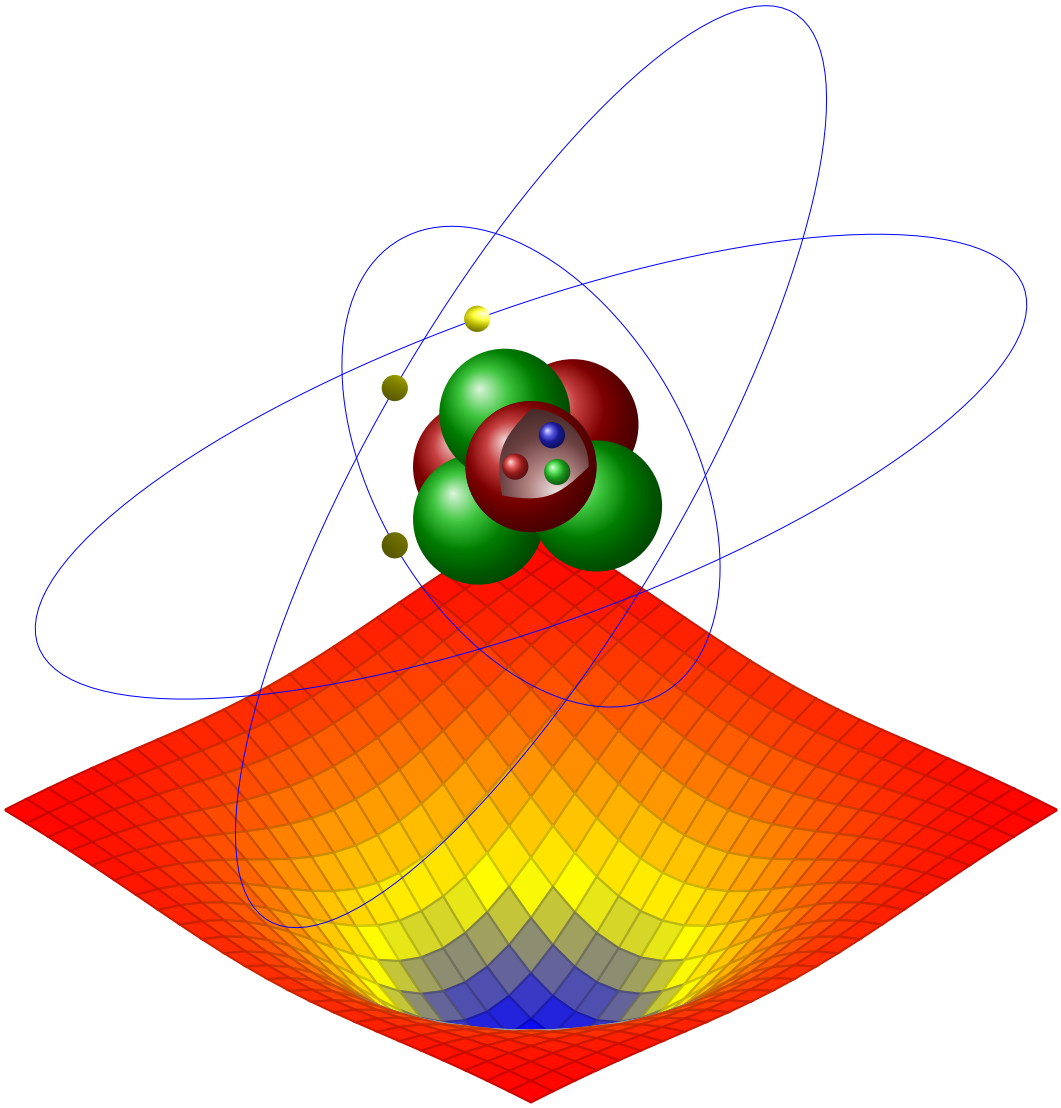
Nature's Building Blocks: Quarks and the Need for Colour



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Name:

Date:

Contents

Course Rationale iii

Course Map iv

Baseline ideas v

1 The Standard Model of Particle Physics 1
- 1.1 Starter: True or False? . . . 1
- 1.2 Fundamentally speaking . . . 2
  - 1.2.1 Classification of Particles . . . 3
- 1.3 Homework: . . . 6

2 The strong force 8
- 2.1 Starter: Particle crossword . . . 8
- 2.2 Fundamental Interactions (Forces) of Nature . . . 9
  - 2.2.1 Force carriers . . . 9
  - 2.2.2 Strong force . . . 10

3 Detecting particles 13
- 3.1 Starter: A 'toy' geometric puzzle . . . 13
- 3.2 What is LEP and the LHC? . . . 14
- 3.3 Particle detectors: . . . 15
- 3.4 LEP experiment: . . . 16
- 3.5 Muons: . . . 16
- 3.6 Electrons: . . . 17
- 3.7 Hadrons: . . . 18
- 3.8 Quarks: . . . 19
- 3.9 Taus: . . . 20
- 3.10 Counting colours . . . 21
- 3.11 Homework: . . . 22

4 Counting colours 26
- 4.1 Method . . . 27
- 4.2 Results - tables . . . 28

5 Result presentation 33
- 5.1 Posters: . . . 33
- 5.2 My poster ideas: . . . 38

6 Feedback 40
- 6.1 Activity 1: Marking your own work . . . 40
- 6.2 Activity 2: Responding to feedback . . . 40
- 6.3 Activity 3: Looking Forwards: Think, Pair, Share . . . 40

A Glossary of Keywords 41

B Timetables **43**

C Mark Scheme **44**

D KS4 Programme 2016/17 - Pupil Feedback Report **45**

E Referencing correctly **46**

F Scientific Papers **48**
F.1 Why write Scientific papers? 48
F.2 Scientific Journals 48
F.3 Scientific paper layout 49

G University Applications Guidance **53**

Course Rationale

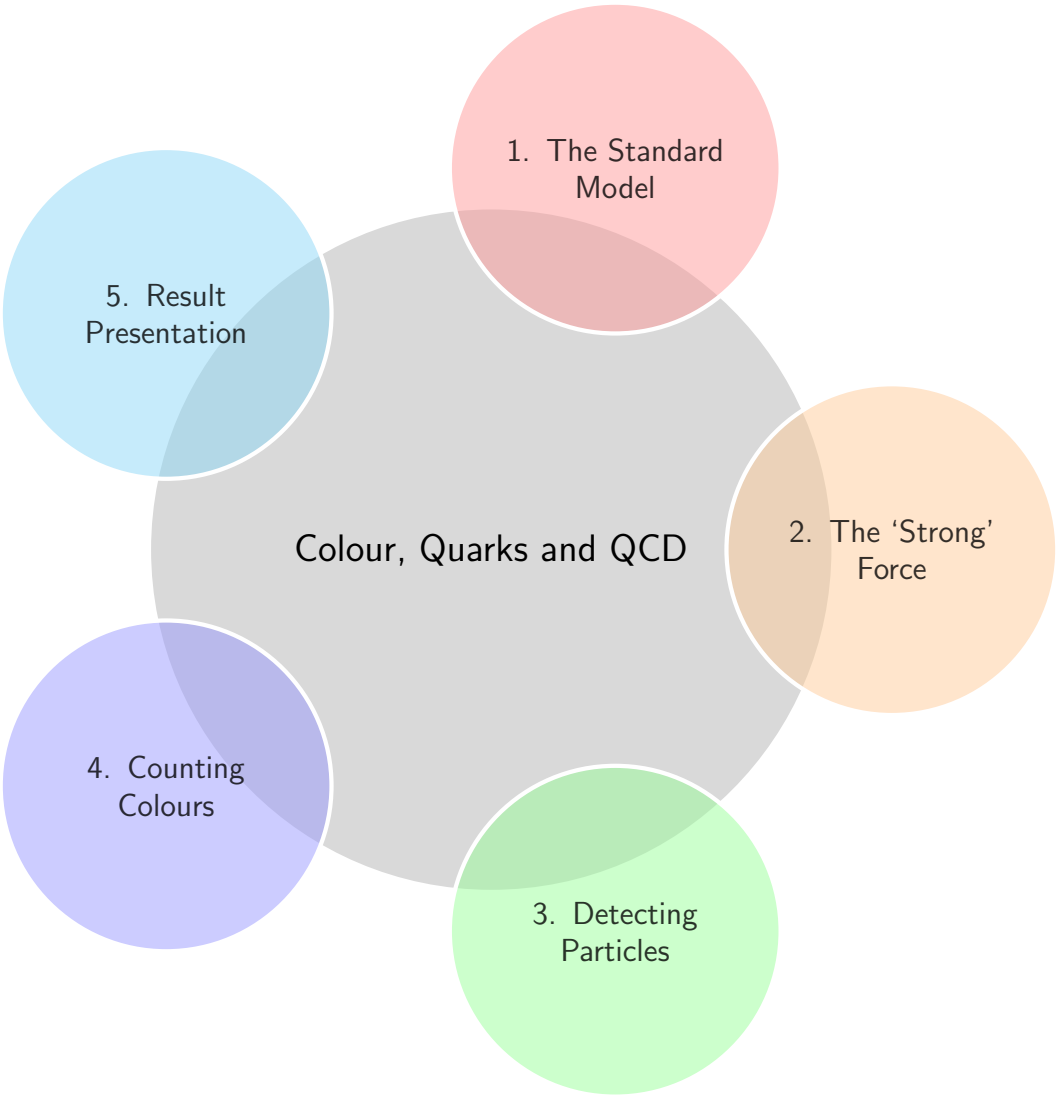
There are many fundamental questions:

- What is our universe made of?
- Where does it come from?
- Why does it behave the way it does?

Researchers in particle physics try to answer these questions. The answers to such fundamental questions have dramatically changed through history, and our current description may, itself, not be complete. This course is aimed at students who are interested in how the development of ideas through research can result in fundamental theories and, subsequently, how these theories are tested.

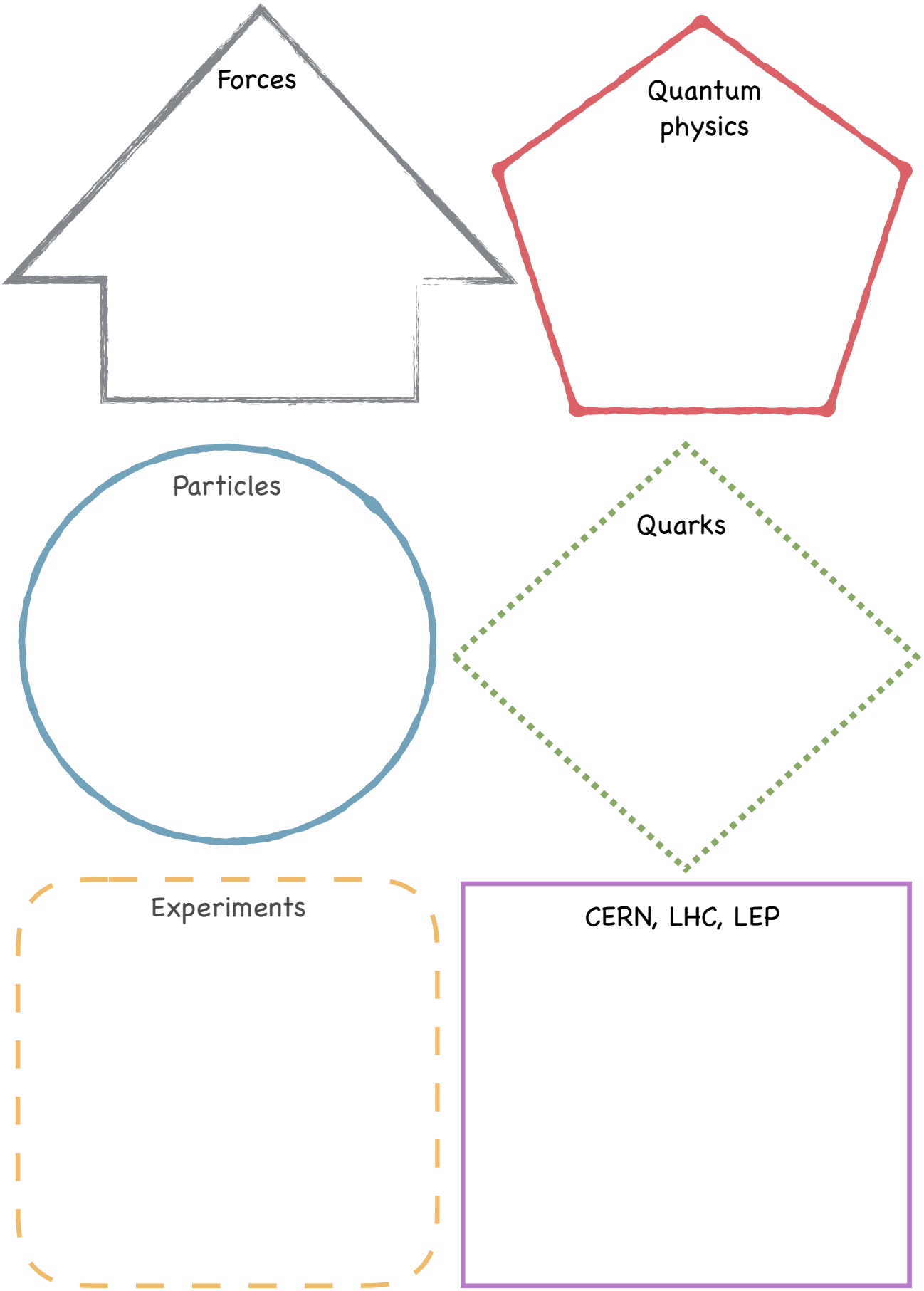
The initial tutorials will introduce basic terminology and concepts of particle physics, such as the names and properties of the fundamental particles, as well as provide an overview of the Standard Model of particle physics. These concepts will be utilised when investigating the means by which theories are tested, such as at the Large Hadron Collider (LHC) experiments in CERN, Geneva. You will analyse results from a similar experiment to determine how many 'colours' are needed in our theoretical description of particles. This analysis, coupled with reading a selection of scientific publications, will allow you to present your findings as a scientific poster.

Course Map


1. The Standard Model
2. The 'Strong' Force
3. Detecting Particles
4. Counting Colours
5. Result Presentation
Colour, Quarks and QCD

Baseline ideas

Fill out as much information as you know about each of the topics in the boxes provided. Sentences, bullet points or single words are all fine. It doesn't matter what you write. There is no right or wrong. The ideas might be from something you heard on TV, read in a book or from science lessons.


Forces
Quantum physics
Particles
Quarks
Experiments
CERN, LHC, LEP

1 The Standard Model of Particle Physics

What is the purpose of this tutorial?

- To provide an introduction to particle physics concepts and terminology.

What are the key questions?

- What is particle physics?
- What is the standard model?

1.1 Starter: True or False?

We will revisit your answers at the end of the course to see if you have changed your mind on any of your answers.

		True	False
1.	The smallest components of an atom are protons, neutrons and electrons	☐	☐
2.	The Large Hadron Collider (LHC) at CERN in Switzerland is 27 km long	☐	☐
3.	Protons travel around the LHC beam-pipe 11,000 times a second	☐	☐
4.	The LHC can collide Lead atoms	☐	☐
5.	The particle collisions at the LHC could create dangerous black holes	☐	☐
6.	99.999999999999% of an atom is just empty space	☐	☐
7.	The coldest place in the universe is outer space	☐	☐
8.	Protons and neutrons actually consist of smaller particles - called quarks	☐	☐
9.	A proton's mass is the sum of the mass of the quarks inside it	☐	☐
10.	There are 4 fundamental forces - Gravity, Electromagnetic, Strong, Weak	☐	☐
11.	Gravity is the strongest fundamental force	☐	☐
11.	Some particles travel through the entire earth without being affected by it	☐	☐
12.	Particles and antiparticles can be created out of energy	☐	☐
13.	Particle accelerator experiments will help us understand the early universe	☐	☐
14.	The world-wide-web was created to store the data from particle accelerators	☐	☐
15.	There are, at least, 80 fundamental particles	☐	☐
16.	The Higgs mechanism gives mass to all particles	☐	☐

1.2 Fundamentally speaking

Throughout history, what constitutes fundamental matter has changed considerably. Fig. 1.1 shows a schematic plot of how the number of different kinds of fundamental matter has changed throughout time. This demonstrates fluctuations between periods of discovery (with large numbers) followed by a theoretical understanding that often leads to a simplification of the overall picture, thus reducing this number. However, as can be seen, this can still be followed by further complications and the pattern often repeats itself. Fig. 1.2 shows the breakdown of a water droplet into ever smaller pieces, finishing with the fundamental quark particle.

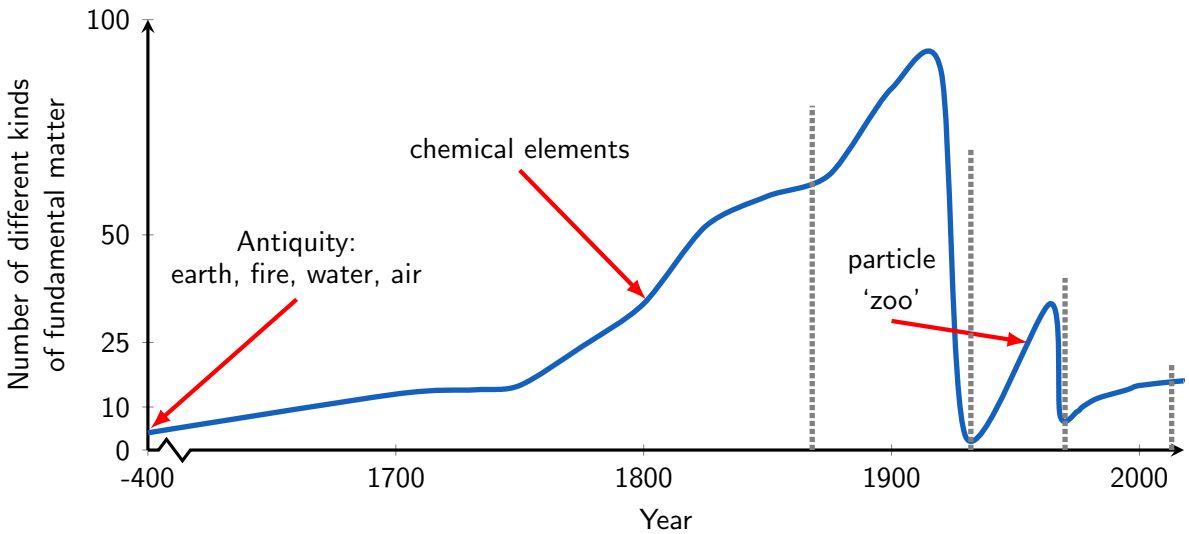


Figure 1.1: A very schematic picture of what the perceived number of fundamental particles/'things' has been throughout history.

- Can you match the following to the dotted lines in Fig. 1.1
  - Discovery of Quarks (the structure of protons and neutrons)
  - Mendeleev: Periodic table
  - Discovery of the Higgs Boson
  - Discovery of the electron, proton and neutron (the structure of the atom)
- What does this graph tell us?

  _____

  _____

  _____

- How do you think the number of fundamental particles will change in the future?

  _____

  _____

  _____

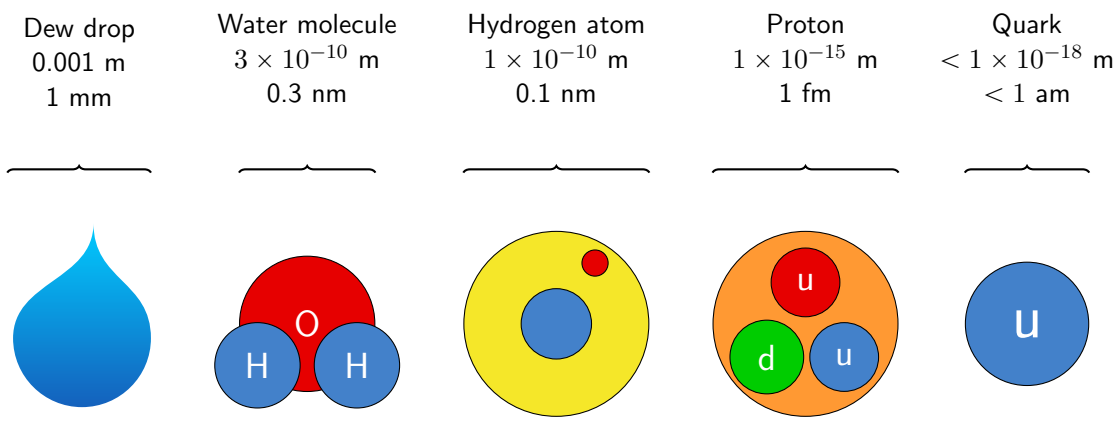


Figure 1.2: The 'breakdown' of a water droplet - the scales (size) of each piece is indicated in meters (m).

1.2.1 Classification of Particles

In the early 20th century, with the discovery of the electron, proton and neutron, we understood atoms as a nucleus and a surrounding cloud of electrons. The electrons play a key role in almost all the behaviour of matter, such as:

- electricity and magnetism
- electronics
- the emission of light
- chemistry
- technology
- ...

Quarks

The nucleus contains almost all the atom's mass and is itself composite. That is, it is made up of smaller particles called quarks. Normal matter that we experience everyday consists of two types of quark:

- up quark or u, charge $+2/3\ e$
- down quark or d, charge $-1/3\ e$

However, this was not the end of the story. Particle physicists discovered four more quarks - two more pairs of heavier copies to the up and down quarks:

- charm quark or c, charge $+2/3\ e$
- top quark or t, charge $+2/3\ e$
- strange quark or s, charge $-1/3\ e$
- bottom quark or b, charge $-1/3\ e$

These are created in high energy physics experiments such as the LHC and LEP, and at the early stages of the universe, shortly after the big bang.

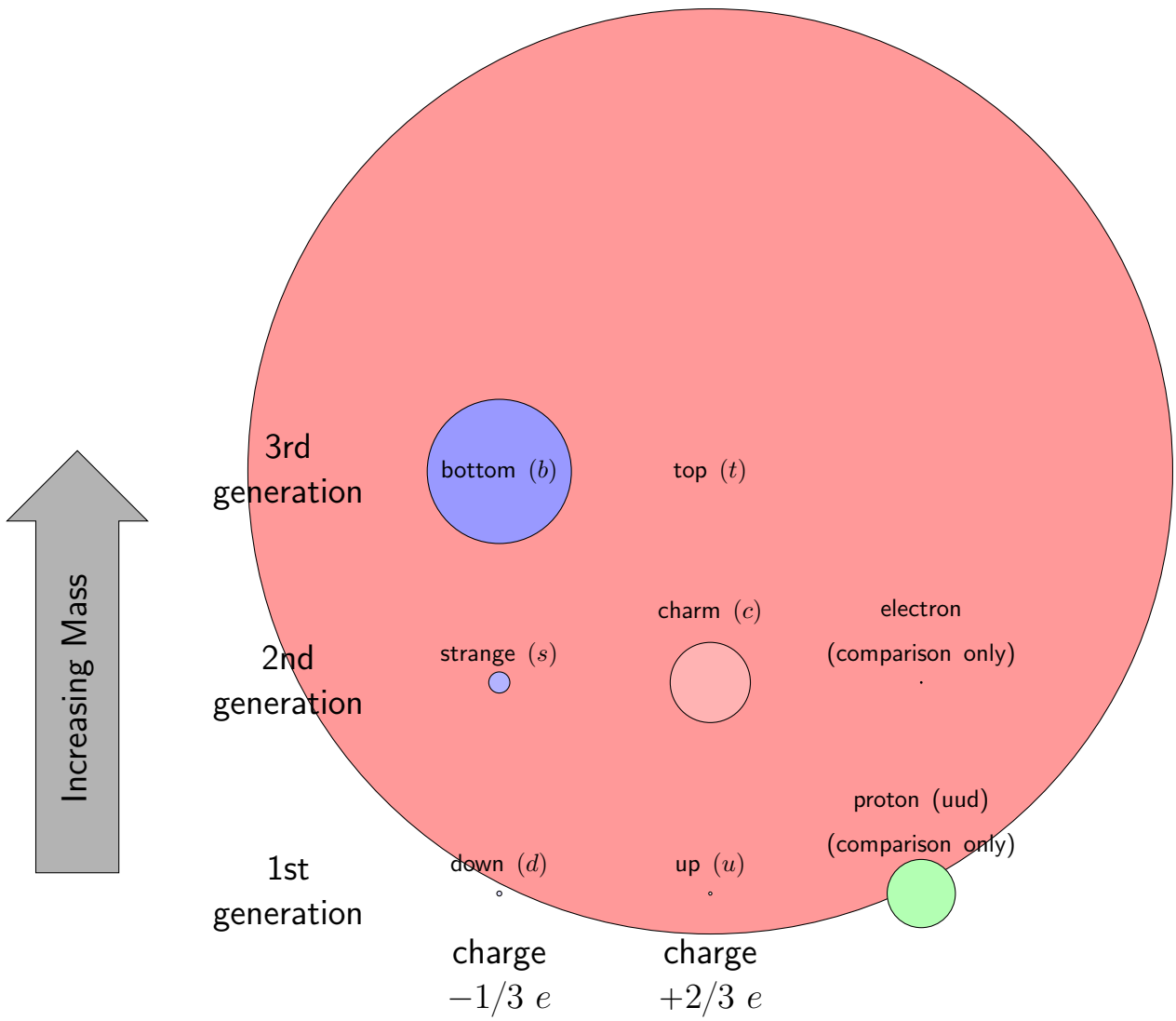


Figure 1.3: The 6 fundamental quark flavours: up (u), down (d), charm (c), strange (s), top (t), bottom (b). The area of each is proportional to its mass - it is not fully understood as to why the top quark is so massive. For comparison the proton and electron are shown - they are NOT quarks. The proton is a bound state of 2 up quarks and 1 down quark. Note that the mass of the proton is much larger than the sum of the 2 up quarks and 1 down quark that make it up.

Leptons

We are almost done, but first we need to introduce the electron's friend - the electron-neutrino, ν_e. This is required to ensure the conservation of energy and momentum in β-decay:

$$n \rightarrow p + e^- + \bar{\nu}_e \tag{1.1}$$

Neutrinos have no charge, and almost no mass. They therefore hardly interact with anything.

There are also heavier copies of the electron and its neutrino

- muon, μ and muon-neutrino, ν_μ
- tau, τ and tau-neutrino, ν_τ

Together these particles are known as leptons. The three 'copies', just like for the quarks, are usually referred to as generations. We are not really sure as to why there are **three** generations. Why not 1 or 2 or 5?

Any more?

We are still not quite done. Last, but by no means least, are the force carriers (Bosons). But we will come to these later. There is also the Higgs Boson. Taken together, all of these particles make up 'the standard model of particle physics'.

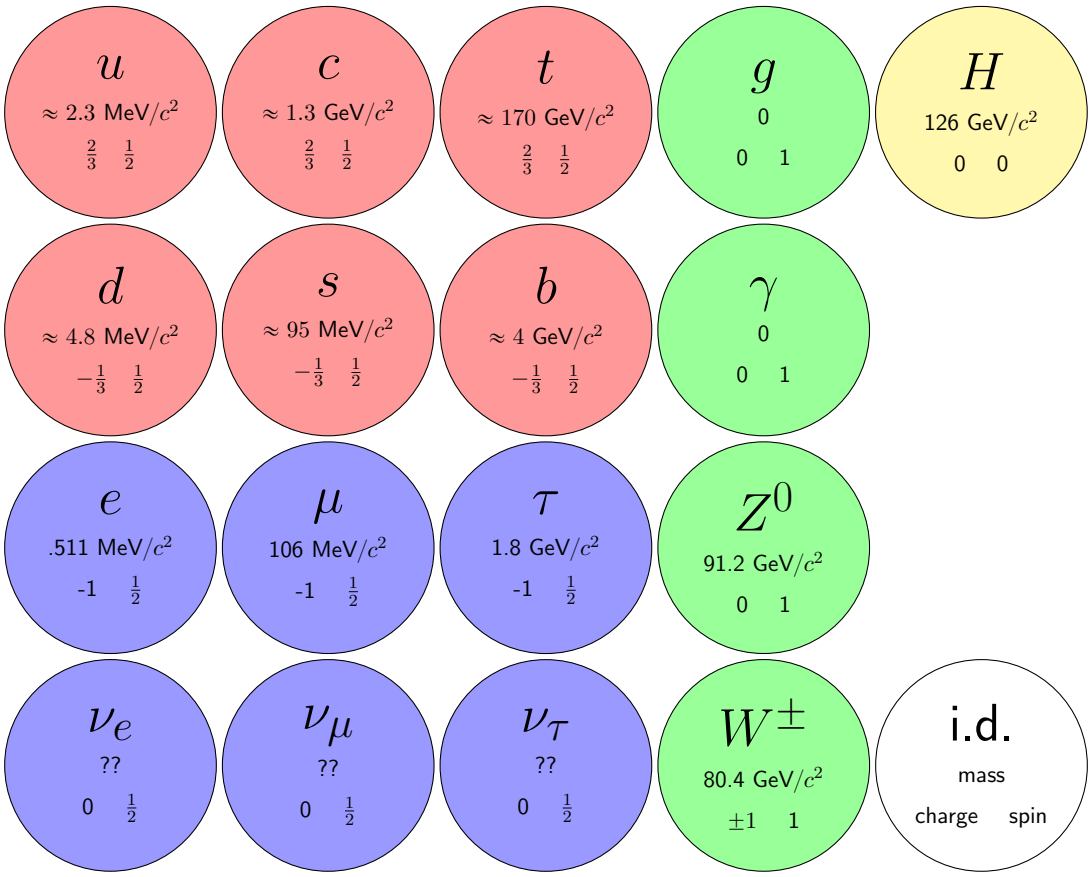


Figure 1.4: The elementary particles of the standard model, including: quarks (red), leptons (blue), gauge bosons (green) and the Higgs boson (yellow). For each, the mass, charge and spin of the particle are given - see the white index particle.

1.3 Homework:

Today's Homework is:

To use the Particle physics app / website 'The particle adventure' to answer:

- What is fundamental? - How has this changed through history?
- What is the world made of? - Add to your Glossary
- What are the four forces of nature? Which is the odd one out?

Notes:

What is fundamental?

Add these words to your glossary:

Boson Generation Neutrino Quarks Lepton Hadron Higg's Boson Colour charge

Gravity:	Strong force:
What is it?:	What is it?:
Discovered/theorised by:	Discovered/theorised by:
Particles involved:	Particles involved:
Electromagnetic force:	**Weak force:**
What is it?:	What is it?:
Discovered/theorised by:	Discovered/theorised by:
Particles involved:	Particles involved:

What 2 questions do you have from Homework 1 and/or Tutorial 1?

1.

2.

2 The strong force

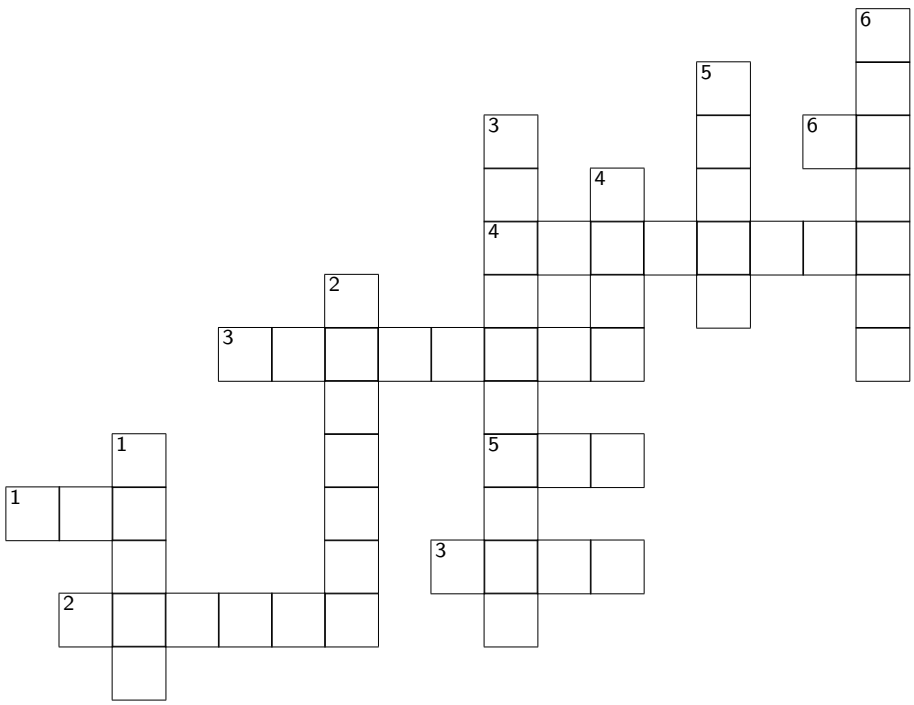
What is the purpose of this tutorial?

- To introduce the Strong force, Quarks and Colour charge.

What are the key questions?

- What is the universe made of?
- How is it held together?

2.1 Starter: Particle crossword



Across:
1. Its greek symbol is τ.
2. Particle discovered in 1911.
3. Quark with charge $-1/3e$.
4. A particle that has almost zero mass.
5. The heaviest type of quark.
6. Quark with charge $+2/3e$.

Down:
1. Hadrons are made of these.
2. A particle that has spin$= 1/2$ is a _____.
3. There are three of these
4. A heavy version of an electron.
5. A heavy version of an up quark.
6. Electrons, muons, taus and neutrinos are all _____.

2.2 Fundamental Interactions (Forces) of Nature

In nature there are four fundamental forces of nature. These are labelled: Gravitational, Weak, Electromagnetic and Strong and each exhibits very different characteristics and affects different types of matter differently. For instance, we all have a good 'feel' for gravity. It affects all matter and is what keeps us stuck to the earth! We also experience the electromganetic force through light, which allows us to see. We are familiar with the idea of light as a wave, however we can also think of it as a particle - known as a photon. The final two forces, the weak and the strong force, are somewhat more abstract to us - we will come to these later. Table 2.1 summarises some of the characteristics for each of the forces.

		Standard Model		
	Gravitational	Weak	Electromagnetic	Strong
Acts on	Mass - Energy	Flavour	Electric charge	Colour charge
Particles experiencing	All	Quarks, leptons	Electrically charged	Quarks, Gluons
Force carriers	Graviton*	$W^{\pm}$, Z^0	Photon γ	Gluons g
Interaction range	long-range $1/r^2$	$\sim 10^{-3}$ fm	long-range $1/r^2$	few fm
Relative strength to em	10^{-41}	10^{-4}	1	60

Increasing strength

Table 2.1: A summary of the four fundamental forces.

2.2.1 Force carriers

Particles influence one another at a distance through the exchange of "gauge" bosons (force carrying particles) emitted by one of the particles. One particle emits the gauge boson which then propagates through space(-time) and is then absorbed by the other particle.

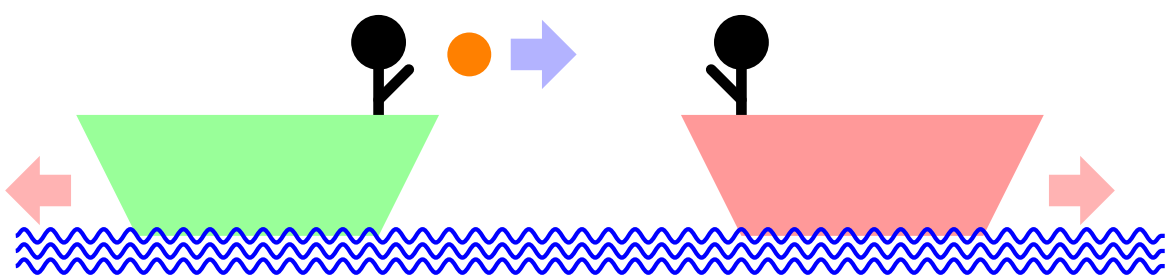
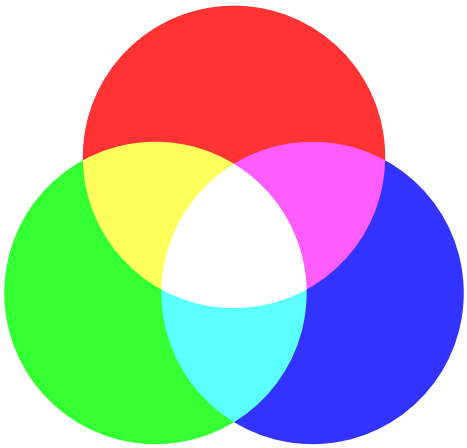


Figure 2.1: This can be represented by two people in boats, throwing a ball between one another - when this is done there is a repulsive force through the exchange of a 'particle' (ball) that carries momentum.

2.2.2 Strong force

Use `http://hyperphysics.phy-astr.gsu.edu/hbase/quacon.html#quacon` to answer:

What is colour?



Strong force

Use the following sources to collect as much information on the subjects in the boxes below:

- http://hyperphysics.phy-astr.gsu.edu/hbase/quacon.html#quacon
- [harder] http://frankwilczek.com/Wilczek_Easy_Pieces/298_QCD_Made_Simple.pdf
- Any other scientifically relevant websites.

Asymptotic freedom

Confinement:

What does this mean for the formation of hadrons from quarks?

Today's Homework is:
to use the sources:

- `http://hyperphysics.phy-astr.gsu.edu/hbase/quacon.html#quacon`
- `http://pdg.lbl.gov/fireworks/intro_eng.swf`
- Harder: `http://frankwilczek.com/Wilczek_Easy_Pieces/298_QCD_Made_Simple.pdf`

to complete your notes on:

- the concept of asymptotic freedom
- confinement
- and what that means for the formation of hadrons from quarks

Notes:

3 Detecting particles

What is the purpose of this tutorial?

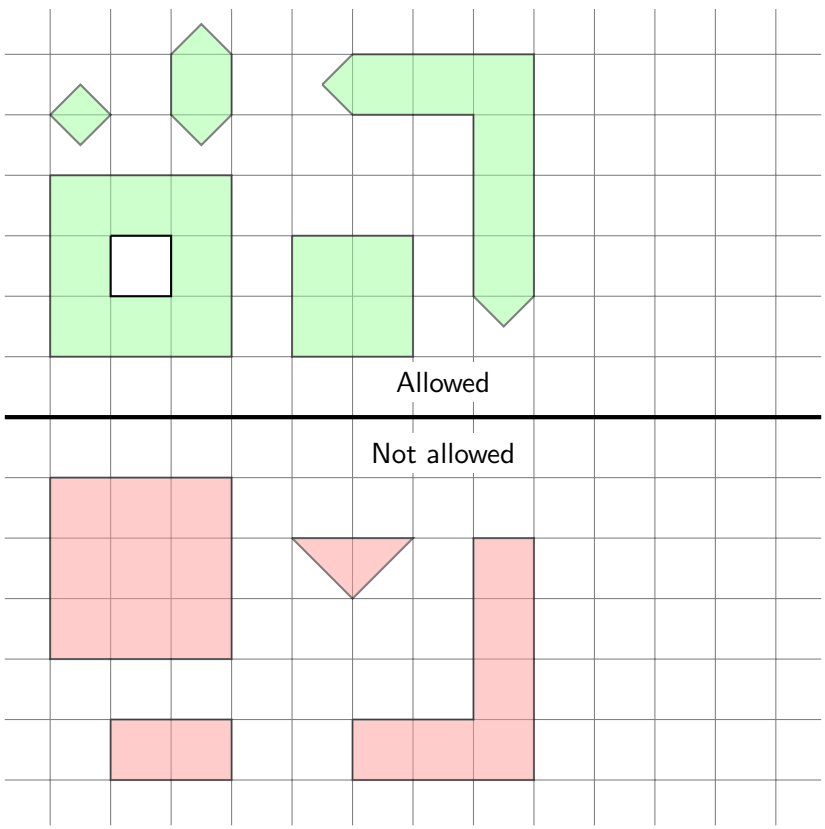
- To understand how we know that these particles exist and how experiments detect these particles

What are the key questions?

- What is a particle accelerator?
- How do we detect particles?

3.1 Starter: A 'toy' geometric puzzle

The following diagram shows a number of allowed (top) and forbidden (bottom) images. You need to identify what shapes the observed images are constructed from, and the rules for their formation[a].



- What two shapes are the observed (allowed) images constructed from?

  1. 2.

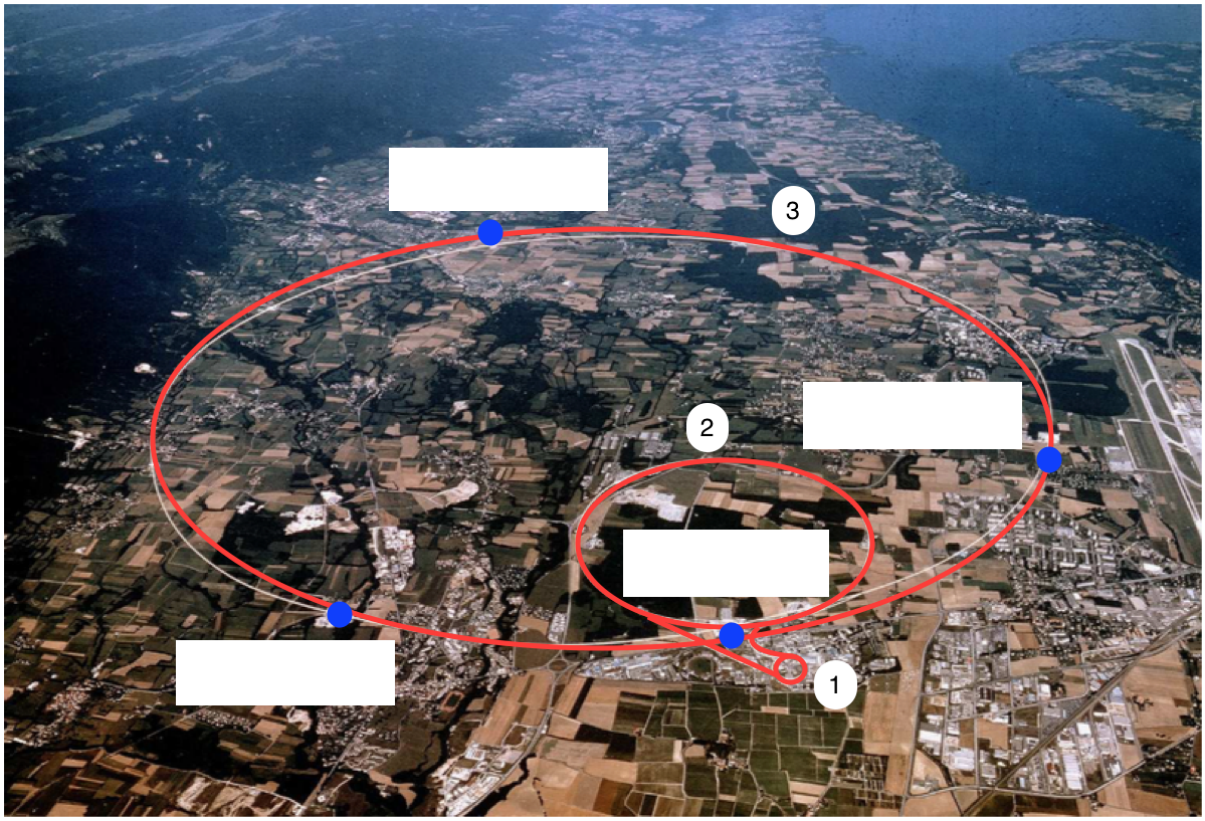
- What two rules govern their combination into the observed (and forbid the unobserved) images?

  1. 2.

- From these rules, draw an additional allowed and a forbidden image above.
- How does this relate to particle physics?

[a] Adapted from CPEP and H.Quinn, "Of Quarks, Antiquarks, and Glue" The Stanford Magazine, Fall, 1983, p.29

3.2 What is LEP and the LHC?



What is LEP and the LHC?

3.3 Particle detectors:

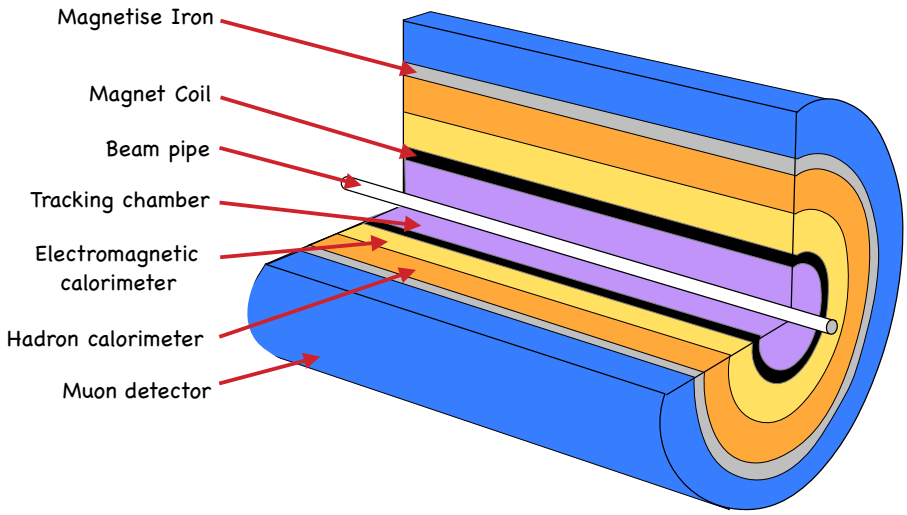


Figure 3.1: A schematic of the OPAL detector, showing its cylindrical design, with the beam pipe at the centre.

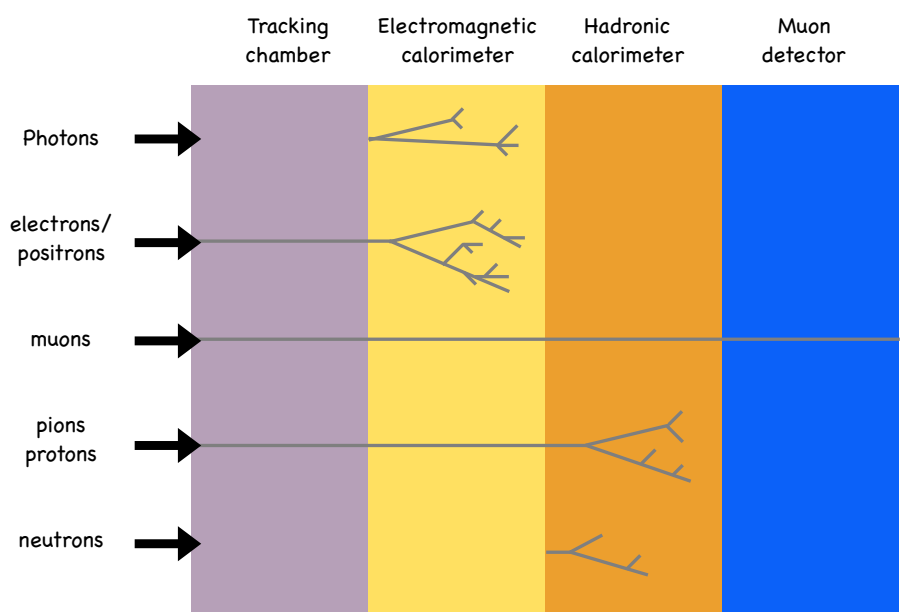


Figure 3.2: A schematic of the OPAL detector, showing which parts of the detector are able to detect each particle.

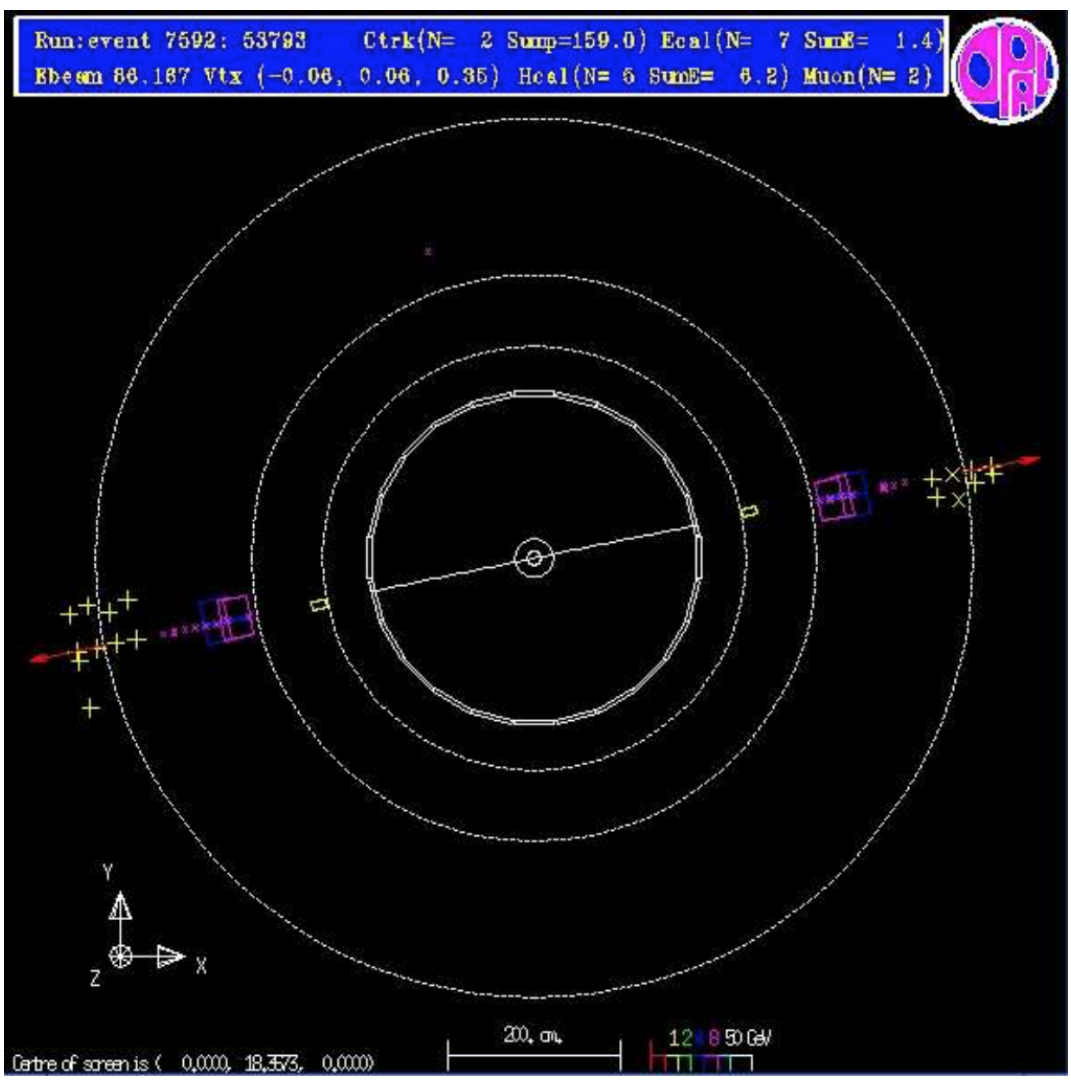
3.4 LEP experiment:

The LEP experiment collided beams of electrons (e^-) and positrons (e^+) to produce a Z^0 boson.The e^- and e^+ in the collision have momenta that are equal and opposite to one another, and so the Z^0 is created at rest (with zero net momentum). The Z^0 subsequently decays after $\sim 10^{-25}\ s$ (a very short time) into other particles, e.g. $\mu^-\ \mu^+$, which fly apart back-to-back. In order to detect such an 'event' the collision zone is surrounded by detectors, which enable us to 'see' the decayed particles (the $\mu^-\ \mu^+$ pair) - from which we can reconstruct what the original particle was (the Z^0).

In this way, the mass of the Z and W were determined. We knew what their decay channels would be, however we did not know their mass and thus the energy at which to collide the electrons and positrons. The experiment therefore did a sweep of energy ranges until the expected decay channels were seen.

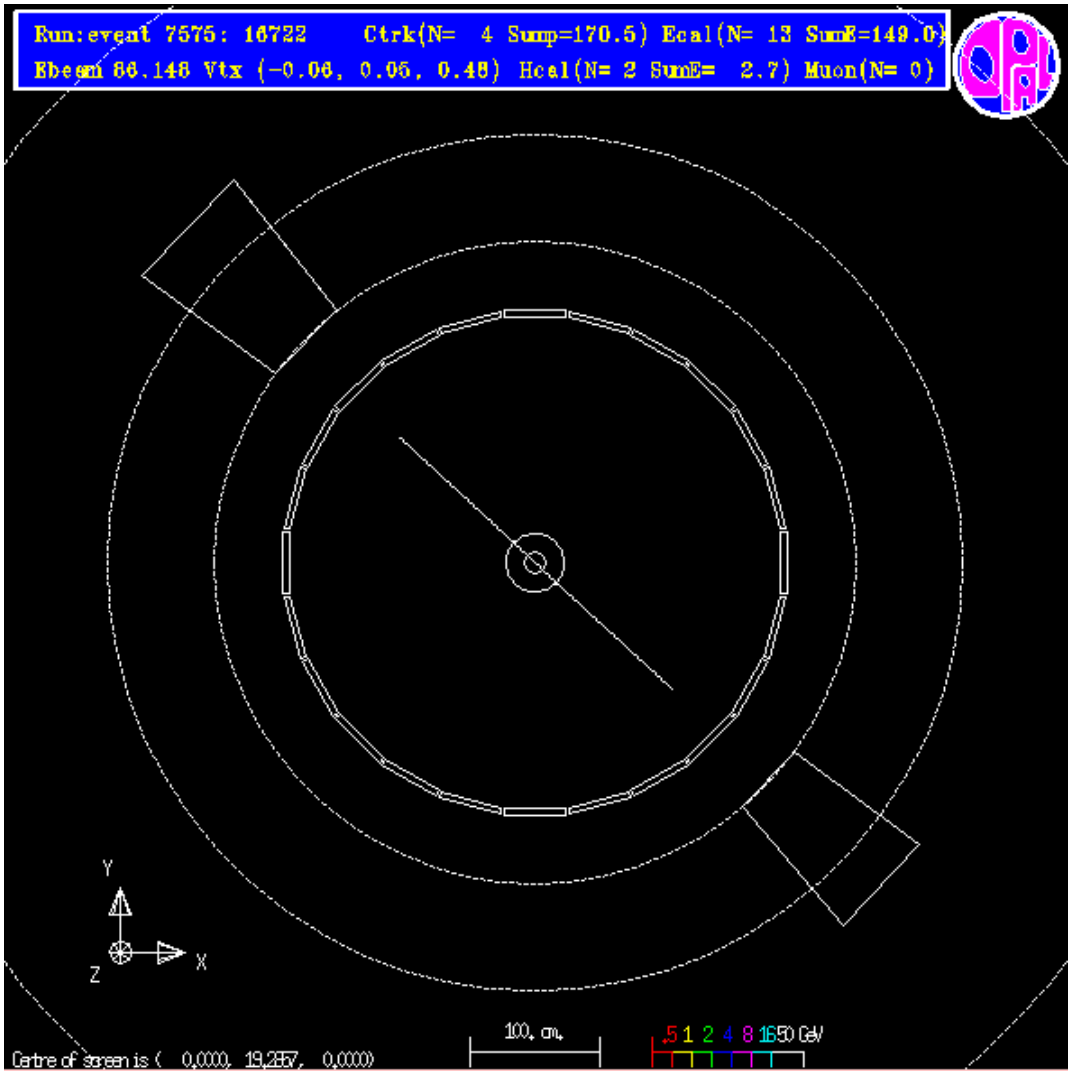
3.5 Muons:

- These are Leptonic modes.
- There is a high probability of the muon passing through all calorimeters to only leave a signal in the muon chamber.



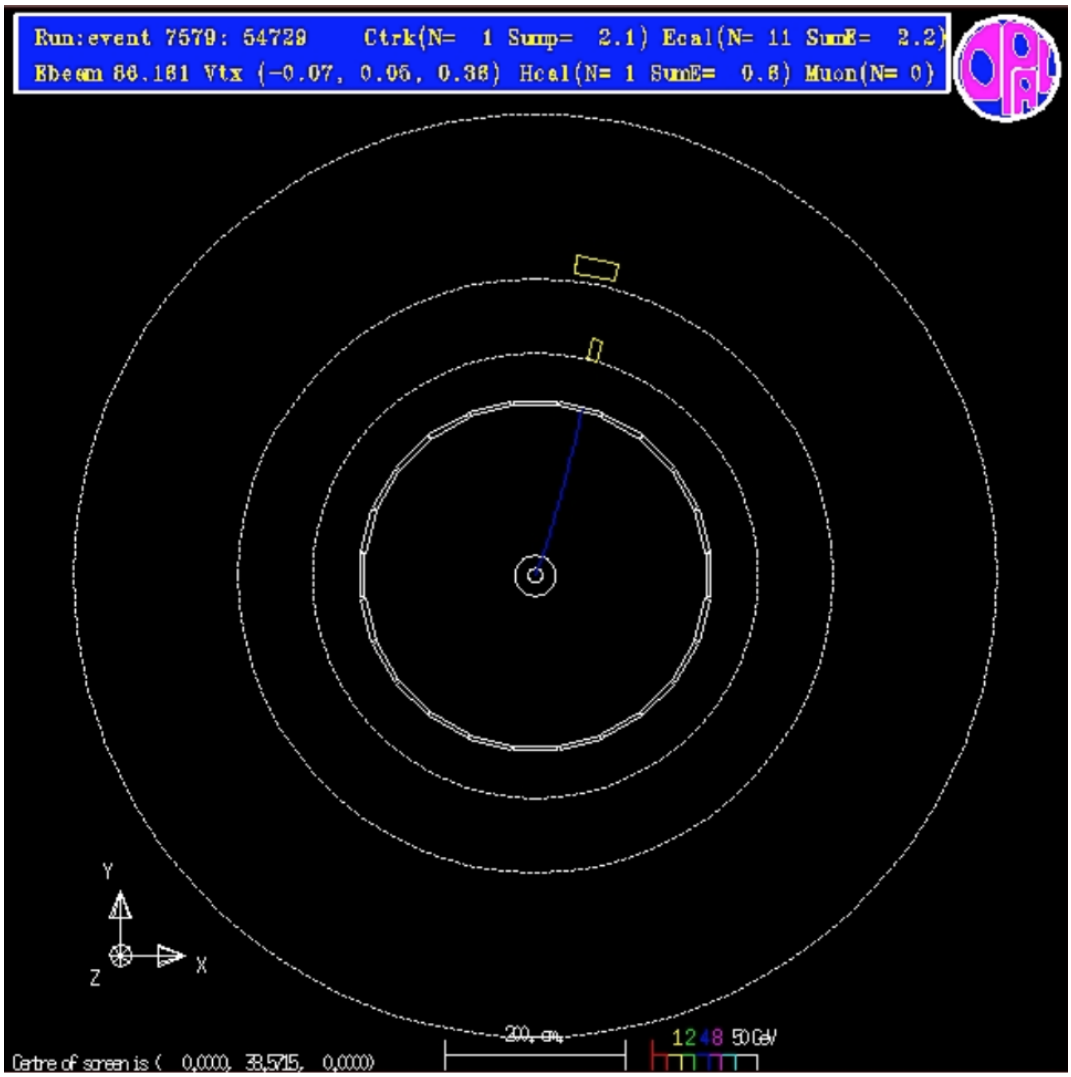
3.6 Electrons:

- These are Leptonic modes.
- They lose all their energy in the electric calorimeter.
- The momentum of the charged track in the tracking chamber should be similar to the energy recorded in the electric calorimeter (same colours).
- There is no signal in the hadronic calorimeter or muon chamber.



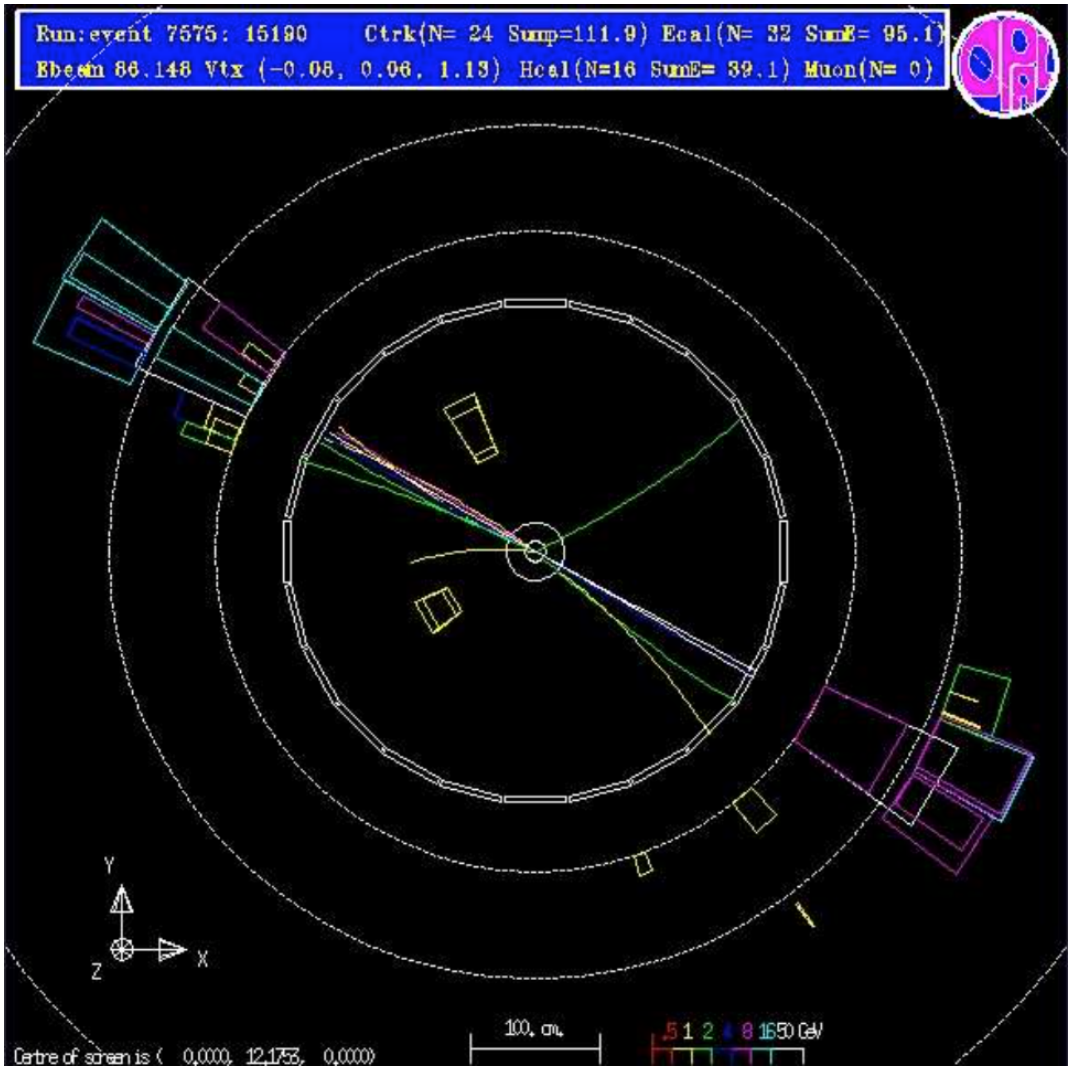
3.7 Hadrons:

- These are Hadronic modes.
- These consist of quarks, antiquarks and gluons.
- There should be no signal in the muon chambers.
- There is often energy in the hadronic calorimeter.
- The momentum in the tracking chamber is usually larger than that dumped in the electric calorimeter.



3.8 Quarks:

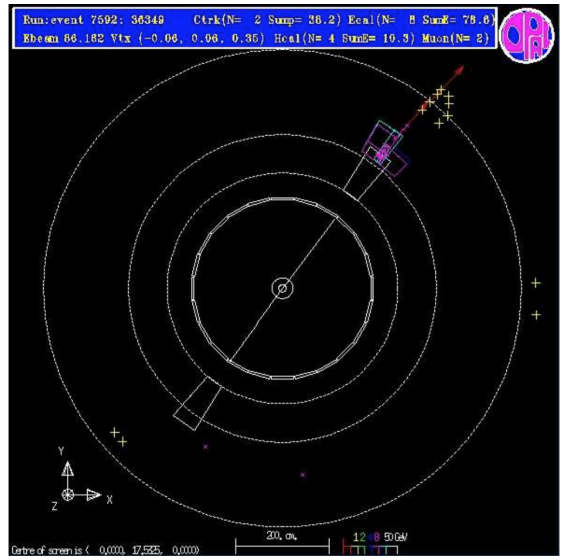
- These are Hadronic modes.
- They are not seen directly, instead we see 'jets' of particles in the direction of the original quark.
- Most particles in the jets are hadrons - we see a number of charged particle tracks in the tracking chamber and energy deposits in the electric and hadronic calorimeters.



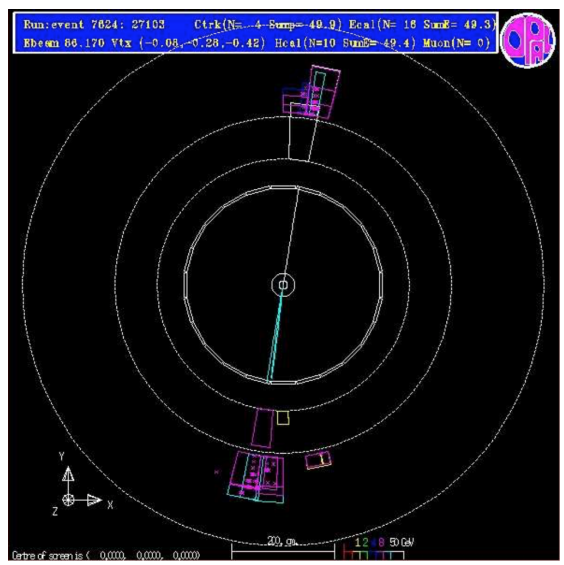
3.9 Taus:

- These are leptonic modes, **BUT** are difficult to spot. There are three types of tau decays:

$$\begin{aligned} e^+e^- &\rightarrow Z^0 \rightarrow \tau^+\tau^- \\ &\rightarrow e + \mu + \text{neutrinos} \end{aligned}$$

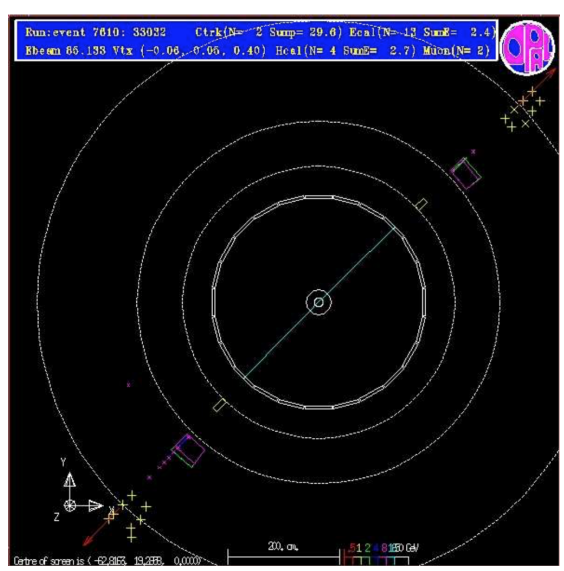


$$\begin{aligned} e^+e^- &\rightarrow Z^0 \rightarrow \tau^+\tau^- \\ &\rightarrow 3 \text{ charged hadrons} \\ &\quad +1 \text{ charged hadron} \\ &\quad + \text{ neutrinos} \end{aligned}$$



$$\begin{aligned} e^+e^- &\rightarrow \tau^+\tau^- \\ &\rightarrow \mu^+\mu^- \\ &\quad + \text{ neutrinos} \end{aligned}$$

Looks like $Z^0 \rightarrow \mu^+\mu^-$, but check the energy



3.10 Counting colours

At the LEP collider, the collision of an electron (e^-) and a positron (e^+) could also produce a W^+ W^- boson pair. We can write this process as:

$$e^+e^- \rightarrow W^+W^- \tag{3.1}$$

where each $W^\pm$ then decays.

The particles that the $W^\pm$ decay to must have less mass than the $W^\pm$, or energy would not be conserved.

- Using the tables and diagrams from tutorial 1, which leptons and quarks can the W decay to?
  - Leptons:
  - Quarks:

The W's decay to a pair of particles and must conserve charge.

- Considering conservation of charge, complete the table below, indicating the possible decay 'channels' for a W^+ and a W^-

	$W^- \rightarrow$	$W^+ \rightarrow$
quark-antiquark $q\bar{q}$	$d\bar{d}$	
		$\bar{s}c$
leptonic	$e\bar{\nu}_e$	

As there is both a W^+ and a W^-, both of which can decay leptonically or into a quark-antiquark pair, there are a total of 3 types of decay:

- Leptonically
- Hadronically: 4-jets (quark-antiquark $\times 2$)
- Mixed (one W decays leptonically and the other hadronically)

Each possible decay channel is equally likely, however remember that there are:

- 3 leptonic modes
- $2n$ quark hadronic modes

where n is the number of colours that quarks come in.

It will be possible to determine what n is from our counting quark lab, by categorising each event into one the three types.

leptonic	mixed	hadronic
l	m	h
9	$12n$	$4n^2$

Table 3.1: the three possible classes of W^+W^- decay

$$
\begin{aligned}
n &= \frac{3}{4}\frac{m}{l} \\
n &= \frac{3}{2}\sqrt{\frac{h}{l}} \\
n &= 3\frac{h}{m}
\end{aligned}
\tag{3.2}
$$

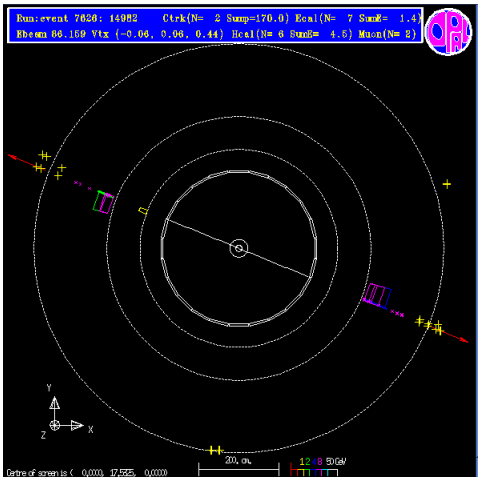
3.11 Homework:

Today's Homework is:

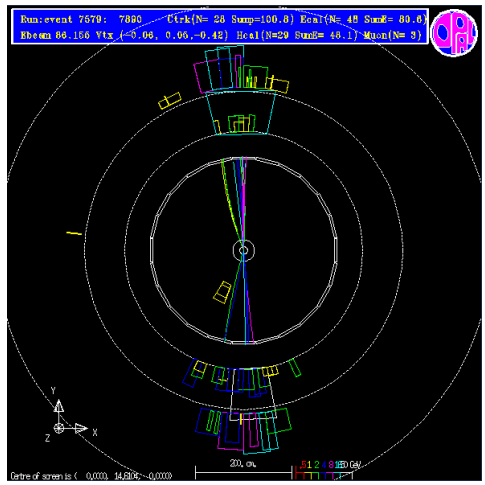
- to classify events 1-12 from the LEP experiment and write down any difficulties you have, in preparation for next tutorial's experiment.
- Extension: starting from table 3.1, derive equations 3.2. Hint - take ratios of the decay classes.

Notes:

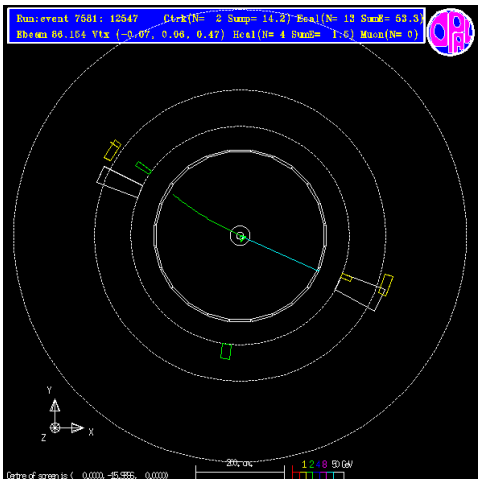
1. leptonic ☐ hadronic ☐ mixed ☐



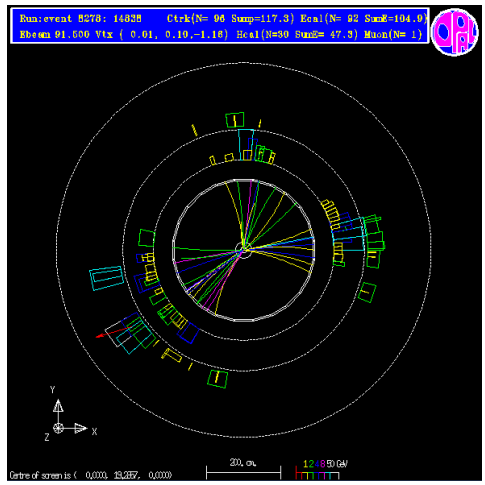
2. leptonic ☐ hadronic ☐ mixed ☐



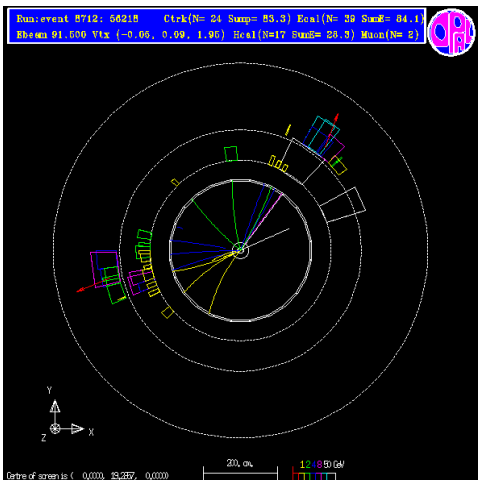
3. leptonic ☐ hadronic ☐ mixed ☐



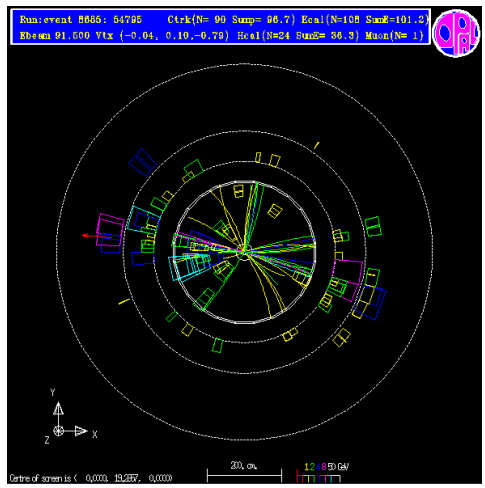
4. leptonic ☐ hadronic ☐ mixed ☐



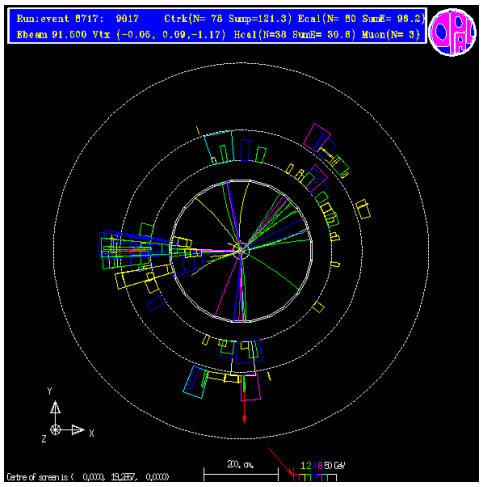
5. leptonic ☐ hadronic ☐ mixed ☐



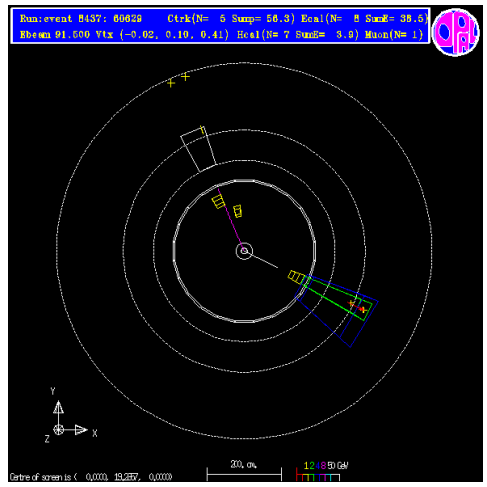
6. leptonic ☐ hadronic ☐ mixed ☐



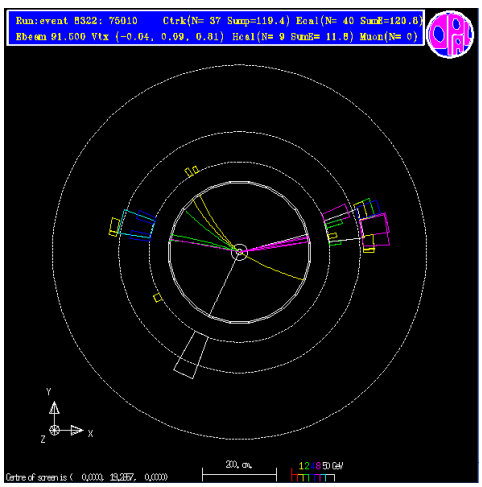
7. leptonic ☐ hadronic ☐ mixed ☐



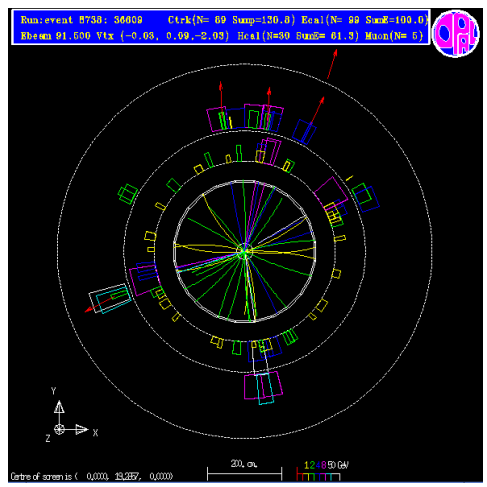
8. leptonic ☐ hadronic ☐ mixed ☐



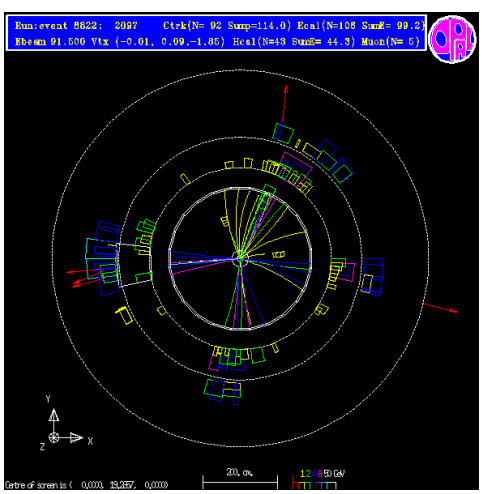
9. leptonic ☐ hadronic ☐ mixed ☐



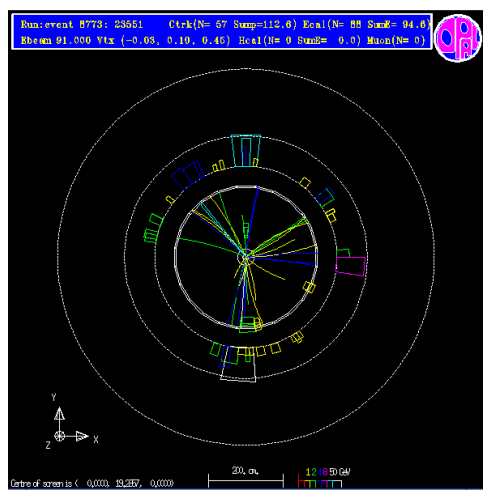
10. leptonic ☐ hadronic ☐ mixed ☐



11. leptonic ☐ hadronic ☐ mixed ☐



12. leptonic ☐ hadronic ☐ mixed ☐



Make a note of any event numbers that you found particularly difficult to classify:

What made these events difficult to classify:

4 Counting colours

What is the purpose of this tutorial?

- To take part in a computer lab analysing a large number of detector 'events' from the LEP experiment.

What are the key questions?

- How many colours are required to explain the experimental data that we are analysing as a class?

We have 100 events to look through. As a group, we need to decide what is the best method for this task. Think about what the Pros and Cons would be for the following:

- Should everyone look at every event?
- Should we split up the data and share it amongst the group?
- Should we have a specialist who we can refer the more difficult ones to?

Then discuss your strategy as a group.

Ideas:

4.1 Method

What did we do?

Are there other methods we could have used?

Why do it this way?

What worked well?

Even better if:

4.2 Results - tables

event no.	leptonic	mixed	hadronic	event no.	leptonic	mixed	hadronic
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
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	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
Total 1							

Table 4.1: Event record 1

event no.	leptonic	mixed	hadronic	event no.	leptonic	mixed	hadronic
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
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	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
Total 2							
Total 1+2							

Table 4.2: Event record 2

event no.	leptonic	mixed	hadronic	event no.	leptonic	mixed	hadronic
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
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	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
	☐	☐	☐		☐	☐	☐
Total 3							
Total 1+2+3							

Table 4.3: Event record 3

Today's Homework is:

- to summarise your results.

Summarise your results:

Summarise your results:

5 Result presentation

What is the purpose of this tutorial?

- To review the results from the previous tutorial and to discuss the best way to present our results.

What are the key questions?

- What did we learn from the counting colours lab?
- How can we present these results?
- What goes into a scientific publication
- How do we write an Abstract, Introduction ...?
- How do we reference others' work?

5.1 Posters:

Posters are a great visual way to advertise your hard work.

Before making your poster, you should consider who your target audience is. Your poster should answer the answer the following questions:

- Why should anyone care?
- What does my work add to current knowledge?
- In how much detail do I need to explain my method?
- Have I told the audience what I found and what I recommend?

Your poster design should:

- leave breathing space around the text for your eyes to rest.
- use plain and simple fonts.
- use the same style throughout.
- not be cluttered - less is more!
- have clear and simple pictures and graphs.

You need to make sure that the poster is easy to read. Posters can be portrait or landscape and are normally printed A0 size. As a guide the text should be

- Title: 85 pt
- Authors: 56 pt
- Sub-headings: 36 pt
- Body text: 24 pt
- Captions: 18 pt

In addition, you should be careful with the colours you choose to use.

There are a number of programs that you can use to design a poster:

- Powerpoint
- Pages
- Latex
- Adobe Illustrator

Figure 5.1 shows an example layout for a poster.

Figures 5.2 & 5.3 show two examples. Annotate them - What is good? What is bad? Who do you think the intended audiences were?

Title - Something catchy & not too long.

Authors - Can be all involved or just the person presenting.

Affiliation - Where you work.

Abstract:

This is a summary of the main result(s) & method, needs to be brief.

Introduction:

This should provide the background information needed to understand your method & results.

It should also say why your work is relevant & interesting.

Method:

What did we do?

Why did we do it this way?

Results:

What is the best way to present the data?

- Table
- Graph
- Both

Is there final number that represents the results?

Does this have an error?

Conclusions:

What do the results tell us?
Link this to the science.

How can we improve the results?

What are the next steps?

Acknowledgements:

Who helped us?

Do we need to reference the work of others?

Figure 5.1: An example poster layout, with content suggestions.

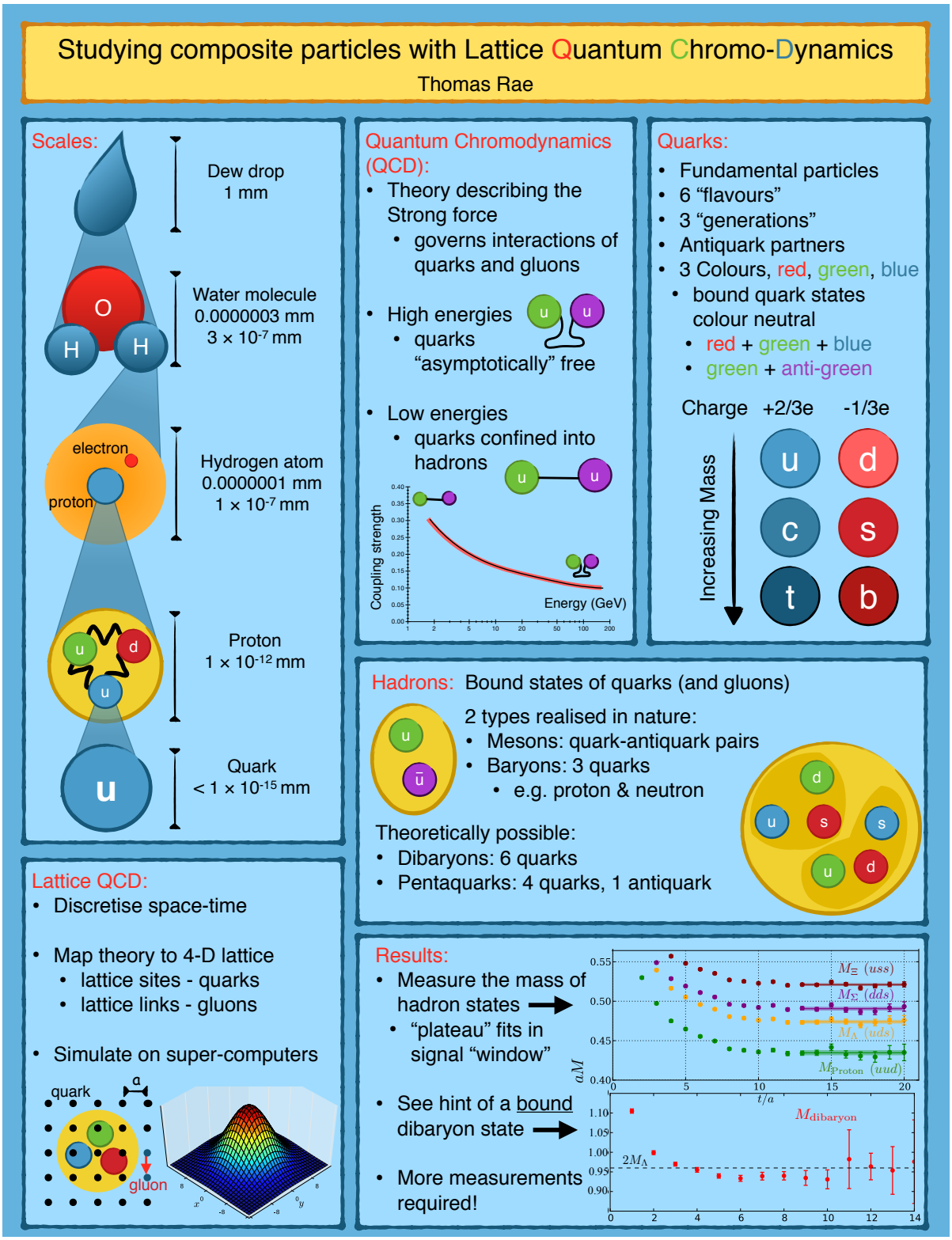


Figure 5.2: Example poster 1.

Two-Baryon Correlation Functions in 2-flavor QCD

Anthony Francis, Chuan Miao, Thomas Rae & Hartmut Wittig

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

HELMHOLTZ ASSOCIATION

Helmholtz Institute Mainz

Introduction

We present an initial study of two-baryon correlation functions with the aim of exploring potential dibaryon bound states, specifically the H-dibaryon [1, 2, 3], which is hypothesized to be a bound state of QCD. In particular, we comment on our first results for two-baryon correlation functions

$$\langle O_{XY}(t) O_{XY}(0)\rangle, \text{where } XY = \Lambda\Lambda, \Sigma\Sigma, N\Xi, \cdots$$

The flavor singlet H-dibaryon

$$BB = -\sqrt{\frac{1}{8}}\Lambda\Lambda + \sqrt{\frac{3}{8}}\Sigma\Sigma + \sqrt{\frac{4}{8}}N\Xi,$$

where the two-baryon interpolating operators are

$$\begin{aligned}
\Lambda\Lambda(x) &= \epsilon^{ijk}\epsilon^{lmn}(d^{i\mathrm{T}}C\gamma_5 s^j)(d^{l\mathrm{T}}C\gamma_5 s^m)(u^{k\mathrm{T}}C\gamma_5 u^n)\\
\Sigma\Sigma(x) &= \epsilon^{ijk}\epsilon^{lmn}(u^{i\mathrm{T}}C\gamma_5 s^j)(d^{l\mathrm{T}}C\gamma_5 s^m)(u^{k\mathrm{T}}C\gamma_5 d^n)\\
N\Xi(x) &= \epsilon^{ijk}\epsilon^{lmn}(u^{i\mathrm{T}}C\gamma_5 d^j)(d^{l\mathrm{T}}C\gamma_5 s^m)(u^{k\mathrm{T}}C\gamma_5 s^n)
\end{aligned}$$

The results are obtained using a 'blocking' algorithm [4, 5] to handle the contractions, which may easily be extended to N-baryon correlation functions.

Effective mass

For our preliminary analysis of the single and two baryon spectrum, we calculate the generalized effective mass [6]

$$ma\,(t) = \frac{1}{t_J}\log\frac{C(t)}{C(t+t_J)}\,,$$

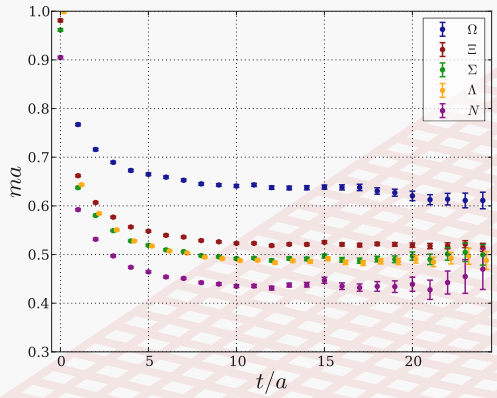
where we choose $t_J = 3$, which improves the stability of the effective mass plot over $t_J = 1$, as neighbouring points are more correlated than those with a larger separation.

Numerical results - single baryons

The calculations use smeared sources and sinks. The measurements are performed using the isotropic CLS ensembles with non-perturbative $\mathcal{O}(a)$ improved Wilson fermions in $N_f = 2$ QCD.

a/fm	$T \times L^3$	L/fm	m_π/MeV	$m_\pi L$	n_{conf}	n_{src}	n_{meas}
0.063	64×32^3	2.02	460	4.7	900	8	7200

Below we show the generalized effective mass plot for the single baryon spectrum.

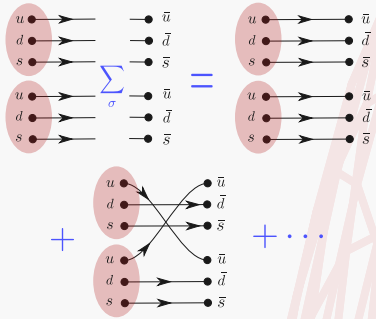


Conclusions & Outlook

- This preliminary study provides promising results for the extraction of two-baryon correlation functions on the CLS ensembles.
- The blocking algorithm effectively handles the large number of contractions required in such calculations.
- We find that $\mathcal{O}(7000)$ measurements are required to begin to resolve the two-baryon effective mass, however it should be increased to check if the H-dibaryon is a bound state of QCD.
- In the future, we intend to extend the study to lighter pion masses and larger lattices.

Blocking algorithm

To handle the large number of full contractions $\mathcal{O}(48)$ for the flavor singlet H-dibaryon system, we implement a blocking algorithm, which is schematically shown below for the $\Lambda\Lambda$ channel.



Specifically,

$$\begin{aligned}
\langle O_{\Lambda\Lambda}(t) O_{\Lambda\Lambda}(0)\rangle = (C\gamma_5)_{\alpha\beta} \sum_{\sigma_u,\sigma_d,\sigma_s} & f(\alpha, \xi'_{\sigma_u(1)}, \xi'_{\sigma_d(2)}, \xi'_{\sigma_s(3)}) f(\beta, \xi'_{\sigma_u(4)}, \xi'_{\sigma_d(5)}, \xi'_{\sigma_s(6)})\\
&\times \epsilon_{c'_1,c'_2,c'_3}\epsilon_{c'_4,c'_5,c'_6}(C\gamma_5)_{\alpha'_2\alpha'_3}(C\gamma_5)_{\alpha'_5\alpha'_6}
\end{aligned}$$

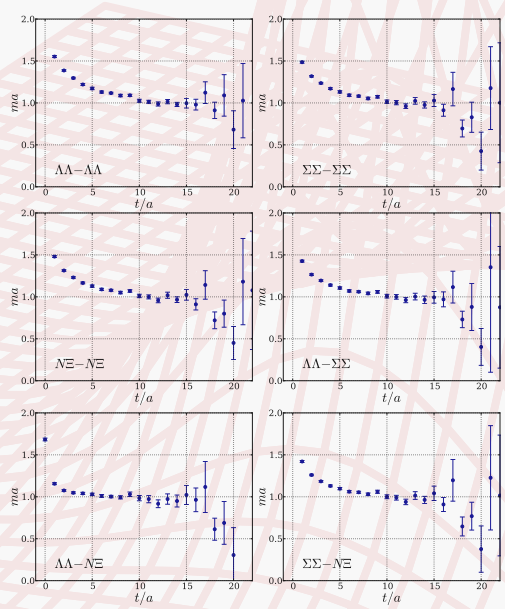
where the sum is over all possible contractions $\sigma_{u,d,s}$ and the blocks

$$f(\alpha_1, \xi'_1, \xi'_2, \xi'_3) = \epsilon_{c_1,c_2,c_3}(C\Gamma_5)_{\alpha_2\alpha_3} S_u(\xi_1, \xi'_1) S_d(\xi_2, \xi'_2) S_s(\xi_3, \xi'_3)$$

are calculated beforehand. Here α is the open sink Dirac index, ξ/ξ' denote the combined color (Roman) and Dirac (Greek) indices at the sink/source, while $S_{u,d,s}$ is a propagator of flavor u, d, s.

Numerical results - two-baryons

Below we show the generalized effective mass plots for the two-baryon correlators $X_1Y_1 - X_2Y_2$ where X_1Y_1 and X_2Y_2 are the two baryons at the source and sink.



References

[1] R. L. Jaffe, Phys. Rev. Lett. 38, 195 (1977)
[2] S. R. Beane et al. [NPLQCD Collaboration], Phys. Rev. Lett. 106 (2011) 162001
[3] T. Inoue et al. [HAL QCD Collaboration], Phys. Rev. Lett. 106 (2011) 162002
[4] T. Doi and M. G. Endres, Comput. Phys. Commun. 184 (2013) 117
[5] W. Detmold and K. Orginos, Phys. Rev. D 87 (2013) 114512
[6] S. R. Beane et al. [NPLQCD Collaboration], Phys. Rev. D 81 (2010) 054505

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Figure 5.3: Example poster 2.

5.2 My poster ideas:

Sketch you poster idea here:

Sketch you poster idea here:

Today's Homework is:

- to write up the counting colours experiment as a poster (or paper).

6 Feedback

What is the purpose of this tutorial?

- To reflect on skills learned in the programme with a view to encouraging resilience.
- To receive feedback on the final assignment.

What are the key questions?

- What strengths have I demonstrated in my work and what areas of development are there left for me to address?
- What steps do I need to take to improve my academic output?

6.1 Activity 1: Marking your own work

Using the mark scheme, identify three things you did well and three things you could improve.

What went well?

1.
2.
3.

What could be improved?

1.
2.
3.

6.2 Activity 2: Responding to feedback

Read through your feedback sheet and highlight on your assignment where you received positive feedback (one colour) and areas for improvement (in a different colour). You might find it helpful to annotate this with a brief comment or two.

6.3 Activity 3: Looking Forwards: Think, Pair, Share

Think about how you can use this feedback in your future school work. Talk to your partner about how you both plan to make changes to your school work in the future as result of this feedback. Share your ideas as a group.

A Glossary of Keywords

Word	Definition

Word	Definition

B Timetables

Timetable - Tutorials

Tutorial	Date	Time	Location
1			
2			
3			
4			
5			

Timetable - Homework Assignments

Homework Assignment	Description	Due Date
Tutorial 1		
Tutorial 2		
Tutorial 3		
Tutorial 4		
Tutorial 5		

Assignment Submission - Lateness and Plaglarism

Lateness	
Submission after	10 marks deducted
Plagiarism	
Some plagiarism	10 marks deducted
Moderate plagiarism	20 marks deducted
Extreme plagiarism	Automatic fail

C Mark Scheme

Key Skill	1st	2.2
Communication	• Writing is coherent and organised logically • Almost faultless spelling, punctuation and grammar • Appropriate language is used for the scientific document (such as a scientific poster)	• At times, the writing is poorly organised, lacking structure • Spelling, punctuation and grammar are not consistently correct • Writing style lacks consistency and is not always appropriate for the document
Application	• Applies course content to new situations accurately and confidently • Avoids the use of irrelevant data, arguments or knowledge	• Course content is reliably applied to familiar situations • Requires direction to apply knowledge to unfamiliar topics • Sometimes introduces irrelevant information
Research Skills	• Outside references are correctly and accurately referenced • Uses additional references to accurately support those within the course material or to add extra relevant information	• Sources mostly referenced correctly • Only sources limited to the course handbook are referenced • Additional references (if included) may be inaccurate or not relevant
Critical thinking and evaluation	• Both the strengths and weaknesses of the data are recognised and commented upon • Provides a well reasoned conclusion from the data • Provides appropriate suggestions for an improvement to the analysis • Demonstrates a logical and systematic approach to the data	• Fails to fully discuss the strengths and weaknesses of the data • Has some understanding of the logical conclusions that may be made from the data • No suggestion for improvements to the analysis • The treatment of the data is not always systematic and lacks consistent logic
Numerical Analysis	• Simple calculations are consistently correct and logically presented • Physical interpretations of quantitative results are consistently correct • Physical units are consistently correct	• Simple calculations are often correct • Attempts are made to interpret numerical results • Physical units are mostly used correctly

D KS4 Programme 2016/17 - Pupil Feedback Report

Grade	Marks	What this means
1st	70+	Performing to an excellent standard at A-level
2:1	60-69	Performing to a good standard at A-level
2:2	50-59	Performing to an excellent standard at current key stage
3rd	40-49	Performing to a good standard at current key stage
Working towards a pass	0-39	Performing below a good standard at current key stage
Did not submit	DNS	No assignment received by The Brilliant Club

Lateness	
Any lateness	10 marks deducted
Plagiarism	
Some plagiarism	10 marks deducted
Moderate plagiarism	20 marks deducted
Extreme plagiarism	Automatic fail

Name of RIS Teacher			
Title of Assignment			
Name of Pupil			
Name of School			
ORIGINAL MARK / 100		FINAL MARK / 100	
DEDUCTED MARKS		FINAL GRADE	

If marks have been deducted (e.g. late submission, plagiarism) the teacher should give an explanation in this section:

Learning Feedback Comment 1 -	
What you did in relation to this Key Learning Priority	How you could improve in the future
Learning Feedback Comment 2 -	
What you did in relation to this Key Learning Priority	How you could improve in the future
Learning Feedback Comment 3 -	
What you did in relation to this Key Learning Priority	How you could improve in the future
Resilience Commet	
How you showed resilience through the course	How you could build learning resilience in the future

E Referencing correctly

When you get to university, you will need to include references in the assignments that you write, so we would like you to start getting into the habit of referencing in your Brilliant Club assignment. This is really important, because it will help you to avoid plagiarism. Plagiarism is when you take someone else's work or ideas and pass them off as your own. Whether plagiarism is deliberate or accidental, the consequences can be severe. In order to avoid losing marks in your final assignment, or even failing, you must be careful to reference your sources correctly.

What is a reference? A reference is just a note in your assignment which says if you have referred to or been influenced by another source such as book, website or article. For example, if you use the internet to research a particular subject, and you want to include a specific piece of information from this website, you will need to reference it.

Why should I reference? Referencing is important in your work for the following reasons:

- It gives credit to the authors of any sources you have referred to or been influenced by.
- It supports the arguments you make in your assignments.
- It demonstrates the variety of sources you have used.
- It helps to prevent you losing marks, or failing, due to plagiarism.

When should I use a reference? You should use a reference when you:

- Quote directly from another source.
- Summarise or rephrase another piece of work.
- Include a specific statistic or fact from a source.

How do I reference? There are a number of different ways of referencing, and these often vary depending on what subject you are studying. The most important thing is to be consistent. This means that you need to stick to the same system throughout your whole assignment. Here is a basic system of referencing that you can use, which consists of the following two parts:

A marker in your assignment: After you have used a reference in your assignment (you have read something and included it in your work as a quote, or re-written it your own words) you should mark this is in your text with a number, e.g. [1]. The next time you use a reference you should use the next number, e.g. [2].

Bibliography: This is just a list of the references you have used in your assignment. In the bibliography, you list your references by the numbers you have used, and include as much information as you have about the reference.

The list below gives what should be included for different sources.

- Websites: Author (if possible), title of the web page, website address, [date you accessed it, in square brackets].

- Books: Author, date published, *title of book* (in italics), pages where the information came from.
- Articles: Author, 'title of the article' (with quotation marks), where the article comes from (newspaper, journal etc.), date of the article.

F Scientific Papers

F.1 Why write Scientific papers?

- To share interesting, useful and novel (original) work and knowledge.
- To organise our work.
- To construct our research and ideas into a comprehensive and logical format.
- To get feedback and to progress the subject as a whole.
- Because its fun!?

F.2 Scientific Journals

Scientific papers come in many different forms, and each journal has a different layout. Different journals are often for different intended audiences. Here are some physics journals, grouped by the intended audience:

- Expert audience - high level of subject knowledge assumed
  - Physical Review series
  - Applied Physics series
  - European Physics Journal Series
- Wider audience ('prestigious' journals) - less specific subject knowledge assumed
  - Science
  - Nature
- General audiences - accessible with a minimal background knowlege
  - Physics Today - American Physical Society journal
  - Physics World - Institute of Physics journal
  - Scientific American - popular science articles
  - American Journal of Physics

F.3 Scientific paper layout

- Title
  - informative: should say the main idea/result/study
  - catchy: should get people interested
  - concise: don't want the title to be a book in itself!
- Authors
  - list all the people who significantly contributed to the work (e.g. alphabetically)
  - include their affiliations (where they work) - research is internationally collaborative
- Abstract
  - This must catch the attention of the reader!
  - There are many articles and you want them to read yours!
  - Must state the major findings/results - numerical if possible
- Introduction
  - Describe how this work fits into the bigger picture
  - State clearly why the work is important
  - Relate to previous relevant research
  - State the organisation of the paper (first we ...., then we ....)
  - Should be able to read alongside the conclusion to get an 'abridged' version of the paper
- Text body - present the main work. The layout:
  - should be organised and logical
  - can be sectioned to improve flow
- Conclusions and Summary
  - Summarise main results
  - What do your results mean for the bigger picture?
  - Does this lead to future work?
  - Round off your work - finish the story!
- Acknowledgements - Have people helped in small ways? Have you used laboratories? Etc.
- References - This is where the papers that you have referenced in the text are listed.
- Appendices - Is there additional information which might help but is not relevant to the main story?

Date, journal name, volume - needed to later reference or find the article

MARCH 15, 1933 PHYSICAL REVIEW VOLUME 43

Author(s) and affiliation (where they work)

Paper title

The Positive Electron

CARL D. ANDERSON, *California Institute of Technology, Pasadena, California*

(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

Editor

Abstract: Should summarise the main procedure and findings (main results)

There is often an introduction before the method. This describes relevant information to the problem at hand. In short papers this is merged with the method.

Method: the scientific procedures are detailed here

ON August 2, 1932, during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber (magnetic field of 15,000 gauss) designed in the summer of 1930 by Professor R. A. Millikan and the writer, the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence in this case of a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron. Later study of the photograph by a whole group of men of the Norman Bridge Laboratory only tended to strengthen this view. The reason that this interpretation seemed so inevitable is that the track appearing on the upper half of the figure cannot possibly have a mass as large as that of a proton for as soon as the mass is fixed the energy is at once fixed by the curvature. The energy of a proton of that curvature comes out 300,000 volts, but a proton of that energy according to well established and universally accepted determinations[1] has a total range of about 5 mm in air while that portion of the range actually visible in this case exceeds 5 cm without a noticeable change in curvature. The only escape from this conclusion would be to assume that at exactly the same instant (and the sharpness of the tracks determines that instant to within about a fiftieth of a second) two independent electrons happened to produce two tracks so placed as to give the impression of a single particle shooting through the lead plate. This assumption was dismissed on a probability basis, since a sharp track of this order of curvature under the experimental conditions prevailing occurred in the chamber only once in some 500 exposures, and since there was practically no chance at all that two such tracks should line up in this way. We also discarded as completely untenable the assumption of an electron of 20 million volts entering the lead on one side and coming out with an energy of 60 million volts on the other side. A fourth possibility is that a photon, entering the lead from above, knocked out of the nucleus of a lead atom two particles, one of which shot upward and the other downward. But in this case the upward moving one would be a positive of small mass so that either of the two possibilities leads to the existence of the positive electron.

In the course of the next few weeks other photographs were obtained which could be interpreted logically only on the positive-electron basis, and a brief report was then published[2] with due reserve in interpretation in view of the importance and striking nature of the announcement.

Figures referenced, do not always appear next to reference in the text. Here it appears on the next page!

MAGNITUDE OF CHARGE AND MASS

It is possible with the present experimental data only to assign rather wide limits to the

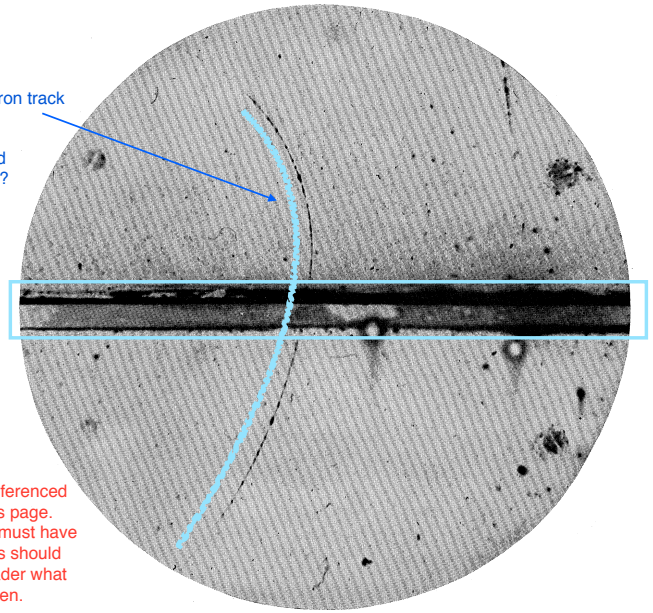
[1] Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances*, p. 294. Assuming $R \propto v^3$ and using data there given the range of a 300,000 volt proton in air S.T.P. is about 5 mm.

[2] C. D. Anderson, Science **76**, 238 (1932).

Superscripts are used to cite other peoples work, the reference is then given in the footnote.

Sometimes this is done using [1] in the text and then the references are all given at the end.

The author is free to choose his own section headings. In this section the author explains the results from the method and the observations in the previous section and finishes with the conclusions



Here is Figure 1 referenced from the previous page. Figures and Tables must have captions. Captions should describe to the reader what should be seen.

FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

magnitude of the charge and mass of the particle. The specific ionization was not in these cases measured, but it appears very probable, from a knowledge of the experimental conditions and by comparison with many other photographs of high- and low-speed electrons taken under the same conditions, that the charge cannot differ in magnitude from that of an electron by an amount as great as a factor of two. Furthermore, if the photograph is taken to represent a positive particle penetrating the 6 mm lead plate, then the energy lost, calculated for unit charge, is approximately 38 million electron-volts, this value being practically independent of the proper mass of the particle as long as it is not too many times larger than that of a free negative electron. This value of 63 million volts per cm energy-loss for the positive particle it was considered legitimate to compare with the measured mean of approximately 35 million volts[3] for negative electrons of 200–300 million volts energy since the rate of energy-loss for particles of small mass is expected to change only very slowly over an energy range extending from several million to several hundred million volts. Allowance being made for experimental uncertainties, an upper limit to the rate of loss of energy for the positive particle can then be set at less than four times that for an electron, thus fixing, by the usual relation between rate of ionization and

[3] C. D. Anderson, Phys. Rev. **43**, 381A (1933).

The format for this paper is two columns. This is fairly common (especially for short papers). Other journals sometimes use single columns.

The margins are usually quite large - this aids with readability.

charge, an upper limit to the charge less than twice that of the negative electron. It is concluded, therefore, that the magnitude of the charge of the positive electron which we shall henceforth contract to positron is very probably equal to that of a free negative electron which from symmetry considerations would naturally then be called a negatron.

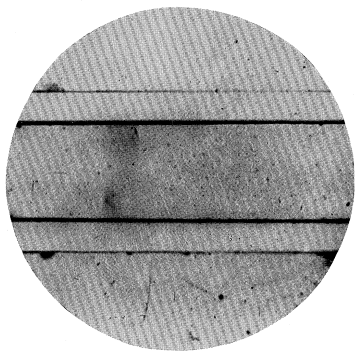


FIG. 2. A positron of 20 million volts energy ($H\rho = 7.1 \times 10^4$ gauss-cm) and a negatron of 30 million volts energy ($H\rho = 10.2 \times 10^4$ gauss-cm) projected from a plate of lead. The range of the positive particle precludes the possibility of ascribing it to a proton of the observed curvature.

Here a physical interpretation of the data is given.

This includes quantitative statements.

When possible quantitative statements are more informatative than qualitative statements.

It is pointed out that the effective depth of the chamber in the line of sight which is the same as the direction of the magnetic lines of force was 1 cm and its effective diameter at right angles to that line 14 cm, thus insuring that the particle crossed the chamber practically normal to the lines of force. The change in direction due to scattering in the lead,[8] in this case about 8° measured in the plane of the chamber, is a probable value for a particle of this energy though less than the most probable value.

The magnitude of the proper mass cannot as yet be given further than to fix an upper limit to it about twenty times that of the electron mass. If Fig. 1 represents a particle of unit charge passing through the lead plate then the curvatures, on the basis of the information at hand on ionization, give too low a value for the energy-loss unless the mass is taken less than twenty times that of the negative electron mass. Further determinations of $H\rho$ for relatively low energy particles before and after they cross a known amount of matter, together with a study of ballistic effects such as close encounters with electrons, involving large energy transfers, will enable closer limits to be assigned to the mass.

To date, out of a group of 1300 photographs of cosmic-ray tracks 15 of these show positive particles penetrating the lead, none of which can be ascribed to particles with a mass as large as that of a proton, thus establishing the existence of positive particles of unit charge and of mass small compared to that of a proton. In many other cases due either to the short section of track available for measurement or to the high energy of the particle it is not possible to differentiate with certainty between protons and positrons. A comparison of the six or seven hundred positive-ray tracks which we have taken is, however, still consistent with the view that the positive particle which is knocked out of the nucleus by the incoming primary cosmic ray is in many cases a proton.

Specific details of what was observed

Highlights strengths and weaknesses of data

What can be inferred?

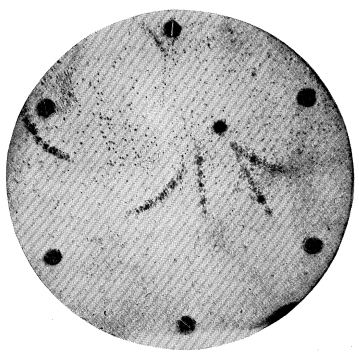


FIG. 3. A group of six particles projected from a region in the wall of the chamber. The track at the left of the central group of four tracks is a negatron of about 18 million volts energy ($H\rho = 6.2 \times 10^4$ gauss-cm) and that at the right a positron of about 20 million volts energy ($H\rho = 7.0 \times 10^4$ gauss-cm). Identification of the two tracks in the center is not possible. A negatron of about 15 million volts is shown at the left. This group represents early tracks which were broadened by the diffusion of the ions. The uniformity of this broadening for all the tracks shows that the particles entered the chamber at the same time.

From the fact that positrons occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from an atomic nucleus. If we retain the view that a nucleus consists of protons and neutrons (and α-

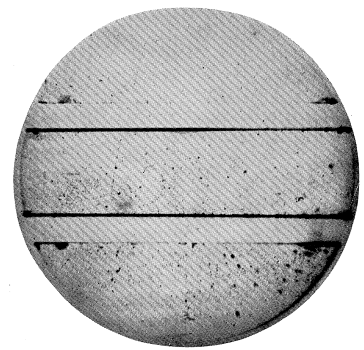


FIG. 4. A positron of about 200 million volts energy ($H\rho = 6.6 \times 10^5$ gauss-cm) penetrates the 11 mm lead plate and emerges with about 125 million volts energy ($H\rho = 4.2 \times 10^5$ gauss-cm). The assumption that the tracks represent a proton traversing the lead plate is inconsistent with the observed curvatures. The energies would then be, respectively, about 20 million and 8 million volts above and below the lead, energies too low to permit the proton to have a range sufficient to penetrate a plate of lead of 11 mm thickness.

particles) and that a neutron represents a close combination of a proton and electron, then from the electromagnetic theory as to the origin of mass the simplest assumption would seem to be that an encounter between the incoming primary ray and a proton may take place in such a way as to expand the diameter of the proton to the same value as that possessed by the negatron. This process would release an energy of a billion electron-volts appearing as a secondary photon. As a second possibility the primary ray may disintegrate a neutron (or more than one) in the nucleus by the ejection either of a negatron or a positron with the result that a positive or a negative proton, as the case may be, remains in the nucleus in place of the neutron, the event occurring in this instance without the emission of a photon. This alternative, however, postulates the existence in the nucleus of a proton of negative charge, no evidence for which exists. The greater symmetry, however, between the positive and negative charges revealed by the discovery of the positron should prove a stimulus to search for evidence of the existence of negative protons. If the neutron should prove to be a fundamental particle of a new kind rather than a proton and negatron in close combination, the above hypotheses will have to be abandoned for the proton will then in all probability be represented as a complex particle consisting of a neutron and positron.

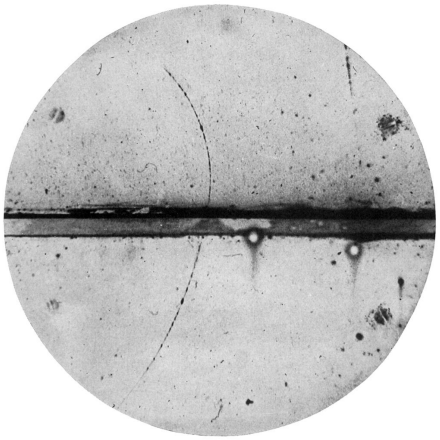
Here the author discuses the impact of the results and suggests possible future work.

While this paper was in preparation press reports have announced that P. M. S. Blackett and G. Occhialini in an extensive study of cosmic-ray tracks have also obtained evidence for the existence of light positive particles confirming our earlier report.

I wish to express my great indebtedness to Professor R. A. Millikan for suggesting this research and for many helpful discussions during its progress. The able assistance of Mr. Seth H. Neddermeyer is also appreciated.

The author recognises other groups performing similar work.

The author acknowledges and gives thanks to people who helped with discussions and ideas to his work



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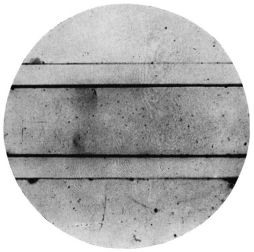

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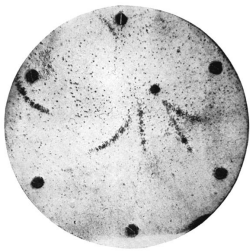

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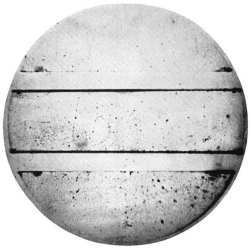

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G University Applications Guidance

- For course choices and careers information:
  `www.brightknowledge.org.uk`
- For information and statistics on universities and courses:
  `www.unistats.direct.gov.uk`
- For comprehensive information on universities, including rankings:
  `www.thecompleteuniversityguide.co.uk`

Acknowledgements

PLEASE NOTE - The Researchers in Schools programme is designed to support the university applications process at your school. The work you complete for the programme should add to your schoolwork rather than detract from it. Please be aware of deadlines and try to manage your workload appropriately. If you are worried about the programme interfering with your schoolwork then please speak to your teacher.