Recent results from charged-current semileptonic B decays at LHCb

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Introduction

$|V_{cb}|$ and form-factors

Motivation

- Precisely measure CPV in quark sector & test CKM unitarity (New Physics?)
- long-standing discrepancy between *inclusive* and *exclusive* measurements:

$|V_{cb}|^{\mathrm{incl}} = (42.19 \pm 0.78) \times 10^{-3}$

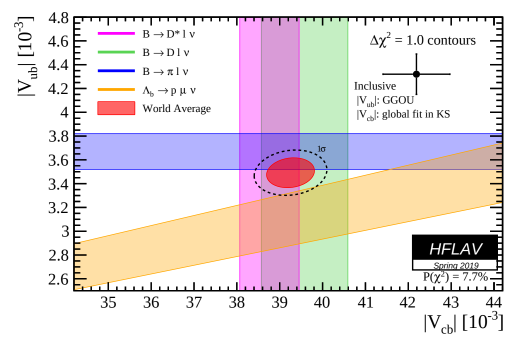
▸ HFLAV Summer '19 incl. Vcb

$|V_{cb}|^{\mathrm{excl}} = (39.25 \pm 0.56) \times 10^{-3}$

▸ HFLAV Summer '19 excl. Vub-Vcb

$\approx 3\sigma$ tension

▸ HFLAV Summer '19 excl. Vub-Vcb



Analyses covered in this talk:

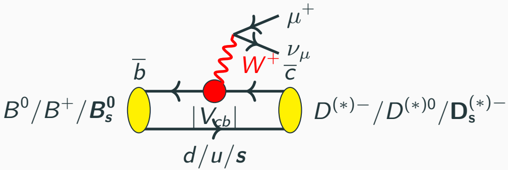
- Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ decays ▸ PhysRevD.101.072004 ▸ arXiv:2001.03225
- Measurement of the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential distribution ▸ arXiv:2003.08453

Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu$ decays

Introduction

PhysRevD.101.072004

- $\overline{b} \to \overline{c}\ell^+\nu_\ell$ transitions: cleanest probe for $|V_{cb}|$
- So far $|V_{cb}|$ has been measured with B^0 and B^+ decays HFLAV Summer '19 excl. Vub-Vcb
- Extending the study to B_s^0 decays might shed light on the discrepancy
- Advantages:
  - Theoretically: better precision in Lattice QCD (heavy spectator quark)
  - Experimentally: less contamination from D_s^{**} feeddown



Target

From form-factors (CLN & BGL)

$$\frac{\mathrm{d}^4\Gamma(B_{(s)} \to D^\star_{(s)}\mu\nu)}{\mathrm{d}w\,\mathrm{d}\cos\theta_\mu\,\mathrm{d}\cos\theta_D\,\mathrm{d}\chi} = \frac{3m_B^3 m_{D^*}^2 G_\mathrm{F}^2}{16(4\pi)^4}\eta_\mathrm{EW}^2 |V_{cb}|^2 |\mathcal{A}(w,\theta_\mu,\theta_D,\chi)|^2,$$

$$\frac{\mathrm{d}\Gamma(B_{(s)} \to D_{(s)}\mu\nu)}{\mathrm{d}w} = \frac{G_\mathrm{F}^2 m_D^3}{48\pi^3}(m_B + m_D)^2\eta_\mathrm{EW}^2 |V_{cb}|^2 (w^2-1)^{3/2}|\mathcal{G}(w)|^2.$$

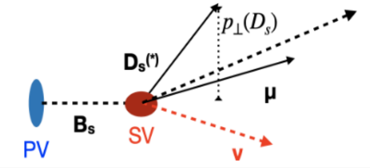
- Target-1: Measure $|V_{cb}|$ and form factors of $B_s^0 \to D_s^{(*)-}(\to [K^+K^-]_{\phi(1020)}\pi^-)\mu^+\nu_\mu$ using $B^0 \to D^{(*)-}(\to [K^+K^-]_{\phi(1020)}\pi^-)\mu^+\nu_\mu$ as a normalisation.
- Target-2 Measure $\mathcal{R}^{(*)} \equiv \frac{\mathcal{B}(B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)}$
- Target-3 Determine $\mathcal{B}(B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu)$

✓ more precise in LQCD

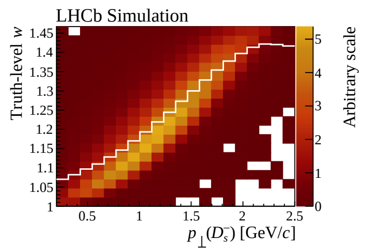
✓ less background than $B^{0,+}$: less contamination from D_s^{**} (only $D_{s1}(2460)^-$ decays to $D_s^{*-}X$)

✓ 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



For $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$:



Selection

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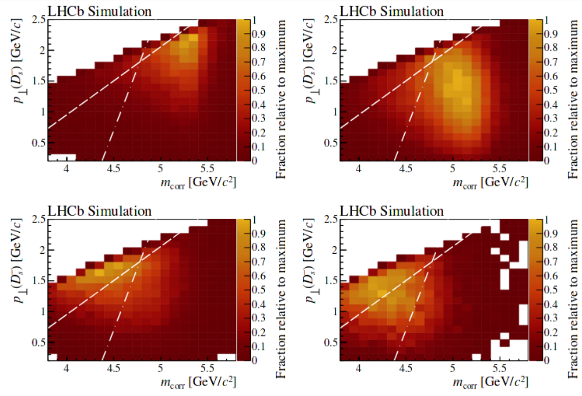
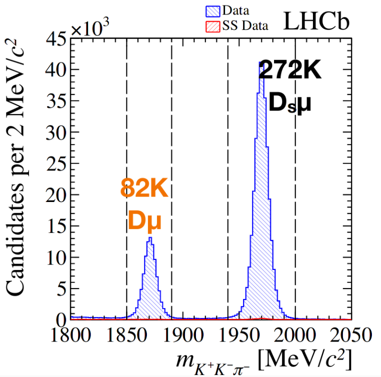
Exploiting the corrected mass, $\mathrm{m_{corr}} \equiv \sqrt{m^2(D_s^- \mu^+) + p_\perp^2(D_s^- \mu^+)} + p_\perp(D_s^- \mu^+)$

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

Signal/normalisation separation



Signal and normalisation fits

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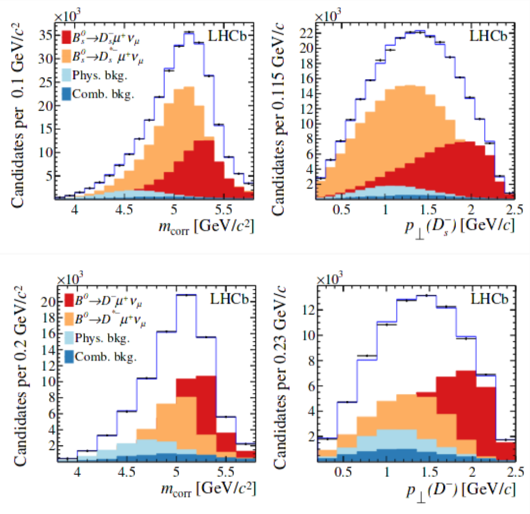
- Simultaneous least-squares fit to $p_{\perp}(D_s^+)$ and $m_{\rm corr}$ for signal (top) and normalisation (bottom) from inclusive $D^-_{(s)}(\to K^+K^-\pi^-)\mu^+$



Obtaining $\mathcal{R}^{(*)}$ and $|V_{cb}|$ ▸ PhysRevD.101.072004

$\mathcal{R}^{(*)}$ is a free parameter in the fit, exploiting:

$$N_{\text{sig}}^{(*)} = N_{\text{ref}}^{(*)}\,\xi^{(*)}\,\mathcal{K}^{(*)}\,\underbrace{\frac{\mathcal{B}(B_s^0 \to D_s^{+(*)-}\mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)}}_{\mathcal{R}^{(*)}},$$

where

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

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

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

$$N_{\text{sig}}^{(*)} = \frac{N_{\text{ref}}^{(*)}\,\xi^{(*)}\,\mathcal{K}^{(*)}}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)}\,\underbrace{\tau\int \frac{\mathrm{d}\Gamma(B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu)}{\mathrm{d}\zeta}\,\mathrm{d}\zeta}_{\mathcal{B}(B_s^0 \to D_s^{+(*)-}\mu^+\nu_\mu)},$$

Form factors (FF)

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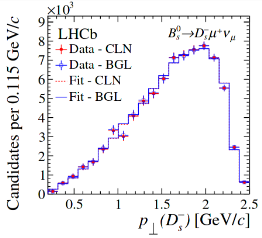
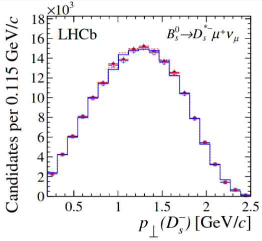
- There are several models (parametrisations) to describe the FF
- **BGL:** the most general; expresses FF with series expansions with arbitrary number of parameters
- **CLN:** the most used in the past; reduces the number of free parameters exploiting more theoretical constraints
- Recent theoretical works: CLN could be problematic at current precision
- $\rightarrow$ 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

CLN & BGL fits to $p_{\perp}(D_s^-)$





Results

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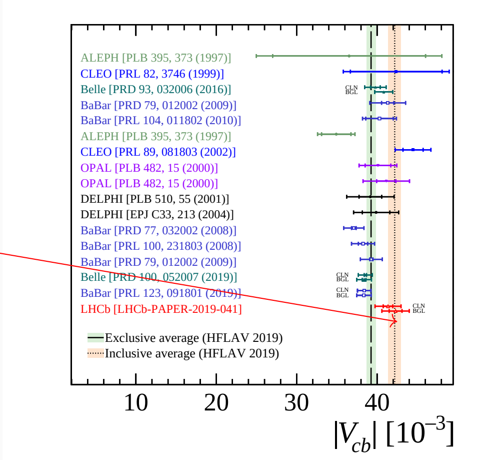
$$\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu) =$$
$$(2.49 \pm 0.12\,(\mathrm{stat}) \pm 0.14\,(\mathrm{syst}) \pm 0.16\ (\mathrm{ext})) \times 10^{-2}\,,$$
$$\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu) =$$
$$(5.38 \pm 0.25\,(\mathrm{stat}) \pm 0.46\,(\mathrm{syst}) \pm 0.30\ (\mathrm{ext})) \times 10^{-2}\,,$$

$$|V_{cb}|_{CLN} =$$
$$(41.4 \pm 0.6\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst}) \pm 1.2\ (\mathrm{ext})) \times 10^{-3}$$
$$|V_{cb}|_{BGL} =$$
$$(42.3 \pm 0.8\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst}) \pm 1.2\ (\mathrm{ext})) \times 10^{-3}$$



- 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, $\mathcal{B}$'s of B^0 and $D_{(s)}^-$ decays
- **First $|V_{cb}|$ exclusive determination from hadron collider and from B_s^0 decay**

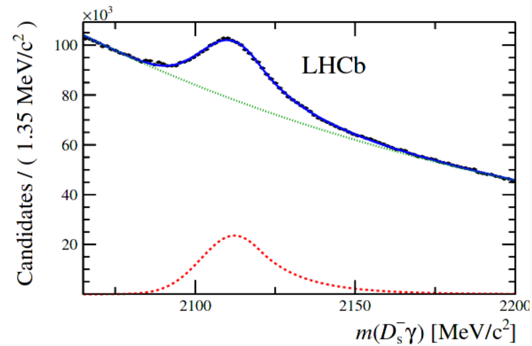
Measurement of the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential distribution

Introduction ▸ arXiv:2003.08453

- 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 $B_s^0 \to D_s^{*-}$ using $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ decays; determine the differential decay rate in bins of w

Selection arXiv:2003.08453

- Fully reconstruct $D_s^{*-} \to D_s^-(\to K^-K^+\pi^-)\gamma$ and match with a μ^+
- Neural network used to separate γ from D_s^{*-} and π^0
- Gauss + power-tail for signal (D_s^{*-})
- exponential for background
- *sPlot* technique to remove combinatorial photons
- Backgrounds: semitauonic B_s^0 decays; double charm; feed-down from excited D_s^+; combinatorial

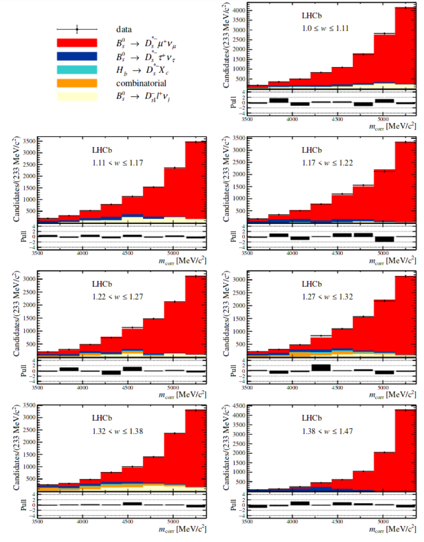


Fit and uncertainties ▸ arXiv:2003.08453

- 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

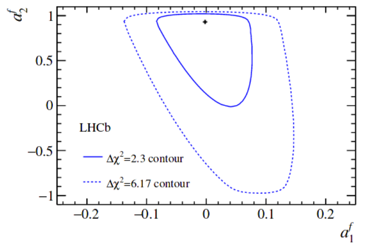
uncertainties:

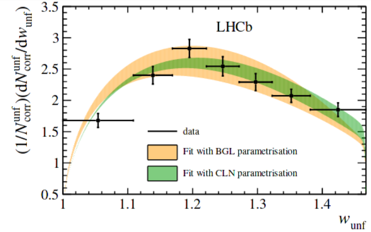
Source	$\sigma(\rho^2)$	$\sigma(a_1^f)$	$\sigma(a_2^f)$
Simulation sample size	0.053	0.036	$^{+0.04}_{-0.35}$
Sample sizes for efficiencies and corrections	0.020	0.016	$^{+0.02}_{-0.16}$
SVD unfolding regularisation	0.008	0.004	–
Radiative corrections	0.004	–	–
Simulation FF parametrisation	0.007	0.005	–
Kinematic weights	0.024	0.013	–
Hardware-trigger efficiency	0.001	0.008	–
Software-trigger efficiency	0.004	0.002	–
D_s^- selection efficiency	–	0.008	–
D_s^{*-} weights	0.002	0.014	–
External parameters in fit	0.024	0.002	0.04
Total systematic uncertainty	0.068	0.046	$^{+0.06}_{-0.38}$
Statistical uncertainty	0.052	0.034	$^{+0.05}_{-0.20}$



Results ▸ arXiv:2003.08453

- Leading FF using CLN and BGL parametrisations: CLN:
  $\rho^2 = 1.16 \pm 0.05\,(\mathrm{stat}) \pm 0.07\,(\mathrm{syst})$
  BGL:
  $a_1^f = -0.002 \pm 0.034\,(\mathrm{stat}) \pm 0.046\,(\mathrm{syst})$
  BGL: $a_2^f = 0.93^{+0.05}_{-0.20}\,(\mathrm{stat})^{+0.06}_{-0.38}\,(\mathrm{syst})$
- Both results within 1σ from HFLAV, as expected by SU(3) symmetry between B^0 and B_s^0
- Result consistent with parametrisations from just discussed ▸ PhysRevD.101.072004
- Uncertainties dominated by systematics, mostly due to the simulation statistics
- **First unfolded normalised differential rate as a function of the recoil**





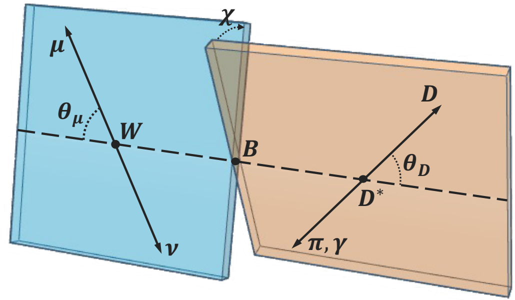
Conclusions and prospects

Conclusions and prospects

- Two recent papers from LHCb on the exclusive $|V_{cb}|$, form factors and the shape of the $B_s^0 \to D_s^{*+} \mu^- \overline{\nu}_\mu$ 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 $B^0 \to D^{*-} \mu^+ \nu_\mu$ decays at LHCb" ongoing

Backup

Definition of angles ▸ PhysRevD.101.072004



Formalism for $B \to D^* \mu\nu$ decays PhysRevD.101.072004

$$\frac{\mathrm{d}^4\Gamma(B \to D^*\mu\nu)}{\mathrm{d}w\,\mathrm{dcos}\,\theta_\mu\,\mathrm{dcos}\,\theta_D\,\mathrm{d}\chi} = \frac{3 m_B^3 m_{D^*}^2 G_\mathrm{F}^2}{16(4\pi)^4}\eta_\mathrm{EW}^2 |V_{cb}|^2 |\mathcal{A}(w,\theta_\mu,\theta_D,\chi)|^2, \tag{1}$$

$$|\mathcal{A}(w,\theta_\mu,\theta_D,\chi)|^2 = \sum_i^6 \mathcal{H}_i(w) k_i(\theta_\mu,\theta_D,\chi), \tag{2}$$

i	$\mathcal{H}_i(w)$	$k_i(\theta_\mu,\theta_D,\chi)$	
		$D^* \to D\gamma$	$D^* \to D\pi^0$
1	H_+^2	$\frac{1}{2}(1+\cos^2\theta_D)(1-\cos\theta_\mu)^2$	$\sin^2\theta_D(1-\cos\theta_\mu)^2$
2	H_-^2	$\frac{1}{2}(1+\cos^2\theta_D)(1+\cos\theta_\mu)^2$	$\sin^2\theta_D(1+\cos\theta_\mu)^2$
3	H_0^2	$2\sin^2\theta_D\sin^2\theta_\mu$	$4\cos^2\theta_D\sin^2\theta_\mu$
4	H_+H_-	$4\sin^2\theta_D\sin^2\theta_\mu\cos 2\chi$	$-2\sin 2\theta_D\sin^2\theta_\mu\cos 2\chi$
5	H_+H_0	$\sin 2\theta_D\sin\theta_\mu(1-\cos\theta_\mu)\cos\chi$	$-2\sin 2\theta_D\sin\theta_\mu(1-\cos\theta_\mu)\cos\chi$
6	H_-H_0	$-\sin 2\theta_D\sin\theta_\mu(1+\cos\theta_\mu)\cos\chi$	$2\sin 2\theta_D\sin\theta_\mu(1+\cos\theta_\mu)\cos\chi$

Formalism of $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ decays ▸ PhysRevD.101.072004

$$\frac{\mathrm{d}^4\Gamma(B_{(s)} \to D^\star_{(s)}\mu\nu)}{\mathrm{d}w\,\mathrm{d}\cos\theta_\mu\,\mathrm{d}\cos\theta_D\,\mathrm{d}\chi} = \frac{3m_B^3 m_{D^*}^2 G_\mathrm{F}^2}{16(4\pi)^4}\eta_\mathrm{EW}^2|V_{cb}|^2|\mathcal{A}(w,\theta_\mu,\theta_D,\chi)|^2,$$

$$|\mathcal{A}(w,\theta_\mu,\theta_D,\chi)|^2 = \sum_i^6 \mathcal{H}_i(w)k_i(\theta_\mu,\theta_D,\chi)\,,$$

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

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

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

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

$$\tilde{H}_0(w) = 1 + \left[(w-1)\left(1 - R_2(w)\right)\right]/(1-r)\,.$$

CLN form-factor parametrisations for $B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$ ▸ PhysRevD.101.072004

CLN (Caprini-Lellouch-Neubert) parametrisation uses based on Heavy Quark Effective Theory, dispersion relations, reinforced unitarity bounds

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

where the conformal variable z is defined as

$$
z \equiv \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}} .
$$

The form factors depend only on **four parameters:** $h_{A_1}(1)$, ρ^2, $R_1(1)$ and $R_2(1)$

BGL form-factor parametrisations for $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$

PhysRevD.101.072004

- 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 $\mathcal{F}_1(w)$:

$$h_{A_1}(w) = \frac{f(w)}{\sqrt{m_B m_{D^*}}(1+w)},$$

$$R_1(w) = (w+1)m_B m_{D^*}\frac{g(w)}{f(w)},$$

$$R_2(w) = \frac{w-r}{w-1} - \frac{\mathcal{F}_1(w)}{m_B(w-1)\,f(w)}.$$

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 $B_s^0 \to D_s^- \mu^+ \nu_\mu$ PhysRevD.101.072004

$$\frac{\mathrm{d}\Gamma(B_{(s)} \to D_{(s)}\mu\nu)}{\mathrm{d}w} = \frac{G_\mathrm{F}^2 m_D^3}{48\pi^3}(m_B + m_D)^2 \eta_\mathrm{EW}^2 |V_{cb}|^2 (w^2 - 1)^{3/2} |\mathcal{G}(w)|^2 .$$

CLN:

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

$\rightarrow$ **parameters:** $\mathcal{G}(0)$ and ρ^2

BGL:

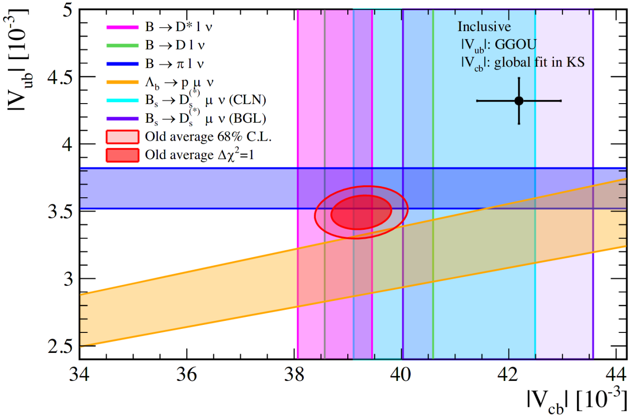
$$|\mathcal{G}(z)|^2 = \frac{4r}{(1+r)^2}|f_+(z)|^2 ,$$

with $r = m_D/m_B$ and

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

$\rightarrow$ **parameters:** series d_n

Zoom onto $|V_{cb}|$ results ▸ PhysRevD.101.072004



CLN and BGL form factors results

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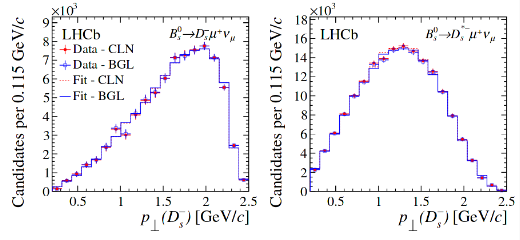
Differential distributions for (left) $B_s^0 \to D_s^- \mu^+ \nu_\mu$ and (right) $B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$



(left) CLN and (right) BGL parameters:

Parameter	Value
$\lvert V_{cb}\rvert$ $[10^{-3}]$	41.4 ± 0.6 (stat) ± 1.2 (ext)
$\mathcal{G}(0)$	1.102 ± 0.034 (stat) ± 0.004 (ext)
$\rho^2(D_s^-)$	1.27 ± 0.05 (stat) ± 0.00 (ext)
$\rho^2(D_s^{*-})$	1.23 ± 0.17 (stat) ± 0.01 (ext)
$R_1(1)$	1.34 ± 0.25 (stat) ± 0.02 (ext)
$R_2(1)$	0.83 ± 0.16 (stat) ± 0.01 (ext)

Parameter	Value
$\lvert V_{cb}\rvert$ $[10^{-3}]$	42.3 ± 0.8 (stat) ± 1.2 (ext)
$\mathcal{G}(0)$	1.097 ± 0.034 (stat) ± 0.001 (ext)
d_1	-0.017 ± 0.007 (stat) ± 0.001 (ext)
d_2	-0.26 ± 0.05 (stat) ± 0.00 (ext)
b_1	-0.06 ± 0.07 (stat) ± 0.01 (ext)
a_0	0.037 ± 0.009 (stat) ± 0.001 (ext)
a_1	0.28 ± 0.26 (stat) ± 0.08 (ext)
c_1	0.0031 ± 0.0022 (stat) ± 0.0006 (ext)