Charm Semileptonic Decays

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Results on charm semileptonic decays from different experiments are reviewed. Measurements of the hadronic contribution involved in these decays are presented and compared with expectations from theoretical models and Lattice QCD results.

The XIth International Conference on Heavy Quarks and Leptons,
June 11-15, 2012
Prague, Czech Republic

1. Introduction

Semileptonic decays of charm hadrons provide a way to measure the non perturbative contribution of QCD. The hadronic effects in those decays are expressed in terms of form factors, which are computed using Lattice QCD methods. The validation of Lattice QCD approaches in their calculations is crucial to trust possible New Physics hints in the b quark sector since Lattice results are usually the theoretical inputs entering in the CKM game. Charm semileptonic decays provide in addition a tool to study S-wave systems ($J^P = 0^+$) interfering with vector mesons in a non-hadronic environment, complementing three body hadronic decay measurements.

Different experiments and techniques are used to measure charm semileptonic decays. At charm threshold colliders, CLEO-c and BES III, tagged and untagged methods are used. In the tagged method one of the D mesons from the $\psi(3770)$ is reconstructed in a hadronic mode and the other D meson in the semileptonic channel. This procedure gives small background and very good $q^2 = (p_{\bar{\ell}} + p_{\nu_\ell})^2$ resolution, where $p_{\bar{\ell}}$ and p_{ν_ℓ} are the four momentum of the lepton and the neutrino, respectively. In the untagged method, used for $D \to P\bar{\ell}\nu_\ell$, only the lepton and the hadron from the D semileptonic decay are reconstructed, and the neutrino energy is inferred from the rest of the event, giving rise to higher background and poorer resolution but higher statistics. At B-Factories charm semileptonic decays are obtained using different techniques. BaBar partially reconstructs $c\bar{c}$ events from the continuum under the $\Upsilon(4S)$ resonance, using $D^* \to D\pi$ decays with an electron and a hadron coming from the D meson. The D direction and the neutrino energy is obtained using information from the rest of the event, and the background is controlled using large samples of data. At Belle a full reconstruction of $c\bar{c}$ events including hadronization particles is performed. One of the D is reconstructed into hadrons and the other in the semileptonic channel, being the neutrino the only missing particle in the event. This method leads to high q^2 resolution but very low efficiency. Measurements have been also performed by previous experiments as the photoproduction experiment FOCUS, where the $D^* \to D\pi$ decay is reconstructed and the D meson decay is selected in the semimuonic channel. Figure 1 shows the signal candidates for $D^0 \to K^- e^+ \nu_e$ decays from BaBar [1] using $75 fb^{-1}$ and for $D^0 \to \pi^- e^+ \nu_e$ from preliminary BES III [2] results using $923 pb^{-1}$.

2. Pseudoscalar decays: $D \to (K, \pi, \eta...)\bar{\ell}\nu_\ell$

The main pseudoscalar modes in charm semileptonic decays are the Cabibbo favoured $D \to K\bar{\ell}\nu_\ell$ and Cabibbo suppressed $D \to \pi\bar{\ell}\nu_\ell$ channels. The differential decay width only depends on one form factor[1], $f_+(q^2)$. Several models and parameterizations are commonly used for $f_+(q^2)$. In the *Simple Pole* and *Modified Pole* form factors models [3] the q^2 variation of the form factor is assumed to be governed by a single meson pole or a double pole with an effective pole at higher mass which accounts for other resonant and non-resonant contributions:

$$f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{m_{pole}^2}} \qquad \text{and} \qquad f_+(q^2) = \frac{f_+(0)}{(1 - \frac{q^2}{M_{meson}^2})(1 - \alpha_{pole}\frac{q^2}{M_{meson}^2})}. \qquad (2.1)$$

Here $f_+(0)$ is the normalization of the form factor at $q^2 = 0$. Experiments determine the parameters

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[1]Neglecting terms proportional to m_ℓ.
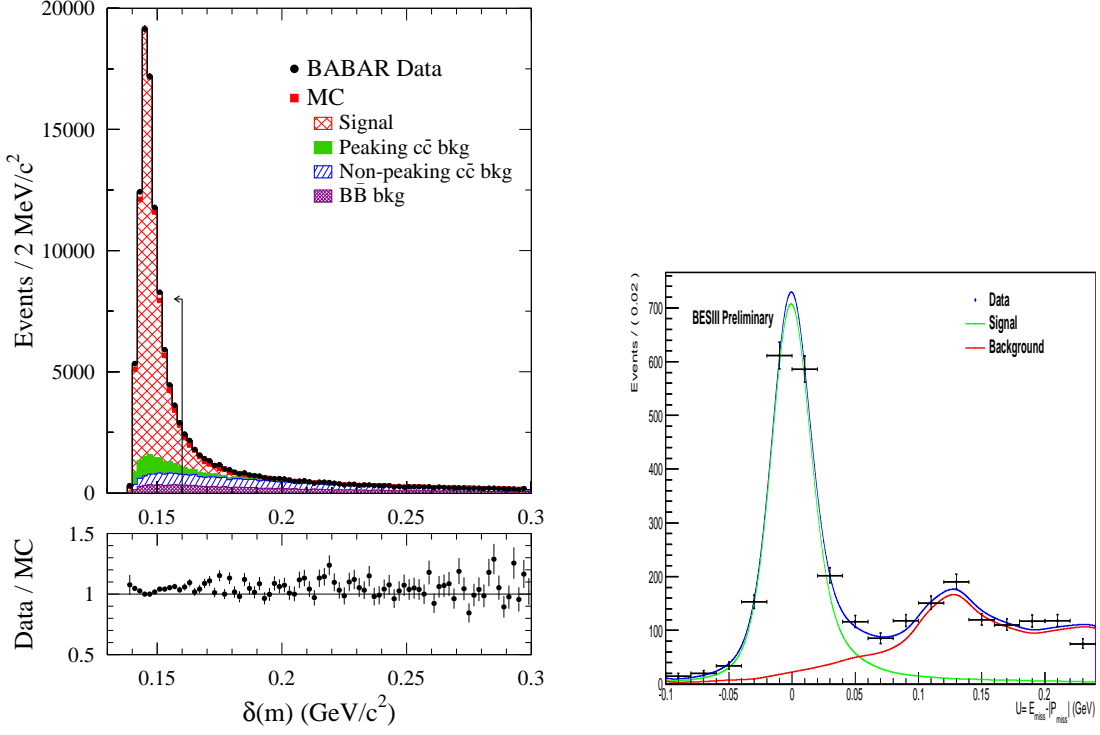
Figure 1: BaBar $D^0 \to K^- e^+ \nu_e$ ($\delta m = m_{D^*} - m_{D^0}$) (left) and BES III $D^0 \to \pi^- e^+ \nu_e$ (missing energy and momentum difference) (right) signal candidates.

m_{pole} or α_{pole}, fixing M_{meson} to the mass of the lowest-lying vector meson contributing to the hadronic current. The normalization of the form factor is also determined at $q^2 = 0$. A general and model independent approach results from a transformation of variables that maps the complex $t = q^2$ plane into the open unit disk with center at $t = t_0$ [4]. The value of t_0 depends on the masses of the particles involved. The form factor is expressed as a Taylor expansion in terms of $z(t, t_0)$. t_0 is usually defined such that $z = 0$ corresponds to the center of the physical z-interval.

$$F(t) = \frac{1}{P(t)\phi(t, t_0)} a_0 \left(1 + \sum_{k=1}^{\infty} r_k(t_0)\, z(t, t_0)^k \right); \quad |z| \ll 1 \qquad (2.2)$$

$P(t)$ and $\phi(t, t_0)$ are analytical functions; zeroes of $P(t)$ correspond to resonances situated below threshold for open production of states contributing in hadronic currents. The parameters a_0 and r_k are measured by experiments. Recent Lattice QCD calculations of the shape of the form factors $f_+^K(q^2)$ and $f_+^{\pi}(q^2)$ are available [5]. Results of the hadronic form factor parameters obtained by the different experiments are given in Tables 1 and 2 for m_{pole} and α_{BK}, and in Tables 3 and 4 for the z expansion, for the Cabibbo favoured and suppressed channels. Values of m_{pole} are far from theoretical expectations: the D_s^* and D^* mass for the $D \to K\bar{\ell}\nu_\ell$ and $D \to \pi\bar{\ell}\nu_\ell$ channels, respectively. Results on α_{pole} are below one as expected from the modified form factor model, and can be used to extract information on higher resonance contributions. Experimental results are at present very

accurate, with a middling agremeent between them. Figures 2 and 3 show the individual results and the combined fit for the z expansion [6]. In Table 5 results on the normalization of the form factor times the corresponding CKM matrix element is given. The experimental accuracy on the form factor normalization is below 1% for $D \to K\overline{\ell}\nu_\ell$. There is a good agreement between Lattice QCD and experimental results for both the $D \to K\overline{\ell}\nu_\ell$ and $D \to \pi\overline{\ell}\nu_\ell$ channels.

Table 1: Results for m_{pole} and α_{BK} from various experiments for $D^0 \to K^-\ell^+\nu_\ell$ and $D^+ \to K_S\ell^+\nu_\ell$ decays. The last entry is a lattice QCD prediction.

$D \to K\overline{\ell}\nu_\ell$ Expt.	Ref.	m_{pole} (GeV/c^2)	α_{BK}
CLEO III	[7]	$1.89 \pm 0.05^{+0.04}_{-0.03}$	$0.36 \pm 0.10^{+0.03}_{-0.07}$
FOCUS	[8]	$1.93 \pm 0.05 \pm 0.03$	$0.28 \pm 0.08 \pm 0.07$
BELLE	[9]	$1.82 \pm 0.04 \pm 0.03$	$0.52 \pm 0.08 \pm 0.06$
BaBar	[1]	$1.889 \pm 0.012 \pm 0.015$	$0.366 \pm 0.023 \pm 0.029$
CLEO-c (tagged)	[10]	$1.93 \pm 0.02 \pm 0.01$	$0.30 \pm 0.03 \pm 0.01$
CLEO-c (untagged, D^0)	[11]	$1.97 \pm 0.03 \pm 0.01$	$0.21 \pm 0.05 \pm 0.03$
CLEO-c (untagged, D^+)	[11]	$1.96 \pm 0.04 \pm 0.02$	$0.22 \pm 0.08 \pm 0.03$
BESIII (prel)	[2]	$1.943 \pm 0.025 \pm 0.003$	$0.265 \pm 0.045 \pm 0.006$
Fermilab lattice/MILC/HPQCD	[12]	–	$0.50 \pm 0.04 \pm 0.07$

Table 2: Results for m_{pole} and α_{BK} from various experiments for $D^0 \to \pi^-\ell^+\nu$ and $D^+ \to \pi^0\ell^+\nu$ decays. The last entry is a lattice QCD prediction.

| $D \to \pi\overline{\ell}\nu_\ell$ Expt.	Ref.	m_{pole} (GeV/c^2)	α_{BK}
CLEO III	[7]	$1.86^{+0.10+0.07}_{-0.06-0.03}$	$0.37^{+0.20}_{-0.31} \pm 0.15$
FOCUS	[8]	$1.91^{+0.30}_{-0.15} \pm 0.07$	–
BELLE	[9]	$1.97 \pm 0.08 \pm 0.04$	$0.10 \pm 0.21 \pm 0.10$
CLEO-c (tagged)	[10]	$1.91 \pm 0.02 \pm 0.01$	$0.21 \pm 0.07 \pm 0.02$
CLEO-c (untagged, D^0)	[11]	$1.87 \pm 0.03 \pm 0.01$	$0.21 \pm 0.05 \pm 0.03$
CLEO-c (untagged, D^+)	[11]	$1.97 \pm 0.07 \pm 0.02$	$0.22 \pm 0.08 \pm 0.03$
BESIII (prel)	[2]	$1.876 \pm 0.023 \pm 0.004$	$0.315 \pm 0.071 \pm 0.012$
Fermilab lattice/MILC/HPQCD	[12]	–	$0.44 \pm 0.04 \pm 0.07$

Results on the pseudoscalar decays $D^+ \to (\eta, \eta')e^+\nu_e$ have been also provided by the CLEO-c experiment using tagged and untagged methods [22].

## 3. Vector decays: $D_{(s)} \to (K^*, \rho, \phi...)\overline{\ell}\nu_\ell$

In case of charm semileptonic decays to vector states the decay rate depends on 5 variables: q^2, the mass of the vector meson, and three angles (θ_V, θ_ℓ and χ). Three form factors are gov-

Table 3: Results for r_1 and r_2 from various experiments, for $D \to K\bar{\ell}\nu_\ell$. The correlation coefficient listed is for the total uncertainties (statistical $\oplus$ systematic) on r_1 and r_2.

Expt. $D \to K\bar{\ell}\nu_\ell$	mode	Ref.	r_1	r_2	ρ
CLEO III		[7]	$0.2^{+3.6}_{-3.0}$	-89^{+104}_{-120}	-0.99
FOCUS		[8]	-2.54 ± 0.75	7 ± 13	-0.97
BaBar		[1]	$-2.5 \pm 0.2 \pm 0.2$	$2.5 \pm 6.0 \pm 5.0$	-0.64
CLEO-c (tagged)	$D^0 \to K^-$	[10]	$-2.65 \pm 0.34 \pm 0.08$	$13 \pm 9 \pm 1$	-0.82
CLEO-c (tagged)	$D^+ \to \overline{K}^0$	[10]	$-1.66 \pm 0.44 \pm 0.10$	$-14 \pm 11 \pm 1$	-0.82
CLEO-c (untagged)	$D^0 \to K^-$	[11]	$-2.4 \pm 0.4 \pm 0.1$	$21 \pm 11 \pm 2$	-0.81
CLEO-c (untagged)	$D^+ \to \overline{K}^0$	[11]	$-2.8 \pm 6 \pm 2$	$32 \pm 18 \pm 4$	-0.84
BES III (prel.)		[2]	$-2.18 \pm 0.36 \pm 0.05$	$5 \pm 9 \pm 1$	
Combined [6]			-2.39 ± 0.17	6.2 ± 3.8	-0.82
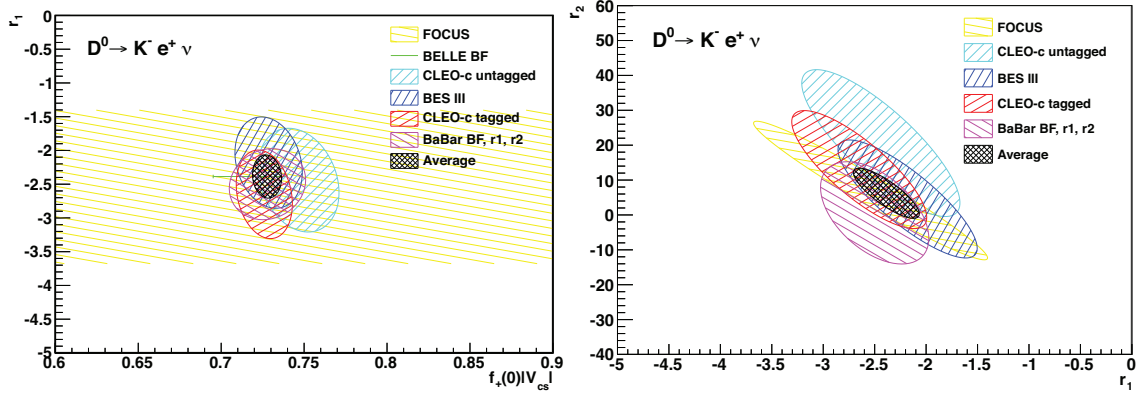
Figure 2: The $D^0 \to K^-\ell^+\nu_\ell$ (left) and $D^0 \to \pi^-\ell^+\nu_\ell$ (right) 68% C.L. error ellipses from the average fit of the 3-parameter z-expansion results from HFAG [6].

Table 4: Results for r_1 and r_2 from various experiments, for $D \to \pi\bar{\ell}\nu_\ell$. The correlation coefficient listed is for the total uncertainties (statistical $\oplus$ systematic) on r_1 and r_2.

Expt. $D \to \pi\bar{\ell}\nu_\ell$	mode	Ref.	r_1	r_2	ρ
CLEO-c (tagged)	$D^0 \to \pi^+$	[10]	$-2.80 \pm 0.49 \pm 0.04$	$6 \pm 3 \pm 0$	-0.94
CLEO-c (tagged)	$D^+ \to \pi^0$	[10]	$-1.37 \pm 0.88 \pm 0.24$	$-4 \pm 5 \pm 1$	-0.96
CLEO-c (untagged)	$D^0 \to \pi^+$	[11]	$-2.1 \pm 0.7 \pm 0.3$	$-1.2 \pm 4.8 \pm 1.7$	-0.96
CLEO-c (untagged)	$D^+ \to \pi^0$	[11]	$-0.2 \pm 1.5 \pm 0.4$	$-9.8 \pm 9.1 \pm 2.1$	-0.97
BES III (prel.)		[2]	$-2.73 \pm 0.48 \pm 0.08$	$4 \pm 3 \pm 1$	
Combined [6]			-2.69 ± 0.32	4.18 ± 2.16	-0.95
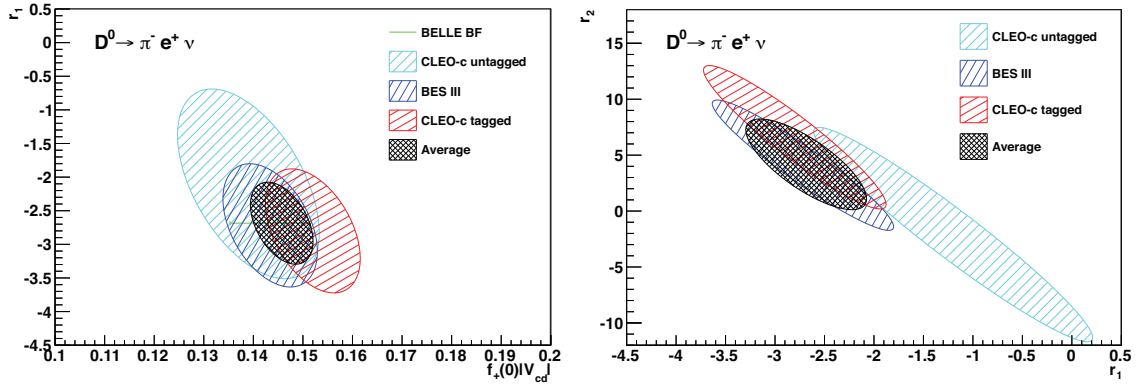
Figure 3: The $D^0 \to \pi^- \ell^+ \nu_\ell$ (left) and $D^0 \to \pi^- \ell^+ \nu_\ell$ (right) 68% C.L. error ellipses from the average fit of the 3-parameter z-expansion results from HFAG [6].

Experiment	Ref.	$f_+^K(0)|V_{cs}|$	$f_+^\pi(0)|V_{cd}|$
E691 (1989)	[13]	$0.69 \pm 0.05 \pm 0.05$	
CLEO (1991)	[14]		
CLEOII (1993)	[15]	$0.76 \pm 0.01 \pm 0.04$	
CLEOII (1995)	[16]		$0.163 \pm 0.031 \pm 0.011$
E687 (1995)	[17]	$0.69 \pm 0.03 \pm 0.03$	
E687 (1996)	[18]		$0.160 \pm 0.018 \pm 0.004$
BESII (2004)	[19]	$0.78 \pm 0.04 \pm 0.03$	$0.164 \pm 0.032 \pm 0.014$
CLEOIII (2005) $*$	[7]		$0.139^{+0.011}_{-0.013}{}^{+0.009}_{-0.006}$
FOCUS (2005)	[8]		$0.137 \pm 0.008 \pm 0.008$
Belle (2006) $*$	[9]	$0.692 \pm 0.007 \pm 0.022$	$0.140 \pm 0.004 \pm 0.007$
BABAR (2007) $*$	[1]	$0.720 \pm 0.007 \pm 0.007$	
CLEO-c (2008)(untagged) $*$	[11]	$0.747 \pm 0.009 \pm 0.009$	$0.139 \pm 0.007 \pm 0.003$
CLEO-c (2009) (tagged) $*$	[10]	$0.719 \pm 0.006 \pm 0.005$	$0.150 \pm 0.004 \pm 0.001$
BESIII (2012)(prel.) $*$	[2]	$0.729 \pm 0.008 \pm 0.007$	$0.144 \pm 0.005 \pm 0.002$
Combined fit ($*$)	[6]	0.728 ± 0.005	0.146 ± 0.003
HPQCD	[20][21]	0.727 ± 0.018	0.150 ± 0.007

Table 5: Normalization of the form factors times the CKM matrix element, $f_+^K(0)|V_{cs}|$ and $f_+^\pi(0)|V_{cd}|$, from different experiments and from Lattice QCD results. Quoted results from Lattice uses values of $V_{cd} = 0.2253$ and $V_{cs} = 09729$, assuming the unitarity of the CKM matrix. The combined fit includes the results marked with $*$ [6].

erning these transitions, expressed in terms of two form factor ratios: $R_2 = A_2(0)/A_1(0)$ and $R_V = V(0)/A_1(0)$. The shapes of $A_1(q^2)$, $A_2(q^2)$ and $V(q^2)$ have been modelled by [23]. In addition, the reconstruction of these decays are sensitive to the S wave systems through the interference effect with the vector meson. BaBar [24] and CLEO-c [25] have reconstructed $D^+ \to K^- \pi^+ \ell^+ \nu_\ell$ events and measured the form factors in these transtions. BaBar uses $347 fb^{-1}$ and performed in addtion a detailed study of the contribution and properties of the $K^*(892)^0$ and higher resonances. BaBar also determines the S-wave contribution and measures its phase, compatible with expectations from $K\pi$ scattering (see Fig. 4 left). CLEO-c performs a measurement of the q^2 dependence of the helicity form factors in $D^+ \to K^- \pi^+ \ell^+ \nu_\ell$ decays. Figure 4 (right) shows the comparison of BaBar and CLEO-c measurements of the helicity form factor components $H_0(q^2)$ and $h_0(q^2)$. Experimental accuracy on form factors is at present much higher than Lattice QCD results. Table 6 lists measurements of R_V and R_2 from several experiments. Most of measurements assume that the q^2 dependence of hadronic form factors is given by a simple pole.

Table 6: Results for R_V and R_2 from various experiments.

Experiment	Ref.	R_V	R_2
$D^+ \to \overline{K}^{*0} l^+ \nu$			
E691	[26]	$2.0\pm 0.6\pm 0.3$	$0.0\pm 0.5\pm 0.2$
E653	[27]	$2.00\pm 0.33\pm 0.16$	$0.82\pm 0.22\pm 0.11$
E687	[28]	$1.74\pm 0.27\pm 0.28$	$0.78\pm 0.18\pm 0.11$
E791 (e)	[29]	$1.90\pm 0.11\pm 0.09$	$0.71\pm 0.08\pm 0.09$
E791 (μ)	[30]	$1.84\pm0.11\pm0.09$	$0.75\pm0.08\pm0.09$
Beatrice	[31]	$1.45\pm 0.23\pm 0.07$	$1.00\pm 0.15\pm 0.03$
FOCUS	[32]	$1.504\pm0.057\pm0.039$	$0.875\pm0.049\pm0.064$
$D^0 \to \overline{K}^0 \pi^- \mu^+ \nu$			
FOCUS	[33]	$1.706\pm0.677\pm0.342$	$0.912\pm0.370\pm0.104$
BaBar	[24]	$1.493 \pm 0.014 \pm 0.021$	$0.775 \pm 0.011 \pm 0.011$
$D_s^+ \to \phi e^+ \nu$			
BaBar	[38]	$1.636\pm0.067\pm0.038$	$0.705\pm0.056\pm0.029$
$D^0, D^+ \to \rho e^+ \nu$			
CLEO	[34]	$1.40\pm0.25\pm0.03$	$0.57\pm0.18\pm0.06$

CLEO-c has also performed a full reconstruction of the supressed decay $D \to \rho e^+ \nu_e$ ($\rho \to \pi\pi$) and measured the form factors ratios [37], which are compatible with the theoretical predictions [23].

Strange charmed meson decays have been measured at BaBar [38] and CLEO-c [39] experiments. BaBar reconstructs $D_s \to K^+ K^- e^+ \nu_e$ events, and finds that the $K^+ K^-$ is primarily coming from the ϕ meson decay. A partial reconstruction technique, similar to the one used for the $D^0 \to K^- e^+ \nu_e$ and $D^+ \to K^- \pi^+ e^+ \nu_e$ analyses is used. With $214 fb^{-1}$ BaBar measures the form factor ratios R_V and R_2 and the simple pole mass m_A, assumed in the axial vector form factor de-
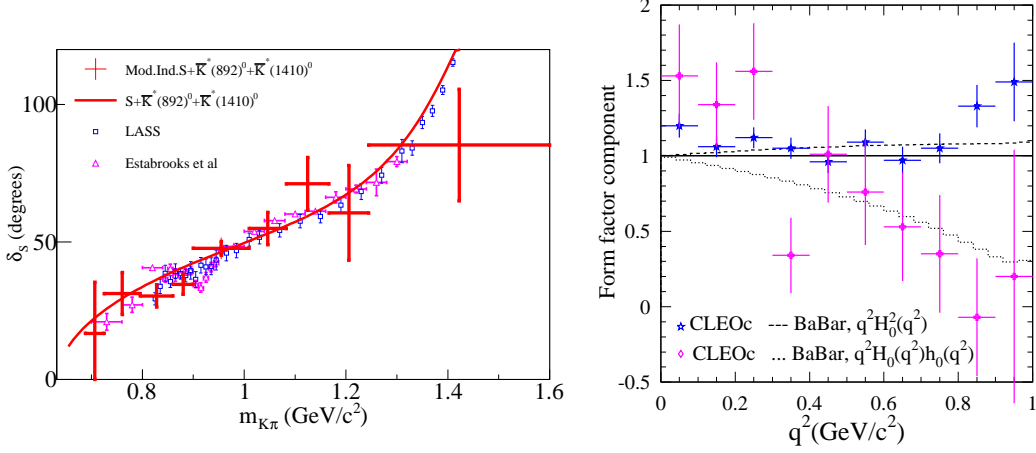
Figure 4: Left: BaBar S-wave measurement (red points) and fitted result (line) compared with $K\pi$ scattering [35] and LASS experiments [36]. Right: Comparison between CLEO-c measurements and BABAR results for the helicity form factors in the $D^+ \to K^-\pi^+\ell^+\nu_\ell$ decay channel.

pendence, in the ϕ region. The normalization of the form factor is also determined. Results are in agreement with recent Lattice QCD calculations [40] although more precise. A first evidence of a S-wave component is observed (presumably $f_0 \to K^+K^-$), giving a relative small contribution, $(0.22^{+0.12}_{-0.08} \pm 0.03)\%$ of the total $D_s \to K^+K^-e^+\nu_e$ rate. This result is consistent with the experimental results of a S-wave for the $B_s \to J/\psi K^+K^-$ channel from D0, CDF and LHCb. The CLEO-c experiment with CESR operating at the energy of 4176 MeV, reconstructs the semileptonic D_s decay into K^+K^- and $\pi^+\pi^-$. In addition to the ϕ meson they observe the 0^+ state $f_0(980) \to \pi^+\pi^-$ and measure its branching fraction. The branching fraction for the $D_s \to \phi e^+\nu_e$ decay channel is measured compatible with the BaBar result, but less precise. Since BaBar cannot reconstruct the final state into pions, both experiments give complementary results of the $f_0(980)$ state.

4. Conclusions

Measurements of charm semileptonic decays are crucial to validate Lattice QCD calculations of the hadronic effects involved in these decays. The experimental effort in the past years has been remarkable. There are many results from several experiments working at different energy and using different techniques resulting in accurate measurements of the form factors. $|V_{cs}|f_+^K(0)$ and $|V_{cd}|f_+^\pi(0)$ have reached a precision of 1% and 2% respectively. In addition, new data is coming from the BES III experiment, and only partial statistics has been used from the B factories, still having room for improvements. There is also an important activity from the Lattice QCD community, and recent Lattice results are more precise. They are in good agreement with experiments. Previous model parameterizations of the form factors, even if theory dependent, let the experimental results to give a physics interpretation of the hadronic states contribution. Experiments also provide important information on the S-wave systems interfering with vector mesons in charm semileptonic decays.

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