

The SUSY Searches in HL-LHC with the CMS Phase-2 Detector

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Abstract

The upgrade of LHC brings future potential for searching signs of new physics, where the detection of supersymmetry is a significant prospect. This work discusses the vision of CMS, the upgrade of CMS detector and several searches in HL-LHC to test the strength of supersymmetry model including searching for $\tilde{\tau}$, light higgsino-like charginos and neutralinos, $\tilde{t}_1$, and dark photons. For accurate identification, limitations on events and objects are imposed, and analysis and results are based on the observation of CMS Phase-2 detector in simulation. Thus HL-LHC is a promising ground for the examination of SUSY model or the naturalness of the SUSY model.

Keywords

HL-LHC, CMS; Supersymmetry; New Physics.

1. Introduction

1.1. High-Luminosity LHC

The LHC completed its second operational run in 2018, and is scheduled Long Shutdown2 (LS2) from 2018 to 2021, during which the LHC and the whole CERN accelerator complex is being upgraded [1]. Extensive work is carried out on all the machines and infrastructures, some equipment being renovated, installed or substituted, to prepare for the development of LHC into the High-Luminosity LHC [2-3].

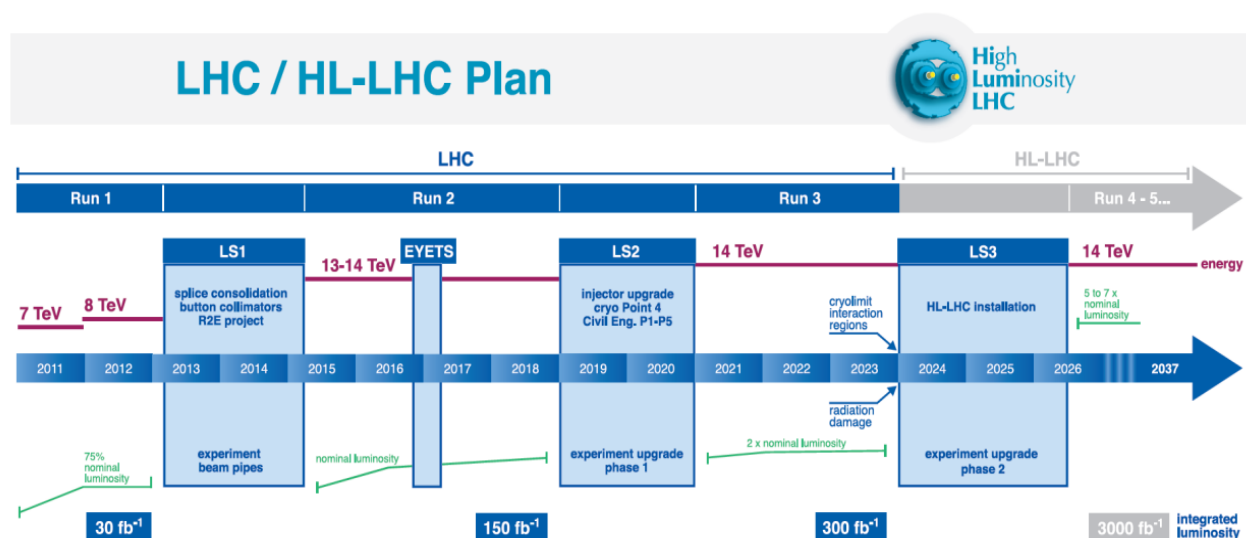


Figure 1. LHC plan of the operation intervals and experiment promotion. This figure is reproduced from Ref. [2].

The goal of future upgrades is to increase the luminosity by a factor of 10, reaching an integrated luminosity of approximately 3000 fb^{-1} and center-of-mass of 14 TeV by 2025, when the HL-LHC will be in work again. Thus the HL-LHC will have the capacity to generate more collisions, accumulating ten times more data than its predecessor[4].

1.2. CMS

The Compact Muon Solenoid is a detector conducting a broad range of physics programs that aims to solve the mysteries around Higgs Boson and dark matter. In the two year shutdown, CMS is preparing for significant upgrades in order to sustain the challenging environments in the HL-LHC while yielding sufficient performance[5]. It will allow more precision measurements of rare phenomena predicted in Standard Model, and potentially detection of new particles giving clues to new physics [6]. This work presents several approached for the study of supersymmetry model using expected CMS data during the HL-LHC run.

1.3. Supersymmetry

Supersymmetry (SUSY) [7] is a prevailing and successful theories beyond standard model (SM) in particle physics and proved capable of dealing with the fine-tuning problem, which is a weakness of standard model. Supersymmetry models propose that each SM particle is associated with its superpartner with the same quantum number but half a unit difference in spinning. The superpartners(Gaugino) of W bosons and U(1) gauge bosons and Higgs bosons are bino, wino and higgsino, and their mixture is the neutral eigenstate, the neutralinos ($\tilde{\chi}_{1,2,3,4}^0$), and wino and higgsino combine electrically charged particles charginos ($\tilde{\chi}_{1,2}^\pm$).

In R-parity conservating cases of SUSY models[8], the lightest supersymmetric particle (LSP) is a likely candidate of dark matter particles[9]. They are a result of the pair production of charginos and neutralinos and decay into final states with SM particles and LSPs. We make the assumption that $\tilde{\chi}_1^0$, the lightest neutralino is LSP.

2. The upgraded CMS detector

The CMS detector[10] will be upgraded to sustain harsh operational environment, cope with the challenges of data taking, for the future physics experiments requirements, with increased luminosity.

The CMS detector will be improved as the following:

- (1) The entire silicon tracking system, which consists of pixel and strip detectors, will be replaced, for higher granularity, reduction of material budget in the tracking volume, improvement in the radiation hardness, and it will extend the geometrical coverage and provide efficient tracking up to pseudorapidities of about $|\eta| = 4$.
- (2) The muon system will be enhanced with improved resistive plate chambers (RPCs), cathode strip chambers (CSC), and drift tubes (DT).
- (3) New muon detectors will be based on gas electron multiplier (GEM) technologies to add redundancy, increase the geometrical coverage up to about $|\eta| = 2.8$, and improve the trigger and reconstruction performance in the forward region.
- (4) A new combined sampling calorimeter (HGCAL) based on silicon pad sensors will be responsible for the endcap region($1.57 < |\eta| < 3.0$). The detector will be capable of providing highly segmented spatial information in both transverse and longitudinal directions, as well as high-precision timing information.
- (5) A minimum ionizing particle(MIP) timing detector(MTD) will be added in both barrel and endcap region, which allows 4-dimensional reconstruction of interaction vertices that significantly offset the CMS performance degradation due to high pileup(PU) rates.

3. Search for the production of $\tilde{\tau}$

$\tilde{\tau}$ is the hypothetical superpartner of the τ lepton. Some final states of $\tilde{\tau}$ makes the search for it in new physics particularly interesting. In Supersymmetric scenario, the $\tilde{\tau}$ is light, leading to final states containing one or more τ leptons. $1.57 < |\eta| < 3.0$, characterized by a light $\tilde{\tau}$ splitting with an almost pure bino-like lightest supersymmetric particle, meet the density consistent with cosmological observations[11].

In many SUSY scenarios, the $\tilde{\tau}$ mass is lighter than the one of selectrons and smuons, so it is likely to be produced and identified in the large data set expected at the HL-LHC. But because $\tilde{\tau}$ has a relatively small probability to be produced, it is a challenge.

In simplified SUSY models, $\tilde{\tau}$ may be obtained from pair production, which includes τ its antiparticle, and decays to a τ lepton and the LSP. Figure 1 presents the Feynman figure of its decay procedure[11].

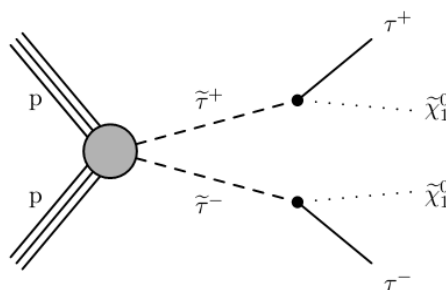


Figure 2. Feynman figure of $\tilde{\tau}$ pair production in simplified SUSY models. This figure is reproduced from Ref. [11]

A search is developed in events with two hadronically decaying τ leptons or one but the other to a muon or electron and neutrinos in the later circumstance (" $\tau_h \tau_h$ " analysis or " $\ell \tau_h$ " analysis)

3.1. Object selection requirements

The particle candidates have to satisfy the requirements:

- (1) Candidate events must contain two or more τ_h candidates, or one τ_h and one muon or electron from τ lepton decays.
- (2) Muons are expected to meet the conditions of transverse momentum $p_T > 30 \text{ GeV}$ and $|\eta| < 1.6$.
- (3) Muons and electrons should satisfy isolation. The measurement is taken to be the scalar sum of p_T of particles surrounding the lepton momentum vector in the volume of a cone with radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$, where the lepton's transverse momentum is required to be smaller than 0.05.
- (4) When jets that are reconstructed are restricted to have $p_T > 30 \text{ GeV}$ while $|\eta| < 2.7$.
- (5) For $\ell \tau_h$ final states, τ_h candidates should possess p_T above 40 GeV.
- (6) For $\tau_h \tau_h$ final state, τ_h candidates ought to possess p_T above 50 GeV.
- (7) The two reconstructed leptons are only accepted with a minimum separation of $\Delta R = 0.3$ to eliminating overlaps.
- (8) The τ_h reconstruction efficiency is tested approximately 30% with about 0.08% misidentification rate.

3.2. Event selection requirements

- (1) Both $\ell \tau_h$ and $\tau_h \tau_h$ final states need to include exactly two reconstructed leptons charging oppositely.

(2) With the purpose of suppressing the background of top quarks, in both cases of final states events in which b-tagged jet appears are rejected.

(3) In $\ell\tau_h$ analysis, the transverse momentum threshold of b-tagged jets is lower at 20 GeV, which helps significantly decrease the noise by W+jets events, W boson decaying to an electron or muon and a neutrino, and a jet misidentified τ_h .

(4) In $\ell\tau_h$ final state, qualified events can only contain at most one jet, with the restriction that the leptons are not separated more than $\Delta R = 3.5$.

3.3. Expected search sensitivity

The 95% CL upper limits and the 5σ discovery contour are computed, which are presented in Fig. 2. The $\tau_h\tau_h$ analysis has the advantage of achieving higher sensitivity, but the extra $\ell\tau_h$ channel broadens the exclusion region by about 60–80 GeV.

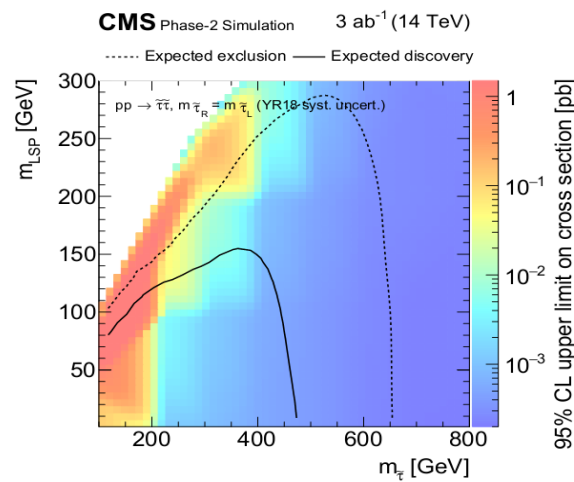


Figure 3. The expected upper limits at the 95% CL and the 5σ discovery potential for the combination of the results of the $\tau_h\tau_h$ and $\ell\tau_h$ channels. This figure is reproduced from Ref. [11].

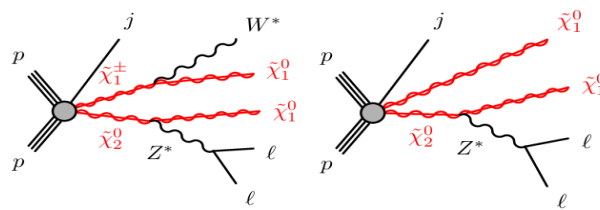


Figure 4. Feynman diagrams for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ (left) and $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ (right) pair production, in which $\tilde{\chi}_2^0$ continues to decay leptonically. This figure is reproduced from Ref. [12]

4. Search for light higgsino-like charginos and neutralinos

$\tilde{\chi}_{1,2}^\pm, \tilde{\chi}_{1,2,3,4}^0$ are the superposition of higgsinos and gauginos respectively. They are formed through pair production and their decay products are SM particles and LSPs. Higgsino is the single state that shows a characteristic of being low-mass in the scenarios of natural supersymmetry, while other particles have masses above the TeV scale. Thus a search for higgsino-like $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ is critical to probe for natural SUSY at HL-LHC [12].

Here a simplified SUSY model is used, where the higgsino-like $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are assumed to be mass-degenerate and to be pair-produced. Therefore $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ and the $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ production, the

Feynman diagrams of which is shown in figure3. These pair productions can only directly decay to $\tilde{\chi}_1^0$ through off-shell W and Z bosons, resulting in SM particles without high P_T . $\tilde{\chi}_1^\pm$ decays to $W^*\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ to $Z^*\tilde{\chi}_1^0$, having 100% branching ratio.

4.1. Event reconstruction requirements

- (1) Muons (electrons) with $5 \leq p_T \leq 30$ GeV and $|\eta| \leq 2.4$ (1.6) can be selected.
- (2) Muons and electrons can be a candidate if the scalar sum of track momenta inside the volume of a cone surrounding the lepton, is below 5 GeV and below 50% of the lepton p_T , whose radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$
- (3) A jet is accepted as a candidate if it has a transverse momentum above 40 GeV and pseudorapidities $|\eta| \leq 4.0$.
- (4) Candidate jets that have $p_T > 200$ GeV and $|\eta| \leq 2.4$ are referred to as jet from initial-state radiation (ISR).
- (5) Candidate leptons and jets are required to have a space separation $\Delta R > 0.4$.

4.2. Search regions requirements

- (1) An event is counted if it contains more than one low- p_T , same-flavor, oppositely charged leptons that qualify to be candidates.
- (2) Events are requested to have $p_T^{miss} \geq 300$ GeV.
- (3) Events are requested to include one or more candidate ISR jet (j_{ISR}) whose transverse momentum is above 200 GeV.
- (4) The p_T^{miss} , along with the SR candidate jet p_T in an event, needs to satisfy the condition $\Delta\phi(p_T^{miss}, p_T(j_{ISR})) \geq 2.0$.
- (5) The number of candidate jets $N_{jet} \leq 4$.
- (6) Events are rejected with one or more b jets.
- (7) Events are accepted only if the two candidate leptons have a angular separation $\Delta R(\ell_1, \ell_2) \leq 2.0$.

4.3. Expected search sensitivity

The 95% confident regions and the 5σ discovery contour are given in Fig. 4 [12].

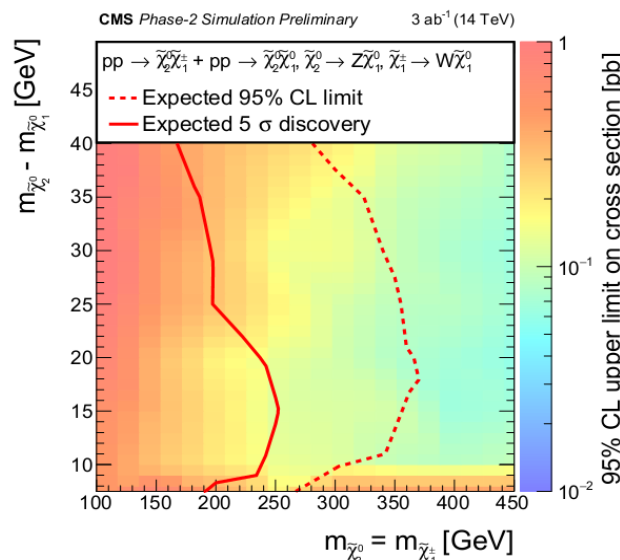


Figure 5. The computed 95% CL excluded regions and 5σ discovery boundary lines, which correspond to the combination of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ and $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ production. Results are presented for $\Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0) > 7.5$ GeV. This figure is reproduced from Ref. [12].

5. Search for dark photons decaying to displaced muons

Besides supersymmetric fields, Dark SUSY models employ a dark sector of fermions and gauge fields. Dark photon is the gauge boson corresponding to the $U_D(1)$ symmetry. It is a massive long-lived boson, with a mass acquired after $U_D(1)$ symmetry breaking [13].

A signature of such long-lived particles (LLPs) is that the standard model (SM) particles appear at a far distance from the primary collision point. Due to their low production cross section, LLPs were absent in the current searches, but HL-LHC may be capable of detecting its existence with higher sensitivity, benefiting from both the increased center-of-mass energy, leading to larger cross-sections, and the significantly larger amount of data.

Dark photons can be formed as the SM Higgs boson cascade decay results that would first decay to a n_1 pairs, which are MSSM-like lightest neutralinos. In the next step a single n_1 decays into one dark neutralino and one dark photon. This process is presented in Fig. 8 [13].

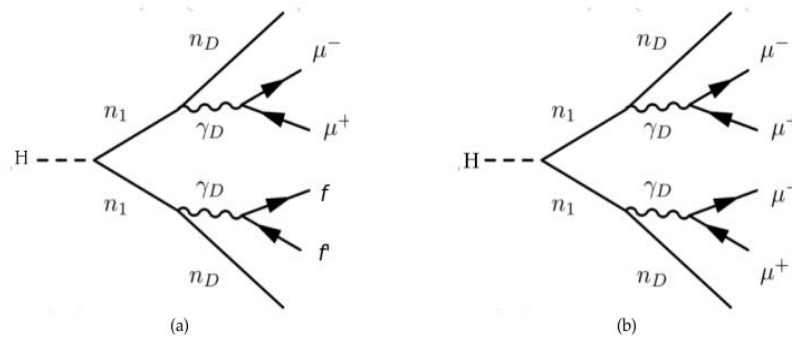


Figure 6. Signal models of the SM Higgs boson decays in Dark SUSY models. (a) Higgs Boson decaying process including two muons. (b) Higgs Boson decaying process including four muons. This figure is reproduced from Ref. [13].

5.1. Event selection

- (1) The DSA muons selected in offline need to satisfy $p_T \geq 15$ GeV and $|\eta| \leq 2.8$
- (2) The threshold of a dedicated displaced single-muon trigger is of $p_T \geq 20$ GeV
- (3) To build muon track with the hits in the muon chambers, the chi-squared divided by the degrees of freedom χ^2/ndof should not be higher than 2.0
- (4) In the region of the new ME0 station $2.4 < |\eta| < 2.8$, the track of the displaced muon has to have at least 17 muon hits for $|\eta| < 2.4$ and 6 hits
- (5) Selected displaced muons should have a transverse impact parameter significance $|d_0|/\sigma(d_0) \geq 5.0$
- (6) Each event should have at least two DSA muons fulfilling the requirements mentioned above. In the case that there are more than two selected muons, we use the two with higher p_T than others.
- (7) The two muons are required to be charged oppositely ($q_{\mu,1} \cdot q_{\mu,2} = -1$) and have a separation of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.05$
- (8) To reduce cosmic ray back-grounds, the angle between the two displaced muons are necessary to be below $\pi - 0.05$
- (9) p_T^{miss} must be at least 50 GeV

Aiming to distinguish signal from the background, R_{Muon} is used to postulate the distance between the primary vertex and the displaced muon track. Dedicated search regions are defined using these distances symmetrically for both muons.

5.2. Search sensitivity results

Given the 95% CL upper limits, Figure 9 give the description of the sensitivity results of the Dark SUSY models [13]. Figure 9 (a) describes the sensitivity results for a dark photon with decay length 1 m relating to the dark photon mass, Figure 9 (b) describes the sensitivity results for a dark photon mass of 20 GeV related to the decay length.

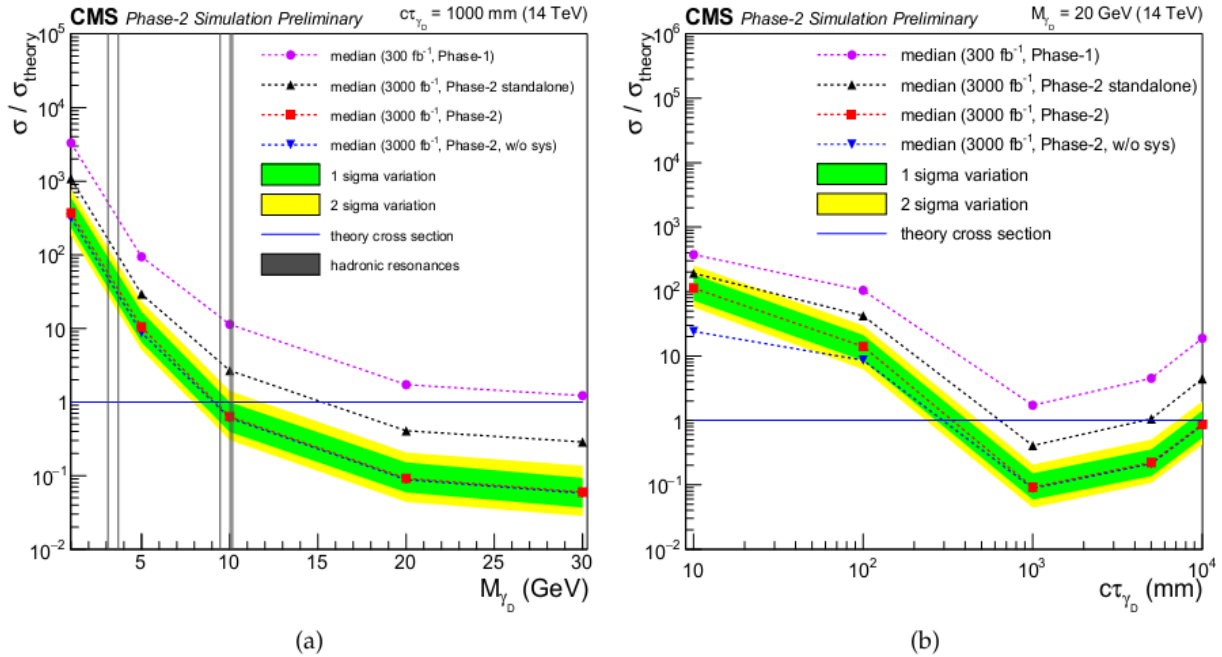


Figure 7. With the fixed decay length τ fixed to 1000 mm, (a) describes the sensitivity results for various dark photon mass hypotheses with 95% CL upper limits on production cross section $\sigma/\sigma_{\text{theory}}$. With the mass M_{γ_D} is fixed to 20 GeV, (b) describes the sensitivity related to decay length of the dark photon results. This figure is reproduced from Ref. [13].

6. Conclusion

The High Luminosity LHC (HL-LHC) run, which has been planned to operate in 2025, is expected to collect an integrated luminosity of approximately 3000 fb^{-1} at $\sqrt{s}=14 \text{ TeV}$. The discovery and study of SUSY will be a major goal of CMS during the HL-LHC run. We present several searches for the superpartner particles on the CMS Phase-2 detector in this article.

First, we discuss a detection for direct production of $\tilde{\tau}$ on the CMS Phase-2 detector, involving the three kinds of final states that contain either two τ leptons that decay hadronically and missing p_T , or one τ lepton that decays hadronically into a muon or electron and neutrinos.

Also, we present a search for the pair production of light higgsino-like charginos $\tilde{\chi}_1^\pm$ and neutralinos $\tilde{\chi}_2^0$ ($\tilde{\chi}_1^\pm \tilde{\chi}_2^0$, $\tilde{\chi}_2^0 \tilde{\chi}_1^0$), assuming that $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ particles are mass-degenerate and decay into the lightest stable superymmetric particle $\tilde{\chi}_1^0$ through off-shell W and Z bosons.

Additionally, in the last part of the article, a search for pairs of displaced muons originating from long-lived dark photons on the Phase-2 CMS detector is presented.

With these presentations, a strong probe of SUSY model or the naturalness of the SUSY model is expected at the HL-LHC, thus providing a large sensitivity to new physics.

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