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(Submitted to Physics Letters)

Abstract

We have studied D* production mechanisms using data from a photoproduction experiment at the Fermilab Tagged Photon Spectrometer. A large sample of charged D*s was selected via the clean signature of the cascade decay $D^* \to D^o \pi+$ and subsequently $D^o \to K^- \pi^+$ or $D^o \to K^- \pi^+ \pi^0$. The cross section for the process $\gamma p \to (D^{*+} X)p$ at an average energy of 105 GeV was measured to be 88±32 nb. Only 11±7 % of D*s were found to be consistent with being accompanied solely by a $\bar{D}^*$ or a $\bar{D}$, the remaining events contain additional particles. The distribution of the production angle of the D* in the photon fragmentation system CM is strongly anisotropic and consistent with the form $f(\Theta^*)=\cos^4\Theta^*$. We set a limit on the associated production process cross section $\sigma(\gamma p \to (\bar{D}^{*-} X)\Lambda_c) < 60$ nb (90 % C.L.).

The Fermilab Tagged Photon Spectrometer (TPS), described in detail elsewhere[1], is unique in combining a large acceptance, complete forward spectrometer with a sophisticated recoil detector. Together with a 1.5 m liquid hydrogen target, the system allows a complete measurement of all four momenta of initial (E_γ, proton target) and final state (large acceptance recoil and forward measurement) particles. This for the first time permits careful study of charm particle production mechanisms. Here we present results of an analysis of D* production based on data taken with the TPS. Photons, produced via the bremsstrahlung of 170 GeV electrons, had energies in the range $40 < E_\gamma < 160$ GeV, with an average of 105 GeV. The integrated photon flux corresponds to a luminosity of 480 nb^{-1}.

The geometrical acceptance in the lab frame for the recoil and forward systems, in terms of pion rapidity, is shown in Fig.1. In the case of single recoil proton events, the recoil detector covered fully the target fragmentation region and the forward spectrometer covered the photon fragmentation region. Twenty nine planes of drift chambers and two large aperture magnets were used to analyze forward charged tracks. Two segmented Cerenkov counters allowed charged particle identification in the momentum range 6-36 GeV/c. Three high resolution segmented electromagnetic shower detectors were used for π^0 detection. A hadron calorimeter and a set of scintillator hodoscopes downstream of an iron filter used for muon identification completed the forward spectrometer system. The recoil detector[2] surrounding the H_2 target consisted of 3 cylindrical MWPCs and a 4 layer scintillator calorimeter in 15 azimuthal sectors covering 94% of 2π. This detector measured the angle and kinetic energy of recoiling tracks (for proton $|t| < 1.2$ $(GeV/c^2)^2$), and identified particle type (π vs p). A high speed ECL-CAMAC trigger processor[3] attached to the recoil system was designed to isolate two selected subclasses of the total charm cross section. The "high mass diffractive" trigger required a single proton at the primary vertex recoiling off the forward system with forward missing mass, $M_x > 2.0$ GeV. The possible contamination from events which had additional, unreconstructed tracks in the recoil system, or from events in which a proton from a secondary interaction was associated with the primary vertex, was estimated to be small (< 10 %), and doesn't affect the results shown. (Both classes of background events tend to mimic a high missing mass). The "target fragmentation" trigger, optimized for Λ_c acceptance by means of a Monte Carlo study, required at least three charged tracks (from the primary vertex) in the recoil detector.

For the present analysis we select a sample of D^{*+} events in which a $D^{*+} \rightarrow D^0\pi^+$ decay was followed by one of the decays $D^0 \rightarrow K^-\pi^+$, $D^0 \rightarrow K^-\pi^+\pi^0$. (Unless specified, the charge conjugate states are implicitly included.) The technique exploits the fact that the $D^{*+}-D^0$ mass difference is only a few MeV larger than the pion mass. As a result, the distribution of the mass difference $M(D^0+\pi^+)-M(D^0)$ shows a clean, narrow peak at the D^*-D^0 mass difference. We consider $K^-\pi^+(\pi^0)$ combinations whose reconstructed invariant masses lie within 50 MeV of the D^0 mass, 1865 MeV. For each $K^-\pi^+(\pi^0)\pi^+$ combination we plot the mass difference $\Delta M = M_{K^-\pi^+(\pi^0)\pi^+} - M_{K^-\pi^+(\pi^0)}$, (see Fig.2). Fitting the data to a background of the form $aQ^{1/2}(1-bQ)$, where $Q=\Delta M - M_\pi$, plus a Gaussian centered at the $D^{*+}-D^0$ difference, 145.5 MeV (σ=1.2 MeV), gives 64±12 $D^0 \rightarrow K^-\pi^+$ events in the D^* peak and 95±15 in the $K^-\pi^+\pi^0$ mode.

Restricting the sample to single recoil proton events, those in which a proton and no other track from the primary vertex has been reconstructed offline in the recoil detector, we have measured the cross section for the recoil elastic process $\gamma p \rightarrow (D^{*\pm} X)p$. (These events come from the "high mass diffractive" trigger.) In the mode with $D^0 \rightarrow K^- \pi^+$ we find 34±8 such events. After correction for the trigger and reconstruction efficiencies and assuming equal production rate for D^{*+} and $\bar{D}^{*-}$ we obtain the cross section of 85±21(stat)±23(syst) nb. The corrections were determined using a full Monte Carlo simulation of the experiment. For the $K^- \pi^+ \pi^0$ mode the corresponding numbers are 36±11 events and 92±30±35 nb. (We have used the branching ratios[4] of 2.4±.4 % and 9.3±2.8 % for the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^0$ respectively, and 64±11 % for the $D^* \rightarrow D^0 \pi^+$.) Combining the two samples we find σ=88±17±27 nb. We have also measured the energy dependence of this cross section:

energy range (GeV)	σ (nb)
40 - 80	24^{+34+8}_{-24}
80 - 120	98 ± 31 ± 32
120 - 160	105 ± 39 ± 33

This measurement is of what is often called the elastic or the diffractive part of the total D* photoproduction cross section. This notion is supported by a sharp falloff in $t'=t-t_{min}$, the four momentum transfer distribution (background subtracted), measured using the target and recoil proton momenta (see Fig.3).

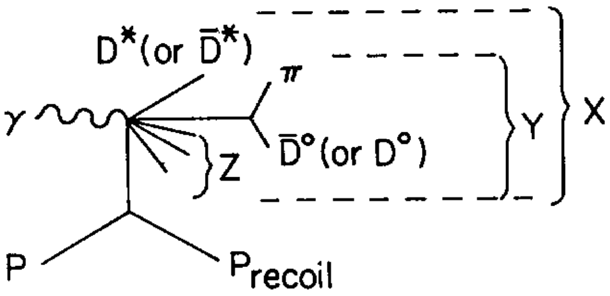
For the t' distribution and for all the distributions shown below that characterize D* production, we have studied those events with ΔM in the range 144-147 MeV. We have subtracted the background contribution estimated from the data by considering events which would have passed cuts except that either a) the pion associated with the D^0 combination was the wrong charge, b) $M_{K^-\pi^+(\pi^0)}$ was outside the D^0 mass region (in 1.65-1.75 and 1.95-2.05 GeV), or c) ΔM was outside the D^*-D^0 mass difference region (in the 160-200 MeV range). The distributions from these three samples were combined and normalized to the amount of the background determined from the fit used for the cross section measurement.

For the single recoil proton D* events we have studied the angular distribution of the D*s in the center-of-momentum (CM) of the photon fragmentation system. We calculate the four momentum of this system from the beam energy and the target and recoil proton momenta. We define Θ^* as the CM angle of the D* with respect to the direction of the photon fragmentation system momentum in the lab (Θ^* is the polar angle of a D* in the helicity frame.) The $\cos\Theta^*$ distribution, corrected for the reconstruction efficiency is shown in Fig.4. It is strongly anisotropic and is consistent with the superimposed fitted distribution $\cos^4\Theta^*$. Using several variables we have also compared the data with Monte Carlo events generated with $\cos^n\Theta^*$ distributions for n=1,2,4,6. Two of these, p_t of the D* and $\cos\Theta_f^*$, are shown in Fig.5. (Θ_f^* is the production angle of the D* in the CMS of the forward system determined by adding the four momenta of observed forward particles, rather than deriving it from E_γ,p_{target} and p_{recoil}, as is done for Θ^*.) The mean values of these two variables for the data and various Monte Carlo samples are listed below:

	$<\cos\theta_f^*>$	$<p_T^{D*}>$
data	.25	.75 GeV/c
flat M.C.	.08	1.44
$\cos^2\theta^*$ M.C.	.13	.99
$\cos^4\theta^*$ M.C.	.23	.80
$\cos^6\theta^*$ M.C.	.36	.65

The data again favours $\cos^4\theta^*$ dependence: the θ^* distribution peaks in the direction of the fragmenting photon system. Enhancement of forward-backward production was suggested by Bjorken[5] in 1978. The backward going quark(antiquark) is "wee" in the lab and thus more likely to interact with the target.

As part of understanding how the $c\bar{c}$ state hadronizes we have studied what accompanies the observed D*. In the following diagram we define the three groups of outgoing forward particles (X,Y and Z) that can be measured to give information on the forward state produced with the D*:



X represents all forward particles, Y is the forward system except the observed D*±, and Z is the forward system exclusive of the observed D* and a presumed but not directly observed D*. Four essentially independent measurements are presented. These are the multiplicity of Y and the masses of Y (determined in two ways) and Z. All indicate that the D* is rarely accompanied solely by a $\bar{D}^*$ or a $\bar{D}$. The observed multiplicity distribution of charged tracks in Y, for all D* events with no secondary interactions is shown in Fig.6. This is compared to what is expected if $Y=\bar{D}^*$ only by using SPEAR Mark II and Lead Glass Wall data[6] smeared by the TPS detection efficiency (dashed line). The mean expected and observed multiplicities are $\langle n_{\bar{D}^*}\rangle=2.09\pm.09$ and $\langle n_Y\rangle=3.20\pm.26$. The difference indicates the presence of at least one additional particle on average.

The mass of the Y system, which should be about 2 GeV for $D^*\bar{D}^*$ (or $D^*\bar{D}$) only production can be measured in two independent ways. The most sensitive is the measurement made by calculating for single recoil proton events the missing mass M_Y^r of everything in the final state except the observed D* and the recoiling proton. The distribution is shown in Fig.7. The dashed lines at ±600 MeV around 2 GeV include 95 % of the Monte Carlo generated distribution for $D^*\bar{D}^*$ events, which peaks at the D* mass. Only 11±7 % of the data falls in this region. This is the strongest indication of the relative rarity of $D^*\bar{D}^*$ or $D^*\bar{D}$ only production. The solid curve shows the Monte Carlo expectation for 11±7 % $D^*\bar{D}^*$, 44.5 % $D^*\bar{D}^*\pi^+\pi^-$, and 44.5 % $D^*\bar{D}^*\pi^+\pi^-\pi^0$. Although this has excellent agreement with the data it is not intended to indicate that this distribution of extra particles is unique in matching the data. Channels with more than 3 πs may contribute and can't be confirmed or ruled out with this technique. A second way of measuring M_Y is to compute it directly from the observed charged and neutral particles. The distribution , M_Y^f, is shown in Fig.8 for all D* events with no secondary interactions. It gives the same conclusion as M_Y^r but because of detection inefficiencies is less sensitive. Here the fraction below 2 GeV (where 92 % of Monte Carlo $D^*\bar{D}^*$ events is contained) is 44±18 %.

The fourth measurement assumes the presence of a second $\bar{D}^*$ and computes M_Z of all particles in the forward system except the two D*s. For $D^*\bar{D}^*$ only production $M_Z=0$. The method is based on an another consequence[7] of the small value of $M_{D^*}-M_{D^o}-M_\pi$ (5.9 MeV). To a very good approximation the momentum of the D* is a constant times that of the π coming from $D^*\to D^o\pi$ decay: $\vec{P}_{D^*} \simeq 14.36\ \vec{P}_\pi$. The four momentum of a D* is then obtained by assuming the D* mass. M_Z is computed for all available correct charge pions using the same approach as for the M_Y^r but here subracting the four momentum of the second D*, obtained in the manner described above. A small part of the resulting distribution in M_Z^2 around zero is shown in Fig.9 with the Monte Carlo expectation for $D^*\bar{D}^*$ only events. The dotted line contains 95% of Monte Carlo events and, at 90% C.L., < 18% of the data. In summary, all four measurements are consistent with the M_Y^r based result that only 11±7 % of D* are accompanied solely by a $\bar{D}^*$ or a $\bar{D}$. The MARK II group at SPEAR has made a similar observation in $e^+e^-\to D\ X$ at $E_{cm}=5.2$ GeV that most of D production is not quasi-two-body[8].

The distributions of Feynman x in the overall CM for the D*s, for all events, and for single recoil proton events are shown in Fig.10. We have fitted both distributions to the form $a(1-x_f)^n$ and obtained the values of $n=1.1\pm.4$ and $1.1\pm.6$ respectively. A similar value of $n\simeq1$ was also observed for pions produced in non-charm single proton events[1].

Finally, we have also addressed the question of the importance of the associated production processes in D* photoproduction. We have used $D^{*\pm}$ events obtained with the Λ_c sensitive trigger to look at the $\bar{D}^*$ - D^* charge asymmetry. In the $K\pi$ mode the difference is 6±5 events, while in the $K\pi\pi^o$ mode it is 13±11 events. Interpreting the asymmetry as coming entirely from the associated production process we obtain, after correcting for trigger and reconstruction efficiencies[9], an upper limit for the cross section $\sigma(\gamma p \to (\bar{D}^{*-} X)\Lambda_c < 60$ nb (90 % C.L.) with an additional 40 % uncertainty in the absolute normalization.

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9. A quasi two-body Monte Carlo model was used to estimate the trigger efficiency for the process $\gamma p \to (\bar{D}^{*-} X)\Lambda_c$. A t distribution of the form exp(-2|t|) was assumed, and Λ_c was allowed to decay into 40 modes. The forward spectrometer efficiency was estimated using Monte Carlo events with a single D* and, on average, two additional pions in the forward system.

Figure captions

Figure 1. TPS lab rapidity acceptance for the recoil and forward detector systems. Calculated for pions assuming $<p_t>=350$ MeV/c, $E_\gamma=100$ GeV.

Figure 2. D* - D mass difference histograms

Figure 3. t' dependence for single recoil proton D* data

Figure 4. Distribution of the D* production angle in the photon fragmentation system CMS

Figure 5. cos Θ_f^* and p_t for single recoil proton D* events. Curves show Monte Carlo simulations for flat and $\cos^4\Theta^*$ dependence of the D* production angle in the photon fragmentation system CMS

Figure 6. Multiplicity of a system accompanying the observed D* (n_Y). Dotted line shows the expected distribution for $D^*\bar{D}^*$ only events.

Figure 7. Distributions of M_Y^r for single recoil proton events.

Figure 8. Distributions of M_Y, computed directly from the observed charged and neutral particles.

Figure 9. Distributions of M_Z^2 for single recoil proton events.

Figure 10. Distributions of D* Feynman x for all events and for single recoil proton events. Results of the fits to the form $a(1-x_f)^n$ are superimposed.

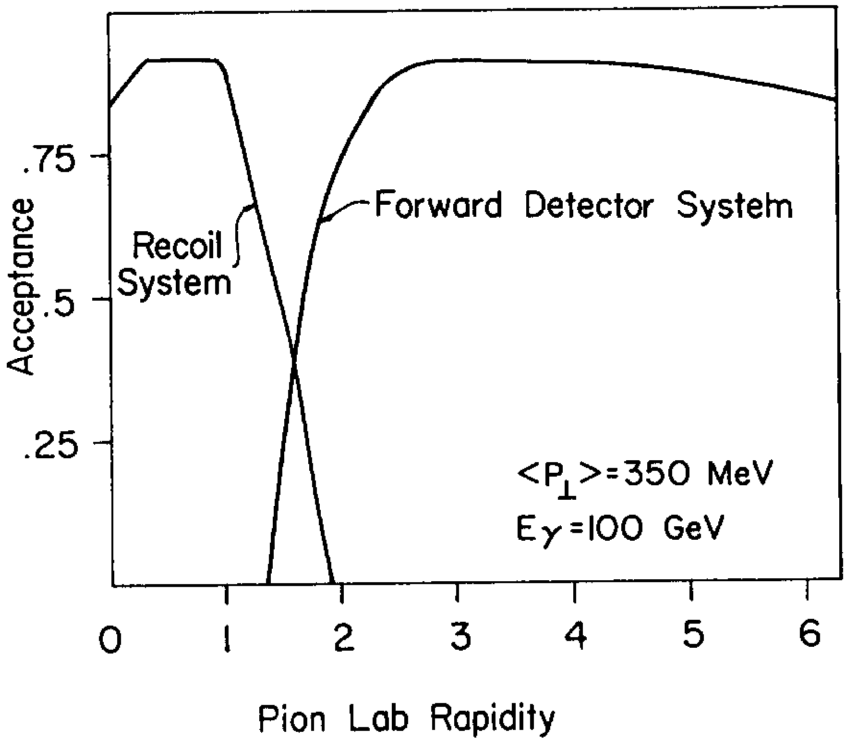

Acceptance
.75
.5
.25
Recoil System
Forward Detector System
$<P_\perp>$=350 MeV
E_γ=100 GeV
0
1
2
3
4
5
6
Pion Lab Rapidity

Figure 1

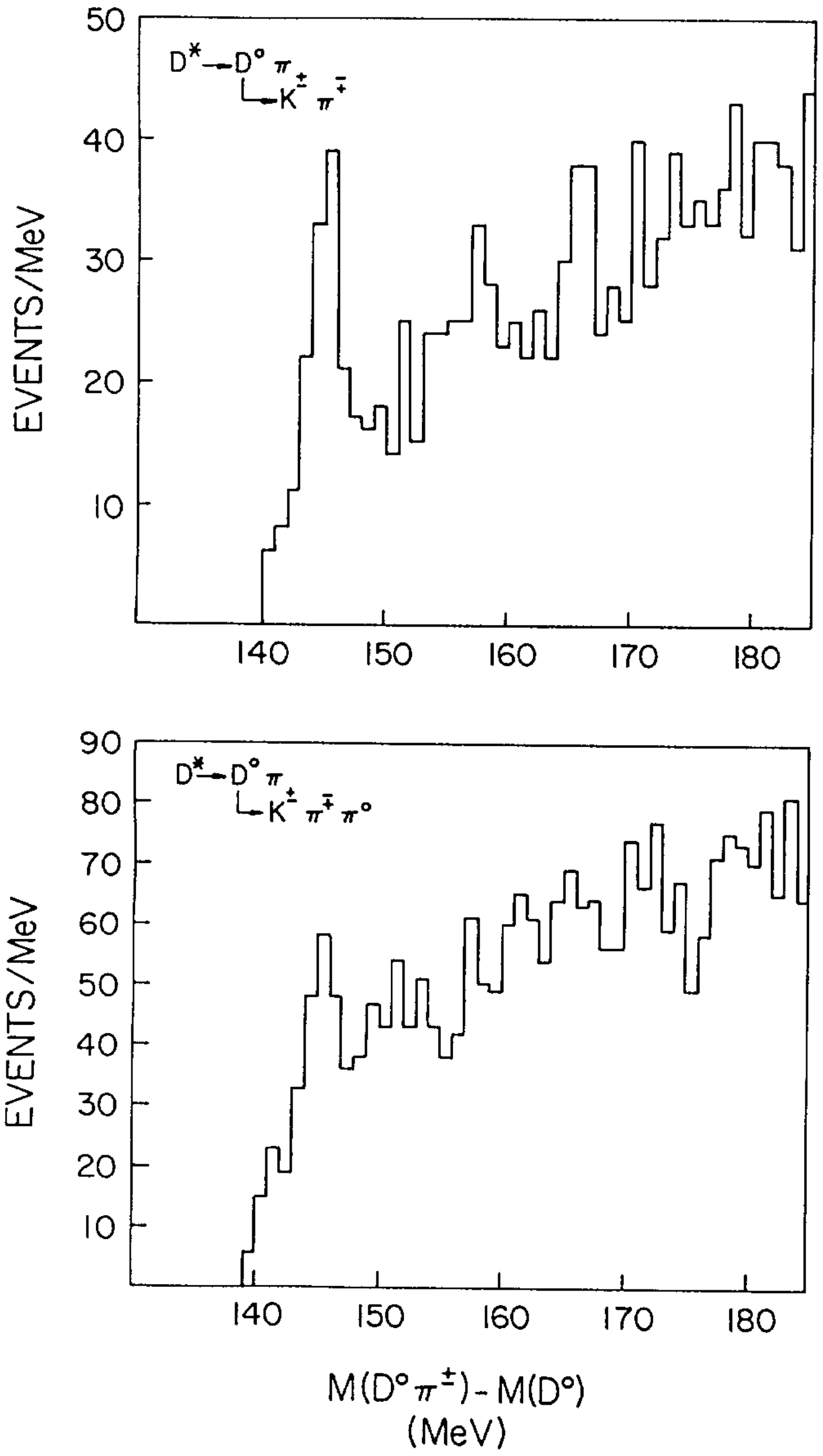

50
40
30
20
10
EVENTS/MeV
$D^* \to D^\circ \pi^\pm$
$\quad \hookrightarrow K^\pm \pi^\mp$
140
150
160
170
180
90
80
70
60
50
40
30
20
10
EVENTS/MeV
$D^* \to D^\circ \pi$
$\quad \hookrightarrow K^\pm \pi^\mp \pi^\circ$
140
150
160
170
180
$M(D^\circ \pi^\pm) - M(D^\circ)$
(MeV)

Figure 2

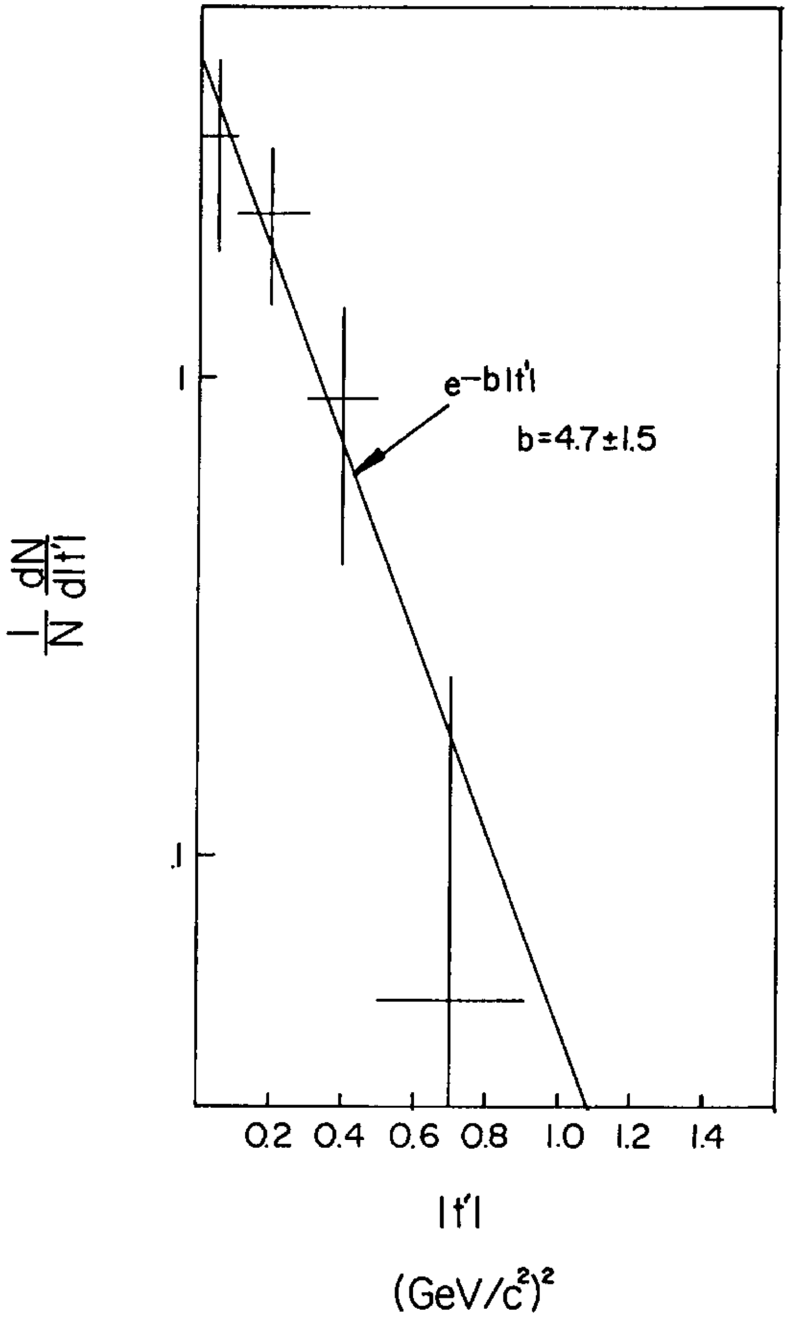


Figure 3

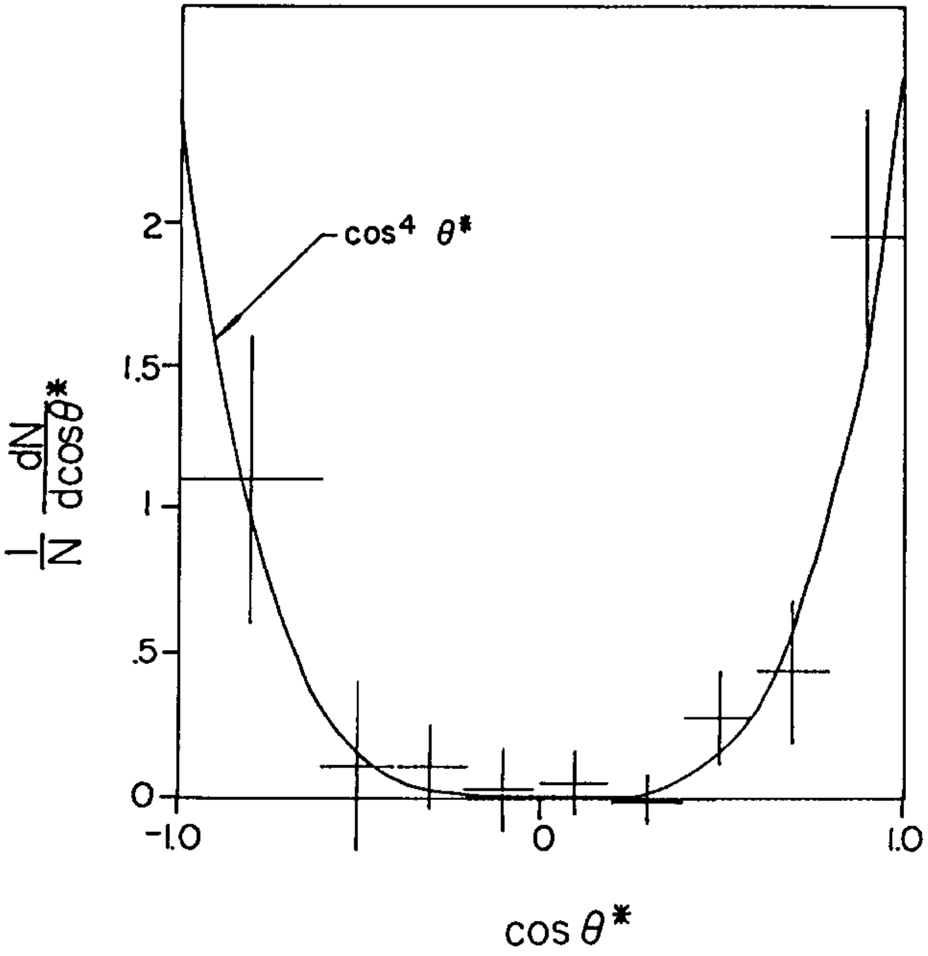
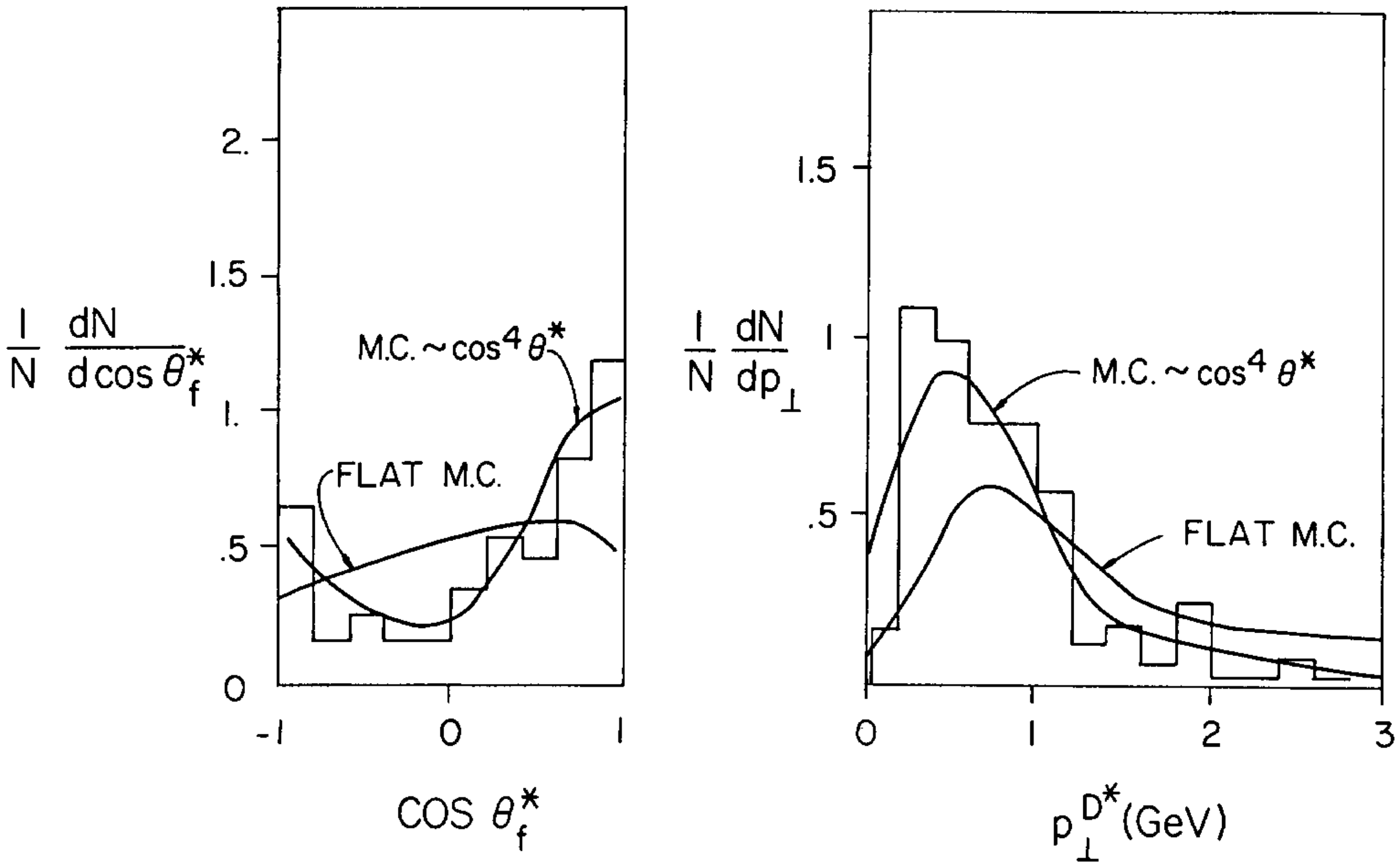


Figure 4



$\frac{1}{N}\frac{dN}{d\cos\theta_f^*}$
2.
1.5
1.
.5
0
-1
0
1
$\cos\theta_f^*$
M.C. ~ $\cos^4\theta^*$
FLAT M.C.
$\frac{1}{N}\frac{dN}{dp_\perp}$
1.5
1
.5
0
1
2
3
$p_\perp^{D^*}$(GeV)
M.C. ~ $\cos^4\theta^*$
FLAT M.C.

Figure 5

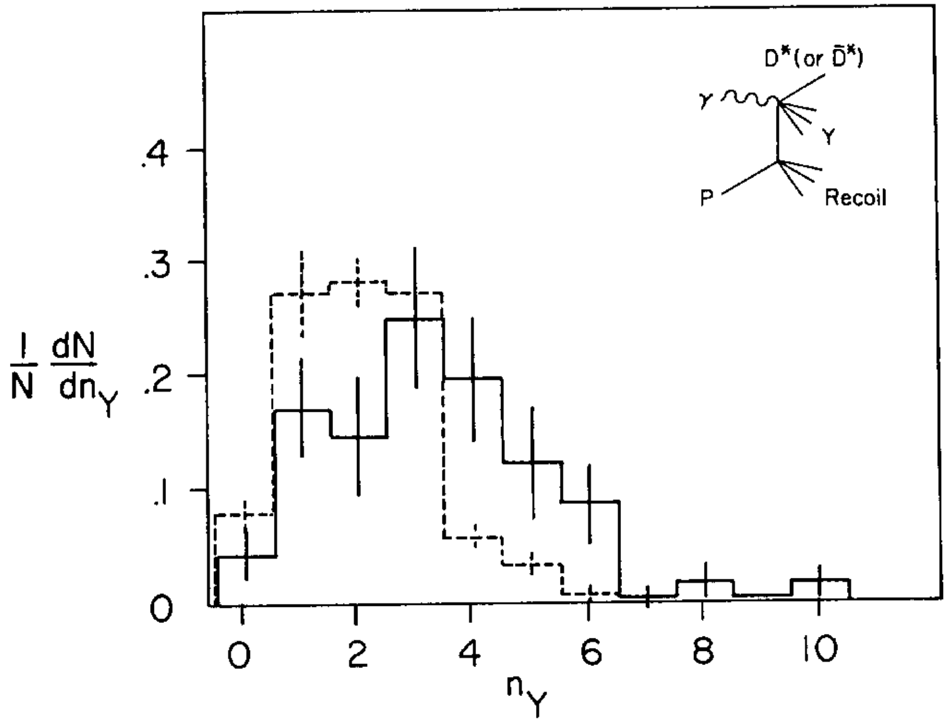


Figure 6

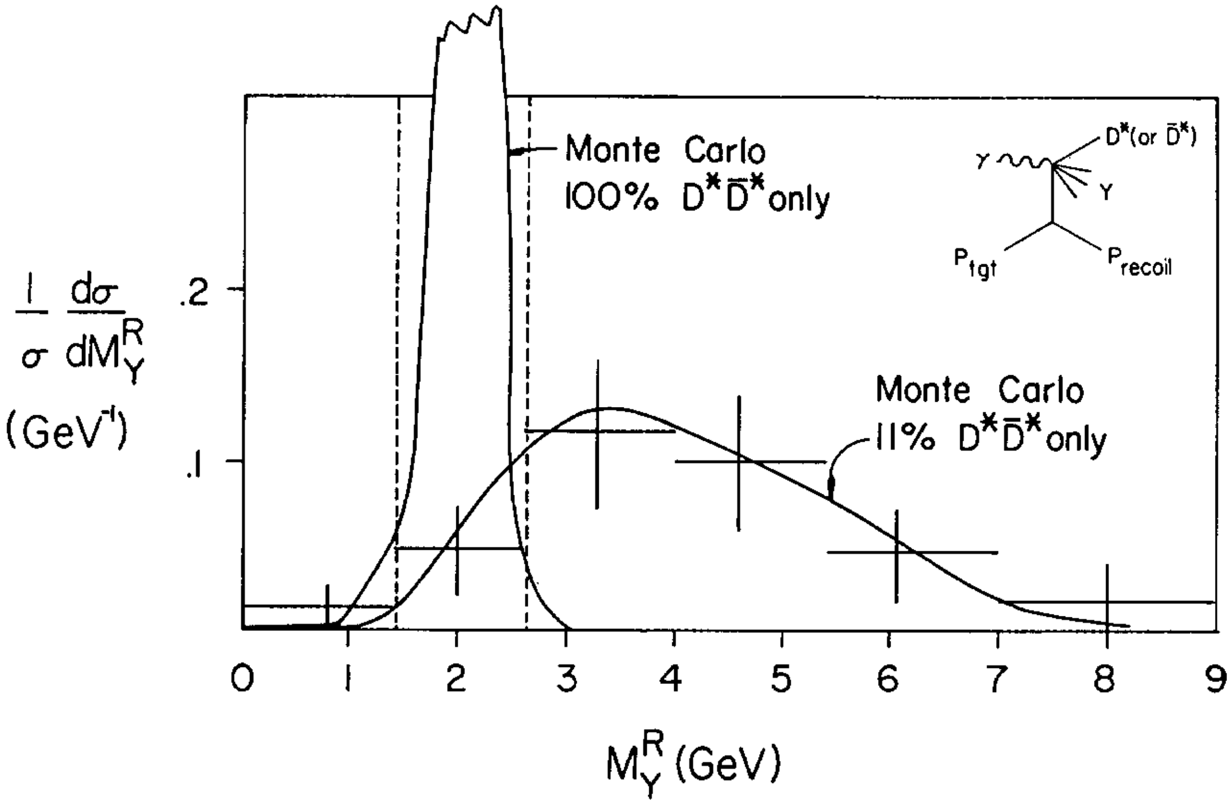

Monte Carlo
100% $D^*\bar{D}^*$ only
Monte Carlo
11% $D^*\bar{D}^*$ only
γ
D^*(or $\bar{D}^*$)
Y
P_{tgt}
P_{recoil}
$\frac{1}{\sigma}\frac{d\sigma}{dM_Y^R}$
(GeV^{-1})
.2
.1
0
1
2
3
4
5
6
7
8
9
M_Y^R (GeV)

Figure 7

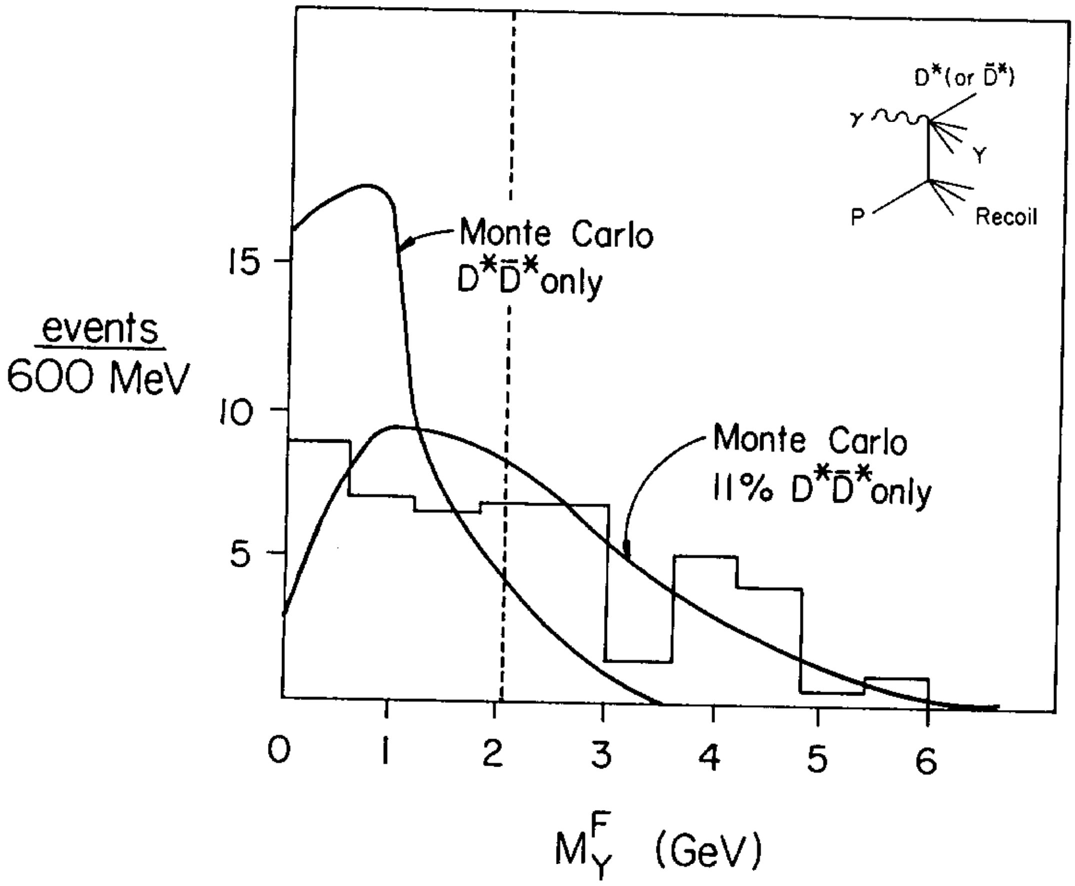

D*(or $\bar{D}$*)
γ
Y
P
Recoil
Monte Carlo
D*$\bar{D}$*only
Monte Carlo
11% D*$\bar{D}$*only
events / 600 MeV
15
10
5
0
1
2
3
4
5
6
M_Y^F (GeV)

Figure 8

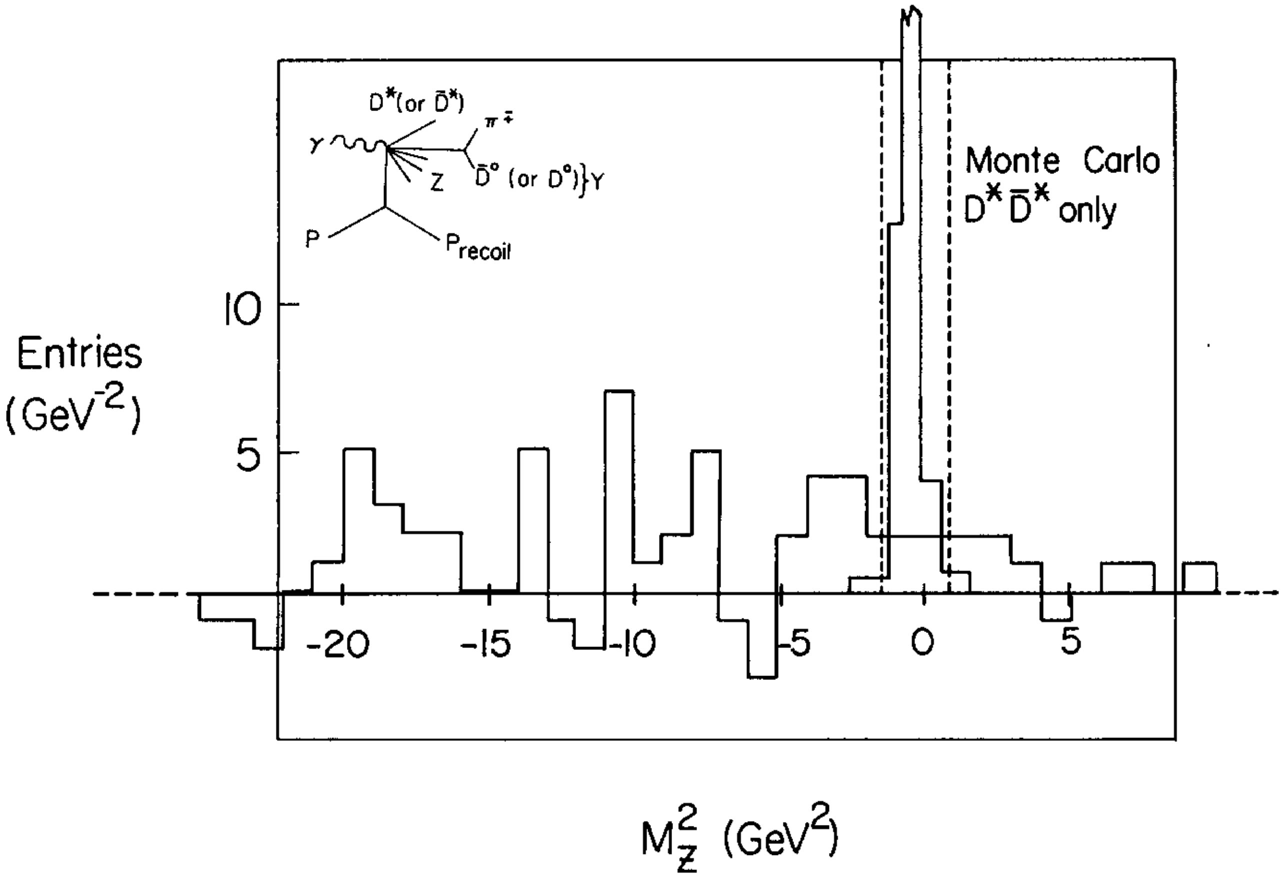

D*(or D̄*)
π∓
γ
Z
D̄° (or D°)}Y
P
P recoil
Monte Carlo
D* D̄* only
10
5
Entries
(GeV⁻²)
-20
-15
-10
-5
0
5
M²_Z (GeV²)

Figure 9

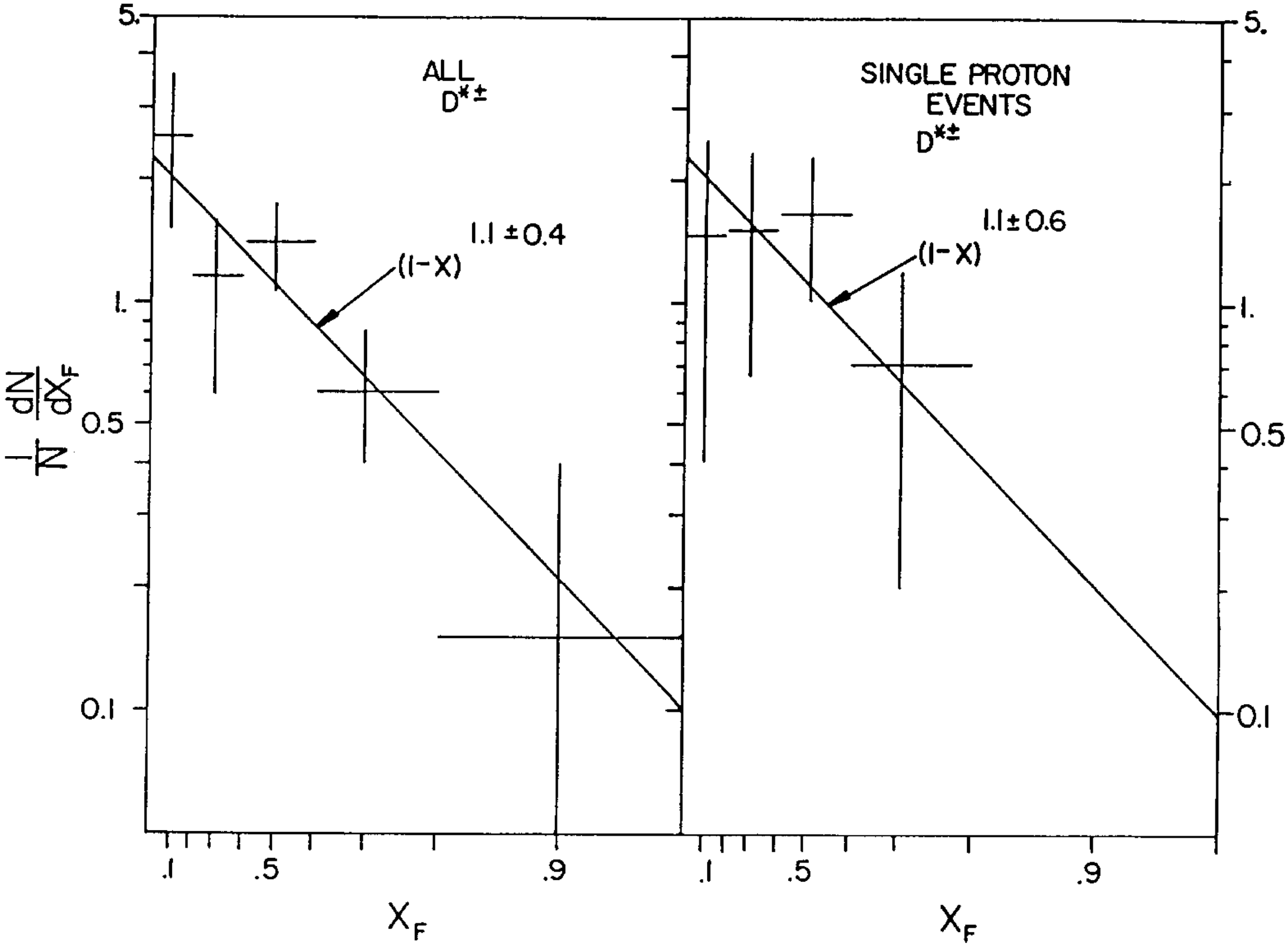

5.
1.
0.5
0.1
$\frac{1}{N}\frac{dN}{dX_F}$
ALL
$D^{*\pm}$
$(1-X)^{1.1\pm0.4}$
.1
.5
.9
X_F
SINGLE PROTON
EVENTS
$D^{*\pm}$
$(1-X)^{1.1\pm0.6}$
.1
.5
.9
X_F
5.
1.
0.5
0.1

Figure 10