DESY 15-130
UT-15-27
August 10, 2015

Testing ATLAS Diboson Excess with Dark Matter Searches at LHC

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Abstract

The ATLAS collaboration has recently reported a 2.6σ excess in the search for a heavy resonance decaying into a pair of weak gauge bosons. Only fully hadronic final states are being looked for in the analysis. If the observed excess really originates from the gauge bosons' decays, other decay modes of the gauge bosons would inevitably leave a trace on other exotic searches. In this paper, we propose the use of the Z boson decay into a pair of neutrinos to test the excess. This decay leads to a very large missing transverse energy and can be probed with conventional dark matter searches at the LHC. We discuss the current constraints from the dark matter searches and the prospects. We find that optimizing these searches may give a very robust probe of the resonance, even with the currently available data of the 8 TeV LHC.

1 Introduction

The ATLAS collaboration has recently reported a search for diboson resonances with W and Z boson-tagged jets at 8 TeV at the Large Hadron Collider (LHC) [1]. The most prominent excess is seen at resonance mass approximately 2 TeV in the WZ final-state channel with a significance of 3.4σ. As only fully hadronic final states are considered, the gauge bosons are not well distinguished in the analysis, and the same excess can also be interpreted as WW (2.6σ) or ZZ (2.9σ) resonance.

The excess is not statistically significant yet and a similar search by the CMS collaboration has seen no clear excess [2]. It is too early to conclude that this is a signal of physics beyond the standard model (SM). Therefore, it is essential to test the excess from many different perspectives. The purpose of this paper is to investigate as model-independent as possible the consistency of the observed excess of boson-tagged jets with other LHC searches.

The direct interpretation of the excess in terms of physics beyond the SM would be a new process $P + P' \to X \to \phi(\to 2j) + \phi'(\to 2j)$, where $P^{(')}$ is a parton, X a new heavy resonance of mass around 2 TeV, $\phi^{(')}$, a resonance of mass around 100 GeV (we note that the observed excess does not necessarily imply that $\phi^{(')}$ is the SM weak gauge boson), and j a quark or gluon jet. One expects collider signals other than the boson-tagged jet resonances once the above process is assumed, the most promising one being the inverse process, $P + P' \to X \to P + P'$, which induces a resonance from two QCD jets (dijet resonance). However, the SM background of the dijet resonance with non boson-tagged jets are much larger than the case of the boson-tagged jets [3, 4], and this process is not so significant at probing the new resonance.

If we further assume that the ϕ's are weak gauge bosons, signals from other exotic searches in addition to analyses mentioned above are expected, as the non-hadronic decays of the gauge bosons will lead to a variety of final states. For instance, searches of $X \to W + V(\equiv W/Z)$ followed by $W \to \ell\nu$ and $V \to 2j$ [5, 6] provide a strong constraint on the 2 TeV resonance. Although the leptonic branching fraction of the Z boson is small, the relatively smaller number of SM background events enables one to impose a stringent constraint with the $X \to Z(\to \ell^+\ell^-) + V(\to 2j)$ channel [5, 7]. Such consistency check in the context of the ATLAS diboson excess has been studied in Refs. [8–15]. There are also studies considering bounds from the decay of the new resonance into heavy quarks or the Higgs boson, such as [16–20], but it should be noted that such considerations are model-dependent.

In this paper, we focus on the decay $Z \to \bar{\nu}\nu$, which is the secondary decay mode of the Z boson. The branching fraction of $X \to Z(\to \bar{\nu}\nu) + V(\to 2j)$ is relatively large, and a significant number of signal events can be expected. The signal is a (boson-tagged) jet plus large missing transverse energy (MET). This channel is not well discussed in the context of the 2 TeV resonance search. However, such signal can be probed with the available LHC dark matter searches of large MET plus a high transverse momentum jet with/without boson tagging [21, 22].

Using the reported LHC dark matter searches, we show that the null results of these searches are constraining the region favored by the ATLAS diboson excess. In addition, we show that by optimizing the MET cuts of the relevant analyses, most of the region can be tested even only with the 8 TeV data. Furthermore, we study the projections of these channels at the next run of the LHC. It is shown that these channels can be a complementary and potentially powerful probe of the diboson resonance.

The rest of the paper is organized as follows. In Sec. 2, we briefly review the status of the dark matter searches at the LHC. We recast constraints from dark matter searches on the observed excess in Sec. 3. In Sec. 4, we discuss the prospect of these dark matter searches for the run 2 of the LHC. Summary and discussion are given in Sec. 5.

2 LHC Dark Matter Search

The search for collider signatures of dark matter is an essential part of the LHC physics program. Presumably dark matter particles are produced recoiling against a hard parton inside the detector, resulting in a single-parton final state accompanied with large MET. These final-state topologies are well-suited to our purposes of constraining diboson channels of which one of the gauge boson decays into a pair of neutrinos (mimicking dark matter in practice), while the other decays into particles visible to the detector. For the case where the gauge boson decays leptonically, i.e., $W \to \ell\nu$ or $Z \to \ell^+\ell^-$, we find that the constraints are less sensitive than the corresponding hadronic channels. We hence hereafter focus on the dark matter searches in the hadronic channels.

We study the channel $X \to Z(\to \bar{\nu}\nu) + V(\to 2j)$ and $m_X \simeq 2$ TeV. In this channel, V is highly boosted and the produced two quarks are almost collinear. Such quarks are detected as a single jet with the conventional jet reconstruction algorithm. By analyzing the substructure of the jet, one can in principle identify that such jets are boson-originated (boson-tagged jets).

Mono-jet Search

Both ATLAS and CMS collaborations have reported searches for a single jet accompanied with large MET (mono-jet) at 8 TeV [22, 23]. We utilize only the ATLAS analysis because a more stringent MET cut is imposed, which results in a better sensitivity towards testing the 2 TeV resonance.

Let us summarize the major features of the event selection for the ATLAS analysis. The analysis requires at least a jet with transverse momentum $p_T > 120$ GeV and no leptons in the final state. Jets are defined by the anti-k_T jet algorithm, with the radius parameter $R = 0.4$ [24]. Several signal regions (SR) are defined according to the strength of the MET cut, with the strongest being > 700 GeV. In addition, the ratio of the leading jet p_T to MET has to be larger than 0.5 to ensure the final state to be mono-jet-like. Strictly speaking, the event topology we are interested in involves two quark partons from the gauge boson decay. However, due to the highly boosted nature of the gauge boson, many events are tagged as a single collimated jet, and this analysis can be sensitive to probing the boosted gauge boson.

Fat-jet Search

In Ref. [21], [1] a hadronically decaying gauge boson accompanied with large MET is looked for by reconstructing a large-radius (fat-jet). The jet is reconstructed with the Cambridge-Aachen algorithm with $R = 1.2$ [26]. A mass-drop filtering procedure is applied to identify the substructure of the fat-jet [27]. The two leading subjets have to satisfy $\sqrt{y} > 0.4$, where

$$\sqrt{y} = \frac{\min(p_{T1}, p_{T2})\Delta R}{m_{\rm jet}}, \tag{1}$$

[1] Very recently the CMS collaboration has also published results on searching for events with boson-tagged jet plus MET [25].

and $\Delta R = \sqrt{(\Delta\phi_{1,2})^2 + (\Delta\eta_{1,2})^2}$, and $m_{\rm jet}$ is the mass of the fat-jet. The fat-jet is required to have 50 GeV $< m_{\rm jet} <$ 120 GeV, such that it is supposed to capture the hadronic W or Z. The fat-jet is further required to satisfy $p_T >$ 250 GeV.

In addition, narrow jet is defined using the anti-k_T jet algorithm, with $R = 0.4$. Events with more than one narrow jet carrying $p_T >$ 40 GeV and separated from the leading fat-jet $\Delta R > 0.9$, or separated from the MET with $\Delta\phi < 0.4$ are rejected. Two SRs are defined according to the MET threshold: 350 GeV and 500 GeV respectively.

3 Interpretation as Resonance Search

In this Section, we impose the constraints on the 2 TeV resonance by recasting reported results of searches for events with a jet (boson-tagged or not) plus large MET. Concerning the optimization procedures, we extrapolate the current analyses by defining new SRs with higher MET cuts in order to derive stronger bounds.

3.1 Simulation Setup

For both signal and background estimations, we have used the programs `MADGRAPH 5 v2.1.2` [28, 29] interfaced to `Pythia 6.4` [30] and `Delphes 3` [31] (which has `FastJet` incorporated [32, 33]).

New Physics Signal

As a benchmark model for the $X \to ZZ$ and W^+W^- channels, we adopt the Randall-Sundrum (RS) graviton [34], which is a spin 2 boson and couples to the SM particle through the energy-momentum tensor. For the case of $X \to WZ$, we assume a W' boson, which couples to SM particles in a similar way to the SM W boson. In both cases, we assume that the total decay width of the resonance is 100 GeV.

SM Background

The SM background for SRs of interest is dominated by Z+jets, W+jets, diboson and top events. In order to study the prospect of the event searches' optimizations, we need to estimate the number of the background events in optimized SRs characterized by the stronger MET cuts. We first generate SM Monte-Carlo events and normalize the total number of events to the one in the ATLAS SRs. For both analyses, the normalization factor is consistent within a few tens of percent, compared to the cross section estimated with `MADGRAPH`.

3.2 Result

In Table 1, we show the current status and prospect of the jet plus MET search at 8 TeV. For reference, we show the observed and expected cross section times branching ratio upper limits on the 2 TeV resonances, with SM background-only hypothesis. In the following, a systematic uncertainty of 10% is assumed for the expected background events. As expected, resonances involving the decay into a Z boson are well constrained. Even though, at present, the observed cross section times branching ratio upper limits are slightly worse than the expected ones, no significant excesses from the SM background is observed. One can see the the upper limits can be significantly improved by increasing the MET cuts.

Next, in Table 2, we show the results of the 8 TeV fat-jet plus MET analysis. Again, no significant excess over the SM background is observed. Compared to the previous mono-jet search, the background is reduced by about 90% while the signal rate is reduced only by approximately 50%. Thanks to the large reduction of the SM background, the sensitivity is hugely improved. Particularly, the MET cut 800 GeV will provide best sensitivity for the 2 TeV resonance searches. It is possible to impose an upper limit as low as 6 fb with this SR.

Table 1: Status and prospect for mono-jet search at 8 TeV. The observed number and expected SM background for MET cuts ≤ 700 GeV are taken from Ref. [22]. For larger MET cuts, we extrapolate the ATLAS analysis, using our simulation results. A systematic uncertainty of 10% is assumed for the background in the extrapolated SRs. Acceptance is calculated assuming a resonance of mass 2 TeV. The expected and observed cross section times branching ratio upper bound are given using $\mathrm{CL_s}$ procedure.

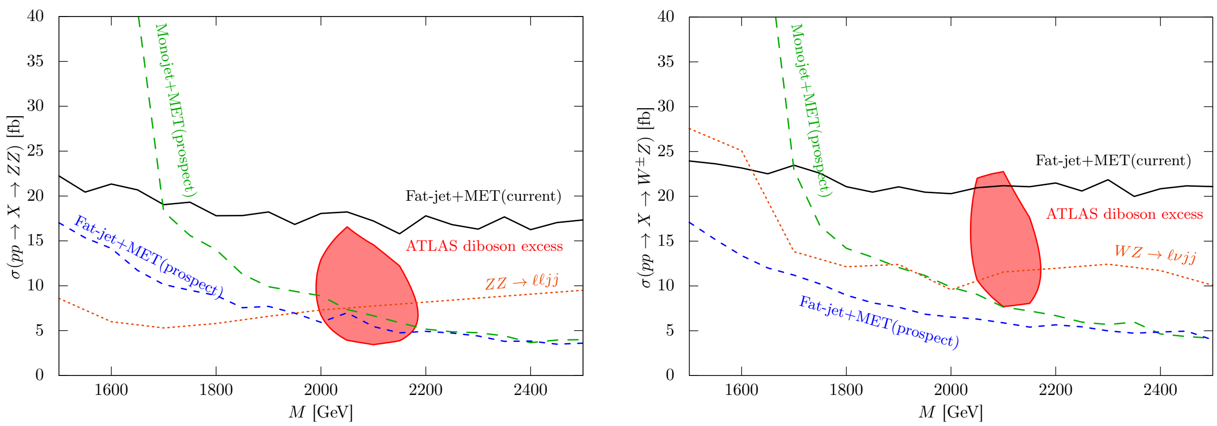
MET cut [GeV]		> 350	> 400	> 500	> 600	> 700	> 800	> 900	> 1000
Observed Number		7988	3813	1028	318	126	-	-	-
SM BG		8300(300)	4000(160)	1030(60)	310(30)	97(14)	36	14	5.4
ZZ	Acceptance	0.20	0.19	0.18	0.15	0.12	0.09	0.06	0.02
	$\sigma_{95\%}^{\mathrm{obs}}$ [fb]	110	61	38	25	24	-	-	-
	$\sigma_{95\%}^{\mathrm{exp}}$ [fb]	150	88	37	23	14	8.8	8.6	16
WZ	Acceptance	0.13	0.13	0.12	0.11	0.10	0.08	0.05	0.01
	$\sigma_{95\%}^{\mathrm{obs}}$ [fb]	170	92	54	33	31	-	-	-
	$\sigma_{95\%}^{\mathrm{exp}}$ [fb]	230	131	53	31	18	11	10	21
WW	Acceptance	0.02	0.02	0.02	0.01	0.01	0.01	0.004	0
	$\sigma_{95\%}^{\mathrm{obs}}$ [fb]	980	560	400	290	310	-	-	-
	$\sigma_{95\%}^{\mathrm{exp}}$ [fb]	1400	820	400	270	180	110	120	-

In Fig. 1, we show the current and prospective constraints on the resonance mass-production cross section plane for the cases $X \to ZZ$ and ZW. The red shaded regions are preferred region (1σ) to explain the ATLAS diboson excess. Here we assume the SM background distribution form $p_1(1-x)^{p_2}x^{p_3}$ with $x = m_{JJ}/\sqrt{s}$ and fit the signal distribution over the background in the dijet mass region of 1050-3550 GeV. Note that the resonance width is fixed to 100 GeV throughout the analysis. Changing the resonance width potentially shifts the 1σ region, i.e. a narrower resonance would shift the red shaded region towards $M = 2000$ GeV in Fig. 1. The solid black lines show the current observed cross section times branching ratio upper bound with the fat-jet plus MET search. The long-dashed green (short-dashed blue) lines represent prospects for mono-jet (fat-jet plus MET) searches. In Fig. 1a, we also show the constraints with $X \to Z(\to \ell^+\ell^-) + Z(\to 2j)$ [7] for reference. Note that in Ref. [7], the constraint for the region $m_X > 2$ TeV is not given. We have extrapolated the constraint assuming the reconstruction efficiency for the "merged region" to be 30%. The dotted line in Fig. 1b shows the constraint with $X \to W(\to \ell\nu) + Z(\to 2j)$ [6]. The current jet plus MET constraints are relatively weak and are not shown in the figure. As can be observed from the figure, even though the current fat-jet plus MET analysis does not constrain the parameter region favoring the excess, a simple optimization MET cut can greatly improve the bound, and a large portion of

Table 2: Status and prospect for fat-jet plus MET search at 8 TeV. The observed number and expected SM background for MET cuts $\leq$ 500 GeV are taken from Ref. [21]. For larger MET cuts, we extrapolate the ATLAS analysis, using our simulation results. A systematic uncertainty of 10% is assumed for the background in the extrapolated SRs. Acceptance is calculated assuming a resonance of mass 2 TeV. The expected and observed upper bound is given using $\mathrm{CL_s}$ procedure.

MET cut [GeV]		> 350	> 500	> 600	> 700	> 800	> 900	> 1000
Observed Number		705	89	-	-	-	-	-
SM BG		707^{+48}_{-38}	89^{+9}_{-12}	30	12	4.7	1.8	0.7
ZZ	Acceptance	0.10	0.09	0.08	0.06	0.05	0.03	0.007
	$\sigma^{\mathrm{obs}}_{95\%}$ [fb]	54	18	-	-	-	-	-
	$\sigma^{\mathrm{exp}}_{95\%}$ [fb]	54	18	11	7.2	6.0	7.3	22
WZ	Acceptance	0.09	0.08	0.07	0.06	0.04	0.03	0.007
	$\sigma^{\mathrm{obs}}_{95\%}$ [fb]	60	20	-	-	-	-	-
	$\sigma^{\mathrm{exp}}_{95\%}$ [fb]	61	20	12	7.5	6.6	7.5	22
WW	Acceptance	0.03	0.02	0.02	0.01	0.007	0.003	0
	$\sigma^{\mathrm{obs}}_{95\%}$ [fb]	169	69	-	-	-	-	-
	$\sigma^{\mathrm{exp}}_{95\%}$ [fb]	173	68	53	44	44	56	-

parameter region can potentially be tested.



(a) $X \to ZZ$

(b) $X \to WZ$

Figure 1: Current and prospective 8 TeV constraints on the diboson resonances ($X \to ZZ/WZ$). The shaded region is the 1σ favored region for explaining the observed excess. The black solid lines are the fat jet plus MET constraints derived with the current ATLAS results [21]. The short-dashed blue lines show the optimized fat jet plus MET constraints, while the long-dashed green lines are the optimized jet plus MET constraints [22]. The dotted lines represent constraints from the semi-leptonic diboson search [6, 7].

4 LHC Run 2 Prospect

In this section, we study projected sensitivities of the mono-jet and fat-jet searches on testing the diboson resonance at 13 TeV. We assume an integrated luminosity of 10 fb^{-1} and 100 fb^{-1}. The number of background events are estimated by using `MADGRAPH`. As compared to the 8 TeV analysis, the only optimization that we have performed is by changing the MET cut to larger values. Further improvements could be achieved by tuning other selection cuts, but an accurate and realistic description is only feasible after the 13 TeV data is collected and analyzed. The projection results presented here are therefore conservative.

4.1 Signal Cross Section

In order to explain the ATLAS diboson excess, the plausible cross section of a pair of the weak bosons mediated by the 2 TeV resonance is around 10 fb for $\sqrt{s} = 8$ TeV. In order to study the prospect at the 13 TeV running LHC, we need to estimate the relevant cross section. The cross section depends on details of the new physics model. Let us consider the case where the production channel of the resonance X is dominated by PP' parton-level collision, i.e. $PP' \to X$. When the narrow width approximation is assumed, the relation between the cross sections at 8 TeV and 13 TeV can be approximately given by

$$\frac{\sigma_{pp\to X}\big|^{PP'}_{\sqrt{s}=13\text{TeV}}}{\sigma_{pp\to X}\big|^{PP'}_{\sqrt{s}=8\text{TeV}}} \simeq \left.\frac{\mathcal{L}^{PP'}_{\sqrt{s}=13\text{TeV}}}{\mathcal{L}^{PP'}_{\sqrt{s}=8\text{TeV}}}\right|_{\sqrt{\hat{s}}=m_X}, \tag{2}$$

where $\mathcal{L}^{PP'}$ is the parton luminosity of the partons P and P'. With these specification, we can estimate the 13 TeV production cross section with the parton luminosity ratio between 8 TeV and 13 TeV. This ratio is shown in Fig. 2. Here we use CTEQ6L [35] and MSTW2008LO [36] PDF sets to indicate the uncertainty of the luminosity ratio. It is seen that for instance, W' dominantly comes from $u\bar{d}$ partons, and the enhancement of the cross section at 13 TeV is around 6. The gluon fusion channel gives the largest 13 to 8 TeV enhancement of the cross section. The $u\bar{u}$ fusion channel performs worst, giving an enhancement factor of about 6.

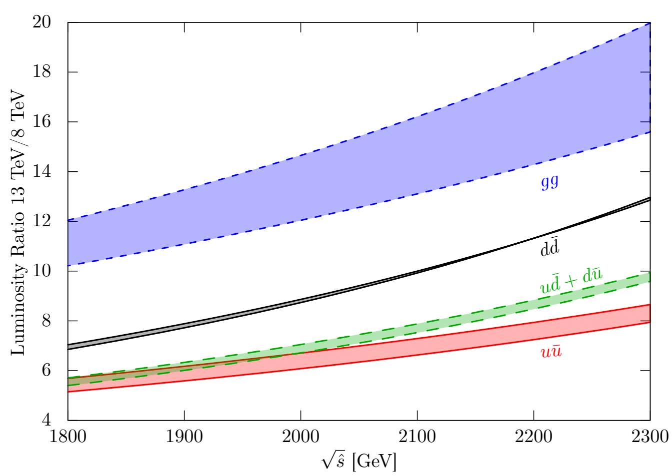


Figure 2: Parton luminosity ratios 13/8 TeV.

4.2 Sensitivity at 13 TeV

As in the 8 TeV analyses, we use the RS graviton (W' boson) as our benchmark model to test the ZZ, WW (WZ) diboson channel. In Tables 3 and 4, we show the expected production cross section times branching ratio upper limits of mono-jet and fat-jet plus MET searches on the 2 TeV with several choices of MET cut up to 1 TeV.

As discussed previously, depending on the dominant production cross section, the signal cross section can be enhanced up to a factor of ten compared to the 8 TeV run. It is however noted that the SM background events are also similarly enhanced by several factors. Therefore, compared to the 8 TeV prospect, the constraint is not so drastically improved, particularly if the resonance production mainly comes from valence quark fusion. If the dominant production is via the gluon fusion channel, as in the case of RS graviton, the obtained constraints are effectively twice stronger at 10 fb^{-1}.

Table 3: Prospect for jet plus MET search at 13 TeV with integrated luminosities of 10 and 100 fb^{-1}. The SM background production cross section is estimated using `MADGRAPH`. A systematic uncertainty of 10% is assumed for the background. Acceptance is calculated assuming a resonance of mass 2 TeV. The expected and observed upper bound is given using CL$_s$ procedure.

	MET cut [GeV]	> 500	> 600	> 700	> 800	> 900	> 1000
	SM BG [fb]	180	70	30	13	6	3
ZZ	Acceptance	0.15	0.13	0.11	0.08	0.05	0.02
	$\sigma^{\rm exp}_{95\%}$ @ 10 fb^{-1} [fb]	230	110	63	44	43	79
	$\sigma^{\rm exp}_{95\%}$ @ 100 fb^{-1} [fb]	220	100	54	34	27	38
ZW	Acceptance	0.12	0.11	0.09	0.08	0.05	0.02
	$\sigma^{\rm exp}_{95\%}$ @ 10 fb^{-1} [fb]	310	130	70	47	47	78
	$\sigma^{\rm exp}_{95\%}$ @ 100 fb^{-1} [fb]	300	120	61	36	30	37
WW	Acceptance	0.01	0.01	0.007	0.005	0.002	0
	$\sigma^{\rm exp}_{95\%}$ @ 10 fb^{-1} [fb]	2800	1400	890	740	973	-
	$\sigma^{\rm exp}_{95\%}$ @ 100 fb^{-1} [fb]	2700	1400	800	550	580	-

5 Summary and Discussion

In this paper, we have discussed the current constraints and prospect for the jet and fat-jet plus MET signal for testing the ATLAS diboson excess. We found that the $V(\to 2j)Z(\to \bar{\nu}\nu)$ mode is one of the most powerful probes of the diboson excesses, and a large portion of the favored region can be tested even with the LHC Run 1 data. Simple optimizations of the MET cut can greatly enhance the sensitivity. If the observed excess is due to new physics-initiated dibosons, we expect to observe excesses in this channel.

This channel provides a strong discriminant, i.e., the channel is very sensitive to the case that the decay product of the heavy resonance includes a Z boson and less sensitive to the $X \to W^+W^-$ channel. Therefore, this channel can provide us information on the decay mode of the resonance X. By combining the searches for the other decay channel, we will get insights into the details of the nature of X.

Table 4: Prospect for fat-jet plus MET search at 13 TeV with integrated luminosities of 10 and 100 fb^{-1}. The SM background production cross section is estimated using `MADGRAPH`. A systematic uncertainty of 10% is assumed for the background. Acceptance is calculated assuming a resonance of mass 2 TeV. The expected and observed upper bound is given using $\mathrm{CL_s}$ procedure.

	MET cut [GeV]	> 500	> 600	> 700	> 800	> 900	> 1000
	SM BG [fb]	25	10	4.5	2.1	1.0	0.5
ZZ	Acceptance	0.07	0.06	0.05	0.04	0.02	0.006
	$\sigma_{95\%}^{\mathrm{exp}}$ @ 10 fb^{-1} [fb]	82	49	36	30	36	83
	$\sigma_{95\%}^{\mathrm{exp}}$ @ 100 fb^{-1} [fb]	70	34	20	14	14	28
ZW	Acceptance	0.06	0.06	0.05	0.04	0.02	0.01
	$\sigma_{95\%}^{\mathrm{exp}}$ @ 10 fb^{-1} [fb]	96	52	37	29	34	67
	$\sigma_{95\%}^{\mathrm{exp}}$ @ 100 fb^{-1} [fb]	81	37	20	14	13	22
WW	Acceptance	0.01	0.01	0.007	0.004	0.002	0
	$\sigma_{95\%}^{\mathrm{exp}}$ @ 10 fb^{-1} [fb]	430	290	270	270	410	-
	$\sigma_{95\%}^{\mathrm{exp}}$ @ 100 fb^{-1} [fb]	360	200	150	130	150	-

We have thus far focused on analyzing the decay products of the weak bosons, which one expects to be model independent. Let us comment on possible model-dependent effects. Depending on the production channel and the model parameter, the momentum distribution of the partons can differ and may influence the cut efficiencies. Moreover, initial state radiation, of which the signal rate is model dependent, can affect the jet-veto cuts employed in the dark matter searches. Therefore, in addition to the simple MET optimizations performed in this paper, further tunings to improve the resonance search is also possible, which would lead to a more powerful probe of the resonance.

Acknowledgments

We thank M. Stoll for providing us useful information about the fat-jet analysis, and T. T. Yanagida for encouragement leading to this work. We are also grateful to K. Hamaguchi for commenting on the manuscript. SPL is supported by JSPS Research Fellowships for Young Scientists and the Program for Leading Graduate Schools, MEXT, Japan.

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