Impact of a colored vector resonance on the collider constraints for top-like top partner

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ABSTRACT: In this work we reappraise the collider constraints on the vector-like colored top partners taking into account the impact of exotic colored vector resonances. These colored states are intrinsic to a broad class of models that employ a strongly interacting sector to drive electroweak symmetry breaking. We translate the recent results in the monolepton + jets channel as reported by CMS at 35.8 fb⁻¹, and dilepton + jets and trilepton + jets channels as reported by ATLAS at 36.1 fb⁻¹ to constrain the parameter space of these class of models. We also comment on the impact and modification of the derived constraints due to the expected fatness of the colored vector resonance, when accounted for beyond the narrow-width approximation.
1 Introduction

The Large Hadron Collider (LHC) experiment is mandated to search for new physics (NP) beyond the Standard Model (SM) at the energy frontier. These discoveries are primarily expected to precipitate through unearthing of exotic states. In this hunt for exotics the colored vector gauge bosons and colored vector-like fermions are low lying fruits. While they have large production cross section owing to their colored charges, they conveniently can be made consistent with electroweak observables measured at the $Z$-pole at the LEP experiment [1]. This may be contrasted with any extra chiral fermion generation which are heavily constrained by the electroweak observables. These states naturally arise in a class of well motivated extensions of the SM like extra dimensional scenarios [2] and composite Higgs framework where the Higgs is identified with a pNGB of the strong sector [3]. In situations where the colored vector-like fermions participate in stabilizing the Higgs sector against quadratic sensitivity to the UV, they are usually labelled as top partners [4, 5]. A huge cache of literature has built up regarding the phenomenology of the top partners [6–30]. In principle the color triplet top partners can be in any representation of the weak gauge group but only certain combination can mix with the SM top in the presence of the SM Higgs doublet. In the context of stabilising the Higgs sector the relevant representations are the so called top-like multiplets that have at-least one state with quantum numbers identical to

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the top that enables linear mixing between the top and the top partner. Focusing on the smaller representations, it is easy to see that the singlet and triplet top like multiplets will lead to stronger mixing with the SM top doublet, leading to stronger constraints from the electroweak observables [1]. In this paper we will instead focus on the top-like top partner that is part of a doublet and primarily mixes with the SM top right.

We will consider the impact of any accompanying colored vector resonances on the constraints on the top partners from collider searches at LHC extending the study done in [31]. While our phenomenological model remains agnostic to the specific UV realisation, a large class of models including the extra-dimensional models and composite Higgs framework lead to scenarios that simultaneously have a top partner and heavy colored vector resonances [32]. An interesting facet of these models is the possibility of these exotic states being broad resonances. Typically a state whose decay width is a sizeable proportion (> 20%) of its mass is considered a broad resonance and the narrow width descriptions starts to fail in maintaining gauge invariance. The large decay width can either be a consequence of large proliferation of the possible decay channel or a large non-perturbative coupling. In this paper we will assume that the colored vector resonance, the so called gluon partner, has a strong coupling with the top-partner, inheriting this from a strongly interacting sector they belong to. This can be considered a paired down version of strongly interacting models of electroweak symmetry breaking, like the composite Higgs framework where the Higgs is a pNGB that couples to SM fermions through partial compositeness [3].

We reappraise the present status of the top like top partners i.e. the vector-like fermions having the same quantum numbers as the SM top, in the light of the Run-2 results from LHC. In this context we recast the constraints on the parameter space of these scenarios from the searches for exotics in the leptonic final states at ATLAS and CMS. We systematically translate the most recent bounds from CMS mono-lepton study [33] and ATLAS di-lepton and tri-lepton [34] searches. We show that the exclusion limit on the top partners are moderately altered due to the presence of the gluon partners. Additionally, the large width effect of the gluon partner is considerable and reconstructing the full 1PI propagator for the fat vector boson is quantitatively significant in most regions of the parameter space of interest. We have compared the results obtained within the narrow width approximation and the full propagator to demonstrate this.

The rest of the paper is organized as follows. In Section 2 we introduce the phenomenological Lagrangian for the top partner and the gluon partner. In Section 3 we discuss the impact of the large width of the vector resonance. In section 4 we systematically translate the constraints on the parameter space of the model from LHC studies in leptonic final states before concluding.

2 Model Lagrangian

In this section we introduce the phenomenological Lagrangian involving the top-like top partner and a colored vector boson. We extend the SM with a new vector-like colored fermion
Figure 1. Branching ratio of $\rho$ as a function of its mass $M_\rho$ for $m_{t'} = 1$ TeV, $\sin \theta_R = 0.1$. Blue (Red) line represents the branching ratio to top quarks (top partner).

$\Psi(3,2,7/6) = \{X,U\}$ with mass $M$ and a colored vector boson (the gluon partner) $\rho_\mu$, having mass $M_\rho$ and a large width $\Gamma_\rho$. A possible origin of such a spectrum in the context of a bottom-up Composite Higgs framework is briefly sketched in Appendix A. It will be assumed that the mixing with the first two generations are suppressed as dictated by the strong constraints from Z-pole observables. Concentrating on the SM third generation, the new state $U$ will mix with the right handed top that is assumed to be a member of a separate strongly interacting sector along with the exotic $X$ and $\rho_\mu$. The Lagrangian after electroweak symmetry breaking can be parametrised as [35],

$$L_{eff} \supset \bar{i} \gamma \cdot D \Psi + i \bar{q}_L D q_L + i \bar{t}_R D t_R + i \bar{b}_R D b_R + \frac{1}{2} M_\rho^2 \rho^\mu \rho_{\mu} - \left[m_{tL}^2 \bar{t}_L t_R + m_{mix} \bar{U}_L t_R + M_{U} \bar{U}_R + h.c. \right],$$  

where, $q_L = \{\bar{t}_L,b_L\}^T$ and two singlets $\bar{t}_R$ and $\bar{b}_R$, are the usual third generation SM quarks in the gauge basis. The covariant derivatives beside containing the usual SM gauge interactions of the colored fermions, include the coupling to the massive colored vector boson $\rho_\mu$, given by,

$$D \supset -ig_i \phi$$

where $g_i = g_*$, for the strong sector resonances viz. $\bar{t}_R$ and $U$, while $g_i = -g_s^2/g_*$ for the elementary states. The latter is a special choice adopted assuming a 5d gauge-Higgs UV completion of these models [32]. In the mass basis the mass terms can be written as,

$$L_{mass} = -m_{tL} \bar{t}_L t_R - m_{t'} \bar{t}_L^\prime t_R^\prime + h.c.$$

(2.3)
where $t$ represent the SM top and the $t'$ is the heavier top-like top partner. The corresponding rotation matrices can be schematically written as,

$$
\begin{pmatrix}
  t_L \\
  t'_L \\
  t_R \\
  t'_R
\end{pmatrix} =
\begin{pmatrix}
  U_{\theta_L} & 0 \\
  0 & U_{-\theta_R}
\end{pmatrix}
\begin{pmatrix}
  \bar{t}_L \\
  \bar{U}_L \\
  \bar{t}_R \\
  \bar{U}_R
\end{pmatrix}
$$

(2.4)

where $U_{\theta}$ are the 2D rotation matrices. The parameters and the mixing angles are correlated as,

$$
\sin \theta_R = \frac{M m_{mix}}{\sqrt{(M^2 - m_t^2)^2 + M^2 m_{mix}^2}} = \frac{M}{m_t} \sin \theta_L
$$

(2.5)

where,

$$
M^2 = \frac{m_{t'}^2 + \sin^2 \theta_R m_t^2 (m_{t'}^2 - m_t^2)}{1 + \sin^2 \theta_R (m_{t'}^2 - m_t^2)}
$$

The couplings of $\rho_{\mu}$ (in the mass basis) with the top and top-partner can be read out from Equations 2.1-2.5,

$$
\mathcal{L}_{\rho t t'} = (g_s \sin^2 \theta_L - \frac{g_s^2}{g_s} \cos^2 \theta_L) \bar{t}_L \rho t_L + (g_s \cos^2 \theta_L - \frac{g_s^2}{g_s} \sin^2 \theta_L) \bar{t}'_L \rho' t_L
$$

$$
- \frac{\cos \theta_L \sin \theta_L}{g_s} (g_s^2 + g_{s*}^2) (\bar{t}'_L \rho t_L + \bar{t}_L \rho' t_L) + g_s (\bar{t}'_R \rho t_R + \bar{t}_R \rho' t'_R)
$$

(2.6)

This effective framework has $m_{t'}$, $\theta_R$, $g_s$, and $M_\rho$ as the free parameters of the model. However to keep the discussion tractable we will consider a benchmark scenario where $g_s/g_{s*}$ will be set at 6 [36] which is in good agreement with large-N calculations in the strongly interacting holographic dual theory of a pNGB composite Higgs model [32].

At the LHC the top partner $t'$ is pair produced through the gluon or through the massive gluon partner ($\rho_{\mu}$). Once they are produced they will dominantly decay to SM states through the channels: $H t$, $Z t$, and $W b$. The branching ratios of $t'$ at $m_{t'} \sim 1$ TeV in the main decay channel are given by: $\text{BR}(t' \to H t) = 0.56$, $\text{BR}(t' \to Z t) = 0.42$ and $\text{BR}(t' \to W b) = 0.02$ [35]. The reduced branching ratio to the $W b$ is a consequence of the exotic state $U$ primarily mixing with the $SU(2)_L$ singlet elementary state $\bar{t}_R$. Here we assume that there are no significant exotic decays of the top partners [37]. The branching ratio of $\rho_{\mu}$ to $t t$ and $t' t'$ as a function of $M_\rho$ for a representative value of the top partner mass $m_{t'} = 1$ TeV is shown in Figure 1. Here and for the rest of this paper we set $\sin \theta_R = 0.1$ which is a conservative choice keeping the framework relatively insulated from the electroweak precision constraints [35]. The choice of the strong sector coupling $g_s$ and the mixing angle $\sin \theta_R$ forms a benchmark scenario that will be utilised in all the phenomenological studies that follow. In Figure 1 we have taken into account both the on-shell and off-shell decays of the gluon partner $\rho_{\mu}$ to $t'$. 

\[ -4 - \]
As is evident from the figure, as soon as the decay to a pair of $t'$ gets kinematically allowed they start dominating owing to the large coupling $g_*$ of the strong sector.

3 Beyond the Breit-Wigner

In the parameter space of interest the total decay width of $\rho_\mu$ ($\Gamma_\rho$) consistently remains above 20% of its mass ($M_\rho$) for the choice of $g_*$, where the decay to a pair of top partner is kinematically possible. In this region, the Breit-Wigner approximation may not be a good approximation and starts to fail. To systematically handle this large width we recalculate the top partner production cross section using the full 1PI summed propagator for the $\rho_\mu$ [31]. The total production cross section for the top partner can be written as

$$\sigma_{\text{total}} = \sigma^G + \sigma_{\text{fat}}^\rho$$

(3.1)

where the first term on the RHS represents the pure QCD contribution while the second term encodes the contribution to the production through the gluon partner. Here we have chosen to neglect the numerically insignificant interference term. The pure $\rho_\mu$ contribution is

$$\sigma_{\text{fat}}^\rho = 2 \int_0^1 d\hat{\tau} \hat{\sigma}(\hat{s}^\text{had}, \hat{\tau})_{\text{fat}} \int_{\hat{\tau}}^1 \frac{dx}{x} \sum_q f_q(x)f_{\bar{q}}(\frac{\tau}{x})$$

(3.2)

where $\hat{S}^\text{had}$ is the hadronic center of momentum energy, $\hat{\sigma}$ is the partonic cross-section and the functions $f_{q/\bar{q}}$ are parton density functions. For the pair production of $t'$ through an $s$-channel $\rho_\mu$ exchange at LHC (including the full 1PI resummed propagator for the $\rho_\mu$), the partonic cross-section is

$$\hat{\sigma}(\hat{s})_{\text{fat}} = \frac{g^2_{\text{prod}}g^2_{\text{dec}}}{27\pi\hat{s}} \sum_{\chi} \frac{\sqrt{\hat{s}(\hat{s} - 4\hat{m}_\chi^2)}}{(\hat{s} - M_\rho^2)^2 + (Im[M^2(\hat{s})])^2} \times (\hat{s} + 2\hat{m}_\chi^2), \quad \chi = t, t'$$

(3.3)

The imaginary part of $M^2(\hat{s})$ in the above expression represents the contribution from one loop corrections to the $\rho_\mu$ propagator. Since in the model $t_R$ is assumed to be a state in the strong sector, both $t$ and $t'$ will contribute in the loop and the relevant expression is given by,

$$Im[M^2(\hat{s})] = -\frac{g^2_{\text{dec}}}{12\pi\hat{s}} \theta(\sqrt{\hat{s}} - 2\hat{m}_\chi) \sqrt{\hat{s} - 4\hat{m}_\chi^2(\hat{s} - \hat{m}_\chi^2)}$$

(3.4)

We will rescale our exclusion plot of the parameter space utilizing the modified production cross section given in Equations 3.1-3.4. We assume that the shape of the event distribution and the corresponding efficiencies remains unaffected by this correction to the the propagator of the $\rho_\mu$. We present a quantitative argument in favour of this approach in Appendix B.
4 LHC Constraints

The effective framework described in Section 2 has been simulated by writing a model file in FeynRules 2.0 [38] and a UFO file was generated. This was imported in MadGraph5 [39] and pair production events of the top partner $t'$ were generated. Events were parton-showered using Pythia8 [40], jet-clustered using FastJet [41] and passed through detector simulation using Delphes-3 [42]. Three different LHC searches were used to constraint the model viz., monolepton + jets [33], dilepton + jets [34], and trilepton + jets [34]. The recast for each were written in MadAnalysis5 [43] and the efficiencies were obtained. To obtain the 95% exclusion we use the following generic template,

$$\left[ \sigma_{NLO}^{QCD}(m_{t'}) + \sigma_{LO}^{\rho}(m_{t'}, \sin \theta_R, M_{\rho}) \right] \times \epsilon \times L \leq N_{signal} \quad (4.1)$$

where $\sigma_{NLO}^{QCD}$ is the QCD pair production cross-section of $t'$ obtained from Top++2.0 [44] at NLO, $\sigma_{LO}^{\rho}$ is the pair production cross-section of $t'$ through a $\rho$ mediator at LO, $\epsilon$ is the efficiency obtained by applying the cutflow on the generated signal events, $L$ is the luminosity at which the LHC analyses were reported and $N_{signal}$ is the 95% exclusion bound on the total number of simulated events presented in the analysis. The $K$-factor for the $\rho$ mediated process is expected to be $\geq 1$ as is usual for the QCD case and which we verify from Top++2.0. This is in consonance with the estimates for the relevant $K$-factor quoted in [45]. Thus the $\sigma_{LO}^{\rho}$ provides a conservative exclusion limit on the parameter space of interest. Note that in Equation 4.1 we have ignored the interference term contribution, which we estimate to be below 3% of the total cross section.

Additional bounds on $\rho$ from direct searches for KK-gluon, through $t\bar{t}$-production in multileptonic and hadronic channels by CMS [46] have been translated to the parameter space of the model. For this we simply translate the bound on the cross section without recasting the experimental search. However we have taken care of the mass dependent decay branching ratios of the gluon partner. In the rest of this section we systematically study the constraints on the benchmark model parameter space from various channels having leptonic final states.

4.1 Monolepton+Jets

In this section we summarize the constraints on the parameter space of our benchmark model from CMS l+jets study at 35.8 fb$^{-1}$ [33]. The simulated signal process for our model is shown in Figure 2a. The dominant background (SM) subprocesses which contribute to the same signal channel are $t\bar{t}$, $W$+jets and single top production. The cuts applied to mimic the search are listed below. To mimic the last cut mentioned in [33], we have minimized the difference between the invariant masses of (a) lepton and neutrino, and (b) the two $b$-jets decaying from the two $W$ bosons as can be seen in Figure 2a.

- In each fit combination exactly one charge lepton (electron or muon) and four jets (clustered using anti-$k_T$ algorithm with a radius parameter 0.4).
Figure 2. (a) Feynman diagram and (b) 95% C.L. exclusion contours from the mono-lepton channel on the \((m'_t, M_\rho)\) plane. In (b) solid blue line is the plot for NWA, dashed blue line represents the plot for fat-width correction, the red excluded region corresponds to the QCD production of the top partner, and the green region is the 95% C.L. exclusion region from KK-gluon search. The regions to the left of the contours are excluded.

- In each fit combination, two jets are taken to be the \(b\)-jets from the \(t'\) decays. We call \(b_l\) the \(b\)-jet accompanying the leptonic \(W\) boson decay, and \(b_h\) the \(b\)-jet accompanying the hadronic \(W\) boson decay. Combinations in which neither of these jets are \(b\)-tagged or only one has a CSVL tag are rejected.

- The four jets in the fitted combination, designated in the order: \(b_h\) jet, \(b_l\) jet, highest-\(p_T\) jet in the hadronic \(W\) boson decay, second-highest-\(p_T\) jet in the hadronic \(W\) boson decay, must satisfy the requirements \(p_T > 200, 100, 100, \) and 30 GeV, respectively.

- For each fitted jet combination a variable \(S_T\) is calculated, defined as the scalar sum of \(p_T^{\text{miss}}\) and the transverse momenta of the lepton and the four jets in that combination: \(S_T = p_T^{\text{miss}} + p_T^l + p_T^{J_1} + p_T^{J_2} + p_T^{J_3} + p_T^{J_4}\), where \(J_i\) (with \(i = 1\) to 4) refers to the four jets and \(S_T\) is evaluated using the measured momenta. To select hard-scattering processes resulting in the production of heavy objects, we require \(S_T > 1\) TeV.

- \(S_L^{fit}/S_T^{fit} < 1.5\), where \(S_L^{fit} = p_L^l + p_L^{J_1} + p_L^{J_2} + p_L^{J_3} + p_L^{J_4}\), and \(p_L\) is the longitudinal momentum of each of the corresponding objects. Both \(S_L^{fit}\) and \(S_T^{fit}\) are calculated using the fitted momenta. This requirement relies on the fact that the final-state objects from the signal process typically have both high-\(p_T\) and moderate-\(p_z\) values.
• The invariant mass of the two jets attributed to the $W$ boson hadronic decay must be in the range 60–100 GeV.

• One $W$ boson decaying from a top has been tuned to decay leptonically and the other has been tuned to decay hadronically. The invariant masses of the decaying lepton and neutrino and the two jets should be similar to a certain level of accuracy. This is done to mimic the last cut mentioned in [33].

To validate the recast code of this search written in MadAnalysis5 we have generated SM $t\bar{t}$ and single top events and matched the cross-section times efficiency times luminosity with those given in Table 2 of [33] within a predefined accuracy. The 95% C.L. exclusion contour from this analysis is shown in Figure 2b. As can be seen from the plot, the constraints on $m_{t'}$ become more severe than the QCD limit (shaded red) for $M_\rho < 2.5$ TeV, some of which is excluded from the direct limit on $M_\rho$ from the KK-gluon search (shaded green). Significant improvement from the QCD limit which is allowed can be seen around $M_\rho = 2.2$ TeV. The effect of fatness of $\rho_\mu$ is more prominent at lower values of $M_\rho$. Note that the direct bound on $M_\rho$ from the kk-gluon search saturates to $\sim 2.0$ TeV ($\sim 1.5$ TeV) for larger (smaller) values $m_{t'}$ in the region of interest.

4.2 Dilepton+Jets

In this section we summarize the constraints on the parameter space of our benchmark model from ATLAS 2l+jets study at 36.1 fb$^{-1}$ [34]. The simulated process from our model is depicted in Figure 3a. The dominant background (SM) subprocesses which contribute to the 2l+jets channel are $Z$+jets, $tt$ and single top production. The cuts applied to mimic the ATLAS search are listed below. To mimic the large R-jet cut we search for two small jets within a distance 1.0.

• In all events at least two leptons (electron or muon) of the same flavor with $p_T > 28$ GeV and with opposite-sign electric charge are required. Out of these the $Z$-boson candidate is identified as the pair having invariant mass closest to $Z$ boson mass. Events in which this invariant mass is greater than 400 GeV are removed.

• Events should have at least two small-R (clustered using anti-$k_T$ algorithm with a radius parameter 0.4) jets with $p_T$ greater than 25 GeV.

• Difference between the invariant mass of the $Z$-boson candidate pair and $Z$-boson mass should be less than 10 GeV ($|m_{ll} - m_Z| < 10$ GeV).

• Events should have at least 2 $b$-tagged jets.

• Events should have either 0 or 1 large-R (clustered using anti-$k_T$ algorithm with a radius parameter 1.0) jets. To mimic this we have checked that two jets are within a distance 1.0 with the same invariant mass and $p_T$ conditions as the large-R jets.
Figure 3. (a) Feynman diagram and (b) 95% C.L. exclusion contours from the di-lepton channel on the $(m_t', M_\rho)$ plane. In (b) solid blue line is the plot for NWA, dashed blue line represents the plot for fat-width correction, the red excluded region corresponds to the QCD production of the top partner, and the green region is the 95% C.L. exclusion region from KK-gluon search. The regions to the left of the contours are excluded.

- $p_T$ of the Z-boson candidate pair should be greater than 250 GeV.

- $H_T$, which is the scalar sum of transverse momenta of all small-R jets should be greater than 800 GeV.

To validate the recast code of this search written in MadAnalysis5 we have generated SM $Z$+jets and $t\bar{t}$ events and matched the cross-section times efficiency times luminosity with those given in Table 9 (1 large-R jet SR column) of [34] within a predefined accuracy. The 95% C.L. exclusion contour from this analysis is shown in Figure 3b. As can be seen from the plot, the constraints on $m_{t'}$ become more severe than the QCD limit (shaded red) for $M_\rho < 2.7$ TeV, some of which is excluded from the direct limit on $M_\rho$ from the KK-gluon search (shaded green). Significant improvement from the QCD limit which is allowed can be seen around $M_\rho = 2.1$ TeV.

4.3 Trilepton+Jets

In this section we summarize the constraints on the parameter space of our benchmark model from ATLAS 3l+jets study at 36.1 fb$^{-1}$ [34]. The simulated process from our model is depicted in Figure 4a. The dominant background (SM) subprocesses in this case are diboson production, $Z$+jets and $t\bar{t}$. The cuts applied to mimic the ATLAS search are listed below.
In all events at least three charged leptons (electron or muon) with $p_T > 28$ GeV are required. Out of these a same-flavored oppositely charged pair is identified as the $Z$-boson candidate having invariant mass closest to $Z$ boson mass. Events in which this invariant mass is greater than 400 GeV are removed.

- Events should have at least two small-R (clustered using anti-$k_T$ algorithm with a radius parameter 0.4) jets with $p_T$ greater than 25 GeV.

- Difference between the invariant mass of the $Z$-boson candidate pair and $Z$-boson mass should be less than 10 GeV ($|m_{ll} - m_Z| < 10$ GeV).

- Events should have at least 1 $b$-tagged jet.

- $p_T$ of the $Z$-boson candidate pair should be greater than 200 GeV.

To validate the recast code of this search written in MadAnalysis5 we have generated SM diboson and $Z$+jets events and matched the cross-section times efficiency times luminosity with those given in Table 13 (SR column) of [34] within a predefined accuracy. The 95% C.L. exclusion contour from this analysis is shown in Figure 4b. As can be seen from the plot, the constraints on $m_{t'}$ become more severe than the QCD limit (shaded red) for $M_\rho < 3.5$ TeV up to $M_\rho \sim 2.0$ TeV, some of which excluded from the direct limit on $M_\rho$ from the KK-gluon search (shaded green).
Figure 5. Summarized 95% C.L. exclusion region from all three (mono-, di-, tri-)lepton searches from the KK-gluon search. Also plotted are the 300 fb$^{-1}$ projections from monolepton (blue), dilepton (black) and trilepton (grey).

4.4 Future projection

LHC in it’s Run III is expected to reach an integrated luminosity of 300 fb$^{-1}$ by the year 2023 before the third Long Shutdown. We present the reach of these searches with the projected luminosity for 300 fb$^{-1}$. A simplistic approach has been followed by scaling up the luminosity keeping the cross-section and efficiency unchanged. This is a very optimistic prediction as with increasing luminosity, the increased pile up is expected to drop the efficiency which we don’t take into account. A combination plot which shows the disallowed region from all the present searches described before and the 300 fb$^{-1}$ projections are presented in Figure 5. The projections indicate significant enhancement of the bounds on the $M_\rho - m_{t'}$ parameter space.

5 Conclusion

In this paper we have revisited the constraints on the charge 2/3, top-like, top partner ($t'$) from the direct searches at LHC run 2 in the relatively clean lepton(s) + jet final state. We study the impact on top partner searches from a massive colored vector boson resonance ($\rho_\mu$), the so called gluon partner, which is generic along with the top partners in a wide class of models where electroweak symmetry breaking is driven by strong dynamics. We demonstrate how these constraints are modified if the $\rho_\mu$ is a broad resonance. We recast the monolepton+jets (CMS), dilepton+jets and trilepton+jets (ATLAS) searches to put constraints on the parameter space of the model. The approach adopted in this paper is to rescale the pair production cross section of $t'$ using the full 1PI corrected propagator for the $\rho_\mu$ expression beyond the narrow-width approximation. We have assumed that the fatness minimally affects
the kinematic shapes and hence the signal efficiencies, which we numerically verify in certain relevant patches of the studied parameter space. As can be seen from the resulting plots, the presence of $\rho_\mu$ increases the bound on the mass of $t'$ ($m_{t'}$) by around 15% for $\rho_\mu$ mass ($M_\rho$) around 2.5 TeV. For values of $M_\rho$ greater than 3 TeV, the contribution from the $\rho_\mu$ mediated process decouples and the constraints essentially reduce to the limits obtained assuming pure QCD production of the top partners. The effect of the fat width correction for $\rho_\mu$ is found to be sizeable (around 12% of the narrow-width approximation). A more accurate analysis taking into account the effect of the fatness of both $\rho_\mu$ and $t'$ on the kinematic distributions as well as the cross sections is in order and will be carried out elsewhere.

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A Composite Higgs Effective Framework

While the Lagrangian for the top partner and gluon partner given in Equation 2.1 is phenomenological it can be embedded into the motivated composite Higgs framework. In this appendix we briefly sketch out the minimal framework that forms the basis of the simplified Lagrangian explored in this article. The gauge hierarchy problem can be readily addressed by considering that the Higgs has a nontrivial extension in space. Such a composite object is naturally associated with a scale $f$ related to the size of the Higgs. However such extension results in serious modification of the Higgs coupling over the SM predictions. Essentially a composite Higgs with $f \sim v$ is ruled out by oblique electroweak parameters. This can however be circumvented if one assumes the Higgs as a pNGB of a strong sector. In the minimal realization such framework contains two distinct sectors with the usual elemental SM sector sans the Higgs on one hand and a strongly coupled sector where the dynamics results in spontaneous symmetry breaking of a continuous global symmetry that results in Nambu-Goldstone modes that can be identified with the Higgs doublet of the SM on the other.

A linear mixing between the operators of the strong sector and the SM states generates the Yukawa couplings for the Higgs states. This partial compositeness framework can be written as,

$$\mathcal{L}_{\text{mix}} = \overline{\Psi}_L^i \mathcal{O}_R^i + \overline{\Psi}_R^i \mathcal{O}_L^i + \text{h.c.} \quad (A.1)$$

where $\Psi_{L/R}^i$ are the standard model fermions, $i$ is the flavor index and the $\mathcal{O}_{R/L}^i$ are operators of the strong sector that are in the $(3, 1, 2/3)$ representation of the SM gauge group. The operators are saturated by resonances of the strong sector, for example $\mathcal{O}_L^3 \supset U_L + \ldots$. The Lagrangian in Equation 2.1 is obtained by assuming that the right handed top mixes
| $M_\rho$ (TeV) | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
|----------------|-----|-----|-----|-----|-----|
| $\Gamma_\rho$ (TeV) | 0.497 | 0.757 | 1.016 | 1.273 | 1.53 |

Table 1. Width of $\rho_\mu$ ($\Gamma_\rho$) for various $M_\rho$.

Table 2. Comparison of cross-section times efficiency times luminosity by (i) full simulation by modifying the propagator in MadGraph, (ii) just modifying the cross-section for a fat resonance and (iii) usual Breit-Wigner (BW) Approximation or Complex Mass Scheme (CMS). Here $m_\nu = 1$ TeV.

considerably with the strong sector resonances. Such a minimal realisation of the partial compositeness framework naturally necessitates the existence of vector operators of the strong sector in the adjoint representation of the color $SU(3)$. We can define,

$$J_\mu \equiv \bar{O} \gamma_\mu O,$$

where $O$ represent the fermionic operators defined in Equation A.1. And one can write down a linear mixing of the form

$$\Delta L_{\text{mix}} = J_\mu G^\mu$$

where $G^\mu$ are the SM gluons. However the large anomalous dimension of strong sector operator $\Delta L_{\text{mix}}$ makes them hopelessly irrelevant. We will assume that the main coupling of the gluon partner to the SM sector is through its couplings with the the top partners. The interactions in Equation 2.1 are given by assuming $J_\mu \supset \rho_\mu$.

B Fat Width Correction

In the region of interest in this paper the total decay width of $\rho_\mu$ is pretty high and often comparable to it’s mass as can be seen for some values of $M_\rho$ in Table 1. These values of the decay width $\Gamma_\rho$ were obtained by setting $g_* = 1.0$.

The narrow width approximation is no longer accurate enough to capture the essential feature of the process with arbitrarily virtual $\rho_\mu$. The usual gauge invariant approach to handle
broad resonances is the Complex Mass Scheme [47], however for massive vector resonances there is no gauge invariance issue with large decay width and basically maps into the usual narrow width results with the appropriate enlarged value of the decay width in the usual Breit-Wigner (BW) propagator. However careful analysis should include the impact of the large width by utilizing the full 1PI propagator in computations of the cross section as given in Equations 3.3,3.4. In order to reduce the computation and avoid expensive simulation utilizing the the full propagator we capture the main impact by normalising the cross-section with the full propagator as indicated in Equation 4.1 with the assumption that the shape of the distribution remains unchanged due to this correction.

We compare the cross-section times efficiency times luminosity obtained by (i) just modifying the cross-section and (ii) modifying the propagator in MadGraph which in turn modifies the shape and (iii) the usual BW. The comparison has been summarized in Table 2. The full simulation exclusion plot closely mimics the plot made by modifying the cross-section while keeping the efficiencies unchanged as can be seen in Figure 6. Considering the computationally expensive simulations including the full corrected propagator we have adopted the cross-section modification approach as explained in Section 3 to put constraints in this paper.

![Figure 6](image)

**Figure 6.** A comparison in the exclusion line between BW (black), cross-section modification (red,dashed) and full simulation (blue,dashed).

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