CKM MATRIX STATUS

J. Rosner – 5th Rencontres du Vietnam – August 6, 2004

Thanks to C.-W. Chiang, M. Gronau, Z. Luo, D. Suprun for enjoyable collaborations

The **Cabibbo–Kobayashi–Maskawa** (CKM) matrix describes the charge-changing weak transitions between quarks with charges $-1/3$ (d, s, b) and 2/3 (u, c, t):

$$V_{\rm CKM} = \left[\begin{array}{ccc} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{array} \right] \simeq \left[\begin{array}{ccc} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar\rho - i\bar\eta) & -A\lambda^2 & 1 \end{array} \right] ~~.$$

Here $\bar\rho \equiv \rho(1-\lambda^2/2)$, $\bar\eta \equiv \eta(1-\lambda^2/2)$. The matrix is unitary: $V^\dagger V = V V^\dagger = 1$. Parametrization due to Wolfenstein; $\lambda \simeq 0.225$, $A \simeq 0.8$, $\bar\eta \simeq 0.36$, $\bar\rho \simeq 0.19$.

Many extensive reviews, e.g., Battaglia *et al.* (hep-ph/0304132), Schubert (2003 Lepton-Photon Symposium), Abele *et al.* (hep-ph/0312150), Ali (hep-ph/0312303), Eigen *et al.* (hep-ex/0312062), Ratcliffe [V_{us}] (hep-ph/0402063), Stocchi (hep-ph/0405038), CKMfitter Group (hep-ph/0406184), HFAG 2004, PDG 2004.

Today's review: procedures for determination of elements; open questions.

OBSERVABLES DISCUSSED HERE

Magnitudes:

V_{ud}: Nuclear, neutron, pion β decays

V_{us}: Hyperons, BNL E-865, Fermilab E-832, NA48, KLOE, lattice

V_{cd}: Nonstrange charm decay; neutrino charm production

V_{cs}: strange charm, W decay

V_{cb}: $b \to c$ inclusive (moments), exclusive (form factors)

V_{ub}: $b \to u$ inclusive ($b \to s\gamma$ helps), exclusive ($B \to \pi\ell\nu, \rho\ell\nu$ form factors)

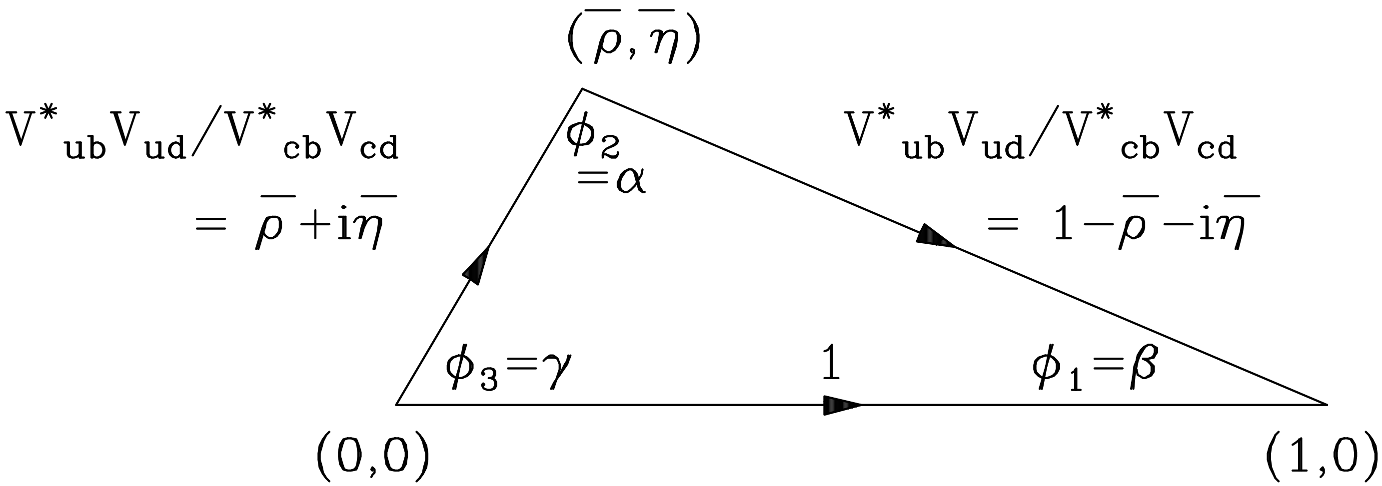
V_{td}: B–$\overline{B}$ mixing (nonstrange and strange); progress on decay constants

V_{ts}: Help from $b \to s\gamma$, unitarity

V_{tb}: Information from top quark decays, unitarity

Constraints from K_L, K^+ decays: CP violation; $K \to \pi\nu\bar{\nu}$

UNITARITY TRIANGLE



Phases:	CKMfitter current status $(\pm 2\sigma)$:
Processes which (should) give β	$(23.8^{+4.5}_{-3.8})^\circ$
α from $B^0 \to \pi^+\pi^-,\ \rho^\pm\pi^\mp, \rho^+\rho^-$	$(94^{+24}_{-16})^\circ$
γ from global fits to $B \to PP$, $B \to VP$ decays	$(62^{+17}_{-24})^\circ$

Beyond the 3×3 unitary CKM matrix:

Fourth family — Exclude $100 < m(b') < 199$ GeV$/c^2$

Exotic quarks and leptons — Predicted in E6

V_{ud} FROM β-DECAYS

Czarnecki, Marciano, Sirlin hep-ph/0406324

Nuclear $0^+ \to 0^+$ transitions (9 measurements) $\to |V_{ud}| = 0.9740(1)(3)(4)$

(1) expt. [each typically (4)], (3) nuclear theory, (4) radiative corrections

Neutron decay $\Rightarrow |V_{ud}|^2(1+3g_A^2)\tau_n = (4908 \pm 4)$ s

$\tau_n = 885.7(7)$ s, $g_A = 1.2720(18) \Rightarrow |V_{ud}| = 0.9729(4)(11)(4)$

(4) τ_n, (11) g_A, (4) radiative corrections

Pion beta decay ($\pi^+ \to \pi^0 e^+ \nu_e$): $|V_{ud}| = 0.9739(39)$; PSI experiment ongoing.

Overall average: $|V_{ud}| = 0.9740(5)$

V_{us} FROM HYPERON DECAYS

Review by N. Cabibbo, BEACH 04 Conference, Chicago, June 28, 2004

New fit by Cabibbo, Swallow, Winston PRL **92**, 251803 (2004):
includes $\Lambda \to pe^-\bar{\nu}$, $\Sigma^- \to ne^-\bar{\nu}$, $\Xi^- \to \Lambda e^-\bar{\nu}$, $\Xi^0 \to \Sigma^+ e^-\bar{\nu}$ (but: g_2?)

Combined hyperon value: $|V_{us}| = 0.2250 \pm 0.0027$

V_{us} FROM $K_{\ell 3}$ DECAYS

Brookhaven E-865: $K^+ \to \pi^0 e^+ \nu \Rightarrow$

$$|V_{us}| = 0.2272 \pm 0.0022_{\rm rate} \pm 0.0007_{\rm f.f.} \pm 0.0018_{f_+(0)}$$

A. Sher +, hep-ex/0305042, AIP Conf. Proc. **698**, 381 (2004)

Radiative corrections were an important part of analysis

Fermilab E-832 (KTeV): $K_L \to \pi \ell \nu \Rightarrow$

$$|V_{us}| = 0.2252 \pm 0.0008_{\rm KTeV} \pm 0.0021_{\rm ext}$$

Alexopoulos +, hep-ex/0406001 (see also hep-ex/0406002, hep-ex/0406003) ⇒ PRL

Radiative corrections by T. Andre, hep-ph/0406006

$|V_{ud}| = 0.9740 \pm 0.0005$, PDG $|V_{us}| = 0.2196 \pm 0.0026$ agreed poorly with unitarity:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9969 \pm 0.0015$$

while expected value of $|V_{us}|$ from unitarity is

$$|V_{us}| = (1 - |V_{ud}|^2 - |V_{ub}|^2)^{1/2} = 0.2265 \pm 0.0023$$

New results soon: CERN NA48, KLOE at DAΦNE (prelim. $K_S \Rightarrow 0.2194 \pm 0.0030$)

Marciano (hep-ph/0402299) advocates use of lattice $f_K/f_\pi = 1.201(8)(15)$ and $K \to \mu\nu$, $\pi \to \mu\nu$ to extract $|V_{us}| = 0.2236(5)(30)$ (non-lattice) (lattice)

V_{cd} FROM CHARM

Decays (also V_{cs}):

CLEO II.V: $D^0 \to \pi^- \ell^+ \nu$ and $D^0 \to K^- \ell^+ \nu \Rightarrow$

$$|f_+^\pi(0)|^2 |V_{cd}|^2 / |f_+^K(0)|^2 |V_{cs}|^2 = 0.038^{+0.006+0.005}_{-0.007-0.003}$$

Fermilab–MILC Collaboration (Okamoto 7/23/04): $n_f = 3$ lattice QCD $\Rightarrow$

$$f_+^{D\to\pi}(0) = 0.64(3)(5) \ , \quad f_+^{D\to K}(0) = 0.73(3)(6) \ , \quad \text{errors (stat)(syst) ;}$$

$$|V_{cd}| = 0.239(10)(19)(20) \ , \quad |V_{cs}| = 0.969(39)(78)(24) \ .$$

Production by neutrinos (measure dileptons):

$\overline{\mathcal{B}}(c \to \ell + X)|V_{cd}|^2 = (4.63 \pm 0.34) \times 10^{-3}$; $\overline{\mathcal{B}}(c \to \ell + X) = (9.23 \pm 0.73)\%$

$$\Rightarrow |V_{cd}| = 0.224 \pm 0.012$$

CLEO-c: $\mathcal{B}(D^0 \to \pi^- e^+ \nu) = (3.73 \pm 0.10 \pm 0.20)\%$ with ~ 57 pb^{-1}

Higher-luminosity running in $e^+e^- \to \psi''(3770) \to D\bar{D}$ to begin in September.

Hoping for 3 fb^{-1}. Lattice errors will be limiting factor in extracting $|V_{cd}|$ to $\mathcal{O}(1\%)$.

V_{cs} FROM W DECAYS

Charm-tagged W decays at LEPII (ALEPH,DELPHI):

$$|V_{cs}| = 0.97 \pm 0.09 \pm 0.07$$

Leptonic branching ratio $\mathcal{B}(W \to \ell\nu)$, no unusual W decays:

$$\frac{1}{\mathcal{B}(W \to \ell\nu)} = 3\left(1 + \left[1 + \frac{\alpha_s(M_W)}{\pi}\right] \sum_{\substack{i=u,c \\ j=d,s,b}} |V_{ij}|^2\right)$$

Implies $\sum |V_{ij}|^2 = 2.039 \pm 0.025$ and hence $|V_{cs}| = 0.996 \pm 0.013$ when contributions of other CKM elements are subtracted

Cabibbo-favored $(c \to s)$ decays of charmed particles at CLEO-c:

Will provide $|V_{cs}|$ at $\mathcal{O}(1\%)$ accuracy if $\mathcal{L}$ goal achieved and lattice cooperates

Can't see violation of two-family unitarity:

$$|V_{ud}|^2 + |V_{us}|^2 = |V_{cd}|^2 + |V_{cs}|^2 = |V_{ud}|^2 + |V_{cd}|^2 = |V_{us}|^2 + |V_{cs}|^2 = 1\ .$$

Reflects on the very hierarchical structure of the CKM matrix.

V_{cb}: INCLUSIVE $b \to c$ DECAYS

At the quark level, $b \to c$ semileptonic decay rate is simple (neglecting m_ℓ):

$$\Gamma(b \to c\bar{\nu}_\ell \ell^-) = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 f\left(\frac{m_c^2}{m_b^2}\right) \quad ,$$

where $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$

Real hadrons in initial and final states: perturbative QCD; expansions in inverse heavy quark mass ("HQE"); lepton energy, hadron mass, $b \to s\gamma$ moments $\Rightarrow$

$$|V_{cb}| = 0.0421 \pm 0.0013 \quad \text{(Schubert's 2003 average)}$$

but quoted by CKMfitter group as $0.0420 \pm 0.0006_{\rm stat} \pm 0.0008_{\rm theo}$.

More recently (e.g.):

BaBar: $|V_{cb}| = (41.4 \pm 0.4_{\rm stat} \pm 0.4_{\rm HQE} \pm 0.6_{\rm theo}) \times 10^{-3}$

CLEO: $|V_{cb}| = (42.4 \pm 0.8_{\rm stat+HQE} \pm (> 0.8)_{\rm theo}) \times 10^{-3}$

These errors are smaller than those in exclusive analyses; view with caution

CKMfitter's inclusive-exclusive average: $|V_{cb}| = (41.1^{+1.4}_{-0.6}) \times 10^{-3}$ ($\sim \surd$ Schubert)

V_{cb}: EXCLUSIVE $b \to c$ DECAYS

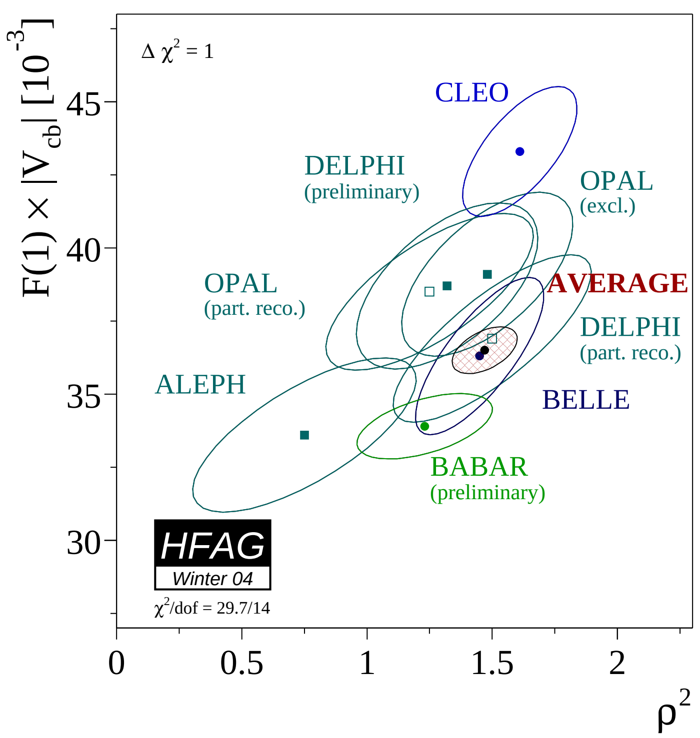
Best determination comes from $B \to D^* \ell \bar{\nu}_\ell$:

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{4\pi^3}|V_{cb}|^2(m_B - m_D^*)^2 m_{D^*}^3 \sqrt{w^2-1}\mathcal{G}(w)|\mathcal{F}(w)|^2$$

One Isgur-Wise form factor $\mathcal{F}(w) \simeq \mathcal{F}(1)[1+\rho^2(w-1)+\ldots]$

Isgur-Wise variable $w = v_B \cdot v_{D^*}$; phase space $\mathcal{G}(w)$ with $\mathcal{G}(1) = 1$:

$\mathcal{F}(1) = \eta_{QCD}[1 + \mathcal{O}(1/m_b^2)] = 0.913^{+0.030}_{-0.035}$ (Lattice, HQET).



Latest $\mathcal{F}(1)|V_{cb}|^2 = (36.5 \pm 0.8) \times 10^{-3}$

$\rho^2 = 1.47 \pm 0.13$: form factor slope parameter

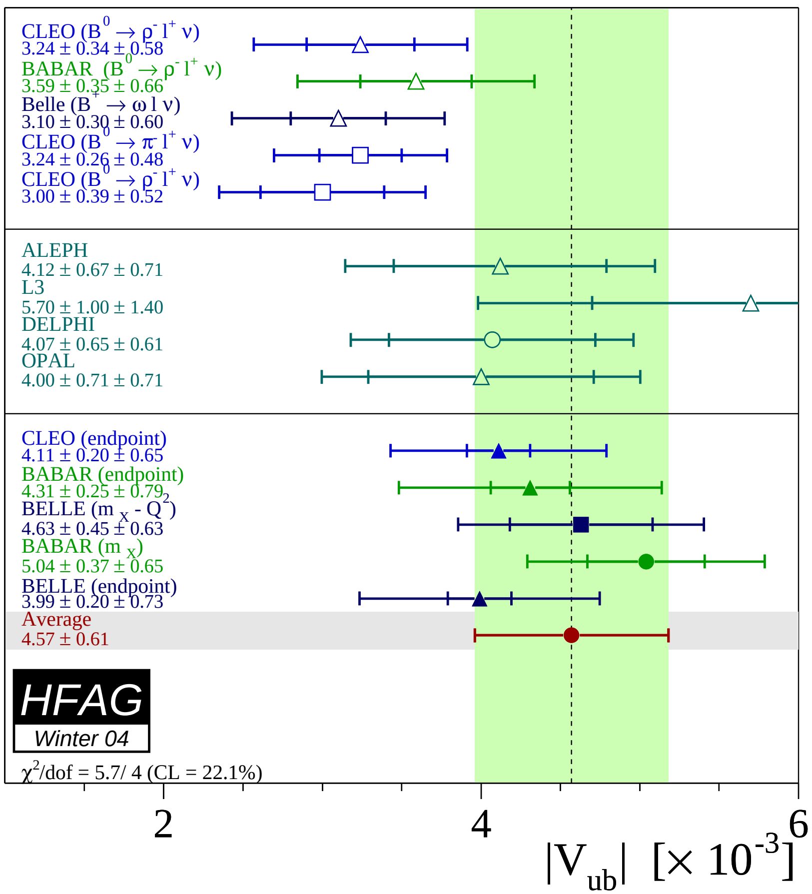
$$|V_{cb}| = (40.1 \pm 0.9_{\rm exp} \pm 1.8_{\rm th}) \times 10^{-3}$$

Form fact. shape fits $B^0 \to D^{(*)-}\pi^+$, $D^{(*)-}D_s^{(*)+}$ rates via factorization (PR D **64**, 094001)

Consistent with inclusive $|V_{cb}|$ but larger errors

V_{ub}: INCLUSIVE $b \to u$ DECAYS

Semileptonic decay $b \to u\bar{\nu}_\ell \ell^-$ again the source of information, but $\Gamma(b \to u\bar{\nu}_\ell \ell^-)$ is only about 2% of $\Gamma(b \to c\bar{\nu}_\ell \ell^-)$. Several strategies have been used:



Leptons beyond $b \to c\bar{\nu}_\ell \ell^-$ end point

Reconstruct hadronic mass $M_X < M_D$

Cut on $q^2 = m^2_{\ell\nu}$

Light-cone-inspired kinematic cut

As in $b \to c\bar{\nu}_\ell \ell^-$, $b \to s\gamma$ photon spectrum pins down hadronic uncertainties

Bottom 5 points:

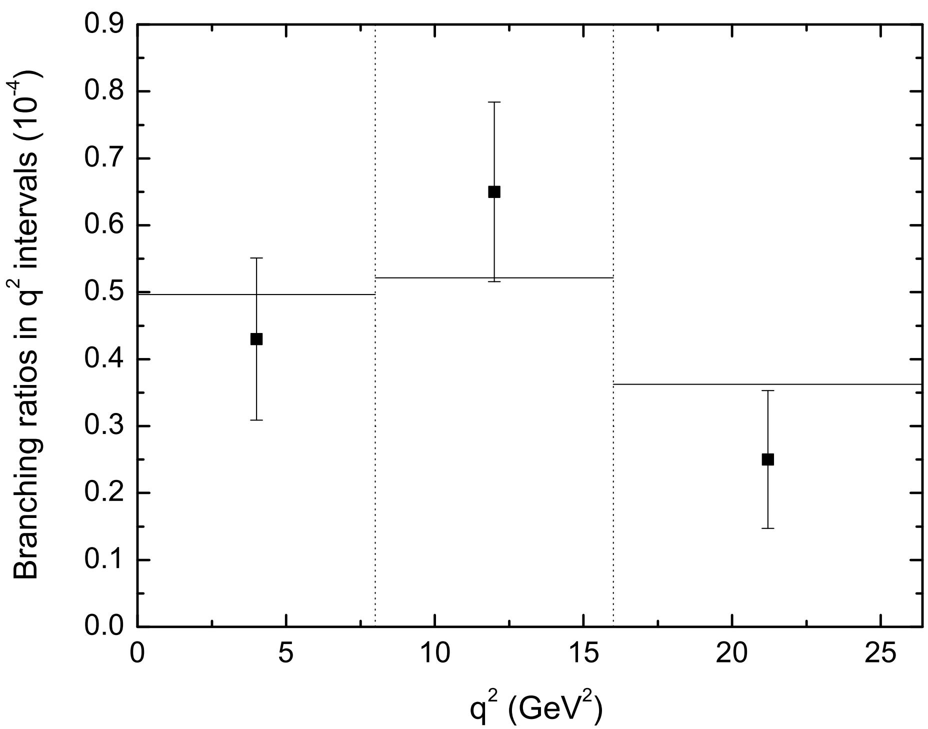
$$|V_{ub}| = (4.57 \pm 0.61) \times 10^{-3}$$

Notably higher than value from exclusive $b \to u$ decays (e.g., $B \to \pi\bar{\nu}_\ell \ell$):

Top 5 plotted points (my average) $\Rightarrow$ $|V_{ub}| = (3.23 \pm 0.62) \times 10^{-3}$

V_{ub}: EXCLUSIVE $b \to u$ DECAYS

CLEO $B \to \pi \bar{\nu}_\ell \ell$ spectrum:



In exclusive average I assigned overall ± 0.60 systematic error

Combining with inclusive value, including scale $S = 1.54 \Rightarrow$

$$|V_{ub}| = (3.91 \pm 0.66) \times 10^{-3}$$

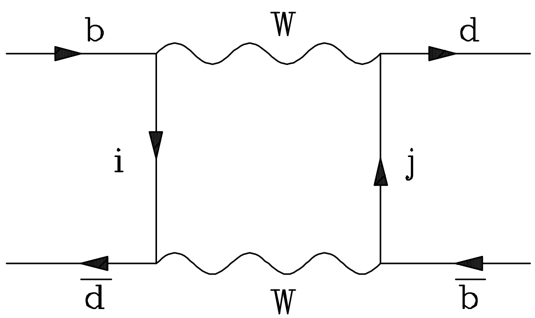
Discrepancy between inclusive, exclusive values merits caution (quark-hadron duality valid?)

Fit to CLEO $\int dq^2 \frac{d\mathcal{B}}{dq^2}(B^0 \to \pi^- l^+ \nu_l)$ spectrum helped relate high-q^2 lattice QCD form factor predictions to q^2 behavior needed for testing factorization: Z. Luo + JLR, PR D **68**, 074010 (2003)

V_{td} FROM B–$\overline{B}$ MIXING

Loop diagram allows $b\bar{d} \leftrightarrow d\bar{b}$ transitions (2nd order weak)

Quarks $i, j = u, c, t$ in loop; t dominates $\Rightarrow$ information on $|V_{td}|$



Crossed diagram contributes $\times 1/3$

f_B^2 (B meson decay constant) governs matrix element of $b\bar{d} \leftrightarrow d\bar{b}$ operator

Parameter $B_B = 1$ if W exchange diagrams dominate

$f_B\sqrt{B_B} = (228 \pm 30 \pm 10)$ MeV and $\Delta m_d \simeq 0.5$ ps^{-1} $\Rightarrow$ 95% c.l. range

$$|V_{td}| = (8.26^{+1.23}_{-1.79}) \times 10^{-3} \Leftrightarrow |1 - \bar{\rho} - i\bar{\eta}| = 0.89^{+0.12}_{-0.20}$$

CKMfitter 95% c.l. range of $|V_{ub}| = (3.87^{+0.73}_{-0.61}) \times 10^{-3} \Rightarrow |\bar{\rho} + i\bar{\eta}| = 0.40^{+0.08}_{-0.06}$

Forthcoming information from $\mathcal{B}(B \to \rho\gamma)/\mathcal{B}(B \to K^*\gamma)$;
expect $\mathcal{B}(B^0 \to \rho^0\gamma) = (0.64 \pm 0.23) \times 10^{-6}$ (cleaner than $\rho^+\gamma$)

CLEO $f_D = (204 \pm 42 \pm 17)$ MeV: Accuracy already approaching that of lattice

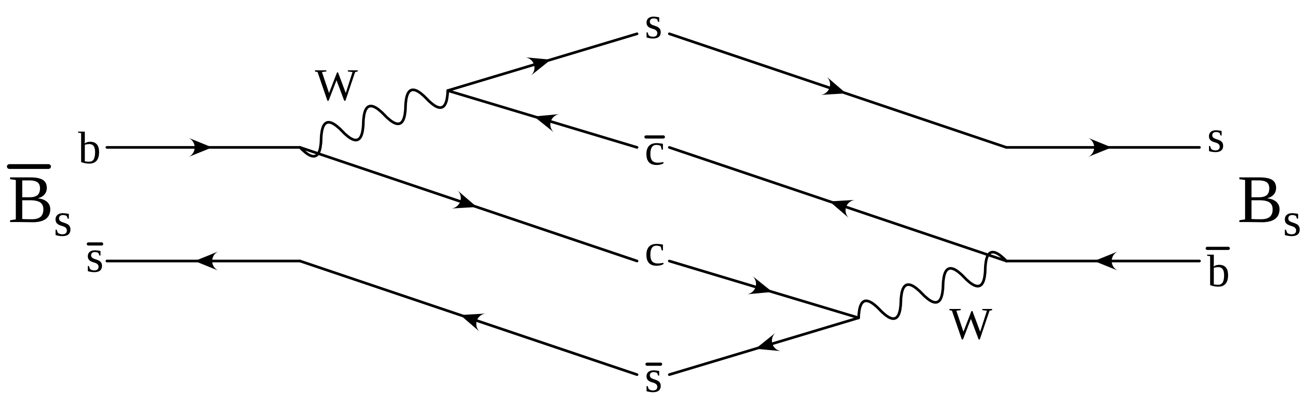
B_s–$\overline{B}_s$ MIXING

Asymmetric error in $|V_{td}|$: restricted on positive side by B_s–$\overline{B}_s$ mixing

Same diagram as before but substitute $d \to s$ and assume $V_{ts} \simeq -V_{cb}$

Lower limit $\Delta m_s > 14.5$ ps^{-1} and $\xi \equiv f_{B_s}\sqrt{B_{B_s}}/f_B\sqrt{B_B} = 1.21 \pm 0.06 \Rightarrow$ lower limit on V_{ts}/V_{td} and hence upper limit on V_{td}

Global CKMfitter fit $\Rightarrow 2\sigma$ prediction $\Delta m_s = 17.8^{+15.2}_{-2.7}$ ps^{-1}



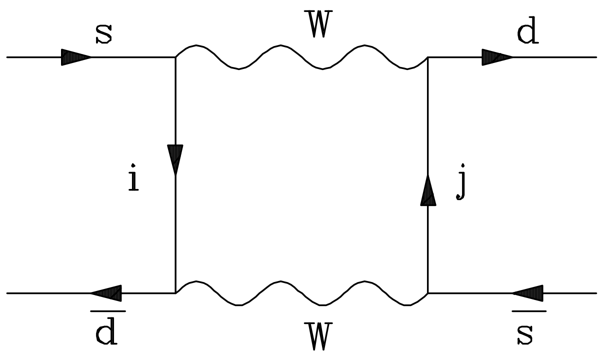
Mixing via shared intermediate states $\Rightarrow \Delta\Gamma_s \simeq -\Delta m_s/200$ ($\sim m_b^2/m_t^2$) or $\Delta\Gamma/\bar{\Gamma} \simeq 0.18(f_{B_s}/200\ \mathrm{MeV})^2$

CDF has recently reported a value of $0.65^{+0.25}_{-0.23} \pm 0.01$ (C. Gay, this conference)

K_L CP VIOLATION

CP-violating K^0–$\overline{K}^0$ mixing dominated by top quarks in loop; charm also

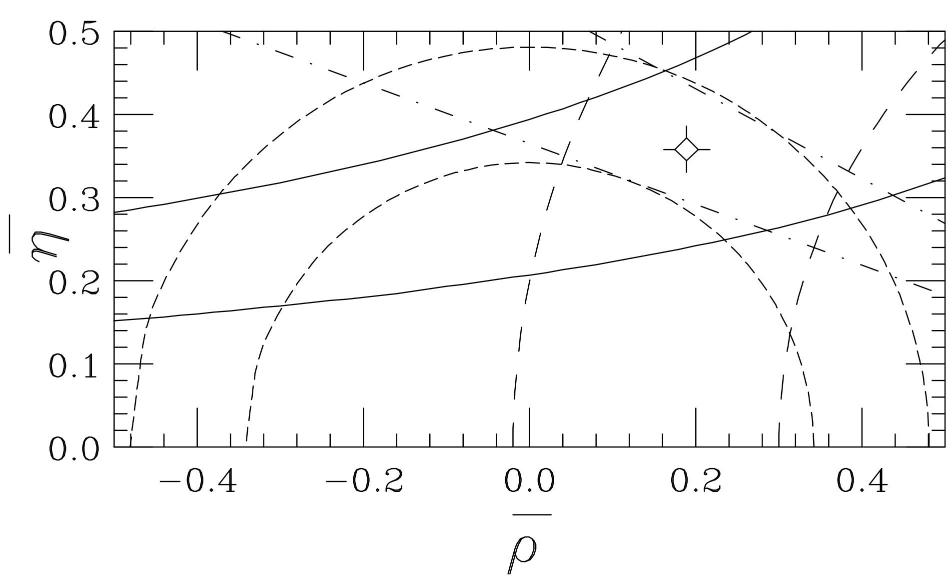
Parameter ϵ_K governing CP violation mostly $\sim$ Im(V_{td}^2) and hence measures $\bar{\eta}(1-\bar{\rho})$



Convenient expressions in Ali, hep-ph/0312303, imply $(\bar{\rho},\ \bar{\eta})$ lie between boundaries

$$\bar{\eta}(1.38-\bar{\rho}) = 0.28\ ,\quad \bar{\eta}(1.26-\bar{\rho}) = 0.50$$

Constraints on $(\bar{\rho},\ \bar{\eta})$ from $|V_{ub}|$ (dotted circles), $|V_{td}|$ (dashed circles), ϵ_K (solid hyperbolae, 1σ), $\sin 2\beta$ (dotdash) select region around (0.19, 0.36) (plotted point)



Point: $(0.19^{+0.09}_{-0.07}, 0.36^{+0.05}_{-0.04})$

Note consistency

Main uncertainty: $|1-\rho-i\eta|$

Direct CPV (ϵ'/ϵ) seen but no constraint (hadronic uncertainty)

$K \to \pi\nu\bar{\nu}$ CONSTRAINTS

Higher-order weak diagrams govern weak quark transition $s \to d\nu\bar{\nu}$. Top quark in loop dominates but also charm contribution $\Rightarrow$ result measures $|1.3 - \bar{\rho} - i\bar{\eta}|$

$K^+ \to \pi^+\nu\bar{\nu}$: Brookhaven experiment E-787, E-949 (hep-ex/0403036) sees 3 events

Branching ratio $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.82}) \times 10^{-10}$ vs. Standard Model prediction $(0.78 \pm 0.12) \times 10^{-10}$ (Buras et al., hep-ph/0405132).

Still consistent with large region in $(\bar{\rho},\ \bar{\eta})$.

Proposals for Fermilab, JPARC seek a sample of 100 events $\Rightarrow |1.3 - \bar{\rho} - i\bar{\eta}|$ to 5%

$K_L \to \pi^0\nu\bar{\nu}$ is purely CP-violating and measures $\bar{\eta}^2$: expect $\mathcal{B} = (3.0 \pm 0.6) \times 10^{-11}$ (hep-ph/0405132)

KEK PS E-391 has taken data whose single-event sensitivity should be an order of magnitude above Standard Model value; tremendous progress in past few years

Eventual experiment at JPARC or Brookhaven: goal of seeing Standard Model rate

V_{ts} AND V_{tb}

Lower limit on $|V_{tb}^* V_{ts}|$ from B_s–$\bar{B}_s$ mixing, theoretical constraint on $\xi \equiv f_{B_s}\sqrt{B_{B_s}}/f_B\sqrt{B_B} = 1.2 \pm 0.1$, B_d–$\bar{B}_d$ mixing

Ali (hep-ph/0312303) concludes $|V_{tb}^* V_{ts}| > 0.034$

Upper limit on $|V_{tb}^* V_{ts}|$ from top quark contribution to $b \to s\gamma$

Ali + Misiak (hep-ph/0304132) $\Rightarrow V_{tb}^* V_{ts} = -0.047 \pm 0.008$ (expected sign)

Top quark decays $t \to b\ell^+\nu_\ell$ dominate over those with no b (CDF):

$$\frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.94^{+0.31}_{-0.24} .$$

CDF Run II (108 pb^{-1}): $0.54^{+0.49}_{-0.39}$

Assumption that CKM matrix is 3×3 is crucial to interpretation of this result as a useful bound on $|V_{tb}|^2$; see PDG review for discussion of almost non-existent lower bounds on 3rd row if there are more than 3 families.

PROCESSES GIVING β

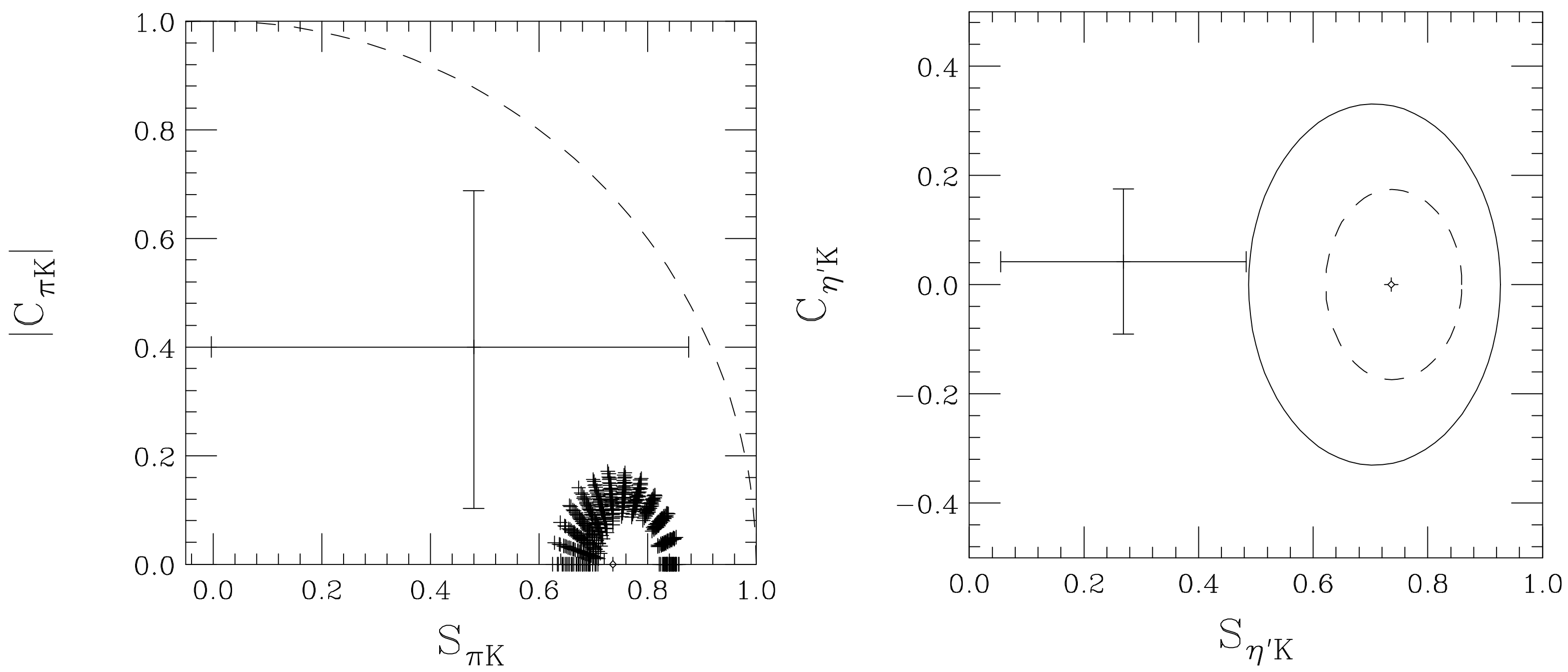
CP asymmetry $A(t) = -C\cos(\Delta m t) + S\sin(\Delta m t)$

Penguin-dominated; expect $C = 0$, $S = \sin(2\beta) = 0.74 \pm 0.05$ (points plotted below)

Contributions from other amplitudes using new measurements and flavor SU(3)

M. Gronau + PL B **579**, 331 (2004) PL B **596**, 107 (2004)

$B^0 \to \pi^0 K_S$ $B^0 \to \eta' K_S$



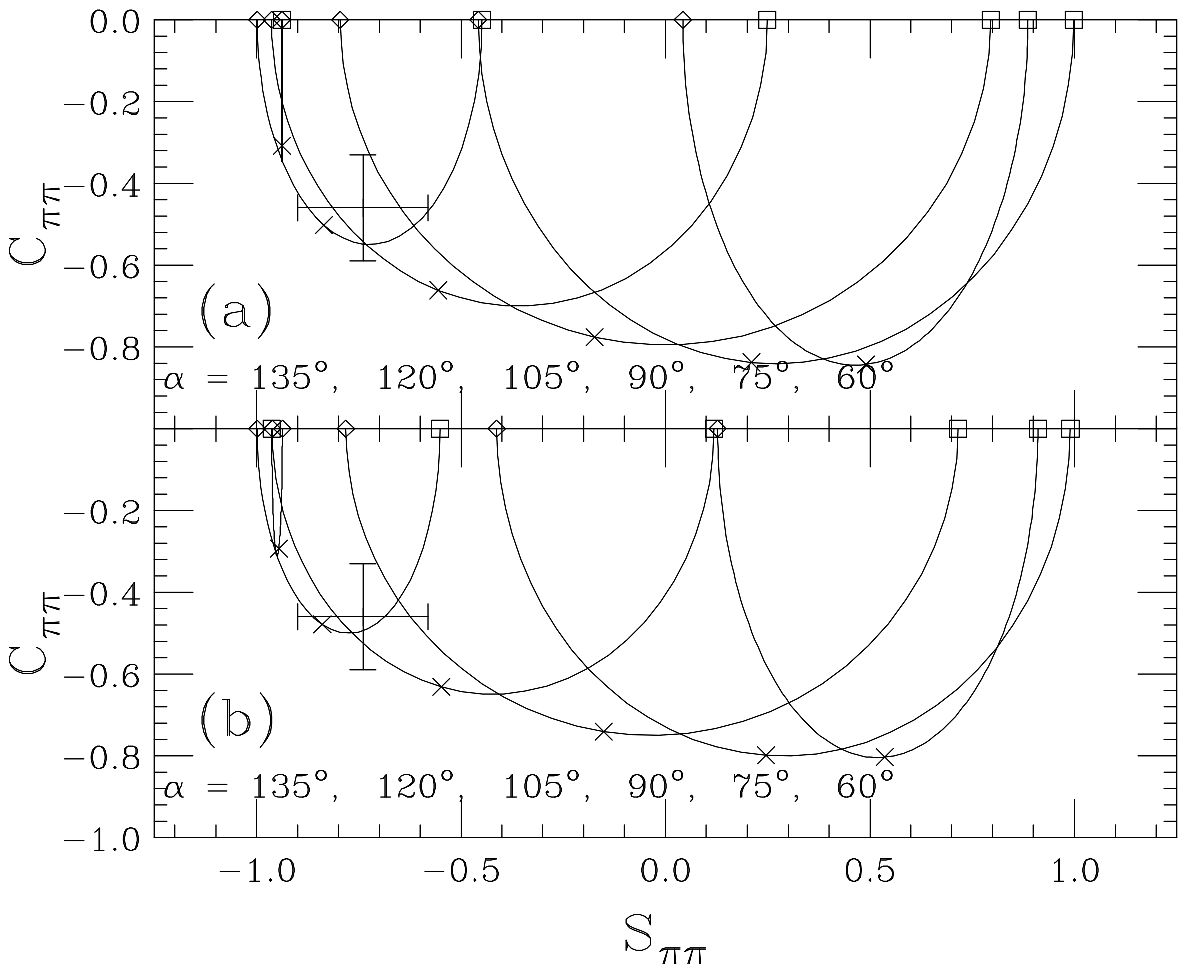
$B^0 \to \pi^0 K_S$: Hatched ellipse = allowed region. $B^0 \to \eta' K_S$, solid curve: bounds based on flavor SU(3) and new measurements of other processes; dashed curve: neglecting processes involving spectator quark.

$B^0 \to \pi^+\pi^-, \ldots$ **AND** α

$\pi^+\pi^-$: M. Gronau + JLR, Phys. Lett. B **595**, 339 (2004)

$$\frac{\Gamma(\overline{B}^0(t) \to \pi^+\pi^-) - \Gamma(B^0(t) \to \pi^+\pi^-)}{\Gamma(\overline{B}^0(t) \to \pi^+\pi^-) - \Gamma(B^0(t) \to \pi^+\pi^-)} = -C_{\pi\pi}\cos(\Delta m t) + S_{\pi\pi}\sin(\Delta m t)$$

Penguin pollution ($\sim 70\%$) from (a) $B^+ \to K^0\pi^+$ or (b) $B^0 \to K^+\pi^-$



Contours: strong phase

$0^\circ > \delta > -180^\circ$

Best bounds from (b):

$\alpha = (103 \pm 17)^\circ$

Gronau + Zupan,

$B^0 \to \rho^\pm\pi^\mp$,

hep-ph/0407002:

$\alpha = (95 \pm 16)^\circ$

BaBar: $B^0 \to \rho^+\rho^-$

$\alpha = (96 \pm 10 \pm 4 \pm 13)^\circ$

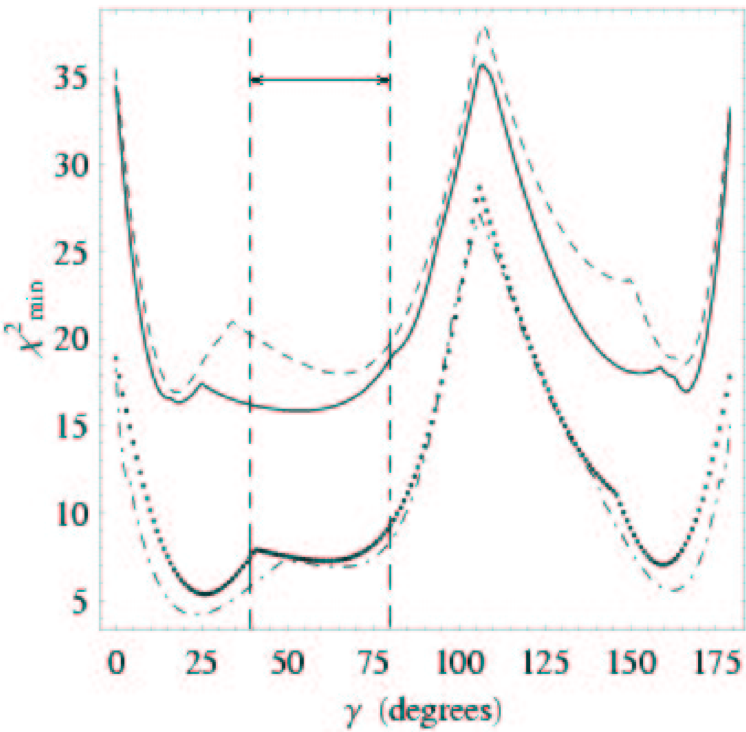
$B \to PP, VP$ AND γ

$P =$ light pseudoscalar meson, $V =$ light vector meson (u, d, s only)

Fits to rates and CP asymmetries in flavor SU(3) (T, P, $C, \ldots$ amplitudes

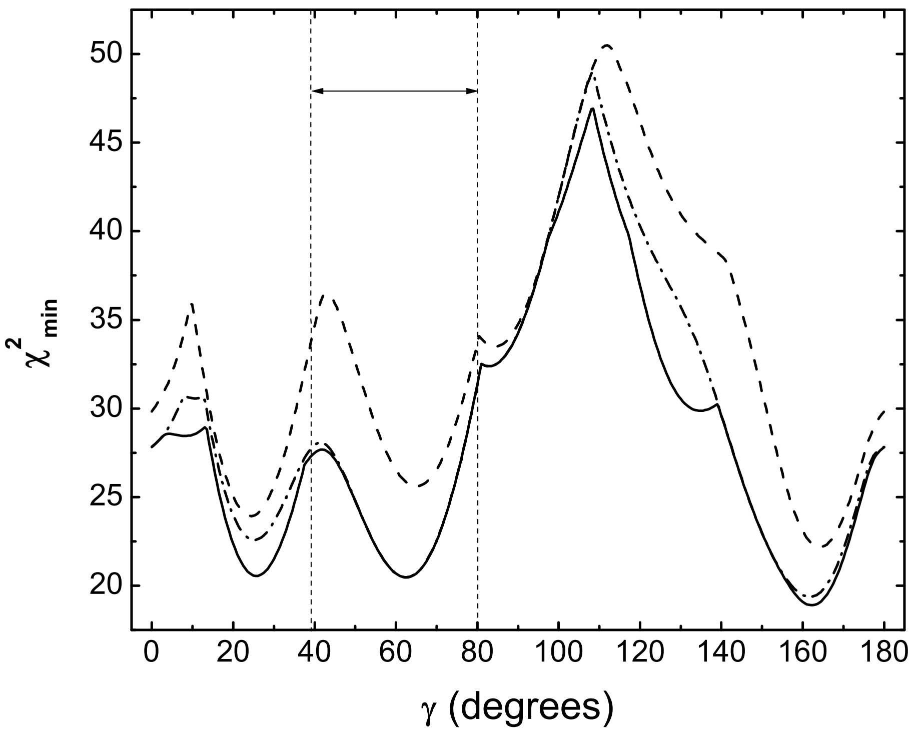
C.-W. Chiang *al.*, PP: hep-ph/0404073 (PR D); VP: PR D **69**, 035009 (2004)

$B \to PP$: 26 observables



Solid: $\chi^2_{\rm min}/{\rm d.f.} = 16.0/13$

$B \to VP$: 34 observables



Solid: $\chi^2_{\rm min}/{\rm d.f.} = 20.5/22$

VP alone: $\gamma = (63 \pm 6)^\circ$; combined (D. Suprun's Ph. D. thesis): $\gamma \simeq 62^\circ$

BEYOND THE 3×3 CKM MATRIX

A fourth family?

Fourth neutrino, if it exists, must be heavy: only 3 light ν in Z decay (e.g., $N_\nu = 2.98 \pm 0.064$ from $e^+e^- \to \gamma + X$ above the Z, L3 at LEP)

Direct search for b' heavier than Z (look for $b' \to bZ$) by CDF at Tevatron, PRL **84**, 835 (2000). Exclude $100 < m(b') < 199$ GeV/c^2

Outside the familiar pattern:

Quark–lepton families: 16-dimensional multiplets of grand unified group SO(10).

16 of SO(10) is **1** + **5*** + **10** of SU(5); **27** of E$_6$ is **16** + **10** + **1** of SO(10).

10 of SO(10): isosinglet quarks "$h, \bar{h}$" (charge $Q = \pm 1/3$), isodoublet leptons.

The SO(10) singlets are candidates for sterile neutrinos, one for each family.

Exotic h quarks can mix with b and push its mass down with respect to t.

$h\bar{h}$ production signatures: T. Andre + JLR, PR D **69**, 034001 (2004):

Decays to $Z + b$, $W + t$, possibly $\mathrm{Higgs} + b$; reach 270–320 GeV/c^2 at Tevatron

SUMMARY

No problem with CKM unitarity relation $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

Improved V_{cd} and V_{cs} still consistent with $V_{cd} = -V_{us}$ and $V_{cs} = V_{ud}$

Errors on $V_{cb} \sim 41\text{–}42 \times 10^{-3}$ from inclusive analyses are being reduced; lattice QCD will help exclusive analyses catch up

Lower V_{ub} in exclusive ($\simeq 3.2 \times 10^{-3}$) than inclusive ($\simeq 4.6 \times 10^{-3}$) $b \to u$ decays. Need better understanding of form factors (exclusive), quark-hadron duality (inclusive); $\Rightarrow \quad \sim 3.9 \times 10^{-3}$

Errors in $|V_{td}| \simeq (8.3^{+1.2}_{-1.8}) \times 10^{-3}$ mainly lattice errors in $f_B\sqrt{B_B}$

Major improvement expected from detection of B_s–$\overline{B}_s$ mixing

SU(3) fit $\Rightarrow \gamma = (63 \pm 6)^\circ$ needs validation, e.g., via $b \to d$ penguins

No evidence against $V_{ts} \simeq -V_{cb}$, $V_{tb} \simeq 1$

It's time for a theory of quark masses and CKM elements!