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Studies of $D\overline{D}$ Correlations in High Energy Photoproduction

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Analysis of data from the Fermilab high energy photoproduction experiment E687 for events containing fully and partially reconstructed pairs of charmed mesons is presented. Correlations from $D\overline{D}$ pairs are used to study production dynamics.

Correlations from $D\overline{D}$ pairs have been exploited to test QCD photoproduction models and the effects of charm quark dressing[1]. We have analyzed data collected by the Fermilab high energy photoproduction experiment E687 for events containing fully and partially reconstructed pairs of charmed mesons. In this paper we establish clean signals for $D\overline{D}$ pairs and make comparisons of their dynamical properties to predictions from a Monte Carlo based on a QCD production model.

The photon beam is derived from an electron beam with an average momentum of 320 GeV/c and with a $\sigma = \pm$ 13% momentum spread. The electron beam impinges on a 27% radiation length lead foil producing bremsstrahlung photons. The photons are directed to an 11% interaction length Be target.[1] The experimental trigger requires that at least 35-50 GeV of energy be deposited in the hadron calorimeter and that at least two tracks be present outside of the region where tracks from Bethe-Heitler e^+e^- pairs lie. A subset of the events required that the radiated energy loss between the recoil and incident electrons exceed 130 GeV. The average photon energy for the data sample was approximately 200 GeV. The E687 detector, which is described in detail elsewhere[2], is a large aperture multiparticle spectrometer with good detection capabilities for charged hadrons and photons. A microvertex detector consisting of 12 planes of silicon microstrips arranged in three views provides high resolution tracking allowing the separation of primary and secondary vertices. Deflections of charged particles by two analysis magnets of opposite polarity are measured by five stations of multiwire proportional chambers. Three multicell Čerenkov counters operating in threshold mode are used for particle identification.

For the sample of events containing fully reconstructed $D\overline{D}$ pairs, we used decay

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[1]Approximately 23% of the data was taken with a 9% interaction length Be target and 1% of the data was taken with an active Si-Be composite target.

modes of the D mesons which are copiously produced with high acceptance, namely, $D^+ \to K^-\pi^+\pi^+$, $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, together with their charged conjugates. The principal cutting tool used to isolate the D signals is the normalized decay flight distance[2] ℓ/σ_ℓ between the production vertex[3] (computed separately for each candidate) and the decay vertex. This variable was required to be larger than a value in the range 0 and 7 depending on the candidate topology.[4] The $D\overline{D}$ signature is shown in the scatter plot of Fig. 1a in which the normalized[5] D invariant mass appears on the vertical axis and the normalized $\overline{D}$ invariant mass on the horizontal. Fig. 1b shows the normalized D invariant mass distribution requiring that the $\overline{D}$ candidate mass was reconstructed within 2σ of the nominal value. Backgrounds were subtracted by averaging sidebands 4-8σ from the nominal mass value. The observed sideband subtracted signal yield is 325 ± 23 with a peak signal to noise ratio of approximately 15.

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[2]The variable ℓ is the signed 3 dimensional separation between vertices and σ_ℓ is the error on ℓ computed on an event by event basis including the effects of multiple Coulomb scattering.

[3]The production, or *primary* vertex is determined by a candidate-driven algorithm[2] in which the momentum vector of D candidate is used to construct a primary vertex track seed. The remaining reconstructed tracks in the event are added to this seed so long as the resulting vertex fit has an acceptable confidence level.

[4]We required less restrictive ℓ/σ cuts for D^0 candidates satisfying a $D^* - D$ mass difference tag consistent with the decay $D^{*+} \to D^0\pi^+$.

[5]We use the normalized mass variable $\Delta M/\sigma$, where ΔM is the difference between the reconstructed mass (with error σ) and the Particle Data Group[3] value for the candidate.

In this paper comparisons of experimental distributions are made to predictions from a Monte Carlo based on the Lund Model[4]. In this Monte Carlo, the charm quarks are produced by the interaction of the beam photon and target nucleon according to the tree-level photon-gluon fusion process. The default options for charm photoproduction are used throughout. The Lund string model is used to dress the quarks into hadrons, and the intrinsic target gluon p_t is Gaussian distributed with an rms width of 0.44 GeV/c.

A study of correlations was made using the fully reconstructed $D\overline{D}$ sample in which the (small) background has been properly subtracted.[6] In Figs. 2a,b the raw transverse momentum-squared distribution of the $D\overline{D}$ pair, $p_t^2(D\overline{D})$, and the rapidity difference $\Delta Y = Y_D - Y_{\overline{D}}$ are plotted. In Fig. 2c we plot the invariant mass distribution of the $D\overline{D}$ pair, $M_{D\overline{D}}$. In these graphs the data are represented by points with error bars and the Monte Carlo results, which reflect apparatus acceptance and resolution effects, are the solid curves and are normalized to the number of events in the data sample. The parent distribution of the model in each variable is indicated with an (arbitrarily normalized) dashed curve and can be used to judge the relative acceptance over the allowed kinematical region in each case. These results indicate good agreement between the model and data, with the exception of the $p_t^2(D\overline{D})$

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[6]The background subtraction procedure consists of assigning a unit weight to events falling into the signal region ($\pm 2\sigma$ about both the nominal D and $\overline{D}$ mass), a weight of -1/2 for events in which only a single-D or $\overline{D}$ was reconstructed ($4-8\sigma$ away from the nominal $\overline{D}$ mass but with the D mass within $\pm 2\sigma$ of its nominal value and vice versa), and a factor of +1/4 for events falling into the four regions $4-8\sigma$ apart from both the D and $\overline{D}$ nominal masses which corrects for the over-subtraction of the single-D background and also subtracts the random combinatoric background.

distribution which is significantly harder in the data sample.

The acoplanarity angle $\Delta\phi$ is defined as the azimuthal angle between the D and $\overline{D}$ momentum vectors in the plane transverse to the photon direction. The E687 spectrometer acceptance varies by less than 5% over the allowed range of 0 to π radians and has a resolution of approximately 13 milliradians over this range.[7] The result is shown in Fig. 3 in which the data and Monte Carlo events are observed to accumulate near π radians. A value of $\Delta\phi = \pi$ radians corresponds to back-to-back $D\overline{D}$ production and is expected in the context of the the tree-level photon-gluon fusion process. Charm quark dressing, and the effects due to intrinsic gluon p_t spreading cause deviations from $\Delta\phi = \pi$. Note that the finite spectrometer resolution does not significantly affect this spreading. The distribution from our data sample tends to be significantly smeared from $\Delta\phi = \pi$ radians and is somewhat flatter than the Monte Carlo model prediction.

Correlations can also be studied over a wider acceptance range using a fully reconstructed charm meson (which we call the recoil charm $\overline{D}_r$) produced against a kinematically tagged soft pion of the correct charge (which we label as $\tilde{\pi}$) from the decay $D^{*+} \rightarrow \tilde{\pi} D^0$ where the daughter D^0 need not be reconstructed. This allows us to greatly expand our charm correlation sample over the fully reconstructed sample due to the relatively large $D^{*+} \rightarrow \tilde{\pi} D^0$ branching fraction and our large acceptance (greater than 80%) for the $\tilde{\pi}$. Because of the low Q value for this decay, the soft pion will have a lab momentum close to that of the parent D^{*+} when scaled up by the inverse of its energy fraction (approximately 13.8). Since $D\overline{D}$ pairs balance p_t^2 within 4 $(\mathrm{GeV/c})^2$ at these photon beam energies (as shown in Fig.2a), the scaled soft pions from the D^{*+} decay should roughly balance the recoil charm transverse momentum,

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[7]This includes effects due to the small angular spread in the incident photon direction.

$\vec{P}_t^{(r)}$. Therefore, one expects an excess in signal $\tilde{\pi}$'s over background pions below $\tilde{\Delta}_t^2 = 4$ (GeV/c)^2 where

$$\tilde{\Delta}_t^2 \;=\; (13.8P_x^{(\pi)} + P_x^{(r)})^2 + (13.8P_y^{(\pi)} + P_y^{(r)})^2.$$

Using a sample of 44,000 ± 300 $\overline{D}_r$ mesons (see Fig.4a), $\tilde{\Delta}_t^2$ is computed for each track emanating from the primary vertex. Fig. 4b shows $\tilde{\Delta}_t^2$ for candidates having the correct charge correlation and the wrong charge correlation.[8]

As an important check of the $\tilde{\pi}$-tagging procedure, we compare the $\tilde{\Delta}_t^2$ distribution for correct charge correlation events to the $p_t^2(D\overline{D})$ distribution from the sample of fully reconstructed $D\overline{D}$ pairs. The two distributions were found to be consistent after accounting for the much better resolution obtainable with fully reconstructed $D\overline{D}$ pairs.[9]

Below 4 (GeV/c)^2 the right sign over wrong sign excess integrates to a yield of 4534 $\tilde{\pi}$-tagged $D\overline{D}$ pairs. After subtracting the wrong charge combinations, the soft $\tilde{\pi}$-tagged candidates can be studied for their correlation properties. We use the soft pion momentum vector, scaled by the factor of 13.8, as an estimate of the parent D^* momentum vector when computing correlations. In Fig. 5a,b the rapidity difference and $D\overline{D}$ pair invariant mass distributions are compared to the Monte Carlo predictions and are observed to be in agreement. In Fig. 5c, the $\Delta\phi$ distribution is compared with that from the fully reconstructed sample after accounting for resolution effects

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[8]We remove pions consistent with the decay $D^{*-} \to \pi\overline{D^0_r}$ by eliminating those wrong-charge candidates lying within 3 MeV of the nominal $D^{*-} - \overline{D^0_r}$ mass difference.

[9]A comparison of $p_t^2(D\overline{D})$ to $\tilde{\Delta}_t^2$ (which has much worse resolution) was made by smearing a scaled, fitted version of Fig. 2a and adding the fitted level of wrong sign events. See caption of Fig. 4.

as follows:[10] for each of the approximately 325 fully reconstructed $D\overline{D}$ events, the D momentum vector is used to emulate a D^* which is decayed isotropically to $D\tilde{\pi}$; the simulated $\tilde{\pi}$ momentum is used to compute an acoplanarity angle which reflects $\tilde{\pi}$ smearing. The resulting $\Delta\phi$ distribution is consistent with the $\tilde{\pi}$-tagged sample with the exception of the first bin. Thus, in addition to providing a consistency check in $\Delta\phi$, the $\tilde{\pi}$-tagged events offer additional model comparisons at larger $D\overline{D}$ invariant mass and rapidity difference.

In conclusion, we have established a clean signal for fully reconstructed $D\overline{D}$ pairs produced in high energy photon interactions. The data are found to be in reasonable agreement with most correlations predicted by the tree-level photon-gluon fusion process and the Lund string fragmentation model. A large sample of partially reconstructed $D\overline{D}$ pairs obtained by tagging the soft pions from the decay $D^{*+} \to \tilde{\pi} D^0$ is found to have production characteristics consistent with the sample of fully reconstructed $D\overline{D}$ pairs over a larger acceptance range. However, significant inconsistencies between the data and model predictions are observed in $\Delta\phi$ and $p_t(D\overline{D})$ distributions using either fully reconstructed $D\overline{D}$ or $\tilde{\pi}$-tagged samples.

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[10]The rms resolution smearing due to the finite energy release in the decay $D^* \to \tilde{\pi} D^0$ was determined from a Monte Carlo study to be 0.3 radians.

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[4] The Monte Carlo program consisted of simulation algorithms for the E687 apparatus[2] combined with the Lund model packages JETSET 7.3 and PYTHIA 5.6:
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T.Sjostrand, H.-U.Bengtsson, Computer Phys. Comm. 43 (1987) 367;
H.-U.Bengtsson, T.Sjostrand, Computer Phys. Comm. 46 (1987) 43.

Figure 1

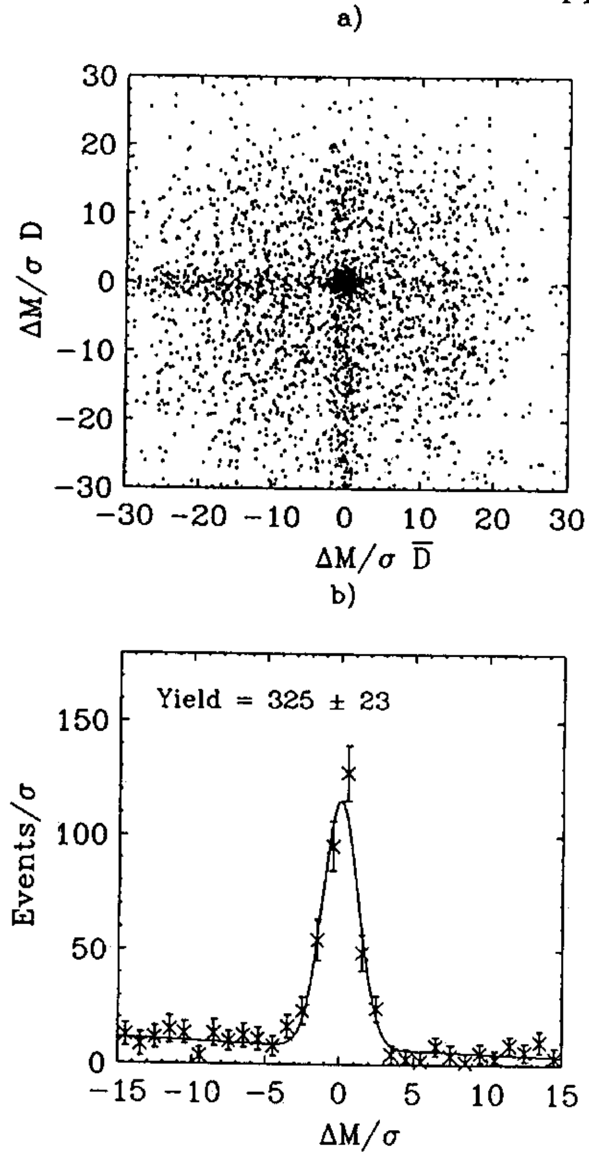

FIG. 1. a) Scatter plot of the normalized mass of detached D candidates versus the normalized mass of the detached, recoil $\overline{D}$ candidates. b) Normalized mass distribution of detached D candidates subject to the presence of a detached, recoiling $\overline{D}$ candidate. The signal reflects a mass cut on the $\overline{D}$ candidate (2σ about the nominal mass) and subtraction of an average of high and low mass sidebands 4-8σ from the nominal mass.

Figure 2

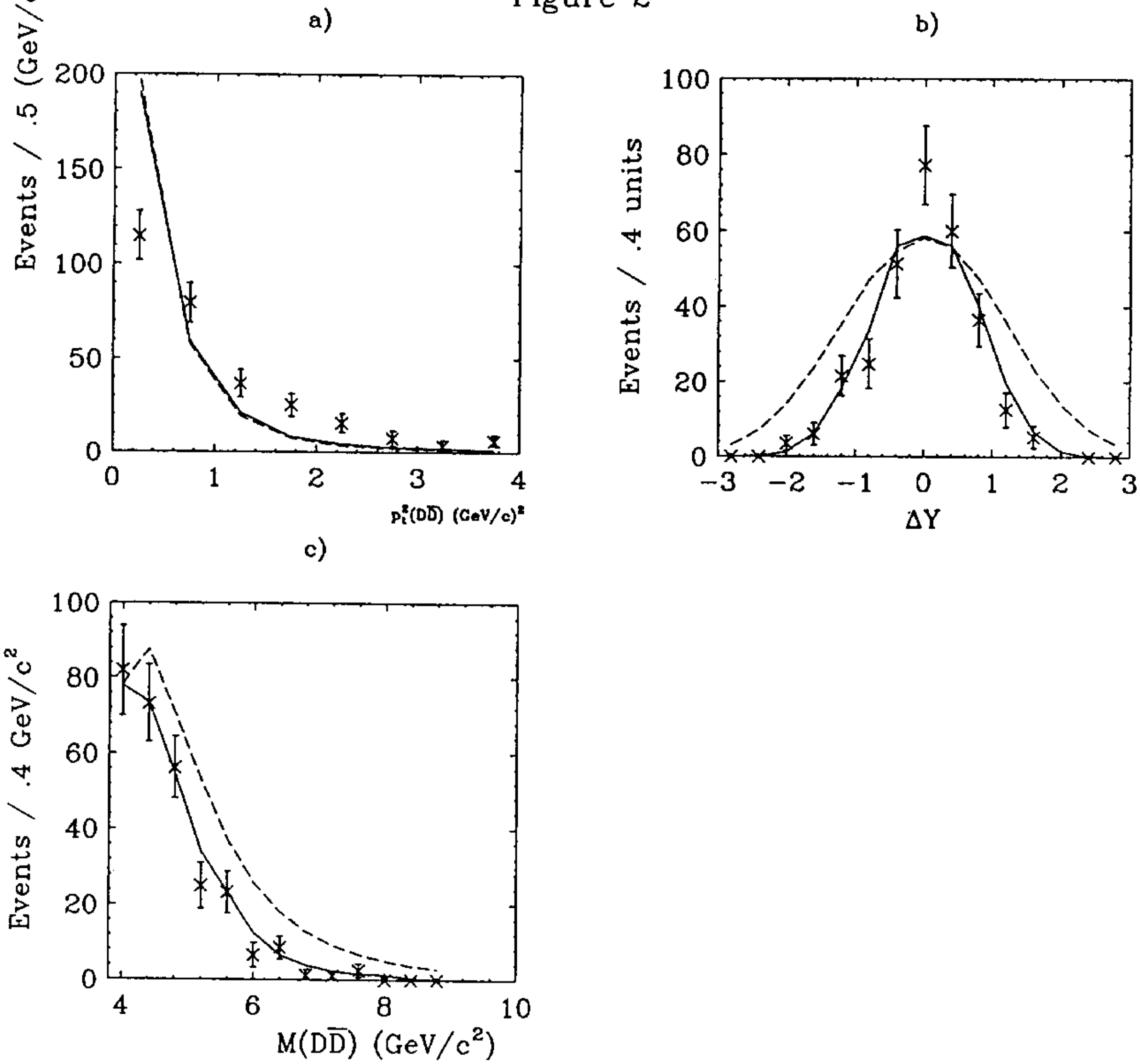

FIG. 2. Correlations for fully reconstructed $D\overline{D}$ pairs: a) the $p_t^2(D\overline{D})$ distribution; b) the $D\overline{D}$ rapidity difference $(Y_D - Y_{\overline{D}})$; c) the invariant mass of the $D\overline{D}$ pair. In these figures the points with error bars represent the background-subtracted distributions while the solid curves represent the Monte Carlo model predictions and reflect apparatus acceptance and resolution conditions. The dashed curves (arbitrarily normalized) represent parent distributions from the Monte Carlo model in the absence of acceptance and resolution effects.

Figure 3

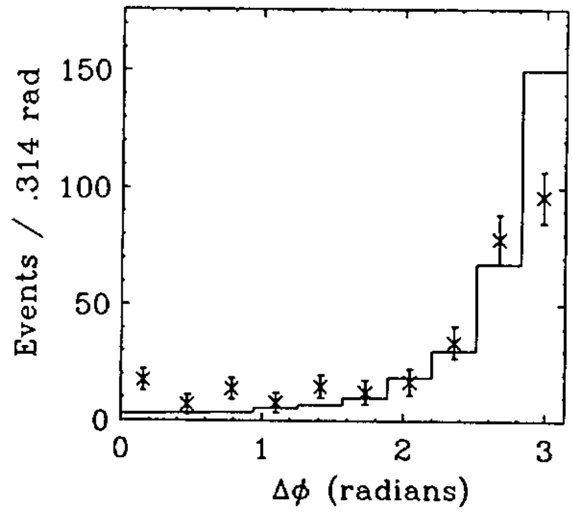

FIG. 3. Background subtracted acoplanarity distribution $\Delta\phi$ for fully reconstructed $D\overline{D}$ pairs compared to the Monte Carlo (solid histogram).

Figure 4

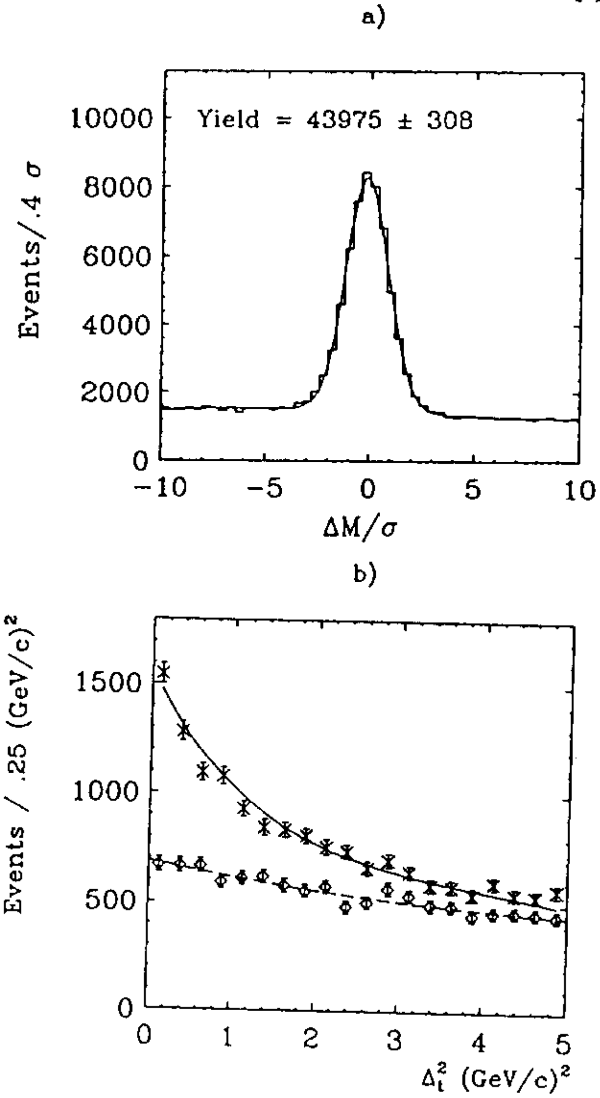

FIG. 4. a) Starting sample of recoil charm mesons $D \to K\pi, K2\pi, K3\pi$ used in the soft pion tagging analysis. These events were required to satisfy $\ell/\sigma > 0$ to 7, depending on the topology. b) Distribution of the p_t balance variable $\tilde{\Delta}_t^2$ for soft $\tilde{\pi}$-tagged events. The upper points are for candidates having the correct charge correlation and the lower points are for candidates having the wrong charge correlation. This result is compared to the fully reconstructed $D\overline{D}$ sample (solid upper curve). The $D\overline{D}$ sample has much better resolution than the $\tilde{\pi}$-tagged sample which is smeared by the motion of the $\tilde{\pi}$ with respect to the D^{*+} center of mass frame. The solid upper curve was therefore generated by smearing a scaled, fitted version of Fig. 2a and adding the fitted level of wrong sign events (lower, dashed curve). Both fits were to the form $dN/dp_t^2 = Ae^{-(ap_t^2+bp_t^4)}$. Based on a Monte Carlo study, the smearing function was parameterized as a function of $\tilde{\Delta}_t^2$ and was determined to have an average rms width of approximately 0.8 GeV/c in $\tilde{\Delta}_{x,y}$.

Figure 5

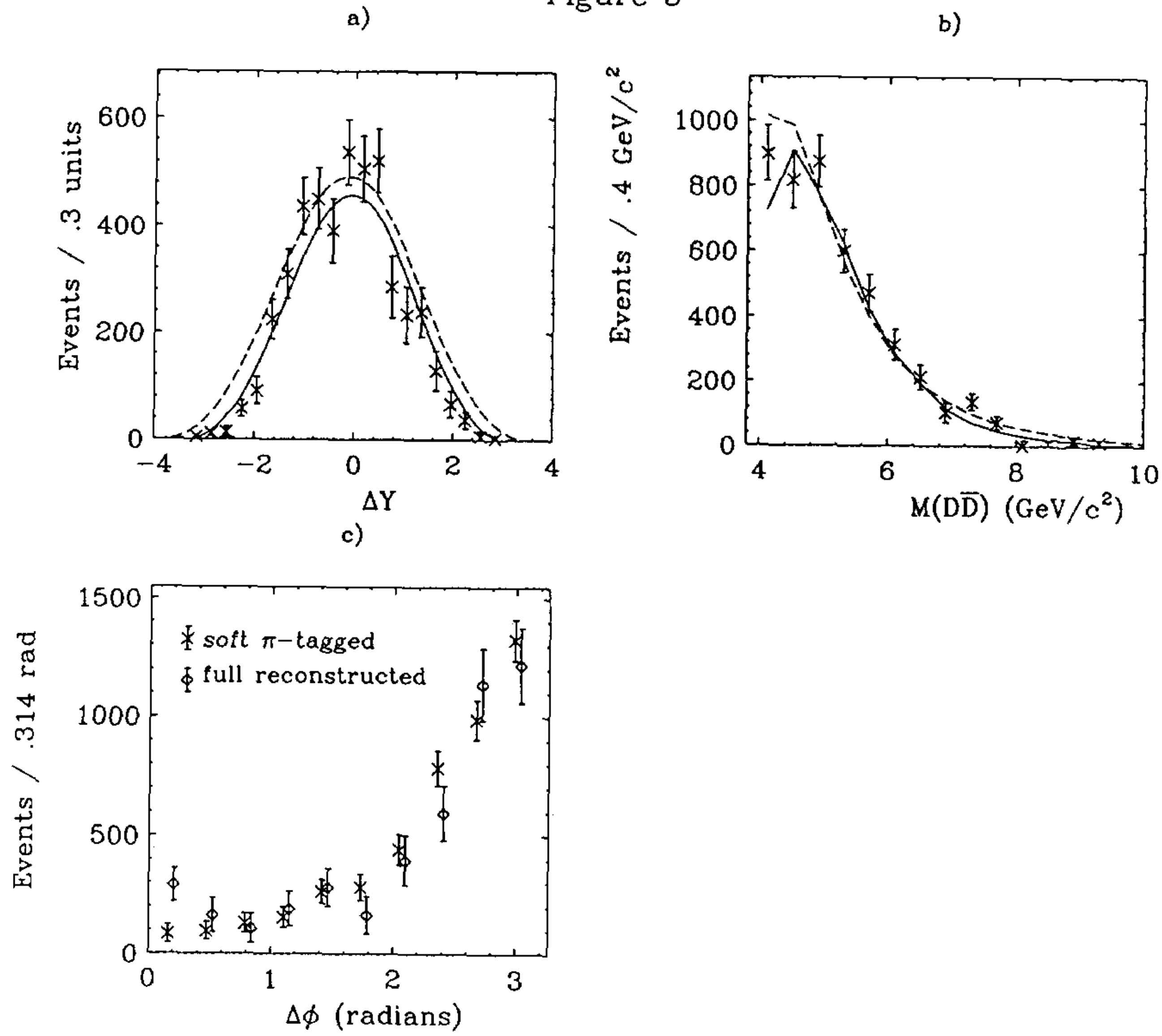

FIG. 5. Correlations for partially reconstructed $D\overline{D}$ pairs: a) rapidity difference $Y_D - Y_{\overline{D}}$; b) the invariant mass of the $D\overline{D}$ pair. In these figures the points with error bars represent the background-subtracted distributions while the solid curves represent the Monte Carlo model predictions and reflect apparatus acceptance and resolution conditions. The dashed curves (arbitrarily normalized) represent parent distributions from the Monte Carlo model in the absence of acceptance and resolution effects. c) Acoplanarity distribution $\Delta\phi$ for the $\bar{\pi}$-tagged sample (cross symbols). A comparison to the fully reconstructed sample (diamond symbols) is made after accounting for resolution effects caused by the smearing in the $\bar{\pi}$-tagging method (see text).