Exploring stau and multiparticle coannihilation regions and SUSY discovery at the LHC

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Introduction

- In models where the LSP is bino-like, coannihilation is needed to deplete the relic density to $\Omega h^2 = 0.1197 \pm 0.0022$ [Planck Collaboration, arXiv:1502.01589 [astro-ph.CO]]
- Coannihilation requires the mass gap between the LSP and the NLSP be small (typically $\lesssim 20$ GeV)
- Relic density is controlled by the ratio

$$\delta_i = \frac{n_i^{eq}}{n^{eq}} = \frac{g_i(1+\Delta_i)^{3/2} e^{-\Delta_i x}}{\sum_j g_j (1+\Delta_j)^{3/2} e^{-\Delta_j x}},$$

where $\Delta_i = (m_i - m_1)/m_1$, g_i are the degrees of freedom of χ_i and $x = m_1/T$. The relic density involved in the integral

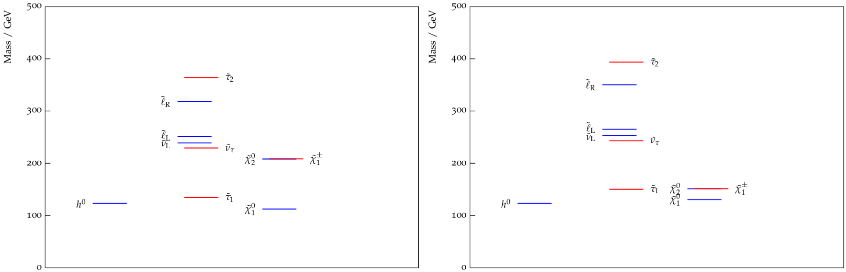
$$J_{x_f} = \int_{x_f}^{\infty} x^{-2} \langle \sigma_{eff} v \rangle dx.$$

SUGRA models

- In previous works, stop[1] and gluino[2] coannihilation have been discussed. [1][B. Kaufman, P. Nath, B. Nelson, A. Spisak, arXiv:1509.02530v2 [hep-ph]]
  [2][P. Nath, A. Spisak, arXiv:1603.04854v2 [hep-ph]]
- Here we extend the study to stau coannihilation models. To achieve stau coannihilation we need non-universal SUGRA ($\tilde{g}$SUGRA): $m_0\,, A_0\,, m_1 = m_2 << m_3\,,\ \tan\beta\,, \text{sign}(\mu)$
  [S. Akula, P. Nath, arXiv:1304.5526 [hep-ph]]
- In multiparticle coannihilation, more than one particle act as coannihilators. Here we have: $m_0\,, A_0\,, m_2 < m_1 << m_3\,,$ $\tan\beta\,, \text{sign}(\mu)$

Sparticle mass hierarchies

- With a small available mass gap between the LSP and the NLSP, decay products are soft. Switch on ISR and FSR
- An exhibition of the sparticle mass hierarchy for two model points with masses < 500 GeV. Left panel: stau coannihilation case. Right panel: multiparticle coannihilation case.
[A. Aboubrahim, P. Nath, and A. Spisak, arXiv:1704.04669v [hep-ph]]



- Searches based on two categories of final states:
  - One and two hadronically decaying taus
  - Multiple light leptons geared to search for electroweakinos
- The SUSY production cross section for all models is dominated by the production of the neutralino $\tilde{\chi}_2^0$ and chargino $\tilde{\chi}_1^{\pm}$
- In nearly every model point the only decay mode of $\tilde{\chi}_2^0$ is via the channel $\tilde{\chi}_2^0 \to \tilde{\tau}\tau$, while the primary decay of the chargino is via the channel $\tilde{\chi}_1^{\pm} \to \tilde{\tau}\nu_\tau$
- The stau always decays through one channel, $\tilde{\tau} \to \tilde{\chi}_1^0\tau$

- Signal regions are based on three Selection Criteria (SC): SC1, SC2 and SC3, searching for hadronically decaying taus in the final state.

Vetos

A veto on muons, electrons and b-jets is carried out in all of the three signal regions.

Missing Energy

A common cut on the missing energy is applied:
100 GeV $< E_T^{\text{miss}} <$ 200 GeV, suitable for soft final states.

Selection Criteria	SC1					
	1τ-A	1τ-B	1τ-C	2τ-A	2τ-B	2τ-C
$p_T(j_1)$ (GeV) $>$	20	20	20	20	20	20
$p_T(j_1)$ (GeV) $<$	100	100	100	100	100	100
$p_T(\tau_{1h})$ (GeV) $>$	20	20	20	20	20	20
$p_T(\tau_{1h})$ (GeV) $<$	50	70	90	50	70	90
$p_T(\tau_{2h})$ (GeV) $>$	-	-	-	20	20	20
$p_T(\tau_{2h})$ (GeV) $<$	-	-	-	40	50	60
$\lvert\eta(\tau_{1h})\rvert <$	1.2	1.2	1.2	1.2	1.2	1.2
$\lvert\eta(\tau_{2h})\rvert <$	-	-	-	1.0	1.0	1.0
$\Delta R(\tau_{1h}, j_1) >$	0.6	0.6	0.6	0.6	0.6	0.6
$\Delta R(\tau_{1h}, j_1) <$	1.8	1.8	1.8	1.8	1.8	1.8
$\Delta R(\tau_{2h}, j_1) >$	-	-	-	2.3	2.3	2.3
$\Delta R(\tau_{2h}, j_1) <$	-	-	-	3.3	3.3	3.3
$N(\tau_h)$	1	1	1	2	2	2

Selection Criteria	SC2					
	1τ-A	1τ-B	1τ-C	2τ-A	2τ-B	2τ-C
$p_T(j_1)$ (GeV) $>$	20	20	20	-	-	-
$p_T(j_1)$ (GeV) $<$	200	200	200	110	110	110
$\|\eta(\tau_{1h})\| <$	1.2	1.2	1.2	1.4	1.4	1.4
$\|\eta(\tau_{2h})\| <$	-	-	-	1.0	1.0	1.0
$\Delta R(\tau_{1h}, j_1) >$	0.6	0.6	0.6	0.8	0.8	0.8
$\Delta R(\tau_{1h}, j_1) <$	1.8	1.8	1.8	1.8	1.8	1.8
$\Delta R(\tau_{2h}, j_1) >$	-	-	-	2.3	2.3	2.3
$\Delta R(\tau_{2h}, j_1) <$	-	-	-	3.3	3.3	3.3
$m_{\rm eff} >$	120	130	140	110	110	110
$m_{\rm eff} <$	200	250	300	250	350	450
$N(\tau_h)$	1	1	1	2	2	2

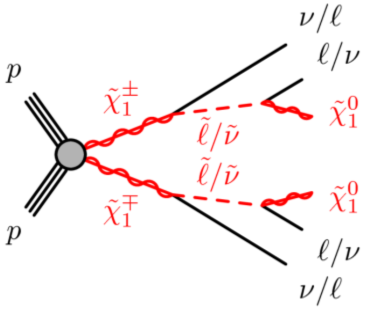
- Note that $m_{\rm eff} = E_T^{\rm miss} + p_T^{\tau_{1h}} + p_T^{\tau_{2h}}$

- This signal region (SR) is based on a variation of an ATLAS SR [ATLAS Collaboration, arXiv:1407.0350v2 [hep-ex]]

Selection Criteria	SC3		
	2τ-A	2τ-B	2τ-C
E_T^{miss} (GeV) $>$	100	100	100
E_T^{miss} (GeV) $<$	200	200	200
$p_T(j_1)$ (GeV) $<$	180	180	180
m_{eff} (GeV) $>$	130	130	130
m_{eff} (GeV) $<$	200	200	200
$m_{\text{T}\tau 1} + m_{\text{T}\tau 2} >$	100	100	50
$m_{\text{T}\tau 1} + m_{\text{T}\tau 2} <$	200	300	500
$\Delta R(\tau_h, \tau_h) >$	2.5	2.5	2.5
$\Delta R(\tau_h, \tau_h) <$	3.5	3.5	3.5

- Note that $m_{\text{T}\tau}(\mathbf{p}_{\text{T}\tau}, \mathbf{p}_{\text{T}}^{\text{miss}}) = \sqrt{2(p_{\text{T}\tau} E_{\text{T}}^{\text{miss}} - \mathbf{p}_{\text{T}\tau} \cdot \mathbf{p}_{\text{T}}^{\text{miss}})}$

- Signal regions designed to look for decays of $\tilde{\chi}_1^+\tilde{\chi}_1^-$ and $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$



[The ATLAS collaboration [ATLAS Collaboration], ATLAS-CONF-2016-096]

- 2-lepton final state: 2ℓ-SF (same flavor opposite sign) and 2ℓ-DF (different flavor opposite sign)
- 3-lepton case: two of the leptons are a SFOS pair, with the third lepton allowed to have the same or different flavor

- The selection criteria used for the signal regions related to the 2 lepton signature:

(The p_T of the leading and sub-leading lepton are required to exceed 25 GeV and 20 GeV, respectively)

Selection Criteria	SF			DF		
	2*l*-SF-A	2*l*-SF-B	2*l*-SF-C	2*l*-DF-A	2*l*-DF-B	2*l*-DF-C
E_T^{miss} (GeV) $>$	100	100	100	100	100	100
light jet p_T (GeV) $<$	20	20	20	30	30	30
b-jet p_T (GeV) $<$	20	20	20	20	20	20
forward jet p_T (GeV) $<$	30	30	30	30	30	30
$\|m_{\ell\ell} - m_Z\|$ (GeV) $>$	10	10	10	-	-	-
m_{T2} (GeV) $>$	90	120	150	90	120	150

- Note that

$$m_{\mathrm{T2}} = \min\left[\max\left(m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}(\ell_1), \mathbf{q}_{\mathrm{T}}), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}(\ell_2), \mathbf{p}_{\mathrm{T}}^{\text{miss}} - \mathbf{q}_{\mathrm{T}})\right)\right]$$

- Tables of benchmark points used in the analysis for stau coannihilation (left) and for multiparticle coannhilation (right), satisfying the Higgs mass and relic density constraints.

Model	m_0	A_0	$m_1 = m_2$	m_3	$\tan\beta$
a.	286	-523	314	3015	10
b.	297	-553	343	3246	10
c.	267	-378	367	2911	10
d.	295	-491	381	2821	13
e.	325	-416	412	3156	14
f.	317	-497	437	3065	14
g.	364	-587	445	3728	14
h.	412	-904	503	4688	13
j.	337	833	593	3626	15
k.	295	-551	302	3165	10

Model	m_0	A_0	m_1	m_2	m_3	$\tan\beta$
i.	345	68	394	287	3690	10
ii.	385	152	403	290	3972	12
iii.	318	248	357	249	2973	12
iv.	386	-47	401	284	3809	13
v.	367	78	409	290	3550	13
vi.	423	-19	431	314	4396	13
vii.	353	202	427	298	3351	13
viii.	390	-161	440	308	3864	13
ix.	321	246	423	296	3328	10
x.	432	264	494	350	4234	15
xi.	304	-745	260	221	2793	11

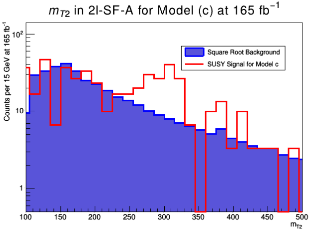
Model	Leading SR	$\mathcal{L}$ (fb^{-1})	Sub-leading SR	$\mathcal{L}$ (fb^{-1})	
k.	2l-SF-A	97	2l-SF-B	185	$m_{\tilde{\chi}_1^0} = 106.2$ GeV
c.	2l-SF-A	165	2l-SF-C	169	
a.	2l-SF-A	187	2l-SF-B	266	
b.	2l-SF-A	362	1τ-SC2-C	416	
d.	2l-SF-A	781	2l-SF-C	884	
f.	2l-SF-A	1110	2l-SF-C	1250	
e.	2l-SF-A	1480	2l-SF-B	1630	
g.	2l-SF-C	1790	2l-SF-A	1850	
h.	2l-SF-C	1660	2l-SF-A	1860	
j.	2l-SF-C	1880	2l-SF-A	2160	$m_{\tilde{\chi}_1^0} = 232.9$ GeV

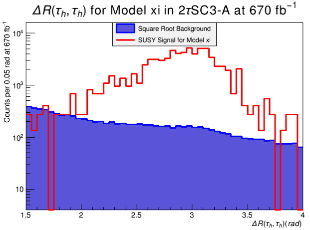
Table: The overall minimum integrated luminosities needed for 5σ discovery for stau coannihilation models

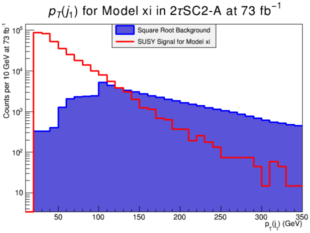
Model	Leading SR	$\mathcal{L}$ (fb^{-1})	Sub-leading SR	$\mathcal{L}$ (fb^{-1})	
xi.	2τ-SC2-A	73	2τ-SC2-B	89	$m_{\tilde{\chi}_1^0} = 89.9$ GeV
iii.	2l-SF-A	181	2τ-SC2-A	200	
ii.	2l-SF-C	273	2l-SF-B	306	
ix.	2l-SF-A	360	2l-SF-B	487	
v.	1τ-SC1-C	411	1τ-SC1-B	475	
i.	2τ-SC2-A	477	2l-SF-A	545	
vii.	1τ-SC1-C	508	1τ-SC1-B	605	
iv.	1τ-SC1-C	532	1τ-SC1-B	575	
vi.	1τ-SC1-C	650	1τ-SC2-C	693	
viii.	1τ-SC1-C	660	2l-SF-A	732	
x.	1τ-SC1-C	1090	1τ-SC1-B	1230	$m_{\tilde{\chi}_1^0} = 184.0$ GeV

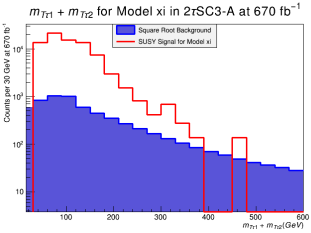
Table: The overall minimum integrated luminosities needed for 5σ for multiparticle coannihilation models

Distributions of some kinematic variables used in the analysis









- The neutralino is $\tilde{\chi}^0 = \alpha\lambda^0 + \beta\lambda^3 + \gamma\tilde{H}_1 + \delta\tilde{H}_2$
- For stau coannihilation: $|\beta| \leq 0.003, |\gamma| \leq 0.015, |\delta| \leq 0.002$
- For multiparticle coann: $|\beta| \leq 0.039, |\gamma| \leq 0.014, |\delta| \leq 0.002$

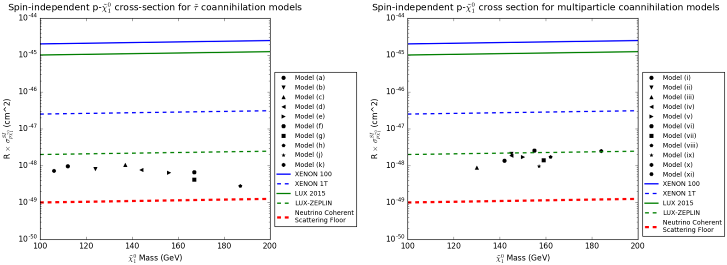


Figure: $R \times \sigma^{SI}_{p,\chi^0_1}$ $(R = \rho_{\tilde{\chi}^0_1}/\rho_c)$ for stau coannihilation models (left panel) and multiparticle coannihilation (right panel) as a function of LSP mass displayed alongside the current and projected range of the XENON and LUX experiments and the neutrino floor.

Conclusion

- The parameter space satisfying the Higgs boson mass constraint mostly gives a neutralino which is bino-like. Hence coannihilation is needed to achieve the correct relic density.

- Because of small mass gaps between the LSP and NLSP, supersymmetric signals arising from stau and multiparticle coannihilation regions are hard to detect at colliders since the decay products are soft. Therefore, high integrated luminosities are required.

- We have shown that such models can be tested by the end of LHC-II and at HL-LHC which is expected to reach an integrated luminosity of 3000 fb^{-1}.