Frascati Physics Series Vol. XXXVI (2004), pp.
DAΦNE 2004: Physics at meson factories – Frascati, June 7-11, 2004
Invited Review Talk in Plenary Session

VIEWS ON FLAVOUR PHYSICS

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Abstract

1 Introduction

The plot of energy vs. time for particle colliders (the Wilkinson plot) features a line which departs from the general, almost exponential, energy increase. This is the line of quark factories: charm (IHEP, Beijing, 1989), strange (DAΦNE, Frascati, 1997), and beauty (PEPII, Stanford, 1999; KEK-b, Tsukuba, 1999), machines specifically addressing the properties of quarks with different flavours:

flavour physics in brief. Results in the same area have also been steadily coming from more general-purpose accelerators, such as the AGS at Brookhaven National Lab and the SPS at CERN, the Tevatron in Fermi Lab and LEP at CERN.

Given the nature of this meeting and the time at my disposal, I shall restrict to a brief review of the most exciting developments in flavour physics at low energy, leaving out e.g. all the new developments coming from the b-factories. Fortunately, it seems to me that low energy flavour physics is quite representative of the main lines in this field: pushing the precision to the limits of the Standard Theory and exploring the dynamics of QCD forces in the making of hadrons out of quarks and antiquarks.

Of course, I shall present a view biased by my personal opinions and I apologize from the start for the many contributions I shall have no time to review.

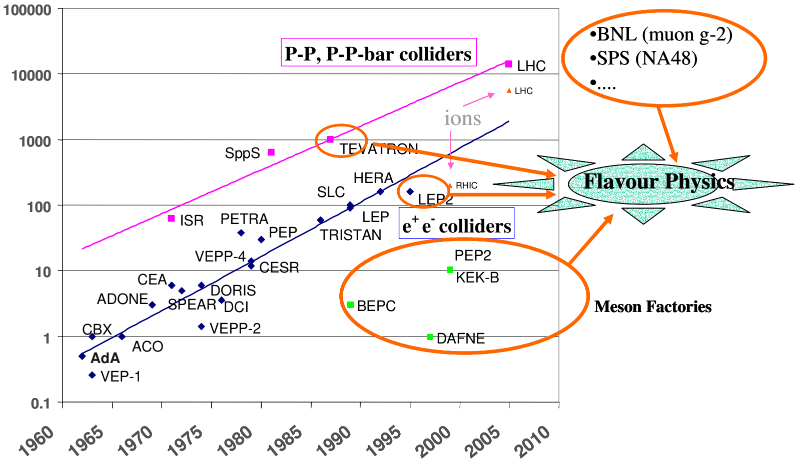

Figure 1: *Contributions to flavour physics.*

2 The muon $g-2$

The most recent results from the Muon $g-2$ Collaboration at BNL (2004 data, positive and negative muons combined) give:

$$a_\mu(\mathrm{exp}) = 11\,659\,208\,(6)\;10^{-10}\;(\mathrm{Muon\,g-2\,Coll.,\,2004\,data}) \qquad (1)$$

SM contributions to the muon anomaly		
Pure QED	11 658 470.35 (0.28) 10^{-10}	
Hadronic (Vac. Pol.)	682.6 (6.4) 10^{-10}	CMD2+KLOE
Electroweak correction	15.4 (0.2) 10^{-10}	two loops included
Hadr. light-by-light scatt.	8 (4) 10^{-10}	
Total: SM prediction	**11 659 176.3 (7.5)** 10^{-10}	
Discrepacy: expt-th	$(32 \pm 10)\ 10^{-10}$	

Table 1: *The different contributions to the muon anomaly in the Standard Theory* [1)]

The prediction of the Standard Theory is shown in Table 1, with a break-up of the different contributions [1)].

Speaking of the muon anomaly, it is customary to praise the level of precision attained by the experiment. It is so, indeed, to the point that while being a property of a lepton, its present experimental value is sensitive to the details of the strong interactions, via the vacuum polarization diagram (a self-energy correction in the photon line exchanged by the lepton external lines) and the light-by-light scattering (four-photon amplitude, one from the external magnetic field and the others attached to the lepton line). Vacuum-polarization gives the most important hadronic contribution and, happily, it can be expressed rigorously in terms of the cross section of $e^+e^- \to hadrons$. Most important is the low energy region, from the $\pi\pi$ threshold to the $\rho(770)$. If one accepts isotopic spin symmetry, a substitute for this cross section is the exclusive semileptonic τ decay rate, where hadrons are excited from the vacuum by the $I = 1$, $I_3 = \pm 1$ components of the vector current, rather than by the $I = 1$, $I_3 = 0$ (the isoscalar component of the e.m. current gives a negligible contribution). This has been tried in the past years and it gave a hadronic vacuum-polarization correction in better agreement with the experimental muon anomaly. High-precision measurements of the $e^+e^- \to hadrons$ cross section have been now perfomed at Novosibirsk [2)], CMD2, and Frascati [3)], KLOE. The two results are quite consistent among themselves:

$$\begin{aligned} & a_\mu^{had-\pi\pi}(0.37\ \mathrm{GeV}^2 < (M_{\pi\pi})^2 < 0.93\ \mathrm{GeV}^2) = \\ & \quad (376.5 \pm 0.8_{stat} \pm 5.9_{sys.+th})10^{-10}\ \text{(KLOE)}; \\ & \quad (378.6 \pm 2.7_{stat} \pm 2.3_{sys.+th})\,10^{-10}\ \text{(CMD2)}. \end{aligned} \tag{2}$$

Unfortunately (or fortunately?) it so happens that the vacuum polarization correction computed from the hadron cross section is about $24 \cdot 10^{-10}$

lower than the one computed from tau decay. Isospin breaking cannot be neglected at this level of precision. In fact, the difference accounts for most part of the discrepancy shown in Table 1. A comparison of the vacuum-polarization correction from $e^+e^- \to hadrons$ and from τ-decay is shown in Fig. 2, taken from a recent talk by Juliet Lee-Franzini [4].

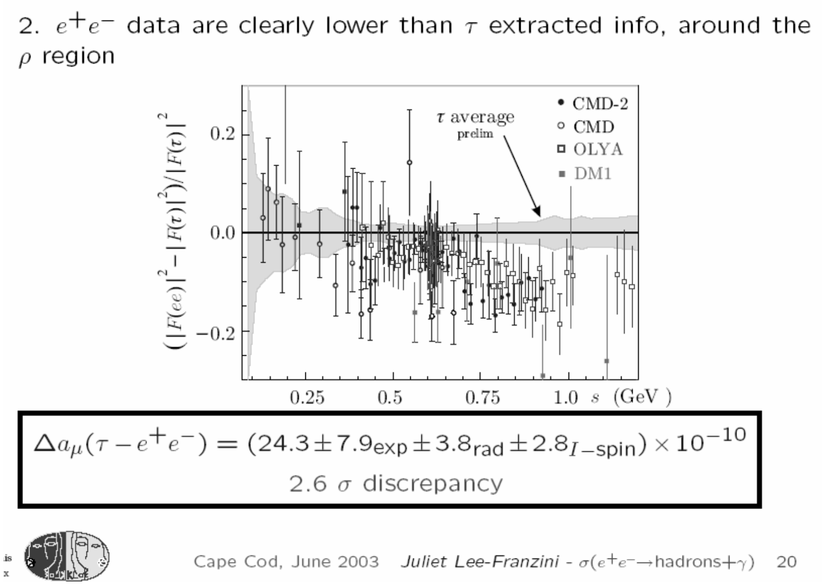

Figure 2: *Comparison of the vacuum-polarization correction from $e^+e^- \to$ hadrons and from τ-decay.*

The light-by-light scattering contribution is the bad guy. It has been estimated on the basis of a simple π-exchange model [5] and there are no perspectives to get a more rigorous estimate, at least for the moment. Nonetheless, the 50% error quoted in the table is most likely conservative and it should give a reasonable estimate of how far can we go in predicting the muon anomaly in the Standard Theory.

The discrepancy shown in Table 1 is 3σ only, still it is 2 times the electroweak corrections [6] and it could very well signal new physics in the energy region of electroweak unification, for example the contributions of light supersymmetric particles. Improving on the error is therefore crucial.

The approximate knowledge of light-by-light scattering leaves a margin for improvement of, say, a factor of 2-3 with respect to the present error. More effort on the measurement of $e^+e^- \to hadrons$ (in particular at higher energy) is justified as well as another round of the $g-2$ experiment. The experiments are clearly worth the effort since the result may have fundamental implications on the planning of the next HEP machine, beyond the LHC.

3 Unitarity of the weak mixing matrix

Very accurate measurements have been recently performed on the neutron beta decay and on the superallowed beta transitions of $I=1, J^P=0^+$ nuclei. They have produced a very precise value of the $u \to d$ weak coupling:

$$|V_{ud}| = 0.9739 \pm 0.0005 \tag{3}$$

Since the contribution of V_{ub} is negligible, the unitarity of the weak mixing (CKM) matrix implies then:

$$\sqrt{1-(V_{ud})^2} = 0.2269 \pm 0.0021 = |V_{us}|_{unit.} \tag{4}$$

In turn, the value of $|V_{us}|$ can be quite accurately measured in Kℓ3 decays, where the Gatto-Ademollo theorem guarantees the vanishing of first order $SU(3)$ symmetry breaking effects, thus affording a very sensitive test of the Standard Theory.

The PDG 2002 value of $|V_{us}|$ disagreed with the prediction given above. The discrepancy has been there for some time, but the new data from E865 [7] at BNL (for K^+) and KLOE [8] at Frascati (for K_S) seem to have resolved it.

An analysis of the previous Kℓ3 results has been made by Cirigliano et al. [9] (see Isidori [10] for details)).To give a flavour of the technicalities involved, I recall that the experimental rate gives the product: $f_+^{K\pi}(0)|V_{us}|$ where f_+ is one of the two form factors for the K to π vector transition. Parallel to the progress in the experimental determination of the rates, a great theoretical effort has gone in the calculation of the form factor at zero momentum transfer. The CKM Working group agrees with the earlier determination [11]: $f_+^{K\pi}(0) = 0.961 \pm 0.008$. The result is:

$$|V_{us}|_{(old)} = 0.2201 \pm 0.0024 \tag{5}$$

corresponding to a 2.2σ discrepancy. The most recent progress is summarized in Fig. 3 (taken from the talk of S. Miscetti at Moriond 04 [12]), which shows a comparison of the BNL and Frascati results with the PDG 02 values. The results look now quite consistent with the prediction from unitarity (grey band). Two other measurements have confirmed the picture, from the KTeV collaboration at FermiLab [13] and from a recent analysis [14] of the hyperon decays data obtained by the NA48 Collaboraton at CERN:

$$|V_{us}|_{KTeV-K_L} = 0.2252 \pm 0.0008_{KTeV} \pm 0.0021_{ext} \quad (6)$$

$$|V_{us}|_{hyp.dec.} = 0.2250 \pm 0.0027 \quad (7)$$

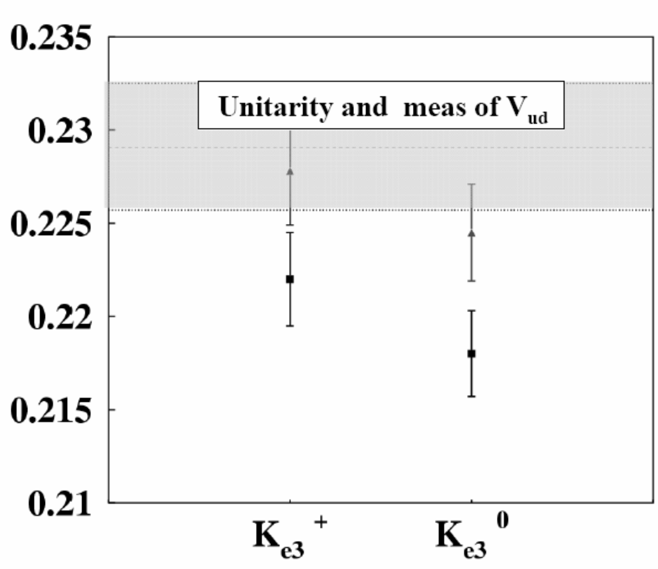

Figure 3: $|V_{us}|$ *measurements from* K^+_{e3} *at* E865 *and from* K^0_{e3} *at* KLOE *(triangles) compared to corresponding* PDG 02 *data (squares). The grey band represents the prediction from Unitarity and* V_{ud} *measurements.*

The accuracy of the present results is about 1%, a remarkable achievement indeed. There seems to be some margin to improve the experimental errors on Kl3 decays and, in addition, to increase the precision on the $\Delta S = 0$, $\pi^+ \to \pi^0$ β-decay [15], thereby reinforcing the determination of the $u \to d$ transition from nuclear decays.

On the theoretical side, isospin and $SU(3)$ breaking, the largest sources of errors, could be kept under control with Chiral Perturbation Theory. A test of the Standard Theory to 0.1% errors seems (perhaps!) possible (but, do not forget the failure of ChpTh in predicting the $\eta \to 3\pi$ decay rate!).

4 A fresh look at the scalar mesons

It's an old concept that two quarks may form a particularly tight state inside a hadronic system (for a recent review see e.g. [16]). The most attractive channel for light quarks is the fully antisymmetric state, $[q_1 q_2]$:

$$[q_1 q_2] = (\bar{3}_{colour}, \bar{3}_{flavour}, spin = 0) \tag{8}$$

The bound-diquark idea has been recently revisited by Jaffe and Wilczeck to explain the observed (but still controversial) exotic baryon states as pentaquark states of the form [17]:

$$[qq] \oplus [qq] \oplus \bar{q} = (0_{colour}, (\bar{10} \oplus 8)_{flavour}, J^P = 1/2^+) \tag{9}$$

A related scheme has been proposed by Lipkin and Karliner [18]. The fully antisymmetric diquark is a boson. However at short distances its fermionic composition should reveal itself and it is unlikely that two diquarks can be in relative S-wave. For this reason, the two diquarks in the pentaquark are assumed to be in P-wave, giving a peculiar overall positive parity, notwithstanding the negative parity that the antiquark brings in.

Jaffe and Wilczeck recalled also the old suggestion that the lowest energy scalar mesons are diquark-antidiquark states. Motivated by the recent observation by KLOE [19] of a low-lying $\pi\pi$ enhancement in $\phi \to \gamma + \pi^0 + \pi^0$, we have re-examined spectrum and decay modes of the lowest scalars as four-quark states [20]:

$$[qq][\bar{q}\bar{q}] = (8 \oplus 1)_{flavour} \tag{10}$$

The $a(980)$, $I = 1$, and the $f(980)$, $I = 0$, fit very well in the picture. For example:

$$a^+ = [su]\,[\bar{s}\bar{d}], \ldots;\ f = \frac{1}{\sqrt{2}}([su]\,[\bar{s}\bar{u}] + [sd]\,[\bar{s}\bar{d}]) \tag{11}$$

Indeed, these particles are almost degenerate ($\Delta m = 10 - 20$ MeV) and $a(980)$ likes to decay in states with a strange quark pair ($\eta\pi, K\bar{K}$), unlike any well-behaved $I = 0$, $q\bar{q}$ state.

To complete the nonet we need:

$$\sigma = [ud]\,[\bar{u}\bar{d}];\ \kappa^{+,0} = [ud][\bar{s}\bar{d}(\bar{u})] \tag{12}$$

The first particle is the $\sigma(480)$, claimed in the past by many groups and seen more recently by the E791 Collaboration in D decays [22] as well as by KLOE [19]. With $\sigma(480)$ and $a(980)$ and quadratic mass formula we find [20] (for earlier work see [23]): $m_\kappa \sim 770$ MeV, fitting very well with the $\kappa(800)$, a resonance that appeared intermittently in the PDG tables and is also seen by E791 [24].

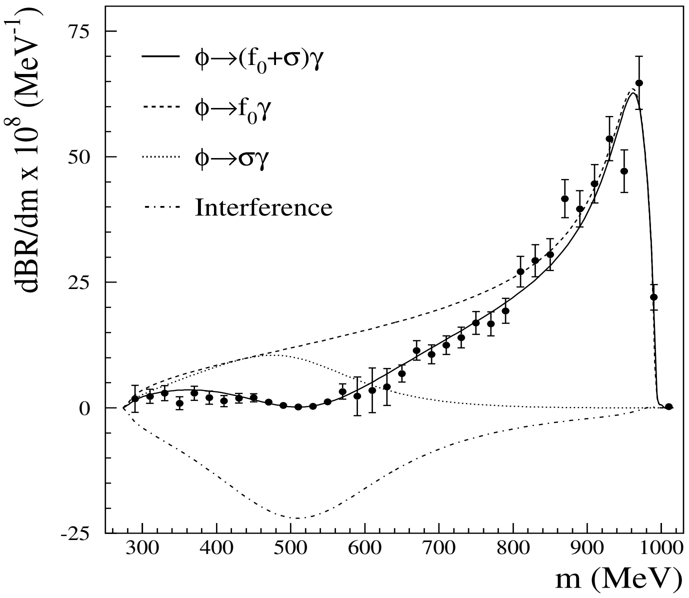

Figure 4: *The $\pi\pi$ mass spectrum in $\phi \to \gamma + \pi^0 + \pi^0$ from* [19]. *Mass and width of σ are taken from* E791 [22]*:* $M_\sigma = (478 \pm 24 \pm 17)$ MeV, $\Gamma_\sigma = (324 \pm 40 \pm 21)$ MeV.

Antisymmetric diquarks explain neatly the opposite properties of the scalar with respect to the vector nonet: the isolated $I = 0$ is the lightest state and it likes to decays in $\pi\pi$.

Diquarks are coloured objects, if we try to separate a diquark from its antidiquark, a quark pair pops out of the vacuum and the state becomes a baryon-antibaryon pair. This is the essence of the baryonium scheme, proposed time ago by Rossi and Veneziano [25] in a different context. However, light scalars are below threshold for baryon-antibaryon decay and a different mechanism has to be envisaged. We can describe the meson-meson decay by assuming that there is a non vanishing amplitude for switching one quark-antiquark pair between the two diquarks thus creating a pair of $q\bar{q}$ colour singlets:

$$[su]\,[\bar{s}\bar{d}] \to (s\bar{s})_{col.singlet}(u\bar{d})_{col.singlet} \tag{13}$$

	$\pi\pi$		KK	
σ	345 MeV	$324 \pm 50 MeV$	-	
f	$g_\pi < 0.02$	$g_\pi = 0.19 \pm 0.05$	$g_K = 0.28$	$g_K = 0.40 \pm 0.6$
	$\eta\pi$			
a	43 MeV	60$\pm$ 13 MeV	23 MeV	12$\pm$ 3 MeV
	$K\pi$			
κ	138 MeV	410 ± 100 MeV	-	

Table 2: *Fit with a single parameter* $A = 2.6$ GeV*. Theoretical predictions on the left of each column,* $g_{\pi,K} = \Gamma_{\pi,K}/p$ *where* p *is the decay momentum. For* g_π *we have reported the upper limit obtained from the* $f - \sigma$ *mixing allowed by the masses.*

The potential barrier provided by the attraction of color singlets is finite (if it exists at all!) and the singlets may proceed into a pair of outgoing mesons. The process is described by a single amplitude, A.

The switch amplitude makes contact with the model describing the scalar mesons $a(980)$ and $f(980)$ as $K\bar{K}$ molecules, but the physics is different. Here, the meson-meson pair results after tunnelling under the barrier which binds the diquark-antidiquark pair and it describes the unbound, final state, particles.

The decay rates into two pseudo scalar mesons thus obtained, with $A = 2.6$ GeV, are given in Table 2.

The full $SU(3)$ invariant couplings are also considered in ref. [20].

The agreement is quite reasonable, considering the large disparity between the widths of $\sigma(480)$ and of $a(980)$ or $f(980)$. We do not use derivative couplings for the pseudo scalar mesons as in ref. [23]. We are far from the soft-pion, Goldstone, regime and derivative couplings would unduly weight the decays of the heaviest particles. The decay $f \to \pi\pi$ is forbidden by the OZI rule and is not well accounted for. One possibility is that it occurs via one-loop diagrams, with a $K\bar{K}$ intermediate state (as in the $K\bar{K}$ molecule picture) or via a $B\bar{B}$ state (as in the baryonium scheme).

If there are diquark-antidiquark bound states, we should see states of this kind with one or more heavy quarks [20, 21]. Consider the case of charm.

– **Hidden charm**: we expect the $SU(3)$ flavor composition:

$$[cq]\,[\bar{c}\bar{q}] = 8 \oplus 1 \tag{14}$$

corresponding to a charmonium nonet with possible decays:

$$a_c(I = 1) \to (D\bar{D}), \eta_c + \pi, \Psi + \rho \tag{15}$$

$$f_c(I=0) \to (D\bar{D}), \Psi + \omega \tag{16}$$

- Open charm [21]:

$$[cq]\,[\bar{q}\bar{q}] = \bar{3} \oplus 6 \to D + ps - meson \tag{17}$$

Unlike the light quark case, we expect exotic states and spectacular signatures. In particular, the representation 6 of $SU(3)$ contains very conspicuous doubly charged states.

Extrapolating boldly from the light scalar decays with the same switch amplitude A=2.6 GeV, one would predict small widths, of the order of ten MeV. Narrow states of this kind are seen in the hadronic final states of B non-leptonic decays, by Belle and PEPII. Some of them are explained by conventional $c - \bar{q}$ bound states, but there may be a wholly new spectroscopy waiting for us there, which we are only now beginning to discover.

In conclusion, there are still many open questions on scalar mesons at low energy, like getting a fully consistent picture of the hadronic widths or of the $\phi(1020) \to \gamma + S$ decays. But, all in all, the diquark-antidiquark picture seems solid. The study of $\gamma\gamma \to$ hadrons may be very useful to clarify the nature of the σ. Narrow states are seen by BABAR, CLEO and BELLE in charm containing hadrons: can they receive a similar explanation?

Other kinds of exotic states have been considered in the past, in addition to $qq - \bar{q}\bar{q}$: glue balls and hybrid (i.e. gluons+quarks) states. A rich spectroscopy is waiting for us at intermediate and low energy, to be tested in heavy flavour systems.

5 Flavour physics: why continue?

Flavour Physics is alive and well. This is true at low energy, as I tried to show with few examples, and at higher energies, where an exciting, new hadron spectroscopy is coming from the observation of D and B decays with high statistics. Here, in Frascati, time is ripe to decide how to continue the DAΦNE line: higher luminosity at $\phi(1020)$, higher energies in the intermediate region up to charm? In this respect, DAΦNE 04 is timely and important: we need to know options and perspectives, more and better. This is indeed one of the goals of this week.

My personal view. The LHC will be coming soon, but the next HEP machine may not be exactly behind the corner. It is important to keep going the intermediate scale projects, to fill the time gap.

Flavour and neutrino physics projects have just the right size and a very, very rich physics.

6 Acknowledgements

I would like to thank Cesare Bini, Paolo Franzini and Gino Isidori for very informative discussions.

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