Learning Physics from ALEPH Events

This document is an adaptation of the Web pages created by Joe Rothberg and Henri Videau at CERN. These pages can be found at `http://aleph.web.cern.ch/aleph/educ/Welcome.html`.

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1 Introduction

The aim of the following project is to provide some means for you to improve your knowledge of particle physics by studying some real data recently collected in the ALEPH experiment. To make it possible we provide some description of the experiment, of its detector and of some physics topics.

It will help greatly if you have a copy of a recent particle physics text book to help you with any new concepts. A suggested text is "Introduction to High Energy Physics" by D.H.Perkins.

You will need to access the world wide web throughout this project. Various URL's (internet addresses) will be provided where you can find additional information on specific points. It is highly recommended that you take advantage of this extra information. You will also need access to your Windows account on the lab PC's, so make sure you have your username validated in advance for this.

2 The Project

The project is intended to require three days (21 hours) of study and work, with an additional 6 hours to write up.

1. On day one you should read the sections on "The LEP Collider", "The ALEPH Experiment" and on "Starting with PAW". After these sections are understood, there are a set of questions to be answered and the answers are to be included in your final report. You will be required to have completed these questions satisfactorily before proceeding to the next part of the project. The answers to the questions should be written up in an "account" form in your write-up, because they are intended to illustrate some basic principles of physics at LEP.
2. On day two you will get to grips with an 'event display'. The events you will study are simulations of leptonic decays of the Z^0. The section to be followed is called "Displaying Events with PAW". This section contains questions within the text, which must be answered. You will later use your answers of this section to form the analysis part of your project.
3. On day three you will finalise any outstanding work from day 2, discuss any outstanding problems and then attempt one of the open ended questions listed below.

4. Finally you must write up your project, including all your answers to the questions, in such a way that the report is a coherent account of the physics at ALEPH and a clear summary of the analysis you have performed.

Day 1

3 Units

Normally energy, momentum, and mass are all specified in units of GeV . Thus the electron mass is approximatley 5×10^{-4} GeV and the muon mass is approximately 0.1 GeV. Since $p = \beta E$, for highly relativistic particles the numerical value of the momentum is nearly the same as the energy.

4 Coordinate Systems

The positive z direction points in the direction of motion of the beam electrons y is upward, x is horizontal and points toward the center of LEP. The polar angle θ is measured with respect to the +z axis and extends between 0 and π radians. The azimuthal angle, ϕ is an angle between 0 and 2π radians measured in the xy plane starting at the x axis. These angles are the same as those defined in spherical polar coordinates. In the side view of an event display one usually plots r, the cylindrical radial coordinate, upward. Often it is given the sign of y but in some displays the event is rotated so that the interesting tracks are nearly perpendicular to the viewing direction.

The LEP Collider

5 Introduction

In the following chapters you will have the opportunity to learn some particle physics from looking at and histograming ALEPH events. However, before any Z-bosons can be created, the electrons and positrons must be accelerated and made to collide. So first you need to have some idea of the LEP accelerator and the concepts of *luminosity* and *cross sections.*

6 The LEP Collider

LEP is the world's largest particle accelerator (26.7 km in circumference - some 100 metres underground) and is situated on the French-Swiss border near Geneva, Switzerland. Take a look at the URL:

`http://www.pp.rhul.ac.uk/~ptd/TEACHING/PH3010/8904001.jpeg`

The first collisions of electrons and positrons were provided by the LEP collider on 13 August 1989. Since then approximately 5 million Z bosons have been provided to each of the four LEP experiments. In 1996 the centre of mass energy was increased to 161 GeV (corresponding to the rest mass energy of *two* W bosons) and then 172 GeV. The centre-of-mass energy was then increased every year; in the year 2000, its final year of operation, LEP reached its maximum collision energy: 209 GeV.

7 The Interaction Point

The electron and positron beams which circulate in the LEP ring collide at the Interaction Point (IP) at the centre of the detector. The beams have a vertical size of about 10 microns, a width of about 120 microns and a length (along direction of motion of the beams) of about 1 cm. The smaller the transverse dimensions of the beams the more likely is an interaction between an electron and a positron. The likelihood of an interaction, of course, also depends on the number of electrons and positrons which are circulating.

8 The Beam Pipe

The electron and positron beams circulate in a beam pipe under very high vacuum. Near the centre of the detector the beam pipe is made of 1.1 mm beryllium. The choice of beryllium serves to reduce the amount of multiple Coulomb scattering of charged particles emerging from the IP. Reducing the amount of scattering permits more precise determination of the decay point of very short-lived particles like tau leptons and B mesons. These particles travel only a few millimeters and their decay point is observed by extrapolating charged particle tracks back inside the beam tube.

9 The Beams

Electrons and positrons circulate in opposite directions in the beam vacuum tube. Under normal operation there are four equally spaced bunches of each type which collide at the four interaction points where the four LEP experiments are situated. Once the beams are injected into the LEP ring and accelerated up to about 45 GeV they circulate for about 12 hours with gradually decreasing intensity. The loss of beam particles is due first to beam beam collisions then to collisions with thermal photons (!), with a beam lifetime of about 80 hours (the beam tube is at “room” temperature) and to collisions with residual gas molecules in the beam tube, with a beam lifetime of about 200 hours. To compensate for energy loss due to synchrotron radiation as the electrons and positrons are deflected in magnetic fields around the LEP ring, their energy is boosted by a high frequency (about 350 MHz) electrical power system located at several points around the ring.

10 Questions on Kinematics and Beams

1) Given that the LEP circumference is 26.66 km and that there are four equally spaced points where the beams collide, show that a collision takes place approximately every 22 microseconds, at each one of the collision points. How many bunches are there in each beam?

2) The average current per beam is about 3mA. How many particles per bunch is that?

3) If an electron from the beam collides head on with a thermal photon, how much energy (in eV) does the electron lose as a result of this collision? (Remember that a typical thermal photon has energy kT, where k is Boltzmann's constant and T is the temperature in Kelvin).

4) Estimate the average magnetic field that is required to keep the beams in orbit around the LEP ring.

5) The *luminosity* L is given by the quantity:

$$L = fn\frac{N_1 N_2}{A}$$

where f is the revolution frequency of electrons around the ring, N_1 and N_2 are the numbers of electrons (or positrons) in each bunch, n is the number of bunches in each beam and A is the cross-sectional area of each beam. From the information you have obtained so far, estimate the luminosity of the LEP collider in $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

6) If a particle interaction has a cross-section of 1 pb how many interactions would you expect to collect in one year of data taking? ($1\,\mathrm{pb} = 10^{-36}\,\mathrm{cm}^2$.)

The ALEPH Experiment

11 Introduction

Before having a look at physics you need to learn about the ALEPH Detector. You will then be able to understand the way the particles interact with the different elements of the detector, leaving a trace of their nature. There is much good information on the internet, so at this point open up a Netscape (or World Wide Web) window and take a look at the following URL:

`http://aleph.web.cern.ch/aleph/aleph/alephgif/aleph1.gif`

Here you can see a three-dimensional diagram of the ALEPH detector. The various components are described in more detail below, but here observe that the electron and positron beams are set up to collide right inside the detector. The detector is made up of various 'layers'. The inner detectors try to measure the particle positions and directions and so are made of light materials so as not to deflect the particle passing through them. The outer detectors are very dense (made of lead or iron) in order to stop any particles (apart from muons and neutrinos - which usually escape the detector) and so 'contain' the event so that its total energy can be measured.

The cylinders at the top of the detector (coloured brown in the diagram) are the cryogenic system, which supplies liquid helium to the superconducting magnet (coloured blue in the diagram). The magnet provides a field of 1.5 T which is uniform inside the magnet. Outside the magnet the magnetic field returns within the iron of the hadronic calorimeter (coloured red in the diagram).

Take a look at the following URL:

`http://aleph.web.cern.ch/aleph/dali/172GeV/`

and click on the second event ("2:06 October 19, 1996") for a bigger picture. This is a two-jet event where a quark and an anti-quark fly off in opposite directions. The quarks then "fragment", converting their kinetic energy into the combined kinetic energy and mass (via $E = mc^2$) of pions, kaons, protons... these are the particles which leave tracks in the detector, and the existence of the original quark can only be inferred from the "jet-like" structure of the event. You can see one jet at "1 o'clock" and another at "7 o'clock". You can also see an isolated photon at "4 o'clock". Take a while to understand the various aspects of this event, including understanding the rz-view (top right of the picture). Have a look at a few more of these events and see if you can understand what is going on. They are real events from data taking in the summer of 1996.

12 The Detector

Open the following URL:

`http://aleph.web.cern.ch/aleph/aleph/SUBDET/aleph.html`

For each of the following subdetectors, click on the relevant point to obtain pictures and further comment. Make sure you are familiar with the general setup of ALEPH and what the various components look like.

ALEPH is a particle detector covering as much of the 4pi solid angle as possible. It is designed to measure the momenta of charged particles, to measure the energy deposited in calorimeters by charged and neutral particles, to identify the three lepton flavors, and to measure the distance of travel of short-lived particles such as the tau lepton and the b and c hadrons. Particular emphasis has been given to momentum resolution up to the highest energies (by means of a tracking system in a 1.5 T magnetic field), electron identification (by means of a highly segmented, projective electromagnetic calorimeter as well as by ionization measurement in the tracking system), muon identification (with sufficient absorber to eliminate the hadrons). photon resolution (with the fine grain electromagnetic calorimeter).

The structure of the detector is like an 'onion', with the light tracking components inside and the heavy calorimeters around. We can look at the detector starting from the centre, the interaction point then pass through the tracking detectors, the calorimeters and finally the outer muon system.

The tracking involves three detectors:

1. a vertex detector, **VDET**, composed of two layers of double-sided silicon microstrips,
2. a drift chamber, **ITC**, with a 30 cm outer radius, and
3. a time projection chamber, **TPC**, with 180 cm outer radius.

Then the calorimetry proceeds in two stages: electromagnetic and hadronic.

1. The electromagnetic calorimeter, **ECAL**, is a 45 layer lead/proportional chamber sandwich,
2. the hadron calorimeter, **HCAL**, is a 23 layer iron/streamer tube sandwich with total thickness of 120 cm of iron (the magnet return yoke).
3. The whole is surrounded by an additional muon detection system, MUON, of two double layers of streamer tubes.
4. Finally, important for precise cross section measurement is the highly segmented luminosity calorimeter composed of twelve-layer tungsten/silicon sandwiches that surround the beam pipe at each end.

13 Vertex DETector (VDET)

Since an important physics goal of ALEPH is to identify very short-lived particles such as tau leptons and B mesons (mesons containing b-quarks) a high resolution position detector very close to the beam pipe is essential. A tau lepton or B meson travels only a few millimeters from the primary interaction point before it decays and the beam pipe has a radius of nearly 6 cm so that there are very severe requirements on the tracking precision of the innermost detector. This detector consists of two concentric arrays of silicon wafers surrounding the beam pipe.

The silicon wafers are fabricated as p-n junction diodes which are reverse biased so as to deplete the entire thickness of the wafer. Depletion means that there are normally no mobile charge carriers in the silicon and almost no current flows. When a charged particle crosses the silicon wafer it ionizes the silicon and the electron-hole pairs that are produced drift under influence of the electric field across the silicon to the electrodes on the surfaces. This charge cloud induces an electrical pulse on metal strips on the surfaces. The silicon wafers normally used in such detectors are 300 microns thick and a minimum-ionizing charged particle most probably loses about 84 keV of energy in traversing it. In silicon the energy required to produce an electron-hole pair is about 3.6 eV. The most probable energy loss results in the creation of about 23,000 electron-hole pairs. High-gain, low-noise amplifiers are needed to convert this small signal to one which can be handled by conventional electronics.

The silicon detectors used in ALEPH and in some other experiments are double-sided strip detectors. Metallized strips with a spacing of about 50 microns are embedded on each surface of the silicon. On the two surfaces the strips are perpendicualr to each other so that when a particle passes through the silicon its position can be determined simultaneously in two perpendicular directions. With a strip spacing of 50 microns a position resolution of about 10 microns is possible. This is achieved by taking advantage of the charge sharing between neighboring strips. Using the quantity of observed charge on each strip one can interpolate and determine the position to a precision well below the strip spacing. The resolution is limited by the signal-to-noise ratio and by the precison of alignment.

In the ALEPH vertex detector, the silicon wafers are 5.3 cm by 6.5 cm rectangles arranged in a row with six wafers per 40 cm long face. The inner layer at a radius of about 6.5 cm from the beam line has 9 such faces and the outer layer at about 11.5 cm radius has 15 faces. The faces are aligned parallel to be beam line (z direction). In the xy view there is some overlap between wafers which permits them to be aligned very precisely with respect to each other.

On each wafer approximately 1024 strips are read-out on the side which gives r-phi information and 640 strips on the opposite side which provides z information. The total number of electronics channels which need to be read out comes to about 100,000. The very large number of strips is handled by multiplexing the strips at several stages and by combining the channels into trains of pulses which are digitized sequentially by a relatively small number (48 = 2 per face) of analogue-to-digital converter circuits.

The vertex detector, together with the other tracking detectors, the ITC and TPC, provides a resolution on the impact parameter of tracks of better than 25 microns in the r-phi view and slightly worse in the z view. This precision allows very precise measurements of particle lifetimes as short as 300 fs (10^{-15} seconds.)

14 Inner Tracking Chamber (ITC)

The ITC, located between the vertex detector and the TPC, is used to measure the $r\phi$ position of a charged particle track with high precision. It is a conventional cylindrical drift chamber with 960 sense wires arranged in 8 concentric cylindrical layers. Each layer consists of 96 or 144 hexagonal drift cells, each of which contains a sense wire on which a pulse will be induced when a charged particle passes through the cell. The active length of the chamber is 2 meters and extends in radius between 16 and 26 cm from the beam line.

When a charged particle originating at the Interaction Point (IP) passes through the ITC, the argon gas within one or two drift cells in each of the eight layers is ionized along the particle track. As the sense wire is held at a positive potential relative to the field wires which define the cell boundaries, electrons drift toward the sense wire. Within a few wire diameters (30 microns) of a sense wire the electric fields are very large and the drifting electrons are accelerated sufficiently to eject other electrons from gas atoms. Thus an avalanche develops and very large amounts of charge are present very close to the sense wire. The negative charge cloud drifts toward the sense wire and the heavier positive charges drift more slowly away from the wire. These charge motions induce a negative electrical pulse on the sense wire. As a consequence of the multiplication of charge (by a factor of 105 or 106) in the avalanche, the induced pulses are large enough to be visible on an oscilloscope but are amplified for further processing using conventional electronics.

The time of arrival of these pulses relative to the time of the beam crossing at the IP provides information on the precise position of the track in the drift cell. The drift velocity is approximately 5 cm/microsecond or 50 microns/nanosecond so that a time measurement at the nanosecond level is adequate.

The measured drift time depends essentially on the perpendicular distance of the track from the sense wire and is available for each cell that the track passes through. At an early stage in the analysis of data, the track parameters are found which best fit the measured positions as determined from the hit cells and their respective drift times. The r phi resolution of the ITC is about 150 microns averaged over the drift cell.

The position of tracks along the beam direction, z, is also determined by measuring the difference in arrival time of the signals at each end of the wires. This z measurement has a resolution of a few cm and is not used in the standard tracking but is used for a track trigger.

15 Time Projection Chamber (TPC)

A Time projection chamber allows one to measure three dimensional coordinate at many points along a charged particle track. Having three dimensional information is important when there are large numbers of tracks within a small angular cone as is the case when “jets” are produced in Z^0 decays into quarks and anti-quarks.

The transverse coordinates (r phi) are determined by wire proportional chambers at the ends of the TPC while the longitudinal (z) coordinate is obtained from the time it takes charges to drift to the ends of the TPC. The wire chambers see a projection in the xy plane of all the tracks; the time of arrival of the charge from each track segment gives its z location.

For each track crossing the TPC about 20 radial coordinates are measured. A longitudinal electric field (11 kV/m) is applied along the z axis. When the charged particle ionizes the gas (argon-methane at 1 atmosphere) in the detector volume electrons drift along the electric field toward either end of the TPC. The drifting electrons retain information on the xy position of the original clump of ionization. The time required to drift to the end of the detector gives information on the z position of the original ionization.

The large number of coordinate measurements thus obtained are used to measure the curvature of the track in the 1.5 T magnetic field and determine the particle momentum precisely. Both the magnetic and electric fields are in the z direction in the TPC. The drifting electrons retain information on the xy coordinates of their starting point.

Additionally the TPC provides dE/dx (energy loss) information which can be used to determine the particle velocity, and together with its momentum, indicates the particle type. The TPC is just outside the ITC and extends in radius to about 1.8 meters from the beam line. Its sensitive length is about 4.4 meters.

Both ends of the TPC are equipped with arrays of “sectors” or proportional wire detectors which detect the drifting electrons. There are 18 sectors at each end. These wire chambers amplify the arriving cloud of electrons by the usual avalanche process and permit a measurement of both the time of arrival and the amount of charge (proportional to the original ionization). The sector wire chambers have concentric rows of cathode pads in proximity to the sense wires. These pads give directly the r-phi coordinate of the hit. Special rows of pads are also used as part of the trigger system.

The time of arrival of these pulses relative to the time of the beam crossing at the IP provides information on the z position of the track element in the TPC. The half length of the TPC is 2 meters and the maximum drift time is about 45 microseconds.

16 ECAL, The Electromagnetic CALorimeter

The calorimeter is made out of a cylindrical part called the barrel and two end caps to close the barrel. Each of these is made out of 12 modules. The modules from barrel and end caps have the same internal structure. It is made of stacks alternating wire chambers and lead sheets. You can distinguish three different stacks: the inner one contains 10 planes, the second one 23 and the last one 12. In the first two stacks the thickness of the lead is 2mm when it is 4 in the last. How many radiation lengths does it make?

The stack rests on a thick back plate and side plates keep the planes in place. On the inner face the pad structure is drawn. It proceeds through the module to create towers pointing toward the interaction region.

The sensitive medium is a wire chamber made of a comb in extruded aluminium. The wires run between the teeth. The comb is closed by a cathod cut into small pads. The pads are interconnected to build a tower looking toward the interaction point. The tower is read in three parts, per stack, called tower storeys.

17 HCAL, The Hadron CALorimeter

The hadron calorimeter is made out of iron slabs which compose the magnet return yoke. The calorimeter is made out of a cylindrical part called the barrel and two end caps to close the barrel. The barrel has 24 half-modules and each end cap has 6 modules. The end caps have sort of a plug penetrating in the barrel, this is meant to improve the homogeneity of the magnetic field. The modules from barrel and end caps have the same internal structure.

The sensitive medium is a wire chamber made of a comb in extruded PVC. The wires run between the teeth. The comb is closed by a cathod cut into pads. The pads are interconnected to build a tower looking toward the interaction point.

18 Muon Chambers

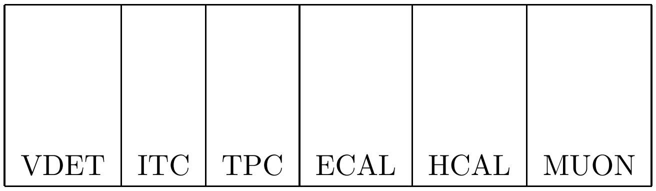
The muon chambers are made of two layers. Each layer is made out of two wire chambers runing in streamer mode, like the hadron calorimeter chambers. These two chambers have their wires orthogonal to provide a point for a muon passing through. High energy muons will pass stright through the detector and so will give ‘hits’ in the muon chambers. Essentially every other particle (apart from neutrinos, which escape the detector without interacting *at all !*) will be stopped in the detector before they reach the muon chambers. In fact, in the ALEPH detector, the segmentation of the HCAL is such that a muon will leave small deposits of energy as it travels, thus leaving a ‘track’ in the calorimeter too. All other particles deposit energy rapidly, so that the energy deposoition is spread out across adjacent calorimeter segments.

19 Questions on Particle Detection

1) Given that an electron with momentum 1 GeV/c moving in the xy plane of the ALEPH detector moves in a *clockwise* circle of radius 2 m, how would a positrion with momentum 2 GeV/c move?

2) How would the electron in question 1) move if it started out at an angle of 30° with respect to the z-axis? (Remember it is only the component of momentum *perpendicular* to a B-field which gives rise to any force).

3) Consider a (simplified and not to scale!) radial slice through ALEPH:



Sketch what you would see in each detector (ie hits or energy depostion) for the following single high energy particles passing radially outwards:
a) 40 GeV electron
b) 40 GeV muon
c) 20 GeV photon
d) 30 GeV neutrino
e) 20 GeV π^+
f) 30 GeV K_L

You should now spend some time to plan how this material will appear in the introduction to your report. You should aim at collating the answers to your questions into a five page summary which is coherent to read and which illustrates the principles of particle detection at LEP, with *quantitative* examples. You are *not* expected to copy out the chapters on detectors above, but rather gather a few essential points to back up the examples you describe.

Starting with PAW

20 Introduction

To learn how to recognize various types of events from their behaviour in the detector, you will be given samples of simulated events for these different cases. You will be required to identify these events and look at some distributions which exhibit interesting behaviour. You will need to look at events in a detailed, but simplified, way and to build distributions using a histogramming package: PAW (Physics Analysis Workstation). PAW is used in high energy physics to plot characteristics of events, select events and fit functions to histograms etc. It is a very versatile package and takes many hours to get a full familiarity with all its features. Here you are introduced to the basics of PAW which will enable you to carry out the rest of the project.

21 Login

Next you will need to login to the Particle Physics linux cluster. First, you must login to your PC and then follow the instructions (which were given to you separately) *"How to log on to the particle physics linux system "linappserv1" from a RHUL PC running Windows"*.

When asked, type the password you were given (case sensitive), and then click OK.

You should then see a screen with a blinking cursor next to something like [user1@linappserv1.pp.rhul.ac.uk], this is where you will input your commands.

In order to set up your account properly (so that you can have access to the required programs and data) you will need to enter the following four linux commands in your linux account, in the order shown below (press [RETURN] at the end of each line):

```
ln -s /home/ptd/ph301 ~/
cp ph301/event.kumac ~/
cp ph301/print.kumac ~/
cp ph301/tdisp.kumac ~/
```

Note that the above four commands need only be executed once: you should NOT repeat them every time you log on to the linux account.

To start PAW type: paw [RETURN]. At the next prompt, hit [RETURN]. A new window will appear which will display any histograms that you produce, but all commands etc. must be entered in your original window. It is worth reducing your original window size with the mouse, or else your origal window will obscure the PAW graphical output.

22 Basics of PAW

A program to help with analysis has been prepared. It reads the table of track parameters. You can then plot histograms and scatter plots for any variables, or combinations, or functions of variables. You can also apply "cuts" (restrict the range of variables for a plot) and fit functions.

The data which PAW uses is arranged in so-called "ntuples". These are essentially tables of real numbers, where the parameters of each event are arranged across one row. So, for example, a set of 4 events will occupy 4 rows of an ntuple. If each event has 3 parameters, eg event number, energy and momentum then the ntuple is structured thus: (The numbers are chosen randomly here for illustration)

event number	energy	momentum
1	33.3	22.1
2	35.2	30.2
3	22.1	16.2
4	24.7	15.5

For the events that you will be analysing, the ntuples are structured with the following row elements:

For **charged** tracks

Symbol	Parameter
ev	Event number
pa	Particle type
th	Theta
ph	Phi
pc	Momentum × Charge
do	d0 - closest distance of track to IP
ee	ECAL energy
eh	HCAL energy
de	dE/dX - rate of loss of energy by ionisation
sa	dE/dx samples
mu	MUON hits

For **photons** (which, of course, are neutral!)

Symbol	Parameter
ev	Event number
pa	Particle type
th	Theta
ph	Phi
pc	Energy
do	Null - not relevant
ee	ECAL energy fraction, stack 1
eh	HCAL energy fraction, stack 2

where the particle types are defined as:

code	particle
0	charged
1	γ
2	e^+
3	e^-
4	ν
5	μ^+
6	μ^-
7	π^0
8	π^+
9	π^-

23 Plot a Variable

Things should be made clearer after a simple example. Let's look at the file 'zee' which is so named because it contains data from the decay $Z^0 \rightarrow e^+e^-$. Note, if you need to retype or edit a command in PAW, it is often easier to type the 'up' arrow key - this recalls the recently entered commands in reverse order.

To read the $Z^0 \rightarrow e^+e^-$ event file type:

```
> exec event zee
```

Now take a look at what is in the ntuple - type:

```
> nt/print 2
```

Here, 2 is just the number of the ntuple, which was arbitrarily chosen and has no further significance. What you now see is a list of the ntuple contents, with their lower and upper bounds. So, for example, the phi angle varies from event to event (ie each row of the ntuple has a different phi value) with minumum value 0.0028 and maximum value 6.28 - look at the row for PH in the list. This is expected because phi should range from 0 to 2π.

Take a look at this graphically, by typing:

```
> nt/plot 2.ph
```

Here, the 2. means " look in ntuple number 2" and the PH means " plot variable PH in this ntuple".

You can also plot variables against each other - you simply insert a % symbol between the variables. For example, to plot the phi angle against the θ angle, type:

```
> nt/plot 2.ph%th
```

Often we want to apply a "cut" to the data. This means we only want to look at data which have certain ranges of a particular parameter (or parameters). So, if we are interested in plotting the momentum of a tracks which have θ less than (.lt.) 2.5 and (.and.) θ greater than (.gt.) 1.3 we can type:

```
> nt/plot 2.pc (th.gt.1.3).and.(th.lt.2.5)
```

Now plot out some variables and get a feel for what is going on.

24 Printing PAW Output

If you want to print out a histogram or ntuple, you need to open a file 'myfile.ps' which will contain the graphical output. You can change this name to anything you want, but you need to remember the name of this file because you will have to print it *after* leaving the paw session. Within PAW type:

```
> for/file 66 myfile.ps
```

If you want to plot graphs then type:

```
> graphics/meta 66 -111
```

Whereas if you want to plot event displays then type:

```
> graphics/meta 66 -112
```

Now execute the PAW commands which produce the ntuple or histogram and when this is complete you type:

```
> close 66
```

Now there will be a file sitting in memory which can be printed out later. If you exit PAW, you can print it to appear at a printer in the HEP lab by typing

```
> lpr myfile.ps
```

To check that you have understood things so far, here is an exercise. You should complete this and have it checked before going on to the next section.

Exercise
Using data from the $Z^0 \rightarrow e^+e^-$ ntuple, plot out a distribution of the polar angle (th) for those tracks with ECAL energy (ee) less than 50 GeV. Obtain a printout of your graph, label it and explain *briefly* what the graph is about (write this on the printout) and say what the distribution is telling you about where most of the final state particles are heading. You should include this in your final report.

25 Histograms

As you have by now seen, PAW is useful for plotting out variables. To do this, PAW chooses its own scale and does everything automatically. However it is often easier to analyze data if it has been put into a "histogram". To form a histogram, one divides up a variable into a set of 'bins' - the name given to an interval in the value of that variable. For each track with its variable lying within the interval, the corresponding 'bin' gets one entry.

So to form a one dimensional histogram one picks a variable or a function of a variable, for example, phi or $\cos\theta$ and for each track or each event adds 1 to a bin which includes the current value of that variable. First a set of "bins" is set up (for example 50 bins) which span the range of variation of the variable. For example, if you are histogramming $\cos\theta$ for tracks then you may want 50 bins extending from -1 to +1. If you are histogramming phi in degrees you may want 60 bins extending from 0 to 360. After having processed many events (adding a 1 to the appropriate bin for each event) you will have a probability distribution for that variable for your event sample.

You may choose to "add 1" for a particular event only if it satisfies some other condition. For example, you may add 1 to the $\cos\theta$ histogram only if the momentum is positive. Then the condition "momentum.gt.0" is called a "cut". As we saw above cuts can be much more complicated and can involve several variables.

26 Analyzing Data with PAW

To read the $Z^0 \rightarrow \mu^+\mu^-$ event file type:

```
 > exec event zmm
```

Now you can plot any variable in the table and make cuts on the variables. Here are some examples; each command is listed:

Let's plot the ECAL energy for the (PA.eq.0) tracks. The next command defines histogram number 101 with the label "ecal,energy" and a range which extends from 0 to 50 (GeV).

```
> defhist 101 ecal,energy 0. 50.
```

the next command fills the histogram 101 for the variable ee which is the ECAL energy and with the "cut" restricting the plot to charged tracks (pa.eq.0) AND energy less than 50 GeV (ee.lt.50).

```
> plothist 101 ee (ee.lt.50).and.(pa.eq.0)
```

Let's plot the phi angular distribution for charged tracks. The next command defines a new histogram for ϕ in degrees.

```
> defhist 102 phi 0. 360.
```

The next command plots ϕ in degrees for charged tracks

```
> plothist 102 180*ph/3.14159 pa.eq.0
```

Let's fit the phi angular distribution to a second order polynomial.

```
> fithist 102
```

The fit parameters and errors will appear in the control window.

Let's make a scatterplot of momentum against $\cos\theta$ The next command defines a scatterplot and the ranges needed(x axis first).

```
> defscatt 201 momentum,$\cos\theta$ -1 1 0 50
```

Now fill and display the scatterplot for charged tracks.

```
> plotscatt 201 abs(pc) cos(th) pa.eq.0
```

Note: In the data tables the values for ECAL energy, HCAL energy, and MUON hits, ee, eh, mu, are set to large positive numbers when those detectors are not hit. When using these variables make a "cut" requiring a value below 50.

Displaying Events with PAW

27 Displaying Events

Several data files exist with either simulated events or real events. The files with simulated events are:

zmm ($Z^0 \rightarrow \mu^+\mu^-$)

zee ($Z^0 \rightarrow e^+e^-$)

The real data file is called: real .

Events from real data have been chosen which are likely to contain either electrons, muons, or tau leptons in the final state. In particular, events with quark (hadron) final states have been excluded.

The data exist on files in the form of tables of track parameters. An event display program runs under PAW and for each track (in each event) 11 numbers are given, as described in the section “Starting with Paw”.

As before,to start PAW, type PAW [Return]. At the next prompt type [Return].

Events in these data files can be displayed in both an xy view (barrel part of detector seen from the end) and a rz view (side view with z along horizontal axis and the radial position plotted vertically.)

To display events in the file for $Z^0 \rightarrow \mu^+\mu^-$ at the prompt type: exec tdisp zmm 0

To display events type [RETURN] at the ? prompt. The events are displayed sequentially. Hit [Return] to see the next event. Type q (for quit) to get back to the control program then you can ask for a new file or type EXIT to exit from PAW.

28 The Display:

The xy view is on the right side. You are looking at the detector in the direction to which the positrons go (towards negative z). The 'side' view is on the left. Positrons move from the right side of the diagram toward the left. Positive z is toward the right. The vertical axis is r, the cylindrical radial coordinate. A cut is made in the azimuthal angle phi, so that the true upward direction is upward in the diagram.

The Electromagnetic Calorimeter (ECAL) and energy deposited are red.

The Hadronic calorimeter and energy deposited are green. The length of the wedge is proportional to energy deposited.

The Muon chambers and the hits are blue. The size of spot is proportional to number of hits.

The Time Projection Chamber (TPC) is yellow. Charged tracks are black, photon path is shown in red.

29 Some Things to Do with Z^0 data

How to distinguish Z decay into a pair of electrons from Z decay into a pair of muons.

zee ($Z^0 \rightarrow e^+e^-$)

zmm ($Z^0 \rightarrow \mu^+\mu^-$)

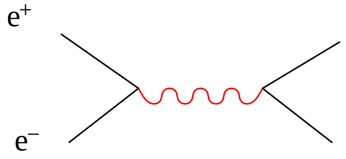
1. Look at a few simulated events of each type on the event display. (the data files are obtained using the names "zee" and "zmm" respectively) How do ECAL, HCAL, and the Muon Chambers respond to electrons and to muons?
2. Histogram the ECAL energy and the HCAL energy for both data samples. How does the energy response of these detectors differ for the two classes of events?
3. Propose a rule (a set of cuts on energy, etc.) to distinguish, as well as possible, between these two types of events.
4. Apply these cuts to your histograms and see whether the two types of events can be distinguished from one another with your cuts. Make plots with both of the files of simulated data to see the behavior of the electron sample and the muon sample.
5. What fraction of wanted events are accepted? (the efficiency)
6. What fraction of unwanted events are accepted? (quality of rejection) (Remember that each entry in your plot is a track and that there are normally two high momentum tracks per event)
7. Now apply your cuts to the real data file, with name "real"
8. The real data file has other final states in addition to the electron and muon events. Some events have a pair of tau leptons in the final state. The τ lepton decays quickly into an electron and two neutrinos, a muon and two neutrinos, a pion and a neutrino, or more complicated states involving several pions. The charged particles from τ decay will, in general, have lower momenta than for the two cases we are studying. For this reason we must also make cuts on momentum, abs(pc) , when working with the real data file. You can get more experience in τ spotting by looking at the file "ztt" with the display program.
9. How many e^+e^- events and how many $\mu^+\mu^-$ events do you find?
10. What is the fraction of contamination of other event types? Base your conclusions on histograms of variables. Now look through the first 50 events using the display program and classify each event 'on inspection' as either e^+e^- or $\mu^+\mu^-$ or $\tau^+\tau^-$ or other. To do this, make a table with columns labelled by these types and enter the event numbers in the appropriate column. What ratio of electron decays to muon decays did you expect? Why? (*hint* 'lepton universality' is the idea that all leptons are equal as far as their couplings to gauge bosons are concerned).

11. The investigation of angular distributions (below) may suggest why the observed number of electron events is different from the observed number of muon events.

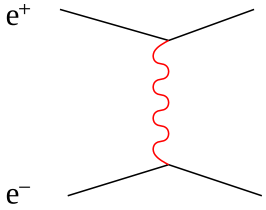
Day 3

30 Theoretical Interlude

We are now in a position to start to understand the angular distributions of our final state leptons in terms of the underlying physics processes. Simple particle interactions can take place via one (or sometimes both) of the following diagrams:



s−channel



t−channel

For the processes of interest in this project, the “exchanged” particle (the wavy line) can be either a Z^0 or a photon γ. It will be part of the project to determine which diagrams contribute to the various processes. It will be sufficient to know that the s-channel diagram gives a quantum-mechanical *amplitude* proportional to $\frac{1}{s-m^2}$ whereas the t-channel diagram is proportional to $\frac{1}{t-m^2}$. In both cases m is the mass of the exchanged particle. For photons $m = 0$ whereas for a Z^0, $m = 91\,\mathrm{GeV/c^2}$. The definition of s and t follow:

$$s = (p_1 + p_2)^2$$

$$t = (p_1 - p_3)^2$$

where the p are the four-momenta of the particles.

Question:

Determine the shape of the angular distribution (in terms of θ and ϕ) for processes that have:
a) pure s-channel contribution
b) pure t-channel contribution
c) equal contributios from s- and t-channels.

Remember The rate of any reaction is proportional to the *mod-square* of the quantum mechanical amplitude.

31 The Angular Distribution of the Outgoing Electron and Muon

12. Plot histograms of the phi and $\cos\theta$ distributions for the e^+e^- and $\mu^+\mu^-$ events (again work with simulated data.) How would you describe the shapes?

13. Explain why the phi distributions look the way they do.

14. It is expected that the weak decay of the Z into lepton pairs gives an angular distribution proportional to $1 + \cos^2\theta$. Do your plots for the muon and for the electron appear consistent with this shape?

15. What might account for any large differences that you observe? (*hint* look back to the discussion at the beginning of this section involving s and t channel processes).

16. Your histograms can be fitted to simple functions. Why is a second order polynomial a good choice?

17. How good is the agreement with expectations?

18. Plot the $cos\theta$ distribution for positive and negative outgoing particles separately. (The sign of pc is the charge.) Do this for the electron sample and also for the muon sample.

19. How do the $cos\theta$ distributions for electrons and positrons differ?

20. How is the muon case different?

21. Perform the fits and print out your resulting distributions. You will need these printouts as part of your writeup, together with any others which you may feel are relevant.

22. What differences in the fundamental reactions account for this difference? *Hint:* Think about how the initial electron and positron are transformed into the outgoing (final state) particles.

23. Is there a way that outgoing electrons can be produced which is not available for muons? (You may need to refer to a textbook for help here.)

32 Open-ended Questions

If you have any remaining time you should attempt this open-ended section for which there will be some bonus marks.

Detailed studies at LEP1 have shown that there can only be three generations of leptons which have light neutrinos. This does not rule out new generations which may have both heavy neutrinos and heavy leptons. Consider how events involving such a heavy lepton may appear in the ALEPH detector, if sufficient energy were provided at LEP2. Discuss the following various scenarios and draw schematic event displays using the provided ALEPH emtpy displays.

The heavy leptons are stable.

The heavy lepton decays very rapidly to the lighter leptons (electron or muon or tau) plus a very heavy neutrino.

The heavy lepton decays within the TPC volume

From what you have learnt above, discuss in general the important aspects of particle detectors which are necessary in order to be sensitive to such new phenomena.

33 Report

You should now write up your report. The first five pages (approximately) should be devoted to describing the ALEPH detector using the results from day 1. The next ten pages should concentrate on discussing the physics of lepton production at LEP and, in particular, the relevant distributions and detector components you have used in this study. Include any relevant plots in your discussion and any tables that you have produced. The report should be about twenty pages in total, to include an introduction and conclusion and any discussion of the open ended questions that you may have had time to address.