Mid-term exam of Particle Physics
Thursday November 14$^{\text{th}}$ 2019
Answers to the questions on the lecture
(Exercice I)

Exercice I

Questions on the lecture

1. Explain the theoretical and experimental logic behind the Cronin and Fitch experiment, which allowed the discovery of CP violation in the neutral-kaons system in 1964.

The lightest neutral kaons (K^0 and $\overline{K}^0$), with a well determined strangeness, decay only by the weak interaction. This interaction not only allows them to decay, but also to oscillate (i.e. a K^0 meson can spontaneously become a $\overline{K}^0$ and vice versa). It results that the state that propagates in space and time (mass eigenstate, with a well determined mass and width) is a K^0-$\overline{K}^0$ mixture, and is not a strangeness eigenstate. Under the hypothesis that CP is a symmetry for weak interactions, the mixtures are CP-eigenstates and are well determined. In this case they are:

$$|K_1^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle) \quad \text{with } CP = +1 \qquad ; \qquad |K_2^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle) \quad \text{with } CP = -1.$$

The experimentally observed states are the K_S^0 and the K_L^0. The former decays essentially to two pions and the latter to three pions; due to the related phase-space difference the two states have very different lifetimes, as indicated by their names. It can be shown that the two-pions final state has $CP = +1$ and the three-pions final state has CP = -1. Therefore, if the K_L^0 decays *only* to three pions, it can be identified with the CP eigenstate K_2^0 and the CP conservation hypothesis holds.

In the Cronin and Fitch experiment a beam of neutral kaons is produced. A detector is placed far enough from the beam-production point, so that practically only K_L^0 states reach it. The signal indicating CP violation is a final state with two opposite-sign pions, with an invariant mass compatible with that of the K_L^0 and that are back to back in the center of mass of the decay. This signal was found, at the level of a few per-mills, indicating that CP is not an exact symmetry of weak interactions.

2. Deep Inelastic Scattering (DIS) experiments use, for instance, the reaction $e^- p \to e^- X$, where X is a system of hadrons, to probe the internal structure of the proton. Explain.

In DIS experiments the invariant mass M_X of the hadronic system X allows to measure the energy transfer, Q^2, from the electron to the proton. The differential cross section of the process as a function of Q^2 is well known for a pointlike particle. The study of this quantity and its comparison to the pointlike case provides an insight on the internal structure of the proton. With increasing energy of the initial electron (increasing inelasticity of the process), smaller structures inside the proton are probed. The study of the ratio of the measured cross section with respect to the theoretical point-like cross section, $\sigma/\sigma_{\rm pl}$, shows a peculiar behaviour: when the process becomes inelastic enough (quantitatively, when the invariant mass of the hadronic system is $\gtrsim 3m_p$), $\sigma/\sigma_{\rm pl}$ tends to a flat distribution, indicating a collision with free pointlike objects inside the proton, carrying a fraction of its energy-momentum. These objects are named *partons*. DIS experiments corroborate the quark model, and indicate the property of asymptotic freedom in QCD.