A STUDY OF BEAUTY AND CHARM MUOPRODUCTION AT THE SPS

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ABSTRACT

We propose an experiment to study beauty and charm muoproduction
via semi-leptonic decays into multi-muon final states. The
apparatus for the experiment is based on the EMC Forward
Spectrometer (NA2) with a factor $\sim$ 500 increase in luminosity.
The measurements proposed include the study of upsilon and B-$\bar{\text{B}}$
production and will provide for a much improved experimental
limit on the amount of D° - $\bar{D^\circ}$ mixing. From a comparison of the
charm decays into 2 and 3-muon final states it is proposed to make
a direct measurement of the intrinsic charm content of the
nucleon. We also comment on possible studies of rare charm and
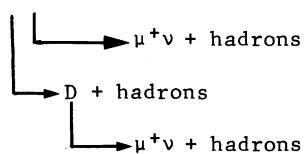beauty decays into multi-muon final states.

1. INTRODUCTION

A study of charm production by muons through multimuon events has been very
fruitful for the insight it provides into QCD, via the Photon-Gluon Fusion model[1],
the measurement of the charm contribution to the nucleon structure function F2, the
measurement of the gluon distribution of the nucleon and the charm quark fragmentation
function. It would be very interesting to repeat these measurements through the
production of bound and unbound beauty particles. The higher masses of beauty quarks
leads to a shorter distance scale and all the models applied to charm production
should work better. For example, the colour singlet model of Berger and Jones[2] has
some difficulty in describing inelastic J/ψ production[3]. This uses an explicit
non-relativisitic wave function and would be expected to work better for beauty quarks
which are a factor of $\sim$ 3 heavier than charmed quarks.

In proposing this experiment we draw heavily on our experience with the European
Muon Collaboration apparatus (NA2) where in addition to 907 bound charm events and
2950 di and trimuon decays of open charm, 1 upsilon candidate and 3 wrong-sign trimuon
events were observed. The upsilon candidate yielded a cross-section x branching ratio
measurement for 280 GeV muons of $\sigma B = 2.5 +/- 2.5 \times 10^{-38}$ cm^2[3]. The BCDMS
experiment (NA4) also performed an upsilon search and produced an upper limit for 280
GeV of $\sigma B < 1.3 \times 10^{-38}$ cm^2[4]. Thus, for the calculations presented here,
we assume a cross-section for upsilon production of $\sigma B = 1.0 \times 10^{-38}$ cm^2.

as The wrong sign trimuon events ($2\mu^+\mu^+\mu^+$ events and $1\mu^+\mu^-\mu^-$) were interpreted

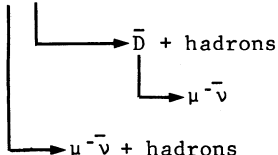$$\mu^+N \rightarrow \mu^+ \, B \, \bar{B} \, X$$

```
          |   L────▶ μ⁺ν + hadrons
          |
          L────▶ D + hadrons
                  L────▶ μ⁺ν + hadrons
```
$(\mu^+\mu^+\mu^+)$

and

$$\mu^+N \rightarrow \mu^+ \, B \, \bar{B} \, X$$

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          |   L────▶ D̄ + hadrons
          |          L──▶ μ⁻ν̄
          |
          L────▶ μ⁻ν̄ + hadrons
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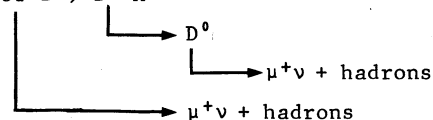$(\mu^+\mu^-\mu^-)$

These events were estimated to contain a background of 2 events from π or K decays in the hadronic showers from conventional deep inelastic scattering events. Taking the mean semileptonic branching ratios for charm and beauty decay to be 10% gave a measured cross-section of $5 \pm 5 \times 10^{-36}$ cm^2[5].

Alternatively these events could be interpreted as originating from charm production with weak interaction mixing changing the D to a $\bar{D}$ or vice-versa. Thus,
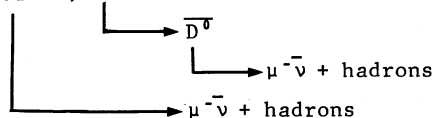
$$\mu^+N \rightarrow \mu^+ \, (D^+ \text{ or } D^0) \, \overline{D^0} \, X$$

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          |         L────▶ D⁰
          |                L────▶ μ⁺ν + hadrons
          |
          L────────────▶ μ⁺ν + hadrons
```
and $(\mu^+\mu^+\mu^+)$

$$\mu^+N \rightarrow \mu^+ \, (D^- \text{ or } \overline{D^0}) \, D^0 \, X$$

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          |         L────▶ D̄⁰
          |                L────▶ μ⁻ν̄ + hadrons
          |
          L────────────▶ μ⁻ν̄ + hadrons
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$(\mu^+\mu^-\mu^-)$

From this an upper limit of 20% (90% confidence level) was set on the probability of D^0-$\overline{D^0}$ mixing by assuming that this was the dominant process [5].

In order to perform a definitive experiment to study these processes we propose an apparatus with a factor of 500 improvement in luminosity over the NA2 experiment. A Uranium target calorimeter is proposed to decrease the background contamination from delayed events arising from π or K decays. We choose to use an open spectrometer of the type used by the EMC NA2 experiment[6]. Whilst this type of spectrometer has lower luminosity than a continuous target apparatus of the BCDMS[7] or BFP[8] type the better resolution allows the reduction of background processes which are a serious

problem in this type of experiment[9]. The apparatus proposed uses most of the
existing pieces of equipment from the EMC Forward Spectrometer with improvements in
the beam region to allow the measurement of low Q^2 events. With this setup we believe
that it will be possible to separate events coming from $D^0\overline{D^0}$ mixing and
$B-\overline{B}$ production by using a combination of the decay muon transverse momentum and the
missing energy carried away by the neutrinos.

2. APPARATUS

Fig. 1 shows a schematic plan of the proposed forward spectrometer system. As
mentioned above this is based on the EMC (NA2) spectrometer which is fully described
elsewhere[6]. Here we discuss the main features of the new pieces of hardware and
the modifications to the existing experimental setup. These are in general not major
changes as we foresee that the experiment should run within the existing EMC area in
EHN2.

In order to minimise the effects of π/K decay and to maximise the target
luminosity we propose to use a Uranium Sampling Total Absorption Calorimeter (STAC) of
the kind used by NA2[10]. In order to retain the same resolution as in the iron
calorimeter of NA2 the sampling has been chosen to be similar with 0.8 cm thick
Uranium sheets interspersed with 0.7 cm sheets of scintillator. The mean density of
material in such a calorimeter is 10.6 g/cm as compared to 6.1 g/cm in the NA2 STAC.
Thus we estimate that the residual π/K decay contamination will be $\sim$ 35%. Whilst
this level of background is rather large it can be calculated and is separable from
the charm and beauty signals via the differences in missing energy and transverse
momentum as it tends to peak at small missing energy and very low values
of P_t[5,11]. For an 8m target the corresponding total target length is 8459 g/cm².
Allowing 5 absorption lengths at the end of the STAC to absorb hadronic showers, the
effective total target length becomes 7324 g/cm² which gives a factor of 5 increase
in target length over the NA2 experiment.

The NA2 data was taken in a single 10-day running period which was reduced to an
effective data-taking period of only 4 days. During this period the NA2 apparatus was
run with a mean beam intensity on target of 1.5×10^7 muons per pulse and a spill
length of around 800 ms. The apparatus envisaged here has been modified to run at an
intensity of 1.0×10^8 muons per pulse with a 2 second spill.

To obtain clean pattern recognition when running under these conditions and at
the same time improve the tracking efficiency in the region close to the beam we
porpose to use 3-stage wire chamber detection distributed regularly along the
spectrometer axis. This consists of a large area drift chamber to cover wide angle
tracks; a medium sized MWPC with the beam region made insensitive to cover the region
from around 7 cm to 25 cm from the beam; and a small beam proportional chamber to
reconstruct tracks within the beam region (radius $\leqslant$ 7 cm). To achieve this the
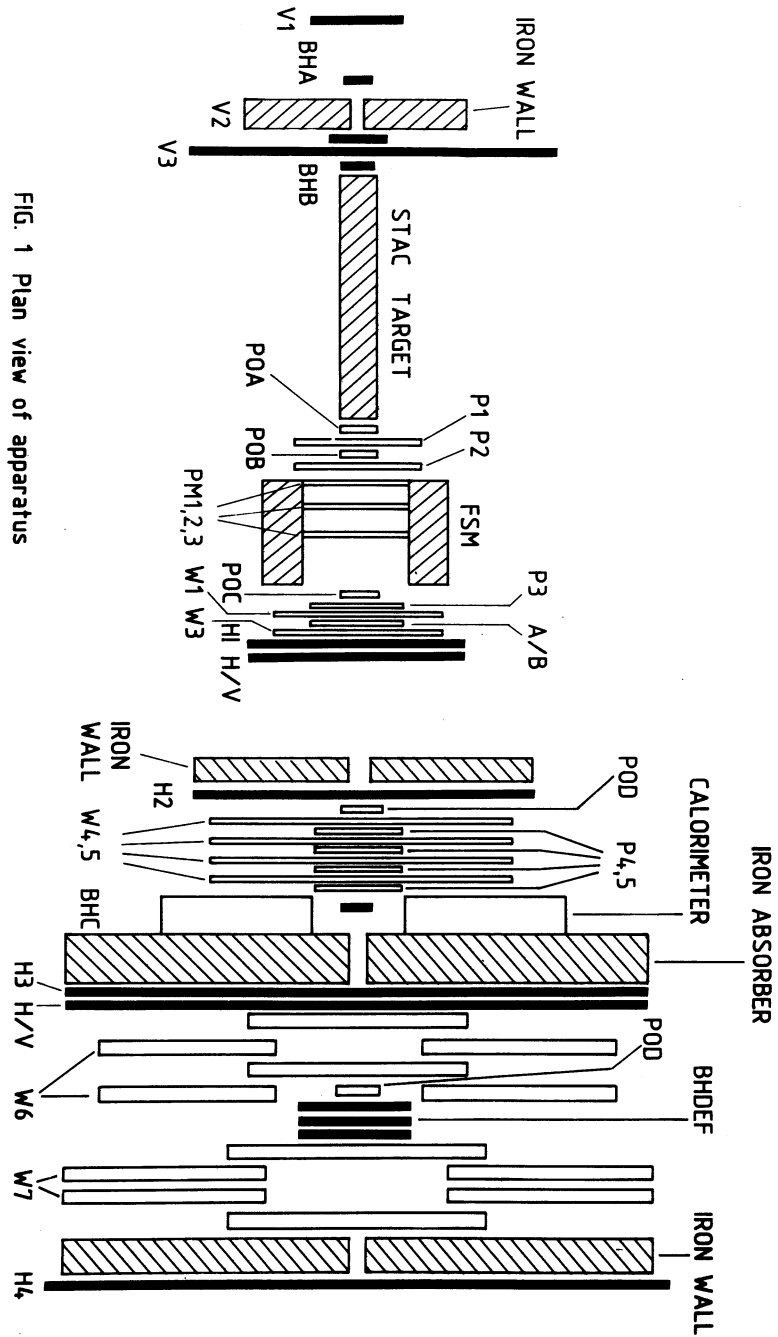following improvements/modifications are foreseen:

FIG. 1 Plan view of apparatus

Fig. 1: Schematic plan of the proposed apparatus

a) The drift chambers upstream of the Forward Spectrometer Magnet (FSM) denoted W1 and W2 have been replaced by 2 mm wire-spacing multiwire proportional chambers (MWPC) P1 and P2. This will provide unambiguous pattern recognition in this region where the soft photon and electromagnetic backgrounds make drift chamber operation very difficult at high beam fluxes.

b) MWPC's POC, P3A/B have been added at the exit of the FSM aperture to improve the tracking efficiency close to the beam.

c) The NA2 Cerenkov counter (C2) has been replaced by an iron wall which will act as a filter for soft and electromagnetic background which is generated downstream of the target and also shields the trigger hodoscope H2 and the drift chambers W4/5 which are mounted directly behind it.

d) The drift chamber W3 situated behind the FSM has been reinforced by the addition of the drift chamber module W1. This provides momentum determination for the outgoing muon track(s) by using only the track information from the detectors in front of the iron wall.

e) MWPC's POD and P4/5 have been added in the region covered by W4/5 to allow for improved low angle muon detection and to provide a lever-arm from POC to POD for momentum determination of tracks in the beam region. P4/5 are interleaved with the drift-chamber modules W4/5.

f) The existing detectors in the beam region are further reinforced by the MWPC POD and the Hodoscopes BHC,D,E,F to allow the detection of small angle scattered muons from low Q^2 events.

.Two basic triggers are proposed for the apparatus. The first, Trigger 1 requires a cluster multiplicity of $\geqslant$ 2 in each of the trigger hodoscopes H1, H2 and H3 with target pointing in the vertical plane imposed by matrix coincidences between the hodoscopes H1, H2, H3 and H4. Horizontal target pointing will be demanded between the hodoscopes H1 and H2. To trigger on lower Q^2 events the Small Angle Interaction Trigger (SAIT) developed for experiment NA28[12] will be utilised. Thus Trigger 2 will require the SAIT trigger plus a vertical target pointing track in H1234 and a horizontal target pointing track in H12. We estimate that these triggers will achieve levels of around 10^{-6} per incident muon giving a trigger rate of $\lesssim$ 100 events per spill which is a rate which can be handled by the EMC data acquisition and monitoring system. These triggers are a factor of $\sim$ 2 more efficient in accepting $\geqslant$ 2 muon events than the original NA2 triggers gaining a factor of 2 increase in luminosity.

Most of the proposed apparatus exists and has been run successfully for experiments NA2 and NA9. The new detectors which will be required are the hodoscope H2, the MWPC's P3A/B, the beam proportional chamber POE and the Uranium STAC.

3. PHYSICS INTEREST OF THE EXPERIMENT

   With the apparatus discussed above and 40 days of data-taking the estimated luminosity of the experiment will be raised by a factor of around 500 over the existing NA2 multi-muon data (assuming a 70% data-taking efficiency). By combining this increase with the experimental results from the NA2 experiment we have calculated the event yields for charm and beauty production listed in Table 1. Using these numbers as a guide we now go on to discuss the principal physics topics covered by the experiment.

3.1 Upsilon Production

   Measurements of the cross-sections for upsilon production will be of particular interest to see if, as one would naively expect, perturbative QCD calculations for this process are more successful than for the J/ψ. Apart from the expected improvement due to moving to a higher quark mass there are many unanswered questions relating to the applicability of the higher order QCD graphs for the photon-gluon fusion process. These were invoked to try to explain the production of "inelastic" J/ψ events ($Z < 0.95$) which were seen by NA2 in roughly equal numbers to the "elastic" events ($Z > 0.95$) which can be well represented by the leading order graph. The models[3] achieved only limited success for the inelastic J/ψ's and it would be of special interest to see if upsilon production exhibits a similar behaviour. The estimated number of events for this experiment should allow the study of the Q^2, ν, Z and P_t-dependences of upsilon production which should provide a good basis for testing these ideas.

3.2 B-$\bar{\text{B}}$ production

   The study of open beauty production is also interesting and with this experiment definitive measurements can be made. Fig. 2 shows the total photoproduction cross-section ($Q^2 = 0$) calculated in leading order photon-gluon fusion together with the NA2 data points for open charm and beauty production. The calculations assume a simple counting-rule glue[13] and take 1.5 GeVand 5.0 GeV for the charm and beauty quark masses respectively. The charm data are well described by the model and the NA2 measurement for B-$\bar{\text{B}}$ production is also consistent with such a model. Clearly, as in the case of hidden or bound beauty discussed above the same arguments relating to the quark mass apply here and it would be of considerable interest to be able to establish a common production mechanism for both open and bound beauty quark systems.

   The shape of the curve for the beauty cross-section in the threshold region is very sensitive to the hard gluon component of the nucleon whereas the large ν region is more sensitive to the beauty quark mass. This experiment is designed to work in the threshold region and is therefore more sensitive to the former. We note that any experiment using the higher energy muon beam foreseen at FERMILAB will have difficulty in studying this region and will be sensitive primarily to the large ν region. Thus

Table 1

Event yields for charm and beauty particle production
(after analysis cuts)

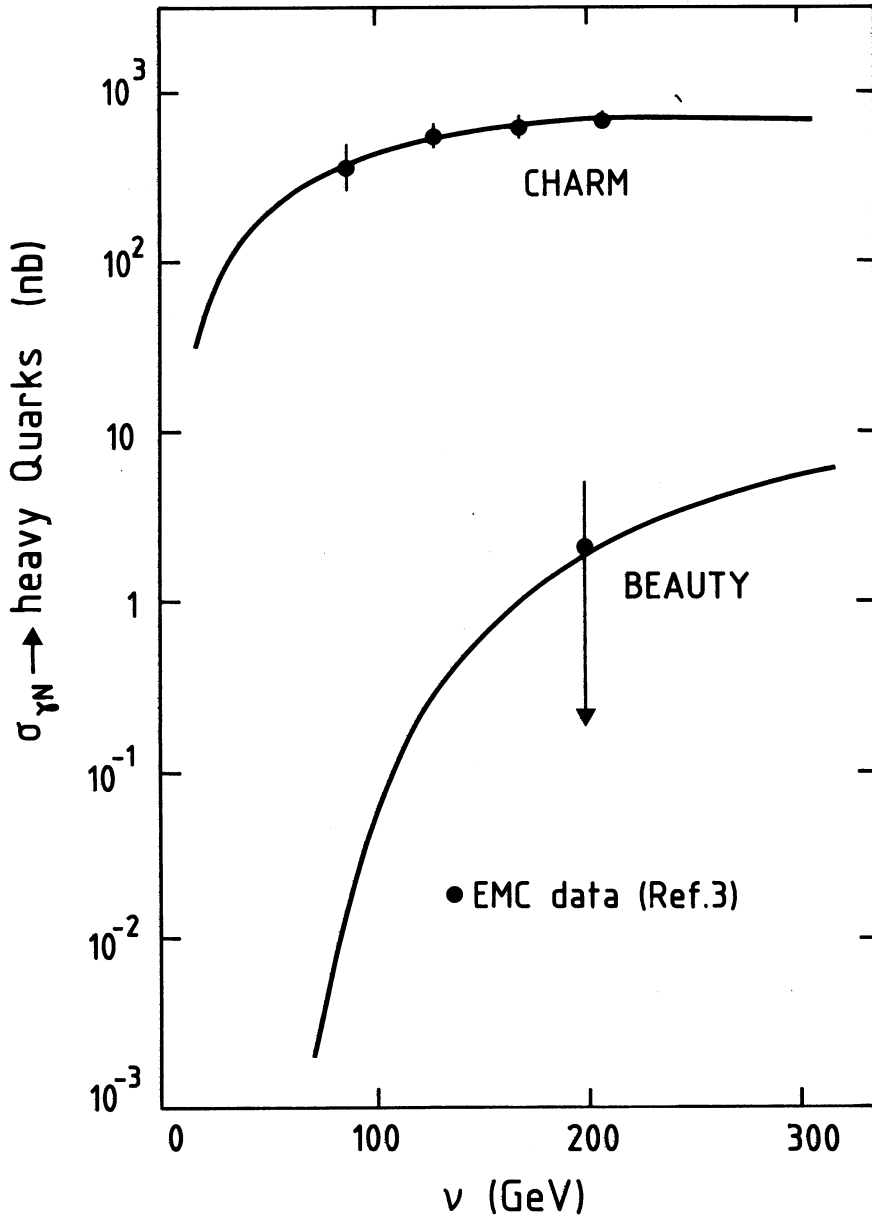| Flavour	Final State		No of events
Beauty	Upsilon		$\sim$ 300
	B-$\bar{\text{B}}$	3-muons	$\sim$ 1000
		4-muons	$\sim$ 50
		5-muons	$\sim$ 5
Charm	J/ψ	Z > 0.95	2.5×10^5
		Z < 0.95	2.5×10^5
	D-$\bar{\text{D}}$	2-muons	1.4×10^6
		3-muons	5.0×10^4

Fig. 2: $\sigma_{\gamma N} \to \nu$ for charm and beauty production. The data points are EMC measurements taken from ref.3) and the curves are the Photon-Gluon Fusion Model predictions discussed in the text.

the two sets of measurements would be complementary and would provide a complete study of the subject. Here again, the projected event yield will allow an investigation of the Q^2, ν, Z, P_t and angular dependences of the cross-sections for B-$\bar{B}$ production in this region.

In addition to the wrong-sign trimuon signal discussed above we estimate that we should see $\sim$ 50 events in which the initial B-$\bar{B}$ pair decays to produce a 4-muon final state and $\sim$ 5 events with 5-muons. Here the additional muons come from the decay of primary B mesons. Such additional events will prove valuable in helping to understand the processes by which B-mesons are produced and decay.

3.3 $D^0\overline{D^0}$ Mixing

Theoretically the amount of D^0-$\overline{D^0}$ mixing is expected to be very small[14]. The present experimental limits are at the level of $\sim$ 5%[15,16,17]. By using the 1000 wrong-sign trimuon events from this experiment we anticipate that we will be sensitive to D^0-$\overline{D^0}$ mixing at the level of $\sim$ 0.1%.

Fig. 3 shows the summed P_t^2 distributions calculated for the decay muons coming from respectively B-$\bar{B}$ decay and from the D^0-$\overline{D^0}$ charm decay scheme discussed earlier. The curves come from the Photon-Gluon Fusion model for the region $Q^2 > 0.1$ GeV^2, assuming a minimum decay muon energy cut of 10 GeV. The two processes have very different dependences and at large P_t^2 beauty decay dominates. By assuming that all of the signal at high P_t^2 is from B$\bar{B}$ production and parameterising the lower P_t^2 region we can set a fairly precise limit on the amount of the total signal which could have come from D^0-$\overline{D^0}$ mixing.

3.4 Charm Studies

The copious production of final states containing charmed particles allows a significantly improved measurement of the content and distribution of the charm quarks inside the nucleon.

Earlier publications[3,5,11,15] have shown that the production yields are well described by the Photon-Gluon Fusion Mechanism[1] but to date only upper limits have been set on the intrinsic charm content of the nucleon[15]. The reason for the latter was that the limit had to be derived using the NA2 charm dimuon signal only, as the luminosity meant that there were too few trimuon events to make a sensible comparison. The larger luminosity of the proposed experiment will provide a much improved study of this subject and will allow a clean separation of photon-gluon and intrinsic charm effects.
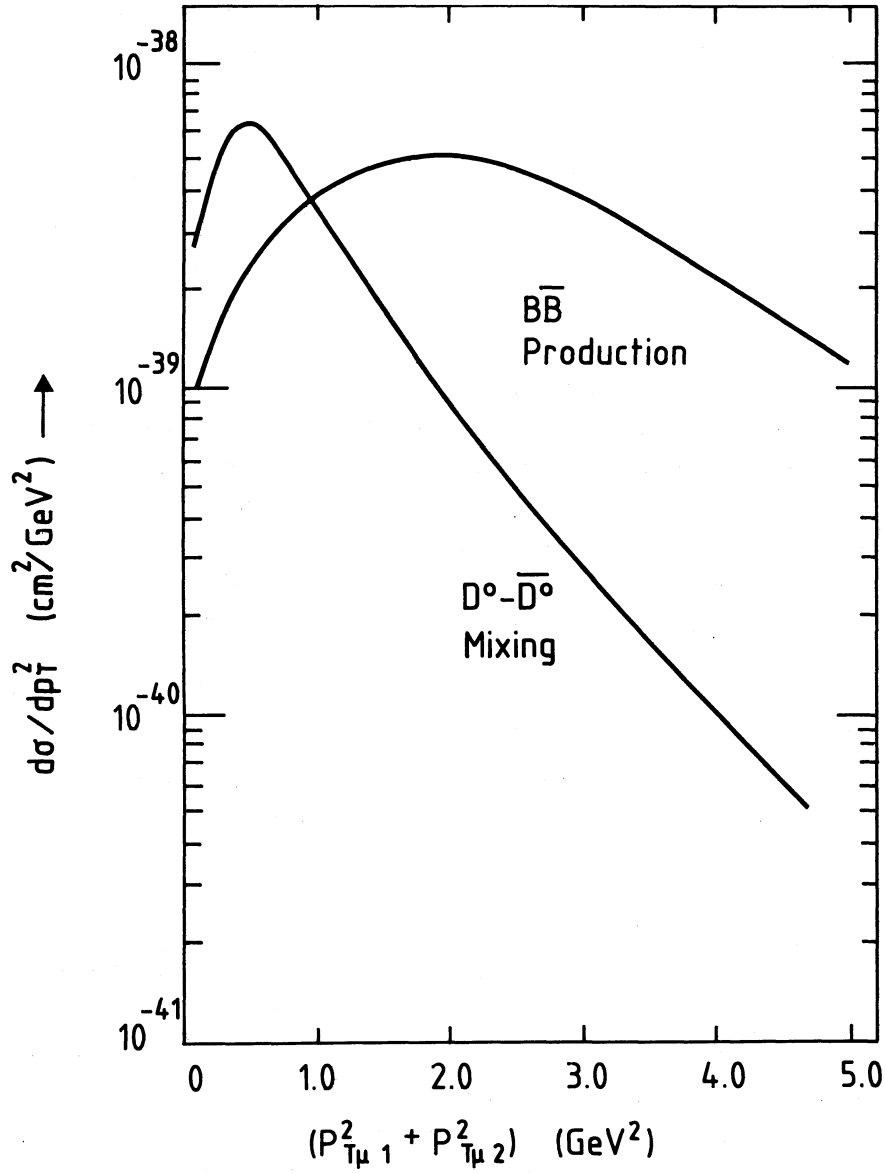
Fig. 3: Comparison of the sum p_t^2 distributions for decay muons coming from D^0 and B decay

Intrinsic charm is observed when one charmed quark fragments in the current fragmentation region and the other fragments in the target fragmentation region. The dimuon events have a contribution from this process which is expected to be significant in the medium to large x region (x > 0.3)[18]. In the trimuon case however the events detected have both decay muons in the current fragmentation region so that intrinsic charm cannot contribute to this signal. Thus the difference between the charm dimuon and trimuon production rates at large x allows a direct measurement of the intrinsic charm content of the nucleon.

The luminosity of this experiment will allow the hadronisation of heavy quarks to be studied in a much more direct way than has been possible in the past. By separating the forward and backward charm-jets in the 3-muon event sample one can study the contributions from hadronisation in both the $c\bar{c}$ system and the system including the spectator quarks in the nucleon. Deviations from the fragmentation seen in a clean $c\bar{c}$ environment such as that of e^+e^- physics are expected[19]. The high statistics also allow the study of the W-dependence of the hadronisation process which to date has not been possible.

By assuming a photon-gluon fusion production mechanism for elastic (Z > 0.95) J/ψ production the gluon distribution for the nucleon can be determined[3]. In view of recent data from the EMC[20] which suggest that there may be differences between bound and free nucleon quark and gluon distributions it would be of particular interest to compare the gluon distribution derived from the EMC iron data with that from Uranium which is proposed here.

3.5 Rare Charm Decay Modes

In this section we briefly discuss a few additional measurements of charm decay which we estimate this experiment will be able to either measure or set upper limits on. In each case the decay mode is rare and to date no experimental measurement exists.

The NA2 experiment set an upper limit of < 1.4 x 10^{-2} (90% confidence level) on the branching ratio for the pure leptonic decay of a D-meson into a muon and a neutrino[11]. Current theoretical estimates place the branching ratio in the region of 10^{-3} - depending upon which particle(s) mediate the decay[21]. Given the luminosity of this experiment we can improve the NA2 limit to < 10^{-3} which will provide a very useful constraint on the particle(s) which mediate the decay.

The signature for these events is a dimuon in which a small amount of energy (< 50 GeV) is deposited in the STAC together with a large missing energy (E_{miss} > 70 GeV). The backgrounds to the signal come from a small residual acceptance for semi-leptonic decays (D → Kμν) and from elastic τ lepton pair production. Both of these processes are calculable and are to some extent separable so that, given the current theoretical estimate of the branching ratio some leptonic events may be seen.

3.6 Other Possibilities

In addition to it's ability to run with very high beam fluxes the apparatus described in this document has a large acceptance over a very wide kinematic region. Taking into account the improvements in the small angle region coming from the SAIT and the proposed MWPC system, the spectrometer has excellent single-muon acceptance for the kinematic region

$$0.10 < Q^2 < 200 \text{ GeV}^2, \ 0.0003 < X < 0.8$$

As this is a substantially larger kinematic region than that covered by any previous counter experiment we would like to point out that this provides an excellent opportunity to perform measurements of the nucleon structure function F2 and attempt to resolve some of the unanswered questions about the relative importance of higher twist effects and the A-dependence of the bound nucleon cross-sections. Such experiments would require around 17 days of data-taking per target running under similar conditions to those foreseen here. Apart from the Uranium STAC target it would be possible to extend the measurements by using liquid or passive heavy targets.

CONCLUSIONS

We propose an experiment to study beauty and charm muoproduction via semi-leptonic decays into multimuon final states. Using a slightly modified version of the existing EMC forward spectrometer and a Uranium target we can obtain a factor of 500 improvement in luminosity over previous measurements in this field.

This luminosity will enable detailed studies of upsilon and beauty meson production and provide valuable tests of the applicability of leading and higher order QCD production mechanisms of heavy quark states. By a detailed study of wrong-sign trimuon events we can substantially improve the experimental limit for amount of D^0-$\overline{D^0}$ mixing.

The copious production of charm dimuon and trimuon events will enable detailed studies of the hadronisation of heavy quarks and a comparison of the two signals provides an excellent way of investigating the intrinsic charm content of the nucleon. Elastic J/ψ production off the Uranium target will allow us to investigate the possibility of a variation in the gluon distribution with nuclear target. We propose also to measure pure leptonic decay rate of the D meson.

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