Monte Carlo Simulation of $\Lambda_c^+$ and $\Xi_c^+$
Lifetime Measurements Using an Asymmetric $e^+e^-$ Collider

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Abstract

A Monte Carlo study was done to understand the effect that a moving center of mass would have on the precision of the measurement of the lifetime of the $\Lambda_c^+$ and $\Xi_c^+$. By writing a code to simulate the setup at BaBar where the electron beam and positron beam collide at unequal energies, we hope to see the $\Lambda_c^+$ and $\Xi_c^+$ travel further on average in the lab frame before decaying, thus making their lifetimes easier to measure. A generator level Monte Carlo program was written in C++ that simulates the production and decay of the two charmed baryons that we are interested in, the $\Lambda_c^+$ and the $\Xi_c^+$. The code applies a Lorentz Transformation to all the particles produced in the $e^+e^-$ collisions and catalogs their momenta in the lab frame, momenta in the center of mass frame and lifetimes (among other things). The code then writes this information to a file that can be read by a program called “Mn_Fit.” In this program, the data generated by the code was analyzed to see whether or not the boosted momentum would really improve the measurement of the $\Lambda_c^+$ and $\Xi_c^+$ lifetimes.

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1 Introduction

Of the hundreds of sub-atomic particles discovered by high-energy physicists, the vast majority are unstable. Some of these unstable particles may last a full second before they decay into different particles. Others only live for about $10^{-17}$ seconds. This span of time is to one second as a second is to the age of the universe!\footnote{Using cosmologists’ assumption that the universe is approximately 15 billion years old.} Needless to say, measuring such an infinitesimal lifetime is very difficult to do precisely. The most common way to approach such a measurement requires several steps.

The first step in measuring a particle’s lifetime is to produce the particle. Subatomic particles are produced in many different particle accelerators all over the world by smashing electrons, protons or other particles into stationary targets or into each other. The particles whose lifetime we wish to measure, the $\Lambda_c^+$ and $\Xi_c^+$, are within the energy domain of the Stanford Linear Accelerator Center (SLAC) and can therefore be produced there through the collisions of electrons with their anti-matter counterpart, positrons. Once the particles have been produced, they have to be “seen” in order for us to gain any knowledge from their presence. The tool that physicists use for such a task is a particle detector. The BaBar detector at SLAC is an example of such a tool. It is approximately six stories tall and is made up of a silicon vertex detector, a drift chamber, a particle identification system, a CsI electromagnetic calorimeter, and a magnet with instrumented flux return. Among other things, the detector is capable of measuring the mass, momentum and decay distance of the particles that it detects. However, the detector has no “clock” and therefore cannot directly measure a particle’s lifetime. But since the detector can measure how far the particle went before decaying and how fast it was going, its lifetime can be extracted fairly easily using

$$L_{lab} = \frac{P_{total}}{\text{Mass}} \tau_c$$  (1)

Where $L_{lab}$ is the decay length of the particle in the lab frame, $P_{total}$ is the total lab frame momentum, Mass is the particle’s mass and $\tau$ is the lifetime for that particle.

The problem with this method is that the distances that these particles travel is often extremely small, of order 100 microns, while detector resol-
tions are around 200 microns. Trying to measure this decay distance would
be like measuring the length of a pencil with a non-etched ruler. Clearly
it is impossible to make a good measurement of something unless the mea-
suring tool is smaller than the object being measured. Without a precise
measurement of the decay distance, we cannot get a precise measurement
of the lifetime, so increasing the particle’s decay distances would prove very
valuable.

At SLAC something quite different is being done from other acceler-
ators that either use stationary targets or two beams of equal energies. For
the BaBar experiment, SLAC is colliding an electron beam with a positron
beam, but the beams have different energies. The electron beam is set around
9.0 GeV while the positrons only have about 3.1 GeV. This energy differ-
ence means that there is also a momentum difference since the electron and
positron have the same mass. We think that measuring the lifetime of the
$\Lambda_c^+$ and $\Xi_c^+$ at BaBar will be made easier because the moving center of mass
will allow the $\Lambda_c^+$ and $\Xi_c^+$ to travel further before they decay.

2 Processes

2.1 Generator Monte Carlo

The first step in the generation of the Monte Carlo data was to learn the
basics of C++. A very simple program that took uniformly distributed
random numbers and converted them to a poisson distribution was modified
to convert the uniform random numbers to an exponential distribution that
had a mean set at the known $\Lambda_c^+$ or $\Xi_c^+$ lifetime. Each random number from
that exponential distribution was arrayed such that each event had a number
drawn from an exponential associated with it. This number was the particle's
generated lifetime.

Next, an arbitrary number, 2.0 GeV, was chosen as the total center of
mass momentum of the particles being modeled. This total momentum was
split into three separate x, y and z components using a spherical coordinate
transformation so that the particles were being produced isotropically in the
center of mass frame. Each of these components of momentum was placed in
a separate array. Later on the total center of mass momentum was changed
from being just a fixed number, 2.0, GeV to resemble a known momentum
distribution for $e^+e^- \rightarrow X\overline{X}$, where X represents any baryon. The Monte
Figure 1: Total center of mass frame momentum for the $\Lambda_c^+$ after using the rejection method.

Carlo method of rejection was used to get the desired momentum spectrum. To do this, the maximum allowed momentum for a $\Lambda_c^+$ or $\Xi_c^+$ in the lab frame was calculated and transformed back into the center of mass frame. The range from zero up to this maximum center of mass frame momentum was subdivided into twenty bins that each had a number between 0 and 1 assigned to them. Higher values were assigned to bins that represented higher probabilities in the desired momentum distribution. For every event a random number was generated. If this random number was less than the number assigned to the bin that the event fell into, the event was accepted. If the random number was greater than the bin’s number, the event was rejected. This step reduced the efficiency of the code to about 85% but gave the desired shape shown in Figure 1.

Since the energy of the electron and positron beams SLAC were not equal for the BaBar experiment, the center of mass of the collisions between electrons and positrons was moving. As a result, the $z$ component of each events’ momentum that was generated had to be boosted into the lab frame via the Lorentz Transformation (the $x$ and $y$ components of momentum were un-
affected because it was assumed that the beams collided head on). The following equation was used to boost the z component of the $\Lambda_c^+$'s and $\Xi_c^+$'s momentum into the lab frame.

$$p_{z,ab} = \gamma(p_{z,CM} + \beta E_{CM})$$

(2)

Where $\beta$ and $\gamma$ refer to the center of mass, not to each individual particle, and are equal to 0.4852 and 1.1437 respectively. $p_{z,ab}$, $p_{z,CM}$, and $E_{CM}$ are the z component of the lab frame momentum of each particle, the z component of center of mass momentum of each particle and the center of mass energy of each particle respectively.

After applying the boost, there were several possible outcomes for each event. In some events the $\Lambda_c^+$ or $\Xi_c^+$ was produced heading mostly in the negative z direction. When the boost was applied to these events, the total momentum in the lab frame was less than the total momentum in the center of mass frame. This situation is much like throwing a baseball backwards off of a moving truck, where the truck represents the center of mass and the baseball is our $\Lambda_c^+$ or $\Xi_c^+$. To an observer on the side of the road, the baseball would be traveling slower than it would if the person on the truck had just held the ball in their hand. Another possibility after the boost, the one that we want to occur more often, was the particles’ total lab frame momentum was greater than their center of mass frame momentum. This would compare to the person throwing the baseball forward off of the moving truck. After this boost on the z component of momentum, approximately 85% of the particles took possibility two and showed an increase in total momentum.

After boosting the z momentum for each event, everything that was needed to calculate the decay distances of the $\Lambda_c^+$ and $\Xi_c^+$ was available. The decay distances were calculated using equation 1. Figure 2 shows a plot of the decay distances in the center of mass frame with the lab frame decay distances overlayed. Note that the height of the bins representing short decay lengths are significantly lower for the lab frame than the center of mass frame. Additionally, the bins further out to the right which represent longer decay lengths are higher for the lab frame.

2.2 Event Selection

After the generic Monte Carlo data was generated it was necessary to eliminate any background decays that could be changing the decay length mea-
Figure 2: Decay distances for $\Lambda_c^+$ in the center of mass frame (dotted line) and lab frame (solid line)
measurements. In other words, we needed to make certain that the $\Lambda_c^+$ and $\Xi_c^+$ were coming directly from the $e^+e^-$ collisions and not from the decay of some other particle. The biggest effect comes from the decay

$$B \rightarrow \Lambda_c^+ X$$

and,

$$B \rightarrow \Xi_c^+ X$$

where $X$ is any particle or particles that are allowed by the conservation laws. These decays were extremely prevalent because of the way the beam energies were chosen at BaBar. The total lab frame energy of the beams was 12.1 GeV. When this energy was transformed into the center of mass frame, it came out to be around 10.58, the mass of the $\Upsilon(4s)$. This specific energy was chosen to maximize B meson production at SLAC since each $\Upsilon(4s)$ decays into two B mesons. Since the code assumes that all particles were produced at one point, we could not use any $\Lambda_c^+$ or $\Xi_c^+$ that came from a B because the B would travel a significant distance before decaying into a $\Lambda_c^+$ or $\Xi_c^+$ and would add to the measured decay distance. Since B mesons have a relatively long lifetime, $1.56 \times 10^{-12}$ seconds, and there were a lot of them, they could have a big effect on the resultant decay distance measurement.

Kinematics was used to find the exact placement of the cut that would eliminate all B meson events from the data sample. If the $\Lambda_c^+$ or $\Xi_c^+$ came from a B meson that was at or very nearly at rest,\(^2\) there would be a maximum momentum that the $\Lambda_c^+$ or $\Xi_c^+$ could have. This maximum momentum would only be achieved when the decay from the B meson was as light as possible. For the $\Lambda_c^+$ the lightest decay possible was

$$B^0 \rightarrow \Lambda_c^+ \bar{\nu}$$

and the maximum lab frame momentum was 4.0065 GeV/c. For the $\Xi_c^+$ the lightest decay possible was

$$B^0 \rightarrow \Xi_c^+ \bar{\nu}$$

and the maximum lab frame momentum was 3.94212 GeV/c.

To apply these cuts an $x$ distribution was formed. Figure 3 shows the $x$ distribution for the $\Xi_c^+$. An $x$ distribution such as the one in Figure 3
\(^2\)This is a good assumption because the B mesons are so heavy that there is just enough energy from the $e^+e^-$ collisions to produce them, via the $\Upsilon(4s)$ decay, but not to give them much kinetic energy.
Figure 3: $x$ distribution for the $\Xi_c^+$ in the lab frame before the cut.

Figure 4: $x$ distribution for the $\Xi_c^+$ in the lab frame after the cut.
is made by taking a momentum distribution and normalizing it so that it goes from 0 to 1. Kinematics was used to find the maximum momentum that the \( \Lambda_c^+ \) or \( \Xi_c^+ \) could have when coming from an \( e^+e^- \) collision. For the \( \Lambda_c^+ \) it was assumed that \( e^+e^- \rightarrow \Lambda_c^+\Lambda_c^- \). In this case, the maximum momentum for the \( \Lambda_c^+ \) is easily found because there are only two bodies involved. The maximum momentum for a \( \Lambda_c^+ \) coming from \( e^+e^- \) was 8.40114 GeV/c. For the \( \Xi_c^+ \) it was assumed that \( e^+e^- \rightarrow \Xi_c^+\Xi_c^- \). Since this is also a two body decay, the calculation was quite simple. The maximum momentum of the \( \Xi_c^+ \) was 8.29717 GeV/c. These maximum momenta values were used to normalize the lab frame momentum distributions. Next, the maximum momentum from a B meson for a \( \Lambda_c^+ \) or \( \Xi_c^+ \) was divided by the normalization momentum for a \( \Lambda_c^+ \) or \( \Xi_c^+ \) to give the x value for the cut. The cut rejected all events for which the x value was less than the maximum allowed x value when the \( \Lambda_c^+ \) or \( \Xi_c^+ \) came from a B meson, and kept any event whose x value was greater than the maximum allowed x value from a B meson. After this cut was applied, all B meson events were eliminated and the efficiency of the code was reduced to about 19%.

3 Results

The goal of this study was to determine whether or not carrying out the lifetime measurements of the \( \Lambda_c^+ \) and \( \Xi_c^+ \) at BaBar would improve the precision, and by how much. The first step in this process was completed based on the knowledge that 85% of the particles have an increased momentum in the lab frame due to the boost. Also, given the beam energies used at BaBar, these decay distance increases are not insignificant but are of order 16% improvements depending on the run. These two findings coupled with the fact that BaBar could have as much as ten times the data that was available at CLEO makes it very reasonable to conclude that the precision of the lifetime measurements of the \( \Lambda_c^+ \) and \( \Xi_c^+ \) will be improved. Figure 3 shows plots of the decay distances for the \( \Lambda_c^+ \) and \( \Xi_c^+ \) in the center of mass and lab frames. In the upper right hand corner of each set of histograms is the mean and R.M.S. for each histogram. Note the substantial increase between the top row (center of mass frame) and the bottom row (lab frame).
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**Figure 5:** Decay distances for the $\Xi^+_c$ in the center of mass (left) and lab (right) frames. Note the increased mean and R.M.S. for the lab frame plot.
Figure 6: Decay distances for the $\Lambda_c^+$ in the center of mass (left) and lab (right) frames. Again, note the increased mean and R.M.S. for the lab frame plot.
4 Future Work

There is still much to be done on this project. As of now the code only does generator level Monte Carlo, meaning it does not take into account any smearing effects that are introduced by the detector. All of the quantities assigned to each event such as momentum, energy, decay distances etc. were assumed to be measured perfectly. To get a better understanding of what is really going on, errors on these measurements will need to be incorporated.

Another task for the future is to look at BaBar’s Monte Carlo package. BaBar’s Monte Carlo package contains far more information than could be produced on the generator level. Analyzing their Monte Carlo data would give better results because it would incorporate detailed effects from the BaBar detector that we cannot model here.

5 Acknowledgments

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