Fermi National Accelerator Laboratory

FERMILAB-Conf-88/191

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December 1988

*Presented at DPF '88: the 1988 Meeting of the Division of Particles and Fields of the American Physical Society, Storrs, Connecticut, August 15-18, 1988.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

HEAVY QUARK PRODUCTION AND QCD

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Abstract

Recent results on charm and beauty production in fixed target experiments are reviewed. Particular emphasis is placed on the most recent results, on the trend favoured by the data, on comparisons with the recently improved QCD predictions and on what may be expected in the near future.

The production of charm is a field that is finally maturing, albeit more slowly than one would wish. The approach here is to simply summarize the physics results and interpret them as opposed to providing detailed descriptions of experiments which can be found in original papers as well as in several excellent reviews.[1-4]

Total cross-sections

R. K. Ellis et al. have recently calculated[5,6] the next-to-leading order terms in the QCD expressions for heavy flavour production. The essential features of the corrections are as follows. While the leading-log expressions for the partonic level $q\bar{q}$, gg and γg cross-sections all approach zero as $\hat{s} \rightarrow \infty$, the next-to-leading-log corrections for the gg and γg case do not – in fact they approach a constant. Hence the corrections are large, especially at high energies and high-p_T. However, the fact that they are large does not necessarily indicate that the series diverges, it merely reflects the fact that the additional gluon diagrams lead to this sort of behaviour.[7-10] The "K-factors" obtained from these calculations are ~3 for charm and ~2 for beauty production.[7]

Results from the major photoproduction experiments[11-15] are listed in table 1. The cross-sections increase with energy as expected and the two high-energy muon experiments are in good agreement with the high-statistics experiment E-691. The question of A-dependence does not seriously affect photoproduced cross-sections as we shall see below. Figure 1 shows the recent calculations

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by R. K. Ellis et al.[6] superimposed on the data. Shown are the curves for two different values of charm quark mass (m_c=1.2 GeV/c^2 and m_c=1.5 GeV/c^2), with the bands representing variations in all parameters except the mass, in particular in the factorization and/or renormalization scale μ. It is clear that the data prefer m_c=1.5 GeV/c^2.

Also listed (in table 2) are the cross-sections for charm production as measured by hadroproduction experiments.[16-23] After extrapolating to all x_F and correcting for non-D charm the pion induced cross-section averages 19.1 ± 1.8μb /nucleon at 400 GeV and 30±6 μb/nucleon at 800 GeV. Both of these results are dominated by the LEBC experiments. At 200 GeV, the result comes mainly from NA32 and is 16.0±0.6 μb/nucleon if we assume that the cross-section depends on A as $A^{0.8}$ (see below). Superimposing these results on E. L. Berger's recent implementation of the R. K. Ellis et al. calculations (see figure 2), we see again that m_c=1.5 GeV/c^2 is slightly favoured. Figure 1 also shows that the recent calculations are in good agreement with measurements of the B cross-section (listed in table 3) from hadroproduction of beauty experiments.[24-26]

A-Dependence

It has long been known that hadrons composed of light quarks are produced with an A-dependence of the form A^{α}, where α is in the range 0.72 to 0.79, depending on beam type. Early indications[27] from E613 were that this is also the case for charm production, but theoretical prejudice prevented immediate acceptance of this result. Recent data[28-32] confirm a slower-than-A increase (tabulated in table 4). It also seems that the A-dependence of ψ production may be explained by an α rather close to 1 (~0.9). Similarly, the photoproduction of open charm may have an α close to 1 because the photoproduction of light-quark hadrons goes like $A^{0.92\pm.01}$ and the photoproduction of ψ is like $A^{0.94\pm.02\pm.03}$.[27]

Differential distributions

By now the differential distributions have been very well measured in photoproduction (see figs. 3 and 4) and results from hadroproduction experiments indicate a general trend. The mean p_T^2 values all range around 1.2 GeV/c^2 and the x_F dependence seems central, perhaps becoming more so with increasing energy (see table 4). Initial results from NA27 and others indicated some enhancement of leading hadrons (charmed hadrons containing a beam valence quark) at high-x_F. However, recent results from NA32[19] seem to completely rule out this possibility (fig. 5). While no single experiment has high-statistics data covering the entire x_F region, photoproduced data do show peaking at $x_F > 0$, just as expected from the favourable beam-target asymmetry.

Experiment	$< E_\gamma >$	σ(nb)	Comments
SHF[11]	20 GeV	$62 \pm 8^{+15}_{-10}$	
EMC[12]	145 GeV	590 ± 80	A^1 8.2% muonic BR
BFP[13]	145 GeV	670 ± 110	$A^{.96 \pm .04}$ 9.3% muonic BR
WA58[14]	40 GeV	230 ± 60	A^1
E-691[15]	145 GeV	$580 \pm 10 \pm 60$	$A^{.93 \pm .01}$

Table 1. The total cross-sections for charm production as measured by various photoproduction experiments. All values are in nb per nucleon. The most recent charm production and decay data suggest that the muon experiments should have used 9.9% for the average D semi-muonic BR.

Experiment	Interaction	$\sigma(\mu b)$	Comments
NA27[16]	360 GeV $\pi^- p$	31.6 ± 5.4	D,$\overline{D}$, all x_F
NA27[17]	400 GeV pp	30.2 ± 3.3	D,$\overline{D}$, all x_F
E743[18]	800 GeV pp	48 ± 9	D,$\overline{D}$, all x_F
NA32[19]	230 GeV π^-Si	12.7 ± 0.5	D,$\overline{D}$, $x_F > 0$
NA32[19]	230 GeV K^-/π^-Si	$0.98 \pm .18$ (Ratio)	D,$\overline{D}$, $x_F > 0$
NA32[19]	230 GeV pSi	$2.3 \pm 0.8^{+.8}_{-.9}$	D,$\overline{D}$, $x_F > 0$
NA25[20]	200 GeV p Freon 360 GeV p Freon	$3.6^{+2.3}_{-1.7}$ $23.3^{+10.}_{-7.7}$	A^1 A^1
WA75[21]	350 GeV π^- Emulsion	10-20	A^1
E515[22]	205 GeV π^- Be	$34 \pm 18^{+14}_{-9}$	A^1 D, $\overline{D}$, $x_F > 0$
E595[23]	350 GeV p Fe 278 GeV π^- Fe	$22.6 \pm 2.1 \pm 3.6$ $17.5^{+5.4}_{-3.9}$	A^1, 8% muonic BR

Table 2. The total cross-sections for charm production as measured by various hadroproduction experiments. All values are in μb per nucleon.

Experiment	Interaction	σ(nb)	Comments
WA75[24]	350 GeV π^- Emulsion	~2.5?	
WA78[25]	320 GeV π^- U	2.0±.3±.9	A[1]
NA10[26]	286 GeV π^- W	14^{+7}_{-6}	A[1]

Table 3. The total cross-sections for beauty production as measured by various hadroproduction experiments. All values are in nb per nucleon.

Experiment	Targets	α	Comments
E613[27]	Be, Cu, W	0.75±.05	400 GeV p $\rightarrow$ beam dump
WA78, π^-[28] WA78, p[29]	Al, Fe, U Al, Fe, U	0.80±.05 0.78±.09	$x_F > .1$ $x_F > .1$
WA82[30]	Si, W	$0.72^{+.12}_{-.16}$	π^- beam
E537, π^-[31] E537, $\bar{p}$[31]	Be, Cu, W Be, Cu, W	0.87±.02 0.90±.03	ψ prod. Not A^α?
E-691[32]	H, Be, Fe, Pb	0.94±.02±.03	ψ prod.

Table 4. The A-dependence of the total charm cross-section. Listed are values of the parameter α as measured by various experiments (the cross-section is assumed to behave as A^α).

Pair distributions

Because of the limited acceptance in x_F, not many experiments have measured distributions in charm pairs. The LEBC-EHS experiments found that distributions in most quantities of interest (pair mass, x_F, rapidity gap, mean p_T^2) agreed with QCD predictions, but poor statistics (<20 events) prevent precise statements. However, there are more data for the angle ϕ between the two charm particles in the transverse plane simply because complete reconstruction is not necessary. LEBC-EHS initially discovered a possible peak at 120°, however, this has not been borne out by their subsequent investigations which show the distribution peaking at 180° as expected. WA75 see the same peaking (at 180°) in 102 events and the emulsion experiment E653 sees a rather flat distribution in ~30 events analysed so far. It will be interesting to see if this trend holds up with their full data sample.

Experiment	Interaction	$< p_T^2 >$ $(\mathrm{GeV/c})^2$	n	Comments
NA14[33]	γ Si	~1.2		
E-691[15]	γ Be	1.[illegible]6±.04	2.95±.22	x_F dist. peaks ~ .2
NA27[17]	400 GeV pp	1.03±.10		
NA27[16]	360 GeV π^-p		7.9±1.5 1.8±0.6	Non-leading Leading
NA32[19]	230 GeV π^-Si 230 GeV K^-Si	1.22±.05	3.9±.2 4.5±.9 3.6±.3 4.4±.3	No leading effect Leading Non-leading
E743[34]	800 GeV pp	1.27±.25	9±2	Central
E653[35]	800 GeV p Emulsion	0.77±.12	15±5	Central

Table 5. The parameters $< p_T^2 >$ and n in fits of the form $\exp(-p_T^2/ < p_T^2 >)$ and $(1\text{-}x_F)^n$ to the p_T^2 and x_F distributions from various experiments.

Conclusions and Future Outlook

In summary, it would be fair to conclude that the total cross-section measurements are now in agreement with QCD predictions with a charm quark mass close to 1.5 GeV/c^2, but high-statistics measurements are needed. Similarly, the A-dependence can now confidently be said to be slower-than-A, however its detailed x_F and p_T dependence awaits a high-statistics experiment. The p_T^2 and x_F distributions agree with QCD, and again better statistics will shed more light, especially in the backward ($x_F < 0$) region. There seems to be no further evidence for a leading particle effect in hadroproduction of charm. Meagre data from NA32 so far do not indicate an enhancement of D_s production by kaons, however higher statistics is again needed. Distributions of quantities describing charm pair production are particularly in need of more data. Some of these open questions will be addressed by results from E-769, WA82, E687 and E653, however conclusive answers will only come from the very high statistics experiment E-791 at Fermilab.

Acknowledgements

I would like to thank Tom Ferbel and Hugh Montgomery for this opportunity. This research was supported by the U.S. Department of Energy.

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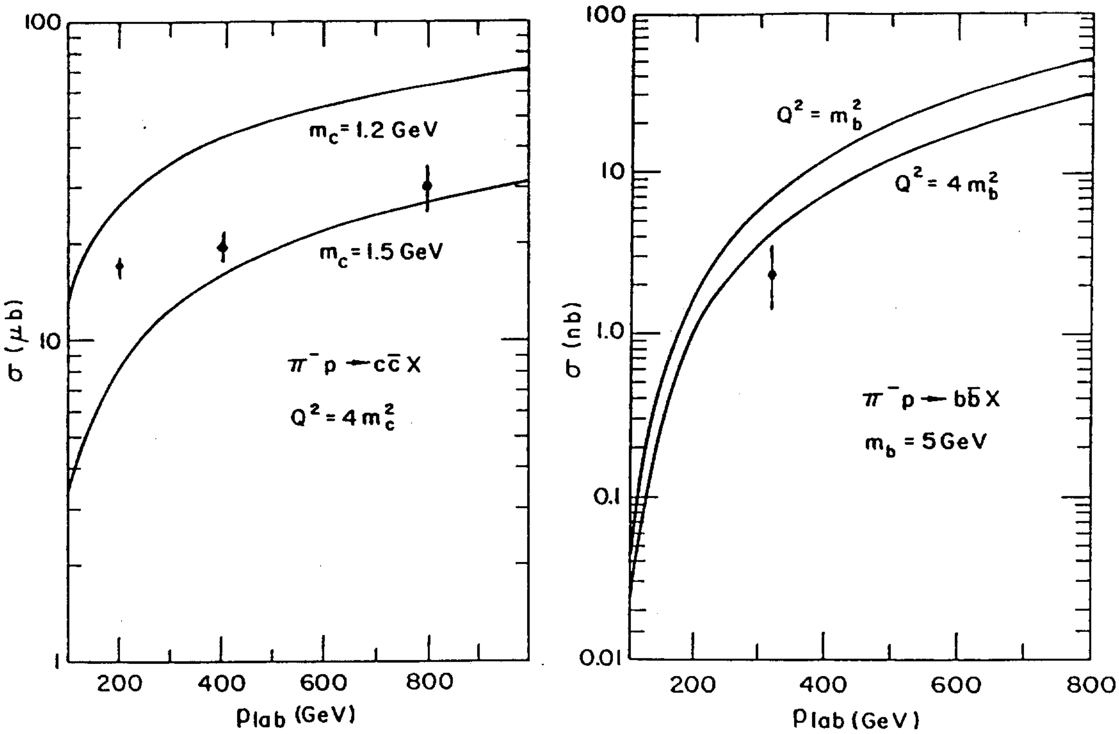

Figure 1. Data and predictions for the total cross-section for charm and beauty production at fixed target energies.

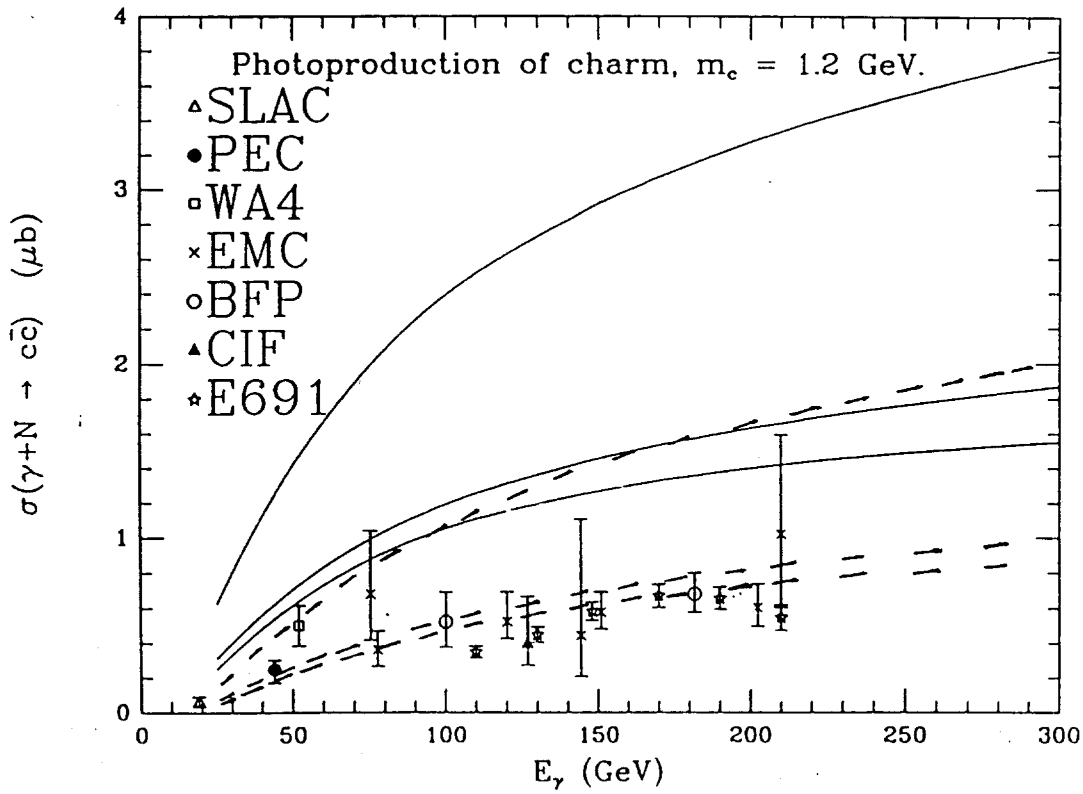

Figure 2. Photoproduction of charm cross-section data and predictions from the recent calculations of R. K. Ellis et al. The dashed curves are for the case m_c=1.5 GeV/c^2.

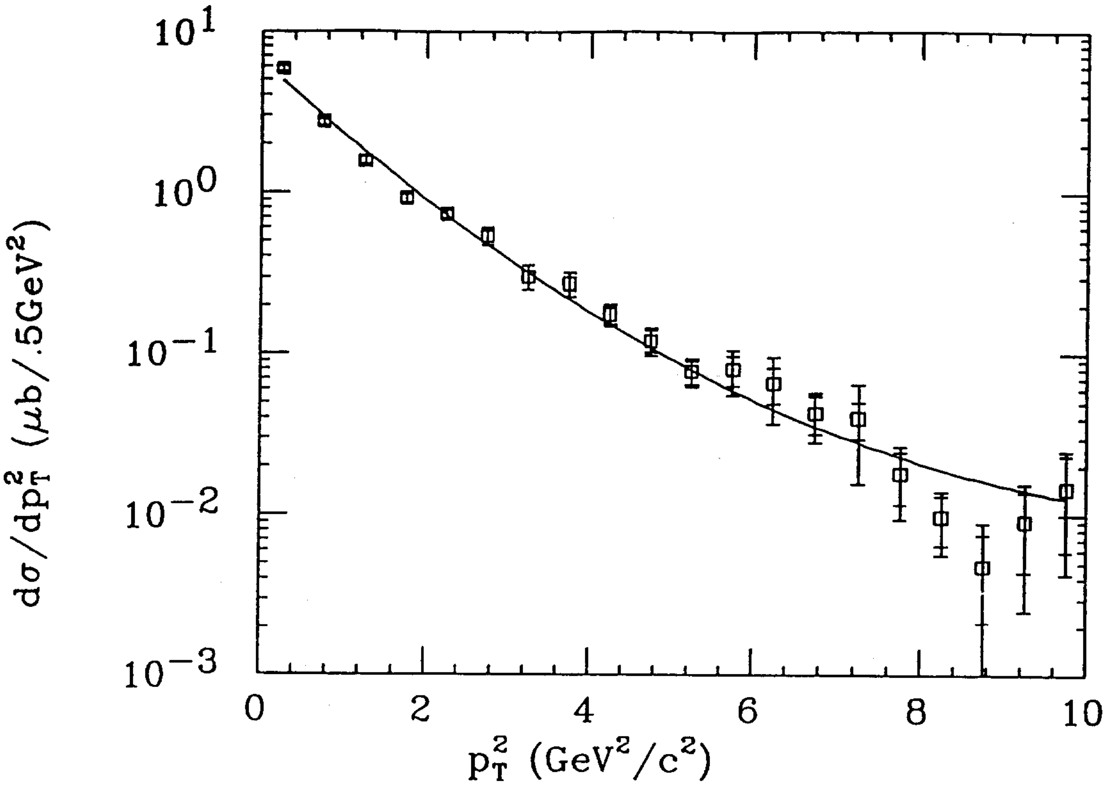

Figure 3. The p_T^2 distribution from the high-statistics experiment E-691. The curve is an empirical fit.

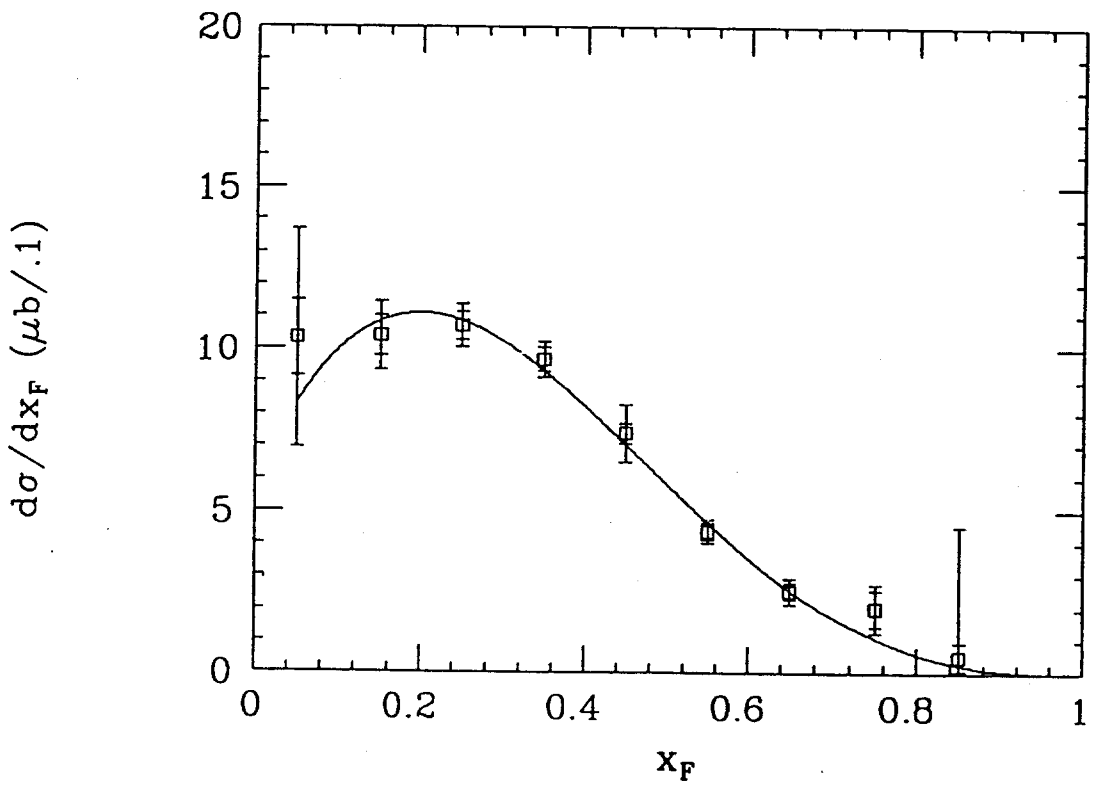

Figure 4. The x_F distribution from the high-statistics experiment E-691. The curve is a fit to the form $(1+\alpha x_F)(1-x_F)^n$.

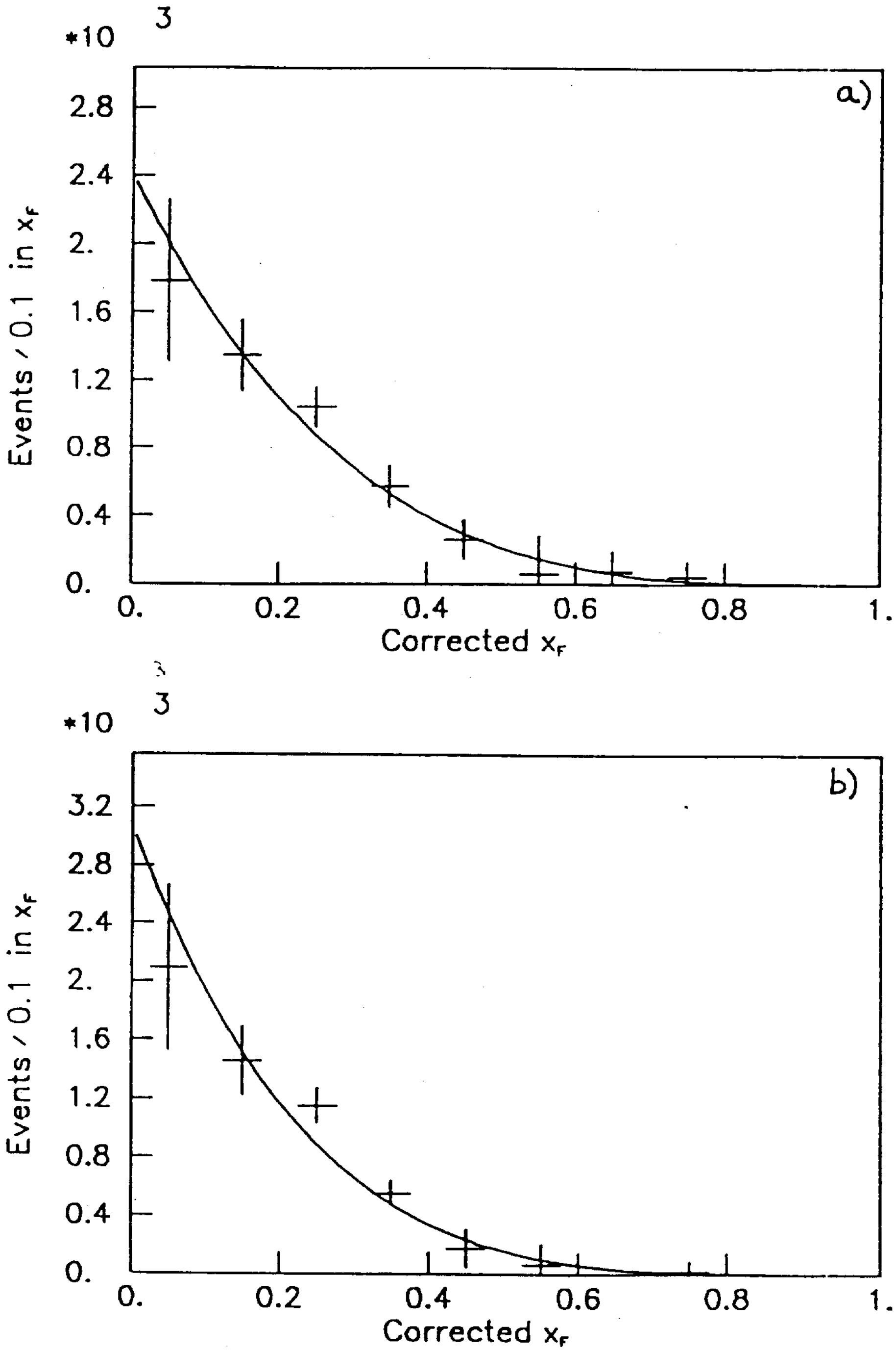

Figure 5. The leading (a) and non-leading (b) x_F distributions from NA32, showing no evidence for the hypothesis that leading charm particles are enhanced in the forward region.