A long-lived stop with freeze-in and freeze-out dark matter in the hidden sector

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Motivation: Hidden sector dark matter

- Under the assumption of $R$-parity conservation, supersymmetry (SUSY) provides a viable candidate for dark matter: the lightest neutralino (LSP).
- However, it is entirely possible that dark matter (DM) resides in hidden sectors which are ubiquitous in supergravity (SUGRA) and string models.
- We discuss a hidden $U(1)_X$ extension of MSSM/SUGRA model with gauge kinetic and Stueckelberg mass mixings between $U(1)_Y$ and $U(1)_X$.
- If a charged particle of the visible particle has suppressed decay into the hidden sector, it can be stable over detector length leaving a discernible track.
The model

- To the MSSM/SUGRA we add an extra $U(1)_{\chi}$ under which all visible sector particles are neutral.

- The extended model contains two vector superfields: $B$ associated to $U(1)_{\gamma}$ and $C$ associated to $U(1)_{\chi}$ and one chiral scalar superfield $S$.

- The contents of the superfields:

  $$B(B_\mu, \lambda_B, D_B), \quad C(C_\mu, \lambda_C, D_C), \quad S(\rho + i a, \chi, F)$$

- The gauge kinetic energy sector of the model is

  $$\mathcal{L}_{gk} = -\frac{1}{4}(B_{\mu\nu}B^{\mu\nu} + C_{\mu\nu}C^{\mu\nu}) - i\lambda_B\sigma^\mu \partial_\mu \bar{\lambda}_B - i\lambda_C\sigma^\mu \partial_\mu \bar{\lambda}_C + \frac{1}{2}(D_B^2 + D_C^2)$$
We allow gauge kinetic mixing between $U(1)_X$ and $U(1)_Y$

$$-\frac{\delta}{2} B^{\mu \nu} C_{\mu \nu} - i \delta (\lambda_C \sigma^\mu \partial_\mu \bar{\lambda}_B + \lambda_B \sigma^\mu \partial_\mu \bar{\lambda}_C) + \delta D_B D_C$$

We rotate into the diagonal basis using the transformation

$$\begin{pmatrix} B^\mu \\ C^\mu \end{pmatrix} = \begin{pmatrix} 1 & -s_\delta \\ 0 & c_\delta \end{pmatrix} \begin{pmatrix} B'^\mu \\ C'^\mu \end{pmatrix}, \quad \begin{pmatrix} \lambda_Y \\ \lambda_X \end{pmatrix} = \begin{pmatrix} 1 & -s_\delta \\ 0 & c_\delta \end{pmatrix} \begin{pmatrix} \lambda'_Y \\ \lambda'_X \end{pmatrix},$$

where $c_\delta = 1/(1 - \delta^2)^{1/2}$ and $s_\delta = \delta/(1 - \delta^2)^{1/2}$

We also assume a Stueckelberg mass mixing between the $U(1)_X$ and $U(1)_Y$ sectors

$$\mathcal{L}_{St} = \int d\theta^2 d\bar{\theta}^2 (M_1 C + M_2 B + S + \bar{S})^2,$$

with $M_1$ and $M_2$ being input mass parameters.
Neutralino mass matrix

- Written in this basis \((\psi_S, \lambda'_X, \lambda'_Y, \lambda_3, \tilde{h}_1, \tilde{h}_2)\) the mass matrix is:

\[
\begin{pmatrix}
0 & M_1 c_\delta - M_2 s_\delta & m_X c_\delta^2 + m_1 s_\delta^2 - 2 M_{XY} c_\delta s_\delta & \mathbf{M_2} & 0 & 0 & 0 \\
M_1 c_\delta - M_2 s_\delta & m_X c_\delta^2 + m_1 s_\delta^2 - 2 M_{XY} c_\delta s_\delta & -m_1 s_\delta + M_{XY} c_\delta & 0 & s_\delta c_\beta s_W M_Z & -s_\delta s_\beta s_W M_Z \\
M_2 & -m_1 s_\delta + M_{XY} c_\delta & m_1 & 0 & -c_\beta s_W M_Z & s_\beta s_W M_Z \\
0 & 0 & 0 & m_2 & c_\beta c_W M_Z & -s_\beta c_W M_Z \\
0 & s_\delta c_\beta s_W M_Z & -c_\beta s_W M_Z & c_\beta c_W M_Z & 0 & -\mu \\
0 & -s_\delta s_\beta s_W M_Z & s_\beta s_W M_Z & -s_\beta c_W M_Z & -\mu & 0
\end{pmatrix}
\]

- The masses of the hidden sector neutralinos are \((M_2 \ll M_1, \delta \ll 1)\):

\[
m_{\xi_1^0} = \sqrt{M_1^2 + \frac{1}{4} m_X^2} - \frac{1}{2} m_X, \quad \text{and} \quad m_{\xi_2^0} = \sqrt{M_1^2 + \frac{1}{4} m_X^2} + \frac{1}{2} m_X
\]
Scan the parameter space of the model while imposing the Higgs boson mass and relic density constraints

The sparticle spectrum contains as the two lightest particles

1. a neutralino $\tilde{\xi}_1$ from the hidden sector which is the LSP
2. a stop $\tilde{t}$ NLSP from the visible sector such that

$$\tilde{t} \rightarrow \tilde{\xi}_1 t$$  (decays outside the detector)

The hidden and visible sectors communicate via the small gauge kinetic mixing $\delta$ and mass mixing $\propto \epsilon = M_2/M_1$

For a mixing $O(10^{-10})$ or less, $\tilde{\xi}_1$ is a FIMP and the stop decay width is suppressed allowing for very late decays
The input parameters from the hidden sector and the visible sector (MSSM)

A. Aboubrahim, WZ. Feng and P. Nath, arXiv:1910.14092 [hep-ph]

| Model | $m_0$   | $A_0$  | $m_1$ | $m_2$ | $m_3$ | $M_1$ | $m_X$ | $\tan \beta$ | $\delta$       |
|-------|---------|--------|-------|-------|-------|-------|-------|--------------|----------------|
| (a)   | 2632    | -6455  | 3150  | 2100  | 1450  | 1305  | 380   | 20           | $1.02 \times 10^{-11}$ |
| (b)   | 4122    | -7760  | 3363  | 2622  | 1165  | 1400  | 380   | 15           | $1.00 \times 10^{-11}$ |
| (c)   | 2106    | -4366  | 3756  | 2080  | 1263  | 1533  | 380   | 18           | $1.03 \times 10^{-11}$ |
| (d)   | 5042    | -9280  | 4163  | 3044  | 1206  | 1522  | 450   | 10           | $1.10 \times 10^{-11}$ |
| (e)   | 3382    | -7593  | 4046  | 2746  | 1695  | 1720  | 510   | 23           | $8.80 \times 10^{-12}$  |
| (f)   | 4825    | -7565  | 4551  | 3862  | 1097  | 1885  | 805   | 13           | $9.50 \times 10^{-12}$  |
| (g)   | 3851    | -6784  | 4950  | 3277  | 1426  | 1973  | 712   | 25           | $9.00 \times 10^{-12}$  |
| (h)   | 5624    | -9330  | 7532  | 5250  | 1434  | 2105  | 850   | 8            | $1.15 \times 10^{-11}$  |
| (i)   | 6158    | -10265 | 5000  | 4895  | 1303  | 1944  | 586   | 28           | $7.00 \times 10^{-12}$  |
| (j)   | 6638    | -11055 | 6532  | 5200  | 1507  | 2036  | 638   | 5            | $8.50 \times 10^{-12}$  |

**Table:** Input parameters for the benchmarks used in this analysis. Here $M_2 = M_{XY} = 0$ at the GUT scale. All masses are in GeV.
High scale models with DM candidates must satisfy the current DM relic density $\Omega h^2 = 0.1198 \pm 0.0012$.

The relic density of $\tilde{\xi}_1^0$ arises from two contributions: freeze-out of the stop and freeze-in of DM.

Stops annihilate rapidly giving rise to a small relic where the DM relic density from freeze-out can be determined by

$$\left( \Omega h^2 \right)_{FO} = \frac{m_{\tilde{\xi}_1^0}}{m_{\tilde{t}}} \left( \Omega h^2 \right)_{\tilde{t}}^{FO}$$

The slow decay of heavier sparticles to $\tilde{\xi}_1^0$ will constitute the second part of its relic abundance after the latter freezes-in owing to Boltzmann suppression for $m > T$. 

\begin{itemize}
  \item N. Aghanim et al. [Planck Collaboration], arXiv:1807.06209 [astro-ph.CO]
\end{itemize}
The FI relic density from $\tilde{t} \rightarrow \tilde{\xi}_1^0 t$ is:

$$(\Omega h^2)_{FI} \propto \frac{m_{\xi_1^0} \Gamma_{\tilde{t}}}{m_{\tilde{t}}^2}$$

Variation of total relic density w.r.t to the DM mass. For the benchmarks shown, a range of $\tilde{\xi}_1^0$ mass can give the correct relic from FI and FO

DM and stop yields from FI as a function of $x$. Saturation is observed around $x \sim 3–5$
The spectrum has the hidden sector neutralino $\tilde{\chi}_1^0$ as the LSP while the stop is the NLSP of the extended model.

Lifetime of the stop is **less than one second** to avoid disrupting BBN predictions for light nuclei abundance.

Higgs boson mass and relic density constraints are satisfied as well as LHC constraints on sparticle masses.

| Model | $h^0$ | $\mu$ | $\tilde{\chi}_1^0$ | $\tilde{\chi}_1^+ \tilde{\chi}_1^0$ | $\tilde{t}$ | $\tilde{g}$ | $(\Omega h^2)_{\text{FO}}$ | $(\Omega h^2)_{\text{FI}}$ | $\Omega h^2$ | $\tau_0$ |
|-------|-------|-------|---------------------|---------------------------------|---------|---------|-----------------|-----------------|-----------|-------|
| (a)   | 124.2 | 3122  | 1416                | 1759                           | 1129    | 1409    | 3218            | 0.044           | 0.076     | 0.119 | 0.79  |
| (b)   | 125.5 | 3168  | 1529                | 2218                           | 1223    | 1502    | 2709            | 0.046           | 0.070     | 0.116 | 0.81  |
| (c)   | 124.4 | 2324  | 1678                | 1727                           | 1355    | 1618    | 2821            | 0.038           | 0.089     | 0.127 | 0.97  |
| (d)   | 125.6 | 3665  | 1907                | 2587                           | 1314    | 1702    | 2817            | 0.047           | 0.065     | 0.112 | 0.43  |
| (e)   | 125.5 | 3556  | 1836                | 2310                           | 1484    | 1804    | 3737            | 0.065           | 0.059     | 0.124 | 0.91  |
| (f)   | 125.4 | 2763  | 2085                | 2773                           | 1525    | 1903    | 2575            | 0.065           | 0.044     | 0.110 | 0.84  |
| (g)   | 125.8 | 2900  | 2254                | 2737                           | 1649    | 2005    | 3224            | 0.073           | 0.050     | 0.122 | 0.96  |
| (h)   | 125.6 | 3513  | 3461                | 3519                           | 1722    | 2102    | 3284            | 0.081           | 0.040     | 0.121 | 0.92  |
| (i)   | 126.8 | 3444  | 2316                | 3465                           | 1673    | 2201    | 3033            | 0.085           | 0.030     | 0.115 | 0.66  |
| (j)   | 123.7 | 4454  | 3034                | 4360                           | 1742    | 2304    | 3460            | 0.088           | 0.031     | 0.119 | 0.55  |
With a particular choice of $A_0$ at the GUT, the stop trilinear coupling at the EW scale can be large enough to generate a considerable mass splitting between the two stop mass eigenstates

$$M_{\tilde{t}}^2 = \begin{pmatrix}
  m_{\tilde{t}_R}^2 & m_t(A_t - \mu \cot \beta) \\
  m_t(A_t - \mu \cot \beta) & m_{\tilde{t}_L}^2
\end{pmatrix}$$

The lightest of the mass eigenstates is $\tilde{t}$. Stop-antistop production proceeds at the partonic level as

$$gg \rightarrow \tilde{t}\tilde{t}^* \quad \text{(dominant contribution)}$$

$$q\bar{q} \rightarrow \tilde{t}\tilde{t}^*$$

The NLO+NLL $\tilde{t}\tilde{t}^*$ production cross-section is calculated at 14 TeV and 27 TeV
The long-lived $R$-hadron is stable over detector length and will leave a track in the inner detector (ID) tracker and/or in the muon spectrometer (due to charge flipping).

In the detector, an $R$-hadron will look like a slow moving muon (small $\beta_s = p/E$) with large transverse momentum $p_T$.

To avoid dealing with charge-flipping of $R$-hadrons, we focus on information from ID only.

### Pre-selection criteria

1. Events are selected by identifying muons/$R$-hadrons tracks which are central and have large $p_T$, i.e. $|\eta| < 2.4$ rad and $p_T > 150$ GeV

2. An electron veto is applied along with a $Z$ veto.
\( \beta_s \) is peaked closer to one for lighter stops while it shifts for smaller values for heavier stops.

A cut on \( \beta_s \) greater than 0.6 will remove a large part of the signal.

Cuts on \( E_T^{\text{miss}} \) and \( p_T(\mu, R_{\tilde{t}}) \) are applied to signal and background.

**Figure:** Distributions in the velocity \( \beta_s \) of candidate \( R \)-hadrons at 14 TeV for points (a)–(f) (left panel) and 27 TeV for all points (right panel).
Introduction

$U(1)_X$-extended MSSM/SUGRA model

Dark matter relic density

Sparticle spectrum and long-lived stop

Stop pair production at the LHC and signature analysis

Conclusions

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LLPs at HL-LHC and HE-LHC
Projected integrated luminosities for discovery at HL-LHC and HE-LHC

**Figure:** Left panel: the integrated luminosity for discovery of the points (a)–(e) which are discoverable at both HL-LHC and HE-LHC. Right panel: the integrated luminosity for discovery of the points (f)–(j) at HE-LHC.
Conclusions

- We presented a $U(1)_X$ extension of the MSSM/SUGRA with ultra weakly coupled DM particle in the hidden sector.

- Small gauge kinetic and mass mixings make $\tilde{t}$ a long-lived particle with late decay to the hidden sector neutralino $\tilde{\xi}^0_1$.

- The DM relic density arises from freeze-out and freeze-in (due to the feebleness of $\tilde{\xi}^0_1$) contributions.

- The charged stop will leave a track in the ID after it hadronizes into a composite particle known as an $R$-hadron.

- We show that half of the benchmarks considered can be discovered at the HL-LHC while all of them are within reach of the HE-LHC.
BACKUP SLIDES
The prototype Stueckelberg Lagrangian couples one abelian vector boson $A_\mu$ to one pseudo-scalar $\sigma$ in the following way

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} (mA_\mu + \partial_\mu \sigma)(mA^\mu + \partial^\mu \sigma)$$

which is gauge invariant if $\sigma$ transforms together with $A_\mu$ according to

$$\delta A_\mu = \partial_\mu \epsilon, \quad \delta \sigma = -m \epsilon$$

Add a gauge fixing term $\mathcal{L}_{gf} = -\frac{1}{2\xi} (\partial_\mu A^\mu + \xi m \sigma)^2$ so that the total Lagrangian reads

$$\mathcal{L} + \mathcal{L}_{\text{int}} + \mathcal{L}_{gf} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{m^2}{2} A_\mu A^\mu - \frac{1}{2\xi} (\partial_\mu A^\mu)^2$$

$$-\frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \xi \frac{m^2}{2} \sigma^2 + g J_\mu A^\mu$$
We assume a Stueckelberg mass mixing between the $U(1)_X$ and $U(1)_Y$ sectors so that

$$\mathcal{L}_{\text{St}} = \int d\theta^2 d\bar{\theta}^2 (M_1 C + M_2 B + S + \bar{S})^2$$

We note that $\mathcal{L}_{\text{St}}$ is invariant under $U(1)_Y$ and $U(1)_X$ gauge transformation so that,

$$\delta_Y B = \Lambda_Y + \bar{\Lambda}_Y, \hspace{1cm} \delta_Y S = -M_2 \Lambda_Y,$$

$$\delta_X C = \Lambda_X + \bar{\Lambda}_X, \hspace{1cm} \delta_X S = -M_1 \Lambda_X$$

In component notation, $\mathcal{L}_{\text{St}}$ is

$$\mathcal{L}_{\text{St}} = -\frac{1}{2} (M_1 C_\mu + M_2 B_\mu + \partial_\mu a)^2 - \frac{1}{2} (\partial_\mu \rho)^2 - i \chi \sigma^\mu \partial_\mu \bar{\chi} + 2 |F|^2$$

$$+ \rho (M_1 D_C + M_2 D_B) + \bar{\chi} (M_1 \bar{\lambda}_C + M_2 \bar{\lambda}_B) + \chi (M_1 \lambda_C + M_2 \lambda_B)$$
We introduce the Majorana spinors, $\psi_S$, $\lambda_X$ and $\lambda_Y$ so that

$$\psi_S = \left( \chi_\alpha \bar{\chi}_{\dot{\alpha}} \right), \quad \lambda_X = \left( \frac{\lambda_C \alpha}{\lambda_{\dot{\alpha}} C} \right), \quad \lambda_Y = \left( \frac{\lambda_B \alpha}{\lambda_{\dot{\alpha}} B} \right)$$

In addition to the above we add a soft SUSY breaking term to the Lagrangian so that

$$\Delta \mathcal{L}_{\text{soft}} = -\left( \frac{1}{2} m_X \bar{\lambda}_X \lambda_X + M_{XY} \bar{\lambda}_X \lambda_Y \right) - \frac{1}{2} m_{\rho}^2 \rho^2,$$

where $m_X$ is mass of the $U(1)_X$ gaugino and $M_{XY}$ is the $U(1)_X$-$U(1)_Y$ mixing mass.

In the unitary gauge, the axion field $a$ is absorbed to generate mass for the $U(1)_X$ gauge boson so that $M_{Z^{'}} \sim M_1$.
After spontaneous electroweak symmetry breaking and the Stueckelberg mass growth the $3 \times 3$ mass squared matrix of neutral vector bosons in the basis ($C_\mu', B_\mu', A_3^\mu$) is given by

$$
\mathcal{M}_V^2 = \begin{pmatrix}
M_1^2 \kappa^2 + \frac{1}{4} g_Y^2 v^2 s_\delta^2 & M_1 M_2 \kappa - \frac{1}{4} g_Y^2 v^2 s_\delta & \frac{1}{4} g_Y g_2 v^2 s_\delta \\
M_1 M_2 \kappa - \frac{1}{4} g_Y^2 v^2 s_\delta & M_2^2 + \frac{1}{4} g_Y^2 v^2 & -\frac{1}{4} g_Y g_2 v^2 \\
\frac{1}{4} g_Y g_2 v^2 s_\delta & -\frac{1}{4} g_Y g_2 v^2 & \frac{1}{4} g_2^2 v^2
\end{pmatrix}
$$

The $Z$ boson mass receives a correction due to gauge kinetic and mass mixings. Knowing that $M_2 \ll M_1$ and $s_\delta \ll 1$, we can write $M_\bot^2$ as

$$
M_\bot^2 \simeq M_Z^2 + \frac{\epsilon}{2} g_Y^2 v^2 \frac{s_\delta}{c_\delta} + \frac{1}{4} g_2^2 v^2 \left( \frac{\epsilon}{\kappa} \right)^2
$$
The 27 TeV collider: HE-LHC

- The High Energy LHC (HE-LHC) is a possible candidate as the next generation $pp$ collider at CERN

- Uses the existing LHC ring with 16 T FCC magnets replacing the current 8.3 T ones

- Center-of-mass energy boosted to 27 TeV with a design luminosity $\sim 5$ times that of the HL-LHC

- This set up necessarily means that a larger part of the parameter space of supersymmetric models beyond the reach of the 14 TeV collider will be probed
Stop pair production cross-sections

| Model | $\sigma_{NLO+NLL}(pp \rightarrow \tilde{t} \tilde{t}^*)$ | $\sigma_{LO}(pp \rightarrow \tilde{t} \tilde{t})$ |
|-------|---------------------------------|---------------------------------|
|       | 14 TeV  | 27 TeV  | 14 TeV  | 27 TeV  |
| (a)   | 0.654   | 13.5    | 0.092   | 1.190   |
| (b)   | 0.387   | 9.03    | 0.060   | 0.840   |
| (c)   | 0.197   | 5.56    | 0.033   | 0.550   |
| (d)   | 0.129   | 4.00    | 0.021   | 0.412   |
| (e)   | 0.075   | 2.69    | 0.013   | 0.290   |
| (f)   | 0.046   | 1.89    | 0.008   | 0.214   |
| (g)   | 0.029   | 1.29    | 0.005   | 0.155   |
| (h)   | 0.018   | 0.92    | 0.003   | 0.115   |
| (i)   | 0.011   | 0.66    | 0.002   | 0.085   |
| (j)   | 0.006   | 0.47    | 0.001   | 0.063   |
The input parameters of the $U(1)_X$-extended MSSM/SUGRA are of the usual non-universal SUGRA model with additional parameters as below (all at the GUT scale)

$$m_0, A_0, m_1, m_2, m_3, [M_1, m_X, \delta, \tan \beta, \text{sgn}(\mu)]$$

The parameter $M_2$ is set to zero at the GUT scale. However, it does develop a small value at the EW scale due to RGE running.

Scan the parameter space of the model while imposing the Higgs boson mass and relic density constraints.

The LSP of the model is the lightest neutralino of the hidden sector, $\tilde{\xi}^0_1$

The NLSP is the stop of the visible sector such that

$$\tilde{t} \rightarrow \tilde{\xi}^0_1 t$$
The hidden sector LSP, $\tilde{\xi}_1$, is an admixture of the $U(1)_X$ gaugino $\lambda_X$, the Majorana spinor $\psi_S$, and the visible sector (MSSM) binos, winos and higgsinos, i.e.

$$\tilde{\xi}_1 = N_{11}\psi_S + N_{12}\lambda_X + N_{13}\lambda_Y + N_{14}\lambda_3 + N_{15}\tilde{h}_1 + N_{16}\tilde{h}_2$$

The $Z$ boson mass receives a correction due to gauge kinetic and mass mixings

$$\simeq M_Z^2 + \frac{\epsilon}{2} g_Y^2 v^2 \frac{s_\delta}{c_\delta} + \frac{1}{4} g_2^2 v^2 \left( \frac{\epsilon}{\kappa} \right)^2$$
One of the reactions contributing to dark matter production via FI is $\tilde{t} \rightarrow \tilde{\xi}^0_1 t$ with a yield

$$Y_{\tilde{\xi}^0_1} = \frac{g_{\tilde{t}}}{2\pi^2} \Gamma_{\tilde{t}} m_{\tilde{t}}^2 \int_{T_0}^{T_R} \frac{dT}{H'(T)s(T)} H_1'(x_{\tilde{t}}, x_{\tilde{\xi}^0_1}, x_t, 1, 0, -1)$$

The FI relic density is then determined by

$$\left(\Omega h^2\right)_{FI} = \frac{m_{\tilde{\xi}^0_1} Y_{\tilde{\xi}^0_1} s_0 h^2}{\rho_c} \propto \frac{m_{\tilde{\xi}^0_1} \Gamma_{\tilde{t}}}{m_{\tilde{t}}^2}$$

The total relic density is

$$\Omega h^2 = (\Omega h^2)_{FO} + (\Omega h^2)_{FI}$$
In our model, the mass gap $\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$ need not be small.

Long-lived stops hadronize forming bound states known as $R$-hadrons with 93% of them being $R$-mesons.

With an increasing stop mass, an inversion in the relative contribution to $\Omega h^2$ from FI and FO is seen.

In realistic models, freeze-in alone is not enough to explain the relic abundance and freeze-out always factors in.
Selection criteria

- Main jet activity in the signal comes from ISR and FSR
- Large missing transverse energy $E_T^{\text{miss}}$ arises due to ISR boosting the $R$-hadron system thus creating a momentum imbalance
- $\beta_s$ of a muon/$R$-hadron must be greater than 0.6 so that an $R$-hadron can be associated with the same bunch crossing and pass the trigger requirement

| Requirement                              | “ID-only” SR |
|------------------------------------------|--------------|
|                                          | 14 TeV       | 27 TeV       |
|                                          | SR-A | SR-B | SR-A | SR-B |
| $N(\text{muons}/R$-hadrons)              | $\geq 1$ | $\geq 1$ | $\geq 1$ | $\geq 1$ |
| $Z$-veto                                 | ✓    | ✓    | ✓    | ✓    |
| $|\eta|$ (rad) $<$                         | 2.4  | 2.4  | 2.4  | 2.4  |
| $E_T^{\text{miss}}$ (GeV) $>$            | 90   | 90   | 120  | 120  |
| $\Delta R(\text{track}, \text{jet}_1)$ (rad) $>$ | 0.4  | 0.4  | 0.6  | 0.6  |
| $\beta_s$ $>$                             | 0.6  | 0.6  | 0.6  | 0.6  |
| $\beta_s$ $<$                             | 0.9  | 0.9  | 0.9  | 0.9  |
| $p_T(\mu, R_\tilde{t})$ (GeV) $>$        | 500  | 600  | 600  | 1200 |
### Estimated integrated luminosities at HL-LHC and HE-LHC

| Model | $\mathcal{L}$ at 14 TeV | $\mathcal{L}$ at 27 TeV |
|-------|--------------------------|-------------------------|
|       | SR-A  | SR-B  | SR-A  | SR-B  |
| (a)   | 259   | 226   | 20    | 21    |
| (b)   | 527   | 396   | 37    | 27    |
| (c)   | 1309  | 756   | 85    | 41    |
| (d)   | 2767  | 1226  | 150   | 55    |
| (e)   | …     | 2128  | 308   | 81    |
| (f)   | …     | 3667  | 591   | 119   |
| (g)   | …     | …     | 1258  | 189   |
| (h)   | …     | …     | 2387  | 285   |
| (i)   | …     | …     | 4831  | 461   |
| (j)   | …     | …     | 9922  | 791   |

Comparison between the estimated integrated luminosity ($\mathcal{L}$) for a $5\sigma$ discovery at 14 TeV (middle column) and 27 TeV (right column) for a stop $R$-hadron following the selection cuts, where the minimum integrated luminosity needed for a $5\sigma$ discovery is given in fb$^{-1}$. Entries with ellipses mean that the evaluated $\mathcal{L}$ is much greater than 3000 fb$^{-1}$.