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Higher Representations and Multi-Jet Resonances at the LHC

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Abstract

The CMS collaboration has recently conducted a search for trijet resonances in multi-jet events at the LHC. Motivated in part by this analysis, we examine the phenomenology of exotic particles transforming under higher representations of $SU(3)$ color, focusing on those representations which intrinsically prohibit decays to fewer than three jets. We determine the LHC discovery reach for a particle transforming in a representation of this sort and discuss several additional theoretical and phenomenological constraints which apply to such a particle. Furthermore, we demonstrate that such a particle can provide a consistent explanation for a trijet excess (an invariant-mass peak of roughly 375 GeV) observed in the recent CMS study.

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I. INTRODUCTION

The advent of data from the Large Hadron Collider (LHC) has already begun to provide a meaningful probe into a wide variety of long-standing scenarios for new physics. Even with only $\mathcal{L}_{\text{int}} \approx 1 \text{ fb}^{-1}$ of data currently under analysis, the ATLAS and CMS experiments have been able to place stringent constraints on many extensions of the Standard Model (SM). At such integrated luminosities, the processes to which these experiments are sensitive are most notably those in which new particles are produced either via strong interactions, or else through an s -channel resonance. Indeed, from limits on processes of this sort, LHC data have already placed stringent constraints on the parameter space of many of the most widely studied extensions of the SM, including many models involving weak-scale supersymmetry, extra dimensions, and additional exotic states such as Z' gauge bosons.

In addition to these popular scenarios, it is worthwhile to look for signals of less traditional extensions of the SM which, for one reason or another, could have been missed by the standard battery of new-physics searches at the LHC. For example, scenarios exist in which a strongly-interacting particle is produced copiously in hadron collisions, but decays in unexpected ways and is consequently overlooked. One example of such a particle is a light gluino in a supersymmetric theory with R-parity violation. Such a particle has a relatively large pair-production cross-section at the LHC; however, since each gluino so produced decays predominately to three jets, evidence for an R-parity-violating gluino would appear only in events with six or more jets in the final state. Typical searches do not consider such high jet multiplicities, and based upon the results of those searches alone, it is almost inevitable that any particle with a decay pattern of this sort would be overlooked. However, searches for multi-jet resonances in high-jet-multiplicity events could potentially reveal evidence of such a particle. Motivated by this consideration, the CMS experiment recently performed a study of the three-jet invariant mass distribution in events with at least six jets [1] with 35.1 pb^{-1} of LHC data. The results of this study (about which we will say more later) now provide the leading constraints on the gluino mass in models with R-parity violation. A similar analysis was also recently performed by the CDF collaboration [2] with 3.2 fb^{-1} of Tevatron data.

Information about supersymmetry is not the only aspect of physics beyond the standard model into which searches for resonances in multi-jet processes could provide an important

window. For example, one of the most fundamental questions in particle physics is whether the SM gauge interactions unify at some high scale, and if so, precisely how this unification takes place and at what scale that might be. Experimental signals which could provide information on unification are therefore immensely valuable from a theoretical perspective. An example of such a signal would be the discovery of an exotic matter field charged under the SM $SU(3)_c$ gauge group. Indeed, a particle of this sort would significantly alter the renormalization-group running of the strong coupling coefficient α_s , particularly if the $SU(3)_c$ representation under which those matter fields transformed was one of particularly large dimension. Thus, the presence of such a field would compel a revision of our projection for the scale of grand unification — potentially dramatically, if the dimension of the representation in which the field or fields transformed were large enough to spoil the asymptotic freedom of $SU(3)_c$. Furthermore, as discussed above, strongly-interacting particles of this sort are precisely the sort of new physics to which LHC data will be sensitive during the first few fb^{-1} of running.

The prospects for observing exotic particles transforming in certain higher representations of $SU(3)_c$ at hadron colliders in final states comprising either four or six jets have been discussed in the literature before [3, 4]. Moreover, a number of searches for new strongly-interacting particles, including gluinos [5–9], diquarks [10–12], fourth-generation quarks [13–15], and miscellaneous color-octet, sextet, and triplet fields [10–12] have been performed both at the Tevatron and at the LHC. To date, no compelling evidence of such particles has been found. However, such searches are generally only sensitive to the presence of particles which can decay either to a pair of strongly-interacting SM fields (quarks or gluons), or else to a final state including some lighter neutral field which appears as missing energy. By contrast, a strongly-interacting particle which is forbidden by symmetry from coupling to any pair of SM fields in a theory in which no lighter, neutral field exists will be unconstrained by bounds from these typical searches. Indeed, this is precisely the case for the R-parity-violating gluino scenario discussed above.

However, a gluino of this sort is by no means the only example of a particle which might have been overlooked in traditional searches for new strongly-interacting fields. For example, as we shall demonstrate, there exist particular representations of $SU(3)_c$ for which an exotic field X , if it transforms under one of these representations, is forbidden by gauge invariance from coupling to any pair of SM fields, but *can* couple to at least one combination of three

SM quarks or gluons. The primary decay channel for such a field would likewise therefore be to three jets, while a two-jet final state would be forbidden.

We have already mentioned some of the theoretical motivations for examining the detection prospects for fields which transform under higher representations of $SU(3)_c$. In addition, there is now also a motivation for such an analysis from LHC data. The aforementioned CMS study [1] did observe an excess in the trijet-invariant-mass distribution at $M_{jjj} \sim 375$ GeV which differs from the SM prediction by more than 2σ (though the significance is reduced to 1.9σ once the look-elsewhere effect is included). The authors compared this observed excess to that which would result from the R-parity-violating decays of a gluino with a mass $M_{\tilde{g}} = 375$ GeV, which turns out to be too small by a factor of roughly three. In other words, for some other field to provide a more compelling explanation of the observed excess, the product of pair-production cross-section for that field would need to be approximately thrice the ~ 15 pb expected for a gluino with $M_{\tilde{g}} = 375$ GeV, assuming the branching fraction for that field into three jets is roughly unity. Indeed, as we shall demonstrate, a particle X transforming in a higher representation of $SU(3)_c$ is capable of yielding an excess of the observed magnitude.

We begin our analysis of the collider phenomenology of an exotic field transforming under a higher representation of $SU(3)_c$ in Sect. II by examining the decay properties of such a field from a representation-theory perspective. In particular, we determine the representations for which the transformation properties of such a field under $SU(3)_c$ and spacetime symmetries alone forbid all direct decays to states involving only two SM quarks or gluons, but permit at least one decay channel involving three such particles. In Sect. III, we investigate the collider phenomenology of exotic fields in such representations, in which (again, due to considerations related to representation theory) pair production via strong interactions plays the dominant role. In Sect. IV, we discuss the implications of the recent CMS multi-jet resonance search for fields in higher representations of $SU(3)_c$ and compare our results for the signals expected from such fields to the excess reported in Ref. [1]. In Sect. V, we conclude.

II. REPRESENTATION THEORY AND DECAYS TO THREE JETS

Our primary aim in this paper is to examine the multi-jet phenomenology of an exotic field X transforming under a higher representation of $SU(3)_c$. However, in order to do

this, we must first establish for which representations such a field is forbidden from coupling directly to any pair of SM particles by $SU(3)_c$ gauge invariance and Lorentz invariance alone, but for which at least one gauge-invariant coupling to three strongly-interacting SM fields exists. In other words, we wish to enumerate the $SU(3)_c$ representations which permit at least one gauge-invariant operator $\mathcal{O}_i^{(3)}$ of the form

$$\mathcal{O}_i^{(3)} = \frac{C_i^{(3)}}{\Lambda^{n_i}} X \tilde{\mathcal{O}}_i^{(3)}(g, q, \bar{q}) , \quad (1)$$

where $\tilde{\mathcal{O}}_i^{(3)}(g, q, \bar{q})$ is an operator consisting of exactly three SM fields charged under $SU(3)_c$ (*i.e.*, quarks, antiquarks, or gluons), $C_i^{(3)}$ is a dimensionless operator coefficient, Λ is the suppression scale for the operator, and the value of the integer n_i depends on whether X is a scalar or a fermion and on the particular collection of SM fields out of which $\tilde{\mathcal{O}}_i^{(3)}(g, q, \bar{q})$ is constructed. At the same time, we require that there not exist any gauge-invariant operator of the form

$$\mathcal{O}_j^{(2)} = \frac{C_j^{(2)}}{\Lambda^{n_j}} X \tilde{\mathcal{O}}_j^{(2)}(g, q, \bar{q}) , \quad (2)$$

where $\tilde{\mathcal{O}}_j^{(2)}(g, q, \bar{q})$ is an operator consisting of exactly two SM fields charged under $SU(3)_c$, and $C_j^{(2)}$ is, once again, a dimensionless coefficient.

In Table I, we list the $SU(3)_c$ representations which appear at least once in the decomposition of each possible direct product of two or three factors, assuming each factor is a **3**, $\bar{\mathbf{3}}$, or **8** representation of $SU(3)_c$. In addition, we display the Lorentz representations which can be built from each of the corresponding three-particle states, up to spin 1. We see from this table that a number of representations exist which do not appear in the decomposition of any two-particle state, but exist in the decomposition of at least one three-particle state. These include the complex representations **15'**, **24**, **35**, and **42** (and their conjugate representations), as well as the real representation **64**.¹ Moreover, we see that if X transforms in the **10** of $SU(3)_c$, it can decay to two SM fields only if it is a boson. A fermionic **10** must therefore decay to at least three strongly-interacting SM fields and, by similar reasoning, so must a bosonic **15**.

In Table II, we list all the combinations of $SU(3)_c$ and Lorentz representations for a field X which prohibit its decays to all final states comprising only two quarks or gluons, but

¹ Note that two distinct fifteen-dimensional representations of $SU(3)_c$ exist, which we refer to here as **15** and **15'**. The latter of these designates the completely symmetric combination of four **3** representations.

Final state	Product	Representations	
		$SU(3)_c$	Lorentz
$q\bar{q}$	$\mathbf{3} \otimes \bar{\mathbf{3}}$	$\mathbf{1}, \mathbf{8}$	S,V
qq	$\mathbf{3} \otimes \mathbf{3}$	$\bar{\mathbf{3}}, \mathbf{6}$	S,V
$\bar{q}\bar{q}$	$\bar{\mathbf{3}} \otimes \bar{\mathbf{3}}$	$\mathbf{3}, \bar{\mathbf{6}}$	S,V
qg	$\mathbf{3} \otimes \mathbf{8}$	$\mathbf{3}, \bar{\mathbf{6}}, \mathbf{15}$	F
$\bar{q}g$	$\bar{\mathbf{3}} \otimes \mathbf{8}$	$\bar{\mathbf{3}}, \mathbf{6}, \bar{\mathbf{15}}$	F
gg	$\mathbf{8} \otimes \mathbf{8}$	$\mathbf{1}, \mathbf{8}, \mathbf{10}, \bar{\mathbf{10}}, \mathbf{27}$	S,V
qqq	$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3}$	$\mathbf{1}, \mathbf{8}, \mathbf{10}$	F
$qq\bar{q}$	$\mathbf{3} \otimes \mathbf{3} \otimes \bar{\mathbf{3}}$	$\mathbf{3}, \bar{\mathbf{6}}, \mathbf{15}$	F
$q\bar{q}\bar{q}$	$\mathbf{3} \otimes \bar{\mathbf{3}} \otimes \bar{\mathbf{3}}$	$\bar{\mathbf{3}}, \mathbf{6}, \bar{\mathbf{15}}$	F
$\bar{q}\bar{q}\bar{q}$	$\bar{\mathbf{3}} \otimes \bar{\mathbf{3}} \otimes \bar{\mathbf{3}}$	$\mathbf{1}, \mathbf{8}, \bar{\mathbf{10}}$	F
gqq	$\mathbf{8} \otimes \mathbf{3} \otimes \mathbf{3}$	$\bar{\mathbf{3}}, \mathbf{6}, \bar{\mathbf{15}}, \mathbf{24}$	S,V
$gq\bar{q}$	$\mathbf{8} \otimes \mathbf{3} \otimes \bar{\mathbf{3}}$	$\mathbf{1}, \mathbf{8}, \mathbf{10}, \bar{\mathbf{10}}, \mathbf{27}$	S,V
$g\bar{q}\bar{q}$	$\mathbf{8} \otimes \bar{\mathbf{3}} \otimes \bar{\mathbf{3}}$	$\mathbf{3}, \bar{\mathbf{6}}, \mathbf{15}, \bar{\mathbf{24}}$	S,V
ggq	$\mathbf{8} \otimes \mathbf{8} \otimes \mathbf{3}$	$\mathbf{3}, \bar{\mathbf{6}}, \mathbf{15}, \mathbf{15}', \bar{\mathbf{24}}, \mathbf{42}$	F
$gg\bar{q}$	$\mathbf{8} \otimes \mathbf{8} \otimes \bar{\mathbf{3}}$	$\bar{\mathbf{3}}, \mathbf{6}, \bar{\mathbf{15}}, \bar{\mathbf{15}}', \mathbf{24}, \bar{\mathbf{42}}$	F
ggg	$\mathbf{8} \otimes \mathbf{8} \otimes \mathbf{8}$	$\mathbf{1}, \mathbf{8}, \mathbf{10}, \bar{\mathbf{10}}, \mathbf{27}, \mathbf{35}, \bar{\mathbf{35}}, \mathbf{64}$	S,V

TABLE I: A list of all representations contained in the decomposition of all combinations of two or three of the particles q , \bar{q} , and g . Repeated occurrences of any single representation in the decomposition of each such product have been suppressed.

permit decays to at least one final state comprising three such particles. Note that we do not impose any additional restriction on the coupling structure of X based on its $U(1)_{\text{EM}}$ charge Q_X ; rather, we require that all operators of the form given in Eq. (2) be excluded on the basis of $SU(3)_c$ and Lorentz structure alone, and then assign X whatever electromagnetic charge is required by gauge invariance. We find that the smallest-dimension $SU(3)_c$ representation for X for which this condition is satisfied (aside from of course a fermionic octet, for which the gluino is the prototypical example) is the $\mathbf{10}$, for which X must be fermionic (or otherwise it could decay to a pair of gluons). We also find that no representations with dimension

greater than 64 can decay to three SM fields alone.

Representation $SU(3)_c$ Lorentz		Q_X	$C_2(r)$	$C(r)$
10, $\overline{10}$	F	$+2, +1, 0, -1$	6	15/2
15, $\overline{15}$	S,V	$+\frac{2}{3}, -\frac{1}{3}, -\frac{4}{3}$	16/3	10
15', $\overline{15}'$	F	$+\frac{2}{3}, -\frac{1}{3}$	28/3	35/2
24, $\overline{24}$	S,F,V	$+\frac{4}{3}, +\frac{1}{3}, -\frac{2}{3}$	25/3	25
35, $\overline{35}$	S,V	0	12	105/2
42, $\overline{42}$	F	$+\frac{2}{3}, -\frac{1}{3}$	34/3	119/2
64	S,V	0	15	120

TABLE II: A list of combined $SU(3)_c$ and Lorentz representations for a hypothetical particle X for which the effective couplings between X and all two-particle combinations of g , q , or \overline{q} are forbidden by symmetries, while an effective coupling between at least one three-particle combination of these same fields is allowed. The invariants $C_2(r)$ (*i.e.*, the quadratic Casimir) and $C(r)$ for these representations are also given. In addition, a list of $U(1)_{\text{EM}}$ charges Q_X for which at least one gauge-invariant $\mathcal{O}_i^{(3)}$ can be constructed is provided for each choice of $SU(3)_c$ and Lorentz representations shown. It should be noted that for the **24**, the specific assignment $Q_X = +\frac{4}{3}$ is consistent for a scalar or vector, but not for a fermion.

One constraint on the presence of additional fields charged under $SU(3)_c$ comes from the requirement that $\alpha_s \equiv g_s^2/(4\pi)$ must be well-behaved up to around the TeV scale. In the presence of an exotic field X charged under an arbitrary representation of $SU(3)_c$, $\alpha_s(\mu)$ is modified at scales $\mu > m_X$ to

$$\alpha_s(\mu) = \frac{\alpha_s(M_Z)}{1 + \frac{\alpha_s(M_Z)}{12\pi} \left[23 \ln \left(\frac{\mu^2}{M_Z^2} \right) - 2 \ln \left(\frac{\mu^2}{m_t^2} \right) - \frac{f_X}{8} C(r) d(r) \ln \left(\frac{\mu^2}{m_X^2} \right) \right]}, \quad (3)$$

where $\alpha_s(M_Z) \approx 0.118$ is the value of $\alpha_s(\mu)$ at $\mu = M_Z \approx 91.19$ GeV and $f_X = 1$ ($f_X = 4$) when X is a scalar field (Dirac fermion). The effect of including an additional field X which transforms under each of the representations of $SU(3)_c$ listed in Table II is shown in Fig. 1. The curves shown in the left panel correspond to the cases in which X is a scalar, while the

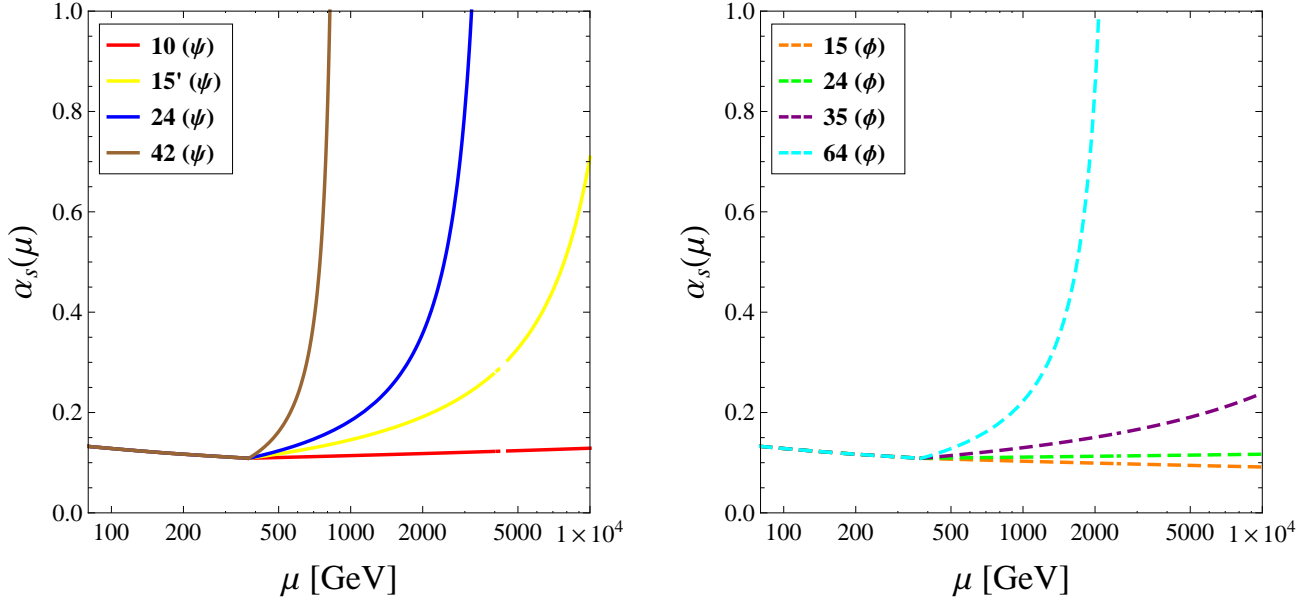


FIG. 1: Curves indicating the renormalization-group evolution of α_s in the presence of a single exotic field X in each of the representations of $SU(3)_c$ enumerated in Table II. The results in the left panel correspond to the cases in which X is a Dirac fermion, while the results in the right panel correspond to the cases in which X is a scalar. In each case, we have taken $m_X = 375$ GeV.

curves in the right panel correspond to the cases in which X is a Dirac fermion. For each case, we have assumed that only a single additional generation of X is present, and we have taken $m_X = 375$ GeV.

It is evident from Fig. 1 that the presence of even a single field X transforming in many of the representations listed in Table II will result in $\alpha_s(\mu)$ developing a Landau pole at a scale $\mu \sim \mathcal{O}(\text{TeV})$. Imposing for theoretical consistency the requirement that such a divergence not appear at scales below $\mu \sim 5$ TeV, we find that both a fermionic **24** and **42**, as well as a scalar **64**, are excluded. However, this constraint does not exclude a fermionic **10** or **15'**, nor does it exclude a scalar **15**, **24**, or **35**. For the rest of the paper we will therefore focus exclusively on these latter representations of low dimension. We note that for a single scalar **15**, the theory remains asymptotically free, but for the other representations, a Landau pole develops for $\alpha_s(\mu)$ at some scale $\mu > 10$ TeV; we assume that a suitable short distance theory regulates this divergence.

Two additional comments are in order concerning the case in which X is a fermion. First, the permissible $SU(3)_c$ representations for a fermionic X , namely **10** and **15'**, are

both complex; this implies that a fermion transforming in any of these representations must be a Dirac rather than a Majorana particle. Second, whenever X has chiral charges, anomaly-cancellation requirements place additional constraints on the theory. Given the unorthodox representation of $SU(3)_c$ in which X is assumed to transform, these constraints are generally quite difficult to satisfy simultaneously in any phenomenologically reasonable model. We will henceforth assume that X is vector-like and thus does not contribute to gauge anomalies.

III. COLLIDER PHENOMENOLOGY

Having now established the representations of $SU(3)_c$ for which an exotic field can decay to no fewer than three jets, we proceed to investigate the collider phenomenology of a field X transforming in one of these representations. We focus here on the case in which X is either a scalar or a Dirac fermion. Since, by construction, no gauge-invariant operators of the form specified in Eq. (2) exist for X , no couplings of the form ggX , qqX , or $\bar{q}qX$ exist either. It therefore follows that X cannot be produced singly as an s -channel resonance. It may be produced in association with some other SM particle or particles through an operator of the form given in Eq. (1), but the corresponding amplitude would be suppressed by powers of Λ . As a result, the pair production of X and \bar{X} (via the coupling $g\bar{X}X$ to the gluon field required by gauge invariance) is the dominant production channel at hadron colliders.

Once produced, we assume that X decays exclusively via operators of the form $\mathcal{O}_i^{(3)}$ to a trijet final state, with $\text{BR}(X \rightarrow jjj) \approx 1$. Indeed, by construction, all two-body decay channels for X are forbidden. Moreover, restrictions on the permissible Q_X assignments for X detailed in Table II imply that all additional three-body decays involving charged leptons are forbidden by charge conservation for all viable $SU(3)_c$ and Lorentz representations of X , save for potentially the fermionic **10**. Even for this representation, such decays may be forbidden either by choosing $Q_X = +2$ or by requiring lepton-number conservation and assigning X a lepton number $L_X = 0$. Consequently, we expect the primary collider signature of X to be analogous to that of an R-parity-violating gluino: a final state consisting of at least six high- p_T jets, from which two combinations of three jets reconstruct to an invariant mass peak at $M_{jjj} \approx m_X$. Moreover, since we are assuming that $\text{BR}(X \rightarrow jjj) \approx 1$, the collider phenomenology of X will be essentially independent of the operator coefficients $C_i^{(3)}$

and the suppression scale Λ appearing in Eq. (1), as long as these quantities are such that X decays promptly.

We begin our analysis of the process $pp \rightarrow \overline{X}X \rightarrow N_j$ jets, where $N_j \geq 6$, at the LHC by deriving expressions for the production cross-section of a scalar or fermionic field X in an arbitrary representation r of $SU(3)_c$ with dimension $d(r)$. For the case in which X is a scalar, the leading-order (LO) partonic cross-sections for the pair production of X from the $q\overline{q}$ and gg initial states are

$$\begin{aligned}\hat{\sigma}_{q\overline{q} \rightarrow \overline{X}X}(\hat{s}) &= \frac{\pi\alpha_s^2}{54\hat{s}} C_2(r) d(r) R^3 \\ \hat{\sigma}_{gg \rightarrow \overline{X}X}(\hat{s}) &= \frac{\pi\alpha_s}{64\hat{s}} C_2(r) d(r) \left(\left[2 \left(1 + \frac{4m_X^2}{\hat{s}} \right) C_2(r) - 1 + \frac{10m_X^2}{\hat{s}} \right] R \right. \\ &\quad \left. - 8 \frac{m_X^2}{\hat{s}} \left[\frac{3m_X^2}{\hat{s}} + \left(1 - \frac{2m_X^2}{\hat{s}} \right) C_2(r) \right] \ln \left(\frac{1+R}{1-R} \right) \right),\end{aligned}\quad (4)$$

where $C_2(r)$ is the quadratic Casimir associated with r , m_X is the mass of X , \hat{s} is the partonic center-of-mass energy, and $R \equiv \sqrt{1 - 4m_X^2/\hat{s}}$. By contrast, for the case in which X is a Dirac fermion, the corresponding partonic cross-sections are found to be

$$\begin{aligned}\hat{\sigma}_{q\overline{q} \rightarrow \overline{X}X}(\hat{s}) &= \frac{2\pi\alpha_s^2}{27\hat{s}} C_2(r) d(r) \left(1 + \frac{2m_X^2}{\hat{s}} \right) R \\ \hat{\sigma}_{gg \rightarrow \overline{X}X}(\hat{s}) &= \frac{\pi\alpha_s^2}{16\hat{s}} C_2(r) d(r) \left(\left[\left(1 + \frac{4m_X^2}{\hat{s}} - \frac{8m_X^4}{\hat{s}^2} \right) C_2(r) + \frac{12m_X^4}{\hat{s}^2} \right] \ln \left(\frac{1+R}{1-R} \right) \right. \\ &\quad \left. - \left[\left(1 + \frac{4m_X^2}{\hat{s}} \right) C_2(r) + 1 + \frac{5m_X^2}{\hat{s}} \right] R \right).\end{aligned}\quad (5)$$

Note that since the gluino is a Majorana fermion, the partonic cross-sections for gluino production [17, 18] are smaller than those obtained from Eq. (5) for an **8** by a factor of two. The total LO production cross-section for the pair-production of X and \overline{X} at the LHC can be written in the form

$$\sigma_{pp \rightarrow \overline{X}X}(s) = \sigma_{q\overline{q} \rightarrow \overline{X}X}(s) + \sigma_{gg \rightarrow \overline{X}X}(s), \quad (6)$$

where $\sigma_{q\overline{q} \rightarrow \overline{X}X}(s)$ and $\sigma_{gg \rightarrow \overline{X}X}(s)$ denote the results of convolving the partonic cross-sections in Eqs. (4) and (5) with the appropriate parton-distribution functions (PDFs) $f_{p/q}(x, Q^2)$,

$f_{p/\bar{q}}(x, Q^2)$, and $f_{p/g}(x, Q^2)$:

$$\begin{aligned}\sigma_{q\bar{q}\rightarrow\overline{X}X}(s) &\equiv 2 \sum_{q=u,d,s,c} \int_{\tau_0}^s \int_{\tau}^1 \frac{1}{\tau} f_{p/q}(x, \tau s) f_{p/\bar{q}}(\tau/x, \tau s) \hat{\sigma}_{q\bar{q}\rightarrow\overline{X}X}(\tau s) dx d\tau \\ \sigma_{gg\rightarrow\overline{X}X}(s) &\equiv \int_{\tau_0}^s \int_{\tau}^1 \frac{1}{\tau} f_{p/g}(x, \hat{s}) f_{p/g}(\tau/x, \hat{s}) \hat{\sigma}_{gg\rightarrow\overline{X}X}(\tau s) dx d\tau .\end{aligned}\quad (7)$$

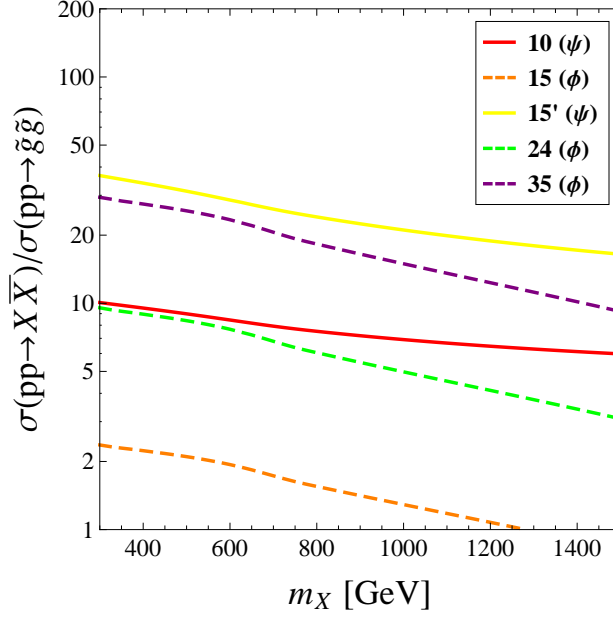


FIG. 2: Ratios of $\sigma(pp \rightarrow X\overline{X})$ to the gluino-pair-production cross section $\sigma(pp \rightarrow \widetilde{g}\widetilde{g})$ at leading-order and in the limit where all squark masses $m_{\widetilde{q}}$ are taken to infinity. The solid lines correspond to the cases in which X is a (Dirac) fermion; the dashed lines correspond to the cases in which X is a scalar.

In Fig. 2, we plot the ratio of $\sigma_{pp\rightarrow\overline{X}X}(s)$ to the total production cross-section for a gluino of the same mass at leading-order (in the limit in which all squark masses are taken to be infinitely heavy) as a function of m_X . The curves shown correspond to all otherwise phenomenologically consistent combinations of $SU(3)_c$ and Lorentz representations for X for which all $\mathcal{O}_i^{(2)}$ are forbidden, but for which at least one $\mathcal{O}_i^{(3)}$ is allowed. For the parton-distribution functions, we have used the CTEQ6L1 [19] PDF set, and we have taken $\sqrt{s} = 7$ TeV. The cross-section enhancement factors are much larger for fermions than for scalars, as one would expect, and each decreases slowly with increasing m_X . For $m_X \sim 375$ GeV, which corresponds to the value of M_{jjj} for which the greatest excess was observed by the CMS collaboration, the cross-section for the pair production of a scalar **15** is roughly twice

that for a gluino. For the fermionic **10** and scalar **24**, the corresponding enhancement factor is roughly ten, and for the fermionic **15'** and scalar **35**, it is far larger.

IV. COMPARISON TO CMS DATA

Having derived results for the pair-production cross-sections for an exotic field X in a higher representation of $SU(3)_c$, we now assess the implications of the recent CMS trijet resonance search [1] for such a particle. In this search, events with at least six jets were considered, and invariant masses M_{jjj} were reconstructed for all twenty possible combinations of three jets from among the six highest- p_T jets in each such event. A series of event-selection criteria were then imposed, including a cut on M_{jjj} designed to reduce the combinatoric background. The prediction for the SM background, to which the QCD background provides the dominant contribution, was obtained by fitting an exponential function of the form $\exp(P_0 + P_1 M_{jjj})$ to the M_{jjj} distribution obtained for $N_j = 4$ events in experimental data (where N_j denotes the number of jets in the event), and then subsequently rescaling the normalization coefficient P_0 on the basis of the average scalar p_T of the triplets observed in the $N_j \geq 6$ data. The prediction for the signal, which was assumed to be from a decaying gluino of mass $M_{\tilde{g}}$ in a supersymmetric model with R-parity violation, was obtained by simulating event samples for a broad range of $M_{\tilde{g}}$. For each value of $M_{\tilde{g}}$, an acceptance $k(M_{\tilde{g}})$, representing the effect of the event-selection criteria on the signal sample, was obtained. From the form of the acceptance function $k(M_{\tilde{g}})$, which was found to be approximately quadratic in $M_{\tilde{g}}$, limits on the gluino production cross-section in such theories — and therefore a limit on $M_{\tilde{g}}$ — was derived.

In order to estimate the corresponding exclusion limits on the mass of a particle X in a given representation of $SU(3)_c$, we make the assumption that the next-to-leading-order (NLO) K-factor for X pair production at the $\sqrt{s} = 7$ TeV LHC is essentially the same as the K-factor for gluino pair production for any given value of m_X within the range of interest. Under this assumption, we may obtain the NLO cross-section for the pair production of X by scaling the NLO cross-section for gluino production by the enhancement factor displayed in Fig. 2. By comparing these results to the observed 95% CL limits on the production cross-section for a heavy particle which decays primarily into three jets, we obtain our exclusion limits on m_X for each of the otherwise phenomenologically viable $SU(3)_c$ representations

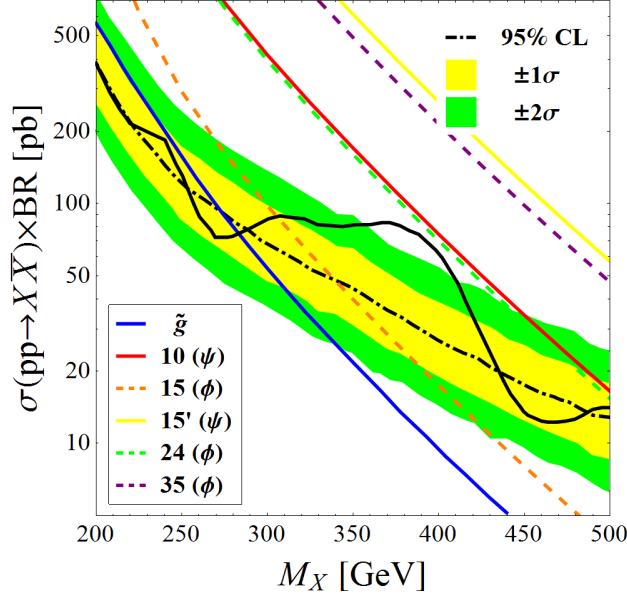


FIG. 3: NLO cross-sections for the pair production of an exotic field X transforming under the phenomenologically allowed representations of $SU(3)_c$ for which X decays exclusively to trijet final states, plotted as a function of m_X . Results are displayed for the cases in which X is a fermionic **10** (solid red curve), a scalar **15** (dashed orange curve), a fermionic **15'** (solid yellow curve), a scalar **24** (dashed green curve), and a scalar **35** (dashed purple curve). For reference, the corresponding NLO cross-section for gluino production in the limit of infinitely heavy squarks (solid blue curve) has also been included for reference. Also shown are the expected (dashed black curve) and observed (solid black curve) 95% CL limits on the production of a trijet resonance obtained in Ref. [1] for $\mathcal{L}_{\text{int}} = 35 \text{ pb}^{-1}$ at the $\sqrt{s} = 7 \text{ TeV}$ LHC, along with the $\pm 1\sigma$ and $\pm 2\sigma$ bands on the expected limit.

for X enumerated in Sect. II. Note that we are also assuming that the cut acceptance is independent of the Lorentz and $SU(3)_c$ representation.

In Fig. 3, we display the NLO production cross-sections for the production of a fermionic **10**, a scalar **15**, a fermionic **15'**, a scalar **24**, and a scalar **35** over the range of m_X pertinent to the CMS trijet analysis. Also shown are the expected and observed 95% confidence-level (CL) exclusion limits on the pair-production cross-section for a particle decaying essentially exclusively to three jets obtained in Ref. [1], along with the $\pm 1\sigma$ and $\pm 2\sigma$ bands on the expected limit. Any value of m_X for which the NLO cross-section exceeds the observed limit can be considered to be excluded at 95% CL. From this figure, it is apparent that a

scalar **15** is clearly excluded for $m_X \lesssim 310$ GeV. For the case in which X is a fermionic **15'** or a scalar **35**, the exclusion limit on m_X from CMS data extends slightly beyond the mass range for which the exclusion contour is displayed in Ref. [1]. One can estimate the exclusion limit on a fermionic **15'** or scalar **35** by examining where the extrapolated curve corresponding to the *expected* 95% CL limit and the NLO pair-production cross-section intersect. Based on this prescription, we find that the CMS data exclude a fermionic **15'** with a mass $m_X \lesssim 680$ GeV and a scalar **35** with a mass $m_X \lesssim 660$ GeV. Similarly, the data can be interpreted as excluding a fermionic **10** and scalar **24** with $m_X \lesssim 530$ GeV and $m_X \lesssim 520$ GeV, respectively. However, it is important to note that for $m_X \sim 375\text{--}400$ GeV, which corresponds to the range of M_{jjj} for which the CMS collaboration reported its greatest excess, the estimated production cross-section for a fermionic **10** or scalar **24** only marginally exceeds the observed 95% CL limit. Given the uncertainties in the NLO estimate for X production, *etc.*, a fermionic **10** or scalar **24** with a mass $m_X \sim 375\text{--}400$ GeV can therefore also be interpreted as being consistent with the data.

Even more intriguing, however, is the fact that the CMS collaboration *did* report a 1.9σ excess in the number of observed jet triplets in the invariant-mass range $350\text{ GeV} \lesssim M_{jjj} \lesssim 450\text{ GeV}$. Specifically, an excess of approximately 30 total jet triplets over an expected SM background of approximately 120 jet triplets was observed in this range. We find that the distribution of these excess events as a function of M_{jjj} can be reasonably well modeled by a Gaussian centered around $M_{jjj} \sim 380$ GeV, with a width of approximately 15 GeV. Given the results for the acceptance function $k(M_{\tilde{g}})$ obtained by the CMS collaboration, we find that this excess is roughly ~ 2.5 times larger than that which would be expected for a gluino with $M_{\tilde{g}} \approx 380$ GeV. In other words, the observed excess could be accounted for by a particle with similar production and decay phenomenology to that of a gluino in an R-parity-violating supersymmetry scenario, but with a production cross-section approximately 2.5 times larger than that for such a particle.

We observe that while it is therefore improbable (though perhaps still possible) that a gluino could account for the observed excess reported by CMS, an additional field X transforming in a higher representation of $SU(3)_c$ provides a more reasonable fit to the data. Indeed, it is apparent from the results shown in Fig. 2 that a new scalar field X with a mass $m_X \approx 380$ GeV which transforms in the **15** representation of $SU(3)_c$ would have just the right cross-section to account for the observed excess. However, we reiterate that

due to the uncertainties in the NLO K-factors, *etc.*, a Dirac fermion of comparable mass transforming in the **10** representation or a scalar transforming in the **24** representation could potentially also explain the observed excess.

V. CONCLUSIONS

In this paper, we have shown that the multi-jet-resonance study performed by the CMS collaboration, which was motivated primarily as a search for a light gluino in R-parity-violating supersymmetric models, can also be used to probe a variety of other scenarios for new physics. In particular, we have shown that there exist several representations of $SU(3)_c$ for which a heavy exotic field X transforming under one of these representations is likewise forced by gauge and Lorentz invariance alone to decay essentially exclusively to a trijet final state. We have examined the detection prospects for such a particle, and have used the results of the CMS study to derive exclusion limits on the representations of $SU(3)_c$ under which X could feasibly transform, given additional constraints from renormalization-group running, *etc.*

Furthermore, we have shown that the $\sim 2\sigma$ excess at a trijet invariant mass of $M_{jjj} \approx 375$ GeV reported in that study can be explained by the presence of an scalar transforming as a **15** or **24** of $SU(3)_c$, or by a Dirac fermion transforming as a **10**. (The scalar **15** provides the best fit to the data.) By contrast, the production cross-section for an R-parity-violating gluino is substantially smaller, and such a particle therefore offers a less compelling explanation for the observed excess. As further data is accumulated by the ATLAS and CMS experiments, it will be interesting to see whether that data corroborate this potential signal of new physics, and if so, whether they remain consistent with the interpretation we have suggested here. More generally, any future excess or peak observed in a multi-jet invariant-mass distribution (in events with or without the presence of substantial missing energy) is amenable to an analysis of the sort.

It should be noted that the assumptions we have made in Sect. IV concerning the K-factors for the production cross-sections for fields in higher representations of $SU(3)$ are certainly reasonable in the absence of explicit NLO calculations, and to date, such calculations have yet to be performed. We note, however, that the true NLO K-factors for these cross-sections may differ — perhaps significantly — from those adopted in this study. In-

deed, examples of situations in which the result of a full NLO calculation turned out to differ significantly from the projected result adopted for the purpose of preliminary analysis do exist in the literature [20]. Given this, the results displayed in this study can be taken as sufficient motivation for detailed NLO analyses of the pair-production cross-sections for fields in higher representations of $SU(3)$. Indeed, the results of such analyses may prove crucial for distinguishing between new-physics explanations for a given signal or data anomaly observed at the LHC.

If any multi-jet resonance is indeed confirmed at the LHC, the next step would be to identify complementary channels in which one could obtain evidence that such a resonance is indeed due to a particle transforming under one of the representations of $SU(3)_c$ which intrinsically forbid all decays to anything other than a trijet final state. Fortunately, in any grand unified (or even partially unified) theory, any field transforming under a higher representation of $SU(3)_c$ would necessarily have to be incorporated into some representation of the unified group. Therefore, if some such field is truly responsible for a given multi-jet resonance, each different unification scenario which could accommodate that field would generically provide a prediction for other new particles which could also potentially be discovered at the LHC. These predictions become particularly explicit for fields in representations which would dramatically alter the running of α_s to the extent that new physics would be required only slightly above the TeV scale to regulate divergences in the theory. Even in less extreme situations, however, any effect on the running of α_s could potentially alter the unification scale, and signals of particles transforming in higher representations of $SU(3)_c$ could thus provide valuable insight into the nature of our universe at high scales.

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