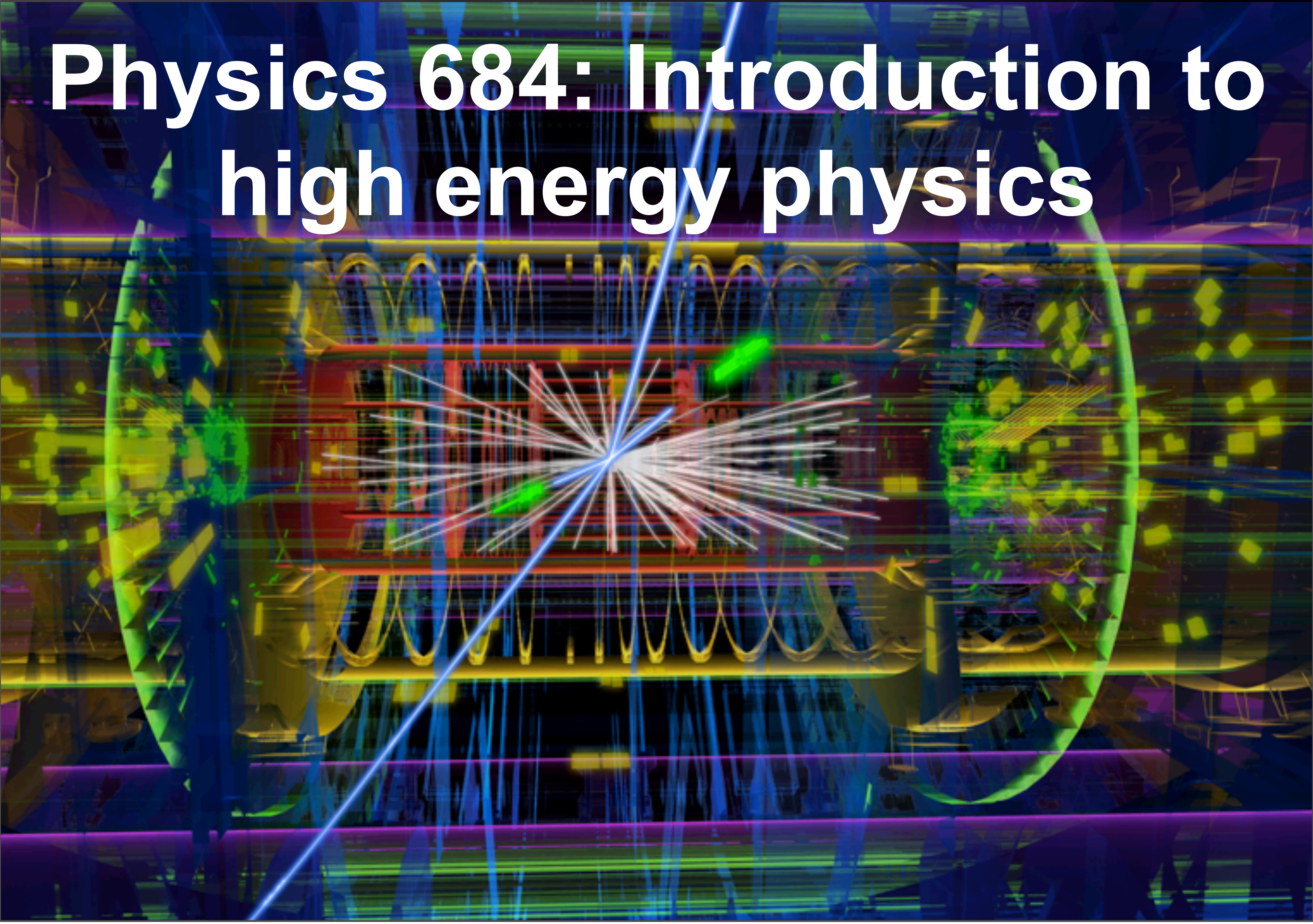
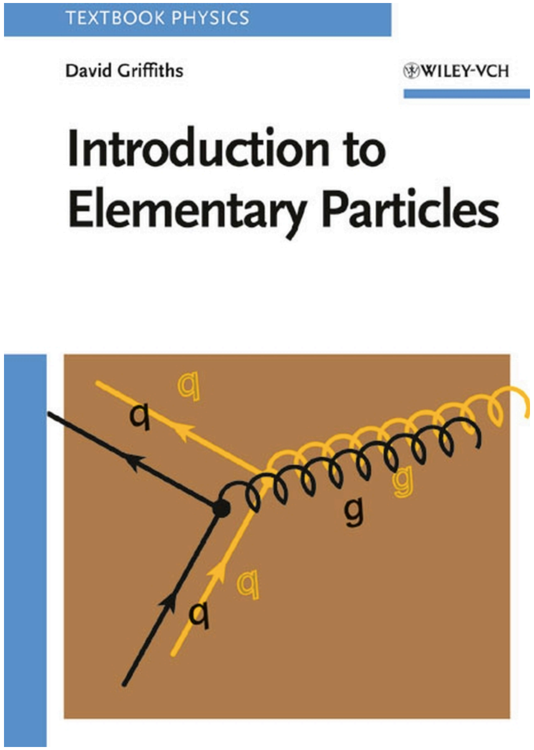
Welcome!



Physics 684: Introduction to high energy physics

Some practical information

- Monday + Wednesday, 6-7:15 pm in LaTourette 227 (aka here)
- Griffiths Introduction to Elementary Particles is the required text
  - Expect a good, basic knowledge of quantum mechanics, though we'll hopefully cover everything you need to know
  - Plan on following the book quite closely, with some important exceptions (see next slides)
- Useful formulas and equations and information in appendix at back of book cover



TEXTBOOK PHYSICS

David Griffiths

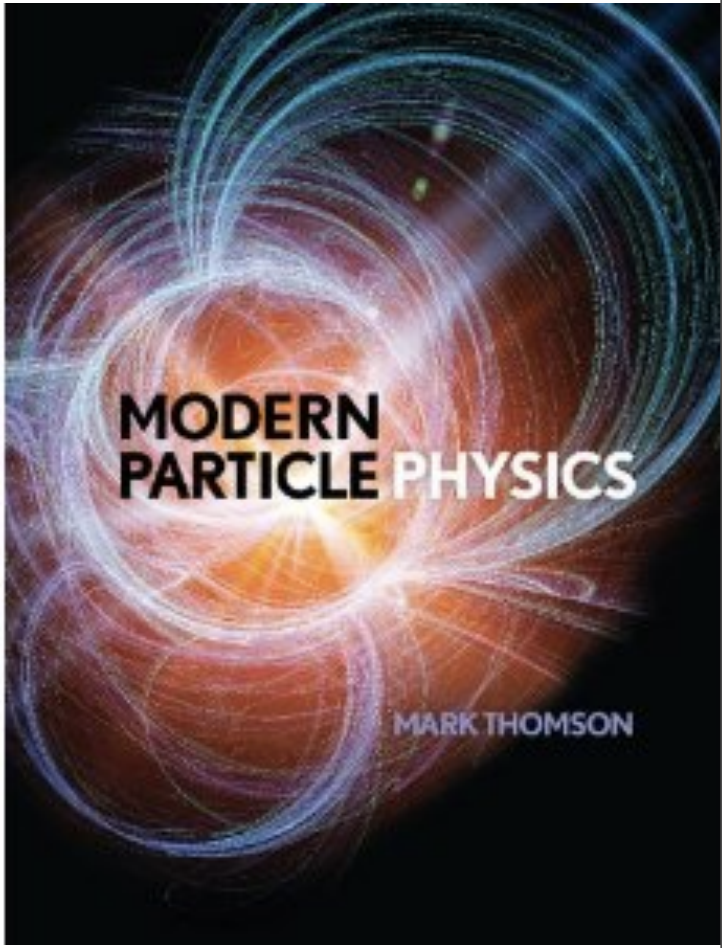
WILEY-VCH

Introduction to
Elementary Particles

When I will diverge from Griffiths

- In terms of material, it is very well explained, but we'll go a bit more in depth on certain topics (and skip others), and fill in the gaps in between equations
- I'll use slightly different notation (natural units!)
- Will cover detectors a bit
- We'll end with some discussion of "real" LHC analyses

Will also be mined for some extra material



What we will cover (partially following Griffiths)

1. Some history of particle physics
2. Particle dynamics and a Standard Model (SM) overview
3. How do particle detectors work? Modern particle physics experiments
4. Relativistic kinematics
5. On symmetries
6. Bound states
7. Feynman rules
8. Quantum electron dynamics, QED
9. Quantum chromo dynamics, QCD (short version)
10. Weak interactions
11. Gauge theories and the Higgs mechanism
12. “Real” particle physics @ the LHC!

With roughly 1 problem set per 1-2 topics above

Grading

- Problem sets every 1-2 weeks, each with the same weight: combined total, 75% of grade
    - All to be due 1 week after they are given, in class, after assignment
    - To be distributed after we finish 1-2 chapters/topics
    - Start the HW early! If you get stuck and need help, please come by during office hours
    - Please ask for help if you don’t understand solutions after they are posted (we’ll briefly go over them in class, but not over everything)
- Final presentation: 25% of grade
- Late homework/exams NOT accepted without valid note or excuse (for sure not if you don’t talk to me as soon as possible)

Final exam

- Final will be a bit different than the usual exam, and will be focused more on “real” particle physics
    - Based on presentations in class (your presentation, and the questions you ask of others during their presentations)
- Dates and schedule TBD

25% of total grade

Grading

- After weighting problem sets and final, the grades will be:
  - A: 85-100%
  - A-: 78-85%
  - B+: 70-77%
  - B: 62-69%
  - B-: 56-61%
  - C+: 48-55%
  - C: 40-47%
  - D: 25-39%
  - F: 25% or less

I reserve the right to shift this scale, but only in the direction that helps you

On homework

- I don’t want to keep you from working with others, but any work that you hand in must be your own
    - Solutions found on the web are a form of plagiarism
    - “Can I copy your solutions” are also plagiarism
    - And “Tell me the Answer” is academically dishonest, as well
        - You will anyway not get credit for answers without showing your work
    - I do want you to help your classmates, however... and don’t forget that office hours are there for those who need assistance, too

Office hours

- Office hours (Faraday 220): Monday and Wednesday 3-4 pm or by appointment
    - I may spend some time at CERN or Argonne or be traveling, so if you want to meet at any time other than during the set office hours please e-mail me (jahred.adelman@niu.edu) to set up an appointment
        - You can always try and stop by, but you will have better luck if you set up an appointment

The class

- Roughly once a week, I will try and post previous slides on the class website for you
  - http://nicadd.niu.edu/~jahreda/phys684/index.html
  - Should not be considered a substitute for attendance, but can hopefully help you in preparations for exams and homework
  - Goal: You should not be worried about copying down every formula, but rather instead be focused on paying attention
  - **Syllabus located on course website**
- We may also work out some problems together in presentations here or on blackboard/whiteboard
  - So you can see that I can also get stuck :)

Attendance

- Please come to class (shouldn't need to ask this of you, but I state it anyway)
  - You can't hand in homework without being here
  - The problems that we go over will be important to follow and understand
  - I am not taking attendance - but this course should be fun, and you will not learn as much if you don't come to class

The classroom

- Please avoid loud food in the classroom
  - I know it's an evening course, but the goal should be to avoid distracting others
  - Again, it's not Physics 101 so I hope it's not a problem
- Cell phones need to stay in your pocket and be turned off
  - If your phone rings, we will know it was you (this class is that small)
  - I know it's an evening class and some people have family or others issues - keep your phone on vibrate if possible, and if you need to take a phone call, step out of the classroom quietly

Seems silly, but mostly - be respectful!

About me ... and you

- For those who do not know me, I am indeed a particle physicist working on measurements of and searches for new physics with Higgs bosons using the ATLAS experiment at the LHC (at CERN)
  - I'll try and point out my research during the class, as appropriate

NIU@CERN! (Even if we don't look very happy, we are)

About me ... and you

- I'll try to update my teaching style as the semester goes on, based on my experience, observations and your feedback
  - If I am going too fast... or too slow, or if my style (or hand-writing) is incomprehensible, please speak up

One last topic

We are small enough - time to introduce yourselves (and apologies in advance when I forget your name)

Before we get to physics...

Any questions?

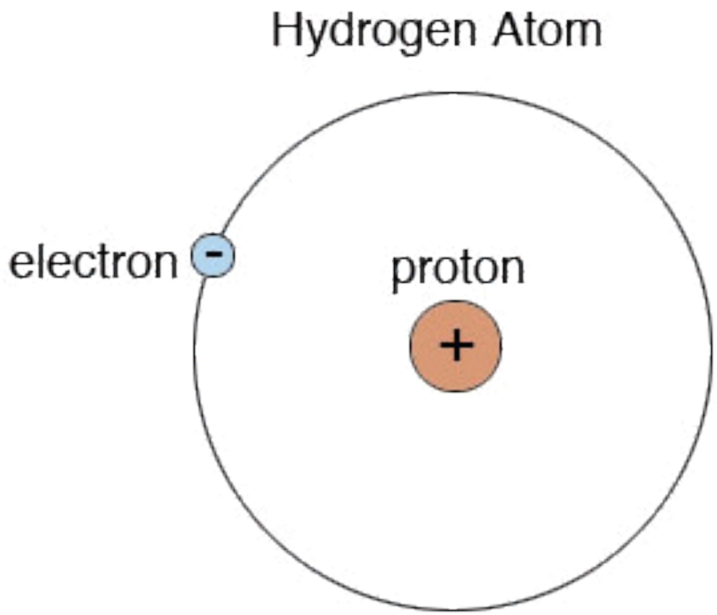
Before we do anything else

Let’s define some units

SI Units

0.15 kg

SI Units

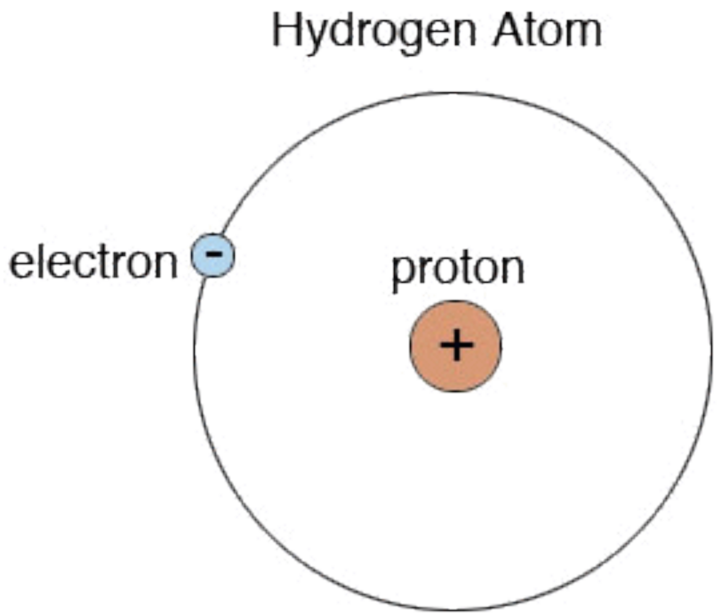


Electron mass = $9\text{x}10^{-31}$ kg

Units

114 meters

Units

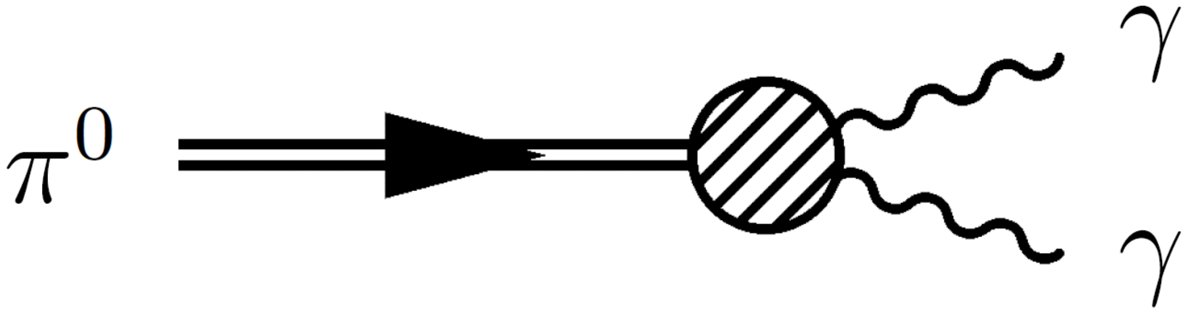


Radius of electron orbit = 0.5 angstroms = 5×10^{-11} meters

Units

This takes 0.4 seconds

Units



Neutral pion lifetime = 8×10^{-17} s

Our everyday experiences...

Do not use convenient particle physics units!

Other issues with SI units

$$\frac{-\hbar^2}{2m}\frac{\partial^2 u(x)}{\partial x^2} + V(x)u(x) = E\,u(x)$$

$\hbar$ are pesky and annoying!

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

$$E^2 = (pc)^2 + (mc^2)^2$$

so are factors of c everywhere!

The units that we will use

$$\hbar = c = 1$$

$$c = 3 \times 10^8 \text{ m/s}$$

$$\hbar = 10^{-34} \text{J s}$$

$$\boxed{1\text{GeV} = 10^9 \text{ ev}} = 1.6 \times 10^{-10}\text{J}$$

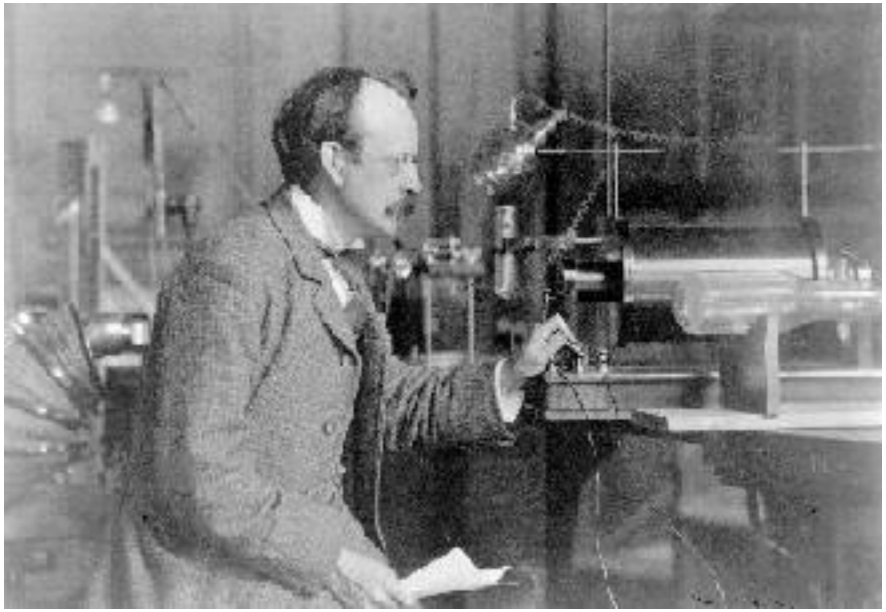
$$\hbar c = 0.2 \times 10^{-15}\text{m} = 0.2 \times 10^{-15}\text{fm}$$

Natural units, with the above choices! Simplifies a lot of notation

	Not our choice	In our choice of natural units
Energy	GeV	GeV
Momentum	GeV/c	GeV
Mass	GeV/c^2	GeV
Time	hbar/GeV	GeV^{-1}
Length	c*hbar/GeV	GeV^{-1}
Area	(c*hbar/GeV)^2	GeV^{-2}

Griffiths disagrees :)

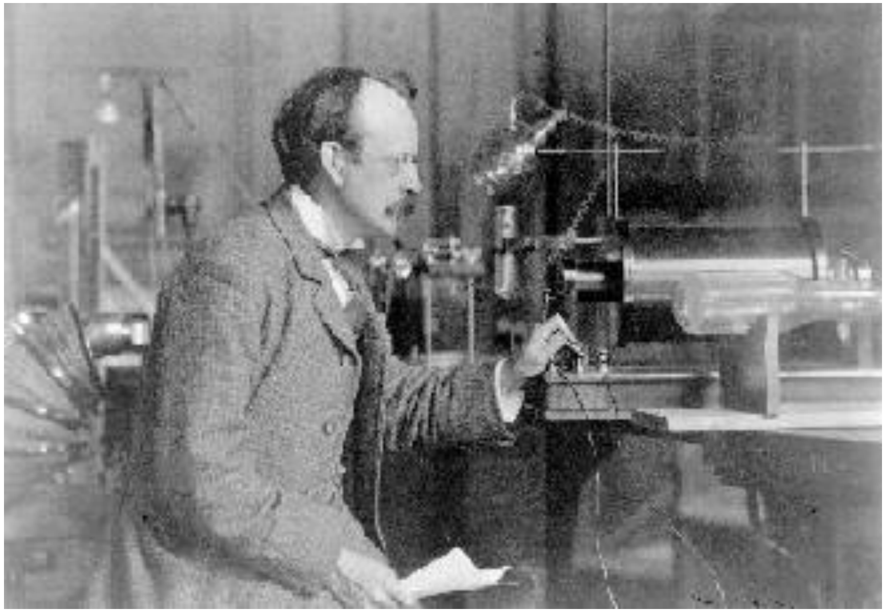
Let’s take a step back in time, now (1897)



JJ Thompson, who measured the charge to mass ratio of “cathode rays” (aka electrons). Any ideas how he found their velocity and, more importantly, q/m? (1.1 in Griffiths)

http://www.phy.cam.ac.uk/history/electron/photos

Let's take a step back in time, now (1897)



Undeflected particle:

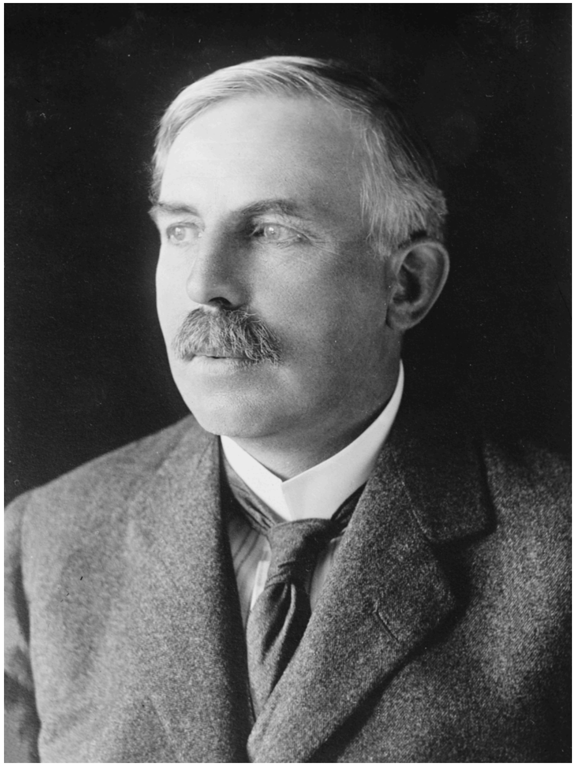
$qE = qvB, v=(E/B)$

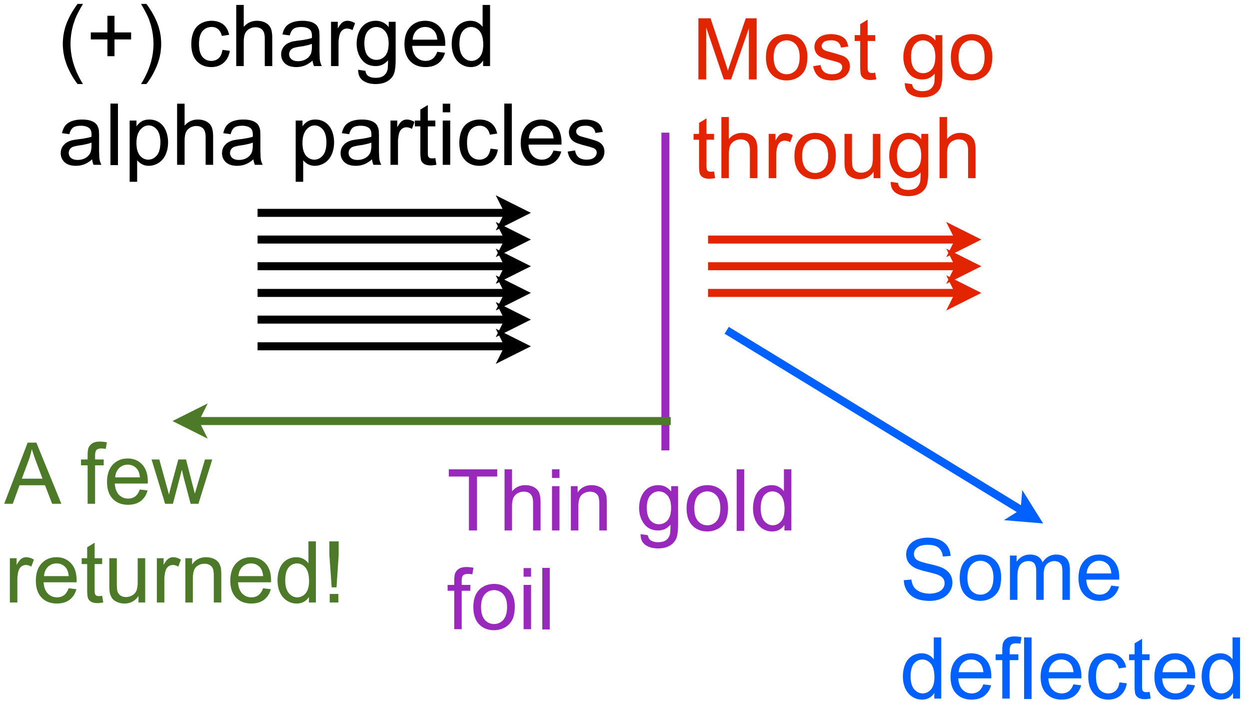
Just magnetic field:

$qvB = mv^2/R$

$(q/m) = v/(BR) = E/(B^2R)$

On to Rutherford (1911)





(+) charged alpha particles

Most go through

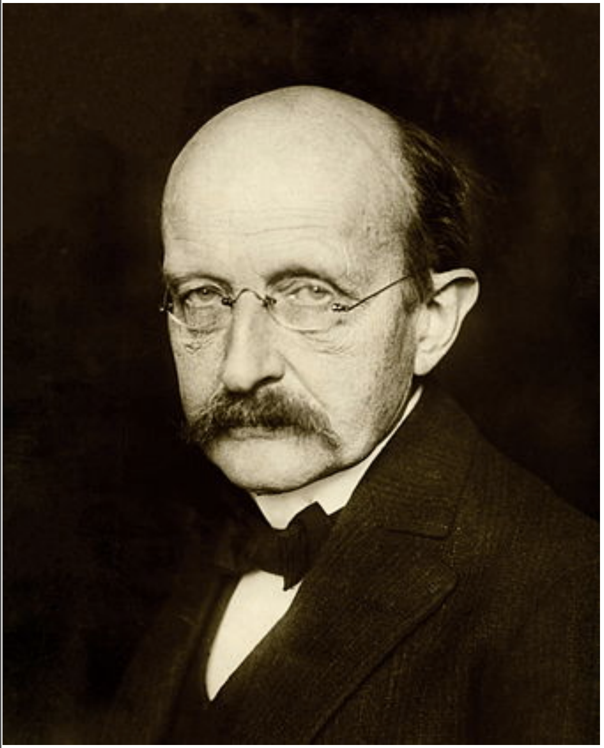
A few returned!

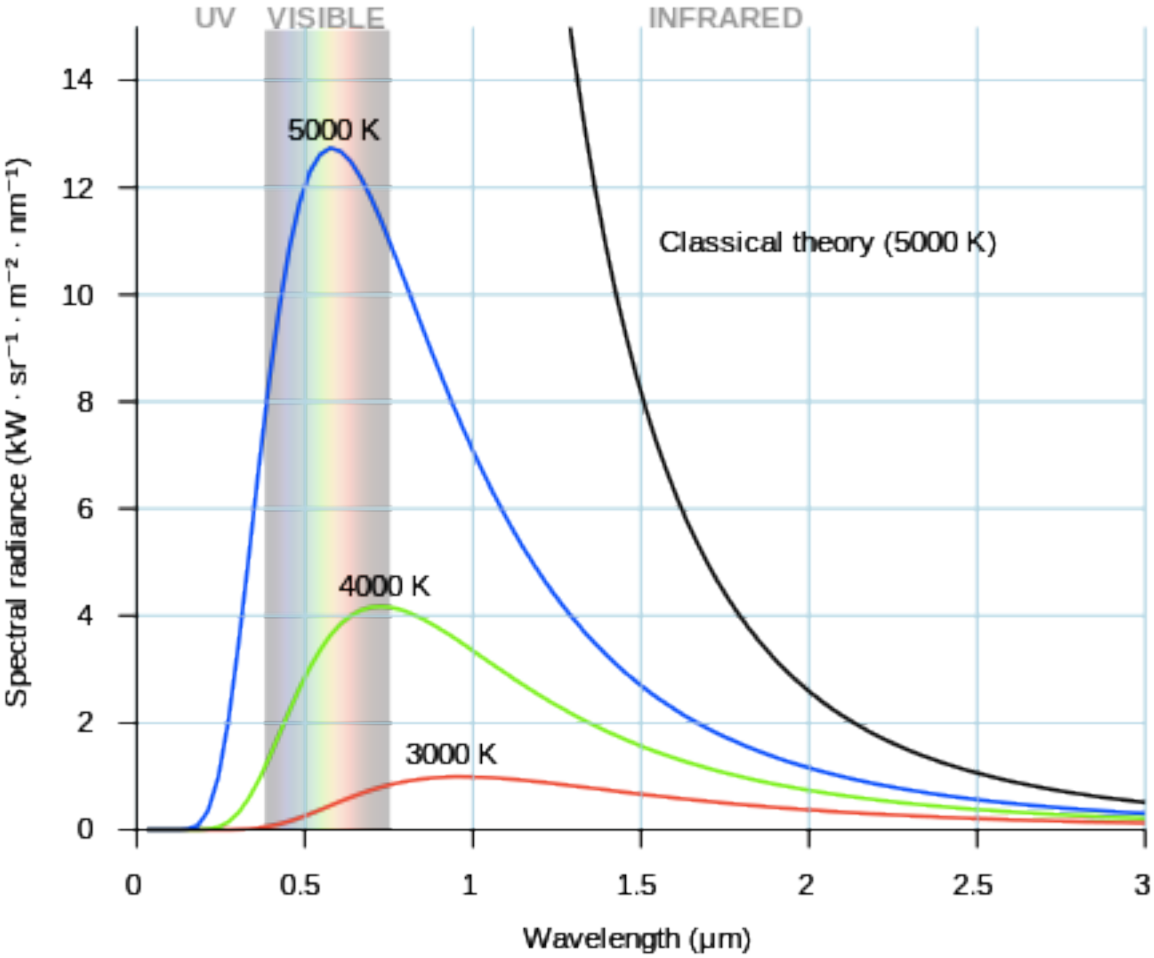
Thin gold foil

Some deflected

“It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.” - let to the idea that positive charge in atom must be concentrated in a small space

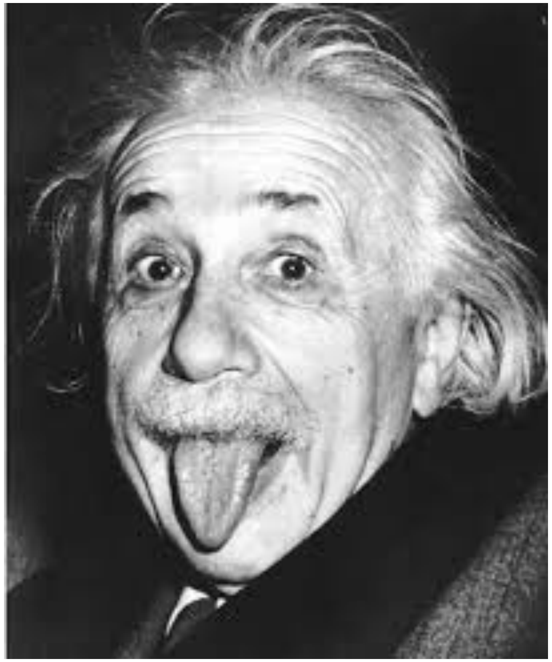
Skipping to Max Planck

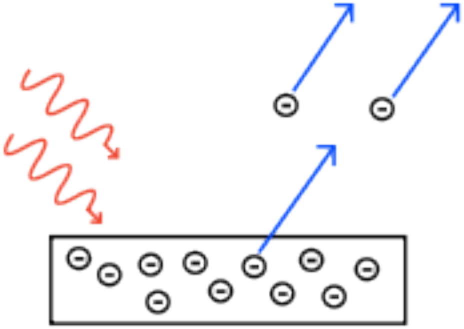




Quantization was “a purely formal assumption and I really did not give it much thought except that no matter what the cost, I must bring about a positive end." (Turns out that Planck didn’t quite realize what he was doing)

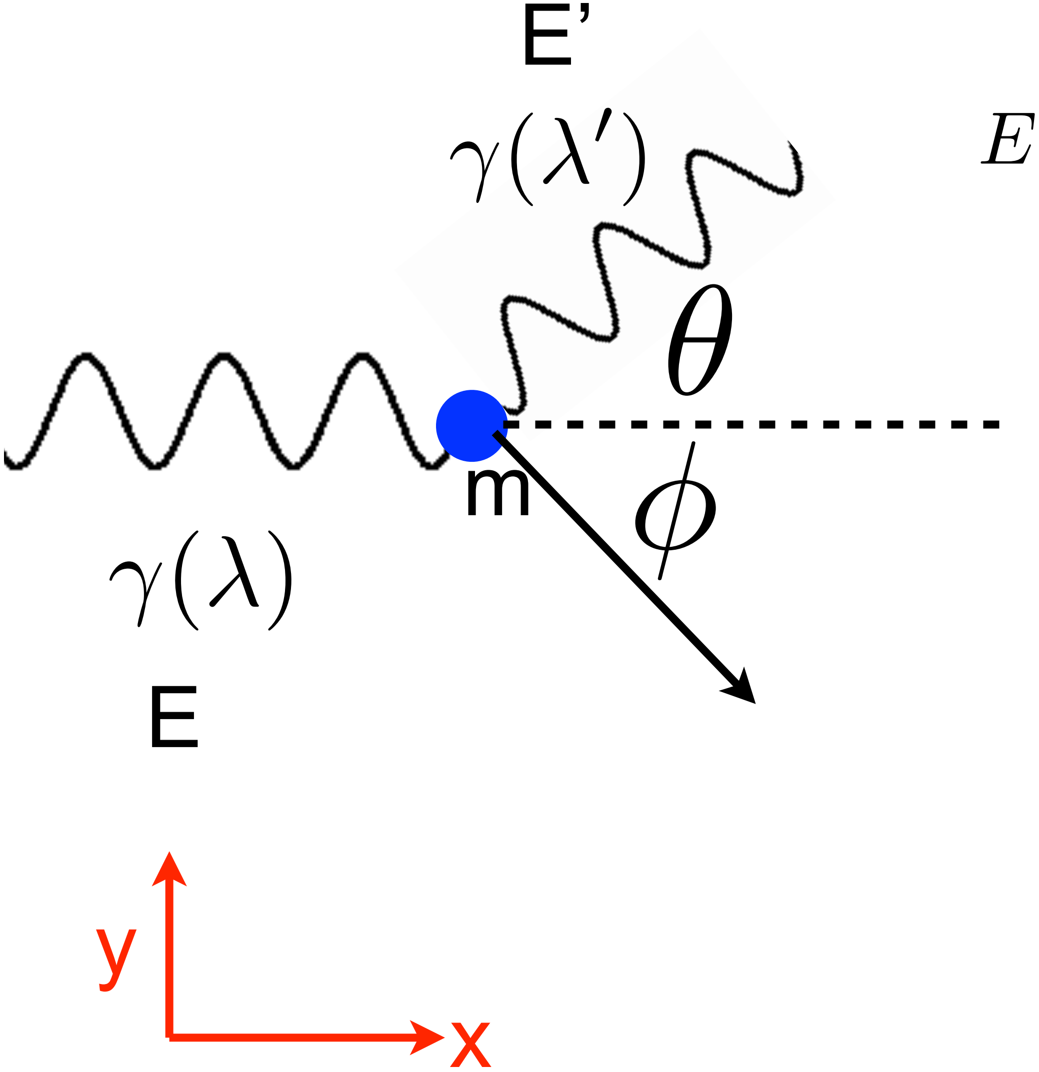
Einstein and the photoelectric effect (1905)





A radical idea! The energy of a photon is quantized, and depends on its frequency (color). Higher intensity light will knock out more electrons, but always of the same energy! Isn't light a wave and not a particle?

Compton scattering (1923)



Conservation of energy

$$E + m = E' + \sqrt{p^2 + m^2}$$

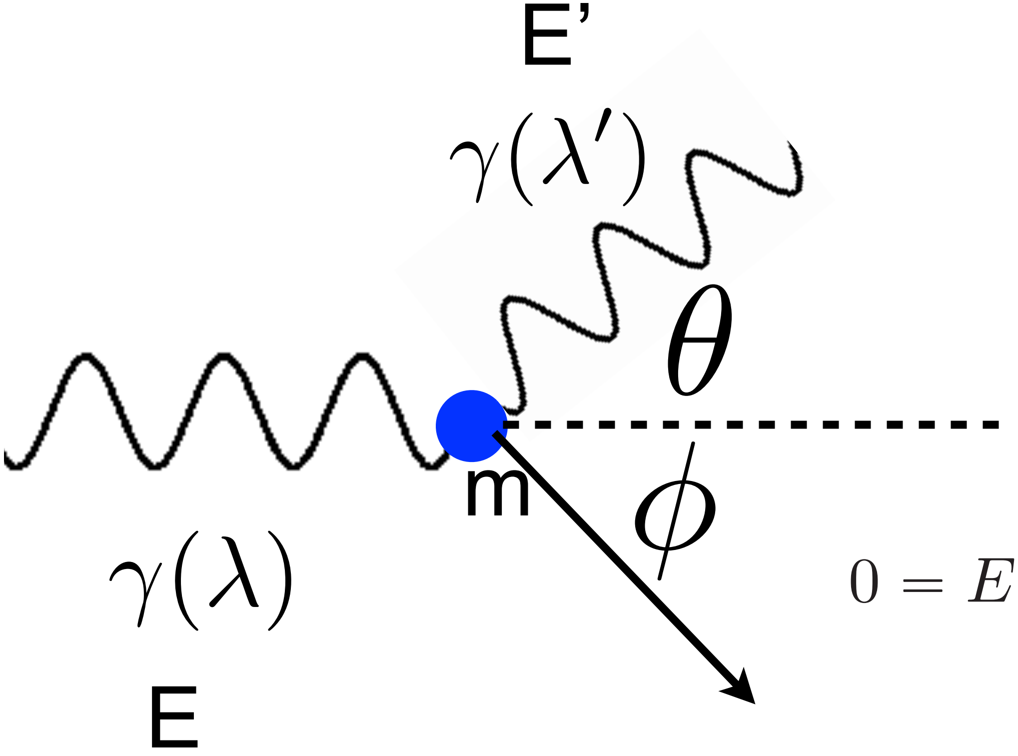
Momentum conservation in x:

$$E = E' \cos\theta + p \cos\phi$$

Momentum conservation in y:

$$0 = E' \sin\theta - p \sin\phi$$

Compton scattering (1923)



Momentum conservation in y:

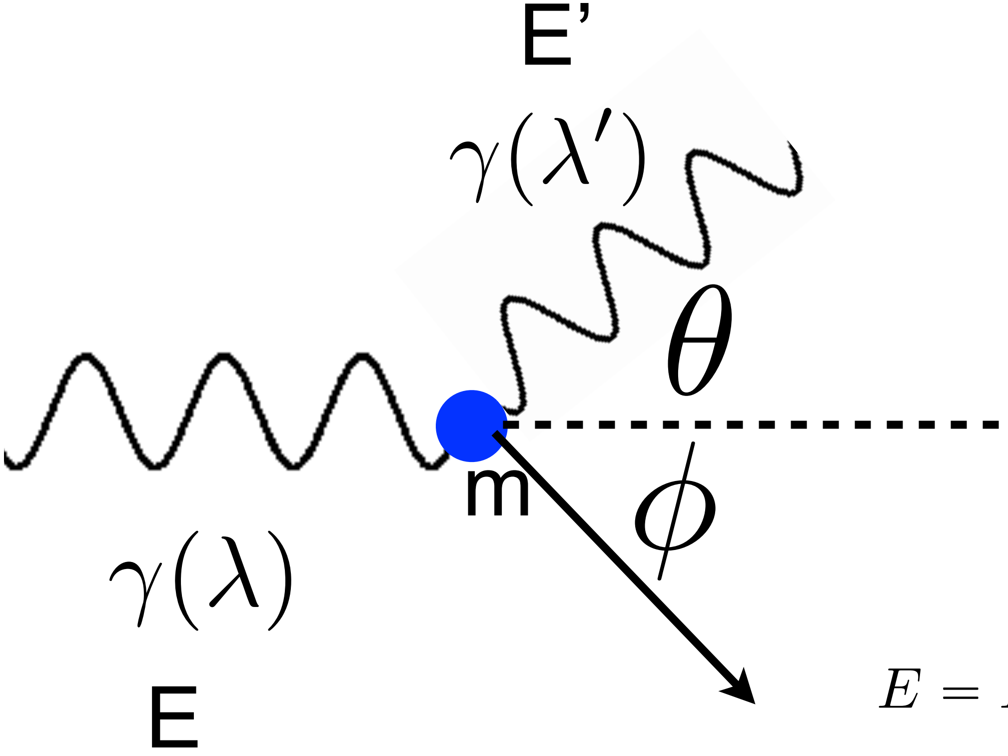
$$0 = E' \sin\theta - p\sin\phi \rightarrow p = \frac{E'\sin\theta}{\sin\phi}$$

$$p^2 \sin^2\phi = E'^2 \sin^2\theta$$

$$p^2(1 - \cos^2\phi) = E'^2 \sin^2\theta$$

$$\cos\phi = \sqrt{1 - \frac{E'^2}{p^2}\sin^2\theta}$$

Compton scattering (1923)



Momentum conservation in x:

$$E = E' \cos\theta + p\cos\phi$$

$$E = E' \cos\theta + p\sqrt{1 - \frac{E'^2}{p^2}\sin^2\theta}$$

$$(E - E'\cos\theta)^2 = p^2\left(1 - \frac{E'^2}{p^2}\sin^2\theta\right)$$

$$E^2 + E'^2\cos^2\theta - 2EE'\cos\theta = p^2 - E'^2\sin^2\theta$$

$$p^2 = E^2 + E'^2 - 2EE'\cos\theta$$

Compton scattering (1923)

Conservation of energy again

$$E + m = E' + \sqrt{p^2 + m^2}$$

$$(E + m - E') = \sqrt{p^2 + m^2}$$

Plug in p^2

$$(E + m - E')^2 = E^2 + E'^2 - 2EE'\cos\theta + m^2$$

$$E^2 + E'^2 + m^2 + 2mE - 2mE' - 2EE' = E^2 + E'^2 - 2EE'\cos\theta + m^2$$

$$2mE - 2mE' = 2EE'(1 - \cos\theta)$$

$$m\left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right) = \frac{1}{\lambda\lambda'}(1 - \cos\theta)$$

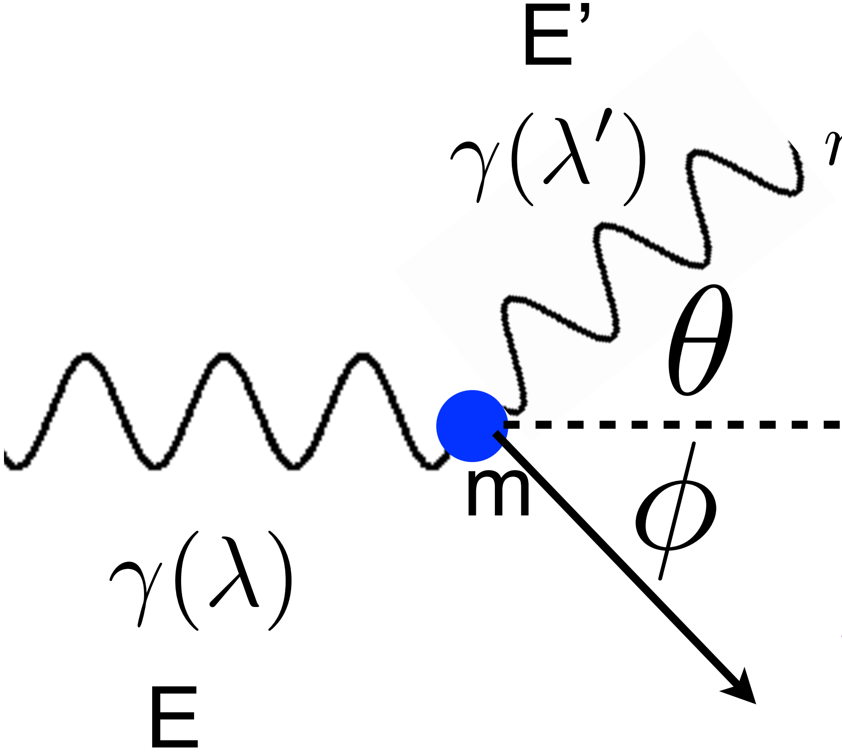
$$E = \frac{1}{\lambda}$$

$$E' = \frac{1}{\lambda'}$$

Nice to have these units

Compton scattering (1923)

Finishing up



$$m\left(\frac{1}{\lambda}-\frac{1}{\lambda'}\right)=\frac{1}{\lambda\lambda'}(1-\cos\theta)$$

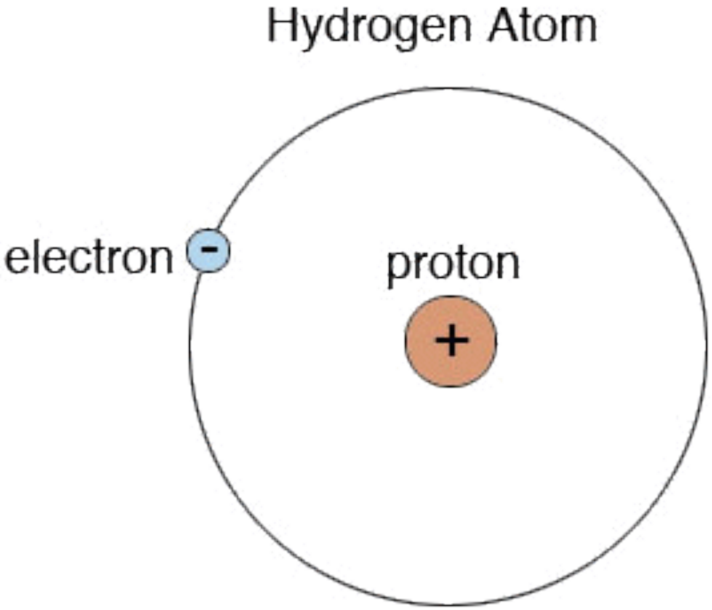
$$m(\lambda'-\lambda)=(1-\cos\theta)$$

$$\boxed{\lambda'=\lambda+\frac{1-\cos\theta}{m}}$$

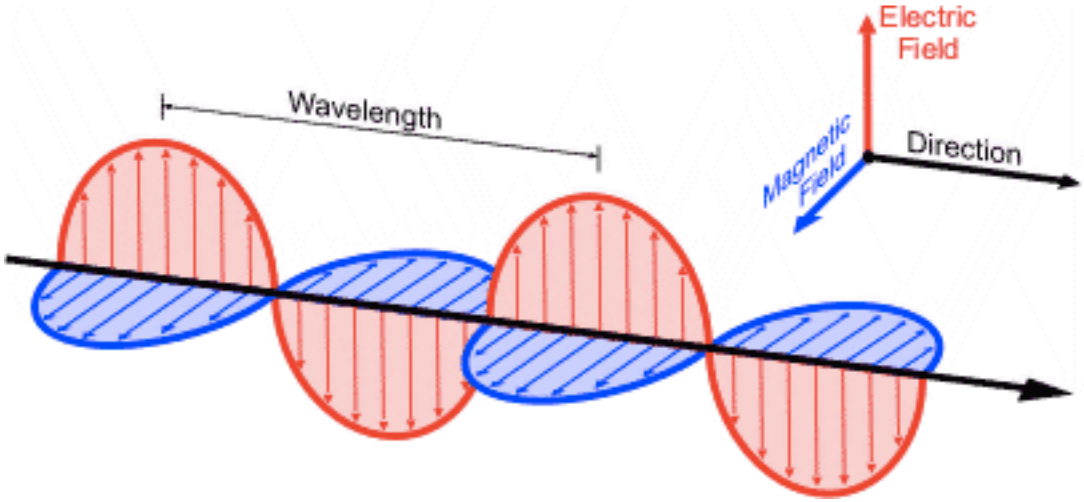
What happens for different angles? Different m?

Note that this assumes particles of light, aka photons! No discussion of waves or interference

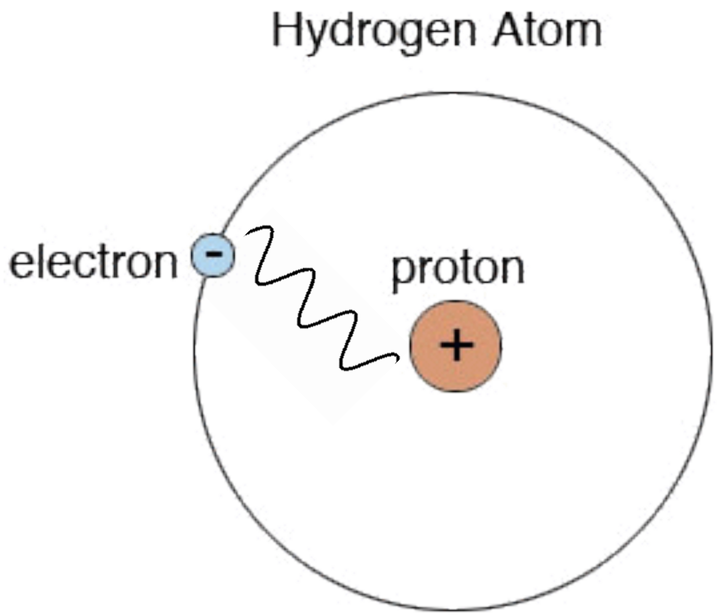
On force carriers



Photon as a wave



On force carriers

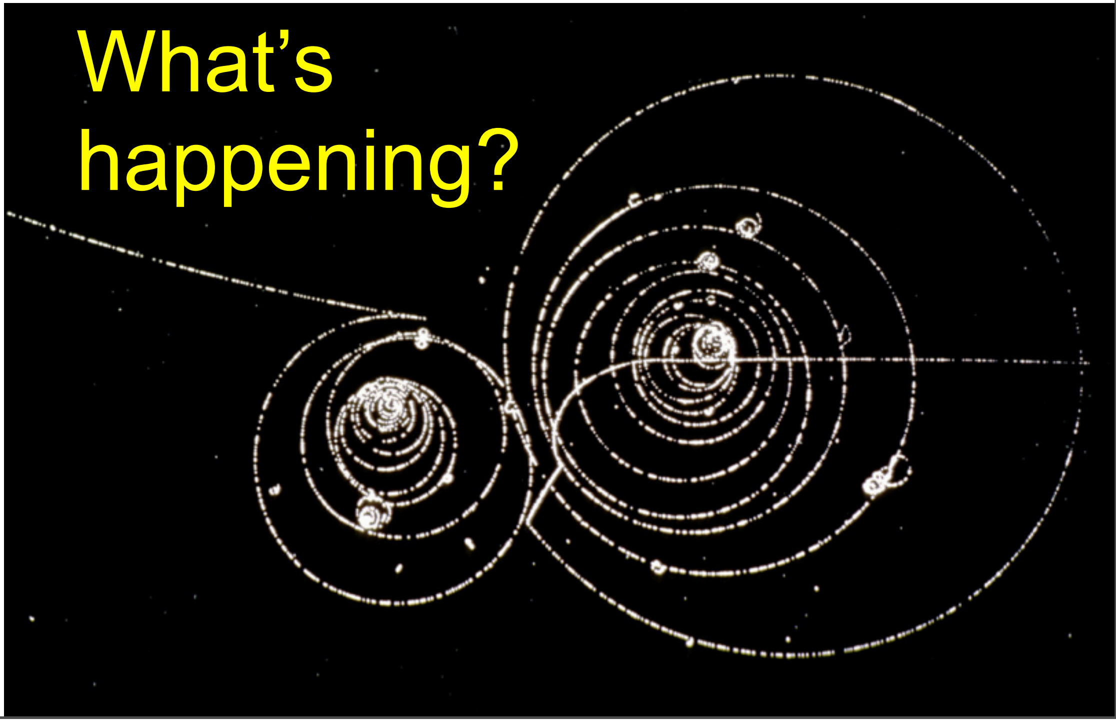


Photon as a particle (classical). But what we really mean is that the field is quantized (here providing an attractive force), and the quantized unit of the field transmits some momentum from one object to another

Early particle detectors - cloud and bubble chambers

A cloud chamber is a collection of supersaturated vapor of alcohol or water. A charge particle can ionize the vapor; the subsequent ions act as seeds for condensation. Magnetic fields can give the charge and momenta of objects. Need to literally take pictures of the chambers!

Bubble chamber is similar, except it uses superheated liquid instead



What's happening?

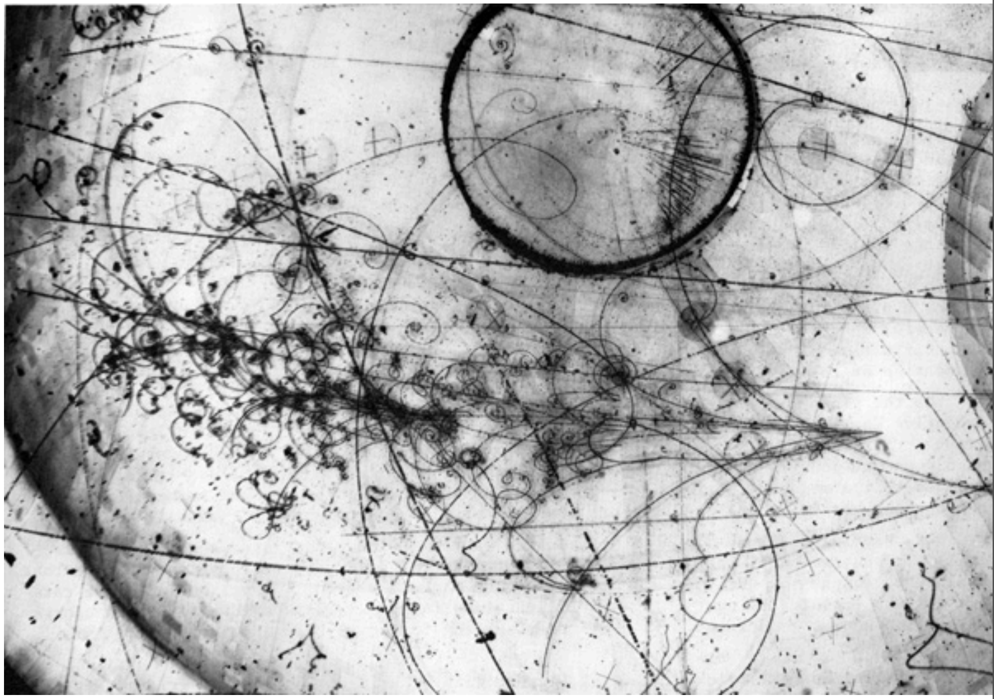
Early particle detectors - cloud and bubble chambers

Glaser invented the bubble chamber (and won a Nobel prize for it).

“Legend has it that while he was on the faculty of the University of Michigan, Glaser was chilling with colleagues over a cold beer, observed the stream of bubbles in his glass, and was inspired to build a device that could track subatomic particles with bubbles. Glaser himself later refuted this story; beer was not his inspiration, although he did use it as a liquid in early prototypes.”

http://www.aps.org/publications/apsnews/201001/physicshistory.cfm

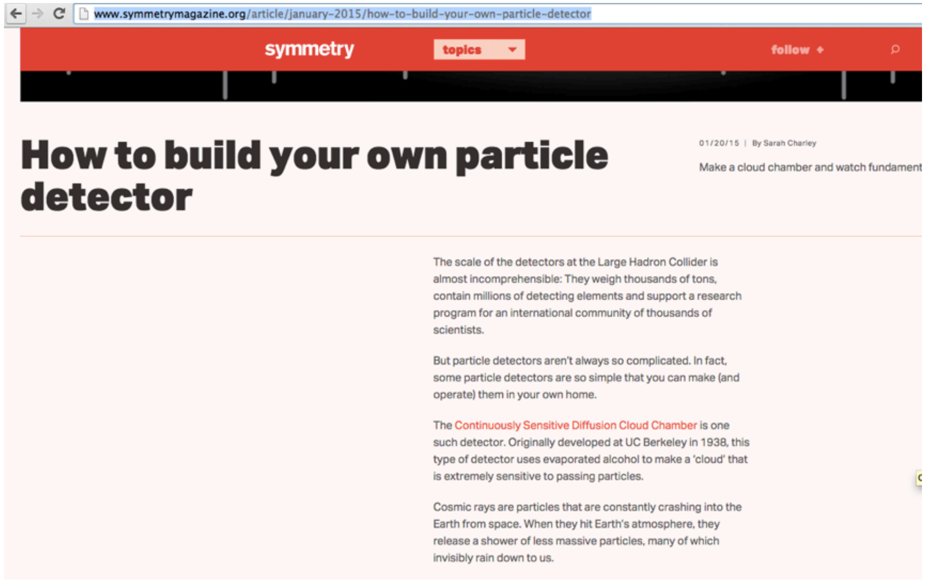
FNAL bubble chamber photo



What’s going on here?

Early particle detectors - cloud and bubble chambers

http://www.symmetrymagazine.org/article/january-2015/how-to-build-your-own-particle-detector



How to build your own particle detector

01/20/15 | By Sarah Charley

Make a cloud chamber and watch fundament

The scale of the detectors at the Large Hadron Collider is almost incomprehensible: They weigh thousands of tons, contain millions of detecting elements and support a research program for an international community of thousands of scientists.

But particle detectors aren't always so complicated. In fact, some particle detectors are so simple that you can make (and operate) them in your own home.

The Continuously Sensitive Diffusion Cloud Chamber is one such detector. Originally developed at UC Berkeley in 1938, this type of detector uses evaporated alcohol to make a 'cloud' that is extremely sensitive to passing particles.

Cosmic rays are particles that are constantly crashing into the Earth from space. When they hit Earth's atmosphere, they release a shower of less massive particles, many of which invisibly rain down to us.

If anyone knows any enterprising undergrads looking for work in the fall, this is something I'd like to get built for STEMfest this year

The strong meson (Yukawa, 1934)

Strong meson (intermediate mass) must be the nuclear force carrier with mass ~150 MeV. See Griffiths HW 1.2 for why this was only a vague estimate - any ideas how he got it (if you haven't read the textbook?)

1946 mesons

There are two such mesons observed in cosmic rays:

$$\pi, \mu$$

VERY different interactions with atomic nuclei (why feels the strong nuclear force, the other does not)

From Griffiths

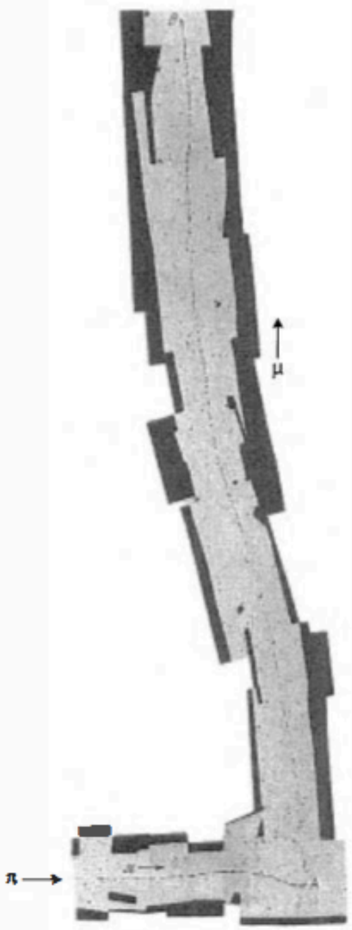


Fig. 1.3 One of Powell's earliest pictures showing the track of a pion in a photographic emulsion exposed to cosmic rays at high altitude. The pion (entering from the left) decays into a muon and a neutrino (the latter is electrically neutral, and leaves no track). (*Source:* Powell, C. F., Fowler, P. H. and Perkins, D. H. (1959) *The Study of Elementary Particles by the Photographic Method* Pergamon, New York. First published in (1947) *Nature* 159, 694.)

1931 Anderson discovers antiparticles

From Griffiths

Hypothesized by Dirac (we'll see why in a few chapters)

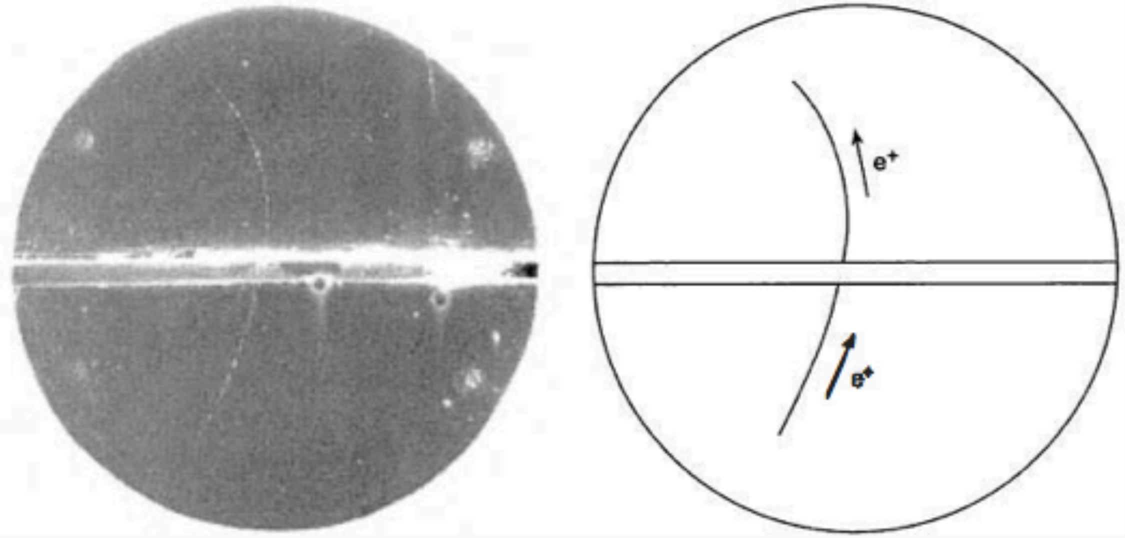


Fig. 1.4 The positron. In 1932, Anderson took this photograph of the track left in a cloud chamber by a cosmic ray particle. The chamber was placed in a magnetic field (pointing into the page), which caused the particle to travel in a curve. But was it a negative charge traveling downward or a positive charge traveling upward? In order to distinguish, Anderson had placed a lead plate across the center of the chamber (the thick horizontal line in the photograph). A particle passing through the plate slows down, and subsequently moves in a tighter circle. By inspection of the curves, it is clear that this particle traveled upward, and hence must have been positively charged. From the curvature of the track and from its texture, Anderson was able to show that the mass of the particle was close to that of the electron. (Photo courtesy California Institute of Technology.)

Antiparticles

Protons vs anti-proton

$$p = (uud)$$

$$\overline{p} = (\overline{uu}\,\overline{d})$$

Neutron vs anti-neutron (note: neutron has no net electric charge!)

$$n = (udd)$$

$$\overline{n} = (\overline{u}\,\overline{dd})$$

$$e^{+} \text{ vs } e^{-}$$

$$\gamma = \overline{\gamma}$$

Crossing symmetry

$$A + B \rightarrow C + D \rightarrow$$

If this then also...

$$A \rightarrow \overline{B} + C + D$$

$$A + \overline{C} \rightarrow \overline{B} + D$$

$$\gamma + e^- \rightarrow \gamma + e^-$$

Implies

$$e^+ + e^- \rightarrow \gamma + \gamma$$

$$\gamma + \gamma \rightarrow e^+ + e^-$$

On crossing symmetry

$$A + B \rightarrow C + D \rightarrow$$

If this then also...

$$A \rightarrow \overline{B} + C + D$$

$$A + \overline{C} \rightarrow \overline{B} + D$$

All that it tells us is whether there are any symmetry rules or conservation laws forbidding such a reaction (ie whether the dynamics are possible). Says nothing about the kinematics

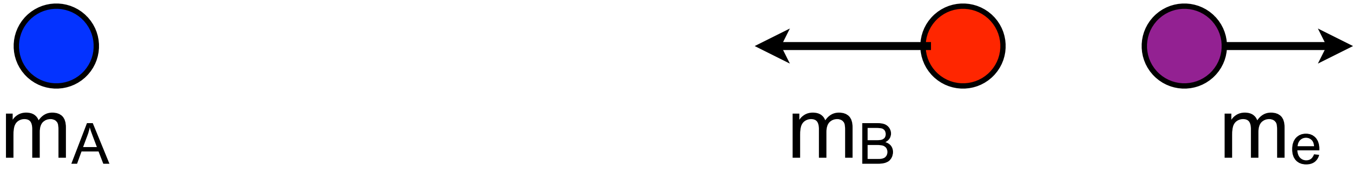
Neutrinos

$$A \rightarrow B + e^-$$

$$n \rightarrow p + e^-$$

What is the energy of the electron in this decay?

Neutrinos



Initially, in center of mass frame, everything is at rest, p = 0

After decay

$$E = m_A$$

$$p = 0$$

$$E = \sqrt{m_B^2 + p_B^2} + \sqrt{m_e^2 + p_e^2}$$

Conservation of momentum: $p_B = p_e = p$

Neutrinos

m_A

m_B m_e

Initially, in center of mass frame, everything is at rest, p = 0

After decay

$$E = \sqrt{m_B^2 + p^2} + \sqrt{m_e^2 + p^2} = m_A$$

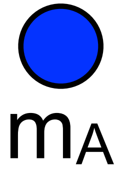
$$m_B^2 + p^2 + m_e^2 + p^2 + 2\sqrt{(m_B^2 + p^2)(m_e^2 + p^2)} = m_A^2$$

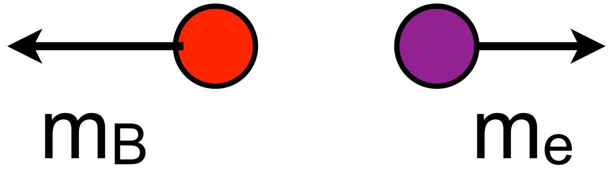
$$2\sqrt{(m_B^2 + p^2)(m_e^2 + p^2)} = m_A^2 - m_B^2 - m_e^2 - 2p^2$$

$$4(m_B^2 + p^2)(m_e^2 + p^2) =$$

$$m_A^4 + m_B^4 + m_e^4 + 4p^4 - 2m_A^2 m_B^2 - 2m_A^2 m_e^2 - 4m_A^2 p^2 + 2m_B^2 m_e^2 + 4m_B^2 p^2 + 4m_e^2 p^2$$

Neutrinos





Initially, in center of mass frame, everything is at rest, p = 0

After decay

$$4m_B^2 m_e^2 + 4m_B^2 p^2 + 4m_e^2 p^2 + 4p^4 =$$

$$m_A^4 + m_B^4 + m_e^4 + 4p^4 - 2m_A^2 m_B^2 - 2m_A^2 m_e^2 - 4m_A^2 p^2 + 2m_B^2 m_e^2 + 4m_B^2 p^2 + 4m_e^2 p^2$$

$$m_A^4 + m_B^4 + m_e^4 - 2m_A^2 m_B^2 - 2m_A^2 m_e^2 - 4m_A^2 p^2 - 2m_B^2 m_e^2 = 0$$

$$p^2 = \frac{1}{4}\left(m_A^2 + (m_B^4 + m_e^4 - 2m_B^2 m_e^2)/m_A^2 - 2m_B^2 - 2m_e^2\right)$$

Neutrinos

Energy of electron is completely specified, but we observe a range of energies in neutron decay! Must be missing some object: neutrinos!

$$4m_B^2m_e^2 + 4m_B^2p^2 + 4m_e^2p^2 + 4p^4 =$$

$$m_A^4 + m_B^4 + m_e^4 + 4p^4 - 2m_A^2m_B^2 - 2m_A^2m_e^2 - 4m_A^2p^2 + 2m_B^2m_e^2 + 4m_B^2p^2 + 4m_e^2p^2$$

$$m_A^4 + m_B^4 + m_e^4 - 2m_A^2m_B^2 - 2m_A^2m_e^2 - 4m_A^2p^2 - 2m_B^2m_e^2 = 0$$

$$p^2 = \frac{1}{4}\left(m_A^2 + (m_B^4 + m_e^4 - 2m_B^2m_e^2)/m_A^2 - 2m_B^2 - 2m_e^2\right)$$

Neutrinos

Energy of electron is completely specified, but we observe a range of energies in neutron decay! Must be missing some object: neutrinos!

From Griffiths

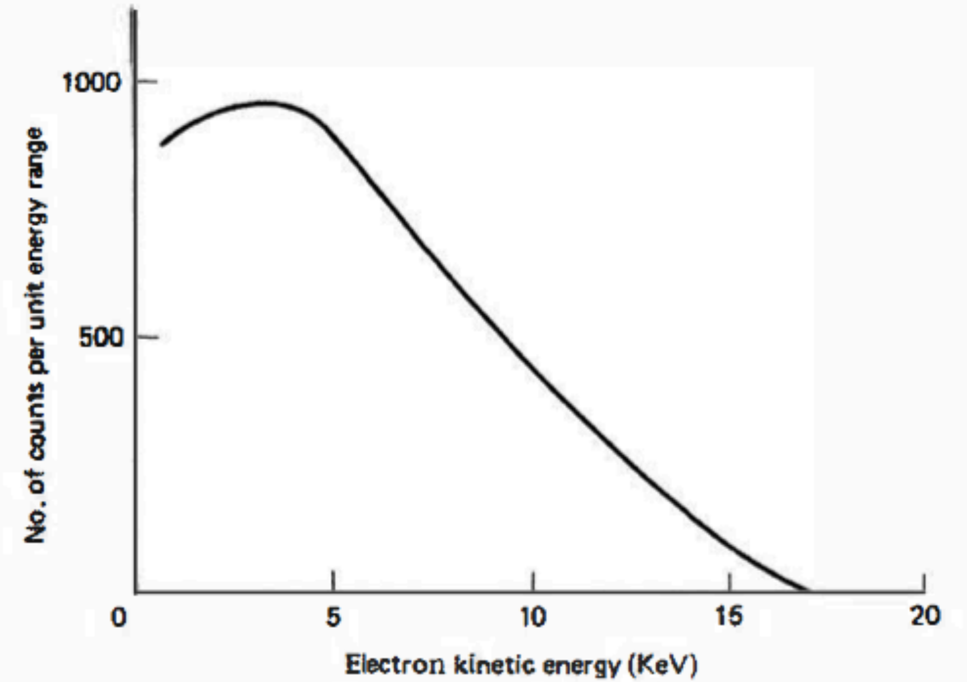


Fig. 1.5 The beta decay spectrum of tritium ($^3_1\mathrm{H} \rightarrow ^3_2\mathrm{He}$). (*Source*: Lewis, G. M. (1970) *Neutrinos*, Wykeham, London, p. 30.)

Neutrinos

"Little neutral one" to distinguish from the neutron. Physicists really cling to the idea of conservation of energy

From Griffiths

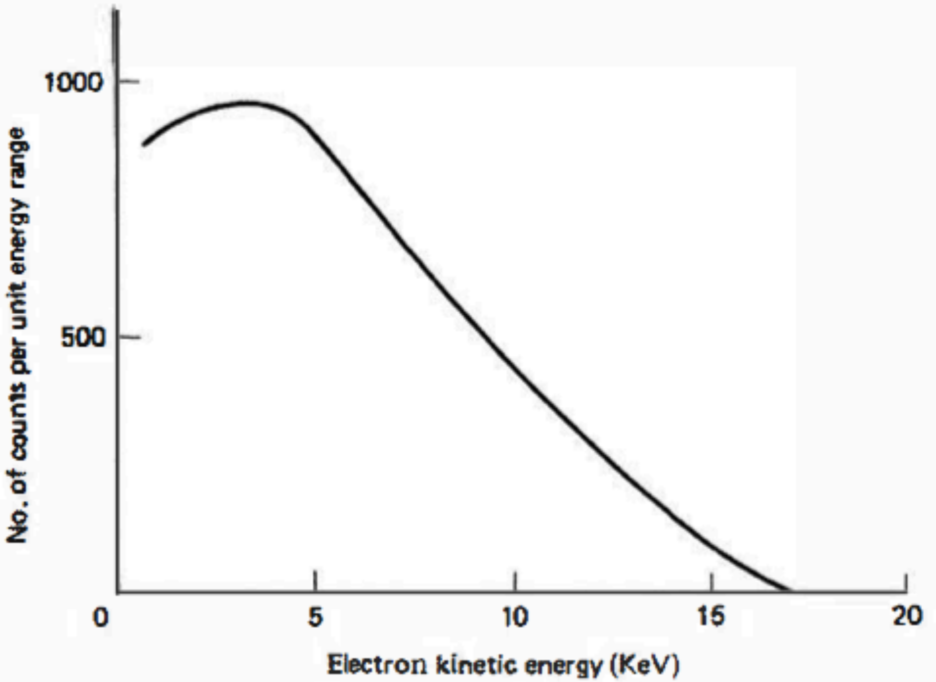
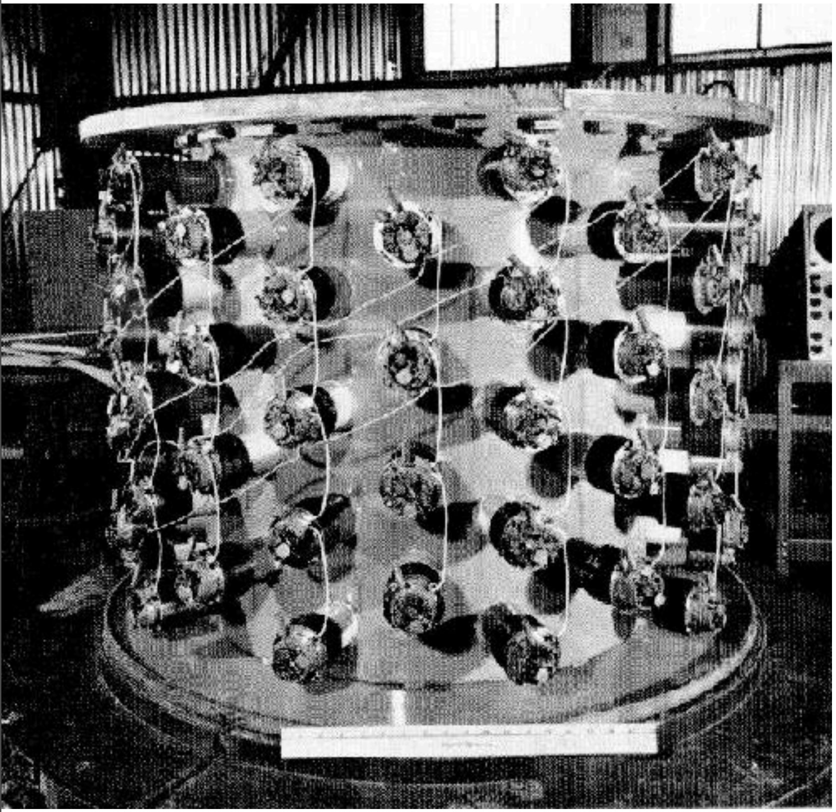


Fig. 1.5 The beta decay spectrum of tritium ($^3_1\mathrm{H} \to {}^3_2\mathrm{He}$). (*Source:* Lewis, G. M. (1970) *Neutrinos*, Wykeham, London, p. 30.)

Neutrinos, Cowan and Reines



Large tank of water mixed with cadmium chloride near a nuclear reactor to look for

$$\bar{\nu} + p \to n + e^+$$

$$e^+ + e^- \to \gamma\gamma$$

What about the neutron? It gets captured by cadmium, which then emits pairs of photons shortly thereafter

Tests with anti-neutrinos?

$$n + \nu \rightarrow p + e^-$$

$$n + \overline{\nu} \nrightarrow p + e^-$$

$$\gamma + \gamma \nrightarrow \mu^+ + e^-$$

$$\mu^- \nrightarrow e^- + \gamma$$

Why not? Well, neutrinos and anti-neutrinos are not the same thing. But also... this violates a conversation law known as conservation of electron number.

Electrons and electron neutrinos carry electron number = +1, and anti-electrons and anti-electron neutrinos = -1

Be careful about what is +1 and what is -1!

Similarly

Define in the same way a "muon number". Muons and muon neutrinos carry muon number = +1, and anti-muons and anti-muon neutrinos = -1

And yet the same thing for taus (which we haven't seen quite yet but we will soon)

Checks to make sure your neutrinos are in the right place

	Before		After	
	e	mu	e	mu
$\overline{\nu_e} + p \longrightarrow n + e^+$	-1	0	-1	0
$\pi^+ \longrightarrow \mu^+ + \nu_\mu$	0	0	0	1-1=0
$\pi^- \longrightarrow \mu^- + \overline{\nu_\mu}$	0	0	0	1-1=0
$\mu^- \longrightarrow e^- + \overline{\nu_e} + \nu_\mu$	0	1	1-1=0	1
$n \longrightarrow p + e^- + \overline{\nu_e}$	0	0	1-1=0	0

Conservation of baryon number

Neutron decay

$$n \rightarrow e^- + \overline{\nu_e} + p$$

No proton decay

$$p \nrightarrow e^+ + \nu_e$$

$$p \nrightarrow e^+ + \nu_e + \gamma$$

Proton decay is not observed! Why not?

Propose conservation of baryon number

B = +1 for neutrons and protons, -1 for anti-neutrons and anti-protons

Proton is lightest baryon, so it cannot decay (well, not in the Standard Model!)

No “conservation of meson” number

Strange things

$$K^0 \rightarrow \pi^+ + \pi^-$$

From Griffiths

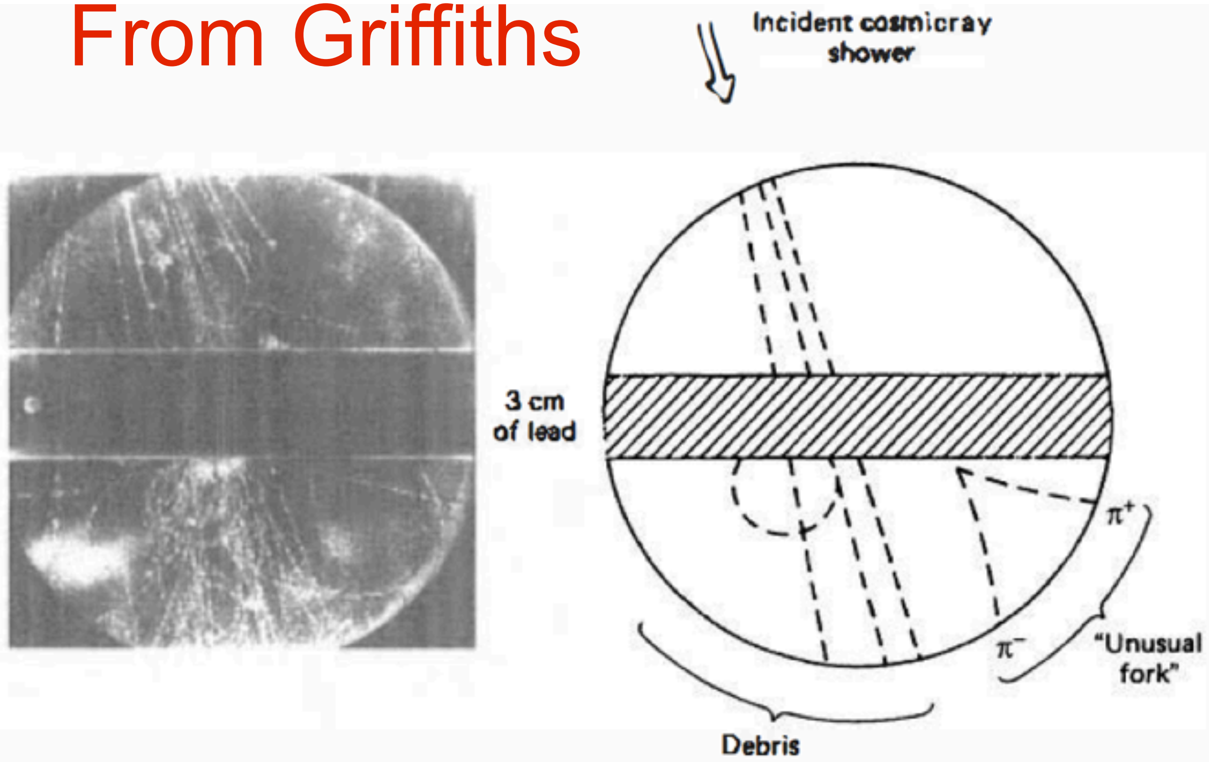


Fig. 1.7 The first strange particle. Cosmic rays strike a lead plate, producing a K^0, which subsequently decays into a pair of charged pions. (Photo courtesy of Prof. Rochester, G. D. (© 1947). *Nature*, **160**, 855. Copyright Macmillan Journals Limited.)

What is this neutral kaon? Can produce them in accelerators, but they decay 13 orders of magnitude slower than expected! Strange...

How to account for these strange particles?

What if kaons are produced by the strong force, but decay typically via the weak force?

Strangeness is conserved in strong interactions but not in weak interactions

$$\pi^- + p \rightarrow K^+ + \Sigma^-$$

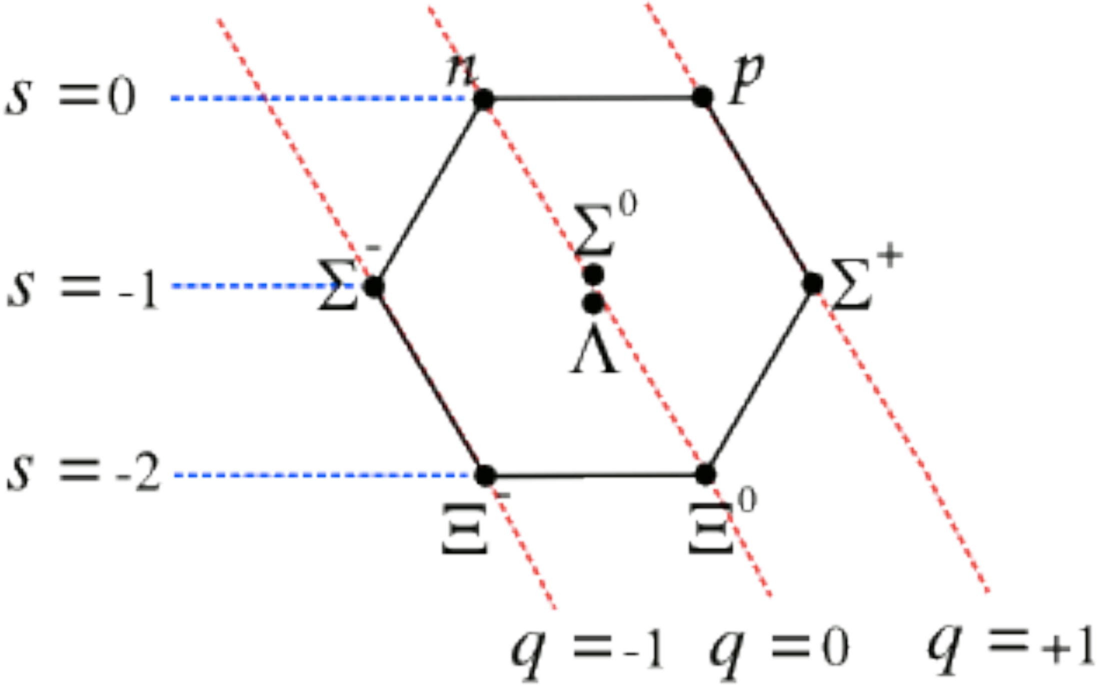
$$\pi^- + p \rightarrow K^0 + \Sigma^0$$

$$\pi^- + p \rightarrow K^0 + \Lambda$$

Initially, have zero strangeness. Assign S=+1 to K^+ and K^0 and S=-1 to Λ and Σ, S remains 0. What does this say about how the above are produced?

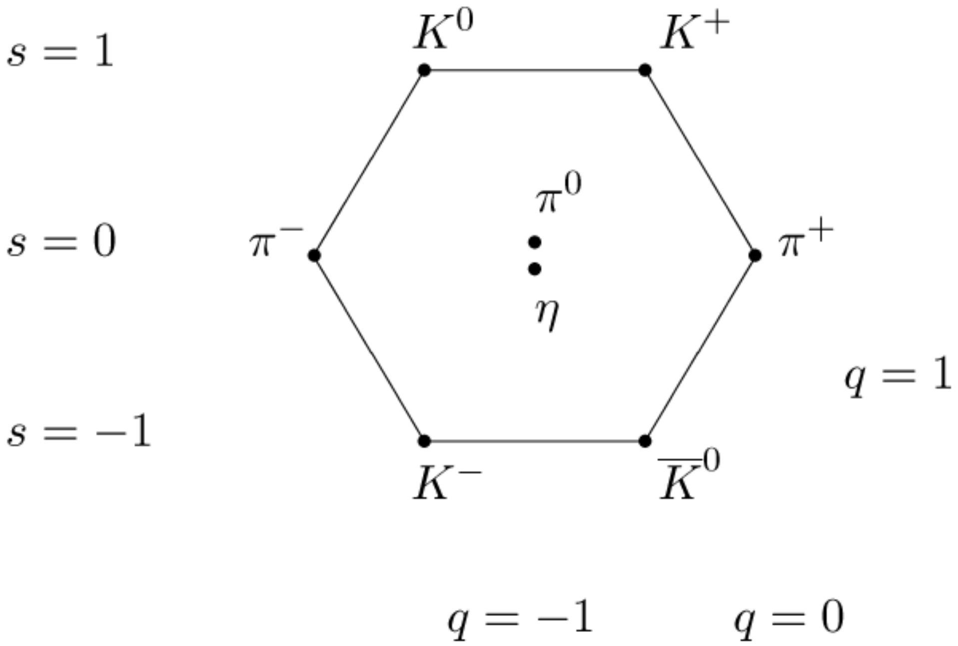
Note: strangeness not conserved in the decay.

And how to start organizing all of this?



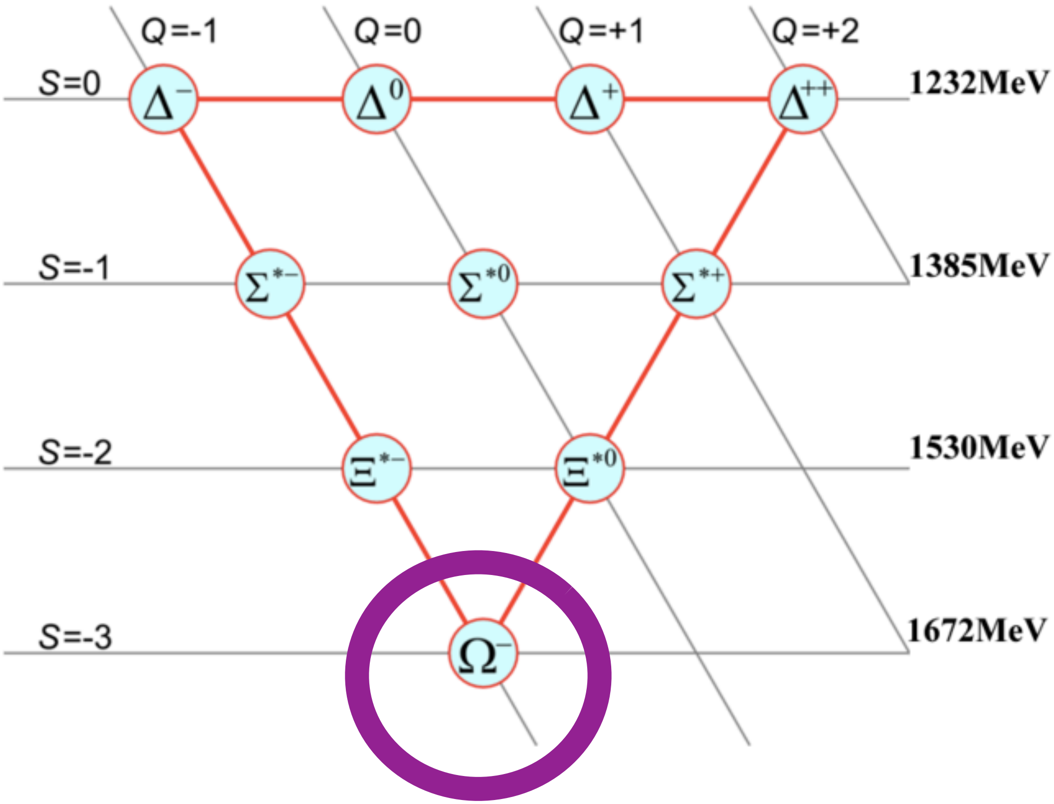
Murray Gell-Man proposed his “Eightfold way” (apparently a slight reference to the Noble Eightfold path of Buddhism)

Moving from baryons to mesons



Similar periodic structure (remind you of anything)?

How was this verified?



This was predicted (including its mass and lifetime!)

We’ve skipped over some of the fun history

The particle ... zoo was becoming a big mess to keep track of

Wolfgang Pauli: "Had I foreseen that, I would have gone into botany"

We’ve skipped over some of the fun history

The particle ... zoo was becoming a big mess to keep track of (for some reason, physicists don’t like botanists, apparently)

Fermi to Lederman: “Young man, if I could remember the names of these particles, I would have been a botanist”

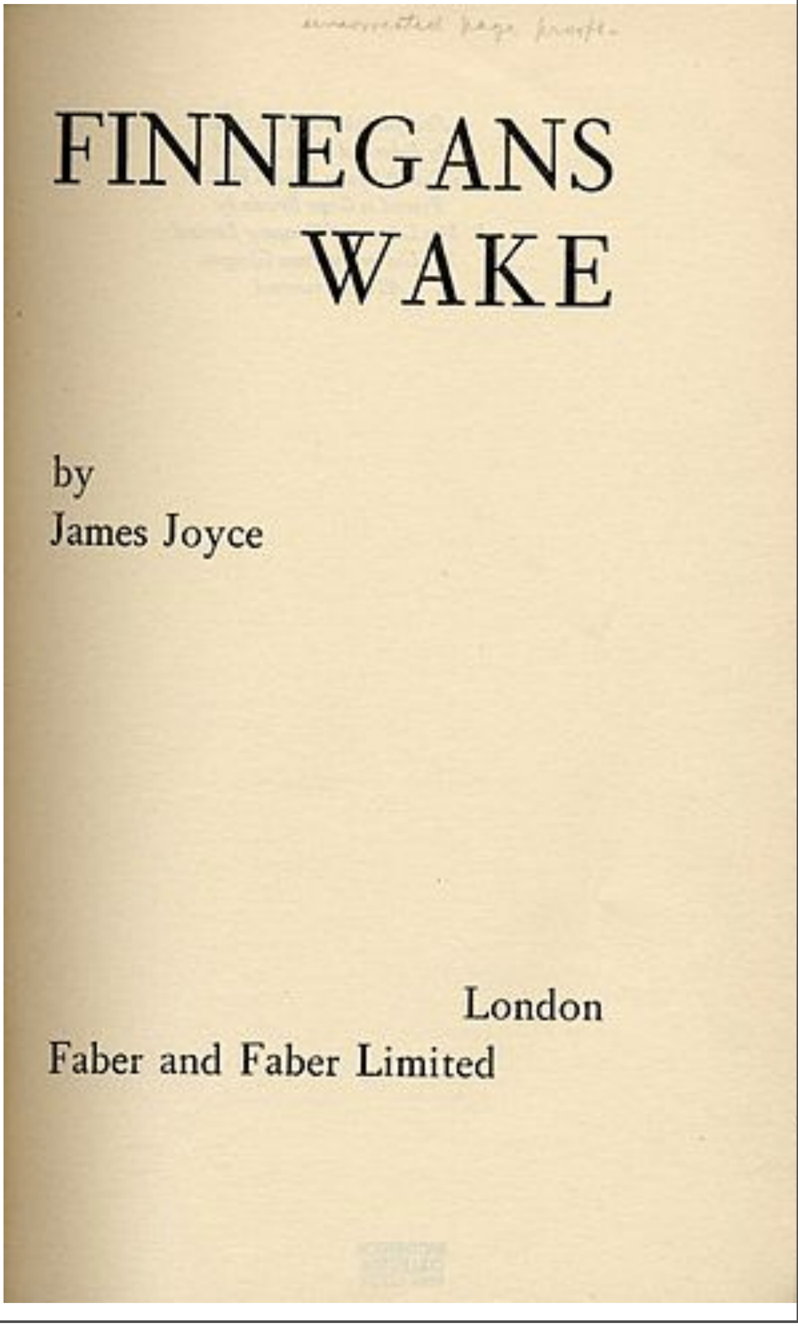
The quark model (Gell-Man and Zweig)

Three quarks for Muster Mark!
Sure he has not got much of a bark
And sure any he has it's all beside the mark.

—James Joyce, *Finnegans Wake*

Quark and not kwork!

Wikipedia: ***Finnegans Wake*** is a novel by Irish writer James Joyce. It is significant for its experimental style and reputation as one of the most difficult works of fiction in the English language.



uncorrected page proofs

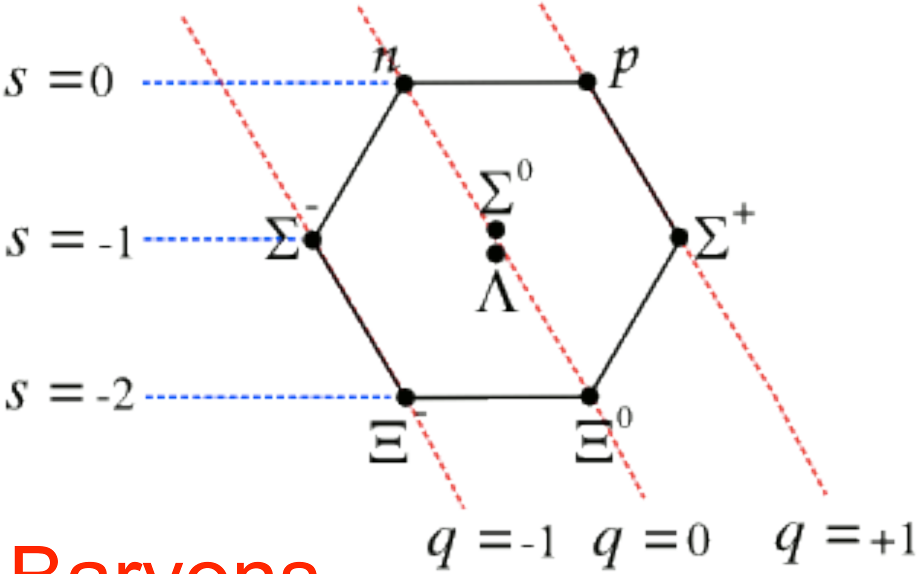
FINNEGANS
WAKE

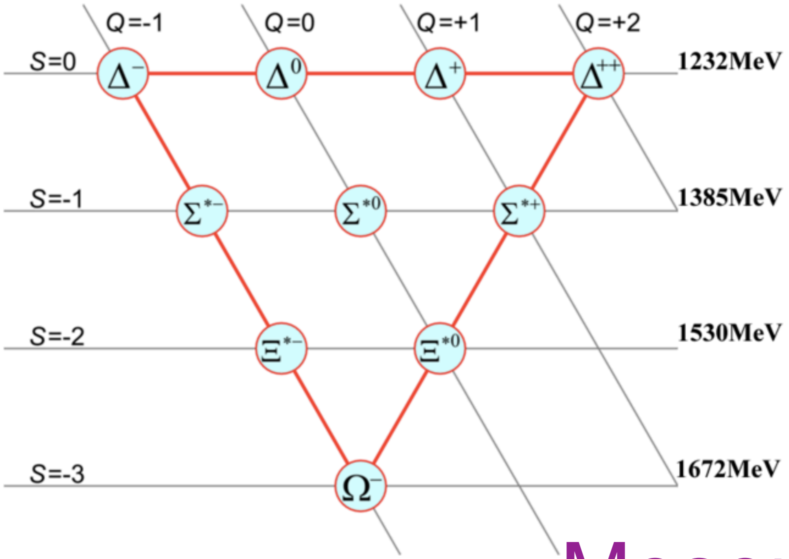
by
James Joyce

London
Faber and Faber Limited

The quark model

Hadrons





Baryons

Mesons

All hadrons (baryons and mesons) are made themselves of smaller pieces called quarks

The quark model (so far)

	Charge (units of e)	Strangeness
u	+2/3	0
d	-1/3	0
s	-1/3	1
ubar	-2/3	0
dbar	+1/3	0
sbar	+1/3	-1

Mesons = one quark and one anti-quark

Baryons = three quarks

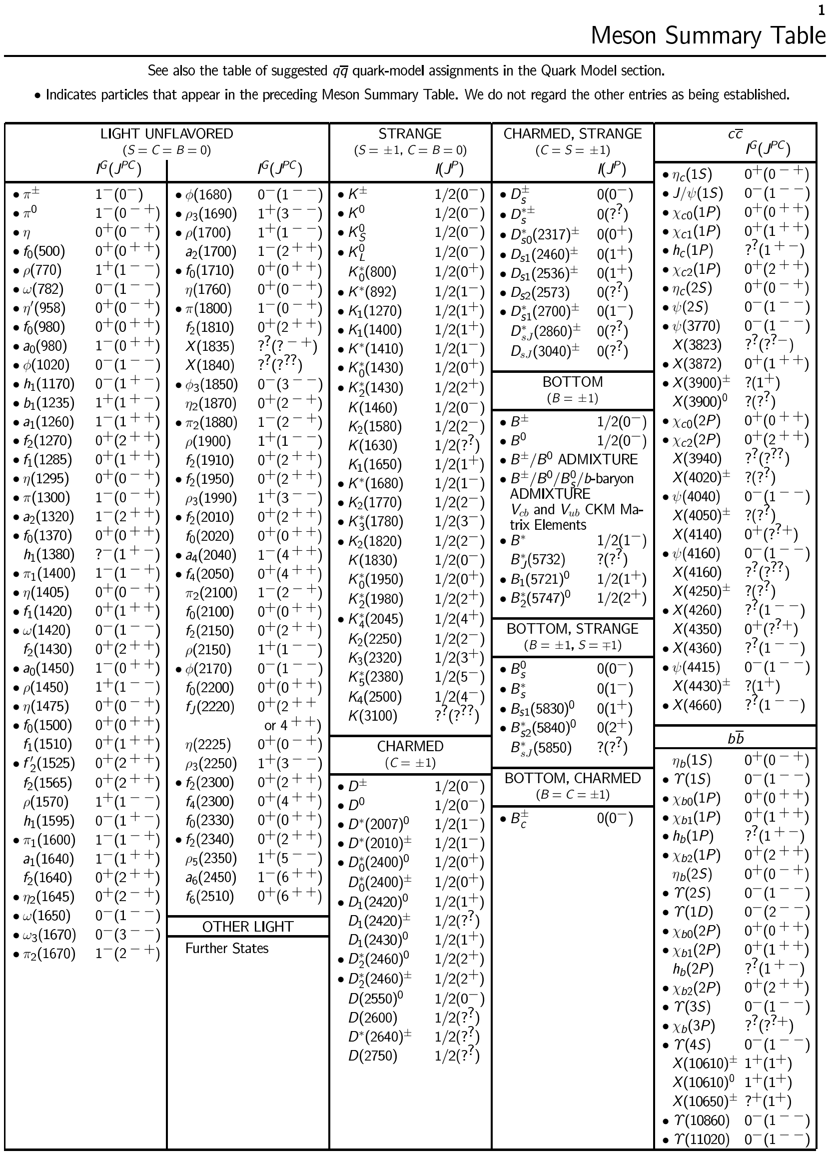
Anti-baryons = three anti-quarks

Example of the baryon decuplet

	Q	S	Baryon	B number
uuu	2	0	Δ^{++}	1
uud	1	0	Δ^{+}	1
udd	0	0	Δ^{0}	1
ddd	-1	0	Δ^{-}	1
uus	1	-1	Σ^{*+}	1
uds	0	-1	Σ^{*0}	1
dds	-1	-1	Σ^{*-}	1
uss	0	-2	Ξ^{*0}	1
dss	-1	-2	Ξ^{*-}	1
sss	-1	-3	Ω^{-}	1

Note that this fills in nicely and makes predictions, but we have yet to account for different energy levels and spin

It really is a particle zoo (from the PDG)



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Meson Summary Table

See also the table of suggested $q\overline{q}$ quark-model assignments in the Quark Model section.

• Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.

LIGHT UNFLAVORED
($S = C = B = 0$)

	$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$
• π^0	$1^-(0^{-+})$
• η	$0^+(0^{-+})$
• $f_0(500)$	$0^+(0^{++})$
• $\rho(770)$	$1^+(1^{--})$
• $\omega(782)$	$0^-(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$
• $a_0(980)$	$1^-(0^{++})$
• $\phi(1020)$	$0^-(1^{--})$
• $h_1(1170)$	$0^-(1^{+-})$
• $b_1(1235)$	$1^+(1^{+-})$
• $a_1(1260)$	$1^-(1^{++})$
• $f_2(1270)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$
• $\eta(1295)$	$0^+(0^{-+})$
• $\pi(1300)$	$1^-(0^{-+})$
• $a_2(1320)$	$1^-(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$
• $\pi_1(1400)$	$1^-(1^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$
• $f_1(1420)$	$0^+(1^{++})$
• $\omega(1420)$	$0^-(1^{--})$
$f_2(1430)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$
• $\rho(1450)$	$1^+(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$
• $f_0(1500)$	$0^+(0^{++})$
$f_1(1510)$	$0^+(1^{++})$
• $f_2'(1525)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$
$\rho(1570)$	$1^+(1^{--})$
$h_1(1595)$	$0^-(1^{+-})$
• $\pi_1(1600)$	$1^-(1^{-+})$
$a_1(1640)$	$1^-(1^{++})$
$f_2(1640)$	$0^+(2^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$
• $\omega(1650)$	$0^-(1^{--})$
• $\omega_3(1670)$	$0^-(3^{--})$
• $\pi_2(1670)$	$1^-(2^{-+})$

	$I^G(J^{PC})$
• $\phi(1680)$	$0^-(1^{--})$
• $\rho_3(1690)$	$1^+(3^{--})$
• $\rho(1700)$	$1^+(1^{--})$
$a_2(1700)$	$1^-(2^{++})$
• $f_0(1710)$	$0^+(0^{++})$
$\eta(1760)$	$0^+(0^{-+})$
• $\pi(1800)$	$1^-(0^{-+})$
$f_2(1810)$	$0^+(2^{++})$
$X(1835)$	$?^?(?^{-+})$
$X(1840)$	$?^?(?^{??})$
• $\phi_3(1850)$	$0^-(3^{--})$
$\eta_2(1870)$	$0^+(2^{-+})$
• $\pi_2(1880)$	$1^-(2^{-+})$
$\rho(1900)$	$1^+(1^{--})$
$f_2(1910)$	$0^+(2^{++})$
• $f_2(1950)$	$0^+(2^{++})$
$\rho_3(1990)$	$1^+(3^{--})$
• $f_2(2010)$	$0^+(2^{++})$
$f_0(2020)$	$0^+(0^{++})$
• $a_4(2040)$	$1^-(4^{++})$
• $f_4(2050)$	$0^+(4^{++})$
$\pi_2(2100)$	$1^-(2^{-+})$
$f_0(2100)$	$0^+(0^{++})$
$f_2(2150)$	$0^+(2^{++})$
$\rho(2150)$	$1^+(1^{--})$
• $\phi(2170)$	$0^-(1^{--})$
$f_0(2200)$	$0^+(0^{++})$
$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
$\eta(2225)$	$0^+(0^{-+})$
$\rho_3(2250)$	$1^+(3^{--})$
• $f_2(2300)$	$0^+(2^{++})$
$f_4(2300)$	$0^+(4^{++})$
$f_0(2330)$	$0^+(0^{++})$
• $f_2(2340)$	$0^+(2^{++})$
$\rho_5(2350)$	$1^+(5^{--})$
$a_6(2450)$	$1^-(6^{++})$
$f_6(2510)$	$0^+(6^{++})$

OTHER LIGHT

Further States

STRANGE
($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K_S^0	$1/2(0^-)$
• K_L^0	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED
($C = \pm1$)

• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2400)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(0^-)$
$D(2600)$	$1/2(?^?)$
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2750)$	$1/2(?^?)$

CHARMED, STRANGE
($C = S = \pm1$)

	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)$	$0(?^?)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{sJ}^*(2860)^\pm$	$0(?^?)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM
($B = \pm1$)

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$
• $B_1(5721)^0$	$1/2(1^+)$
• $B_2^*(5747)^0$	$1/2(2^+)$

BOTTOM, STRANGE
($B = \pm1$, $S = \mp1$)

• B_s^0	$0(0^-)$
• B_s^*	$0(1^-)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED
($B = C = \pm1$)

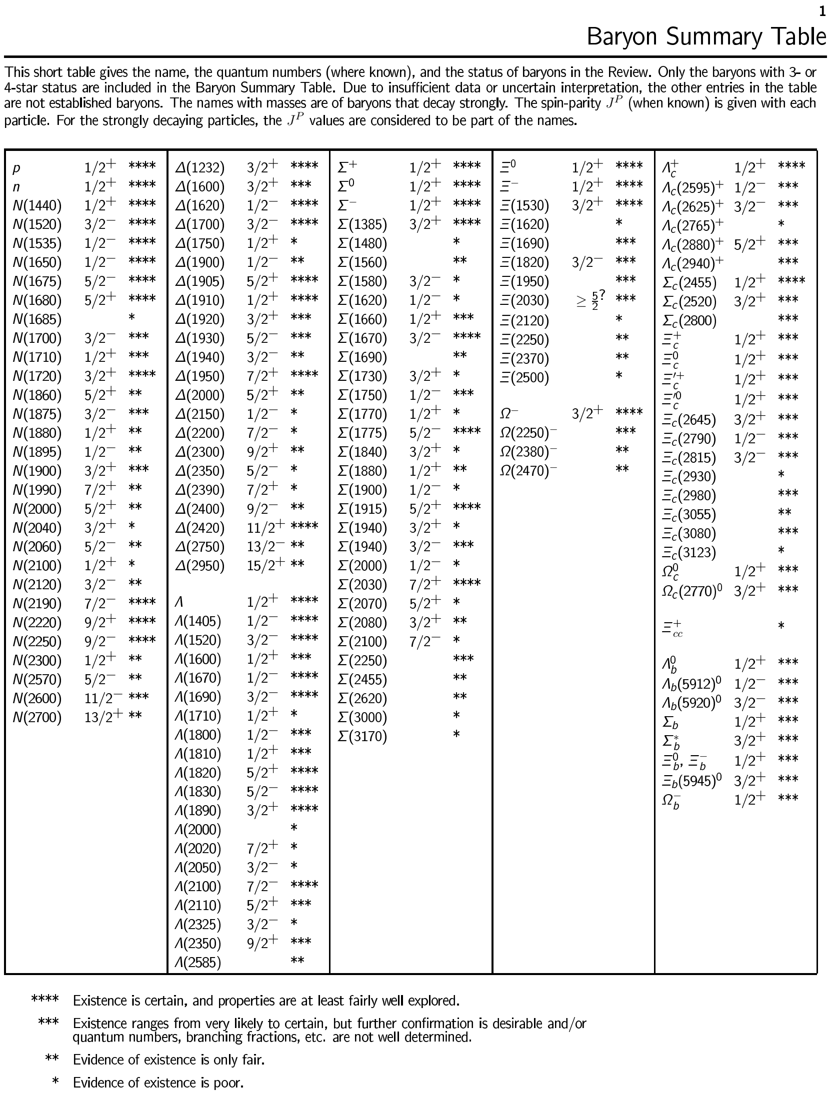
• $B_c^\pm$	$0(0^-)$

$c\overline{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
$X(3823)$	$?^?(?^{?-})$
• $X(3872)$	$0^+(1^{++})$
• $X(3900)^\pm$	$?(1^+)$
$X(3900)^0$	$?(?^?)$
• $\chi_{c0}(2P)$	$0^+(0^{++})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
$X(4020)^\pm$	$?(?^?)$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4250)^\pm$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$X(4430)^\pm$	$?(1^+)$
• $X(4660)$	$?^?(1^{--})$

$b\overline{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$?^?(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$?^?(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_b(3P)$	$?^?(?^{?+})$
• $\Upsilon(4S)$	$0^-(1^{--})$
$X(10610)^\pm$	$1^+(1^+)$
$X(10610)^0$	$1^+(1^+)$
$X(10650)^\pm$	$?^+(1^+)$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$



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Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the table are not established baryons. The names with masses are of baryons that decay strongly. The spin-parity J^P (when known) is given with each particle. For the strongly decaying particles, the J^P values are considered to be part of the names.

p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1685)$		*
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	***
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	**
$N(1895)$	$1/2^-$	**
$N(1900)$	$3/2^+$	***
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1710)$	$1/2^+$	*
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$		*
$\Lambda(2020)$	$7/2^+$	*
$\Lambda(2050)$	$3/2^-$	*
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1690)$		**
$\Sigma(1730)$	$3/2^+$	*
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1770)$	$1/2^+$	*
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1840)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1900)$	$1/2^-$	*
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^+$	*
$\Sigma(1940)$	$3/2^-$	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}^?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
Ξ_{cc}^+		*
Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
Ω_b^-	$1/2^+$	***

****	Existence is certain, and properties are at least fairly well explored.
***	Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.
**	Evidence of existence is only fair.
*	Evidence of existence is poor.

So why can’t we observe quarks directly?

Quarks are **confined** to hadrons, and cannot be observed as bare objects. In other words, they are social beasts, and don’t like to exist on their own. We’ll discuss them more later on

What about Pauli exclusion principle?

sss hadron (Ω^-) should violate Pauli exclusion principle (multiple times!) There needs to be some fundamental difference between the quarks for this to be allowed: QCD color charge (beware comparisons to real “color”)

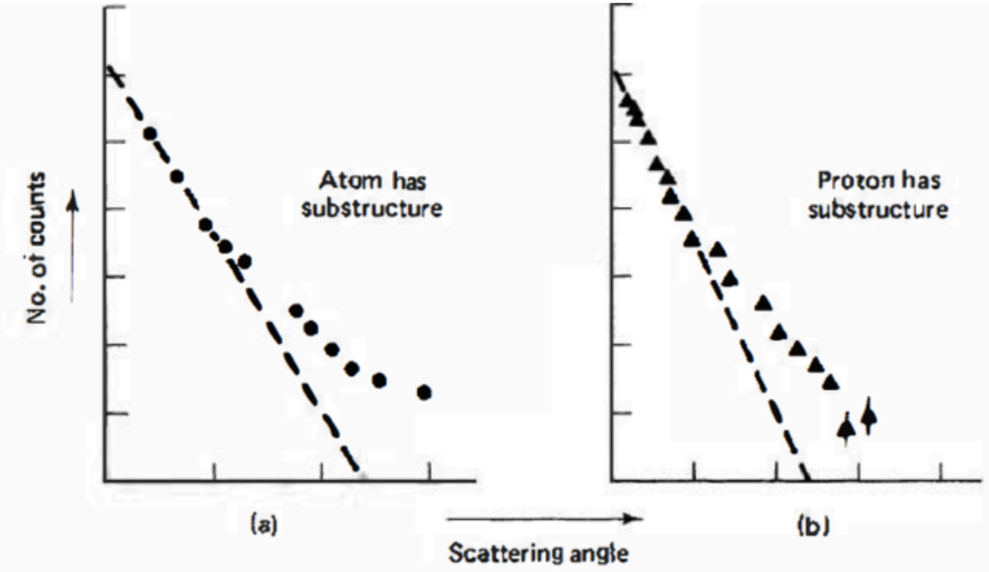
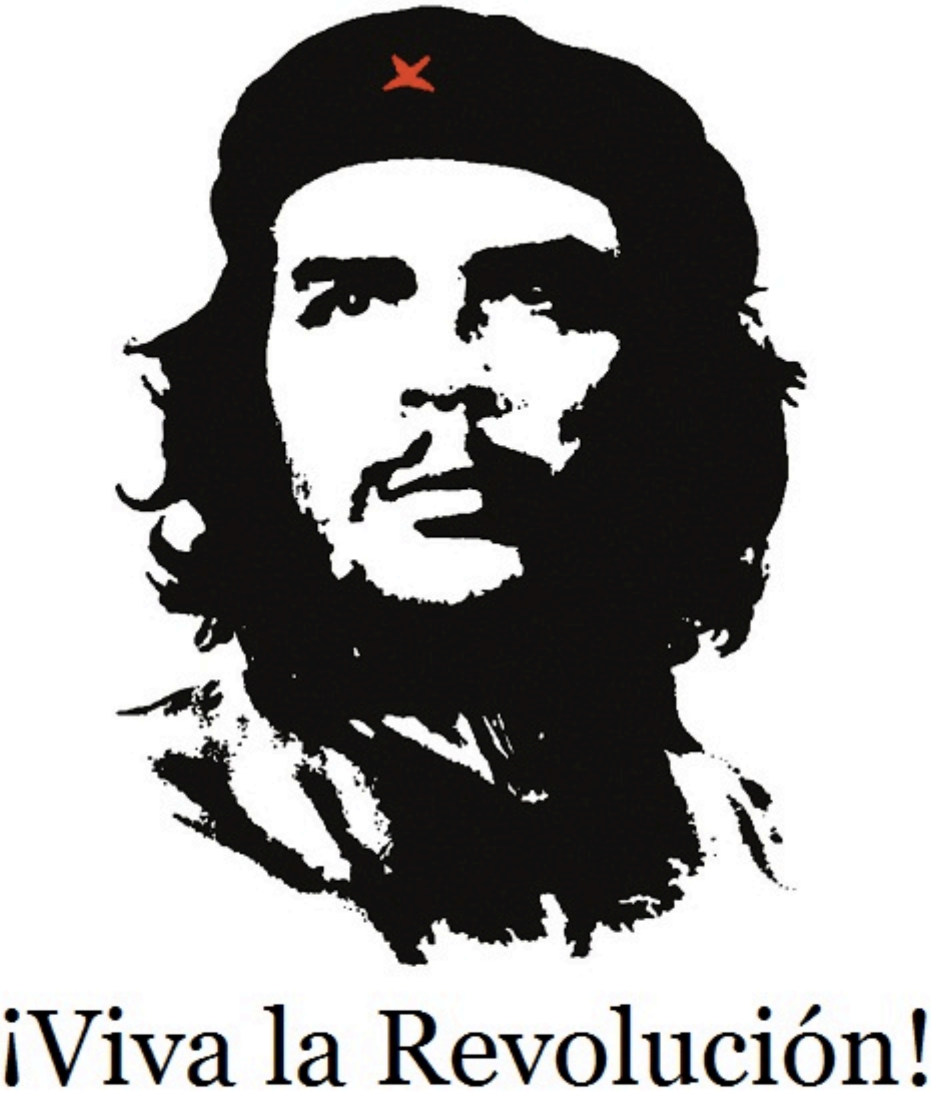


Fig. 1.11 (a) In Rutherford scattering, the number of particles deflected through large angles indicates that the atom has internal structure (a nucleus). (b) In deep inelastic scattering, the number of particles deflected through large angles indicates that the proton has internal structure (quarks). The dashed lines show what you would expect if the positive charge were uniformly distributed over the volume of (a) the atom, (b) the proton. (*Source*: Halzen, F. and Martin, A. D. (1984) *Quarks and Leptons*, John Wiley & Sons, New York, p. 17. Copyright © John Wiley & Sons, Inc. Reprinted by permission.)

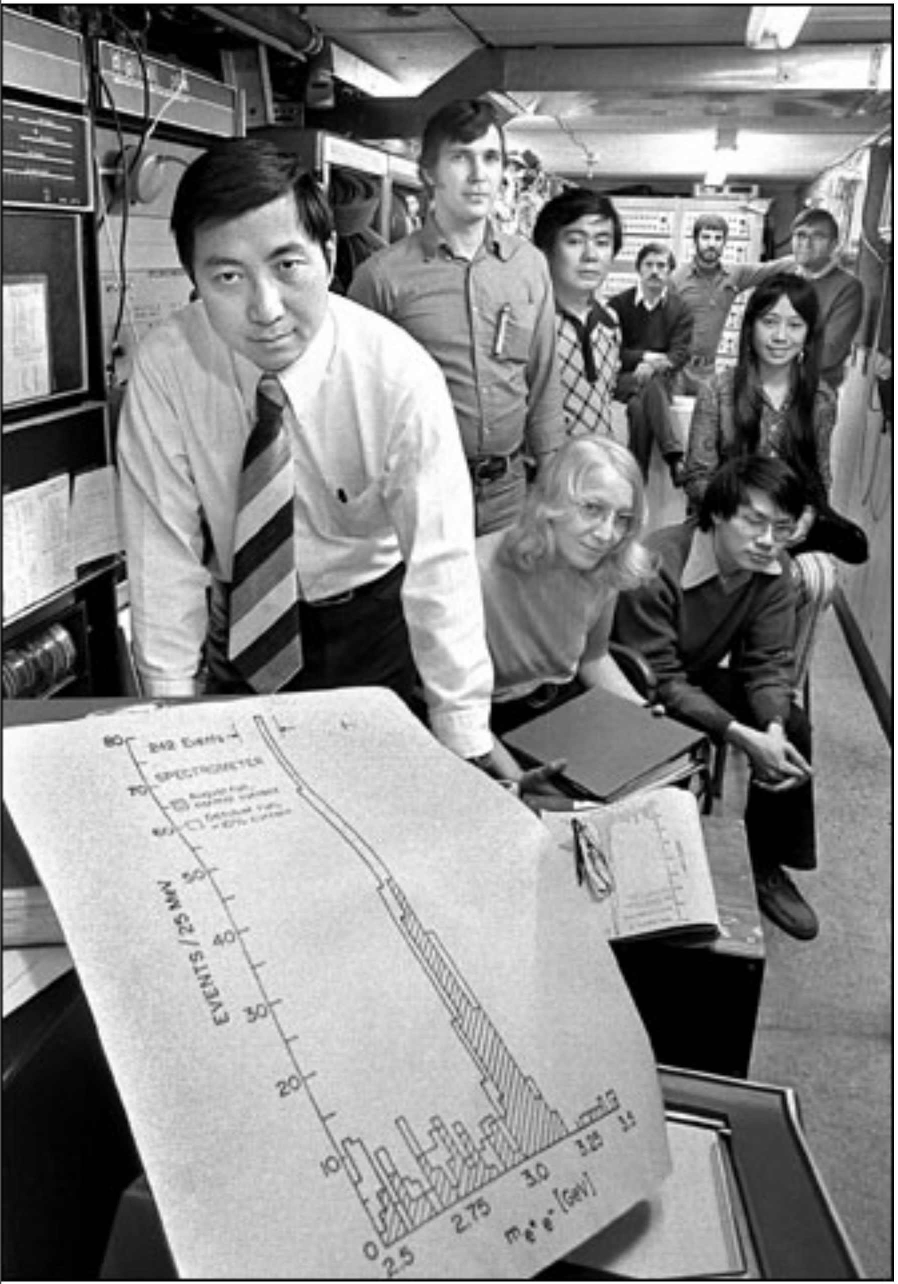
Colorless objects only: Explains why we don’t have qq (or q) final states

November revolution

November 1974, ψ meson discovered at SLAC, J meson at Brookhaven. Hence the name J/ψ, a new, electrically neutral particle with a long lifetime. Began the "November revolution"



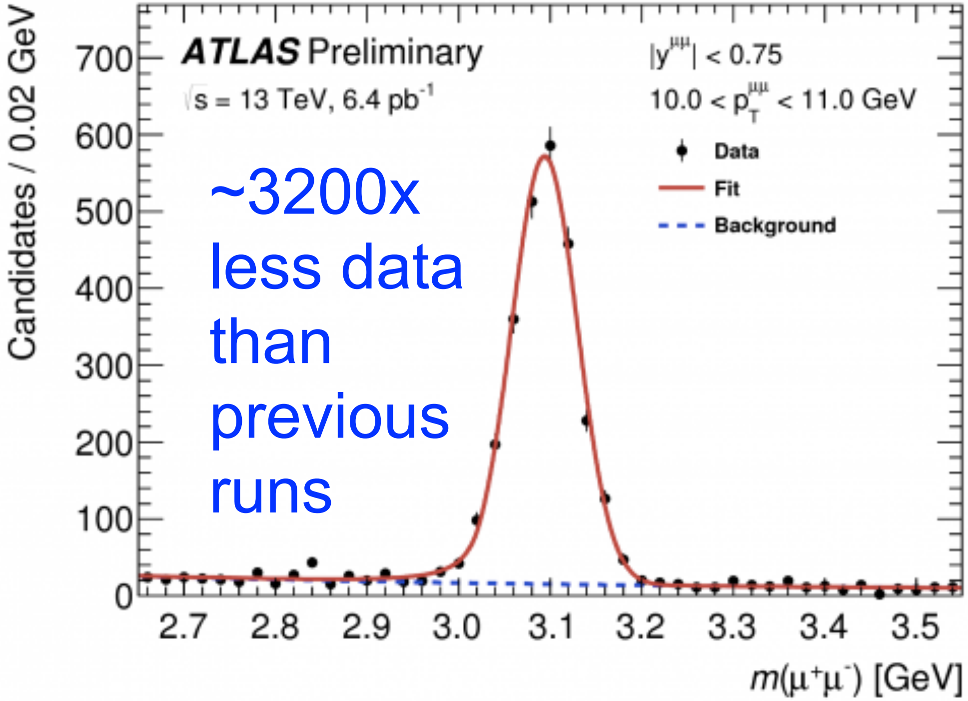
How was it discovered?



https://www.bnl.gov/bnlweb/history/nobel/nobel_76.asp

Sam Ting and his team, showing a plot of mass of e^+e^- pairs. As we will see shortly, the mass of objects is an invariant even after decay, so we see a bump at 3.1 GeV = JPsi mass

And these days



~3200x less data than previous runs

We know that the JPsi is a charm-anticharm bound state with spin = 1

Add in the third generation

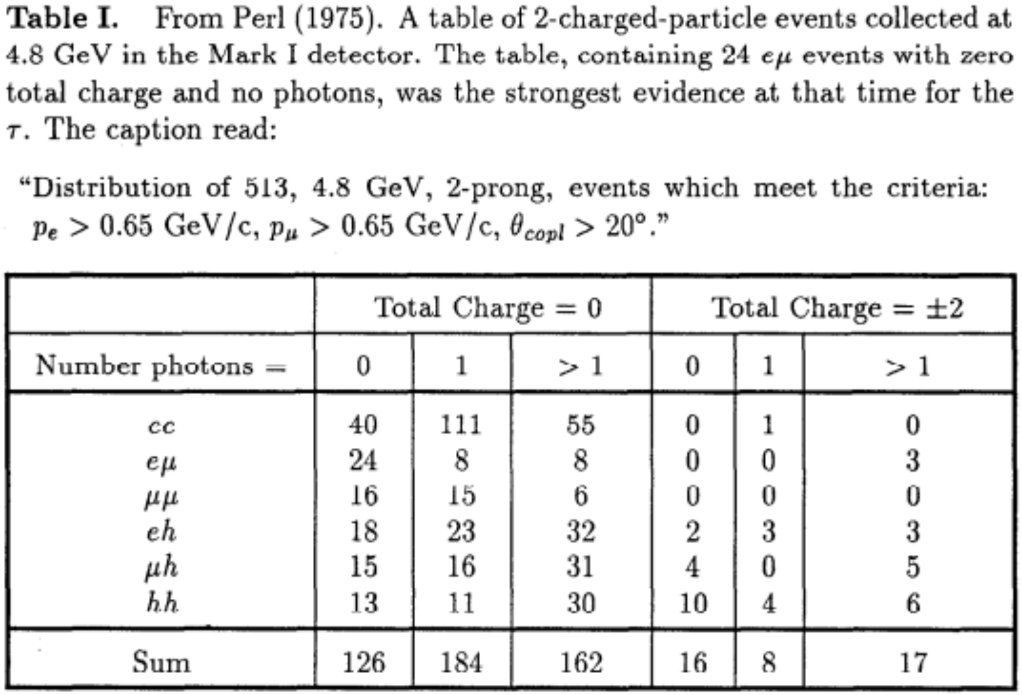


Table I. From Perl (1975). A table of 2-charged-particle events collected at 4.8 GeV in the Mark I detector. The table, containing 24 $e\mu$ events with zero total charge and no photons, was the strongest evidence at that time for the τ. The caption read:

"Distribution of 513, 4.8 GeV, 2-prong, events which meet the criteria: $p_e > 0.65$ GeV/c, $p_\mu > 0.65$ GeV/c, $\theta_{copl} > 20°$."

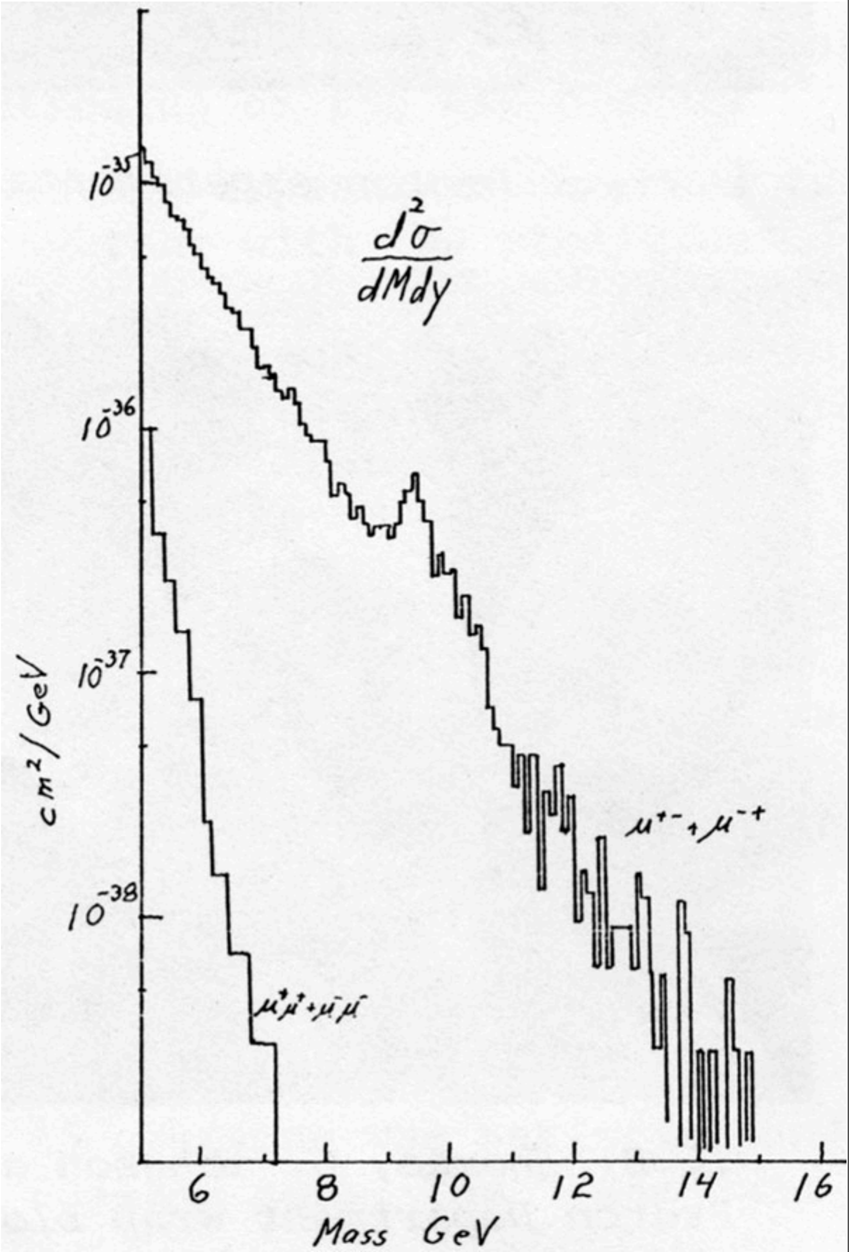
	Total Charge = 0			Total Charge = ±2		
Number photons =	0	1	> 1	0	1	> 1
cc	40	111	55	0	1	0
$e\mu$	24	8	8	0	0	3
$\mu\mu$	16	15	6	0	0	0
eh	18	23	32	2	3	3
μh	15	16	31	4	0	5
hh	13	11	30	10	4	6
Sum	126	184	162	16	8	17

Martin Perl (1975) discovery of
tau lepton (tau neutrino not until 2000!)

Add in the third generation

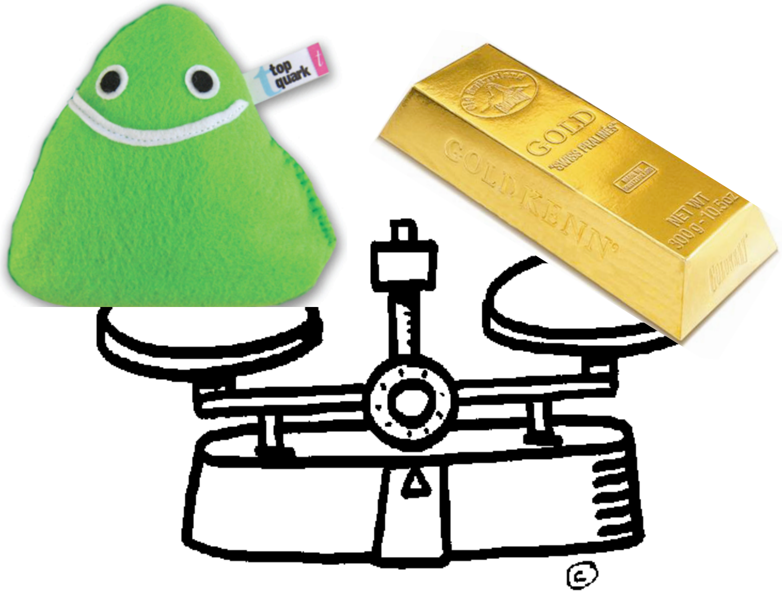
Lederman and E288 collaborators - discovery of the bottom quark at nearby Fermilab:

$$\Upsilon = b\bar{b}$$



Top quark discovery

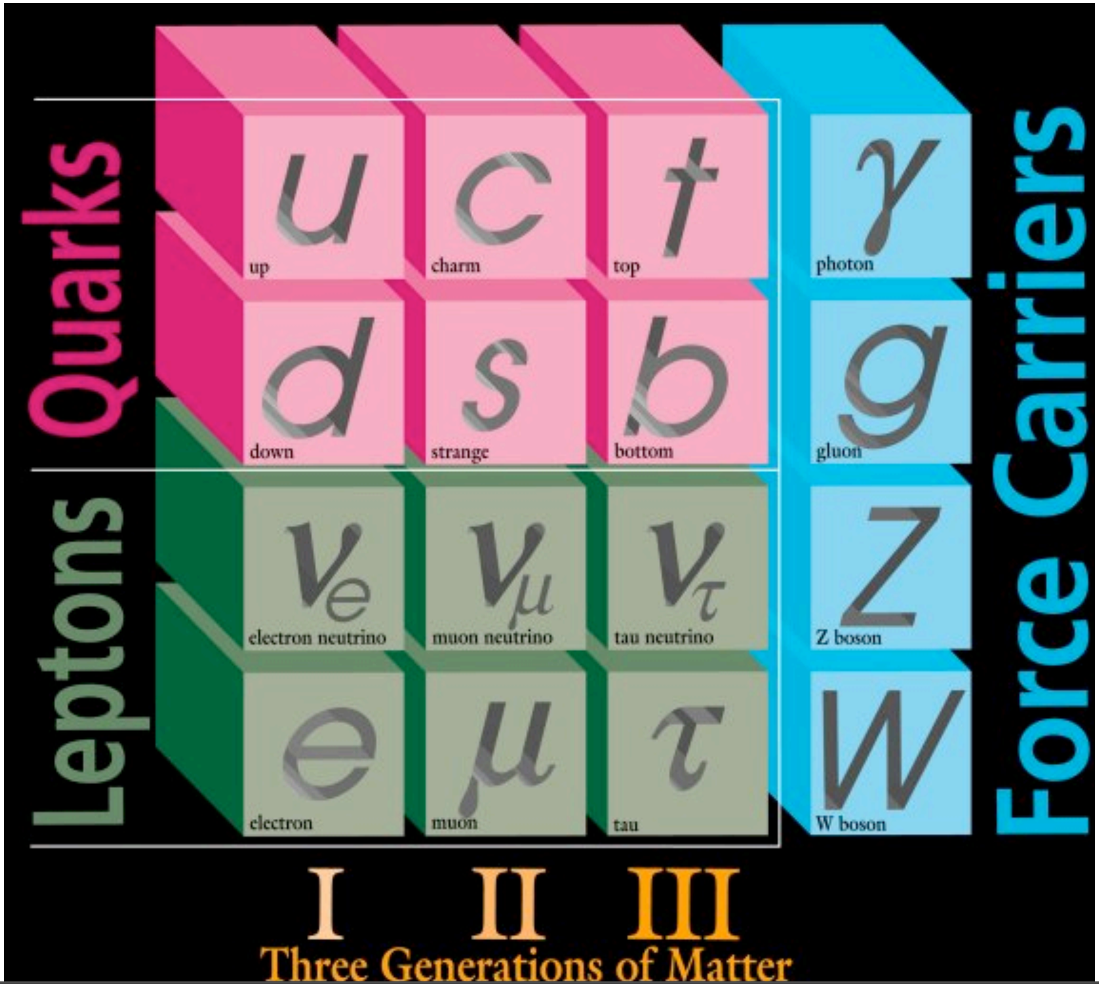
Announced jointly 1994-1995 by DZero and CDF (at Fermilab) in proton-antiproton collisions, but top quarks decay so quickly that they do not form stable/metastable bound states. Mass of top quark = 173 GeV!



Fun aside: UA1 at CERN made a “discovery” of the top quark in 1984 with a mass of 40 +/- 10 GeV

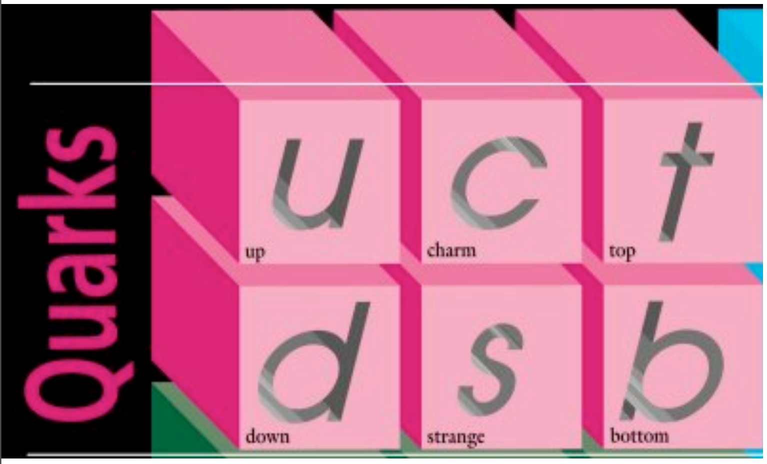
Putting it all together, aka the Standard Model (SM)

Fermions Bosons



This is really the full Standard Model (modulo the Higgs boson, h), though it of course ... hides some details

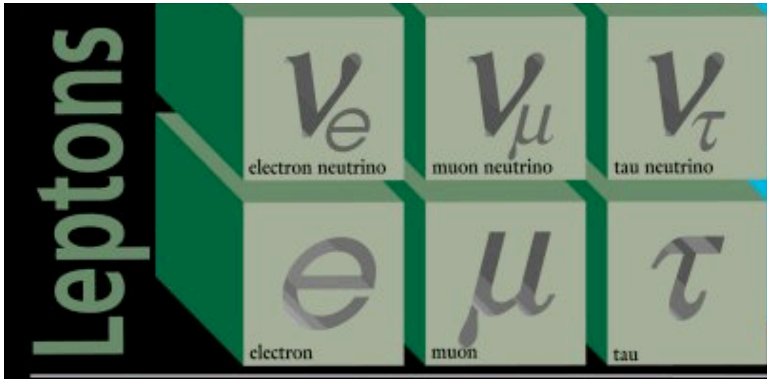
The quarks



Are there additional generations of quarks? We've been looking for them

Three generations of quarks, with each generation getting more massive. Each quark carries electric charge (+2/3,-1/3), and also QCD color (rgb). Quarks are confined, and do not exist alone in nature, but rather only in hadrons: baryons and mesons. Quarks also contain "flavor" (strangeness, topness, etc) that is conserved in QCD, but not in weak interactions. Anti-quarks not shown

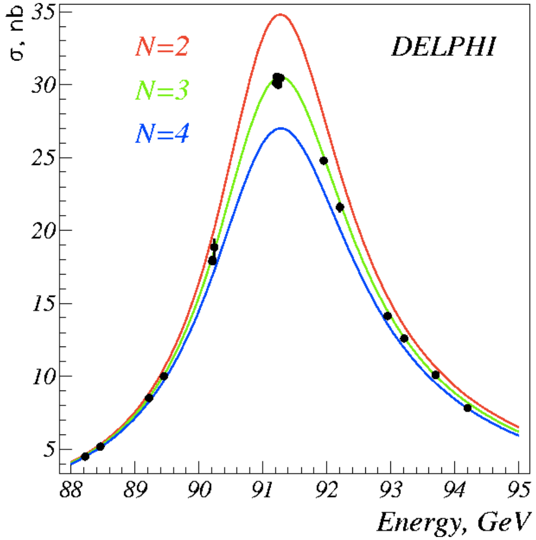
The leptons



Three generations of leptons, with each generation (at least of charged leptons) getting more massive. Charged leptons carry electric charge, neutrinos do not. All leptons carry electron, muon and tau number, which is conserved. Anti-particles not shown

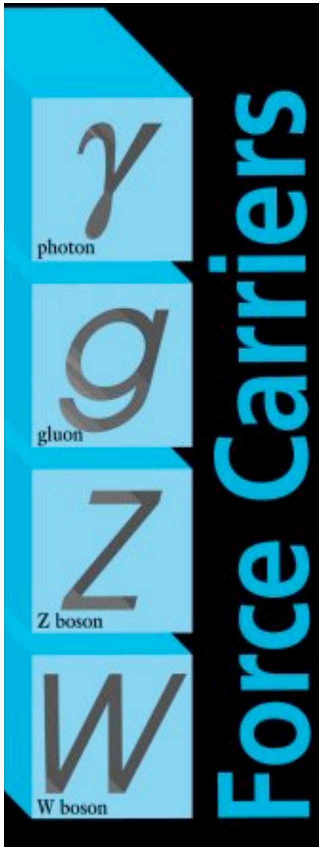
Are there additional leptons? We've been looking for them, though, though extra neutrinos have to be very massive or rarely interact. Masses of observed neutrinos unknown, but are very small

Study number of light neutrinos with Z production at e^+e^- machines



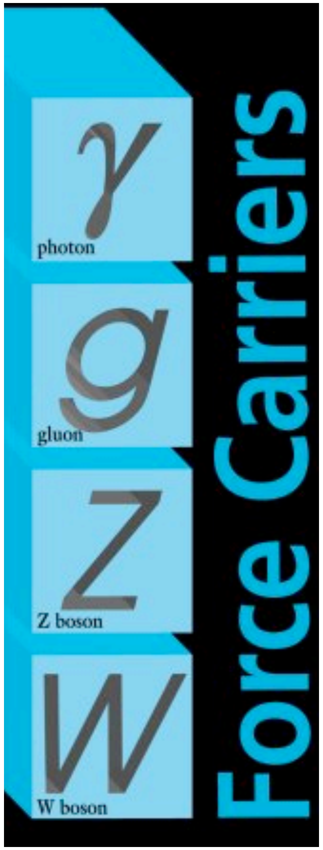
The bosons

Photon never changes matter flavor



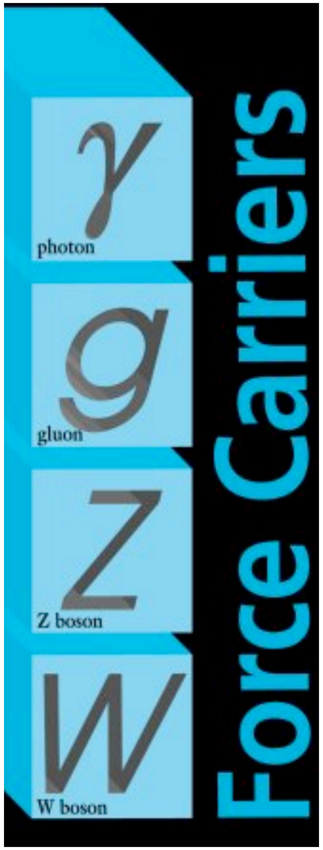
Force carriers are bosons with integer spin. The photon is the force carrier from E&M, and has spin-1 (it’s a vector boson) and zero mass. Interacts only with electrically charged particles

Gluon never changes matter flavor



The gluon is the force carrier of QCD, and has spin 1 (it’s a vector boson) and zero mass. It has no electric charge, but it carries QCD color charge (there are 8 types of gluons). Hence, it couples not only to quarks, but also to itself and other gluons (but not leptons)

The bosons



W bosons always change matter flavor, Z bosons do not

The $W^{\pm}$ and Z^{0} bosons are the weak force carriers, with spin-1 (vector bosons) and both having large, non-zero mass (W~80 GeV, Z~91 GeV). The weak force is called exactly that due to their large mass. Weak force carriers are special - they are the only way to change one quark generation into another (see JPsi lifetime!), and have other special properties that we'll get to. Responsible for nuclear β-decay and fusion

The Higgs boson

The Higgs boson (h) was hypothesized in 1960s, but was not discovered until July 2012. Long timeline! We'll see later in the course how the Higgs mechanism explains why the weak force carriers are so weak/massive, and why the fermions have mass