Overview of CP Violation in the Quark Sector

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Outline

- Introduction to CP violation
  - Definitions and Background
  - CP Violation in the Flavor sector of Standard Model: CKM Matrix, Unitarity Triangle
  - Experimental Physics Goals

- How do we do measurements?
- A few Major Experimental Results

- Conclusion
  - What do we know today?
  - Future
Definitions and Background

- **Symmetry:** Transformation of a system that does not change the physics laws formulation for this system

- **The Parity P:** Inversion of the spatial coordinates, image in a mirror
  \[ \vec{x} \rightarrow -\vec{x} \]

- **The Charge conjugation C:** Change of all the charge quantum numbers into their opposite, transforms a particle into its anti-particle
  \[ q_i \rightarrow -q_i \]

**CP Violation \(\Leftrightarrow\) the world is not symmetric under CP transformation**

In the **Standard Model** of Particle Physics (SM):

- C and P are symmetries of strong and electromagnetic interactions.
- C and P symmetries are violated by weak interaction
- CP symmetry is **slightly violated by weak interaction**
CP Violation with Escher’s Images

CP (anti-matter in a mirror)

P (mirror)  C (anti-matter)

White geese fly right  White geese fly left  White geese fly right

Slight breaking of CP (look at the tails…)

Analogy to weak interaction in the Standard Model.
**The CKM Matrix**

In the Quark sector: Week Int. eigenstates ≠ Mass eigenstates

↔ Quarks that participate in weak processes are linear combinations of mass eigenstates

↔ Existence of 3X3 unitary matrix describing the **mixing of quarks**: the CKM Matrix

**The CKM Matrix:**

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix}
= 
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}_M
\]

**Expansion in powers of \( \lambda \) at the order \( \lambda^3 \) with \( \lambda = \sin(\theta_{\text{cabibbo}}) \approx 0.22 \)**

**Wolfenstein parameterization:**

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

**10 free parameters in the Flavor sector of the SM**

- 6 quark masses
- 4 CKM parameters (Wolfenstein: \( \lambda, A, \rho, \eta \))

**~ half of the SM**
From CKM Matrix to Unitarity Triangle

CP Violation is possible in the Standard Model only if $V_{\text{CKM}}$ is complex $\Leftrightarrow \eta \neq 0 \Leftrightarrow$ Unitarity Triangle is not flat

We want to determine $\rho$ and $\eta$ experimentally.

**From CKM Matrix to Unitarity Triangle**

**CKM matrix**

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

**Wolfenstein parameterization:**

**$V_{\text{CKM}}$ Unitarity $\Rightarrow$**

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

Other unitarity conditions (triangles) are difficult to use: Sides are very different. Try it with second and third columns...

**CP Violation is possible in the Standard Model only if $V_{\text{CKM}}$ is complex $\Leftrightarrow \eta \neq 0 \Leftrightarrow$ Unitarity Triangle is not flat**

**We want to determine $\rho$ and $\eta$ experimentally**

Eli Ben-Haim             ECT* Trento, June 27th 2007 6
Examples of Weak Processes

\[ B^0 (\bar{b}d) , \bar{B}^0 (\bar{b}d) , B^+ (\bar{b}u) , B^- (b\bar{u}) \]

- **Semileptonic Decay of** \( B^0 \)

  Provide information on \( V_{ub} (V_{cb}) \)

- **\( B^0 \leftrightarrow \bar{B}^0 \) Oscillations**

  \[ \propto (V_{td} V^*_{tb})^2 \]
More on B Oscillations

With the weak int. eigenstates:

\[ |B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle \]
\[ |B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle \]

Oscillation frequency, width difference:

\[ \Delta M_d = m_{B_H} - m_{B_L} \]
\[ \Gamma_d = \Gamma_{B_H} - \Gamma_{B_L} \]

Time evolution of a B meson that was a B^0 at t=0:

\[ |B^0(t)\rangle = e^{-im_B t} e^{-\Gamma_d t/2} \]

Oscillation term

\[ \left[ \cos \left( \frac{\Delta m_d t}{2} \right) |B^0\rangle + \frac{i}{p} q \sin \left( \frac{\Delta m_d t}{2} \right) |\bar{B}^0\rangle \right] \]

Decay term

Competition between oscillation and decay

To study oscillations, need to identify the species of the B meson at time t=0.
To follow its time evolution, need to measure time.
Two Types of CP Violation

- **Direct CP Violation:** \( B \rightarrow f \neq \bar{B} \rightarrow \bar{f} \), with \( f \neq \bar{f} \)

  - To measure it, only need to count events.
  - Rates are different \( \Leftrightarrow \) CP is violated
  - Only type of CP violation for charged B mesons

- **CP violation in the interference between decay and mixing:**

\[ B^0 \rightarrow f \neq \bar{B}^0 \rightarrow \bar{f} \]

**Analogy to “Double-Slit” experiment**

*In the double-slit experiment,* there are two paths to the same point on the screen.

In the B experiment, we must choose final states into which both a \( \bar{B}^0 \) and a \( B^0 \) can decay. *We perform the B experiment twice* (starting from \( B^0 \) and from \( \bar{B}^0 \)). We then compare the results.
How to Get $\rho$ and $\eta$ from Experiments?

Kaon Physics

$\text{Br}(K\to \pi\nu\nu)$ (future)
$\varepsilon_K \sim \frac{1}{\eta}(1-\rho)$

$B$ decays

$\text{Br}(b\to ul\nu X)$
$\text{Br}(b\to cl\nu X)$

Charm Physics

$m_c, m_b, \mu_\pi, \text{Form Factors, } F(1), \text{duality...}$

Moment analysis

( $b\to s\gamma...$ )

Oscillations

$\Delta m_d, \Delta m_s$

$\xi, f_B, B_B$

$B\to \pi\pi, \rho\pi, \rho\rho...$

$B\to DK$

Radiative decays $X_s\gamma, X_d\gamma, X_sll$

Charm Physics (Dalitz)

$\alpha$

$\text{Br}(B\to \pi\pi)$
$\text{Br}(B\to K\pi)$

$a_{cp}(J/\Psi, K^0)$

+other charmonium

+from Penguins

Theory Error small!
Quantify CP Violation within the Standard Model with precision measurements of its angles and sides

Test the Standard Model, by over-constraining the Unitarity Triangle with redundant measurements. If there is New Physics (not described by the Standard Model), we might see some incompatibilities between several independent measurements of the same parameter of the UT.
Intermediate Summary, What do We know by Now?

- CP and CP violation
- CKM Matrix and the Unitarity Triangle
- B mixing

Goals and motivations for studying CP violation:
- Constrain the Standard Model by measuring its free parameters. Flavor sector in one of its less known parts before B-Factories
- Test the Standard Model and eventually challenge it by showing discrepancies between several measurements of the same parameters → a window for discovery of New Physics
- It is also one of the necessary conditions to explain matter-antimatter asymmetry in the universe

Sakharov, JETP Lett. 5, 24 (1967).
Experiments designed for precision measurements of CP violation in the B meson (and Charm) sector

Two active B-Factories experiments:
- BaBar, in Stanford Linear Accelerator Center (California)
- Belle, in KEKB (Japan)

The BaBar experiment:

\[ e^{-}(9 \text{ GeV})/e^{+}(3.1 \text{ GeV}) \text{ collision} \]
\[ E_{CM} = m(\Upsilon(4S)) = 10.58 \text{ GeV} \]
\[ e^{+}e^{-} \rightarrow \Upsilon(4S) \rightarrow B/\bar{B} \]

almost at rest in the CM frame boost of \( \Upsilon(4S) \) with \( \beta \gamma = 0.56 \)
Two boosted $B$ mesons are produced in a coherent state.
$\Rightarrow$ until the first $B$ decay, there is exactly one $B^0$ and one $\bar{B}^0$.

Problem:

If we want to study a decay

Where $f$ is also accessible by an anti-$B^0$

And we want to see if

We need to find a clever way to know the $B$ flavor
Time Dependent Measurements, Flavor Tagging

Solution:

• There is coherent evolution until $B_{\text{tag}}$ decays
• At $t_{\text{tag}}$ the flavor of $B_{\text{reco}}$ is the opposite of the $B_{\text{tag}}$’s flavor
• $B_{\text{reco}}$’s flavor determined from $B_{\text{tag}}$’s flavor and $\Delta t$
• Boost: $\Delta t$ measured via space length measurement between $B_{\text{tag}}$ and $B_{\text{reco}}$ $\Delta z$
• Flavor of the $B_{\text{tag}}$ determined by its decay product: charge of leptons, K, $\pi$
Measurement of $\sin(2\beta)$ with $B^0 \to J/\psi K^0_S$

- Final state accessible to $B^0$ and $\bar{B}^0 \to J/\psi K^0_S$
- Time dependent asymmetry:

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to J/\psi K_S) - \Gamma(B^0(t) \to J/\psi K_S)}{\Gamma(B^0(t) \to J/\psi K_S) + \Gamma(\bar{B}^0(t) \to J/\psi K_S)} = S \sin(\Delta m_d t) - C \cos(\Delta m_d t)$$

- Only one amplitude
- $C_f = 0$
- $S_f = -\eta_{CP} \sin 2\beta$

$\Rightarrow$ Extraction of $\sin(2\beta)$ from $A_{cp}$
Measurement of $\sin(2\beta)$ with $B^0 \rightarrow J/\psi K^0_S$

- This measurement is theoretically clean (at 1%)
- Benefits from a large data sample
- $\sin(2\beta)$ gives the best constraint on $\rho$-$\eta$ plane

$\sin(2\beta) \equiv \sin(2\phi_1)$

$\beta \equiv \phi_1$

$b \rightarrow ccs \ C_{CP}$

$\sin(2\beta) \neq 0 \Rightarrow$ non flat triangle i.e. CP violation
Measurement of $\sin(2\beta)$ with “s Penguins”

Standard Model contribution

New Physics contribution

Tensions between $\sin 2\beta$ from $b\rightarrow ccs$ and $b\rightarrow qqs$
**B_{s}^{0} Oscillations: \Delta m_{s} Measurement at the TeVatron**

\[ \Delta m_{d} = 0.509 \pm 0.006 \, \text{ps}^{-1} \]
\[ \Delta m_{s} \sim 30 \times \Delta m_{d} \]

⇒ Rapid oscillations for B_{s}^{0}

**Behavior in proper time**

\[ P(t)_{B_{s}^{0} \rightarrow B_{s}^{0}} = \frac{1}{2\tau} e^{-t/\tau} (1 + \cos \Delta m t) \]
\[ P(t)_{\bar{B}_{s}^{0} \rightarrow \bar{B}_{s}^{0}} = \frac{1}{2\tau} e^{-t/\tau} (1 - \cos \Delta m t) \]

In this case, they are able to determine the flavor at decay and at production.

**Determine asymmetry**

\[ A_{0}(t) = \frac{N(t)_{\text{unmixed}} - N(t)_{\text{mixed}}}{N(t)_{\text{unmixed}} + N(t)_{\text{mixed}}} = \cos \Delta m t \]

- "unmixed": same flavor at decay and at production
- "mixed": different flavor

In a perfect world, they do not have the sensitivity to measure it this way.

BUT
$\Delta m_s$ Measurement: Fourier Analysis

Two domains to fit for oscillation:

Time domain:

- fit for $\Delta m_s$ in $P(t) \sim (1 \pm D \cos \Delta m_s t)$

Frequency domain: amplitude scan

- introduce amplitude:
  $P(t) \sim (1 \pm \alpha D \cos \Delta m_s t)$
- fit for $\alpha$ at different $\Delta m_s$
- obtain frequency spectrum
- true $\Delta m_s \Rightarrow \alpha = 1$, else $\alpha = 0$
- traditionally used for $B^0_s$ mixing search
- easy to combine experiments

Courtesy of G. Gomes-Ceballos, FPCP 2006, Vancouver, Canada
CDF obtained the first direct evidence of $\Delta m_s$!

$\Delta m_s = 17.77 \pm 0.10 \text{ (stat)} \pm 0.07 \text{ ps}^{-1}$
Comparison of $K$, $B_d$ and $B_s$ Oscillations

- Analogy: coupled Harmonic Oscillator
- Oscillations (mixing) characterized by mass and lifetime differences between the two eigenstates of weak interaction.
- Differences between flavors:
  - $K$: very different states
  - $B_d$: Oscillation and decay are comparable
  - $B_s$: Rapid oscillations

Mind the scales!
An experimental challenge!
Both BaBar and Belle observed mixing (Winter 2007)
Results are consistent with SM
Charm: only place where CP violation with down-type quarks in the mixing diagram can be explored.

No evidence for CP violation
We need more Measurements with different techniques to get \( x \) and \( y \) parameters.

\[
x = \frac{m_1 - m_2}{\Gamma}
\]
\[
y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}
\]
\[
\Gamma = \frac{1}{2} (\Gamma_1 + \Gamma_2)
\]

SM: D mixing expected at \( \leq 1\% \) level

\[
x = (8.7 \pm 3.3) \times 10^{-3}
\]
\[
y = (6.7 \pm 2.1) \times 10^{-3}
\]

No-mixing point excluded at 5.7\( \sigma \)
In this talk I have only focused of a few recent results on CP violation

After many results from B-Factories and measurement of $\Delta m_s$ by CDF All the independent constraints superimpose in a small region of the ($\rho, \eta$) plane!

Great success of the Standard Model and the CKM Picture
There are still small tensions in the fit

However, if there is physics beyond the Standard Model, the present results constrain it strongly

Possible New Physics scenarios are likely to have a similar flavor structure similar to the one of the SM (MFV models).

Eventual New physics should appear as “corrections” to the CKM picture.

There is room for additional effort in the Flavor sector

Super-B Factory?
I would like to thank Julie Malcles and Achille Stocchi, who authorized me to use materiel which has greatly benefited this talk