STUDIES OF ENERGY LOSS AND MULTIPLE SCATTERING FOR A B-FACTORY SILICON DETECTOR.
STUDIES OF ENERGY LOSS AND MULTIPLE SCATTERING FOR A $B$ FACTORY SILICON DETECTOR

ALAN BREAKSTONE
University of Hawaii, Honolulu, USA

ABSTRACT

Using the GEANT detector simulation program, I studied the effects of the material in a $B$ factory beam pipe and silicon detector on the mass resolution for three processes which produce low momentum charged particles. In particular the effects of multiple Coulomb scattering and fluctuations in energy loss were simulated. The main degradation in mass resolution is due to multiple scattering, with fluctuations in energy loss of secondary importance.

1. Introduction

There has been some concern that the material in the beam pipe and silicon detector will seriously degrade the reconstruction of events containing low momentum particles. In particular, at the time of these studies, there was no adequate simulation of the effects of fluctuations in the energy loss of low momentum particles in the ASLUND simulation. The GEANT detector simulation program does have an adequate simulation of multiple Coulomb scattering and energy loss, so provides a way to study these effects. In particular, I studied the degradation of the mass resolution for the following processes which produce low momentum charged pions:

1) $\bar{B}^0 \rightarrow D^{*+} \mu^-$
2) $B^0 \rightarrow D^{*+} D^{*-}$
3) $\tau^- \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^- \nu$

where $D^{*+} \rightarrow D^0 \pi^+$ and $D^0 \rightarrow K^- \pi^+$ are the only decays allowed.

2. Details of the Simulation

Since I did not have a $B$ factory kinematics package integrated into the GEANT simulation, I used the expedient of getting momentum four vectors for the various particles from the ASLUND simulation. These were provided by Art Snyder for processes 1) and 2) and by Helmut Mariske for process 3). The four vectors provided were those generated, not smeared by any detector resolution effects. Thus, by combining the appropriate daughter particles, one would get the exact mass of the parent particle.

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The detector simulation had only two objects, the beam pipe and the silicon detector. The beam pipe inner radius was 26 mm. Then followed a 25 μm copper liner, 0.5 mm of beryllium, an air gap of 1 mm, and another 0.5 mm of beryllium, for a total thickness at normal incidence of 0.004 radiation lengths. The air gap is meant to simulate a possible high pressure gaseous helium coolant. If, instead, water were used, it would increase the overall thickness to 0.007 X₀. The silicon detector simulated was very similar to that given by Vera Lüth in reference [1], figure 2. It has three barrel layers, four forward endcap layers, and two backward endcap layers. The endcap silicon modules are arranged in a lampshade-like arrangement with a 4° angle to the beam axis. The thickness of the silicon was varied from 300 to 600 μm (0.0032 to 0.0064 X₀) per layer to study the material thickness dependence of the mass resolution. No attempt was made to model support structures nor readout chips, cables, etc.

3. Results of the Simulation

The first result I present is a check to see that the simulation of the energy loss is reasonable. Figure 1 shows the distribution of energy loss for 100 MeV/c π⁺ and 200 MeV/c K⁻ normally incident on the beam pipe and barrel silicon detector. The distributions show the expected Landau shape, indicating that they represent a reasonable simulation of energy loss. The average value and standard deviation of these distributions serve as a measure of the energy loss and fluctuation in energy loss so one can see their behavior as a function of momentum and polar angle as given in figure 2. Pions with momenta less than about 50 MeV/c do not get out of the beam pipe, nor do kaons with momenta less than about 150 MeV/c. As expected the energy loss decreases monotonically with increasing momentum. The typical fluctuation in energy loss for pions in the momentum range from 100 to 300 MeV/c is 0.5 MeV, increasing somewhat with decreasing momentum below 100 MeV/c. There is also an increase in both the energy loss and its fluctuations with increasing polar angle, except for the region around cos θ = 0.7, where there is a transition from the barrel to endcap silicon detector, such that the particles are more nearly normally incident on the barrel modules. To give a feel for how much the fluctuations in energy loss affect the momentum resolution, I show in figure 3 the fractional error in momentum (Δp/p) as a function of momentum for pions and kaons at various polar angles. Below 100 MeV/c, this may dominate other sources which degrade the momentum resolution.

After verifying that the energy loss simulation was reasonable, I studied the mass resolution for various combinations of particles for the above three processes. Because one can independently turn on or off multiple scattering and energy loss, I was able to determine the effects of each. First I turned off both to verify that the resolution was perfect, as it should be if the simulation is not putting in any extraneous effects. Then, by turning on each in turn, I determined that actually it is the multiple scattering which dominates the mass resolution, although the energy loss contribution is by no means negligible.

Figure 4 shows the mass distribution for the appropriate combinations of particles to form D⁰ and D⁺⁺ mesons for process B⁺ → D⁺⁺D⁻, including the effects
of multiple scattering and energy loss. Only the correct combinations are used. On the average, particles from all three processes go through 1.9% $X^0$ for the case of 300 $\mu$m thick silicon and 3.0% $X^0$ for 600 $\mu$m thick silicon. Tables 1 and 2 give the averages and standard deviations of these mass distributions for processes $B^0 \to D^{*+}\mu^-$ and $B^0 \to D^{*+}D^{*-}$, respectively. Also, for $B^0 \to D^{*+}D^{*-}$, I give the mass of the $D^{*+}D^{*-}$, which should add up to the $B^0$ mass. The degradation of the mass resolution for the $D^* - D$ mass difference is about 1 $MeV/c^2$ for 300 $\mu$m thick silicon and about double that for 600 $\mu$m thick silicon.

For $\tau^- \to \pi^-\pi^+\pi^-\pi^+\pi^-\nu$ the concern is that the effects of multiple scattering and energy loss fluctuations will degrade the measurement of the $\nu$ mass, so the only data generated was near the endpoint of the mass spectrum. In this case I compare, on an event-by-event basis, the 5 pion mass based on the generated momenta minus that based on the momentum vectors after traversing the beam pipe and silicon detector. For 300 $\mu$m thick silicon, the average mass difference is 1.7 $MeV/c^2$ and the width (standard deviation) of the mass difference distribution is 4.3 $MeV/c^2$, whereas for 600 $\mu$m thick silicon, the average is 2.0 $MeV/c^2$ and the width is 6.0 $MeV/c^2$. Thus, the energy loss leads to an average mass loss of about 2 $MeV/c^2$, but the combined effects of multiple scattering and energy loss fluctuations lead to a broadening of the mass resolution ranging from about 4 to 6 $MeV/c^2$, depending on the silicon thickness.

Table 1

<table>
<thead>
<tr>
<th>Combination</th>
<th>Silicon Thickness ($\mu$m)</th>
<th>Average Mass ($MeV/c^2$)</th>
<th>Mass Error ($\sigma$) ($MeV/c^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^-\pi^+$</td>
<td>300</td>
<td>1862.7</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>1862.2</td>
<td>2.6</td>
</tr>
<tr>
<td>$K^-\pi^+\pi^+$</td>
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<tr>
<td></td>
<td>600</td>
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<tr>
<td>$D^* - D^0$</td>
<td>300</td>
<td>145.6</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>145.7</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Table 2
Average mass and mass resolution of mass combinations for $B^0 \rightarrow D^{*+}D^{*-}$, $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$. 

<table>
<thead>
<tr>
<th>Combination</th>
<th>Silicon Thickness ($\mu$m)</th>
<th>Average Mass (MeV/c^2)</th>
<th>Mass Error ($\sigma$) (MeV/c^2)</th>
</tr>
</thead>
<tbody>
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<td>1.9</td>
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<tr>
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<tr>
<td>$D^* - D^0$</td>
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<tr>
<td></td>
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<tr>
<td>$D^{<em>+}D^{</em>-}$</td>
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<td>5270.7</td>
<td>4.6</td>
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<tr>
<td></td>
<td>600</td>
<td>5266.9</td>
<td>4.8</td>
</tr>
</tbody>
</table>

4. Conclusions
The effects of energy loss fluctuations and multiple scattering due to the material in a B factory beam pipe and silicon detector have been modeled using the GEANT simulation package for three processes which produce low momentum charged particles. Their effect, of which the multiple scattering is the main contribution, lead to a broadening of the mass resolution for $D^0$ and $D^*$ of 2 to 3 MeV/c^2 and roughly 1 MeV/c^2 broadening of the $D^* - D^0$ mass difference. For the $\tau$ endpoint, the effect is larger, roughly 4 to 6 MeV/c^2.

REFERENCES
FIGURE CAPTIONS

1) Energy loss distribution for 300 particles traversing the beam pipe and barrel silicon detector at normal incidence (cos $\theta = 0$) for a) 100 MeV/c $\pi^+$ and b) 200 MeV/c $K^-$. The average and standard deviations of these distributions are also shown. Note the suppressed zero on the horizontal axis.

2) a) Average energy loss and b) fluctuations in energy loss as a function of momentum for charged pions at various polar angles and charged kaons at normal incidence. The transition from the barrel to endcap silicon detector occurs at around $\cos \theta = 0.7$.

3) Fractional error in momentum due to energy loss fluctuations as a function of momentum for charged pions at various polar angles and for charged kaons at normal incidence.

4) Mass combinations a) $K^-\pi^+$, b) $K^-\pi^+\pi^+$, and c) $D^{*-} - D^0$ for the process $B^0 \rightarrow D^{**} D^{*-}$. The results for two silicon thicknesses are shown. No incorrect combinations are used. The averages and standard deviations of the distributions are given in Table 2.
Figure 1

Beam Pipe: 25μm Cu + 1mm Be
Silicon: 300μm/Layer × 3 Layers
No Silicon Supports

π⁺
cos(θ)=0.0
p=0.1 GeV/c

⟨E_{loss}⟩=1.59 ± 0.02 MeV
σ_{E_{loss}}=0.27 ± 0.01 MeV

K⁻
cos(θ)=0.0
p=0.2 GeV/c

⟨E_{loss}⟩=3.79 ± 0.04 MeV
σ_{E_{loss}}=0.64 ± 0.03 MeV
Figure 2
Figure 3
Figure 4