Study of the Leptonic Decay $D^+ \to \mu\nu^\dagger$

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Abstract

The Beijing Spectrometer (BES) experiment has studied the purely leptonic decays of the D^+ meson produced in $e^+e^- \to D^*D$ at a center mass energy of 4.03 GeV. A search was performed for $D^+ \to \mu\nu$ recoiling from $\pi^0 D^+(\to K^-\pi^+\pi^+, K^0\pi^+)$ and $\pi^+ D^0(\to K^-\pi^+, K^-\pi^+\pi^+\pi^-, K^0\pi^+\pi^-)$. A single event candidate was found in the reaction, $e^+e^- \to D^{+*}D^-$, where, $D^{*+} \to \pi^+ D^0$ with the D^0 decaying into $K^-\pi^+$ and the recoiling decay is $D^- \to \mu\nu$. This yields a preliminary result for the 90% C.L. branching ratio limit of BR$(D^+ \to \mu^+\nu_\mu) < 0.32\%$.

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I. INTRODUCTION

The purely leptonic decays of the D meson proceed via the annihilation of the charm and anti-down quarks into a virtual W boson. The decay rate of this process is determined by the wavefunction overlap of the two quarks at the origin and is parametrized by the meson decay constant f_D. The decay width of the D^+ can be written as [1]:

$$\Gamma(D^+ \to \ell^+\nu) = \frac{G_F^2|V_{cd}|^2}{8\pi} f_D^2 m_D m_\ell^2 (1 - \frac{m_\ell^2}{m_D^2})^2 \tag{1}$$

where G_F is the Fermi constant, V_{cd} is the c$\rightarrow$d CKM matrix element [2], m_D is the D mass, and m_ℓ is the lepton mass.

There are many theoretical models to predict f_{D_s} and f_D(Cabbibo-suppressed decay), varying from 90 to 350 MeV [1,3–8]. The measurements of f_D and f_{Ds} are of special value for theoretical extrapolations of f_B which are very difficult to directly measure as the branching ratio for $B^+ \to \mu\nu$ is expected to be very small. However, the value of f_B is of considerable importance to predictions of $B^0\bar{B}^0$ mixing [9] and hence imformation on leptonic charm meson decays will be very useful. To date, there are a few experimental measurements on f_{D_s} from the WA75 [10] , CLEO [11] and BES [12] groups. Only a branching ratio upper limit for $D^+ \to \mu^+\nu_\mu$ of 0.07% (corresponding to f_D¡290 MeV at 90% C.L.) has been set by the Mark III [13].

In this paper preliminary results of a search for the Cabbibo suppressed decay $D^+ \to \mu^+\nu$ are reported [14]. The data was collected by the BES detector at the Beijing e^+e^- Collider(BEPC). A total integrated luminosity of 22.3 $(pb)^{-1}$ (from large angle Bhabha scattering events) was taken at a center of mass energy of 4.03 GeV. At this energy, $D^*\bar{D}^*$, $D^*\bar{D}$ and $D\bar{D}$ events are produced. These reactions can be selected by detecting the hadronic D^0 or D^+ decay in the momentum ranges of 0-340, 340-700 and 760 MeV, respectively. A large cross-section for D^*D production is observed and this reaction is used in this paper to detect $D \to \mu\nu$ recoiling against either π^+D^0 in $e^+e^- \to D^{*+}D^- \to \pi^+D^0D^-$ or $(\gamma,\pi^0)D^+$ in $e^+e^- \to D^{*+}D^- \to (\gamma,\pi^0)D^+D^-$. In this analysis only the D^0 or D^+ hadronic decays and the muon track are fully reconstructed. The neutrino is indirectly detected by the missing mass (recoiling from the detected muon and hadronic D decay) which is nearly zero due to the massless neutrino and low energy soft pion. In a Monte Carlo study, the charged π from D^{+*} is found to be too low in energy to be reconstructed and consequently this track is ignored in this analysis.

II. BES DETECTOR

The BES(BEijing Spectrometer) is a solenoidal magnetic detector [15]. The four-layer central drift chamber(CDC) outside beampipe is used for the trigger. Charged tracks are measured (spacial position and energy loss) in a forty-layer main drift chamber(MDC) which covers 85% total solid angle. The momentum resolution is 1.7% $\sqrt{1+p^2}$(p in GeV/c) and the dE/dx resolution is about 11% for hadron tracks. The 48 scintillation counters give the time-of-flight(TOF) measurement of charged tracks with a resolution of 450 ps for hadrons. A 12 radiation length, lead-gas barrel shower counter(BSC), operating in self-quenching streamer mode, measures the energies of electrons and photons over 80% total solid angle with an energy resolution of $28\%/\sqrt{E}$(GeV). The solenoidal magnet provides a 0.4 T magnetic field in the central tracking region of the detector. Three double layers of muon counters instrument the magnet flux return, and serve to identify muons of momentum greater than 0.5 GeV/c. Endcap time-of-flight and shower counters extend coverage to the forward and backward regions.

The event trigger requires at least one barrel TOF hit within a time window of 40 ns, one hit in the outer two layers of the CDC and one charged track reconstructed by the online trigger logic using the hit pattern in the MDC, and a total energy in the BSC above 200 MeV.

III. ANALYSIS METHOD

The analysis begins with a selection of the hadronic $D^{\pm}$ and D^0 decays. Two $D^{\pm}$ decay modes $(K^-\pi^+\pi^+, K^0\pi^+)$ and three D^0 decay modes $(K^-\pi^+, K^-\pi^+\pi^+\pi^-, K^0\pi^+\pi^-)$ were studied. Each of the charged tracks except those from K^0 candidates was required to come from within 1.0 cm of the interaction point in the transverse plane, and from within 15 cm along the beam direction. Also, the polar angle(θ) of the charged tracks had to satisfy $\mid cos\theta \mid\leq 0.85$ to provide reliable tracking and barrel TOF information. The dE/dx and TOF measurements were required to be consistent with the mass hypothesis assigned to the track. The kaon assignment required, ${\chi^2}_K < {\chi^2}_\pi$, where the χ^2 is the joint chi-square of the available dE/dx and TOF information for the track in question. The momentum range of the reconstructed D^+ and D^0 is restricted from 400 to 600 MeV to ensure it is from $e^+e^- \to D^{+*}D^-$ decay mode. Also the lower momentum limit will remove background from misidentified $e^+e^- \to D_sD_s$ events which would have a momentum below 400 MeV. For the K^0, the invariant mass of $\pi^+\pi^-$ is limited to 498 ± 30 MeV and the decay time estimated from the decay length was from 0.02 ns to 0.35 ns. The resulting mass plots of the charged and neutral decay modes are shown in Fig.1(a),(b),(c),(d),(e).

In order to normalize the number of produced D^*D events in this data sample, only the $D^+ \to K^-\pi^+\pi^+$ inclusive decay mode was used. The invariant mass of $K^-\pi^+\pi^+$ candidates is plotted in Fig.1(a) and a clear signal at the D^+ mass position is seen. An unbinned maximum likelihood fit yields a D^+ mass value of 1868.6 ± 1.1 MeV and 1407 ± 72 $D^+ \to K^-\pi^+\pi^+$ events. The curve shown in Fig.1(a) corresponds to the fitted result.

The formula used to calculate the production cross section of $D^{+*}D^-$ is:

$$\begin{aligned} N = & L\sigma(e^+e^- \to D^{+*}D^-)\varepsilon Br(D^+ \to K^-\pi^+\pi^+) \\ & \times(1 + Br(D^{+*} \to \pi^0D^+)) \end{aligned} \tag{2}$$

where ε is the efficiency for reconstructing $D^+ \to K^-\pi^+\pi^+$, and L is the integrated luminosity of the data. N is the observed number of $D^+ \to K^-\pi^+\pi^+$ events. The efficiency was calculated by Monte Carlo simulation to be 21.5%. From equation (2), a production cross section of $\sigma(e^+e^- \to D^{+*}D^-) = 2.47 \pm 0.22$ nb is obtained. Including the measured production rate, the efficiencies, and the known D^+ and D^0 branching ratios, the number of D^+ and D^0 events were estimated and listed in the second column of TABLE I. The total sample of observed $D*^+ D^-$ events corresponds to $\sim$4700.

Using the above sample of selected D^*D events and requiring the mass of the hadronic decay to be within 3 standard deviations of the D^+ or D^0 mass, the leptonic decay, $D \to \mu\nu$, was investigated in the recoil system. The recoiling portion of the event is required to have a single charged track identified as a muon. The track momentum must be from 700 MeV to 1,250 MeV. In this momentum range, the track is required to have at least two hits in the muon counters with the hits in the muon counters lying within 5σ of the extrapolated drift chamber track. For the events with the D^0 decay modes, no isolated photons [16] are allowed. For the events with the D^+ decay modes which can have a slow π^0, if there are more than two isolated photons or the maximum photon energy is larger than 400 MeV, the event is rejected.

After the above selections are applied to the D^*D event sample, there are only a few remaining muon event candidates in the hadronic modes, $K\pi\pi$, $K\pi\pi\pi$ and $K\pi$. Two-dimensional plots of muon momentum(Y axis) vs the square of missing mass(X axis) are shown in Fig.2 for the three decay modes which have some remaining events. The data events appear as solid black dots in Fig. 2. Monte Carlo simulations for signal and backgrounds were performed. In Fig. 2, the left contour is the Monte Carlo signal(D muon decay) region and the right contour is the Monte Carlo background(D semileptonic decay) region. The signal and backgrounds regions are well separated. One signal candidate is observed in $K^-\pi^+$ tag mode(Fig.2(b)) in the left signal region. The properties of the candidate are listed in TABLE II and the event display is shown in Fig.4. The event is very clean with 2 hits in the muon counter for the muon track, no extra photons and pion and kaon tracks that are well identified by the dEdX and TOF systems

To estimate backgrounds a high statistics Monte Carlo simulation was performed including D_sD_s and D^*D production. Their total contributions in the signal region are listed in the fourth column of TABLE I. The main backgrounds are found to be $D^- \to \pi^-\bar{K}^0$, $D^- \to \mu^-\bar{\nu}\bar{K}^0$ and $D^- \to \mu^-\bar{\nu}\pi^0$ for the first three modes and from D_sD_s in the last two modes in TABLE I.

As a further check, the region outside the signal area was studied. Two events in Fig.2(a) ($K^-\pi^+\pi^+$ mode), two events in Fig.2(b) ($K^-\pi^+$ mode) and one event in Fig.2(c) ($K^-\pi^+\pi^+\pi^-$ mode) are observed. Using Monte Carlo simulation, the D semi-leptonic decays were found to be the largest contributor in this region. The calculated number of events outside the signal region was estimated to be 7.2 and is consistent with the number of observed events.

IV. RESULTS

For the calculation of an upper limit and a branching ratio of $D^- \to \mu^-\bar{\nu}$, a likelihood function was constructed combining Poisson distributions of each decay mode. The Poisson distribution included the number of observed events, the estimated background and the detector efficiencies of the five channels used in this analysis. The efficiency has been summarized in the third column of TABLE I. The likelihood function plot is shown in Fig. 3. By integrating the likelihood function we obtain a 90% upper limit for the branching ratio of

$$Br(D^- \to \mu^-\bar{\nu}) < 0.32\%. \tag{3}$$

If we assume that the single event is a $D^- \to \mu^- \bar{\nu}$ decay, the resulting branching ratio from the likelihood curve with fit errors is, Br($D^- \to \mu^- \bar{\nu}$)=$0.063^{+0.151}_{-0.039}$%. The one standard deviation fit errors on the branching ratio are set by 68% of the area between the peak of the likelihood (0.063) and infinity for the plus error and 68% of the area between the 0 and 0.063 for the minus error.

The systematic errors are estimated by varying the event selection criteria, the background estimates by 50% and the value of $L \times \sigma$ by 1 standard deviation. Adding these errors linearly, the value for the systematic errors are obtained. The final value for the branching ratio is

$$Br(D^- \to \mu^- \bar{\nu}) = 0.063^{+0.151+0.189}_{-0.039-0.019}\%. \tag{4}$$

where the first errors are due to the fit and the second are the systematic errors. By using equation 1 and relation $Br(D^- \to \mu^- \bar{\nu}) = \frac{\tau_D}{\hbar}\Gamma(D^- \to \mu^- \bar{\nu})$, the D meson decay constant f_D is estimated. The 90% C.L. upper limit for f_D is

$$f_D < 554\text{MeV} \tag{5}$$

and for a single event signal, it is

$$290^{+200+290}_{-170-50}\text{MeV}. \tag{6}$$

The first error is the statistical, determined from the likelihood function, and the second error is the systematic error caused by uncertainties in the efficiency, the cross section and background estimation.

V. CONCLUSIONS

In summary we have searched for the leptonic decay $D^+ \to \mu\nu$. One event candidate was observed. An upper limit was obtained and a branching ratio was estimated. Both results are preliminary. The estimate of the branching ratio based on one event is equal upper limit set by the Mark III experiment which did not detect any events. From theoretical estimations, we expect f_D to be comparable to f_{Ds} and in comparison to recent measured values of f_{Ds} our results are consistent.

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FIGURES

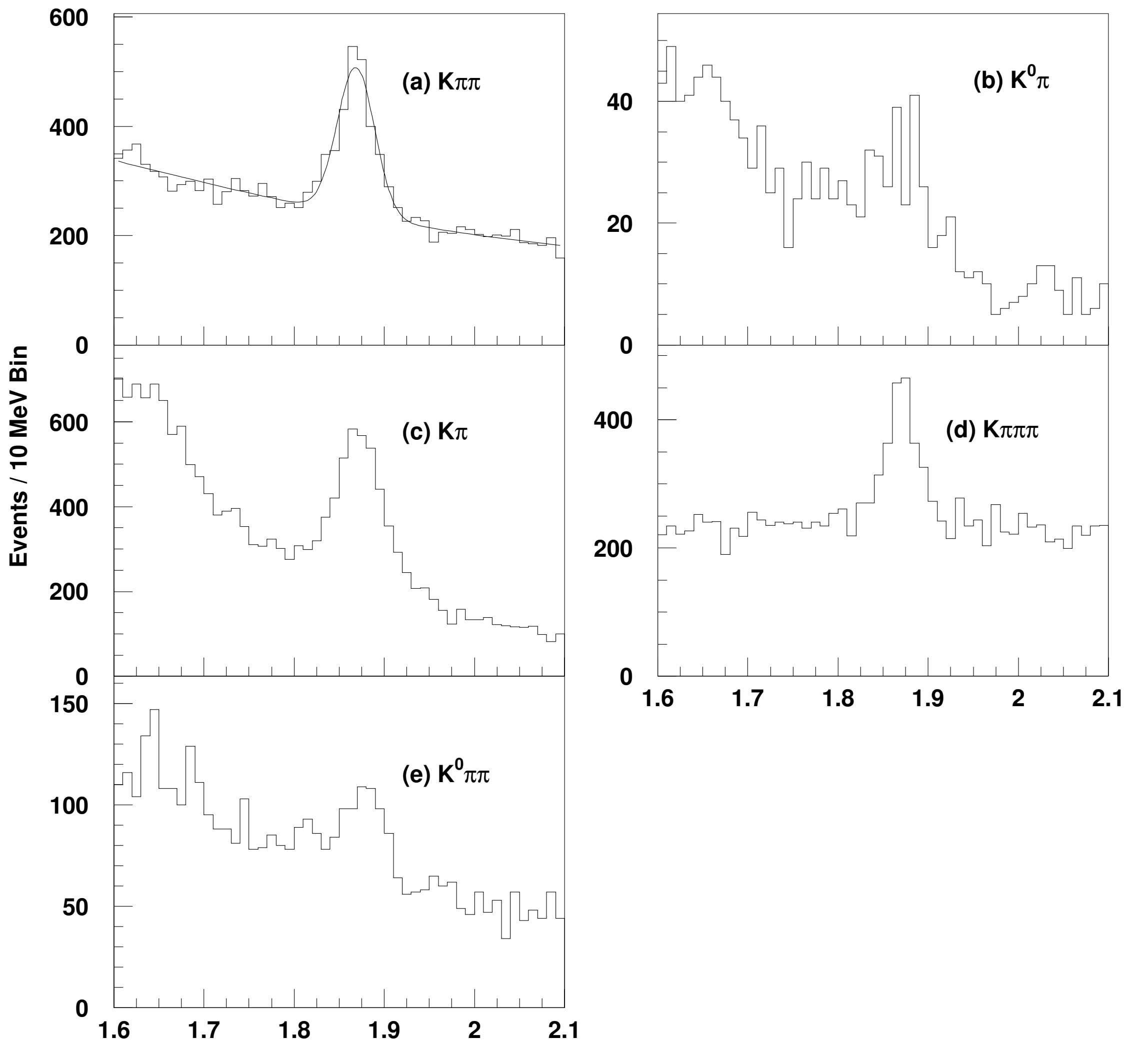

FIG. 1. Invariant Mass of Each Decay Mode

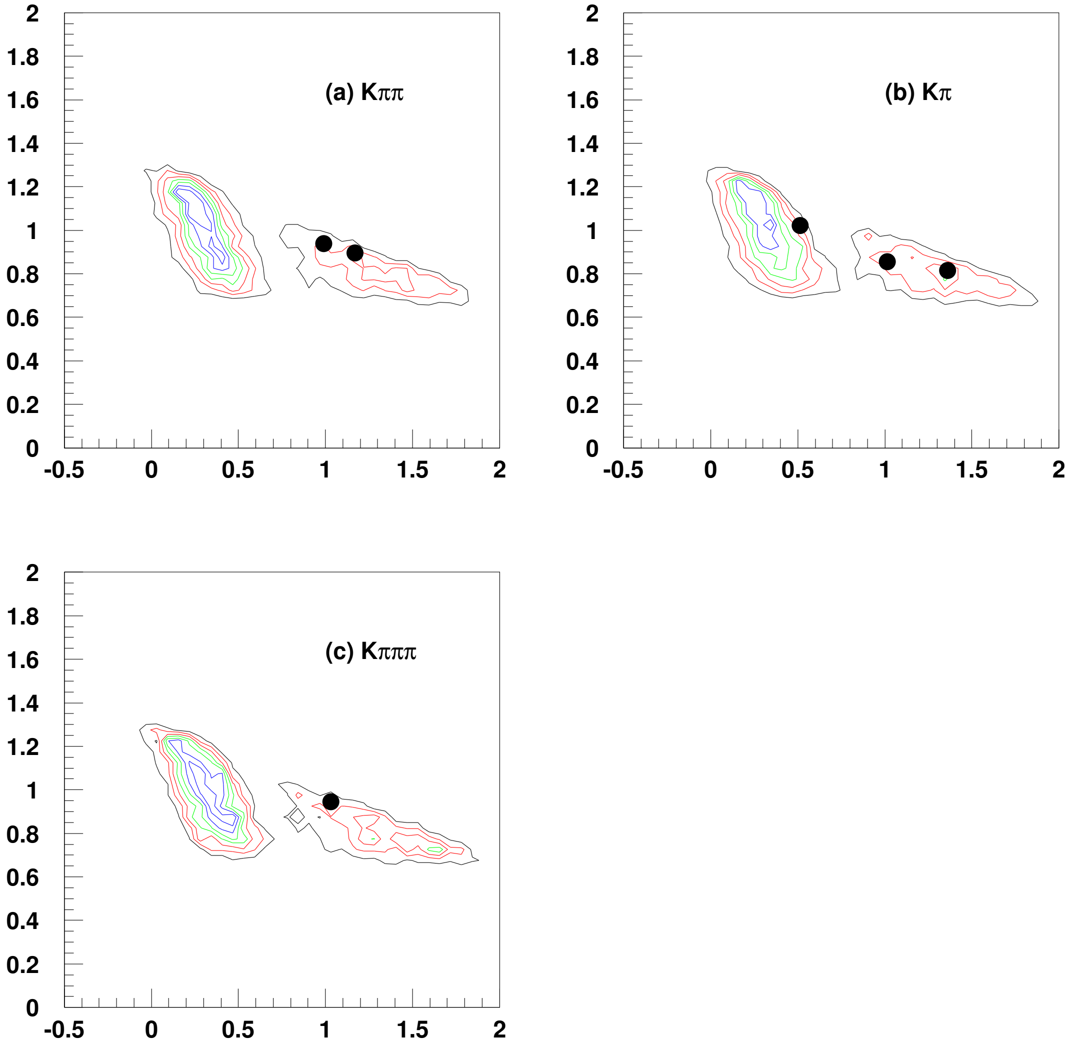

FIG. 2. Muon Momentum vs $M^2{}_{miss}$

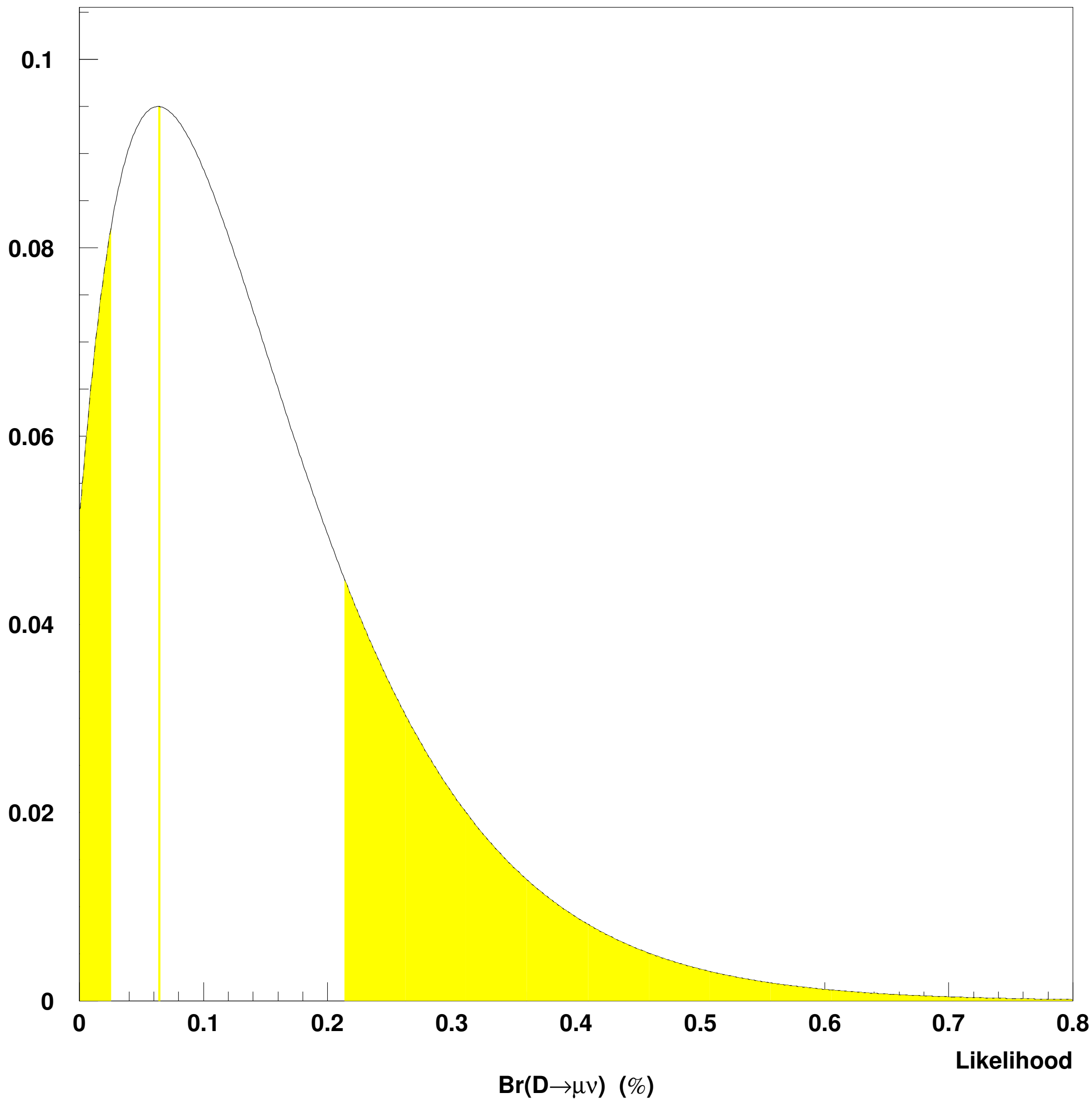

FIG. 3. Likelihood function of $(D^- \to \mu^- \bar{\nu})$ branching ratio

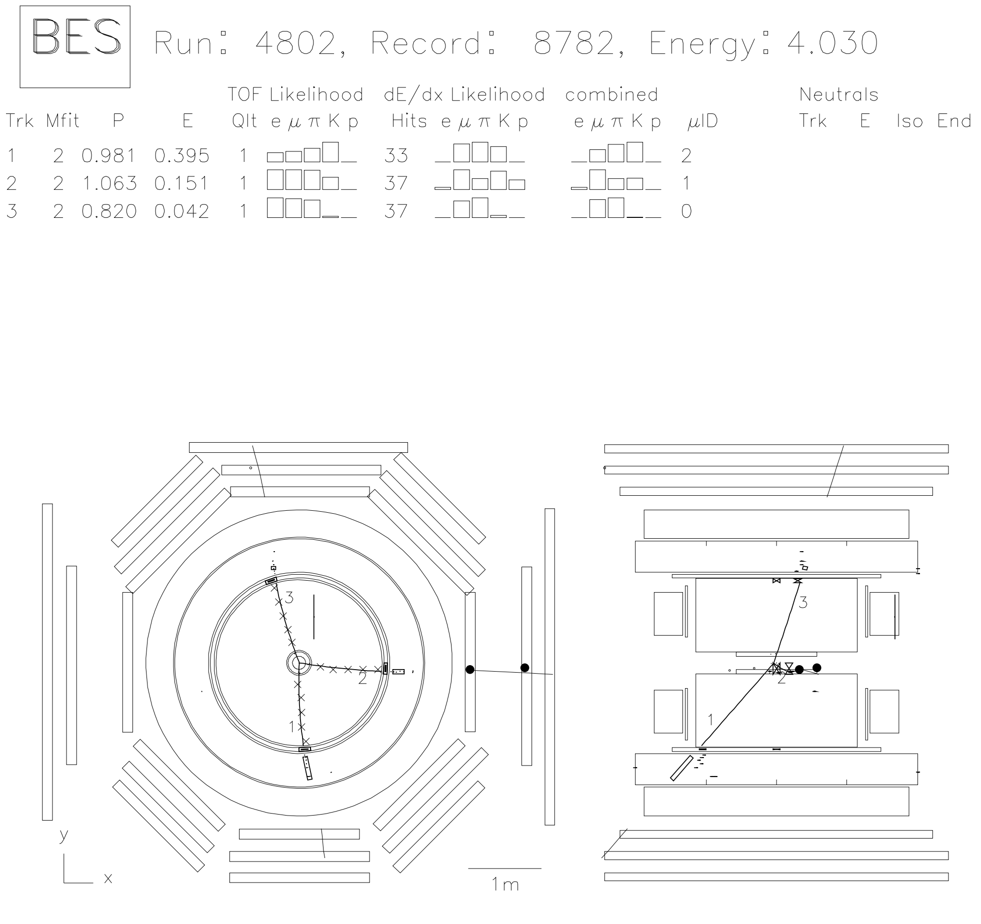

FIG. 4. ($D^- \to \mu^- \bar{\nu}$) Event Candidate Display

TABLES

TABLE I. $D^{\pm *}D^{\mp}$ decay modes

i	Decay Mode	N_i	Efficiency(%)	BG(bg_i)
1	$K^-\pi^+$	2144	19.1±0.3	0.064
2	$K^-\pi^+\pi^+\pi^-$	883	9.5± 0.3	0.044
3	$K^0\pi^+\pi^-$	190	3.3± 0.2	0.006
4	$K^-\pi^+\pi^+$	1407	15.9± 0.3	0.221
5	$K^0\pi^+$	124	5.3± 0.2	0.128
	total	4748		0.463

TABLE II. D^+ Leptonic Decay Candidate Properties

D Decay	Mass(MeV)	P_μ(MeV)	${M^2}_{miss}(GeV^2)$
$K^-\pi^+$	1,850	1,048	0.533