CDF note 8499

Measurement of the branching ratio of the Cabibbo-suppressed decay $D^+ \to \pi^-\pi^+\pi^+$.

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We present a measurement of the relative branching ratio of Cabibbo-suppressed D^+ decays into three charged pions using 193 pb^{-1} of CDF II data. We measure $\mathcal{B}(D^+ \to \pi^-\pi^+\pi^+)/\mathcal{B}(D^+ \to K^-\pi^+\pi^+) = (3.461 \pm 0.038(stat) \pm 0.040(syst))\%$. Using the world average absolute branching ratio $\mathcal{B}(D^+ \to K^-\pi^+\pi^+) = (9.51 \pm 0.34)\%$, we find $\mathcal{B}(D^+ \to \pi^-\pi^+\pi^+) = (3.29 \pm 0.11) \times 10^{-3}$.

Preliminary Results for Autumn 2006 Conferences

I. INTRODUCTION

The phenomenon of CP violation has so far been demonstrated in the decays of kaons and in B mesons. In charmed hadrons, CP violation is expected to be suppressed, due to the dominance of Cabibbo-allowed $c \to s$ transitions and due to the absence of a top quark in loop diagrams, resulting in a very effective GIM suppression.

Cabibbo-suppressed charm decays are perhaps the most accessible channels for discovering CP violation in the charm system, due to the interference between the Cabibbo-suppressed tree contribution and the Cabibbo-allowed penguin contribution, resulting in asymmetries at the 10^{-3} level [1, 2].

Direct CP violation in charm manifests itself as a difference in the decay rate between $D \to f$ and $\bar{D} \to \bar{f}$. Searches for direct CP violation have so far not resulted in observations [3–7] but the charm samples recorded at e^+e^- and hadron collider experiments are larger by up to two orders of magnitude than the samples collected at fixed target experiments and have revived the hope for observation of CP violation in the charm sector.

Previously, CDF has searched for direct CP violation in single Cabibbo-suppressed D^0 decays and measured their branching ratios [5]. In the present analysis, a first step is set towards extending this search to D^+ decays, by establishing the $D^+ \to \pi^-\pi^+\pi^+$ signal at a hadron collider and measuring its branching ratio.

Throughout this text, charge conjugate modes are implicitly included.

II. THE CDF II DETECTOR

CDF II is a general-purpose particle detector, built with cylindrical symmetry around one of the two collision points of the Tevatron $p\bar{p}$ collider operating at a center-of-mass energy of $\sqrt{s} = 1.96\,\mathrm{TeV}$, and is described in detail elsewhere [8]. Charged particles are detected with the tracking system, immersed in a 1.4 T solenoidal magnetic field. A 7-layer silicon tracking system, ranging in radius from 1.5 to 28 cm, provides space-points of particle trajectories with an accuracy of approximately $15\,\mu$m. A proportional drift chamber provides up to 96 measurements of every charged particle trajectory from radii of 40 to 137 cm. This analysis uses $\approx$193 pb^{-1} of CDF II data collected between February 2002 and August 2003.

III. DATA SAMPLE AND EVENT SELECTION

Inelastic interactions of interest are selected in real time from the 1.7 MHz bunch crossing rate with a three-level trigger system. Charm decays are selected by requiring at least two charged particle tracks with a momentum transverse to the beam line of 2 GeV/c and a transverse displacement from the beam of at least $120\,\mu$m. The position of the two-track vertex is required to be displaced by at least $200\,\mu$m from the average beam line.

At the end of a typical 24-hour $p\bar{p}$ 'store' of the Tevatron, the instantaneous luminosity has dropped by a factor of four. To make optimal use of the available trigger bandwidth, three versions of the two-track trigger have been implemented:

- The *low-p_T* trigger, as described above, active only at low luminosity.
- The *medium-p_T* trigger requires in addition that the two tracks have opposite charge, and that the sum of the transverse momenta, $p_{T1}+p_{T2} \geq 5.5\,\mathrm{GeV}/c$. The fraction of events taken during a store is adjusted to maximize the yield while minimizing the detector dead-time.
- The *high-p_T* trigger requires $p_T \geq 2.5\,\mathrm{GeV}/c$ for each track and $p_{T1} + p_{T2} \geq 6.5\,\mathrm{GeV}/c$. All interactions satisfying these conditions are recorded.

We reconstruct D^+ candidates by combining three tracks in the detector acceptance with a minimum of three measurements in the silicon detector and transverse momentum $p_T \geq 0.6\,\mathrm{GeV}/c$ that form a vertex with a fit quality $\chi^2 \leq 20$. At least one pair of tracks satisfies the trigger requirements. In addition, we remove backgrounds from $D^{*+} \to D^0\pi^+$ decays by requiring that $\Delta m \geq 160\,\mathrm{MeV}/c^2$, where $\Delta m \equiv m(K^-\pi^+\pi^+) - m(K^-\pi^+)$ for the $K^-\pi^+\pi^+$ mode, and $\Delta m \equiv m(\pi^-\pi^+\pi^+) - m(\pi^-\pi^+)$ for the $\pi^-\pi^+\pi^+$ mode. Backgrounds from $D^+ \to K^0_S\pi^+$ are rejected by requiring $480 \leq m(\pi^+\pi^-) \leq 520\,\mathrm{MeV}/c^2$. No particle identification is used in the candidate selection.

With these loose criteria, we reconstruct $\approx 2.6 \times 10^6$ $D^+ \to K^-\pi^+\pi^+$ decays, with a signal-to-background ratio of approximately 3:1. However, the signal-to-background ratio of 1:10 for $D^+ \to \pi^-\pi^+\pi^+$ is too poor for an accurate measurement of its branching fraction. The selection criteria are tightened to obtain the smallest expected uncertainty on the branching ratio $D^+ \to \pi^-\pi^+\pi^+$, by minimizing the value of $S/\sqrt{S+B}$, where S is the expected number of $D^+ \to \pi^-\pi^+\pi^+$ decays, obtained from the $D^+ \to K^-\pi^+\pi^+$ yield in data, and rescaling it by the relative branching

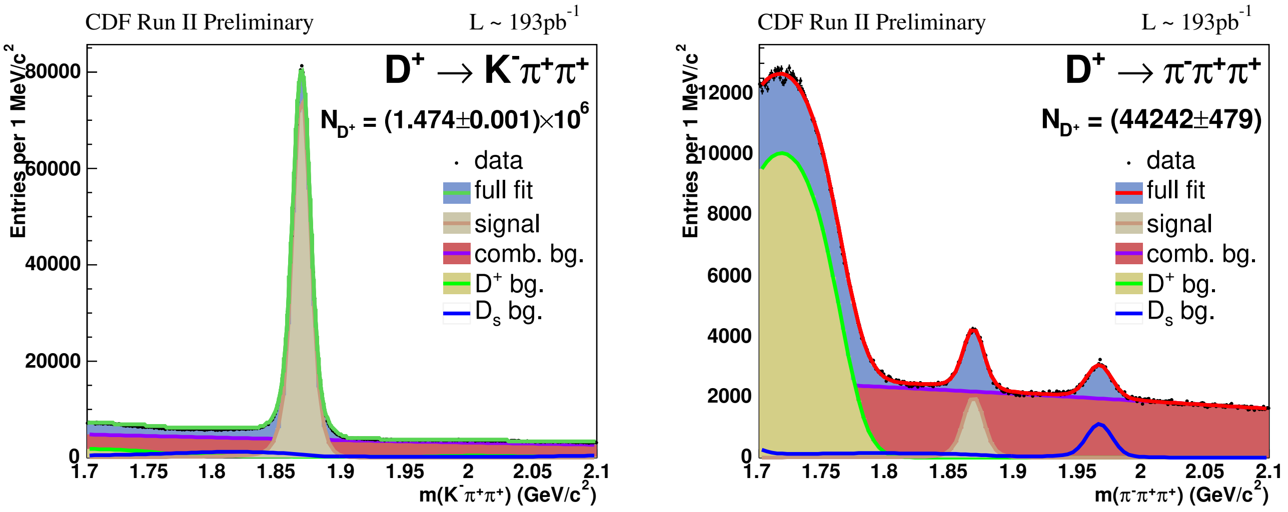

FIG. 1: Invariant mass spectra of the $D^+ \to K^-\pi^+\pi^+$ (left) and $D^+ \to \pi^-\pi^+\pi^+$ (right) candidates. The curves indicate fits to the signal and background contributions, described in the text.

ratio. B is the expected number of background events, estimated from the mass-sidebands at a distance of $3-7\sigma$ from the $D^+ \to \pi^-\pi^+\pi^+$ signal. The optimum is found to correspond to a vertex fit quality $\chi^2 \leq 4$, an impact parameter of the three-track combination $d_0(D) \leq 80\,\mu$m, and a proper lifetime $ct \geq 350\,\mu$m. The three-track invariant mass distributions with this selection are shown in Figure 1.

Both invariant mass distribution show a peak consistent with the D^+ mass. In the $\pi^-\pi^+\pi^+$ mass plot, the large structure on the low mass end is the reflection from the much more frequent $K^-\pi^+\pi^+$ mode, where a kaon is miss-assigned with the pion mass. On the high mass side of the signal, at around 1.96 GeV, appears the peak from $D_s^+ \to \pi^-\pi^+\pi^+$.

IV. SIGNAL YIELDS

We determine the branching ratio of the two modes as follows:

$$\frac{\mathcal{B}(D^+ \to \pi^-\pi^+\pi^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = \frac{N_{\pi^-\pi^+\pi^+}}{N_{K^-\pi^+\pi^+}} \cdot \frac{\varepsilon_{K^-\pi^+\pi^+}}{\varepsilon_{\pi^-\pi^+\pi^+}},$$

where $N_{\pi^-\pi^+\pi^+}$ ($N_{K^-\pi^+\pi^+}$) is the D^+ yield in the given channel, and $\varepsilon_{\pi^-\pi^+\pi^+}$ ($\varepsilon_{K^-\pi^+\pi^+}$) the selection efficiency.

To extract the signal yields for the $K^-\pi^+\pi^+$ and $\pi^-\pi^+\pi^+$ modes, we perform a binned χ^2 fit with three components to the invariant mass spectra: a D^+ signal component, a component for reflections from misreconstructed charm decays, and a combinatoric component, modeled as a second order polynomial.

The shape of the signal peaks is determined from a simulation of the signal modes, parameterized by a double Gaussian with common mean and a radiative tail that describes both the energy loss in the detector material and final state radiation, i.e. the process $D^+ \to K^-\pi^+\pi^+\gamma$, simulated with the PHOTOS package [9].

Reflections are obtained from simulated inclusive charm decays, shown in Figure 2. We find that the $D_s^+ \to K^-K^+\pi^+$ decay contributes significantly to the $K^-\pi^+\pi^+$ mass distribution. Partially reconstructed D_s^+ decays, such as $\pi^-\pi^+\pi^+\gamma$ and $K^-\pi^+\pi^+\pi^0$, add up to a non-trivial structure near the $D^+ \to \pi^-\pi^+\pi^+$ signal.

Simulation studies have shown that contributions from B decay, from charmed baryons, and from orbitally excited charm mesons have a similar shape as the combinatorial background, and can be absorbed into it.

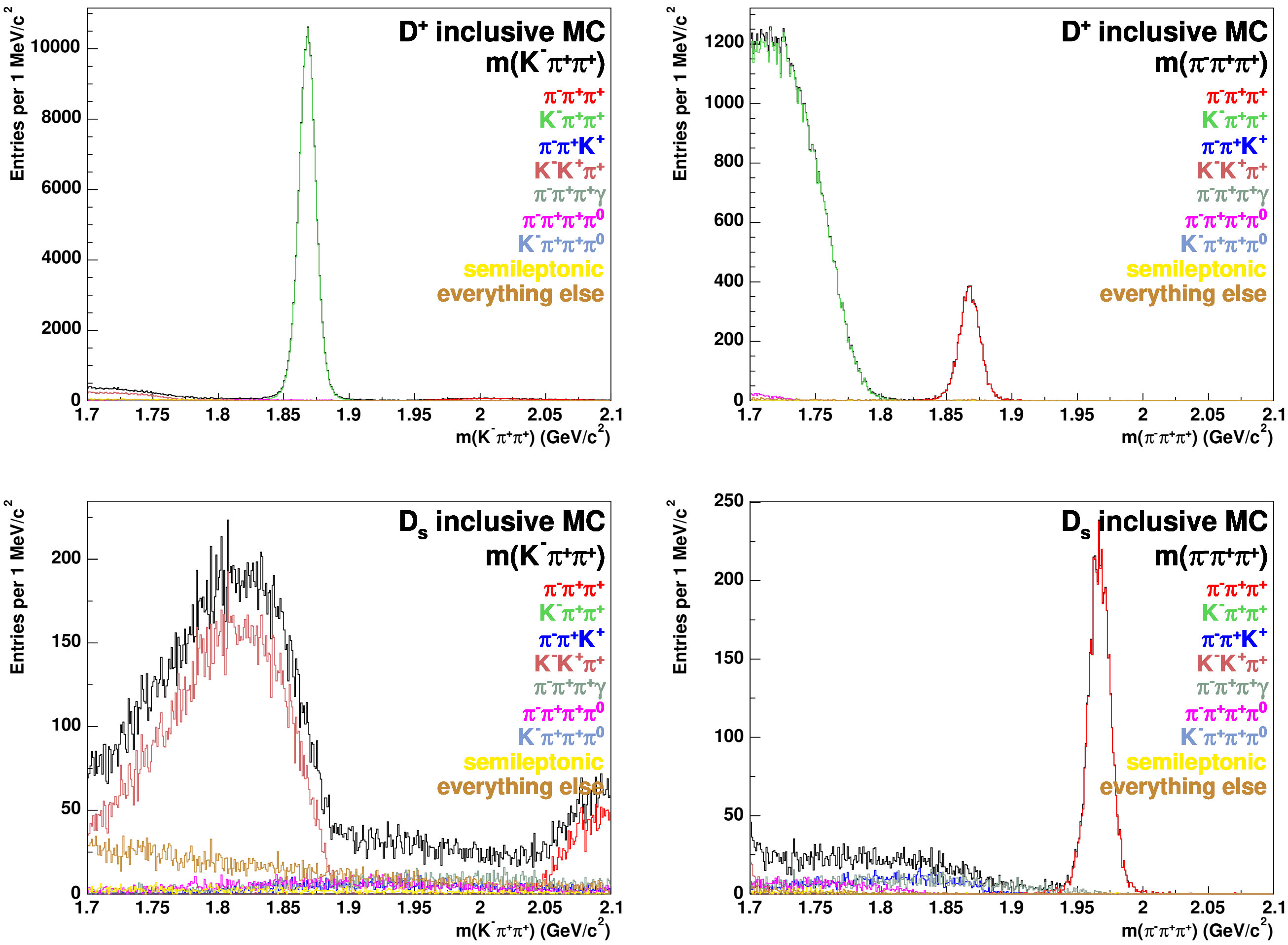

FIG. 2: Reflections from inclusive D^+ and D_s^+ decays, reconstructed as $D^+ \to K^-\pi^+\pi^+$ (left) and $D^+ \to \pi^+\pi^-\pi^-$ (right). Individual modes are differentiated by color, while the sum of all modes is drawn in black.

In the fit to the data, we let the position and width of the signal peaks float, but fix the shape and relative size of the radiative tails. The overall normalizations of D^+ and D_s^+ reflections are free parameters, while the relative fractions of each reflection are fixed from Monte Carlo.

We find $N_{\pi^-\pi^+\pi^+} = (44.24 \pm 0.48) \times 10^3$, $N_{K^-\pi^+\pi^+} = (1473.9 \pm 1.5) \times 10^3$, leading to a raw yield ratio $N_{\pi^-\pi^+\pi^+}/N_{K^-\pi^+\pi^+} = (3.002 \pm 0.033)\%$.

V. SELECTION EFFICIENCIES

To extract $\varepsilon_{\pi^-\pi^+\pi^+}/\varepsilon_{K^-\pi^+\pi^+}$, the relative efficiency of the two decays, we count the fraction of simulated signal events that pass the trigger and reconstruction requirements and the candidate selection. While the detector simulation is based on a detailed GEANT description of the detector, some effects crucial for this measurements are known to be poorly simulated and need corrections based on data.

Kaons and pions exhibit different ionization properties in the volume of the drift chamber. For a given momentum, pions travel faster than kaon, and therefore they ionize more, producing a larger number of hits in the drift chamber. This affects in particular the trigger, which has very tight requirements on the number of drift chamber hits. We use $D^+ \to K^-\pi^+\pi^+$ decays to select tracks that are unbiased by the trigger and measure the trigger efficiency for both pions and kaons as a function of the variable $\ln(p/m)/\sin(\theta)$, which is strongly correlated to the deposited energy. Corrections are applied until the efficiency in the simulation matches the efficiency measured in data.

We determine the prescale factors for the three different trigger thresholds for seven distinct periods from the

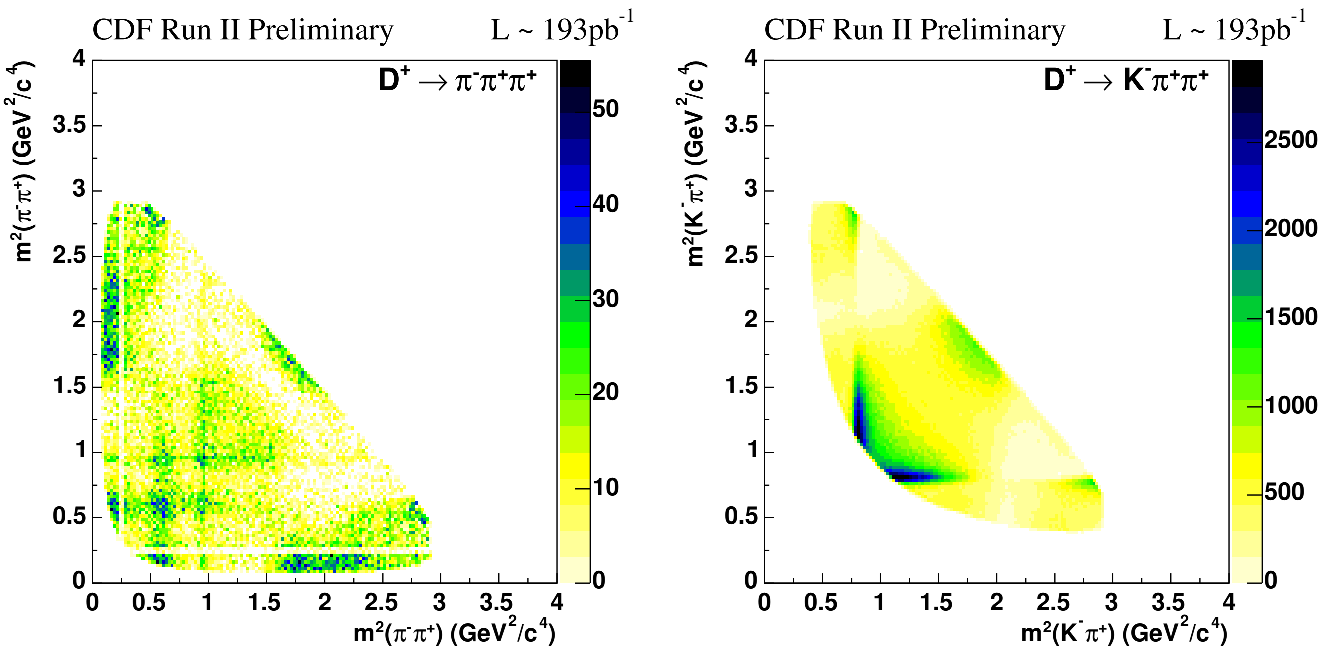

FIG. 3: Dalitz plots of the $D^+ \to \pi^-\pi^+\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ modes before acceptance correction. The normalization is arbitrary.

overlap of trigger decisions in the $D^+ \to K^-\pi^+\pi^+$ signal. Weights are applied to the detector simulation to emulate this effect.

Three-body decays typically occur through intermediate resonance states, which are well visible in a Dalitz plot, where the decays are ordered by the invariant mass squared of two combinations of the decay products, as shown in Figure 3. Since the selection efficiency depends on these variables, an accurate simulation of the resonance structure is essential. Previous measurements of the $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \pi^-\pi^+\pi^+$ resonance structures were based on small statistics, and we found they do not well describe our data. We therefore perform fits to the Dalitz plots using the same resonances as used in Ref. [10, 11] and reweight the simulation accordingly. Finally, the simulation is reweighted to reproduce the p_T spectrum measured in data.

After applying these corrections, we find a relative efficiency of $\varepsilon_{\pi^-\pi^+\pi^+}/\varepsilon_{K^-\pi^+\pi^+} = 0.8673 \pm 0.0023$, where the uncertainty is from MC statistics only.

VI. SYSTEMATIC UNCERTAINTIES

Several assumptions made in this analysis carry uncertainties that affect both the signal extraction and the relative efficiencies. The evaluated uncertainties and their effect on this measurement are summarized in Table I and described in more detail here.

$D^+ \to \pi^-\pi^+\pi^+$ decays have more final state radiation than $D^+ \to K^-\pi^+\pi^+$ decays, resulting in a more substantial tail. To account for the uncertainty with which the radiative effects may be simulated in the PHOTOS package, we vary the size of the radiative tail by $\pm 30\%$, corresponding to the largest deviations observed between next-to-leading order QED calculations and the leading order PHOTOS package, resulting in a relative uncertainty of 0.67%.

In the signal extraction, the properties of the second Gaussian are free parameters for the $K^-\pi^+\pi^+$ mode, but, due to lower statistics, they are fixed to the MC values for the $\pi^-\pi^+\pi^+$ mode. The difference in signal yield when fixing the properties of the second Gaussian also for the $K^-\pi^+\pi^+$ is small 0.03%, which we take as a systematic.

To estimate the uncertainty of our Dalitz Monte Carlo weighting, we perform the same fits on our data without the use of σ and κ resonances. This changes the relative efficiency by 0.33(0.56)% for the $\pi^-\pi^+\pi^+(K^-\pi^+\pi^+)$ modes.

To evaluate the uncertainty on the track trigger efficiency, we simplify the parameterization to depend only on p_T, which results in a 0.24% change in the relative efficiency. The track trigger efficiency uses sideband-subtracted $D^+ \to K^-\pi^+\pi^+$ signals. To account for possible reflections contaminating the left and right sidebands in different ratios, we evaluate the difference between using only the left or right sidebands, resulting in a difference of the relative efficiency of 0.26%.

Reweighting the D^+ transverse momentum spectrum by either the measured spectrum in the $K^-\pi^+\pi^+$ or the $\pi^-\pi^+\pi^+$ channel gives a difference of 0.32%.

The uncertainty on the PDG D^+ lifetime, $\tau(D^+) = 311.8 \pm 2.1\mu$m [12] translates into a an uncertainty of 0.06% on the relative efficiency.

The probability of a hadron to interact with the detector material before fully traversing the tracking system and being fully reconstructed differs between pions and kaons. We attribute a systematic uncertainty of 25% on the hadronic interaction probability, of which 20% is due to the uncertainty on the amount of material in the tracking volume and 15% is due to the uncertainty on the hadronic interaction cross-sections, which leads to an uncertainty of 0.43% on the relative efficiency for $\varepsilon_{\pi^-\pi^+\pi^+}/\varepsilon_{K^-\pi^+\pi^+}$.

We add the systematic uncertainties in quadrature and find a relative selection efficiency of $D^+ \to \pi^-\pi^+\pi^+$ to $D^+ \to K^-\pi^+\pi^+$ of 0.8673 ± 0.0083.

Uncertainty source	Assigned error (%)
$N_{\pi^-\pi^+\pi^+}/N_{K^-\pi^+\pi^+}$	
Radiative tail	0.67
Width parameter treatment	0.03
Total, signal extraction	0.67
$\varepsilon_{\pi^-\pi^+\pi^+}/\varepsilon_{K^-\pi^+\pi^+}$	
$\pi^-\pi^+\pi^+$ Dalitz structure	0.33
$K^-\pi^+\pi^+$ Dalitz structure	0.56
track trigger efficiency, fit variable	0.24
track trigger efficiency, sideband subtraction	0.26
p_T spectra rescaling	0.32
D^+ lifetime	0.06
material interactions	0.43
Monte Carlo statistics	0.26
Total, relative efficiency	0.96
ALL	1.17

TABLE I: Summary of relative systematic uncertainties.

VII. RESULT AND CONCLUSIONS

Combining the event yields, $N_{\pi^-\pi^+\pi^+}/N_{K^-\pi^+\pi^+} = (3.002 \pm 0.033 \pm 0.020)\%$, and the relative efficiency, $\varepsilon_{\pi^-\pi^+\pi^+}/\varepsilon_{K^-\pi^+\pi^+} = 0.8673 \pm 0.0083$, we find the branching ratio to be:

$$\frac{\mathcal{B}(D^+ \to \pi^-\pi^+\pi^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = (3.461 \pm 0.038(stat) \pm 0.040(syst))\%.$$

In Figure 4 we compare our preliminary measurement with the five published measurements [11, 13–16] used for the PDG2006 average [12], The six measurements are in good agreement and the CDF measurement is about three times more precise than the best published measurement.

Using the world average absolute branching ratio of $D^+ \to K^-\pi^+\pi^+$, $(9.51 \pm 0.34)\%$ [12], we find $\mathcal{B}(D^+ \to \pi^-\pi^+\pi^+) = (3.29 \pm 0.11) \times 10^{-3}$.

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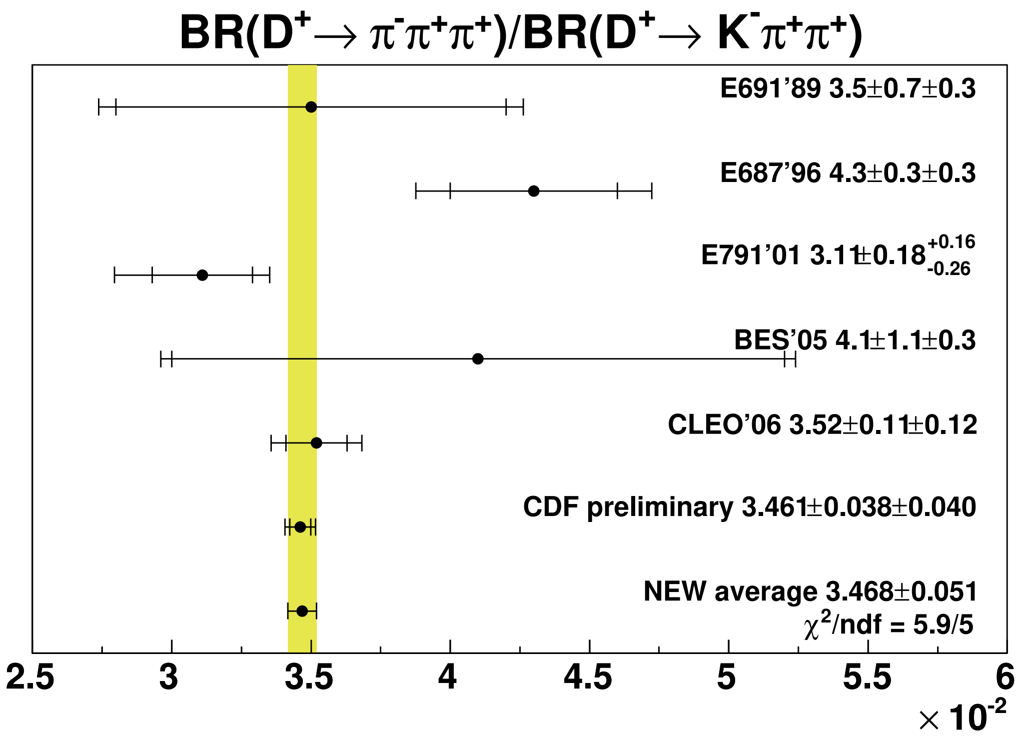

FIG. 4: Comparison of the CDF preliminary measurement of $\mathcal{B}(D^+ \to \pi^-\pi^+\pi^+)\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$ with the five published measurements used for the PDG2006 average.

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