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

Amin Aboubrahim

Northeastern University
Boston, MA

2019 Meeting of the Division of Particles & Fields of the American Physical Society

Northeastern University, Boston, MA
29 July to 2 August 2019

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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

$$\mathcal{L}_{\rm gk} = -\frac{1}{4}(B_{\mu\nu}B^{\mu\nu} + C_{\mu\nu}C^{\mu\nu}) - i\lambda_B\sigma^\mu\partial_\mu\bar{\lambda}_B - i\lambda_C\sigma^\mu\partial_\mu\bar{\lambda}_C + \frac{1}{2}(D_B^2 + D_C^2)$$

- 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

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

  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

$$\left(\begin{array}{cc|cccc}
0 & M_1 c_\delta - M_2 s_\delta & M_2 & 0 & 0 & 0 \\
M_1 c_\delta - M_2 s_\delta & m_X c_\delta^2 + m_1 s_\delta^2 - 2 M_{XY} c_\delta s_\delta & -m_1 s_\delta + M_{XY} c_\delta & 0 & s_\delta c_\beta s_W M_Z & -s_\delta s_\beta s_W M_Z \\
\hline
M_2 & -m_1 s_\delta + M_{XY} c_\delta & m_1 & 0 & -c_\beta s_W M_Z & s_\beta s_W M_Z \\
0 & 0 & 0 & m_2 & c_\beta c_W M_Z & -s_\beta c_W M_Z \\
0 & s_\delta c_\beta s_W M_Z & -c_\beta s_W M_Z & c_\beta c_W M_Z & 0 & -\mu \\
0 & -s_\delta s_\beta s_W M_Z & s_\beta s_W M_Z & -s_\beta c_W M_Z & -\mu & 0
\end{array}\right),$$

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 δ 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)

A. Aboubrahim and P. Nath, Phys. Rev. D **99**, no. 5, 055037 (2019)

Model	m_0	A_0	m_1	m_2	m_3	M_1	m_X	$\tan\beta$	δ
(a)	300	1838	885	740	4235	473	600	14	2.0×10^{-5}
(b)	546	-3733	828	761	3657	426	392	16	4.7×10^{-6}
(c)	529	-3211	864	482	3777	461	400	15	6.0×10^{-6}
(d)	680	-5198	1166	806	3945	503	198	15	2.5×10^{-6}
(e)	563	-1850	1214	598	3856	579	380	21	2.4×10^{-6}
(f)	500	-2698	1286	893	4165	523	65	15	2.5×10^{-6}
(g)	515	-261	1451	1265	4830	682	258	25	1.4×10^{-6}
(h)	645	1009	1621	1160	5374	714	100	26	1.3×10^{-6}

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

Model	h^0	μ	$\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm$	$\tilde{\tau}$	$\tilde{\nu}_\tau$	$\tilde{\xi}_1^0$	$\tilde{t}$	$\tilde{g}$	Ωh^2	$c\tau_0$
(a)	123.0	4127	359.9	556.9	275.1	434.3	260.1	6306	8459	0.116	243.6
(b)	123.1	4417	343.3	595.2	291.0	572.4	272.9	5118	7372	0.123	199.9
(c)	123.4	4426	350.3	350.5	319.3	459.8	302.5	5376	7621	0.109	147.0
(d)	124.6	4998	495.2	633.2	428.0	671.4	413.6	5347	7916	0.121	177.6
(e)	123.1	4236	449.0	449.2	440.5	570.6	419.4	5607	7764	0.111	307.6
(f)	124.2	4669	546.0	699.7	500.0	653.6	491.5	5926	8326	0.119	387.3
(g)	123.2	4852	619.4	1009	583.0	864.7	565.1	6997	9553	0.114	424.1
(h)	123.4	5193	692.8	911.3	680.8	877.3	665.7	7816	10572	0.120	561.3

Table: Display of the Higgs boson (h^0) mass, the μ 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.

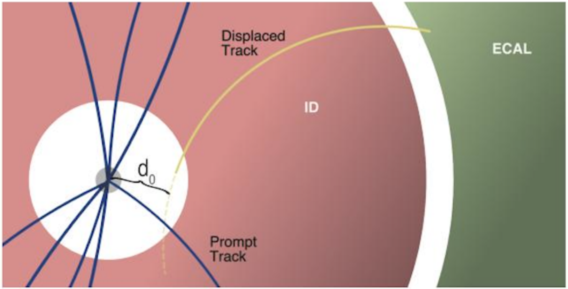
- High scale models with DM candidates must satisfy the current DM relic density $\Omega h^2 = 0.1198 \pm 0.0012$ N. Aghanim et al. [Planck Collaboration], arXiv:1807.06209 [astro-ph.CO]
- Including coannihilation, one can have three processes responsible for the observed relic density of $\tilde{\xi}^0_1$, namely,

$$\begin{aligned} \tilde{\xi}^0_1\ \tilde{\xi}^0_1 &\to \mathrm{SM}, && (\text{negligible}) \\ \tilde{\xi}^0_1\ \tilde{\tau} &\to \mathrm{SM}', && (\text{negligible}) \\ \tilde{\tau}\ \tilde{\tau} &\to \mathrm{SM}''. && (\text{dominant}) \end{aligned}$$

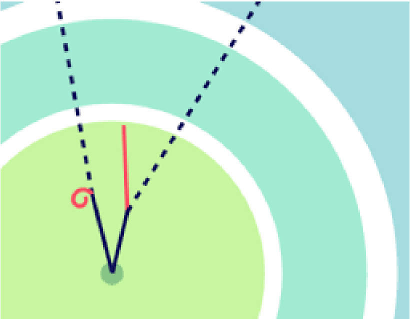
- $\tilde{\xi}^0_1$ possesses very weak couplings with SM particles making it in a category between WIMPs and FIMPs
- If $\Gamma_{\tilde{\tau}} > H(T)$ then $\tilde{\tau} \leftrightarrow \tilde{\xi}^0_1\ \tau$ followed by coannihilation sets the relic abundance

- Stau pair production proceeds via γ, Z and Z' s-channel processes, i.e. $q\bar{q} \to \gamma, Z, Z' \to \tilde{\tau}^+\tilde{\tau}^-$
- The end products of the decay chain and the relevant final states are

$$pp \to \tilde{\tau}^+\tilde{\tau}^- \to \tau^+\tau^-\tilde{\xi}_1^0\tilde{\xi}_1^0 \to \tau_h, \ell + E_T^{\rm miss},$$
$$pp \to \tilde{\tau}^\pm\tilde{\nu}_\tau \to \tau^\pm\tilde{\xi}_1^0\tau^\pm W^\mp \to \tau_h, 2\ell + E_T^{\rm miss}$$



- 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



- The kinematic variables used for discriminating the signal from the background

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

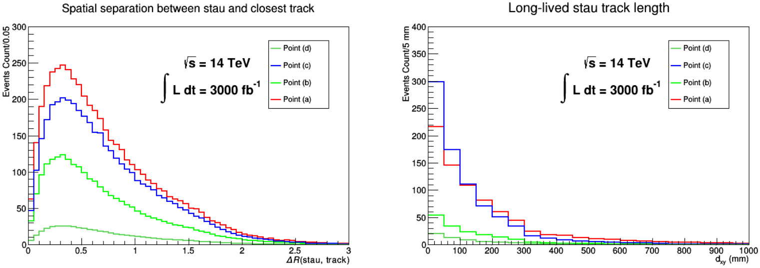


Figure: Left panel: Minimum spatial separation between the stau LLP and its closest lepton track, $\Delta R(\tilde{\tau}, \text{track})$. Right panel: the track length d_{xy}, of the long-lived stau.

- Pile-up events (interactions per bunch crossing) are added to the main interaction
- Pile-up mitigation is handled by PUPPI

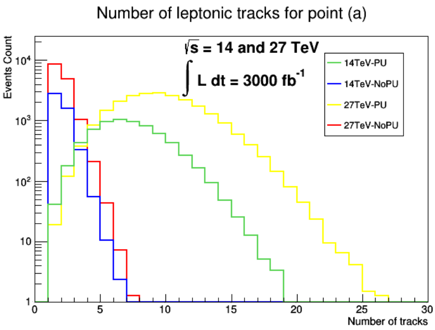


Figure: A comparison between the number of leptonic tracks for the cases of no pile-up (NoPU) and pile-up (PU) at 14 TeV and at 27 TeV for point (a).

Results: predicted number of events at HL-LHC and HE-LHC

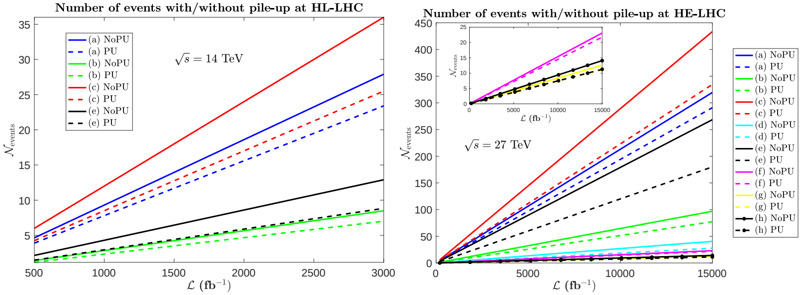


Figure: Left panel: Estimated number of events for various integrated luminosities for benchmarks (a), (b), (c) and (e) in cases of no pile-up (solid lines) and pile-up (dashed lines) at HL-LHC. Right panel: same as the left panel but for HE-LHC for all the benchmarks.

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 $\tilde{\tau} \to \tilde{\xi}_1^0\ \tau$
- Phase space suppression and small δ, ϵ 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

BACKUP SLIDES

- The prototype Stueckelberg Lagrangian couples one abelian vector boson A_μ to one pseudo-scalar σ 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 σ transforms together with A_μ according to

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

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

$$\begin{aligned}\mathcal{L} + \mathcal{L}_{\rm int} + \mathcal{L}_{\rm gf} =& -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{m^2}{2}A_\mu A^\mu - \frac{1}{2\xi}(\partial_\mu A^\mu)^2 \\ & -\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \xi\frac{m^2}{2}\sigma^2 + gJ_\mu A^\mu\end{aligned}$$

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

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

We note that $\mathcal{L}_{\rm St}$ 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, $\mathcal{L}_{\rm St}$ is

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

In unitary gauge the axion field a is absorbed to generate mass for the $U(1)_X$ gauge boson

- We introduce the Majorana spinors, ψ_S, λ_X and λ_Y so that

$$\psi_S = \begin{pmatrix} \chi_\alpha \\ \bar{\chi}^{\dot{\alpha}} \end{pmatrix}, \quad \lambda_X = \begin{pmatrix} \lambda_{C\alpha} \\ \bar{\lambda}_C^{\dot{\alpha}} \end{pmatrix}, \quad \lambda_Y = \begin{pmatrix} \lambda_{B\alpha} \\ \bar{\lambda}_B^{\dot{\alpha}} \end{pmatrix}$$

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

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

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 3×3 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 as

$$M_-^2 \simeq M_Z^2 + \frac{\epsilon}{2} g_Y^2 v^2 \frac{s_\delta}{c_\delta} + \frac{1}{4} g_2^2 v^2 \left(\frac{\epsilon}{\kappa}\right)^2$$

- For fast decay and inverse decay of $\tilde{\tau}$ (which sets the chemical equilibrium between $\tilde{\xi}_1^0$ 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 $n_{\tilde{\xi}_1^0}$ and $n_{\tilde{\tau}}$ is fixed
  2. If $T_f^{\text{co-scattering}} > T_f^{\text{coannihilation}}$ then conversion $\tilde{\xi}_1^0 \longleftrightarrow \tilde{\tau}$ 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

Model	$\sigma_{\rm NLO}(pp \to \tilde{\tau}^+\tilde{\tau}^-)$		$\sigma_{\rm NLO}(pp \to \tilde{\tau}^+\tilde{\nu}_\tau)$		$\sigma_{\rm NLO}(pp \to \tilde{\tau}^-\tilde{\nu}^*_\tau)$	
	14 TeV	27 TeV	14 TeV	27 TeV	14 TeV	27 TeV
(a)	2.70	8.05	2.05	6.45	0.90	3.42
(b)	2.03	6.17	0.48	1.67	0.19	0.84
(c)	1.74	5.53	1.94	6.39	0.83	3.30
(d)	0.41	1.50	0.17	0.68	0.06	0.32
(e)	0.49	1.85	0.74	2.84	0.29	1.37
(f)	0.21	0.85	0.21	0.90	0.08	0.42
(g)	0.10	0.45	0.05	0.24	0.02	0.11
(h)	0.04	0.25	0.06	0.32	0.02	0.13

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

Cuts	(a)	(c)	(f)	$t\bar{t}$	t+jets	$W/Z/\gamma^*$+ jets	$WW/ZZ/\gamma\gamma$
$N(\ell) \geq 1$	1.61	1.35	0.0795	236731	38618	4.39×10^6	79831
$N(\tau_h) \leq 1$	1.60	1.34	0.0794	236126	38596	4.38×10^6	79796
$\lvert d_0 \rvert > 4$ mm	0.27	0.29	0.04	1803	190	6063	101
$p_T^{e\ [\mu]} > 15$ [10] GeV	0.084	0.096	0.0093	1494	142	4871	81
$p_T^{\rm tracks} > 50$ GeV	0.050	0.061	0.0036	1168	103	2902	48
Isolated lepton tracks	0.016	0.021	0.00057	1.02	0.09	0	0
$d_{xy} > 20$ mm	0.015	0.0197	0.00055	0	0	0	0
$\Delta R(\tilde{\tau}, \rm track) < 0.6$	0.011	0.013	0.00042	0	0	0	0
$\beta < 0.95$	0.0093	0.012	0.00040	0	0	0	0

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)

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

- 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, $\tilde{\xi}_1^0$
- The NLSP is the stau of the visible sector such that

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

- The hidden sector LSP, $\tilde{\xi}_1^0$, is an admixture of the $U(1)_X$ gaugino λ_X, the Majorana spinor ψ_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

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

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

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

$$\simeq M_Z^2 + \frac{\epsilon}{2} g_Y^2 v^2 \frac{s_\delta}{c_\delta} + \frac{1}{4} g_2^2 v^2 \left(\frac{\epsilon}{\kappa}\right)^2$$

Cut-flow analysis: 27 TeV, no pile-up

Cuts	Signal (a)	Signal (c)	Signal (f)	$t\bar{t}$	t+jets	$W/Z/\gamma^*+$ jets	$WW/ZZ/\gamma\gamma$
$N(\ell) \geq 1$	4.90	4.36	0.33	884189	111761	8.28×10^6	145077
$N(\tau_h) \leq 1$	4.88	4.33	0.32	881736	111689	8.27×10^6	144975
$\|d_0\| > 4$ mm	0.70	0.80	0.152	6579	546	11851	188
$p_T^{e\ [\mu]} > 15$ [10] GeV	0.22	0.27	0.036	5491	407	9671	162
$p_T^{\text{tracks}} > 50$ GeV	0.13	0.16	0.014	4225	296	5392	111
Isolated lepton tracks	0.04	0.057	0.0024	1.90	0	0	0
$d_{xy} > 20$ mm	0.038	0.053	0.0023	0	0	0	0
$\Delta R(\tilde{\tau}, \text{track}) < 0.6$	0.027	0.037	0.0018	0	0	0	0
$\beta < 0.95$	0.021	0.029	0.0015	0	0	0	0

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

Cut	14 TeV	27 TeV
$\|d_0\|$ [mm]	> 8	> 20
p_T^{tracks} [GeV]	> 50	> 90
d_{xy} [mm]	> 20	> 80
$E_T^{\text{miss,PUPPI}}/\sqrt{H_T^{\text{PUPPI}}}$ [GeV$^{-1/2}$]	> 12	> 6

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