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Z^0 Resonance Analysis Program in ROOT

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“Z^0 Resonance Analysis Program in ROOT”

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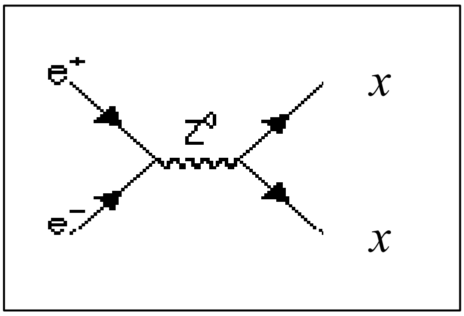
Objectives of the project are to convert a Z^0 resonance analysis program from PAW to ROOT and to introduce working techniques used in high energy particle physics to students. This program is suitable to be used in advanced laboratory course in universities.

INTRODUCTION

The software for data analysis and graphical presentation in high energy physics is a crucial tool to deal with very large amounts of data from accelerators. For example, the data that the Large Hadron Collider’s experiments will collect estimated to several petabytes per year. In 1986 CERN had developed the Physics Analysis Workstation (PAW) which has been a standard tool in the high energy physics field for decades. It is based on and intended for interoperation with components of CERNLIB, an extensive collection of Fortran libraries. However, now it has recently been losing ground to the C++ based ROOT package which also developed by CERN , for instance, physicists are expected to analyze LHC’s data by using ROOT. Moreover, at the present time, students are familiar with C++ more than Fortran. Therefore, an advanced practice for students should be upgraded to ROOT instead of the last version which is available in PAW.

Z^0 resonance

It is important to mention Z^0 resonance in the beginning of this work because the purpose of the advanced practice is to make student be able to find the properties of Z boson and understand what happen in electron-positron colliding at Z^0 resonance. The determined properties of Z boson are the mass, the width and the maximum cross section. The way to find these properties is fitting cross-section of particles which are final states of Z decay by using Breit-Wigner distribution.



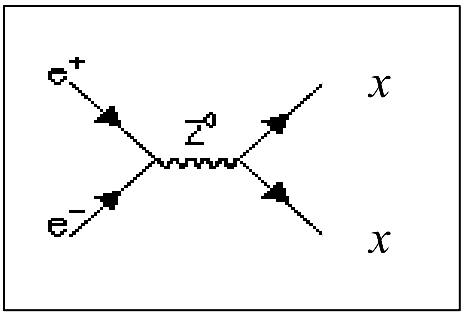


Figure 1. γ exchange ***Figure 2. Z^0 resonance***

The annihilation of electrons and positrons in a particle-collider can produce a new particle if the centre of mass energy of the electron-positron pair matches the energy corresponding to the mass of the particle. These interactions are understood in terms of exchanges of gammas and Z bosons which shown in figure 1 and 2 respectively. As seen in figure 3, the curve shows the cross-section (σ_μ) for the production of muons as a function of the center of mass energy. At the lower collision energy, the cross section decrease due to gamma exchange. Nevertheless, when electron and positron beams collided with enough energy they usually interact by the Z boson. At this peak, it is a Z^0 resonance. Gamma exchange is negligible at the peak because it is only one event out of one thousand.

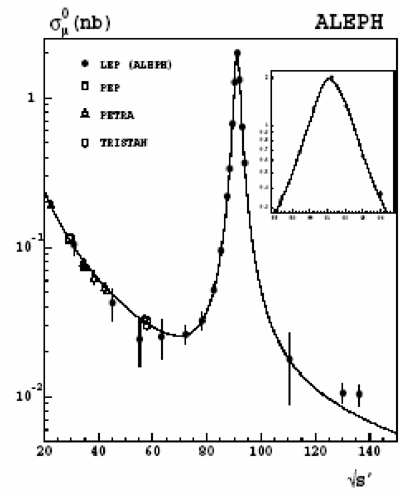


Figure 3. The muon production cross-section over a wide energy range from measurement at different experiments **[1]**

One can describe the annihilation as a two step process. Firstly Z boson is produced and then within about 10^{-25} second it decays in pairs of charged leptons (electron and positron, muon and antimuon, tau and antitau), in neutrino-antineutrino pairs (one pair for each charged lepton pair), or in quark-antiquark pairs, which will end up in some hadrons. These processes can be represented by the diagrams below.

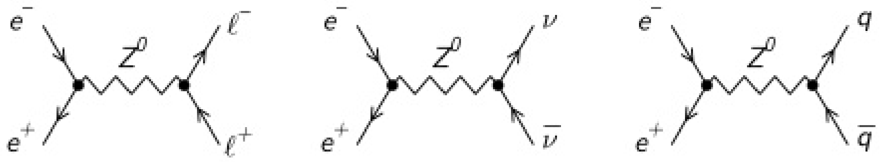


Figure 4. The diagrams of the possible final states of Z decay

The Z boson arises in the Standard Model of particle physics as a result of the unification of the electromagnetic and weak interactions. There is more information hidden in the resonance curve of the Z, for example, the numbers of nuetrino families are figured out by studying Z^0 resonance.

Properties of Z boson

The mass and the total width of the Z boson were determined by measuring of cross-sections of the four final states corresponding to Z decays : $e^+e^- \rightarrow$ hadrons, $e^+e^- \rightarrow e^+e^-$ (also called Bhabha scattering), $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$. The shape of the cross section curve is described by the Breit – Wigner distribution. From a simultaneous fit to all the four distributions in cross section, three quantities can be determined e.g. the value of invariant mass corresponding to the maximum cross-section which is the mass of the Z boson, the width of the distribution at half maximum cross-section which leads to the determination of the total width (Γ_Z) and the maximum value of the cross-section which is proportional to the product of the two partial widths. Normally, unstable particles are described by their lifetimes or decay widths (Γ) which are related to each other via the relation $\Delta E \cdot \Delta t \geq \hbar$. Moreover, the ratio of a partial width to the total width (Γ_Z) gives the fraction of time Z decays into a given final state, for example the ratio $\Gamma_{\mathrm{hadron}}/\Gamma_Z$ gives the fraction of Z decaying via the hadronic mode. By the way, from performance with data taken at the Z^0 resonance by the experiments operating at the electron–positron colliders SLC and LEP, the mass and total width of the Z boson reported on the final electroweak measurements are $m_Z = 91.1875 \pm 0.0021$ GeV, $\Gamma_Z = 2.4952 \pm 0.0023$ GeV [2]

METHODOLOGY

The analysis software and the main process of creating the *"Z^0 Resonance Analysis Program in ROOT"* are briefly described below.

ROOT

ROOT is an object-oriented program and library developed by CERN. It was originally designed for particle physics data analysis and contains several features specific to this field, but it is also commonly used in other applications such as astronomy and data mining.

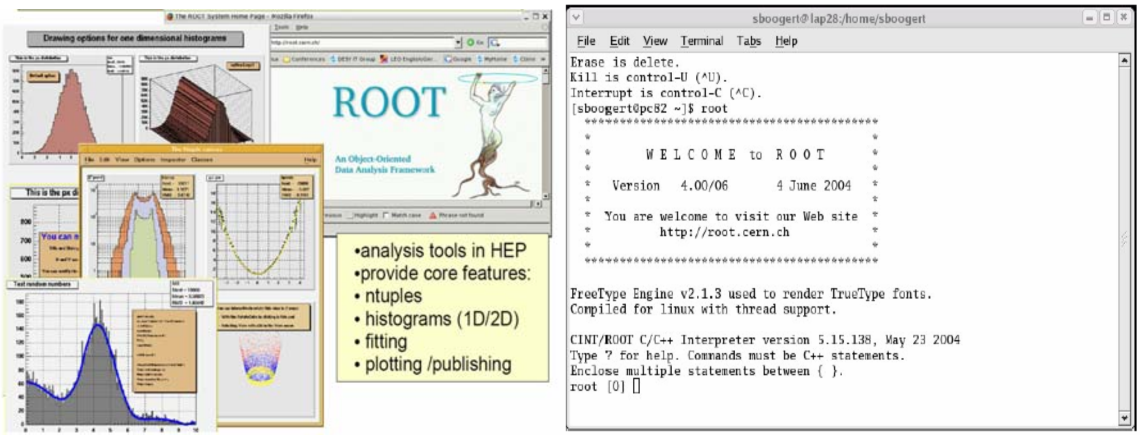


Figure 5. ROOT- an analysis Tool in high energy physics field

ROOT provides platform independent access to a computer's graphics subsystem and operating system using abstract layers. Parts of the abstract platform are: a graphical user interface and a GUI builder, container classes, reflection, a C++ script and command line interpreter (CINT), object serialization and persistence. A key feature of ROOT is a data container called *tree*, with its substructures *branches* and *leaves*. A tree can be seen as a sliding window to the raw data, as stored in a file. Data from the next entry in the file can be retrieved by advancing the index in the tree. This avoids memory allocation problems associated with object creation, and allows the tree to act as a lightweight container while handling buffering invisibly.

Convert PAW to ROOT

There are two programs provided by PAW in the last version of *"Z^0 Resonance Analysis Program"*. First one is a program to select and plot histogram of particles produced in electron positron collider. Another one is a program to receive cross sections of particles at vary invariant masses then plot and fit a graph by Breit-Wigner distribution. In this work, mentioned programs above which are available by Fortran in PAW have been created by C++ in ROOT.

The aim of the first program is to select the events of hadrons, e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states at high efficiencies within the largest possible acceptance. The separation of hadronic, and leptonic (electrons, muons and taus) events is using the information from the electromagnetic and hadronic calorimeters and the muon chambers collected by Opal detector. The data fed in this program come from both Monte Carlo simulation and Opal experiment. The Monte Carlo simulation is used to determine the set of simple cuts that later applies to data from experiments in order to obtain the number of four-final-state events. The final cuts which are used in this work are display in table 1.

Table 1: event-selecting cuts

	hadrons	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$
Energy_ecal	$30 \le E \le 80$	≥ 76	≤ 18	$6 \le E \le 60$
Energy_hcal		≤ 8	≤ 25	≤ 30
Ncharged	≥ 8	≤ 5	≤ 3	≤ 7
Pcharged		≥ 30	≥ 75	$5 \le p \le 55$
Cos_thru				$-0.9 \le c\theta_T \le 0.9$

Next, the cross-sections shown in table 2 are determined from the number of selected events of four Z-decay modes. Sets of cross sections of each fermion are calculated By using Mathematica (or Mable), and then sent with their center of mass energies to the second program which is a Breit-Wigner fitting. Finally, the properties of Z boson e.g. the mass, the width, the maximum cross section are extracted in from of fitting parameters.

Table 2 : cross sections (nbarn)

Invariant mass	σ_{hadron}	σ_{e+e-}	$\sigma_{\mu+\mu-}$	$\sigma_{\tau+\tau-}$
88.48021	7.357±0.013	0.440±0.029	0.315±0.020	0.372±0.027
89.46928	14.37±0.140	0.900±0.038	0.696±0.028	0.690±0.033
90.22604	25.94±0.212	1.349±0.441	1.242±0.036	1.215±0.042
91.24186	41.09±0.220	1.898±0.022	1.961±0.018	1.945±0.021
91.96859	29.35±0.274	1.227±0.046	1.422±0.043	1.338±0.050
92.96836	13.84±0.200	0.419±0.037	0.529±0.035	0.576±0.044
93.71685	8.271±0.134	0.329±0.026	0.387±0.025	0.419±0.031

Result and Discussion

Sample histograms from event-selecting program created in ROOT are shown in the figure 6 and 7. Figure 6 shows the number of events from Monte Carlo simulation which pass through the selecting cuts for $\tau^+\tau^-$ decay mode; (a) and (b) plot number of events versus energy loss in electromagnetic (Energy_ecal) and hadronic calorimeters (Energy_hcal), (c) and (d) plot number of events versus the number of charged tracks (Ncharged) and Scalar sum of track momenta in the jet chamber (Pcharged), (e) and (f) plot number of events versus cos(polar-angle) of the beam axis and the thrust axis and cos(polar-angle) of the incoming e^+ and the outgoing positive charged particle in order.

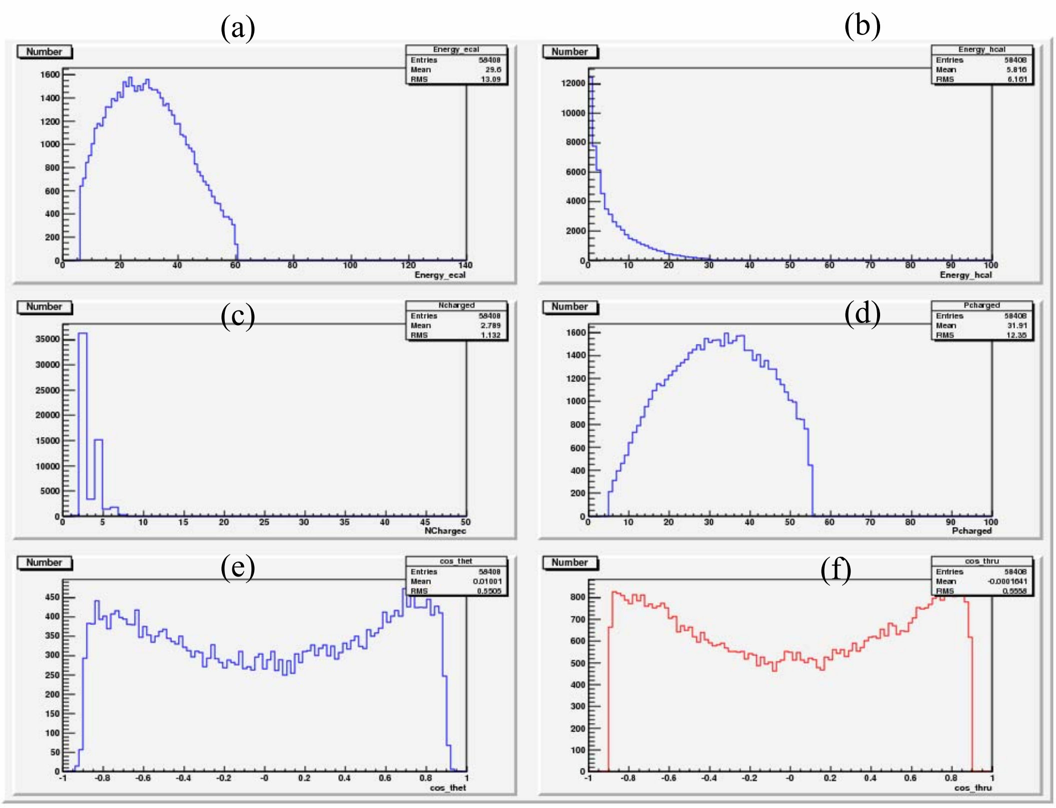


Figure 6. the number of $e^+e^- \to \tau^+\tau^-$ ***events from Monte Carlo simulation selected by a defined cut in ROOT(*** $6 \le Energy\_ecal \le 60,\ Energy\_hcal \le 30, Ncharged \le 7,$

$5 \le Pcharged \le 55 - 0.9 \le Cos\_thru \le 0.9$***)***

Figure 7 shows the number of four final states which decay from Z boson as a function of the scalar sum of track momenta (Pcharged): (a), (b), (c) and (d) stand for $Z^0 \to$ hadrons, $Z^0 \to e^+e^-$, $Z^0 \to \mu^+\mu^-$, and $Z^0 \to \tau^+\tau^-$ respetively. When the cuts in table 1 are applied to the Z decay modes simulated from Monte Carlo, the number of events which pass through the cut can be observed from the number of entries. For example, the events of $Z^0 \rightarrow$ hadrons are equal to 134165.

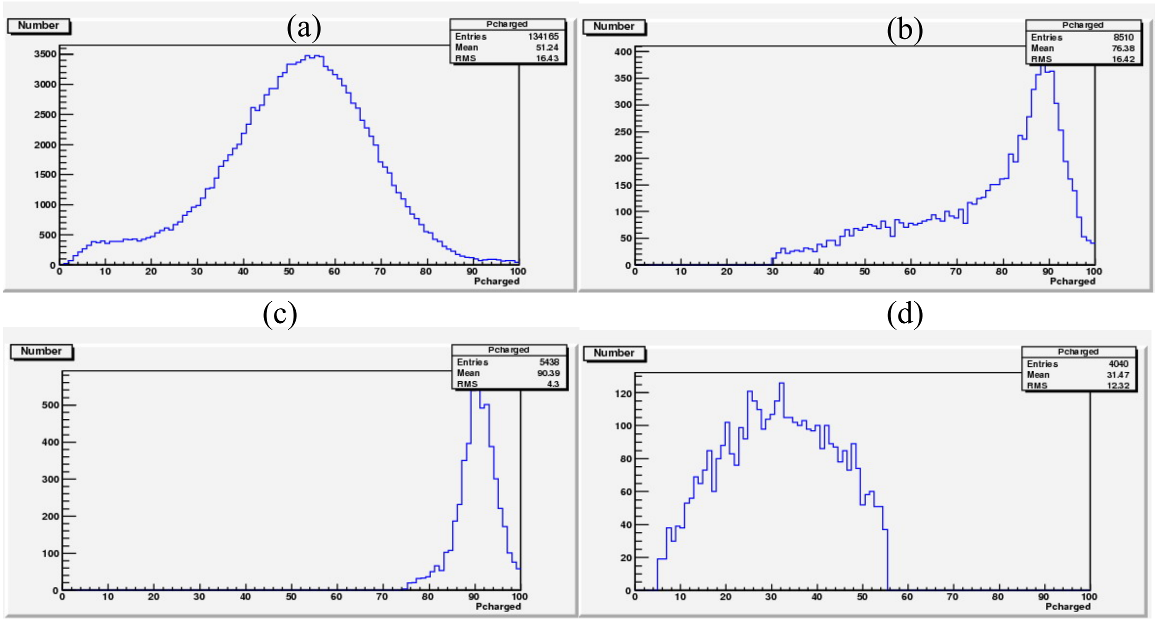


Figure 7. the event- number of Z decay modes, (a) hadrons,(b) e^+e^-, (c) $\tau^+\tau^-$ and (d) $\mu^+\mu^-$, as a function of Pcharged from Opal experiment's data selected by a defined cut in ROOT

Next, the sample result of fitting - program in PAW and ROOT is shown. Figure 8 demonstrates behavior of hadrons cross-section as a function of invariant mass. The distributions is explained by the Breit-Wigner distribution. From fitting the distribution of cross-section, three parameters can be obtained. Parameter 0 is the value of collision energy corresponding to the maximum value of the cross-section which imply to the mass of the Z boson. Parameter 1 is the width which leads to the total width of Z boson. Parameter 2 is the maximum cross section is proportional to the product of the two partial widths.

(a) (b)

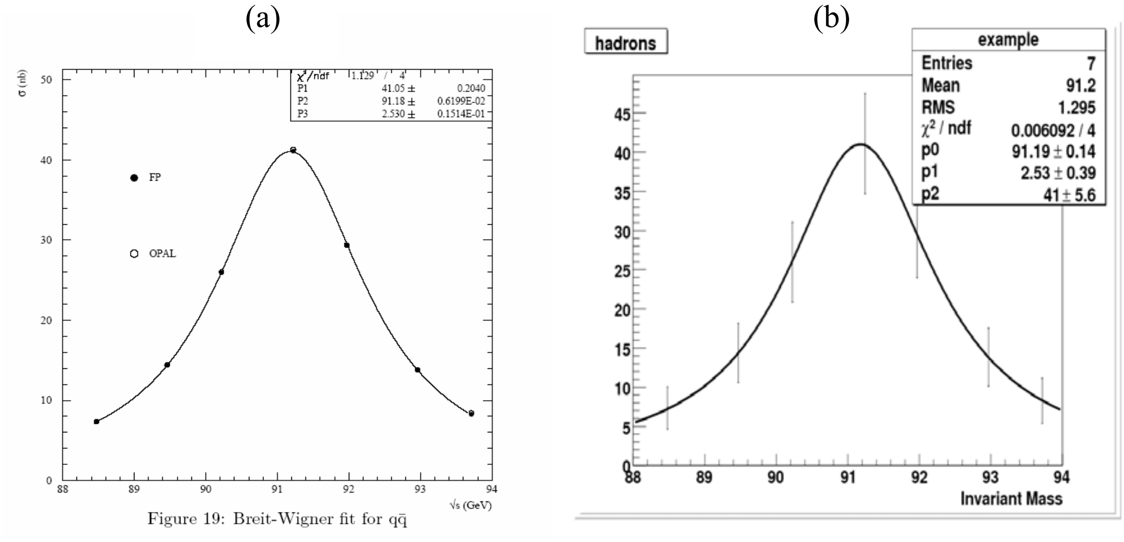


Figure 8. fitted graphs by Breit-Wigner distribution created (a) in PAW (b) in ROOT

From using PAW and ROOT to fit Briet-Wigner resonance curves to the cross sections, which indicated in table 2, of the different decay modes of the Z^0, the three acquired properties of Z boson are given the Table 3 and 4. When the results are compared, the values of mass, width, and maximum cross section calculated from Root are in agreement with PAW.

Table 3. Comparison of the final state cross-section which obtained from PAW and ROOT

Maximum cross section	PAW	error	ROOT	error
σ_h	41.05	0.20	41.00	5.6
σ_e	1.974	0.027	1.966	1.340
σ_μ	1.972	0.018	2.007	1.260
σ_τ	1.945	0.021	1.921	1.247

Table 4. Comparison of the z-properties which obtained from PAW and ROOT

Properties	PAW	error	ROOT	error
m_Z	91.11	0.02	91.11	0.50
Γ_Z	2.487	0.044	2.457	1.422

Since this is the first time of convert *"Z^0 Resonance Analysis Program"* from PAW to ROOT thus, the programs in this work have one weak point. As seen from the table 3 and 4, the errors from programs created in ROOT are larger than ones from PAW. This might be because of two reasons, one is the difference between Breit –Wigner formula in PAW and ROOT, and second one is the difference in error-computing method. To calculate the error, sample least square is used in PAW but in ROOT the error is computed from the square root of the bin content. This point is still waiting to figure out.

CONCLUSION

"Z^0 Resonance Analysis Program" is now available in ROOT. The main procedure in this work is still the same as one which is available in PAW. First step, the $e^+e^- \rightarrow f\,\bar{f}$ events detected from the Opal detector will be selected by cutting criteria which is the the energy loss in electromagnetic calorimeter, number of charged tracks, momentum of charged particles, etc. Next, the number of events for reaction $e^+e^- \rightarrow f\,\bar{f}$ is extracted and cross sections of fermions pairs are calculated. Finally, by using a Breit – wigner distribution, Z^0 resonance as well as the mass and the width of Z boson are determined. From this work, m_Z =91.11 ± 0.50 GeV, Γ_Z = 2.457 ± 1.422 GeV which is in agreement with the last version in PAW except the errors which are larger than ones in PAW.

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