Flavour Physics: Week: VI

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Problem 1. A recent development in elementary particle physics is the discovery of charmed nonstrange mesons (called D^+, D^0, and their charge conjugates) with masses around 1870 MeV/c^2.

(a) Knowing the charge of charmed quark to be 2/3, give the quark contents of the D^+ and —D^0 mesons

(b) The D mesons decay weakly into ordinary mesons (π, K, ...). Use $\theta_c = 13.1^o$ to give estimates (with your reasoning) for the branching ratios of the following two-body decays:

- $\frac{\mathcal{B}(D^0 \to K^- K^+)}{\mathcal{B}(D^0 \to K^- \pi^+)}$
- $\frac{\mathcal{B}(D^0 \to \pi^- \pi^+)}{\mathcal{B}(D^0 \to K^- \pi^+)}$
- $\frac{\mathcal{B}(D^0 \to K^+ \pi^-)}{\mathcal{B}(D^0 \to K^- \pi^+)}$

(c) How would you show that the decay of D mesons is by means of weak interaction?

(d) In a colliding beam at c.m. energy 4.03 GeV, a D^+ meson (mass = 1868.3 MeV/c^2) and a D^{*-} meson (mass = 2008.6 MeV/c^2) are produced. The D^{*-} decays into a $\overline{D}^0$ (mass = 1863.3 MeV/c^2) and a π^-. What is the maximum momentum in the laboratory of the D^{*-}? of the π^-?

Problem 2. How well is satisfied unitarity from the measured CKM elements?

(a) Check the unitarity condition and compute its uncertainty. Note: check the individual values from the PDG https://pdg.lbl.gov/2024/web/viewer.html?file=../reviews/rpp2024-rev-ckm-matrix.pdf (Hint: It suffice to prove that one of the rows is normalized)

(b) Did the values change from 2021? (Hint: Look for the $|V_{ud}|$ measurement and try to justify the change).

Problem 3. Consider the CKM Matrix in the Wolfenstein parametrization:

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4). \qquad (1)$$

(a) Determine the Wolfenstein parameters (λ, A, ρ, η) from:

$$\begin{aligned} \Gamma(\mathrm{K}^+ \to \mu^+ \nu_\mu)^{\text{exp}} &= 3.3793(79) \times 10^{-8}\,\text{eV} \\ \Gamma(\mathrm{B}^+ \to \tau^+ \nu_\tau)^{\text{exp}} &= 4.38(96) \times 10^{-8}\,\text{eV} \\ \Delta M_{B_d}^{\text{exp}} &= 3.333(13) \times 10^{-10}\,\text{MeV} \\ \Delta M_{B_s}^{\text{exp}} &= 1.1688(14) \times 10^{-8}\,\text{MeV} \end{aligned}$$

using:

$$\begin{aligned} \Gamma(P \to l\nu) &= |V_{uq}|^2 \frac{f_P^2 m_P m_l^2}{16\pi v^4}(1 - \frac{m_l^2}{m_P^2})^2(1+\delta_P) \\ \Delta M_{B_q} &= |V_{tb}V_{tq}|^2 \frac{m_{B_q} f_{B_q}^2 m_W^2}{12\pi^2 v^4} B_1^q S_1(m_b) \end{aligned}$$

(with $P = \{K, B\}$ and $q = \{d, s, b\}$ depending on the case), and the numerical parameters given in the table at the end of the exercise sheet.

Advise: Determine first the quantities $(\{|V_{us}|, |V_{ub}|, |V_{tb}V_{td}|, |V_{tb}V_{ts}|\})$, and then use the Wolfenstein parametrization to order $\mathcal{O}(\lambda^4)$ to determine (λ, A, ρ, η). You will need a computer.

- $v = 246.21965(6)\,\text{GeV}$
- $G_F = 1.166 \cdot 10^{-5}\,\text{GeV}^{-2}$
- $\alpha(m_b) = 1/132$
- $m_{\mathrm{W}} = 80.379(12)\,\text{GeV}$
- $m_\mu = 105.6583745(24)\,\text{MeV}$
- $m_\tau = 1.77686(12)\,\text{GeV}$
- $\delta_K = 0.0107(21)$
- $\delta_B \sim 0$
- $m_{\mathrm{K}^\pm} = 493.677(16)\,\text{MeV}$
- $m_{\mathrm{B}^\pm} = 5.27932(14)\,\text{GeV}$
- $m_{\mathrm{B}_d} = 5.27963(15)\,\text{GeV}$
- $m_{\mathrm{B}_s^0} = 5.36689(19)\,\text{GeV}$

- $f_{\mathrm{K}^{\pm}} = 155.7(0.3)\,\mathrm{MeV}$
- $f_{\mathrm{B}^{\pm}} = 190.0(1.3)\,\mathrm{MeV}$
- $f_{\mathrm{B}^0_\mathrm{s}} = 230.3(1.3)\,\mathrm{MeV}$
- $f^2_{\mathrm{B}_d} B^d_1 = 0.0297(17)\,\mathrm{GeV}^2$
- $f^2_{\mathrm{B}^0_\mathrm{s}} B^s_1 = 0.0432(22)\,\mathrm{GeV}^2$
- $S_1(m_b) = 1.9848$
- $\lambda = 0.22537(46)$
- $A = 0.828(21)$
- $\rho = 0.194(24)$
- $\eta = 0.391(48)$
- $\tau_{\mathrm{B}^0_\mathrm{s}} = 1.527(11) : 10^{-12}\,\mathrm{s}$
- $1s = 1.5 \cdot 10^{24}\,\mathrm{GeV}^{-1}$
- $C^{SM}_{10}(m_b) = -4.309$

Problem 4. The $\mathrm{B}^0 \to \pi^-\pi^+$ decay involves change of flavour and, thus, grants access to element(s) of the CKM matrix.

(a) Draw the Feynmann diagram for this decay, and point out what CKM matrix element (V_{ij}) this decay is sensitive to.

(b) The reconstruction of this decay involves the combination of two opposite charged tracks (particles). Look in the PDG potential backgrounds for this decay. Hint: look for decays of b-hadrons with similar mass to the B^0 (B^0, B^0_s and Λ^0_b) to two tracks in the final state (the π can be misidentificated as K or p).

(c) Search for the branching ratio of these decays and compare them with that of the signal decay ($\mathrm{B}^0 \to \pi^-\pi^+$). Considering that B^0 production is four times higher than B^0_s production at LHC ($f_s/f_d(13\,\mathrm{TeV}) \sim 0.25$) and and three times higher than Λ^0_b ($f_{\Lambda^0_b}/(f_d + f_u)(13\,\mathrm{TeV}) \sim 0.33$), what is the level of contamination that you can expect from these decays?

(d) Considering the shift in mass due to the wrong reconstruction (incorrect mass hypothesis), and the different initial particle (B^0 or Λ^0_b), where would you expect the background reconstruction to be?