Analyses of Semileptonic D^+ Decays

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Abstract

The preliminary analyses of the branching fraction for the decay $D^+ \to \mu^+ X$, and of the electron momentum spectrum of the decay $D^+ \to e^+ X$, are presented in this paper. The analyses rely on the recoil charge technique to identify semileptonic decays of the D^+ meson which recoils against a $\overline{D}$ meson fully reconstructed in a hadronic mode. The Lorentz boost of the D^+ is estimated with good precision by reversing the momentum of the $\overline{D}$. The electron momentum in the D^+ rest frame is obtained. Both measurements represent the first such results on the D^+.

1 Introduction

Much progress has been made in heavy flavor physics since the discoveries of open charm and bottom[1]. In particular, experimental studies of semileptonic decays of charmed hadrons have made it possible to improve the theoretical description of heavy flavored mesons [2]. However, branching fraction of the decay $D^+ \to \mu^+ X$ has not been measured. The published lepton momentum spectra for semileptonic charm decay are those of D^0 and D^+ combination produced at the $\psi(3770)$ resonance [3]. A direct measurement of the electron momentum spectrum of the D^+ remains to be done [2],[4]. The measurement of $B(D^+ \to \mu^+ X)$ can be compared to $B(D^+ \to e^+ X)$, and is useful for a test of lepton universality. The electron spectrum is important for several studies of B physics, for which $D^+ \to e^+ X$ is often the significant background.

This paper describes the work of a first measurement of the inclusive decay branching fraction[1] for $D^+ \to \mu^+ X$, and of the electron momentum spectrum of semi-electronic decays of the D^+, from analyses of the BES data collected in e^+e^- annihilations at 4.03 GeV center of mass energy.

[1]Throughout this letter, charge conjugation is implied.

2 The BES Detector and Data Sample

The BES detector has been described in details in[5]. Here we briefly describe detector elements crucial to this measurement.

Tracking is provided by a 10 superlayer main drift chamber (MDC) operated inside a 0.4 T axial magnetic field. Each superlayer contains four layers of sense wires measuring both the position and the ionization energy loss (dE/dx) of charged particles. The MDC is surrounded by a time-of-flight counter array (TOF) and an electromagnetic calorimeter (ECAL) composed of streamer tubes and lead blocks with a z position resolution of 4 cm. The muon detector system lies outside of the ECAL and consists of four layers of streamer tubes, measuring the coordinates of muons in z and in $r\phi$ with resolutions of 5 cm and 3 cm, respectively.

This analysis is based on hadronic events recorded with the BES detector during the 1992, 1993 and 1994 runs. An integrated luminosity of 22.3 pb^{-1} was collected in e^+e^- annihilations at a center-of-mass energy of 4.03 GeV at the BEPC collider[6]. The BES trigger conditions, and the criteria for the selection of hadronic events have been described elsewhere[7].

3 Analysis Techniques

3.1 Selection of Semileptonic Charm Decays

In e^+e^- annihilations at 4.03 GeV center of mass energy, charm mesons D^0 and D^+ are predominantly produced from the final states $D^*(2010)^+D^-$, $D^*(2007)^0\overline{D}^0$, $D^*(2010)^+D^*(2010)^-$, and $D^*(2007)^0\overline{D}^*(2007)^0$. Initial state radiation process $e^+e^- \to \psi(3s)\gamma$, followed by $\psi(3s) \to D\overline{D}$, and direct reaction $e^+e^- \to D\overline{D}$ also contribute to D^0, D^+ production. For all these reactions, D and $\overline{D}$ are always produced in pairs, and hadrons from sources other than D^0, D^+ decays are too slow to be well reconstructed by the BES detector. Leptons detected in a fully reconstructed D event must be from the decay of the $\overline{D}$. Using fully reconstructed D events as a sample, we can measure the inclusive decays of the D^0 and D^+.

In this paper we search for an e, or a μ recoiling against a reconstructed charm meson to select semileptonic D^+ decay events.

3.2 The Recoil Charge Technique for D^+ Identification

The identification of the D^+ is achieved by applying the recoil charge technique. The recoil charge technique has been documented in details elsewhere [8], and will be described here only briefly.

At 4.03 GeV, $D^*\overline{D}^*$ and $D^*\overline{D}$ are produced with no additional charged tracks. Charged pions arising from D^* decays are very slow, and are undetected in the BES detector. As a result, only charged particles from decays of $D^0\overline{D}^0$, $D^+\overline{D}^0$, and D^+D^- pairs are visible to BES. Let Q_D be the charm flavor of the reconstructed D meson, and Q_{rec} be the total charge of tracks recoiling against the D meson. Ideally, Q_{rec} would be 0 for a recoiling neutral D, and ± 1e for a recoiling charged D. In reality, limited acceptance of the detector results in loss of charged tracks, which smears the Q_{rec} distribution. Furthermore, Q_D and Q_{rec} are anti-correlated for a charged D in the recoil. The recoil charge technique selects neutral and charged D mesons according to

$$Q_{rec} = 0, \quad \text{or} \quad Q_{rec} = Q_D = +1, \quad \text{or} \quad Q_{rec} = Q_D = -1 \quad \text{for} \quad \mathrm{D}^0 \tag{1}$$

and

$$Q_{rec} \cdot Q_D < 0 \quad \text{for} \quad \mathrm{D}^+ \tag{2}$$

The selections allow for a maximum error of ± 1e in Q_{rec}. Table 1 summarizes the efficiencies, and the misidentification rates of the recoil charge tag for D^0 and D^+, as measured with kinematically selected $e^+e^- \to D^+D^-$, and $e^+e^- \to D^0\overline{D}^0$ events. These numbers are checked with Monte Carlo simulations. We find excellent agreements between the simulation and the data.

Table 1. Efficiencies and Misidentification Rates of the D Charge Tag

Method of Measurement	D Meson Type	ε_D Tag Efficiency (%)	f Tag Misid (%)
Monte Carlo	D^0	74.3±1.7	20.4±0.9
	D^+	77.2±1.3	19.6±0.7
	D^0,D^+ average	76.1±1.1	20.0±0.5
$e^+e^- \to D\overline{D}$ data	D^0	74±8	19±6
	D^+	83±8	13±7
	D^0,D^+ average	79±4	16±4

3.3 Reconstruction of Electron Momentum

The momentum of the electron, measured in the lab frame, must be transformed back to the D^+ rest frame in order to measure its momentum spectrum.

The momentum of the D^+ meson in the BES data lies in the range 50−600 MeV/c, corresponding to a Lorentz boost factor $\beta\gamma$=0.0.3−0.32. This boost is very small for electrons resulted from semileptonic D^+ decays, which are highly relativistic because of the small electron mass. For example, for a 510 MeV/c electron the $\beta\gamma$ factor is 1000, far larger than that of the D meson. The difference between the observed electron momentum in the lab frame, and its momentum in the D^+ rest frame, is very small along the direction of the D^+ meson.

The reversed momentum vector of the fully reconstructed $\overline{D}$ meson is used as an estimate for the D^+ meson which decays semileptonically. Figure 1 shows the cosine of the angle between the estimated D^+ direction and the true direction for this method. The rms deviation of the angle estimate is 8^o about the true momentum direction. Figure 2a−b show the uniformity, and the resolution, of the electron momentum. This resolution is determined to be 16 MeV/c, with a small shift of -2 MeV that is due to the final state radiation of the electron. To set the scale, the momentum measurement of BES carries errors of 10 MeV, and 24 MeV, for electrons of 500 MeV/c, and 1.0 GeV/c in momentum, respectively. Taking into account of all the errors, the overall resolution on the electron momentum is adequate for a measurement of the electron spectrum of the decay $D^+ \to e^+X$.

Figure 3a–b compare the reconstructed electron momenta in the D^+ rest frame to the generated distribution. The two distribution exhibit the same shape, very close means and rms spreads.

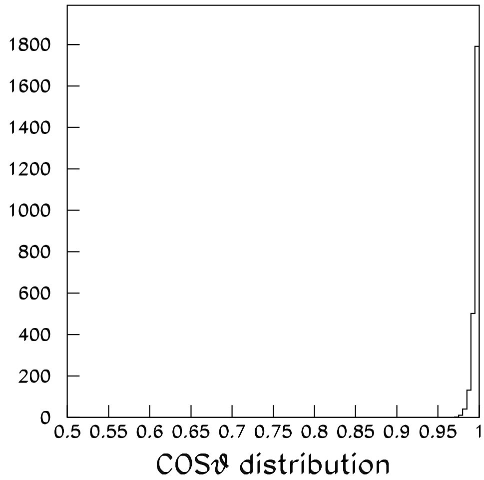

Figure 1: Deviation between the estimated D^+ direction, and the true D^+ direction, for simulated $e^+e^- \to D^*\overline{D}$, $D^+ \to e^+X$ events.

4 The Analysis

4.1 Event Selection and Particle Identification

The event selection, particle identification, reconstruction of charmed mesons, and identification of the D$^+$ are identical to those used in [8].

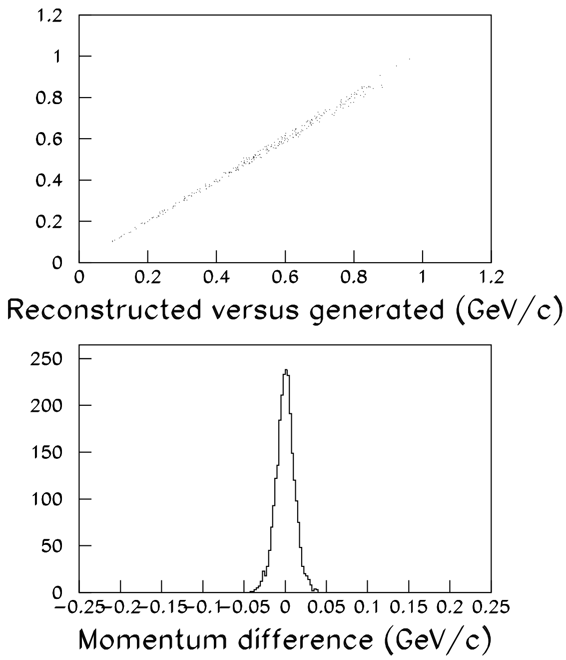

Figure 2: (a) Reconstructed electron momentum versus the generated electron momentum; (b) difference between the reconstructed electron momentum and the generated electron momentum, of simulated $e^+e^- \to D^*\overline{D}$, $D^+ \to e^+X$ decays.

A correction of ionization energy loss in the beam pipe is made for all charged tracks. A small correction of -0.42% is also applied to momenta of all charged tracks to compensate for a shift in the BES magnetic field.

4.2 Monte Carlo Simulations

In our simulation we generate physics interactions $\mathrm{e^+e^-} \to \mathrm{D^*\overline{D}}$ and $\mathrm{e^+e^-} \to \mathrm{D^*\overline{D^*}}$. Several combinations of $\mathrm{D^0\overline{D^0}}$, $\mathrm{D^+\overline{D^0}}$ and $\mathrm{D^+D^-}$ are selected from the intermedia states $\mathrm{D^*\overline{D}}$ and $\mathrm{D^*\overline{D^*}}$. The $\mathrm{D^0}$ and $\mathrm{D^+}$ mesons are decayed into final states $\mathrm{K^-n(\pi)^{0+}}$, where n=1,3 for $\mathrm{D^0}$ and n=2 for $\mathrm{D^+}$, which are the modes through which we reconstruct these charm mesons in the measurement. The $\mathrm{D^-}$ is decayed into $\ell^-\pi^0\nu$, $\ell^-\mathrm{K^0}\nu$, and $\ell K^{0*}\nu$.

The generated physics events are processed by the BES detector simulation program, and are reconstructed using the BES offline reconstruction package. These simulated events are analyzed to guide the selection of cuts and to determine the detection efficiencies relevant

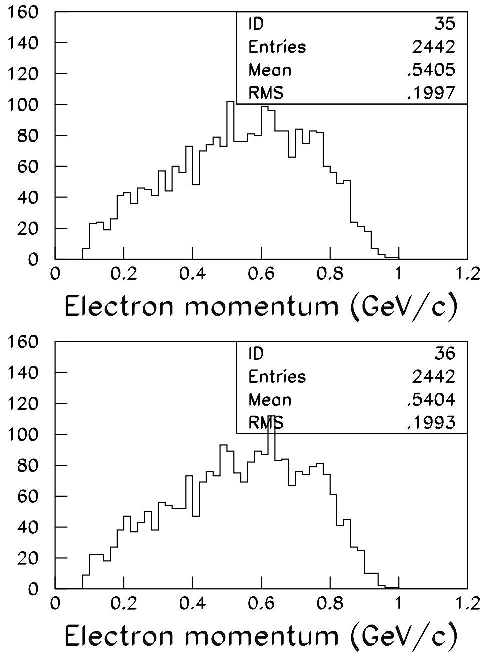

Figure 3: (a) spectrum of generated electron momentum (top); (b) spectrum of reconstructed electron momentum (bottom), of simulated $e^+e^- \to D^*\overline{D}$, $D^+ \to e^+X$ decays.

to our measurements.

4.3 Reconstruction of D Mesons and Identification of the D^+

The reconstruction of D mesons and the identification of the D^+ in analysis are identical to the procedure described in [8].

The distributions of $Kn\pi$ combinations are shown in Figure 4a−c, where clear signal is observed in each mode. A total of 8944±164 D^+, D^0 events are reconstructed in this single D tag sample. We determine that, for this sample, the recoiling side of the D events contain 6159±135 D^0's, and 2785±92 D^+'s, where the errors are statistical only. To estimate the systematic uncertainty on the numbers of neutral and charged D mesons in the recoil, we include the errors on the efficiency and misidentification of the recoil charge tag which are measured directly from data using $\mathrm{e}^+\mathrm{e}^- \to \mathrm{D}\overline{\mathrm{D}}$ events. We estimate the systematic error on each D specie to be ±268 events.

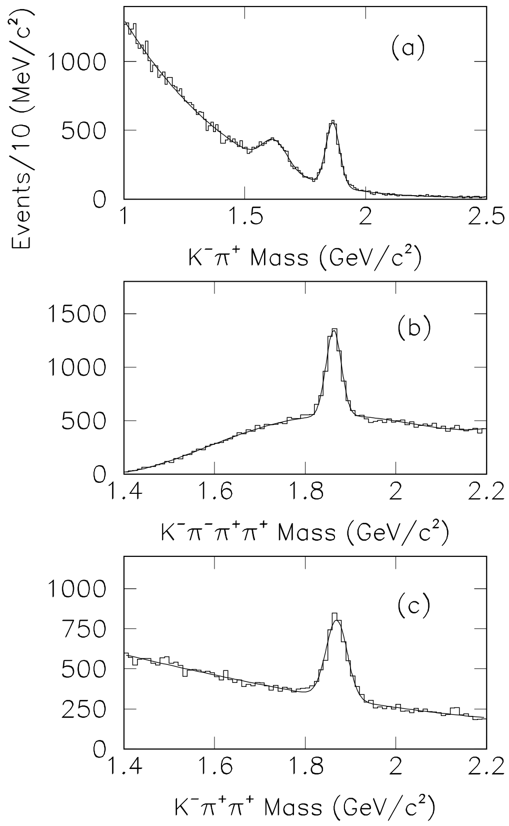

Figure 4: The invariant mass distribution of (a) $K^-\pi^-$, (b) $K^-\pi^+\pi^+\pi^-$, and (c) $K\pi^+\pi^+$.

4.4 Reconstruction of $\mathrm{D}^+ \rightarrow \mu^+\mathrm{X}$ Events

Muons are identified based on their associated muon counter hits only. For a track with transverse momentum greater than 0.75 GeV/c, at least two good muon layer hits have to be matched to the track. Above a transverse momentum of 0.95 GeV/c, all three muon layers must have good associated hits. Here good hits are those that are within the projected ϕ angle range of the charged track, where this range is determined from studying a cosmic ray muon sample

A muon is searched in the recoil against the $Kn\pi$ combination. For events that pass this selection, the $Kn\pi$ mass of the surviving events are fit to determine the number of $D-\mu$ candidates. To evaluate the background due to muon misid, a wrong sign, *i. e.,* the $\mathrm{D}\mu^+$ events, is also studied as an control sample.

Table 2 summarizes the preliminary numbers of $D-\mu$ events. After wrong sign subtraction, 95$\pm$21 $D \rightarrow \mu^+X$ decays are found. Note that there can be additional backgrounds that a wrong sign subtraction does not eliminate. In that case, the actual number of $D \rightarrow \mu^+X$ signal events would be lower.

Table 2. $D^{0,+} \to \mu^+ X$ Events (*preliminary*)

Mode	No of Dμ^-	No of Dμ^+	Excess
$D^0 \to K^-\pi^+$	35±7	14±6	21±9
$D^0 \to K^-(3\pi)^+$	69±12	30±9	39±15
$D^+ \to K^-(2\pi)^{++}$	45±9	10±5	35±10
Total	149±17	54±12	95±21

The charged D tag is applied to the $Kn\pi - \mu$ events to identify $D^+ \to \mu^+ X$ events. In all D decay modes, clear signals are observed in the right sign $(D - \mu^-)$ combinations, while few events are seen in the wrong sign $(D - \mu^+)$ combinations. Figure 5 shows the $Kn\pi$ mass distributions for events containing an identified muon as being from D^+ decays. An excess of 58±12 events in the right sign $D\mu$ over the wrong sign, corresponding to $D^+ \to \mu^+ X$, is observed. The branching fraction for $D^+ \to \mu^+ X$ will be determined in a future analysis

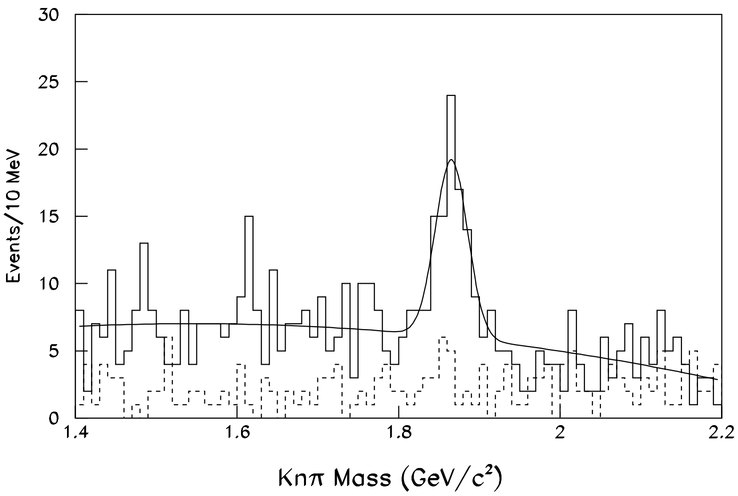

Figure 5: The invariant mass distribution of $K^- n\pi^+$ for right sign $D\mu$ combination (solid histogram), and wrong sign combination (dashed histogram).

work.

4.5 Momentum Spectrum of $D^+ \to e^+X$ Events

Three detector components, the main drift chamber, the TOF, and the shower counter, are used for electron identification. The dE/dx and TOF measurements for charged tracks must be consistent with those of an electron. The E/p ratio, where E is the total shower energy deposited by the charged track in the shower counter, is required to be within a range about 1.0. The range is determined from a sample of radiative Bhabha events and depends on the momentum of the track.

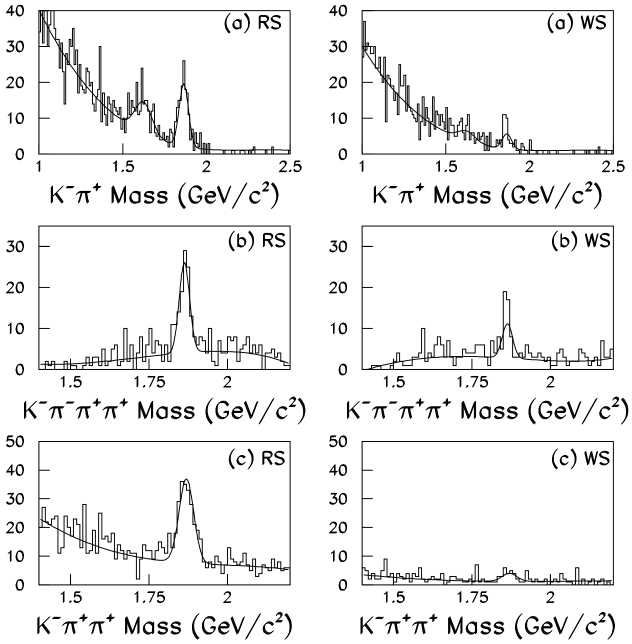

Figure 6: The invariant mass distribution of (a) $K^-\pi^-$; (b) $K^-\pi^+\pi^+\pi^-$; and (c) $K^-\pi^+\pi^+$, for events containing an electron candidate, after the charged D tag has been applied.

Similar to the muon analysis, the $Kn\pi$ versus e events are searched, the resulting $Kn\pi$ mass distributions are shown in Figure 6a$-c$. The fit numbers of events are presented in Table 3, for right (wrong) sign combinations. An excess of 306$\pm$27 events in the right sign combination is observed, corresponding to the decay $D \to e^+X$.

Table 3. $D^+ \to e^+X$ Events (*preliminary)*

Mode	No of De$^-$	No of De$^+$	Excess
$D^0 \to K^-\pi^+$	121±13	28±7	93±21
$D^0 \to K^-(3\pi)^+$	91±11	35±8	56±14
$D^+ \to K^-(2\pi)^{++}$	173±16	16±6	157±17
Total	385±23	79±12	306±27

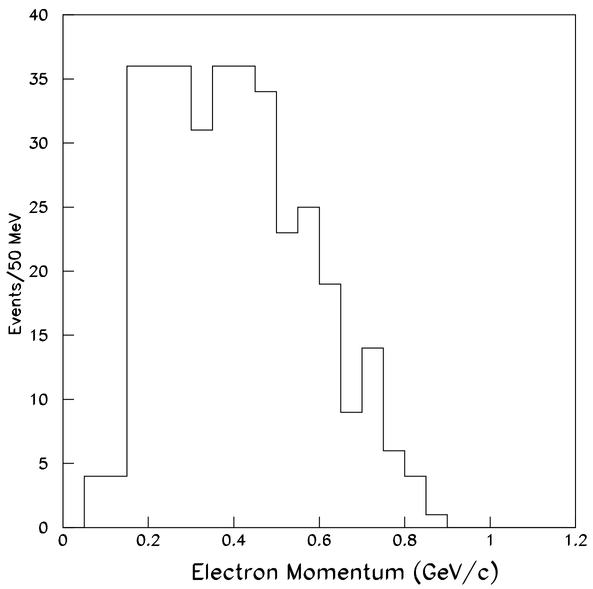

Figure 7: Measured electron momentum distribution inside D^+ rest frame. A wrong sign background subtraction has been performed. Other possible backgrounds can present in the distribution.

Figure 7 shows the observed (*without efficiency correction*) momentum distribution of 306±27 $D^+ \to e^+X$ events selected. Note that this spectrum is obtained with only wrong sign subtraction; backgrounds can remain, and will be further studied.

5 Results

Clear excess in $D-\mu^-$ over $D-\mu^+$ in the BES data corresponds to the decay $D^+ \to \mu^+X$. A direct measurement of $B(D^+ \to \mu^+X)$ will be performed in the near future. This would be a first such measurement.

The $D^+ \to e^+X$ analysis yields a statistical significant sample for studying electron momentum, as displayed in Figure 7. The observed electron momentum spectrum is consistent with that of a D sample with approximately equal mixture of D^+ and D^0 [2]. The fact that the distribution extends to 0.8 GeV, and that very few events go beyond this momentum value, is consistent with exclusive measurements of $D^+ \to e^+X$ which is found to be dominated by the Cabibbo allowed process $c \to se^+\nu$ [4].

As a consistent check, we evaluate semi-electronic branching fraction for the D^+ corresponding to the observed events. The detection efficiency, including detector acceptance, electron identification and the recoil charge efficiency, is determined to be 54%. From a total of 2785±92±268 D^+ decays, we estimate $B(D^+ \to e^+X)$ to be (20.3±1.8±2.1)%, where the first error is statistical, the second is the systematic error due to the uncertainty on the total number of D^+ mesons in the recoil. No other systematic errors have been evaluated and assigned. This estimated branching fraction agrees well with the value of (17.2±1.9)% of PDG96 [4].

6 Summary

Based on a sample of 8944±164±79 D^0, D^+ events reconstructed in the BES data, we have observed semileptonic D^+ decays in both e and μ modes. A first direct measurement of $B(D^+ \to \mu^+X)$ is possible and will be carried out in BES. The electron momentum spectrum for the decay $D^+ \to e^+X$ has been directly measured for the first time.

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