Experimental Particle Physics

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This lecture series aims to give an overview of experimental particle physics. In five lectures it will cover the topics listed below, from particle sources and accelerators to the use of collider experiments for physics.

Contents

Learning Outcomes

At the end of this course you should:

- Understand why high energy particle collisions are studied

- Be able to describe the different sources of high energy particles used
- Know the advantages and disadvantages of different types of particle accelerator
- Be able to quantify the relative benefits of collider and fixed target experiments
- Be able to quantitatively describe the different interactions of charged particles with matter
- Be able to describe the different ways in which particles are detected
- Be able to determine which type of detector is suitable for a given task
- Know how to identify different particles and processes in a general-purpose collider experiment
- Understand the use of Monte Carlo simulations in high energy physics
- Be able to calculate the significance of an excess of data above an estimated background

References

- Most standard texts (e.g. Perkins, although he uses Heaviside-Lorentz units) have a chapter or two on accelerators and experimental techniques
- *The* standard reference is the Particle Data Group's Review of Particle Physics, S. Eidelman et al., **Phys. Lett. B 592**, 1 (2004) available online at http://pdg.lbl.gov/2005/reviews/contents_sports.html#expmethetc

1 Introduction

Particle physics is the study of nature at the smallest length scales that we can reach. From the de Broglie relationship $\lambda = h/p$ or the Heisenberg uncertainty principle $\Delta p \Delta x \geq \hbar/2$ there is a correspondence between small length scales and large momentum (and hence energy) scales. It should also be noted that From Boltzmann's equation $\langle E \rangle = n_{dof}/2kT$ there is a correspondence between high energies and high temperatures and from

Table 1: **Natural Units**

Energy, momentum:	GeV
Length, time:	GeV^{-1}
$\hbar c = 1 = 197$ MeV.fm	

Table 2: **Useful Quantities**

$$\text{Mass of a proton} \approx 1\ \text{GeV}/c^2 \approx 1.7 \times 10^{-27}\ \text{kg}$$
$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \approx \frac{1}{137}$$
$$c \approx 1\ \text{foot/ns}$$

cosmology a correspondence between high temperatures and the early stages of the universe. Thus by investigating the interactions of high momentum particles, we are examining the laws of physics at the smallest length scales, the highest temperatures and the earliest fractions of a second after the Big Bang that we can reach.

This relationship between dimensions is why particle physicists normally use natural units:

$$\hbar = c = 1$$

The only dimension needed is then energy (normally GeV). However, experimentalists tend to use whichever units happen to be most convenient or just habitual: kg, cm, barns, mils, tons, megabucks....

2 Particle Sources

There are several properties that influence the choice of a particle source for a particular experiment. Among the more important are type of particle, kinetic energy, intensity and how easily it can be controlled and/or predicted.

The first high energy particle experiments were performed using decay products from radioisotopes, e.g. Rutherford's famous alpha scattering experiment. Although readily available and easy to control and quantify, the type of particles and available energy range is severely limited (below a few MeV).

It was soon discovered that there was a constant flux of particles from cosmic sources. These range from low energy (keV) protons from the sun (mainly trapped in the Van Allen belts by the earth's magnetic field) to the highest energy particles ever observed (10^{20} eV!!). Incoming cosmic rays will normally interact with the atmosphere producing a variety of secondaries, some of which may penetrate to ground level. Taking detectors to high altitude (mountains or balloons) where the intensity is greater led to many discoveries in the 30s, 40s and 50s, including the positron, muon, pion and strange particles.

Current experiments using extraterrestrial particle sources include particle astrophysics (ground-based, airborne and satellite), and neutrino and dark matter (underground). Secondary muons are a useful tool for calibrating detectors, but the low intensities and unpredictability of cosmic rays limit their use.

"Artificially" produced neutrons and neutrinos are available in abundance from nuclear reactors (this is how the neutrino was first directly observed) and in fact reactor neutrinos are currently being used for neutrino oscillation experiments. As with natural radiation, the energies and particle types available are very limited.

Obtaining large numbers of free particles at "rest" is very simple: electrons crowd out of heated metal filaments, and ionising hydrogen produces protons. Artificially accelerating such charged particles is now the primary tool of particle physicists, providing intense, controllable, high energy beams.

3 Particle Accelerators

3.1 Linear

Accelerators have developed from the cathode ray tubes of the late 1800s into giant underground machines many kilometres long. The simplest, like the CRTs, use a DC voltage to accelerate the particles according to $\Delta E = qV$. DC voltages of up to a few megavolts are possible using, for example, Van de Graaff or Cockroft-Walton generators.

For higher energies, it is much more practical to use radiofrequency AC voltages for acceleration. A typical linear accelerator (LINAC) consists of a series of microwave resonant cavities through which bunches of particles pass in succession. If the timing is correct, the standing wave in each cavity will accelerate the passing charged particles. Notice that this forces the particles to be bunched.

Accelerating fields in LINACs can reach 10s of megavolts per metre, the final energy of the beams being limited by the number of cavities and so the total length of the machine (the largest built so far was at SLAC, accelerating electrons to 45 GeV over 3 km).

3.2 Cyclic

Particles with momentum p (GeV/c) and charge qe moving through a constant magnetic field B (T) will follow a circular path with a radius R (m) given by

$$p = 0.3qBR$$

The earliest cyclic accelerators were cyclotrons, consisting of a disk-shaped vacuum vessel placed in a uniform external magnetic field. Particles would be injected near the centre of the disk and accelerated by an AC field across its width, spiralling outwards as their energy increased.

Although efficient for low energy particles ($\sim$ MeV), for which they are still used in medical applications, large cyclotrons quickly become impractical. Almost all modern cyclic machines are synchrotrons, in which the magnetic field is ramped up as the particles accelerate, keeping the radius of curvature constant. In practice, synchrotrons are built as a sequence of discrete components including accelerating cavities, dipole magnets (providing the bending field), higher order magnets (for focusing) and various other control and diagnostic elements, surrounding a high quality vacuum.

3.3 Synchrotron Radiation

All charged particles radiate when accelerated; for highly relativistic particles in circular motion this is known as synchrotron radiation and the power loss P is given by the formula:

$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2v^4}{c^3R^2}\gamma^4$$

The relativistic γ in this expression means that $P \sim \text{mass}^{-4}$ so electrons lose energy at 10^{13} the rate of protons. As well as an overall reduction, the quantised nature of synchrotron radiation will result in a spread in the beam energy. The intense X-rays generated can be used for medical and other sciences, and several synchrotron "light sources" have been built for this purpose.

4 Types of Accelerator Experiment

4.1 Fixed Target

Electrons and protons (or other ionised nuclei) can be accelerated and directed onto targets for experiments. Such "fixed-target" experiments consist of a succession of detectors downstream from the target to analyse the secondary particles produced.

4.2 Secondary Beams

Rare particles among the secondary particles produced when a particle beam hits a target can be filtered, focused and steered to form a secondary beam, This allows experiments with kaon, pion or even more exotic beams.

Sometimes intense secondary beams are allowed to decay, producing beams of their decay products in turn. A pion beam will soon become a neutrino beam, for example.

In the same fashion antiproton or positron beams can be made, but since these particles are stable, they can be accumulated in storage rings before accelerating to create high intensity beams. At Fermilab, antiprotons are created by colliding 120 GeV protons into a target - about 100,000 p per $\bar{p}$ - over several hours until about 10^{12} are accumulated. (The tricky part is actually to control the antiprotons as they are decelerated and stored).

4.3 Collider

The energy available to create a new particle in a collision is the energy in the centre-of-momentum frame, $\sqrt{s}$. In a fixed-target experiment this is very small due to the high boost of the centre-of-momentum frame with respect to the lab. By colliding two equal momentum beams, this is overcome and all of the beams' energies are available.

Although more technically challenging, collider experiments are extremely powerful and many have been or are being built. Especially aesthetically pleasing are particle/antiparticle colliders as not only do all conserved quantities in the initial state (except energy) cancel, but a synchrotron configured to accelerate a particle will automatically accelerate its antiparticle in the opposite direction (other combinations require two separate beam pipes, sets of magnets etc).

pp or $p\bar{p}$ collisions provide the highest energy reach (negligible synchrotron losses) but pointlike e^+e^- collisions are easier to interpret. Other possibilities include ep (for proton structure) and heavy ions (quark-gluon plasma studies).

The intensity of the interacting beams at a collider is known as **luminosity** and is normally given the symbol $\mathcal{L}$ and measured in cm^{-2}s^{-1}. The probability of a given interaction per unit luminosity is the cross section (σ), so the interaction rate = $\mathcal{L}\sigma$. and the total number of interactions over time is given by $\sigma \int \mathcal{L} dt$. (Confusingly the integrated luminosity is never measured in cm^{-2} but in nb^{-1} etc.) The luminosity is given by

$$\mathcal{L} = f n_1 n_2 / A$$

where f is the frequency at which bunches collide, n_1 and n_2 are the number of particles in the colliding bunches and A is their effective cross sectional area.

4.4 Accelerator Complexes

Any given synchrotron is only able to handle particles within a particular energy range, typically around one order of magnitude (e.g. 100 MeV to 1 GeV). To reach the highest energies therefore, accelerators are grouped in complexes with particles passing through a succession of machines (including DC and LINACs as well as up to three rings).

5 Charged Particle Detectors

5.1 Ionisation Losses

Most detectors work by collecting and measuring the free charges liberated from a detection medium by the passage of a high energy particle. The mean energy lost by a particle due to ionisation and excitation as it traverses a medium is given by the Bethe-Block equation:

$$-\frac{dE}{dx} = Kq^2 \frac{Z}{A\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

where K is a constant, qe is the charge of the particle, Z and A are the atomic number and mass of the medium, I is the mean excitation energy, δ is a small correction for density effects and x is in density-normalised units (typically g cm^{-2}). T_{max} is the maximum energy that can be transfered to a free electron and to first order $T_{max} \sim 2m_e c^2 \beta^2 \gamma^2$.

The Bethe-Block equation fairly accurately describes the energy loss of most particles over the range $0.1 < \beta\gamma < 500$. Its main features are

- only a weak dependence on material, as $Z/A \approx 2$ for most elements
- low energy behaviour $\sim 1/\beta^2$
- a minimum at $\gamma \approx 3$ of 1-1.5 MeV/(g cm^{-2})
- high energy behaviour $\sim \ln\gamma$

Particles with energy losses close to the minimum (effectively most with $\beta\gamma > 1$) are known as Minimum Ionising Particles, or **MIP**s.

It should be emphasised that the Bethe-Block equation only describes the mean statistical energy loss. Considerable fluctuations will occur, and electrons (δ rays) can be ejected from the medium with sufficient energy (keV) to leave a secondary ionisation trail.

5.2 Non-electronic Detectors

The microscopic ionisation trail left by such high energy particles can be used to nucleate macroscopic chemical or physical processes. The two most common examples of this have been in the use of photographic emulsions and bubble chambers.

Photographic emulsions (traditionally coated onto glass plates) are exposed to particles and then developed in a similar fashion as conventional photographs. The ionisation tracks can then be examined using a microscope.

In a bubble chamber, a liquid (commonly hydrogen) is maintained close to boiling point under pressure. The pressure is suddenly reduced just as the particles enter the pressure vessel, and the ionisation trails will nucleate bubble formation in the now superheated liquid. A photograph is taken for later examination.

Although extremely high precision, neither of these detectors is well suited to high rate collider experiments.

5.3 Scintillation Detectors

In a field-free, dense medium, empty atomic energy levels created by ionisation or excitation will quickly (ns) be filled by electronic transitions. Some of these transitions will generate visible photons, or UV photons that can be converted to visible wavelengths via fluorescence.

The emitted light can be detected by the naked eye (e.g. Rutherford's scattering experiment) but it is normally more convenient to use a photodetector (PMT, photodiode etc.) often placed remotely and connected to the detector via optical fibres.

The most commonly used scintillators fall into one of two types. Inorganic scintillators tend to be very dense crystals and are often used to completely absorb the incoming particles, measuring the total energy. Organic scintillators are lightweight, versatile and cheap. Yields vary a lot depending on the material, but about 1 photon per 100 eV is typical.

5.4 Wire Chambers

The first electrical particle detectors consisted of high voltage electrodes placed in a gas. Electrons created in the ionisation trail are collected and measured on the anode, and the positive ions may similarly be detected at the cathode.

Since the number of electrons generated is small ($\sim 100\ e^-/\text{cm}$ along the trail) large amplification is needed to detect a signal. This can be provided by an external amplifier, but if the field is large enough the primary electrons will gain sufficient energy to ionise gas molecules themselves, the secondary electrons subsequently ionising further molecules and so on. The resulting "avalanche" of charge can effectively provide amplification by many orders of magnitude. The geometry of the field near a thin wire ($E \sim 1/r$) naturally provides high fields even with a relatively low voltage applied. A detector built to operate in such a fashion is normally called a proportional chamber due to the linear gain.

At very high electric fields, the gain becomes highly non-linear and eventually saturates (i.e. the same signal is collected irrespective of the primary charge deposition). Such detectors are often referred to as counters, and for extreme field strengths complete breakdown of the entire gas volume may occur (the Geiger-Muller effect).

Common detector types that utilise these basic concepts are:

- Geiger Counter.
- Flash/Spark Chamber: a volume filled with small pulsed Geiger counters, often transparent tubes which have a visible discharge and can be recorded on a photograph.
- Streamer Chamber: a large volume with a uniform field applied via transparent electrodes with a very short (ns) pulse. Breakdown occurs along the ionisation trail producing visible light, but there is insufficient time for it to spread through the entire gas volume.
- Multiwire Proportional Wire Chamber (MWPC): a large, flat detector with many parallel anode wires between two plates. A spatial mea-

surement in one dimension is given by the anode, and frequently the cathode planes are segmented to provide an orthogonal measurement.

5.5 Drift Detectors

The spatial resolution of a MWPC is determined by its wire spacing. However, if the drift speed of the electrons in the gas is known, it is possible to calculate the distance between the particle's trajectory and the anode by the time taken for the generated charge to be detected. Drift chambers typically use field shaping wires to create a uniform low-field drift region, while keeping a high-field avalanche anode region. The slower the drift speed the higher the spatial resolution, with typical values being about 100 μm for electrons drifting at a speed of a few cm/μs over 5 cm.

A single drift chamber can have many thousands of anode wires. If the incident particles are travelling in the y direction, the wires will normally be parallel to the z axis with the field in the x direction. As incident particles traverse the detector, each successive wire measures an x distance allowing the particle trajectory to be reconstructed. The addition of "stereo" wires at a small angle to the z axis allows a 3D position to be calculated.

The use of drift time is taken a step further in a time projection chamber (TPC). A uniform field is provided over the entire detector volume, drifting the primary electrons to one end where a 2D detector (often a MWPC) measures the positions in the xy plane. The position of the charge generation in the z direction is calculated directly from the time delay.

The operation of all wire chambers and TPCs are highly dependent on the gas, voltage, geometry and external conditions such as magnetic fields. Detectors with long drift times may be unsuitable for experiments with high interaction rates and breakdown of gaseous detectors may be induced by large particle fluxes.

5.6 Solid State Detectors

Using electric fields to collect generated charge works in media other than gases. Some examples are liquid argon, plastics and even diamond. By far the most common in use at the moment is silicon, where semiconductor processing techniques can be used to (relatively) cheaply produce very precise detectors. The increased density and lower ionisation or excitation energy of these materials means a much larger generated signal than in a gas.

A simple silicon detector consists of a wafer of n-type silicon 300 μm thick, with the back side held at a constant positive voltage, V. The front side has parallel strips of highly doped p-type silicon implanted using photolithography techniques similar to those used to make integrated circuits with a sub-micron feature size. In particle detectors, a typical strip pitch p would be 50 μm.

If the implant strips are held at 0 V, the potential difference across the wafer reverse-biases the diodes formed by the p-n junctions. This creates a depletion region with a thickness of

$$d \approx 0.5\sqrt{\rho(V+0.5)}\ \mu\text{m}$$

where ρ is the resistivity of the n-type silicon in Ω.cm (typically 1-10 kΩ.cm) and V is in volts. Silicon detectors are normally operated with sufficient voltage for full depletion.

A MIP passing through 300 μm of silicon will create approximately 22,000 electron-hole pairs. If the sensor is fully depleted, all of the holes will drift in the field to the closest implanted strip where the charge can be measured. The spatial resolution of an ideal strip detector is given by $p/\sqrt{12}$, so extremely precise tracking can be achieved.

5.7 Cerenkov and Transition Radiation Detectors

Cerenkov radiation is created when a charged particle travels through a medium faster than the local speed of light. Transition radiation occurs when a charged particle pases between regions with different densities. Although negligible in magnitude compared to ionisation energy loss, both Cerenkov and transition radiation are utilised in particle detectors and can be particularly useful for identifying particles.

6 Particle Interactions with Matter

Ionisation losses were discussed above.

6.1 Radiation Losses

Above some critical energy (1-500 MeV for electrons, $\gg$ 100 GeV for muons or other particles) the rate of energy loss by a charged particle by ionisation is overtaken by that from radiation. The particle interacts with a nucleus, emitting a photon (often a hard gamma ray) in a process known as "bremsstrahlung". The energy loss for electrons is given by

$$dE/dx = -E/X_0$$

with the radiation length,

$$X_0 = \frac{716.4 \text{ g cm}^{-2}\ A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

6.2 Photon Absorption

At low energies, photons are predominantly absorbed via the photoelectric effect. At high energies (> 10 MeV or so) the dominant effect is the production of e^+e^- pairs in the nuclear field. The characteristic length scale is almost identical that of bremsstrahlung, with the probability of a photon pair-producing being given by

$$\frac{dP_{pair}}{dx} = \frac{7}{9X_0}$$

6.3 Electromagnetic Showers

It is therefore expected that within about X_0 of entering a detector, a single electron has produced an additional photon, and a single photon has converted into an electron and a positron. In both cases, a single particle has converted into two particles each with about half of the energy of the incident particle. After a further X_0, a similar doubling of particle numbers and halving of energies can be expected, and this increase in particle numbers will continue until the energies of the particles are low enough for ionisation losses and photon absorption to dominate. This is known as an **electromagnetic shower**.

6.4 Hadronic Showers

Hadrons will develop showers in a similar fashion as they interact with nuclei, the characteristic length scale being given by the nuclear interaction length

$$\lambda \approx 35\text{g.cm}^{-2}A^{1/3}$$

6.5 Multiple Scattering

As it traverses a medium, a charged particle will not only lose energy via interactions with the electrons, but will scatter elastically from many nuclei. For a thin layer, the amount of scattering will approximately follow a Gaussian distribution with a width given by

$$\theta_{rms} \approx \frac{13.6 \text{ MeV}}{\beta cp} q\sqrt{x/X_0}$$

7 Categories of Collider Detectors

1. **Tracking Detectors.** Optimised to measure the trajectories of particles. Good position resolution with a minimum of material to reduce multiple scattering and other interactions. Often gaseous (TPC, drift chamber) for large volumes, but silicon is becoming popular.

2. **Vertex Detectors.** Very precise tracking detectors placed very close to the interaction point. Normally silicon.

3. **Calorimeters.** Designed to completely absorb incident particles, measuring their total energy. Can be homogeneous or sampling, in which a dense absorber is interspersed with layers of detectors. Normally work by measuring ionisation of particles in a shower. and split into electromagnetic and hadronic sections.

   - Electromagnetic: High Z to reduce X_0, relatively compact. Often homogeneous crystal, glass or liquid but can be fine-grained sampling, e.g. lead-scintillator.
   - Hadronic: Deep and massive, almost always sampling e.g. uranium absorber with layers of proportional chambers.

4. **Particle ID.** Time-of-flight or Cerenkov detectors measuring β directly. Help differentiate pions, kaons and protons (some ID information can be obtained by dE/dx in tracker).

5. **Muon Detectors.** Simple particle counters or tracking chambers placed behind calorimeters.

8 A Collider Experiment

In order to carry out physics measurements, particle beams have to be accelerated and collided. The particles produced in these collisions have to be detected and the whole event analysed to reconstruct the basic physics process that took place. To demonstrate how all of the concepts and techniques discussed so far can be brought together to do this, the example of the CDF detector at the Tevatron will be used.

8.1 Proton - Antiproton Collisions

Protons and antiprotons are compound objects, made up of partons (quarks and gluons) tightly bound together by the strong nuclear force. The total

$p\overline{p}$ interaction cross section is therefore large and comparable to the physical size of the proton (around 1 $\text{fm}^2 \equiv 10$ mb). At high energies (small length scales) however, the collisions become effectively parton-parton interactions. This results in the following complications:

1. The initial state is not known, as quarks of any flavour or even gluons could have been involved.

2. The momentum (in the beam direction) and effective centre of mass energy are not known as the interacting partons carry an unknown fraction of the proton's momentum. This means that momentum conservation can only be applied in the plane transverse to the beam.

3. There will be an "underlying event" due to the remnants of the proton and antiproton not directly involved in the hard collision.

8.2 The Tevatron

The Tevatron accelerator started operating at Fermilab in 1983 with a 512 GeV proton beam. It has been used as a $p\overline{p}$ collider since 1984, and two dedicated experiments, CDF and DØ, take collision data in parallel. CDF and DØ discovered the top quark in 1995 when the Tevatron was running at $\sqrt{s} = 1.8$ TeV.

In 2001 the Tevatron started Run II, with upgraded energy and luminosity. It is expected that by 2009 it will have delivered 4–8 fb^{-1} at $\sqrt{s} = 1.96$ TeV.

The spacing between particle bunches is 396 μs. At an instantaneous luminosity of 100×10^{30} $\text{cm}^{-2}\text{s}^{-1}$ each bunch crossing will produce an average of about 3 individual $p\overline{p}$ collisions. For many interesting physics processes however, the cross sections are so low that there may only be a handful of events per year.

8.3 CDF

The CDF detector was optimised for excellent tracking in the central region. (DØ, by contrast, was optimised for calorimetry). From the interaction region outwards the main components of CDF are:

1. Silicon vertex detector and tracker. There are eight layers of silicon with radii from 1.5 cm to 28 cm.

2. Central Outer Tracker (COT). An open cell drift chamber with maximum drift times less than 200 ns, it provides up to 96 hits (axial and stereo) between a radius of 44 and 132 cm.

3. Time of Flight: Scintillator with good time resolution to provide particle ID.

4. Solenoid. A superconducting magnet providing a 1.4 T field enabling momentum measurement in the silicon and COT.

5. Electromagnetic Calorimeter. A lead/scintillator sandwich structure, designed to completely contain EM showers.

6. Hadronic Calorimeter. Iron/scintillator sandwich.

7. Muon Detectors. A variety of simple drift and scintillation detectors outside the calorimeters, some behind additional steel shielding.

The entire CDF detector consists of about a million channels of electronics that have to be read out, processed and stored for later analysis. This requires a sophisticated data acquisition (DAQ) system from the front end (electronic processing on the detectors themselves) through several levels of computing to the permanent storage medium (tape cassettes).

There is also a sophisticated trigger system, designed to look at events as they occur and decide whether they are interesting enough to be saved to tape. CDF can only save the data from about 100 events per second, so only 1 in 20,000 bunch crossings is selected.

9 Event Reconstruction

Data collected by the detectors allows the measurement and identification of the particles produced in the hard collision. This information can be used in turn to try to deduce the physics process that took place and the presence of particles that were not directly detected. At the Feynman diagram level, the particles that could have been produced are just the fundamental Standard Model components.

- Electrons: leave a track in the silicon and COT and then shower in the EM calorimeter, so both momentum and energy can be directly measured (and should be compatible)

- Muons: leave a track in the silicon and COT, energy consistent with a MIP in the calorimeters and then register hits in the muon detectors.

- Taus: lifetime ~ 0.2 ps so decay after travelling a short distance (typically < 1 mm) into a few charged and neutral particles. The tau can be identified and reconstructed from its decay products, and it may also be possible to measure the distance it travelled before decaying with the vertex detector.

- Neutrinos: interact so weakly that they are never detected. Their presence can only be inferred from an imbalance of transverse momentum.

- u, d, s quarks, gluons: produce collimated jets of hadrons. Charged hadrons $(K^{\pm}, \pi^{\pm}, p)$ leave tracks and both charged and neutral will shower in the calorimeter. Due to the nature of the hadronisation, it is impossible to tell which flavour was produced and energy resolution is poor.

- c, b quarks: will produce jets as light quarks do, but these heavy quarks will hadronise, travel a few mm and then decay (lifetimes about 1 ps). These decays can be observed by a vertex detector, or if one of the decay products is a muon or electron, thus "tagging" the jet as being a c or b jet. The b lifetime is about twice as long making it easier to tag.

- t quark, W, Z: decay instantaneously and so are observed by reconstruction of their decay products.

- Photon: leaves no track but will shower in the EM calorimeter.

As an example, consider the production of a top quark pair, i.e. the interaction[1]

$$q\overline{q} \rightarrow t\overline{t}$$

Although the top decays via the weak force, it has a lifetime much shorter than that of other quarks and will decay effectively instantaneously, before hadronisation and jet formation. The branching ratio $Br(t \rightarrow Wb) \approx 100\%$, so the event topology will depend on the decay of the two Ws. A W will decay to two quarks (u, d, c, s) 70% of the time, or to a lepton and a neutrino with a 10% branching ratio for each lepton flavour.

In the case with one $W \rightarrow e\nu$ and the other $W \rightarrow q\overline{q}$ (which will occur 14% of the time), the hard interaction is

$$q\overline{q} \rightarrow t\overline{t} \rightarrow be^{+}\nu_{e}\, \overline{b}q\overline{q}$$

(or its charge conjugate) and the fully reconstructed event will contain:

[1] This and all interactions discussed are *inclusive*, meaning that the final state may contain any number of particles in addition to those explicitly stated.

- Two b jets
- Two light or charm quark jets
- An electron
- An imbalance in transverse momentum due to the neutrino
- Possible extra final state particles from higher order processes
- Some low transverse momentum particles from the underlying event
- Possibly the products of any extra collisions that took place during the same bunch crossing.

There are specific triggers and offline analysis programs designed to search for any event with these characteristics and classify them as $t\bar{t}$ candidates. Measurements of the jet and electron energies and the missing momentum allow the mass of the top quark to be calculated.

10 Physics Analysis

Several things have to be brought together to make a complete physics measurement. The signal process and the way it will appear in the detector have to be understood, as do any possible background processes that could be confused with the signal. Statistical and systematic errors have to be quantified and taken into account. To illustrate this, the search for a light Higgs boson at CDF will be used.

10.1 Monte Carlo

For many quantities reliable estimates are difficult to obtain from the data alone, so Monte Carlo computer simulation has to be used. Artificial physics events are generated randomly according to theoretical distributions and then sent to a program that models the detector response. These simulated events can be passed through the same reconstruction and analysis programs as the real data.

This is an extremely powerful technique allowing known signal and background processes to be followed through every stage of a measurement. Monte Carlo simulation is also used extensively to design future experiments.

As well as consuming a lot of computing power, Monte Carlo simulations must be carefully compared to real data to ensure that the modelling of the detector response and background processes are correct.

10.2 Higgs Signal

If a Higgs Boson exists with a mass between 115 GeV (the current experimental limit from LEP) and about 140 GeV it will decay predominantly as $H \to b\bar{b}$. The cross section predicted by the Standard Model is

$$\sigma(p\overline{p} \to H \to b\bar{b}) \sim 1 \text{ pb}$$

or 1-2 Higgs per day of running. Unfortunately, the signal of two b jets is impossible to extract from the enormous number of QCD two-jet events ($\sigma \sim 1$ nb) with "fake" b tags and genuine $p\overline{p} \to b\bar{b}$ ($\sigma \sim 1$ μb).

A more promising channel is

$$p\overline{p} \to WH \to l\nu \; b\bar{b}$$

where l means an electron or a muon. The cross section is only about 20 fb for both leptons in total, but the electron or muon is easily identified, and the backgrounds are much lower.

If the total number of signal events in the data sample is N, and n of them are correctly identified, the signal efficiency is defined as

$$\epsilon = \frac{n}{N}$$

Efficiency can be calculated from a combination of data and Monte Carlo studies. In this channel, after requiring clean identification of a lepton, missing transverse momentum and two jets (at least one of which has a b tag) it has been shown to be about 10%.

10.3 Backgrounds

Every process that can produce a $l\nu qb$ final state, or is likely to be misidentified as such, must be considered. These include top, WW, ZZ, and $\tau\tau$ production, all of which are modelled in Monte Carlo. The dominant background in this analysis is $p\overline{p} \to W + 2 \; jets$, W production with additional QCD activity. The extra jets may be real b or c jets or they may be b tagged in error. Simulations indicate that one $W + 2 \; jets$ event approximately every 40 pb^{-1} will be consistent with a 120 GeV Higgs.

10.4 Statistical Errors

The number of events observed will follow a Poisson distribution (Gaussian for a sufficiently large number of events) and so the error from N events is $\sqrt{N}$. There will also be an error on quantities derived from Monte Carlo based on the number of events simulated. For example, if a selection efficiency ϵ is calculated by simulating N events then the distribution is binomial and $\sigma(\epsilon) = \sqrt{\epsilon(1-\epsilon)/N}$.

10.5 Systematic Errors

Uncertainties in detector response, background levels from theory, simulation parameters and many other factors must be estimated. This is normally done by changing inputs to the Monte Carlo and observing the effect on the output.

10.6 Significance

After all of the errors have been propagated through and combined, the significance of the data can be calculated. This is a measure of how much the data differs from the expected background. If N data events are observed with an expected background N_B, the significance is

$$S = \frac{N - N_B}{\sigma_{tot}}$$

If systematic errors are small then $\sigma_{tot} \sim \sqrt{N_B}$ so the significance of N_S signal events would be

$$S \sim \frac{N_S}{\sqrt{N_B}}$$

Traditionally in high energy physics, new discoveries are claimed on results exceeding $S = 5$ which corresponds to a probability of about 10^{-5} of being a random fluctuation in background.

In 1 fb^{-1} of data, CDF will expect to see 2 WH events in the $W \to e\nu$ or $W \to \mu\nu$ channel. In the same data there will be about 25 background $W + 2\ jets$ events selected, so the predicted signal significance will be only be 0.4 (ignoring systematic errors). The maximum integrated luminosity the Tevatron is expected to deliver over its life is 8 fb^{-1} so the final Higgs sensitivity in this channel will be around $S = 1.6$.[2]

If the Higgs is to be discovered at 120 GeV or even higher masses (where the cross section decreases) a new accelerator with much higher energy and luminosity is therefore required. Fortunately this accelerator is currently under construction at CERN and is due to start colliding protons in 2007.

[2]The combination of different channels and of both CDF and DØ data, along with expected improvements in the analysis mean that the Tevatron expects $S \sim 3$ after 8 fb^{-1}.