Physics with Charm

by JEFFREY A. APPEL

Physicists recognize that the Standard Model conceals as much as it reveals about the ultimate workings of matter. Might the study of the charm quark help open the way to the physics beyond the Standard Model?

MAYBE WE SHOULD CALL IT something different. “The Standard Model” sounds so definite, so final. Perhaps another name would better describe the part-monument, part-punching-bag nature of the world’s best theory of how matter is put together at the smallest scale. The Standard Model *is* a monument—a monument to the power of theory and experiment to explore and explain the seemingly trackless inner reaches of the matter around us. But it is a punching bag, too, the so-far intact target of experimental jabs and thrusts attempting to expose its weaknesses. The punches have included searches for forbidden processes, neutrino mass, and other symmetry violation. Now, in a dizzying mix of metaphor, the Standard Model has become something else as well—a curtain that physicists know is about to go up, revealing the true drama on the stage behind it: The Physics Beyond the Standard Model. For we know that the Standard Model conceals as much as it reveals about the ultimate workings of matter. We know that marvelous scenes will unfold before us, if only we can find which rope to pull to make the curtain rise.

Most of the theoretical and experimental energy of the field of particle physics at the end of the twentieth century is concentrated on raising the Standard Model curtain on the drama that will be twenty-first century physics. And most of these efforts are devoted to pulling on two ropes: high-energy searches for the origin of mass and the quest to find matter-antimatter asymmetry in the behavior of mesons containing the bottom quark. But besides these mainstream efforts, might there be another way to raise the curtain? Might we at least lift its corner by using—charm?

> ***The charm quark has intrigued particle physicists as a unique particle, the first of the heavy quarks—and more.***

Since its famous discovery almost a quarter century ago, the charm quark has intrigued particle physicists as a unique particle, the first of the heavy quarks—and more. It is the only quark with charge +2/3 that is both unstable (unlike the up quark) and yet survives long enough (unlike the top quark) to bind with other quarks and form observable particles. Thus the charm quark offers a unique way to discover effects that may occur only in this "up-quark" neighborhood of the particle world. Such effects might never show up in the down, strange and bottom quarks, with their −1/3 charges. Charm might give us a longed-for peek beyond the Standard Model curtain.

FASCINATION OF CHARM

Until 1974, three kinds of quarks had appeared in experiments: up, down and strange. But theorists, reasoning that quarks should come in even numbers, predicted a fourth kind, dubbed charm. If it existed, besides evening up the quark score, charm would explain a puzzle: why do neutral kaons decay only very rarely into a pair of muons? Charm did indeed materialize, simultaneously on the east and west coasts of the United States, and it proved to have the properties the theorists had said it would. Since its appearance, the charm quark has taught physicists much about the strong and weak nuclear forces and how they interact.

Charm also teaches us about ordinary matter. Most of the matter that we see is made of quarks, held together by gluons, in neutrons and protons. Producing charm particles at fixed-target experiments (where beams of moving particles hit stationary matter, instead of colliding with beams of particles coming the other way) has elucidated the distribution of the gluons inside garden-variety hadrons containing up and down quarks, and even within less ordinary hadrons containing strange quarks. (A hadron is a particle made of quarks held together by gluons.)

The fusion of a photon with a gluon from a target hadron is the dominant process for producing charm-anticharm pairs with a photon beam. The fusion of two gluons in hadron-hadron interactions is the dominant process for creating charm quarks in that environment. Both of these processes depend on the distributions of gluons in hadrons. By carefully studying the characteristics of charm production, we work backward to the way gluons are distributed in target neutrons and protons, as well as in beam hadrons, such as pions, kaons and protons. Gluon distributions in pions and kaons (each comprising a quark and an antiquark held together by gluons) appear to be similar. In protons, which are made of three quarks, the gluons are "softer," that is they keep closer to the quarks. Charm particles interest the experimenter because they allow the identification of well-defined gluon interactions and give us a window into what is going on in the mainstream matter of the Universe.

In the story of charm, as in the story of all particle physics, technology is the *deus ex machina* that moves the plot forward. Advances in accelerator, detector, and computing technology have let us make the acquaintance of charm, and advances in technology will take us still further in the study of its character. Learning more about charm will not only help us understand the gluons, but illuminate the differences between the quarks and—and!—get to that physics beyond the You-Know-What. For charm particles may hold clues to why, for example, charm is one of only six quarks, and why those six come two by two, like creatures from Noah's Ark.

THE DISCRETE CHARM OF FERMILAB FIXED-TARGET EXPERIMENTS

The fixed-target run that ended in September 1997 may have seen the last dedicated charm experiment at Fermilab. This moment—the end of an era of charm—is a good time to look at where we have come so far in charm research and at where we might be going.

Today, precision results on charm physics come from electron-positron collision experiments at Cornell's CESR and from Fermilab's fixed-target experiments. Where Fermilab's precision measurements come to the fore, we can credit the large numbers of fully reconstructed decays observed and the cleanliness (with respect to background) of the experimental signals. The Fermilab experiment with the most prodigious sample of clean, reconstructed charm decays now has 200,000; but it will soon relinquish its title to a charm experiment from the last fixed-target run that projects a million or more, all told. When we consider that charm appears only once in every 200 relevant photon interactions and once in every thousand hadron interactions, and add in the fact that experiments typically reconstruct only about half a percent of these, we realize that experimenters are looking for one clean decay in about 100,000 interactions.

The nature of fixed-target experiments can lead to clean charm signals. Most of the charm particles produced move rapidly in the direction of the incident beam. They live long enough (about a picosecond) to move a few millimeters beyond their production point before they decay. Experimenters can observe this distance, but it requires precision measurement of the trajectories of the decay products, uncluttered by a lot of distracting "junk" in the way. Depending on how the charm particle decays, knowing the identity of the decay products leads to the cleanest signals. In the electron-positron machines used so far to study charm, the charm particles are at rest or moving slowly at production, so they decay on top of the production point—a much messier situation. In fixed-target experiments, physicists can use the decay topology to select only those interactions that could contain charm particles. For those, they then examine only those particles coming from single vertices.

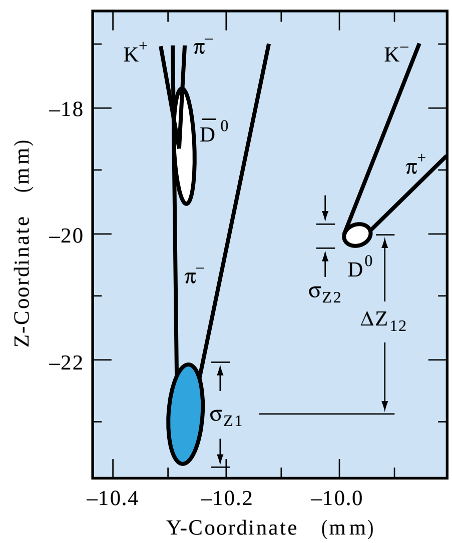
The combination of these steps helps to select the precious charm events from the more copious, uninteresting false candidate events. Applying selection criteria using vertex separation and particle identification reduces background much faster than signal. The more certain we are that a charm decay vertex candidate is separated cleanly from the event's interaction vertex, the more certain we can be that we have observed a real charm decay.

The methods developed for these fixed-target experiments have not only bagged many a charm particle, but have influenced the design for hadron colliders doing bottom and top quark research and for asymmetric *B* factories where we need to measure the separation between the decay sites of the particles containing bottom quarks.

TECHNOLOGY OF CHARM

Advances in three areas of technology have produced today's large, clean samples of charm in fixed-target experiments. Silicon microstrip detectors (SMDs), videotape storage, and computer farms—all linked together—have taken charm physics to new levels.

The figure above right shows how the history of production and decay of charm particles in one event can be reconstructed from the trajectories of the resulting charged particles. Tracks (the records of particle trajectories) emerging from the primary interaction vertex and the two charm decay vertices (one for the charm and one for the simultaneously produced

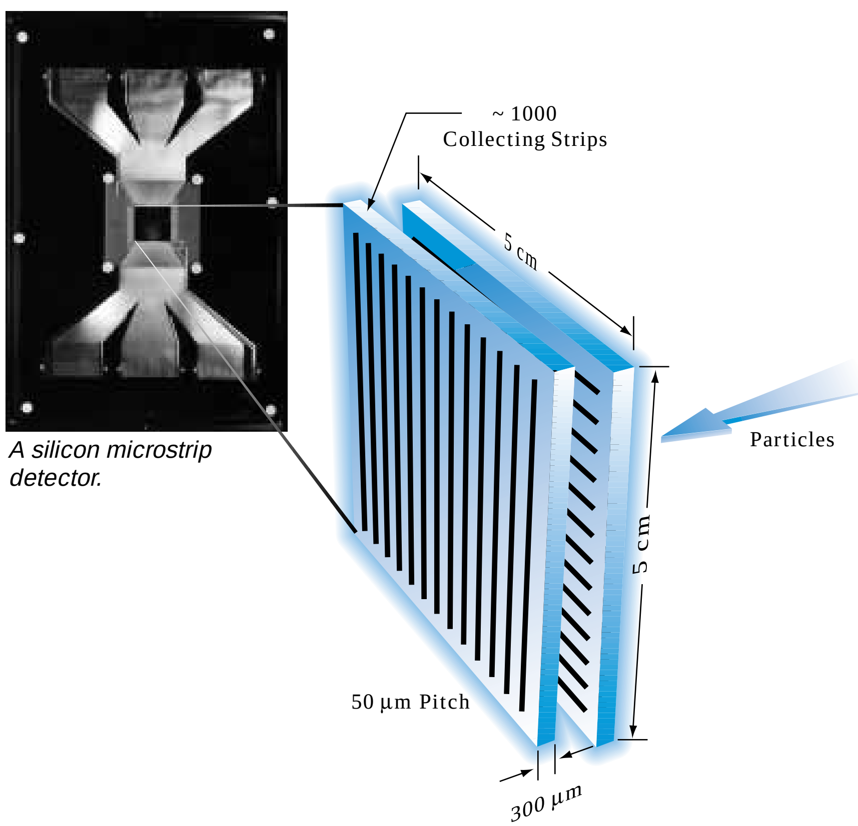


A charm production event from Fermilab experiment E691. The two white areas represent regions from which tracks emerge and are separated from the initial collision point. This indicates that charm particles D^0 and $\bar{D}^0$ were produced and decayed in these regions.

Silicon Microstrip Detectors

MODERN MICROELECTRONIC TECHNIQUES make possible the silicon microstrip detectors that have brought charm physics such a long way. How do SMDs work? When a charged particle traverses a thin crystal of pure silicon, it deposits energy that frees electric charges to migrate.

If an appropriate voltage is applied across the crystal, the migrating charges will produce signals on metal electrodes. The signals, suitably amplified by sensitive electronics off the silicon plate, are digitized and recorded for later analysis. On SMDs, the electrodes are closely spaced



A silicon microstrip detector.

strips, typically 25 to 50 microns from center to center, with amplifiers attached to each strip. The large number of strips allows experimenters to record the passage of many charged particles through each detector, reduces the capacitative load on the fronts of the amplifiers, and improves the achievable spatial resolution. The SMD signal collection takes just a few billionths of a second, making SMDs useful in the intense, high-rate environments that characterize more and more particle physics experiments.

anticharm) appear to emerge from distinct vertices. This is only possible if the charm particles live long enough, if they are moving fast enough, and if the tracking resolution is sufficiently fine. A charm meson that decays after one typical lifetime has traveled several millimeters in the direction parallel to the incident beam and 150 microns in the transverse direction. SMDs provide resolutions about ten times more precise than these distances. This provides powerful separation between combinations of tracks that emerge from charm decay vertices and background.

Over the past fifteen years, the raw data from fixed-target experiments has gone from a few gigabytes to 50,000 gigabytes. It would have cost a fortune to handle so much data using the old open-reel magnetic tape system. Fortunately, new technology in the form of 8 mm videotape came to the rescue with greater capacity at a far lower price. However, because of the less-than-lightning speed of an individual 8-mm tape-writing device, one fixed-target charm experiment used 42 of the tape drives writing out events in parallel. The data-acquisition architecture supported this parallel tape writing, along with parallel-path data accumulation from the front-end electronics.

Massive new data sets also required greater economy in analysis computing. Charm experiment E691 first used massive parallel-processing computer farms at Fermilab for this purpose. At that time, experimenters used laboratory-designed, single-board computers (over a hundred in one system) with commercial CPU chips and home-built control software.

Later, commercial workstations tied together with custom software became more cost effective. This approach of using large data sets combined with simple early event selection offers certain advantages, including the ability to do analysis after detector calibrations are tuned up and sophisticated computer codes are debugged. The analysis can then apply final track- and vertex-finding. This approach works better than the use of only the cruder information available at data-taking time, which necessarily throws away some of the interesting charm events. It also helped that the price of computing power dropped rapidly in the interval between the purchase of systems for on-line and those for off-line use.

CHARM OF THE FUTURE

Massive data storage, massively parallel computing and silicon microstrip detectors have all become part of the standard tool box for modern high-energy physics experiments. The experiments that discovered the top quark at Fermilab's Tevatron collider, the experiments that study bottom quark physics in Z decay at SLAC and CERN, and experiments that will study CP violation in asymmetric B factories all used, use or will use these techniques. Charm showed the way.

But now, whither charm physics itself? Have the present technologies run their course for charm? A look at the likely landscape of future physics experiments shows few if any long runs of sufficiently energetic beams to produce great numbers of charm particles. Would-be charm investigators will need some sort of new environment to pursue their explorations. Two possibilities suggest themselves: asymmetric electron-positron colliders and the forward regions of hadron colliders. Both remain to be explored, although both offer the promise of opening new realms of charm.

As in the past, we will need new technologies to deepen our knowledge of charm. But if we are inventive enough, and alert to new technical opportunities, it is possible that we may look to charm for its unique potential to raise the curtain on the opening act of that riveting all-star production, "Physics Beyond the Standard Model," coming soon to a theater near you.

Growth of Data Acquisition Parallelism at Fermilab's Tagged Photon Laboratory

Year	Experiment	Number Events (M)	Data Set Size (GB)	Number Reconstructed Charm Decays
1980–81	E516	20	70	100
1984–85	E691	100	400	10,000
1987–88	E769	400	1500	4000
1991–92	E791	20,000	50,000	200,000

8 Millimeter Tape Technology

Don Summers

THE FIRST 8 MM videotapes held the equivalent of thirteen of the old open-reel tapes in use before 1990, and current versions hold two times that amount. To put it in perspective, a typical weekend of data-taking in experiment E769 resulted in a forklift of open-reel tapes (see photo above). In the next series of fixed-target runs, E791 recorded a comparable amount of data in three hours and stored it in a tray of 8 mm tapes (see photo below).

Fermilab Visual Media Services

Fermilab physicist Catherine James holds a tray of 8 mm tapes.