

Light gravitino production in association with gluinos at the LHC

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ABSTRACT: We study the jets plus missing energy signature at the LHC in a scenario where the gravitino is very light and the gluino is the next-to-lightest supersymmetric particle and promptly decays into a gluon and a gravitino. We consider both associated gravitino production with a gluino and gluino pair production. By merging matrix elements with parton showers, we generate inclusive signal and background samples and show how information on the gluino and gravitino masses can be obtained by simple final state observables.

Contents

1	Introduction	1
2	Light gravitino production at the LHC	3
2.1	Gluino-gravitino associated production	3
2.2	Gluino pair production	5
3	Merging matrix elements with parton showers	6
3.1	Physics parameters and observables	7
3.2	Technical setup for simulations	8
3.3	Validation	8
4	Jets plus missing energy	10
5	Summary	13
A	Effective gravitino interaction Lagrangian	14

1 Introduction

Identification and interpretation of new physics signals are formidable challenges at the LHC. A promising and rather general signature for probing new physics at hadron colliders is jets plus missing transverse energy ($\cancel{E}_T$) [1]. Particularly, the signature has been commonly studied in the context of the minimal supersymmetric extension of the Standard Model (SM) and also simplified models with the lightest neutralino as the lightest supersymmetric particle (LSP). In these models, strongly-interacting superpartners (gluinos and/or squarks) are copiously produced and decay into gluons/quarks and stable neutralinos, leading to a signal containing multiple jets and missing energy. So far no excess over the SM background expectation has been observed at the Tevatron [2–5] and the LHC [6, 7], which is interpreted as exclusion limits in the traditional $m_0 - m_{1/2}$ plane or in the gluino–squark mass plane. On the other hand, another interesting LSP candidate is the gravitino, and such scenarios have not been fully explored in the jets+ $\cancel{E}_T$ signature.¹ This is the primary target in this article.

Gravitinos are the spin-3/2 superpartners of gravitons and become massive via the super-Higgs mechanism by absorbing massless spin-1/2 goldstinos [12–14]. While the interactions of the helicity 3/2 components of the gravitino are suppressed by the Planck scale, those of the helicity 1/2 components are suppressed by the SUSY breaking scale if

¹The gravitino LSP scenarios have often been searched in diphoton events with missing energy for the lightest neutralino as the next-to-lightest supersymmetric particle (NLSP) [8–11].

the gravitino mass is much smaller than the energy scale of the interactions. Therefore, if the SUSY breaking scale is low, the gravitino interactions, i.e. the goldstino interactions, can be important at colliders. We also note that, as a consequence of the super-Higgs mechanism, the gravitino mass is related to the scale of SUSY breaking as well as the Planck scale,

$$m_{3/2} \sim (M_{\text{SUSY}})^2/M_{\text{Pl}}. \quad (1.1)$$

Therefore, low-scale SUSY breaking scenarios, e.g. gauge mediated SUSY breaking (GMSB) [15], provide a gravitino LSP.

Several studies of the jets+ $\cancel{E}_T$ signature in gravitino production at hadron colliders have been performed especially for very light gravitinos with $m_{3/2} \sim \mathcal{O}(10^{-14} - 10^{-12} \text{ GeV})$ [16–21]. In such a very light gravitino case, production in association with a gluino (or squark) can be dominant or comparable to usual gluino pair production.² The subsequent gluino decays into a gluon and a gravitino will give rise to monojet and dijet signals with missing energy. The associated gravitino production is significant only for very light gravitinos since the production rate is inversely proportional to the square of the Planck scale times the gravitino mass, $\sigma \propto 1/(M_{\text{Pl}} m_{3/2})^2$. The case for the gravitino mass of $m_{3/2} \sim \mathcal{O}(10^{-9} \text{ GeV})$ in GMSB has also been studied in gluino NLSP scenarios [22, 23], where the dijet+ $\cancel{E}_T$ signal can be significant. No realistic study including parton shower and hadronization effects, however, has been conducted, mainly due to the limited availability of simulation tools for processes involving gravitinos.

To be able to identify new physics in such a multi-jet signature at the LHC, a reliable and precise simulation of the signal as well as of the QCD background is crucial. This can be provided by merging matrix elements (ME) with parton showers (PS). In the last decade several techniques to consistently merge multi-parton final states as obtained by a ME computation with PS (ME+PS) have been developed [24]. They are now implemented in various event generators, and tested against experimental data (see [25] for a review). Moreover, the importance of the ME+PS merging for new physics has been pointed out in different contexts [26–31].

In this article we consider a scenario where the gravitino is the LSP and the gluino is the NLSP and promptly decays into a gluon and a gravitino ($\tilde{g} \rightarrow g + \tilde{G}$). We study the jets plus missing transverse energy signature

$$pp \rightarrow \text{jets} + \cancel{E}_T, \quad (1.2)$$

where the missing energy is due to two gravitinos. For simplicity, all other superparticles are assumed to be too heavy to be produced on-shell. We consider a very light gravitino case, where two main production mechanisms contribute to the above signal: gluino-gravitino associated production ($pp \rightarrow \tilde{g}\tilde{G}$) and gluino pair production ($pp \rightarrow \tilde{g}\tilde{g}$), to be described in detail in section 2. Thanks to the availability of new simulation tools it is now possible to apply the ME+PS merging procedure to avoid double counting for such a signal which

²Reference [20] assumes that all SUSY particles except for the gravitino are too heavy to be produced on-shell.

contains two different types of subprocesses.³ We generate the merged inclusive signal samples as well as the SM background sample, and analyse the distributions of the jets and missing transverse energy to extract information on the gluino and gravitino masses.

The article is organized as follows. In section 2, the two production subprocesses contributing to the jets plus missing energy at the LHC are presented, i.e. gluino-gravitino associated production and gluino pair production. In section 3, we briefly describe the matrix element and parton shower merging technique employed in this work and the validation of our generation. In section 4 we examine basic selection cuts to curb the SM background, and discuss how distributions of the jets and missing transverse energy can be used to determine the SUSY particle masses. Section 5 is devoted to our summary. In appendix A, we give the effective gravitino interaction Lagrangian relevant to our study.

2 Light gravitino production at the LHC

We investigate LSP gravitino production processes in R -parity conserving scenarios that lead to jets+ $\cancel{E}_T$ at the LHC. We consider gluinos to be the NLSP and to promptly decay into a gluon and a gravitino. We assume the masses of all other SUSY particles large enough to prevent them from being produced on-shell. The missing energy will be carried by two gravitinos due to the R -parity conservation, and two processes, *gluino-gravitino associated production* and *gluino pair production*, whose importance varies with the gravitino and gluino masses, can contribute to the final state

$$pp \rightarrow \text{partons} + \tilde{G}\tilde{G}. \quad (2.1)$$

Before considering the two processes in detail, we remark that gravitino pair production ($pp \rightarrow \tilde{G}\tilde{G}$), where a graviton and the scalar superpartners of the goldstinos (the so-called sgoldstinos) s -channel exchange diagrams and the t, u -channel gluino exchange diagrams are involved, as well as sgoldstino pair production, might give rise to the jets+ $\cancel{E}_T$ signal when extra QCD radiation is significant.⁴ However, those contributions are suppressed by the SUSY breaking scale squared and the signal events can be expected only in the low p_T region. Therefore, we expect them to be negligible in our signal region and we do not include them in this work.

2.1 Gluino-gravitino associated production

Gravitino production associated with a gluino and the subsequent gluino decay,

$$pp \rightarrow \tilde{g}\tilde{G} \rightarrow g\tilde{G}\tilde{G}, \quad (2.2)$$

³A similar issue might arise in neutralino LSP scenarios when $\tilde{q} \rightarrow q + \tilde{\chi}_1^0$. $\tilde{q}\tilde{\chi}_1^0$ associated production leads to monojet+ $\cancel{E}_T$, while $\tilde{q}\tilde{q}$ production gives dijet+ $\cancel{E}_T$. However, the $\tilde{q}\tilde{\chi}_1^0$ production rate is much smaller than the $\tilde{q}\tilde{q}$ production due to the weak gauge coupling [32].

⁴The gravitino pair and the sgoldstino pair production in photon-photon collisions ($\gamma\gamma \rightarrow$ “nothing”) were studied in [33], while the inverse processes ($\tilde{G}\tilde{G} \rightarrow \gamma\gamma/f\bar{f}$) were investigated in [34]. We also note that ref. [20] studied $\tilde{G}\tilde{G}g/q$ final states at hadron colliders by means of the effective Lagrangian approach and the collinear approximation, where all the SUSY particles except gravitinos are assumed to be heavy.

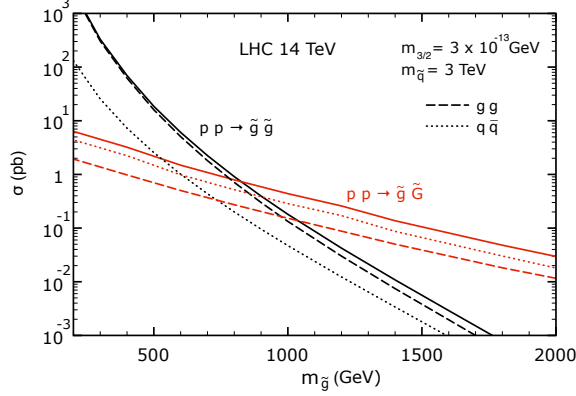


Figure 1. Total cross sections of the gluino-gravitino associated production for the gravitino mass $m_{3/2} = 3 \times 10^{-13}$ GeV, $pp \rightarrow \tilde{g}\tilde{G}$ (red), and the gluino pair production, $pp \rightarrow \tilde{g}\tilde{g}$ (black), at the LHC with $\sqrt{s} = 14$ TeV as a function of the gluino mass. The dashed and dotted lines represent the contributions of the gg and $q\bar{q}$ initial states, respectively. The squark masses are fixed at 3 TeV.

arises from the gg and $q\bar{q}$ initial states, and leads to a mono-jet plus missing energy signal at the leading order (LO). The partonic cross section can be computed by using the effective gravitino interaction Lagrangian, given in appendix A, and the analytic expression can be found, e.g., in [21].⁵ The cross section for the process is inversely proportional to the square of the Planck scale times the gravitino mass

$$\sigma(pp \rightarrow \tilde{g}\tilde{G}) \propto 1/(M_{\text{Pl}} m_{3/2})^2, \quad (2.3)$$

and therefore it becomes significant at colliders only when the gravitino is very light, $m_{3/2} \sim \mathcal{O}(10^{-12}$ GeV) or less. As expected, gravitino production associated with other SUSY particles also follows the scaling of eq. (2.3). The current experimental bound on the gravitino mass is given by the mono-photon plus missing-energy signal in neutralino-gravitino associated production at the LEP as a function of the neutralino and selectron masses, e.g.

$$m_{3/2} \gtrsim 10^{-14} \text{ GeV}, \quad (2.4)$$

for $m_{\tilde{\chi}_1^0} = 140$ GeV and $m_{\tilde{e}} = 150$ GeV [36]. At the Tevatron a similar bound on the gravitino mass is set from the $\gamma + \cancel{E}_T$ [37] and jet + $\cancel{E}_T$ [38] channels, where it is assumed that all the other SUSY particles are too heavy to be produced on-shell [20].

Figure 1 presents the total cross section of the gluino-gravitino associated production (2.2) for $m_{3/2} = 3 \times 10^{-13}$ GeV at the LHC with $\sqrt{s} = 14$ TeV as a function of the gluino mass. The CTEQ6L1 parton distribution functions [39] are employed, and the renormalization and factorization scales are fixed at the average mass of the final state particles, i.e. $\mu_R = \mu_F = (m_{\tilde{g}} + m_{3/2})/2 \sim m_{\tilde{g}}/2$. As the cross section scales as $m_{3/2}^{-2}$, we fix the gravitino mass here so that the production cross section becomes comparable to the

⁵The analytic helicity amplitudes for $q\bar{q} \rightarrow \tilde{g}\tilde{G}$ is also available in [35] after some substitutions for the masses and couplings in the $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{G}$ process.

gluino pair production process (shown by black lines). We also show contributions of each subprocess, the gg and $q\bar{q}$ initial state, with a dashed and dotted line, respectively. The gg subprocess depends only on the gluino mass once the gravitino mass is fixed, while the $q\bar{q}$ initiated cross section also depends on the t - and u -channel-exchanged squark masses. Here, the masses of the left-handed and right-handed squarks are fixed at 3 TeV. It should be noted that those contributions are not decoupled in the large squark mass, and the heavier squark exchange increases the cross section since the gravitino-quark-squark couplings are proportional to the squark mass squared. Therefore, as one can see in figure 1, the cross section of the $q\bar{q}$ channel can be larger than that of the gg channel even at the LHC.

2.2 Gluino pair production

In the scenario where the gravitino is the LSP and the gluino the NLSP, gluino pair production gives rise to a di-jet plus missing energy signature at the lowest order:

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow gg\tilde{G}\tilde{G}. \quad (2.5)$$

The LO cross section is shown in figure 1 as a function of the gluino mass.⁶ Unlike the $\tilde{g}\tilde{G}$ associated production, the $\tilde{g}\tilde{g}$ production needs the partonic energy to be at least twice the gluino mass, and hence the cross section falls rapidly with the increase of the gluino mass. For light gluinos the contribution from the gg initial state is dominant, while for heavy gluinos the production via the $q\bar{q}$ initial state becomes considerable.

As one can see in figure 1 with the fact of the $m_{3/2}^{-2}$ scaling behavior of $\sigma(pp \rightarrow \tilde{g}\tilde{G})$, the different gravitino and gluino masses alter the n -jet topology in the final state. In other words, the kinematic distributions and the number of jets in the final state might be able to give us some information on the gluino mass and/or the gravitino mass. However, as mentioned in section 1, the detailed analysis of the multi-jet events requires the ME+PS merging prescription. In the next section, therefore, we will promote the previous LO studies [16–19, 21] to a full-fledged simulation via a state-of-the-art event generator.

Before turning to the ME+PS merging procedure, we briefly mention the decay width of the NLSP gluino. The partial width of a gluino decay into a gluon and a gravitino is given by

$$\Gamma(\tilde{g} \rightarrow g\tilde{G}) = \frac{m_{\tilde{g}}^5}{48\pi\overline{M}_{\text{Pl}}^2 m_{3/2}^2}, \quad (2.6)$$

where $\overline{M}_{\text{Pl}} \equiv M_{\text{Pl}}/\sqrt{8\pi} \sim 2.4 \times 10^{18}$ GeV is the reduced Planck mass and the gravitino mass in the phase space is neglected. For instance, for $m_{\tilde{g}} = 800$ GeV and $m_{3/2} = 3 \times 10^{-13}$ GeV, the width is 4.1 GeV. In our simplified SUSY mass spectrum the branching ratio is unity, $B(\tilde{g} \rightarrow g\tilde{G}) = 1$, while one in the usual SPS7 and SPS8 GMSB benchmarks is discussed in [21]. We remind the reader that the $\tilde{g} \rightarrow g\tilde{G}$ decay is isotropic, and hence the gluon jet distribution is given by purely kinematical effects of the decaying gluino.

⁶In addition to the SUSY QCD interaction diagrams, there is the t - and u -channel gravitino exchange contribution, which is, however, negligible when $m_{3/2} > 10^{-13}$ GeV [16–19].

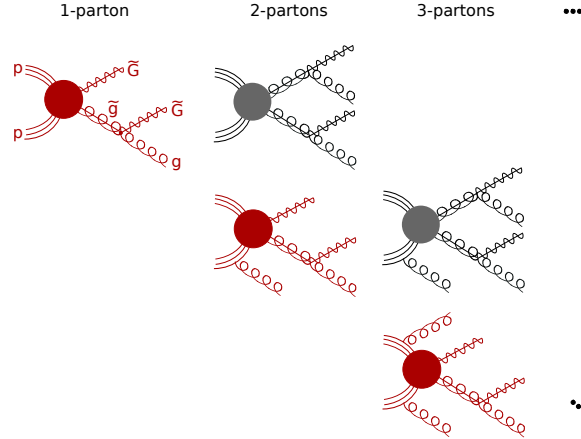


Figure 2. Schematic diagrams for $pp \rightarrow \text{partons} + \tilde{G}\tilde{G}$. In the first row the leading gluino-gravitino (red) and gluino-pair (black) diagrams are sorted. The diagrams are ordered with the number of additional QCD partons in rows, while with the total parton multiplicity in columns.

3 Merging matrix elements with parton showers

In this section, we discuss the procedure used in this work to merge matrix elements (ME) and parton showers (PS) for the process (2.1) as well as for the SM background, and show the validation of our simulations.

At the LO, $\tilde{g}\tilde{G}$ and $\tilde{g}\tilde{g}$ production are expected to lead to missing energy in association with mono-jet and di-jet, respectively. However, for production processes with large partonic center-of-mass energy such as for heavy gluino production, initial and final state QCD radiation becomes important, resulting in multi-jet final states, and might modify or alter the LO predictions for the relevant observables. In the present study, therefore, we consider the processes beyond the LO ones, schematically presented in figure 2.

In general the signal may contain not only hard jets from the decay of the gluinos as well as well-separated QCD radiation, but also soft and/or collinear jets, which, if not properly treated, lead to large logarithms. In event simulations, the hard partons are described well by a fixed-order ME approach, while the soft and collinear partons can be correctly described by a PS approach.

To combine the two approaches avoiding double counting, one needs an appropriate merging procedure. Several multi-jet merging algorithms have been proposed (see also [25]): the CKKW-based method [40, 41], the MLM scheme [24, 42], the pseudo-shower algorithm [43], and the shower- k_T scheme [28].

In our analysis we make use of the shower- k_T scheme, which is based on event rejection, as implemented in MADGRAPH [44, 45] for fixed-order ME generation and interfaced to PYTHIA6.4 [46] for PS and hadronization. In this scheme, ME multi-parton events are generated with a minimum separation, Q_{cut} and $p_{T_{\text{min}}}$, between final-state partons (ij) and between final- and initial-state partons (iB) characterized by the k_T jet measure:

$$d_{ij}^2 = \min(p_{T_i}^2, p_{T_j}^2) \Delta R_{ij}^2 > Q_{\text{cut}}^2, \quad d_{iB}^2 = p_{T_i}^2 > p_{T_{\text{min}}}^2, \quad (3.1)$$

with $\Delta R_{ij}^2 = 2[\cosh(\eta_i - \eta_j) - \cos(\phi_i - \phi_j)]$, where p_{T_i} , η_i and ϕ_i are the transverse momentum, pseudorapidity and azimuth of particle i [47]. The renormalization scale for α_s for each QCD emission vertex is set to the k_T value, while the factorization scale for the parton densities and the renormalization scale for the hard $2 \rightarrow 2$ process is given by the transverse mass of the particles produced in the central process. The ME-level events are then passed to PYTHIA and showered using the p_T -ordered shower, and PYTHIA reports the scale $Q_{\text{hardest}}^{\text{PS}}$ of the hardest emission in the shower. For lower parton-multiplicity samples an event is rejected if $Q_{\text{hardest}}^{\text{PS}} > Q_{\text{cut}}$, while for the highest multiplicity sample an event is rejected if $Q_{\text{hardest}}^{\text{PS}} > Q_{\text{softest}}^{\text{ME}}$, the scale of the softest ME parton in the event. See more details in [28].

3.1 Physics parameters and observables

Throughout the present study, we consider a gluino with mass $m_{\tilde{g}} = 800$ GeV, which lies above the exclusion limit for certain simplified SUSY models or general gauge mediation models [7, 23], and conduct analyses for the LHC at $\sqrt{s} = 14$ TeV. All the left- and right-handed squarks are fixed at 3 TeV. The corresponding LO gluino-pair production cross section $\sigma(\tilde{g}\tilde{g})$ is about 1 pb at the 14-TeV LHC; see figure 1. As discussed in detail in section 2.1, the gluino-gravitino associated production cross section $\sigma(\tilde{g}\tilde{G})$ strongly depends on the gravitino mass. In the following we focus on three different gravitino masses which exemplify the different final states. First, we fix the gravitino mass at 3×10^{-13} GeV so that $\sigma(\tilde{g}\tilde{G}) \sim \sigma(\tilde{g}\tilde{g})$. We subsequently take a lighter and a heavier gravitino as

$$\text{A } (m_{3/2} = 1 \times 10^{-13} \text{ GeV}) : \quad \sigma^{\text{A}}(\tilde{g}\tilde{G}) \sim 9 \times \sigma(\tilde{g}\tilde{g}), \quad (3.2a)$$

$$\text{B } (m_{3/2} = 3 \times 10^{-13} \text{ GeV}) : \quad \sigma^{\text{B}}(\tilde{g}\tilde{G}) \sim \sigma(\tilde{g}\tilde{g}), \quad (3.2b)$$

$$\text{C } (m_{3/2} = 9 \times 10^{-13} \text{ GeV}) : \quad \sigma^{\text{C}}(\tilde{g}\tilde{G}) \sim \frac{1}{9} \times \sigma(\tilde{g}\tilde{g}). \quad (3.2c)$$

Hence, $\tilde{g}\tilde{G}$ associated production is dominant for case A, while $\tilde{g}\tilde{g}$ production is the main channel of the gravitino production for case C. The two production processes are comparable in case B. The LHC may be able to explore the above mass range beyond the current bound, eq. (2.4).

We have fixed the above benchmarks based on the LO predictions for the cross sections. It is well known, however, that higher order QCD corrections can enhance the expected rates. For instance, the next-to-leading order (NLO) cross section for the gluino pair is 1.96 times larger than the LO cross section for $m_{\tilde{g}} = 800$ GeV with $m_{\tilde{q}} = 3$ TeV at the 14-TeV LHC [48], while NLO corrections to $pp \rightarrow \tilde{g}\tilde{G}$ have not yet appeared in the literature. We note that our analyses can be easily redone with a different overall normalization and yet the main features will not change. In any case our approach is complementary to a fixed-order NLO calculation which reliably predicts cross sections and observables involving at most one jet, while ME+PS merged computations provide a reliable prediction for multi-jet based observables and more exclusive quantities that can be directly used in experimental simulations.

Within the present study, the relevant observables are related either to jets or missing energy. Here, we will focus on the following variables:

- transverse momentum of the leading and second jets, $p_T = |\vec{p}_T|$;
- missing transverse energy, $\cancel{E}_T$;
- sum of all the jet p_T 's, $H_T \equiv \sum_j p_T^j$;
- jet multiplicity.

3.2 Technical setup for simulations

To simulate the signal process (2.1), we have implemented the effective gravitino interaction Lagrangian (A.1) into FEYNRULES [49, 50], which provides the UFO model file [51, 52] for ME generators. We use MADGRAPH5 [45] to generate the ME multi-parton events both for the gravitino signal and the SM background, and employ PYTHIA6.4 [46] for PS and hadronization. The shower- k_T scheme is applied for the ME+PS merging as described above. We have checked that all the ME-level results as well as the merged results agreed with those by MADGRAPH/MADEVENT v4 with the gravitino code [53] and also the goldstino code [54].

In the following analyses, we generate signal events with parton multiplicity from one to three, $pp \rightarrow \tilde{G}\tilde{G} + 1, 2, 3$ partons, and merging separation parameters $Q_{\text{cut}} = 100$ GeV and $p_{T_{\text{min}}} = 50$ GeV. The choice of the merging parameters will be discussed in section 3.3. Note that the employment of the ME+PS merging scheme allows us to treat different contributing processes (e.g. the $\tilde{g}\tilde{G}$ and $\tilde{g}\tilde{g}$ production processes in our case) within one event simulation and without double counting.

We also consider the irreducible Z +jets SM background, $pp \rightarrow Z(\rightarrow \nu\bar{\nu}) + 1, 2, 3$ partons, with merging separation parameters $Q_{\text{cut}} = p_{T_{\text{min}}} = 30$ GeV. Simulation of the other main background, e.g. W +jets and top pair, which requires more dedicated analysis, is beyond the scope of the present study, and we refer to, e.g., [27] for details and to [6, 7] for the experimental analysis.

For the jet clustering, we employ FASTJET [55]. Jets are defined by the anti- k_T algorithm [56] with a distance parameter of 0.5, and are required to satisfy $|\eta_j| < 4.5$ and $p_{T_j} > 50$ GeV. We order the clustered jets by their transverse momentum.

3.3 Validation

Although the above merging parameters have been chosen in accordance with the guidelines in [28], we have explicitly checked the stability of the cross section with respect to the variation of the arbitrary scale Q_{cut} .

The smoothness of distributions across the transition between ME and PS regimes was also examined for various Q_{cut} values and kinematical distributions. Solid lines in figure 3 show the inclusive signal samples of $pp \rightarrow \text{jets} + \cancel{E}_T$ in the H_T (left) and $\cancel{E}_T$ (right) distributions. One can see the smooth distributions for all the three benchmark points A, B, and C in (3.2) for $m_{3/2} = 1, 3$, and 9×10^{-13} GeV, respectively.

In addition, as a nontrivial validation check, we have generated the gravitino production subprocesses separately: $pp \rightarrow \tilde{g}(\rightarrow g\tilde{G})\tilde{G} + 0, 1$ partons and $pp \rightarrow \tilde{g}(\rightarrow g\tilde{G})\tilde{g}(\rightarrow g\tilde{G}) + 0, 1$ partons, employing the same merging procedure with the full signal sample, and

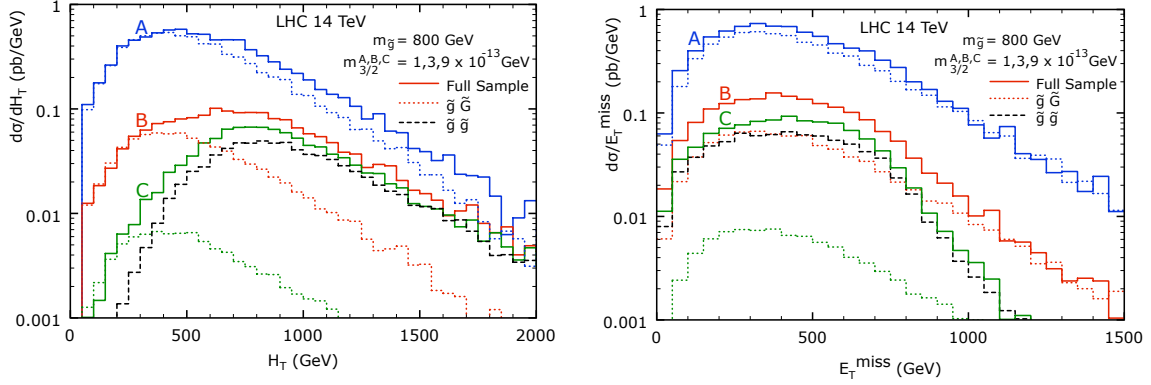


Figure 3. Shower k_T merging results for inclusive signal samples of $pp \rightarrow \text{jets} + \cancel{E}_T$ at $\sqrt{s} = 14$ TeV, where the gravitino mass is taken to be $m_{3/2}^{A,B,C} = 1, 3, 9 \times 10^{-13}$ GeV and the gluino mass is fixed at 800 GeV. The contributions of the gluino-gravitino associated production and the gluino-pair production are also separately shown by dotted and dashed lines, respectively.

verified that the sum of those samples reproduces the full inclusive results. In figure 3, we present contributions of each subprocess, the $\tilde{g}\tilde{G}$ production (dotted) and the $\tilde{g}\tilde{g}$ production (dashed). The sum of the two samples agrees with the full samples (solid). We note that the cross section for the $\tilde{g}\tilde{G}$ production follow the $m_{3/2}^{-2}$ scaling, while the $\tilde{g}\tilde{g}$ production is independent of the gravitino mass.

For case B, as requested in (3.2b), the full signal cross section consists of two equally relevant contributions coming from the $\tilde{g}\tilde{G}$ and $\tilde{g}\tilde{g}$ production processes. In contrast, the signal of the lighter gravitino (case A) is dominated by the $\tilde{g}\tilde{G}$ associated production process, and the signal for the heavier gravitino (case C) consists mainly of the $\tilde{g}\tilde{g}$ production process.

The H_T distributions for the $\tilde{g}\tilde{G}$ production have a peak around half of the gluino mass since there is a gluon coming from the gluino decay, whose energy is $m_{\tilde{g}}/2$ in the gluino rest frame. On the other hand, the $\tilde{g}\tilde{g}$ production exhibits a peak around $m_{\tilde{g}}$ due to the two gluino decays.

The missing transverse energy $\cancel{E}_T$ is defined as the absolute value of the vectorial sum of the transverse momenta of the two gravitinos. The gluino-gravitino associated production leads to higher $\cancel{E}_T$ events than the gluino-pair production, since a gravitino is directly produced in association with a gluino and hence can have higher p_T than the ones resulting from the gluino decays.

Finally, we show the $\cancel{E}_T$ distribution for the irreducible $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ background in figure 4, where $\cancel{E}_T = p_{T_Z}$. Since the background overwhelms the signal and dominates in the low $\cancel{E}_T$ region, we impose the minimal missing transverse energy cut

$$\cancel{E}_T > 200 \text{ GeV} \quad (3.3)$$

in the following analyses.

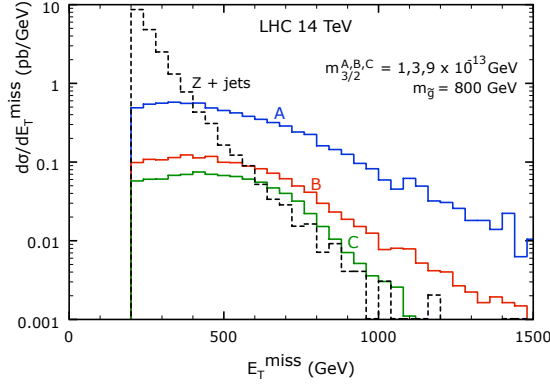


Figure 4. The same as the right plot in figure 3 with the irreducible $Z(\rightarrow \nu\bar{\nu})$ +jets background (dashed), where the $\cancel{E}_T > 200$ GeV cut is imposed.

4 Jets plus missing energy

We now investigate the kinematical distributions further, focusing on the correlation between the p_T of the leading jet and the missing transverse energy, in order to differentiate our three benchmark signals as well as to identify basic selection cuts to curb the irreducible background.

Figure 5 presents scatter plots in the $(p_T^{\text{1st jet}}, \cancel{E}_T)$ plane for the three cases defined in eqs. (3.2), where the minimal $\cancel{E}_T > 200$ GeV cut is applied. For case A, where gluino-gravitino associated production is dominant, we find a strong correlation between the two observables as $\cancel{E}_T \sim p_T^{\text{1st jet}}$, especially for the high p_T region, and this can be explained as follows. One of two gravitinos in the final state is produced in association with a gluino, and hence $\vec{p}_{T_{\tilde{G}}} = -\vec{p}_{T_{\tilde{g}}}$ at LO. The produced gluino decays into a gluon and a (almost) massless gravitino, and those are boosted along the gluino momentum direction and can share the momentum like $\vec{p}_{T_g} \sim \vec{p}_{T_{\tilde{G}}} \sim \vec{p}_{T_{\tilde{g}}}/2$. This leads to a balance between the p_T of the gluon jet and the missing transverse energy, which is the vectorial sum of the two gravitino momenta. QCD radiation will alter this naive expectation and most of the events which

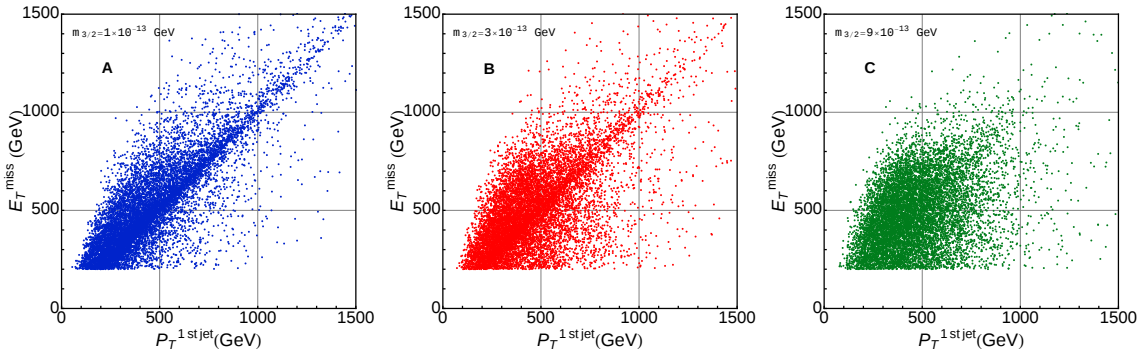


Figure 5. Scatter plots of the $pp \rightarrow \text{jets} + \cancel{E}_T$ signal at $\sqrt{s} = 14$ TeV in the $(p_T^{\text{1st jet}}, \cancel{E}_T)$ plane for $m_{3/2}^{A,B,C} = 1, 3, 9 \times 10^{13}$ GeV from left to right, where the gluino mass is 800 GeV.

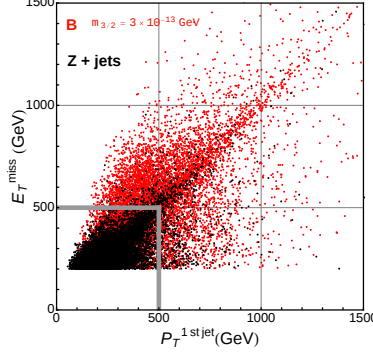


Figure 6. The same as the middle plot in figure 5 with the Z +jets background (black dots).

	σ (pb)	A	B	C	bkg
$\cancel{E}_T > 200$ GeV		7.50	1.53	0.90	19.4
+ $p_T^{\text{1st jet}} > 500$ GeV or $\cancel{E}_T > 500$ GeV		3.81	0.85	0.55	0.81

Table 1. Cross sections for the signals and the background at the 14-TeV LHC, with the minimal $\cancel{E}_T$ cut (3.3) and with the additional selection cuts (4.1).

scatter apart from the $\cancel{E}_T = p_T^{\text{1st jet}}$ line come from samples with extra partons.

For case C, in contrast, where gluino-pair production is the main subprocess and both gluino decays are a source of the leading jet, there is no such a strong correlation between $p_T^{\text{1st jet}}$ and $\cancel{E}_T$. In the high p_T region, i.e. for the highly-boosted gluino-pair production, a similar argument could be applied yet a cancellation between the back-to-back gravitinos occurs, hence events with large $\cancel{E}_T$ are suppressed. This can be already observed in figure 3. Case B lies in between cases A and C, where the both production subprocesses contribute.

In figure 6 the SM Z +jets background is added on the scatter plot for case B with black dots. Also here, we find (a weaker) $\cancel{E}_T \sim p_T^{\text{1st jet}}$ correlation resulting from the $Z + j$ sample. The background events are concentrated in the low p_T and $\cancel{E}_T$ region, typically less than 500 GeV, while the gravitino signal events are mainly scattered to the higher energy region up to about 800 GeV, i.e. the gluino mass, as well as to the $\cancel{E}_T \sim p_T^{\text{1st jet}}$ region for cases A and B. Therefore, besides the minimal $\cancel{E}_T$ cut in (3.3), we impose the selection cuts

$$p_T^{\text{1st jet}} > 500 \text{ GeV} \quad \text{or} \quad \cancel{E}_T > 500 \text{ GeV}, \quad (4.1)$$

shown by thick grey lines in figure 6.

We present cross sections for the gravitino signals and the Z +jets background in table 1, where the minimal $\cancel{E}_T$ cut (3.3) and the additional selection cuts (4.1) are taken into account. After the selection cuts, the background is reduced quite effectively, while about half of the signal events pass those cuts.

Distributions of the relevant observables given in section 3.1 are collected in figure 7 for the gravitino signals as well as the Z +jets background. Compared to figure 3, events in the low H_T and $\cancel{E}_T$ regions are removed by the kinematical cuts (3.3) and (4.1). In the

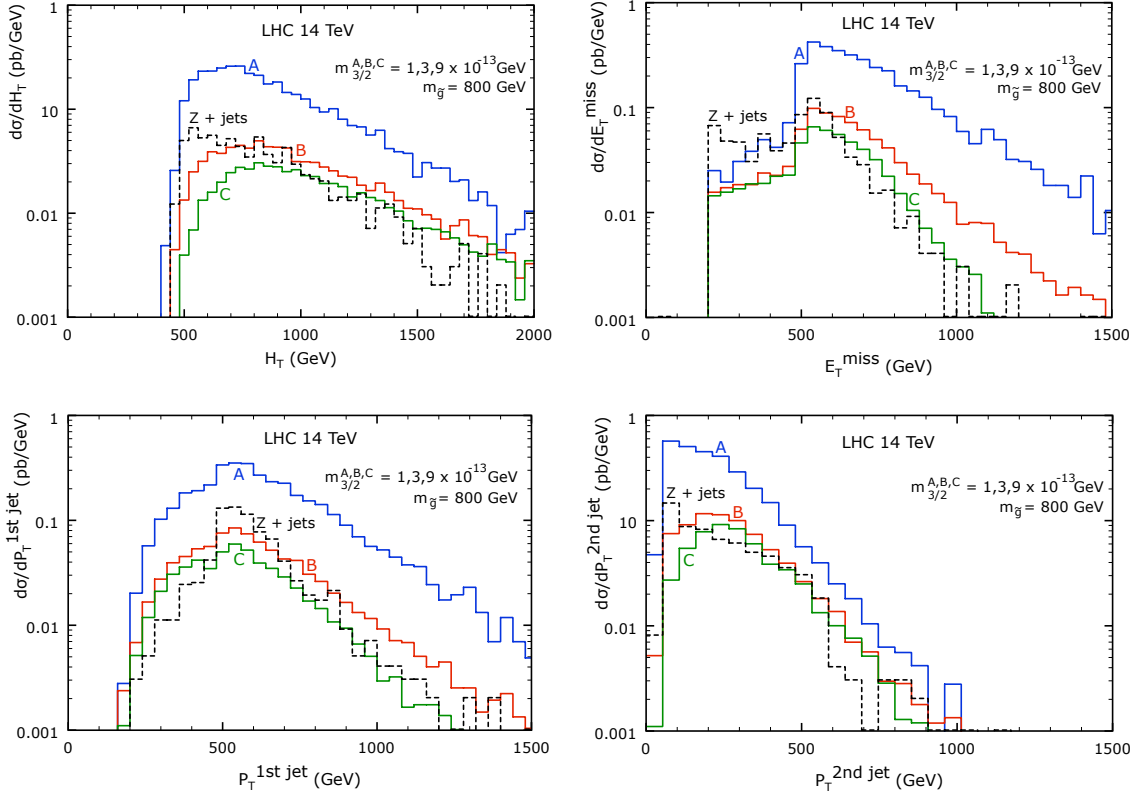


Figure 7. Distributions of the jets+ $\cancel{E}_T$ events at the 14-TeV LHC for the gravitino signal with $m_{3/2}^{A,B,C} = 1, 3, 9 \times 10^{-13}$ GeV and $m_{\tilde{g}} = 800$ GeV as well as for the Z +jets background. Besides the minimal missing transverse energy cut $\cancel{E}_T > 200$ GeV, the selection cuts, $p_T^{1st\,jet} > 500$ GeV or $\cancel{E}_T > 500$ GeV, are imposed.

missing energy distribution, as discussed above, the lighter gravitino results in higher $\cancel{E}_T$ events.

The shapes of the p_T of the leading jet are similar for the three cases since the hard jets mainly come from the gluino decays, but the p_T distribution of the lighter gravitino case is slightly harder than that of the heavier gravitino due to the higher boost effect from the $\tilde{g}\tilde{G}$ associated production. We also note that the signal events for all the three cases dominate the background in the $p_T^{1st\,jet} < 500$ GeV region. The distributions of the p_T of the second jet are more distinctive, especially in the low p_T region. Two gluino decays in the gluino-pair production lead to two hard gluon jets. On the other hand, the second jet resulting from the $\tilde{g}\tilde{G}$ production as well as the Z +jets background comes from QCD radiation, and tends to be soft.

Finally, we present jet multiplicities for an integrated luminosity of $\mathcal{L} = 10 \text{ fb}^{-1}$ in figure 8. The jet multiplicity depends on the requirement of the minimal p_T of jets, and we take the different p_{Tj} cuts of 50 GeV (left) and 150 GeV (right). Case A as well as the SM background have a peak at a lower multiplicity than cases B and C, as expected. When we count only jets whose p_T is larger than 150 GeV, i.e. only very hard jets, distributions of the jet multiplicity recover the LO expectations: the $\tilde{g}\tilde{G}$ associated production tends to

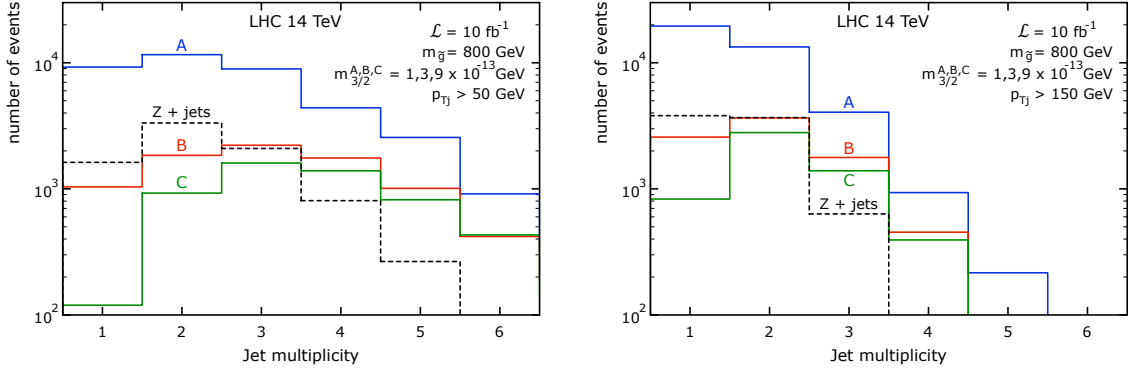


Figure 8. Jet multiplicities for an integrated luminosity of 10 fb^{-1} , with $p_{T_j} > 50 \text{ GeV}$ (left) and $p_{T_j} > 150 \text{ GeV}$ (right). The detail is the same as figure 7.

produce mono-jet events, while the $\tilde{g}\tilde{g}$ production is likely to give di-jet events.

As seen in figures 7 and 8, the distributions are significantly different among the three benchmarks as well as between the signal and the background. In other words, they are sensitive to the gravitino mass when it is light enough so that the $\tilde{g}\tilde{G}$ associated production process can contribute to the signal. We note that, although we fixed the gluino mass at 800 GeV in the present study, a different gluino mass also alters the distributions, which could allow us to explore both the gravitino and gluino masses at the LHC.

5 Summary

We have studied a jets plus missing energy signature at the LHC in a scenario where the gravitino is the LSP and the gluino is the NLSP which promptly decays into a gluon and a gravitino. We considered a very light gravitino of $m_{3/2} \sim \mathcal{O}(10^{-13} \text{ GeV})$, where two production subprocesses can yield jets+ $\cancel{E}_T$: gluino-gravitino associated production and gluino-pair production. By using the shower- k_T ME+PS merging scheme implemented in MADGRAPH, we have simulated the inclusive signal samples as well as the SM Z +jets irreducible background.

Special attention has been devoted to the ME+PS merging procedure to avoid double counting for such a signal which contains two different types of subprocesses. In addition to checking the Q_{cut} independence of the cross sections and the smoothness of the distributions, we have generated the merged $\tilde{g}\tilde{G}$ and $\tilde{g}\tilde{g}$ signal samples separately and confirmed that the sum of them reproduced the full inclusive results.

To show how distributions of the jets+ $\cancel{E}_T$ signature can provide information on the gravitino and gluino masses, we have investigated three benchmark scenarios which exemplify the different final states. Due to the fact that the distributions are quite different between the $\tilde{g}\tilde{G}$ and $\tilde{g}\tilde{g}$ production processes and due to the $m_{3/2}^{-2}$ scaling of the $\tilde{g}\tilde{G}$ production cross section, the kinematical distributions and the jet multiplicity exhibit distinctive features among the three cases as well as between the signal and the background. The LHC may be able to explore the parameter space around our benchmark points and hence to

provide information on the gluino mass as well as the gravitino mass, yielding information on the SUSY breaking scale.

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A Effective gravitino interaction Lagrangian

We briefly present the relevant terms of the effective gravitino Lagrangian in our study. In the high energy limit $\sqrt{s} \gg m_{3/2}$, due to the goldstino equivalence theorem, the effective gravitino interaction Lagrangian can be obtained by the replacement of the spin-3/2 gravitino field (ψ_μ) by the spin-1/2 goldstino field (ψ) as $\psi_\mu \sim \sqrt{2/3} \partial_\mu \psi / m_{3/2}$ in the gravitino Lagrangian (see, e.g., eq. (2) in [53]); see more details in [54]. The effective interaction Lagrangian among gravitino, quark and squark, ψ - f - ϕ , and among gravitino, gluino and gluon(s), ψ - λ - A (- A), in non-derivative form is

$$\begin{aligned} \mathcal{L}_{\text{int}} = & \pm \frac{im_{\phi_{L/R}}^2}{\sqrt{3} \bar{M}_{\text{Pl}} m_{3/2}} [\bar{\psi} P_{L/R} f^i (\phi_{L/R}^i)^* - \bar{f}^i P_{R/L} \psi \phi_{L/R}^i] \\ & - \frac{m_\lambda}{4\sqrt{6} \bar{M}_{\text{Pl}} m_{3/2}} \bar{\psi} [\gamma^\mu, \gamma^\nu] \lambda^a F_{\mu\nu}^a, \end{aligned} \quad (\text{A.1})$$

where $\phi_{L/R}$ denotes the left-/right-handed squark, $P_{L/R} = \frac{1}{2}(1 \mp \gamma^5)$ is the chiral projection operator, and $F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g_s f^{abc} A_\mu^b A_\nu^c$ is the field-strength tensor of the $SU(3)_C$ gauge group ($a = 1, \dots, 8$).

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