RWTH Aachen University
Physics Institute III
Laboratory Class Particle Physics

Experiment 17: D0 Experiment - Production and Decay of W Bosons

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Accompanying Web page: http://web.physik.rwth-aachen.de/ hebbeker/fprakt/windex.html

0. Preliminary remarks:

This ‘experiment’ does not foresee to set up an experimental device nor to take data with an existing apparatus. The objective is the evaluation of data recorded in the years 2004 to 2006 with the D0 particle detector at the $p\bar{p}$ collider Tevatron at FERMILAB near Chicago. This is a typical large scale particle physics project which, of course, cannot be reproduced in a laboratory class. The analysis of huge amounts of experimental data is an important and typical activity of experimental particle physicists. This ‘experiment’ allows to make precise measurements of fundamental constants of nature.

For the data analysis the students will use the Linux computers in the CIP-Pool of the physics center or their own laptops (Linux or Windows). The required programs are written in C++ using the ROOT Data Analysis Framework (root.cern.ch).

Suggestions for improvements are most welcome.

1. Subject:

Analysis of the reaction

$$p\bar{p} \to W \to e\nu \tag{1}$$

and measurements of

- the corresponding cross section
- the mass of the W particle, the charged boson of weak interactions, and
- the electroweak mixing angle.

2. Duration:

3 days

3. Literature:

A) Mandatory:

HEB T. Hebbeker, presentation **Elementary particle physics I and II**, http://web.physik.rwth-aachen.de/~hebbeker/lectures/elementary-particles-1_introduction_2018-19.pdf http://web.physik.rwth-aachen.de/~hebbeker/lectures/elementary-particles-2_introduction_2019.pdf

D01 **First Publication of the D0 Collaboration on the Measurement of the W Mass, (PRL 77 (1996) 3309)**, http://web.physik.rwth-aachen.de/~hebbeker/fprakt/d0_pub_033.pdf

D02 **Conference Report of the D0 Collaboration on the Measurement of W Production, (D0Note 4403-CONF, 2004)**, http://web.physik.rwth-aachen.de/~hebbeker/fprakt/E06.pdf

L3W **L3 Collaboration: Measurement of the Mass and the Width of the W Boson at LEP, (Eur.Phys.J.C45:569-587,2006)**, especially chapter 6, http://arxiv.org/abs/hep-ex/0511049

OR

OPA **OPAL Collaboration: Measurement of the Mass and Width of the W Boson, (Eur.Phys.J.C45:307-335,2006)**, especially chapter 8, http://arxiv.org/abs/hep-ex/0508060

B) Further reading:

D03 **D0 Collaboration: Measurement of the W Boson Mass (Phys. Rev. Lett. 103, 141801 (2009)**, http://arxiv.org/abs/0908.0766

MAR B. Martin and G. Shaw, **Particle Physics**, 4th edition, Wiley, 2017

PER D. Perkins, **Introduction to High Energy Physics**, 4th edition, Cambridge University Press, 2000,
especially chapters 7 and 8

4. Prior knowledge:

Basic knowledge of elementary particle physics (quarks, leptons, gauge bosons, detectors, luminosity) is assumed.

The data analysis is performed on computers with a Linux or Windows operating system. Programming examples are available, so only basic knowledge of C++ is required. Links to Linux, C++ and ROOT tutorials can be found on the laboratory class website accompanying this experiment. The appendix list some ROOT commands.

We use a system of units where $c = \hbar = 1$, see appendix.

5. Introduction:

5.1. $p\bar{p}$ physics at the W resonance:

Figure 1 shows the elementary particles of the Standard Model of elementary particle physics.

- Matter particle = fermions (leptons and quarks) with spin 1/2, and their antiparticles. Quarks come in three color states.
- Exchange particles = gauge bosons with spin 1.

In the addition there is a scalar particle, the spin-0 Higgs boson which provides mass to all fermions and to the heavy gauge bosons.

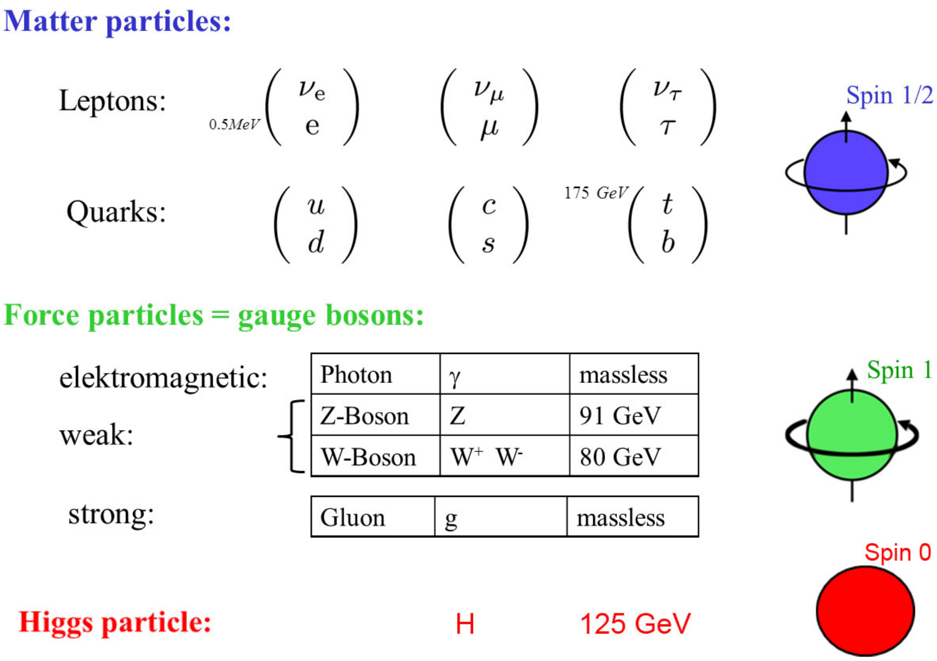

Fig. 1 - Particles of the Standard Model

The photon γ is the exchange particle of the electromagnetic force, the heavy bosons $W^{\pm}$ and Z play a similar role for the weak interaction. These two forces together with the strong interaction are summarized and described mathematically by the **Standard Model of elementary particle physics**. There is a strong connection between electromagnetic and weak interaction, therefore one speaks of the **electroweak force**. An important parameter of the Standard Model is the so-called **electroweak mixing angle** (also called **Weinberg angle**), which is normally quoted as $sin^2\theta_W$. It describes the interplay between electromagnetic and weak interactions and was measured to $sin^2\theta_W \approx 0.23$.

The numerical values of the W boson mass m_W and the electroweak mixing angle θ_W **cannot** be predicted theoretically, they have to be measured or calculated from suitable measured quantities.

The properties of the **W** boson can be studied in high energy proton-antiproton collisions. The resulting **W** boson decays quickly into leptons or quarks. It is a very short-lived particle that can be observed as a resonance phenomenon.

The **W** boson is produced by quark-antiquark annihilation. Those quarks and antiquarks are constituents of the colliding proton and antiproton. For the corresponding Feynman graph (in leading order of perturbation theory) see Fig. 2. In the following we often speak generically of quarks and dont't distinguish between particles and antiparticles.

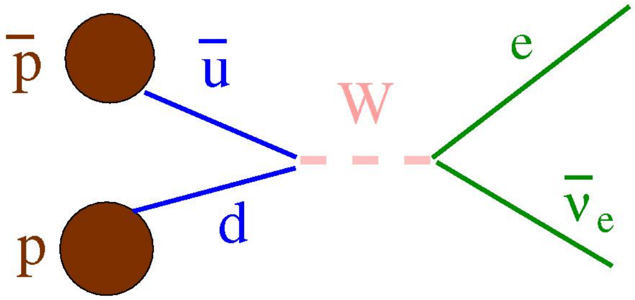

Fig. 2 - Feynman diagram describing W production and decay

Depending on the kind of quarks involved a W^+ or a W^- boson is produced, which is here referred to as a **W** implying either electrical charge. The **W** boson decays into fermion-antifermion pairs, for example $\mathrm{e}^-\bar{\nu}_\mathrm{e}$, $\mathrm{e}^+\nu_\mathrm{e}$ or $\mathrm{q}\bar{\mathrm{q}}$. The quarks are not directly observable but transform into a number of hadrons. These bunches of hadrons are called jets. In the center of mass system of the W boson the two leptons or quark jets fly apart in opposite directions. To produce a **W** boson the center of mass energy $\sqrt{\hat{s}}$ of the two colliding quarks must (almost) satisfy $\sqrt{\hat{s}} = E_q + E_{\bar{q}} = m_W$. “Almost“ because of the W boson's width Γ_W, see below. $\sqrt{\hat{s}}$ is only a fraction of the center of mass energy $\sqrt{s} = 1960\,\mathrm{GeV}$ (Tevatron) of the $p\bar{p}$ system, see below. In hadron accelerator experiments the boost of the partons (as constitutents of the protons) along the beam axis is not known. Therefore only components of a physical quantity transverse to the beam axis (= z-direction) are suitable for the analysis, i.e. x- and y-components. One speaks of **transverse momentum** p_T (magnitude), **transverse energy** E_T etc. The transverse energy is calculated by using

$$E_T = \frac{p_T}{p} \cdot E \tag{2}$$

thus we introduce an energy vector (!) which is projected onto the transverse plane.

Another important quantity is the **transverse mass**: To obtain the mass M of a decaying particle from its decay products i one would calculate the Lorentz-invariant mass m:

$$m^2 = (\sum_i p_i)^2 \tag{3}$$

which is often called ‘invariant mass’. p_i describes the four-momentum of particle i. The square of a four-momentum is:

$$p^2 = E^2 - \vec{p}^2 \tag{4}$$

Of course all daughter particles i have to be taken into account; then one gets $m = M$. If only the transverse components of the decay products are known, the so-called **transverse mass** m_T is calculated by using only the transverse components of the momentum vectors p_i and the energies E_i. This quantity m_T differs from M ($m_T \leq M$) and has a broad distribution (in contrast to a sharp peak for m) if calculated for many events, since the neglected longitudinal components differ from event to event. Nevertheless, the m_T distribution contains information about M, so that m_T can be used to measure the W mass in a hadron collider experiment.

The following equations combine the measurable cross sections with fundamental parameters of the Standard Model of elementary particle physics like the W mass or the electroweak mixing angle θ_W. However, these equations cannot be derived here, see literature.

The total cross section for $q\bar{q} \to W \to e\nu$ is increased due to a resonance for center of mass energies $\sqrt{\hat{s}}$ of the quark-antiquark system close to the W mass. It can be described by a Breit-Wigner distribution:

$$\hat{\sigma} = \hat{\sigma}_0 \cdot \frac{\hat{s}\,\Gamma_W^2}{(\hat{s} - m_W^2)^2 + m_W^2 \Gamma_W^2} \tag{5}$$

where

$$\Gamma_W = 1/\tau_W \tag{6}$$

is the total decay width of the W boson and τ_W is its mean lifetime. The width can be calculated with the help of the Standard Model and it was also determined experimentally. The mean value is

$$\Gamma_W = (2.085 \pm 0.042)\,\mathrm{GeV} \tag{7}$$

It should be noted that m_W is the mean mass. Generally a W boson can be produced with energies differing from the mean value, for example $\sqrt{\hat{s}} = m = m_W \pm \Gamma_W$. We must always distinguish between the varying mass m of one particular collision event and the mean W mass m_W! The peak cross section

$$\sigma_0 = \frac{12\pi}{m_W^2} \cdot \frac{\Gamma_{qq'}\,\Gamma_{e\nu}}{\Gamma_W^2} \tag{8}$$

depends on both the initial state and the final state. The corresponding partial width $\Gamma_{ff'}$ (f = fermion) for a certain decay channel is universally defined as the product of the total width Γ and the branching fraction (or banching ratio) B:

$$\Gamma_{ff'} = B_{ff'} \cdot \Gamma_W \tag{9}$$

It is a measure of the coupling strength between the W boson and the respective fermions. Therefore the coupling of light quarks (which are constituents of the proton and antiproton, respectively) to the W in the initial state are described by Γ_{ud} and $\Gamma_{e\nu}$ represents the W-$e\nu$ coupling in the final state. Note that the branching ratio is also used to describe the quark-W coupling in the initial state, because the coupling constants are the same for $f\bar{f}' \to W$ and $W \to f\bar{f}'$.

In the framework of the Standard Model of electroweak and strong interactions one can calculate the partial widths[1]:

$$\Gamma_{ff'} = \frac{N_C}{12} \cdot \frac{\alpha}{\sin^2\theta_W} \cdot m_W \tag{10}$$

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[1] neglecting quark mixing

where the color factor $N_C = 3$ is to be applied only to quarks. Apart from this factor the partial width are all the same, independent of the final state. $\alpha \approx 1/137$ is the fine-structure constant[2] and θ_W is the electroweak mixing angle. The total width of the W is the sum of all partial widths:

$$\Gamma_W = 3\,\Gamma_{e\nu} + 2\,\Gamma_{ud} = 9\,\Gamma_{e\nu} \tag{11}$$

The factor 3 takes into account that there are three lepton generations. For quarks the factor is 2 because the top-bottom pair is too heavy to be produced on the W resonance. The branching fraction $B(W \to e\nu)$ is found to be $1/9 \approx 11\%$ because $\Gamma_{ud} = 3\,\Gamma_{e\nu}$.

The formulae are valid in the lowest order of perturbation theory (more on this below).

So far we have only given the cross section $\hat{\sigma}$ for the interaction of point-like quarks, but we need the cross section σ for the annihilation of proton and antiproton! Since the quarks carry only a (variable) fraction x (between 0 and 1) of the nucleon momentum, the center of mass energy $\sqrt{\hat{s}}$ of the quark-antiquark system is smaller than the center of mass energy $\sqrt{s}$ of the $p\bar{p}$ system:

$$\hat{s} = x_p\, x_{\bar{p}}\, s \tag{12}$$

The probability to find a quark of type q with momentum fraction x_p inside the proton is given by the **parton density function (PDF)** $f_q(x_p)$, which have been determined experimentally. With this knowledge one can calculate the cross section σ for the process $p\bar{p} \to W \to e\nu$ as:

$$\sigma = \frac{1}{N_C} \int_0^1 dx_p \int_0^1 dx_{\bar{p}} \left(\sum_{i,j} f_i(x_p)\, f_j(x_{\bar{p}})\ \hat{\sigma} \right) \tag{13}$$

One needs to integrate over the parton density functions. The sum extends over all quarks (especially u and d in this case). The factor $1/N_C$ takes into account that a quark and antiquark can only annihilate into a colorless W if they have the same (anti-)color. For a random distribution of colors that condition is fulfilled only for $1/3$ of the quark-antiquark pairs.

The analysis in this experiment is carried out in the framework of the Standard Model of electroweak and strong interactions. Its validity is assumed and the free parameters are to be measured.

5.2. The D0 Experiment:

Prior to the launch of the LHC the **Tevatron** was the largest hadron collider in the world. With its help important physical insights were gained since 1983. Among others, the top quark was discovered in 1995.

Inside the Tevatron, protons and antiprotons are accelerated and brought to collision at two interaction points. The D0 detector at which the data for this laboratory experiment was recorded is located at one of these interaction points. Figures 3 to 5 show the structure of the detector. Figures 6 and 7 show typical events within the detector.

The main detector components for this analysis are the inner tracking detector (tracker) and the liquid argon calorimeter, in particular its inner layers in which electromagnetic showers are absorbed.

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[2] more precisely: $\approx 1/128$, since the value depends on the energy of the process considered (in this case m_W)

To measure a particle's momentum a strong magnetic field ($|\boldsymbol{B}| = \mathbf{2\,T}$) is required. This field is provided by a superconducting solenoid located between tracker and calorimeter.

An electron flying off from the collision point is initially registered in the tracker as a trace. The tracker consists of a silicon detector in which the point of passage is detected with the help of the produced electron-hole pairs, and thin scintillating fibers in which the passage of a particle generates a little flash of light.
Then, the electron flies through the solenoid into the calorimeter, consisting of a high density absorber with a high atomic number (uranium), where an electromagnetic shower (electron-positron-photon) develops. In the active material (liquid argon) the particles are detected through their ionization. The total amount of ionization is proportional to the shower energy.

At its peak, the Tevatron reached a center of mass energy of $\sqrt{s} = \mathbf{1.96\,TeV}$. Prior to the commissioning of the LHC in 2010 with an initial center of mass energy of $\sqrt{s} = \mathbf{7\,TeV}$ the Tevatron had a monopoly in the search for the Higgs boson and new particles such as supersymmetric particles.

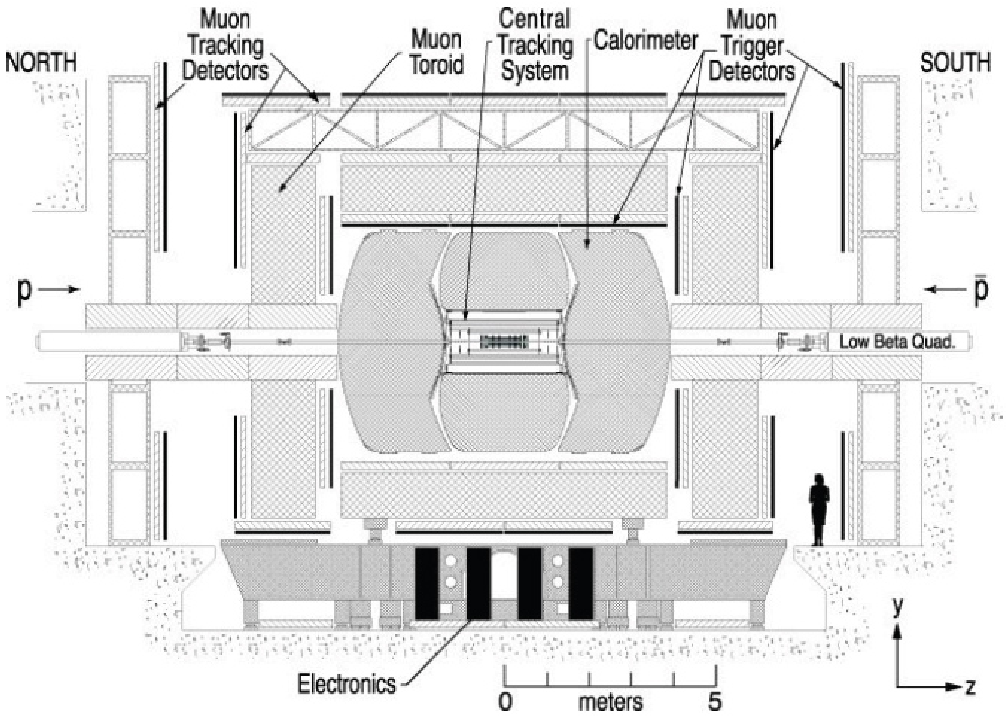

Fig. 3 - The D0 detector.

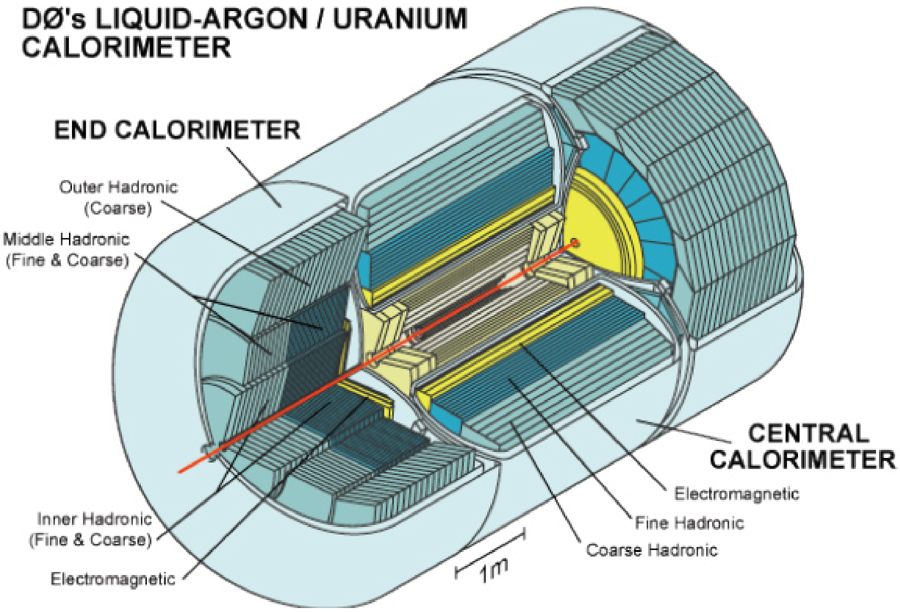

Fig. 4 - D0 calorimeter within cryostats (at a temperature of $90\,\mathrm{K}$).

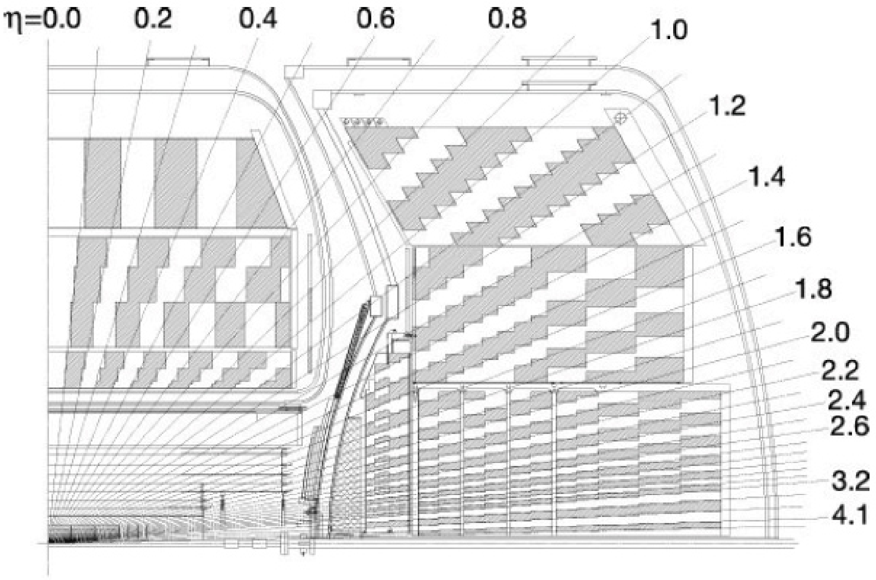

Fig. 5 - D0 detector, cross section: tracking chamber (lower left) and calorimeter. The gray and white areas indicate which cells of the calorimter are read out collectively.

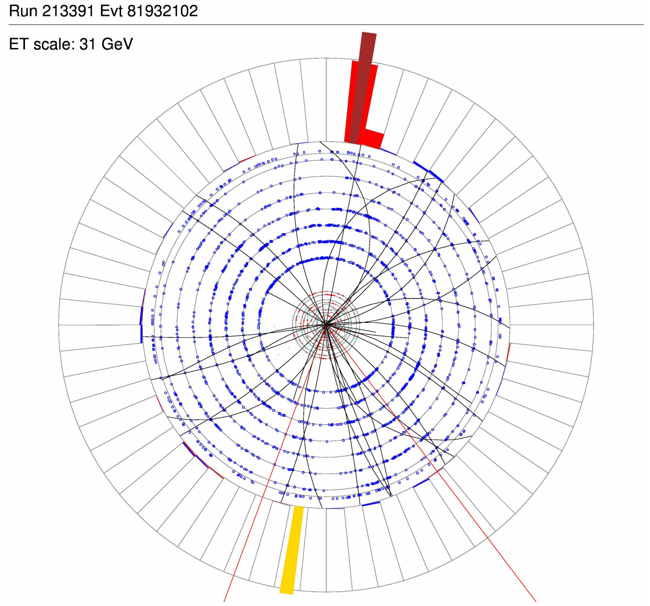

Fig. 6 - $W \rightarrow e\,\nu$-event in transverse plane, measured by D0. One can see the traces in the tracker and the deposited energy in the calorimeter (bars inside the ring structure). The missing energy is indicated by the yellow bar at the bottom.

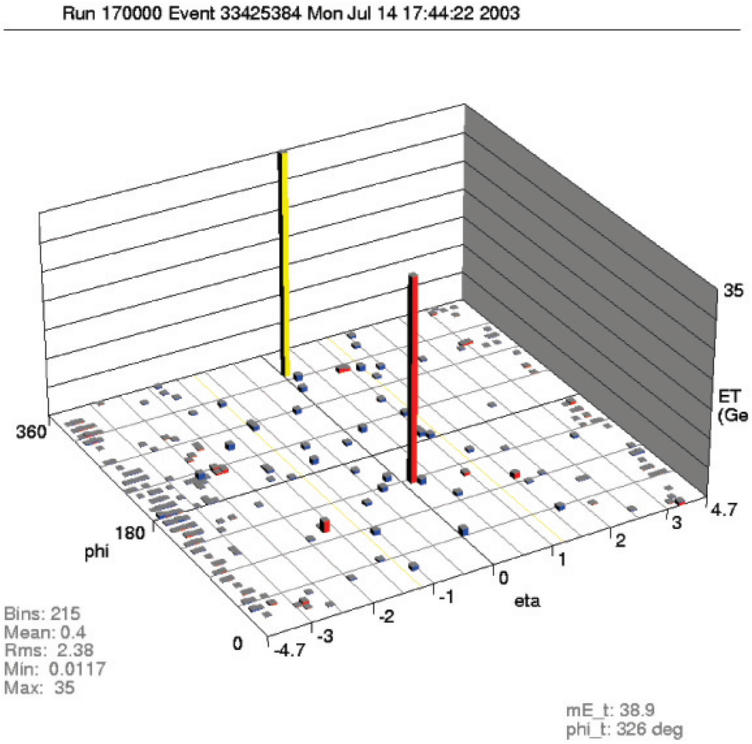

Fig. 7 - A so-called lego plot of a $W \rightarrow e\nu$-event, D0 experiment. Plotted is the transverse energy deposited in the detector as a function of the direction (azimuth angle ϕ and pseudorapidity η, see below). The electron can be seen in the middle (red). Also shown is the missing transverse energy (yellow0, which is the peak at $\phi \approx 310^0$.

5.3. Objectives:

The main objective of this experiment is the direct determination of the W boson mass m_W from the data recorded by D0.
In addition, the cross section of the event $p\,\bar{p} \;\rightarrow\; W \;\rightarrow\; e\,\nu$ is to be measured. Finally, the electroweak mixing angle θ_W, the color factor N_C and the width Γ_W can be determined. Proposals for methods and workflows are presented below.

5.4. Monte Carlo data set:

In addition to the actual measured data (file: '*d0.root*') a set of Monte Carlo events is available (file: *mc_all.root*). This data set was generated for a given W mass of $80.3946\,\mathrm{GeV}$. It contains events of type[3] $q\,\bar{q} \;\rightarrow\; W \;\rightarrow\; e\,\nu$. The measured data set on the other hand contains also background events from other electron producing reactions (for example $q\,\bar{q} \;\rightarrow\; Z \;\rightarrow\; e^+\,e^-$ with one electron undetected)[4]. The data sets contain only electron candidates; other particles, especially hadrons, have already been removed.

First, the remaining background has to be largely eliminated. Then the measured data can be compared to Monte Carlo data with different W masses. This comparison leads to the desired W mass m_W and its uncertainty. Here we will work with 19 different closely adjacent mean W masses as the base for the Monte Carlo calculations. Those are chosen symmetrically around the initial Monte Carlo W mass of $80.3946\ \mathrm{GeV}$ with a step size of $0.05\ \mathrm{GeV}$. So they range from $79.446\ \mathrm{GeV}$ to $80.8446\ \mathrm{GeV}$ (see appendix).

Generating those 19 data sets implies a major effort, which we try to avoid. We therefore use a trick commonly used in particle physics:

Once the Monte Carlo data are generated for one particular mean W mass $m_W^{default}$ and corresponding resonance width Γ_W (in the following example, Figure 8, these are $m_W^{default} = 80\,\mathrm{GeV}$ and $\Gamma_W = 2.08\,\mathrm{GeV}$) one gets the corresponding Breit-Wigner distribution of the W mass (see Figure 8). With the known theoretical description of this distribution (i.e. a Breit-Wigner formula) one can generate further mass distributions with the same peak cross section and width but different mean values (and thus different mean W masses, in this example $79\,\mathrm{GeV}$). Weights have to be calculated according to equation (14) as a relative change in the values of the former distribution with respect to the newly generated distribution for each parameter m:

$$g(m, m_W^{wish}) = \frac{f(m, m_W^{wish}, \Gamma_W)}{f(m, m_W^{default}, \Gamma_W)} \tag{14}$$

The function f has the properties of a Breit-Wigner distribution, see equation (5). The fact that Γ_W is a function of the W mass can be ignored as long as m_W^{wish} deviates only slightly from $m_W^{default}$. If for any physical quantity (for example, the electron momentum) a histogram is filled using the

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[3] and additionally events of type $q\,\bar{q} \;\rightarrow\; W \;\rightarrow\; \tau\,\nu \;\rightarrow\; (e\,\nu\nu)\,\nu$ representing a small background which can be reduced only by kinematic selection cuts. This is because only electrons (or positrons) can be detected in leptonic tau decays, due to the very short lifetime of the τ leptons. These τ events make up the last eight percent (33705 events) of *mc_all.root*

[4] A large proportion of these background events has already been eliminated by us before you will get the data for further analysis. In particular the set does not contain any events in which the W decays into jets. In addition, a number of other selection cuts were performed, which you can find in the appendix.

initial Monte Carlo data, we get the expected distribution for $m_W^{default}$. If we assign to each event a weight according to (14), the resulting weighted histogram represents a distribution matching the selected value of m_W^{wish}. The generated mass m must be known for each event in order to be able to calculate $g(m, m_W^{wish})$. Note again the distinction between the mean W boson mass m_W and the event-by-event fluctuating mass m.

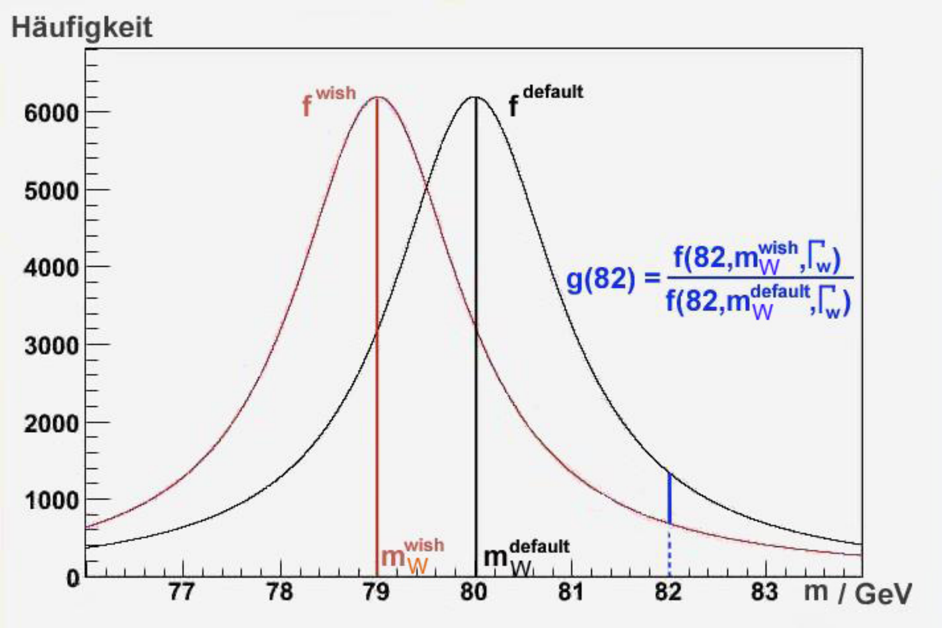

Fig. 8 - Example of determining the weights: The initial MC data distribution $f^{default}$ is valid for a mean W mass of $80\ \mathrm{GeV}$. f^{wish} is the desired distribution of m for a mean W mass of $79\ \mathrm{GeV}$. The formula shows the calculation of the weight g for the parameter $m = 82\ \mathrm{GeV}$

In this experiment the Monte Carlo data is based on a mean W mass of $80.3946\ \mathrm{GeV}$. Moreover, we provide you with 19 sets of weights which were determined according to equation (14). Which set of weights corresponds to which W mass can be looked up in the appendix.

6. Analysis:

6.1 Method:

These steps are intended to assist in the analysis during the lab periods. You are very welcome to explore and apply other analysis methods. Your tutors will be pleased to help and assist you.

Convention for histograms: Measured data are typically represented as points including error bars, Monte Carlo data as bar histograms.

- Convince yourself that the given weights actually result in other masses than that of $80.3946\ \mathrm{GeV}$, which is the basis for the Monte Carlo calculations: Plot several MC data distribution for different W masses m. To do this, use the mass mc_w_m which is stored for every MC event.

- Plot some characteristic variables or derived quantities such as E_T, ${E_T}^{miss}$, m_T, η, ϕ, ϕ_{miss}, $\Delta\phi$, Δz ... for both the measured data and the MC data set, where:

  E_T =transverse electron energy

  ${E_T}^{miss}$ = missing transverse energy (neutrino!). This value is calculated from all the observed particles in the detector.

  m_T = transverse W mass

  η = Pseudorapidity[5] $\eta = -\ln\tan\theta/2$, where θ is the (polar) angle between the electron and the proton trajectory.

  ϕ = Azimuthal angle of the electron in the transverse plane

  ϕ_{miss} = Azimuthal angle of the vector of the missing energy in the transverse plane

  $\Delta\phi$ = Difference between the two azimuthal angles

  Δz = Distance on the z-axis (beam axis) between the primary vertex and the intersection of the projected electron track with the z-axis[6]

  Consider one or more selective cuts to eliminate the background from the measured data. Wwhich effects or events could lead to background? The same selection cuts must be applied to the MC data set. Ideally, the Monte Carlo data and experimental data should result in the same distribution (for the same mass). Note that the D0 data set contains only those events which were accepted online by the trigger system. Only for electrons with $E_T > 25\,\mathrm{GeV}$ the trigger efficiency is close to 100%. The trigger was not simulated within the MC calculation, therefore the MC data set still contains low-energy events. Do not use all of the available quantities for the event selection (a list with descriptions can be found in the example program w_analyse.C), but limit yourself to kinematic variables such as energy and direction and 2-3 quantities that can distinguish the electron from other particles (such as the amount of energy in the electromagnetic calorimeter or the 'energy isolation' which describes the amount of energy found in the vicinity of the electron).

- Normalisation: Due to different numbers of events in the D0 data set and the Monte Carlo sample, it is necessary to scale the distributions. Therefore, scale the Monte Carlo data according to the integrated luminosity. For the measured data this is $L_{int} = (198 \pm 20)pb^{-1}$. The given uncertainty is of systematic nature, the Monte Carlo data should therefore be weighted with

$$w = \frac{L_{int}}{L_{MC}} \cdot 0.90 = \frac{\sigma}{N_{gen}} \cdot L_{int} \cdot 0.90 \tag{15}$$

  Here $L_{MC} = N_{gen}/sigma$ is the effective luminosity of the Monte Carlo data, σ is the theoretical cross section of the studied process (see equation (20)) and $N_{gen} = 1164699$ is the number of initially generated Monte Carlo events. The factor 0.90 is a correction factor which takes into account that the Monte Carlo simulation predicts a higher efficiency than the real D0 detector achieves.

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[5] Differences in these variables are invariant under Lorentz boosts along the beam axis.

[6] Study Δz by plotting $|el\_track\_z - met\_vertex\_z|$ since the unmeasurable z vertex coordindate of the missing energy is set to the primary vertex z coordinate of the event in the D0 software.

- Determine the cross section for the reaction $p\bar{p} \rightarrow W \rightarrow e\,\nu$. For the number N of selected measured events after all cuts one has:

  $$N = \epsilon \cdot A \cdot corr \cdot \sigma \cdot L_{int} \tag{16}$$

  The product $efficiency \cdot acceptance = \epsilon \cdot A$ can be obtained from the Monte Carlo data and is equal to

  $$\frac{number\,of\,MC\,events\,after\,all\,selection\,cuts}{initial\,number\,of\,generated\,MC\,events} \tag{17}$$

  This quantity takes into account that some events are not measurd because the detection efficiency is not 100% or they are unseen due to the limited geometrical acceptance of the detector or due to the selection cuts which are applied. Since the number of events is large (statistics) we can assume that $\epsilon \cdot A$ has negligibly small uncertainties. Furthermore, the formula contains the already mentioned correction factor $corr = 0.90 \pm 0.10$. The given systematic uncertainty of 0.10 also includes various uncertainties of the Monte Carlo simulation.

- Compare the measured data with the various Monte Carlo data sets and determine the W mass and its uncertainty by using the χ^2 fit method. Make use of the m_T distribution normalised to 1. Calculate - prior to the lab days - the transverse mass m_T of the W boson using the transverse component of the neutrino energy ${E_T}^{miss}$, the transverse component of the electron energy E_T and the difference $\Delta\Phi$ between the two azimuthal angles of these particles.

  Notes on W mass determination:
  - Calculate the χ^2 function for each of the 19 masses and then interpolate in between those masses.
  - The minimum of the χ^2 function as a function of m_W is most easily obtained from a graphical representation.

- Repeat the mass determination. Now use the distribution of the variable E_T of the electron instead of m_T. Decide yourself on how to transfer the knowledge you have gained in the analysis of the transverse mass distriubution to the new analysis. You may also pursue alternative methods. Compare your two measured mass values and assess and discuss these results.

  This second measurement is used to check the first result and to learn about the uncertainties from studying the differences between the results. However, one must note that the observables m_T and E_T are not independent of each other so that averaging is not trivial. Use a two-dimensional diagram to show that the two variables are correlated for the D0 data set and determine the correlation coefficient.

- Determine the electroweak mixing angle and the color factor.
  Make use of the Standard Model relation for the boson mass ratio,

  $$\frac{m_W}{m_Z} = \cos\theta_W \tag{18}$$

  Use here (and below) one of the two W mass values determined by you, namely the one with the smaller relative uncertainty. Take the Z mass from the literature. State the result in the usual form and compare it with the world average. Note that in literature often $\sin^2\theta_W$ is given. It is derived from the electroweak couplings and due to radiative corrections it should be about 4% larger than the value determined by you.

The W cross section was calculated in the framework of the Standard Model for a color factor N_C = 3 to

$$\sigma(p\bar{p} \rightarrow W \rightarrow e\nu) = (2.58 \pm 0.09)\,\mathrm{nb} \tag{19}$$

The underlying calculation for this cross section takes into account that the (anti-)quarks bear only a fraction x of the (anti-)proton momentum.

- Compare your measurement of the cross section with the theoretical value. Discuss whether you can determine the color factor N_C from this comparison of the measured cross section and the theoretically predicted value for $N_C = 3$, and the difficulties you may encounter.
- Derive Γ_W from your measured W mass. Make use of the formulae for the partial widths and include a correction factor for the total width of 1.03 ± 0.01 which takes into account the effects of higher orders. Compare your result with the value of Γ_W given earlier.
- Discuss in detail the **systematic** uncertainties in the W mass measurement, for the hadron collider experiments (reference [D01]), and once for measurements in e^+e^--annihilations (reference [L3W] *or* [OPA]). Which uncertainties dominate, which can or cannot be reduced with more data? Which are common to both accelerator experiments, which are different?
- At the end of the third lab day, please present your results (including graphs and uncertainty discussion) to your tutor in a final discussion. Discuss the difficulties that occurred during the analysis and point out possible improvements to this experiment.

6.2 General Aspects concerning the analysis:

- The events generated by MC simulations are not an exact description of the measured data. Reasons may be an incomplete model of the materials in the detector, an imperfect calibration of the data, faulty detector components and background reactions not considered in the simulation.
- Please calculate the statistical uncertainties and give an estimate for the systematic uncertainty with every intermediate or final result.
- Use reasonable simplifications and approximations during error propagation. Only those input variables should be taken into account which provide the biggest contributions to the uncertainty of the output variables. In most cases a simple numerical error estimate is recommended:

  $$\Delta(f(x)) = \frac{1}{2} \cdot |f(x + \Delta x) - f(x - \Delta x)|$$

  Correlations can often be neglected..
- In order to estimate the systematic uncertainty resulting from the limited accuracy of the MC simulation please vary the selection criteria within reasonable limits, and then calcule the resulting change of the measured values of the cross section and W mass.

- Another systematic uncertainty which you can not determine by yourself is the aberror of the electron energy calibration. We will use $0.2\% \cdot E$ as published by D0 in 1996, see references [D01].
- Compare all your conclusions with published results.

7. Technical Aspects:

- The analysis is usually done in the CIP pool of the Physikzentrum under the account of the respective user (set up by Mr. Markus Winkler). Please make sure that you have such an account by the start of the lab days.
- All required files can be downloaded from

  `http://web.physik.rwth-aachen.de/˜hebbeker/fprakt/windex.html`

- For the analysis of all data the analysis package *ROOT* (developed at CERN) will be used. It is able to interpret or compile C++ code. The data will be presented in the usual form of so-called Trees which are instances of the *ROOT* class *TTree*.
- Storing data in these Trees offers several advantages over other storage methods. For example one can access parts of the data without having to read in the whole Tree. Moreover, the data will be highly compressed if handled correctly.

We cannot go into all the aspects and details here, but want to give you a rough but sufficient overview. Moreover, you can inform yourself under 'Reference Guide' on this website:

`http://root.cern.ch/`

Suppose you have a *ROOT* Tree named *student* in the file *bsptree.root*[7] containing name, age and number of semesters for different students. You can read such a Tree by running ROOT and then executing the command

```
root [0] TFile f("bsptree.root")
```

In this case you name the read file *f*. By calling

```
root [1] .ls
```

you can see which objects, Trees, etc. are loaded into memory. In addition, the names of these objects are displayed. Now you can browse through the Tree by using

---

[7] You can download this file from the laboratory class website.

```
root [2] student->StartViewer()
```

In our example, you would now see the three so-called *Leafs*, each containing one of the data sets 'name', 'age' and 'semesters'. Double-click on one of these *Leafs* causes *ROOT* to immediately create a histogram containing the requested data set[8]. To get a quick overview of the data of different *Leafs*, you can use

```
root [3] student->Scan("name:age")
```

You will now receive a tabular listing of the content of the *Leafs name* and *age*. You can list any number of *Leafs* as long as their names are separated by ':' in the prompt.

To display the content of the n-th entry, use

```
root [4] student->Show(n)
```

Basically you can enter all the commands directly at the *ROOT* prompt. If the commands extend over multiple lines you want to start the first line with '{' and end the last one with '}'. In this case you have to complete every command line (as usual in C++) with ';'. Most of the times it is more convenient to write small programs which are then interpreted by *ROOT*. Such as the example program *w_analyse.C* which can be started in a *ROOT* session with the call

```
root [5] .x w_analyse.C
```

You will get two files containing the Trees: *d0.root* which contains the data of the D0 detector and *mc_all.root* in which the Monte Carlo data is stored. In addition, we provide a dummy program *w_analyse.C*. It reads some of the data from the Trees and creates histograms for this data. The used commands are described in the file itself. Whether you modify this dummy for your further analysis or you write other programs is up to you.

We wish you interesting lab days and much success and fun with the analysis.

---

[8] Alternatively, you can also use the command *TBrowser b* to browse through the directories and go to the corresponding *Leaf*. It is not even necessary to read in the Tree beforehand.

Appendix: Units

Since elementary particle physics is based on relativity and quantum mechanics the constants c (speed of light) and $\hbar$ (reduced Planck constant) occur in practically all calculations. Examples:

$$E^2 = c^2p^2 + c^4m^2 \qquad \lambda_{Compton} = \frac{2\pi\hbar}{m_e c}$$

For simplicity a system of units in which $c = 1$ and $\hbar = 1$ is introduced. Length, mass, time and energy can then be expressed by just one unit, for example by powers of GeV.

'Beginners' may need some practice to make themselves familiar with this system and take advantage of its benefits. Therefore, here are some useful conversion factors:

$$\begin{aligned} 1\,\mathrm{s} &= 3.00 \cdot 10^{8}\,\mathrm{m} \\ 1\,\mathrm{s} &= 1.52 \cdot 10^{24}\,\mathrm{GeV}^{-1} \\ 1\,\mathrm{m} &= 5.08 \cdot 10^{15}\,\mathrm{GeV}^{-1} \end{aligned}$$

Furthermore the unit Barn (as well as parts and multiples) occurs often in the context of cross section and luminosity:

$$1\,\mathrm{b} = 10^{-28}\,\mathrm{m}^2 = 2.58 \cdot 10^{3}\,\mathrm{GeV}^{-2}$$

Appendix: Specification of Weights

The specification of the weights determined by us with respect to the masses is as follows:

$weight[0] \rightarrow 79.9446\,GeV$
$weight[1] \rightarrow 79.9946\,GeV$
$weight[2] \rightarrow 80.0446\,GeV$
$weight[3] \rightarrow 80.0946\,GeV$
$weight[4] \rightarrow 80.1446\,GeV$
$weight[5] \rightarrow 80.1946\,GeV$
$weight[6] \rightarrow 80.2446\,GeV$
$weight[7] \rightarrow 80.2946\,GeV$
$weight[8] \rightarrow 80.3446\,GeV$
$weight[9] \rightarrow 80.3946\,GeV$ The initially generated Monte Carlo W mass.
$weight[10] \rightarrow 80.4446\,GeV$
$weight[11] \rightarrow 80.4946\,GeV$
$weight[12] \rightarrow 80.5446\,GeV$
$weight[13] \rightarrow 80.5946\,GeV$
$weight[14] \rightarrow 80.6446\,GeV$
$weight[15] \rightarrow 80.6946\,GeV$
$weight[16] \rightarrow 80.7446\,GeV$
$weight[17] \rightarrow 80.7946\,GeV$
$weight[18] \rightarrow 80.8446\,GeV$

Appendix: Preselection

In section 5.4 it was pointed out out that we have already cut a variety of events from the raw data before you get your data for analysis. The data sets only contain events that meet the following criteria:

- Electrons whose shower-shape corresponds to an electromagnetic (and not a hadronic) cascade.
- The shower in the calorimeter has an associated track in the inner tracking detector within a small distance.
- The electron must be isolated. Meaning that in the region around the shower only little energy may be deposited in the calorimeter.
- The pseudorapidity η has to satisfy $|\eta| < 1.1$ so that we restrict ourselves to the central part of the detector ($\theta = 37^o - 143^o$).
- The event must not include a hadronic jet with a transverse momentum $> 15\,\mathrm{GeV}$.
- The primary vertex of the proton-proton collision must not be more than $60\,\mathrm{cm}$ away from the center of the detector along the beam axis (z-axis).

Appendix: Variables

An explanation of the physical variables that are included in the Tree of the measured data and the Monte Carlo data can be found in the file *w_analyse.C*. Variables such as el_px oder $mety\_calo$ may be used in your analysis for the selection of events or to compare distributions (measured data $\leftrightarrow$ MC).

Appendix: ROOT

A short list of useful commands and objects for ROOT:

TFile — class used to read/write data(objects) from/to .root-files

TTree — A tree structure with object data. The relevant data fields are stored here

TTree::SetBranchAddress(); — Sets the link between the data fields in the .root-file and the local variables
TTree::getEntry(); — Returns a data set (event) an writes the results to the data field defined by SetBranchAddress()
TTree::getEntries(); — Returns the total number of events

TH1F — Class for creating one-dimensional histograms with floating point input values

TH1F::Fill(); — Fills a value into the histogram. Optionally, a weighting of the value can be conducted (otherwise $= 1$).
TH1F::Integral(); — Calculates the integral of a histogram

TH1F::GetBinContent(); — Returns the value of a specific bar in a histogram
TH1F::Scale(); — Scales the histogram by a factor

TF1 — Class for the numerical description of a function with one variable

TF1::GetMinimum(); — Returns the minimum of the function
TF1::GetMinimumX(); — Returns the x value of the function's minimum
TF1::GetX(); — Returns the x value to a given y value
TF1::GetParameter(); — Returns the parameters of a fit or a function respectively

TCanvas — Class to manage the canvas

TCanvas::Divide(); — Split canvas
TCanvas::cd(); — Switch to a specific canvas

TGraph — Class to manage and display a collection of (x, y)-pairs

TGraph::Fit(); — Fitting a function to a given graph
TGraph::Draw(); — Drawing a graph

TMath

TMath::Sqrt(); — Square root
TMath::Fabs(); — Absolute value
TMath::Power(); — Exponent

Descriptions with examples for these and other commands are located under 'Reference Guide' at

`http://root.cern.ch/`