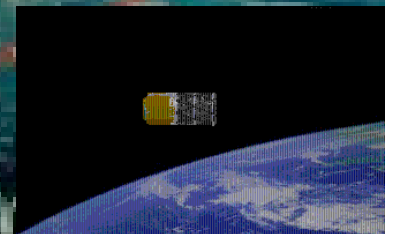


# *Physics 424:* **Particle Physics**

**Dr. Justin Albert**  
*(call me Justin!)*

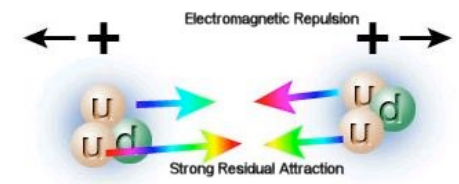
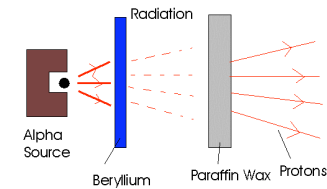
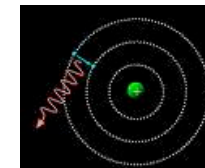
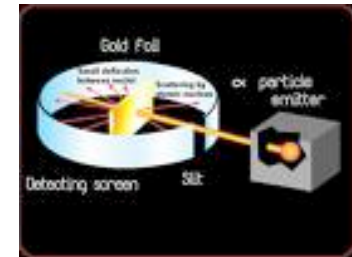


# A Brief History of Particle Physics Discoveries

(Or: Figuring out What the  
Universe is Made Of ... 😊 )

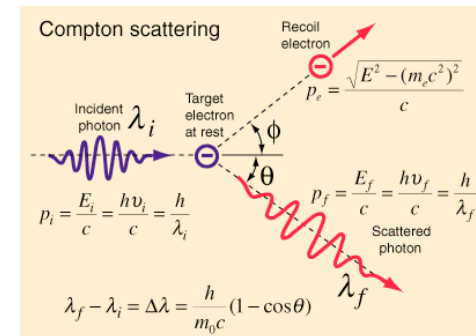
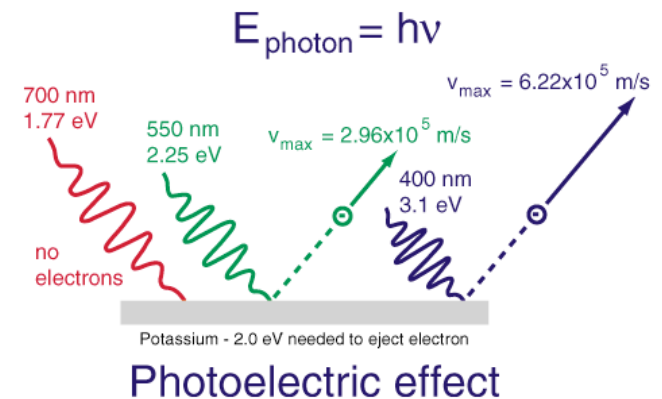
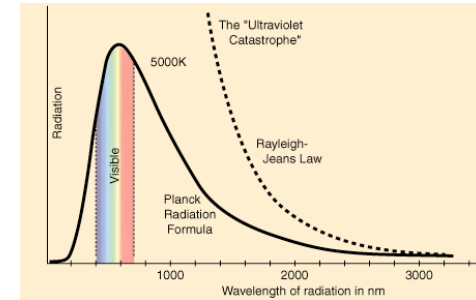
# Looking Inside the Atom: $e^-$ , $p$ , and $n$

- 1897: J.J. Thomson discovers that the charge/mass ratio of cathode rays is fixed, and  $q/m \gg$  ions  $\Rightarrow$  Electron is discovered
- 1909: Rutherford observes large-angle scattering of alpha particles from a thin gold foil, implying atoms have a compact nucleus with most of atomic mass
- 1914: Bohr proposes “orbital model” of hydrogen and calculates emission spectrum
- 1932: Chadwick discovers the neutron (solves puzzle of why atomic number and atomic mass differ)
- 1934: Yukawa proposes a theory of the strong force that holds the nucleus together, predicts particle with mass  $\sim m_p/6$  mediating the strong force



# The Carrier of Electromagnetism: $\gamma$

- 1899: Planck proposes that the radiation emitted by a black body is quantized in units of  $h\nu$
- 1905: Einstein explains the photoelectric effect using Planck's EM quantum (the photon)
- 1916: Millikan does precision measurements of the photoelectric effect, finds agreement with Einstein's prediction, measures  $h$  to 0.5%.
- 1923: Compton observes wavelength shift when light is scattered off electrons, confirming both the existence and the particle nature of photons.



# Dirac and Antimatter

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- 1927: Dirac combines QM and special relativity in an elegant equation.

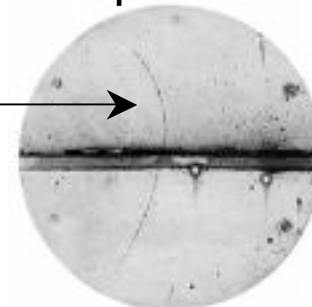
$$H\phi \equiv i\frac{\partial\phi}{\partial t} = (-i\alpha\cdot\nabla + \beta m)\phi$$

We will learn more about this equation later.

Two solutions for the wavefunction  $\phi$  arise unavoidably (since  $E^2 = p^2 + m^2$  admits two solutions for the energy, one positive and one negative).

Dirac postulates a “sea” of negative energy electrons. Excitations of the sea would appear as positive energy “holes” of positive charge.

- 1932: Anderson discovers a positron (from a cosmic ray) in a cloud chamber.



# ***Holding the Nucleus Together: The Strong Force***

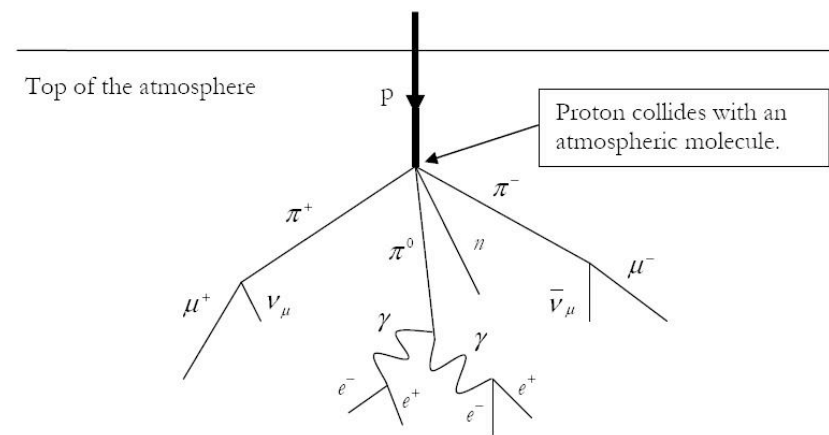
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- 1934: Yukawa proposes a theory of the strong force. Like EM and gravity, it employs a field, but in this case it has a massive, rather than a massless, quantum.
- A massive quantum implies a short range  $\sim \hbar / m_\pi c$
- In order to agree with known nuclear binding energies, the exchanged quantum (a “meson”) would have mass  $\sim m_p/6$ .

This theory of the strong interaction is not correct; it would be another 30 years before the world of quarks and gluons would be revealed. However, in an appropriate limit (low energies), Yukawa theory is an effective theory of the strong interaction, and the form of the Lagrangian he used recurs in many modern theories.

# Mesons

- 1937: A new particle is seen in cosmic rays by two groups. The mass is reasonably close to the expectation for the pion, however,
  - Lifetime was too long?!?
  - Different mass measurements were inconsistent
- 1946: It was seen that these cosmic ray particles (at sea level) appeared to interact weakly with nuclei (pion should interact strongly)
- 1947: Powell looks at cosmic rays at high altitude and shows that there are two mesons:  $\pi$  and  $\mu$ 
  - $\pi$  is the Yukawa particle, is short-lived ( $10^{-8}$  s), and decays to  $\mu$  (plus a  $\nu$ )
  - $\mu$  lives for  $10^{-6}$  s, does not interact strongly, decays to  $e$  (plus two  $\nu$ )



# Beta Decay, Neutrinos

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- Radioactivity sometimes leads to emission of  $e^-$  (and in a few cases  $e^+$ )
- The energy of the electron is less than expected for the two-body decay  $A \rightarrow B + e$ :

$$m_A c^2 = \sqrt{m_B^2 c^4 + (E_e^2 - m_e^2 c^4)} + E_e$$

$$E_e = \frac{m_A^2 - m_B^2 + m_e^2}{2m_A} c^2$$

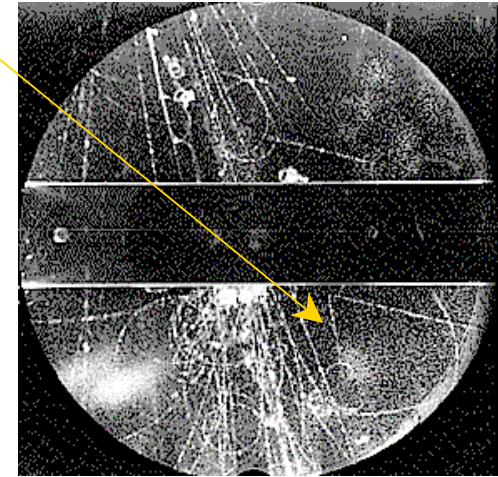
$p_B = p_e$  for a  
2-body decay

- 1930: Pauli proposes a missing neutral particle
- 1933: Fermi proposes theory of beta decay involving a “neutrino”
- Neutrinos are also (not) seen in the decay in the decays of charged pions (one missing) and in muons (two missing)
- 1962: neutrinos from pion decay, incident on nuclei, produce  $\mu$ , not  $e$ :  $\nu_\mu$  and  $\nu_e$  are separate particles.

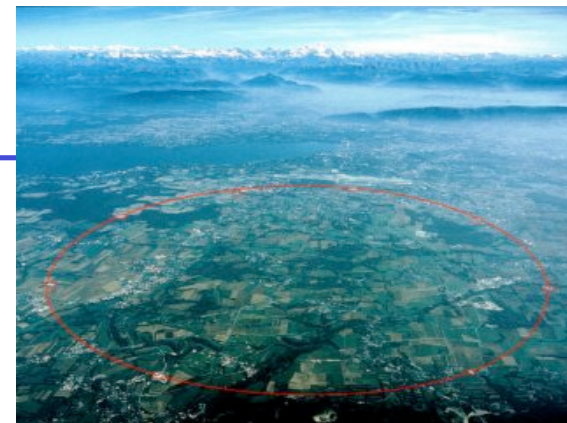


# Strange Particles

- 1947: Rochester and Butler discover  $K^0 \rightarrow \pi^+ \pi^-$  in a cloud chamber picture of a cosmic ray.
- 1949: Powell discovers  $K^+ \rightarrow \pi^+ \pi^- \pi^+$
- 1950: Anderson discovers  $\Lambda \rightarrow p \pi^-$
- 1953: Brookhaven Cosmotron and Berkeley Bevatron make strange particles in the laboratory.
- Some mysteries:
  - Produced strongly but decay slowly
  - Two particles of equal mass have opposite parity; one decays to two pions, the other to three pions...
- New quantum number -- strangeness -- assigned to these new particles; conserved by strong & EM forces, but not by weak
- Amazing phenomenology -- we'll study the K system later on



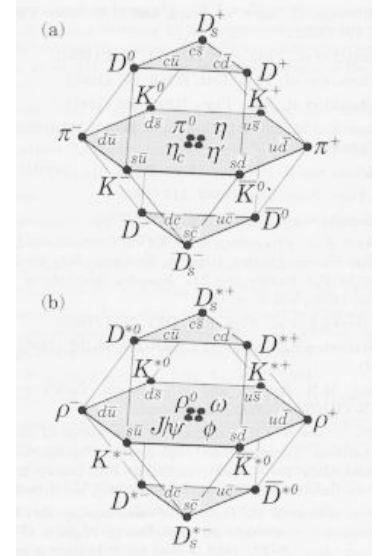
# Manmade Accelerators



- 1929: Cyclotron invented by E.O. Lawrence
- 1953: Brookhaven Cosmotron reaches 3.3 GeV
- 1954: Berkeley Bevatron (6.3 GeV)
- 1960s: AGS (30 GeV) at Brookhaven, PS (28 GeV) at CERN
- 1970s: Fermilab main ring, CERN SPS (300-400 GeV)
- 1970s: 5-30 GeV  $e^+e^-$  colliding beam machines (SLAC, DESY, Cornell, Frascati)
- 1980s: p-pbar colliders (CERN SPPS, Fermilab Tevatron)
- 1990s: High-energy  $e^+e^-$  colliders (CERN LEP, SLAC SLC)
- This year (2008): LHC to start at CERN (14 TeV pp collider)
- Intensities must rise with energy in order to be useful, since cross-sections fall as  $1 / E_{cm}^2$  !!

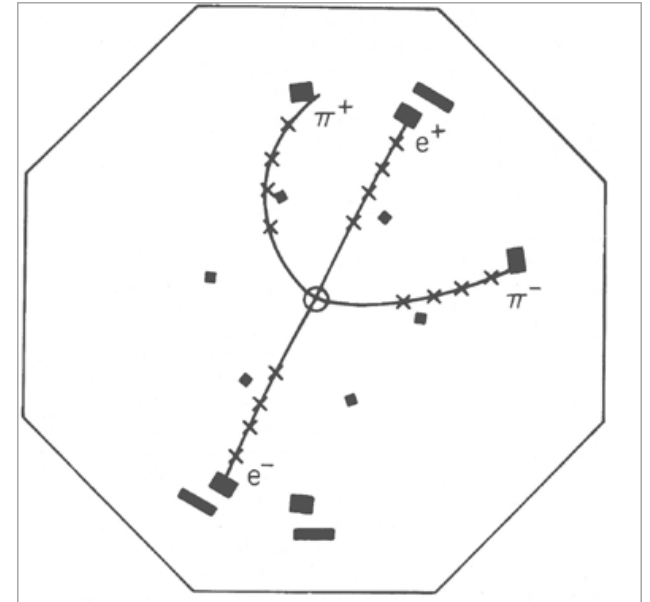
# Quark Model

- Many hadrons (mesons and baryons) were discovered by 1964
- Attempts to classify this “zoo” led to the suggestion of quarks (Murray Gell-Mann):
  - 3 types of quarks: up, down, and strange (u, d, s)
  - Carry charges (+2/3, -1/3, -1/3)
  - Appear in combinations of either quark+antiquark, or 3 quarks (or 3 antiquarks)
  - Existing hadrons fit nicely into this scheme
- Scattering e- and  $\nu$  off nuclei show evidence for substructure, in particular 3 “partons” within each nucleon.
- Why are there no free quarks?
- Pauli exclusion principle should forbid the  $\Omega^-$  baryon (3 s quarks) but it's seen
  - Quark model is wrong, or
  - There is another hidden quantum number (colour)



# Charm, and the “November Revolution”

- New massive (3.1 GeV) “J/ψ” particle seen at Brookhaven ( $p+N \rightarrow \mu^+\mu^-X$ ) and SLAC ( $e^+e^- \rightarrow$  hadrons) in November 1974
  - Narrow width (i.e. long lifetime) incompatible with existing quark constituents
  - Classified as a bound state of a new quark and antiquark
  - Charm quark is heavy ( $\sim 1.4$  GeV) compared with u, d, and s

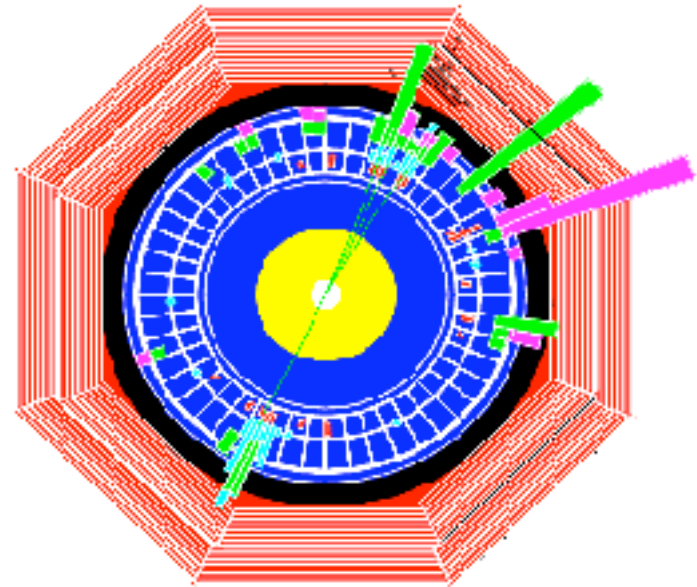


- Particles with charm flavor (D mesons: c quark + u or d antiquark) seen subsequently
- Restores symmetry between quarks and leptons: 2 generations with 2 members each ( $e, \nu_e$ ), ( $\mu, \nu_\mu$ ) and (u,d), (s,c)
- However, symmetry didn't last long...

# ***Tau: a 3rd Charged Lepton***

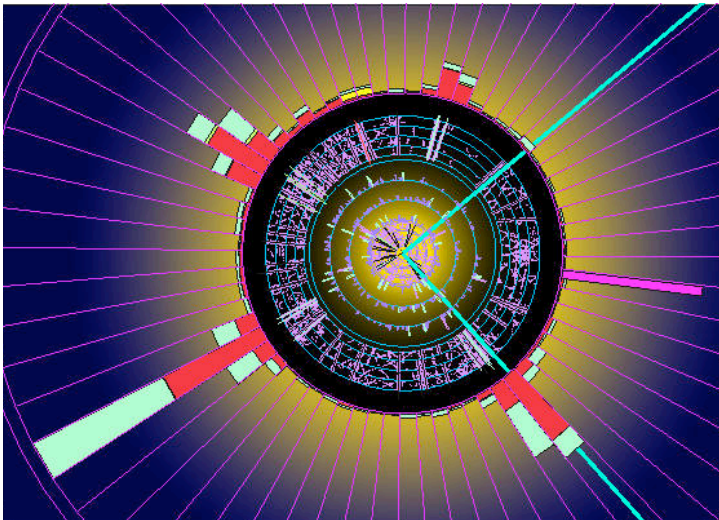
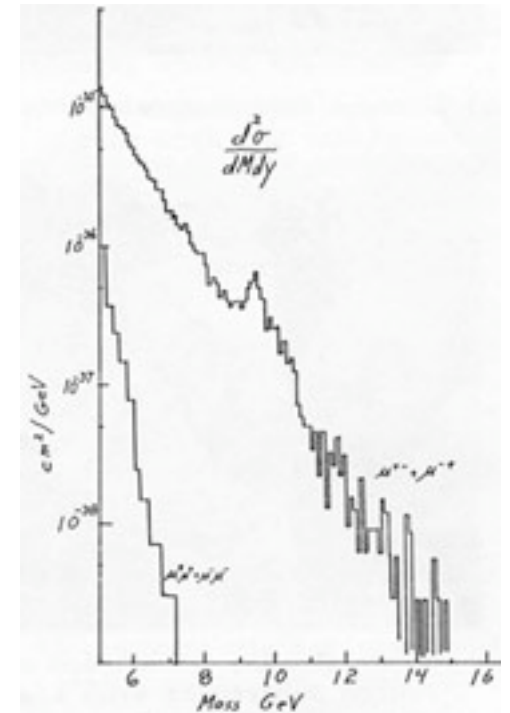
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- Shortly after the discovery of the  $J/\psi$  some unusual events were seen at SLAC; e.g.  $e^+e^- \rightarrow e^+\mu^- + \text{missing momentum}$
- Determined to be from the  $\tau$ , a heavier (x17) cousin of the  $\mu$
- An additional neutrino ( $\nu_\tau$ ) was also assumed
- Nature apparently has (at least) 3 generations of leptons
- The discovery suggested that 3rd generation of quarks might exist...



# Bottom and Top

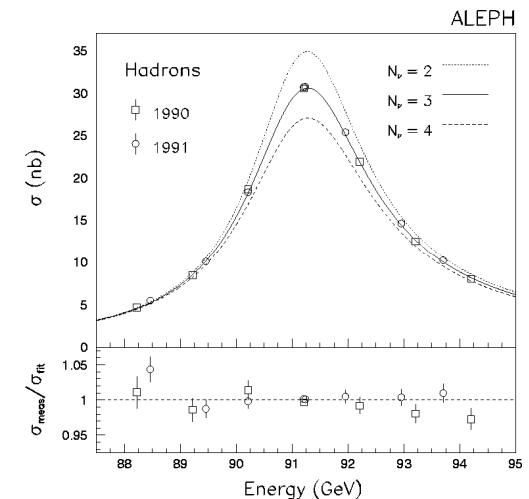
- 1977: Lederman et al. find  $Y$  (upsilon) meson in invariant mass of  $\mu^+\mu^-$  pairs; evidence for 5th “b” quark with mass of  $\sim 5$  GeV
- Implies that at least 3 generations of quarks exist
- 1983: b-flavoured particles seen at Cornell
- Rich phenomenology (and applicability to open questions) makes study of  $B$  mesons still a forefront activity today.



- Top quark is much, much heavier than the others (174 GeV!)
- First seen at Fermilab in 1995, after many years of effort.

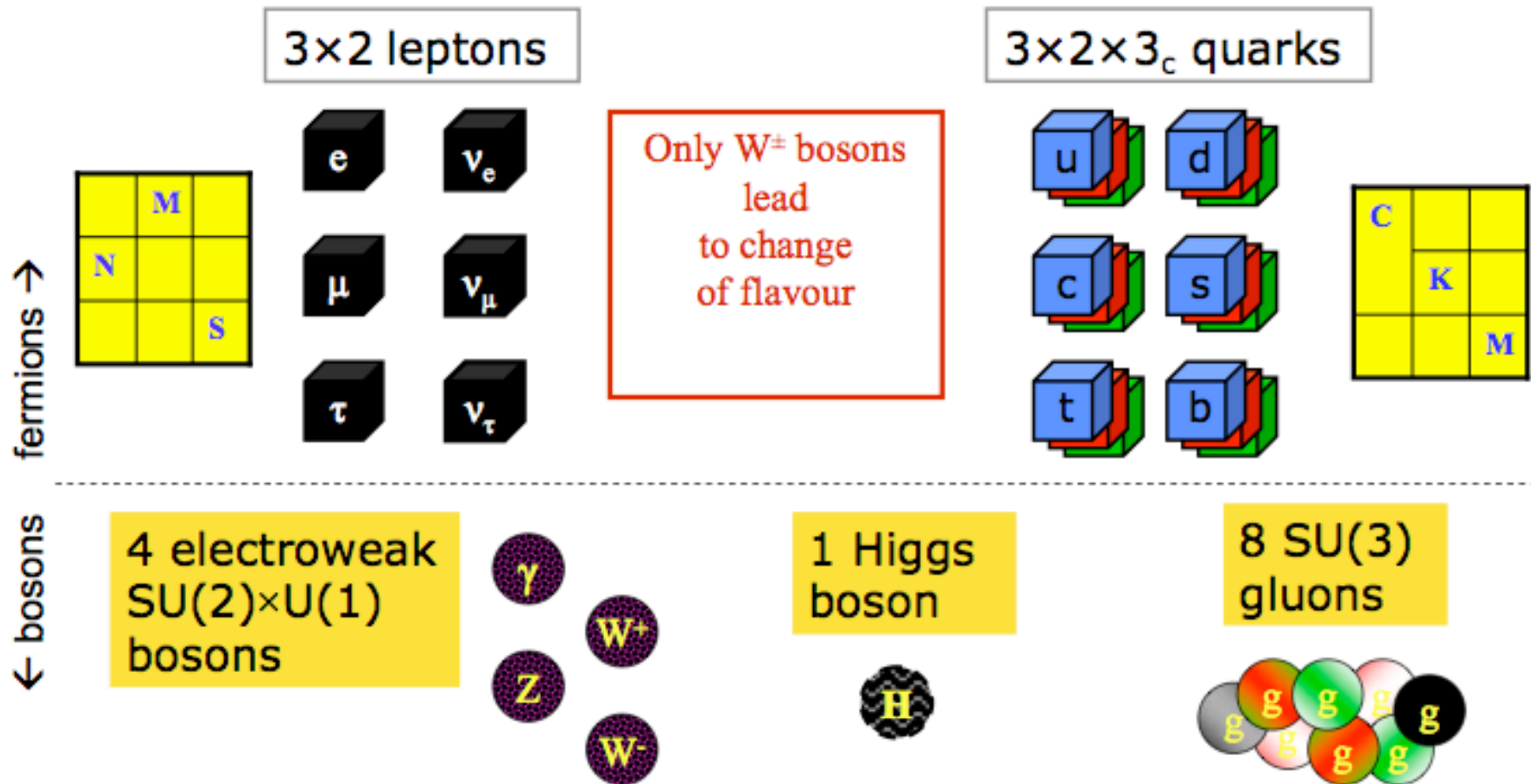
# W and Z and ...

- By early 1970s the Standard Model was being formed
- Predicted massive vector bosons as the carriers of the weak force
- Predicted neutral weak currents; seen at CERN in 1973
  - Requires  $\nu$ -induced interactions to avoid being masked by much stronger EM interactions
- CERN SPPS produces W and Z in 1983, confirming electroweak unification
- LEP collider at CERN and SLC at SLAC produce Z in  $e^+e^-$  collisions; detailed studies confirm SM and limit the number of light neutrino species to 3
- The Higgs boson is the main missing link in the Standard Model (more on that in future lectures)



# ... the Standard Model

~25 'fundamental' parameters  
(masses, couplings, mixings)





# Natural Units

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- The constants  $\hbar$  and  $c$  can be used to form conversion factors between mass, length, time, momentum and energy, e.g.
  - $[\text{energy}] = [\text{mass}] * c^2$
  - $[\text{energy}] = [\text{momentum}] * c$
  - $[\text{length}] = [\text{time}] * c$
  - $[\text{energy}] = [\text{time}]^{-1} * \hbar$
  - $[\text{length}] = [\text{energy}]^{-1} * \hbar c$
  - ...
- Set  $\hbar = 1$  and  $c = 1$ , put in actual values at the end of the calculation if needed
- Useful number to memorize:  $\hbar c = 0.2 \text{ GeV}\cdot\text{fm}$ , where  $1 \text{ fm} = 10^{-15} \text{ m}$

# How this course is structured

# Problem sets, exams, etc.

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- Lectures, info, etc. will all be on the web at:  
<http://particle.phys.uvic.ca/~jalbert/424/>
- We'll have weekly problem sets.
  - These are due on Monday at the beginning of class (first one will be handed out on Monday, due following Monday).
  - Answer keys will be provided the following week.
  - Late homework counts 50% if it is done before the answer key is provided the following week. If it is done afterwards, it counts 10% (it is still somewhat worthwhile to copy over the answers in order to learn how they were done.) We will drop your lowest homework score, so if you have to miss 1 problem set for any reason, it won't impact you. Sorry, no exceptions to this (other than death in the immediate family, signed doctor's note). Problem sets count for 35% of the total grade.
- There will be a midterm (tentatively to be handed out Feb. 19) and a final. These will count for 25% and 40% respectively.

# *Textbook, contact info, etc.*

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- The textbook is David Griffiths, Introduction to Elementary Particles, J. Wiley & Sons Press, 1987. It is a fairly well-written textbook, as are all of Griffith's 3 physics textbooks, in my opinion. A good selection of alternative textbooks and course notes can be found on the webpage.
- My e-mail is **jalbert@uvic.ca**. I'm in **Elliott 213**. My office phone is **7742**. Please do drop by or call anytime if you have questions. Cell: **(250) 661-7066**.
- Office hours: Come by anytime (if it happens to be a bad time I'll suggest a better one). I'll make an effort to be in my office for an hour after each class. E-mail or call if you want to make sure I'll be around at some given time. Dates in the near future that I'll be out of town are on the whiteboard in the Elliott 2nd floor hallway (JA).

**Questions??**

## *Some of the current open problems...*

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- 1) What is **dark matter** made of?
- 2) What is **dark energy** made of?
- 3) Why is there more **matter than antimatter** in the universe?
- 4) How **heavy are the neutrinos**? What was their role in the formation of the universe?
- 5) Is there a **quantum theory of gravity** that can describe the universe we live in?
- 6) What is the **number of dimensions** in a fundamental theory of nature?

***More on these toward the end of the course ...***