Constraints for a Z' boson with non-universal couplings in a supersymmetric model

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Outline

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- One of the important searches for the physics beyond the Standard Model (BSM) is for the $Z^{\prime}$ boson.
- It can be predicted by extensions to the SM's gauge symmetry, such as $SU(3)_C \quad SU(2)_L \quad U(1)_Y \quad U(1)_X$.
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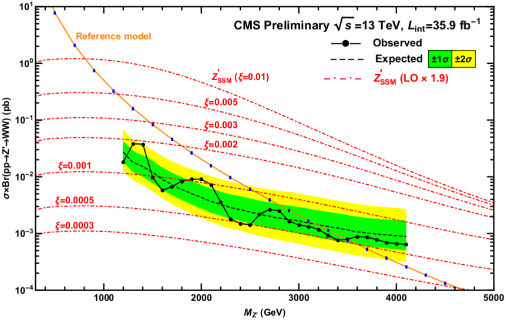

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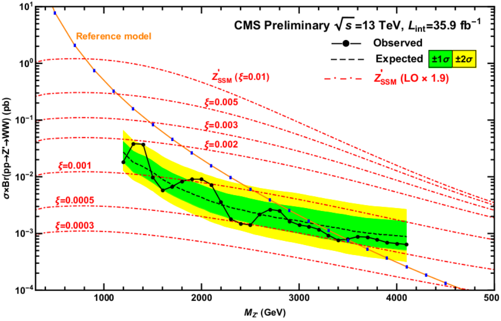

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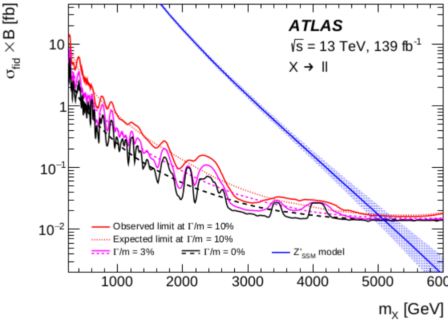

Phys. Lett. B. 197, 68-87

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The non-supersymetric model (Phys. Rev. D 95, 095037)

General Remarks

- The SM's symmetry is extended to $SU(3)_C$ $SU(2)_L$ $U(1)_Y$ $U(1)_X$ Z_2.
- The $U(1)_X$ Z_2 sector was chosen non universal for explaining naturally the fermion mass hierarchy.
- For cancelling chiral anomalies fermions fields were considered. They get their mass with a scalar singlet , that also breaks the $U(1)_X$.

Scalar bosons	X	$\mathbf{Z}_2$
Higgs doublets		
$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{h_1+v_1+i\eta_1}{\sqrt{2}} \end{pmatrix}$	$2/3$	$+$
$\phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{h_2+v_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$	$1/3$	$-$
Higgs singlets		
$\chi = \frac{\xi_\chi+v_\chi+i\zeta_\chi}{\sqrt{2}}$	$-1/3$	$+$
σ	$-1/3$	$-$

The masses of neutral vector bosons are
$M_A = 0$ M_Z $\frac{gv}{C_w}$ M_{Z^0} $\frac{g_X v}{3}$.

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$$\begin{pmatrix} A \\ Z \\ Z' \end{pmatrix} = \begin{pmatrix} S_W & C_W & 0 \\ C_W C_Z & S_W C_Z & S_Z \\ C_W S_Z & S_W S_Z & C_Z \end{pmatrix} \begin{pmatrix} W^3 \\ B \\ B' \end{pmatrix}$$

where, being $tan \quad = v_1 = v_2$,

$$\sin \quad _Z = (1 + \cos^2 \quad) \frac{2g_X \cos \quad _W}{3g} \quad \frac{M_Z}{M_{Z'}} \quad ^2$$

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The mixing between the interaction eigenstates changes respect to the SM.

Fermionic content

Quarks	X	$\mathbf{Z}_2$	Leptons	X	$\mathbf{Z}_2$
SM fermionic isospin doublets					
$q_L^1 = \begin{pmatrix} U^1 \\ D^1 \end{pmatrix}_L$	$+1/3$	$+$	$\ell_L^e = \begin{pmatrix} \nu^e \\ e^e \end{pmatrix}_L$	0	$+$
$q_L^2 = \begin{pmatrix} U^2 \\ D^2 \end{pmatrix}_L$	0	$-$	$\ell_L^\mu = \begin{pmatrix} \nu^\mu \\ e^\mu \end{pmatrix}_L$	0	$+$
$q_L^3 = \begin{pmatrix} U^3 \\ D^3 \end{pmatrix}_L$	0	$+$	$\ell_L^\tau = \begin{pmatrix} \nu^\tau \\ e^\tau \end{pmatrix}_L$	-1	$+$
SM fermionic isospin singlets					
$U_R^{1,3}$	$+2/3$	$+$	$e_R^{e,\tau}$	$-4/3$	$-$
U_R^2	$+2/3$	$-$	e_R^μ	$-1/3$	$-$
$D_R^{1,2,3}$	$-1/3$	$-$			
Non-SM quarks			Non-SM leptons		
T_L	$+1/3$	$-$	$\nu_R^{e,\mu,\tau}$	$1/3$	$-$
T_R	$+2/3$	$-$	$N_R^{e,\mu,\tau}$	0	$-$
$J_L^{1,2}$	0	$+$	$E_L, \mathcal{E}_R$	-1	$+$
$J_R^{1,2}$	$-1/3$	$+$	$\mathcal{E}_L, E_R$	$-2/3$	$+$

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The Higgs mass in a supersymetric standard model

- Supersymmetry relates fermions and bosons: They both can be merged into the superfield.
- It protects the Higgs from divergent mass renormalization.
- A second Higgs doublet superfield $\hat{}^{\prime}_{1}$ must be considered in order to cancel quantum anomalies.
- For getting the right SM's bosons masses, the vacuum expectation values shall fulfill:

$$\sqrt{v_1^2 + v_1^{\prime 2}} = v = 246 GeV$$

https://www.americanscientist.org/article/going-nowhere-fast

The Higgs mass in a supersymetric standard model

- For large tan $\;\; = v_1^{\theta}$=v_1, loop corrections due to stops should be as large as the tree level in order to get a 125 GeV mass. This can be seen from the approximate mass expression:
  $m_h^2 = m_Z^2 \cos^2 2 \;\; + \Delta m_h^2,$

  where Δm_h^2 comes from stops loop corrections.

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The Higgs sector in the supersymetric model

- The eld content is doubled for cancelling quantum anomalies.
- The VEV of the doublets are constrained by the electroweak boson masses:

$$\sqrt{v_1^2 + v_2^2 + v_1'^2 + v_2'^2} = v = 246\text{GeV}$$

The most general superpotential respecting the symmetry is given by

$$W = {}_1 \hat{\ }^0_1 \hat{\ }_1 \quad {}_2 \hat{\ }^0_2 \hat{\ }_2 \quad \hat{\ }^0 \hat{\ } \quad \hat{\ }^0 \hat{\ } + {}_1 \hat{\ }^0_1 \hat{\ }_2 \hat{\ }^0 + {}_2 \hat{\ }^0_2 \hat{\ }_1$$

Higgs potential: scalar elds

The scalar sector of the Higgs potential has three contributions:

- F-terms. $V_{F\ terms} = \sum_i F_i F_i$, where $F_i = \frac{@W[A_1;A_2;:::;A_n]}{@A_i}$.
- D-terms. $V_{D\ terms} = \sum_s D^a_s D^a_s$, with $D^a_s = g_s T^a_{ij} A_i A_j$. This part ensures the gauge symmetry.
- Soft-supersymmetry breaking potential:

$$V_{soft} = m_1^2 {}^y_1 {}_1 \quad m_1^{02} {}^{0y}_1 {}^0_1 \quad m_2^2 {}^y_2 {}_2 \quad m_2^{02} {}^{0y}_2 {}^0_2 \quad m^2 {}^y \quad m^{02} {}^{0y} {}^0 \quad m^2 {}^y \quad m^{02} {}^{0y} {}^0$$
$$+ {}^2_{11} {}_{ij} ({}^{0i}_1 {}^j_1) + {}^2_{22} {}_{ij} ({}^{0i}_2 {}^j_2) + {}^2 ({}^0) + {}^2 ({}^0) \quad \sim_1 {}^{0y}_1 {}_2 {}^0 \quad \sim_2 {}^{0y}_2 {}_1$$
$$+ \frac{2^p \bar{2}}{9} (k_1 {}^y_1 {}_2 {}^0 \quad k_2 {}^y_1 {}_2 \quad + k_3 {}^{0y}_1 {}^0_2 \quad k_4 {}^{0y}_1 {}^0_2 {}^0) + h{:}c{:}$$

The last terms break also the parity symmetry. If they weren't there, there would be scalar particles lighter than the Higgs boson.

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Scalar mass spectrum

Charged bosons: There is a goldstone boson that gives mass to the W particles. Additionally, there are three masive charged scalar particles with a mass at the soft-SUSY breaking scale and also the $U(1)_X$ breaking scale.

CP-odd bosons: There are two goldstone bosons that give mass to Z and Z'. There are additionally 6 massive CP-odd particles, also at the soft-SUSY breaking scale and the $U(1)_X$ breaking scale.

CP-even masses: There is a scalar boson at the electroweak scale. The other 7 massive particles of this kind are on the other higher energy scales. The mass of the lightest can be written as:

$$m_h^2 \quad m_Z^2 \quad \cos^2 2\tilde{} + \frac{4}{9}\frac{g_X^2}{g^2 + g'^2}(\cos 2 \ _1 + \cos 2 \ _2)^2$$

where $\tan^2 \tilde{} = \frac{v_1^2 + v_2^2}{v_1'^2 + v_2'^2}$, $\tan \ _1 = \frac{v_1}{v_1'}$ and $\tan \ _2 = \frac{v_2}{v_2'}$.

Higgs boson mass constraints on the new interaction

The squared Higgs mass gets a contribution proportional to the square coupling constant g_X^2.

A Montecarlo exploration was made on the parameter space v_1^0 vs g_X and v_2 vs g_X for obtaining the Higgs mass 125.3 ± 0.4 GeV at 95% confidence level.

Since $m_t \propto v_1$ and $m_b \propto v_2^0$, the domains for the exploration were $[170 - 200]$GeV and $[3 - 7]$GeV respectively. v_2 had full freedom, $[0 - 246]$GeV. v_1^0 is then constrained for obtaining the right SM boson masses, $v_1^0 = \sqrt{v^2 - v_1^2 - v_2^{0\,2} - v_2^2}$.

Z' interaction with SM bosons and fermions

The previous results showed that $g_X > 0.63$. This gives strong implications on the lower mass bounds of the Z'.

The Z' interacts with the W bosons due to a mixing with Z:

$$\begin{pmatrix} A \\ Z \\ Z' \end{pmatrix} = \begin{pmatrix} s_W & c_W & 0 \\ c_W c_Z & s_W c_Z & s_Z \\ c_W s_Z & s_W s_Z & c_Z \end{pmatrix} \begin{pmatrix} B \\ W^3 \\ B' \end{pmatrix}$$

where, being $\tan\beta = \sqrt{v_1^2 + v_1'^2} / \sqrt{v_2^2 + v_2'^2}$,

$$\sin\theta_Z = (1 + \cos^2\beta) \frac{2g_X \cos\theta_W}{3g} \left(\frac{M_Z}{M_{Z'}} \right)^2$$

The Z' also interacts with SM's fermions

$$\mathcal{L}_{int;QB'} = \frac{g_X}{3} \bar{u}^i \gamma^\mu P_L u^i B'_\mu + \frac{2g_X}{3} \bar{u}^i \gamma^\mu P_R u^i B'_\mu + \frac{g_X}{3} \bar{d}^i \gamma^\mu P_L d^i B'_\mu \quad \frac{g_X}{3} \bar{d}^i \gamma^\mu P_R d^i B'_\mu ;$$

$$\mathcal{L}_{int;eB'} = \quad \frac{4g_X}{3} \bar{e}^e \gamma^\mu P_R e^e B'_\mu \quad \frac{g_X}{3} \bar{e}^\mu \gamma^\mu P_R e^\mu B'_\mu \quad g_X \bar{e}^\tau \gamma^\mu P_L e^\tau B'_\mu \quad \frac{4g_X}{3} \bar{e}^\tau \gamma^\mu P_R e^\tau B'_\mu$$

The total cross sections of the decays $pp \to W^+W^-$ and $pp \to l^+l^-$ were calculated using MADGRAPH5 together with PHYTHIA 6 for introducing the PDF and parton shower, and Delphes 3 for detector simulation.

Z' constraints from $pp \to w^+ w^-$ and $pp \to l^+ l^-$

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Conclusions

- The Higgs boson mass gets a contribution from the D-term coming from $U(1)_X$ at tree level.
- For obtaining a mass of 125 GeV Higgs boson, the coupling constant of the new symmetry is bounded from below, $g_X > 0:63$.
- Diboson production constraints the Z' mass to be $M_{Z^0} > 5$ TeV, similar with analyses from other authors. However, since $g_X > 0:63$, the dilepton production constraints were much stronger, giving approximately $M_{Z^0} > 8$ TeV.

References

Constraints from other authors:

- Phys. Rev. D 96, 055040
- Phys. Lett. B. 197, 68-87

The non-supersymmetric model

- Phys. Rev. D 95, 095037

The supersymmetric model

- Phys. Rev. D 100, 055037

Other $U(1)_X$ extended models

- J. High Energy Phys. 05 113
- Phys. Rev. D 89, 056008
- Phys. Rev. D 98, 015038

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