update on $|\nu_{xb}|$ 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 $|V_{cb}|$ & $|V_{ub}|$ and related puzzles (see also talk T. Blanke and round table)

Focus on

- 2016 update & news
- Prospects
Twenty years of CKM refinement

M. Calvi, Southampton, 1999
Inclusive

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

The End
Exclusive \( V_{cb} \) determination

\[ B \rightarrow D(\ast)\ell\nu \]

Massless leptons limit

\[
\frac{d\Gamma}{d\omega}(B \rightarrow D\ell\nu) = \frac{G_F^2}{48\pi^3} (m_B + m_D)^2 m_D^3 (\omega^2 - 1)^{3/2} |V_{cb}|^2 |\eta_{EW}|^2 |\mathcal{G}(\omega)|^2
\]

\[
\frac{d\Gamma}{d\omega}(B \rightarrow D^*\ell\nu) = \frac{G_F^2}{48\pi^3} (m_B - m_{D^*})^2 m_{D^*}^3 \chi(\omega)(\omega^2 - 1)^{1/2} |V_{cb}|^2 |\eta_{EW}|^2 |\mathcal{F}(\omega)|^2
\]

\[
\mathcal{F}(\omega = 1) = 1 + O\left(\frac{1}{m^2}\right) \quad \mathcal{G}(\omega = 1) = 1 + O\left(\frac{1}{m}\right)
\]

Luke’s theorem

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

Non perturbative corrections beyond HM limit \((m= m_b, m_c)\)
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 → D*ℓν 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 \( a \), ...

| Uncertainty | \( |V_{cb}| \) |
|-------------|---------------|
| 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)

PRD 14, 1403.0635
PRD 09 + HFAG data
Bailey, lattice 14

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

$$F(1) = 0.86 \pm 0.02$$

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

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

Gambino, Mannel, Uraltsev, 1206.2296+HFAG 12
Gambino Schwanda 1307.4551
Two new lattice Nf=2+1 calculations at non-zero recoil with massive leptons

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

1) Fermilab/MILC 1503.07237

2) HPQCD 1505.03925

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

Based on NRQCD action for bottom and the HISQ action for charm quarks
2) BGL parameterization

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

\[ G(1) = 1.0541 \pm 0.0083 \]

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

Slightly more precise (more lattice input)

\[ \eta_{EW}|V_{cb}| = (41.10 \pm 1.14) \times 10^{-3} \]
Inclusive decays $B \to X_c \ell \nu$

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

Double series in $a_s$ and $1/m$

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

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

**STATUS**

✓ Completed $O(a_s^2)$ corrections

  to leading term (parton model)

  to power suppressed coefficients $O(a_s^2 \frac{\Lambda^2}{m_b^2})$

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

  computed and estimated up order $O\left( \frac{1}{m_b^5} \right)$

Aquila et al 05, Pak et al 08, Biswas et al 10

Becher et al 07, Alberti et al 12-13, Mannel et al 14

Gremm et al 96, Dassinger et al 06, Mannel et al 10,
Heinonen et al 14, Gambino et al 16
### $|V_{cb}|$ summary

#### Exclusive decays

| Decay Mode | Theory | $|V_{cb}| \times 10^3$ |
|------------|--------|---------------------|
| $\bar{B} \to D^* l \bar{\nu}$ | Rome (Lattice quenched $\omega \neq 1$) [15, 16] | $37.4 \pm 0.5_{\text{exp}} \pm 0.8_{\text{th}}$ |
| | FNAL/MILC (Lattice unquenched) [13] | $39.04 \pm 0.49_{\text{exp}} \pm 0.53_{\text{latt}} \pm 0.19_{\text{QED}}$ |
| | HFAG (Lattice unquenched) [33, 13] | $38.94 \pm 0.48_{\text{exp}} \pm 0.58_{\text{th}}$ |
| | HFAG (Sum Rules) [17, 18, 34] | $41.6 \pm 0.6_{\text{exp}} \pm 1.9_{\text{th}}$ |
| $\bar{B} \to D l \bar{\nu}$ | HFAG (Lattice unquenched $\omega = 1$) [33] | $39.45 \pm 1.42_{\text{exp}} \pm 0.88_{\text{th}}$ |
| | FNAL/MILC (Lattice unquenched $\omega \neq 1$) [19] | $39.6 \pm 1.7_{\text{exp+QCD}} \pm 0.2_{\text{QED}}$ |
| | HPQCD (Lattice unquenched $\omega \neq 1$) [26] | $40.2 \pm 1.7_{\text{latt+stat}} \pm 1.3_{\text{syst}}$ |
| | Belle (CLN) [30, 19] | $39.86 \pm 1.33$ |
| | Belle (BGL) [30, 19, 26] | $40.83 \pm 1.13$ |
| | Global fit [31] | $40.49 \pm 0.97$ |

#### Inclusive decays

| Decay Mode | Theory | $|V_{cb}| \times 10^3$ |
|------------|--------|---------------------|
| | HFAG (global fit, kin scheme) [33] | $42.46 \pm 0.88$ |
| | Gambino et al. (global fit, kin scheme) [35] | $42.11 \pm 0.74$ |

#### Indirect fits

| Method | $|V_{cb}| \times 10^3$ |
|--------|---------------------|
| UTfit [36] | $41.70 \pm 0.56$ |
| CKMfitter ($3\sigma$) [37] | $41.80^{+0.97}_{-1.64}$ |
|V_{ub}| exclusive determination

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

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

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

Non-perturbative predictions for $f_+$ usually confined to regions of $q^2$

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

Alpha and HPQCD 2016 new results;
Phenomenology not yet there

| UTfit | $3.63 \pm 0.12$ |
| CKMfitter (at 3\sigma) | $3.71_{-0.20}^{+0.17}$ |
new exclusive players

\[ \Lambda^0_b \rightarrow p \mu \nu \]

\[ \frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda^0_b \rightarrow p\mu\nu)_{q^2>15 \text{ GeV}^2}}{\mathcal{B}(\Lambda^0_b \rightarrow \Lambda_c(\rightarrow pK\pi)\mu\nu)_{q^2>7 \text{ GeV}^2}} R_{FF} \]

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

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

Ratio of relevant form factors

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

Detmond, Lehner, Meinel 1503.01421

PDG 2014

\[ |V_{cb}^{excl}| = (39.5 \pm 0.8) \times 10^{-3} \]

M. Fiore 15 for LHCb
new exclusive players

\[ B \rightarrow \omega \ell \nu, B \rightarrow \rho \ell \nu \]

2015 LCSR ff computation available at \( q^2 < 12 \text{ GeV} \)

+2013 Belle (2012 Babar) data

consistently lower, about 10%:

possible S-wave background not separated in exp analysis of \( B \rightarrow \rho \ell \nu \);

estimated 5% change

\[
\begin{array}{l|c}
\hline
\bar{B} \rightarrow \pi \bar{\nu}_\ell \\
\hline
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\hline
\Lambda_b \rightarrow p \nu \nu_\mu \\
\hline
\text{Rosner 2015 (LHCb, lattice)} & 3.50 \pm 0.17_{\text{exp}} \pm 0.17_{\text{FP}} \pm 0.06_{|\nu_\mu|} \\
\end{array}
\]

Corrections for the \( \rho \) lineshape in \( B \rightarrow \pi \pi \ell \nu \) experimental distribution

Kang et al. 1312.1193

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

Bernlochner, Ligeti, Turczyk 1408.2516
Inclusive $|V_{ub}|$

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

$X_u$

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 $b \rightarrow c$):

- Final gluon radiation strongly inhibited: soft and collinear singularities

- Perturbative expansion of spectra affected by large logarithms

\[ a_s^n \log^{2n}(2 E_X/m_X) \]

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)
\[ |V_{ub}| \text{ determination status} \]

### Exclusive decays

\[ |V_{ub}| \times 10^3 \]

\[ \bar{B} \rightarrow \pi l \bar{\nu}_l \]
- Fermilab/MILC 2015 [56] \[3.72 \pm 0.16\]
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\[ \Lambda_b \rightarrow p \mu \bar{\nu}_\mu \]
- Rosner 2015 (LHCb, lattice) \[3.50 \pm 0.17_{\text{exp}} \pm 0.17_{\text{FF}} \pm 0.06_{|V_{cb}|}\]

### Long standing tension

\[ \sim 2-3\sigma \]

### Babar inclusive average

\[ |V_{ub}| = 4.33 \pm 0.24_{\text{exp}} \pm 0.15_{\text{th}} \]

### Inclusive decays \(|V_{ub}| \times 10^3\)

<table>
<thead>
<tr>
<th></th>
<th>BNLP [96, 97, 98]</th>
<th>GGOU [99]</th>
<th>ADFR [100, 101, 102]</th>
<th>DGE [103]</th>
</tr>
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<td>BaBar [95]</td>
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</table>
Leptonic decays

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

Experimental branching fractions consistent with SM

| Experiment | Tag             | \( B \) (units of \(10^{-4} \)) | \( |V_{ub}| f_{B^+} \) (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 \pm 0.22                    | 0.72 \pm 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 \pm 0.48                    | 1.01 \pm 0.14               |
| Our average|                | 1.06 \pm 0.20                    | 0.77 \pm 0.07               |

Still quite large syst errors and background

Several th determination of \(f_B\) with lattice or QCD SR

\[ f_{B^+} = 187.0(2.9) \text{ MeV} \]

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

exp     th  1.4\(\sigma\) higher than from baryon decay

Rosner1509.02220
Conclusions

- XII QCHS → XII book of odyssey (Ὀδύσσεια)
- "|V_{Xq}| 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^+/0/0 (WA), q^2 tail (duality)...

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