MONTE CARLO CHECKS

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2003 REU: Nevis Laboratories
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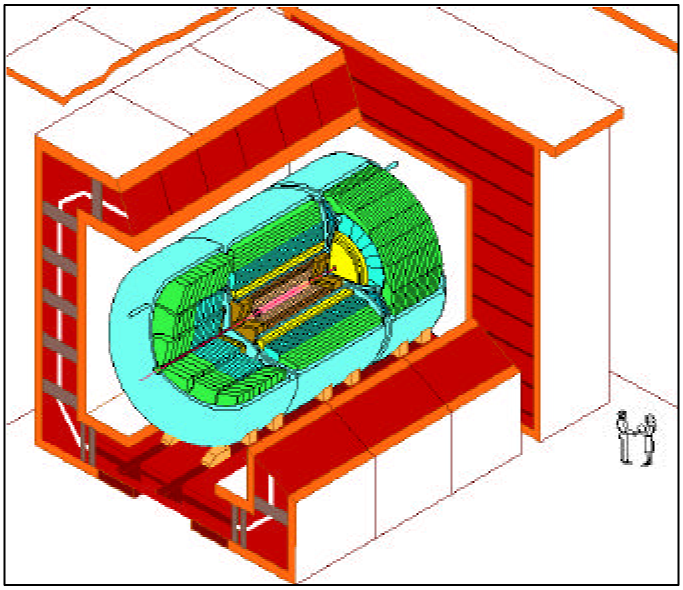
Abstract: In this paper I seek to explain what I accomplished this summer as part of the National Science Foundation (NSF) Research Experience for Undergraduate (REU) program at Columbia University. To do this I will give background on D∅, the experiment with which I worked, discuss Monte Carlo generation, and give examples of my contribution to the group.

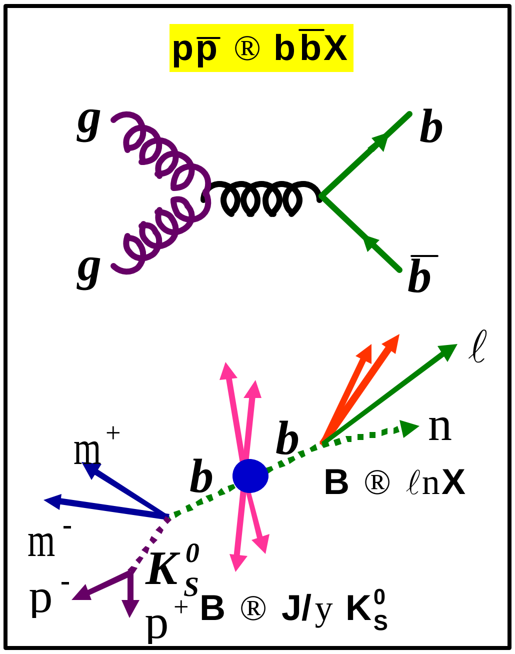
I. Introduction – Over the course of this summer I had the privilege of participating in the National Science Foundation's Research Experience for Undergraduates Program. In this unique program undergraduates in all branches of science are placed throughout the country at different universities to get a taste of actual research science. This summer I was accepted by Columbia University (New York, NY) to work at Nevis Laboratories on High Energy Particle Physics. My actual work was with Dr. Hal Evans and the D-Zero collaboration, specifically in B-physics. In the next few pages I will give a brief overview of the D∅ experiment and B-physics, tell you about the value of Monte Carlo generation, and give you examples of the analyses I worked on in my ten weeks of employment.

II. D-Zero – At Fermi National Laboratory in Batavia, IL some of the most exciting new physics in the world happens every day. To be truthful, this physics isn't something new that a bunch of Ph.D's just decided to make happen, it the most basic science of all, that of fundamental particles. It is here in conjunction with the Tevatron high-energy proton-antiproton collider that the D-Zero (D∅) detector makes it home. The D∅ collaboration consists of more than six hundred and fifty scientists and engineers from seventy-three institutions in eighteen countries and boasts two particle discoveries: the bottom quark in an upsilon by Lederman in 1977 and the top quark along with CDF in 1995. Beyond the amazing physics analysis that comes out of this project, the detector itself is a marvel of science and engineering. After protons and anti-protons have been properly accelerated to 1960 GeV in opposite directions within the four-mile beam pipe they are set to intersect in the D∅ collision hall. To the right is a diagram of the D∅ detector illustrating its many complex layers and immense size. When these particles collide, especially in hard scatters, which I will explain later, hundreds of new particles are created and shower out to be met by three main detector subsystems. First is the silicon track trigger that has only a thirty-inch radius, but gives very precise tracking information. Next, there is an electromagnetic calorimeter filled with liquid argon that detects energy deposits of passing particles. Lastly, a detection system exists layered with solid iron magnets in an attempt to slow down, deflect, and detect the most persistent escaping particles, muons. Between these three major detection techniques and many more subtle systems there are nearly 800,000 electronic channels detecting



2.5 million collisions per second. Along with the basic detection there are also trigger systems that choose on a number of time scales which events are "interesting" and should be kept and which can be discarded.

At the D∅ detector the main physics emphases are in top quark physics, electroweak interactions, quantum chromo-dynamics (QCD), physics beyond the standard model, and bottom physics, the latter of which I worked with. A hard scatter, or head on collision, between the proton and anti-proton that produces bottom (b) quarks characterizes B-physics. The bottom quark, one of the six quarks currently allowed by the Standard Model, was discovered at FNL in 1977 and is intentionally "created" and studied for a number of reasons. First of all, it is the most massive of the easily produced hadrons in a field where more mass equates more energy and also more new physics. B- hadrons are also associated with electroweak symmetry breaking or CP violation. These particular collisions are also great places to study the CKM matrix and QCD along with perturbation. Here is a diagram of a B-physics event.

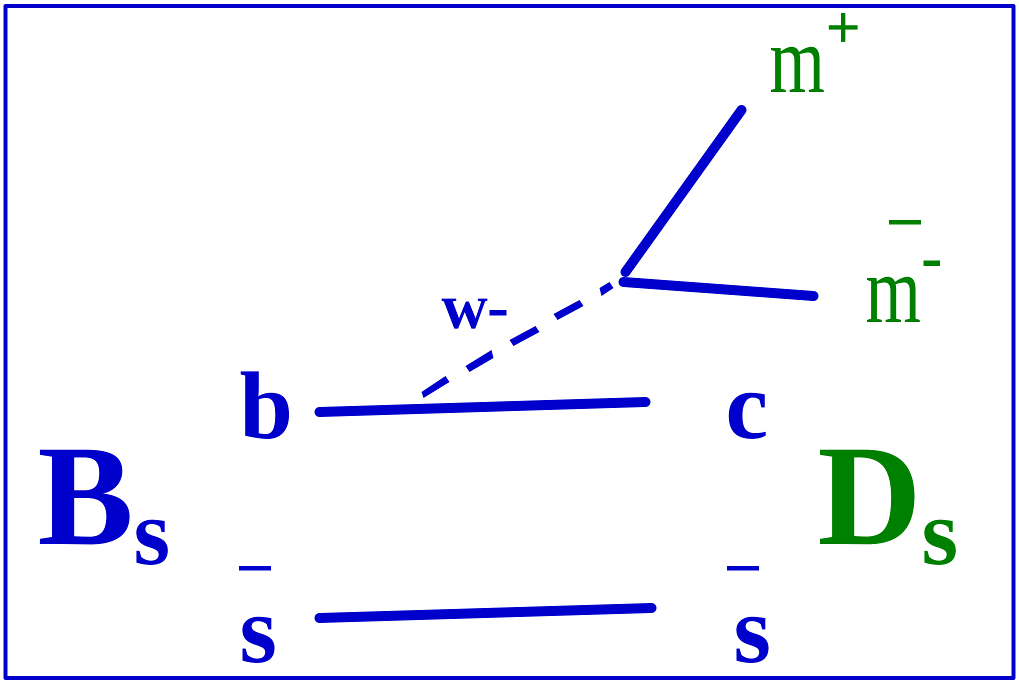


While the detector and true events are necessary for the discovery of new physics there is another crucial step in the analysis process that deals with artificial decays. Monte Carlo (MC) generation is a technique used in many branches of science where large samples of data, whether they are physics or biology related, are simulated as a source of preparation, cross checking, and further study. These samples help those that wish to investigate real data design their analyses for optimal performance with regards to signal and background distinction, cut efficiency, and many other subtleties. Due to the fact that these MC events are generated with control over their decay modes and characteristics they aid in the probing of phenomenological processes that have not yet been "seen" by the detector but are guided by certain known or theorized principles.

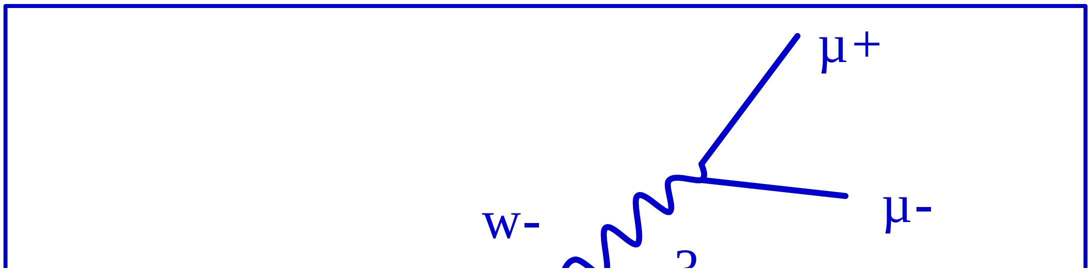
At D∅ there are four main steps to Monte Carlo production being generation, detector simulation, and the parallel steps of reconstruction along with triggering. In generation, the basic decay is created with the simulation of a hard scatter (main head-on collision), the underlying event (the other pieces of the primary particles), parton production, hadronization, and eventually all the unstable particle decays. It is here that pre-selection cuts are made and someone looking for only a certain decay, ie. B_S -> D_S μ- X, can set variables and keep only the events he/she is interested in. The next step is that of detector simulation where the decay from the previous process is translated into what the detector would actually "see" in terms of energy deposits and read out to the electronics. The two final steps that work in conjunction are those of reconstruction and triggering. Reconstruction is just what its name entails, the work of calculating and piecing together things like tracks and jets from the event. Triggering is a varied level selection process incorporated into the detector and a means of paring down millions of events into a manageable and interesting collection. Putting Monte Carlo data through triggering is another way to make sure it truly parallels events that would actually come out of the detector. The final, unofficial, step to Monte Carlo is independent verification where the sample is analyzed to make sure that it includes what it claims to include and can be used for study.

III. My Work – The course of my work revolved around the systematic checks of three Monte Carlo samples generated by others in my group. These samples were all B-hadron events with different decay product outcomes. Here are diagrams of the decays in question.

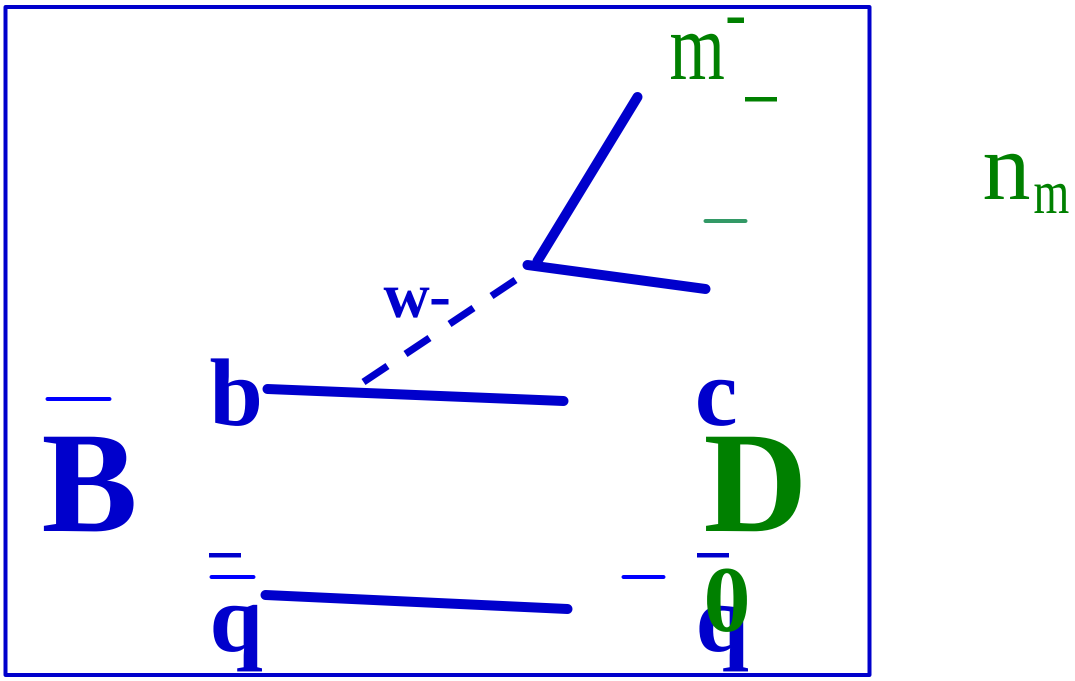
B_s -> D_s μ- X
11,000 events



B -> K* μ μ **10,000 events**

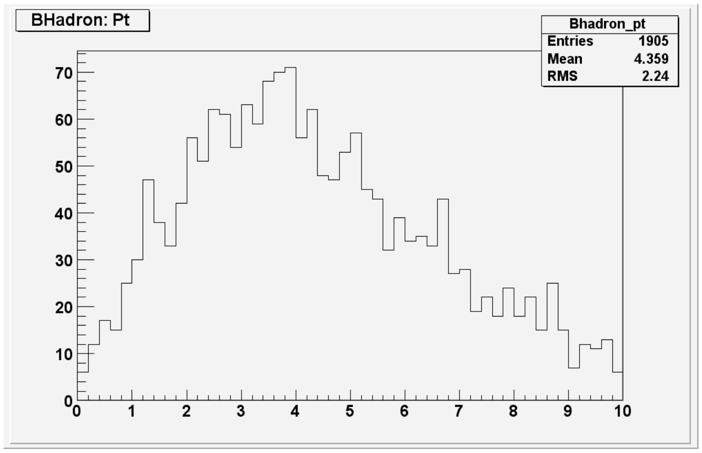


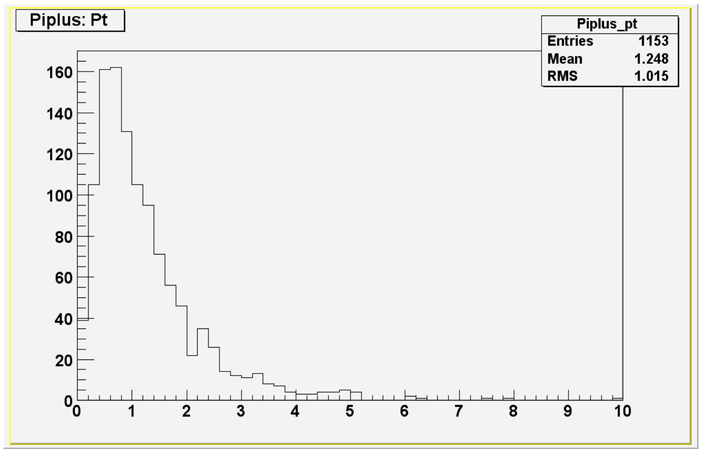
B -> D^0 μ- X **1000 events**



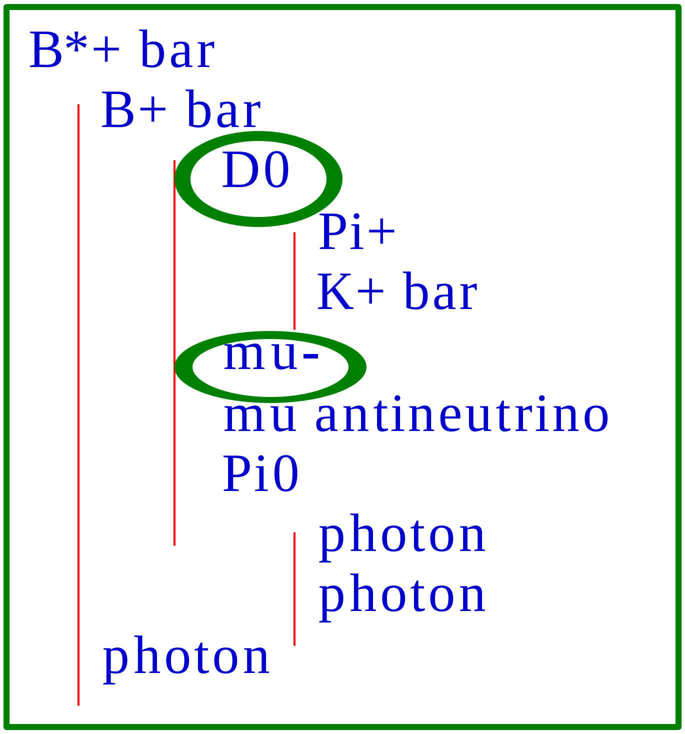
The goal for my summer REU project was basically to investigate these samples and verify that the processes supposedly happening were indeed. I was also to write tools or functions that would enable those doing analysis to match particles with their reconstructions and trace lineage. I went about my checks in a number of ways including identification, plotting characteristic variables, and confirming decay modes through lineage. In every event there exist hundreds of thousands of particles, each with their own data set of variables such as momentums and directions. One of the most important of these variables is the “pdgid” or particle id number. A very complex system is in place for D∅ that assigns every possible particle an identification number based on its type and composition with the antiparticles being the negative of that number. By running code then that recognizes a particle with a pdgid of 421, for example, you can look at all the D^0 hadrons in an event.

After we can pick out particles we are interested in we are then able to plot certain characteristic variables to see that things are in order. For all of the decays I studied I looked at variables such as transverse momentum and the angles phi and eta of detection. Transverse momentum for one is to have a peak value that gets lesser further down the decay chain as conservation of momentum is observed for decaying particles. Here are three diagrams that clearly illustrate the transfer of momentum from a B Hadron to its D^0 daughter and Pi^{+} granddaughter.

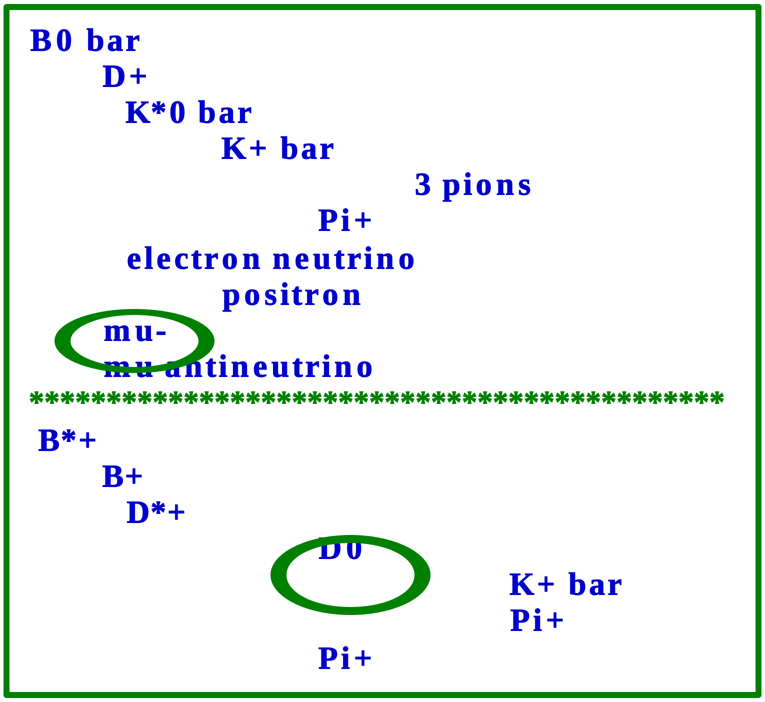




The final step in my MC checks was that of lineage, or tracing what decays particles came from, based on simple logic and particle id numbers. As I mentioned earlier, if you were to output the most basic information you have about all of the particles in an event you would get a list of something like nine hundred thousand pdgids. It is relatively simple to write a recursive code based on vertex information that puts these particles in order and outputs their lineage in a reasonable fashion. Here is an example of a decay, which happens to be correct, with the vertical lines denoting generation and the particles of interest circled.



With these types of checks in mind I worked through the three samples of Monte Carlo diagrammed earlier and developed my tools. One of my most significant finds happened as I was working on the last sample of **B -> D^0 μ- X.** As a reminder to what I've covered earlier I'll walk you through the abridged process of Monte Carlo generation. When another member of my group created this sample there were millions of events simulated with more than 500 parameters possibly set. Pre-selection was made on decays with both a D^0 hadron and muon occurring in them, hopefully signifying the event we were looking for. After detector simulation, reconstruction, and triggering cuts we were left with a sample of 1000 events. When I ran my checks though only 957 of them passed the lineage test performed with arrays, giving an error of 4.3% in what we thought was a pretty straightforward decay pattern. Here is a trimmed output of one of these failing events with the starred line denoting a break in lineage.



As you can see the D^0 and muon are indeed both in this event, but do not come from the same immediate family. Where we wanted them to have the same parent or grandparent they end up being not related at all, actually coming from opposite sides of the decay. This illustration proves that the careful combing through of these events is necessary if we wish to produce accurate and trustworthy Monte Carlo samples.

IV. Conclusion – After ten weeks of writing C++ code, debugging, recompiling (ad infinitum), and analyzing histograms what have I actually accomplished? Overall, I learned more about particle physics incorporated with D-zero and became familiar enough to navigate my way through their coding system. I further explored my understanding of the program ROOT, which no one ever really knows completely. I developed a system of checking Monte Carlo samples to plot characteristic variables and trace lineage of the decays in question. With regards to my actual contribution to the group, I provided necessary independent verification to ensure that the processes believed to be happening were indeed present in the each of the three samples. For example, even though the 4% error in the B -> D^0 μ- X sample will not have great repercussions, it is important to know it is there and understand how it came about. I feel it is clear that I have accomplished my initial goal of investigation and confirmation of Monte Carlo samples and have had a great summer in the meantime.

V. Acknowledgments – First and foremost, I would like to extend my gratitude to Dr. Hal Evans, my mentor in this project, for his guidance and patience. I would also like to thank the National Science Foundation and Columbia University for sponsoring this incredible program. I believe it is an invaluable experience for undergraduates to see actual research science in action and get a taste for graduate school. One of my group members, Dave Kettler also deserves acknowledgement for answering my programming questions. Lastly, I would like to thank the Physics department and chair, Dr. Jim Dugan, of Hastings College (Nebraska) for the solid physics education and support they've afforded me.