New Physics Opportunities in the Boosted Di-Higgs plus $E_T$ Signature

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The Higgs field in the standard model (SM) may couple to new physics sectors related with dark matter and/or massive neutrinos. In this paper we propose a novel signature, the boosted di-Higgs boson plus $E_T$ (which is either a dark matter or neutrino), to probe those new physics sectors. In a large class of models, in particular the supersymmetric SMs and low scale seesaw mechanisms, this signature can play a key role. The signature has clear background, and at the $\sqrt{s} = 14$ TeV high luminosity (HL-) LHC, we can probe it with production rate as low as $\sim 0.1$ fb. We apply it to benchmark models, supersymmetry in the bino(singlino)-Higgsino limit and the canonical seesaw model, finding that masses of Higgsino and right-handed neutrino can be discovered up to $\sim 800$ GeV and 500 GeV, respectively.

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New physics below the iceberg Discovery of Higgs boson at the large hadronic collider (LHC) almost completes the standard model (SM). At the same time, however, it opens a new era for particle physics: This new resonance might be just a small tip of a big iceberg, and below it could hide a mystery of new world. Looking around this small tip, we may find clues for new physics. Actually, we do have convincing arguments to support this belief from several motivations for new physics beyond the SM.

The most common theoretical argument for new physics is from the notorious gauge hierarchy problem caused by the quadratic divergence of (Higgs mass)$^2$ parameter. Solutions to this problem introduce new particles coupled to the SM Higgs doublet $H$. In particular, in the supersymmetric SMs (SSMs), two Higgs doublets $H_{u,d}$ participate in quite a few interactions which are potential to produce Higgs boson. The second argument for new physics is from dark matter (DM), whose interactions with the visible sector may be through the Higgs boson $H$ (Higgs portal DM). Last but not the least, neutrinos in the renormalizable SM are massless in conflict with the observation. Mechanisms to generate neutrino masses may again introduce new couplings to $H$. The most well known examples include various seesaw mechanisms. Therefore, it is well motivated to search for hints of new physics through signatures containing one or even more Higgs bosons.

Surprisingly, such a simple observation is more or less overlooked by the LHC community. It is partially due to the fact the SM-like Higgs boson $h$ dominantly decays into $b\bar{b}$ (hadronic decay), and thus it is easily buried under the huge QCD background at the LHC. However, things can change substantially, if the Higgs boson(s) are boosted, which usually happens when they are produced from heavy particle decay.

**Boosted di-Higgs bosons plus $E_T$ as a powerful probe** Power of the boosted topologies involving Higgs bosons can be best illustrated in di-Higgs boson search, which is one of the focuses in the upcoming LHC run, aiming at examining the Higgs potential and thus probing possible new physics in the Higgs sector [2, 3]. Compared with the $(b\bar{b})(\tau\tau)$ and $(b\bar{b})(\gamma\gamma)$ channels, the $(b\bar{b})(b\bar{b})$ channel ($4b$ for short) was thought to be undetectable [4, 5], despite of the largest branching ratio. Nevertheless, considering the boosted region, it has been shown that this channel can be discovered at the end of LHC run [6]. As a consequence, the accuracy of Higgs self-coupling measurement can be increased to 20%, hence becomes sensitive to the typical new physics effects [2]. There are some other event topologies which involve boosted Higgs boson(s), either SM-like or extra Higgs states, in various contexts [7–11].

In these examples, in particular the di-Higgs boson signature (it is specified to the $4b$ channel hereafter), a small $R_{fat}$ serves as a powerful discriminator at LHC. $R_{fat}$ is the radius of Higgs jet constructed using the Cambridge/Aachen (C/A) algorithm [12]. On one hand, the loss of signal events for di-Higgs is under control by finding out a value of $R_{fat}$ that retains most of the events, denoted by $R_{fat}^{max}$. For a moderately boosted Higgs boson, the efficiency of Higgs tagging can reach $\sim 20\%$, given $b-$tagging efficiency $70\%$. It becomes slightly larger when the Higgs boson is boosted more. On the other hand, the backgrounds (BGs) of di-Higgs events are effectively suppressed by applying a smaller $R_{fat}$. More specifically, we have to deal with two kinds of BGs. One is the irreducible BGs, dominated by the QCD 4b ($861$ pb @ LHC14TeV) and Z$bb$ ($109$ pb @ LHC14TeV) final states. The other is the reducible BGs, dominated by the semi-leptonic $tt$ pair ($382$ pb @ LHC14TeV) which however was ignored by the previous analysis [8]. Here the 4b BG is due to the detector effects, i.e., a charged lepton is either missed or mis-identified as a jet (thus...
avoiding lepton veto that will be used) and moreover the light flavour jets are mis-tagged as $b$-jets. In our numerical simulation, both signal and BGs are generated by MadGraph5_aMC@NLO \cite{13}, and passed to Pythia6 \cite{14} for parton showering and hadronization. Delphes3 \cite{15} is used for simulating the detector effects. At the last stage, we use the fastjet \cite{16} to study jet substructure. The tagging rates for $c$- and light-flavored jets are assumed to be 0.1 and 0.015 \cite{17}, respectively.

From Table \[1\] it is noted that for $R_{\text{max}}^\text{flat} \lesssim 1.6$, almost all BGs are suppressed substantially except for the robust QCD 4$b$ BG. Then, what if the signature moreover involves a large missing transverse energy ($E_T$)? Obviously, it helps to clear the QCD BGs. Therefore, the boosted $2h + E_T$ has little competing BGs and hopefully new physics effect will show up in this signature much earlier than in the pure di-Higgs measurement. Before proceeding towards its details, we first present simplified models that give rise to the signature under consideration.

| $M$ (GeV) | $R_{\text{max}}^\text{flat}$ | $S$ | $t\bar{t}$ | Z$b$ | QCD |
|-----------|----------------------------|-----|----------|------|-----|
| 200       | 2.0                        | 2.1 | 5.2      | 13.9 | 591.8 |
| 300       | 1.8                        | 2.5 | 3.9      | 9.2  | 399.4 |
| 400       | 1.6                        | 3.2 | 2.4      | 5.6  | 241.7 |
| 500       | 1.6                        | 3.9 | 2.4      | 5.6  | 241.7 |
| 700       | 1.4                        | 5.4 | 1.3      | 2.9  | 117.1 |
| 1000      | 1.0                        | 6.8 | 0.46     | 0.41 | 14.5 |
| 2000      | 0.8                        | 8.8 | 0.19     | 0.1  | 3.2  |

TABLE I: The best jet sub-structure parameters for different masses of new particle, with invisible particle assumed to be massless. The production cross section for signals are choose to be 100 fb. Events numbers for signals and BGs after Higgs-tag are shown at 1 fb$^{-1}$.

**Simplified models for $2h + E_T$** For generality, we start from an simplified effective model analysis. Two classes of models are of interest. In one class, the missing particle is DM (or any long-lived neutral particle at the LHC), while in the other class, missing one is a neutrino.

Let us start with the first class of modelss, assuming the dark sector consists of a couple of dark states (we will use this term to genetically refer to particles undiscovered), two for concreteness. They have proper mass hierarchy and interact with the Higgs boson as the following

$$\lambda_f h \chi_1 \chi_2, \quad \mu_h S_1 S_2,$$

where $\chi_1$ ($S_1$) is a Majorana fermion (real scalar) DM, with mass $M_1$ ($m_1$) simply set to zero. The heavier dark state mass is $M_2$ ($m_2$) in the sub-TeV mass region $^1$.

Moreover, it has almost full electroweak interactions and thus can be produced abundantly via the Drell-Yan processes (in a complete model, additional dark states that are not included in the simplified model may also contribute to productions of the heavier states, and it will be discussed specifically later). The SSMs provide quite a few good examples. In the minimal SSM (MSSM) the effective model is nothing but the Higgsino-bino limit: $h \approx \chi_1$ and Higgsino $\tilde{H}_u \approx \chi_2$ for which we have $\lambda_1 \approx g_1/2$. The Higgsino-wino limit also leads to the effective model. Scalar DM example is also provided in SUSY like in the supersymmetric seesaw models with a right-handed neutrino dominated $\tilde{N} \approx S_1$ and the left-handed sneutrino as NLSP $\tilde{\nu}_L \approx S_2$ \cite{18} \cite{19}. Then from the soft term $A_{\nu} L H_u \tilde{N}$ we get Eq. \[1\]. The non-supersymmetric DM models with singlet-doublet and singlet-triplet mixing\cite{20}, etc., also fit the effective mode. A peculiar scenario arises even $S_1$ are charged under QCD: $S_1$ is a stealthy light stop $t_1$ which could be missed due to a compressed spectrum \cite{21}, and the heavier stop $\tilde{t}_2 = S_2$ may leave hint in $t_2 \rightarrow t_1 + h$, whose branching ratio can be as large as 30\% \cite{22}.

In particular, the simplified model is well motivated in the SSMs beyond MSSM for enhancing the SM-like Higgs boson mass. It is around 126 GeV, relatively heavy in the MSSM thus incurring a large fine-tuning \cite{23}. To alleviate this problem, new couplings to $H_u$ are introduced. The next-to MSSM (NMSSM) is a good example which is well known for its term $\lambda_S H_u H_u$ with $\lambda \sim 1$. In this model, the singlino and Higgsino would play the roles of $\chi_1$ and $\chi_2$, respectively, and then the first operator in Eq. \[1\] will give a good description of this scenario. Another example is a model with weak hypercharge $Y = \pm 1$ triplets that allow the coupling $\lambda_\nu H_u T H_u$ \cite{24} with $\lambda_\nu \sim 1$. We will show shortly that it is also inspired by the supersymmetric seesaw models for massive neutrinos.

We now move to the second class with neutrino as the missing particle. The simple effective description is given by the term

$$\lambda_\nu h N \nu_L,$$

that generates the decay of heavy right-handed neutrino (RHN) $N$ into an active neutrino plus Higgs boson. The type-I and type-III seesaw mechanisms give representative examples, where the RHMs are a SM singlet and the neutral component of a SM triplet fermion, respectively. In the type-II seesaw mechanism, the triplet $T$ will couple to a pair of Higgs doublets through $H_u T H_u$, so that $\lambda_\nu h N \nu_L$.

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$^1$ In the low scale SUSY-breaking models, $\chi_1$ may be replaced by gravitino, the spin-3/2 fermion, while the NLSP is dominated by Higgsino, i.e., $H_u \sqrt{F} G_u^\dagger$. But only the SUSY-breaking scale $\sqrt{F}$ is very low such that the decay is prompt at LHC.
only in the supersymmetric version mentioned before we do have a chance to produce di-Higgs plus $E_T$.

**Production and decay in the benchmark models**

Production and decays of new particles are fairly model dependent. Therefore, in order to demonstrate the utility of our new signature, we will work in several complete models. In general, the production of the heavier dark states are pair produced either via the Drell-Yan processes due to their electroweak charges (or even colored charge) or via decay of a new resonance.

The former is well studied and we give two benchmark models. First, we consider the bino(singlino)-Higgsino limit in SSM. In this model we actually have three Majorana neutralinos, $(\tilde{H}_1^0, \tilde{H}_2^0, B/S)$. For our purpose, the Higgsino mass $\mu$ is around 500 GeV, much heavier than the bino/singlino mass which is assumed to be less than 100 GeV. In the mass basis, two Higgsinos constitute a pseudo Dirac fermion pair $(\chi_2, \chi_3)$, with mass splitting of a few GeVs. In the limit $M_{2,3}^2 - M_1^2 \gg M_1^2$, we can apply the Goldstone equivalence theorem and obtain the following equations for decay branching ratios of $\chi_{2,3}$ (we refer to [25] for relevant discussions):

$$\frac{\Gamma(\chi_2 \rightarrow h + \chi_1)}{\Gamma(\chi_3 \rightarrow Z + \chi_1)} \approx \frac{\Gamma(\chi_2 \rightarrow Z + \chi_1)}{\Gamma(\chi_3 \rightarrow h + \chi_1)}. \quad (3)$$

This theorem is robust throughout the paper, since we always work in the limit where it holds. As for the production, the mode $\bar{q}q \rightarrow Z^* \rightarrow \chi_2 \chi_3$ is dominant because the diagonal couplings of $\chi_1$ to $Z$ are suppressed by the small mass splitting between $\chi_2$ and $\chi_3$. Therefore, in order to approach the maximal branching ratio of the di-Higgs boson channel, $\Gamma(\chi_1 \rightarrow h + \chi_1) \approx \Gamma(\chi_1 \rightarrow Z + \chi_1)$ is favored. When the Higgs sector is in the decoupling limit and moreover $|\mu| \approx |M_{2,3}| \gg M_1$, that equality holds. Explicitly, now all the partial decay widths are approximated by

$$\Gamma \approx \frac{\theta_h^2}{64 \pi} \tan^2 \theta \mu^2 |\mu|, \quad (4)$$

with $\theta_h = 1/\sqrt{2}$ being the mixing angle between two Higgsinos. Next we consider the sneutrino system ($\tilde{\nu}_L, \tilde{\nu}_R$), which is similar to the bino-Higgsino system. If the lepton number is (or at least highly) conserved \textsuperscript{14}, the (approximately) complex field $\tilde{\nu}_L$ will couple to $Z$ via $Z_{\mu} \tilde{\nu}_L^\dagger \partial^\mu \tilde{\nu}_L$. Thereby it can be pair produced by DY process. In addition, we have $\Gamma(\tilde{\nu}_L \rightarrow h + \tilde{\nu}_R) = \Gamma(\tilde{\nu}_L \rightarrow Z + \tilde{\nu}_R)$ again by virtue of the equivalence theorem. A more detailed discussion is cast in Appendix.\textsuperscript{1}

Now we turn our attention to the production via a new resonance, which may be more effective near the TeV region where the Drell-Yan processes can not give an appreciable cross section. The resonance is either a new heavy scalar $\phi$ or vector boson $Z'$, and both are well motivated in new physics. Usually, $Z'$ couples to light quarks at tree level, while $\phi$ couples to gluon at loop level through its CP-even component of the SM Higgs doublet. If $Z'$ also couples to leptons universally such as in the gauged $B-L$ models, the di-lepton resonance search at LHC will impose very stringent bounds on $m_{Z'}$ and $g'$ (the new gauge coupling) \textsuperscript{20}. As a consequence, the production rate of $Z'$ is quite limited. Hence in what follows we focus on $H$. This particle may be the physical degree of a field $S$ which is used to produce mass term and/or breaking extra symmetries. It is supposed that $S$ mixes with the SM Higgs doublet, e.g., via the Higgs portal coupling $\lambda_{s\phi}|S|^2H^2$. If $S$ is a SM singlet, one can also have $\mu_{s\phi}|H|^2$. Given a sizable mixing angle $\sin \theta \sim O(0.1)$, the gluon-gluon fusion production of $\phi$ can be effective. To describe it, we follow the description of SM-like Higgs boson production, by introducing the dimension-five operator for $\phi \rightarrow gg$:

$$\mathcal{L}_{g\phi} = \frac{1}{4} C_{g\phi} H G^a \mu_{\mu\nu} \phi^a \phi, \quad (5)$$

with $C_{g\phi} \propto -\sin \theta \alpha_s/\pi$. In addition, the dominant decay branching ratio of $\phi$ is assumed to be a pair of heavier dark states.

Let us make a more detailed discussion about the mixing angle. For simplicity, we consider the minimal case, i.e., the real singlet \textsuperscript{2} $S = (v + S_R)/\sqrt{2}$. Similarly, we denote the neutral CP-even component of $H$ as $H_R/\sqrt{2}$. Two extra parameters are relevant to describe the extended Higgs sector, the mass of heavier Higgs boson $m_H$ and the mixing angle $\theta$. The mass and flavor eigenstates are related by

$$h = \cos \theta H_R + \sin \theta S_R, \quad \phi = -\sin \theta H_R + \cos \theta S_R. \quad (6)$$

The current data tells that the Higgs boson is quite SM-like, and the measured Higgs signal strength imposes an upper bound $\sin \theta \lesssim 0.43$ \textsuperscript{27}.\textsuperscript{3} The masses of $h_{SM}$ is approximated to be

$$m_h^2 \approx \lambda_h v^2 - \frac{\sin^2 \theta}{4} m_\phi^2, \quad (7)$$

in the small mixing angle. Here $\lambda_h$ is from the quartic term $\frac{1}{2}(H^2 H)^2$. Noticeably, the appearance of heavy $\phi$ with a sizable mixing with $h_{SM}$ may solve the metastability problem of Higgs potential near the Plank scale, which is attributed to the relatively small Higgs quartic coupling, $\lambda_h \approx 0.26$. Here, to compensate the pulling-down mixing effect on the SM-like Higgs boson mass, we need a larger $\lambda_h$. For example, for $m_H = 1.5$ TeV and $\sin \theta = 0.3$, now we need $\lambda_h \approx 1.1$.

\textsuperscript{1} In the $B-L$ models or like, $S$ is complex but its imaginary part may be the dominant component of the Goldstone boson, thus being eaten. Then it reduces to the real singlet case.

\textsuperscript{2} Using $\delta t$ and $W$ boson mass, this paper derives an even more stringent bound on the mixing angle, $\sin \theta \lesssim 0.2$ for heavy $H$. But it is true only in the Higgs singlet plus doublet model.
The type-I seesaw mechanism in the gauged $B-L$ models furnishes the benchmark example, where $S$ is a $B-L$ charged scalar introduced to break $B-L$. At the same time, it generates Majorana masses for RHNs via a term like $\lambda_N S N^2/2$ with suitable $B-L$ charge assignments. The production of RHNs, which are SM singlets, is usually highly suppressed. The most hopeful way is via the $Z' = Z_{B-L}$ resonance, but as mentioned before, it is negligible owing to the dilepton resonance search. While the conventional production mechanism relies on a non-trivial flavor structure in the RHNs such that sizable mixings between the sterile neutrinos and active neutrinos are allowed $^{28,29}$. However, the mixing would be vert small in more generic cases. To our knowledge, utilizing the $\phi$ resonance to produce RHNs is novel. It may offer the unique chance to probe the low scale type-I seesaw mechanism at colliders. It is supposed that RHN dominantly decays into $W$ plus charged leptons $^{30,31}$. In the relatively heavier RHN region the branching ratio of $N \to h + \nu_L$ approaches the fixed value $1/6$ $^{30}$:

$$\Gamma(\nu_h \to \nu h_{SM}) \approx \Gamma(\nu_h \to \nu Z) = \frac{1}{4} \Gamma(\nu_h \to \ell W).$$

We comment on the situation in other popular models. In the type-III seesaw mechanism $N$ is the neutral component of the triplet $T = (T^+, T^0, T^-)$, so it does not couple to $Z$ (but the resonant production via $H$ still works). We should take $T^\pm$ into account. Due to the electroweak radiative corrections, $T^\pm$ are slightly heavier than $T^0$, with mass splitting $\sim O(0.1)$ GeV. They make three-body decay into $T^0 + e + \nu_e$, but the produced $e$ and $\nu_e$ are too soft to be observed. As a result, $T^\pm$ behaves as $T^0$ and thus $ud \to W^* \to T^* T^0$ gives rise to $T^0$ (or $N$) pair. Additionally, the singlet $S$ in the NMSSM also provides such a resonance, i.e., $S_R$, the CP-even part of the spin-0 component of $S$ (we still work in the singlino-Higgsino system considered before). Given a sufficiently large $\lambda$, $S_R \to \tilde{H}_u \tilde{H}_d$ can be the dominant decay mode of $S_R$.

**How far can we reach?** With respect to this di-Higgs plus $E_T$ signature, the main BGs actually are the same as the pure di-Higgs signature. For the irreducible BGs, $E_T$ comes from the limited detector resolution. It depends on the center energy of collider, e.g., at 7 TeV LHC it respects a Gaussian distribution with center value $\sim 0.5 \sqrt{\sum p_T}$ GeV $^{32}$. We have shown before applying Higgs fat-jet cuts leaves only the QCD 4b BG, which can be suppressed by a large $E_T$. Since we are considering pair production of mother particles, each subsequently decaying into $h$ plus an invisible particle, $m_{T_2}$ $^{33}$, which reflects the mass scale of the mother particle, will be very useful to further suppress BGs.

In Fig. 1 we show the distributions of $E_T$ and $m_{T_2}$ for two mother particle masses, $M = 200$ GeV and $M = 500$ GeV (with two different choices of $R^{max}_{\text{fat}}$), respectively. Note that the major of QCD and $Zbb$ backgrounds can be suppressed by requiring $E_T \gtrsim 100$ GeV for both cases, while the $t\bar{t}$ has very similar $E_T$ distribution with the signal of low mass. Both the $E_T$ and $m_{T_2}$ cuts become very effective for $M \gtrsim 500$ GeV. In terms of these analysis, for different mass of mother particle we accordingly apply the cuts given in Table I. The most sensitive signal region for each mass is indicated by the signal region name. For $M > 500$ GeV, SR500 is always the most sensitive one.

![FIG. 1: $E_T$ (left) and $m_{T_2}$ (right) distributions for signals with $M = 200$ GeV (upper) and $M = 500$ GeV (lower). All BGs are normalized to its production cross section at 14 TeV. All the signals are normalized to 100 fb.](image)

**TABLE I: Optimised cuts for different mass of signals.**

| signal region | Selection cuts | $E_T$/GeV | $m_{h_1}$/GeV | $m_{h_2}$/GeV | $M_{T_2}(h_1, h_2)$ |
|---------------|----------------|-----------|---------------|---------------|-------------------|
| SR200         | Lepton veto & tau veto Two Higgs tagged jets | $>100$ | $[90,150]$ | $[80,140]$ | $>130$ |
| SR300         | $>100$ | $[90,150]$ | $[70,150]$ | $>170$ |
| SR400         | $>200$ | $[90,150]$ | $[80,140]$ | $>215$ |
| SR500         | $>300$ | $[90,150]$ | $[80,140]$ | $>300$ |

**TABLE II: Optimised cuts for different mass of signals.**

Now we are at the position to demonstrate the probing limit of the signature. The significance of the signal is defined as $S/\sqrt{S+B}$, and the discovery of a signal requires $S/\sqrt{S+B} \geq 3$, which corresponds to the cross section of signal production,

$$\sigma_S \geq \frac{1}{\epsilon_S} \frac{9 + \sqrt{81 + 36 \times \sigma_B \epsilon_B L}}{2}.$$  

At LHC with $L = 3000$ fb$^{-1}$, the discovery limit is shown in Fig. 2 where one can see that this signature indeed provides a very promising probe to new physics: e.g., for $M > 500$ GeV the production rate as small as 0.3 fb can be discovered. For illustration, we apply our general results to the benchmark models given before: (I) In the type-I seesaw mechanism with resonant RHN production
we take \( C_{Hgg} = 0.4 \) and \( \text{Br}(H \rightarrow \nu_R \nu_R) = 1 \); (II) In the bino-Higgsino model, the total branching ratio of the neutral Higgsino pair to Higgs pair is assumed to be 20%. The results are displayed in Fig. 2. From it we see that, the right handed neutrino of mass smaller than \( 500 \) GeV can be excluded while Higgsinos can be probed up to \( 800 \) GeV; (III) Sneutrino system with pair produced \( \tilde{\nu}_L \) followed by \( \tilde{\nu}_L \rightarrow \tilde{N} + h \) with branching ratio 50%. It hardly can be probed, owing to the small production rate of let-handed sneutrino.

\[ \mathcal{L} = 3000 \text{ fb}^{-1} \text{ Reach} \]

**FIG. 2:** (At 14 TeV 3000 fb\(^{-1}\) LHC) Discovery reach of the signature \( 2h + E_T \) shown on the \( M - \sigma_S \) plane and the shaded region can be discovered at the 3\( \sigma \) CL. We also show the signal production rate from right-handed neutrino (orange line) produced through a heavy Higgs resonance decay, Higgsino (blue line) and sneutrino (cyan line) produced via Drell-Yan processes.

**Conclusion** The boosted di-Higgs boson in the 4\( b \) channel is important in examining the SM Higgs potential. We propose an incidental (in the sense of requiring merely a simple extra cut in searching for the SM boosted di-Higgs) but powerful signature, i.e., boosted di-Higgs plus \( E_T \). Moreover, it is well expected from new physics hidden behind the Higgs field, in particular in supersymmetric SMs and low scale seesaw mechanisms. The signature has clear backgrounds, and at the LHC\( @14\text{ TeV} \) with high luminosity, we can probe extremely weak signature rate as low as 0.1 fb.

This signature may be even more powerful at future colliders with much higher energy, such as the 100 TeV hadron collider. At this machine heavy particles of a few TeV can be produced in abundance and then the boosted Higgs can be captured more effectively. Moreover, BGs can be greatly suppressed by using even smaller Higgs-jet cone size. We leave this topic for further study.

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**Substructure in the BDRS analysis**

In this appendix we give the details about technique of boosted Higgs tagging. The \( bb \) pairs from the boosted Higgs decay are collinear, forming fat jets. We adopt the BDRS [41] algorithm to tag them. In our analysis, the mass drop condition and the asymmetric splitting factor are chosen as \( \mu = 2/3 \) and \( \Delta \text{cut} = 0.09 \), respectively. For those fat jets with substructure, we perform the filter procedure to subtract the underlying events, where only three leading subjets with \( R_{\text{filter}} = \min(R_{j_1}, R_{j_2}/2, 0.3) \) are chosen. And we also require the two leading sub-jets \( j_1, j_2 \) are \( b \)-tagged.

**FIG. 3:** In this figures, all background are normalised to its production cross section at 14 TeV. And all the signals are normalised to 100 fb. \( \Delta R \) is the fat jet cone size in jet-substructure analysis. Several benchmark values of \( M \) are chosen for comparison. The resulting \( R_{\text{fat}}^{\text{max}} \) are already shown in Table 1.

For different mass of the mother particle, \( M \), the fat-jet cone size \( R_{\text{fat}} \) should be chosen carefully so as to retain most of the events. The corresponding cone size is labelled as \( R_{\text{fat}}^{\text{max}} \), which is got by scanning \( R_{\text{fat}} \) within the range \( [0.6, 3.0] \) for each given \( M \). This is displayed on the left panel of Fig. 3, where we show the number of events of signals and backgrounds for varying \( R_{\text{fat}} \) after using BDRS tagging. For illustration, in the right panel of Fig. 3 we further impose Higgs mass cuts, requiring that both masses of the Higgs-jet lie within a wide window [85, 165] GeV (In the actual analysis employed in the text, they have been optimized.). Then, it clearly seen that, if we choose an appropriate \( R_{\text{fat}} \), the background events can already be suppressed to the same amount of signal events, except for the QCD background.

**Demonstration of the equivalence theorem in the sneutrino system**

Models with Dirac neutrinos thus conserved lepton number gives a simple example to demonstrate the equivalence theorem. Other examples can be understood in a similar way. The relevant Lagrangian in the case of a single family is given by [18]

\[ -\mathcal{L}_N = m_{\tilde{\nu}_L}^2 |\tilde{\nu}_L|^2 + m_{\tilde{N}}^2 |\tilde{N}|^2 + \left(A_N \tilde{\nu}_L H_u^0 \tilde{N} + c.c. \right). \]
For our simplifying discussion, $m_L \gg m_N$ and therefore $N \approx S_1$ is the LSP. Terms in the bracket of Eq. (10) lead to the decay $S_2 \approx \tilde{\nu}_L \to S_1 + h$. At the same time they induce a very small mixing between $\tilde{\nu}_L$ and $\tilde{N}^* \chi_4$; $\sin \theta \approx A_{\nu_4} v_\nu/m_L^2$. As a consequence, decay $S_2 \to S_1 + Z$ happens via the $\tilde{\nu}_L$ coupling to $Z$ boson:

$$-i g_2 \bar{\nu}_L \gamma^\mu \nu_L Z_\mu = \frac{g_2}{c_w} \bar{\nu}_L \gamma^\mu \nu_R Z_\mu,$$

(11)

where $\tilde{\nu}_L = (\tilde{\nu}_L + i \tilde{\nu}_R)/\sqrt{2}$. The decay width of $S_1 Z$ is enhanced by the factor $m_Z^2/M_Z^2 \gg 1$, that compensates the suppression from mixing angle. Then both channels have partial widths

$$\Gamma(\tilde{\nu}_L \to \tilde{N} + h/Z) \approx \frac{A_N^2}{16\pi} \frac{1}{m_{\nu_L}}.$$  

(12)

A parallel analysis can be directly applied to the low scale seesaw models, in which light right-handed-like sneutrino states are introduced and moreover the lepton number is see-saw models, in which light right-handed-like sneutrino states are introduced and moreover the lepton number is merely softly broken [19].

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