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

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# Outline

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# The Z' boson

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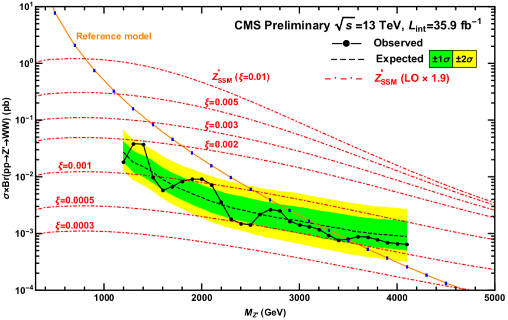


Phys. Rev. D 96, 055040

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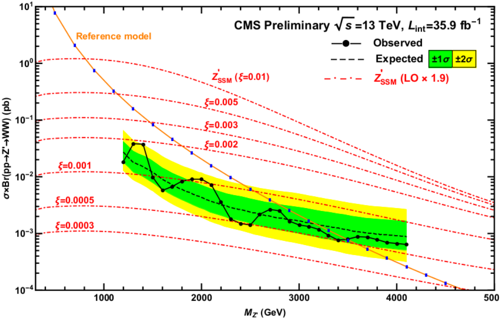


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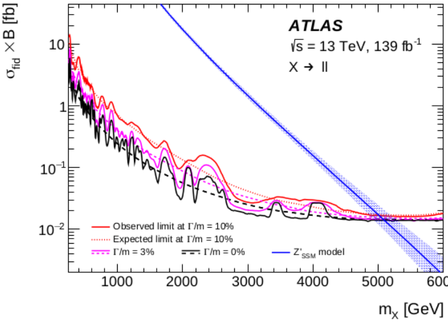


Phys. Lett. B. 197, 68-87

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

## General Remarks

- The SM's symmetry is extended to $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X \times \mathbb{Z}_2$.
- The $U(1)_X \times \mathbb{Z}_2$ 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 $\chi$, that also breaks the $U(1)_X$.

| Scalar bosons | $X$ | $\mathbb{Z}_2$ |
|---|---|---|
| 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 | | |
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| $\sigma$ | $-1/3$ | $-$ |

The masses of neutral vector bosons are

$M_A = 0 \qquad M_Z \approx \frac{gv}{C_w} \qquad M_{Z'} \approx \frac{g_X v_\chi}{3}$.

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$$\begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix} = \begin{pmatrix} S_W & C_W & 0 \\ C_W C_Z & -S_W C_Z & S_Z \\ -C_W S_Z & S_W S_Z & C_Z \end{pmatrix} \begin{pmatrix} W^3_\mu \\ B_\mu \\ B'_\mu \end{pmatrix}$$

where, being $tan\beta = v_1/v_2$,

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

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

# Fermionic content

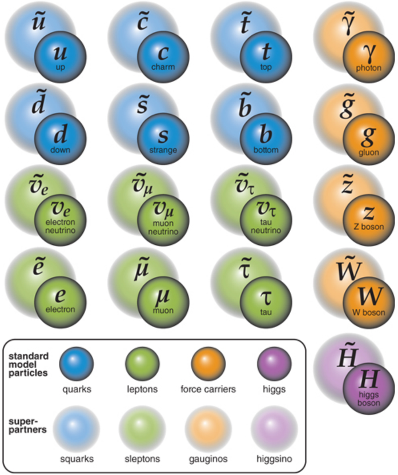
| Quarks | $X$ | $\mathbf{Z}_2$ | Leptons | $X$ | $\mathbf{Z}_2$ |
|---|---|---|---|---|---|
| SM fermionic isospin doublets | | | | | |
| $q_L^1 = \begin{pmatrix} U^1 \\ D^1 \end{pmatrix}_L$ | $+1/3$ | $+$ | $\ell_L^e = \begin{pmatrix} \nu^e \\ e^e \end{pmatrix}_L$ | $0$ | $+$ |
| $q_L^2 = \begin{pmatrix}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

# Outline

# 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 $\hat{\phi}_1'$ must be considered in order to cancel quantum anomalies.
- For getting the right SM's bosons masses, the vacuum expectation values shall fulfill:

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

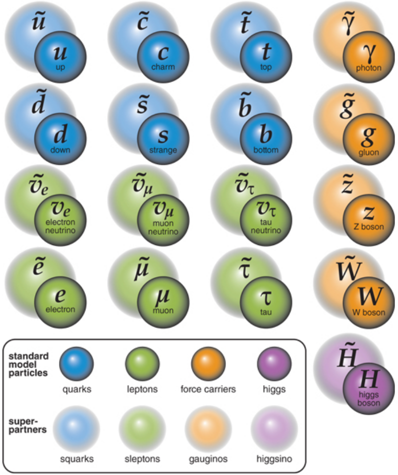



https://www.americanscientist.org/article/going-nowhere-fast

# The Higgs mass in a supersymetric standard model

- For large $\tan\beta = v_1'/v_1$, 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:
  $m_h^2 = m_Z^2 \cos^2 2\beta + \Delta m_h^2,$

  where $\Delta m_h^2$ comes from stops loop corrections.

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# The Higgs sector in the supersymetric model

| Higgs Doublets | $X^{\pm}$ | $Y$ | Higgs Singlets | $X^{\pm}$ | $Y$ |
|---|---|---|---|---|---|
| $\hat{\Phi}_1 = \begin{pmatrix} \hat{\phi}_1^{+} \\ \frac{\hat{h}_1+v_1+i\hat{\eta}_1}{\sqrt{2}} \end{pmatrix}$ | $+2/3^{+}$ | $+1$ | $\hat{\chi} = \frac{\hat{\xi}_\chi+v_\chi+i\hat{\zeta}_\chi}{\sqrt{2}}$ | $-1/3^{+}$ | $0$ |
| $\hat{\Phi}_2 = \begin{pmatrix} \hat{\phi}_2^{+} \\ \frac{\hat{h}_2+v_2+i\hat{\eta}_2}{\sqrt{2}} \end{pmatrix}$ | $+1/3^{-}$ | $+1$ | $\sigma = \frac{\hat{\sigma}_\chi+i\hat{\zeta}_\sigma}{\sqrt{2}}$ | $-1/3^{-}$ | $0$ |
| $\hat{\Phi}'_1 = \begin{pmatrix} \frac{\hat{h}'_1+v'_1+i\hat{\eta}'_1}{\sqrt{2}} \\ \hat{\phi}_1^{-\prime} \end{pmatrix}$ | $-2/3^{+}$ | $-1$ | $\hat{\chi}' = \frac{\hat{\xi}'_\chi+v'_\chi+i\hat{\zeta}'_\chi}{\sqrt{2}}$ | $+1/3^{+}$ | $0$ |
| $\hat{\Phi}'_2 = \begin{pmatrix} \frac{\hat{h}'_2+v'_2+i\hat{\eta}'_2}{\sqrt{2}} \\ \hat{\phi}_2^{-\prime} \end{pmatrix}$ | $-1/3^{-}$ | $-1$ | $\sigma' = \frac{\hat{\xi}'_\sigma+i\hat{\zeta}'_\sigma}{\sqrt{2}}$ | $+1/3^{-}$ | $0$ |

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

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

The most general superpotential respecting the symmetry is given by
$W_\phi = -\mu_1\hat{\Phi}'_1\hat{\Phi}_1 - \mu_2\hat{\Phi}'_2\hat{\Phi}_2 - \mu_\chi\hat{\chi}'\hat{\chi} - \mu_\sigma\hat{\sigma}'\hat{\sigma} + \lambda_1\hat{\Phi}'_1\hat{\Phi}_2\hat{\sigma}' + \lambda_2\hat{\Phi}'_2\hat{\Phi}_1\sigma$

# Higgs potential: scalar fields

The scalar sector of the Higgs potential has three contributions:

- F-terms. $V_{F-terms} = \sum_i F_i^* F_i$, where $F_i^* = -\frac{\partial W[A_1, A_2, \ldots, A_n]}{\partial A_i}$.
- D-terms. $V_{D-terms} = \sum_s D_s^a D_s^a$, with $D_s^a = -g_s T_{ij}^a A_i^* A_j$. This part ensures the gauge symmetry.
- Soft-supersymmetry breaking potential:

$$\begin{aligned} V_{soft} &= -m_1^2 \Phi_1^\dagger \Phi_1 - m_1'^2 \Phi_1'^\dagger \Phi_1' - m_2^2 \Phi_2^\dagger \Phi_2 - m_2'^2 \Phi_2'^\dagger \Phi_2' - m_\chi^2 \chi^\dagger \chi - m_\chi'^2 \chi'^\dagger \chi' - m_\sigma^2 \sigma^\dagger \sigma - m_\sigma'^2 \sigma'^\dagger \sigma' \\ &+ \Big[ \mu_{11}^2 \epsilon_{ij} (\Phi_1'^i \Phi_1^j) + \mu_{22}^2 \epsilon_{ij} (\Phi_2'^i \Phi_2^j) + \mu_{\chi\chi}^2 (\chi \chi') + \mu_{\sigma\sigma}^2 (\sigma \sigma') - \tilde{\lambda}_1 \Phi_1'^\dagger \Phi_2 \sigma' - \tilde{\lambda}_2 \Phi_2'^\dagger \Phi_1 \sigma \\ &+ \frac{2\sqrt{2}}{9} (k_1 \Phi_1^\dagger \Phi_2 \chi' - k_2 \Phi_1^\dagger \Phi_2 \chi^* + k_3 \Phi_1'^\dagger \Phi_2' \chi - k_4 \Phi_1'^\dagger \Phi_2' \chi'^*) + h.c. \Big] \end{aligned}$$

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

# Outline

# Scalar mass spectrum

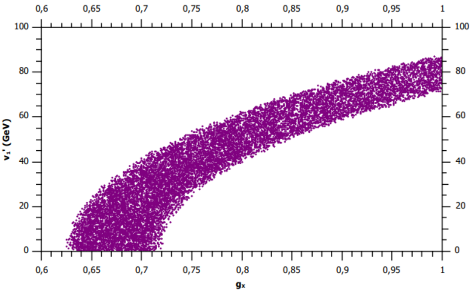
- **Charged bosons:** There is a goldstone boson that gives mass to the $W^{\pm}$ particles. Additionally, there are three masive charged scalar particles with a mass at the soft-SUSY breaking scale and also the $U(1)_X$ breaking scale.
- **CP-odd bosons:** There are two goldstone bosons that give mass 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:

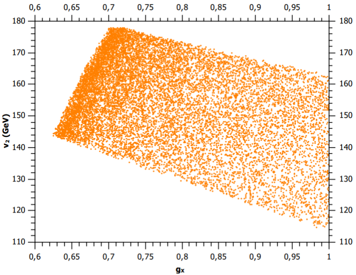
$$m_h^2 \approx m_Z^2 \left( cos^2 2\tilde{\beta} + \frac{4}{9} \frac{g_X^2}{g^2 + g'^2} (cos 2\beta_1 + \cos 2\beta_2)^2 \right)$$

where $\tan^2 \tilde{\beta} = \frac{v_1^2 + v_2^2}{v_1'^2 + v_2'^2}$, $\tan \beta_1 = \frac{v_1}{v_1'}$ and $\tan \beta_2 = \frac{v_2}{v_2'}$.

# 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 $v_1'$ vs $g_X$ and $v_2$ vs $g_X$ for obtaining the Higgs mass $125.3 \pm 0.4$ GeV at 95% confidence level.
- Since $m_t \sim v_1$ and $m_b \sim v_2'$, the domains for the exploration were $[170 - 200]$GeV and $[3 - 7]$GeV respectively. $v_2$ had full freedom, $[0 - 246]$GeV. $v_1'$ is then constrained for obtaining the right SM boson masses, $v_1' = \sqrt{v^2 - v_1^2 - v_2'^2 - v_2^2}$.



# 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 $W^{\pm}$ bosons due to a mixing with Z:

$$\begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix} = \begin{pmatrix} S_W & C_W & 0 \\ C_W C_Z & -S_W C_Z & S_Z \\ -C_W S_Z & S_W S_Z & C_Z \end{pmatrix} \begin{pmatrix} W^3_\mu \\ B_\mu \\ B'_\mu \end{pmatrix}$$

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

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

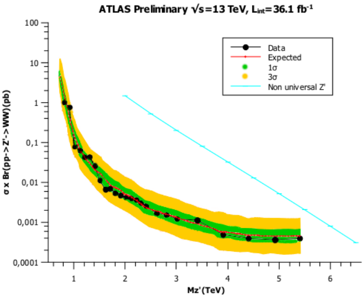
The $Z'$ also interacts with SM's fermions

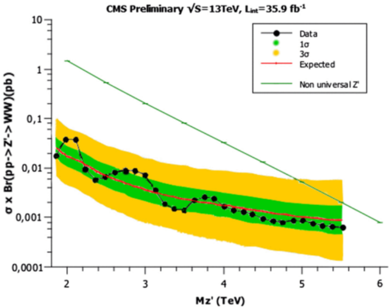
$$\begin{aligned}\mathcal{L}_{int,QB'} &= \frac{g_X}{3}\bar{u}^1\gamma^\mu P_L u^1 B'_\mu + \frac{2g_X}{3}\bar{u}^i\gamma^\mu P_R u^i B'_\mu \\ &+ \frac{g_X}{3}\bar{d}^1\gamma^\mu P_L d^1 B'_\mu - \frac{g_X}{3}\bar{d}^i\gamma^\mu P_R d^i B'_\mu,\end{aligned}$$

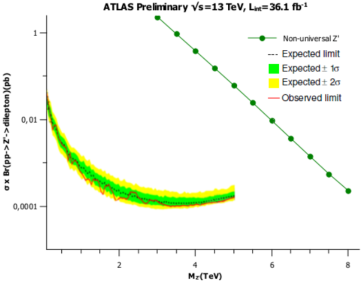
$$\begin{aligned}\mathcal{L}_{int,eB'} &= -\frac{4g_X}{3}\bar{e}^e\gamma^\mu P_R e^e B'_\mu - \frac{g_X}{3}\bar{e}^\mu\gamma^\mu P_R e^\mu B'_\mu \\ &- g_X\bar{e}^\tau\gamma^\mu P_L e^\tau B'_\mu - \frac{4g_X}{3}\bar{e}^\tau\gamma^\mu P_R e^\tau B'_\mu\end{aligned}$$

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

# Z' constraints from $p\bar{p} \to w^+w^-$ and $p\bar{p} \to l^+l^-$



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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 $M_{Z'} > 5$ TeV, similar with analyses from other authors. However, since $g_X > 0.63$, the dilepton production constraints were much stronger, giving approximately $M_{Z'} > 8$ 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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