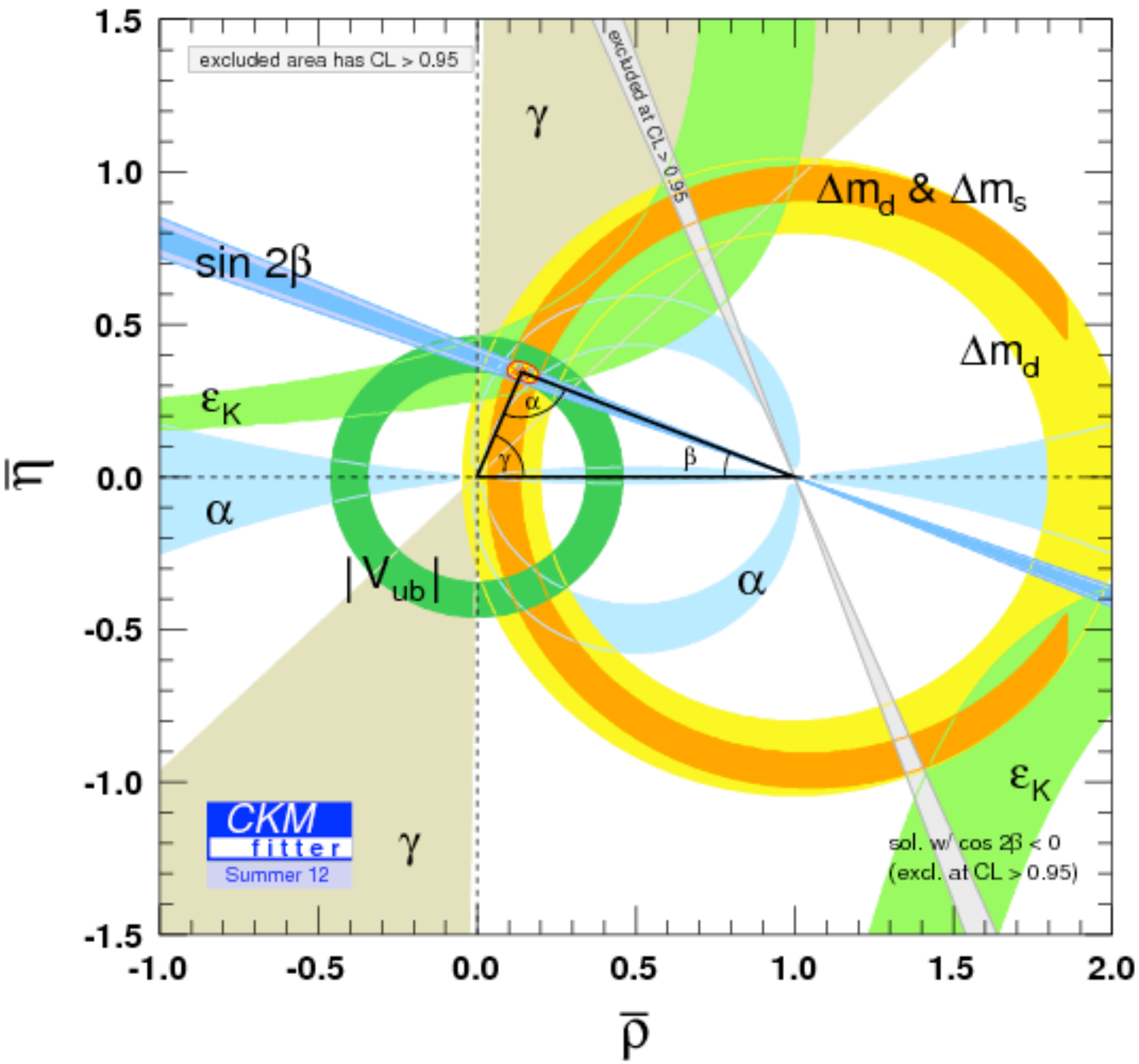
Particle Physics

Dr Victoria Martin, Spring Semester 2013

Lecture 15: Measuring *CP* Violation



★Mixing and decays of kaons

★CKM Matrix revisited

★The unitarity triangle

Reminder: Guest Seminars

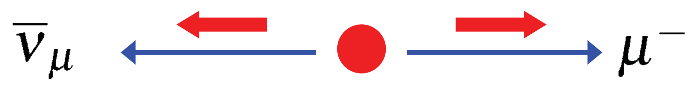
- From Edinburgh University researchers on their work.

- Monday (18th March) in tutorial:
    - Guest seminar from Dr Greig Cowan on B-physics at LHCb

- Following Monday (25th March) in tutorial
    - Guest seminar from Dr Wahid Bhimji on Higgs physics at ATLAS

Parity Violation in Pion Decays

- Consider charged pion decay at rest, $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$
- Charged pion has $S = 0$
    - ➡ muon and neutrino produced with equal & opposite spin
        - ➡ The muon and neutrino will have identical helicities



Helicity: +1 (RH) Helicity: +1 (RH)

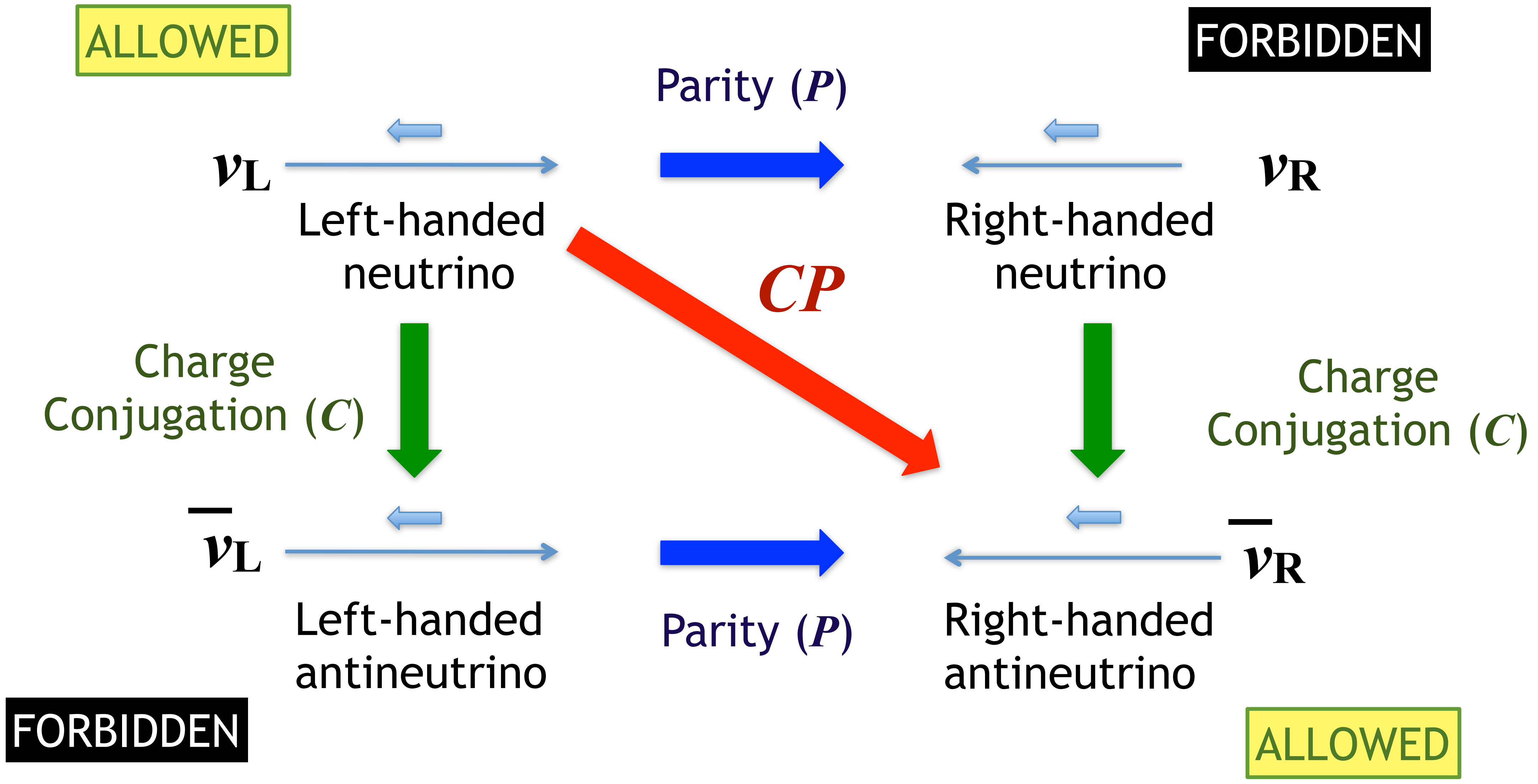
chirality: RH chirality: LH

$$\hat{h} = \frac{\vec{\sigma} \cdot \vec{p}}{|\vec{p}|}$$

- ➡ Experiments observe muon helicity is always right-handed
- ➡ **Conclusion**: Only right-handed anti-neutrinos exist!

- Similarly for $\pi^+ \rightarrow \mu^+ + \nu_\mu$ anti-muon helicity is always left-handed
    - ➡ only left-handed neutrinos exist!
- This observation also explains why $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$ is preferred over $\pi^- \rightarrow e^- + \overline{\nu}_e$
    - ➡ Weak force decay produces **particles with left handed chirality** and **antiparticles with right handed chirality**
    - ➡ The amount of LH chiral in a RH helicity state is related to **β** of the lepton. In terms of lepton (***ℓ***) mass: $\propto \dfrac{m_\ell}{m_\pi + m_\ell}$

Neutrino States



ALLOWED

FORBIDDEN

Parity (*P*)

ν_L Left-handed neutrino

ν_R Right-handed neutrino

CP

Charge Conjugation (*C*)

Charge Conjugation (*C*)

$\bar{\nu}_L$ Left-handed antineutrino

Parity (*P*)

$\bar{\nu}_R$ Right-handed antineutrino

FORBIDDEN

ALLOWED

Parity changes the direction of momentum, but not spin:
Left handed helicity → right handed helicity

Charge conjugation changes the sign of all charges:
particle → anti-particle

The existence of the ν_L and $\bar{\nu}_R$ suggests that *CP* is a good symmetry in the weak interaction

From Last Lecture: Summary

- Parity ***P*** and Charge Conjugation ***C*** are maximally violated in weak interactions due to vector − axial vector structure of interaction vertex.
  - Conserved in strong and electromagnetic interactions.

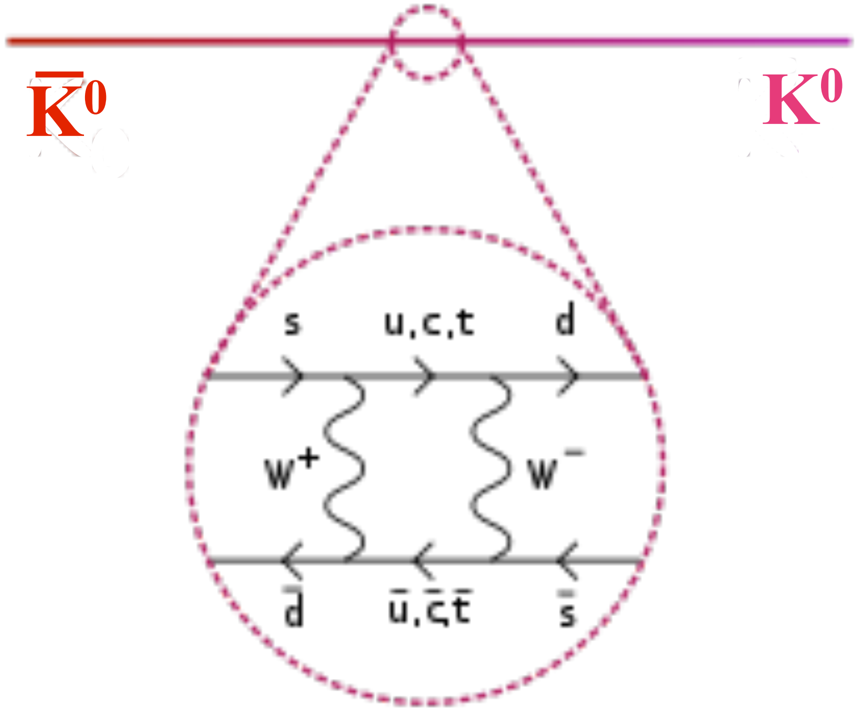
- The combined symmetry ***CP*** describes the difference between matter and anti-matter
  - The existence of only LH neutrinos and RH anti-neutrinos suggest ***CP*** is good symmetry in the weak force.

- ***CPT*** symmetry must be conserved… it’s one of the foundations of QM and field theory!

Neutral Meson Mixing

- Second order weak interactions can mix long-lived neutral mesons with their antiparticles:
  - ➡ $\mathbf{K^0\,(\bar{s}\,d)}$, $\mathbf{D^0\,(\bar{c}\,u)}$, $\mathbf{B^0\,(\bar{b}\,d)}$, $\mathbf{B_s\,(\bar{b}\,s)}$ $\quad$ $\mathbf{K^0 \leftrightarrow \overline{K}^0}$ $\;\mathbf{D^0 \leftrightarrow \overline{D}^0}$ $\;\mathbf{B^0 \leftrightarrow \overline{B}^0}$ $\;\mathbf{B_s \leftrightarrow \overline{B}_s}$

- e.g. take the neutral kaons $\mathbf{K^0}$ & $\mathbf{\overline{K}^0}$ as an example:



$$P\,|\mathrm{K}^0\rangle = -|\mathrm{K}^0\rangle \qquad P\,|\overline{\mathrm{K}}^0\rangle = -|\overline{\mathrm{K}}^0\rangle$$

$$CP\,|\mathrm{K}^0\rangle = -|\overline{\mathrm{K}}^0\rangle \qquad CP\,|\overline{\mathrm{K}}^0\rangle = -|\mathrm{K}^0\rangle$$

  - The ***CP*** eigenstates are:

$$|\mathrm{K}_1\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{K}^0\rangle - |\overline{\mathrm{K}}^0\rangle\right) \qquad CP = +1$$

$$|\mathrm{K}_2\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{K}^0\rangle + |\overline{\mathrm{K}}^0\rangle\right) \qquad CP = -1$$

Neutral Kaon Decay

- Decay eigenstates are (approximately) $\mathbf{K_1}$ (CP=+1) and $\mathbf{K_2}$ (CP=−1)
  - **not** the same as the flavour eigenstates $\mathbf{K^0}$ and $\mathbf{\overline{K}^0}$

- Two common decay modes of kaons $\mathbf{2\pi}$ and $\mathbf{3\pi}$
  - $\pi^0\pi^0$ and $\pi^+\pi^-$ have $CP = +1$
  - $\pi^0\pi^0\pi^0$ and $\pi^+\pi^-\pi^0$ have $CP = -1$

- If CP is a good symmetry in kaon decay (which it nearly is) we expect:
  - $K_1 \rightarrow \pi^0\pi^0\ ,\ \pi^+\pi^-$ $CP = +1$ conserved
  - $K_2 \rightarrow \pi^0\pi^0\pi^0$ and $\pi^+\pi^-\pi^0$ $CP = -1$ conserved

- $\mathbf{K_1 \rightarrow \pi\pi}$ has large phase space ⇒ quick decay, travels ~ cm before decay
  - named "**K**-short" or $\mathbf{K_S}$ with $\boldsymbol{\tau_S = 0.09}$ **ns**
- Decay $\mathbf{K \rightarrow \pi\pi\pi}$ has small phase space ⇒ slow decay, travels ~ 10 m before decay
  - "**K**-long" or $\mathbf{K_L}$ with $\boldsymbol{\tau_L = 51}$ **ns**

Neutral Kaons continued

- Because the kaons can mix, a kaon state can be described as a superposition of $\mathbf{K^0}$ and $\mathbf{\overline{K}^0}$:

$$\psi(t) = \begin{pmatrix} a(t)|\mathrm{K}^0\rangle \\ b(t)|\overline{\mathrm{K}}^0\rangle \end{pmatrix}$$

- The hamiltonian will describe both the mixing the decay in terms of two hermitian matrices:

$$i\frac{\partial\psi(t)}{\partial t} = \hat{H}\psi(t) = (\hat{M} - \frac{i}{2}\hat{\Gamma})\psi(t)$$

$$\hat{M} - \frac{i}{2}\hat{\Gamma} = \begin{pmatrix} M_{\mathrm{K}} & \Delta m_{\mathrm{K}} \\ (\Delta m_{\mathrm{K}})^* & M_{\mathrm{K}} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{\mathrm{K}} & \Delta\Gamma_{\mathrm{K}} \\ (\Delta\Gamma_{\mathrm{K}})^* & \Gamma_{\mathrm{K}} \end{pmatrix}$$

- Mass difference $\mathbf{\Delta m_K = m_S - m_L = 3.52(1)\ x10^{-12}\ MeV = 0.53\ x\ 10^{-10}\ s^{-1}}$ is a measure of the oscillation frequency

Neutral Kaon Properties

K_S^0

$I(J^P) = \frac{1}{2}(0^-)$

Mean life $\tau = (0.8954 \pm 0.0004) \times 10^{-10}$ s (S = 1.1) Assuming *CPT*

Mean life $\tau = (0.89564 \pm 0.00033) \times 10^{-10}$ s Not assuming *CPT*

$c\tau = 2.6844$ cm Assuming *CPT*

K_S^0 DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Hadronic modes			
$\pi^0\pi^0$	(30.69 ± 0.05) %		209
$\pi^+\pi^-$	(69.20 ± 0.05) %		206

K_L^0

$I(J^P) = \frac{1}{2}(0^-)$

$m_{K_L} - m_{K_S}$

$= (0.5293 \pm 0.0009) \times 10^{10}\ \hbar\ s^{-1}$ (S = 1.3) Assuming *CPT*

$= (3.484 \pm 0.006) \times 10^{-12}$ MeV Assuming *CPT*

$= (0.5289 \pm 0.0010) \times 10^{10}\ \hbar\ s^{-1}$ Not assuming *CPT*

Mean life $\tau = (5.116 \pm 0.021) \times 10^{-8}$ s (S = 1.1)

$c\tau = 15.34$ m

K_L^0 DECAY MODES			Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic modes					
$\pi^\pm e^\mp \nu_e$ Called K_{e3}^0.		[*n*]	(40.55 ± 0.11) %	S=1.7	229
$\pi^\pm \mu^\mp \nu_\mu$ Called $K_{\mu 3}^0$.		[*n*]	(27.04 ± 0.07) %	S=1.1	216
$(\pi\mu\text{atom})\nu$			$(1.05 \pm0.11) \times 10^{-7}$		188
$\pi^0\pi^\pm e^\mp \nu$		[*n*]	$(5.20 \pm0.11) \times 10^{-5}$		207
$\pi^\pm e^\mp \nu e^+ e^-$		[*n*]	$(1.26 \pm0.04) \times 10^{-5}$		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*	[*p*]	$(1.967\pm0.010) \times 10^{-3}$	S=1.5	206
$\pi^0\pi^0$	*CPV*		$(8.64 \pm0.06) \times 10^{-4}$	S=1.8	209

http://pdg.lbl.gov/2012/tables/rpp2012-tab-mesons-strange.pdf

Neutral Kaons with *CP* Violation

- The *CP* eigenstates are **K₁** and **K₂**

$$|\mathrm{K}_1\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{K}^0\rangle - |\overline{\mathrm{K}}^0\rangle\right) \qquad CP = +1$$

$$|\mathrm{K}_2\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{K}^0\rangle + |\overline{\mathrm{K}}^0\rangle\right) \qquad CP = -1$$

- The decay $\mathbf{K_S}$ and $\mathbf{K_L}$ are not quite identical to the *CP* eigenstates; in terms of a (small) parameter **ε**:

N is an overall normalisation factor

$$|\mathrm{K}_\mathrm{S}\rangle = \frac{1}{N}\left((1+\epsilon)|\mathrm{K}^0\rangle - (1-\epsilon)|\overline{\mathrm{K}}^0\rangle\right)$$

$$|\mathrm{K}_\mathrm{L}\rangle = \frac{1}{N}\left((1+\epsilon)|\mathrm{K}^0\rangle + (1-\epsilon)|\overline{\mathrm{K}}^0\rangle\right)$$

- Both $\mathbf{K_S}$ and $\mathbf{K_L}$ contain slightly more $\mathbf{K^0}$ (matter) than $\mathbf{\overline{K}^0}$ (antimatter). The decay states contain both $CP = +1$ and $CP = -1$: *CP* is violated in weak force decay

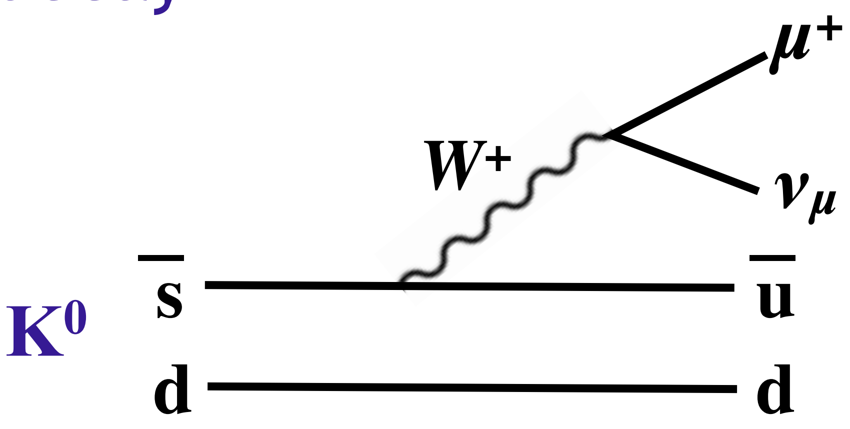
$$|\mathrm{K}_\mathrm{S}\rangle = \frac{1}{N}\left(|\mathrm{K}_1\rangle - \epsilon|\mathrm{K}_2\rangle\right)$$

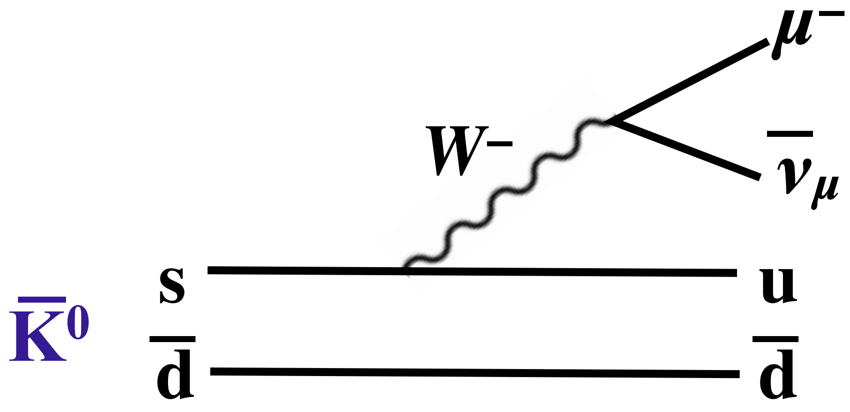
$$|\mathrm{K}_\mathrm{L}\rangle = \frac{1}{N}\left(|\mathrm{K}_2\rangle + \epsilon|\mathrm{K}_1\rangle\right)$$

- **ε** is measured to be $|\varepsilon| \sim 2 \times 10^{-3}$, the amount of **indirect *CP* violation**

CP and *T* Violation in $\mathrm{K_L} \to \pi\,\ell\,\nu$

- *CP* violation is also observed in the semileptonic decay $\mathrm{K_L} \to \pi\,\ell\,\nu$
  - ➡ ℓ stands for e or μ
  - ➡ $\mathrm{K^0}$ can only decay as $\mathrm{K^0} \to \pi^-\,\ell^+\,\nu$
  - ➡ $\overline{\mathrm{K}}{}^0$ can only decay as $\overline{\mathrm{K}}{}^0 \to \pi^+\,\ell^-\,\bar{\nu}$
- $\mathrm{K_L} = 1/\mathrm{N}\ [\,(1+\varepsilon)\,\mathrm{K^0} + (1-\varepsilon)\,\overline{\mathrm{K}}{}^0\,]$





- Measure asymmetry in $\mathrm{K_L}$ decay rates:

$$\delta = \frac{\Gamma(\mathrm{K_L} \to \pi^-\ell^+\nu) - \Gamma(\mathrm{K_L} \to \pi^+\ell^-\bar{\nu})}{\Gamma(\mathrm{K_L} \to \pi^-\ell^+\nu) + \Gamma(\mathrm{K_L} \to \pi^+\ell^-\bar{\nu})}$$

$$\delta = \frac{(1+\epsilon)^2 - (1-\epsilon)^2}{(1+\epsilon)^2 + (1-\epsilon)^2} = 2\,\mathcal{R}e\,(\epsilon)$$

- Measured to be $\delta = 3.27(12) \times 10^{-3}$
- *CP* violation due to the mixing of the *CP* eigenstates

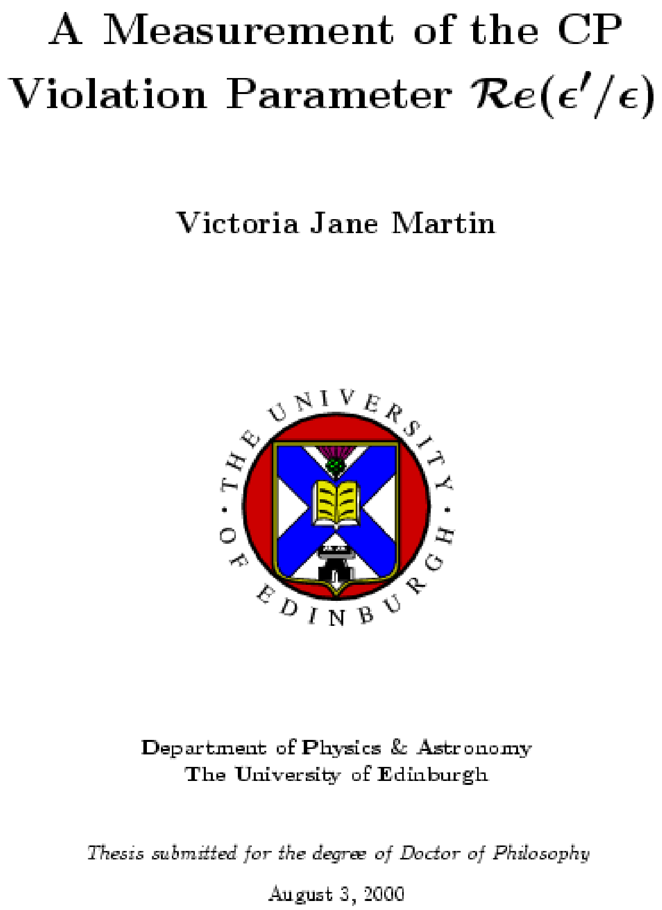
CP Violation in $K \rightarrow \pi\pi$

- $K_L \sim K_2 + \varepsilon K_1$ mainly $CP = -1$ plus a little $CP = +1$
    - K_L is observed decay into both $\pi\pi\pi$ ($CP = -1$) and $\pi\pi$ ($CP = +1$)

- Measured rate of $K_L \rightarrow \pi\pi$ is slightly larger than can be accommodated by ε

- A small amount (ε') of the K_2 in K_L decays **directly** to $\pi\pi$.
    - Known as **direct *CP* violation**, measured to be $|\varepsilon'/\varepsilon| = 1.65(26) \times 10^{-3}$

- **It took 40 year's of effort to measure these effects!**
    - (including VJM's PhD thesis →)



A Measurement of the CP
Violation Parameter $\mathcal{R}e(\epsilon'/\epsilon)$

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The University of Edinburgh

Thesis submitted for the degree of Doctor of Philosophy

August 3, 2000

- The observed amount of *CP* violation in these experiments is very small $\sim 10^{-3}$
- *CP* is nearly a good symmetry in the weak interaction

Types of *CP* Violation

For reference, three types of *CP* violation are classified:

1. **Direct *CP* violation** in decay amplitudes
   - Can occur in both charged and neutral particle decays
   - e.g. ε', the $CP=-1$ state decays directly to $CP=+1$ final state

2. ***CP* violation in neutral meson mixing**
   - e.g. rate for $K^0 \to \bar{K}^0$ not equal to rate for $\bar{K}^0 \to K^0$, measured in semileptonic decay by δ

3. **Indirect *CP* violation due to interference between mixing and decay**
   - e.g. ε measures decay mixing between $CP=-1$ and $CP=+1$ states

Summary

- The *CP* symmetry describes the difference between matter and anti-matter - almost a good symmetry in the weak interactions.

- Small amounts of *CP* violation observed in $\mathbf{K^0}$ $\mathbf{B^0}$ $\mathbf{D^0}$ $\mathbf{B_s{}^0}$ through decays and mixing.

- Three types of *CP* violation:
    1. Direct *CP* violation in decay amplitudes
    2. *CP* violation in neutral meson mixing
    3. Indirect *CP* violation due to interference of mixing and decay.

- *CP* violation is accommodated in the Standard Model through a complex phase in the CKM matrix.

- The unitarity triangle of the CKM matrix is used to understand observation of the *CP* violation, and see if measurements are consistent.