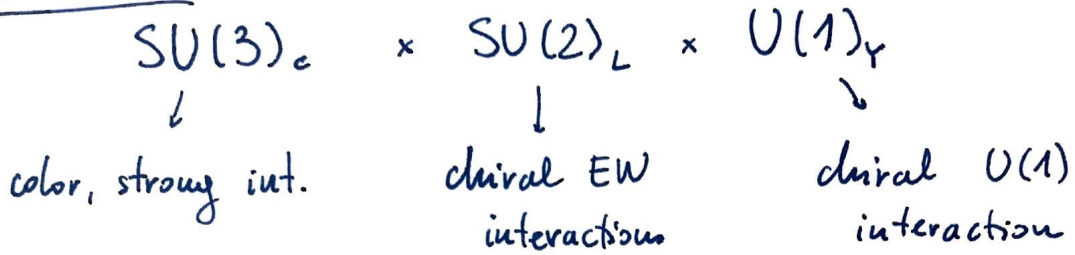


# 1) QUICK REVIEW OF THE SM

## • Interactions



$S=1$  gauge bosons :  $G^a(x)$        $W^\pm, Z, \gamma$   
 8 gluons      3  $\times$   $SU(2)$  bosons,  $M \sim v$   
 $m_g = 0$       1 massless photon

• massless states have two d.o.f. for two polarizations  
 massive  $W$  and  $Z$  have  $2s+1 = 3$  dof.

• strength of interactions  $d = \frac{g^2}{4\pi}$

$$d_s \Big|_{M_Z} = 0.118, \quad d_w \Big|_{M_Z} = \frac{g_w^2}{4\pi} = 0.033, \quad d_e \Big|_{\mu=0} = \frac{1}{137}$$

$S=1/2$  fermions  $\Psi = \Psi_L + \Psi_R$  Dirac spinors have  
 four components for 2 spins of particles and  
 anti-particles.

• Matter content

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

$$u_R, s_R, t_R$$

$$d_R, s_R, b_R$$

$$m_u = 2 \text{ MeV} \quad m_b = 4.2 \text{ GeV}$$

$$m_d = 5 \text{ MeV} \quad m_t = 174 \text{ GeV}$$

$$m_s = 93 \text{ MeV}$$

$$m_c = 1.3 \text{ GeV}$$

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

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

- This matter content only makes sense above  $\Lambda_{QCD} \sim \text{GeV}$ , say at colliders or at high  $T$  in the early universe.
- Below  $\Lambda_{QCD}$  we have bound states of three quarks BARYONS ( $p, n, \Lambda, \dots$ ) and  $q-\bar{q}$  states like MESONS ( $\pi, K, \rho, \dots$ ).

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

$$e_R, \mu_R, \tau_R$$

$$m_e = 0.5 \text{ MeV} \quad \Delta m^2 \sim 10^{-5} \text{ eV}^2$$

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

$$m_\tau = 1.8 \text{ GeV} \quad m_{\text{min}}^2 = ?$$

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

• Scalar content

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

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

•  $v = 246 \text{ GeV}$  and  $h$  is the only remaining

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

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

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• Chiral  $SU(2)_L$  only the  $\Psi_L$  components of Dirac fermions interact. This is particularly relevant

for neutrinos. We only have  $\nu_L$  in the SM,

no  $\nu_R$  and thus  $m_\nu$  is predicted to be zero.

Importantly only 2 d.o.f. for each generation

of  $\nu_e$  will interact with  $W$  and  $Z$  and

thermalize.