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PHYSIKALISCHES
INSTITUT

Advanced Physics Laboratory Course

II

E213 Analysis of Z^0 Decay

Last Revision: February 2021

Contents

Chapter 1

Introduction

The objective of the experiment *E213 Analysis of Z^0 Decays* is to give you a first insight into the analytical methods of experimental particle physics. Furthermore we want to acquaint you with the following topics:

- Elementary particles, their properties and interactions
- Interaction of particles with matter
- Particle detectors
- Particle identification
- e^+e^- physics in storage rings at high energies
- Analysis methods in modern particle physics

During this experiment you will analyse data obtained from e^+e^- collisions with the OPAL (Omni-Purpose Apparatus for LEP) detector at the LEP (Large Electron-Positron Collider) storage ring. Computer workstations will be used to access these data and to evaluate them on a graphical and statistical basis.

Apart from the instructions for the experiment, this script also contains a few introductory chapters about particle detectors and elementary particle physics needed for the conducting the experiment and the analysis of the data. We recommend reading this script in the order as is.

For accesing data related to particles such as masses, cross-sections, branching ratios etc. the **PDG (Particle Data Group)** Booklet can be used. Although printed versions are often available it can be faster to use the PDG web page (`http://pdg.lbl.gov/`) for accessing information. A 'live' version of PDG web page (`http://pdglive.lbl.gov/Viewer.action`) also provides interactive tables and items that can be used to access the needed information conveniently. The following books can be used for learning the topics in deeper detail:

- General/Theory
  - D. H. Perkins, *Introduction to High Energy Physics*, Cambridge University Press
  - M. D. Schwartz, *Quantum Field Theory and the Standard Model*, Cambridge University Press
  - D. Griffiths, *Introduction to Elementary Particles*, Wiley-VHC
  - M. Thomson, *Modern Particle Physics*, Cambridge University Press
  - D. V. Schroeder and M. E. Peskin, *An Introduction To Quantum Field Theory*, CRC Press
- Particle Detectors

- K. Kleinknecht, *Detectors for Particle Radiation*, Cambridge University Press
- W. R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, Springer-Verlag

- Statistics and Data Analyses
  - R. J. Barlow, *Statistics: A Guide to the Use of Statistical Methods in the Physical Sciences*, Wiley
  - O. Behnke, K. Kroninger, G. Schott and T. Schorner-Sadenius, *Data Analysis in High Energy Physics: A Practical Guide to Statistical Methods*, Wiley-VCH

1.1 Experimental Procedure

The experiment E213 consists of two main tasks. In the first part single events are analyzed in detail based on graphical event displays, in order to learn how to associate them with certain processes. In the second part a more quantitative approach is applied and events are analyzed using statistical techniques in order to answer physical questions, e.g. the measured "energy" in the calorimeters or the number of charged tracks.

1.1.1 Part I: Graphic Analysis of Events

The aim of this part of the experiment is to get acquainted with the properties of the various Z^0 particle decay modes using single events. Above all, you should learn how to find criteria that allow to classify the different events. For this task it is necessary to have a good understanding of the detector characteristics and their signatures.

1.1.2 Part II: Statistical Analysis of Z^0 Decays

Using the knowledge obtained in Part I you will then analyse large amounts of data. The main problems to be solved are the measurements of the resonant parameters of the Z^0 boson (mass, width) and of the *Weinberg angle*, which can be measured from the forward-backward-asymmetry in the reaction $e^+e^- \to \mu^+\mu^-$.

Chapter 2

e^+e^- Interactions at High Energies

2.1 Elementary Particles and Their Interactions

It has always been an important aim in the world of physics to look for a unified theory that explains the multitude of observed natural phenomena. It turned out that in principle all processes could be explained with only a few basic modules, which, according to present day knowledge, are the structureless elementary particles and their respective interactions. The elementary particles are classified into two groups according to their spin: the fermions and the bosons. The fermions, which are themselves divided up into three generations of quarks and leptons, form the fundamental basic modules of matter, whereas bosons in the form of gauge bosons (spin=1), act as the mediators of the fundamental interactions: Electromagnetic, Weak and Strong interactions. These interactions are described in the so called Standard Model by means of quantum field theories that are based on the principle of local gauge invariance. The strength of the interactions is described by the respective coupling constant. The fourth fundamental interaction, gravitation, is too weak to play any role in particle physics.

The theory of electroweak interactions (Glashow, Salam and Weinberg) was impressively confirmed in 1983 at CERN with the discovery of the massive gauge bosons $W^{\pm}$ and Z^0 (gauge bosons of the weak interaction). A promising gauge theory, the Quantum Chromodynamics (QCD) was developed in analogy describing the interactions between quarks. This theory requires eight massless gauge bosons know as gluons, as the mediators for the strong interaction.

A particularly successful process for testing the basic statements made by the Standard Model is the annihilation of electrons and positrons. The great advantage of e^+e^- storage rings in comparison with hadron storage rings is the fact that the states before and after the collision are known precisely. Therefore one can calculate the reaction cross section for each channel within the known theories.

According to the Standard Model, e^+e^- collisions yield lepton-antilepton and quark- antiquark pairs most of the time. Quarks and radiated gluons then fragment into hadrons.

2.1.1 Electroweak Interaction

Quantum Electrodynamics (QED) is a gauge theory and describes the interaction between charged particles through the exchange of photons. An equivalent theory for the weak interaction was sought after. The theory introduced at first involved the W^+ and W^- bosons and described only processes in the low energy range. Searching for a gauge theory the SU(2) symmetry was chosen, which in turn led to the introduction of three gauge bosons W^+, W^- and W^0. This led to an important prediction: the existence of neutral currents (i.e. exchange of a W^0). The coupling strength of this field is g (corresponding to the charge e in the electric field), with the following association:

$$G_F = \frac{\sqrt{2} \cdot g^2}{8M_W^2} = 1.1663 \cdot 10^{-5}\mathrm{GeV}^{-2} \tag{2.1}$$

where $M_W = W$ is the boson mass.

At high energies the coupling strength of the field does not differ much from that of the electromagnetic interaction. This encouraged a unified description of both theories. A second symmetry U(1) with the field quantum Y^0 was introduced for the electromagnetic interaction. The SU(2) x U(1) symmetry acts on left-handed fermion pairs:

$$(e^- \nu_e) \quad (\mu^- \nu_\mu) \quad (\tau^- \nu_\tau) \quad (d\ u) \quad (s\ c) \quad (b\ t)$$

The theoretical gauge particles are identical with observable states only in the case of the charged W bosons. Therefore one would assume that the Y^0 is identical with the photon. But this would mean that the Y^0 couples to neutrinos which doesn't occur in nature. As a result one has to assume that the photon field is a quantum mechanical mixture of the W^0 and the Y^0 fields. The result is the Z^0 field which is perpendicular to the photon field. The mixing angle is called *Weinberg angle.*

In the original formulation of the theory all bosons are massless. Then the problem arises to reformulate the theory in such a way that three of the four particles obtain a mass but without changing the original properties of the theory. This is done with the so called Higgs-Kibble mechanism (spontaneous violation of symmetry) which leads to the prediction of a new particle with spin 0, the Higgs boson. This prediction was confirmed, again at CERN in 2012 with the discovery of the Higgs Boson. Peter Higgs and François Englert was awarded Nobel Prize on 2013 "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

The three parameters of the electroweak theory were at first measured at low centre-of-mass energies:

- α, the electromagnetic fine structure constant
- G_F, Fermi's constant
- $\sin^2\theta_{\mathrm{w}}=e^2/g^2$, derived from the comparison of the reactions of neutrinos with $W^\pm$ (charged current) and Z^0 exchange (neutral current).

All other constants can be expressed in terms of these parameters. Example: the mass of the W boson is related to the coupling constant and the Weinberg angle θ_W:

$$M_W^2 \cdot \sin^2\theta_W = \frac{\sqrt{2} \cdot g^2}{8G_F} \cdot \sin^2\theta_W = \frac{\pi \cdot \alpha}{\sqrt{2}G_F} \tag{2.2}$$

For the masses of the gauge bosons $W^\pm$ and Z^0 one finds the following relation:

$$\frac{M_W}{M_Z} = \cos\,\theta_W \tag{2.3}$$

The masses of the fermions and of the Higgs boson can not be predicted by the theory.

2.1.2 Strong Interaction

Quantum Chromodynamics (QCD) is a gauge theory for the strong interaction just as the QED is for the electroweak interaction. Instead of the electric charge being the source of the fields, we have the colour "charges" (red, green and blue) of the quarks. Each quark has an inner degree of freedom which allows it to take one of three different states. Forces only act between particles with colour. The field quanta are particles without mass and with spin 1, called gluons. The symmetry for the strong interaction is the group SU(3), which implies the existence of eight different gluons.

Opposed to the photon which carries no electric charge, gluons themselves carry colour charges composed of a colour and an anticolour index. Therefore gluons can experience strong interaction among themselves as opposed to photons. As a consequence, the strong interaction becomes very weak at small distances (asymptotic freedom) and very strong at greater distances ($>$ a few 10^{-13}cm) (see Appendix D).

The QCD coupling constant α_s replaces the electromagnetic coupling constant α which characterizes the strength of the force. As in the QED, the vacuum polarization in the QCD leads to a running coupling constant as $\alpha_s(\mathrm{q}^2)$. But, as already has been mentioned, $\alpha_s(\mathrm{q}^2)$ becomes smaller with larger q^2, opposite to the QED :

$$\alpha_s(\mathrm{q}^2) = \frac{12\pi}{(33 - 2N_\mathrm{f}) \cdot \log(\frac{\mathrm{q}^2}{\Lambda^2})} \tag{2.4}$$

Λ is the scale parameter of the QCD which has to be measured experimentally, N_f is the number of types of quarks (also called flavours) which can be observed in the process ($N_\mathrm{f} = 5$ at $E_\mathrm{CMS} \approx M_Z$). and q^2 is the characteristic momentum transfer squared. For small q^2, i.e. large distances, α_s becomes so large that the interaction cannot be described by means of perturbative theories. Phenomenological models must be used instead.

An important application of the QCD is the description of the hadronic final states after an e^+e^- annihilation. This process is shown schematically in Fig 2.1. In the first step a quark-antiquark pair is produced which flies apart, thereby a strong force between the quarks arises. Due to the high energy in the QCD field created between the quarks, further quarks can be produced.

This process repeats itself until q^2 becomes small enough so that the quarks form colourless hadrons. These follow approximately the same paths as the original quarks. Two particle jets appear. At high centre-of-mass energies we find more gluon radiation processes involving hard gluons. This can result in the creation of more than two jets: These cascade-like transitions from quarks with colour to colourless (white) hadrons, also called fragmentation process, cannot be observed directly. Only the stable particles in the final state can be seen in the experiment.

2.2 Physics at Energies Near Z^0 Resonance

In e^+e^- interactions several processes occur:

- Elastic e^+e^- scattering (Bhabha scattering)
- Annihilation of the e^+e^- pair into a virtual photon or Z^0 which decays into a fermion-anti-fermion pair.
- Inelastic e^+e^- scattering with two virtual photons, one coming from the incoming electron, one from the incoming positron. The two photons can interact and produce hadrons (two-photon-processes).
- Annihilation of the e^+e^- pair into two or three real photons.

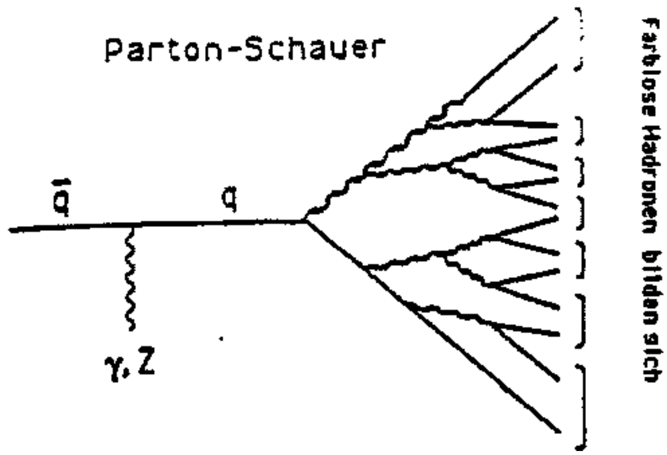


Figure 2.1: Schematical Illustration of the Fragmentation

In all of these processes it is possible that the e^+ or the e^- radiates one or more real photons. The total cross section depending on the energy is shown in Figure 2.2.

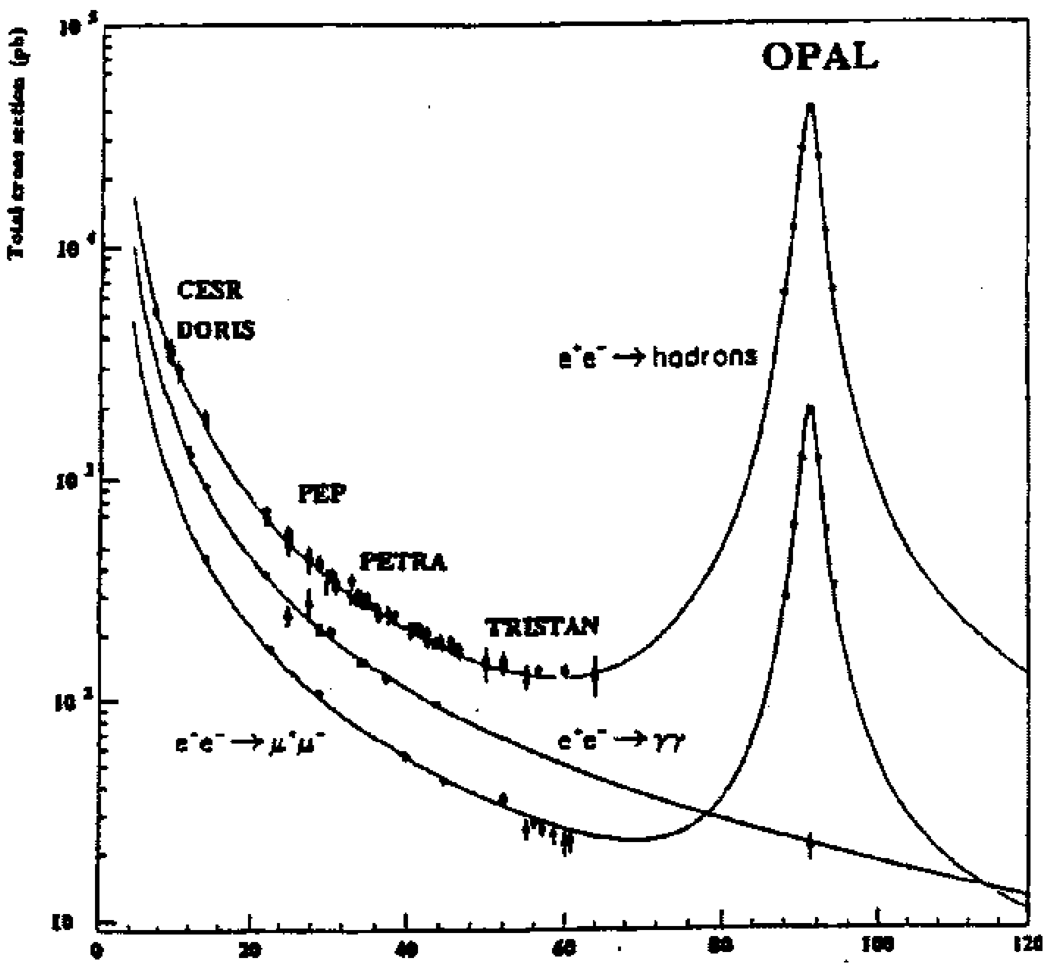


Figure 2.2: Total cross section as a function of center-of-mass energy.

The production of fermion-pairs in e^+e^- interactions, i.e. the process $e^+e^- \to f\bar{f}$, mediated by the neutral gauge bosons, photon and Z^0, are well described in the Standard Model. The electromagnetic interaction between charged fermions is generated from the electric charge Q_f of the fermions. Concerning the weak neutral current, every fermion has two couplings: a vector coupling g_V and an axial vector coupling g_A:

$$g_V^f = I_3^f - 2Q_f \sin^2\theta_W \tag{2.5}$$

$$g_A^f = I_3^f \tag{2.6}$$

I_3^f is the third component of the weak isospin (weak charge). If the centre-of-mass energy is near the Z^0 mass, real Z^0 bosons can be produced and the cross section is resonant ($M_{Z^0}/\Gamma_{Z^0} \approx 10^3$). The final states can contain the following fermions:

- Charged Leptons: e, μ, or τ
- Neutrinos: ν_e, ν_μ, or ν_τ
- Quarks: u, d, s, c, or b (t is too heavy)

The most important properties of the Z^0 boson are its mass and the partial decay widths. The total decay width is the sum of all partial decay widths:

$$\Gamma_Z = \Gamma_e + \Gamma_\mu + \Gamma_\tau + \Gamma_h + \Gamma_\nu + \Gamma_{\text{unknown}} \tag{2.7}$$

Up to now, Γ_{unknown} is consistent with zero. From Equation 2.7 it is possible to determine the number of generations of light neutrinos.

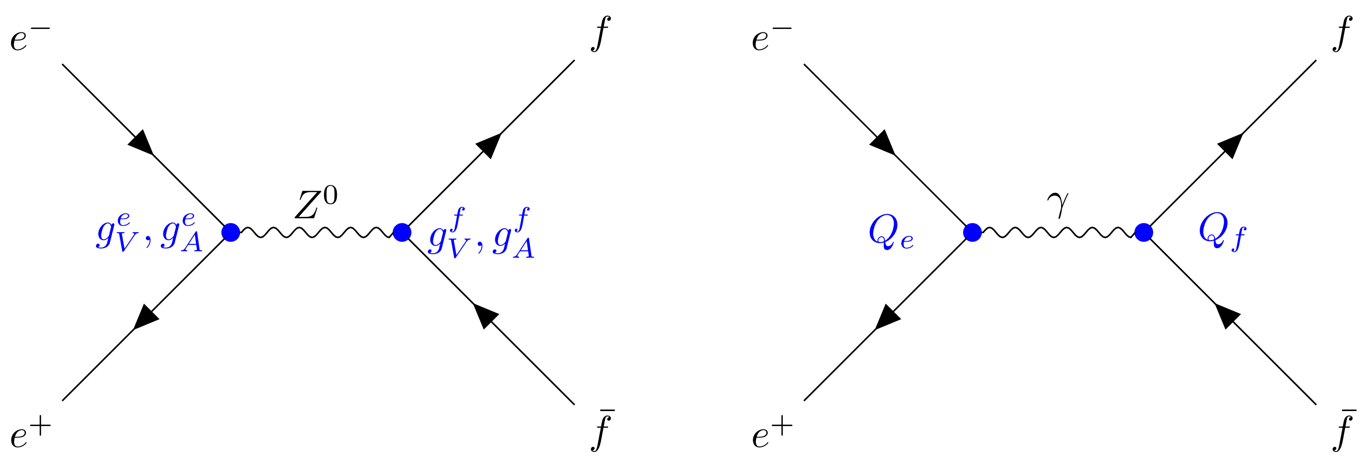
The Feynman-diagrams at lowest order for the process $e^+e^- \to f\bar{f}$ are shown in Figure 2.3. The cross section for this process consists of a pure Z^0 part, a pure γ part and an interference part:

$$\sigma(e^+e^- \to f\bar{f}) = \sigma_Z + \sigma_\gamma + \sigma_{Z^0\gamma} \tag{2.8}$$

Setting the fermion masses equal to zero one obtains:

$$\begin{aligned} \sigma_{Z^0} &= \sigma_{\text{QED}} \cdot (v_e^2 + a_e^2) \cdot (v_f^2 + a_f^2) \cdot \mid \chi(s) \mid^2 \\ \sigma_\gamma &= \sigma_{\text{QED}} \cdot Q_f^2 \\ \sigma_{Z^0\gamma} &= \sigma_{\text{QED}} \cdot (-1) \cdot Q_f \cdot v_e \cdot v_f \cdot \text{Re}(\chi(s)) \end{aligned} \tag{2.9}$$

using the following abbreviations:



(a) $e^+e^- \to e^+e^-$ (b) $e^+e^- \to \mu^+\mu^-$

Figure 2.3: Feynman diagrams for $e^+e^- \to f\bar{f}$.

$$\begin{aligned}
\sin^2\theta_W &= 0.2312 \\
M_Z &= 91.182 \text{ GeV} \\
N_c^f &= \text{Colour Factor (1 for Leptons, 3 for Quarks)} \\
Q_f &= \text{Electric charge in units of the elementary charge} \\
\chi(s) &= \tfrac{s}{(s-M_Z^2)+is\Gamma_Z/M_Z} \text{ (Propagator)} \\
\sigma_{QED} &= \tfrac{4\pi}{3}\cdot\tfrac{\alpha^2}{s}\cdot N_c^f \\
v_f &= \tfrac{(I_3^f-2Q_f\sin^2\theta_W)}{(2\sin\theta_W\cos\theta_W} = \tfrac{g_V^f}{(2\sin\theta_W\cos\theta_W)} \\
a_f &= \tfrac{I_3^f}{(2sin\ \theta_W\ cos\theta_W)} = \tfrac{g_A^f}{(2\sin\ \theta_W\ \cos\theta_W)} \\
\text{s} &= E_{\text{CMS}}^2 = \text{Square of the center-of-mass energy}
\end{aligned}$$

At the Z^0 resonance the cross section of $e^+e^- \to f\bar{f}$ is dominated by the contribution from σ_Z which follows the Breit-Wigner distribution for spin-1 particles. Using the partial width of the fermions,

$$\Gamma_f = \frac{N_c^f}{3}\cdot\alpha(M_Z^2)\cdot M_Z(v_f^2+a_f^2) = \frac{N_c^f\cdot\sqrt{2}}{12\pi}\cdot G_F\cdot M_Z^3((g_V^f)^2+(g_A^f)^2) \tag{2.10}$$

the cross section can be written as

$$\sigma_f = \frac{12\pi\cdot\Gamma_e\cdot\Gamma_f}{s\cdot M_Z^2}\cdot\mid\chi(s)\mid^2 = \frac{12\pi}{M_Z^2}\cdot\frac{s\cdot\Gamma_e\cdot\Gamma_f}{(s-M_Z^2)^2+(s^2\frac{\Gamma_Z^2}{M_Z^2})} \tag{2.11}$$

Near the resonance the above formula reduces to ($s = M_Z^2$)

Channel	Partial Width
$\Gamma_e = \Gamma_\mu = \Gamma_\tau = \Gamma_\ell$	83.8 MeV
$\Gamma_{\nu_e} = \Gamma_{\nu_\mu} = \Gamma_{\nu_\tau} = \Gamma_\nu$	167.6 MeV
$\Gamma_u = \Gamma_c$	299 MeV
$\Gamma_d = \Gamma_s = \Gamma_b$	378 MeV

Table 2.1: Decay width for fermion pairs omitting the fermion masses.

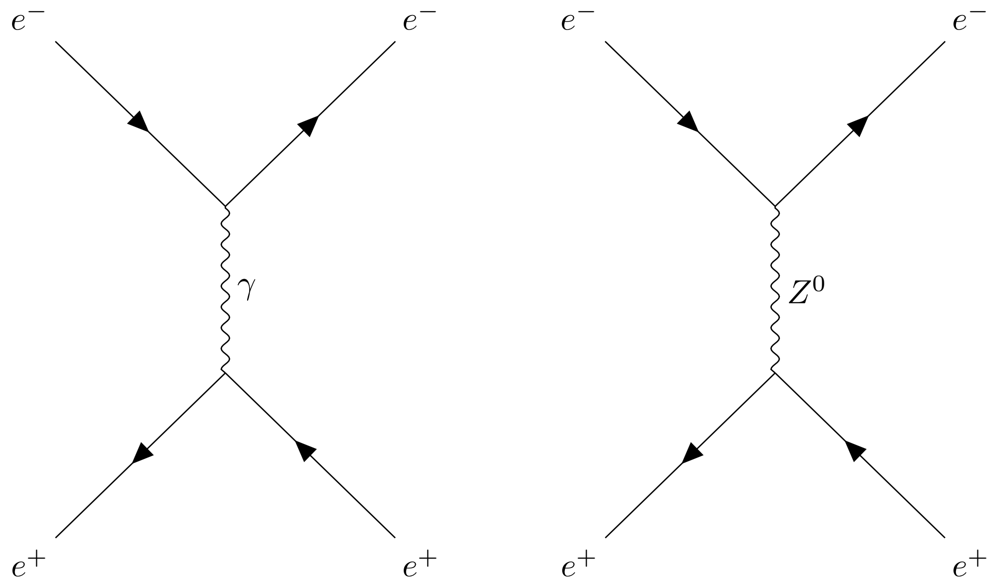
$$\sigma_f^{\text{peak}} = \frac{12\pi}{M_Z^2}\cdot\frac{\Gamma_e}{\Gamma_Z}\cdot\frac{\Gamma_f}{\Gamma_Z} \tag{2.12}$$

The partial decay widths predicted from theory are given in Table 2.1.
In the reaction $e^+e^- \to e^+e^-$ also t-channel diagrams contribute to the total cross section (Figure 2.4). For large scattering angles Θ (defined as the angle between the incoming and the outgoing electron) the s-channel is dominant, $\frac{d\sigma}{d\Omega} \sim (1+\cos^2\Theta)$, whereas for small angles Θ the t-channel is dominant, $\frac{d\sigma}{d\Omega} \sim (1-\cos\Theta)^{-2}$.

2.3 Forward-Backward Asymmetry $A_{\mathbf{FB}}$

At lowest order of perturbation theory the differential cross section for the reaction $e^+e^- \to f\bar{f}$ is given by

$$\frac{d\sigma_f}{d\Omega} = \frac{\alpha^2\cdot N_c^f}{4s}\{F_1(s)\cdot(1+\cos^2\Theta)+2F_2(s)\cdot\cos\Theta\} \tag{2.13}$$



(a) Photon (b) Z^0 Boson

Figure 2.4: Scattering diagrams (t-channel) for the $e^+e^- \rightarrow e^+e^-$.

with

$$F_1(s) = Q_f^2 - 2v_e \cdot v_f \cdot Q_f \cdot \mathrm{Re}(\chi) + (v_e^2 + a_e^2) \cdot (v_f^2 + a_f^2) \cdot |\chi|^2 \tag{2.14}$$

$$F_2(s) = -2a_e \cdot a_f \cdot Q_f \cdot \mathrm{Re}(\chi) + 4v_e \cdot a_e \cdot v_f \cdot a_f \cdot |\chi|^2 \tag{2.15}$$

In this experiment you will measure the forward-backward asymmetry A_{FB} in the process $e^+e^- \rightarrow \mu^+\mu^-$. Experimentally, the asymmetry can be determined from the cross sections in the forward and the backward hemispheres (Θ is the angle between the incoming positron and the outgoing μ^+):

$$\begin{aligned} A_{\mathrm{FB}}^f &= \frac{\left(\int_0^1 \frac{d\sigma}{d\cos\Theta} d\cos\Theta - \int_{-1}^0 \frac{d\sigma}{d\cos\Theta} d\cos\Theta\right)}{\left(\int_0^1 \frac{d\sigma}{d\cos\Theta} d\cos\Theta + \int_{-1}^0 \frac{d\sigma}{d\cos\Theta} d\cos\Theta\right)} \\ &= \frac{3}{4}\frac{F_2}{F_1} \end{aligned} \tag{2.16}$$

Above and below the Z^0 resonance maximum the asymmetry is dominated by the interference term F_2, and A_{FB} can approximately be written as

$$A_{\mathrm{FB}}^f \simeq \frac{-3}{2} \frac{a_e \cdot a_f \cdot Q_f \cdot Re(\chi)}{(v_e^2 + a_e^2) \cdot (v_f^2 + a_f^2)} \tag{2.17}$$

This contribution is zero if the centre-of-mass energy is exactly on the resonance maximum, thus for $\sqrt{s} = M_{Z^0}$ the asymmetry A_{FB} reduces to

$$A_{\mathrm{FB}}^{f,\mathrm{peak}} = 3 \ \frac{v_e \cdot a_e}{(v_e^2 + a_e^2)} \ \frac{v_f \cdot a_f}{(v_f^2 + a_f^2)} = 3 \ \frac{(v/a)_e}{[1 + (v/a)_e^2]} \ \frac{(v/a)_f}{[1 + (v/a)_f^2]} \tag{2.18}$$

For leptons the ratio $v_\ell/a_\ell = 1 - 4\sin^2\theta_W$ is very small, leading to a small asymmetry on the resonance:

$$A_{\mathrm{FB}}^{\ell,\mathrm{peak}} \simeq 3 \ (v_\ell/a_\ell)^2 \tag{2.19}$$

From the measurement of A_{FB} at the resonance maximum it is thus possible to directly calculate v_ℓ/a_ℓ and $\sin^2\theta_W$.

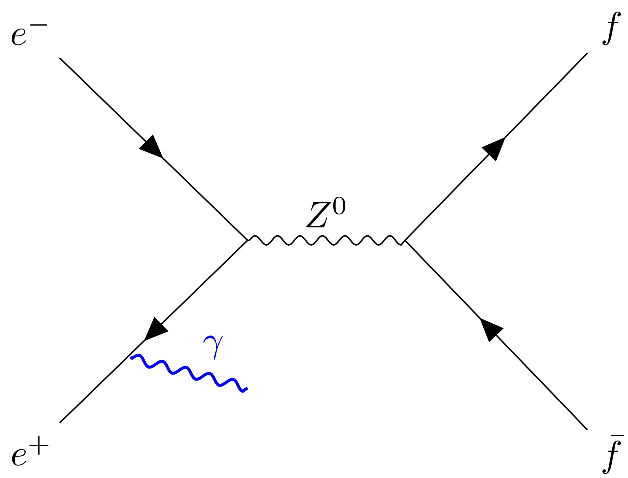
2.4 Radiative Corrections

For making a comparison of experimental results with theoretical predictions, one has to take into account corrections due to detector inefficiencies and cuts. On the other hand the lowest level of perturbation theory (Born level/approximation) might not be sufficient with regard to the high centre-of-mass energy at LEP and the aspired precision of testing the Standard Model. Therefore further corrections (radiative corrections), i.e. higher order Feynman diagrams have to be taken into account. One distinguishes between real, virtual (electroweak) and QCD-corrections.

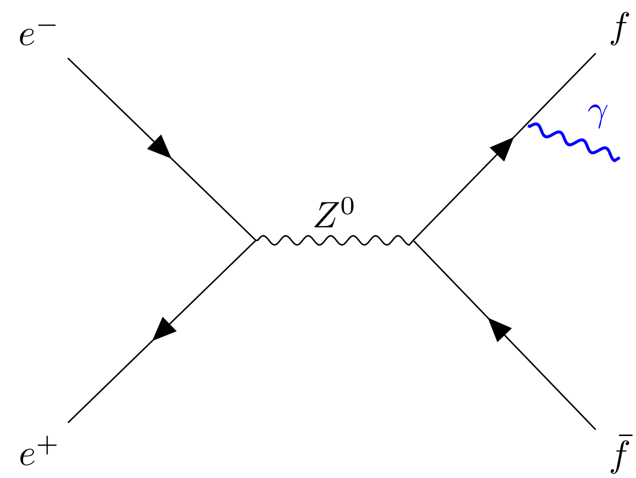
The real radiation processes (QED) are composed of the *initial state radiation* (ISR), the *final state radiation* (FSR), and the interference between both effects (Figure 2.5).

Virtual radiation processes (vertex and propagator corrections) are characterized; unlike the Bremsstrahlung corrections (real photon radiation), by the same final state as in the Born approximation (Figure 2.6).

In case of hadronic final states, gluon radiation processes have to be taken into account (Figure 2.7). The shape and the maximum of the resonance curve are modified by these radiative corrections. For the process of photon radiation in the initial state (Figure 2.8), there exists a simple explanation for this: The radiation of photons reduces the center-of-.mass energy of the electron, or positron, or both, which is therefore different from $\sqrt{s}$. The exact calculations of the radiative corrections are very expensive in practice. For our purposes the changes in energies due to radiative corrections are listed in Table 5.9.



(a) Initial state radiation.



(b) Final state radiation.

Figure 2.5: Feynman diagrams for <u>real</u> QED radiative corrections.

2.5 Event Selection

The different final states can be distingushed with the help of the measured data in the detector. All fermion pairs with a mass smaller than $M_{Z^0}/2$ can be produced. We classify these final states into leptonic (e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$) and hadronic (decay into quark and antiquark pairs) states. These events can be categorized into 4 types, whose topologies in OPAL detector event display can be seen in Figure 2.9.

The main decay channel is the q$\bar{\text{q}}$ final state containing 88% of the observed events. A high number of charged track ($\approx$ 20% on average) and the high energy deposited in both calorimeters are typical for these

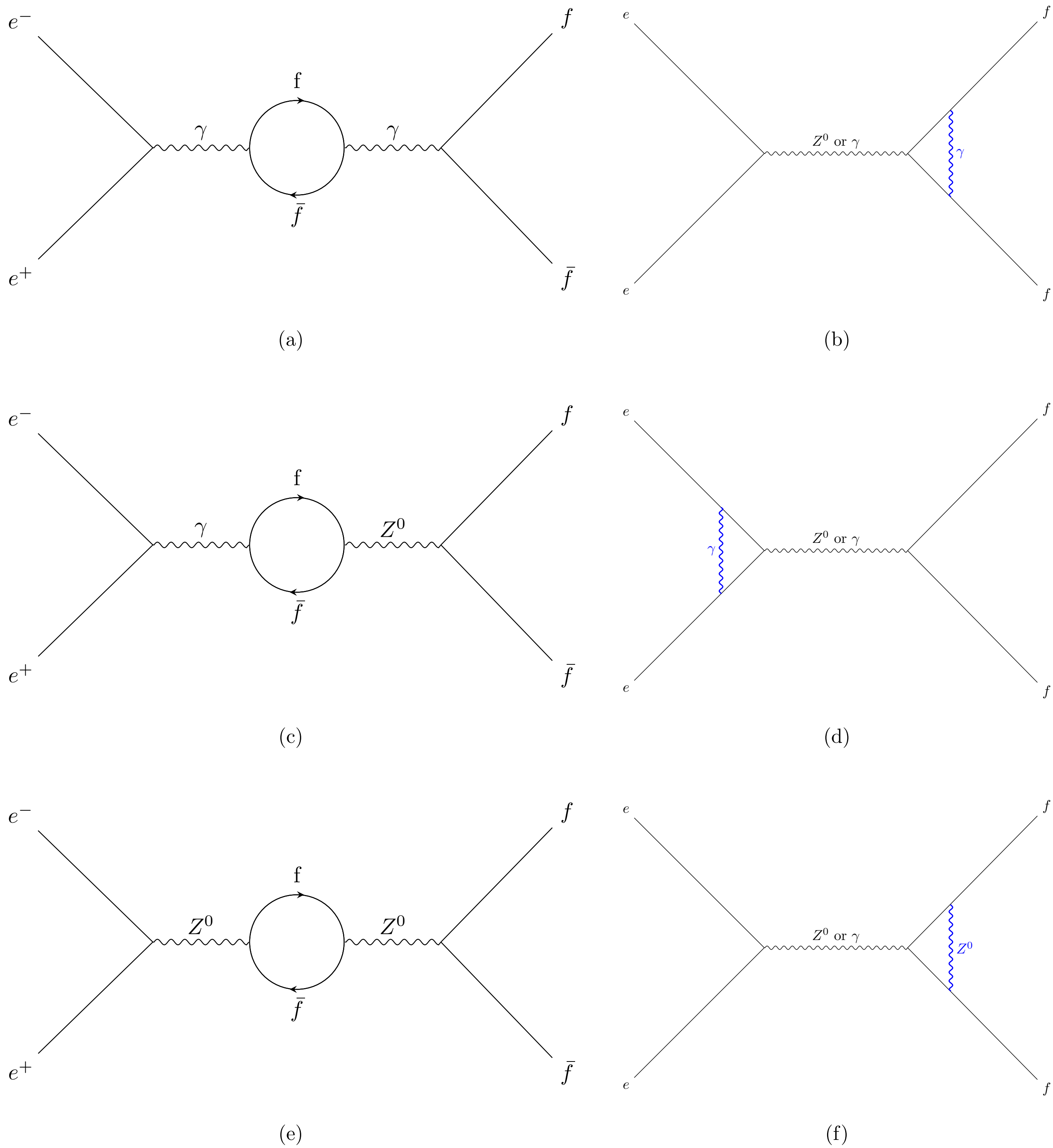


Figure 2.6: Feynman diagrams for virtual QED radiative corrections.

events. The charged hadrons form two (or more) particle bundles (jets). A further classification of the $q\bar{q}$ final states according to their flavours is complicated and would be too difficult for an Advanced Physics Laboratory Course.

In contrast to this, leptonic events show a small multiplicity. The e^+e^- events are distinguishable by two oppositly charged and almost collinear tracks whose momentum coincides more or less with that of the beam and by the energy measured in the electromagnetic calorimeter (ECAL). The $\mu^+\mu^-$ reactions differ from the e^+e^- reactions by depositing hardly any energy in neither calorimeter. The τ^- leptons are short lived particles

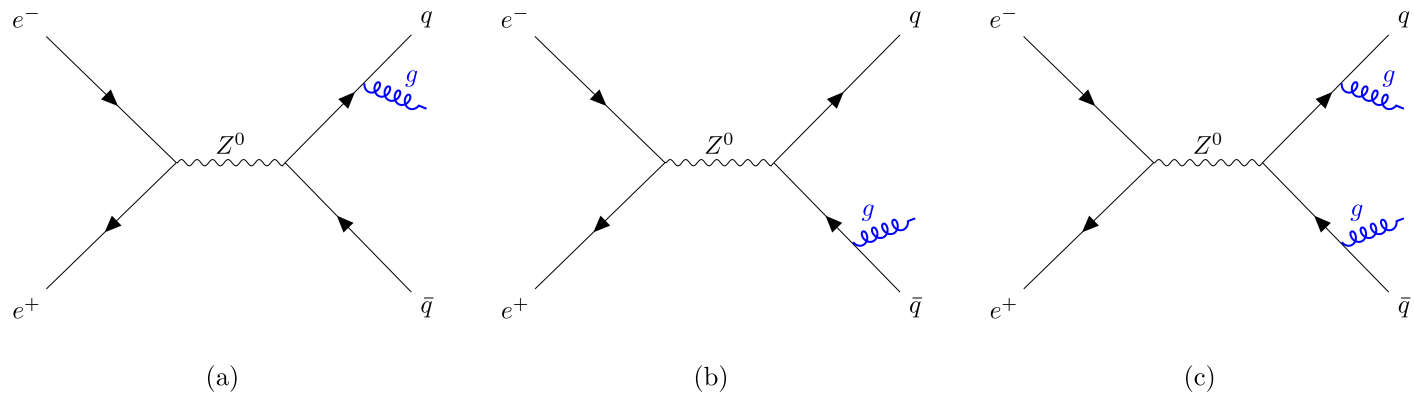


Figure 2.7: Feynman diagrams for QCD radiative corrections.

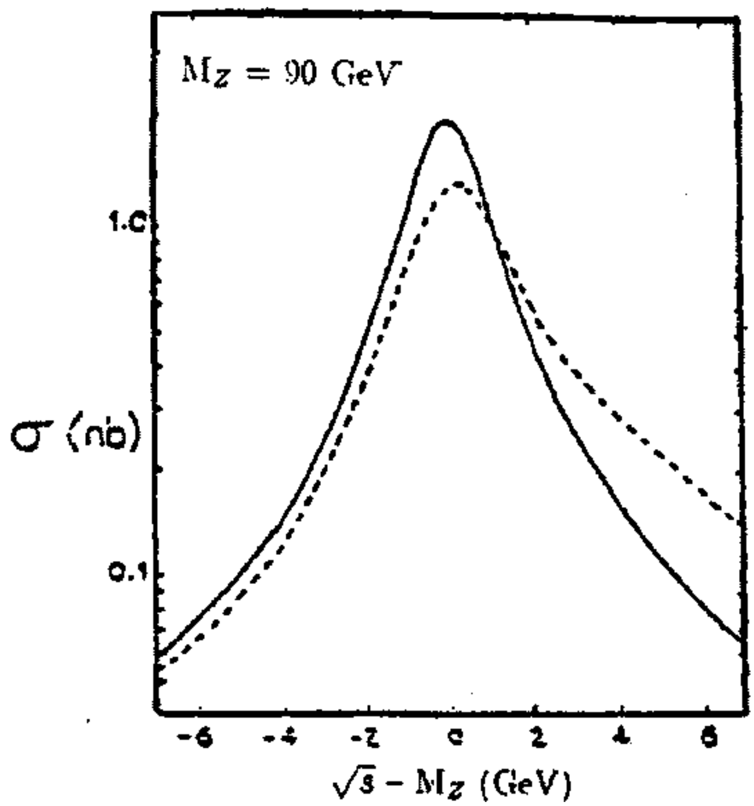
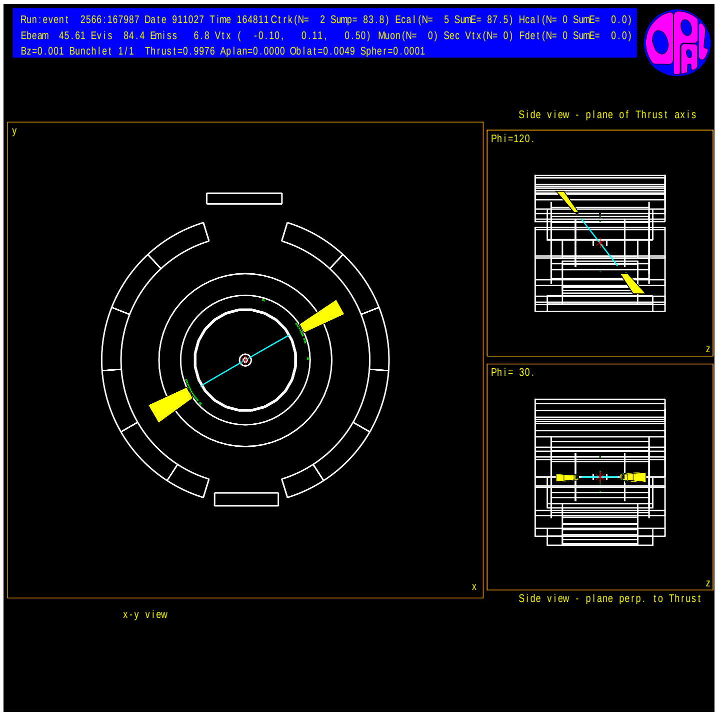
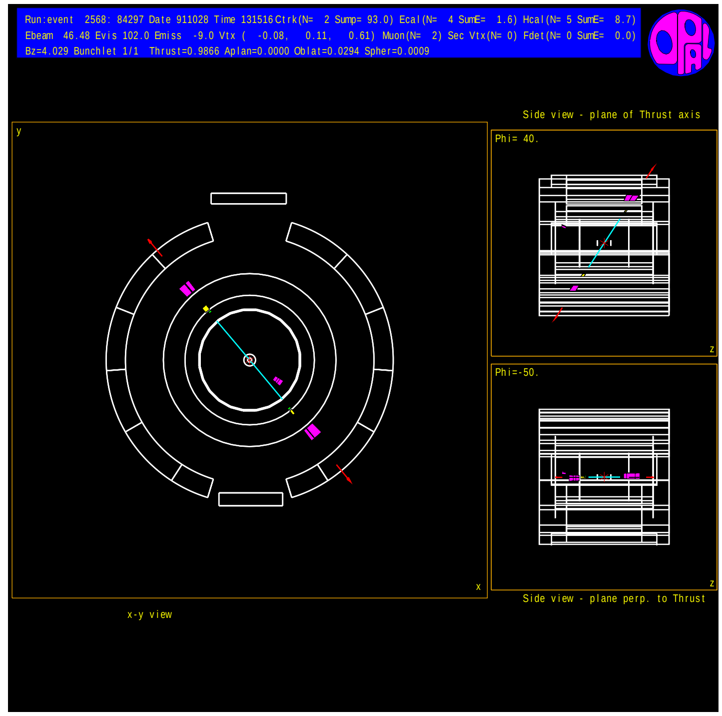


Figure 2.8: Line-shape of Z^0 with and without corrections of photon radiation in the initial state.

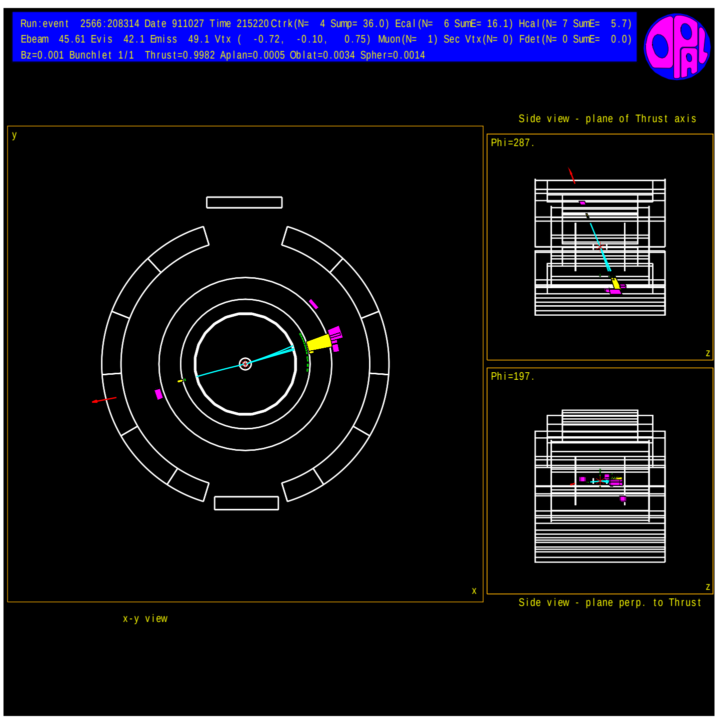
from which only the decay products can be detected. Typical τ^- decays are those with one or three charged tracks in the final state. Those events show little energy in the detectors (neutrinos!).



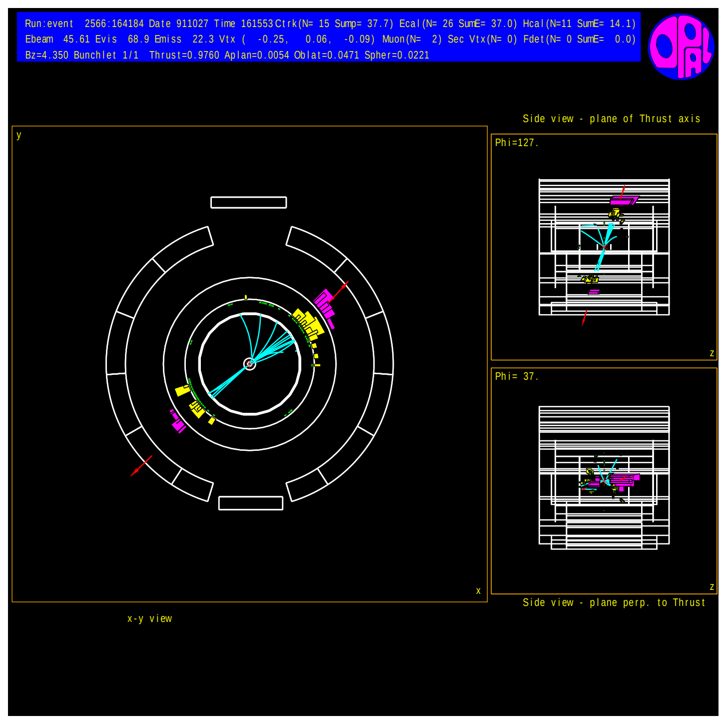
(a) $e^+e^- \to e^+e^-$



(b) $e^+e^- \to \mu^+\mu^-$



(c) $e^+e^- \to \tau^+\tau^-$



(d) $e^+e^- \to q\bar{q}$

Figure 2.9: Graphical representation of an event in the OPAL detector.

Chapter 3

The OPAL Experiment

3.1 The LEP Storage Ring

CERN is the European Organization for Nuclear Research, currently the world's largest particle physics center, and was founded in 1959. It is located at the border between France and Switzerland, just outside Geneva. At the time of it's completion in 1989, the LEP ("Large Electron-Positron storage ring") was CERN's biggest accelerator with a circumference of 27 kilometers (8.5 km diameter). This same tunnel today is hosting LHC (Large Hadron Collider). Particles are stored and brought to collision at four special locations, equipped with large detectors surrounding the interaction areas and monitoring the final states of the collisions.

3.2 LEP Detectors

Prerequisite for high precision tests of the Standard Model parameters axe detectors monitoring the highest possible rate of Z^0 decays into pairs of fermions. High energy collisions of electron-positron pairs typically lead to events characterized by a very high number of (charged and neutral) particles, emitted into arbitrary directions. Ideally, a particle detector should cover most of the space around the interaction region. Likewise it should have a high spatial resolution, and it should provide most of the accessible information about every event completely. In the following we will describe some of the most important components of a general detector system. Mainly there are two parts, one of which monitors the track of charged particles (tracking detectors), which allows to measure the momentum of the particles in the presence of an external magnetic field to a high precision. The other part are the calorimeters which measure the energy of charged and neutral particles, and serve to identify them.

3.3 Important Detector Components

3.3.1 Proportional Chambers

When passing a gas-filled volume, charged particles ionize the gas. An electron liberated by ionization ("primary electrons") will drift towards the positively charged, thin (counting-) wires (anodes) which are stretched within the gas volume. Near the anodes, i.e. within the strong electric field, the electrons gain enough kinetic energy for ionizing further atoms of the gas. This chain of processes leads to an avalanche of (secondary, etc.) electrons and positive ions. An advancement of the proportional counter is the multi wire proportional counter (G. Charpak, Nobel Prize 1992). This device consists of many parallel anodes (counting-wires) stretched in a plane between two cathode planes. Every wire serves as an independent "detector". The precision of measuring the localization of the particles (in space) depends on the distance between the wires.

Assuming a constant drift velocity, the time difference between the passage of the particle and the response of the wire is proportional to the distance of the trajectory of the charged particle from the wire. Measuring this time difference provides a high spatial precision, using only a few wires. This is the principle of the **Drift Chamber**.

The **Jet Chamber** is a big cylindrical drift chamber. This device is especially well suited for hadronic events (Jets) where one needs a good spatial resolution of double trajectories!

The **Time Projection Chamber** (TPC) is a big cylindrical drift chamber, too. But, in addition, it contains a layer of proportional counters at its endcaps. The charged particles ionize the gas along their trajectory within the TPC. The electric and magnetic field are parallel and point both into axial direction. Following the field the ionization electrons drift to one of the endcaps. There, they are detected by the secondary ionizations within the wire chambers. The avalanche of electrons caused by the primary electrons drift to the anodes. The cathodes consist of little pads on which a signal is induced. The pads allow to reconstruct the radial positions, r, and the azimuthal angles, ϕ of the points of the trajectory of a primary particle. The axial position, i.e. the 3rd component, z, of the cylindrical coordinates, is accessible by measuring the drift time of the electrons within the gas-volume of the TCP.

3.3.2 Shower Detectors/Calorimeters

In shower counters one uses the electromagnetic and strong interaction of the elementary particles with matter. They are constructed as sandwiches: between passive layers (plates) of bulk matter active detector devices are to be find. Shower detectors have to be very hefty devices, for the primary particles shall lose as much as possible of their energy in form of a cascade (the shower) of particles with decreasing energy. Part of the energy is deposed as heat ("calorimeter"). (The raise of temperature amounts to $\approx 10^5$ centigrade and is therefore unusable for monitoring the energy.) The rest of the energy produces a signal which is proportional to the primary particle's energy. Shower detectors are used as particle detectors mainly due to their following properties:

- their sensitivity to charged as well as uncharged particles (except neutrinos)
- the cascade (shower) formation depends on the particle's nature
- they are applicable at high event rates
- good spatial and directional resolutions are possible

Between **electromagnetic** showers (induced by electrons and photons) and **hadronic** showers (induced by p, n, $\pi^{\pm}$ for instance) exist significant differences which reflect the distinct nature of both effects. Nevertheless, both have in common that the size of the detector device depends only logarithmic on the energy of the particles to be monitored.

Electrons passing bulk matter lose their energy by Bremsstrahlung whereby photons are produced, which in turn are absorbed by creation of $e^{+}e^{-}$ pairs. Those again produce further photons by Bremsstrahlung. The so created cascade of photons, electrons and positrons stops when the energy of the electrons and positrons reaches a certain critical energy E_c. (E_c is the energy where losses by Bremsstrahlung and ionization are equal.)

The radiation length X_0 is an important quantity for the characterization of an electromagnetic shower. It depends on the mean free path of an electron (particle) in matter. Roughly a cascade develops as follows: an electron of E_0 creates when traversing a thickness E_0 of medium in average one) electron of energy between E_0 and E_0/e (e=Eulerian number). Within the next spatial interval of length X_0 the photon creates with a probability of about 54% a $e^{+}e^{-}$ pair an electron and another photon, so that after $2X_0$ there remain in average 4 particles with an averaged energy of $E_0/4$.

The averaged energy decreases rapidly, the electrons lose energy by ionization and the cascade breaks off. The major part of the energy of the incoming electrons or photons is converted into ionization energy which is proportional to the primary energy. The length of the shower depends logarithmically on the energy of the incoming particle. The spread of the shower is laterally limited. A characteristic quantity for it is the Molièr-radius, ρ_m

$$\rho_m = \frac{21\text{MeV}}{E_c} X_0 \tag{3.1}$$

A counter (of infinite length) with radius $2\rho_m$ monitors virtually the whole ($\approx 95\%$) shower energy.

The inaccuracy of the energy measurement is governed by statistical fluctuation in the shower formation. The highest fidelity is reached by blocks of scintillation material (e.g. Nal or BGO). Mostly, shower counter devices are used consisting of alternating layers of passive absorber materials (e.g. Pb) and active detector components (scintillator). The active layers detect only part of the shower energy, i.e. they monitor samples of the energy ("sampling calorimeter").

A hadronic shower happens if a strongly interacting particle (hadrons, e.g. p, n, $\pi^{\pm}$) hits an absorber. In the sequel a series of inelastic nuclear collisions produce further (secondary) hadrons which again take part in inelastic collisions. (Bremsstrahlung is unimportant because of the high mass of the primary particles.) This cascade breaks off once the shower particles have such a low energy that they are absorbed. The specification of a hadronic shower is difficult since a multitude of different particles are produced. Compared to shower counters for electrons and photons, in a hadron calorimeter the whole energy of a particle is not transformed into ionization energy, totally. Part of it is either carried away by neutrinos which don't interact, used for the creation of muon pairs which are not absorbed, or produces nuclear excitations.

	Electromagnetic Shower	Hadronic Shower
Duplication Process	Bremsstrahlung and Pair Creation	Decays and nuclear reactions
Secondary Particles	Electrons, Positrons, Photons	All types of particles often nucleon and Pions
Shower Length	$\approx 10 - 30$ X_0	$\approx 5 - 10$ λ_0
Shower Width	$2 \cdot \rho_m$	$\approx \lambda_0$

The characteristic dimensions of the cascade are determined by the nuclear absorption length λ_0

$$\lambda_0 = \frac{A}{N_A \cdot \rho \cdot \sigma} \tag{3.2}$$

with A atomic number, ρ density, N_A Avogadro's number and σ reaction cross section for inelastic scattering of hadrons by nucleons. The differences between hadronic and electromagnetic showers are shown in the table above.

3.4 Luminosity

For calculating the reaction cross section by using the observed event rates (of final states) of a particular experiment, one has to measure simultaneously the rate of another process of which the reaction cross section is exactly known. Out of it the luminosity might be calculated which is a measure for the interaction rate (for known reaction cross section)

$$\frac{dn}{dt} = \sigma \cdot L, \qquad n = \sigma \int L dt \tag{3.3}$$

$\frac{dn}{dt}$ the event rate of a process with reaction cross section σ. This equation defines the luminosity L. It is determined, as in all storage ring experiments, for known scattering angles, by elastic e^+e^- scattering (Bhabha scattering). In this kinematical sector, the theory of quantum electrodynamics (QED) provides approximative results for the reaction cross section matching the experimental results better than 1%. Typical values for e^+e^- storage rings lie in the order of magnitude of 10^{30} - 10^{31} $(\text{cm}^2 \cdot \text{sec})^{-1}$.

3.5 The OPAL-Detector

OPAL was one of the four detector devices at LEP. The data used in this physics laboratory course stem from OPAL. The OPAL collaboration consisted of 31 institutes from 9 countries. Their projects ranged from data analysis to design, construction, assembling of the device and machine maintenance. The group from Bonn took part in the construction of the jet chamber and forward detector.

3.5.1 The Detector System

The principal construction of the OPAL device is depicted in Figure 3.1. The coordinate system is defined as follows: the origin lies in the nominal e^+e^- collision point, the x axis directs horizontally towards the LEP center point. The y axis lies vertical and the z axis points in the direction of the electron beam. The polar angle θ is measured from the z axis, and the azimuthal angle ϕ is measured from the x axis counterclockwise around the z axis; $\phi \in [-\pi, \pi]$

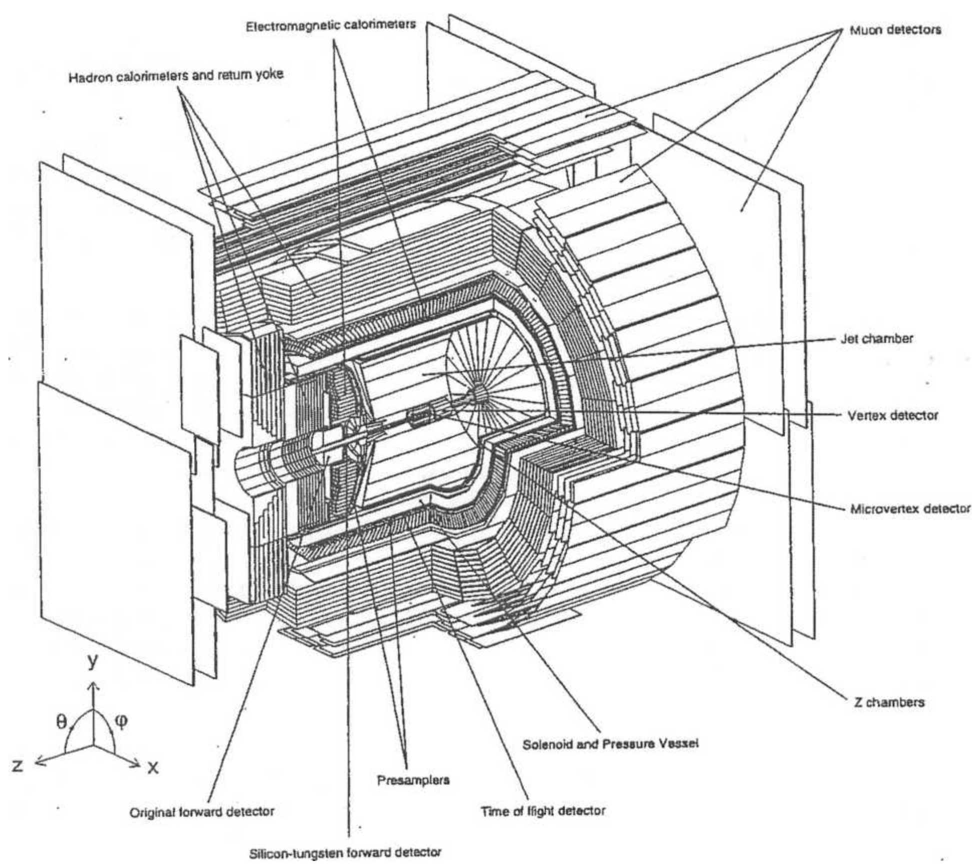


Figure 3.1: The OPAL detector.

The collision point is surrounded by the central detector which consists of the following components (from inside on): closest to the collision point lies the μ-vertex-detector, a semiconductor detector consisting of silicon stripes. It is surrounded by the vertex chamber, the jet chamber, and finally the Z-chamber.

The whole device is situated within an autoclave. It contains a mixture of 88.2% argon, 9.8% methane, and 2.0% isobutane at a pressure of 4 bar. The tank is surrounded by a solenoid of a length of 6.3m and a diameter of 4.36m. Inside the solenoid exists a homogenous magnetic field of 0.435T, parallel to the beam. In radial direction the solenoid is followed by the “Time-of-Flight System” (TOF). It consists of 160 scintillation counters arranged parallel to the beam axis with a conic section. The counters have a length of 6.84m, a width of 89 - 91mm, and a thickness of 45mm. The scintillation light is registered at the beginning and the end of the device. The output of the TOF system is used for triggering the detector and for measuring the flight time of the particles. All around the TOF the presampler, consisting of 16 streamer chamber, is situated. The endcaps of the electromagnetic calorimeter contain the forward detectors (FCAL). Outside of the solenoid the hadronic calorimeter (HCAL), which serves as flux return for the magnetic field, and four layers of muon chambers (MUON) are installed.

The **Vertex Chamber** is a multiwire proportional counter with a high resolution. It consists of an inner part similar to a jet chamber. Axial wires are arranged in 36 layers around the beam axis. The outer part provides the resolution in z direction. Further on, the z coordinate is determined by the different drift times of the pulses on the wires towards both endcaps. The spatial resolution averages 55μm.

The most important tracking detector at OPAL is the big cylindrical jet chamber with a length of 4 m and an outer and inner diameter of 3.7m and 0.5m, respectively. The chamber is subdivided into 24 identical sectors. Every sector contains a plane with 159 counter wires, stretched parallel to the beam axis. Between the anode wires reside, in an alternating order, special potential wires forming the field. Layers of cathode wires axe stretched between the layers of anode and potential wires. The maximal drift distance varies between 3cm, close to the beam axis, and 25 cm at the outer most wires. The signals of the wires are used also for measuring the energy, lost (dE/dx) of a charged track. The drift time delivers to a high accuracy the radial position (r) and the azimuthal angle (ϕ) of the points of a particle trajectory. The r-ϕ-resolution averages 135μm. The 3rd spatial component (z) is determined by a charge splitting in the jet chamber, i.e. the quotient of the charges arriving at the ends of a counter wire. The exactness of this method, as a matter of principle, is determined by the length of the wire and amounts to about 6cm. The jet chamber is surrounded by 24 Z-chambers (one for every sector, respectively) in which the wires are stretched in radial direction. Therefore the z-resolution is very good and amounts to about 100-200μm. The momentum resolution of the central detector is given by the relation

$$\frac{\sigma_{\mathrm{p_{xy}}}}{\mathrm{p_{xy}}} \approx \sqrt{0.02^2 + (0.0015 \cdot \mathrm{p_{xy}})^2} \left(\frac{\mathrm{GeV}}{\mathrm{c}}\right) \tag{3.4}$$

The **electromagnetic calorimeter** (ECAL) consists of 9440 lead glass blocks. It is separated into a central part, formed like a barrel, surrounding the jet chamber (barrel) and two endcaps, which together cover 98% of the steradian. The blocks have a thickness of 22 (endcaps) to 26 (barrel) radiation lengths. Energy and position of electromagnetic showers are determined by the signals from cathode pads, arranged behind the blocks. The energy resolution is

$$\frac{\sigma_E}{E} \approx \frac{5\%}{\sqrt{E}} \tag{3.5}$$

The **hadronic calorimeter** (HCAL) consists, like the ECAL, of a central part and two endcaps. Between iron layers, the data selection is done by use of chambers which are performing in the “limited streamer mode”. These chambers resemble proportional counters, but the voltage at the wires is much higher, so that the secondary ionization at the wires is independent of the ionization density of the primary particles. The achieved energy resolution amounts to

$$\frac{\sigma_E}{E} \approx \frac{120\%}{\sqrt{E}}. \tag{3.6}$$

The measuring of the luminosity is done by the **forward detectors** (FCAL). Arranged close to the beam pipe they detect Bhabha scattering at small angles by detecting coinciding electrons and positrons. The FCAL consists of a sandwich of lead glass and wire chamber of 24 radiation lengths. It covers an interval of 58 $< \Theta <$ 120mrad which corresponds to a Bhabha reaction cross section of about 24nb. The energy resolution is

$$\frac{\sigma_E}{E} \approx \frac{17\%}{\sqrt{E}} \tag{3.7}$$

where energy E is in GeV.

3.6 The Trigger

Event rates at LEP are mainly conditioned by beam-gas-events and particles which leave the beam tube and hit the detector, in virtue of their momentum deviating from the standard value. The actual event rate of the sought-after processes, $e^+e^- \rightarrow Z^0 \rightarrow f\bar{f}$, is about 0.5 Hz. The **trigger** device serves as a filter to suppress the aforementioned perturbations by background events as good as possible, and, at the same time, to initialize the monitoring and recording of the desired measurement data. Thereby one has to pay attention to the possible occurrence of unforeseen decays of the Z^0, i.e. the trigger has to be adjusted in a way to allow for detecting such new and unexpected events. The trigger process a multitude of fast signals from different detector components to define the conditions of the trigger. Altogether these data allow to cover the whole area of predictable physical processes.

Chapter 4

Identification of Particles and Classification of Events

Your first task in this physics laboratory course will be the identification of the different Z^0-decays with the aid of pictorial event representations on the computer screen, and the separation of the proper decays from the background events by using of only a few measurands. The following chapter is intended to provide you with the most relevant basics.

4.1 Particle Identification at the OPAL Detector

An efficient particle identification is an important prerequisite for the classification of the specific processes. First we divide all particles into charged (visible trajectories in the tracking chambers) and uncharged ones.

4.1.1 Charged Particles

Charged hadrons differ from electrons by the "form" and the beginning of the shower in the electromagnetic calorimeter (ECAL). The electromagnetic shower caused by an electron is completely situated within the ECAL and has only a small lateral spread. In contrast, hadronic shower, as a general rule, start to develop later. They are wider and extend into the hadronic calorimeter (HCAL). The differences between hadronic and electromagnetic showers decrease with increasing particle energy. Below 2 GeV, hadrons and electrons are indistinguishable by showers. At low energies, particle identification becomes possible by virtue of the specific energy lost dE/dx in the jet chamber. Muons traversing a calorimeter do not produce any shower. The energy lost ($m_\mu \gg m_e$) by ionization dE/dx, according to the Bethe-Bloch law, is small. Therefore they penetrate hefty layers of bulk matter (see Figure 4.1)

4.1.2 Neutral Particles

The identification of neutral particles is done by the different profiles of the showers (length, width). Neutral particles which decay into charged particles exhibit two tracks with a typical V form. The tip of the V, i.e. the location of the decay, lies outside of the primary vertex. The π^0 particle decays "immediately" into two photons. The angle between the photon trajectories depends on the energy of the π^0. With increasing energy they get closer (Lorentz boost) and are therefore indistinguishable from a single photon, not steaming from a π^0 decay. Photons are identified by electromagnetic showers, neutral pions by two electromagnetic showers lying at close quarters. In both cases, no track must be found pointing towards the showers. Before entering the ECAL, photons may decay into e^+e^- pairs within matter. Since practically the whole matter (or the total radiation length) is concentrated, more or less, in the walls of the central detector and the solenoid, the probability of the aforementioned conversion to take place in these regions is very high. A converted photon is identified by two charged tracks (in V form) and by two electromagnetic showers. Tracks and showers have

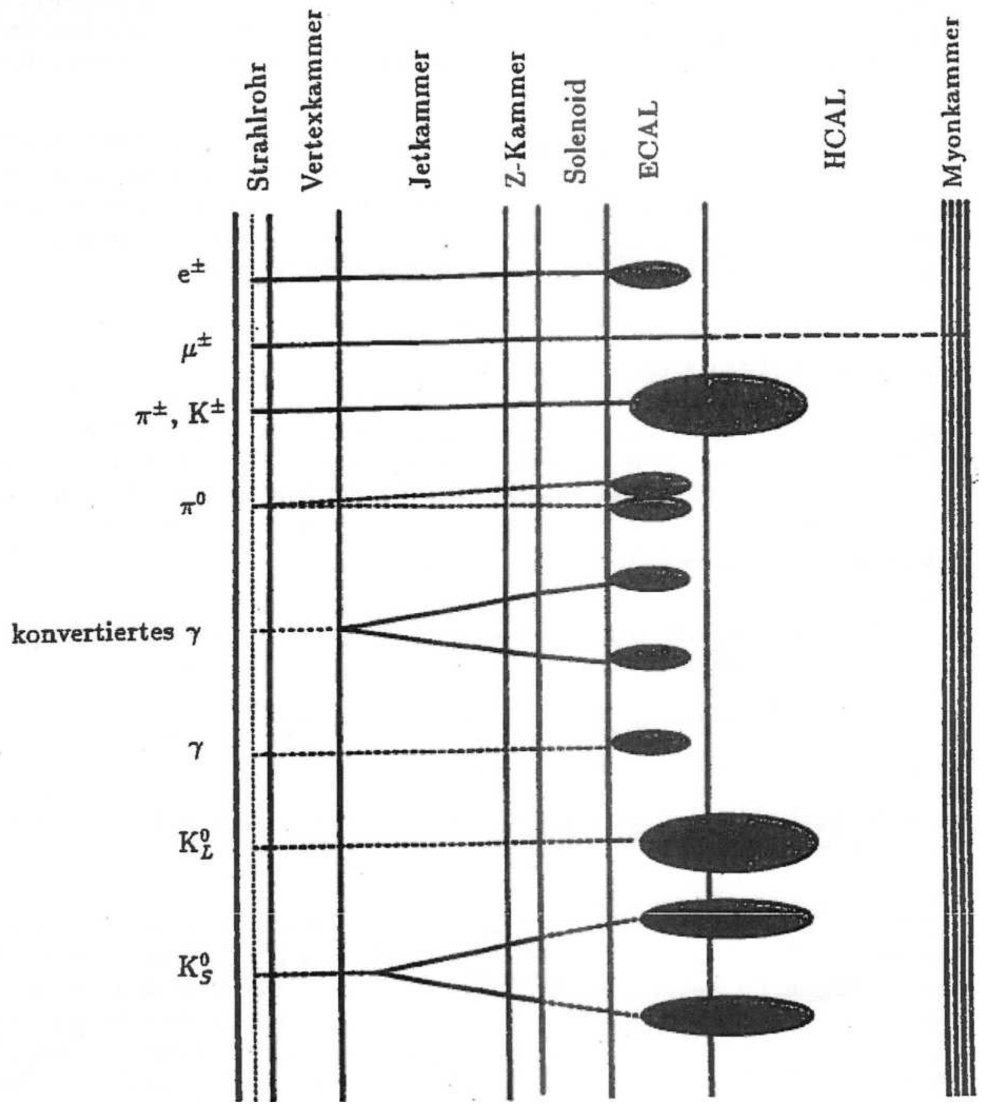


Figure 4.1: Schematical representation of the signature of elementary particles at the OPAL detector. Solid lines in the tracking chamber signify tracks of charged particles. Dashed lines signify "not found tracks" of neutral particles. Drawn in bubbles represent the contours of electromagnetic and hadronic showers.

to be correlated non-ambiguously.

Neutral hadrons with a big flight time are identified by hadronic showers, to which no track points. In Figure 4.1 one finds also the decay of a K_S^0 into two charged pions as an example for a signature of a short-lived neutral hadron. The branching rate of this decay is $\approx 69\%$. The decay of a K_S^0 into two neutral pions with a branching rate of $\approx 31\%$ is not shown. The signature of it, however, should be easily identified.

4.2 Measurands and Cuts

Beside the particular signature of particles at OPAL, the global variables Ncharged, Pcharged, E_ecal and E_hcal serve as further auxiliary means for the distinction of Z° decays in this laboratory course. They permit a computer aided analysis of the recorded events at OPAL (OPAL experiments until 1992 has recorded $\approx$ 1200000 hadronic events). These variables have the following meaning:

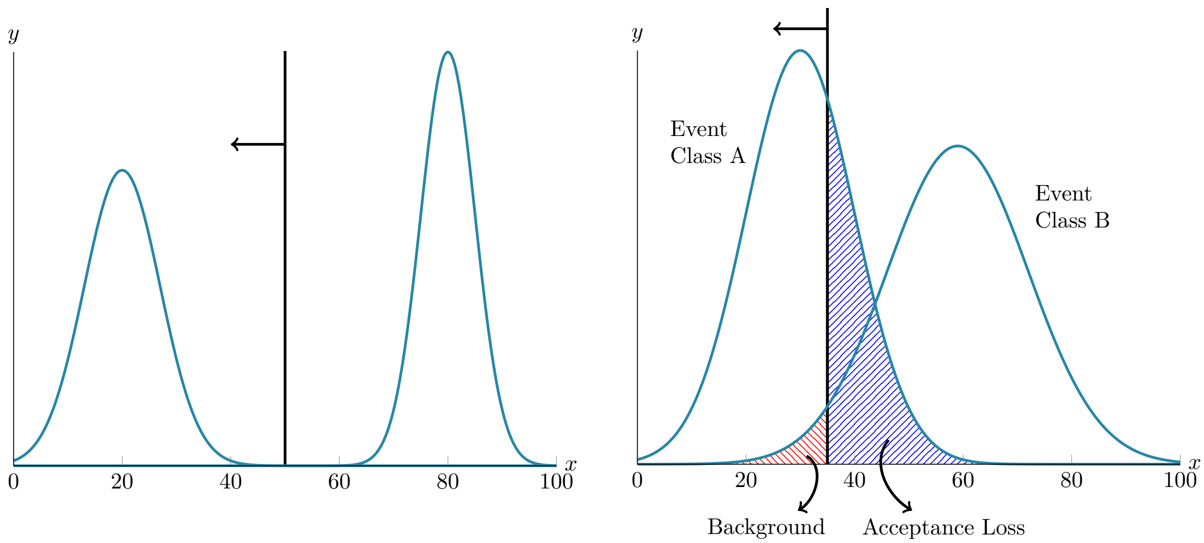
- Ncharged: Number of tracks of charged particles of an event found in the tracking chamber.
- Pcharged: Scalar sum of momenta of all charged tracks of an event, measured in the vertex/jet/Z-chambers.
- E_ecal: Total energy of an event measured in ECAL.
- E_hcal: Total energy of an event measured in HCAL.

As an example for the use of the aforementioned measurands, we regard the separation between the following events: $Z^0 \rightarrow e^+e^-$ and $Z^0 \rightarrow \mu^+\mu^-$. Both event classes differ only slightly in the variables Ncharged and Pcharged. Little differences may be caused by the higher probability for photon emissions, originating from Bremsstrahlung processes, in the $Z^0 \rightarrow e^+e^-$ channel.

But they differ considerably in the total energy, i.e. the variable E_ecal. For the $Z^0 \rightarrow e^+e^-$ the center of mass energy should be measured. For the $Z^0 \rightarrow \mu^+\mu^-$ events, little energy depositions of (energy equivalent) ≈ 2 GeV in the ECAL are expected. No energy is deposed in the HCAL for $Z^0 \rightarrow e^+e^-$ events. The muons penetrate the ECAL and HCAL, and depose together an averaged energy equivalent of ≈ 5 GeV in the HCAL.

The separation of both events may be achieved by a cut on the variable E_ecal. E_hcal should be greater than a certain value, which is to be determined by the student/group (your job!). The goal should be to choose the cut (or a set of several cuts for the different variables) in a way that a maximum portion of "desired" events fulfill the cut criterion(s) and that the unwanted background effects may be reduced as much as possible.

The acceptance of a cut is defined by the ratio of the events of a certain class fulfilling the cut criterion and the total number of events of the same class. The achieved acceptance and background suppression depend on the mean values and the distribution widths. See Figure 4.2 for two hypothetical examples. In Figure 4.2 (a) the distributions A and B are totally disjoint with respect to x. Choosing a cut between 40 and 60 allows for an acceptance of 100%, a total suppression of background effects, i.e. the ideal case. Normally one finds oneself in the situation (b) of Figure 4.2. For a very pure set of events of class A a cut of X < CUT, CUT $\in]20,40[$ should be chosen. For CUT $\in]40,60[$ the resultant set of events contains (among others) almost all events of class A. For separating a special event class from the rest of data one needs generally further cuts in different measurands. Furthermore, cuts may be applied to measurands composed of several observables. For instance, the restriction $X^2 + Y^2 < A$ cuts out a disc of radius $\sqrt{A}$ in the 2 dimensional X-Y-space. The aim of this cutting procedure is to find a well suited set of (cut) restrictions and variables consisting of the purest possible event classes.



(a) Well separated distributions.

(b) Overlapping distributions.

Figure 4.2: Example for cutting procedure.

4.2.1 Simulation of Events (Monte-Carlo)

Generally, cuts cause losses in the class of sought-after events, as Figure 4.2 shows. Also, unwanted background effects still may be extant and therefore influence the statistical analysis. For' calculating reaction cross sections (also part of this laboratory course), beside the integrated luminosity, the “exact” number n of events of a certain class is needed. After the use of cuts, the number of observed events N_{obs} has to be corrected. A correction of N_{obs}, based only on measured data (see Figure 4.2 (b)) is not possible. In the experiment, the distributions of the measurand x of the event classes A, respectively B are not particularly known, but only their sum.

Event simulations on computers provide a facility to determine the lost of events caused by cuts. For this purpose, a significant number of events of a specific class are simulated as follows: At first, leaking fermion-antifermion pairs are created out of elastic scattering processes. Subsequently, the decay of unstable particles is simulated. For quark-antiquark pairs the simulation of the hadronization process has to be performed beforehand. The last and very expensive step concerns the simulation of all detector signals originating from traversing particles, so that finally the received informations resemble results from “real” events. Observed and simulated results may now be analyzed by the'same program. For the event simulation, all known theoretical and experimental informations are used. Simulated results include beside the informations contained in the real data details on the created particles and allow therefore the study of the detector output with respect to particular events.

Simulating the event classes A and B, respectively, the particular distributions of the measurand X may be determined separately. The acceptance may now be obtained easily by employing the same steps as in the case of the “real” data. The same method may now be used to calculate the background. But a relative normalization between the distributions of classes A, respectively B is needed. This may be achieved by fitting the data to the superimposed particular distributions. The result of this fitting is the relative part of events of the class A with respect to the event class B.

4.3 Classification of Z^0 Events

First we discuss effects concerning all Z^0 decay channels likewise.

- Electronic noise, superimposing the signals from the detectors, may affect a signal which could be misinterpreted. For instance, one may find single isolated track points in the jet chamber which can not be associated with a particle track. Electronic noise may affect also little energy depositions in the calorimeters. Therefore, photons of an energy less than ≈ 1 GeV can not be verified.

- The verification probability of all detector components is always less than 100%. It may for instance happen, that only 3 of the 4 layers of the muon chamber respond. Also, well monitored tracks in the tracking chamber may lack some points.

- Between several modules of the calorimeter and in the forward-backward sector (where the beam pipe zigzags) openings may be found caused by the construction of the Detector. Particles passing these openings produce wrong energy measurements. For charged particles the tracks may be extrapolated from the trajectories within the calorimeters, to see whether an opening was passed by a particle.

- Charged particles may emit Bremsstrahlung. "Initial state" Bremsstrahlung is emitted by the incoming electrons (positrons), whereas "Final state" Bremsstrahlung is emitted by the charged particles produced in the collision (after the interaction). For the identification of the $Z^0 \to e^+e^-$ process, for instance, a topology where electrons accompanied by photons appear has to be taken into account. Electrons must not have diametrical trajectories, and the "charged energy" may be smaller than expected.

- An important aspect for the identification of electrons, muons, and especially τ leptons, which steam from leptonic decays of the Z^0, is the redundancy caused by the production in pairs of particle and antiparticle. For instance, the identification of a τ^- lepton, coming from a Z^0 decay, implies automatically the existence of a τ^+ lepton. This necessary property allows for testing the criterion used in the analysis, and permits a calculation of the verification probability.

- The aforementioned converted photons my cause some problems when using the "charged multiplicity" as a cut criterion. Selecting $Z^0 \to e^+e^-$ pairs with two charged particles, for instance, events with a converted Bremsstrahlung photon marking a nice track are lost. But, demanding that tracks start at or very close to the vertex these events may be recaptured to a considerably amount.

- One source of background signals are beam-gas events. These are scattering of electrons or positrons on particles of the rest gas in the vacuum beam pipe. Such events are characterized by vertex positions which lie outside of the detector central point and final state particles, practically all of which fly either into the forward or backward direction.

4.3.1 $e^+e^- \to e^+e^-$

Three Feyman-diagrams contribute to this process in the lowest order of perturbation theory (Figure 4.3 a, b and c). By concentrating on the s-channel exchange between Z^0 and photon one will find that the photon exchange and the interference term are weakened by two and three orders of magnitude. But the t-channel shown in Figure 4.3 (c) plays an important role. This process has a very high cross section for small scattering angles (θ) and is used to measure the luminosity because the exact cross section can be calculated. (See Figure 4.4 a)

4.3.2 $e^+e^- \to \mu^+\mu^-$

This event class is identified by two muons that penetrate the HCAL and trigger signals in the muon chambers. The hits in the muon chamber have to be correlated to the tracks in the central detector (see Figure 4.4 b) The magnetic field has to be considered when extrapolating the trace from the central detector.

4.3.3 $e^+e^- \rightarrow \tau^+\tau^-$

The τ-lepton can decay into numerous final states. A correspondence to a certain decay channel would not be feasible within the timescale of this experiment. One distinguishes between the tau decays by counting the prongs. The decay is called a n-prong decay if the τ decays into n charged particles. 1-prong decays are dominant with 86%. To cut $\tau^+\tau^-$ from hadronic events the multiplicity is chosen to be small. But this cut will not separate these events from the leptonic ones. Every tau decay emits a neutrino which carries some of the energy out of the detector remaining undetected. By choosing the energy deposited in the ECAL as being much smaller than the center-of-mass energy, one can separate the tau events from the leptonic events. The cut against $Z^0 \rightarrow \mu^+\mu^-$ is done by demanding that the charged energy be smaller that the centre-of-mass energy.. Many more cuts have been developed to identify the tau lepton. In Figure 4.4 (c) you can see an $Z^0 \rightarrow \tau^+\tau^-$ event measured with the OPAL detector. It depicts a decay of a tau lepton into an electron and two neutrinos. The second tau is a example for a 3-prong-decay. For an overview of the most frequent τ decays see Table 4.1.

Decay Mode	Branching Ratio [%]	'prong'
$\pi^-\pi^0\nu_\tau$	24.0 ± 0.6	1-prong
$e^-\bar{\nu}_e\nu_\tau$	17.9 ± 0.3	1-prong
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.6 ± 0.3	1-prong
$\pi^-\nu_\tau$	11.6 ± 0.4	1-prong
$\pi^-\pi^-\pi^+\nu_\tau$	5.6 ± 0.7	3-prong
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.4 ± 1.6	3-prong
$\pi^-\pi^0\pi^0\pi^0\nu_\tau$	3.0 ± 2.7	1-prong

Table 4.1: The decay modes of the τ lepton with the largest branching ratios (shown for the τ^- decay).

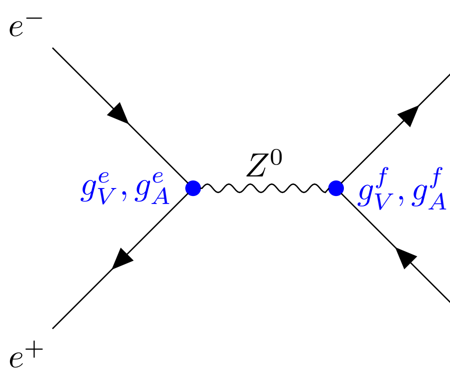
4.3.4 $e^+e^- \rightarrow \nu\bar{\nu}$

The decay products of this decay cannot be measured, hence the name "invisible decay modes". Nevertheless this deacy mode can be measured by selecting events with nothing but a single photon from initial state radiation.

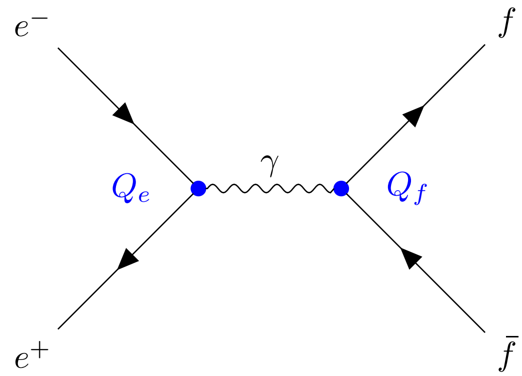
4.3.5 $e^+e^- \rightarrow q\bar{q}$

The average measured multiplicity (number of reconstucted charged tracks) in hadronic events is about 30, being much greater than that of leptons (see Figure 4.4 d). During the process of hadronisation a large number of neutral hadrons is produced, predominantly π^0s.

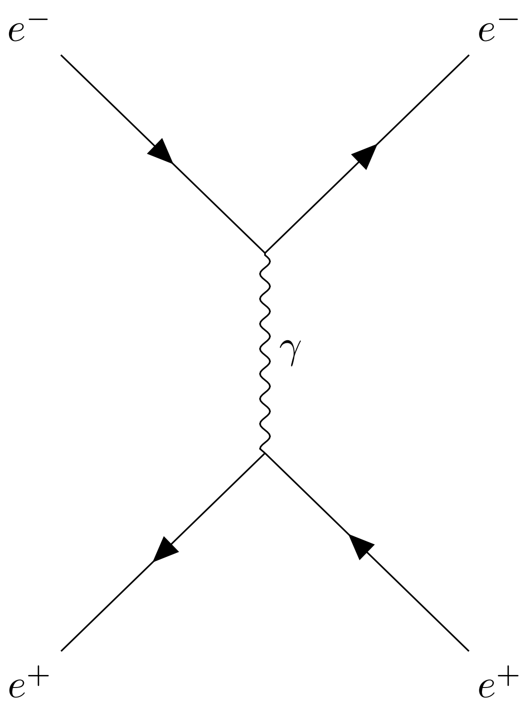
Hadronic events are easy distinguished from all the other events with a cut on the charged multiplicity. In principle one has to consider an additional process as possible background to the hadronic decay mode which has not yet been mentioned: the two-photon reactions, as seen in Figure 4.3 (d). Both electron and a positron radiate a virtual bremsstrahlung photon, which anihilate into a a fermion-antifermion pair ($f\bar{f}$). If this happen to be a quark-antiquark pair, they hadronise into observable particles. Since electron and positron don't scatter much, they stay inside the vacuum tube or hit the ECAL. One obtains an event with relatively high multiplicity. But the total energy in such events is small, making a cut in the energy channel an effective selection.



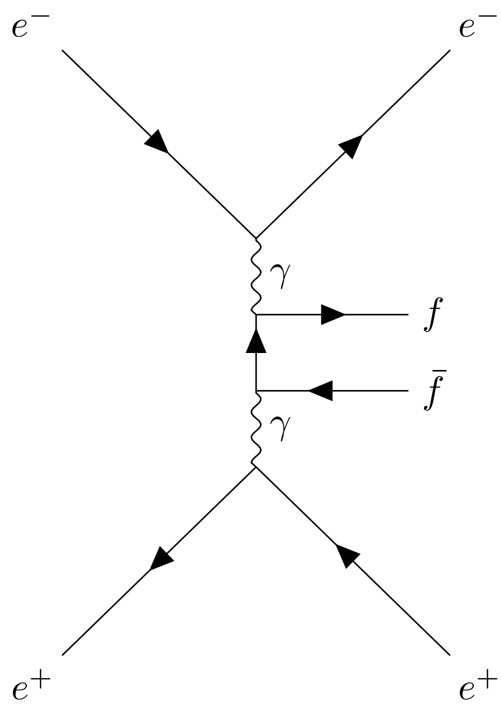
(a) s-Channel exchange of Z^0.



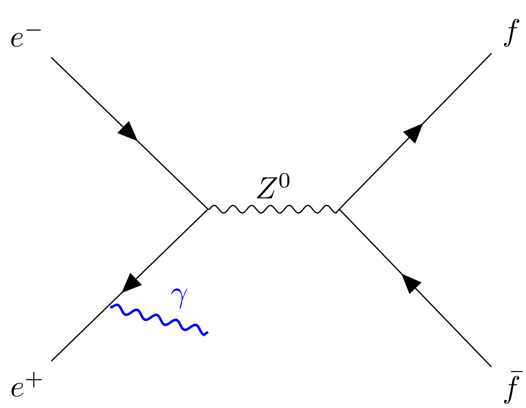
(b) s-Channel exchange of γ.



(c) t-Channel exchange of γ.

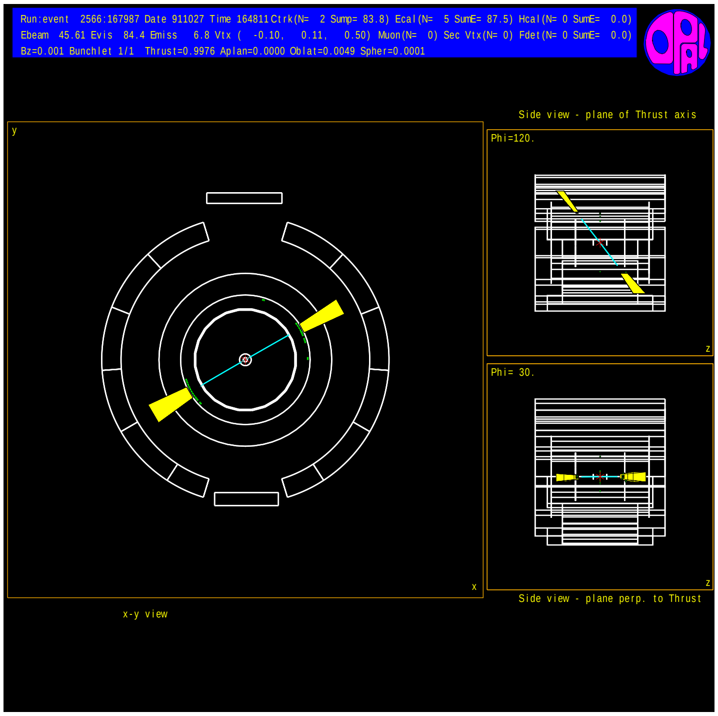


(d) Two-photon process.

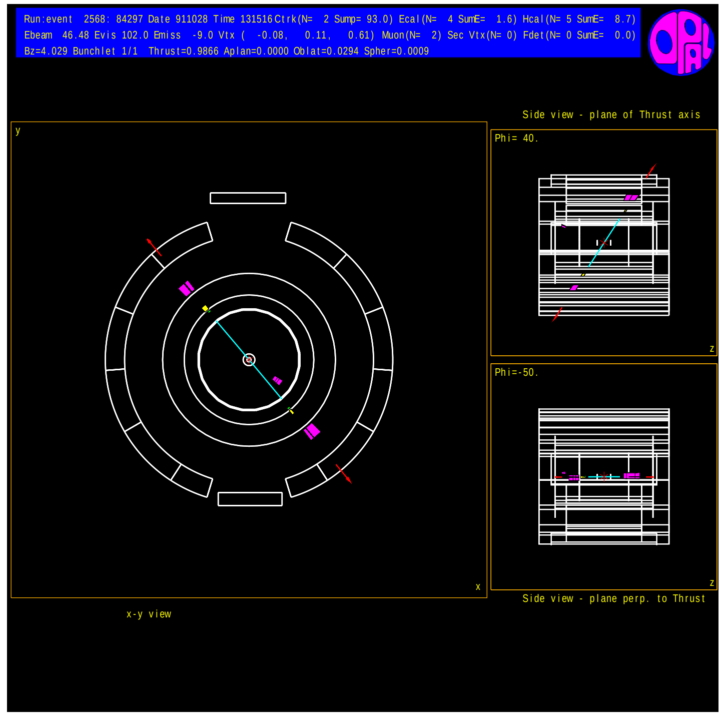


(e) An example Bremsstrahlung process.

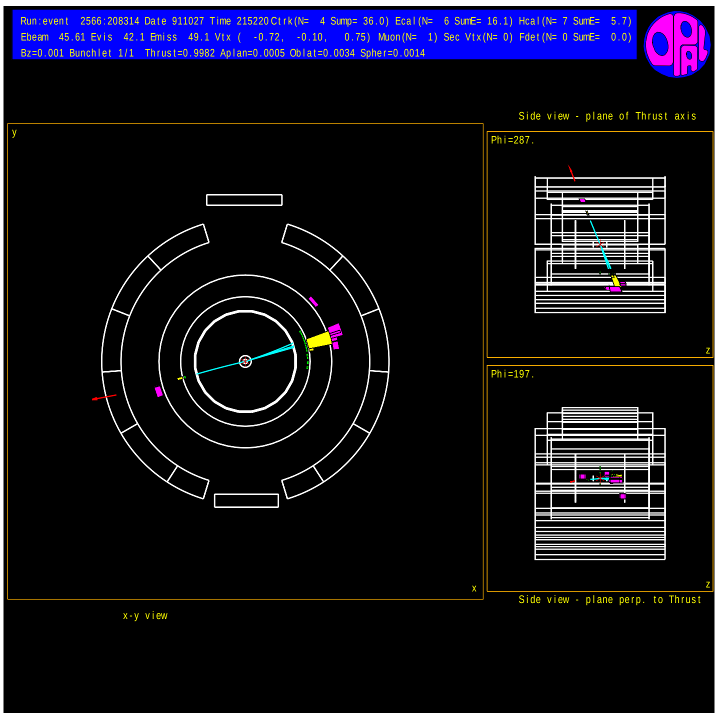
Figure 4.3: Feynman diagrams of the most important processes.



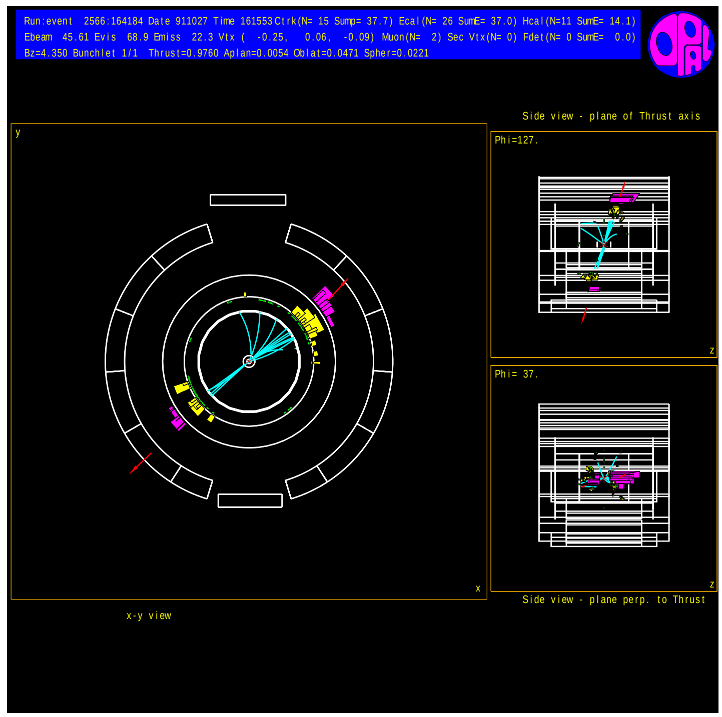
(a) $e^+e^- \to e^+e^-$



(b) $e^+e^- \to \mu^+\mu^-$



(c) $e^+e^- \to \tau^+\tau^-$



(d) $e^+e^- \to q\bar{q}$

Figure 4.4: Event displays for four different decay modes of e^+e^-.

Chapter 5

Instructions for the Course

This chapter presents, in steps, the questions and tasks needed to conduct the experiment. The formulae which you need to solve the problems in section 5.1, 5.2, and 5.3 can be found in Section 2. Questions provided on section 5.1 are of theoretical nature and can be solved without conducting the experiment and gathering data. Not all questions are to be done during the actualy laboratory sessions. Each question has labels [**Lab**] or [**Home**] to specifiy whether that task it to be done during the lab or later at home for the report. Section 5.2 describes the first part of the experiment in which event displays are investigated to distinguish the events. Section 5.3 describes the second main task of the experiment, namely the statistical analysis of Z^0 decays. In Section 5.4 Breit-Wigner fit of cross section task is described. This is to be done after the experiment and questions on this section should be answered based on the cross-section fit result. Your solutions to all questions must be included in your final report.

5.1 Pre-Lab Questions

- **Q.5.1** [**Home**] Calculate the decay widths for the following decays and compare your results with the numbers from Table 2.1.
  - a) $Z^0 \to e^+e^-$
  - b) $Z^0 \to \mu^+\mu^-$
  - c) $Z^0 \to \tau^+\tau^-$
  - d) $Z^0 \to q^+q^-$
- **Q.5.2** [**Home**] Calculate,
  - a) the total Z^0 decay width
  - b) the hadronic decay width
  - c) the 'charged' decay width
  - d) the 'neutral' (invisible) decay width
  - e) the partial cross section at the maximum of the resonance
- **Q.5.3** [**Home**] Imagine that the decay into an additional pair of light fermions (u, d, e, ν) is possible. What would be the change (in percent) of the width of the Z^0 resonance curve?
- **Q.5.4** [**Home**] Draw the expected angular distribution for the processes $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$. In the case of $e^+e^- \to e^+e^-$ also plot the different contributions.
- **Q.5.5** [**Home**] Calculate the forward-backward asymmetry in the process $e^+e^- \to \mu^+\mu^-$ for the nine combinations of center of mass energies and Weinberg angles ($\sin^2\theta_w$) shown on Table 5.1:

GeV/Angle	0.21	0.23	0.25
89.225			
91.225			
93.225			

Table 5.1: Table of energy-angle combinations for the Question 5.5.

5.2 Part I: Analysis of event displays

In this first part of the experiment you will learn, on the basis of event displays (using the screenshot images from the program `GRope`), how to distinguish the different decay modes of the Z^0 boson ($Z^0 \to e^+e^-$, $Z^0 \to \mu^+\mu^-$, $Z^0 \to \tau^+\tau^-$ and $Z^0 \to q^+q^-$).

An event can be characterized by several quantities. Those available on event display images are provided with their abbreviations and descriptions in the following list;

- `Ctrk(N)`: Number of charged tracks
- `Ctrk(Sump)`: Momentum of all charged tracks
- `Ecal(SumE)`: Total energy in the electromagnetic calorimeter
- `Hcal(SumE)`: Total energy in the hadronic calorimeter

Under `EventDisplays` folder you are provided with 8 different samples each having its own folder. There are four *pure* samples and four *mixed* samples with events recorded with the `OPAL` detector. Each pure sample contains only one decay-mode of the Z^0, i.e., there is one pure sample with $Z^0 \to e^+e^-$ events only, one with $Z^0 \to \mu^+\mu^-$ events only, one with $Z^0 \to \tau^+\tau^-$ events only and one with $Z^0 \to q^+q^-$ events only. These samples are for training purposes. Since the events in pure samples are already identified, one can study them to recognize the common characteristics (such as high/low number of tracks, high/low energy deposits at Ecal etc.) of a particular decay mode. As a corollary, one could then be able to distinguish two different type of decay-modes from one another through comparing the previously identified characteristics.

You should equip yourself with the above-mentioned capabilities which are necessary for the next stage of the experiment. The knowledge gained through this study is to be used on the mixed samples, in which, events from all 4 types of decay modes of the Z^0 are present. The task then is to categorize these different decay-modes into one of the 4 possible candidates for each event in each mixed sample. You are going to do this on **Question 5.6** in steps.

All samples have 20 events in their corresponding folder except hadrons, which has 19 events. The information related to samples and files are summarized on Table 5.2. Please do not rename or move any of the files/folders.

The most common way to plot data in particle physics is making a **histogram** of it. Histograms are the main data visualization tools in experimental analysis and are a part of a particle physicist's daily life. A histogram displays a distribution of a variable as a collection of discrete units called **bin**s. A bin collects and counts the number of events falling within its defined range. The binning is done on the x-axis and number of events for each bin is displayed on the y-axis. An example can be seen on Figure 5.1. The variable NCharged we just drawn, is already a discrete variable i.e. number of tracks are integer numbers. Here each track number is corresponding to one bin. For example there are more than 50000 events with non-zero number of charged tracks.

Samples			
Name	Type	Folder Name	Number of Events
Electrons	Pure	ee	20
Muons	Pure	mm	20
Taus	Pure	tt	20
Hadrons	Pure	qq	19
Test 1	Mixed	test1	20
Test 2	Mixed	test2	20
Test 3	Mixed	test3	20
Test 4	Mixed	test4	20

Table 5.2: Summary of information regarding the samples and files.

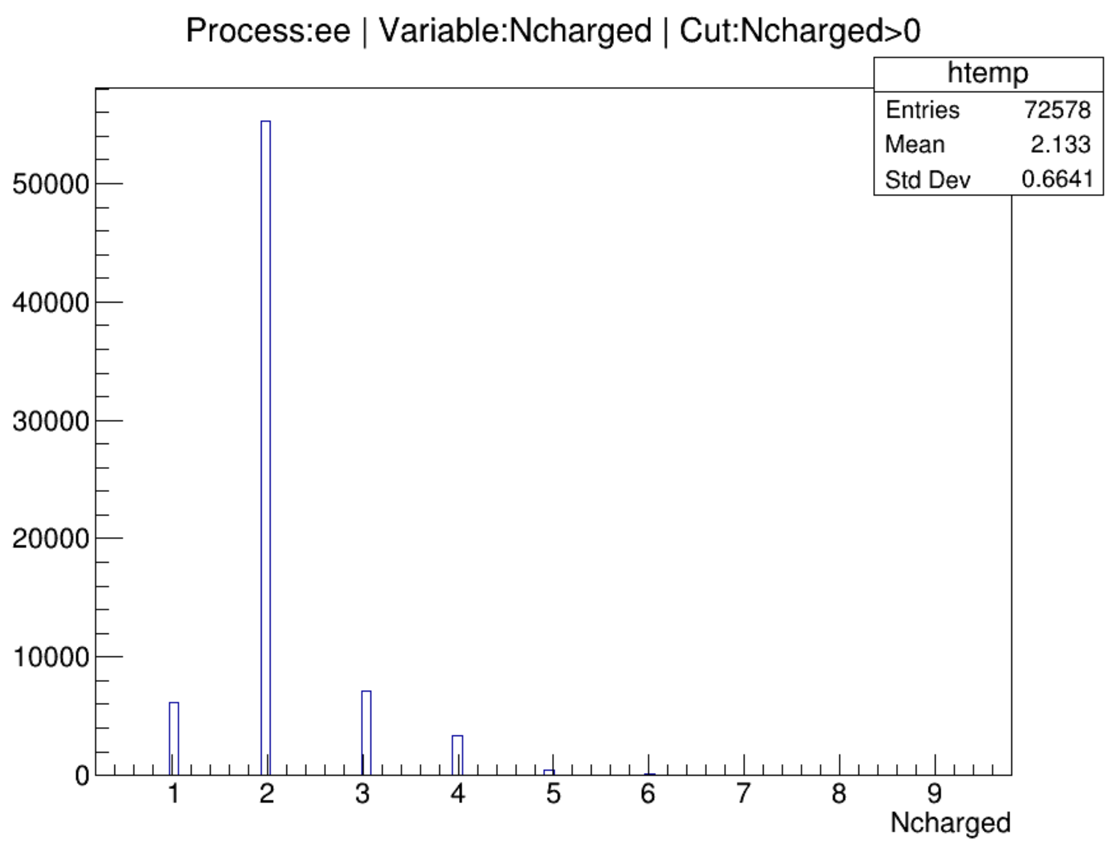


Figure 5.1: Histogram showing the distribution of the variable NCharged for the process e^+e^-.

- **Q.5.6 [Lab]**
  - **a)** Make a table like Table 5.3 in which you write down the quantities that characterize each event. This should be done for each event in each of the four pure samples.

RUN	EVENT	Ctrk(N)	Ctrk(Sump)	Ecal(SumE)	Hcal(SumE)	Comment
	1					
	2					
	⋮					
	20					

Table 5.3: Example table template for Question 5.6.

  - **b)** For each quantity and pure sample make a histogram using all events (choose a sensible binning).
  - **c)** Determine from the histograms where to set cuts for an optimal separation of the four different Z^0 decay modes. Using combination of cuts on different variables together will give a better result than using just one variable.
  - **d)** With the help from the above results, choose one of the mixed samples and assign each event in that sample to a certain physical process.

5.3 Part II: Statistical Analysis of Z^0 decays

For a precise measurement of the mass and decay width of the Z^0, the number of generations of light neutrinos, and the Weinberg angle; the analysis of events displays is not an appropriate procedure. The large number of events needed for the measurements are analyzed on a statistical basis with the software ROOT. Under the folder `RootFiles`, there are 10 files with `.root` extension. In a `.root` file the necessary information is made up in an tree-like structure, called *ntuple*. The contents of physical variables in the ntuples is listed in Table 5.4. There are two categories with several ntuples each, which are described below and summarized on the Table 5.4.

- **Data:** These are ntuples from events that were recorded with the OPAL detector at energies around the Z^0 resonance maximum.
- **Monte Carlo (MC):** These are *simulated* events. For a specific process the four-vectors of the outcoming particles are calculated and then the detector response to the particles is simulated in full detail. Simulated events can then be reconstructed in the same way as 'real' events.

5.3.1 Working with the ROOT Data Analysis Program

ROOT, the software with which you analyze the ntuples will be explained by the lab assistant. Some information and example commands relevant to the practical execution of this task is given below. ROOT accepts C++ syntax.

- How to Start ROOT?
  1. **Go to `Rootfiles` Folder:** For the convenience of our work it is better to set this directory-where files are located- to default. Simply enter this folder through usual interface.

Ntuples		
Name	Type	File Name (.root)
Electrons	MC	ee
Muons	MC	mm
Taus	MC	tt
Hadrons	MC	qq
Data 1	Data	data1
Data 2	Data	data2
Data 3	Data	data3
Data 4	Data	data4
Data 5	Data	data5
Data 6	Data	data6

Table 5.4: Summary of information regarding the samples.

Variables in the ntuples	
Name	Description
RUN	Run number
EVENT	Event Number
NCHARGED	Number of charged tracks
PCHARGED	Total scalar sum of track momenta
E_ECAL	Total energy in electromagnetic calorimeter
E_HCAL	Total energy in hadronic calorimeter
E_LEP	LEP beam energy (= $\sqrt{\mathrm{s}}/2$)
COS_THRU	cos(polar angle) between beam axis and thrust axis
COS_THET	cos(polar angle) between incoming positron and outgoing positive particle

Table 5.5: List of variables in NTuples.

2. **Open the Terminal:** When you are in the `Rootfiles` folder, right click the mouse on an empty space within the folder and click on "Open in Terminal". This should open a Terminal with a command prompt set to `Rootfiles` folder.

3. **Start ROOT:** First type "`module load root/6.14.04`" on terminal. You can now start root by typing "`root`" on terminal and clicking enter. After this, you should see a blue box with Root Logo for couple of seconds. After this box disappears, your command prompt at the terminal should read "`root [0]`". You are now ready to use ROOT.

- Many ROOT commands start with a dot in front of them. To execute a command one has to press enter button upon typing the command to ROOT terminal prompt. Some basic examples are as follows:

  - **.q** This command closes the Root i.e. it will bring you to the standard terminal prompt without "`root [0]`". Sometimes ROOT may not respond. Then you can try `Ctrl+C` and/or `Ctrl+Z` and afterwards `.q` again.

  - **root myfile.root** By typing `root myfile.root` you can open an already existing root file with ROOT. This can also be done directly while starting root (as described on 3. above). Most commands on ROOT requires a `.root` file to execute. For the following list of commands to work, a `.root` file needs to be opened. We can for instance work with `ee.root`. As described, type "`root ee.root`" and press enter.

- The objects in ROOT have a letter **T** infront of them. For example a ROOT Tree is a *TTree* and a ROOT Browser is a *TBrowser*.

  - **.ls** This command will display the information regarding the `ee.root` file and tree structure. Upon typing `.ls` and pressing enter you can see that this file has one `TTree` with the name *h3*. A ROOT file might contain multiple trees, and in complicated physics analyses this is often the case. In our experiment, we will have one tree per root file. The name of the tree is needed to tell ROOT tools where to look for the information.

  - `mytree->Print()` This command will display the **branch**es of the tree *mytree*. Branches are the variables available in the file. In our case `h3->Print()` will display information regarding the 8 variables available in our tree. This way of displaying the branches is often cumbersome due to many unnecessary information about the file size. A more elegant view can be achieved by typing `h3->Print("toponly")`. This command will list the branches in an easily readible manner.

  - `mytree->Draw("mybranch")` This command plots the content of the branch "mybranch" under the tree mytree, as a histogram. In our case an example command would be `h3->Draw("Ncharged")`, which plots the number of charged tracks. It is always important to check whether the named branch really exists under the tree and its name is typed correctly.

- Applying cuts:

  - `mytree->Draw("mybranch","myvariable>x")` This command plots the variable with the specified cut of `myvariable>x`.
    For example the command `h3->Draw("Ncharged","Ncharged>3")` will plot the events having more than 3 number of charged particles. In addition to basic > and < conditions following set of logical operators can be used:

Operator	Command	Example Application
>=	$\geq$	`h3->Draw("Ncharged","Ncharged>=3")`
=<	$\leq$	`h3->Draw("Ncharged","Ncharged=<3")`
&&	AND	`h3->Draw("Ncharged","Pcharged>3 && E_ecal>150")`
||	OR	`h3->Draw("Ncharged","Pcharged>150 || E_ecal>150")`
==	EQUAL	`h3->Draw("Ncharged","Pcharged==400)`
!=	NOT EQUAL	`h3->Draw("Ncharged","Pcharged!=400)`

- Multiple cuts can be applied together for a more complex selection. For example;

  ```
  h3->Draw("Ncharged","(Ncharged>3 && E_ecal>150) || (Ncharged!=2 && E_ecal<200)")
  ```

  will only plot events that have more than 3 charged tracks and 150 GeV energy deposit in the ECAL <u>or</u> events that does not have 2 charged tracks and less than 200 GeV energy deposit in the ECAL.

- If you would like to apply an interval cut such as `20<X<40` it has to be provided as a logical combination of two separate cuts i.e. `X>20 && X<40`.

In order to simplify the computer related parts, three ROOT **macro**s are provided. A macro is a series of commands that are executed in order to get a specific output, basically a minimal computer program. The three macros are named as `cutplotter.C`, `multivar.C` and `multismp.C`. Each of them takes certain inputs such as the names of processes, variables or cuts. Based on inputs the macros will produce and display some plots.

To execute a macro one should type "`.x mymacro.C(inputs)`" into the ROOT command prompt and press enter. Each input type has to be entered within " and separated by commas. The order of inputs do matter. Description of macros are given below and summarized on Table 5.6 and exemplified on Table 5.7:

- `cutplotter.C("File Name","Variable Name","Cuts")` This macro will plot a single variable of a single process with specified cuts.
  For example `.x cutplotter.C("ee","Ncharged","Ncharged>2")` will plot the variable Ncharged for the values above 2 for the $e^+e^- \to e^+e^-$ MC sample.

- `multivar.C("File Name","Cuts")` This macro will plot 6 variables of a single process with specified cuts. For example the command `.x multivar.C("mm","Ncharged<4")` will plot the distributions for all the variables in $e^+e^- \to \mu^+\mu^-$ MC sample using the events that are having less than 4 charged tracks.

- `multismp.C("Variable Name","Cuts")` This macro will plot the distribution of the specified variable for 4 different MC samples according to provided cuts.
  For example the command `.x multismp.C("E_ecal","E_ecal>10")` will plot the 4 distributions of the energy in ECAL for each process using the events that have more than 10 GeV energy deposit in ECAL.

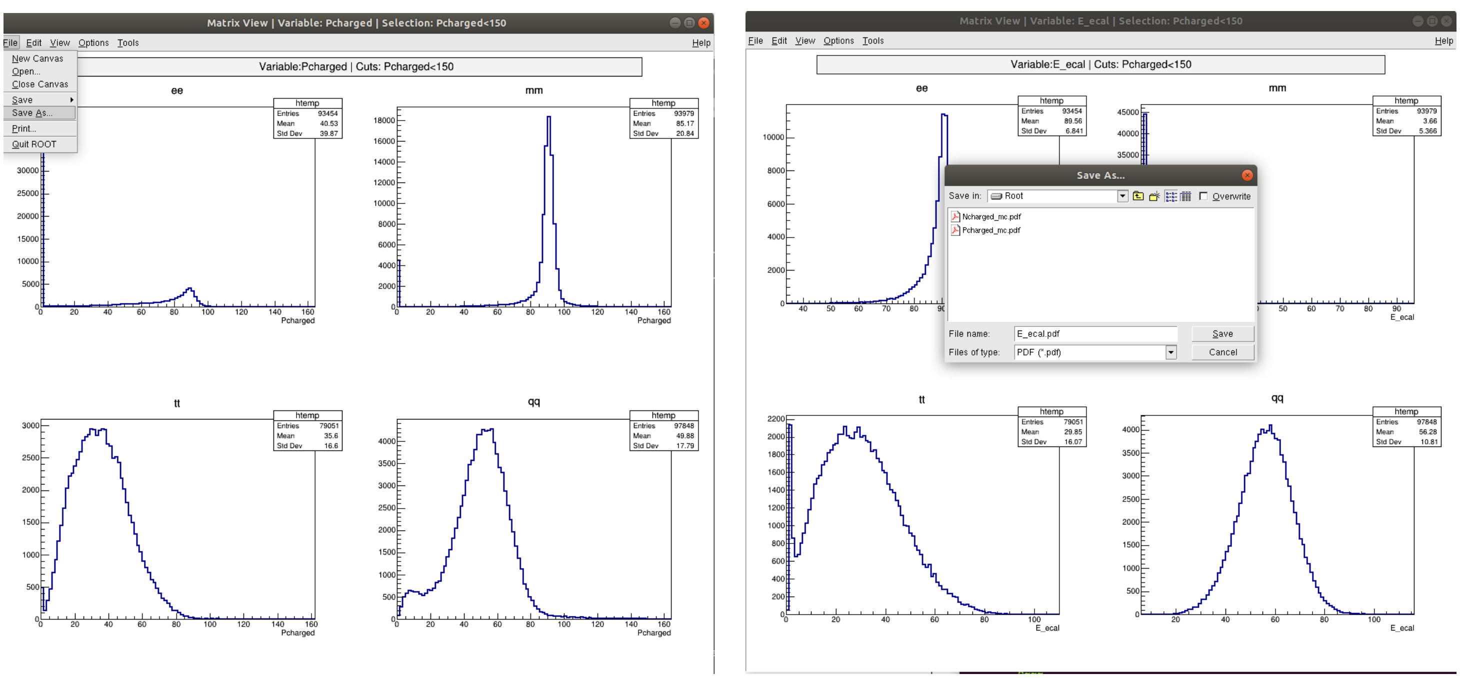
- **Q.5.7 [Lab]** Get familiar with ROOT by plotting histograms of some variables in the MC samples and compare them for the different types of events. Make a strategy on how to proceed. Always keep in mind what the goal of the experiment is (which quantities are you going to measure). How can you optimize the cuts? Which information do you need in order to solve all the problems below? Concentrate especially on the measurement of the forward—backward asymmetry with muons.

ROOT Macros Description			
File Name (.C)	Plots	Inputs [Type]	Output
`cutplotter.C`	**One variable** of **one process**	Filename [String] Variable name [String] Cuts [String]	1 Histogram
`multivar.C`	**Multiple variables** of **one process**	Filename [String] Cuts [String]	2x3=6 Histograms
`multismp.C`	**One variable** of **many processes**	Variable name [String] Cuts [String]	2x2=4 Histograms

Table 5.6: Summary of information regarding the ROOT macros provided.

- **Q.5.8** [**Lab**] How can you separate the s-channel from the t-channel in the $Z \rightarrow ee$ decay mode? Why is this important? As a hint you can recapitulate Question 5.4, and understand how the angular distributions can be used to distinguish these two channels. Remember that the cuts you develop here for the separation must also be used for all subsequent parts where electron channel is used.

  ■ **Contact the lab assistant** when you consider your cuts to be final. The lab assistant will pick one of the six data samples for you to analyze. Print the distribution of all variables for each of the four Monte Carlo NTuples and for one data sample. You can print what you see on the screen via clicking on `File` on the upper left corner of the display window and choose `Save As` command. This will open a new window where you can choose a name, format and location for your file to save. `Save` command is a faster option but it will save all files under same name (c1.pdf) therefore the files will be overwritten and only last file saved will be available at the end.



(a) File (b) Configure save options

Figure 5.2: Saving event display images.

- **Q.5.9** The efficiency of a process is defined as the ratio of number of events left after a cut, to the total number of events without a cut. For example if a cut i is applied to a process j, the efficiency is

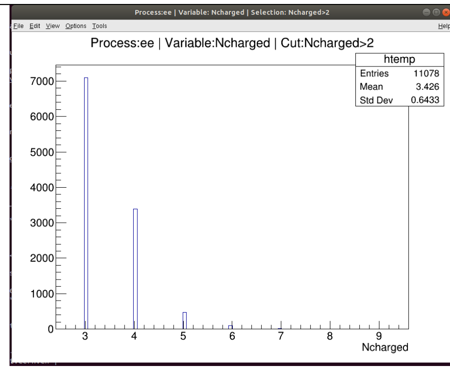
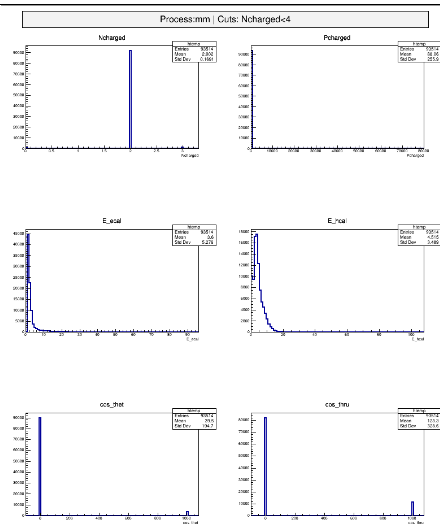
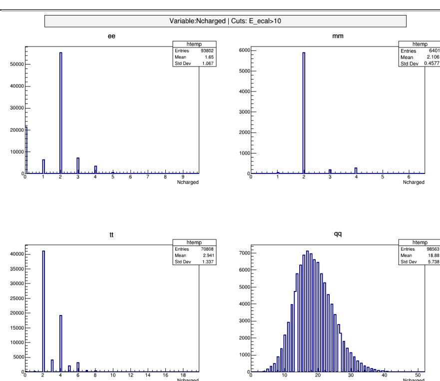
<table>
<tr><td colspan="2">Example for plotting one variable of one process with specified cuts</td></tr>
<tr><td>File Name (.C)</td><td>`cutplotter.C`</td></tr>
<tr><td>Input Command</td><td>`.x cutplotter.C("ee","Ncharged","Ncharged>2")`</td></tr>
<tr><td>Output</td><td>
</td></tr>
<tr><td colspan="2">Example for plotting multi-variables of one process with specified cuts</td></tr>
<tr><td>File Name (.C)</td><td>`multivar.C`</td></tr>
<tr><td>Input Command</td><td>`.x multivar.C("mm","Ncharged<4")`</td></tr>
<tr><td>Output</td><td>
</td></tr>
<tr><td colspan="2">Example for plotting one variable of multiple processes with specified cuts</td></tr>
<tr><td>File Name (.C)</td><td>`multismp.C`</td></tr>
<tr><td>Input Command</td><td>`.x multismp.C("Ncharged","E_ecal>10")`</td></tr>
<tr><td>Output</td><td>
</td></tr>
</table>

Table 5.7: Example demonstration of how to use the provided ROOT macros.

given by $\epsilon_{ij} = \frac{\mathrm{N_i^{i,cut}}}{\mathrm{N_j^{j,all}}}$. To make it concrete: if the cuts for e^+e^- process are considered with the process itself $\epsilon_{ee,ee} = \frac{\mathrm{N_{ee}^{ee,cut}}}{\mathrm{N_{ee}^{ee,all}}}$, which is simply the number of events after the cut, divided by the total number of events in the $Z^0 \to e^+e^-$ process. Same cut can be applied to another process such as $Z^0 \to \mu^+\mu^-$, $\epsilon_{ee,mm} = \frac{\mathrm{N_{mm}^{ee,cut}}}{\mathrm{N_{mm}^{mm,all}}}$, which is number of events left in $Z^0 \to \mu^+\mu^-$ process after the cuts for $Z^0 \to e^+e^-$ are applied, divided by total number of events in $Z^0 \to \mu^+\mu^-$. Since the cuts in this example are optimized for selecting e^+e^- events, the $\epsilon_{ee,ee}$ should be high (ideally 1) and $\epsilon_{ee,mm}$ is expected to be small, or ideally zero.

- **a)** [**Lab**] Determine the efficiency and the amount of background for each Z^0 decay channel. Use the MC events e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ and $q\bar{q}$. Represent the result in a 4x4 matrix form as shown below. Also present the values used in the efficiency calculations.
- **b)** [**Home**] Do you expect any patterns for the efficiency matrix elements and their values? Think carefully about how you have to correct the measured electron rates. Don't forget to calculate the errors!

$$\epsilon = \begin{pmatrix} \frac{\mathrm{N_{ee}^{ee,cut}}}{\mathrm{N_{ee}^{ee,all}}} & \frac{\mathrm{N_{mm}^{ee,cut}}}{\mathrm{N_{mm}^{mm,all}}} & \frac{\mathrm{N_{tt}^{ee,cut}}}{\mathrm{N_{tt}^{tt,all}}} & \cdots \\ \frac{\mathrm{N_{ee}^{mm,cut}}}{\mathrm{N_{ee}^{ee,all}}} & \frac{\mathrm{N_{mm}^{mm,cut}}}{\mathrm{N_{mm}^{mm,all}}} & & \\ \frac{\mathrm{N_{ee}^{tt,cut}}}{\mathrm{N_{ee}^{ee,all}}} & & \ddots & \\ \vdots & & & \ddots \end{pmatrix}$$

- **Q.5.10**
  - **a)** [**Lab**] For each of the seven center-of-mass energies listed in Table 5.9 determine the number of events in the hadronic channel and in the three leptonic channels for the data sample. Note that the center-of-mass energies in the dataX.root files are half the actual values given on the table.
  - **b)** [**Home**] Correct for the efficiencies calculated in **Question 5.9**.
  - **c)** [**Home**] Calculate the differential cross sections for the hadronic and the leptonic channels using corrected number of events and adding the radiation corrections from Table 5.9. Don't forget to calculate the uncertainties (errors)!

$\sqrt{\mathrm{s}}$ [GeV]	$\int$Ldt [nb^{-1}]					
	Data 1	Data 2	Data 3	Data 4	Data 5	Data 6
88.47	675.9 ± 5.7	372.0 ± 3.6	403.1 ± 3.8	464.0 ± 4.2	464.0 ± 4.2	675.9 ± 5.7
89.46	543.6 ± 4.8	488.5 ± 4.4	545.0 ± 4.8	667.5 ± 5.7	472.7 ± 4.3	800.8 ± 6.6
90.22	419.8 ± 4.0	378.5 ± 3.7	542.7 ± 4.8	486.8 ± 4.4	510.2 ± 4.6	873.7 ± 7.1
91.22	3122.2 ± 22.3	2072.8 ± 15.2	2080.0 ± 15.3	2246.6 ± 16.4	3898.6 ± 27.5	7893.5 ± 54.3
91.97	639.8 ± 5.6	540.7 ± 4.9	493.6 ± 4.5	536.0 ± 4.8	518.7 ± 4.7	825.3 ± 6.9
92.96	479.2 ± 4.5	369.4 ± 3.7	340.8 ± 3.5	450.6 ± 4.3	624.6 ± 5.5	624.6 ± 5.5
93.71	766.8 ± 6.5	353.5 ± 3.6	622.5 ± 5.5	709.7 ± 6.1	709.7 ± 6.1	942.2 ± 7.7

Table 5.8: Luminosity values for different data samples.

$\sqrt{s}$ [GeV]	A_{FB} Correction	Rad. Correction [nb] Hadronic	Leptonic
88.47	0.021512	+2.0	+0.09
89.46	0.019262	+4.3	+0.20
90.22	0.016713	+7.7	+0.36
91.22	0.018293	+10.8	+0.52
91.97	0.030286	+4.7	+0.22
92.96	0.062196	-0.2	-0.01
93.71	0.093850	-1.6	-0.08

Table 5.9: Radiations and A_{FB} corrections for the cross section measurement. The radiation corrections are given for all center-of-mass energies and must be added to the measured asymmetry. For example if the measured value of A_{FB} at $\sqrt{s} = 91.22$ GeV is 0.002194, then 0.018293 must be added. Thus the A_{FB}-corrected asymmetry is 0.020487.

- **Q.5.11**
  - **a)** **[Lab]** Measure the forward-backward asymmetry for the data and the Monte Carlo events in muon final states.
  - **b)** **[Home]** Take into account the radiation corrections and A_{FB} corrections from Table 5.9. Calculate $\sin^2\theta_w$ (Weinberg angle).
- **Q.5.12** **[Home]** Test the lepton universality from the total cross sections on the peak for $Z^0 \to e^+e^-$, $Z^0 \to \mu^+\mu^-$ and $Z^0 \to \tau^+\tau^-$ events. What is the ratio of the total cross section of the hadronic channel to the leptonic channels on the peak? Compare with the ratios obtained from the branching ratios and discuss possible differences.

5.4 Breit-Wigner Fit of Cross Section

In this task you will fit a Breit-Wigner distribution to the measured cross sections in the four decay channels. For this you need the results from **Question 5.10**, namely the cross sections for all four decay channels at all seven energies, including their errors. Some information regarding the Breit-Wigner distribution is available on Appendix C.

- **Q.5.13** **[Home]** From the measured cross sections determine the mass of the Z^0 (m_{Z^0}), the width (Γ_{Z^0}), and the peak cross sections of the resonance for the hadronic and the leptonic channels.

  Compare your results to the OPAL cross sections from **Question 5.10** and the theoretical predictions from **PDG** booklet. How many degrees of freedom does the fit have? How can you judge if the model is compatible with the measured data? Calculate the confidence levels.

- **Q.5.14** **[Home]** Calculate the partial widths for all channels from the measured cross sections on the peak. Which is the best partial width to start with? Compare them with the theoretical predictions from the PDG booklet and the values that you have calculated in **Question 5.2**.
- **Q.5.15** **[Home]** Determine the number of generations of light neutrinos from your results. Which assumptions are necessary?

- **Q.5.16 [Home]** Discuss in detail the systematic uncertainties in the whole procedure of the analysis. Which assumptions were necessary? Think of the parameters you do not have control over.

A Constants, Units and Kinematics

Constants

c	$=$	$2.99792458 \cdot 10^8\ m/s$	Speed of Light
e	$=$	$1.60217733 \cdot 10^{-19} C$	Electron Charge
$\hbar$	$=$	$h/2\pi = 6.582122 \cdot 10^{-22}\mathrm{MeV} \cdot s$	Planck's Constant / 2π
$\hbar c$	$=$	$1.973 \cdot 10^{-11}\mathrm{MeV} \cdot \mathrm{cm} =$	$0.1973\ \mathrm{GeV} \cdot \mathrm{fm}$
α	$=$	$e^2/4\pi\varepsilon_0\hbar c = 1/137.035989$	Fine Structure Constant
m_e	$=$	$0.510999\mathrm{MeV}/c^2$	Electron Mass
m_p	$=$	$938.27231 \cdot \mathrm{MeV}/c^2$	Proton Mass
ε_0	$=$	$8.8541878 \cdot 10^{-12}\mathrm{As/Vm}$	Permittivity of Free Space
G_F	$=$	$1.1663 \cdot 10^{-5}\mathrm{GeV}^{-2}$	Fermi-Coupling Constant

Units

Length:	1 Fermi	$=$	1 fm	$=$	10^{-15}m
Cross Section:	1 barn	$=$	1 b	$=$	$10^{-24}\mathrm{cm}^2 = 10^9$ nb

In particle physics one uses units where $\hbar$ = c = 1. But when doing explicit calculations one should use the proper values of $\hbar$ und c.

Energy: 1 MeV = 10^6 eV = 10^{-3} GeV = 1.6022 $\cdot 10^{-13}$ J

Mass and momentum can be given in MeV since c=1, whereas the momentum is given in MeV/c and seldom the mass is given in MeV/c^2 in order to avoid confusion.

Mandelstam Variables

To describe the kinematics of a process usually relativistic momentum-energy four-vectors $p = (\vec{p}, E)$ are used. The inner product of four-vectors is invariant under Lorentz transformations:

$$r \cdot q = r' \cdot q' \tag{5.1}$$

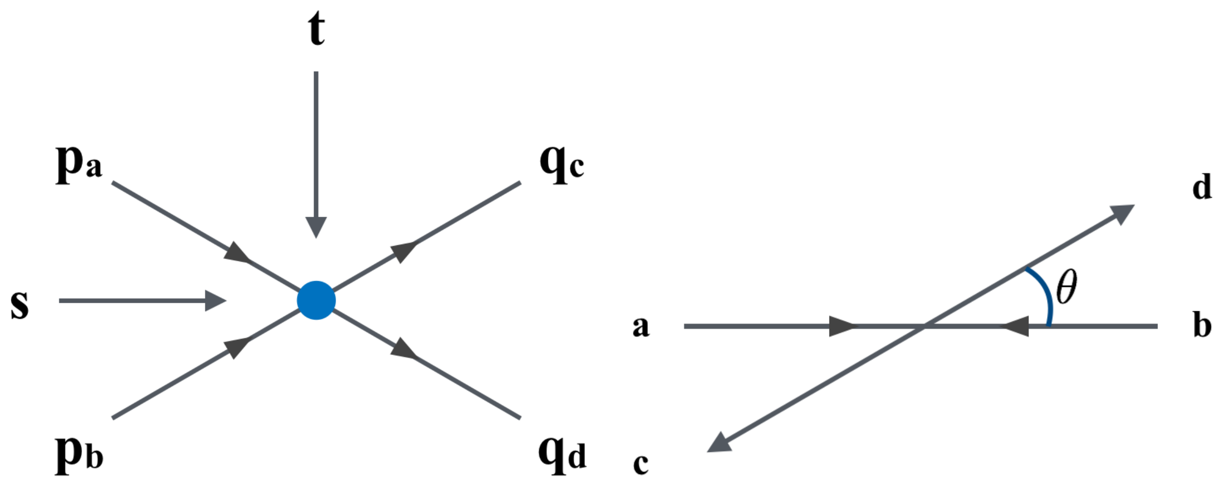
Particularly:

$$p^2 = p \cdot p = E^2 - \vec{p}^2 c^2 = m_0^2 c^4 \tag{5.2}$$

or with c = 1

$$p^2 = E^2 - \vec{p}^2 = m_0^2 \tag{5.3}$$

For a two particle process $a + b \to c + d$ e.g. (see Figure 5.3)



(a) Momenta. (b) Angle.

Figure 5.3: Definition of Mandelstam variables s and t.

$$e^+(p_a) + e^-(p_b) \to \bar{f}(q_c) + f(q_d)$$

one can describe the kinematics of the initial and the final states with relativistic four-vectors as described in the following.

The total centre-of-mass energy can be calculated from:

$$s = (p_a + p_b)^2 = (q_c + q_d)^2$$

In the centre-of-mass system this is obvous, since $\mathbf{p_a} = -\mathbf{p_b}$. Using the beam energy E_b one obtains:

$$s = (p_a + p_b)^2 = 4E_b^2 = E_{\text{CMS}}^2$$

In order to describe the kinematic one needs the energy and the scattering angle Θ_{CMS} in the centre-of-mass system, with Θ_{CMS} being the angle between p_a and q_c

This angle can be derived from:

$$t = (q_c - p_a)^2 = -2E_b^2(1 - \cos\Theta_{\text{CMS}}) < 0$$

where s and t are called Mandelstam variables.

B The Photon Transfer Process

As an example for a cross section calculation using the rules for Feynman diagrams we will discuss the QED process (Figure 5.4)

$$e^+e^- \rightarrow \gamma^* \rightarrow f\bar{f} \qquad f \neq e$$

In the first step a virtual photon γ^*, is being created. If e^+ and e^- have the same energy E and opposite momenta (e.g. at LEP) the photon obtains all the energy (2E) and has no momentum. This photon is virtual and time-like. It can only exist for the limited time allowed by the uncertainty principle and must decay into a fermion-antifermion pair. The transition amplitude to a certain final state $f\bar{f}$ is given by:

$ee\gamma^*$ Vertex	γ^*-Propagator	$\gamma^*\ f\bar{f}$ Vertex
$Q_e \cdot \sqrt{\alpha}$	$1/\sqrt{s}$	$Q_f \cdot \sqrt{\alpha}$

with α being the fine structure constant, $\sqrt{s}$ being the centre-of-mass energy and Q_f the fermion charge in units of an electron charge. With Q_e = -1 the entire amplitude proportional to

$$-\frac{Q_f \alpha}{\sqrt{s}} \tag{5.4}$$

with missing normalization factor

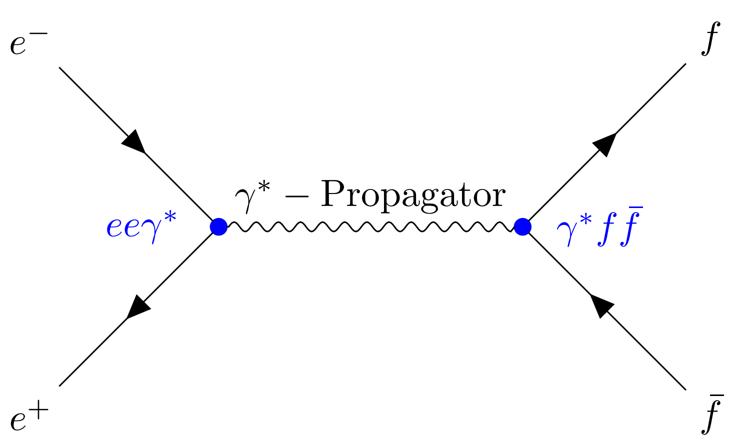


Figure 5.4: Sketch of the QED Process $e^+e^- \rightarrow \gamma^* \rightarrow f\bar{f}$

$$\frac{4\pi}{3} \cdot (\hbar c)^2 \qquad \hbar c = 0.1973 \text{ GeV} \cdot \text{fm}$$

and the color factor

$$N_c^f = 1 \text{ for leptons and } = 3 \text{ for quarks}$$

one obtains the following formula for the cross section:

$$\sigma(e^+e^- \to f\bar{f}) = \frac{4\pi}{3} \cdot (\hbar c)^2 \cdot \frac{\alpha^2}{s} \cdot Q_f^2 \cdot N_c^f \tag{5.5}$$

for certain final states this becomes (using the convention $\hbar = c = 1$):

$$\begin{array}{lclclrcl}
\sigma(e^+e^- \to \mu^+\mu^-) & = & \frac{4\pi}{3} \cdot \frac{\alpha^2}{s} & = & (Q_f = \; -1, & N_c^f & = & 1) \\
\sigma(e^+e^- \to u\bar{u}) & = & \frac{16\pi}{9} \cdot \frac{\alpha^2}{s} & = & (Q_f = +2/3, & N_c^f & = & 3) \\
\sigma(e^+e^- \to d\bar{d}) & = & \frac{4\pi}{9} \cdot \frac{\alpha^2}{s} & = & (Q_f = -1/3, & N_c^f & = & 3)
\end{array}$$

The ratio of the total hadronic cross section to the $\mu^+\mu^-$ cross section is given by

$$R = \frac{\sigma(e^+e^- \to \text{Hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3 \sum_q Q_q^2 \tag{5.6}$$

for five quark flavours we obtain

$$R = \frac{11}{3}$$

C The Breit-Wigner Form

The damped harmonic oscillator can be described using the following differential equation

$$m\ddot{x} - \beta\dot{x} + Kx = 0 \tag{5.7}$$

Using the impelling force

$$F_0 e^{i\omega t}$$

and the ansatz

$$x = ae^{i(\omega t - \phi)} \tag{5.8}$$

one obtains following expression

$$\left(\frac{a}{F_0}\right)^2 = \frac{1}{m^2}\ \frac{1}{[(\omega - \omega_0)(\omega + \omega_0)]^2 + \frac{\beta^2\omega^2}{m^2}} \tag{5.9}$$

For $\omega \sim \omega_0$

$$\left(\frac{a}{F_0}\right)^2 \sim \frac{1}{4\omega_0^2 m^2} \cdot \frac{1}{(\omega - \omega_0)^2 + \beta^2/4m^2} \tag{5.10}$$

where

$$\omega = \sqrt{\frac{K}{m} - \frac{\beta^2}{4m^2}} \qquad \omega_0 = \sqrt{\frac{K}{m}}$$

the quantum mechanical equivalence is obtained by using $E = \hbar\omega$ and $E_0 = \hbar\omega_0$

$$\sim \frac{1}{(E - E_0)^2 + \Gamma^2/4} \tag{5.11}$$

where $\Gamma = \frac{\hbar\beta}{m}$ = resonance width. The resonance width depends on the number of possible decay channels. This energy dependance is described by the so called Breit-Wigner curve. The width of the resonance is correlated with the lifetime via Heisenberg's uncertainty principle:

$$\Gamma \cdot \tau = \hbar$$

From the analogy to the harmonic oscillator this energy dependence justifies the term resonance for unstable particles with defined invariant mass M, width Γ and lifetime τ.. Even in non-relativistic quantum mechanics we observe an energy dependence following a Breit- Wigner distribution for unstable states. This can be understood directly with the following calculations: The decay law for unstable particles reads:

$$N(t) = N(0)e^{-\lambda t} \tag{5.12}$$

The wave function for a given particle at rest is:

$$\psi(t) = \psi(0)e^{-iEt/\hbar} \qquad |\psi(t)|^2 = |\psi(0)|^2 \tag{5.13}$$

i.e. the particle does not decay for real E. Therefore a small imaginary component is added to E:

$$E = E_0 - \frac{1}{2} i\Gamma \qquad mit \qquad \Gamma = \lambda\hbar \tag{5.14}$$

Then the time dependence of the wave function for an unstable particle is:

$$\psi(t) = \psi(0) e^{-iE_0 t/\hbar} e^{-\Gamma t/2\hbar} \tag{5.15}$$

Since the energy can be measured, is it sensible to have an imaginary component? To find out, we perform a Fourier transformation $\phi(\omega)$ on the wave function::

$$\phi(\omega) = (2\pi)^{-1/2} \int_{-\infty}^{+\infty} dt \psi(t) e^{+i\omega t} \tag{5.16}$$

$$= \frac{\psi(0)}{\sqrt{2\pi}} \frac{i\hbar}{(\hbar\omega - E_0) + i\Gamma/2} \tag{5.17}$$

With $E = \hbar\omega$ and after taking the square and normalization to 1 one obtains the above Breit- Wigner form.

$$P(E) = \frac{\Gamma}{2\pi} \frac{1}{(E - E_0)^2 + (\Gamma/2)^2} \tag{5.18}$$

The imaginary part of the energy is responsible for the decay and broadens the state. The width of the state due to the decay is called *natural line width.* T is the width at half height.

D The q^2 Dependence of the Coupling Constant

From the point of view of quantum field theory, an electron is not only a "naked" electron, it is rather accompanied by a cloud of virtual particles (photons and electron-positron pairs) that it emits and absorbs constantly (vacuum polarization).

These screen the negative charge of the naked electron: When very close to the naked charge, the electron-positron-pairs are polarized, i.e. the virtual positrons are attracted and the virtual electrons are repelled by the charge. The naked charge is partially compensated and in greater distance one can only measure the difference between the naked charge and the combined charged of the virtual positrons. This means that measured value of the test charge depends on the distance. When approaching the electron one penetrates the positron cloud which screens the electron charge. This effect is known as *screening*. (Figure 5.5).

This effect can precisely be calculated within the QED. Both mass and charge of the naked electron are not predicted by the theory. The mass and charge of the joint system of electrons and virtual particles can be measured, e.g. by electron-electron scattering, and they must have finite values in all steps of the calculation. According to the QED the calculations take the following form:

$$\alpha_{\mathrm{eff}}(\mathrm{q}^2) = \frac{\alpha_0}{1 - \alpha_0 \mathrm{B}(\mathrm{q}^2)} \tag{5.19}$$

with q^2 momentum transfer to the virtual photon squared and $\alpha_0 = \frac{e_0^2}{4}$ the coupling of the naked electron.

The explicit form of $\mathrm{B}(\mathrm{q}^2)$ divergences that can be treated using a procedure called **renormalisation**. To do so, an experimental electric coupling α is defined by the behaviour of the electric potential at large distances (Thompson Limit):

$$\alpha = \alpha_{\mathrm{eff}}(\mathrm{q}^2 = 0) \cong \frac{1}{137} \tag{5.20}$$

which leads to:

$$\alpha_{\mathrm{QED}}(q^2) \equiv \alpha_{\mathrm{eff}}(q^2) = \frac{\alpha}{1 - (\alpha/3\pi)\log(q^2/m_e^2)} \tag{5.21}$$

The theory of strong interaction (QCD) is a gauge theory like the QED. The quanta of the colour fields are called gluons. All eight gluons are massless and have spin 1. Like the photon, they are vector bosons without charge, but all of them carry colour and anti-colour. That is why they can interact with themselves, as opposed to the photons, which carry no charge at all.

Such theories where the field quanta interact with each other are called **non-Abelian** Theories. Just as for the electric charge in the QED, the same idea can be applied the colour charge in QCD: A quark is surrounded by a cloud of gluons and quark-antiquark-pairs just as the electron is surrounded by virtual particles. The colour charge of the quark (e.g. red) is partially compensated by the surrounding cloud of quark-antiquark-pairs. But the virtual gluons surrounding the quark have their own colour charge and can form pairs of gluons (self-coupling) as opposed to the chargeless virtual photons surrounding the electron.

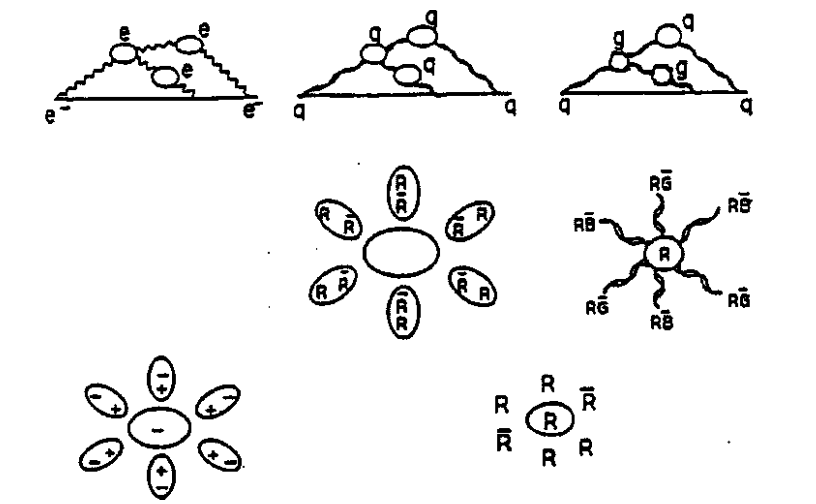


Figure 5.5: QCD Screening

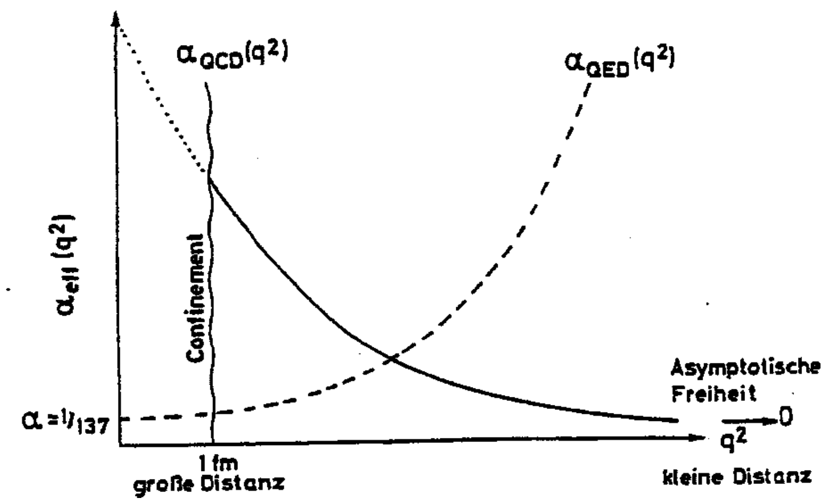


Figure 5.6: QCD vs. QED running coupling constants.

In the case of the QCD these additional terms do not screen but enhance the quark's colour charge (anti-screening). A distant gluon or quark not only feels the colour charge of the central quark but also that of the virtual gluons and the quark-antiquark-pairs. But it feels solely the force of the naked quarks if it penetrates the virtual particle cloud.

The calculation of the coupling constant of the QCD's is a difficult task and only first order diagrams have been calculated yet. That is the reason why we will use an effective coupling of the strong interaction constant which is also used in present analysis:

$$\alpha_s(q^2) = \frac{12\pi}{(33 - 2n_f)\log(q^2/\Lambda^2)} \tag{5.22}$$

with Λ being a mass scale introduced by the theory. As can be seen in the equation, becomes smaller with diminishing distances (rising q^2) (Asymptotic Freedom), as opposed to the QED's coupling constant, so that the interaction can be computed be means of perturbation theory. Due to $2n_f < 33$ this is given if the number of quarks is less than seventeen (6 quarks have been discovered yet). At small q^2 (great distances) as $\alpha_s(q^2)$ becomes so large that the quarks are confined within the hadrons and are not observable as free particles. (Figure 5.6)

E Checklist for Tasks

During the Lab Session:

- Part I
  - Q.5.6: a) Table b) Include the histograms c) Specify the best cuts d) identification of events in one of the mixed samples. Specify which sample you have used.
- Part II
  - Q.5.8: How did you separate the s-channel from the t-channel? Explain your method and reasoning.
  - Q.5.9: a) Do you have the 4x4 efficiency matrix?
  - Q.5.10: a) Have you calculated the center-of-mass energies at seven energies for four samples?
  - Q.5.11: a) Have you measured the forward-backward asymmetry for the muon final state events in the data and also for the muon Monte Carlo sample?

For the written report:

- Pre-Lab Questions: Have you completely answered the all parts of Questions 1 to 5?
- Q.5.9: b) What pattern do you expect the efficiency matrix values to follow, is this the case with your efficiency matrix elements? Have you calculated the errors?
- Q.5.10: b) Have you applied the efficiency correction?
- Q.5.10: c) Have you calculated the differential cross section for four samples with radiation corrections applied and including the errors?
- Q.5.11: b) Have you calculated the Weinberg angle with the inclusion of A_{FB} and radiation corrections?
- Q.5.12: Have you tested the lepton universality from the total peak cross section of three leptonic channels? Have you calculated the ration of total cross section of hadronic channel to the leptonic channels on the peak? Have you compared them to the ratios obtained from the branching rations and discussed the possible differences?
- Q.5.13: Have you determined the Z boson mass, width and peak cross sections of the resonance for four channels? Have you compared your results with the ones from Q.5.10 and the theoretical predictions from the PDG booklet? Have you calculated the degrees of freedom the fit has? Did you explain how the fit model can be judged compatible or not with the data and what is the situation in your case? Have you calculated the confidence levels?
- Q.5.14: Have you calculated the partial widths for four channels? Have you stated the best one? Have you compared them to the theoretical predictions from the PDG booklet as well as the values you have calculated on Q.5.2?

- Q.5.15: Have you calculated the number of generations of light neutrinos? Have you stated the assumptions that you have made for this calculation?
- Q.5.16: Have you discussed possible systematic uncertainties that could have affected the final result? Have you described the assumptions that have been made?

F Suggestions for Writing a Proper Report

This section is not intended as a exhaustive list of rules or tips to make writing a proper laboratory report possible, but rather a reminder that a scientific report has certain quality standards and it is a part of this laboratory course's grading policy and your responsibility to pay attention to.

- There are useful documents prepared by the organizers of the laboratory course, providing examples of data analysis, plotting, as well as a mock lab report to demonstrate LaTeXusage, all with source codes included.
  Files can be found here: `https://uni-bonn.sciebo.de/s/AxoJEil2swYBK6h?path=%2F`
  During the grading of your written report you will be assumed to be knowing these informations.
- The first and foremost rule of thumb in giving yourself a sense of how the report should be written is that; a reader that has not conducted the experiment should be able to understand what you did and ideally be a able reproduce and check your results.
- Answer all the questions and show that you have completed all the tasks. For example if you just write "we did a check and therefore concluded this result" it is not clear to the reader what check you did and how it lead to that conclusion. Describe and share the measurements/calculations you have made, so that reader can also follow your path.
- If there is something unusual in your results/findings acknowledge it and discuss it.
- The laboratory report must be typed in LaTeX, not Word, Open Office or some other program.
- Using material(text, image, table etc.) from a source without citing it properly will be interpreted as plagiarism and leads to a failing grade of 5.0 independent of the content of the rest of the report.
- You have one month to write and submit the report starting from the last day of your laboratory session. Tutors can grant one week of extension in case you request it at least one week before the original submission date. Having requested the extension does not mean you have got the extension. Please always make sure you have received an E-Mail from the tutor certifying the agreed new date of submission. Failing to submit the report on the day of submission will lead to a failing grade of 5.0. If your date of submission is 1st of April and you submit on 2nd of April 00:01, you will fail. Please do not wait for the last minute (or even day) and risk your prospects.

G Glossary

Anti-particle: An anti-particle has most of it's counterpart characteristics same except for one or a few quantum numbers, i.e. charge and baryon number, which have opposite values.
Anti-proton: The anti-particle of the proton with negative charge.

Barn: cross section unit: 1 Barn = 10^{-24}cm^2
Baryon: Name for all *hadron*s that are *fermion*s and have a mass $\geq m_{\text{proton}}$.
Bhabha-scattering: Elastic $e^+e^- \rightarrow e^+e^-$ scattering.
Born Approximation: Lowest order process.
Boson: Every particle is either a boson or a fermion. Bosons are particles with integer spin. They follow the Bose-Einstein statistics and are the carriers of all fundamental interactions. See *Fermion.*
Breit-Wigner Resonance: See Appendix C.
Bremsstrahlung: Ger. Breaking radiation. Radiation in form of photons, radiated by charged particles in an electromagnetic field.

CERN (Centre Européen pour la Recherche Nucléaire): European Centre for Elementary Particle Physics in Geneva, Switzerland.
Charged Current: Part of the *weak interaction*, mediated by $W^{\pm}$ gauge bosons.
Collider: An accelerator where two particle beams collide.
Colour: Name given to the threefold quantum number of quarks and gluons. They are named after three basic colours: red, green and blue.
Confinement: Describes the fact that quarks cannot exist as free particles.
Cosmic Radiation: Extremely high energy radiation with origin in the universe that arrives on earth. High energy muons emerging from interactions of this radiation with the atmosphere, lead to background events.
Coupling Constant: A measure for the strength of an interaction. The coupling constants of the gauge theories are not constant but depend on the momentum transfer.
Critical Energy: Energy of a charged particle at which the energy loss through ionisation equals that through bremsstrahlung. At higher energies the loss due to bremsstrahlung is higher.
Cross Section: The area that describes quantitatively the probability of interaction between two particles.

DESY (Deutsches Elektronen Synchrotron): German Centre for Elementary Particle Physics. It has two locations in Hamburg and in Zeuthen.
Detector: A device or a machine that can be sued to detect particles and to observe their characteristics.
Drift Chamber: A type of detector that can measure the trajectory of charged particles. A further development is the *proportional chamber.*

Electromagnetic Calorimeter: An incoming γ, e^- or e^+ desposits all of its energy in the calorimeter in form of a cascade. The calorimeter allows to measure the energy of a particle.
Electromagnetic Interaction: The long range force that acts between electric charges, currents and magnets and is mediated by the photon.
Electron: Spin 1/2 fermion. The lightest of all charged leptons that has 1/1836 of the proton's mass.
Electroweak Interaction: A fundamental interaction that represents the unification of the electromagnetic

and the weak interaction.
Elementary Particles: Particles that are not composed of other particles. According to present day knowledge quarks, leptons and gauge bosons are elementary.

Fermion: see *Boson*. Fermions are particles with spins of odd multiples of 1/2. They obey the Fermi-Dirac statistics whose basic modules (quarks and leptons) are fermions.
Feynman Diagrams: Diagrams introduced by Feynman to describe the elementary interaction mechanisms with corresponding rules of calculation.
Flavour: A term used to describe a type of quark (up, down, strange, charm, bottom and top)
Form Factor: A factor that appears in the cross-section formula and considers the deviation from the point charge.
Fragmentation: The process where coloured quarks and gluons become jets of 'white' particles. see *Colour*.
Fundamental Interactions: The *strong interaction*, the *electroweak interaction*, and the *gravitation*.

GeV (Giga-eV): 10^9 eV = 10^3 MeV
Gluon: Vector boson that mediate the strong interaction. Eight different gluons with their respective colours and anticolours are known to exist.
Gravitation: A long range force that acts on all massive particles. It is so weak that it is only important when considering macroscopic objects.
Graviton: The hypothetical boson with zero mass that mediates the gravitational force.
Gauge Bosons: Vector bosons that carry the fundamental forces between Fermions. We know of 12 gauge bosons: 8 Gluons, the photon, W^+, W^- and Z^0.
GUT (Grand Unified Theories): A mathematic formalism to unify the fundamental interactions.

Hadrons: Particles that underlie the strong interaction. These include the mesons and the baryons and are composed of quarks and antiquarks.
Higgs Boson: A zero spin gauge boson that explains how $W^\pm$ and Z^0 acquire their masses due to the Higgs-mechanism.
Higgs Mechanism: A mechanism that gives mass to a field particle without breaking the gauge symmetry by using a zero spin particle as a mediator.

Interaction: Process at which energy and momentum are transfered between two particles (elastic scattering) or particles are created or destroyed (inelastic scattering).
Isospin: A quantum number used in the characterization of the particles subject to strong force. One distinguishes between strong and weak isospins.

JET Chamber: Large drift chamber in the OPAL detector.

LEP (Large Electron-Positron storage ring): e^+e^- storage ring at CERN.
Lepton: Spin 1/2 fermion. One of six known (up to the present day) elementary particles on which the weak but not the strong interaction acts, those being the electron, the muon and the tau lepton with their respective neutrinos.
Luminosity: A term that describes the intensity of the interaction in a storage ring. The luminosity is proportional to the interaction rate.

Mandelstam-Variable: see Appendix A.
Muon: Spin 1/2 fermion. A charged lepton 200 times heavier than the electron.

Neutral Current: Part of the weak interaction mediated by Z^0 gauge bosons.
Neutrino: Spin 1/2 fermion. One of three known leptons with neither charge nor mass, each associated to a charged lepton. Neutrinos only feel the weak force. Due to experimentally observed phenomenon of neutrino

oscillations, neutrinos are known to change flavours, requiring them to be massive. However, this mass is extremely small and so far there haven't been any measurements.
Neutron: A chargeless hadron with the approximate mass of the proton, which is made of three quarks like the proton.

OPAL (Omni-Purpose-Aparatus for LEP): Name of one of four LEP experiments, the other three being ALEPH, DELPHI and L3.

Partial Cross Section: Cross-section for an interaction with a specific final state.
Particle Accelerator: An instrument which accelerates charged particles in order to increase their energy. Usually stable particles like the electron, the proton or ions are accelerated.
Particle Physics: The sub field of Physics in which the subnuclear particles, both elementary and compound, and the forces that describe their interactions are studied.
Photon: A massless boson with spin 1 acting as the mediator of the electromagnetic force. Electromagnetic radiation consists of photons.
Positron: The positively charged antiparticle of the electon.
Proton: A hadron with positive charge. Being the lightest baryon it consists of three quarks and is part of all nuclei.

QCD (Quantum Chromo-Dynamics): Theory of the strong interaction that describes the interaction between quarks and gluons using the colour field.
QED (Quantum Electro-Dynamics): Theory of the electromagnetic force that describes the interaction of charged particles in an electromagnetic field.
Quarks (Antiquarks): Spin 1/2 fermions. All six different quarks (see flavour) and their antiquarks are elementary particles whose charges are fractions (1/3 and 2/3) of the electron charge. They don't exist as free particles but are combined to quark-antiquark pairs (Mesons, e.g. Pions, Kaons) and to three quark states (baryons, e.g. proton, neutron) via the strong interaction. Each quark has three degrees of freedom.

Radiation Length: Penetration length in a material, after which the number of electrons drops down to 1/e of the original number.
Real Photons: Real photons are the only ones that can become independent from their sources. They fulfill $E^2 = m^2 + \vec{p}^2$. Momentum and energy are equal, since photons have no mass.

Standard Model: The combined theories of strong, electromagnetic and weak forces which describes everything we know about nuclear and particles physics.
Strong Interaction: A short ranged interaction and the strongest one. It acts on quarks and all particles made of quarks (hadrons) but not on leptons. It is described by the QCD and its mediators are the gluons.
Synchrotron Radiation: Electromagnetic radiation emmited by deflected charged particles, like in a ring accelerator (e.g. LEP).

Tau-(r)-Lepton: Spin 1/2 fermion. The heaviest known lepton.
Thrust: $T = \max_{\vec{n}} \frac{\sum_i |\vec{p_i} \cdot \vec{n}|}{\sum_i |\vec{p_i}|}$, where $\vec{n}$ is a unit vector in direction of the thrust axis and $\vec{p_i}$ are the momenta of all involved particles.
Total Cross-Section: The integral over all possible final states of the cross-section for an interaction.
TPC: (Time Projection Chamber) Further development of the *drift chamber*.

Vector Bosons: Bosons with spin 1. Gauge bosons belong to this category.
Vector Mesons: Hadrons with spin parity $J_P = 1^-$.
Virtual Photons: Mediators of the electromagnetic interaction between charged particles. They can only exist as free particles for the time allowed by the uncertainty principle. Virtual Photons can be time-like

(E>p) or space-like (E<p).
Virtual Particles: see *Virtual Photons.*

W^-, W^+, and Z^0 Bosons: The three mediators of the weak force. They areall bosons with spin 1.
Weak Interaction: A weak force with short range that acts on all quarks and leptons. It is responsible for the decay of many particles (e.g. Neutron 0-decay).
Weinberg Angle: An angle which characterizes the ratio between the charged and the neutral current.

Acknowledgements

Pre-2019: At this point we want to thank the FP assistants at the Physikalisches Institut der Universität Heidelberg. It was here that this experiment was first conceived and realised. Our special gratitude goes to Dr. Martin Wunsch.

2019: We would like to thank Mrs. Valja Gebhardt for the pdf to text scanning of the old English manual as well as Dr. Marc Lehmacher for providing the Tex files of the old manual in German.

2021: Barbara and Eckhardt

Changelog

July 2019: Porting of PAW files into the root files. Updating old manual into new LaTeX script including modernisation fo some tables and figures.

February 2021: Minor changes based on feedback from students and tutors to make certain tasks and descriptions more clear to understand. BDT task.