\tau \eta) \cdot \mathcal{B}(\eta \to \text{ visibles}) + \mathcal{B}(\tilde{\chi}_1^0 \to \nu_\tau \eta') \cdot \mathcal{B}(\eta' \to \text{ visibles}) \\
&+\mathcal{B}(\tilde{\chi}_1^0 \to \nu_\tau \omega) \cdot \mathcal{B}(\omega \to \text{ visibles})
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{B}(\pi^0 \to \text{ visibles}) &= 0, \mathcal{B}(\rho^0 \to \text{ visibles}) = 1, \\
\mathcal{B}(\omega \to \text{ visibles}) &= \mathcal{B}(\omega \to \pi^+\pi^-) + \mathcal{B}(\omega \to \pi^+\pi^-\pi^0), \\
\mathcal{B}(\eta \to \text{ visibles}) &= \mathcal{B}(\eta \to \pi^+\pi^-\pi^0) + \mathcal{B}(\eta \to \pi^+\pi^-\gamma), \\
\mathcal{B}(\eta' \to \text{ visibles}) &= \mathcal{B}(\eta' \to \pi^+\pi^-\eta) + \mathcal{B}(\eta' \to \rho^0\gamma) \cdot \mathcal{B}(\rho^0 \to \text{ visibles}) \\
&\quad +\mathcal{B}(\eta' \to \pi^0\pi^0\eta) \cdot \mathcal{B}(\eta \to \text{ visibles}) \\
&\quad +\mathcal{B}(\eta' \to \omega\gamma) \cdot \mathcal{B}(\omega \to \text{ visibles}).
\end{aligned}
$$

Visible branching fractions of the neutralino: $\lambda'_{312} \neq 0$

$$\begin{aligned}\mathcal{B}(\tilde{\chi}_1^0 \to \text{ visibles}) = \; & \mathcal{B}(\tilde{\chi}_1^0 \to \nu_\tau K^{*0}) \cdot \mathcal{B}(K^{*0} \to \text{ visibles}) \\ & + \mathcal{B}(\tilde{\chi}_1^0 \to \nu_\tau K_S) \cdot \mathcal{B}(K_S \to \text{ visibles})\end{aligned}$$

$$\begin{aligned}\mathcal{B}(K^{*0} \to \text{ visibles}) &= \mathcal{B}(K^{*0} \to K^\pm \pi^\mp), \\ \mathcal{B}(K_S \to \text{ visibles}) &= \mathcal{B}(K_S \to \pi^+ \pi^-)\end{aligned}$$

Further Background estimate

- One possible background: $\tau^- \to \pi^- K_L \nu_\tau$ with $K_L \xrightarrow{disp.} \pi^+\pi^-\pi^0$
  - Mass resolution for $\pi^+\pi^-\pi^0$: 4 MeV while $|m_\eta - m_{K_L}| \approx 50$ MeV
- Another background for $\tilde{\chi}_1^0 \to \eta\nu_\tau$: $\tau^- \to \pi^-\pi_p^0 K_L \nu_\tau$ with $K_L \to \pi^\pm \ell^\mp \nu$
  - Only π_p^0 is available to fake the η signal, resulting in a factor of 3 suppression relative to the background from $K_L \to \pi^+\pi^-\pi^0$
  - Further suppressed to the sub-percent level by rejecting DVs formed by a lepton
  - Overall, its contribution is expected to be smaller than that of $K_L \to \pi^+\pi^-\pi^0$
- Background in the $\tilde{\chi}_1^0 \to \eta'\nu_\tau$ channel is much smaller than in the $\tilde{\chi}_1^0 \to \eta\nu_\tau$ channel
  - the higher mass of the η'
  - the dominant decays $\eta' \to \eta\pi^+\pi^-$ and $\rho\gamma$ provide an additional intermediate hadron (η, and to some extent, ρ) for which a mass cut can be used for background rejection

Fiducial volume choice

- $10 < r < 80$ cm, $-40 < z < 120$ cm
- The 10 cm $< r$ limit rejects most DVs that arise from material interaction and K_S decays
- The other limits correspond to the size of the Belle II tracking systems

Estimate of $\epsilon_{\rm det}$

- $\epsilon_{\rm acc}$ depends on the neutralino boost, lifetime, and travel direction, as well as the geometry of the acceptance volume
- Pythia 8.243: `WeakSingleBoson:ffbar2ffbar(s:gm)`, 1.5×10^4 $e^- e^+ \to \tau^- \tau^+$ events including ISR

$$
\begin{aligned}
\epsilon_{\rm acc} &= \frac{1}{2\,N_{\rm MC}} \sum_{i=1}^{2\,N_{\rm MC}} \epsilon^i_{\rm acc} \\
\epsilon^i_{\rm acc} &= e^{-z_i^I/\lambda_i^z} \cdot (1 - e^{-z_i^O/\lambda_i^z}) \\
z_i^I &\equiv \min(Z, |R_I/\tan\theta_i|) \\
z_i^O &\equiv \min(Z, |R_O/\tan\theta_i|) - z_i^I \\
\lambda_i^z &\equiv \beta_i^z\,\gamma_i\,c\,\tau_{\tilde{\chi}_1^0}
\end{aligned}
$$

- $R_I(R_O) = 10(80)$ cm: the inner(outer) radii of the acceptance volume
- $Z = 120$ cm for $\tan\theta_i > 0$ and 40 cm for $\tan\theta_i < 0$