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HIGHLIGHTS ON THE 2006 PDG EDITION, KAON SECTIONS*

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I overview the changes and the new results in the 2006 Particle Data Group Edition of the kaon sections. I also review the major improvements in the whole PDG.

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1. Introduction and general informations about the PDG

Due to the overwhelming experimental and theoretical efforts, the 2006 Particle Data Group (PDG) Edition [1] has several changes compared to the previous ones. It is a pleasure to discuss it at "The Final Euridice Meeting" in Kazimierz since substantial contributions have come from the Euridice Collaboration. In fact some highlights of the 2006 PDG Edition come from the flavour physics and in particular from the kaon physics. In this last subject the Euridice Collaboration has been very active. I will give first a general introduction on the PDG and then I will go in some details of the 2006 edition.

Michael Barnett is PDG coordinator, in the 2006 we have celebrated the PDG 50th Anniversary with a beautiful workshop and festivities. It has been impressive to see the progress in the different fields.

I have been responsible for the kaon sessions since the end of 2003 jointly with Tom Trippe: he is the "overseer". Many experimentalists from KLOE, NA48, KTEV, ISTRA help us as well as theorists from the whole Euridice Collaboration. Before me, our loved and appreciated colleague Gianni Conforto was helping Tom. So far only routine: we read the experimental and theory papers and we try to do our best. Of course, we have some ideas

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how to change the next editions but we are pleased to hear criticism. The published version comes out every two years while we have the web-updated every year. In this last edition we have analyzed 41 papers plus more than 20 reviews and theory papers. Overall we had 113 new measurements for these sections.

2. Highlights of the 2006 PDG Edition

In the whole 2006 PDG Edition we have analyzed **689 new papers with 2633 new measurements, 110 reviews (most are revised or new)**. I am repeating here how Michael Barnett has summarized the Highlights on the 2006 PDG Edition with

- Complete rearrangement of the neutrino listings, including a neutrino mixing section that now contains measurements of the mixing angles and mass differences in the three-neutrino framework.
- Latest from B-meson physics: 186 papers with 780 measurements: CP violation, mixing, polarization in B decays, determination of $V(cb)$ and $V(ub)$ *etc.*
- Many new results in the sections on strongly-decaying mesons; 140 papers with 717 measurements.
- Latest high precision $K(L)$ branching ratios and CP violation amplitudes.
- Major improvements in $K(l3)$ form factors data and review.
- New review on the "CKM quark-mixing matrix".
- New reviews on "Determination of $V(cb), V(ub)$," and "$V(ud), V(us)$, Cabibbo angle and CKM unitarity".
- New review on muon anomalous magnetic moment $(g-2)$.
- New review on extra-dimensions.
- Updated astroparticle physics reviews including WMAP3 results.
- Major update of the top quark review.
- Revised "Quark Model" review with new section on lattice QCD.
- New and revised sections in Particle Detectors review, especially on photodetectors and collider superconducting magnets.

3. The K^+ lifetime and the KLOE measurement

One way to start to understand how a single measurement can change dramatically the full K^+-section is by looking the actual determination of the K^+ lifetime, τ_{K^+}. As we see in Fig. 1 this is a result of the averaging over two different ways to measure τ_{K^+}: in flight (left bump) or at rest (the other 4 data points).

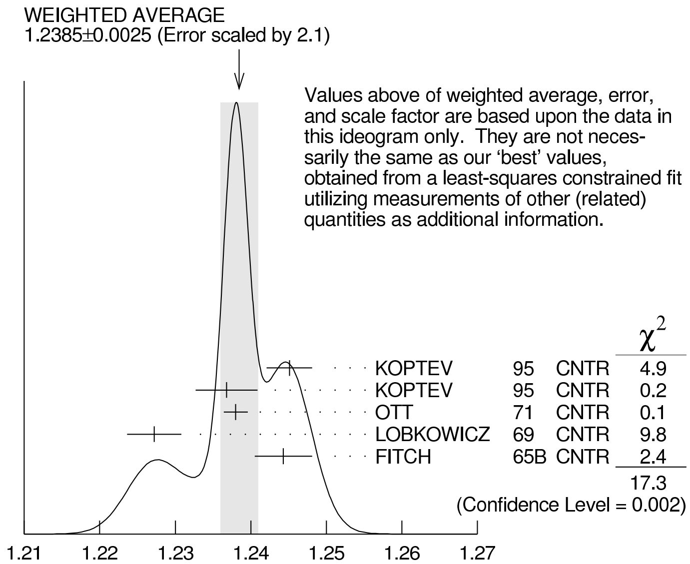

Fig. 1. $K^{\pm}$-mean life (10^{-8} s). The actual PDG determination of τ_{K^+} is obtained as a result of an averaging of two kinds of measurements: in flight (left bump) or at rest (the other 4 data points).

The preliminary KLOE data

$$\tau_{K^+} = 12.377 \pm 0.044 \pm 0.065 \text{ ns}$$

at the moment is sitting over our average value [2].

4. K^+: V_{us} related measurements

It is interesting to explain the reasons why we did not include the determination of the $B(K^+ \to \pi^0 e^+ \nu)$ by BNL 865 [3] in the 2004 PDG Edition [4]. Before this paper, there was a 2.2 σ's discrepancy between the V_{us} determination obtained from the PDG value of $B(K^+ \to \pi^0 e^+ \nu)$ and the one from the CKM unitarity relation

$$|V_{us}|^2 = 1 - |V_{ud}|^2 - |V_{ub}|^2 \simeq 1 - |V_{ud}|^2 \,, \tag{1}$$

where we have neglected the small mixing $|V_{ub}|^2$ and taken V_{ud} from superallowed beta transitions. This was the first measurement, followed afterwards by KTeV, NA48, KLOE and ISTRA that pointed towards a value for $B(K^+ \to \pi^0 e^+ \nu)$ different from the old PDG value, obtained from old semileptonic branchings [5] but in agreement with the CKM unitarity relation in 1; however it was published at the end 2003 (30th December) while our cut-off line was X-mas 2003. I recall that in October 2003 I was at WIN03 in LAKE GENEVA, Winsconsin, and BNL 865 was presenting their data: Julia Thompson tried very hard to convince me of the robustness of their data. However I did not see the paper before the deadline... I am sorry.

We included however in the 2004 PDG Edition the ISTRA data showing non-vanishing K^+_{e3}-quadratic slopes. Of course in the 2006 PDG Edition we included the measurement of $B(K^+ \to \pi^0 e^+ \nu)$ by BNL 865 along with the related ones by KTeV, NA48, KLOE. We also have included the polar, linear and quadratic parametrizations and the alternative channel $K^+ \to \mu^+ \nu$. Tom Trippe has updated his review in the PDG including linear, quadratic and polar parametrizations and new review on V_{ud} and V_{us} by Blucher and Marciano has been added in PDG 06 [1]. For an extended discussion on this subject see this review or more recent Refs. [5].

5. K^+: other measurements

The NA48/2 Collaboration at CERN has accumulated a lot of charged kaons and has studied the decay $K^+ \to \pi^+\pi^0\pi^0$ with an accurate scan in the $\pi^0\pi^0$-invariant mass distribution, $M_{\pi^0\pi^0}$, finding a cusp at $M_{\pi^0\pi^0} = M_{\pi^+\pi^-}$ [6]. This result has been nicely investigated by Cabibbo and others [7], which explain the "cusp" as an effect due to the opening of the $\pi^+\pi^-$-threshold. Since the rescattering $\pi^+\pi^- \to \pi^0\pi^0$ is proportional to the difference in the scattering lengths $a_0 - a_2$, we can measure this observable:

$$\left.\frac{d\Gamma(K^+ \to \pi^+\pi^0\pi^0)}{dM_{\pi^0\pi^0}}\right|_{\mathrm{NA48}} \quad \Rightarrow \quad \text{cusp for } M_{\pi^0\pi^0} = M_{\pi^+\pi^-}$$
$$\stackrel{\text{cusp}}{\Rightarrow} \quad a_0 - a_2 \,.$$

Of course this new effect has forced us to consider a new definition of linear and quadratic slope in $K \to 3\pi$, which would account for this rescattering. We write the total amplitude as a sum of two contributions [7]:

$$\begin{aligned} &M_0 \;+\; M_1 \,, \\ &M_0 \;=\; 1 + g_0 \, \frac{(s_3 - s_0)}{2m^2_{\pi^+}} + \frac{h'^2}{2m^4_{\pi^+}} \,. \end{aligned} \tag{2}$$

M_1 accounts for the non-analytic piece due to $\pi\pi$-rescattering amplitude, a_0 and a_2:

$$g_0 \sim g^{\rm PDG}, \qquad h' \sim h^{\rm PDG} - \left(\frac{g}{2}\right)^2 .$$

In the CP sector important improvements have been obtained in the channel $K^+ \to \pi^+\pi^0\pi^0$ measuring the slope asymmetry. This measurement is sensitive to New Physics contributions [8] and up to PDG 04 the limits were very loose:

$$\frac{\Delta g}{2g} = \frac{g_+ - g_-}{g_+ + g_-} < \begin{cases} 10^{-5} & \text{for SM}\,, \\ 7 \times 10^{-3} & \text{for PDG}\,, \\ 10^{-4} & \text{for NP}\,. \end{cases}$$

Now new data from TNF ISTRA and NA48 have improved the status

$$\frac{\Delta g}{2g} = \begin{cases} (1.7 \pm 2.8) \times 10^{-4} & \text{for NA48}\,, \\ (2 \pm 20) \times 10^{-4} & \text{for TNF ISTRA}\,. \end{cases}$$

The final $K^+ \to \pi^+\nu\bar{\nu}$ analysis by BNL (B949) reports a total of 3 events but very much in agreement with SM. BNL (B949) has also improved the analysis of the diphoton invariant mass spectrum in the low mass region for $K^+ \to \pi^+\gamma\gamma$ and obtained a new bound $K^+ \to \pi^+\gamma$.

5.1. $K \to \pi\pi\gamma$-decays

Due to the recent/upcoming data from KEK-E470, ISTRA+, KTeV and NA48 $K \to \pi\pi\gamma$-decays it is worth to summarize the present status. We decompose $K(p) \to \pi(p_1)\pi(p_2)\gamma(q)$ amplitudes according to the gauge and Lorentz invariance in electric (E) and magnetic (M) terms. One generally separates in the electric transitions the bremsstrahlung amplitude $E_{\rm B}$, firmly predicted theoretically by the Low theorem. Summing over photon helicities there is no interference among electric and magnetic terms. Defining $z_i = p_i\, q/m_K^2 \quad z_3 = p_{_K}\, q/m_K^2$ we obtain: $d^2\Gamma/(dz_1 dz_2) \sim |E(z_i)|^2 + |M(z_i)|^2$. The present experimental status of the direct emission branchings and the leading multipoles can be summarized as

$$\boldsymbol{B}(\mathrm{DE_{exp}})$$

$$\begin{array}{lcl} K_{\rm S} \to \pi^+\pi^-\gamma & < 9 \times 10^{-5} & \mathrm{E1}\,, \\ K^+ \to \pi^+\pi^0\gamma & (0.44 \pm 0.07) \times 10^{-5} & \mathrm{M1, E1}\,, \\ K_{\rm L} \to \pi^+\pi^-\gamma & (2.92 \pm 0.07) \times 10^{-5} & \mathrm{M1, VMD}\,. \end{array}$$

Furthermore for the decay $K^+ \to \pi^+\pi^0\gamma$ it is useful to use as kin. variables the charged pion kinetic energy in the kaon rest-frame, $T_{\rm c}^*$ and W^2 from

$z_3 z_+ = \frac{m_{\pi^+}^2}{m_K^2} W^2$. Then the interference term, $E_{\rm DE}/eA$, and the DE electric and magnetic contributions can be studied from the double differential distribution

$$\frac{\partial^2 \Gamma}{\partial T_c^* \partial W^2} = \frac{\partial^2 \Gamma_{\rm IB}}{\partial T_c^* \partial W^2} \left[1 + \frac{m_{\pi^+}^2}{m_K} 2{\rm Re} \left(\frac{E_{\rm DE}}{eA} \right) W^2 + \frac{m_{\pi^+}^4}{m_K^2} \left(\left| \frac{E_{\rm DE}}{eA} \right|^2 + \left| \frac{M_{\rm DE}}{eA} \right|^2 \right) W^4 \right],$$

where $A = A(K^+ \to \pi^+ \pi^0)$. In Fig. 2 we show a typical Dalitz plot distribution for an interference term. An accurate study of the Dalitz plot may

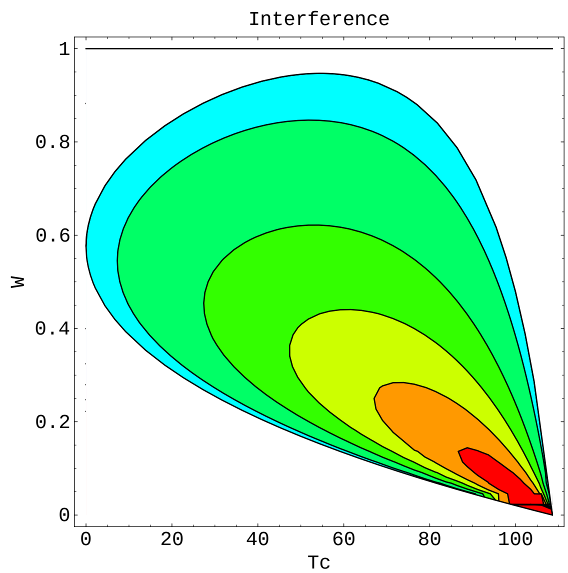

Fig. 2. $T_c^* - W$-Dalitz plot. In this contour plot we show where the interference gives larger contribution; the red area corresponds to the more dense region.

lead to the determination of the interference and the DE terms as shown recently by NA48/2 in Ref. [11]:

NA48		$T_c^* \in [0, 80]$ MeV
Frac(DE)	$=$	$(3.35 \pm 0.35 \pm 0.25) \times 10^{-2}$
Frac(INT)	$=$	$(-2.67 \pm 0.81 \pm 0.73) \times 10^{-2}$

This is the first evidence of non-vanishing interference [11]. Recently we have investigated if the presence of the form factor in the magnetic contribution may alter the evidence of the interference term [12]. The conclusion is that while an interference effect cannot be only due to the presence of a form factor in the magnetic term, for a precise determination of the electric term this effect must be taken into account.

6. K^0 section

The recent kinematical study of the decay $K_\mathrm{L} \to \pi^+\pi^-e^+e^-$ by KTeV [13] has led to a determination of the K^0 mean square radius measured, $\langle R^2 \rangle$, to be compared to the previous values obtained in the same way by NA48 and the one by Molzon *et al.* in '78 which instead measured directly the electromagnetically produced K^0:

$\langle R^2 \rangle$ [fm^2]	TECN	Comment
$-0.077 \pm 0.007 \pm 0.011$	KTeV	$K_\mathrm{L} \to \pi^+\pi^-e^+e^-$
-0.090 ± 0.021	NA48	$K_\mathrm{L} \to \pi^+\pi^-e^+e^-$
-0.054 ± 0.026	Molzon *et al.*	K_S regen. by electrons

The first determination of the K_S-semileptonic branching by KLOE [14] and related measurements, like the CP-asymmetry,

$$A_\mathrm{S} = \frac{\Gamma(K_\mathrm{S} \to \pi^-e^+\nu) - \Gamma(K_\mathrm{S} \to \pi^+e^-\nu)}{\Gamma(K_\mathrm{S} \to \pi^-e^+\nu) + \Gamma(K_\mathrm{S} \to \pi^+e^-\nu)}$$

has allowed the determination of various CPT related quantities:

- $\mathrm{Re}(y)$ (a non-zero value would violate CPT in $\Delta S = \Delta Q$ amplitudes),
- $\mathrm{Re}(x_-)$ (a non-zero value would violate CPT in $\Delta S \neq \Delta Q$ amplitudes) and
- $\mathrm{Re}(x_+)$ (a non-zero value would violate $\Delta S = \Delta Q$ in CPT conserving amplitudes).

KLOE Collaboration, Gino and myself have shown also how the Bell–Steinberger relations improve our knowledge of CP and CPT violation parameters in the neutral kaon system [15]. The time evolution of the neutral kaon system is described by

$$i\frac{\partial}{\partial t}\Psi(t) = H\,\Psi(t) = \left(M - \frac{i}{2}\Gamma\right)\Psi(t)\,, \tag{3}$$

where M and Γ are 2×2 time-independent Hermitian matrices and $\Psi(t)$ is a two-component state vector in the K_0–$\overline{K}_0$ space. The eigenstates of Eq. (3) can be written as

$$K_{\rm L,S} = \frac{1}{\sqrt{2\,(1+|\epsilon_{\rm L,S}|^2)}}\left[(1+\epsilon_{\rm L,S})\,K^0 \mp (1-\epsilon_{\rm L,S})\,\bar{K}^0\right], \tag{4}$$

$$\begin{aligned}\epsilon_{\rm L,S} &= \frac{-i{\rm Im}\,(m_{12}) - \frac{1}{2}{\rm Im}\,(\Gamma_{12}) \pm \frac{1}{2}\left[m_{K_0} - m_{\overline{K}_0} - \frac{i}{2}\left(\Gamma_{K_0} - \Gamma_{\overline{K}_0}\right)\right]}{m_{\rm L} - m_{\rm S} + i(\Gamma_{\rm S} - \Gamma_{\rm L})/2} \\ &= \epsilon \pm \delta\,,\end{aligned} \tag{5}$$

such that $\delta = 0$ in the limit of exact CPT invariance.

Unitarity allows us to express the four entries of Γ in terms of appropriate combination of kaon decay amplitudes:

$$\Gamma_{ij} = \sum_f A_i(f) A_j(f)^*, \tag{6}$$

where the sum runs over all the accessible final states. Using this decomposition in Eq. (5) leads to the BS relation: a link between ${\rm Re}\,(\epsilon)$, ${\rm Im}\,(\delta)$ and the physical kaon decay amplitudes. In particular, without any expansion in the CPT-conserving parameters and neglecting only $\mathcal{O}(\epsilon)$ corrections to the coefficient of the CPT-violating parameter δ, we find

$$\left[\frac{\Gamma_{\rm S}+\Gamma_{\rm L}}{\Gamma_{\rm S}-\Gamma_{\rm L}} + i\tan\phi_{\rm SW}\right]\left[\frac{{\rm Re}(\epsilon)}{1+|\epsilon|^2} - i{\rm Im}(\delta)\right] = \frac{1}{\Gamma_{\rm S}-\Gamma_{\rm L}}\sum_f A_{\rm L}(f) A^*_{\rm S}(f)\ , \tag{7}$$

where $\phi_{\rm SW} = \arctan[2(\Gamma_{\rm S}-\Gamma_{\rm L})/(m_{\rm L}-m_{\rm S})]$. An evidence for a non-vanishing ${\rm Im}(\delta)$ resulting from this relation can only be attributed to violations of: (i) CPT invariance; (ii) unitarity; (iii) the time independence of M and Γ in Eq. (3).

The advantage of the neutral kaon system is that only few decay modes give significant contributions to the r.h.s. in Eq. (7): in practice, only the $\pi\pi(\gamma)$, $\pi\pi\pi$ and $\pi\ell\nu$ modes turn out to be relevant up to the 10^{-7} level.

7. $K_{\rm S}$ section

The whole $K_{\rm S}$-section and absolute $K_{\rm S}$-branchings has been affected by an important new measurement by KLOE [16], which is substantially different from the results presented in the PDG 04

$$\frac{{\rm B}(K_{\rm S}\to\pi^+\pi^-)}{{\rm B}(K_{\rm S}\to\pi^0\pi^0)} = \begin{cases} 2.11 \pm 0.09 & \text{for PDG 04}\,, \\ 2.2549 \pm 0.0054 & \text{for KLOE}\,. \end{cases}$$

NA48 has measured the interference of the $K_S \to \pi^+\pi^-\pi^0$-amplitude (including the phase) with the one of $K_L \to \pi^+\pi^-\pi^0$ [17] generating a branching $B(K_S \to \pi^+\pi^-\pi^0) = (4.7 \pm 2.8) \times 10^{-7}$. NA48 and KLOE with respectively 7 M and 37.8 M of K_S have generated our limit $\mathrm{BR}(K_S \to 3\pi^0) < 1.2 \times 10^{-7}$ at 90% C.L.

As already mentioned KLOE has given an important breakthrough with the measurement of $B(K_S \to \pi e \nu)$. The K_S^{l3} linear form factor has also been measured.

8. K_L lifetime and BRs

The K_L lifetime has been measured by KLOE in **two** different ways: (*i*) in a direct way by tagging the K_L's by $K_S \to \pi^+\pi^-$ [18] and (*ii*) indirect: the four major K_L BRs (K_{l3}, $K_L \to 3\pi$) are measured and the remainder is taken from PDG04; imposing the sum must be equal to 1, KLOE gets an independent K_L lifetime measurement [19].

We have taken into account all correlations (matrix involving the different decay channels) to include this independent measurement.

KTEV has driven big changes by measuring K_L-branching fractions:

$$\frac{\mathrm{B}(K_L \to \pi^+\pi^-\pi^0)}{\mathrm{B}(K_L \to \pi^\pm e^\pm \nu)} = \begin{cases} 0.3078 \pm 0.0005 \pm 0.0017 & \text{for KTeV}, \\ 0.336 \pm 0.003 \pm 0.007 & \text{for PDG} \end{cases} \tag{8}$$

their results solve many problems with previous measurements in the PDG. Similarly, measurements for

$$\frac{\mathrm{B}(K_L \to 3\pi^0)}{\mathrm{B}(K_L \to \pi^\pm e^\mp \nu)}, \qquad \frac{\mathrm{B}(K_L \to \pi^\pm \mu^\mp \nu)}{\mathrm{B}(K_L \to \pi^\pm e^\mp \nu)} \qquad \text{and} \qquad \mathrm{B}(K_L \to \pi^\pm \mu^\mp \nu)$$

were improved drastically by KTEV and KLOE.

Also improving in $B(K_L \to \pi^+\pi^-)$ by KTEV and KLOE has led to a more accurate determination of the CP violating parameter ϵ and as result an improvement on CKM fits.

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