ENIGMASS+ WP1

Elementary Particles & Search for New Physics

Theory perspective

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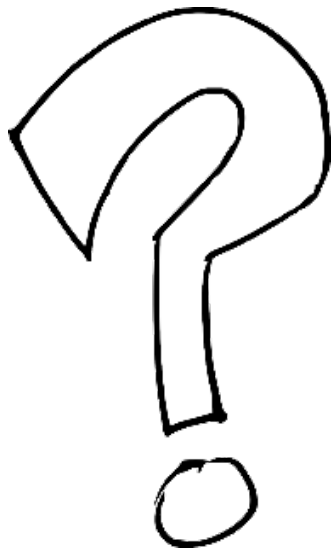
In Pursuit of an Ancient Quest

What are we

(and everything else)

made of

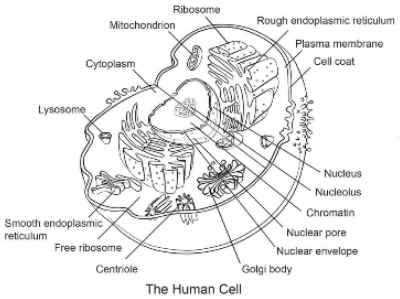


The Standard Model of Particle Physics

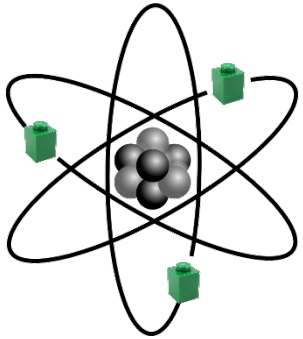
a major legacy of the 20th century

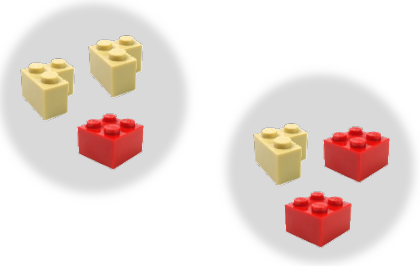
Three Bricks

We (and *almost* everything else) are compounds of only **3 elements**



The Human Cell





1m ***10^{-5}m*** ***10^{-10}m*** ***10^{-15}m***


electron

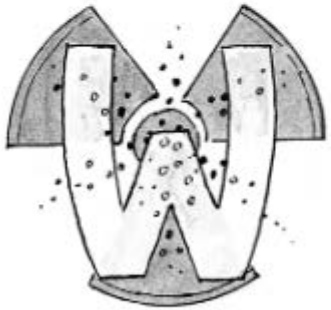

up-quark


down-quark

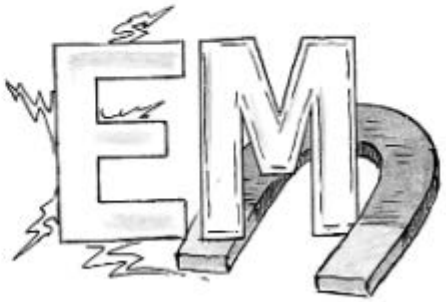
Four Forces

gravity

strong force



weak force



electromagnetism

Four Forces

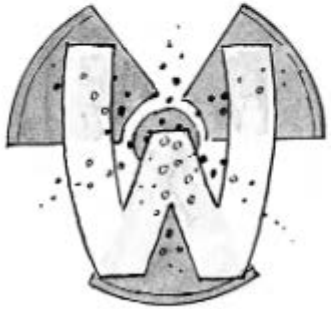
graviton

gravity

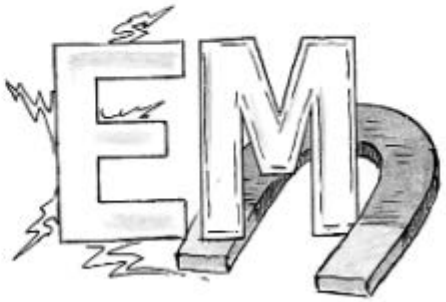
strong force

gluons

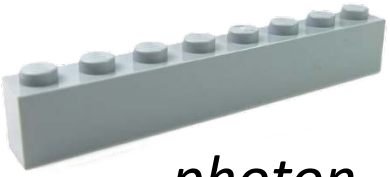
W/Z *bosons*



weak force



electromagnetism



photon

Four Forces

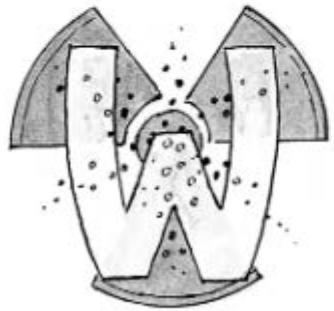
binding agents

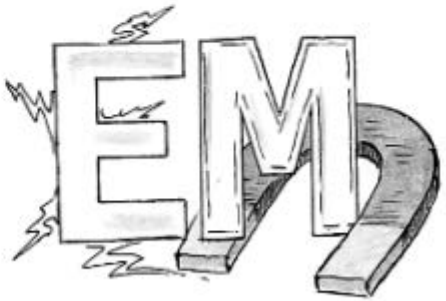
solar systems,
galaxies,
…

nuclei

decaying agent

$$n \rightarrow p + e^{-} +$$
$$(udd) \quad (uud)$$





atoms

neutrino

(the tiny one we often miss)

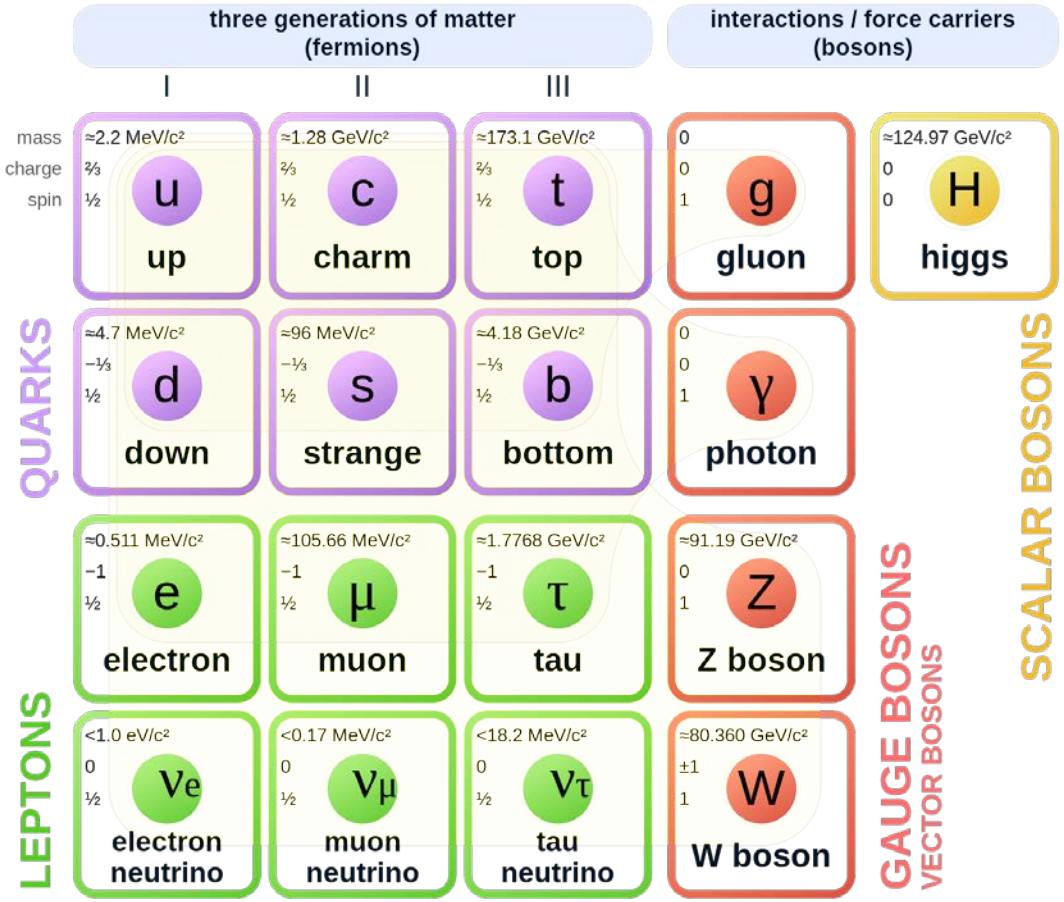
Matter Always Rings Thrice (and that's it)

same bricks, only heavier

don't know what they're here for

but allows for CP violation

The new Mendeleiev table



"who ordered that?"

– I. Rabi

The Standard Model

Building instructions are given by the SM Lagrangian

action

$$S_{\rm SM} = \int dx \sqrt{-g} \mathcal{L}_{\rm SM}$$

$$\mathcal{L}_{\rm SM} = -\tfrac{1}{4} F_{\mu\nu}^2 + i\bar{\psi}_i \not{D} \psi_i + |D_\mu H|^2 - m_H^2 |H|^2 - \lambda |H|^4 - Y_{ij} \bar{\psi}_i H \psi_j + \text{h.c.}$$

strong, weak & EM forces ruled by gauge invariance

Higgs interactions

$$+(16\pi G)^{-1}(R - 2\Lambda)$$

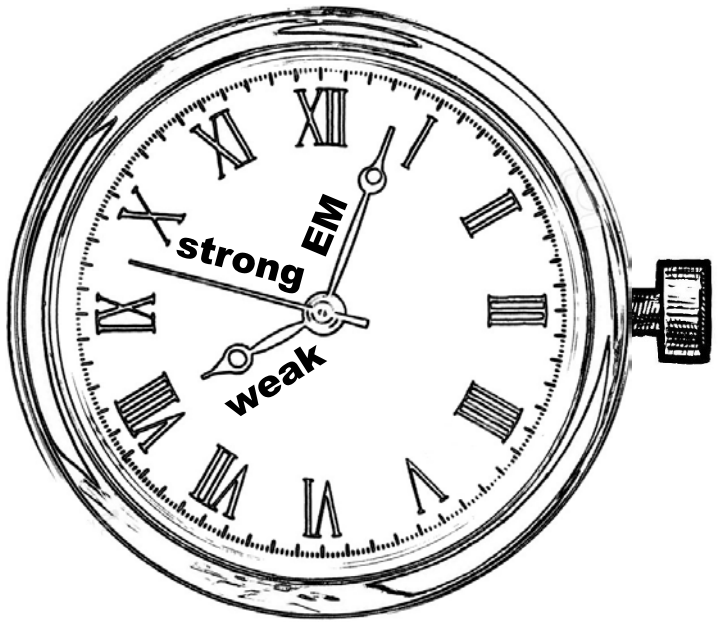
gravity ruled by diffeomorphism invariance

Following the recipes of Quantum Field Theory (QM + relativity)

$$Z = \int [D\varphi] e^{i/\hbar S[\varphi]}$$

path integral

Behind the SM



Behind the SM

Accidental symmetries

B# & L# conservation

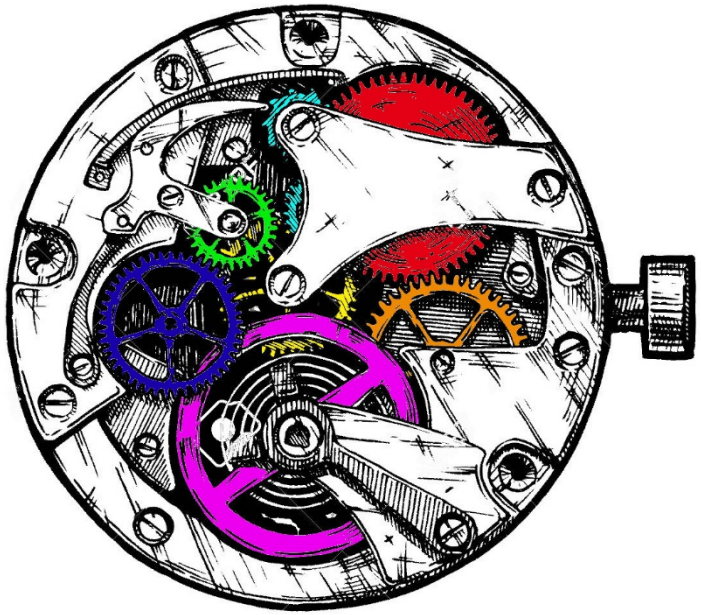
(only approximate due to anomalies)

CP violation

KM mechanism

Flavor violation

GIM mechanism



EW symmetry breaking

Higgs mechanism

Unitarity

Higgs boson

Unification

gauge couplings

(only approximately)

Stability

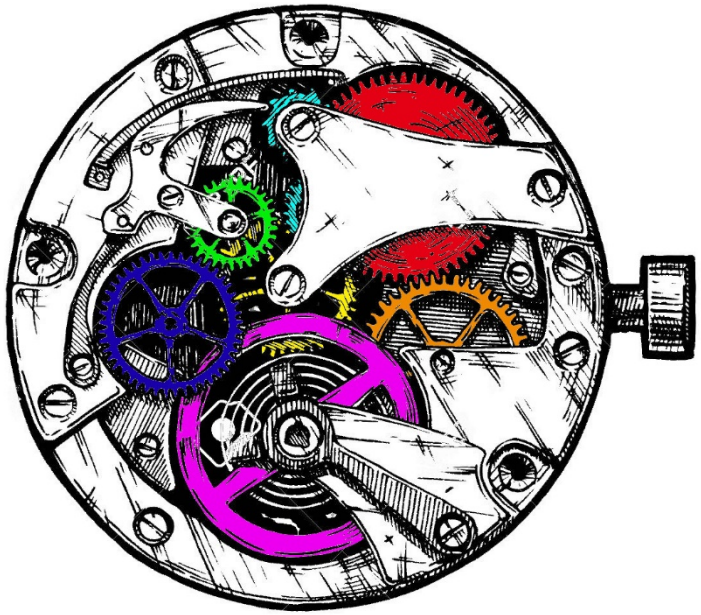
Higgs potential

Behind the SM

entails the origin of mass

EW symmetry breaking
Higgs mechanism

Accidental symmetries
B# & L# conservation
(only approximate due to anomalies)



Unitarity
Higgs boson

CP violation
KM mechanism

Flavor violation
GIM mechanism

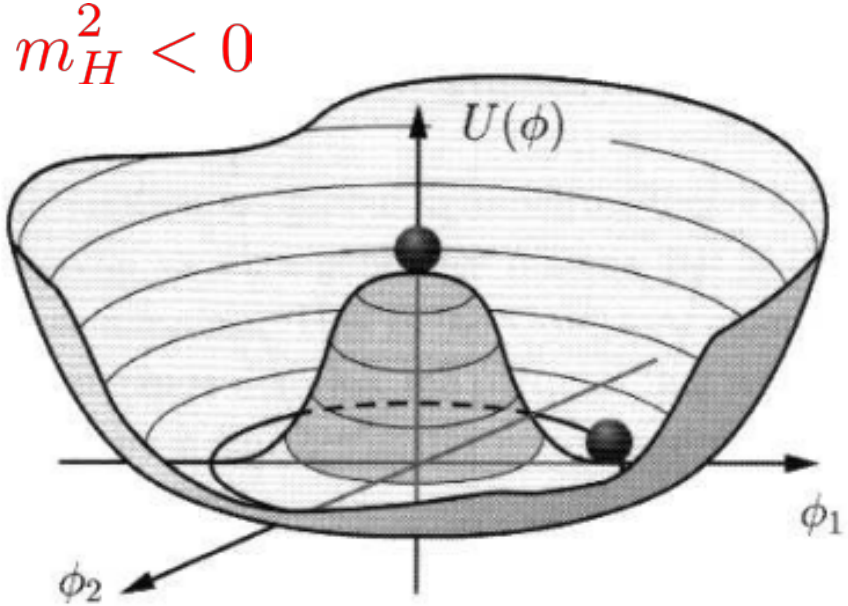
Unification
gauge couplings
(only approximately)

Stability
Higgs potential

The Origin of Mass

Bricks get massive through the **Brout-Englert-Higgs mechanism**

$$\mathcal{L}_{\rm SM} \supset |D_\mu H|^2 - m_H^2 |H|^2 - \lambda |H|^4 \quad - Y_{ij} \bar{\psi}_i H \psi_j + \text{h.c.}$$



A Higgs "fluid" fills up the vacuum

(like a relativistic aether)

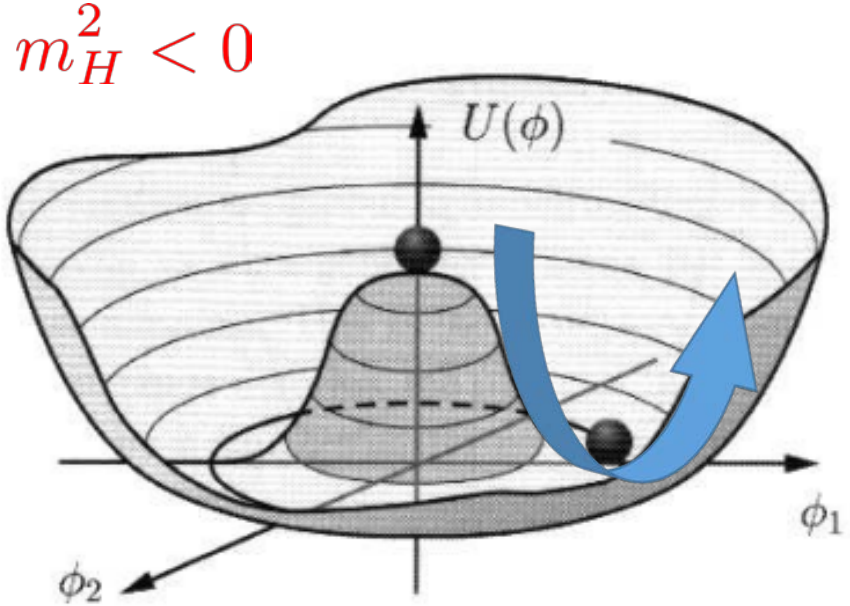
$$\langle H \rangle \neq 0$$

The stronger its coupling to this "molasse" the more massive the particle appears

The Origin of Mass

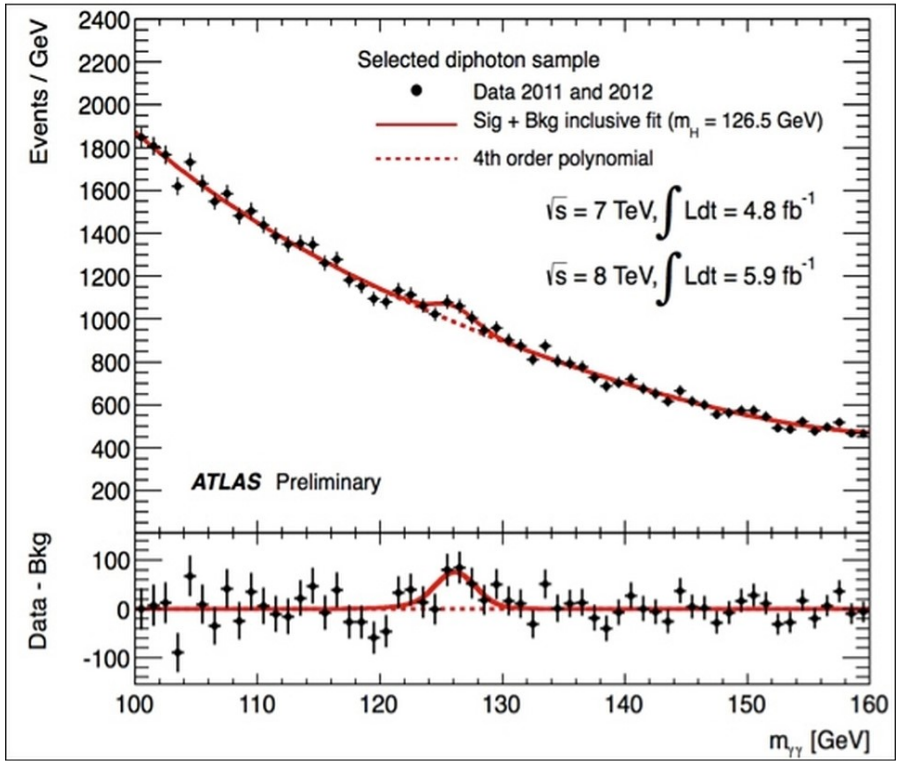
One smocking-gun prediction: the **Higgs boson**

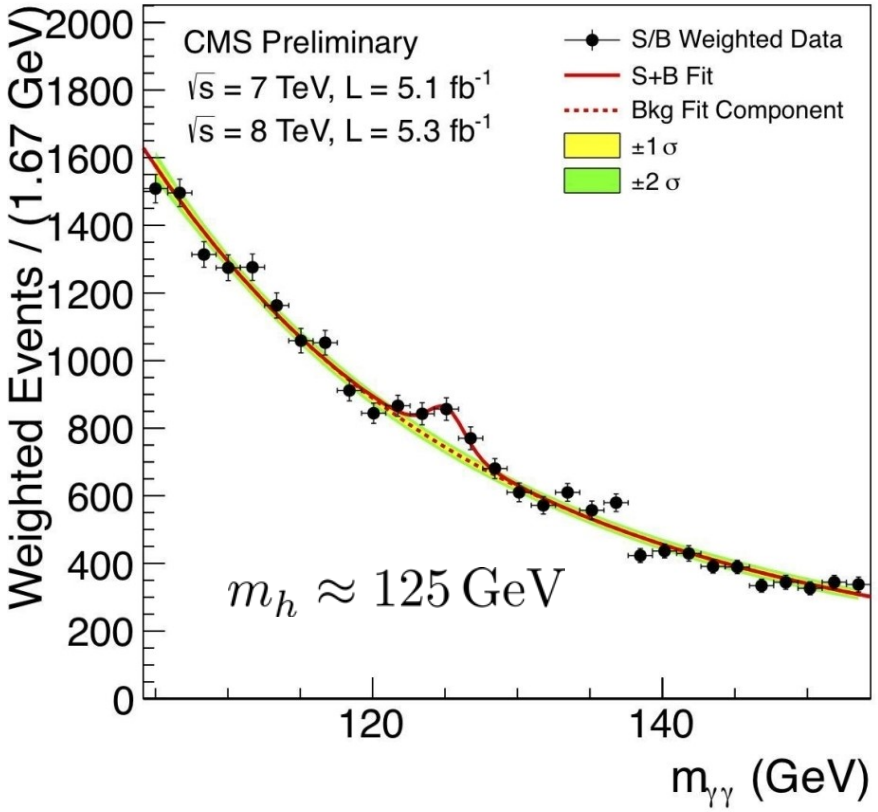
(known since the 60's)



The molasse *vibrates*!
"sound-waves" propagate in this fluid
Higgs bosons are quanta of such waves

July 4th





After ~50 years of relentless hunting,
Higgs bosons were finally **observed in 2012**
by the ATLAS and CMS experiments at CERN

Forever SM ?

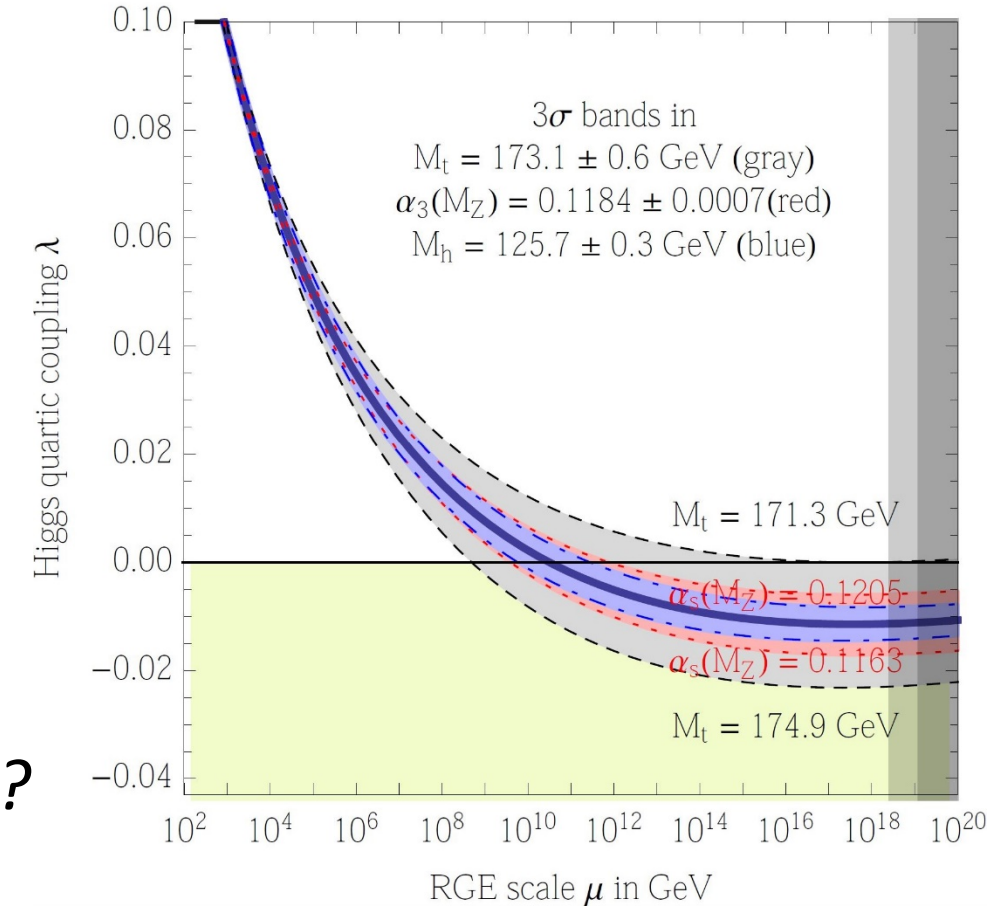
The Higgs mass fixes (in the SM) its self-interactions

$$\mathcal{L}_{\rm SM} \supset |D_\mu H|^2 - m_H^2 |H|^2 - \lambda |H|^4$$

$$\lambda(125\,{\rm GeV}) \approx 0.13$$

Top-quark fluctuations make it smaller at higher energies, until $\lambda < 0$

SM is a consistent theory down to very short distances! $\ell_{\rm Pl} \sim 10^{-33}{\rm m}$?



Case closed ?

Quite the opposite…

Beyond the SM

when the plot thickens

Missing pieces

The SM describes all we see in Nature but:

neutrino oscillations

$0 < m_{\nu_i} \lesssim \mathrm{eV}$

matter/antimatter asymmetry

$\frac{n_\psi - n_{\bar{\psi}}}{n_\gamma} \approx 6 \times 10^{-10}$

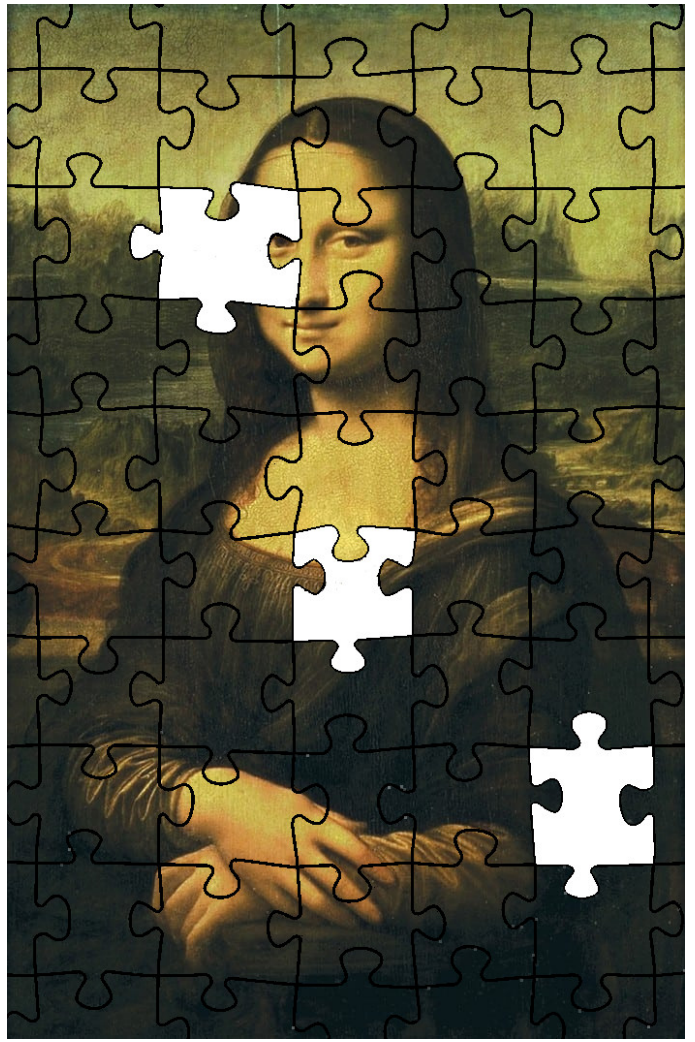
dark matter

$\Omega_{\mathrm{DM}} \approx 0.25$

+ quantum gravity *above* Planck scale

$M_{\mathrm{Pl}} = G^{-1/2} \sim 10^{19}\,\mathrm{GeV}$

is still an open problem



a standard model *ca.* 1506

An important lesson

Physics Beyond the SM has already been discovered! (yes, indirectly)

The name of the game is to understand its structure

SM itself provides some good leads

The Higgs Problem

Quantum fluctuations bury away the weak force
down to much shorter distances

$$\mathcal{L}_{\rm SM} \supset -m_H^2 |H|^2 \qquad m_H^2 = (m_H^2)_{\rm cl.} + \mathcal{O}(M^2/16\pi^2) \approx -(90\,{\rm GeV})^2$$

If $M \to M_{\rm Pl}$, $m_H^2 \sim 10^{32}\, m_{H,\rm obs}^2$

from new particle of mass M
beyond the SM,
fluctuating in the vacuum

If $M \gg 4\pi m_W \sim {\rm TeV}$
we have a (naturalness) problem,
unless there is a mechanism protecting the Higgs mass

The Strong CP problem

In principle, QCD violate CP symmetry through the topological operator

$$\alpha_s \theta \, \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} / 8\pi \qquad\qquad \theta \sim \mathcal{O}(1)$$

which induces at low energy an electric dipole moment for the neutron that is *not* observed experimentally

$$H \supset -\vec{d_n} \cdot \vec{E}$$

$$|\vec{d_n}| \sim e\theta m_q / m_n^2 \lesssim 10^{-26}\,\text{e.cm}$$

In practice, QCD is found to respect CP to a very-high degree, *why?*

$$\theta \lesssim 10^{-10} \ll \mathcal{O}(1)$$

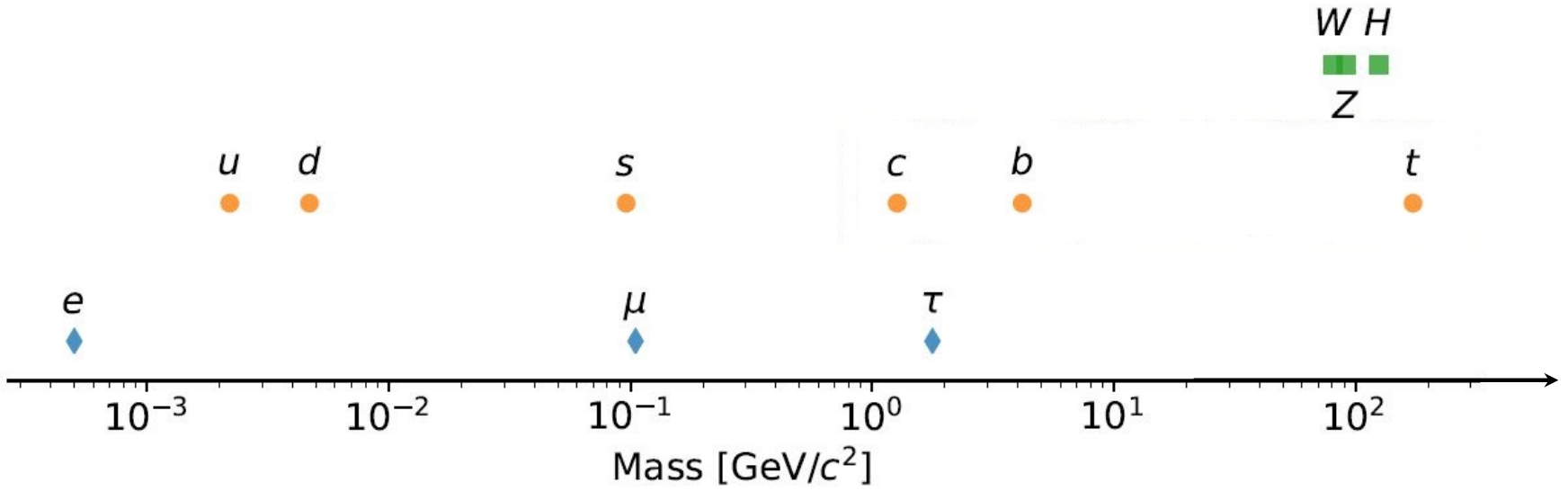
The Flavor Puzzles

Fermion masses arise from one *single* source (the Higgs field) $\propto Y^{ij}_{u,d,e}$

But differ by *many* orders of magnitude, *why?*

$Y_t \sim 1$

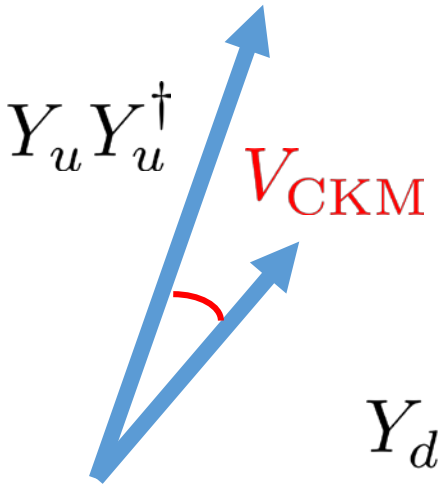
$Y_e \sim 10^{-6}$



The Flavor Puzzles

Fermion masses arise from one *single* source (the Higgs field) $\propto Y^{ij}_{u,d,e}$

Quark families almost don't talk to each other, *why?*



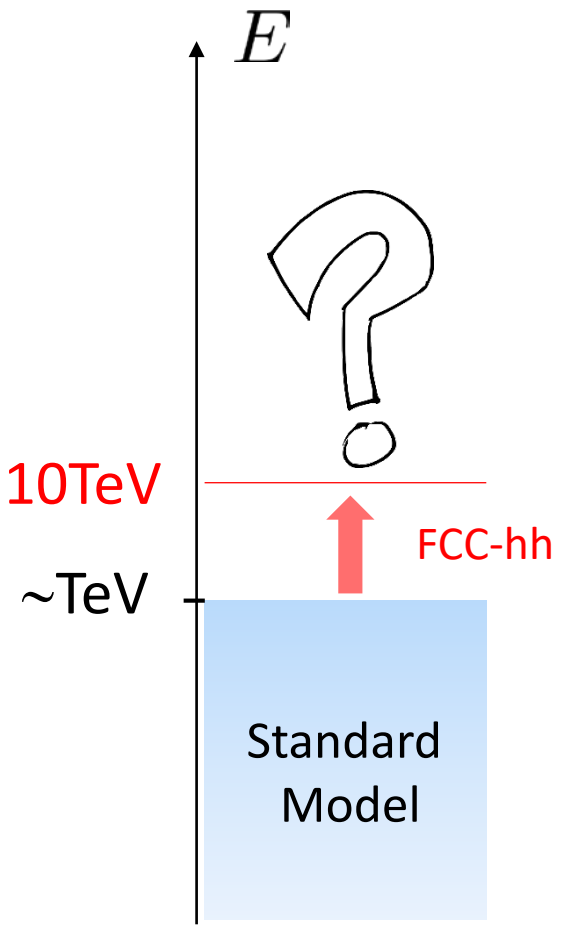
Nearly aligned in flavor space

$$V_{\rm CKM} = \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} \blacksquare & \lambda & \lambda^3 \\ \cdot & \blacksquare & \lambda^2 \\ \cdot & \cdot & \blacksquare \end{pmatrix} \end{array} \begin{array}{c} u \\ c \\ t \end{array} \sim \mathbb{1}$$

$$V_{us} \simeq \sin\theta_C \equiv \lambda \approx 0.22$$

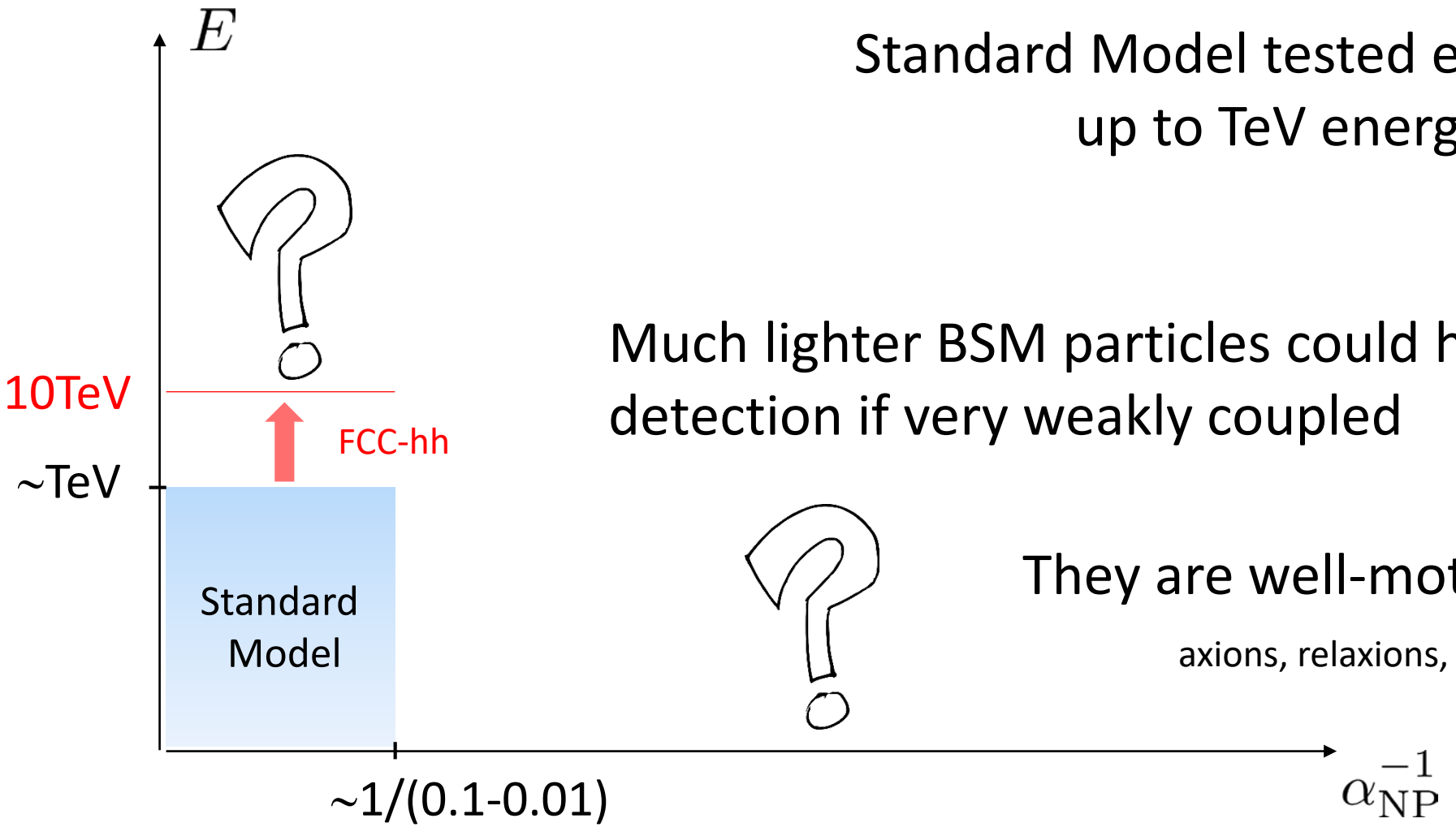
Cabibbo angle

Where to look?



Standard Model tested experimentally
up to TeV energies at the LHC

Where to look



Standard Model tested experimentally up to TeV energies at the LHC

Much lighter BSM particles could have escaped detection if very weakly coupled

They are well-motivated candidates

axions, relaxions, dilaton…

Thanks for listening

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