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Precision Measurements of CP Violation and D^0 - $\bar{D}^0$ Mixing at CDF

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The CDF collaboration presents prospects for updating previous measurements of charm mixing and CP violation with a sample corresponding to an integrated luminosity of 5.2 fb^{-1}. We previously reported evidence for D^0 - $\bar{D}^0$ mixing with a significance equivalent to 3.8 standard deviations based on the time-dependent ratio of the decay rates for $D^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$, and charge-conjugates. That measurement was based on an integrated luminosity of 1.5 fb^{-1} and achieved sensitivities of $\pm 0.35 \times 10^{-3}$ and $\pm 7.6 \times 10^{-3}$ on the mixing parameters x'^2 and y', respectively. A different analysis measured CP-violating asymmetries in D*-tagged $D^0 \to \pi^+\pi^-$ decays, where any enhancement from the standard model prediction (of the order of 10^{-3}) would be unambiguous evidence for New Physics. A technique combining asymmetries of $\pi^+\pi^-$, and $K^-\pi^+$ D^0 decays highly suppresses systematic uncertainties due to detector charge-asymmetric efficiencies allowing a measurement limited only by statistical uncertainties.

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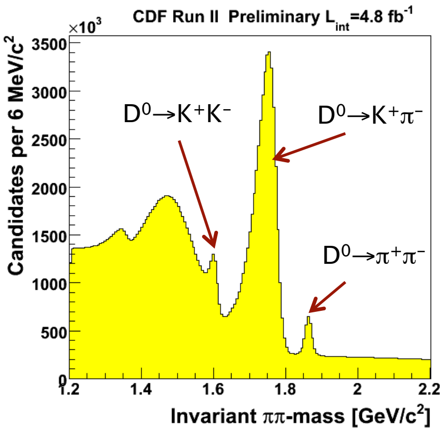

Figure 1: Invariant $\pi\pi$ mass distribution for CDF with $4.8 fb^{-1}$ integrated luminosity. There are approximately 1.7×10^6 events with $D^0\to\pi^+\pi^-$, 4.7×10^6 with $D^0\to K^+K^-$, and 47×10^6 with $D^0\to K^-\pi^+$

1. Introduction

Mixing describes how neutral mesons, like K^0 and B^0, can oscillate from particle to antiparticle, due to differences between the strong and weak eigenstates. CP violation has been observed for these mesons as well. By comparison, the charm meson D^0 has much smaller mixing parameters and CP violation. (A detailed summary for mixing and CPV is available from the Particle Data Group [1].) The first experimental evidence for charm mixing was not seen until 2007, and no single measurement has reached 5σ significance. Combining all results for charm mixing excludes no-mixing at the 10.2σ level [2]. Results are consistent with no CP violation. [2]

Better precision from both experiment and theory are needed to see if there is any discrepancy not accounted for by the standard model. There are a number of models using New Physics that can enhance charm mixing and CPV.

The CDF II detector is located at point B0 on the Fermilab Tevatron. It has a displaced vertex trigger to select heavy flavor decays. Although optimized for B physics, it also accepts a substantial number of charm decays, as seen in Fig. 1. The results from CDF are competitive with the B factories, as the large signal statistics compensates for the higher background present from hadronic collisions. Results for the current data sample are not ready yet, but comparisons can be made with previously published results.

2. Charm Mixing with $D^0\to K\pi$ Decays

The first analysis to be discussed uses reconstructed $D^{*\pm}\to\pi^\pm D^0$, $D^0\to K^-\pi^+$ and $K^+\pi^-$. The D^* is used to determine whether the neutral charm meson started as a D^0 or a $\bar{D}^0$. The Cabibbo favored (CF) decay is $D^0\to K^-\pi^+$, and is called “right-sign” (RS). The D^0 can also decay to $K^+\pi^-$ (“wrong-sign” or WS), either by a doubly Cabibbo suppressed (DCS) decay, or by oscillating to $\bar{D}^0$ followed by a Cabibbo favored decay.

The ratio R of $D^0\to K^+\pi^-$ to $D^0\to K^-\pi^+$ decay rates can be approximated as a simple quadratic function of t/τ, where t is the proper decay time and τ is the mean D^0 lifetime. This form

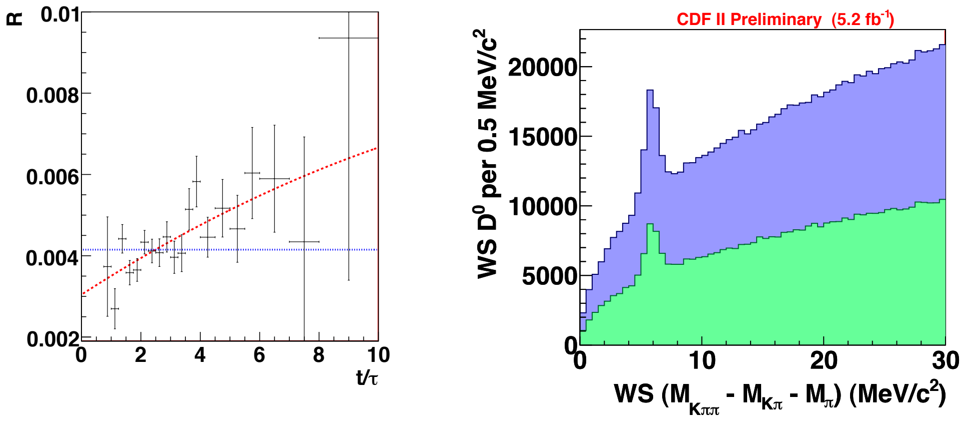

Figure 2: The left plot shows previously published CDF result for the ratio of WS to RS events [3], as a function of proper time (t) divided by the D^0 lifetime (τ). The blue line is the best fit assuming no mixing, while the red line is the best fit allowing mixing. The right plot shows the number of WS D^0 versus the WS mass difference. The peak near $6MeV/c^2$ are from D^*, with the remainder of the events being D^0 combined with a random pion to form a false D^* candidate. Light green is the previously published result with 12800 WS D^*. The blue events are with integrated luminosity of $5.2fb^{-1}$, with approximately 26000 WS D^*.

is valid assuming CP conservation and small values for the parameters $x = \Delta M/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, where ΔM is the mass difference between the D^0 meson weak eigenstates, $\Delta\Gamma$ is the decay width difference, and Γ is the average decay width of the eigenstates. Under the assumptions stated above,

$$R(t/\tau) = R_D + \sqrt{R_D}y'\,(t/\tau) + \frac{x'^2 + y'^2}{4}\,(t/\tau)^2,$$

where R_D is the squared modulus of the ratio of DCS to CF amplitudes, $x' = x\cos\delta + y\sin\delta$, $y' = -x\sin\delta + y\cos\delta$, and δ is the strong interaction phase difference between the DCS and CF amplitudes. Although the mixing parameters (x, y) are not measured directly, this ratio gives information about the amplitude of mixing. In the absence of mixing, $x' = y' = 0$ and $R(t/\tau) = R_D$.

CDF published a measurement based on an integrated luminosity of 1.5 fb^{-1} and achieved sensitivities of $\pm 0.35 \times 10^{-3}$ and $\pm 7.6 \times 10^{-3}$ on the mixing parameters x'^2 and y', respectively [3].The current data sample, corresponding to 5.2 fb^{-1}, has approximately twice as much signal, as seen in Fig. 2. If we make the simplistic estimate that the uncertainties on the signal scale as $1/\sqrt{N}$, the no-mixing hypothesis will be excluded at near the 5σ level.

3. CP Violation with $D^0 \to h^+h^-$ Decays

The second analysis to be discussed reconstructs $D^0 \to h^+h^-$, where h is either K or π. In addition to direct CP violation, D^0 oscillations can generate time dependent CP asymmetries that survive integrating over time. The time-integrated CP violating asymmetry for charm mesons decaying into charged pions is given by:

$$A_{CP}(\pi^+\pi^-) = \frac{\Gamma(D^0 \to \pi^+\pi^-) - \Gamma(\bar{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^+\pi^-) + \Gamma(\bar{D}^0 \to \pi^+\pi^-)}$$

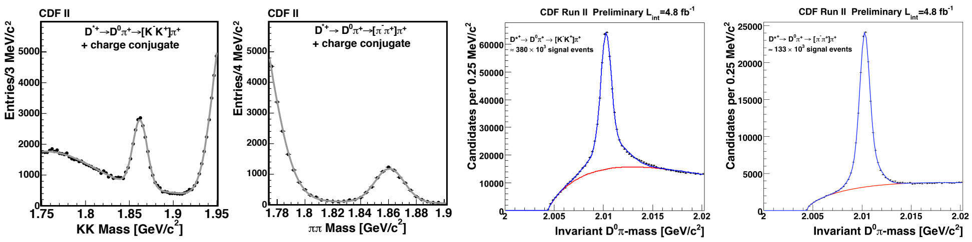

Figure 3: The two plots on the left are $D^0 \to KK, \pi\pi$ from the previously published CDF result using 0.123 fb^{-1} [4]. The two plots on the right illustrate the number of $D^{*+} \to \pi^+ D^0, D^0 \to KK, \pi\pi$ using 4.8 fb^{-1}. There are a comparable number of D^{*-}.

Experiment	$N(D^0 \to \pi^+\pi^-)$	$A_{CP}(\pi^+\pi^-)$ (%)
CDF ($0.123 fb^{-1}$)	7.3 K	1.0 ± 1.3 (stat) ± 0.6 (syst)
CDF ($4.8 fb^{-1}$)	273 K	$xxx \pm 0.19$ (stat) $\pm xxx$ (syst)
BaBar ($386 fb^{-1}$)	64 K	-0.24 ± 0.52 (stat) ± 0.22 (syst)
Belle ($540 fb^{-1}$)	51 K	0.43 ± 0.52 (stat) ± 0.12 (syst)
Experiment	$N(D^0 \to K^+K^-)$	$A_{CP}(K^+K^-)$ (%)
CDF ($0.123 fb^{-1}$)	16.2 K	2.0 ± 1.2 (stat) ± 0.6 (syst)
CDF ($4.8 fb^{-1}$)	781 K	$xxx \pm 0.11$ (stat) $\pm xxx$ (syst)
BaBar ($386 fb^{-1}$)	129 K	$0. \pm 0.34$ (stat) ± 0.13 (syst)
Belle ($540 fb^{-1}$)	120 K	-0.43 ± 0.30 (stat) ± 0.11 (syst)

Table 1: Projections for time-integrated CP asymmetry measurements at CDF with $4.8 fb^{-1}$ for $D^0 \to \pi\pi, KK$. Also included are previously published results by CDF [4], BaBar [5], and Belle [6].

CDF published an early result, with integrated luminosity of 0.123 fb^{-1} [4]. As mentioned earlier, any CP violation is expected to be very small. To make precision measurement, we need to correct for detector systematics that can bias the asymmetry. The published result used Monte Carlo to simulate detector efficiencies. Our understanding of the detector has improved since then. The updated result will use a data-driven technique using $\pi^+\pi^-$, and $K^-\pi^+$ decays to highly suppress systematic uncertainties due to detector charge-asymmetric efficiencies, allowing a measurement limited only by statistical uncertainties. This takes advantage of the larger number of signal events compared to the earlier result (as seen in Fig. 3).

The projections for the current data sample assumes the number of particles (N) is similar to the number of antiparticles ($\bar{N}$), and that the uncertainty on the number of events is $\sigma_N \cong 1/\sqrt{N}$. The estimate for the asymmetry uncertainty is $\sigma_{A_{CP}} \cong 1/\sqrt{N+\bar{N}}$. The projections, and previously measured results, are shown in table 1. The systematic uncertainties are not complete yet, but are expected to be on the order of 0.1%, comparable to the projected statistical uncertainties.

4. Conclusion

CDF has a mature detector with well understood systematic effects, and substantial charm samples. We are working to update two previous measurements for charm mixing and CP violation [7]. Since mixing for charm mesons is small, and CP violation not yet observed, we are working to improve the precision of the systematic uncertainties. These results are expected to be comparable or better than current experimental results. Improvements in experiment and theory standard model predictions will test if there is room for New Physics.

References

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[7] A new public result for the $D^0 \to \pi\pi$ analysis was released after the conference and before the proceedings were submitted, with $A_{CP}(D^0 \to \pi^+\pi^-) = [+0.22 \pm 0.24(stat) \pm 0.11(syst)]$. http://www-cdf.fnal.gov/physics/new/bottom/100916.blessed-Dpipi6.0