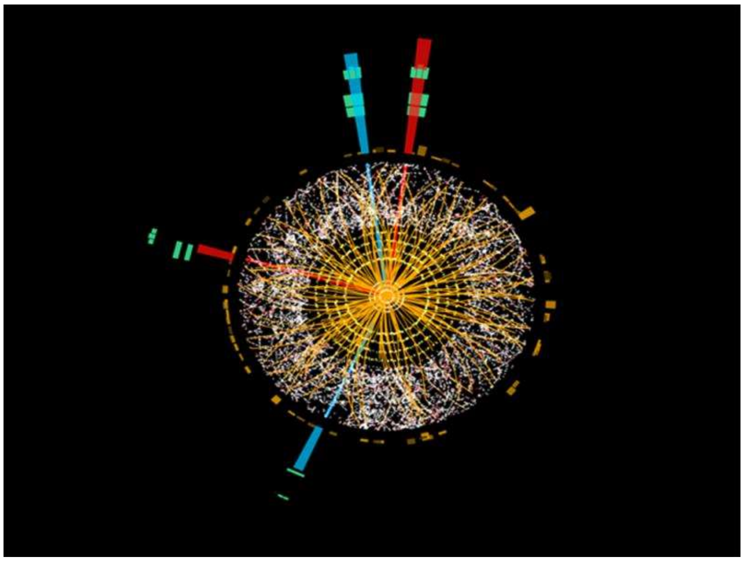


PARTICLE PHYSICS

ABSTRACT

Explore the exciting world of electrons, particles of light, the famous Higgs boson, and more. Learn about the fundamental forces and conservation laws that govern this world of particles, and, by extension, our world. In addition to the underlying physics concepts, Learn about how modern science is done by actually doing it. Work in teams to analyze real data from modern particle experiments such as the CMS experiment at CERN. Decide what particle to focus on and figure out how to separate collisions in which your particle is produced from background "look-alike" events. The skills you will develop, such as statistical analysis, are used not only by particle physics, but also by professionals in astronomy, genetics, epidemiology, and the new field of data science.

Brokk Toggerson
University of Massachusetts

Summer Pre-College
2016

Contents

University of Massachusetts
Amherst
4111 Hasbrouck Laboratory
666 North Pleasant St.
Amherst, MA 01003-9300

Department of Physics

voice: 413.545.2407
fax: 413.545.1691

July 11, 2016

Dear Student,

Congratulations on being admitted to the Summer Pre-College Particle Physics Course at UMass Amherst. I am very excited to meet all of you and explore together the exciting world of particle physics.

First a bit about me, I am a lecturer in the physics department here at UMass, Amherst with current interests in physics education. However, particle physics is really what got me excited about physics when I was in high school and thus I pursued a Ph.D. in the subject at University of California, Irvine on the ATLAS experiment at CERN's Large Hadron Collider.

Enclosed with this letter you will find a document detailing what we will be discussing. Also included is a course syllabus with what you need to bring and a rough schedule of our two weeks together. Please note that we will be having a poster session open to UMass faculty on the last day so you may want to dress accordingly (a golf or dress-shirt without tie type level would be my recommendation). The other days will involve a lot of activities so you will want to be comfortable. Please do not hesitate to email me at toggerson@physics.umass.edu if you have any questions regarding the course materials!

Looking forward to meeting you,

Brokk K. Toggerson

Brokk Toggerson

Lecturer
toggerson@physics.umass.edu
413.545.1761

Summer College Particle Physics Syllabus

Summer 2016
Dr. Toggerson

"Piled Higher and Deeper" by Jorge Cham. www.phdcomics.com

OFFICE: Hasbrouck Lab 133
EMAIL: toggerson@physics.umass.edu
PHONE: 413-545-1761

MEETING TIMES: July 11 – July 22; Daily from 9am until 4pm with a break for lunch at noon and other short breaks throughout the day.

MEETING LOCATION: Goodell 608

WHAT TO BRING: I would recommend a laptop if you have one. If you do not, there will be laptops in the room we are using, but you would probably want a small flash drive to save materials. I would also recommend a notebook (spiral is my preference but if you prefer loose-leaf) for thoughts, notes, etc. All other materials will be provided.

ABOUT THE PROGRAM: In this program you will be learning and working on the very frontiers of modern particle physics. We will go over the basic components of the Standard Model of particle physics and you will learn how about the statistical nature of modern physics analyses. Finally, you will be working in small teams (all particle physics is done in teams!) to do your very own analyses on real LHC data from the CMS experiment which you will present to your colleagues.

SCHEDULE: A sample schedule is attached to provide you with an idea of what we will be doing. I reserve the right to make changes if I deem it necessary.

COMPONENTS: 60% Labs and 40% project. ***Attendance to all lectures and labs is mandatory!***

HOMEWORK: We will run a journal club on a few articles and plots. I expect you to read these and come prepared to discuss them.

GRADING: 2 Credits. Pass/Fail

HONESTY POLICY: Students are expected to be familiar with and follow the Code of Student Conduct http://www.umass.edu/dean_students/codeofconduct and the Academic Honesty Policy http://www.umass.edu/dean_students/campus-policies

DISABILITY SERVICES: It is my and the University's goal that learning experiences be as accessible as possible. If you anticipate or experience physical or academic barriers based on disability, please let me know immediately so that we can discuss options. You are also welcome to contact Disability Services (413-545-0892) to establish reasonable accommodations. Please be aware that the accessible table and chairs in this room should remain available for students who find that standard classroom seating is not usable.

Tentative Schedule

Week 1	Monday	Tuesday	Wednesday	Thursday	Friday

Morning
9 – 11am
	• Welcome
	  ○ Overview
	  ○ Teams
	  ○ History of the Universe
	  ○ Fermi problems
	• UCards and other administration
		• Fermi problem
		• Overview of the particles of the Standard Model (SM)
		• Quark Workbench
			• Fermi problem
			• Overview of SM forces and the Higgs
			• Feynman diagrams
				• Fermi problem
				• Using data analysis techniques to learn about the composition of pennies statistical lab
					• Fermi problem
					• Background in searches for J/ψ
					• Classifying CMS events as *W*, *Z*, or h decay

	Lunch	Lunch	Lunch	Lunch	Lunch
Afternoon **1 – 4pm**	• Overview of α, β, and γ radiation • Units of particle physics • Cloud chambers and experimental design	• Detectors • Motion of a charged particle in a magnetic field	• Understanding measurement • Measuring the height of a building	• Relativistic math and conservation laws in the context of $t\bar{t} \rightarrow \ell\nu jj$ events	• Measuring the mass of the *Z*-boson using $Z \rightarrow \mu\mu$ decays
Week 2	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Morning **9 – 11am**	• Fermi • Where is the anti-matter? • Setting up projects	• Fermi problem • Dark matter and Supersymmetry • Work on projects	• Fermi problem • Interview with physicist at CERN	• Extra dimensions and gravitational waves • Work on projects	• Open questions • Practice presentations • Present to each other
	Lunch	Lunch	Lunch	Lunch	Lunch
Afternoon **1 – 4pm**	• Work on projects	• About the collaboration • *Particle Fever* • Prep for interview with CERN physicist	• Work on projects	• Work on posters	• Poster session • Goodbyes

What are we going to learn in this class?

These are the fundamental goals that I would hope that you will take away from this experience many years from now…

1. The Standard Model of Particle Physics is made up a small number of forces and particles

Particle physics is not as complicated as it sounds. There are 118 chemical elements that form the basis of chemistry. Particle physics only has 17 basic building blocks! Specifically, I hope that you will be able to:

- List the fundamental particles of the standard model
- Classify the fundamental particles based upon several different characteristics:
    - Lepton, vs. quark
    - Charge
    - Generation
    - Stability
    - Which are their own anti-particles
- Describe how quarks combine into hadrons and mesons
- List some hadrons and mesons
- Describe in what ways particles are different from anti-particles and in what ways they are the same
- Describe what happens when particles and anti-particles annihilate
- List the forces of the standard model
    - Rank the strength of each force
    - Use the strength of each force to predict the relative rates of different reactions
    - Identify the particle associated with each force
    - Identify which particles each force acts upon
- Represent an interaction in a Feynman diagram
- Use Feynman diagrams to predict possible outcomes using the allowed vertices and conservation laws

2. These forces and particles obey some key conservation laws

One of the beautiful aspects of physics is how much can be explained and understood through the application of *conservation laws*. Conservation laws describe quantities, such as energy, that do not change. The use of conservation laws is particularly important in particle physics. Specifically, I hope that you will be able to:

- List some conservation laws important to the standard model
    - Electric charge
    - Energy
    - Momentum
- Classify each conserved quantity as a vector or scalar
- Use the relationship $E^2 = p^2c^2 + m^2c^4$ to:

    - Determine the momentum of a particle from its energy and mass
    - Calculate the mass of a particle in eV
- Recall the units of each conserved quantity (eV, eV/c^2, eV/c, and e)
- Manipulate 2-D vectors:
    - Decompose a 2-D vector into its components using a protractor and ruler
    - Add a vectors in two dimensions
- Use the relationship $E^2 = p^2c^2 + m^2c^4$ and vector addition for a collection of particles to:
    - Determine the energy of a collection of particles
    - Determine the invariant mass of a collection of particles
    - Calculate the missing energy of a system

3. That properties of the invisible world can be inferred through clever design of experiments

On the extreme frontiers of modern physics it is rare (but not impossible!) that you can make advancements with "simple" experiments like you may learn about in school. In general you need to be quite clever in designing your apparatus. Specifically, I hope that you will be able to:

- List the components of the LHC complex
    - Accelerators
    - Detectors
- List the key elements of a general purpose detector such as ATLAS or CMS
    - Trackers
    - Calorimeters
    - Muon systems
    - Magnets
- Describe the functions of each system
- Explain why the systems are arranged in the order they are

4. An appreciation and understanding of the statistical nature of measurement

Data are noisy – you never measure the same value twice. This fact informs the way scientists should report and interpret numerical data. Specifically, I hope that you will be able to:

- Explain why you do not get the same result on each measurement
    - Inherent variation
    - Systematic uncertainty
- Build and interpret a histogram

5. Understanding a scientific workflow

Being able to plan and conduct research is truly a skill that takes a combination of curiosity and forethought – you need to plan ahead and let your results and curiosity lead you. Specifically, I hope that you will be able to:

- Formulate a research question appropriate for the data available (in modern large experiments you do not get to control exactly what data you get!)
- Develop a plan to answer that question
- Use the results of graphs to inform your next steps

- Explain your work to your peers through informative graphs
- Evaluate the work of others
- Solve problems through "Fermi analysis"

6. Appreciate that the "solitary genius" image of a scientist which is so pervasive in our culture no longer exists (if they ever did)…

Science, all science, is now done in teams. Particle physics in particular is known for having massive collaborations with memberships in the thousands. I hope that you will be able to:

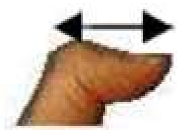
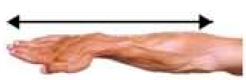
- Practice working with others in a scientific team
- Manage team work to achieve common objectives
- Reflect on different experiences working at large experiments like CERN

7. Appreciate the limitations of knowledge and the sources of current big questions

During these two weeks, we will be going to the edge of human knowledge. I hope that by the end you are in a position to at least grasp some of the big un-answered questions.

Scales

For solving Fermi problems, and for our discussions on the nature of measurement, you may find it useful to have a record of your personal scales as well as some basic measurements. We will talk about this on the afternoon of the first day.

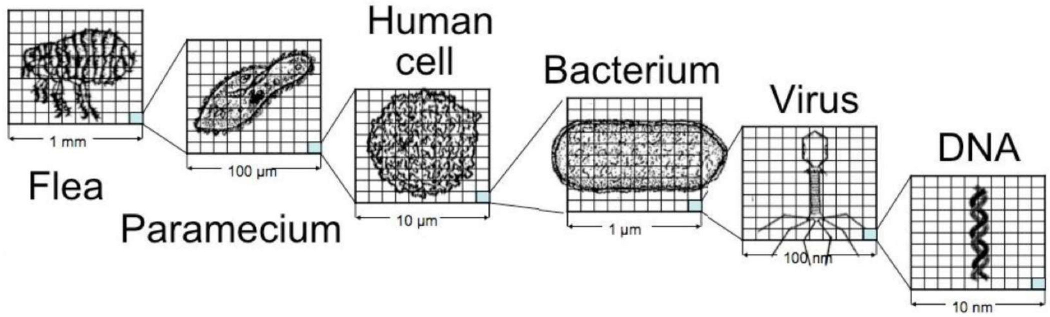
	in	cm
First digit of thumb 		
Open hand-span 		
Forearm (cubit) 		
Full height 		

Scales

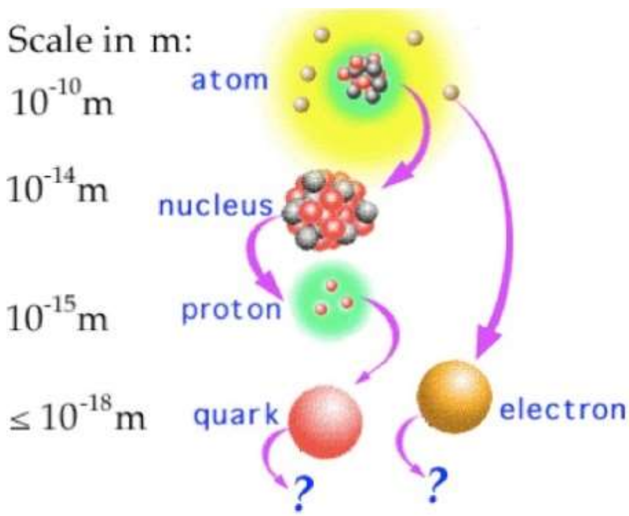
The Prefixes Used with SI Units			
Prefix	Symbol	Meaning	Scientific Notation
exa-	E	1,000,000,000,000,000,000	10^{18}
peta-	P	1,000,000,000,000,000	10^{15}
tera-	T	1,000,000,000,000	10^{12}
giga-	G	1,000,000,000	10^{9}
mega-	M	1,000,000	10^{6}
kilo-	k	1,000	10^{3}
hecto-	h	100	10^{2}
deka-	da	10	10^{1}
—	—	1	10^{0}
deci-	d	0.1	10^{-1}
centi-	c	0.01	10^{-2}
milli-	m	0.001	10^{-3}
micro-	μ	0.000 001	10^{-6}
nano-	n	0.000 000 001	10^{-9}
pico-	p	0.000 000 000 001	10^{-12}
femto-	f	0.000 000 000 000 001	10^{-15}
atto-	a	0.000 000 000 000 000 001	10^{-18}

Numbers	
Number of people on Earth	~7 billion (7×10^9)
Number of people in USA	~300 million (300×10^6)
Circumference of Earth	~24,000 mi (1000 mi /time zone @ equator)
Distance across USA	~3000 mi
Radius of Earth	$2\pi \times 10^7$m
Mass of sun	10^{30} kg
Population of NYC	~8 million
Number of stars in galaxy	~100 billion
Distance to moon	1 light-second
Size of atom	~1 Å (10^{-10}m) (think a for atom!)

Scales



Flea
1 mm
Paramecium
100 µm
Human cell
10 µm
Bacterium
1 µm
Virus
100 nm
DNA
10 nm



Scale in m:
10^-10 m
atom
10^-14 m
nucleus
10^-15 m
proton
≤ 10^-18 m
quark
electron
?
?

Equation Sheet

Magnetic force on a charged particle

____

Radius of curvature for a charged particle in a magnetic field:

$$R = \frac{p}{qB}$$

Volume of a cylinder:

$$V = \pi r^2 h$$

Density:

$$\rho = \frac{m}{V}$$

Momentum of a particle with mass:

$$p = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Energy – momentum – mass relationship:

$$E^2 = p^2c^2 + m^2c^4$$

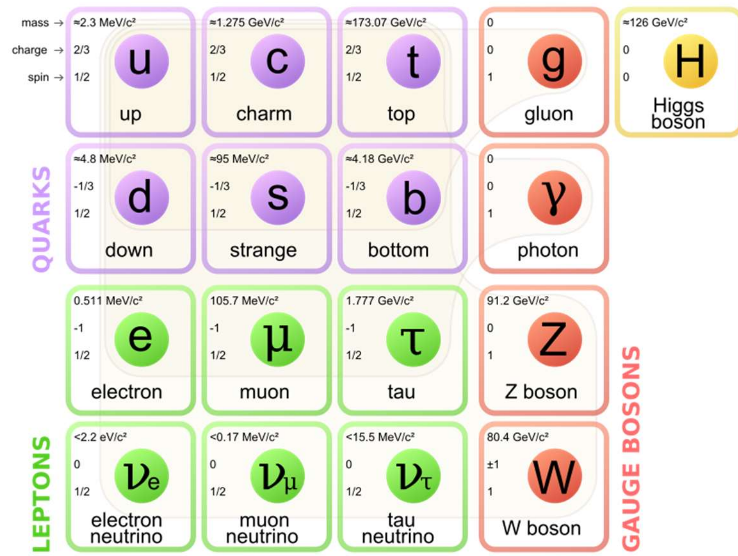
Mean:

$$\mu = \frac{1}{n}\sum_i^n x_i$$

Standard deviation:

$$\sigma^2 = \frac{1}{n}\sum_i^n (x_i - \mu)^2$$

Summary of the Standard Model



The particles of the Standard Model of Particle Physics.

Particle Content

- Quarks and Leptons comprise the “matter” particles
- The forces are mediated by the gauge bosons – the forces are detailed below
- Each particle has an anti-particle with opposite charge. The photon, Z, and Higgs are their own anti-particles
- Matter particles come in three “generations” (the columns in the picture) which differ from each other only in terms of mass
- Only up quarks, electrons, neutrinos, photons, and gluons are stable all other particles decay

Basic Rules for Drawing Feynman Diagrams

- Time runs to the right
- Vertical spacing is meaningless
- Matter particles are drawn as arrows going forward in time, an arrow going backwards in time represents an anti-particle. Arrows must be continuous!
- Charge must be conserved at each vertex (where two particles meet)
- For *decays* the *final* end state must have less mass than what you started with (for collisions you can ignore this as $E = mc^2$ allows you to convert the kinetic energy of the collision into mass)
- Only weak interactions via W bosons change particle *type*:
  - W’s can convert any charged lepton to its associated neutrino: $e \leftrightarrow \nu_e$, $\mu \leftrightarrow \nu_\mu$, $\tau \leftrightarrow \nu_\tau$. No mixing between lepton generations.
  - W’s can convert any up-type quark to any down-type quark, including across generations. However, the more generations crossed the less likely the process is.

Summary of the Standard Model

The Forces

The Strong Force

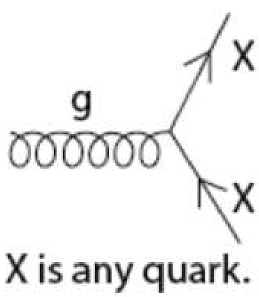
The force

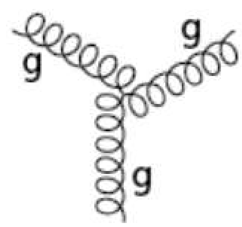
- Holds quarks together inside hadrons
  - Baryons are made of three quarks and include the proton (uud) and the neutron (udd)
  - Mesons are made of a quark and an antiquark such as $\pi^+ = u\bar{d}$
- Also holds protons and neutrons together inside nuclei
- Very short range ~1fm

Mediated by gluon (g)

- Massless – travels at the speed of light
- No electric charge
- Carries color
- Interacts only with colored particles (gluons and quarks)

Base diagrams





Summary of the Standard Model

The Electromagnetic Force

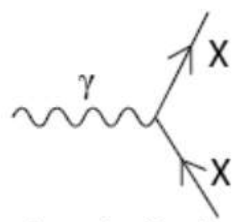
The force

- Holds atoms together and atoms into molecules
- All forces in your daily experience that are not gravity are ultimately this force
- Light is an electromagnetic phenomenon
- Infinite range

Mediated by photon (γ)

- Massless – travels at the speed of light
- No electric charge – photons do not interact directly with other photons
- Interacts with all charged particles (quarks, charged leptons, and W's)

Base diagram



X is electrically charged.

Summary of the Standard Model

The Weak Force

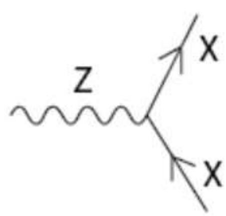
The force

- Responsible for radioactive decay
- Only way for neutrinos to interact
- Very short range due to fact that W and Z's are unstable

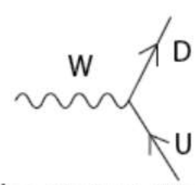
Mediated by W and Z bosons

- Massive: $m_W = 80.4 \text{ GeV}$, $m_z = 91 \text{ GeV}$
- W's carry charge, Z's are neutral
- Interacts with all particles
- Z's do not change the particle type
- W's change particle type
    - Can change charged lepton for associated neutrino: $e \leftrightarrow \nu_e, \mu \leftrightarrow \nu_\mu, \tau \leftrightarrow \nu_\tau$
    - Can change any up-type quark (u, c, t) for any down-type quark (d, s, b)
        - Most likely within the same generation
        - Probability drops the more generations you need to cross

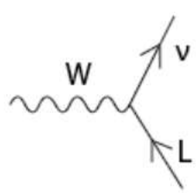
Base diagrams



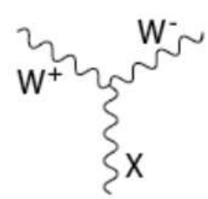
X is any matter particle



U is a up-type quark;
D is a down-type quark.



L is a lepton and v is the corresponding neutrino.



X is a photon or Z-boson.

The Higgs mechanism

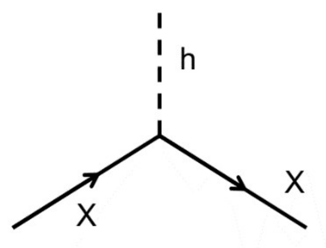
The mechanism

- Responsible for the mass of all massive particles

Mediated by higgs boson (h)

- Discovered in 2012
- Massive: $m_h \approx 126 \text{ GeV}$
- Couples to any particle with mass – the more massive the more likely the interaction

Basic diagram

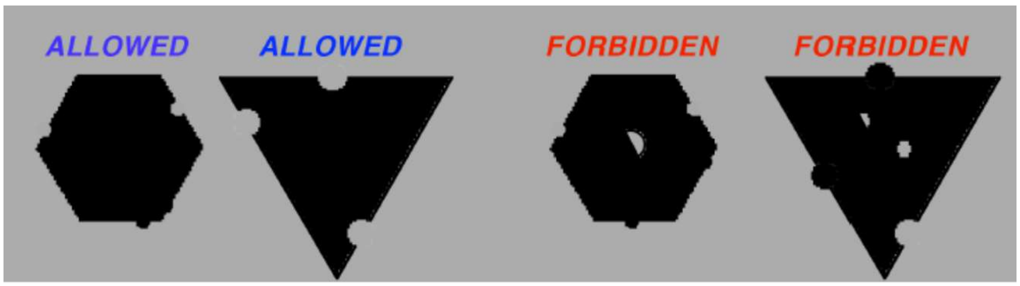


X is any particle with mass

Quark Workbench[1]

Instructions

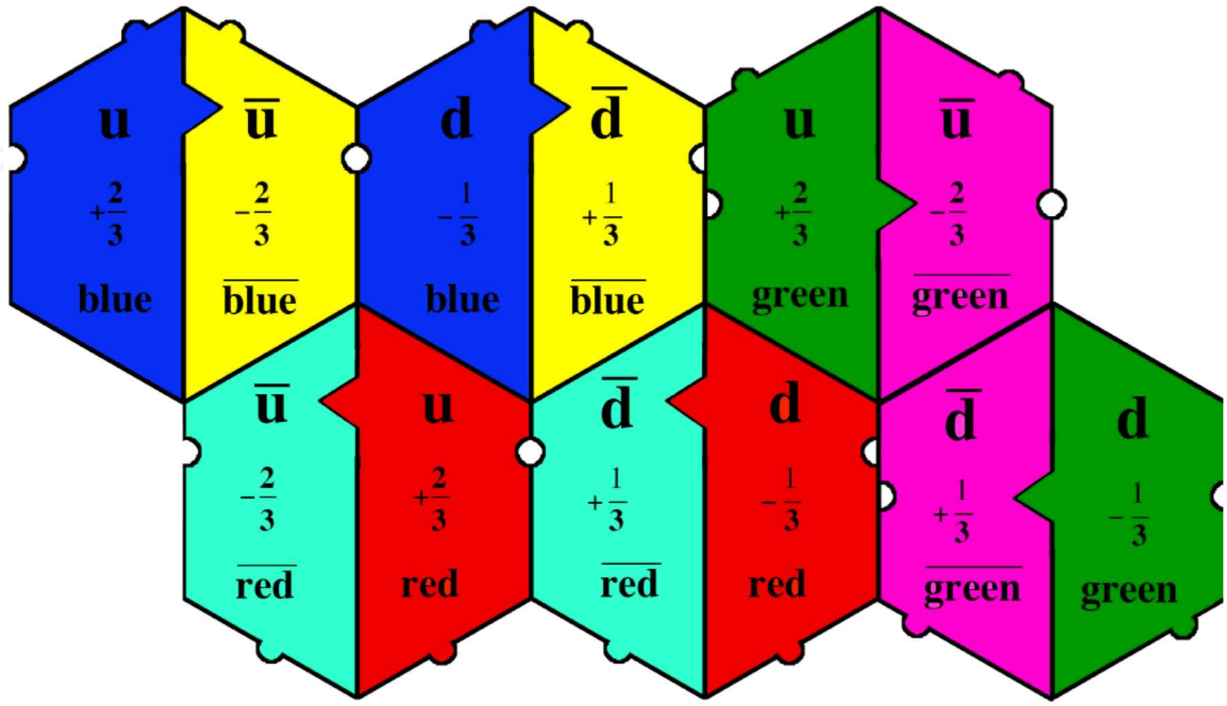
- Cut out the quarks. Each will be one color or anti-color. Discard white dots.
- There are extra ups and downs
- Quark pieces must fit together like puzzle pieces: no overlapping. There be no white dots/gaps *inside* the space. Dips and bumps on the outside are OK.

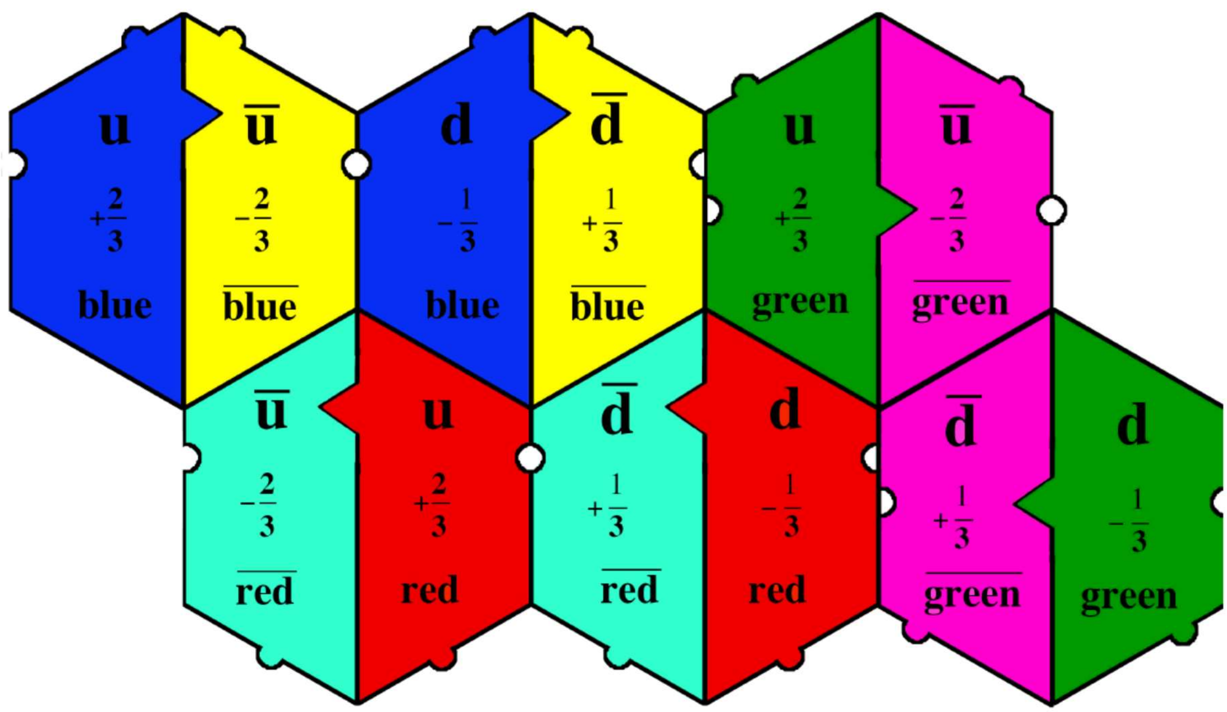


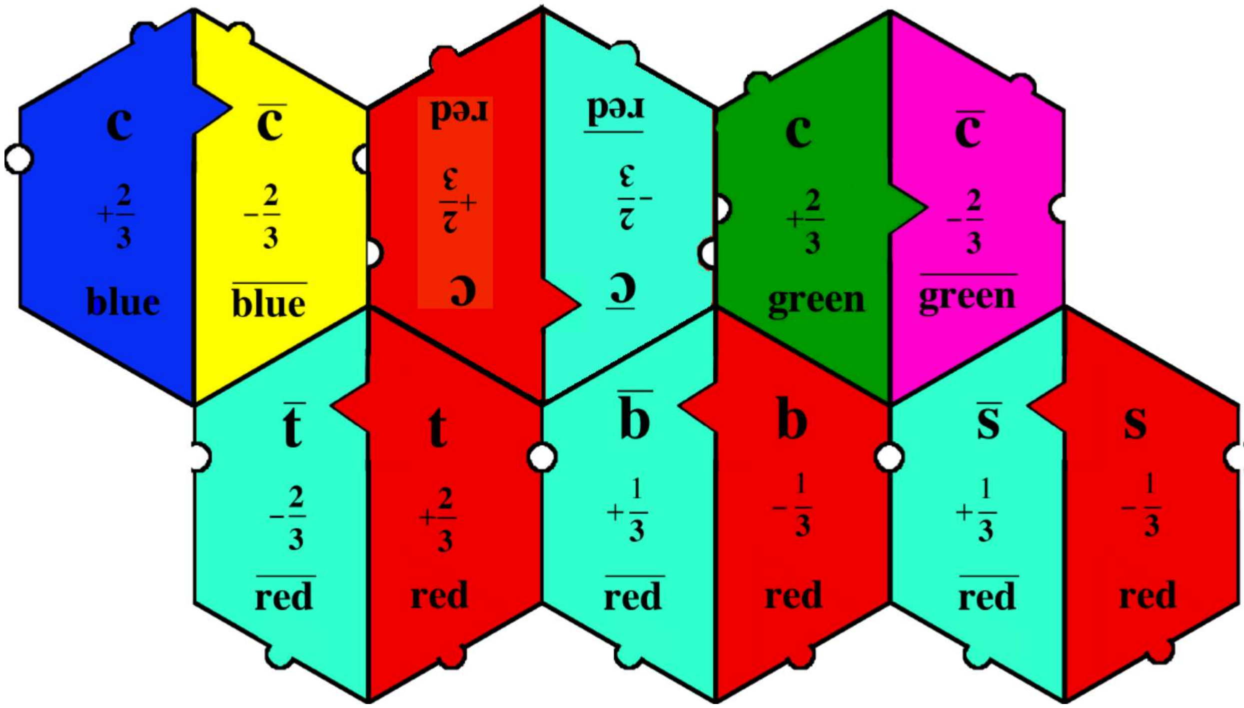
- What shapes can you make (hint look at above!)
- What patterns do you recognize?
    - Colors?
    - Numbers of quarks vs. anti-quarks?

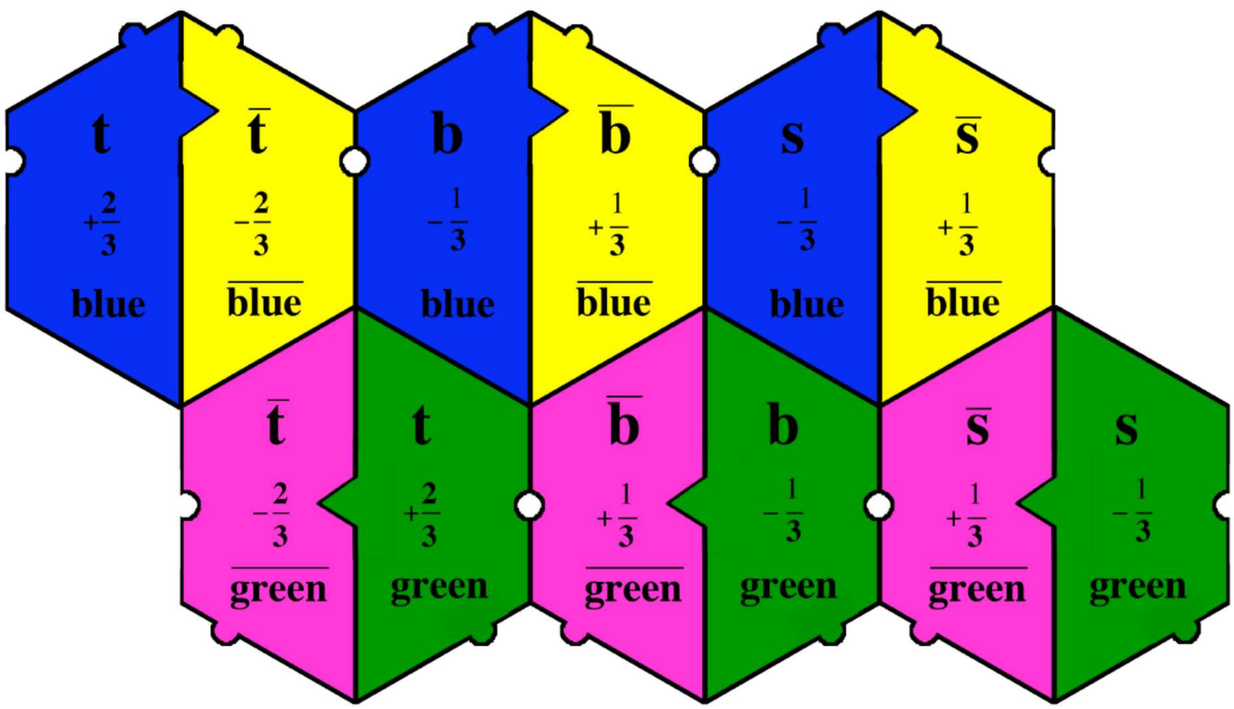
[1] From *Quark Workbench.* QuarkNet. https://quarknet.i2u2.org/data-portfolio/activity/quark-workbench

Quark Pieces





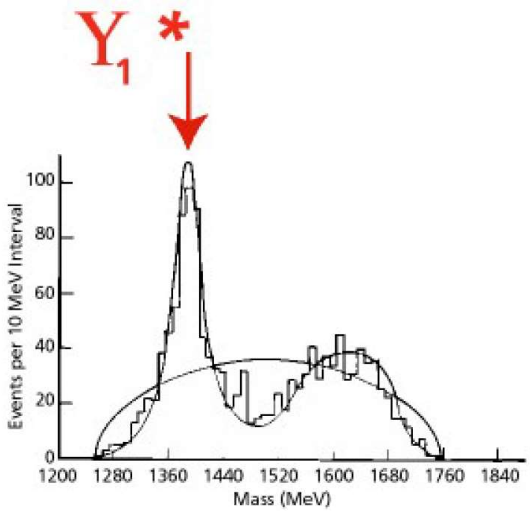

c $+\frac{2}{3}$ blue
$\bar{c}$ $-\frac{2}{3}$ $\overline{\text{blue}}$
c $+\frac{2}{3}$ red
$\bar{c}$ $-\frac{2}{3}$ $\overline{\text{red}}$
c $+\frac{2}{3}$ green
$\bar{c}$ $-\frac{2}{3}$ $\overline{\text{green}}$
$\bar{t}$ $-\frac{2}{3}$ $\overline{\text{red}}$
t $+\frac{2}{3}$ red
$\bar{b}$ $+\frac{1}{3}$ $\overline{\text{red}}$
b $-\frac{1}{3}$ red
$\bar{s}$ $+\frac{1}{3}$ $\overline{\text{red}}$
s $-\frac{1}{3}$ red


t $+\frac{2}{3}$ blue
$\bar{t}$ $-\frac{2}{3}$ $\overline{\text{blue}}$
b $-\frac{1}{3}$ blue
$\bar{b}$ $+\frac{1}{3}$ $\overline{\text{blue}}$
s $-\frac{1}{3}$ blue
$\bar{s}$ $+\frac{1}{3}$ $\overline{\text{blue}}$
$\bar{t}$ $-\frac{2}{3}$ $\overline{\text{green}}$
t $+\frac{2}{3}$ green
$\bar{b}$ $+\frac{1}{3}$ $\overline{\text{green}}$
b $-\frac{1}{3}$ green
$\bar{s}$ $+\frac{1}{3}$ $\overline{\text{green}}$
s $-\frac{1}{3}$ green

Pennies Lab[2]

Introduction

Particle physicists use graphs like the one shown on this page to look at the results of their experiments. By putting their mass readings on a histogram, they can see the peaks that show separate particles.



Since we don't have ready access to particles, or the machines to make them, we are going to look at something more readily available, pennies. There are lots of pennies in circulation. Are they all the same? They all represent $0.01 and may be similar in color, but is that the only thing they have in common?

Instructions

Obtain a set of pennies from your instructor. Measure as many properties of each penny as you can observe. Organize your data in a table.

Draw at least one histogram to represent your data.

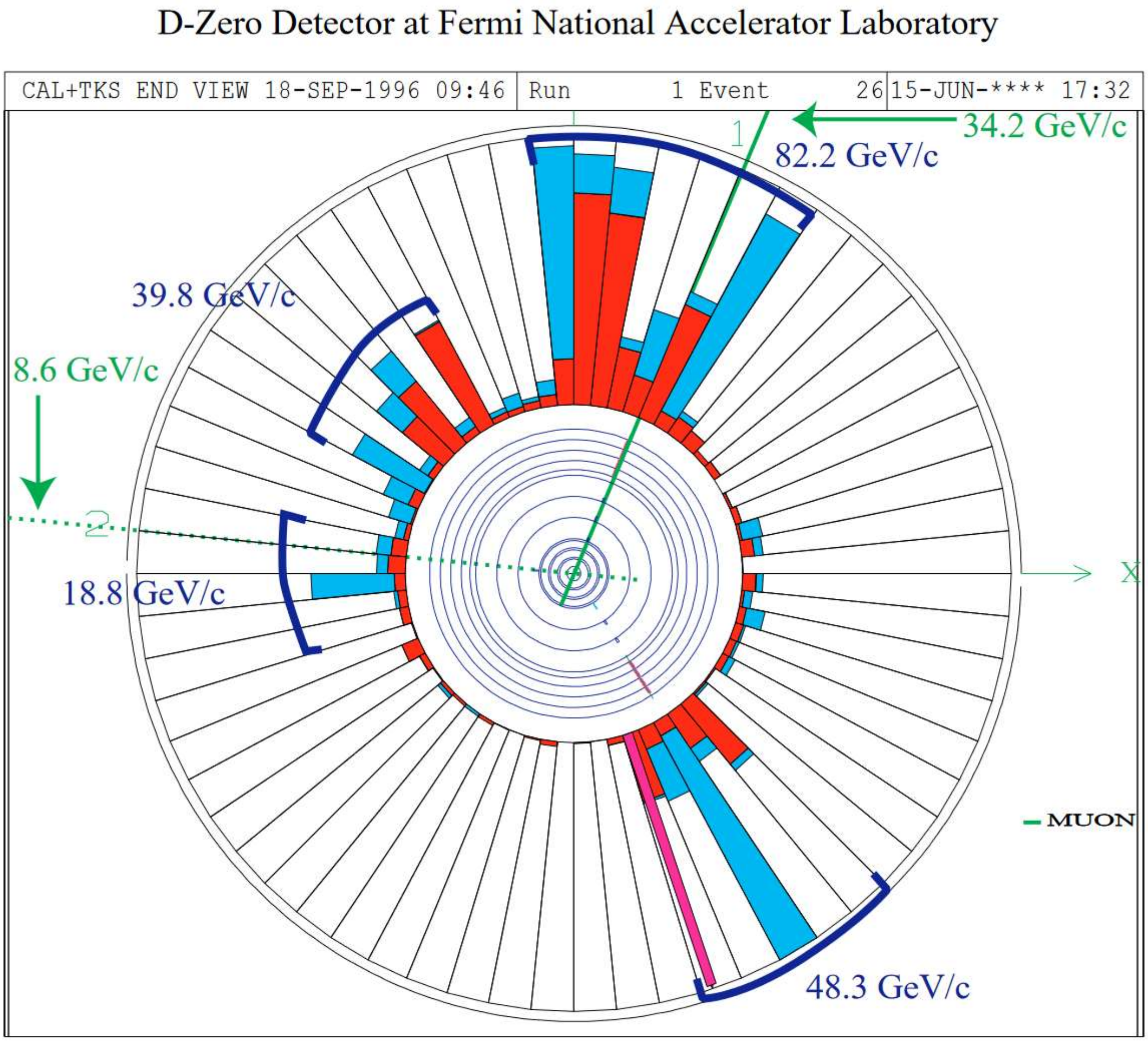
Answer the following questions on a sheet of paper. Show all calculations.

1. What is the most common penny mass in your data set? In the class data set?
2. How would you describe the masses of the pennies in your set? Be as descriptive as you can.
3. Can you provide an explanation for the masses that you see? What evidence can you provide to support your explanation?
4. Are there more pennies from recent years or from prior years? Can you suggest an explanation for this? How would you test this idea?
5. Which year is represented by the most pennies? By the second most? By the third most? What would you graph instead of mass to make this more evident?

---

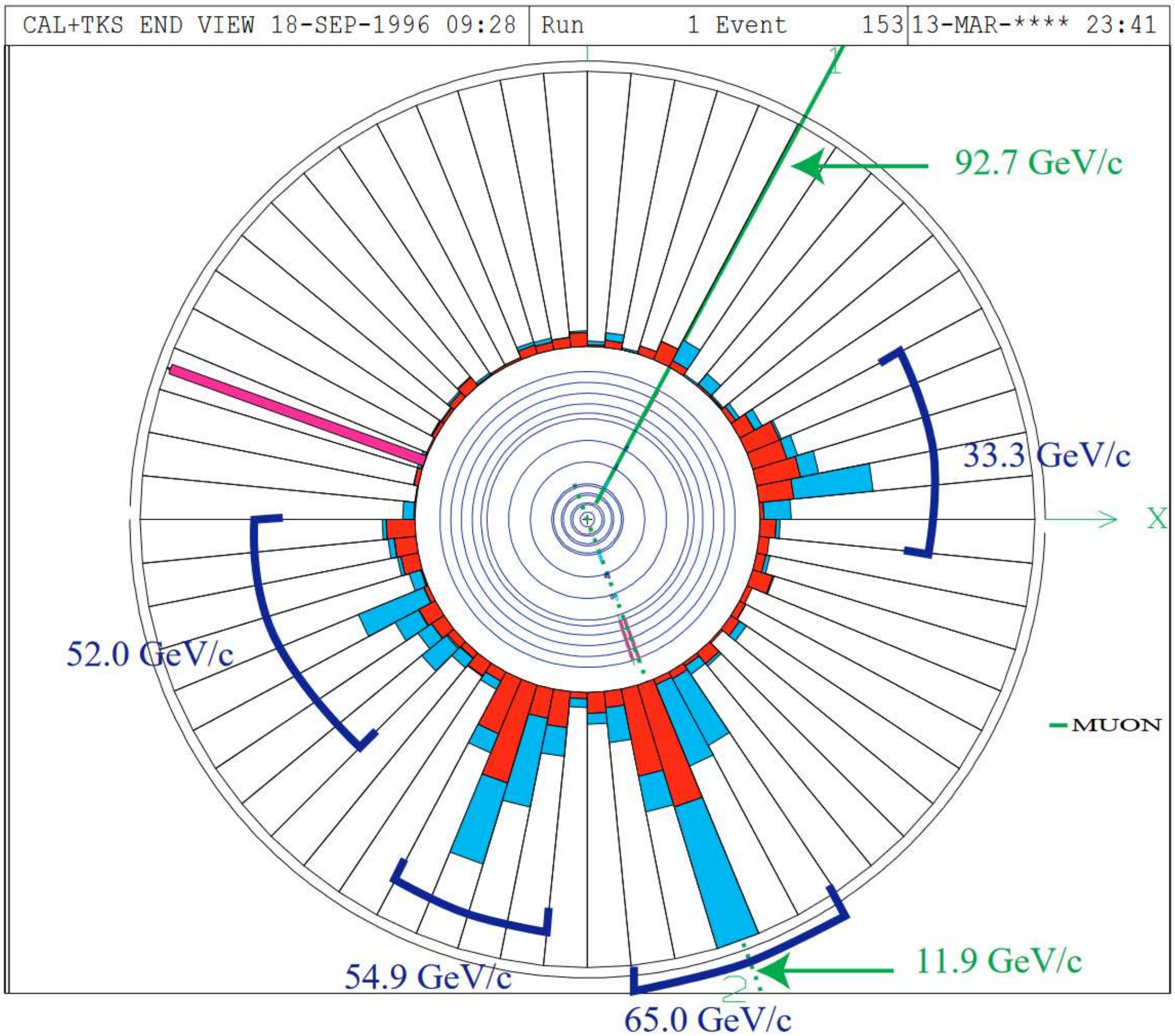
[2] From *Mass of U.S. Pennies.* QuarkNet. https://quarknet.i2u2.org/data-portfolio/activity/mass-us-pennies with additions from *Measuring the Density of Pennies.* SciPhile. Guy Blalock. http://sciphile.org/lessons/measuring-density-pennies

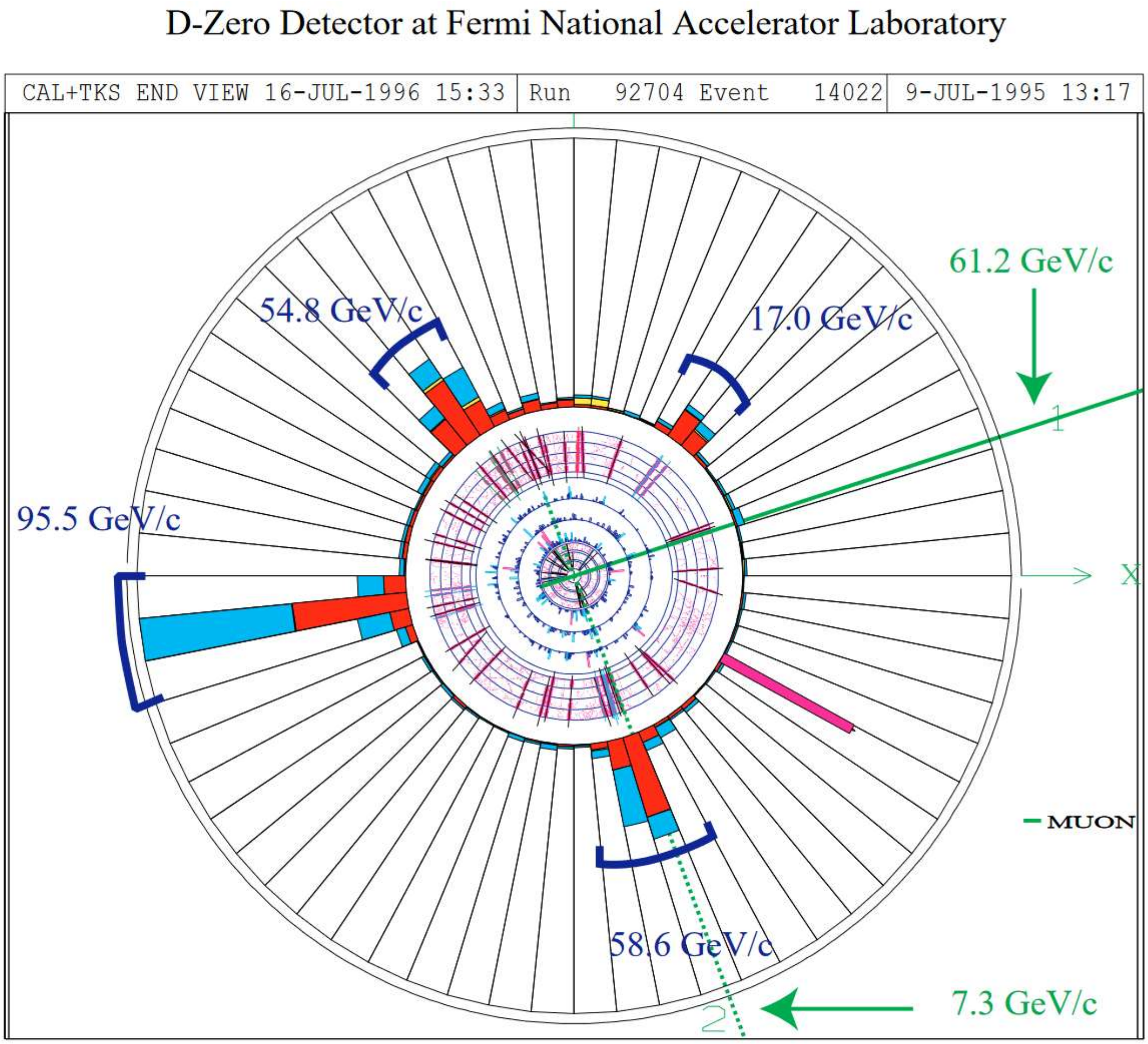
$t\bar{t} \rightarrow \ell\nu jj$ Events from DØ at FermiLab[3]



[3] From *Calculate the Top Quark Mass.* QuarkNet. https://quarknet.i2u2.org/data-portfolio/activity/calculate-top-quark-mass

D-Zero Detector at Fermi National Accelerator Laboratory




D-Zero Detector at Fermi National Accelerator Laboratory
CAL+TKS END VIEW 16-JUL-1996 15:33
Run 92704 Event 14022
9-JUL-1995 13:17
61.2 GeV/c
54.8 GeV/c
17.0 GeV/c
95.5 GeV/c
X
MUON
58.6 GeV/c
7.3 GeV/c
1
2

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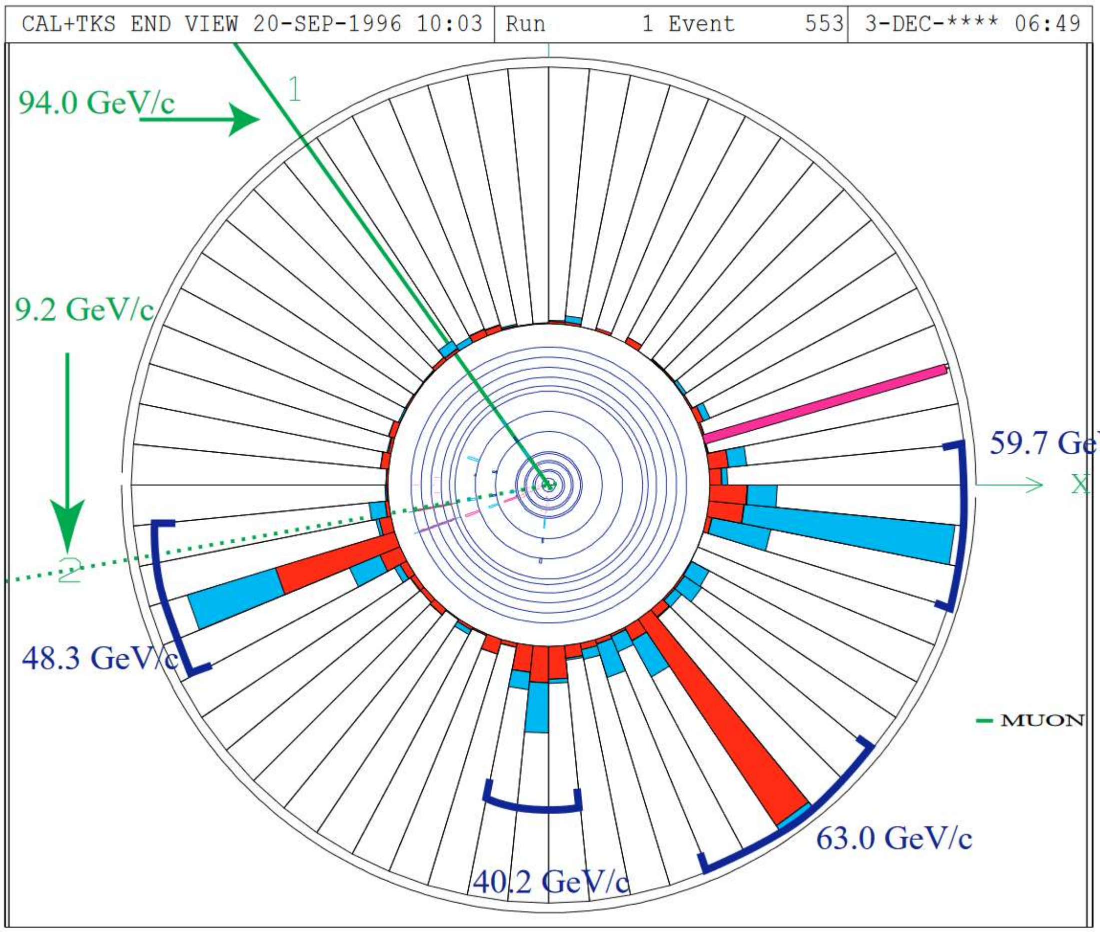


Understanding backgrounds via J/ψ to understand discoveries[4]

Description

The J/Ψ particle is important in LHC discovery science. It is a well-known particle, so the location and width of the mass plot give physicists a good idea of how the detector is performing. J/Ψ can decay into a muon-antimuon pair; therefore the J/Ψ candidate events are "dimuon" events. You will make a histogram from data provided from experimental measurements and the background model to determine if this mass plot yields a mass in line with the well-known mass of a J/Ψ particle. This process of collecting data from well-understood particle is called "calibration" and is a crucial technique for understanding the data from any detector. The analysis of these mass plot histograms will enable youto interpret plots from similar discoveries to decide if the data provides evidence for a new particle.

Physicists working at CERN's Large Hadron Collider (LHC) may have discovered a new particle. Is there evidence to support the claim of the discovery of a new particle? Why is this true?

You will review this result by first learning from a well-understood, previous result. Your review will involve analyzing the main features of mass plots. These features include: peak, width and background.

Analysis Part 1: Rediscovery of the J/ψ:

Physicists discovered the J/Ψ meson in 1974. Its mass is well understood. "Seeing" it in modern detectors allows physicists to be sure that the detector is performing as expected.

The table contains the result of measurements near the mass of the J/Ψ. The detector measures the energy and momentum of the particles. The table has three columns:

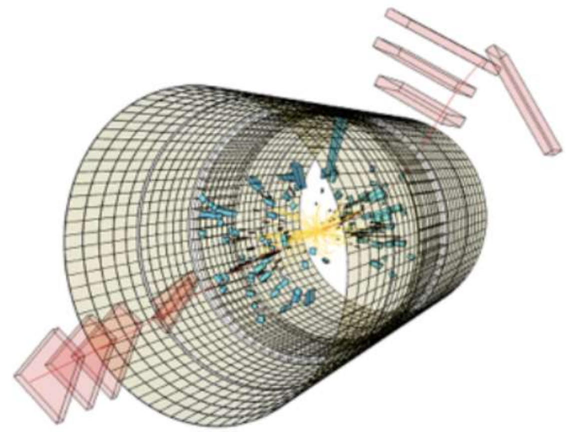
- Mass (GeV): The mass of the particle that decayed
- Data: The number of events ($\times 10^3$) observed with that mass
- Background model: The number of events expected because of other physics (i.e. NOT the J/Ψ meson)

[4] From *Plotting LHC Discovery.* QuarkNet. https://quarknet.i2u2.org/data-portfolio/activity/plotting-lhc-discovery

Understanding backgrounds via J/ψ to understand discoveries

CMS 2010 Dimuon Data

Mass (GeV)	Data	Background model
2.7	72,000	70,000
2.74	72,000	70,000
2.78	70,000	68,000
2.82	70,000	68,000
2.86	70,000	68,000
2.9	76,000	68,000
2.94	84,000	68,000
2.98	112,000	64,000
3.02	238,000	64,000
3.06	474,000	64,000
3.1	624,000	62,000
3.14	384,000	60,000
3.18	176,000	60,000
3.22	86,000	58,000
3.26	64,000	58,000
3.3	58,000	56,000
3.34	58,000	54,000
3.38	56,000	54,000



The image shows a "dimuon" event in the CMS detector. The two red tracks indicate a muon and an antimuon. The pink boxes indicate parts of the CMS muon system through which these muons passed. If there was a parent particle, it existed at the vertex of the two muon tracks.

Draw a histogram to represent these data.

After you have made your plot discuss with your team. Here are a few points for you to consider:

- Explain the peak
- Determine the contribution to the peak from the background model
- What processes could contribute to the background (i.e. have the same di-muon final state but not be from the J/Ψ? Draw the Feynman diagrams.
- What is the mass of the J/Ψ? Compare with a published result online.
- Explain the distribution around the peak of the histogram. How does the width of the distribution impact your confidence in the value of the mass?
- Can you get an estimate of the lifetime of the J/Ψ? You may want to look at http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/parlif.html.
- Is this detector calibrated? Provide evidence and reasoning to support your claim.

Place your answers to these questions in a short presentation which you will give to the class.

Analysis Part 2: Discoveries

Your team will be given a recent discovery plot. The analysis software used filters to select particles that are more likely to have come from the decay of an unobserved particle. Use what you learned in Part 1 to identify:

- Where the signal rises above the background to form a peak or "bump."
- The mass value at the peak.
- The meaning of and uncertainty in the mass value at the peak.

Again, in your small group, discuss and make a determination of the mass at the peak as well as your confidence in that mass. Take a position on whether you think this is a discovery. Make a short set of slides to defend your reasoning.