Georgi-Machacek model: a benchmark for Higgs triplets

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Introduction

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$\rightarrow$ **Scalar particle discovered in 2012 with mass of $\sim$ 125 GeV at the Large Hadron Collider (LHC)**.
ATLAS, Phys.Lett. B716 (2012), and CMS, Phys. Lett. B 716 (2012).

The SM is complete but we know it cannot be the whole story.

- Gravity.
- Neutrinos' masses.
- Enough CP-violation: to support Sakharov's condition for baryogenesis.
- Dark Matter: Several indirect evidence: Galaxy rotation curves, Gravitational lensing, Cosmic microwave background, etc.
- ...

Extensions of the SM scalar sector tackle some of these!

LHC's experimental data is SM-like:
$\rightarrow$ Pushing more precise computations and/or elaborate models with new phenomenological signatures.

Motivation for the Georgi-Machacek (GM) model for triplet studies

In the SM, the ρ parameter is the ratio between the strengths of neutral to charged currents

$$\rho = \left(\frac{g^2}{c_W^2 M_Z^2}\right) \times \left(\frac{g^2}{M_W^2}\right)^{-1} = \frac{M_W^2}{c_W^2 M_Z^2} = 1 \text{ (in the SM at tree-level).} \quad (1)$$

Measured value: $\rho = 1.00039 \pm 0.00019$ [global fit - PDG]

As we explore triplets and higher dimentional representations

$$\rho = \frac{\sum_i c_i [T_i(T_i+1) - Y_i^2/4] v_i^2}{\sum_i Y_i^2 v_i^2/2}, \quad (2)$$

- Model with triplets that enables Gauge-Higgs bosons couplings larger than the SM while maintaining $\rho = 1$ at tree-level, without fine-tuning.
- It is a natural benchmark model for collider analysis with triplets.
- The $\mathbb{Z}_2$ symmetry version allows for a dark matter sector.

Goal:
→ study the vacuum structure,
→ to check for unphysical global minima that might coexist with physical metastable vacua,
→ in order to constrain the parameter space.

The $\mathbb{Z}_2$ Georgi-Machacek

Georgi-Machacek (GM) model

1985

First proposed by Georgi and Machacek, and later (same year) by Chanowitz and Golden in 1985.

Consists of usual doublet Φ ($T = 1/2$) plus two triplets ($T = 1$) written in bi-tuplet representation

Real Ξ (Y=0) and **complex** χ with Y=2

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{+*} & \phi^{0} \end{pmatrix}, \qquad X = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+} \\ \chi^{++*} & -\xi^{+*} & \chi^{0} \end{pmatrix} \tag{3}$$

where the $SU(2)_L \times SU(2)_R$ transformation can be written as

$$(\Phi' \text{ or } X') = \exp(iT^a\theta_L^a)(\Phi \text{ or } X)\exp(-iT^b\theta_R^b). \tag{4}$$

Most general potential for $SU(2)_L \times SU(2)_R$ global symmetry

$$\begin{aligned} V(\Phi, X) = {} & \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) \\ & + \lambda_3\mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)\mathrm{Tr}(X^\dagger t^a X t^b) \\ & - M_1\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)(UXU^\dagger)_{ab} - M_2\mathrm{Tr}(X^\dagger t^a X t^b)(UXU^\dagger)_{ab}. \end{aligned} \tag{5}$$

$\mathbb{Z}_2$ symmetric potential, $X \to -X$

Potential

$$V(\Phi, X) = \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_2 \mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) + \lambda_3 \mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5 \mathrm{Tr}(\Phi^\dagger \tau^a \Phi \tau^b)\mathrm{Tr}(X^\dagger t^a X t^b)$$

Given the symmetries the most general vacuum expectation value (VEV) for the fields reads

Two $SU(2)_L \times SU(2)_R$ transformations, first with $\theta_L = \theta_R$ and second $\theta_L = -\theta_R$

$$\Phi = \begin{pmatrix} v_1 & 0 \\ 0 & v_1 \end{pmatrix}, \qquad X = \begin{pmatrix} v_8 - iv_9 & v_6 & 0 \\ -v_{10} + iv_{11} & v_5 & v_{10} + iv_{11} \\ 0 & -v_6 & v_8 + iv_9 \end{pmatrix}. \tag{6}$$

There are at least two possible vacua:

- **Dark Matter vacuum** - $(v_1 \neq 0 \wedge v_i = 0) \Rightarrow \rho = 1$ at and $\mathbb{Z}_2$ symmetry is not spontaneously broken.
- **Custodial vacuum** - $(v_1 \neq 0 \wedge v_5 = v_8 \wedge v_i = 0) \Rightarrow \rho = 1$ at tree-level.

We started by setting the imaginary part to zero!

Unphysical vacua

Charge-breaking (5 solutions)

1. $v_5 = v_8 = 0$
2. $v_1 = v_5 = v_8 = 0 \wedge v_6 = \pm v_{10}$
3. $v_5 = v_8 = 0 \wedge v_6 = \pm v_{10}$

Corresponding gauge bosons' mass matrix (W^1, W^2, W^3, B)

$$M^2 = \begin{pmatrix} \frac{1}{4}g^2\left(v_1^2 + 4v_{10}^2\right) & 0 & 0 & 0 \\ 0 & \frac{1}{4}g^2\left(v_1^2 + 4\left(v_6^2 + v_{10}^2\right)\right) & 0 & 0 \\ 0 & 0 & \frac{1}{4}g^2\left(v_1^2 + 4v_6^2\right) & -\frac{1}{4}v_1^2 g g' \\ 0 & 0 & -\frac{1}{4}v_1^2 g g' & \frac{1}{4}g'^2\left(v_1^2 + 4v_{10}^2\right) \end{pmatrix} \tag{7}$$

There is no null eigenvalue $\rightarrow$ photon is massive!

Wrong-Electroweak (Hypercharge is not spontaneously broken, 2 solutions)

1. $v_1 = v_8 = v_{10} = 0$
2. $v_1 = v_5 = v_8 = v_{10} = 0$

Corresponding gauge bosons' mass matrix (W^1, W^2, W^3, B)

$$M^2 = \begin{pmatrix} g^2 v_5^2 & 0 & g^2 v_5 v_6 & 0 \\ 0 & g^2\left(v_5^2 + v_6^2\right) & 0 & 0 \\ g^2 v_5 v_6 & 0 & g^2 v_6^2 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{8}$$

There are two null eigenvalues $\rightarrow$ Only two gauge bosons are massive!

Bilinear formalism and some results

The symmetric version of the potential allows to use the bilinear formalism, since there are no cubic terms

$$V = A^T X + \frac{1}{2} X^T B X \tag{9}$$

with A, B a vector and a matrix, respectively, of the parameters of the potential and X a vector of the VEVs.

Let X_1 and X_2 be two different coexisting vacua, let also V_1' and V_2' be the gradient of the potential at those minima, respectively, then it follows that

Relative heights

$$V_2 - V_1 = \frac{1}{2}(X_2^T V_1' - X_1^T V_2') \tag{10}$$

The right-hand terms can be written as a function of physical observables of one of the vacua, such as masses.

This allows to check the height relationship based on physical quantities of one vacuum alone.

Charge-breaking vs. dark matter

- For CB1 vs. DM:
  - for $\lambda_5 > 0$

$$V_{CB1} - V_{DM} = \frac{1}{2}(v_{6,CB1}^2 + v_{10,CB1}^2)m_{2,DM}^2 + \frac{1}{4}v_{1,CB1}^2\lambda_5(v_{6,CB1} - v_{10,CB1})^2 > 0 \qquad (11)$$

  - for $\lambda_5 < 0$

$$V_{CB1} - V_{DM} = \frac{1}{2}(v_{6,CB1}^2 + v_{10,CB1}^2)m_{1,DM}^2 - \frac{1}{4}v_{1,CB1}^2\lambda_5(v_{6,CB1} + v_{10,CB1})^2 > 0 \qquad (12)$$

- For CB2 vs. DM:

$$V_{CB2} - V_{DM} = \frac{1}{2}v_{6,CB2}^2 m_{1,DM}^2 > 0 \qquad (13)$$

- For CB3 vs. DM:

$$V_{CB3} - V_{DM} = \frac{1}{6}v_{6,CB3}^2(m_{1,DM}^2 + 2m_{2,DM}^2) > 0 \qquad (14)$$

- For CB4/5 vs. DM:

$$\boxed{V_{CB4/5} - V_{DM} = \frac{1}{64\lambda_1}\left(m_{h,DM}^2 + 32\lambda_1\mu_3^2 v_{6,CB4/5}^2\right)} \qquad (15)$$

Conclusions

Conclusion

- ...still ongoing project.
- Theory: understand the symmetry breaking patterns with triplets using the GM model.
- Catalog the vacua and constrain the parameter space from the theory side.
- Search for unique phenomenological signatures, specially for DM searches.

Thank you!

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