CDF: B-physics from 10 meters to 10 microns

In high energy physics the constituents of matter are studied with particle beams and detectors analogous to studying small objects with a microscope: the accelerator provides the "light" in the form of particle beam radiation with the smallest possible wavelength, and the detectors provide the optics to collect the scattered "light" into a visual image of the object at a human scale. Recent events at the Collider Detector at Fermilab (CDF) illustrate just how apt this microscope analogy has become.

CDF is a complex instrument which records 115,000 pieces of information about each selected event. With the 1992 installation of a silicon microstrip vertex detector (SVX), CDF became capable of observing the character of proton-antiproton ($\bar{p}$ p) collisions at the scale of 10 microns (about 0.0004 inch). Event details inside the Tevatron vacuum beam pipe can now be studied even though no detector resides inside that beampipe. In 1992 the original 4,500 ton detector was also upgraded by the addition of 2500 new muon wire chambers and 630 tons of steel, all required to make some of these special event observations possible.

The detector is an intelligent microscope, capable of selecting only the events of interest out of the 500,000 $\bar{p}$ p collisions occurring each second during the 1992 collider run. Approximately 28 events of the type described below have been seen so far out of a sample of 9 pb^{-1} (approximately 5×10^{11} collisions). Compared to the classical microscope, this is like having an instrument which can be programmed to select the one exciting specimen out of a collection of 20 billion slides.

Events containing quarks are the specimens of interest described here. CDF looks for collisions resulting in a B meson (containing a b quark) plus anything else; the B mesons are unstable and decay after living only 1.3×10^{-13} seconds. Some of the time the B's decay into a J-Psi (J/ψ) particle and a K-star particle (K^*); subsequently the J/ψ decays into two muons (μ) of opposite charge and the K^* decays into a K meson (K) and a pi meson (π) of opposite charges. We look for the process $\bar{p}p \to \mu^+ + \mu^- + K^\pm + \pi^\mp + X$. The "X" is shorthand for all other particles which may be produced in the event.

The figure shows a computer generated graphic of an event recorded on magnetic tape. In this view the proton and antiproton beams head into and out of the page at the center of the diagram. The detector forms a <u>10 meter</u> square box around the beam collision point. The red circle in the lower right hand corner is an expanded view of the innermost 1 centimeter of the 10 meter box.

In the full size figure, the red and blue shaded areas indicate detector components containing many layers of lead and steel; the yellow shading indicates solid steel. Particles that come from the interaction point and penetrate all this material are, typically, charged muons. Such particles deposit energy in the muon wire chambers behind the lead and steel, and that energy is shown in the graphic as +'s. CDF also has a region of magnetic field generated by a superconducting solenoid inside the lead and steel components. Charged particles in this region are detected in another wire chamber and the detected particle path is shown in the center of the graphic as a curved line. This particular event was selected by the detector triggering system because it had two muon candidates and two matching curved tracks. The momentum information from these two muons can be combined to measure the mass of the parent J/ψ particle.

Next we zoom in to see what the SVX tells us about the event details right at the interaction point (look at the inset graphic in the lower right hand corner of the picture). The SVX is a 20-centimeter diameter device with 46,000 strips etched in silicon wafers at separations of 60 microns between the strips. There are four layers of silicon and these four position measurements can be used to extrapolate the particle paths deep inside the Tevatron vacuum beampipe. The inset figure shows these extrapolated tracks inside a circle with <u>1 centimeter</u> diameter. The tiny circle in the center of the expanded picture represents the Tevatron beam -- 90% of the Tevatron beam is inside a circle about 70 microns in radius. Using the tracks from the primary vertex in a given event, the SVX can determine the actual position of a particular $\bar{p}\,p$ interaction to about 10 microns.

If a B meson moves at nearly the speed of light, then it travels a finite distance before decaying. This distance can be simply calculated by multiplying speed by its short lifetime of 1.3×10^{-13} seconds to give 390 microns. This is the average lifetime; some B's live a longer time and some a shorter time. One can see that the muons in this event do not appear to come from the beam spot but instead come from a secondary position seven hundred microns away from the beam. This is just what we expect for a B-meson. Looking closely you will see that two other tracks also come from this secondary vertex. These are the K meson and the π meson; the reconstructed mass from these two particles is consistent with the mass of the K^*. The information from the μ^+, μ^-, K and π tracks can be combined to measure the mass of this meson as 5.3 GeV. This is almost exactly the known value of the B-meson mass and confirms that we are probably looking at a B-meson.

Finally, in the inset figure notice there is <u>another</u> secondary vertex located <u>below</u> the Tevatron beam. The complete process is $\bar{p}p \rightarrow B + \bar{B} + X$; we now see evidence of the other B meson ! The decay of the second B is unconstrained -- we did not demand that it undergo the decay into μ μ K π and so now we can begin to study the properties of B-mesons in general by looking at the second after triggering on the first of the pair. While the combined branching ratio for B-mesons into J/ψ followed by J/ψ into $\mu^+\mu^-$ is only about one in every 1500 decays, other decay modes have higher probabilities. For example, the most obvious B characteristic is its short lifetime and subsequent decay leading to a potentially visible secondary vertex. <u>Every</u> B-meson has this property.

Once the collaboration devises a fast trigger to select these events with secondary vertices, CDF will open a new window for the detailed study of one of the six fundamental quarks.