8.811 Lecture 1

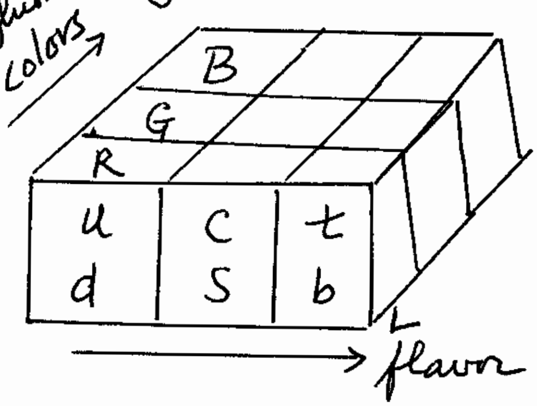
Building blocks & their interactions

Carrier of forces

→ W with coupling g_2

$Q = \frac{2}{3}$

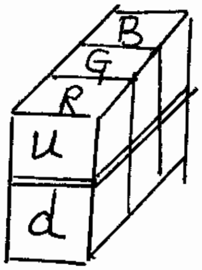
$-\frac{1}{3}$



$S = \frac{1}{2}$ fermions

$B = \frac{1}{3}$, $L = 0$

$\uparrow I_3$



carrier of force B with coupling g_1

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \quad \begin{matrix} Q = 0 \\ = 1 \end{matrix} \quad B = 0, \; L = 1 \quad \begin{matrix} \nu \\ e^- \end{matrix}$$

∴ Q is not diagonized

Also $M_{W^0} \neq M_Z$ & $g_2 \neq g_{Z^0}$

∴ Z^0 is not W^0, γ is not B,

g_1 interaction is not QED

Need a Quantum # independent of isospin family

Thus take hypercharge

$$Y \equiv 2(Q - I_3) = -1 \text{ for } \begin{pmatrix} \nu \\ \ell^- \end{pmatrix}_L \qquad \begin{aligned} &= 0 \text{ for } \nu_R \\ &= -2 \quad \ell_R \end{aligned}$$

$$= \frac{1}{3} \qquad \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{aligned} &= \frac{4}{3} \quad u_R \\ &= -\frac{2}{3} \quad d_R \end{aligned}$$

$S = \frac{1}{2}$

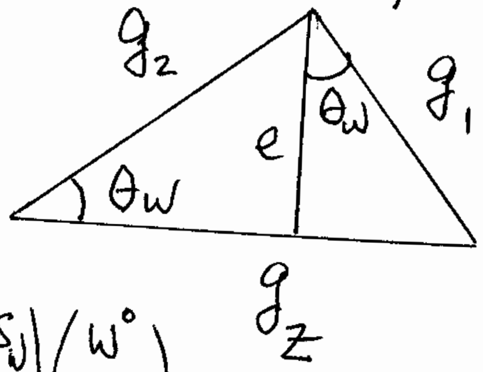
all obey Dirac Eq.

carriers of forces Spin = 1

color Strong I.	SU_3	g_3	8 gluons
Isospin	SU_2	g_2	$W^\pm, W^0$
Y	U_1	g_1	B

Spin = 1 , all obey (massive) Maxwell Eq.

$$\alpha_s = \frac{g_3^2}{4\pi} = 12\pi / [(33-2n_f)\ln Q^2/\Lambda^2 + \text{2nd order}]$$



$$g_2 = \frac{e}{\sin\theta_W}$$

$$g_1 = \frac{e}{\cos\theta_W}$$

$$g_Z = \frac{e}{\sin\theta_W \cos\theta_W}$$

$$\begin{pmatrix} Z \\ \gamma \end{pmatrix} = \begin{pmatrix} c_W & -s_W \\ s_W & c_W \end{pmatrix} \begin{pmatrix} W^0 \\ B \end{pmatrix}$$

θ_W : mixing angle

$c_W \equiv \cos\theta_W$

$s_W \equiv \sin\theta_W$

between Weak & EM interactions.

$$\alpha = \frac{e^2}{4\pi\hbar c} = \frac{1}{137} \quad \text{or} \quad e = \sqrt{4\pi\alpha}$$

with $\hbar c = 1973 \text{ eV-}\AA \Rightarrow 1$

- Fermion masses: $m_f \langle \psi | \psi \rangle = [\langle \psi_L \psi_R \rangle + \langle \psi_R \psi_L \rangle] m_f$

  ψ_L transform like SU_2 doublet

  ψ_R U_1 singlet

  Not gauge invariant, thus arbitary values

  Thus $m_f \equiv 0$!

- H^0, Higgs, invented to generate masses.

  ($S=0$, $Q=0$, $B=L=0$)

  H^0 obeys K-G Eq. since $S=0$

  H^0 is also required, to prevent

  $\sigma(W^+W^- \to Z^0 Z^0)$ from divergent !

  <u>Unitarity</u> !

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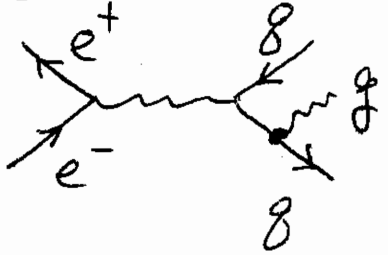
Running Coupling Constants

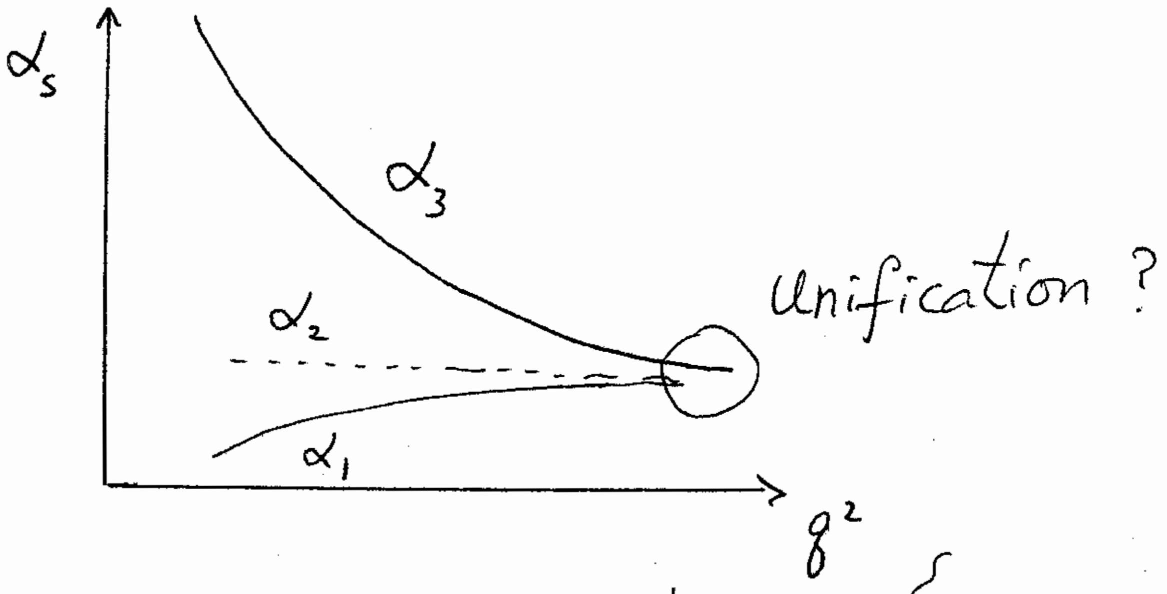
$$\alpha_s = \frac{g_3^2}{4\pi} = \frac{12\pi}{(33-2n_f)\ln\frac{q^2}{\Lambda^2} + \text{2nd order}}$$

$\Lambda \sim 0.1$ GeV determined from gluon emmision.

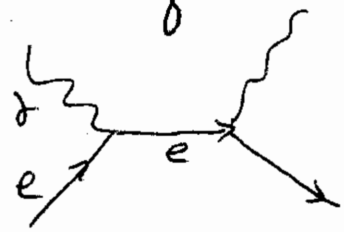


$\alpha_s \to \infty$ as $q^2 \to (0.1\,\text{GeV})^2$

$\alpha_s \sim 0.1$ at $q^2 \sim (100\,\text{GeV})^2$



e or α is determined from



$$\sigma_{th} = \frac{8\pi}{3}\left(\frac{\alpha}{m_e}\right)^2 = \frac{2}{3}\alpha^2(4\pi R_e^2)\ ;\ \sigma_T(\pi p) = \alpha_s^2(4\pi R_p^2)$$

$R_p \sim \frac{1}{m_\pi}$

α_2, θ_W determined from μ, Z^0 decays.

α: $\quad \sigma_{Th}(\gamma e \to \gamma e) = \frac{8\pi}{3}\left(\frac{\alpha}{m_e}\right)^2 = \frac{2}{3}\alpha^2(4\pi R_e^2)$

$$\boxed{\alpha^{(m_e)} = \frac{e^2}{(4\pi)\hbar c} = \frac{1}{137.0360}} \quad R_e = \frac{\hbar}{m_e c}$$

$$\boxed{\alpha(m_Z) = \frac{1}{128}}$$

g_2^2: μ decays

$$\tau = \frac{192\pi^3}{G_F^2 m^5} \qquad \therefore\ G_F = \frac{10^{-5}}{m_N^2} = \frac{\sqrt{2}\, g_2^2(m_\mu)}{8\, m_W^2}$$

$$= 1.16632 \times 10^{-5}\ \text{GeV}^{-2}$$
$\pm .00002$

g_3 : $\tau \to \pi + \nu$

$$\frac{\sigma(3\ \text{jets})}{\sigma(2\ \text{jets})}$$

$$\boxed{\begin{array}{ll} \alpha_s = 10 \longrightarrow & 0.1 \\ E = 0.1 & 100\ \text{GeV} \end{array}}$$

Gravity $\frac{K M_p^2}{(4\pi)\hbar c} = 4.6 \times 10^{-40}$

S.I. Carriers of S.I. are:

gluons: double colors

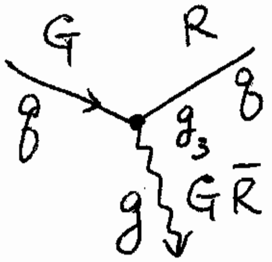
$$\overline{SU_3} \otimes SU_3 \quad \text{or} \quad \begin{pmatrix}\bar{R}\\ \bar{G}\\ \bar{B}\end{pmatrix} \otimes (R,G,B)$$

8 gluons

$\bar{R}G$, $\bar{G}B$, $\bar{R}B$, $\bar{G}R$, $\bar{B}R$, $\bar{B}G$

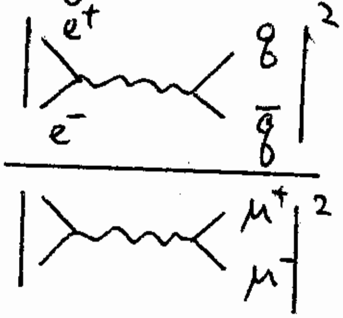
$$\frac{\bar{R}R-\bar{G}G}{\sqrt{2}}, \quad \frac{\bar{R}R+\bar{G}G-2\bar{B}B}{\sqrt{6}}$$

Plus the ninth colorless $\frac{\bar{R}R+\bar{G}G+\bar{B}B}{\sqrt{3}}$ = whit



$$g_3 \simeq \sqrt{\alpha_s 4\pi}$$

Why color = 3 ?

2) 

$$= \frac{n_c \sum Q_i^2}{1}\left(1+\frac{\alpha_s}{\pi}+1.41\frac{\alpha_s^2}{\pi^2}+64.8\frac{\alpha_s^3}{\pi^3}+\cdots\right)$$

1) Why color? ground state $L=S=I=0$

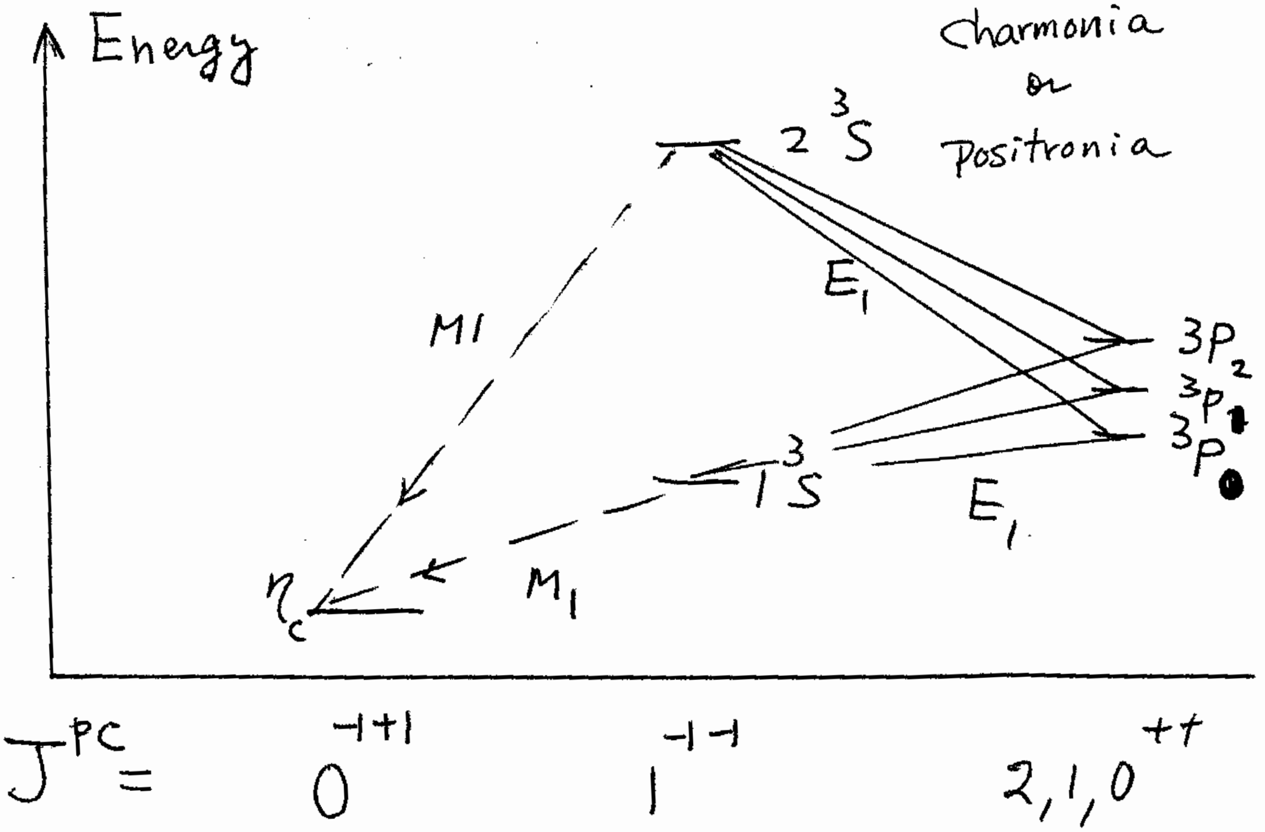
$$\Psi_{q_1q_2} = +\Psi_{q_2q_1}(-1)^L(-1)^{S+1}(-1)^{I+1} = \Psi_{q_2q_1} \quad \text{if } q_1=q_2$$

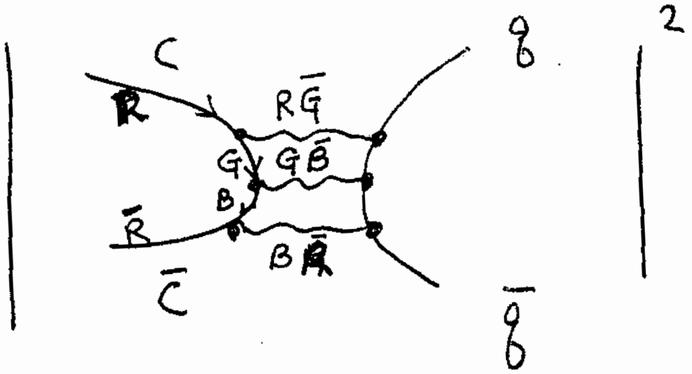
5) violates Pauli exclusion Principle!

Mesons are $q\bar{q}$ system $\qquad P=(-1)^{L+1}$

$$(-1)^{L+1}(-1)^{S+1}C=+1$$

$$\therefore C=(-1)^{l+S}$$





$$\propto \alpha_s^6(M) \ll 1$$

That is why $J\,(1^{--})$ is long lived!

6)

The Thirty-Year's Anniversary of the November Revolution

The Methodical Revolution

Thirty years ago this month, particle physics made a gigantic quantum jump. In an extraordinary turn of events, two unrelated teams of experimenters employing two different pieces of machinery at two dissimilar laboratories on opposite sides of the continent announced the discovery of one and the same heavy particle with unexpected long life-time, which, for the first time, firmly established the quark model. The episode became known as the November Revolution.

The Discovery

The excitement has to do with the doldrums of experimental physics by the early 1970s. Gone were the days of the "particle zoo," when theorists struggled to make sense of the crazy array of experimental data. The SU(3) scheme of the 1960s successfully ordered hadrons into patterns. But although it predicted hitherto some unknown particles (e.g. the Ω^-) and their properties accurately using extrapolation (from Δ, the Σ, and the Ξ series), the computation for most other particle properties were done poorly with ~30% accuracy. Even Gell-mann declared that quarks might be just a mathematical tool, little to do with reality (at his seminar at MIT in 1970). Whether or not one believed that a triplet of quarks (up, down, and strange) lay behind the SU(3) scheme did not matter. By 1974, experimenters were no longer advancing a frontier, but doing clean-up duty, comparing their data with inaccurate theories. "The experimentalists by now must feel like ants, or like pharaoh's slaves building the pyramid," said physicist John Polkinghorne at a conference held at Fermilab in 1972.

In the fall of 1974, the experimentalists suddenly opened a completely new chapter.

At Brookhaven National Laboratory's Alternating Gradient Synchrotron (AGS), a team led by Samuel Ting of the Massachusetts Institute of Technology was looking for new vector particles with widths of few hundred MeV (the proposal was almost rejected because some committee members insisted that no resonances with such high masses would be as narrow as a few hundred MeV), which decay into e^+e^- pairs. Across the country at the Stanford Linear Accelerator Center facility's Stanford Positron-Electron Accelerating Rings (SPEAR), a team lead by Burton Richter was doing the reverse: looking for broad vector and other particles produced by collisions of e^+e^- pairs.

The exciting sequence of events by which each team zeroed in on a surprisingly narrow 3.1 GeV, the new particle's energy, has been recounted – day by day, even hour by hour– in several books, including one by Robert Crease and Charles Mann, *The Second Creation* and one by Michael Riordan, *The Hunting of the Quark (in this book, on p269, the J mass spectrum data labeled as Becker's data, is actually Min Chen's data)*. Richter's team happened on 3.1 GeV and their "psi" particle in Nov after searching at higher energies. Ting's team had solid evidence of what they called the "J" by October 13 after confirmed by two independent analysis teams led by Becker and Chen separately, and had even discussed it with outsiders, but – hoping for even more – withheld publishing. Ting, indeed, was almost scooped, and scrambled to announce only after learning of Richter's plans to publicize his team's one-month old finding.

The news of Monday morning November 11, astonished physicists for several reasons. One was simply the coincidence that the same rare object was discovered simultaneously at two very different machines. The second was the particle itself, whose mass was three times that of the proton, but whose lifetime was a thousand times longer than that of other massive hadron resonances. New physics was clearly involved. Nobody was surprised when Ting and Richter shared the 1976 Nobel Prize for the particle now called the "J/psi" by everyone except Ting's and Richter's teams, who refer to it as the J and the psi, respectively.

The Impact

The impact of the J/psi discovery was theoretical, experimental, and instrumental. J/psi is the equivalent of the hydrogen spectrum in atomic physics. The reason that one could not accurately compute the masses and the properties of the low lying states formed by u, d and s quarks is because the coupling constant of the Strong Interactions at these distances or energies is too big for perturbative calculations to be meaningful. The J/psi family is sufficiently heavy that its coupling constant becomes much smaller than one, which allows accurate perturbative calculations feasible. This unprecedented success finally made us sit up and take quarks for real. While some theorists had argued for the existence of quarks, for the existence of a fourth quark called "charm" (the J/psi is a charm-anti-charm meson), they had wrongly predicted a 5 MeV broad charmonium, too broad for its decay into e^+e^- pairs to be observable. According to Chen, in mid-Oct, Glashow, while visiting the counting room, tried to convince Chen to switch the spectrometer from detecting e^+e^- pairs to π-k pairs to look for charm. Glashow sketched in the back of Chen's J-spectrum, which Chen had quickly turned over to conceal from him, to show why the branching ratio of the charmonium into e^+e^- pairs would be too small to be observable. The long lived J/psi suddenly mainstreamed these ideas after we realized the Strong coupling constant J/psi is smaller than previously thought. At early Morning of Nov 12, Glashow rushed to the CPT room of MIT to meet with Chen and MIT theorists. After gazing at Chen's J peak for about 30', he suddenly announced that he understood the reason why the lifetime is so long. He went to the blackboard and drew the charm-anti-charm annihilated into 3-gluon diagram and showed the decay rate is proportional to the Strong coupling constant to the 6th power, which strongly suppressed the decay rate. The quark model was transformed from an inaccurate mathematical tool, as Gellman himself put it, with sometime mysteriously helpful Rube Goldberg [clumsy contraption, like in the case of extrapolating to the Ω^-] into a serious intellectual edifice with many precision predictions which can be and since then, have been checked with equally precise experimental data."

Experimentally, the J/psi discovery revitalized spectroscopy, the study of particle states. While strange spectroscopy was virtually dead, it opened up the entirely new field of precision charm spectroscopy, or the study of particles with a charmed quark. This required further development of techniques for neutrino and rare event physics.

And instrumentally, the J/psi demonstrated the continued viability of the AGS, whose high intensity was suited to looking for rare events. A FNAL detector, similar to the BNL vertical bending double arm spectrometer originally designed by Min Chen, was built to discover the Upsilon family (bound states of the 5th quark) in 1978. "Richter's Mark I detector," says Riordan, "a large cylinder surrounding the point where energetic electrons and positrons meet, became the prototype for succeeding generations of ever larger and more sophisticated collider detectors."

Revolutions seldom happen without some bitter legacy. Many members of Ting's team are angry that Ting repeatedly refused to publish earlier, even after strongly pressured by them to publish immediately. Chen was so worried about SPEAR that he said each night he would call SLAC to find out what energy SPEAR was running. After he was told SPEAR had gone up to 4.2 GeV, they beamed at each other and said that SPEAR had missed 'our particle'. They relaxed and stopped calling. When Ting was leaving to serve on the SLAC advisory committee on Nov 10th, Chen urged him to send out the paper again. Chen even warned him, should Panofsky ask him about what energy Spear should run, Ting would have a hard time to not say 3.1 GeV! At 3AM on Nov 11, Ting called Chen to immediately announce the discovery of the J particle and to send out the paper to PRL. The simultaneity of the discovery has sometimes led to understandable but unsubstantiated speculation that word somehow spread from Brookhaven to SLAC during the one month period from Oct to Nov, 1974. And physicists found it difficult to know what to call the particle without entering crossfire. Physicists at DESY, Riordan says, were the first to finesse this by calling it the J/psi. But tension remained. Ten years after the discovery, when the Particle Data Group at Berkeley proposed a "Systematic Naming of Mesons and Heavy Baryons" that reverted to calling it the "psi," Ting asked associates to protest the effort "to cover up the history of the discovery of the J particle at Brookhaven by deleting the J symbol." The J remained.

Conclusion

This revolution is a sudden transition for Particle Physics to jump from inaccurate guessing games to precise predictions, from vague ideas to a well-defined quark model, and calculations from being divergent to convergent. J/psi to the Standard Model is like hydrogen spectrum to Atomic Models, where the revolution is from classical mechanics to the Atomic age. It is indeed an epoch-making event involving an overturning of fundamental notions.