Counting Muons
Emmett Windisch

In the most comprehensive theory of fundamental particles and their interactions, the branching ratios of all possible decays would be known. To that end, experimental searches must be conducted for decays whose branching ratios have yet to be measured. These decays and their branching ratios are valuable both in the insight they give into the particle theory and their ability to confirm or contradict current and proposed theories of particle physics.

Theory

The search we are conducting is for the rare decay of the $D^0$ meson to two muons, $D^0 \rightarrow \mu\mu$. This decay mode is highly suppressed in the standard model and so observing it and determining or limiting its branching ratio is extremely valuable. The process that we’re studying is:

$$D^* \rightarrow D^0 \pi \rightarrow \mu\pi\pi$$

In terms of the quarks involved the decay process is

$$\bar{c}s \rightarrow \bar{c}u\pi \rightarrow \mu\mu\pi$$

where a bar indicates an antiparticle. The branching for this decay would be a very useful tool for verifying or contradicting existing and future theories.

In order to make an accurate measurement of this branching ratio, we need to be able to accurately detect muons, as they are the final product of the reaction. The muon detectors at CDF are on the outside of the detector and are designed so that only sufficiently energetic muons will reach them, but there is the possibility of the muon detectors not registering a muon that has reached them, or for another particle, such as a pion, to make it to the detectors and
generate a muon signal where no actual muon existed. Understanding these uncertainties is necessary to achieve the highest possible level of accuracy in the final result and so the bulk of my time this summer was spent analyzing them.

We began by examining the first of these: the efficiency of the muon detectors. In order to count muons effectively in future searches, it is necessary to know how often actual muons are missed by the detectors. To study this, we examined J/Ψ particles, which decay to two muons, to use as a source of muons for calibration. In order to examine these decays, we look at events in which two tracks branching from a point separated from the beam combine to give a reconstructed mass close to 3.096 GeV, the mass of the J/Ψ particle. Each track has with it an associated muon likelihood, a probability calculated from the track information that a given particle is a muon, and this is the quantity we will plot efficiency against. This gives an idea of how efficient the detectors are as a function of the likelihood that a particle is a muon. Eventually, the goal was to observe the way these plots change for changing values of other parameters like momentum and direction. The efficiency calculation is made by comparing the reconstructed mass plots for various values of muon likelihood. In our analysis, one mass plot requires that one and only one of the tracks satisfied the given likelihood value, while the other requires that both tracks met the requirement. Since the muons are created in pairs, we get an idea of how many were being missed by examining the following values:

\[
eff = \frac{2N_1}{2N_1 + N_2}
\]
Where $N_1$ is the number of events in which only one of the tracks made the likelihood cut and $N_2$ is the number of events in which both tracks made the likelihood cut. The error on this value (which depends on the errors in $N_1$ and $N_2$) are also given. The definitions of $N_1$ and $N_2$ are shown, the subscripts ‘s’ and ‘b’ refer to signal and background respectively, and the factor of one half comes from averaging the number of background events on a window twice the size the of the signal window. The errors on $n_{1s}$, $n_{1b}$, $n_{2s}$, and $n_{2b}$ are approximated by the binomial error: $n_i^{1/2}$. The value $\text{eff}$ gives the efficiency of the muon detectors and was eventually plotted against muon likelihood for differing values of various other parameters, including the momentum, the angle the tracks came off of the beamline at, and the fiduciality of each track. The fiduciality of a track is an integer value between zero and fifteen that indicates the direction of the particle and is used to determine whether a given track is headed for one of the muon detectors. This value is very important because the muon detectors do not cover the entire CDF; there are gaps and holes. Plotting against this parameter allows us to see if there is any change in efficiency when a particle is headed for a given muon detector, or when a particle hits the edge of a detector as opposed to the center.
As mentioned above, the values $N_1$ and $N_2$ are calculated using sideband subtraction, in which the number of background events per GeV of mass is estimated on either side of the signal peak and then subtracted from the signal window to count how many actual events there are in the peak. This assumes that the background is linear and can be approximated by a straight line underneath the signal peak. The average number of background events per GeV is calculated by a subfunction named Sideband.C that is called by the analysis script. The writing of the efficiency analysis script, which was named JPsiEffvsLkhdvs.C, and Sideband.C were what I spent the majority of my time on. Short descriptions of these scripts are included in the “Implementation” section.

Once we were able to calculate the efficiency of the muon detectors, and the errors associated with counting real muons, it remained to examine the effects of other particles “faking” the presence of a muon by making it to the muon detectors and registering a signal.

There are two main processes by which a non-muon particle, typically a pion, can fake the existence of a muon. The first is simply by penetrating all of the matter between the interaction point and the muon detectors and registering in one of them. The second is called “decay in-flight,” in which some non-muon particle, again typically a pion, decays into a muon (or a muon, anti-muon pair) while traveling from the interaction point to the detectors. These resulting muons then show up in the muon detector. While this isn’t a “fake” in that the wrong particle is identified as a muon, it associates a muon or muons with a process
that did not directly produce any. To address this issue we then calculated the misidentification rate for muons.

To perform the calculation, a source of pions (the chief offender of misidentification) was required. Since the D* decays into the D^0 and a pion, we used this process as our source. The method was very similar to the one used for the efficiency calculation, using reconstructed mass plots both with and without muon likelihood requirements to calculate the probability that a pion was misidentified as a muon either by making it to the detectors or by decaying into a muon. The misidentification rate and the associated error were calculated as follows.

\[ misid = \frac{N_1}{N_0} \]

\[ \sigma_{misid}^2 = \left( \frac{misid}{N_0} \right)^2 \left[ \sigma_{N_1}^2 + \left( \frac{N_1}{N_0} \right)^2 \sigma_{N_0}^2 \right] \]

\[ N_1 = n_{1s} - \frac{1}{2} n_{1b} \quad N_0 = n_{0s} - \frac{1}{2} n_{0b} \]

\[ \sigma_{N_1}^2 = n_{1s}^2 + \frac{1}{4} n_{1b}^2 \quad \sigma_{N_0}^2 = n_{0s}^2 + \frac{1}{4} n_{0b}^2 \]

As in the efficiency calculation, the values of N_1 and N_0 were calculated using sideband subtraction using Sideband.C. The misidentification rate was then plotted against muon likelihood for varying values of several variables, in the same way as the efficiency calculation.

Between the efficiency and misidentification analysis scripts, hundreds of histograms were created which will allow us to observe the behavior of the
detectors as various parameters are adjusted. This will allow for optimization of search criteria to get the best performance while discarding the least amount of data.

Implementation

The code that makes the above calculations possible is a combination of several scripts, all of which were designed to run in the object-oriented computing framework used by CDF called ROOT. The parts of the code that retrieve data from the CDF computers, turning raw information into event candidates with track information, are simply modified versions of existing code. We took sample analyses that we obtained from Mark Mattson’s webpage and tailored them to the specific decays we were working with. These became JPsiAna.cc and DsDPiAna.cc, the code that we used to fill n-tuples with the necessary data for the calculations we wished to perform. Since the goal is to optimize the analysis, it was necessary to find out how the misidentification and efficiency rates vary with parameters such as momentum and direction. This was done chiefly by JPsiEffvsLkhdvs.C and DsDPiMisIDvsLkhdvs.C, original scripts designed to generate histograms that plot efficiency or misidentification rate against muon likelihood for a given value of some other variable (which was passed as an input parameter). These scripts work on the output of JPsiAna.C and DsDPiAna.C, which came from templates for histogram creation built into ROOT. They create histograms from the data returned by JPsiAna.cc and DsDPiAna.cc (which are called from the scripts runJPsi.C and runDsDPI.C respectively). These histograms, most of them two dimensional, contain the
information necessary to make plots of efficiency or misidentification rate against muon likelihood for a specific range of some other variable. This is what JPsiEffvsLkhdv.C and DsDPiMisIDvsLkhdv.C were written to do. These scripts generate series of histograms, the total number of which is determined by how many bins JPsiAna.C and DsDPiAna.C created in the other variable. The names “JPsiEffvsLkhdv.C” and “DsDPiMisIDvsLkhdv.C” end with “vs” because each one can accept a TString input that will determine what other variable to use, eliminating the need for a new script for every new variable.

Experiments must always take into consideration their own limitations, and the work done this summer will hopefully help to explicitly quantify some of the limitations of this experiment. There is still more work to be done though because the efficiency of the muon detectors and the misidentification of pions do not even constitute the greatest source of error in the search for $D^0 \rightarrow \pi \pi$. This is work that I will continue to do during the upcoming school year.