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HEAVY QUARK PRODUCTION

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HEAVY QUARK PRODUCTION

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ABSTRACT

This review covers the hadro- and photo-production of charm and beauty particles. The most recent experimental results on charm are compared with the next-to-leading order QCD calculations. Results on beauty production at hadronic colliders are presented and indicate that these machines may also be regarded as beauty factories.

1.INTRODUCTION

This paper presents the most recent experimental results on charm and beauty production by photons and hadrons. The comparison of those results with perturbative Quantum Chromo Dynamics (QCD) calculations is a check of this theory if the perturbative approach is valid (i.e. if the mass of heavy quark is $\gg \Lambda_{QCD}$). This is considered to be true for the B-quark, while it is an experimental problem to establish if the C-quark is heavy enough. There are two measurements that are crucial for this purpose:

a) the (non-)existence of leading particle effect

b) the nucleon number dependence of charm production

We will go in more details about these measurements in the following. I here just want to observe that they are better (or uniquely) done in fixed target hadroproduction experiments. The study of charm hadroproduction should then establish the applicability of perturbative QCD to charm physics. Once this is done, photoproduction may be easier to interpret since there is only one leading order diagram (the photon-gluon fusion) and only one gluon distribution, all that makes the calculations less dependent on the distribution assumed.

In the framework of the QCD parton model the heavy quark production cross section can be parametrized as

$$\sigma_{Q\overline{Q}}(s) = \sum_{ij} \int dx_i dx_j G_{i/A}(x_i) G_{j/B}(x_j) \sigma_{ij}(\hat{s})$$

where:

$\sigma_{ij}(\hat{s})$ = cross section for the subprocess $i + j \rightarrow Q\overline{Q}$

$\hat{s}$ = c.m.s. energy squared of the subprocess ($\hat{s} \cong x_i x_j s$)

$G_{i/A}$ = probability to find a parton i with a fraction x_i of the momentum of the hadron A.

The lowest order diagrams, shown in figure 1, do not account for all of the charm cross section. Next-to-leading order calculations [1] introduce new subprocesses (like, in case of the hadroproduction, $gg \to Q\overline{Q}g, g\overline{q} \to Q\overline{Q}\overline{q}, q\overline{q} \to Q\overline{Q}g$) and find a rather good agreement with data as we will see later. The large K factor ($K_c = \sigma_{c\bar{c}}(\alpha_s^3)/\sigma_{c\bar{c}}(\alpha_s^2) \sim 3$; while $K_B \sim 2$) is anyhow not fully satisfactory and may point to still large higher order corrections.

The dominant diagrams are those where two gluons (or a photon and a gluon) fuse to produce a $Q\overline{Q}$ pair. It is therefore believed that the measurement of the differential heavy quark cross section should be a good way of determining the gluon structure functions. This approach has in principle the advantage of allowing the direct measurement of the gluon density, while in the standard deep inelastic scattering measurement the gluon distribution is found as a higher order correction.

In this paper I first discuss charm cross section and nuclear number dependence, I'll then present some recent results about beauty production and I'll finally indicate the short term perspectives of this kind of studies.

2. CHARM DIFFERENTIAL CROSS SECTION

The charm differential cross section is usually parametrized as

$$\frac{d^2\sigma}{dX_F dp_T^2} \propto (1 - |X_F|)^n \ e^{-bp_T^2} \tag{1}$$

There is no quantitative theory behind this parametrization, but simply a historical justification since all the light quark data accumulated during the last two decades are presented in this form.

There has always been good agreement amongst the experiments studying charm about the p_T distribution, much less about the X_F dependence.

(a) p_T distribution

In hadroproduction, assuming an intrinsic parton K_T such that $< K_T^2 > = 0.64$ GeV^2 as measured in Drell-Yan experiments, we expect, from lowest order QCD calculations [2], $< p_T > = 0.9$ GeV, or $b \approx 1$ GeV^2 in equation (1). All experiments agree reasonably well on the value of b and follow the parametrization (1) if $p_T^2 < 5$ GeV^2. Recent results from WA82 [3] extend up to 16 GeV^2; in this case a fit of type (1) does not cover the full p_T range (see figure 2), while a satisfactory representation of the data is obtained using leading order QCD calculations [3].

In photoproduction there is only one parton in the initial state, therefore the intrinsic K_T of the gluons is half as important as in hadroproduction. E691 [4] has fitted $d\sigma/dp_T^2$ (excluding the region $p_T^2 < 2$ GeV^2 in order to minimize the intrinsic K_T corrections) with the photon-gluon fusion [5] model and has determined $m_c = 1.74^{+0.13}_{-0.18}$ GeV and $n_g = 7.1 \pm 2.2$. NA14 [6] has fixed the gluon structure function distribution $[x\ G(x) = (1-x)^5]$ and has then measured the charm mass obtaining $m_c = 1.58 \pm 0.07$ GeV.

Both these charm mass determination should be considered with the proviso that the charm quark may be too small to apply perturbative QCD.

(b) X_F distribution

Calculations to $O(\alpha_s^3)$ have been performed at $\sqrt{s} = 23$ GeV [1], where most of the experimental data exist. The X_F distribution obtained (see figure 3) is similar to $(1-|X_F|)^n$ with $n \sim 3.5$. The small difference for $X_F > 0.5$ between c and $\bar{c}$ production is due to the interference between the diagrams $qg \to c\bar{c}$ and $q\bar{q} \to c\bar{c}$ and it has nothing to do with the leading particle effect. This effect (more forward production of a hadron if it has a quark in common with the projectile) is not explained in QCD.

Early results from NA16 and NA27 [7] (see figure 4), confirmed by a beam dump experiment [8], indicated a substantial enhancement of leading charmed mesons in pion induced reactions. More recent results from NA32 [9] (see figures 5) do not show any significant difference between the leading and the non leading sample and find values of n compatible with $O(\alpha_s^3)$ calculations.

WA82 has compared the X_F-distribution of D^- and D^+ produced by π^-. The results (see figure 6a) show an indication of leading particle effect, not as strong as the one claimed in ref.[7]. The comparison of the X_F-distribution of charmed and anticharmed mesons (see figure 6b) does not indicate any effect of interference between the diagrams $qg \rightarrow c\bar{c}$ and $q\bar{q} \rightarrow c\bar{c}$.

The agreement between $O(\alpha_s^3)$ QCD calculations and data is quite good (see figure 7).

In the following table the values of n as recently measured in experiments that study charm production by pions are summarized.

TABLE 1

Experiment	n leading	n non leading	n all
NA32	$3.55\pm^{0.26}_{0.25}$	$4.37\pm^{0.29}_{0.28}$	3.93 ± 0.19
WA82	$2.8 \pm .2 \pm .3$	$3.7 \pm .2 \pm .3$	$2.9 \pm .1 \pm .3$
E769	2.7 ± 0.3	3.4 ± 0.4	3.1 ± 0.3

The study of $d\sigma_c/dX_F$ in photoproduction does not provide the same kind of information as in hadroproduction. There is in fact no leading particle effect because there are not quarks left in the beam jet.

3. CHARM TOTAL CROSS SECTION AND FLAVOUR DEPENDENCE

Calculation to next-to-leading order give good agreement with data (see figure 8) using a reasonably high (1.5 GeV) value of the charm quark mass; agreement was possible in lowest order QCD calculations only by using $m_c = 1.2$ GeV. $O(\alpha_s^2\alpha_{em})$ calculations compared with the total charm photoproduction cross-section (figure 9) favour again $m_c \sim 1.5$ GeV.

All the measurements available to date do not show any dependence on the nature of the incident hadron. NA27 has reported [7]:

$$\sigma_c(\pi^- p \rightarrow D/\overline{D} + X) = 31.2 \pm 5.4 \mu b$$

$$\sigma_c(pp \rightarrow D/\overline{D} + X) = 30.2 \pm 2.2\mu b$$

using a 360 GeV π^- beam and a 400 GeV proton beam.

While NA32 has published [8],assuming $\alpha = 1$:

$$\sigma_c(\pi^- N \rightarrow D/\overline{D} + X) = 9.5 \pm 0.4 \pm 1.9\mu b/\text{nucleon}$$

for $X_F > 0$

$$\sigma_c(K^- N \rightarrow D/\overline{D} + X) = 8.5 \pm 1.6 \pm 1.2\mu b/\text{nucleon}$$

using a 230 GeV meson beam.

More precise results should soon be obtained by E769, it is anyhow already clear that gluon-gluon diagrams dominate.

4. A DEPENDENCE

The dependence of a cross section on the nuclear mass number A of the target is usually parametrized as:

$$\sigma \propto A^\alpha$$

where $\alpha \sim 2/3$ for the light quarks [10], in this case α is also a function of X_F and p_T [11] (see figure 10).

The importance of determining α for charm is two-fold:

(a) To establish if QCD is applicable in case of charm (the QCD parton model predicts the charm cross section as an incoherent sum of elementary processes on partons and then proportional to the number of quarks in the nucleon, therefore $\alpha \sim 1$).

(b) To reconcile the results of charm hadroproduction experiments performed with different target materials.

Previous evaluations of α have been done either by measuring lepton yields in beam dump experiments [12] or by comparing results from various experiments [13] each performed using different target materials. Both methods are model dependent and need large correction factors, their results show conflicting indications as illustrated in the table below.

TABLE 2

Experiment	Technique	X_F–range	α
E613	Beam dump	$X_F > 0.15$	0.75 ± 0.05
WA78	Beam dump	$X_F > 0.20$	0.80 ± 0.05
NA25-NA27	Bubble chamber	$X_F > 0$	$1.12^{+0.12}_{-0.10}$

The first direct measurements of A-dependence of charm production has been performed by WA82 [14]. In this case a thin target is divided vertically into two equal sections respectively of tungsten and silicon and the beam is steered so that both sections receive approximately the same intensity. The geometry of the targets, reflected in the primary vertex distribution along the vertical coordinate (figure 11(a)), allows a simultaneous measurement of σ_w/σ_{si} both for ordinary interactions and for charm production. Using a signal of about one thousand D mesons (figure 11 (b)) over a background of ~ 250 they have determined

$$\alpha_{\text{charm}} = 0.88 \begin{matrix} +0.04 \\ -0.05 \end{matrix}$$

(statistical error only), a control measurement has been made using the K^0_s signal that has gone through the same selection and cuts made for charm. The result

$$\alpha_{K^0_s} = 0.70 \pm 0.005$$

is in agreement with previous measurements [10].

A preliminary plot of the X_F dependence of α_{charm} (figure 11 (c)) does not indicate any decreasing trend, as it is the case for light quarks, but rather a constant behaviour.

A new measurement of α has been recently presented to a conference[15] by the E769 collaboration. The experimental method used is slightly different from the

WA82 one: the target is made of 26 thin metal foils (see figure 12 (a)) crossed by the beam. The advantages are that there is no need of recording the beam flux end that there are four points to measure the A-dependence (Be, Al, Cu, W), the main disadvantage is that the signal over noise ratio at the charm peak is worse because some of the secondary interactions mimic charm decays (see figure 12 (b)). The preliminary values of α for D^0 and D^+ are shown in figure 13.

Both experiments using clean charm signals (i.e. invariant mass peaks) to measure α give compatible results. Moreover these results are also compatible with the (more precise) measurement of α for hidden charm (J/ψ), that has recently been published by E772 [16] ($\alpha = 0.92 \pm 0.008$). In this case the data are sufficiently copious that α can be studied as a function of X_F and p_T. The trend (see figure 14) is the same as for light quarks, but less pronounced.

E772 has also measured [17] the α dependence of hidden beauty (Υ) obtaining:

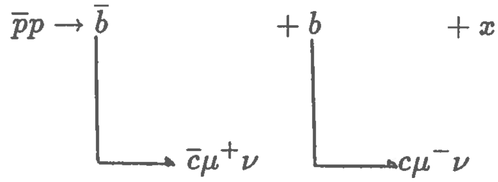
$$\alpha = 0.962 \pm 0.06 \pm 0.08 \qquad \text{for} \quad < X_F >= 0.23 \quad \text{and} \quad < p_T >= 1.16 \;\; \text{GeV}$$

5. BEAUTY PRODUCTION

Beauty production is a better testing ground than charm production for perturbative QCD, because of the higher mass of the b-quark.

The only recent results on this item come from experiments UA1 and CDF at hadronic colliders.

The experiment UA1 ($\sqrt{s} = 630$ GeV, $\int Ldt = 4pb^{-1}$) has led the way in demonstrating that hadron collider may be useful beauty factories. The signature that UA1 used consisted in μ-pairs arising from heavy flavour semileptonic decays according to the reaction:



The additional requests:

(a) $p_T(\mu) > 3$ GeV and (b) $6 < m_{\mu\mu} < 35$ GeV

allow to enrich the sample in beauty rejecting the K and π decays (a), and eleminating μ pairs coming from the same beauty decay (b, lower limit) or from Z^0 decays (b, upper limit).

The inclusive b-quark cross section is then derived from the data using the ISAJET Monte Carlo model [18].

The results (figure 15) are compared with the $O(\alpha_s^3)$ QCD calculations. Normalizing the QCD predictions to the first three data points, UA1 obtains a value of total cross section for b production of [19]:

$$\sigma(p\overline{p} \rightarrow b\overline{b} + x) = 19.3 \pm 7(\mathrm{exp}) \pm 9(\mathrm{th})\mu b \quad \mathrm{at} \quad \sqrt{s} = 630\mathrm{GeV}$$

The experiment CDF ($\sqrt{s} = 1800$ GeV, $\int Ldt = 4pb^{-1}$) has, for the first time, successfully used the ψ tag to identify beauty decays.

CDF finds rather clean ψ and ψ' signals (figure 16 a) after cutting on:

$p_T(\mu) > 5\mathrm{GeV}$ and $\eta(\mu) < 0.5$

ψ can come from:

(a) direct production: $p\overline{p} \rightarrow \psi + x$ (b) $p\overline{p} \rightarrow \chi + x \rightarrow (\psi + \gamma) + x$

(c) $p\overline{p} \rightarrow B + x \rightarrow (\psi + y) + x$ (d) $p\overline{p} \rightarrow \psi' + x \rightarrow (\psi\pi^+\pi^-) + x$

calculations indicate that only (b) and (c) contribute appreciably (for about, respectively, 1/3 and 2/3).

ψ' can, on the contrary, only come from

$$p\bar{p} \to B + x \to (\psi' + y) + x$$

comparing the ratio $\frac{\#\psi'}{\#\psi}$ in pp collisions and in e^+e^- collisions at the $\Upsilon 4s$ (see figure 16 b) and assuming that all the ψ and ψ' at the $\Upsilon 4s$ come from B decay, CDF could measure the fraction F of ψ that come from B decays [20]:

$F = 64\% \pm 15\%$ (stat.CDF) $\pm 5\%$ (syst.) $\pm 23\%$ (stat.CLEO)

This means that in the CDF data sample about $10^3 \psi$ come from B decays. This allows to look for exclusive decays like $\psi K^{\pm}$ or ψK^{*0}. The invariant mass distribution for the sum of the above combinations is shown in figure 17, where a signal of 35 ± 9 events is visible at the B-meson mass. CDF will, in the near future, increase the integrated luminosity and will put in operation a microstrip vertex detector to reconstruct beauty decays. This should allow to detect more interesting channels, like ψK_s^0 where a large CP violation is expected.

6. SHORT TERM PERSPECTIVES IN BEAUTY HADROPRODUCTION

I have already indicated what the near future may be at the Fermilab proton collider.

New results should also come, in the next couple of years, from fixed target experiments.

There are two complementary approaches:

a) Experiment E771 at FNAL will look for exclusive channels containing a ψ. The trigger will be based on multi-muons. Once a ψ is reconstructed, it will be checked if this particle emerges from a secondary vertex. This vertex must then be a beauty decay. This method is based on a rather strong signature for beauty identification, but is seeking for a small ($\sim 7 \cdot 10^{-4}$) branching ratio. High luminosity ($\sim 10^7$ interactions/second) is therefore needed in order to observe the number of beauty decays (500 $B \rightarrow \psi + x$) that should allow the measurements of σ_B, τ_B and $B^0/\overline{B}^0$ oscillations.

b) Experiment WA92 (BEATRICE) at CERN (see figure 18) will look for any B decay channel (but especially those with a lepton in the final state). The trigger will be based on the detection of secondary vertices. Those vertices will be recognized by a pixel processor [21] with distributed intelligence acting on the information provided by a silicon microstrip telescope (figure 18 c). The beauty identification will be based on the detection of the peculiar topology of the beauty events where one production vertex should be followed by at least four decay vertices few millimeters apart. Those decay vertices should be observed with a special apparatus called decay detector (figure 18 b). The decay detector is a set of 16 planes of 10 μm pitch microstrips 1 mm apart from each others designed to contain and detect a large fraction of charm and beauty decays. Aim of the experiment is the identification of $\sim 10^3$ beauty decays, these should be used to measure σ_B, τ_{B^0} and τ_{B^+} separately and, possibly, $B^0/\overline{B}^0$ mixing.

3. CONCLUSIONS

Next-to-leading order QCD calculations agree fairly well with charm data, both in hadroproduction and in photoproduction. The observation of a (small) leading particle effect and the measurement that $\alpha \sim 0.9 < 1.0$ indicate nevertheless that charm is not heavy enough for a straightforward application of perturbative QCD. Therefore the evaluation of QCD parameters like the charm quark mass or the gluon structure function from charm data must be considered with some caveat.

Recent results on beauty physics from collider data, indicate the possibility of reconstructing invariant mass peaks of B-mesons using the distinctive signature of a J/ψ. There is a lot of room for improving these results especially if we consider that neither the detectors nor the trigger were optimized for B search. It is likely that hadron colliders will be one of the possible beauty factories of the near future.

3. AKNOWLEDGMENTS

I am indebted with Jeff Appel (E769), Mike Koratzinos (NA14) and Laura Perasso (E687) for providing me with the latest results of their experiments.

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I finally want to thank Laura Opisso for the careful typing of the manuscript in the very short time left before the deadline.

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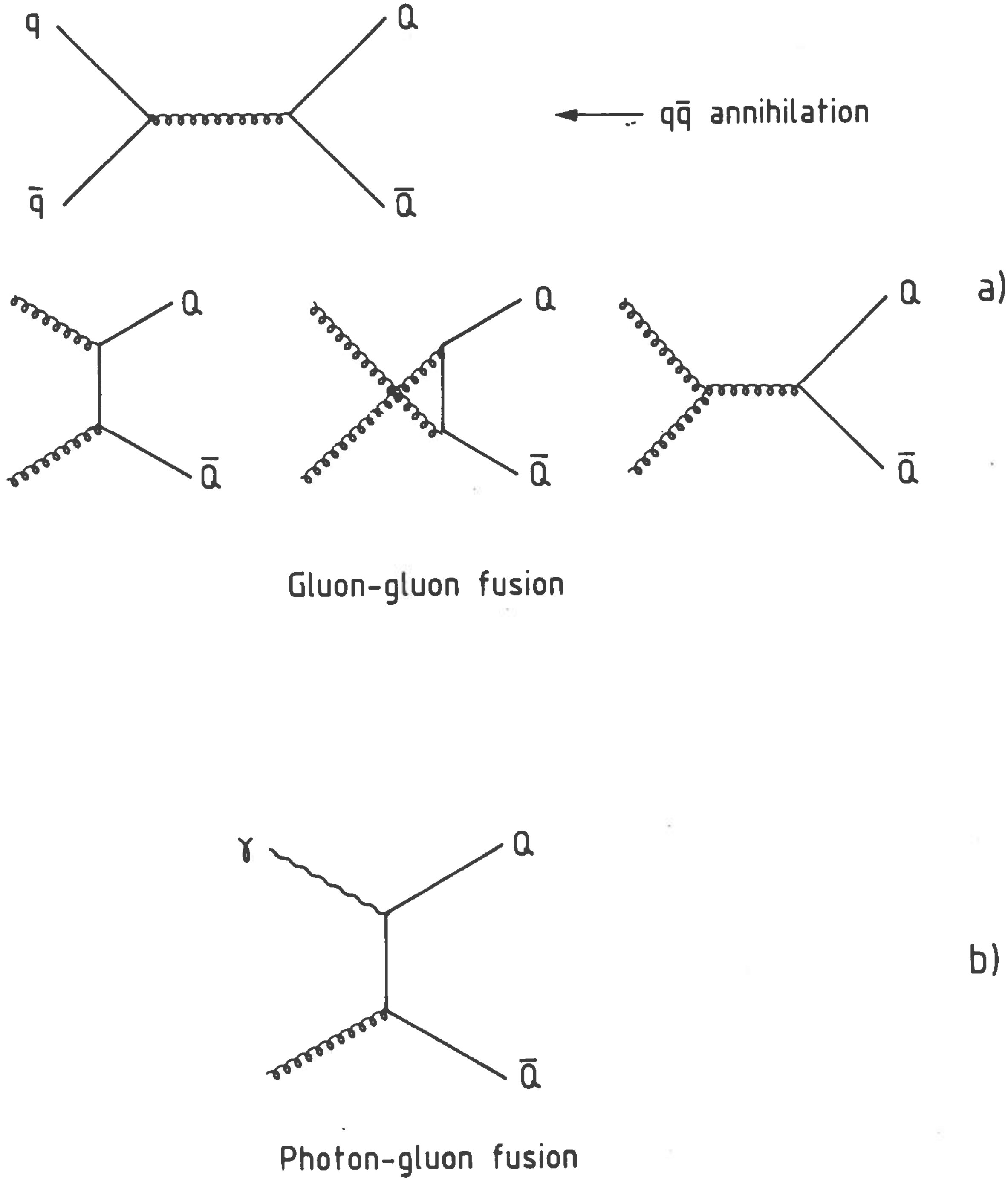


Fig.1 - The lowest-order QCD diagrams for heavy quark hadroproduction (a) and photoproduction (b).

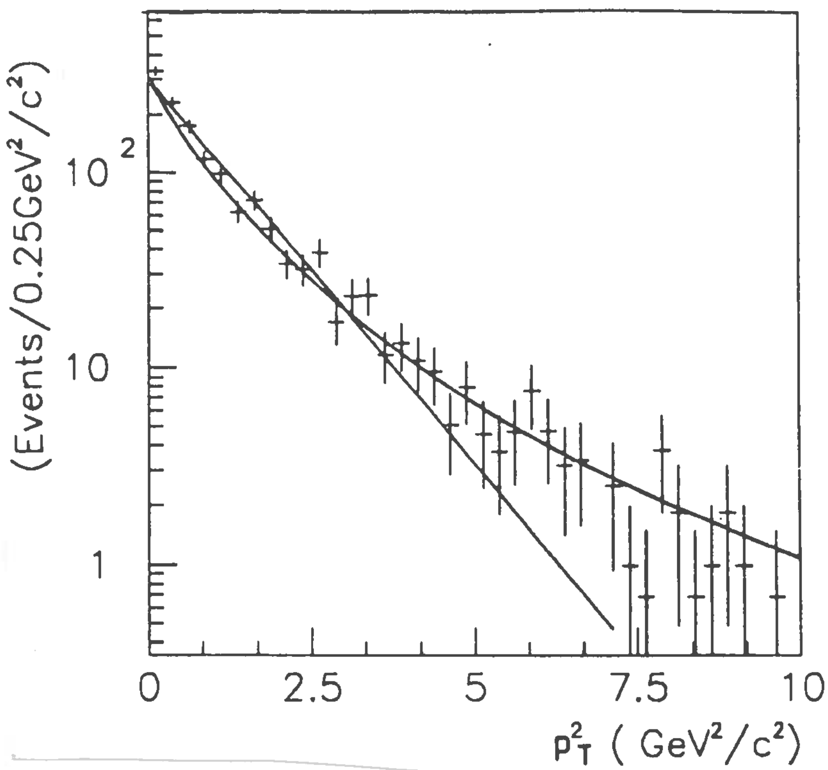


Fig.2 - Charm production cross section, as measured by the experiment WA82, versus: p_T^2. The straight line ($e^{-0.86 p_T^2}$) is a fit of the data for $p_T^2 < 5$ GeV^2. The curve is a fit of the data in the full p_T^2 range according to reference [3].

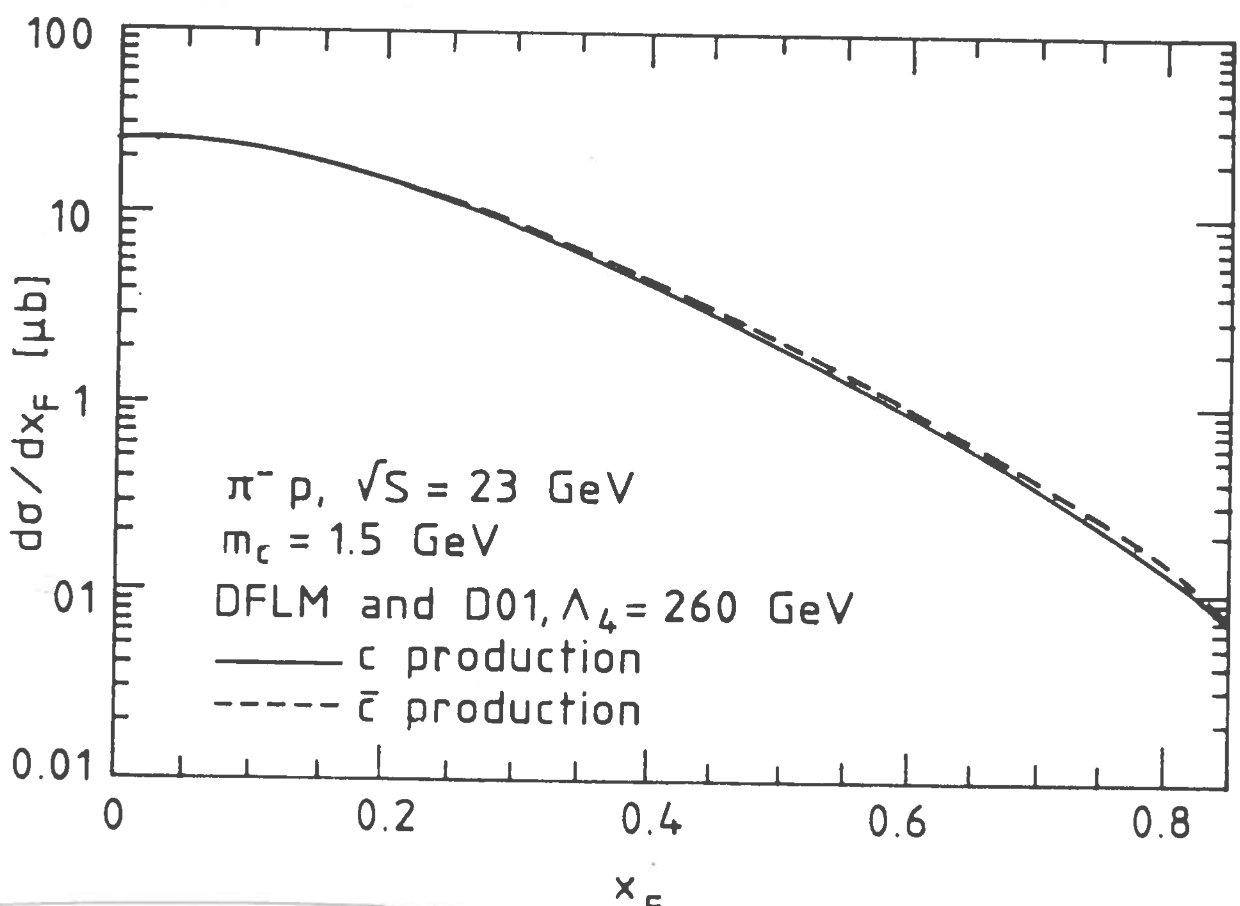


Fig.3 - Differential charm cross section versus X_F as calculated in ref.[1].

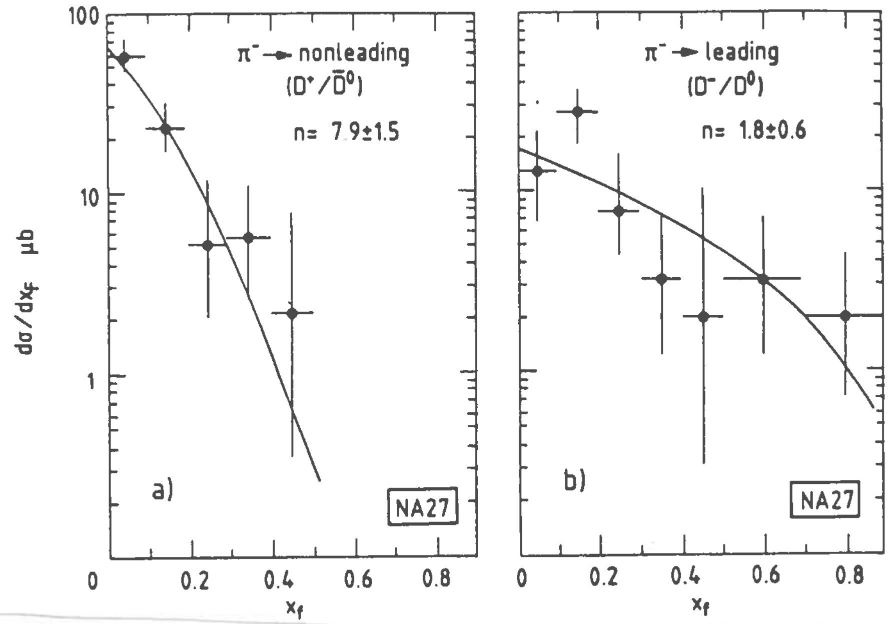


Fig.4 - Differential charm cross section versus X_F as measured by NA27 in $\pi^- p$ interactions at 360 GeV: (a) non-leading D mesons, (b) leading D mesons.

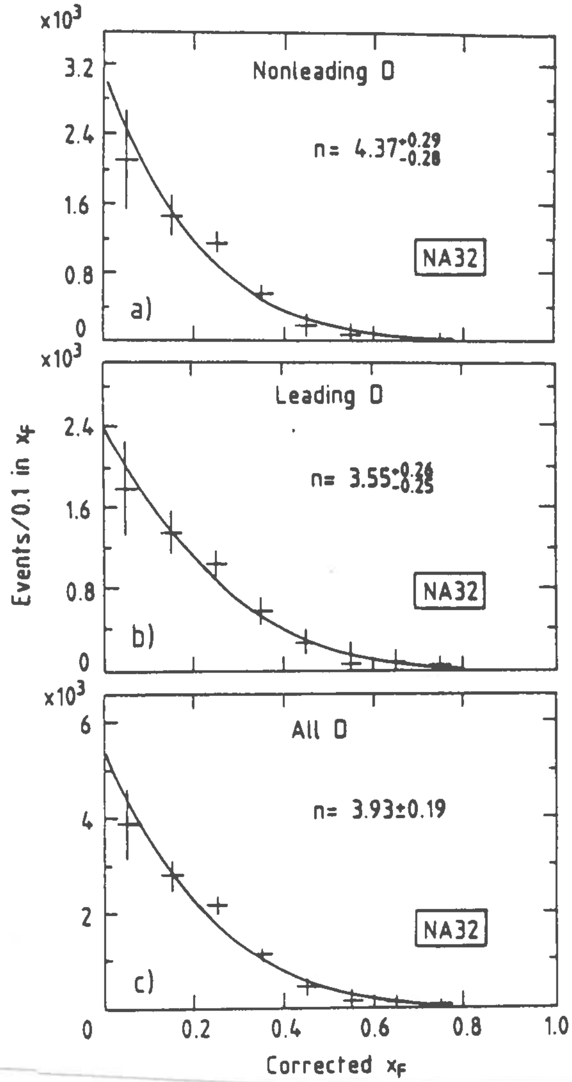


Fig.5 - X_F distribution for charm production as measured by NA32 in $\pi^- Cu$ interactions at 230 GeV: (a) non-leading D mesons, (b) leading D mesons, (c) the sum of (a) and (b).

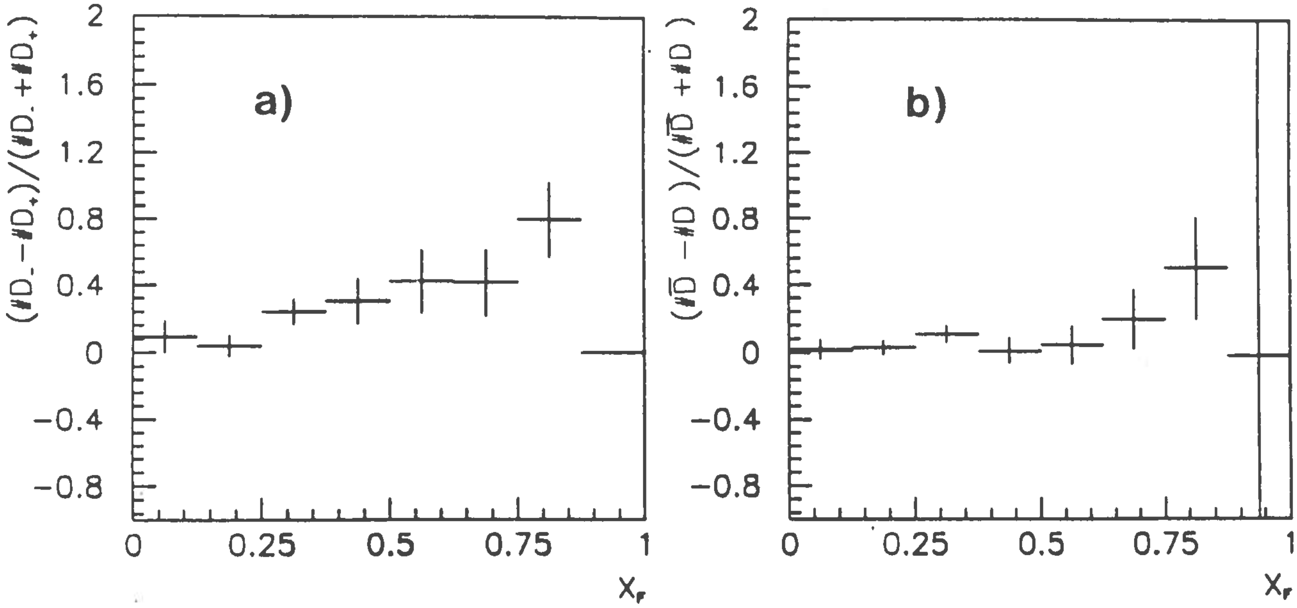


Fig.6 - X_F distribution of the ratios

(a) $\frac{D^- - D^+}{D^- + D^+}$ (b) $\frac{\overline{D} - D}{\overline{D} + D}$

as measured by WA82.

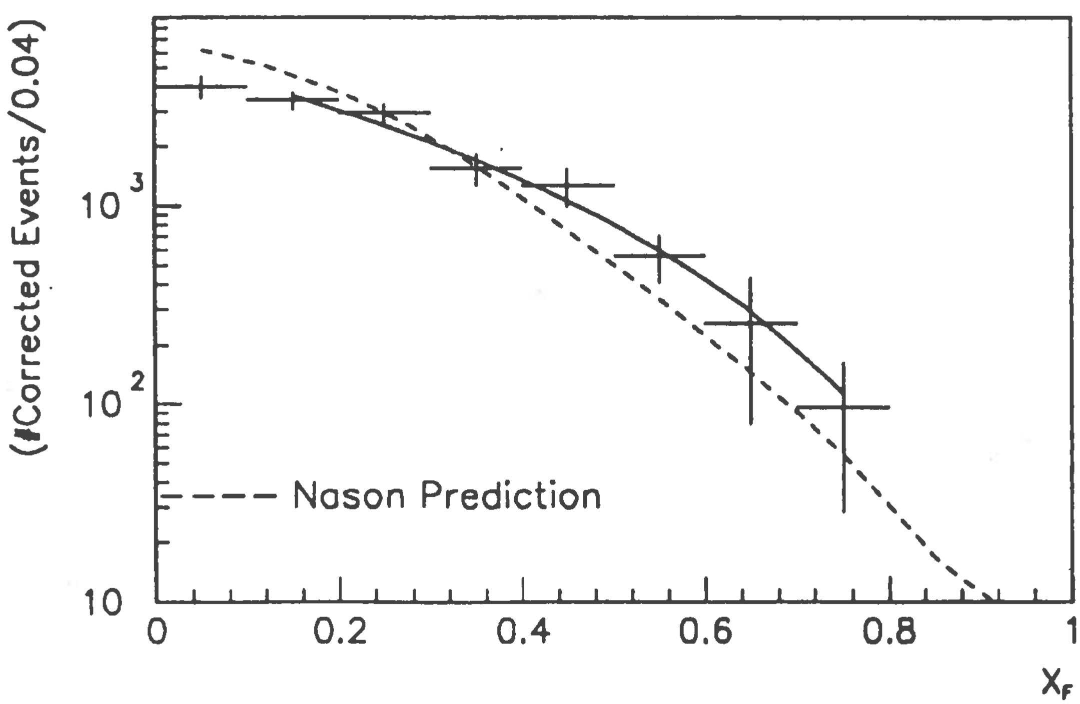


Fig.7 - $d\sigma_c/dX_F$ as measured by WA82. The $O(\alpha_s^3)$ predictions are shown too (dashed line). The curve $(1 - X_F)^{2.9}$ obtained fitting the data is shown as a full line.

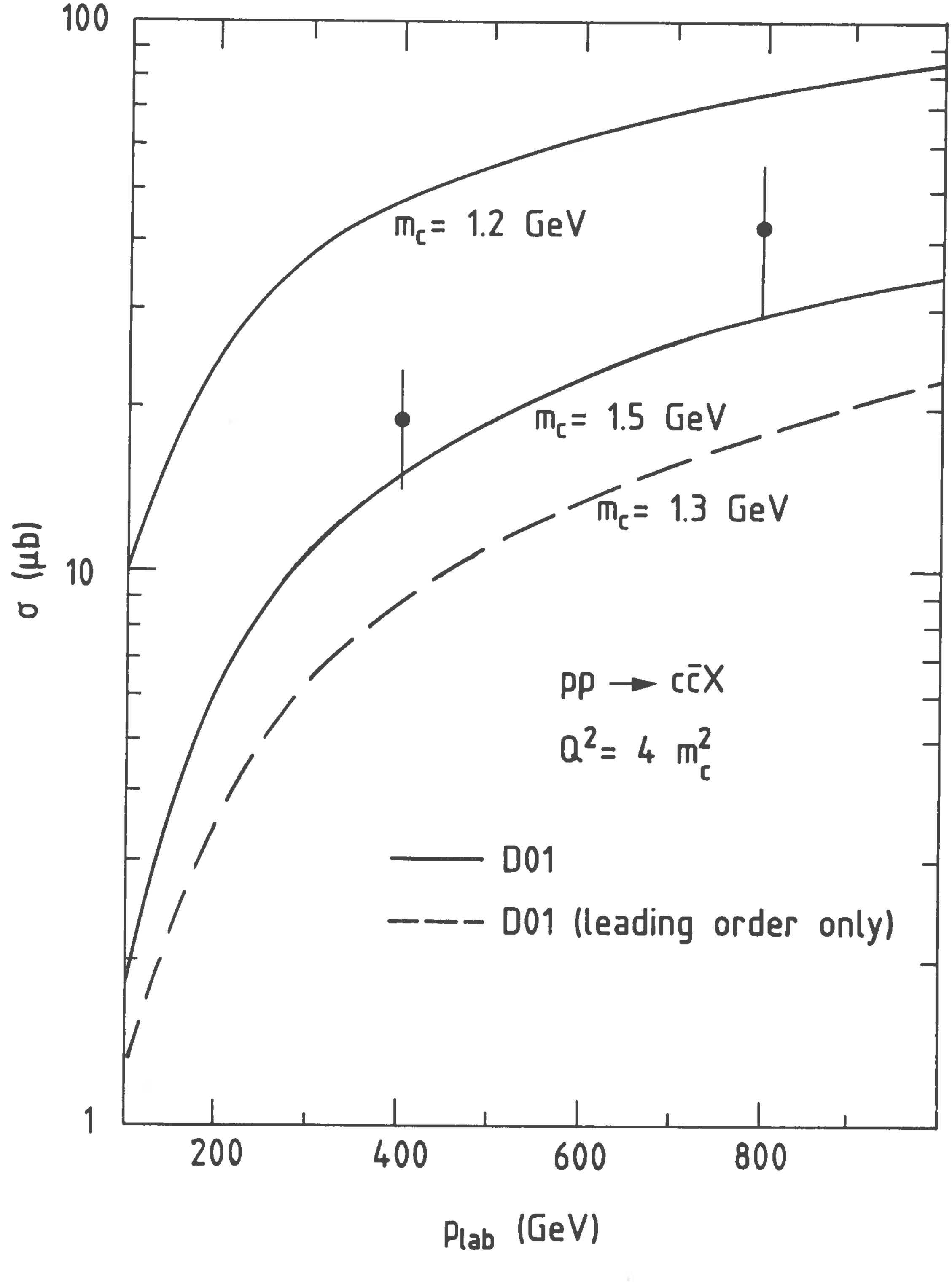


Fig.8 - Variations of $\sigma_{c\bar{c}}$ with energy, the curves shown are QCD parton model predictions. The dashed curve has been calculated taking into account only the leading order QCD diagrams while for the full curves the next-to-leading order terms have been included. In both cases the structure functions proposed by Duke and Owens have been used. The data are from bubble chamber experiments NA27 and E743.

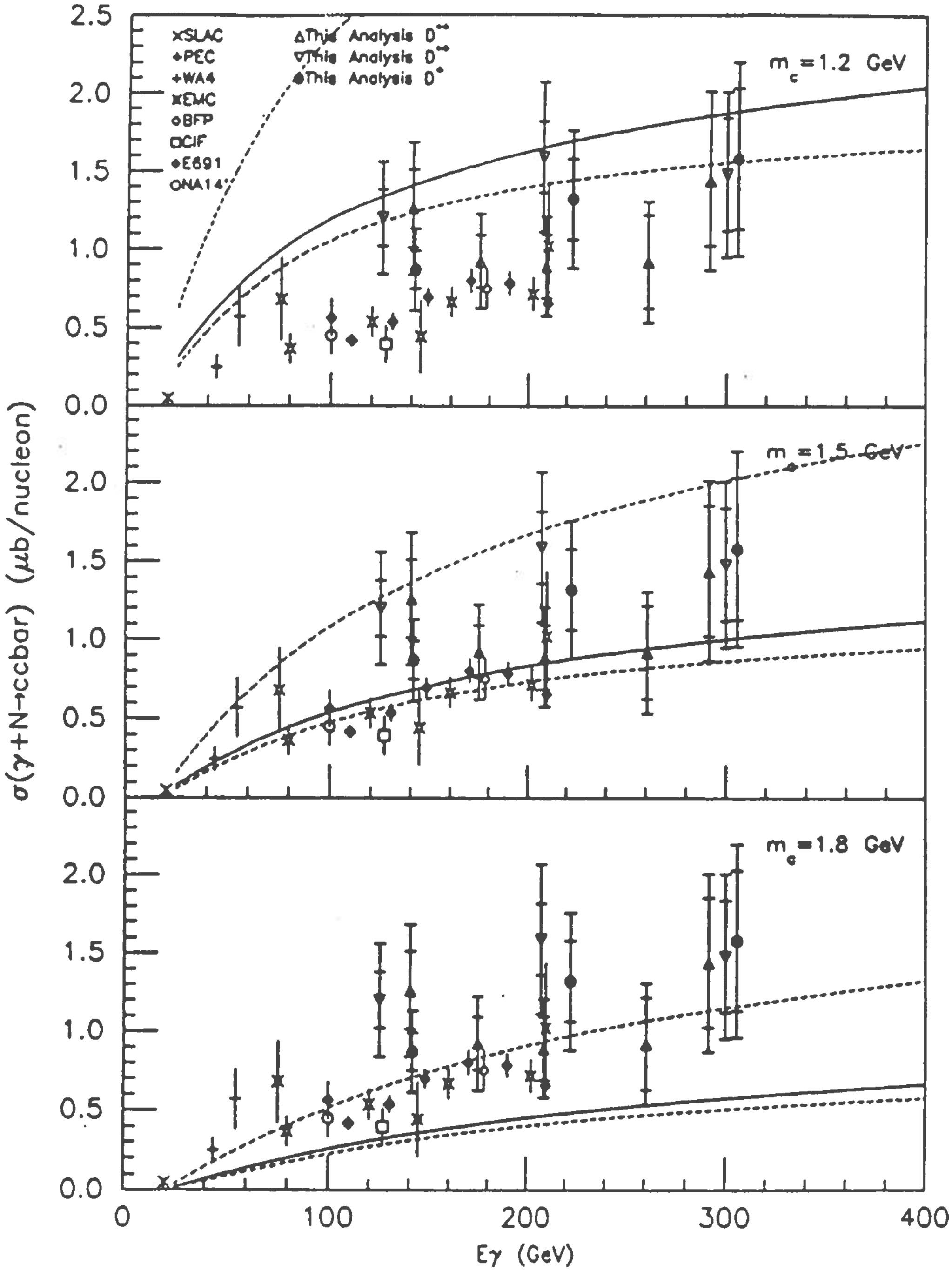
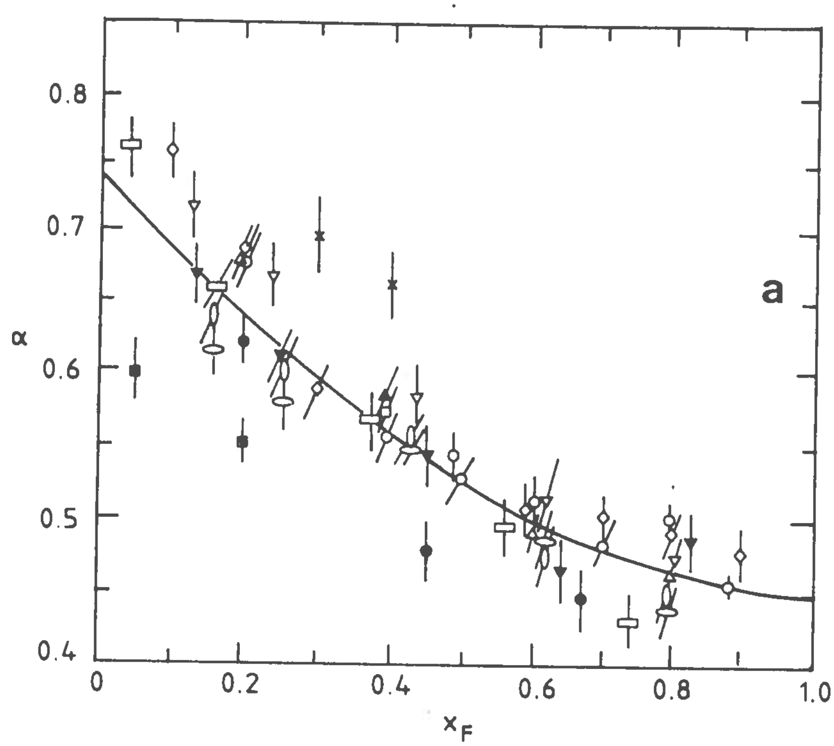


Fig.9 - Compilation of charm photoproduction cross section data versus photon energy compared with $O(\alpha_s^2\alpha_{em})$ QCD calculations.



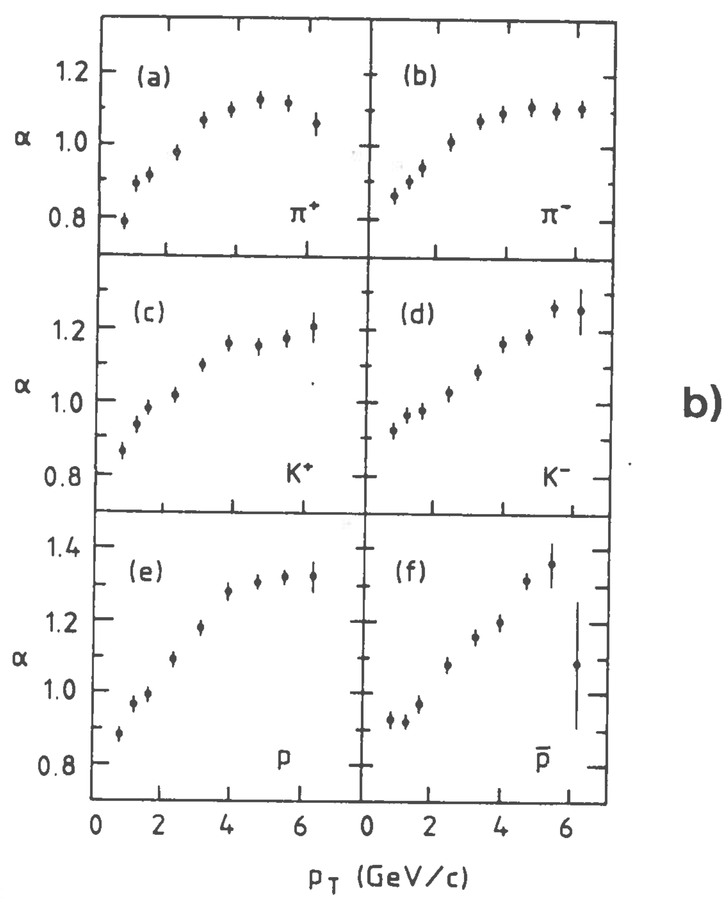


Fig.10 - Variation of the atomic number dependence parameter α with X_F (a) and p_T (b). These figures are taken respectively from refs.[9] and [10].

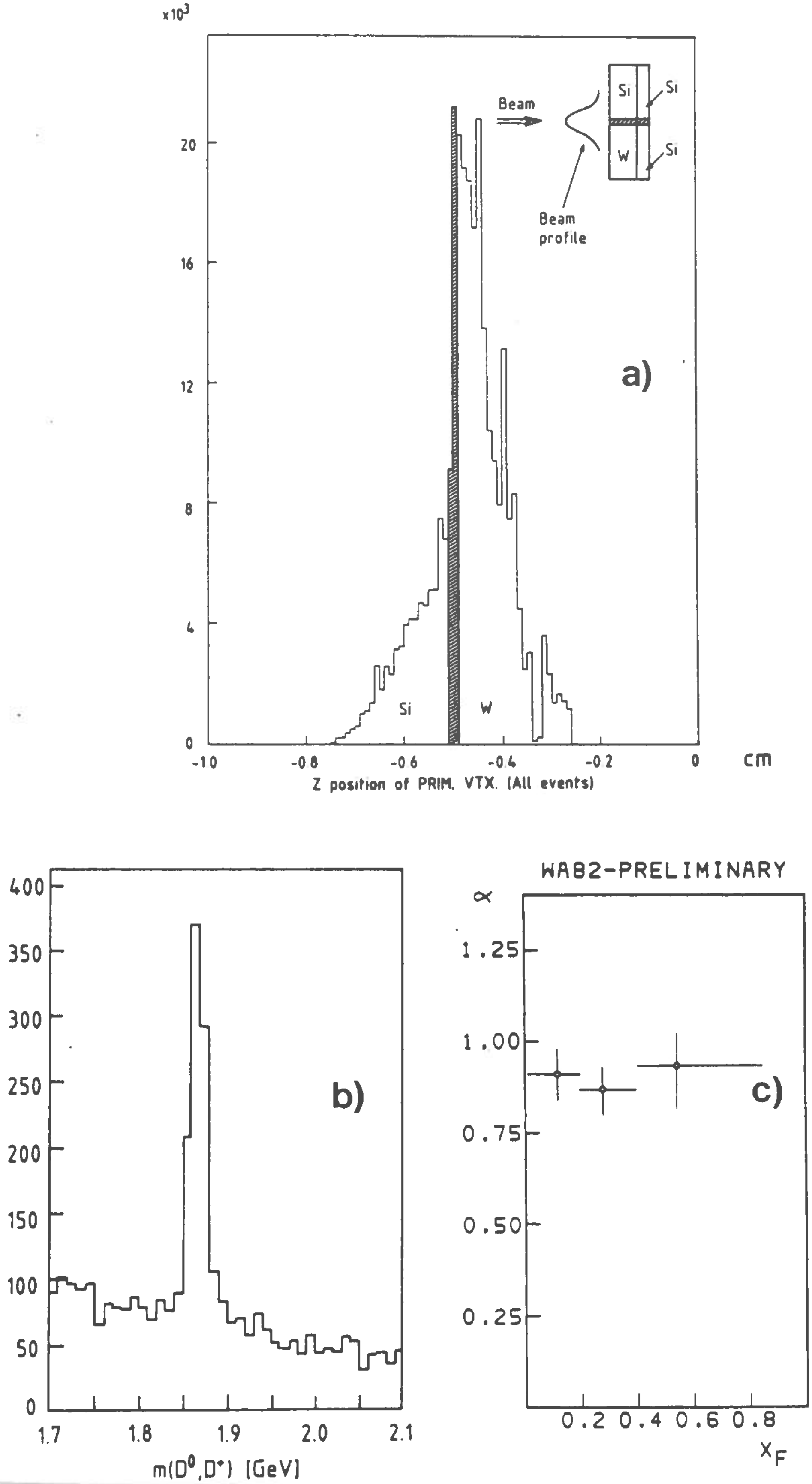


Fig.11 - (a) Distribution of the primary vertex position along the vertical coordinate in the WA82 experiment. The shadowed region (boundary between silicon and tungsten) is excluded from the α measurement. (b) Charm invariant mass peak used

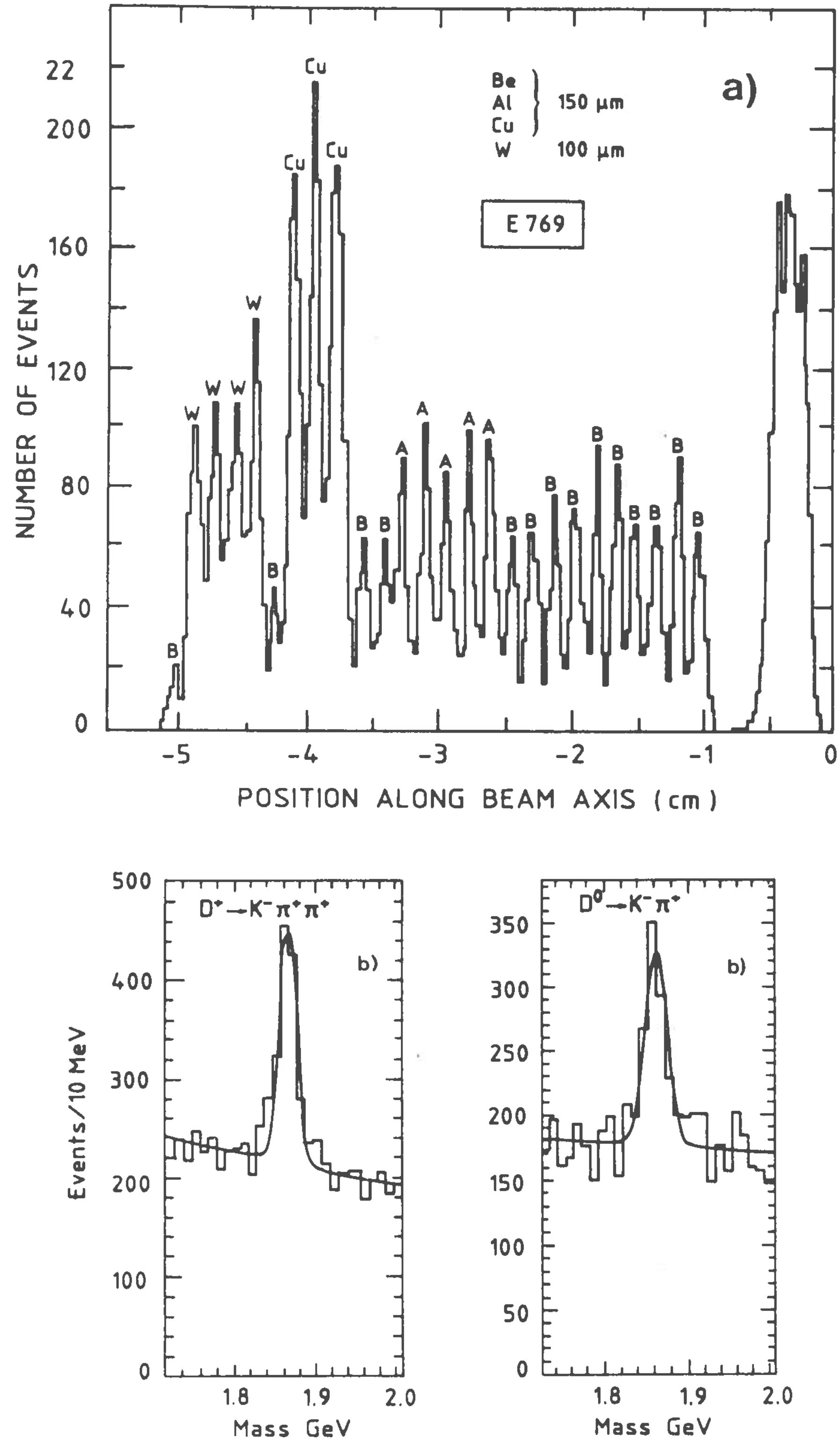
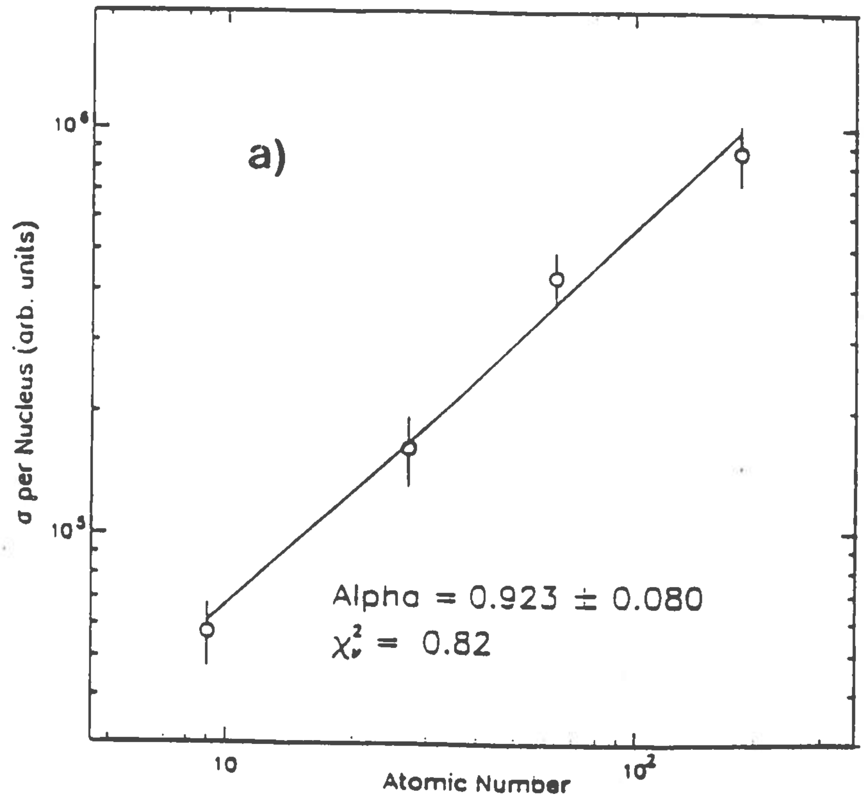


Fig.12 -

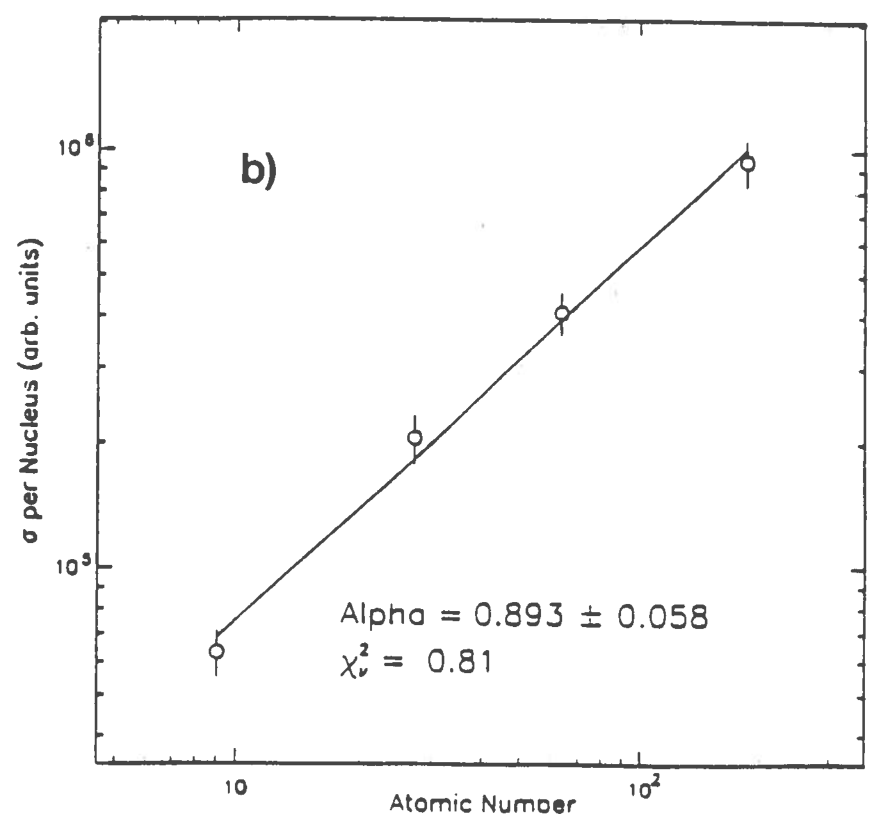
(a) Distribution of the primary vertex position along the beam in the E769 experiment. The 26 foil targets appear as peaks in this distribution.

(b) Charm invariant mass peaks used for the α measurement.

$D^0 \rightarrow K\pi$



$\pi^{\pm}$ produced $D^+ \rightarrow K^-\pi^+\pi^+$ + cc



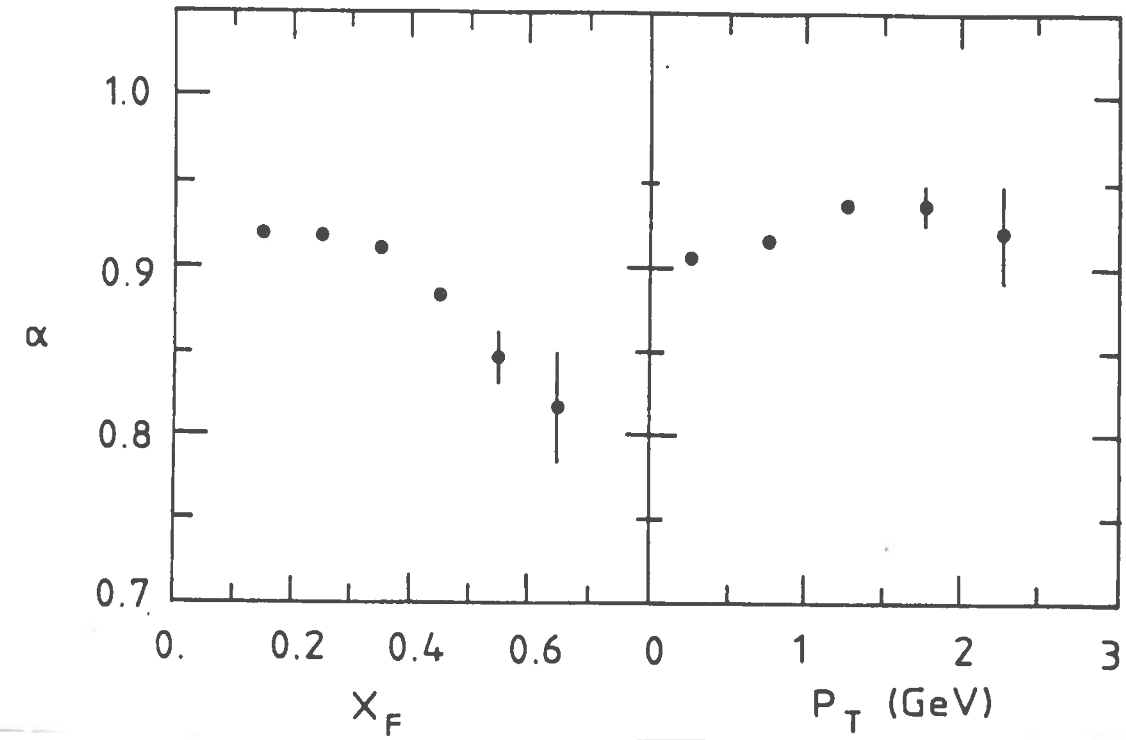


Fig.14 - Variation of the atomic number dependence parameter α with X_F and p_T for the J/ψ resonance (from experiment E772).

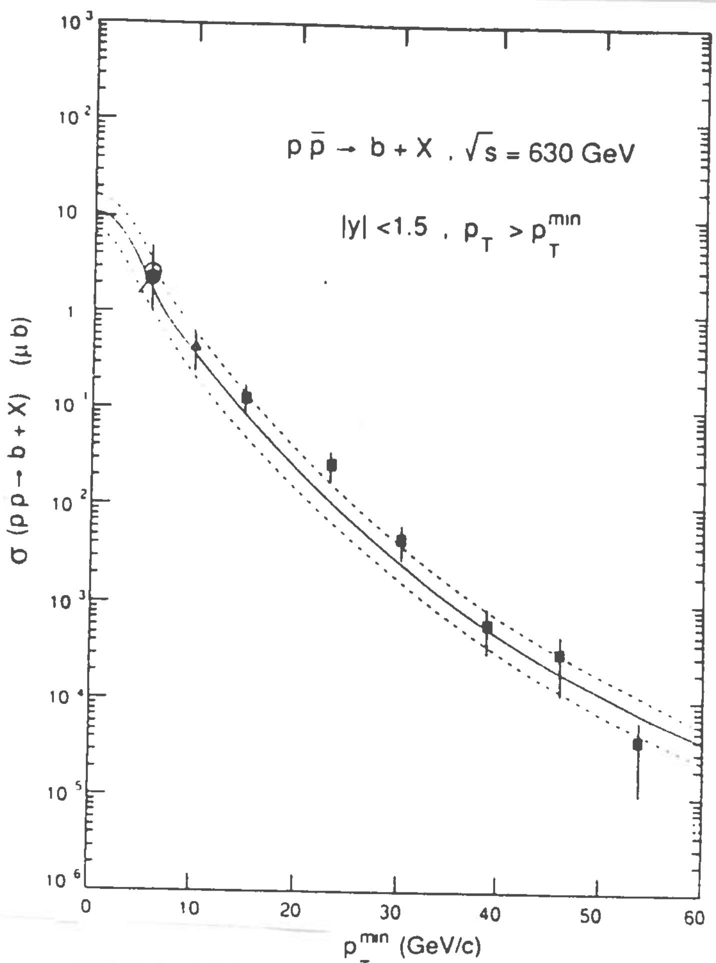


Fig.15 - The inclusive b-quark cross-section for $|y| < 1.5$ versus the b-quark trans-

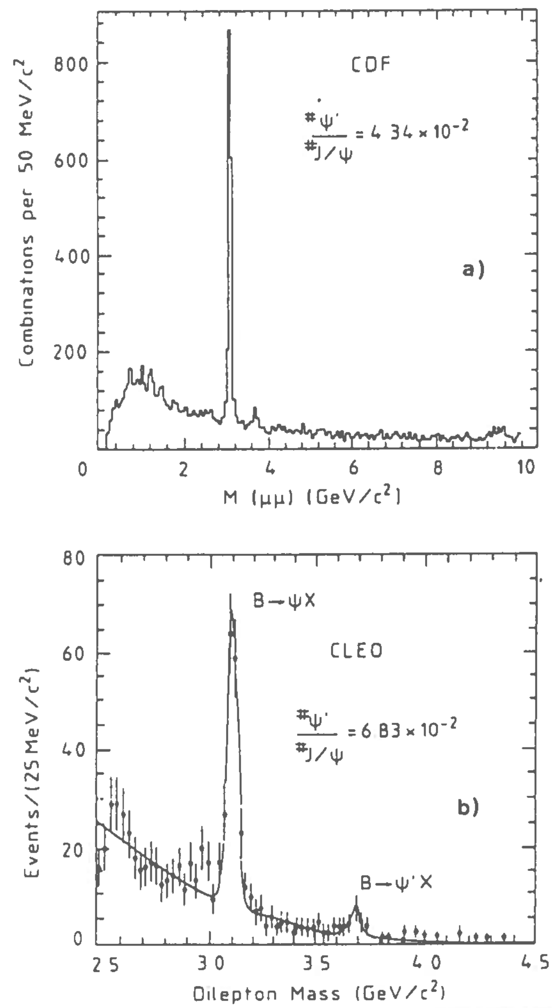


Fig.16 - The ψ signal as measured by the experiments: a) CDF, b) CLEO

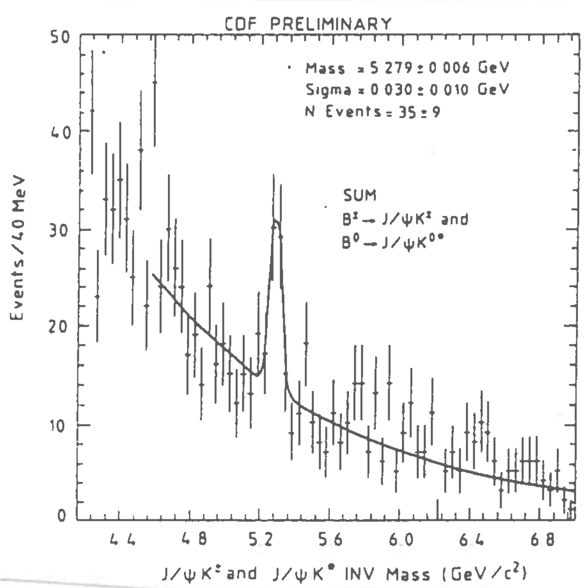


Fig.17 - Invariant mass distribution of the combinations $\psi K^{\pm}$ and ψK^{*0} summed together.

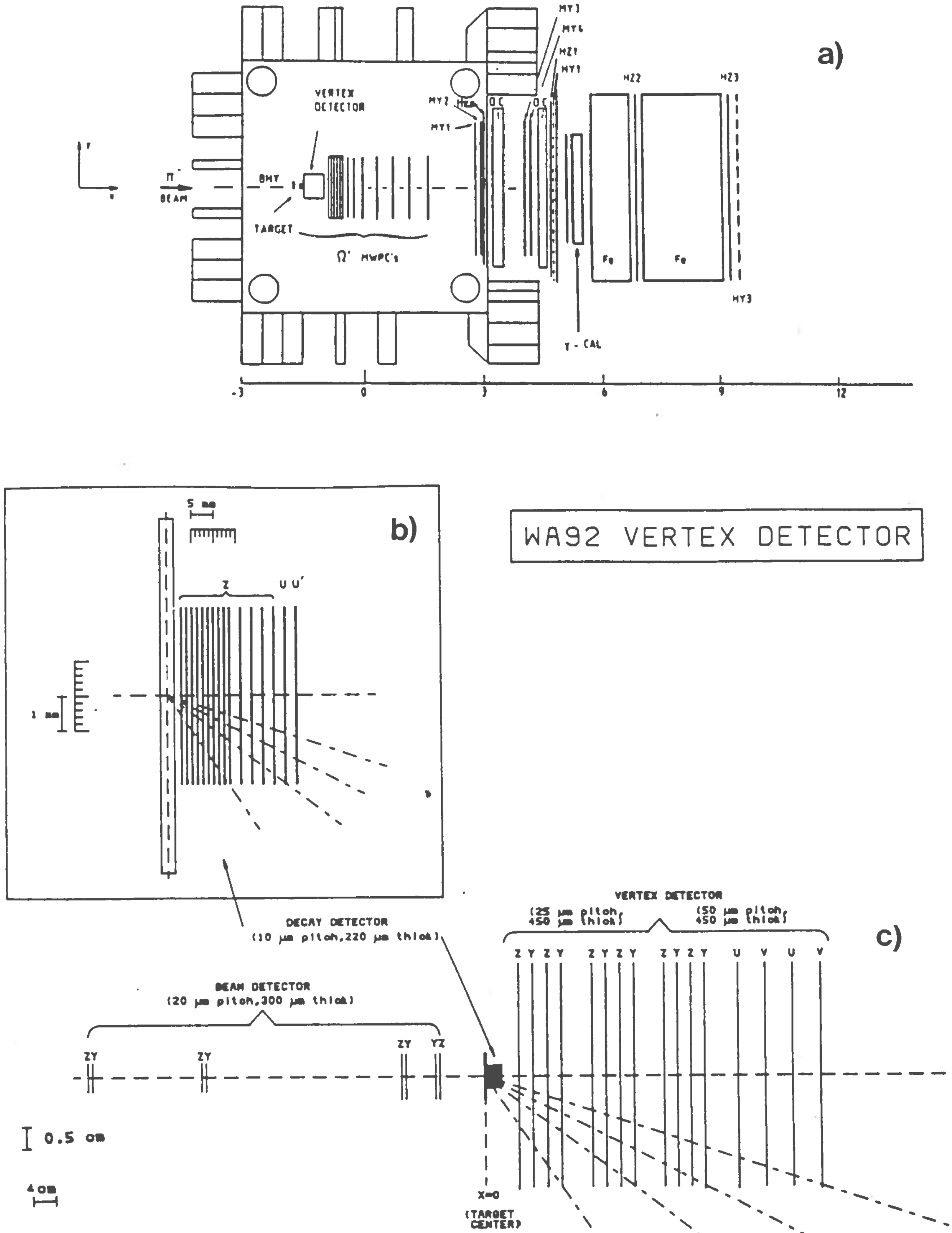


Fig.18 - The layout of the WA92 experiment

a) the full spectrometer

b) the decay detector

c) the microstrip vertex detector