Teaching the Standard Model in IB Physics

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This curriculum unit is recommended for:
High School Physics IB seniors (12)

Keywords: Physics, Particle Physics, Standard Model, International Baccalaureate Physics

Teaching Standards: See Appendix 1 for teaching standards addressed in this unit.

Synopsis: This curriculum unit will explore how to teach the Standard Model to International Baccalaureate seniors. The aims of the International Baccalaureate Physics course is to expose students to the most fundamental experimental science, which seeks to explain the universe from the smallest particles to an understanding of the origins of the universe. Yet more importantly, students will study the impact of physics on society, the moral and ethical dilemmas, and the social economic and environmental impact of the work of scientists in a global context. A unit of study in the IB physics core curriculum is on the structure of matter; students will develop an understanding that matter consists of six quarks and six leptons. Quarks were postulated on a completely mathematical basis in order to explain patterns observed in properties of particles. Later large-scale collaborative experimentation led to the discovery of the predicted fundamental particles. Students will become proficient in their understanding of the standard model and how conservation laws are applied in particle reactions.[i]

I plan to teach this unit during the coming year in to 15 students in Physics grades12.

Teaching the Standard Model in IB Physics

Debra B. Semmler

Introduction

What is the smallest particle of matter? This is a question that has been explored by scientists since the beginning of time. The Greek philosophers were the first to ponder the fundamental constitution of matter. They considered, that if you could cut matter into smaller and smaller pieces you would end up with the smallest bits they called the atom, which means that which cannot be cut. The search for the smallest particle started with J.J. Thomson's discovery of the electron in 1897 and was thought complete with Rutherford's discovery of the positive atomic nucleus and Niels Bohr's orbital atomic model at the beginning of the twentieth century. As experiments with the nucleus became more sophisticated at higher and higher energies the number of small bits of matter multiplied a hundred fold. Using Einstein's famous $E=mc^2$ formula a remarkable trade off between energy and matter was able to transform energy of motion into new bits of matter. The rules that control all matter transmutations are the most basic laws of nature, in the conservation of energy, electric charge and momentum. After much work a model describing the known particles in nature emerged, the Standard Model. It consists of only twelve particles-six quarks and six leptons.[ii] This curriculum unit will explore how to teach the Standard Model to International Baccalaureate seniors.

Classroom and School Environment

I teach at an urban, partial magnet high school with a total population of roughly 2,000 students, with approximately 900 students who are part of the International Baccalaureate (IB) magnet. The school is comprised of approximately 52 % Africans American, 25 % white, 16% Hispanics and 6 % Asian. More than 60% of the student population is on free or reduced lunch. I will be using the curriculum unit in my IB physics III class; the students in this course are on their third year in physics, having completed an honors-level physics class as sophomores and as seniors they have completed science courses in biology, earth and environmental science and honors chemistry. The IB physics course is a college level physics curriculum divided over two years that includes a minimum of 40 hours of experimental work.

Rational

The aims of the International Baccalaureate Physics course is to expose students to the most fundamental experimental science, which seeks to explain the universe from the smallest particles to an understanding of the origins of the universe. Yet more importantly, students will study the impact of physics on society, the moral and ethical dilemmas, and the social economic and environmental impact of the work of scientists in a global context. A unit of study in the IB physics core curriculum is on the structure of matter; students will develop an understanding that matter consists of six quarks and six leptons. Quarks were postulated on a completely mathematical basis in order to explain patterns observed in properties of particles. Later large-scale collaborative experimentation led to the discovery of the predicted fundamental particles. Students will become proficient in their understanding of the standard model and how conservation laws are applied in particle reactions.[iii]

Scientific Background

Discovery of the neutrino

There are three nuclear decay processes where the atomic mass remains constant and the atomic number increases or decreases by one. They are all classified as beta decay, β. The first is β^- decay where a neutron in the nucleus changes into a proton with the emission of an electron from the nucleus. The beta particle is the electron in this case. In β+ decay, a proton in the nucleus changes into a neutron and a positron (the beta particle) is released from the nucleus. With electron capture (EC) a proton in the nucleus changes into a neutron by capturing an atomic electron, usually from the inner shell. The isotopes on the neutron-rich side of the line of stability will tend to decay by β^- emission, while those on the proton-rich side will most likely decay by β+ or electron capture.[iv]

The following reaction represents the β^- decay of ^{210}Bi.

$$^{210}_{83}\mathrm{Bi} \rightarrow {}^{210}_{84}\mathrm{Po} + \mathrm{e}^-$$

In this case the parent nucleus, $^{210}_{83}\mathrm{Bi}$, decays into a daughter nucleus, $^{210}_{84}\mathrm{Po}$, and an electron (β^- particle) is emitted. Notice that the atomic mass number, A, is the same for the parent and daughter nuclei. The β^- decay has changed the balance of protons compared to neutrons in the daughter nucleus. We can calculate the amount of energy released in the decay by calculating the Q value for the reaction. The Q value is the difference between the rest energy of the parent nucleus and the sum of the rest energies of the products of the decay. In this case, the Q value is 1.16 MeV. The energy released by the decay should be seen as the kinetic energy of the emitted electron. This predicts that the kinetic energy of the electron should be the same each time this particular decay takes place. However, experimentally, the energies of the electrons emitted in this beta decay are observed to vary from zero to the maximum energy available E_{max}= Q. Figure 1 shows the energy spectrum of the electron emitted in this decay. The electrons is observed to have a range of kinetic energies, not one unique value as would be expected assuming energy, mass and momentum conservation.

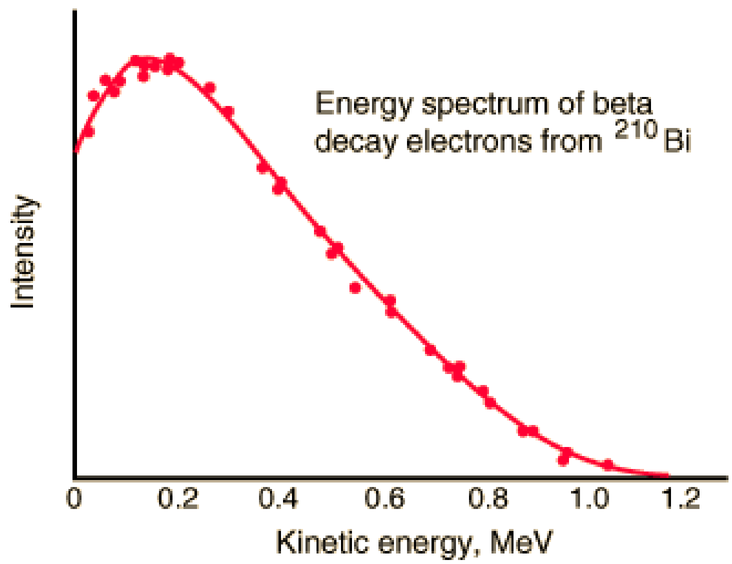


Figure 1. Experimental energy spectrum for decay electrons from Bismuth 210[v]

The result is that in a particular β^- decay event the electron carries away less energy then the difference between the rest energy of the parent and daughter. This would result in energy and momentum not being conserved. The solution to this problem was first suggest by Wolfgang Pauli in 1930 when he proposed that a third particle was emitted in β^- decay that carried the energy, linear and angular momentum necessary to conserve these quantities in each individual decay event. This new particle did not carry electric charge and had a mass much les than that of an electron. In 1933 Enrico Fermi developed a quantum theory of β^- decay that incorporated this proposal and called the new particle the neutrino ("little neutral one" in Italian.) In 1956, in an experiment performed by Clyde Cowan and Frederick Reines, the first neutrinos were observed in the laboratory. The decay of ${}^{210}_{83}\mathrm{Bi}$ now correctly written as

$$ {}^{210}_{83}\mathrm{Bi} \rightarrow {}^{210}_{84}\mathrm{Po} + \mathrm{e}^- + \overline{\upsilon} $$

Where the $\overline{\upsilon}$ represents the neutrino (in this case is it antineutrino).[vi]

Particle Zoo

Since the discovery of the electron neutrino, physicists have identified 13 fundamental constituents of matter. Just three of these-the up quark (u), the down quark (d), and the electron are needed to make protons and neutrons and to form atoms and molecules. There are four fundamental forces that act in nature: the strong force, the weak force, the electromagnetic force and the gravitational force. The strong force is responsible for binding the particles in the nucleus (protons and neutron) together. The electromagnetic force binds electrons to the atomic nuclei to form atoms. The weak force helps the decay of heavy particles. The gravitational force acts between massive objects and has no roll on the subatomic scale. Particles transmit forces through exchange particles. Each force has its own exchange particle.[vii]

- The gluon mediates the strong forces; it “glues” quarks together
- The photon carries the electromagnetic force; it also transmits light
- The W and Z bosons represent the weak force; they induce different types of decays

Physicists suspect that the gravitational force may be associated with a boson particle hypothetically called the graviton.

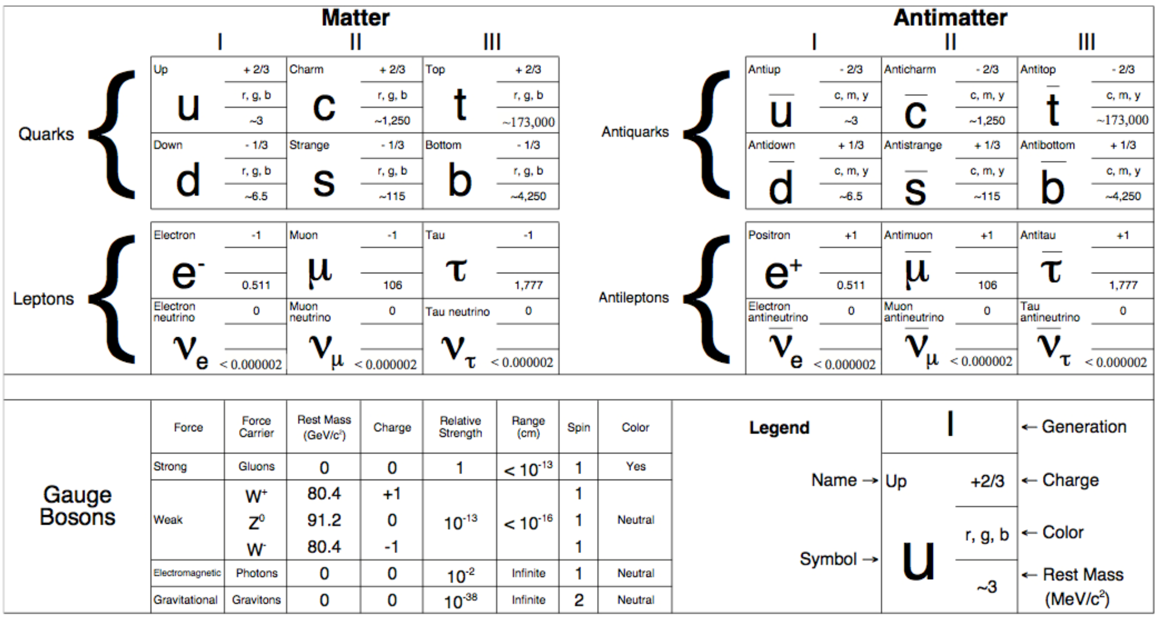
Antimatter

For every particle that physicists have discovered a corresponding antiparticle exists. Antiparticles have the opposite properties of their corresponding particles. For example, an antiproton has a negative electric charge while a proton is positively charged. In the mid-1990’s physicists at CERN and Fermilab created the first anti-atoms, by carefully adding a positron and an antiproton to form antihydrogen. Storing antimatter is difficult task because as soon as an antiparticle and a particle meet they annihilate, disappearing in a flash of energy.[viii]

The Standard Model

Physicist call the framework that describes the interaction between elementary building blocks (quarks and leptons) and the force carriers (bosons) the Standard Model. Gravity is not yet part of this framework. The biggest success of the Standard Model is the unification of the electromagnetic and the weak forces into the electroweak force. This milestone is comparable to the unification of the electric and magnetic forces into a single theory by Maxwell in the 19^{th} century.

Even though the Standard Model describes the interaction the sub atomic world, it does not explain the whole picture. The theory does not incorporate the gravitational force or explain questions such as what is dark matter. The Standard Model may only be a small part of a bigger picture and new information from experiments will continue to describe the functioning of the subatomic world.[ix]



	Matter	Name	Symbol	Charge	Color	Mass	Antimatter	Name	Symbol	Charge	Color	Mass
Quarks	I	Up	u	+ 2/3	r, g, b	~3	I	Antiup	u	- 2/3	c, m, y	~3
Quarks	II	Charm	c	+ 2/3	r, g, b	~1,250	II	Anticharm	c	- 2/3	c, m, y	~1,250
Quarks	III	Top	t	+ 2/3	r, g, b	~173,000	III	Antitop	t	- 2/3	c, m, y	~173,000
Quarks	I	Down	d	- 1/3	r, g, b	~6.5	I	Antidown	d	+ 1/3	c, m, y	~6.5
Quarks	II	Strange	s	- 1/3	r, g, b	~115	II	Antistrange	s	+ 1/3	c, m, y	~115
Quarks	III	Bottom	b	- 1/3	r, g, b	~4,250	III	Antibottom	b	+ 1/3	c, m, y	~4,250

	Matter	Name	Symbol	Charge	Mass	Antimatter	Name	Symbol	Charge	Mass
Leptons	I	Electron	e^-	-1	0.511	I	Positron	e^+	+1	0.511
Leptons	II	Muon	μ	-1	106	II	Antimuon	μ	+1	106
Leptons	III	Tau	τ	-1	1,777	III	Antitau	τ	+1	1,777
Leptons	I	Electron neutrino	ν_e	0	< 0.000002	I	Electron antineutrino	ν_e	0	< 0.000002
Leptons	II	Muon neutrino	ν_μ	0	< 0.000002	II	Muon antineutrino	ν_μ	0	< 0.000002
Leptons	III	Tau neutrino	ν_τ	0	< 0.000002	III	Tau antineutrino	ν_τ	0	< 0.000002

Gauge Bosons	Force	Force Carrier	Rest Mass (GeV/c^2)	Charge	Relative Strength	Range (cm)	Spin	Color
	Strong	Gluons	0	0	1	$< 10^{-13}$	1	Yes
	Weak	W^+	80.4	+1	10^{-13}	$< 10^{-16}$	1	Neutral
		Z^0	91.2	0			1	
		W^-	80.4	-1			1	
	Electromagnetic	Photons	0	0	10^{-2}	Infinite	1	Neutral
	Gravitational	Gravitons	0	0	10^{-38}	Infinite	2	Neutral

Legend: I ← Generation; Name → Up; +2/3 ← Charge; r, g, b ← Color; Symbol → u; ~3 ← Rest Mass (MeV/c^2)

Table 1 The Standard Model of matter [x]

Quarks

There are six quarks grouped into three generations. All have fractional electric charge and distinct antiparticles. It is the quarks and antiquarks that bind together in multitude of ways to form more than 200 particles in the particle zoo and accounting for the vast majority of the visible mass of the universe. The bound states of the quarks and antiquarks are call hadrons and there are two subgroups of hadrons. Three group quark combinations are called baryons, which the proton and the neutron are the two most common examples and when a quark and antiquark combine they form mesons.[xi]

Leptons

There are three generations of leptons each consisting of a charged lepton and its related neutrino as shown in Table 1. The electron is the most familiar of the charged leptons and the only one that is stable. Each charged lepton has a distinct antiparticle and for each neutrino there is also an antineutrino although at this point in time it is possible that the two are not distinct like the photon is its own antiparticle. Unlike the quarks there are not lepton-lepton bound states. Leptons are also referred to having three flavors: electron, muon, and tau.[xii]

Feynman diagrams

Feynman diagrams are space-time diagrams, that is, time (ct) versus space graphs, used to describe interaction of quarks, leptons and the mediator of these interactions. They are used to compute lifetimes and cross section for particle interaction events. The time (ct) and space (x) axes are normally not drawn but time (ct) is positive upward and generally drawn with time flowing horizontally toward the right as shown in Figure 2. Straight lines with an arrow represent particles. A particle line whose arrow points backward in time is interpreted as the corresponding antiparticle moving forward in time thus omitting the use of over-bars for antiparticles. The lines are symbolic and do not represent the particle trajectories. The diagrams show the interactions between particles and electromagnetic phenomena. Interactions occur at the vertices and photons are shown as a wiggly line.[xiii]

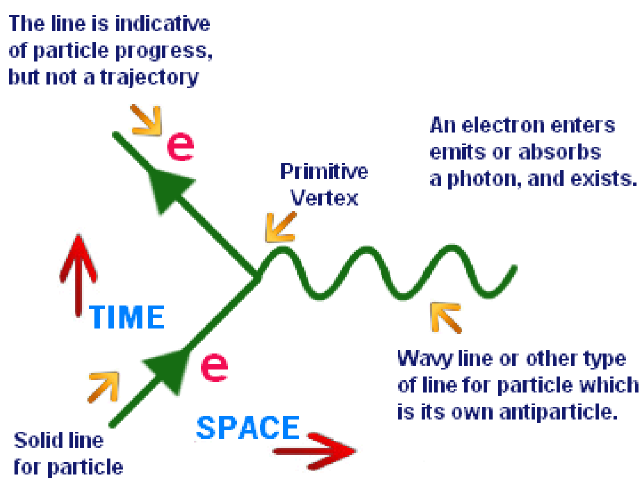


Figure 3 Feynman diagram[xiv]

Student activities

Appendix 2 has four student activities to aid them in understanding the nature and experimental background of particle physics. The first is a worksheet reviewing how to read a particle physics chart; the goal is to familiarize the students with the families of matter and their relationship with forces. The second, is a tutorial into how to draw Feynman diagrams adapted from quantum diaries website. After completion of this activity students should be able to draw eight required Feynman diagrams. The final two student activities are using actual experimental data. The first is to observe the tracks of particles in a bubble chamber. The second is to use actual data from a proton-proton collision to determine the mass of the top quark. These student activities are adapted from Topics in Modern Physics Particles by Leon Lederman Fermi lab group. Also included with student activities are teacher notes and answers to the student worksheet.

Appendix 1: Implementing Teaching Standards

The Structure of Matter[xv]

Predictions: Our present understanding of matter is called the Standard Model, consisting of six quarks and six leptons. Quarks were postulated on a completely mathematical basis in order to explain patterns in the properties of particles. It was much later that large-scale collaborative experimentation led to the discovery of the predicted fundamental particles.

Student should understand

- Quarks, leptons and their antiparticles.
- Hadrons, baryons and mesons.
- The conservation laws of charge, baryon number, lepton number and strangeness.
- The nature and range of the strong nuclear force, weak nuclear force and electromagnetic force
- Exchange particles
- Feynman diagrams
- Confinement
- The Higgs boson

Students should be able to:

- Describe the Rutherford-Geiger-Marsden experiment that led to the discovery of the nucleus
- Applying conservation laws in particle reactions
- Describing protons and neutrons in terms of quarks
- Comparing the interaction strengths of the fundamental forces, including gravity
- Describing the mediation of the fundamental forces through exchange particles
- Sketching and interpreting simple Feynman diagrams
- Describing why free quarks are not observed

Appendix 2 Student Activities and Handouts

THE STANDARD MODEL OF ELEMENTARY PARTICLES CHART THE ULTIMATE PERIODIC TABLE WHAT CAN WE LEARN FROM IT?[xvi]

The purpose of this activity is to familiarize you with the Standard Model of Elementary Particles by studying the Standard Model of Elementary Particles Chart.

As you look at the Chart, you will see that it is divided into four sections. The two top sections list a total of 24 elementary particles. You will need information from these two sections to answer the following questions.

1. The two top sections are labeled ________________ and __________________ .

2. For the time being, let's disregard the right hand side of the Chart and look at the left side labeled Matter. This category is further divided into two groups of six particles. These groups of particles are given the names _________________ and _______________ .

3. List the flavors (names) of the six quarks.

   _______________ , _______________ , _______________ ,

   _______________ , _______________ , _______________

4. List the flavors (names) of the six leptons.

   _______________ , _______________ , _______________ ,

   _______________ , _______________ , _______________

5. The symbol for each quark is ____________________________ .

6. Using the Chart, write the symbols for the following particles:

   up quark ________ down quark _______ top quark _______ charm quark _______

7. Look at the leptons on the Chart. Their symbols (except for the electron) are Greek letters. Fill in the symbols below

Lepton	Symbol	Name of Greek letter

Since there are three different neutrinos, how do their symbols distinguish them from one another? ______________________________

Write the symbol for an electron neutrino: ___________

8. Given the list of particles below, circle the quarks. (Do this without looking at the Chart if you can.)

up, neutrino, electron, down, tau, charm, strange

9. Using the legend in the lower right-hand corner of the Chart, write down the charge and approximate mass of each of the following:

Particle	Charge	Mass
up		
strange		
top		
electron		
tau		
Electron neutrino		

10. Why can mass be measured in MeV/c^2 ?

11. Using the Chart complete the following: _______________ have charges that are integers, and _______________ have charges that are fractions.

12. Baryons are particles that are made from quarks. The most common baryons are the neutron and the proton. Applying the law of conservation of charge (that is, no charge

can be created or destroyed), what is the minimum number of quarks that must be joined to make up one baryon that has a charge of either +1, -1, or 0? _________

Show the proof of your answer here.

13. List three combinations of quarks that will give you a baryon with a charge of:

a) +1 b) -1 c) 0

EXAMPLE: A baryon composed of ccs has a charge of +2/3 + 2/3 - 1/3 = +1.

QUARK COMBINATIONS FOR: +1 -1 0

________	________	________
________	________	________
________	________	________

14. The quarks and leptons in column 1 of the Chart make up all the stable matter such as protons and neutrons. (Neutrons are stable relative to other particles, although they can decay.) Apply this information to write the quark configuration for a proton and for a neutron.

proton _______________ neutron _______________

15. Which leptons are found in Column (or Family) I? ______________ Do you think these are stable too? __________________

Now let's look at the right side of the Chart, marked Antimatter. Using the Chart, explain how the antiparticles differ from the particles in:

a) Charge _________________________

b) Mass _________________________________

c) Symbol ___________________________

(Which particle is an exception?) _________________________

d) Color ____

An antibaryon is made from antiquarks. EXAMPLE: The antiquark configuration for an antiproton is uud since it has a charge of -1; strangeness = 0.   Write the antiquark configuration for the following:

Antineutron (η)

Antisigma minus (Σ)

Antiomega plus (Ω□)

The Chart in the bottom left-hand corner lists the Gauge bosons. These are the carriers of the four fundamental forces in nature. List the four forces and their carriers.

Force	Carrier

1. Which particles are charged? ________________

2. Which force has the shortest range? ___________

3. Which force(s) is/are affected by the color? ________________

4. Which force is the weakest? _____________

5. Which force holds the quarks together to form baryons? ___________________

Matter

Category	Generation	Name	Symbol	Charge	Color	Rest Mass (MeV/c²)
Quarks	I	Up	u	+ 2/3	r, g, b	~3
Quarks	II	Charm	c	+ 2/3	r, g, b	~1,250
Quarks	III	Top	t	+ 2/3	r, g, b	~173,000
Quarks	I	Down	d	- 1/3	r, g, b	~6.5
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Antimatter

Category	Generation	Name	Symbol	Charge	Color	Rest Mass (MeV/c²)
Antiquarks	I	Antiup	$\bar{u}$	- 2/3	c, m, y	~3
Antiquarks	II	Anticharm	$\bar{c}$	- 2/3	c, m, y	~1,250
Antiquarks	III	Antitop	$\bar{t}$	- 2/3	c, m, y	~173,000
Antiquarks	I	Antidown	$\bar{d}$	+ 1/3	c, m, y	~6.5
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Antiquarks	III	Antibottom	$\bar{b}$	+ 1/3	c, m, y	~4,250
Antileptons	I	Positron	e^+	+1		0.511
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Antileptons	II	Muon antineutrino	$\bar{\nu}_\mu$	0		< 0.000002
Antileptons	III	Tau antineutrino	$\bar{\nu}_\tau$	0		< 0.000002

Gauge Bosons

Force	Force Carrier	Rest Mass (GeV/c²)	Charge	Relative Strength	Range (cm)	Spin	Color
Strong	Gluons	0	0	1	$< 10^{-13}$	1	Yes
Weak	W^+	80.4	+1	10^{-13}	$< 10^{-16}$	1	Neutral
	Z^0	91.2	0			1	
	W^-	80.4	-1			1	
Electromagnetic	Photons	0	0	10^{-2}	Infinite	1	Neutral
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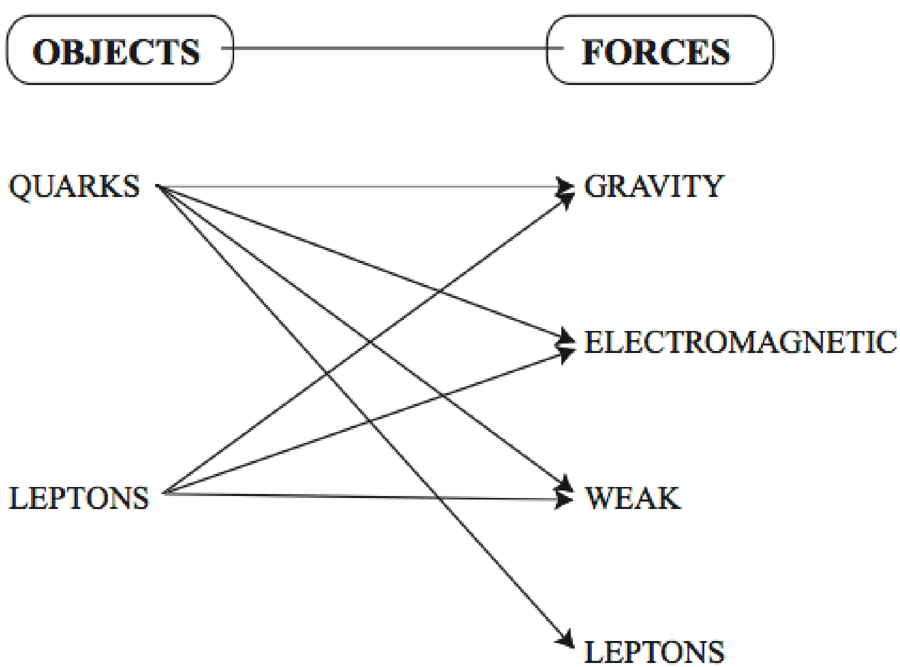
Legend

	I	← Generation
Name →	Up +2/3	← Charge
	r, g, b	← Color
Symbol →	u ~3	← Rest Mass (MeV/c²)



Answer Key

1. matter, antimatter
2. quarks, leptons
3. up, charm, top   down, strange, bottom
4. electron, muon, tau electron neutrino, muon neutrino, tau neutrino
5. the first letter of its name
6. u, d, t, c
7. μ□τ, ν,subscript,ν_e
8. up, down, charm, strange
9. +2/3, 3 MeV/c^2 -1/3, 115 MeV/c^2 +2/3, 175,000 MeV/c^2 -1, 0.511 MeV/c^2 -1, 1784 MeV/c^2 0, < 3□10^{-6} MeV/c^2
10. mass-energy equivalence
11. leptons, quarks
12. 3; two quarks will have a total charge of +1/3, +4/3, or -2/3.
13. Some of the possible combinations are: +1 (ucd, utb, ucs); -1 (dsb, dds, ddb); 0 (uds, cdb, tsb)
14. proton = uud, neutron = udd
15. electron, electron neutrino, yes
16. strong, gluons weak, W^+, W^-, Z^o electromagnetic, photons gravity, gravitons
17. W^+, W^-
18. weak
19. strong
20. gravity
21. strong

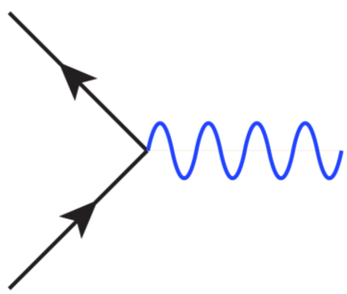
How to draw Feynman Diagrams
Adapted from Quantum Diaries[xvii]

For now, think of this as a game. You'll need a piece of paper and a pen/pencil. The rules are as follows (read these carefully):

You can draw two kinds of lines, a straight line with an arrow or a wiggly line:

You can draw these pointing in any direction.

You may *only* connect these lines if you have two lines with arrows meeting a single wiggly line.



Note that the orientation of the arrows is important! You *must* have exactly one arrow going into the vertex and exactly one arrow coming out.

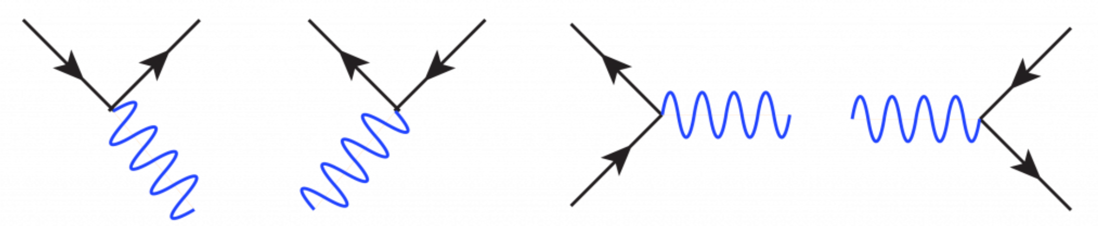
Your diagram should only contain connected pieces. That is every line must connect to at least one vertex. There shouldn't be any disconnected part of the diagram.

What does it all mean?
Now we get to some physics.
Each line in rule (1) is called a **particle**.
The vertex in rule (2) is called an **interaction**.
The rules above are an outline for a theory of particles and their interactions. We called it QED, which is short for **quantum electrodynamics**.
The lines with arrows are matter particles ("fermions").
The wiggly line is a force particle ("boson"), which, in this case, mediates electromagnetic interactions: it is the **photon**.

The diagrams tell a story about how a set of particles interacts.

We read the diagrams from left to right, so if you have up-and-down lines you should shift them a little so they slant in either direction. This left-to-right reading is important since it determines our interpretation of the diagrams.
Matter particles with arrows pointing from left to right are **electrons**.
Matter particles with arrows pointing in the other direction are **positrons** (antimatter).
In fact, you can think about the arrow as pointing in the direction of the flow of electric charge. As a summary, we our particle content is: e+ is a positron, e- is an electron, and the gamma is a photon… think of a gamma ray.
From this we can make a few important remarks:
The interaction with a photon shown above secretly includes information about the conservation of electric charge: for every arrow coming in, there must be an arrow coming out.

But wait: we can also rotate the interaction so that it tells a different story. Here are a few examples of the different ways one can interpret the single interaction (reading from left to right):

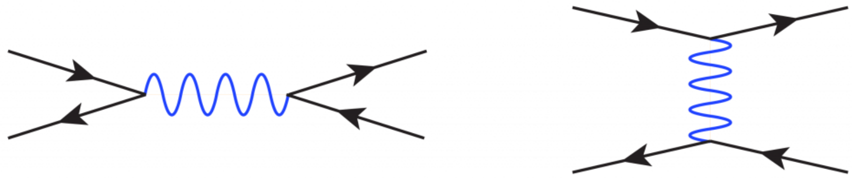


These are to be interpreted as: (1) an electron emits a photon and keeps going, (2) a positron absorbs a photon and keeps going, (3) an electron and positron annihilate into a photon, (4) a photon spontaneously “pair produces” an electron and positron.

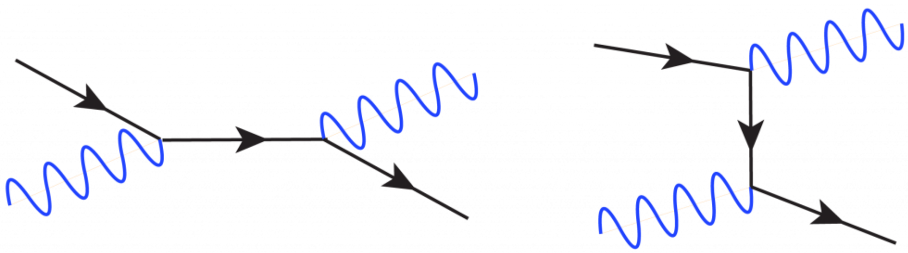
On the left side of a diagram we have “incoming particles,” these are the particles that are about to crash into each other to do something interesting. For example, at the LHC these ‘incoming particles’ are the quarks and gluons that live inside the accelerated protons. On the right side of a diagram we have “outgoing particles,” these are the things which are detected after an interesting interaction.

For the theory above, we can imagine an electron/positron. In these experiments an electron and positron collide and the resulting outgoing particles are detected. In our simple QED theory, what kinds of “experimental signatures” (outgoing particle configurations) could they measure? (e.g. is it possible to have a signature of a single electron with two positrons? Are there constraints on how many photons come out?)
So we see that the external lines correspond to incoming or outgoing particles. What about the internal lines? These represent **virtual** particles that are never directly observed. They are created quantum mechanically and disappear quantum mechanically, serving only the purpose of allowing a given set of interactions to occur to allow the

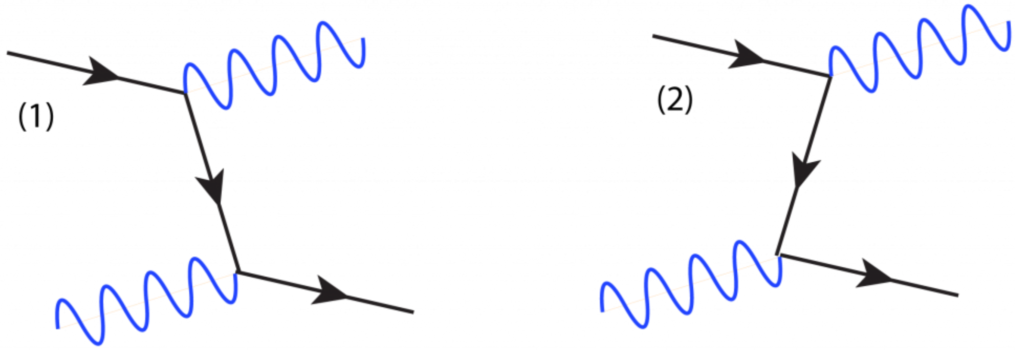
incoming particles to turn into the outgoing particles. Here is an example where we have a virtual photon mediating the interaction between an electron and a positron.



In the first diagram the electron and positron annihilate into a photon, which then produces another electron-positron pair. In the second diagram an electron tosses a photon to a nearby positron (without ever touching the positron). This creates a visual description of the idea that force particles are just quantum object that mediate forces. However, our theory treats force and matter particles on equal footing. We could draw diagrams where there are photons in the external state and electrons are virtual as shown below:



This is a process where light (the photon) and an electron bounce off each other and is called Compton Scattering. (1) that the electron emits a photon and then scatters off of the incoming photon, or (2) we can say that the incoming photon pair produced with the resulting positron annihilating with the electron to form an outgoing photon:



Anyway, this is the basic idea of Feynman diagrams. They allow us to write down what interactions are possible. There is a much more mathematical interpretation of these diagrams that produces the mathematical expressions that predict the probability of these interactions to occur, and so there is actually some rather complicated mathematics. However, just like a work of art, it's perfectly acceptable to appreciate these diagrams at face value as diagrams of particle interactions.

You should be able to draw Feynman diagrams for the following interactions;

1. Electron scattering
2. Beta decay
3. Pion decay
4. Electron positron annihilation
5. Pair production
6. Muon decay
7. Quark interactions
8. Photon -photon scattering

BUBBLE CHAMBER TRACK ANALYSIS

In this October, 1973 photo, 300 GeV protons are incident in the 30-inch hydrogen bubble chamber. The electron spirals are counter-clockwise. Therefore, clockwise deflection indicates a positive charge.

1. At point A we have a proton-proton interaction, which produces a π^+ and many other particles.

2. The π^+ moves to B, where it recoils from an elastic collision with a proton.

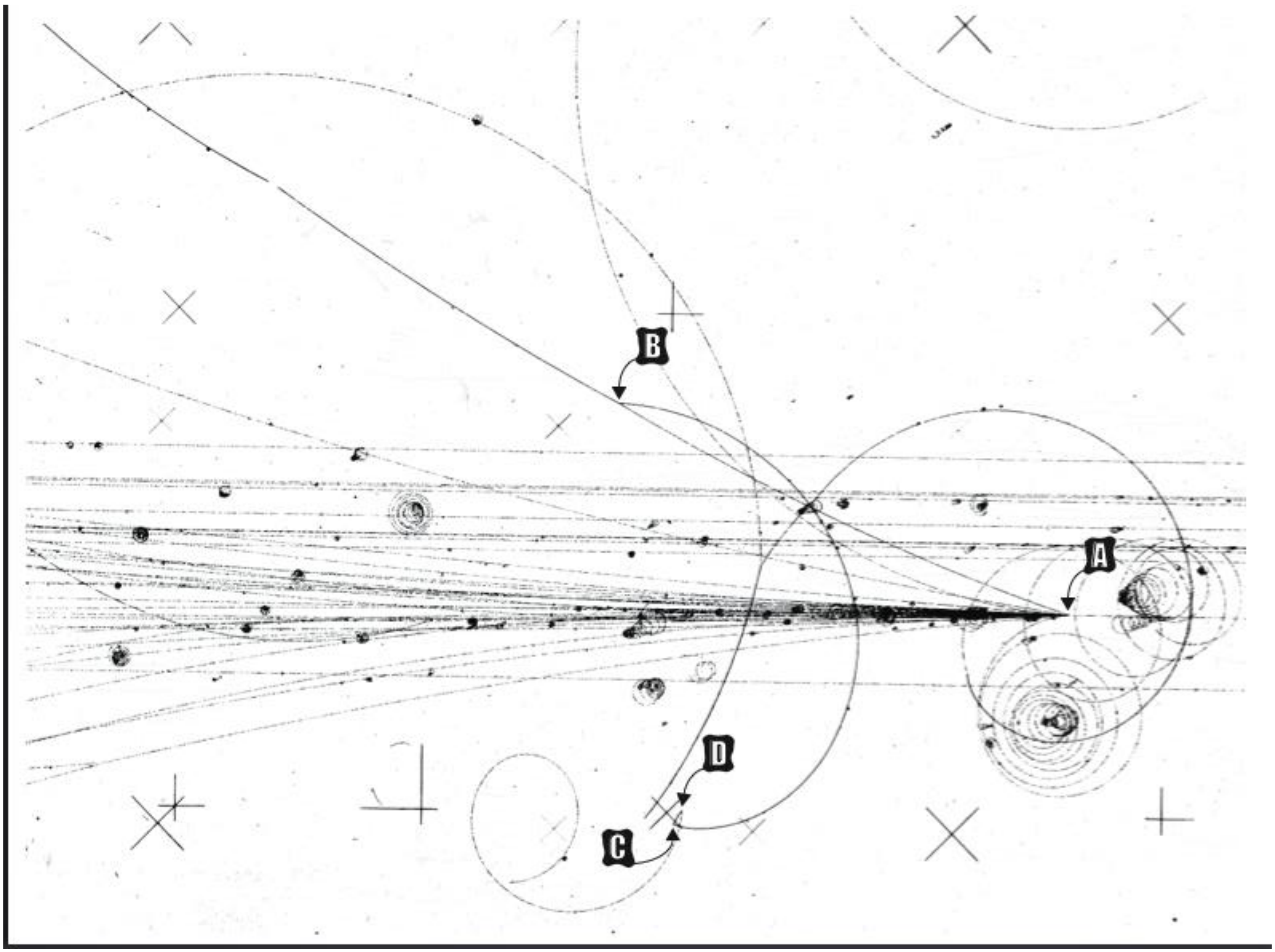
3. The recoiling π^+ slows as it travels to C. At C it decays according to the reaction:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

The lack of forward momentum beyond point C indicates μ the likelihood of a decay of a particle (π^+), which was essentially at rest.

4. The μ^+ produced at point C travels to point D. At D it decays according to the reaction:

$$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$$


A
B
C
D

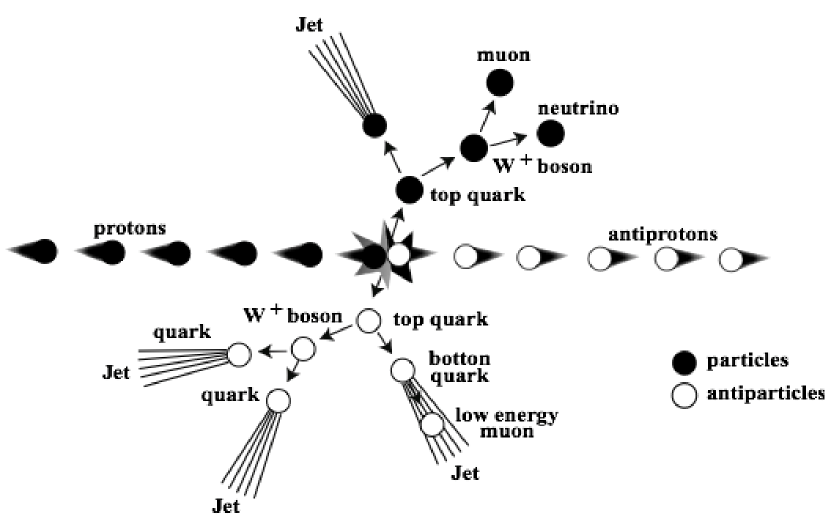
Determining the mass of the top quark using $E = mc^2$ Analysis of DZero Data from Fermi National Accelerator Laboratory Student Handout

Introduction: Today, you will use Einstein's famous equation and actual experimental data collected in 1995 from a special event that is two-dimensional rather than three-dimensional to determine the mass of the top quark. The top quark is the most massive quark ever discovered.

Procedure - Part One: You will be given a computer-generated plot of a collision between a proton and an antiproton. You will need to determine the momentum of each bit of debris that comes from the collision. Be sure to remember that momentum has direction.

The collision may be represented in a general way as shown below. Your plot will show this "top signature" but may not show the debris going in the directions shown here.

While this event looks complex at first, it may be summarized by noting that a proton and antiproton collide to create a top-antitop pair that exists for a very short time. Almost immediately the very massive top and antitop decay into the constituents that are known as their signature. These include four "jets" (large blasts of particles) that are the result of decays of W bosons and some less massive quarks. It is important to note that one of the jets will often contain a low energy or "soft" muon. Soft muons help identify jets as bottom quark jets. In addition, a muon and a neutrino come out as debris from the collision.



A Top-Antitop Quark Event from the DZero Detector at Fermilab

You will notice that there is no information given about the neutrino except the magenta tower indicating its direction on the color plot. While scientists can predict with confidence that it comes out of the collision, it cannot be detected very easily. Still, a careful consideration of the momenta before the collision and after the collision may give you a clue about how much momentum this particle has!

Procedure - Part Two: Make a momentum vector diagram to determine the momentum of the muon neutrino. Be sure to remember that the total momentum of the system must be zero, so any "missing" momentum must belong to the neutrino.

Question 1. What is the momentum of the missing neutrino?

Procedure - Part Three: It turns out that if you are careful about your choice of units, it is possible to equate momentum and energy in a way that is similar to the way mass and energy are related. Specifically, it may be shown that the momentum you measured above is the same numerical value as the energy or mass of the particle. In other words,

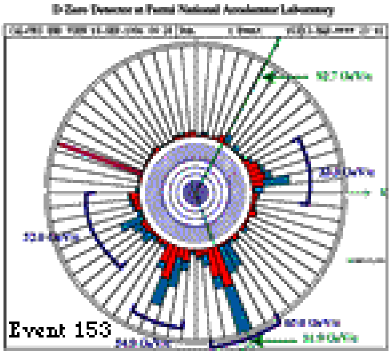
E (in GeV) = p (in GeV/c) = m (in GeV/c^2) This shows then that the total energy that came from the two top quarks that were formed is equal to the *numerical sum* of all the momenta discovered in the collision. Fill in all the momentum values from your color plot in the table below. Finally, add the measured value for the neutrino that you just

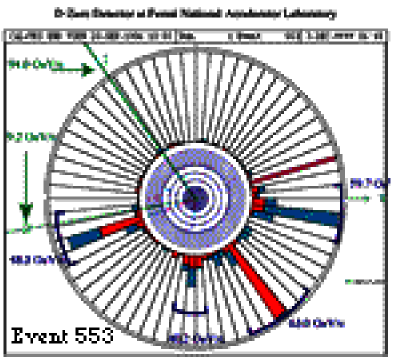
Momentum Energy or Mass	Jet 1	Jet 2	Jet 3	Jet 4	Muon	Soft Muon	Neutrino

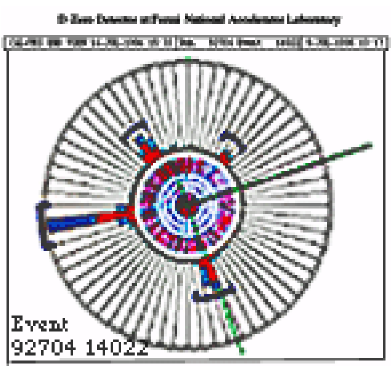
determined at the end of this table.

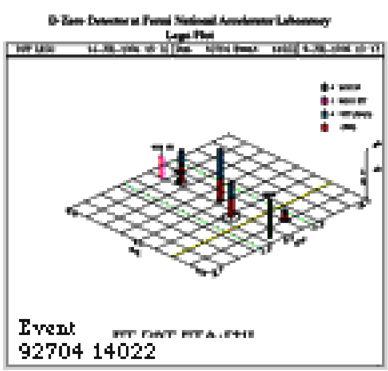
Question 2. What do you determine the mass of the top quark to be?

Go to the website for the Calculate the Top Quark Mass activity:
[xviii]*http://ed.fnal.gov/samplers/ hsphys/activities/top_quark_index.shtml*. Under "Data and Graphics," there are three views of one event called **Run 92704 Event 14022**. These are computer-generated pictures that represent the event discussed previously. To help visualize the event, you may wish to first look at the color plot labeled **Event 92704 14022 R-Z View**, which gives a perspective from the side of the detector. Next, look at the plot called **Event 92704 14022 End View.** Here the event is viewed in only two dimensions, as seen from the end of the detector. Finally, you may view the color plot called **Event 92704 14022 Lego**, which shows how the debris could be mapped if the **End View** were unwrapped starting at the "X" axis. Below are images from the web site


D-Zero Detector at Fermi National Accelerator Laboratory
Event 153


D-Zero Detector at Fermi National Accelerator Laboratory
Event 553


D-Zero Detector at Fermi National Accelerator Laboratory
Event
92704 14022


D-Zero Detector at Fermi National Accelerator Laboratory
Lego Plot
Event
92704 14022

Background Information for the Teacher
Energy, Mass and Momentum Calculations

In order for your students to find the mass of the top quark, they need to understand that their discovery of the missing momentum of the neutrino is crucial. This value gives them all they need to find the mass of the top quark. You will need to supply them with the following information.

A common relation in high-energy physics is the following: $E^2 - p^2 = m^2$

The reason energy, momentum and mass are shown as equal is actually due to the convention of choosing a system where the speed of light, c, is set equal to one. In this case, where particles are traveling with speeds of almost c, $E = mc^2$ becomes $E = m$ and $p = mv$ becomes $p = mc$ or $p = m$. This does change scale somewhat to be sure, but it allows for a simpler conversion between energy, mass and momentum.

In our particular case, it follows that one should write energy and momentum in terms of the mass of the top quark.

$E^2 - p^2 = (2m\ )^2\ t$

When one observes that the net momentum before the collision is the same as the momentum after and that value is zero, we write: or, taking the square root of both sides,

$E^2 = (2m\ )^2\ t$

$E = 2m_t$

Because almost all of the energy of the collision is the result of top and antitop decay, we simply add the energies of the four jets, the soft muon, the muon and the muon neutrino before dividing by the two tops (actually a top and an antitop quark) to obtain the mass of the most recently discovered quark.

Students will use the values they calculated for momentum (now as energy values) and incorporate their new value for the missing neutrino (in bold print below) before adding all the energies as scalars to find 2mt.

61.2 GeV + 7.3 GeV + 95.5 GeV + 58.6 GeV +

54.8 GeV + 17.0 GeV + **53.8 GeV** = 348.2 GeV

348.2 GeV/2 = 174.1 GeV, which is very close to the currently accepted value of about 175 GeV. As was indicated, the “missing momentum” may be found in a more careful analysis of the event as well as a better understanding of the event.

This relatively simple procedure may be repeated by your students in events generated by the Fermilab computers that were directed to simulate various collisions that would show this type of event.

Conclusion: The final result of this exercise should be that the students have gained some experience in using actual data to see how scientists analyze collisions. Further, your students will begin to understand that the latest pieces in the Standard Model puzzle have been assembled from the energy in the Fermilab collider. Mass does indeed come from energy as Einstein predicted.

This activity will build on your class’s understanding of vector addition and depend upon only a short particle physics explanation from the instructor. The goal of this activity is simple. Your students will determine the mass of the top quark.

Part I: Calculations of Momenta of Products of the Collision

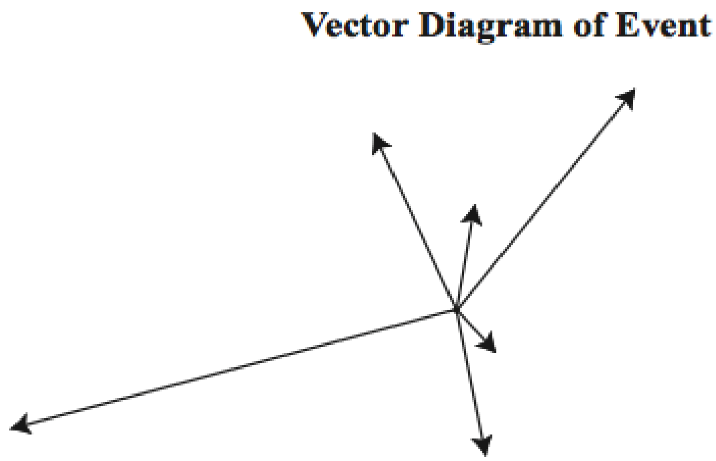
The momentum of each jet or particle was determined by computer and is printed on the color End View plots. These numbers will be used in creating a vector diagram of the debris that comes from the collision as students attempt to find the momentum of the “undetectable” neutrino.

Explain to the students that this is an exercise in momentum conservation. They are to determine the momentum of the “undetectable” neutrino by adding up the vectors with directions shown on the diagram and magnitudes indicated by the numbers listed. The result should be a value close to the same number the computer determines for each event. These values for the actual event and several computer-simulated events, each of which has an End View plot available at the website, are listed below for the teacher’s reference.

The direction of each neutrino may be verified by examining the color plots. Please be aware that the students will not all get the exact values given above nor will they get the precise directions shown on the pictures. This is due to their selection of the directions of the debris in the first place as well as effects introduced by problems similar to the one noted below.

Still, after vector diagrams are drawn by various groups of students, a reasonable value for the momentum of each of neutrino may be found.

An example of a possible vector diagram for event 14022 is shown below for the teacher’s convenience.



It is important to realize that this only works if the debris has no motion in the direction of the beams which we define as the z direction. The event takes place in a plane perpendicular to the axis of the proton and antiproton.

Resources

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[i] (International Baccalaureate Organization 2007)
[ii] (Gleiser 2012)
[iii] (International Baccalaureate Organization 2007)
[iv] (Tipler and Llewellyn 2008)
[v] (G. J. Neary 2016)
[vi] (Bardeen 2006)
[vii] ibid
[viii] ibid
[ix] (CERN 2016)
[x] (CERN The Standard Model 2016)
[xi] (Bardeen 2006)
[xii] ibid
[xiii] ibid
[xiv] (Pearson NCS 2016)
[xv] (International Baccalaureate Organization 2007)
[xvi] (CERN The Standard Model 2016)
[xvii] (Quantum Diaries 2010)
[xviii] *http://ed.fnal.gov/samplers/ hsphys/activities/top_quark_index.shtml*