

V_{cb} and V_{ub} CKM Matrix Elements

OMITTED FROM SUMMARY TABLE

See the related review(s):
[Semileptonic \$B\$ Hadron Decays, Determination of \$V_{cb}\$ and \$V_{ub}\$](#)

V_{cb} MEASUREMENTS

For the discussion of V_{cb} measurements, which is not repeated here, see the review on “Determination of $|V_{cb}|$ and $|V_{ub}|$.”

The CKM matrix element $|V_{cb}|$ can be determined by studying the rate of the semileptonic decay $B \rightarrow D^{(*)} \ell \nu$ as a function of the recoil kinematics of $D^{(*)}$ mesons. Taking advantage of theoretical constraints on the normalization and a linear ω dependence of the form factors ($F(\omega)$, $G(\omega)$) provided by Heavy Quark Effective Theory (HQET), the $|V_{cb}| \times F(\omega)$ and ρ^2 can be simultaneously extracted from data, where ω is the scalar product of the two-meson four velocities, $F(1)$ is the form factor at zero recoil ($\omega=1$) and ρ^2 is the slope. Using the theoretical input of $F(1)$, a value of $|V_{cb}|$ can be obtained.

$|V_{cb}| \times F(1)$ (from $B^0 \rightarrow D^{*-} \ell^+ \nu$)

VALUE (units 10^{-2})	DOCUMENT ID	TECN	COMMENT
3.522±0.037 OUR EVALUATION (Produced by HFLAV) with $\rho^2=1.139 \pm 0.020$ and a correlation 0.268. The fitted χ^2 is 63.2 for 27 degrees of freedom.			
3.62 ±0.05 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.			
3.66 ±0.05	¹ PRIM	24	BELL $e^+ e^- \rightarrow \Upsilon(4S)$
3.676±0.028±0.086	² ADACHI	23J	BEL2 $e^+ e^- \rightarrow \Upsilon(4S)$
3.506±0.015±0.056	³ WAHEED	21	BELL $e^+ e^- \rightarrow \Upsilon(4S)$
3.59 ±0.02 ±0.12	⁴ AUBERT	09A	BABR $e^+ e^- \rightarrow \Upsilon(4S)$
3.92 ±0.18 ±0.23	⁵ ABDALLAH	04D	DLPH $e^+ e^- \rightarrow Z^0$
4.31 ±0.13 ±0.18	⁶ ADAM	03	CLE2 $e^+ e^- \rightarrow \Upsilon(4S)$
3.55 ±0.14 ^{+0.23} _{−0.24}	⁷ ABREU	01H	DLPH $e^+ e^- \rightarrow Z$
3.71 ±0.10 ±0.20	⁸ ABBIENDI	00Q	OPAL $e^+ e^- \rightarrow Z$
3.19 ±0.18 ±0.19	⁹ BUSKULIC	97	ALEP $e^+ e^- \rightarrow Z$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
3.64 ±0.09	¹⁰ PRIM	23	BELL $e^+ e^- \rightarrow \Upsilon(4S)$, Repl. by PRIM 24
3.483±0.015±0.056	³ WAHEED	19	BELL Repl. by WAHEED 21
3.46 ±0.02 ±0.10	¹¹ DUNGEL	10	BELL Rep. by WAHEED 19
3.59 ±0.06 ±0.14	¹² AUBERT	08AT	BABR Repl. by AUBERT 09A
3.44 ±0.03 ±0.11	¹³ AUBERT	08R	BABR Repl. by AUBERT 09A
3.55 ±0.03 ±0.16	¹⁴ AUBERT	05E	BABR Repl. by AUBERT 08R
3.77 ±0.11 ±0.19	¹⁵ ABDALLAH	04D	DLPH $e^+ e^- \rightarrow Z^0$

3.54 ± 0.19 ± 0.18	¹⁶ ABE	02F	BELL	Repl. by DUNGEL 10
4.31 ± 0.13 ± 0.18	¹⁷ BRIERE	02	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
3.28 ± 0.19 ± 0.22	ACKERSTAFF	97G	OPAL	Repl. by ABBIENDI 00Q
3.50 ± 0.19 ± 0.23	¹⁸ ABREU	96P	DLPH	Repl. by ABREU 01H
3.51 ± 0.19 ± 0.20	¹⁹ BARISH	95	CLE2	Repl. by ADAM 03
3.14 ± 0.23 ± 0.25	BUSKULIC	95N	ALEP	Repl. by BUSKULIC 97

¹ PRIM 24 value established from a complete set of angular coefficients for exclusive $B \rightarrow \bar{D}^* \ell^+ \nu_\ell$ decays with hadronic tag-side reconstruction. The $|V_{cb}| \times F(1)$ is derived from the extracted the BGL and CNL form factor parameters: $|V_{cb}|_{\text{BGL}} = (40.7 \pm 0.7) \times 10^{-3}$ with the zero-recoil lattice QCD point $F(1) = 0.900 \pm 0.009$ and $|V_{cb}|_{\text{CNL}} = (40.3 \pm 0.6) \times 10^{-3}$.

² ADACHI 23J result comes from differential shapes of exclusive $B \rightarrow D^* \ell^- \nu_\ell$ ($\ell = e$ or μ) decays. Using CNL form factor parametrization and the zero-recoil lattice QCD point $F(1) = 0.906 \pm 0.013$ ADACHI 23J finds $|V_{cb}|_{\text{CNL}} = (40.57 \pm 0.31 \pm 0.95 \pm 0.58) \times 10^{-3}$ where the last uncertainty is due to the prediction of $F(1)$. Also reports a measurement of $|V_{cb}|_{\text{BGL}} = (40.13 \pm 0.27 \pm 0.93 \pm 0.58) \times 10^{-3}$ using BGL form factors parametrization.

³ WAHEED 21 uses fully reconstructed $D^{*-} \ell^+ \nu$ events ($\ell = e$ or μ) and $\eta_{EW} = 1.0066$.

⁴ Obtained from a global fit to $B \rightarrow D^{(*)} \ell \nu_\ell$ events, with reconstructed $D^0 \ell$ and $D^+ \ell$ final states and $\rho^2 = 1.22 \pm 0.02 \pm 0.07$.

⁵ Measurement using fully reconstructed D^* sample with a $\rho^2 = 1.32 \pm 0.15 \pm 0.33$.

⁶ Average of the $B^0 \rightarrow D^*(2010)^- \ell^+ \nu$ and $B^+ \rightarrow \bar{D}^*(2007) \ell^+ \nu$ modes with $\rho^2 = 1.61 \pm 0.09 \pm 0.21$ and $f_{+-} = 0.521 \pm 0.012$.

⁷ ABREU 01H measured using about 5000 partial reconstructed D^* sample with a $\rho^2 = 1.34 \pm 0.14^{+0.24}_{-0.22}$.

⁸ ABBIENDI 00Q: measured using both inclusively and exclusively reconstructed $D^{*\pm}$ samples with a $\rho^2 = 1.21 \pm 0.12 \pm 0.20$. The statistical and systematic correlations between $|V_{cb}| \times F(1)$ and ρ^2 are 0.90 and 0.54 respectively.

⁹ BUSKULIC 97: measured using exclusively reconstructed $D^{*\pm}$ with a $a^2 = 0.31 \pm 0.17 \pm 0.08$. The statistical correlation is 0.92.

¹⁰ Measured from differential shapes of exclusive $B \rightarrow D^* \ell^- \nu_\ell$ decays with hadronic tag-side reconstruction and extracting the CNL and BGL form factor parameters. PRIM 23 finds $|V_{cb}|_{\text{CNL}} = (40.2 \pm 0.9) \times 10^{-3}$ with the zero-recoil lattice QCD point $F(1) = 0.906 \pm 0.013$. PRIM 23 provides also a measurement of $|V_{cb}|_{\text{BGL}} = (40.7 \pm 1.0) \times 10^{-3}$.

¹¹ Uses fully reconstructed $D^{*-} \ell^+ \nu$ events ($\ell = e$ or μ).

¹² Measured using the dependence of $B^- \rightarrow D^{*0} e^- \bar{\nu}_e$ decay differential rate and the form factor description by CAPRINI 98 with $\rho^2 = 1.16 \pm 0.06 \pm 0.08$.

¹³ Measured using fully reconstructed D^* sample and a simultaneous fit to the Caprini-Lellouch-Neubert form factor parameters: $\rho^2 = 1.191 \pm 0.048 \pm 0.028$, $R_1(1) = 1.429 \pm 0.061 \pm 0.044$, and $R_2(1) = 0.827 \pm 0.038 \pm 0.022$.

¹⁴ Measurement using fully reconstructed D^* sample with a $\rho^2 = 1.29 \pm 0.03 \pm 0.27$.

¹⁵ Combines with previous partial reconstructed D^* measurement with a $\rho^2 = 1.39 \pm 0.10 \pm 0.33$.

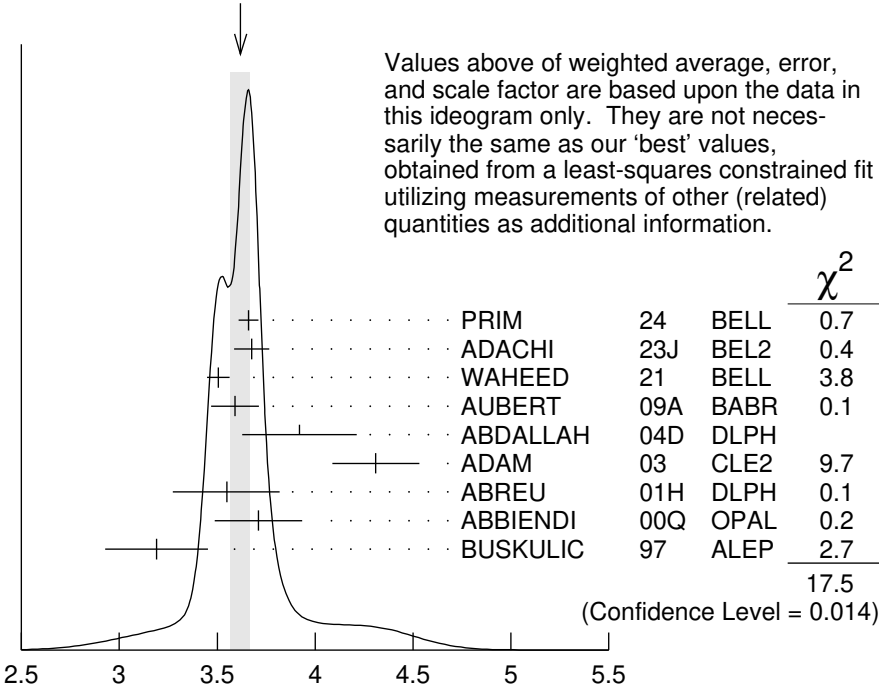
¹⁶ Measured using exclusive $B^0 \rightarrow D^*(892)^- e^+ \nu$ decays with $\rho^2 = 1.35 \pm 0.17 \pm 0.19$ and a correlation of 0.91.

¹⁷ BRIERE 02 result is based on the same analysis and data sample reported in ADAM 03.

¹⁸ ABREU 96P: measured using both inclusively and exclusively reconstructed $D^{*\pm}$ samples.

¹⁹ BARISH 95: measured using both exclusive reconstructed $B^0 \rightarrow D^{*-} \ell^+ \nu$ and $B^+ \rightarrow D^{*0} \ell^+ \nu$ samples. They report their experiment's uncertainties $\pm 0.0019 \pm 0.0018 \pm 0.0008$, where the first error is statistical, the second is systematic, and the third is the uncertainty in the lifetimes. We combine the last two in quadrature.

WEIGHTED AVERAGE
 3.62 ± 0.05 (Error scaled by 1.6)



$|V_{cb}| \times F(1)$ (from $B^0 \rightarrow D^{*-} \ell^+ \nu$)

$|V_{cb}| \times G(1)$ (from $B \rightarrow D^- \ell^+ \nu$)

VALUE (units 10^{-2}) DOCUMENT ID TECN COMMENT
4.121 ± 0.100 OUR EVALUATION (Produced by HFLAV) with $\rho^2 = 1.128 \pm 0.033$ and a correlation 0.747. The fitted χ^2 is 4.8 for 8 degrees of freedom.

4.17 ± 0.08 OUR AVERAGE

4.109 ± 0.116	¹ LEES	24	BABR	$e^+ e^- \rightarrow \Upsilon(4S)$
4.229 ± 0.137	² GLATTAUER	16	BELL	$e^+ e^- \rightarrow \Upsilon(4S)$
4.23 ± 0.19 ± 0.14	³ AUBERT	10	BABR	$e^+ e^- \rightarrow \Upsilon(4S)$
4.31 ± 0.08 ± 0.23	⁴ AUBERT	09A	BABR	$e^+ e^- \rightarrow \Upsilon(4S)$
4.16 ± 0.47 ± 0.37	⁵ BARTELT	99	CLE2	$e^+ e^- \rightarrow \Upsilon(4S)$
2.78 ± 0.68 ± 0.65	⁶ BUSKULIC	97	ALEP	$e^+ e^- \rightarrow Z$

• • • We do not use the following data for averages, fits, limits, etc. • • •

4.11 ± 0.44 ± 0.52	⁷ ABE	02E	BELL	Repl. by GLATTAUER 16
3.37 ± 0.44 ^{+0.72} _{-0.49}	⁸ ATHANAS	97	CLE2	Repl. by BARTELT 99

¹ Obtained from a 2D fit to the combined $B \rightarrow \bar{D} \ell^+ \nu_\ell$ sample with a model-independent parametrization according to Boyd-Grinstein-Lebed (BGL), in which a hadronic decay of the second B meson is fully reconstructed.

² Obtained from a fit to the combined partially reconstructed $B \rightarrow \bar{D} \ell \nu_\ell$ sample while tagged by the other fully reconstructed B meson in the event. Also reports fitted $\rho^2 = 1.09 \pm 0.05$.

³ Obtained from a fit to the combined $B \rightarrow \bar{D} \ell^+ \nu_\ell$ sample in which a hadronic decay of the second B meson is fully reconstructed and $\rho^2 = 1.20 \pm 0.09 \pm 0.04$.

⁴ Obtained from a global fit to $B \rightarrow D^{(*)} \ell \nu_\ell$ events, with reconstructed $D^0 \ell$ and $D^+ \ell$ final states and $\rho^2 = 1.20 \pm 0.04 \pm 0.07$.

- ⁵ BARTELT 99: measured using both exclusive reconstructed $B^0 \rightarrow D^- \ell^+ \nu$ and $B^+ \rightarrow D^0 \ell^+ \nu$ samples.
- ⁶ BUSKULIC 97: measured using exclusively reconstructed D^\pm with a $a^2 = -0.05 \pm 0.53 \pm 0.38$. The statistical correlation is 0.99.
- ⁷ Using the missing energy and momentum to extract kinematic information about the undetected neutrino in the $B^0 \rightarrow D^- \ell^+ \nu$ decay.
- ⁸ ATHANAS 97: measured using both exclusive reconstructed $B^0 \rightarrow D^- \ell^+ \nu$ and $B^+ \rightarrow D^0 \ell^+ \nu$ samples with a $\rho^2 = 0.59 \pm 0.22 \pm 0.12^{+0.59}_{-0}$. They report their experiment's uncertainties $\pm 0.0044 \pm 0.0048^{+0.0053}_{-0.0012}$, where the first error is statistical, the second is systematic, and the third is the uncertainty due to the form factor model variations. We combine the last two in quadrature.

$|V_{cb}|$ (from $D_s^{*-} \mu^+ \nu_\mu$)

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
$41.4 \pm 0.6 \pm 0.9 \pm 1.2$	¹ AAIJ	20E	LHCB pp at 7, 8 TeV

¹ Measured from an inclusive sample of $D_s^- \mu^+$ candidates using CNL parameterization of the form factor. AAIJ 20E provides also measurement of $|V_{cb}| = (42.3 \pm 0.8 \pm 0.9 \pm 1.2) \times 10^{-3}$ using BGL parameterization of the form factor. The third uncertainty is due to the external inputs used in the measurement.

V_{ub} MEASUREMENTS

For the discussion of V_{ub} measurements, which is not repeated here, see the review on "Determination of $|V_{cb}|$ and $|V_{ub}|$."

The CKM matrix element $|V_{ub}|$ can be determined by studying the rate of the charmless semileptonic decay $b \rightarrow u \ell \nu$. The relevant branching ratio measurements based on exclusive and inclusive decays can be found in the *B* Listings, and are not repeated here.

V_{cb} and V_{ub} CKM Matrix Elements REFERENCES

LEES	24	PR D110 032018	J.P. Lees <i>et al.</i>	(BABAR Collab.)
PRIM	24	PRL 133 131801	M.T. Prim <i>et al.</i>	(BELLE Collab.)
ADACHI	23J	PR D108 092013	I. Adachi <i>et al.</i>	(BELLE II Collab.)
PRIM	23	PR D108 012002	M.T. Prim <i>et al.</i>	(BELLE Collab.)
WAHEED	21	PR D103 079901	E. Waheed <i>et al.</i>	(BELLE Collab.)
AAIJ	20E	PR D101 072004	R. Aaij <i>et al.</i>	(LHCb Collab.)
WAHEED	19	PR D100 052007	E. Waheed <i>et al.</i>	(BELLE Collab.)
GLATTAUER	16	PR D93 032006	R. Glattauer <i>et al.</i>	(BELLE Collab.)
AUBERT	10	PRL 104 011802	B. Aubert <i>et al.</i>	(BABAR Collab.)
DUNGEL	10	PR D82 112007	W. Dungel <i>et al.</i>	(BELLE Collab.)
AUBERT	09A	PR D79 012002	B. Aubert <i>et al.</i>	(BABAR Collab.)
AUBERT	08AT	PRL 100 231803	B. Aubert <i>et al.</i>	(BABAR Collab.)
AUBERT	08R	PR D77 032002	B. Aubert <i>et al.</i>	(BABAR Collab.)
AUBERT	05E	PR D71 051502	B. Aubert <i>et al.</i>	(BABAR Collab.)
ABDALLAH	04D	EPJ C33 213	J. Abdallah <i>et al.</i>	(DELPHI Collab.)
ADAM	03	PR D67 032001	N.E. Adam <i>et al.</i>	(CLEO Collab.)
ABE	02E	PL B526 258	K. Abe <i>et al.</i>	(BELLE Collab.)
ABE	02F	PL B526 247	K. Abe <i>et al.</i>	(BELLE Collab.)
BRIERE	02	PRL 89 081803	R. Briere <i>et al.</i>	(CLEO Collab.)
ABREU	01H	PL B510 55	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ABBIENDI	00Q	PL B482 15	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
BARTELT	99	PRL 82 3746	J. Bartelt <i>et al.</i>	(CLEO Collab.)
CAPRINI	98	NP B530 153	I. Caprini, L. Lellouch, M. Neubert	(BCIP, CERN)

ACKERSTAFF	97G	PL B395 128	K. Ackerstaff <i>et al.</i>	(OPAL Collab.)
ATHANAS	97	PRL 79 2208	M. Athanas <i>et al.</i>	(CLEO Collab.)
BUSKULIC	97	PL B395 373	D. Buskulic <i>et al.</i>	(ALEPH Collab.)
ABREU	96P	ZPHY C71 539	P. Abreu <i>et al.</i>	(DELPHI Collab.)
BARISH	95	PR D51 1014	B.C. Barish <i>et al.</i>	(CLEO Collab.)
BUSKULIC	95N	PL B359 236	D. Buskulic <i>et al.</i>	(ALEPH Collab.)
