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750 GeV diphotons: implications for supersymmetric unification

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ABSTRACT: A recent signal of 750 GeV diphotons at the LHC can be explained within the framework of supersymmetric unification by the introduction of vector quarks and leptons with Yukawa couplings to a singlet S that describes the 750 GeV resonance. We study the most general set of theories that allow successful gauge coupling unification, and find that these Yukawa couplings are severely constrained by renormalization group behavior: they are independent of ultraviolet physics and flow to values at the TeV scale that we calculate precisely. As a consequence the vector quarks and leptons must be light; typically in the region of 375 GeV to 700 GeV, and in certain cases up to 1 TeV. The 750 GeV resonance may have a width less than the experimental resolution; alternatively, with the mass splitting between scalar and pseudoscalar components of S arising from one-loop diagrams involving vector fermions, we compute an apparent width of 10s of GeV.

KEYWORDS: Supersymmetry Phenomenology

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If the recently announced data on a 750 GeV resonance decaying to diphotons [1–4] is confirmed, what are the implications for the framework of supersymmetric unification? Neither the Minimal Supersymmetric Standard Model (MSSM) nor its extension to include a gauge singlet chiral multiplet can account for the resonance (see, however, [5, 6]). In this paper we show that a simple addition to the theory, that maintains supersymmetric gauge coupling unification at $M_G \sim 2 \times 10^{16}$ GeV, can account for the resonance and leads to new vector-like quarks, with masses below 1 TeV in the vast majority of parameter space, and couplings predicted from the infrared behavior of renormalization group equations. (For the first studies of the 750 GeV excess that appeared after the announcement, see refs. [7–16].)

We take the resonance to be the scalar component of a gauge singlet chiral multiplet S . Production and decay of S is accomplished by coupling to TeV-scale multiplets Φ_i and $\bar{\Phi}_i$, so that the effective theory below M_G is described by

$$W_{\text{eff}} = W_{\text{MSSM}} + S \sum_i \lambda_i \Phi_i \bar{\Phi}_i + \frac{\mu_S}{2} S^2 + \mu_i \Phi_i \bar{\Phi}_i. \quad (1)$$

To preserve precision supersymmetric gauge coupling unification, we study theories where Φ_i and $\bar{\Phi}_i$ form complete multiplets of $SU(5)$. We study the complete set of such theories: the “ $(\mathbf{5} + \bar{\mathbf{5}})_{N_5}$ ” theory containing $N_5 = 1, 2, 3$ or 4 copies of $(\bar{D}, \bar{L}) + (D, L)$, the “ $\mathbf{10} + \bar{\mathbf{10}}$ ” theory containing $(Q, U, E) + (\bar{Q}, \bar{U}, \bar{E})$, and the “ $\mathbf{15} + \bar{\mathbf{15}}$ ” theory that contains a full generation of vector quarks and leptons. In the $(\mathbf{5} + \bar{\mathbf{5}})_4$ and $\mathbf{15} + \bar{\mathbf{15}}$ theories, the standard model gauge couplings near M_G are in the strong coupling regime, so they correspond to the scenario of strong “unification” [17, 18], rather than precision perturbative unification, which applies to the other theories.

The parameters μ_S and μ_i are assumed to be of order the TeV scale, with an origin that may be similar to that of the supersymmetric Higgs mass parameter. Any S^3 coupling in the superpotential is assumed to be sufficiently small not to affect our analysis. The effective theory of eq. (1) possesses a parity on the vector matter, so that the lightest Φ_i is stable. We therefore add Yukawa interactions between these vector quarks and leptons and the standard model quarks and leptons via the MSSM Higgs doublets; this can be done without violating R -parity if Φ_i and $\bar{\Phi}_i$ are R -parity odd. We take these couplings to be sufficiently small that they do not affect the production and decay of the 750 GeV resonance, and do not violate bounds on flavor-changing processes. This allows the vector quarks and leptons to have prompt decays to known quarks and leptons with the emission of W, Z or h , the 125 GeV Higgs boson. (An alternative possibility will be discussed at the end of the paper.)

Soft supersymmetry breaking masses for the scalar components of $S, \Phi_i, \bar{\Phi}_i$ are present, as well as A and B type soft trilinears and bilinears. For simplicity, these parameters are chosen so that S does not acquire a vacuum expectation value. Furthermore, we assume that the scalar components of Φ_i and $\bar{\Phi}_i$ are sufficiently heavy that they do not contribute significantly to the production or decay of $S(750)$.¹ The bilinear scalar interaction, $\mathcal{L} \supset$

¹For example, for the soft supersymmetry breaking masses of a TeV, the contributions from the scalar components change the lower bounds on μ_i by at most 10%.

$-b_S S^2/2 + \text{h.c.}$, leads to a mass splitting between the two mass eigenstate scalars S_1 and S_2 , leading to three distinct descriptions of the diphoton excess. For a large mass splitting, the 750 GeV state is described by S_1 alone, which has a narrow width much smaller than the experimental resolution. If b_S is one-loop suppressed the S_1 - S_2 mass difference could be 10s of GeV, leading to an apparent width of this order [15, 19], which is mildly preferred by data. Finally, smaller values for b_S give a width below the experimental resolution.

The effective theory below M_G described by eq. (1) can result from a wide variety of unified theories. Some unified theories have specific boundary conditions on λ_i and μ_i at M_G , for example $\lambda_D = \lambda_L$ and $\mu_D = \mu_L$ in the “ $(\mathbf{5} + \bar{\mathbf{5}})_1$ ” theory, with corrections of order M_G/M_* from higher dimension operators, where M_* is the cutoff of the unified theory. However, such boundary conditions could be absent, for example if D and L arise from different unified multiplets, as occurs in theories where boundary conditions in extra dimensions breaks the unified symmetry. Below we make a simplifying assumption that the phases of λ_i are common in the basis that μ_i are real and positive. (This requires only coincidences of the signs if the relevant terms respect CP .) Under this assumption, we find that the production and decay of $S(750)$ is insensitive to any boundary condition on λ_i , but critically dependent on boundary conditions for μ_i . Allowing arbitrary phases only reduces the diphoton signal, because of a possible cancellation in the amplitude for decays to diphotons, so that the upper bounds we derive on vector quark masses are conservative. We stress that our analysis depends only on the effective theory, and does not depend on the unified gauge group or whether unification occurs in 4 dimensions [20, 21], higher dimensions [22, 23], or in string theory [24, 25].

The production of $S(750)$ at LHC occurs via gluon fusion induced by virtual vector quarks, and the decay to photons is via loops of vector quarks and leptons. An analysis of Run 1 and Run 2 data from both ATLAS and CMS leads to $\sigma B_{\gamma\gamma} \simeq (6 \pm 2)$ fb at $\sqrt{s} = 13$ TeV [13, 26]. This requires couplings λ_i at the TeV scale of order unity, and a key question is whether this is consistent with couplings not hitting a Landau pole up to M_G . In figure 1, we plot $\lambda_{D,L}(\text{TeV})$ for the $(\mathbf{5} + \bar{\mathbf{5}})_1$ theory (left panel) and $\lambda_{Q,U,E}(\text{TeV})$ in the $\mathbf{10} + \bar{\mathbf{10}}$ theory (right panel) as a function of the unified coupling λ_G as computed from one-loop renormalization group running. (The effects from two loops on the low energy values of these couplings are small, $\lesssim 2$ –3% in these theories and \lesssim a few % for $(\mathbf{5} + \bar{\mathbf{5}})_4$ and $\mathbf{15} + \bar{\mathbf{15}}$.) A striking feature is that as λ_G becomes larger than unity so the low energy couplings lose their sensitivity to the high scale value. Thus in most of the region where $\sigma B_{\gamma\gamma}$ is large enough to explain the diphoton data, our results are independent of λ_G and, indeed, independent of whether the couplings unify. The predicted values of the TeV scale couplings in the various theories are given in table 1. The splittings between the TeV scale values of λ_i arise from running of the standard model gauge couplings and are calculable; QCD running ensures that the couplings to vector quarks are larger than to vector leptons.

For the case that μ_i unify at M_G , the overall scale of $\mu_i(\text{TeV})$ depends on the unified mass, μ_G , while the splitting between $\mu_{D,L}$ or between $\mu_{Q,U,E}$ is again computed from gauge running. Relative values for the physical masses μ_i are shown in table 1 for each of our theories, assuming that they all take a common value at M_G . With these results, we compute $\sigma B_{\gamma\gamma}$ in terms of just one parameter, which we take to be the lightest vector lepton

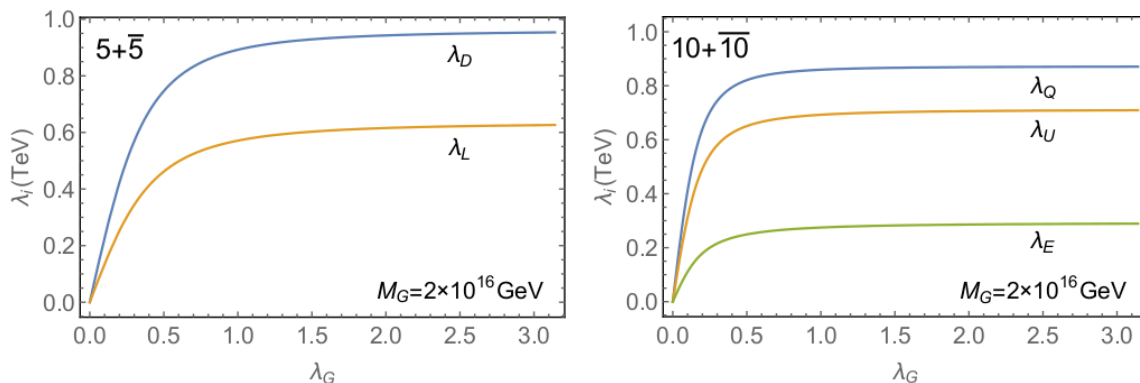


Figure 1. $\lambda_{D,L}$ (TeV) for the $(\mathbf{5} + \bar{\mathbf{5}})_1$ theory (left panel) and $\lambda_{Q,U,E}$ (TeV) in the $\mathbf{10} + \bar{\mathbf{10}}$ theory (right panel) as a function of the unified coupling λ_G , computed from one-loop renormalization group running.

		D	L	Q	U	E
$(\mathbf{5} + \bar{\mathbf{5}})_1$	λ_i	0.96	0.63	—	—	—
	μ_i/μ_L	1.5	1	—	—	—
$(\mathbf{5} + \bar{\mathbf{5}})_2$	λ_i	0.77	0.46	—	—	—
	μ_i/μ_L	1.7	1	—	—	—
$(\mathbf{5} + \bar{\mathbf{5}})_3$	λ_i	0.70	0.36	—	—	—
	μ_i/μ_L	1.9	1	—	—	—
$(\mathbf{5} + \bar{\mathbf{5}})_4$	λ_i	0.67	0.27	—	—	—
	μ_i/μ_L	2.5	1	—	—	—
$\mathbf{10} + \bar{\mathbf{10}}$	λ_i	—	—	0.87	0.71	0.29
	μ_i/μ_E	—	—	3.0	2.5	1
$\mathbf{15} + \bar{\mathbf{15}}$	λ_i	0.61	0.24	0.84	0.65	0.19
	μ_i/μ_E	3.2	1.3	4.5	3.4	1

Table 1. Predictions for λ_i (TeV) and physical mass ratios $\mu_i/\mu_{L,E}$ at one loop level. The mass ratios assume a common value for μ_i at M_G .

mass, as shown in figure 2. In the numerical plots of this paper, we include contributions from both the scalar and pseudoscalar in S . If the resonance is produced solely by the scalar (pseudoscalar) then $\sigma B_{\gamma\gamma}$ is reduced, by a factor of 4/13 (9/13) in the heavy vector limit. Also we determine the QCD K -factor (i.e. normalize the production cross section of scalar particles) so that it reproduces the production cross section of a standard model-like Higgs boson of mass 750 GeV at $\sqrt{s} = 14$ TeV [27]. Including this factor, and both scalar

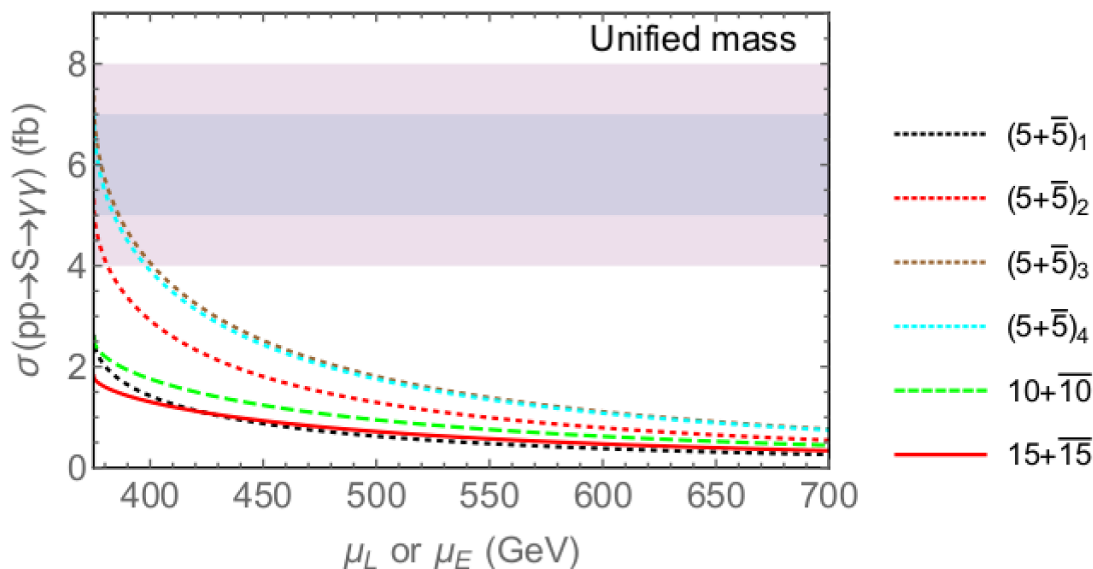


Figure 2. Theories with unified mass relations: prediction for $\sigma_{B\gamma\gamma}$ at $\sqrt{s} = 13$ TeV as a function of the lightest vector lepton mass.

and pseudoscalar contributions, gives a local analytic approximation

$$\sigma_{B\gamma\gamma} \sim 1 \text{ fb} \left(\sum_i N_i \lambda_i Q_i^2 \frac{500 \text{ GeV}}{\mu_i} \right)^2, \quad (2)$$

where Φ_i contains N_i states of electric charge Q_i . This local approximation is valid for $\mu_i \gtrsim 500$ GeV; for lighter masses the dependence on μ_i is steeper, as seen in figure 2.

In the $(\mathbf{5} + \bar{\mathbf{5}})_1$, $\mathbf{10} + \bar{\mathbf{10}}$, and $\mathbf{15} + \bar{\mathbf{15}}$ theories, the prediction is far too small to explain the observed value of $\sigma_{B\gamma\gamma}$, indicated by the horizontal shaded bands. From eq. (2), the contribution from Φ_i is proportional to Q_i^4 , leading to the importance of charged leptons and up-type quarks compared to down-type quarks. Thus, it is at first surprising to see that the $\mathbf{10} + \bar{\mathbf{10}}$ and $\mathbf{15} + \bar{\mathbf{15}}$ theories fail to account for the data. However, other effects are also important: table 1 shows that as more vector states are added so the predicted value of the couplings λ_i (TeV) are reduced. This results from the increasing renormalization of the S field and decreases the signal. Furthermore, the splittings $\mu_i/\mu_{L,E}$ increase due to the larger value of the unified gauge coupling. Since $\mu_{L,E}$ must be larger than $\mu_S/2$, this increases the masses of the vector quarks, again decreasing the signal. The $(\mathbf{5} + \bar{\mathbf{5}})_{2,3,4}$ theories can account for the diphoton resonance, but only if there are 2, 3 or 4 charged vector leptons lighter than about 400 GeV. In this case, the D vector quarks are near 1 TeV. This avoids the bounds on vector quarks from Run 1 even if they decay into the third generation quarks [28]. The bounds are weaker if they decay mainly into the first two generation quarks [29].

Unified boundary conditions on λ_i play no role under the common phase assumption, since we need large couplings leading to insensitivity to the ultraviolet. However, unified boundary conditions on μ_i are extremely constraining: most regions of parameter space are

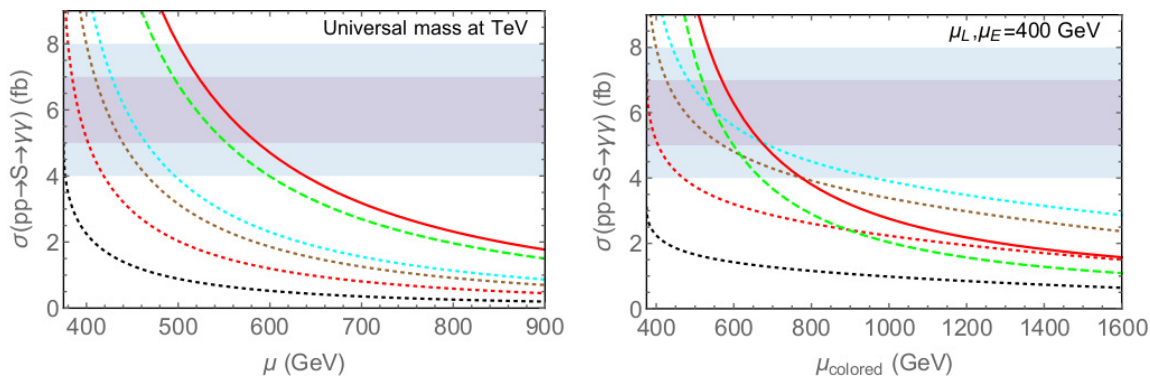


Figure 3. Theories without unified mass relations: prediction for $\sigma B_{\gamma\gamma}$ at $\sqrt{s} = 13$ TeV as a function of (i) the degenerate mass of all vector quarks and leptons (left panel), (ii) the degenerate mass of the vector quarks, with vector lepton masses fixed at 400 GeV (right panel). The definitions of colored lines are the same as in figure 2.

far from explaining the 750 GeV diphotons, and only a narrow range of vector lepton masses between 375 GeV and 400 GeV in the $(\mathbf{5} + \overline{\mathbf{5}})_{2,3,4}$ theories account for the data. Next we explore the case without unified boundary conditions on μ_i . This readily happens in theories where boundary conditions in extra dimensions break the unified symmetry [22, 23], but it can also occur in 4 dimensions if these masses pick up unified symmetry breaking effects at an $O(1)$ level.² Predictions for $\sigma B_{\gamma\gamma}$ are shown in figure 3 for all the theories for two sample spectra. In the left panel, all vector quarks and leptons are taken degenerate, opening up a large region for the $\mathbf{10} + \overline{\mathbf{10}}$ and $\mathbf{15} + \overline{\mathbf{15}}$ theories with masses up to 600 GeV or more. Vector quarks of these masses are not excluded if they decay mainly into the first two generation quarks [29]. From eq. (2), we see that both the charged leptons and charge 2/3 quarks are particularly important, and it is clear that degeneracy of the states is not required but is a simple choice for illustration. Even without unified boundary conditions on μ_i , QCD running tends to make the vector quarks heavier than the vector leptons. Hence in the right panel, we hold the vector lepton masses fixed at 400 GeV and allow the vector quark masses to vary to higher values. This allows even heavier vector quarks, up to mass 700 GeV for $\mathbf{10} + \overline{\mathbf{10}}$, 800 GeV for $\mathbf{15} + \overline{\mathbf{15}}$, and about a TeV for $(\mathbf{5} + \overline{\mathbf{5}})_{3,4}$. Relaxing the condition of unified μ_i greatly expands the possibilities for explaining the 750 GeV diphoton data, and leads to the exciting expectation of many vector quarks and leptons in reach of LHC in the region of 400 GeV–1 TeV.

In generic gravity mediation, we expect that the soft parameter b_S is of order the square of the supersymmetry breaking scale, so that the scalar and pseudoscalar components of S are well split. In this case, all the results given above for $\sigma B_{\gamma\gamma}$ should be multiplied by about 4/13 (9/13) for the 750 GeV state identified as the scalar (pseudoscalar). However, if the mediation mechanism leads to a suppression of b parameters, the splitting may be smaller; in this case there is an irreducible one-loop contribution arising from virtual Φ_i ,

²If the masses μ_i are generated mainly by terms involving a condensation(s) of a unified symmetry breaking field(s), then mass splittings among fields in a single unified group multiplet can be $O(1)$. This can happen, for example, if the unified symmetry breaking field is charged under some symmetry.

leading to a mass splitting between the scalar and pseudoscalar of

$$\begin{aligned} \Delta m_{\text{irred}} &\simeq \frac{1}{4\pi^2} \frac{1}{2m_S} \sum_i N_i \lambda_i^2 \mu_i^2 \ln \frac{\mu_i^2 + m_i^2}{\mu_i^2} \\ &\simeq 15\text{--}30 \text{ GeV} \left(\frac{\mu_i}{500 \text{ GeV}} \right)^2 \ln \frac{\mu_i^2 + m_i^2}{\mu_i^2}, \end{aligned} \quad (3)$$

where m_i^2 is the soft supersymmetry breaking mass parameter for Φ_i , and in the last expression we have assumed a common value for μ_i and m_i^2 , and used λ_i from table 1. The pre-factor range of 15–30 GeV reflects the range obtained in the various theories. This could easily lead to a mass splitting of 10s of GeV, so that more data will reveal two nearby resonances, with one having a signal about 9/4 of the other, for sufficiently large μ_i . This could account for the current mild preference for a width of about 40 GeV. Finally, as m_i^2 drops below μ_i^2 a supersymmetric cancellation suppresses Δm_{irred} , so that a narrow resonance emerges with width below the experimental resolution. In this case, and in the case of two nearby resonances, the signal to be compared with current data is the sum of scalar and pseudoscalar contributions, as presented in our plots.

For vector squarks/sleptons heavier than 1 TeV the corrections to the diphoton rate are very small; below a TeV they give a subdominant contribution to the diphoton signal, slightly weakening our bounds on the upper limit on the vector quark/lepton masses, for example by about 10%. We note that if λ_i have different phases, the various contributions in eq. (3) may partially cancel. Furthermore, with a phase in b_S the scalar and pseudoscalar from S mix, affecting the diphoton signal strength.

Finally, we mention the possibility that vector matter parity is unbroken leading to stability of the lightest vector fermion, which could be dark matter. This is of particular interest for the case of R -parity violation where the lightest supersymmetric particle cannot be dark matter. With vector matter parity, flavor changing masses via the Higgs expectation value allow heavy vector quarks to cascade to lighter ones, and similarly for vector leptons; however, this still leads to stability of the lightest vector quark and lepton. However, R -parity violating operators such as $\Phi_Q \Phi_L D$ allow vector quarks to decay to vector leptons, so only the lightest vector lepton is stable. In theories containing a neutral vector lepton Φ_N as well as the doublet Φ_L , the Yukawa coupling $\Phi_L \Phi_N H$ mixes the doublet and singlet vector leptons leading to the well known simple possibility of ‘‘Singlet-Doublet’’ dark matter [30, 31].

Summarizing, the diphoton resonance can be explained by the addition of vector quarks and leptons and a singlet to the MSSM. Requiring perturbativity to unified scales implies that several such states are sufficiently light to yield multiple signals at the LHC. Direct pair production yields signals from the decay of each to a quark/lepton together with a W , Z or standard model Higgs boson. In addition, signals of the 750 GeV resonance will be visible in gg , $Z\gamma$, ZZ , and WW modes as well as $\gamma\gamma$ (see the appendix). In cases where fewer than five μ_i are independent, the signal strength of these modes will be over-constrained, allowing us to test consistency of the theory. Furthermore, if the new vector matter is discovered and μ_i are measured, then we could determine (some of) λ_i from the rates of these two gauge boson modes and see if they are consistent with the assumption of large λ_i

at the unification scale. Such discoveries would provide a new window to high scales that could strengthen the case for supersymmetric unification and have important implications for unified theories. Other predictions of unified theories would also be impacted, such as quark and lepton mass relations and proton decay.

Acknowledgments

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A Other decay modes of the singlet

In this appendix, we show predictions for the production cross sections of WW , ZZ , $Z\gamma$, and gg through the decay of the singlet S . Figures 4, 5, and 6 show predictions of theories at the 8 TeV LHC, respectively for the cases with unified mass relations, degenerate masses for all the vectorlike quarks and leptons at the TeV scale, and degenerate masses for the vector quarks with lepton masses fixed at 400 GeV. In the parameter regions consistent with the observed diphoton rate, the constraints from those decay modes [32–35] are all satisfied. The production cross sections at the 13 TeV LHC is 4.8 times those at the 8 TeV LHC.

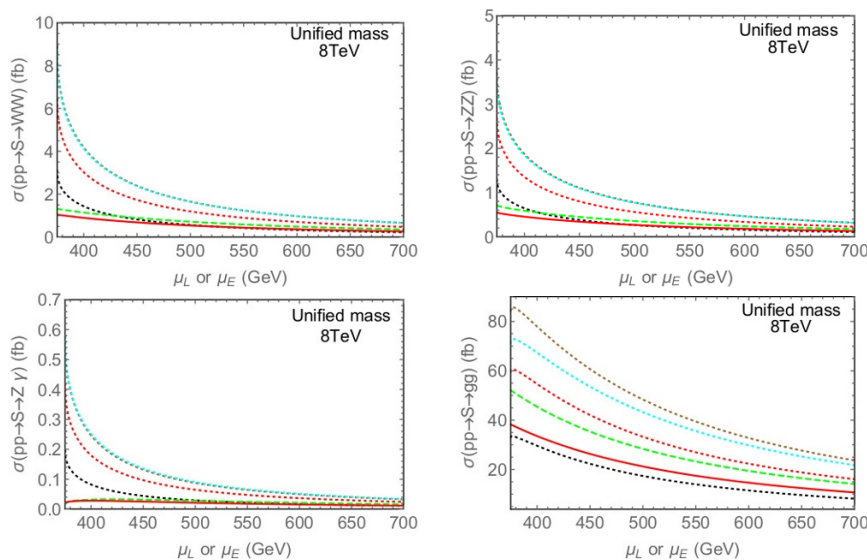


Figure 4. Theories with unified mass relations: predictions for $\sigma(pp \rightarrow S)$ times branching ratios into WW , ZZ , $Z\gamma$, and gg at $\sqrt{s} = 8$ TeV as a function of the lightest vector lepton masses. The definitions of colored lines are the same as those in figure 2.

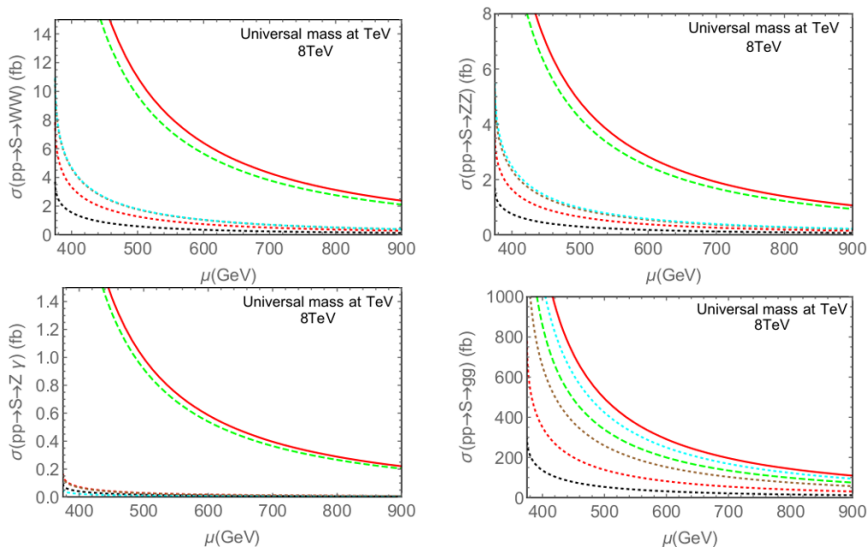


Figure 5. Theories without unified mass relations: predictions for $\sigma(pp \rightarrow S)$ times branching ratios into WW , ZZ , $Z\gamma$, and gg at $\sqrt{s} = 8\text{ TeV}$ as a function of the degenerate mass of all the vector quarks and leptons. The definitions of colored lines are the same as those in figure 2.

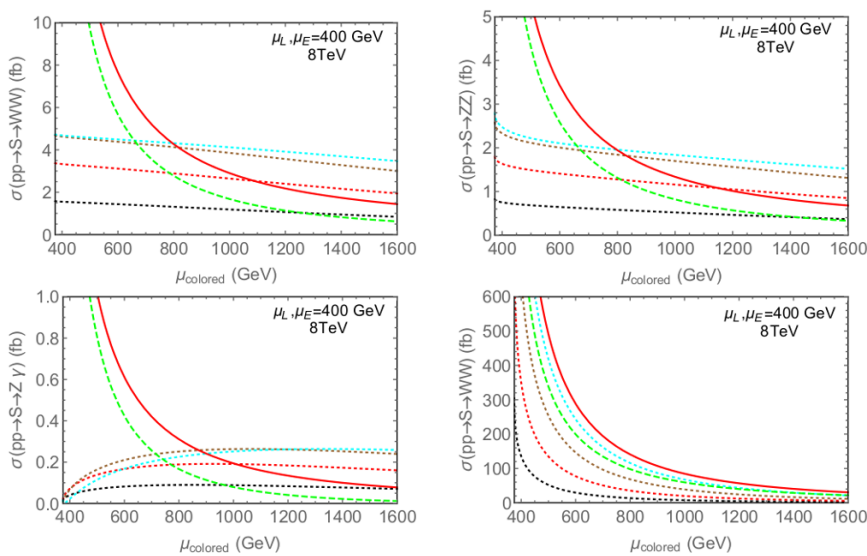


Figure 6. Theories without unified mass relations: predictions for $\sigma(pp \rightarrow S)$ times branching ratios into WW , ZZ , $Z\gamma$, and gg at $\sqrt{s} = 8\text{ TeV}$ as a function of the degenerate mass of the vector quarks, with the vector lepton masses fixed at 400 GeV. The definitions of colored lines are the same as those in figure 2.

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