Cracking the Unitarity Triangle
— A Quest in $B$ Physics —

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Outline

- Introduction to the Unitarity Triangle
  - The Standard Model, the CKM matrix, and CP violation
  - CP asymmetry in the $B^0$ meson decays
- Experiments at the $B$ Factories
- Results from $BABAR$ and Belle
  - Angles $\alpha$, $\beta$, $\gamma$ from CP asymmetries
  - $|V_{ub}|$ from semileptonic decays
  - $|V_{td}|$ from $B^0$ and $B_s$ mixing
- Current status and outlook

Results presented in this talk are produced by the $BABAR$, Belle, and CLEO Experiments, the Heavy Flavor Averaging Group, the CKMfitter Group, and the UTfit Collaboration.
What are we made of?

- Ordinary matter is made of electrons and up/down quarks
- Add the neutrino and we have a complete “kit”
- We also know how they interact with “forces”

<table>
<thead>
<tr>
<th>leptons</th>
<th>quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q = 1 )</td>
<td>( u ) ( Q = +\frac{2}{3} )</td>
</tr>
<tr>
<td>( Q = 0 )</td>
<td>( d ) ( Q = \frac{1}{3} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>strong</th>
<th>E&amp;M</th>
<th>weak</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u )</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>( d )</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>( e^- )</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>( \nu_e )</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Simplified Standard Model

- **Strong force** is transmitted by the **gluon**
  \[ u \rightarrow g \rightarrow d \]

- **Electromagnetic force** by the **photon**
  \[ u \rightarrow \gamma \rightarrow u \]

- **Weak force** by the **$W^\pm$ and $Z^0$ bosons**
  \[ u \rightarrow Z^0 \rightarrow u \]

Note $W^\pm$ can “convert” $u \leftrightarrow d$, $e \leftrightarrow \nu$
Three generations

- We’ve got a neat, clean, predictive theory of “everything”

<table>
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<tr>
<td>$e^-$</td>
<td>$u$</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$d$</td>
</tr>
</tbody>
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</tr>
</thead>
<tbody>
<tr>
<td>$g$</td>
<td>$\gamma$</td>
<td>$W^\pm$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Z^0$</td>
</tr>
</tbody>
</table>

- Why 3 sets (= generations) of particles?
  - How do they differ?
  - How do they interact with each other?

It turns out there are two “extra” copies of particles.
A spectrum of masses

- The generations differ only by the masses
- The structure is mysterious
- The Standard Model has no explanation for the mass spectrum
- All 12 masses are inputs to the theory
- The masses come from the interaction with the Higgs particle
  - ... whose nature is unknown
  - We are looking for it with the Tevatron, and with the Large Hadron Collider (LHC) in the future

The origin of mass is one of the most urgent questions in particle physics today
If there were no masses

- Nothing would distinguish \( u \) from \( c \) from \( t \)
  - We could make a mixture of the wavefunctions and pretend it represents a physical particle

\[
\begin{align*}
  u & \quad u \\
  c & = M \quad c \\
  t & \quad t
\end{align*}
\]

\[
\begin{align*}
  d & \quad d \\
  s & = N \quad s \\
  b & \quad b
\end{align*}
\]

- Suppose \( W^\pm \) connects \( u' \leftrightarrow d', c' \leftrightarrow s', t' \leftrightarrow b' \)

\[
\begin{align*}
  u & \quad u \\
  c & = M^{-1} \quad c \\
  t & \quad t
\end{align*}
\]

\[
\begin{align*}
  d & \quad d \\
  s & = M^{-1}N \quad s \\
  b & \quad b
\end{align*}
\]

- That’s a poor choice of basis vectors

\( M \) and \( N \) are arbitrary 3×3 unitary matrices

Weak interactions between \( u, c, t, \) and \( d, s, b \) are “mixed” by matrix \( V \)
Masses uniquely define the $u$, $c$, $t$, and $d$, $s$, $b$ states

- We don’t know what creates masses
  - We don’t know how the eigenstates are chosen
  - $M$ and $N$ are arbitrary
- $V$ is an arbitrary $3 \times 3$ unitary matrix

The Standard Model does not predict $V$
- ... for the same reason it does not predict the particle masses

<table>
<thead>
<tr>
<th>$u$</th>
<th>$d$</th>
<th>$V_{ud}$</th>
<th>$V_{us}$</th>
<th>$V_{ub}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>$V$</td>
<td>$V_{cd}$</td>
<td>$V_{cs}$</td>
<td>$V_{cb}$</td>
</tr>
<tr>
<td>$t$</td>
<td>$b$</td>
<td>$V_{td}$</td>
<td>$V_{ts}$</td>
<td>$V_{tb}$</td>
</tr>
</tbody>
</table>

Cabibbo-Kobayashi-Maskawa matrix or CKM for short
Structure of the CKM matrix

- The CKM matrix looks like this ➔
  - It’s not completely diagonal
  - Off-diagonal components are small
    - Transition across generations is allowed but suppressed

There seems to be a “structure” separating the generations

- Matrix elements can be complex
  - Unitarity leaves 4 free parameters, one of which is a complex phase

This phase causes “CP violation”

Kobayashi and Maskawa (1973)
What are we made of, again?

- Dirac predicted existence of anti-matter in 1928
  - Positron (= anti-electron) discovered in 1932

- Our Universe contains (almost) only matter

I do not believe in the hole theory, since I would like to have the asymmetry between positive and negative electricity in the laws of nature (it does not satisfy me to shift the empirically established asymmetry to one of the initial state)

Pauli, 1933 letter to Heisenberg

- Translation: he would like the laws of physics to be different for particles and anti-particles
**CP symmetry**

<table>
<thead>
<tr>
<th>C</th>
<th>charge conjugation</th>
<th>particle ↔ anti-particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>parity</td>
<td>$x \rightarrow -x$, $y \rightarrow -y$, $z \rightarrow -z$</td>
</tr>
</tbody>
</table>

- **C** and **P** symmetries are broken in weak interactions
  - Lee, Yang (1956), Wu et al. (1957), Garwin, Lederman, Weinrich (1957)
- Combined **CP** symmetry seemed to be good
  - Anti-Universe can exist as long as it is a mirror image of our Universe
- To create a matter-dominant Universe, **CP** symmetry must be broken

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One of the three necessary conditions (Sakharov 1967)
\textit{CP} violation

- \textit{CP} violation was discovered in $K_L$ decays
  - $K_L$ decays into either 2 or 3 pions
    - $K_L$ + + (33\%) \quad CP = 1
    - $K_L$ + (0.3\%) \quad CP = +1
  - Final states have different \textit{CP} eigenvalues
- Couldn’t happen if \textit{CP} was a good symmetry of Nature
  - Laws of physics apply differently to matter and antimatter
- The complex phase in the CKM matrix causes \textit{CP} violation
  - It is the only source of \textit{CP} violation in the Standard Model
  - Nothing else?
The CKM mechanism fails to explain the amount of matter-antimatter imbalance in the Universe...
... by several orders of magnitude

New Physics beyond the SM is expected at 1-10 TeV scale

- e.g. to keep the Higgs mass < 1 TeV/c²
- Almost all theories of New Physics introduce new sources of CP violation (e.g. 43 of them in supersymmetry)

New sources of CP violation almost certainly exist

- Precision studies of the CKM matrix may uncover them
The Unitarity Triangle

- $V^\dagger V = 1$ gives us
  
  \[
  V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0
  \]
  
  \[
  V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0
  \]
  
  \[
  V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0
  \]

  This one has the 3 terms in the same order of magnitude

- A triangle on the complex plane

- Experiments measure the angles $\alpha, \beta, \gamma$ and the sides
The UT 1998 → 2006

- We did know something about how the UT looked in the last century
- By 2005, the allowed region for the apex has shrunk to about 1/10 in area

The improvements are due largely to the \textit{B Factories} that produce and study \textit{B mesons} in quantity.
Anatomy of the $B^0$ system

- The $B^0$ meson is a bound state of $\bar{b}$ and $d$ quarks

<table>
<thead>
<tr>
<th>Particle</th>
<th>charge</th>
<th>mass</th>
<th>lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 = (\bar{b}d)$</td>
<td>0</td>
<td>5.28 GeV/c^2</td>
<td>1.5 ps</td>
</tr>
<tr>
<td>$\bar{B}^0 = (bd)$</td>
<td>0</td>
<td>5.28 GeV/c^2</td>
<td>1.5 ps</td>
</tr>
</tbody>
</table>

- They turn into each other spontaneously

- This is called the $B^0$-$\bar{B}^0$ mixing

Indistinguishable from the outside
Time-dependent Interference

Starting from a pure $|B^0\rangle$ state, the wave function evolves as

Suppose $B^0$ and $\bar{B}^0$ can decay into a same final state $f_{CP}$

$|B^0\rangle$  $|\bar{B}^0\rangle$

$B^0$ $\bar{B}^0$

$t = 0$ $t = t$

Ignoring the lifetime

Two paths can interfere

Decay probability depends on:

- the decay time $t$
- the relative complex phase between the two paths
Consider $B^0 J/ K^0$

Direct path

Mixing path

Phase difference is

$$\arg(V_{cs} V_{cb}^*) \arg(V_{td}^2 V_{tb}^* V_{cb} V_{cs}^* V_{cs}^2 V_{cd}^2) = 2 \arg(V_{cd} V_{cb}^*) \arg(V_{td} V_{tb}^*) = 2$$
Time-dependent $CP$ Asymmetry

- Quantum interference between the direct and mixed paths makes $B^0(t) \ J/ \ K^0$ and $\bar{B}^0(t) \ J/ \ K^0$ different.
- Define time-dependent $CP$ asymmetry:

$$A_{CP}(t) = \frac{N(\bar{B}^0(t) \ \ J/ \ K^0)}{N(\bar{B}^0(t) \ \ J/ \ K^0) + N(B^0(t) \ J/ \ K^0)} = \sin(2mt) \sin(mt)$$

- We can measure the angle of the UT.
- What do we have to do to measure $A_{CP}(t)$?
  - Step 1: Produce and detect $B^0 \rightarrow f_{CP}$ events
  - Step 2: Separate $B^0$ from $\bar{B}^0$
  - Step 3: Measure the decay time $t$
**B Factories**

- Designed specifically for precision measurements of the $CP$ violating phases in the CKM matrix

**SLAC PEP-II**

**KEKB**

Produce $\sim 10^8 B$/year by colliding $e^+$ and $e^-$ with $E_{CM} = 10.58$ GeV

$$e^+ + e^- \rightarrow (4S) \ B\bar{B}$$
Asymmetric $B$ Factory

- Collide $e^+$ and $e^-$ with $E(e^+) \neq E(e^-)$
  - PEP-II: 9 GeV $e^-$ vs. 3.1 GeV $e^+ \rightarrow \beta\gamma = 0.56$

Moving in the lab

Decay products often allow us to distinguish $B^0$ vs. $\bar{B}^0$

Step 1: Reconstruct the signal $B$ decay

Step 2: Identify the flavor of the other $B$

Step 3: Measure $\Delta z \rightarrow \Delta t$
Detectors: \textit{BABAR} and Belle

- Layers of particle detectors surround the collision point
  - We reconstruct how the $B$ mesons decayed from their decay products
A $B^0 \rightarrow J/\psi K_S$ candidate ($r$-$\phi$ view)

Muons from $J/\psi$

Pions from $K_S^+$

Red tracks are from the other $B$, which was probably $\bar{B}^0$
CPV in the Golden Channel

- \( BABAR \) measured in \( B^0 \rightarrow J/\psi + K_S \) and related decays

\[
\sin 2 \phi = 0.722 \pm 0.040 \text{(stat.)} \pm 0.023 \text{(syst.)}
\]

227 million \( B\overline{B} \) events

9 May 2006
M. Morii, Harvard
Three angles of the UT

$CP$ violation measurements at the $B$ Factories give

<table>
<thead>
<tr>
<th>Angle (degree)</th>
<th>Decay channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$B^0 \rightarrow \pi\pi, \rho\pi, \rho\rho$</td>
</tr>
<tr>
<td>$21.7^{+1.3}_{-1.2}$</td>
<td></td>
</tr>
<tr>
<td>$\beta$</td>
<td>$B^0 \rightarrow (cc)K^0$</td>
</tr>
<tr>
<td>$63^{+15}_{-12}$</td>
<td></td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$B^0 \rightarrow D^<em>(</em>)K^(*)$</td>
</tr>
</tbody>
</table>

Precision of $\beta$ is 10 times better than $\alpha$ and $\gamma$
CKM precision tests

- Measured angles agree with what we knew before 1999
  
  The CKM mechanism is responsible for the bulk of the CP violation in the quark sector

- But is it all?

- We look for small deviation from the CKM-only hypothesis by using the precise measurement of angle $\beta$ as the reference

Next steps

- Measure $\beta$ with different methods that have different sensitivity to New Physics
- Measure the sides
Angle $\beta$ from penguin decays

- The Golden mode is $b c\bar{c}s$
- Consider a different decay e.g., $b s\bar{s}s$
  - $b$ cannot decay directly to $s$
  - The main diagram has a loop

- The phase from the CKM matrix is identical to the Golden Mode
- We can measure angle $\beta$ in e.g. $B^0 \rightarrow \phi + K_S$
The loop is entirely virtual
- $W$ and $t$ are much heavier than $b$
- It could be made of heavier particles unknown to us

Most New Physics scenarios predict multiple new particles in 100-1000 GeV
- Lightest ones close to $m_{\text{top}} = 174$ GeV
- Their effect on the loop can be as big as the SM loop
- Their complex phases are generally different

Comparing penguins with trees is a sensitive probe for New Physics
Measured $CP$ asymmetries show a suspicious trend

$\sin 2\beta$ (penguin) $< \sin 2\beta$ (tree)

Naive average of penguins give $\sin 2\beta = 0.50 \pm 0.06$

Marginal consistency from the Golden Mode (2.6$\sigma$ deviation)

Need more data!
The sides

- To measure the lengths of the two sides, we must measure $|V_{ub}| \approx 0.004$ and $|V_{td}| \approx 0.008$
  - The smallest elements – not easy!

- Main difficulty: Controlling theoretical errors due to hadronic physics
  - Collaboration between theory and experiment plays key role
$|V_{ub}|$ – the left side

- $|V_{ub}|$ determines the rate of the $b \rightarrow u$ transition
  - Measure the rate of $b \rightarrow u\ell\nu$ decay ($\ell = e$ or $\mu$)

\[
(b \ u \ \bar{\nu}) = \frac{G_F^2}{192} |V_{ub}|^2 m_b^5
\]

- The problem: $b \rightarrow c\ell\nu$ decay is much faster

\[
\frac{(b \ u \ \bar{\nu})}{(b \ c \ \bar{\nu})} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \frac{1}{50}
\]

- Can we overcome a $50 \times$ larger background?
Detecting $b \rightarrow u \ell \nu$

- Use $m_u << m_c \rightarrow$ difference in kinematics

$E_\ell = \text{lepton energy}$
$q^2 = \text{lepton-neutrino mass squared}$
$m_X = \text{hadron system mass}$

$u$ quark turns into 1 or more hardons

- Signal events have smaller $m_X \rightarrow$ Larger $E_\ell$ and $q^2$

Not to scale!
Figuring out what we see

- Cut away $b \rightarrow c \ell \nu \rightarrow$ Lose a part of the $b \rightarrow u \ell \nu$ signal
  - We measure

\[
(B \begin{bmatrix} X_u \end{bmatrix}) \cdot f_C = |V_{ub}|^2 
\]

- Theoretical uncertainty
  - Theoretical error on $|V_{ub}|$ was $\sim 15\%$ in 2003

- Winter 2006:
  \[
  \frac{V_{ub}}{V_{ub}} = (3.5_{\text{expt}} \ 2.8_{\text{model}} \ 4.1_{\text{SF}} \ 4.2_{\text{theory}})\% 
  \]
  \[
  = 7.4\% 
  \]
  - HFAG Moriond 2006 average

- What happened in the last 2+1/2 years?
Progress since 2003

- Experiments combine $E_\ell$, $q^2$, $m_X$ to maximize $f_C$
  - Recoil-$B$ technique improves precisions
  - Loosen cuts by understanding background better

- Theorists understand the $b$-quark motion better
  - Use information from $b \to s\gamma$ and $b \to c\ell\nu$ decays
  - Theory error has shrunk from $\sim15\%$ to $\sim4\%$ in the process
Status of $|V_{ub}|$

- CLEO (endpoint)
  $4.09 \pm 0.48 \pm 0.36$

- BELLE (endpoint)
  $4.82 \pm 0.45 \pm 0.30$

- BABAR (endpoint)
  $4.41 \pm 0.29 \pm 0.31$

- BABAR ($E_e, q^2$)
  $4.10 \pm 0.27 \pm 0.36$

- BELLE $m_X$
  $4.06 \pm 0.27 \pm 0.24$

- BELLE sim. ann. ($m_X, q^2$)
  $4.37 \pm 0.46 \pm 0.29$

- BABAR ($m_X, q^2$)
  $4.75 \pm 0.35 \pm 0.32$

World Average $4.45 \pm 0.33$

\[ \chi^2/\text{dof} = 5.5/6 \]  
\[ \chi^2/\text{dof} = 5.5/6 \]

Measures the length of the left side of the UT
- Why can’t we just measure the $t \rightarrow d$ decay rates?
  - Top quarks are hard to make
  - $(t \ d)/ (t \ b) = V_{td}^2 / V_{tb}^2 < 10^{-4}$

- Must use loop processes where $b \rightarrow t \rightarrow d$
  - Best known example: $B^0$-$\overline{B}^0$ mixing combined with $B_s^0$-$\overline{B}_s^0$ mixing

- $B^0$ oscillation frequency
  - $m_d$ / $|V_{td}|^2$

- $B_s$ oscillation frequency
  - $m_s$ / $|V_{ts}|^2$

- $\Delta m_d = (0.509 \pm 0.004) \text{ ps}^{-1}$

- News from the Tevatron:
  - $m_s = 17.33^{+0.42}_{-0.21} \pm 0.07$
  - $17 < m_s < 21 (90\%CL)$
  - CDF: $|V_{td}| / |V_{ts}| = 0.208^{+0.008}_{-0.007}$
  - DØ
Radiative penguin decays

- Look for a different loop that does $b \rightarrow t \rightarrow d$

- Radiative-penguin decays

\[
\frac{(B)}{(B \ K^*)} \frac{|V_{td}|^2}{|V_{ts}|^2}
\]

- $B (B \ K^*) = (4.0 \pm 0.2) \cdot 10^5$

- Latest results from the $B$ Factories:

<table>
<thead>
<tr>
<th></th>
<th>$B(B \rightarrow \rho \gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BABAR$</td>
<td>$(0.6 \pm 0.3) \times 10^{-6}$</td>
</tr>
<tr>
<td>Belle</td>
<td>$(1.3 \pm 0.3) \times 10^{-6}$</td>
</tr>
<tr>
<td>Average</td>
<td>$(</td>
</tr>
</tbody>
</table>
Impact on the UT

- We can now constrain the right side of the UT.

Mixing measurements pinned down $|V_{td}/V_{ts}|$ as precisely as $\sin 2\beta$.

- $B \to \rho\gamma$ provides a crosscheck, with sensitivity to New Physics.
The UT today

Angles from CP asymmetries

Sides + $K_L$ decays

Combined
The UT today

- The $B$ Factories have dramatically improved our knowledge of the CKM matrix
  - All angles and sides measured with multiple techniques
  - New era of precision CKM measurements in search of NP
- The Standard Model is alive
  - Some deviations observed ➔ require further attention

New Physics seems to be hiding quite skillfully
Constraining New Physics

- New Physics at \( \sim \) TeV scale should affect low-energy physics
  - Effects may be subtle, but we have precision
  - Even absence of significant effects helps to identify NP

- In addition to the UT, we explore:
  - rare \( B \) decays into \( X_s\gamma, X_s\ell^+\ell^-, \tau\nu \)
  - \( D^0 \) mixing and rare \( D \) decays
  - lepton-number violating decays

Precision measurements at the \( B \) Factories place strong constraints on the nature of New Physics

---

Two Higgs doublet model

\[
\begin{align*}
m_H \text{ (GeV)} & \quad \tan\beta \\
0 & \quad 0 \\
1000 & \quad 100 \\
800 & \quad 80 \\
600 & \quad 60 \\
400 & \quad 40 \\
200 & \quad 20 \\
0 & \quad 0
\end{align*}
\]

- Allowed by \( BABAR \) data
- \( b \to s\gamma \)
- \( B \to \tau\nu \)
Outlook

- The $B$ Factories will pursue increasingly precise measurements of the UT and other observables over the next few years.
- Will the SM hold up?
  - Who knows?
- At the same time, we are setting a tight web of constraints on what New Physics can or cannot be.

What the $B$ Factories achieve in the coming years will provide a foundation for future New Physics discoveries.