Basics of particle physics & the SM

What are we going to be talking about?

- How do we describe particle physics?
- How do we construct the SM?

why SM? huge agreement.

bibliography
Schwartz, 2014
QFT and the SM.

Assuming knowledge of QFT. We will have to assume some things.

— What is a particle?

Definition: Irreducible unitary representation of the $\underbrace{\text{Poincaré Group}}$

symmetries of space-time: translations
rotations
boosts

$|\psi\rangle \longrightarrow P\,|\psi\rangle$. Set of states that mix under P is called representation

$\phi(x) \xrightarrow{T} \phi(x+a)$. $\phi(x)$ at all points correspond to a representation

irreducible means there is no sub set which transforms among themselves.

Unitary is a condition from QM to conserve probability (is it).

Wigner showed that unitary irreps of Poincaré are uniquely defined by mass and spin, where

$J = 0, 1/2, 1, 3/2, 2, \ldots$ ← it can be shown that we can only go up to 2

(Quevedo, Schachner, 2409.09211 4.2. Soft theorems).

How to describe particles.

Newtonian physics ⇒ $S = \int_{t_1}^{t_2} L \, dt$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = 0 \leftarrow \Big/ \boxed{L = T - V} \rightarrow = f(x, \dot{x}).$$

Field theories $\mathcal{L}(\phi(x), \partial\phi(x))$, $S = \int d^4x \, \mathcal{L}$

$$\partial_\mu\left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_i)}\right) - \frac{\partial \mathcal{L}}{\partial \phi_i} = 0$$

E.L. $\xRightarrow{\text{minimizing the action}}$ Equations of motion.

$\Downarrow$ $\boxed{\text{We want to build a Lagrangean}}$

Rules of the game

Ingredients: particle content
symmetries

how do the particles transform under the symmetry (representations).

$\mathcal{L}$ = everything we can write.

Symmetries

What is a symmetry?

Kinetic term of a complex scalar.

$$\mathcal{L} = (\partial_\mu \varphi^\dagger)(\partial^\mu \varphi)$$

this Lagrangean has a global symmetry

u(1) symmetry ← exponential mapping.

$$\varphi \to e^{iq\theta} \varphi$$

When i perform this transformation $\mathcal{L} \to \mathcal{L}$

What happens if we have $\theta(x)$, local transformation which depends on spacetime coordinates?

$$\partial_\mu \varphi \to \partial_\mu \left(e^{iq\theta(x)}\varphi\right)$$

$$= iq(\partial_\mu\theta)\varphi + e^{iq\theta(x)}\partial_\mu\varphi$$

Not invariant. We need to include a new degree of freedom to compensate this:

$A_\mu \longrightarrow A_\mu - \frac{1}{g}\partial_\mu\theta$ and add to the Lagrangean $igqA^\mu$, we recover $\mathcal{L}\to\mathcal{L}$

we can repackage it into a covariant derivative

$$\partial_\mu \to \underline{D_\mu} = \partial_\mu + igq\underline{A_\mu}$$

$$D_\mu\varphi \longrightarrow e^{iq\theta(x)} D_\mu\varphi$$

We introduce a new field, a vector boson (spin=1).

Let's write a mass term for A_μ?

$\mathcal{L} \supset m_A^2 A_\mu A^\mu$. It is not gauge invariant.

We cannot write a mass term for our

gauge boson.

A local symmetry implies a massless vector boson which couples to particles charged under that symmetry.

A local symmetry will also imply a global one: Noether's theorem means that we have a conserved charge.

1h.

Kinetic term for A_μ:

$$\mathcal{L} \supset \frac{1}{4} F_{\mu\nu} F^{\mu\nu},$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu .$$

in a gauge-invariant manner, gauge bosons will only appear through the covariant derivative and field-strength tensor.

let's go back to the kinetic terms of the scalar field

$$(\partial_\mu \phi + i g q A_\mu \varphi) \rightarrow i q \cancel{(\partial_\mu \theta) e^{iq\theta(x)}} \phi$$

$$+ e^{iq\theta(x)} (\partial_\mu \phi) + i g q A_\mu e^{iq\theta} \phi - i g \cancel{\partial_\mu \theta} \cancel{e^{iq\theta(x)}}$$

$$-iq\theta \quad t)$$

$$D_\mu \phi^\dagger D_\mu \phi \to \left(e^{-iq\theta(x)} \partial_\mu \phi^\dagger - igq A_\mu e \phi\right)$$
$$\left(e^{iq\theta(x)} \partial_\mu \phi + igq A_\mu e^{iq\theta} \phi\right)$$

this is actually only gauge-invariant because we took q to be a number. If instead we have a matrix generating the transformation, $[q^a, q^b] \neq 0$, this no longer holds. this is exactly what happens for non-abelian symmetries, when the group elements do not commute.

Group theory: $G \times G \to G$. ...

Lie group is a continuous group, all elements $g \in G$ depend on a continuous set of parameters, α_a.

Lie group has infinity elements, but finite sum.

$$R(\alpha) = \exp(i \alpha_a X_a)$$

generators of the group.

Lie algebra is defined by

$$[X_a, X_b] = f^{abc} X_c$$

So the final Kinetic term of a gauge boson from a non-abelian symmetric reads:

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + ig f^{abc} A^b_\mu A^c_\nu .$$

selfinteraction

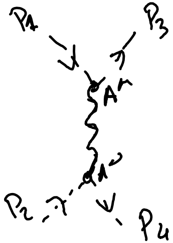
term, absent in Abelian theories.

— Mollen scattering

We are now ready to write down a consistent $U(1)$ theory: scalar QED.

$$\mathcal{L} = (D_\mu \phi^\dagger)(D^\mu \phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

What is the probability of $\phi\phi \rightarrow \phi\phi$?



interactions, feynman rules can be calculated from Lagrangean: $\mathcal{L} \supset -ig A_\mu \phi^\dagger \partial^\mu \phi$

$+ ig(\partial_\mu \phi^\dagger) A^\mu \phi$

Kinetic term calculates the propagator.

$$i\mathcal{M}_t = (-ig)\,(p_1^\mu + p_3^\mu)\; -i\left[\frac{g_{\mu\nu}}{k^2}\right](-ig)(p_2^\nu + p_4^\nu)$$

$\boxed{s, t, u}$

↳ explore why only t, u channels.

Follow Schwartz, p.146-147 for the rest.

— Fermions.

The last exercise was done in scalar QED, but we are actually interested in fermions which is what we find in Nature to be charged under EM.

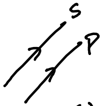
$$\mathcal{L} \supset \bar\Psi \gamma_\mu D^\mu \Psi \qquad \not{D}$$

gamma matrices.

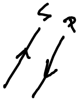
it is set by Lorentz symmetry.

Fermions can be right - a left - handed. (chirality)

RH



LH



$P_R = \frac{(1+\gamma_5)}{2}$ $P_L = \frac{1-\gamma_5}{2}$

$P_R + P_L = 1$
$P_R P_L = 0$
$P_R P_R = 1$

Weyl vs Dirac.
$P_R P_L = 0$

mass term needs both:

$$\mathcal{L} \supset m \bar\Psi_L \Psi_R + h.c.$$

— Discrete symmetries

C ⟷ particles to anti-particles

P → $\vec{x} \to -\vec{x}$, for $\vec{x}$ a vector. Pseudovectors are not affected (spin).

$$\Psi_R \xrightarrow{CP} \Psi_L$$

$$T \to t \to -t$$

All Lorentz invariant QFTs must respect CPT.

— Spontaneous symmetry breaking.

Lagrangean is invariant under symmetry but the ground state is not.

$\neq$ Explicit symmetry breaking
term in Lagrangean which breaks
the symmetry

$\downarrow$

Usually associated with phase transitions.

The effects of SSB will depend on whether the symmetry is global or local:

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$$

$$\mathcal{L} = (\partial_\mu \phi^*)(\partial^\mu \phi) - \mu^2(\phi^*\phi) - \lambda(\phi^*\phi)^2$$

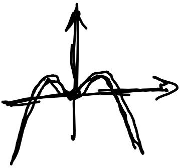
$$= \frac{1}{2}(\partial_\mu \phi_1)(\partial^\mu \phi_1) + \frac{1}{2}(\partial_\mu \phi_2)(\partial^\mu \phi_2) - \frac{1}{2}\mu^2(\phi_1^2 + \phi_2^2)$$

$$- \frac{1}{4}\lambda(\phi_1^2 + \phi_2^2)^2 .$$

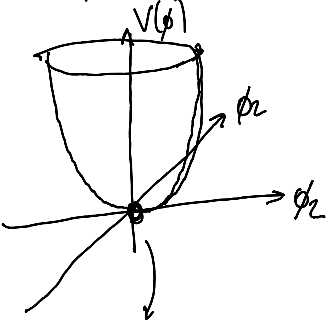
$U(1)$, $\phi \to e^{i\alpha}\phi$

$\underline{\lambda > 0}$, otherwise the potential does not have a finite minima

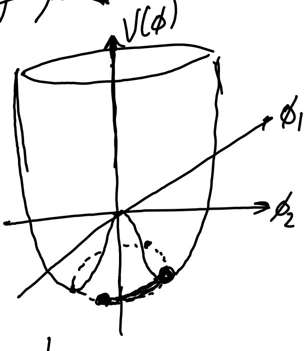
$$V(\phi) = \mu^2\phi^2 - \lambda\phi^4$$



if $\mu^2 > 0$:



if $\mu^2 < 0$



minimum at

$\phi_1 = \phi_2 = 0$

↳ minimum at

$\phi_1^2 + \phi_2^2 = -\frac{\mu^2}{\lambda} = v^2$

↳ vaccum expectation value. vev.

Let us choose the minimum to be $(\phi_1, \phi_2) = (v, 0)$.

$\phi_1(x) = v + \eta(x)$
$\phi_2(x) = \xi(x)$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) + \frac{1}{2}(\partial_\mu \xi)(\partial^\mu \xi) - V(\eta, \xi)$$

with $\mu^2 = -\lambda v^2$

$$V(\eta, \xi) = -\frac{1}{4}\lambda v^4 + \boxed{\lambda v^2 \eta^2} + \lambda v \eta^3 + \frac{1}{4}\lambda \eta^4 + \frac{1}{4}\lambda \xi^4 + \lambda v \eta \xi^2 + \frac{1}{2}\lambda \eta^2 \xi^2$$

massless scalar: goldstone boson.

$\boxed{m_\eta^2 = \lambda v^2}$ → predicted from orignal theory.

Goldstone theorem: SSB of continuos symmetry results in massless scalar.

Let's go back to our starting point, but now consider that the symmetry is local:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + (D_\mu\phi)^*(D^\mu\phi) - \mu^2(\phi^*\phi) - \lambda(\phi^*\phi)^2$$

Expanded:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + (\partial_\mu\phi)^*(\partial^\mu\phi) - V(\phi)$$

$$- ig B_\mu \phi^*(\partial^\mu\phi) + ig(\partial_\mu\phi^*)B^\mu\phi + g^2 B_\mu B^\mu \phi^*\phi.$$

$$\text{if } \lambda > 0 \;\; \mu < 0 : \quad \phi_1 + i\phi_2 = \vartheta$$

$$\phi(x) = \frac{1}{\sqrt{2}}\left(\vartheta + \eta(x) + i\xi(x)\right)$$

Substituting.

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) - \lambda v^2\eta^2 + \frac{1}{2}(\partial_\mu\xi)(\partial^\mu\xi)$$

$$-\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \frac{1}{2} g^2\vartheta^2 B_\mu B^\mu - V(\eta, \xi)$$

$$+ \underline{g v B_\mu \partial^\mu \xi}.$$

We have a massive gauge boson!

this term seems to imply that spin 1 can turn into spin-0 ...

We can get rid of this:

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \xi)(\partial^\mu \xi) + \frac{1}{2} g^2 v^2 B_\mu B^\mu + g v B_\mu \partial^\mu \xi$$

$$= \frac{1}{2} g^2 v^2 \Big[\underbrace{B_\mu + \frac{1}{g v} \partial_\mu \xi}\Big]^2$$

this is exactly how a gauge boson transforms.

So we can perform a gauge transformation which removes ξ, which is "eaten" by the gauge boson and turns into the longitudinal d.o.f.

$$\boxed{m_B = g v}$$

defined by charge and vev.

— Role of symmetries

Spacetime: Conservation of Energy, momentum and angular momentum

Discrete: CPT

Global continuous: conserved changes

Local continuous: massless gauge bosons

SSB Global: Goldstone bosons

SSB Local: mass generation for gauge bosons.

— The Standard Model

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

$$G^a_{\mu\nu} \sim (8,1,0) \qquad W^a_{\mu\nu} \sim (1,3,0) \qquad B_{\mu\nu} \sim (1,1,0)$$

3 families $\leftarrow$ $u_R^{\textcircled{i}} \sim (3,1,2/3)$ $\qquad$ $e_R^i \sim (1,1,-1)$

$d_R^i \sim (3,1,-1/3)$ $\qquad$ $l_L^i \sim (1,2,-1/2) \searrow \begin{pmatrix} e_L \\ \nu_L \end{pmatrix}$

$Q_L^i \sim (3,2,1/6) \rightarrow \begin{pmatrix} u_L \\ d_L \end{pmatrix}$

the SM is a chiral theory, right-and left-handed particles transform differently.

Problem: massive fermions and vector bosons.

$\downarrow$

we cannot write the term

$\mathcal{L} \supset m_f \bar{q}_L u/d_R \rightarrow$ doesn't respect symmetries

mass of gauge bosons?

$\hookrightarrow$ related to this unitarity of $WW \rightarrow WW$

SSB solves these issues.

We need a scalar which will break $\overset{3+1}{SU(2) \times U(1)} \rightarrow U(1)_{em}$ 1

$$\phi \quad \begin{pmatrix} \phi_1 + i\,\phi_2 \\ \phi_3 + i\,\phi_4 \end{pmatrix} \qquad \phi = (1, 2, 1/2).$$

↑ photon is still massless.

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2.$$

Once again, if $\mu^2 < 0$, minimum $\frac{v^2}{2} = \frac{-\mu^2}{2\lambda}$

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1(x) + i\,\phi_2(x) \\ v + \eta(x) + i\,\phi_4(x) \end{pmatrix}$$

↓ instead of repeating everything go directly to unitary gauge.

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

← this will be the Higgs.

$$D_\mu \phi = \left[\partial_\mu + i g_W \frac{\sigma^a}{2} W_\mu^a + i g_B \frac{1}{2} B_\mu \right] \phi.$$

$$(D_\mu \phi^\dagger)(D^\mu \phi) = \frac{1}{2}(\partial_\mu h)(\partial^\mu h) + \frac{1}{8} g_W^2 (W^1_\mu + i W^2_\mu)$$

$$(W^{1,\mu} - i W^{2\mu})(v+h)^2 + \frac{1}{8}\cancel{g_W}(g_W W^3_\mu - g_B B_\mu)(g_W W^{3\mu} - g_B B^\mu)$$

$$(v+h)^2$$

"mass terms"

$$\frac{1}{8} v^2 g_W^2 (W^1_\mu W^{1\mu} + W^2_\mu W^{2\mu}) +$$

$$\boxed{m_W = \frac{1}{2} v g_W}$$

W_3 and B are mixing. The physical gauge propagate as independent physical eigenstates.

$$\mathcal{L} \supset \frac{v^2}{8} (W^3_\mu \; B_\mu) \, M \begin{pmatrix} W^3 \\ B_\mu \end{pmatrix}$$

$$M = \begin{pmatrix} g_W^2 & -g_W g_B \\ -g_W g_B & g_B^2 \end{pmatrix} \leftarrow \underline{\text{Diagonalize}}$$

$$\downarrow$$

$$\frac{1}{2} \begin{pmatrix} A_\mu & Z_\mu \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & g_W^2 + g_B^2 \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix}$$

$$\Downarrow$$

massless photon

$$\boxed{m_Z = \frac{1}{2} v \sqrt{g_W^2 + g_B^2}}$$

Defining $\tan \theta_W = \frac{g_B}{g_W}$, $\frac{m_W}{m_Z} = \cos\theta_W$

$\downarrow$

$\frac{m_W}{m_Z \cos\theta_W} = 1$, custodial symmetry.

extremely predictive

— Fermion masses.

With the higgs boson we can now write

$$\begin{pmatrix} \bar{u}_L & \bar{d}_R \end{pmatrix} \begin{pmatrix} 0 \\ h+v \end{pmatrix} d_R$$

$(2 \times 2) = 1.$

$$\mathcal{L}^f = y_u \overline{Q_L} \phi d_R + \overset{y_d}{\overline{Q_L}} \tilde{\phi} u_R + y_e \overline{L_L} \phi e_R + h.c.$$

$$\tilde{\phi}^i = \varepsilon_{ij} \phi_j^*$$

We have 3 families of fermions: $Q_L^\alpha, L_L^\alpha, u_R^\alpha, d_R^\alpha, e_R^\alpha$

$\alpha_u = \{u, c, t\}$
$\alpha_d = \{d, s, b\}$
$\alpha_e = \{e, \mu, \tau\}$
$\alpha_\nu = \{\nu_e, \nu_\mu, \nu_\tau\}.$

} difference will only be their masses.

So, Yukawas are actually matrices

$$\mathcal{L} \supset y_d^{\alpha\beta} \overline{Q_L}^\alpha \phi d_R^\beta$$

When $\phi = \begin{pmatrix} 0 \\ h+v \end{pmatrix}$

$$\mathcal{L}^{Yuk} = -\frac{1}{\sqrt{2}} (h+v) \left(y_u^{\alpha\beta} \overline{u_L}^\alpha u_R^\beta + y_d^{\alpha\beta} \overline{d_L}^\alpha d_R^\beta + y_e^{\alpha\beta} \overline{e_L}^\alpha e_R^\beta + h.c. \right).$$

Mass mixing. What do we have to do? Diagonalize.

$U^{f}_{L,R}$ is applied to each chiral family.

$f = \{u, d, \ell\}$

$u_L \to U_L^{u} u_L$

$$\mathcal{L}^{m} = -\frac{v}{\sqrt{2}} \Big(\overset{\text{diagonal}}{m_i^{u}} \, \bar{u}_L^{i} u_R^{i} + m_i^{d} \bar{d}_L^{i} d_R^{i} + m_i^{e} \bar{e}_L^{i} e_R^{i} + h.c.$$

You can show that for Z and A couplings they do not mix ups and downs, so the unitary matrices cancel out. For the $W^\pm$ couplings however

$$\mathcal{L} \supset -\frac{g_W}{2\sqrt{2}} \, \bar{u}_L^{i} \gamma^{\mu} d_L^{i} W_\mu^{+} + h.c.$$

Rotation to mass basis

$$-\underline{g_W} \, \bar{u}_L^{i} \gamma^{\mu} \left(U_L^{u\dagger} U_L^{d} \right) d_L^{j} W_\mu^{+} + h.c.$$

$2\sqrt{2}$

$\boxed{V_{CKM}}$ → Cabibbo-Kobayashi-Maskawa

Flavour changing charged currents

For leptons the same would happen.

$$\mathcal{L}^{\ell} = y_e^{\alpha\beta}\, \overline{\ell_L}^{\alpha}\, \phi\, e_R^{\beta} + h.c.$$

U_{PMNS} → Pontecorvo-Maki-Nakagawa-Sakata.

$$\mathcal{L}^{cc} \supset -\frac{g}{2\sqrt{2}}\, \bar{e}_L^{i}\, \gamma^{\mu} \overbrace{\left(U_L^{\ell\dagger} U_L^{\nu}\right)}^{U_{PMNS}} \nu_L^{j}\, W^{+} + h.c.$$

because there is no mass term for ν's, we are free to choose $U_L^{\nu} = U_L^{\ell}$ keeping the interactions flavour diagonal.

Neutrinos are named in the W-interaction basis.

LFV would be proportional to neutrino masses and beyond experimental reach. Any LFV measurement would be a signal of BSM physics.

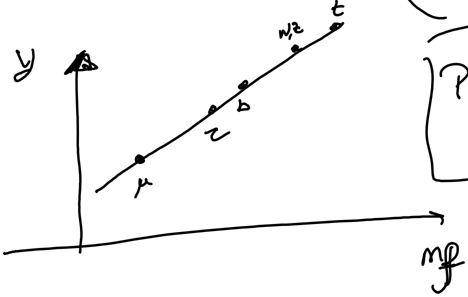
What about the Higgs term?

Remember: $\mathcal{L} \supset \frac{1}{\sqrt{2}} (\underline{\underline{h}} + \underline{\underline{v}}) \, y^u_{\alpha\beta} \, \bar{u}_L^{\alpha} u_R^{\beta} + h.c.$

$$m_f = y^u \frac{v}{\sqrt{2}}$$

coupling with higgs will be diagonal and proportional to mass

$$\mathcal{L} \supset h \, \bar{u}_L^{\alpha} u_R^{\alpha} \left(\frac{m_f}{v} \right)$$



Prediction from Higgs mechanism

The CKM matrix.

$$V_{CKM} = \begin{pmatrix} & 3 \times 3 & \end{pmatrix}$$ unitary matrix.

but how many "physical" parameters are in the CKM?

A (3×3) unitary matrix has 9 degrees of freedom

a real $O(3)$ matrix would have 3 angles. So we are left with 6 phases.

But $$m^{\alpha}\,\bar{d}_L^{\alpha}\,d_R^{\alpha} + m^{\beta}\,\bar{u}_L^{\beta}\,u_R^{\beta}$$

$$d_L^{j} \to e^{i\alpha_j} d_L^{j} \qquad d_R^{j} \to e^{i\alpha_j} d_R^{j}$$

$$u_L^{i} \to e^{i\beta_j} u_L^{j} \qquad u_R \to e^{i\beta_j} u_R .$$

V changes but not the theory. So we should remove 6 phases, except $\underbrace{\alpha_j = \beta_j}_{\text{no changes on } V.}$

So we are left with 3 angles and 1 phase

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - & & \\ & \cdots & \end{pmatrix}$$

$\delta \to$ CP-violation

$$|V| \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 \\ -\lambda & 1-\frac{\lambda^2}{2} & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein parametrization.

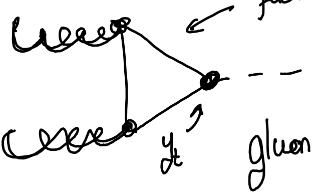
No explanation as to why this is the flavour structure of the SM.

— Colour. why not $\bar{q}_L \phi e_R$

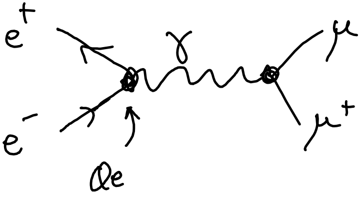
We've been saying that quarks are charged under colour. (3 colours).

How can we verify this

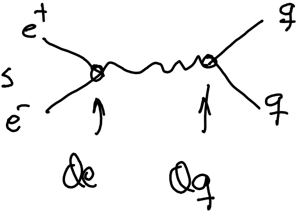
factor of 3 is needed



gluon fusion is actually the most common process to generate higgses.



vs



neglecting masses

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \sum_i Q_i^2$$

For $\sqrt{s} < 2m_c \sim 4$ GeV:

$$R \simeq \underbrace{\left(\frac{2}{3}\right)^2}_{u} + \underbrace{2\left(\frac{1}{3}\right)^2}_{d,s}$$

$R_{exp} \simeq 2$. We need the extra factor of 3 from colour.

Renormalizability .

$$V(\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$

why not more terms ? why not $(\phi^\dagger\phi)^3$?

Units : natural units $[\hbar] = [c] = 1$.

$\downarrow$

$E = \hbar f$ $\qquad \frac{m}{s}$, $[L] = [T]$

$[E] = [T]^{-1}$

$[E] = [M]\, c^2$ $\qquad$ high-energy → short-distance

$[S] = 1$

$S = \int d^4x\, \mathcal{L}$, so $[\mathcal{L}] = 4$

$\mathcal{L}^s = D_\mu \varphi^\dagger D^\mu \varphi$ $\qquad \partial_\mu = \frac{\partial}{\partial x_\mu}$

$\hookrightarrow 2[\phi] = 4 - 2[D_\mu] \Leftrightarrow [\phi] = 1$.

$\mathcal{L}^\psi = \bar{\Psi}\, \gamma_\mu D^\mu \psi$ $\qquad [\psi] = 3/2$

$\mathcal{L}^F = -\frac{1}{4}\left(\partial_\mu A_\nu - \partial_\nu A_\mu\right)^2$ $\qquad [A_\mu] = 1$.

$$\mathcal{L} \supset \lambda(\varphi^\dagger\varphi)^2 + \qquad [\lambda]=0$$

$$K(\varphi^\dagger\varphi)^3 \qquad [K]=-2$$

$$\downarrow$$

$$K \sim \frac{k}{\Lambda^2}$$

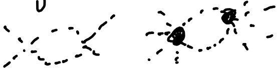
new mass scale.

this would imply new physics at scale Λ.

this is also suppressed.

$$[\mathcal{O}] \leq 4.$$

Define renormalizability?



— Some questions.

Higgs decays. What is the predominant decay?

How would the Higgs decay to photons?

— Shotcomings of the SM.

Neutrino masses: we have not described neutrino masses. But neutrinos oscillate between the flavour eigenstates, so they must have a mass.

Dark matter: Gravitational evidence which strongly points to it being a particle.

Baryon assymmetry: We are dominated by baryons instead of anti-baryons. The CP-violation in the CKM is not sufficient to account for the observed asymmetry.

Sakharov derived 3 conditions for baryogenesis to occur:

1- B number violation
2- CP-violation
3- Departure from thermal equilibrium

↓

usually thought of a first-order phase transition.

Strong-CP problem:

$$\mathcal{L}^{QCD} \supset \theta G \tilde{G}$$

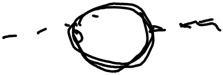
[illegible] $G^a_{\mu\nu} \epsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta}$

However, measurements of CP-violation in the strong sector give $|\theta| \lesssim 10^{-11}$.

Cosmology: No inflation and dark energy explanation.

Hierarchy problem:

Higgs mass is not protected by symmetry.

 $\sim \Lambda^2$

— Beyond the Standard Model

model-driven or top-down.

Extend the SM degrees of freedom.

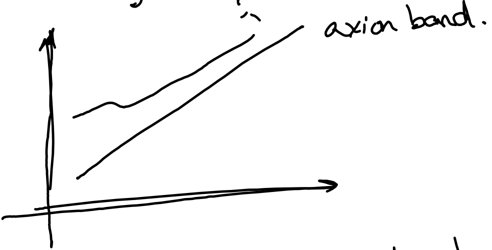
A lot of model building of the past decades followed from attempts to solve the hierarchy problem ← most frameworks also presented DM candidates

SUSY and Composite Higgs Models.

Another example is the axion

$$a G\tilde{G} \longrightarrow \langle a \rangle \simeq 0$$

The axion dynamics will then be defined by QCD. Extremely predictive scenario



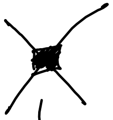
these approaches are called top-down because you suppose what the high-energy, UV, physics is (extend the SM with the appropriate d.o.f) and compute observables for these models.

Effective Field Theories

Say i have a theory where only leptons exist? How do i describe the muon decay?

$\mu^+ \longrightarrow e^+ \bar{\nu}_\mu \bar{\nu}_e$

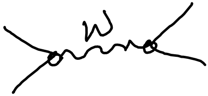
Neglecting renormalizability, we can describe this with



$(\bar{\mu} \gamma_\mu \nu_\mu)(\bar{\nu}_e \gamma^\mu e)$

↳ G_F. i measure this coupling with mass dimension $\underline{\underline{-2}}$

just by measuring muon decay i know there must be new physics nearby.



$\sim \frac{g^2}{m_W^2 - k^2}$ in low-energy limit

$\sim \frac{g^2}{m_W^2} + \mathcal{O}\left(\frac{1}{m_W^4}\right)$

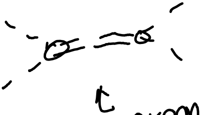
We would have known about the existence of a new particle purely by measuring a non-zero non-renormalizable interaction in the low-energy theory, this is called a bottom-up approach.

hence why

The SMEFT includes all possible operators which can be built with the SM fields.

The coefficients are kept arbitrary. ← no assumption on the UV theory which would generate it.

For instance $S(\phi^\dagger\phi)$



expand propagator → $C(D_\mu\varphi^\dagger)(D_\mu\varphi)(\varphi^\dagger\cdot\varphi)$

- then you calculate observables in terms of these coefficients.

A non-zero coefficient means new physics.

Note: EFTs can only capture physics from heavy particles (vs EW scale). For light particles, the expansion does not converge fast enough.

— Final thoughts.

- The foundation of theory is well established
  QM + SR really stringent in terms of what we can write down.

- SM is an extremely sucessful theory.
  20 or so parameters describe thousends of observations.

- Despite this, we are left with several unanswered questions.
  Some theoretical, some experimental.