Cornering Compressed Gluino at the LHC

Natsumi Nagata\textsuperscript{1}, Hidetoshi Otono\textsuperscript{2}, and Satoshi Shirai\textsuperscript{3}

\textsuperscript{1} Department of Physics, University of Tokyo, Tokyo 113-0033, Japan
\textsuperscript{2} Research Center for Advanced Particle Physics, Kyushu University, Fukuoka 812-8581, Japan
\textsuperscript{3} Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study, The University of Tokyo, Kashiwa 277-8583, Japan

Abstract

We discuss collider search strategies of gluinos which are highly degenerate with the lightest neutralino in mass. This scenario is fairly difficult to probe with conventional search strategies at colliders, and thus may provide a hideaway of supersymmetry. Moreover, such a high degeneracy plays an important role in dark matter physics as the relic abundance of the lightest neutralino is significantly reduced via coannihilation. In this paper, we discuss ways of uncovering this scenario with the help of longevity of gluinos; if the mass difference between the lightest neutralino and gluino is \( \lesssim 100 \) GeV and squarks are heavier than gluino, then the decay length of the gluino tends to be of the order of the detector-size scale. Such gluinos can be explored in the searches of displaced vertices, disappearing tracks, and anomalously large energy deposit by (meta)stable massive charged particles. We find that these searches are complementary to each other, and by combining their results we may probe a wide range of the compressed gluino region in the LHC experiments.
1 Introduction

Supersymmetric (SUSY) extensions of the Standard Model (SM) have been thought of as the leading candidate of physics beyond the SM. In particular, weak-scale SUSY has various attractive features—the electroweak scale is stabilized against quantum corrections, gauge coupling unification is achieved, and so on—and therefore has widely been studied so far. This paradigm is, however, under strong pressure from the results obtained at the Large Hadron Collider (LHC). Direct searches of SUSY particles impose stringent limits on their masses, especially those of colored particles such as squarks and gluino [1]. In addition, the observed value of the mass of the SM-like Higgs boson [2], \( m_h \simeq 125 \text{ GeV} \), may also imply that SUSY particles are rather heavy. In the minimal supersymmetric Standard Model (MSSM), the tree-level value of the SM-like Higgs boson mass is smaller than the \( Z \)-boson mass [3], and we need sizable quantum corrections in order to explain the discrepancy between the tree-level prediction and the observed value. It turns out that sufficiently large radiative corrections are provided by stop-loop diagrams [4] if the stop masses are much larger than the electroweak scale.

The SUSY SM with heavy SUSY particles (or, equivalently, with a high SUSY-breaking scale) have various advantages from the phenomenological point of view [5–14]; i) severe limits from the measurements of flavor-changing processes and electric dipole moments can be evaded [15, 16]; ii) heavy sfermions do not spoil successful gauge coupling unification if gauginos and Higgsinos remain around the TeV scale [17]; iii) the dimension-five proton decay caused by the color-triplet Higgs exchange [18], which was problematic for weak-scale SUSY [19], is suppressed by sfermion masses and thus the current proton decay bound can be evaded if SUSY particles are heavy enough [20], making the minimal SUSY SU(5) grand unification [21] viable; iv) cosmological problems in SUSY theories, such as the gravitino problem [22, 23] and the Polonyi problem [24] can be avoided. Nevertheless, high-scale SUSY models may have a potential problem regarding dark matter. In SUSY SMs with \( R \)-parity conservation, the lightest SUSY particle (LSP) is stable and thus can be a dark matter candidate. In particular, if the LSP is the lightest neutralino, its relic abundance is determined by the ordinary thermal freeze-out scenario. Then, it turns out that if the mass of the neutralino LSP is well above the weak scale, its thermal relic abundance tends to exceed the observed value of dark matter density, \( \Omega_{\text{DM}} h^2 \simeq 0.12 \) [25]. Thus, the requirement of \( \Omega_{\text{DM}} h^2 \lesssim 0.12 \) imposes a severe constraint on models with high-scale SUSY breaking.\(^1\)

In order to avoid over-production of the neutralino LSP in the high-scale SUSY scenario, it is necessary to assure a large annihilation cross section for the LSP. A simple way to do that is to assume the neutralino LSP to be an almost pure SU(2)\(_L\) multiplet, \( i.e. \), a wino or Higgsino. In such cases, the LSP has the electroweak interactions and thus has a relatively large annihilation cross section, which is further enhanced by the so-called Sommerfeld effects [26]. Indeed, the thermal relic abundance of wino and Higgsino with a mass of around 3 TeV [27] and 1 TeV [28], respectively, is

\(^1\)In fact, environmental selection with multiverse may naturally give the condition \( \Omega_{\text{DM}} h^2 \lesssim 0.12 \) and favor a “Spread SUSY”-type spectrum [7, 8, 14].
found to be in good agreement with the observed dark matter density $\Omega_{\text{DM}} h^2 \simeq 0.12$ [25]. Smaller masses are also allowed by the observation; in such cases, their thermal relic accounts for only a part of the total dark matter density and the rest should be filled with other dark matter candidates and/or with non-thermal contribution via, e.g., the late-time decay of gravitinos [29]. For previous studies of wino and Higgsino dark matter, see Refs. [8, 26, 27, 29–40] and Refs. [41, 42], respectively, and references therein.

On the other hand, bino-like dark matter in general suffers from over-production, and thus a certain mechanism is required to enhance the annihilation cross section. For example, we may utilize the s-channel resonant annihilation through the exchange of the Higgs bosons (called funnel) [43]. Coannihilation [43] may also work if there is a SUSY particle that is degenerate with the LSP in mass and has a large annihilation cross section; stau [44], stop [45–47], gluino [46–50], wino [30, 49, 51, 52], etc., can be such a candidate. In particular, only the latter two can have a mass close to the LSP in the case of the split-SUSY type models [5–14]. In this paper, we especially focus on the neutralino-gluino coannihilation case as this turns out to offer a variety of interesting signatures at colliders and thus can be probed in various search channels at the LHC. For a search strategy of the bino-wino coannihilation scenario at the LHC, see Ref. [52].

In order for the neutralino-gluino coannihilation to work, the neutralino LSP and gluino should be highly degenerate in mass. For instance, if the neutralino LSP is bino-like, the mass difference between the LSP and gluino, $\Delta m$, needs to be less than around 100 GeV and squark masses should be less than $\mathcal{O}(100)$ TeV for coannihilation to be effective [50]. Such a small mass difference makes it difficult to probe this scenario in the conventional LHC searches as hadronic jets from the decay products of gluinos tend to be soft. In the previous work [50], however, it is pointed out that such a compressed gluino with heavy squarks has a decay length of $\gtrsim \mathcal{O}(1)$ mm and therefore may be probed by using searches for displaced vertices (DVs). In fact, it was shown in Ref. [50] that the DV search at the LHC can investigate a wide range of parameter space where the correct dark matter abundance is obtained for the bino LSP through coannihilation with gluinos.

In this paper, we further study the prospects of the LHC searches to probe this compressed gluino scenario. In particular, we discuss search strategies for the very degenerate case, i.e., $\Delta m \lesssim \mathcal{O}(10)$ GeV. Such an extremely small mass difference considerably narrows down the reach of DV searches. We however find that for such a small mass difference, long-lived gluinos leave disappearing track signals when they form charged $R$-hadrons, and thus can be probed in the disappearing track searches. In addition, for gluinos which have a decay length of $\gtrsim 1$ m, searches for anomalously large energy deposit by (meta)stable heavy charged particles can be exploited. We see below that these three searches are complementary to each other. Hence, by combining the results from these searches we can thoroughly study the compressed gluino scenario at the LHC.
2 Properties of compressed gluino

Here we discuss the compressed gluino signatures at colliders. If the masses of squarks are very large and/or the mass difference between the gluino and the neutralino LSP $\Delta m$ is quite small, the gluino decay width is strongly suppressed and its decay length can be as large as the detector-size scale. We briefly discuss this feature in Sec. 2.1.\footnote{For detailed discussions on the decay of (long-lived) gluinos, see Refs. [53, 54].} When the gluino lifetime is longer than the QCD hadronization time scale, gluinos produced at colliders form $R$-hadrons. We discuss the properties of $R$-hadrons and their implications on the LHC searches in Sec. 2.2.\footnote{For previous studies on the $R$-hadron properties in the split-SUSY, see Ref. [55].}

\subsection*{2.1 Gluino decay}

The decay of gluinos is induced by the diagrams shown in Fig. 1. Here, we focus on the case where the mass difference $\Delta m$ is rather small ($\Delta m \lesssim 100$ GeV) and squark masses are much larger than the electroweak scale; \textit{i.e.}, $\tilde{m} \gtrsim 10$ TeV, where $\tilde{m}$ denotes the typical scale of squark masses.\footnote{We however note that gluinos can be long-lived even though $\tilde{m}$ is around the TeV scale if the mass difference $\Delta m$ is small enough. This possibility is briefly discussed in Sec. 4.} In this case, the tree-level three-body decay process shown in Fig. 1a is proportional to $(\Delta m)^5$, and thus its decay width is strongly suppressed for compressed gluinos. For the loop-induced two-body decay in Fig. 1b, on the other hand, the decay width strongly depends not only on the mass difference but also on the nature of the lightest neutralino. If the neutralino LSP is a pure bino and left-right mixing of the scalar top quarks is small, the matrix element of the two-body decay process is suppressed by a factor of $m_{\tilde{g}} - m_{\tilde{B}}$ ($m_{\tilde{g}}$ and $m_{\tilde{B}}$ are the gluino and bino masses, respectively), which originates from a chirality flipping in the external lines. As a result, the two-body decay rate also goes as $\Gamma(\tilde{g} \to \tilde{B}g) \propto (\Delta m)^5$, which makes the three-body decay channel dominate the two-body one. If the LSP is a pure wino, the two-body decay is suppressed by the SU(2)$_L$ gauge symmetry, and thus the three-body decay is again the dominant channel. Contrary to these cases, if the LSP is Higgsino-like, the two-body decay is the main decay process. In this case, the dominant contribution to this decay process comes from the top-stop loop diagram and its matrix element is proportional to the top mass $m_t$. Thus, the two-body decay rate goes as $\Gamma(\tilde{g} \to \tilde{H}^0g) \propto m_t^2(\Delta m)^3$. In addition, this loop contribution is logarithmically enhanced as the masses of the scalar top quarks get larger.
The tree-level decay process is, on the other hand, suppressed by small Yukawa couplings since the stop exchange process, which is large because of the top Yukawa coupling, is kinematically forbidden for compressed gluinos.

Eventually, we see that the gluino decay length is approximately given by

\[
ct\bar{g} = \begin{cases} 
O(1 - 10) \text{ cm} \times \left( \frac{\Delta m}{10 \text{ GeV}} \right)^{-5} \left( \frac{\tilde{m}}{10 \text{ TeV}} \right)^4 & \text{(bino or wino LSP)} \\
O(0.01 - 0.1) \text{ mm} \times \left( \frac{\Delta m}{10 \text{ GeV}} \right)^{-3} \left( \frac{\tilde{m}}{10 \text{ TeV}} \right)^4 & \text{(Higgsino LSP)}
\end{cases}
\]  

(1)

The dependence of these approximated formulae on \(\Delta m\) is captured by the above discussions. From these expressions, we find that compressed gluinos generically have decay lengths of the order of the detector size when the squark mass scale is \(\gtrsim 10\) TeV. We make the most of this observation to probe the compressed gluino scenario.

There are several situations where the above tendency of gluino decay may be altered. For the bino LSP case, the two-body decay channel can be important if the left-right mixing in the scalar top sector is large and \(\Delta m\) is very small. This decay branch can also be enhanced if there is a sizable bino-Higgsino mixing. In addition, if \(\Delta m \ll 10\) GeV, the parton-level description gets less appropriate, and the hadronic properties of decay products significantly affect the gluino decay. Further dedicated studies are required to give a precise theoretical calculation of the gluino decay rate for this very small \(\Delta m\) region, which is beyond the scope of this paper.

## 2.2 \(R\)-hadrons

A long-lived gluino forms a bound state with quarks and/or gluons once they are produced at colliders. Such bound states, being \(R\)-parity odd, are called \(R\)-hadrons [56]. \(R\)-hadrons are categorized into several classes in terms of their constituents; if \(R\)-hadrons are composed of a gluino and a pair of quark and anti-quark, \(\tilde{g}qq\), they are called \(R\)-mesons; if they consist of a gluino and three quarks (anti-quarks), \(\tilde{g}qqq\) (\(\tilde{g}q\bar{q}\bar{q}\)), they are called \(R\)-baryons (\(R\)-antibaryons); a bound state which is made of a gluino and a gluon, \(\tilde{g}\bar{g}\), is referred to as an \(R\)-glueball.

The production fractions of \(R\)-hadron species have a direct impact on the gluino search sensitivities discussed below, as some of these search strategies rely on the production of charged \(R\)-hadrons. A computation [57] in which hadronization is performed using \textsc{Pythia} [58] shows that the production rates of \(R\)-mesons dominate those of \(R\)-baryons. The production fraction of \(R\)-glueball is, on the other hand, theoretically unknown and thus regarded as a free parameter. In the analysis of Ref. [57], this fraction is set to be 10%, which is the default value used in \textsc{Pythia}. Then, it is found that the fraction of \(R\)-mesons is 88.5% while that of \(R\)-baryons is only 1.6%. Among them, charged \(R\)-hadrons are 44.8%. This value however significantly decreases if we set the \(R\)-glueball fraction to be a larger value. Taking this ambiguity into account, in the following analysis, we take different values for the \(R\)-glueball fraction and regard the resultant changes as theoretical uncertainty.
The mass spectrum of $R$-hadrons, especially that of $R$-mesons and $R$-glueball, also affects the $R$-hadron search strategy significantly. An estimation [59] based on a simple mass formula for the lowest hadronic states [60], which is derived from the color-spin interaction given by one gluon exchange, indicates that the lightest $R$-meson state is “$R$-rho”, namely, a bound state which consists of a gluino and a vector iso-triplet made of up and down quarks. The mass of “$R$-pion” (a bound state of a gluino and a spin-zero iso-triplet made of up and down quarks) is found to be larger than the $R$-rho mass by about 80 MeV. This observation is consistent with the calculations using the bag model [61] and QCD lattice simulation [62], which predict $R$-rho to be lighter than $R$-pion by 40 MeV and 50 MeV, respectively. On the other hand, there is controversy about the estimation of the $R$-glueball mass. An estimation by means of the constituent masses of partons shows that $R$-glueball is heavier than $R$-rho by 120 MeV [57]. The bag-model calculation [61] also predicts $R$-glueball to be slightly heavier than $R$-rho. However, the lattice result [62] shows that the $R$-rho mass is larger than the $R$-glueball mass by 47 MeV, though we cannot conclude by this result that these results are incompatible with each other since the uncertainty of this calculation is as large as 90 MeV (and the former two estimations also suffer from uncertainties of similar size). We here note that if $R$-glueball is lighter than $R$-rho and the mass difference between them is larger than the pion mass, then an $R$-rho can decay into an $R$-glueball and a pion via strong interactions. Other $R$-mesons may also decay into $R$-glueball. This considerably reduces the number of tracks associated with charged $R$-mesons, and thus weakens the discovery reach of $R$-hadrons. In the following analysis, we assume that such decay channels are kinematically forbidden, as is supported by the above calculations of the $R$-meson and $R$-glueball mass spectrum. As for $R$-baryons, the flavor singlet $J = 0$ state, which has a non-zero strangeness, is the lightest [63, 64]. In addition, there are flavor octet states which are stable against strong decays and heavier than the singlet state by about a few hundred MeV. Their weak-decay lifetime is likely to be sufficiently long so that they can be regarded as stable at colliders [65].

While $R$-hadrons are propagating through a detector, they may scatter off nuclei in it. Such processes are potentially important since they may change $R$-hadron species. For instance, by scattering a nucleon in the detector material, an $R$-meson or $R$-glueball can be converted into an $R$-baryon with emitting a pion. However, the reverse process is unlikely since pions are rarely found in the detector material and the process itself suffers from kinematical suppression. For this reason, although $R$-mesons and $R$-glueball are dominantly produced at the outset, we have a sizable fraction for $R$-baryons in the outer part of detectors, such as in the Muon Spectrometer. The nuclear reaction rates of $R$-hadrons are evaluated in Refs. [59, 65–67], and it is found that an $R$-hadron interacts with nucleons about five times while propagating in 2 m of iron. Therefore, most of $R$-mesons and $R$-glueballs may be converted into $R$-baryons before they enter into the Muon Spectrometer. In the analysis discussed below, however, we focus on the $R$-hadron searches using the Inner Detector, on which the nucleon interactions have little impact as the matter density up to the Inner Detector region is very low. This makes our search strategies free from uncertainties originating from the
estimation of $R$-hadron interactions in detectors—we neglect these effects in the following analysis.

3 LHC searches

Next, we discuss the LHC signatures of the compressed gluinos. Depending on the gluino lifetime and the gluino-LSP mass difference, we need adopt several strategies to catch gluino signals. In this paper, we focus on the ATLAS detector. The performance of the CMS detector is similar to that of the ATLAS, though.

3.1 ATLAS experiment

The ATLAS detector is located at one of the interaction points of the LHC, which consists of the Inner Detector, the calorimeters, the Muon Spectrometer, and the magnet systems [68]. The long-lived gluino searches discussed in this paper make full use of the Pixel detector and the SemiConductor Tracker (SCT) in the Inner Detector. Various dedicated techniques, which have been developed to search for new long-lived particles, can be applied to the long-lived gluino searches in order to maximize its discovery potential. Here, we briefly review the detectors used in the searches relevant to this work.

Pixel detector

The Pixel detector is the sub-detector closest to the interaction point, which has a four-layer cylindrical structure with a length of about 800 mm in the barrel region. The innermost layer called Insertable B-Layer (IBL), which was installed before the LHC-Run2 started [69], has silicon pixel sensors of $50 \times 250 \, \mu m$ and is located at a radius of 33 mm. The other layers have silicon pixel sensors of $50 \times 400 \, \mu m$ at radii of 50.5 mm, 88.5 mm, and 122.5 mm. The Pixel detector can measure the energy deposit along the trajectory of each charged particle, i.e., $dE/dx$, which is sensitive to slow-moving (meta)stable particles according to the Bethe-Bloch formula.

SCT

The SCT surrounds the Pixel detector, which has four layers in the barrel region with a length of about 1500 mm at radii of 299 mm, 371 mm, 443 mm, and 514 mm. A module on each layer consists of two 80 $\mu m$-pitch strip silicon sensors with a stereo angle of 40 mrad between strip directions. The SCT does not have a capability to measure $dE/dx$ in contrast to the Pixel detector, since the SCT employs binary readout architecture.
3.2 ATLAS searches

Gluinos give rise to various signatures at colliders depending on the decay lifetime. In this work, we consider the following four search strategies,\(^5\) which are sensitive to different ranges of the gluino decay length:

**Prompt decay [1]:** \(c\tau_{\tilde{g}} \lesssim 1\) mm

Searches for a new particle which is assumed to decay at the interaction point are also sensitive to long-lived particles. The ATLAS experiment reconstructs tracks whose transverse impact parameters \((d_0)\) are less than 10 mm, then checks a correspondence with primary vertices. As a result, a portion of the decay vertices of long-lived particles is merged with one of the primary vertices.

Generally, for metastable gluinos, these inclusive searches get less effective for \(c\tau_{\tilde{g}} \gg 1\) cm, since jets from the gluino decay are displaced from the primary vertex and fail the event selection criteria [71]. In the compressed gluino case, however, these searches are less sensitive to the gluino lifetime, since it is jets from the initial state radiation that play a main role in the conventional jets + MET searches. For this reason, even for a gluino with a decay length greater than \(\mathcal{O}(1)\) m, the resultant mass bound will be similar to that for a prompt decay compressed gluino.

**Displaced-vertex search [72]:** \(c\tau_{\tilde{g}} \gtrsim 1\) mm

A long-lived gluino decaying to quarks or a gluon leaves a displaced vertex (DV) away from the interaction point. In order to reconstruct tracks from such a DV, the requirement on the transverse impact parameter for tracks is loosen such that 2 mm < \(|d_0|\) < 300 mm. As a result, the sensitivity is maximized for particles with a decay length of \(\mathcal{O}(10)\) mm.

The sensitivity becomes worse as the mass difference between gluino and the LSP gets smaller [50], since the invariant mass of DVs is required to be larger than 10 GeV in order to separate signal events from background fake vertices. Due to this requirement, the gluino-LSP mass difference of \(\lesssim 20\) GeV is hard to probe.

**Disappearing-track search [73]:** \(c\tau_{\tilde{g}} \gtrsim 10\) cm

Originally, the disappearing-track search has been developed for the search of long-lived charged winos with the neutral wino being the LSP [9, 74, 75]. This technique may also be applicable to long-lived gluinos for the following reason. As we discuss in the previous section, a certain fraction of long-lived gluinos form charged \(R\)-hadrons. If the gluino and the LSP are degenerate in mass, the track associated with a charged \(R\)-hadron seems to disappear when the gluino in the \(R\)-hadron decays, since the jet emission from the gluino decay is very soft. As mentioned above, the DV search

---

\(^5\)Some of these search strategies have already been considered in the context of long-lived gluino searches in Refs. [50, 70].
does not work efficiently when the gluino-LSP mass difference is very small. Such a degenerate mass region can instead be covered by the disappearing-track search.

A candidate track in the disappearing-track search should have four hits in the Pixel detector and the SCT with no activity after the last hit required. Thanks to the installation of IBL, the minimum length of disappearing tracks which can be searched for by this strategy is shortened from 299 mm to 122.5 mm in the LHC Run2. This allows the range of decay lengths covered by the disappearing-track search to be slightly wider than that in the DV search.

**Pixel dE/dx search [76]:** $c\tau_{\tilde{g}} \gtrsim 1 \text{ m}$

A particle with a mass of the order of the electroweak scale or larger tends to travel with a low velocity after it is produced at the LHC, which may be observed as a large $dE/dx$ in the Pixel detector. Hence, by searching for this signature, we can probe charged $R$-hadrons. While a minimum ionization particle is expected to give $\sim 1.2 \text{ MeV} \cdot \text{cm}^2/\text{g}$ of $dE/dx$, the threshold for the Pixel $dE/dx$ search is set to be $1.8 \text{ MeV} \cdot \text{cm}^2/\text{g}$ with a small correction depending on $\eta$. For the track selection, at least seven hits in the Pixel detector and the SCT are required, which corresponds to the minimum track-length of 371 mm. Note that this search strategy does not require decay of particles, and thus is also sensitive to completely stable particles. For this reason, the cover-range of decay lengths by the Pixel $dE/dx$ search is quite broad.

### 3.3 LHC Prospects

Now, we show the sensitivities of the searches listed in Sec. 3.2 to the compressed gluino scenario. In this study, we use the program MADGRAPH5 [77]+PYTHIA8 [58, 78]+DELPHES3 [79] and estimate the production cross sections of SUSY particles with PROSPINO2 [80] or NLL-fast [81].

In Fig. 2, we show the prospects of each search in the $c\tau_{\tilde{g}}-m_{\tilde{g}}$ plane with an integrated luminosity of 40 fb$^{-1}$ at the 13 TeV LHC. The blue dashed lines show the expected limits from the DV search with the gluino-LSP mass difference set to be $\Delta m = 100$ GeV, 20 GeV, and 15 GeV from top to bottom. We use the same event selection requirements as in the 8 TeV study [52] except that we require missing energy $E_T^{\text{miss}}$ to be greater than 200 GeV as a trigger, which was $E_T^{\text{miss}} > 100$ GeV in the 8 TeV study [52]. We expect the number of background events for this signal is as small as in the case of the 8 TeV run [72]; here, we assume it to be 0–10 and the systematic uncertainty of the background estimation to be 10%. The upper (lower) border of each band corresponds to the case where the number of the background events is 0 (10). It is found that the sensitivity of the DV search is maximized for a gluino with a decay length of $\sim 10$ cm, and may reach a gluino mass of about 2.2 TeV (1.2 TeV) for $\Delta m = 100$ GeV (15 GeV). We also find that the DV search becomes less powerful when the gluino-LSP mass difference gets smaller, as mentioned in Sec. 3.2.

The red dashed lines show the expected reaches of the disappearing-track search. As we discussed above, this search relies on the production of charged $R$-hadrons, but the estimate of the charged
Figure 2: The expected limits from the searches considered in Sec. 3.2 with an integrated luminosity of 40 fb$^{-1}$ at the 13 TeV LHC. The blue dashed, red solid, and green long-dashed lines correspond to the DV search, the disappearing-track search, and the Pixel $dE/dx$ search, respectively.

$R$-hadron production rates suffers from uncertainty due to the unknown $R$-glueball fraction. To take this uncertainty into account, in Fig. 2, we set the $R$-glueball fraction to be 10% and 50% in the top and bottom lines, respectively. To estimate the prospects, we basically adopt the same selection criteria as the charged wino search at the LHC Run 1 [82], including the isolation criteria and the detection efficiency of a disappearing track. To consider the update in the LHC Run 2, we refer to the result presented in Ref. [83]. In addition, to take into account the improvement because of the IBL, we assume the detection efficiency 60% for $|\eta| < 1.5$ and $13 < r < 30$ cm, which was zero at the Run 1 study [82]. We further adopt the following kinematic cut: $E_T^{miss} > 140$ GeV and the leading jet with a transverse momentum of $P_T > 140$ GeV. The number of background events is assumed to be 10 and its uncertainty is supposed to be 10% for 40 fb$^{-1}$. The result in Fig. 2 shows that the disappearing track search is sensitive to a decay length of $\sim 1$ m, and can probe a longer lifetime region than the DV search. Notice that even for $c\tau_{\tilde{g}} = \mathcal{O}(10)$ cm, around which the sensitivity of the DV search is maximized, the reach of the disappearing-track search may exceed that of the DV search if the gluino-LSP mass difference is very small.

The expected reach of the Pixel $dE/dx$ search is plotted in the green long-dashed lines. Here again, we set the $R$-glueball fraction to be 10% and 50% in the top and bottom lines, respectively, to show the uncertainty from the unknown $R$-glueball fraction. For this analysis, we adopt the same event selection as in the study of ATLAS with $\sqrt{s} = 13$ TeV and an integrated luminosity of 3.2 fb$^{-1}$ [84], where the $R$-glueball fraction is set to be 10%. We have estimated the number of background
Figure 3: The expected limits on the compressed gluino parameter space from the 13 TeV LHC with an integrated luminosity of 40 fb$^{-1}$. The shaded areas with the blue dashed, red solid, green long-dashed, and orange dash-dotted borders can be probed with the searches of DVs, disappearing tracks, anomalous energy deposit ($dE/dx$) in the Pixel detector, and prompt gluino decays, respectively. The black dotted lines show a contour plot for the gluino decay length $c\tau_{\tilde{g}}$.

To show the prospects of the above searches for probing the compressed gluino scenario, in Fig. 3, we show their expected reaches with the 13 TeV 40 fb$^{-1}$ LHC data in the $m_{\tilde{g}}$–$\Delta m$ plane, where the shaded areas with the blue dashed, red solid, green long-dashed, and orange dash-dotted borders correspond to the searches of DVs, disappearing tracks, anomalous energy deposit ($dE/dx$) in the Pixel detector, and prompt gluino decays, respectively. We also show a contour plot for the gluino decay length $c\tau_{\tilde{g}}$ in the black dotted lines. All squark masses (collectively denoted by $m_{\tilde{q}}$) are set to be 10 TeV and 50 TeV in Figs. 3a and 3b, respectively, and the LSP is assumed to be a pure bino. To obtain the expected sensitivity of the prompt gluino decay search with the 40 fb$^{-1}$ data, we adopt the event cut criteria used in Ref. [1] and estimate the number of background events by rescaling the result of the 13.3 fb$^{-1}$ case. These figures show that the highly compressed region can be probed with the disappearing-track search and the Pixel $dE/dx$ search, while if the gluino-LSP mass splitting is large enough (such that $c\tau_{\tilde{g}} \ll 1$ mm), only the traditional gluino searches can have sensitivities. Between these two regions, the DV search offers the best sensitivity. We also find that the reach of the DV search strongly depends on the squark masses. To obtain a gluino decay length of $c\tau_{\tilde{g}} \sim 10$ cm, to which the DV search is most sensitive, a smaller $\Delta m$ is required for lighter squarks (see Eq. (1)). As noted above, the sensitivity of the DV search is considerably reduced for a small $\Delta m$; for this reason, the reach of the DV search shrinks for small squark masses. On the other
Figure 4: Testable regions of the gluino-LSP mass difference $\Delta m$ and the gluino decay length $c\tau_{\tilde{g}}$ from the $dE/dx$, disappearing track, displaced vertex, and prompt inclusive searches at 13 TeV LHC with an integrated luminosity of 40 fb$^{-1}$. Here we fix the gluino mass to be 1.5 TeV.

hand, the disappearing-track and Pixel $dE/dx$ searches are rather robust on the change of $m_{\tilde{q}}$, as these searches do not rely on the jet emission from the gluino decay. In any case, Fig. 3 shows that the experimental strategies discussed in Sec. 3.2 play complementary rolls in searching for long-lived gluinos, and by combining the results from these searches we can probe a wide range of parameter space in the compressed gluino scenario.

4 Conclusion and discussion

The compressed-gluino parameter region in the MSSM, where gluino and the LSP are highly degenerate in mass, can evade the over-abundance of dark matter and thus is still viable. Therefore, it is important to test this possibility experimentally. It is however difficult to probe this scenario using the conventional search strategy at the LHC based on the jets plus missing energy signatures, since jets emitted from the gluino decay tend to be very soft. In this paper, we have discussed the LHC search strategies which are sensitive to the compressed gluino scenario. They include the searches of DVs, disappearing tracks, and anomalous energy deposit in the Pixel detector, on top of the ordinary inclusive searches. Then we have found that these searches are indeed sensitive to long-lived gluinos.

In summary, we show the cover areas of these search strategies in the $\Delta m-c\tau_{\tilde{g}}$ plane in Fig. 4, where we set the gluino mass to be 1.5 TeV and consider the 13 TeV LHC run with an integrated
luminosity of 40 fb$^{-1}$. As seen in this figure, depending on the lifetime and the gluino-LSP mass difference, we can adopt different search strategies. When the gluino decay length is $\gtrsim 1$ m, the Pixel $dE/dx$ search offers the best sensitivity to gluinos. For $0.1$ m $\lesssim c\tau_\tilde{g} \lesssim 10$ m, the disappearing-track search is quite promising. The DV search can cover the range of $1$ mm $\lesssim c\tau_\tilde{g} \lesssim 1$ m, though its sensitivity strongly depends on the gluino-LSP mass difference. The $c\tau_\tilde{g} < 1$ mm region can be probed by ordinary prompt-decay gluino searches. As a consequence, these searches complement each other, which allows us to investigate a broad range of the compressed gluino region in the LHC experiments.

Notice that although we have focused on the cases with a high sfermion mass scale ($\tilde{m} \gtrsim 10$ TeV), the search strategies discussed in this paper, especially the disappearing-track search and the $dE/dx$ search, can also be powerful for $\tilde{m} < 10$ TeV if the gluino-LSP mass difference is small enough to make gluino long-lived. Such a possibility may be interesting since it offers a refuge for (semi)natural SUSY models, which may be uncovered by the long-lived gluino searches.

In this paper, we discuss long-lived gluinos whose longevity comes from small mass difference between the gluino and the LSP. Actually, in not only the gluino case but more general “co-LSP” scenarios, we may have such a long-lived particle. For instance, in the very compressed stau-LSP and stop-LSP cases, metastable charged particles may appear and thus can be observed in the long-lived particle searches at the LHC. As it turns out, for instance, by using the setup of the disappearing track search discussed above, we can probe a right-handed stau (stop) with a mass of around 200 (950) GeV at the LHC Run 2 for $c\tau = 10$ cm. Detailed studies of such generalization are out of the scope of the present paper and will be discussed elsewhere.

Acknowledgments

This work was supported by World Premier International Research Center Initiative (WPI), MEXT, Japan.

References

[1] Further searches for squarks and gluinos in final states with jets and missing transverse momentum at $\sqrt{s} = 13$ TeV with the ATLAS detector, Tech. Rep. ATLAS-CONF-2016-078 (CERN, Geneva, 2016); Search for pair production of gluinos decaying via top or bottom squarks in events with b-jets and large missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Tech. Rep. ATLAS-CONF-2016-052 (CERN, Geneva, 2016); Search for new physics in the all-hadronic final state with the MT2 variable, Tech. Rep. CMS-PAS-SUS-16-015 (CERN, Geneva, 2016).

[2] G. Aad et al. (ATLAS), Phys.Lett. B716, 1 (2012), arXiv:1207.7214 [hep-ex]; S. Chatrchyan
et al. (CMS), Phys.Lett. B716, 30 (2012), arXiv:1207.7235 [hep-ex]; G. Aad et al. (ATLAS, CMS), Phys.Rev.Lett. 114, 191803 (2015), arXiv:1503.07589 [hep-ex].

[3] K. Inoue, A. Kakuto, H. Komatsu, and S. Takeshita, Prog.Theor.Phys. 67, 1889 (1982); R. A. Flores and M. Sher, Annals Phys. 148, 95 (1983).

[4] Y. Okada, M. Yamaguchi, and T. Yanagida, Prog.Theor.Phys. 85, 1 (1991); Y. Okada, M. Yamaguchi, and T. Yanagida, Phys.Lett. B262, 54 (1991); J. R. Ellis, G. Ridolfi, and F. Zwirner, Phys.Lett. B257, 83 (1991); H. E. Haber and R. Hempfling, Phys.Rev.Lett. 66, 1815 (1991); J. R. Ellis, G. Ridolfi, and F. Zwirner, Phys.Lett. B262, 477 (1991).

[5] J. D. Wells, (2003), arXiv:hep-ph/0306127 [hep-ph]; J. D. Wells, Phys.Rev. D71, 015013 (2005), arXiv:hep-ph/0411041 [hep-ph].

[6] N. Arkani-Hamed and S. Dimopoulos, JHEP 0506, 073 (2005), arXiv:hep-th/0405159 [hep-th]; G. Giudice and A. Romanino, Nucl.Phys. B699, 65 (2004), arXiv:hep-ph/0406088 [hep-ph]; N. Arkani-Hamed, S. Dimopoulos, G. Giudice, and A. Romanino, Nucl.Phys. B709, 3 (2005), arXiv:hep-ph/0409232 [hep-ph].

[7] L. J. Hall and Y. Nomura, JHEP 1201, 082 (2012), arXiv:1111.4519 [hep-ph].

[8] L. J. Hall, Y. Nomura, and S. Shirai, JHEP 1301, 036 (2013), arXiv:1210.2395 [hep-ph].

[9] M. Ibe, T. Moroi, and T. Yanagida, Phys.Lett. B644, 355 (2007), arXiv:hep-ph/0610277 [hep-ph].

[10] M. Ibe and T. T. Yanagida, Phys.Lett. B709, 374 (2012), arXiv:1112.2462 [hep-ph]; M. Ibe, S. Matsumoto, and T. T. Yanagida, Phys.Rev. D85, 095011 (2012), arXiv:1202.2253 [hep-ph].

[11] A. Arvanitaki, N. Craig, S. Dimopoulos, and G. Villadoro, JHEP 1302, 126 (2013), arXiv:1210.0555 [hep-ph].

[12] N. Arkani-Hamed, A. Gupta, D. E. Kaplan, N. Weiner, and T. Zorawski, (2012), arXiv:1212.6971 [hep-ph].

[13] J. L. Evans, M. Ibe, K. A. Olive, and T. T. Yanagida, Eur.Phys.J. C73, 2468 (2013), arXiv:1302.5346 [hep-ph]; J. L. Evans, K. A. Olive, M. Ibe, and T. T. Yanagida, Eur.Phys.J. C73, 2611 (2013), arXiv:1305.7461 [hep-ph].

[14] Y. Nomura and S. Shirai, Phys.Rev.Lett. 113, 111801 (2014), arXiv:1407.3785 [hep-ph].

[15] F. Gabbiani, E. Gabrielli, A. Masiero, and L. Silvestrini, Nucl.Phys. B477, 321 (1996), arXiv:hep-ph/9604387 [hep-ph].
[16] T. Moroi and M. Nagai, Phys.Lett. B723, 107 (2013), arXiv:1303.0668 [hep-ph]; D. McKeen, M. Pospelov, and A. Ritz, Phys.Rev. D87, 113002 (2013), arXiv:1303.1172 [hep-ph]; W. Altmannshofer, R. Harnik, and J. Zupan, JHEP 1311, 202 (2013), arXiv:1308.3653 [hep-ph]; K. Fuyuto, J. Hisano, N. Nagata, and K. Tsumura, JHEP 1312, 010 (2013), arXiv:1308.6493 [hep-ph].

[17] J. Hisano, T. Kuwahara, and N. Nagata, Phys.Lett. B723, 324 (2013), arXiv:1304.0343 [hep-ph].

[18] N. Sakai and T. Yanagida, Nucl. Phys. B197, 533 (1982); S. Weinberg, Phys. Rev. D26, 287 (1982).

[19] T. Goto and T. Nihei, Phys.Rev. D59, 115009 (1999), arXiv:hep-ph/9808255 [hep-ph]; H. Murrayama and A. Pierce, Phys.Rev. D65, 055009 (2002), arXiv:hep-ph/0108104 [hep-ph].

[20] M. Liu and P. Nath, Phys.Rev. D87, 095012 (2013), arXiv:1303.7472 [hep-ph]; J. Hisano, D. Kobayashi, T. Kuwahara, and N. Nagata, JHEP 1307, 038 (2013), arXiv:1304.3651 [hep-ph]; M. Dine, P. Draper, and W. Shepherd, JHEP 1402, 027 (2014), arXiv:1308.0274 [hep-ph]; N. Nagata and S. Shirai, JHEP 1403, 049 (2014), arXiv:1312.7854 [hep-ph]; L. J. Hall, Y. Nomura, and S. Shirai, JHEP 06, 137 (2014), arXiv:1403.8138 [hep-ph]; J. L. Evans, N. Nagata, and K. A. Olive, Phys.Rev. D91, 055027 (2015), arXiv:1502.00034 [hep-ph]; B. Bajc, S. Lavignac, and T. Mede, JHEP 01, 044 (2016), arXiv:1509.06680 [hep-ph]; J. Ellis, J. L. Evans, F. Luo, N. Nagata, K. A. Olive, and P. Sandick, Eur. Phys. J. C76, 8 (2016), arXiv:1509.08388 [hep-ph]; J. Ellis, J. L. Evans, A. Mustafayev, N. Nagata, and K. A. Olive, Eur. Phys. J. C76, 592 (2016), arXiv:1608.05370 [hep-ph].

[21] N. Sakai, Z.Phys. C11, 153 (1981); S. Dimopoulos and H. Georgi, Nucl.Phys. B193, 150 (1981).

[22] H. Pagels and J. R. Primack, Phys. Rev. Lett. 48, 223 (1982); S. Weinberg, Phys. Rev. Lett. 48, 1303 (1982); M. Yu. Khlopov and A. D. Linde, Phys. Lett. B138, 265 (1984).

[23] M. Kawasaki, K. Kohri, and T. Moroi, Phys. Rev. D71, 083502 (2005), arXiv:astro-ph/0408426 [astro-ph]; M. Kawasaki, K. Kohri, T. Moroi, and A. Yotsuyanagi, Phys. Rev. D78, 065011 (2008), arXiv:0804.3745 [hep-ph].

[24] G. D. Coughlan, W. Fischler, E. W. Kolb, S. Raby, and G. G. Ross, Phys. Lett. B131, 59 (1983).

[25] P. A. R. Ade et al. (Planck), Astron. Astrophys. 594, A13 (2016), arXiv:1502.01589 [astro-ph.CO].
[26] J. Hisano, S. Matsumoto, and M. M. Nojiri, Phys.Rev.Lett. 92, 031303 (2004), arXiv:hep-ph/0307216 [hep-ph]; J. Hisano, S. Matsumoto, M. M. Nojiri, and O. Saito, Phys.Rev. D71, 063528 (2005), arXiv:hep-ph/0412403 [hep-ph].

[27] J. Hisano, S. Matsumoto, M. Nagai, O. Saito, and M. Senami, Phys.Lett. B646, 34 (2007), arXiv:hep-ph/0610249 [hep-ph].

[28] M. Cirelli, A. Strumia, and M. Tamburini, Nucl.Phys. B787, 152 (2007), arXiv:0706.4071 [hep-ph].

[29] T. Gherghetta, G. F. Giudice, and J. D. Wells, Nucl. Phys. B559, 27 (1999), arXiv:hep-ph/9904378 [hep-ph]; T. Moroi and L. Randall, Nucl. Phys. B570, 455 (2000), arXiv:hep-ph/9906527 [hep-ph].

[30] N. Arkani-Hamed, A. Delgado, and G. F. Giudice, Nucl. Phys. B741, 108 (2006), arXiv:hep-ph/0601041 [hep-ph].

[31] S. Shirai, F. Takahashi, and T. T. Yanagida, Phys. Lett. B680, 485 (2009), arXiv:0905.0388 [hep-ph]; M. Ibe, S. Matsumoto, S. Shirai, and T. T. Yanagida, JHEP 1307, 063 (2013), arXiv:1305.0084 [hep-ph]; M. Ibe, S. Matsumoto, S. Shirai, and T. T. Yanagida, Phys. Lett. B741, 134 (2015), arXiv:1409.6920 [hep-ph].

[32] J. Hisano, K. Ishiwata, and N. Nagata, JHEP 06, 097 (2015), arXiv:1504.00915 [hep-ph].

[33] M. Ibe, S. Matsumoto, and R. Sato, Phys. Lett. B721, 252 (2013), arXiv:1212.5989 [hep-ph].

[34] T. Cohen, M. Lisanti, A. Pierce, and T. R. Slatyer, JCAP 1310, 061 (2013), arXiv:1307.4082 [hep-ph]; J. Fan and M. Reece, JHEP 10, 124 (2013), arXiv:1307.4400 [hep-ph]; A. Hryczuk, I. Cholis, R. Iengo, M. Tavakoli, and P. Ullio, JCAP 1407, 031 (2014), arXiv:1401.6212 [astro-ph.HE].

[35] B. Bhattacherjee, M. Ibe, K. Ichikawa, S. Matsumoto, and K. Nishiyama, JHEP 07, 080 (2014), arXiv:1405.4914 [hep-ph].

[36] M. Cirelli, F. Sala, and M. Taoso, JHEP 10, 033 (2014), [Erratum: JHEP01,041(2015)], arXiv:1407.7058 [hep-ph].

[37] M. Baumgart, I. Z. Rothstein, and V. Vaidya, JHEP 04, 106 (2015), arXiv:1412.8698 [hep-ph].

[38] K. Harigaya, K. Ichikawa, A. Kundu, S. Matsumoto, and S. Shirai, JHEP 09, 105 (2015), arXiv:1504.03402 [hep-ph].

[39] M. Ibe, S. Matsumoto, S. Shirai, and T. T. Yanagida, Phys. Rev. D91, 111701 (2015), arXiv:1504.05554 [hep-ph]; K. Hamaguchi, T. Moroi, and K. Nakayama, Phys. Lett. B747, 523 (2015), arXiv:1504.05937 [hep-ph].
[40] V. Lefranc, E. Moulin, P. Panci, F. Sala, and J. Silk, JCAP **1609**, 043 (2016), arXiv:1608.00786 [astro-ph.HE].

[41] N. Nagata and S. Shirai, JHEP **01**, 029 (2015), arXiv:1410.4549 [hep-ph].

[42] K. Cheung, C.-W. Chiang, and J. Song, JHEP **04**, 047 (2006), arXiv:hep-ph/0512192 [hep-ph]; K. Cheung, S. Y. Choi, and J. Song, Phys. Lett. **B677**, 54 (2009), arXiv:0903.3175 [hep-ph]; V. A. Beylin, V. I. Kuksa, G. M. Vereshkov, and R. S. Pasechnik, Int. J. Mod. Phys. **A24**, 6051 (2009), arXiv:0903.4201 [hep-ph]; K. S. Jeong, M. Shimosuka, and M. Yamaguchi, JHEP **09**, 050 (2012), arXiv:1112.5293 [hep-ph]; P. J. Fox, G. D. Kribs, and A. Martin, Phys. Rev. **D90**, 075006 (2014), arXiv:1405.3692 [hep-ph]; J. L. Evans, M. Ibe, K. A. Olive, and T. T. Yanagida, Phys. Rev. **D91**, 055008 (2015), arXiv:1412.3403 [hep-ph]; E. J. Chun, S. Jung, and J.-C. Park, (2016), arXiv:1607.04288 [hep-ph]; A. Dedes, D. Karamitros, and V. C. Spanos, Phys. Rev. **D94**, 095008 (2016), arXiv:1607.05040 [hep-ph].

[43] K. Griest and D. Seckel, Phys.Rev. **D43**, 3191 (1991).

[44] J. R. Ellis, T. Falk, and K. A. Olive, Phys. Lett. **B444**, 367 (1998), arXiv:hep-ph/9810360 [hep-ph]; J. R. Ellis, T. Falk, K. A. Olive, and M. Srednicki, Astropart. Phys. **13**, 181 (2000), [Erratum: Astropart. Phys.15,413(2001)], arXiv:hep-ph/9905481 [hep-ph]; T. Nihei, L. Roszkowski, and R. Ruiz de Austri, JHEP **07**, 024 (2002), arXiv:hep-ph/0206266 [hep-ph]; M. Citron, J. Ellis, F. Luo, J. Marrouche, K. A. Olive, and K. J. de Vries, Phys. Rev. **D87**, 036012 (2013), arXiv:1212.2886 [hep-ph].

[45] C. Boehm, A. Djouadi, and M. Drees, Phys. Rev. **D62**, 035012 (2000), arXiv:hep-ph/9911496 [hep-ph]; J. R. Ellis, K. A. Olive, and Y. Santoso, Astropart. Phys. **18**, 395 (2003), arXiv:hep-ph/0112113 [hep-ph]; M. A. Ajai, T. Li, and Q. Shafi, Phys. Rev. **D85**, 055021 (2012), arXiv:1111.4467 [hep-ph]; J. Ellis, K. A. Olive, and J. Zheng, Eur. Phys. J. **C74**, 2947 (2014), arXiv:1404.5571 [hep-ph].

[46] A. De Simone, G. F. Giudice, and A. Strumia, JHEP **06**, 081 (2014), arXiv:1402.6287 [hep-ph].

[47] S. P. Liew and F. Luo, (2016), arXiv:1611.08133 [hep-ph].

[48] S. Profumo and C. E. Yaguna, Phys. Rev. **D69**, 115009 (2004), arXiv:hep-ph/0402208 [hep-ph]; D. Feldman, Z. Liu, and P. Nath, Phys. Rev. **D80**, 015007 (2009), arXiv:0905.1148 [hep-ph]; J. Ellis, F. Luo, and K. A. Olive, JHEP **09**, 127 (2015), arXiv:1503.07142 [hep-ph]; J. Ellis, J. L. Evans, F. Luo, and K. A. Olive, JHEP **02**, 071 (2016), arXiv:1510.03498 [hep-ph].

[49] K. Harigaya, K. Kaneta, and S. Matsumoto, Phys.Rev. **D89**, 115021 (2014), arXiv:1403.0715 [hep-ph].
[50] N. Nagata, H. Otono, and S. Shirai, Phys. Lett. B748, 24 (2015), arXiv:1504.00504 [hep-ph].

[51] H. Baer, T. Krupovnickas, A. Mustafayev, E.-K. Park, S. Profumo, et al., JHEP 0512, 011 (2005), arXiv:hep-ph/0511034 [hep-ph]; M. Ibe, A. Kamada, and S. Matsumoto, Phys.Rev. D89, 123506 (2014), arXiv:1311.2162 [hep-ph].

[52] N. Nagata, H. Otono, and S. Shirai, JHEP 10, 086 (2015), arXiv:1506.08206 [hep-ph].

[53] H. E. Haber and G. L. Kane, 11th International Symposium on Lepton and Photon Interactions at High Energies Ithaca, New York, August 4-9, 1983, Nucl. Phys. B232, 333 (1984); H. Baer, V. D. Barger, D. Karatas, and X. Tata, Phys. Rev. D36, 96 (1987); R. Barbieri, G. Gamberini, G. F. Giudice, and G. Ridolfi, Nucl. Phys. B301, 15 (1988); H. Baer, X. Tata, and J. Woodside, Phys. Rev. D42, 1568 (1990); M. Toharia and J. D. Wells, JHEP 02, 015 (2006), arXiv:hep-ph/0503175 [hep-ph]; P. Gambino, G. F. Giudice, and P. Slavich, Nucl. Phys. B726, 35 (2005), arXiv:hep-ph/0506214 [hep-ph].

[54] R. Sato, S. Shirai, and K. Tobioka, JHEP 11, 041 (2012), arXiv:1207.3608 [hep-ph]; R. Sato, S. Shirai, and K. Tobioka, JHEP 10, 157 (2013), arXiv:1307.7144 [hep-ph].

[55] W. Kilian, T. Plehn, P. Richardson, and E. Schmidt, Eur. Phys. J. C39, 229 (2005), arXiv:hep-ph/0408088 [hep-ph]; J. L. Hewett, B. Lillie, M. Masip, and T. G. Rizzo, JHEP 09, 070 (2004), arXiv:hep-ph/0408248 [hep-ph].

[56] G. R. Farrar and P. Fayet, Phys. Lett. B76, 575 (1978).

[57] M. Fairbairn, A. C. Kraan, D. A. Milstead, T. Sjostrand, P. Z. Skands, and T. Sloan, Phys. Rept. 438, 1 (2007), arXiv:hep-ph/0611040 [hep-ph].

[58] T. Sjostrand, S. Mrenna, and P. Z. Skands, JHEP 05, 026 (2006), arXiv:hep-ph/0603175 [hep-ph].

[59] A. C. Kraan, Eur. Phys. J. C37, 91 (2004), arXiv:hep-ex/0404001 [hep-ex].

[60] A. De Rujula, H. Georgi, and S. L. Glashow, Phys. Rev. D12, 147 (1975).

[61] M. S. Chanowitz and S. R. Sharpe, Phys. Lett. B126, 225 (1983).

[62] M. Foster and C. Michael (UKQCD), Phys. Rev. D59, 094509 (1999), arXiv:hep-lat/9811010 [hep-lat].

[63] G. R. Farrar, Phys. Rev. Lett. 53, 1029 (1984).

[64] F. Buccella, G. R. Farrar, and A. Pugliese, Phys. Lett. B153, 311 (1985).
arXiv:0905.4749 [hep-ph]; W. Beenakker, S. Brensing, M. Kramer, A. Kulesza, E. Laenen, et al., JHEP 0912, 041 (2009), arXiv:0909.4418 [hep-ph]; W. Beenakker, S. Brensing, M. Kramer, A. Kulesza, E. Laenen, et al., Int.J.Mod.Phys. A26, 2637 (2011), arXiv:1105.1110 [hep-ph].

[82] G. Aad et al. (ATLAS), Phys. Rev. D88, 112006 (2013), arXiv:1310.3675 [hep-ex].

[83] M. Saito, https://kds.kek.jp/indico/event/22451/session/15/contribution/185/material/slides/0.pdf.

[84] M. Aaboud et al. (ATLAS), Phys. Rev. D93, 112015 (2016), arXiv:1604.04520 [hep-ex].