Detecting hidden sector dark matter at HL-LHC and HE-LHC via long-lived stau decays

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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, a displaced track signature at the LHC can be detected
The model

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

- The extended model contains two vector superfields: $B$ associated to $U(1)_Y$ and $C$ associated to $U(1)_X$ and one chiral scalar superfield $S$.

- The contents of the superfields

  \[ B(B_{\mu}, \lambda_B, D_B), \quad C(C_{\mu}, \lambda_C, D_C), \quad S(\rho + ia, \chi, F) \]

- 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

$$\begin{pmatrix} B^\mu \\ C^\mu \end{pmatrix} = \begin{pmatrix} 1 & -s_\delta \\ 0 & c_\delta \end{pmatrix} \begin{pmatrix} B'^\mu \\ C'^\mu \end{pmatrix},$$

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

We 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

- Rotate \((\psi_S, \lambda_X, \lambda_Y, \lambda_3, \tilde{h}_1, \tilde{h}_2) \longrightarrow (\psi_S, \lambda'_X, \lambda'_Y, \lambda_3, \tilde{h}_1, \tilde{h}_2)\) so that

\[
\begin{pmatrix}
0 & M_1c_\delta - M_2s_\delta & 0 & 0 & 0 \\
M_1c_\delta - M_2s_\delta & M_Xc_\delta^2 + m_1s_\delta^2 - 2M_XYc_\delta s_\delta & -m_1s_\delta + M_XYc_\delta & 0 & 0 \\
M_2 & M_2 & M_2 & M_2 & M_2 \\
0 & 0 & 0 & 0 & 0 \\
0 & s_\delta c_\beta s_W M_Z & -c_\beta s_W M_Z & c_\beta c_W M_Z & 0 \\
0 & -s_\delta s_\beta s_W M_Z & s_\beta s_W M_Z & -s_\beta c_W M_Z & -\mu
\end{pmatrix},
\]

where \(s_\beta \equiv \sin \beta, \ c_\beta \equiv \cos \beta, \ s_W \equiv \sin \theta_W, \ c_W \equiv \cos \theta_W\) with \(M_Z\) being the \(Z\) boson mass. We label the mass eigenstates as

\[\tilde{\xi}_1^0, \tilde{\xi}_2^0; \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0\]

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

\[
m_{\tilde{\xi}_1^0} = \sqrt{M_1^2 + \frac{1}{4}m_X^2 - \frac{1}{2}m_X}, \quad \text{and} \quad m_{\tilde{\xi}_2^0} = \sqrt{M_1^2 + \frac{1}{4}m_X^2 + \frac{1}{2}m_X}.
\]
• 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 $\tilde{\xi}_1^0$ from the hidden sector which is the LSP
  2. a stau $\tilde{\tau}$ NLSP from the visible sector such that

$$
\tilde{\tau} \longrightarrow \tilde{\xi}_1^0 \tau
$$

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

• The stau decay width is small due to phase space suppression, $(m_{\tilde{\tau}} - m_{\tilde{\xi}_1^0}) \ll m_{\tilde{\xi}_1^0}$, and small mixing between the two sectors
The input parameters from the hidden sector and the visible sector (MSSM)


<table>
<thead>
<tr>
<th>Model</th>
<th>$m_0$</th>
<th>$A_0$</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$m_3$</th>
<th>$M_1$</th>
<th>$m_X$</th>
<th>$\tan\beta$</th>
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<td>473</td>
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<td>$2.0 \times 10^{-5}$</td>
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<tr>
<td>(b)</td>
<td>546</td>
<td>-3733</td>
<td>828</td>
<td>761</td>
<td>3657</td>
<td>426</td>
<td>392</td>
<td>16</td>
<td>$4.7 \times 10^{-6}$</td>
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<tr>
<td>(c)</td>
<td>529</td>
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<td>864</td>
<td>482</td>
<td>3777</td>
<td>461</td>
<td>400</td>
<td>15</td>
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<tr>
<td>(d)</td>
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<td>1166</td>
<td>806</td>
<td>3945</td>
<td>503</td>
<td>198</td>
<td>15</td>
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<tr>
<td>(e)</td>
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<td>-1850</td>
<td>1214</td>
<td>598</td>
<td>3856</td>
<td>579</td>
<td>380</td>
<td>21</td>
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<tr>
<td>(f)</td>
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<td>893</td>
<td>4165</td>
<td>523</td>
<td>65</td>
<td>15</td>
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<td>1451</td>
<td>1265</td>
<td>4830</td>
<td>682</td>
<td>258</td>
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<td>$1.4 \times 10^{-6}$</td>
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<tr>
<td>(h)</td>
<td>645</td>
<td>1009</td>
<td>1621</td>
<td>1160</td>
<td>5374</td>
<td>714</td>
<td>100</td>
<td>26</td>
<td>$1.3 \times 10^{-6}$</td>
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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.
The extended MSSM/SUGRA sparticle spectrum

<table>
<thead>
<tr>
<th>Model</th>
<th>$h^0$</th>
<th>$\mu$</th>
<th>$\tilde{\chi}_1^0$</th>
<th>$\tilde{\chi}_1^\pm$</th>
<th>$\tilde{\tau}$</th>
<th>$\tilde{\nu}_\tau$</th>
<th>$\tilde{\xi}_1^0$</th>
<th>$\tilde{t}$</th>
<th>$\tilde{g}$</th>
<th>$\Omega h^2$</th>
<th>$c\tau_0$</th>
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<tr>
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<td>(b)</td>
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<td>4417</td>
<td>343.3</td>
<td>595.2</td>
<td>291.0</td>
<td>572.4</td>
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<td>7372</td>
<td>0.123</td>
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<td>(c)</td>
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<td>350.5</td>
<td>319.3</td>
<td>459.8</td>
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<td>7621</td>
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<td>147.0</td>
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<td>570.6</td>
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<td>7764</td>
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<tr>
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<td>4669</td>
<td>546.0</td>
<td>699.7</td>
<td>500.0</td>
<td>653.6</td>
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<td>8326</td>
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<tr>
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<td>4852</td>
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<td>864.7</td>
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<tr>
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<td>680.8</td>
<td>877.3</td>
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<td>7816</td>
<td>10572</td>
<td>0.120</td>
<td>561.3</td>
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Table: Display of the Higgs boson ($h^0$) mass, the $\mu$ parameter, the stau mass, the relevant electroweak gaugino masses, and the relic density for the benchmarks computed at the electroweak scale. The track length, $c\tau_0$ (in mm) left by the long-lived stau is also shown. All masses are in GeV.
High scale models with DM candidates must satisfy the current DM relic density $\Omega h^2 = 0.1198 \pm 0.0012$.

Including coannihilation, one can have three processes responsible for the observed relic density of $\tilde{\xi}_1^0$, namely,

- $\tilde{\xi}_1^0 \tilde{\xi}_1^0 \rightarrow \text{SM}$, (negligible)
- $\tilde{\xi}_1^0 \tilde{\tau} \rightarrow \text{SM}'$, (negligible)
- $\tilde{\tau} \tilde{\tau} \rightarrow \text{SM}''$. (dominant)

$\tilde{\xi}_1^0$ possesses very weak couplings with SM particles making it in a category between WIMPs and FIMPs.

If $\Gamma_{\tilde{\tau}} > H(T)$ then $\tilde{\tau} \leftrightarrow \tilde{\xi}_1^0 \tau$ followed by coannihilation sets the relic abundance.
• Stau pair production proceeds via $\gamma$, $Z$ and $Z'$ s-channel processes, i.e. $q\bar{q} \rightarrow \gamma, Z, Z' \rightarrow \tilde{\tau}^+\tilde{\tau}^-$

• The end products of the decay chain and the relevant final states are

\[
pp \rightarrow \tilde{\tau}^+\tilde{\tau}^- \rightarrow \tau^+\tau^- \tilde{\xi}_1^0\tilde{\xi}_1^0 \rightarrow \tau_h, \ell + E_T^{\text{miss}}, \\
pp \rightarrow \tilde{\tau}^\pm\tilde{\nu}_\tau \rightarrow \tau^\pm \tilde{\xi}_1^0\tau^\pm W^\mp \rightarrow \tau_h, 2\ell + E_T^{\text{miss}}
\]
Since our stau is long-lived, it will leave a track in the inner detector (ID) tracker characterized by **low speed and large invariant mass**.

Since the lepton track is soft (of low $p_T$), the combination of the stau and lepton tracks constitute what is known as a **kinked track**.

Lepton tracks are highly displaced with large impact parameter $d_0$. 

![Diagram of kinked track](image-url)
The kinematic variables used for discriminating the signal from the background

\[ |d_0|, \ p_T^e [\mu], \ p_T^{\text{tracks}}, \ \Delta R(\tilde{\tau}, \text{track}), \ \beta = p/E, \ d_{xy} \]

**Figure:** Left panel: Minimum spatial separation between the stau LLP and its closest lepton track, $\Delta R(\tilde{\tau}, \text{track})$. Right panel: the track length $d_{xy}$, of the long-lived stau.
- Pile-up events (interactions per bunch crossing) are added to the main interaction
- Pile-up mitigation is handled by PUPPI

**Figure:** A comparison between the number of leptonic tracks for the cases of no pile-up (NoPU) and pile-up (PU) at 14 TeV and at 27 TeV for point (a).
Results: predicted number of events at HL-LHC and HE-LHC

Figure: Left panel: Estimated number of events for various integrated luminosities for benchmarks (a), (b), (c) and (e) in cases of no pile-up (solid lines) and pile-up (dashed lines) at HL-LHC. Right panel: same as the left panel but for HE-LHC for all the benchmarks.
Conclusions

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

- The LSP is the lightest neutralino of the hidden sector and the NLSP is the MSSM $\tilde{\tau}$ with $\tilde{\tau} \rightarrow \tilde{\xi}_1 \tau$

- Phase space suppression and small $\delta, \epsilon$ makes $\tilde{\tau}$ a long-lived particle.

- The charged stau will leave a track in the ID before decaying into the hidden sector dark matter.

- We show that half of the eight benchmark points considered can be discovered at the HL-LHC while all of those points are within reach of the HE-LHC.
Introduction
$U(1)_X$-extended MSSM/SUGRA model
Dark matter relic density
$\tilde{\tau} \tilde{\tau}$ and $\tilde{\tau} \tilde{\nu}_\tau$ production at the LHC and signature analysis
Conclusions

BACKUP SLIDES
The prototype Stueckelberg Lagrangian couples one abelian vector boson $A_\mu$ to one pseudo-scalar $\sigma$ in the following way

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

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

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

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

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

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

$$\delta_Y B = \Lambda_Y + \bar{\Lambda}_Y, \quad \delta_Y S = -M_2 \Lambda_Y,$$
$$\delta_X C = \Lambda_X + \bar{\Lambda}_X, \quad \delta_X S = -M_1 \Lambda_X$$

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

$$\mathcal{L}_{St} = -\frac{1}{2} (M_1 C_\mu + M_2 B_\mu + \partial_\mu a)^2 - \frac{1}{2} (\partial_\mu \rho)^2 - i \chi \sigma^\mu \partial_\mu \bar{\chi} + 2 |F|^2$$
$$+ \rho (M_1 D_C + M_2 D_B) + \bar{\chi} (M_1 \bar{\lambda}_C + M_2 \bar{\lambda}_B) + \chi (M_1 \lambda_C + M_2 \lambda_B)$$

In unitary gauge the axion field $a$ is absorbed to generate mass for the $U(1)_X$ gauge boson
We introduce the Majorana spinors, $\psi_S$, $\lambda_X$ and $\lambda_Y$ so that

$$\psi_S = \left( \begin{array}{c} \chi_\alpha \\ \bar{\chi}_{\dot{\alpha}} \end{array} \right), \quad \lambda_X = \left( \begin{array}{c} \lambda_{C,\alpha} \\ \bar{\lambda}_{\dot{C},\dot{\alpha}} \end{array} \right), \quad \lambda_Y = \left( \begin{array}{c} \lambda_{B,\alpha} \\ \bar{\lambda}_{\dot{B},\dot{\alpha}} \end{array} \right)$$

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 $M_2^2$ as

$$
M_2^2 \simeq M_Z^2 + \frac{\epsilon}{2} g_Y^2 v^2 \frac{s_\delta}{c_\delta} + \frac{1}{4} g_2^2 v^2 \left(\frac{\epsilon}{\kappa}\right)^2
$$
For fast decay and inverse decay of $\tilde{\tau}$ (which sets the chemical equilibrium between $\tilde{\xi}_0^1$ and $\tilde{\tau}$), co-scattering processes do not contribute to the relic density and the latter is merely determined by coannihilation (i.e. by $\tilde{\tau}$ self-annihilation)

When the decay width of $\tilde{\tau}$ falls below the Hubble parameter around freeze-out, coannihilation and co-scattering freeze-out will determine the final relic abundance:

1. If $T_f^{\text{coannihilation}} > T_f^{\text{co-scattering}}$ then coannihilation freezes-out earlier and $n_{\tilde{\xi}_0^1}$ and $n_{\tilde{\tau}}$ is fixed
2. If $T_f^{\text{co-scattering}} > T_f^{\text{coannihilation}}$ then conversion $\tilde{\xi}_0^1 \leftrightarrow \tilde{\tau}$ stops and NLSPs are removed by self-annihilation (relic density is set by co-scattering)

Proton-neutralino scattering cross-sections are far too small to be measured at direct detection experiments
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
### NLO cross-sections

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<tr>
<th>Model</th>
<th>$\sigma_{\text{NLO}}(pp \rightarrow \tilde{\tau}^+ \tilde{\tau}^-)$</th>
<th>$\sigma_{\text{NLO}}(pp \rightarrow \tilde{\tau}^+ \tilde{\nu}_\tau)$</th>
<th>$\sigma_{\text{NLO}}(pp \rightarrow \tilde{\tau}^- \tilde{\nu}_\tau^*)$</th>
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<td></td>
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<td>27 TeV</td>
<td>14 TeV</td>
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<td>2.03</td>
<td>6.17</td>
<td>0.48</td>
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<tr>
<td>(c)</td>
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<td>5.53</td>
<td>1.94</td>
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<td>(d)</td>
<td>0.41</td>
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<td>0.17</td>
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<td>(e)</td>
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<tr>
<td>(f)</td>
<td>0.21</td>
<td>0.85</td>
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<td>(g)</td>
<td>0.10</td>
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<tr>
<td>(h)</td>
<td>0.04</td>
<td>0.25</td>
<td>0.06</td>
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**Table:** The NLO production cross-sections, in fb, of a stau pair, $\tilde{\tau}^+ \tilde{\tau}^-$ (second and third columns), and $\tilde{\tau} \tilde{\nu}_\tau$ (fourth, fifth, sixth and seventh columns), at $\sqrt{s} = 14$ TeV and at $\sqrt{s} = 27$ TeV for all benchmarks.
Cut-flow analysis: 14 TeV, no pile-up

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<th>Cuts</th>
<th>(a)</th>
<th>(c)</th>
<th>(f)</th>
<th>(t\bar{t})</th>
<th>(t+jets)</th>
<th>(W/Z/\gamma^* + jets)</th>
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<td>$</td>
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</tr>
<tr>
<td>$p_T^{e[\mu]} &gt; 15$ GeV</td>
<td>0.084</td>
<td>0.096</td>
<td>0.0093</td>
<td>1494</td>
<td>142</td>
<td>4871</td>
<td>81</td>
</tr>
<tr>
<td>$p_T^{tracks} &gt; 50$ GeV</td>
<td>0.050</td>
<td>0.061</td>
<td>0.0036</td>
<td>1168</td>
<td>103</td>
<td>2902</td>
<td>48</td>
</tr>
<tr>
<td>Isolated lepton tracks</td>
<td>0.016</td>
<td>0.021</td>
<td>0.00057</td>
<td>1.02</td>
<td>0.09</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$d_{xy} &gt; 20$ mm</td>
<td>0.015</td>
<td>0.0197</td>
<td>0.00055</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta R(\tilde{\tau},$ track) $&lt; 0.6$</td>
<td>0.011</td>
<td>0.013</td>
<td>0.00042</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\beta &lt; 0.95$</td>
<td>0.0093</td>
<td>0.012</td>
<td>0.00040</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table:** Cut-flow for parameter points (a), (c) and (f) and SM background at $\sqrt{s} = 14$ TeV for the case of no pile-up. Samples are normalized to their respective cross-sections (in fb).
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)

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

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 stau of the visible sector such that

$$\tilde{\tau} \rightarrow \tilde{\xi}^0_1 \tau$$
The hidden sector LSP, $\tilde{\xi}_1^0$, 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.

$$\tilde{\xi}_1^0 = N_{11}\psi_S + N_{12}\lambda_X + N_{13}\lambda_Y + N_{14}\lambda_3 + N_{15}\tilde{h}_1 + N_{16}\tilde{h}_2$$

The coupling between the stau and the LSP is proportional to

$$\frac{i\sqrt{2}}{2} \left( g_Y N_{13}^* \tilde{D}_{13}^\ell + g_2 N_{14}^* \tilde{D}_{13}^\ell - g_Y N_{12}^* \tilde{D}_{13}^\ell s_\delta - \frac{2m_\tau}{v_d} N_{15}^* \tilde{D}_{16}^\ell \right) P_L$$

$$+ i \left[ \sqrt{2}g_Y \tilde{D}_{16}^\ell \left( -N_{13} + N_{12}s_\delta \right) - \frac{\sqrt{2}m_\tau}{v_d} \tilde{D}_{13}^\ell N_{15} \right] P_R$$

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

$$\simeq M_Z^2 + \frac{\epsilon}{2} g_Y v^2 \frac{s_\delta}{c_\delta} + \frac{1}{4} g_2^2 v^2 \left( \frac{\epsilon}{\kappa} \right)^2$$
Cut-flow analysis: 27 TeV, no pile-up

<table>
<thead>
<tr>
<th>Cuts</th>
<th>Signal (a)</th>
<th>Signal (c)</th>
<th>Signal (f)</th>
<th>$t\bar{t}$</th>
<th>$t+$jets</th>
<th>$W/Z/\gamma^*$+ jets</th>
<th>WW/ZZ/γγ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(\ell) \geq 1$</td>
<td>4.90</td>
<td>4.36</td>
<td>0.33</td>
<td>884189</td>
<td>111761</td>
<td>$8.28 \times 10^6$</td>
<td>145077</td>
</tr>
<tr>
<td>$N(\tau_h) \leq 1$</td>
<td>4.88</td>
<td>4.33</td>
<td>0.32</td>
<td>881736</td>
<td>111689</td>
<td>$8.27 \times 10^6$</td>
<td>144975</td>
</tr>
<tr>
<td>$</td>
<td>d_0</td>
<td>&gt; 4$ mm</td>
<td>0.70</td>
<td>0.80</td>
<td>0.152</td>
<td>6579</td>
<td>546</td>
</tr>
<tr>
<td>$p_T^{e/\mu} &gt; 15$ [10] GeV</td>
<td>0.22</td>
<td>0.27</td>
<td>0.036</td>
<td>5491</td>
<td>407</td>
<td>9671</td>
<td>162</td>
</tr>
<tr>
<td>$p_T^{tracks} &gt; 50$ GeV</td>
<td>0.13</td>
<td>0.16</td>
<td>0.014</td>
<td>4225</td>
<td>296</td>
<td>5392</td>
<td>111</td>
</tr>
<tr>
<td>Isolated lepton tracks</td>
<td>0.04</td>
<td>0.057</td>
<td>0.0024</td>
<td>1.90</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$d_{xy} &gt; 20$ mm</td>
<td>0.038</td>
<td>0.053</td>
<td>0.0023</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta R(\tau, track) &lt; 0.6$</td>
<td>0.027</td>
<td>0.037</td>
<td>0.0018</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\beta &lt; 0.95$</td>
<td>0.021</td>
<td>0.029</td>
<td>0.0015</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table:** Cut-flow for parameter points (a), (c) and (f) and SM background at $\sqrt{s} = 27$ TeV for the case of no pile-up. Samples are normalized to their respective cross-sections (in fb).
New and modified cuts for case of pile-up/run time

<table>
<thead>
<tr>
<th>Cut</th>
<th>14 TeV</th>
<th>27 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>d_0</td>
<td>[mm]$</td>
</tr>
<tr>
<td>$p_T^{\text{tracks}} [GeV]$</td>
<td>&gt; 50</td>
<td>&gt; 90</td>
</tr>
<tr>
<td>$d_{xy} [mm]$</td>
<td>&gt; 20</td>
<td>&gt; 80</td>
</tr>
<tr>
<td>$E_T^{\text{miss, PUPPI}} / \sqrt{H_T^{\text{PUPPI}}} [GeV^{-1/2}]$</td>
<td>&gt; 12</td>
<td>&gt; 6</td>
</tr>
</tbody>
</table>

**Table:** The top three are modification of the original cuts, while the bottom cut is additional.

![Figure: Estimated runtime, in years, for the potential discovery of benchmark points (a), (b), (c), and (d) that are within reach of both HL-LHC and HE-LHC. Blue bars represent HL-LHC and yellow bars are for HE-LHC.](image-url)