

The Role of Theory Input for Exclusive V_{cb} Determinations

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based on work in progress with Dante Bigi and Paolo Gambino
and Phys.Lett. B769 (2017) 441-445 [1703.06124]

Inclusive vs. Exclusive V_{cb}

Status: HFAG V_{cb} averages

[HFAG, 1612.07233v2]

$$|V_{cb}| = (42.19 \pm 0.78) \cdot 10^{-3} \quad \text{from } B \rightarrow X_c l \nu$$

$$|V_{cb}| = (39.05 \pm 0.47_{\text{exp}} \pm 0.58_{\text{th}}) \cdot 10^{-3} \quad \text{from } B \rightarrow D^* l \nu$$

$$|V_{cb}| = (39.18 \pm 0.94_{\text{exp}} \pm 0.36_{\text{th}}) \cdot 10^{-3} \quad \text{from } B \rightarrow D l \nu$$

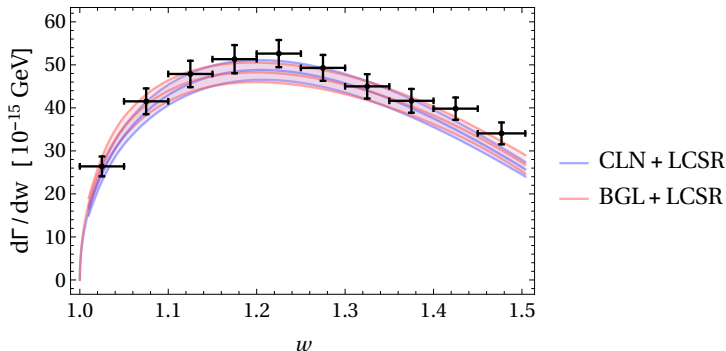
Including latest Belle results

[Bigi Gambino, 1606.08030]

$$|V_{cb}| = (40.49 \pm 0.97) \cdot 10^{-3} \quad \text{from } B \rightarrow D l \nu$$

Belle has new (preliminary) $B \rightarrow D^* l \nu$ data

- First time w and angular **deconvoluted distributions independent** of parametrization.
↳ Possible to use **different parametrizations**.



$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}, \quad q^2 = (p_B - p_{D^*})^2$$

Model independent form factor parametrization

[Boyd Grinstein Lebed (BGL), hep-ph/9412324, hep-ph/9504235, hep-ph/9705252]

Boyd Grinstein Lebed parametrization

$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{\infty} a_n^i z^n,$$
$$z = \frac{\sqrt{1+w} - \sqrt{2}}{\sqrt{1+w} + \sqrt{2}}, \quad w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}.$$

- $0 < z < 0.056$ for $B \rightarrow D^* l \nu \Rightarrow$ truncation at $N = 2$ enough, $z^3 \sim 10^{-4}$.
- $P_i(z)$: “Blaschke factor”: removes poles.
- $\phi_i(z)$: phase space factors.
- Limit of **massless** leptons:
 - 3 form factors g (vector), f and \mathcal{F}_1 (axial vector).
- **Massive** lepton $m_\tau \neq 0$: additional form factor \mathcal{F}_2 (pseudoscalar).

Unitarity Constraints

Use **basic properties** of QCD:

Unitarity, **crossing** symmetry, **analyticity**, dispersion relations.

(Weak) Unitarity Conditions

- **Vector** current:

$$\sum_{i=0}^{\infty} (a_n^g)^2 \leq 1.$$

- **Axial vector** current:

$$\sum_{i=0}^{\infty} \left((a_n^f)^2 + (a_n^{\mathcal{F}_1})^2 \right) \leq 1.$$

Strong Unitarity Constraints and HQET Input

- Use information about further $b \rightarrow c$ channels:

$$B \rightarrow D, B^* \rightarrow D, B^* \rightarrow D^*.$$

↳ Unitarity bounds get **stronger**:

[BGL, hep-ph/9705252]

$$\sum_{i=1}^H \sum_{n=0}^{\infty} b_{in}^2 \leq 1.$$

- Coefficients of other channels can be related to $B \rightarrow D^*$ by **Heavy Quark Effective Theory (HQET)**. [Caprini Lellouch Neubert (CLN), hep-ph/9712417]

Caprini Lellouch Neubert: Use HQET relations between form factors

- **Less** parameters, **slope** of form factor ratios R_i **fixed**.

$$h_{A_1}(w) = h_{A_1}(1) \left(1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3 \right),$$

$$R_1(w) = R_1(1) - 0.12(w - 1) + 0.05(w - 1)^2, \quad \text{HQET: } R_1(1) = 1.27$$

$$R_2(w) = R_2(1) + 0.11(w - 1) - 0.06(w - 1)^2 \quad \text{HQET: } R_2(1) = 0.80$$

Uncertainties on fixed parameters **never included** in exp. analyses.

Different results for V_{cb}

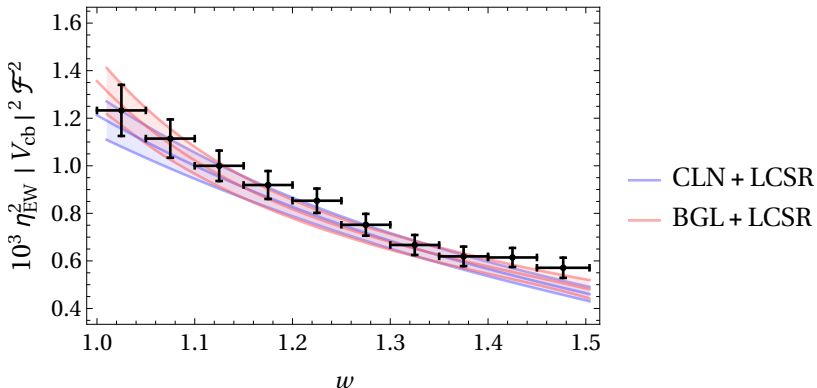
[Bigi Gambino Schacht, 1703.06124, agreeing with Grinstein Kobach, 1703.08170]

BGL Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	27.9/32	31.4/35
$ V_{cb} $	$0.0417 \left(\begin{smallmatrix} +20 \\ -21 \end{smallmatrix} \right)$	$0.0404 \left(\begin{smallmatrix} +16 \\ -17 \end{smallmatrix} \right)$

CLN Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	34.3/36	34.8/39
$ V_{cb} $	$0.0382 (15)$	$0.0382 (14)$

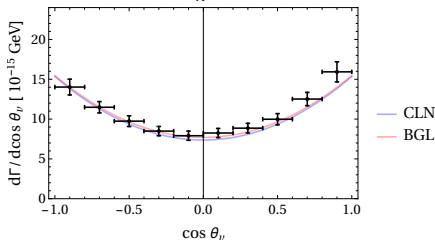
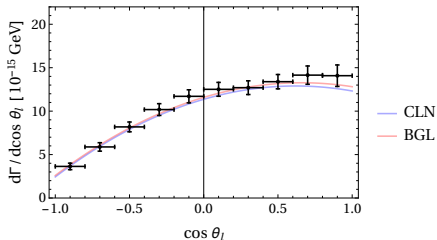
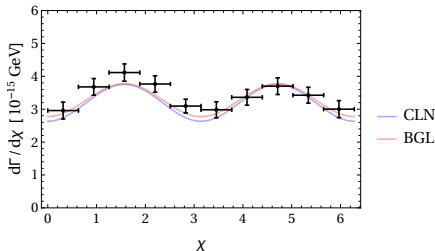
- $|V_{cb}|$ central values deviate by 9% and 6% (with LCSR).
- **LCSR**: Light Cone Sum Rule results [Faller, Khodjamirian, Klein, Mannel 0809.0222]
 $h_{A_1}(w_{\max}) = 0.65(18)$, $R_1(w_{\max}) = 1.32(4)$, $R_2(w_{\max}) = 0.91(17)$.
- **Lattice**: $h_{A_1}(1) = 0.906 \pm 0.013$. [FNAL/MILC 1403.0635]

Fit results for $B \rightarrow D^* l \nu$



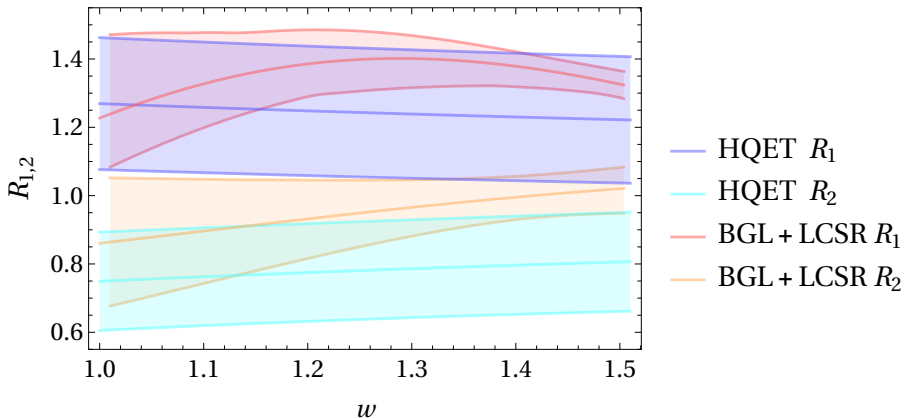
- CLN fit has **limited flexibility** of slope.
↳ CLN band **underestimates** all three **low recoil** points.
- Extrapolation near $w = 1$ **crucial**: Lattice input for V_{cb} extraction.
- CLN fit with free floating $R_{1,2}$ slopes (wo LCSR): $|V_{cb}| = 0.0415(19)$.
- **Intrinsic uncertainties** of CLN fit can no longer be neglected.

Angular Dependence



- Angular bins have **little sensitivity** to low recoil region.
- **Dilute information** of first bins in w spectrum.
- **CLN fit without** angular bins:
 $|V_{cb}| = 0.0409_{-17}^{+16}$.

Comparison to HQET



- BGL fit compatible with HQET within uncertainties.

Future Scenario of Lattice Input

Future lattice fits	χ^2/dof	$ V_{cb} $
CLN	56.4/37	0.0407 (12)
CLN+LCSR	59.3/40	0.0406 (12)
BGL	28.2/33	0.0409 (15)
BGL+LCSR	31.4/36	0.0404 (13)

- Fits including a **hypothetical future lattice** calculation giving

slope information at **5%**: $\left. \frac{\partial \mathcal{F}}{\partial w} \right|_{w=1} = -1.44 \pm 0.07.$

- Additional theory input **stabilizes** the results.

Lepton Flavor Nonuniversality (LNU)

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}l\nu)}$$

- **Combined discrepancy** with SM prediction from literature 4.0σ .
- Possible New Physics scenario: New Scalars, Leptoquarks, W' ,
- Possible connection of LNU in $b \rightarrow c$ and $b \rightarrow s$ transitions.

Status of $R(D^*)$

- **HFAG average** (BaBar, Belle, LHCb): $0.310 \pm 0.015 \pm 0.008$. [1612.07233]
- **SM predictions:**
 - Based on CLN HQET input: 0.252 ± 0.003 . [Fajfer Kamenik Nisandzic, 1203.2654]
 - HQET update: 0.257 ± 0.003 . [Bernlochner Ligeti Papucci Robinson (BLPR), 1703.05330]

$$\text{Anatomy of } R(D^*) \equiv \frac{\int_1^{w_{\tau,\max}} dw d\Gamma_{\tau}/dw}{\int_1^{w_{\max}} dw d\Gamma/dw}$$

Differential decay rate for $B \rightarrow D^* \tau \nu_{\tau}$

[BGL, hep-ph/9705252]

$$\begin{aligned} \frac{d\Gamma_{\tau}}{dw} &= \frac{d\Gamma_{\tau,1}}{dw} + \frac{d\Gamma_{\tau,2}}{dw} \\ \frac{d\Gamma_{\tau,1}}{dw} &= \left(1 - m_{\tau}^2/q^2\right)^2 \left(1 + m_{\tau}^2/(2q^2)\right) \frac{d\Gamma}{dw} \\ \frac{d\Gamma_{\tau,2}}{dw} &= |V_{cb}|^2 m_{\tau}^2 \times \text{kinematics} \times \mathcal{F}_2(z)^2 \end{aligned}$$

- $d\Gamma/dw$: **Measured** differential decay rate of $B \rightarrow D^* l \nu$ with $m_l = 0$, depends on axial vector form factors f , \mathcal{F}_1 and vector form factor g .
- \mathcal{F}_2 : Additional **unconstrained** pseudoscalar **form factor**.
- $d\Gamma_{\tau,2}/dw$ contributes $\sim 10\%$ to $R(D^*)$.
- Common normalization/notation:

$$R_0 = m_{D^*} \left(\frac{1+w}{1+m_{D^*}/m_B} \right) \frac{\mathcal{F}_2}{f} = 1 \quad \text{in heavy quark limit} \quad [\text{BGL, hep-ph/9705252}]$$

Predicting $R_0(w)$

HQET at $O(\Lambda/m_{c,b})$

[recent update: Bernlochner Ligeti Papucci Robinson (BLPR), 1703.05330,

Neubert, Phys. Lett. B264 (1991) 455; hep-ph/9408290, hep-ph/9306320]

$R_0(w)$ given as a function of sum rule parameters.

$$\eta(1) = 0.62 \pm 0.02 \quad \eta'(1) = 0 \pm 0.2 \quad \hat{\chi}_2(1) = -0.06 \pm 0.02$$

How large could higher order corrections beyond $O(\Lambda/m_{c,b}, \alpha_s)$ be?

Rough dimensional analysis:

$$\Lambda^2/m_c^2 \sim 10\% \quad \alpha_s(m_c)^2 \sim 16\% \quad \alpha_s(m_c)\Lambda/m_c \sim 12\%$$

Comparison of HQET and Lattice QCD Results:

Form factor ratios at $w = 1$ show deviations up to $\sim 12\%$.

➡ For prediction of $R(D^*)$ vary $R_0(w)$ in a band of 12%.

Overview on Sources of Uncertainty

preliminary results

- Our analysis leads to a **central value** $R(D^*) = 0.258$.
↳ Very good agreement to [BLPR, 1703.05330].

Error due to **experimental** error of measurement of $B \rightarrow D^* l \nu$.

$$\delta R(D^*) = 0.005$$

Theory error due to **sum rule** parameters.

$$\delta R(D^*) = 0.002$$

Theory error due to **higher order** effects.

$$\delta R(D^*) = \begin{matrix} +0.007 \\ -0.006 \end{matrix}$$

Total Result (Experiment: $0.310 \pm 0.015 \pm 0.008$ (HFAG, [1612.07233]))

$$R(D^*) = 0.258^{+9}_{-8}$$

Conclusions

- Belle has **new data**: Deconvoluted, independent of parametrization.
- Different parametrizations give **different results** for $|V_{cb}|$.
- HQET input **still useful**, but carries **non-negligible uncertainty**.
- $R(D^*)$ depends to an amount of $\sim 10\%$ on the unconstrained form factor \mathcal{F}_2 , which has to be **estimated by theory**.
↳ **No lattice** calculation available, use **HQET** input from BLPR.
- Our **central value 0.258 agrees** well with the literature.
- We find a **larger uncertainty**, coming from **three sources**:
 - Experimental error in $B \rightarrow D^* l \nu$: **0.005** .
 - Sum rule parameters: **0.002** .
 - Higher order HQET corrections: $\begin{matrix} +0.007 \\ -0.006 \end{matrix}$.
- The **anomaly is persistent**.

[numbers: preliminary results]