CP Violation and the Determination of the CKM Matrix

Frank Porter (Caltech, *BaBar*)

- 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 3×3 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,τ)
  - Nothing on EDM
  - For neutrino sector (PMNS matrix), see talks by Lisi, Bellerive, Nakaya, and Piquemal
  - For β_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.

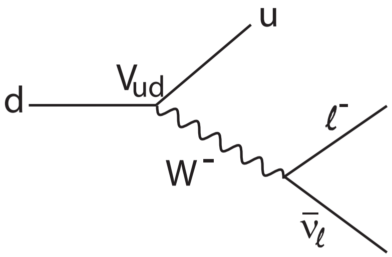
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}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

(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: $|V_{ud}|$

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

2008 RPP

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

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

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

$$|V_{ud}| = 0.97425 \pm 0.00022$$

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

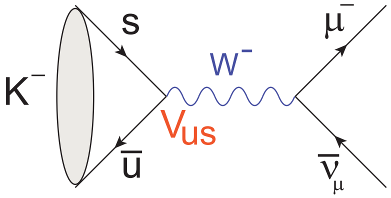
The magnitudes: $|V_{us}|$

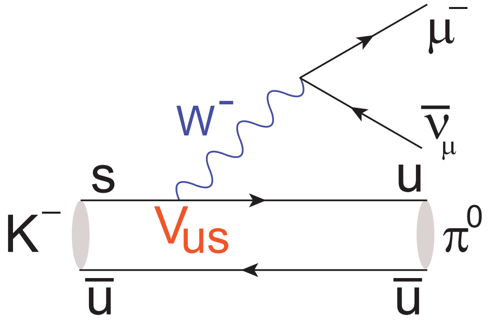
2008 RPP

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

$|V_{us}|$ from kaon decays

☐ New averages from FlaviaNet Kaon Working Group, arXiv:1005.2323 [hep-ph] (2010), see also KLOE (Archilli, 1085)





- $K_{\ell 3}$: $|V_{us}|f_+(0) = 0.2163(5)$ or $|V_{us}| = 0.2254 \pm 0.0013$ with $f_+(0) = 0.959(5)$ (lattice, Boyle et al., arXiv1004:0886 (2010))
- $K_{\ell 2}$: $\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = 0.2758(5)$ or $\frac{|V_{us}|}{|V_{ud}|} = 0.2312 \pm 0.0013$ with $f_K/f_\pi = 1.193(6)$ (lattice average)
- Combining, obtain $|V_{us}|(K) = 0.02253 \pm 0.0009$

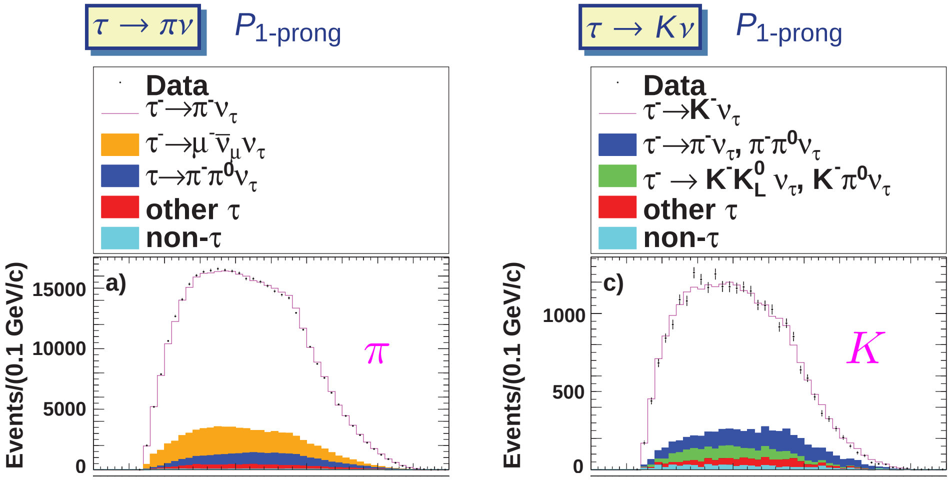
$|V_{us}|$ from tau decays

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

$$R_{K/\pi} \equiv \frac{\mathcal{B}(\tau^- \to K^-\nu_\tau)}{\mathcal{B}(\tau^- \to \pi^-\nu_\tau)}$$

$$= 0.06531 \pm 0.00056 \pm 0.00093$$

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



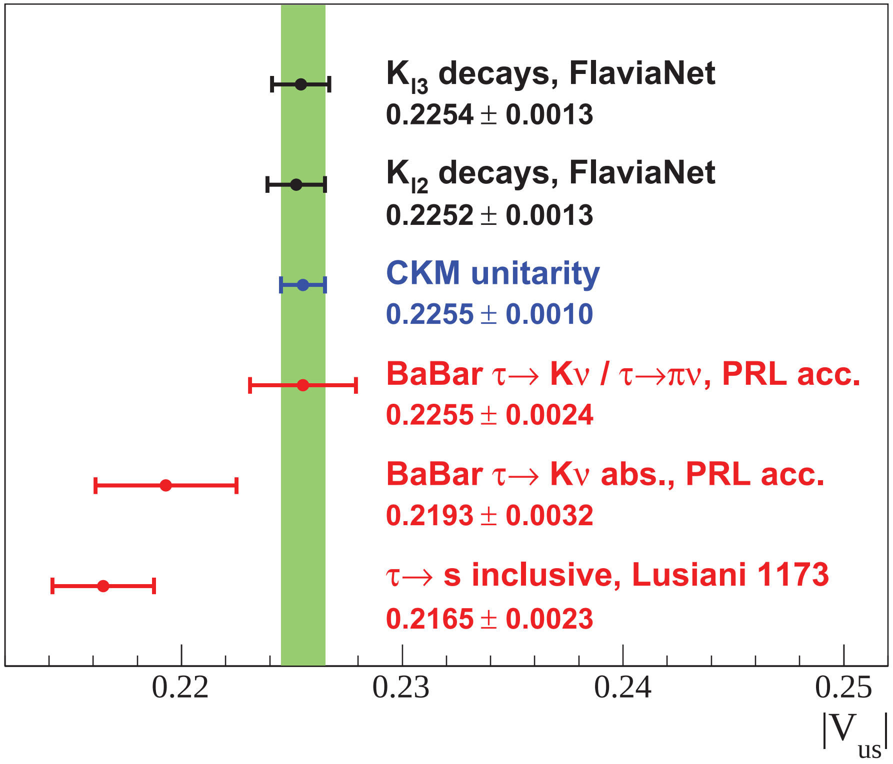
CM momentum of π or K (0 to 5 GeV)

  - 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, 3.2σ 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*, Λ_c decays (Hartmann, 557)]

$|V_{us}|$ summary

Lusiani 1173 (HFAG-τ) compilation, Preliminary



My average $|V_{us}| = 0.2253 \pm 0.0008$, does not include $\tau \to s$ inclusive

The magnitudes: $|V_{ub}|$

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

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

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

BLNP	PRD **72** (2005) 073006
DGE	arXiv:0806.4524 [hep-ph]
GGOU	JHEP **0710** (2007) 058
ADFR	Eur Phys J C **59** (2009) 831

(and references therein)

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

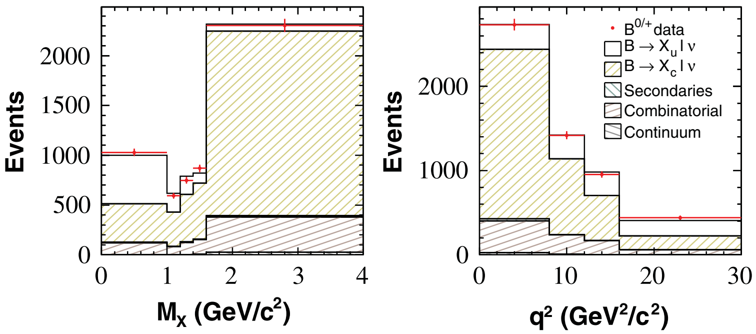


TABLE II. Values for $|V_{ub}|$ with relative errors (in %).

Theory	$\lvert V_{ub}\rvert \times 10^3$	Stat	Syst	m_b	Th.
BLNP [5]	4.37	4.3	4.0	$^{+3.1}_{-2.7}$	$^{+4.3}_{-4.0}$
DGE [6]	4.46	4.3	4.0	$^{+3.2}_{-3.3}$	$^{+1.0}_{-1.5}$
GGOU [7]	4.41	4.3	4.0	1.9	$^{+2.1}_{-4.5}$

My average Belle inclusive: $0.00441 \pm 0.00026(\text{expt}) \pm 0.00024(\text{thy})$

Inclusive $|V_{ub}|$ (continued)

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

– *BABAR* inclusive (Sigamani, 732):

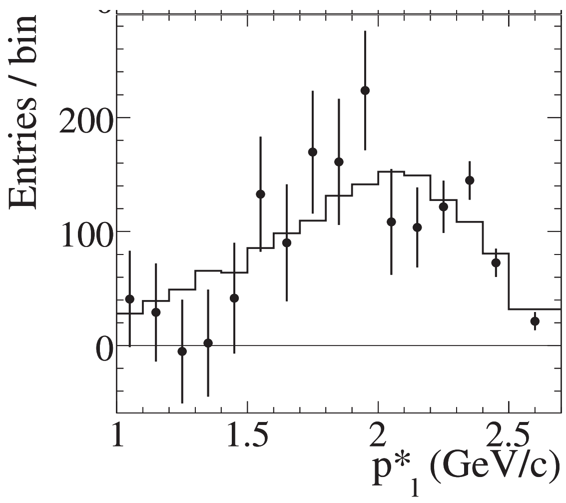
Measure Partial Branching Fractions for $B \to X_u \ell \bar{\nu}$

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 $B \to X_u \ell \bar{\nu}$ 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 $B \to \pi \ell \nu$ with $\ell = e$ or μ, to good approximation a single form factor contributes:

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

  - Belle (Ha, 944) Exclusive $B^0 \to \pi^- \ell^+ \nu$, untagged 605 fb^{-1} $\mathcal{B}(B^0 \to \pi^- \ell \nu) = (1.49 \pm 0.04(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-4}$ $|V_{ub} f_+(0)| = (9.24 \pm 0.18(\text{stat}) \pm 0.20(\text{syst}) \pm 0.07(\tau_B)) \times 10^{-4}$ $|V_{ub}| = (0.00343 \pm 0.00033)$ (using FNAL-MILC PRD **79** (2009) 054507)
  - *BABAR* (Wulsin, 1180) $B \to \pi \ell \nu$ ($\rho \ell \nu$)

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.41 \pm 0.05 \pm 0.07) \times 10^{-4}$$

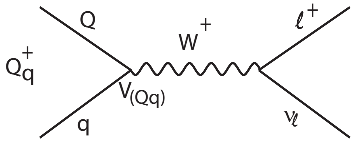
$$\mathcal{B}(B^0 \to \rho^- \ell^+ \nu) = (1.75 \pm 0.15 \pm 0.27) \times 10^{-4}$$

TABLE XIII: $|V_{ub}|$ derived from $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$ 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 $B \to \rho \ell \nu$ form-factor integrals are not available.)

	q^2 Range (GeV^2)	$\Delta\zeta$ (ps^{-1})	$|V_{ub}|$ (10^{-3})
$B \to \pi \ell \nu$			
LCSR [15]	$0 - 16$	5.44±1.43	$3.63 \pm 0.12^{+0.59}_{-0.40}$
HPQCD [22]	$16 - 26.4$	2.02±0.55	$3.21 \pm 0.17^{+0.55}_{-0.36}$
$B \to \rho \ell \nu$			
LCSR [16]	$0 - 16.0$	13.79	2.75 ± 0.24
ISGW2 [14]	$0 - 20.3$	14.20	2.83 ± 0.24

For $B \to \pi \ell \nu$ 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: $|V_{ub}| = 0.00326 \pm 0.00054$



V_{ub} in leptonic B decays

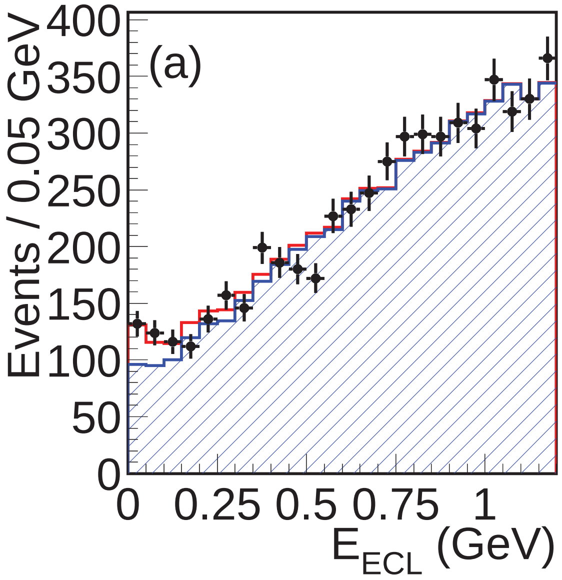
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

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

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

  E_{ECL} = residual energy in calorimeter



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

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

$|V_{ub}|$ summary

Recent measurements

Measurement	Experiment	V_{ub}
Inclusive	Belle	0.00441 ± 0.00024
Inclusive	*BABAR*	0.00431 ± 0.00035
Exclusive $\pi\ell\nu$	Belle	0.00343 ± 0.00033
Exclusive $\pi\ell\nu$	*BABAR*	0.00326 ± 0.00054
$B \to \tau\nu$	Belle	0.00484 ± 0.00079
$B \to \tau\nu$	*BABAR*	0.0057 ± 0.0019

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

- ❑ CKMfitter average $|V_{ub}| = 0.00392 \pm 0.00009 \pm 0.00045$ (based on HFAG end of 2009 preliminary)

First row unitarity

In SM (V is 3×3 unitary), must have:

$$\begin{aligned} 1 &= |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \\ &= 0.99995 \pm 0.00057 \end{aligned}$$

Limit (Bayesian) on possible 4th generation:

$$\begin{aligned} |V_{u4}| &= \sqrt{1 - |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2} \\ &< 0.031 \text{ (90\% CL, flat prior in } |V_{u4}|^2\text{)} \\ &< 0.061 \text{ (90\% CL, flat prior in } |V_{u4}|\text{)} \end{aligned}$$

In spite of “four-nines” sum, numbers from first two generations not sufficiently precise to require the third generation

The magnitudes: $|V_{cd}|$

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

2008 RPP remains up-to-date $|V_{cd}| = 0.230 \pm 0.011$

- ❏ 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: $|V_{cs}|$

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

RPP 2008: Leptonic D_s decays; semileptonic D decays

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

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

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 fb^{-1}

  $$\mathcal{F}(1)|V_{cb}| = 0.0345 \pm 0.0002 \pm 0.0010$$

  $\mathcal{F}(1)$ 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): $\mathcal{F}(1) = 0.921 \pm 0.013 \pm 0.020$

  $$|V_{cb}| = 0.0375 \pm 0.0015$$

- *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)

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

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:

$$|V_{td}/V_{ts}| = 0.209 \pm 0.001 \pm 0.006 \text{ (2008 RPP)}$$

  - Using this, and $|V_{ts}|$ obtain slightly more precise result: $V_{td} = 0.0081 \pm 0.0005$
- *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 $B^0 \to \pi^+\pi^-\gamma$ with $B^0 \to K^+\pi^-\gamma$. Analysis uses 7 such pairs of modes.
  - Result is

$$\frac{\mathcal{B}(b \to d\gamma)}{\mathcal{B}(b \to s\gamma)} = 0.033 \pm 0.009 \pm 0.003$$

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: $|V_{ts}|$

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

$|V_{ts}|$ from B_s mixing

2008 RPP

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

Dominant uncertainties from lattice QCD

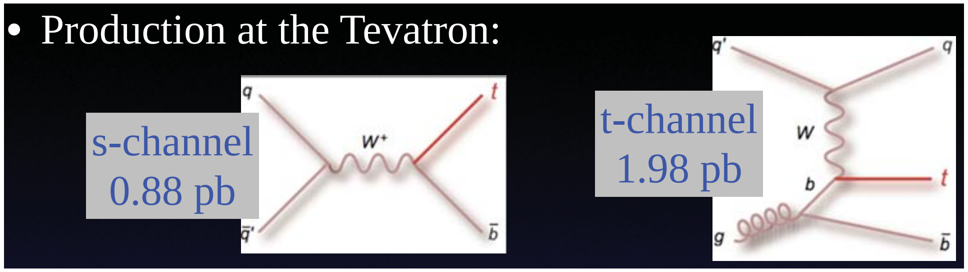
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The magnitudes: $|V_{tb}|$

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

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

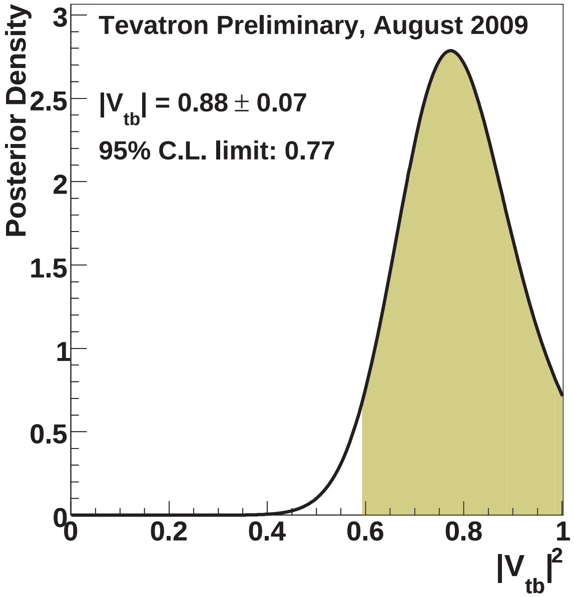
- Can be measured in single top production, without assuming 3 generation unitarity (but assuming $|V_{tb}| \gg |V_{td}|, |V_{ts}|$)



- 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

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

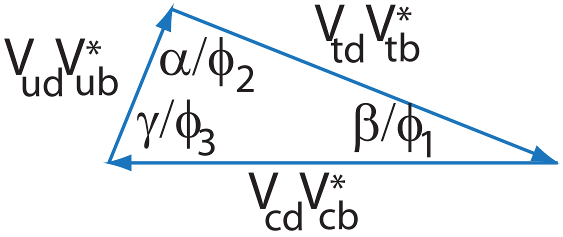
All CP violation from CKM in SM

Manifests as "unitarity triangle" relations with area $\neq 0$

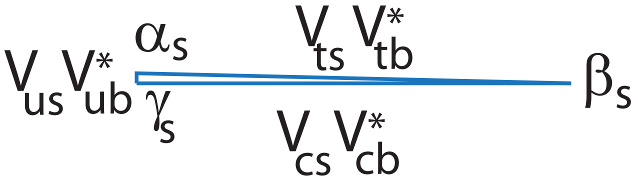
$$VV^\dagger = V^\dagger V = 1$$

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

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



$$0 = V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = O(\lambda^4) + O(\lambda^2) + O(\lambda^2)$$



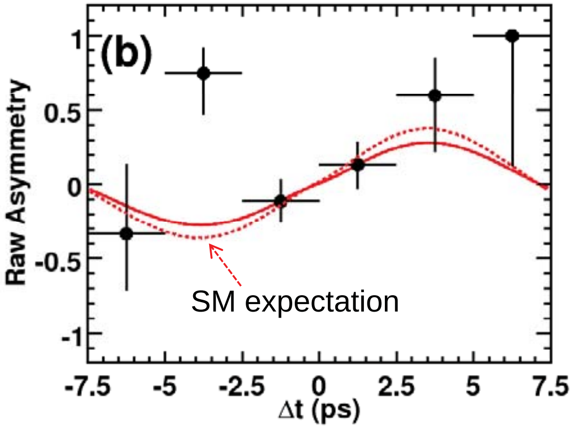
The angles: β/ϕ_1

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

- ☐ Belle (Higuchi, 1094) Analysis of $\sin 2\phi_1$ in $B \to c\bar{c}K^0$ [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 $B^0 \to \bar{D}^0\pi^+\pi^-$ Understanding time-dependent DP for $B^0 \to D_{CP}\pi^+\pi^-$ towards measurement of $\sin 2\beta$ and $\cos 2\beta$. Preliminary BFs presented.
- ☐ Belle (Higuchi, 1094) Time-dependent Dalitz plot analysis of $B^0 \to K^+K^-K^0_S$ ($b \to ss\bar{s}$ penguin)
  - Find four solutions; preferred solution yields

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

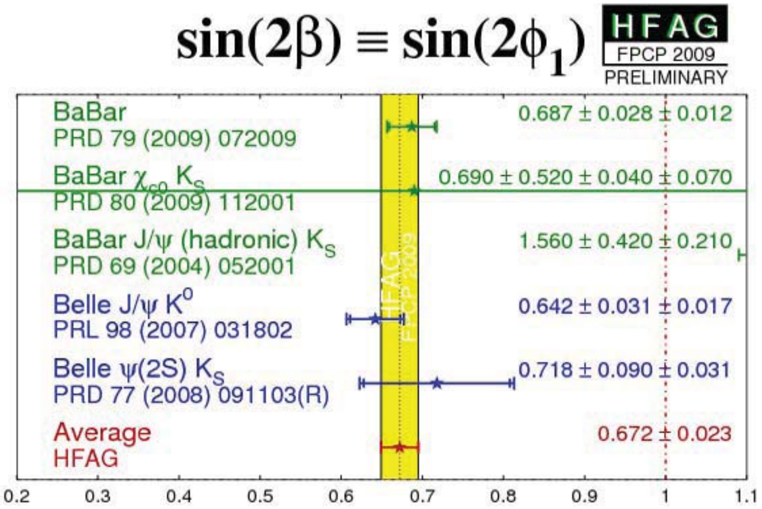
$$\phi_1^{\rm eff}(f_0(980)K^0_S) = (31.3 \pm 9.0 \pm 3.4 \pm 4.0(\text{DP model}))^\circ$$

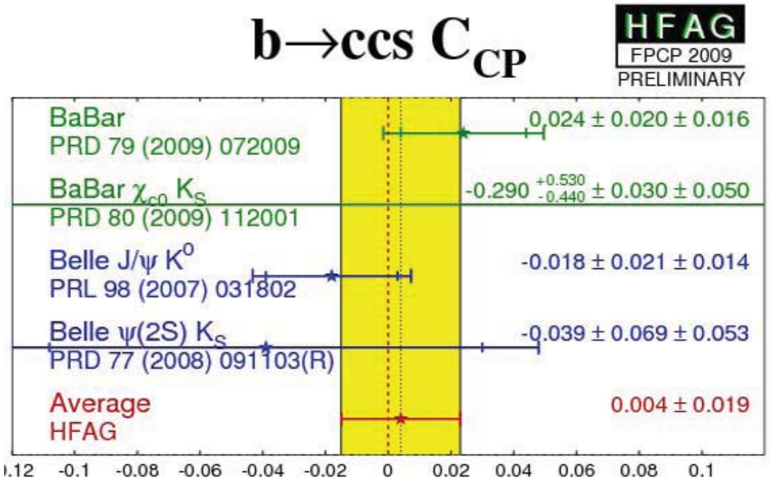


(ϕ mass region)

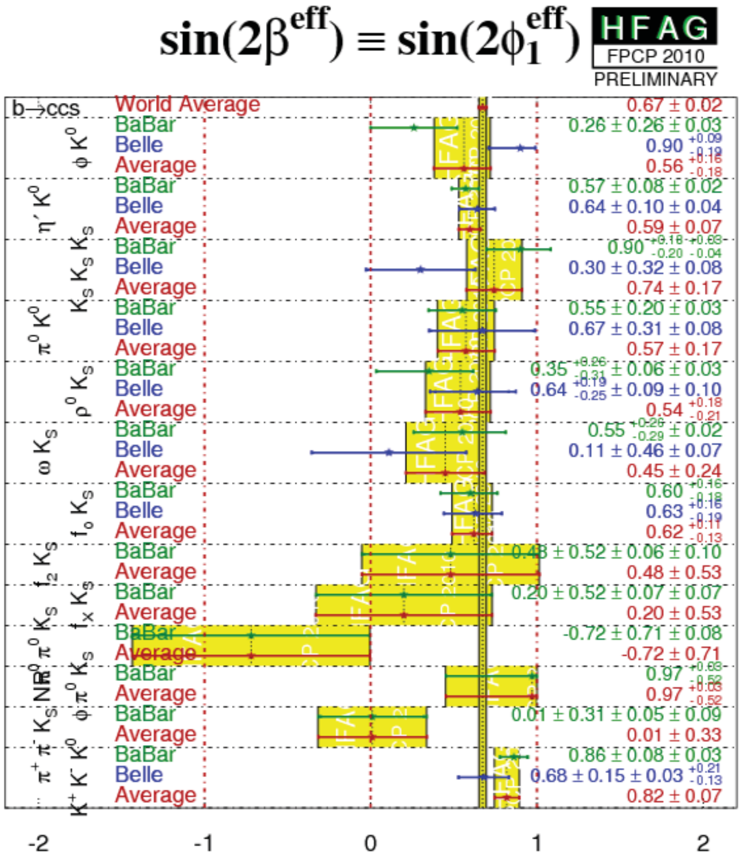
Consistent with $\phi_1^{\rm eff} = \phi_1$

$\sin 2\beta$ from the $b \to c\bar{c}s$ "golden" modes



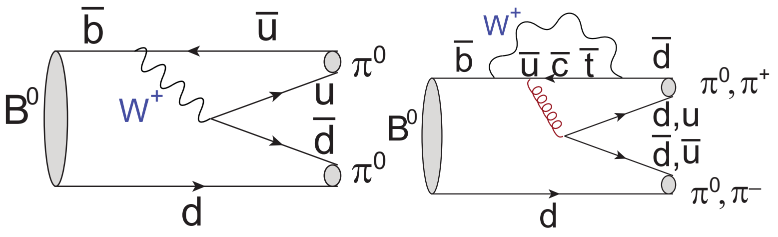


Compare with Penguin modes



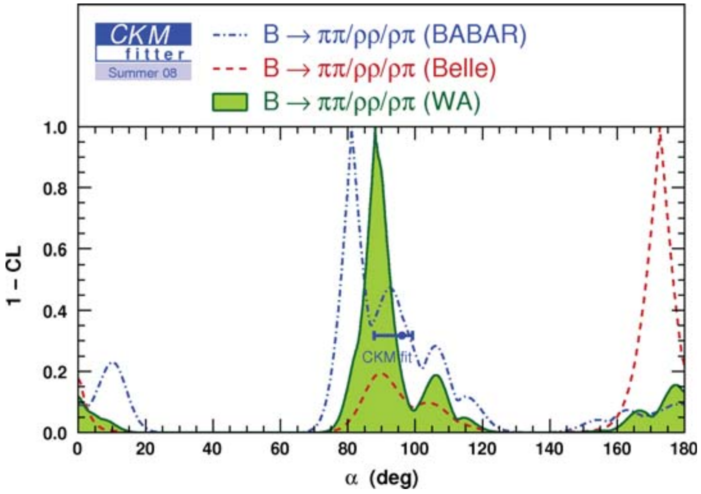
NP in loop can give rise to deviations from β/ϕ_1

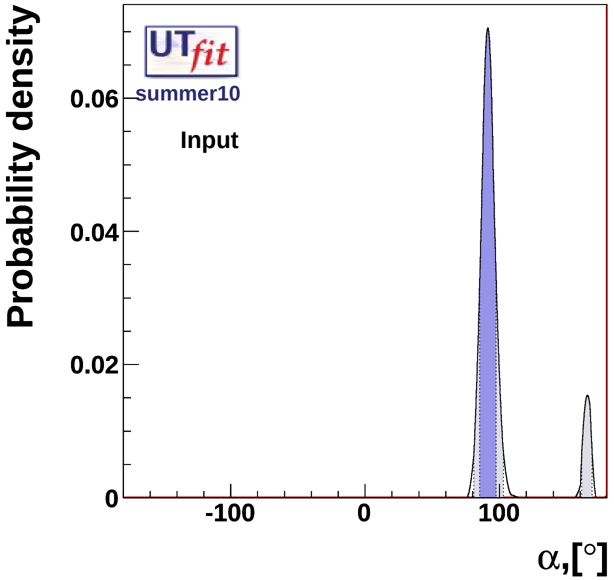
The angles: Measuring α/ϕ_2



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

- Measure in $b \to u\bar{u}d$
  - E.g., $B \to \pi^+\pi^-,\ \rho^+\rho^-,\ \pi^+\pi^-\pi^0,\ a_1^\pm\pi^\mp$
  - Penguin contributions (involving different CKM phase) complicate analysis. Isospin analysis permits isolation of tree amplitude [Gronau and London, PRL **65** (1990) 3381]





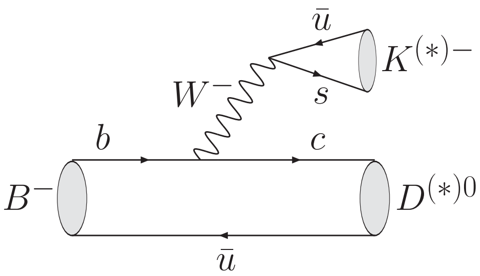
CKMfitter input: $(88.2^{+6.1}_{-4.8})^\circ$

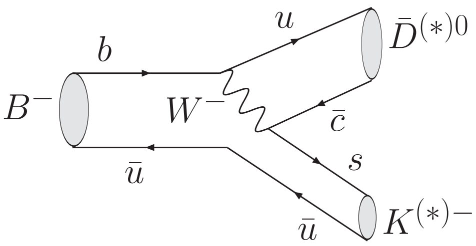
UTfit input: $(91.4 \pm 6.1)^\circ$

The angles: Measuring γ/ϕ_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.



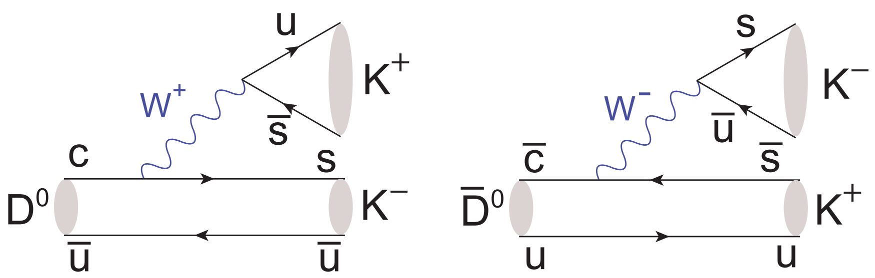


Compare B^- and B^+

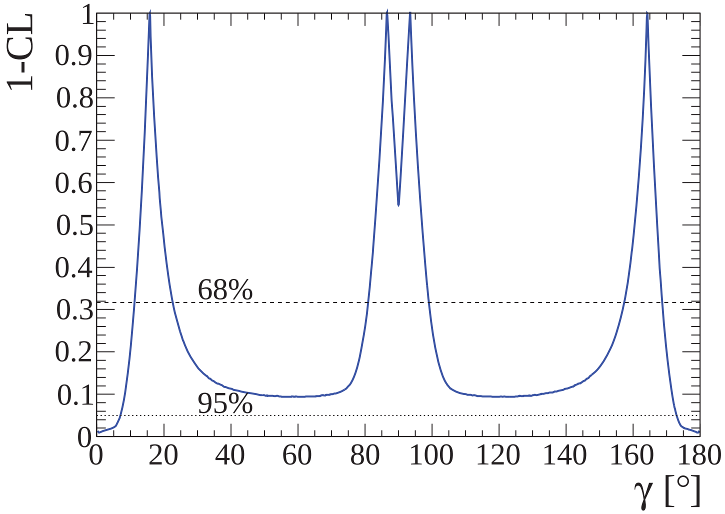
Various approaches ($D^0\bar{D}^0$ mixing is neglected):

The angles: Measuring γ/ϕ_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.



- *BABAR* (Martinez-Vidal, 1175) Preliminary $B^\pm \to D_{CP}K^\pm$, with $D_{CP+} \to \pi^-\pi^+, K^-K^+$ and $D_{CP-} \to K^0_S\pi^0, K^0_S\phi, K^0_S\omega$:

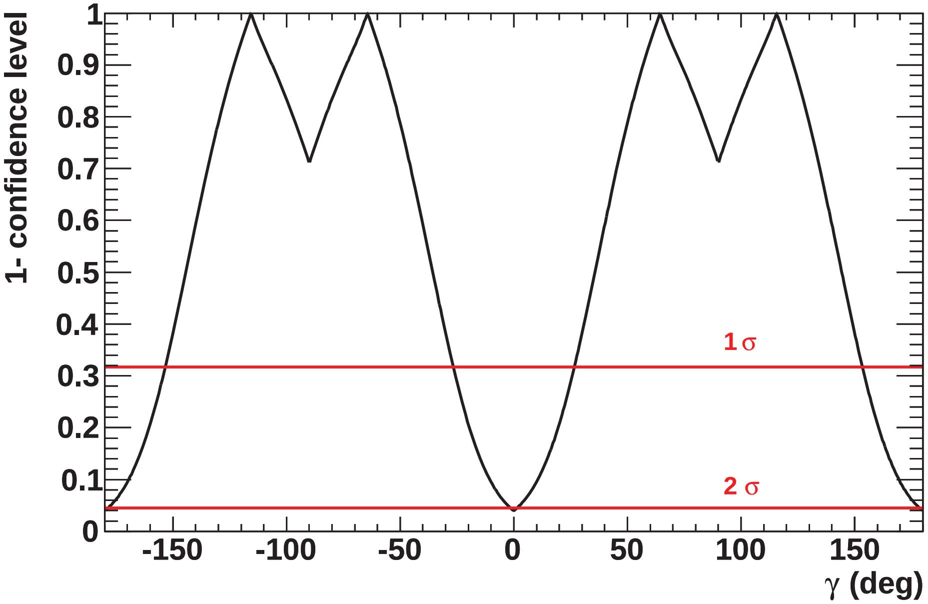


	$\gamma \mod 180\ [^\circ]$	r_B
68% CL	[11.3, 22.7]	[0.24, 0.45]
	[80.9, 99.1]	
	[157.3, 168.7]	
95% CL	[7.0, 173.0]	[0.06, 0.51]

The angles: Measuring γ/ϕ_3 (ADS)

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

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

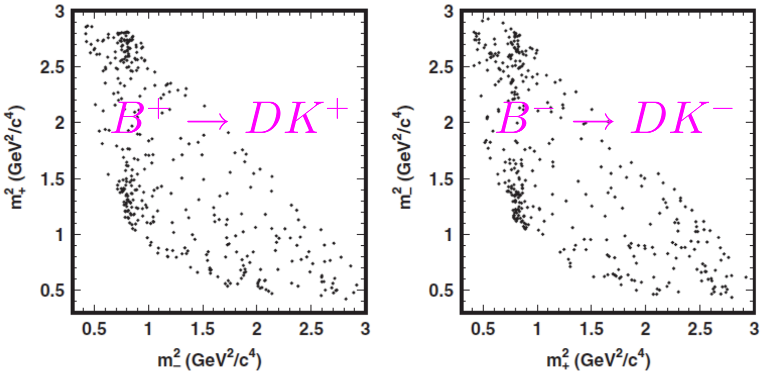


The angles: Measuring γ/ϕ_3 (GGSZ)

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

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

  Dalitz Plot analysis $B \to D^{(*)}K$, $D \to K_S\pi^+\pi^-$ (Cabibbo allowed; large strong phases; need Dalitz plot analysis) $B \to DK \to K_S\pi^+\pi^-$ 657M $B\bar{B}$ $\qquad m_\pm = m(K_S\pi^\pm)$



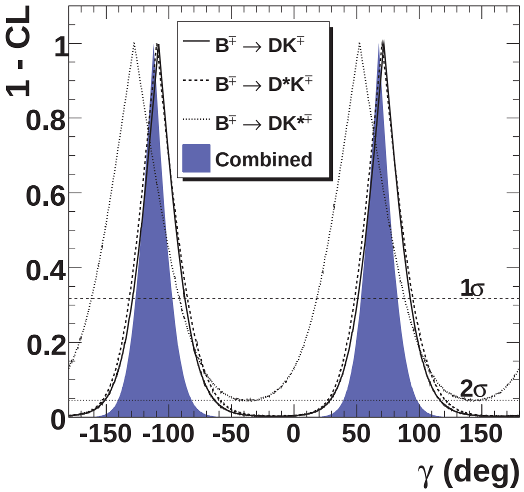
$$\phi_3(\text{mod } 180) = [78.4^{+10.8}_{-11.6} \pm 3.6(\text{syst}) \pm 8.9(\text{model})]^\circ \qquad r_B = \left|\frac{A(b \to u)}{A(b \to c)}\right| = 0.160^{+0.40}_{-0.38}(DK)$$

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

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

  $\gamma(\text{mod } 180) = [68 \pm 14 \pm 4(\text{syst}) \pm 3(\text{model})]^\circ$

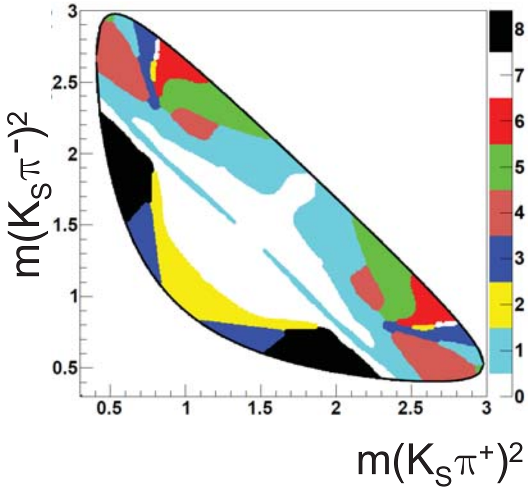
  $r_B = 0.096 \pm 0.029$

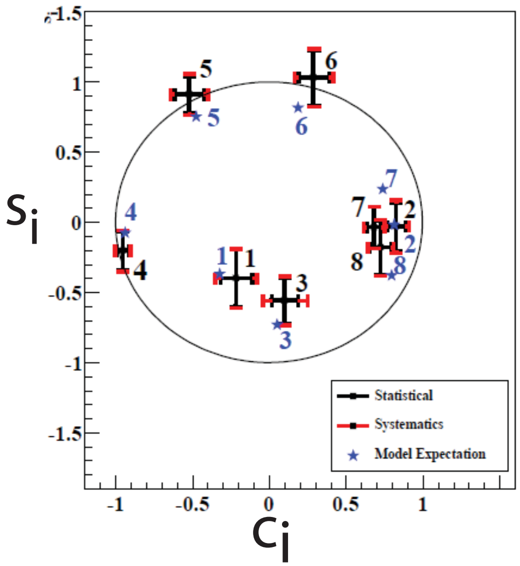


Understanding D decays

We have seen that measuring γ/ϕ_3 is intimately connected with D decays; motivated to understand D decays to reduce model dependence. CLEO-c (Wilkinson, 702) use quantum correlations at $\psi(3770) \to D^0\bar{D}^0$ to measure strong phase differences between $D^0 \to K^0_S\pi^+\pi^-$ and $\overline{D}^0 \to K^0_S\pi^+\pi^-$ (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 $D \to K_S\pi^+\pi^-$ 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

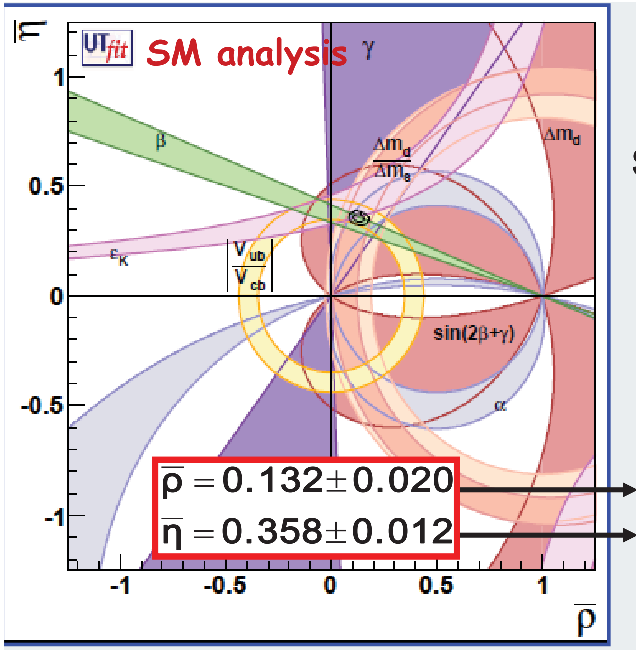


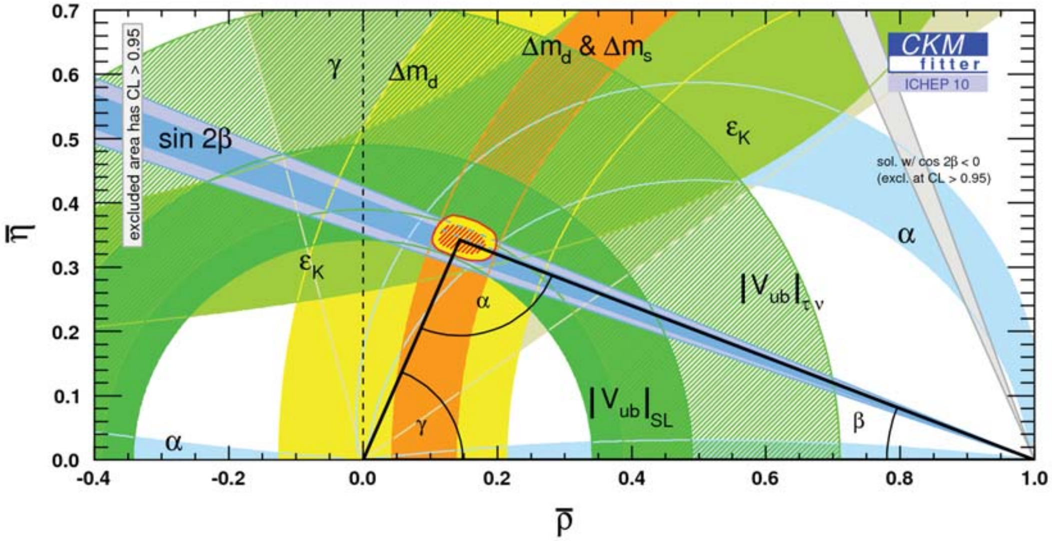


Searches for new physics in CP violation

- 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 $K_S \pi \pi e e$ decays
- CP violation in τ decays
  - Belle (Shapkin, 1093) CP violation in $\tau^\pm \rightarrow K_S \pi^\pm \nu_\tau$

The global fits

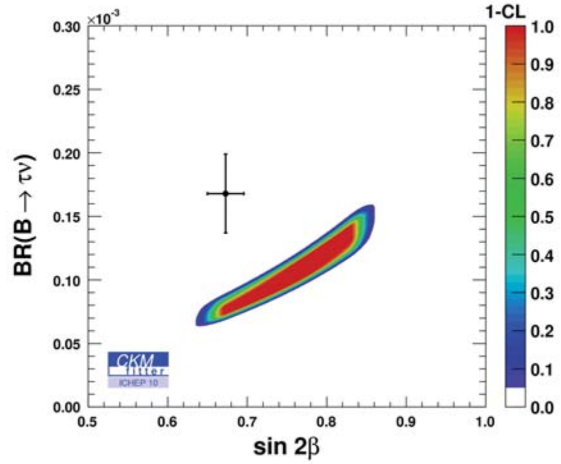


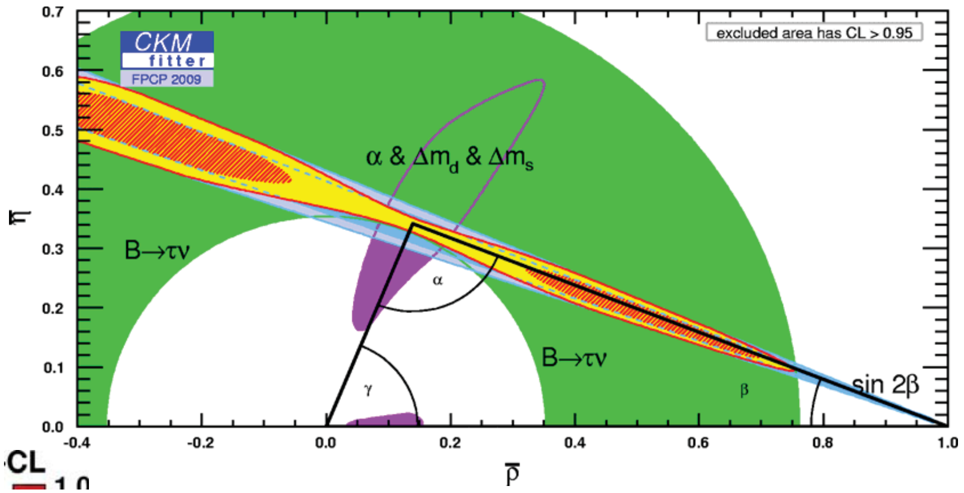


- Both UTfit (Tarantino, 1081) and CKMfitter (T'Jampens, 190) identify $\sin 2\beta$ ($2.6\sigma/2.6\sigma$) and $\mathcal{B}(B \to \tau\nu)$ ($3.2\sigma/2.8\sigma$) as areas of discrepancy.
  – UTfit in addition mentions ϵ_K as discrepant by 1.7σ.
  – Global consistency from CKMfitter at 2σ

Characterizing the discrepancy

- Two-dimensional value of $(\sin 2\beta, \mathcal{B}(B \to \tau\nu))$ in conflict with B_{B_d}, α, γ constraints.



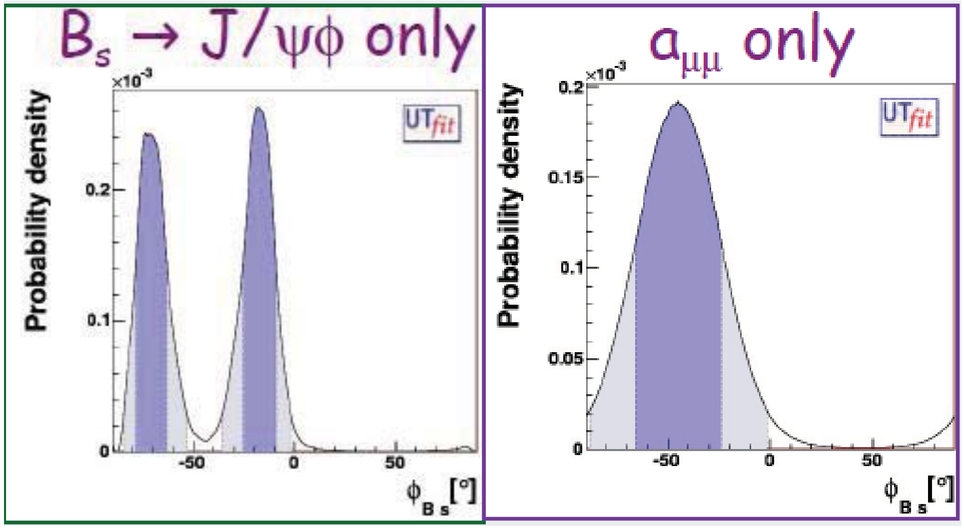


- What is it? Could be…
  - Measurement error
  - Lattice error
  - New physics

See also (Soni, 908)

The B_s sector

UTfit with new D0 results (awaiting CDF likelihood), 3.1σ from SM in ϕ_{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 × 3 unitarity, SM)

	CKMfitter, ICHEP10	UTfit, ICHEP10
A	$0.812^{+0.013}_{-0.027}$	
λ	0.22543 ± 0.00077	
$\bar{\rho}$	0.144 ± 0.025	0.132 ± 0.020
$\bar{\eta}$	$0.342^{+0.016}_{-0.015}$	0.358 ± 0.012
$\alpha(^\circ)$	91.0 ± 3.9	
$\sin 2\beta$	$0.689^{+0.023}_{-0.021}$	
$\gamma(^\circ)$	67.2 ± 3.9	

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

- Some "2σ" hints
- τ 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]