FERMILAB-TM-1805

Topics in Modern Physics

Teacher Resource Materials

Elementary Particles

First Revision
August 1996

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LEON M. LEDERMAN

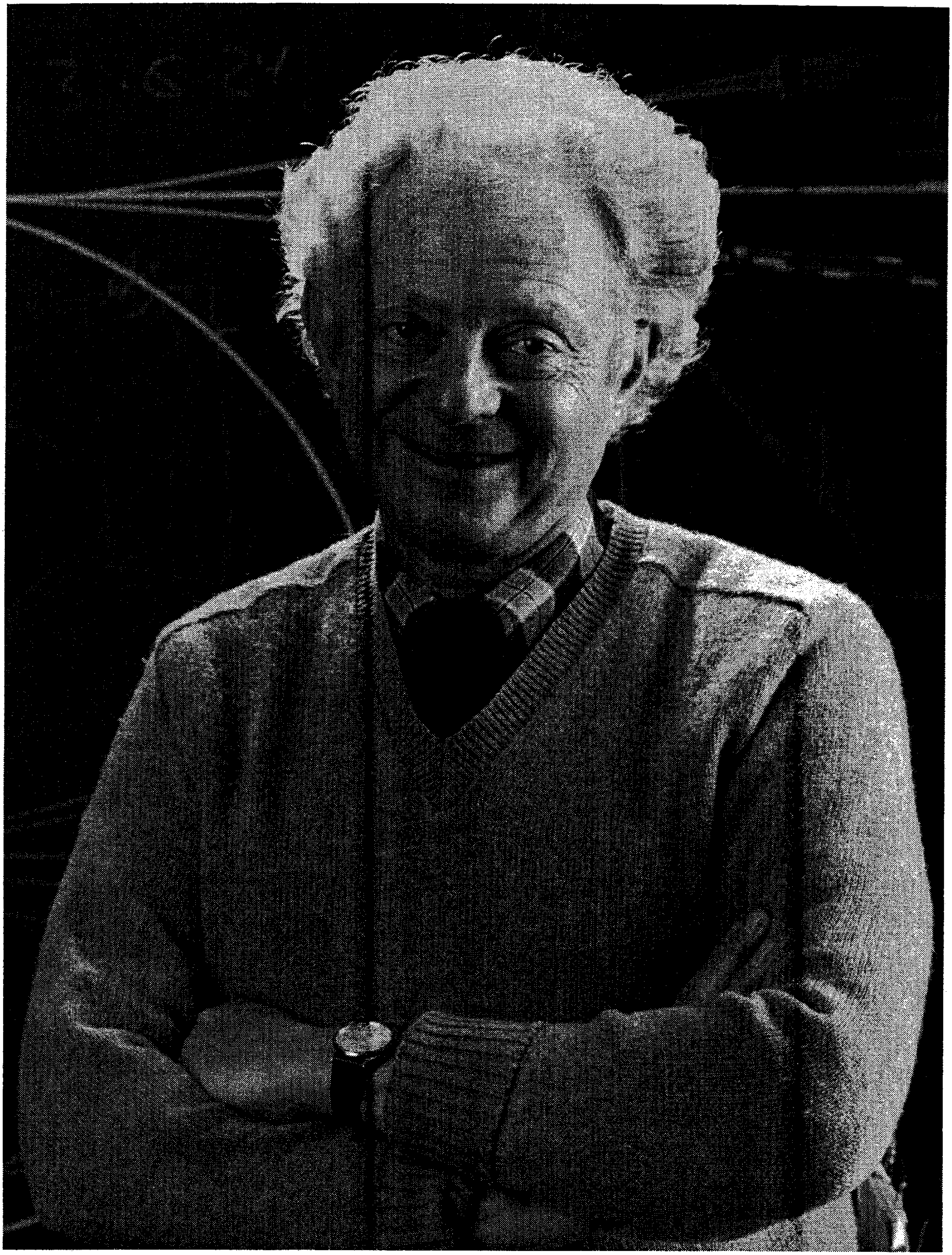
Leon M. Lederman, internationally known specialist in high-energy physics, is the director emeritus of Fermi National Accelerator Laboratory in Batavia, Illinois, and was the Eugene Higgins Professor at Columbia University. He has been associated with Columbia as a student and faculty member for more than thirty years, and he was director of Nevis Laboratories in Irvington, which was the Columbia physics department center for experimental research in high-energy physics from 1961 until 1979. With colleagues and students from Nevis he has led an intensive and wide ranging series of experiments which have provided major advances in the understanding of weak interactions. His research was based on accelerators at Nevis, Brookhaven, CERN, Berkeley, Rutherford, Cornell and Fermilab. His publication list runs to 200 papers. Lederman was the director of Fermi National Accelerator Laboratory from 1979 until 1989.

Lederman is a member of the National Academy of Sciences and has received numerous awards including the National Medal of Science (1965), the Elliot Cresson Medal of the Franklin Institute (1976), the Wolf Prize in Physics (1982), and the Nobel Prize in Physics (1988). He has served as founding member of the High-Energy Physics Advisory Panel and the International Committee for Future Accelerators.

LEON LEDERMAN ON SCIENCE EDUCATION

"I do not believe there is anything more important to the future of the nation than a population that is more science 'savvy' than we are now. From global climate change to genetic manipulation to the neuroscience's progress on the working of human minds, we have issues which have political, social and economic consequences of vast implications. For this we need science education K - 100!"

August 1996



INTRODUCTION

Before you is a set of resource materials that we hope will have a positive effect on modern physics education in the introductory physics classroom. The book is arranged with teacher materials accompanying each activity.

There are five major sections in this book.

Part I contains overheads that might be helpful to those teachers who choose to introduce certain topics to their students.

Part II contains activities that are fairly short in duration that could be used in a wide variety of ways.

Part III contains a very thorough class activity that would be appropriate in an involved treatment of particle physics.

Part IV contains information on computer programs, Internet resources, videocassettes, and printed material relating to one or more of our topics.

Part V contains color computer printouts that may be used in activities from Part II.

The loose-leaf format is intended to allow easy reproduction of teacher-selected materials. Permission is granted to copy for non-profit purposes all materials which have not been copyrighted elsewhere. Some teachers will choose to rearrange the various book sections. The loose-leaf format readily allows this. Ideally, teachers using this resource book will have the opportunity to participate in a workshop in order to familiarize themselves with the contents, purposes, and possible uses of the various materials.

Special thanks must be given to several parties who have been instrumental in helping to make this project a reality. Thanks go to the National Science Foundation, the Department of Energy Office of Research and Development, Fermi National Accelerator Laboratory, and the Friends of Fermilab. The encouragement and support of Marjorie Bardeen and Stanka Jovanovic are greatly appreciated. We thank former director Dr. Leon Lederman, present director Dr. John Peoples, the physicists and staff at Fermilab for their professional and technical assistance. Finally, thanks to the participants in the Conference on Teaching Modern Physics (see the list in Part III.) for their ideas and inspiration, and especially to the contributors whose work appears in this resource.

William Conway
Robert Grimm
Ward Haselhorst
JoAnn Johnson
Patrick LaMaster
James Ruebush
Walter Schearer
Brian Wegley

August 1996

Matter

Quarks

	I	II	III
Name	Up	Charm	Top
Symbol	u	c	t
Charge	+2/3	+2/3	+2/3
Color	R,G,B	R,G,B	R,G,B
Rest Mass	~ 5	~ 1500	~180000
Name	Down	Strange	Bottom
Symbol	d	s	b
Charge	-1/3	-1/3	-1/3
Color	R,G,B	R,G,B	R,G,B
Rest Mass	~ 8	~ 160	~ 4250

Leptons

	I	II	III
Name	Electron	Muon	Tau
Symbol	e	μ	τ
Charge	-1	-1	-1
Rest Mass	0.511	105.7	1777
Name	Electron Neutrino	Muon Neutrino	Tau Neutrino
Symbol	ν_e	ν_μ	ν_τ
Charge	0	0	0
Rest Mass	~ 0	~ 0	< 70

Antimatter

Quarks

	I	II	III
Name	Anti Up	Anti Charm	Anti Top
Symbol	$\bar{u}$	$\bar{c}$	$\bar{t}$
Charge	+2/3	+2/3	+2/3
Color	R,G,B	R,G,B	R,G,B
Rest Mass	~ 5	~ 1500	~180000
Name	Anti Down	Anti Strange	Anti Bottom
Symbol	$\bar{d}$	$\bar{s}$	$\bar{b}$
Charge	-1/3	-1/3	-1/3
Color	R,G,B	R,G,B	R,G,B
Rest Mass	~ 8	~ 160	~ 4250

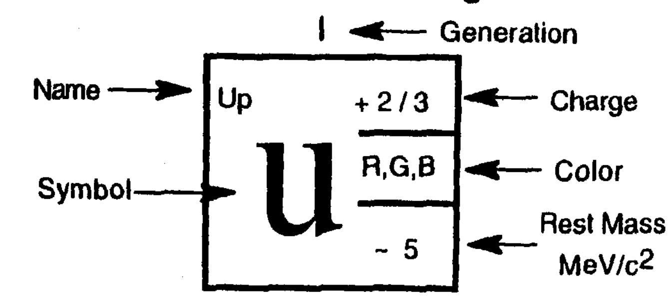
Leptons

	I	II	III
Name	Positron	Antimuon	Antitau
Symbol	e^+	$\bar{\mu}$	$\bar{\tau}$
Charge	-1	-1	-1
Rest Mass	0.511	105.7	1777
Name	Electron Antieutrino	Muon Antieutrino	Tau Antieutrino
Symbol	$\bar{\nu}_{e^+}$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$
Charge	0	0	0
Rest Mass	~ 0	~ 0	< 70

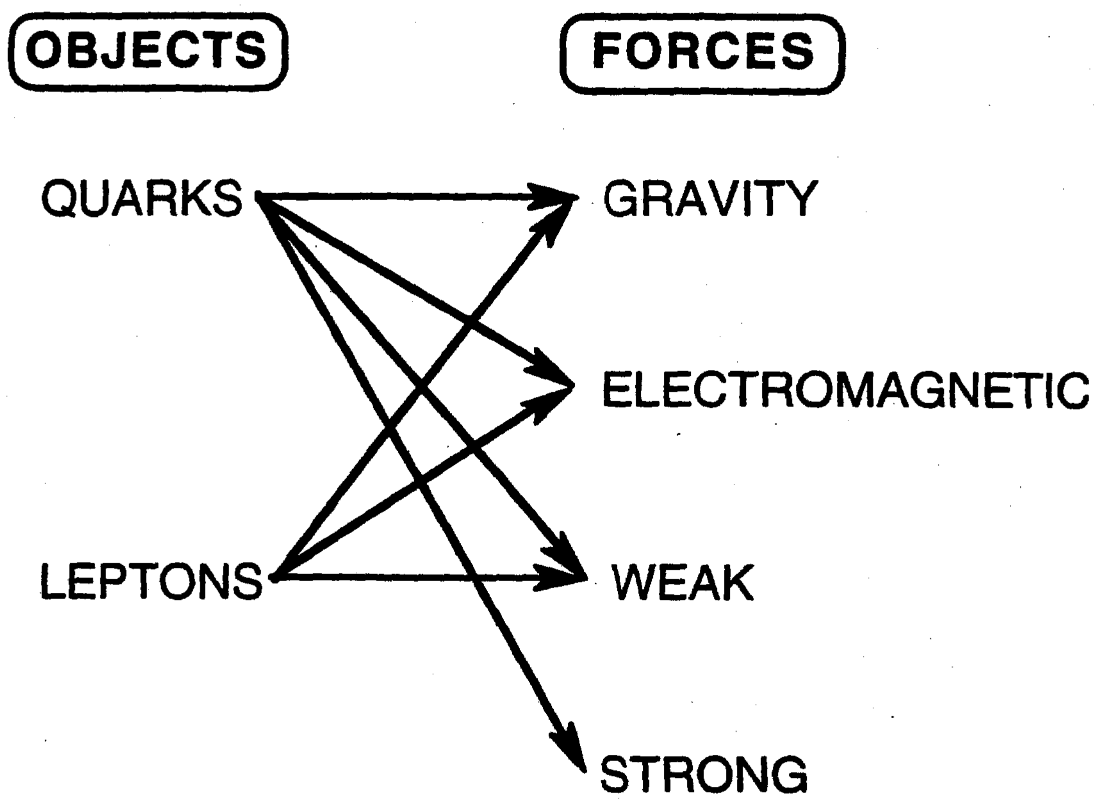
Gauge Bosons

Force	Force Carrier	Rest Mass $\frac{GeV}{c^2}$	Charge	Spin	Relative Strength	Range	Color
Strong	Gluons	0	0	1	1	$< 10^{-13}$ cm	Yes
Weak	W^+ W^- Z^0	81 81 93	+1 -1 0	1 1 1	10^{-13}	$< 10^{-16}$ cm	Neutral
Electro-Magnetism	Photons	0	0	1	10^{-2}	Infinite	Neutral
Gravity	Graviton	0	0	2	10^{-38}	Infinite	Neutral

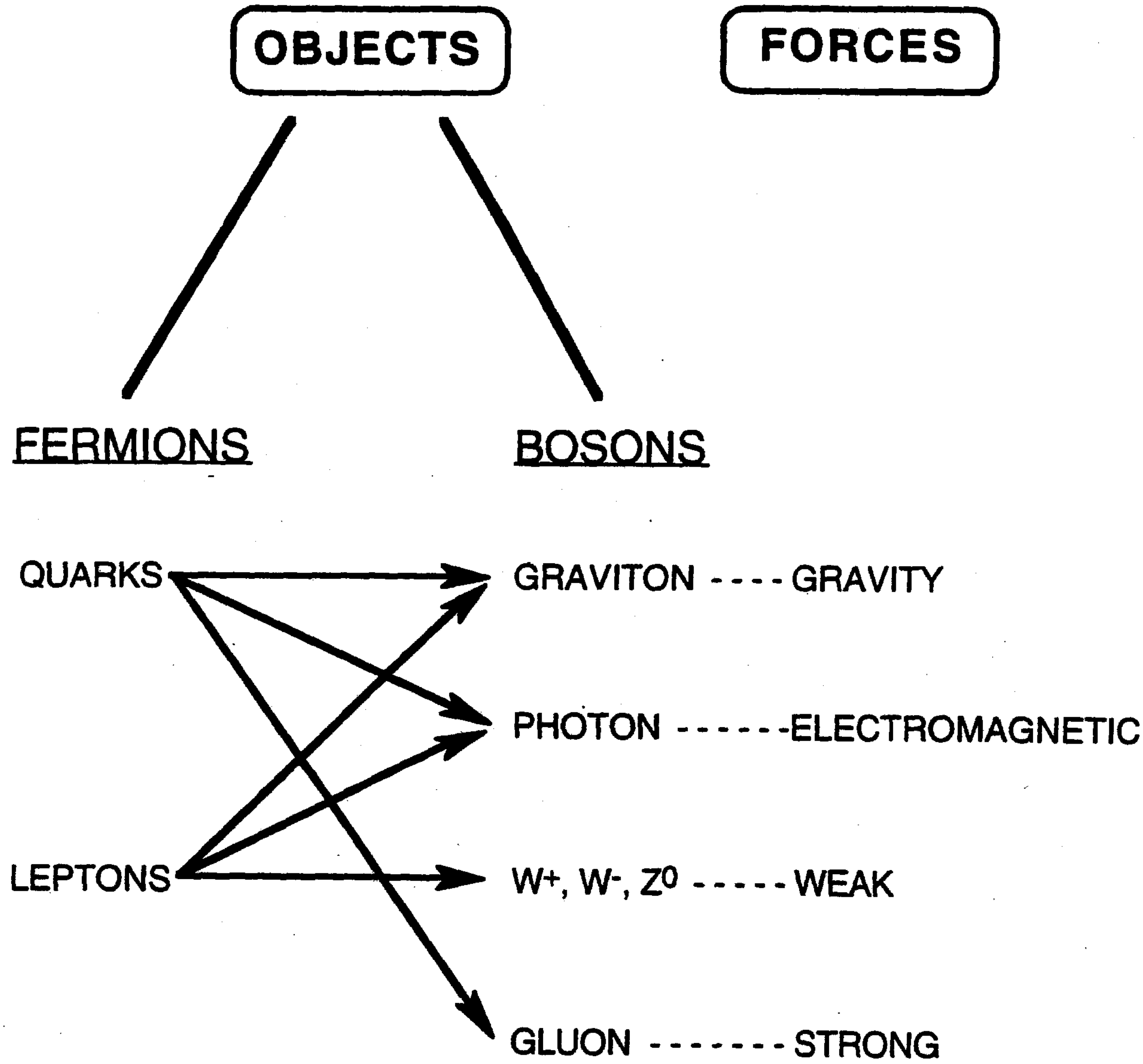
Legend

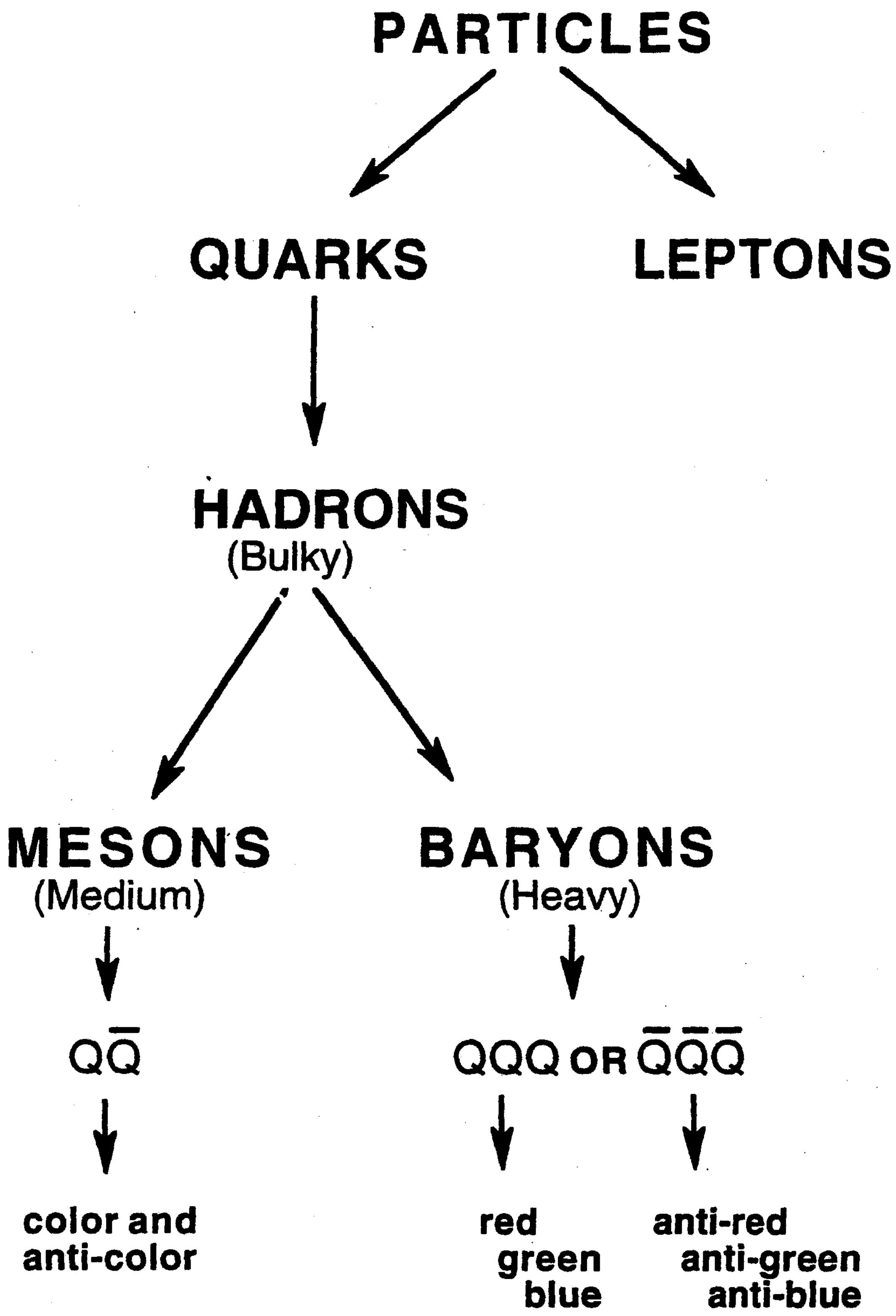


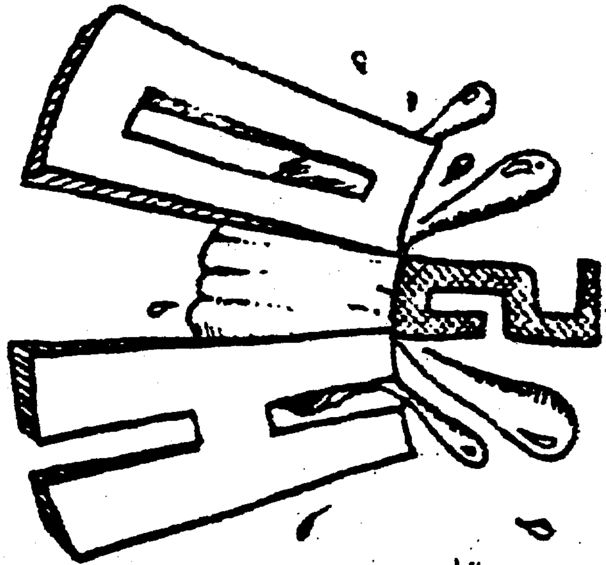
STANDARD MODEL

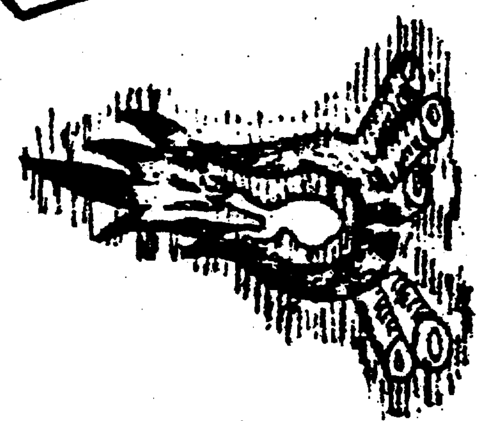


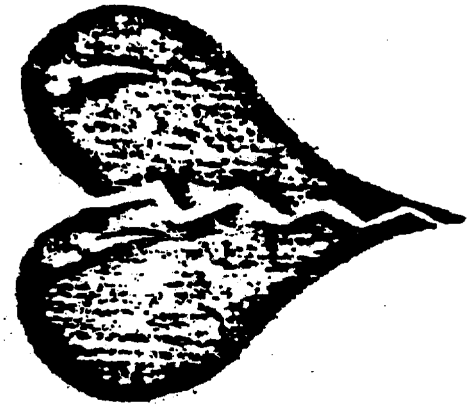
STANDARD MODEL

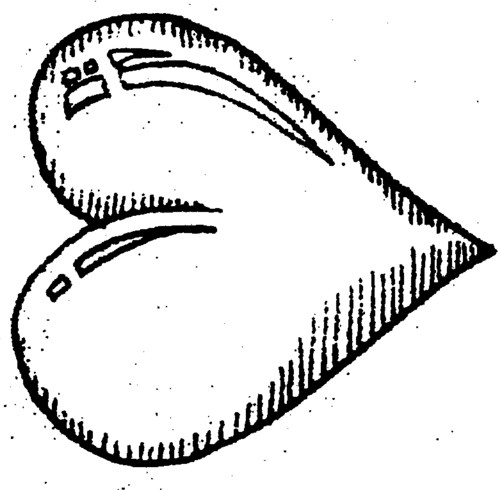



PARTICLES
QUARKS
LEPTONS
HADRONS
(Bulky)
MESONS
(Medium)
BARYONS
(Heavy)
Q$\bar{Q}$
QQQ OR $\bar{Q}\bar{Q}\bar{Q}$
color and anti-color
red green blue
anti-red anti-green anti-blue


H2O







Teacher Notes

An Explanation of Overheads

The previous five pages represent several ideas that are easily presented to students as an introduction to particle physics. The pages may be used as the teacher sees fit. They have been designed to allow the teacher a very free hand in explaining some of the basics of sub-nucleon physics.

Some notes on each of the pages follows.

Overhead One - Page 2 **The Standard Model Chart**

This chart lists the major players in The Standard Model. The six quarks that make up our world are listed under the heading "Matter." A similar listing for the "Antimatter" particles completes the major portion of the chart. These particles are only found in groups in nature.

Below the quarks, the lighter particles or Leptons are listed. These particles are found by themselves in nature.

Guage Bosons or those particles that are responsible for carrying the basic forces of nature are listed lower on the chart.

A great deal of information is included in this chart. The entire chart will make sense to one who completes the activity that begins on page 32 of this book.

Overhead Two - Page 3 **Objects and Forces Chart**

This chart shows the connections between objects or particles and the forces that exist in nature. An arrow indicates that a particular particle responds to a particular force.

Overhead Three - Page 4 **Objects, Bosons and Forces Chart**

This chart also shows the connections between objects or particles and the forces that exist in nature as well as the bosons that carry the forces. An arrow indicates that a particular particle responds to a particular force utilizing the bosons shown.

Overhead Four - Page 5 **Particle Classification Chart**

This chart shows the formation of various classifications of particles. The chart shows how quarks combine to create other classifications of particles. Notice that leptons are stable by themselves.

Overhead Five - Page 6 **The First Periodic Chart**

This whimsicle chart shows the "Earth, Air, Fire and Water" periodic chart first thought to be complete by the ancients. These things were thought to be unbreakable. Of course, anyone who thought that was the complete list had their heart broken with the discovery of elements, protons or any other intermediate steps or later steps that have been taken by scientists over the years.

Teacher Notes

HOW DOES THE UNIVERSE WORK?

A PUZZLE ANALOGY

Introduction: The ability to see relationships and patterns in nature and to develop these into theories is a necessary skill of the particle physicist. Using experimental evidence, or the lack thereof, the physicist can develop theories to answer the basic question, "How does the universe work?" To answer that question, students need to answer two other questions.

1. What are the basic objects?

2. What are the basic forces?

In order to understand the reasoning by which physicists begin to determine the answers to these questions, the puzzle on the following page is presented. The puzzle uses the analogy of the "observed" and "not observed" as seen in particle interactions. The puzzle presents the the same type of data to the student. However in the puzzle the questions become:

1. What are the shapes (basic objects) from which the observed figures are constructed?

2. What are the rules for connecting (basic forces) the shapes?

The student now is free to study both the "observed" and "not observed" figures in an attempt to answer the two questions. Ask students to support their theories with examples from both the "observed" and "not observed" areas. Can their shapes be further reduced to more basic shapes? Once students feel confident about the answer to question 1, they can proceed with the development of rules for question 2. Remind students that the rules must explain both the "observed" and "not observed" figures. It is these connecting rules which lead to some figures being observed while others are not observed. As much can be learned from considering what is not observed as from what is observed.

Discuss possible theories with the entire group of students. Is there more than one theory? Which is the best theory? Why?

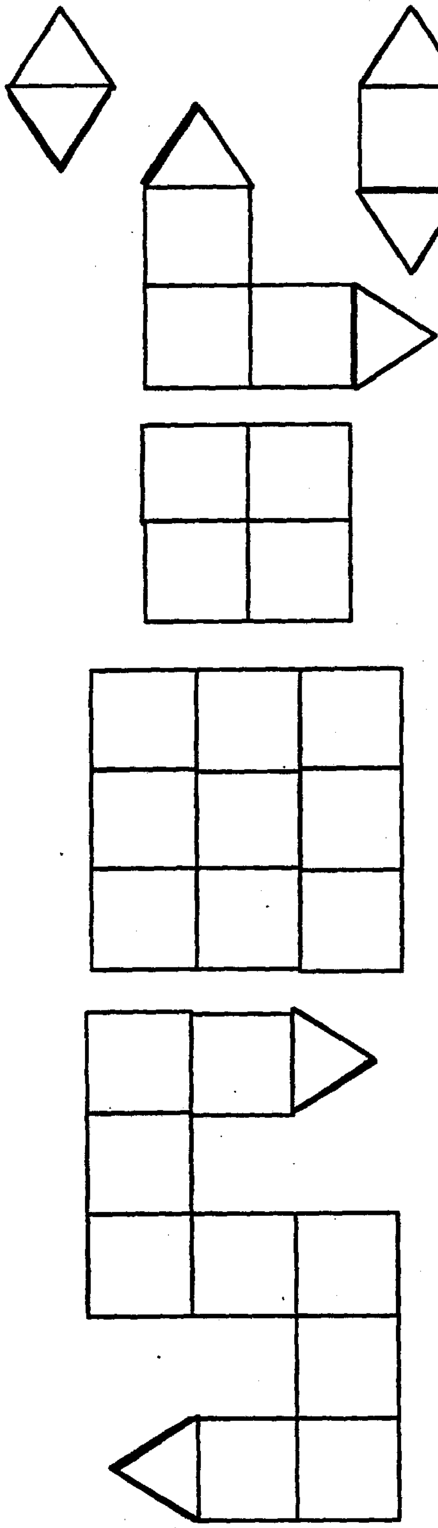
One possible solution is given on the next page. The basic shapes are triangles and squares. There are two connection rules. Triangles must connect on one, and only one, side. Squares must be connected on two, and only two, sides.

At this point it might be interesting to ask students to develop some additional "observable" figures, which follow the answers to the two basic questions. This is similar to the physicist looking for a previously unseen particle in an attempt to verify a theory.

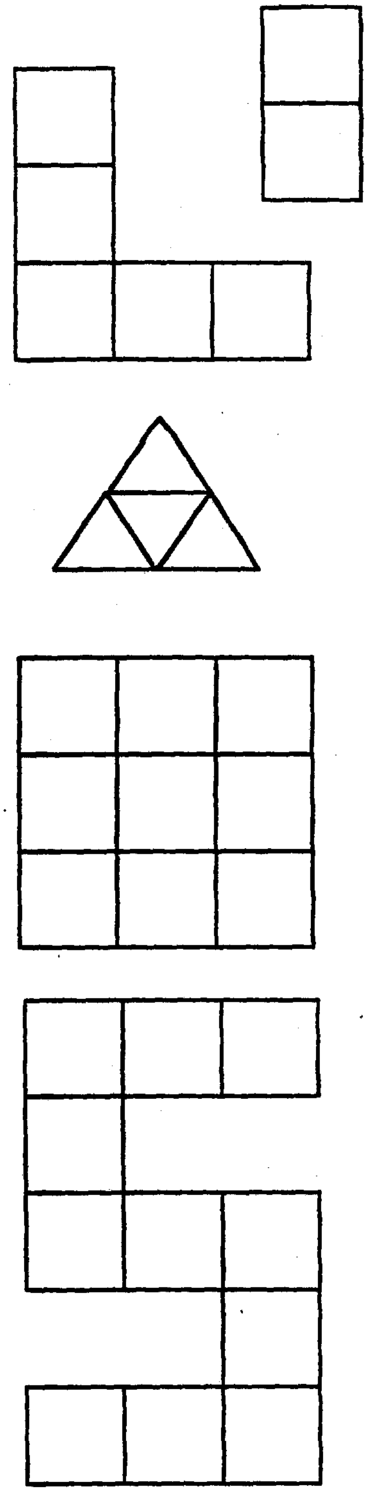
Puzzle adapted from Helen Quinn, "Of Quarks, Antiquarks, and Glue," The Stanford Magazine.

POSSIBLE PUZZLE SOLUTION

OBSERVED



NOT OBSERVED



Student Worksheet

HOW DOES THE UNIVERSE WORK?

A PUZZLE ANALOGY

Introduction: The ability to see relationships and patterns in nature and to develop these into theories is a necessary skill of the particle physicist. Using experimental evidence, or the lack thereof, the physicist can develop theories to answer the basic question, "How does the universe work?" To answer that question, you need to answer two other questions.

1. What are the basic objects?

2. What are the basic forces?

Procedure: In order to understand the reasoning by which physicists begin to determine the answers to these questions, the puzzle on the following page is presented. The puzzle uses the analogy of the "observed" and "not observed" as seen in particle interactions. Your job is to determine the "rules of the universe" through an analogy of finding the rules for this puzzle.

The figures on the left of the page are observed, while the figures on the right have not been observed. The puzzle involves these two questions:

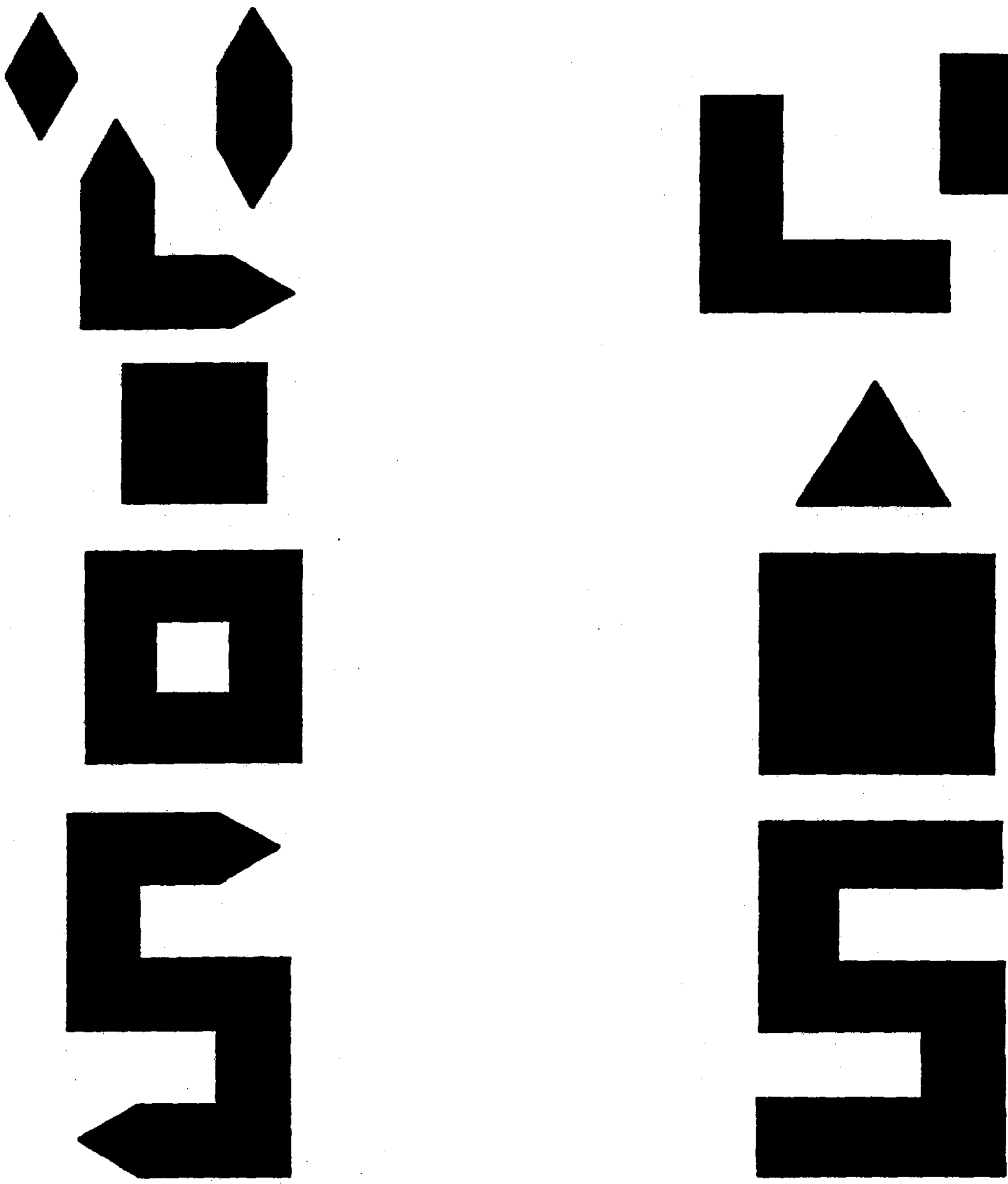
1. What are the shapes (basic objects) from which the observed figures are constructed?

2. What are the rules for connecting (basic forces) the shapes?

The same two shapes can be used to form both the "observed" and "not observed" figures. It is the connecting rules which lead to some figures being observed and others not being observed. Remember that you can learn as much from considering what is not observed (white figures) as from what is observed (black figures).

HOW DOES THE UNIVERSE WORK?

OBSERVED NOT OBSERVED



Teacher Notes

$E=mc^2$ Student Activity

Introduction: Einstein's celebrated equation is verified daily in particle accelerators around the world. Physicists go about the business of converting energy into mass almost as commonly as high school students flip through channels on the television. Still, this revolutionary idea is not often treated as a classroom activity simply because it seems to be so difficult to convey in a "hands on" manner. We are able to do just that using a special event from Fermilab's D0 Detector. Most events analyzed by the physicists are more complex than this event nature serendipitiously supplied.

The idea that mass and energy are interchangeable is essential to those interested in understanding how two top quarks (actually a top and an antitop) are created from the collision of two protons (actually a proton and an antiproton). The experiment might be thought of as the collision of two ping-pong balls resulting in the production of two ball bearings of the same size but **considerably** greater mass. The highly energetic protons collide to create top quarks of about 180 times the mass of the protons. The **energy** of the less massive protons is converted into the huge **mass** of the resultant top quarks.

Perhaps the conversion between energy and mass makes more sense when one considers that the proton and antiproton pair were traveling so close to the speed of light that together they had about 1.8×10^{12} eV worth of energy to work with. This energy then becomes the mass of the newly discovered quarks.

Scientist measure the energy of these subatomic particles in units of electron volts. Electron volts are units of energy just as Joules are units of energy. They measure their mass in units of electron volts/c^2, energy divided by c^2 where c = the speed of light. Here, we are talking about mass and using the fact that $E = mc^2$ to write mass in units of eV/c^2. To simplify the units, physicists use a unit called a GeV (a giga electron volt, pronounced two ways, "gee ee vv" or "jev." 1 GeV equals 10^9 eV.

Scientists at Fermilab first discovered the top quark in 1995 when they collided protons and antiprotons with energies of 900 GeV/c^2. The masses of these particles scientists measured are shown below.

Mass of Proton	9.38×10^8 eV/c^2	.938 GeV/c^2
Mass of Top Quark	1.75×10^{11} eV/c^2	175 GeV/c^2

To help the students understand this idea, this activity examines the fingerprint of a top/antitop collision that took place in the D-Zero Detector at Fermilab on July 9, 1995. An artist's rendition of the event is one of the color plates at the end of the book. A smaller, black and white version is included with the student activity page.

Make an overhead of this event to show the students what the production of a top and an antitop quark might look like if one were to see it in the center of the Fermilab accelerator. It is important to point out that the top and antitop quarks are actually very short-lived particles. They quickly decay into daughter particles and then in turn into "granddaughter" and "great granddaughter" particles. It is these offpsring that are actually detected by the scientists at Fermilab.

This event shows that the top and antitop quarks (shown as t and t-bar respectively) are never actually directly detected because they decay so rapidly into four "jets" (large blasts of particles) and a muon (green) and a neutrino (magenta), shown in the upper right of the picture.

This may appear first to be complex. but the mass of the top is easy to calculate from a computer-generated plot of the same event taken from the D-Zero detector.

Teacher Primer

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.

At the back of this book 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 **CAL+TKS R-Z VIEW** which gives a perspective from the side of the detector. Next, look at the plot called **CAL+TKS 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 **DST LEGO** which shows how the debris could be mapped if the **END VIEW** were unwrapped starting at the "X" axis.

Once you are familiar with the three views, you should focus attention on the **CAL+TKS END VIEW.** This view is most similar to the artist's drawing and will be the working document for this activity. Notice the four blue and red "jets" which are the four jets shown on the artist's picture of the event above. You will also notice a solid green line which represents the muon's track. If you look closely at the jet near the bottom of the picture, you will also see a green dotted line. This is a "soft muon" that is hidden in a jet. Also notice that all of the momenta have been measured and are written on the plot.

You will also see that the computer has calculated the energy of the neutrino and drawn it on the diagram in magenta. Neutrinos are not detectable in most cases, so their existence is found by looking at the total momentum of the system in a collision though the momenta of the particles are far from zero. The total momentum is equal to zero before and after the collision. The process of finding the missing momentum is what your students will do to determine the mass of the top quark. Notice that the momentum for this particle is not included on the picture.

Teacher Instructions For Classroom Presentation

Show the students the artist's picture of the event followed by the three color plots just mentioned. As the complexity of the event might be confusing the first time through, all of this activity will focus only on the **END VIEW**.

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 are listed below for the teacher's reference.

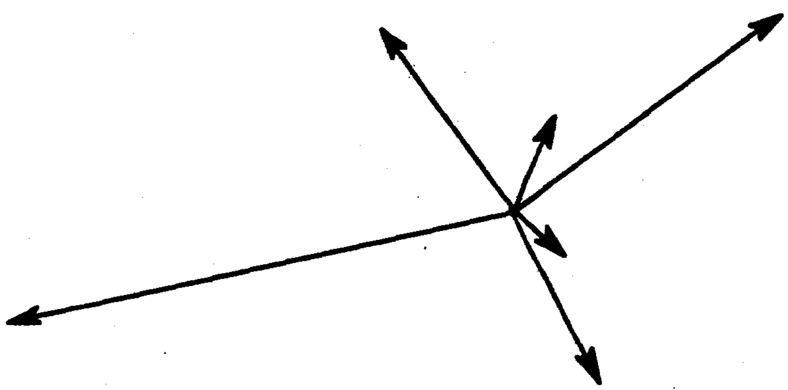
Actual Event	14022	momentum of neutrino	53.9 GeV/c
Computer Simulated Event	26	momentum of neutrino	76.1 GeV/c
Computer Simulated Event	153	momentum of neutrino	43.6 GeV/c
Computer Simulated Event	553	momentum of neutrino	45.3 GeV/c

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[2].

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.

Vector Diagram of the Event



[2] It is important to realize that this only works if the debris has no motion in the z direction. The event takes place in a plane perpendicular to the axis of the proton and anti-proton. The third color plot labeled **DST LEGO** shows that Mother Nature was indeed kind in giving us this type of event. Notice that all of the tracks happen to lie close to the ETA = 0.0 axis. This allows us to approximate this as a two-dimensional problem. You will also see that there is some "noise" seen on the computer plot. This will adversely affect your vector diagram and represents the uncertainty that is present in any experiment.

Background Energy, Mass and Momentum Calculations for the Teacher

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. In all honesty, much of this material is beyond the scope of high school physics, (and many college courses as well), but the leap is not so great that it cannot be done. Perhaps a bit of faith is needed here. The teacher is certainly the best judge.

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.

$$E^2 - p^2 = (2m_t)^2$$

When one observes that the net momentum before the collision is the same as the momentum after and that value is zero, we write:

$$E^2 = (2m_t)^2$$

or, taking the square root of both sides,

$$E = 2m_t$$

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 $2m_t$.

61.2 GeV + 7.3 GeV + 95.5 GeV + 58.6 GeV +
54.8 GeV + 17.0 GeV + **53.9 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 machine which could reduce the noise detected in the color plot.

This relatively simple procedure may be repeated by your students in events generated by the

Fermilab computers that were directed to try various collisionsthat 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 last 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.

Student Worksheet

$E=mc^2$ Used in the Creation of the Most Massive Quark Yet Discovered!

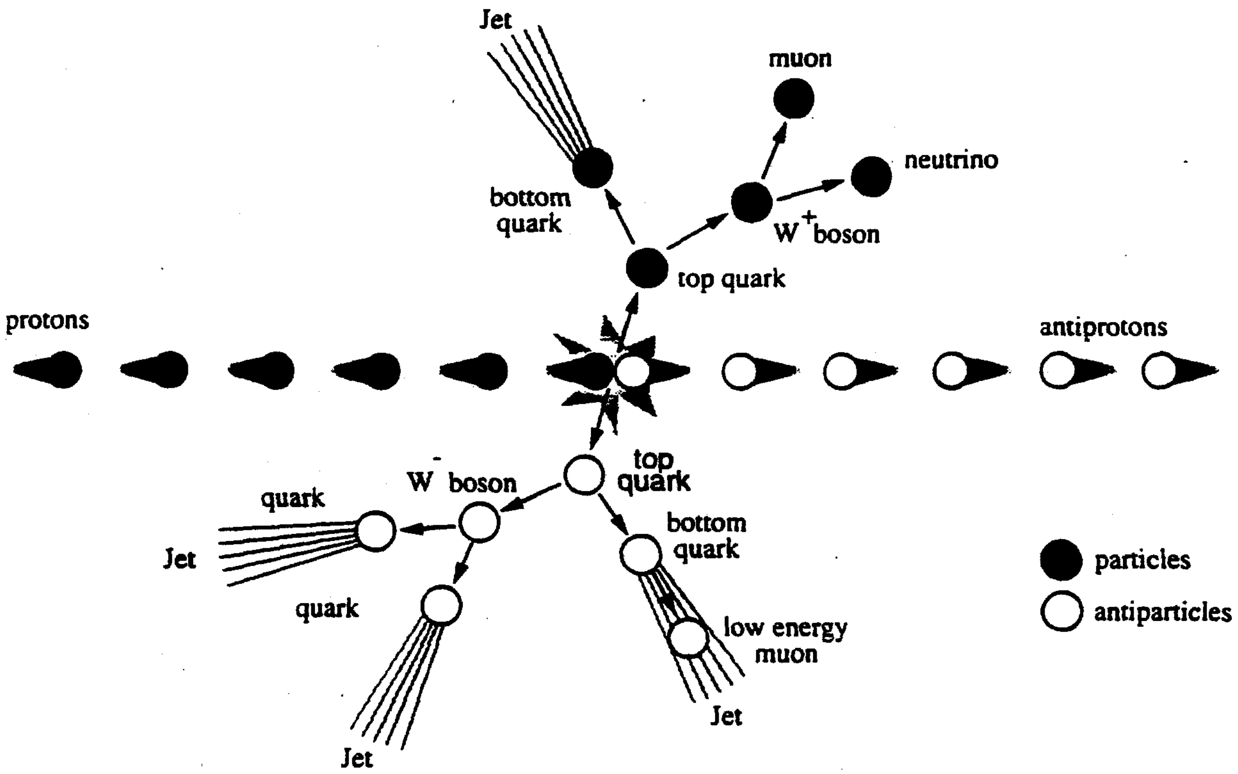
Analysis of D-Zero Data From Fermi National Accelerator Laboratory

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 exist 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 D-Zero 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 One: 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 Two: 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,

$$E \text{ (in GeV)} = p \text{ (in GeV/c)} = m \text{ (in GeV/}c^2\text{)}$$

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 determined at the end of this table.

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

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

Teacher Notes

FUNDAMENTAL UNITS

THE STANDARD MODEL OR THE MILLIKAN EXPERIMENT

Introduction: The Millikan Experiment and The Standard Model both require that students recognize that charge and matter are observed in discrete units. This activity can be used as an introduction to either of these topics.

Discussion: An understanding of the nature of fundamental particles helps students recognize both the complexity and simplicity of nature. Just as all the words in the English language are combinations of subsets of 26 letters, atomic physics showed that atoms of the many elements are combinations of three particles - the proton, neutron, and electron. As the number of "elementary particles" identified in cosmic ray showers and other high-energy interactions proliferated, some began to believe they were complex, composite particles created from a few, more fundamental particles. This activity will help students identify common elements of their "atoms" and also suggest that what is determined to be fundamental indeed has a substructure - an introduction to The Standard Model.

Activity: Using standard-size index cards place them in multiples of three into a number of standard-size envelopes. For example, for a class size of 25 students, prepare envelopes as follows.

# of envelopes	# of index cards per envelope
42	3
52	6
42	9
40	12
30	15
28	18
16	21
250	

Mix up the prepared envelopes and distribute 10 to each student. Each envelope may be used to represent a "particle" as identified in some high-energy reaction. Have the students mass their "particles" and share this information on a class data chart, or enter into a computer graphing program. (A student worksheet follows for use if you are not using a computer graphing program.) The use of top-loading analytical balances, with rounding to the nearest 0.1g, will greatly speed the data collection process. Examine the graph and note similarities in masses. Group and regraph the data, note that all differences occur in some "fundamental" unit, i.e., the mass of three index cards. After students have predicted the mass of the "fundamental particle," discuss how you might investigate if this fundamental particle itself might have an internal structure. Suggest that if greater energies were used to look inside the particle one might discover its structure. When an envelope is opened, students will notice that what they had assumed to be the "fundamental" unit was in fact itself made of three smaller particles just as the proton and neutron each have an internal structure made of three quarks.

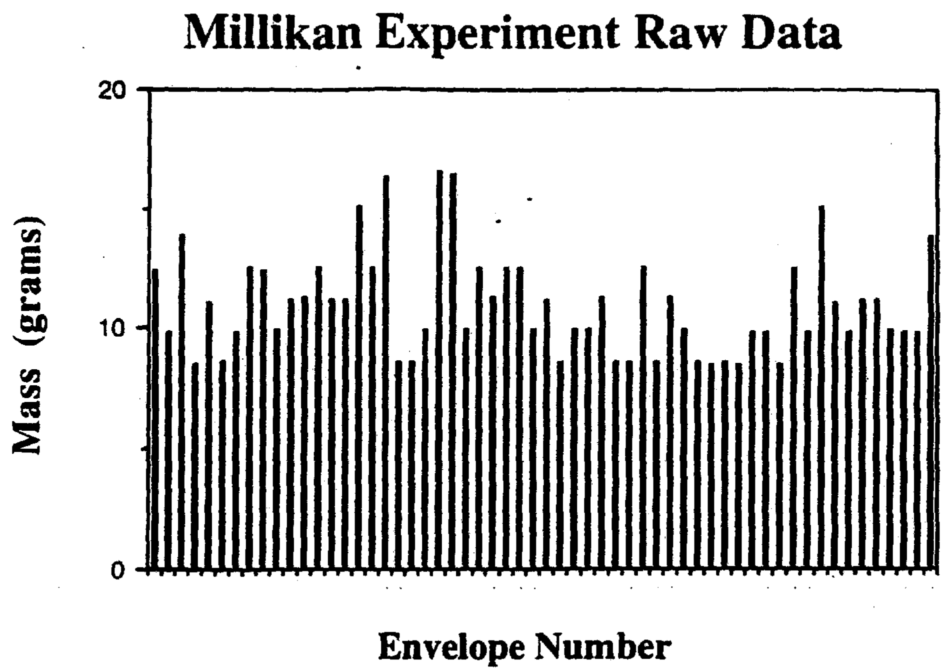
Some helpful data and graphs follow.

FUNDAMENTAL UNIT RAW DATA

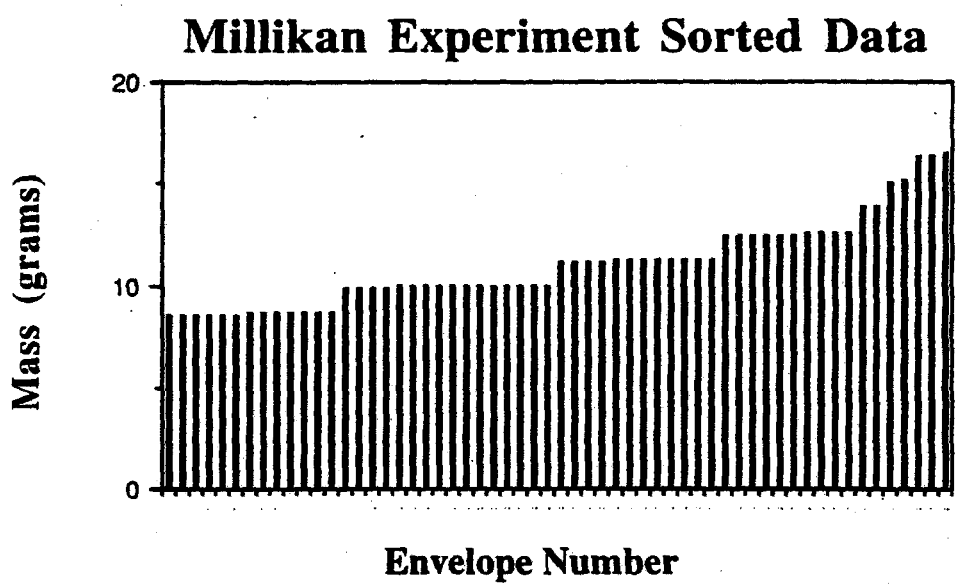
ENVELOPE	MASS (g)	ENVELOPE	MASS (g)
1	12.40	59	12.52
2	9.85	60	8.61
3	13.82	61	8.56
4	8.49	62	12.49
5	11.09	63	12.41
6	8.61	64	15.09
7	9.88	65	11.22
8	12.52	66	11.23
9	12.39	67	12.44
10	9.98	68	9.80
11	11.22	69	8.59
12	11.23	70	8.58
13	12.46	71	11.19
14	11.12	72	9.86
15	11.18	73	9.88
16	15.04	74	12.52
17	12.50	75	8.57
18	16.30	76	9.93
19	8.59	77	11.10
20	8.60	78	12.49
21	9.94	79	12.43
22	16.49	80	9.87
23	16.39	81	9.86
24	9.92	82	11.25
25	12.47	83	12.44
26	11.23	84	8.57
27	12.49	85	11.11
28	12.53	86	9.80
29	9.90	87	15.09
30	11.14	88	13.76
31	8.63	89	16.40
32	9.94	90	8.55
33	9.91	91	11.11
34	11.24	92	9.88
35	8.64	93	11.20
36	8.55	94	8.53
37	12.48	95	8.63
38	8.58	96	11.18
39	11.23	97	11.18
40	9.89	98	12.43
41	8.56	99	11.16
42	8.53	100	11.17
43	8.58	101	11.26
44	8.51	102	12.50
45	9.84	103	8.60
46	9.86	104	12.40
47	8.54	105	12.41
48	12.46	106	9.85
49	9.83	107	13.82
50	15.11	108	8.50
51	11.10	109	9.87
52	9.87	110	16.37
53	11.20	111	11.16
54	11.22	112	8.60
55	9.92	113	8.60
56	9.87	114	16.45
57	9.88	115	15.05
58	13.82	116	12.57

FUNDAMENTAL UNIT SORTED DATA

ENVELOPE	MASS (g)	ENVELOPE	MASS (g)
1	8.49	59	8.50
2	8.51	60	8.53
3	8.53	61	8.55
4	8.54	62	8.56
5	8.55	63	8.57
6	8.56	64	8.57
7	8.58	65	8.58
8	8.58	66	8.59
9	8.59	67	8.60
10	8.60	68	8.60
11	8.61	69	8.60
12	8.63	70	8.61
13	8.64	71	8.63
14	9.83	72	9.80
15	9.84	73	9.80
16	9.85	74	9.85
17	9.86	75	9.86
18	9.87	76	9.86
19	9.87	77	9.87
20	9.88	78	9.87
21	9.88	79	9.88
22	9.89	80	9.88
23	9.90	81	9.93
24	9.91	82	11.10
25	9.92	83	11.11
26	9.92	84	11.11
27	9.94	85	11.16
28	9.94	86	11.16
29	9.98	87	11.17
30	11.09	88	11.18
31	11.10	89	11.18
32	11.12	90	11.19
33	11.14	91	11.20
34	11.18	92	11.22
35	11.20	93	11.23
36	11.22	94	11.25
37	11.22	95	11.26
38	11.23	96	12.40
39	11.23	97	12.41
40	11.23	98	12.41
41	11.24	99	12.43
42	12.39	100	12.43
43	12.40	101	12.44
44	12.46	102	12.44
45	12.46	103	12.49
46	12.47	104	12.49
47	12.48	105	12.50
48	12.49	106	12.52
49	12.50	107	12.52
50	12.52	108	12.57
51	12.53	109	13.76
52	13.82	110	13.82
53	13.82	111	15.05
54	15.04	112	15.09
55	15.11	113	15.09
56	16.30	114	16.37
57	16.39	115	16.40
58	16.49	116	16.45



Millikan Experiment Raw Data
20
10
0
Mass (grams)
Envelope Number



Millikan Experiment Sorted Data
20
10
0
Mass (grams)
Envelope Number

Student Worksheet

Fundamental Units

Introduction: An understanding of the nature of fundamental particles helps students recognize both the complexity and simplicity of nature. Just as all the words in the English language are combinations of subsets of 26 letters, atomic physics showed that atoms of the many elements are combinations of three particles - the proton, neutron, and electron. As the number of "elementary particles" identified in cosmic ray showers and other high-energy interactions proliferated, some began to believe they were complex, composite particles created from a few, more fundamental particles.

Procedure:

1. You will be given a number of envelopes. **Do <u>not</u> open the envelopes!** Measure the mass of each envelope to the nearest 0.1 gram and record the mass below and on the board.

2. Record the masses of all the envelopes from your class.

3. List all of the envelope masses in ascending order. Envelope #1 will be the lightest.

4. Construct a bar graph of envelope # (horizontal axis) versus envelope mass.

5. What do you notice about the envelope masses on the finished graph?

6. List the "average" mass for each of the envelope "types."

7. What is the mass difference between the successive averages found in step 6?

8. What does this difference represent? Explain.

Teacher Notes

A Laboratory Exercise in Indirect Measurement

Introduction: Modern physics depends heavily on indirectly determining physical properties of objects. The following activity may help convince students that indirect determinations are important methods of obtaining accurate information. This exercise can be used as an introduction to a discussion of the Rutherford model of the atom. This activity simulates an experiment in particle physics where a target material would be bombarded by high-speed particles and the collisions studied. It gives students a chance to use a "Monte Carlo" technique.

Problem: Determine the radius of a single target circle indirectly.

Procedure: Use copies of either of the circle sets on the following pages. Have students place the circled paper on the floor, face down over a sheet of carbon paper. Working in pairs, have students drop marbles or ball bearings from head height so that they hit the paper within the marked boundaries. The sphere must be caught after the first bounce. Repeat this at least 100 times. It may be more convenient to drop the marbles from just above the paper; however, one should then take care to distribute the hits as randomly as possible over the entire target area.

Analysis: Have students count the total number of dots on the paper within the marked rectangular boundaries (hits), as well as the number of dots which are completely within a circle (circle hits). Determine the total area of the paper within the marked boundaries (rectangular area), and count the total number of circles on the paper. If we have uniform circles and a random distribution of hits, then we can assume:

$$\frac{\text{circle hits}}{\text{hits}} = \frac{\text{area of all circles}}{\text{rectangular area}}$$

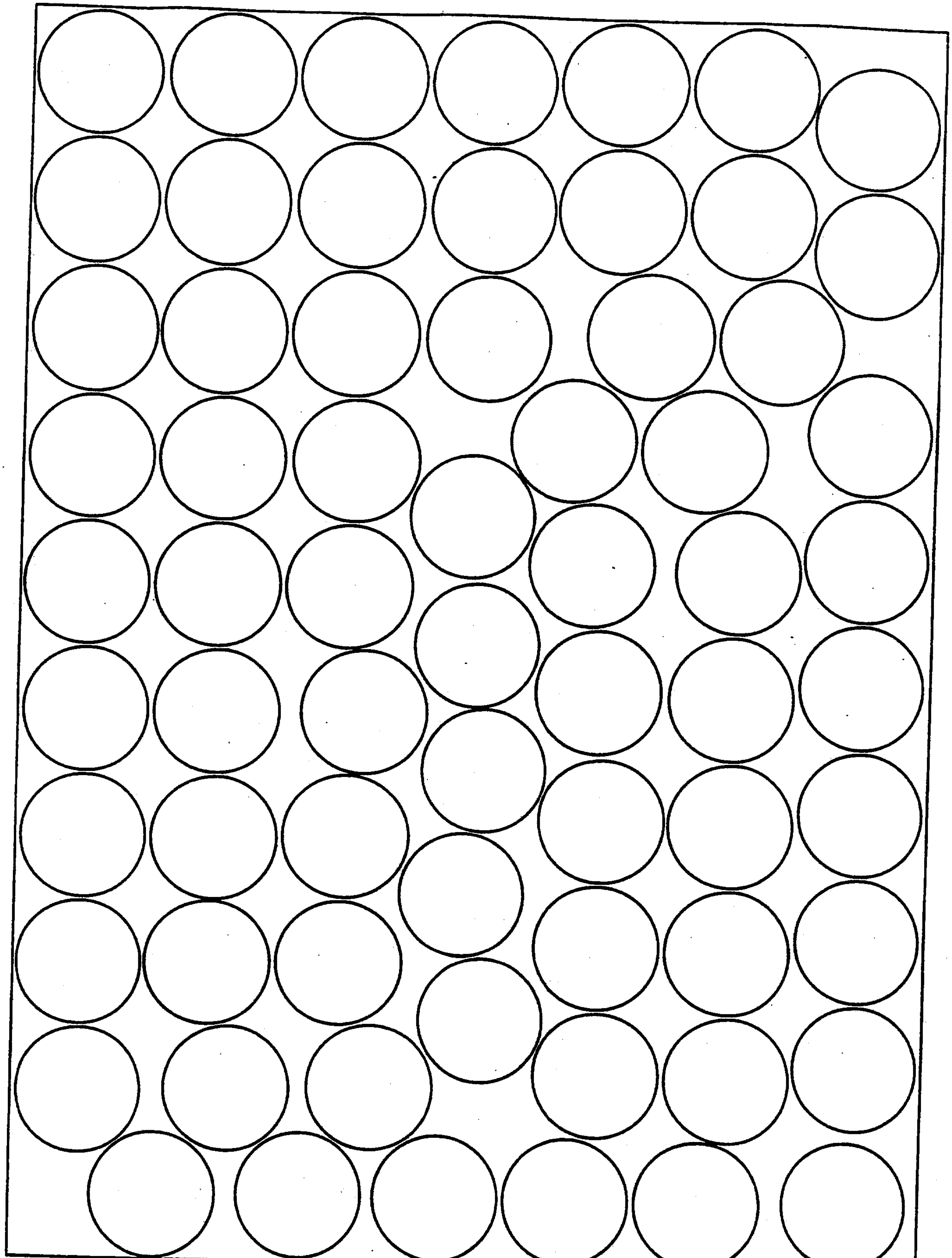
Therefore you can calculate:

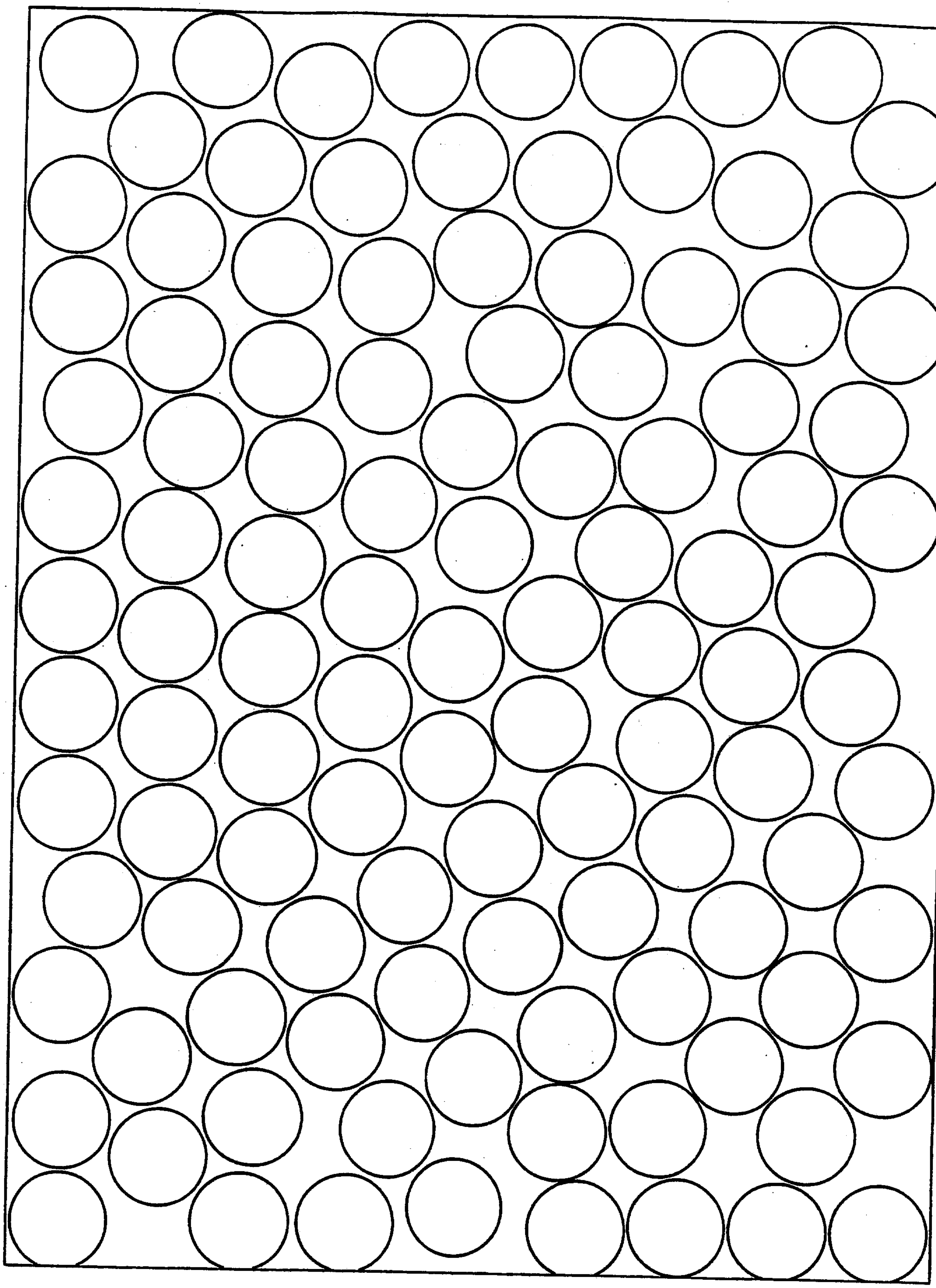
$$\text{total area of all the circles} = \frac{\text{(circle hits) (rectangular area)}}{\text{(hits)}}$$

Subsequently you can calculate:

$$\text{area of one circle} = \frac{\text{(total area of all the circles)}}{\text{(total number of circles)}}$$

The area of one circle can be used to calculate the radius of a circle: area = $3.14(\text{radius})^2$. This calculated radius may then be compared with a direct radius measurement.





Student Worksheet

A Laboratory Exercise In Indirect Measurement

Introduction: Modern physics depends heavily on indirectly determining physical properties of objects. The following activity will help convince you that indirect determinations are important methods of obtaining accurate information.

Problem: Determine the radius of a single target circle indirectly.

Procedure: Use copies of either of the circle sets given to you by your teacher. Place the circled paper on the floor, face down over a sheet of carbon paper. Drop marbles or ball bearings from head height so that they hit the paper within the marked boundaries. The sphere must be caught after the first bounce. Repeat this at least 100 times. It may be more convenient to drop the marbles from just above the paper; however, one should then take care to distribute the hits as randomly as possible over the entire target area.

Analysis: Count the total number of dots on the paper within the marked rectangular boundaries (hits) as well as the number of dots which are completely within a circle (circle hits). Determine the total area of the paper within the marked boundaries (rectangular area), and count the total number of circles on the paper. If we have uniform circles and a random distribution of hits, then we can assume:

$$\frac{\text{circle hits}}{\text{hits}} = \frac{\text{area of all circles}}{\text{rectangular area}}$$

Therefore you can calculate:

$$\text{total area of all the circles} = \frac{(\text{circle hits})(\text{rectangular area})}{(\text{hits})}$$

Subsequently you can calculate:

$$\text{area of one circle} = \frac{(\text{total area of all the circles})}{(\text{total number of circles})}$$

The area of one circle can be used to calculate the radius of a circle: area = $3.14(\text{radius})^2$. This calculated radius may then be compared with a direct radius measurement.

Teacher Notes

An In-Depth Look at The Standard Model

The following 28 pages are a very thorough look at the current state of understanding of many aspects of The Standard Model of particle physics.

For the teacher, these pages may prove to be a great "primer" to be completed before dedicating a large amount of classroom time to the study of particle physics. This is almost certainly a more thorough treatment than is offered in undergraduate curricula in particle physics.

The pages may also be used by students working in groups or individually. The directions are clear and many examples are given. In any case, this exercise will give a very clear understanding of all of the particles and how they interact to whomever works through these pages.

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

This activity can be done as a lecture-discussion presentation or can be used by individual students to learn about The Standard Model from The Standard Model Chart.

To the student: The purpose of this activity is to familiarize yourself with The Standard Model of Elementary Particles by studying The Standard Model of Elementary Particles Chart referred to from now on as the Chart. You will need to have a copy of the Chart in front of you to do this activity. (A small version of the Chart is shown on page 2, and a poster-size Chart is available from the Fermilab Education Office by using the order form found in Part III of this book.)

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 lets 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 of matter.

_______________ , _______________ , _______________ ,

_______________ , _______________ , _______________

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
muon	_______	mu
tau	_______	tau
neutrino	_______	nu

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 first 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		
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.

CHECK THIS ANSWER WITH THE INSTRUCTOR BEFORE CONTINUING.

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. Add up the masses of the quarks to find the minimum mass of the proton and neutron.

proton _____________ neutron _____________

16. Which leptons are found in Column (or Family) I? _____________ Do you think these are stable too? ________

17. The quarks from Columns II and III form particles that have lifetimes that are much shorter than the proton and neutron, yet they do live long enough to be detected. These particles can be formed from quarks from all three columns. The flavor of the quarks is determined by charge, mass and by the presence or absence of certain properties that are not completely understood but have been given the following names: strangeness, charm, beauty or bottomness, truth or topness. To use the quark model to build these baryons you need more information about the baryons and the quarks. This information is found on the "Quark & Lepton Properties" (page 37) and "Baryon Properties" (page 38) charts. You can get these charts from your instructor. (You will note that truth and beauty are not on the latter chart because no baryons have been detected that possess these properties although there are other particles called mesons that do.)

EXAMPLE: Determine the quark configuration of a sigma minus (S^-). From the chart we find that the sigma minus has a charge of -1, mass of 1197, and strangeness of -1. A strange quark is needed for the strangeness of -1. The strange quark also has a charge of -1/3. Since charm, beauty and truth are all zero, the other quarks must come from Column I and have a charge of -1/3 each. Only the down quark qualifies. Conservation of mass is not violated since the mass of the three quarks is less than the mass of the sigma minus. Therefore, the quark configuration of the sigma minus is dds.

Determine the quark configuration for the following:

Lambda zero (Λ^o)

Omega minus (Ω^-)

Xi minus (Ξ^-)

Check your answers to #17 before going on to #18.

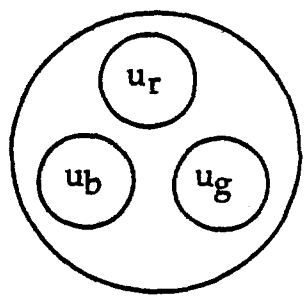
18. Perhaps you were bothered in #17 that a baryon could contain two quarks of the same kind. Since the Pauli Exclusion Principle prohibits an atom from containing two electrons with the same quantum numbers, you may have wondered if this would apply in some way to quarks in a baryon. Well, the answer is yes. Although a baryon may contain two or three quarks of the same flavor, these quarks differ in another property. Scientists are not certain of the physical significance of this property, but in The Standard Model it is given the name color. Quarks are assigned the colors of red, green or blue. Each baryon contains a quark of each color to form the color white. Where on the Chart does it indicate the colors of the quarks? ____________________

Do leptons have color? __________

19. Sketch the baryons in #14 and #17 and assign colors to the quarks. Let circles represent the baryons and smaller circles represent the quarks. EXAMPLE: Proton representation:

Neutron:
(n^o)

Lambda zero
(Λ^o)



Xi minus (Ξ^-)

Omega minus (Ω-)

20. Now lets 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 ______________________________

21. An antibaryon is made from antiquarks.
EXAMPLE: The antiquark configuration for an antiproton is since it has a charge of -1, strangeness = 0.

Write the antiquark configuration and make diagrams as in #19 for the following:

antineutron

antisigma minus

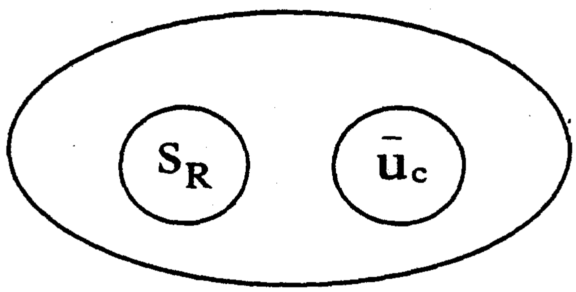
antiomega plus

HAVE THESE ANSWERS CHECKED BEFORE YOU CONTINUE.

22. Mesons are particles that are short-lived but nevertheless detected. They are composed of one quark and one antiquark. Their colors are complementary, that is, they must add up to be white or neutral.

EXAMPLE: a K minus (K^-) has charge = -1, strangeness = -1, charm = 0, beauty = 0, truth = 0. K minus is composed of an s quark (strangeness = -1, charge = -1/3) and an anti-up quark (charge = -2/3).

$s\bar{u}$ (red + cyan = white)



Using the "Meson Properties" (page 40) and "Quark & Lepton Properties" (page 35) charts, write and draw the quark configuration of the following mesons:

Anti K zero

B zero

Eta

D plus

Can you have more than one configuration for any of these?_____ If so, write out all possibilities.

23. 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
____________________	____________________________
____________________	____________________________
____________________	____________________________
____________________	____________________________

24. Which particles are charged? _______________

25. Which force has the shortest range? __________

26. Which force(s) is/are affected by the color? _______________

27. Which force is the weakest? ____________

28. Which force holds the quarks together to form baryons? __________________

THE ULTIMATE PERIODIC TABLE
Answer Key

1. matter, antimatter
2. quarks, leptons
3. up, charm, top/truth
   down, strange, bottom/beauty
4. electron, muon, tauon
   electron's neutrino, muon's neutrino, tauon's neutrino
5. the first letter of its name
6. u, d, t, c
7. μ, τ, υ, subscript, υ_e
8. up, down, charm, strange
9. +2/3, 310
   -1/3, 505
   +2/3, >22 500
   -1, .511
   -1, 1784
   0, 0
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. 930, 930
16. electron, electron's neutrino, yes
17. uds, sss, dss
18. second row between charge and mass, no
19. udd, uds, dss, sss
20. a) opposite b) same c) same symbol with line over it, positron d) cyan, magenta, yellow
21. $\bar{u}\bar{u}\bar{d}$, $\bar{s}\bar{u}\bar{u}$, $\bar{s}\bar{s}\bar{s}$
22. $s\bar{d}$, $\bar{b}d$, $u\bar{u}$ or $d\bar{d}$, $c\bar{d}$
    yes, eta
23. strong, gluons
    weak, W^+, W^-, Z^0
    electromagnetic, photons
    gravity, gravitons
24. W^+, W^-
25. weak
26. strong
27. gravity
28. strong

QUARK AND LEPTON PROPERTIES

Quark Flavor	Symbol	Charge	Mass (MeV)	Baryon #	Strangeness	Charm	Bottomness or Beauty	Topness or Truth
UP	u	+2/3	5	+1/3	0	0	0	0
DOWN	d	-1/3	8	+1/3	0	0	0	0
CHARM	c	+2/3	1500	+1/3	0	1	0	0
STRANGE	s	-1/3	160	+1/3	-1	0	0	0
TOP	t	+2/3	>180,000	+1/3	0	0	0	1
BOTTOM	b	-1/3	~4250	+1/3	0	0	-1	0
ANTI-UP	u	-2/3	5	-1/3	0	0	0	0
ANTI-DOWN	d	+1/3	8	-1/3	0	0	0	0
ANTI-CHARM	c	-2/3	1500	-1/3	0	-1	0	0
ANTI-STRANGE	s	+1/3	160	-1/3	1	0	0	0
ANTI-TOP	t	-2/	>180,000	-1/3	0	0	0	-1
ANTI-BOTTOM	b	+1/3	~4250	-1/3	0	0	1	0

Lepton Flavor	Symbol	Charge	Mass (MeV)	Electron #	Muon #	Tauon #
ELECTRON	e or e^-	-	0.511	1	0	0
MUON	μ or μ^-	-1	105.7	0	1	0
TAUON	τ or τ^-	-1	1777	0	0	1
ELECTRON NEUTRINO	ν_e	0	<15 eV	1	0	0
MUON NEUTRINO	ν_μ	0	<250 KeV	0	1	0
TAUON NEUTRINO	ν_τ	0	<50	0	0	1
ANTI-ELECTRON	e or e^+	1	0.511	-1	0	0
ANTI-MUON	μ or μ^+	1	105.7	0	-1	0
ANTI-TAUON	τ or τ^+	1	1777	0	0	-1
ELECTRON ANTI-NEUTRINO	ν_e	0	<15 eV	-1	0	0
MUON ANTI-NEUTRINO	ν_μ	0	<250 KeV	0	-1	0
TAUON ANTI-NEUTRINO	ν_τ	0	<50	0	0	-1

Additional data may be found in the **Particle Properties Data Booklet**, available from:
Technical Information Department - MS 90-2125 - Lawrence Berkeley Laboratory - Berkeley, CA 94720

BARYON PROPERTIES

Use the chart of "QUARK & LEPTON PROPERTIES" to determine the quark composition of the following baryons. A method for determining baryon composition is shown on the following page. Use your answers from this exercise to fill the appropriate circles on the "BARYON COMPOSITION" exercise that follows.

BARYON NAME	SYMBOL	CHARGE	MASS (MEV)	STRANGENESS	CHARM	SPIN	BARYON NUMBER
Proton	P	+1	938	0	0	1/2	+1
Antiproton	P	-1	938	0	0	1/2	-1
Neutron	N	0	940	0	0	1/2	+1
Antineutron	N	0	940	0	0	1/2	-1
Lambda	Λ^0	0	1116	-1	0	1/2	+1
Antilambda	Λ^0	0	1116	+1	0	1/2	-1
Charmed Lambda Plus	Λ_c^+	+1	2282	0	1	1/2	+1
Sigma Plus	Σ^+	+1	1189	-1	0	1/2	+1
Antisigma Minus	Σ^-	-1	1189	+1	0	1/2	-1
Sigma Zero	Σ^0	0	1192	-1	0	1/2	+1
Antisigma Zero	Σ^0	0	1192	+1	0	1/2	-1
Sigma Minus	Σ^-	-1	1197	-1	0	1/2	+1
Antisigma Plus	Σ^+	+1	1197	+1	0	1/2	-1
Xi Zero	Ξ^0	0	1315	-2	0	1/2	+1
Antixi Zero	Ξ^0	0	1315	+2	0	1/2	-1
Xi Minus	Ξ^-	-1	1321	-2	0	1/2	+1
Antixi Plus	Ξ^+	+1	1321	+2	0	1/2	-1
Omega Minus	Ω^-	-1	1672	-3	0	3/2	+1
Antiomega Plus	Ω^+	+1	1672	+3	0	3/2	-1
Delta Zero	Δ^0	0	1237	0	0	3/2	+1
Antidelta Zero	Δ^0	0	1237	0	0	3/2	-1
Delta Minus	Δ^-	-1	1239	0	0	3/2	+1
Delta Plus	Δ^+	+1	1235	0	0	3/2	+1
Delta Two Plus	Δ^{++}	+2	1233	0	0	3/2	+1
Sigma Star Plus	Σ^{*+}	+1	1382	-1	0	3/2	+1
Sigma Star Zero	Σ^{*0}	0	1385	-1	0	3/2	+1
Sigma Star Minus	Σ^{*-}	-1	1388	-1	0	3/2	+1
Xi Star Minus	Ξ^{*-}	-1	1530	-2	0	3/2	+1
Xi Star Zero	Ξ^{*0}	0	1530	-2	0	3/2	+1

DETERMINING BARYON COMPOSITION

1. Baryons consist of three quarks.
2. If the baryon number is +1, you have $\overline{Q}\,\overline{Q}\,\overline{Q}$.
3. If the baryon number is -1, you have $Q\,Q\,Q$.
4. What is the charge on the baryon?
5. What combinations of three quark charges (±2/3, ±1/3) will yield the total charge on the baryon?
6. What does the baryon mass indicate about possible quark combinations?
7. A spin of 3/2 will account for a larger mass.
8. What do the strangeness, charm, beauty (bottomness), and truth (topness) numbers indicate?

Example:

What is the quark composition of the Σ^0?

a) The baryon number is +1. Therefore it consists of three quarks.

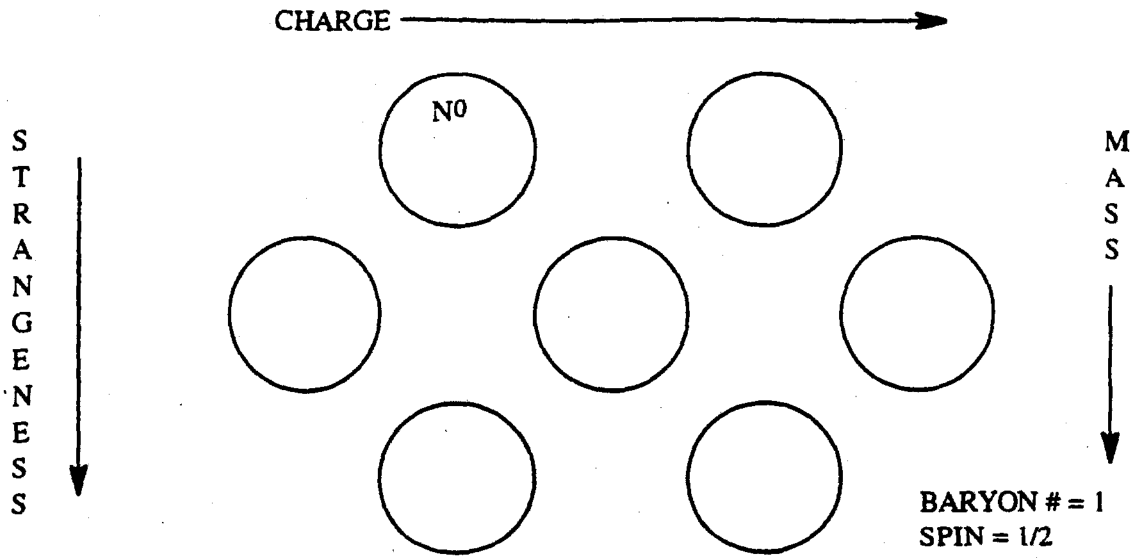
b) The charge is zero. To get this total charge, the quarks must have charges of +2/3, -1/3, and -1/3 respectively. The +2/3 quark could be up, charm, or top. The -1/3 quarks could be down,strange, or bottom.

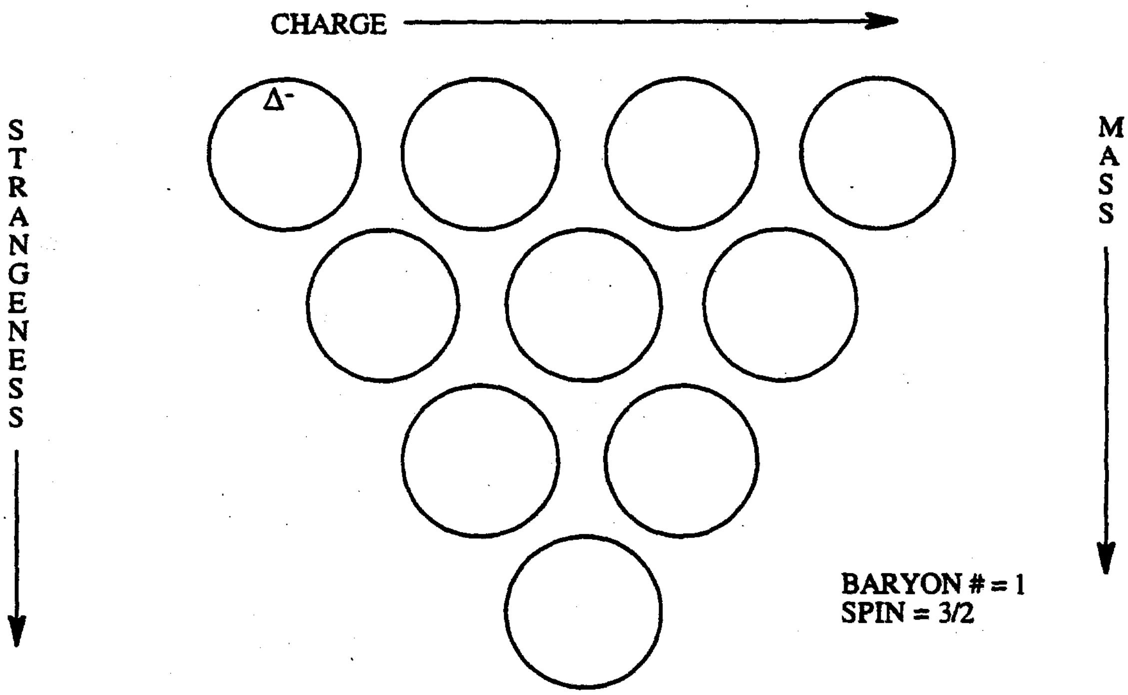
c) The mass is 1.192 MeV. This eliminates the more massive charm, bottom, and top quarks. Therefore the +2/3 quark must be up. The -1/3 quark could be either down or strange.

d) The strangeness is -1. Therefore one, and only one, strange quark must be included.

e) The composition is up, strange, down (**usd**).

BARYON COMPOSITION



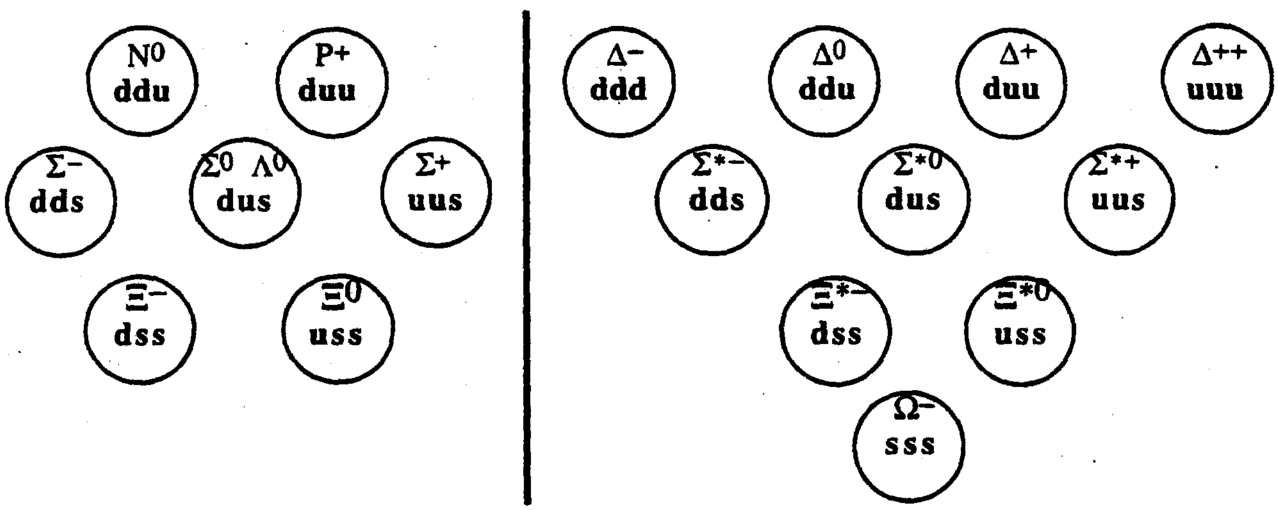


The "Baryon Composition" sheet is designed to be used after the "Baryon Properties" sheet has been completed. It will show the relationships among the various baryons in terms of mass, charge, strangeness, and composition. Note that the upper set of baryons have a spin of 1/2, while the lower grouping has spin of 3/2. Use your answers from the "Baryon Properties" sheet to fill each circle with the name of the baryon and its quark composition. The circles should be filled in a pattern whereby charge increases from left to right, and both mass and strangeness increase from top to bottom.

BARYON PROPERTIES AND BARYON COMPOSITION ANSWER KEYS

BARYON NAME	COMPOSITION
Proton	duu
Antiproton	$\bar{d}\bar{u}\bar{u}$
Neutron	ddu
Antineutron	$\bar{d}\bar{d}\bar{u}$
Lambda	dus
Antilambda	$\bar{d}\bar{u}\bar{s}$
Charmed Lambda Plus	duc
Sigma Plus	uus
Antisigma Minus	$\bar{u}\bar{u}\bar{s}$
Sigma Zero	dus
Antisigma Zero	$\bar{d}\bar{u}\bar{s}$
Sigma Minus	dds
Antisigma Plus	$\bar{d}\bar{d}\bar{s}$
Xi Zero	uss
Antixi Zero	$\bar{u}\bar{s}\bar{s}$
Xi Minus	dss
Antixi Plus	$\bar{d}\bar{s}\bar{s}$
Omega Minus	sss
Antiomega Plus	$\bar{s}\bar{s}\bar{s}$
Delta Zero	ddu
Antidelta Zero	$\bar{d}\bar{d}\bar{u}$
Delta Minus	ddd
Delta Plus	duu
Delta Two Plus	uuu
Sigma Star Plus	uus
Sigma Star Zero	dus
Sigma Star Minus	dds
Xi Star Minus	dss
Xi Star Zero	uss

****



MESON PROPERTIES

Use the chart of "QUARK & LEPTON PROPERTIES" to determine the quark composition of the following mesons. A method for determining meson composition is shown on the following page. Use your answers from this exercise to fill the appropriate boxes on the "MESON COMPOSITION" exercise that follows.

MESON NAME	SYMBOL	CHARGE	MASS (MEV)	STRANGENESS	CHARM	BEAUTY/ BOTTOMNESS	TRUTH/ TOPNESS
Pi Zero	π^0	0	135	0	0	0	0
Pi Minus	π^-	−1	140	0	0	0	0
Pi Plus	π^+	+1	140	0	0	0	0
Rho	ρ^0	0	776	0	0	0	0
Eta	η^0	0	549	0	0	0	0
K Zero	K^0	0	498	+1	0	0	0
Anti K Zero	K^0	0	498	-1	0	0	0
K Plus	K^+	+1	494	+1	0	0	0
K Minus	K^-	-1	494	-1	0	0	0
D Zero	D^0	0	1865	0	+1	0	0
Anti D Zero	D^0	0	1865	0	-1	0	0
D Plus	D^+	+1	1869	0	+1	0	0
D Minus	D^-	-1	1869	0	-1	0	0
F Plus	F^+	+1	1971	+1	+1	0	0
F Minus	F^-	-1	1971	-1	-1	0	0
J/Psi	J/Ψ	0	3097	0	0	0	0
B Zero	B^0	0	5274	0	0	+1	0
Anti B Zero	B^0	0	5274	0	0	-1	0
B Plus	B^+	+1	5271	0	0	+1	0
B Minus	B^-	-1	5271	0	0	-1	0
Phi	ϕ	0	1020	0	0	0	0
Upsilon	Ψ	0	9460	0	0	0	0

DETERMINING MESON COMPOSITION

1. Mesons consist of a quark and an antiquark ($Q\bar{Q}$).

2. What is the charge on the meson?

3. What combinations of quark and antiquark charges ($\pm 2/3$, $\pm 1/3$) will yield the total charge on the meson?

4. What does the meson mass indicate about possible quark/antiquark combinations?

5. What do the strangeness, charm, beauty (bottomness), and truth (topness) numbers indicate?

Example:

What is the composition of D^- ?

a) It is a meson, so we have QQ.

b) The charge is -1. Therefore the quark/antiquark charges must be -1/3 and -2/3. We must have a quark charge of -1/3 (down, strange, or bottom) and an antiquark charge of -2/3 (antiup, anticharm, or antitop).

c) The mass is 1869 MeV. This eliminates the bottom and antitop.

d) The charm is -1. This requires the anticharm.

e) The strangeness is zero. This eliminates the strange quark.

f) We are left with the down/anticharm (**d$\bar{c}$**) combination for the D^-.

MESON COMPOSITION

The "Meson Composition" sheet is designed to be used after the "Meson Properties" sheet has been completed. It will show the quark composition relationships among the various mesons. In the table below insert the names of the known mesons formed from each quark/antiquark combination.

	$\bar{u}$	$\bar{d}$	$\bar{c}$	$\bar{s}$	$\bar{t}$	$\bar{b}$
u	π^o ρ^o η^o					
d		π^o ρ^o η^o				
c						
s						
t						
b						

MESON PROPERTIES AND MESON COMPOSITION ANSWER KEYS

MESON NAME	COMPOSITION QUARK/ANTIQUARK		MESON NAME	COMPOSITION QUARK/ANTIQUARK	
Pi Zero	u/d	$\bar{u}/\bar{d}$	D Plus	c	$\bar{d}$
Pi Minus	d	$\bar{u}$	D Minus	d	$\bar{c}$
Pi Plus	u	$\bar{d}$	F Plus	c	$\bar{s}$
Rho	u/d	$\bar{u}/\bar{d}$	F Minus	s	$\bar{c}$
Eta	u/d	$\bar{u}/\bar{d}$	J/Psi	c	$\bar{c}$
K Zero	d	$\bar{s}$	B Zero	d	$\bar{b}$
Anti K Zero	s	$\bar{d}$	Anti B Zero	b	$\bar{d}$
K Plus	u	$\bar{s}$	B Plus	u	$\bar{b}$
K Minus	s	$\bar{u}$	B Minus	b	$\bar{u}$
D Zero	c	$\bar{u}$	Phi	s	$\bar{s}$
Anti D Zero	u	$\bar{c}$	Upsilon	b	$\bar{b}$

****

	$\bar{u}$	$\bar{d}$	$\bar{c}$	$\bar{s}$	$\bar{t}$	$\bar{b}$
u	π^0 ρ^0 η^0	π^+ ρ^+	$\overline{D^0}$	K^+		B^+
d	π^- ρ^-	π^0 ρ^0 η^0	D^-	K^0		B^0
c	D^0	D^+	J/Ψ	F^+		
s	K^-	$\overline{K^0}$	F^-	ϕ		
t						
b	B^-	$\overline{B^0}$				Ψ

ANALYSIS OF ELEMENTARY PARTICLE REACTIONS

In order to analyze elementary particle reactions at a beginning level you must consider conservation of charge, baryon number, electron number, muon number, and tauon number. Energy is also conserved, but may appear in a variety of forms, some of which forms are difficult to quantify. Therefore you will need to examine kinetic energy before the reaction. If there is only minimal initial kinetic energy (as in decays), then the rest energy (mass) total for the products should be less than the rest energy of the reactant. In a strong interaction strangeness also will be conserved.

Example:

Complete the reaction:

Property	$\Lambda^0 \longrightarrow$	p^+ +	e^- +	?
Charge	0	+1	-1	***0***
Mass (MeV)	1116	938	.5	***<177***
Baryon Number	1	1	0	***0***
Electron Number	0	0	+1	***-1***
Muon Number	0	0	0	***0***
Tauon Number	0	0	0	***0***

In order to conserve the various properties, the unknown particle will need the properties indicated in ***bold italics***. Therefore it must be the electron's antineutrino $(\overline{\nu_e})$.

ELEMENTARY PARTICLES REACTIONS - I

Use the conservation laws to supply the missing particles(s) in each of the following reactions.

A) WEAK NON-LEPTONIC DECAYS OF HADRONS

1.	K^+	π^+	+		
2.	Λ^0	N^0	+		
3.	K^0	π^+	+		
4.	Λ^0	P^+	+		
5.	Σ^+	P^+	+		
6.	K^+	π^+	+	π^+	+
7.	Ξ^0	Λ^0	+		
8.	K^0	π^0	+		
9.	Σ^+	N^0	+		
10.	Ω^-	Ξ^0	+		
11.	Ξ^-	Λ^0	+		
12.	Σ^-	N^0	+		

B) WEAK, LEPTONIC DECAYS OF HADRONS AND LEPTONS

13.	π^+	μ^+	+		
14.	π^0	γ	+	e^+	+
15.	π^-	π^0	+	e^-	+
16.	K^+	ν_μ	+		

17.	K^0	π^+	+	ν_e	+
18.	N^0	P^+	+	e^-	+
19.	μ^-	e^-	+		+
20.	Λ^0	P^+	+	e^-	+
21.	τ^+	μ^+	+		+
22.	D^0	K^0	+	π^+	+

C) **STRONG, HADRONIC REACTIONS** (Assume sufficient incident energy.)

23.	N^0	+	P^+	P^+	+	P^+	+
24.	P^+	+	P^+	P^+	+	π^+	+
25.	P^+	+	π^+	Σ^+	+		
26.	π^0	+	P^+	P^+	+	π^+	+
27.	K^-	+	P^+	Σ^+	+		
28.	K^-	+	P^+	Σ^-	+		
29.	K^-	+	P^+	Λ^0	+		
30.	π^-	+	P^+	N^0	+	π^-	+

ELEMENTARY PARTICLE REACTIONS-II

Indicate the validity of each of the following decay processes. For any reactions which are not valid, state a reason.

1.	K^-	μ^-	+	ν_μ		
2.	π^+	μ^+	+	ν_μ		
3.	Λ^0	p^+	+	π^-		
4.	π^-	μ^+	+	ν_e		
5.	π^-	μ^-	+	ν_μ		
6.	N^0	p^+	+	π^-		
7.	Σ^+	N^0	+	π^0		
8.	N^0	p^+	+	e^-	+	ν_e
9.	μ^+	e^-	+	ν_e	+	ν_μ
10.	K^+	μ^+	+	π^0	+	ν_e
11.	π^0	e^+	+	e^-	+	ν_e
12.	μ^-	e^-	+	ν_e	+	ν_μ
13.	Ξ^0	Λ^0	+	π^0		
14.	K^0	π^0	+	π^0	+	π^+
15.	Λ^0	N^0	+	π^0	+	ν_e

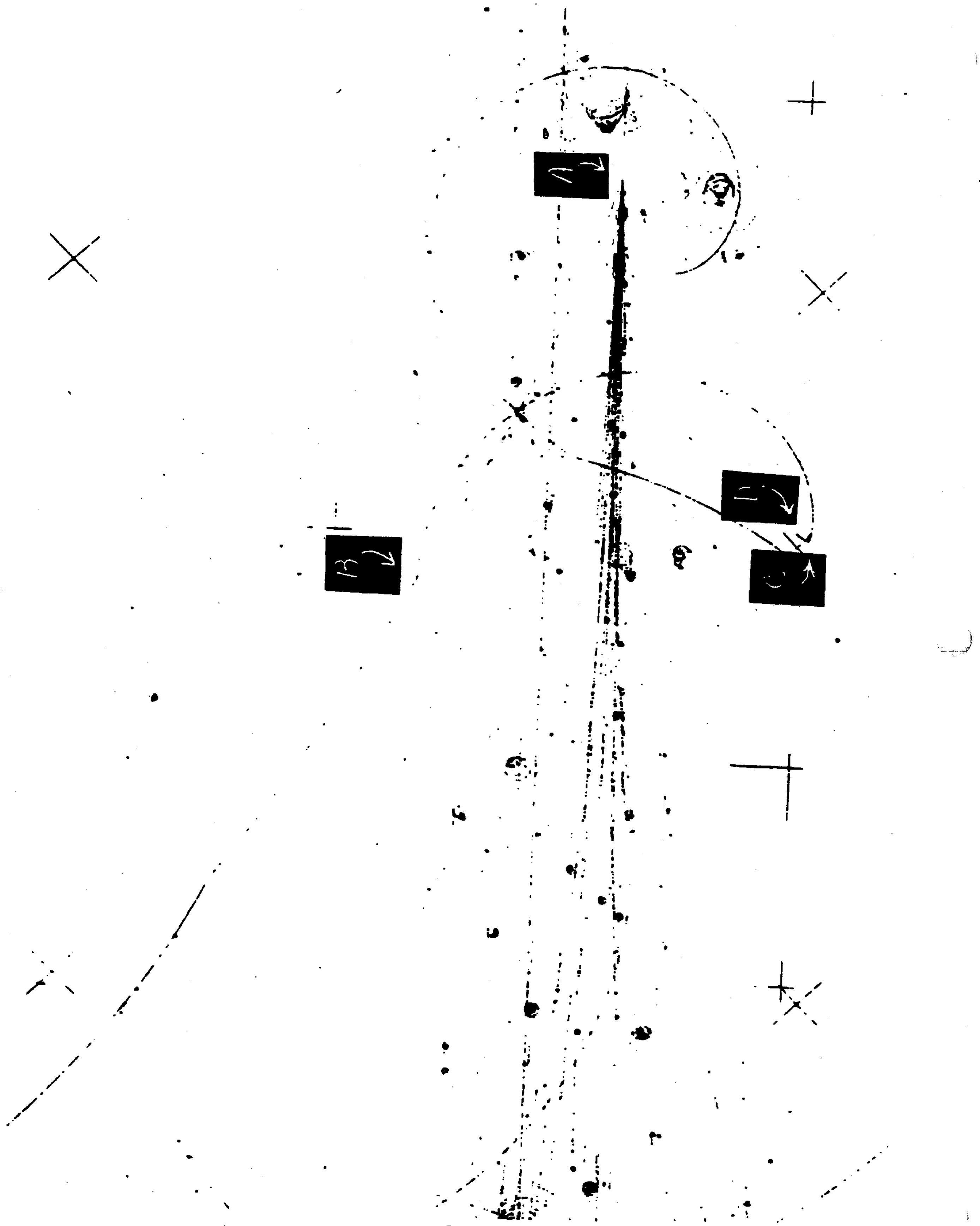
ELEMENTARY PARTICLE REACTIONS
ANSWER KEYS

SHEET I

1. Pi Zero
2. Pi Zero
3. Pi Minus
4. Pi Minus
5. Pi Zero
6. Pi Minus
7. Pi Zero
8. Pi Zero
9. Pi Plus
10. Pi Minus
11. Pi Minus
12. Pi Minus
13. Muon Neutrino - See "Bubble Chamber Track Analysis - II" (pages 49-50). This reaction occurs at point C.
14. Electron
15. Electron Antineutrino
16. Mu Plus
17. Electron
18. Electron Antineutrino
19. Electron Antineutrino & Muon Neutrino
20. Electron Antineutrino
21. Tauon Antineutrino & Muon Neutrino
22. Pi Minus
23. Pi Minus
24. Neutron
25. K Plus
26. Pi Minus
27. Pi Minus
28. Pi Plus
29. Pi Zero
30. Pi Plus

SHEET II

1. Valid
2. Valid - See "Bubble Chamber Track Analysis - II" (pages 49-50). This reaction occurs at point C.
3. Valid
4. Invalid - Charge, muon family number, and electron family number are not conserved.
5. Invalid - Muon family number is not conserved.
6. Valid
7. Invalid - Charge is not conserved.
8. Valid
9. Invalid - Electron family number is not conserved. See "Bubble Chamber Track Analysis - II" (pages 49-50). The corrected version of this reaction occurs at point D.
10. Invalid - Muon family number and electron family number are not conserved.
11. Invalid - Electron family number is not conserved.
12. Invalid - Electron family number is not conserved.
13. Valid
14. Invalid - Charge is not conserved.
15. Invalid - Electron family number is not conserved.



BUBBLE CHAMBER TRACK ANALYSIS - II

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:

   $\pi^+ \longrightarrow \mu^+ + \nu_\mu$. The lack of forward momentum beyond point C indicates the likelihood of a decay of a particle (π^+) which was essentially at rest. Note that this is reaction 13 from the worksheet "Elementary Particle Reactions - I" (page 45), as well as being reaction 2 from the worksheet "Elementary Particle Reactions - II" (page 47).

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

   $\mu^+ \longrightarrow e^+ + \nu_e + \overline{\nu_\mu}$. Note that this is the corrected version of reaction 9 from the worksheet "Elementary Particle Reactions - II" (page 47).

WHAT DID YOU LEARN?
ELEMENTARY PARTICLES

NAME ______________________________

Part A - True or False

____ 1. Earth, air, fire, and water are not currently considered as the fundamental particles of nature.

____ 2. The fundamental particles of modern physics are the proton, neutron, and electron.

____ 3. Quarks have electrical charges equal to 1/3 or 2/3 of the electron or proton charge.

____ 4. All leptons are electrically neutral.

____ 5. For every particle type there is believed to exist an antiparticle type.

____ 6. The mass of an elementary particle is typically expressed in terms of its energy equivalent in joule units.

____ 7. An antiparticle has the same mass as its particle counterpart.

____ 8. Quark flavors include: up, down, charm, strange, top, and bottom.

____ 9. The electron, muon, and the tauon are the only known leptons.

____ 10. Threee types of neutrinos are believed to exist.

____ 11. The graviton is a theoretically massless particle that has yet to be observed.

Part B - Match each particle type in Column I with the best description in Column II.

	Column I	Column II
____	12. hadrons	A. fundamental particles bound in groups of two or three by the strong force
____	13. mesons	B. fundamental particles not affected by the strong force
____	14. baryons	C. composed entirely of particles of neutral electrical charge
____	15. quarks	D. three quarks in combination
____	16. leptons	E. general group consisting of mesons and baryons
		F. one quark and one antiquark in combination

Part C - Match each fundamental force in Column I with its carrier in Column II.

	Column I	Column II
____	17. gravitational	A. weak bosons (weakons)
____	18. strong nuclear	B. photons
____	19. weak nuclear	C. gravitons
____	20. electromagnetic	D. klingons
		E. gluons

For questions #21-26 use your knowledge of quark and lepton properties and the conservation laws, as well as the particle data at the bottom of the page.

Determine the quark (or antiquark) composition of the following particles.

	Baryon #	Charge	Mass (MeV)	Spin	Strangeness	Charm	Composition
21.	-1	-1	1235	3/2	0	0	____
22.	0	-1	1971	0	-1	-1	____

Complete the following reactions.

23. $P^{+} + \pi^{+} \longrightarrow \Sigma^{+} +$ ____

24. $K^{+} \longrightarrow \nu_{\mu} +$ ____

For the following reactions indicate which are valid. If a reaction is not valid, state a reason.

25. $\pi^{0} \longrightarrow e^{+} + e^{-} + \nu_{e}$ ____________

26. $\Xi^{0} \longrightarrow \Lambda^{0} + \pi^{0}$ ____________

PARTICLE DATA

NAME	BARYON #	CHARGE	MASS (MEV)	SPIN	STRANGENESS	CHARM
π^0	0	0	135	0	0	0
π^-	0	-1	140	0	0	0
π^+	0	+1	140	0	0	0
K^0	0	0	498	0	1	0
K^+	0	+1	494	0	1	0
K^-	0	-1	494	0	-1	0
P^+	1	+1	938	1/2	0	0
N^0	1	0	940	1/2	0	0
Λ^0	1	0	1116	1/2	-1	0
Σ^+	1	+1	1189	1/2	-1	0
Σ^0	1	0	1192	1/2	-1	0
Σ^-	1	-1	1197	1/2	-1	0
Ξ^-	1	-1	1321	1/2	-2	0
Ξ^0	1	0	1315	1/2	-2	0

F

For questions #21-26 use your knowledge of quark and lepton properties and the conservation laws, as well as the particle data at the bottom of the page.

Determine the quark (or antiquark) composition of the following particles.

	Baryon #	Charge	Mass (MeV)	Spin	Strangeness	Charm	Composition
21.	1	0	1385	3/2	-1	0	____
22.	0	-1	1869	0	0	0	____

Complete the following reactions.

23. $K^- + P^+ \longrightarrow \Sigma^+ +$ ____

24. $\pi^+ \longrightarrow \mu^+ +$ ____

For the following reactions indicate which are valid. If a reaction is not valid, state a reason.

25. $N^0 \longrightarrow P^+ + e^- + \overline{\nu_e}$ ____________

26. $\mu^+ \longrightarrow e^- + \nu_e + \overline{\nu_\mu}$ ____________

PARTICLE DATA

NAME	BARYON #	CHARGE	MASS (MEV)	SPIN	STRANGENESS	CHARM
p0	0	0	135	0	0	0
p-	0	-1	140	0	0	0
p+	0	+1	140	0	0	0
KO	0	0	498	0	1	0
K+	0	+1	494	0	1	0
K-	0	-1	494	0	-1	0
P+	1	+1	938	1/2	0	0
NO	1	0	940	1/2	0	0
LO	1	0	1116	1/2	-1	0
S+	1	+1	1189	1/2	-1	0
SO	1	0	1192	1/2	-1	0
S-	1	-1	1197	1/2	-1	0
X-	1	-1	1321	1/2	-2	0
XO	1	0	1315	1/2	-2	0

For questions #21-26 use your knowledge of quark and lepton properties and the conservation laws as well as the particle data at the bottom of the page.

Determine the quark (or antiquark) composition of the following particles.

	Baryon #	Charge	Mass (MeV)	Spin	Strangeness	Beauty	Composition
21.	1	-1	1530	3/2	-2	0	____
22.	0	0	5274	0	0	1	____

Complete the following reactions.

23. $\pi^- + P^+ \longrightarrow N^0 + \pi^- +$ ____

24. $K^0 \longrightarrow \pi^+ + \nu_e +$ ____

For the following reactions indicate which are valid. If a reaction is not valid, state a reason.

25. $\pi^- \longrightarrow \mu^- + \nu_\mu$ ____________

26. $\Lambda^0 \longrightarrow N^0 + \pi^0 + \nu_e$ ____________

PARTICLE DATA

NAME	BARYON #	CHARGE	MASS (MEV)	SPIN	STRANGENESS	CHARM
π^0	0	0	135	0	0	0
π^-	0	- 1	140	0	0	0
π^+	0	+ 1	140	0	0	0
K^0	0	0	498	0	1	0
K^+	0	+ 1	494	0	1	0
K^-	0	- 1	494	0	- 1	0
P^+	1	+ 1	938	1/2	0	0
N^0	1	0	940	1/2	0	0
Λ^0	1	0	1116	1/2	- 1	0
Σ^+	1	+ 1	1189	1/2	- 1	0
Σ^0	1	0	1192	1/2	- 1	0
Σ^-	1	- 1	1197	1/2	- 1	0
Ξ^-	1	- 1	1321	1/2	- 2	0
Ξ^0	1	0	1315	1/2	- 2	0

WHAT DID YOU LEARN?
ELEMENTARY PARTICLES

Answer Key

Part A

1. True
2. False
3. True
4. False
5. True
6. False
7. True
8. True
9. False
10. True
11. True

Part B

12. E
13. F
14. D
15. A
16. B

Part C

17. C
18. E
19. A
20. B

Version 1

21. $\overline{uud}$
22. $s\bar{c}$
23. K^+
24. μ^+
25. Invalid, electron number is not conserved.
26. Valid

Version 2

21. uds
22. $d\bar{c}$
23. π^-
24. ν_μ
25. Valid
26. Invalid, charge and electron number are not conserved.

Version 3

21. ssd
22. $\bar{d}b$
23. π^+
24. e^-
25. Invalid, muon number is not conserved.
26. Invalid, electron number is not conserved.

CLASSROOM VIDEO REFERENCES

The following videos contain up-to-date information and will add to your classroom instruction.

1. **Creation of the Universe**
   Available through the Education Office at Fermi National Accelerator Laboratory, P.O. Box 500 M.S. 777, Batavia, IL 60510-0500, 630-840-8258

   Still one of the best student primers on high energy physics and it's connections with cosmology. It is highly recommended that the teacher take advantage of the teacher's guide and the student activities sheets.

2. **Race for the Top 1990**
   This is a Nova film, reference it's purchase through Nova. 60 minutes

   Nice representation of the women in physics also. Why search for the top promotes new technologies, prestige, verification of theory. Good presentation of how all the aspects of an experiment work together, getting the machine to work. Nice introduction and then back to the history preceding the search for top. Small victories, big jumps, the J/¥. Interesting comparisons of Cern vs. Fermilab advantages and disadvantages. Good examples of the interpretation of event diagrams. Some outdated references to the now defunct SSC. Really need a follow-up of what has happened in the last 7 years and how Fermilab finally found it.

3. **Quarks: A Christmas Lecture**
   Leon M. Lederman
   Available through the Education Office at Fermi National Accelerator Laboratory, P.O. Box 500 M.S. 777, Batavia, IL 60510-0500, 630-840-8258.

   This is a lecture given at Illinois Math and Science Academy. Leon talks to the camera most of the time (this is good for a video; it makes you feel part of the presentation), using a blackboard to illustrate points. Good lighting for a lecture video, Leon does a nice job of presenting the history of high-energy physics from ancient Greeks to present day. If you have never seen a lecture by Dr. Lederman it is well worth it. Great examples and metaphors. Interactions with the students are interesting. Added graphics and simulations add to the presentation.

4. **Welcome to Fermilab**
   Available through the Education Office at Fermi National Accelerator Laboratory, P.O. Box 500 M.S. 777, Batavia, IL 60510-0500, 630-840-8258

   An introduction to the history of high-energy physics and an overview of the mission and accomplishments of Fermilab. Good graphics, good basic explanations, introduction to The Standard Model, and the operation of the accelerator.

5. **A Brief on High-Energy Physics**
   Available through the Education Office at Fermi National Accelerator Laboratory, P.O. Box 500 M.S. 777, Batavia, IL 60510-0500, 630-840-8258.

   A very brief overview of the questions, theories and tools used by high-energy physics. A very good introduction in only 9 minutes. Includes some clips from Creation of the Universe.

6 . **To The Heart of the Matter**
Available through the Education Office at Fermi National Accelerator Laboratory, P.O. Box 500 M.S. 777, Batavia, IL 60510-0500, 630-840-8258.

Great video for students to watch for an introduction to what high-energy physicists do. It includes information on the machines and The Standard Model as presented by some of the foremost physicists at Fermilab.

COMPUTER PROGRAM RESOURCES

These references will give a teacher a start at the programs and Internet sites that are available and useable in a high school classroom. Because of the rate at which this information changes, it is likely to be up to date for only a short time. Still, the persistent teacher will be able to discover some very good resources using these pages as a guide.

1. **Program Name: Chamber Works**
   Program Description: *Chamber Works* is a unique program that simulates the motion of charged particles in a detection chamber. It allows students to experience high energy physics within their own classroom. The program allows students to control the size of the detection chamber, control the energy of incoming particles and control the magnetic field within the chamber. A user can insert muons or pions, make decay measurements, mass measurements (including how mass and decay time change as energy increase) and much more by using a projection window that allows users to make direct measurements of radius of curvature or decay length.

   This is a program that you need to start with the manual. You can play without it, but the power of the program to simulate decaying particles and make meaningful measurements become apparent when sitting down and following some directions. For instance, the decay window can be rotated about any axis to view the event from many different perspectives.

   Creator: Robert Estes
   Manufacturer: OnScreen Science, Inc.
   46 Wallace St.
   Somerville, MA 02144
   Phone: (800) 617-6416 or
   (617) 776-6416
   or e-mail: info@onscreen-sci.com and Website: www.onscreen-sci.com
   Platform: Mac
   Price: $99.

2. **Program Name: PEARLS 3.0**
   Program Description: This is a set of thirty-five independent simulations and animations that comprehensively address topics that are usually found in an introductory physics course. These include Blackbody radiation, the Bohr atom, and Brownian motion as they address basic quantum effects. Pearls also includes four interactive simulations that make clear the Doppler effect for both light and sound, time dilation, and introduce simultaneous events.

   Creator: Peter Crame - Case Western Reserve University
   Manufacturer: Physics Academic Software
   Box 8202
   North Carolina State University
   Raleigh, NC 27695-8202
   Fax: (919) 515-2682 Phone: (800) 955-8275L or
   (919) 515-7447
   or On-Line Ordering http://www.aip.org/forms/pasorder.html
   Platform: Mac or PC Windows
   Price: $275 Single Copy
   $1,100 10-Copy Lab Pack
   $1,375 High School Site License
   ISBN: Windows 1-56396-511-9
   Mac 1-56396-513-5

3. **Program Name: Atomic Scattering**
Program Description: *Atomic Scattering* demonstrates aspects of particle interaction that can't be seen easily in traditional experiments: how the potential's attractive and repulsive properties affect particle motion; how the velocities of particles change with particle separation to conserve total energy; and how impact parameter and initial energy affect the outcome of a scattering event.

Manufacturer: Physics Education Group - Visual Quantum Mechanics
Platform: Mac

Price:	$49.95	Single Copy
	$149.95	10-Copy Lab Pack
	$199.80	High School Site License

4. **Program Name: Uncertainty Principle**
Program Description: This program enables students to explore the Heisenberg uncertainty relation. They accomplish this exploration by creating a momentum distribution for a particle and having the computer display the spatial wavefunction for this same particle. By clicking in the wavelength window the students define the relative size of the wavelength and amplitude for the contribution to the overall wavefunction. That contribution is then added to other contributions which they select and the result is displayed in the top or wavefunction window.

Manufacturer: Physics Education Group - Visual Quantum Mechanics
Platform: Mac

Price:	$49.95	Single Copy
	$149.95	10-Copy Lab Pack
	$199.80	High School Site License

5. **Program Name: ATOMIC PHYSICS**
Program Description: Some of this material is at the end of the general physics course, but most will be found in the college sophomore/junior level atomic physics course. Animations and illustrations make the material easy for a beginner to understand. This is a very big program with 75 subsections covering the whole subject. Included are: **Quantum Mechanics** (foundations, particles & waves, wave function, Schrödinger equation), **Atoms** (electromagnetic spectrum, hydrogen atom, larger atoms, lasers), **Nucleus** (Rutherford scattering, nuclear structure, radioactive decay, reactors), and what we are interested in, **Elementary Particles** (groups of particles, conservation laws, quarks).

Manufacturer: Cross Educational Software
P.O. Box 1536
508 E. Kentucky Avenue
Ruston, LA 71270 USA
Phone: 318-255-8921 or 800-768-1969 voice or fax. VISA and Mastercard accepted.
Platform: Mac

Price:	$35	Single Copy
	$70	Network License

6. **Program Name: Interactive Physics**
Program Description: Versatile program allowing study of charged interactions and much, much more!

Manufacturer: Knowledge Revolution
66 Bovet Road, Suite 200

San Mateo, CA 94402
Fax: (415) 574-7541 Phone: (415) 574-7777 or (800) 766-6615
E-mail: info@krev.com

Platform: Mac or PC Windows
Price: $249

7. **Program Name: Relativistic Collisions**
Program Description: This program is graphically oriented and develops understanding and intuition about relativistic particle interactions. Particle collisions, pair creation, transformation, decay and the annihilation of particles moving in one or two spatial dimensions can be analyzed and solved.

Creator: Edwin F. Taylor - Massachusetts Institute of Technology
Manufacturer: Physics Academic Software
Box 8202
North Carolina State University
Raleigh, NC 27695-8202
Fax: (919) 515-2682 Phone: (800) 955-8275L or
`(919) 515-7447
or On-Line Ordering: http://www.aip.org/forms/pasorder.html

Platform: Mac or PC Windows

Price:	$80	Single Copy
	$320	10-Copy Lab Pack
	$400	High School Site License
ISBN:	PC Windows	0-88318-679-9
	Mac	0-88318-899-6

8. **Program Name: Modern Physics Simulations**
Program Description: The Consortium for Upper-Level Physics Software (CUPS) has developed a comprehensive series of nine book/software packages that Wiley will publish between September, 1994 and June, 1995. CUPS is an international group of 27 physicists, all with extensive backgrounds in the research, teaching, and development of instructional software, that have been carefully developing this series over the last three years.
Each package is comprised of a paperback text and one, two or three 3.5" diskettes. All of the computer simulations have been provided in executable form and, although they can be run without reading the text, the text is necessary to achieve an understanding of the underlying physics and for exploring alternative ways to use the programs. The individual chapters and computer programs cover "mainstream" topics that are found in the standard textbooks for each course. Modern Physics Simulations cover: Historic Experiments in Electron Diffraction, Laser Cavities and Dynamics, Classical Scattering, Nuclear Properties and Decays, Special Relativity, Quantum Mechanics, and Hydrogen Atom and the h2+ Molecule.

Creators: Douglas Brandt, Eastern Illinois University, John Hiller, University of Minnesota @Duluth, Michael Moloney, Rose Hulman Institute.
Manufacturer: John Wiley & Sons, Inc.
One Wiley Drive
Somerset, NJ 08875
Please call 1-800-JWILEY-NET (594-5396) to order.

Platform: PC
ISBN: 0-4711-54882-0

9. **Program Name: Nuclear and Particle Physics Simulations**
Program Description: *Nuclear and Particle Physics Simulations* cover: Nuclear Energetics and Counting, Nuclear Shell Model, Interaction of Radiation with Matter, Electron-Nucleus Scattering, The Two-Nucleon Problem, Relativistic Kinematics Particle Detector Simulation.

Creators: Roberta Bigelow, Willamette University; John Philpott, Florida State University, and Joseph Rothberg, University of Washington.
Manufacturer: John Wiley & Sons, Inc.
One Wiley Drive
Somerset, NJ 08875
Please call 1-800-JWILEY-NET (594-5396) to order.
Platform: PC
ISBN: 0-471-54883-9

10. **Program Name: Spacetime**
Program Description: Time dilation, Lorentz contraction, the twin paradox, and the Doppler shift are all covered. It introduces special relativity, performs mathematical calculations, and comes with a user's manual that contains interesting projects and exercises that will reinforce student understanding of special relativity.

Creator: Edwin F. Taylor - Massachusetts Institute of Technology
Manufacturer: Physics Academic Software
Box 8202
North Carolina State University
Raleigh, NC 27695-8202
Fax: (919) 515-2682 Phone: (800) 955-8275L or (919) 515-7447
or On-Line Ordering http://www.aip.org/forms/pasorder.html
Platform: Mac or PC Windows

Price:	$90	Single Copy
	$360	10-Copy Lab Pack
	$450	High School Site License
ISBN:	PC Windows	0-88318-676-4
	Mac	0-88318-897-X

11. **Program Name: RelLab**
Program Description: You can create simulations of physical systems in two space dimensions and view them in real time. You can design any scenario imaginable, as long as it does not violate the presently known laws of nature. Good graphics and simulations.

Creators: Paul Horwitz, Edwin F. Taylor, Kerry Shetline, BBN Systems and Technologies: Bolt Beranek and Newman.
Manufacturer: Physics Academic Software
Box 8202
North Carolina State University
Raleigh, NC 27695-8202
Fax: (919) 515-2682 Phone: (800) 955-8275L or (919) 515-7447
or On Line-Ordering http://www.aip.org/forms/pasorder.html
Platform: Mac

Price:	$90	Single Copy
	$360	10-Copy Lab Pack
	$450	High School Site License
ISBN:	Mac	1-56396-160-1

INTERNET SITES FOR HIGH-ENERGY PHYSICS WWW PAGES

1. **Fermi National Laboratory** has set up a home page that is updated with high-energy sites regularly. It can be accessed at:
   http://www-ed.fnal.gov/samplers/hsphys/tmp_int_rcs.html

2. **The Particle Adventure** - An Interactive Tour of the Inner Workings of the Atom and the Tools for Discovery. Sponsored by Contemporary Physics Education Project (CPEP) and Particle Data Group. It can be accessed at:
   http://www-pdg.lbl.gov/cpep/adventure.html

3. **The Particle Physics Booklet** - Table of Contents to Images high-energy physics Database. It can be accessed at:
   http://www-pdg.lbl.gov/rpp/booklet/contents.html

ANNOTATED BOOKS

The following printed material is arranged in two large groupings. First, books are listed followed by articles. In all cases, the following can serve as a rating guide for a high school teacher creating a unit in particle physics.

* = BEST (Annotations provided by Andria Erzberger and Patrick LaMaster)
E = EASY
D = DIFFICULT

REFERENCE BOOKS

1. D - *Readings from Scientific American: Particles and Forces at the Heart of the Matter*, Richard A Carrigan and W. Peter Trower, W. H. Freeman and Co., New York, 1990. A collection of articles on particles physics from the years 1970 to 1989.

2. E - *Scientific American Sourcebooks: The World of Atoms and Quarks*, Albert Stwerka, twenty-first Century Books, Division of Henry Holt and Company, New York, 1995. A good review of the subject from atoms to The Standard Model.

3. E - *Particle Physics: The New View of the Universe*, Christopher Lampton, Enslow Publishing, Hillside, NJ, 1991. An overview of the history of discovery in particle physics.

4. E* -*The God Particle*, Leon M. Lederman, Houghton Mifflin Co., New York NY, 1993. An excellent, well-written and humorous look at the history and evolution of scientific discovery in an effort to understand the nature of the universe. Very readable.

5. D - *Taming the Atom*, Hans Christian von Baeyer, Random House, New York, 1992. A look at understanding the atom including past, present and future possibilities.

6. D - *Atom*, Isaac Asimov, Truman Talley Books, Dutton, New York, 1991. 300 pages. A rigorous and complete summary of modern physics.

7. E - *Atoms, Molecules and Quarks*, Melvin Berger, G. P. Putnam's Sons, New York, 1986. A look to understand atoms to quarks with an emphasis on experimental evidence.

8. D - *It's All Elementary*, Necia H. Apfel, Lathrop, Lee and Shepard Books, New York, 1985. A history of the discovery of the structure of matter.

9. E - *Lonely Hearts of the Cosmos: The Scientific Quest for the Secrets of the Universe*, Dennis Overbye, Harper Collins, 1991. The title says it all.

10. * - *The Particle Explosion*, Close, Marten and Sutton, Oxford University Press, 1987. Large format with many photos. Odd numbered chapters describe in more detail the discoveries discussed in the other chapters. Applications of modern physics.

11. * - *The Second Creation*, Robert Crease and Charles Mann, MacMillian, New York, 1986.
Very readable story, much from interviews with the people involved in modern physics.

12. E - *Superforce*, Paul Davies, Simon and Schuster, New York, 1984.
Easy reading about cosmology, particles, strings.

13. D*- *The Ideas of Particle Physics - An Introduction for Scientists*, J. E. Dodd, Cambridge University Press, Cambridge, England, 1984.
"bridges gap between textbooks on particle physics and popular accounts" glossary, good bibliography.

14. D - *QED*, Richard Feynman, Princeton University Press, Princeton, NJ, 1985.
Probability diagrams for photons, electrons, interactions, QED, a little on quarks.

15. * - *Particle Hunters*, Yuval Ne'Eman and Yoram Kirsh, Cambridge University Press, Cambridge, England, 1986.
Non-mathematical history from electrons to W and Z by two physicists.

16. D*- *Inward Bound*, Abraham Pais, Clarendon Press, Oxford, 1986.
History from x-rays to 1983, including personal insights of why discoveries happened. More detailed than Segre's.

17. *From X-rays to Quarks*, Emilio Segre, W. H. Freeman and Co., San Francisco, 1980.
History and personal reminiscences from Becquerel to Weinberg and Salam.

18. E - *The Particle Connection*, Christine Sutton, Simon and Schuster, New York, 1984.
Story of search for W and Z particles. Starts with overview.

19. *Story of W & Z*, P. M. Watkins, Cambridge University Press, Cambridge, England, 1986.
A member of the CERN team, he tells of the work leading to the particles. This reference is especially good on accelerators and detectors.

20. *Elementary Particles - Supplemental Unit A for Project Physics Course*, Haven Whiteside, Holt, Rinehart, and Winston, New York, 1971.
(Out of Print)

21. *Fearful Symmetry*, A. Zee, MacMillian, New York, 1986.
"Then I heard about Noether's insight and I was profoundly impressed." ". . . most memorable in my years as a scientist."

ADDITIONAL REFERENCE BOOKS (In the Popular Press)

1. *The Cosmic Onion: Quarks and the Nature of the Universe*, F. E. Close, Heinemann Educational Books, London and Exeter, NH, 1983.

2. *Quarks*, H. Fritsch, Basic Books, New York, 1983.

3. *Particle and Fields, Introduction by William Kaufmann*, Readings from Scientific American, W. H. Freeman & Co., New York, 1980.
   Articles by Schrodinger, Gell-Mann, Glashow, Weinberg, et al. span the 1953-1979 period.

4. *Physics Through the '90's: Elementary Particle Physics*, National Academy Press, Washington, 1986.

5. *From Atoms to Quarks*, J.S. Trefil, Charles Scribner's Sons, New York, 1980.

6. *The Discovery of Subatomic Particles*, Steven Weinberg, W. H. Freeman and Sons, San Francisco, 1983.

ANNOTATED ARTICLES

1. "Resource Letter NP - 1: New Particles", Jonathan Rosner, *American Journal of Physics*, Vol. 48, No. 2, February, 1980, page 90+.
   Some mention is made of pre-1974 articles, but emphasis is on 1974-1979. Items are classed as elementary, intermediate, and advanced.

2. "Gauge Theories of the Forces between Elementary Particles," Gerrard t'Hooft, *Scientific American*, Vol. 242, No. 6, June, 1980, page 104+.
   This article provides an extensive look at the application of gauge theories to understand elementary particles and their interactions. There are numerous excellent diagrams. This article is more advanced than Hill's "Science Teacher" articles of 1982.

3. "A Unified Theory of Elementary Particles and Forces," Howard Georgi, *Scientific American*, Vol. 242, No. 4, April, 1980, page 104+.
   The article details a grand unification theory of the electromagnetic, weak, and strong forces. The level is intermediate to advanced.

4. "Quarks and Leptons - It's Elementary," Christopher Hill, *Science Teacher*, September, 1982, page 22+.
   Hill provides an easily read introduction to the basic particles of nature.

5. "Gauge Bosons - The Ties that Bind," Christopher Hill, *Science Teacher*, October, 1982 page 7+.
   The role and nature of the interaction particles in mediating the electromagnetic, weak, and strong forces are examined. The presentation is elementary.

6. "The Structure of Quarks and Leptons," Haim Harari, *Scientific American*, April, 1983, Vol. 248, No. 4, pages 56-68.
   A discussion of possible prequark theories (preons, rishons, ...) is presented along with

possibilities for experimental verification.

7. "The Eleventh Dimension," Paul Davies, *Science Digest*, Vol. 92, No. 1, January, 1984, page 72.
Many believe one can only make sense of the subatomic world in the context of a multi-dimensional universe. It is suggested that gravitational, electromagnetic, strong, and weak forces are warps in a multidimensional-space.

8. "CERN: The World's Capital of High-Energy Physics," Charles Mann & Robert Crease, *Science Digest*, Vol. 92, No. 9, September, 1984, page 51.
A brief insight into the men and machines involved in particle physics. It should be interesting reading for students not interested in the technical development of the topic.

9. "The Ultimate Theory of Everything," Gary Taubes, *Discover*, Vol. 6, No. 4, April, 1985, page 52+.
Gives general insight to the growth of particle physics through the interplay between experiment and theory. From the experimentally verified W and Z particles to super-symmetry, this is a good article for student reading.

10. "Worlds Within the Atom," John Boslough, *National Geographic*, Vol. 167, No. 5, May, 1985, pages 634-663.
A wide-ranging historical overview of high-energy physics is given. The development of our ideas about particles and forces is presented at a level suitable for high school students.

11. "Is Nature Supersymmetric?", H. Haber & G. Kane, *Scientific American*, Vol. 252, No. 6, June, 1986, pages 52-60.
This article extends The Standard Model with supersymmetry theory. It details the properties of fermion and boson superpartners, and it discusses experiments needed to verify the theory. Use this article after you are comfortable with The Standard Model.

12. "Everything's Now Tied to Strings," Gary Taubes, *Discover*, Vol. 7, No. 11, November, 1986, pages 34-56.
In a ten-dimensional universe the fundamental buildingblocks of matter and energy are one-dimensional strings.

ADDITIONAL REFERENCE ARTICLES

1. "Elementary Particles and Forces," Chris Quigg, *Scientific American*, Vol 245, No. 4, April 1985.
This is an excellent must read for those seriously looking into particle physics for their classroom.

2. "The Weak Interaction," S. B. Treiman, Scientific American, Vol. 200, No. 3, March, 1959, page 72+.

3. "The Structure of the Proton and Neutron," H. Kendall & W. Panofsky, Scientific American, Vol. 224, No. 6, June, 1971, page 60+.

4. "The Search for New Families of Elementary Particles," D. Cline, A. Mann, & C. Rubbia, *Scientific American*, Vol. 234, No. 6, January, 1976, page 44+.

5. " Fundamental Particles with Charm," Roy Schwitters, *Scientific American*, Vol. 237, No. 4, October, 1977, p. 56+.

6. "Heavy Leptons," M. Perl & W. Kirk, *Scientific American*, Vol. 238, No. 3, March, 1978, page 50+.

7. "The Upsilon Particle," Leon Lederman, *Scientific American*, Vol. 239, No. 4, October, 1978, page 72+.

8. "The Search for Intermediate Vector Bosons," D. Cline, C. Rubbia, & S. van der Meer, *Scientific American*, Vol. 246, No. 3, March, 1982, page 48+.

9. "Of Quarks, Antiquarks, and Glue," Helen Quinn, *Stanford Magazine*, Fall, 1983, page 28+.

10. "To Understand the Universe," Leon Lederman, *Issues in Science and Technology*, Summer, 1985, page 55+.

11. "Elementary Particle Physics and The Superconducting Super Collider," Christopher Quigg and Roy Schwitters, *Science*, Vol. 231, No. 4745, March 28, 1986, pages 1522-1527.

12. "Superstrings," Michael Green, *Scientific American*, Vol. 252, No. 3, September, 1986, page 48+.

13. "The Higgs Boson," Martinus Veltman, *Scientific American*, Vol. 253, No. 5, November, 1986, page 76+.

14. "Mirror, Mirror," Phil Yam, *Scientific American*, Vol. 275, No. 1, July, 1996.

15. "The Tevetron," Leon Lederman, *Scientific American*, Vol. 264, No. 3, March, 1991, page 48.

16. "Beyond Truth and Beauty," Dave Cline, *Scientific American*, Vol. 259, No. 2, August, 1988, page 60.

17. "Particles of History," I. Peterson, *Science News*, Vol. 142, September 12, 1992, page 174-5.

18. "Your the Top," Phil Yam, *Scientific American*, Vol. 271, No. 1, July, 1994, page 24.

19. "Evolution of the Universe," P. James Peebles, *Scientific American*, Vol. 271, No. 4, October, 1994, page 52-57.

PHYSICS FOLKLORE

By Lynne Zielinski

Sometime after World War II physicists began to change their way of giving names to theoretical ideas. Before then, new ideas were given titles such as "special relativity theory" or "neutrons." A precursor of the new kinds of names came in 1953 when Murray Gell-Mann and Kazuhiko Hishijima decided to name one of the properties of subatomic particles "strangeness." Gell-Mann accelerated the trend in 1961 by calling his group-theoretic way of explaining the properties of particles "The Eight-Fold Way." Gell-Mann's crazy names finally reached the consciousness of the general public in 1964 when he described the particles involved in the next stage of his thinking as "quarks." pg. 508, source B

Where did the names of the particles come from? Oftentimes physicists are whimsical in naming things, as termed by Chuck Brown, "they are random and poetic in nature." So, below, in alphabetical order, I've done my best to try to give you the true origin of the various particle names.

atom -
Troubled by the apparent "chaos" of the everyday world, ancient Greek philosophers sought an underlying order, or "cosmos," in nature. Leucippus and Democritus viewed the world as composed of tiny particles, or "atoms"--from the Greek word "atomos" for "uncuttable" or "indivisible."

baryon -
Baryon number is something that only heavy particles could have, therefore baryon was taken from the Greeks because baros means "heavy."

bosons -
Particles that obey the statistical system set up by an Indian physicist M. K. Bose were originally called "Bose particles," and the name was later shortened to "boson."

cascade particle (X) -
This particle denoted by the Greek letter "xi" was called the "cascade" because it decayed into a cascade of lighter fragments. pg. 64, source D

charm -
In 1964, Glashow had written an article with Bjorken suggesting a possible fourth quark. "We called our construct the 'charmed quark,'" recalled Glashow, "for we were fascinated and pleased by the symmetry it brought to the subnuclear world." Later in 1974 Glashow was pushing scientists to find the charm. In doing so, he stated at a conference that there were three possibilities: "One, charm is not found, and I eat my hat. Two, charm is found by spectroscopists, and we celebrate. Three, charm is found by "outlanders" (other kinds of physicists who did neutrino scattering or measured electron-positron collisions in storage rings), and you eat your hats." pg. 210, source D

In 1976, charm was found by "outlanders," and a year later Glashow gave a rabble-rousing talk titled "Charm Is Not Enough." Then they all had a big laugh as the spectroscopists present finally ate their hat --Mexican candy hats supplied by the organizers. pg. 321, source D

color -
In the autumn of 1971, Gell-Mann and Harald Fritszch began trying to understand how neutral pions decayed. However, these particles decayed nine times too quickly. On the other hand, this

small problem would not occur if each quark came in three different kinds, increasing the decay rate ninefold. In this picture, each quark had to have some new physical property, something that made them in fact different, which Gell-Mann with characteristic aplomb dubbed merely color. It was a 'natural choice,' he recalled. With Feynman in the late 1950s, he had advocated 'red' and 'blue' neutrinos to distinguish two different kinds of these ghosts, names that never caught on. Now he resurrected the old terminology and applied it to quarks, which henceforth came in red, white, and blue varieties. He did not mean that quarks actually had visible colors; that was absurd. "Color" was just another name among many, plucked from everyday discourse to help physicists communicate. Next, it was found that the grouping of quarks had to combine so that they became "colorless"--that is, have zero net color. Because of this, physicists later adopted a new terminology of red, green, and blue quarks over Gell-Mann's original, more patriotic choice because red, green, and blue light can add up neatly to give white, colorless light. pg. 228-229, source D

eight-fold way -
In 1961, Gell-Mann reached into Chinese literature to christen his classification scheme the "Eight-fold Way," a name that soon captured the imagination of physicists around the world.
The phrase comes from an aphorism attributed to Buddha, about the appropriate path to Nirvana:

> Now this, O monks, is noble truth that leads to the cessation of pain;
> this is the noble Eightfold Way: namely, right views, right intention,
> right speech, right action, right living, right effort,
> right mindfulness, right concentration. pg. 90-91, source D

pg. 508, source B
pg. 106, source C

fermion -
Particles that obey the statistical system set up by Enrico Fermi were originally called "Fermi particles" and later shortened to "fermions."

flavors -
Although the names used currently for the original three quarks are only a little peculiar--up, down, and strange--they also were known at one time as vanilla, chocolate, and strawberry. This accounts for the different kinds of quarks being called different flavors of quark. pg. 508, source B

gluons -
Gluons are the "glue" that holds the partons together in the nucleons. pg. 508, source B

hadron -
Hadron comes from the Greek word hadros meaning "thick" or "heavy." pg. 54, source C
The implication here is that it is a "strong particle," and these particles are thus named because they interact strongly. pg. 12, source C

isospin -
The word isospin is a combination of isotope, meaning "same form," and spin. pg. 54, source C

J/Y particle -
The J/Y particle is a combination of two names. J was the name given to the particle by S. Ting's group at MIT. Y was the name given to the particle by B. Richter's group at SLAC. Each group had found the particle independently and almost simultaneously. As the story goes . . .

On Sunday, November 10, 1974, after searching for the charm quark around 3 GeV, B. Richter's group found a peak at 3.105 GeV. Richter called one of his friends, Bjorken, just as BJ had sat down to dinner and gave him the startling news. "I couldn't believe such a crazy thing was so low in mass, was so narrow, and had such a high peak cross-section," Bjorken recalled. "It was sensational." He returned to the table a few minutes later, seemingly in a daze. His wife and children then watched open-mouthed as he unthinkingly heaped a large tablespoon of horseradish onto his baked potato and quietly began munching away, staring absent-mindedly off into space. "BJ," his wife finally counseled, "I think you'd better go down to the lab now."

As the word of the fantastic discovery leaked out into the SLAC community, a crowd of happy onlookers began to gather in the SPEAR control room. Somehow amid the euphoria, the physicists remembered the champagne. It ran low real fast, plus a shortage of glasses. Recruits departed for more supplies. Meanwhile, Goldhaber's original draft of the discovery paper had been made a shambles by more recent data, so Richter began writing another version. The new particle needed a name, and he first tried calling it the "SP" after the first two letters of SPEAR. But nobody liked that very much, so Richter went over to Leo Resvanais, a Greek physicist with the University of Pennsylvania and asked him what Greek letters were still unused. Resvanais went down the list alphabetically, until he came to iota, but Richter didn't like that very much because it also meant something small, which this discovery was clearly not. The next available letter was psi, or Ψ, which Richter thought might be confused with the Greek symbol for the wave function, but Resvanais told him that psi was a good choice because this discovery was certainly something big (psi's meaning). Most of the others liked the name, especially after Goldhaber pointed out that it contained the letters s and p in reverse order.

Meanwhile Ting was unaware of the rumors circulating at Brookhaven about the particles's discovery. His own discovery of the same particle had been achieved on October 31. On November 4 or 5, Ting showed his results to Weisskopf who told him he was crazy not to publish immediately. Ting, however, wanted to be very careful and make certain that he wasn't in error. By coincidence, on November 10, Ting was headed for SLAC for a scheduled meeting. Unaware of the rumors circulating at Brookhaven, Kycia asked Ting if he had discovered anything yet. Ting replied no. Little did Ting know then of the rude shock awaiting him in California. While Ting was in flight, his group at Brookhaven heard the news. Ting called in at 1 a.m., and his experimenters had convinced themselves that this was just a lousy practical joke being played on them. Ting, however, agreed to check it out anyway when he got to SLAC the next day. But immediately after he arrived at his motel, Ting received a call that SLAC had indeed discovered a resonance. Worried now, Ting called Stanley Brodsky, a SLAC theorist he knew, and learned that yes, indeed, there had been a big discovery that would be announced tomorrow. For Ting, it was the moment of truth. He was about to be scooped on the greatest discovery of the year, if not the decade. His weeks of cautious silence now had to be undone overnight. The battle began, each group trying to get the paper in first. By the time Ting's paper was written, Ting had dubbed his particle the "J," a letter that closely resembled the Chinese ideogram for Ting. pg. 276-289, source D

The touchy issue of what to call the first particle, J or psi, had been smoldering ever since it became obvious that each group was sticking by its own name. So physicists began deliberately using the dual label J/Ψ in their talks and papers, to avoid getting caught in the crossfire. This was the label that stuck.

Just as a side note, in the first few months the contest over which name to use seemed to be fairly good-natured. Ting's troops began to offer and wear T-shirts with "J-3.1 GeV" emblazoned on the front. SLAC-LBL physicists kidded that "the particles themselves preferred the Ψ label." To prove their point they passed around photos of a computer display showing a Ψ disintegrating into two pions and the two muons. The four visible tracks had arranged themselves neatly into the four arms of a near-perfect letter psi. pg. 311-313, source D

lepton -
Lepton comes from the Greek word meaning "light" (opposite of heavy) or "small." It was originally the name of a small Greek coin. pg. 53, source E, pg. 183, source A

meson -
The meson was originally called the "X-particle" by Carl Anderson and Seth Neddermeyer. Eventually it was found to be a middleweight particle, or "middle particles" between the light lepton and the heavy baryon. The Caltech group promoted the name "mesotron" for it, from the Greek "mesos" for "intermediate" or "middle." This was the name generally used, although the particle was also called the "meson" or "heavy electron" in Europe. pg. 50-51, source D, pg. 183, source A

muon -
Cecil Powell used the nomenclature more common to Europe to name the light particle the "mu-meson" or "m-meson" from the Greek letter "mu" or "m." Today the name has been shortened to "muon." pg. 52, source D

neutrino -
In 1930, Pauli postulated that an invisible particle was emitted during radioactive beta decay along with the electron, which carries off missing energy and angular momentum. The original reaction conserved electric charge so the new particle must be neutral. On the strength of this, Fermi called it the neutrino. Neutrino is the Italian word for "little neutral one" and is denoted by the Greek letter "nu" or "u." pg. 67, source D; pg. 40, source A

omega particle (W) -
If the eight-fold way was true, then theory suggested that there had to be a tenth baryon resonance, since nine had been previously found. The Greek letter omega (W) seemed an appropriate choice by Gell-Mann for this final member of the baryon decimet because it was the last letter in the Greek alphabet.

parton -
Parton means "partial particles." R. P. Feynmam called them partons because the hadron was made of many particles.

pion -
Cecil Powell used the nomenclature more common to Europe to name this heavy particle the "pi-meson" or "p." Today, it has been shortened to pion. pg. 52, source D

positron -
Carl Anderson, a postdoc under Robert Millikan, had been working alone, taking photographs o cosmic ray tracks at Caltech. Anderson showed a curious photo to Millikan, who agreed with Anderson that the track shown could only be positive. They dubbed the particle the "positron," for "positive electron."

quark -
The quark model was introduced independently by M. Gell-Mann and G. Zweig in 1964. Gell-Mann called the triplet of the new particles "quarks," and Zweig called them "aces," like the aces in playing cards. pg. 104, source C

Gell-Mann's crazy names finally reached the consciousness of the general public in 1964 when he described the particles involved in the next stage of his thinking as "quarks." Gell-Mann and

Zweig pointed out that the representations of SU(3) [Special Unitary group of transformations of dimension 3] which were occupied by particles, could be chosen from among all those mathematically possible by assuming them to be generated by just two combinations of the fundamental representation. pg. 57, source A; pg 508, source B

Gell-Mann called the entities in the fundamental representation quarks. This is the rather idiosyncratic use of a German word meaning curds or slop (abstracted for this purpose from the novel *Finnegan's Wake* by James Joyce). And this is how it all began . . . .

Gell-Mann had a luncheon conversation with Columbia theorist Robert Serber, Tsung Dao Lee, and others. While they were eating, Serber mentioned why a fundamental triplet did not appear in nature. According to Serber, Gell-Mann's immediate reply was, "That would be a funny quirk!" Tsung Dao Lee chimed in, calling it "a terrible idea." Pulling out pen and napkin, Gell-Mann showed Serber why. Such a triplet, if it existed at all, had to have fractional charges of 2/3, -1/3, and -1/3. Serber had to agree that these were odd birds, indeed; ever since Robert Millikan's famous oil-drop experiment, nothing but whole-number charges had ever been observed.

While a visiting lecturer at MIT that year, Gell-Mann had been seeking a simple basis for the Eight-fold Way. He knew about triplets but always passed them over without much thought because of the fractional charges involved. Serber's offhand query now catalyzed his thinking. Later that evening and the following morning, Gell-Mann began to realize that fractional charges were not completely absurd--as long as they could never appear in nature. Gell-Mann began calling these whimsical motes quorks, a nonsense word he had used previously, in the spirit of Lewis Caroll, to mean "those funny little things." Serber thought it was a play on the word quirk used at lunch. Whatever the case, Gell-Mann mentioned these quorks in his next lecture, giving Serber credit for proposing the fundamental triplet. Although he quickly moved on to other topics, quorks were a favorite subject of discussion at the subsequent coffee hour. Gell-Mann was in no great hurry to publish the quork idea. There were a number of puzzles to resolve, and he had other commitments demanding his attention. Back at Caltech that fall, he began working out the details in earnest. In a phone call to his old MIT thesis adviser, Victor Weisskopf, Gell-Mann mentioned he was working on a new and exciting idea: that baryons and mesons were composed of three fractionally charged entities. "Please, Murray, let's be serious," came Weisskopf's reply. "This is an international call."

By then the widely read theorist had found a telltale passage in James Joyce's enigmatic novel *Finnegan's Wake* :

> Three quarks for Muster Mark!.
> Sure he hasn't got much of a bark,
> And sure any he has it's all beside the mark.
> But O, Wreneagle Almighty, wouldn't un be a sky of a lark
> To see that old buzzard whooping about for uns shirt in the dark
> And he hunting round for uns speckled trousers around by Palmerston Park?

This poem is the drunken dream of Humphrey Chimpden Earwicker as he lies passed out on the floor of his Dublin tavern. Gell-Mann happily borrowed the quark spelling for his imaginary triplet. No doubt he also enjoyed the irony of the last few lines. There is an obvious parallel between the trials of Muster Mark and the seemingly hopeless plight of eager experimenters who would inevitably go searching for motes they could never possibly find.

Meanwhile at Caltech, George Zweig was reading publications of bubble chamber experiments in 1963 and was puzzled as to why some particles elected to decay by the most difficult path available. He first guessed that a conservation law was at work because it was the only one allowed. While fiddling with group theories, Zweig inadvertently discovered that he could get collections of particles if baryons were built from three constituents with fractional charges.

At first, it seemed an artificial solution. Then things began to fall into place. That fall at CERN, Zweig wrote up his discoveries for publication, calling his fractionally charged particles aces. Mesons, which were built from pairs of these aces, formed the deuces and baryons the treys in his deck of cards. Just cut the deck, shuffle the cards, and you could deal all kinds of poker hands. pg. 102-104, source D

Just so I don't leave you hanging, I don't know the reason why the name quark beat out the name aces. But I do know that while the two theories were essentially the same physics, stylistically they were poles apart. Sorry! (If you do find out, please tell me.)

strange -
In 1947, the English physicists G. D. Rochester & C. C. Butler observed new particles which were a thousand times more massive than the electron. These particles were often associated with V-shaped tracks; they were at first called V particles. Their origin and purpose were an entire mystery. For the following six years, the V particles were observed, and two kinds became apparent. Those whose decay products always include a proton and are called hyperons, and those whose decay products consist only of mesons are called K mesons or kaons. The hyperons and kaons soon became known as the strange particles because of their anomalous (strange) behavior. pg. 49-50, source A

Originally, strangeness was introduced to explain why some hadrons decay quickly by the strong nuclear force while others decay slowly by the weak force. pg. 185, source A

Strange came from the fact that something "strange" was going on with a third particle that was neither an up nor a down quark. (Drasko Jovanovic) Lacking any good explanation, theorists simply dubbed them "strange" particles, a name that has survived to this day as the label for a completely new property of matter.

strangeness -
"Strangeness" is a term, a name, for a property of matter seen only in violent collisions of subatomic particles; it has no corresponding meaning in the everyday world of our senses that language was originally developed to describe. Physicists have had to create a new nomenclature in order to begin talking with each other about the weird subatomic landscape. One way they do so is to borrow words from everyday language and use them in entirely new ways.

top/bottom or truth/beauty -
As two more quarks came to be required in 1978 and following years, it was no longer surprising that some physicists would call the new ones beauty and truth. Theorists had predicted the quarks long before they were found, naming them the "t" and "b" quarks for top and bottom--varients of the labels "up" and "down." Top and bottom came from the fact that there had to be a pair of particles, heavier in nature, with up and down spins also. (Drasko Jovanovic)

The more whimsically inclined favored "truth" and "beauty," so that experimenters might begin the search for naked truth and beauty. However, at this point, more prosaic imaginations prevailed, so most physicists call beauty-bottom and truth-top. In any case, when physicists searched for the existence of the last two quarks to be named, they had an interesting choice as to how to describe their work to outsiders. Since the object was to find the beauty or bottom quark in undisguised form, they could choose to say they were looking for either "bare bottom" or "naked beauty." The search was serious, even if the names were playful. pg. 508, source B, pg. 331, source D

upsilon -
In 1975, Leon Lederman and his group finally began searching for particles like the J/Y with masses above 5 GeV. In 1976, they thought they had found one. Observing electron-positron pairs produced in the collisions of 400 GeV protons with beryllium nuclei, they found only

twenty-seven at high mass. But twelve of these pairs clustered around a mass of 6 GeV, suggesting the existence of a neutral, spin-1 particle. Lederman and company published their find, dubbing their particle the U. Upsilon was determined when Leon Lederman and his group at Fermilab were in a portacamp. Around 3 a.m. they tried to write down all the Greek letters that hadn't been used before. (Chuck Brown)

When they repeated the experiment that summer, however, the peak withered away. The peak must have been just a statistical fluctuation that had fooled the group. Jokes began to circulate around Fermilab that they had only discovered the "oops Leon." Not long after this, experimenters noticed another small bump. Once burned and twice shy, they checked their analysis and began preparing yet another experiment. In August 1977, Lederman presented the combined data revealing three peaks. He recommended calling these particles U, U', and U" as this label was obviously no longer needed for the 6 GeV peak. pg 329-330, source D

up/down -
Originally, depending on whether the spin of the nucleon (this is the quark part of the nucleon) was parallel or anti-parallel to the direction of the angular momentum, it was called up or down respectively. (Drasko Jovanovic)

W particle -
The W stands for "weak."

Z particle -
The Z means that there is "zero" charge.

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SOURCE B
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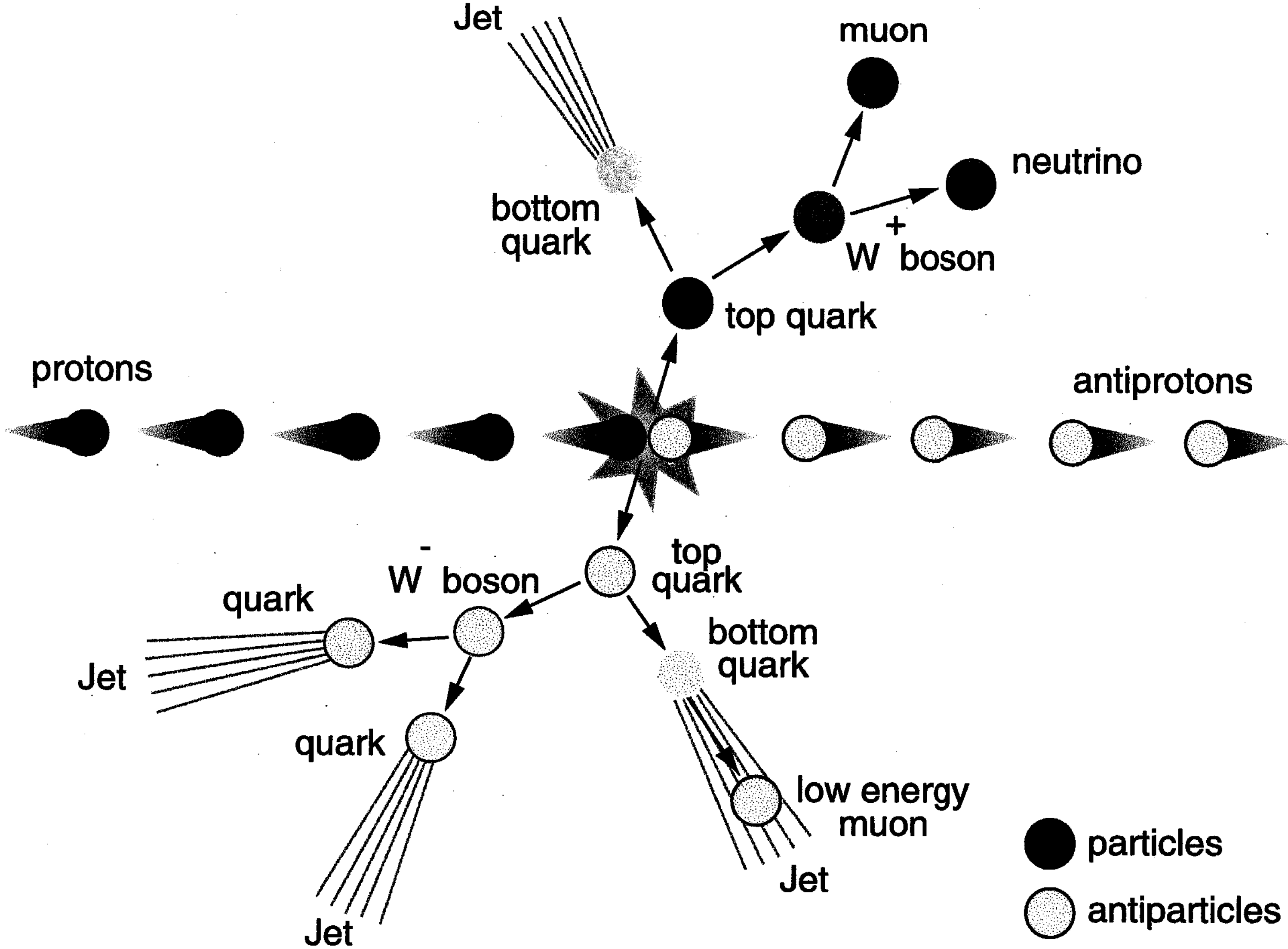
SOURCE C
Quarks - Frontiers in Elementary Particle Physics, Y. Nambu, World Scientific, Philadelphia, 1985.

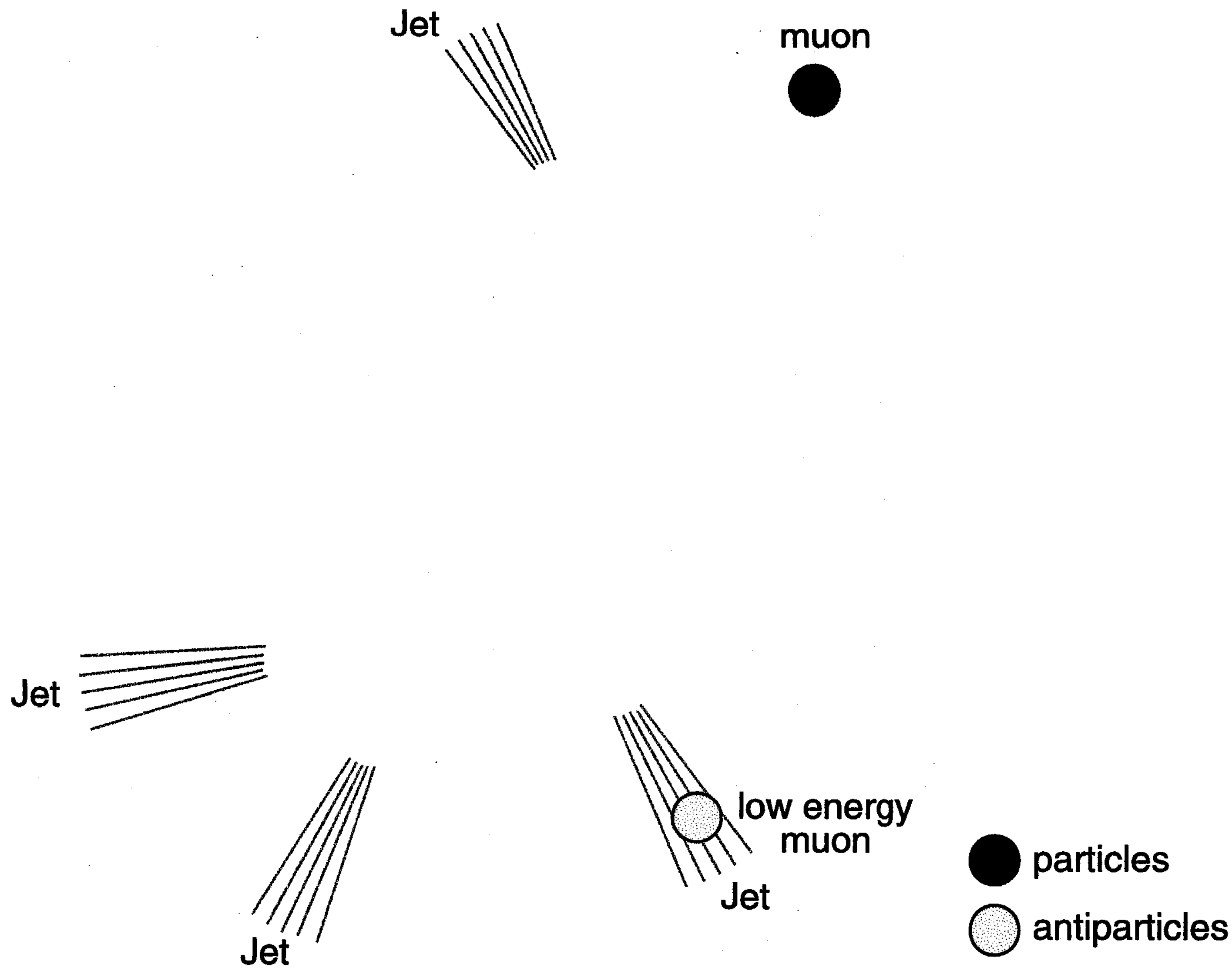
SOURCE D
The Hunting of the Quark, Michael Riordan, Touchstone Books, New York, 1987.

SOURCE E
The Cosmic Onion, Frank Close, Heinemann Educational Books, London, 1983.

Many of the stories were confirmed or told by the following people:
- Chuck Brown
- Drasko Jovanovic
- Leon Lederman

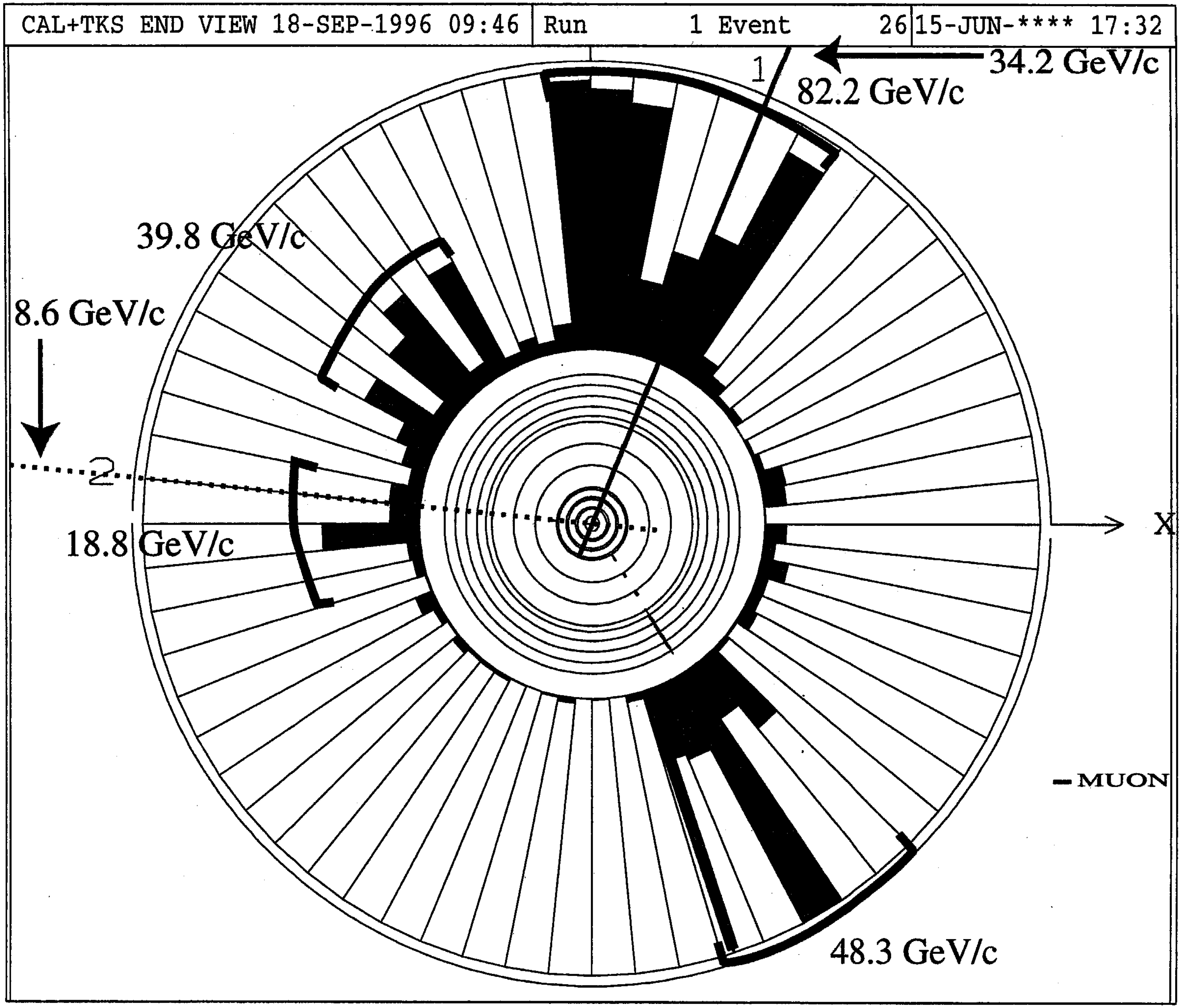


A Top Antitop Quark Event from the D-Zero Detector at Fermilab

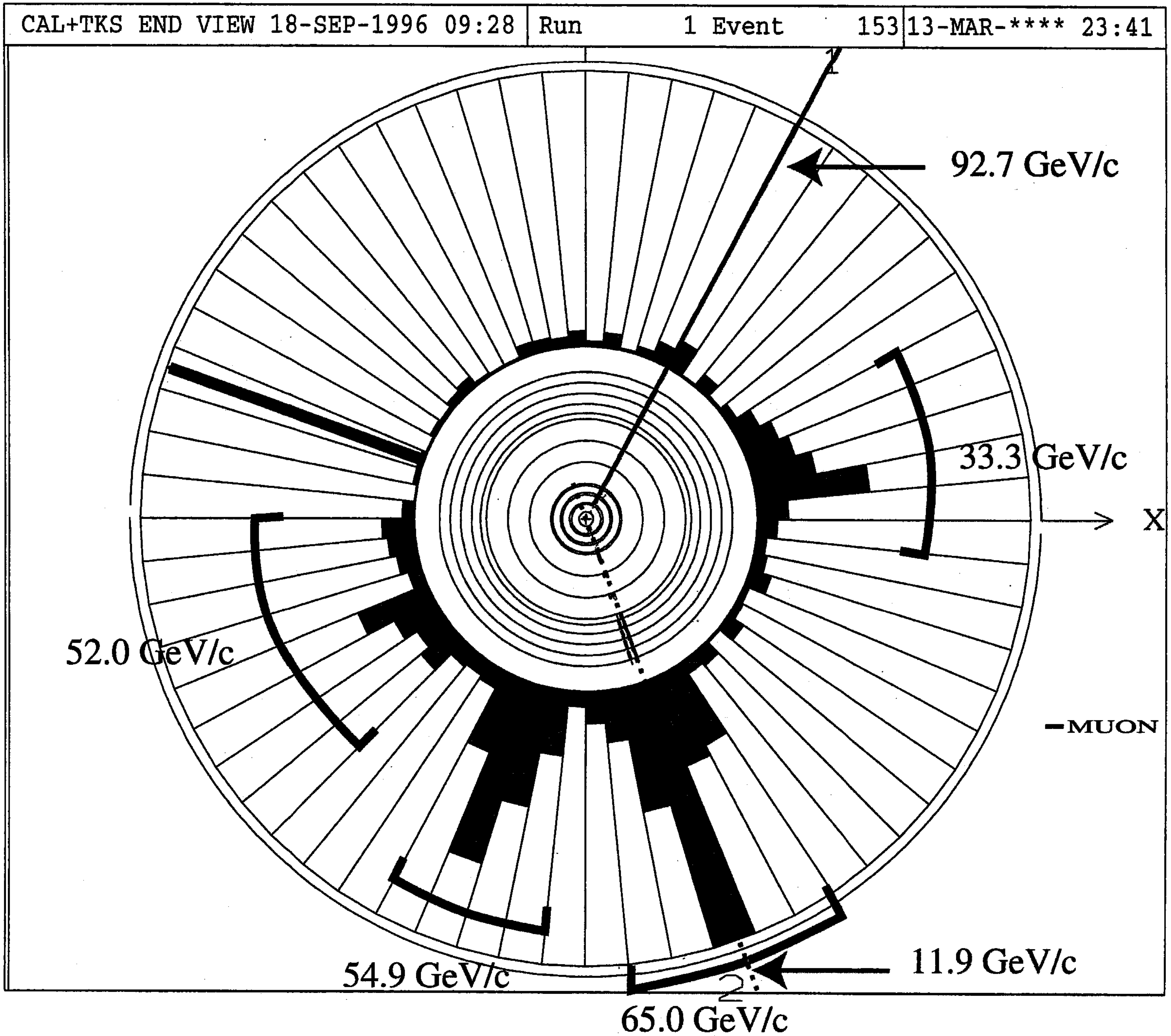


Particles Seen by the D-Zero Detector at Fermilab
in a Top Antitop Quark Event.

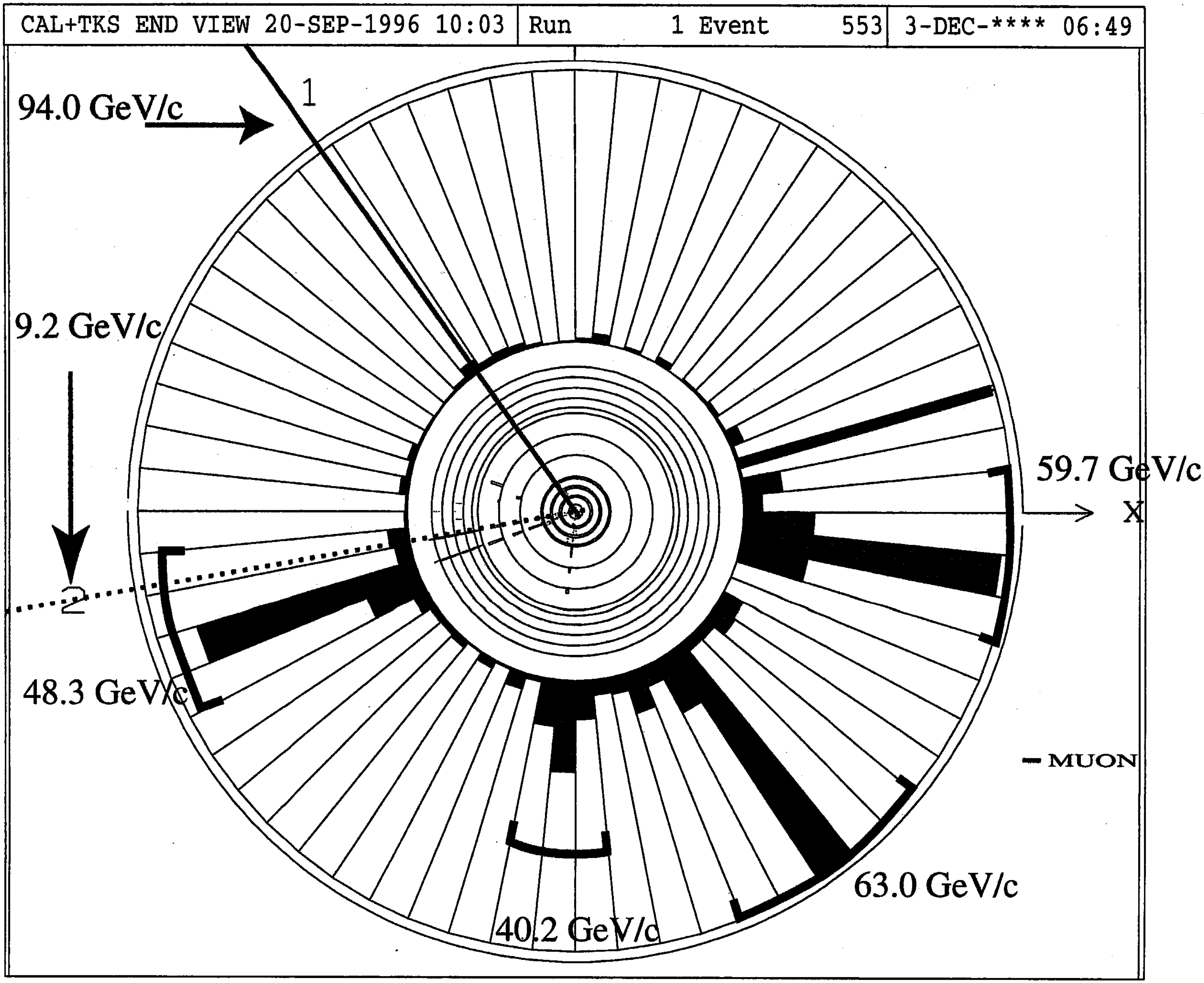
D-Zero Detector at Fermi National Accelerator Laboratory



D-Zero Detector at Fermi National Accelerator Laboratory



D-Zero Detector at Fermi National Accelerator Laboratory



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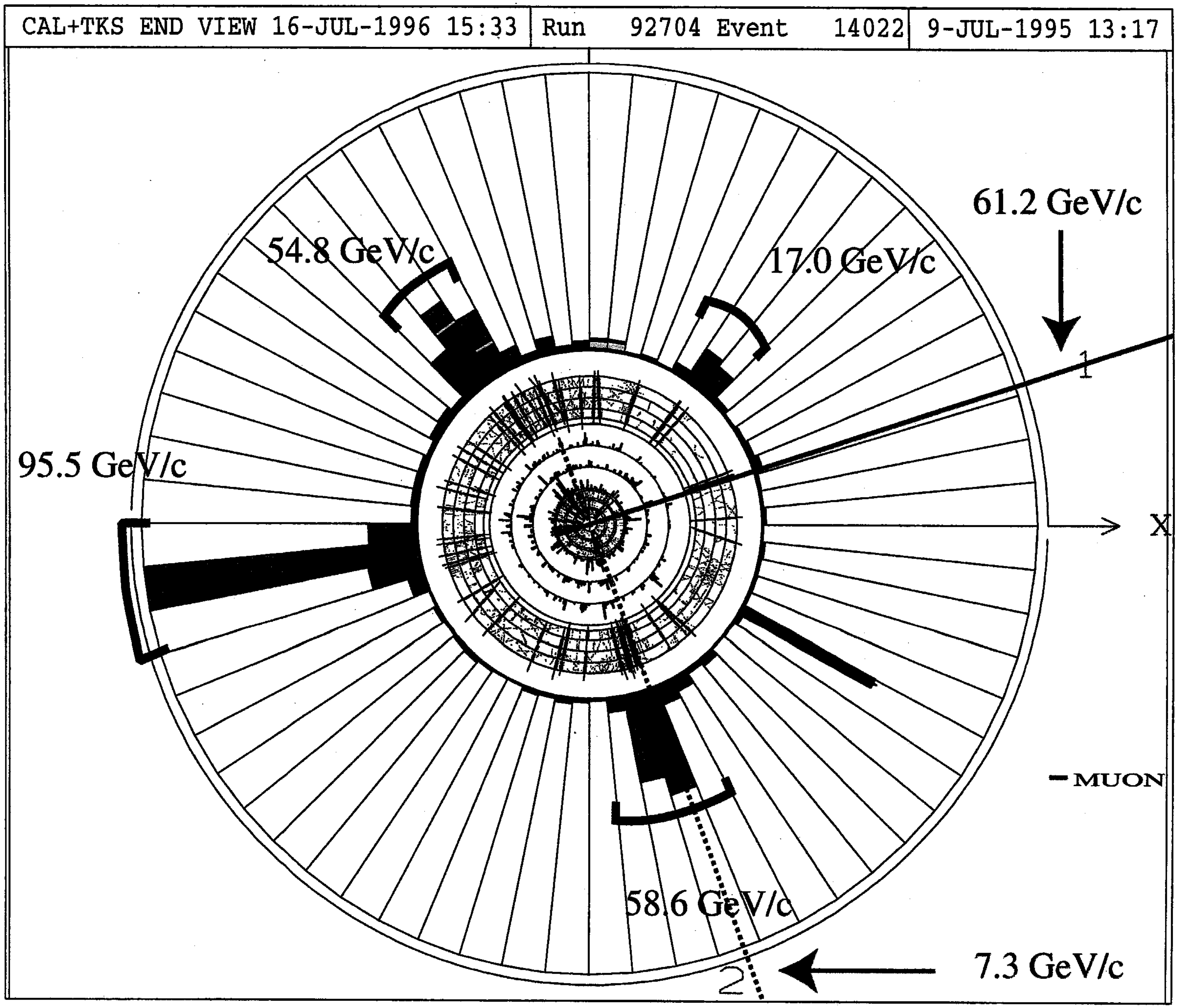

D-Zero Detector at Fermi National Accelerator Laboratory

Lego Plot

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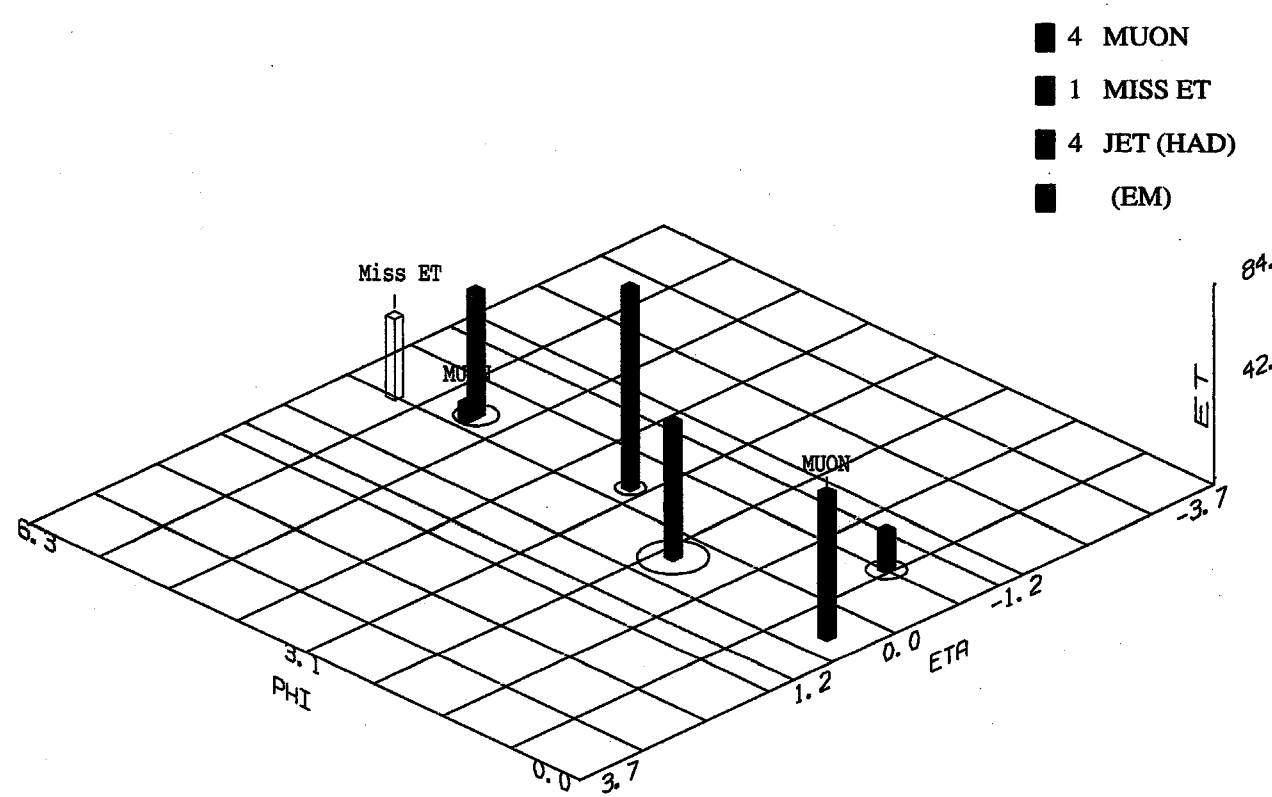

ET DST ETA-PHI

D-Zero Detector at Fermi National Accelerator Laboratory - Side View