Recent results from charged-current semileptonic B decays at LHCb

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Table of contents

1 Introduction

2 Measurement of $|V_{cb}|$ with $B^0_s \rightarrow D_s^{(*)-} \mu^+ \nu_\mu$ decays

3 Measurement of the shape of the $B^0_s \rightarrow D_s^- \mu^+ \nu_\mu$ differential distribution

4 Conclusions and prospects
Introduction
Motivation

- Precisely measure CPV in quark sector & test CKM unitarity (New Physics?)
- long-standing discrepancy between inclusive and exclusive measurements:
  \[ |V_{cb}|^{\text{incl}} = (42.19 \pm 0.78) \times 10^{-3} \]
  \[ |V_{cb}|^{\text{excl}} = (39.25 \pm 0.56) \times 10^{-3} \]
  \[ \approx 3\sigma \text{ tension} \]

Analyses covered in this talk:

- Measurement of \(|V_{cb}|\) with \(B^0_s \rightarrow D_s^{(*)-}\mu^+\nu_\mu\) decays
- Measurement of the shape of the \(B^0_s \rightarrow D_s^{*-}\mu^+\nu_\mu\) differential distribution
Measurement of $|V_{cb}|$ with $B_s^0 \rightarrow D_s^{(*)-} \mu^+ \nu_\mu$ decays
- $\bar{b} \rightarrow \bar{c} \ell^+ \nu_\ell$ transitions: cleanest probe for $|V_{cb}|$
- So far $|V_{cb}|$ has been measured with $B^0$ and $B^+$ decays
- Extending the study to $B^0_s$ decays might shed light on the discrepancy
- Advantages:
  - **Theoretically**: better precision in Lattice QCD (heavy spectator quark)
  - **Experimentally**: less contamination from $D_{s}^{**}$ feeddown

\[
\frac{d^4\Gamma(B_{(s)} \rightarrow D_{(s)}^* \mu \nu)}{dw \, d\cos \theta_\mu \, d\cos \theta_D \, d\chi} = \frac{3m_B^3 m_D^2 G_F^2}{16(4\pi)^4} \eta_{EW} |V_{cb}|^2 |A(w, \theta_\mu, \theta_D, \chi)|^2,
\]

\[
\frac{d\Gamma(B_{(s)} \rightarrow D_{(s)} \mu \nu)}{dw} = \frac{G_F^2 m_D^3}{48\pi^3} (m_B + m_D)^2 \eta_{EW} |V_{cb}|^2 (w^2 - 1)^{3/2} |G(w)|^2.
\]
• **Target-1**: Measure $|V_{cb}|$ and form factors of $B_s^0 \to D_s^{(*)-} \to [K^+ K^-] \phi(1020) \pi^-$ $\mu^+ \nu_\mu$ using $B^0 \to D^{(*)-} \to [K^+ K^-] \phi(1020) \pi^-$ $\mu^+ \nu_\mu$ as a normalisation.

• **Target-2** Measure $\mathcal{R}^{(*)} \equiv \frac{\mathcal{B}(B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^{(*)-} \mu^+ \nu_\mu)}$

• **Target-3** Determine $\mathcal{B}(B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu)$

✓ more precise in LQCD

✓ less background than $B^{0,+}$: less contamination from $D_s^{**}$ (only $D_{s1}(2460)^-$ decays to $D_s^- X$)

✓ suppress efficiency biases: same final state and similar kinematics between signal and normalisation

- recoil variable,
  \[ w = v_B \cdot v_{D^*} = (m_B^2 + m_{D^*}^2 - q^2)/(2m_B m_{D^*}) \]
- Use proxy variable: $p_{\perp}(D_{(s)})$ correlated with $w$
Exploiting the corrected mass, $m_{\text{corr}} \equiv \sqrt{m^2(D_s^- \mu^+) + p^2_{\perp}(D_s^- \mu^+) + p_{\perp}(D_s^- \mu^+)}$

**Top:** (left) $B_s^0 \to D_s^- \mu^+ \nu \mu$ and (right) $B_s^0 \to D_s^*^- \mu^+ \nu \mu$

**Bottom:** (left) $B_s^0$ feed-down & doubly-charmed backgrounds, and (right) $B^0$ cross-feed & semitauonic $B_s^0$ decays
Simultaneous least-squares fit to $p_\perp(D_s^+)$ and $m_{\text{corr}}$ for signal (top) and normalisation (bottom) from inclusive $D_s^-(\rightarrow K^+ K^- \pi^-)\mu^+$
\( R(\ast) \) is a free parameter in the fit, exploiting:

\[
N_{\text{sig}}^{(\ast)} = N_{\text{ref}}^{(\ast)} \xi^{(\ast)} K^{(\ast)} \frac{\mathcal{B}(B_s^0 \to D_s^{+(\ast)-} \mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^{(\ast)-} \mu^+\nu_\mu)},
\]

where

\[
K \equiv \frac{f_s}{f_d} \frac{\mathcal{B}(D_s^- \to K^+K^-\pi^-)}{\mathcal{B}(D^- \to K^+K^-\pi^-)},
\]

\[
K^{\ast} \equiv \frac{f_s}{f_d} \frac{\mathcal{B}(D_s^- \to K^+K^-\pi^-)}{\mathcal{B}(D^- \to K^+K^-\pi^-) \mathcal{B}(D^*^- \to D^- X) \mathcal{B}(D^- \to K^+K^-\pi^-)},
\]

Obtaining \( |V_{cb}| \): expand the signal BF and \( |V_{cb}| \) as a free parameter in the fit; use decay rate formula (slide 3)

\[
N_{\text{sig}}^{(\ast)} = \frac{N_{\text{ref}}^{(\ast)} \xi^{(\ast)} K^{(\ast)}}{\mathcal{B}(B^0 \to D^{(\ast)-} \mu^+\nu_\mu)} \tau \int \frac{d\mathcal{G}(B_s^0 \to D_s^{+(\ast)-} \mu^+\nu_\mu)}{d\zeta} d\zeta,
\]

\[
\mathcal{B}(B_s^0 \to D_s^{+(\ast)-} \mu^+\nu_\mu) \mathcal{B}(B^0 \to D^{(\ast)-} \mu^+\nu_\mu) \]
• There are several models (parametrisations) to describe the FF
• **BGL**: the most general; expresses FF with series expansions with arbitrary number of parameters
• **CLN**: the most used in the past; reduces the number of free parameters exploiting more theoretical constraints
• Recent theoretical works: CLN could be problematic at current precision
• → It’s important to test the value of $|V_{cb}|$ obtained against the use of the different parametrisations
• This is done in the most recent results from Belle and BaBar, and it’s done also in this analysis
• See Backup for details on the CLN&BGL formalism
\( \mathcal{B}(B_s^0 \rightarrow D^- \mu^+ \nu_\mu) = (2.49 \pm 0.12 \text{ (stat)} \pm 0.14 \text{ (syst)} \pm 0.16 \text{ (ext)}) \times 10^{-2}, \)

\( \mathcal{B}(B_s^0 \rightarrow D^{*-} \mu^+ \nu_\mu) = (5.38 \pm 0.25 \text{ (stat)} \pm 0.46 \text{ (syst)} \pm 0.30 \text{ (ext)}) \times 10^{-2}, \)

\( |V_{cb}|_{CLN} = (41.4 \pm 0.6 \text{ (stat)} \pm 0.9 \text{ (syst)} \pm 1.2 \text{ (ext)}) \times 10^{-3} \)

\( |V_{cb}|_{BGL} = (42.3 \pm 0.8 \text{ (stat)} \pm 0.9 \text{ (syst)} \pm 1.2 \text{ (ext)}) \times 10^{-3} \)

- CLN and BGL are compatible between each other accounting for their correlation; \( |V_{cb}| \) in agreement with previous excl. & incl. determinations

- Uncertainty dominated by external inputs: \( f_s/f_d \), \( B \)'s of \( B^0 \) and \( D_s^- \) decays

- First \( |V_{cb}| \) exclusive determination from hadron collider and from \( B_s^0 \) decay
Measurement of the shape of the $B_s^0 \rightarrow D_s^{*-} \mu^+ \nu_{\mu}$ differential distribution
Motivation: exclusive determination of $|V_{cb}|$ relies heavily on FF determination (esp. near zero-recoil, $w = 0$, i.e. maximum $q^2$ transfer); lack of experimental input; crucial for $R(D_s^*)$

Goal: Measure leading hadronic form factors for the transition $B_s^0 \rightarrow D_s^{*-}$ using $B_s^0 \rightarrow D_s^{*-} \mu^+ \nu_\mu$ decays; determine the differential decay rate in bins of $w$
• Fully reconstruct $D^{*-}_{s} \rightarrow D^{-}_{s} (\rightarrow K^{-} K^{+} \pi^{-}) \gamma$ and match with a $\mu^{+}$
• Neural network used to separate $\gamma$ from $D^{*-}_{s}$ and $\pi^{0}$
• Gauss + power-tail for signal ($D^{*-}_{s}$)
• exponential for background
• $sPlot$ technique to remove combinatorial photons
• Backgrounds: semitauonic $B^{0}_{s}$ decays; double charm; feed-down from excited $D^{+}_{s}$; combinatorial
• Fit (binned max-likelihood) the corrected mass in 7 bins of $w$ and extract the yield; fit efficiency-corrected decay distribution using CLN and BGL param.
• Templates from simulation uncertainties:

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma(p^2)$</th>
<th>$\sigma(a_1^2)$</th>
<th>$\sigma(a_2^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation sample size</td>
<td>0.053</td>
<td>0.036</td>
<td>+0.04</td>
</tr>
<tr>
<td>Sample sizes for efficiencies and corrections</td>
<td>0.020</td>
<td>0.016</td>
<td>+0.02</td>
</tr>
<tr>
<td>SVD unfolding regularisation</td>
<td>0.008</td>
<td>0.004</td>
<td>-0.16</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>0.004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulation FF parametrisation</td>
<td>0.007</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Kinematic weights</td>
<td>0.024</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>Hardware-trigger efficiency</td>
<td>0.001</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>Software-trigger efficiency</td>
<td>0.004</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>$D^-_s$ selection efficiency</td>
<td>0.002</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>$D^-_s$ weights</td>
<td>0.002</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td>External parameters in fit</td>
<td>0.024</td>
<td>0.002</td>
<td>0.04</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>0.068</td>
<td>0.046</td>
<td>+0.06</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.052</td>
<td>0.034</td>
<td>+0.05</td>
</tr>
</tbody>
</table>
• Leading FF using CLN and BGL 
  parametrisations: CLN:
  \( \rho^2 = 1.16 \pm 0.05 \) (stat) \( \pm 0.07 \) (syst) 
  BGL:
  \( a_1^f = -0.002 \pm 0.034 \) (stat) \( \pm 0.046 \) (syst) 
  BGL: \( a_2^f = 0.93^{+0.05}_{-0.20} \) (stat) \( ^{+0.06}_{-0.38} \) (syst) 

• Both results within 1\( \sigma \) from HFLAV, as 
  expected by SU(3) symmetry between \( B^0 \) and \( B^0_s \) 

• Result consistent with parametrisations 
  from just discussed \( \textbf{PhysRevD.101.072004} \) 

• Uncertainties dominated by systematics, 
  mostly due to the simulation statistics 

• First unfolded normalised differential 
  rate as a function of the recoil 
  parameter
Conclusions and prospects
Conclusions and prospects

- Two recent papers from LHCb on the exclusive $|V_{cb}|$, form factors and the shape of the $B_s^0 \rightarrow D_s^{*+} \mu^- \bar{\nu}_\mu$ differential distribution in the recoil variable $w$
- For the first time $|V_{cb}|$ at hadron collider and first time with $B_s^0$
- $|V_{cb}|$ compatible with both exclusive and inclusive measurements
- CLN and BGL parametrisations give compatible results for (i) $|V_{cb}|$ and (ii) the differential distributions in $w$
- Similar techniques can be used for other b-hadrons:
  “Measurement of $|V_{cb}|$ with $B^0 \rightarrow D^*- \mu^+ \nu_\mu$ decays at LHCb” ongoing
Backup
Definition of angles

\[ \theta, \phi, \mu, \nu, W, B, \pi, \gamma, D, D^*, \theta_\mu, \theta_D \]
Formalism for $B \rightarrow D^* \mu \nu$ decays

$$\frac{d^4\Gamma(B \rightarrow D^* \mu \nu)}{dw \, d\cos \theta_{\mu} \, d\cos \theta_D \, d\chi} = \frac{3m_B^3 m_{D^*}^2 G_F^2}{16(4\pi)^4} \eta_{EW}^2 |V_{cb}|^2 |A(w, \theta_{\mu}, \theta_D, \chi)|^2,$$

(1)

$$|A(w, \theta_{\mu}, \theta_D, \chi)|^2 = \sum_i \mathcal{H}_i(w) k_i(\theta_{\mu}, \theta_D, \chi),$$

(2)

<table>
<thead>
<tr>
<th>$i$</th>
<th>$\mathcal{H}_i(w)$</th>
<th>$k_i(\theta_{\mu}, \theta_D, \chi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$H^2_+$</td>
<td>$\frac{1}{2}(1 + \cos^2 \theta_D)(1 - \cos \theta_{\mu})^2$</td>
</tr>
<tr>
<td>2</td>
<td>$H^2_-$</td>
<td>$\frac{1}{2}(1 + \cos^2 \theta_D)(1 + \cos \theta_{\mu})^2$</td>
</tr>
<tr>
<td>3</td>
<td>$H^0_0$</td>
<td>$2 \sin^2 \theta_D \sin^2 \theta_{\mu}$</td>
</tr>
<tr>
<td>4</td>
<td>$H^+<em>+ H^-</em>-$</td>
<td>$4 \sin^2 \theta_D \sin^2 \theta_{\mu} \cos 2\chi$</td>
</tr>
<tr>
<td>5</td>
<td>$H^+_0 H^-_0$</td>
<td>$\sin 2\theta_D \sin \theta_{\mu}(1 - \cos \theta_{\mu}) \cos \chi$</td>
</tr>
<tr>
<td>6</td>
<td>$H^-_0 H^+_0$</td>
<td>$-\sin 2\theta_D \sin \theta_{\mu}(1 + \cos \theta_{\mu}) \cos \chi$</td>
</tr>
</tbody>
</table>

$D^* \rightarrow D \gamma$  $D^* \rightarrow D \pi^0$
Formalism of $B_s^0 \rightarrow D_s^{*-} \mu^+ \nu_\mu$ decays

$$\frac{d^4 \Gamma(B_s \rightarrow D_s^{*}(s) \mu \nu)}{dw \, d\cos \theta_\mu \, d\cos \theta_D \, d\chi} = \frac{3 m_B^3 m_{D^*}^2 G_F^2}{16 (4\pi)^4} \eta_{\text{EW}}^2 |V_{cb}|^2 |A(w, \theta_\mu, \theta_D, \chi)|^2,$$

$$|A(w, \theta_\mu, \theta_D, \chi)|^2 = \sum_i H_i(w) k_i(\theta_\mu, \theta_D, \chi),$$

The helicity amplitudes are expressed by three form factors, $h_{A_1}(w)$, $R_1(w)$ and $R_2(w)$:

$$H_{\pm/0}(w) = 2 \sqrt{\frac{m_B m_D^*}{m_B + m_{D^*}}} (1 - r^2)(w + 1)(w^2 - 1)^{1/4} h_{A_1}(w) \tilde{H}_{\pm/0}(w),$$

with $r = m_{D^*}/m_B$ and

$$\tilde{H}_{\pm}(w) = \frac{\sqrt{1 - 2wr + r^2}}{1 - r} \left[ 1 \mp \frac{w - 1}{w + 1} R_1(w) \right],$$

$$\tilde{H}_0(w) = 1 + \left[ (w - 1) \left( 1 - R_2(w) \right) \right] / (1 - r).$$
CLN (Caprini-Lellouch-Neubert) parametrisation uses based on Heavy Quark Effective Theory, dispersion relations, reinforced unitarity bounds

\[
\begin{align*}
    h_{A_1}(w) &= h_{A_1}(1) \left[ 1 - 8 \rho^2 z + (53 \rho^2 - 15)z^2 - (231 \rho^2 - 91)z^3 \right], \\
    R_1(w) &= R_1(1) - 0.12(w - 1) + 0.05(w - 1)^2, \\
    R_2(w) &= R_2(1) - 0.11(w - 1) - 0.06(w - 1)^2,
\end{align*}
\]

where the conformal variable \( z \) is defined as

\[
z = \frac{\sqrt{w + 1} - \sqrt{2}}{\sqrt{w + 1} + \sqrt{2}}.
\]

The form factors depend only on four parameters: \( h_{A_1}(1) \), \( \rho^2 \), \( R_1(1) \) and \( R_2(1) \).
BGL form-factor parametrisations for $B^0_s \rightarrow D^{*-}_s \mu^+ \nu_\mu$

- BGL (Boyd-Grinstein-Lebed) parametrisation follows from more general arguments based on dispersion relations, analyticity, and crossing symmetry
- FFs are written in terms of three functions, $f(w)$, $g(w)$ and $\mathcal{F}_1(w)$:

\[
h_{A1}(w) = \frac{f(w)}{\sqrt{m_B m_{D^*} (1 + w)}},
\]
\[
R_1(w) = (w + 1) m_B m_{D^*} \frac{g(w)}{f(w)},
\]
\[
R_2(w) = \frac{w - r}{w - 1} \frac{\mathcal{F}_1(w)}{m_B (w - 1) f(w)}.
\]

These functions are expanded as convergent power series of $z$ as

\[
f(z) = \frac{1}{P_{1+}(z) \phi_f(z)} \sum_{n=0}^{\infty} b_n z^n,
\]
\[
g(z) = \frac{1}{P_{1-}(z) \phi_g(z)} \sum_{n=0}^{\infty} a_n z^n,
\]
\[
\mathcal{F}_1(z) = \frac{1}{P_{1+}(z) \phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{\infty} c_n z^n.
\]

Parameters: series $a_n$, $b_n$ and $c_n$
CLN & BGL form-factor parametrisations for $B_s^0 \to D_s^- \mu^+ \nu_\mu$.

$$
\frac{d\Gamma(B(s) \to D(s)\mu\nu)}{dw} = \frac{G_F^2 m_D^3}{48\pi^3} (m_B + m_D)^2 \eta_{EW}^2 |V_{cb}|^2 (w^2 - 1)^{3/2} \left| G(w) \right|^2.
$$

**CLN:**

$$
G(z) = G(0) \left[ 1 - 8 \rho^2 z + (51 \rho^2 - 10)z^2 - (252 \rho^2 - 84)z^3 \right].
$$

→ parameters: $G(0)$ and $\rho^2$

**BGL:**

$$
\left| G(z) \right|^2 = \frac{4r}{(1+r)^2} \left| f_+(z) \right|^2,
$$

with $r = m_D/m_B$ and

$$
f_+(z) = \frac{1}{P_{1-}(z)\phi(z)} \sum_{n=0}^{\infty} d_n z^n.
$$

→ parameters: series $d_n$
Differential distributions for (left) $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ and (right) $B_s^0 \rightarrow D_s^{*-} \mu^+ \nu_\mu$

(left) CLN and (right) BGL parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{cb}</td>
</tr>
<tr>
<td>$G(0)$</td>
<td>1.102 ± 0.034 (stat) ± 0.004 (ext)</td>
</tr>
<tr>
<td>$\rho^2(D_s^-)$</td>
<td>1.27 ± 0.05 (stat) ± 0.00 (ext)</td>
</tr>
<tr>
<td>$\rho^2(D_s^{*-})$</td>
<td>1.23 ± 0.17 (stat) ± 0.01 (ext)</td>
</tr>
<tr>
<td>$R_1(1)$</td>
<td>1.34 ± 0.25 (stat) ± 0.02 (ext)</td>
</tr>
<tr>
<td>$R_2(1)$</td>
<td>0.83 ± 0.16 (stat) ± 0.01 (ext)</td>
</tr>
</tbody>
</table>