Beyond the *Standard Model* & Higgs - I

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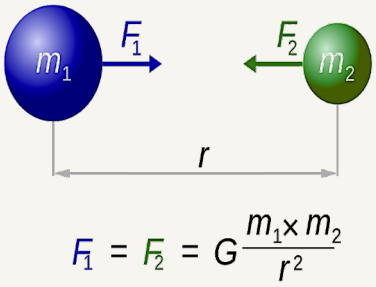
Probing the Mysteries of the Universe

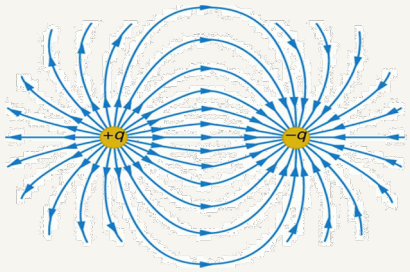
Monday Jan 10, 2022

Forces in Nature.



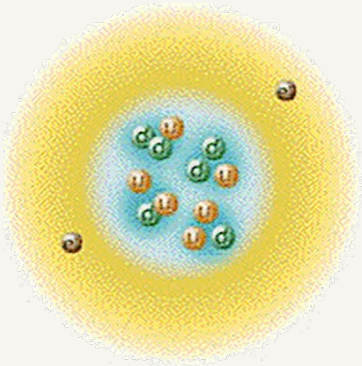
Gravity

Attractive force between two massive objects.



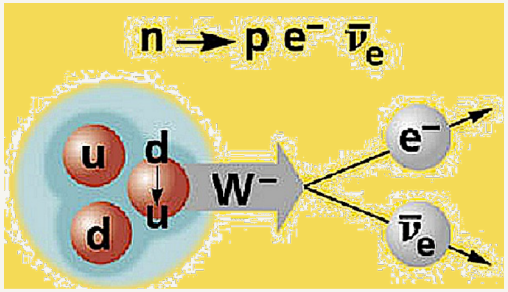
Electromagnetism

- Attracts particles of opposite charge, between and within atoms.
- Is mediated by photons.



Strong Force

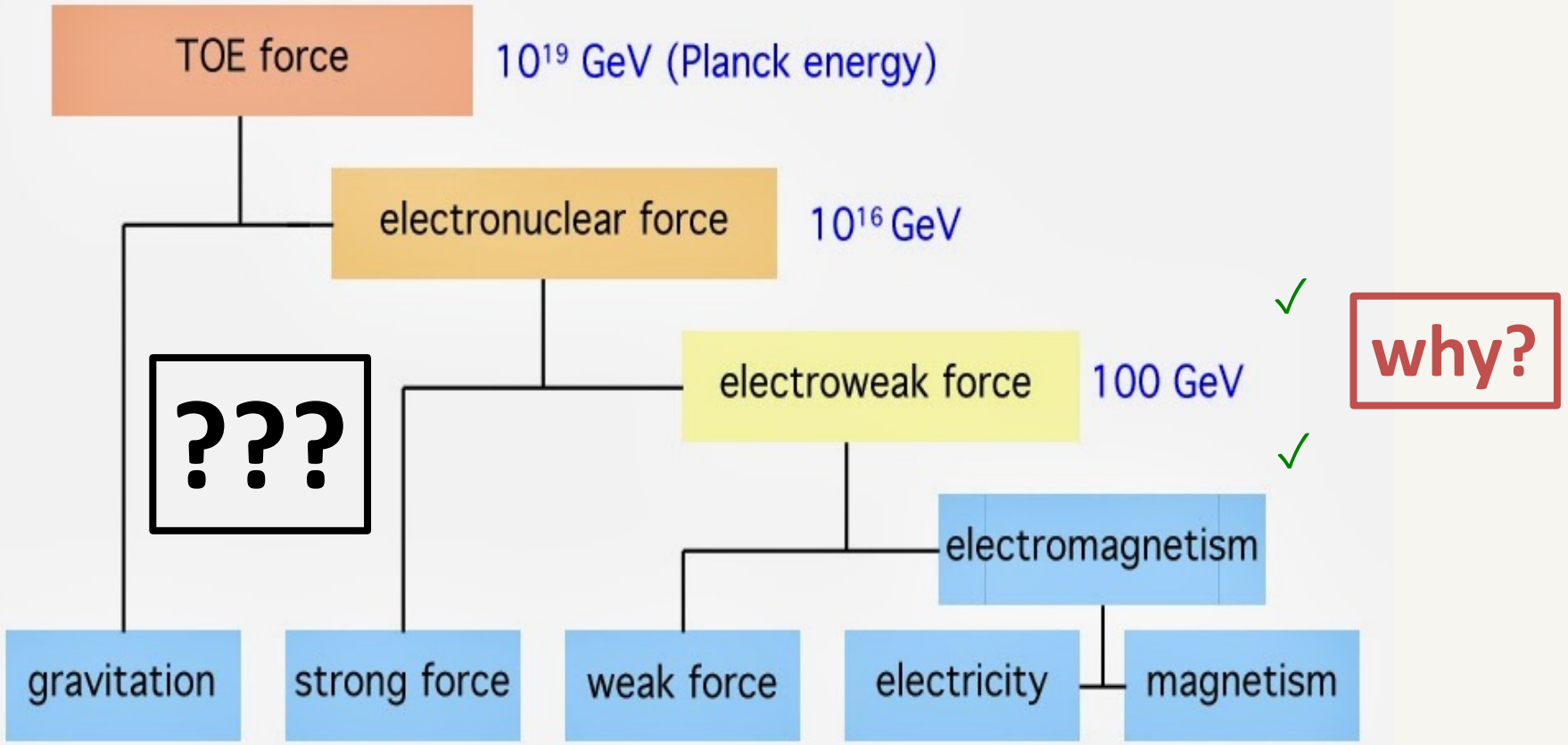
- Binds protons and neutrons to form atomic nuclei.
- proton: **uud**
- neutron: **udd**
- Formed by 3 quarks bound together by gluons of the strong interactions.



Weak Force

- Mediates particle transformations
- e.g., **β-Decay**
- Is mediated by massive W/Z bosons.

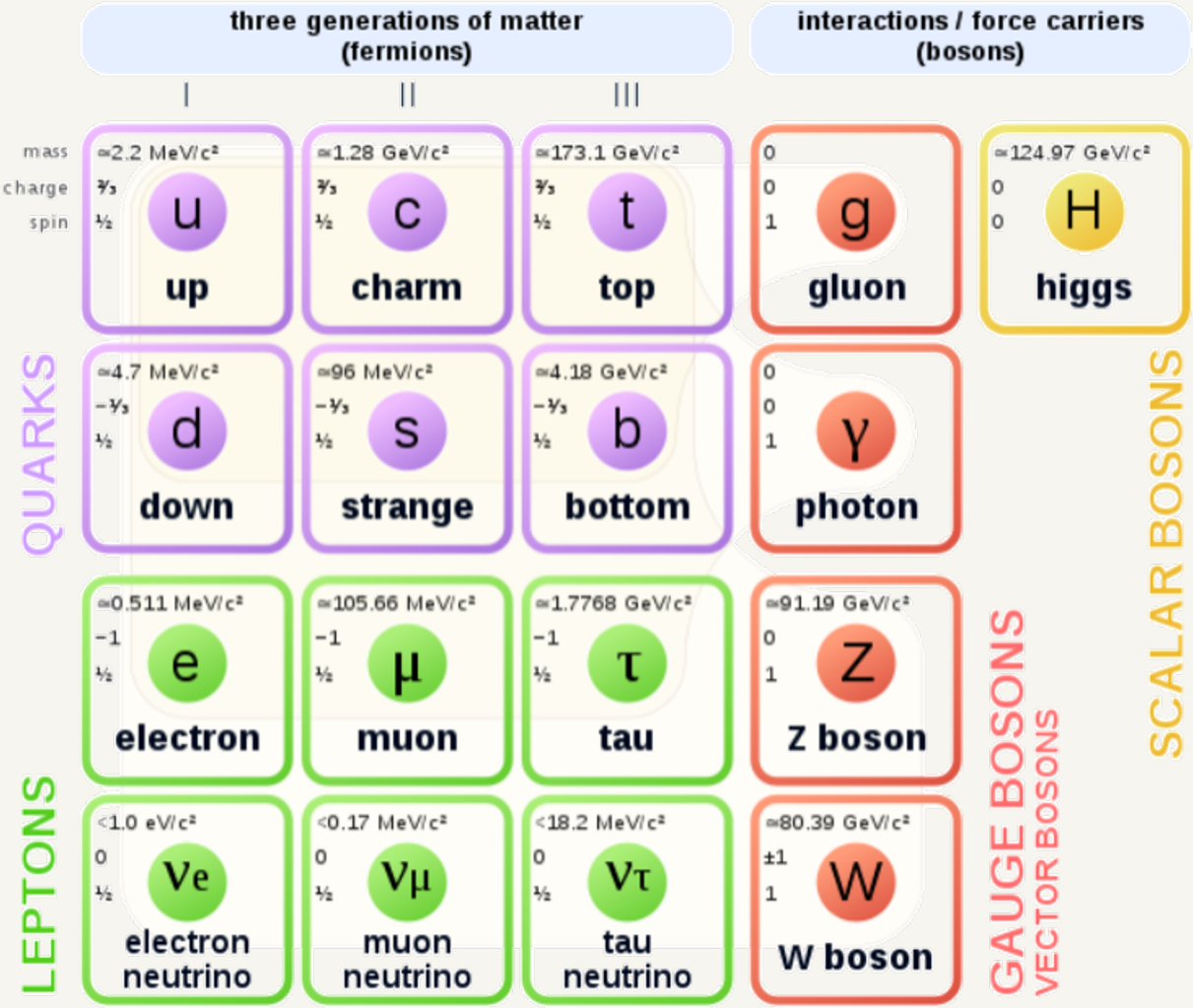
Big Picture



What is Dark Matter?

The Beloved *Beautiful* (& EMPIRICAL)

Standard Model



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

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

WHY????

What is Dark Matter?

SM Lagrangian

SM Lagrangian (**Dynamics + interactions**) based on

Minimality
Unitarity & Renormalizability
Symmetries

Symmetries (**Transformations** which leaves Lagrangian *invariant*):

Lorentz Symmetries
Gauge (local) Symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y$
(Demands presence of "Gauge bosons")

"Accidental" global symmetries may arise, for eg:

In absence of masses: Flavor symmetry for fermions
Lepton and Baryon number
Etc…

Gauge (Local) Symmetries

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

Eg: Scalar with charge "*e*" under U(1): $\Phi(x) \longrightarrow e^{i\,e\,\beta(x)}\,\Phi(x)$

KE term NOT invariant!!

$$\left|\partial_\mu \Phi\right|^2$$

REQUIRES presence of massless gauge boson ($\boldsymbol{A_\mu}$) in "covariant" derivative.
KE term ($\left|\mathcal{D}_\mu \Phi\right|^2$) invariance is preserved:

$$\mathcal{D}_\mu = \partial_\mu + i\,e\,A_\mu$$
$$A_\mu(x) \longrightarrow A_\mu(x) + \partial_\mu\,\beta(x)$$

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

Fermion symmetries:

C: Strong (triplets: Red, Green, Blue)*
L: Weak (doublets: 2 component)
Y: Hypercharge

Gauge Bosons:

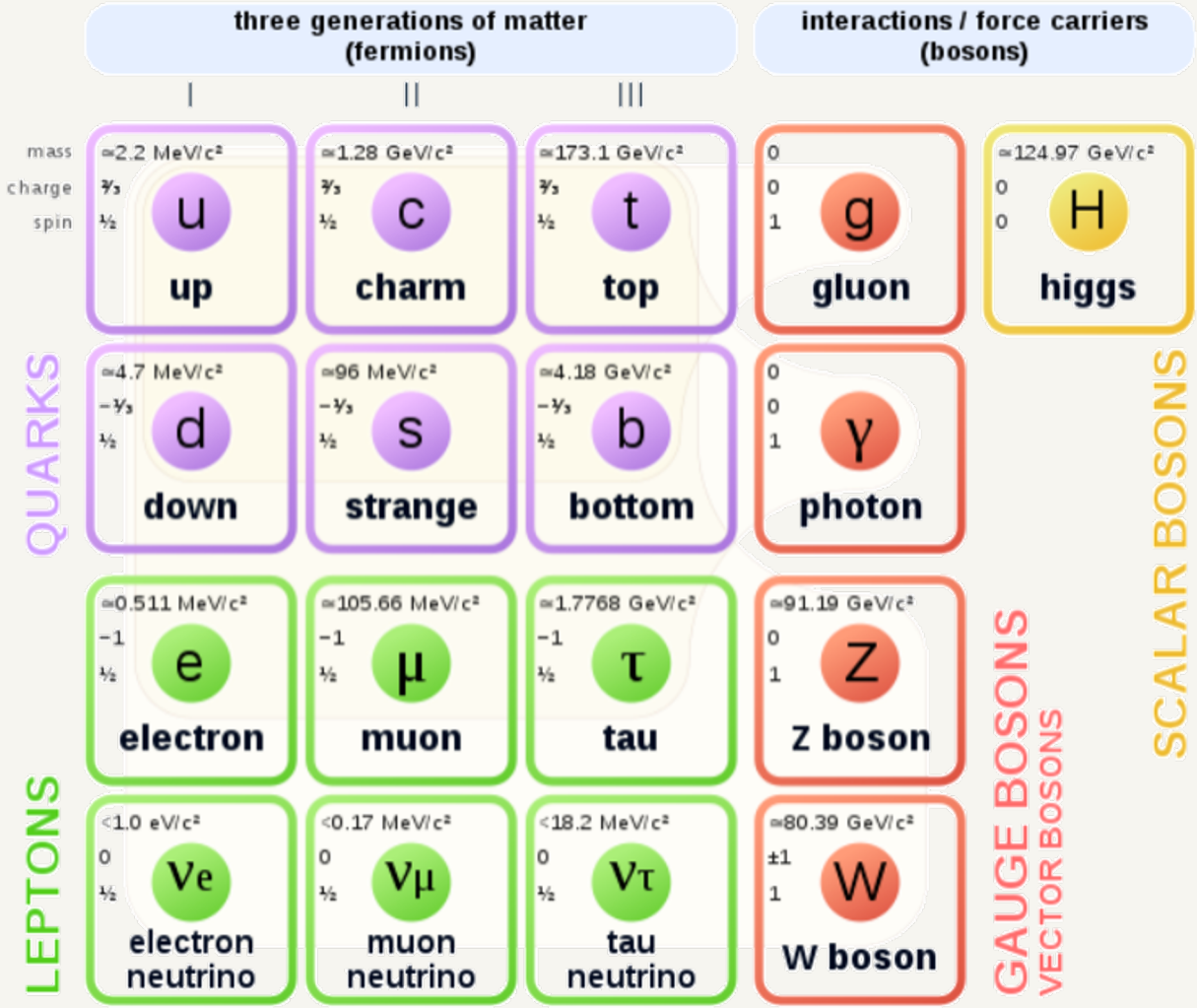
SU(3) : G^i_μ , i = 1, … , 8
SU(2): W^i_μ , i = 1, 2 , 3
U(1): B_μ

Gauge couplings: $\mathbf{g_s, g, g'}$

*: [charge assignments, NOT actual colors]

The Beloved *Beautiful* (& EMPIRICAL)

Standard Model



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

Non-Minimal
Unnatural

Arbitrary Content
Arbitrary Masses
Arbitrary Mixings

Arbitrary Higgs Mechanism

The Beloved *Beautiful* (& EMPIRICAL)

Standard Model

Only ***Left*** handed fermions charged under the weak SM gauge group.

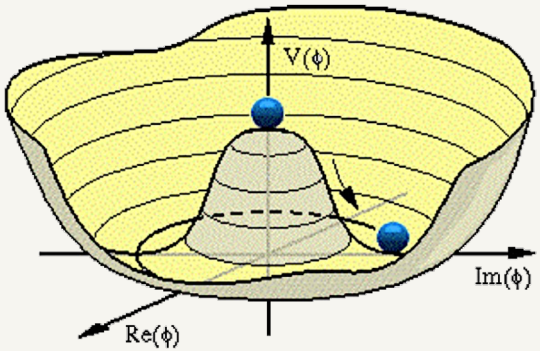
Fermion and gauge boson masses **FORBIDDEN** by symmetry.

Whatever gives rise to fundamental particle masses has to break electroweak symmetry (EWSB).

The Higgs Mechanism.

Spontaneous Breakdown of the symmetry:
$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

A scalar (Higgs) field is introduced. The Higgs field acquires a nonzero value to minimize its energy.



$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

Vacuum becomes source of energy
= a source of mass

$< H^0 > = v$

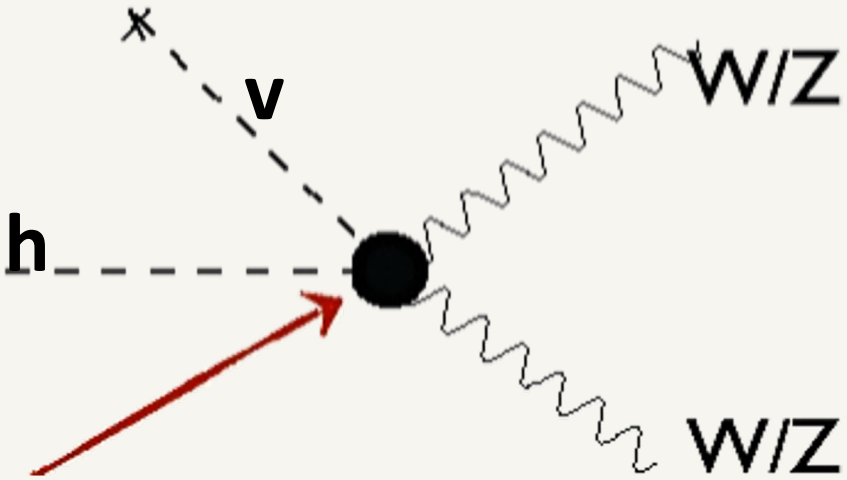
Masses of fermions and gauge bosons proportional to their couplings to the Higgs field:

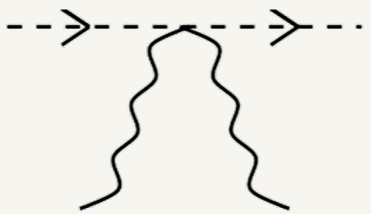
$M_{Z,W} = g_{Z,W}\, v$ $\quad m_t = h_t\, v$ $\quad m_h^2 = \lambda\, v^2$

v = 246 GeV

How do scalars interact with gauge bosons?

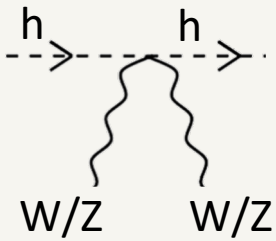
$$|D_\mu\phi|^2 = (\partial_\mu\phi + ieA_\mu\phi)(\partial^\mu\phi^* - ieA^\mu\phi^*)$$

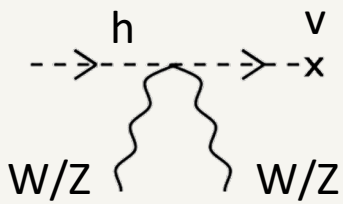


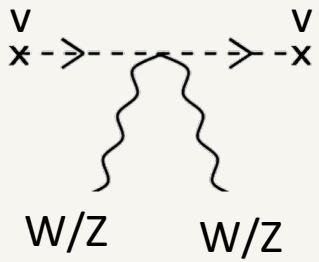


$e^2A^2|\phi|^2$

$\phi \to h + v$







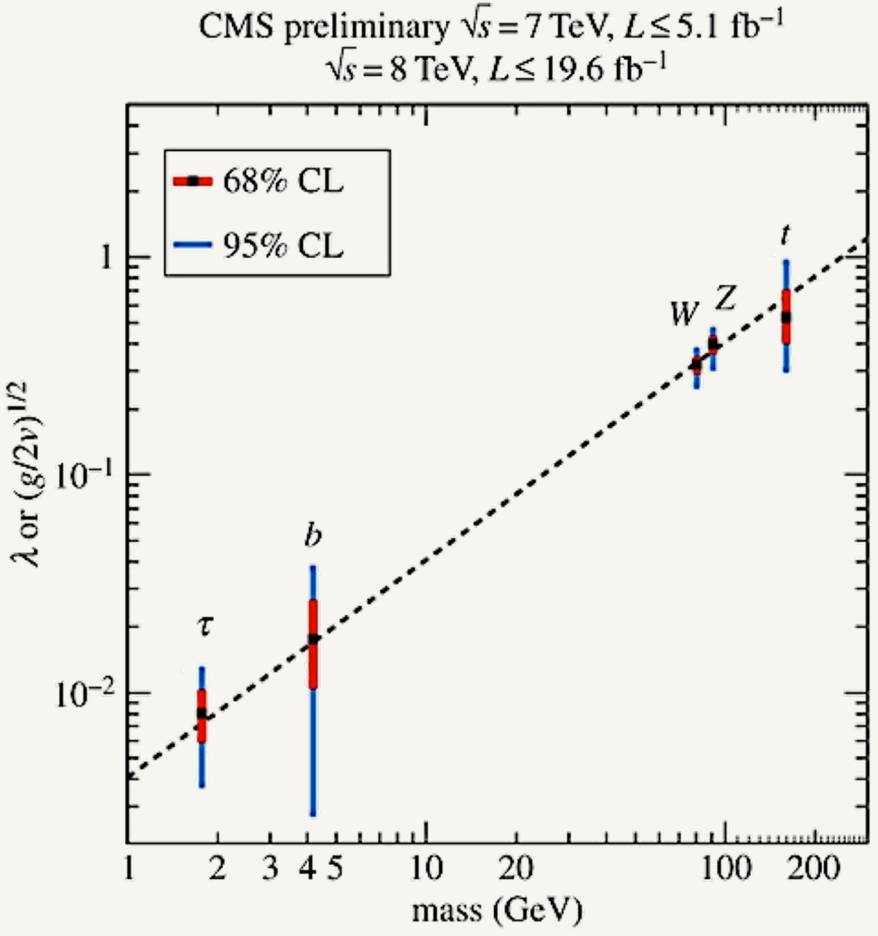
We have seen that the Higgs couples to W/Z, with approximately the right strength!!

SM-Like Higgs!

Higgs generates masses of the SM particles!

P. Higgs:

"My first paper was rejected because it was not relevant for phenomenology"



Quark Mixing: CKM Matrix

$$\mathcal{L}_{\rm yuk} = -Y_d^{ij}\bar{Q}_L^i\phi D_R^j - Y_u^{ij}\bar{Q}_L^i\tilde{\phi}U_R^j - Y_e^{ij}\bar{L}_L^i\phi e_R^j + \text{h.c.},$$

$V_{CKM} = U_L^\dagger D_L$

{U_L, D_L} define admixture of weak eigenstates in mass eigenstates:
unknown 3x3 rotation matrices.

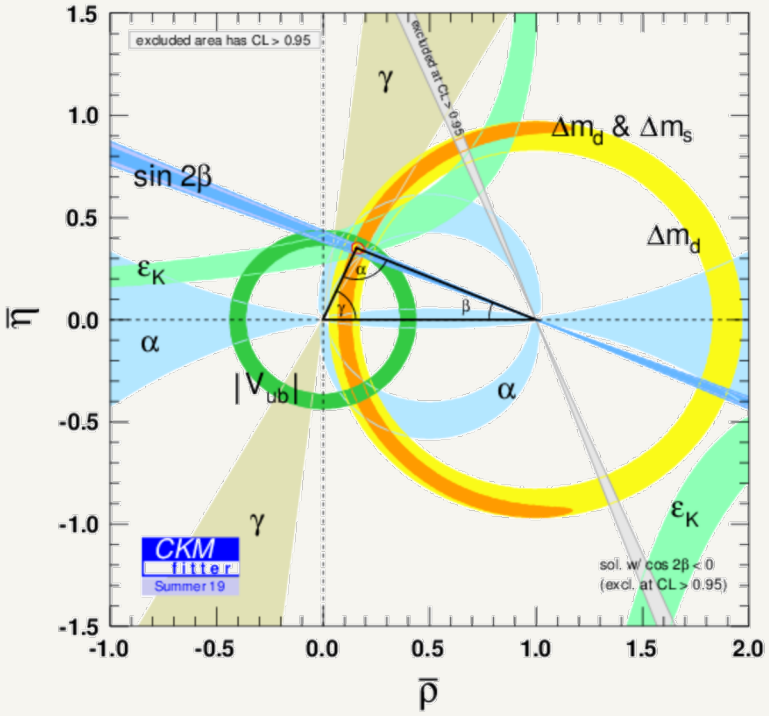
No way to extract U_L and D_L independently in SM.
Only information about product (V_{CKM}) from flavor changing processes.

Choosing $U_L = 1$, can interpret:

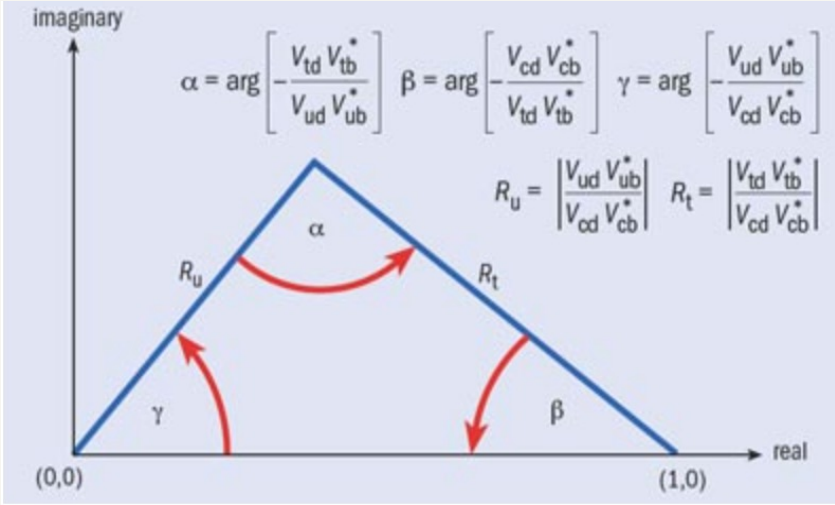
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

$$-\frac{g}{2}\bar{Q}_L^i\gamma^\mu W_\mu^a\tau^a Q_L^i \xrightarrow{\text{mass-basis}} -\frac{g}{\sqrt{2}}\begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{pmatrix}\gamma^\mu W_\mu^+ V \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

http://ckmfitter.in2p3.fr/www/results/plots_summer19/png/rhoeta_large.png



Unitary SM V_{CKM}



https://physicsworld.com/a/a-triangle-that-matters/

Experimental measurement:

https://en.wikipedia.org/wiki/Cabibbo%E2%80%93Kobayashi%E2%80%93Maskawa_matrix

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}$$

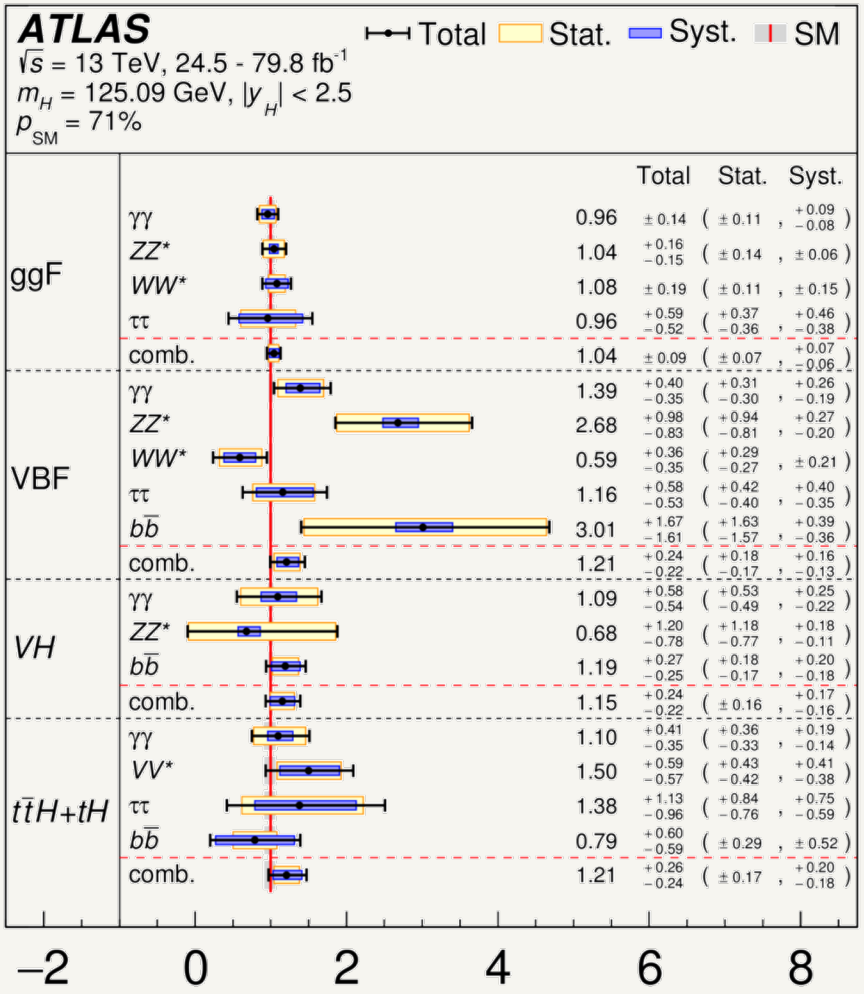
$V_{CKM} = U_L^\dagger D_L$

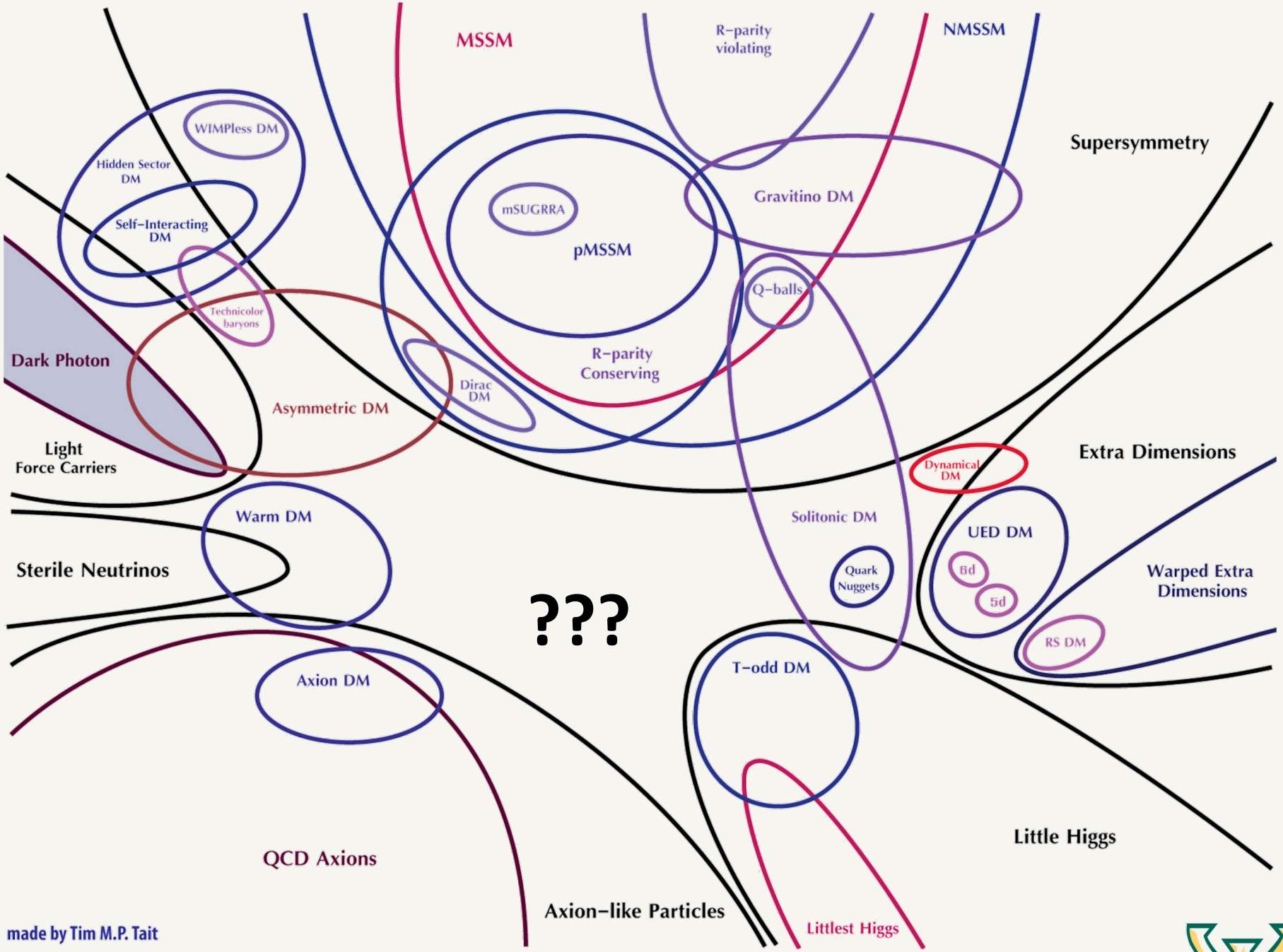
Much smaller!

Is there something special about the 3rd generation??

Still large uncertainties in couplings…
but compatible with SM expectations.

Observed Higgs Production x Branching Ratios as a ratio to SM expectation

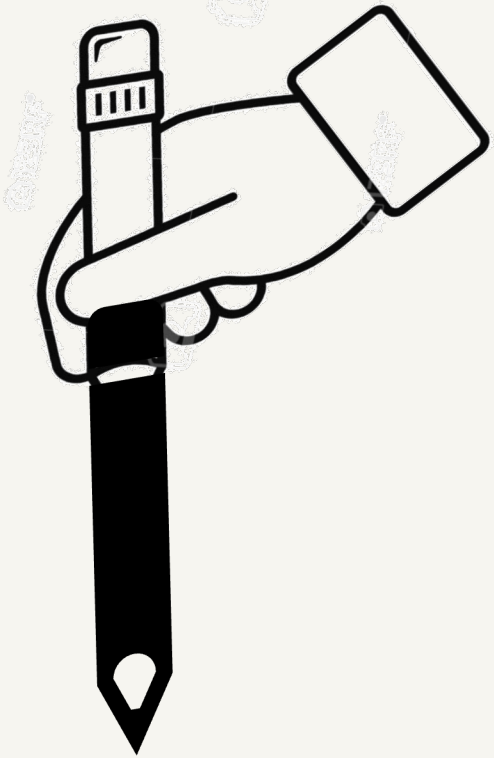



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRRA
pMSSM
Gravitino DM
Q-balls
Technicolor baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
???
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
made by Tim M.P. Tait

UV Symmetries?

UV Structure?

Fine-Tuning ?



Prediction?

Accidental?


https://www.pinterest.com/pin/304978206018018128/


https://www.pinterest.com/pin/334744184798019537/?d=t&mt=login

Beyond the Standard Model with the Higgs.

SM Higgs is a **Doublet**

- The Higgs *FIELD* is a two component weakly charged doublet.
- *h* is the neutral particle we think we have observed at the LHC: h_{125}
- *v* is the SM vev: 246 GeV.
- $G^{+/-}$ and G^0 are "eaten" by the W and Z gauge bosons to give them mass.

$$H_{\mathrm{SM}} = \begin{pmatrix} G^{\pm} \\ \frac{1}{\sqrt{2}}(h+v) + iG^0 \end{pmatrix}$$

Why do we want more???

More Doublets??

The Higgs vev generates the SM fermion masses

Large Hierarchy!!

Maybe because different Higgs vevs generate different masses?

This is what happens in Supersymmetric (SUSY) Models

SUSY requires AT LEAST TWO Higgs Doublets!

Maybe there are multiple extra dimensions?

Different Higgs Doublets get different vevs due to different warping in ED

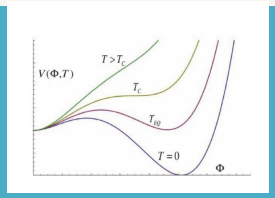
Consider a model of two Higgs doublets as a case study: 2HDM

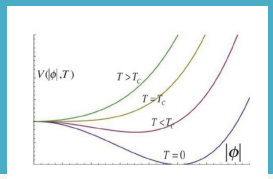
Dark Higgs??

Scalar with no electric, weak or strong charge = SM Singlet *S*

Dark Matter has no electric or strong charge.
Singlets as Portal to Dark Matter?
Singlets as Dark Matter Candidates?

Matter-Antimatter asymmetry? Baryogenesis!
As the Universe cools down, Higgs field develops a vev.
For successful Baryogenesis, need first-order phase transition.
SM: Roll over
Singlets can make it happen!



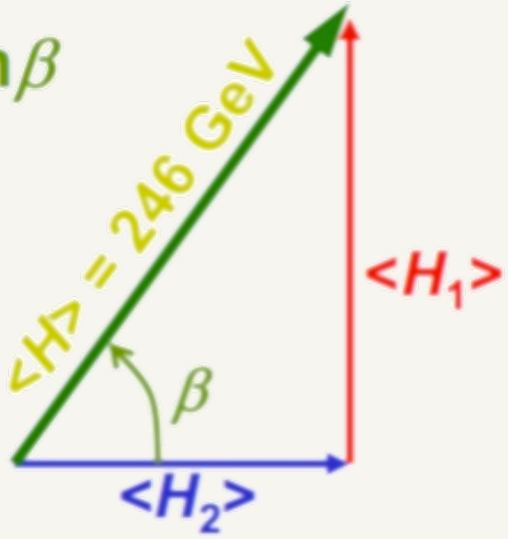


Consider 2HDM + S Higgs sector

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

2 Higgs Doublet Model (2HDM).

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



In SUSY Need 2 Higgs doublets:

H_u –Couples only to up-type quarks

H_d –Couples only to down-type quarks and leptons.

$m_A \sim m_H$

$\tan\beta = v_u / v_d$

5 Physical Higgs bosons:

CP-Even: **h, H**

CP-Odd: **A**

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

SM-Like Higgs.

<H> 246 GeV

<h> ~ <H_{SM}>

$v \sin^2 \beta$

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

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

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!

<H_d> = $v \cos\beta$

<H_u> = $v \sin\beta$

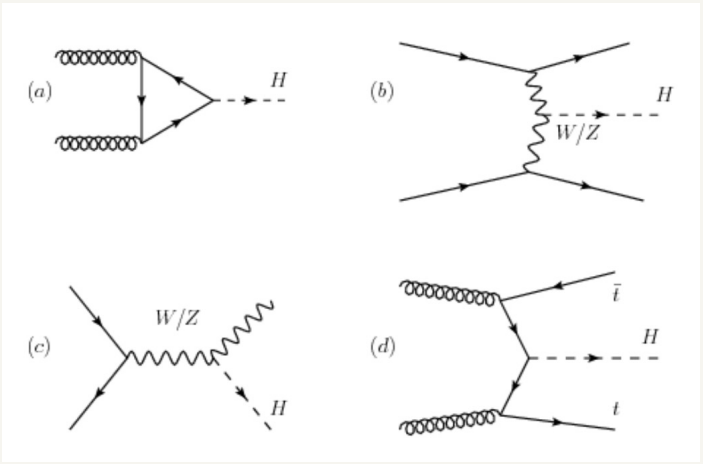
$\Rightarrow$ <H_{SM}> = v

<H_{NSM}> = 0

SM-like HIGGS

ALIGNMENT

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 ....



Singlets vs. Doublets??

How are they produced?
How do they decay?

Later + Prof. Sharma's talk