LLCP searches at FCC-he

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1 Introduction

We consider signatures at the FCC-he from long-lived charged particles (LLCPs), consulting the minimal supersymmetric standard model (MSSM) as the working scenario.

In fact, the HL-LHC ($\sqrt{s} = 14\,\mathrm{TeV}$ and $\int \mathcal{L} = 3\,\mathrm{ab}^{-1}$) is expected to be more sensitive for most of theoretically-motivated scenarios, because the energy of the FCC-he will be limited as $\sqrt{s} = 2\sqrt{50\,\mathrm{TeV} \times 60\,\mathrm{GeV}} = 3.5\,\mathrm{TeV}$. We nevertheless try to obtain the expected reach of FCC-he in order to quantify its potential.

2 Benchmark models

There are three ways to have a long-lived particle in the MSSM: (a) mass degeneracy, which results in a smaller phase space, (b) small couplings due to gravitational interactions (or interactions with axions), and (c) small couplings due to R-parity violating (RpV) interactions. There are several scenarios that realize the case (a), but as shown below, the decay length is determined by the model. Tuning mass parameters may also realize the case (a), which is usually very unnatural but the decay length can be arbitrary. The cases (b) and (c) may have arbitrary couplings and thus decay lengths are also flexible, though they are not the main stream of SUSY phenomenology. Note that the charged daughter particle is always soft in the case (a), while it can be hard in the other cases.

We consider four simple scenarios, in which only one MSSM particle is light. In all of them, the production at the FCC-he is four-body process, such as $qe \to qe\tilde{\chi}\tilde{\chi}$, and thus the cross section is limited compared to those at the LHC.

We can have three-body production processes by introducing another light MSSM particle, which we call "co-production." We will see two non-working co-production case, and then three viable scenarios with co-production.

2.1 Models with a single light MSSM particle

There are four possible scenarios with LLCP.

Pure-wino LSP Case (a) with a rigid decay length shown in Table 1. All SUSY particles except for winos ($\tilde{W}^{\pm}$ and $\tilde{W}^{0}$) are decoupled. As electroweak radiative corrections make the charged wino $\tilde{W}^{\pm}$ slightly heavier than the neutral wino $\tilde{W}^{0}$, the NLSP $\tilde{W}^{\pm}$ becomes an LLCP and decays with $c\tau \sim$ 60–70 mm [1] as $\tilde{W}^{\pm} \to \tilde{W}^{0}\pi^{\pm}$.[1] Note that the charged daughter particle is soft.

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[1] We also have a channel $\tilde{W}\pm \to \tilde{W}e^{\pm}\nu$ but ignore it because of its small branching ratio $\sim 2\%$.

This scenario with $m_{\tilde{W}} < 430\,\mathrm{GeV}$ is excluded by ATLAS search [3].

Pure-higgsino LSP Case (a). Similarly to the pure-wino LSP scenario, all SUSY particles except for Higgsinos ($\tilde{H}^{\pm}_{\mathrm{u,d}}$ and $\tilde{H}^{0}_{u,d}$) are decoupled, and the Higgsino-like electroweakinos ($\tilde{\chi}^0_{1,2}$ and $\tilde{\chi}^{\pm}_1$) are degenerate. The mass differences $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^{\pm}_1}$ and $m_{\tilde{\chi}^{\pm}_1} - m_{\tilde{\chi}^0_1}$ are both positive at the tree level [4], which is $\mathcal{O}(100)\,\mathrm{MeV}$ for $M_1, M_2 > \mathcal{O}(10)\,\mathrm{TeV}$. With such huge gaugino masses, the mass difference is dominated by the electroweak correction δm shown in Table 2, and the decay length becomes as short as $\lesssim 10\,\mathrm{mm}$. Note that the charged daughter particle is soft.

Slepton NLSP decaying to gravitino Case (b). The decay length is given by

$$\Gamma(\tilde{l} \to l\tilde{G}) = \frac{1}{48\pi M_*^2}\frac{m_{\tilde{l}}^5}{m_{\tilde{G}}^2}\left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2}\right) \Longrightarrow c\tau \sim 1.8\times10^{-5}\,\mathrm{m}\left(\frac{m_{\tilde{l}}}{100\,\mathrm{GeV}}\right)^{-5}\left(\frac{m_{\tilde{G}}}{1\,\mathrm{eV}}\right)^{2} \quad (1)$$

with the reduced Planck mass $M_* = 2.4\times10^{18}\,\mathrm{GeV}$, hence it can be tuned by choosing the gravitino mass $m_{\tilde{G}}$, which though has to be consistent with cosmology.

If the slepton left–right mixing is negligible, a sneutrino $\tilde{\nu}_l$ is always lighter than the corresponding charged slepton $\tilde{l}_{\mathrm{L}}$:

$$m^2_{\tilde{e}_{\mathrm{L}}} - m^2_{\tilde{\nu}_e} \simeq -m_W^2 \cos 2\beta. \quad (2)$$

To avoid the unwanted decay$\tilde{l}_{\mathrm{L}} \to \tilde{\nu} \bar{f} f$, the sneutrino should be heavier than the lighter slepton. Thus we just assume that the lighter slepton is right-handed.

Slepton LSP with RpV Case (c). As we only consider right-handed sleptons $\tilde{l}_{\mathrm{R}k}$, the decay is induced by the interaction $\lambda_{ijk} L_i L_j \bar{E}_k$. We simply assume only one coupling λ_{ijk} is present, which leads the decays $\tilde{l}^-_{\mathrm{R}k} \to l^-_i \nu_j$ or $\nu_i l^-_j$. The total decay rate and the resulting decay length are given by

$$\Gamma_{\mathrm{tot}} \simeq \frac{\lambda^2_{ijk}}{8\pi} m_{\tilde{l}} \Longrightarrow c\tau \sim 0.50\,\mathrm{m}\left(\frac{m_{\tilde{l}}}{100\,\mathrm{GeV}}\right)^{-1}\left(\frac{\lambda_{ijk}}{10^{-8}}\right)^{-2}. \quad (3)$$

Though all of the four scenarios are realized without parameter tuning, they do not have any strong motivation. For example, the thermal relic from the wino or higgsino scenarios will have much smaller relic density than the observed dark matter (DM) density. The higgsino scenario is also excluded by the direct detection if all the DM is made of higgsino. In the gravitino case the gravitino is a warm/hot DM, and it is difficult to realize the observed relic density. The RpV case does not provide DM candidates.

2.2 Co-production scenarios

We can introduce two of the relevant particles ($\tilde{\chi}^{\pm}$, $\tilde{\chi}^0$, and $\tilde{l}$) to realize an LLCP. Especially, there are three scenarios that have a qualitative difference compared to the simplest models, in which the three-body production processes are available at the FCC-he.

A pedagogical scenario is models that have the (right-handed) selectron as the NLSP and the bino as the LSP. The bino allows the production process $eq \to \tilde{B}\tilde{e}q'$, which is three-body and thus has a much larger cross section. However, the slepton decay rate approximated for a very small mass difference, $\delta m := m_{\tilde{l}} - m_{\tilde{B}} - m_l$, is given by

$$\Gamma = \frac{g_1^2 Y^2}{4\pi}\left(1 - \frac{m_{\tilde{B}}^2}{m_{\tilde{l}}^2} - \frac{m_l^2}{m_{\tilde{l}}^2}\right)\|\boldsymbol{p}\| \approx \frac{g_1^2 Y^2}{\sqrt{2}\pi}\sqrt{\frac{m_l^3 \delta m}{m_{\tilde{l}}^2}}, \tag{4}$$

or

$$c\tau \approx 1.9 Y^{-2}\,\mathrm{mm}\left(\frac{m_{\tilde{l}}}{100\,\mathrm{GeV}}\right)\left(\frac{\delta m}{1\,\mathrm{eV}}\right)^{-1/2}\left(\frac{m_l}{m_e}\right)^{-3/2}, \tag{5}$$

where $Y = 1$ $(-1/2)$ and

$$\|\boldsymbol{p}\| = \frac{\sqrt{s}}{2}\lambda^{1/2}\left(\frac{m_l^2}{s}, \frac{m_{\tilde{B}}^2}{s}\right), \qquad \lambda^{1/2}(x,y) = \sqrt{(1-x-y)^2 - 4xy}, \qquad s = m_{\tilde{l}}^2. \tag{6}$$

Therefore a very unnatural degeneracy is required to have an LLCP, and we do not consider this possibility, even though this is well-known as the co-annihilation scenario for the dark matte relic density.

One may think of replacing the bino by $\tilde{H}_\mathrm{u}$ or $\tilde{H}_\mathrm{d}$. Then selectrons decay only through the neutralino mixing in the former case, while through the small Yukawa coupling in the latter case.[2] However, the three-body production $eq \to \tilde{H}\tilde{e}q'$ is also diminished by the smaller interaction, and the collider signature is equivalent to the two last scenarios in the previous section but more elusive because the daughter charged particles are very soft.

We instead consider the following two scenarios.

Selectron decaying to gravitino with Bino co-production This is the "slepton NLSP decaying to gravitino" scenario, but the Bino is also light and slightly heavier than the selectron. Then, the three-body processes $ep \to \tilde{e}\tilde{B}q$ is allowed, and a larger cross section is available. The bino immediately decays as $\tilde{B} \to e\tilde{e}$ with a decay rate

$$\Gamma(\tilde{B} \to e\tilde{e}_\mathrm{R}) = \frac{g_Y^2}{16\pi} m_{\tilde{B}}(1 + r_e - r_{\tilde{e}})\lambda^{1/2}(r_e, r_{\tilde{e}}) \tag{8}$$

with $r_e = m_e^2/m_{\tilde{B}}^2$ etc.; here the daughter electron is very soft and invisible.

Note that the wino cannot be the co-production partner because the selectron should be right-handed.

Selectron LSP with RpV and Bino co-production The RpV case is also compatible with bino co-production. The only difference from the gravitino case is the flavor of the lepton produced in the decay of a slepton.

Pure-wino LSP co-produced with left-handed selectron This is the "Pure-wino LSP" scenario but with light left-handed selectron (and electron sneutrino). The production processes are $e^- p \to \tilde{W}^\pm \tilde{e}^- q$, $\tilde{W}^0 \tilde{e}^- q$, $\tilde{W}^- \tilde{\nu}_e q$, and $\tilde{W}^0 \tilde{\nu}_e q$, followed by a selectron/sneutrino

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[2] Even for $m_{\tilde{H}_\mathrm{d}^0} \ll m_{\tilde{e}}$ (i.e., no phase-space suppression), the decay rate is already as as

$$\Gamma(\tilde{e} \to e\tilde{H}_\mathrm{d}^0) \approx \frac{m_e^2}{64\pi v^2 \cos^2\beta} m_{\tilde{e}} = (0.046\,\mathrm{mm})^{-1}\left(\frac{m_{\tilde{e}}/\cos^2\beta}{100\,\mathrm{GeV}}\right). \tag{7}$$

decay to a wino and a lepton. The decay rates are given by

$$\Gamma(\tilde{\nu}_e \to \tilde{W}^+ e^-) = \frac{g_2^2}{16\pi} m_{\tilde{\nu}_e} (1 - r_1 - r_2) \lambda^{1/2}(r_1, r_2), \tag{9}$$

$$\Gamma(\tilde{\nu}_e \to \tilde{W}^0 \nu_e) = \frac{g_2^2}{32\pi} m_{\tilde{\nu}_e} (1 - r_1 - r_2) \lambda^{1/2}(r_1, r_2), \tag{10}$$

$$\Gamma(\tilde{e}^- \to \tilde{W}^- \nu_e) = \frac{g_2^2}{16\pi} m_{\tilde{e}} (1 - r_1 - r_2) \lambda^{1/2}(r_1, r_2), \tag{11}$$

$$\Gamma(\tilde{e}^- \to \tilde{W}^0 e^-) = \frac{g_2^2}{32\pi} m_{\tilde{e}} (1 - r_1 - r_2) \lambda^{1/2}(r_1, r_2), \tag{12}$$

where r_1 and r_2 are the relevant squared mass ratios $m_{\tilde{W}^+}^2 / m_{\tilde{\nu}_e}^2$ etc. The decay of $\tilde{e}$ into $\tilde{\nu}_e$ is three-body and thus negligible. The contribution from the light sleptons to the mass difference δm is negligible.

As the sneutrino is lighter than the selectron but heavier than the winos, the wino–selectron mass difference is not very tiny. Therefore linear colliders are also sensitive to this model if the selectron is lighter than the collider energy $\sqrt{s}$. Also, at the FCC-he, the daughter electron from the prompt decays, e.g. $\tilde{\nu}_e \to \tilde{W}^+ e^-$, may be identified by the detectors.

3 Model parameters

We summarize the parameters of the models we consider, together with simplifying assumptions.

Pure-wino LSP The parameters are $m_{\tilde{\chi}^+}$ only, which is assumed a pure-wino. The LSP mass and the LLCP decay rate are determined [1] as Table 1.

Pure-wino LSP co-produced with left-handed selectron We use the tree-level mass relation (2) for sneutrino mass, setting $\tan\beta = 3$, i.e., $m_{\tilde{\nu}_e}^2 \equiv m_{\tilde{e}_\mathrm{L}}^2 - (72\,\mathrm{GeV})^2$, and take $(m_{\tilde{\chi}^+}, m_{\tilde{e}_\mathrm{L}})$ as the free parameters. However, the collider phenomenology does not depend on the slepton mass as long as $m_{\tilde{e}_\mathrm{L}} \lesssim m_{\tilde{\chi}^+} + 10\,\mathrm{GeV}$, and we will only consider $m_{\tilde{\chi}^+}$ as the parameter. The decay of $\tilde{\nu}_e$ and $\tilde{e}_\mathrm{L}$ are simulated according to Eqs. (9)–(12), their three body decays being neglected. The decay length of $\tilde{W}^\pm$ is taken from Table 1, since the slepton contribution to the mass difference is negligible.

Pure-higgsino LSP We neglect the tree-level mass difference, and set $m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm} - \delta m$ with the one-loop level values in Table 1. Then we have only one parameter $m_{\tilde{\chi}^+}$. As we are interested in LLCPs, we assume both $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ are invisible and we just consider the decay $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \pi^\pm$, not to $\tilde{\chi}_2^0 \pi^\pm$.

Slepton LLCP scenarios (without Bino co-production) As the co-production is only available for selectron LLCP, we assume the LLCP is the right-handed selectron. Note that the signature is similar for right-handed smuon LLCP, where co-production is unavailable, while more elusive in the case with a stau LLCP.

In the gravitino scenario, the LLCP slepton decays with $\mathrm{Br}(\tilde{e}_\mathrm{R} \to e\tilde{G}) = 100\%$. In the RpV scenario it depends on introduced RpV couplings. We introduce only the coupling

λ_{121}, which results in $\mathrm{Br}(\tilde{e}_\mathrm{R} \to e\nu) = \mathrm{Br}(\tilde{e}_\mathrm{R} \to \mu\nu) = 50\%$. Introducing other RpV parameters λ_{ijk} allows the slepton to decay into a tau-lepton, which makes the signal more elusive.

In this set-up, these two scenarios are very similar to each other, and the only difference is due to the different detector responses (acceptance and efficiency) to e and μ. As we ignore the difference, we will analyze these two scenarios together. We take the slepton mass and its decay length, $(m_{\tilde{e}}, c\tau)$ as free parameters, neglecting the gravitino and lepton masses.

Slepton LLCP scenarios with Bino co-production Just as the previous case, we treat the two scenarios together, and we use the same assumptions, together with $m_{\tilde{\chi}_1^0} = m_{\tilde{e}} + 1\,\mathrm{GeV}$.

4 Overall crosssection

As a first observation, we show the overall crosssections without considering any acceptances and efficiencies in Fig. 1. Note in particular that these crosssections include a very short-lived LLCPs with $c\tau \ll 10\,\mathrm{mm}$.

We observe that, without co-production, all the scenarios have ~ 100 times larger crosssections at the 14 TeV LHC than the FCC-he. Thus we expect that models without co-production will firstly be discovered at the HL-LHC, and the FCC-he may be used just as a confirmation.

If we include co-production, we can enhance the production cross section at the FCC-he, except for the Higgsino LSP scenario. For example, in Wino LSP scenario, the FCC-he cross-section becomes ×30 larger (compare the thinner and thicker lines). Then, the factor between LHC and FCC-he cross sections becomes roughly ×35 for the Wino scenarios and ×3 for the slepton scenarios, and the FCC-he may win against the LHC14, depending on the detector design, sensitivity, and background events.

5 Primitive detector simulation

Now we consider the detector acceptance and efficiency at the FCC-he.[3] The detection efficiency for an LLCP is given by a function $\epsilon_\mathrm{LLCP}(p_\mathrm{T}, \eta, l_\mathrm{T})$, where the transverse flight l_T is given by the position of its decay vertex (x, y, z) as $l_\mathrm{T} = \sqrt{x^2 + y^2}$. However, to obtain the efficiency, we need a detailed design of the detector as well as a full detector simulation. As the detector design is not available, here we perform a very primitive simulation, based on `delphes_card_FCCeh.dat` by Uta Klein (dated 22.12.16).

In our simulation, we set

$$\epsilon_\mathrm{LLCP}(p_\mathrm{T}, \eta, l_\mathrm{T}) = \begin{cases} 1 & \text{if } p_\mathrm{T} > 50\,\mathrm{GeV},\ -5.0 < \eta < 5.2, \text{ and } l_\mathrm{T} > l_\mathrm{min}, \\ 0 & \text{otherwise}, \end{cases} \tag{13}$$

where l_min is a constant. We consider four reference points $l_\mathrm{min} = \{10, 30, 50, 100\}\,\mathrm{mm}$, though the first two are too optimistic because the ATLAS IBL (the last layer of the pixel detector) locates at 33.25 mm (122.5 mm) from the beam axis.

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[3] We may also study prospects of these scenarios at the HL-LHC once the detailed reconstruction efficiencies are provided by ATLAS or CMS collaboration.

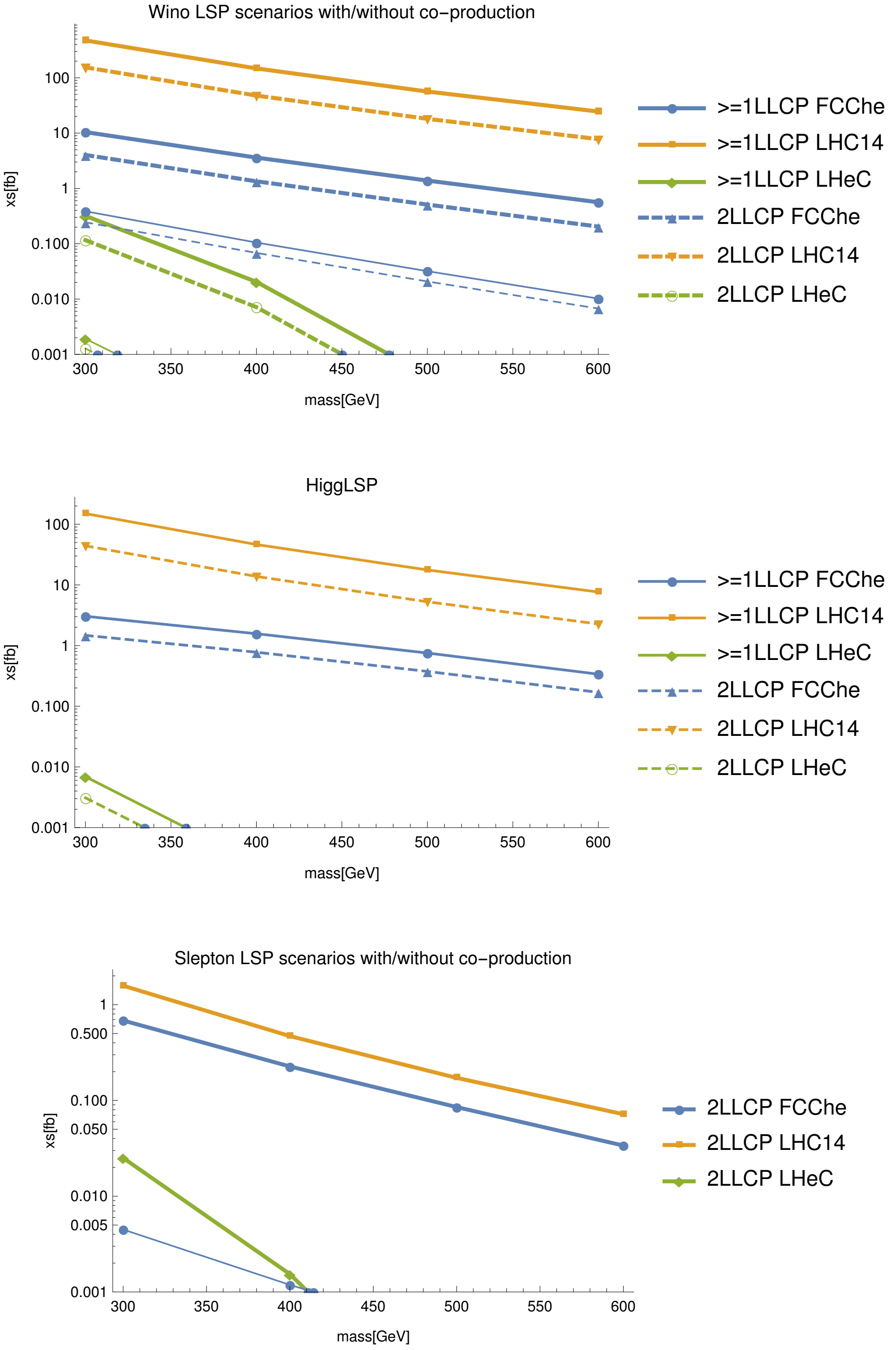

Figure 1: Overall crosssection of LLCP production. Top: Pure-wino scenarios. The thicker (thinner) lines are the scenarios with (without) co-production. For the LHC, they overlap each other. For co-production models we fixed $\tan\beta = 3$ and $m_{\tilde{e}_{\rm L}} = m_{\tilde{\chi}^0_1} + 9\,\mathrm{GeV}$, though the cross section is insensitive to the parameters. Middle: Pure-Higgsino scenario. Bottom: Slepton scenarios, where LLCPs are always produced in pair. The thicker (thinner) lines are the scenarios with (without) co-production. For the LHC, they overlap each other.

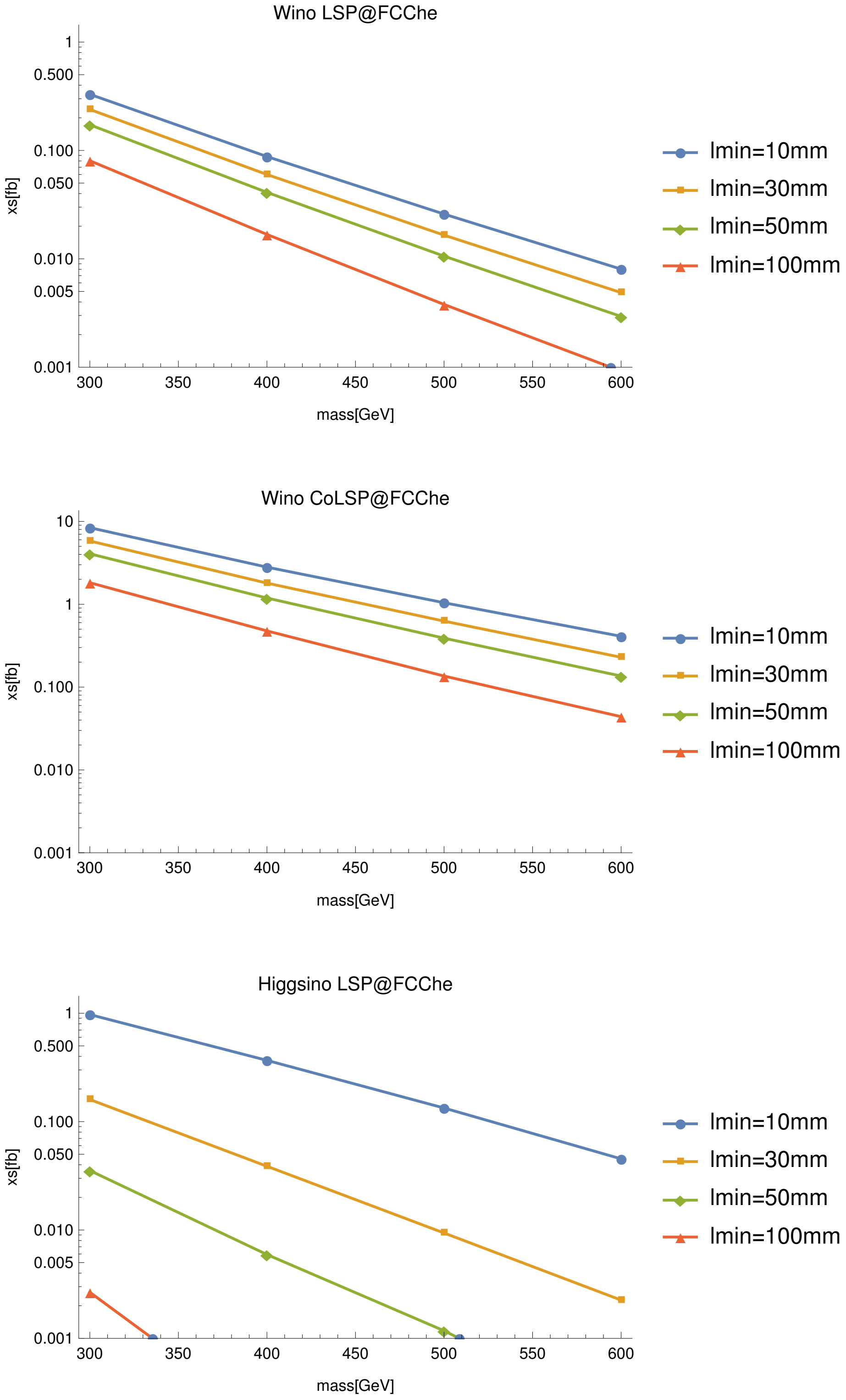

Figure 2: Results of the detector simulation for “ino” scenarios, for which the decay length $c\tau$ is fixed. Events with at least one LLCPs are selected. The lines correspond to the different reconstruction efficiency, i.e., an LLCP is detected with 100% efficiency if and only if $\beta\gamma c\tau > l_{\min}$

The results for chargino LLCP are shown in Fig. 2. As the Higgsino scenario has a decay length shorter than 10 mm, we need $l_{\mathrm{m}}in \lesssim 30\,\mathrm{mm}$ to capture the decays. However, considering that the IBL at the ATLAS detector locates at $r = 33\,\mathrm{mm}$, we expect it is very difficult to cover the Higgsino scenario at the FCC-hh. On the other hand, the Wino scenario with co-production, which is already excluded for $m_{\tilde{\chi}_1^\pm} < 430\,\mathrm{GeV}$, may be a good working scenario for FCC-he.

The slepton co-production LLCP is more interesting at the FCC-he, as shown in Fig. 3.[4] Assuming that $l_{\mathrm{min}} = 50\,\mathrm{mm}$, the FCC-he will have sensitivity for models with $c\tau \gtrsim 10$–$20\,\mathrm{mm}$, Even in a worse case with $l_{\mathrm{min}} = 100\,\mathrm{mm}$, models with $c\tau \gtrsim 50\,\mathrm{mm}$ will be captured well. As the FCC-hh will be competitive in this scenario with the LHC, performing detailed analysis based on this scenario will be an interesting future work.

6 Summary and discussion

In this note we observed the importance of "co-production." In the simplest models the FCC-he will have a smaller production cross section of LLCPs than the LHC. However, when the LLCP is degenerate with another particle, co-production process enhances the cross section.

The co-production is available for the Wino LLCP scenario and the slepton LLCP scenario. In the former case, though the FCC-he will have a certain sensitivity, the HL-LHC is sensitive enough. Thus the scenario should be used just as a benchmark scenario.

On the other hand, in the slepton co-produced LLCP scenario, the FCC-he will be as prospective as the LHC. Furthermore, as the LLCP decay in this scenario ($\tilde{e} \to e\tilde{G}$ or $\to l\nu$) provides a hard charged lepton, the sensitivity will be enhanced if we may be able to detect the secondary track from the lepton, which is known as a kink signature [5].

In this note we only consider the disappearing track search, which requires a considerable $c\tau$ so that it hits several layers of the tracker. In addition to that, the slepton scenario can be searched for by the non-pointing track searches,[5] which utilize the track from the charged daughter of the LLCP. As the non-pointing track searches are efficient for smaller $c\tau$, combining these two searches may cover the whole region of the slepton scenario.

References

[1] M. Ibe, S. Matsumoto, and R. Sato, *Mass Splitting between Charged and Neutral Winos at Two-Loop Level*, Phys. Lett. **B721** (2013) 252–260 [`arXiv:1212.5989`].

[2] S. D. Thomas and J. D. Wells, *Phenomenology of Massive Vectorlike Doublet Leptons*, Phys. Rev. Lett. **81** (1998) 34–37 [`hep-ph/9804359`].

[3] **ATLAS** Collaboration, *Search for long-lived charginos based on a disappearing-track signature in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, ATLAS–CONF–2017–017 (2017).

[4] G. F. Giudice and A. Pomarol, *Mass degeneracy of the Higgsinos*, Phys. Lett. **B372** (1996) 253–258 [`hep-ph/9512337`].

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[4] We do not consider the scenario without co-production because it has a tiny production cross section.

[5] This does not apply to Higgsino- and Wino-scenarios, where the charged daughter is a very soft pion.

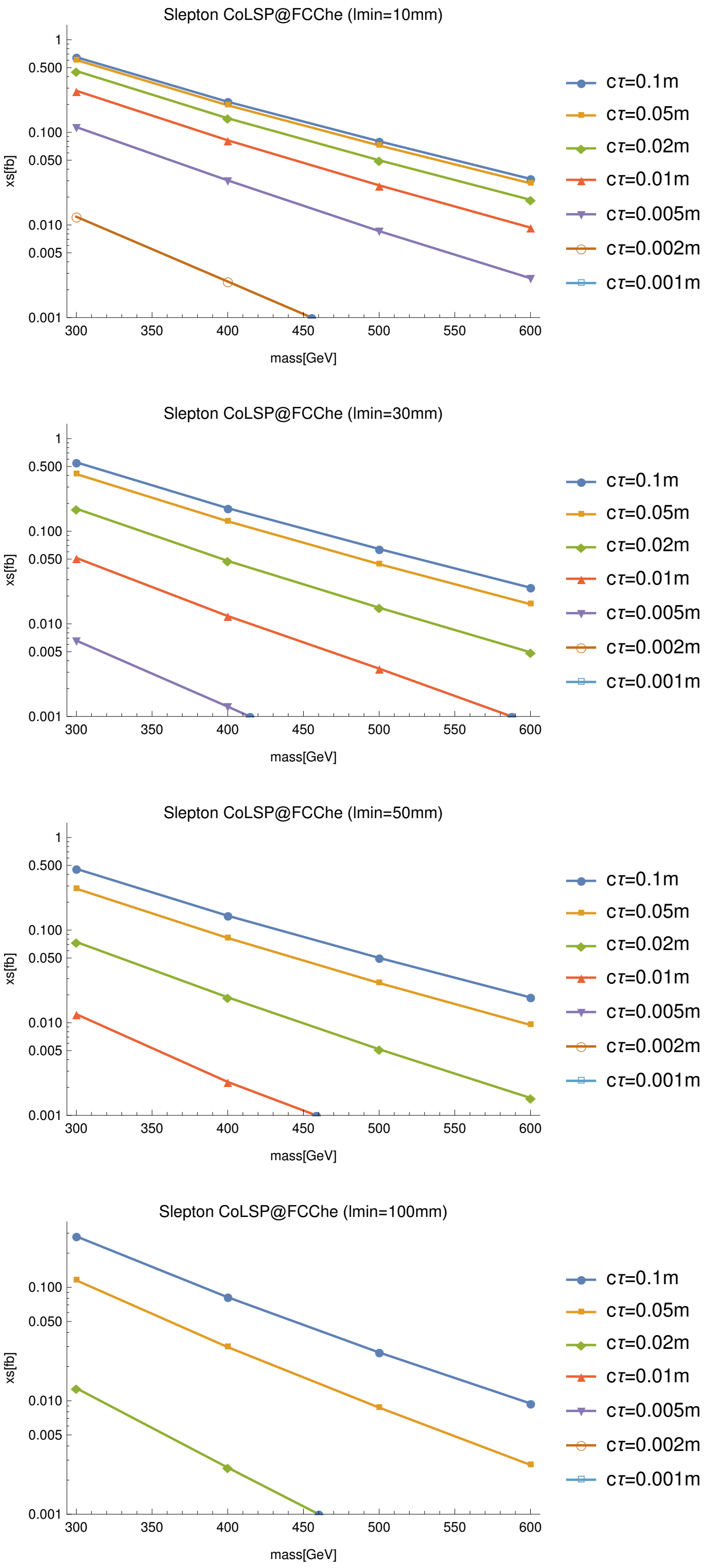

Figure 3: Results of the detector simulation for the slepton with Bino co-production scenario. Contrary to Fig. 2, the lines correspond to different decay length, $c\tau$, and l_{min} is fixed in each figure.

[5] S. Asai, Y. Azuma, M. Endo, K. Hamaguchi, and S. Iwamoto, *Stau Kinks at the LHC*, JHEP **12** (2011) 041 [`arXiv:1103.1881`].

Table 1: The mass difference $\delta m := m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ and the decay length $c\tau$ of the lighter chargino $\tilde{\chi}_1^\pm = \tilde{W}^\pm$ in pure-wino LSP scenario, i.e., when all the SUSY particles except for winos are decoupled [1].

$m_{\tilde{W}}$ [GeV]	200	250	300	350	400	450	500	550	600	700	800	900
δm [MeV]	159	160	161	162	162	163	163	163	163	164	164	164
$c\tau$ [mm]	71	67	64	63	62	61	60	60	59	59	59	59

Table 2: The mass difference $\delta m := m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ and the decay length $c\tau$ of the lighter chargino $\tilde{\chi}_1^\pm = \tilde{H}_{\mathrm{u,d}}^\pm$ in pure-higgsino LSP scenario, i.e., when all the SUSY particles except for higgsinos are decoupled [2].

$m_{\tilde{H}}$ [GeV]	200	250	300	350	400	450	500	550	600	700	800	900
δm [MeV]	297	306	313	319	323	326	329	331	333	336	338	340
$c\tau$ [mm]	11	10	9.4	8.9	8.5	8.2	8.0	7.8	7.7	7.4	7.2	7.1