1) QUICK REVIEW OF THE SM

- Interactions

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

$SU(3)_c$ ↓ color, strong int.

$SU(2)_L$ ↓ chiral EW interactions

$U(1)_Y$ ↘ chiral $U(1)$ interaction

s = 1 gauge bosons : $G^a(x)$ — 8 gluons, $m_g = 0$

$W^{\pm}, Z, \gamma$ — $3 \times SU(2)$ bosons, $M \sim v$; 1 massless photon

- massless states have two d.o.f. for two polarizations

massive W and Z have $2s+1 = 3$ d.o.f.s

- strength of interactions $\alpha = \frac{g^2}{4\pi}$

$$\alpha_s\Big|_{M_Z} = 0.118 \,, \quad \alpha_W\Big|_{M_Z} = \frac{g_2^2}{4\pi} = 0.033 \,, \quad \alpha_e\Big|_{\mu=0} = \frac{1}{137}$$

s = 1/2 fermions $\psi = \psi_L + \psi_R$ Dirac spinors have four components for 2 spins of particles and anti-particles.

- ## Matter content

QUARKS

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \; , \quad c_R \; , \quad t_R$$
$$d_R \; , \quad s_R \; , \quad b_R$$

$m_u = 2$ MeV $m_b = 4.2$ GeV

$m_d = 5$ MeV $m_t = 174$ GeV

$m_s = 93$ MeV

$m_c = 1.3$ GeV

$Q_{em}(u, c, t) = \frac{2}{3}$

$Q_{em}(d, s, b) = -1/3$

- this matter content only makes sense above $\Lambda_{QCD} \sim$ GeV, say at colliders or at high T in the early universe.

- Below Λ_{QCD} we have bound states of three quarks BARYONS $(p, n, \Lambda, \dots)$ and q-$\bar{q}$ states like MESONS $(\pi, K, \eta, \rho, \dots)$.

LEPTONS

$$L_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$e_R \quad \mu_R \quad \tau_R$$

$m_e = 0.5$ MeV $\Delta m^2 \sim 10^{-[illegible]}$ eV^2

$m_\mu = 105$ MeV $\Delta m^2 \sim 10^{-5}$

$m_\tau = 1.8$ GeV $m_{min} = ?$

$Q_{em}(e, \mu, \tau) = -1$, $Q(\nu_{e,\mu,\tau}) = 0$

- <u>Scalar content</u>

$$\phi = \begin{pmatrix} G^+ \\ \frac{h+v+iG^0}{\sqrt{2}} \end{pmatrix}$$

- G^+, G^0 are the 3 d.o.f.s that go in the massive W, Z

- $v = 246$ GeV and h is the only remaining

$\boxed{S=0}$ $Q_{em}(h) = 0$ $m_h = 125$ GeV

- $\mathcal{L}_y = y \bar{\Psi}_L \phi \Psi_R \Rightarrow m_f = yv/\sqrt{2}$, $M_{W,Z} \propto gv$, $m_h \propto \sqrt{\lambda} v$

- <u>Chiral $SU(2)_L$</u> only the Ψ_L components of Dirac fermions interact. This is particularly relevant for neutrinos. We only have ν_L in the SM, no ν_R and thus m_ν is predicted to be zero. Importantly only 2 d.o.f. for each generation of ν_e will interact with W and Z and thermalize.