The Case for Generation Dependent Higgs Doublets

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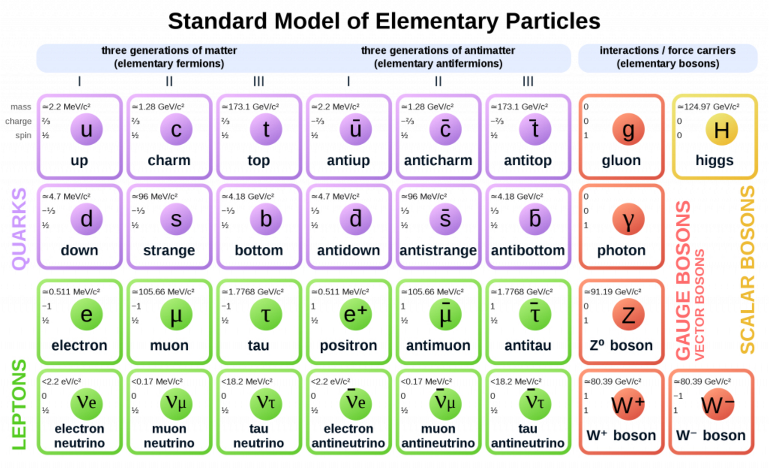
Outline

Introduction: The discovered boson at the LHC may not be the only one



The Standard Model is compatible with one Higgs Doublet, but it is not a prediction, it is just the simplest choice.

$$\mathcal{L} = -Y^d_{ij}\,\overline{Q}_{L\,i} H d_{R\,j} - Y^u_{ij}\,\overline{Q}_{L\,i} H^* u_{R\,j} + \text{h.c.},$$

When H acquires a vacuum expectation value, the quarks acquire mass proportional to the vev of H

$$\langle H \rangle = \left(\begin{array}{c} 0 \\ \frac{v}{2} \end{array} \right),$$

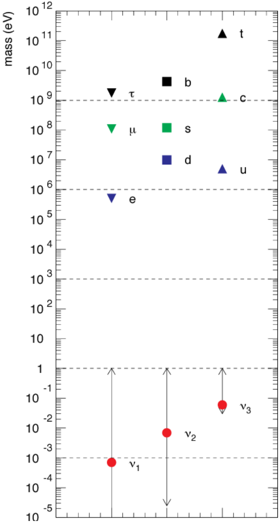
the physical states are obtained by diagonalizing $Y^{u,d}$ with $V^f_L Y^f V^{f\dagger}_R \frac{v}{2}$, with $f = u, d$.

There is one peculiarity: there is a strong hierarchy among the couplings

$$y_u \ll y_c \ll y_t \sim \mathcal{O}(1),$$
$$y_s \ll y_d \ll y_b \ll y_t.$$

In fact, not the couplings, but the masses. So it could be also possible that each of the masses it is instead proportional to a vev of a different Higgs boson

$$m_d \approx v_1,\ m_s \approx v_3,\ m_b \approx v_5,$$
$$m_u \approx v_2,\ m_c \approx v_4,\ m_t \approx v_6.$$



Multiple Higgs Doublets

The most general matter Lagrangian involving the matter fields $\overline{Q}$, (quark $SU(2)_L$ doublet respectively), u_R, d_R (quark singlets) and different Higgs doublets is given by

$$-\mathcal{L} = \overline{Q}_{Li} \left[(Y_1^d)_{ij} H_1 + (Y_3^d)_{ij} H_3 + (Y_5^d)_{ij} H_5\right] d_{Rj} + \\ + \overline{Q}_{Li} \left[(Y_2^u)_{ij} H_2 + (Y_4^u)_{ij} H_4 + (Y_6^u)_{ij} H_6\right] u_{Rj} + \text{h.c.},$$

where Y_i^q are the Yukawa matrices associated with each Higgs field. This seems an overkilling but at the end we have six different quark flavours!

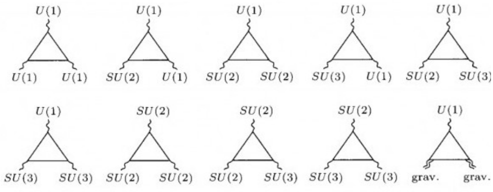
How do we construct models?

Same Guiding Principles that we know work in the SM

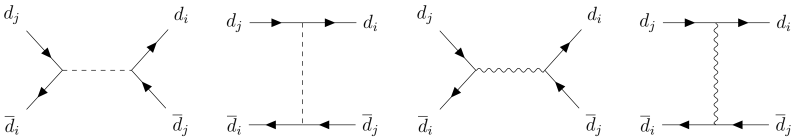
- Start with a simple $U(1)_F$ gauge model and ensure anomaly cancellation among the SM fermions
- Guiding principle to avoid large Flavour Changing Neutral Currents (FCNC)

Most important constraints

- Anomaly Cancellation



- Tree-level Vector and Scalar FCNC



- Oblique parameters

Anomaly Cancellation

	$u_{L\,i}$	$u_{R\,i}$	$d_{L\,i}$	$d_{R\,i}$	$\nu_{L\,i}$	$e_{L\,i}$	$e_{R\,i}$	F_{Li}	f_{Ri}
e_f	$\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	-1	1		
$2\,\mathcal{Y}_f$	$\frac{1}{3}$	$-\frac{4}{3}$	$\frac{1}{3}$	$\frac{2}{3}$	-1	-1	2		
I_3^f	$\frac{1}{2}$	0	$-\frac{1}{2}$	0	$\frac{1}{2}$	$-\frac{1}{2}$	0		
$U(1)_F$	$c_{Q_{L\,i}}$	$c_{u_R\,i}$	$c_{Q_{L\,i}}$	$c_{d_R\,i}$	c_{L_i}	c_{L_i}	$c_{e_R\,i}$	$c_{F_{L_i}}$	$c_{f_{Ri}}$

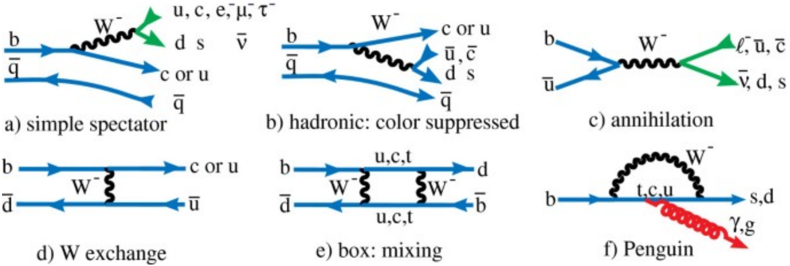
Table: SM Quantum Numbers

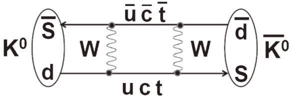
Anomaly Cancellation Conditions

$$
\begin{aligned}
6\,A_1 &= \sum_{i=1}^{3}[c_{Q_L i} - 8\,c_{u_R\,i} - 2\,c_{d_R\,i} + 3\,c_{L_L\,i} - 6c_{e_R\,i}] + X_1], \\
2\,A_2 &= \sum_{i=1}^{3}[3\times c_{Q_L\,i} + c_{L_L\,i}] + X_2], \\
2A_3 &= \sum_{i=1}^{3}[2\times c_{Q_L\,i} - c_{u_R\,i} - c_{d_R\,i}] + X_3], \\
2A_F &= \sum_{i=1}^{3}\left[c_{Q_L\,i}^2 - 2\,c_{u_R\,i}^2 + c_{d_R\,i}^2 - c_{L_L\,i}^2 + c_{e_R\,i}^2\right] + X_F], \\
2A_F^3 &= \sum_{i=1}^{3}\left[6\,c_{Q_L\,i}^3 - 3\left(c_{u_R\,i}^3 + c_{d_R\,i}^3\right) + 2\,c_{L_L\,i}^3 - c_{e_R\,i}^3\right] + X_F^3], \\
2\,U(1)_F^2\,U(1)_Y &= \sum_{i=1}^{3}\left[c_{Q_L\,i}^2 - c_{L_L\,i}^2 - 2c_{u_R\,i}^2 + c_{d_R\,i}^2 + c_{e_R\,i}^2\right],
\end{aligned}
$$

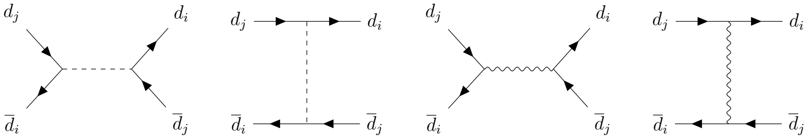
X_F is the correspond to the contribution of additional matter

Constraints from FCNC:





Taking into account all the possible interactions allowed by the new Higgs doublets and the Z_F that we have



FCNC: They impose some constraints on Yukawa Couplings (conservative values)

1. Δm_K:
   $\mathrm{Re}\left(\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i12}}+\mathrm{Y}^{\mathrm{d}}_{\mathrm{i21}}\right), \mathrm{Re}\left(\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i12}}-\mathrm{Y}^{\mathrm{d}}_{\mathrm{i21}}\right) < 2.6\times 10^{-7}$,
2. From Δm_D:
$$\mathrm{Re}\left(\mathrm{Y}^{\mathrm{u}*}_{\mathrm{i12}}+\mathrm{Y}^{\mathrm{u}*}_{\mathrm{i21}}\right), \mathrm{Re}\left(\mathrm{Y}^{\mathrm{u}*}_{\mathrm{i12}}-\mathrm{Y}^{\mathrm{u}*}_{\mathrm{i21}}\right) < 2.6\times 10^{-7},$$
$$\mathrm{Im}\left(\mathrm{Y}^{\mathrm{u}*}_{\mathrm{i12}}+\mathrm{Y}^{\mathrm{u}}_{\mathrm{i21}}\right)=0, \quad \mathrm{Im}\left(\mathrm{Y}^{\mathrm{u}*}_{\mathrm{i12}}-\mathrm{Y}^{\mathrm{u}}_{\mathrm{i21}}\right)=0$$
3. From Δm_{B_d}:
$$\mathrm{Re}\left(\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i13}}+\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i31}}\right), \mathrm{Re}\left(\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i13}}-\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i31}}\right) < 4.8\times 10^{-5},$$
$$\mathrm{Im}\left(\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i13}}+\mathrm{Y}^{\mathrm{d}}_{\mathrm{i31}}\right)=0, \quad \mathrm{Im}\left(\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i13}}-\mathrm{Y}^{\mathrm{d}}_{\mathrm{i31}}\right)=0$$
4. From Δm_{B_s}:
$$\mathrm{Re}\left(\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i23}}+\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i32}}\right), \mathrm{Re}\left(\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i23}}-\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i32}}\right) < 2.8\times 10^{-4},$$
$$\mathrm{Im}\left(\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i23}}+\mathrm{Y}^{\mathrm{d}}_{\mathrm{i32}}\right)=0, \quad \mathrm{Im}\left(\mathrm{Y}^{\mathrm{d}*}_{\mathrm{i23}}-\mathrm{Y}^{\mathrm{d}}_{\mathrm{i32}}\right)=0$$

Oblique Parameters

Quantify deviations from the SM in terms of radiative corrections to the gauge-boson two point functions.

They are a very useful way to constrain new physics parameters, when the new particles couple to the SM Z and/or $W^{\pm}$ bosons.

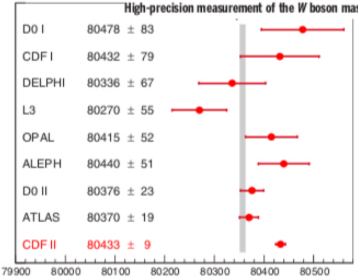
In our scenario the NP scale($\sim$ TeV), the three parameters, S, T and U can encapsulate the oblique corrections at one loop level. The best fit values are Particle DataGroup, 2020

$$S = -0.01 \pm 0.10 \quad T = 0.03 \pm 0.12\,,$$
$$U = 0.02 \pm 0.11\,.$$

The CDF Collaboration made an announcement of the W-boson mass measurement with unprecedented precision Aaltonen, T. et. al.

"High-precision measurement of the W boson mass with the CDF II

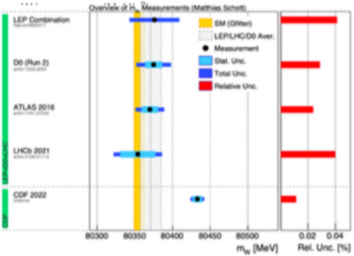
Fig. 5. Comparison of this CDF II measurement and past M_W measurements with the SM expectation. The latter includes the published estimates of the uncertainty (4 MeV) due to missing higher-order quantum corrections, as well as the uncertainty (4 MeV) from other global measurements used as input to the calculation, such as m_t. c, speed of light in a vacuum.



Science Paper from CDF 2022

CDF I result with a quarter of the data of CDFII

https://non-trivial-solution.blogspot.com/2022/04/do-we-have-finally-found-new-physics.html



The value $M_W^{\rm SM} = 80,357 \pm 6$ MeV, shows a 7σ discrepancy. If confirmed by future experiments, it will be a clear signal of NP. Although, more likely to be drastically reduced (some issues with the way the CDF collaboration uses some fitting algorithms).

The NP contribution to the M_W is related to the S, T and U parameters as

$$\Delta M_W = -\frac{\alpha M_W^{\rm SM}}{4(c_W^2 - s_W^2)}\left(S - 2c_W^2 T - \frac{c_W^2 - s_W^2}{2s_W^2} U\right).$$

With T-parameter only, we have

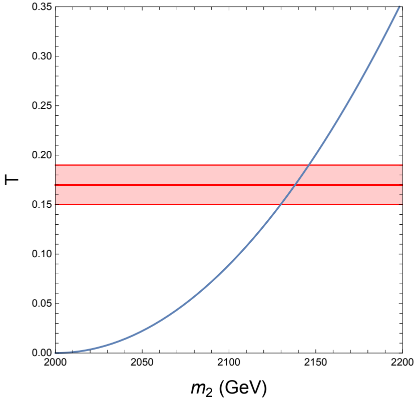
$$\Delta M_W \approx 450\, T\, \mathrm{MeV},$$

showing that $T \approx 0.17 \pm 0.02$ can explain the M_W anomaly. We can see that a large enhancement is required in the T parameter compared with the central value of $T = 0.03 \pm 0.12$.

For the scalar contributions the most stringent constraint comes from the T parameter The multi-Higgs contribution to the T parameter is

$$
\begin{aligned}
T \quad = \quad & \frac{1}{16\pi s_W^2 m_W^2}\Bigg\{ \sum_{a=2}^{6}\sum_{m=3}^{7}\Big|\sum_{k=1}^{6}(S_\varphi)_{mk}U^*_{ka}\Big|^2 F((m_a^+)^2,(m_m^p)^2) \\
& + \sum_{a=2}^{6}\sum_{n=1}^{7}\Big|\sum_{k=1}^{6}(S_\sigma)_{nk}U^*_{ka}\Big|^2 F((m_a^+)^2,(m_n^s)^2) \\
& - \sum_{m=3}^{7}\sum_{n=1}^{7}\Big[\sum_{k=1}^{6}(S_\varphi)_{mk}(S_\sigma)_{nk}\Big]^2 F((m_m^p)^2,(m_n^s)^2) \\
& -2\sum_{a=2}^{5}\sum_{a'=a+1}^{6}\Big|(U^\dagger U)_{aa'}\Big|^2 F((m_a^+)^2,(m_{a'}^+)^2) \\
& +3\sum_{n=1}^{7}\Big[\sum_{k=1}^{6}(S_\varphi)_{1k}(S_\sigma)_{nk}\Big]^2\Big[F(m_Z^2,(m_n^s)^2)-F(m_W^2,(m_n^s)^2)\Big] \\
& -3\Big[F(m_Z^2,m_h^2)-F(m_W^2,m_h^2)\Big]\Bigg\},
\end{aligned}
$$

Using the conservative bounds on Yukawa couplings (and based on an specific value of charges cancelling the triangle anomalies) we can get into the region pointed out by the CDFII measurement (m_2 second lightest Higgs boson)



Summary

- SM assumption about the existence of a single Higgs doublet is the simplest choice
- Naturally to extend the theory with more Higgs doublets
- We have found some simply solutions using Anomaly Cancellation and avoiding FCNC constraints
- We do not concentrate on the examples found but treat them as a proof of principle that it is possible to add those Higgs doublets to the SM theory.

Excellent opportunity for ILC Physics!! The ILC is a proposed next-generation e^+e^- collider. It starts with $\sqrt{s} = 250$ GeV as the Higgs factory. The precision study of the Higgs boson is the next major goal in collider physics; the ILC will reach important benchmarks in the measurement of the Higgs boson couplings. Such high precision measurements will provide guidance to the next energy scale for future facilities.