R-parity Violation and Light Neutralinos at CODEX-b, FASER, and MATHUSLA

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bctp

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Motivation

- Light neutralinos are still allowed in R-parity-violating-SUSY (RPV-SUSY). For small RPV couplings and small mass these neutralinos can be long-lived enough to escape the reach of the LHC detectors
- It is expected that the LHC will deliver up to $3000/fb$ of luminosity in the coming 20 years
- New proposals to search for long-lived particles (LLPs): CODEX-b, FASER and MATHUSLA, all based on the idea to exploit LHC's large luminosity
- We estimate the sensitivity reach of these detectors for discovering long-lived light neutralinos singly produced from $D-$ and $B-$mesons via RPV $LQ\bar{D}$ couplings, and compare them with each other
- We also interpret our studies in a model independent way, independently of the RPV couplings

RPV-SUSY, Production & Decay of Light Neutralinos

$$W_{\text{RPV}} = \kappa_i L_i H_u + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c$$

- Assume the lightest neutralino is the lightest supersymmetric particle (LSP)
- Neutralinos lighter than $D-$ and $B-$mesons are dominantly bino-like
- Only one $LQ\bar{D}$ coupling switched on:
  only possibility allowed by kinematic constraints: λ'_{112},
  $$K^0_{L/S} \to \tilde{\chi}^0_1 \nu, \ \tilde{\chi}^0_1 \to K^\pm l^\mp$$
  $m_{K^0_{L/S}} - m_{K^\pm} = 4$ MeV $\to$ very small kinematically allowed neutralino mass range ✗
- Two distinct non-vanishing $LQ\bar{D}$ operators: one for the production of a neutralino and the other for its decay ✓
- Throughout this work, we assume that all sfermions have degenerate masses $m_{\tilde{f}}$

Decay Number

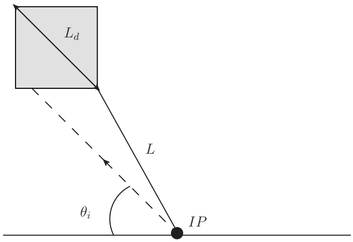
$$N_{\chi}^{\text{prod}} = \sum_{M} N_M \cdot \Gamma(M \to \tilde{\chi}_1^0 + l) \cdot \tau_M$$

$$\langle P[\tilde{\chi}_1^0 \text{ in d.r.}] \rangle = \frac{1}{N_{\tilde{\chi}_1^0}^{\text{MC}}} \sum_{i=1}^{N_{\tilde{\chi}_1^0}^{\text{MC}}} P[(\tilde{\chi}_1^0)_i \text{ in d.r.}]$$

- Use `Pythia 8.205` to perform MC simulation in order to calculate $\langle P[\tilde{\chi}_1^0 \text{ in d.r.}] \rangle$
- Calculate $P[(\tilde{\chi}_1^0)_i \text{ in d.r.}]$ for each detector by geometrical consideration with the exponential decay law

$$N_{\tilde{\chi}_1^0}^{\text{obs}} = N_{\chi}^{\text{prod}} \cdot \langle P[\tilde{\chi}_1^0 \text{ in d.r.}] \rangle \cdot \text{BR}(\tilde{\chi}_1^0 \to \text{char.})$$

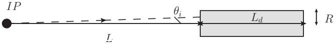
Detectors: CODEX-b



CODEX-b, a Compact Detector for Exotics at LHCb: $10m \times 10m \times 10m$
[arXiv : 1708.09395]

$$P[(\tilde{\chi}_1^0)_i \text{ in d.r.}] = \begin{cases} \frac{0.4}{2\pi} e^{-\frac{L}{\lambda_i}} (1 - e^{-\frac{L_d}{\lambda_i}}), & \eta_i \in [0.2, 0.6], \\ 0, & \text{else,} \end{cases}$$

Detector	$L_d(m)$	$L(m)$	$\phi/2\pi$	η	$\mathcal{L}(fb^{-1})$
CODEX-b	10	25	0.06	[0.2, 0.6]	300



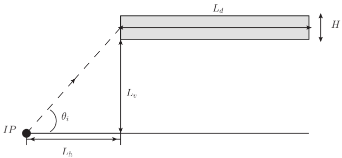
FASER: ForwArd Search ExpeRiment, a cylindrical detector in very forward direction along beam axis
[arXiv : 1708.09389, 1806.02348]

$$P[(\tilde{\chi}_1^0)_i \text{ in d.r.}] = e^{-\frac{L}{\lambda_i^z}}(1 - e^{-\frac{L_i}{\lambda_i^z}}),$$

$$L_i = \begin{cases} 0\,, & \tan\theta_i > \frac{R}{L}\,, \text{misses the decay chamber} \\ L_d\,, & \tan\theta_i < \frac{R}{L+L_d}\,, \text{passes through it} \\ \frac{R}{\tan\theta_i} - L\,, & \text{else, exits through the side.} \end{cases}$$

Detector	$L_d(m)$	$L(m)$	$R(m)$	$\phi/2\pi$	η	$\mathcal{L}(fb^{-1})$
FASER	10	470	1	1	$[6.87, \infty]$	3000

Detectors: MATHUSLA



MATHUSLA: [arXiv : 1606.06298]
MAssive Timing Hodoscope for Ultra Stable neutraL pArticles:
surface detector above the CMS IP:
$200m \times 200m \times 20m$

$$P[(\tilde{\chi}_1^0)_i \text{ in d.r.}] = \frac{1}{4} e^{-\frac{L_i}{\lambda_i^z}} (1 - e^{-\frac{L_i'}{\lambda_i^z}}),$$

$$L_i = \min\left(\max\left(L_h, \frac{L_v}{\tan\theta_i}\right), L_h + L_d\right),$$

$$L_i' = \min\left(\max\left(L_h, \frac{L_v + H}{\tan\theta_i}\right), L_h + L_d\right) - L_i$$

Detector	$L_d(m)$	$L_h(m)$	$L_v(m)$	$H(m)$	$\phi/2\pi$	$\mathcal{L}(fb^{-1})$
MATHUSLA	200	100	100	20	1/4	3000

Benchmark Scenario 1: $\lambda'_{122}, \lambda'_{112}$

Summary of decay topologies

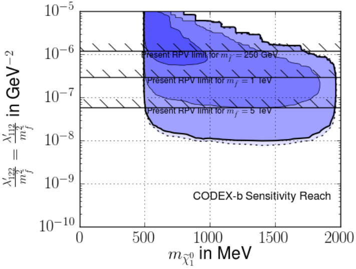
λ'_P for production	λ'_{122}
λ'_D for decay	λ'_{112}
produced meson(s)	D_s
visible final state(s)	$K^\pm e^\mp$, $K^{*\pm} e^\mp$
invisible final state(s) via λ'_P	$(\eta, \eta', \phi) + (\nu_e, \bar{\nu}_e)$
invisible final state(s) via λ'_D	$(K^0_L, K^0_S, K^*) + (\nu_e, \bar{\nu}_e)$

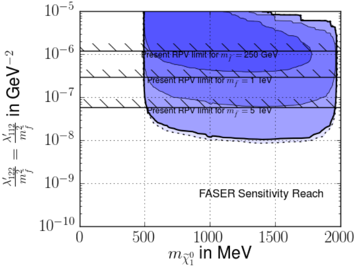
$$\lambda'_{122} : \begin{cases} D_s \to \tilde{\chi}^0_1 + e^\pm \,, & \text{(production)} \\ \tilde{\chi}^0_1 \to (\eta/\eta'/\phi) + \nu_e \,, & \text{(decay via } \lambda'_{122}\text{)} \end{cases}$$

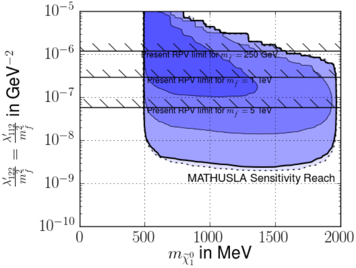
$$\lambda'_{112} : \tilde{\chi}^0_1 \to \begin{cases} K^{(*)\pm} + e^\mp \,, \\ K^0_{S,L} + \nu_e \,. \end{cases} \qquad \text{(decay via } \lambda'_{112}\text{)}$$

Benchmark Scenario 1: $\lambda'_{122}, \lambda'_{112}$

Plots in the plane $\frac{\lambda'_{122}}{m^2_{\tilde{f}}} = \frac{\lambda'_{112}}{m^2_{\tilde{f}}}$ vs. $m_{\tilde{\chi}^0_1}$

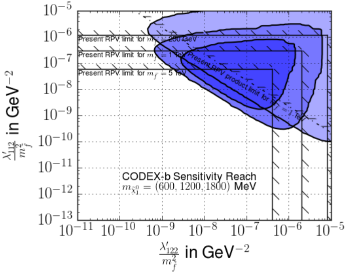


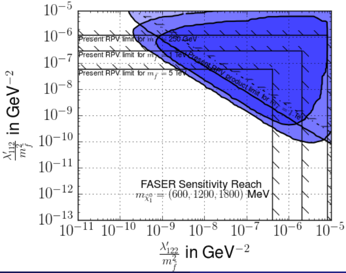


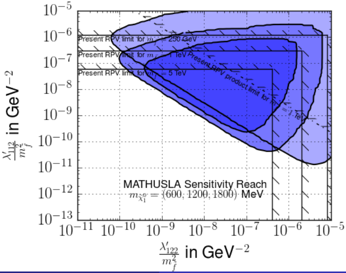


Benchmark Scenario 1: $\lambda'_{122}, \lambda'_{112}$

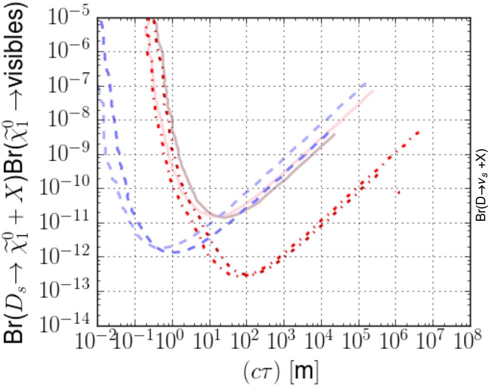
Plots in the plane $\frac{\lambda'_{122}}{m^2_{\tilde{f}}}$ vs. $\frac{\lambda'_{112}}{m^2_{\tilde{f}}}$ for different $m_{\tilde{\chi}^0_1}$ values

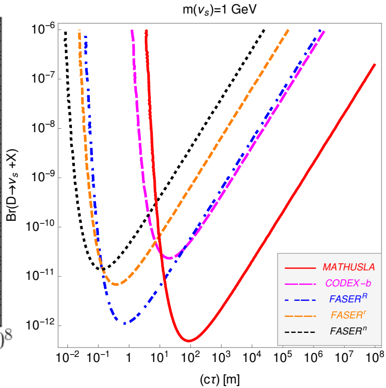






Benchmark Scenario 1: $\lambda'_{122}, \lambda'_{112}$

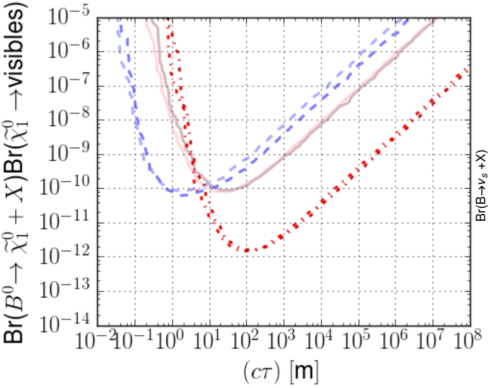


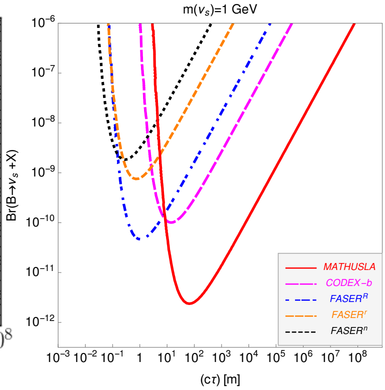


$m_{\tilde{\chi}_1^0} = 600, 1200$ MeV

[arXiv : 1803.02212] with HNLs

Benchmark Scenario 2: $\lambda'_{313}, \lambda'_{312}$

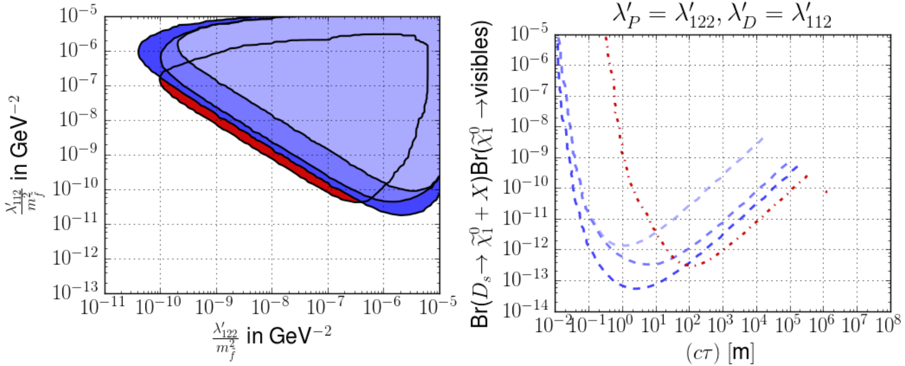




$m_{\tilde{\chi}_1^0} = 2500, 3750$ MeV

[arXiv : 1803.02212] with HNLs

1. L-FASER: $R = 5$m, $L_d = 80$m, sitting at $400 - 480$m ($L = 400$m),
2. R-FASER: $R = 15$m, $L_d = 10$m, sitting at $390 - 400$m ($L = 390$m).



FASER/R-FASER/L-FASER, MATHUSLA

Conclusion

- LHC(LHCb) up to 3000(300)/fb luminosity by 2035. Great discovery potential for LLLPs
- New proposed detectors: `CODEX-b`, `FASER` and `MATHUSLA`
- Example model: $\tilde{\chi}_0^1$ in the RPV-SUSY: $M_1 \to \tilde{\chi}_0^1 + X, \tilde{\chi}_0^1 \to M_2 + l$
  - $\lambda'/m_{\tilde{f}}^2$ reach: `FASER` and `CODEX-b` show very similar sensitivity reach with `MATHUSLA` the strongest
  - BR reach: `FASER` slightly stronger than `CODEX-b` in case of scenarios with D-meson decays. In all cases `MATHUSLA` shows the largest sensitivity reach.
- Masses of the produced meson and the LLP are important for the model independent results. Our results can be applied to a large class of LLP models different from RPV as long as they share similarities to the topologies discussed here
- A longer version of `FASER` may possess greater potential

Thank You!