Level 3 General Experiment
Identification of Particle Physics Events and test of Three Colours

Objective: To be able to interpret "event pictures" from the OPAL detector - a particle physics experiment which is currently running at CERN. To test the feature of the standard model that quarks come in three "colours". The experiment is computer based and comes in three parts. The first part is a tutorial to teach yourself how to identify the different types of events at OPAL. In the second part we carry out an analysis of 1000 events which are of "two-fermion" type. From the analsis we should be able to check that quarks exist in three colours. In the final part we look at decays involving two W-particles.

Background : Particle Physics experiments are possibly the most complicated machines made by humans. It is a very complicated process to record and interpret the results and the physics collaborations are very large. (With up to 500 physicists "group" skills are very important!) In this lab we will learn how to examine to "event pictures" produced by the computer reconstruction programmes and to identify the underlying physics processes.

The LEP experiment is a colliding beams experiment where electrons are collided with positrons moving in the opposite direction. The LEP experiment came in two phases LEP-I and LEP-II. During LEP-I (1989-1995) the two beams had an energy of $45.5GeV$. Thus the centre of mass energy was just enough to produce a Z^0 particle. This part of the experiment was studying the behaviour and decays of the Z^0 particle. The Z^0 and its charged partner the $W^{\pm}$, both discovered at CERN in 1983, are responsible for the "weak" force. During this phase about 20,000 Z^0 were produced each day. Our data sample is a small fraction of that available to analyse. During LEP-II (1995-2001) the energy has been increased until the "W-threshhold" where the energy is just enough to create two W particles. Unlike LEP-I, very few W-pairs are produced - just a few W-pairs are produced each day. Our data for W-pairs is a significant fraction of the total data.

Apparatus : PC and CDrom of events.

Procedure 1: The OPAL particle identification software is in the 'masterclass' directory on the CDrom (the first page is 'home.html'). You may have seen some of this in level 1, but you should work through it all now. You should work your way through the explanatory sections and through parts 1-4. You should then carry out Part 5. In part five, you should identify all the events and record the processes, together with your reasoning in the lab diary. Discuss these results with the lab demonstrator. This completes the initial part of the experiment.

Procedure 2:

The 'zzero' directory of the CDrom contains 1000 events selected from OPAL (in gif format so a graphics package such as *AGS...* may be a useful way to view these.). The events are chosen to be *particle-antiparticle pair* events but otherwise you may regard them as random. Work through the 1000 events and identify the events into the four classes

$$
\begin{aligned}
A &: e^+ + e^- \rightarrow q + \bar{q} \\
B &: e^+ + e^- \rightarrow e^+ + e^- \\
C &: e^+ + e^- \rightarrow \mu^+ + \mu^- \\
D &: e^+ + e^- \rightarrow \tau + \tau^-
\end{aligned}
$$

Most events are of the first type. Keep a record in your lab diary of the "event-numbers" of the other three types. By measuring the ratio of events where the final state are quarks as opposed to leptons we can check that there are three colours of quark.

Corrections to the number of events of type B

We now must "correct" the events of type B. The events have been selected to correspond to intermediate Zs. When the Z^0 decays to resultant two fermions will come off randomly at all angles. Unfortunately if the Z^0 decays to $e^+ + e^-$ these events are difficult to distinguish from those where the electrons just scatter elestically without a Z being involved. For this reason events

$$e^+ + e^- \to e^+ + e^-$$

have been discarded is the angle, *theta*, of the outgoing electrons/positron to the beam pipe is less than 45 degrees. This *cut* is so that we discard the (numerous) events where the electrons just scatter elestically without a Z being involved. If you look back at the events you will observe that the selected events of type B are all at large angles to the beam directions whereas the other types of event occur at all angles. This means we have undercounted the events of type B. (Amonst the discarded events are the elastic scattering which we wish to discard but also a few of the events which we really wanted.) To make up from this we multiply these by a factor K. A fine fudge factor! **Calculate** what K should be. (*Hint:* The events should come out randomly through all of the 4π of solid angle. What is the amount of solid angle in the region $0 \le \phi \le 2\pi, \pi/4 \le \theta \le 3\pi/4$.) Now correct the number of events of type B.

Analysis: theory Here we explain how the ratio of jet events to $\mu^- + \mu^+$ events depends upon the number of colours. Remember that in quantum mechanics a particle such as the Z^0 can decay in all the ways for which Feynman diagams can be drawn and Feynman rules give the numerical probabilities. Although, I haven't given Feynman rules in a specify situation, when taking the ratios many things cancel. Consider the simple situation of a photon decaying. It also can decay to any of the six quarks and the three charged leptons. The Feynman diagram is the same in all cases *apart* from the coupling at the vertex thus

$$\frac{\sigma(\gamma \to u + \bar{u})}{\sigma(\gamma \to \mu^- + \mu^+)} = \frac{(2/3)^2}{1^2}$$

It is squared because the feyman rules involve squaring the Feynman diagrams (to obtain a positive number). Of course, we cannot tell which quark forms the jets so for the ratio

$$\frac{\sigma(\gamma \to two \ \ jets)}{\sigma(\gamma \to \mu^- + \mu^+)}$$

we must sum over all possible quarks. Here is where the number of colours comes in. If there are N_c colours then the photon is N_c times more likely to decay to jets. The ratio is

$$\frac{\sigma(\gamma \to two \ \ jets)}{\sigma(\gamma \to \mu^- + \mu^+)} = N_c \times 3 \times \left((2/3)^2 + (1/3)^2\right) = N_c \times \frac{5}{3}$$

(the three comes from the three families). For Z^0 at OPAL a similar analysis gives

$$\frac{\sigma(Z^0 \to two \ \ jets)}{\sigma(Z^0 \to \mu^- + \mu^+)} = N_c \times 6.94$$

Analysis: what to do From your results evaluate

$$\frac{\sigma(e^+ + e^- \to two\ \ jets)}{\sigma(e^+ + e^- \to \mu^- + \mu^+)}$$
$$\frac{\sigma(e^+ + e^- \to two\ \ jets)}{\sigma(e^+ + e^- \to charged\ \ leptons)}$$
$$\frac{\sigma(e^+ + e^- \to (e^+ + e^-)}{\sigma(e^+ + e^- \to \mu^- + \mu^+)}$$
$$\frac{\sigma(e^+ + e^- \to \tau^- + \tau^+}{\sigma(e^+ + e^- \to \mu^- + \mu^+)}$$

and determine your statistical errors. Are these results in agreement (up to the error) with theoretical expectations and $N_c = 3$. Are $N_c = 2$ and $N_c = 4$ excluded? Where do you think the worst *systematic* errors lie in your analsis?

Procedure 3:

The 'wpair' folder contains 500 events from LEP-II.

This set of data contains many W-pair events but also some Z^0 events. (events with just a Z^0 still ocur at LEP-II). You will have to separate the events into the following possibilities,

$$\begin{aligned} A &: e^+ + e^- \to Z^0 \to ?? \\ B &: e^+ + e^- \to W^+ + W^- \to qq\bar{q}\bar{q} \\ C &: e^+ + e^- \to W^+ + W^- \to l^{\pm}\nu q\bar{q} \\ D &: e^+ + e^- \to W^+ + W^- \to l^+\nu l^- \bar{\nu} \end{aligned}$$

Events of type B, C, D are known as *hadronic* , *semi-leptonic* and *leptonic* decays repsectively.

For the data identify which of the four possibilities is occuring and evaluate the ratios ,

$$\frac{\text{number of semi-leptonic decays}}{\text{number of hadronic decays}}$$
$$\frac{\text{number of leptonic decays}}{\text{number of hadronic decays}}$$

Assuming that each of the W's decays (independently) to hadrons with probability p or to leptons with probability $(1-p)$, determine the theoretical values of the above ratios in terms of p. Are the two measured ratios consistent with this assumption? Determine p.

This lab is closely tied to the course PH305,

Dave Dunbar, June 2005