Scale-Invariant Resonance Tagging in Multijet Final States

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In this contribution we study the resonant pair production of heavy particles in hadronic final states using jet substructure techniques. We discuss a recently proposed resonance tagging strategy, which interpolates between the highly boosted and fully resolved regimes, leading to uniform signal efficiencies and background rejection rates for a broad range of masses. With this method, one can efficiently replace independent experimental searches, based on different final state topologies, with a single common analysis. We show using this strategy that the LHC has sensitivity to the enhanced resonant production of Higgs boson pairs decaying into $b\bar{b}$ pairs in generic New Physics scenarios.

XXI International Workshop on Deep-Inelastic Scattering and Related Subjects – DIS2013,
*22-26 April 2013*
Marseille, France

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arXiv:submit/0746742 [hep-ph] 26 Jun 2013

PoS(DIS 2013)141

Scale-invariant resonance tagging.   Searches for new physics in multijet events are an important ingredient of the LHC physics program. A challenge in such searches for new phenomena is the overwhelming QCD multijet background. A range of techniques becomes necessary in order to identify important categories of jets [1], and thus improve the QCD background rejection. In particular, jet substructure tools have been the subject of substantial development in the last years [2], and allow to improve the signal over background ratio of an important number of boosted and semi-boosted final states.

In an important class of new physics models, paired production of resonances dominates. These processes are generically of the form $pp \rightarrow X \rightarrow 2Y \rightarrow 4$ partons, with X and Y being heavy particles, as illustrated schematically in Fig. 1. The mediator X of this production could be an exotic particle from a new strongly coupled sector, or a resonance from extra dimensions. The Y resonance could be either some BSM particle or on the other hand some SM particle (W, Z or Higgs) that subsequently decays into quarks and gluons, observed as jets in the LHC detectors.
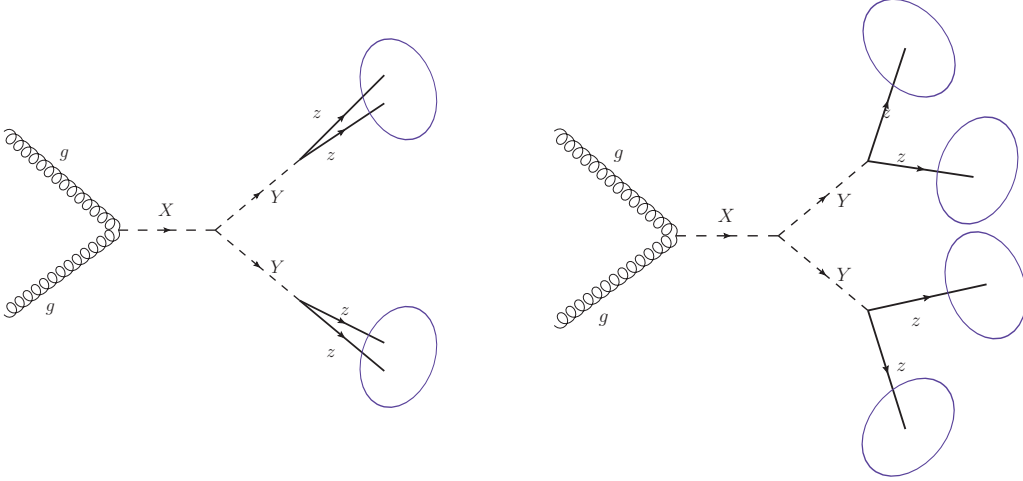

Figure 1: Schematic diagrams for the generic process $pp \rightarrow X \rightarrow 2Y \rightarrow 4z$ in the boosted (left plot) regime, corresponding to large values of the mass ratio $r_M = M_X/2M_Y$, and in the resolved (right plot) regime, corresponding to small values of r_M.

The generic four-parton processes lead to distinct final state signatures depending on the interplay between the masses of the two intermediate resonances, M_X and M_Y, which is characterized by the dimensionless variable $r_M \equiv M_X/2M_Y$. For a large mass ratio, $M_X \gg M_Y$, the Y resonances will be produced boosted, and typically the decay products of each of the two Y resonances will be collimated into a single *fat* jet. On the other hand, for $M_X \sim 2M_Y$, the Y resonances will be produced nearly at rest, decaying into four well separated jets. Existing searches assume either the highly boosted or fully resolved regimes, and by doing so exclude a potentially large region of the new physics parameter space.

In Ref. [3] we introduced a jet reconstruction and analysis strategy that can be applied simultaneously to the boosted and resolved regimes, and that provides a smooth interpolation between them. This was achieved by merging the boosted-regime strategies, based on the BDRS mass-drop tagger [4], with a suitable strategy for the resolved four-jet regime, in our case dijet mass pairings. A set of quality requirements on the p_T and angular separation of jets and subjets was imposed to ensure a roughly constant tagging efficiency and a smooth interpolation between the two limit-

ing regimes. This strategy has the potential to make the experimental searches for this particular topology more efficient and to allow a wider range of new physics scenarios to be explored within a single analysis.

The method sketched above was implemented into a code based on `FastJetv3` [5]. We used the anti-k_T jet clustering algorithm with $R = 0.5$, though as discussed below the dependence of our results with R is very mild. In Fig. 2 we show the efficiency of the resonance pair tagging algorithm as a function of r_M for events for the $pp \to X \to 2Y \to 4z$ topology. Parton level events were produced with an in-house toy MC event generator, and then showered with `Pythia8` to produce realistic hadron level events. In Fig. 2 we show that the total tagging efficiency at parton level is approximately constant over most of the r_M range, with the boosted topology (2-tag sample) dominating at large r_M, the resolved topology dominating at small r_M (0-tag sample), with the 1-tag topology providing a smooth interpolation in the intermediate r_M region. This approximate constant tagging efficiency also holds true at hadron level.
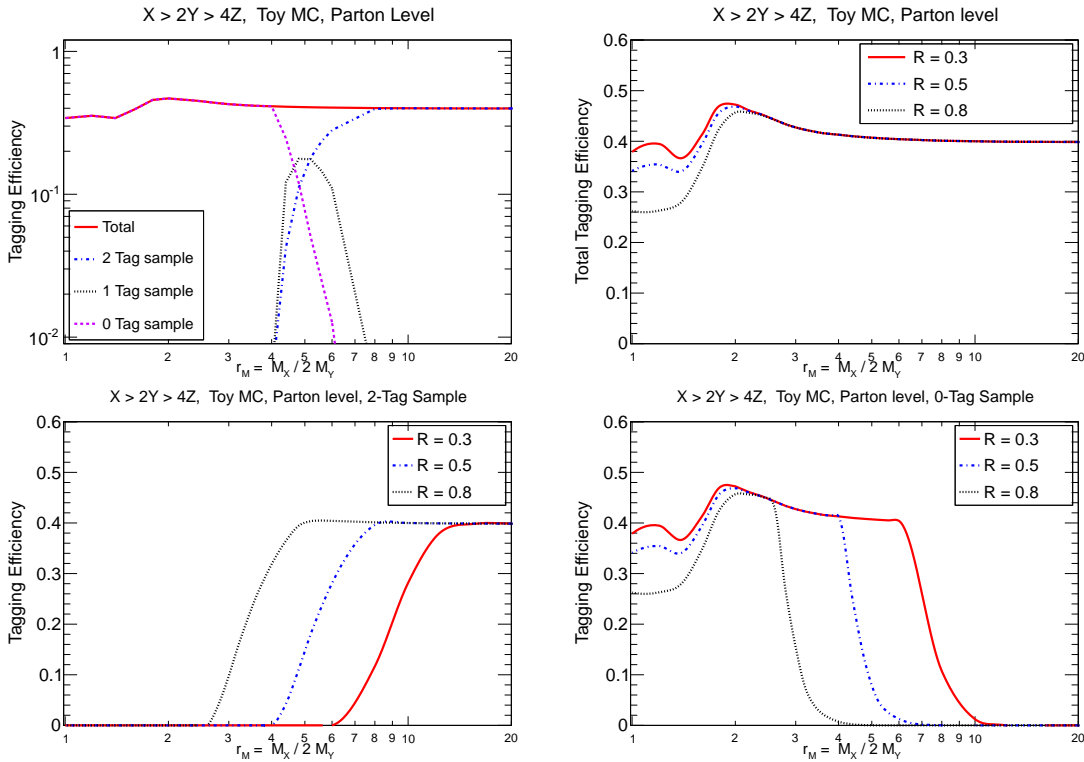
Figure 2: Upper left plot: The efficiency of the resonance pair tagging algorithm as a function of resonances mass ratio for parton-level toy Monte Carlo events. We show both the total efficiency and the break-up for the boosted, intermediate and resolved categories. Upper right plot: the total tagging efficiency for different values of the jet radius R. Lower plots: the tagging efficiencies for the boosted category (left plot) and for the resolved category (right plot), for different values of the jet radius R.

We also show in Fig. 2 that the tagging efficiency is independent of the value of the jet radius R used, except close to production threshold. Such a stability with respect to R is an useful feature of an analysis technique, since it allows to adjust the value of R to the specific process under con-

sideration[1], while keeping constant the overall efficiencies for all values of the candidate resonance mass. As shown in the lower plots of Fig. 2, the relative fraction of boosted over resolved topologies depends strongly in the value of jet radius R, but thanks to the quality requirements adopted in our resonance tagging strategy, their sum turns out to be R-independent to a good approximation.

Background rejection. For multijet topologies with at most four leading jets, but without high p_T leptons or missing E_T, the dominant Standard Model background is QCD jet production. There are several ways in which QCD radiation can mimic the conditions for resonance tagging, for instance, fake mass drops can be generated with sufficiently symmetric splitting of a quark or gluon.

We define the dijet cross section, for each value M of the candidate resonance mass, as the number of QCD events that survive the basic selection cuts and lead to an invariant mass within the mass resolution window around M given by $[M(1 - f_m), M(1 + f_m)]$, and with the the two leading jets are separated in rapidity by less than Δy_{max}. After resonance tagging was applied to the QCD multijet events, b-tagging was also required, with the condition that at least one b-quark should be identified within each of the two Higgs candidate jets. The settings for b-tagging were taken to be similar to the default ones in ATLAS and CMS. QCD multijet background events has been generated with `Pythia8` [7].

In Fig. 3 we show the background rejection factors, defined as the fraction of the QCD dijet events which are mistagged as arising from a heavy resonance, both with and without b-tagging. We show both the total mistag probability and the division in 2-tag, 1-tag and 0-tag cathegories. Is clear that the background rejection probability is approximately scale invariant, thanks to the consistent contributon of each of the cathegories: the 0-tag cathegory dominates at small M, while the 2-tag cathegory dominates at large M.
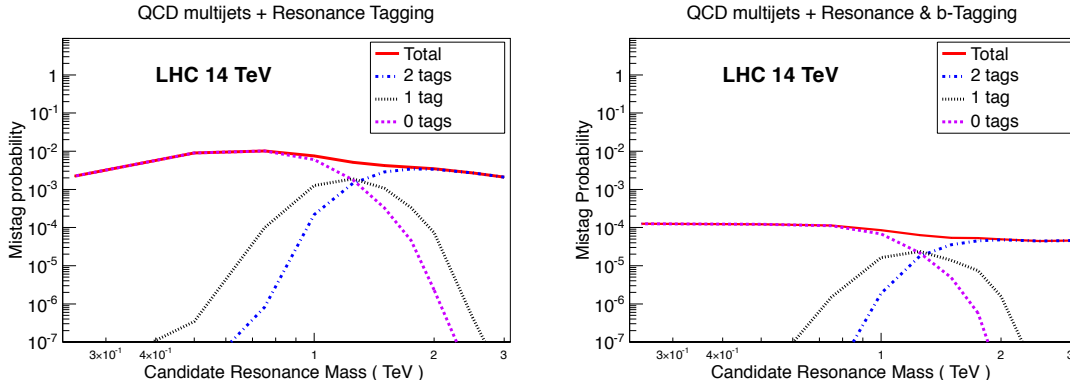


Figure 3: The mistag probability of QCD multijet events, after resonance tagging (left plot) and after resonance and b-tagging (right plot). We show both the total mistag rate and its decomposition into the three possible categories: 0-tag (where QCD multijets mimic the signal resolved topology), 1-tag and 2-tags (where now the background events mimic the boosted topology by means of fake mass drop tags). The total mistag probability is reasonably independent of the candidate resonance mass.

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[1]For instance, in the case of a heavy resonance decaying into jets, a large value of R is advantageous to improve mass resolution since it collects most of the final state radiation. [6]

New physics in the $2H \rightarrow 4b$ **final state.** As a phenomenologically relevant application of the scale-invariant resonance tagging technique, the method was applied in Ref. [3] to study the discovery potential of resonant Higgs pair production in the $4b$ final state at the LHC. We derived first of all model-independent bounds to generic BSM scenarios that lead to enhanced resonant Higgs pair production, and then interpreted these bounds in terms of Radion and Graviton production in the context of warped extra dimensions models [8]. The theory predictions for Radion and Graviton production were obtained from MadGraph5 [9] interfaced to Pythia8 for the parton shower.

In Fig. 4 we show the values of the massive KK graviton-gluon coupling c_g that can be excluded at the 95% CL as a function of the graviton mass for 8 and 14 TeV using the scale-invariant resonance tagging in the $4b$ final state. We find that most of the relevant parameter space for radion and graviton production in warped extra-dimensions scenarios can be excluded using the $4b$ final state, and our technique allows to cover most of the relevant Graviton mass range. Therefore, using our technique the $4b$ final states becomes a complementary handle to the searches for similar BSM phenomena in other final states. In Fig. 4 we also show the signal plus background dijet b-tagged cross section corresponding for the case of $M_g = 3$ TeV Graviton production, compared to the predictions from QCD multijet production only. A clear signal mass peak arises on top of the monotonically decreasing QCD background.
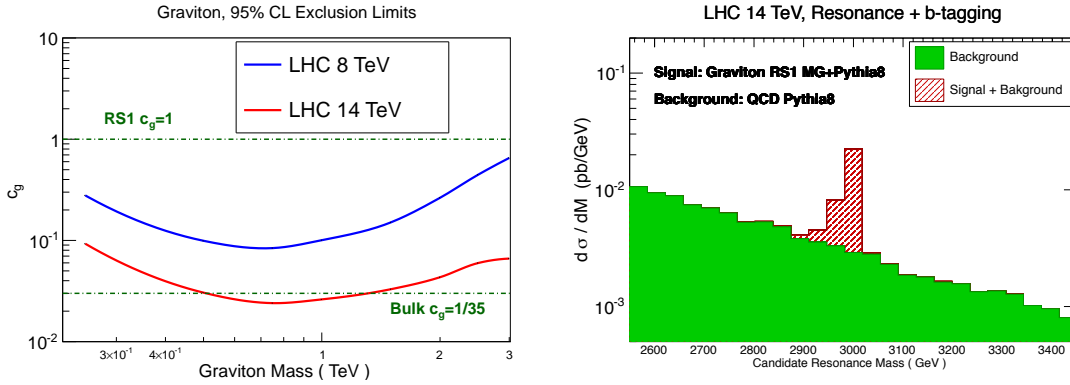
Figure 4: Left plot: the values of the massive KK graviton-gluon coupling c_g that can be excluded at the 95% CL as a function of the graviton mass at the LHC 8 and 14 TeV. Right plot: the signal plus background dijet tagged cross section, for the case of a $M_g = 3$ TeV KK Graviton production, compared to the prediction from QCD multijet production only, after resonance and b-tagging have been applied both to signal and background events.

Applications of the scale-invariant resonance tagging idea to other relevant problems include merging the threshold and boosted searches in fully hadronic top quark production and the search for enhanced Higgs pair production in other production channels such as vector-boson-fusion.

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