Fixed Target Charm Physics

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Here I recount some history of fixed-target charm physics, and describe how such experiments were / are done. Next, I highlight some of the main results from fixed target charm experiments, including in areas of charm mixing, searches for CP violation and for rare decays, studies of semileptonic decays and charm baryons, as well as Dalitz-plot based analyses and studies of charm production.

1. Introduction

Historically, although charm was discovered at SLAC and BNL [1], and even open charm (D mesons) was first observed [2] by e^+e^- experiments, many charm results flowed from experiments which utilized hadronic beams impinging on fixed targets. The fixed target charm experiments considered here are mainly from Fermilab. While there were many beamlines and experiments which produced charm particles, a few of these ran through a sequence of experiments which ended in experiments such as E791, FOCUS, SELEX etc. [4] The bulk of these experiments collected data in the 1980's and 1990's with many publications in the 1990's and final results coming out during the current decade.

2. An example of a Fixed Target Experiment: Fermilab E791

As an example, let us consider the fixed target experiment Fermilab E791. The Fermilab Tevatron delivered a proton beam to the beamline in a spill which lasted approximately 23 seconds, at a repetition rate of roughly a minute. In turn, this primary beam generated a secondary π^- beam of intensity roughly $2{\times}10^6$ particles per second. This pion beam impinged on a fixed target which consisted of 5 foils: a 0.5 mm platinum target followed by four 1.6 mm carbon (diamond) targets. The total thickness was 1.9% pion interaction lengths, leading to a $\sim$40 KHz interaction rate. Atfer selecting events based on calorimeter transverse energy equal to or greater than $\sim$2.5 GeV, the trigger rate was $\sim$9 KHz. Events were acquired by the experiment's data acquisition system and were roughly 2.5 KB each in length.

A total of 2×10^{10} events were recorded by the experiment's data acquisition system leading to to a total data set approximately 50 Terabytes in size, all recorded on Exabyte tapes. In 1991, this data set was considered enormous, and importantly a new era of large datasets had begun. Many experimenters were apalled by this approach, and considered it a reflection on the experimenters' lack of ingenuity in creating a masterful trigger system. Of course, today such systems with high-speed DA and minimal triggers are commonplace and no one would expect the LHC experiments to record only the Higgs and exotic events.

Of the 2×10^{10} events recorded by the experiment, due to a reconstruction efficiency of around 10% and a $\sim 10^{-3}$ charm production fraction, only about 2×10^6 charm particles were reconstructed, still a major achievement in 1991. Some of the efficiency loss is due to the forward nature of the detector, while some is due to tight vertex separation cuts required to reduce the large backgrounds. After factoring in branching fractions in charm decays, the reconstructed sample of, e.g., $D^{*\pm} \to D^0\pi^\pm$, followed by $D^0 \to K\pi^\pm$ is roughly 20,000 events. Further, due to backgrounds, this is a 100σ signal, equivalent to 10^4

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background-free events.

3. $D^0 - \overline{D}^0$ Mixing

One of the holy grails of charm physics is the discovery and understanding of mixing between D^0 and $\overline{D}^0$ mesons. Mixing in the kaon sector has yielded rich dividends in years past, and one expects a study of charm mixing to be similarly rewarding. A commonly used measure of charm mixing is the parameter R_M, defined by

$$r \equiv \frac{\Gamma(D^0 \to \overline{D}^0 \to \overline{f})}{\Gamma(D^0 \to f)} \tag{1}$$

where, for instance, the final state f can be $K^-\pi^+$ and then $\overline{f}$ would be $K^+\pi^-$.

In the early days of charm, semileptonic decays were touted as a fertile hunting ground for $D^0 - \overline{D}^0$ Mixing due to the lack of a doubly-Cabibbo-suppressed (DCS) background. An early experiment, E615, had reported that $R_M < 0.56\%$ [5], albeit with certain assumptions about charm production etc. Another experiment, E691, reported a mixing-rate limit of 0.7% [6] using a measurement based on the rate of like-sign dimuons. Today, while $D^0 - \overline{D}^0$ Mixing has been observed in hadronic decays by BaBar and Belle [7,8], a measurement of R_M using semileptonic decays continues to be elusive.

3.1. Mixing results from E791

Based on E791's sample of $\sim$100σ D^* decays mentioned earlier, the experiment utilized the $K^\mp\pi^\pm$ and $K^\mp\pi^\pm\pi^\pm\pi^\mp$ decay modes to search for $D^0 - \overline{D}^0$ Mixing [9]. This analysis was greatly aided by the "D* trick" which allows one to get a clean D^0 signal *and* tells us the charm quantum number of the D^0 at birth.

Figure 1 shows the right-sign and wrong-sign signals from E791 data; the wrong-sign is consistent with being due to background and no mixing signal is seen; upper limits on R_M are in the 0.4% to 1.0% range, depending on assumptions. E791 actually also produced a competitive result from semileptonic decays: $R_M < \sim 0.7\%$ [10]. Similarly, the FOCUS experiment produced competitive results for $D^0 - \overline{D}^0$ Mixing. In the $K^\mp\pi^\pm$ decay case, they performed various fits to the data and found that $R_M <\sim 0.63\%$.

Another charm decays topic that was historically first attacked by fixed target experiments was the issue of lifetime difference measurements. Today the B-factories routinely measure lifetimes in the K^+K^- and $\pi^+\pi^-$ decay modes of the D^0 and compare them to the lifetime in the $K^-\pi^+$ mode; indeed Belle's contribution to the discovery of mixing has been in this area [8]. However, there was a time when we marveled that B factories might ever measure the D^0 lifetime, let alone precisely, given their relatively poor event-by-event lifetime resolution. Of course, in time they have shown the power of high statistics. The first lifetime difference measurements and their consequences for the mixing parameter $y \equiv \frac{\Delta\Gamma}{2\Gamma}$ were made by fixed target experiments [11].

4. Charm Baryons

In the charm baryon sector fixed target experiments have taken advantage of hadronic production as well as baryon beams to produce many interesting results. Examples of such analyses include measurements of Λ_c^+ resonant decay analysis parameters in the decay $\Lambda_c^+ \to pK^-\pi^+$. This analysis was quite interesting because the spins of the baryons required a 5-dimensional fit, and because the result was a measurement not only of the usual decay amplitudes, but also of the Λ_c^+ polarization as well as information on CP violation in Λ_c^+ decays [12]. Figure 2 shows the results of the Λ_c^+ polarization measurement.

5. Rare and Forbidden Decays and CPV searches

Rare and forbidden charm meson decays typically fall into a few categories:

- FCNC (Flavor Changing Neutral Current) These decays might proceed via higher-order diagrams in the SM, but the branching fractions are in the range 10^{-8}-10^{-6}. Examples include $D^0 \to l^+l^-$, $D^+ \to hl^+l^-$, etc.

- LFV: Lepton Flavor violating decays. Examples of these are $D^0 \to \mu^+e^-$, $D^+ \to$

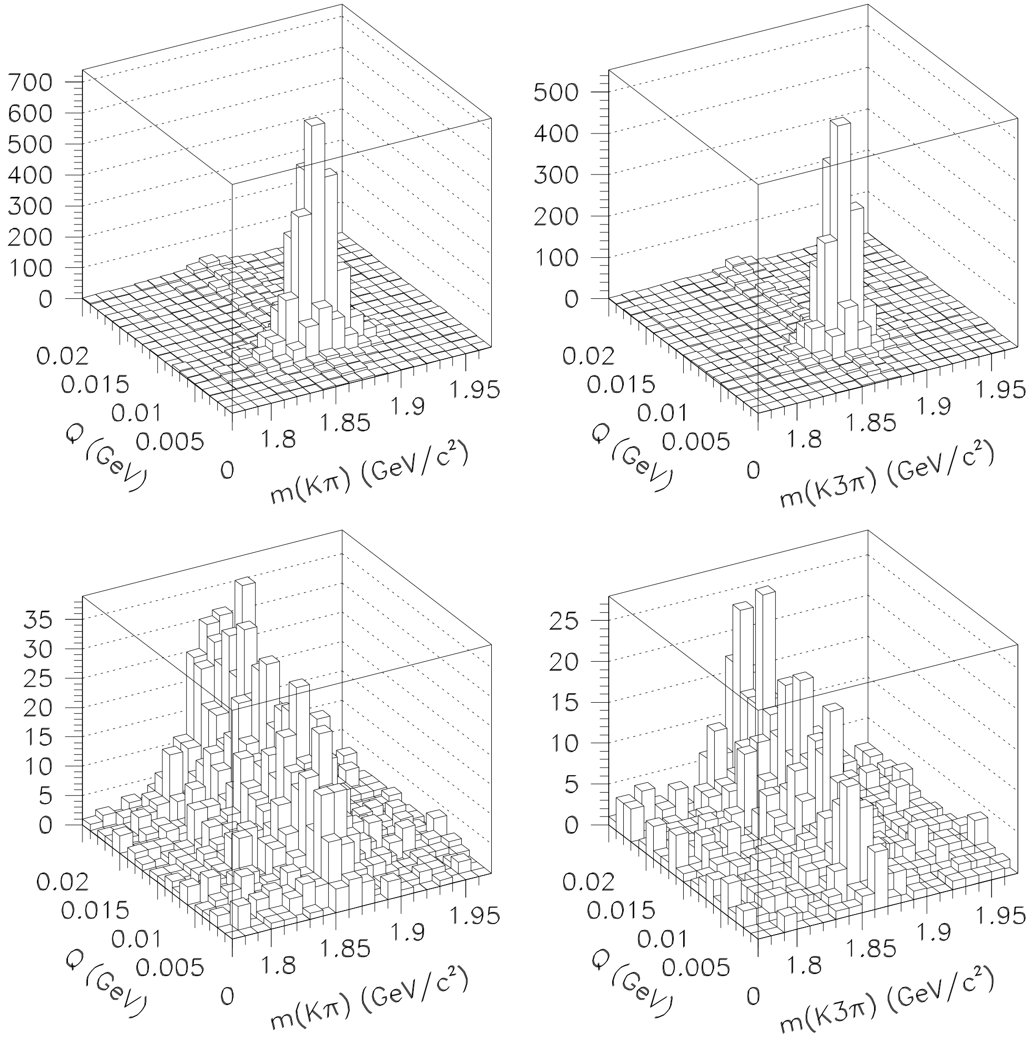

Figure 1. Right sign (upper) and wrong-sign (lower) distributions of hadronic decays of the D^0 from E791 data (decays into the $K^{\mp}\pi^{\pm}$ and $K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$ modes).

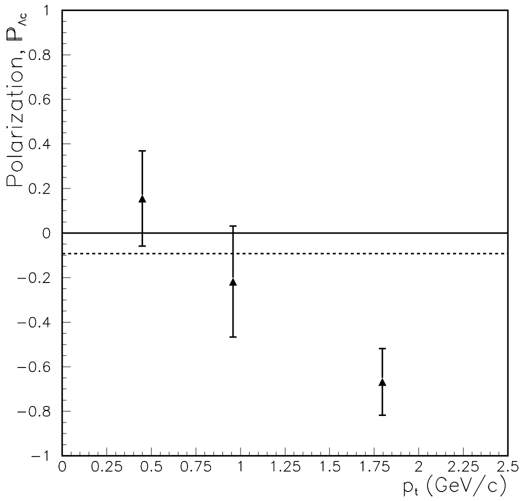

Figure 2. Polarization of the produced Λ_c^+ baryons as measured by the E791 experiment.

$h\mu^+e^-$, etc.

- LNV: Lepton Number Violating decays. Examples of these include $D^+ \to h^-\mu^+\mu^+$ decays.

Experiment E791 obtained limits in 24 different such decay modes [13], all of which were either the lowest limits when published or were competitive with the best limits. In addition, fixed target experiments conducted important searches for CP Violation in charm decays. Singly Cabibbo-Suppressed (SCS) charm decays are good places to look for direct CP violation because of the interference of tree and penguin diagrams [15]. For instance, the search for CP violation in the SCS mode $D^+ \to K^-\pi^+\pi^+$ by E791 [16] resulted in limits in the non-resonant $K^-\pi^+\pi^+$ mode as well as in the $\phi\pi^+$, $\overline{K}^{*0}K^+$ and $\pi^+\pi^-\pi^+$ final states of the order of a few %. These limits have since been improved upon by B-factories [14].

6. Dalitz Analyses

Analysis of 3-body decays of charm mesons has been a very fertile ground to study low-mass resonances and their properties. Indeed, there have been many publications in this area fueled by fixed-target experiments; measurements are still far from complete and the ensuing debates have definitely not been settled. It is fair to say that a big industry has been initiated that will hopefully leave us in the end with a good understanding of strong dynamics.

The story begins ca. 1987 when Mark III published an analysis of $D^+ \to K^-\pi^+\pi^+$ decays. In 1993, E691 confirmed the main features of this decay: a strong non-resonant amplitude and a poor fit! The poor fit was not due to a lack of data but rather due to inadequacies in the phenomenological model: the usual isobar model could not accomodate the data even with insertion of various resonant intermediate states [21]. Also, around 1987, LASS published $K^-\pi^+$ scattering results [18]. Around 1996, W. M. Dunwoodie of SLAC suggested that E791 with their high-statistics data should do a detailed study of $D^+ \to K^-\pi^+\pi^+$ decays to obtain the scattering amplitude in a model-independent way and compare to LASS results. In the meanwhile, E791 was studying other Dalitz decays of charm mesons and found evidence for a σ in $D^+ \to \pi^-\pi^+\pi^+$ decays [19] and a κ in $D^+ \to K^-\pi^+\pi^+$ decays [20]. These fits found marked improvements in fit quality with the inclusion of these broad low-mass scalars. For instance, in the $D^+ \to \pi^-\pi^+\pi^+$ fit the confidence level went up from $\sim 10^{-5}$ to $\sim 76\%$.

Although the postulated low-mass scalars provide excellent fits and “resolve” the problem, not everyone is convinced of their existence. It has been suggested that these resonances are not real, and that alternative parameterizations based on better models of the underlying physics might provide fits that are just as good.

At least two different paths have been suggested in place of the low-mass scalars. One such path, investigated first by E791 [22], involves a model-independent parameterization of the $K\pi$ amplitude. The idea is that the high statistics allow extraction of the amplitude as a function of $K\pi$ mass independent of any model. Extraction of such an amplitude is aided in the $D^+ \to K^-\pi^+\pi^+$ mode since the amplitude must be symmetrized with respect to exchange of the two pions and can interfere with itself. This analysis has been done fairly recently by E791 [22] and is likely to be repeated by the BaBar and other collaborations. The $K\pi$ scattering amplitude extracted by E791 does agree with the LASS measurement and obviates the need for any low-mass scalars. A second approach, championed by another fixed target experiment (FOCUS) emphasizes that the traditional isobar model violates unitarity in some cases and therefore a K-matrix approach is more appealing [3].

6.1. Summary of Dalitz Analyses

In summary, new techniques for analyzing the amplitude describing a Dalitz plot distribution have been pioneered by several fixed-target collaborations, and most recently by E791 in $D^+ \to K^-\pi^+\pi^+$ decays. The model-independent measurements of the complex amplitude of the $K^-\pi^+$ S-wave system yields a good description of the data provided a good model for the P- and D-waves is used. New measurements for invariant masses below 825 MeV/c^2, down to threshold, have been presented. It is found that a better parameterization of the P-wave amplitude is needed: perhaps the B-factories can conduct a model-independent measurement of S-, P- and D-waves using their high-statistics data. More recently, the K-matrix approach championed by FOCUS has been found to give as good a result as the E791 isobar fit with a κ: a CL = 7.7% has been achieved vs. 7.5% for the isobar fit. While the K-matrix approach respects unitarity in $K\pi$ scattering, it is not clear whether this restriction applies in D-meson decays where re-scattering can occur; other parameterizations which account for re-scattering may work just as well. Further, the K-matrix approach itself has complications: it requires an ad-hoc parameterization of the non-resonant amplitude.

7. Conclusions

Does the summary above of Dalitz results mean that the conclusion from the K-matrix work, that no broad new scalars are required, is correct? Or has E791 presented incontrovertible evidence for the presence of such scalars? Regardless of how this debate is settled, we can conclude that useful results from fixed target experiments continue to fuel important directions in charm physics. One important contribution from fixed-target charm experiments that we must acknowledge however is the introduction to particle physics of massively parallel, high-speed and inclusive data-taking which facilitated all these beautiful results in charm physics.

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