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August 8, 2001

Theoretical motivations for work done with the D0 group at Nevis Laboratories as a part of the REU program

Symmetry considerations have been at the heart of many theoretical advances in physics. If nature is symmetric with regard to some transformation, then this simply means that the initial system and the conjugate system will obey the same physical laws, so forces will interact identically with a particle and its conjugate particle. If symmetry holds, the physical description of all processes in the world and the conjugate world will be exact, and so no physical test will be able to distinguish between the two worlds. Another consequence of symmetry is that any process in the conjugate world will also be a possible physical process in our world. And because anything that can happen in particle physics should happen, symmetry considerations make definite predictions about rates of fundamental particle processes.

Symmetry considerations are such useful physics tools because every physical symmetry is correlated with a conservation law, a statement established by Noether's theorem. The proof for this will not be given here, but it can be intuitively understood in this way: if the physical descriptions of some system and its conjugate system under some transformation X are identical, then one would guess that there was some characteristic of each system which correlates them, since they can be described perfectly by the same rules. Symmetry considerations also give physics a very profound beauty and aesthetic appeal. For example, translational symmetry, which says that if you translated

your system in space it should behave the same, establishes that nature does not prefer any particular point in space over all the others. Conservation of momentum underlies translational symmetry. Conservation laws are the very basis for our physical description of nature, and symmetry considerations can often point us directly to these laws. So the importance of symmetry as a theoretical tool in physics should now be evident.

As an example of a symmetry consideration, one could consider whether or not the mirror image of a process that has been observed in nature is also a possible physics process, or one might ask if the physics of a system would fundamentally change if it were observed backwards with respect to time or if the charge of its constituent particles were changed. The previous transformations are known respectively as mirror symmetry, time reflection symmetry, and charge symmetry. Parity is similar to mirror symmetry expect all three spatial coordinates are reversed. These three are particularly important to physicists because it is believed that CPT is a perfect symmetry in nature. In other words, if you changed the charge, parity, and direction of time in our world, the resulting world should behave according to the same physical rules that our world obeys. So nothing should seem weird or unnatural in our CPT conjugate world. These three symmetry principles have historically also been considered individually.

Of the three, it seems most likely that parity should be symmetric by itself since the mirror image of our world seems to us to be just as ‘natural’ as what happens on the other side of the mirror, but it was observed that nature did indeed have a parity bias. For example, right-handed neutrinos do not exist, although left-handed neutrinos do. Then a temporary consolation came when it was recognized that in some P-violating systems, this asymmetry could be compensated for if the parity transformation was applied

together with the charge transformation; in other words it was thought that although individually charge and parity are imperfect symmetries, CP symmetry might be a perfect symmetry. This was supported by the fact that right-handed anti-neutrinos, which are the CP conjugate of the left-handed neutrino, does exist. Alas, however, CP symmetry was found to be violated in the neutral K system.

The neutral K meson has two decays, one of which is the CP conjugate of the other. If this process were CP symmetric then both of these decays should occur with the same frequency since all physical laws for symmetric systems must be the same. However, experiments have shown that one of the decays occurs more frequently than the other. The CP transformation is theoretically interesting to think about because it basically transforms a particle into its antiparticle. Since nature is not CP symmetric, this means that there is an absolute way to define matter: it can be defined as the decay mode of the neutral K that happens more frequently.

The mechanism through which CP symmetry is broken is a complicated one that is certainly beyond the scope of this paper, and indeed is not even completely understood. Very basically, CP symmetry is broken because there exists a force that interacts differently with a system and its CP conjugate system, thus leading to differing production and decay rates in the two systems.

CP violations is especially intriguing to study because it might also explain why there seems to be a dominance of matter over antimatter in the universe today. At the time of the big bang, an equal amount of particles and antiparticles were created from radiation, so it would seem unavoidable that they would destroy each other. However, because CP violating processes exist, the created particles would have undergone

processes different from the antiparticles, leading to differences in their production and decay rates. That could have led to an excess of matter after the other particles and antiparticles had annihilated. So it seems that CP violation is at least in part responsible for the dominance of matter in our universe today, although it is still not know whether CP violation is big enough to account for all the excess matter in our universe today.

So now that physicists have established that CP symmetry is violated, they would like to be able to measure how big this asymmetry is in any given system. This measurement would be valuable for several reasons. A measure of CP violation will reveal whether the asymmetry is big enough to account for all the matter in our universe today. Understanding the nature of this asymmetry is also very important because it might hint at physics beyond the standard model because right now the reason it is broken is not understood, only the mechanism by which it is broken can be mathematically described. The size of the CP asymmetry could also hint at physics beyond the standard model. New physics theories beyond the standard model make predictions for CP Violation, so measuring the asymmetry might nudge us in the right direction to look for new physics.

Measuring the CP asymmetry in a specific system was at the heart of my summer research at Nevis. I was specifically interested in certain decay modes of the neutral B meson that are particularly useful to make one particular measure of the CP asymmetry. The first problem in designing an experiment to study a decay process of the neutral B meson to specified daughter particles, in our case either pions or kaons, is to be able to somehow isolate particles undergoing this process to study. This process happens inside the DO detector at Fermilab when a proton and antiproton collide, then a gluon from each

interact to form a b bbar pair, then one of these enter into a bound state with a lighter quark to for the meson, which will then decay according to specific branching ratios. This process that we are looking for is rather rare compared to a generic proton-antiproton collision, so most of that data collected is not going to be useful to our study. The other, unwanted data only obscures those infrequent but significant events that we want to study, so often one of the most crucial elements of a study at Fermilab is the filtering of a data set for the information that is important to you. For my project, I wanted to be able to trigger on the specific decay modes that I was interested so that their data could be isolated to study CP asymmetry. My major goal was to find some way to distinguish between pions or kaons originating from the B parent as opposed to pions and kaons coming from elsewhere. Pions specifically are produced in abundance in proton antiproton collisions because the pion is so light, so it is vital to be able to separate the relevant events from the unwanted ones if you want to be able to study this decay mode.

I investigated possible triggers not by working with real data but by working with simulated data. The obvious reason for this is that in a real data set I would not be able to identify the pions that I want to study since that is the very problem of my investigation. More basically though, before one works with real data coming from the actual detector, it is good practice to look at simulated data. Working with simulated data is extremely important to sort of 'calibrate' the analysis that you will be doing with actual data. I used a program called pythia to generate the physics events that happen inside the detector. Pythia basically contains all the physics recipes for what can happen following a proton antiproton collision. Pythia takes certain parameters that you specify, like the initial energy of the collision and certain observational cuts, both of which are determined by

the detector that you are working with. I also specified how I wanted the B meson to decay. Pythia produces a 'random' series of events, based of course on what statistically what happens in nature. Basically, every time that the program encounters a B meson that it has created, it will decay it to the daughter particles that I have specified. If I did not specify how I wanted these B mesons to decay and just let them decay according to the branching ratios of all the possibilities, I would have had to generate considerably more events to get just a few events containing the decay mode that I was interested in since these processes are so rare in nature. This is, of course, how it works when you are working with actual data. If the process that you want to study is infrequent or rare, you simply must let your experiment run for longer to gather more data. Generating events with pythia also takes time, so you typically produce only a small sample at first to verify that your software is working sensibly, and then once this is verified you can generate a much bigger number of events. The final output of pythia stores the chain of particles that it produced from the initial reaction, what their energies are, where their vertices are, and other data the mirrors the data that you would collect in a detector.

Of course, what really makes this software so useful is that is also stores information that you cannot collect from a detector. For example, in this simulated environment, particle identity is know directly rather than deduced from energy considerations, because it is stored as a standard identification number in the final output. Even more important to my study was that in this simulated environment you can directly trace the parentage of a particle, because the chain of particle history is also stored. Thus, you don't have to try to deduce what particle came from which decay by reconstruction. So secluding the pions originating from the B meson from the mass number of pions in

the event is almost trivial in the simulated environment, so then you can study these pions to see what observable features they have different from the other pions in the detector. This is the information you will then use on actual data to deduce which pions come from the B parent in the real physics events in the detector.

Following the initial generation of these events using pythia, I would run the output file through another software package called MCExam, which would weed out any events not containing the decay mode that I was interested in. Finally I would run the output of MCExam thorough another software package called MCAnalyze, which would basically just package the data into an ntuple for easier analysis in root. Small macros can then be written to explore the physics of the processes you are studying.

The main observational that I investigated as a trigger was the transverse momentum. So basically I wanted to see if the transverse momentum spectrum of the pions or kaons origination from the B parent was different enough from the spectrum of undifferentiated pions to distinguish the two. Plots demonstrated that the average transverse momentum for the pions coming form the B meson is much higher than for the unselected pions. This is largely in part because of a kinematical cut coming from the detector itself which sets a lower energy limit on the B mesons which it can detect, which in turn means that its daughter particles are also going to have a higher average energy. Thus it would make sense to make some sort of trigger based on this plot, but even at that peak of this plot, the number of background pions is still going to overwhelm the number of interesting pions. So obviously the next task would be to investigate the possibility of a second filter to further reduce the data, or to find a new filter all together. Investigating further trigger possibilities was beyond the scope of my summer project.

So, to summarize, if we could isolate certain decay modes of the neutral B meson we could then measure how 'big' CP Violation is, which would then lead to many interesting speculations about our universe and physics beyond the standard model. While finding a way to isolate the interesting events from the other processes that occur in the detector may seem far less glamorous and mundane than theoretical speculations that began this paper, it is a very real and challenging task for any physicist at a particle accelerator. Indeed, it is central to designing a study in high-energy physics today. If you can't get a reliable data set, then you have no experiment.