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Experimental Results on Heavy Flavour Hadro- and Photo-Production*

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(Moriond)

Results from experiments on the production of beauty and charm with hadron and photon beams are reviewed. Beauty production experiments are beginning to obtain $b\bar{b}$ cross-sections with hadron beams. Hadroproduction of charm is a somewhat more mature field, although high statistics are still eagerly sought. The situation is most promising with charm photoproduction experiments where total cross-sections, p_T^2 and x_F distributions and other production characteristics are now known in considerable detail.

INTRODUCTION

We shall begin by briefly reviewing models of hadro- and photo-production of charm. Predictions from perturbative QCD and, in the case of photo-production, of vector meson dominance will be presented and discussed. Known problems with the models will also be mentioned.

We then proceed to isolate the physics accessible to experiments. Apart from the obvious aspects of measuring total and differential cross-sections, complications arise from several factors. The A-dependence of heavy quark production is a major uncertainty for instance. Leading particle effects may be important in hadroproduction experiments and the age-old question of overlap between perturbative and non-perturbative effects continues to plague the field. Recent photo-production studies from E-691 indicate a large enough data sample from which extraction of the gluon structure function should be possible.

Models of Heavy Quark Production

In perturbative QCD, heavy quark production in hadronic processes [1] proceeds via quark-antiquark fusion or by gluon-gluon fusion and in photon induced reactions by photon-gluon fusion [2]. Fundamentally, these leading order diagrams are expected to work because the coupling constant $\alpha_S(Q^2)$ is 0.25 or less: i.e., creation of heavy masses ($>$ 4 GeV/c^2) must occur at short time scales so that non-perturbative effects (higher order corrections) are small. However, one assumes that when the final state at the parton level contains colour it is dressed into hadrons in a way that does not affect the dynamics appreciably. There are also uncertainties about the argument of the function $\alpha_S(Q^2)$. Furthermore, the structure functions that are inputs to calculations of total and differential cross-sections are not very well known at present, especially the gluon structure function.

In the case of photoproduction a model known as the Vector Meson Dominance model (VMD) [3] has been successfully used to predict total cross-sections. In this model one assumes that the photon fluctuates to a vector meson, such as the J/Ψ for charm production, which then interacts hadronically to produce charm. An essential ingredient is the assumption that the coupling of real photons to heavy vector mesons is the same as the coupling when the heavy meson decays leptonically via an off-shell virtual photon. This assumption clearly is less appealing when the virtual photon is far off-shell as in heavy vector meson decays. Another serious drawback of this model is its predictive power: the cross-section for the photoproduction of charm is related to the hadronic cross-section of the J/Ψ by

$$\sigma(\gamma N \to X) = \left(\frac{4\pi\alpha}{\gamma_\psi^2}\right)\sigma(\Psi N \to X) = \frac{3\Gamma_{ee}}{\alpha M_\psi}\sigma(\Psi N \to X) \tag{1}$$

The total hadronic cross-section is not accurately known and little, if anything, is known about the differential cross-section.

Beauty Production

There are now three experiments [4-6] which claim evidence for open beauty production. WA75 has reported a single event which is identified as containing a B^--$\overline{B}^0$ pair in emulsion where the muons are further identified in a downstream detector. WA78 has examined trimuon events from π^-U interactions at a beam energy of 320 GeV. Trimuons are expected from the semi-muonic decays of beauty and its charm products. Using a Monte Carlo to fit the 13 events with a high total muonic p_T (> 3.2 GeV/c) and a large missing energy (> 50 GeV) they find that the total cross-section per nucleon assuming an A^1 dependence is $\sigma_{b\bar{b}}$=4.5±1.4±1.4 nb. UA1 has also examined their sample of dimuon events where the dimuons have a high mass (> 6 GeV/c^2) and both muons have a high p_T (each > 3 GeV/c). Using the fact that muons from bottom decays are expected to be in jets, they require that the muons be non-isolated, i.e., a large transverse energy relative to the muons be found in a cone around the muons. For $|\eta| < 2$, $p_T^b > 5$ GeV/c, they find that $\sigma(p\bar{p} \to b\bar{b}X)$=1.1±0.1±0.4 μb, in good agreement with an ISAJET estimate [6] of 1.7 μb.

While it is clear that beauty cross-sections are beginning to be measured, it is very important to settle on their exact values. For instance, one possible interpretation of the above numbers is that at UA1 energies ($\sqrt{s}$=630 GeV) experiment and theory are in rough agreement, while at fixed target energies ($\sqrt{s}$=24.5 GeV) one needs a K-factor of 3–5 to explain the difference between the WA78 cross-section and the prediction based on perturbative QCD which is 0.7–2 nb [7]. The total cross-section determines the statistics which will be obtained in fixed-target and collider experiments planned for doing bottom physics. In particular, testing standard model predictions for CP violation in the $B\overline{B}$ system and finding rare B decay modes are greatly facilitated if $\sigma_{TOT}(b\bar{b})$ is large.

Hadroproduction of Charm

There are several reviews of hadroproduction experiments [8]. From these it is clear that the mean p_T^2 in hadroproduced charm is approximately 1 GeV^2, a result that agrees well with the fusion model if the mean parton k_T^2 is assumed to be ~0.65 GeV^2. When hadroproduction experiments parameterize their x_F distributions with the form

$$\frac{dN}{dx_F} \sim (1 - x_F)^n \tag{2}$$

they find values of n which vary from 1 to 7. There is some evidence that leading charmed mesons have flatter x_F distributions. Fusion model calculations tend to predict softer distributions which fit the data well below x_F=0.3.

Total cross-sections are hard to compare because it is not obvious how to compare data from different nuclear targets. When cross-sections for hadroproduction of lighter mesons are parameterized as having an A^α dependence, it is known that α has a strong x_F dependence, varying from 0.75 at x_F=0 to 0.45 at x_F=1. Fermilab experiment E-613, a neutrino sensitive beam dump experiment, obtained the value α=0.75$\pm$0.05 for charm production [9]. However, comparisons of LEBC-EHS data with E595 [8a] or ACCMOR [8b] lead to somewhat larger values of α (0.8–1). This problem may be circumvented altogether by comparing experiments using the same nuclear target. In the case of proton targets, LEBC data [10] indicate cross-sections of the order of 20μb at $\sqrt{s}$=27 GeV and $\sim$30μb at $\sqrt{s}$=39 GeV with a ratio of $1.7^{+0.6}_{-0.5}$. ISR data [11] indicate a much larger charm production cross-section (several hundred μb) at $\sqrt{s}$=60 GeV based on their observations of Λ_c^+. Fusion model calculations are in good agreement with the energy rise seen by LEBC (although the ratio has large errors – see fig. 5), but there is considerable uncertainty regarding the total cross-section itself. Older calculations [10b] indicate that the observed cross-sections are higher by a factor of $\approx$2–3 compared to fusion model calculations, while a more recent calculation [2d] indicates that the theoretical uncertainties are larger than believed earlier and may in fact cover the measured cross-sections, except possibly for ISR data.

Detailed data on the correlations between $D\overline{D}$ pairs are beginning to become available. The LEBC-EHS group [12] has studied distributions of the x_F, p_T^2, mass, rapidity gap and ϕ_T for 12 clean $D\overline{D}$ pairs (53 in the case of the ϕ_T distribution). They have tried to fit this data with the fusion model followed by three different types of fragmentation (Lund, Peterson and a δ-function) as well as with a phase-space model where the D and $\overline{D}$ are uncorrelated except for energy-momentum conservation. They find that the distributions are fit well by all models except for the p_T^2 distribution. The mean observed $p_T^2(D\overline{D})$ is 1.65$\pm$ 0.40 GeV/c^2, well in excess of predictions of $\sim$ 0.65 GeV/c^2 from the fusion models, but in agreement with the phase space model. They also report a possible peak at 120° in the ϕ_T distribution, which is around the 2σ level.

Clearly, higher statistics data are needed to throw light on the questions posed by the correlation data. There is an upcoming experiment, E-769, which will use the E-691 apparatus (with minor changes) and is expected to record around 300 million events on tape! E-769 and other planned or proposed experiments [13] will yield information on the total and differential charm cross-sections, including the A-dependence. Another topic of interest which will be studied is the relative production of various charmed particles and the enhancement of the total cross-section when kaon and hyperon beams are used. New results can be expected starting a year from now and over the next few years.

Photoproduction of Charm

Before discussing open charm production, a brief mention is made of a recent result on J/Ψ production. Motivated by the EMC result [14] $[\sigma(\mathrm{Fe})/\sigma(\mathrm{H,D})]_{\Psi}=1.45\pm0.12\pm0.22$, E-691 measured the ratio of J/Ψ production cross-sections on four different targets: H, Be, Fe and Pb. They parameterized coherent and incoherent cross-sections as a function of A using the form $\sigma=\sigma_0 A^{\alpha}$ and found $\alpha_{incoh}=0.94\pm0.02\pm0.03$ and $\alpha_{coh}=1.40\pm0.06\pm0.04$ [15]. The α_{incoh} disagrees with the EMC result which can be interpreted as $\alpha_{EMC}=1.10\pm0.03$ ±0.04 but is in good agreement with a SLAC experiment [16] which reported $\alpha_{SLAC}=0.94$ ±0.03.

Why do we study photoproduction of open charm when the cross-section for charm production via hadrons is so much higher? In fact, photon beams of known energy are obviously harder to produce than hadron beams. We briefly summarize the advantages of photoproduction below:

	Hadroproduction	Photoproduction
$\sigma_{c\bar{c}}/\sigma_{TOT}$	(0.5–1.)x10^{-3}	~0.5x10^{-2}
Number of structure functions involved	$q\bar{q}$ fusion and gg fusion	γg fusion only
Power to which structure functions enter	$\{F(x)\}^2$	F(x)
Power to which QCD coupling constant enters	α_s^2	α_s
Higher order corrections	Larger corrections due to more colour combinations	Smaller corrections due to fewer colour combinations
Leading particle effects	Possibly a problem	No such effect

Prominent among the photoproduction experiments are E-87, the SLAC Hybrid photon experiment, WA58 and a ψ production experiment, E-401. Two major muon experiments, the EMC and BFP, also provide data from virtual photons which can be extrapolated to $Q^2=0$ for comparisons with production from real photons. Important results from these experiments are summarized below:

Experiment [Ref.]	Results	Comments
E-87 [3c]	$< p_T > \sim 1/2$ GeV for D^*	
SLAC Hybrid [17]	$\sigma_{TOT}=(62\pm 8^{+15}_{-10})\times 10^{-3}\mu$b $\sigma(\overline{D}\Lambda_c^+ X)/\sigma_{TOT}=(71\pm 11\pm 6)\%$	at $E_\gamma=20$ GeV
WA58 [18]	$\sigma_{TOT}=(0.23\pm.06)\mu$b $\sigma(\overline{D}\Lambda_c^+ X)/\sigma_{TOT}=(28\pm 23)\%$ $\sigma(\overline{D}DX)/\sigma_{TOT}=(70\pm 21)\%$	(assuming A^1 dependence) at 20 GeV $< E_\gamma <$ 70 GeV
E-401 [8]	σ(200 GeV)/σ(100 GeV)=1.56±0.20	$\gamma N \to \psi N$ (elastic) (statistical errors only)
EMC [19]	Good agreement with PGF for Q^2, ν, p_T and $\Delta\phi$ distributions. σ(200 GeV)/σ(100 GeV)=1.53±0.20	$\mu\mu$ and $\mu\mu\mu$ events from virtual photons. Agreement achieved without floating normalization. $xG(x)=3(1-x)^5$ (statistical errors only)
BFP [20]	Good agreement with PGF as for EMC. σ(200 GeV)/σ(100 GeV)=1.44±0.20	Comments as for EMC

Table 2. Results from major photoproduction experiments prior to E-691.

As we can see, there are three experiments with data on the rise of the total charm cross-section, if we assume that the E-401 result holds for open charm production. Prior to E-691, there was no good information on the p_T^2 and x_F distributions of charmed mesons, or the total cross-section. There is no information on the A-dependence of open charm production. It would appear that associated production decreases dramatically from 20 GeV (SLAC experiment) to the somewhat higher energy range (20-70 GeV) of WA58. Whether this trend continues is a very interesting question as it throws light on how the $c\bar{c}$ pair is hadronized. Hadronization when the quark couples to a diquark in the target nucleus would favour lower values of x_F for particles as opposed to antiparticles, leading to an enhancement of $\overline{D}$ mesons in experiments such as E-691 which only cover the forward ($x_F>0$) region.

Recently, E-691 has reported results [17] from a preliminary analysis of 30% of their data sample (see figs. 1 and 2) i.e., 30 million of their recorded total of 100 million events. The results include information about x_F distibutions (fig. 3) which when fit to the form (2) in the $x_F>0.2$ region yield $n=2.7\pm.1\pm.6$, in good agreement with a Monte Carlo which uses photon-gluon fusion and the Lund Monte Carlo [22] for hadronization. The $< p_T^2 >$ of D mesons is determined to be 1.34±.05±.08 GeV^2 (fig. 4), also in good agreement with the value 1.35 GeV^2 expected from the same Monte Carlo. In their (mostly forward) acceptance region, they find that the ratio of antiparticles to particles is 1.02±.05. This indicates that there is little associated production at E-691 energies ($< E_\gamma >$=170 GeV for charm events). The total cross-section for charm production was measured in the x_F >0.2 region for D^0 and D^+ mesons. Using their Monte Carlo, E-691 extrapolate this information to cover all x_F and the charmed particles other than D mesons. The result is $\sigma_{c\bar{c}}$=(3.17±.22±.8)μb *per Be nucleus*. The ratio of cross-sections at 200 GeV and 100 GeV is determined to be 1.83±.29±.37 (fig. 6), consistent with previous experiments and the PGF model.

They expect to continue studies of photoproduction of charm, concentrating in particular on improving their understanding of the detector acceptance and extracting the gluon structure function from the sample of events where both charmed particles are fully reconstructed. Since the total charm cross-section is sensitive to m_c and the energy rise to the power of (1-x) in the gluon structure function, together with the two-charm events E-691 should be able to extract this structure function quite well.

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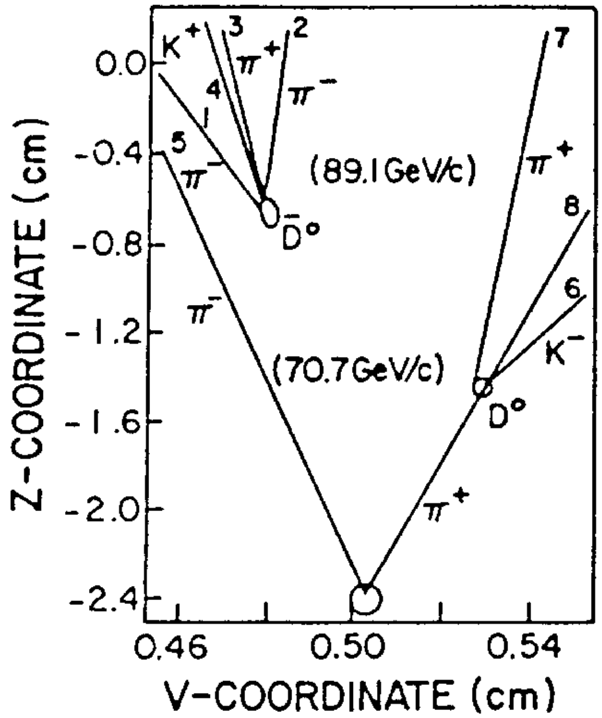

Figure 1. An E-691 charm event: magnified view of the vertex.

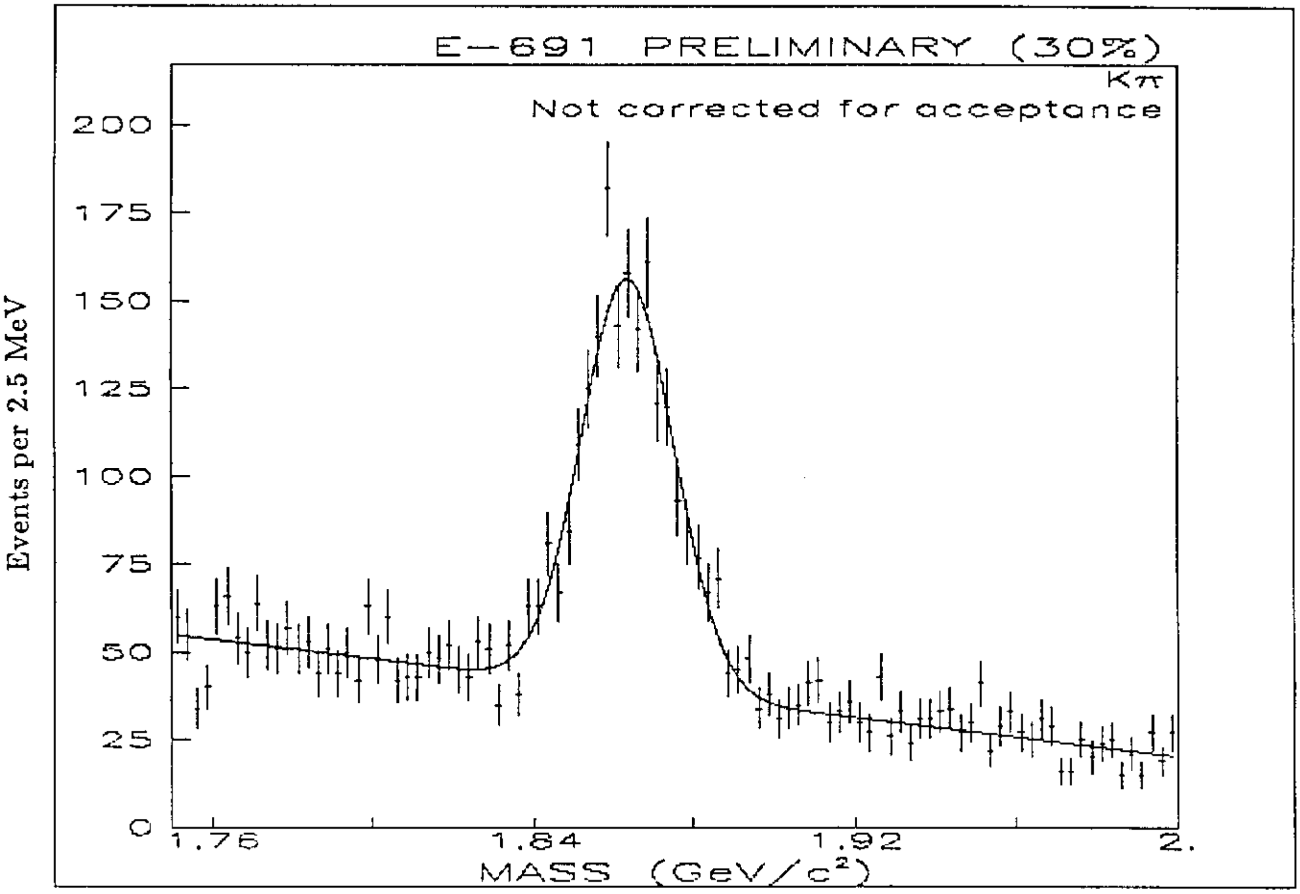

Figure 2. The $D^0 \to K^-\pi^+$ mass plot.

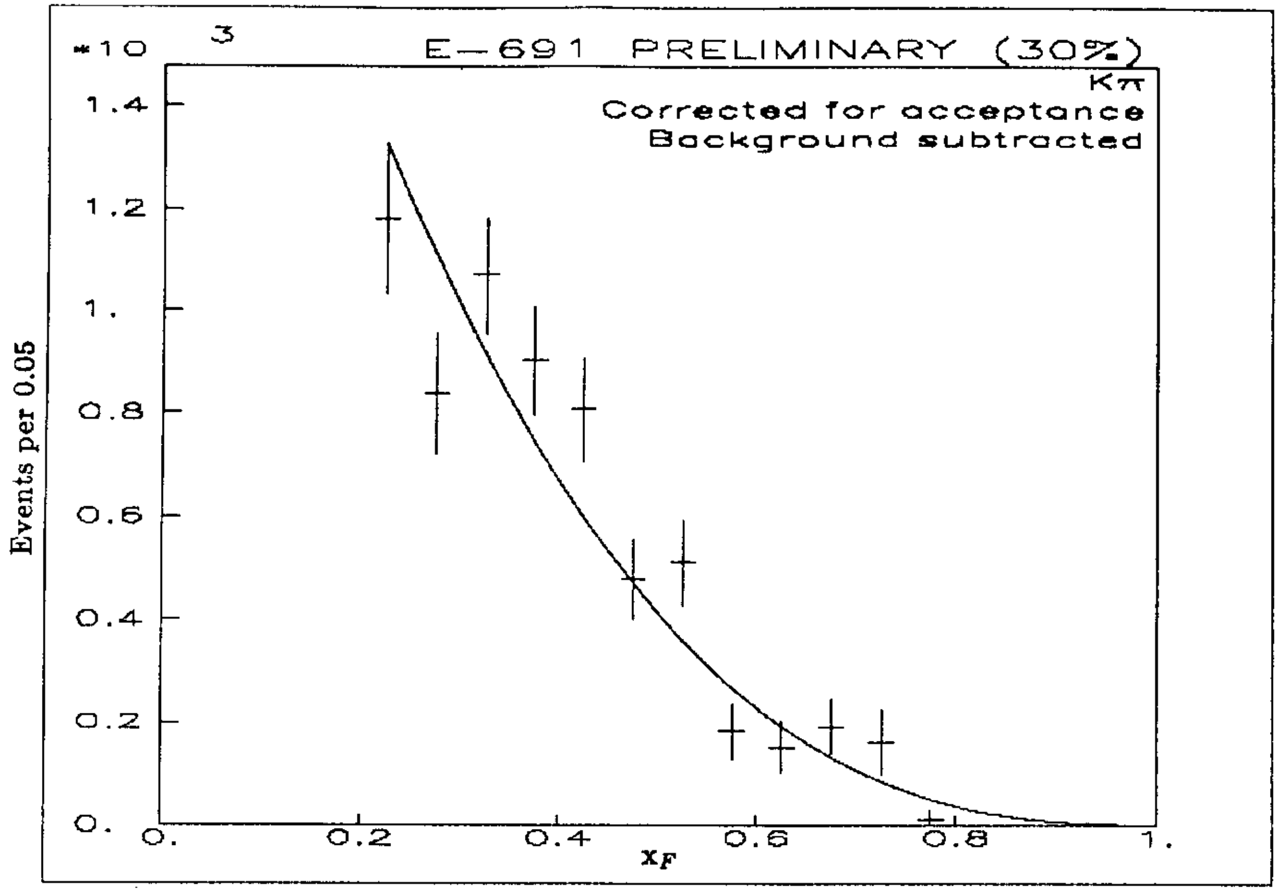

Figure 3. The x_F distribution for the $D^0 \rightarrow K^-\pi^+$ mode for $x_F > 0.2$. The solid line is the fit described in the text.

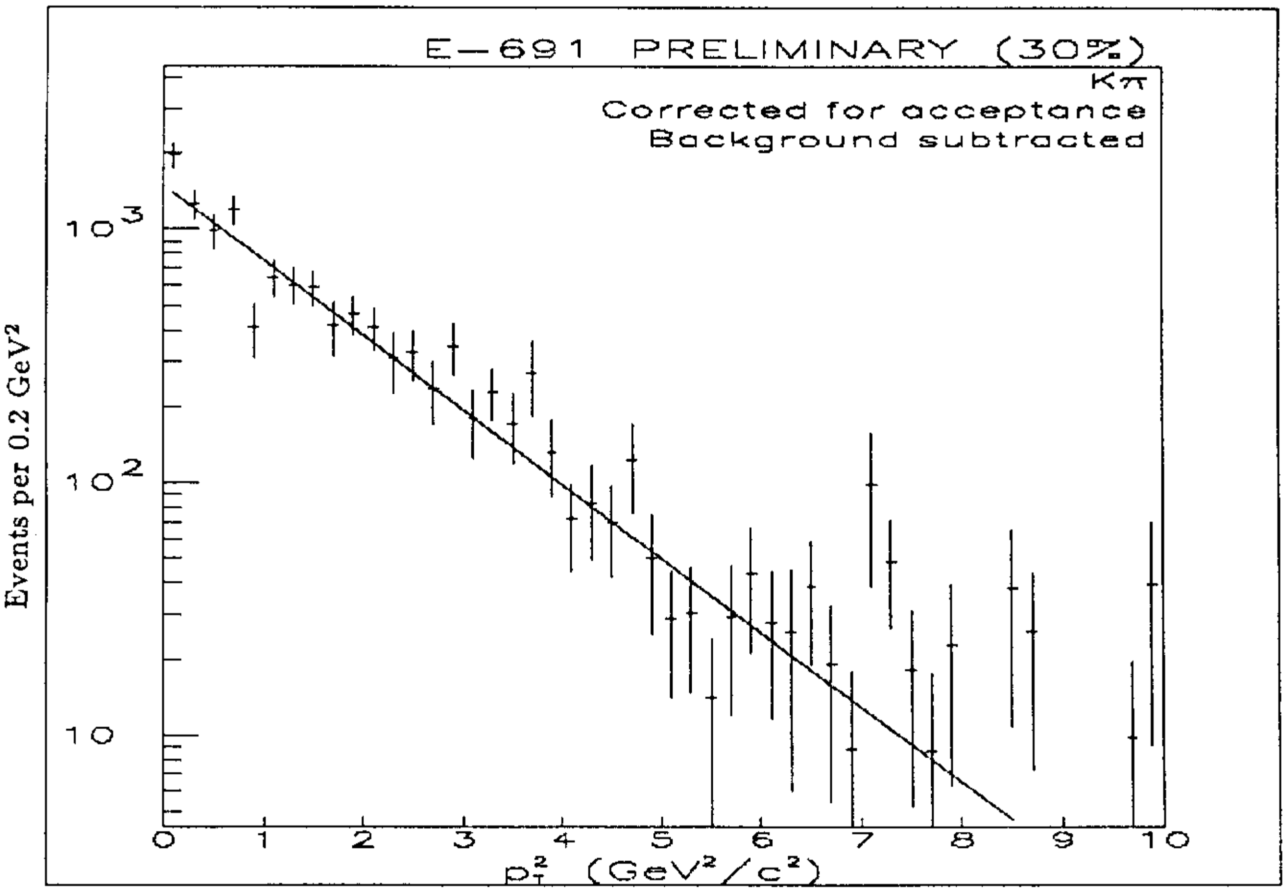

Figure 4. The p_T^2 distribution for the $D^0 \rightarrow K^-\pi^+$ mode. The solid line is an exponential fit.

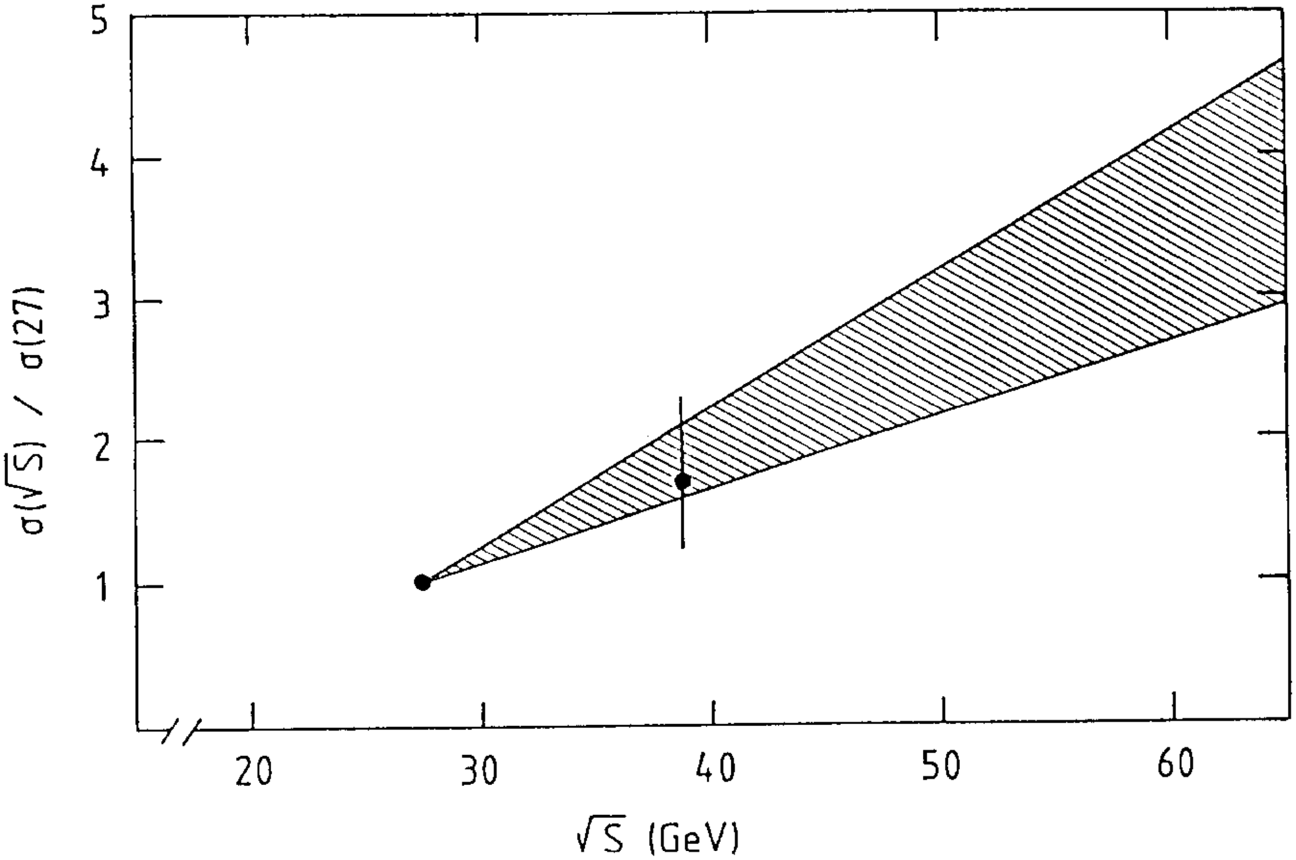

Figure 5. The rise of the D cross-section from the LEBC group. The shaded region indicates the range of fusion model predictions.

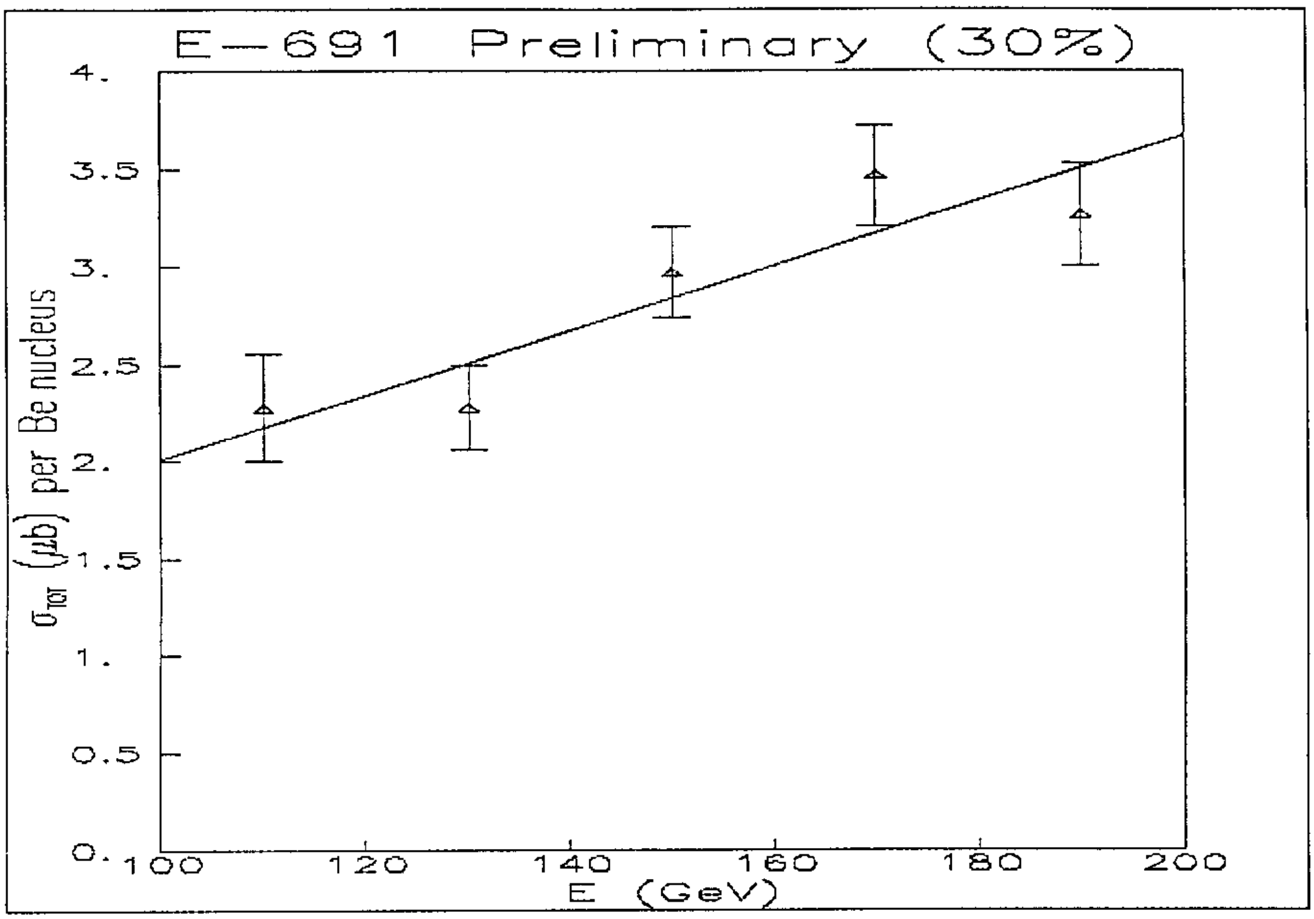

Figure 6. The rise of the D meson cross-section from E-691 fit by a straight line.