Phys 330 Spring 2020

lecture #18 Particles II

historical development -

- Rutherford 1911 nucleus with virtually entire atomic mass and charge +Z inside nucleus roughly 0.1nm/1fm = 1/10^7 atomic diameter
- Moseley 1913 atomic Z using X-rays
- Chadwick 1928 discovery of neutron photo-disintegration of deuteron

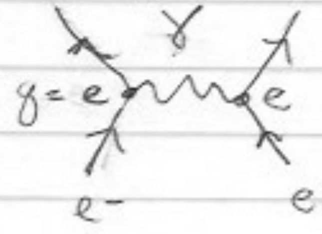
$$^2_1D + \gamma(2.6\,\text{MeV}) \rightarrow {}^1_1H + n$$

Particles are e^-, p, n as of 1928

- Yukawa 1935 nuclear force

in quantum electrodynamics, Coulomb potential results from exchange of massless photon. In modern Feynman diagramatic formalism. (represents a mathematical amplitude)

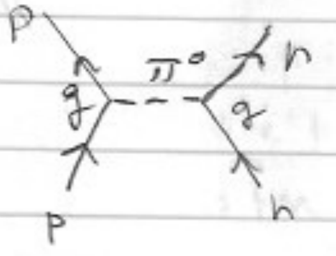
amplitude =



$\propto e^2$

$$V(r) = \frac{\alpha\hbar c}{r} \propto e^2$$

exchange of massive pion (π) gives rise to short distance potential



$$\Rightarrow V = \frac{g^2}{r} e^{-r/r_0}$$

where distance r_0 can be thought of as arising from uncertainty principle

Virtual π "violates" E conservation for time $\Delta t = r_0/c$ $\quad \Delta E = m_\pi c^2$

$$\Delta E \Delta T \sim \hbar/2$$

$$m_\pi c^2 \left(\frac{r_0}{c}\right) = \hbar/2 \quad r_0 = \frac{\hbar c}{2 m_\pi c^2}$$

$\hbar c \cong 200$ eV·nm $= 200$ meV·fm (conveniently)

so $r_0 \sim 1$ fm gives $m_\pi c^2 = \frac{200 \text{ meV·fm}}{2\cdot(1 \text{ fm})} = 100$ meV

predicts new massive particle we call π

3 types π^+, π^0, π^-

π^- should interact in matter by being trapped in atomic orbit, $r = a_0 \left(\frac{m_e}{m_\pi}\right) = a_0/200$ and get absorbed by nucleus.

π^+ would stop in material and decay.

Cosmic Rays - nature's accelerator

high energy protons, Fermi accelerated in galactic magnetic fields strike upper atmosphere and produce "showers" of particles

particle	discovered by	year
e^+	Anderson	1932
$\mu^\pm$	Anderson	1936 looking for π $\tau_\mu \approx 2\mu s$, $m_\mu = 106$ meV
$\pi^\pm$	Anderson, Neddermeyer Street, Stevenson	1937

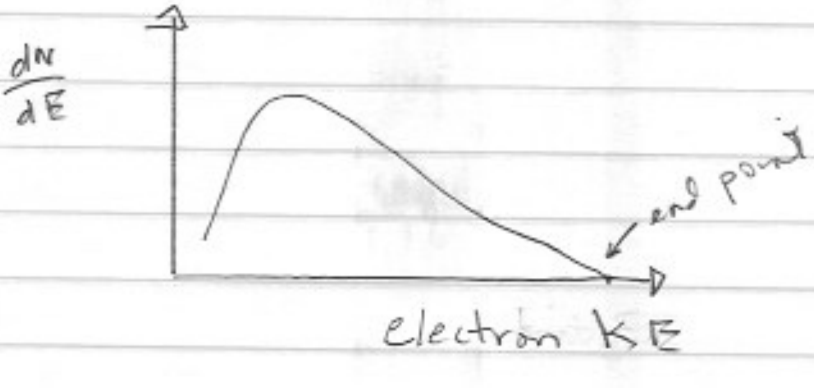
$$\pi^+ \to \mu^+ + \nu_\mu \qquad \tau_{\pi^\pm} = 26 \text{ ns}$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu \qquad m_\pi \cong 140 \text{ meV}$$

neutrino proposed by Pauli (1930) to explain β-decay spectrum

$$^{Z}_{A}N \to \underbrace{^{Z+1}_{A}N + e^-}_{} + \nu$$

2 body decay would give e^- definite p, E from nuclear mass difference

Sketch of β- decay spectrum



ν takes no kinetic energy

neutral π^0 decays electromagnetically

$\pi^0 \to \gamma\gamma \qquad \tau_{\pi^0} \sim 10^{-16}\,s$

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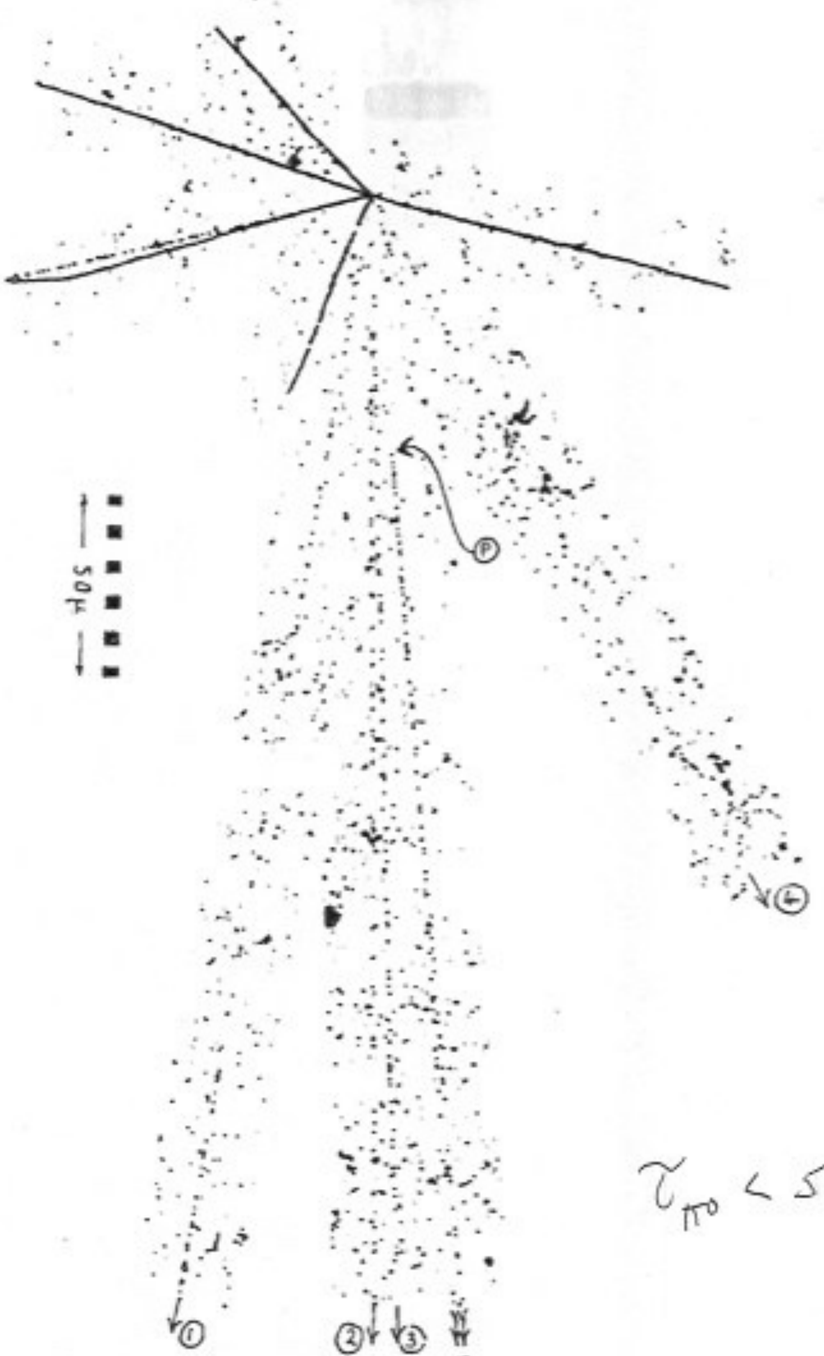
from Cahn and Goldhaber
Experimental Foundations of Particle Physics



$\tau_{\pi^0} < 5\times10^{-14}$ s

Figure 2.3. An emulsion event showing an e^+e^- pair created by conversion of a photon from π^0 decay. The conversion occurs at the point marked P. (Ref. 2.7)

Accelerators   cyclotron E.O. Lawrence circa 1930

Syncrotron - increase field β to keep beam at fixed radius (r)
at high energy $v = c$

$$p = m\gamma c = eBr$$

recall antiproton $\bar{p}$ discovered by Chamberlain and Segrè 1955 at Bevatron

Resonances

$\pi^+ p \to \pi^+ p$ elastic
$\pi^- p \to \pi^0 n$ charge exchange
$\pi^- p \to \pi^- p$ elastic

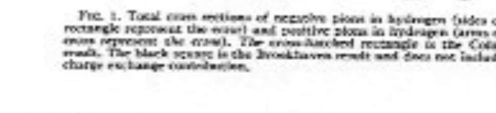


FIG. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

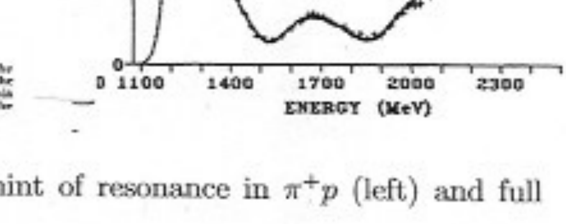


Figure 3: $\pi^{\pm}p$ elastic scattering hint of resonance in π^+p (left) and full $\Delta(1232)$ resonance (right)

Breit-Wigner resonance

$$\sigma(E) = \sigma_{max} \frac{\Gamma^2/4}{(E-m)^2+\Gamma^2/4}$$

m = mass of resonance

Γ = FWHM   lifetime $\tau = \hbar/\Gamma$

$m_\Delta c^2 = 1232$ mev

$\Gamma_\Delta = 115$ mev $c\tau = \frac{200 \text{ mev}\cdot\text{fm}}{115 \text{ mev}} = 1.7 \text{ fm}$

$$\tau = \frac{1.7\times10^{-15} \text{ m}}{3\times10^{8} \text{ m/s}} = 5.7\times10^{-24} \text{ s}$$

typical of strong decay :

$\Delta^{++} \rightarrow \pi^+ p$

$\Delta^{+} \rightarrow n\pi^+, p\pi^0$

$\Delta^{0} \rightarrow p\pi^-, n\pi^0$

$\Delta^{-} \rightarrow n\pi^-$

there is no Δ^{--} !

typical weak decay lifetime

$\mu^\mp \rightarrow e^\mp \nu_e \nu_\mu$ $c\tau = 659$ m

$\tau = 2.2\times10^{-6}$ s

$\pi^\mp \rightarrow \mu^\mp \nu_\mu$ $c\tau = 7.8$ m

$\tau = 2.6\times10^{-8}$ s

Baryons & Mesons a zoo of strongly interacting particles

Baryons - spin $\frac{1}{2}, \frac{3}{2}, \ldots$ Fermions

mesons - spin $0, 1, \ldots$ Bosons

Rule - Baryons are assigned an additive quantum number +1 baryons and -1 for anti baryons such that in a reaction baryon number B is conserved.

mesons (like photons) have no such conservation law. They have B = 0

$$p + p \rightarrow p + p + p + \bar{p}$$

$B \quad 1 + 1 = 1 + 1 + 1 - 1$

$Q \quad 1 + 1 = 1 + 1 + 1 - 1$

$$p + p \rightarrow n + p + p + \bar{p} + \pi^+$$

$B \quad 1 + 1 = 1 + 1 + 1 - 1 + 0$

$Q \quad 1 + 1 = 0 + 1 + 1 - 1 + 1$

B, Q are both conserved, additive Q.N.

lightest Baryon (p) is absolutely stable

$$p \not\rightarrow e^+ + \pi^0 \qquad \tau > 1.6 \times 10^{34}\, y$$

<u>lepton number</u> - additive quantum number

sign is convention

e^-	$L_e = +1$	μ^-	$L_\mu = +1$
e^+	$L_e = -1$	μ^+	$L_\mu = -1$
ν_e	$L_e = +1$	ν_μ	$L_\mu = +1$
$\bar{\nu}_e$	$L_e = -1$	$\bar{\nu}_\mu$	$L_\mu = -1$

muon decay:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$L_e \quad 0 = 1 - 1 + 0$

$L_\mu \quad 1 = 0 + 0 + 1$

$Q \quad -1 = -1 + 0 + 0$

pion decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$L_\mu \quad 0 = -1 + 1$

$Q \quad 1 = 1 + 0$

Isospin

strong force identical for p, n
Make this symmetry explicit by introducing (analogous to spin-angular momentum) isospin. nucleon n is an isospin doublet

p $I = \frac{1}{2}, I_z = \frac{1}{2}$
n $I = \frac{1}{2}, I_z = -\frac{1}{2}$

Pion is $I = 1$

(I, I_z)
$\pi^+ = (1, +1)$
$\pi^0 = (1, 0)$
$\pi^- = (1, -1)$

Δ is $I = 3/2$

$\Delta^{++} = (3/2, +3/2)$
$\Delta^{+} = (3/2, +1/2)$
$\Delta^{0} = (3/2, -1/2)$
$\Delta^{-} = (3/2, -3/2)$

<u>Puzzle</u> Deuteron pn exists
dineutron nn doesn't

deuteron is weakly bound (2.6 MeV binding)

$\psi = \psi(\text{space})\,\psi(\text{spin})\,\psi(\text{isospin})$
must be anti-symmetric

because deuteron is weakly bound,
only ground state ($l=0$, symmetric exists)

for spin or isospin

$$\tfrac{1}{2} \otimes \tfrac{1}{2} = 0 \oplus 1$$

antisymmetric, symmetric

isospin antisymmetric
$\psi(pn) = (pn - np)/\sqrt{2}$ deuteron

must have spin 1 (symmetric)

isospin symmetric

pp ← unbound due to Coulomb force
$(pn + np)\frac{1}{\sqrt{2}}$
nn

must have spin = 0 antisymmetric

<u>Solution</u>: strong force is <u>spin dependent</u>
↑↑ stronger than ↑↓

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Strangeness

$K^+ \to \pi^+ \pi^+ \pi^-$ $\quad m_{K^\pm} = 493.7$ mev
$\tau = 1.2 \times 10^{-8}$ s

$\Lambda \to p\ \pi^-$ $\quad m_n = 1115.7$ meV
$\quad\to n\ \pi^0$ $\quad \tau = 2.6 \times 10^{-10}$ s

$Q=0 \quad B=1 \quad$ spin ½

Strongly produced in pairs, weakly decaying. S additive QN

$\pi^- + p \to K^0 + \Lambda$
S $\quad 0 + 0 = 1 - 1$
$\pi^- + p \not\to K^0 + n$
S $\quad 0 + 0 \neq 1 + 0$

Gell-mann Nishijima equation

$$Q = I_z + \frac{(B+S)}{2}$$

<u>Quarks</u> : u up — three flavors
d down
s strange

quark	Q	I_z	B	S	$I_z + \frac{B+S}{2}$
u	$+2/3$	$1/2$	$1/3$	0	$+2/3$
d	$-1/3$	$-1/2$	$1/3$	0	$-1/3$
s	$-1/3$	0	$1/3$	-1	$-1/3$

<u>fractionally charged!</u> no fractionally charged particles ever found!

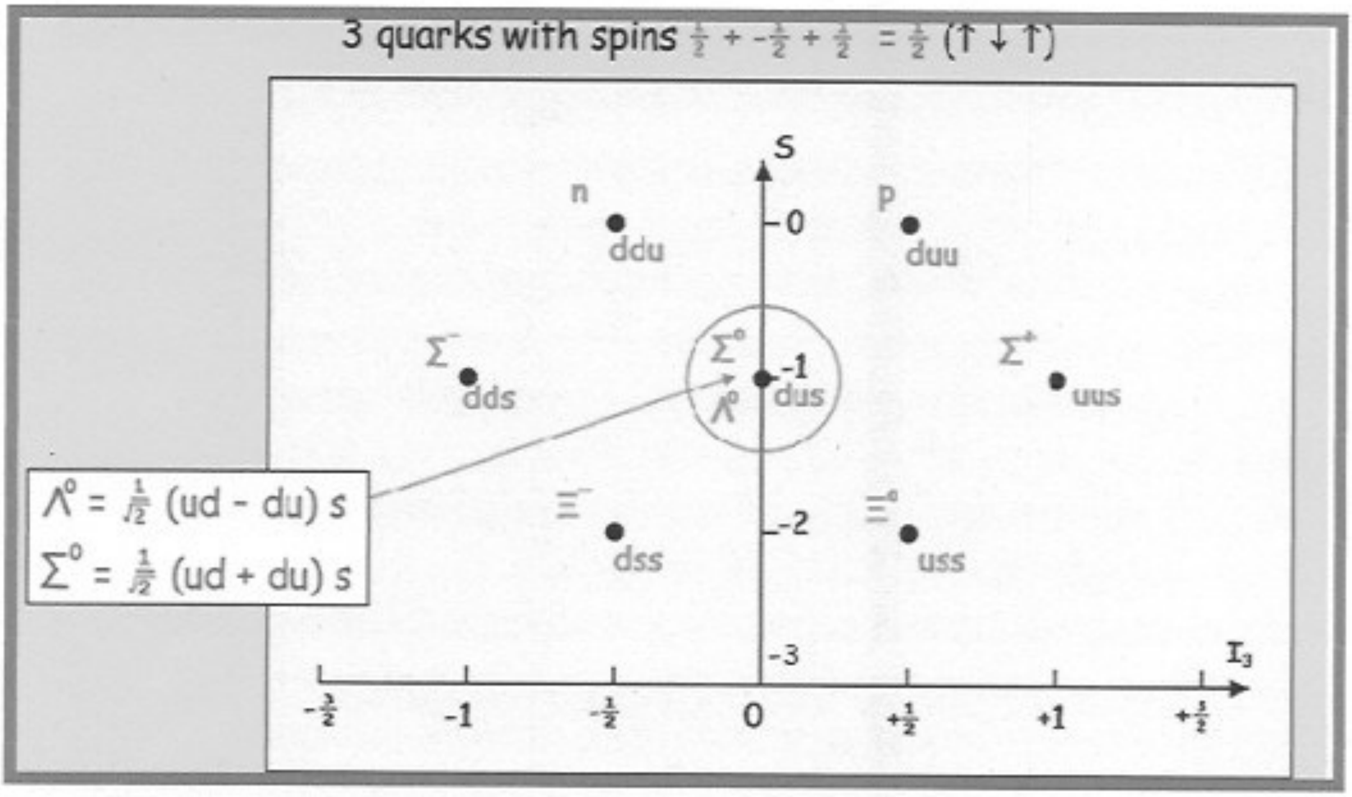
flavor symmetry is $SU(3)$
more complicated group.

2 octets have different antisymmetrization

$$\underset{\sim}{3} \otimes \underset{\sim}{3} \otimes \underset{\sim}{3} = \underset{\sim}{1} \oplus \underset{\sim}{8} \oplus \underset{\sim}{8} \oplus \underset{\sim}{10}$$

Baryon Octet

Spin $\frac{1}{2}$ Baryons



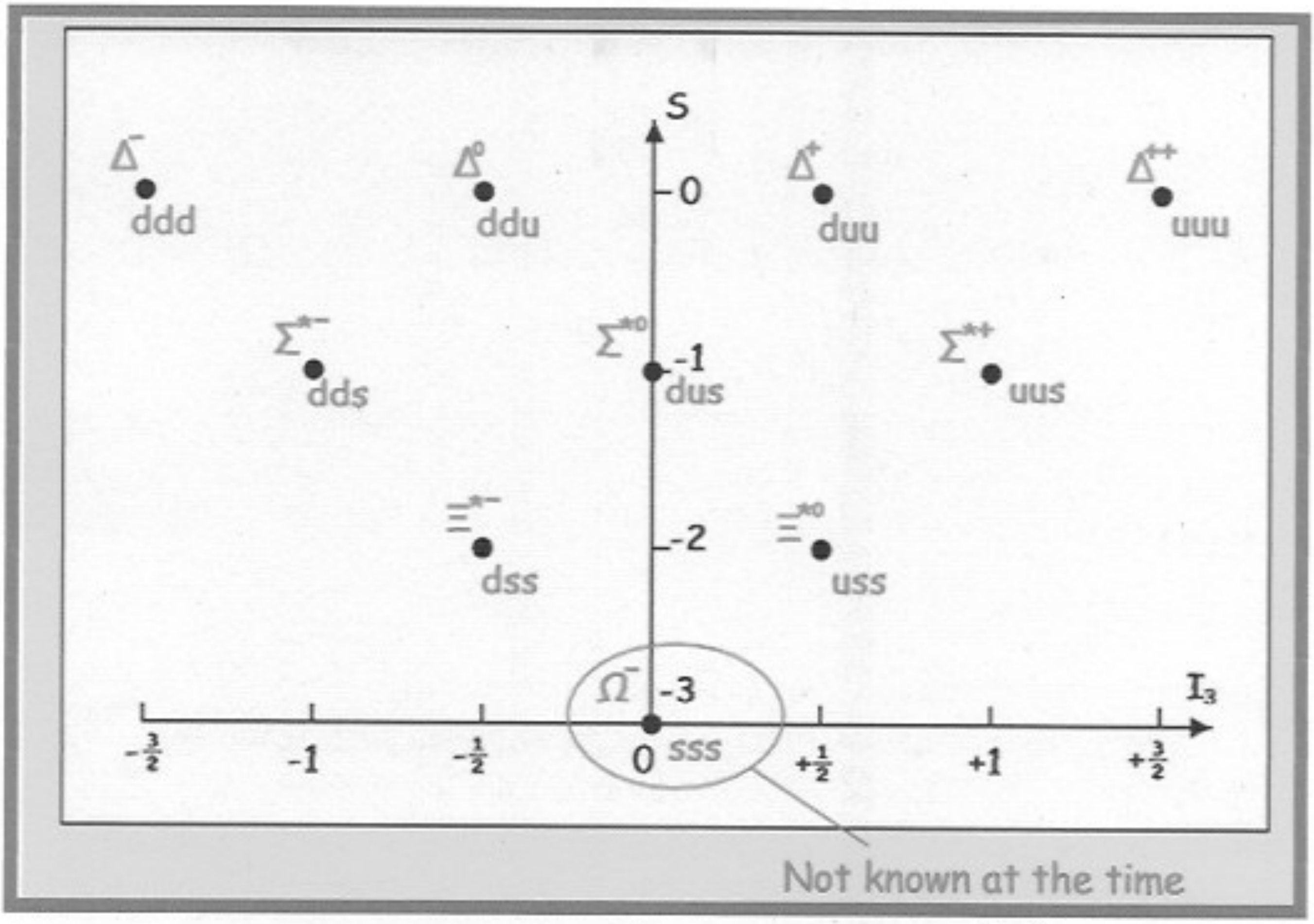
3 quarks with spins $\frac{1}{2} + -\frac{1}{2} + \frac{1}{2} = \frac{1}{2}$ (↑ ↓ ↑)

$\Lambda^0 = \frac{1}{\sqrt{2}}(ud - du)s$

$\Sigma^0 = \frac{1}{\sqrt{2}}(ud + du)s$

Baryon Decuplet

Spin $\frac{3}{2}$ Baryons



Gell-Mann, 1961

$\psi_{\Omega^-} = \psi_{space}\,\psi_{spin}\,\psi_{isospin}$

ψ_{space} = symmetric lowest lying

ψ_{spin} = symmetric ↑↑↑

$\psi_{isospin}$ symmetric sss

Invent new Q.N.

Color r b g

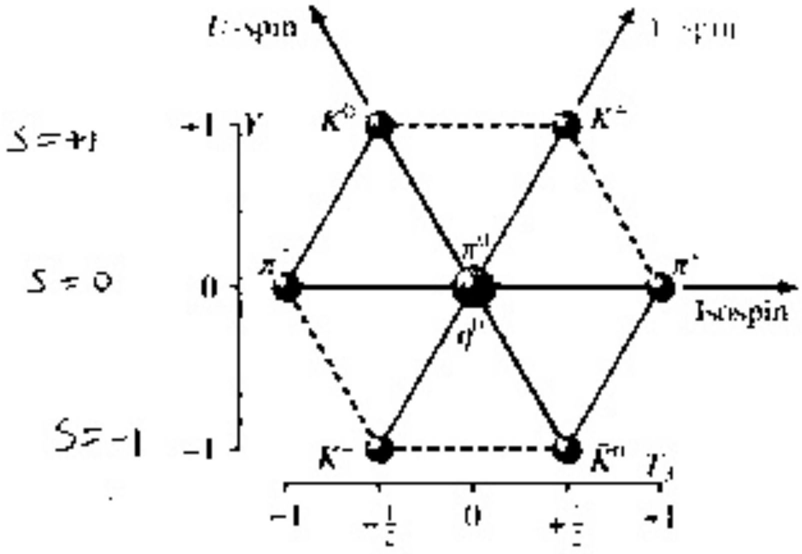
Color antisymmetric

$(s{\uparrow}r)(s{\uparrow}b)(s{\uparrow}g)$

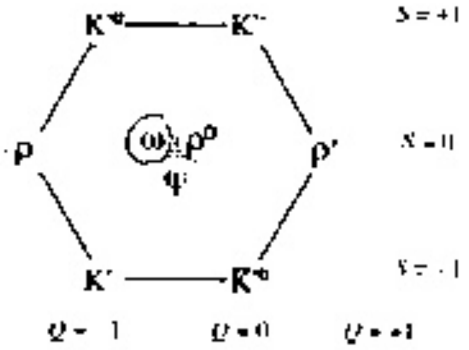
mesons are quark-antiquars.

SU(3) decomposition into irreducible representatoi

$$\underset{\sim}{3}\otimes\underset{\sim}{\bar{3}} = \overset{\text{one}}{\underset{\sim}{1}}\oplus\overset{\text{eight}}{\underset{\sim}{8}}$$



spin 0 mesons



Spin 1 mesons

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discovery of Ω^-

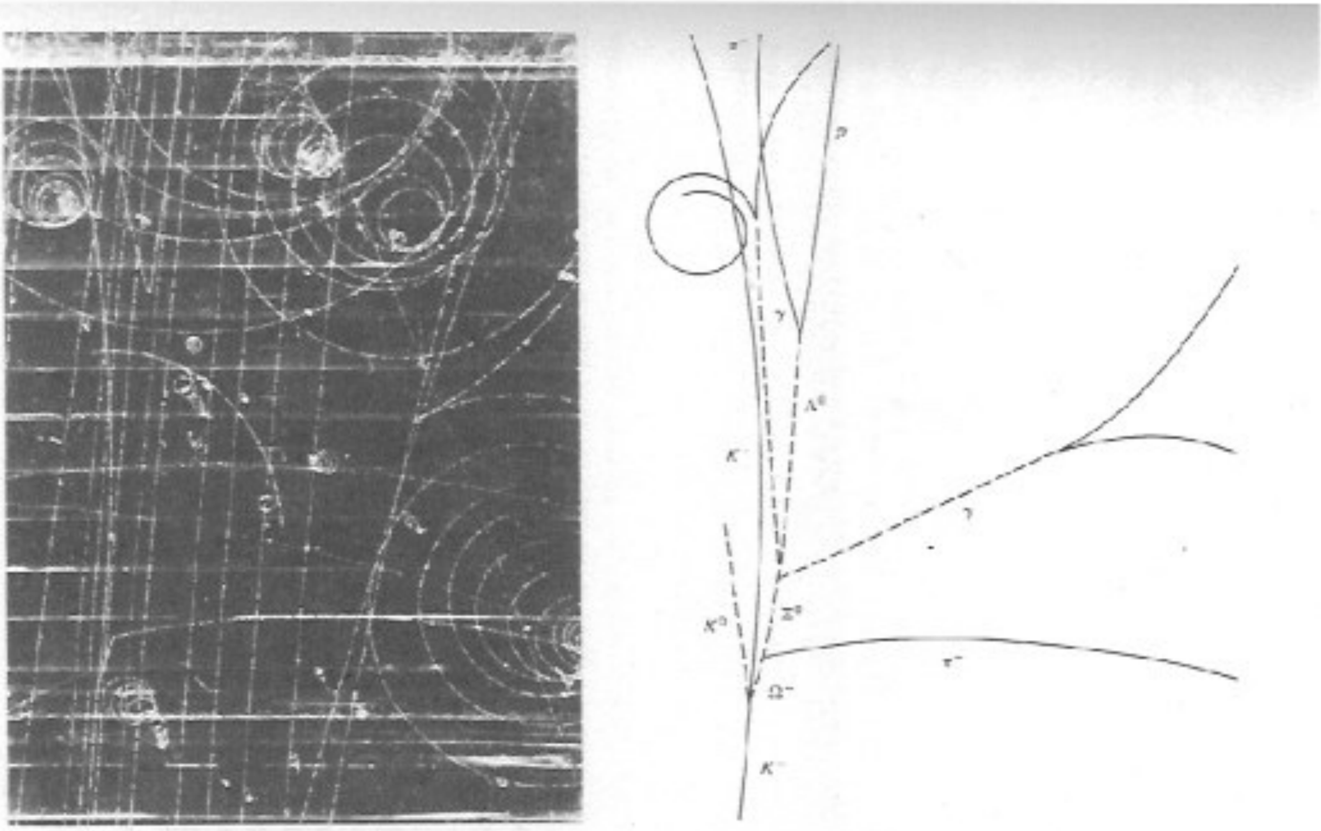
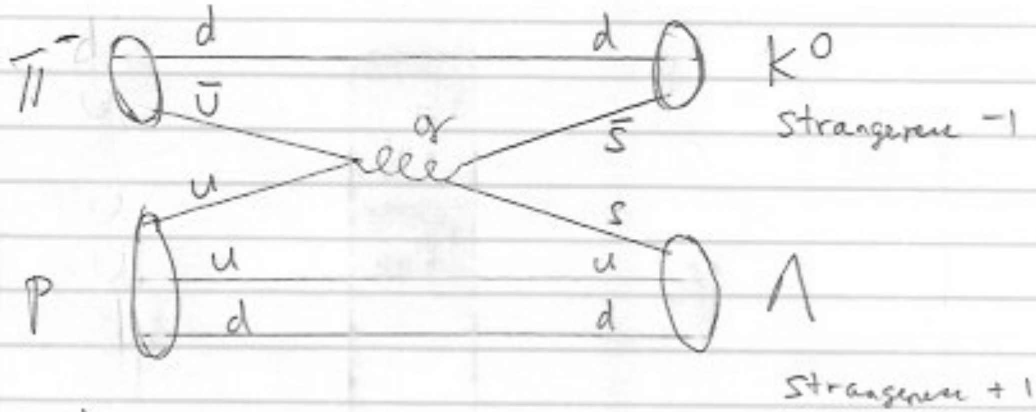


Figure 1.10 The discovery of the Ω^-. The actual bubble chamber photograph is shown on the left; a line diagram of the relevant tracks on the right. (Photo courtesy Brookhaven National Laboratory.)

discovered 1964

18-16 a

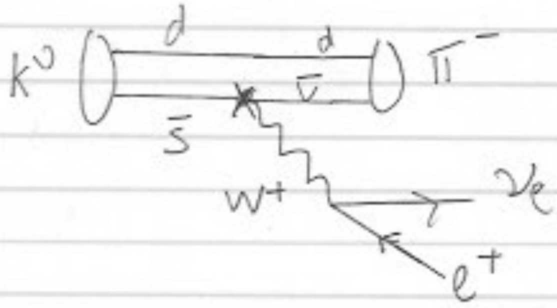
$$\pi^- + p \to K^0 + \Lambda$$



strong production

A Weak decay mode

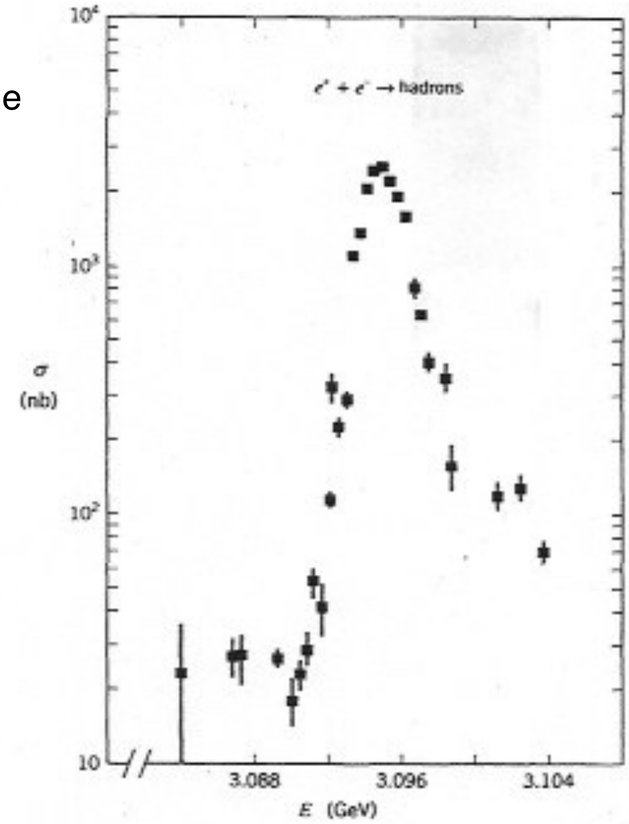
$$K^0 \to \pi^- e^+ \nu_e$$



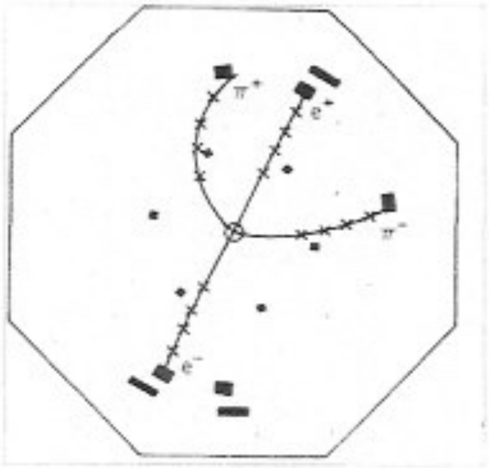
Weak interaction ($W^\pm$) changes quark flavor

Suprise discovery - <u>charm</u>, a new flavor

note log scale

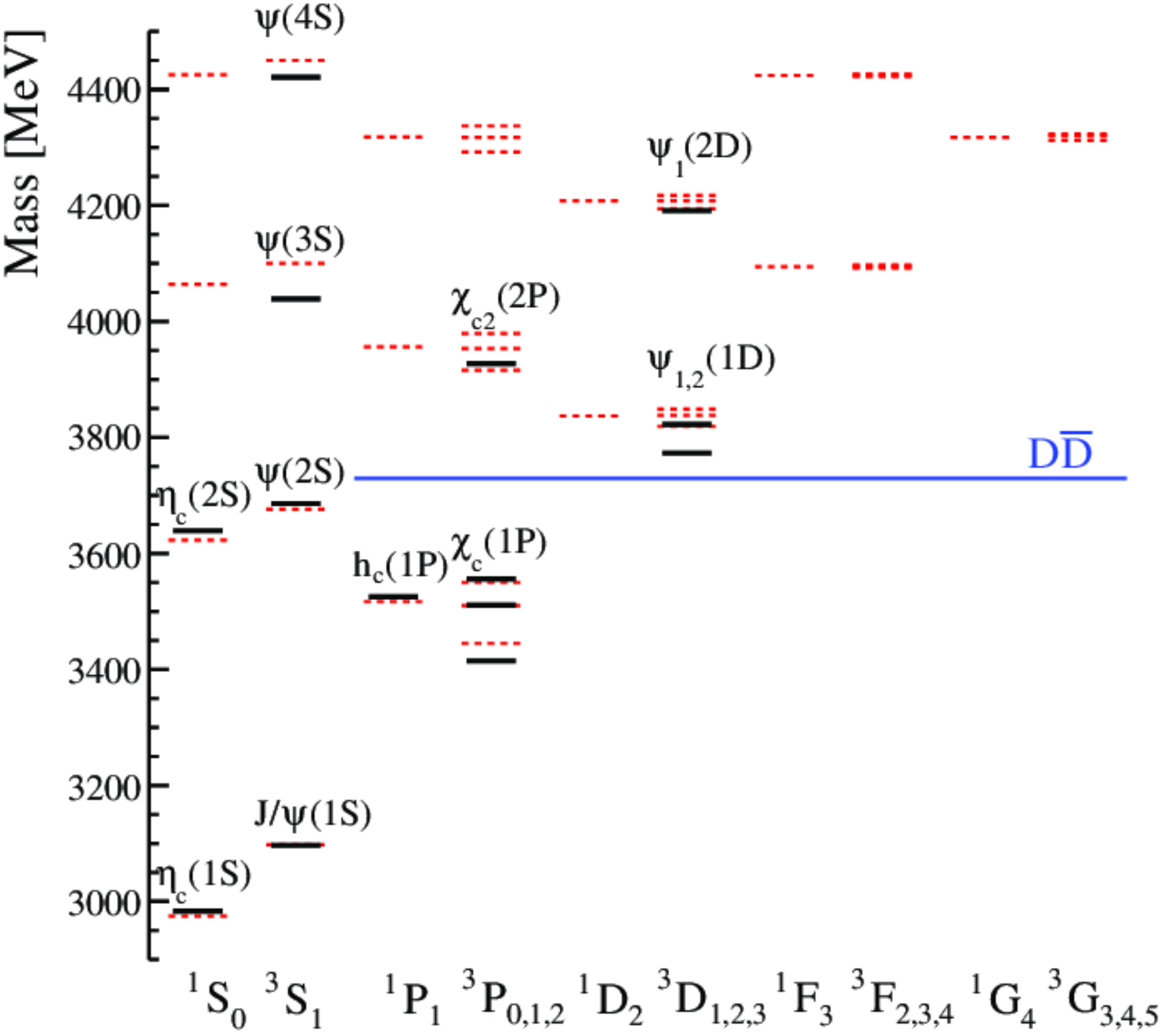


$e^+e^- \rightarrow (c\bar{c}) \rightarrow$ hadrons



$$e^+e^- \rightarrow \psi' \rightarrow \pi^+\pi^-\psi$$
$$\hookrightarrow e^+e^-$$

ψ' - excitation of $c\bar{c}$ bound state



Mass [MeV]
4400
4200
4000
3800
3600
3400
3200
3000
ψ(4S)
ψ(3S)
ψ(2S)
J/ψ(1S)
η_c(2S)
η_c(1S)
h_c(1P)
χ_c(1P)
χ_c2(2P)
ψ_1(2D)
ψ_1,2(1D)
DD̄
¹S₀
³S₁
¹P₁
³P₀,₁,₂
¹D₂
³D₁,₂,₃
¹F₃
³F₂,₃,₄
¹G₄
³G₃,₄,₅

Strong hypercharge $Y = (B+F)/2$

F flavor QN generalizes strangeness

$Q = I_3 + Y$

flavor	Q	B	I_3	F	mass (mev)
u	$2/3$	$1/3$	$1/2$	0	~2
d	$-1/3$	$1/3$	$-1/2$	0	~4.5
c	$2/3$	$1/3$	0	1	1270
s	$-1/3$	$1/3$	0	-1	93
t	$2/3$	$1/3$	0	1	173,000
b	$-1/3$	$1/3$	0	-1	4180

3 families. Why?

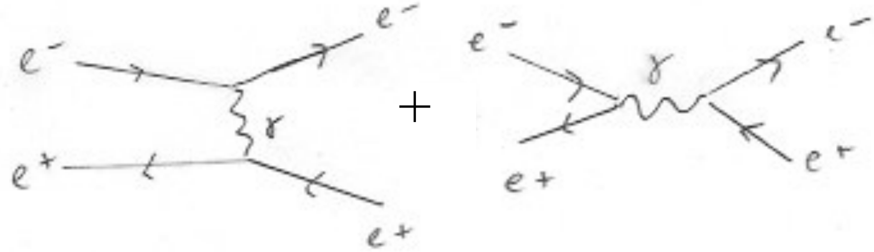
Flavor symmetry: approximate equality of masses plus all quarks have same strong charge.

works well for u, d, s

works OK for u, d, s, c

Electron-positron scattering and R ratio

Bhabha scattering $e^+e^- \to e^+e^-$

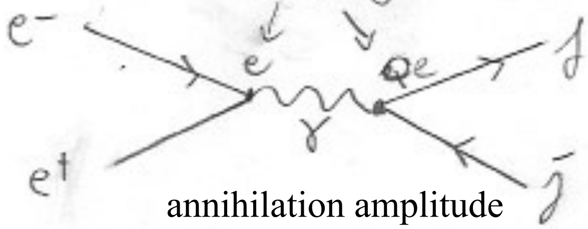


exchange + annihilation amplitude

$e^+e^- \to f\bar{f}$ fermion not e^-

coupling to photon (charge) at vertices

$A_{f\bar{f}} =$



$\propto e^2 Q$

annihilation amplitude

$$\sigma \propto |A_{f\bar{f}}|^2 \propto e^4 Q^2$$

$$R = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3 \sum Q_i^2$$

↑ color

flavors that can be produced at collision energy

$e^+e^- \to$ hadrons

Color string fragments into colorless hadrons

later b bottom quark
much later t top quark

top is <u>very</u> heavy decays before bound state can form

masses (MeV)

u	~2	c	1270	t	173,000
d	~4.5	s	~93	b	4180

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

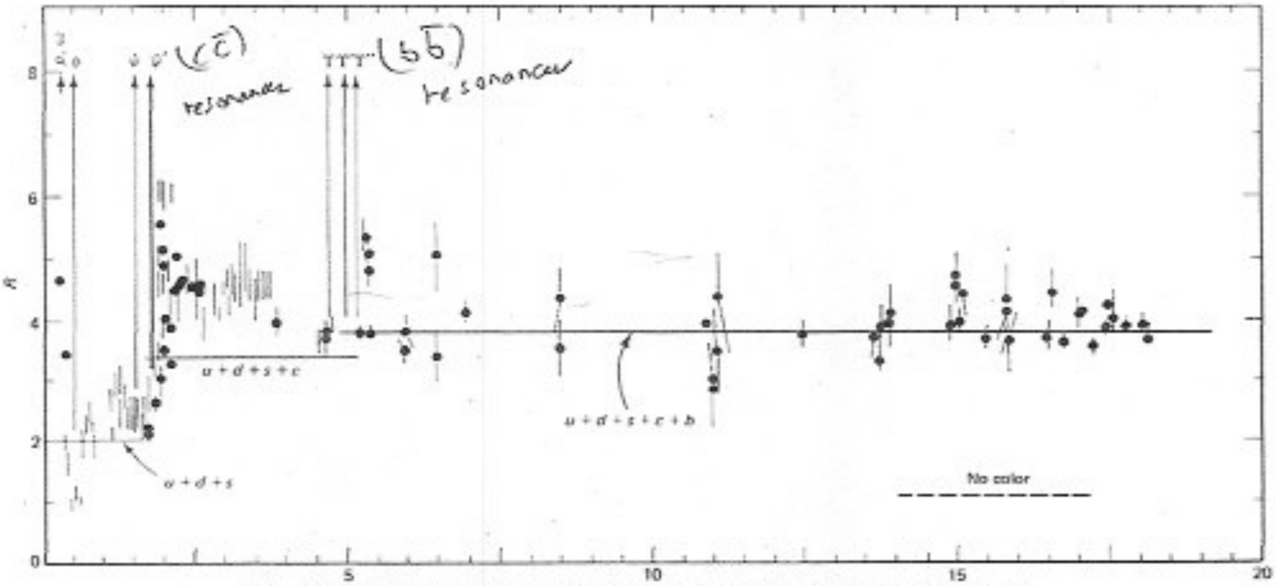


Figure 8.3 *R* is plotted against electron energy (in GeV). (*Source:* F. Halzen and A. D. Martin, *Quarks and Leptons* (New York: Wiley, copyright © 1984, p. 229. Reprinted by permission of John Wiley & Sons, Inc.)

$$R = \underset{\substack{\uparrow \\ \text{Color}}}{3} \times \underset{\text{quarks}}{\sum} Q_i^2 = \begin{cases} 2 & u, d, s \\ 2 + \frac{4}{3} & u, d, s, c \\ 2 + 5/3 & u, d, s, c, b \end{cases}$$

The new quantum number color introduced to satisfy Ferm statistics is a new type of interaction charge.

Color and Quantum Chromodynamics (QCD)

analogous to QED electric charge ±e

QCD color charges $r \ b \ g$ color

$\bar{r} \ \bar{b} \ \bar{g}$ anti-color

QED U(1) gauge symmetry

$A^\mu = (\phi, \vec{A})$ scalar potential ϕ

vector potential A

related to fields as

$$\vec{E} = -\vec{\nabla}\phi - \frac{\partial \vec{A}}{\partial t} \ ; \quad \vec{B} = \vec{\nabla} \times \vec{A}$$

local gauge invariance - local phase change

$$\psi(x^\mu) \rightarrow e^{-ie\lambda(x^\mu)} \psi(x^\mu)$$

$\lambda(x^\mu)$ arbitrary phase at each space-time point x^μ

U(1) implies single, charge = 0, photon

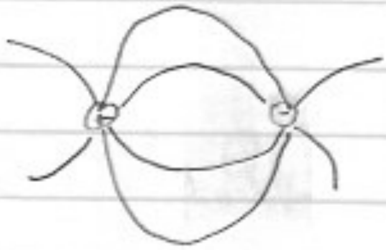
QCD

$$\psi(x^\mu) \rightarrow e^{-ig\sum_{i=1}^{8} \lambda_i(x^\mu)\hat{T}_i} \psi(x^\mu)$$

SU(3) has $3^2 - 1 = 8$ generators

8 colored gluons

QED versus QCD



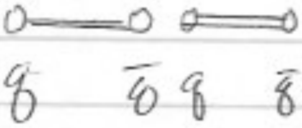
electric field lines "repel"

QCD because gluons have color, color field lines attract

Pion:

flux string tension ~Mev/fm

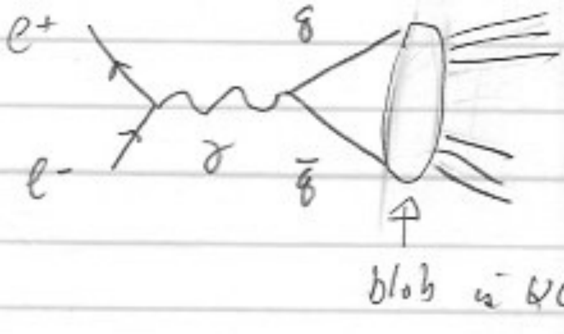
stretching $q\bar{q}$ breaks string, producing pion pair



no free quarks! QCD gives quark confinement
no observed fractional charge!

Due to confinement, strong force is short ranged even though gluon is massless.

quarks appear as "jets" of hadrons by fragmentation process



jets correlated w/ quark momentum

blob is QCD interaction

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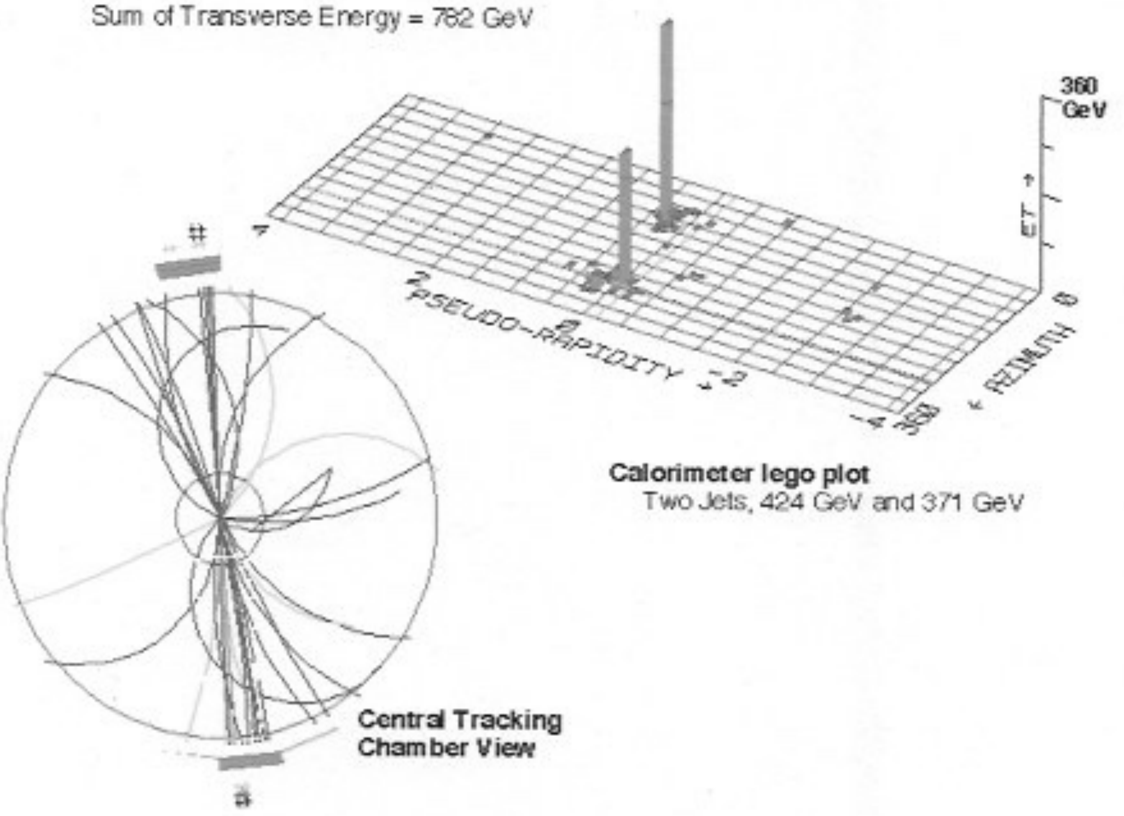
A 2 jet event

CDF: Highest Transverse Energy Event from the 1988-89 Collider Run

Sum of Transverse Energy = 782 GeV



Calorimeter lego plot
Two Jets, 424 GeV and 371 GeV

Central Tracking Chamber View

18.23

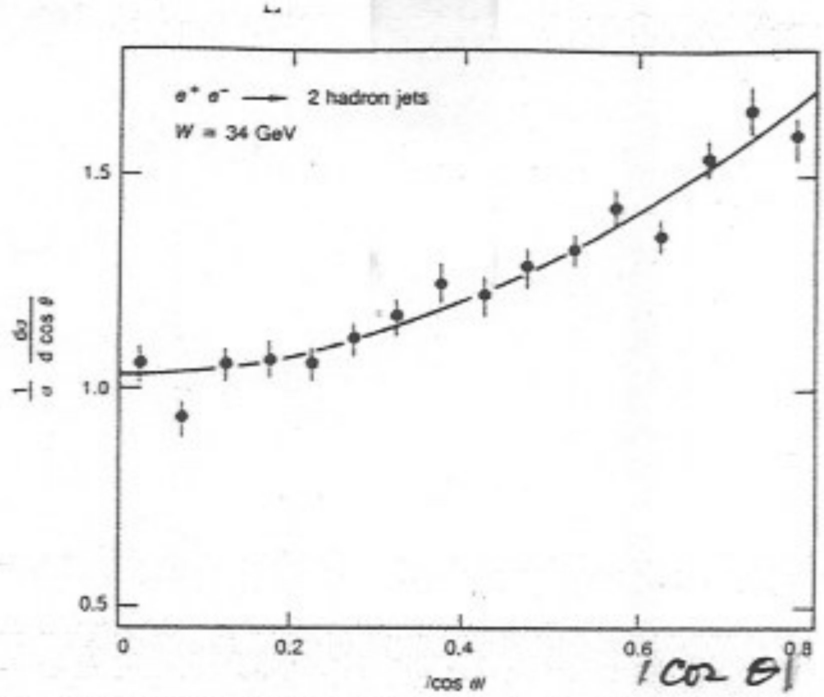
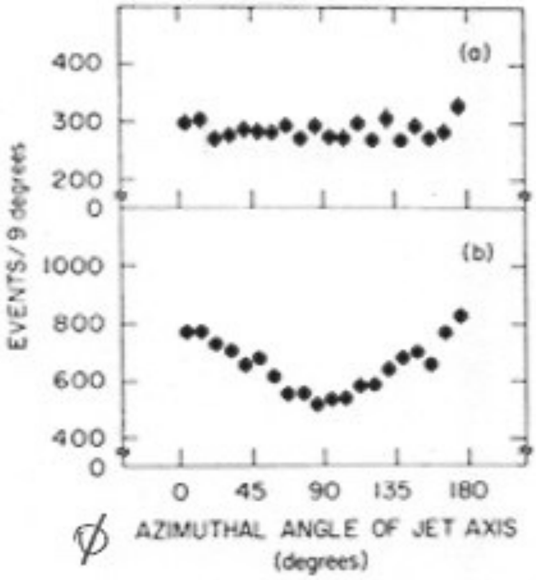


Figure 8.14 Center-of-mass angular distribution of the two hadron jets (as in Fig. 2.23) relative to the beam axis in e^+e^- annihilation at high energy. It is consistent with a $(1 - \cos^2\theta)$ distribution, as expected if the fundamental process is $e^+e^- \to Q\bar{Q}$.

Expected angular distribution for point-like, spin-1/2 fermions of charge Qe in $e^+e^- \to f\bar{f}$ in the CM (lab) frame is given by $\frac{d\sigma}{d\Omega} = \frac{Q^2(\alpha\hbar c)^2}{4E_{cm}^2}[1+\cos^2(\theta)]$. The distribution of the Jet axis shows the underlying quarks are spin-1/2

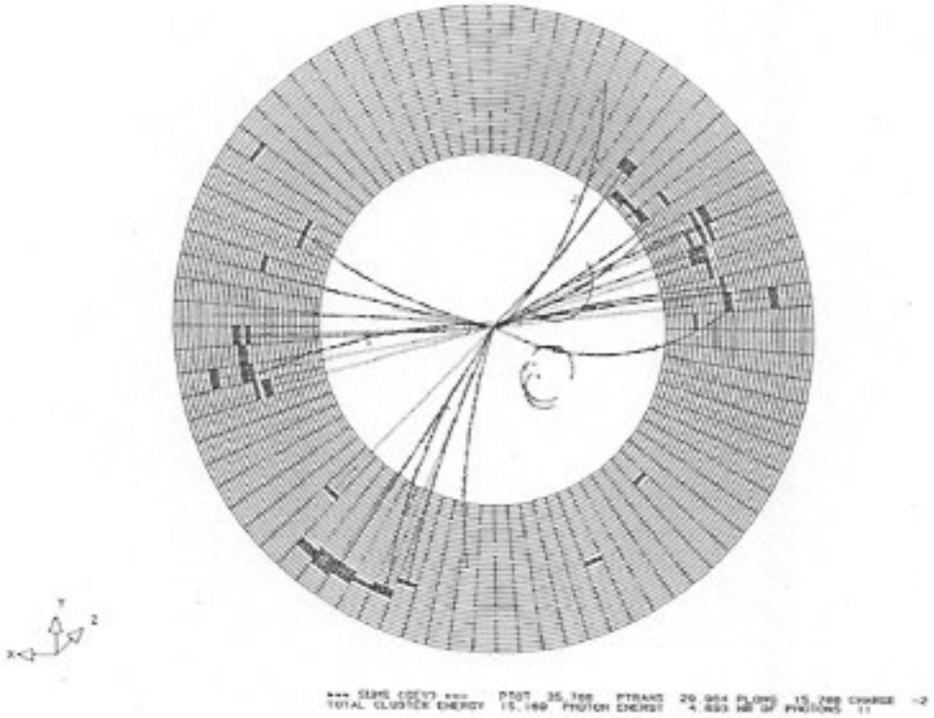
18-24



With e^+e^- beams polarized transverse the circulating beams, the cross section shows a ϕ depedance predicted for spin-1/2 quarks (polarization P): $\frac{d\sigma}{d\Omega} = \frac{Q^2(\alpha\hbar c)^2}{4E_{cm}^2}[1+\cos^2(\theta)+P^2\sin^2(\theta)\cos(2\phi)]$

↑
azimuthal

18-25



The gluon is observed as a <u>third jet</u> in e^+e^- by the JADE detector.

gluon