Georgi-Machacek and Beyond

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Outline

1. Introductory motivations
2. The Model
   - pre-custodial
   - Georgi-Machacek
   - The ρ parameter
   - The custodial multiplets
   - $\delta\rho$ in Georgi-Machacek
3. 'conclusion'

Introductory motivations

Many motivations to go beyond the SM, that we all know!

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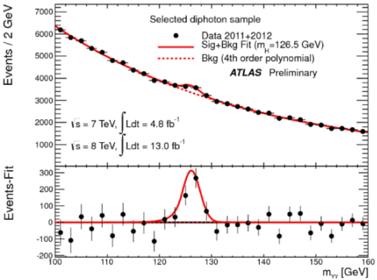

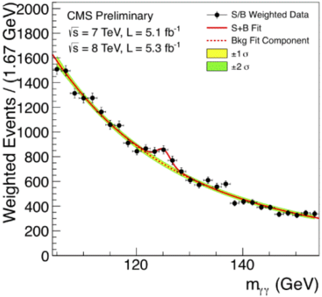

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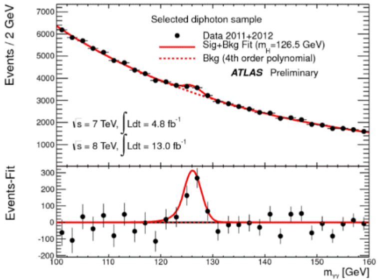

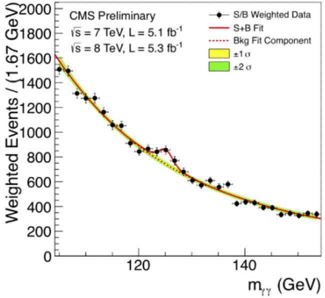

a theorem by Nelson Mandela

(not to be confused with the Coleman-Mandula theorem)

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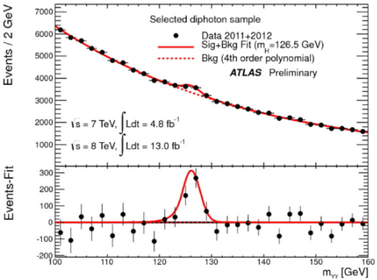

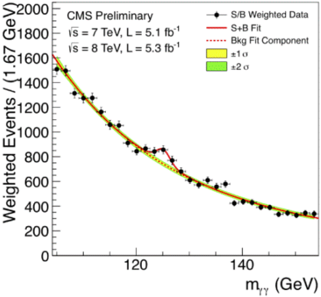

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$\rightarrow$ Some SM-extensions with scalar triplets can relate this to Majorana neutrinos masses; e.g. type-II seesaw,

$$\mathcal{L}_{Yukawa} \supset Y_\nu L^T C \otimes i\sigma_2 \underset{\substack{\downarrow \\ SU(2)_L \text{triplet}}}{A} L$$

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The scalar sector consists of the standard Higgs weak doublet H and two colorless scalar fields A, B transforming as triplets under the $SU(2)_L$ gauge group with hypercharges $Y_A = 2$, $Y_B = 0$:

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$H \sim (1, 2, 1)$, $A \sim (1, 3, 2)$, $B \sim (1, 3, 0)$ under $SU(3)_c \times SU(2)_L \times U(1)_Y$.

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$$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \; A = \frac{1}{\sqrt{2}} \begin{pmatrix} \chi^+/\sqrt{2} & -\chi^{++} \\ \chi^0 & -\chi^+/\sqrt{2} \end{pmatrix}, \; B = \frac{1}{\sqrt{2}} \begin{pmatrix} \xi^0/\sqrt{2} & -\xi^+ \\ -\xi^{+*} & -\xi^0/\sqrt{2} \end{pmatrix}$$

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The most general, renormalizable, $SU(2)_L \times U(1)_Y$-invariant Lagrangian:

$$H \to e^{i\alpha}\mathcal{U}_L H, \;\; A \to e^{i2\alpha}\mathcal{U}_L A \mathcal{U}_L^\dagger, \;\; B \to \mathcal{U}_L B \mathcal{U}_L^\dagger,$$

$$\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) + Tr[(D_\mu A)^\dagger (D^\mu A)] + \frac{1}{2} Tr[(D_\mu B)^\dagger (D^\mu B)] - V(H, A, B) + \mathcal{L}_{Yukawa} + \dots$$

The model: pre-custodial

$$V_{\text{p-c}} = V_{\text{p-c}}^{(2,3)} + V_{\text{p-c}}^{(4)}$$

dim-2, -3 operators

$$\begin{aligned} V_{\text{p-c}}^{(2,3)} &= -m_H^2 H^\dagger H + M_A^2 Tr(AA^\dagger) + \frac{1}{2} M_B^2 Tr(B^2) \\ &+ [\mu_A (H^T i\sigma^2 A^\dagger H) + \text{h.c.}] + \mu_B H^\dagger B H + \mu_{AB} Tr(AA^\dagger B), \end{aligned}$$

dim-4 operators

$$\begin{aligned} V_{\text{p-c}}^{(4)} &= \frac{\lambda_H}{4}(H^\dagger H)^2 + \frac{\lambda_A^{(1)}}{4}(Tr\, AA^\dagger)^2 + \frac{\lambda_A^{(2)}}{4} Tr(AA^\dagger)^2 + \frac{\lambda_B}{4!}(TrB^2)^2 \\ &+ \lambda_{AH}^{(1)} H^\dagger H \; Tr\, AA^\dagger + \lambda_{AH}^{(2)} H^\dagger A A^\dagger H + \frac{\lambda_{BH}}{2} H^\dagger H \; TrB^2 \\ &+ \frac{\lambda_{AB}^{(1)}}{2} Tr\, AA^\dagger \; TrB^2 + \frac{\lambda_{AB}^{(2)}}{2} Tr\, AB \; Tr\, A^\dagger B \\ &+ \frac{i}{2} \lambda_{ABH} (H^\top \sigma^2 A^\dagger B H - H^\dagger B A \sigma^2 H^*). \end{aligned}$$

The model: pre-custodial $\to$ Georgi-Machacek

To increase the symmetry of the purely scalar sector to $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}^\mathrm{global}$, correlations (fine-tuning) are needed among (tree-level) mass parameters and couplings $\to$ GM model:

$$M_A^2 = M_B^2, \; \mu_B = \sqrt{2}\mu_A,$$

$$\lambda_A^{(1)} = 2\lambda_{AB}^{(1)} + 3\lambda_{AB}^{(2)}, \; \lambda_A^{(2)} = -2\lambda_{AB}^{(2)}, \; \lambda_{ABH} = \sqrt{2}\lambda_{AH}^{(2)},$$
$$\lambda_B = 3(\lambda_{AB}^{(1)} + \lambda_{AB}^{(2)}), \; \lambda_{BH} = \lambda_{AH}^{(1)} + \frac{1}{2}\lambda_{AH}^{(2)} \, .$$

The model: Georgi-Machacek

$$\mathcal{L} = \frac{1}{2} Tr[(D_\mu \Phi)^\dagger (D^\mu \Phi)] + \frac{1}{2} Tr[(D_\mu X)^\dagger (D^\mu X)] - V_{\text{G-M}} + \mathcal{L}_{Yukawa} + \dots$$

$$V_{\text{G-M}} = V^{(2,3)}_{\text{G-M}} + V^{(4)}_{\text{G-M}}$$

$$\begin{aligned} V^{(2,3)}_{\text{G-M}} =& \frac{\mu_2^2}{2} Tr\Phi^\dagger\Phi + \frac{\mu_3^2}{2} TrX^\dagger X \\ & - \left(M_1 Tr\Phi^\dagger \tau^a \Phi \tau^b + M_2 TrX^\dagger t^a X t^b \right) (UXU^\dagger)_{ab} \\ V^{(4)}_{\text{G-M}} =& \hat{\lambda}_1 (Tr\Phi^\dagger\Phi)^2 + \hat{\lambda}_2 Tr(\Phi^\dagger\Phi) Tr(X^\dagger X) + \hat{\lambda}_3 Tr(X^\dagger X X^\dagger X) \\ & + \hat{\lambda}_4 (TrX^\dagger X)^2 - \hat{\lambda}_5 Tr(\Phi^\dagger \tau^a \Phi \tau^b) Tr(X^\dagger t^a X t^b) \end{aligned}$$

$$\Phi \equiv \begin{pmatrix} \overset{H^c}{\phi^{0*}} & \overset{H}{\phi^+} \\ -\phi^{+*} & \phi^0 \end{pmatrix}, X \equiv \begin{pmatrix} \overset{A^c}{\chi^{0*}} & \overset{B}{\xi^+} & \overset{A}{\chi^{++}} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix}$$

The model: Georgi-Machacek

...the gauge/scalar sector

$$\frac{1}{2} Tr[(D_\mu \Phi)^\dagger (D^\mu \Phi)] + \frac{1}{2} Tr[(D_\mu X)^\dagger (D^\mu X)] - V_{\text{G-M}}$$

invariant under: $\Phi \to U_L \Phi U_R^\dagger$ & $X \to U_L X U_R^\dagger$ for $g'_{U(1)_Y} \to 0$

$$\mathrm{SU(2)_L \times SU(2)_R} \xrightarrow[\text{EWSB}]{??} \mathrm{SU(2)_{L+R}} \equiv \mathrm{SU(2)_{custodial}}$$

only if $U_{L+R} \langle X \rangle U_{L+R}^\dagger = \langle X \rangle$, i.e. iff $\langle A \rangle = \langle B \rangle$.

The ρ parameter

Recall: $$\rho := \frac{M_W^2}{M_Z^2 \cos^2\theta_W},$$

$$\text{“}\rho_0^{Fit}\text{”} = 1.00038 \pm 0.00020 \ \ (\mathrm{PDG2020})$$

$$\rho_{tree}^{theo} = \frac{\sum v_i^2 \left[I_i(I_i+1) - \frac{1}{4}Y_i^2\right]}{\sum \frac{1}{2} v_i^2 Y_i^2} (\text{@tree} - \text{level, general})$$

$\rightarrow$ depends on the group reps. and possibly on the vacuum structure.

$\rightarrow$ $\rho_{tree}^{theo} = 1$, $\forall v_i$ for:

- $I_i = \frac{1}{2}, 0$; $Y_i = 1, 0$, Higgs doublet + replicas + singlets,
- but also for more exotic replicas, $I_i = 3, \frac{25}{2}, 48, \frac{361}{2}, \ldots; Y_i = 4, 15, 56, 209, \ldots$

$\rightarrow$ or, $\rho_{tree}^{theo} = 1$ for special relations between the v_i $\rightarrow$ dynamics?

e.g. SM + 1 complex and 1 real n-plets, with $\mathrm{n} > 2$

- $I_A = I_B = 1$, 8, 49,..., $Y_A = 2$, 12, 70,..., $Y_B = 0$;
- $I_A = I_B = 2$, 24,..., $Y_A = 3$, 30,..., $Y_B = 0$;
- etc.

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Let us look under the light of symmetries

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$H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--}$
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4 physical masses:

- 5 degenerate states with mass m_5
- 3 degenerate states with mass m_3
- m_{h^0}, m_{H^0}

and some selection rules,
e.g. $H^0_{3,5} \not\rightarrow h^0 h^0, H^0 H^0, h^0 H^0$, no coupling of H_5 to fermions, ...

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But rad. corr. break $\mathrm{SU}(2)_{\mathrm{custodial}}$ and the degeneracy and the selection rules...

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In particular the presence of a doubly-charged state opens up possibilities not allowed by $\mathrm{SU(2)_L}$ doublets/singlets:
e.g. unitarity in the *WW* scattering $\rightarrow$ sum rules:

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$\rightarrow$ this and other similar sum-rules allow non-standard neutral scalar states to have larger couplings to *WW* (*ZZ*) than in the SM!

$\delta\rho$ in Georgi-Machacek

$\rightarrow$ radiative corrections to the ρ parameter: different status of custodial symmetry breaking with triplets as compared to doublets!

- in the SM beyond tree-level, $\rho = 1 + \delta\rho$ with $\delta\rho$ finite and uniquely defined
- in the GM model $\delta\rho$ is divergent and needs to be renormalized. Also, divergent $H_5 - H_3$, $H_5^+ - W^+$ mixings.

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→ many of the pheno features of the GM become renormalization scheme and scale dependent...(including precision observables, $\delta\rho$, M_W, *etc.*).

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La parole est à François