Purdue University Department of Physics

Physics 56400
Introduction to Elementary Particle Physics I

Lecture 12
Fall 2019 Semester

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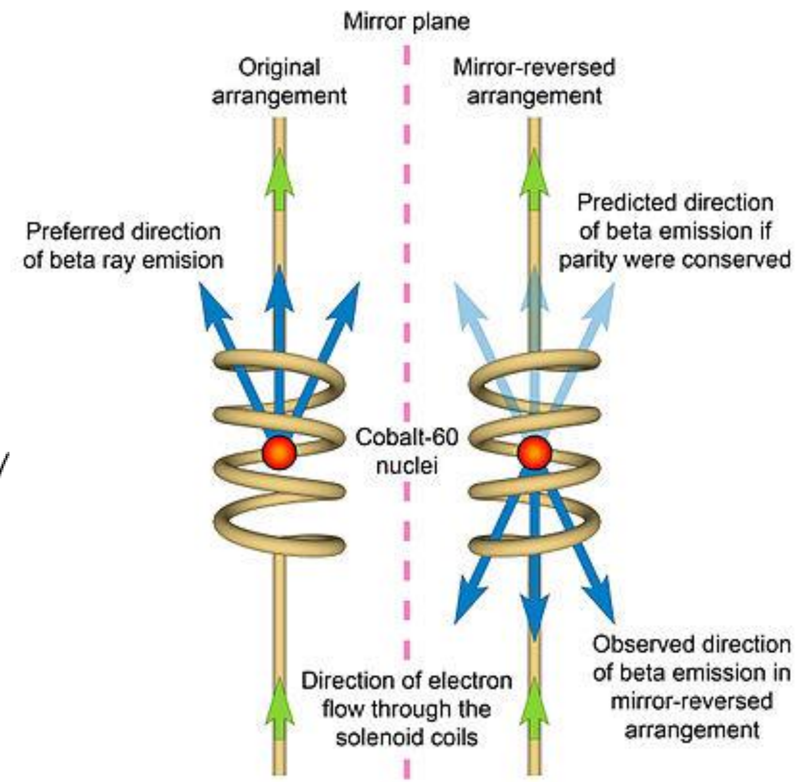
Parity Violation in Weak Interactions

- We already saw that, perhaps, weak interactions do not conserve parity.
- In fact, weak interactions maximally violate parity conservation

$$^{60}_{27}\mathrm{Co} \to {}^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e + 2\gamma$$



Helicity and Chirality

- Helicity is the projection of the spin onto the momentum axis:

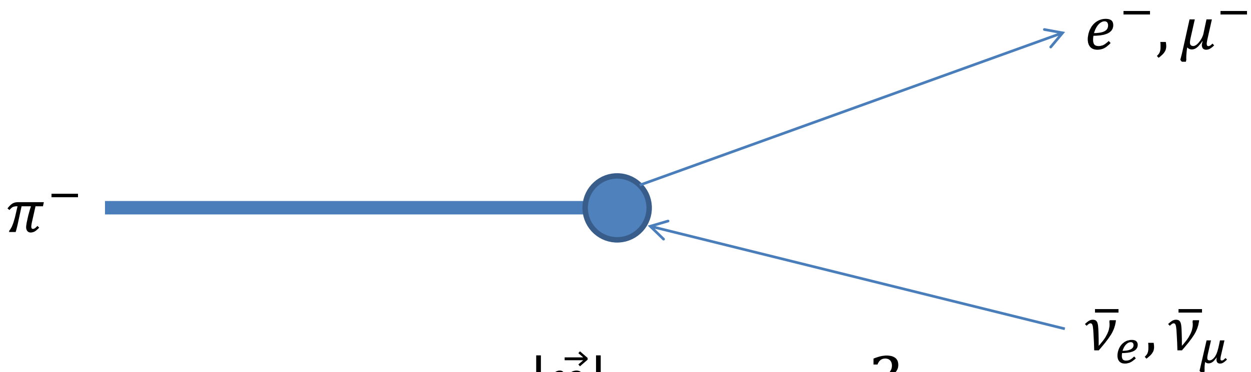
$$\lambda = \vec{s} \cdot \hat{p}$$

- Right-handed fermions have $\lambda = +1/2$
- Left-handed fermions have $\lambda = -1/2$
- Helicity is not Lorentz invariant
  - You can boost to a frame in which the direction of $\vec{p}$ has been reversed
- Chirality similar to helicity but it is Lorentz invariant
  - We will study it in more detail when we look at QED
- In the limit where $v \to c$, they are the same.

Helicity and Chirality

- It would seem that the weak interaction only acts on left-handed fermions or right-handed anti-fermions
- This is exact for chirality and almost exact for helicity
- Neutrinos are so light (essentially massless) that for all practical purposes there are only left-handed neutrinos and right-handed anti-neutrinos
  - There *might(?)* be right-handed neutrinos or left-handed anti-neutrinos, but nothing couples to them
- The weak interaction strongly prefers to couple to the left-handed helicity components of charged leptons (or right-handed anti-leptons).
- In the limit where $v \to c$, the weak interaction does not couple to right-handed leptons (or left-handed anti-leptons).

Leptonic Decays of Pions



$$\Gamma = \frac{|\vec{p}|}{8\pi M} \left|\mathcal{M}_{fi}^{\pi}\right|^2$$

- Decay to muons: $\frac{|\vec{p}|}{8\pi M} = 0.0086$
- Decay to electrons: $\frac{|\vec{p}|}{8\pi M} = 0.0200$
- We might expect the decay to $e^- \bar{\nu}_e$ to dominate but it does not…

Leptonic Decays of Pions

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+ \nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+ \nu_\mu \gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+ \nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+ \nu_e \gamma$	[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70

- To conserve angular momentum, both final state particles must have right-handed helicity.
- The anti-neutrinos are essentially massless so they are always right-handed.
- But $\beta_\mu = 0.27$ while $\beta_e = 0.99997$
- There is a much greater probability of finding the muon in a left-handed *chirality* state.
- This is called "helicity suppression"

Leptonic Decays of Kaons

K^+ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
	Leptonic and semileptonic modes		
$e^+ \nu_e$	$(1.582 \pm 0.007) \times 10^{-5}$		247
$\mu^+ \nu_\mu$	(63.56 ± 0.11) %	S=1.2	236

$$\frac{Br(K^- \to e^- \bar{\nu}_e)}{Br(K^- \to \mu^- \bar{\nu}_\mu)} = 2.5 \times 10^{-5}$$

$$\beta_\mu = 0.9190, \beta_e = 0.999998$$

- Although the weak interaction does not conserve parity, perhaps it conserves CP

Neutral Kaons

- Kaons produced by strong interactions have eigenstates $K^0 = (d\bar{s})$ and $\overline{K}^0 = (s\bar{d})$
- Both have parity P=-1 but they can mix to form CP eigenstates:

$$K_1 = \frac{1}{\sqrt{2}}(K^0 + \overline{K}^0) \qquad \text{CP=+1}$$

$$K_2 = \frac{1}{\sqrt{2}}(K^0 - \overline{K}^0) \qquad \text{CP=-1}$$

- The K_1 can decay to $\pi^+\pi^-$ (CP even) while the K_2 must decay to a state with 3 pions (CP even).

K-long and K-short

- The decay to two pions ($p = 209\ \mathrm{MeV}$) has much greater available phase-space than the decay to three pions ($p_{max} = 139\ \mathrm{MeV}$)
- For this reason, they decay rate to two pions is greater than the decay rate to three pions
- The K_2 lifetime is longer than the lifetime of the K_1:

$$\tau(K_L^0) = 51.16\ \mu s,\ c\tau = 15.34\ \mathrm{m}$$

$$\tau\left(K_S^0\right) = 0.09\ \mathrm{ns},\ c\tau = 2.68\ \mathrm{cm}$$

- These are the physical states with well-defined masses that propagate in free space.

Strong vs Weak Eigenstates

- When a strange quark is produced via the strong interaction, the flavor state is well defined
- It is an equal mixture of the $K_2 \approx K_L^0$ and $K_1 \approx K_S^0$ eigenstates:

$$K^0 = \frac{1}{\sqrt{2}}(K_1 + K_2) \approx \frac{1}{\sqrt{2}}\left(K_S^0 + K_L^0\right)$$
$$\overline{K}^0 = \frac{1}{\sqrt{2}}(K_1 - K_2) \approx \frac{1}{\sqrt{2}}\left(K_S^0 - K_L^0\right)$$

- Initially, we have equal probability of observing either K_L^0 or K_S^0 decay.
- However, the short-lived component decays faster and eventually we will have a pure K_L^0 component.

Regeneration

- When a pure beam of K_L^0 interact with mater, the $(d\bar{s})$ and $(s\bar{d})$ components have different cross sections.
  - Only $(s\bar{d})$ can annihilate down-quarks in nuclei
- This changes the (initially equal) fraction of $(d\bar{s})$ and $(s\bar{d})$ in the beam
- The beam that emerges has a new K_S^0 component
- In fact, this component is coherent with the unreacted K_L^0 component

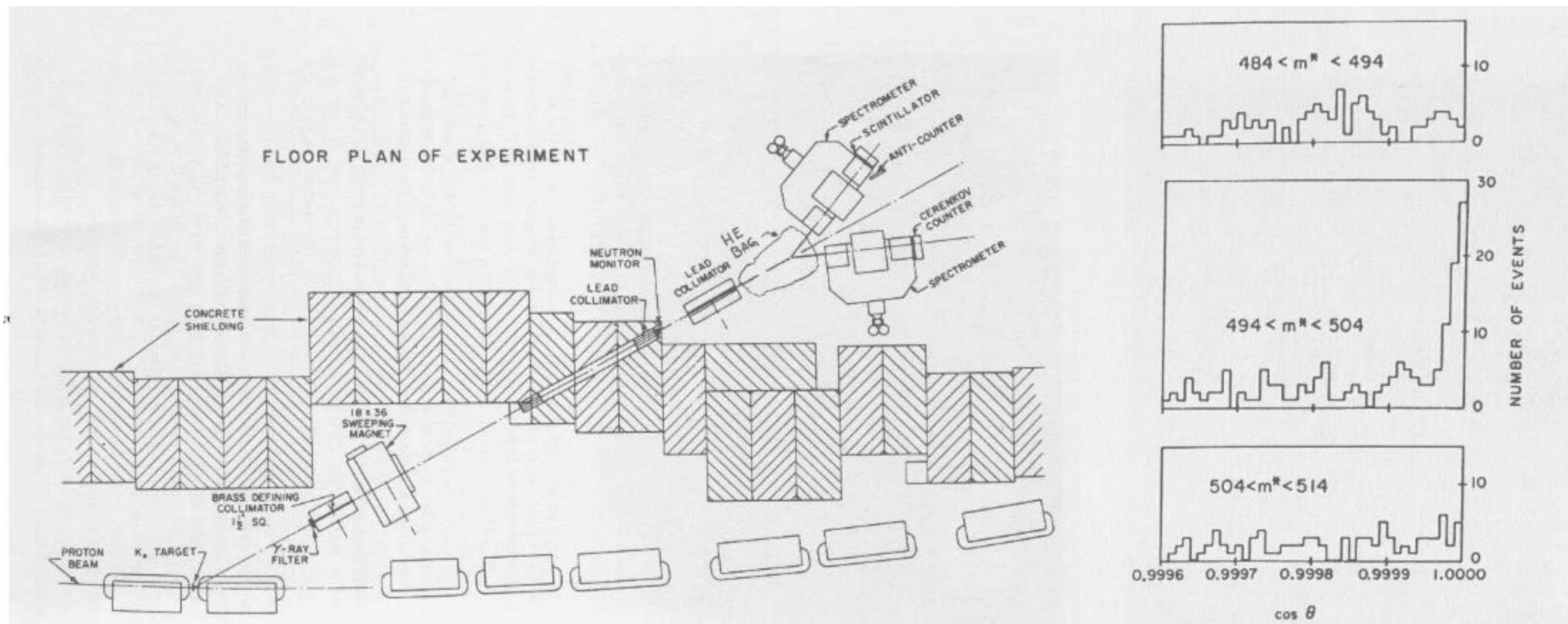
(Pais & Piccioni, 1955)

CP Violation

- Since we can prepare a pure beam of K_L^0, it is easy (Ha!) to search for CP violation in the form of

$$K_L^0 \to \pi^+\pi^-$$

- Fitch-Kronin experiment (Brookhaven, 1964)



CP Violation

- So the K_S^0 and K_L^0 are not quite K_1 and K_2 eigenstates.

$$K_S^0 = \frac{1}{\sqrt{1+|\varepsilon|^2}}(K_1 + \varepsilon K_2)$$

$$K_L^0 = \frac{1}{\sqrt{1+|\varepsilon|^2}}(\varepsilon K_1 + K_2)$$

- It turns out that $Re(\varepsilon) \sim 10^{-3}$ which is small, but definitely not zero.

K_L^0 DECAY MODES			Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic modes					
$\pi^\pm e^\mp \nu_e$		[hh]	(40.55 ± 0.11) %	S=1.7	229
Called K_{e3}^0.					
$\pi^\pm \mu^\mp \nu_\mu$		[hh]	(27.04 ± 0.07) %	S=1.1	216
Called $K_{\mu3}^0$.					
$(\pi\mu \text{atom})\nu$			$(1.05 \pm 0.11) \times 10^{-7}$		188
$\pi^0 \pi^\pm e^\mp \nu$		[hh]	$(5.20 \pm 0.11) \times 10^{-5}$		207
$\pi^\pm e^\mp \nu e^+ e^-$		[hh]	$(1.26 \pm 0.04) \times 10^{-5}$		229
Hadronic modes, including Charge conjugation×Parity Violating (*CPV*) modes					
$3\pi^0$			(19.52 ± 0.12) %	S=1.6	139
$\pi^+\pi^-\pi^0$			(12.54 ± 0.05) %		133
$\pi^+\pi^-$	*CPV*	[jj]	$(1.967 \pm 0.010) \times 10^{-3}$	S=1.5	206
$\pi^0\pi^0$	*CPV*		$(8.64 \pm 0.06) \times 10^{-4}$	S=1.8	209

Kaon Oscillations

- Suppose the strong interaction produced an initial state with S=+1:

$$K^0 = (d\bar{s}) \approx \frac{1}{\sqrt{2}}\left(K_S^0 + K_L^0\right)$$

- The phases of each state evolves with time:

$$|\Psi(t)\rangle = \frac{1}{\sqrt{2}}\left(e^{-im_S t - \Gamma_S t/2} K_S^0 + e^{-im_L t - \Gamma_L t/2} K_L^0\right)$$

- The probability of observing a K_S^0 or K_L^0 decay is:

$$P\left(K_S^0\right) = \left|\left\langle K_S^0 \middle| \Psi(t)\right\rangle\right|^2 = \frac{1}{2} e^{-\Gamma_S t}$$

$$P\left(K_L^0\right) = \left|\left\langle K_L^0 \middle| \Psi(t)\right\rangle\right|^2 = \frac{1}{2} e^{-\Gamma_L t}$$

Kaon Oscillations

- But, we can also write

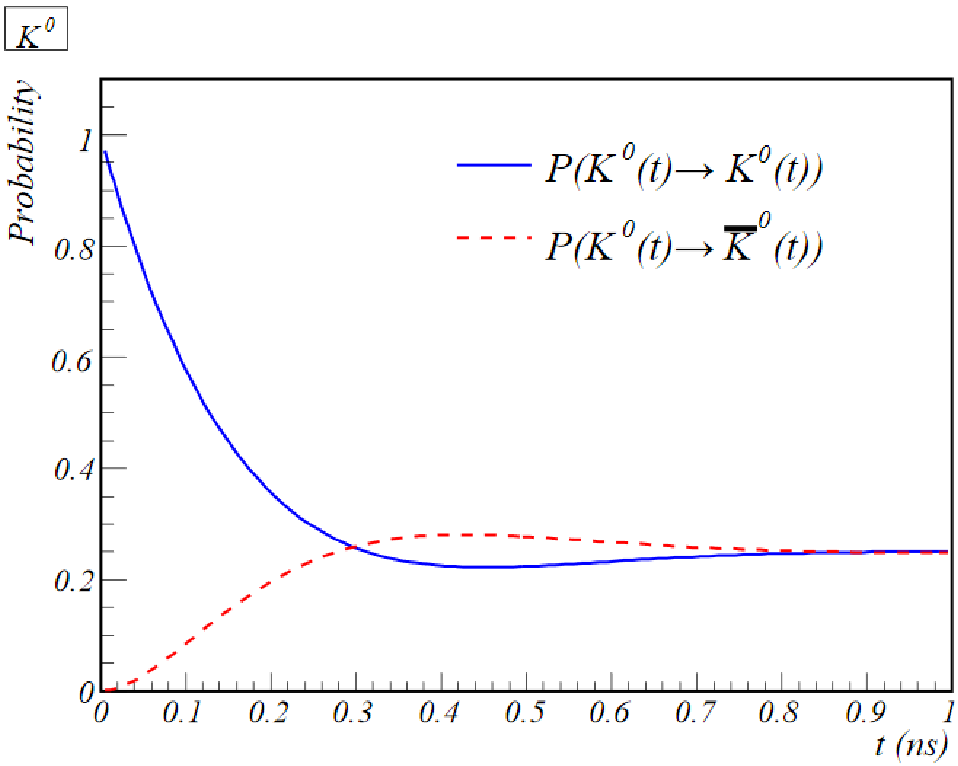
$$|\Psi(t)\rangle$$
$$= \frac{1}{2}\left[e^{-im_S t - \Gamma_S t/2} + e^{-im_L t - \Gamma_L t/2}\right]K^0$$
$$+ \frac{1}{2}[\left[e^{-im_S t - \Gamma_S t/2} - e^{-im_L t - \Gamma_L t/2}\right]\overline{K}^0$$

- The probability of observing a K^0 state is then

$$P(K^0) = |\langle K^0|\Psi(t)\rangle|^2$$
$$= \frac{1}{4}\left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-\frac{(\Gamma_S+\Gamma_L)t}{2}} Re\left(e^{i\Delta m\, t}\right)\right]$$
$$= \frac{1}{2}[\frac{e^{-\Gamma_S t} + e^{-\Gamma_L t}}{2} + e^{-\overline{\Gamma} t}\cos(\Delta m t)]$$

Kaon Oscillations

- Before the K_S^0 component has completely decayed, it can interfere constructively or destructively with the K_L^0 component.



These are $|\Delta S| = 2$ transitions.

Cabibbo Rotation

- Cabibbo observed that amplitudes for the $\Delta S = 0$ weak transitions

$$u \leftrightarrow d \qquad e \leftrightarrow \nu_e \qquad \mu \leftrightarrow \nu_\mu$$

were similar, but amplitudes for $\Delta S = 1$ transitions were smaller by about a factor of 4.

- In 1963, Cabibbo suggested that the weak interaction couples to a linear combination of d and s quarks:

$$d' = d\ \cos\theta_C + s\ \sin\theta_C$$
$$s' = -d\ \sin\theta_C + s\ \cos\theta_C$$

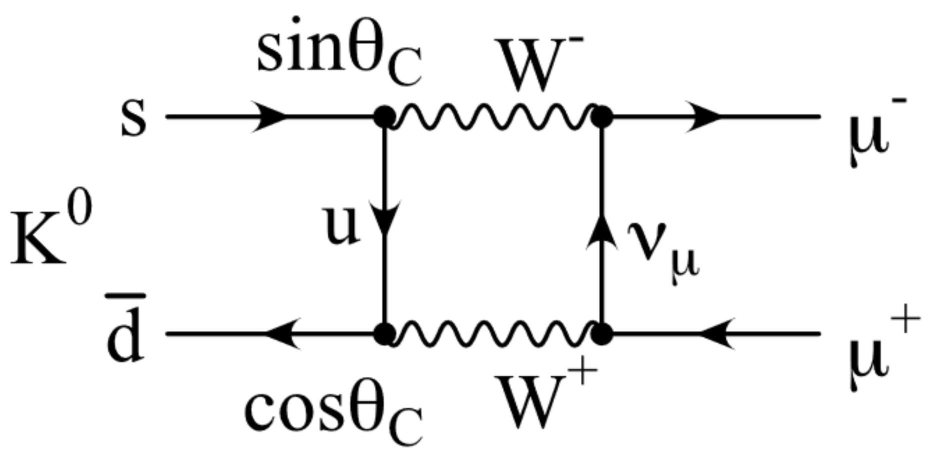
Cabibbo Rotation

- Probabilities for weak transitions then look like this:

$$|\langle u|d\rangle|^2 \sim \cos^2\theta_C \approx 1$$
$$|\langle u|s\rangle|^2 \sim \sin^2\theta_C \approx 0.05$$

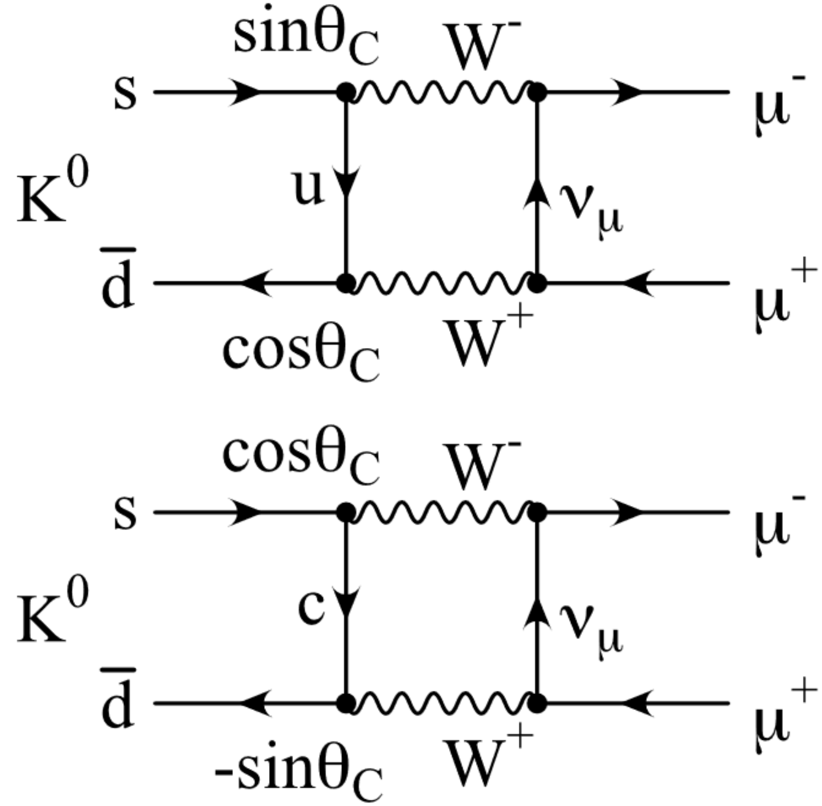
- But then we should observe $K^0 \rightarrow \mu^+\mu^-$ with a large branching fraction whereas in fact

$$Br(K^0 \rightarrow \mu^+\mu^-) < 8 \times 10^{-10}$$



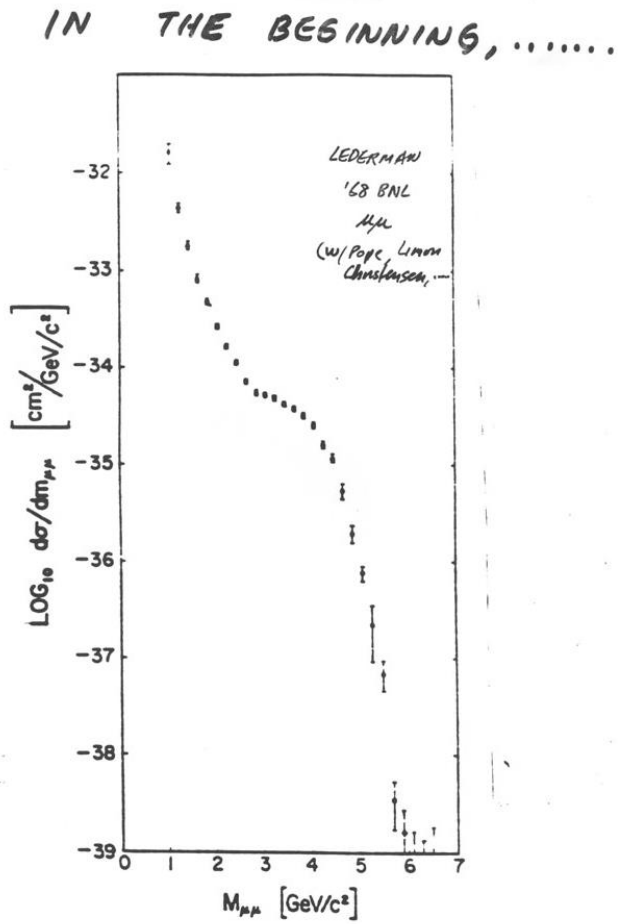
GIM Suppression

- In 1970, Glashow, Illiopoulos, and Maiani proposed that this amplitude must be cancelled by another process:



- This required that there be a charge +2/3 partner to the strange quark in the same family.

Observation of $(c\bar{c})$ States



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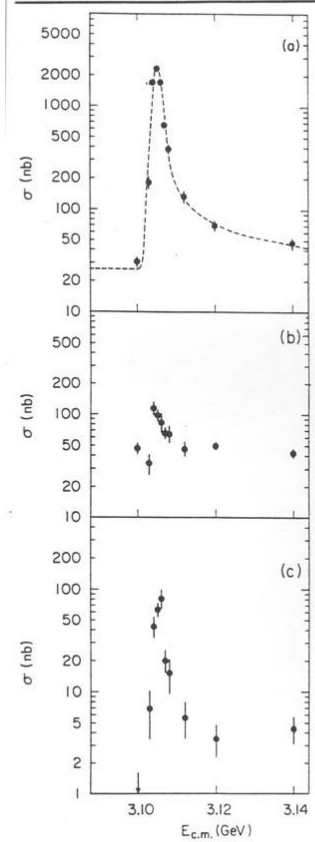

ᶠIG. 1. Cross section versus energy for (a) multi-
iron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$,
π^-, and K^+K^- final states. The curve in (a) is the ex-
cted shape of a δ-function resonance folded with the
ussian energy spread of the beams and including
diative processes. The cross sections shown in (b)

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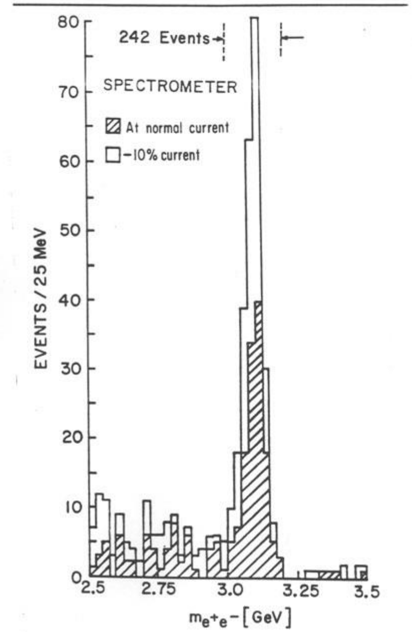


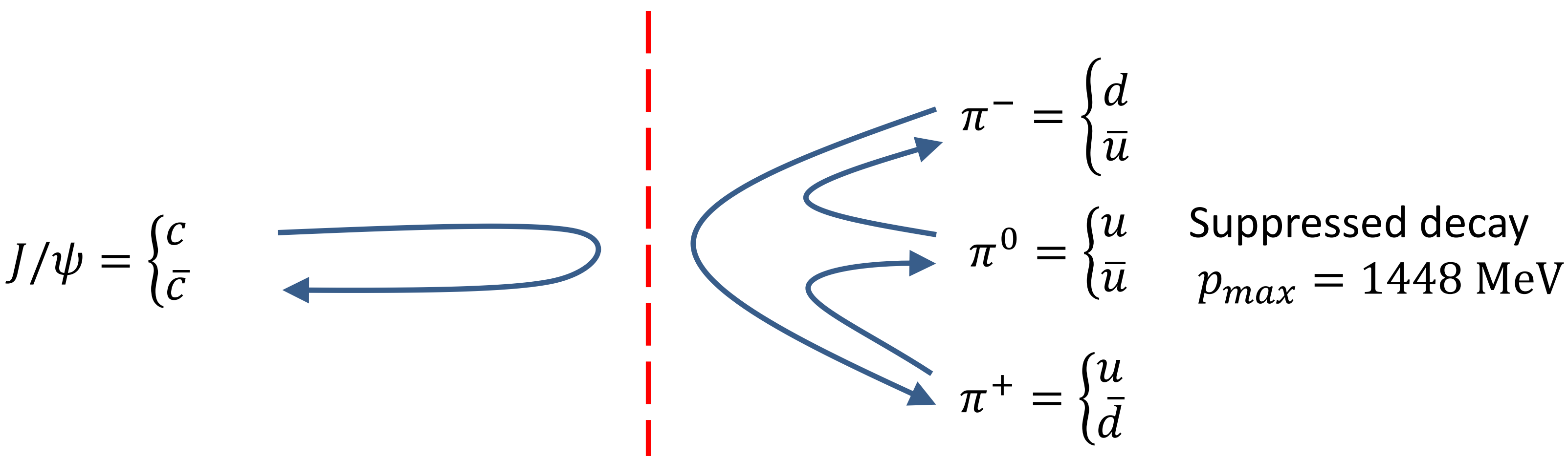
ᶠIG. 2. Mass spectrum showing the existence of J.
sults from two spectrometer settings are plotted
owing that the peak is independent of spectrometer
rents. The run at reduced current was taken two
nths later than the normal run.

Brookhaven 30 GeV AGS

SPEAR e^+e^- storage ring

Observation of $(c\bar{c})$ States

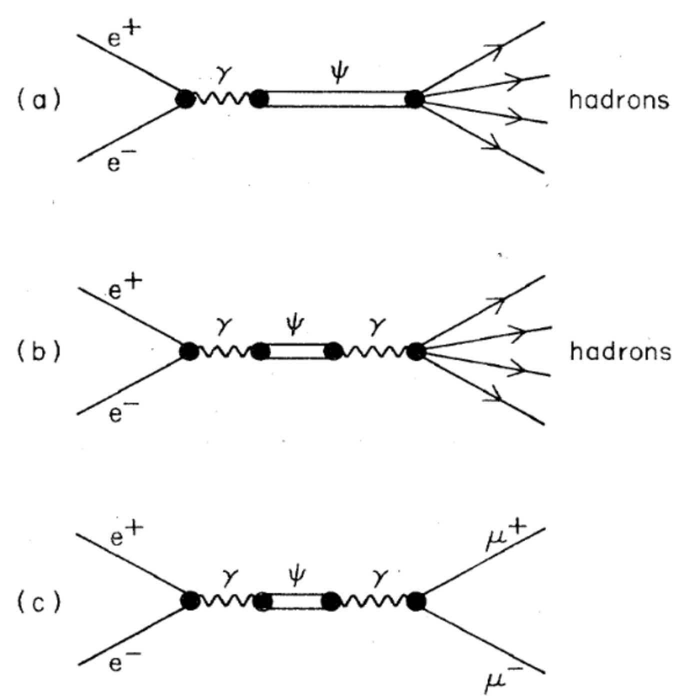
- Interpretation:
  - The states had a very small width because of OZI suppression



$$\Gamma = 5.55 \text{ keV}$$

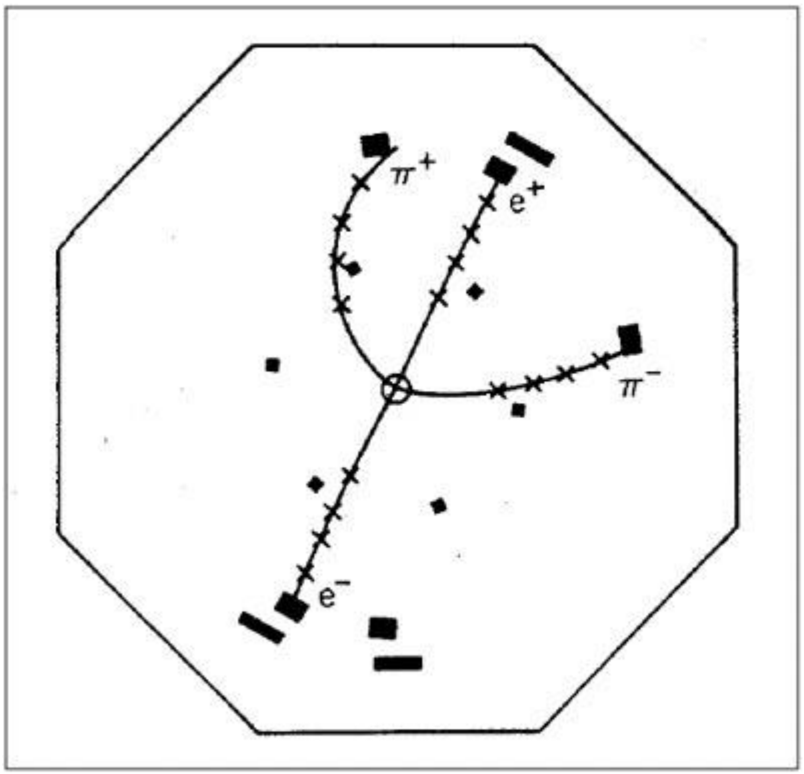
Observation of $(c\bar{c})$ States

- This is a vector meson with the same quantum numbers as the photon



Observation of $(c\overline{c})$ States

- SLAC continued to scan the beam energy above the J/ψ mass and observed another narrow resonance.



$\psi' \rightarrow J/\psi\,\pi^+\pi^-$

$$m(\psi') = 3686.1\ \text{MeV}$$
$$\Gamma = 2.33\ \text{keV}$$

If this really was evidence for a new quark, where were the charm flavored mesons?

Observation of $(c\bar{c})$ States

- The lightest charm flavored mesons ("open charm") are the D mesons:

$$m(D^+) = 1869.7 \text{ MeV}$$
$$m(D^0) = 1864.8 \text{ MeV}$$

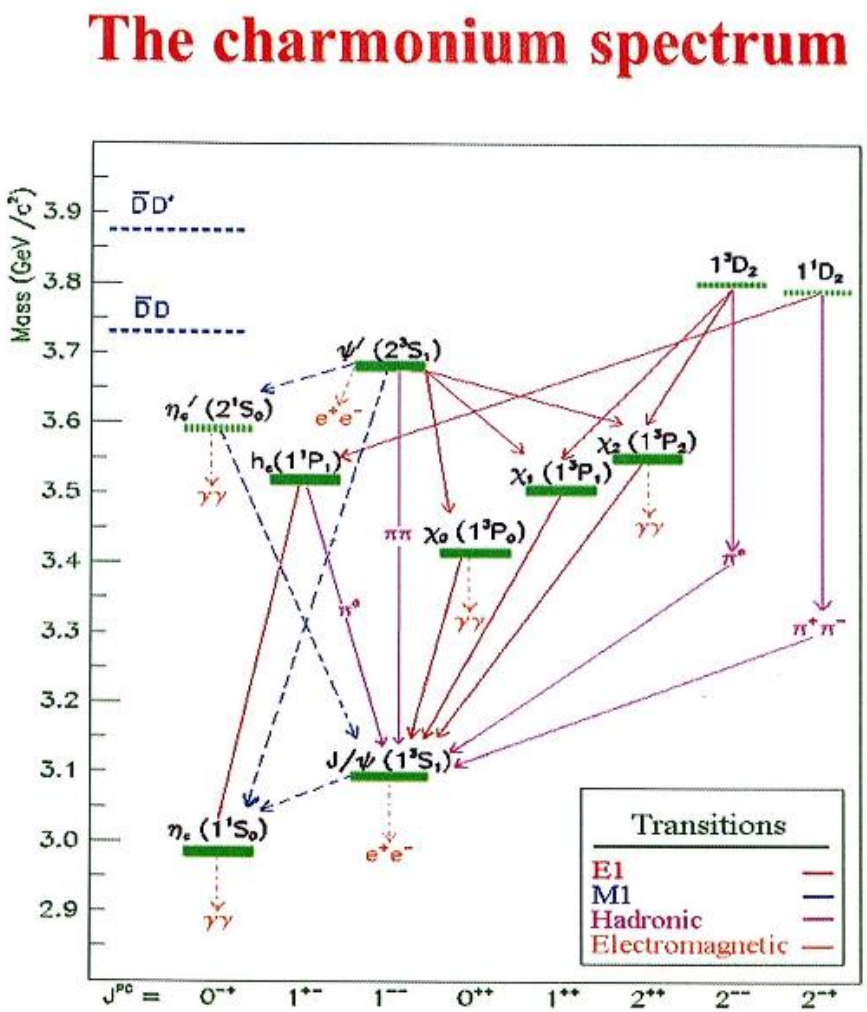
- Bound states of $(c\bar{c})$ will not decay to D mesons unless $m_{c\bar{c}} > 2m_D \sim 3740 \text{ MeV}$
- Eventually, the $\psi(3770)$ was observed with a much larger width:

$$\Gamma = 27.2 \text{ MeV}$$

(more characteristic of strongly decaying resonance)

Charm Spectroscopy

- Charm quarks are heavy and the bound state of $(c\bar{c})$ is practically nonrelativistic.
- The energies of bound states can be calculated using the same techniques used to calculate the emission spectrum of Hydrogen atoms.
  - The J/ψ is the $J^{PC} = 1^{--}$ ground state
  - The ψ' is the $n = 2$ radial excitation
  - The ψ'' is the $n = 3$ radial excitation



Charm Spectroscopy

- Quantum numbers of Hydrogen-like systems:

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 - \frac{e^2}{4\pi\epsilon_0 r}\right)\psi(r,\theta,\phi) = E\psi(r,\theta,\phi)$$

Quantum Numbers n	l	m_l	Eigenfunctions
1	0	0	$\psi_{100} = \frac{1}{\sqrt{\pi}}\left(\frac{Z}{a_0}\right)^{3/2} e^{-Zr/a_0}$
2	0	0	$\psi_{200} = \frac{1}{4\sqrt{2\pi}}\left(\frac{Z}{a_0}\right)^{3/2}\left(2-\frac{Zr}{a_0}\right) e^{-Zr/2a_0}$
2	1	0	$\psi_{210} = \frac{1}{4\sqrt{2\pi}}\left(\frac{Z}{a_0}\right)^{3/2}\frac{Zr}{a_0} e^{-Zr/2a_0}\cos\theta$
2	1	±1	$\psi_{21\pm1} = \frac{1}{8\sqrt{\pi}}\left(\frac{Z}{a_0}\right)^{3/2}\frac{Zr}{a_0} e^{-Zr/2a_0}\sin\theta\, e^{\pm i\varphi}$
3	0	0	$\psi_{300} = \frac{1}{81\sqrt{3\pi}}\left(\frac{Z}{a_0}\right)^{3/2}\left(27-18\frac{Zr}{a_0}+2\frac{Z^2r^2}{a_0^2}\right) e^{-Zr/3a_0}$
3	1	0	$\psi_{310} = \frac{\sqrt{2}}{81\sqrt{\pi}}\left(\frac{Z}{a_0}\right)^{3/2}\left(6-\frac{Zr}{a_0}\right)\frac{Zr}{a_0} e^{-Zr/3a_0}\cos\theta$
3	1	±1	$\psi_{31\pm1} = \frac{1}{81\sqrt{\pi}}\left(\frac{Z}{a_0}\right)^{3/2}\left(6-\frac{Zr}{a_0}\right)\frac{Zr}{a_0} e^{-Zr/3a_0}\sin\theta\, e^{\pm i\varphi}$

We also need to couple the spins of the quarks to the orbital angular momentum:

$$\vec{S} = \vec{s}_1 + \vec{s}_2$$

$$\vec{J} = \vec{L} + \vec{S}$$

Weak Decays of Charm Mesons

- Cabibbo favored transitions:

$$\left.\begin{array}{c} u \leftrightarrow d \\ c \leftrightarrow s \end{array}\right\} \quad \cos\theta_C$$

- Cabibbo suppressed transitions:

$$\left.\begin{array}{c} u \leftrightarrow s \\ c \leftrightarrow d \end{array}\right\} \quad \sin\theta_C$$

D^+ DECAY MODES	Fraction (Γ_i/Γ)
Inclusive modes	
e^+ semileptonic	(16.07 ± 0.30) %
μ^+ anything	(17.6 ± 3.2) %
K^- anything	(25.7 ± 1.4) %
$\overline{K}^0$ anything + K^0 anything	(61 ± 5) %
K^+ anything	(5.9 ± 0.8) %
$K^*(892)^-$ anything	(6 ± 5) %
$\overline{K}^*(892)^0$ anything	(23 ± 5) %
$K^*(892)^0$ anything	< 6.6 %
η anything	(6.3 ± 0.7) %
η' anything	(1.04 ± 0.18) %
ϕ anything	(1.03 ± 0.12) %

D^0 DECAY MODES		Fraction (Γ_i/Γ)
Inclusive modes		
e^+ anything	[eee]	(6.49 ± 0.11) %
μ^+ anything		(6.7 ± 0.6) %
K^- anything		(54.7 ± 2.8) %
$\overline{K}^0$ anything + K^0 anything		(47 ± 4) %
K^+ anything		(3.4 ± 0.4) %
$K^*(892)^-$ anything		(15 ± 9) %
$\overline{K}^*(892)^0$ anything		(9 ± 4) %
$K^*(892)^+$ anything		< 3.6 %
$K^*(892)^0$ anything		(2.8 ± 1.3) %
η anything		(9.5 ± 0.9) %
η' anything		(2.48 ± 0.27) %
ϕ anything		(1.05 ± 0.11) %