Particle Physics Phenomenology (examination 01-04-2014) time9:00 in 5118-156

Some data sheets of the Particle Data Group have been added to provide the necessary information concerning useful constants and the data of various mesons. You need to consult them for answering these questions. The accuracy of your calculations should be at least three significant digits, unless instructed otherwise or limited by the accuracy as given in the datasheets.

Question 1 (35 pt)

To study the properties of Kaons the DAΦNE accelerator produces ϕ mesons at rest using a ring collider of electrons and positrons. In your answers, distinguish when you are referring to a neutral Kaon, whether you mean a $K^0, \bar{K}^0, K_S^0$, or K_L^0.

Useful to know: With source $I(t) = I_0 e^{-\frac{t}{\tau}}$, source at rest $\langle t \rangle = \frac{\int_0^\infty tI(t)dt}{\int_0^\infty I(t)dt} = \tau$

and decay rate $R(t) = -\frac{d}{dt}I(t) = I(t)/\tau$.

1. (2 pt) What is the energy of the electron and positron beam to produce the ϕ mesons?
2. (2 pt) What is the velocity (in natural units) of the neutral and charged K mesons?
3. (2 pt) What is the most likely sequence of decay events to occur when two neutral Kaons are produced (Give the time order of the Kaon decays, give for each of these an example of likely decay products and the corresponding probability of that decay)?
4. (4 pt) The distance traveled by the neutral and charged Kaons will differ, what are the mean distances they travel before decay? (Answer for each of the 4 different Kaon particles)
5. (16 pt) In the following, one has selected events where the neutral Kaon that traveled the shortest distance decays into a π^+ and e^-, also defining $t = 0$. The other Kaon may decay, among other possibilities, in a $\pi^+\mu^-$ or in $\pi^-\mu^+$. (The neutrinos are not measured of course.) Such decays are said to define the neutral Kaon as a K^0or $\bar{K}^0$ and that at $t = 0$ the wave function describing the double Kaon system collapses.
   a. (2 pt) Explain in a few words what this means by considering the quark content of the neutral Kaon as a $K^0, \bar{K}^0, K_S^0$, or K_L^0.

   As a function of its proper time one measures the asymmetry for the second Kaon decay as

$$A(t) = \frac{R(\pi^+\mu^-) - R(\pi^-\mu^+)}{R(\pi^+\mu^-) + R(\pi^-\mu^+)} \approx 2\left[\frac{e^{-\frac{t}{2\tau_S}}}{1 + e^{-\frac{t}{\tau_S}}} - \frac{4\Re(\epsilon)e^{-\frac{t}{\tau_S}}}{\left(1 + e^{-\frac{t}{\tau_S}}\right)^2}\right] \cos \Delta mt + 2\Re(\epsilon).$$

   Find the relevant values of the parameters of this function in the PDG sheets.

   b. (2 pt) Give the value of Δm in units of $\frac{1}{\tau_S}$.

c. (2 pt) Make a sketch of $A(t)$ revealing its relevant dependence (evaluate values at $t = 0, t = \infty$, and $\Delta mt = \frac{\pi}{2}, \frac{3\pi}{2}$) and use units of time in factors of τ_S, take $\Re(\epsilon) = 0.01$ to make its effect more visible).

d. (2 pt) What are the physical essential concepts associated with Δm and ϵ. (one line each).

e. (3 pt) Consider the measurement

$$B(t) = \frac{R(\pi^+\pi^-) - R(\pi^+\pi^-\pi^0)}{R(\pi^+\pi^-) + R(\pi^+\pi^-\pi^0)},$$

Made under same condition as before, i.e. the first Kaon decay is into π^+e^-. What is the value of $B(t = 0)$ and $B(t \gg \tau_S)$, assume CP conservation.

f. (3 pt) Give the value of $A(t = 0)$, $A(t \gg \tau_S)$, $B(t = 0)$, and $B(t \gg \tau_S)$ for the case where the first Kaon decay is $\pi^+\pi^-$. You may assume CP conservation.

g. (2 pt) As in f, how large is $B(t = 0)$ and $B(t \gg \tau_S)$ when CP violation is taken into account?

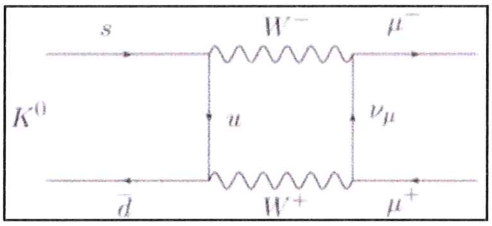
6. (9 pt) The ϕ meson can also decay into a neutral meson and a photon, in particular the channels $\phi \to \pi^0\gamma$ and $\phi \to \eta\gamma$, the π^0 and η mesons both decay preferentially into two photons. Assume a partitioned detector that covers the full solid angle allowing to find events with only three photons for which energies and directions can be measured.

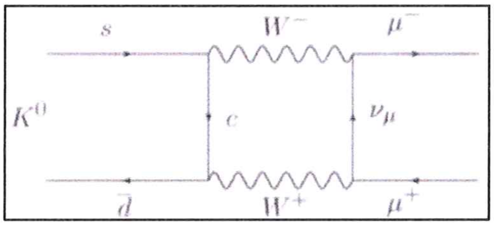
   a. (4 pt) Give two methods to identify the two decay channels. (Give also a formula associated with each method using masses of the particles and/or energy and angles of the photons)

   b. (5 pt) What is the lowest and highest possible energy of the photons emitted.

Question 2 (20 pt)

1. (3 pt) Draw Feynman diagrams for the $K^+ \to \pi^+\pi^0$ and the $K^- \to \pi^0\pi^-$. Also draw Feynman diagrams for their most likely leptonic and semi-leptonic decay. How do the decay rates depend on the Cabbibo angle.
2.
   a. (4 pt) Show that in the approximation that the u and c quark have the same mass the decay amplitudes shown in the two diagrams below cancel (GIM mechanism).



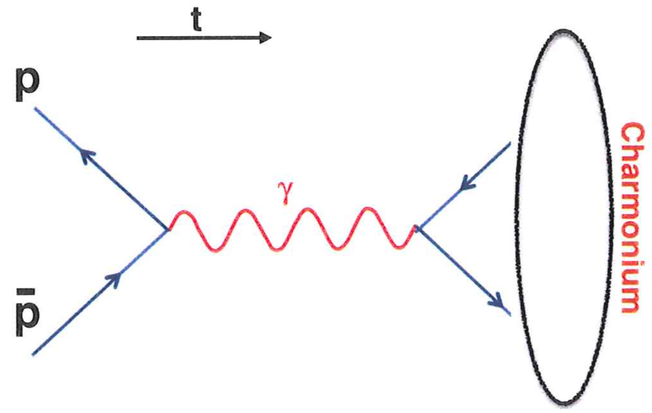


   b. (2 pt) The contribution of such diagrams to the decay rate due to the top quark is usually ignored. What is the reason for that?
   c. (2 pt) The contribution of the top quark cannot be ignored when considering CP violation. Why is it important in this case?
3.
   a. (4 pt) The K^+ decay ratios $\frac{\Gamma(e^+\nu_e)}{\Gamma(\mu^+\nu_\mu)} \ll 1$ and $\frac{\Gamma(\pi^0 e^+\nu_e)}{\Gamma(\pi^0\mu^+\nu_\mu)} \approx 1$. Discuss the longitudinal polarization (draw spin and momentum directions) of the outgoing leptons to explain why these ratios are so different.
   b. (2 pt) The actual decay rate for $K^+ \to e^+\nu_e$ is given by the expression

$$\Gamma(\,K^+ \to e^+\nu_e\,) = \frac{G_F^2}{8\pi} f_{K^+}^2 m_e^2 M_{K^+}\left(1-\frac{m_e^2}{M_{K^+}^2}\right)^2 |V_{us}|^2,$$

   The factor f_{K^+} is related to the wave-function overlap of the quark and antiquark in the K meson. What is the dimension of the factor f_{K^+}?
   c. (3 pt) Calculate what the ratio $\Gamma(\,D^+ \to \mu^+\nu_{\mu})/\Gamma(D^+ \to \tau^+\nu_{\underset{\tau}{\mu}})$ should be.

Question 3: "Charmonium" (25 pt)



The future PANDA experiment plans to study charmonium ($c\bar{c}$ bound states) via the annihilation of a beam of antiprotons ($\bar{p}$) on a proton (p) target at rest. Consider the production of the vector-meson state, ψ', with a mass of 3686 ~~G~~MeV and a $J^{PC} = 1^{--}$ via the "fusion" reaction $p\bar{p} \rightarrow \psi'$. The figure above illustrates one of the possible production mechanisms.

1. (5 pt) Which orbital angular momenta (L) are allowed of the $c\bar{c}$ system for a vector meson? Motivate your answer.
2. (5 pt) Calculate the momentum of the incident beam of antiprotons that is needed to populate the ψ'. (Take the proton mass to be 938 MeV)
3. (5 pt) The ψ' decays predominantly, with a branching fraction of 34%, to the lowest lying vector meson state of charmonium, the J/ψ, with the emission of a pair of pions, i.e. $\psi' \longrightarrow J/\psi + \pi^+\pi^-$. On the other hand, the decay $\psi' \longrightarrow J/\psi + \pi^0$ is suppressed with a branching fraction of only 0.12%. Motivate this suppression and give arguments why the latter decay is non-zero.
4. (5 pt) Consider the decay $J/\psi \longrightarrow \pi^0\pi^+\pi^-$. Sketch the dominant quark and gluon lines (Feynman diagram) of this decay.
5. (5 pt) The widths of the J/ψ ($\Gamma = 93$ keV) and ψ' ($\Gamma = 303$ keV) are much smaller than the width of the higher-lying ψ'' state ($\Gamma = 27$ MeV). The ψ'' is also a vector-meson state of charmonium with a mass of 3770 ~~G~~MeV. Explain qualitatively the large difference in width between these vector mesons. [Hint: the lightest "open-charm" D meson has a mass of 1869 MeV]

Question 4: "Deep-Inelastic Scattering" (20 pt)

A beam of electrons with 4-momentum $k_\mu = (E, \vec{k})$ scatters on a proton target. The 4-momentum of the scattered electrons is $k_\mu{}' = (E', \vec{k}')$. The mass of the electron can be neglected.

1. (5 pt) Show that $Q^2 \equiv -q^2 = M^2 + 2M\nu - W^2$ where $q^2 (= \sum_\mu q_\mu q^\mu) = (k - k')^2$ is the square of the four-momentum transfer, M is the mass of the proton (938 MeV), $\nu = E - E'$ is the energy transfer in the rest frame of the proton, and W^2 the invariant mass of all the final-state products of the proton after the interaction.
2. (5 pt) Show or argue that $Q^2 \geq 0$ for the electron scattering case.
3. Consider the quasi-elastic scattering process of the electron on the valence down-quark inside the proton, $e^- + d_v \longrightarrow e^- + d_v$. The incident electron beam has an energy of 10 GeV and the scattered electrons are observed at an angle of $\theta = 40$ degrees in the laboratory frame. Assume that the down-quark, d_v, carries 1/3 of the proton momentum and mass, i.e. there are no interactions with other valence quarks and there are no sea quarks present.
    a. (5 pt) Calculate Q^2 and ν for this process. You can make use of the recoil formula $E' = E/\left(1 + \frac{E}{M}(1 - \cos\theta)\right)$.
    b. (5 pt) Estimate the differential cross section of the quasi-elastic scattering process on the down-quark inside the proton in units of nb/sr. You can make use of the analogous cross section expression for the elastic scattering of an electron on a proton of mass M, as given by

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4(\theta/2)} \left(\frac{E'}{E}\right) \left(G_1(Q^2)\cos^2\left(\frac{\theta}{2}\right) + 2\tau G_2(Q^2)\sin^2\left(\frac{\theta}{2}\right)\right)$$

with

$$\tau = \frac{Q^2}{4M^2}$$

and G_1, G_2 the structure functions representing the squares of the electric and magnetic form factors of the proton. The fine-structure constant $\alpha = 1/137$.

1. PHYSICAL CONSTANTS

Table 1.1. Reviewed 2013 by P.J. Mohr (NIST). Mainly from the "CODATA Recommended Values of the Fundamental Physical Constants: 2010" by P.J. Mohr, B.N. Taylor, and D.B. Newell in Rev. Mod. Phys. **84**, 1527 (2012). The last group of constants (beginning with the Fermi coupling constant) comes from the Particle Data Group. The figures in parentheses after the values give the 1-standard-deviation uncertainties in the last digits; the corresponding fractional uncertainties in parts per 10^9 (ppb) are given in the last column. This set of constants (aside from the last group) is recommended for international use by CODATA (the Committee on Data for Science and Technology). The full 2010 CODATA set of constants may be found at `http://physics.nist.gov/constants`. See also P.J. Mohr and D.B. Newell, "Resource Letter FC-1: The Physics of Fundamental Constants," Am. J. Phys. **78**, 338 (2010).

Quantity	Symbol, equation	Value	Uncertainty (ppb)
speed of light in vacuum	c	$299\,792\,458$ m s^{-1}	exact*
Planck constant	h	$6.626\,069\,57(29)\times10^{-34}$ J s	44
Planck constant, reduced	$\hbar\equiv h/2\pi$	$1.054\,571\,726(47)\times10^{-34}$ J s	44
		$=6.582\,119\,28(15)\times10^{-22}$ MeV s	22
electron charge magnitude	e	$1.602\,176\,565(35)\times10^{-19}$ C $=4.803\,204\,50(11)\times10^{-10}$ esu	22, 22
conversion constant	$\hbar c$	$197.326\,9718(44)$ MeV fm	22
conversion constant	$(\hbar c)^2$	$0.389\,379\,338(17)$ GeV^2 mbarn	44
electron mass	m_e	$0.510\,998\,928(11)$ MeV$/c^2=9.109\,382\,91(40)\times10^{-31}$ kg	22, 44
proton mass	m_p	$938.272\,046(21)$ MeV$/c^2=1.672\,621\,777(74)\times10^{-27}$ kg	22, 44
		$=1.007\,276\,466\,812(90)$ u $=1836.152\,672\,45(75)\,m_e$	0.089, 0.41
deuteron mass	m_d	$1875.612\,859(41)$ MeV$/c^2$	22
unified atomic mass unit (u)	(mass ^{12}C atom)$/12=(1$ g$)/(N_A$ mol)	$931.494\,061(21)$ MeV$/c^2=1.660\,538\,921(73)\times10^{-27}$ kg	22, 44
permittivity of free space	$\epsilon_0=1/\mu_0c^2$	$8.854\,187\,817\ldots\times10^{-12}$ F m^{-1}	exact
permeability of free space	μ_0	$4\pi\times10^{-7}$ N A$^{-2}=12.566\,370\,614\ldots\times10^{-7}$ N A^{-2}	exact
fine-structure constant	$\alpha=e^2/4\pi\epsilon_0\hbar c$	$7.297\,352\,5698(24)\times10^{-3}=1/137.035\,999\,074(44)^{\dagger}$	0.32, 0.32
classical electron radius	$r_e=e^2/4\pi\epsilon_0m_ec^2$	$2.817\,940\,3267(27)\times10^{-15}$ m	0.97
(e^- Compton wavelength)$/2\pi$	$\lambda\!\!\!^{-}_e=\hbar/m_ec=r_e\alpha^{-1}$	$3.861\,592\,6800(25)\times10^{-13}$ m	0.65
Bohr radius ($m_{\text{nucleus}}=\infty$)	$a_\infty=4\pi\epsilon_0\hbar^2/m_ee^2=r_e\alpha^{-2}$	$0.529\,177\,210\,92(17)\times10^{-10}$ m	0.32
wavelength of 1 eV/c particle	$hc/(1$ eV$)$	$1.239\,841\,930(27)\times10^{-6}$ m	22
Rydberg energy	$hcR_\infty=m_ee^4/2(4\pi\epsilon_0)^2\hbar^2=m_ec^2\alpha^2/2$	$13.605\,692\,53(30)$ eV	22
Thomson cross section	$\sigma_T=8\pi r_e^2/3$	$0.665\,245\,8734(13)$ barn	1.9
Bohr magneton	$\mu_B=e\hbar/2m_e$	$5.788\,381\,8066(38)\times10^{-11}$ MeV T^{-1}	0.65
nuclear magneton	$\mu_N=e\hbar/2m_p$	$3.152\,451\,2605(22)\times10^{-14}$ MeV T^{-1}	0.71
electron cyclotron freq./field	$\omega^e_{\text{cycl}}/B=e/m_e$	$1.758\,820\,088(39)\times10^{11}$ rad s^{-1} T^{-1}	22
proton cyclotron freq./field	$\omega^p_{\text{cycl}}/B=e/m_p$	$9.578\,833\,58(21)\times10^{7}$ rad s^{-1} T^{-1}	22
gravitational constant‡	G_N	$6.673\,84(80)\times10^{-11}$ m^3 kg^{-1} s^{-2}	1.2×10^5
		$=6.708\,37(80)\times10^{-39}\,\hbar c\,(GeV/c^2)^{-2}$	1.2×10^5
standard gravitational accel.	g_N	$9.806\,65$ m s^{-2}	exact
Avogadro constant	N_A	$6.022\,141\,29(27)\times10^{23}$ mol^{-1}	44
Boltzmann constant	k	$1.380\,6488(13)\times10^{-23}$ J K^{-1}	910
		$=8.617\,3324(78)\times10^{-5}$ eV K^{-1}	910
molar volume, ideal gas at STP	$N_Ak(273.15$ K$)/(101\,325$ Pa$)$	$22.413\,968(20)\times10^{-3}$ m^3 mol^{-1}	910
Wien displacement law constant	$b=\lambda_{\max}T$	$2.897\,7721(26)\times10^{-3}$ m K	910
Stefan-Boltzmann constant	$\sigma=\pi^2k^4/60\hbar^3c^2$	$5.670\,373(21)\times10^{-8}$ W m^{-2} K^{-4}	3600
Fermi coupling constant**	$G_F/(\hbar c)^3$	$1.166\,378\,7(6)\times10^{-5}$ GeV^{-2}	500
weak-mixing angle	$\sin^2\widehat{\theta}(M_Z)$ ($\overline{\text{MS}}$)	$0.231\,26(5)^{\dagger\dagger}$	2.2×10^5
$W^\pm$ boson mass	m_W	$80.385(15)$ GeV$/c^2$	1.9×10^5
Z^0 boson mass	m_Z	$91.1876(21)$ GeV$/c^2$	2.3×10^4
strong coupling constant	$\alpha_s(m_Z)$	$0.1185(6)$	5.1×10^6

$\pi=3.141\,592\,653\,589\,793\,238$ e $=2.718\,281\,828\,459\,045\,235$ $\gamma=0.577\,215\,664\,901\,532\,861$

1 in $\equiv0.0254$ m   1 G $\equiv10^{-4}$ T   1 eV $=1.602\;176\;565(35)\times10^{-19}$ J kT at 300 K $=[38.681\;731(35)]^{-1}$ eV

1 Å $\equiv0.1$ nm   1 dyne $\equiv10^{-5}$ N   1 eV$/c^2=1.782\;661\;845(39)\times10^{-36}$ kg   0 °C $\equiv273.15$ K

1 barn $\equiv10^{-28}$ m^2 1 erg $\equiv10^{-7}$ J $2.997\;924\;58\times10^9$ esu $=1$ C   1 atmosphere $\equiv760$ Torr $\equiv101\;325$ Pa

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* The meter is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second.

† At $Q^2=0$. At $Q^2\approx m_W^2$ the value is $\sim1/128$.

‡ Absolute lab measurements of G_N have been made only on scales of about 1 cm to 1 m.

** See the discussion in Sec. 10, "Electroweak model and constraints on new physics."

†† The corresponding $\sin^2\theta$ for the effective angle is 0.23155(5).

LEPTONS

e

$J=\frac{1}{2}$

Mass $m=(548.57990946\pm0.00000022)\times10^{-6}$ u

Mass $m=0.510998928\pm0.000000011$ MeV

$\left|m_{e^+}-m_{e^-}\right|/m<8\times10^{-9}$, CL = 90%

$\left|q_{e^+}+q_{e^-}\right|/e<4\times10^{-8}$

Magnetic moment anomaly

$(g{-}2)/2=(1159.65218076\pm0.00000027)\times10^{-6}$

$(g_{e^+}-g_{e^-})\;/\;g_{\text{average}}=(-0.5\pm2.1)\times10^{-12}$

Electric dipole moment $d<10.5\times10^{-28}$ $e$cm, CL = 90%

Mean life $\tau>4.6\times10^{26}$ yr, CL = 90% [a]

μ

$J=\frac{1}{2}$

Mass $m=0.1134289267\pm0.0000000029$ u

Mass $m=105.6583715\pm0.0000035$ MeV

Mean life $\tau=(2.1969811\pm0.0000022)\times10^{-6}$ s

$\tau_{\mu^+}/\tau_{\mu^-}=1.00002\pm0.00008$

$c\tau=658.6384$ m

Magnetic moment anomaly $(g{-}2)/2=(11659209\pm6)\times10^{-10}$

$(g_{\mu^+}-g_{\mu^-})\;/\;g_{\text{average}}=(-0.11\pm0.12)\times10^{-8}$

Electric dipole moment $d=(-0.1\pm0.9)\times10^{-19}$ $e$cm

Decay parameters [b]

$\rho=0.74979\pm0.00026$

$\eta=0.057\pm0.034$

$\delta=0.75047\pm0.00034$

$\xi P_\mu=1.0009^{+0.0016}_{-0.0007}$ [c]

$\xi P_\mu\delta/\rho=1.0018^{+0.0016}_{-0.0007}$ [c]

$\xi'=1.00\pm0.04$

$\xi''=0.7\pm0.4$

$\alpha/A=(0\pm4)\times10^{-3}$

$\alpha'/A=(-10\pm20)\times10^{-3}$

$\beta/A=(4\pm6)\times10^{-3}$

$\beta'/A=(2\pm7)\times10^{-3}$

$\overline{\eta}=0.02\pm0.08$

μ^+ modes are charge conjugates of the modes below.

μ^- DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$e^-\overline{\nu}_e\nu_\mu$		$\approx 100\%$		53
$e^-\overline{\nu}_e\nu_\mu\gamma$		[d] (1.4 ± 0.4) %		53
$e^-\overline{\nu}_e\nu_\mu e^+e^-$		[e] $(3.4\pm0.4)\times10^{-5}$		53
		Lepton Family number (*LF*) violating modes		
$e^-\nu_e\overline{\nu}_\mu$	*LF*	[f] < 1.2 %	90%	53
$e^-\gamma$	*LF*	< 2.4 $\times10^{-12}$	90%	53
$e^-e^+e^-$	*LF*	< 1.0 $\times10^{-12}$	90%	53
$e^-2\gamma$	*LF*	< 7.2 $\times10^{-11}$	90%	53

$\boxed{\tau}$

$J = \frac{1}{2}$

Mass $m = 1776.82 \pm 0.16$ MeV

$(m_{\tau^+} - m_{\tau^-})/m_{\text{average}} < 2.8\times10^{-4}$, CL = 90%

Mean life $\tau = (290.6 \pm 1.0)\times10^{-15}$ s

$c\tau = 87.11$ μm

Magnetic moment anomaly > -0.052 and < 0.013, CL = 95%

$\text{Re}(d_\tau) = -0.220$ to 0.45×10^{-16} $e\,$cm, CL = 95%

$\text{Im}(d_\tau) = -0.250$ to 0.0080×10^{-16} $e\,$cm, CL = 95%

Weak dipole moment

$\text{Re}(d^w_\tau) < 0.50\times10^{-17}$ $e\,$cm, CL = 95%

$\text{Im}(d^w_\tau) < 1.1\times10^{-17}$ $e\,$cm, CL = 95%

Weak anomalous magnetic dipole moment

$\text{Re}(\alpha^w_\tau) < 1.1\times10^{-3}$, CL = 95%

$\text{Im}(\alpha^w_\tau) < 2.7\times10^{-3}$, CL = 95%

$\tau^\pm \to \pi^\pm K^0_S\nu_\tau$ (RATE DIFFERENCE) / (RATE SUM) = (-0.36 ± 0.25)%

Decay parameters

See the τ Particle Listings for a note concerning τ-decay parameters.

$\rho(e \text{ or } \mu) = 0.745 \pm 0.008$

$\rho(e) = 0.747 \pm 0.010$

$\rho(\mu) = 0.763 \pm 0.020$

$\xi(e \text{ or } \mu) = 0.985 \pm 0.030$

$\xi(e) = 0.994 \pm 0.040$

$\xi(\mu) = 1.030 \pm 0.059$

$\eta(e \text{ or } \mu) = 0.013 \pm 0.020$

$\eta(\mu) = 0.094 \pm 0.073$

$(\delta\xi)(e \text{ or } \mu) = 0.746 \pm 0.021$

$(\delta\xi)(e) = 0.734 \pm 0.028$

$(\delta\xi)(\mu) = 0.778 \pm 0.037$

$\xi(\pi) = 0.993 \pm 0.022$

$\xi(\rho) = 0.994 \pm 0.008$

$\xi(a_1) = 1.001 \pm 0.027$

$\xi(\text{all hadronic modes}) = 0.995 \pm 0.007$

τ^+ modes are charge conjugates of the modes below. "$h^\pm$" stands for $\pi^\pm$ or $K^\pm$. "ℓ" stands for e or μ. "Neutrals" stands for γ's and/or π^0's.

τ^- DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
		Modes with one charged particle		
particle$^-$ ≥ 0 neutrals $\geq 0K^0\nu_\tau$ ("1-prong")		(85.35 ± 0.07) %	S=1.3	–
particle$^-$ ≥ 0 neutrals $\geq 0K^0_L\nu_\tau$		(84.71 ± 0.08) %	S=1.3	–
$\mu^-\overline{\nu}_\mu\nu_\tau$	[g]	(17.41 ± 0.04) %	S=1.1	885
$\mu^-\overline{\nu}_\mu\nu_\tau\gamma$	[e]	$(3.6 \pm0.4)\times10^{-3}$		885
$e^-\overline{\nu}_e\nu_\tau$	[g]	(17.83 ± 0.04) %		888
$e^-\overline{\nu}_e\nu_\tau\gamma$	[e]	(1.75 ± 0.18) %		888
$h^- \geq 0K^0_L\,\nu_\tau$		(12.06 ± 0.06) %	S=1.2	883
$h^-\nu_\tau$		(11.53 ± 0.06) %	S=1.2	883
$\pi^-\nu_\tau$	[g]	(10.83 ± 0.06) %	S=1.2	883
$K^-\nu_\tau$	[g]	$(7.00 \pm0.10)\times10^{-3}$	S=1.1	820
$h^- \geq 1$ neutralsν_τ		(37.10 ± 0.10) %	S=1.2	–
$h^- \geq 1\pi^0\nu_\tau(\text{ex.}K^0)$		(36.58 ± 0.10) %	S=1.2	–
$h^-\pi^0\nu_\tau$		(25.95 ± 0.09) %	S=1.1	878
$\pi^-\pi^0\nu_\tau$	[g]	(25.52 ± 0.09) %	S=1.1	878
$\pi^-\pi^0\text{non-}\rho(770)\nu_\tau$		$(3.0 \pm3.2)\times10^{-3}$		878
$K^-\pi^0\nu_\tau$	[g]	$(4.29 \pm0.15)\times10^{-3}$		814

LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u}-d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^{\pm} \to \ell^{\pm}\nu\gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$		[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$		[c]	$(2.00 \pm0.25) \times 10^{-4}$		30
$e^+\nu_e$		[b]	$(1.230 \pm0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$		[c]	$(7.39 \pm0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$			$(1.036 \pm0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$			$(3.2 \pm0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$			$< 5 \times 10^{-6}$	90%	70
Lepton Family number (*LF*) or Lepton number (*L*) violating modes					
$\mu^+\overline{\nu}_e$	*L*	[d]	$< 1.5 \times 10^{-3}$	90%	30
$\mu^+\nu_e$	*LF*	[d]	$< 8.0 \times 10^{-3}$	90%	30
$\mu^- e^+ e^+ \nu$	*LF*		$< 1.6 \times 10^{-6}$	90%	30

π^0

$I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 134.9766 \pm 0.0006$ MeV (S = 1.1)
$m_{\pi^{\pm}} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV
Mean life $\tau = (8.52 \pm 0.18) \times 10^{-17}$ s (S = 1.2)
$c\tau = 25.5$ nm

For decay limits to particles which are not established, see the appropriate Search sections (A^0 (axion) and Other Light Boson (X^0) Searches, etc.).

π^0 DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ		(98.823 ± 0.034) %	S=1.5	67
$e^+e^-\gamma$		(1.174 ± 0.035) %	S=1.5	67
γpositronium		$(1.82 \pm0.29) \times 10^{-9}$		67
$e^+e^+e^-e^-$		$(3.34 \pm0.16) \times 10^{-5}$		67
e^+e^-		$(6.46 \pm0.33) \times 10^{-8}$		67
4γ		$< 2 \times 10^{-8}$	CL=90%	67
$\nu\overline{\nu}$		[e] $< 2.7 \times 10^{-7}$	CL=90%	67
$\nu_e\overline{\nu}_e$		$< 1.7 \times 10^{-6}$	CL=90%	67
$\nu_\mu\overline{\nu}_\mu$		$< 1.6 \times 10^{-6}$	CL=90%	67
$\nu_\tau\overline{\nu}_\tau$		$< 2.1 \times 10^{-6}$	CL=90%	67
$\gamma\nu\overline{\nu}$		$< 6 \times 10^{-4}$	CL=90%	67
Charge conjugation (*C*) or Lepton Family number (*LF*) violating modes				
3γ	*C*	$< 3.1 \times 10^{-8}$	CL=90%	67
μ^+e^-	*LF*	$< 3.8 \times 10^{-10}$	CL=90%	26
μ^-e^+	*LF*	$< 3.4 \times 10^{-9}$	CL=90%	26
$\mu^+e^- + \mu^-e^+$	*LF*	$< 3.6 \times 10^{-10}$	CL=90%	26

η

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 547.862 \pm 0.018$ MeV
Full width $\Gamma = 1.31 \pm 0.05$ keV

C-nonconserving decay parameters

$\pi^+\pi^-\pi^0$ left-right asymmetry $= (0.09^{+0.11}_{-0.12}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ sextant asymmetry $= (0.12^{+0.10}_{-0.11}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ quadrant asymmetry $= (-0.09 \pm 0.09) \times 10^{-2}$
$\pi^+\pi^-\gamma$ left-right asymmetry $= (0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ β (*D*-wave) $= -0.02 \pm 0.07$ (S = 1.3)

CP-nonconserving decay parameters

$\pi^+\pi^-e^+e^-$ decay-plane asymmetry $A_\phi = (-0.6 \pm 3.1) \times 10^{-2}$

Dalitz plot parameter

$\pi^0\pi^0\pi^0$ $\quad \alpha = -0.0315 \pm 0.0015$

η DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
	Neutral modes		
neutral modes	(72.12 ± 0.34) %	S=1.2	–
2γ	(39.41 ± 0.20) %	S=1.1	274
$3\pi^0$	(32.68 ± 0.23) %	S=1.1	179
$\pi^0 2\gamma$	$(\ 2.7\ \pm0.5\ ) \times 10^{-4}$	S=1.1	257
$2\pi^0 2\gamma$	$< 1.2 \times 10^{-3}$	CL=90%	238
4γ	$< 2.8 \times 10^{-4}$	CL=90%	274
invisible	$< 1.0 \times 10^{-4}$	CL=90%	–
	Charged modes		
charged modes	(28.10 ± 0.34) %	S=1.2	–
$\pi^+\pi^-\pi^0$	(22.92 ± 0.28) %	S=1.2	174
$\pi^+\pi^-\gamma$	$(\ 4.22\pm0.08)$ %	S=1.1	236
$e^+e^-\gamma$	$(\ 6.9\ \pm0.4\ ) \times 10^{-3}$	S=1.3	274
$\mu^+\mu^-\gamma$	$(\ 3.1\ \pm0.4\ ) \times 10^{-4}$		253
e^+e^-	$< 5.6 \times 10^{-6}$	CL=90%	274
$\mu^+\mu^-$	$(\ 5.8\ \pm0.8\ ) \times 10^{-6}$		253
$2e^+2e^-$	$(\ 2.40\pm0.22) \times 10^{-5}$		274
$\pi^+\pi^-e^+e^-(\gamma)$	$(\ 2.68\pm0.11) \times 10^{-4}$		235
$e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	CL=90%	253
$2\mu^+2\mu^-$	$< 3.6 \times 10^{-4}$	CL=90%	161
$\mu^+\mu^-\pi^+\pi^-$	$< 3.6 \times 10^{-4}$	CL=90%	113
$\pi^+e^-\overline{\nu}_e +$ c.c.	$< 1.7 \times 10^{-4}$	CL=90%	256
$\pi^+\pi^-2\gamma$	$< 2.1 \times 10^{-3}$		236
$\pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	CL=90%	174
$\pi^0\mu^+\mu^-\gamma$	$< 3 \times 10^{-6}$	CL=90%	210

Charge conjugation (*C*), Parity (*P*), Charge conjugation × Parity (*CP*), or Lepton Family number (*LF*) violating modes

$\pi^0\gamma$	*C*	< 9	$\times 10^{-5}$	CL=90%	257
$\pi^+\pi^-$	*P,CP*	< 1.3	$\times 10^{-5}$	CL=90%	236
$2\pi^0$	*P,CP*	< 3.5	$\times 10^{-4}$	CL=90%	238
$2\pi^0\gamma$	*C*	< 5	$\times 10^{-4}$	CL=90%	238
$3\pi^0\gamma$	*C*	< 6	$\times 10^{-5}$	CL=90%	179
3γ	*C*	< 1.6	$\times 10^{-5}$	CL=90%	274

$4\pi^0$	*P,CP*		< 6.9	$\times 10^{-7}$	CL=90%	40
$\pi^0e^+e^-$	*C*	[f]	< 4	$\times 10^{-5}$	CL=90%	257
$\pi^0\mu^+\mu^-$	*C*	[f]	< 5	$\times 10^{-6}$	CL=90%	210
$\mu^+e^- + \mu^-e^+$	*LF*		< 6	$\times 10^{-6}$	CL=90%	264

$f_0(500)$ or σ [g]
was $f_0(600)$

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = (400\text{–}550)$ MeV
Full width $\Gamma = (400\text{–}700)$ MeV

$f_0(500)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	dominant	–
$\gamma\gamma$	seen	–

$\rho(770)$ [h]

$I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 775.26 \pm 0.25$ MeV
Full width $\Gamma = 149.1 \pm 0.8$ MeV
$\Gamma_{ee} = 7.04 \pm 0.06$ keV

$\rho(770)$ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi\pi$		~ 100 %		363
		$\rho(770)^\pm$ decays		
$\pi^\pm\gamma$		$(\ 4.5\ \pm0.5\ ) \times 10^{-4}$	S=2.2	375
$\pi^\pm\eta$		$< 6 \times 10^{-3}$	CL=84%	152
$\pi^\pm\pi^+\pi^-\pi^0$		$< 2.0 \times 10^{-3}$	CL=84%	254
		$\rho(770)^0$ decays		
$\pi^+\pi^-\gamma$		$(\ 9.9\ \pm1.6\ ) \times 10^{-3}$		362
$\pi^0\gamma$		$(\ 6.0\ \pm0.8\ ) \times 10^{-4}$		376
$\eta\gamma$		$(\ 3.00\pm0.20\ ) \times 10^{-4}$		194
$\pi^0\pi^0\gamma$		$(\ 4.5\ \pm0.8\ ) \times 10^{-5}$		363
$\mu^+\mu^-$	[i]	$(\ 4.55\pm0.28\ ) \times 10^{-5}$		373
e^+e^-	[i]	$(\ 4.72\pm0.05\ ) \times 10^{-5}$		388
$\pi^+\pi^-\pi^0$		$(\ 1.01^{+0.54}_{-0.36}\pm0.34) \times 10^{-4}$		323
$\pi^+\pi^-\pi^+\pi^-$		$(\ 1.8\ \pm0.9\ ) \times 10^{-5}$		251
$\pi^+\pi^-\pi^0\pi^0$		$(\ 1.6\ \pm0.8\ ) \times 10^{-5}$		257
$\pi^0e^+e^-$		$< 1.2 \times 10^{-5}$	CL=90%	376

$\omega(782)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 782.65 \pm 0.12$ MeV (S = 1.9)
Full width $\Gamma = 8.49 \pm 0.08$ MeV
$\Gamma_{ee} = 0.60 \pm 0.02$ keV

ω(782) DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi^+\pi^-\pi^0$	(89.2 ± 0.7) %		327
$\pi^0\gamma$	(8.28 ± 0.28) %	S=2.1	380
$\pi^+\pi^-$	$(1.53^{+0.11}_{-0.13})$ %	S=1.2	366
neutrals (excluding $\pi^0\gamma$)	$(8 \ {}^{+8}_{-5}) \times 10^{-3}$	S=1.1	–
$\eta\gamma$	$(4.6 \pm 0.4) \times 10^{-4}$	S=1.1	200
$\pi^0 e^+ e^-$	$(7.7 \pm 0.6) \times 10^{-4}$		380
$\pi^0 \mu^+ \mu^-$	$(1.3 \pm 0.4) \times 10^{-4}$	S=2.1	349
$e^+ e^-$	$(7.28 \pm 0.14) \times 10^{-5}$	S=1.3	391
$\pi^+\pi^-\pi^0\pi^0$	$< 2 \times 10^{-4}$	CL=90%	262
$\pi^+\pi^-\gamma$	$< 3.6 \times 10^{-3}$	CL=95%	366
$\pi^+\pi^-\pi^+\pi^-$	$< 1 \times 10^{-3}$	CL=90%	256
$\pi^0\pi^0\gamma$	$(6.6 \pm 1.1) \times 10^{-5}$		367
$\eta\pi^0\gamma$	$< 3.3 \times 10^{-5}$	CL=90%	162
$\mu^+\mu^-$	$(9.0 \pm 3.1) \times 10^{-5}$		377
3γ	$< 1.9 \times 10^{-4}$	CL=95%	391

Charge conjugation (C) violating modes

$\eta\pi^0$	C	$< 2.1 \times 10^{-4}$	CL=90%	162
$2\pi^0$	C	$< 2.1 \times 10^{-4}$	CL=90%	367
$3\pi^0$	C	$< 2.3 \times 10^{-4}$	CL=90%	330

$\eta'(958)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 957.78 \pm 0.06$ MeV
Full width $\Gamma = 0.198 \pm 0.009$ MeV

η'(958) DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi^+\pi^-\eta$	(42.9 ± 0.7) %		232
$\rho^0\gamma$ (including non-resonant $\pi^+\pi^-\gamma$)	(29.1 ± 0.5) %		165
$\pi^0\pi^0\eta$	(22.2 ± 0.8) %		239
$\omega\gamma$	(2.75 ± 0.23) %		159
$\gamma\gamma$	(2.20 ± 0.08) %		479
$3\pi^0$	$(2.14 \pm 0.20) \times 10^{-3}$		430
$\mu^+\mu^-\gamma$	$(1.08 \pm 0.27) \times 10^{-4}$		467
$\pi^+\pi^-\mu^+\mu^-$	$< 2.2 \times 10^{-4}$	90%	401
$\pi^+\pi^-\pi^0$	$(3.8 \pm 0.4) \times 10^{-3}$		428
$\pi^0\rho^0$	< 4 %	90%	111
$2(\pi^+\pi^-)$	$< 2.4 \times 10^{-4}$	90%	372
$\pi^+\pi^- 2\pi^0$	$< 2.5 \times 10^{-3}$	90%	376
$2(\pi^+\pi^-)$ neutrals	< 1 %	95%	–
$2(\pi^+\pi^-)\pi^0$	$< 1.9 \times 10^{-3}$	90%	298
$2(\pi^+\pi^-)2\pi^0$	< 1 %	95%	197
$3(\pi^+\pi^-)$	$< 5 \times 10^{-4}$	90%	189
$\pi^+\pi^- e^+ e^-$	$(2.4 \ {}^{+1.3}_{-1.0}) \times 10^{-3}$		458
$\pi^+ e^- \nu_e +$ c.c.	$< 2.1 \times 10^{-4}$	90%	469
$\gamma e^+ e^-$	$< 9 \times 10^{-4}$	90%	479
$\pi^0\gamma\gamma$	$< 8 \times 10^{-4}$	90%	469
$4\pi^0$	$< 5 \times 10^{-4}$	90%	380
$e^+ e^-$	$< 2.1 \times 10^{-7}$	90%	479
invisible	$< 5 \times 10^{-4}$	90%	–

Charge conjugation (C), Parity (P), Lepton family number (LF) violating modes

$\pi^+\pi^-$	P,CP		$< 6 \times 10^{-5}$	90%	458
$\pi^0\pi^0$	P,CP		$< 4 \times 10^{-4}$	90%	459
$\pi^0 e^+ e^-$	C	[f]	$< 1.4 \times 10^{-3}$	90%	469
$\eta e^+ e^-$	C	[f]	$< 2.4 \times 10^{-3}$	90%	322
3γ	C		$< 1.0 \times 10^{-4}$	90%	479
$\mu^+\mu^-\pi^0$	C	[f]	$< 6.0 \times 10^{-5}$	90%	445
$\mu^+\mu^-\eta$	C	[f]	$< 1.5 \times 10^{-5}$	90%	273
$e\mu$	LF		$< 4.7 \times 10^{-4}$	90%	473

$f_0(980)$ [j]

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 990 \pm 20$ MeV
Full width $\Gamma = 40$ to 100 MeV

$f_0(980)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	dominant	476
$K\overline{K}$	seen	36
$\gamma\gamma$	seen	495

$a_0(980)$ [j]

$I^G(J^{PC}) = 1^-(0^{++})$

Mass $m = 980 \pm 20$ MeV
Full width $\Gamma = 50$ to 100 MeV

$a_0(980)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\pi$	dominant	319
$K\overline{K}$	seen	†
$\gamma\gamma$	seen	490

$\phi(1020)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1019.455 \pm 0.020$ MeV (S = 1.1)
Full width $\Gamma = 4.26 \pm 0.04$ MeV (S = 1.4)

$\phi(1020)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
K^+K^-	(48.9 ± 0.5) %	S=1.1	127
$K_L^0 K_S^0$	(34.2 ± 0.4) %	S=1.1	110
$\rho\pi + \pi^+\pi^-\pi^0$	(15.32 ± 0.32) %	S=1.1	–
$\eta\gamma$	(1.309 ± 0.024) %	S=1.2	363
$\pi^0\gamma$	$(1.27 \pm 0.06) \times 10^{-3}$		501
$\ell^+\ell^-$	—		510
e^+e^-	$(2.954 \pm 0.030) \times 10^{-4}$	S=1.1	510
$\mu^+\mu^-$	$(2.87 \pm 0.19) \times 10^{-4}$		499
ηe^+e^-	$(1.15 \pm 0.10) \times 10^{-4}$		363
$\pi^+\pi^-$	$(7.4 \pm 1.3) \times 10^{-5}$		490
$\omega\pi^0$	$(4.7 \pm 0.5) \times 10^{-5}$		171
$\omega\gamma$	< 5 %	CL=84%	209
$\rho\gamma$	$< 1.2 \times 10^{-5}$	CL=90%	215
$\pi^+\pi^-\gamma$	$(4.1 \pm 1.3) \times 10^{-5}$		490

$f_0(980)\gamma$	$(3.22 \pm 0.19) \times 10^{-4}$	S=1.1	29
$\pi^0\pi^0\gamma$	$(1.13 \pm 0.06) \times 10^{-4}$		492
$\pi^+\pi^-\pi^+\pi^-$	$(4.0 \; {}^{+2.8}_{-2.2}) \times 10^{-6}$		410
$\pi^+\pi^+\pi^-\pi^-\pi^0$	$< 4.6 \times 10^{-6}$	CL=90%	342
$\pi^0 e^+e^-$	$(1.12 \pm 0.28) \times 10^{-5}$		501
$\pi^0\eta\gamma$	$(7.27 \pm 0.30) \times 10^{-5}$	S=1.5	346
$a_0(980)\gamma$	$(7.6 \pm 0.6) \times 10^{-5}$		39
$K^0\overline{K}^0\gamma$	$< 1.9 \times 10^{-8}$	CL=90%	110
$\eta'(958)\gamma$	$(6.25 \pm 0.21) \times 10^{-5}$		60
$\eta\pi^0\pi^0\gamma$	$< 2 \times 10^{-5}$	CL=90%	293
$\mu^+\mu^-\gamma$	$(1.4 \pm 0.5) \times 10^{-5}$		499
$\rho\gamma\gamma$	$< 1.2 \times 10^{-4}$	CL=90%	215
$\eta\pi^+\pi^-$	$< 1.8 \times 10^{-5}$	CL=90%	288
$\eta\mu^+\mu^-$	$< 9.4 \times 10^{-6}$	CL=90%	321
Lepton Faminly number (LF) violating modes			
$e^\pm\mu^\mp$	*LF* $< 2 \times 10^{-6}$	CL=90%	504

$h_1(1170)$

$I^G(J^{PC}) = 0^-(1^{+-})$

Mass $m = 1170 \pm 20$ MeV
Full width $\Gamma = 360 \pm 40$ MeV

$h_1(1170)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	308

$b_1(1235)$

$I^G(J^{PC}) = 1^+(1^{+-})$

Mass $m = 1229.5 \pm 3.2$ MeV (S = 1.6)
Full width $\Gamma = 142 \pm 9$ MeV (S = 1.2)

$b_1(1235)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\omega\pi$	dominant		348
[D/S amplitude ratio = 0.277 ± 0.027]			
$\pi^\pm\gamma$	$(1.6 \pm 0.4) \times 10^{-3}$		607
$\eta\rho$	seen		†
$\pi^+\pi^+\pi^-\pi^0$	< 50 %	84%	535
$K^*(892)^\pm K^\mp$	seen		†
$(K\overline{K})^\pm\pi^0$	< 8 %	90%	248
$K_S^0 K_L^0 \pi^\pm$	< 6 %	90%	235
$K_S^0 K_S^0 \pi^\pm$	< 2 %	90%	235
$\phi\pi$	< 1.5 %	84%	147

STRANGE MESONS
$(S=\pm1,\ C=B=0)$

$K^+ = u\overline{s}$, $K^0 = d\overline{s}$, $\overline{K}^0 = \overline{d}s$, $K^- = \overline{u}s$, similarly for K^*'s

$K^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 493.677 \pm 0.016$ MeV [a] $(S = 2.8)$
Mean life $\tau = (1.2380 \pm 0.0021) \times 10^{-8}$ s $(S = 1.9)$
$c\tau = 3.712$ m

Slope parameter g [b]

(See Particle Listings for quadratic coefficients and alternative parametrization related to $\pi\pi$ scattering)

$K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ $g = -0.21134 \pm 0.00017$
$(g_+ - g_-) / (g_+ + g_-) = (-1.5 \pm 2.2) \times 10^{-4}$
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ $g = 0.626 \pm 0.007$
$(g_+ - g_-) / (g_+ + g_-) = (1.8 \pm 1.8) \times 10^{-4}$

$K^{\pm}$ decay form factors [c,d]

Assuming μ-e universality
$\lambda_+(K^+_{\mu3}) = \lambda_+(K^+_{e3}) = (2.97 \pm 0.05) \times 10^{-2}$
$\lambda_0(K^+_{\mu3}) = (1.95 \pm 0.12) \times 10^{-2}$

Not assuming μ-e universality
$\lambda_+(K^+_{e3}) = (2.98 \pm 0.05) \times 10^{-2}$
$\lambda_+(K^+_{\mu3}) = (2.96 \pm 0.17) \times 10^{-2}$
$\lambda_0(K^+_{\mu3}) = (1.96 \pm 0.13) \times 10^{-2}$

K_{e3} form factor quadratic fit
$\lambda'_+ (K^{\pm}_{e3})$ linear coeff. $= (2.49 \pm 0.17) \times 10^{-2}$
$\lambda''_+(K^{\pm}_{e3})$ quadratic coeff. $= (0.19 \pm 0.09) \times 10^{-2}$

K^+_{e3} $|f_S/f_+| = (-0.3^{+0.8}_{-0.7}) \times 10^{-2}$
K^+_{e3} $|f_T/f_+| = (-1.2 \pm 2.3) \times 10^{-2}$
$K^+_{\mu3}$ $|f_S/f_+| = (0.2 \pm 0.6) \times 10^{-2}$
$K^+_{\mu3}$ $|f_T/f_+| = (-0.1 \pm 0.7) \times 10^{-2}$
$K^+ \rightarrow e^+\nu_e\gamma$ $|F_A + F_V| = 0.133 \pm 0.008$ $(S = 1.3)$
$K^+ \rightarrow \mu^+\nu_\mu\gamma$ $|F_A + F_V| = 0.165 \pm 0.013$
$K^+ \rightarrow e^+\nu_e\gamma$ $|F_A - F_V| < 0.49$
$K^+ \rightarrow \mu^+\nu_\mu\gamma$ $|F_A - F_V| = -0.24$ to 0.04, CL = 90%

Charge Radius

$\langle r \rangle = 0.560 \pm 0.031$ fm

***CP* violation parameters**

$\Delta(K^{\pm}_{\pi ee}) = (-2.2 \pm 1.6) \times 10^{-2}$
$\Delta(K^{\pm}_{\pi\mu\mu}) = 0.010 \pm 0.023$
$\Delta(K^{\pm}_{\pi\pi\gamma}) = (0.0 \pm 1.2) \times 10^{-3}$
$A_{FB}(K^{\pm}_{\pi\mu\mu}) = \frac{\Gamma(cos(\theta_{K\mu})>0)-\Gamma(cos(\theta_{K\mu})<0)}{\Gamma(cos(\theta_{K\mu})>0)+\Gamma(cos(\theta_{K\mu})<0)} < 2.3 \times 10^{-2}$, CL = 90%

***T* violation parameters**

$K^+ \rightarrow \pi^0\mu^+\nu_\mu$ $P_T = (-1.7 \pm 2.5) \times 10^{-3}$
$K^+ \rightarrow \mu^+\nu_\mu\gamma$ $P_T = (-0.6 \pm 1.9) \times 10^{-2}$
$K^+ \rightarrow \pi^0\mu^+\nu_\mu$ $\text{Im}(\xi) = -0.006 \pm 0.008$

K^- modes are charge conjugates of the modes below.

K^+ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Leptonic and semileptonic modes			
$e^+\nu_e$	$(1.581 \pm 0.008) \times 10^{-5}$		247
$\mu^+\nu_\mu$	(63.55 ± 0.11) %	S=1.2	236
$\pi^0 e^+\nu_e$	(5.07 ± 0.04) %	S=2.1	228
Called K^+_{e3}.			
$\pi^0\mu^+\nu_\mu$	(3.353 ± 0.034) %	S=1.8	215
Called $K^+_{\mu3}$.			
$\pi^0\pi^0 e^+\nu_e$	$(2.2 \pm 0.4) \times 10^{-5}$		206
$\pi^+\pi^- e^+\nu_e$	$(4.254 \pm 0.032) \times 10^{-5}$		203
$\pi^+\pi^-\mu^+\nu_\mu$	$(1.4 \pm 0.9) \times 10^{-5}$		151
$\pi^0\pi^0\pi^0 e^+\nu_e$	$< 3.5 \times 10^{-6}$	CL=90%	135
Hadronic modes			
$\pi^+\pi^0$	(20.66 ± 0.08) %	S=1.2	205
$\pi^+\pi^0\pi^0$	(1.761 ± 0.022) %	S=1.1	133
$\pi^+\pi^+\pi^-$	(5.59 ± 0.04) %	S=1.3	125
Leptonic and semileptonic modes with photons			
$\mu^+\nu_\mu\gamma$	[e,f] $(6.2 \pm 0.8) \times 10^{-3}$		236
$\mu^+\nu_\mu\gamma(\text{SD}^+)$	[c,g] $(1.33 \pm 0.22) \times 10^{-5}$		–
$\mu^+\nu_\mu\gamma(\text{SD}^+\text{INT})$	[c,g] $< 2.7 \times 10^{-5}$	CL=90%	–
$\mu^+\nu_\mu\gamma(\text{SD}^- + \text{SD}^-\text{INT})$	[c,g] $< 2.6 \times 10^{-4}$	CL=90%	–

$e^+ \nu_e \gamma$		$(9.4 \pm 0.4) \times 10^{-6}$		247
$\pi^0 e^+ \nu_e \gamma$	[e,f]	$(2.56 \pm 0.16) \times 10^{-4}$		228
$\pi^0 e^+ \nu_e \gamma$(SD)	[c,g]	$< 5.3 \times 10^{-5}$	CL=90%	228
$\pi^0 \mu^+ \nu_\mu \gamma$	[e,f]	$(1.25 \pm 0.25) \times 10^{-5}$		215
$\pi^0 \pi^0 e^+ \nu_e \gamma$		$< 5 \times 10^{-6}$	CL=90%	206

Hadronic modes with photons or $\ell \overline{\ell}$ pairs

$\pi^+ \pi^0 \gamma$(INT)		$(-4.2 \pm 0.9) \times 10^{-6}$		–
$\pi^+ \pi^0 \gamma$(DE)	[e,h]	$(6.0 \pm 0.4) \times 10^{-6}$		205
$\pi^+ \pi^0 \pi^0 \gamma$	[e,f]	$(7.6 \, {}^{+6.0}_{-3.0}) \times 10^{-6}$		133
$\pi^+ \pi^+ \pi^- \gamma$	[e,f]	$(1.04 \pm 0.31) \times 10^{-4}$		125
$\pi^+ \gamma \gamma$	[e]	$(1.10 \pm 0.32) \times 10^{-6}$		227
$\pi^+ 3\gamma$	[e]	$< 1.0 \times 10^{-4}$	CL=90%	227
$\pi^+ e^+ e^- \gamma$		$(1.19 \pm 0.13) \times 10^{-8}$		227

Leptonic modes with $\ell \overline{\ell}$ pairs

$e^+ \nu_e \nu \overline{\nu}$	$< 6 \times 10^{-5}$	CL=90%	247
$\mu^+ \nu_\mu \nu \overline{\nu}$	$< 6.0 \times 10^{-6}$	CL=90%	236
$e^+ \nu_e e^+ e^-$	$(2.48 \pm 0.20) \times 10^{-8}$		247
$\mu^+ \nu_\mu e^+ e^-$	$(7.06 \pm 0.31) \times 10^{-8}$		236
$e^+ \nu_e \mu^+ \mu^-$	$(1.7 \pm 0.5) \times 10^{-8}$		223
$\mu^+ \nu_\mu \mu^+ \mu^-$	$< 4.1 \times 10^{-7}$	CL=90%	185

Lepton Family number (*LF*), Lepton number (*L*), $\Delta S = \Delta Q$ (*SQ*) violating modes, or $\Delta S = 1$ weak neutral current (*S1*) modes

$\pi^+ \pi^+ e^- \overline{\nu}_e$	*SQ*		$< 1.3 \times 10^{-8}$	CL=90%	203
$\pi^+ \pi^+ \mu^- \overline{\nu}_\mu$	*SQ*		$< 3.0 \times 10^{-6}$	CL=95%	151
$\pi^+ e^+ e^-$	*S1*		$(3.00 \pm 0.09) \times 10^{-7}$		227
$\pi^+ \mu^+ \mu^-$	*S1*		$(9.4 \pm 0.6) \times 10^{-8}$	S=2.6	172
$\pi^+ \nu \overline{\nu}$	*S1*		$(1.7 \pm 1.1) \times 10^{-10}$		227
$\pi^+ \pi^0 \nu \overline{\nu}$	*S1*		$< 4.3 \times 10^{-5}$	CL=90%	205
$\mu^- \nu e^+ e^+$	*LF*		$< 2.1 \times 10^{-8}$	CL=90%	236
$\mu^+ \nu_e$	*LF*	[i]	$< 4 \times 10^{-3}$	CL=90%	236
$\pi^+ \mu^+ e^-$	*LF*		$< 1.3 \times 10^{-11}$	CL=90%	214
$\pi^+ \mu^- e^+$	*LF*		$< 5.2 \times 10^{-10}$	CL=90%	214
$\pi^- \mu^+ e^+$	*L*		$< 5.0 \times 10^{-10}$	CL=90%	214
$\pi^- e^+ e^+$	*L*		$< 6.4 \times 10^{-10}$	CL=90%	227
$\pi^- \mu^+ \mu^+$	*L*	[i]	$< 1.1 \times 10^{-9}$	CL=90%	172
$\mu^+ \overline{\nu}_e$	*L*	[i]	$< 3.3 \times 10^{-3}$	CL=90%	236
$\pi^0 e^+ \overline{\nu}_e$	*L*		$< 3 \times 10^{-3}$	CL=90%	228
$\pi^+ \gamma$		[j]	$< 2.3 \times 10^{-9}$	CL=90%	227

K^0

$I(J^P) = \frac{1}{2}(0^-)$

50% K_S, 50% K_L

Mass $m = 497.614 \pm 0.024$ MeV (S = 1.6)

$m_{K^0} - m_{K^\pm} = 3.937 \pm 0.028$ MeV (S = 1.8)

Mean Square Charge Radius

$\langle r^2 \rangle = -0.077 \pm 0.010$ fm^2

***T*-violation parameters in K^0-$\overline{K}^0$ mixing** [d]

Asymmetry A_T in K^0-$\overline{K}^0$ mixing $= (6.6 \pm 1.6) \times 10^{-3}$

***CPT*-violation parameters** [d]

Re $\delta = (2.5 \pm 2.3) \times 10^{-4}$

Im $\delta = (-1.5 \pm 1.6) \times 10^{-5}$

Re(y), K_{e3} parameter $= (0.4 \pm 2.5) \times 10^{-3}$

Re(x_-), K_{e3} parameter $= (-2.9 \pm 2.0) \times 10^{-3}$

$\left| m_{K^0} - m_{\overline{K}^0} \right| / m_{\text{average}} < 6 \times 10^{-19}$, CL = 90% [k]

$(\Gamma_{K^0} - \Gamma_{\overline{K}^0}) / m_{\text{average}} = (8 \pm 8) \times 10^{-18}$

Tests of $\Delta S = \Delta Q$

Re(x_+), K_{e3} parameter $= (-0.9 \pm 3.0) \times 10^{-3}$

K^0_S

$I(J^P) = \frac{1}{2}(0^-)$

Mean life $\tau = (0.8954 \pm 0.0004) \times 10^{-10}$ s (S = 1.1) Assuming *CPT*

Mean life $\tau = (0.89564 \pm 0.00033) \times 10^{-10}$ s Not assuming *CPT*

$c\tau = 2.6844$ cm Assuming *CPT*

***CP*-violation parameters** [l]

Im(η_{+-0}) $= -0.002 \pm 0.009$

Im(η_{000}) $= (-0.1 \pm 1.6) \times 10^{-2}$

$\left| \eta_{000} \right| = \left| A(K^0_S \to 3\pi^0) / A(K^0_L \to 3\pi^0) \right| < 0.018$, CL = 90%

CP asymmetry *A* in $\pi^+ \pi^- e^+ e^- = (-0.4 \pm 0.8)\%$

K^0_S DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
		Hadronic modes		
$\pi^0\pi^0$		(30.69 ± 0.05) %		209
$\pi^+\pi^-$		(69.20 ± 0.05) %		206
$\pi^+\pi^-\pi^0$		$(3.5\ ^{+1.1}_{-0.9}) \times 10^{-7}$		133
		Modes with photons or $\ell\bar{\ell}$ pairs		
$\pi^+\pi^-\gamma$	[f,n]	$(1.79\pm0.05) \times 10^{-3}$		206
$\pi^+\pi^-e^+e^-$		$(4.79\pm0.15) \times 10^{-5}$		206
$\pi^0\gamma\gamma$	[n]	$(4.9\ \pm1.8\ ) \times 10^{-8}$		231
$\gamma\gamma$		$(2.63\pm0.17) \times 10^{-6}$	S=3.0	249
		Semileptonic modes		
$\pi^\pm e^\mp \nu_e$	[o]	$(7.04\pm0.08) \times 10^{-4}$		229
		***CP* violating (*CP*) and $\Delta S = 1$ weak neutral current (*S1*) modes**		
$3\pi^0$	*CP*	$< 1.2 \quad \times 10^{-7}$	CL=90%	139
$\mu^+\mu^-$	*S1*	$< 9 \quad \times 10^{-9}$	CL=90%	225
e^+e^-	*S1*	$< 9 \quad \times 10^{-9}$	CL=90%	249
$\pi^0e^+e^-$	*S1* [n]	$(3.0\ ^{+1.5}_{-1.2}) \times 10^{-9}$		230
$\pi^0\mu^+\mu^-$	*S1*	$(2.9\ ^{+1.5}_{-1.2}) \times 10^{-9}$		177

$\boxed{K^0_L}$

$I(J^P) = \frac{1}{2}(0^-)$

$m_{K_L} - m_{K_S}$
$= (0.5293 \pm 0.0009) \times 10^{10}\ \hbar\ s^{-1}$ (S = 1.3) Assuming *CPT*
$= (3.484 \pm 0.006) \times 10^{-12}$ MeV Assuming *CPT*
$= (0.5289 \pm 0.0010) \times 10^{10}\ \hbar\ s^{-1}$ Not assuming *CPT*
Mean life $\tau = (5.116 \pm 0.021) \times 10^{-8}$ s (S = 1.1)
$c\tau = 15.34$ m

Slope parameter g [b]

(See Particle Listings for quadratic coefficients)
$K^0_L \to \pi^+\pi^-\pi^0$: $g = 0.678 \pm 0.008$ (S = 1.5)

K_L decay form factors [d]

Linear parametrization assuming μ-e universality
$\lambda_+(K^0_{\mu3}) = \lambda_+(K^0_{e3}) = (2.82 \pm 0.04) \times 10^{-2}$ (S = 1.1)
$\lambda_0(K^0_{\mu3}) = (1.38 \pm 0.18) \times 10^{-2}$ (S = 2.2)

Quadratic parametrization assuming μ-e universality
$\lambda'_+(K^0_{\mu3}) = \lambda'_+(K^0_{e3}) = (2.40 \pm 0.12) \times 10^{-2}$ (S = 1.2)
$\lambda''_+(K^0_{\mu3}) = \lambda''_+(K^0_{e3}) = (0.20 \pm 0.05) \times 10^{-2}$ (S = 1.2)
$\lambda_0(K^0_{\mu3}) = (1.16 \pm 0.09) \times 10^{-2}$ (S = 1.2)

Pole parametrization assuming μ-e universality
$M^\mu_V\ (K^0_{\mu3}) = M^e_V\ (K^0_{e3}) = 878 \pm 6$ MeV (S = 1.1)
$M^\mu_S\ (K^0_{\mu3}) = 1252 \pm 90$ MeV (S = 2.6)

Dispersive parametrization assuming μ-e universality
$\Lambda_+ = (0.251 \pm 0.006) \times 10^{-1}$ (S = 1.5)
$\ln(C) = (1.75 \pm 0.18) \times 10^{-1}$ (S = 2.0)
K^0_{e3} $|f_S/f_+| = (1.5^{+1.4}_{-1.6}) \times 10^{-2}$
K^0_{e3} $|f_T/f_+| = (5^{+4}_{-5}) \times 10^{-2}$
$K^0_{\mu3}$ $|f_T/f_+| = (12 \pm 12) \times 10^{-2}$
$K_L \to \ell^+\ell^-\gamma$, $K_L \to \ell^+\ell^-\ell'^+\ell'^-$: $\alpha_{K^*} = -0.205 \pm 0.022$ (S = 1.8)
$K^0_L \to \ell^+\ell^-\gamma$, $K^0_L \to \ell^+\ell^-\ell'^+\ell'^-$: $\alpha_{DIP} = -1.69 \pm 0.08$ (S = 1.7)
$K_L \to \pi^+\pi^-e^+e^-$: $a_1/a_2 = -0.737 \pm 0.014$ GeV^2
$K_L \to \pi^0 2\gamma$: $a_V = -0.43 \pm 0.06$ (S = 1.5)

CP-violation parameters [l]

$A_L = (0.332 \pm 0.006)\%$
$|\eta_{00}| = (2.220 \pm 0.011) \times 10^{-3}$ (S = 1.8)
$|\eta_{+-}| = (2.232 \pm 0.011) \times 10^{-3}$ (S = 1.8)
$|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$ (S = 1.8)
$|\eta_{00}/\eta_{+-}| = 0.9950 \pm 0.0007$ [p] (S = 1.6)
$\mathrm{Re}(\epsilon'/\epsilon) = (1.66 \pm 0.23) \times 10^{-3}$ [p] (S = 1.6)

Assuming *CPT*
$\phi_{+-} = (43.51 \pm 0.05)^\circ$ (S = 1.2)
$\phi_{00} = (43.52 \pm 0.05)^\circ$ (S = 1.3)
$\phi_\epsilon = \phi_{SW} = (43.52 \pm 0.05)^\circ$ (S = 1.2)
$\mathrm{Im}(\epsilon'/\epsilon) = -(\phi_{00} - \phi_{+-})/3 = (-0.002 \pm 0.005)^\circ$ (S = 1.7)

Not assuming *CPT*

$\phi_{+-} = (43.4 \pm 0.5)°$ (S = 1.2)

$\phi_{00} = (43.7 \pm 0.6)°$ (S = 1.2)

$\phi_{\epsilon} = (43.5 \pm 0.5)°$ (S = 1.3)

CP asymmetry *A* in $K_L^0 \rightarrow \pi^+\pi^-e^+e^- = (13.7 \pm 1.5)\%$

β_{CP} from $K_L^0 \rightarrow e^+e^-e^+e^- = -0.19 \pm 0.07$

γ_{CP} from $K_L^0 \rightarrow e^+e^-e^+e^- = 0.01 \pm 0.11$ (S = 1.6)

j for $K_L^0 \rightarrow \pi^+\pi^-\pi^0 = 0.0012 \pm 0.0008$

f for $K_L^0 \rightarrow \pi^+\pi^-\pi^0 = 0.004 \pm 0.006$

$|\eta_{+-\gamma}| = (2.35 \pm 0.07) \times 10^{-3}$

$\phi_{+-\gamma} = (44 \pm 4)°$

$|\epsilon'_{+-\gamma}|/\epsilon < 0.3$, CL = 90%

$|g_{E1}|$ for $K_L^0 \rightarrow \pi^+\pi^-\gamma < 0.21$, CL = 90%

T-violation parameters

Im(ξ) in $K_{\mu 3}^0 = -0.007 \pm 0.026$

CPT invariance tests

$\phi_{00} - \phi_{+-} = (0.34 \pm 0.32)°$

$\text{Re}(\frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00}) - \frac{A_L}{2} = (-3 \pm 35) \times 10^{-6}$

$\Delta S = -\Delta Q$ in $K_{\ell 3}^0$ decay

Re $x = -0.002 \pm 0.006$

Im $x = 0.0012 \pm 0.0021$

K_L^0 DECAY MODES			Fraction (Γ_i/Γ)	Scale factor/ Confidence level	*p* (MeV/c)
Semileptonic modes					
$\pi^{\pm}e^{\mp}\nu_e$ Called K_{e3}^0.		[o]	(40.55 ±0.11) %	S=1.7	229
$\pi^{\pm}\mu^{\mp}\nu_{\mu}$ Called $K_{\mu 3}^0$.		[o]	(27.04 ±0.07) %	S=1.1	216
$(\pi\mu\text{atom})\nu$			(1.05 ±0.11) × 10^{-7}		188
$\pi^0\pi^{\pm}e^{\mp}\nu$		[o]	(5.20 ±0.11) × 10^{-5}		207
$\pi^{\pm}e^{\mp}\nu e^+e^-$		[o]	(1.26 ±0.04) × 10^{-5}		229
Hadronic modes, including Charge conjugation×Parity Violating (*CPV*) modes					
$3\pi^0$			(19.52 ±0.12) %	S=1.6	139
$\pi^+\pi^-\pi^0$			(12.54 ±0.05) %		133
$\pi^+\pi^-$	*CPV*	[q]	(1.967±0.010) × 10^{-3}	S=1.5	206
$\pi^0\pi^0$	*CPV*		(8.64 ±0.06) × 10^{-4}	S=1.8	209
Semileptonic modes with photons					
$\pi^{\pm}e^{\mp}\nu_e\gamma$		[f,o,r]	(3.79 ±0.06) × 10^{-3}		229
$\pi^{\pm}\mu^{\mp}\nu_{\mu}\gamma$			(5.65 ±0.23) × 10^{-4}		216
Hadronic modes with photons or $\ell\bar{\ell}$ pairs					
$\pi^0\pi^0\gamma$			< 2.43 × 10^{-7}	CL=90%	209
$\pi^+\pi^-\gamma$		[f,r]	(4.15 ±0.15) × 10^{-5}	S=2.8	206
$\pi^+\pi^-\gamma$(DE)			(2.84 ±0.11) × 10^{-5}	S=2.0	206
$\pi^0 2\gamma$		[r]	(1.273±0.033) × 10^{-6}		231
$\pi^0\gamma e^+e^-$			(1.62 ±0.17) × 10^{-8}		230
Other modes with photons or $\ell\bar{\ell}$ pairs					
2γ			(5.47 ±0.04) × 10^{-4}	S=1.1	249
3γ			< 7.4 × 10^{-8}	CL=90%	249
$e^+e^-\gamma$			(9.4 ±0.4) × 10^{-6}	S=2.0	249
$\mu^+\mu^-\gamma$			(3.59 ±0.11) × 10^{-7}	S=1.3	225
$e^+e^-\gamma\gamma$		[r]	(5.95 ±0.33) × 10^{-7}		249
$\mu^+\mu^-\gamma\gamma$		[r]	(1.0 $^{+0.8}_{-0.6}$) × 10^{-8}		225
Charge conjugation × Parity (*CP*) or Lepton Family number (*LF*) violating modes, or $\Delta S = 1$ weak neutral current (*S1*) modes					
$\mu^+\mu^-$	*S1*		(6.84 ±0.11) × 10^{-9}		225
e^+e^-	*S1*		(9 $^{+6}_{-4}$) × 10^{-12}		249
$\pi^+\pi^-e^+e^-$	*S1*	[r]	(3.11 ±0.19) × 10^{-7}		206
$\pi^0\pi^0e^+e^-$	*S1*		< 6.6 × 10^{-9}	CL=90%	209
$\pi^0\pi^0\mu^+\mu^-$	*S1*		< 9.2 × 10^{-11}	CL=90%	57
$\mu^+\mu^-e^+e^-$	*S1*		(2.69 ±0.27) × 10^{-9}		225

Citation: J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012) and 2013 partial update for the 2014 edition (URL: http://pdg.lbl.gov)

CHARMED MESONS
$(C = \pm1)$

$D^+ = c\overline{d}$, $D^0 = c\overline{u}$, $\overline{D}^0 = \overline{c}u$, $D^- = \overline{c}d$, similarly for D^*'s

$D^\pm$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1869.62 \pm 0.15$ MeV (S = 1.1)
Mean life $\tau = (1040 \pm 7) \times 10^{-15}$ s
$c\tau = 311.8\ \mu$m

c-quark decays

$\Gamma(c \rightarrow\ \ell^+ \text{anything})/\Gamma(c \rightarrow\ \text{anything}) = 0.096 \pm 0.004$ [a]
$\Gamma(c \rightarrow\ D^*(2010)^+ \text{anything})/\Gamma(c \rightarrow\ \text{anything}) = 0.255 \pm 0.017$

***CP*-violation decay-rate asymmetries**

$A_{CP}(\mu^\pm\nu) = (8 \pm 8)\%$
$A_{CP}(K^0_S\pi^\pm) = (-0.41 \pm 0.09)\%$
$A_{CP}(K^\mp 2\pi^\pm) = (-0.1 \pm 1.0)\%$
$A_{CP}(K^\mp\pi^\pm\pi^\pm\pi^0) = (1.0 \pm 1.3)\%$
$A_{CP}(K^0_S\pi^\pm\pi^0) = (0.3 \pm 0.9)\%$
$A_{CP}(K^0_S\pi^\pm\pi^+\pi^-) = (0.1 \pm 1.3)\%$
$A_{CP}(\pi^\pm\pi^0) = (2.9 \pm 2.9)\%$
$A_{CP}(\pi^\pm\eta) = (1.0 \pm 1.5)\%$ (S = 1.4)
$A_{CP}(\pi^\pm\eta'(958)) = (-0.5 \pm 1.2)\%$ (S = 1.1)
$A_{CP}(K^0_S K^\pm) = (-0.23 \pm 0.31)\%$
$A_{CP}(K^+K^-\pi^\pm) = (0.3 \pm 0.6)\%$
$A_{CP}(K^\pm K^{*0}) = (0.1 \pm 1.3)\%$
$A_{CP}(\phi\pi^\pm) = (0.42 \pm 0.28)\%$
$A_{CP}(K^\pm K^*_0(1430)^0) = (8^{+7}_{-6})\%$
$A_{CP}(K^\pm K^*_2(1430)^0) = (43^{+20}_{-26})\%$
$A_{CP}(K^\pm K^*_0(800)) = (-12^{+18}_{-13})\%$
$A_{CP}(a_0(1450)^0\pi^\pm) = (-19^{+14}_{-16})\%$
$A_{CP}(\phi(1680)\pi^\pm) = (-9 \pm 26)\%$
$A_{CP}(\pi^+\pi^-\pi^\pm) = (-2 \pm 4)\%$
$A_{CP}(K^0_S K^\pm\pi^+\pi^-) = (-4 \pm 7)\%$
$A_{CP}(K^\pm\pi^0) = (-4 \pm 11)\%$

***T*-violation decay-rate asymmetry**

$A_T(K^0_S K^\pm\pi^+\pi^-) = (-12 \pm 11) \times 10^{-3}$ [b]