# Heavy Neutral Fermions at the HL-LHC


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**Abstract**

Long-lived light particles (LLLPs) appear in many extensions of the standard model. LLLPs are usually motivated by the observed small neutrino masses, by dark matter or both. Typical examples for fermionic LLLPs are sterile neutrinos or the lightest neutralino in R-parity violating supersymmetry. The high luminosity LHC is expected to deliver up to 3/ab of data. Searches for LLLPs in dedicated experiments at the LHC could then probe the parameter space of LLLP models with unprecedented sensitivity. Here, we compare the prospects of several recent experimental proposals, FASER, CODEX-b and MATHUSLA, to search for HNFs and discuss their relative merits.

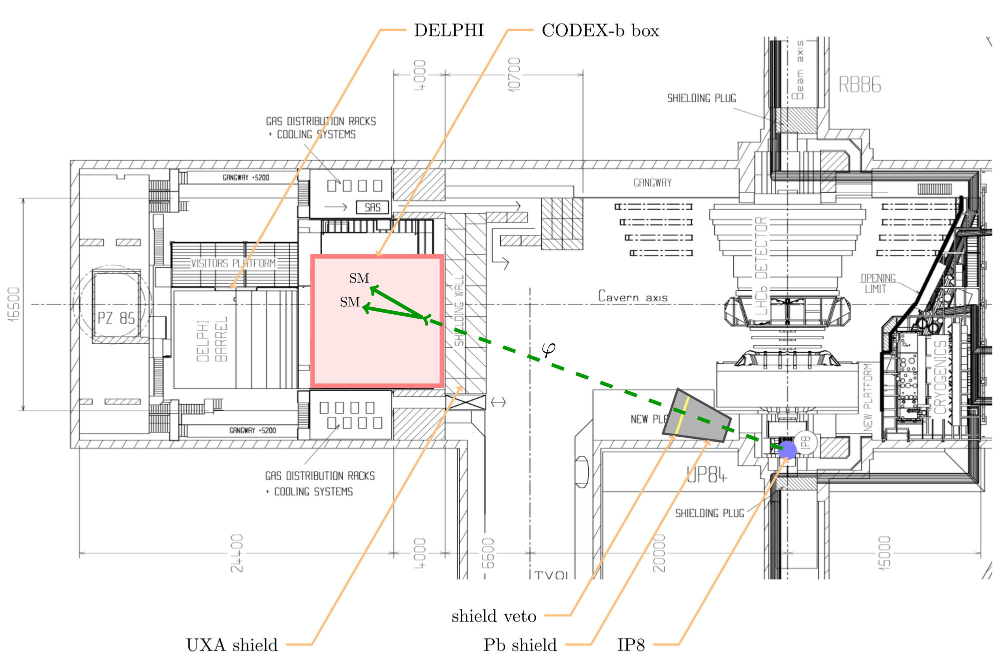

## Introduction

Light long-lived particles (LLLPs) appear in many extensions of the standard model (SM). They can be scalars, fermions, and vector bosons, etc. In particular, fermionic LLLPs are also often called heavy neutral fermions (HNF). On ther other hand, it is expected that the LHC will deliver up to 3000/fb of luminosity over the next 15 - 20 years. Unsurprisingly, there have appeared new proposals to search for LLLPs: MATHUSLA [1], CODEX-b [2] and FASER [3, 4], all based on the idea to exploit LHCs large luminosity. Candidates of HNFs include:

- sterile neutrinos
- $\tilde\chi_1^0$ in the R-parity-violating MSSM (RPV-MSSM)
- $\cdots$

## Future Detectors

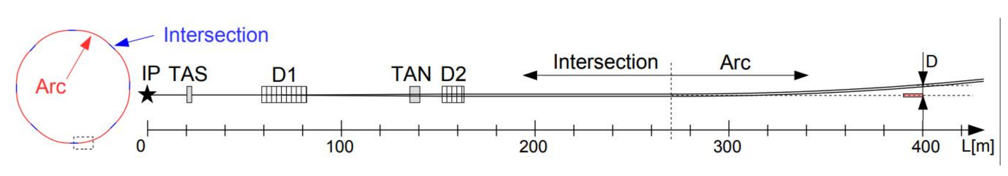
### CODEX-b




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

| | $L_{min}(m)$ | $L_{max}(m)$ | $\phi$ | $\eta$ | $\mathcal{L}(fb^{-1})$ |
|---|---|---|---|---|---|
| CODEX-b | 25 | 35 | 0.4 | [0.2, 0.6] | 300 |

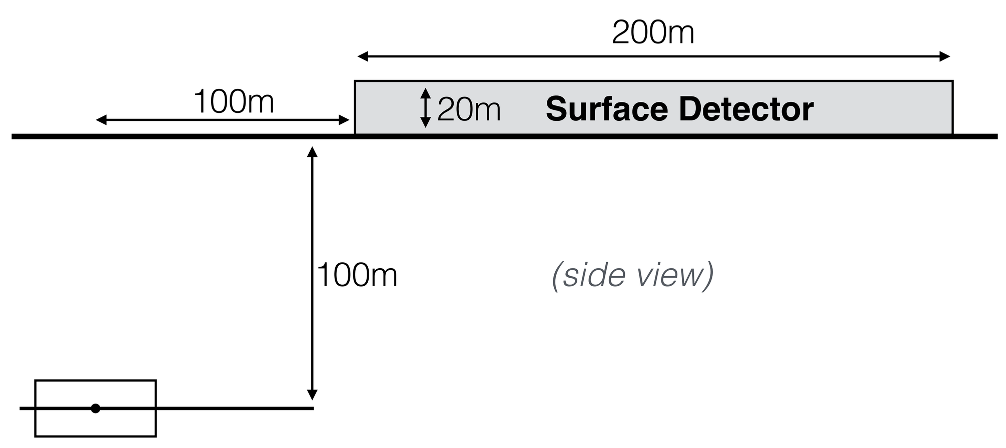
### FASER




FASER: ForwArd Search ExpeRiment, a cylindrical detector in very forward direction along beam axis

| | $L_{min}(m)$ | $L_{max}(m)$ | $\phi$ | $\eta$ | $\mathcal{L}(fb^{-1})$ | $r(m)$ |
|---|---|---|---|---|---|---|
| FASER$^r$ | 390 | 400 | $2\pi$ | [8.3,+∞] | 3000 | 0.2 |
| FASER$^R$ | 390 | 400 | $2\pi$ | [6.68,+∞] | 3000 | 1 |
| FASER$^n$ | 145 | 150 | $2\pi$ | [8.92,+∞] | 3000 | 0.04 |

### MATHUSLA



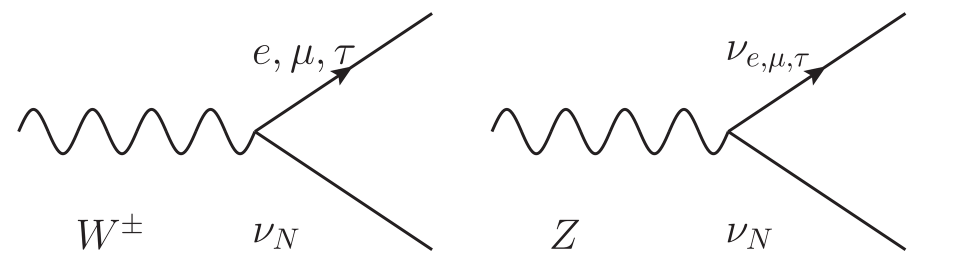

MATHUSLA: MAssive Timing Hodoscope for Ultra Stable neutraL pArticles surface detector above the ATLAS IP: $200m \times 200m \times 20m$

| | $L_{min}(m)$ | $L_{max}(m)$ | $\phi$ | $\eta$ | $\mathcal{L}(fb^{-1})$ |
|---|---|---|---|---|---|
| MATHUSLA | 141 & 269 | 170 & 323 | $\pi/2$ | [0.88, 1.65] | 3000 |

## Models & Simulation

### Type-I Seesaw

$$\mathcal{L} = \frac{g}{\sqrt{2}} V_{\alpha N_j} \bar{l}_\alpha \gamma^\mu P_L \nu_{S_j} W^-_{L\mu} + \frac{g}{2\cos\theta_W} \sum_{\alpha,i,j} V^L_{\alpha i} V^*_{\alpha N_j} \overline{\nu_{S_j}} \gamma^\mu P_L \nu_i Z_\mu$$




- $|V_{\alpha N_j}|^2$ controls **both** production **and** decay of $\nu_S$
- For simplicity, only one of $|V_{eN}|$ & $|V_{\mu N}|$ assumed non-zero
- Production: decays of D- and B-mesons, W, Z and Higgs

### RPV-MSSM

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

- Consider only trilinear lepton number violating (LNV) terms
- LSP: $\tilde\chi_1^0$, decays via RPV couplings
- Trilinear LNV terms $\Rightarrow \Gamma(\chi_1^0 \to ljj) \sim (\lambda^{(\prime)})^2 \frac{m^5_{\chi_1^0}}{m^4_{\tilde f}}$
- Production: $pp \to Z \to \chi_1^0 \chi_1^0$
- Production & decay of neutralinos **not** related by the same parameter
- Experimental upper bound of $\Gamma(Z \to \chi_1^0 \chi_1^0) \lesssim 0.1\,\%$ at $90\,\%$ c.l. from LEP experiment
- Assume only one of $\lambda^{(\prime)} \neq 0$

### Simulation

| Channel | Model & Spectrum | Simulation & Cuts on $\eta$ |
|---|---|---|
| $W, Z, h$ | SARAH4 & SPheno4 | MADGRAPH5 + MadAnalysis5 |
| $D, B$ | PYTHIA8 + $\nu_4$ | |

- $W, Z, h$ generated on-shell & decay
- $D$ and $B$ mesons generated & showering by PYTHIA8

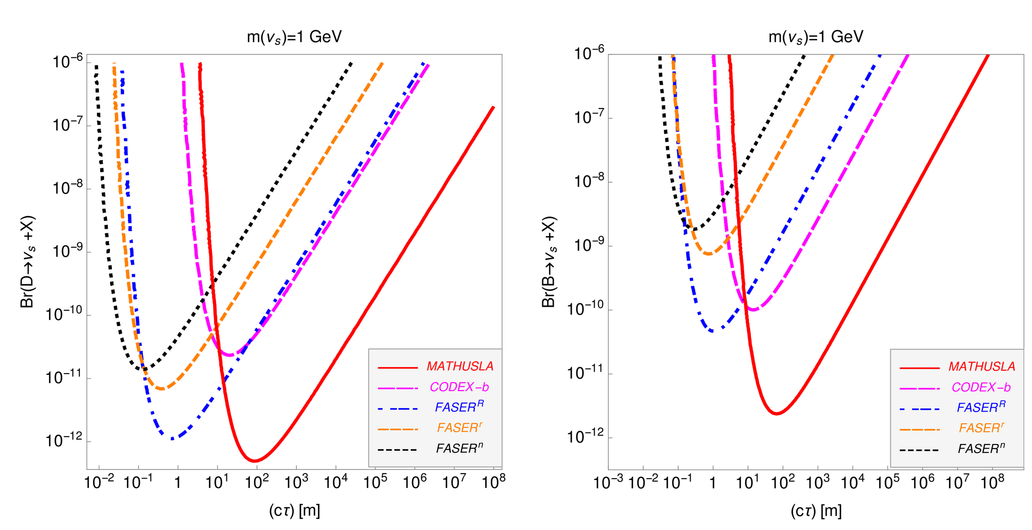
Decay number formula:

$$N_{\rm decay} = N_{\rm total}\, f_{\rm window} \left( e^{[-L_{\rm min}/L_{\rm decay}]} - e^{[-L_{\rm max}/L_{\rm decay}]} \right)$$

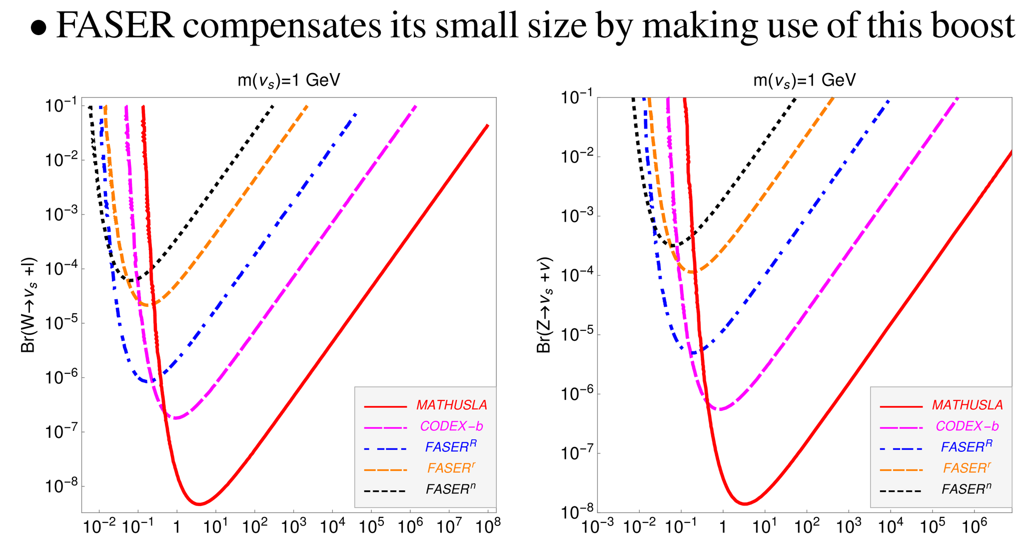
- $L_{\rm decay} = \beta\gamma c\tau$
- $N_{\rm total}$, $f_{\rm window}$ and $\langle \beta \cdot \gamma \rangle$, fitted to functions of the mass of the LLLPs.
- $N_{\rm total}$ normalized from experimental data
- $\Gamma(\nu_S)$: formulas given in [arXiv : 0901.3589]
- $\Gamma(\chi_1^0)$: from SPheno spectrum files

## Results

### Model-Independent Plots



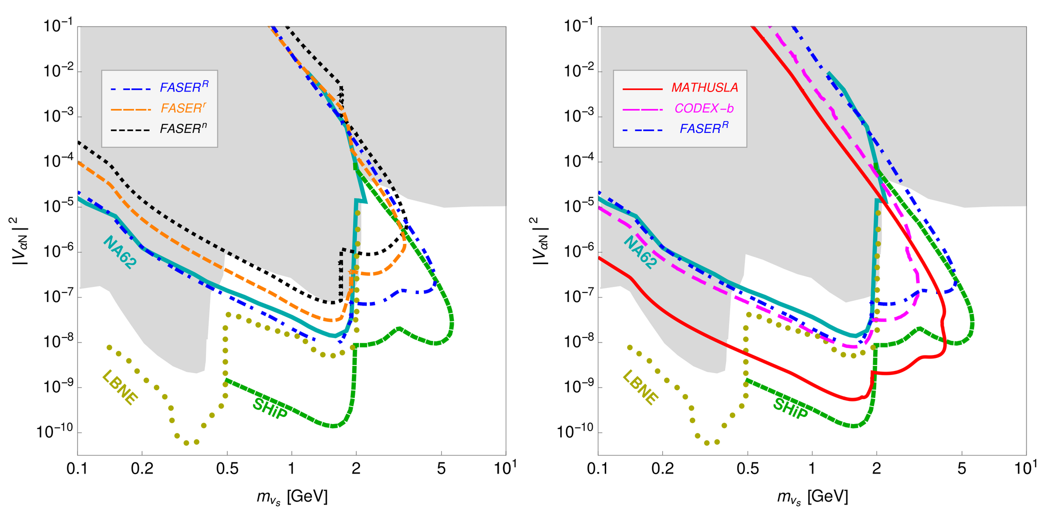

- $D$ & $B$ mesons have large boost in the very forward direction
- FASER compensates its small size by making use of this boost




- $W$ & $Z$ are heavier; no more boost in the forward direction
- CODEX-b outperforms FASER despite its smaller luminosity

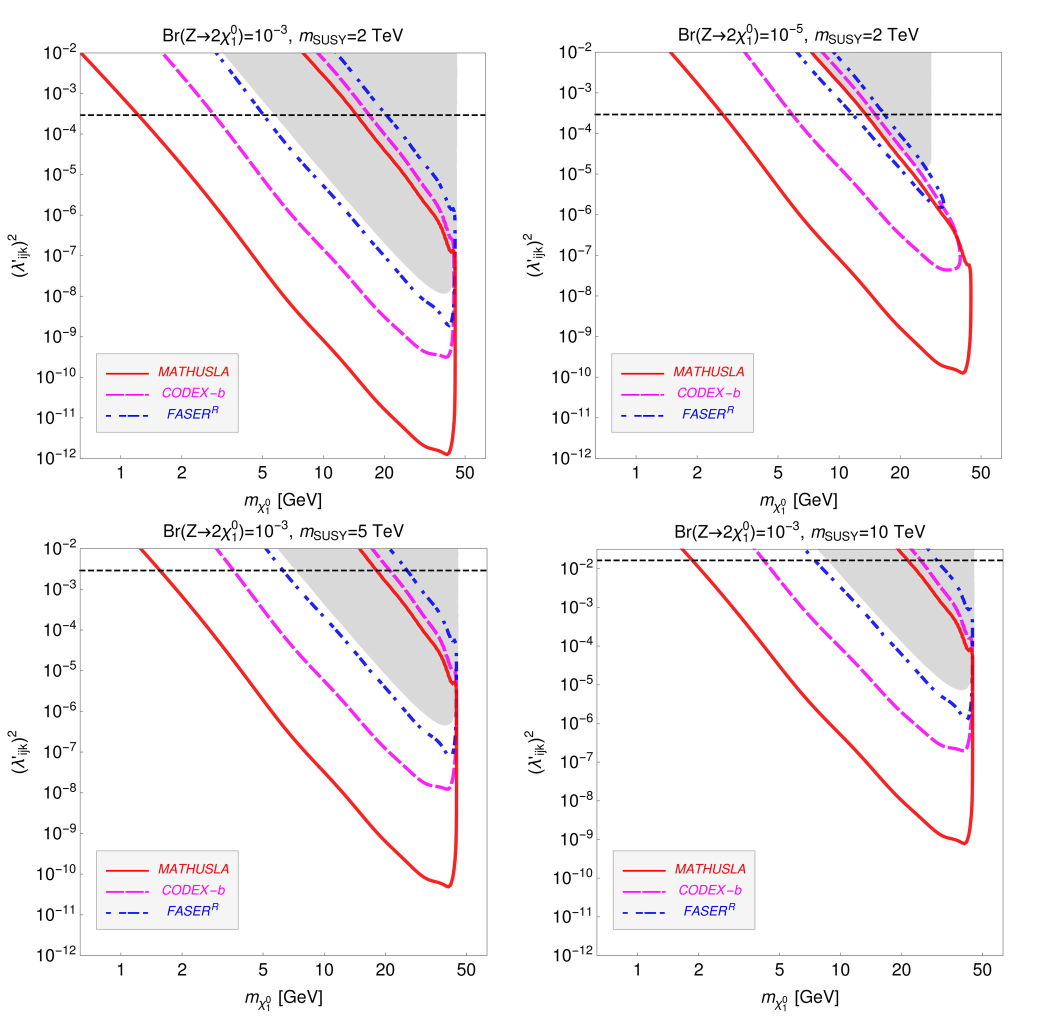
### Model-Dependent Plots

#### Sterile Neutrino




- FASER$^R$ explores more parameter space than FASER$^r$ and FASER$^n$
- CODEX-b similar reach to FASER$^R$
- MATHUSLA better than FASER and CODEX-b, even competent with SHiP

#### The Lightest Neutralino




- Reach $(\lambda_{ijk})^2$ orders of magnitude smaller than the strongest existing upper bound
- Reach mass as large as half $m_Z$

## Conclusions

- LHC(LHCb) up to 3000(300)/fb luminosity by 2035. Great discovery potential for LLLPs
- New proposed detectors: CODEX-b, MATHUSLA and FASER
- Example model I: sterile neutrino
  - FASER$^R$ and CODEX-b show very similar sensitivities,
  - MATHUSLA is more sensitive than both FASER$^R$ and CODEX-b, even competitive with the fixed target experiment SHiP.
- Example model II: the lightest neutralino in the RPV-MSSM
  - FASER$^R$, CODEX-b and MATHUSLA cover interesting parts of the parameter space if the lightest neutralino has a mass in the range of a few GeV up to $m_Z/2$.
- MATHUSLA shows the best sensitivity but has the largest instrumented volume. FASER setups considered so far are quite small, and hence interesting to study.

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## References


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