CP Violation and the Determination of the CKM Matrix

Frank Porter (Caltech, \(B\bar{A}B\bar{A}\R))

- Cabibbo-Kobayashi-Maskawa (CKM) matrix “\(V\)”
  - Fundamental in Standard Model (SM)
  - Four parameters \((\theta_{12}, \theta_{13}, \theta_{23}, \phi \leftrightarrow A, \lambda, \rho, \eta)\)
  - Source of \(CP\) violation in SM

- Testing the SM – \(V\) is unitary \(3 \times 3\) matrix in SM
  - Additional generations can make non-unitary
  - Can test unitarity relations with measurements of magnitudes and/or phases

- New physics can show up in loops, often at same order as SM graphs
  - Look for differences among quantities that should be the same in SM, or for deviations from SM predictions
Scope, with apologies for the many topics left out

- Heavy flavors \((s,c,b,t,\tau)\)
- Nothing on EDM
- For neutrino sector (PMNS matrix), see talks by Lisi, Bellerive, Nakaya, and Piquemal
- For \(\beta_s\), like sign di-muon asymmetry, see Borissov’s talk [Also Belle (Wicht, 1204)]
- Not much discussion beyond the SM (but an underlying theme)
- For theory, see talk by Isidori (Lattice – Kuramashi)
- Omit \(CPT\) tests (see Lusiani, 1173; Kundu, 270)
- Omit future prospects

CKM – magnitudes of elements

CKM - CP violation
The Cabibbo-Kobayashi-Maskawa mixing matrix

Relates quark mass eigenstates to weak eigenstates.

\[
V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
= \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]

(Wolfenstein parameterization)

Often define \(\bar{\rho} \equiv \rho(1 - \lambda^2/2), \bar{\eta} \equiv \eta(1 - \lambda^2/2)\)

- Magnitudes
- Phases (i.e., “angles of unitarity triangles”)

Determinations assume standard model, but not using unitarity. Inconsistencies could be signs of new physics.
The magnitudes: $|V_{ud}|$

2008 RPP

$|V_{ud}| = 0.97418 \pm 0.00027$

Best determinations in superallowed $0^+ \to 0^+$ nuclear $\beta$ decays.

Recent analysis from Hardy and Towner PRC 79 (2009) 055502 yields:

$|V_{ud}| = 0.97425 \pm 0.00022$
The magnitudes: $|V_{us}|$

2008 RPP

$|V_{us}| = 0.2255 \pm 0.0019$

$|V_{us}|$ from kaon decays


- $K_{\ell 3}$: $|V_{us}|f_{+}(0) = 0.2163(5)$ or $|V_{us}| = 0.2254 \pm 0.0013$ with $f_{+}(0) = 0.959(5)$ (lattice, Boyle et al., arXiv:1004:0886 (2010))

- $K_{\ell 2}$: \[ \frac{|V_{us}| f_K}{|V_{ud}| f_{\pi}} = 0.2758(5) \text{ or } \frac{|V_{us}|}{|V_{ud}|} = 0.2312 \pm 0.0013 \]

with $f_K/f_{\pi} = 1.193(6)$ (lattice average)

- Combining, obtain $|V_{us}|(K) = 0.02253 \pm 0.0009$
$|V_{us}|$ from tau decays

- **BABAR** (Lusiani, 1173) Measure in exclusive $\tau$ decays with 467 fb$^{-1}$

$$R_{K/\pi} \equiv \frac{B(\tau^- \to K^- \nu_\tau)}{B(\tau^- \to \pi^- \nu_\tau)} = 0.06531 \pm 0.00056 \pm 0.00093$$

$$= \frac{f_K^2 |V_{us}|^2 \left(1 - \frac{m_K^2}{m_\tau^2}\right)^2}{f_\pi^2 |V_{ud}|^2 \left(1 - \frac{m_\pi^2}{m_\tau^2}\right)^2} \left(1 - \delta_{LD}\right)$$

- Approach avoids absolute strange decay constant ($f_K^2$), replacing with ratio to pion. Use $f_K/f_\pi = 1.189 \pm 0.007$ and $\delta_{LD} = 0.0003 \pm 0.0044$

- Result is: $|V_{us}| = 0.2255 \pm 0.0024$

- **$\tau \to s$ inclusive**
  - At ICHEP08, 3.2$\sigma$ discrepancy: $|V_{us}| = 0.2159 \pm 0.0030$
  - 2010 preliminary evaluation (Lusiani, 1173) $|V_{us}| = 0.2165 \pm 0.0023$
  - Discrepancy = 3.6$\sigma$

[see also BABAR, $\Lambda_c$ decays (Hartmann, 557)]
$|V_{us}|$ summary

Lusiani 1173 (HFAG-$\tau$) compilation, Preliminary

My average $|V_{us}| = 0.2253 \pm 0.0008$, does not include $\tau \rightarrow s$ inclusive
The magnitudes: $|V_{ub}|$

2008 RPP $|V_{ub}| = 0.00393 \pm 0.00036$, combined exclusive and inclusive (dominant)

- Inclusive semileptonic decays $B \rightarrow X\ell\nu$ where $X = X_u$
  - Select $B$ decays by reconstructing recoil $B$, either fully or partially
  - Huge background from $b \rightarrow c$ transitions ($X = X_c$)
  - Can restrict kinematic region, e.g., to $m_X < m_D$
  - Can use MM$^2$ to preferentially select single missing $\nu$ (and low multiplicity)
  - Use theory to extrapolate from restricted kinematic region to full phase space

BLNP : PRD 72 (2005) 073006
GGOU : JHEP 0710 (2007) 058
ADFR : Eur Phys J C 59 (2009) 831
(see references therein)

- Belle inclusive (PRL 104 (2010) 021801) on full sample 657M $B\bar{B}$:

| Theory   | $|V_{ub}| \times 10^3$ | Stat  | Syst  | $m_b$ |
|----------|------------------------|-------|-------|-------|
| BLNP [5] | 4.37                   | 4.3   | 4.0   | $+3.1$| $+4.3$ |
| DGE [6]  | 4.46                   | 4.3   | 4.0   | $+3.2$| $+1.0$ |
| GGOU [7] | 4.41                   | 4.3   | 4.0   | 1.9   | $+2.1$ |

My average Belle inclusive: $0.00441 \pm 0.00026$ (expt) $\pm 0.00024$ (thy)
Inclusive $|V_{ub}|$ (continued)

- **BABAR inclusive** (Sigamani, 732):

Measure Partial Branching Fractions for $B \to X_u \ell \nu$

$B$ tag is via exclusive reconstruction of recoil $B$ in $B \to \bar{D}^{(*)}h$, where $h = \pi$ or $h = K$

For $p^{*}_\ell > 1.0$ GeV, with a 2-D fit to $(M_X, q^2)$, and averaging (consistent) results according to (BLNP, DGE, GGOU, ADFR), obtain

$$|V_{ub}| = 0.00431 \pm 0.00035 \text{ (preliminary)}$$

Background-subtracted lepton momentum distribution in $B \to X_u \ell \nu$ decays
$|V_{ub}|$ in exclusive semileptonic decays

Exclusive semileptonic decays to light quark states
- Constraints reduce background, but also lower statistics
- Theory for form factors
  E.g., for $B \rightarrow \pi \ell \nu$ with $\ell = e$ or $\mu$, to good approximation a single form factor contributes:

$$
\frac{d\Gamma(B^0 \rightarrow \pi^- \ell^+ \nu)}{dq^2 d\cos\theta_{W\ell}} = |V_{ub}|^2 \frac{G_F^2 p^3_\pi}{32\pi^3} \sin^2 \theta_{W\ell} |f_+(q^2)|^2.
$$

- Belle (Ha, 944) Exclusive $B^0 \rightarrow \pi^- \ell^+ \nu$, untagged 605 fb$^{-1}$ $\mathcal{B}(B^0 \rightarrow \pi^- \ell \nu) = (1.49 \pm 0.04 \text{(stat)} \pm 0.07 \text{(syst)}) \times 10^{-4}$ $|V_{ub} f_+(0)| = (9.24 \pm 0.18 \text{(stat)} \pm 0.20 \text{(syst)} \pm 0.07(\tau_B)) \times 10^{-4}$ $|V_{ub}| = (0.00343 \pm 0.00033)$ (using FNAL-MILC PRD 79 (2009) 054507)

- BABAR (Wulsin, 1180) $B \rightarrow \pi \ell \nu$ ($\rho \ell \nu$)

$$
\mathcal{B}(B^0 \rightarrow \pi^- \ell^+ \nu) = (1.41 \pm 0.05 \pm 0.07) \times 10^{-4}
$$
$$
\mathcal{B}(B^0 \rightarrow \rho^- \ell^+ \nu) = (1.75 \pm 0.15 \pm 0.27) \times 10^{-4}
$$

For $B \rightarrow \pi \ell \nu$ and simult. fit to FNAL/MILC lattice, $|V_{ub}| = 0.00295 \pm 0.00031$

My average for BABAR $\pi \ell \nu$, including error for spread: $|V_{ub}| = 0.00326 \pm 0.00054$

TABLE XIII: $|V_{ub}|$ derived from $B \rightarrow \pi \ell \nu$ and $B \rightarrow \rho \ell \nu$ decays for various $q^2$ regions and form-factor calculations. Quoted errors are experimental uncertainties and theoretical uncertainties of the form-factor integral $\Delta \zeta$. (Uncertainties for the $B \rightarrow \rho \ell \nu$ form-factor integrals are not available.)

| $q^2$ Range (GeV$^2$) | $\Delta \zeta$ (ps$^{-1}$) | $|V_{ub}|$ (10$^{-3}$) |
|-----------------------|-----------------|------------------|
| LCSR [15] 0 – 16 5.44±1.43 3.63 ± 0.12±0.59 |
| HPQCD [22] 16 – 26.4 2.02±0.55 3.21 ± 0.17±0.55 |
| B $\rightarrow \pi \ell \nu$ |
| LCSR [16] 0 – 16.0 13.79 2.75 ± 0.24 |
| ISGW2 [14] 0 – 20.3 14.20 2.83 ± 0.24 |
| B $\rightarrow \rho \ell \nu$ |

Frank Porter, ICHEP2010, Paris, 27 July 2010
\( V_{ub} \) in leptonic \( B \) decays

For \( Q_q^+ = \pi^+, K^+, D^+, D_s^+, B^+ \), with \( V_{(Qq)} = V_{Qq} \) or \( V_{qQ} \) as appropriate:

\[
\Gamma(Q_q^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} m_{Q_q}^3 \left( \frac{m_\ell}{m_{Q_q}} \right)^2 \left( 1 - \frac{m_\ell^2}{m_{Q_q}^2} \right)^2 |V_{(Qq)}|^2 f_{Q_q}^2,
\]

- Belle 711 fb\(^{-1}\) (Stypula, 1097) \( B \rightarrow \tau \nu \) (and \( B \rightarrow D^* \tau \nu \)); exclusive semileptonic tag measure \( f_B |V_{ub}| = (9.3^{+1.2}_{-1.1} \pm 0.9) \times 10^{-4} \) GeV, from \( \mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau) = (1.54^{+0.38}_{-0.37} \text{(stat)}^{+0.29}_{-0.31} \text{(syst)}) \times 10^{-4} \) (significance 3.6\( \sigma \)) Gives \( |V_{ub}| = 0.00489 \pm 0.00079 \) for \( f_B = 0.19 \) GeV

\( E_{\text{ECL}} \) = residual energy in calorimeter

- \( \text{BABAR} \) (De Nardo, 581) \( \mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau) = (1.80^{+0.57}_{-0.54} \text{(stat)} \pm 0.26 \text{(syst)}) \times 10^{-4} \), significance 3.6\( \sigma \)

Combine with semileptonic tags: \( \mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau) = (1.76 \pm 0.49) \times 10^{-4} \)
$|V_{ub}|$ summary

Recent measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Experiment</th>
<th>$V_{ub}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>Belle</td>
<td>0.00441 ± 0.00024</td>
</tr>
<tr>
<td>Inclusive</td>
<td>$BABAR$</td>
<td>0.00431 ± 0.00035</td>
</tr>
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</tr>
<tr>
<td>$B \to \tau\nu$</td>
<td>Belle</td>
<td>0.00484 ± 0.00079</td>
</tr>
<tr>
<td>$B \to \tau\nu$</td>
<td>$BABAR$</td>
<td>0.0057 ± 0.0019</td>
</tr>
</tbody>
</table>

Longstanding inclusive/exclusive discrepancy remains. For example, comparing Belle inclusive with Belle exclusive the difference is 2.3$\sigma$.

CKMfitter average $|V_{ub}| = 0.00392 ± 0.00009 ± 0.00045$ (based on HFAG end of 2009 preliminary)
First row unitarity

In SM (V is $3 \times 3$ unitary), must have:

$$1 = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$$

$$= 0.99995 \pm 0.00057$$

Limit (Bayesian) on possible 4th generation:

$$|V_{u4}| = \sqrt{1 - |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2}$$

$$< 0.031 \ (90\% \ CL, \ flat \ prior \ in \ |V_{u4}|^2)$$

$$< 0.061 \ (90\% \ CL, \ flat \ prior \ in \ |V_{u4}|)$$

In spite of “four-nines” sum, numbers from first two generations not sufficiently precise to require the third generation
The magnitudes: $|V_{cd}|$

$|V_{cd}| = 0.230 \pm 0.011$

- 2008 RPP remains up-to-date
- From neutrino charm production (di-muons/single muons, CDHS, CCFR, CHARM II + CHORUS)
- Prospects for leptonic and semileptonic $D$ (and $D_s$ for $|V_{cs}|$) to contribute, once theoretical uncertainties in decay constants and form factors are reduced further. (see also Melikhov 254)

The magnitudes: $|V_{cs}|$

$|V_{cs}| = 1.04 \pm 0.06$

RPP 2008: Leptonic $D_s$ decays; semileptonic $D$ decays
The magnitudes: $|V_{cb}|$

2008 RPP $|V_{cb}| = 0.0412 \pm 0.0011$ (combined exclusive and inclusive)

- New results in exclusive $B \to$ charm
  - Belle (Dungel, 943) New result for $B^0 \to D^{*-}\ell^+\nu$, signal side reconstructed, $711 \text{ fb}^{-1}$
    \[ F(1)|V_{cb}| = 0.0345 \pm 0.0002 \pm 0.0010 \]
    $F(1)$ is the hadronic form factor at zero recoil ($w = v_B \cdot v_D^* = 1$) Use HQET (Caprini, Lellouch, Neubert NPB 530 (1998) 153) for $w$-dependence of form factor. Lattice QCD (Bernard et al., PRD 79 (2009) 014506): $F(1) = 0.921\pm0.013\pm0.020$

  \[ |V_{cb}| = 0.0375 \pm 0.0015 \]

- BABAR (Petrella, 1179) [PRL 104 (2010) 011802] $B \to D\ell\nu$, fully reconstructed tags (average of charged and neutral $D$ modes)
  \[ G(1)|V_{cb}| = 0.0423 \pm 0.0019 \pm 0.0014 \]
  $G(1)$ is the hadronic form factor at zero recoil ($w = v_B \cdot v_D = 1$)
  \[ V_{cb} = 0.0392 \pm 0.0018 \pm 0.0013 \pm 0.0009 \text{ (lattice)} \]

Lattice form factor: Okamoto et al., NucPhysB 140 (2005) 461
The magnitudes: $|V_{cb}|$

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

- New results in inclusive $B \to$ charm
  - *BABAR* (Petrella, 1179) [PRD 81 (2010) 032003] Measurement and Interpretation of Moments in Inclusive Decays $B \to X_c \ell \nu$ Rates and Moments analysis of inclusive $B \to X_c \ell \nu$, based on (OPE) Benson, Bigi, Mannel, Uraltsev, NP B665 (2003) 367

\[
|V_{cb}| = 0.04205 \pm 0.0045 \pm 0.0070
\]

- As with $|V_{ub}|$ the inclusive results tend to be higher than the exclusive results
- CKMfitter average $|V_{cb}| = 0.04089 \pm 0.00038 \pm 0.00059$ (based on HFAG end of 2009 preliminary)
The magnitudes: $|V_{td}|$

2008 RPP

$|V_{td}| = 0.0081 \pm 0.0006$

- $|V_{td}|$ from $B$ mixing
  - Uncertainty dominated by lattice QCD uncertainties.
  - Some uncertainty cancels in ratio $|V_{td}/V_{ts}|$, measured using $B$ and $B_s$ mixing:
    $|V_{td}/V_{ts}| = 0.209 \pm 0.001 \pm 0.006$ (2008 RPP)
  - Using this, and $|V_{ts}|$ obtain slightly more precise result: $V_{td} = 0.0081 \pm 0.0005$

- $\textbf{BABAR}$ (Bard, 1177) Another approach: Measure $|V_{td}/V_{ts}|$ in “inclusive” ratio of radiative $B$ decays related by $d \leftrightarrow s$ with 471M $B\bar{B}$
  - Penguin decays, so possible NP in loop, hence tests SM in comparison with other determination
  - For example, compare $B^0 \rightarrow \pi^+\pi^-\gamma$ with $B^0 \rightarrow K^+\pi^-\gamma$. Analysis uses 7 such pairs of modes.
  - Result is
    \[
    \frac{\mathcal{B}(b \rightarrow d\gamma)}{\mathcal{B}(b \rightarrow s\gamma)} = 0.033 \pm 0.009 \pm 0.003
    \]

  from which we obtain (using (NLO) Ali, Asatrian Greub PLB 429 (1998) 87): $|V_{td}/V_{ts}| = 0.199 \pm 0.022(\text{stat}) \pm 0.024(\text{syst}) \pm 0.002(\text{thy})$
The magnitudes: $|V_{ts}|$

$|V_{ts}|$ from $B_s$ mixing

2008 RPP

$|V_{ts}| = 0.0387 \pm 0.0023$

Dominant uncertainties from lattice QCD
The magnitudes: $|V_{tb}|$

2008 RPP $|V_{tb}| > 0.74$ 90% CL, $\sigma(p\bar{p} \rightarrow tX)$

$|V_{tb}| = 0.77^{+0.18}_{-0.24}$ EW fit, top loops in $Z \rightarrow b\bar{b}$

- Can be measured in single top production, without assuming 3 generation unitarity (but assuming $|V_{tb}| \gg |V_{td}|, |V_{ts}|$)

- Production at the Tevatron:
  - s-channel 0.88 pb
  - t-channel 1.98 pb

- CDF/D0 (Quinn, 1132) arXiv:/0908.2171 [hep-ex] Combined CDF(3.2 fb$^{-1}$)&D0(2.3 fb$^{-1}$) $|V_{tb}| = 0.88 \pm 0.07$
**CP violation, the unitarity triangles**

All CP violation from CKM in SM

Manifests as “unitarity triangle” relations with area \( \neq 0 \)

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

Yields six distinct relations from the off-diagonal components. Two of these are under active investigation:

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

\[ 0 = V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = O(\lambda^4) + O(\lambda^2) + O(\lambda^2) \]
The angles: $\beta/\phi_1$

RPP 2008 $\sin 2\beta = 0.681 \pm 0.025$, $b \rightarrow c\bar{c}s$ decays to $CP$ eigenstates

- **Belle** (Higuchi, 1094) Analysis of $\sin 2\phi_1$ in $B \rightarrow c\bar{c}K^0$ [ie, the “golden modes”] on final data sample of 772M $B\bar{B}$, in progress; expected error $\delta(\sin 2\phi_1) \approx 0.024$.

- **BABAR** (Latham, 559) BaBar Dalitz-plot analysis of $B^0 \rightarrow \bar{D}^0\pi^+\pi^-$ Understanding time-dependent DP for $B^0 \rightarrow D_{CP}\pi^+\pi^-$ towards measurement of $\sin 2\beta$ and $\cos 2\beta$. Preliminary BFs presented.

- **Belle** (Higuchi, 1094) Time-dependent Dalitz plot analysis of $B^0 \rightarrow K^+K^-K^0_S (b \rightarrow ss\bar{s}$ penguin)
  - Find four solutions; preferred solution yields

$$
\phi_1^{\text{eff}}(\phi(1020)K^0_S) = (32.2 \pm 9.0 \pm 2.6 \pm 1.4(\text{DP model}))^\circ
$$

$$
\phi_1^{\text{eff}}(f_0(980)K^0_S) = (31.3 \pm 9.0 \pm 3.4 \pm 4.0(\text{DP model}))^\circ
$$

Consistent with $\phi_1^{\text{eff}} = \phi_1$
\[
\sin 2\beta \text{ from the } b \to c\bar{c}s \text{ “golden” modes}
\]

\[
\sin(2\beta) = \sin(2\phi_1)
\]

Compare with Penguin modes

NP in loop can give rise to deviations from \(\beta/\phi_1\)
The angles: Measuring $\alpha/\phi_2$

RPP 2008  $\alpha = (88^{+6}_{-5})^\circ$ from $B \rightarrow \pi\pi, \rho\rho, \rho\pi$

Measure in $b \rightarrow w\bar{u}d$

- E.g., $B \rightarrow \pi^+\pi^-, \rho^+\rho^-, \pi^+\pi^-\pi^0, a_1^\pm\pi^\mp$


CKMfitter input: $(88.2^{+6.1}_{-4.8})^\circ$

UTfit input: $(91.4 \pm 6.1)^\circ$
The angles: Measuring $\gamma/\phi_3$

$$\gamma \equiv \arg \left( \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right)$$

Accessible in interference between $b \to c\bar{u}s$ ($O(\lambda^3)$) and $b \to u\bar{c}s$ ($O(\lambda^3)$, color-suppressed) amplitudes. A suitable pair of channels is $B^- \to D^{(*)0}K^-$ and $B^- \to \bar{D}^{(*)0}K^-$, where interference may occur when the $D$ and $\bar{D}$ decay to common final states.

Compare $B^-$ and $B^+$

Various approaches ($D^0\bar{D}^0$ mixing is neglected):
The angles: Measuring $\gamma/\phi_3$ (GLW)

GLW (Gronau, London, Wyler): Uses $D, \bar{D}$ decays to $CP$ eigenstates, eg, $K^+K^-$ or $K_S\pi^0$. In this case, both $D$ and $\bar{D}$ decays are Cabibbo suppressed.

$W^+ W^-$

$D^0 $ $\bar{D}^0$

$\bar{c}$ $s$ $u$

$\bar{u}$ $s$ $u$

$K^+$ $K^-$

$K^+$ $K^-$

$B^\pm \rightarrow D_{CP}K^\pm$, with $D_{CP+} \rightarrow \pi^-\pi^+, K^-K^+$ and $D_{CP-} \rightarrow K^0_\pi^0, K^0_\phi, K^0_\omega$:

<table>
<thead>
<tr>
<th>$\gamma \mod 180$ [$^\circ$]</th>
<th>$r_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>68% CL</td>
<td>[11.3, 22.7] [0.24, 0.45]</td>
</tr>
<tr>
<td></td>
<td>[80.9, 99.1]</td>
</tr>
<tr>
<td></td>
<td>[157.3, 168.7]</td>
</tr>
<tr>
<td>95% CL</td>
<td>[7.0, 173.0] [0.06, 0.51]</td>
</tr>
</tbody>
</table>
The angles: Measuring $\gamma/\phi_3$ (ADS)

ADS (Atwood, Dunietz, Soni): Use $D^0 \rightarrow K^+\pi^-$ (doubly Cabibbo suppressed); $\bar{D}^0 \rightarrow K^+\pi^-$ (Cabibbo favored), giving interfering amplitudes of similar order, although branching fractions are small.

$\textbf{BABAR}$ (Martinez-Vidal, 1175) $B^- \rightarrow D^{(*)}K^-$ $r_B = (9.5^{+5.1}_{-4.1})\%$, $r_B^* = (9.6^{+3.5}_{-5.1})\%$. 

![Graph showing confidence level vs angle γ (deg)]
The angles: Measuring $\gamma/\phi_3$ (GGSZ)

GGSZ (Giri, Grossman, Soffer, Zupan): Look at the Dalitz plot for three-body $D$ decays, e.g., $D \to K_S^+\pi^\mp$. This mode is Cabibbo favored for both $D^0$ and $\bar{D}^0$.

Belle (Joshi, 1096) PRD 81 (2010) 112002

Dalitz Plot analysis $B \to D^{(*)}K$, $D \to K_S^+\pi^\mp$ (Cabibbo allowed; large strong phases; need Dalitz plot analysis) $B \to DK \to K_S\pi^+\pi^-$

$657M \bar{B}\bar{B} \quad m_\pm = m(K_S\pi^\pm)$

$\phi_3$ (mod 180) = $[78.4^{+10.8}_{-11.6} \pm 3.6$(syst) $\pm 8.9$(model)]°

$\phi_3$ (mod 180) = $[78.4^{+10.8}_{-11.6} \pm 3.6$(syst) $\pm 8.9$(model)]°

$P$-value for $CP$ conservation is $5 \times 10^{-4}$ (combined $B^{\pm} \to D^{(*)}K^{\pm}$)

BABAR (Martinez-Vidal, 1175) $B^{\mp} \to D^{(*)}K^{(*)\mp}$ exclude $\gamma = 0$ at $3.5\sigma$

$\gamma$ (mod 180) = $[68 \pm 14 \pm 4$(syst) $\pm 3$(model)]°

$r_B = 0.096 \pm 0.029$
Understanding $D$ decays

We have seen that measuring $\gamma/\phi_3$ is intimately connected with $D$ decays; motivated to understand $D$ decays to reduce model dependence. CLEO-c (Wilkinson, 702) use quantum correlations at $\psi(3770) \rightarrow D^0\bar{D}^0$ to measure strong phase differences between $D^0 \rightarrow K_S^0\pi^+\pi^-$ and $\bar{D}^0 \rightarrow K_S^0\pi^+\pi^-$ (818 pb$^{-1}$). Updated analysis; new analysis of $K_SK^+K^-$. Idea is can tag $D$ eigenstate (either flavor or $CP$), eg, with tag $D$ going to $CP$ eigenstate such as $K^+K^-$ ($CP$-even), hence signal $D \rightarrow K_S\pi^+\pi^-$ is $CP$-odd $D$ state.

$c_i$ and $s_i$ are cosines and sines of strong $D - \bar{D}$-decay phase differences, averaged over bin $i$. 
Searches for new physics in $CP$ violation

- $CP$ violation in $B$ decays
  - Belle (Higuchi, 1094) Direct $CP$ in $B^+ \rightarrow J/\psi K^+$
  - Belle (Sahoo, 969) New result for time-dependent $CP$ analysis of $B^0 \rightarrow \phi K_S \gamma$

- $CP$ violation in $D$ mixing and decay
  - BABAR (Bellis, 1172) $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ and $D^0 \rightarrow K_S^0 K^+ K^-$ Dalitz plot analysis
  - Belle (Ko, 1092) $CP$ violation in $D \rightarrow K_S (\pi, K, \eta, \eta')$ and $D_{(s)} \rightarrow \phi \pi$
  - CDF (Mattson, 1082) $CP$ violation in $D^0 \rightarrow h^+ h^-$

- $CP$ violation in kaons
  - KEK E391a (Watanabe, 734) Final results on $K_L \rightarrow \pi^0 \nu \bar{\nu}$
  - NA48 (Winhart, 1080) $CP$ measurements in $K^\pm \rightarrow \pi \ell^+ \ell^-$ and $K_S \pi \pi ee$ decays

- $CP$ violation in $\tau$ decays
  - Belle (Shapkin, 1093) $CP$ violation in $\tau^\pm \rightarrow K_S \pi^\pm \nu_\tau$
Both UTfit (Tarantino, 1081) and CKMfitter (T’Jampens, 190) identify $\sin 2\beta$ ($2.6\sigma/2.6\sigma$) and $B(B \rightarrow \tau\nu)$ ($3.2\sigma/2.8\sigma$) as areas of discrepancy.
- UTfit in addition mentions $\epsilon_K$ as discrepant by $1.7\sigma$.
- Global consistency from CKMfitter at $2\sigma$
Characterizing the discrepancy

Two-dimensional value of $(\sin 2\beta, B(B \rightarrow \tau\nu))$ in conflict with $B_{B_d, \alpha, \gamma}$ constraints.

What is it? Could be...

- Measurement error
- Lattice error
- New physics

See also (Soni, 908)
The $B_s$ sector

UTfit with new D0 results (awaiting CDF likelihood), $3.1\sigma$ from SM in $\phi_{B_s}$ (but new CDF result should pull it closer to SM).
Conclusions

\[ |V| = \begin{pmatrix} 0.97418 \pm 0.00027 & 0.2253 \pm 0.0008 & 0.00392 \pm 0.00046 \\ 0.230 \pm 0.011 & 1.04 \pm 0.06 & 0.0409 \pm 0.0007 \\ 0.0081 \pm 0.0005 & 0.0387 \pm 0.0023 & 0.88 \pm 0.07 \end{pmatrix} \]

Still plenty of room for a fourth generation.

ICHEP 2010 averages (assuming $3 \times 3$ unitarity, SM)

CKMfitter, ICHEP10  UTfit, ICHEP10

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CKMfitter</th>
<th>UTfit, ICHEP10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$0.812^{+0.013}_{-0.027}$</td>
<td></td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$0.22543\pm0.00077$</td>
<td></td>
</tr>
<tr>
<td>$\bar{\rho}$</td>
<td>$0.144 \pm 0.025$</td>
<td>$0.132 \pm 0.020$</td>
</tr>
<tr>
<td>$\bar{\eta}$</td>
<td>$0.342^{+0.016}_{-0.015}$</td>
<td>$0.358 \pm 0.012$</td>
</tr>
<tr>
<td>$\alpha($°$)$</td>
<td>$91.0 \pm 3.9$</td>
<td></td>
</tr>
<tr>
<td>$\sin 2\beta$</td>
<td>$0.689^{+0.023}_{-0.021}$</td>
<td></td>
</tr>
<tr>
<td>$\gamma($°$)$</td>
<td>$67.2 \pm 3.9$</td>
<td></td>
</tr>
</tbody>
</table>

Warning: errors may not scale as normal errors; see references.

Some “$2\sigma$” hints

- $\tau$ to $s$ inclusive puzzle
- Exclusive vs inclusive differences for $|V_{ub}|$ and $|V_{cb}|$
- $\sin 2\beta$ and $B \to \tau \nu$ discrepancy with SM
- Like sign dimuon discrepancy with SM
- Heavy flavors will continue to offer insights/constraints on possible new physics [LHC, high intensity kaons, super $B$ factories, tau/charm threshold]