Fermi National Accelerator Laboratory

FERMILAB-Conf-94/201

A High-Rate Fixed-Target Charm Experiment

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July 1994

Presented at the *Workshop on the Future of High Sensitivity Charm Experiments (CHARM2000)*, June 7-9, 1994.

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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Abstract

A fixed-target experiment capable of reconstructing $> 10^8$ charm decays is described.

1 Introduction

In the P865 Letter of Intent [1], we have proposed a fixed-target experiment aimed at achieving high sensitivity to decays both of charm and of beauty. I describe here a revised version which is somewhat more optimized for charm and less so for beauty. The rationale for this change of emphasis is two-fold: by the time a new fixed-target experiment might run ($\approx$ Year 2000), it is likely that studies of beauty at the level proposed in P865 will no longer be competitive; furthermore, it may well be that charm is even more interesting than beauty, since the background to rare processes beyond the Standard Model is so much smaller in charm than in beauty. At this workshop, Pakvasa has emphasized that rare and forbidden processes such as D^0 mixing, charm-changing neutral currents, and lepton-family-violating currents must exist at some level if we are ever to have an understanding of the fermion masses and mixings; some extensions of the Standard Model predict effects detectable at the level of sensitivity discussed here.

2 Beam and Target

To achieve charm sensitivity three orders of magnitude beyond that achieved in E687 and E791 and two orders of magnitude beyond that expected from CLEO, E831, and E781, i.e. $\gtrsim 10^8$ reconstructed decays, probably requires a primary proton beam, since it may be difficult to produce a sufficient rate of high-energy photons, pions, or hyperons. For the sake of discussion, I therefore assume a beam of 800 GeV protons.[1] Then given $\sigma(pN \to D\,X) + \sigma(pN \to \overline{D}\,X) \approx 40\,\mu$b/nucleon at 800 GeV [2] and $\sigma(pN \to D^0\,X) \propto A^{1.0}$ [3], and assuming that the cross section to produce D_s and charmed baryons is $\approx 15\%$ that of D mesons, I estimate that charmed particles are produced at the rate of 7×10^{-3}/interaction if a high-A target (e.g. Au) is used. A 1 mm Au target is suitable, representing 1% of an interaction length and on average 14% of a radiation length for outgoing secondaries. Alternatively (as suggested at this workshop by D. Summers), a low-Z target such as ^{13}C-diamond may be favored to minimize scattering of low-momentum pions from D^* decay;

[1] Though 900 GeV or more may become available, this is unlikely to occur by the Year 2000.

then a 2 mm target is suitable, representing ≈1% of an interaction length and ≈1% of a radiation length and producing charm at the rate 3×10^{-3}/interaction.

Based on experience in ACCMOR, E672, E687, E789, and E791, a single short target is desirable. This allows attention to be focused on decays occurring in air or vacuum downstream of the target, and decays inside the target (for which backgrounds are substantially larger[2]) to be excluded, and it simplifies secondary-vertex triggers. Given the typical Lorentz boost $\gamma \approx 20$, a 1-2 mm target is short enough that a substantial fraction even of charmed baryons will decay outside it.

I take as a benchmark a 5 MHz interaction rate, which then requires 500 MHz of beam or 10^{10} protons per 20 s Tevatron spill, an intensity easily attainable.

3 Spectrometer Design

3.1 Rate capability

A significant design challenge is posed by radiation damage to the silicon detectors. To configure detectors which can survive at the desired sensitivity, we choose suitable maximum and (in one view) minimum angles for the instrumented aperture, arranging the detectors along the beam axis with a small gap through which pass the uninteracted beam and secondaries below the minimum angle (Figs. 1, 2).[3] Thus the rate is spread approximately equally over several detector planes, with large-angle secondaries measured close to the target and small-angle secondaries farther downstream. Along the beam axis the spacing of detectors increases approximately geometrically, making the lever arm for vertex reconstruction independent of production angle. Since small-angle secondaries tend to have high momentum, the multiple-scattering contribution to vertex resolution is also approximately independent of production angle. The instrumented angular range is $|\theta_x| \leq 200\,\text{mr}$, $4 \leq \theta_y \leq 175\,\text{mr}$, corresponding to the center-of-mass rapidity range $|y| \lesssim 1.9$ and containing over 90% of produced secondaries.

To maximize the rate capability of the spectrometer, the tracking is performed entirely with silicon and scintillating-fiber planes. The rate per unit area (and hence the radiation fluence) in a detector element can easily be estimated based on the uniform-pseudorapidity approximation. Fig. 3 shows the rate calculation for an annular area dA located a transverse distance r from the beam and of thickness dr. Since the operational limit of present-day silicon detectors is 10^{14} particles/cm^2, the charged multiplicity per unit pseudorapidity in 800 GeV proton-nucleus collisions is $n \approx 4$ for high-A targets [4] (less for C), and a typical run will yield up to $n_{\text{int}} \equiv (5 \times 10^6\,\text{interactions/s}) \times (4 \times 10^6\,\text{s}) = 2 \times 10^{13}$ interactions, we

[2]This has been emphasized by several other speakers at this workshop, notably J. Cumalat and L. Moroni.

[3]An alternative approach with no gap may also be workable if the beam is spread over sufficient area to satisfy rate and radiation-damage limits, however the approach described here probably allows smaller silicon detectors and is "cleaner" in that the beam passes through a minimum of material.

can derive the "minimum survivable" inner detector radius

$$r_{\rm min} = \left(\frac{n}{2\pi}\frac{n_{\rm int}}{10^{14}}\right)^{\frac{1}{2}},$$

or $r_{\rm min} = 3.5\,{\rm mm}$, which we set as the half-gap between the two detector arms. This ensures that the detectors will survive for the entire run (or at most will need to be replaced once[4]).

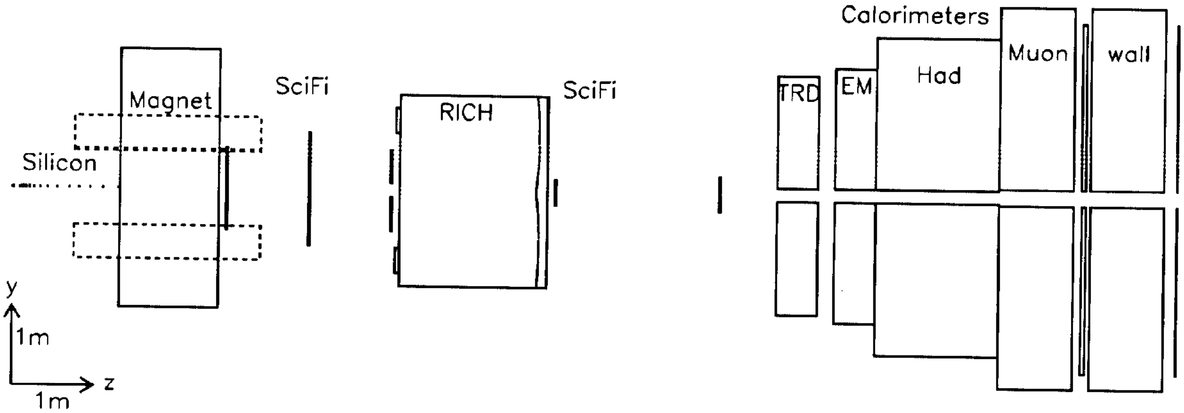


Figure 1: Spectrometer layout (bend view).

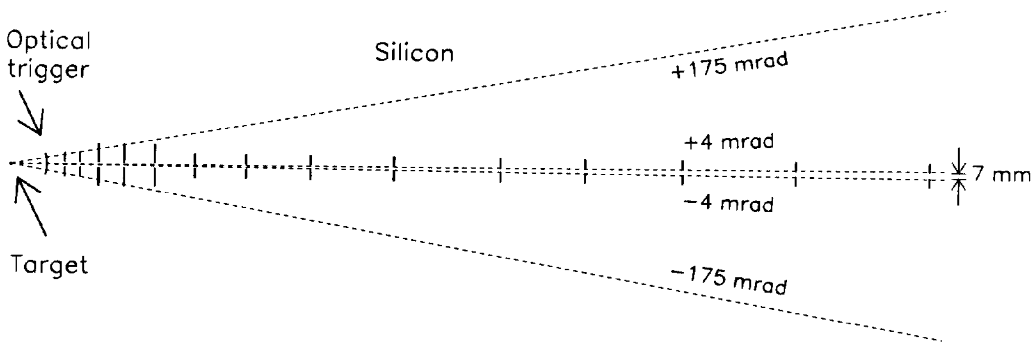
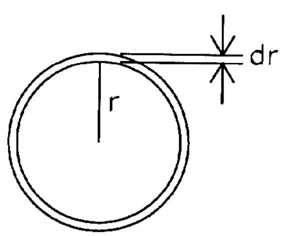


Figure 2: Detail of vertex region (showing optional optical impact-parameter trigger).



$$\frac{dN}{d\eta} \doteq \text{constant} \equiv n$$

$$d\eta = \frac{dr}{r}$$

$$dA = 2\pi r dr$$

$$\frac{dN}{dA} = \frac{dN}{d\eta}\frac{d\eta}{dA}$$

$$= n/2\pi r^2$$

Figure 3: Calculation of rate per unit area in an annulus.

[4]In E789 we operated silicon detectors at fluence up to $\approx 5 \times 10^{13}\,{\rm cm}^{-2}$ with negligible efficiency loss.

To cover the desired angular range, we configure 14 double-sided silicon strip detectors[5] above and 14 below the beam as shown in Fig. 2, such that at all angles of interest there are at least six measurements per track (and more at small angles where the occupancy is highest). Since the green-scintillating 3HF/PTP fibers are more radiation-hard than silicon detectors [1], and (due to occupancy; see below) the beam gap between fiber planes is larger than that in the silicon, radiation damage of the fibers is not anticipated to be a problem.

The scintillating fibers are deployed in staggered doublets in three views. They are read out using cryogenic solid-state "visible-light photon counters" (VLPCs) [5], which feature high quantum efficiency (up to 85% for green light [6]), low noise, and high speed: up to 30-MHz rate capability has been demonstrated, with single-electron noise rates of several kHz [7]. At this workshop Ruchti has reported the successful operation of a large scintillating-fiber tracking system with VLPC readout in a cosmic-ray test carried out for D0. The long fibers (3 m of scintillator with 8 m of clear waveguide) used in that test with 99% efficiency represent a more challenging application than that discussed here.

We assume 1-bucket (<19 ns) recovery times for all detectors, so that there is no pile-up due to out-of-time interactions. Designs capable of this performance have been presented [1, 4, 8] for all detectors except the TRD.[6]

Detector-element occupancies also follow from the derivation of Fig. 3. For an element of height dy located a transverse distance y from the beam and covering $-x_{\max} < x < x_{\max}$, the occupancy per event (neglecting magnetic bending) is

$$\frac{n}{\pi}\frac{dy}{y}\arctan\frac{x_{\max}}{y}\,.$$

For 800 μm fiber diameter, this implies $\approx$16% occupancy at $y = 1$ cm, $\approx$8% at 2 cm, and $\approx$4% at 4 cm. A full trackfinding simulation will be required to assess the maximum acceptable occupancy, but this suggests $\approx$1 cm as the minimum acceptable half-gap in the scintillating-fiber planes. The fibers near the gap could be split at $x = 0$ and read out at both ends, halving their occupancies. Since shorter fibers have less attenuation, a smaller diameter could be used near the gap, reducing occupancy still further.

3.2 Spectrometer performance

I have carried out a simple Monte Carlo simulation of the spectrometer sketched above. Assuming a 1.2-m-long analyzing magnet with pole pieces tapered to give 0.5 GeV p_t kick, I obtain (56 $\pm$ 1)% geometrical acceptance for $D^0 \to K^-\pi^+$ decays and (44 $\pm$ 1)% for $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$, comparable to those of existing open-geometry spectrometers despite the beam gap. With silicon detectors of 25 μm pitch read out digitally (i.e. no

[5] I assume silicon strip detectors for definiteness, but silicon pixel detectors would be better if available with sufficient readout speed and radiation hardness; because of their radiation hardness, diamond detectors, if available, should also be considered (see talk by Tesarek at this workshop).

[6] It may be that a TRD for electron identification is not cost-effective and a hadron-blind detector [9] or preshower detector should be used instead.

pulse-height information) and 800 μm scintillating-fiber pitch, and assuming $\pm 10°$ stereo, Gaussian fits to the reconstructed distributions give rms resolutions of 6 MeV in mass (a factor ≈ 2 better than that of existing spectrometers) and 11 μm (bend-view) and 21 μm (nonbend-view) in impact parameter, giving 40 fs decay proper-time resolution, comparable to that of existing spectrometers. Since the mass resolution is dominated by scattering, minimization of material is crucial, for example use of helium bags and avoidance of threshold Cherenkov counters employing heavy gas mixtures. The performance parameters just given are a snapshot of work in progress and probably can be improved with further optimization.

4 Trigger

While the most successful previous charm hadroproduction experiments (E769 and E791) used very loose triggers and recorded most inelastic interactions, this approach is unlikely to extrapolate successfully by three orders of magnitude! (Consider that E791 recorded 2×10^{10} events – tens of terabytes of data – on 20,000 8 mm tapes.) Thus our sensitivity goal requires a highly selective trigger. However, we wish to trigger on charm-event characteristics which bias the physics as little as possible. Lepton triggers, used successfully by E653, while capable of great selectivity ($\sim 10^3$ rejection for minimum-bias events), have only $\sim 10\%$ charm efficiency. The E_t triggers used by E769 and E791, while highly efficient for charm, have poor selectivity ($\lesssim 10$ minimum-bias rejection). I therefore assume a first-level trigger requiring calorimetric E_t OR'ed with high-p_t-lepton and lepton-pair triggers. At second level, secondary-vertex requirements can be imposed on the E_t-triggered events to achieve a rate (~ 100 kHz) which is practical to record.

Analyses of the efficacy of an E_t trigger carried out using E791 data [10] and the PYTHIA Monte Carlo [11] agree on minimum-bias rejection vs. charm efficiency (though due to nuclear effects not simulated in PYTHIA, they differ as to the E_t threshold corresponding to a given rejection). Fig. 4 shows the efficiencies for charm and minimum-bias events as a function of the PYTHIA E_t threshold. A considerable degradation results if there is significant probability for two interactions to pile up in the calorimeter. Given the 53 MHz rf structure of the Tevatron beam and the typical $\approx 50\%$ effective spill duty factor, at the benchmark 5 MHz mean interaction rate there is a $\approx 20\%$ probability for a second simultaneous interaction. Thus at a 5 GeV PYTHIA E_t threshold (corresponding to a $\approx$10 GeV actual threshold [10]), the minimum-bias rejection factor is 5, i.e. pile-up degrades the rejection by a factor ≈ 2, even for a calorimeter with one-bucket resolution. The charm efficiency at this threshold is about 50%, for a charm enrichment of ≈ 2.5. (These are rough estimates based on a relatively crude calorimeter [11], and an optimized calorimeter may provide better rejection.) Such an E_t trigger yields a 1 MHz input rate to the next level.

While it may be technically feasible by the Year 2000 to record events at a 1 MHz rate, an additional factor $\approx$10 in trigger rejection is desirable and can be achieved by requiring evidence of secondary vertices. Existing custom trackfinding trigger processors [12], while perhaps capable of this rejection, typically fall short by $\approx$ one order of magnitude in speed. At ~ 1 MIPS-s/event, an on-line farm of commercial processors would need a capacity of

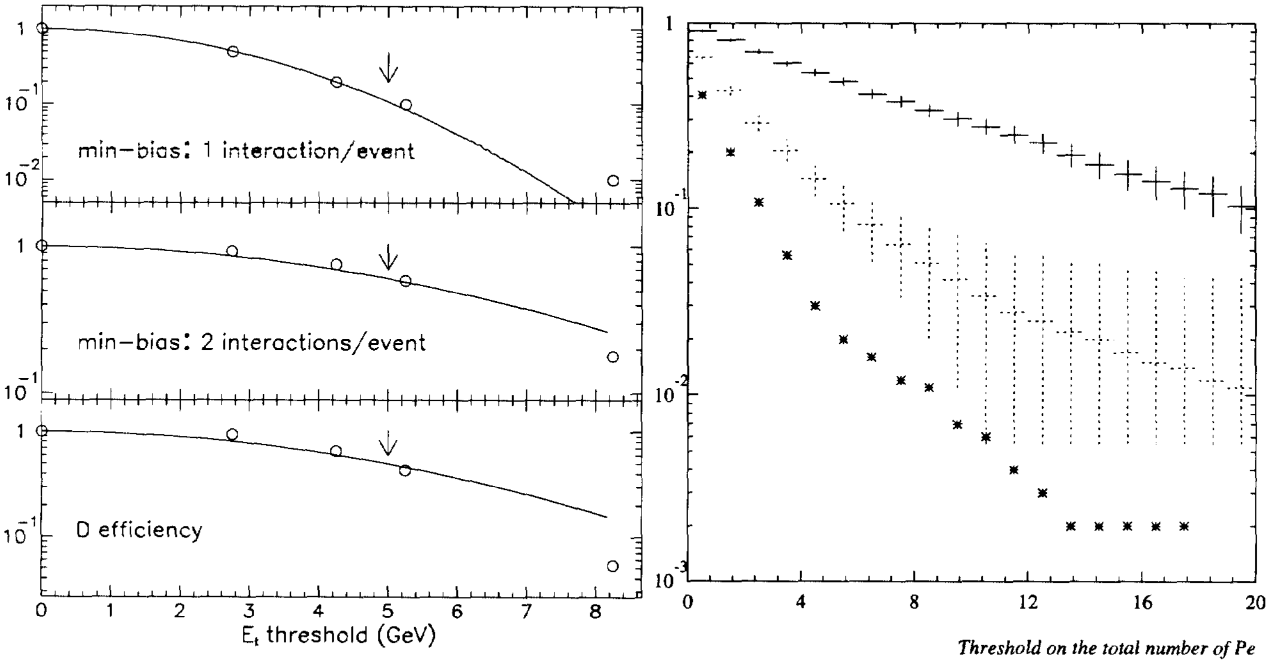


Figure 4: Left: minimum-bias and D efficiencies vs. E_t threshold; points are from PYTHIA simulation of Ref. [11], curves are fits of the form $\exp(-aE_t^2)$, and arrows indicate the 5 GeV threshold discussed in text. Right: estimated optical-trigger efficiency for minimum-bias (solid crosses), PYTHIA charm (dashed crosses), and $B^0 \to \pi\pi$ events (stars) vs. threshold in photoelectrons (from [1]).

$\sim 10^5 - 10^6$ MIPS, which may be prohibitive even in the Year 2000. It is likely that by then a sufficiently fast custom trackfinding processor can be developed. This would require fast buffering (~ 100 ns) and readout ($\sim 1\,\mu$s) of event information in order not to impose excessive deadtime. Trackfinding secondary-vertex triggers benefit from the use of focused beam and a single thin target, which allow simplification of the algorithm since the primary vertex location is known *a priori*. Since low-p_t tracks have poor vertex resolution [13], a trigger which discriminates p_t is more effective than one which is purely topological; such discrimination may be simply accomplished by placing the vertex detectors in a weak magnetic field and looking for straight tracks.[7]

As an alternative to iterative trackfinding at a 1 MHz event rate, three other approaches also appear worth pursuing. The first is a secondary-vertex trigger implemented using fast parallel logic, e.g. PALs, neural networks, or pre-downloaded fast RAMs, to look quickly for patterns in the silicon detectors corresponding to tracks originating downstream of the target. The others are fast secondary-vertex trigger devices originally proposed for beauty: the optical impact-parameter trigger [14] and Cherenkov multiplicity-jump trigger [15]; while results from prototype tests so far suggest undesirably low charm efficiency, these might with further development provide sufficient resolution to trigger efficiently on charm. For example, Fig. 4 shows the efficiency for minimum-bias, charm, and beauty events projected for a version of the optical trigger [1], indicating 40% charm efficiency for a factor 5 minimum-

[7]As suggested by D. Christian.

Table 1: Estimated yields of reconstructed events (antiparticles included)

mode	charm frac.	BR	accept.	trigger eff.	reconst. eff.	yield
$D^0 \to K\pi$	0.6	0.0365	0.56	0.2	0.5	1.2×10^8
$D^+ \to K^*\mu\nu$	0.3	0.027	0.4	0.5	0.5	8×10^7
$\to K\pi\mu\nu$						
all	1	≈ 0.1	≈ 0.4	≈ 0.2	≈ 0.5	4×10^8

bias rejection. The resulting ≈200 kHz event rate can be processed or recorded using existing technology.

5 Yield

The charm yield is straightforwardly estimated. Assuming a Au target and a typical fixed-target run of 3×10^6 live beam seconds, 10^{11} charmed particles are produced. The reconstructed-event yields in representative modes are estimated in Table 1 assuming (for the sake of illustration) that the optical trigger is used for all-hadronic modes (but not for leptonic modes, for which the first-level trigger rate should be sufficiently low to be recorded directly) and performs as estimated above. Although due to off-line selection cuts not yet simulated, realistic yields could be a factor $\approx 2-3$ below those indicated, the total reconstructed sample is in excess of 10^8 events. Given the factor ≈ 2 mass-resolution improvement compared to E791, one can infer a factor ~ 50 improvement in statistical significance in a typical decay mode. Since the charm cross section at 120 GeV proton-beam energy may be several % of that at 800 GeV, and the geometrical acceptance remains $\approx 50\%$, interesting charm sensitivity may also be available using Main Injector beam during Tevatron Collider running; at the least, there will be opportunity to debug and test the spectrometer thoroughly so that full-energy beam may be used with optimal efficiency.

6 Summary

A fixed-target hadroproduction experiment capable of reconstructing in excess of 10^8 charm events is feasible using detector, trigger, and data acquisition technologies which exist or are under development. A typical factor ~ 50 in statistical significance of signals may be expected compared to existing experiments. The cost of the design sketched here has been estimated at under $10M [1]. I anticipate an exciting future for charm physics at the turn of the century.

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