Experimental reach for CKM angles and sides.

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UK HEP Forum on Heavy Flavour Physics
Cosener's House,
21-22nd June 2007
Outline of the next 45 minutes

- **Motivation.**
- **Angles:**
  - Standard Model viewpoint of $\beta$, $\alpha$, $\gamma$.
  - Looking for New Physics contributions.
- **Sides:**
  - $R_b$.
  - $R_t$.
- Combination of results.
- Unexplored territory.
- Conclusions.
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Study decays involving $b \rightarrow u$ and $t \rightarrow d$ transitions to probe the weak phase of $V_{ub}$ and $V_{td}$.

B-factories have measured $\beta$ to $\sim 1^\circ$ in $c\bar{c}s$, and starting to do precision measurements in charmless $b \rightarrow s$ penguin decays.

$\alpha$ is measured to $7^\circ$.

Now starting to constrain $\gamma$.
The unitarity triangle

- Study decays involving $b \to u$ and $t \to d$ transitions to probe the weak phase of $V_{ub}$ and $V_{td}$.

$$R_b = \frac{V_{ud}^* V_{ub}}{V_{cd}^* V_{cb}} = \frac{V_{td}^* V_{tb}}{V_{td}^* V_{ts}} = R_t$$

- $B \to \pi\pi, \rho\pi, \rho\rho$ etc.
- $B \to \pi\pi, \rho\pi, \rho\rho$ etc.
- $B \to D(*)K(*)$ etc.
- $B \to D(*)K(*)$ etc.
- $B \to c\bar{c}s$ (e.g. $J/\psi K^0$),
- $B \to c\bar{c}s$ (e.g. $J/\psi K^0$),
- $c\bar{c}d$ (e.g. $J/\psi \pi^0$),
- $c\bar{c}d$ (e.g. $J/\psi \pi^0$),
- $\eta', \omega, \phi K^0$ etc.
- $\eta', \omega, \phi K^0$ etc.

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Think of the UT for BaBar and Belle results.
More triangles are studied with $B_S$ decays.
That’s LHCb & SuperB’s job.
The unitarity triangle

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Questions still unanswered

- Why is the level of CPV described by CKM too small?
  - What makes up the difference?
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- Why is the level of CPV described by CKM too small?
  - What makes up the difference?

- Is the triangle unitary?
  - Over-constraining the CKM matrix is the only way to check this.

Recall that there are 6 triangles that can be used to over-constrain the CKM matrix. We’re only concentrating on a few of them with B-physics.
Questions still unanswered

- Why is the level of CPV described by CKM too small?
  - What makes up the difference?

- Is the triangle unitary?
  - Over-constraining the CKM matrix is the only way to check this.

- Are tree and higher order angle measurements the same?
  - Are there non-trivial New Physics flavour couplings at TeV energies?
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Measuring $\beta$

- Main goal of the current B-factories.
  - Observation of CP violation in B decays (2001).

- … but this was the tip of the iceberg.
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… but this was the tip of the iceberg.
Lots more physics to do.
- Cross-check tree level with loops.
- Cross-check different tree/loop processes to compare topologies.
- Control standard model uncertainties on measurements.
- Search for new physics.

+…
$\beta$ from $b \to c\bar{c}s$ decays

HFAG average of results:

$$\sin(2\beta) = 0.678 \pm 0.022^{\text{STAT}} \pm 0.012^{\text{SYST}}$$

$$\beta = (21.3 \pm 1.0)^\circ$$

- Good agreement in different channels (BaBar results shown) for $\sin 2\beta$.
- $1^\circ$ precision has been attained.
- This measurement was the raison d'être of the current B-factories.

| Sample                  | $N_{tag}$ | $P(\%)$ | $\sin 2\beta$ | $|\lambda|$ |
|------------------------|-----------|---------|----------------|-----------|
| Full CP sample         | 12677     | 75      | 0.714 $\pm$ 0.032 | 0.952 $\pm$ 0.022 |
| $J/\psi K_S^0 (\pi^+\pi^-)$ | 4459   | 96      | 0.702 $\pm$ 0.042 | 0.976 $\pm$ 0.030 |
| $J/\psi K_S^0 (\pi^0\pi^0)$ | 1086   | 88      | 0.617 $\pm$ 0.103 | 0.812 $\pm$ 0.058 |
| $\psi(2S)K_S^0$        | 687       | 83      | 0.947 $\pm$ 0.112 | 0.867 $\pm$ 0.079 |
| $\chi_{c1}K_S^0$       | 313       | 89      | 0.759 $\pm$ 0.170 | 0.804 $\pm$ 0.102 |
| $\eta_c K_S^0$         | 328       | 69      | 0.778 $\pm$ 0.195 | 0.948 $\pm$ 0.141 |
| $J/\psi K^0_0$         | 4748      | 55      | 0.734 $\pm$ 0.074 | 1.061 $\pm$ 0.063 |
| $J/\psi K^0_1$         | 1056      | 66      | 0.477 $\pm$ 0.271 | 0.954 $\pm$ 0.083 |
| $J/\psi K^0_0$         | 10275     | 76      | 0.697 $\pm$ 0.035 | 0.966 $\pm$ 0.025 |
| $J/\psi K_S^0$         | 5547      | 94      | 0.686 $\pm$ 0.039 | 0.950 $\pm$ 0.027 |

hep-ex/0703021
PRL 98 031802 (2007)
\[ \beta \text{ from } b \to c\bar{c}s \text{ decays} \]

HFAG average of results:

\[ \sin(2\beta) = 0.678 \pm 0.022_{STAT} \pm 0.012_{SYST} \]

\[ \beta = (21.3 \pm 1.0)^\circ \]

- Experiments agree well.

\[ V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]
$\beta$ from $b \to c\bar{c}s$ decays

HFAG average of results:

$$\sin(2\beta) = 0.678 \pm 0.022_{\text{STAT}} \pm 0.012_{\text{Syst}}$$

$$\beta = (21.3 \pm 1.0)^{\circ}$$

Experiments agree well.

- $\cos2\beta$ from $J/\psi K^*, K^+K^0, D^0(K_s\pi^+\pi^-)h^0 D^{*+}D^*-K_s$ favours $\beta=21.3^\circ$ over $\beta=68.7^\circ$.
- Expect
  - LHCb: $0.3^\circ$ measurement (stat) $(10\text{fb}^{-1})$
  - Super LHCb: $0.1^\circ$ measurement (stat) $(100\text{fb}^{-1})$
  - Super B: $0.2^\circ$ measurement $(75\text{ab}^{-1})$

Negative solution disfavoured by $\cos2\beta$ measurements.

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

hep-ex/0703021
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\textbf{\( \beta \) from \( b \to c\bar{c}d \) decays}

- Tree dominated decays, perhaps with some penguin contribution

  - Same tree topology as \( c\bar{c}s \) – just replace the ‘s’ quark for a ‘d’ quark.

  - Sizable deviation from \( \beta \) in \( c\bar{c}s \) decays would indicate New Physics

    - Measurements are consistent with tree level expectation.

  - \( B^0 \to J/\psi \pi^0 \) can be used to estimate SM uncertainty to \( c\bar{c}s \) \( \beta \) calculation at the level of \( 10^{-2} \).
\( \beta \) from \( b \rightarrow s \) penguins

- Tree level \( \beta \) is known to 1°.
- What is \( \beta \) measured in loop processes?

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

\( V \)
\( \beta \) from \( b \to s \) penguins

- Tree level \( \beta \) is known to 1°.
- New physics loop contributions can have new CP phases.

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

H + quarks?
β from $b\to s$ penguins

- Tree level $\beta$ is known to 1°.
- New physics loop contributions can have new CP phases.

This would result in different:
  - rate measurements.
  - CP asymmetries (i.e. $\sin^2\beta_{\text{TREE}} \neq \sin^2\beta_{\text{LOOP}}$).
Naive average is $2.6\sigma$ different from the tree level $\beta$ measurement.
Naive average is $2.6\sigma$ different from the tree level $\beta$ measurement.

Different channels have different theoretical uncertainties.

\begin{align*}
\Delta S_f & \quad \text{QCDF} & \quad pQCD & \quad \text{SCET} \\
\phi K_S & \quad 0.02 \pm 0.01 & \quad 0.020^{+0.005}_{-0.008} & \quad \text{ } \\
\omega K_S & \quad 0.13 \pm 0.08 & \quad \text{ } & \quad \text{ } \\
\rho^0 K_S & \quad -0.08^{+0.08}_{-0.12} & \quad \text{ } & \quad \text{ } \\
\eta' K_S & \quad 0.01 \pm 0.01 & \quad \text{ } & \quad \text{ } \\
\eta K_S & \quad 0.10^{+0.11}_{-0.07} & \quad -0.03 \pm 0.17 & \quad \text{ } \\
\pi^0 K_S & \quad 0.07^{+0.05}_{-0.04} & \quad 0.06^{+0.02}_{-0.03} & \quad 0.08 \pm 0.03 \\
f_0 K_S & \quad 0.02 \pm 0.00 & \quad \text{ } & \quad \text{ } \\
\alpha_0 K_S & \quad 0.02 \pm 0.01 & \quad \text{ } & \quad \text{ } \\
\bar{K}_0^* \pi^0 & \quad 0.00^{+0.03}_{-0.02} & \quad 0.02^{+0.03}_{-0.02} & \quad \text{ } \\
\end{align*}

Chua hep-ph/0605301

\[
\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}}) \quad \text{(HFAG Preliminary)}
\]
\( \beta \) from \( b \to s \) penguins

- Naive average is 2.6\( \sigma \) different from the tree level \( \beta \) measurement.

- Different channels have different theoretical uncertainties.

- Need to compare each mode with the tree level value.
  - Can’t do this with the current statistics.
  - Need to wait for the next generation machines.
Naive average is $2.6\sigma$ different from the tree level $\beta$ measurement.

Different channels have different theoretical uncertainties.

Need to compare each mode with the tree level value.
  - Can’t do this with the current statistics.
  - Need to wait for the next generation machines.
  - LHCb can do $B_d \to \phi K_s$ and $B_s$ equivalent decays.
  - Super LHCb might be re-optimised to do other $B_d$ channels.
  - Super B would compliment the range of measurements that one has from LHCb.

$$\sin(2\beta_{\text{eff}}) = \sin(2\phi_1^{\text{eff}})$$

$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$
\( \beta_s \) @ the next generation

- LHCb + Super LHCb:
  - Improve upon knowledge of \( \beta \) to 0.1°.
  - Open up the study of \( \phi_s \) in \( B_s \) decays.
    - 0.003 (10 %) measurement in \( B_s \rightarrow J/\psi \phi \) decays.
    - 0.014 measurement in \( B_s \rightarrow \phi \phi \) decays.
    - Search for NP in \( B_s \) sector.

- Super B:
  - Comparable \( \beta_s \) measurement ~0.2°.
  - Complementary measurements of \( b \rightarrow s \) decays from \( B_d \).
  - ~3° measurement of \( \beta_s \) from \( B_s \rightarrow J/\psi \phi \) with 30ab\(^{-1}\) at Y(5S).

- Tevatron starting to constrain \( \phi_s \)
  \[ \phi_s(D\emptyset) = -0.79 \pm 0.56^{+0.14}_{-0.01} \]

GW LHCb upgrade WS, Jan 07
\[ \beta_s \] @ the next generation

- LHCb + Super LHCb:
  - Improve upon knowledge of $\beta$ to 0.1°.
  - Open up the study of $\phi_s$ in $B_s$ decays.
    - 0.003 (10 %) measurement in $B_s \rightarrow J/\psi \phi$ decays.
    - 0.014 measurement in $B_s \rightarrow \phi \phi$ decays.
    - Search for NP in $B_s$ sector.
  \}

@100fb^{-1} 

- Super B:
  - Comparable $\beta$ measurement \sim 0.2°.
  - Complementary measurements of $b \rightarrow s$ decays from $B_d$.
  - \sim 3° measurement of $\beta_s$ from $B_s \rightarrow J/\psi \phi$ with 30ab^{-1} at Y(5S).
    - Use the sign of $\Delta t$ to measure $\text{Re}(\lambda)$ and $\text{Im}(\lambda)$.

hep-ph/0703258 

GW LHCb upgrade WS, Jan 07
Measuring $\alpha$

- CP violation in $B^0 \rightarrow h^+ h^-$, $h = \pi, \rho, a_1$

\[ V_{td}^* : \beta \]

\[ V_{ub} : \gamma \]

\[ C_{hh} = 0 \]
\[ S_{hh} = \sin(2\alpha) \]

- Measure $\alpha_{\text{eff}}$.
- Need to bound $|\alpha_{\text{eff}} - \alpha|$ (shift from loops).
- Different $|\text{Penguin} / \text{Tree}|$ for different decays.
- More complicated for non-CP eigenstates like $\rho \pi$.

\[ \alpha_{\text{eff}} \]

\[ S_{hh} = \sqrt{1 - C_{hh}^2} \sin(2\alpha_{\text{eff}}) \]

\[ \delta = \delta_P - \delta_T \]
B→ππ isospin analysis

- $\alpha \sim 50^\circ$ excluded.
- Several ambiguities to resolve between solutions.
- Difference between BaBar and Belle constraints on $\alpha$ is driven by the different values of C obtained by each experiment.

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

hep-ex/0703016
PRL 98 211801 (2007)
$B \to \pi \pi$ isospin analysis

- $\alpha \sim 50^\circ$ excluded.
- Several ambiguities to resolve between solutions.
- Difference between BaBar and Belle constraints on $\alpha$ is driven by the different values of $C$ obtained by each experiment.
$\mathbf{B}\rightarrow\rho\rho$ isospin analysis

- $\alpha \sim 50^\circ$, $130^\circ$ excluded.
- Several ambiguities to resolve between solutions.
- Difference between BaBar and Belle constraints on $\alpha$ is driven by the different values of $C$ obtained by each experiment.

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

arXiv:0705.2157
hep-ex/0702009
**B→ρπ Dalitz analysis**

- Constraint on $\alpha$ is weak at the $3\sigma$ level.
- Several ambiguities to resolve between solutions.
- Difference between BaBar and Belle constraints on $\alpha$ is driven by statistical fluctuations between the two samples.

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

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hep-ex/0703008
PRL 98 221602 (2007)
Overall

- $\alpha \sim 50^\circ$, $130^\circ$ excluded.

- Ambiguities to resolve between solutions.

- Combining different measurements gives us a measurement of $\alpha$ compatible with the Standard Model at almost $2\sigma$.

- Need more statistics to rule out incompatibilities.

- Compare the value of $\alpha$ measured with individual channels.
### LHCb
- $\sigma(\alpha)$ from $\rho\pi$ will be 4.5° with 10fb$^{-1}$.
- SU(3) methods can be used with $\pi^+\pi^-/K\pi$ to obtain $\alpha/\gamma$.
- S and C measurements from $\rho^0\rho^0$ will help a lot.
- $a_1\pi$ the jury is still out on how useful these modes will be.

### Super LHCb
- Upgrade to accumulate 100fb$^{-1}$ $\sigma \sim 1.4^\circ$ from $\pi^+\pi^-\pi^0$.

### SuperB
- 75ab$^{-1}$ accumulated at the Y(4S).
  - $\sigma(\alpha) \sim 0.75^\circ$ using $\rho\rho$ decays
  - $\sigma(\alpha) \sim 1-2^\circ$ using $\pi\pi$ decays
  - See AB at the 5th Super B Workshop in Paris

See [AB at the 5th Super B Workshop in Paris](http://events.lal.in2p3.fr/conferences/SuperBFactory/index.html) for more details.
Measuring $\gamma$

- Gives an over-constraint of the triangle.
- Least well known of UT angles.
- Need LHCb to give a precision measurement.
- $\gamma$: safety in numbers.
  - No single channel will dominate precision.
    - $\gamma$: $B \rightarrow DK$ etc.,
    - $2\beta + \gamma$: $D^*\pi$ etc.
  - Need to average many methods to obtain ultimate precision.
  - Use $\pi\pi/K\pi$ or $\rho\rho/K^*\rho$ with SU(3) as cross-check.
$B \rightarrow D^{(*)0} K^{(*) -}$

- **GGSZ:**
  - Structure of Dalitz plot gives access to $\gamma$, $r_B$, $\delta_B$.
  - $D^0 \rightarrow K_s \pi^+ \pi^-$ final state is accessible through many different decays.

$$A(B^-) = |A_b(D^0 K^-)| \times \begin{pmatrix} m^+ \\ m^- \\ m^2 - m^2^+ \end{pmatrix} + r_B e^{i(\delta_B - \gamma)} \times A_D(m^2-, m^2+) \times A_D(m^2+, m^2^-)$$

- Sensitivity varies strongly over Dalitz plane
  - Model + mixture ADS+GLW
\[ \mathbf{B} \rightarrow \mathbf{D}^{(*)0} \mathbf{K}^{(*)} - \]

- **GGSZ:**
  - Structure of Dalitz plot gives access to \( \gamma, r_{B}, \delta_{B} \).
  - \( \mathbf{D}^{0} \rightarrow \mathbf{K}_{s} \pi^{+} \pi^{-} \) final state is accessible through many different decays.

![Dalitz plot graph](image)

\[ \phi_{3} \gamma = (77 \pm 31)^{\circ} \]

CKM-Fitter@1\sigma:

[52.8, 70.1]°

\( r_{B}(\mathbf{D}\mathbf{K}) < 0.13, \; r_{B}(\mathbf{D}^{*}\mathbf{K}) < 0.13, \; r_{B}(\mathbf{D}\mathbf{K}^{*}) < 0.27 \) at 90% C.L.
Relate $K^{*0}\rho^+$ to the penguin amplitude in $\rho^+\rho^-$ and use $S_{\rho^+\rho^-}$ and $C_{\rho^+\rho^-}$ to constrain $\gamma$.

$$A(B^0 \rightarrow \rho^+\rho^-) = T e^{i\gamma} + P e^{i\delta_{TP}}$$

- Introduce theory uncertainty of a few degrees.
- Reduced experimental uncertainty on penguin contamination.
- Uses $\beta$ from charmonium to extract $\gamma$.
- With small $\delta$,

$$\gamma = (68.5^{+6.4}_{-7.0})^\circ$$

arXiv:0705.2157
Beneke et al., PLB 638 p68 (2006)
**B→ππ SU(3) analysis**

- The analogous method to constrain $\gamma$ using $\pi\pi$ decays uses $B\to K\pi$ to contain the penguin.

\[
A(B^0 \to \pi^+\pi^-) = Te^{i\gamma} + Pe^{i\delta}
\]

\[
C_{\pi\pi} = \frac{2r \sin \delta \sin(\beta + \alpha)}{R_{\pi\pi}}, \\
S_{\pi\pi} = \frac{\sin 2\alpha + 2r \cos \delta \sin(\beta - \alpha) - r^2 \sin 2\beta}{R_{\pi\pi}}, \\
R_{\pi\pi} \equiv 1 - 2r \cos \delta \cos(\beta + \alpha) + r^2,
\]

- Can relate C and S to values of $\gamma$, r and $\delta$.
- N.B. $\beta$ is input from ccs decays, so the only angle left to determine is $\gamma$ in this convention.
- Uncertainties are larger than $\rho\rho$ case, but this provides a good cross-check.

$\gamma = (74 \pm 4^{+10}_{-8})^\circ$

Gronau & Rosner arXiv:0704.3459
The difficulty in measuring $\gamma$ comes from the small value of $r_B$.

- Need larger data sets to do precision measurements.
- Need to combine many channels to reach the ultimate precision.
\( \gamma @ \text{The next generation} \)

- **LHCb goals for measuring CKM angle \( \gamma \)**
  - \( B^0 \rightarrow D^0 K^{*0}, B^\pm \rightarrow D K^{\pm} \) & \( B_s^0 \rightarrow D_s^{\mp} K^{\pm} \)
    - Two interfering tree processes in neutral or charged B decay
  - Use decays common to \( D^0 \) and anti-\( D^0 \)
    - Cabbibo favoured self-conjugate D decays
      - e.g. \( D^0 \rightarrow K_S \pi^0 \), \( K_S K K \), \( K K \pi \pi \) Dalitz analysis
    - Cabbibo favoured, single & doubly Cabbibo suppressed D decays
      - e.g. \( D^0 \rightarrow K_{\pi} \), \( K K \), \( K_{\pi \pi \pi} \) ADS (GLW) method
  - \( B_s \rightarrow D_s^{\pm} K^{\mp} \) - two tree decays (\( b \rightarrow c \) and \( b \rightarrow u \)) of \( O(\lambda^3) \)
    - Interference via \( B_s \) mixing

- **\( \gamma \) Sensitivity**
  - Expected precision for ADS and Dalitz \( \sigma(\gamma) \sim 5^\circ -15^\circ \) in 2 fb\(^{-1}\)

- **Motivation for LHCb Upgrade**
  - Theoretical error in SM is very small < 1\(^\circ\)
  - Large statistics helps to reduce systematic error to similar level
  - With 100 fb\(^{-1}\) estimate precision \( \sigma(\gamma) \sim 1^\circ \)
  - Requires 1\(^{st}\) level detached vertex trigger for hadronic decays

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

\( \text{c.f. Super B precision} \sim 1-2^\circ \text{ @75 ab}^{-1} \)
Looking for new physics: summary

- $\beta$
  - Standard model (tree level) reference point from $c\bar{c}s$ decays.
  - Many crosschecks that are loop dominated, or have loop contributions. These can be used for NP searches.
  - $\beta_s$ measurements – $B_s$ decay equivalents.

- $\alpha$
  - 3 comparable measurements: cross-checks.
  - … more if SU(3) based approaches are used.

- $\gamma$
  - Several channels to compare and combine. $2\beta + \gamma$ measurements provide useful constraints on the $\rho$-$\eta$ plane.
  - These angle measurements over-constrain the triangle.
    - Inconsistencies can indicate NP.
Outline of the next 45 minutes

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  - Looking for New Physics contributions.
- Sides:
  - $R_b$.
  - $R_t$.
- Combination of results.
- Unexplored territory.
- Conclusions.
Compliment the angles.
- Semileptonic decays \( (V_{ub}, V_{cb}) \) using \( X_{u/c} \nu \).
- Rare decays \( B^+ \rightarrow l^+ \nu \)
- \( \ldots + \varepsilon_K, K \rightarrow \pi \nu \bar{\nu} \) tell us about \( R_b \) and \( R_t \).  
  
Any Inconsistencies with other constraints indicate new physics.
- Alternatively search for new physics using \( \tau^+ \nu \), \( B \), \( A_{CP} \) in \( b \rightarrow s \gamma \).
\( |V_{ub}|^2 \propto \mathcal{B}(B \rightarrow X_u l \nu) \) in a limited region of phase space.

Reconstruct other B in the event & \( X_u l \nu \) signal using the other B + beam information to reconstruct \( \nu \).

Measure \( \mathcal{B} \) as a function of \( q^2 \) (\( l \nu \)), \( m_X \) or lepton energy.

Need theory to interpret result in terms of \( |V_{ub}| \).

- Several models on the market: BLNP, BLL, DGE.
- Significant theoretical uncertainty on average.
**Inclusive $V_{ub}$: $b \to u \ell \nu$**

- Take BLNP as an example scheme.

$$|V_{ub}|_{\text{incl}} = (4.52 \pm 0.19 \pm 0.27) \times 10^{-3}$$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CLEO ($E_e$)</strong></td>
<td>$4.09 \pm 0.48 \pm 0.37$</td>
</tr>
<tr>
<td><strong>BELLE</strong> (sim. ann. ($m_X$, $q^2$))</td>
<td>$4.37 \pm 0.46 \pm 0.29$</td>
</tr>
<tr>
<td><strong>BELLE</strong> ($E_e$)</td>
<td>$4.82 \pm 0.45 \pm 0.30$</td>
</tr>
<tr>
<td><strong>BABAR</strong> ($E_e$)</td>
<td>$4.39 \pm 0.25 \pm 0.32$</td>
</tr>
<tr>
<td><strong>BABAR</strong> ($E_e$, $s^{\text{max}}_b$)</td>
<td>$4.57 \pm 0.31 \pm 0.42$</td>
</tr>
<tr>
<td><strong>BELLE</strong> ($m_X$)</td>
<td>$4.06 \pm 0.27 \pm 0.24$</td>
</tr>
<tr>
<td><strong>BABAR</strong> ($m_X$, $q^2$)</td>
<td>$4.75 \pm 0.35 \pm 0.31$</td>
</tr>
</tbody>
</table>

Average +/- exp +/- (mb, theory)

$$4.52 \pm 0.19 \pm 0.27$$

$\chi^2$/dof = 6/5 (CL = 41 %)

OPE-HQET-SCET (BLNP)


$m_\nu$ input from $b \to c \ell \nu$ and $b \to s \gamma$ moments
Inclusive $V_{ub}$: $b \rightarrow u \ell \nu$

- Take BLNP as an example scheme.

$$|V_{ub}|_{\text{incl}} = (4.52 \pm 0.19 \pm 0.27) \times 10^{-3}$$

<table>
<thead>
<tr>
<th>Observable</th>
<th>$B$ Factories (2 ab$^{-1}$)</th>
<th>SuperB (75 ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ (exclusive)</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ (inclusive)</td>
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<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ (exclusive)</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ (inclusive)</td>
</tr>
</tbody>
</table>

CLEO ($E_e$)
4.09 ± 0.48 ± 0.37

BELLE sim. ann. ($m_X$, $q^2$)
4.37 ± 0.46 ± 0.29

BELLE ($E_e$)
4.82 ± 0.45 ± 0.30

BABAR ($E_e$)
4.39 ± 0.25 ± 0.32

BABAR ($E_e$, $s_b^{\text{max}}$)
4.57 ± 0.31 ± 0.42

BELLE ($m_X$)
4.06 ± 0.27 ± 0.24

BABAR ($m_X$, $q^2$)
4.75 ± 0.35 ± 0.31

Average $\pm$ exp $\pm$ (mb, theory)
4.52 ± 0.19 ± 0.27

$\chi^2/\text{dof} = 6/5$ (CL = 41%)
OPF-FOET-SCET (BLNP)

$m_b$ input from $b \rightarrow c \ell \nu$ and $b \rightarrow s \ell \nu$
Compliment the angles.

- $b \rightarrow d \gamma/s \gamma$ to extract $|V_{td}/V_{ts}|$.

\[
R_t = \frac{\Gamma(B \rightarrow K^* \gamma)}{\Gamma(B \rightarrow \rho \gamma)} = \frac{|V_{td}|^2}{|V_{ts}|^2} \frac{(m_B - m_\rho)^3}{(m_B - m_{K^*})^3} \left( \frac{T^\rho(0)}{T^{K^*}(0)} \right)^2 (1 + \Delta R)
\]

\[
O(0) \quad O(1)
\]

\[
\left| \frac{V_{td}}{V_{ts}} \right|_{\rho/\omega \gamma} = 0.202^{+0.017}_{-0.016} \pm 0.015
\]

8.2% 7.4%


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

June 2007  
Adrian Bevan  
46
■ Compliment the angles.
  ■ $b \rightarrow d \gamma/s \gamma$ to extract $|V_{td}/V_{ts}|$.
  ■ $\Delta m_s$ from the Tevatron.

$\Delta m_s = 17.77 \pm 0.10 \text{(stat)} \pm 0.07 \text{(syst)}$

$|V_{td}|/|V_{ts}| = 0.2060 \pm 0.0007 \text{(exp)} \pm 0.0081\text{(theo)}$

$LHCb$ will do a precision measurement of $\Delta m_s$
Impact on $\rho$-$\eta$

\[ v = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]
Outline of the next 45 minutes

- Motivation.
- Angles:
  - Standard Model viewpoint of $\beta$, $\alpha$, $\gamma$.
  - Looking for New Physics contributions.
- Sides:
  - $R_b$.
  - $R_t$.
- Combination of results.
- Unexplored territory.
- Conclusions.
Combination of results.

- [See talk by M. Bona in this session]
  Current Precision with all constraints.

Extrapolating existing measurements to Super LHCb / super-B luminosity.
Outline of the next 45 minutes

- Motivation.
- Angles:
  - Standard Model viewpoint of $\beta$, $\alpha$, $\gamma$.
  - Looking for New Physics contributions.
- Sides:
  - $R_b$.
  - $R_t$.
- Combination of results.
- **Unexplored territory.**
- Conclusions.
Prediction for 2020?

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

$\beta$ measured to a precision of 0.2° by either Super LHCb or Super B.
Prediction for 2020?

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

$\alpha$ measured to $0.75^\circ$ using an isospin analysis of $\rho\rho$ decays at SuperB.
Prediction for 2020?

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

\( \gamma \) measured to 1° at Super LHCb using DK modes.
Prediction for 2020?

\[ \frac{V}{V_{ud}} \approx \frac{V_{us}}{V_{cd}} \approx \frac{V_{cs}}{V_{cd}} \approx \frac{V_{cb}}{V_{cd}} \]

\[ \frac{V_{ud}}{V_{cd}} \approx \frac{V_{us}}{V_{cd}} \approx \frac{V_{cs}}{V_{cd}} \approx \frac{V_{cb}}{V_{cd}} \]

\[ \rho \sim 0.75^\circ \]
\[ \beta \sim 0.2^\circ \]
\[ \gamma \sim 1^\circ \]

\[ \bar{\rho} = 0.133 \pm 0.005 \quad (3.8\%) \]
\[ \bar{\eta} = 0.338 \pm 0.003 \quad (0.9\%) \]
Past evolution

- UT fit’s evolution of the measurement of the unitarity triangle:
  - All available information from indirect and direct constraints.
The next 13 years?

- My prediction of the evolution of the measurement of the unitarity triangle:
  - Using only $\alpha$ ($\rho\rho$ isospin) and $\beta$ measurements.

![Diagram showing evolution from Now (2008/9) to (2020)]
Unexplored territory

- Go back and look at the BaBar physics book…
  - You won’t correctly identify the best methods to measure $\alpha$ and $\gamma$ (and a number of other observables).
  - With data in hand, the current B-factories have appreciated how to do the job better than was thought 10-15 years ago. *History usually repeats itself...*
  - Having two collaborations helped keep up the momentum and exchange of ideas.
  - We’re just beginning to study $B_s$ in detail at the Tevatron.
  - We can look forward to results from LHCb complementing the existing measurements (2008?).
  - Hopefully we will also see Super B augmenting the flavour programme (2015?).
Outline of the next 45 minutes

- Motivation.
- Angles:
  - Standard Model viewpoint of $\beta$, $\alpha$, $\gamma$.
  - Looking for New Physics contributions.
- Sides:
  - $V_{ub}$.
  - $V_{td}$.
- Combination of results.
- Undiscovered territory.
- Conclusions.
Conclusions

- Using 1ab$^{-1}$ of data from the B-factories have established:
  - CP Violation in B decays (indirect and direct).
  - 7° test of the closure of the unitarity triangle.
  - Observe some tension at the 1.5$\sigma$ level between constraints.
  - Seen evidence for D mixing.
  - … and done a lot of other things in the meantime.

- The B-factories will push ahead to collect up to 2ab$^{-1}$.

- The next generations of experiment will take up the challenge soon:
  - LHC(b): Initial impact in $\gamma$ and $B_s$ + lots of other physics. [See J. Libby on Friday]  
    http://lhcb.web.cern.ch/lhcb/
  - SuperB: Same program as BaBar and Belle + $B_s$ etc. [See T. Gershon on Friday]  
    http://www.pi.infn.it/SuperB/
Additional material
SU(2) based methods.

- SU(2) isospin relates the different $B \rightarrow hh'$ amplitudes ($h, h' = \pi, \rho$): Gronau London (GL) method.

\[ \frac{1}{\sqrt{2}} A^{+-} = A^{+0} - A^{00}, \]
\[ \frac{1}{\sqrt{2}} A^{++} = A^{+0} - A^{00}, \]
\[ |A^{+0}| = |A^{+0}| \]

- $\delta \alpha_{ij} = \alpha_{ij}^{eff} - \alpha$ parameterise penguin pollution in $+-$ and $00$ charged final states.

- Relationship to S and C:

\[ \sin(2\alpha_{eff}^{+-}) = \frac{S^{+-}}{\sqrt{1 - (C^{+-})^2}}, \]
\[ \sin(2\alpha_{eff}^{00}) = \frac{S^{00}}{\sqrt{1 - (C^{00})^2}}, \]
Impact on $\bar{\rho}$ and $\bar{\eta}$

From $\gamma$ measurements

From $2\beta + \gamma$ measurements

$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$
$\mathbf{B}^+ \rightarrow \tau^+ \nu$

- Suppressed by $V_{ub}$

- Within the SM, this measurement can be used to constrain $f_B$.

- Can constrain the apex of the unitarity triangle using this measurement
  - Complements the angle measurements

\[
\mathcal{B}_{SM}(B^+ \rightarrow l^+ \nu_l) = \frac{G_F^2 m_B m_{l_i}^2}{8\pi} \left(1 - \frac{m_{l_i}^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B
\]

SM prediction $(1.59 \pm 0.40) \times 10^{-4}$

Shaded region = 95% Prob.

http://utfit.roma1.infn.it/
\[
B^+ \rightarrow \tau^+ \nu
\]

- Suppressed by \( V_{ub} \)

- Can replace \( W^+ \) with \( H^+ \)

- \( B \) can be suppressed or enhanced by a factor of \( r_H \).

\[
r_H = \left( 1 - \frac{m_B^2}{m_H^2} \tan^2 \beta \right)^2
\]


http://utfit.roma1.infn.it/
Reconstruct signal decay.
and other B in the event:
- Belle: fully reconstruct B mesons in 180 channels.
- BaBar: Tag with $B \to D(*)\nu$.
Look at the remaining energy in the calorimeter:
signal peaks at $E_{ECL/extra} = 0$.

$\mathcal{B} = (1.79^{+0.56+0.39}_{-0.49-0.46}) \times 10^{-4}$
(revised). 3.5 $\sigma$ significance

$\mathcal{B} = (0.88^{+0.68}_{0.67} \pm 0.11) \times 10^{-4}$
$BF < 1.80 \times 10^{-4} @ 90\% CL$

Belle: fully reconstruct B mesons in 180 channels.
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$\mathcal{B} = (0.88^{+0.68}_{0.67} \pm 0.11) \times 10^{-4}$
$BF < 1.80 \times 10^{-4} @ 90\% CL$
\[ B^+ \rightarrow \tau^+\nu \]

- Multi TeV search capability for large \( \tan\beta \).

\[ r_H = \left( 1 - \tan^2\beta \frac{m_B^2}{m_H^2} \right)^2 \]

\[ r_H = \left( 1 - \frac{\tan^2\beta}{1 + \varepsilon_0 \tan\beta \frac{m_B^2}{m_H^2}} \right)^2 \]

Charm equivalent:

\[ D_s^+ \rightarrow \mu^+\nu, \tau^+\nu \]
$B^+ \to e^+ \nu, \mu^+ \nu$

- Same physics motivation as $\tau^+ \nu$.

$$
\mathcal{B}_{SM}(B^+ \to l^+ \nu_l) = \frac{G_F^2 m_B m_l}{8\pi} \left(1 - \frac{m_l^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B
$$

- These searches give null results. Upper limits are shown for BaBar and Belle.

- Consistent with SM.

- Best limits within a factor of 2 of SM

BaBar: $229 \times 10^6$ B pairs
Belle: $277 \times 10^6$ B pairs

$B(B^+ \to e^+ \nu_e) < 7.9 \times 10^{-6}$ (90% CL)
$B(B^+ \to e^+ \nu_e) < 9.8 \times 10^{-7}$ (90% CL)
$B(B^+ \to \mu^+ \nu_\mu) < 6.2 \times 10^{-6}$ (90% CL)
$B(B^+ \to \mu^+ \nu_\mu) < 1.7 \times 10^{-6}$ (90% CL)
B→dγ transitions: ωγ, ργ

- Both experiments observe b→dγ decays.
- With very consistent results.

\[ \mathcal{B}(B \to ργ, ωγ) = (1.25 \pm 0.25 \pm 0.09) \times 10^{-6} \]

\[ \frac{\mathcal{B}(B \to ργ, ωγ)}{\mathcal{B}(B \to K^∗γ)} = 0.030 \pm 0.006 \]

\[ \left| \frac{V_{td}}{V_{ts}} \right| = 0.200 \pm 0.020 \pm 0.015 \]

\[ \mathcal{B}(B \to ργ, ωγ) = (1.32^{+0.34}_{-0.31} \pm 0.10) \times 10^{-6} \]

\[ \frac{\mathcal{B}(B \to ργ, ωγ)}{\mathcal{B}(B \to K^∗γ)} = 0.032 \pm 0.006 \pm 0.002 \]

\[ \left| \frac{V_{td}}{V_{ts}} \right| = 0.199 \pm 0.026^{+0.018}_{-0.015} \]
**B→dγ transitions: ωγ, ργ**

- Can constrain the unitarity triangle using $B \rightarrow K^* \gamma$
  - Orthogonal to constraint from $B^+ \rightarrow \tau^+\nu$
  - Compliments angle measurements (Y.J. Kwon’s talk @ KEKTC6 Feb 2007)

![Graphs showing ρ₀γ and ρ±γ](http://utfit.roma1.infn.it/Shaded region = 95% Prob.)