Sensitivity of the R$_{Jets}$ measurement to new physics models

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Abstract

The R$_{Jets}$ measurement is a ratio of W to Z boson production and is expressed as a function of event kinematics such as the energy of the accompanying jets. As the phase space is restricted to higher energies, the value of this ratio becomes sensitive to contributions coming from new physics processes. Given the ATLAS detector and the actual LHC environment, a Monte Carlo (MC) based study is performed in order to assess the potential of this technique for discovery of three selected models: W$'$, leptoquark and t$'$. For each model, the kinematic variables and the definition of the R$_{Jets}$ ratio are varied and tested to optimize the sensitivity to new physics.

Contents

1 Introduction

The electroweak gauge bosons, W and Z, have been observed in high-energy physics experiments since their discovery at CERN in 1983. The thorough knowledge of their behaviour acquired from experiments at LEP, SLC, Tevatron and HERA has paved the way for an understanding of W and Z boson production at the LHC[1]. These particles' leptonic decays, W→ $\ell\nu$ and Z→ $\ell\ell$ where $\ell = e$ or μ, leave clear signatures in a detector like ATLAS and are particularly relevant for performance studies. These events, with their accompanying jets, are interesting in their own right, since they are involved as background in almost all searches for physics beyond the Standard Model[2]. At the same time, the accurate predictions possible with the R$_{Jets}$ measurement make it possible to directly test the Standard Model (SM) in parts of the phase space where contributions from new physics processes could come into play. The goal of this study is to assess the potential of the R$_{Jets}$ technique for new physics discoveries and to explore some variations in its definition.

R$_{Jets}$ is defined as the ratio of the W and Z cross-sections:

$$R_{Jets} = \frac{\sigma(pp \to W + N_{Jets}) \times \mathcal{B}(W \to \mu\nu)}{\sigma(pp \to Z + N_{Jets}) \times \mathcal{B}(Z \to \mu\mu)} \quad (1)$$

The ratio is expressed as a function of the kinematics of N$_{Jets}$, the number of jets in the events. Typically, this chosen kinematics will be E_T^{jet} and $H_T = E_T^{jet1} + E_T^{jet2}$ in the 1-jet and 2-jets cases respectively. This quantity has no direct physical interpretation; instead, its value (around ~ 10) is the product of

- the parton distribution functions (PDFs) of the protons that favor the W production
- the difference between the W and Z masses

- the difference in the branching ratios: the W decays leptonically roughly ~ 3 times more often than does the Z

The cross-sections in eq. 1 are measured experimentally by

$$\sigma = \frac{N_{data} - N_{bkg}}{A \cdot \epsilon \cdot L_{int}} \tag{2}$$

where N_{data} and N_{bkg} are respectively the number events of signal and background. Many experimental uncertainties automatically cancel by taking a ratio, including the integrated luminosity L_{int} and the jet resolution and energy scale. Some parts of the acceptance A and efficiency ϵ also cancel in the ratio, despite the fact that there is one lepton (electron or muon) in $W \to \ell\nu$ but two in $Z \to \ell\ell$ events [3, 4].

The R_{Jets} measurement was tested on three new physics models for which MC samples provided by the ATLAS Exotic group were readily available: W′, leptoquark and t′[5]. To best examine this selection, various strategies were developed according to the topologies expected in the final state of each new physics model. The study is aimed at early 7 TeV data and assumes an integrated luminosity of $100\,\mathrm{pb}^{-1}$. Two variations on the baseline ratio have been proposed, each of which may increase the sensitivity to some type of new physics. First, there may be a discernable advantage to examining W^- events exclusively, as this would increase the proportion of new physics events for W-like decays[1]. Second, examining R_{Jets} in terms of Jet E_T plus the transverse momentum of one of the leptons in the event may increase the sensitivity to any new physics models producing highly energetic leptons. This study examines both of these possibilities and tests them for each of the three new physics models.

2 Baseline analysis for the R_{Jets} measurement

2.1 R_{Jets} measurement overview

The Monte Carlo (MC) datasets for each physics process considered, along with their cross-sections and event numbers, are listed in table 1. For both W and Z, these MC files are divided into categories based on the number of partons (up to 5) defined by to the MLM matching scheme [6]. A filter for jets with a threshold of $p_T > 20\,GeV$ was applied during event generation.

The baseline analysis compares the W and Z productions expressed in terms of the transverse energy of the jets in the event. Three topologies are investigated in parallel: one jet, two jets, and two or more jets. In the first case, the kinematic variable under consideration is the E_T of the single jet, while for the other two cases the scalar sum $H_T = E_T^{jet1} + E_T^{jet2}$ is used instead. The distributions of the expected number of events, binned in the standard intervals of 10 GeV, are scaled individually with the cross-sections and selected luminosity. After merging these scaled distributions in both the numerator and denominator, the resulting W and Z histograms are used to compute R_{Jets}. Instead of making a differential measurement (i.e. dividing bin-by-bin), this study considers cumulative plots in which each bin contains all events above or equal to a certain energy. This method reduces the migration of events between bins, avoiding the necessity of unfolding. According to this definition, R_{Jets} is expected to match the SM predictions at low energy, providing a chance to check the corrections for acceptance and efficiencies. As the phase space is restricted to higher kinematic regions, the contributions from new physics processes should start to noticeably affect the value of the ratio.

[1] In new physics models, events with the topologies of W^+ and W^- are produced in equal amounts, unlike SM processes.

Process	Dataset	Nevents	σ (pb)
W $\to \mu\nu +$ 0 partons	mc09_7TeV.107690.AlpgenJimmyWmunuNp0_pt20	1387000	6871.1
W $\to \mu\nu +$ 1 parton	mc09_7TeV.107691.AlpgenJimmyWmunuNp1_pt20	256000	1294.7
W $\to \mu\nu +$ 2 partons	mc09_7TeV.107692.AlpgenJimmyWmunuNp2_pt20	188000	376.08
W $\to \mu\nu +$ 3 partons	mc09_7TeV.107693.AlpgenJimmyWmunuNp3_pt20	51000	100.72
W $\to \mu\nu +$ 4 partons	mc09_7TeV.107694.AlpgenJimmyWmunuNp4_pt20	7993	25.993
W $\to \mu\nu +$ 5 partons	mc09_7TeV.107695.AlpgenJimmyWmunuNp5_pt20	3500	7.1300
Z $\to \mu\mu +$ 0 partons	mc09_7TeV.107660.AlpgenJimmyZmumuNp0_pt20	304000	652.731
Z $\to \mu\mu +$ 1 parton	mc09_7TeV.107661.AlpgenJimmyZmumuNp1_pt20	63000	133.855
Z $\to \mu\mu +$ 2 partons	mc09_7TeV.107662.AlpgenJimmyZmumuNp2_pt20	19000	40.7568
Z $\to \mu\mu +$ 3 partons	mc09_7TeV.107663.AlpgenJimmyZmumuNp3_pt20	5500	11.2173
Z $\to \mu\mu +$ 4 partons	mc09_7TeV.107664.AlpgenJimmyZmumuNp4_pt20	1500	2.83234
Z $\to \mu\mu +$ 5 partons	mc09_7TeV.107665.AlpgenJimmyZmumuNp5_pt20	500	0.756621
W′ (1 TeV)	mc09_7TeV.105610.Pythia_Wprime_emutau_1000	16339	2.3726
Leptoquark	mc09_7TeV.105540.Pythia_LQ_cmu_200	20000	10.393
t′ (300 GeV)	CompHep_t4_j3_300_7TeV.recon.v156107	5000	0.4894

Table 1: W, Z and new physics MC datasets, with the number of events generated and the cross-section for each.

2.2 Event selection

For the sake of simplicity, the analysis is restricted to the muon case ($\ell = \mu$) and uses truth information instesad of reconstructions for the leptons and jets. Table 2 lists the basic cuts applied in the R_{Jets} analysis.

Cut Name	Allowed Values of Variables
GoodLepton	$-2.5 < \eta_{lep} < 2.5$ Lepton $P_T > 15$ GeV for all leptons in event
1 lepton analysis (W-like)	
Missing Transverse Energy	MET > 25 GeV
Transverse Mass	MT > 40 GeV
2 leptons analysis (Z-like)	
Opposite Charge	charge of $\mu_1 \neq$ charge of μ_2
Invariant Mass	81 GeV/c^2 < $M_{\mu\mu}$ < 101 GeV/c^2
GoodJets	$\eta_{jet} < 3.1$ for all jets in event
Lep-Jet Separation	No lepton within $\Delta R < 0.6$ of any jet

Table 2: Cuts applied in the standard R_{Jets} analysis.

These are relatively standard cuts on all the variables. No muons with η greater than 2.5 can be accepted due to the design of ATLAS: this is the limit for reconstructed muons which can combine measurements from both the muon spectrometer and inner detector. Jets can be well reconstructed up to an η of 3.1, therefore the GoodJets cut is made up to this angle instead. If a jet is detected with η anywhere up to 5, it is still counted while determining the number of jets in the event, but the event is discarded. Counting all jets but considering only those within the acceptible η range, as opposed to only counting good jets, prevents mislabelling of events which have jets outside the acceptance range. The analysis also demands that the minimum separation between any muon and any jet in the event must be greater than $\Delta R = 0.6$, because any lepton too close to a jet will not be accurately reconstructed.

There are two pairs of cuts specific to W-like or Z-like decays. For the W-like events, those which produce one muon and one neutrino, the first requirement is that the event have missing transverse energy of at least 25 GeV. By selecting only events with a significiant amount of missing energy, it can be determined that there is most likely a neutrino in the event responsible for this undetected energy. The second requirement is for a transverse mass of the lepton-MET system to be greater than 40 GeV, which further reduces the background. The Z-like events are selected with a different pair of cuts. First, the analysis demands that the two muons produced are of opposite charge. Second, it requires that the invariant mass of the two leptons be close to the known mass of the Z, which reduces the possible sources of background well below the percent level.

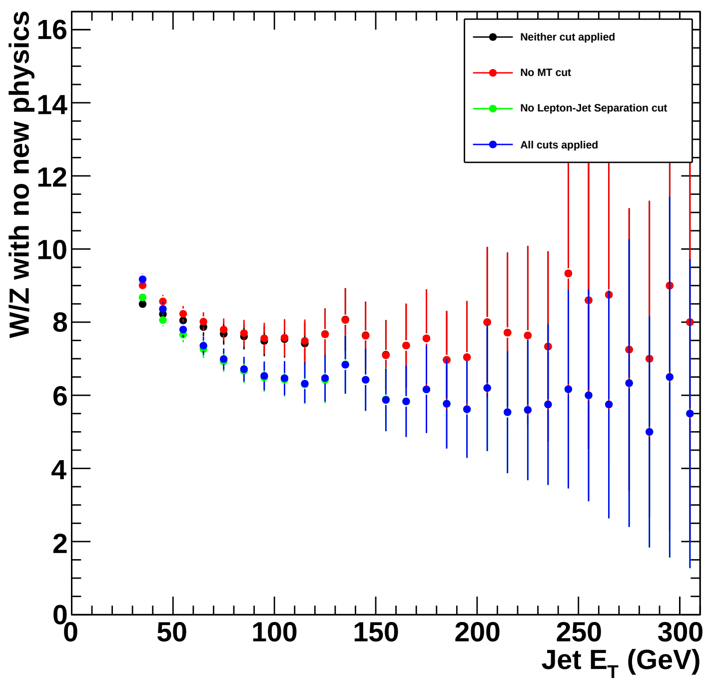


Figure 1: Ratio in E_T under application of various cuts, taken for the 1-jet case.

In order to understand the baseline R_{Jets} and how it might be varied to find new physics, only a subset of these cuts were applied to see how the ratio changed. The difference between some cut combinations was significant, as shown in figure 1. This plot gives the ratio of W over Z with no new physics but with varying cuts applied and represents the 1-jet case. For the black line, only the GoodLepton cut, the Missing Transverse Energy (or Opposite Charge, for Z bosons) cut, and the GoodJets cut are applied. The red line is the ratio when all cuts except for Transverse or Invariant Mass are applied, the green line is the ratio when all cuts except Transverse Mass (or Invariant Mass, for Z bosons) are applied, and the blue line is when all five of the cuts from the table above are used.

The behaviour of the ratio under application of various cuts will be relevant when the new physics models are added. In some cases, for instance if the mass of the new particle differs significantly from that of the W or Z, then the application of these cuts may have large impact on whether the new physics can be easily observed.

3 Addition of new physics to the baseline

Each of the three new physics models can now be added to the baseline ratio. Sensitivity to the addition, as well as the way in which the ratio changes, will be unique to the model examined. For instance, because W′ decays mimic those of W bosons, their presence in the data should be observed as an increase in the ratio over the baseline, whereas the two-leptons topology of leptoquarks should cause a decrease in the ratio.

The number of jets in the selected events will affect the observed deviations, since each type of new physics model tends to occur in events with different signature numbers of jets. W′ events, for instance, are much more likely to occur with one jet than with two or more. Throughout the report, plots given for the W′ will deal with the 1-jet case. The leptoquark and t′ models favour two or more jets instead, so when they are studied it is these events which will be considered.

Because of the models' different natures, variations in the applied cuts will have different effects in each case. In figure 2 below, the four cuts options are compared when the W′ contribution is added. In the top section of each plot, the yellow band corresponds to the R_{Jets} curve without new physics and with an artificial error superimposed[2]. Interpreted here as the theoretical predition, this workaround allows the performance of sensitivity studies without having to wait for the detailed theoretical uncertainties. The black points give R_{Jets} with new physics included. In the lower portion of each plot, the ratio of the statistical difference between the plots with and without new physics is divided by the errors at that point: the larger the value, the more significant the deviation.

In the case of a 1 TeV W′ shown here, the sensitivity is clearly weak, although slightly enhanced by removing the cut on lepton-jet separation but keeping the cut on transverse mass. Throughout the rest of this study, it is this set of cuts which will be used in the examination of the W′. Similar analyses for the leptoquark and t′ models can be seen in the appendix in figures 6 and 7 respectively. In the case of the leptoquark model, a large deviation is visible when the cut on the invariant mass of the Z-like particles (equivalent to the transverse mass for the W decays) is removed. There is little apparent difference between the plots when the lepton-jet separation cut is removed, so for now we will keep that cut and examine leptoquarks with all cuts applied except that on mass. In the case of t′, there is no significant deviation in any case, but the results obtained by removing the transverse mass cut alone are very slightly better than the others, so that selection will be maintained throughout the study.

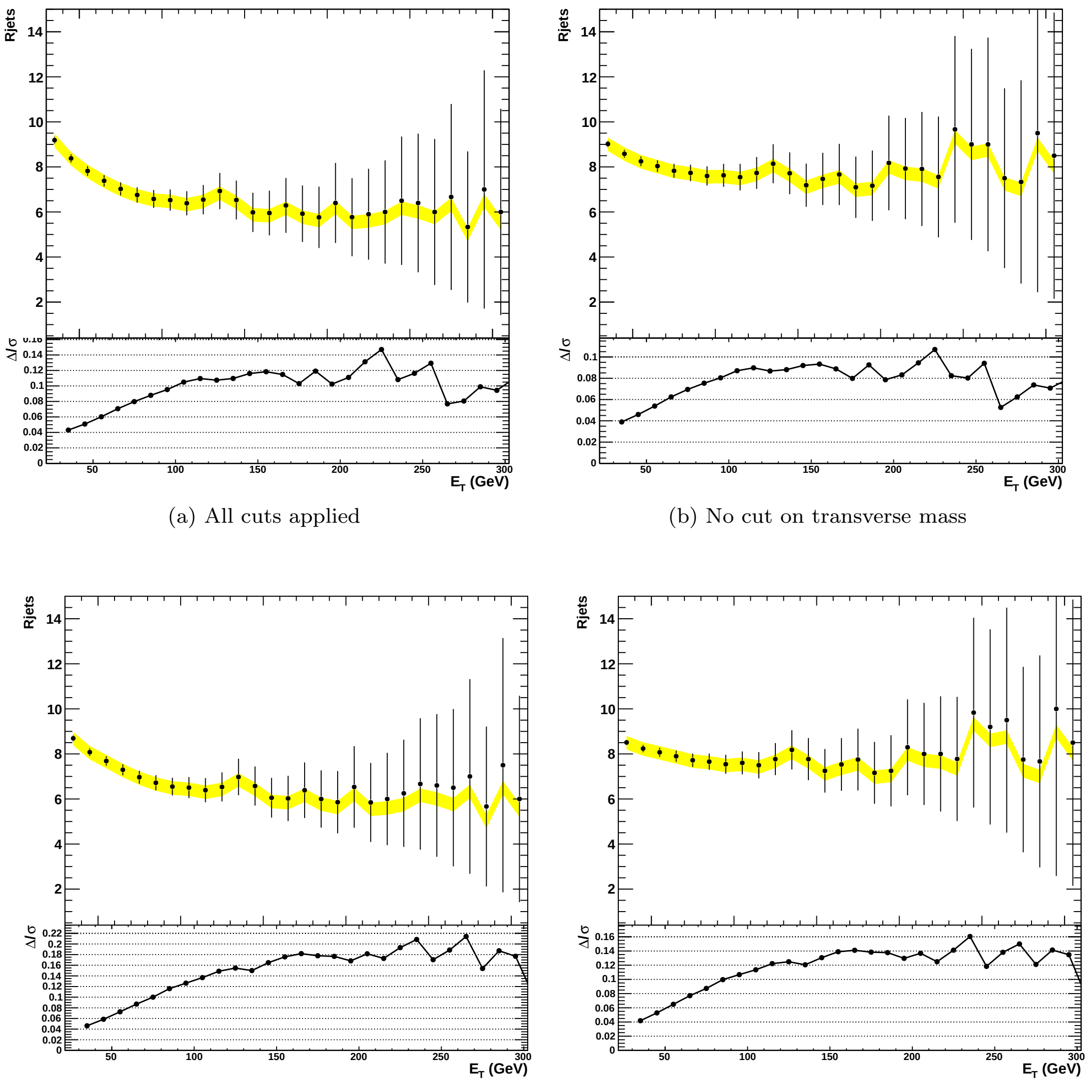
4 Variations in the definition of R_{Jets}

4.1 Separation of W^+ and W^-

Because the LHC is a proton-proton collider, it does not produce W^+ and W^- bosons in equal numbers. The lack of anti-quarks in the collisions means that the W particles produced consist of about 60 percent W^+ to 40 percent W^-[7]. By generating R_{Jets} using only bosons of one charge or the other, we can increase sensitivity to W-like types of new physics. Clearly, some particle which mimics W decays will be counted in the numerator of the ratio. If the number of W events is decreased, then the addition of the same number of new physics events will now constitute a greater proportion of the total events, and therefore make a more noticeable difference in the ratio.

The most obvious problem with this scheme is that decreasing the statistics will increase the size of the error bars, and therefore it will actually be no easier to observe a statistically significant deviation from the baseline ratio. However, because W bosons overall are produced at about ten times the rate of Z bosons, then even if only 40 or 60 percent of the total W statistics are used, the limitation in Z number will still dominate the statistical uncertainty. Overall, the errors will change less than will the ratio.

[2] A constant value of 0.3 is chosen to mimic (and overestimate) the current theoretical errors on the predictions



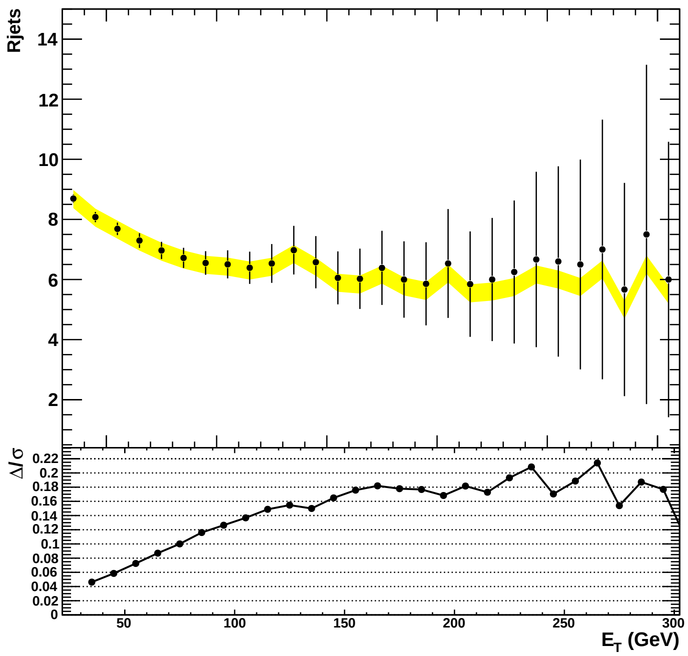
(a) All cuts applied

(b) No cut on transverse mass

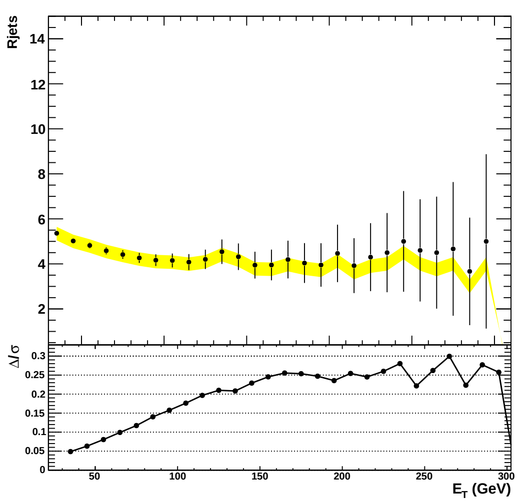
(c) No cut on lepton-jet separation

(d) Neither MT nor separation cuts

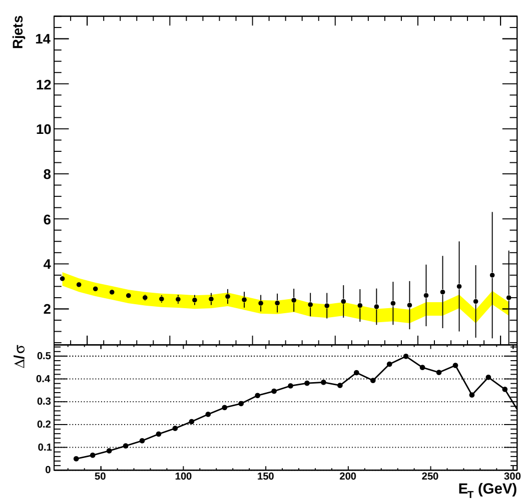
Figure 2: R_{Jets} in E_T with W′ statistics under the application of various cuts (1-jet topology only).



(a) All W events



(b) Only W^+ events



(c) Only W^- events

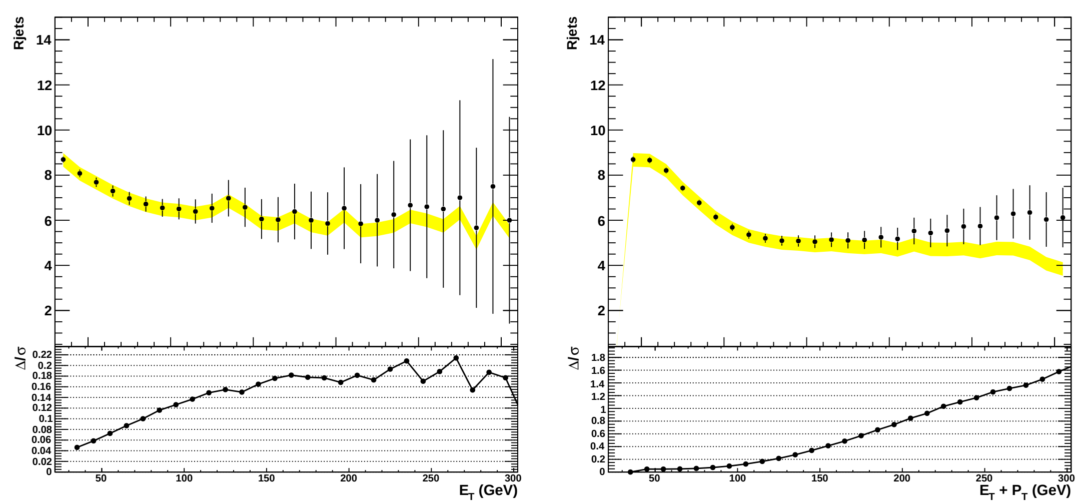
Figure 3: Ratio with W′ physics when all or a subset of W events are used.

Figure 3 shows the difference in the ratio with W′ events caused by separating the W^+ and W^-. Part 3a is the ratio with all W events considered, part 3b is the same ratio but using only W^+ events, and 3c uses only W^- events. Once again, the sensitivity of each approach can be estimated by looking at the lower portion of the plot. Both the W^+ and W^- plots show a greater discrepancy between the baseline and the new physics ratio than does the plot with all W events. The t′ decays to a W, so separation of W^+ from W^- has the same effect on R_{Jets} here as it does for the W′. Observation of fig. 8 in appendix shows that, while there are still no very visible differences between the plots with and without new physics, there is still a slight benefit due to separation of the W types.

4.2 Ratio as a function of $E_T^{jet}+P_T^{lep}$

For some new physics models, the leptons created may have a much higher energy than those typically formed by W or Z decays. This usually occurs where the new particle has a high rest mass, since the extra mass energy allows it to produce muons of very high P_T. In such cases, this provides one more method of distinguishing between pure W or Z events and new physics: muon P_T can be taken into account when plotting the ratio. In this analysis, it is possible to simply change the variable with respect to which R_{Jets} is plotted. Instead of using E_T of one or two jets in the event, the cross-section can be plotted against $E_T^{jet}+P_T^{lep}$, the scalar sum of the same jet E_T variable that would usually be used and the transverse momentum of one of the leptons in the event. For W and W-like decays, there is only one lepton in the event; for Z and Z-like decays, one of the two leptons produced was selected at random.

Instead of having the typical flat behaviour, these plots exhibit a sudden drop at low $E_T^{jet}+P_T^{lep}$ and then level out after that point (see figure 4 for the W′ case). The sharp initial drop is worrying since migrations into adjacent bins won't cancel and a tricky unfolding procedure becomes unavoidable. However, the line does level out at moderate values of $E_T^{jet}+P_T^{lep}$, certainly well before the deviations expected due to new physics, so in the end it may not have any adverse effects. The plots do show a significant increase in sensitivity with the new variable.



(a) R_{Jets} in terms of E_T (b) R_{Jets} in terms of $E_T + P_T$

Figure 4: Ratio with W′ physics, all W statistics, contrasting R_{Jets} in terms of E_T versus $E_T^{jet}+P_T^{lep}$.

In the leptoquark case, little difference in sensitivity is observed between R_{Jets} in terms of H_T and its counterpart in $H_T^{jet}+P_T^{lep}$ (see fig 9 in the appendix). The choice between the two is insignificant in this case; either would do. For the t′ model (see figure 10), there is again no discernable improvement when

$H_T^{jet}+P_T^{lep}$ is used, and the variable change has the added effect of increasing the slope of the curve. The comparatively tiny t′ cross-section could be largely responsible for the very low sensitivity observed.

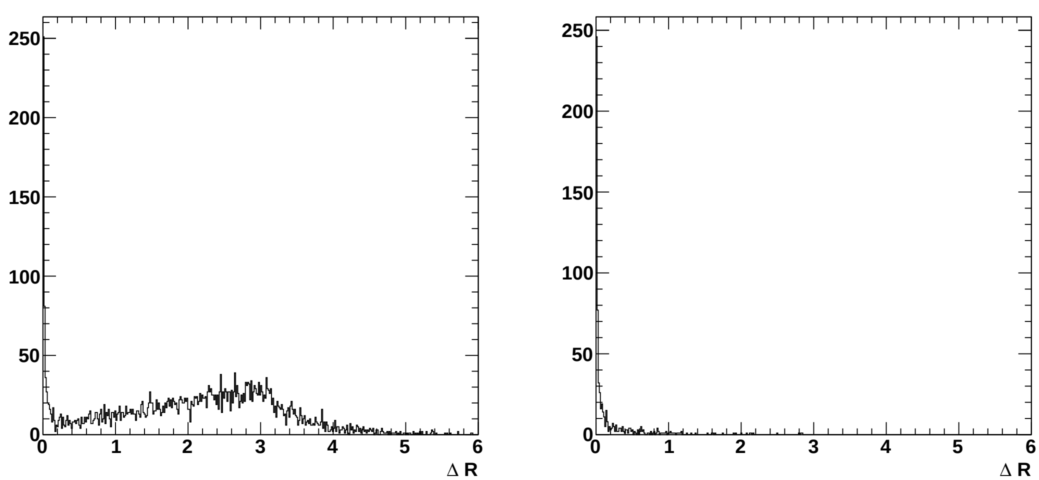
5 High-energy photons affecting the W′ analysis

During the investigation of R_{Jets} with the addition of W′ physics, the presence of spurious photons colinear to the muons was observed. When the Monte Carlo file containing simulated W′ events was processed with the same analysis code used on the W and Z events, about one in six events were being removed by the lepton-jet separation cut. Further investigation showed that in these cases, a high-energy photon was being emitted by the parent W′ in such a direction that it overlapped almost perfectly with the truth muon in the event. Table 3 gives the details.

Table 3: Statistics on W′ events with high-energy photons close to the muon

Number of W′ events analyzed	6755
Number of events in which the W′ emits a photon	3347
Number of these in which at least one photon has $E_T > 30$ GeV	1031
Number of these high-E_T events which fail the lepton-jet separation cut	922
Total number of events passing all but lepton-jet separation cut	1201

In an attempt to determine whether these photons were indeed responsible for the events being removed by this final cut, the value of ΔR between the muon in each event and the jet nearest to it was plotted. The same histogram was then made, but considering only events with a high-energy photon from the W′. Figure 5 gives the results in the 1-jet case; the plots for two or more jets look almost identical.



(a) All events

(b) Only events with a high-P_T photon

Figure 5: ΔR between the muon from a W′ decay and the jet nearest to it.

The spike at ΔR near zero in 5a is almost identical to the entirety of the statistics in 5b. It seems safe to conclude that the jets near to the muons and responsible for the removal of these events by the lepton-jet separation cut are caused by the high-energy photons emitted by the W′. Why this should be the case has not yet been determined. Either related to a physical property of the W′ decays or a feature coming from the generation, it remains a significant effect that should be investigated further.

6 Conclusion

The R_{Jets} method is a promising line of investigation for some types of new physics. Results varied amongst the three new physics models examined, W', leptoquark and t'. In the first two cases, a sensitivity up to the 1.5-sigma level could be obtained with a simple analysis and $100\,\mathrm{pb}^{-1}$ of data[3]. No significant sensitivity to the t' was observed for any parameters of the ratio and a more thorough study with larger statistics is needed to rule out reasons other than the low cross-section of this particular model. For W-type topologies, the greatest sensitivity was obtained by discarding the lepton-jet separation, while for leptoquarks, removing the transverse mass cut had a similar effect. These are not representative of all possible new physics models, but the method of determining the best set of cuts could be applied to any other type of W-like or Z-like new physics.

Separation of W^+ and W^- events was demonstrated to statistically improve sensitivity to the W' model, and theory suggests that it should be equally useful for any W-like decay. It is not useful for Z-like decays, but should still be developed as a line of investigation because of its use for W-like events. Expressing R_{Jets} in terms of Jet E_T plus muon P_T was found to be highly useful for distinguishing W' events. This study is also worth pursuing farther, since only a small sample of representative new physics models have so far been tested.

[3]This estimate is based purely on the statistics and does not takes into account systematics

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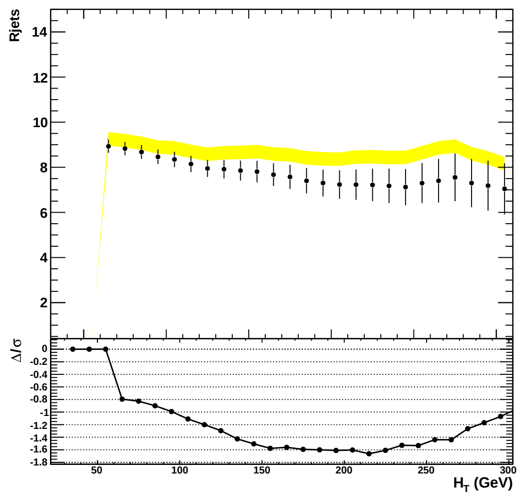
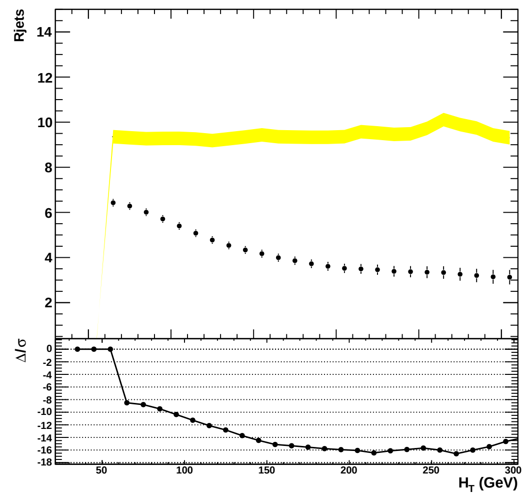
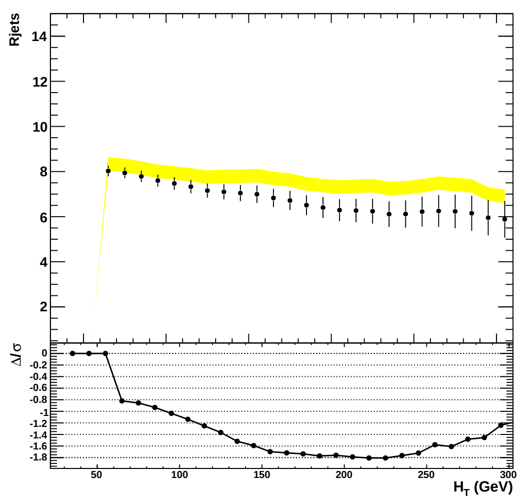
7 Appendix



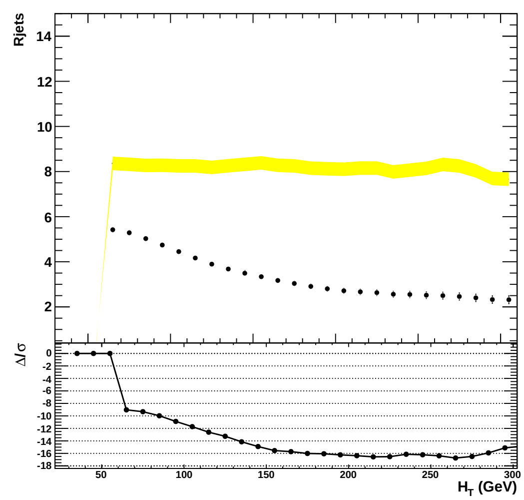
(a) All cuts applied



(b) No cut on transverse mass

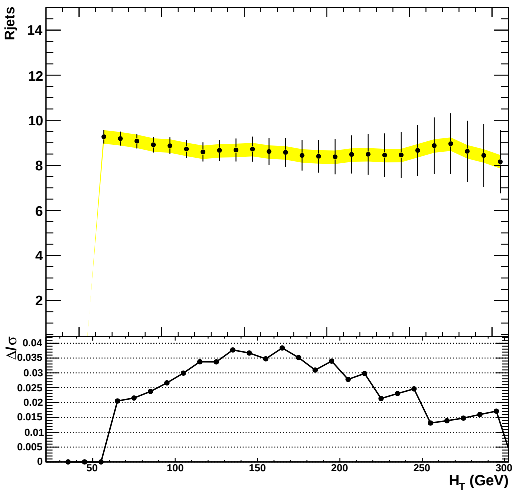


(c) No cut on lepton-jet separation

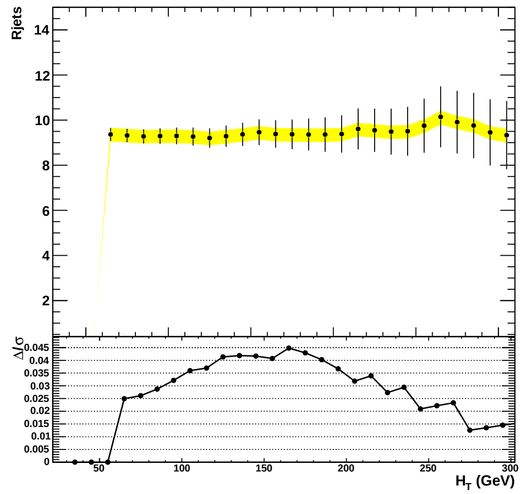


(d) Neither MT nor separation cuts

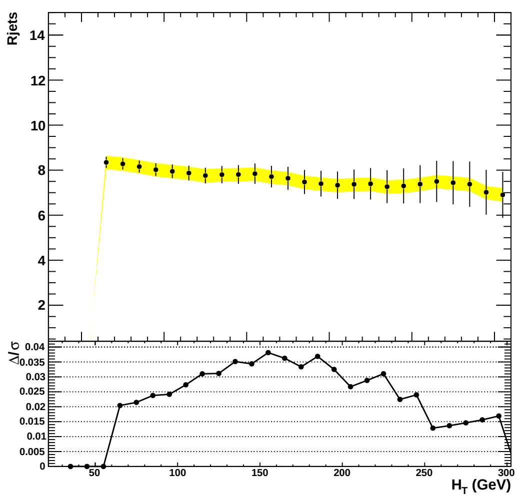
Figure 6: R_{Jets} in H_T with Leptoquark statistics under the application of various cuts. Events with 2 or more jets are considered.



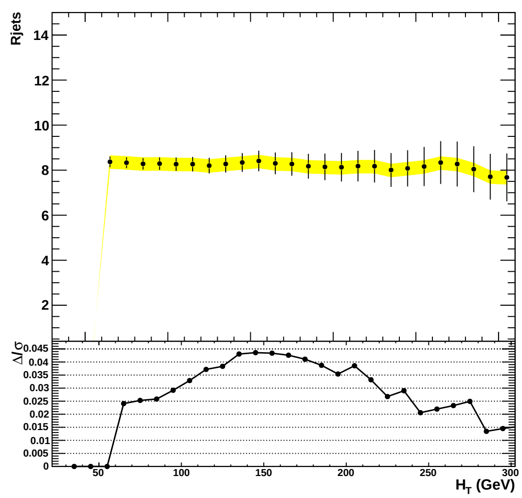
(a) All cuts applied



(b) No cut on transverse mass

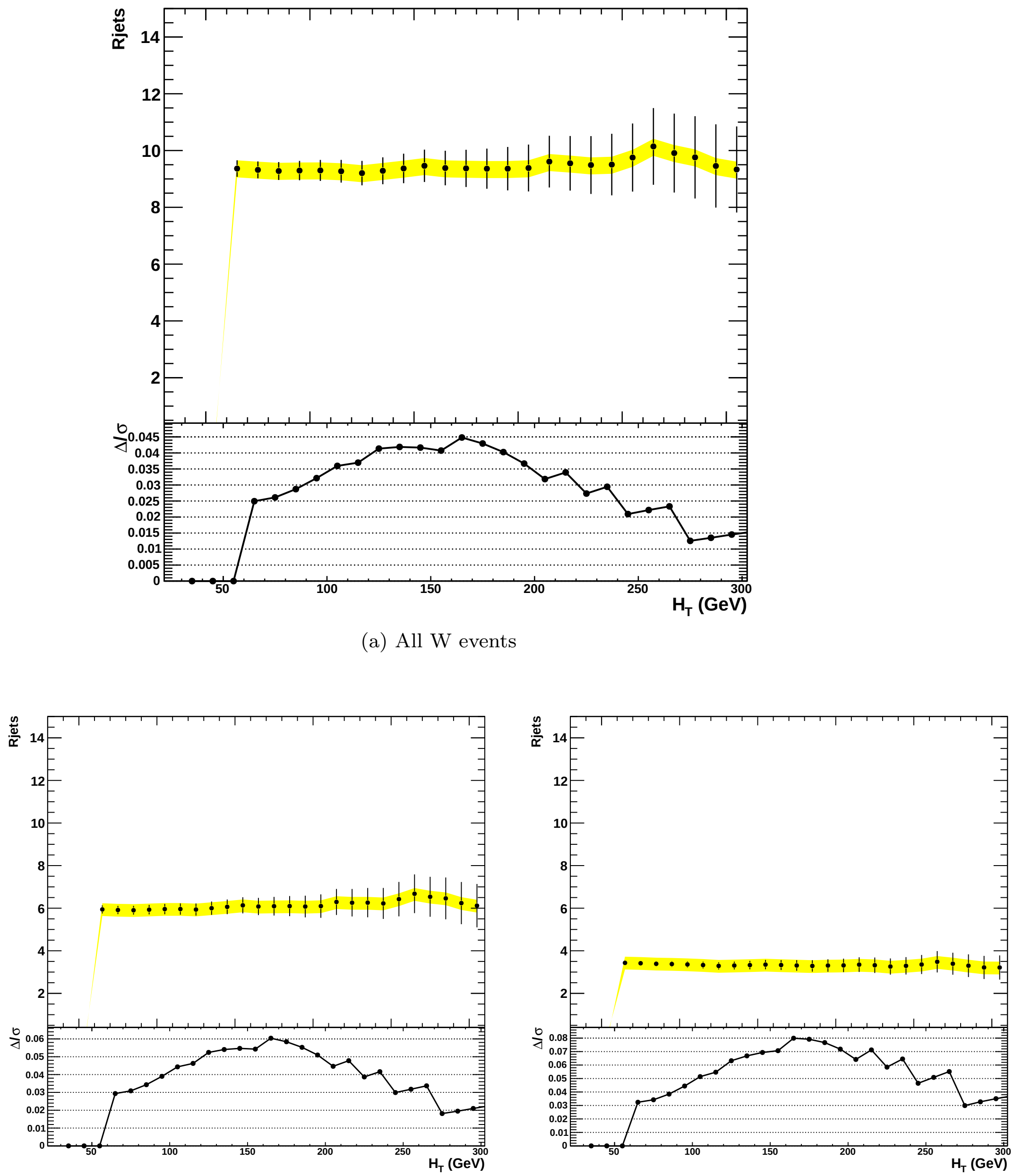


(c) No cut on lepton-jet separation



(d) Neither MT nor separation cuts

Figure 7: R_{Jets} in H_T with t′ statistics under the application of various cuts. Events with two or more jets are considered.

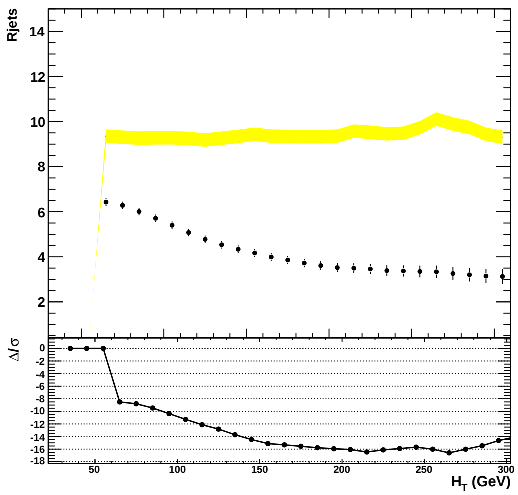


(a) All W events

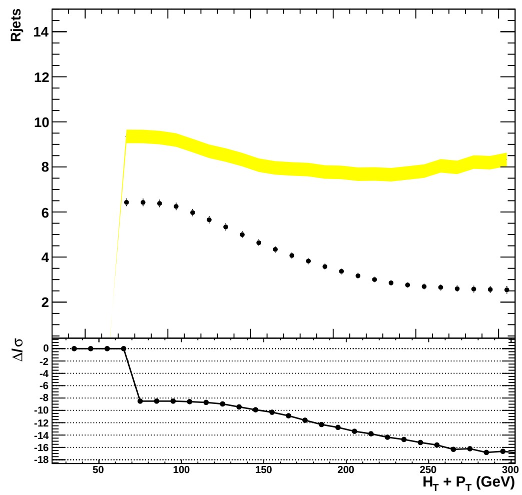
(b) Only W^+ events

(c) Only W^- events

Figure 8: Ratio with t′ physics when all or a subset of W events are used.

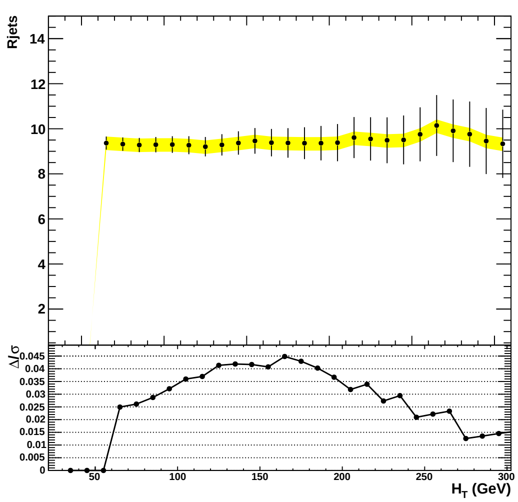


(a) R_{Jets} in terms of H_T

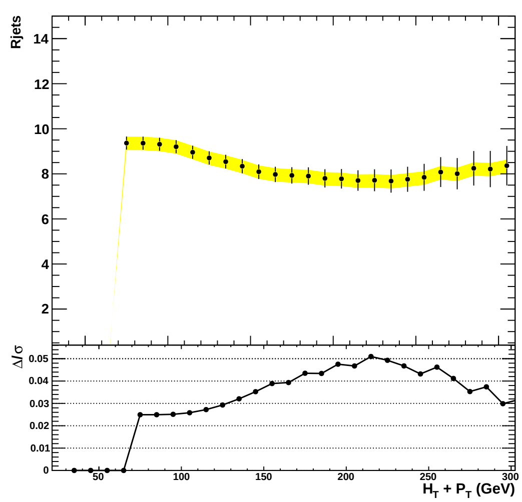


(b) R_{Jets} in terms of H_T+ P_T

Figure 9: Ratio with leptoquark physics, all W statistics, contrasting R_{Jets} in terms of H_T versus H_T+ P_T.



(a) R_{Jets} in terms of H_T



(b) R_{Jets} in terms of H_T+ P_T

Figure 10: Ratio with W′ physics, all W statistics, contrasting R_{Jets} in terms of H_T versus H_T+ P_T.