

## PSEUDOSCALAR-MESON DECAY CONSTANTS

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### *Charged mesons*

The decay constant  $f_P$  for a charged pseudoscalar meson  $P$  is defined by

$$\langle 0 | A_\mu(0) | P(\mathbf{q}) \rangle = i f_P q_\mu , \quad (1)$$

where  $A_\mu$  is the axial-vector part of the charged weak current after a Cabibbo-Kobayashi-Maskawa mixing-matrix element  $V_{qq'}$  has been removed. The state vector is normalized by  $\langle P(\mathbf{q}) | P(\mathbf{q}') \rangle = (2\pi)^3 2E_q \delta(\mathbf{q} - \mathbf{q}')$ , and its phase is chosen to make  $f_P$  real and positive. Note, however, that in many theoretical papers our  $f_P/\sqrt{2}$  is denoted by  $f_P$ .

In determining  $f_P$  experimentally, radiative corrections must be taken into account. Since the photon-loop correction introduces an infrared divergence that is canceled by soft-photon emission, we can determine  $f_P$  only from the combined rate for  $P^\pm \rightarrow \ell^\pm \nu_\ell$  and  $P^\pm \rightarrow \ell^\pm \nu_\ell \gamma$ . This rate is given by

$$\Gamma(P \rightarrow \ell \nu_\ell + \ell \nu_\ell \gamma) = \frac{G_F^2 |V_{qq'}|^2}{8\pi} f_P^2 m_\ell^2 m_P \left(1 - \frac{m_\ell^2}{m_P^2}\right)^2 [1 + \mathcal{O}(\alpha)] . \quad (2)$$

Here  $m_\ell$  and  $m_P$  are the masses of the lepton and meson. Radiative corrections include inner bremsstrahlung, which is independent of the structure of the meson [1–3], and also a structure-dependent term [4,5]. After radiative corrections are made, there are ambiguities in extracting  $f_P$  from experimental measurements. In fact, the definition of  $f_P$  is no longer unique.

It is desirable to define  $f_P$  such that it depends only on the properties of the pseudoscalar meson, not on the final decay products. The short-distance corrections to the fundamental electroweak constants like  $G_F |V_{qq'}|$  should be separated out. Following Marciano and Sirlin [6], we define  $f_P$  with the following form for the  $\mathcal{O}(\alpha)$  corrections:

$$1 + \mathcal{O}(\alpha) = \left[ 1 + \frac{2\alpha}{\pi} \ln\left(\frac{m_Z}{m_\rho}\right) \right] \left[ 1 + \frac{\alpha}{\pi} F(x) \right]$$

$$\times \left\{ 1 - \frac{\alpha}{\pi} \left[ \frac{3}{2} \ln \left( \frac{m_\rho}{m_P} \right) + C_1 + C_2 \frac{m_\ell^2}{m_\rho^2} \ln \left( \frac{m_\rho^2}{m_\ell^2} \right) + C_3 \frac{m_\ell^2}{m_\rho^2} + \dots \right] \right\}, \quad (3)$$

where  $m_\rho$  and  $m_Z$  are the masses of the  $\rho$  meson and  $Z$  boson. Here

$$F(x) = 3 \ln x + \frac{13 - 19x^2}{8(1 - x^2)} - \frac{8 - 5x^2}{2(1 - x^2)^2} x^2 \ln x \\ - 2 \left( \frac{1 + x^2}{1 - x^2} \ln x + 1 \right) \ln(1 - x^2) + 2 \left( \frac{1 + x^2}{1 - x^2} \right) L(1 - x^2),$$

with

$$x \equiv m_\ell/m_P, \quad L(z) \equiv \int_0^z \frac{\ln(1 - t)}{t} dt. \quad (4)$$

The first bracket in the expression for  $1 + \mathcal{O}(\alpha)$  is the short-distance electroweak correction. A quarter of  $(2\alpha/\pi) \ln(m_Z/m_\rho)$  is subject to the QCD correction  $(1 - \alpha_s/\pi)$ , which leads to a reduction of the total short-distance correction of 0.00033 from the electroweak contribution alone [6]. The second bracket together with the term  $-(3\alpha/2\pi) \ln(m_\rho/m_P)$  in the third bracket corresponds to the radiative corrections to the point-like pion decay ( $\Lambda_{\text{cutoff}} \approx m_\rho$ ) [2]. The rest of the corrections in the third bracket are expanded in powers of  $m_\ell/m_\rho$ . The expansion coefficients  $C_1$ ,  $C_2$ , and  $C_3$  depend on the hadronic structure of the pseudoscalar meson and in most cases cannot be computed accurately. In particular,  $C_1$  absorbs the uncertainty in the matching energy scale between short- and long-distance strong interactions and thus is the main source of uncertainty in determining  $f_{\pi^+}$  accurately.

With the experimental value for the decay  $\pi^+ \rightarrow \mu^+ \nu_\mu + \mu^+ \nu_\mu \gamma$ , one obtains

$$f_{\pi^+} = 130.7 \pm 0.1 \pm 0.36 \text{ MeV}, \quad (5)$$

where the first error comes from the experimental uncertainty on  $|V_{ud}|$  and the second comes from the uncertainty on  $C_1$  ( $= 0 \pm 2.4$ ) [6]. Similarly, one obtains from the decay  $K^+ \rightarrow \mu^+ \nu_\mu + \mu^+ \nu_\mu \gamma$  the decay constant

$$f_{K^+} = 159.8 \pm 1.4 \pm 0.44 \text{ MeV}, \quad (6)$$

where the first error is due to the uncertainty on  $|V_{us}|$ .

For the heavy pseudoscalar mesons, uncertainties in the experimental values for the decay rates are much larger than the radiative corrections. The  $D^+$  constant is much improved since our 2004 edition. It is

$$f_{D^+} = 222.6 \pm 16.7_{-3.4}^{+2.8} \text{ MeV} \quad , \quad (7)$$

based on  $47 \pm 7 D^+ \rightarrow \mu^+ \nu_\mu$  events from the CLEO Collaboration [7]. The  $D_s^+$  decay constant is discussed in a separate note in the  $D_s^+$  Data Listings. The value obtained there is

$$f_{D_s^+} = 294 \pm 27 \text{ MeV} \quad . \quad (8)$$

Recently the Belle collaboration has reported the first evidence of the decay  $B^+ \rightarrow \tau^+ \nu_\tau$  using  $414 \text{ fb}^{-1}$  of data and fully reconstructing one of the  $B$  mesons in hadronic modes [8]. Based on the measured branching ratio of  $(1.06_{-0.28-0.16}^{+0.34+0.18}) \times 10^{-4}$ , they derived the first direct measurement of the  $B$  meson decay constant:

$$f_{B^+} = 176_{-23-19}^{+28+20} \text{ MeV} \quad . \quad (9)$$

There have been many attempts to extract  $f_P$  from spectroscopy and nonleptonic decays using theoretical models. Since it is difficult to estimate uncertainties for them, we have listed here only values of decay constants that are obtained directly from the observation of  $P^\pm \rightarrow \ell^\pm \nu_\ell$ .

### ***Light neutral mesons***

The decay constants for the light neutral pseudoscalar mesons  $\pi^0$ ,  $\eta$ , and  $\eta'$  are defined by

$$\sqrt{2} \langle 0 | A_\mu^a(0) | P(q) \rangle = i f_P^a q_\mu \quad (10)$$

where  $A_\mu^a$  is a neutral axial-vector current [9,10]. Restricting ourselves to the three light flavors, the index  $a = 0, 3, 8$  refers to the usual set of Gell-Mann matrices, including the flavor singlet. In case of exact isospin symmetry (which is for most applications a very good approximation) we have only one decay constant for the  $\pi^0$  meson ( $f_{\pi^0}^3 \equiv f_{\pi^0}$ ) and two decay constants each for  $\eta$  and  $\eta'$  ( $f_\eta^8, f_\eta^0$ , and  $f_{\eta'}^8, f_{\eta'}^0$ ).

In the limit of  $m_P \rightarrow 0$ , the Adler-Bell-Jackiw anomaly [11,12] determines the matrix elements of the two-photon decay  $P \rightarrow \gamma\gamma$  through the decay constants  $f_P^a$ . In the case of  $f_{\pi^0}$ , the extrapolation to  $m_\pi \neq 0$  gives only a tiny effect, and the value of  $f_{\pi^0}$  can be extracted from the  $\pi^0 \rightarrow \gamma\gamma$  decay width. The experimental uncertainty in the  $\pi^0$  lifetime dominates in the uncertainty of  $f_{\pi^0}$ :

$$f_{\pi^0} = 130 \pm 5 \text{ MeV} . \quad (11)$$

This value is compatible with  $f_{\pi^\pm}$ , as it is expected from isospin symmetry.

The four decay constants of the  $\eta$ - $\eta'$  system cannot be extracted from the two-photon decay widths alone. Also, the extrapolation to  $m_{\eta(\eta')} \neq 0$  may give a larger effect here, and therefore the dominance of the Adler-Bell-Jackiw anomaly is perhaps questionable. Thus, an assessment of the values of the  $\eta$  and  $\eta'$  decay constants requires additional theoretical and phenomenological input about flavor symmetry breaking and  $\eta$ - $\eta'$  mixing; see Ref. 13 for a review. Most analyses find similar values for the octet decay constants:  $f_\eta^8 \simeq 1.2 f_\pi$  and  $f_{\eta'}^8 \simeq -0.45 f_\pi$ . The situation concerning the singlet decay constants,  $f_P^0$ , is less clear.

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