

Exercises: Stefan Liebler (stefan.liebler@kit.edu) (Office 12/03 - Build. 30.23)
Shruti Patel (shruti.patel@kit.edu) (Office 12/14 - Build. 30.23)

Exercise 1: W pair production in the high-energy limit

We consider the scattering process

$$e^-(p_1)e^+(p_2) \rightarrow W^-(p_3)W^+(p_4)$$

in the high-energy limit with $s := k^2 \gg m_W^2$, with $k = p_1 + p_2 = p_3 + p_4$. The gauge-boson masses cannot be neglected, in contrast to the fermion masses, which we set to zero.

- (a) Assume that there is no three gauge-boson self interaction in the Standard Model. Show that in leading order in $\frac{m_W^2}{s}$, i.e. $m_W^2 \ll s, t, u$, the averaged squared amplitude, which only emerges from a t -channel neutrino exchange, is given by

$$\overline{|\mathcal{M}|^2} \approx -\frac{e^4}{16s_W^4 m_W^4} t(s+t) = \frac{\alpha^2 \pi^2}{4s_W^4} \frac{s^2}{m_W^4} (1 - \cos^2 \theta),$$

where s and $t = (p_1 - p_3)^2 = m_W^2 - 2p_1 \cdot p_3 = (p_2 - p_4)^2 = m_W^2 - 2p_2 \cdot p_4$ are Mandelstam variables and θ denotes the scattering angle between the incoming electron e^- and the outgoing W^- in the center-of-mass frame. The sine of the weak mixing angle is $s_W := \sin \theta_W$ and the fine structure constant is defined by $\alpha = \frac{e^2}{4\pi}$.

Hint: Argue why the polarisation sum of the W bosons can be approximated by $\sum_{\lambda} \epsilon_{\mu}(p, \lambda) \epsilon_{\nu}^*(p, \lambda) \approx \frac{p_{\mu} p_{\nu}}{m_W^2}$. Neglect all non-leading terms in $\frac{m_W^2}{s}$ in the calculation of the trace. A collection of relevant Feynman rules is given at the end of this exercise.

- (b) Determine the total cross section in leading order in $\frac{m_W^2}{s}$ in the center-of-mass system of the incoming particles, based on the calculation of the squared amplitude in the previous exercise. What happens to the cross section in the high-energy limit, i.e. $s \rightarrow \infty$?
- (c) The correct high-energy behaviour is obtained, when the three gauge-boson self-interaction is added. The calculation of the total cross section for this case is however quite lengthy, such that we consider the high-energy limit only for one helicity combination. Examine the amplitude for $e_R^- e_L^+ \rightarrow W_L^- W_L^+$ for an incoming right-handed electron and left-handed positron and two outgoing longitudinally polarised W bosons and show that in leading order in $\frac{m_W^2}{s}$ the sum of all diagrams yields

$$\mathcal{M}(e_R^- e_L^+ \rightarrow W_L^- W_L^+) \approx \frac{ie^2}{2c_W^2} \frac{1}{s} \bar{v}_R(p_2) (\not{p}_4 - \not{p}_3) u_R(p_1).$$

Hint: Use the equation of motions for massless fermions being $\bar{v}(p_2) \not{p}_2 = 0$ and $\not{p}_1 u(p_1) = 0$ as well as the approximation, that the polarisation vector of the longitudinal W boson in the high-energy limit is given by $\epsilon_L^{\mu}(p) \approx \frac{p^{\mu}}{m_W}$. If you failed in (a) or (b), you can also restart here.

- (d) Determine the total cross section for $e_R^- e_L^+ \rightarrow W_L^- W_L^+$ and examine the behaviour in the high-energy limit, i.e. $s \rightarrow \infty$.
- (e) The Goldstone-boson equivalence theorem states that the amplitudes of longitudinally polarised gauge boson in the high-energy limit equal the amplitudes, in which the gauge bosons are replaced through their Goldstone bosons (except from an unobservable phase). Show the equivalence of

$$\mathcal{M}(e_R^- e_L^+ \rightarrow \phi^- \phi^+) = \mathcal{M}(e_R^- e_L^+ \rightarrow W_L^- W_L^+)$$

in leading order in $\frac{m_W^2}{s}$.

- (f) Determine the amplitude for $e_L^- e_R^+ \rightarrow W_L^- W_L^+$ for an incoming left-handed electron and right-handed positron and two outgoing longitudinally polarised W bosons using the Goldstone-boson equivalence theorem and lastly obtain the total cross section for $e^- e^+ \rightarrow W_L^- W_L^+$.

Relevant Feynman rules for the interactions are given by the following expressions:

The image shows four Feynman diagrams with their corresponding mathematical expressions:

- Top-left:** A vertex where an electron (e^-) and a positron (e^+) meet and emit a photon (γ). The rule is $-ie\gamma^\mu(P_L + P_R)$.
- Top-right:** A vertex where an electron (e^-) and a neutrino (ν_e) meet and emit a W boson. The rule is $\frac{ie}{\sqrt{2}s_W}\gamma^\mu P_L$.
- Middle-left:** A vertex where an electron (e^-) and a positron (e^+) meet and emit a Z boson. The rule is $\frac{ie}{s_W c_W}\gamma^\mu \left((-\frac{1}{2} + s_W^2)P_L + (s_W^2)P_R \right)$.
- Middle-right:** A vertex where a Goldstone boson (ϕ^-) and a Goldstone boson (ϕ^+) meet and emit a Z boson. The rule is $\frac{ie(\frac{1}{2} - s_W^2)}{c_W s_W}(p_- - p_+)^\mu$.
- Bottom-left:** A vertex where a W^- boson and a W^+ boson meet and emit a photon (γ) with momentum q . The rule is $ief^{\mu\nu\rho}$.
- Bottom-right:** A vertex where a W^- boson and a W^+ boson meet and emit a Z boson with momentum q . The rule is $\frac{iec_W}{s_W}f^{\mu\nu\rho}$.

Therein the momentum flow is indicated through the additional arrows. The left- and right-handed projection operators are given by $P_L = \frac{1-\gamma_5}{2}$ and $P_R = \frac{1+\gamma_5}{2}$. Moreover it yields $f^{\mu\nu\rho} = g^{\mu\nu}(p_- - p_+)^\rho + g^{\nu\rho}(-q - p_-)^\mu + g^{\rho\mu}(q + p_+)^\nu$. Again s_W and c_W are defined through $\sin\theta_W$ and $\cos\theta_W$, respectively. The propagators of the photon and the Z boson in R_ξ gauge (see sheet 5) are given by

$$\frac{-i\left(g_{\mu\nu} - (1-\xi)\frac{k_\mu k_\nu}{k^2}\right)}{k^2} \quad \text{and} \quad \frac{-i\left(g_{\mu\nu} - (1-\xi)\frac{k_\mu k_\nu}{k^2 - \xi m_Z^2}\right)}{k^2 - m_Z^2}, \quad \text{respectively.}$$

Make a convenient gauge choice. Goldstone bosons do not couple to massless fermions.