Flavour Non-Universal UMSSM with Minimal Number of Exotics

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"Family Non-Universal U(1)′ Model with Minimal Number of Exotics"
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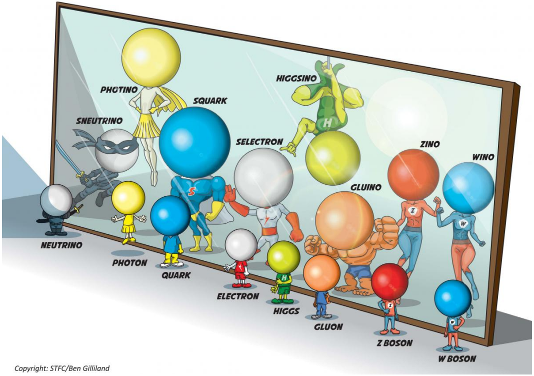
Outline

- Supersymmetry (SUSY) is one of the most studied NP theories at LHC, since it has remarkable advantages.,



- Supersymmetry (SUSY) is one of the most studied NP theories at LHC, since it has remarkable advantages.,
  - The Hierarchy Problem.
  - Natural light Higgs boson.
  - Unification of the gauge couplings.
  - WIMP candidate in order to solve the DM puzzle.
- Minimal Supersymmetric Standard Model (MSSM) is the simplest SUSY extension of the SM.

$$W_{MSSM} = \mu H_u H_d + Y_u \hat{Q} H_u \hat{U} + Y_d \hat{Q} H_d \hat{D} + Y_e \hat{L} H_d \hat{E}$$

Little Hierarchy Problem!!!

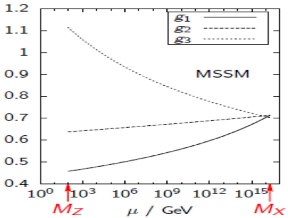
$$(m_h^{pole})^2 \approx m_Z^2 cos^2 2\beta + \Delta m_h^2$$

$$m_h^{pole} \approx 125\,GeV$$

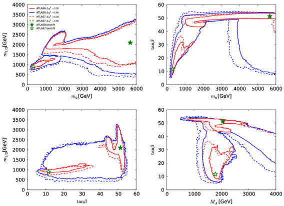
$$m_Z \approx 91\,GeV$$

$$\Delta m_h \gtrsim 87\,GeV$$

μ problem!!!



Excluded Parameter Space!!!



UMSSMs

- U(1) extended MSSMs (UMSSMs) have been broadly worked upon the literature, e.g. E_6 motivated, $B - L$ and Secluded UMSSMs.
- Such extensions can stem from Superstring and Grand Unified Theories (GUTs).
- These models can dynamically generate the μ term at the EW scale by introducing new singlet Higgs field as $\mu = \frac{1}{2}\lambda \langle S \rangle$.
- They also introduce a new massive neutral gauge boson, called Z' and U(1)$'$ charges must satisfy the Anomaly Cancellation Conditions (ACCs) stemming from the additional U(1)$'$ group insertion.

Motivations

- ACCs can be satisfied with two different ways.
  - Adding exotics into the model.
  - Using non-holomorphic terms without any exotics, called minimal UMSSM in which the $U(1)'$ **charges can be flavour non-universal.**
- A family non-universal Z' boson can explain the experimental results on R_K and R_{K^*} that deviate from SM.
- Numerous well-motivated U(1)′ sub-models which give new and different signals for the detection of the extra Z'.

- Following a hybrid approach, in which we will study a supersymmetric $U(1)'$ model with an additional exotic quark superfield, $\widehat{D_x}$ with non-universal $U(1)'$ charges in the lepton sector.
- Finding the possible charge configurations which satisfy not only the ACCs but also experimental low energy constraints.
- Seeking evidence of the new Z' state precisely from its signals involving the other new features of the model, i.e., the coloured exotic states and the anomalous leptonic couplings.
- The potential signatures of the exotics and the non-universality of the $U(1)'$ charges at both hadron and lepton colliders, both present and future ones.

Gauge Structure:

$$SU(3) \times SU(2) \times U(1) \times U(1)'$$

Superpotential:

$$\widehat{W} = h_u \widehat{Q} \cdot \widehat{H}_u \widehat{U} + h_d \widehat{Q} \cdot \widehat{H}_d \widehat{D} + h_\tau \widehat{L}_3 \cdot \widehat{H}_d \widehat{E}_3 + \lambda \widehat{S} \widehat{H}_u \cdot \widehat{H}_d + h_\nu \widehat{L} \cdot \widehat{H}_u \widehat{N} + \kappa \widehat{S} \widehat{D}_x \widehat{\overline{D}}_x$$

Non-Holomorphic Terms:

$$-\mathcal{L}^{NH} = T'_e \tilde{L}_1 H_u \tilde{E}^c_1 + T'_\mu \tilde{L}_2 H_u \tilde{E}^c_2 + h.c.$$

The Charges:

Gauge group/Field	$\widehat{Q}$	$\widehat{U}$	$\widehat{D}$	$\widehat{L}_i$	$\widehat{N}_i$	$\widehat{E}_i$	$\widehat{H}_u$	$\widehat{H}_d$	$\widehat{S}$	$\widehat{D}_x$	$\widehat{\overline{D}}_x$
$SU(3)_C$	3	$\overline{3}$	$\overline{3}$	1	1	1	1	1	1	3	$\overline{3}$
$SU(2)_L$	2	1	1	2	1	1	2	2	1	1	1
$U(1)_Y$	1/6	-2/3	1/3	$-1/2$	0	1	1/2	$-1/2$	0	Y_{D_x}	$-Y_{D_x}$
$U(1)'$	Q_Q	Q_U	Q_D	Q_{L_i}	Q_{N_i}	Q_{E_i}	Q_{H_u}	Q_{H_d}	Q_S	Q_{D_x}	$Q_{\overline{D}_x}$

Anomaly Cancellation

$$\begin{aligned}
U(1)' - SU(3)_C - SU(3)_C \to 0 &= 3(2Q_Q + Q_U + Q_D) + n_{D_x}(Q_{D_x} + Q_{\overline{D}_x}) \\
U(1)' - SU(2)_L - SU(2)_L \to 0 &= 3(3Q_Q + Q_L) + Q_{H_d} + Q_{H_u} \\
U(1)' - U(1)_Y - U(1)_Y \to 0 &= 3(\frac{1}{6}Q_Q + \frac{1}{3}Q_D + \frac{4}{3}Q_U + \frac{1}{2}Q_L + Q_E) \\
&+ \frac{1}{2}(Q_{H_d} + Q_{H_u}) + 3n_{D_x}Y_{D_x}^2(Q_{D_x} + Q_{\overline{D}_x}) \\
U(1)' - graviton - graviton \to 0 &= 3(6Q_Q + 3Q_U + 3Q_D + 2Q_L + Q_E + Q_N) + 2Q_{H_d} \\
&+ 2Q_{H_u} + Q_S + 3n_{D_x}(Q_{D_x} + Q_{\overline{D}_x}) \\
U(1)' - U(1)' - U(1)_Y \to 0 &= 3(Q_Q^2 + Q_D^2 - 2Q_U^2 - Q_L^2 + Q_E^2) - Q_{H_d}^2 + Q_{H_u}^2 \\
&+ 3n_{D_x}Y_{D_x}(Q_{D_x}^2 - Q_{\overline{D}_x}^2) \\
U(1)' - U(1)' - U(1)' \to 0 &= 3(6Q_Q^3 + 3Q_D^3 + 3Q_U^3 + 2Q_L^3 + Q_E^3 + Q_N^3) + 2Q_{H_d}^3 \\
&+ 2Q_{H_u}^3 + Q_S^3 + 3n_{D_x}(Q_{D_x}^3 + Q_{\overline{D}_x}^3).
\end{aligned}$$

+ Gauge Invariance Conditions from Yukawa and Non-Holomorphic Terms

The Exotic Sector

- Having same charges as the down quarks.
- Colour triplet and vector-like with respect to the MSSM, but chiral under the $U(1)'$ symmetry.
- Only interaction with S and cannot mix with SM fermions
- Expected to have masses larger than 1 TeV (CMS-B2G-18-005).

The mass of the exotic fermion:

$$m_{D_x} = \frac{1}{\sqrt{2}} v_S \kappa.$$

The mass squared matrix of the supersymmetric partners of the exotics:

$$m^2_{\tilde{D}_x} = \begin{pmatrix} m^2_{\tilde{D}^L_x} & \frac{1}{2}\left(\sqrt{2} v_S T_\kappa - v_d v_u \lambda\kappa\right) \\ \frac{1}{2}\left(\sqrt{2} v_S T_\kappa - v_d v_u \lambda\kappa\right) & m^2_{\tilde{D}^R_x} \end{pmatrix},$$

$$m^2_{\tilde{D}^L_x} = \frac{1}{12}\mathbf{1}\left(6g'^2 Q_{D_x}\left(Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_S v_S^2\right) + g_1^2\left(-v_u^2 + v_d^2\right)\right) + \frac{1}{2}\left(2m_X^2 + v_S^2 \kappa^2\right),$$

$$m^2_{\tilde{D}^R_x} = \frac{1}{12}\mathbf{1}\left(6g'^2 Q_{\bar{D}_x}\left(Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_S v_S^2\right) + g_1^2\left(-v_d^2 + v_u^2\right)\right) + \frac{1}{2}\left(2m_{\bar{X}}^2 + v_S^2 \kappa^2\right).$$

Z' boson

The $Z - Z'$ mass matrix:

$$\mathbf{M_Z^2} = \begin{pmatrix} M_{ZZ}^2 & M_{ZZ'}^2 \\ M_{ZZ'}^2 & M_{Z'Z'}^2 \end{pmatrix} = \begin{pmatrix} 2g_1^2 \sum_i t_{3i}^2 \left|\langle\phi_i\rangle\right|^2 & 2g_1 g' \sum_i t_{3i} Q_i \left|\langle\phi_i\rangle\right|^2 \\ 2g_1 g' \sum_i t_{3i} Q_i \left|\langle\phi_i\rangle\right|^2 & 2g'^2 \sum_i Q_i^2 \left|\langle\phi_i\rangle\right|^2 \end{pmatrix}$$

The mixing angle $\alpha_{ZZ'}$:

$$\tan 2\alpha_{ZZ'} = \frac{2M_{ZZ'}^2}{M_{Z'Z'}^2 - M_{ZZ}^2}.$$

The physical mass states of the Z and Z':

$$M_{Z,Z'}^2 = \frac{1}{2}\left[M_{ZZ}^2 + M_{Z'Z'}^2 \mp \sqrt{\left(M_{ZZ}^2 - M_{Z'Z'}^2\right)^2 + 4M_{ZZ'}^4}\right].$$

The couplings of the Z' boson to fermions are related to their currents as

$$J'^{\mu} = \sum_i \bar{f}_i \gamma^{\mu} [\epsilon_L^i P_L + \epsilon_R^i P_R] f_i,$$
$$= \frac{1}{2} \sum_i \bar{f}_i \gamma^{\mu} [g_v^i - g_a^i \gamma^5] f_i.$$

Parameter Space

- SARAH (version 4.14.3)
- SPheno (version 4.0.0)
- MicrOMEGAs (version 5.0.9)
- MG5_aMC (version 2.6.6)

Parameter	Scanned range	Parameter	Scanned range
m_0	$[0, 9]$ TeV	T_λ	$[-2.5, 2.5]$ TeV
$M_{1/2}$	$[0, 9]$ TeV	T_κ	$[-2.5, 2.5]$ TeV
$\tan\beta$	$[1, 50]$	v_S	$[5, 45]$ TeV
λ	$[0.01, 0.4]$	T'_e	$[-2, 2]$ TeV
κ	$[0.01, 0.8]$	T'_μ	$[-2, 2]$ TeV
T_0	$[-3m_0, 3m_0]$		

Constraints

$$
\begin{aligned}
& m_h = 122 - 128 \text{ GeV}, \\
& m_{\tilde{g}} \geq 2 \text{ TeV}, \\
& 0.8 \times 10^{-9} \leq \mathrm{BR}(B_s \rightarrow \mu^+\mu^-) \leq 6.2 \times 10^{-9} \ (2\sigma \text{ tolerance}), \\
& m_{\tilde{\chi}_1^{\pm}} \geq 103.5 \text{ GeV}, \\
& m_{\tilde{\tau}} \geq 105 \text{ GeV}, \\
& 2.99 \times 10^{-4} \leq \mathrm{BR}(B \rightarrow X_s\gamma) \leq 3.87 \times 10^{-4} \ (2\sigma \text{ tolerance}), \\
& 0.15 \leq \frac{\mathrm{BR}(B_u \rightarrow \tau\nu_\tau)_{\mathrm{UMSSM}}}{\mathrm{BR}(B_u \rightarrow \tau\nu_\tau)_{\mathrm{SM}}} \leq 2.41 \ (3\sigma \text{ tolerance}), \\
& 0.0913 \leq \Omega_{\mathrm{CDM}} h^2 \leq 0.1363 \ (5\sigma \text{ tolerance}).
\end{aligned}
$$

Z' Mass Limits

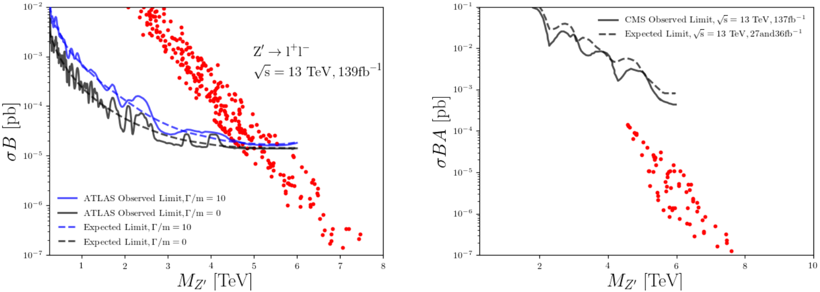


Figure 1: *The Z' boson mass limits on $\sigma(pp \to Z' \to ll)$ vs $M_{Z'}$ (left panel) and $\sigma(pp \to Z' \to \text{jets})$ vs $M_{Z'}$ (right panel), where l describes electron and muon while jets refer to contributions from both the SM and exotic quarks. All points plotted here satisfy all experimental constraints given in the previous section. In the right panel, we have additionally applied the Z' mass constraint from the left panel.*

$U(1)'$ Charges

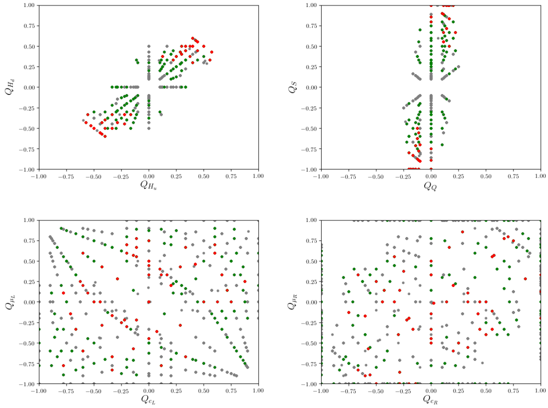


Figure 2: *The distributions of the $U(1)'$ charges allowed by various theoretical and experimental conditions over the following planes. All points are consistent with REWSB, ACCs and neutralino LSP. Green points are a subset of the gray ones as they also satisfy all experimental constraints. Red points are a subset of the green ones as they are also compatible with the Z' boson mass bounds.*

Z' Decays

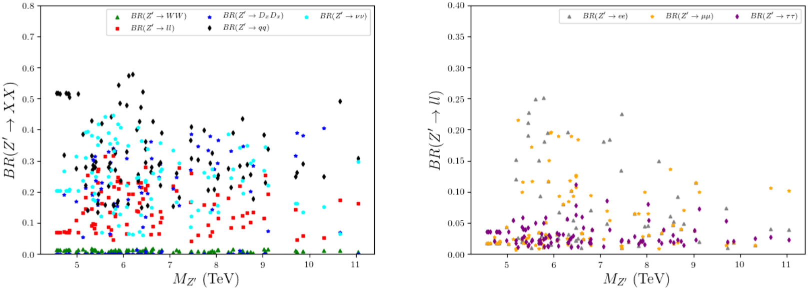


Figure 3: *The BRs of the Z' for different decay channels, $BR(Z' \to XX)$ as a function on $M_{Z'}$ (left panel) and $BR(Z' \to ll)$ as a function on $M_{Z'}$ (right panel), where XX represents all two-body final states while ll describes individual leptonic final states.*

SUSY Mass Spectrum

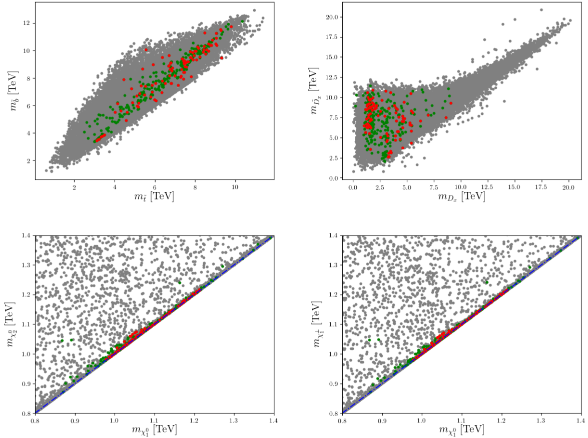


Figure 4: *The mass spectrum of the lightest chargino, two lightest neutralinos, stops, sbottoms and exotic (both fermionic and scalar) states.*

Colliders Signatures at LHC-Exotics

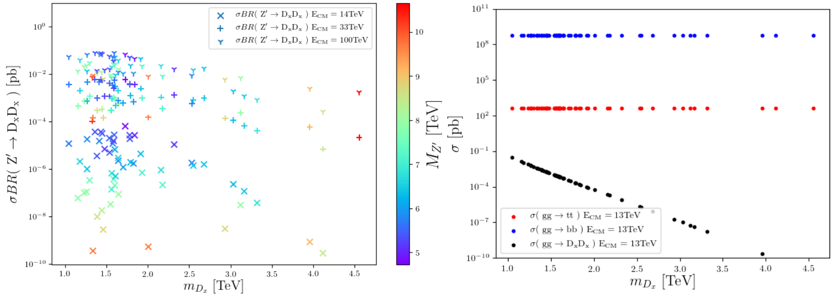


Figure 5: *The pair production cross sections of all exotic quarks through Z' mediation in terms of relevant Z' mass (left panel) at the HL-LHC (14 TeV), HE-LHC (33 TeV) and VLHC/FCC-hh (100 TeV) and those mediated by QCD (right panel), the latter alongside those for top and bottom quarks at 13 TeV.*

Colliders Signatures at LHC-Non-Universality

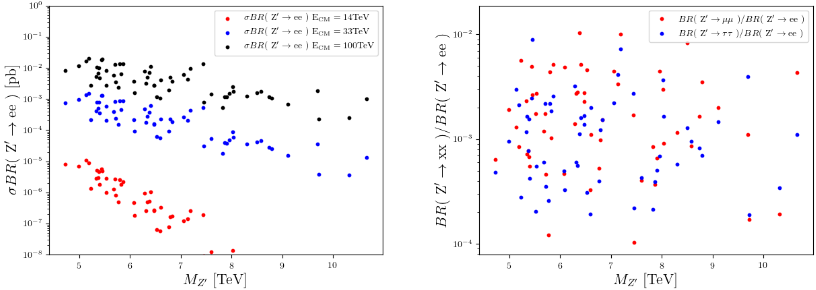


Figure 6: *The production cross sections of electron pairs (left panel) through the Z' at the HL-LHC, HE-LHC and VLHC/FCC-hh and the ratio of the BRs of $Z' \to \mu\mu$ and $Z' \to \tau\tau$ relative to that of $Z' \to ee$ (right panel).*

Colliders Signatures at CLiC-Exotics

Parameters	BP-I	BP-II
Q_Q	0.156	-0.125
Q_U	0.373	0
Q_D	0.313	-0.25
Q_{L_1}	0.071	0.875
Q_{L_2}	-0.36	0.25
Q_{L_3}	-0.12	-0.5
Q_{N_1}	0.45	-1
Q_{N_2}	0.89	-0.375
Q_{N_3}	0.65	0.375
Q_{E_1}	-0.6	-0.75
Q_{E_2}	-0.17	-0.125
Q_{E_3}	0.59	0.125
Q_{H_u}	-0.53	0.125
Q_{H_d}	-0.47	0.375
Q_S	1	-0.5
Q_{D_x}	-0.53	0.125
$Q_{\overline{D}_x}$	-0.47	0.375
$M_{Z'}$	5388 GeV	5452 GeV
m_{D_x}	1362 GeV	1386 GeV

Table 1: *U(1)′ charges, Z′ and exotic quark masses for two Benchmark Points (BPs) of the UMSSM: BP-I and BP-II.*

Colliders Signatures at CLiC-Exotics

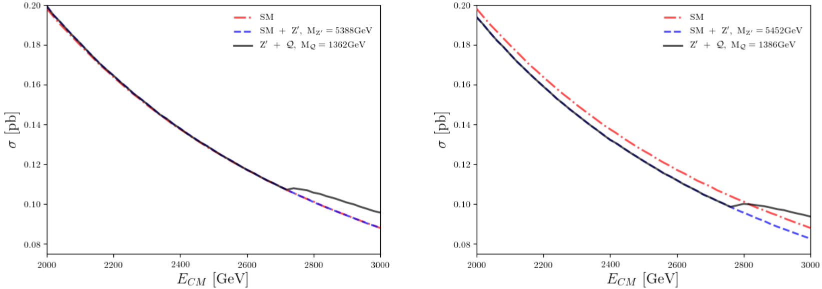


Figure 7: *The predicted cross section for quark pair production versus collision energy at CLiC in the case of the SM, SM + Z' and SM + Z' + exotic quarks for BP-I (left) and BP-II (right).*

Colliders Signatures at CLiC-Non-Universality

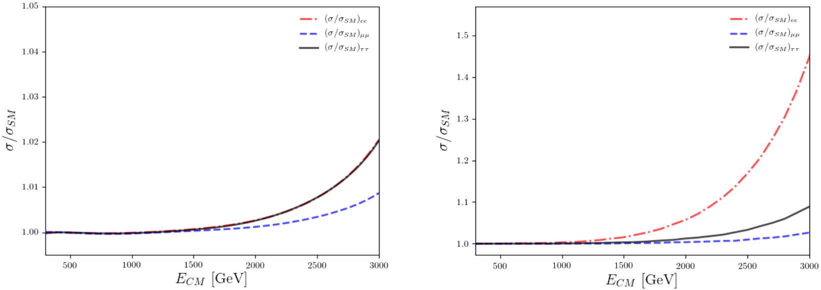


Figure 8: *The ratio of the predicted cross section for electron, muon and tauon pair production in the UMSSM relative to the SM values as a function of the collision energy at CLiC for BP-I (left) and BP-II (right).*

- Studied potential effects of family non-universal $U(1)'$ charges emerging in an UMSSM containing exotic coloured states onto observables at colliders, both present and future ones.
- Done after implementing both theoretical and experimental constraints.
- The surviving charges produce UMSSM configurations inducing phenomenological manifestations that could be probed at hadronic (HL-LHC, HE-LHC and VLH/FCC-hh) and leptonic (CLiC) accelerators.
- Collider signatures are investigated in final states capturing either the presence of the exotic states (i.e., hadronic ones) or that of electron, muons and tauons (i.e., leptonic ones) in proportions different from those predicted by the SM, possibly exploiting Z' mediation.

- A future e^+e^- machine operating well beyond the TeV scale would be the ideal laboratory almost free from backgrounds to test this dynamics while future *pp* ones would suffer from limitations connected to either small signal cross sections or overwhelming QCD noise.
- The study of the processes $e^+e^- \to$ hadrons and $e^+e^- \to l\bar{l}$ could result in the possibility of extracting the parameters of both the exotic and leptonic sector so as to guide the formulation of the true theory yielding the UMSSM as its low scale manifestation.

Thank You for Your Attention!!!