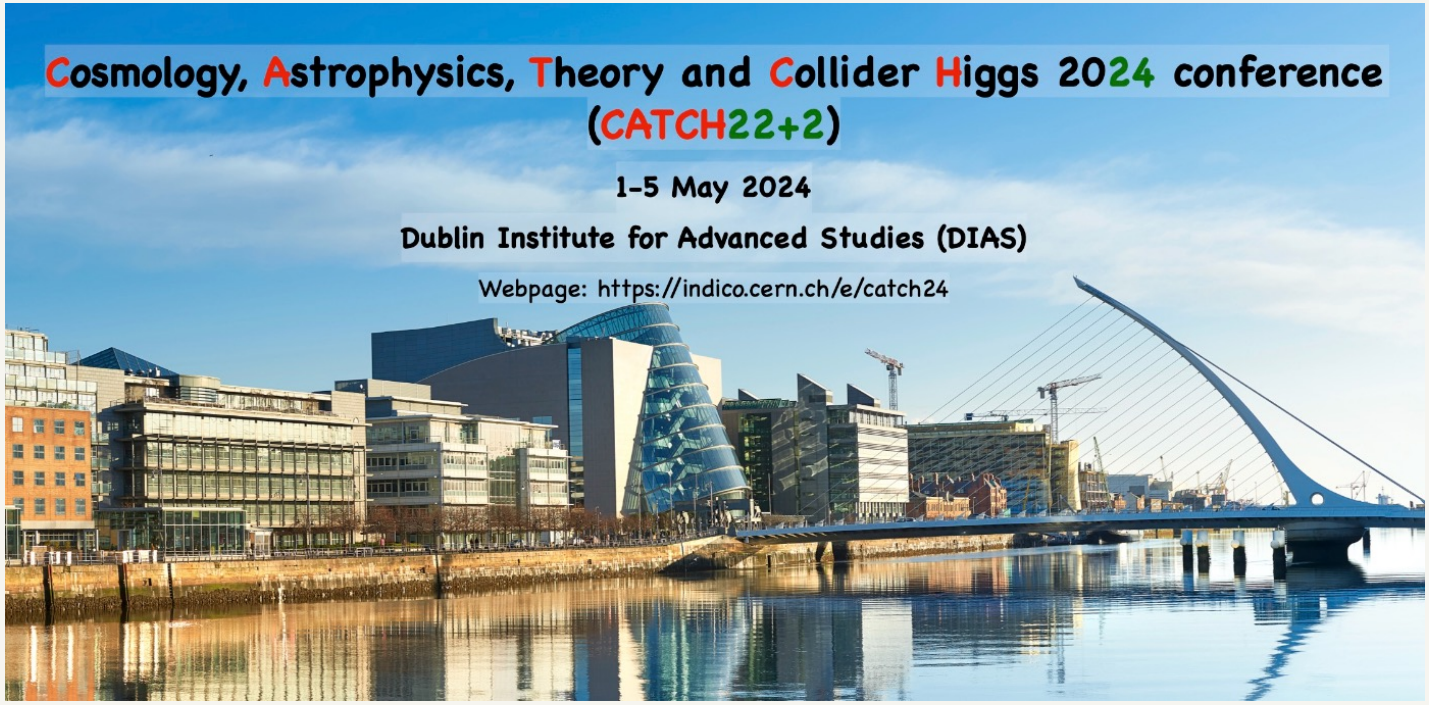
# Deconstructing Flavor: The Privately Democratic Higgs

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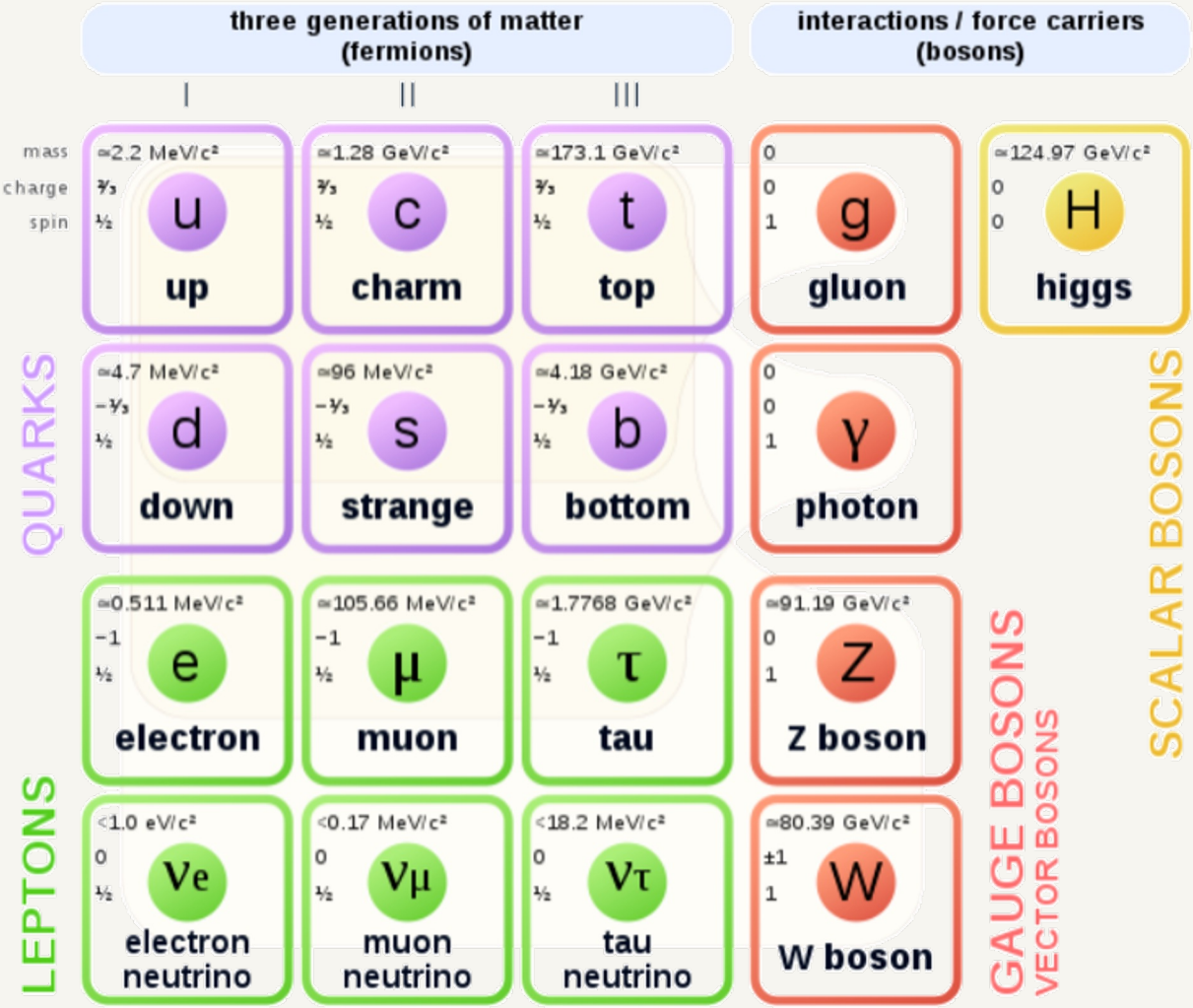
Sat May 4, 2024

WAYNE STATE UNIVERSITY

# The Beloved *Beautiful* (& Unnatural)

# Standard Model

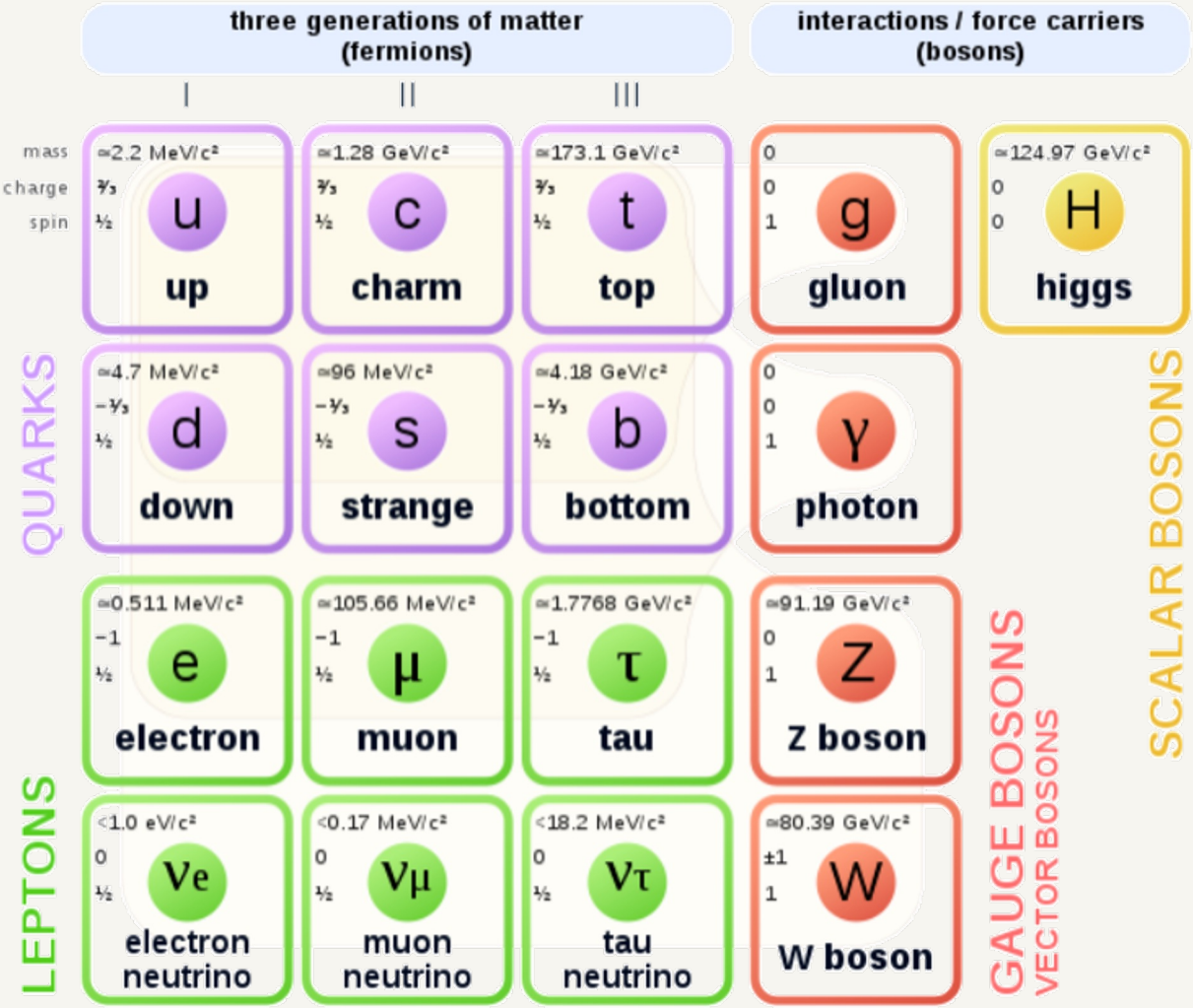



https://en.wikipedia.org/wiki/Elementary_particle

3 generations of matter
$SU(3)_C \times SU(2)_L \times U(1)_Y$

# The Beloved *Beautiful* (& Unnatural)

# Standard Model

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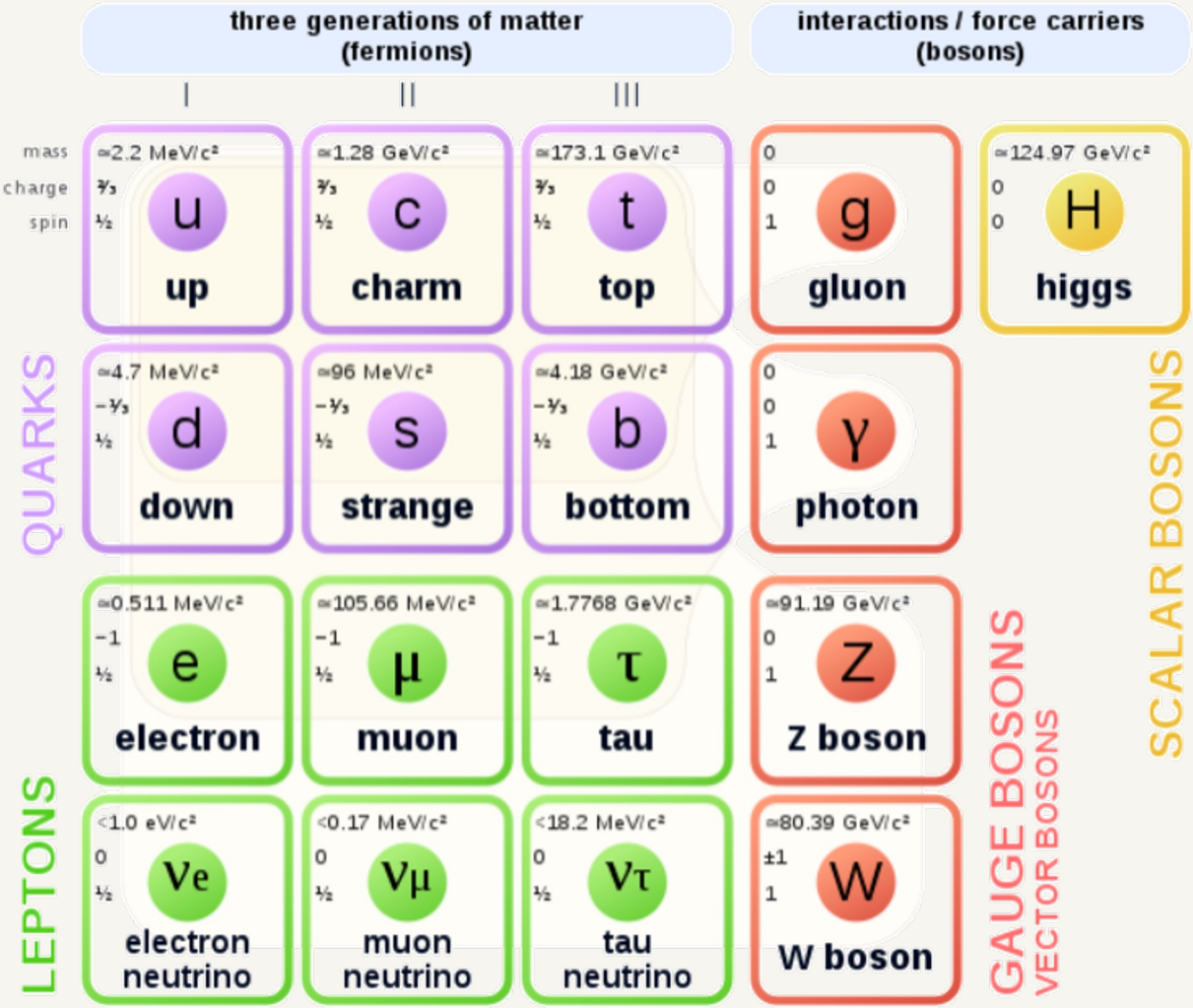
3 generations of matter
$SU(3)_C \times SU(2)_L \times U(1)_Y$

**WHY????**

# The Beloved *Beautiful* (& Unnatural)

## Standard Model



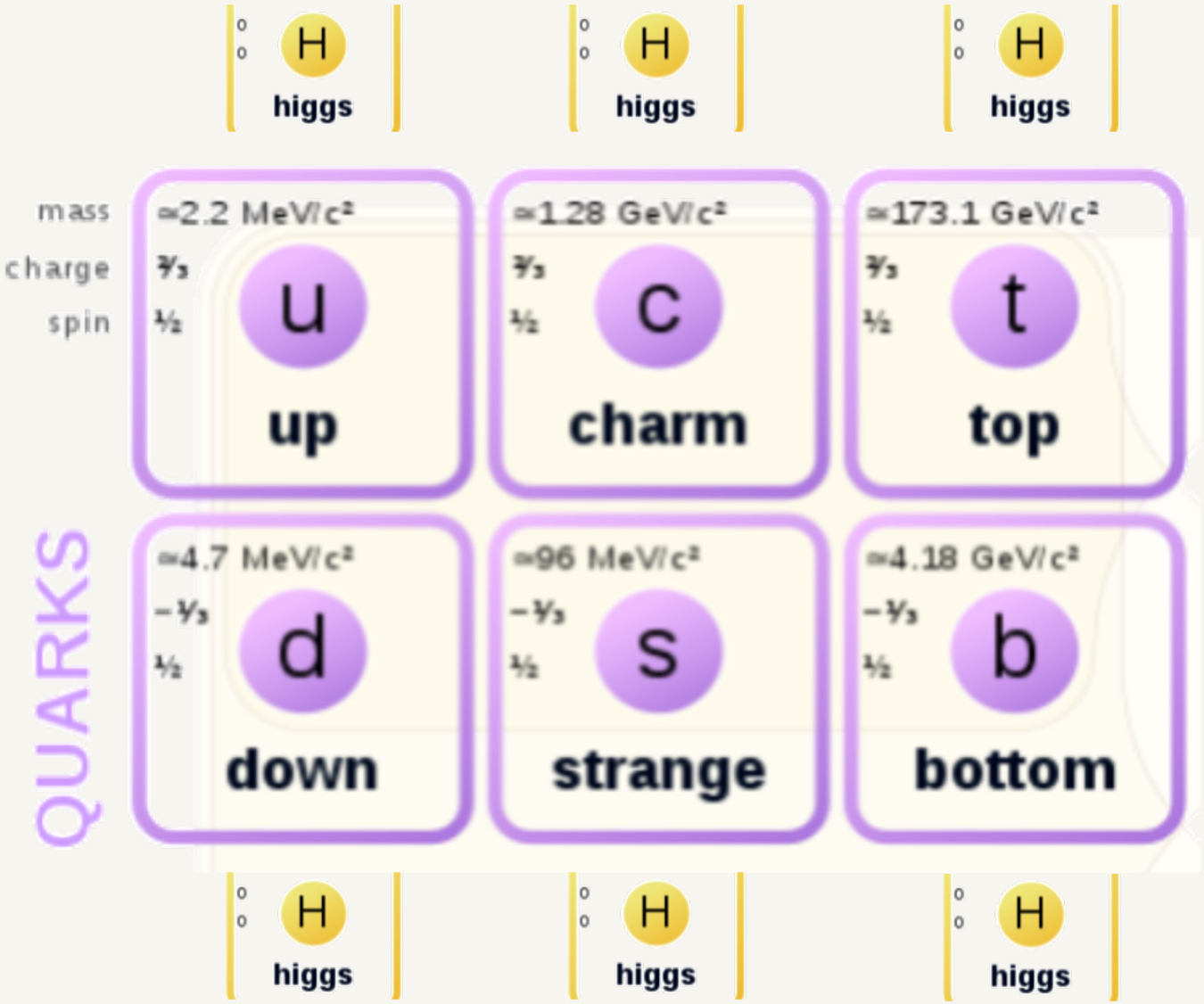

https://en.wikipedia.org/wiki/Elementary_particle

**Non-Minimal**
**Unnatural**

Arbitrary Content
Arbitrary Masses
Arbitrary Mixings

**Arbitrary Higgs Mechanism**

# A *PLETHORA* OF HIGGS

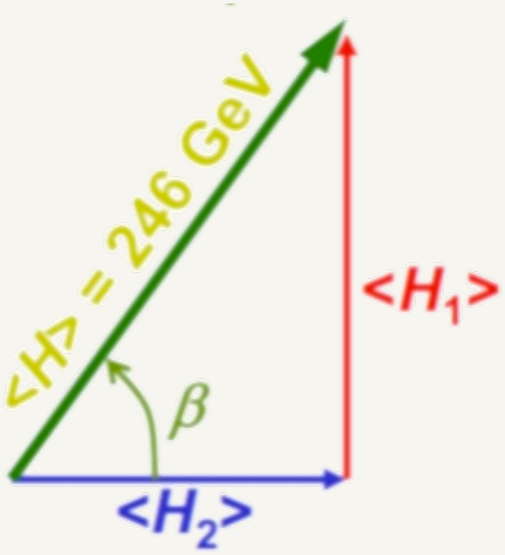



$$\langle H_f \rangle \sim m_f$$

$$y_f \sim 1$$

But we **SEE** a SM-like Higgs!

# 2 Higgs Doublet Model (2HDM).




$\langle H_1 \rangle$ , $\langle H_2 \rangle$ → $\langle H \rangle$ , $\tan\beta$

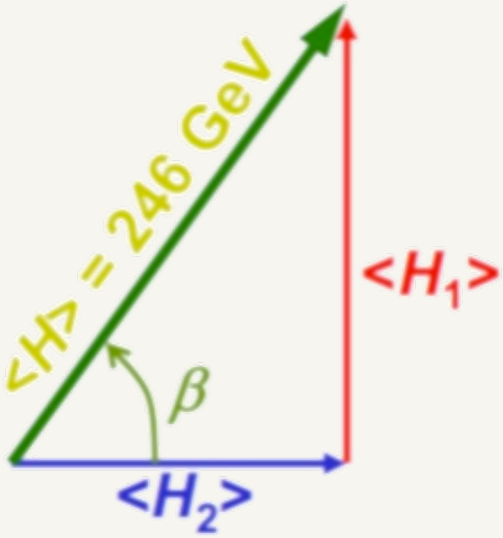
5 Physical Higgs bosons:

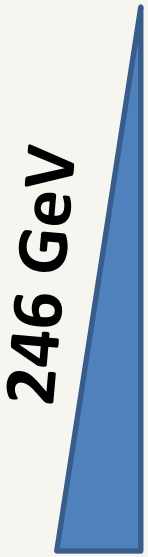
CP-Even: **h, H**

CP-Odd: **A**

Charged Higgs: $\mathbf{H^{+,-}}$

# 2 Higgs Doublet Model (2HDM).




$\langle h \rangle \sim \langle H_{SM} \rangle$

$\langle H_1 \rangle$ , $\langle H_2 \rangle \rightarrow \langle H \rangle$ , $\tan\beta$

5 Physical Higgs bosons:

CP-Even: **h, H**

CP-Odd: **A**

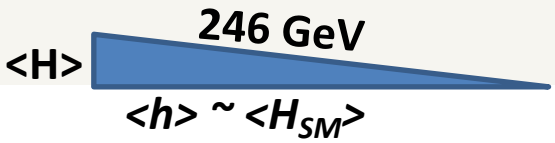
Charged Higgs: $\mathbf{H^{+,-}}$

**SM: Only 1 Higgs which then acquires a vev and leads to EWSB.**

**This is what we want!**

**ALIGNMENT**

# Recipe: SM-Like Higgs.




$v \sin^2 \beta$

$$H_{SM} = \sin\beta H_u + \cos\beta H_d \quad \leftarrow v \cos^2 \beta$$

$$H_{NSM} = -\cos\beta H_u + \sin\beta H_d$$

**SM: Only 1 Higgs which then acquires a vev and leads to EWSB.**

**This is what we want!**

**Lighter (*h*) is 125 GeV SM-like Higgs.**

**Additional states can exist!**

**Additional States can be light!**

Haber and Gunion, '03, M. Carena, I. Low, N.R.S. & C. Wagner, '13, A. Delgado, G. Nardini & M. Quiros, '13, N. Craig, J. Galloway & S. Thomas,'13, P. Dev, A. Pilaftsis '14, M. Carena, H. Haber, I. Low, N.R.S. & C. Wagner '14 & '15 etc ....

$\langle H_d \rangle = v \cos\beta$

$\langle H_u \rangle = v \sin\beta$

$\Rightarrow \langle H_{SM} \rangle = v$

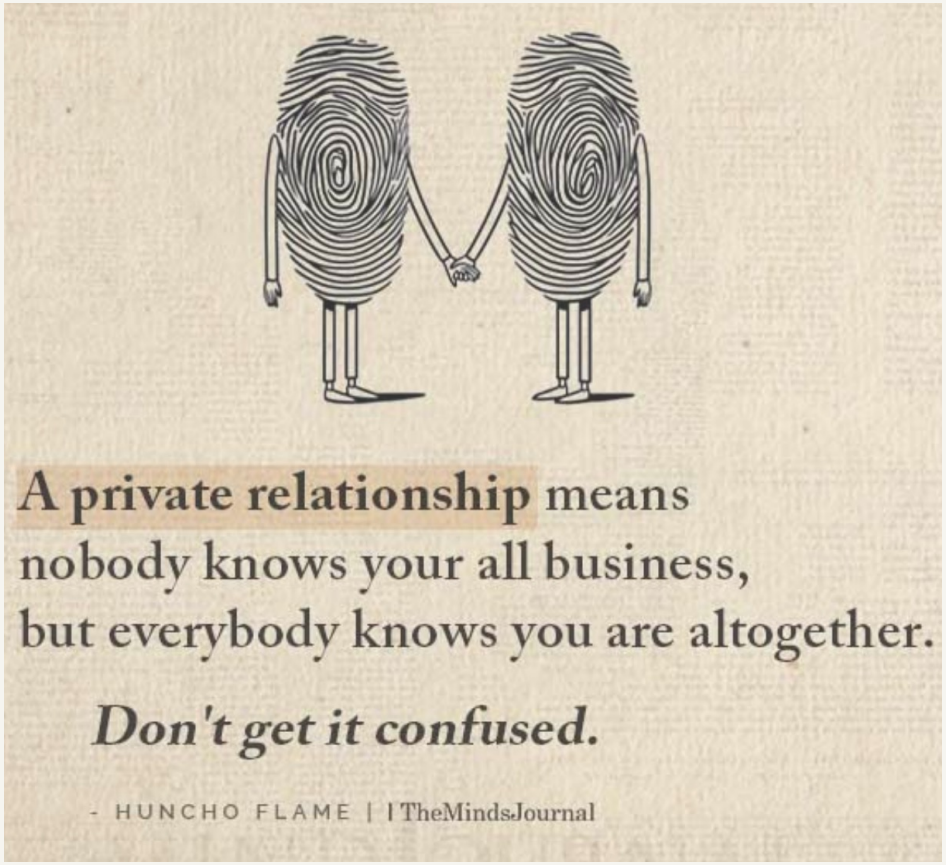
$\langle H_{NSM} \rangle = 0$

**SM-like HIGGS**

**ALIGNMENT**

https://themindsjournal.com/quotes/a-private-relationship-means-nobody-knows/

$$\sum m_f^2 \approx m_t^2 \approx v_{SM}^2$$




# PRIVATE HIGGS

Or is it SECRET instead !?!

$$\langle H_f \rangle \sim m_f$$
$$y_f \sim 1$$

# Private Higgs

R. Porto & A. Zee '07 + follow ups

A private Higgs for every SM fermion!
Plus additional singlets
Impose Symmetries

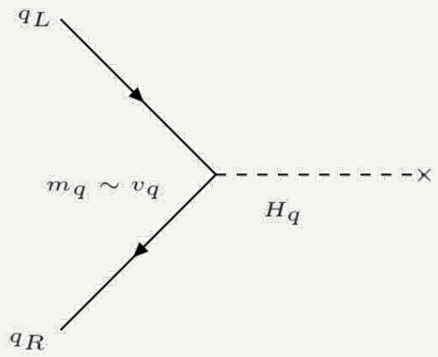
$v_t \sim v_{SM}$ , $H_t \sim H_{SM} = H_{125}$ ,
Usual negative mass squared terms to induce EWSB
Additional singlets w/ masses and vevs ~ $v_t$.

$$\mathcal{L}_{H_f} \sim M_f^2 H_f^\dagger H_f - \lambda\, S S H_f^\dagger H_t$$

$$v_f^2 \ll v_t^2, f \neq t,$$

Assume $M_f \gg m_t$

$$\mathcal{L} \supset \sum_j \left( \bar{Q'}^j_L H_d^j d_R^j + \bar{Q'}^j_L \tilde{H}_u^j u_R^j \right) + \text{h.c.}$$




"Scalar see-saw" mechanism:

Hierarchy: $y_f \rightarrow v_f \sim \frac{v_t^3}{M_f^2}$

COMPLETELY diagonal structure.
No CKM!

# Higgs Pheno??

$$\mathcal{L}_{H_f} \sim M_f^2 H_f^\dagger H_f - \lambda S S H_f^\dagger H_t$$

$$v_f \sim \frac{v_t^3}{M_f^2}$$

Lightest "Heavy" Higgs → $H_b$
$M_b \sim 1$ TeV
Produced via gluon fusion, bottom loops
Decays to $b\bar{b}$

Can consider low energy theory via either mixing or "integrating out"

Y. BenTov & A. Zee '12

$$\mathcal{L}_{H_t b\bar{b}} = -\frac{m_b}{v_t}\left(1 - \Gamma_t \frac{v_t^2}{\mathcal{M}_b^2}\right) H_t b\bar{b} + h.c.$$

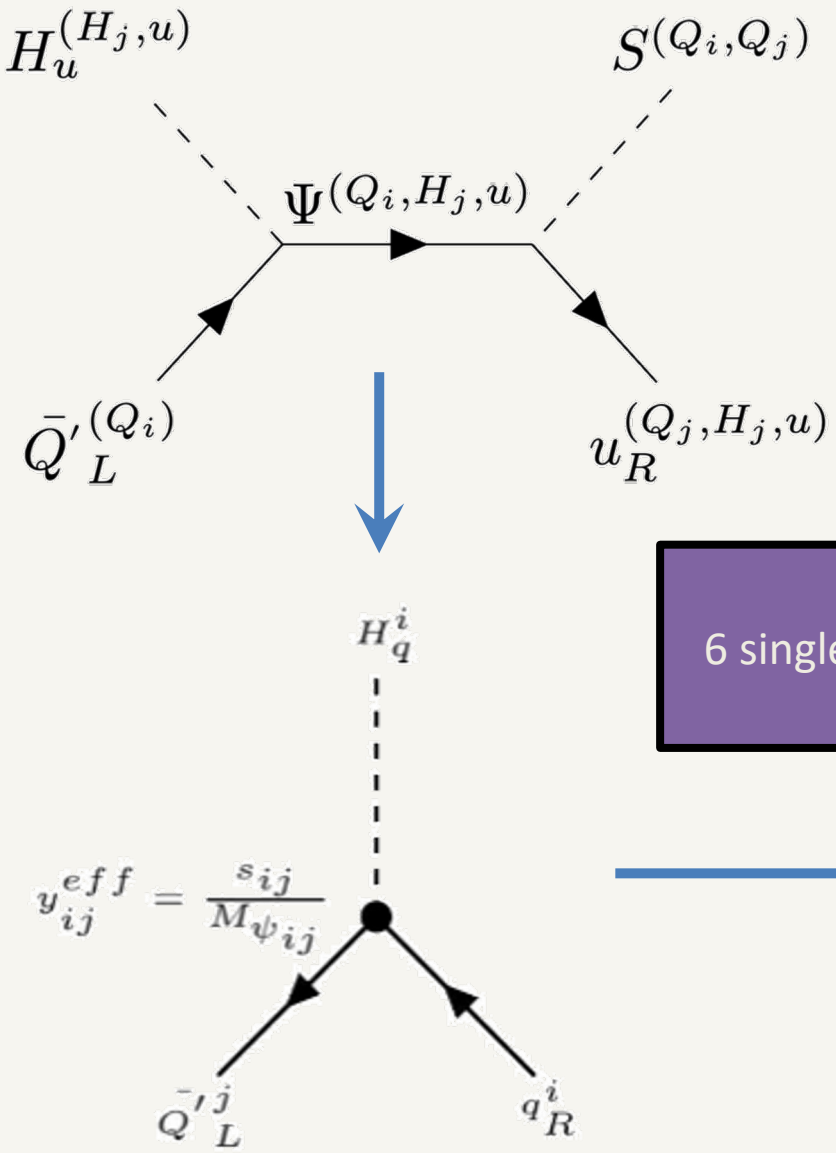
$H_t \sim H_{SM} = H_{125}$

**Higgs Precision in the future??**

[Many singlets $\sim\mathcal{O}$ (100 GeV) floating around…]

$$\mathcal{L}_q \supset \sum_{i,j} \left( \bar{Q'}^j_L \, H^i_q \psi^{ij}_q + \bar{\psi}^{ij}_q S^{ij} q^i_R \right) + \text{h.c.}$$

# CKM ??




Impose $Z_2$s to allow only interactions we want

For each $Q_i$ Quark generation: $Z_2^{Q_i}$

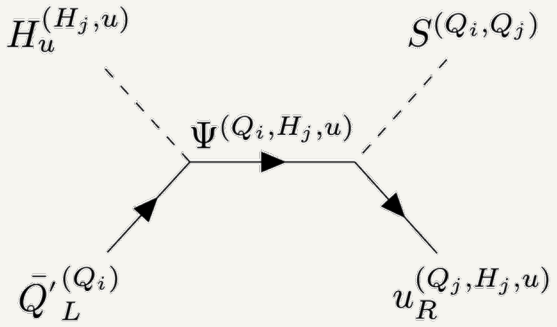
For each $H_{ui}$ coupling to u-type quarks: $Z_2^{H_{ui}}$

For each $H_{di}$ coupling to d-type quarks: $Z_2^{H_{di}}$

3 Additional Singlets $S^{i,j}$ with vevs $s_{i,j} = s_{j,i}$
6 singlet Vector-like Quarks $\Psi^{i,uj}$ with masses $M_{i,j} \neq M_{j,i}$
$i \neq j$

CKM ☺

# Complexities …




VLQ heavy
Mixing effects with SM quarks or integrate them out

Leads to rescaling of SM quarks kinetic terms
Canonically normalize them

Rescaling of SM quarks – *W* couplings absorbed in CKM

SM quarks – *Z* couplings leads to NON-UNIVERSAL *Zqq* couplings (patience!!)

CKM ☺

$$\begin{bmatrix} \frac{\lambda_{11} v_u}{x m_u} & \frac{\lambda_{12} v_c \alpha_{12} s_{12}}{M_{12} y m_c} & \frac{\lambda_{21} v_t \alpha_{21} s_{21}}{M_{21} z m_t} \\ \frac{\lambda_{21} v_u \alpha_{21} s_{21}}{M_{21} x m_u} & \frac{\lambda_{22} v_c}{y m_c} & \frac{\lambda_{23} v_t \alpha_{23} s_{23}}{M_{23} z m_t} \\ \frac{\lambda_{31} v_u \alpha_{31} s_{31}}{M_{31} x m_u} & \frac{\lambda_{32} v_c \alpha_{32} s_{32}}{M_{32} y m_c} & \frac{\lambda_{33} v_t}{z m_t} \end{bmatrix}$$

$$x = \sqrt{1 + (\tfrac{\alpha_{12} s_{12}}{M_{12}})^2 + (\tfrac{\alpha_{13} s_{13}}{M_{13}})^2},$$
$$y = \sqrt{1 + (\tfrac{\alpha_{21} s_{21}}{M_{21}})^2 + (\tfrac{\alpha_{23} s_{23}}{M_{23}})^2},$$
$$z = \sqrt{1 + (\tfrac{\alpha_{31} s_{31}}{M_{31}})^2 + (\tfrac{\alpha_{32} s_{32}}{M_{32}})^2}$$

# What do we Learn?

(Actually $V_{CKM}^{-1}$)

$$\begin{bmatrix} \frac{\lambda_{11} v_u}{x m_u} & \frac{\lambda_{12} v_c \alpha_{12} s_{12}}{M_{12} y m_c} & \frac{\lambda_{21} v_t \alpha_{21} s_{21}}{M_{21} z m_t} \\ \frac{\lambda_{21} v_u \alpha_{21} s_{21}}{M_{21} x m_u} & \frac{\lambda_{22} v_c}{y m_c} & \frac{\lambda_{23} v_t \alpha_{23} s_{23}}{M_{23} z m_t} \\ \frac{\lambda_{31} v_u \alpha_{31} s_{31}}{M_{31} x m_u} & \frac{\lambda_{32} v_c \alpha_{32} s_{32}}{M_{32} y m_c} & \frac{\lambda_{33} v_t}{z m_t} \end{bmatrix}$$

$\lambda, \alpha \sim 1$ couplings

$v_f \sim m_f$

$V_{CKM}$ *dictates* ratio of $s_{ij}/M_{ij}$!

$$|V_{CKM}| = \begin{pmatrix} 0.97446 \pm 0.0001 & 0.2245 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.0001}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}.$$

$$M_{12} \approx M_{21} \approx 4 S_{12},$$

$$M_{23} \approx M_{32} \approx 25 S_{23}$$

$$M_{31} \approx 265 S_{31}, M_{13} \approx 115 S_{13}$$

Assumed singlet vevs ~ SM vev
Nothing requires it so far…

# Diagonal matrix *C*:

$$g^{NP}_{z\bar{f}_i f_i} = g^{SM}_{z\bar{f}f} \times \left(1 - \frac{\sin^2\theta_w Q \sum_{j=1,2,3}^{i\neq j} \frac{|\lambda^u_{ij}|^2}{M^2_{ij}} \nu^{u2}_j}{T^3 - \sin^2\theta_w Q}\right)$$

Non-universal, but still diagonal in original basis

$$Z\, \overline{q_i}\, C\, q_i$$

After rotating to mass basis …

$$M_{12} \approx M_{21} \approx 4S_{12},$$
$$M_{23} \approx M_{32} \approx 25S_{23}$$
$$M_{31} \approx 265S_{31}, M_{13} \approx 115S_{13}$$

$$g^u = V_{CKM} C V^\dagger_{CKM}. \quad \neq \mathbb{I}!!!$$

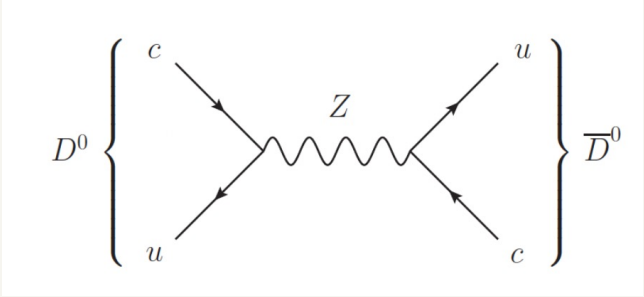
$$\begin{array}{c} \\ \bar{u} \\ \bar{c} \\ \bar{t} \end{array} \begin{array}{c} \begin{array}{ccc} u & c & t \end{array} \\ \begin{bmatrix} \left|-0.2367 + \frac{0.23\text{GeV}^2}{S^2_{13}} + \frac{0.27\text{GeV}^2}{S^2_{23}}\right| & \left|\frac{-0.05\text{GeV}^2}{S^2_{13}} + \frac{1.15\text{GeV}^2}{S^2_{23}}\right| & \left|\frac{0.05\text{GeV}^2}{S^2_{23}}\right| \\ \left|\frac{-0.05\text{GeV}^2}{S^2_{13}} + \frac{1.15\text{GeV}^2}{S^2_{23}}\right| & \left|-0.2367 + \frac{0.01\text{GeV}^2}{S^2_{13}} + \frac{5\text{GeV}^2}{S^2_{23}}\right| & \left|\frac{-0.21}{S^2_{23}}\right| \\ \left|\frac{0.05\text{GeV}^2}{S^2_{23}}\right| & \left|\frac{0.21\text{GeV}^2}{S^2_{23}}\right| & 0.2367 \end{bmatrix} \end{array}$$

# Any more Luck?

$$
\begin{array}{c} \\ \bar{u} \\ \bar{c} \\ \bar{t} \end{array}
\begin{array}{c}
\begin{array}{ccc} u & c & t \end{array} \\
\begin{bmatrix}
\left|-0.2367 + \frac{0.23\text{GeV}^2}{S_{13}^2} + \frac{0.27\text{GeV}^2}{S_{23}^2}\right| & \left|\frac{-0.05\text{GeV}^2}{S_{13}^2} + \frac{1.15\text{GeV}^2}{S_{23}^2}\right| & \left|\frac{0.05\text{GeV}^2}{S_{23}^2}\right| \\
\left|\frac{-0.05\text{GeV}^2}{S_{13}^2} + \frac{1.15\text{GeV}^2}{S_{23}^2}\right| & \left|-0.2367 + \frac{0.01\text{GeV}^2}{S_{13}^2} + \frac{5\text{GeV}^2}{S_{23}^2}\right| & \left|\frac{-0.21}{S_{23}^2}\right| \\
\left|\frac{0.05\text{GeV}^2}{S_{23}^2}\right| & \left|\frac{0.21\text{GeV}^2}{S_{23}^2}\right| & 0.2367
\end{bmatrix}
\end{array}
$$

For s ~ 100 GeV, corrections $\lesssim 10^{-4}$ to diagonal couplings

FCNC: D-D mixing




Not constrained by current measurements if $s_{ij} \gtrsim 150$ GeV

FCNC: $t \to Zu, Zc$
Only constrains $\lesssim 10^{-2}$ for off-diagonal couplings…

# Many Avenues to Explore

Rich phenomenology:

Many new particles expected

**LHC signatures**?

Precision Higgs/SM physics?

Dark Matter connections?

Cosmology +
Gravitational Waves…

$\Psi_{ij}$

$M_{12} \approx M_{21} \approx 4S_{12}$,

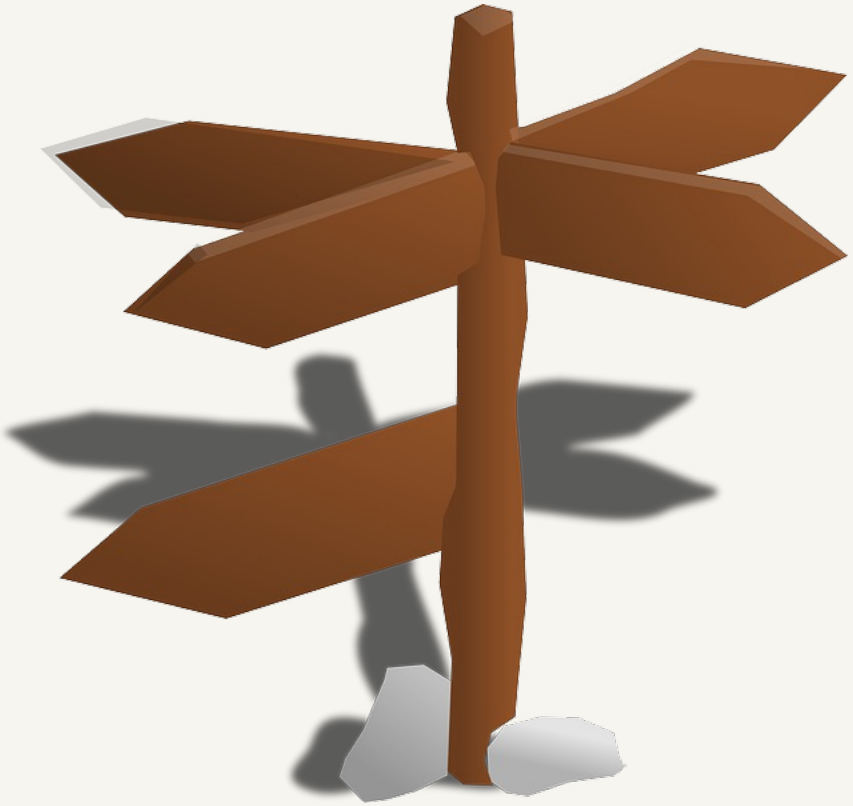
$M_{23} \approx M_{32} \approx 25S_{23}$

$M_{31} \approx 265S_{31}, M_{13} \approx 115S_{13}$

$s_{ij}$~100 GeV

$M_{H_f} \gg$ TeV (except $b$)

$M_{S_{ij}}$??



# Thank You!


**SM works beautifully…**

But it's a pretty **RIDICULOUS** model!!

**What are the right questions?**

Hypothesize an at-least-as-ridiculous(!!!) BSM model.
Seems rather difficult to probe…

**Data + Theory: Where to look next!**

**???**

**Absence of Evidence != Evidence of Absence**

Data driven age: Collider + Precision + Astrophysical Probes …
**HOPE blooms ETERNAL!!!**