D0 Analysis of W->e+ ν

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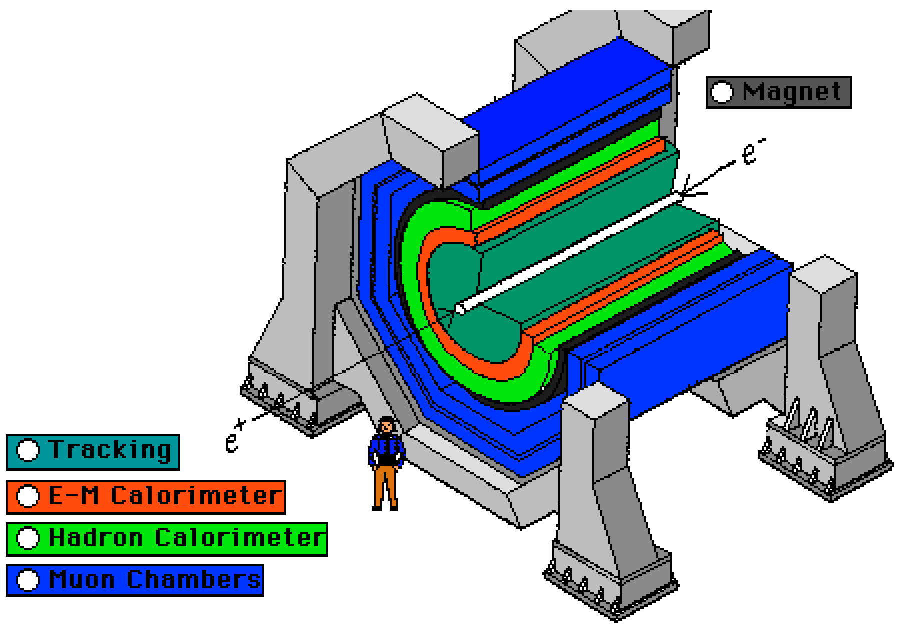
Abstract:
This note describes d0 analysis of W decaying into an electron and a neutrino. Particles involved in the decay are introduced along with various cuts applied to see the signature of W bosons.

Introduction to D0 calorimeter

The D0 calorimeter consists of an inner Electromagnetic section with fine segmentation and an outer hadronic section. The calorimeter as a whole is 7-11 interactions lengths. Nothing but muons and neutrinos gets out.

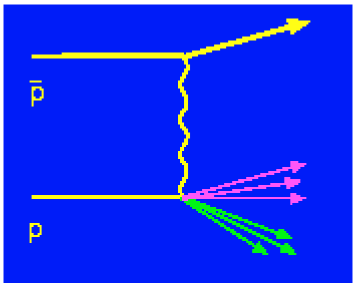
This is a schematic design of a typical modern detector.

Figure 1: Typical Detector



Tracking detectors supplement calorimeters by measuring particle trajectories. Only when trajectories and energy measurements are combined can scientists identify and characterize particles.
Vertex chamber contains thousands of fine wires, charged with different voltages, that can be used to locate the vertex of an event – the precise spot within the beam pipe where a proton and an antiproton collided.

Figure 2: D0 Physics - Protons and Anti-protons:



Fermilab, short for Fermi National Accelerator Laboratory (FNAL), basically accelerates protons and antiprotons and bends the trajectory of the particles into a circular path using magnets inside the Tevatron, currently the world's largest accelerator. The configuration is that these two types of particles are collected and are bunched into a beam, where the antiprotons (denoted as $\bar{p}$) are sent counterclockwise down a beam pipe inside the Tevatron and the protons are sent clockwise. When the Tevatron is then set to collider mode, the two beams are sent hurling towards each other until they collide inside the ring.

All physics at D0 starts with the collision of a proton with an anti-proton. Protons are made up of quarks, anti-quarks and gluons collectively called partons.

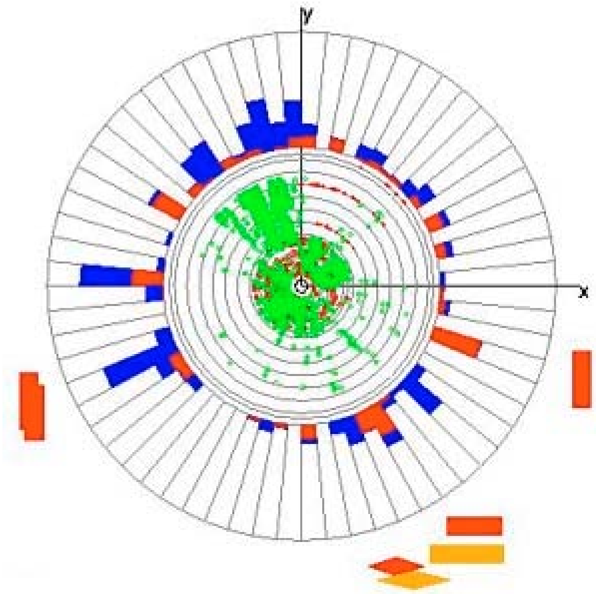


Figure 3: Events in D0 – Live from Fermilab

This display is from the experiment called D0 (DZero), and it shows a “proton beam’s-eye view” of the detector, which is like a huge, layered cylinder surrounding the beam pipe where the high-energy protons and antiprotons collide. The beam comes in, unseen, along the center of the image from in front of and behind the picture. The inner part, with the concentric circles, shows the locations, to scale, of the tracking detectors. Hits are shown as small circles. The outer ring represents amounts of energy deposited in the calorimeters, where each colored block shows the total energy at that angle to the beam direction. The red blocks show electromagnetic energy, deposited by electrons, positrons and photons, while the blue blocks show energy deposited by hadrons. The sizes of the blocks are proportional to the amount of energy deposited.

http://hepweb.rl.ac.uk/ppUKpics/POW/pr_011024a.html

What happens when high energy particles collide.

When proton and antiprotons collide they form virtual particles.

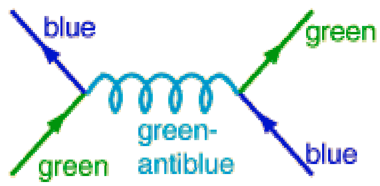
$$p + \overline{p} \to q + \overline{q} \to W^{-}W^{+}$$

$$p + \overline{p} \to q + \overline{q} \to ZZ$$

$$e^{+} + e^{-} \to \gamma \to q + \overline{q}$$

For a brief moment the quarks fly apart as free particles, but when they reach a separation distance of around 10^{-15} m (the diameter of hadron), their interaction is so great that new quark-antiquark pairs are produced – this time mainly from gluons.

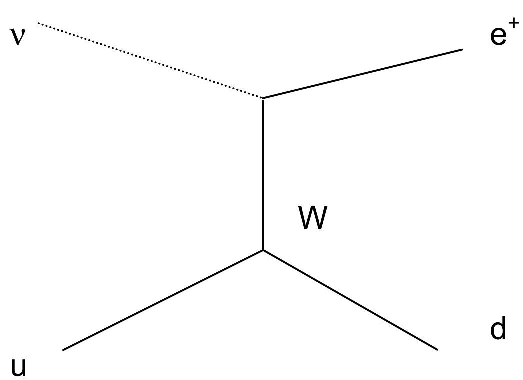
These quarks and antiquarks join together in myriad combinations to make the mesons and baryons that are actually recorded at the detector. In all the debris there is one unmistakable footprint left behind by the original quark-antiquark pair; the hadrons emerge in two back-to-back "jets,"one along the direction of the primordial quark, the other marking the direction of the antiquark. Occasionally once sees a three-jet event, indicating that a gluon carrying a substantial fraction of the total energy was emitted in conjuntion with the original $q\bar{q}$ production.



Feynman diagram for an interaction between quarks generated by a gluon.

Introduction to W boson

W boson: Q=e m=80.4 GeV/c^2 - decays to $q\bar{q}$, l,ν couples to $q\bar{q}$, l, ν, γ, Z



The W boson is an elementary carrier particle, having an electric charge of just plus one and minus one, and a mass of 80.411 GeV. The discovery of W boson occured in 1983 at CERN laboratory.

W interactions

The W boson is best known for the following reactions:

Beta decay $n \rightarrow p + e + \nu_e$

Electron capture $p + e \rightarrow n + \nu_e$

Since protons and electrons are not fundamental particles, it is quarks that interact

$$d \rightarrow W^{-} + u$$
$$u \rightarrow W^{+} + d$$

As W bosons are massive particles they only have a short lifetime. This means that the W bosons are never directly observed, only their decay products are measured. W bosons decay into two fermions. A W^- can decay into a lepton and anti-neutrino or a $q\bar{q}$ pair. Branching ratios are

$$\mathrm{Br}(W \rightarrow e\bar{\nu}_e) = 0.1046 \pm 0.0042 \pm 0.0014,$$
$$\mathrm{Br}(W \rightarrow \mu\bar{\nu}_\mu) = 0.1050 \pm 0.0041 \pm 0.0012,$$
$$\mathrm{Br}(W \rightarrow \tau\bar{\nu}_\tau) = 0.1075 \pm 0.0052 \pm 0.0021,$$
$$\mathrm{Br}(W \rightarrow q\bar{q}) = 0.6832 \pm 0.0061 \pm 0.0028.$$

In each case the first error is statistical and the second systemetic. With each W boson being able to decay into a leption and a neutrino or quarks, this means that there are effectively three possible final states; Two leptons and two neutrinos, $\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$, known as the leptonic chanel. Two quarks and two anti-quarks , know as the hadronic channel. Finally, there is a final state of a lepton, a neutrino, a quark and an anti-quark, known as the semi-leptonic channel. The branching ratios for these three channels are 45.6%, 10.5% and 43.9% respectively.

Signatures of W bosons:

The signatures of W^+W^- production are therefore four jets of hadrons, or two jets of hadrons together with an energetic isolated lepton and missing energy, or a pair of leptons with missing energy

- One high pT lepton + missing energy + two jets
- Two opposite charge high pT leptons $\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ + missing energy

❖ Four jets

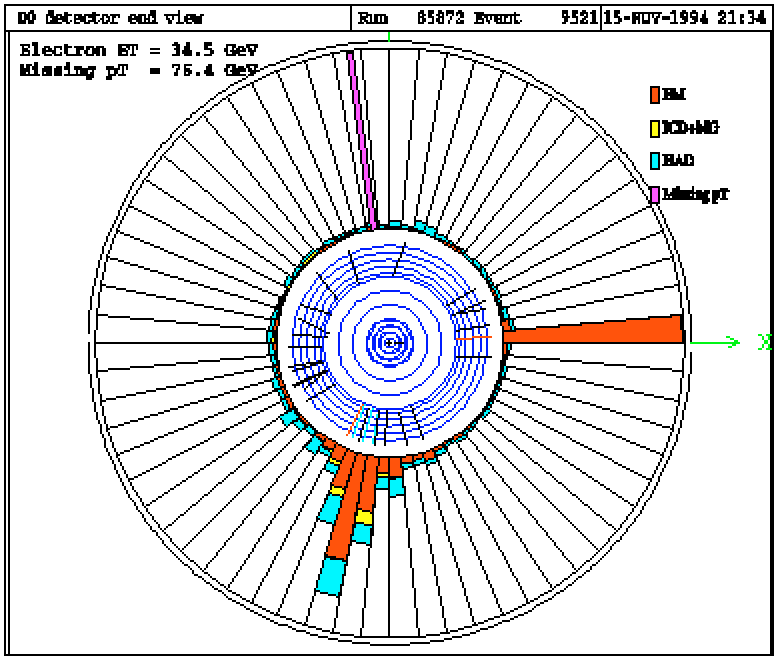
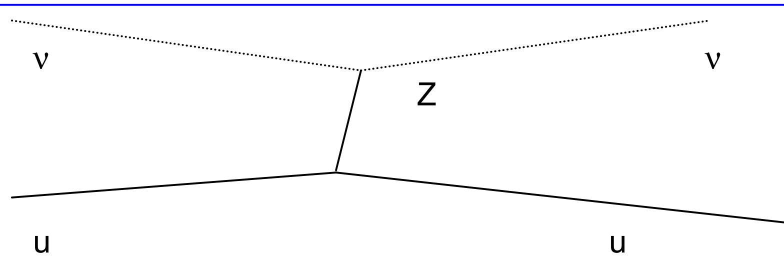


Figure 5: W event
http://hepweb.rl.ac.uk/ppUKpics/images/POW/1998/980204.gif

Introduction to Z boson

Z boson: Q=0 m=91.19 GeV/c^2 decays to $q\bar{q}$, l,ν couples to $q\bar{q}$, l, ν, γ, Z, W



Signature of ZZ production:

- ➢ Two high pT isolated leptons + 2 jets
- ➢ Four high pT isolated leptons
- ➢ Four jets

Importance of W and Z bosons:

The W and Z bosons are the key to our understanding of the weak force, which in turn can tell us how stars, radioactivity and other nuclear processes work. W & Z bosons play an important role in understanding the breaking of Electroweak symmetry and the precise measurement of the top quark mass, along with precise measurement of W boson mass can provide information on the mass of the Higgs boson, a hypothetical, extremely massive boson arising in the theory of the electroweak force.

The measurement of M_W in the D0 experiment use W bosons produced in proton anti-proton collisions at 1.8 TeV at the Fermilab Tevatron colloder. The Ws subsequently decays into W->eν.

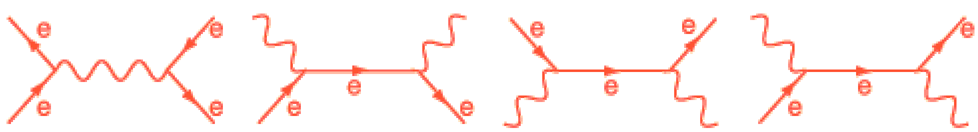
Introduction to electron

Electron: Q=-e m=0.511 MeV/c^2 stable couples to γ, W, Z

The discovery of electron in 1887 by J. J Thompson started the birth of particle
physics. Electron responds to electromagnetic, weak interactions and gravity. When a relativistic charged particle, such as electron, passes through matter, it knocks electron out of atoms as it passes by. The particle losses energy and the loss is reasonably independent of the particle or material type.
dE/dx ~ 2 MeV/cm * x * ρ * [gm/cm^3]

The energy loss shows up as low energy electrons and photons and can be detected optically or electronically.
Electron energy loss is defined by electro-magnetic interactions

- ee pair production
- photo nuclear reactions
- bremsstrahlung
- ionization



electron-positron attraction   electron-positron annihilation   electron-positron pair production   Compton scattering

Introduction to Photon

Photon γ : m=0 Q=0 couples to charge - force carrier for ElectroWeak

Feynman diagram for the electromagnetic force between two charges.

Photon was invented by Planck to explain the blackbody spectrum for the electromagnetic radiation emitted by a hot object. Statistical mechanics, which had proved brilliantly successful in explaining other thermal processes, led to the famous “ultraviolet catastrophe” predicting that the total power radiated should be infinite. Planck found that he could fit the experimental curve if he assumed that electromagnetic radiation is quantized with energy $E = h\nu$ where ν is the frequency and h is the planck’s constant.

In 1905, Einstein adapted photon to explain photoelectric effect. When electromagnetic radiation strikes a metal surface, electrons come popping out. Einstein suggested that an incoming light quantum, that is photon, hits an electron in the metal, giving up its energy $h\nu$; the excited electron then breaks through the metal surface, losing in the process energy w (work function of the material). The electron thus emerges with energy $E \leq h\nu - w$.

Electromagnetic shower

Bremsstrahlung and electron pair production are the dominant processes for high-energy electrons and photons; their cross-sections become nearly independent of energy above 1 GeV. Secondaries produced in electromagnetic processes are again mainly electrons, positrons and photons and most of the energy is consumed for particle production. The cascade develops through repeated similar interactions. The shower maximum, with the largest number of particles, is reached when the average energy per particle becomes low enough to stop further multiplications. From this point the shower decays slowly through ionization losses for electrons or by Compton scattering for photons.

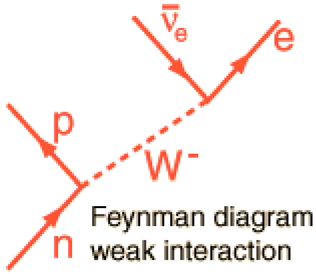
An electromagnetic shower is characterized by two factors:

- The radiation length x_0 linked to the energy loss by $E(x) = E_0 e^{-x/x_0}$. A material thickness corresponding to 20 radiation lengths is enough to contain more than 99% of the shower.
- The Molier radius which corresponds to the transversal extension of the shower due to multiple scattering of the low energy electrons inside the matter. This radius is defined by the relation

$R_{Molire} = 21x_0 / E_c(MeV)$. Here again, 3 Molier radii are enough to contain more than 99% of the shower.

Introduction to neutrino

neutrino: ν Q=0 - m=? - stable particle - couples to W,Z



Feynman diagram for weak interaction involved in beta decay.

In beta decay a radioactive nucleus A is transformed into a slightly lighter nucleus B, with the emission of an electron:

$$A \rightarrow B + e^-$$

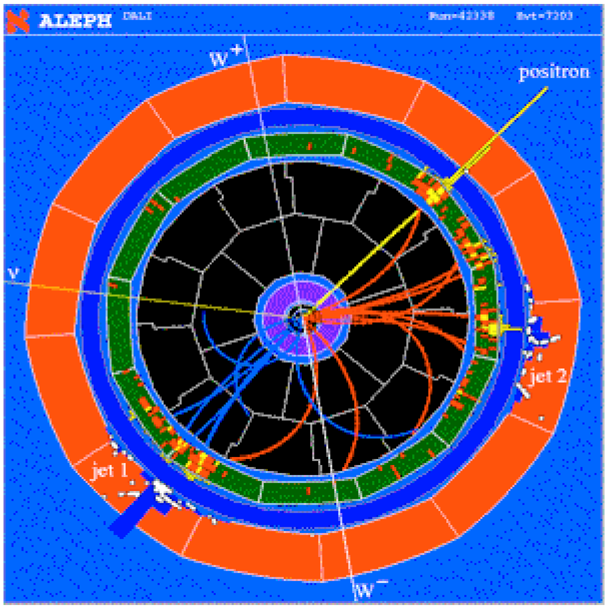
It is characteristic of tow-body decays that the outgoing energies are determined, in the center-of-mass frame. Specially, if the "parent" nucleus (A) is at rest, so that B and e^- come out back-to-back with equal and opposite momenta, then conservation of energy dictates that the electron energy is

$$E = (m_A^2 - m_B^2 + m_e^2)c^2 / 2m_A$$

Once the three masses are specified, the energy E is fixed. Unfortunately from experiment it was found that emitted electrons vary considerably in energy. It was a disturbing sinario but Pauli came to the rescue and suggested that another particle was emitted along with the electron, a silent accomplice that carries off the "missing" energy. It had to be electrically neutral to conserve charge and also because it left no tracks.

Neutrino was a theoritical construct, invented by Pauli, to save conservation of momentum from being violated in a beta decay. For decades neutrinos were treated as massless left handed particles. New evidence implies that neutrinos have very tiny masses [http://physicsweb.org/article/news/2/6/2/1] and can spin in either direction [http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/pub/nuosc98.submitted.pdf].

Neutrinos are neutral leptons but unlike charged leptons - like electrons, muons and tau - they only interact through weak interactions and gravity. Weak force is the weakest known force (apart from gravity), about a hundred million times weaker than electromagnetism at low energies, which means that it acts a hundred millions times more slowly . It is precisely this lack of interaction strength that makes the neutrino so elusive and are therefore able to pass through great distances in matter without being affected by it.



http://hepweb.rl.ac.uk/ppUKpics/images/POW/1999/990127_sm.gif

Figure 6: $p\bar{p} \rightarrow W^{+}W^{-} \rightarrow 2\,\text{jets} + \nu e^{+}$

Event selection and Background reduction

In particle physics, an event is a single collision of two particles. A collsision (preferable term is scattering) means any process which results in a deflection in the path of the original particle or their annihilation. In a typical run, millions of events take place but not all events relate to new physics or phenomena under study. Hence the term trigger , a event selction criteria, comes into picture. The selection criteria of trigger is broad based because there are dozens of group with conflicting interests.

Introduction of important Variables

- *EM_pX, EM_pY,EM_pZ,EM_pT*

The definition of these variables depend on whether or not EMparticle has an associated track, pT,pX,pY,pZ are given at the reconstructed PRIMARY vertex (if not associated track) or are computed using the matching track θ *and* ϕ *, and the EMparticle energy as follows:*

$$pX = E \times \cos(\phi) \times \sin(\theta),$$

$$pY = E \times \sin(\phi) \times \sin(\theta),$$

$$pZ = E \times \cos(\theta),$$

$$pT^2 = pX^2 + pY^2$$

Kinematic quantities: the transverse momenta of electrons, neutrinos, and the W or Z bosons are denoted $p_T(e), p_T(\nu), p_T(W), p_T(Z)$.
The $p_T(\nu)$ is determined from the missing transverse energy in the event. The invariant mass of two electrons is denoted by m_{ee}.

- *EM*_isol returns1 if the particle is isolated

Electron isolation: the calorimeter energies are used to define an isolation, $f_{iso} = (E_{full} - E_{core}) / E_{core}$ where E_{core} is the energy in the EM calorimeter while *R=0.2* of the electron direction, E_{full} is the energy in the full calorimeter within *R=0.4.*

- *EM*_iso isolation for cluster selection
- EMfrac cluster EMfraction

EM fraction: the fraction, EMF, of energy within a cluster that is deposited in the EM portion of the calorimter.

- EM_HA cluster energy in all hadronic layers
- EM_id EMparticle id
- abs(id)=11
    - ✓ pass EMfraction, p_T and isolation criteria; has an associated track
    - ✓ pass isolation criterium; has an associated track; does not pass EMfraction and p_T criteria
- id=10
    - ✓ pass EMfraction, p_T and isolation criteria; does not have an associated track. An electron with no associated track, would have id=10.

Criteria for passing the cuts were E_t>1.5 GeV and EMfraction<=90%

For detail see “The D0 Electron/Photon Analysis Package EMAnalyze” by F. Fleuret

- EM_phi EMparticle phi
- EM_eta EMparticle eta
- m_{ee} Invariant mass of dielectron

- M_W Transverse mass of W

The values of η *and* ϕ is either from the reoconstructed PRIMARY vertex or are given by the matching track.
Eta is the pseudorapidity of the EM cluster in the calorimeter, measuring from the center of the detector. The axial position of the EM cluster in the EM calorimter is denoted by $z_{clus.}$

$$\eta = \ln \tan(\theta / 2)$$

Signature of $W \rightarrow e\nu$ is one high p_T lepton and missing energy. Electrons leave tracks in tracking chamber and interact mostly in EM calorimeter (EMfraction>0.9). Hence the information stored in Emcl (EMparticle branch) and Trks (Charged particle branch) is necessary to select events with the characteristic signature of W boson production. For this analysis only those em particles were selected where the charge particle had track in the tracking chamber.

Good quality cuts for electrons

Cut	W boson	Z boson
p_T (Leading)	>30 GeV	>25 GeV
(Next Leading)		>20 GeV
Met (Missing transverse energy)	>30 GeV	
iso	-0.05<iso<0.15	-0.05<iso<0.15
Shower shape (HMx8)	150	200
EM fraction	>0.9	>0.9
Z_{vertex}	<80 cm	<100 cm
Eta	$\|\eta\| < 2.5$	$\|\eta\| < 2$
EM particle id	$\|id\| = 11$	$\|id\| = 11$
E(cluster)/p(track)	<2.0	

Good quality cuts for jets

emf EM fraction 0.05 < emf <0.95
chf CH fraction chf <0.1
hotf hot >10.0
hotf is the ratio of hottest and next-to-hottest cell ETs.
n90 n90>1
n90 is the number of towers comprising >=90% of jet scalar ET
f90 <0.8-0.5*chf or chf<0.1

Background to W ->eν

- W-> μν and W->τν act as background to W->eν but because of the branching ratio suppression and the low electron momentum, this background is small(1.6% of the W boson sample).
- The second background arises from Z->ee events in which one electron is misreconstructed or lost. The missing electron is likely to be an edge electron.
- The third background for the W sample is due to QCD multijet events in which a jet is misreconstructed as an electron.

Background to Z-> ee

The background for the Z boson sample is composed of QCD multijet events with jets misidentified as electrons. This background is evaluated from the dielectron mass distributions with two “bad” electrons, one in the edge region and one in the non-edge region. There is an exponentially decreasing shape of the background as a function of m_{ee}.

Units used in the analysis

Energy is measured in eV, the energy picked up by an electron in going through 1 V potential.
1 GeV is 10^9 eV or 1.602E-10
1 TeV is 10^{12} eV
Momentum is measured in GeV/c
Mass is measured in GeV/c^2
Angle is measured in radian and
vertex distance in cm

Invariant mass of Z

Since particles at Fermilab are relativistic, invariant mass of Z is calculated using Paul Dirac’s equation

$$(\sum E)^2 - (\sum p)^2 = M_{ee}{}^2$$

Transverse mass of W

The vairables used for the W boson are the transverse mass, and the transverse momenta of the electron and neutrino, $p_T(e)$ and $p_T(\nu)$.

$$m_T = \sqrt{(2 \times p_T(e) \times p_T(\nu) \times (1 - \cos(\phi_e - \phi_\nu))}$$

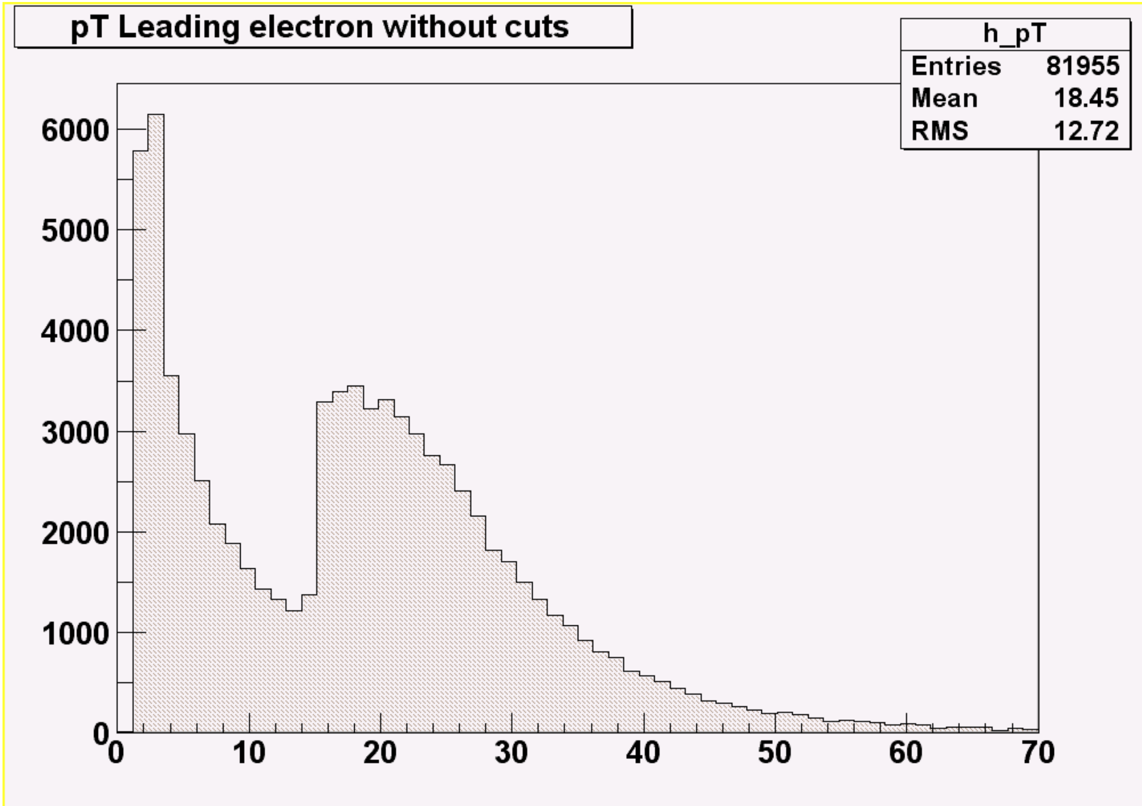


Figure 7: Transverse momentum of leading electron without cuts

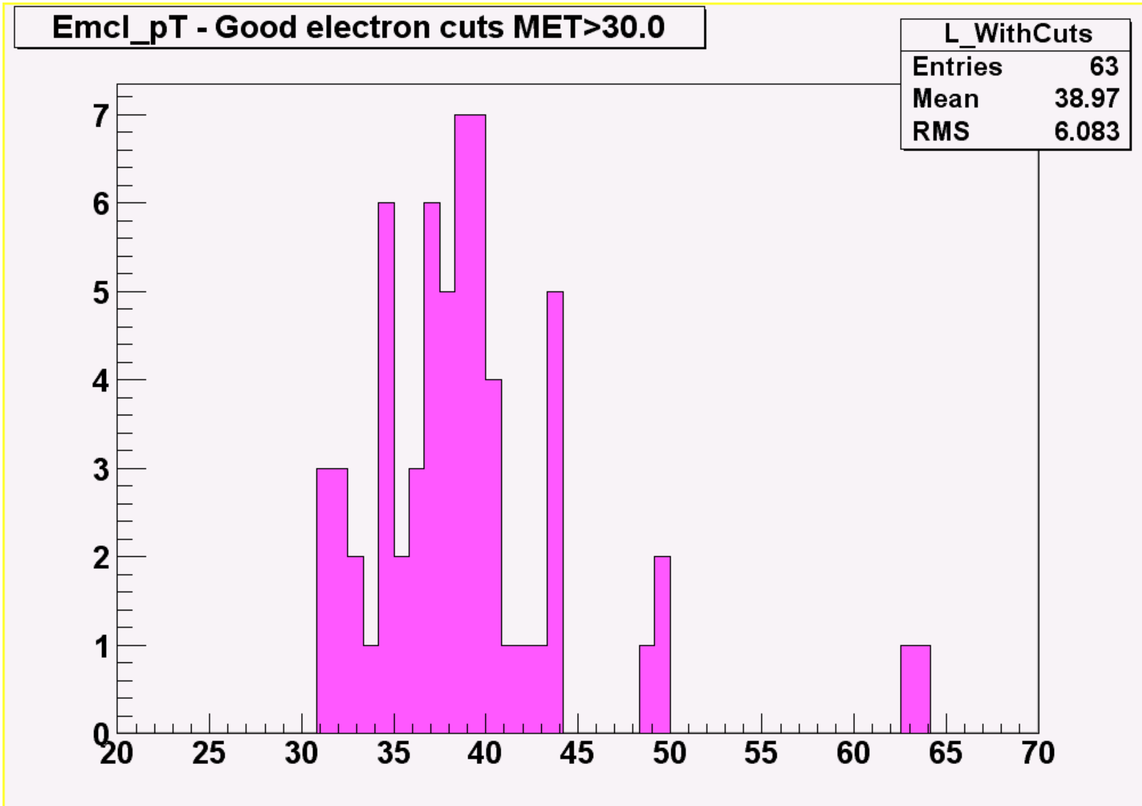


Figure 7: Transverse momentum of leading electron with good quality cuts. There is a peak around 40.0 GeV which is what I expected if W bosons are nearly at rest when they decay but there is also a background showing as a peak around 35 GeV.

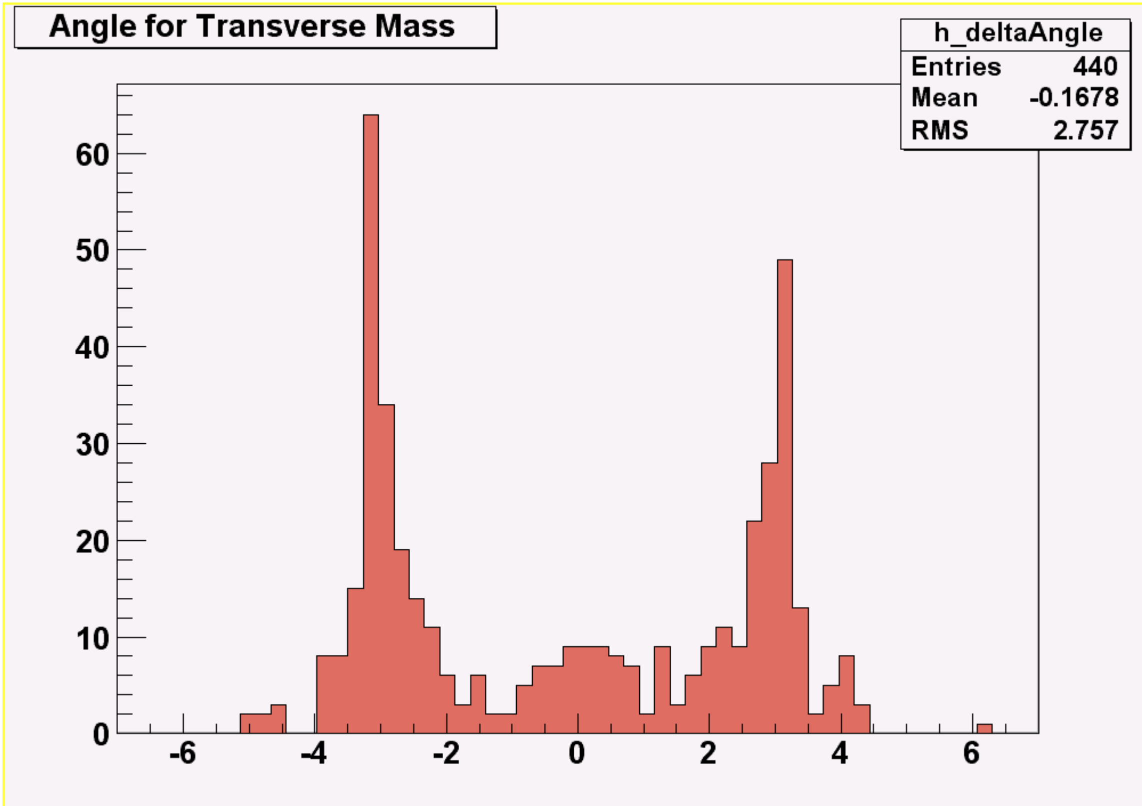


Figure 8: Azimuthal angle of separation between the electron and the neutrino

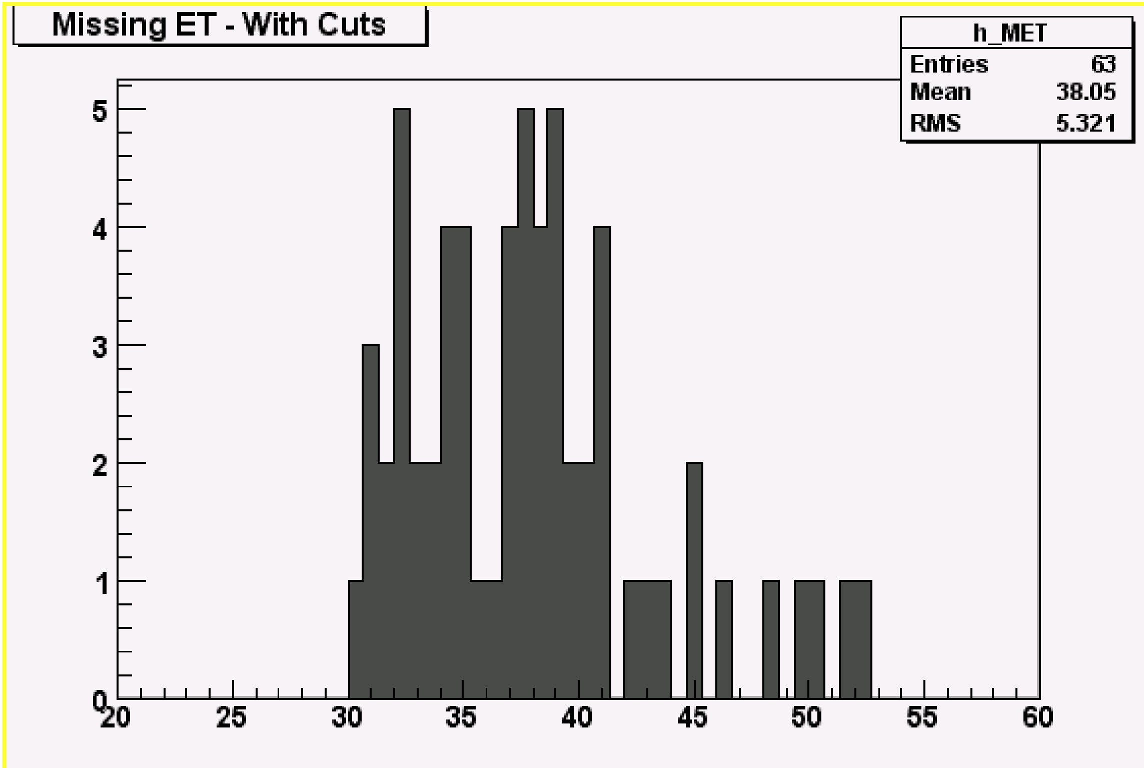


Figure 9: Missing ET with good quality cuts

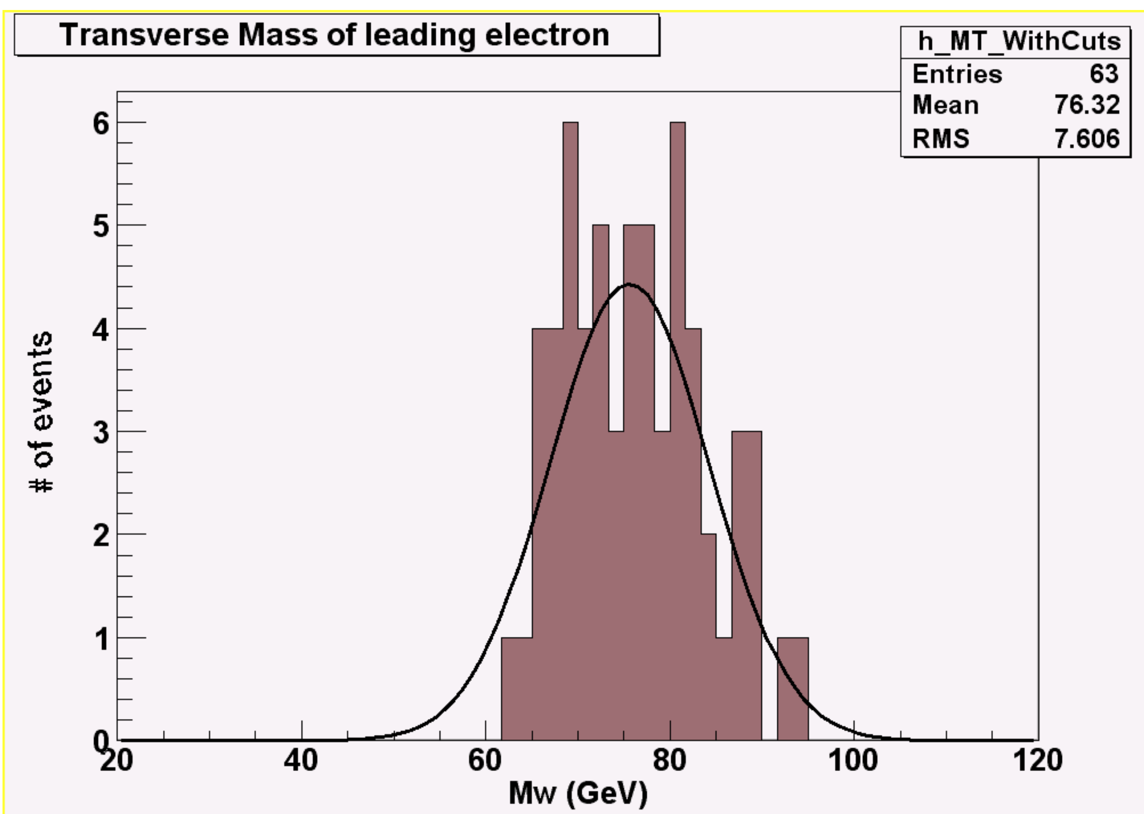


Figure 10: Transverse mass distribution.

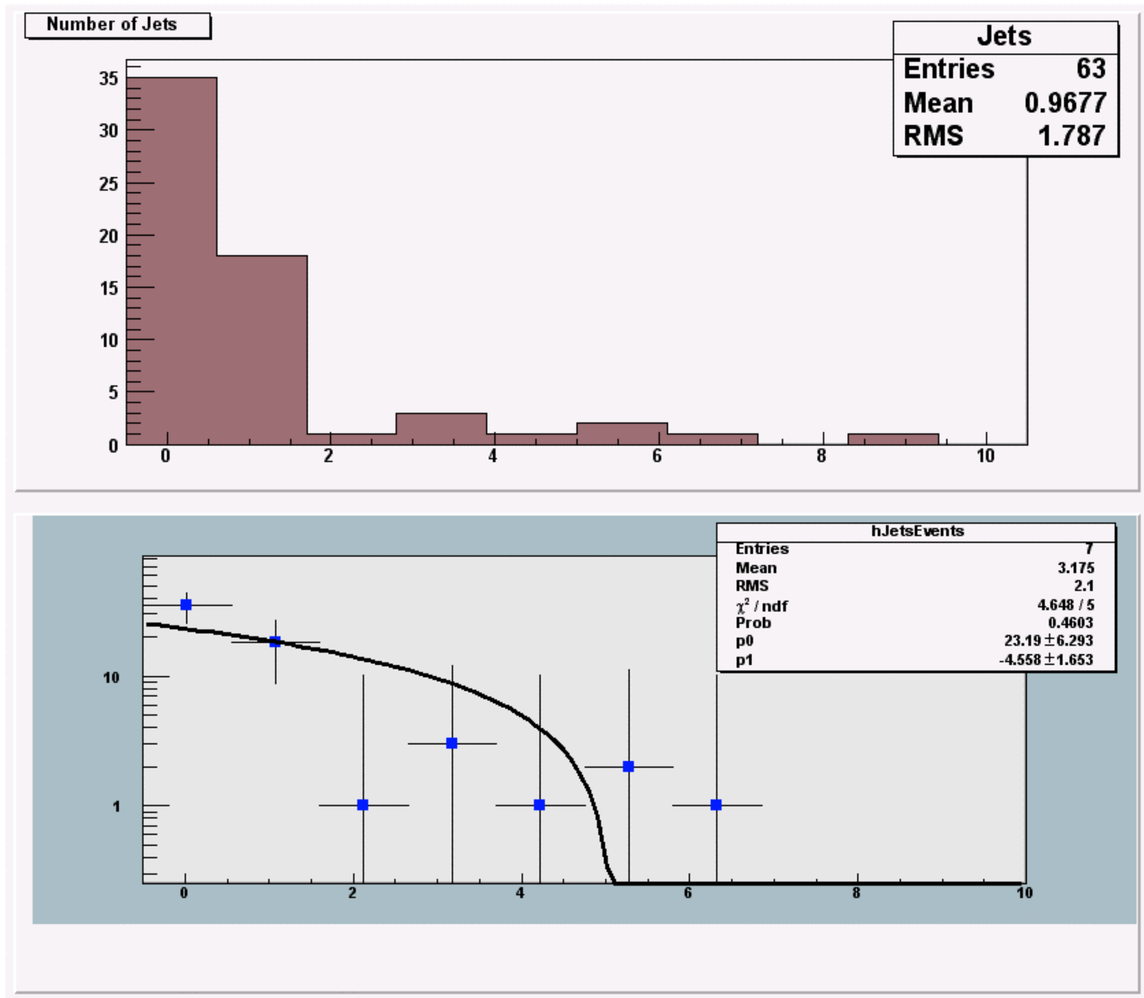


Figure 11: Number of jets associated with W

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http://www.phys.ufl.edu/~ming/WWW/cdf/exotic/leptoquark/offline_selection_cuts.html
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http://fnlib2.fnal.gov/MARION/AAE-9321
http://pdg.web.cern.ch/pdg/particleadventure/frameless/modern_detect.html
http://physics.bu.edu/quarknet/2002/particle_detection.pdf
http://hyperphysics.phy-astr.gsu.edu/hbase/particles/expar.html

Books:
1) Los Alamos Science by Los Alamos National Laboratory Number 25
2) Introduction to Elementary Particles, David Griffiths, 1987 John Wiley & sons, Inc

Script File to run the d0 analysis:

```
{
    gROOT->ProcessLine(".x MakeTMBTreeClasses_so.C");
    gROOT->ProcessLine(".O 0");
    gROOT->ProcessLine(".L TMBTree_bu.C");
    TChain tt("TMBTree");
    tt.Add("tmb_tree.root");
    tt.Add("First.root");
    tt.Add("Second.root");
    tt.Add("Third.root");
    tt.Add("Fourth.root");
    TMBTree_bu t(&tt);
    t.Loop();
}
```