XVIII Mexican Workshop on Particles and Fields
November 21st - 25th

Reduction of couplings in two-Higgs-doublet models with natural flavour conservation

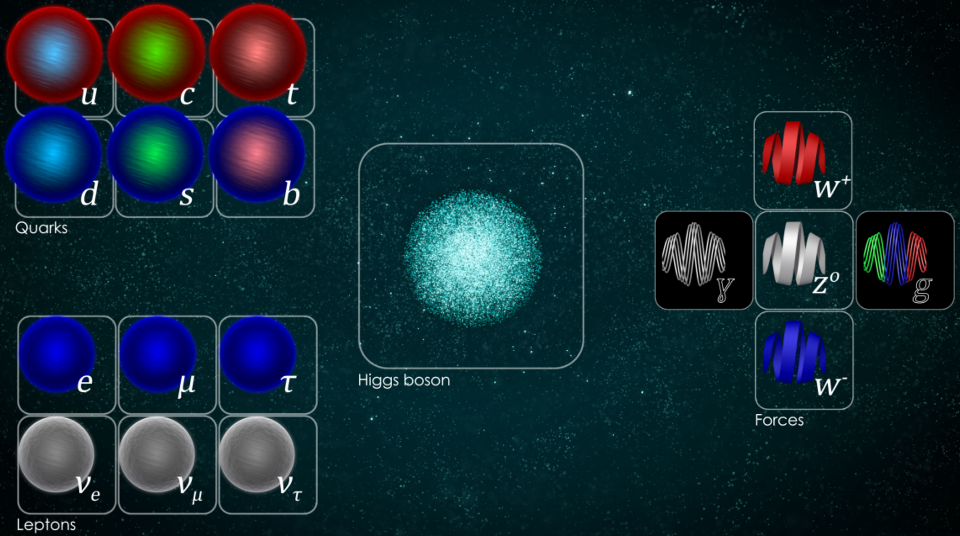
Puebla, México

Miguel Angel May Pech

Dra. Myriam Mondragón Ceballos

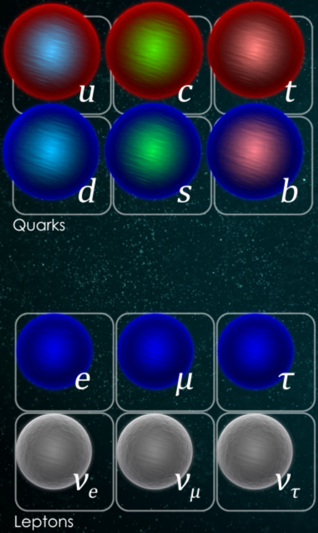
November 25th, 2022

I. The Standard Model of Particle Physics



I. The Standard Model of Particle Physics

$$\mathcal{L}_{SM} = \mathcal{L}_f + \mathcal{L}_g + \mathcal{L}_H + \mathcal{L}_Y$$



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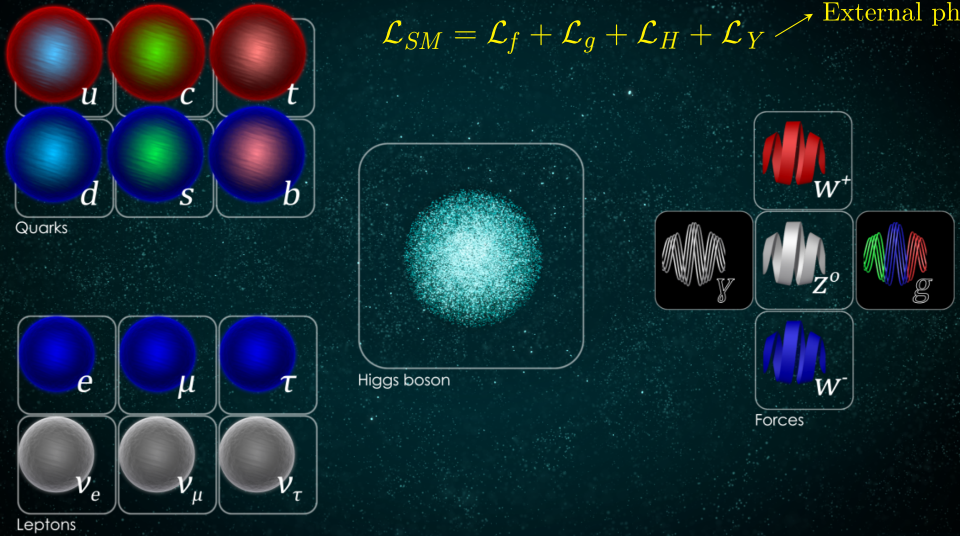
→ External phenomena



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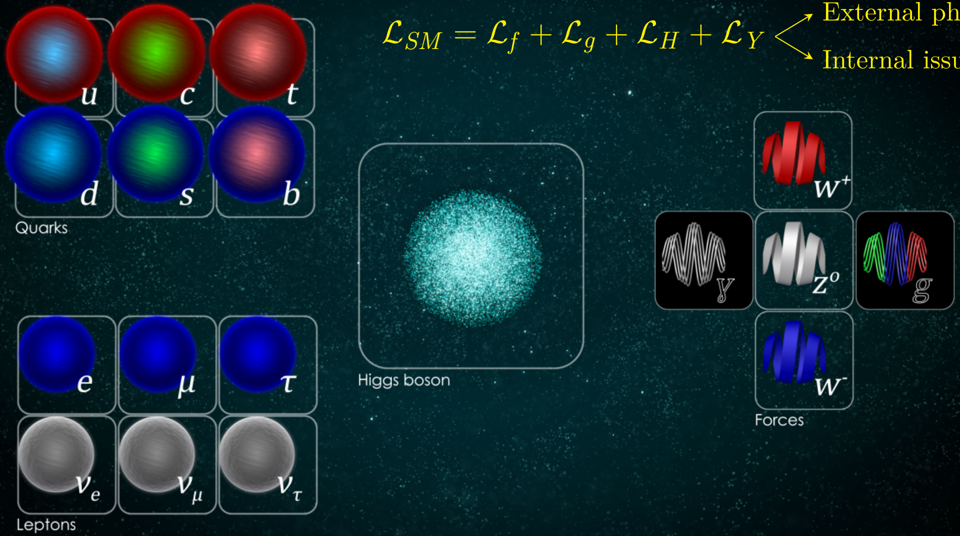
$$\mathcal{L}_{SM} = \mathcal{L}_f + \mathcal{L}_g + \mathcal{L}_H + \mathcal{L}_Y$$

- External phenomena
- Internal issues



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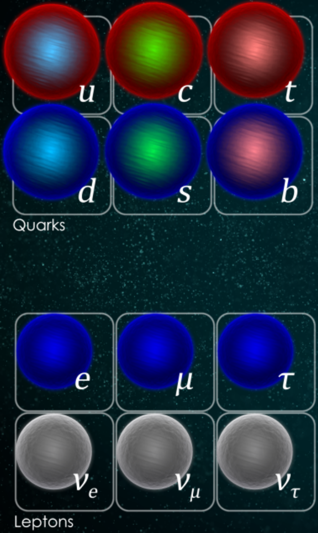

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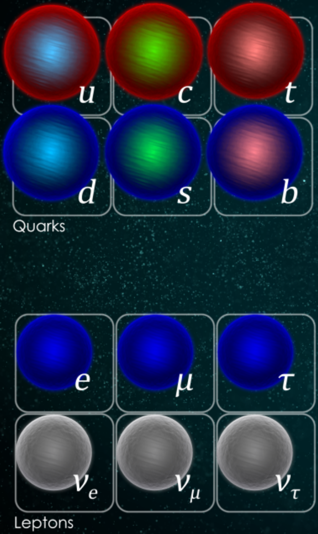

Gravity

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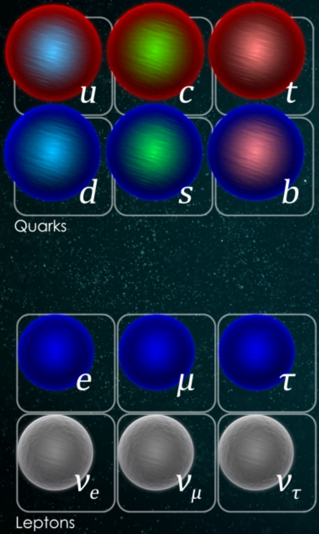
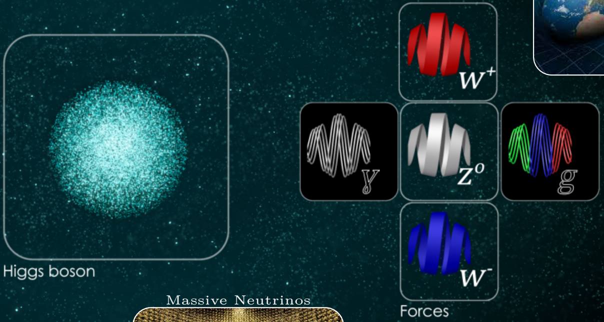
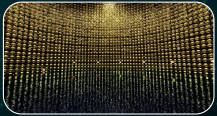




Gravity

Massive Neutrinos



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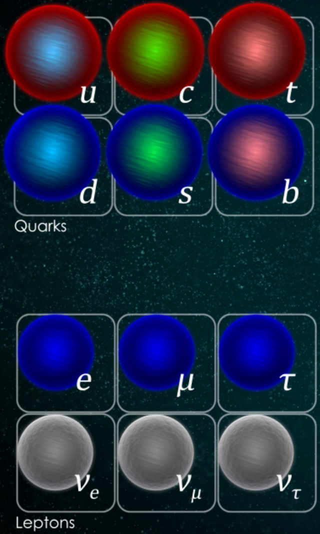

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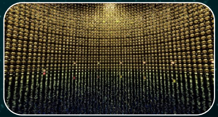

Dark Matter

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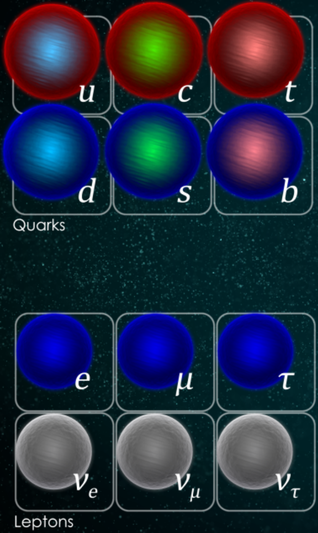

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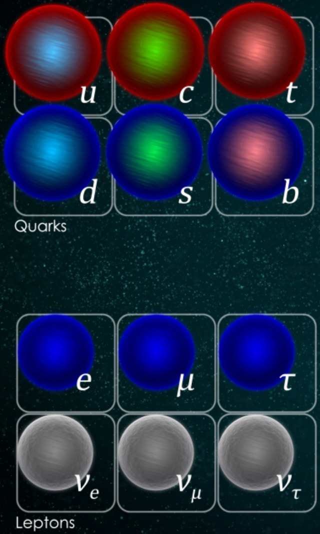
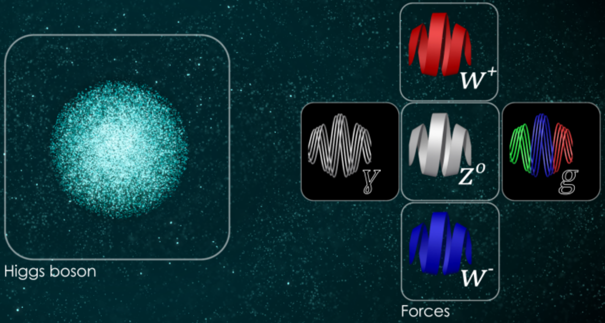
$$\mathcal{L}_{SM} = \mathcal{L}_f + \mathcal{L}_g + \mathcal{L}_H + \mathcal{L}_Y \rightarrow$$ *Free parameters problem*





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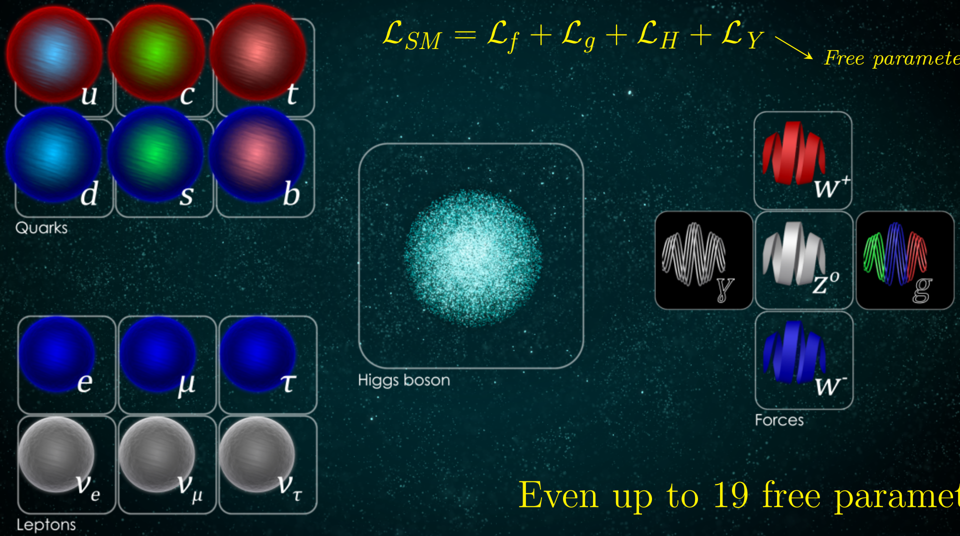

Even up to 19 free parameters!

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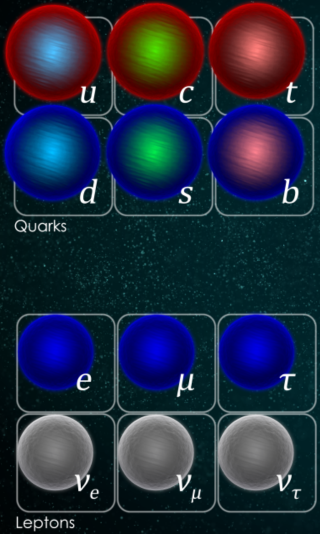
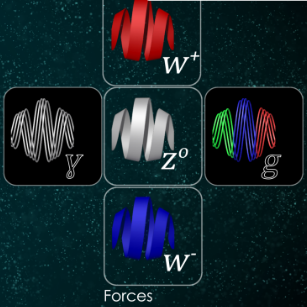
→ *Free parameters problem*

↓

Reduction of Couplings





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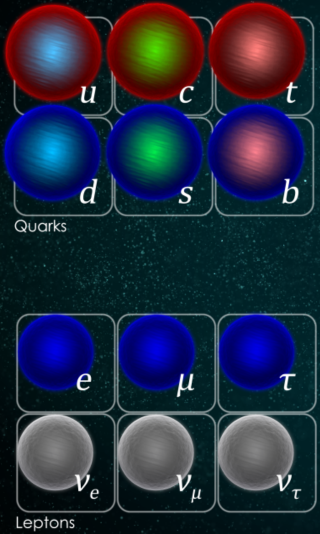

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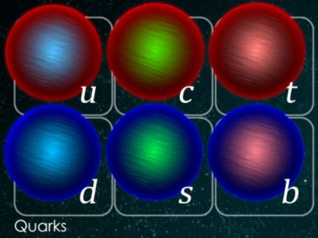
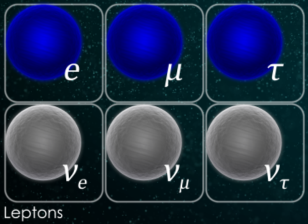
multi-Higgs models ← External phenomena

Free parameters problem → **Reduction of Couplings**





II. Reduction of Couplings Method

Given a model with $n+1$ coupling parameters: $\lambda_0, \lambda_1, .., \lambda_n$...

$$\lambda_j = \lambda_j(\lambda_0) \quad (1)$$

1st Condition: *Renormalization groups equations* (RGEs) or β_j functions on the *reduced system* must fulfil

$$\left[k\frac{\partial}{\partial k} + \sum_j \beta_j \frac{\partial}{\partial \lambda_j} + \gamma\right]\tau = 0 \rightarrow \left[k\frac{\partial}{\partial k} + \beta' \frac{\partial}{\partial \lambda_0} + \gamma'\right]\tau' = 0$$

Reducibility condition

$$\beta' \frac{\mathrm{d}\lambda_j}{\mathrm{d}\lambda_0} = \beta_j \quad (2)$$

Zimmermann W. (1985) *Reduction in the number of coupling parameters.* Commun. Math. Phys. 97,211-225

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2nd Condition: Weak coupling limit

$$\lim_{\lambda_0 \to 0} \lambda_j(\lambda_0) = 0$$

Complete solutions of the reduction equations

$$\lambda_i(\lambda_0) = \lambda_i^{(0)}\lambda_0 + \lambda_i^{(1)}\lambda_0^2 + \lambda_i^{(2)}\lambda_0^3 + \cdots , \quad (3)$$

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HIGGS AND TOP MASS FROM REDUCTION OF COUPLINGS

J. KUBO*, K. SIBOLD** and W. ZIMMERMANN

Max-Planck-Institut für Physik und Astrophysik Werner-Heisenberg-Institut für Physik Föhringer Ring 6, 8000 München 40, Federal Republic of Germany

Received 15 April 1985

We reduce the couplings in the standard model with one Higgs doublet and n generations and obtain for three generations 61 GeV and 81 GeV for the mass of the Higgs particle and the top quark respectively. The error is estimated to be about 10–15%.

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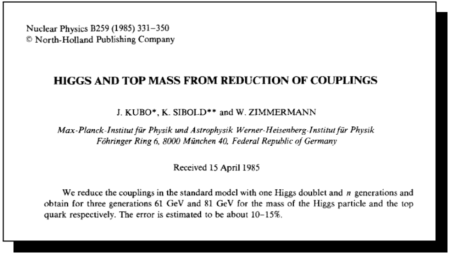
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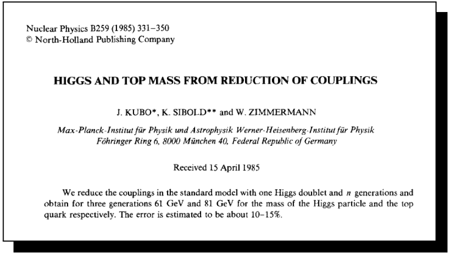
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$$m_t = 81 \text{ GeV}$$
$$m_H = 61 \text{ GeV}$$

III. multi-Higgs Models

4.1 Motivations

- It is one of the easiest extensions to implement...
- The notion of generations can be brought in a more natural way
- Allows for a large amount of phenomenology:
  - Several Higgs bosons, charged and neutral.
  - Flavour Changing Neutral currents (FCNC) at tree level.
  - Additional forms of CP violation.
  - Opportunities for cosmology, as are dark matter candidates.

Ivanov (Prog. Part. Nucl. Phys. 95 (2017) 160-208).

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3.2 Implementation

Scalar Sector

Yukawa Sector

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$$\mathcal{L}_H = \sum_{i,j=1}^{N} (D_\mu \Phi_i)^\dagger (D_\mu \Phi_j) - V(\Phi),$$

Yukawa Sector

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Yukawa Sector

$$\mathcal{L}_Y = -\left(G_i^{(\ell)} \bar{L}_L \Phi_i \ell_R + G_i^{(d)} \bar{Q}_L \Phi_i d_R + G_i^{(u)} \bar{Q}_L \tilde{\Phi}_i u_R \right) + \text{h.c.}$$

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3.2 Implementation

Scalar Sector

$$\mathcal{L}_H = \sum_{i,j=1}^{N} (D_\mu \Phi_i)^\dagger (D_\mu \Phi_j) - V(\Phi),$$

where

$$V(\Phi) = \mu_{ij} \Phi_i^\dagger \Phi_j + \Lambda_{ijkl} (\Phi_i^\dagger \Phi_j)(\Phi_k^\dagger \Phi_l).$$

Yukawa Sector

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$$\mu_{ij} = \mu_{ji}^*,$$

$$\Lambda_{ijkl} = \Lambda_{klij} = \Lambda_{jilk}^*,$$

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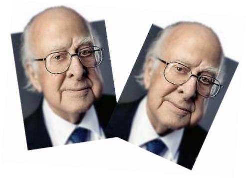
$$\mathcal{L}_Y = -\left(G_i^{(\ell)} \bar{L}_L \Phi_i \ell_R + G_i^{(d)} \bar{Q}_L \Phi_i d_R + G_i^{(u)} \bar{Q}_L \tilde{\Phi}_i u_R \right) + \text{h. c.}$$

IV. Two-Higgs-doublet models (2HDM)



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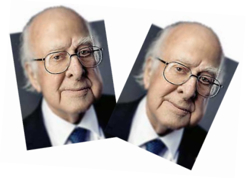

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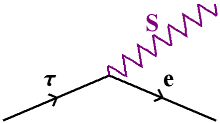

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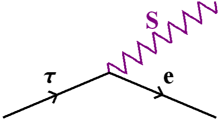

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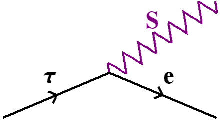

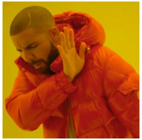

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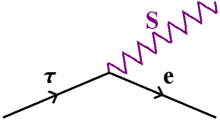

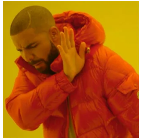

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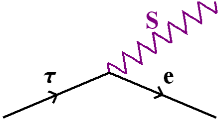

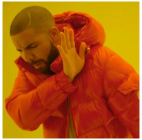

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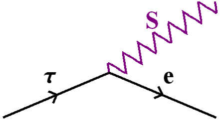

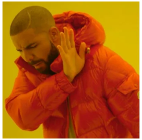

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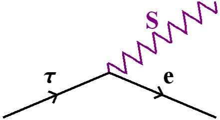

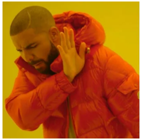

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Model	u_R	d_R	ℓ_R
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific (X)	Φ_2	Φ_2	Φ_1
Flipped (Y)	Φ_2	Φ_1	Φ_2

4.3 The Model

Denner (Nuclear Physics B, Volume 347, Issues 1–2, 24 December 1990, Pages 184-202).

Scalar sector

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Higgs self-coupling conditions

$$\lambda_4 < 0, \qquad \lambda_1 > 0, \qquad \lambda_2 > 0, \qquad \sqrt{\lambda_1 \lambda_2} + \lambda_3 + \lambda_4 > |\lambda_5|;$$

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4.3 The Model

Masses of Particles

With the vacuum expectation values given as follows:

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix};$$

four Higgs particles will be obtained, whose masses at the tree level are expressed as:

$$m_H^2 = \tfrac{1}{2}\eta_+, \qquad m_h^2 = \tfrac{1}{2}\eta_-, \qquad m_{H\pm}^2 = -\tfrac{1}{2}(\lambda_4 + \lambda_5)\, v^2, \qquad m_A^2 = -\lambda_5\, v^2,$$

where

$$\eta_\pm = \lambda_1 v_1^2 + \lambda_2 v_2^2 \pm \sqrt{(\lambda_1 v_1^2 - \lambda_2 v_2^2)^2 + 4(\lambda_3 + \lambda_4 + \lambda_5)^2 v_1^2 v_2^2}.$$

For diagonal Yukawa matrices the fermion masses will be given as:

$$m_i^{(f)} = \tfrac{1}{\sqrt{2}} G_i^{(f)} v_j;$$

since fermions couples to only one of the Higgs.

4.3 The Model

Masses of Particles

With the vacuum expectation values given as follows:

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix}, \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix};$$

four Higgs particles will be obtained, whose masses at the tree level are expressed as:

$$m_H^2 = \tfrac{1}{2}\eta_+, \qquad m_h^2 = \tfrac{1}{2}\eta_-, \qquad m_{H^\pm}^2 = -\tfrac{1}{2}(\lambda_4+\lambda_5)v^2, \qquad m_A^2 = -\lambda_5 v^2,$$

where

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V. Reduction of Couplings in 2HDM with NFC

Renormalization Groups Equations

$$16\pi^2\beta_{g_1} = 7g_1^3,$$
$$16\pi^2\beta_{g_2} = -3g_2^3,$$
$$16\pi^2\beta_{g_3} = -7g_3^3.$$

$$16\pi^2\beta_{G_j^{(\ell)}} = G_j^{(\ell)}\Big(-\big(\tfrac{15}{4}g_1^2+\tfrac{9}{4}g_2^2\big)+\tfrac{3}{2}G_j^{(\ell)2} + \sum_k\big(a_1G_k^{(\ell)2}+3a_2G_k^{(d)2}+3a_3G_k^{(u)2}\big)\Big),$$

$$16\pi^2\beta_{G_j^{(d)}} = G_j^{(d)}\Big(-\big(\tfrac{5}{12}g_1^2+\tfrac{9}{4}g_2^2+8g_3^2\big)+\tfrac{3}{2}G_j^{(d)2} + a_4G_j^{(u)2}+\sum_k\big(a_5G_k^{(\ell)2}+3a_6G_k^{(d)2}+3a_7G_k^{(u)2}\big)\Big),$$

$$16\pi^2\beta_{G_j^{(u)}} = G_j^{(u)}\Big(-\big(\tfrac{17}{12}g_1^2+\tfrac{9}{4}g_2^2+8g_3^2\big)+\tfrac{3}{2}G_j^{(u)2} + a_8G_j^{(d)2}+\sum_k\big(a_9G_k^{(\ell)2}+3a_{10}G_k^{(d)2}+3a_{11}G_k^{(u)2}\big)\Big);$$

$$16\pi^2\beta_{\lambda_1} = \tfrac{3}{4}g_1^4+\tfrac{3}{2}g_1^2g_2^2+\tfrac{9}{4}g_2^4-3g_1^2\lambda_1-9g_2^2\lambda_1+12\lambda_1^2+4\lambda_3^2+4\lambda_3\lambda_4 + 2\lambda_4^2+2\lambda_5^2$$

$$16\pi^2\beta_{\lambda_2} = \tfrac{3}{4}g_1^4+\tfrac{3}{2}g_1^2g_2^2+\tfrac{9}{4}g_2^4-3g_1^2\lambda_2-9g_2^2\lambda_2+12\lambda_2^2+4\lambda_3^2+4\lambda_3\lambda_4 + 2\lambda_4^2+2\lambda_5^2+\Big(-12G_b^4-12G_t^4-4G_\tau^4+\big(12G_b^2+12G_t^2+4G_\tau^2\big)\lambda_2\Big)$$

$$16\pi^2\beta_{\lambda_3} = \tfrac{3}{4}g_1^4-\tfrac{3}{2}g_1^2g_2^2+\tfrac{9}{4}g_2^4-3g_1^2\lambda_3-9g_2^2\lambda_3+(\lambda_1+\lambda_2)(6\lambda_3+2\lambda_4) + 4\lambda_3^2+2\lambda_4^2+2\lambda_5^2+\big(6G_b^2+6G_t^2+2G_\tau^2\big)\lambda_3$$

$$16\pi^2\beta_{\lambda_4} = 3g_1^2g_2^2-(3g_1^2+9g_2^2)\lambda_4+2\lambda_1\lambda_4+2\lambda_2\lambda_4+8\lambda_3\lambda_4+4\lambda_4^2+8\lambda_5^2 + \big(6G_b^2+6G_t^2+2G_\tau^2\big)\lambda_4$$

$$16\pi^2\beta_{\lambda_5} = \lambda_5\Big(-3g_1^2-9g_2^2+2\lambda_1+2\lambda_2+8\lambda_3+12\lambda_4 + \big(6G_b^2+6G_t^2+2G_\tau^2\big)\Big)$$

V. Reduction of Couplings in 2HDM with NFC

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$$16\pi^2\beta_{G_j^{(\ell)}} = G_j^{(\ell)}\Big(-\big(\tfrac{15}{4}g_1^2 + \tfrac{9}{4}g_2^2\big) + \tfrac{3}{2}G_j^{(\ell)2} + \sum_k \big(a_1 G_k^{(\ell)2} + 3a_2 G_k^{(d)2} + 3a_3 G_k^{(u)2}\big)\Big),$$

$$16\pi^2\beta_{G_j^{(d)}} = G_j^{(d)}\Big(-\big(\tfrac{5}{12}g_1^2 + \tfrac{9}{4}g_2^2 + 8g_3^2\big) + \tfrac{3}{2}G_j^{(d)2} + a_4 G_j^{(u)2} + \sum_k \big(a_5 G_k^{(\ell)2} + 3a_6 G_k^{(d)2} + 3a_7 G_k^{(u)2}\big)\Big),$$

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$$16\pi^2\beta_{\lambda_1} = \tfrac{3}{4}g_1^4 + \tfrac{3}{2}g_1^2g_2^2 + \tfrac{9}{4}g_2^4 - 3g_1^2\lambda_1 - 9g_2^2\lambda_1 + 12\lambda_1^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 2\lambda_5^2$$

$$16\pi^2\beta_{\lambda_2} = \tfrac{3}{4}g_1^4 + \tfrac{3}{2}g_1^2g_2^2 + \tfrac{9}{4}g_2^4 - 3g_1^2\lambda_2 - 9g_2^2\lambda_2 + 12\lambda_2^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 2\lambda_5^2 + \Big(-12G_b^4 - 12G_t^4 - 4G_\tau^4 + \big(12G_b^2 + 12G_t^2 + 4G_\tau^2\big)\lambda_2\Big)$$

$$16\pi^2\beta_{\lambda_3} = \tfrac{3}{4}g_1^4 - \tfrac{3}{2}g_1^2g_2^2 + \tfrac{9}{4}g_2^4 - 3g_1^2\lambda_3 - 9g_2^2\lambda_3 + (\lambda_1 + \lambda_2)(6\lambda_3 + 2\lambda_4) + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + \big(6G_b^2 + 6G_t^2 + 2G_\tau^2\big)\lambda_3$$

$$16\pi^2\beta_{\lambda_4} = 3g_1^2g_2^2 - (3g_1^2 + 9g_2^2)\lambda_4 + 2\lambda_1\lambda_4 + 2\lambda_2\lambda_4 + 8\lambda_3\lambda_4 + 4\lambda_4^2 + 8\lambda_5^2 + \big(6G_b^2 + 6G_t^2 + 2G_\tau^2\big)\lambda_4$$

$$16\pi^2\beta_{\lambda_5} = \lambda_5\Big(-3g_1^2 - 9g_2^2 + 2\lambda_1 + 2\lambda_2 + 8\lambda_3 + 12\lambda_4 + \big(6G_b^2 + 6G_t^2 + 2G_\tau^2\big)\Big)$$

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$$16\pi^2\beta_{\lambda_4} = 3g_1^2g_2^2 - (3g_1^2 + 9g_2^2)\lambda_4 + 2\lambda_1\lambda_4 + 2\lambda_2\lambda_4 + 8\lambda_3\lambda_4 + 4\lambda_4^2 + 8\lambda_5^2 + \big(6G_b^2 + 6G_t^2 + 2G_\tau^2\big)\lambda_4$$

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$$16\pi^2\beta_{\lambda_4} = 3g_1^2g_2^2 - (3g_1^2 + 9g_2^2)\lambda_4 + 2\lambda_1\lambda_4 + 2\lambda_2\lambda_4 + 8\lambda_3\lambda_4 + 4\lambda_4^2 + 8\lambda_5^2 + \big(6G_b^2 + 6G_t^2 + 2G_\tau^2\big)\lambda_4$$

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$$16\pi^2\beta_{\lambda_1} = \tfrac{3}{4}g_1^4 + \tfrac{3}{2}g_1^2g_2^2 + \tfrac{9}{4}g_2^4 - 3g_1^2\lambda_1 - 9g_2^2\lambda_1 + 12\lambda_1^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 2\lambda_5^2$$

$$16\pi^2\beta_{\lambda_2} = \tfrac{3}{4}g_1^4 + \tfrac{3}{2}g_1^2g_2^2 + \tfrac{9}{4}g_2^4 - 3g_1^2\lambda_2 - 9g_2^2\lambda_2 + 12\lambda_2^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 2\lambda_5^2 + \Big(-12G_b^4 - 12G_t^4 - 4G_\tau^4 + \left(12G_b^2 + 12G_t^2 + 4G_\tau^2\right)\lambda_2\Big)$$

$$16\pi^2\beta_{\lambda_3} = \tfrac{3}{4}g_1^4 - \tfrac{3}{2}g_1^2g_2^2 + \tfrac{9}{4}g_2^4 - 3g_1^2\lambda_3 - 9g_2^2\lambda_3 + (\lambda_1+\lambda_2)(6\lambda_3 + 2\lambda_4) + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + \left(6G_b^2 + 6G_t^2 + 2G_\tau^2\right)\lambda_3$$

$$16\pi^2\beta_{\lambda_4} = 3g_1^2g_2^2 - (3g_1^2 + 9g_2^2)\lambda_4 + 2\lambda_1\lambda_4 + 2\lambda_2\lambda_4 + 8\lambda_3\lambda_4 + 4\lambda_4^2 + 8\lambda_5^2 + \left(6G_b^2 + 6G_t^2 + 2G_\tau^2\right)\lambda_4$$

$$16\pi^2\beta_{\lambda_5} = \lambda_5\Big(-3g_1^2 - 9g_2^2 + 2\lambda_1 + 2\lambda_2 + 8\lambda_3 + 12\lambda_4 + \left(6G_b^2 + 6G_t^2 + 2G_\tau^2\right)\Big)$$

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$$\beta_0\frac{d\lambda_j}{d\lambda_0} = \beta_j$$

$$16\pi^2\beta_{G_j^{(\ell)}} = G_j^{(\ell)}\Big(-\left(\tfrac{15}{4}g_1^2 + \tfrac{9}{4}g_2^2\right) + \tfrac{3}{2}G_j^{(\ell)2} + \sum_k\left(a_1 G_k^{(\ell)2} + 3a_2 G_k^{(d)2} + 3a_3 G_k^{(u)2}\right)\Big),$$

$$16\pi^2\beta_{G_j^{(d)}} = G_j^{(d)}\Big(-\left(\tfrac{5}{12}g_1^2 + \tfrac{9}{4}g_2^2 + 8g_3^2\right) + \tfrac{3}{2}G_j^{(d)2} + a_4 G_j^{(u)2} + \sum_k\left(a_5 G_k^{(\ell)2} + 3a_6 G_k^{(d)2} + 3a_7 G_k^{(u)2}\right)\Big),$$

$$16\pi^2\beta_{G_j^{(u)}} = G_j^{(u)}\Big(-\left(\tfrac{17}{12}g_1^2 + \tfrac{9}{4}g_2^2 + 8g_3^2\right) + \tfrac{3}{2}G_j^{(u)2} + a_8 G_j^{(d)2} + \sum_k\left(a_9 G_k^{(\ell)2} + 3a_{10} G_k^{(d)2} + 3a_{11} G_k^{(u)2}\right)\Big);$$

$$16\pi^2\beta_{\lambda_1} = \tfrac{3}{4}g_1^4 + \tfrac{3}{2}g_1^2g_2^2 + \tfrac{9}{4}g_2^4 - 3g_1^2\lambda_1 - 9g_2^2\lambda_1 + 12\lambda_1^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 2\lambda_5^2$$

$$16\pi^2\beta_{\lambda_2} = \tfrac{3}{4}g_1^4 + \tfrac{3}{2}g_1^2g_2^2 + \tfrac{9}{4}g_2^4 - 3g_1^2\lambda_2 - 9g_2^2\lambda_2 + 12\lambda_2^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 2\lambda_5^2 + \Big(-12G_b^4 - 12G_t^4 - 4G_\tau^4 + \left(12G_b^2 + 12G_t^2 + 4G_\tau^2\right)\lambda_2\Big)$$

$$16\pi^2\beta_{\lambda_3} = \tfrac{3}{4}g_1^4 - \tfrac{3}{2}g_1^2g_2^2 + \tfrac{9}{4}g_2^4 - 3g_1^2\lambda_3 - 9g_2^2\lambda_3 + (\lambda_1+\lambda_2)(6\lambda_3 + 2\lambda_4) + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + \left(6G_b^2 + 6G_t^2 + 2G_\tau^2\right)\lambda_3$$

$$16\pi^2\beta_{\lambda_4} = 3g_1^2g_2^2 - (3g_1^2 + 9g_2^2)\lambda_4 + 2\lambda_1\lambda_4 + 2\lambda_2\lambda_4 + 8\lambda_3\lambda_4 + 4\lambda_4^2 + 8\lambda_5^2 + \left(6G_b^2 + 6G_t^2 + 2G_\tau^2\right)\lambda_4$$

$$16\pi^2\beta_{\lambda_5} = \lambda_5\Big(-3g_1^2 - 9g_2^2 + 2\lambda_1 + 2\lambda_2 + 8\lambda_3 + 12\lambda_4 + \left(6G_b^2 + 6G_t^2 + 2G_\tau^2\right)\Big)$$

V. Reduction of Couplings in 2HDM with NFC

Renormalization Groups Equations

$$16\pi^2\beta_{g_1} = 7g_1^3,$$
$$16\pi^2\beta_{g_2} = -3g_2^3,$$
$$16\pi^2\beta_{g_3} = -7g_3^3.$$

$$\beta_0 \frac{d\lambda_j}{d\lambda_0} = \beta_j$$

$$16\pi^2\beta_{G_j^{(\ell)}} = G_j^{(\ell)}\Big(-\big(\tfrac{15}{4}g_1^2 + \tfrac{9}{4}g_2^2\big) + \tfrac{3}{2}G_j^{(\ell)2} + \sum_k \big(a_1 G_k^{(\ell)2} + 3a_2 G_k^{(d)2} + 3a_3 G_k^{(u)2}\big)\Big),$$

$$16\pi^2\beta_{G_j^{(d)}} = G_j^{(d)}\Big(-\big(\tfrac{5}{12}g_1^2 + \tfrac{9}{4}g_2^2 + 8g_3^2\big) + \tfrac{3}{2}G_j^{(d)2} + a_4 G_j^{(u)2} + \sum_k \big(a_5 G_k^{(\ell)2} + 3a_6 G_k^{(d)2} + 3a_7 G_k^{(u)2}\big)\Big),$$

$$16\pi^2\beta_{G_j^{(u)}} = G_j^{(u)}\Big(-\big(\tfrac{17}{12}g_1^2 + \tfrac{9}{4}g_2^2 + 8g_3^2\big) + \tfrac{3}{2}G_j^{(u)2} + a_8 G_j^{(d)2} + \sum_k \big(a_9 G_k^{(\ell)2} + 3a_{10} G_k^{(d)2} + 3a_{11} G_k^{(u)2}\big)\Big);$$

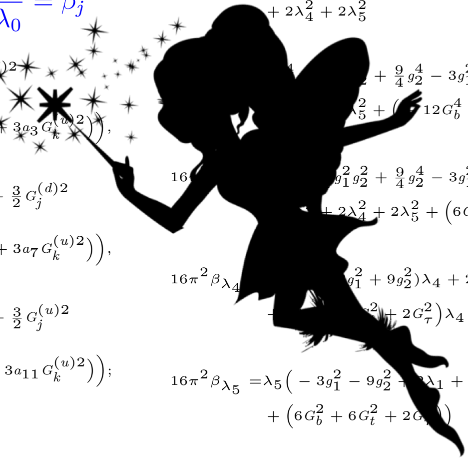
$$16\pi^2\beta_{\lambda_1} = \tfrac{3}{4}g_1^4 + \tfrac{3}{2}g_1^2g_2^2 + \tfrac{9}{4}g_2^4 - 3g_1^2\lambda_1 - 9g_2^2\lambda_1 + 12\lambda_1^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 2\lambda_5^2$$

$$\ldots + \tfrac{9}{4}g_2^4 - 3g_1^2\lambda_2 - 9g_2^2\lambda_2 + 12\lambda_2^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 \ldots \lambda_5^2 + \big(\ldots 12G_b^4 - 12G_t^4 - 4G_\tau^4 + \big(12G_b^2 + 12G_t^2 + 4G_\tau^2\big)\lambda_2\big)$$

$$16\ldots g_1^2g_2^2 + \tfrac{9}{4}g_2^4 - 3g_1^2\lambda_3 - 9g_2^2\lambda_3 + (\lambda_1 + \lambda_2)(6\lambda_3 + 2\lambda_4) \ldots + 2\lambda_4^2 + 2\lambda_5^2 + \big(6G_b^2 + 6G_t^2 + 2G_\tau^2\big)\lambda_3$$

$$16\pi^2\beta_{\lambda_4} \ldots g_1^2 + 9g_2^2)\lambda_4 + 2\lambda_1\lambda_4 + 2\lambda_2\lambda_4 + 8\lambda_3\lambda_4 + 4\lambda_4^2 + 8\lambda_5^2 + \ldots + 2G_\tau^2\big)\lambda_4$$

$$16\pi^2\beta_{\lambda_5} = \lambda_5\big(-3g_1^2 - 9g_2^2 + \ldots\lambda_1 + 2\lambda_2 + 8\lambda_3 + 12\lambda_4 + \big(6G_b^2 + 6G_t^2 + 2G\ldots\big)\big)$$



V. Reduction of Couplings in 2HDM with NFC

Reduction Equations

$$-14x\frac{\mathrm{d}u}{\mathrm{d}x} = -6u^2 + 14u,$$

$$-14x\frac{\mathrm{d}v}{\mathrm{d}x} = 14v^2 + 14v,$$

$$-14x\frac{\mathrm{d}\rho_{\ell_j}}{\mathrm{d}x} = 2\rho_{\ell_j}\Big(-\left(\tfrac{15}{4}v + \tfrac{9}{4}u\right) + \tfrac{3}{2}\rho_{\ell_j} + \sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right) + 7\Big),$$

$$-14x\frac{\mathrm{d}\rho_{d_j}}{\mathrm{d}x} = 2\rho_{d_j}\Big(-\left(\tfrac{5}{12}v + \tfrac{9}{4}u\right) + \tfrac{3}{2}\rho_{d_j} - \tfrac{3}{2}\rho_{u_j} + \sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right) - 1\Big),$$

$$-14x\frac{\mathrm{d}\rho_{u_j}}{\mathrm{d}x} = 2\rho_{u_j}\Big(-\left(\tfrac{17}{12}v + \tfrac{9}{4}u\right) + \tfrac{3}{2}\rho_{u_j} - \tfrac{3}{2}\rho_{d_j} + \sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right) - 1\Big),$$

$$-14x\frac{\mathrm{d}\rho_1}{\mathrm{d}x} = \tfrac{3}{4}v^2 + \tfrac{3}{2}vu + \tfrac{9}{4}u^2 - 3v\rho_1 - 9u\rho_1 + 12\rho_1^2 + 4\rho_3^2 + 4\rho_3\rho_4 + 2\rho_4^2 + 2\rho_5^2 + 14\rho_1,$$

$$-14x\frac{\mathrm{d}\rho_2}{\mathrm{d}x} = \tfrac{3}{4}v^2 + \tfrac{3}{2}vu + \tfrac{9}{4}u^2 - 3v\rho_2 - 9u\rho_2 + 12\rho_2^2 + 4\rho_3^2 + 4\rho_3\rho_4 + 2\rho_4^2 + 2\rho_5^2 + 14\rho_2 + 4\rho_2\sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right) - 4\sum_k\left(\rho_{\ell_k}^2 + 3\rho_{d_k}^2 + 3\rho_{u_k}^2\right),$$

$$-14x\frac{\mathrm{d}\rho_3}{\mathrm{d}x} = (\rho_1 + \rho_2)(6\rho_3 + 2\rho_4) + 4\rho_3^2 + 2\rho_4^2 + 2\rho_5^2 + 14\rho_3 + 2\rho_3\sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right),$$

$$-14x\frac{\mathrm{d}\rho_4}{\mathrm{d}x} = 2\rho_1\rho_4 + 2\rho_2\rho_4 + 8\rho_3\rho_4 + 4\rho_4^2 + 8\rho_5^2 + 14\rho_4 + 2\rho_4\sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right),$$

$$-14x\frac{\mathrm{d}\rho_5}{\mathrm{d}x} = \Big(2\rho_1 + 2\rho_2 + 8\rho_3 + 12\rho_4 + 14 + 2\sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right)\Big)\rho_5.$$

V. Reduction of Couplings in 2HDM with NFC

Reduction Equations

$$-14x\frac{\mathrm{d}u}{\mathrm{d}x} = -6u^2 + 14u,$$
$$-14x\frac{\mathrm{d}v}{\mathrm{d}x} = 14v^2 + 14v,$$

$$-14x\frac{\mathrm{d}\rho_{\ell_j}}{\mathrm{d}x} = 2\rho_{\ell_j}\Big(-\left(\tfrac{15}{4}v + \tfrac{9}{4}u\right) + \tfrac{3}{2}\rho_{\ell_j} + \sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right) + 7\Big),$$

$$-14x\frac{\mathrm{d}\rho_{d_j}}{\mathrm{d}x} = 2\rho_{d_j}\Big(-\left(\tfrac{5}{12}v + \tfrac{9}{4}u\right) + \tfrac{3}{2}\rho_{d_j} - \tfrac{3}{2}\rho_{u_j} + \sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right) - 1\Big),$$

$$-14x\frac{\mathrm{d}\rho_{u_j}}{\mathrm{d}x} = 2\rho_{u_j}\Big(-\left(\tfrac{17}{12}v + \tfrac{9}{4}u\right) + \tfrac{3}{2}\rho_{u_j} - \tfrac{3}{2}\rho_{d_j} + \sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right) - 1\Big),$$

$$x = \frac{g_3^2}{4\pi}, \quad u = \frac{g_2^2}{g_3^2}, \quad v = \frac{g_1^2}{g_3^2}, \quad \rho_i^{(f)} = \frac{{G_i^{(f)}}^2}{g_3^2}, \quad \rho_i = \frac{\lambda_i}{g_3^2};$$

$$-14x\frac{\mathrm{d}\rho_1}{\mathrm{d}x} = \tfrac{3}{4}v^2 + \tfrac{3}{2}vu + \tfrac{9}{4}u^2 - 3v\rho_1 - 9u\rho_1 + 12\rho_1^2 + 4\rho_3^2 + 4\rho_3\rho_4 + 2\rho_4^2 + 2\rho_5^2 + 14\rho_1,$$

$$-14x\frac{\mathrm{d}\rho_2}{\mathrm{d}x} = \tfrac{3}{4}v^2 + \tfrac{3}{2}vu + \tfrac{9}{4}u^2 - 3v\rho_2 - 9u\rho_2 + 12\rho_2^2 + 4\rho_3^2 + 4\rho_3\rho_4 + 2\rho_4^2 + 2\rho_5^2 + 14\rho_2 + 4\rho_2\sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right) - 4\sum_k\left(\rho_{\ell_k}^2 + 3\rho_{d_k}^2 + 3\rho_{u_k}^2\right),$$

$$-14x\frac{\mathrm{d}\rho_3}{\mathrm{d}x} = (\rho_1 + \rho_2)(6\rho_3 + 2\rho_4) + 4\rho_3^2 + 2\rho_4^2 + 2\rho_5^2 + 14\rho_3 + 2\rho_3\sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right),$$

$$-14x\frac{\mathrm{d}\rho_4}{\mathrm{d}x} = 2\rho_1\rho_4 + 2\rho_2\rho_4 + 8\rho_3\rho_4 + 4\rho_4^2 + 8\rho_5^2 + 14\rho_4 + 2\rho_4\sum_k\left(\rho_{\ell_k} + 3\rho_{d_k} + 3\rho_{u_k}\right),$$

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V. Reduction of Couplings in 2HDM with NFC

Solutions: Complete Reduction

In the so-called **complete reduction**, the reduction equations must satisfy:

$$\rho_i(x) = \rho_i^{(0)} + \rho_i^{(1)} x + \rho_i^{(2)} x^2 + \cdots$$

$U(1)$ coupling

$$-14x\frac{\mathrm{d}v}{\mathrm{d}x} = 14v^2 + 14v,$$

$$-14x\frac{\mathrm{d}}{\mathrm{d}x}\left(v^{(0)}\right) = 0 = 14(v^{(0)})^2 + 14v^{(0)},$$

$$\therefore$$

$$v_-^{(0)} = -1, \qquad v_+^{(0)} = 0;$$

$SU(2)$ coupling

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$$\therefore$$

$$u_-^{(0)} = 0, \qquad u_+^{(0)} = \frac{7}{3} > 1$$

Results

Solutions for all types of 2HDM with NFC

- For gauge couplings, only trivial solutions are physically acceptable:

$$v(x) = 0 \rightarrow g_1(g_3) = 0$$

$$u(x) = 0 \rightarrow g_2(g_3) = 0$$

- Given the previous result, the only solution that satisfies the physical conditions is also the trivial one

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Solutions for Yukawa and Higgs couplings

Type I and X

$$G_t(g_3) \approx \sqrt{\tfrac{2}{9}}\, g_3 + \dots$$
$$\lambda_1(g_3) = 0$$
$$\lambda_2(g_3) \approx 0.03469\, g_3 + \dots$$
$$\lambda_3(g_3) = 0$$
$$\lambda_4(g_3) = 0$$
$$\lambda_5(g_3) = 0$$

Type II and Y

$$G_t(g_3) \approx \sqrt{\tfrac{1}{5}}\, g_3 + \dots$$
$$\lambda_1(g_3) \approx 0.0285714\, g_3 + \dots$$
$$\lambda_2(g_3) \approx 0.0285714\, g_3 + \dots$$
$$\lambda_3(g_3) \approx 0.0285714\, g_3 + \dots$$
$$\lambda_4(g_3) \approx -0.028868\, g_3 + \dots$$
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Results

Mass predictions: Type I y X

At the scale of the m_Z the strong coupling constant is given as $x = \frac{g_3^2}{4\pi} = 0.1179(9)$ (PDG, 2021), with this the constants will take the values:

$$G_t \approx 0.573793 \qquad m_t \leq 100 \text{ GeV}$$

$$\lambda_2 \approx 0.513947 \qquad m_H \leq 56 \text{ GeV}$$

$$\lambda_1 = \lambda_3 = \lambda_4 = \lambda_5 = 0$$

Results

Mass predictions: Type II y Y

At the scale of the M_Z the strong coupling constant is given as $x = \frac{g_3^2}{4\pi} = 0.1179(9)$ (PDG, 2021), with this the constants will take the values:

$$G_t \approx 0.544348$$
$$\lambda_1 \approx 0.0423307$$
$$\lambda_2 \approx 0.0423307$$
$$\lambda_3 \approx 0.0423307$$
$$\lambda_4 \approx -0.0427701$$
$$\lambda_5 = 0$$

$$m_t \approx 94.7 \text{ GeV}$$
$$m_H \approx 50.6 \text{ GeV}$$
$$m_h \approx 1.7 \text{ GeV}$$
$$m_{H^\pm} \approx 36 \text{ GeV}$$
$$m_A = 0$$

Conclusions

- The Reduction of Couplings Method (RCM) is presented as an attractive tool to deal with the ***free parameters problem***.
- Although the preliminary results obtained seem not to agree with the phenomenology, this doesn't discard the method
- Dr. M. Mondragón et al. searches in the MSSM has given more accurated results
- Given the physical possibilities that multi-Higgs models offer, we will continue the exploration of these models using the RCM.

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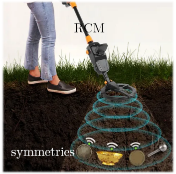

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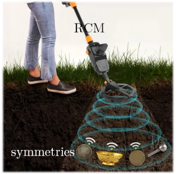

Thanks for your atention!