Diphoton and Diquark Resonances in U(1) Extension of the MSSM

Qaisar Shafi

Bartol Research Institute
Department of Physics and Astronomy
University of Delaware

with George Lazarides [Phys.Rev. D93 (2016) no.11, 111702]

ICHEP 2016, Chicago, USA August 2016

New physics beyond the Standard Model suggested by:

- Absence of plausible dark matter candidate;
- Lack of gauge coupling unification;
- Neutrino oscillations;
- Gauge hierarchy problem;
- Charge quantization;

Merging SM with TeV scale SUSY, with unbroken 'matter' parity, has two important implications:

- Stable DM candidate;
- Gauge coupling unification.

To incorporate neutrino oscillations one could introduce right handed neutrinos and provide masses for them in at least two ways:

- With $U(1)_{B-L}$ gauge symmetry present to ensure that right handed neutrinos acquire masses only after this symmetry is spontaneously broken.

  Note: SO(10) broken to SU(3)$_c\times$U(1)$_{em}$ using only tensor fields yields an unbroken Z_2 symmetry which is precisely matter parity.
  [Kibble, Lazarides, Shafi, Phys.Lett. B113 (1982) 237-239]
- Gauge invariant mass terms, for example motivated by E_6.

Two Examples will be discussed based on local $U(1)_{B-L}$ and $U(1)_{\psi'}$ symmetries.

- The first case with $U(1)_{B-L}$ requires the introduction of three right handed neutrinos in order to cancel the gauge anomalies.

- Observable diphoton and diquark resonances arise by introducing additional vector-like fields in the TeV mass range.

- The second example with $U(1)_{\psi'}$ is motivated by E_6 grand unification and its decomposition $E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$.

  In this case vector-like fields are present in order to ensure an anomaly free theory and their masses are controlled by the symmetry breaking scale of $U(1)_{\psi'}$(a linear combination of $U(1)_\psi$ and $U(1)_\chi$).

- Mechanisms exist for resolving the MSSM μ problem in both cases.

Recall the MSSM superpotential which respects Z_2 matter parity:

$$W = y_u H_u q u^c + y_d H_d q d^c + y_e H_d l e^c + \mu H_u H_d.$$

Ignoring non-perturbative effects, W respects three global symmetries, namely $U(1)_B$, $U(1)_L$ and $U(1)_R$.

The R charges are as follows:

H_u,$H_d \rightarrow 1$

q,u^c,d^c,l, $e^c \rightarrow \frac{1}{2}$

W $\rightarrow$ 2

Motivated by the MSSM example we require that the relevant W is determined by the gauge symmetry, global B and L conservation, and a U(1) R symmetry. However, in contrast to the MSSM case with radiative electroweak breaking, we require tree level breaking at scale M of $U(1)_{B-L}$, with supersymmetry remaining unbroken.

$$\begin{aligned} W &= y_u H_u q u^c + y_d H_d q d^c + y_\nu H_u l \nu^c + y_e H_d l e^c \\ &\quad + \kappa S(\Phi\bar{\Phi} - M^2) + \lambda_\mu S H_u H_d + \lambda_{\nu^c} \bar{\Phi} \nu^c \nu^c \end{aligned}$$

The Z_2 subgroups of $U(1)_R$, $U(1)_{B-L}$ coincide with matter parity.

Superfields	Representations under G_{SM}	Global Symmetries B	L	R
	Matter Superfields			
q	$(\mathbf{3}, \mathbf{2}, 1/6)$	$1/3$	0	1
u^c	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	$-1/3$	0	1
d^c	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$-1/3$	0	1
l	$(\mathbf{1}, \mathbf{2}, -1/2)$	0	1	1
ν^c	$(\mathbf{1}, \mathbf{1}, 0)$	0	-1	1
e^c	$(\mathbf{1}, \mathbf{1}, 1)$	0	-1	1
	Higgs Superfields			
H_u	$(\mathbf{1}, \mathbf{2}, 1/2)$	0	0	0
H_d	$(\mathbf{1}, \mathbf{2}, -1/2)$	0	0	0
S	$(\mathbf{1}, \mathbf{1}, 0)$	0	0	2
Φ	$(\mathbf{1}, \mathbf{1}, 0)$	0	-2	0
$\bar{\Phi}$	$(\mathbf{1}, \mathbf{1}, 0)$	0	2	0

- W is the most general renormalizable superpotential which obeys the symmetries of the model.
- Without B and L symmetries and keeping only $U(1)_{B-L}$, the terms $\bar{D}ql$, $Du^c e^c$, and $\bar{D}d^c \nu^c$ would be present.

$\Longrightarrow$ Rapid proton decay.

- The 'bare' MSSM μ term is replaced by SH_uH_d. After SUSY breaking S acquires a non-zero VEV which induces the μ-term.

G. R. Dvali, G. Lazarides, and Q. Shafi, Phys. Lett. B 424 , 259 (1998); S. F. King and Q. Shafi, Phys. Lett. B 422 , 135 (1998)

Analysis of the Model

Consider the potential

$$V = \kappa^2|\Phi\bar{\Phi} - M^2| + \kappa^2|S|^2(|\Phi|^2 + |\bar{\Phi}|^2) + \mathrm{D} - \mathrm{terms}.$$

- Where M, κ are made real and positive by field rephasing.
- Vanishing of the D-terms yields $|\Phi| = |\bar{\Phi}| \implies \bar{\Phi}^* = e^{i\varphi}\Phi$.
- The F-terms vanish for $S = 0$, $\Phi\bar{\Phi} = M^2$, requiring $\varphi = 0$.
- Rotating Φ, $\bar{\Phi}$ to the positive real axis by a $B - L$ transformation, we find the SUSY vacuum

$$S = 0 \quad \text{and} \quad \Phi = \bar{\Phi} = M.$$

- The mass spectrum of the scalar $S - \Phi - \bar{\Phi}$ system is constructed by writing $\Phi = M + \delta\Phi$ and $\bar{\Phi} = M + \delta\bar{\Phi}$.
- **For unbroken SUSY, we find two complex scalar fields S and $\theta = (\delta\Phi + \delta\bar{\Phi})/\sqrt{2}$ with equal masses** $m_S = m_\theta = \sqrt{2}\kappa M$. (Note: m$_{Z'} \approx \sqrt{6} g_{B-L}$ M)
- Soft SUSY breaking can, of course, mix these fields and generate a mass splitting.
- For example, the trilinear soft term $A\kappa S\Phi\bar{\Phi}$ yields a mass^2 splitting $\pm\sqrt{2}\kappa M A$ with mass eigenstates $(S + \theta^*)/\sqrt{2}$, $(S - \theta^*)/\sqrt{2}$.

- Consider the soft SUSY breaking potential terms

$$V_1 = A\kappa S\Phi\bar{\Phi} - (A - 2m_{3/2})\kappa M^2 S, \quad A \sim m_{3/2}$$

  arising from the W term $\kappa S(\Phi\bar{\Phi} - M^2)$.

- In minimal SURGA, the coefficients of the trilinear and linear soft terms are related as shown.

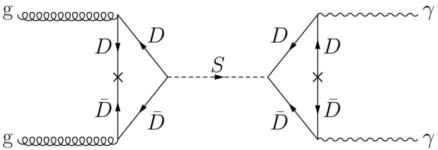
- Substituting $\Phi = \bar{\Phi} = M$, we obtain a linear term in S which, together with the mass term $2\kappa^2 M^2 |S|^2$, generates a VEV:

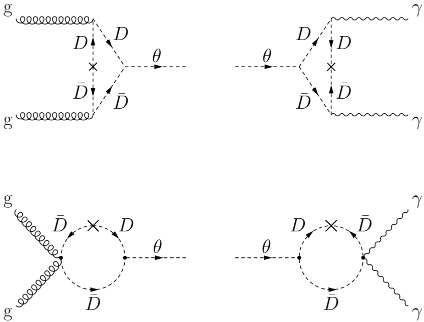
$$\langle S \rangle = -\frac{m_{3/2}}{\kappa}.$$

- From $\lambda_\mu S H_u H_d$, we obtain the μ term with $\mu = -\lambda_\mu m_{3/2}/\kappa$.

- How can we test this?
- Recall that unification of gauge couplings remains intact if we include, say, $5+\bar{5}$ fields;
- Up to 4 such pairs can be introduced without spoiling perturbative unification.
- In our case these fields (D, $\bar{D}$ and L, $\bar{L}$) acquire masses from their couplings to S;
- This explains why vector-like masses in this model are comparable to the TeV SUSY breaking scale.
- With this formulation the S-Φ-$\bar{\Phi}$ system, together with D-$\bar{D}$ fields, can be observed as diphoton (and diquark) resonances at LHC.

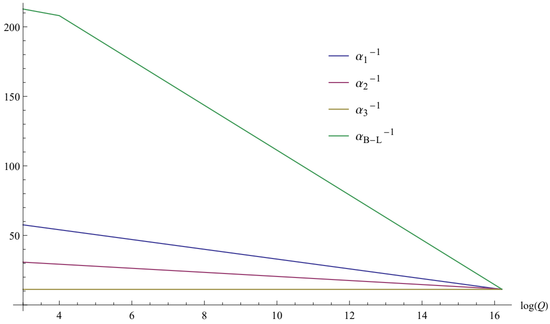
Superfields	Representations under G_{SM}	Global Symmetries B	L	R
		Matter Superfields		
q	$(\mathbf{3}, \mathbf{2}, 1/6)$	$1/3$	0	1
u^c	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	$-1/3$	0	1
d^c	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$-1/3$	0	1
l	$(\mathbf{1}, \mathbf{2}, -1/2)$	0	1	1
ν^c	$(\mathbf{1}, \mathbf{1}, 0)$	0	-1	1
e^c	$(\mathbf{1}, \mathbf{1}, 1)$	0	-1	1
		Higgs Superfields		
H_u	$(\mathbf{1}, \mathbf{2}, 1/2)$	0	0	0
H_d	$(\mathbf{1}, \mathbf{2}, -1/2)$	0	0	0
S	$(\mathbf{1}, \mathbf{1}, 0)$	0	0	2
Φ	$(\mathbf{1}, \mathbf{1}, 0)$	0	-2	0
$\bar{\Phi}$	$(\mathbf{1}, \mathbf{1}, 0)$	0	2	0
		Vector-like Diquark Superfields		
D	$(\mathbf{3}, \mathbf{1}, -1/3)$	$-2/3$	0	0
$\bar{D}$	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$2/3$	0	0



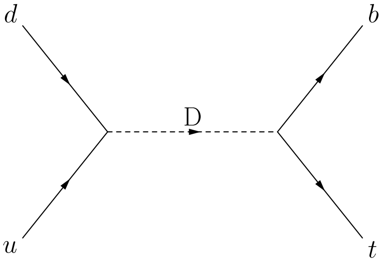


(a) (b)

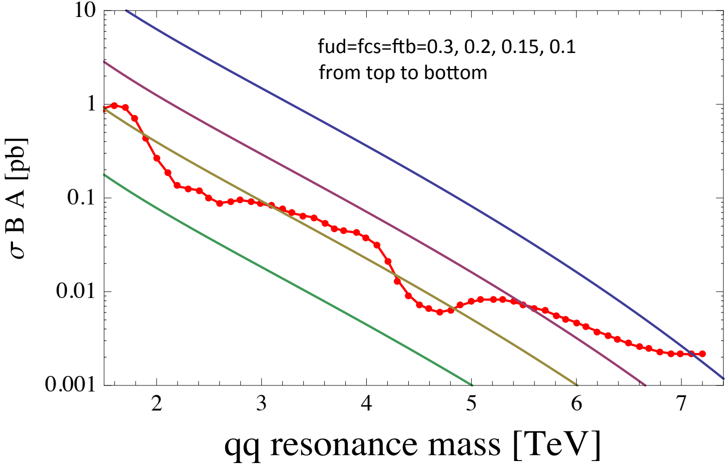
- $m_{Z'} = \sqrt{6} g_{B-L} M > 3 \text{ TeV} \implies g_{B-L} M \gtrsim 1225 \text{ GeV}.$
- Setting $m_{3/2} = 50 \text{ GeV}$, we obtain $\kappa \simeq 0.066$, $M \simeq 8040 \text{ GeV}$, $\lambda_{\nu^c} \gtrsim 0.047$, and $g_{B-L} \gtrsim 0.15$.
- A gravitino in this mass range is a plausible cold matter candidate.


200
150
100
50
4
6
8
10
12
14
16
log(Q)
$\alpha_1{}^{-1}$
$\alpha_2{}^{-1}$
$\alpha_3{}^{-1}$
$\alpha_{B-L}{}^{-1}$

Diquark Resonance



CMS constraints on Color Triplet Diquark production at LHC Run 2



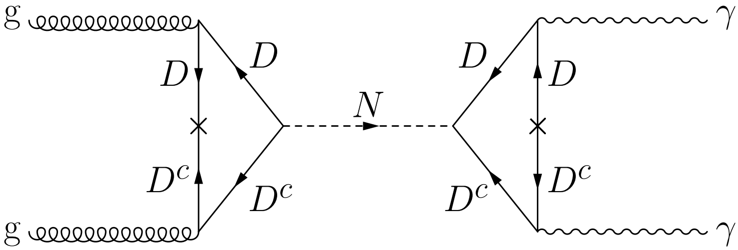
- Motivated by $E_6 \supset SO(10) \times U(1)_\psi \supset SU(5) \times U(1)_\chi \times U(1)_\psi$.
- Matter fields: $27 \rightarrow 16_1 + 10_{-2} + 1_4$
- Vectorlike color triplets (diquarks) can remain light if U$(1)_\psi$ breaking scale is in the TeV range.
- This may also resolve the MSSM μ problem.
- One example is provided by using U$(1)_{\psi'}$, a linear combination of the χ and ψ generators, such that the right-handed neutrino is neutral under U$(1)_{\psi'}$.

E. Ma, Phys. Lett. B 380 , 286 (1996); P. Langacker and J. Wang, Phys.Rev. D58 115010 (1998); C. Callaghan, S. F. King and G. K. Leontaris, JHEP 1312 , 037 (2013); J. L. Rosner, Mod. Phys. Lett. A, 30, 1530013 (2015),...

Superfields	Representations under G_{SM}	Charges R	$2\sqrt{10}Q_{\psi'}$
	Matter Superfields		
q	$(\mathbf{3}, \mathbf{2}, 1/6)$	$1/2$	1
u^c	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	$1/2$	1
d^c	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$1/2$	2
l	$(\mathbf{1}, \mathbf{2}, -1/2)$	$1/2$	2
ν^c	$(\mathbf{1}, \mathbf{1}, 0)$	1	0
e^c	$(\mathbf{1}, \mathbf{1}, 1)$	$1/2$	1
$H_u^{2,3}$	$(\mathbf{1}, \mathbf{2}, 1/2)$	1	-2
$H_d^{2,3}$	$(\mathbf{1}, \mathbf{2}, -1/2)$	1	-3
D_i	$(\mathbf{3}, \mathbf{1}, -1/3)$	1	-2
D_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	1	-3
N_i	$(\mathbf{1}, \mathbf{1}, 0)$	1	5
	Higgs Superfields		
H_u^1	$(\mathbf{1}, \mathbf{2}, 1/2)$	1	-2
H_d^1	$(\mathbf{1}, \mathbf{2}, -1/2)$	1	-3
S	$(\mathbf{1}, \mathbf{1}, 0)$	2	0
N	$(\mathbf{1}, \mathbf{1}, 0)$	0	5
$\bar{N}$	$(\mathbf{1}, \mathbf{1}, 0)$	0	-5

$$W = \kappa S(N\bar{N} - M^2) + \lambda_D D_i D_i^c N + \lambda_N H_u^1 H_d^1 N + \ldots$$

Minimal model yields diphoton resonances beyond the reach of LHC (but 100 TeV collider may find it.)


g
g
D
D
D^c
D^c
N
D
D
D^c
D^c
γ
γ

Summary

- Realistic $U(1)$ extensions of the MSSM predict resonances observable at the LHC and/or future colliders.
- Symmetries prevent the μ parameter and the masses of vector-like fields and a gauge singlet field from being arbitrarily large.
- In $U(1)_{B-L}$ model, four spin zero resonances arise from a gauge singlet scalar and a pair of conjugate Higgs superfields responsible for $B-L$ breaking.
- $U(1)_{\psi'}$ model (ψ'MSSM) predicts vector-like fields which may be accessible at the LHC.
- In minimal model the diphoton resonance production cross section is suppressed. (due to constraint from Z' boson)