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# Nonstandard, strongly interacting spin one $t\bar{t}$ resonances.

Rohini M. Godbole

*Centre for High Energy Physics, Indian Institute of Science, Bangalore 560012, India.*

Debajyoti Choudhury

*Dept. of Physics and Astrophysics, University of Delhi, Delhi 110007, India.*

Examining theories with an extended strong interaction sector such as axigluons or flavour universal colorons, we find that the constraints obtained from the current data on  $t\bar{t}$  production at the Tevatron are in the range of  $\sim \mathcal{O}$  TeV and thus competitive with those obtained from the dijet data. We point out that for large axigluon/coloron masses, the limits on the coloron mass may be different than those for the axigluon even for  $\cot \xi = 1$ . We also compute the expected forward-backward asymmetry for the case of the axigluons which would allow it to be discriminated against the SM as also the colorons. We further find that at the LHC, the signal should be visible in the  $t\bar{t}$  invariant mass spectrum for a wide range of axigluon and coloron masses that are still allowed. We point out how top polarisation may be used to further discriminate the axigluon and coloron case from the SM as well as from each other.

## 1. INTRODUCTION

The importance of the study of top quark physics at the current stage in Particle Physics can hardly be overemphasized. Apart from its crucial role in the test of the Standard Model (SM) at the loop level, the closeness of the top mass to the Electroweak Symmetry Breaking (EWSB) scale accord it a special role in virtually any alternative to the Higgs mechanism. Thus, the production of top quarks at the colliders can be a **low** energy probe of the **high** scale physics that might be triggering the EWSB. Already at the Tevatron, this is a topic of much attention [1, 2] and a top factory such as the LHC would provide valuable information on the SM as well as physics beyond it [3].

In our work [4], we revisit the issue of strongly interacting spin one gauge bosons and their contribution to  $t\bar{t}$  production at hadronic colliders. We consider two classes of models : 1) Flavour universal colorons which are present in theories of extended color gauge theories and 2) Axigluons which exist in theories of chiral colour. Although neither of these have preferentially larger couplings to the  $t\bar{t}$  pair, unlike Kaluza Klein gluons [5] or extended technicolour models, we demonstrate that even the current data on  $t\bar{t}$  production yield very competitive constraints on the masses and coupling of these gauge bosons.

## 2. Axigluon and Flavour Universal Coloron Models

Arising in unifiable models of chiral colour [6, 7], Axigluons are massive, strongly interacting gauge bosons with an axial vector coupling  $\frac{1}{2}g_s\gamma_\mu\gamma_5\lambda^a$ , where  $\lambda_a$  are the usual Gell-Mann matrices. In the simplest models, a high scale strong interaction gauge group of  $SU(3)_L \times SU(3)_R$  is broken to the familiar  $SU(3)_c \equiv SU(3)_{L+R}$ , resulting in massive states with the aforementioned coupling. This carries through for all generalisations of chiral color. Embedding this in a unified group implies  $m_A \sim 250$  GeV and hence was searched for very actively at the Tevatron.

Flavour universal Colorons [8] arise in models with an extended colour gauge group. The latter were part of the general effort to understand the mechanism of EW symmetry breaking and the large mass of the top in the same framework. With a top quark condensate enhancing  $m_t$  as well as driving EWSB, specific examples of this idea are topcolor [9, 10] and topcolor assisted technicolor [11]. The colour group at the high scale is  $SU(3)_I \times SU(3)_{II}$ —both being vector-like— which then breaks to  $SU(3)_c$  giving rise to the massive ‘colorons’. Variants of the model essentially differ in the way generations couple to the colorons. The one we consider is the simplest and is characterised by a universal coupling ( $\frac{1}{2}g_s \cot \xi \gamma_\mu \lambda^a$ ) to *all* the quarks. These models can be grafted into a single Higgs doublet model and has a **naturally** heavy top. Understandably, EW precision measurements restrict the model in the mass-coupling ( $M_C$ – $\cot \xi$ ) plane.

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### 3. PHENOMENOLOGY AT THE TEVATRON

The broad, strongly interacting axigluon and coloron resonances,  $A, C$ , can be copiously produced at a hadronic collider and thus could show up as an additional, resonant contribution to the dijet production cross-section ( $q\bar{q} \rightarrow A^*(C^*) \rightarrow q'\bar{q}'$ ). At the Tevatron, the dominance of the  $q\bar{q}$  flux implies that these contributions can be quite large. At the time of writing the paper [4], the best available limits on the axigluon and coloron masses came from the dijet sample [12, 13, 14] which rules out an axigluon of mass less<sup>1</sup> than 980 GeV. The same limit is quoted for coloron for  $\cot \xi = 1$  for the flavour universal case. In the approximation of neglecting the width and interference with background, the limit on coloron masses can get only stricter with increasing  $\cot \xi$ .

Note, though, that the axigluon and coloron cases differ in a crucial manner: while the  $s$ -channel coloron exchange amplitude can interfere with a similar QCD amplitude (for simplicity, let us consider  $q \neq q'$ ), this is nonexistent for the axigluon. For small masses, the resonance is narrow; with the difference being negligible, the limits for axigluon and coloron with  $\cot \xi = 1$  would be nearly identical. However, as we will see shortly, the approximation may not be justified for higher mass resonances and it would be interesting to examine how the limits obtained from dijet analysis are affected.

In this work, we are interested in  $t\bar{t}$  production. At the tree level, the presence of either  $A$  or  $C$  can affect  $t\bar{t}$  production only as far as the  $q\bar{q}$ -initiated subprocess is concerned, leaving the  $gg$ -initiated subprocess unaltered. We refrain from reproducing the expressions for differential cross-sections which are available in Ref. [4].

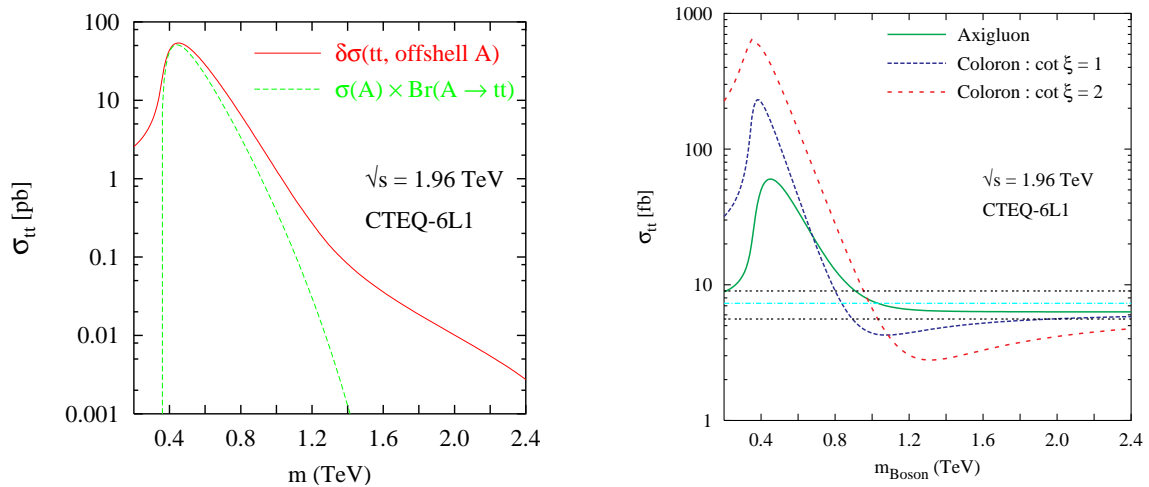


Figure 1: (a) A comparison of the deviation of the total  $t\bar{t}$  cross section caused by the presence of an axigluon (solid line) with the resonant production followed by decay. (b)  $\sigma(t\bar{t})$  at the Tevatron as a function of the axigluon (coloron) mass. The solid (green) line corresponds to the axigluon case. The short- (blue) and long-dashed (red) lines correspond to the flavour universal coloron for  $\cot \xi = 1$  (2) respectively. The horizontal lines correspond to the CDF central value and the 95% confidence level band [1]. CTEQ-6L1 parton distributions evaluated at  $Q = m_t$  were used alongwith the appropriate  $K$ -factor [15].

The widths are substantial for either of  $A/C$  capable of decaying into a top-pair. Furthermore, the partial widths into a top-pair are different even for  $\cot \xi = 1$ . The large widths imply that the (narrow-width) approximation of resonant production and subsequent decay is no longer a good one. This is borne out by Fig.1a, wherein we compare the narrow-width contribution to  $t\bar{t}$  production, viz.  $\sigma(A) \times BR(A \rightarrow t\bar{t})$  with the exact result, namely  $\delta\sigma \equiv \sigma_A(t\bar{t}) - \sigma_{SM}(t\bar{t})$ . The effect is indeed substantial. For the dijet case the effect will be smaller, but may still be non-negligible and hence might affect the limits on axigluon/coloron masses obtained from the dijet data. Further,

<sup>1</sup>At this conference newer limits have been quoted. These are not included in this report.

it is to be noted that the axial coupling of the  $A$  gives rise to a forward-backward asymmetry for the  $t$  quark [16]. For colorons, of course, no such asymmetry can exist.

In Figure 1b, the results of the  $t\bar{t}$  cross-sections expected for the coloron/axigluons at the Tevatron are shown as a function of the mass of the boson and for different values of  $\cot \xi$ . A few facts are to be noted.

- For axigluon case due to the different parity of the SM amplitude and the axigluon amplitude, the interference term does not contribute to the total rate.
- For coloron the interference term contributes and also changes sign as  $q\bar{q}$  subprocess energy passes through  $M_C$ , depending on  $\cot \xi$ .
- For masses of massive gluon above  $2m_t$  not just the interference term but the squared contribution of the new amplitude are different for coloron and axigluon.

The data indicated by the horizontal lines in Figure 1b and taken from [1] corresponds to:

$$\sigma(p + \bar{p} \rightarrow t + \bar{t} + X; \sqrt{s} = 1.96 \text{ TeV}) = 7.3 \pm 0.5 (stat) \pm 0.6 (syst) \pm 0.4 (lum) \text{ pb.}$$

Using these, we get for the axigluon  $M_A > 910$  GeV at 95% C.L., whereas for the coloron, for  $\cot \xi = 1$ ,  $800 < M_C < 895$  and  $M_C > 1960$  are allowed at the same C.L. These limits are quite competitive with those available from the dijet analysis and are in fact different for the coloron and the axigluon even for  $\cot \xi = 1$ . Furthermore, the coloron mass limits depend on  $\cot \xi$  non-monotonically (a consequence of the interference term), as is evident in both Figs. 1b&2a, the second displaying the exclusion region for the coloron in the  $\cot \xi - m_C$  plane. Note that the

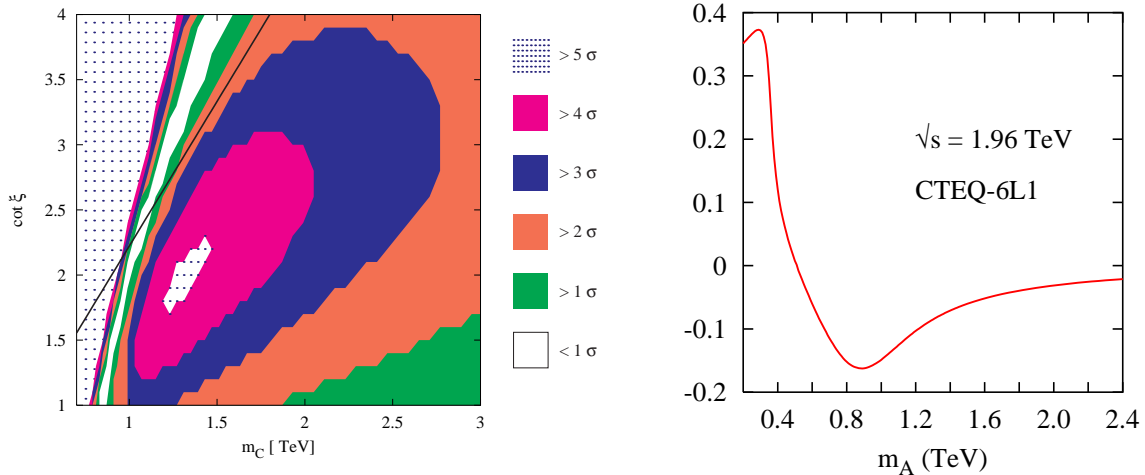


Figure 2: Left panel gives the exclusion region in the  $\cot \xi - m_C$  plane using the  $t\bar{t}$  data at Tevatron [1]. The solid curve shows the constraint imposed by the  $\rho$  parameter  $m_C / \cot \xi \gtrsim 450$ . The right panel shows the FB asymmetry in  $t\bar{t}$  production at the LHC as a function of the axigluon mass

consistency of certain regions in the parameter space with the data cannot be interpreted as evidence for the colorons as the same data are consistent with the SM as well.

The parity violating axigluon coupling would also lead to a forward-backward asymmetry at the Tevatron as shown in Figure 2b. Two things are to be noted here. Our calculation corrects a mistake in Ref. [16]. Secondly for the masses accessible at the Tevatron these are quite sizable and substantially larger than the one expected due to QCD radiative corrections [17]. This agrees with the detailed comparisons of the latter with those expected for axigluon contribution performed in Ref. [18], which appeared soon after our work. In fact the asymmetry caused by the axigluon resonance will have a different dependence on the phase space variables from those caused by QCD effects. With this, one could in fact use these asymmetries (or absence thereof) to obtain constraints on the axigluons.

## 4. PHENOMENOLOGY AT THE LHC

With the Tevatron pushing the limits on the axigluon and coloron masses higher, it is natural to investigate the prospects at the LHC. As gluon fluxes would dominate over  $q\bar{q}$ , it is imperative to look at differential distributions, in particular that in the invariant mass of the  $t\bar{t}$  pair. We see from the right panel of Figure 3 that, for the first peak, assuming even only a 10% efficiency, there will be about  $\sim 10^4$  events with  $10 \text{ fb}^{-1}$  and thus a good chance of being able to see them at the LHC. For such masses, the effect of  $m_t$  on the decay width is negligible and, for  $\cot \xi = 1$ , the differential cross sections are virtually the same at the resonance.

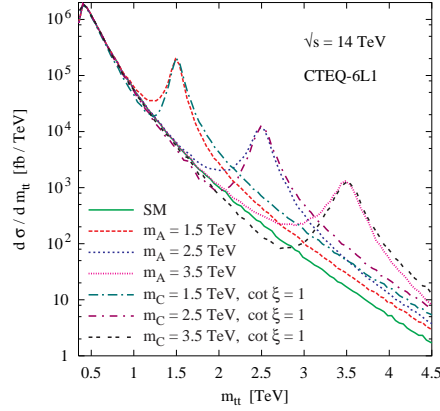


Figure 3: The expected  $m_{t\bar{t}}$  spectrum at the LHC in presence of either axigluons or colorons of a specified mass, along with the SM expectations.

Unfortunately, LHC being a  $pp$  machine, no FB asymmetry can be constructed for the axigluon case. However, the correlation between helicities of  $t$  and  $\bar{t}$  carry the information on the heavy gluon contribution. Instead one can construct  $\mathcal{R}_\Delta(m_{tt}) \equiv \left[ \int_{m_{tt}-\Delta}^{m_{tt}+\Delta} dm_{tt} \frac{d\sigma_-}{dm_{tt}} \right] \left[ \int_{m_{tt}-\Delta}^{m_{tt}+\Delta} dm_{tt} \frac{d\sigma_+}{dm_{tt}} \right]^{-1}$ , where  $\sigma_\pm$  refer to the cross sections for the product of the  $t$  and  $\bar{t}$  helicities to be  $\pm 1$  respectively. These are, in essence, like the spin-spin correlation measurements which have been suggested for the study of  $CP$ /spin properties of a resonance which can decay into a  $t\bar{t}$  [19]. In fact, this can then provide an additional handle to distinguish between the two cases at hand.

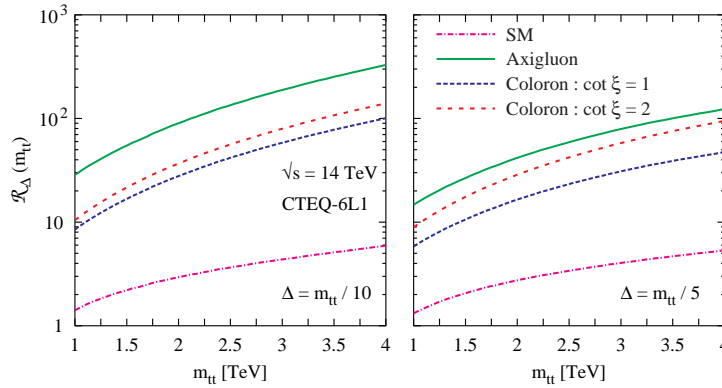


Figure 4: The ratio of the partial cross-sections  $\mathcal{R}_\Delta(m_{tt} = m_{\text{Boson}})$  as a function of the boson mass. The two panels correspond to different values of  $\Delta$ .

## 5. CONCLUSIONS

In conclusion, constraints on the axigluons and colorons obtained from  $t\bar{t}$  production at the Tevatron are indeed competitive with those from dijets. The forward-backward asymmetry at the Tevatron can help constrain the axigluon further. Nature of interference term with the SM amplitude are different for axigluon and coloron cases. The limits obtained from  $t\bar{t}$  production on coloron masses depend on  $\cot\xi$  non monotonically. The zero width approximation too crude at larger masses and mass limits obtained for dijets for coloron may not be the same as that of an axigluon, even for  $\cot\xi = 1$ . At the LHC differential distribution in  $m_{t\bar{t}}$  can show up evidence for colorons and axigluons. Their effect is measurable. Further, a variable similar to the spin spin correlations can help distinguish between the two further.

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