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WG V Conveners' Report: Charm Inputs for CKM Physics

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We introduce the contributions to the proceedings of Working Group V. The main topics were: present and future experiments dedicated to charm physics, the interplay between high-precision measurements and better control over theoretical uncertainties, and searches for signals of new physics in the charm sector. The comparison of Lattice QCD calculations with precise measurements of charm semi-leptonic and leptonic decays can have a major impact on the determination of CKM matrix elements from measurements of B meson decays.

1 Introduction

Working Group V, dedicated to charm inputs for CKM parameters, was newly formed for the second workshop in this series. Its formation reflects the fact that determinations of CKM parameters, as well as unitarity checks, are increasingly dominated by theoretical uncertainties in hadronic matrix elements, which cannot be computed in perturbation theory [1]. Although lattice simulations of QCD are based on first principles, systematic errors in current simulations – most notably those due to neglecting the effects of dynamical quarks (quark loops) – are still rather large.

The growing importance of charm physics for the study of CKM parameters is underlined by the decisions to commission future high-luminosity charm facilities, such as CESR-c and BEPCII. The availability of high-precision data in the charm sector will enable the validation of recent theoretical progress in lattice QCD, aiming at a substantial reduction of systematic errors [2, 3, 4]. Direct measurements of the leptonic decay constants f_D and f_{D_s}, as well as semi-leptonic form factors, will challenge the lattice community to compute these quantities with much greater precision than currently possible [5]. Decay constants, form factors and other quantities can also be computed using QCD sum rules. As for lattice simulations, the comparison of results obtained in the charm sector with experiment serves to validate the method.

In this sense, the charm sector serves as a testbed for several theoretical methods which are needed to fully exploit the data samples taken at the B-factories. In addition to the more supportive rôle of charm physics for the b-quark sector, there is also the potential to discover new physics by studying processes involving charm quarks.

In this report we first discuss several general issues in both theory and experiment, before detailing recent progress made for a number of quantities.

2 Charm Physics: Theory and Experiment

2.1 High-Luminosity Charm Facilities

As noted in the review by D. Cassel [6], experimental activity in the charm sector will be greatly boosted by the CLEO-c/CESR-c programme at Cornell, as well as the proposed BESIII/BEPCII programme in Beijing. CLEO-c will study e^+e^- collisions at $\sqrt{s} = 3-5$ GeV, and it is expected that 1.5 million $D_s\bar{D}_s$ pairs, 30 million $D\bar{D}$ pairs, and 1 billion ψ decays will be observed. These performance targets imply that many processes can be studied with unprecedented precision in the charm threshold region.

The physics programme of CLEO-c will focus on measuring absolute charm branching fractions, semi-leptonic form factors and the direct measurement of the leptonic decay constants f_D and f_{D_s}. The expected high precision for these quantities presents a challenge to lattice QCD to determine them with equal accuracy. In addition, CLEO-c will look for new physics. In particular, the observation of (large) CP-violation in charm decays is a clear and unambiguous signature for new physics. Other signs are related to $D\bar{D}$ mixing parameters and rare charm decays [7, 8]. Accurate determinations of $D\bar{D}$ mixing parameters will also provide additional information which helps to pin down the CKM angle γ.

2.2 Lattice QCD

In the past decade, simulations of QCD on a space-time lattice have contributed enormously to studies of CKM parameters, by providing non-perturbative, model-independent information on decay constants, form factors and B-parameters. As suggested by A. Buras and emphasised by P. Mackenzie in his plenary talk [9], the most promising strategy to exploit lattice results is to concentrate on "gold-plated" quantities, which are easiest for both theory and experiment. Thus, one-hadron processes involving stable particles, such as $B \to \pi\ell\nu$ are favoured over $B \to \rho\ell\nu$. In particular, multi-particle final states with all their complications due to final-state interactions are (still) very difficult to treat in simulations.

A lot of experience has been gained in quantifying systematic errors in lattice simulations. However, most results have so far been obtained only in the "quenched approximation", where quark loops are neglected in the simulations. Nevertheless, various techniques developed over the years make it possible to control effects due to the discretisation and the renormalisation of local operators at the level of 5% or better. This implies that systematic errors in lattice results are dominated by quenching effects, as well as uncertainties arising from extrapolations to the physical u and d quark masses, from the region around the strange quark mass. At present the latter issue is hotly debated [10], as it strongly affects quantities like f_{D_s}/f_D and $\xi = f_{B_s}\sqrt{B_{B_s}}/f_B\sqrt{B_B}$, which directly enter fits of the CKM parameters (see also the contribution by D. Becirević to WG II [11]).

2.3 QCD Sum Rules

QCD sum rules [12] have been applied over many years to compute non-perturbative hadronic effects in weak decay amplitudes [13]. On the theoretical level, this approach is complementary to that of lattice QCD. Furthermore, QCD sum rule predictions for the charm sector can be compared with experimental data, thereby allowing tests of the stability of sum rules for the corresponding b-decays.

As pointed out in the contribution by A. Khodjamirian [14], the transition from the D- to the B-sector is realised in the sum rule approach, by replacing

$$m_c \to m_b, \quad m_D \to m_B, \ldots \tag{1}$$

This simple replacement, however, does not mean that the sum rules in the two quark sectors are equally reliable. In the case of leptonic decays, the sum rule in the b-sector actually turns out to be more stable. Still, direct comparisons of sum rule predictions with experimental data and lattice results in the charm sector help to check the method as such.

3 Charm lifetimes

Accurate knowledge of lifetimes of charmed particles is a crucial ingredient in the conversion of measured relative branching fractions to partial decay rates, which are obtained by theory. In addition, precise theoretical predictions of charm lifetimes are important for the understanding of issues like power-suppressed corrections in heavy-quark expansions and quark-hadron duality. D. Pedrini, for the FOCUS collaboration, reviewed their recent measurements of charm hadron lifetimes [15], with typical accuracies that exceed those of the presently quoted PDG averages [16]. Results by FOCUS have now clearly established the hierarchy of lifetimes in the mesonic and baryonic sectors:

$$\begin{aligned} &\tau(D^0) < \tau(D_s^+) < \tau(D^+) \\ &\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+). \end{aligned} \tag{2}$$

We note that an accurate measurement of the D^0 lifetime is important for the determination of the lifetime difference in the $D^0\,\overline{D}^0$ system, and consequently for new physics searches.

4 Semi-leptonic D decays

Semi-leptonic decays like $D \to K\ell\nu_\ell$ and $D \to \pi\ell\nu_\ell$ serve to determine the CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$. At the workshop, new results for the decays $D^0 \to K^-\ell^+\nu_\ell$ and $D^+ \to \overline{K}^{0^*}\ell^+\nu_\ell \to K^-\pi^+\ell^+\nu_\ell$ from FOCUS were reported by D. Pedrini [15]. In the course of their analysis of the $D \to K^-\pi^+\ell^+\nu_\ell$ decay, a big forward-backward asymmetry was detected, which can be modelled by including an additional S-wave (see Ref. [15] for more details). FOCUS reported results for the relative branching ratio of $D^+ \to K^-\pi^+\ell^+\nu_\ell$ and $D^+ \to K^-\pi^+\pi^+$ decays, including the S-wave interference:

$$\frac{\Gamma(D^+ \to K^-\pi^+\ell^+\nu_\ell)}{\Gamma(D^+ \to K^-\pi^+\pi^+)} = 0.602 \pm 0.010 \pm 0.021. \tag{3}$$

As noted in [15], this number is $1.6\,\sigma$ lower than CLEO's result, and $2.1\,\sigma$ higher than the E691 measurements.

FOCUS also reported results for ratios of semi-leptonic form factors:

$$\begin{aligned} R_V &\equiv V(0)/A_1(0) = 1.504 \pm 0.057 \pm 0.039 \\ R_2 &\equiv A_2(0)/A_1(0) = 0.875 \pm 0.049 \pm 0.064. \end{aligned} \tag{4}$$

Lattice results for R_V, R_2 [17, 18] are in agreement with these numbers, although the error on R_2 is $\gtrsim 20\%$.

Semi-leptonic $D \to K\ell\nu_\ell$ and $D \to \pi\ell\nu_\ell$ have been studied theoretically, using both QCD sum rules and lattice calculations. Here, the differential decay rates are related to the CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$ via the form factors $f^+_{DK}(q^2)$ and $f^+_{D\pi}(q^2)$, respectively. Calculations of these form factors using light-cone sum rules (LCSR) were reviewed by A. Khodjamirian [14]. The most recent results compare favourably with lattice calculations:

$$f^+_{D\pi}(0) = \begin{cases} 0.65 \pm 0.11 & \text{LCSR} \quad [19] \\ 0.57 \pm 0.06\,(^{+0.01}_{-0.00}) & \text{Lattice} \quad [20] \end{cases} \tag{5}$$

$$f^+_{DK}(0) = \begin{cases} 0.78 \pm 0.11 & \text{LCSR} \quad [19] \\ 0.66 \pm 0.04\,(^{+0.01}_{-0.00}) & \text{Lattice} \quad [20] \end{cases} \tag{6}$$

Moreover, the resulting integrated decay widths are consistent with experiment [16]. It should be noted, though, that the LCSR for f_{DK} depends quite strongly on the value of the strange quark mass. This underlines the importance of accurate values of the light quark masses for studies of this kind. Further details are presented in Section 6.

CLEO-c will be able to measure semi-leptonic branching ratios with relative errors of less than about 1%. This is due to efficient particle identification and background subtraction. A striking example for the efficiency is the clean separation of the (Cabibbo suppressed) decay $D^0 \to \pi^- e^+ \nu_e$ from the allowed $D^0 \to K^- e^+ \nu_e$, whose branching fraction is an order of magnitude larger [6]. In order to exploit this level of experimental precision, the form factors must also be known with an accuracy at the 1% level. If lattice simulations are able to meet this challenge, the resulting accuracy on $|V_{cd}|$ and $|V_{cs}|$ will be 2% or better.

The total decay width of the D^*, recently measured by CLEO [21], allows a determination of the strong coupling of D-mesons to P-wave pions, $g_{D^*D\pi}$, which can be compared with results from lattice simulations and QCD sum rules:

$$g_{D^*D\pi} = \begin{cases} 17.9 \pm 0.3 \pm 1.9 & \text{CLEO} \quad [21] \\ 18.8 \pm 2.3^{+1.1}_{-2.0} & \text{Lattice} \quad [22] \\ 10.5 \pm 3.0 & \text{LCSR} \quad [23] \end{cases} \tag{7}$$

While there is good agreement between experiment and quenched lattice calculations, the LCSR result differs significantly. In view of the fact that LCSRs produce estimates for form factors and decay constants which agree with lattice predictions, this discrepancy seems rather puzzling. As noted by A. Khodjamirian [14], the fairly crude ansatz of simple quark-hadron duality could be responsible for this. One possible scenario, pointed out in [24] proposes the inclusion of a large, negative contribution from radial excitations to the sum rule, thereby modifying the simple D^*-pole dominance in $D \to \pi \ell \nu_\ell$ decays.

5 Leptonic D decays

Measurements of the branching fractions of $D^+ \to \ell^+ \nu_\ell$ and $D_s^+ \to \ell^+ \nu_\ell$ decays can be used to determine $f_{D^+}|V_{cd}|$ and $f_{D_s}|V_{cs}|$. However, these branching fractions are rather small: so far only $\mathscr{B}(D_s^+ \to \ell\nu_\ell)$ has been measured by several collaborations [16, 25], with $\mathscr{B}(D^+ \to \ell\nu_\ell)$ being even smaller by an order of magnitude, due to Cabibbo-suppression. For B-mesons, the measurement of the corresponding branching fractions (at the level expected) is out of reach for the current generation of experiments. Leptonic decay constants of heavy-light mesons have, on the other hand, been computed using lattice QCD and QCD sum rules. In order to validate these calculations and to assess their reliability for B-meson decays, it is highly desirable to compare with experimental determinations in the charm sector.

For lattice calculations, the D_s meson is particularly appealing, since both the charm and the strange quark can be treated directly in simulations, i.e. no extrapolations are required to make contact with the physical values of the valence quark masses.

At the workshop, a recent benchmark calculation of f_{D_s} in the quenched approximation was presented by Rolf [26]. The quoted value is [1].

$$f_{D_s} = 252 \pm 9\,\text{MeV}. \tag{8}$$

It is worth emphasising that all lattice artefacts have been eliminated from this result through an extrapolation to the continuum limit. Therefore, the only uncertainty that remains is due to quenching. A crude estimate suggests that this could amount to $-20\,\text{MeV}$, but it is clear that simulations with dynamical quarks are needed for a reliable quantitative estimate of the effect.

The uncertainties in this calculation can be compared with the accuracy expected from CLEO-c measurements of $D_s \to \mu\nu$ and $D_s \to \tau\nu$, about $\pm 1.7\%$ for each mode – assuming $f_{D_s} = 260$ MeV. These estimates include a common systematic uncertainty that is about $\pm 1\%$, so averaging the two results will result in an uncertainty of about $\pm 1.5\%$.

Lattice determinations of f_D involve an extrapolation in the light quark mass from values around $m_s/2$ down to m_u, m_d. Recently, it was pointed out [27] that chiral logarithms introduce a large uncertainty in estimates of ratios like f_{B_s}/f_B and f_{D_s}/f_D. Although double ratios like

$$\left(\frac{f_{B_s}}{f_B}\right) \Big/ \left(\frac{f_{D_s}}{f_D}\right), \tag{9}$$

in which the chiral logarithms largely cancel [28, 29], may lead to better estimates for, say, f_{B_s}/f_B, it is implicitly assumed that the region of validity of Chiral Perturbation Theory extends to quark masses of $\gtrsim m_s/2$.

Recent sum rule determinations for f_D and f_{D_s} are discussed in A. Khodjamirian's contribution [14], and can be summarised as

$$\begin{aligned} f_D &= 200 \pm 20\,\text{MeV} \\ f_{D_s}/f_D &= 1.11 - 1.27. \end{aligned} \tag{10}$$

[1] We employ a normalisation in which $f_\pi = 132$ MeV.

The quoted errors are dominated by the uncertainty in the charm quark mass. Improvements in the sum rule calculations are discussed in [14].

6 Charm Quark Mass

Despite not being one of the input parameters that are used directly in fits to the CKM parameters, the mass of the charm quark is nevertheless required in several theoretical approaches that determine, for instance, f_D or semi-leptonic form factors. Non-perturbative methods must be applied to determine m_c from experimentally accessible quantities such as m_D or the J/ψ leptonic width.

The status of quark mass determinations using lattice QCD and QCD sum rules was reviewed at the workshop by R. Gupta [30]. Recently, several results for m_c obtained from simulations of quenched QCD have appeared:

$$m_c^{\overline{\rm MS}}(m_c) = \begin{cases} 1.301(34)\,\mathrm{GeV} & [31] \\ 1.26(4)(12)\,\mathrm{GeV} & [32] \\ 1.33(8)\,\mathrm{GeV} & [33] \end{cases} . \tag{11}$$

Despite different systematics, these results are in good agreement. In Refs. [31] and [32] the bare charm mass was related non-perturbatively to the $\overline{\rm MS}$-scheme. Furthermore, the continuum limit was taken in [31]. As in the case of f_D one concludes that the errors within the quenched approximation are under good control, while a reliable quantitative estimate of the quenching error must await further studies. In addition to the absolute mass values, the ratio m_c/m_s was quoted in Ref. [31]:

$$m_c/m_s = 12.0 \pm 0.5. \tag{12}$$

At the workshop, A. Khodjamirian reviewed QCD sum rule determinations of m_c (see Table 1 of [14]). Typical results for $m_c^{\overline{\rm MS}}(m_c)$ vary between 1.2 and 1.37 GeV, while the quoted uncertainties for individual calculations range from 20 to 100 MeV. Thus one observes reasonable agreement between QCD sum rules and lattice calculations.

We have already noted in Section 4 that QCD sum rule determinations of the form factor f_{DK}^+ depends strongly on the strange quark mass. In his review at the workshop Gupta compared lattice estimates for m_s with recent QCD sum rule calculations. Lattice results for m_s in the quenched approximation can be summarised as (see also [34])

$$m_s^{\overline{\rm MS}}(2\,\mathrm{GeV}) = 95 - 115\,\mathrm{MeV}, \quad n_\mathrm{f} = 0, \tag{13}$$

where the quoted range largely reflects the systematic effect arising from choosing different quantities to set the lattice scale. Simulations with $n_\mathrm{f} = 2, 3$ flavours of dynamical quarks yield $m_s^{\overline{\rm MS}}(2\,\mathrm{GeV}) = 70 - 90\,\mathrm{MeV}$. Thus, one observes a marked decrease in m_s when dynamical quark effects are taken into account. On the other hand, the most recent QCD sum rule estimates employing the pseudoscalar or scalar sum rules yield

$$m_s^{\overline{\rm MS}}(2\,\mathrm{GeV}) = 100 - 115\,\mathrm{MeV} \pm 15\%. \tag{14}$$

So while the more recent sum rule calculations have resulted in lower values than had previously been obtained with this method, they are still not easily reconciled with lattice results for $n_\mathrm{f} = 2, 3$. It should be noted though, that uncertainties are still quite large, and that dynamical lattice simulations need to mature, before the situation can be re-assessed.

7 New Physics

The Standard Model (SM) is a very constrained system, which implements a remarkably simple and economic description of all CP-violating processes in the flavour sector by a single CP-violating parameter, the phase of the CKM matrix. This fact relates all CP-violating observables in bottom, charm and strange systems and provides an excellent opportunity for searches of physics beyond the Standard Model. Yet, even with the huge amounts of data currently available, straightforward tests of the Standard Model such as CKM unitarity (for example, via measurements of the areas of charm unitarity triangles) could be quite complicated. This is in part due to the smallness of CP-violating contributions to charm transition amplitudes, which makes the charm unitarity triangles "squashed".

On the other hand, large statistics available in charm physics experiment makes it possible to probe small effects that might be generated by the presence of new physics particles and interactions. As was discussed by A. Petrov [7], a program of searches for New Physics in charm is complementary to the corresponding programs in bottom or strange systems. This is in part due to the fact that loop-dominated processes such as $D^0 - \overline{D}^0$ mixing or flavour-changing neutral current (FCNC) decays are sensitive to the dynamics of ultra-heavy *down-type particles*. Also, in many dynamical models of New Physics the effects in s, c, and b systems are correlated.

Even with the FCNC transitions observed in the nearest future, care should be taken in the interpretation of the observed transitions, which ultimately stems from the fact that the charm quark mass is not far above $\Lambda \sim 1$ GeV, the scale of non-perturbative hadronic physics. A good example is provided by the charm-anticharm mixing studies.The current experimental upper bounds on $D^0 - \overline{D}^0$ mixing parameters $x = \Delta M/\Gamma$ and $y = \Delta\Gamma/2\Gamma$ (with ΔM and $\Delta\Gamma$ being the mass and lifetime differences of mass eigenstates of D^0) are on the order of a few times 10^{-2} [35], and are expected to improve in the coming years. One would need high confidence that the Standard Model predictions for x and y lie well below currently available experimental limits, if any future discovery of $D^0 - \overline{D}^0$ mixing is to be regarded as a discovery of New Physics. This is hard, as in the Standard Model mixing parameters are generated only at the second order in $SU(3)_F$ symmetry breaking [36],

$$x,y \sim sin^2\theta_C \times [SU(3)\ \text{breaking}]^2 . \tag{15}$$

Another possible manifestation of new physics interactions in the charm system is associated with the observation of (large) CP-violation. This is due to the fact that all quarks that build up the hadronic states in weak decays of charm mesons belong to the first two generations. Since 2×2 Cabibbo quark mixing matrix is real, no CP-violation is possible in the dominant tree-level diagrams that describe the decay amplitudes. In the Standard Model CP-violating amplitudes can be introduced by including penguin or box operators induced by virtual b-quarks. However, their contributions are strongly suppressed by the small combination of CKM matrix elements $V_{cb}V_{ub}^*$. It is thus widely believed that the observation of (large) CP violation in charm decays or mixing would be an unambiguous sign for new physics.

Finally, rare decays of D-mesons also probe the effects of FCNC. At the workshop, S. Fajfer discussed the dominant mechanisms in radiative D-decays and their potential to detect new physics [8]. Transitions like $c \to u\gamma$ are strongly suppressed in the SM, with branching ratios estimated at 3×10^{-8} [37]. However, in the MSSM gluino exchange can enhance the branching ratio by two orders of magnitude [38]. A similar enhancement occurs in transitions like $c \to u\ell^+\ell^-$, whose branching ratios in the SM are at the level of 10^{-10}. The amplitudes of rare D-decays are typically dominated by long-distance effects. The most promising decay channels to search for new physics are $D^0 \to \rho\gamma$ and $D^0 \to \omega\gamma$, which could be detected at CLEO-c. The two branching ratios can be combined so as to mostly cancel the long-distance effects. Another possibility is the $B_c \to B_u^*\gamma$ decay, for which long-distance contributions are expected to be much smaller. It should be added, though, that the observation of rare decays will be extremely hard experimentally.

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