Physics 129: Particle Physics
Lecture 23: CP Violation

Nov 12, 2020

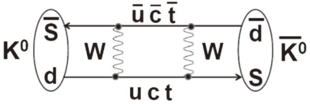
- Suggested Reading:
  - Thomson Chapter 14
- Reminder: Quiz #3 must be taken by midnight tonight

Our Weak Interaction Roadmap

- Unlike strong and EM, weak interactions don't conserve parity
  - Vertex selects left-handed state for of particles (and right handed state for anti-particles)
    - Discussed Nov 3
- $W^{\pm}$ coupling to leptons respect flavor familes (e, μ, τ) but coupling to quarks do not
  - Coupling not diagonal in quark flavor: Need to change basis
    - Discussed Nov 5
  - Introduction of this change in basis gives new phenomenology, including mixing and CP violation
    - Mixing discussed this Tuesday
    - Today: CP Violation
- $W^{\pm}$ has charge, so it couples to photon
  - Cannot write down a weak theory independent of QED
  - Unified electroweak theory includes Z^0 as well as $W^{\pm}$ and γ
    - Topic for the week of Nov 17
- Need mechanism to give $W^{\pm}$ and Z^0 mass
  - This is the Higgs mechanism
    - Discuss this after Thanksgiving

Review: Flavor mixing for neutral mesons: K^0 example (I)

- Since flavor conserved in strong interactions K^0 $(\bar{s}d)$ and $\overline{K}^0$ $(s\bar{d})$ are separate particles and eigenstates of strong interaction
- Weak interactions don't conserve flavor ($W^{\pm}$ changes quark flavor)
  - 2^{nd} order weak interactions connect K^0 and $\overline{K}^0$ states



- When only strong interactions considered, two eigenstates K^0 and $\overline{K}^0$ are degenerate
- Weak diagram acts as a perturbation
  - Perturbation breaks the degeneracy
  - As always with degenerate PT, need to move to new basis to find correct eigenstates
  - This is done by diagonalizing the energy matrix $\langle i|\, H\, |i\rangle$

Review: Flavor mixing for neutral mesons: K^0 example (II)

- Last time: Found correct basis under *assumption* that CP is a good symmetry of the weak interactions
  - We'll see today that isn't strictly true but it is useful to start with this intermediate situation
- Neutral Kaons transform under CP (not unique definition)

$$\begin{aligned} CP\left|K^0\right\rangle &= \left|\overline{K}^0\right\rangle \\ CP\left|\overline{K}^0\right\rangle &= \left|K^0\right\rangle \end{aligned}$$

- Therefore, we can write

$$\left|K_1\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\overline{K}^0\right\rangle\right) \qquad CP\left|K_1\right\rangle = \left|K_1\right\rangle$$

$$\left|K_2\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\overline{K}^0\right\rangle\right) \qquad CP\left|K_2\right\rangle = -\left|K_2\right\rangle$$

- $\left|K_1\right\rangle$ and $\left|K_2\right\rangle$ are CP eigenstates and *almost* the physical basis

Review: Flavor mixing for neutral mesons: K^0 example (II)

- Associating the CP states with the decays:

$$|K_1\rangle \to 2\pi$$
$$|K_2\rangle \to 3\pi$$

- However, very little phase space for 3π decay: Lifetime of $|K_2\rangle$ much longer than of $|K_1\rangle$
- Physical states called "K-long" and "K-short":

$$\tau(K_S) = 0.9 \times 10^{-10} \text{ sec}$$
$$\tau(K_L) = 0.5 \times 10^{-7} \text{ sec}$$

- We'll use distinction that $|K_1\rangle$, $|K_2\rangle$ are the CP eigenstates and $|K_S\rangle$, $|K_L\rangle$ are true mass eigenstates (including CP violation)

A More Formal Treatment of Mixing

- Write our state ψ as linear combination of K^0 and $\overline{K}^0$:

$$\psi = \alpha \left| K^0 \right\rangle + \beta \left| \overline{K}^0 \right\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

- Schrodinger eq tells us

$$i \frac{d\psi}{dt} = H\psi$$

  where H is Hermitian matrix: "generalized mass matrix"

- In matrix form:

$$H = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M^*{}_{12} - \frac{i}{2}\Gamma^*{}_{12} & M - \frac{i}{2}\Gamma \end{pmatrix}$$

- Diagonal elements equal from CPT
- If CP is a good symmetry, M_{12} and Γ_{12} are real
- Find eigenstates by diagonalizing the matrix

$$\begin{array}{ll} M = (m_1 + m_2)/2 & \Delta m \equiv M_{12} = (m_1 - m_2)/2 \\ \Gamma \equiv \Gamma_{12} = (\Gamma_1 + \Gamma_2)/2 & \Delta\Gamma = (\Gamma_1 - \Gamma_2)/2 \end{array}$$

Time Dependence (I)

- Write wave functions (ignoring for now CP violation)

$$
\begin{aligned}
|K_1(t)\rangle &= e^{-im_1 t - \Gamma_1 t/2}\,|K_1\rangle \\
|K_2(t)\rangle &= e^{-im_2 t - \Gamma_2 t/2}\,|K_2\rangle
\end{aligned}
$$

- Writing this in terms of strong eigenstates

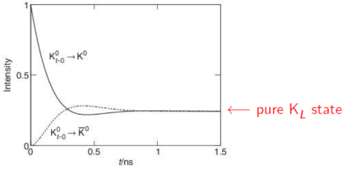
$$
\begin{aligned}
\left|K^0\right\rangle_{\text{at } t=0} &\Rightarrow \frac{1}{\sqrt{2}}\left[e^{-im_1 t - \Gamma_1 t/2}\,|K_1\rangle + e^{-im_2 t - \Gamma_2 t/2}\,|K_2\rangle\right] \\
\left|\overline{K}^0\right\rangle_{\text{at } t=0} &\Rightarrow \frac{1}{\sqrt{2}}\left[e^{-im_1 t - \Gamma_1 t/2}\,|K_1\rangle - e^{-im_2 t - \Gamma_2 t/2}\,|K_2\rangle\right]
\end{aligned}
$$

- If a state ψ that is purely $\left|K^0\right\rangle$ is produced at $t = 0$, at a later time it will be a combination of $\left|K^0\right\rangle$ and $\left|\overline{K}^0\right\rangle$
- We saw Tuesday that over time the neutral kaon oscillates between K^0 and $\overline{K}^0$ (while decaying away)

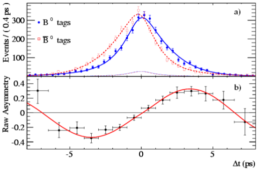
$$
\begin{aligned}
\left|\left\langle K^0\right|\left|\psi(t)\right\rangle\right|^2 &= \frac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} + 2e^{-(\Gamma_1+\Gamma_2)t/2}\cos(\Delta m t)\right] \\
\left|\left\langle \overline{K}^0\right|\left|\psi(t)\right\rangle\right|^2 &= \frac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} - 2e^{-(\Gamma_1+\Gamma_2)t/2}\cos(\Delta m t)\right]
\end{aligned}
$$

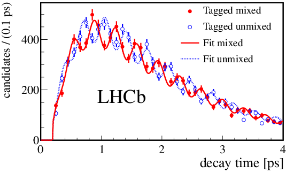
Time Dependence (II)

- Different neutral meson systems have different values for $\Delta\Gamma$ and Δm
- How the oscillations look will therefore depend on the system
- For kaons, mass difference small enough that oscillation period longer than lifetime: only first ocillation visable



- In B system (due to contributions of different CKM matrix elements in the box diagram), different δm for B^0 and B_s





Why might CP be a good symmetry when C and P are violated?

- Why CP might be a good symmetry:
  - We know weak interactions don't conserve P since ν are LH and $\overline{\nu}$ are RH
  - Parity would turn a LH ν into a RH ν
  - But Charge Conjugation turns a ν into a $\overline{\nu}$
  - Hence, CP turns a a LH ν into a RH $\overline{\nu}$
  - Same argument holds for all other Dirac particles: CP seems to map correctly between the physic states
- Weak Interaction Lagrangian appears on the surface to be CP invariant
- In fact, CP is violated in CKM matrix ($\sim 10^{-3}$ effect) due to the presence of an imaginary phase
- The implications of CP violation are huge
  - We know our Universe is mainly matter with very little antimatter
    - CP violation necessary ti explain this fact (see next slide)
    - CP violation in the weak interactions, however, seems smaller than we need
- Today, we'll review how CP violation was discovered and what we know now

Matter-Antimatter Asymmetry of the Universe

- The universe is made largely of matter with very little antimatter

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 10^{-9}$$

Why is this the case?

- Matter dominance occured during early evolution of the Universe
- Assume Big Bang produces equal numbers of B and $\overline{B}$
- At high temperature, baryons in thermal equilibrium with photons

$$\gamma + \gamma \leftrightarrow p + \overline{p}$$

- Temperature and mean energy of photons decrease as Universe expands
  - Forward reaction ceases
  - Baryon density becomes low and thus backward reaction rare
  - Number of B and $\overline{B}$ becomes fixed: "Big-Bang" baryogenesis
- Need a mechanism to explain the observed matter-antimatter asymmetry

The Sakharov Conditions

- Sakharov (1967) showed that 3 conditions needed for a baryon dominated Universe
  1. A least one B-number violating process so $N_B - N_{\overline{B}}$ is not constant
  2. C and CP violation (otherwise, for every reaction giving more B there would be one giving more $\overline{B}$)
  3. Deviation from thermal equilibrium (otherwise, each reaction would be balanced by inverse reaction)
- Is this possible?
  - Options exist for $\#1$ (eg Grand Unified Theories)
  - $\#3$ will occur during phase transitions as temperature falls below mass of relevant particles (bubbles)
  - $\#2$ is the subject of today's lecture.

Discovery of CP Violation (1964)

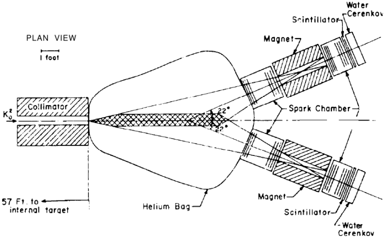


Fig. I. Plan view of the apparatus as located at the A. G. S.

(Cronin and Fitch)

- Create neutral kaon beam
- Long enough decay pipe for K_S to decay away
  - Since K_L has much longer lifetime, it hasn't yet decayed way
- Search for CP violating decay

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

- Handles are:
  - Mass of $\pi^+\pi^-$ pair should be $M(K^0)$
  - Momentum of $\pi^+\pi^-$ points along beam direction

$$\left(\sum_{\pi^+\pi^-} \vec{p} \right)_{\perp} = 0$$

What Was Seen

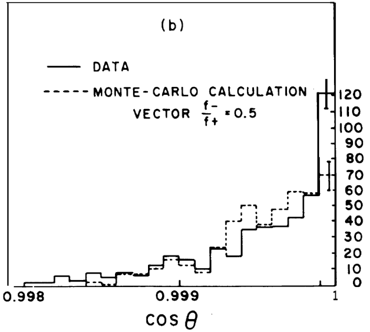
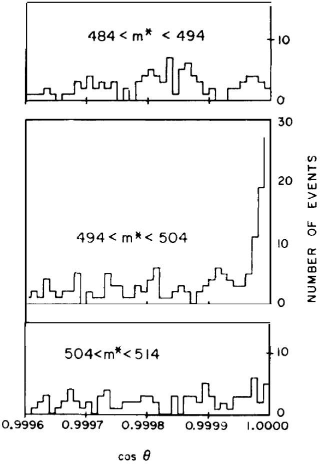


Fig. 2. Angular distributions of those events in the appropriate mass range as measured by a coarse measuring machine.



Clear evidence of $K_L \to \pi^+\pi^-$

How big is the 2π Amplitude?

- Define observed CP parameter

$$|\eta_{+-}| \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = 2.27 \times 10^{-3}$$

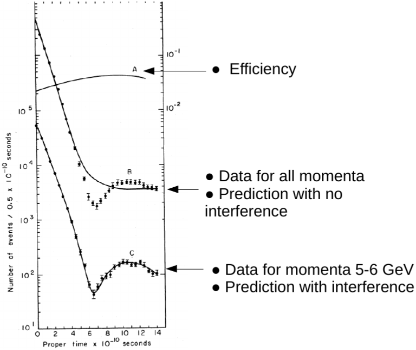
- Suggests CP violation is small but non-zero
- But original experiment couldn't rule out other possibilities
  - Is there a very low mass 3^{rd} particle released in the decay?
  - Are the "π"'s really pions?
- New experiment by Fitch *et al* the next year to rule these possibilities out

Are the Particles Observed in $K_L \to \pi^+\pi^-$ Really Pions?

- Neutral K beam with long decay pipe so only K_L left
- Use regenerator to create K_s. Regenerator amplitude

$$A_R = i\pi N\Lambda \left(\frac{f-\overline{f}}{k}\right)\left(i\delta+\frac{1}{2}\right)^{-1}$$

  k: wave number of incident kaon, f and $\overline{f}$: forward scattering amplitudes, N: number density of the material, Λ: the mean decay length of the K_s, and $\delta = (M_S - M_L)/\Gamma_S$
- $K_L \to \pi^+\pi^-$ yield is proportional to $|A_R + \eta_{+-}|^2$
- Study rate as a function of A_R
  - Pick regenerator so that A_R and η_{+-} similar in size



- Fit data allowing relative phase of η_{+-} and δ as free parameter
- Evidence that K_S and K_L are decaying to the same final state and have constructive interference

More Evidence for CP Violation

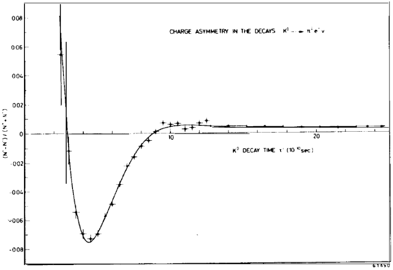


Fig. 3. Time dependence of the charge asymmetry of semileptonic decays.

- Clear Evidence of CP Violation in semileptonic decays as well

$$\delta_\ell = \frac{\Gamma(K_L \to \pi^- \ell^+ \nu_\ell) - \Gamma(K_L \to \pi^+ \ell^- \overline{\nu}_\ell)}{\Gamma(K_L \to \pi^- \ell^+ \nu_\ell) + \Gamma(K_L \to \pi^+ \ell^- \overline{\nu}_\ell)}$$
$$= 3.3 \times 10^{-3}$$

One Additional Observable: $\eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}$

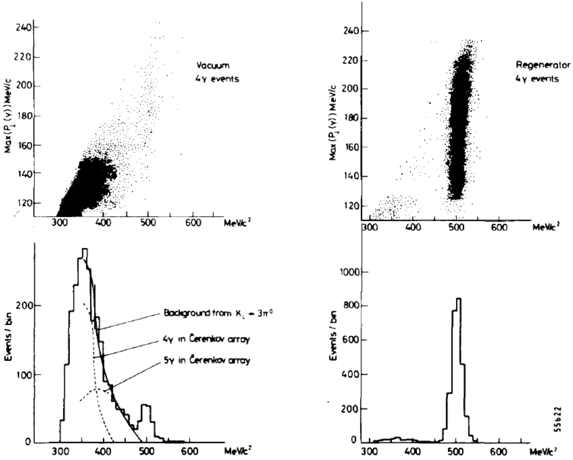
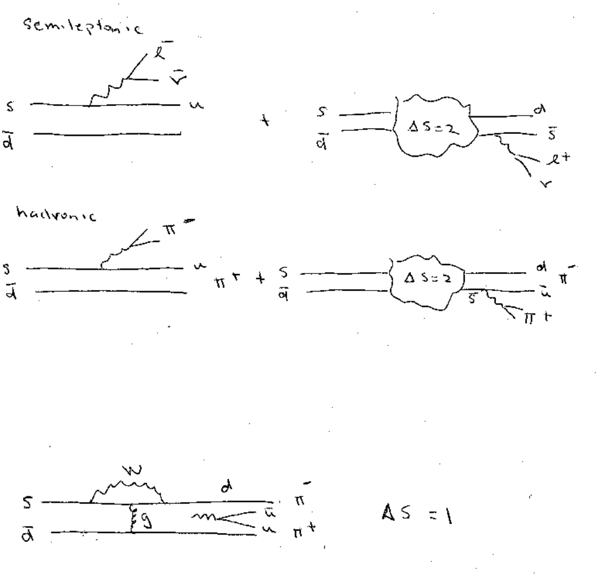


Fig. 4. Distributions of reconstructed $K_L \to \pi^0\pi^0$ events, and regenerated $K_s \to \pi^0\pi^0$ events

$$|\eta_{00}| = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = 2.2 \times 10^{-3}$$

Characterizing CP Violation (I)



- Mixing diagrams may contain CP-violating terms. [They do in the SM (CKM)]

  These diagrams have $\Delta S = 2$
- Both semi-leptonic and hadronic decays can have $\Delta S = 2$
- There may also be diagrams with CP violating terms that have nothing to do with mixing
- These occur via WI because strangeness can't be conserved. We have

  $\Delta S = 1$ (Example shown to left)
- Only hadronic decays can have $\Delta S = 1$

Characterizing CP Violation (II)

- $\Delta S = 2$ required for semi-leptonic decays but both $\Delta S = 2$ and $\Delta S = 1$ possible for hadronic decays
- δ, η_{00} and η_{+-} all have similar size: indicates that $\Delta S = 2$ dominates
- CP violation in the mixing can be described by saying K_L has a bit of $|K_1\rangle$ and K_S has a bit of $|K_2\rangle$

$$\begin{aligned} |K_S\rangle &= \frac{(|K_1\rangle + \epsilon\,|K_2\rangle)}{\sqrt{1+|\epsilon|^2}} \\ |K_L\rangle &= \frac{(|K_2\rangle + \epsilon\,|K_1\rangle)}{\sqrt{1+|\epsilon|^2}} \end{aligned}$$

- Note: $|K_S\rangle$ and $|K_L\rangle$ are NOT orthoginal
- Expressing above in terms of K^0 and $\overline{K}^0$:

$$\begin{aligned} |K_S\rangle &= \frac{1}{\sqrt{2}}\frac{1}{\sqrt{1+|\epsilon|^2}}\left((1+\epsilon)\left|K^0\right\rangle + (1-\epsilon)\left|\overline{K}^0\right\rangle\right) \\ |K_L\rangle &= \frac{1}{\sqrt{2}}\frac{1}{\sqrt{1+|\epsilon|^2}}\left((1+\epsilon)\left|K^0\right\rangle - (1-\epsilon)\left|\overline{K}^0\right\rangle\right) \end{aligned}$$

CP Violation From Mixing Vs Direct CP Violation

- We saw last time

$$i\frac{d\psi}{dt} = \left(\begin{array}{cc} M - i\frac{i}{2}\Gamma/2 & M_{12} - i\frac{i}{2}\Gamma_{12}/2 \\ M^*{}_{12} - i\frac{i}{2}\Gamma^*{}_{12}/2 & M - i\frac{i}{2}\Gamma/2 \end{array} \right)\psi$$

- If we write $\delta m = \delta m_R + i\delta m_I$ can show

$$\epsilon = \frac{i\delta m_I}{m_L - m_S + i\Gamma_S/2}$$

- You will show on HW that

$$\delta_\ell = 2\mathrm{Re}\ \epsilon$$

- If direct CP violation ($\Delta S = 1$) will need one additional parameter (called ϵ').
  - In K system, this is small, even when compared to ϵ

Measurement of ϵ'/ϵ

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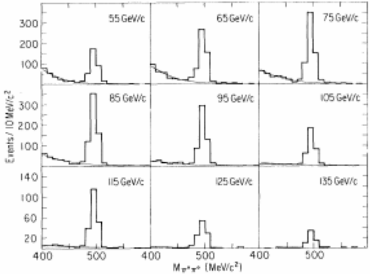


FIG. 2. Invariant-mass distributions for $K_L \to 2\pi^0$ candidates with $P_T^2 < 2500$ (MeV/c)^2. A fit to the background is superimposed.

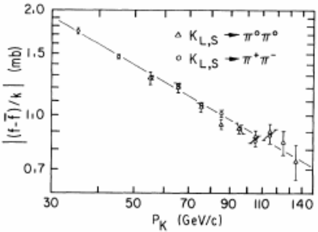
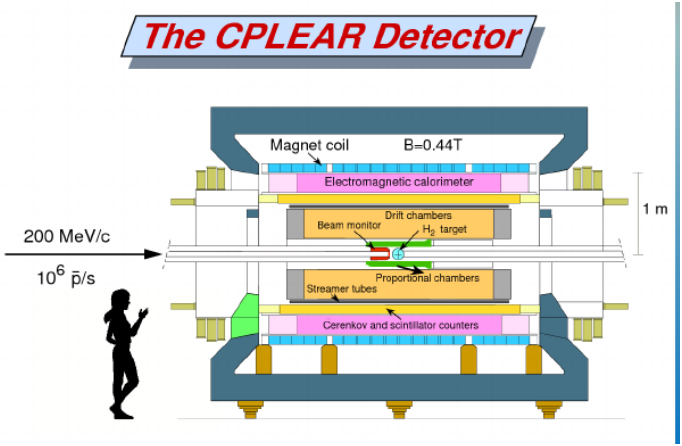


FIG. 3. $|(f-\bar{f})/k|$ for carbon vs momentum from $\pi^+\pi^-$ and $\pi^0\pi^0$ samples. The best power-law fit is superimposed. Were $\epsilon'/\epsilon = 0.01$, the neutral points would lie about 3% above the charged points.

- Must have precision to determine that η_{00} and η_{+-} have different values

  2014 PDG Average: $Re(\epsilon'/\epsilon) = (1.66 \pm 0.23) \times 10^{-3}$

A Higher Statisitcs K^0 CP Experiment: CPLear

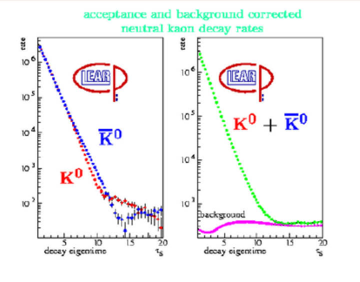


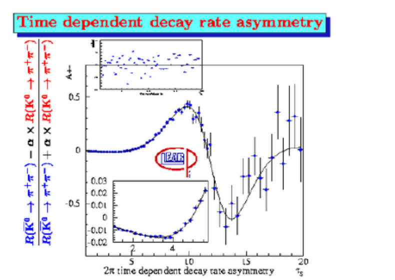
- Data taking 1990-1996 at CERN
- Anti-protons stopped in hydrogen target

$$p\bar{p} \rightarrow K^{\pm}\pi^{\mp}K^0$$

- Strangeness of neutral kaon at production tagged by charge of charged kaon

CPLear Measurement of η_{+-}





$$A_{+-}(\tau) = -\frac{2|\eta_{+-}|e^{\frac{1}{2}(1/\tau_S - 1/\tau_L)\tau}\cos(\Delta m \cdot \tau - \varphi_{+-})}{1 + |\eta_{+-}|^2 e^{(1/\tau_S - 1/\tau_L)\tau}}$$

$$|\eta_{+-}| = (2.264 \pm 0.023_{sta.} \pm 0.026_{sys.} \pm 0.007_{\tau_S}) \times 10^{-3}$$
$$\varphi_{+-} = 43.19^\circ \pm 0.53^\circ_{sta.} \pm 0.28^\circ_{sys.} \pm 0.42^\circ_{\Delta m}$$

with $\Delta m = (530.1 \pm 1.4) \times 10^7 \hbar s^{-1}$ PDG '98

published in Phys. Lett. B 458 (1999) 545

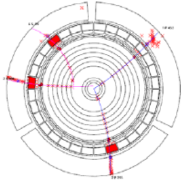
$$A_{2\pi} = \frac{R(\overline{K}^0 \to \pi\pi)(\tau) - \alpha \times R(K^0 \to \pi\pi)(\tau)}{R(\overline{K}^0 \to \pi\pi)(\tau) + \alpha \times R(K^0 \to \pi\pi)(\tau)}$$
$$= -2|\eta_{\pi\pi}|\cos(\Delta m\tau - \varphi_{\pi\pi})\frac{e^{\frac{1}{2}(\Gamma_S - \Gamma_L)\tau}}{1 + |\eta_{\pi\pi}|^2 e^{(\Gamma_S - \Gamma_L)\tau}}$$

- α **is a free parameter in the fit,** $\alpha = \frac{\varepsilon(K^+)}{\varepsilon(K^-)}[1 + 4\mathbb{R}(\varepsilon_T + \delta)]$ **used as rate normalization in other decay channels**

With Δm free in the fit, not assuming CPT,
$\Delta m = (524.0 \pm 4.4 \pm 3.3) \times 10^7 \hbar s^{-1}$

CPLear Measurement of δ

Analysis of $K^0 \to \pi^{\mp} e^{\pm} \nu$

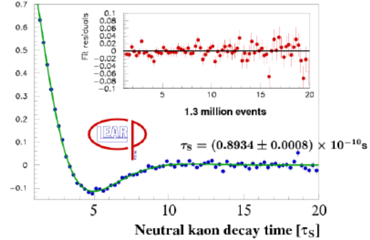


- kinematical constraints
- electron identification based on:
- dE/dx in the scintillators,
- number of photo-electrons in the Čerenkov,
- number of hits in the calorimeter

$K_L - K_S$ Mass Difference

$$A_{\Delta m} = \frac{N_{K^0 \leftarrow K^0, \bar{K}^0 \leftarrow \bar{K}^0} - N_{\bar{K}^0 \leftarrow K^0, K^0 \leftarrow \bar{K}^0}}{N_{K^0 \leftarrow K^0, \bar{K}^0 \leftarrow \bar{K}^0} + N_{\bar{K}^0 \leftarrow K^0, K^0 \leftarrow \bar{K}^0}}$$

$$= 2\frac{e^{-\bar{\Gamma}\tau}\cos\Delta m\tau + 2\Im(x_-)e^{-\bar{\Gamma}\tau}\sin\Delta m\tau}{[1+2\Re(x_+)]e^{-\Gamma_S\tau} + [1-2\Re(x_+)]e^{-\Gamma_L\tau}}$$



$$\Delta m = (529.5 \pm 2.0_{stat.} \pm 0.3_{syst.}) \times 10^7 \hbar s^{-1}$$

$$\Delta m = (348.5 \pm 1.3) \times 10^{-9}\ \mathrm{eV/c^2}$$

$\Delta S = \Delta Q$ violating decays or wrong tagging:

$$\Re e\, x_+ = (-1.8 \pm 4.1_{stat.} \pm 4.5_{syst.}) \times 10^{-3}$$

Best single measurements: Phys.Lett. B444 (1998) 38

Precise measurement of the oscillation frequency Δm (setting $\Im(x_-)$=0) :

Δm and $\Im(x_-)$ are strongly correlated, >0.99.
With $\Delta m = (530.1 \pm 1.4) \times 10^7 \hbar s^{-1}$ obtain
$\Im(x_-) = (-0.8 \pm 3.5) \times 10^{-3}$

A Modern Treatment of CP Violation

- Reminder:

$$
\begin{aligned}
V_{CKM} &= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{ds} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \\
&\approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}
\end{aligned}
$$

- Note, from the explicit form, you can prove:

$$\rho + i\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

- Unitarity insures $VV^\dagger = V^\dagger V = 1$. Thus

$$
\begin{aligned}
\sum_i V_{ij}V_{ik}^* &= \delta_{jk} \text{ column orthogonality} \\
\sum_j V_{ij}V_{kj}^* &= \delta_{ik} \text{ row orthogonality}
\end{aligned}
$$

- Eg:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

The Unitarity Triangle

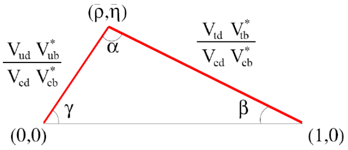
- From previous page

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- Divide by $|V_{cd}^* V_{cb}|$:

$$\frac{V_{ud}V_{ub}^*}{|V_{cd}^* V_{cb}|} - 1 + \frac{V_{td}V_{tb}^*}{|V_{cd}^* V_{cb}|} = 0$$

- Think of this as a vector equation in the complex plane
- Orient so that base is along x-axis

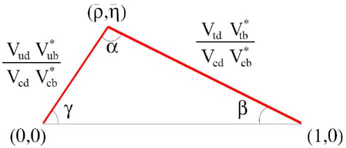


- Reminder from previous page:

$$\rho + i\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

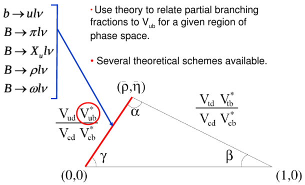
The Measurement Game Plan

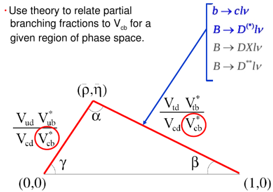
- Want to test if matrix is unitary
  - Failure of unitarity means new physics
- Make *many* measurements of sides and angles to over-constrain the triange and test that it closes

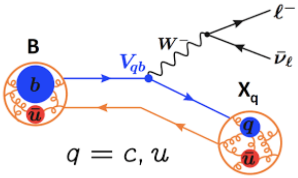


$$
\begin{aligned}
\alpha &\equiv arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*] \\
\beta &\equiv arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*] \\
\gamma &\equiv arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]
\end{aligned}
$$

Measuring the Sides (example): B and D Decays







- Sides are combinations of magnitudes of CKM matrix elements
- Heavy flavor decays one way to measure these
  - V_{cd} from $D_s \to K\ell\nu$, $D \to \pi\ell\nu$
  - V_{cs} from $D_s^+ \to \mu^+\nu$, $D \to K\ell\nu$
  - V_{cb} from $B \to X_c\ell\nu$ ($X_c \equiv D, D^*$, etc)
  - V_{ub} from $B \to X_d\ell\nu$ ($X_d \equiv \pi, \rho$, etc)
- Requires precise measurement of branching fractions
- Must correct for fact that c or b-quark is bound in a meson
  - Need theory for this

Angle Measurements: Types of CP Violation

- Three different categories
  - Direct CP Violation

$$Prob(B \to f) \neq Prob(\overline{B} \to \overline{f})$$

  - Indirect CP Violation (CPV in mixing)

$$Prob(B \to \overline{B}) \neq Prob(\overline{B} \to B)$$

  - CP Violation between mixing and decay
    - B^0 and $\overline{B}^0$ can decay to the same final particles
    - Two diagrams are

$$B^0 \to f \quad \text{and} \quad B^0 \to \overline{B} \to f$$

- Third category cleanest theoretically since no issues of final state interations
- Always need more than one amplitude to allow interference

The Angles of the Unitarity Triangle

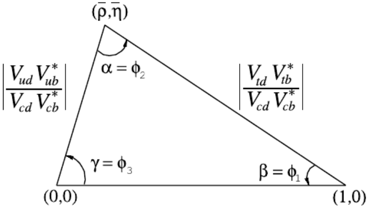


Figure 12.1: Sketch of the unitarity triangle.

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$
$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- CP violating phase in V_{ub} and V_{td}
  - By convention: can do rotations to move the phase to other elements
- $|A|^2$ is real for any single amplitude
  - Need at least 2 amplitudes to see CP violating effects
- Only cases where all 3 generations are involved exhibit CP violation

Classifying CP Violating Effects

- CP Violation in Decays

$$\Gamma(P \to f) \neq \Gamma(\overline{P} \to \overline{f})$$

or (even better) if $f = \overline{f}$

$$\Gamma(P^0 \to f) \neq \Gamma(\overline{P}^0 \to f)$$

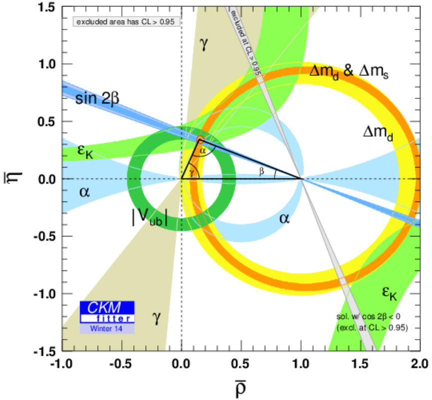
- CP Violation in Mixing

$$Prob(P^0 \to \overline{P}^0) \neq Prob(\overline{P}^0 \to P^0)$$

- CP Violation in Interference
  - Time dependent asymetry dependent on fraction of P^0 at time t

B-decays will provide a rich laboratory for studying all three of these

Combined Results



- Unlike K system, B decays provide MANY ways to measure CP violation
- Want to determine if all consistent with single value of (ρ, η)
- Pick measurements where theoretical uncertainties under control