Axigluon Phenomenology using ATLAS dijet data

Bastián Díaz and Alfonso R. Zerwekh*

Departamento de Física and
Centro Científico-Tecnológico de Valparaíso
Universidad Técnica Federico Santa María
Casilla 110-V, Valparaíso, Chile

May 11, 2014

Abstract

In recent years, there has been a renewed interest on axigluons as part of a possible extension of strong interactions at high energies. In this work, we use recent ATLAS measurements of the dijet spectrum in order to set limits on the axigluon mass and coupling to quarks. We pay special attention to the methodology used to extract the resonant contribution from theoretical simulations. Finally, we present some predictions for the next LHC run at \( \sqrt{s} = 14 \) TeV.

1 Introduction

The Standard Model (SM) has proven to be extremely successful describing collider data. Even the discovery of the new 125 GeV scalar state \([1,2]\), which seems to behave like the so-long awaited Higgs boson, has unexpectedly confirmed the validity of the SM at the Fermi scale. At the moment, we don’t have any collider hint of New Physics except, maybe, the anomaly on the forward-backward asymmetry in the top–anti-top production \((A_{FB}^{tt})\) observed at the Tevatron \([3–5]\). One of the possible explanations of this phenomenon is the existence of a color-octet spin-1 field with axial coupling to quarks, the so called axigluon. Many particular axigluon models have been advanced in order to explain the \(A_{FB}^{tt}\) anomaly \([6–20]\). On the other hand, at the LHC, ATLAS \([21,22]\) and CMS \([23–26]\) have performed axigluon searches in the dijet spectrum although considering only the minimal model. Moreover, there has been some controversy about the correct procedure for comparing the experimental data and theoretical computations \([27]\). In this work, after recalling the theoretical framework for axigluon physics (section 2) we use recent ATLAS dijet data and

*alfonso.zerwekh@usm.cl
update the limits on the axigluon mass for the minimal universal model (section 3). More importantly, in 4 we reinterpret the existing data in order to set limits on the axigluon coupling to quarks. In this process, we pay special attention to the methodology used to extract the resonant contribution from theoretical simulations. In section 5 we present some predictions for the next LHC run at $\sqrt{s} = 14$ TeV. Finally, in section 6 we summarize and state our conclusions.

2 Theoretical Framework

The axigluon arises in models where the strong interaction gauge group is extended in order to provide a non-trivial chiral structure to it [28, 29]. This kind of models are generally called chiral color models. The minimal example is to consider the group $SU(3)_L \times SU(3)_R$ and assume that left-handed quarks transform under fundamental representation of $SU(3)_L$ while right-handed quarks are triplets of $SU(3)_R$. This symmetry is then broken to the diagonal group which is identified with the usual color group. After the symmetry breaking, it is found in the physical spectrum a massless gauge boson with vector coupling to quarks (the gluon) and a massive spin-1 field with axial-vector coupling to quarks, the so called axigluon (which we will denote by $A_\mu$). If we assume that the coupling constants associated with the left group ($g_L$) and the right group ($g_R$) happen to be equal ($g_L = g_R = g$) then the usual QCD coupling constant (defined by the coupling of quarks to gluon) is given by $g_{QCD} \equiv g/\sqrt{2}$. In this simple scenario, which we call the Minimal Axigluon Model, the axigluon has a pure axial coupling and its associated coupling constant is just $g_{QCD}$. However, if $g_L \neq g_R$ the coupling of the axigluon to quarks is described by the following Lagrangian [7]:

$$\mathcal{L}_{A\bar{q}q} = g_{QCD} \bar{q} \sigma^{\mu \nu} \left( \frac{g}{\sin(2\theta)} \gamma_5 \right) A^a_{\mu} q$$

(1)

where $\theta$ is a mixing angle defined by $\tan(\theta) = g_R/g_L$. Notice that in this case the axigluon interaction has a vector part as well as an axial-vector part and the coupling constant of the axial-vector part is greater than $g_{QCD}$. Additionally, it is easy to see that in this scenario the axigluon interaction is universal.

It is possible, however, to extend these ideas in order to obtain a more flexible axigluon with modified and even non-universal couplings. Two mechanisms are described in the literature that make possible such an extension. The first one consists in introducing new heavy exotic vector-like quarks to which normal quarks can mix up [11]. The axigluon coupling to (normal) quarks is then modified by the presence of functions of a new mixing angle in the quark sector. This mixing may be flavor dependent and, hence, universality is broken. The second mechanism is based on the introduction of extra spin-1 color octet fields [30]. A simple realization of this idea is to extend the chiral color group to $SU(3)_1 \times SU(3)_2 \times SU(3)_3 \times SU(3)_4$ and, using the ideas of Deconstruction Theory, “delocalize” quarks in the different groups [12]. After the symmetry breaking process, and using an appropriated delocalization pattern, the axigluon
interaction is modified by the delocalization parameter. Of course, each flavor of quark may be delocalized in a different way and, as a consequence, universality is lost again.

In both mechanisms, the resulting axigluon coupling constant can be arbitrary large or small depending on the value of the mixing or delocalization parameter even in the case where the coupling constants associated to the different groups are all equal.

In this work, we adopt a phenomenological approach and we consider an axigluon interaction term of the form:

\[ \mathcal{L}_{A\bar{q}q} = k g_{QCD} \lambda^a \frac{\gamma^\mu \gamma_5}{2} A^a_{\mu} q \]  

(2)

where \( k \) is a (flavor independent) constant which measure the deviation from the minimal model.

3 Limits on Axigluon Mass

3.1 Methodology

In recent years, ATLAS and CMS have searched for new resonances in the dijet spectrum. One of them is the axigluon\(^1\). Unfortunately, a proton-proton collider like the LHC is not the best place to search for axigluons. The reason is that an axigluon resonance can only be produced by quark–anti-quark annihilation, but this mechanism is suppressed at the LHC due to a parton distribution function (PDF) conspiracy. That means that in a proton-proton collider it is difficult to find anti-quarks with large momentum and therefore it is difficult to produce a very massive axigluon on-shell. The consequence of this suppression is that a large amount of dijet events originated by an axigluon in the s-channel are in fact produced at low dijet invariant masses by an off-shell axigluon. Nevertheless, in actual measurements, this large tail is hidden under the usual QCD background. For the theoretical side, it means that only the resonant part of the cross section must be extracted from any simulation destined to be compared to experimental data. ATLAS and CMS have used different criteria for such an extraction in their setting up of limits for the axigluon mass \( [27] \). CMS made their simulation relying on the well known Narrow Width Approximation. ATLAS, on the other hand, computed the leading order cross section considering all the possible channels (not only the s-channel) and then integrated the differential cross section in the neighborhood of the resonance (specifically in the interval \([0.7M, 1.3M]\) where \( M \) is the axigluon mass) \( [21] \). These different criteria lead to significantly different limits which originate some level of controversy.

In this work, however, we implement a different procedure. Using CalcHEP \( [31] \), we generate events for dijet production due to axigluon exchange taking into account s-channel and t-channel contributions. Then, after applying the appropriated kinematic cuts, we fit the dijet invariant mass cross section distribution

---

\(^1\)Unfortunately, it seems that ATLAS has not updated its limits on axigluons since 2011
around the peak by using a Breit-Wigner plus a second order polynomial. We
define the extracted resonant cross section as the integral of the Breit-Wigner
function. Of course, this procedure is equivalent to the Narrow-Width Approx-
imation for narrow resonances produced in the s-channel but is generalizable to
the case of wider resonances.

3.2 Results

Usually, experimental collaborations set limits on axigluon mass based only on
the Minimal Axigluon Model (that is, \( k = 1 \) in (2)). In order to compare our
results with existing limits, as a first step, we focus in this simple case. As
explained above, we use CalcHEP to generate events for dijet production due to
axigluon exchange. In order to compare to ATLAS measurements of the dijet
spectrum, we impose the following cuts:

\[
\begin{align*}
|y_i| &< 2.8 \quad (i = 1, 2) \\
|y_1 - y_2| &< 1.2 \\
M_{jj} &> 1000 \text{ GeV} \\
p_{T,i} &> 150 \text{ GeV} \quad (i = 1, 2)
\end{align*}
\]

where \( y_i \) and \( p_{T,i} \) are the rapidity and transverse momentum of each jet while
\( M_{jj} \) represents the invariant mass of the dijet system. After extracting the res-
onant part of the cross section, as explained above, we compare our results with
the limits obtained by ATLAS for resonances decaying into dijets at \( \sqrt{s} = 8 \text{ TeV} \)
and \( \mathcal{L} = 13 \text{ fb}^{-1} \) [32]. The result is shown in figure 1. The continuous line rep-
resents our extracted resonant cross section for different values of the axigluon
mass. The line with dots is the experimental limit set by ATLAS for resonances.
Every resonance producing a cross section above the experimental limit is ex-
cluded. We see that, in the context of the Minimal Axigluon Model, that the
axigluon is excluded if it is lighter than 4100 GeV. This limit is comparable with
recent limits obtained by CMS [33].

Our second step is to investigate the influence of detector effects on our limit.
In our case, we focus on the resolution of the calorimeter. A typical resolution
for a hadron calorimeter is:

\[
\frac{\Delta E}{E} = \frac{0.5}{\sqrt{E(\text{GeV})}} \oplus 0.03
\]

where \( \Delta E \) is the energy resolution.

We smeared our events using this parametrization for the resolution of the
calorimeter and we re-extracted the resonant cross section using the same cuts.
Of course, due to the smearing procedure we fitted the peak with a gaussian
function and not a Breit-Wigner one. Our new predicted cross sections are
represented in figure 1 by the dotted line. We see that this time axigluons are
excluded if they are lighter than 3700 GeV.
Figure 1: Predicted resonant cross sections with (continuous line) and without (dashed line) detector resolution compared to ATLAS upper limits to narrow resonances decaying into dijet (dots with continuous line). In both cases we used $k = 1$

4 Limits on Axigluon Couplings

4.1 Narrow Axigluon

A limitation of the usual axigluon searches is that it is based on the Minimal Axigluon Model. That means that it is always assumed that the axigluon couples to quarks with QCD intensity. Nevertheless, this is far from being the general case. In fact, it is a simple but very special scenario. For this reason, we reinterpret the ATLAS limits in order to constrain the coupling of the axigluon to quarks.

We assume that the axigluon interaction with quarks is given by Lagrangian (2). If the axigluon is relatively narrow the following relation among cross sections must hold:

$$\sigma_{k \neq 1} = k^2 \sigma_{k = 1}$$

(4)

On the other hand, if the axigluon has remained invisible it must happen that:

$$\sigma_{k \neq 1} \leq \sigma_{\text{ATLAS}}$$

(5)

where $\sigma_{\text{ATLAS}}$ represents the limit on cross section imposed by ATLAS searches. Thus, we can extract limits on the parameter $k$:
Figure 2: Limits on the $k$ factor defined as $|k| = g_{A\bar{q}q}/g_{QCD}$

$$k^2 \leq \frac{\sigma_{ATLAS}}{\sigma_{k=1}}$$

The resulted limits are shown in figure 2.

Axigluons with masses ranging in the $[1.5, 2.5]$ TeV interval are still allowed provided that they are fairly weakly coupled, with $|k|$ in the $[0.1, 0.2]$ interval.

4.2 Broad Axigluon

So far, we have considered an axigluon which decays only into standard quarks with universal coupling. This kind of axigluon is relatively narrow with $\Gamma/M \sim 0.1$. Nevertheless, phenomenologically it is more important the case of a broad axigluon ($\Gamma/M \gtrsim 0.2$) since it is a viable explanation for the $A_{FB}$ anomaly observed at the Tevatron. An axigluon may be broad if its width is dominated by a strong decay channel into non-standard particles or even to the top-quark. We tried to remain model-agnostic and we studied a broad axigluon in an illustrative case. Again, we generated events for dijet production due to axigluon exchange but this time we set the ratio $\Gamma/M$ to a fixed value: $\Gamma/M = 0.3$. For axigluon heavier than 3 TeV it is impossible to fit any resonant structure and consequently the axigluon is unobservable by searches in the dijet spectrum. However, for masses in the range 1 TeV $\leq M < 3$ TeV, resonant structures are recognizable and the resonant cross sections can be extracted. In figure 3, we compare the extracted resonant cross section for the broad axigluon (continuous line) with the one obtained previously for a narrow axigluon (dashed lined). In both cases
we used $k = 1$. We see that the broad axigluon produces larger cross sections. This is mainly due to the fact that, in the broad axigluon case, the axigluon resonance explores lower invariant masses suffering less PDF suppression and thus enhancing the integrated cross section.

5 Axigluon at $\sqrt{s} = 14$ TeV

We now move toward our expectations for the next run of the LHC at $\sqrt{s} = 14$ TeV. In figure 4 two curves are shown. The first one (dots with continuous line) represents the resonant cross section predicted by the Minimal Axigluon Model. The second one, (squares with continuous line) represents the resonant cross section obtained considering the maximum value of $k$ allowed by current data for each axigluon mass. Our results tell us that if a (narrow) axigluon exists but has escaped our searches because it is couple to quarks weakly enough, then it would be produced at the 14 TeV LHC with maximum resonant cross section laying somewhere in the range $0.1 - 1$ pb.

6 Summary and Conclusions

The axigluon, although it may be seen as an exotic kind of New Physics, has an interesting phenomenology and may be a natural explanation of an observed,
Figure 4: Resonant cross section predicted for the 14 TeV LHC using $k = 1$ (dots with continuous line) and the maximum value of $k$ allowed by current data (squares with continuous line)

and still not understood, anomaly. In this work, we have used recent ATLAS measurements of the dijet spectrum to set limits on the mass and couplings of the axigluon in a more general theoretical context than the one usually consider by experimental searches. The coupling of axigluon with mass below 3 TeV to light quarks is highly constrained for narrow and broad axigluon. In contrast, a broad axigluon with $\Gamma/M = 0.3$ is eventually invisible in the dijet spectrum for masses larger than 3 TeV. Additionally, we have defined a methodology for extracting the resonant cross section which is generalizable beyond the narrow resonance case.

Acknowledgement

ARZ has received financial support from Fondecyt grant nº 1120346

References

[1] G. Aad *et al.* [ATLAS Collaboration], “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,” Phys. Lett. B 716 (2012) 1 [arXiv:1207.7214 [hep-ex]].
[2] S. Chatrchyan et al. [CMS Collaboration], “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” Phys. Lett. B 716 (2012) 30 [arXiv:1207.7235 [hep-ex]].

[3] T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 101 (2008) 202001 [arXiv:0806.2472 [hep-ex]].

[4] T. Aaltonen et al. [CDF Collaboration], “Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production,” Phys. Rev. D 83 (2011) 112003 [arXiv:1101.0034 [hep-ex]].

[5] V. M. Abazov et al. [D0 Collaboration], “First measurement of the forward-backward charge asymmetry in top quark pair production,” Phys. Rev. Lett. 100 (2008) 142002 [arXiv:0712.0851 [hep-ex]].

[6] P. Ferrario and G. Rodrigo, “Massive color-octet bosons and the charge asymmetries of top quarks at hadron colliders,” Phys. Rev. D 78 (2008) 094018 [arXiv:0809.3354 [hep-ph]].

[7] M. V. Martynov and A. D. Smirnov, “Chiral color symmetry and possible G-prime-boson effects at the Tevatron and LHC,” Mod. Phys. Lett. A 24 (2009) 1897 [arXiv:0906.4525 [hep-ph]].

[8] P. Ferrario and G. Rodrigo, “Constraining heavy colored resonances from top-antitop quark events,” Phys. Rev. D 80 (2009) 051701 [arXiv:0906.5541 [hep-ph]].

[9] P. H. Frampton, J. Shu and K. Wang, Phys. Lett. B 683 (2010) 294 [arXiv:0911.2955 [hep-ph]].

[10] Q.-H. Cao, D. McKeen, J. L. Rosner, G. Shaughnessy and C. E. M. Wagner, “Forward-Backward Asymmetry of Top Quark Pair Production,” Phys. Rev. D 81 (2010) 114004 [arXiv:1003.3461 [hep-ph]].

[11] Y. Bai, J. L. Hewett, J. Kaplan and T. G. Rizzo, “LHC Predictions from a Tevatron Anomaly in the Top Quark Forward-Backward Asymmetry,” JHEP 1103 (2011) 003 [arXiv:1101.5203 [hep-ph]].

[12] A. R. Zerwekh, “The Axigluon, a Four-Site Model and the Top Quark Forward-Backward Asymmetry at the Tevatron,” Phys. Lett. B 704 (2011) 62 [arXiv:1103.0956 [hep-ph]].

[13] M. I. Gresham, I. -W. Kim and K. M. Zurek, “On Models of New Physics for the Tevatron Top $A_{FB}$,” Phys. Rev. D 83 (2011) 114027 [arXiv:1103.3501 [hep-ph]].

[14] A. Djouadi, G. Moreau and F. Richard, “Forward-backward asymmetries of the bottom and top quarks in warped extra-dimensional models: LHC predictions from the LEP and Tevatron anomalies,” Phys. Lett. B 701 (2011) 458 [arXiv:1105.3158 [hep-ph]].
[15] U. Haisch and S. Westhoff, “Massive Color-Octet Bosons: Bounds on Effects in Top-Quark Pair Production,” JHEP 1108 (2011) 088 [arXiv:1106.0529 [hep-ph]].

[16] G. Marques Tavares and M. Schmaltz, “Explaining the t-tbar asymmetry with a light axigluon,” Phys. Rev. D 84 (2011) 054008 [arXiv:1107.0978 [hep-ph]].

[17] J. A. Aguilar-Saavedra and M. Perez-Victoria, “Shaping the top asymmetry,” Phys. Lett. B 705 (2011) 228 [arXiv:1107.2120 [hep-ph]].

[18] G. Z. Krnjaic, “Very Light Axigluons and the Top Asymmetry,” Phys. Rev. D 85 (2012) 014030 [arXiv:1109.0648 [hep-ph]].

[19] H. Wang, Y. -k. Wang, B. Xiao and S. -h. Zhu, “New color-octet axial vector boson revisited,” Phys. Rev. D 84 (2011) 094019 [arXiv:1107.5769 [hep-ph]].

[20] M. Cvetic, J. Halverson and P. Langacker, “Ultraviolet Completions of Axigluon Models and Their Phenomenological Consequences,” JHEP 1211 (2012) 064 [arXiv:1209.2741 [hep-ph]].

[21] G. Aad et al. [ATLAS Collaboration], “Search for New Physics in Dijet Mass and Angular Distributions in pp Collisions at $\sqrt{s} = 7$ TeV Measured with the ATLAS Detector,” New J. Phys. 13 (2011) 053044 [arXiv:1103.3864 [hep-ex]].

[22] G. Aad et al. [ATLAS Collaboration], “Search for New Physics in the Dijet Mass Distribution using 1 fb$^{-1}$ of pp Collision Data at $\sqrt{s} = 7$ TeV collected by the ATLAS Detector,” Phys. Lett. B 708 (2012) 37 [arXiv:1108.6311 [hep-ex]].

[23] V. Khachatryan et al. [CMS Collaboration], “Search for Dijet Resonances in 7 TeV pp Collisions at CMS,” Phys. Rev. Lett. 105 (2010) 211801 [arXiv:1010.0203 [hep-ex]].

[24] S. Chatrchyan et al. [CMS Collaboration], “Search for Resonances in the Dijet Mass Spectrum from 7 TeV pp Collisions at CMS,” Phys. Lett. B 704 (2011) 123 [arXiv:1107.4771 [hep-ex]].

[25] S. Chatrchyan et al. [CMS Collaboration], “Search for narrow resonances and quantum black holes in inclusive and b-tagged dijet mass spectra from pp collisions at $\sqrt{s} = 7$ TeV,” JHEP 1301 (2013) 013 [arXiv:1210.2387 [hep-ex]].

[26] S. Chatrchyan et al. [CMS Collaboration], “Search for narrow resonances using the dijet mass spectrum in pp collisions at $\sqrt{s} = 8$ TeV,” arXiv:1302.4794 [hep-ex].
[27] R. M. Harris and K. Kousouris, “Searches for Dijet Resonances at Hadron Colliders,” Int. J. Mod. Phys. A 26 (2011) 5005 [arXiv:1110.5302 [hep-ex]].

[28] P. H. Frampton and S. L. Glashow, “Unifiable Chiral Color With Natural Gim Mechanism,” Phys. Rev. Lett. 58 (1987) 2168.

[29] P. H. Frampton and S. L. Glashow, “Chiral Color: An Alternative to the Standard Model,” Phys. Lett. B 190 (1987) 157.

[30] A. R. Zerwekh, “Axigluon Couplings in the Presence of Extra Color-Octet Spin-One Fields,” Eur. Phys. J. C 65 (2010) 543 [arXiv:0908.3116 [hep-ph]].

[31] A. Belyaev, N. D. Christensen and A. Pukhov, Comput. Phys. Commun. 184 (2013) 1729 [arXiv:1207.6082 [hep-ph]].

[32] [ATLAS Collaboration], “Search for New Phenomena in the Dijet Mass Distribution updated using 13.0 fb-1 of pp Collisions at $\sqrt{s} = 8$ TeV collected by the ATLAS Detector,” ATLAS-CONF-2012-148.

[33] [CMS Collaboration], “Search for Narrow Resonances using the Dijet Mass Spectrum with 19.6 fb-1 of pp Collisions at $\sqrt{s}=8$ TeV,” CMS-PAS-EXO-12-059.