Updating bounds on R-parity-violating supersymmetry with a long-lived light bino

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in collaboration with

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Paper to be released very soon!

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Table of Contents

1. R-parity violating MSSM with a light bino

1.1 R-parity violating (RPV-) MSSM …

- LHC has ruled out the MSSM up to $\mathcal{O}(100\,\mathrm{GeV} \sim 1\,\mathrm{TeV})$

- Are we missing something?

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

$$W_{\mathrm{RPV}} = \kappa_i L_i H_u + \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

1. R-parity violating MSSM with a light bino

1.1 R-parity violating (RPV-) MSSM …

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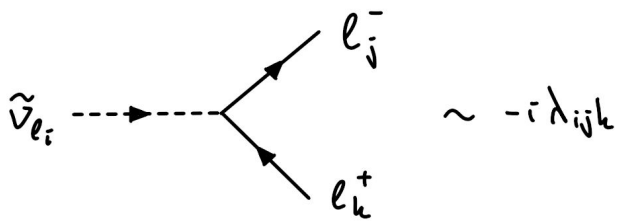
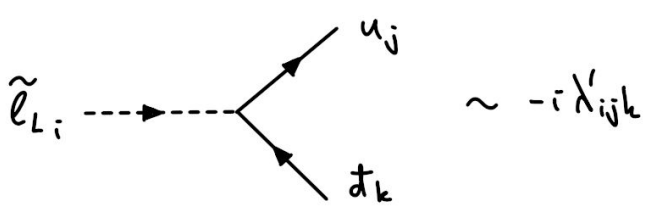




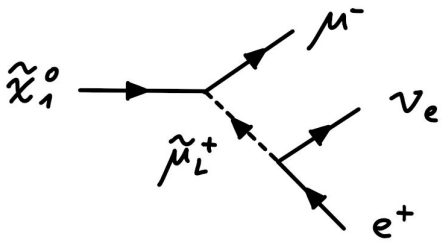
1. R-parity violating MSSM with a light bino

1.2 … with a light bino

- LEP bound on LSP neutralino: $m_{\tilde{\chi}_1^0} > 46\,\mathrm{GeV}$, assuming $M_1 \approx \frac{1}{2} M_2$
- ~~$M_1 \approx \frac{1}{2} M_2$~~ → Neutralino mass unconstrained!

! Cosmologically excluded stable neutralino: $0.7\,\mathrm{eV} < m_{\tilde{\chi}_1^0} < 24\,\mathrm{GeV}$

RPV ↔ { Cosmologically unstable neutralino, but might be "long lived" at the detector level!



2. Heavy neutral leptons

2.1 Heavy neutral leptons

- Simple theory with one kinematically relevant HNL:

$$\mathscr{L} \supset -\frac{g}{\sqrt{2}} U_4^i W_\mu^- \ell_i^\dagger \bar{\sigma}^\mu N - \frac{g}{2c_W} U_4^i Z_\mu \nu_i^\dagger \bar{\sigma}^\mu N + \text{h.c.}$$

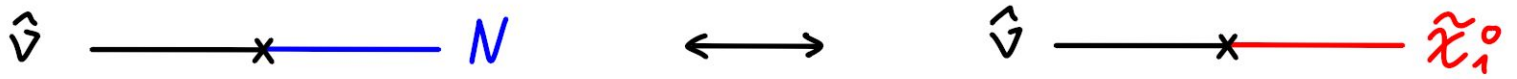
where $U_i \equiv U_4^i \equiv (Y_\nu^*)_1^i \frac{v}{\sqrt{2}M}$

3. Recasting procedure

3.1 The phenomenology connecting the light bino LSP and the HNL

- Bilinears ($\kappa_i L_i H_u$): Integrating out the heavy higgsinos in the neutral lepton sector yields

$$\mathcal{L} \supset \frac{g'}{2}\left(v_i - \frac{v_d \kappa_i}{\kappa^0}\right)\hat{\nu}_i \tilde{\chi}_1^0 + \text{h.c.}$$



$$U_4^i = (Y_\nu^*)_1^i \frac{v}{\sqrt{2}M}$$

$$U_4^i = \frac{g'}{2m_{\tilde{\chi}_1^0}}\left(v_i - \frac{v_d \kappa_i}{\kappa^0}\right)$$

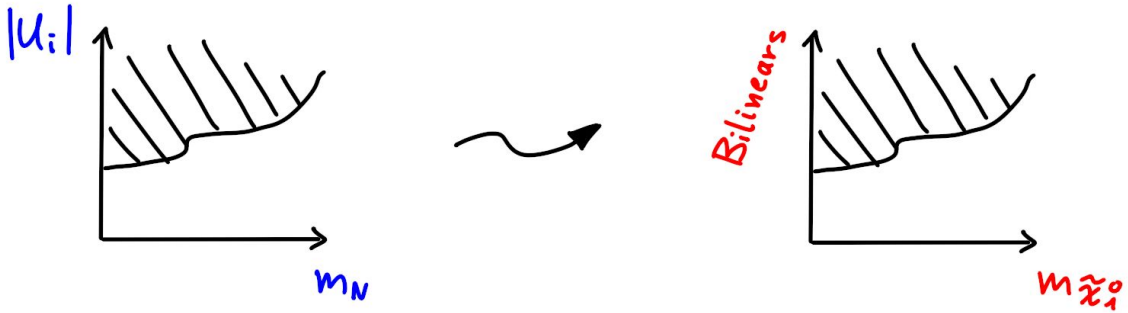
3. Recasting procedure

Bilinears mimic HNL mixing

↓

Translate bounds on HNLs to bounds on RPV-MSSM, using

- **All up-to-date constraints**



3. Recasting procedure

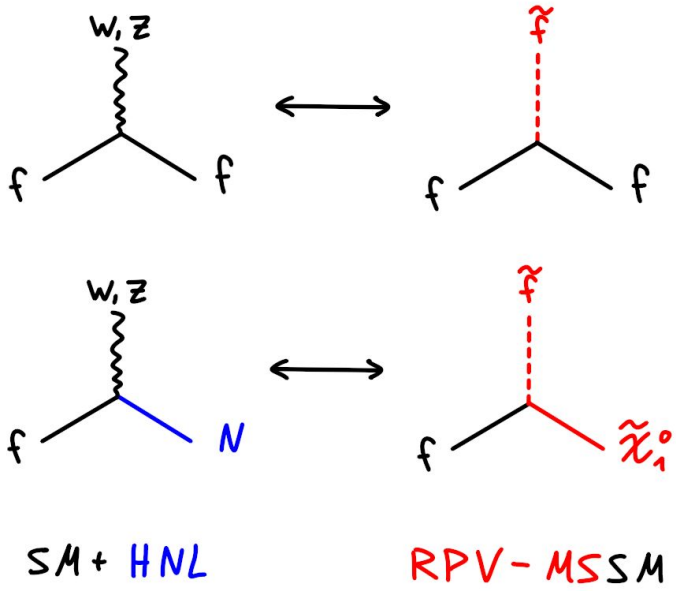
3.1 The phenomenology connecting the light bino LSP and the HNL

- Phenomenological level:

  Trilinear Yukawas ($LL\bar{E},\ LQ\bar{D}$)

  cause effects similar to the HNL

  theory!



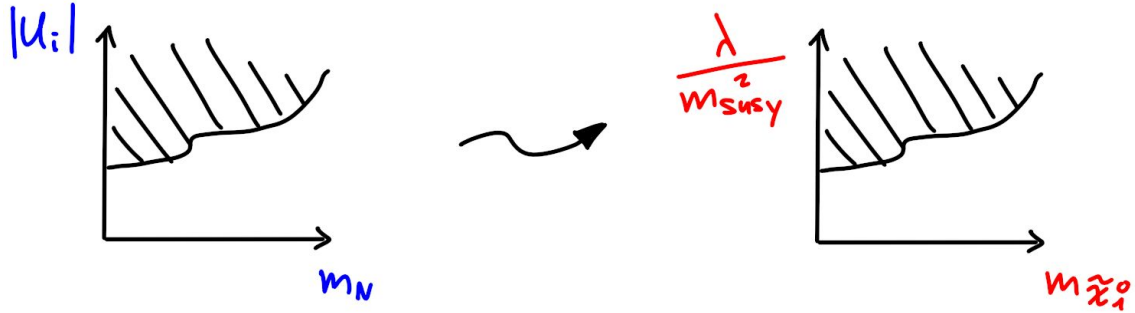
3. Recasting procedure

HNLs can be produced from meson decays

↓

Translate bounds on HNLs to bounds on RPV-MSSM, using

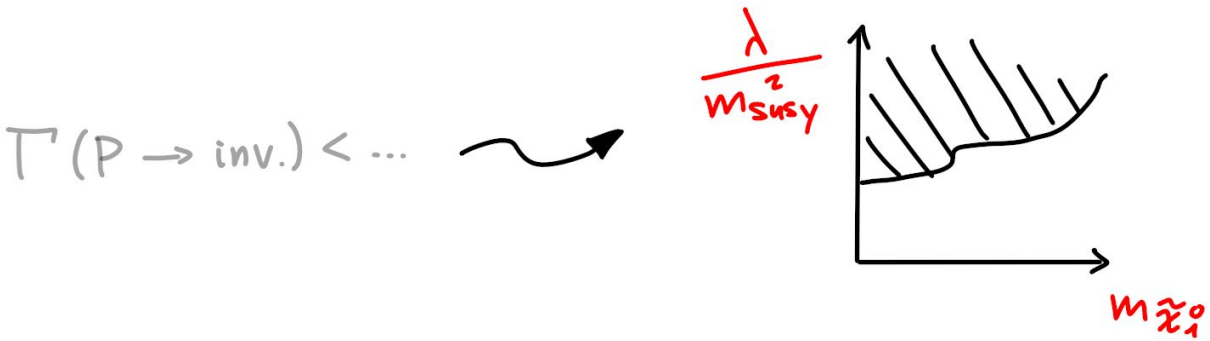
- **Direct decay searches**
- **Displaced vertex searches**



3. Recasting procedure

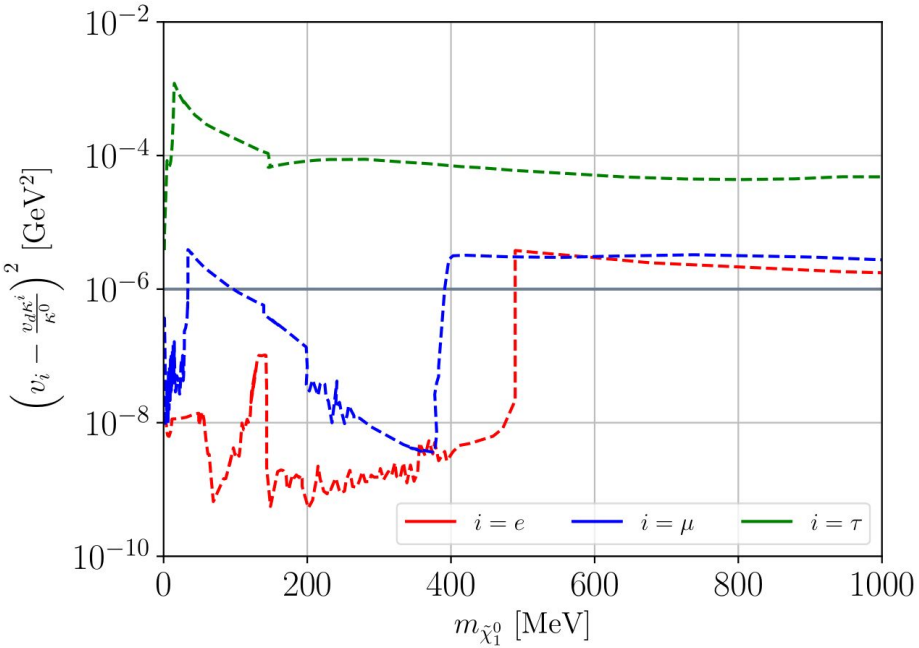
RPV-MSSM opens new, invisible particle decay channels

Translate invisible widths to bounds on RPV-MSSM



4. Updating RPV-MSSMwLB bounds: Bilinears

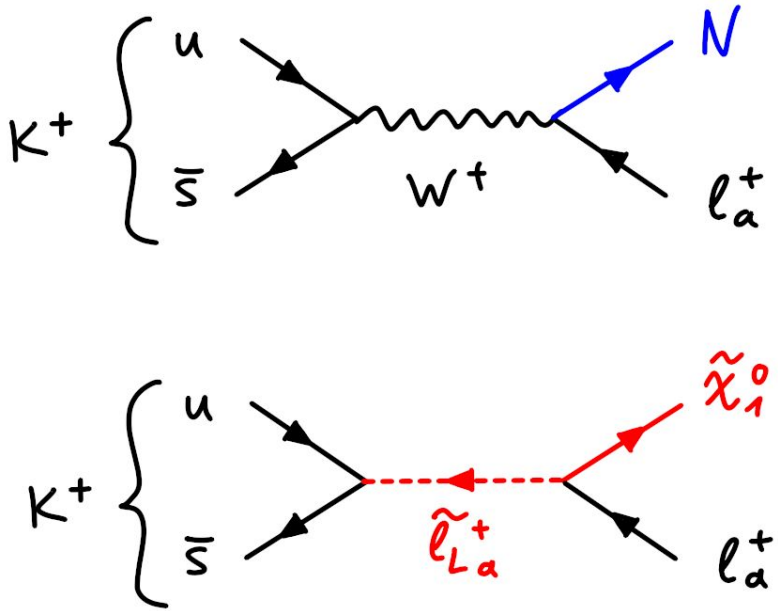
Bilinears produce $U_4^i = \frac{g'}{2m_{\tilde{\chi}_1^0}}\left(v_i - \frac{v_d \kappa_i}{\kappa^0}\right)$



4. Updating RPV-MSSMwLB bounds: Trilinears

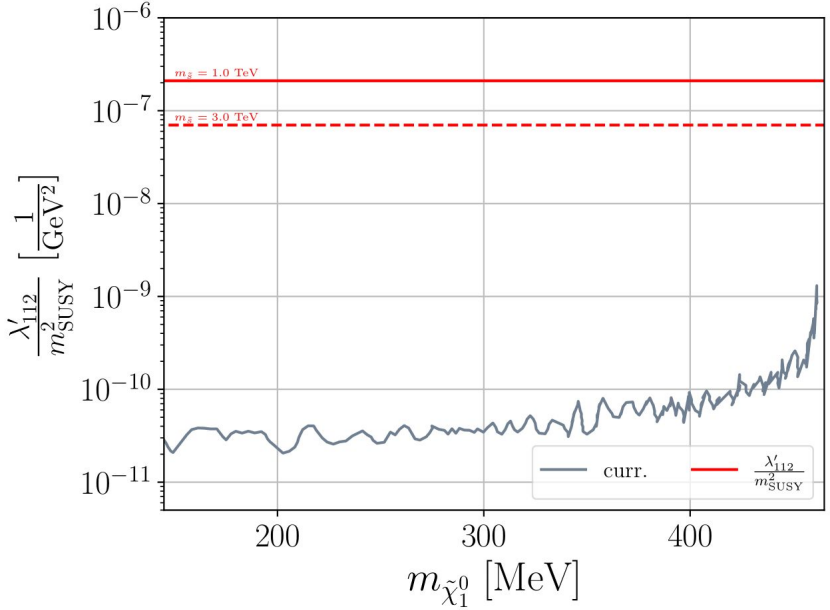
Example 1: $K^{\pm} \to \ell_a^{\pm} + \tilde{\chi}_1^0$

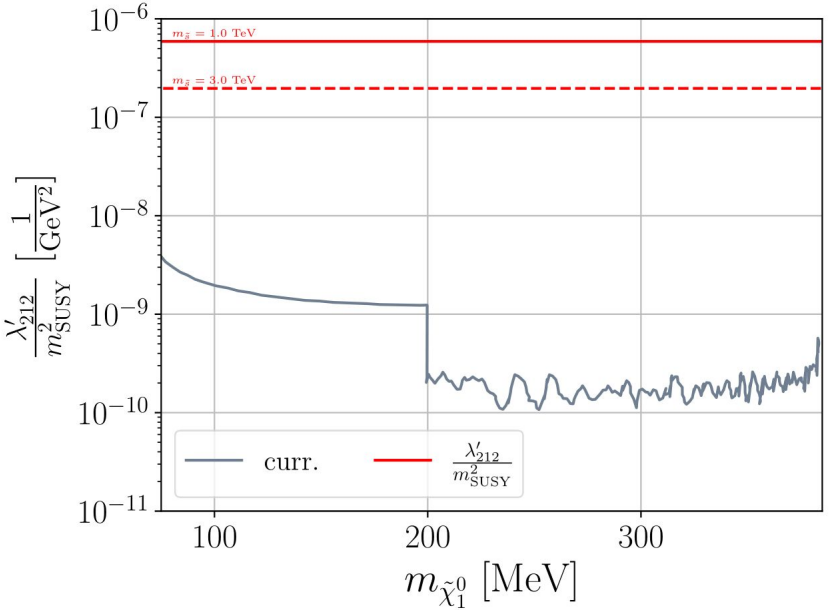
- Couplings: $\lambda'_{a12},\ a \in \{1, 2\}$
- Peak search
  - `NA62` [3, 4]
  - `KEK` [5, 6]



[3] arXiv:2005.09575
[4] arXiv:2101.12304
[5] Asano:1981he
[6] Hayano:1982wu

4. Updating RPV-MSSMwLB bounds: Trilinears



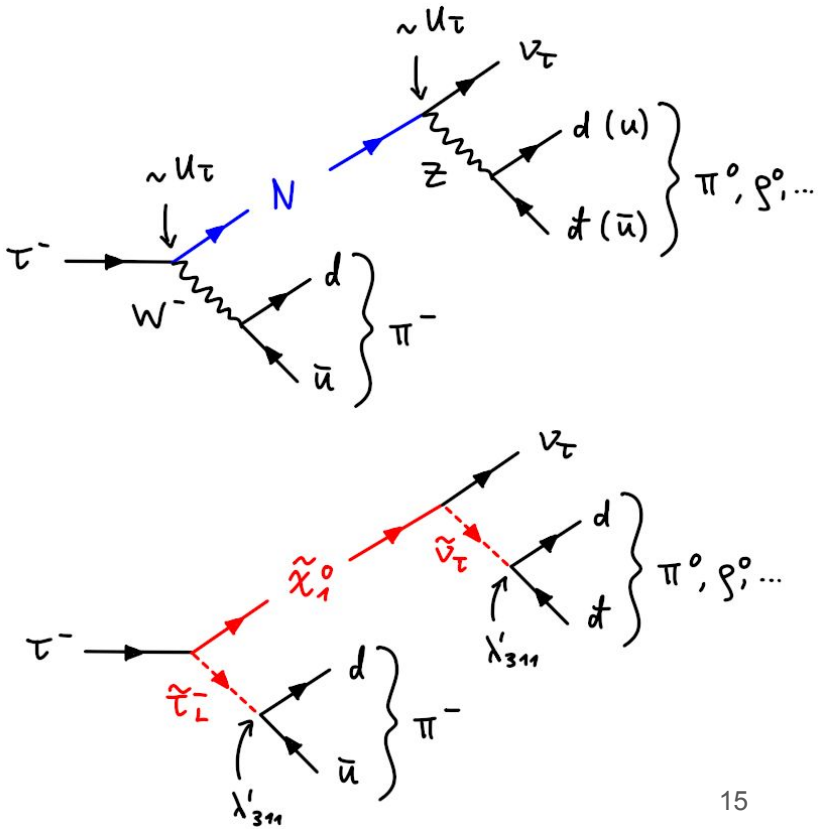


4. Updating RPV-MSSMwLB bounds: Trilinears

Example 2: $\tau^{\pm} \to \pi^{\pm} + \tilde{\chi}_1^0$

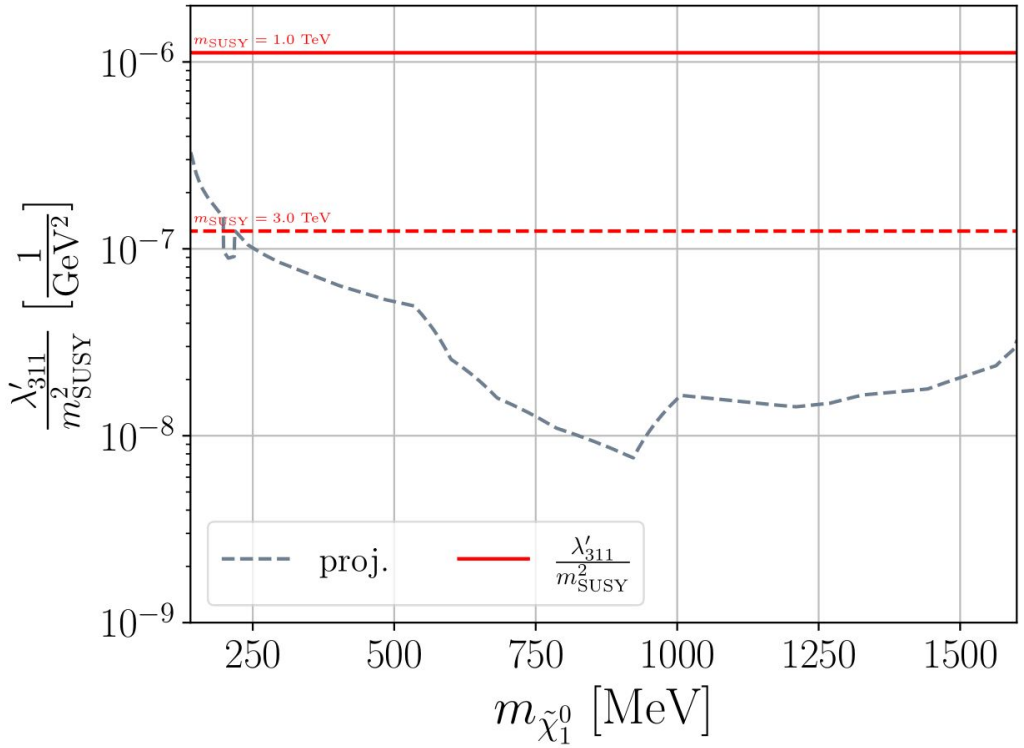
$\tilde{\chi}_1^0 \to \nu_\tau + \{\pi^0, \rho^0, \eta, \eta', \omega\}$

- Coupling: $\lambda'_{a11},\ a \in \{1, 2\}$
- Beam-dump: Displaced vertex search
  - DUNE [7]



[7] arXiv:1905.00284

4. Updating RPV-MSSMwLB bounds: Trilinears

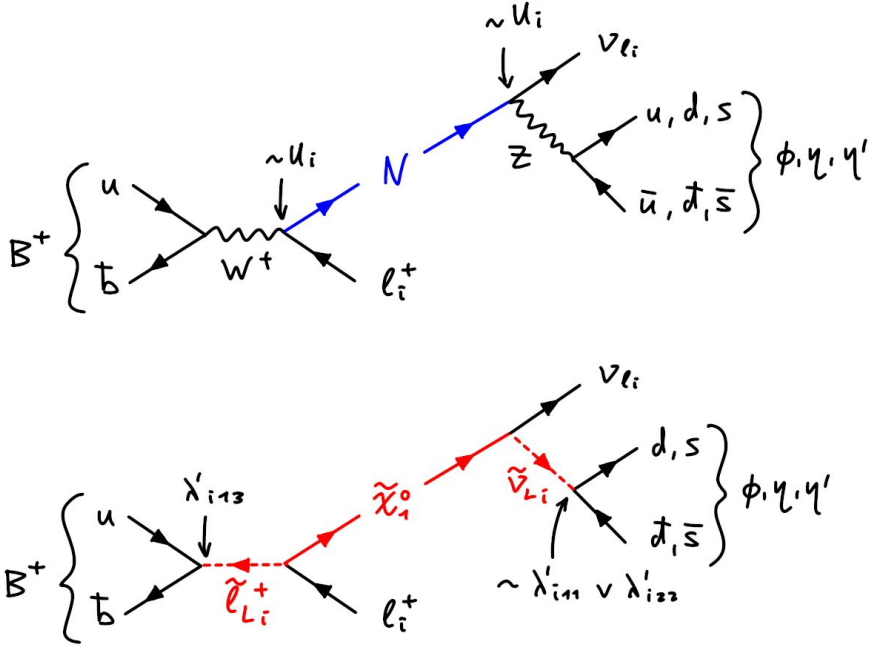


4. Updating RPV-MSSMwLB bounds: Trilinears

Example 3: $B^{\pm}(B^0) \to \ell_i^{\pm}(\nu_{\ell_i}) + \tilde{\chi}_1^0$

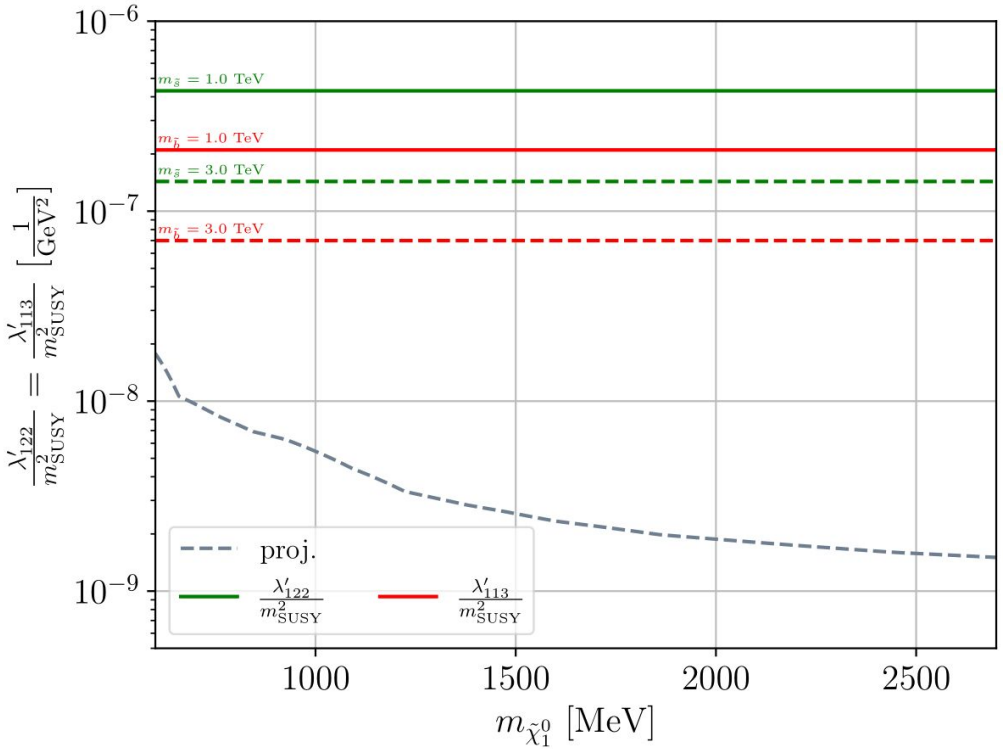
$\tilde{\chi}_1^0 \to \nu_{\ell_i} + \{\phi, \eta, \eta'\}$

- Couplings
  - Production: $\lambda'_{i13},\ i \in \{1,2,3\}$
  - Decay: $\lambda'_{i11} \vee \lambda'_{i22},\ i \in \{1,2,3\}$
- Collider: Displaced vertex search
  - FASER [8]



[8] arXiv:1801.08947

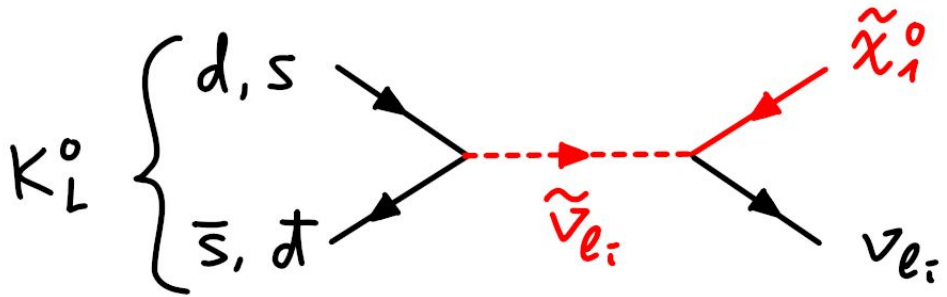
4. Updating RPV-MSSMwLB bounds: Trilinears



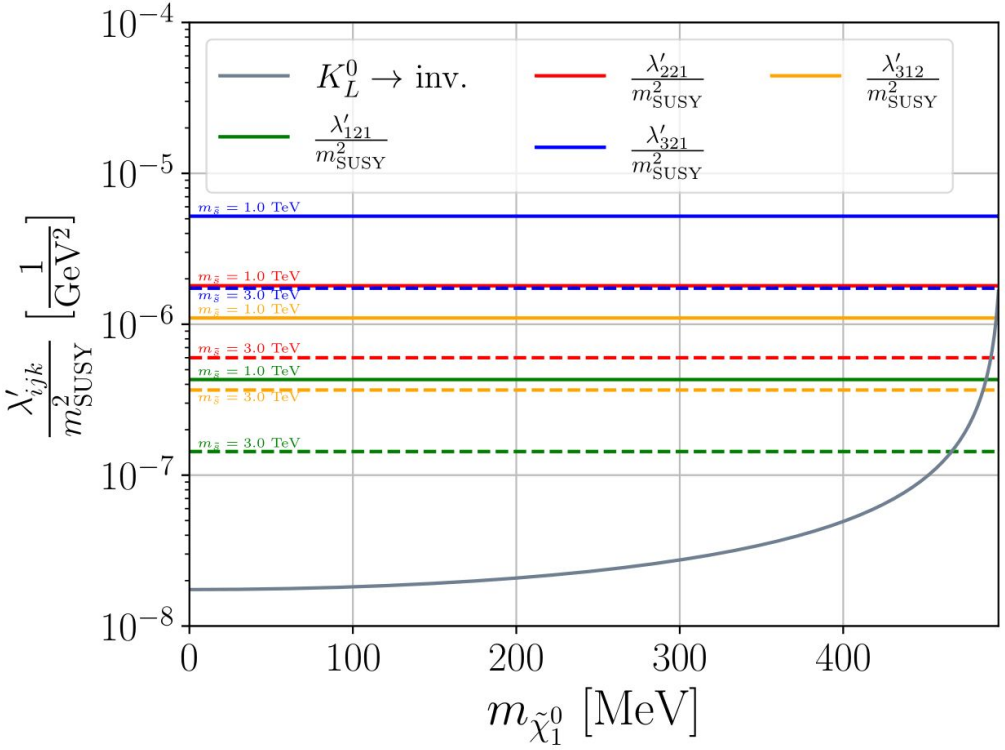
4. Updating RPV-MSSMwLB bounds: Trilinears

Example 4: $K_L^0 \to \text{inv.}$

- Couplings: $\lambda'_{i12} \vee \lambda'_{i21},\ i \in \{1,2,3\}$
- $\Gamma(K_L^0 \to \text{inv.})$ derived from the current uncertainty on Γ_{tot}



4. Updating RPV-MSSMwLB bounds: Trilinears



5. Conclusions

- **RPV-MSSM with a light bino mimics HNL phenomenology**
  - **directly (through bilinears)**
  - **indirectly (through trilinears)**
- **RPV bounds can be extended by several orders of magnitude by**
  - **Recasting current HNL bounds**
  - **Considering invisible particle decays**
- **Related work:** Rebeca Beltrán *et al.* [arXiv:2302.03216]

  Enrique Fernández-Martínez *et. al* [arXiv:2304.06772]

Heavy neutral leptons

0.1 Heavy neutral leptons

- $\mathscr{L} \supset i\hat{N}^\dagger \bar{\sigma}^\mu \partial_\mu \hat{N} - \left[(Y_\nu)^i_\alpha \left(\Phi^0 \hat{\nu}_i \hat{N}^\alpha - \Phi^+ \ell_i \hat{N}^\alpha \right) + \frac{1}{2} M^\alpha_\beta \hat{N}_\alpha \hat{N}^\beta + \text{h.c.} \right]$
- EWSB: Neutral lepton mass matrix,

$$M_{\nu N} = \begin{pmatrix} \mathbb{0}_{3\times 3} & M_D \\ M_D^T & M \end{pmatrix} \qquad \text{where} \qquad (M_D)^i_\alpha = (Y_\nu)^i_\alpha v/\sqrt{2}$$

- Diagonalize with U. One kinematically relevant HNL: $U_i \equiv U^i_4 \equiv (Y^*_\nu)^i_1 \dfrac{v}{\sqrt{2}M}$
- $\mathscr{L} \supset -\dfrac{g}{\sqrt{2}} U^i_4 W^-_\mu \ell^\dagger_i \bar{\sigma}^\mu N - \dfrac{g}{2c_W} U^i_4 Z_\mu \nu^\dagger_i \bar{\sigma}^\mu N + \text{h.c.}$

Experiments

0.2 HNL searches: Direct decay

Search Strategy	Experiment	Status	HNL Mixing	HNL Mass region
Peak	PIENU	curr.	$\|U_e\|$	65-153 MeV
	PIONEER	proj.	$\|U_\mu\|$	15.7-33.8 MeV
	PIONEER	proj.	$\|U_e\|$	65-135 MeV
	SIN	curr.	$\|U_\mu\|$	1-16 MeV
	NA62	curr.	$\|U_\mu\|$	144-462 MeV
	NA62	curr.	$\|U_e\|$	200-384 MeV
	KEK	curr.	$\|U_\mu\|$	160-230 MeV
	KEK	curr.	$\|U_\mu\|$	70-300 MeV
Branching Ratio	PIENU	curr.	$\|U_e\|$	0-65 MeV
	PIONEER	proj.	$\|U_e\|$	0-65 MeV

Experiments

0.3 HNL searches: Displaced vertices

Search Strategy	Experiment	Status	HNL Mixing	HNL Mass region
Beam-dump	DUNE	proj.	$\|U_e\|$, $\|U_\mu\|$, $\|U_\tau\|$	0-1968.34 MeV
	T2K	curr.	$\|U_e\|$, $\|U_\mu\|$	10-490 MeV
	CHARM	curr.	$\|U_e\|$, $\|U_\mu\|$	300-1869.65 MeV
	CHARM	curr.	$\|U_\tau\|$	290-1600 MeV
	NuTeV	curr.	$\|U_\mu\|$	259-2000 MeV
	MicroBooNE	curr.	$\|U_\mu\|$	20-200 GeV
	BEBC	curr.	$\|U_e\|$, $\|U_\mu\|$	500-1750 MeV
	BEBC	curr.	$\|U_\tau\|$	100-1650 MeV
	SK	curr.	$\|U_e\|$, $\|U_\mu\|$	150-400 MeV
Collider	FASER	proj.	$\|U_e\|$, $\|U_\mu\|$, $\|U_\tau\|$	0-6274.9 MeV
	MoEDAL-MAPP1	proj.	$\|U_e\|$	0-6274.9 MeV
	BaBar	curr.	$\|U_\tau\|$	100-1360 MeV

Experiments

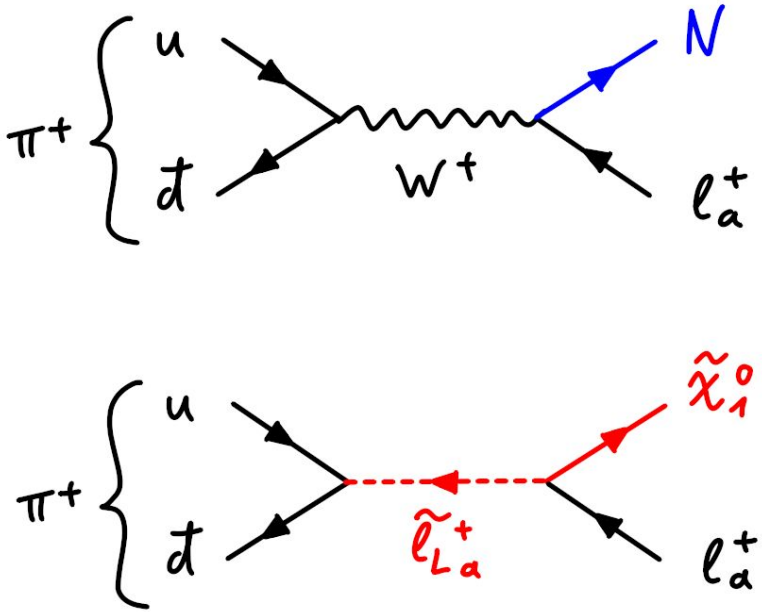
0.4 Missing energy searches

Search Strategy	Experiment	Status	BR	Bino Mass region
Missing Energy	NA62	curr.	BR($\pi^0 \to$ inv.)	0-134.97 MeV
	BaBar	curr.	BR($B^0 \to$ inv.)	0-5279.65 MeV

Updating RPV-MSSMwLB bounds: Trilinears

Example 0: $\pi^{\pm} \to \ell_a^{\pm} + \tilde{\chi}_1^0$

- Couplings: $\lambda'_{a11},\ a \in \{1, 2\}$
- Peak search + Branching ratio search
  - `PIENU` [1]
  - `PIONEER` [2]



[1] arXiv:1712.03275
[2] arXiv:2203.05505

Updating RPV-MSSMwLB bounds: Trilinears