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Probing Compressed Bottom Squarks with Boosted Jets and Shape Analysis

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A feasibility study is presented for the search of the lightest bottom squark (sbottom) in a compressed scenario, where its mass difference from the lightest neutralino is 5 GeV. Two separate studies are performed: (1) final state containing two vector boson fusion (VBF) like tagged jets, missing transverse energy, and zero or one b-tagged jet; and (2) final state consisting of initial state radiation (ISR) jet, missing transverse energy, and at least one b-tagged jet. An analysis of the shape of the missing transverse energy distribution for signal and background is performed in each case, leading to significant improvement over a cut and count analysis, especially after incorporating the consideration of systematic uncertainty and pileup. The shape analysis in the VBF-like tagged jet study leads to a 3σ exclusion potential of sbottoms with mass up to 530 (462) GeV for an integrated luminosity of 300 fb^{-1} at 14 TeV, with 5% systematic uncertainty and PU = 0 (50).

Introduction - Weak-scale supersymmetry addresses the hierarchy problem, gives gauge coupling unification, and (in R-parity conserving models) provides a robust dark matter (DM) candidate, the lightest neutralino ($\tilde{\chi}^0_1$). As such, it is one of the most widely studied frameworks for physics beyond the Standard Model (SM).

The exclusion bounds on supersymmetric colored particles belonging to the first two generations are already quite strong. For comparable squark ($\tilde{q}$) and gluino ($\tilde{g}$) masses, the collider data exclude these particles up to approximately 1.5 TeV at 95% C.L. with 20 fb^{-1} of integrated luminosity [1–5].

On the other hand, the bounds on the masses of the colored third generation sparticles are much weaker due to smaller production cross sections. Given that a new boson consistent with the SM-like Higgs has been observed, with mass in the region of 125 GeV [6], this weakly coupled light scalar must have its mass stabilized against quantum corrections. Probing top squarks (stops) is a high-priority for the future given its importance in this context.

Since left handed bottom squark (sbottoms, $\tilde{b}$) come in the same electroweak doublet, it is equally important to search for light sbottoms. Moreover, light sbottoms can play a role in obtaining the correct relic density of a neutralino DM candidate, through coannihilation effects [7]. Sbottom pairs produced from QCD interactions will decay to the lightest superpartner, which we will assume to be a stable neutralino, through the direct decay $\tilde{b} \to b\tilde{\chi}^0_1$. When the mass difference between the sbottom and the neutralino is large, the b-tagged jet has large p_T or is sufficiently boosted. In that case, the standard procedure for the sbottom search involves final states containing two jets, at least one of which is b-tagged, and large missing transverse energy $\not{E}_T$ coming from the neutralino. This has been the strategy of sbottom searches at CMS and ATLAS.

The current exclusion bounds on sbottoms are as follows. With 20 fb^{-1} of data at 8 TeV, the ATLAS Collaboration has ruled out sbottom up to 650 GeV, for neutralino mass at 300 GeV [8], and up to 255 GeV for the mass-degenerate scenario [9]. Similar exclusion bounds have been obtained by the CMS Collaboration when the similar search strategy is employed [3, 10].

The purpose of this paper is to propose a new search strategy for sbottoms in compressed regions of parameter space, where the $m_{\tilde{b}} - m_{\tilde{\chi}^0_1}$ mass difference is small (we have kept this value at 5 GeV throughout this study). This region is cosmologically very interesting since the coannihilation diagrams start contributing to the calculation of relic abundance [7]. The challenge in the compressed region is that both $\not{E}_T$ and the p_T of the b-tagged jets become small, due to insufficient boosting of the objects coming from the sbottom decay. We point out that this can be overcome in final state topologies containing two boosted forward jets in opposite hemispheres (reminiscent of vector boson fusion jets). Gluons radiated off of the forward jets can produce sbottoms which decay to b-tagged jets and $\not{E}_T$ in the central region of the detector. To balance the high initial p_T of the incoming partons, the centrally produced decay products are boosted, even in the compressed region.

This topology has been proposed by some of the authors as a probe of both colored and non-colored supersymmetric particles. Charged and neutral Wino production followed by decays to $\tilde{\chi}^0_1$ via a light slepton has been studied in [11, 12], while searches for Winos and Higgsinos in the final state of two VBF-tagged jets and $\not{E}_T$ has been proposed in [13]. Moreover, top squarks have been studied in the compressed region using this topology [14].

The search strategy using the initial state radiation (ISR) jet has been already employed by the CMS and ATLAS Collaborations, and has shown a good sensitivity for signals with compressed spectra [3, 9]. We also consider a separate study with a final state consisting of an ISR jet, $\not{E}_{\mathrm{T}}$, and at least one b-tagged jet.

In each case, the shapes of the $\not{E}_{\mathrm{T}}$ distributions for signal and background are studied using a binned likelihood following the test statistic based on the profile likelihood ratio which we call the shape analysis. We find that the shape analysis, compared to a simple cut and count analysis (where we compare the numbers of signal events and the background events after optimizing all possible cuts), yields a significant improvement of the compressed sbottom mass reach after incorporating the effects of systematic uncertainty and pileup.

In the rest of the paper, we present results first from the analysis with VBF-like tagged jets in the final state, and next the analysis with a ISR jet in the final state. The sensitivities of these analysis are estimated with an assumption of 5% systematic uncertainty on the signal ($BF(\tilde{b} \rightarrow b\tilde{\chi}_1^0) = 1$) and backgrounds and an integrated luminosity of 300 fb^{-1} at 14 TeV. We end with our discussions.

VBF-like Tagged Jets Study - For this feasibility study, inclusive $\tilde{b}\tilde{b}^* +$ multijets samples are generated with $\tilde{b}$ masses in the range of 15–1000 GeV, keeping $m_{\tilde{b}} - m_{\tilde{\chi}_1^0} \sim 5$ GeV. Both QCD and weak production processes are included. The $\tilde{\chi}_1^0$ in our studies is mostly Bino and the sbottom decays entirely through the canonical channel $\tilde{b} \rightarrow b\tilde{\chi}_1^0$. The other colored particles, neutralinos and charginos are assumed to be much heavier.

Signal and background samples are generated with `MADGRAPH5 V2.1.1` [15] followed by the parton showering and hadronization with `PYTHIA 6` [16] and the detector simulation using `DELPHES 3.0.9.1` [17]. One advantage of the `DELPHES` simulation is that it can simulate pileup pp interactions, which was not possible with other fast simulation programs available in the HEP community. We used the Snowmass detector configuration as defined in [18], which represents the typical performance of the CMS and ATLAS detectors. We perform a 14 TeV study for pileup PU = 0, 50, and 140 scenarios, with an assumption of 5% systematic uncertainty on the signal and background. PU= 0 case represents idealistic scenario. We think that PU= 50 is more realistic Snowmass configuration while the PU= 140 is pessimistic.

Given the compressed spectrum, we explored the sensitivity with two VBF-like tagged jets and large missing transverse energy in the final state. We also found that with the VBF-like event signature, the b jets from the sbottom decays also get boosted in the central part of the detector, providing another approach for probing this compressed signal. Overall, two studies are performed: (1) final state with two VBF-like tagged jets, $\not{E}_{\mathrm{T}}$ and zero b-tagged jet and (2) final state with two VBF-like tagged jets, $\not{E}_{\mathrm{T}}$, and one b-tagged jet.

The cuts employed are as follows.

(1) $\not{H}_{\mathrm{T}}$-$\not{E}_{\mathrm{T}}$ asymmetry cut: the condition

$$\frac{|\not{H}_{\mathrm{T}} - \not{E}_{\mathrm{T}}|}{\not{H}_{\mathrm{T}} + \not{E}_{\mathrm{T}}} < 0.2\,(0.5) \;\text{ for PU} = 0(140) \qquad (1)$$

is imposed to protect against occasional loss of high p_{T} jets due to the aggressive pileup subtraction in `DELPHES 3.0.9.1`. Here, $\not{H}_{\mathrm{T}}$ is defined as the negative vectorial sum of jets with $p_{\mathrm{T}} \geq 30$ GeV, muons, electrons, and photons. The $\not{H}_{\mathrm{T}}$ was found to be less pileup dependent, and used instead of $\not{E}_{\mathrm{T}}$ in this analysis.

(2) Boosted jet cuts: the event is required to have the presence of at least two jets (j_1, j_2) satisfying: (i) $p_{\mathrm{T}}(j_1) \geq 50(200)$ GeV and $p_{\mathrm{T}}(j_2) \geq 50(100)$ GeV for PU $= 0\,(140)$ in $|\eta| \leq 5$; (ii) $|\Delta\eta(j_1, j_2)| > 3.5$; ($iii$) $\eta_{j_1}\eta_{j_2} < 0$; (iv) dijet invariant mass $M_{j_1 j_2} > 1500$ GeV; (v) missing transverse energy $\not{H}_{\mathrm{T}} > 50$ GeV.

(3) Vetoes: We veto electrons, muons and tau-tagged jets. In the final state study with two VBF-like tagged jets, $\not{E}_{\mathrm{T}}$ and zero b-tagged jet, a b-tagged jet veto is also applied at this stage.

(4) b-tagged jet requirements (for 1 b-tagged jet study): For the tagged jets plus $\not{E}_{\mathrm{T}}$ plus b study, we require exactly one tight b-tagged jet in the final state, with $p_{\mathrm{T}} < 80$ GeV to suppress the $t\bar{t}$ background.

(5) $\not{H}_{\mathrm{T}}$ cut: We require $\not{H}_{\mathrm{T}} > 200$ GeV.

(6) $\Delta\phi_{jj}$: From the search for invisible Higgs boson in the vector boson fusion at CMS [22], the QCD background is reduced to a low level by requiring the azimuthal separation between the VBF-tagged jets to be small. Here, we require $\Delta\phi_{jj} < 1.8$.

The cut flow table for the benchmark point for PU = 0 in the VBF-like tagged jets, $\not{H}_{\mathrm{T}}$, and zero b-tagged jet study is presented in Table I. The cross-sections presented in the table are leading order.

TABLE I: Cut flow table for $m_{\tilde{b}} = 500$ GeV with PU = 0, in the final state with two VBF-like tagged jets, $\not{H}_{\mathrm{T}}$, and zero b-tagged jets.

Selection	Signal (pb)	Background (pb)
Boosted jets	$5.6 \cdot 10^{-3}$	10.2
b-tagged jet veto	$5.5 \cdot 10^{-3}$	9.8
Lepton veto	$5.4 \cdot 10^{-3}$	6.5
$\not{H}_{\mathrm{T}} > 200$	$3.3 \cdot 10^{-3}$	0.6
$\Delta\phi$	$2.1 \cdot 10^{-3}$	0.25

Figure 1 shows the distributions of $\not{H}_{\mathrm{T}}$ normalized to unity for signal (green dotted histogram) and the dominant $V(W, Z)$+jets background (black solid histogram) after all selections except $\not{H}_{\mathrm{T}}$ requirement, for the benchmark point with $m_{\tilde{b}} = 500$ GeV, $m_{\tilde{\chi}_1^0} = 495$ GeV, in the case of PU = 0 for the VBF-like tagged jets plus $\not{H}_{\mathrm{T}}$

study. The $t\bar{t}$ is 10% of the V+jets for zero b-tagged analysis due to b jet veto. In the case of one b-tagged jet analysis, with the upper cut on the b-tagged jet p_{T} is optimized to suppress the $t\bar{t}$ background, the $t\bar{t}$ background is comparable with the V+jets background. Based on this distribution, and similar $\not{H}_{\mathrm{T}}$ distributions for the VBF-like tagged jets, $\not{H}_{\mathrm{T}}$, plus one b-tagged jet study, a shape analysis was performed with different pileup scenarios. A local p-value is calculated as the probability under a background only hypothesis to obtain a value of the test statistic as large as that obtained with a signal plus background hypothesis. The significance z is then determined as the value at which the integral of a Gaussian between z and ∞ results in a value equal to the local p-value.

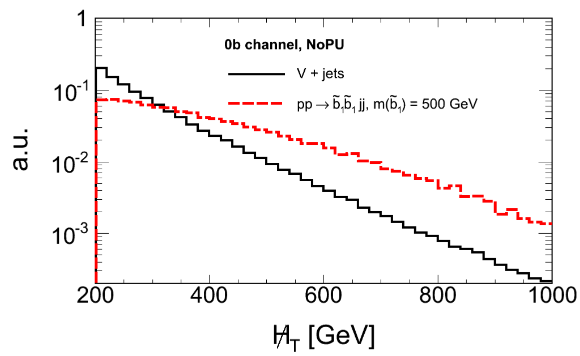

FIG. 1: **VBF-like tagged jets study:** Distributions of $\not{H}_{\mathrm{T}}$ normalized to unity for signal (green dotted histogram) and dominant V+jets background (black solid histogram) after all selections except $\not{H}_{\mathrm{T}}$ requirement, for the benchmark point with $m_{\tilde{b}} = 500$ GeV, $m_{\tilde{\chi}_1^0} = 495$ GeV, in the case of PU = 0, for the channel with VBF-like tagged jets, $\not{H}_{\mathrm{T}}$, and zero b-tagged jet.

In Figure 2, we show the significances of the compressed scenario with $m_{\tilde{b}} - m_{\tilde{\chi}_1^0} = 5$ GeV, at 300 fb^{-1} with the cut and count method (left panel) and the shape analysis (right panel), using joint likelihood to combine the studies with and without b-tagged jets. A systematic uncertainty of 5% is uniformly assumed. From top to bottom, the black solid, red dashed, and green dotted curves show the cases of PU = 0, 50, and 140, respectively. The red solid horizontal lines denote the 3σ and 1.69σ levels. The shape analysis leads to a 3σ exclusion potential of sbottoms with mass up to 530 (462) GeV with 5% systematic uncertainty and PU = 0 (50). (The 95% CL exclusion reach for the PU = 50 case at 300 fb^{-1} is 541 GeV.) For the most conservative PU = 140 case, using the shape (cut and count) analysis, it is possible to probe compressed sbottoms at the 3σ level up to $m_{\tilde{b}} = 380\,(300)$ GeV.

ISR Monojet study - We now turn to our second analysis, in which the final state consists of an initial state radiation (ISR) jet, $\not{H}_{\mathrm{T}}$, and at least one b-tagged jet. Our analysis follows [21], which studied this scenario with selections optimized for the 8 TeV LHC. The event selection is as follows. The $\not{H}_{\mathrm{T}}$ asymmetry cut is applied as above to protect against occasional loss of high p_{T} jets due to pileup subtraction. The leading jet is required to be non b-tagged, and have $p_{\mathrm{T}} > 120$ GeV. At least one b-tagged jet with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$ is required. The leading b-tagged jet is required to satisfy $p_{\mathrm{T}}(b_1) < 100$ GeV, with $\Delta\phi(p_{\mathrm{T}}(b_1), \not{E}_{\mathrm{T}}) < 1.8$. Leptons are vetoed. We also require $\not{H}_{\mathrm{T}} \geq 430$ GeV, and the top quark transverse mass to satisfy $M_T^t > 200$ GeV.

The $\not{H}_{\mathrm{T}}$ distribution (after all cuts except $\not{H}_{\mathrm{T}}$ cut), normalized to unity, for signal (red dotted histogram) and dominant V+jets background (black solid histogram) is shown in Figure 3 for $m_{\tilde{b}} = 500$ GeV and $m_{\tilde{\chi}_1^0} = 495$ GeV, in the case of PU = 0.

A shape analysis is performed following the method described above. This yields the significance plot shown in Figure 4 for $m_{\tilde{b}} - m_{\tilde{\chi}_1^0} = 5$ GeV with 300 fb^{-1} of data. From top to bottom, the black solid, red dashed, and green dotted lines show the cases of PU = 0, 50, and 140, respectively. The red solid horizontal lines denote the 3σ and 1.69σ levels. In the ISR + b-tagged jets study, we found the 3σ level reach to be 250 (170) GeV for the PU = 0 (50) case.

Discussion of Snowmass Simulation- For the study with VBF-like tagged jets, we have performed a joint analysis of the zero and one b-tagged jet final states and displayed the exclusion reach in the right panel of Figure 2. Figure 5 shows the separate significances in the two final states, after shape analysis, assuming PU = 0 and a systematic uncertainty of 5%. It is clear that the performance is dominated by the zero b-tagged jet channel, due to the small mass difference of 5 GeV between the sbottom and $\tilde{\chi}_1^0$. For larger mass difference, it is expected that the final state containing one b-tagged jet would perform better.

In the one b-tagged jet analysis, we found that the b-tagging efficiency for low p_{T} jets is critical in probing compressed scenarios. From the Snowmass detector simulation, the efficiency of b-tagging reaches 60% at jet p_{T} around 100 GeV [18], while CMS and ATLAS have showed the ability to tag b jet with 60% efficiency for jets with p_{T} above 30 GeV [19, 23]. Thus the VBF-like tagged jet plus one b-tagged jet analysis can be significantly improved with more efficient and robust b-tagging.

Figures 2 and 4 show the degradation in significance with higher number of pileup for both VBF-like and Monojet analysis. From [24], the expected jet performance of the CMS detector in pileup of 50 is comparable with the performance simulated in the Snowmass sample [18], while the Snowmass samples have much degraded performance in the 140 pileup condition. With the upgraded CMS and ATLAS detectors optimized for the high-luminosity LHC condition and development in the pileup mitigation technique, we are expecting better physics object performance in the 140 pileup scenario and thus improved reach of sbottoms in the 140 pileup

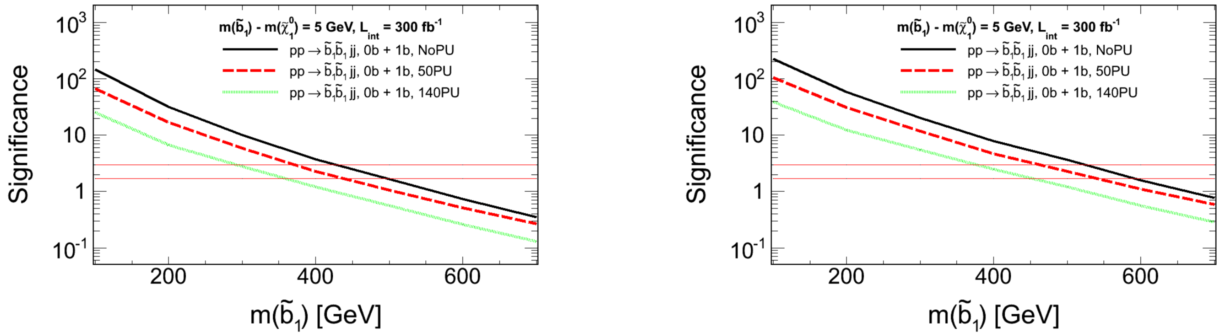

FIG. 2: **VBF-like tagged jets study:** The exclusion reach for the compressed sbottom scenario with $m_{\tilde{b}} - m_{\tilde{\chi}_1^0} = 5$ GeV. A systematic uncertainty of 5% is assumed throughout. **Left panel:** The significance at 300 fb^{-1} as a function of $m_{\tilde{b}}$ in the cut and count method, for the joint studies with and without b-tagged jets. From top to bottom, the black solid, red dashed, and green dotted lines show the cases of PU = 0, 50, and 140, respectively. The red solid horizontal lines denote the 3σ and 1.69σ levels. **Right panel:** The significance at 300 fb^{-1} as a function of $m_{\tilde{b}}$ with the shape analysis method, for the joint studies with and without b-tagged jets. The legend is identical to the left panel.

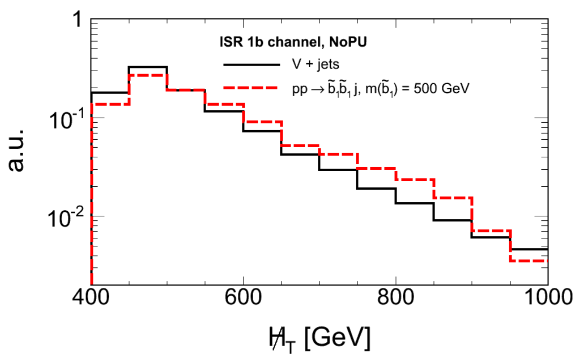

FIG. 3: **ISR + b-tagged jet study:** Distributions of $\not{H}_T$ normalized to unity for signal (red dotted histogram) and dominant V+jets background (black solid histogram) after all selections except $\not{H}_T$ requirement, for the benchmark point with $m_{\tilde{b}} = 500$ GeV, $m_{\tilde{\chi}_1^0} = 495$ GeV, in the case of PU = 0, for the channel with ISR jet, one b-tagged jet, and $\not{H}_T$.

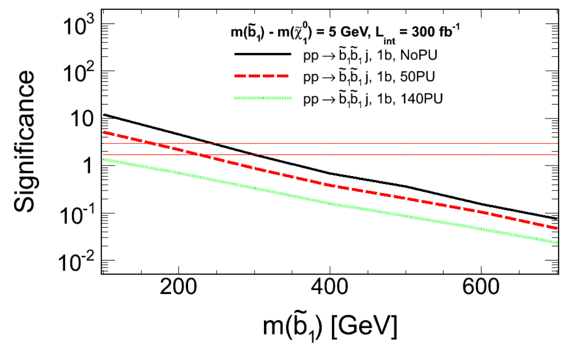

FIG. 4: **ISR + b-tagged jet study:** The exclusion reach is shown for the compressed sbottom scenario with $m_{\tilde{b}} - m_{\tilde{\chi}_1^0} = 5$ GeV, for the channel with ISR jet, at least one b-tagged jet, and $\not{H}_T$. The significance at 300 fb^{-1} as a function of $m_{\tilde{b}}$ after shape analysis is displayed. A systematic uncertainty of 5% is assumed. From top to bottom, the black solid, red dashed, and green dotted lines show the cases of PU = 0, 50, and 140, respectively. The red solid horizontal lines denote the 3σ and 1.69σ levels.

condition at HL-LHC.

Conclusions - The main result of this paper is that the boosted jet topology can provide a feasible strategy to search for compressed bottom squarks with mass difference of sbottom and lightest neutralino being 5 GeV. A shape based analysis is used to estimate the significances. There is 3σ exclusion potential up to 530 (462) GeV for an integrated luminosity of 300 fb^{-1} at 14 TeV, with 5% systematic uncertainty and PU = 0 (50). Instead of 5%, if we use 10% uncertainty then the significance reduces by 25% for the range of sbottom mass shown in the figures. We also performed an ISR + b-tagged jet study, and found the exclusion reach to be 250 (170) GeV for PU = 0 (50).

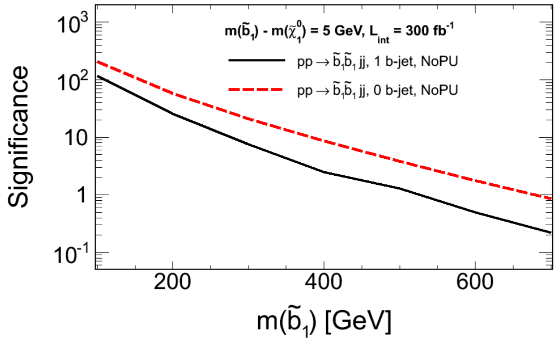

FIG. 5: **VBF-like tagged jets study:** A comparison of the exclusion reach with $m_{\tilde{b}} - m_{\tilde{\chi}_1^0} = 5$ GeV, for final states containing zero b-tagged jet (red dotted curve) and one b-tagged jet (black solid line), along with the VBF-like tagged jets and $\not{H}_{\rm T}$. The significance at 300 fb^{-1} is given as a function of $m_{\tilde{b}}$ after shape analysis, assuming PU $= 0$ and a systematic uncertainty of 5%.

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