Particle physics research for first year students

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Abstract. The first physics laboratory course for undergraduate students at the University of Oslo is briefly presented. The last part of the course introduces the students to currently ongoing research projects at the department of physics. An exercise in practical data analysis relating to a high energy physics experiment at the LEP accelerator at CERN is discussed in some detail. The selection of $e^+e^- \rightarrow e^+e^-(+n\gamma)$ events for luminosity determination is discussed. The students study event kinematics and detector performance. The entire exercise is based on real data.

Sammendrag. Det første laboratoriekurset for laveregradsstudenter ved Universitetet i Oslo blir kort presentert. Den siste delen av kurset lar studentene komme i kontakt med pågående forskningsprosjekter ved Fysisk Institutt. En øvelse i praktisk data-analyse i forbindelse med et høyenergifysikk-eksperiment ved LEP-akseleratoren ved CERN diskuteres i noen detalj. Utvelgelse av $e^+e^- \rightarrow e^+e^-(+n\gamma)$ hendelser for luminositetsbestemmelse blir diskutert. Studentene studerer kinematikk og detektoregenskaper. Hele øvelsen er basert på reelle data.

1. Introduction

As pointed out in [1], undergraduate students seldom come in close contact with frontline particle physics research. The aim of this note is to point out that laboratory exercises relating to current active research projects at the department of physics have been offered to first year physics students at the University of Oslo for almost ten years. In particular an exercise in particle physics data analysis is briefly described.

First year physics students start the first semester on a full year laboratory course being run in parallel to, but independent from, the theoretical courses. The course is different from earlier physics laboratory courses at the department in that it aims at educating the students in the techniques of measuring, completely independent from their progress in theoretical courses. The measurement and its description are the central points, and the students do measurements on a variety of electric and electronic systems, often without knowing the details of the underlying physics. After one year and twenty laboratory experiments, the students are offered (and required !) to choose one out of typically eight exercises which are offered by the various research groups at the department [2]. The selection of experiments is time dependent and reflects the research activities of the research groups.

Most of the exercises consist of practical measurements, covering subjects from biophysics, cosmic physics, solid state and structural physics, and low energy nuclear physics. One of the exercises, however, is a first introduction to some of the techniques of practical data analysis. That exercise, which has been offered yearly since 1991, is described in some detail in the next section.

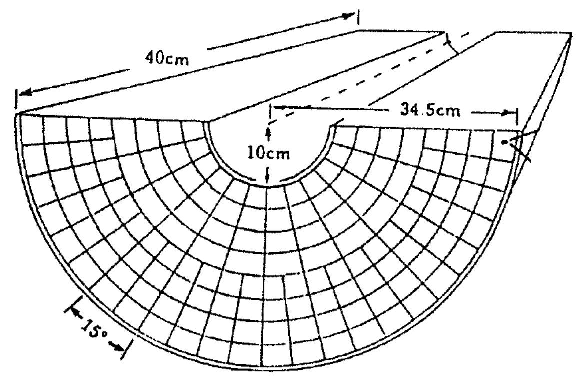

Figure 1. A SAT calorimeter halfbarrel. Each halfbarrel is subdivided into 144 readout elements.

2. An undergraduate exercise studying Bhabha scattering at LEP

Contrary to the other exercises performed throughout the year-long course, this exercise consists of pure data analysis.

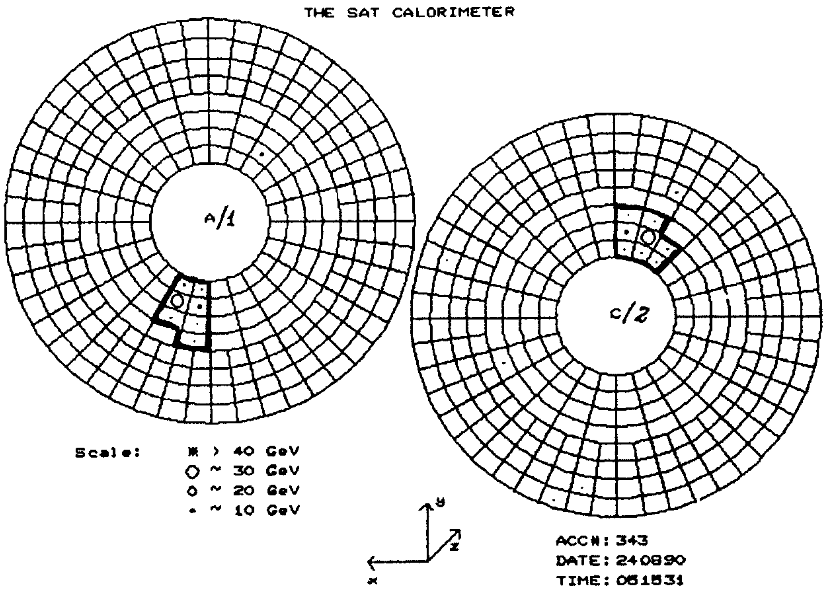

Figure 2. Energy depositions in the two calorimeters for a Bhabha event. The size of the rings which are drawn inside the hit elements is proportional to the deposited energy. Elements inside the borders drawn with a thick line are combined to clusters.

2.1. Background material included in the text of the exercise.

The students are first introduced to the field of high energy physics as performed on e^+e^- colliders. After a short introduction to the DELPHI experiment [3] at the LEP [4] accelerator, the term *luminosity* is introduced as the constant L relating the event rate $\dot{N}(t)$ of a given process at time t to the cross section σ of that process: $\dot{N}(t) = L(t)\sigma$. To determine an unknown cross section σ from a given efficiency corrected number of events N_{eff}, one needs to measure the time-integrated luminosity $\mathcal{L} = \int_{\Delta t} L(t)\mathrm{d}t$ where Δt denotes the duration of the data collection period. (The instantaneous luminosity L (in units of $\mathrm{cm}^{-2}\mathrm{s}^{-1}$) depends on the beam parameters in the accelerator, and is in general time dependent.) Thus

$$\sigma = \frac{N_{\text{eff}}}{\mathcal{L}} \tag{1}$$

It is then explained how one can count the effective number of events of a process with *known* cross section, and thus measure the time–integrated luminosity $\mathcal{L}$ from equation (1).

Interested students are offered a short popular talk which aims at introducing the Z^0 line shape measurements [5] and pointing out the crucial role played by the luminosity measurement in these measurements.

It is then pointed out that the process used for the luminosity measurement should satisfy a number of criteria:

- It should have a clear experimental signature with low background.
- It should have a large effective cross section (cross section integrated over the detector used)—at least of the same size as the largest cross sections which are to be measured.
- Its theoretical cross section should be known with high accuracy (better than the precision aimed for in the cross section measurements).

It is pointed out that small angle Bhabha scattering, i.e. the process

$$e^+e^- \to e^+e^-(+n\gamma) \tag{2}$$

where $n\gamma$ denotes radiated photons, fulfills these criteria.

The attention is then turned to the problem of detecting Bhabha events. In the DELPHI experiment the main luminosity monitor when this exercise was developped was the Small Angle Tagger (SAT). Since this consisted of two electromagnetic calorimeters [6], the principles of electromagnetic calorimetry are briefly sketched†. The two calorimeters are placed symmetrically with respect to the interaction point (the point where the electrons and positrons collide), with the entrance 230 cm away from the interaction point. Each calorimeter consists of two halfbarrels, fixed together to make up a full barrel (a cylindrical volume with an inner hole to allow for the beam tube. The nominal beam line

† In addition one of the calorimeters was equipped with a precise position detector in front, but since this is not included in the exercise it will not be mentioned further.

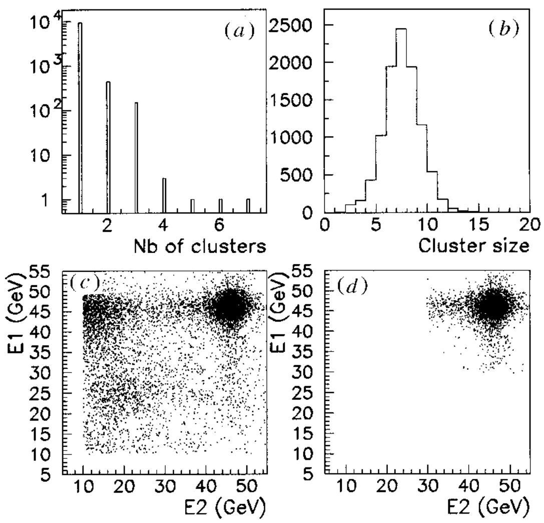

Figure 3. (a): Distribution of number of clusters per calorimeter. The data are observed to be largely dominated by one cluster per calorimeter (note the logarithmic scale). (b): Distribution of cluster size. (c): Energy in calorimeter 1 versus energy in calorimeter 2. No new cuts applied. Radiative tails and effects arising from a masking technique applied (see [5]) are clearly visible. (d): As in (c), but after the application of Bhabha event selection cuts (see the text).

coincides with the cylinder axis). The detector volume of each calorimeter is divided into 2×144 cells, and the energy depositions in each of these 288 (per calorimeter) cells are read out individually. One halfbarrel is shown in figure 1, including the layout of the read-out elements and some relevant dimensions.

Energy depositions in neighbouring elements are grouped into *energy clusters* as illustrated in figure 2. To each cluster is associated an energy, a radial and an azimuthal coordinate, and a cluster size (number of readout elements building up the cluster). The energy clusters form the basic entities on which the subsequent analysis is based.

The analysis is done with the CERN-developped Physics Analysis Workstation, or PAW, system [7]. A simple introduction to the necessary commands is given in terms of examples.

2.2. The steps of the practical exercise

The SAT data are organized in *ntuples*, fixed length strings of numbers which are interfaced to PAW. One ntuple corresponds to one event candidate. The first task in the exercise is to investigate and understand the structure of the ntuples. The students are instructed to use a simple and easily understandable fraction of the ntuples, which in addition contain book-keeping variables (dates, run numbers, event numbers, LEP fill numbers etc) and some variables for detector specialists only. The variables which the students work with are given in table 1.

2.2.1. Understanding the data. Bhabha event selection The students now are familiarizing themselves with the data. Simple plots of number of clusters per calorimeter, cluster size, and energy in calorimeter 1 versus energy in calorimeter 2 are made, as shown in figure 3 (*a*), (*b*), and (*c*). The plots are commented and explained in the exercise text. The students are asked to identify cuts which have been applied to the data before being written to the ntuples. The various structures in figure 3 (*c*) naturally induces a discussion on Bhabha event kinematics, radiative effects, and detector details. According to this discussion, a set of cuts for selecting Bhabha events is defined, and figure 3 (*d*) shows the energy-plot after application of the Bhabha selection. The part on Bhabha event identification is concluded by an empirical determination of the angular distribution of the scattered electrons. The students are instructed to plot the radial distribution, and fit an R^{-x} distribution to it. They are informed that the theory predicts x to be an integer number, and they find from the fit (easily performed in PAW) that $x = 3$, see figure 4.

2.2.2. Kinematics The simple process (2) allows some simple and instructive demonstrations of kinematics. In the absence of photons, the outgoing electrons (when no confusion is likely to arise, the term electron is used also for the positrons) are strictly back to

Table 1. The SAT ntuple variables which are used in the analysis.

Variable name	Meaning	Unit
NCL1	Nb of clusters in calorimeter 1	
NCL2	Nb of clusters in calorimeter 2	
E1	Energy of largest cluster, calorimeter 1	GeV
E2	Energy of largest cluster, calorimeter 2	GeV
R1	Radial position, largest cluster, calorimeter 1	cm
R2	Radial position, largest cluster, calorimeter 2	cm
Phi1	Azimuthal angle Φ, largest cluster, calorimeter 1	deg
Phi2	Azimuthal angle Φ, largest cluster, calorimeter 2	deg
Siz1	Cluster size, largest cluster, calorimeter 1	
Siz2	Cluster size, largest cluster, calorimeter 2	

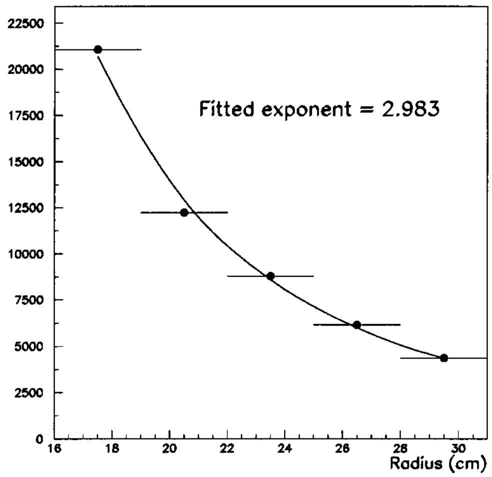

Figure 4. The radial distribution of Bhabha event energy clusters. A radial dependence $f(R)$ = constant $\times R^{-x}$ is fitted to the data. A value of $x = 2.983$ is found, consistent with the theoretical prediction of $x = 3$.

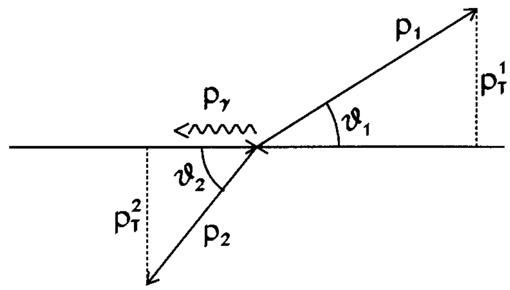

Figure 5. Kinematics of Bhabha event with initial state radiation. See the text.

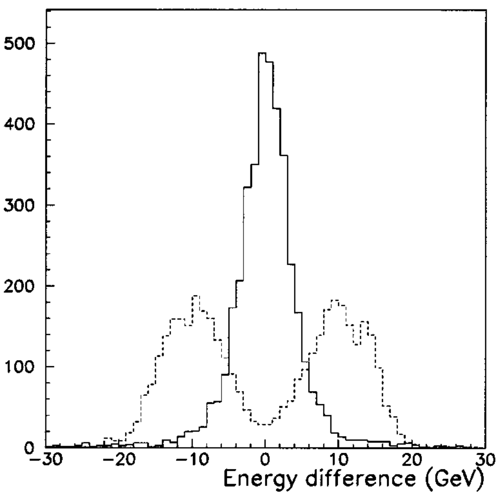

Figure 6. The dashed histogram shows the distribution of the energy difference between calorimeters 1 and 2 for Bhabha events with large difference in radial impact, leading to an event sample with initial state radiation. Large radiative effects are seen. The solid histogram shows, for the same events, the difference between the energy in calorimeter 1 and the energy expected from the energy in calorimeter 2 and the radial positions, using transverse momentum balance as explained in the text.

back, each carrying the beam momentum. This picture is modified when radiated photons are taken into account. Since the radiated photons have a large probability of being radiated at a very small angle with respect to the radiating electron, basically two topologies exist:

(i) The photon is radiated by a final state electron. In this case the electron and the photon will in general merge in the detector, and only in the relatively few cases where there is an appreciable angle between the electron and the radiated photon the effect will be observable.

(ii) The photon is radiated by an initial state electron, and escapes undetected down the beam pipe. This corresponds effectively to a collision between an electron and a positron of different energies. However, since in general the photon is emitted at a small angle with respect to the radiating electron, no transverse momentum in the final state electron positron system is created—i.e. their transverse momenta p_T are to a good approximation balancing each other, as illustrated in figure 5.

So in both cases above we have approximate transverse momentum balance, which can be expressed $p_1 \sin\theta_1 = p_2 \sin\theta_2$. In the approximation of small angle and vanishing electron mass, this can be expressed

$$E_1 R_1 = E_2 R_2 \tag{3}$$

The students are then instructed to illustrate this by studying events with photon radiation. Such events are selected by requiring a large acolinearity in the event by demanding $|R_1 - R_2| > 3$ cm. In the same figure is plotted first the energy difference $E_1 - E_2$ which show large radiative effects, and second, the difference between E_1 and the value of E_1 expected from E_2, R_1, and R_2 via equation (3), i.e. they plot $E_1 - E_2 R_2/R_1$ which clearly illustrates the approximate charged track transverse momentum balance. The plots are shown in figure 6.

2.2.3. Understanding the detector from data The final part of the exercise points out to the students that a lot can be learnt about a detector by studying the data which the detector provides. As a simple introduction to this subject, they are asked to find out from the data whether the two halfbarrels (figure 1) are connected in the vertical or horizontal plane. This is an easy task, since for several reasons there are very few events close to the junction of the two halves. Then the exercise finally brings up the question of energy calibration. How do we know that the measured energies are correct, and with which precision are the energies determined ?

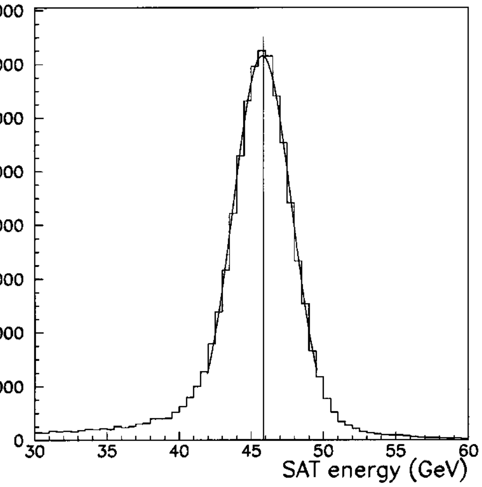

Figure 7. The SAT energy spectrum for Bhabha events. A Gaussian is fitted to the peak. The vertical line indicates the average beam energy as measured at the LEP accelerator.

This allows for a general discussion on the importance of calibration of physics measurement devices, and naturally also leads to an introductory discussion on statistics, including the Gaussian distribution.

The measurement is based on the fact that the scattered electrons' energies cluster sharply around the precisely known LEP beam energy. The scatter of the reconstructed energies in the SAT calorimeter is completely dominated by the detector resolution. The students are asked to plot the SAT energies for Bhabha events and fit a Gaussian to the peak (by a straightforward command in PAW). The result is as in figure 7, and from the parameters of the fit the students determine the absolute and relative energy resolution.

3. Conclusions

The first physics laboratory course which undergraduate students meet at the University of Oslo was briefly presented. It was pointed out that this course introduces the students to current research projects in physics. It is believed that this represents an important stimulus to the students, in addition to establishing potentially useful connections between students and active researchers at an early stage of the study. An exercise in practical data analysis from a currently ongoing high energy physics experiment at LEP was discussed in some detail.

Acknowledgments

The work by A I Vistnes in the design and initial phase of the laboratory course is warmly acknowledged. The author is also grateful to his colleagues in the DELPHI experiment, and in particular to the members of the SAT group.

References

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[2] The laboratory course, including the system with current research project exercises, was designed by Dr A I Vistnes.
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