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Heavy Flavor Production in Fixed-Target Experiments *

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HEAVY FLAVOR PRODUCTION IN FIXED-TARGET EXPERIMENTS

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ABSTRACT

This presentation is a review of recent measurements on charm production at fixed-target experiments. The measurements are relevant to a number of basic physics issues: tests of perturbative QCD, fragmentation, and basic hadronic structure.

We now have high quality, high statistics data from several fixed-target experiments. These include a total of about 30,000 fully reconstructed open charm decays and even more copious J/Ψ, Ψ' and Υ decays. Reconstruction of the full data is now reaching completion and we await final results for systematic physics interpretations.

This review of the current situation will be followed by a brief look beyond, toward beauty production at fixed-target experiments.

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INTRODUCTION

The contribution of fixed-target experiments to heavy flavor physics entered a new era with the application of precision vertexing techniques. These techniques have allowed the collection of large samples of charm decays with very good signal to background. The current round of experiments include the use of emulsions, charge coupled devices and silicon microstrip detectors. While the techniques vary, they have in common two important features: 1) the selection of heavy flavor events from among the much larger number of less interesting interactions and 2) the reduction of the potential combinations of particle tracks in an event to only those which come from a common secondary (decay) vertex. These features allow fixed-target experiments to be at least an equal partner with e^+e^- colliders in exploring heavy flavor physics. In fact, some measurements are better made in fixed-target experiments than in colliders, making these experiments complementary to and extending e^+e^- measurements in many cases, even for decay physics (see presentation by John Cumalat in these proceedings).

Figure 1 shows a particularly clean photoproduction event in which a D^0 and an anti-D* are seen to decay. The farther downstream of the primary interaction point, the more likely such reconstructions are to result from the decay of heavy flavor particles. Figure 2 shows a scatter plot of the secondary vertex distance downstream of the primary vertex in units of the separation resolution vs. the effective mass of $K\pi$ combinations. Projections of such scatter plots onto the effective mass axis for various cuts on the downstream significance are shown in Fig. 3. As the cut is increased, the D^0 signal to background increases dramatically. These data are for photoproduction in Fermilab's E-691.[1] Even cleaner charm signals have been generated in hadroproduction by CERN's NA32.[2] The benefits of the higher spatial resolution of the charge coupled devices used in that experiment and the demand that the decays appear in the region downstream of the target material are evident in Fig. 4. Trade-offs of sample size and cleanliness are varied within an experiment and from experiment to experiment depending on the particular physics of the measurement being made.

Table 1 lists the measurements for which new data are recently available. These data come from a variety of experiments at CERN and Fermilab. New data has become available on absolute and differential cross sections and their dependance on energy, Feynman x, p_t, the target material atomic weight (A) and incident particle type. In addition, new data is available on correlations in charm pair production. Unfortunately there is no new fixed-target data on open beauty decays.

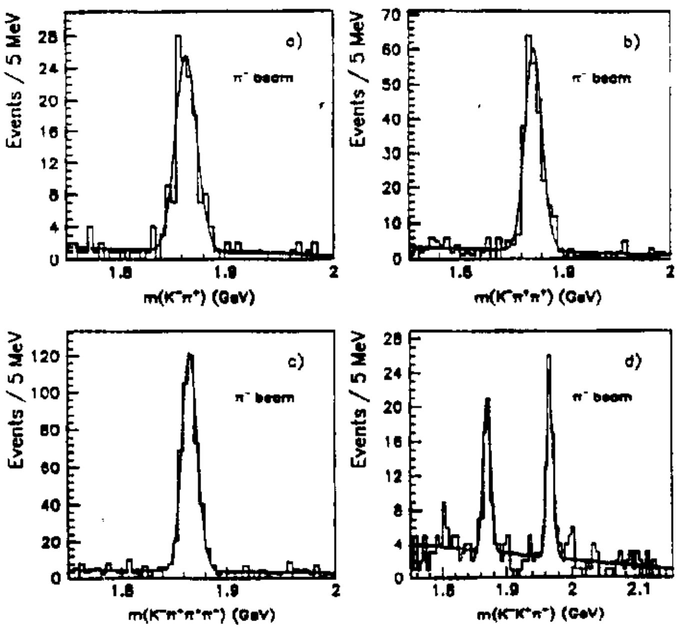

Fig. 4. NA32 charm signals showing that good signal to background is also achievable in hadroproduction.

THE PHYSICS OF HEAVY FLAVOR PRODUCTION

The production of charm appears to be well described by photon-gluon and gluon-gluon fusion mechanisms. The next to leading order complete calculation for these processes has become available in the last two years.[3]

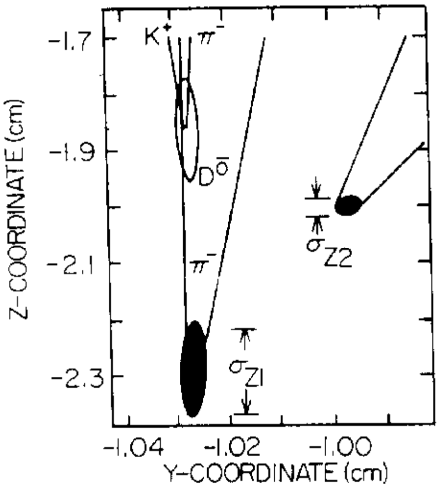

Fig. 1. E-691 reconstructed charm event.

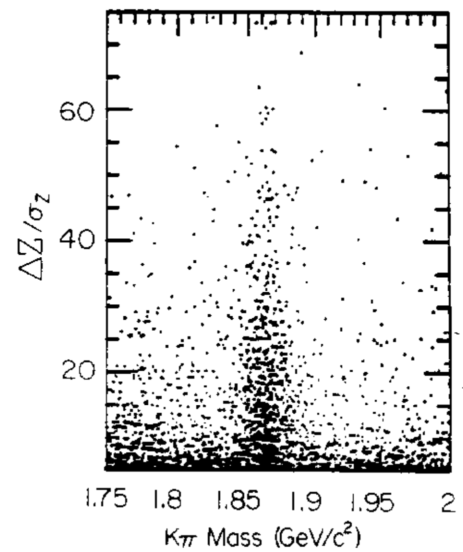

Fig. 2. E-691 candidate charm event scatter plot.

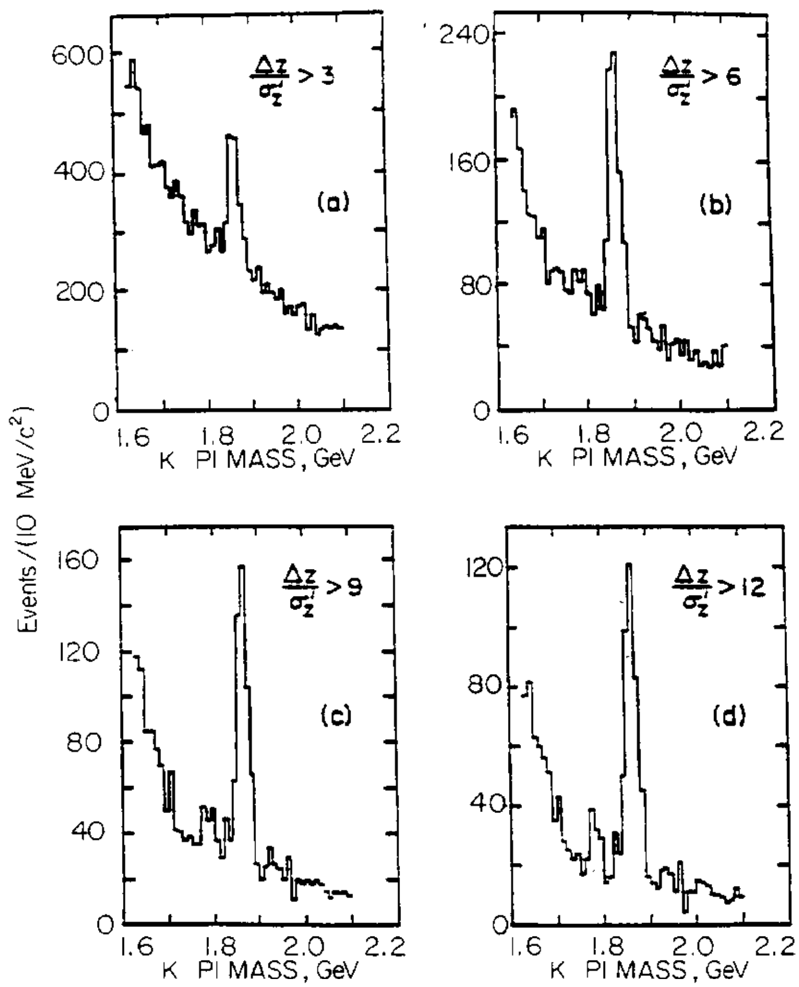

Fig. 3. E-691 photoproduction showing improvement in signal to background with increasing vertex separation cut.

TABLE 1.

NEW HEAVY FLAVOR PRODUCTION INFORMATION

Photoproduction of Open Charm		
E-691	Fermilab	- Tagged Photon Laboratory (TPL)
E-687	Fermilab	- Broad Band Beam (PB)
Hadroproduction of Open Charm		
E-653	Fermilab	- Hybrid Emulsion with π, p
E-769	Fermilab	- Hadrons at TPL (PE)
NA32	CERN	- ACCMOR
WA82	CERN	- Impact Parameter Trigger/Ω Spect.
γ, Hadro- and Muo- Production of J/ψ and Υ		
E-687	Fermilab	- Broad Band Beam (PB)
E-537	Fermilab	- High Intensity Lab (PW)
E-772	Fermilab	- Mass Focusing Spectrometer (ME)
NMC	CERN	- New Muon Collaboration
Open Beauty		
No New Results		

These calculations now provide agreement in both absolute and differential cross sections without invoking unphysically small charm quark mass values or other unbelievable parameters. In fact, the agreement seems to surprise even the theorists who have done the calculations for charm production.

The first order diagrams which describe heavy flavor production are shown in Fig. 5. In calculating these processes, one must know the distribution of quarks and gluons in the initial particles. These distributions, the structure functions, enter the cross section directly. It is for this reason that these processes should be a good way of determining the parton distributions, in particular the gluon distributions which dominate. Heavy flavor production has the advantage of this direct measure of structure functions, unlike the

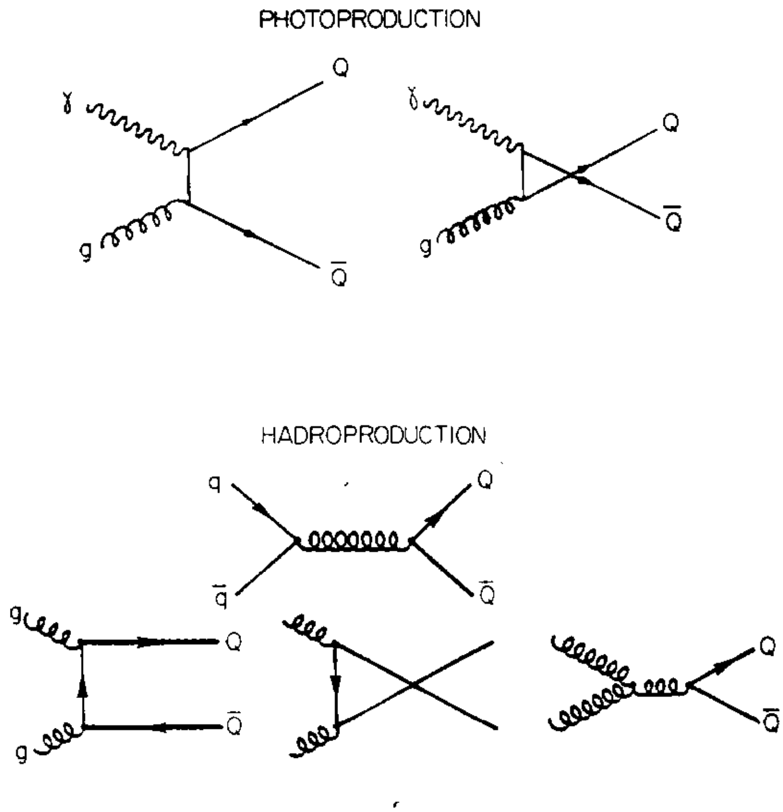

Fig. 5. Basic heavy flavor production mechanisms in leading order.

deep inelastic scattering in which the gluon distribution is found as a higher order correction and unlike direct photon production where there are larger corrections for other processes. In this case, the heavy flavor of the final state is a tag of the interactions which involve primary gluons. This is another case where the object of the search of earlier days has become a tool for later investigations.

In a similar way, since the outgoing quarks must dress themselves as hadrons, the hadronization is both a complication and a topic unto itself. Thus, the production of heavy flavor particles can be used as a test of nonperturbative QCD. Furthermore, the understanding of the basic processes is necessary if we are to understand some of the signatures anticipated for quark-gluon plasma in heavy ion collisions. This may already be true in the case of the J/ψ to Drell-Yan ratio in the heavy ion experiment at CERN, NA38.[4]

CROSS SECTION

The energy range of photoproduction of charm has been extended by recent, preliminary results from E-687[5] moved from 90 GeV from CERN NA14'[6] to 145 GeV in Fermilab's E-691[7] and now, 250 GeV in E-687.

Other recent open charm cross section data are listed in Table 2. Where absolute branching ratios are known, the cross sections can be quoted. Where a particular final state is used and the branching fraction is unknown (D_s and the charm baryons) the cross section times branch ratio is quoted. The ACCMOR Collaboration, CERN's NA32, is finishing its analysis and reports final values being submitted for publication. Slightly revised 200 GeV data ($5.9 + 0.07 - 0.06 \pm 0.03$, using more recent branching ratios)[2] can be compared to the new 230 GeV pion data. Another noteworthy feature of these recent results is the near equality of Λ_c and anti-Λ_c production in a negative pion beam.[8] This is as one would expect for the gluon-flusion mechanism, but does not lend any support for leading particle production effects. Similarly, the kaon cross section equals the pion cross section within statistics. An early NA32 result on the ratio of kaon to pion cross section of 1.2 ± 0.4[9] is compared to the new data which gives 0.90 ± 0.2.[2] The NA32 data is quoted for x_F greater than 0. One surprising fluctuation is that NA32 observes seven anti-Λ_c's ($\bar{u}\bar{d}\bar{c}$) produced with a K^- beam ($s\bar{u}$ quarks) and no Λ_c's (udc).[8]

The only experiment having an acceptance in the backward direction is the hybrid emulsion experiment, Fermilab E-653. Starting with multiprong vertices, their cross section for 800 GeV protons is equal to what one might expect from lower energy pion data when it is extended to all charm final states and all x_F. This is consistent with a harder gluon distribution in the pions and kaons. This harder glue raises the effective center of mass interaction energy at the parton level for mesons relative to protons. This

TABLE 2.

RECENT OPEN CHARM CROSS-SECTION DATA

Exp't	Particle	# Events	σ or σB μb/nucleon $x_F > 0$	Ref.
NA32	D^o	543	$\sigma = 6.3 \pm 0.3 \pm 1.2$	[2]
π^-	D^+	249	$\sigma = 3.2 \pm 0.2 \pm 0.7$	[2]
230 GeV				
	All D	792	$\sigma = 9.5 \pm 0.4 \pm 1.9$	[2]
	D_s	60	$\sigma B = 0.067 \pm 0.011 \pm 0.010$	[2]
	D^*	147	$\sigma = 3.4 \pm 0.3 \pm 0.8$	[2]
	$\Lambda_c \rightarrow pK\pi$	147	$\sigma B = 0.18 \pm 0.02 \pm 0.03$	[8]
	$\Xi_c^o \rightarrow pKK^*(892)$	3	$\sigma B = 0.019 \pm 0.011 {}^{+0.066}_{-0.009}$	[10]
	$\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$	3	$\sigma B = 0.013 \pm 0.08 {}^{+0.05}_{-0.08}$	[11]
	$\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$	2	$\sigma B = 0.012$	[11]
NA32	All D	31	$\sigma = 8.5 \pm 1.6 \pm 1.2$	[2]
			$(K^-N \rightarrow D/\pi^-N \rightarrow D) = 0.9 \pm 0.2$	
K^-	D_s	4	$\sigma B = 0.11 \pm 0.06 \pm 0.02$	[2]
230 GeV	Λ_c	7	All $\bar{\Lambda}_c$!	[8]
	Ξ_c^o	1		[10]
	Ξ_c^+	1		[11]
E-653	$c, \bar{c}$	288 + 44	$\sigma_{All\ x_F} = 32 \pm 4 \pm 12$	[12]
p				
800 GeV				

needs to be made more quantitative. An example of such analysis is the way that photoproduction E-691 has recently converted their production cross section measurements to physics parameters of general interest.[13]

In order to make the transformation from measurements to physics, E-691 has needed to use Monte Carlo techniques including hadronization of the produced quarks. One of the more dramatic results is the evidence for string fragmentation type hadronization rather than independent fragmentation of the produced charm quarks. This is evident in the distribution of the number of charged particles in the charm photoproduced events. Given that, and using next to leading order total cross section and leading order differential cross section shapes, E-691 has performed a maximum likelihood fit to obtain the gluon distribution parameter for nucleons and the charmed quark mass. The four measurements are the absolute charm cross section, the growth of that cross section with energy, and the Feynman x and p_t distributions of the charm particles. The gluon structure function result can be compared to structure functions obtained from BCDMS, for example, where there is a dramatic change in the distribution depending on whether the analysis is done with leading order or next to leading order QCD calculations.[14] The former provide a gluon structure function shape which appears to go something like $(1\text{-}x)^{11}$ and the latter $(1\text{-}x)^{7}$. The photoproduction results come dominantly from the growth with energy and the differential cross section shapes. Neither of these is significantly affected by the next to leading order calculation. The shapes remain basically unchanged.

New hadroproduction data have become available from Fermilab Experiments E-769,[15] the hadroproduction experiment at the Tagged Proton Laboratory which uses the same spectrometer as the E-691 photoproduction experiment and E-653. In addition, the ACCMOR collaboration, NA32, has slightly revised numbers as they send it for publication. WA82, the CERN impact parameter triggered hadroproduction experiment, has not yet added to the results presented last year at this conference.[16] New results from the full data set are anticipated from them and from E-769 in the fall. The E-769 signals and data are shown in Fig. 6, giving an indication of what one can expect from the four times greater data in the full sample. E-653 data is from the full sample of their incident proton data of the 1984-85 fixed-target run at Fermilab. They will also have data from the 600 GeV pion beam run in 1987-88. Tables 3 and 4 summarize these and somewhat earlier data on the x_F and p_t dependence of the cross sections. The experiments get

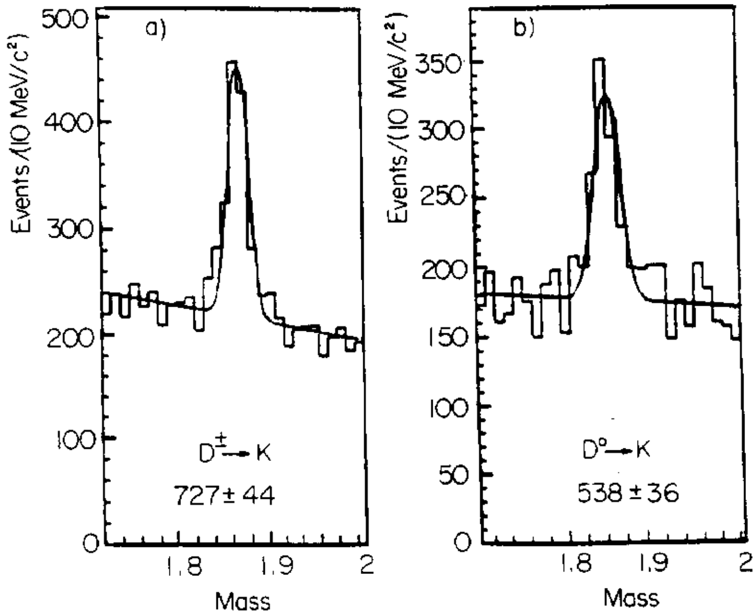

Fig. 6. E-769 hadroproduced charm signals from 25% of the data, and without Cherenkov cuts.

comparable values for the fairly narrow energy range of the pion and kaon data (230-360 GeV). Similarly, the p_t dependence seems fairly uniform across the range of meson and incident proton beam data. Since the p_t dependence is largely due to the charm quark mass, one should anticipate a uniform value here. However, the x_F dependence seen in the proton data is quite varied. Starting at 400 GeV, the proton production seems increasingly more central as the energy is raised. This suggests that structure function evolution will be important in interpreting production data. This needs to be checked and more fully understood. New proton data is anticipated from E-769 at 250 GeV, extending the range lower for protons. However one will have to wait for E-791, the 500 GeV π^- beam follow-on to E-769 at Fermilab, and E-653 before higher energy meson data is available. E-791 is just starting to run now. No new information on leading particle effects have appeared since last year's conference. However, the data summarized here will soon be used for this analysis, too.

TABLE 3.

RECENT x_F DEPENDENCE DATA

$d\sigma/dx_F \sim (1 - x_F)^n$				
NA32	230 GeV π^-	All D	$n = 3.74 \pm 0.23$	[2]
		Λ_c	$n = 3.52 {}^{+0.51}_{-0.49}$	[8]
E-769	250 GeV π^-	$D^\pm$	$n = 3.8 \pm 0.4$	[15]
		D^o	$n = 4.1 \pm 0.6$	[15]
WA82	340 GeV π^-	All D	$n = 3.40 \pm 0.45$	[16]
NA27	360 GeV π^-	All D	$n = 3.8 \pm 0.63$	[17]
NA32	230 GeV K^-	All D	$n = 3.56 {}^{+1.08}_{-0.99}$	[2]
NA27	400 GeV p	$c,\bar{c}$	$n = 4.9 \pm 0.5$	[18]
E-743	800 GeV p	$c,\bar{c}$	$n = 8.6 \pm 2.0$	[19]
E-653	800 GeV p	$c,\bar{c}$	$n = 11.0 \pm 2.0$	[12]
		$(D\bar{D})$	$n = 7.5 {}^{+2.0}_{-1.7}$	[12]

TABLE 4.

RECENT p_t DEPENDENCE DATA

$d\sigma/dp_t^2 \sim e^{-bp_t^2}$				
NA32	230 GeV π^-	All D	$b = 0.83 \pm 0.03$	[2]
		Λ_c	$b = 0.84 {}^{+0.09}_{-0.08}$	[8]
E-769	250 GeV π^-	$D^\pm$	$b = 0.98 \pm 0.07$	[15]
		D^o	$b = 0.95 \pm 0.09$	[15]
WA82	340 GeV π^-	Ds	$b = 1.27 \pm 0.18$	[16]
NA27	360 GeV π^-	All D	$b = 1.18 \pm 0.17$	[17]
NA32	230 GeV K^-	All D	$b = 1.36 {}^{+0.32}_{-0.26}$	[2]
NA27	400 GeV p	$c,\bar{c}$	$b = 1.0 \pm 0.1$	[18]
E-743	800 GeV p	$c,\bar{c}$	$b = 0.8 \pm 0.2$	[19]
E-653	800 GeV p	$c,\bar{c}$	$b = 1.1 \pm 0.2$	[12]
		$(D\bar{D})$	$b = 0.80 \pm 0.15$	[12]

In an early experiment on the hadroproduction of J/ψ, E-537, the data have been recently analyzed for the x_F dependence and implied gluon structure functions of the incident hadrons.[20] This has been done for both negative pions and anti-protons at 125 GeV and for beryllium and tungsten targets in the case of the pions. A much harder gluon distribution is observed for the pions ($n = 1.2$ and 1.98 for the beryllium and tungsten targets respectively with small errors) than for the anti-protons ($n = 7$). The same sort of analysis is being performed by the New Muon Collaboration on their muon produced J/ψ. Here, they obtain 4.8 ± 0.93 for the power of 1-x in the target nucleon.[21] Additionally, they have detailed p_t distributions in bins of inelasticity.

There is one WA82 result which has been made available during the last year. This is a mass plot of D^+ and D_s signals from $\phi\pi$ combinations.[22] These are interesting at this point primarily as an indication of what one can anticipate from the full data sample, over 100 D_s decays to $\phi\pi$.

INCIDENT PARTICLE EFFECTS

The data taken recently is dominated by negative pion and proton beam experiments. One of the important anticipated results from data already taken is from the tagged negative and positive beam from E-769. In particular, the large positive beam sample (approximately 250 million recorded events) is nearly evenly divided among tagged pions, kaons, and protons. The production dynamics studied in the same experiment, with data taken at the same time from tagged pions, kaons, and protons should allow comparison of structure functions of these three incident hadron types. Not only do experimental factors cancel in the comparison, but some of the theoretical uncertainties should be removed in the comparison, too. For example, the mass of the charm quark, whatever it may be, the gluon distributions in the target, whatever they may be, and such theoretical uncertainties as renormalization scale should also be common or nearly so in these data. Any variations in the produced charm particles should be due to the hardness of the incident particle gluon distributions. This should allow comparison of quark/anti-quark states with and without heavy (strange) quarks and between two and three quark states (comparing pions and protons at the same energy), etc.

ATOMIC WEIGHT, A, DEPENDENCE OF THE CHARM CROSS SECTION

Although all the hadroproduction experiments have assumed A^1 dependence, this has been done in the face of some early evidence from indirect measurements that the cross section might go as weakly as $A^{0.75}$.[23] The A dependence used seems to provide reasonable agreement among experiments with different target materials. More recently, the measurements of WA82, E-769, and E-772 all provide a range of $A^{0.9}$ to A^1 (Table 5).

TABLE 5.

RECENT A DEPENDENCE DATA

$\sigma \sim A^{\alpha}$			
Photoproduction			
Still no open charm data on A dependence			
E-691	$\gamma A \to J/\psi$	$\alpha = 0.94 \pm 0.02 \pm 0.03$	[24]
Hadroproduction			
WA82	$\pi^- A \to D$'s	$\alpha = 0.89 \pm 0.05 \pm 0.05$	[16]
E-769	$\pi^- A \to D^{\pm}$	$\alpha = 0.97 \pm 0.07$ (stat. only)	[15]
	$\pi^- A \to D^{o}$	$\alpha = 0.92 \pm 0.08$ (stat. only)	[15]
E-672	$\pi^- A \to J/\psi$	$\alpha = 0.85 \pm 0.06$	[25]
E-772	$pA \to J/\psi, \psi'$	$\alpha = 0.92$	[26]
	$pA \to \Upsilon(1s)$	$\alpha = 0.97$	[26]

At last year's Physics in Collision Conference, Leonardo Rossi reported on the WA82 A dependence measurement.[16] The measurement came from side by side targets of silicon and tungsten. The extraction of the A dependence result requires knowledge of the beam shape and of the A dependence of the interactions used to monitor the position of the beam. In order to avoid these difficulties, Fermilab's E-769 used a series of 26 thin metal foils and a beam which traverses the entire target assembly. An A^{α} parameterization appears quite adequate in describing the various nuclear material results. Thus, the results should not depend very much on which target material is used to extract the value of α. However, the data is now becoming rich enough to anticipate checking the A dependence as a function of x_F and p_t. This information may be useful in understanding differences between these results and earlier results.

There is new, very precise data from E-772 at Fermilab on the A dependence of J/ψ and upsilon production.[26] Unlike the Drell-Yan dimuon production which comes from quark-antiquark annihilation, the J/ψ and Υ production is thought to be dominated by gluon production (possibly largely through intermediate χ states). In any event, the heavy flavor onium states have an A dependence unlike Drell-Yan and may be viewed as relevant here, too. This data set is also sufficiently copious that one can see the x_F and p_t dependence of the parameter α (Fig. 7).

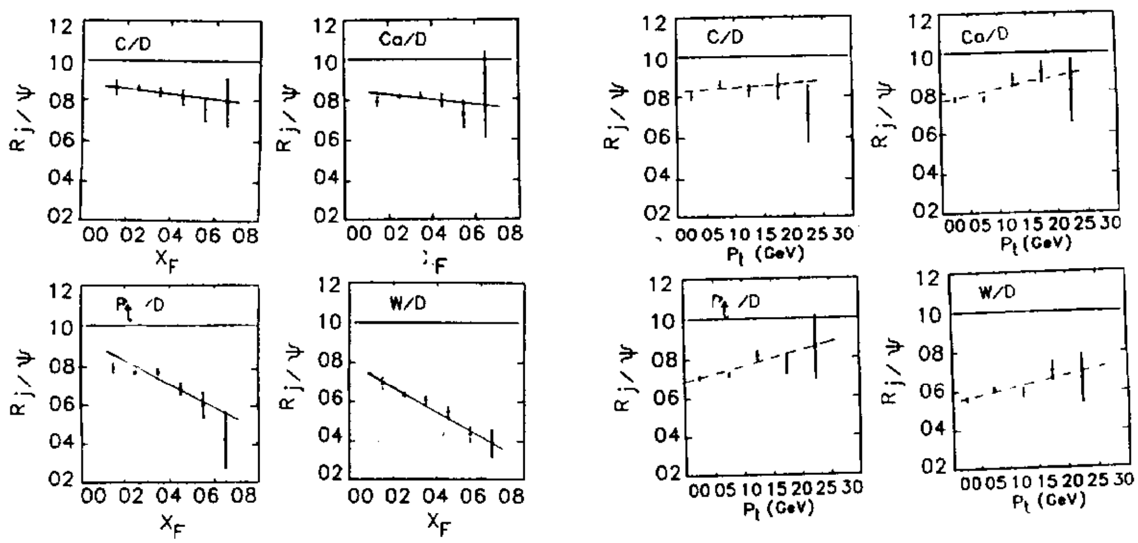

Fig. 7. E-772 preliminary ratio of J/ψ yield per nucleon vs. x_F and p_t.

The New Muon Collaboration at CERN also has J/ψ production data on hydrogen, deuterium, carbon and tin which should allow a check of the E-691 result.

CORRELATIONS IN CHARM-ANTICHARM PRODUCTION

One of the most unique features of the data from the hybrid emulsion experiment, E-653, is the large acceptance observation of pairs of charm particles. A total of 44 such events with two multiprong decays has been observed.[12] As seen in Tables 3 and 4, the pairs are produced with x_F and p_t dependences similar to those of the single particles! This already implies a correlation. One also sees explicitly a correlation in the angle in the plane transverse to the beam; as expected in lowest order parton models, the two particles being produced at 180° with respect to each other in this plane. In fact, the correlation is enhanced for particles where the pair has a large p_t or high-effective mass (Fig. 8). The same correlation is enhanced for the larger

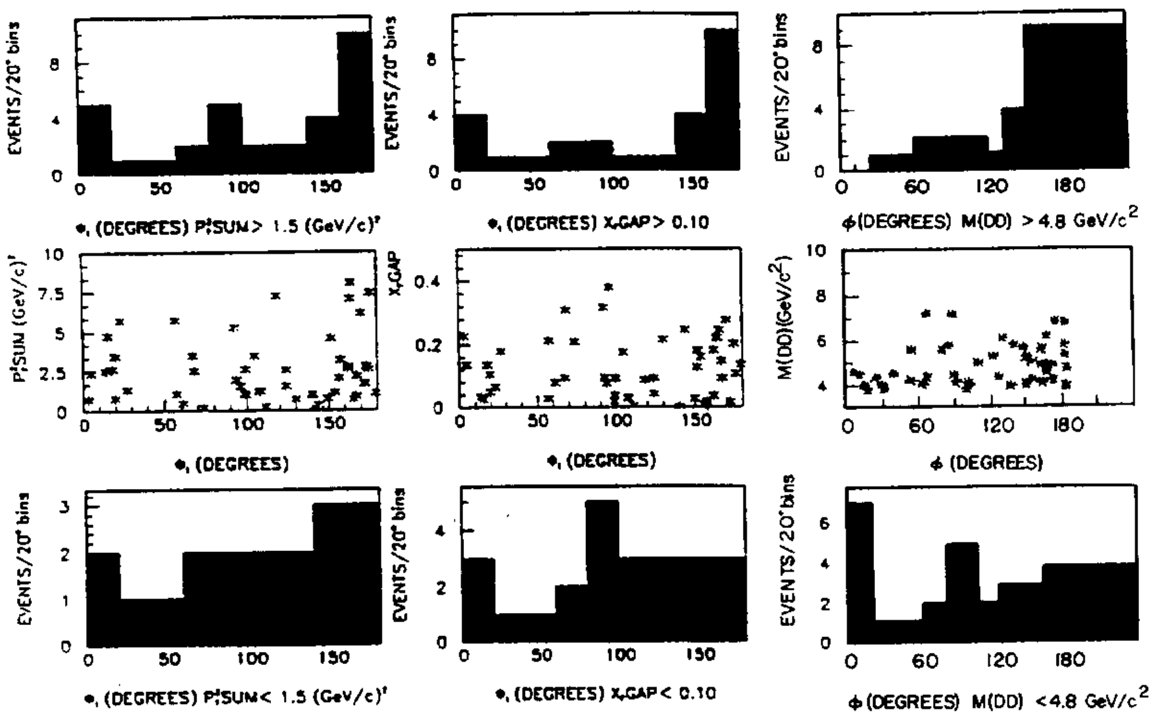

Fig. 8. E-653 correlation angle in the transverse plane vs. production parameters, showing increased correlations with increased sum p_t, x_F gap and M(DD̄).

differences in x_F of the two produced particles. These details must be explained by any complete theoretical understanding of the process.

BEAUTY PRODUCTION

There are no new results on beauty production since the last Physics in Collision Conference. However, experiments are gearing up to pursue this goal at Fermilab and there has been a recent positive recommendation for a follow-on to Experiment WA82 at CERN. How well can we expect fixed-target programs to do on beauty?

There are three major approaches to beauty research in the coming efforts. They differ in their selection of beauty events and the final states on which they concentrate. Several experiments (E-687, E-791, and the WA82 follow-on) all focus on the dominant beauty decay through open charm. These experiments have fairly open triggers (independent of final state), but are more limited in their rate capability. They will look for the most copious B decays. A second approach is to concentrate on decays containing the J/ψ with its subsequent decay into lepton pairs (E-771 at Fermilab). Such an effort can also trigger on the single high p_t muons from semileptonic decays. Finally, one Fermilab experiment (E-789) is focusing on the two body decays of beauty. This experiment is the most specialized in the final states it seeks. They have the smallest branching fractions and the experiment is designed to take the highest interaction rate of any of these efforts. However, the geometry is semi-closed. There is no line of sight between the downstream detectors and the target.

Table 6 summarizes the general capability of these experiments with some attempt to equalize the optimism expressed by the proponents. In general, the outlook is that each has the opportunity to find a couple hundred fully reconstructed beauty decays in a reasonable run. Physics results may also be

TABLE 6.

FIXED-TARGET b PHYSICS
(per 10^7 spill seconds)

	Open Geometry via D's (eg. $B \to Dx$)	Open Geometry via ψ's (eg. $B \to \psi x$)	Restricted Geometry (eg. $B \to hh$)
Inclusive Cross Section (QCD) & Lifetimes	700 $B \to Dx$ ↳ chg'd ↳ chg'd	800 $B \to \psi x$ ↳ chg'd ↳ $\mu\mu$	1000 $B \to hh$ total in ~5 modes w/BR = 10^{-5} each
B_s	70 $B_s \to D_s x$, DKx ↳ chg'd ↳ chg'd ↳ chg'd ↳ chg'd	80 $B_s \to \psi x$ ↳ chg'd ↳ $\mu\mu$ depends on BR ($B_s \to \psi x$)	20/mode (more if avg. BR larger)
B_s Mixing	Insufficient Rate	Insufficient Rate	Insufficient Rate
CP Violation	Insufficient Rate	Insufficient Rate	Insufficient Rate
Issues	Computing Load in Hadroproduction $\int \mathcal{L}dt$ in Photoprod.	10^7 int/sec Data Achievable	Si w/ 5×10^8 int/sec Linkup of Si & Dnstr. Signal/Background
ASSUMPTIONS			
$(\sigma_b + \sigma_{\bar{b}})A^{.25}B\int \mathcal{L}dt$	9×10^5	15×10^5	1×10^5
Geom. Accept.	40%	15%	1%
Add'l BR's	($D \to$ chg'd)16% ($x \to$ chg'd)13%	($\psi \to \mu\mu$) 7% ($x \to$ chg'd) 33%	100%
Trig/Cuts Effic.	10%	15%	20%
Net Accept.*Effic.	0.08%	0.05%	0.2%

expected from the more copious less-than-fully-reconstructed B's (e.g., D's which do not point back to the primary interaction). It would be phenomenal if any of these approaches could attain the sensitivity required to do B_s mixing or CP violation. On the other hand, they promise genuine physics results which will be useful in determining the most appropriate approach, even in other environments such as colliders, to the greatly desired chance to see CP violation in a system other than the neutral kaons. These early physics results may also be important in top quark searches at colliders.

SUMMARY

The current situation for charm is that there is a great deal of new data being fully reconstructed and made available for analysis. The immediate task at hand is to complete the reconstruction of these large data samples and systematize the results. Next, one must move from the details of measurement to the more fundamental physics interpretation of the results. We can anticipate genuine contributions in the areas of perturbative and nonperturbative QCD and in gluon structure function determinations for the widest variety of mesons and baryons.

For beauty, we are only at the very earliest stages of such a program. It is premature to speculate overly precisely on how well the next generation of experiments will be able to do, or what their limitations are. We have been surprised before by fixed-target capabilities in heavy-flavor physics. However, it will take a lot of effort before this happens again. We will see how well those dedicated to this approach can do. We will be delighted to make use of their instrumental advances and physics insights both for heavy-flavor physics and beyond.

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