I Intro to the framework

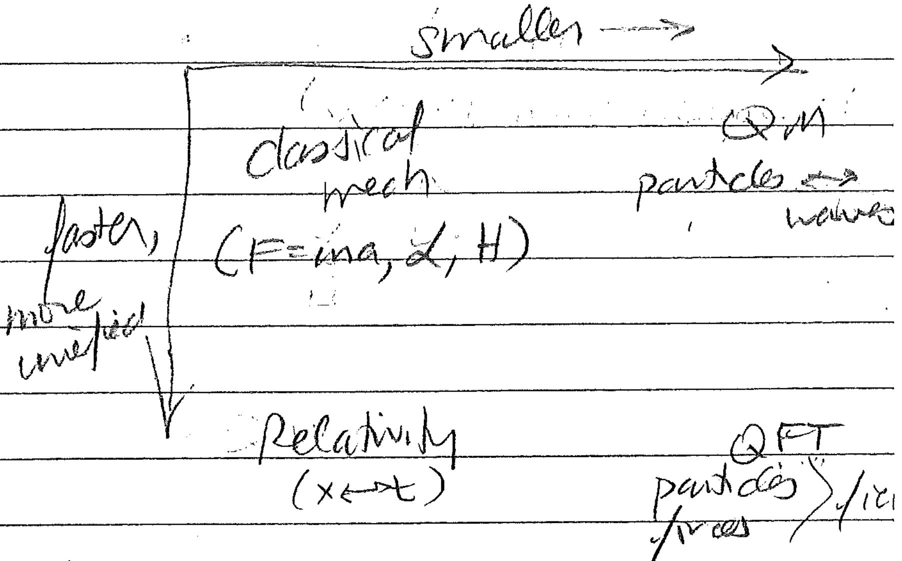
Particle physics studies the fundamental structure of nature –
the constituents
particles ⇐ what can be detected, manipulated

interactions ← it turns out that these are particles too

Notice the distinction between

<u>Force Laws</u> <u>Frameworks</u>

Ex –
Gravitation
E & M



Not 1-to-1 mapping.
Both of these force laws can be studied in all of these frameworks

What's new in this course:
There are (at least) 2 more forces
whose range is so short (⇒ "smaller")

"Small" + "relativistic" does not mean "peripheral"
Strong force binds nuclei + is basis of Periodic Table
Weak force produces nuclear disintegration - drives stellar process

and whose properties cannot be described w/o relativity (e.g., massless particles) that to discuss them we must operate in the "QFT" portion of the framework.

"faster"

i.e., Particle Physics IS "Applied QFT"

Goal of the course

We will apply QFT to
Ch7 E&M (historically the first)
Ch8 Strong Force (framework built by analogy to E&M)
Ch9,11 Weak Force (extend E&M, maintain analogy)

- we mostly skip Gravity (theory) as it is not yet well enough understood, probably because it is so weak that it is hard to test quantum mechanically / relativistically
Will will talk about gravitational wave detection.

In order to approach the goal, we need to develop "vocabulary" + "grammar":

- names + characteristics of
  - Ch 1,2 → particles — {quarks, leptons, ... also pairs complex names like "bottomonium"}
  - Ch 5 → bound (composite) states (heavy, light, extended, pointlike)

Focus on bound states tells us how the particles respond to the forces

Ch 4
- properties of wavefunctions (symmetries)
  - families of particles that respond similarly to a particular force (groups)
  - properties of forces (conservation laws)

◦ Calculational tools —

Ch 3 → • Special Rel

Ch 6 → ◦ Feynman Calculus (shorthand for integrals)

At the end of the course:

◦ The basis for unification of Strong, Weak, EM:

Ch 10 → "Gauge Symmetry"

◦ Open questions whose answers would provide

Ch 12 → further unification

Notice philosophical preference/drive toward unification.

Discussion of particle detection + acceleration will be scattered throughout.

II. How to isolate elementary particles for study

(1) Nature does it for us. Some extreme acceleration mechanism produces cosmic ray particles. These are particles ("ray" is a relic)

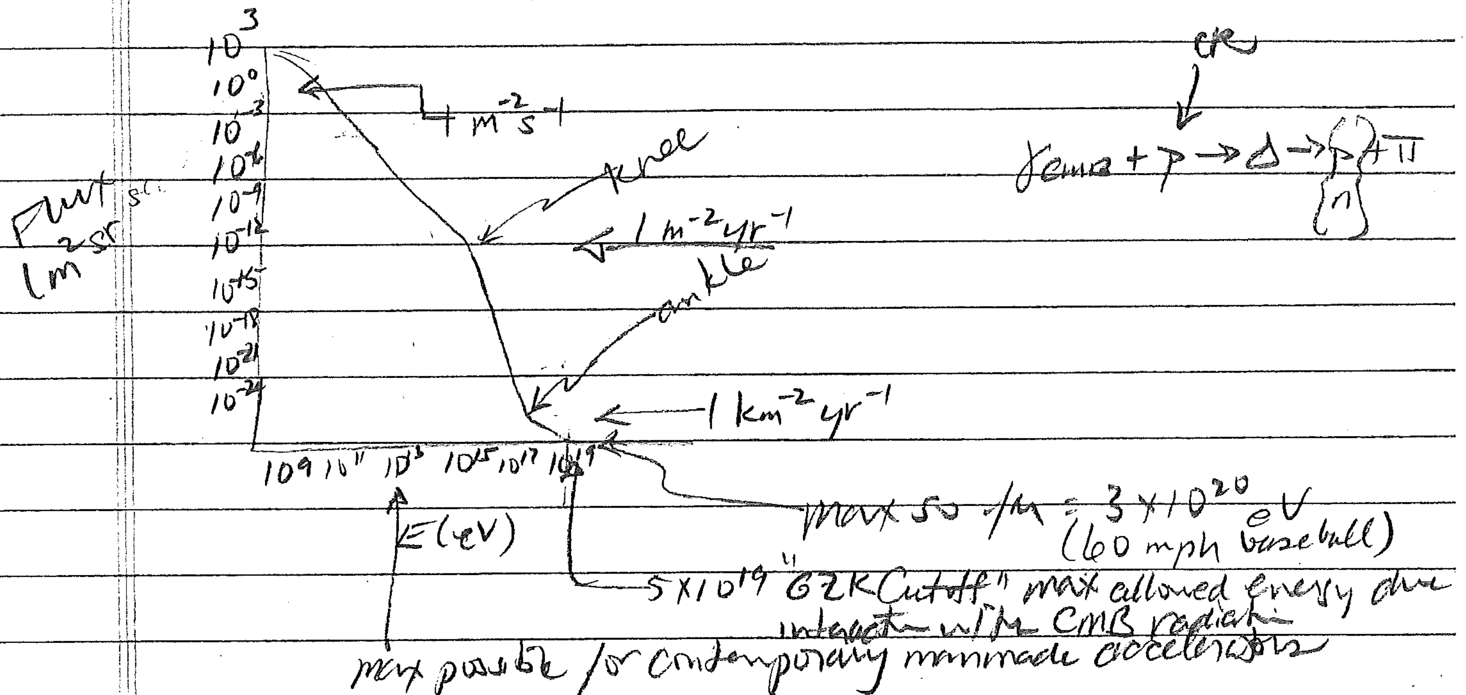
89% - p

10% - He nuclei (2p2n)

1% - heavier elements

<1% - electrons

⑥



$1\ m^{-2}s^{-1}$

$1\ m^{-2}yr^{-1}$

$1\ km^{-2}yr^{-1}$

max 50 J/m = 3×10^{20} eV (60 mph baseball)

5×10^{19} "GZK Cutoff" max allowed energy due interaction w/ the CMB radiation

max possible for contemporary manmade accelerators

$$\gamma_{cmb} + \overset{\overset{CR}{\downarrow}}{p} \to \Delta \to \left\{ \begin{matrix} p \\ n \end{matrix} \right\} + \pi$$

Points of interest –

(i) Different sectors of the graph are produced by different acceleration mechanisms

- solar flares (low E)

speculated for UHECR

- AGN (black holes at galactic centers)? see Pierre Auger
- radio galaxy lobes?
- shocks during galaxy formation?

∴ These are all called "primary cosmic rays"

- secondary CR (produced by collisions of primary CR w/ interstellar medium)

(ii) They strike the upper atmosphere of earth & produce showers of lighter particles (μ, π)

(iii) Initiate nucleosynthesis of Li, Be, B . . . and earth bound radioisotopes (C^{14}, . . .)

(iv) some speculation that UHECR with E > GZK cutoff are actually dark matter.

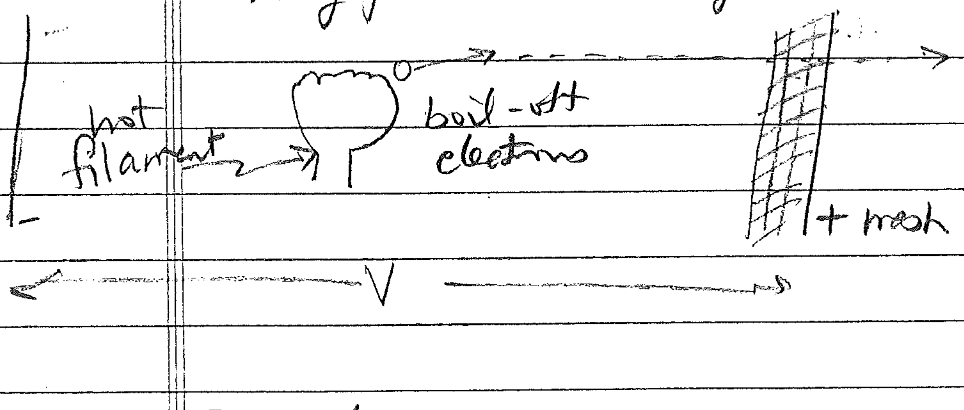
(2) Nuclear reactors

disintegration produces $\alpha\ (2p\ 2n)$
$\beta\ (e^-, e^+)$
γ
ν
n

Point of interest
: This is how the neutrino was discovered and remains a method for studying ν properties

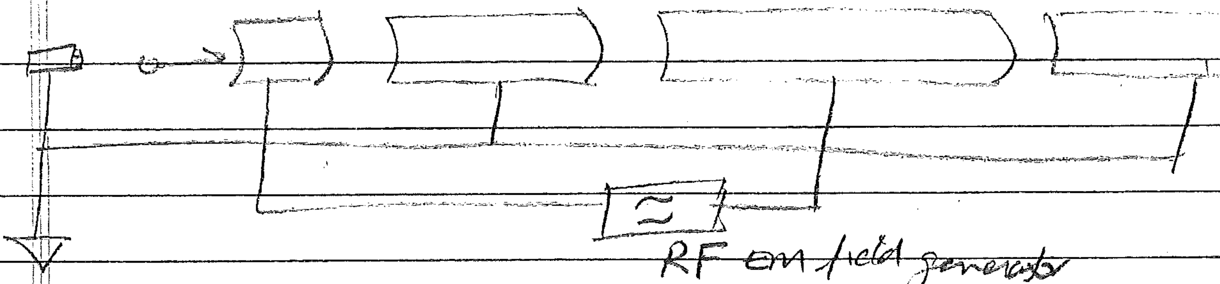
(3) particle accelerators

Any particle with charge can be accelerated.



To accelerate protons or other ions, surround the filament with a gas (~argon) whose atoms become ionized by collision with the e^-: The duoplasmatro

Next stage: Linac



particle rides on EM waves like a beach ball on the sea.

Tubes are Faraday cages

Next acceleration appears in the gaps

Next stage: Synchrotron

Curved path & magnets with varying magnetic fields and oscillating (RF) $\vec{E}$.

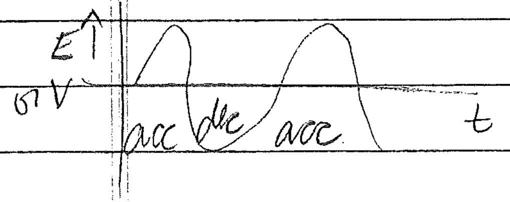
Adjusting B, E keeps particle on constant path as they accelerate

B turns the particles

E accelerates them

Limited by saturation of magnet cores. Then, increase ring radius or use superconducting magnets.

all spin domains are aligned



Requires bunching particles so they respond only to the acc portion.

Additional use of the synchrotron:

Direct p onto $\overset{W}{\text{(target)}}$, nuclear interactions &

$$\left\{\begin{matrix} p+n \\ \text{-or} \\ p+p \end{matrix}\right\} \begin{matrix} \bar{p}, \pi, K, \text{other particles} \\ \rightarrow \text{Each type has a unique} \\ \text{mass.} \end{matrix}$$

Pass them through a magnet.
Each path curves $\sim \frac{1}{\text{mass}}$.

Select desired type.

To get μ or ν, use fact that $\pi \Rightarrow \mu\nu$.

Last stage: storage ring.

Keep beams circulating for hours.
Requires:
(1) high vacuum. $P_{LHC} \sim 10^{-10}$ torr $= 3\times10^{4}$ mbar
(comparable to atmosphere @ 10^4 m above earth.
LHC Pumped vacuum volume is 9000 m³, size of a cathedral, not all beam volume, some for insulating cryomagnets.

(2) constant application of energy to beam, to replace radiation-

An accelerating (direction-changing) charged particle loses energy via synchrotron radiation, Rate of energy loss $\sim \text{acc} \sim \frac{1}{\text{mass}}$

⇒ make ring as large as possible to minimize turning radius
⇒ include straight sections (race track form)
⇒ storing p requires less energy than storing e.

- Discussion of detectors will be integrated with results -

I what kinds of beams are there?

- E.O. Lawrence's accelerator: 80 keV p – 1931

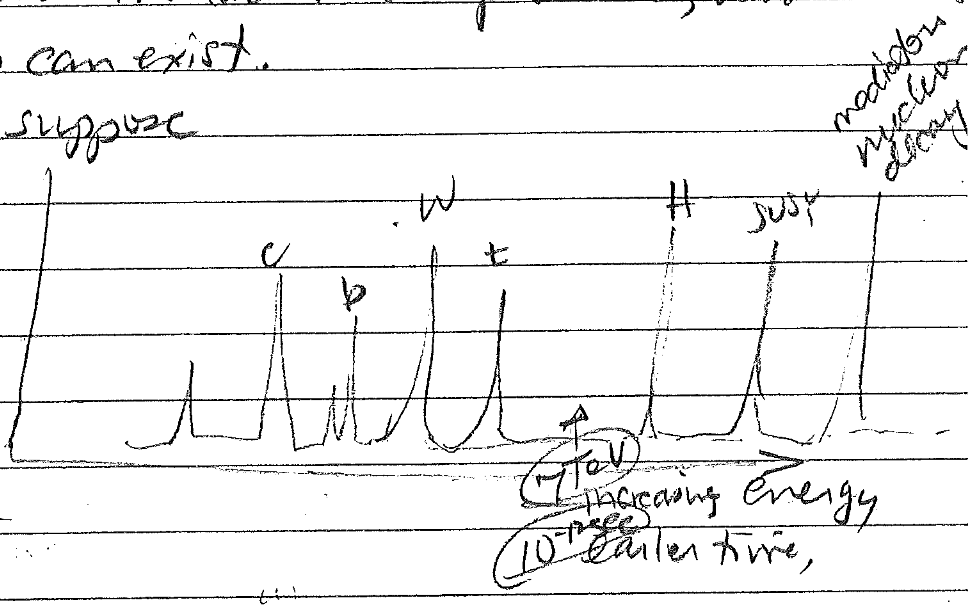
i) proton-proton (LHC, CERN, Geneva)

goal: achieve largest possible c-o-m energy.

Higher energy replicates earlier era of the universe.

See what interaction are possible, what species can exist.

Ex, suppose



at earlier times, universe had higher energy density, production rate of heavy species was higher.

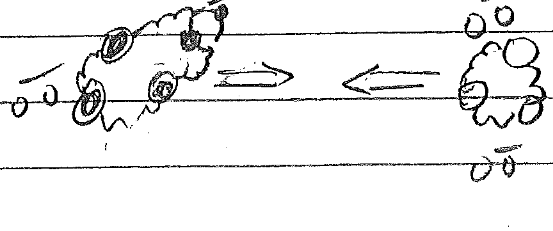
limit now: superconducting magnet technology

ii) proton-antiproton (Tevatron, Fermilab, Chicago)

same as pp, but provides a zero-quantum # initial state.

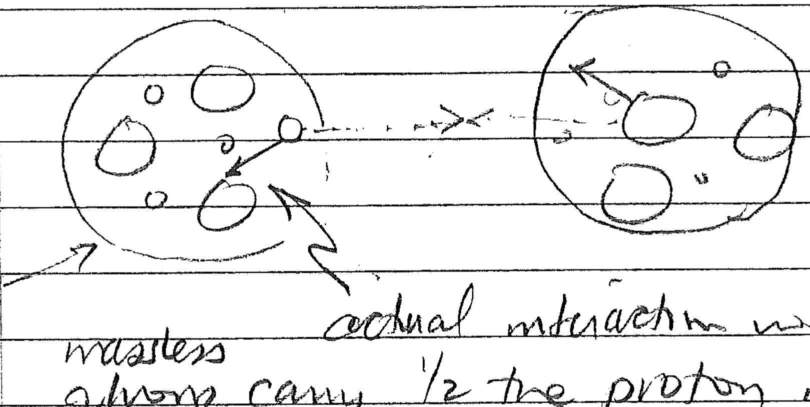
This is how top was discovered

drawback of both: imprecise knowledge of the primary vertex - location, participants, momentum



actual collision is between 2 constituents. (could be valence q, sea q, gluons)

This is not about the size of the bunch. It is about the composition of the proton and the intrinsic momentum of the constituents



proton "bag"

actual interaction would be boosted "left"

massless gluons carry ½ the proton momentum

off axis constituent momentum: "k_T" ← transverse to the beamline

$p = \hbar k$

so $k = \frac{p}{\hbar}$

iii) e^+e^-

goal: produce new states but with precise knowledge of vertex

because e^+, e^- are pointlike.

No currently operating e^+e^- colliders

This is how c, b, W, Z were discovered.

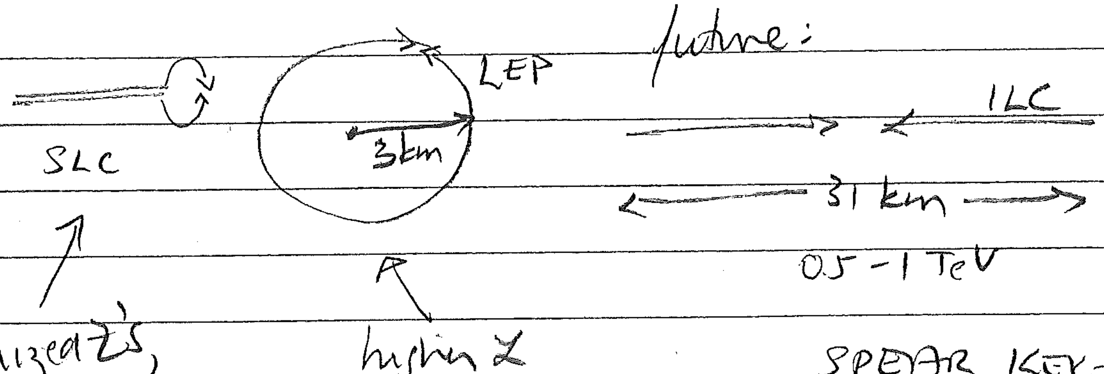
These were rings.

Drawback: Charged particles radiate when accelerated,

Power ~ $\frac{1}{\rho^2}$ and as $\frac{1}{m^4}$ $\left[\text{Note} \left(\frac{m_p}{m_e}\right)^4 \approx 10^{13}\right]$

ρ ← radius of curvature

For cost-effective acceleration need large ring or linear collider



polarized Z's, lower Z because beams are dumped

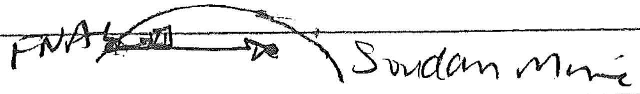
higher Z tunnel now used for LHC

SPEAR, KEK-B, DORIS ...

initially tuned to Z mass, ~80 GeV

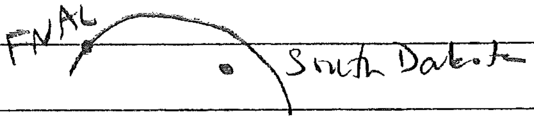
iv) e - p collider
goal: use e^- as a probe of the structure of the p.
Realised as HERA (Hamburg), 1992-2007
30 GeV e, 820 GeV p

v) neutrinos (fixed target, not collider)
Ex# NUMI, neutrinos at the Main Injector, aimed at 2 detectors, one near FNAL, one underground in Minnesota 450 miles distant. Search for evidence of change in beam composition: "neutrino mixing"



Expt is called MINOS, Main Injector Neutrino Osc. Search

Ex#2 LBNE, using target 1000 km distant at proposed DUSEL



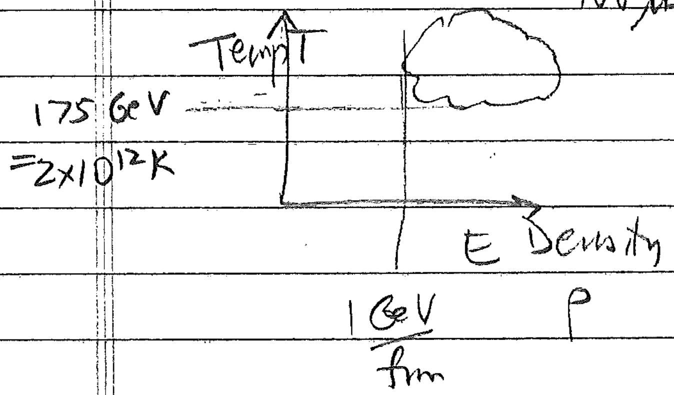
LHC/ALICE BNL/RHIC

vi) relativistic heavy ions (Pb, Au)

goal: temporarily liberate the q and g from the p, to reproduce early universe's "quark gluon plasma."

~100 μs

2nd order phase transition



turns out to be a liquid not a plasma

strongly interacting but almost frictionless

Note RHIC data may be used to explore AdS/CFT correspondence which links (string theory + gravity) in 1 space to a gravity-less QFT in a lower dimension space on the boundary

vii) future: muon collider (FNAL)

goal: high c-o-m like proton collider, but good vertex resolution like e^+e^- collider (μ are pointlike) and lower radiated power

$\left(\frac{m_\mu}{m_e} \sim 200\right)$

III Units

(1) Energy = eV electron Volts, 1.6×10^{-19} J.

(2) Let $c = 1$
" $\hbar = 1$

Then $m = \frac{E}{c^2}$ has units of eV

$\text{time} = \frac{\hbar}{E}$ has units of eV^{-1}

This is reasonable, as the higher the energy of a projectile, the less time it spends participating in an interaction

(3) Note "eV" is inconveniently small for most HEP applications

$m_{proton} = 938 \times 10^6$ eV = 938 MeV $\approx$ 1 GeV

$m_{electron} \simeq$ 0.5 MeV

$m_{up\ quark} \simeq$ 3 MeV

{origin/meaning of these values is not understood}

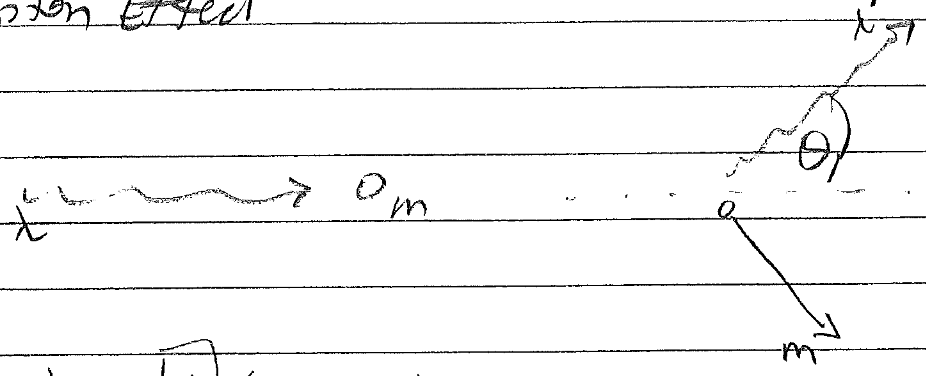
$m_{top\ quark}$ = 174 GeV

E_{LHC} = 7 TeV

$0.04 < m_{\nu} < 0.4$ eV

II. Extracted info from the historical intro
(what you need to know as background)

- electrons exist
- protons "
- neutrons "
  $\alpha = 2p2n$
- photons
  - energy $E = h\nu$. This is natural for a light wave with a frequency ν. Later inverted to predict a freq. ν for any particle with energy E.
  - Note $E \neq E(I)$
    Increase $I \rightarrow$ increase $\#\gamma$'s. Demonstrated w/ photoelectric Effect.
  - Compton Effect



$$\lambda' = \lambda + \boxed{\frac{h}{mc}}(1 - \cos\theta)$$

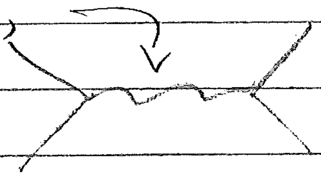
"The Compton wavelength of the targe

Interest: This effect can be predicted with $E, \vec{p}$ conservation only if γ is a particle not a wave.

Thomson scattering predicts same λ for incoming and outgoing γ's

(Prediction for classical wave is Thomson scattering, does not describe Compton effect at low intensity)

Interest: eventually discover that γ is the carrier of EM force, e.g.,



Mediator is not just a mechanical transferer of $\vec{p}$.
Extend concept to mediators of all fundamental forces

- common sense motivation for Strong Force
  - without it, nuclei would disintegrate from proton repulsion
  - What properties must it have? Range ~ nuclear diameter ~ few fermi
- Relationship between force range + carrier mass:

Yukawa predicted that finite range implies massive exchange particle. Why:

Insist on relativity: $E^2 = p^2c^2 + m^2c^4$

" " QM: $E \to i\hbar \frac{\partial}{\partial t}$

$p \to -i\hbar\vec{\nabla}$

$$\downarrow$$

$$-\hbar^2 \frac{\partial^2}{\partial t^2} = -\hbar^2 c^2 \nabla^2 + m^2 c^4$$

x by $\frac{-1}{\hbar^2 c^2}$ $\downarrow$

$$\frac{1}{c^2}\frac{\partial^2}{\partial t^2} = \nabla^2 + \frac{m^2c^2}{\hbar^2}$$

Pakins p.36

Act with this on a wavefunction ψ.
This means: evolve the associated particle in space (∇) and time ($\frac{\partial}{\partial t}$).

$$\frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} = \nabla^2\psi + \frac{m^2c^2\psi}{\hbar^2}$$

The Klein Gordon Eq.
(discovered before the Schroedinger Eq.)

If that particle is the mediator of a force, let $\psi \to U$

If the force is static, $U = U(r, \text{not } t)$

So $\frac{\partial^2 U}{\partial t^2} = 0$

Then we have

$$0 = \frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dU}{dr}\right) + \frac{m^2c^2U}{\hbar^2}$$

Integrate: $U(r) = \frac{g}{4\pi r}e^{-rc/\hbar m}$ g = integ. constant

Note rate of fall off with distance $\sim\frac{1}{m}$

Yukawa noted that the nuclear radius is $\sim 10^{-15}$ m
so predicted $M_{\substack{\text{strong}\\ \text{mediator}}} \sim 100$ MeV.

He was wrong in the case of the strong force
because Klein-Gordon Eq does not include spin
($M_{\text{photon}} = 0$, short range because $U \propto kr$)
but this argument is qualitatively reasonable for the weak force

$$U \sim \frac{1}{r} e^{-x}, \quad M_{\substack{\text{weak}\\ \text{mediators}}} = 80, 91 \text{ GeV}$$

- many new particles discovered in cosmic rays, 1940's-50's

—These turned out to be
(i) bound states of quark-antiquark with masses
$\sim$ 100-500 MeV "medium" mass
$\downarrow$
mes-on $\leftarrow$ Gr. root of "to be"

(ii) bound states of q-q-q
a little heavier : bary-on

Subsequently Once quarks were understood, these combinations were not surprising.
The names are not good as now we know of mesons composed of heavy quarks that are heavier than baryons composed of light quarks.

—also discover muon - misnamed "mu meson" - it is not a meson but like an electron

Pion = π meson = $\boxed{u\bar{d}}$ discovered with photographic emulsion paper (see photo)

(Use microscope to examine $\frac{3000 \text{ traces}}{(3\text{ cm})^2 \text{ photographic plate}} \times 20000$ plates

Names

meson } made of quarks { "hadrons" }
baryon }

quarks interact
via the strong force

They also interact via the EM force (because they have electric charge) and the weak force but the strong interaction is what distinguishes them.

The other family of constituents, "electron-like":

leptons

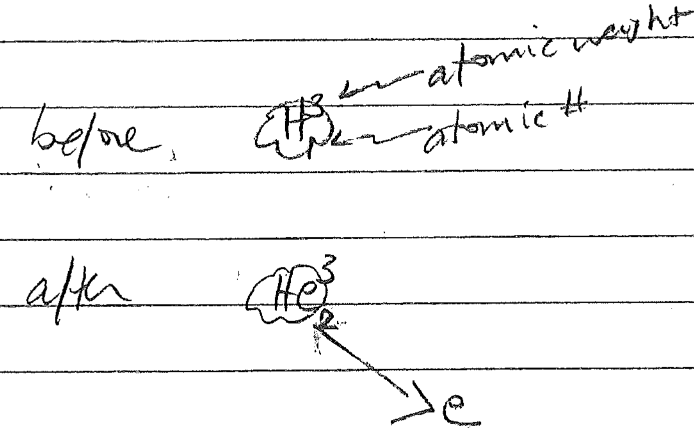
light, not heavy. Also bad choice as there is a member of the family (τ) that is heavy.

Do not interact strongly.

Cosmic rays were also used to discover antimatter (specifically e^+): more on that when we get to the Dirac Eq.

- Indication of the weak force (radioactive decay) and the neutrino (variable energy of β-decay electrons)

Macroscopic view of nuclear decay (say tritium):



If these are the only 2 final state particles, then the measured energy of the e must be constant if energy is conserved

$E_{before} = E_{after}$ It never hurts to make a relativistic calculation. At most it is overkill.

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

$$m_H = \sqrt{m_{He}^2 + p_{He}^2} + E_e$$

In c-om, for 2 body decay, $p_e = p_{He}$

$$m_H = \sqrt{m_{He}^2 + p_e^2} + E_e$$

$$m_H = \sqrt{m_{He}^2 + (E_e^2 - m_e^2)} + E_e$$

$$(m_H - E_e)^2 = m_{He}^2 + E_e^2 - m_e^2$$

$$m_H^2 - 2m_H E_e + \cancel{E_e^2} = m_{He}^2 + \cancel{E_e^2} - m_e^2$$

$$E_e = (m_H^2 - m_{He}^2 + m_e^2)/2m_H$$