Symmetries and CP violation
Thanks to A Hocker and M. Bona
Today’s topics

• Symmetries
  – Broken symmetries
• Neutral kaon mixing
• CP violation
  – Matter / anti-matter asymmetry
• The CKM matrix
What do we mean by conservation/violation of a symmetry?

- Define a quantum mechanical operator $O$.
- If $O$ describes a good symmetry:
  
  Physics ‘looks the’ same before and after applying the symmetry i.e. the observed quantity associated with $O$ is conserved (same before and after the operator is applied). e.g. conservation of energy-momentum etc.

  e.g. probabilities are the same for matter and antimatter doing something.

- If this condition is not met – the symmetry is broken.
  
  That is, the symmetry is not respected by nature. So $O$ is (at best) a mathematical tool used to help our understanding of nature.

  Slightly broken symmetries (like isospin in EW interactions) can be very useful!

  e.g. Isospin symmetry assumes that $m_u=m_d$. In doing so we can estimate branching fractions where the final state differs by a $\pi^0$ vs a $\pi^\pm$ etc. The difference comes from a Clebsch-Gordan coefficient.
Continuous Symmetries and Conservation Laws

In classical mechanics, we have learned that to each continuous symmetry transformation, which leaves the scalar Lagrange density invariant, can be attributed a conservation law and a constant of movement (E. Noether, 1915).

Continuous symmetry transformations lead to additive conservation laws.

<table>
<thead>
<tr>
<th>Symmetry</th>
<th>Invariance under movement in time</th>
<th>Homogeneity of space</th>
<th>Isotropy of space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformation</td>
<td>Translation in time</td>
<td>Translation in space</td>
<td>Rotation in space</td>
</tr>
<tr>
<td>Conserved quantity</td>
<td>Energy</td>
<td>Linear momentum</td>
<td>Angular momentum</td>
</tr>
</tbody>
</table>

No evidence for violation of these symmetries seen so far.
Continuous Symmetries and Conservation Laws

In general, if \( U \) is a symmetry of the Hamiltonian \( H \), one has:

\[
[H, U] = 0 \Rightarrow H = U^\dagger H U
\]

\[
\langle f' | H | i' \rangle = \langle U f | H | U i \rangle = \langle f | U^\dagger H U | i \rangle = \langle f | H | i \rangle
\]

Accordingly, the Standard Model Lagrangian satisfies local gauge symmetries (the physics must not depend on local (and global) phases that cannot be observed):

- **U(1) gauge transformation** → **Electromagnetic interaction**
- **SU(2) gauge transformation** → **Weak interaction**
- **SU(3)_C gauge transformation** → **Strong interaction (QCD)**

Conserved additive quantum numbers:

- **Electric charge** (processes can move charge between quantum fields, but the sum of all charges is constant)
- Similar: color charge of quarks and gluons, and the weak charge
- **Quark (baryon) and lepton numbers** (however, no theory for these, therefore believed to be only approximate asymmetries) → evidence for lepton flavor violation in “neutrino oscillation”
Discrete Symmetries

Discrete symmetry transformations lead to multiplicative conservation laws

The following discrete transformations are fundamental in particle physics:

❖ **Parity** $P$ ("handedness"):  
Reflection of space around an arbitrary center;  
$P$ invariance $\rightarrow$ cannot know whether we live in this world, or in its mirror world

❖ **Particle-antiparticle transformation** $C$:
Change of all additive quantum numbers (for example the electrical charge) in its opposite ("charge conjugation")

❖ **Time reversal** $T$:
The time arrow is reversed in the equations;  
$T$ invariance $\rightarrow$ if a movement is allowed by a the physics law, the movement in the opposite direction is also allowed

---

Time reversal symmetry (invariance under change of time direction) does certainly not correspond to our daily experience. The macroscopic violation of $T$ symmetry follows from maximising thermodynamic entropy (leaving a parking spot has a larger solution space than entering it). In the microscopic world of single particle reactions thermodynamic effects can be neglected, and $T$ invariance is realised.
Time reversal \( T \) (invariance under change of time direction) does certainly not correspond to our daily experience. The macroscopic violation of \( T \) symmetry follows from maximising thermodynamic entropy (leaving a parking spot has a larger solution space than entering it). In the microscopic world of single particle reactions thermodynamic effects can be neglected, and \( T \) invariance is realised.
# C, P, T Transformations and the CPT Theorem

<table>
<thead>
<tr>
<th>Quantity</th>
<th>P</th>
<th>C</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space vector</td>
<td>−x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Time</td>
<td>t</td>
<td>t</td>
<td>−t</td>
</tr>
<tr>
<td>Momentum</td>
<td>−p</td>
<td>p</td>
<td>−p</td>
</tr>
<tr>
<td>Spin</td>
<td>s</td>
<td>s</td>
<td>−s</td>
</tr>
<tr>
<td>Electrical field</td>
<td>−E</td>
<td>−E</td>
<td>E</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>B</td>
<td>−B</td>
<td>−B</td>
</tr>
</tbody>
</table>

The CPT theorem (1954): “Any Lorentz-invariant local quantum field theory is invariant under the successive application of C, P and T”

**Fundamental consequences:**

- Relation between spin and statistics: fields with integer spin (“bosons”) commute and fields with half-numbered spin (“fermions”) anticommute → Pauli exclusion principle
- Particles and antiparticles have **equal mass and lifetime**, equal magnetic moments with opposite sign, and **opposite quantum numbers**

**Best experimental test:** \[ \left| \frac{m_{K^0} - m_{\bar{K}^0}}{m_{K^0}} \right| < 10^{-18} \]
EM and strong interactions are (so far) C, P, and T invariant

Example: \( \pi^0 \rightarrow \gamma \gamma \) but not \( \pi^0 \rightarrow \gamma \gamma \gamma \)

\[
\pi^0 = \frac{1}{\sqrt{2}} [u \bar{u} - d \bar{d}]_{L=0,S=0} \Rightarrow C|\pi^0\rangle = +|\pi^0\rangle
\]
\[
C \cdot \vec{B}, \vec{E} = -\vec{B}, \vec{E} \Rightarrow C|\gamma\rangle = -|\gamma\rangle
\]

Thus initial and final states are C even, \textit{C is conserved}

In general:

\[
P|q \bar{q}\rangle = (-1)^{L+1}|q \bar{q}\rangle, \quad C|q \bar{q}\rangle = (-1)^{L+S}|q \bar{q}\rangle
\]

Experimental tests of P and C invariance of the EM interaction:

C invariance: \( \text{BR}(\pi^0 \rightarrow 3\gamma) < 3.1 \times 10^{-8} \)

P invariance: \( \text{BR}(\eta \rightarrow 4\pi^0) < 6.9 \times 10^{-7} \)

Experimental tests of C invariance of strong interaction: Compare rates of positive and negative particles, like \( pp \rightarrow \pi^+ \pi^- X, \quad K^+ K^- X, \ldots \)
And … the Surprise in Weak Interaction!

T.D. Lee and C.N. Yang pointed out in 1956 (to explain the observation of the decays $K \rightarrow 2\pi$ and $3\pi$ - the cosmic-ray $\theta/\tau$ puzzle) that $P$ invariance had not been tested in weak interaction $\rightarrow$ C.S. Wu performed in 1957 the experiment they suggested and observed parity violation.

Angular distribution of electron intensity:

$$I(\theta) = 1 + \alpha \frac{\vec{\sigma} \cdot \vec{P}_e}{E_e} = 1 + \left( \frac{\nu}{c} \right) \cos \theta$$

where:  
- $\vec{\sigma}$ - spin vector of electron  
- $\vec{P}_e$ - electron momentum  
- $E_e$ - electron energy  
- $\alpha = \begin{cases} -1 & \text{for electron} \\ +1 & \text{for positron} \end{cases}$

It was found that parity is even maximally violated in weak interactions!
Neutral Kaon Mixing

- Neutral kaons “mix” through the charged weak current, which does not conserve strangeness, neither $P$ nor $C$. Weak interaction cannot distinguish $K^0$ from $\bar{K}^0$.

- Simple picture: they mix through common virtual states:

  $K^0$ \xrightarrow{\text{virtual states}} (\pi\pi)^0 \xrightarrow{\text{virtual states}} \bar{K}^0

  $\bar{K}^0$ \xrightarrow{\text{virtual states}} (\pi\pi)^0 \xrightarrow{\text{virtual states}} K^0

- Because $\Delta m(K) = m(K_L) - m(K_S) = 3.5 \times 10^{-12}$ MeV > 0, a $K^0$ will change with time into a $\bar{K}^0$ and vice versa.

- These oscillations are described in QCD by $\Delta S = 2$ Feynman “box” diagrams:

  \[ \begin{array}{c}
  \bar{s} \quad [\Delta S=2] \quad \bar{d} \\
  K^0 \quad t, c \quad W^+ \quad \bar{t}, \bar{c} \quad W^- \quad \bar{s} \\
  d \end{array} \]
Neutral Kaon Mixing

- An initially pure $K^0$ state, will evolve into a superposition of states:

$$|K(t)\rangle = g(t)|K^0\rangle + h(t)|\bar{K}^0\rangle$$

- The time dependence is obtained by solving the time-dependent Schrödinger equation:

$$i \frac{d}{dt} \left( \begin{array}{c} K^0(t) \\ \bar{K}^0(t) \end{array} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \begin{array}{c} K^0(t) \\ \bar{K}^0(t) \end{array} \right)$$

with 2x2 matrices $M, \Gamma$, of which the off-diagonals proportional to $\Delta m, \Delta \Gamma$ govern the mixing.

- The respective time-dependent intensities are found to be (neglecting $CP$ violation):

$$I_{K^0}(t) \propto e^{-\Gamma t} + 2e^{-\Gamma t/2} \cos(\Delta m \cdot t)$$

$$I_{\bar{K}^0}(t) \propto e^{-\Gamma t} - 2e^{-\Gamma t/2} \cos(\Delta m \cdot t)$$

- After several $K_S$ lifetimes, only $K_L$ are left.

\[ T = t / \tau_S \]
Neutral Kaon Mixing and $CP$ Violation

Since $K_S$ and $K_L$ are not $CP$ eigenstates, the time dependence has to be slightly modified by the size of $\varepsilon$, giving rise to an additional sine term.

Asymmetry:

$$A_{\pi\pi} = \frac{\Gamma(\bar{K}^0 \rightarrow \pi^+\pi^-) - \Gamma(K^0 \rightarrow \pi^+\pi^-)}{\Gamma(\bar{K}^0 \rightarrow \pi^+\pi^-) + \Gamma(K^0 \rightarrow \pi^+\pi^-)} \propto |\varepsilon| \cos(\Delta m \cdot t - \varphi)$$

Neglecting other sources of $CP$ violation & assuming $\arg(\varepsilon) = \pi/4$. 

[Graph showing the decay rates and asymmetry as a function of time with data from CPLEAR 1999.]
There are in Fact Four Meson Systems with Mixing

Pairs of self-conjugate mesons that can be transformed to each other via flavor changing weak interaction transitions are:

\[ K^0 = |sd\rangle, \quad D^0 = |cu\rangle, \quad B_d^0 = |bd\rangle, \quad B_s^0 = |bs\rangle \]

They have very different oscillation properties that can be understood from the “CKM couplings” (see later in this lecture) occurring in the box diagrams.
CP violation

From Schrödinger eqn:
\[ |K_{S,L}(t)\rangle = e^{-i m_{S,L} t} e^{-\Gamma_{S,L} t/2} |K_{S,L}(0)\rangle \]

3 types of CP violation:
- violation in mixing
  \[ \text{Prob}(K^0 \to \bar{K}^0) \neq \text{Prob}(\bar{K}^0 \to K^0) \]
- violation in interference
  \[ \text{Prob}(K^0(t) \to \pi^+\pi^-) \neq \text{Prob}(\bar{K}^0(t) \to \pi^+\pi^-) \]
- violation in decays
  \[ \text{Prob}(K \to f) \neq \text{Prob}(\bar{K} \to \bar{f}) \]

Parameter \( \epsilon \) "indirect" CP violation

Parameter \( \epsilon' \) "direct" CP violation
At least two amplitudes with different \( CP \)-violating (weak) \textit{and} conserving (strong) phases have to contribute to the decay for direct CPV. This suppresses this type of CPV, so that the observable effect should be small compared to \( \varepsilon \).

To allow for (\textit{small}) direct CPV, we need to slightly modify our previous definitions:

\[
|\varepsilon + \varepsilon'|^2 = \frac{\Gamma(K_L \rightarrow \pi^+\pi^-)}{\Gamma(K_S \rightarrow \pi^+\pi^-)} \quad \text{and use also:} \quad |\varepsilon - 2\varepsilon'|^2 = \frac{\Gamma(K_L \rightarrow \pi^0\pi^0)}{\Gamma(K_S \rightarrow \pi^0\pi^0)}
\]

This can be expressed as

\[
\left|\frac{\Gamma(K_L \rightarrow \pi^0\pi^0)}{\Gamma(K_S \rightarrow \pi^0\pi^0)}\right| = \frac{\left|\varepsilon - 2\varepsilon'\right|^2}{\left|\varepsilon + \varepsilon'\right|^2} \ll \varepsilon
\]

If the observed \( CP \) violation is different in the two decay modes, we have a prove for a contribution from direct \( CP \) violation. From the measurement of the \textit{ratio of these decay-rate ratios} we can determine \( \varepsilon' \):

\[
\frac{\Gamma(K_L \rightarrow \pi^0\pi^0)}{\Gamma(K_S \rightarrow \pi^0\pi^0)} \left/ \frac{\Gamma(K_L \rightarrow \pi^+\pi^-)}{\Gamma(K_S \rightarrow \pi^+\pi^-)} \right| = \left|\varepsilon - 2\varepsilon'\right|^2 \ll \varepsilon
\]

\[
\approx 1 - 6 \times \Re\left\{ \frac{\varepsilon'}{\varepsilon} \right\}
\]

\[\text{First order Taylor expansion}\]

\[\text{“Clebsch-Gordon isospin” factor when passing from charged to neutral pions}\]

The observable
The Discovery of CP Violation in the Decay

- Due to the smallness of the effect, it took several experiments and over 30 years of effort to establish the existence of direct CPV.

- Feynman graphs:
  
  \[ \bar{K}_0 \]  
  
  "Tree" (born-level) amplitudes

  \[ \bar{K}_0 \]  
  
  "Penguin" (loop-level) amplitude

Experimental average

Indeed, a very small CPV effect!

\[ (16.7 \pm 2.3) \times 10^{-4} \]
Combining quantum mechanics with special relativity, and the wish to linearize $\delta/\delta t$, leads Dirac to the equation

$$i\gamma^\mu \partial_\mu \psi(x,t) - m\psi(x,t) = 0$$

(1928)

for which **solutions with negative energy** appear.

Vacuum represents a “sea” of such negative-energy particles (fully filled according to Pauli’s principle).

Dirac identified holes in this sea as “antiparticles” with opposite charge to particles … (however, he conjectured that these holes were protons, despite their large difference in mass, because he thought “positrons” would have been discovered already).

An electron with energy $E$ can fill this hole, emitting an energy $2E$ and leaving the vacuum (hence, the hole has effectively the charge $+e$ and positive energy).
**Particles and Antiparticles Annihilate**

What happens if we bring particles and antiparticles together?

- A particle can annihilate with its antiparticle to form gamma rays.

- An example whereby matter is converted into pure energy by Einstein’s formula $E = mc^2$.

- Conversely, gamma rays with sufficiently high energy can turn into a particle-antiparticle pair.
Particles and Antiparticles Annihilate

What happens if we bring particles and antiparticles together?

**ALEPH**

Higgs candidate

\[ e^+ e^- \rightarrow ZH(Z) \rightarrow q\bar{q} b\bar{b} \]
So the Standard Model can handle both particles and anti-particles 

in most cases with the same couplings

What about anti-matter in our Universe?
Antimatter in the Universe?

Does stable antimatter exist in the universe?
- No antinuclei (e.g., Antihelium) seen in cosmic rays (relative limit from BESS: $< 10^{-6}$)
- No significant (diffuse) cosmic $\gamma$ rays from nucleon-antinucleon annihilation in the boundary between matter & antimatter regions

No evidence of antimatter in our domain of the universe ($\sim 20$ Mpc = $0.6 \times 10^8$ light years)

Could our universe be like inverse Swiss cheese, with distant matter or antimatter regions(*)?

Difficult within the current limits

Likely: no antimatter in our universe
(apart from the antimatter created dynamically in particle collisions)

The voids would create anisotropy in CMB spectrum, which is not seen

(*) “If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. In fact there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them from present astronomical methods.” P. A. M. Dirac, Nobel Lecture (1933)
CP violation and the baryon asymmetry

We can estimate the magnitude of the baryon asymmetry of the Universe caused by KM CP violation

\[
\frac{n_B - n_B}{n_Y} \approx \frac{n_B}{n_Y} \sim \frac{J \times P_u \times P_d}{M^{12}}
\]

\[
J = \cos(\theta_{12}) \cos(\theta_{23}) \cos^2(\theta_{13}) \sin(\theta_{12}) \sin(\theta_{23}) \sin(\theta_{13}) \sin(\delta)
\]

\[
P_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)
\]

\[
P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)
\]

- The Jarlskog parameter $J$ is a parametrization invariant measure of CP violation in the quark sector: $J \sim O(10^{-5})$
- The mass scale $M$ can be taken to be the electroweak scale $O(100 \text{ GeV})$
- This gives an asymmetry $O(10^{-17})$:

much much below the observed value of $O(10^{-10})$
We need more CP violation!

To create a larger asymmetry, require:

- **new sources of CP violation**
  - that occur at high energy scales

Where might we find it?

- **lepton sector**: CP violation in neutrino oscillations
- **quark sector**: discrepancies with KM predictions
- **gauge sector, extra dimensions, other new physics**:
  - precision measurements of flavour observables are generically sensitive to additions to the Standard Model
CP violation and flavor asymmetries in the SM
Parameters of the Standard Model

- 3 gauge couplings
- 2 Higgs parameters
  - 6 quark masses
  - 3 quark mixing angles + 1 phase
  - 3 (+3) lepton masses
  - (3 lepton mixing angles + 1 phase)

flavour parameters

( ) = with Dirac neutrino masses
What breaks the flavour symmetries?

- In the Standard Model, the vacuum expectation value of the Higgs field breaks the electroweak symmetry.
- Fermion masses arise from the Yukawa couplings of the quarks and charged leptons to the Higgs field (taking $m_v = 0$).
- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks.
- Consequently, the only flavour-changing interactions are the charged current weak interactions:
  - no flavour-changing neutral currents (GIM mechanism)
  - not generically true in most extensions of the SM
  - flavour-changing processes provide sensitive tests.
Flavour for new physics discoveries

A lesson from history:

- New physics shows up at precision frontier before energy frontier
  - GIM mechanism before discovery of charm
  - CP violation / CKM before discovery of bottom & top
  - Neutral currents before discovery of Z

- Particularly sensitive – loop processes
  - Standard Model contributions suppressed / absent
  - Flavour changing neutral currents (rare decays)
  - CP violation
  - Lepton flavour / number violation / lepton universality

FCNC suppressed
ΔS=2 suppressed wrt ΔS=1
CKM matrix in the Standard Model

The charged current interaction gets a flavor structure, encoded in the Cabibbo Kobayashi Maskawa (CKM) matrix $V$.

$$L_{CC} = -\frac{g}{\sqrt{2}} \left( \bar{U}_L \gamma^\mu W^\mu_L V \bar{D}_L + \bar{D}_L \gamma^\mu W^\mu_D V^\dagger \bar{U}_L \right).$$

$V_{ij}$ connects left-handed up-type quark of the $i$th gen. to left-handed down-type quark of $j$th gen. Intuitive labelling by flavor:

$$V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \quad V_{13} = V_{ub} \text{ etc}
$$

Via $W$ exchange is the only way to change flavor in the SM.
CKM matrix in the Standard Model

- Quarks change type in weak interactions:

\[ W^+ \xrightarrow{V_{ij}} q_i = u, c, t \quad q_j = \bar{d}, \bar{s}, \bar{b} \]

\[ V = \begin{pmatrix} \rho & \eta \\ \eta & 1 \end{pmatrix} \]

Relative magnitudes

- We parameterise the couplings \( V_{ij} \) in the CKM matrix:

\[ V = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix} \]

where here I use the Buras correction to the Wolfestein parameterisation

\[ \bar{\rho} = \rho (1 - \frac{\lambda^2}{2}) \quad \bar{\eta} = \eta (1 - \frac{\lambda^2}{2}) \]
 Either way, if the CKM matrix describes all possible states, it should be unitary!
Unitarity relations

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

multiply with its conjugate transpose

\[VV^\dagger = V^\dagger V = 1\]

\[
\sum_i V_{ij} V_{ik}^* = \delta_{jk}
\]
column orthogonality

\[
\sum_j V_{ij} V_{kj}^* = \delta_{ik}
\]
row orthogonality
Unitarity relations

\[ V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* \simeq \mathcal{O}(\lambda) + \mathcal{O}(\lambda) + \mathcal{O}(\lambda^5) = 0 \]

Areas have to be the same
→ Jarlskog parameter

\[ V_{ub}V_{us}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* \simeq \mathcal{O}(\lambda^4) + \mathcal{O}(\lambda^2) + \mathcal{O}(\lambda^2) = 0 \]

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* \simeq \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) = 0 \]
Third unitarity relation

\[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* \sim \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) = 0 \]

\( V_{id} V_{ib}^* = 0 \) represents the orthogonality condition between the first and the third column of the CKM matrix (the orientation depends on the phase convention)

re-scaled version where sides have been divided by \( |V_{cd} V_{cb}^*| \)

In terms of the Wolfenstein parameterization, the coordinates of this triangle are \((0,0)\), \((1,0)\) and \((\rho, \eta)\):
the two sides are \((\rho - i\eta)\) and \((1 - \rho + i\eta)\).
Probing the structure of the CKM mechanism

\[ V_{ud}V_{ub}^* + V_{td}V_{tb}^* + V_{cd}V_{cb}^* = 0 \]

The angles can be written in terms of CKM matrix elements as:

- \( \alpha = \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*] \)
- \( \beta = \arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*] \)
- \( \gamma = \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*] \)

• We need to measure the angles and sides to over-constrain this triangle, and test that it closes.
• Need experiments to measure these quantities
Constraining the angles

Theoretically clean (SM uncertainties ~10^{-2} to 10^{-3}) tree dominated decays to Charmonium + K^0 final states.

\[
\begin{align*}
\frac{V_{ud}}{V_{cd}} & \frac{V_{ub}^*}{V_{cb}^*} \\
\frac{V_{td}}{V_{cd}} & \frac{V_{tb}^*}{V_{cb}^*} \\
\end{align*}
\]

(0,0) \quad (1,0)

\[\gamma \quad \alpha \quad \beta\]

- $b \rightarrow c\bar{c}s$
- $B^0 \rightarrow J/\psi K_L^0$
- $B^0 \rightarrow J/\psi K_S^0$
- $B^0 \rightarrow \psi(2S)K_S^0$
- $B^0 \rightarrow \Upsilon_{1c} K_S^0$
- $B^0 \rightarrow \eta_c K^0$
- $B^0 \rightarrow J/\psi K^0$
- $B \rightarrow J/\psi \pi^0$
- $B \rightarrow D^{(*)}D^{(*)}$
- $B \rightarrow \eta'K^0$
- $B \rightarrow \rho K^0$
- $B \rightarrow \omega K^0$
- $B \rightarrow \pi^0 K^0$
- $B \rightarrow \phi K^{(*)}$
- $B \rightarrow K K K^0$
- $B \rightarrow f^0(980)K^0$
Constraining the angles

\[ b \to \bar{u}ud \text{ transitions with possible loop contributions. Extract } \alpha \text{ using}
\]
- SU(2) Isospin relations.
- SU(3) flavour related processes.

\[ \begin{align*}
\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} & \quad \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} \\
(0,0) & \quad (1,0)
\end{align*} \]
Constraining the angles

\[ b \rightarrow c \text{ interfering with } b \rightarrow u \]
\[ B \rightarrow D^{(s)} \bar{K}^{(s)} \]
\[ B^0 \rightarrow D^{-} K^0 \pi^+ \]
\[ B^0 \rightarrow D^{(*)} \pi \]
\[ B^0 \rightarrow D^{(*)} \rho \]
\[ + \text{ charmless} \]

\[ (\bar{\rho}, \bar{\eta}) \]
\[ \frac{V_{ud}}{V_{cd}} \frac{V_{ub}^*}{V_{cb}^*} \]
\[ \frac{V_{td}}{V_{cd}} \frac{V_{tb}^*}{V_{cb}^*} \]
\[ \gamma \]
\[ (0,0) \]

\[ \alpha \]

\[ (1,0) \]

\[ b \rightarrow u \bar{u} d \]
\[ B \rightarrow a_1, \pi \]
\[ \rho \pi \]
\[ B \rightarrow a_1, \rho \]
\[ B \rightarrow a_l, a_l \]

\[ b \rightarrow c \bar{c} s \]
\[ B^0 \rightarrow J/\psi K_s^0 \]
\[ B^0 \rightarrow J/\psi K_s^0 \]
\[ B^0 \rightarrow \psi (2S) K_s^0 \]
\[ B^0 \rightarrow \chi_{1s} K_s^0 \]
\[ B^0 \rightarrow \eta_c K_s^0 \]
\[ B^0 \rightarrow J/\psi K_s^0 \]

\[ B \rightarrow J/\psi \pi^0 \]
\[ B \rightarrow D^{(*)+} D^{(*)-} \]
\[ B \rightarrow \eta' K^0 \]
\[ B \rightarrow \rho K^0 \]
\[ B \rightarrow \omega K^0 \]
\[ B \rightarrow \pi^0 K^0 \]
\[ B \rightarrow \phi K^{(*)0} \]
\[ B \rightarrow KKK^0 \]
\[ B \rightarrow f^0 (980) K^0 \]
So far it closes – all measurements consistent
**CP violation: Searching for new physics**

- $\sin 2\beta$ has been measured to $O(1^\circ)$ accuracy in $b \to \bar c c s$ decays.
- Can use this to search for signs of New Physics (NP) if:
  - Identify a rare decay sensitive to $\sin 2\beta$ (loop dominated process).
  - Measure $S$ precisely in that mode ($S_{\text{eff}}$).
  - Control the theoretical uncertainty on the Standard Model ‘pollution’ ($\Delta S_{\text{SM}}$).
  - Compute $\Delta S_{\text{NP}} = S_{\text{eff}} - S_{c\bar c s} - \Delta S_{\text{SM}}$.

- In the presence of NP: $\Delta S_{\text{NP}} \neq 0$

- Many tests have been performed in:
  - $B \to d$ processes.
  - $B \to s$ processes.

- Unknown heavy particles can introduce new amplitudes that can affect physical observables of loop dominated processes.

- Observables that might be affected include branching fractions, CP asymmetries, forwardbackward asymmetries ... and so on.

- A successful search requires that we understand Standard Model contributions well!
Summary

◎ The B-factories have tested the CKM mechanism to an unprecedented level:

\[ \sigma(\bar{\rho}) \sim 15\% \quad \sigma(\bar{\eta}) \sim 3\% \]

◎ CKM works at this level.
  - Still not enough CP violation to explain the universal matter-antimatter asymmetry!

◎ Need more precise searches for new physics and possible deviations from CKM.

◎ The unitarity triangle fit is an useful tool to exploit all the flavour physics contributions to extract SM and NP parameters and also insight on the NP scale.

◎ LHCb and the next generation B factory will start to build on the knowledge of BaBar and Belle soon.
Summary

- The study of CP violation is a fundamental part of particle physics, and cosmology.
  - It revolves around EPR experiments with correlated B, D, K, mesons, and quantum interference studies.
- We don’t really understand it.
  - The CKM mechanism works well but it is incomplete. It is only a small part of the story. We don’t know if CP violation in leptons, or some new physics scenario really explains the matter-antimatter asymmetry questions arising from the Big Bang.
  - Eventually we hope to understand the reason behind this conundrum, and in doing so we will either find new particle physics, or new cosmological effects.
  - Given that its very hard to have an asymmetry in the big bang that doesn’t get washed out by inflation – the money is on new physics effects/ particles to be discovered!
One slide: The CKM Matrix and the Unitarity Triangle

\[ V_{\text{CKM}} = \begin{pmatrix} d & s & b \\ u & c & t \end{pmatrix} \]

\[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]

\[ \left( \propto A\lambda^3 \propto -A\lambda^3 \propto A\lambda^3 \right) \]

\[ \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} + 1 + \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} = 0 \]

\[ \arg(...) \approx \gamma \]

\[ \arg(...) \approx \beta \]

Phase invariant:

\[ (\rho, \eta) \]

\[ (1, 0) \]

\[ CP \text{ Violation (Im[...])} \approx 0 \]

Q \rightarrow q

\[ W^- \]

Kobayashi-Maskawa, 1973

\[ V_{q\bar{q}} \]
One slide: The CKM Matrix and the Unitarity Triangle

Culminating Point
SM or new phases (fields)?
Observables for direct CP

CPV effect small, direct CPV expected to be even smaller or zero

If no direct CPV then the observable ratios of $K_L, S$ to $\bar{B}^+B^-$ and $B^0\bar{B}^0$ should both equal $\eta$:

$$\eta_{+-} = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} = \varepsilon + \varepsilon'$$
$$\eta_{00} = \frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

The ratio between the rates related to the ratio of direct to indirect CPV:

$$\text{Re}(\varepsilon' / \varepsilon) \approx \frac{1}{6} \left[ \left| \eta_{+-} \right|^2 - 1 \right] \approx \frac{1}{6} \left[ \frac{\Gamma(K_L \rightarrow \pi^+\pi^-)}{\Gamma(K_S \rightarrow \pi^+\pi^-)} \right] - 1$$

From theory:

- Standard Model: $\text{Re}(\bar{B}'/\bar{B}) \sim 0 - 30 \times 10^{-4}$
- Superweak theory: $\text{Re}(\bar{B}'/\bar{B}) = 0$

A=amplitude  
$\bar{B}$=decay rate