Dijet resonances, widths and all that

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Abstract

The search for heavy resonances in the dijet channel is part of the on-going physics programme, both at the Tevatron and at the LHC. Lower limits have been placed on the masses of dijet resonances predicted in a wide variety of models. However, across experiments, the search strategy assumes that the effect of the new particles is well-approximated by on-shell production and subsequent decay into a pair of jets. We examine the impact of off-shell effects on such searches, particularly for strongly interacting resonances.

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1 Introduction

Dijet production is an integral part of studies conducted at any hadron collider. Apart from being important for the ratification of our understanding of QCD, this process also provides a fertile ground for new physics searches, particularly searches for new particles that may appear as resonances in the dijet invariant mass spectrum. The large production cross-sections mean that significant conclusions may be drawn even with low integrated luminosities. Of course, QCD itself gives rise to a large background which is a challenge that any new physics search has to contend with. However, in case the new physics signal appears in the form of a localised excess in production rates in a particular region of phase space (*e.g.* a resonance), it is often possible to subdue the background with appropriate kinematic cuts.

While no new physics beyond the Standard Model (SM) has been discovered yet, experimental collaborations at both the Tevatron and the LHC have been using the dijet channel to place limits on masses of new particles in a wide variety of models [1, 2, 3]. The strategy has been to compute upper bounds on $\sigma \cdot \mathcal{B} \cdot \mathcal{A}$ (where σ is the cross-section for on-shell production of the particle, $\mathcal{B}$ is the branching fraction into a pair of jets and $\mathcal{A}$ is the experimental acceptance) and hence rule out certain mass ranges for the new particles. In essence, $\sigma \cdot \mathcal{B}$ is the excess that arises due to the presence of the new particle. This implies the assumption that the new particle under consideration has a small width. However, for some strongly decaying particles, which the Tevatron/LHC have excluded upto a large mass, this assumption may not hold true. Examples are particles such as axigluons and colorons which typically have a width $\gtrsim 10\%$ of their mass and, are certainly not 'narrow resonances'. However, in the context of a hadron collider, it is also important to remember that the 'observed width' as would be measured from the invariant mass distribution is not the true decay width of the particle associated with the resonance. The shape of the resonance gets distorted by fluxes of the initial state particles which, in turn, depend on the parton level center-of-mass energy. Further, experimental reconstruction of jets is a challenging task. Limitations of detector resolution and reconstruction algorithms affect the resolution of the jet-jet invariant mass m_{jj}. If the aforementioned effects overwhelmingly dominate the observed width, then the theoretical approximation of 'narrow-width' may be inconsequential. In this note, we examine such aspects of dijet resonance searches in an attempt to compare the relative merits of different search strategies.

The rest of this article is organised as follows. We begin by briefly recapitulating, in Section 2, a few model templates with particular emphasis on their status *vis à vis* searches at the Tevatron and the LHC. Section 3 details our calculations and delineates the numerical effects due to the off-shell contributions. Finally, we conclude in Section 4.

2 Dijets and new physics

With both the Tevatron and the LHC accumulating substantial luminosity, several studies have looked at possible resonances. While resonances decaying into leptons (such as a hypothetical Z') are relatively easy to look for, of particular interest are particles that preferentially decay into hadronic states. Indeed, considerable interest has been generated by two Tevatron measurements, viz. the reported excess [4] in the Wjj final state on the one hand, and the longstanding discrepancy in the forward-backward asymmetry in $t\bar{t}$ production [5] on the other. While several models have been proposed as solutions to these deviations from the SM, it is imperative that they be examined *vis à vis* other processes. With each such explanation positing new couplings involving quarks, dijet production is a natural theatre for such investigations [6]. Indeed, a recent study [7] has attempted a model independent study of colored resonances.

The simplest algorithms for new particle searches naturally concentrate on situations wherein the role of the said particle, in any process involving only SM particles as asymptotic states, can be well-approximated by a narrow resonance. Unfortunately though, this approximation is often rendered invalid. Further, under certain conditions, even the assumption of a constant width may need correction. Numerous examples abound in low-energy hadron physics (see for example, Ref. [8]). Indeed, this effect turned out to be significant even for a narrow resonance such as the Z [9]. More recently, this question has been examined in the context of production of top-pairs [10, 11], dijets [12], a heavy SM Higgs boson [13] and hypothetical W's [14] and Z's [1] [15].

In this study, we consider axigluons[2] and colorons as templates for broad dijet resonances. These are color octet gauge bosons appearing in certain classes of models that hypothesize an extended color gauge group $SU(3)_A \otimes SU(3)_B$ at high energies. The extended gauge symmetry is broken spontaneously to $SU(3)_C$ that one associates with strong interactions in the SM. Axigluons and colorons correspond to the broken generators in the respective models and, hence, are massive. The coupling of axigluons to quarks is given by $g_s \gamma_\mu \gamma_5$ while that of colorons is $g_s \gamma_\mu \cot\xi$, ξ being the angle that characterizes the mixing between the two $SU(3)$ groups. In certain variants of the model, the coloron couples preferentially to the third generation quarks. However, here we consider only the *flavor-universal* coloron, for which $\cot\xi \lesssim 4$ in order that the model remains in its Higgs phase. Details of axigluon and coloron models can be found in Refs. [18, 19] and Refs. [20, 21] respectively. Over the years, limits on axigluon and coloron mass (denoted henceforth by $\mathrm{M_A}$and $\mathrm{M_C}$, respectively) have been upgraded continuously based on experiments that have been in operation at various times [22]. The current experimental limits are due to searches in the dijet channel at the LHC. The ATLAS experiment has ruled out $\mathrm{M_A} < 3.32$ TeV [3] while CMS has ruled out axigluons and colorons of mass below 2.47 TeV [2]. Before this, the CDF experiment at the Tevatron had placed a lower limit of 1250 GeV on $\mathrm{M_A}$, $\mathrm{M_C}$ [1]. However, barring the analysis of Ref. [10] (included by the Particle Data Group [23]), the rest implicitly incorporate the narrow-width approximation, and thus need to be accepted with care.

3 Numerical Analysis

In this analysis, for the Tevatron as well as the LHC, we consider representative masses of the aforementioned particles in the range that is well within the kinematical reach of the respective machines. Then, for each such representative case, we compute the signal in two ways – first, by considering *on-shell* production and subsequent decay of the new particle, and second, by computing the *full* cross-section including off-shell effects and all contributing amplitudes (s-, t- and u- channel etc.). We label these two cases by `OS` and `FL` respectively.

The computations are performed using CalcHEP [24]. The CTEQ6L parton distributions [25] are used along with the compatible value for α_s as obtained using the 2-loop β-function[3]. The renormalization and factorization scales are set to the sub-process center of mass energy.

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[1] Although particles such as a heavy SM Higgs, W' or Z' do not decay strongly, their large masses ($\gtrsim 600\,\mathrm{GeV}$) still result in a substantially large width. Of particular importance is the fact that, for such widths, the interference with non-resonant contributions to the amplitude become important, thereby rendering the on-shell approximation rather inaccurate.

[2] Axigluons are of particular interest in the context of the forward-backward asymmetry in $t\bar{t}$ production. See, for example, Refs. [10, 16, 17].

[3] While this might seem paradoxical given that we are computing only the leading-order matrix elements, note that the CTEQ collaboration uses α_s calculated at NLO to extract the CTEQ6L distributions. Furthermore, the use of CTEQ6L1 distributions alongwith α_s(LO) does not qualitatively change our conclusions.

3.1 At the Tevatron

As a representative example close to the lower bound achieved by CDF, we consider an axigluon of mass $\mathrm{M_A}$= 1.2 TeV. The natural width of this particle is 100 GeV. To enhance the signal to background (SM) ratio, we only generate events where the jets have a p_T of at least[4] 150 GeV. Since we are primarily interested in a localised excess in the m_{jj} distribution, we must effect a fit to the m_{jj} spectrum significantly away from the excess. An excellent fit is obtained [1] in terms of the four-parameter function $f(x) = a_0\,(1-x)^{a_1}\,x^{a_2+a_3\ln x}$ where $x \equiv m_{jj}/\sqrt{s_{pp}}$. Interestingly, a Gaussian in x gives a (three-parameter) fit that is virtually as good (in terms of χ^2 per degree of freedom).

Once the aforementioned (theoretical) SM spectrum is obtained, the invariant mass spectrum for both the `OS` and `FL` case can, then, be compared with it. In the infinite resolution limit, the `OS` distribution would be characterised by a sharp spike in the bin corresponding to $m_{jj} = 1.2$ TeV. However, in an experimental situation, the spike gets smeared due to detector resolution effects. Bearing this in mind, we apply a Gaussian smearing to the energy of all the final state particles with $\delta E_T/E_T = 50\%/\sqrt{E_T(\mathrm{GeV})} \oplus 3\%$ (this being the resolution of the central hadron calorimeter for CDF [1]). To account for possible upward scaling of the energy, we now impose $p_T > 200$ GeV on the two leading jets. The resultant m_{jj} distribution is plotted in Fig.1(a). The difference between the `OS` and the `FL` cases is clearly visible even to the naked eye and this shows that, even after smearing, the difference between the two distributions is discernible.

It could be argued that, in making Fig.1(a), we have taken the liberty of finely binning the events. While this demonstrates the difference between the two situations very well, such small bin sizes may not be achievable in practice. The study of Ref. [1], for example, uses a bin width of $0.1 m_{jj}$. To examine the effect of this reduced resolution, we redistribute the events accordingly. The result is shown in Fig.1(b).

Understandably, the difference between the `FL` and the `OS` approximation is reduced to an extent. Nonetheless, a significant difference between the two does persist as it does with the SM. At this point, one must ask how significant the difference is statistically. To this end, we calculate the binwise significance $\mathcal{S}_i$ defined as

$$\mathcal{S}_i \equiv S_i/\sqrt{B_i}\ ,$$

where $S_i\,(B_i)$ are the number of signal (background) events in a given bin[5]. The results, plotted in Fig.2(a), bring out two facts. First, near the resonance, the significance obtained is much larger for the `OS` case. Larger expectations of significance imply greater sensitivity and allow the model to be ruled out at higher confidence levels. However, in this case, the greater significance is but an artefact of the narrow-width approximation which, as demonstrated by Fig.1(a), is clearly not applicable in this case. Second, away from the resonance, cross-sections are suppressed and are *lower* than the SM prediction if one considers the full (`FL`) amplitude[6]. This is an effect of the interference of the multiple axigluon-

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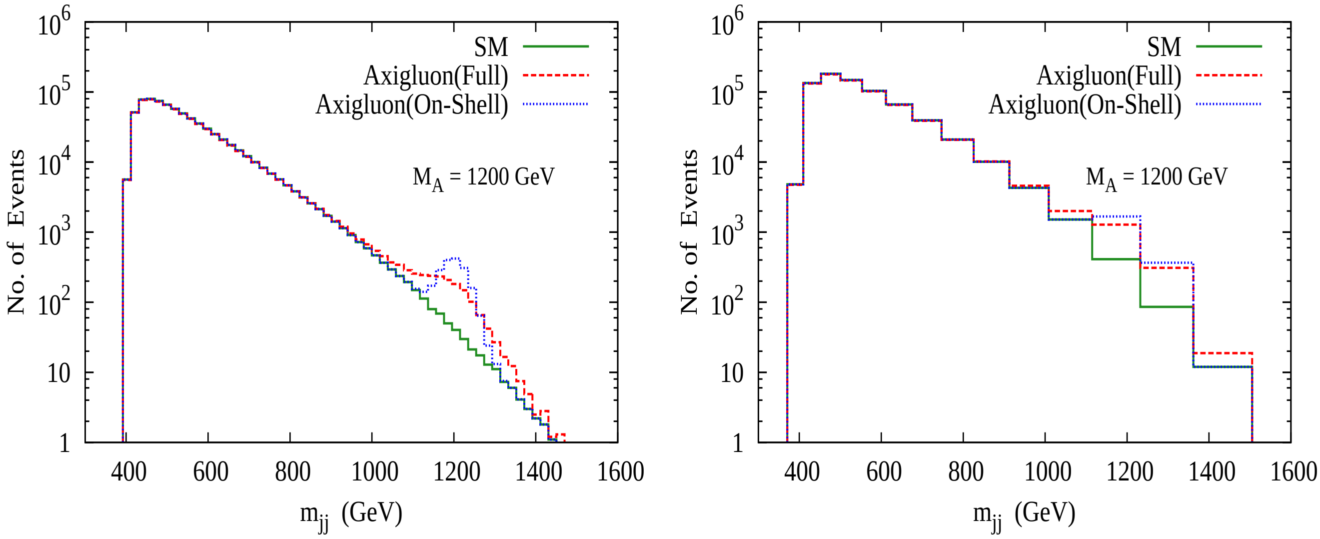
[4] This is nothing but the imposition of CKIN(3) > 150 GeV in PYTHIA [26].

[5] With the rebinning, the number of events in each bin is large enough for the Poisson-distributed number of events to be well-approximated by Gaussians.

[6] This suppression was not visible in Fig.1(a) simply on account of the scale of the plots.



(a)

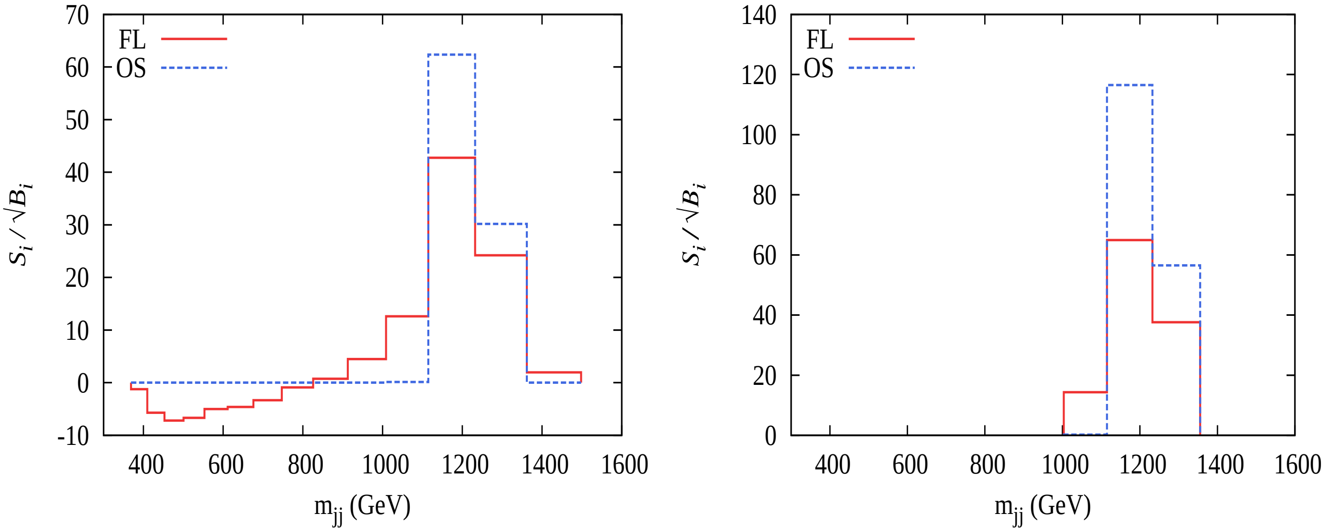
(b)

Figure 1: *The dijet invariant mass spectrum at the Tevatron corresponding to* $\mathrm{M_A} = 1200$ GeV *(the corresponding width is* $\Gamma_{\mathrm{A}} = 100$ GeV*). An integrated luminosity of* 10 fb^{-1} *has been assumed and a restriction of* $p_T > 200$ GeV *imposed on each of the two highest* p_T *jets. The left panel corresponds to a constant* m_{jj} *bin width, while the right panel redistributes the events in bins with* $\delta m_{jj} = m_{jj}^{\rm av}/10$.

mediated contributions (including $t-$ and u–channel diagrams) with the SM amplitudes. In fact, with $p_T^{min} = 200$ GeV, the total cross-section is slightly lower than the corresponding SM prediction. While the dominant new physics contributions pertain to $q_i\bar{q}_i \to q_j\bar{q}_j$, even subdominant processes such as $q_i q_j \to q_i q_j$ are suppressed on account of the destructive interferences engendered by the t-channel axigluon exchange contributions. Understandably, no such suppression exists in the `OS` approximation.

It is interesting to contemplate the impact of kinematic cuts on this difference. It seems plausible that placing a strong cut on the jet rapidities would not only eliminate a larger fraction of the SM background, but also significantly reduce the contribution from the interference of the axigluon amplitudes with the t-channel gluon-exchange ones. In effect, the imposition of stronger requirements on the jet transverse momenta would be expected to push the new physics contribution closer to the `OS` approximation. In Fig.2(b), we show the results for the significance on demanding $p_T^{\rm min} = 500$ GeV and $|y| < 0.7$. Comparing it to Fig.2(a), the increase in significance levels is obvious. What is even more striking is that the increase in significance is more pronounced for the `OS` approximation than it is for the full (`FL`) calculation. In other words, even the imposition of such strong cuts does not validate the `OS` approximation, and the large sensitivity is partly illusory. The absence of a dip in the differential cross section (as compared to Fig.2(a)) is understandable as the corresponding m_{jj} bins have been eliminated by the imposition of the strong p_T cut.

Further, if one considers the background subtracted excess (as shown in Fig. 3), one finds that, in case of `OS`, the excess may be approximated by a Gaussian distribution. On the



(a) (b)

Figure 2: *Binwise significance expected, at the Tevatron, for an axigluon of mass* 1.2 TeV *and bin-widths of* $m_{jj}/10$. *The two panels correspond to differing requirements on the two leading jets* (a) $p_T \geq 200$ GeV, *and* (b) $p_T \geq 500$ GeV, $|y| < 0.7$.

other hand, the `FL` distribution is asymmetric and is not amenable to fitting by a simple functional form. Quite naturally then, if one were to attempt an extraction of parameters such as the mass and width, `FL` and `OS` would give rise to different values. In fact, this is borne out quite clearly by Fig. 3. Not only is the position of the peak visibly shifted in case of `FL`, the shape too is sufficiently skewed to disallow an agreement with an `OS` Monte Carlo.

While the above discussion involved the invariant mass distribution which is the crucial observable in any resonance search, it is possible to appreciate the difference between `OS` and `FL` even by considering just the deviation in the total cross-sections, albeit with strong kinematic cuts. In Fig.4 we show the deviation from the SM dijet cross-section as a function of $\mathrm{M_A}$. It is clear that considering simply on-shell production results in over-estimation of the signal for most cases that are within the kinematic reach of the Tevatron. Again, this is a consequence of the multiple interference terms involving gluon/axigluon mediated s-, t- and u-channel amplitudes. In fact, were one to relax the cuts (for example, imposing only $p_T^{min} = 200$ GeV with no restriction on rapidity), the effect of the interference would drive the total cross-section below the SM cross-section. It should be noted though that claiming a discovery (or otherwise) based on total rates alone is fraught with danger as this observable is particularly sensitive to higher order corrections, uncertainty in parton distributions etc.

The case of the coloron is even more curious. The coupling strength is $g_s \cot\xi$. With $1 \leq \cot\xi \leq 4$, the widths could easily be much larger than that for an axigluon of similar mass ($\sim$ 30% of the mass with $\cot\xi$ of just 2). As a result, it would be very difficult, if not impossible, to identify the excess as a resonance (see Fig.5). Although it might be

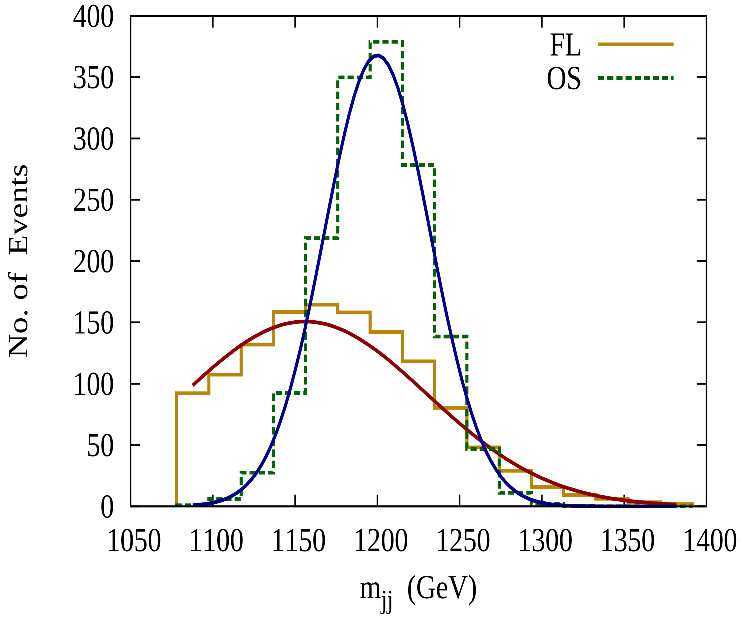


Figure 3: *The excess at the Tevatron (assuming* $\mathrm{M_A} = 1200$ GeV *and with* $p_T^{\min} = 200$ GeV*) after subtracting the SM background for the two scenarios* `FL` *and* `OS`*. The curves depict the result of the fitting when a Gaussian distribution is assumed.*

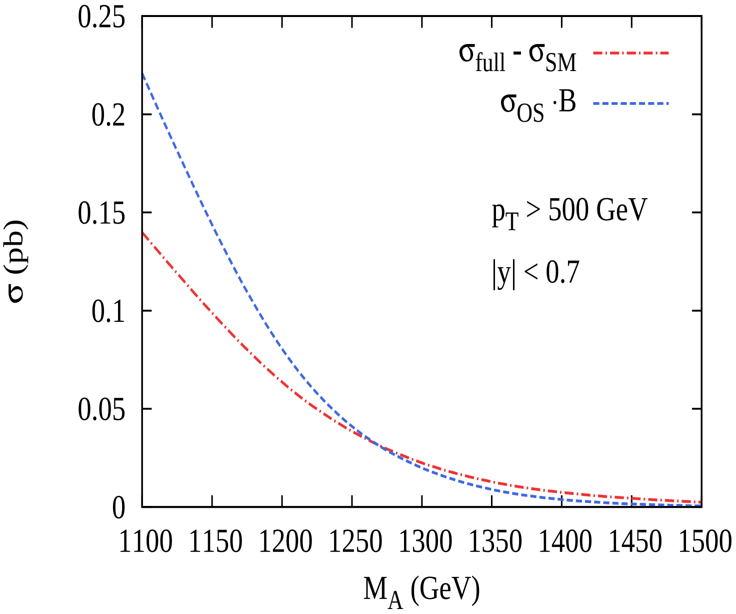


Figure 4: *The excess dijet cross section at the Tevatron as a function of the axigluon mass once each of the two leading jets have been required to satisfy* $p_T > 500$ GeV *and* $|y| < 0.7$.

argued that the enhancement in rates in the high m_{jj} region[7], in itself, would constitute a smoking gun signal, note that the task is not as straightforward. The wide region (in the m_{jj} spectrum) of the coloron's influence means that virtually no part of the spectrum can be termed to be essentially SM-like, thereby changing the entire nature of the fit algorithm. Thus, a much more sophisticated algorithm, including a higher order calculation of the SM dijet spectrum, would be necessitated; in particular, such corrections can, and do, change the shape of the spectrum.

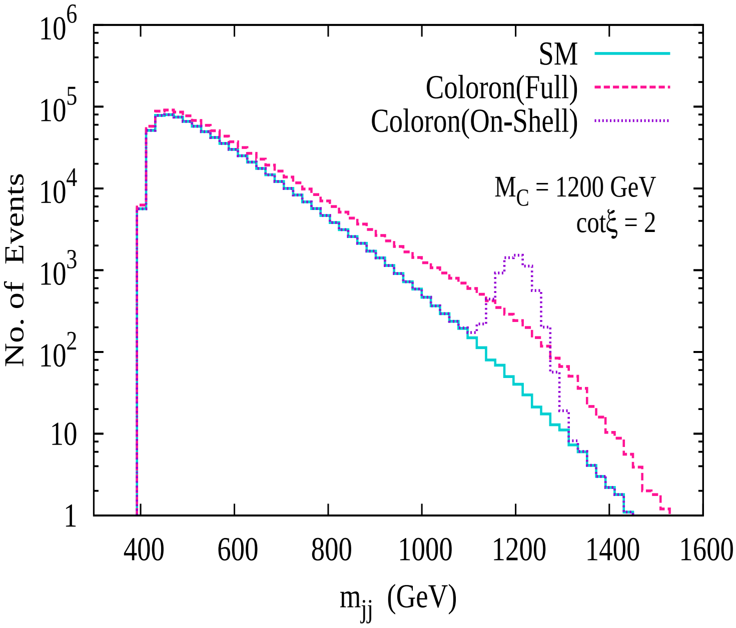


Figure 5: *The dijet invariant mass distribution, at the Tevatron, in the presence of a coloron with* $\mathrm{M_C}$= 1200 GeV *and* $\cot\xi = 2$ *(this translates to* Γ_C= 408.5 GeV*). Each of the two leading jets is required to have* $p_T > 200$ GeV *and an integrated luminosity of* 10 fb^{-1} *has been assumed.*

3.2 At the LHC

At the LHC, the pitch is queered by the low fluxes for antiquarks in the initial state. Due to this, the contribution from the s-channel amplitude suffers a reduction as compared to the contribution from the t- and u-channel amplitudes which may have two quarks in the initial state. Consequently, the `OS` approximation is less likely be valid here as compared to the case of the Tevatron. For the SM background, a fit analogous to that for the Tevatron can be made [2], of course with differing parameters. Once again, a Gaussian fit works almost as well.

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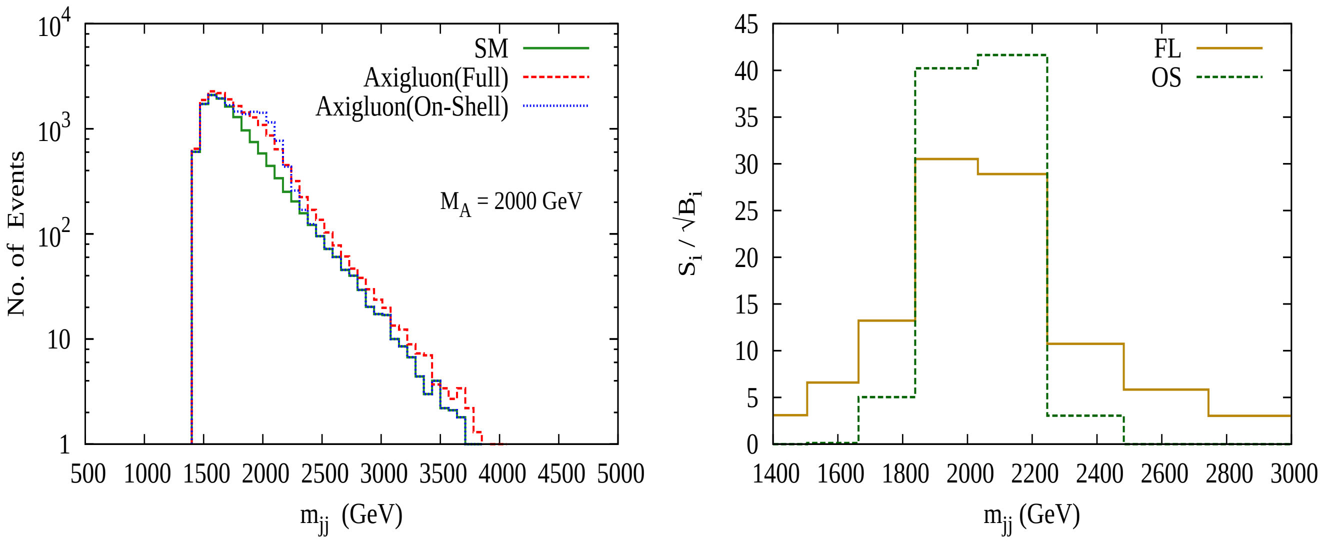
[7] In fact, one of the motivations behind the proposal of the flavor-universal coloron model was the excess reported by the CDF collaboration in the tail of the E_T-spectrum for inclusive jet production [27]. However, when more data was analysed, this discrepancy disappeared [28].

With the mass reach of the LHC being greater, we consider $\mathrm{M_A}$= 2.0 TeV (Γ_A= 160.2 GeV), and, to enhance the signal to background ratio, we impose cuts much stricter than those for the Tevatron, namely $p_T^{min} = 700$ GeV and $|y| < 0.7$. For the energy resolution, we assume $\delta E_T/E_T = 70\%/\sqrt{E_T(\mathrm{GeV})} \oplus 8\%$ [29]. After smearing, a resonance-like structure seems apparent for the `OS` case, though no such claim can be made for `FL` (Fig. 6(a)). However, once larger (and experimentally more reasonable) bin-widths[8] are considered, the difference is expected to reduce. Note that part of this effect is offset by the increased statistics in each bin. As Fig. 6(b) shows, even with larger bin-widths, `OS` yields higher values for significance close to the resonance, whereas `FL` gives rise to significant deviations away from the resonance.



(a)

(b)

Figure 6: (a) *The dijet invariant mass spectrum at the LHC corresponding to* $\mathrm{M_A}$= 2.0 TeV (Γ_A= 160.2 GeV). An integrated luminosity of 10 fb^{-1} has been assumed and a restriction of $p_T > 700$ GeV and $|y| < 0.7$ has been imposed on each of the two highest p_T jets. *(b)* Expected binwise significance for the same case.

Finally, we present the comparison between the invariant mass distributions for a coloron with $\mathrm{M_C}$= 2.0 TeV and $\cot\xi = 2$ (Γ_C= 645.7 GeV) in Fig.7. As with the case of the Tevatron, the `OS` approximation is demonstrably a very poor one and almost the entire dijet mass spectrum gets modified.

3.2.1 Other Observables

We have, until now, concentrated only on the invariant mass distribution as a discriminator, not only between the SM and new physics, but also amongst various forms of the latter. With the resolving power decreasing as the natural width increases, the case for other variables such as angular distributions becomes progressively stronger. For example, it has been

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[8] Though we use bin-widths of $0.1m_{jj}$ here, at ATLAS, for example, a resolution of $0.05m_{jj}$ is possible [30].

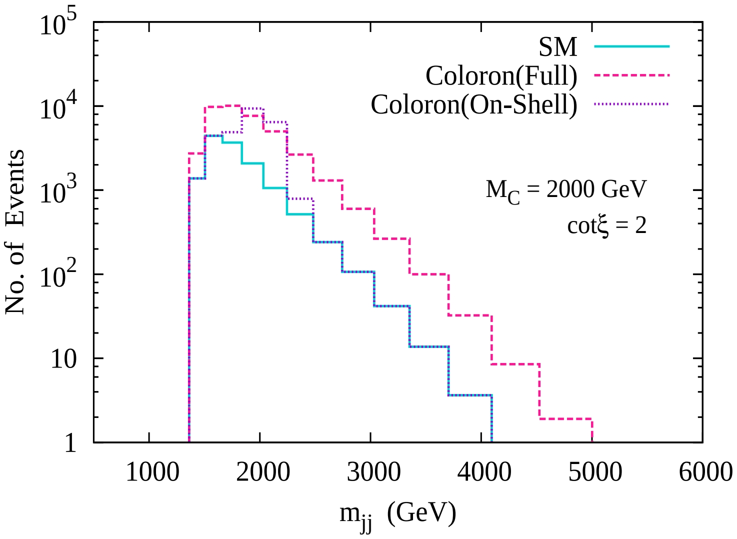

Figure 7: *The dijet invariant mass spectrum at the LHC corresponding to* $\mathrm{M_C}$= 2.0 TeV *and* $\cot\xi$ = 2 (Γ_C= 645.7 GeV). An integrated luminosity of 10 fb^{-1} has been assumed and a restriction of $p_T > 700$ GeV and $|y| < 0.7$ has been imposed on each of the two highest p_T jets.

argued [12] that the latter could be used to distinguish between a broad resonance and contact interactions.

In this context, we re-examine a variable that has been used by the ATLAS collaboration [31] to obtain limits on quark contact interactions. In essence, they compare the number of events where both jets satisfy $|y^*| < 0.6$ (where y^* is the rapidity in the partonic CM frame) with that where the extent of centrality is relaxed to $|y^*| < 1.7$. To be precise, $F_\chi(m_{jj})$ is defined as [31]

$$F^i_\chi(m_{jj}) = \frac{N^i_{events}(|y^*| < 0.6)}{N^i_{events}(|y^*| < 1.7)},$$

where, the superscript i denotes the i^{th} bin in the m_{jj} distribution. We compute the F_χ distributions for an axigluon of mass 2000 GeV for each of the `FL` and `OS` cases. As suggested by Ref. [31], the F_χ distribution is indeed sensitive to mass dependent changes in production rates in the central rapidity region. But that is not all. It is also sensitive to the assumption of a narrow-width approximation. In other words, as can be seen in Fig. 8(a) the shape of the distribution is markedly different in the two cases[9]. The difference persists even when the bin-size is increased (Fig.8(b)).

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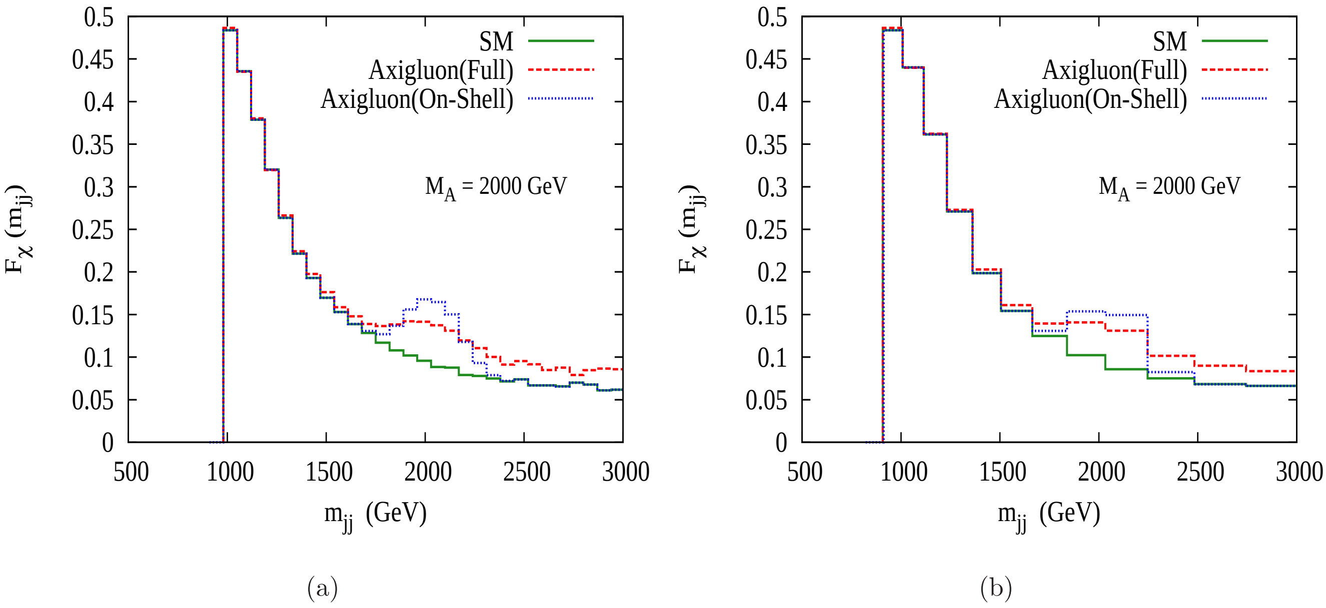
[9] That the shape of our SM curve are different from that in Ref. [31] is attributable to the strong p_T cut imposed by us.



(a)

(b)

Figure 8: *The* $F_\chi(m_{jj})$ *distribution at the LHC for* $\mathrm{M_A}$= 2.0 TeV *with* p_T^{min}= 500 GeV*. In (b), the bin-width taken to be* $0.1 m_{jj}$*.*

4 Summary

New physics scenarios often predict resonances in the dijet channel. Very often, search strategies focus on setting limits on $\sigma \cdot \mathcal{B}$, the product of the cross section for on-shell production and the branching fraction into the dijet channel. While this strategy is perfectly valid in many cases, its applicability is questionable in the case of particles which have large widths due to either strong interactions or large masses. It has been argued in the literature [1], though, that the natural width plays only a subservient role to detector resolution effects, and, consequently, the former is oft neglected in experimental strategies.

To examine this assertion in a qualitative manner, we considered two models and, for each, performed a simple analysis comparing the signal profile with and without the 'narrow-width approximation'. The dominant experimental effects (resolution) were incorporated through a smearing of the energies of the final-state particles[10]. We do find that the profiles can be substantially different in the two cases. For example, in the axigluon case, the natural width broadens the invariant mass distribution to a significant extent over and above the broadening due to resolution. A further complication arises from the fact that, in addition to the s-channel diagrams, we also have t– and u–channel contributions. While these can be safely neglected for a narrow resonance, their importance increases as the width becomes larger. In addition, channels such as $u\bar{d} \to u\bar{d}$ which do not proceed through s-channel diagrams do receive contributions from a t-channel axigluon exchange. In totality, it transpires that inclusion of such effects would lead to tangible *worsening* of the exclusion limits.

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[10] Indeed, we made a conservative choice of resolution parameters so as to enhance the experimental effects.

At the LHC, these effects could be even more important. The reason is not difficult to fathom. At the LHC, the $\bar{q}$ is a sea-quark and, consequently, its density is relatively small for high Bjorken-x, the regime that producing a very heavy resonance would require. On the other hand, t-channel axigluon contributions to $qq \to qq$ remain unsuppressed. Thus, a careful analysis is even more mandatory in that arena.

The signal to background ratio is, of course, dependent on the kinematical cuts. We have demonstrated that this dependance itself is quite different for the `OS` case as compared to the full calculation. Thus, we feel that the analyses should preferably be done with the inclusion of all diagrams and, possibly retuning the selection cuts so as to obtain robust exclusion limits. Moreover, while we have presented only tree-level results here, contributions from higher orders in perturbation theory would also have to be taken into account, both for the SM as well as the relevant new physics scenario.

While the preceding discussion has largely focussed on the axigluon, it is by no means the only example of a colored resonance with a large width. Indeed, colorons generically have even larger widths. As we have shown explicitly, considering even $\cot\xi = 2$ (where, theoretically, $1 \leq \cot\xi \lesssim 4$) would render the width quite large and would almost totally obliterate a resonance. Rather, a very broad excess would be visible. Such an excess, in principle, could stand out once the background has been subtracted. However, the very width makes it virtually impossible to fit a functional form to the observations away from an excess, for, indeed, the excess spans almost the entire available invariant mass range. Hence, identification of the excess would require either a very precise knowledge of the SM prediction and perhaps even new experimental techniques.

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