Elementary Particle Theory – PHY452

Fall Semester 2020

Exercise Sheet 13

Exercise 1: Vector boson interactions at the LHC

In the parton model, proton-proton collisions at high energy are described in terms of partonic processes initiated by the quark, antiquark and gluon constituents of the protons. Sketch the parton model picture and all relevant Feynman diagrams (at tree level) for the following electroweak processes, mediated by γ, Z, $W^{\pm}$, at the LHC:

a) $pp \to e^+e^-$

b) $pp \to e^+\nu_e^-$

c) $pp \to \nu_e\bar{\nu}_e$

d) $pp \to e^+\nu_e\gamma$

e) $pp \to e^+\nu_e + \text{jet}$

List all possible gauge-boson pair-processes $pp \to V_1V_2$ with $V_{1,2} \in \{\gamma, Z, W^{\pm}\}$ and draw the relevant Feynman diagrams.

Exercise 2: Higgs production and decays

The Higgs gauge and self-interactions are described in the SM by

$$\mathcal{L}_H = (D_\mu\Phi)^\dagger (D_\mu\Phi) - \frac{\lambda}{4}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 , \tag{1}$$

where $v = (\sqrt{2}G_F)^{-1/2}$ is the electroweak vacuum expectation value and λ is the quartic Higgs coupling, and its interactions with fermions are described by the Yukawa Lagrangian,

$$\mathcal{L}_{\text{Yuk.}} = -\lambda_d\,\overline{Q}_L\Phi d_R - \lambda_u\,\overline{Q}_L\Phi_c u_R - \lambda_e\,\overline{L}_L\Phi e_R + \text{h.c.}\,, \tag{2}$$

where $\Phi_c = i\sigma_2\Phi^*$ is the conjugate Higgs doublet and λ_f ($f = u, d, e$) are the fermion mass matrices, which we assume to be diagonal. In this exercise, we will discuss the main mechanisms for the Higgs boson production in different types of colliders.

a) Write down the Feynman rules for the Higgs boson interactions in the SM.

b) What would be the dominant process mechanism for Higgs production in an electron-positron collider?

c) What are the dominant production channels of the Higgs at the LHC?

d) What are the leading contributions to the production of Higgs-boson pairs in a proton-proton collider?

e) Discuss which are the main decay channels of the Higgs.

Exercise 3: CKM matrix and unitarity

The Unitarity Triangle (UT) is defined in the complex plane $z = \bar{\rho} + i\,\bar{\eta}$ by the equation,

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0\,, \tag{3}$$

as illustrated in Fig. 1. The three internal angles are denoted by α, β and γ.

a) Show that

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)\,, \qquad \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)\,, \qquad \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)\,, \tag{4}$$

b) Show that these angles are invariant under phase redefinitions of quark fields: $q_i \to e^{i\,\alpha_i} q_i$.

c) Show that the area of the triangle is proportional to the quantity

$$J = \mathrm{Im}(V_{ud}V_{cd}^*V_{cb}V_{ub}^*)\,, \tag{5}$$

which is also referred too as the "Jarlskog invariant".

d) Which are the simplest tree-level mesons decays that can be used to extract $|V_{ij}|$ for different flavor indices i, j?

Hint: *The valence content of the lighest charged pseudoscalar mesons are* $\pi^- = \bar{u}d$, $K^- = \bar{u}s$, $D^- = \bar{c}d$, $D_s^- = \bar{c}s$ *and* $B^- = \bar{u}b$.

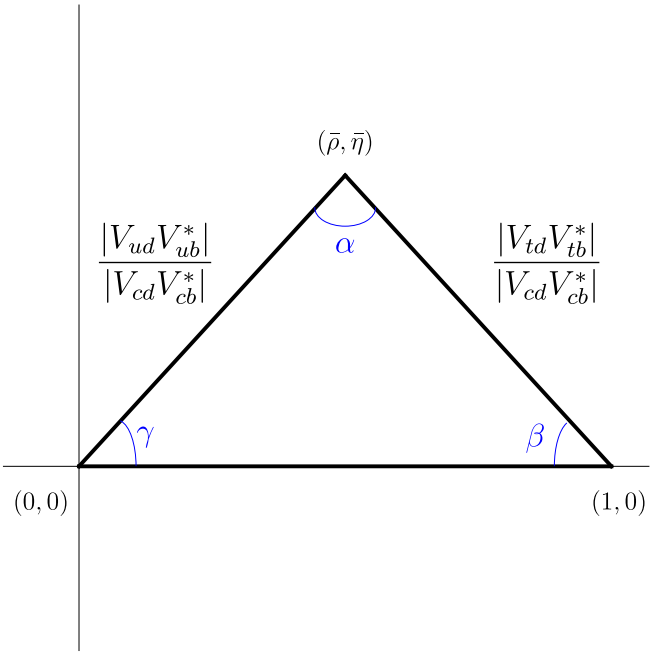

Figure 1: *Unitarity triangle.*