Update on $|V_{xb}|$ determination

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XIIth Quark Confinement and the Hadron Spectrum

from 28 August 2016 to 4 September 2016
Europe/Athens timezone

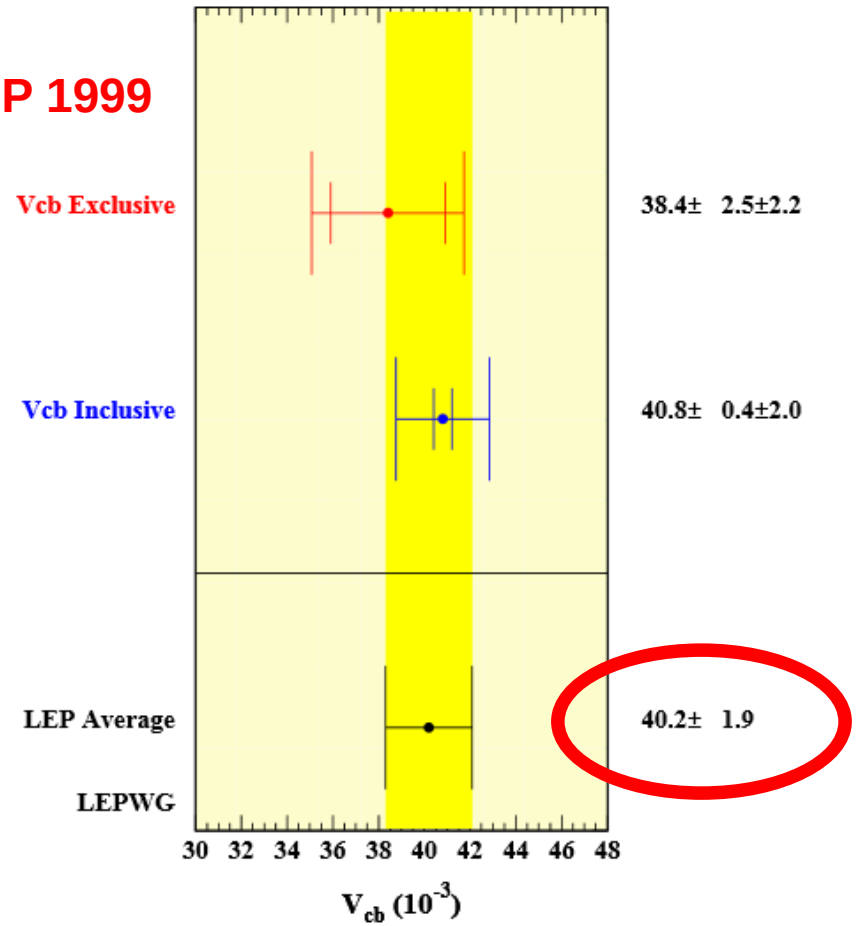
Overview

- Inclusive-exclusive determinations of |Vcb| & |Vub| and related puzzles (see also talk T. Blanke and round table)

- Focus on
- 2016 update & news
- Prospects

Twenty years of CKM refinement

LEP 1999



M. Calvi, Southempton, 1999

Inclusive

$$|V_{ub}| = (4.05^{+0.62}_{-0.74}) \times 10^{-3}$$

latest PDG (nov 2015)

$$|V_{ub}| = (4.09 \pm 0.39) \times 10^{-3} \quad \text{(average)}$$

latest PDG (nov 2015)

$$|V_{cb}| = (40.5 \pm 1.5) \times 10^{-3} \quad \text{(average)}$$

Beauty Factories interlude

Error reduction not The End

Exclusive $|V_{cb}|$ determination

$B \to D^{(*)}\ell\nu$

Massless leptons limit

$$\omega = \frac{p_{D(*)} \cdot p_B}{m_B\, m_{D(*)}}$$

$$\frac{d\Gamma}{d\omega}(B \to D l \nu) = \frac{G_F^2}{48\pi^3}(m_B + m_D)^2 m_D^3 (\omega^2 - 1)^{\frac{3}{2}} |V_{cb}|^2 |\eta_{EW}|^2 |\mathscr{G}(\omega)|^2$$

$$\frac{d\Gamma}{d\omega}(B \to D^* l \nu) = \frac{G_F^2}{48\pi^3}(m_B - m_{D^*})^2 m_{D^*}^3 \chi(\omega)(\omega^2 - 1)^{\frac{1}{2}} |V_{cb}|^2 |\eta_{EW}|^2 |\mathscr{F}(\omega)|^2$$

$$\mathscr{F}(\omega = 1) = 1 + O\left(\frac{1}{m^2}\right) \qquad \mathscr{G}(\omega = 1) = 1 + O\left(\frac{1}{m}\right)$$

Luke's theorem

Exp preferred: less suppressed exp rate and high-order corrections

Non perturbative corrections beyond HM limit ($m = m_b, m_c$)

Lattice

Naively → unless $m_b a \ll 1$ discretization errors out of control and no direct simulation is possible. As of today

$$m_b \sim 1/a$$

Ways out:

- effective theories (HQET, NRQCD) that eliminate high degrees of freedom (systematic expansion in $1/m_b$)

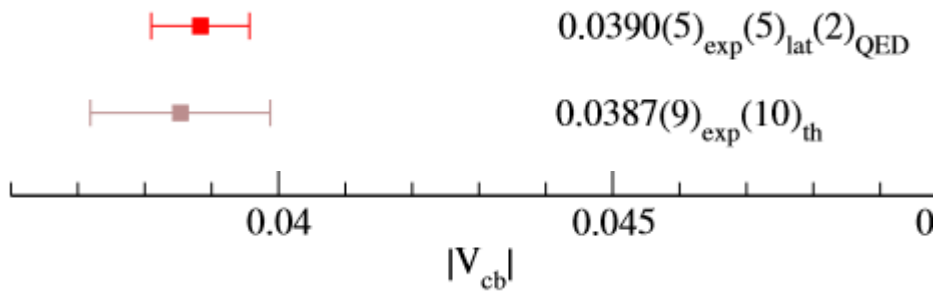
Each approach introduces new source of errors (matching of HQET to QCD, renormalization, control of extrapolation, …).

$B \to D^* \ell \nu$ Lattice: no 2015/16 updates

✓ FNAL/MILC Nf=2+1
Relativistic b-quark
(HQET inspired)

$$\mathcal{F}(1) = 0.906 \pm 0.004 \pm 0.012$$

Same analysis,
higher stats, smaller a, …



PRD 14, 1403.0635

PRD 09 + HFAG data

Bailey, lattice 14

Uncertainty	$\lvert V_{cb}\rvert$
QCD	1.4%
QED	0.5%
Expt	1.3%

Kronfeld 2014

Experimental data taken at non-zero recoil due to kinematic suppression

At this level of precision, important to extend unquenched calculations to non-zero recoil

✓ only quenched results at the non-recoil point
(«step scaling» method)

de Divitiis et al 0707.0582

LCSR

All sum rules based on the general idea of calculating a relevant quark-current correlation function and relating it to the hadronic parameters of interest via a dispersion relation.

- $B \to D^* \ell \nu$ **no further progress**

✓ More recent zero-recoil SR calculations have incorporated higher order effects and an improved estimates of inelastic corrections in the sum rule

$$\mathscr{F}(1) = 0.86 \pm 0.02$$

Gambino, Mannel, Uraltsev, 1206.2296+HFAG 12
Gambino Schwanda 1307.4551

-resulting smaller FF implies higher $|V_{cb}|$ **(closer to inclusive)**

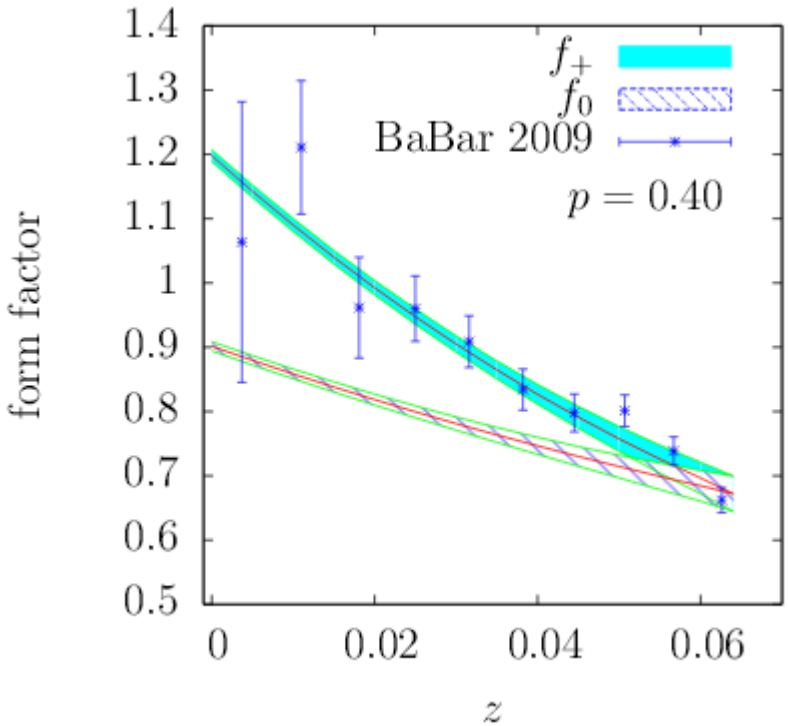
-Much larger th error (More than twice on $|V_{cb}|$)

$B \to D \ell \nu$: 2015

✓ Two new lattice Nf=2+1 calculations at non-zero recoil with massive leptons

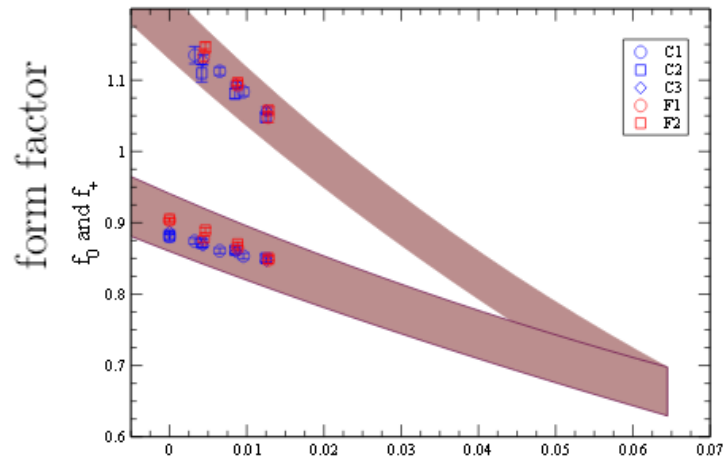
$$|V_{qb}| \langle X | \bar{b} \gamma_\mu q | B^0 \rangle \quad \to \quad f_+(q^2),\ f_0(q^2)$$

1) Fermilab/MILC 1503.07237



form factors calculated for a range of recoil momenta
dependence on momentum transfer parameterized using z -expansion BGL
hep-ph/9412324

2) HPQCD 1505.03925



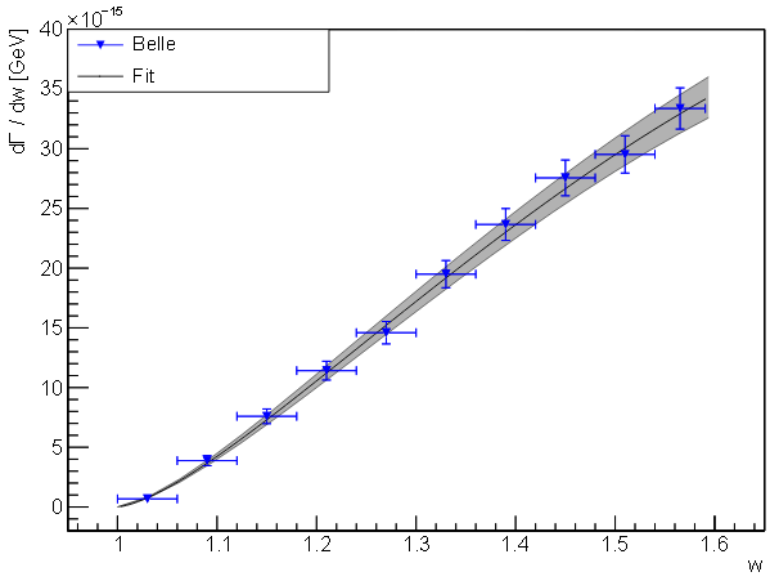
based on NRQCD action for bottom and the HISQ action for charm quarks

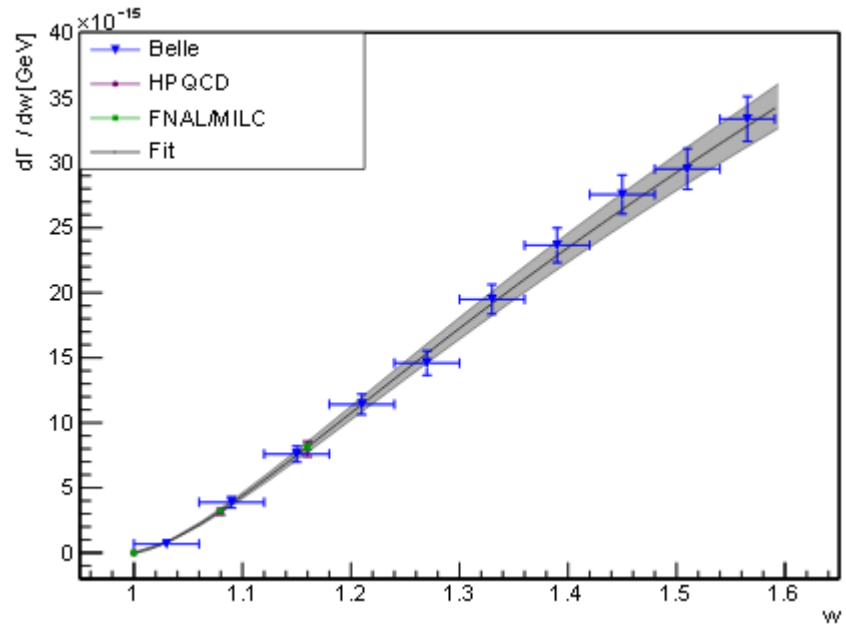
More recent Belle determination 1510.03657

2) BGL parameterization

NPB 461 (1996) 493

$$\mathcal{G}(w) = \frac{\sqrt{4M_D/M_B}}{1+M_D/M_B}\frac{1}{P_i(z)\phi_i(z)}\sum_{n=0}^{N} a_{i,n} z^n$$





$$\mathcal{G}(1) = 1.0541 \pm 0.0083$$

1503.07237

$$\eta_{\rm EW}|V_{cb}| = (40.12 \pm 1.34) \times 10^{-3}$$

Slightly more precise (more lattice input)
1503.07237, 1505.03925

$$\eta_{\rm EW}|V_{cb}| = (41.10 \pm 1.14) \times 10^{-3}$$

Inclusive decays $B \to X_c\, l\, \nu$

HQE for sufficiently inclusive quantities (total width, moments of kinematical distributions) away from perturbative singularities

Double series in α_s and 1/m

$$\Gamma(B \to X_q l \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{qb}|^2 \left[c_3 \langle O_3 \rangle + c_5 \frac{\langle O_5 \rangle}{m_b^2} + c_6 \frac{\langle O_6 \rangle}{m_b^3} + O\left(\frac{\Lambda_{QCD}}{m_b^4}, \frac{\Lambda_{QCD}}{m_b^3 m_c^2} + \ldots \right) \right.$$

$$m_c^2 \sim \Lambda_{\{QCD\}}\, m_b$$

STATUS

- ✓ Completed $O(a_s{}^2)$ corrections

  to leading term (parton model) — Aquila et al 05, Pak et al 08, Biswas et al 10

  to power suppressed coefficients $0(\alpha_s{}^2 \frac{\Lambda^2}{mb^2})$ — Becher et al 07, Alberti et al 12-13, Mannel et al 14

- ✓ Neglecting perturbative corrections, i.e. working at tree level

  computed and estimated up order $O(\frac{1}{m_b^5})$ — Gremm et al 96, Dassinger et al 06, Mannel et al 10, Heinonen et al 14, Gambino et al 16

$|V_{cb}|$ summary

Exclusive most precise →

Error below 2%

Exclusive decays	$\lvert V_{cb}\rvert \times 10^3$
$\bar{B} \to D^* l \bar{\nu}$	
Rome (Lattice quenched $\omega \neq 1$) [15, 16]	$37.4 \pm 0.5_{\rm exp} \pm 0.8_{\rm th}$
FNAL/MILC (Lattice unquenched) [13]	$39.04 \pm 0.49_{\rm exp} \pm 0.53_{\rm latt} \pm 0.19_{\rm QED}$
HFAG (Lattice unquenched) [33, 13]	$38.94 \pm 0.48_{\rm exp} \pm 0.58_{\rm th}$
HFAG (Sum Rules) [17, 18, 34]	$41.6 \pm 0.6_{\rm exp} \pm 1.9_{\rm th}$
$\bar{B} \to D l \bar{\nu}$	
HFAG (Lattice unquenched $\omega = 1$) [33]	$39.45 \pm 1.42_{\rm exp} \pm 0.88_{\rm th}$
FNAL/MILC (Lattice unquenched $\omega \neq 1$) [19]	$39.6 \pm 1.7_{\rm exp+QCD} \pm 0.2_{\rm QED}$
HPQCD (Lattice unquenched $\omega \neq 1$) [26]	$40.2 \pm 1.7_{\rm latt+stat} \pm 1.3_{\rm syst}$
Belle (CLN) [30, 19]	39.86 ± 1.33
Belle (BGL) [30, 19, 26]	40.83 ± 1.13
Global fit [31]	40.49 ± 0.97
Inclusive decays	
HFAG (global fit, kin scheme) [33]	42.46 ± 0.88
Gambino et al. (global fit, kin scheme) [35]	42.11 ± 0.74
Indirect fits	
UTfit [36]	41.70 ± 0.56
CKMfitter (3σ) [37]	$41.80^{+0.97}_{-1.64}$

$|V_{ub}|$ exclusive determination

- Traditionally extracted by the decay $B \to \pi \ell \nu$ (only a single form factor in massless limit)

$$\frac{d\Gamma(\overline{B}^0 \to \pi^+ \ell \bar{\nu})}{dq^2} = \frac{G_F^2 |\vec{p}_\pi|^3}{24\pi^3} |V_{ub}|^2 |f_+(q^2)|^2$$

$$\langle \pi^+(p)|\bar{u}\gamma_\mu b|\bar{B}^0(p+q)\rangle = f_+(q^2)(2p_\mu + q_\mu)$$

Non-pert th predictions for f_+ usually confined to regions of q^2

Exclusive decays	$\lvert V_{ub}\rvert \times 10^3$
$\bar{B} \to \pi l \bar{\nu}_l$	
Fermilab/MILC 2015 [56]	3.72 ± 0.16
RBC/UKQCD 2015 [57]	3.61 ± 0.32
HFAG 2014 (lattice) [50]	3.28 ± 0.29
HFAG 2014 (LCSR) [63, 50]	3.53 ± 0.29
Imsong et al. 2014 (LCSR, Bayes an.) [67]	$3.32^{+0.26}_{-0.22}$
Belle 2013 (lattice + LCSR) [68]	3.52 ± 0.29

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Exclusive decays	$\|V_{ub}\| \times 10^3$
$\bar{B} \to \pi l \bar{\nu}_l$	
FLAG 2016 [65]	3.62 ± 0.14
Fermilab/MILC 2015 [56]	3.72 ± 0.16
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Belle 2013 (lattice + LCSR) [71]	3.52 ± 0.29

Latest lattice determinations higher values

↓

agreement with indirect fits

UTfit	3.63 ± 0.12
CKMfitter (at 3σ)	$3.71^{+0.17}_{-0.20}$

Alpha and HPQCD 2016 new results; Phenomenology not yet there

new exclusive players

$\Lambda^0_b \to p\,\mu\,\nu$

Ratio of relevant form factors

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu\nu)_{q^2>15\ \mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c(\to pK\pi)\mu\nu)_{q^2>7\ \mathrm{GeV}^2}} R_{FF}$$

lattice 2+1 flavors of dynamical domain-wall fermions, RBC & UKQCD Configurations

Detmond, Lehner, Meinel 1503.01421

$$\left|\frac{V_{ub}}{V_{cb}}\right|_{LHCb} = 0.084 \pm 0.006$$

$$\left|V_{cb}^{excl}\right| = (39.5 \pm 0.8) \times 10^{-3}$$

PDG 2014

$$|V_{ub}| = (3.27 \pm 0.23) \times 10^{-3}$$

M. Fiore 15 for LHCB

new exclusive players

$B \to \omega \ell \nu$, $B \to \rho \ell \nu$

2015 LCSR ff computation available-at q^2 <12 GeV +2013Belle(2012 Babar) data

$\bar{B} \to \pi l \bar{\nu}_l$	
Fermilab/MILC 2015 [56]	3.72 ± 0.16
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$\bar{B} \to \omega l \bar{\nu}_l$	
Bharucha et al. 2015 (LCSR) [70]	$3.31 \pm 0.19_{exp} \pm 0.30_{th}$
$\bar{B} \to \rho l \bar{\nu}_l$	
Bharucha et al. 2015 (LCSR) [70]	$3.29 \pm 0.09_{exp} \pm 0.20_{th}$
$\Lambda_b \to p \mu \nu_\mu$	
Rosner 2015 (LHCb, lattice)	$3.50 \pm 0.17_{exp} \pm 0.17_{FF} \pm 0.06_{\lvert V_{cb} \rvert}$

consistently lower, about 10%;

possible S-wave background not separated in exp analysis of $B \to \rho \ell \nu$; estimated 5% change

Meissner, Wang 1311.5420

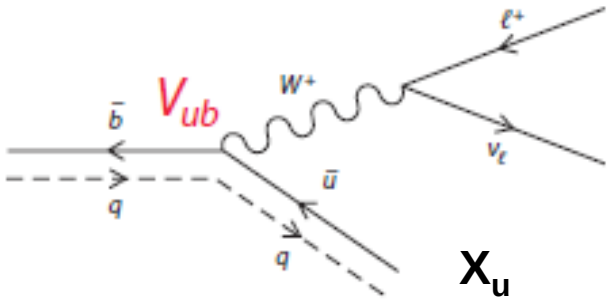
Corrections for the ρ lineshape in $B \to \pi \pi \ell \nu$ experimental distribution

Kang et al. 1312.1193

BSM: Right-handed currents for $B \to \rho \ell \nu$ (data disfavoured)

Bernlochner, Ligeti, Turczyk 1408.2516

Inclusive $|V_{ub}|$



large $b \to c$ background ($|V_{cb}/V_{ub}|^2 \approx 100$)

Need experimental phase space cuts to reduce background; in general

$$m_X \ll E_X$$

Phase space regions where OPE fails become dominant; new unwelcome effects (with respect to semileptonic $b \to c$):

- Final gluon radiation strongly inhibited: soft and collinear singularities
- perturbative expansion of spectra affected by large logarithms

  $$a_s^n \quad \log^{2n}(2\, E_X/m_X)$$

  to be resummed at all orders in PT
- non-perturbative effects related to a small vibration of the b quark in the B meson (Fermi motion) enhanced

- Experimental progress
  - Belle & Babar results access 90% data
- Theoretical approaches
  - predictions based on parameterizations of shape function, and OPE constraints
    - *several cuts* — Bosch, Lange, Neubert , Paz (BLNP), Gambino, Giordano, Ossola, Uraltsev (GGOU)
    - *m_X-q^2 cut* — Bauer, Ligeti, Luke (BLL)
    - *Lepton momentum spectrum* — Leibovich, Low, Rothstein (LLR), Lange, Neubert, Paz (LNP)
    - *global fit* — Ligeti, Stewart, Tackmann
  - predictions based on resummed pQCD

    Andersen, Gardi (DGE),

    Aglietti, Di Lodovico, Ferrera , GR (ADFR)

$|V_{ub}|$ determination status

Exclusive decays	$\lvert V_{ub}\rvert \times 10^3$
$\bar{B} \to \pi l \bar{\nu}_l$	
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$\bar{B} \to \omega l \bar{\nu}_l$	
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$\Lambda_b \to p \mu \nu_\mu$	
Rosner 2015 (LHCb, lattice)	$3.50 \pm 0.17_{\rm exp} \pm 0.17_{\rm FF} \pm 0.06_{\lvert V_{cb}\rvert}$

Long standing tension

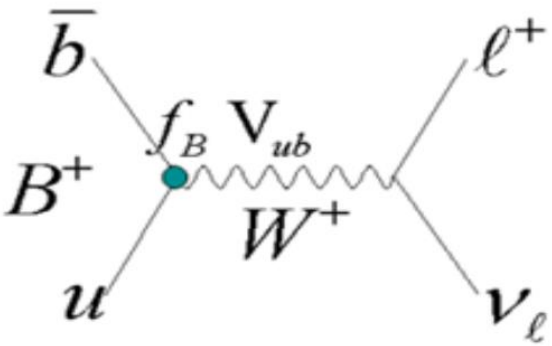
~2-3σ

Babar inclusive average

$$|V_{ub}| = 4.33 \pm 0.24_{\rm exp} \pm 0.15_{\rm th}$$

Inclusive decays ($\lvert V_{ub}\rvert \times 10^3$)	BNLP [96, 97, 98]	GGOU [99]	ADFR [100, 101, 102]	DGE [103]
BaBar [95]	$4.28 \pm 0.24^{+0.18}_{-0.20}$	$4.35 \pm 0.24^{+0.09}_{-0.10}$	$4.29 \pm 0.24^{+0.18}_{-0.19}$	$4.40 \pm 0.24^{+0.12}_{-0.13}$
Belle [94]	$4.47 \pm 0.27^{+0.19}_{-0.21}$	$4.54 \pm 0.27^{+0.10}_{-0.11}$	$4.48 \pm 0.30^{+0.19}_{-0.19}$	$4.60 \pm 0.27^{+0.11}_{-0.13}$
HFAG [50]	$4.45 \pm 0.16^{+0.21}_{-0.22}$	$4.51 \pm 0.16^{+0.12}_{-0.15}$	$4.05 \pm 0.13^{+0.18}_{-0.11}$	$4.52 \pm 0.16^{+0.15}_{-0.16}$

Leptonic decays



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

$\mathcal{B}(B \to e\nu) \sim 10^{-11}$

$\mathcal{B}(B \to \mu\nu) \sim 10^{-7}$

$\mathcal{B}(B \to \tau\nu) \sim 10^{-4}$

Experimental branching fractions consistent with SM

Experiment	Tag	$\mathcal{B}$ (units of 10^{-4})	$\lvert V_{ub}\rvert f_{B^+}$ (MeV)
Belle [197]	Hadronic	$0.72^{+0.27}_{-0.25} \pm 0.11$	
Belle [198]	Semileptonic	$1.25 \pm 0.28 \pm 0.27$	
Belle [198]	Average	0.91 ± 0.22	0.72 ± 0.09
BaBar [199]	Hadronic	$1.83^{+0.53}_{-0.49} \pm 0.24$	
BaBar [200]	Semileptonic	$1.7 \pm 0.8 \pm 0.2$	
BaBar [199]	Average	1.79 ± 0.48	1.01 ± 0.14
Our average		1.06 ± 0.20	0.77 ± 0.07

Still quite large syst errors and background

Several th determination of f_B with lattice or QCD SR

$f_{B^+} = 187.0(2.9)$ MeV

Rosner1509.02220

$$|V_{ub}| = 4.12(37)(6) \times 10^{-3}$$

exp th

1.4σ higher than from baryon decay

Conclusions

- XII QCHS → XII book of odyssey (Ὀδύσσεια)
- "|Vxq| παζλ (puzzle) " → Between Scilla (Σκύλλα) and Cariddi (Χάρυβδις)

Round-table conclusions plus

new exclusive measurements
(B → ρ/ω lν, baryon decays, ecc.)
limited by theory uncertainties

phenomenology from lattice recent results

inclusive benefits: higher statistics, better
b→ c background subtraction, separation
$B^{+,-/0}$ (WA), q^2 tail (duality)…

prospective smaller errors in in experiment
b.f. for leptonic B decays (BelleII)