CKM elements measurements with semi-leptonic B decays at LHCb

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Outline

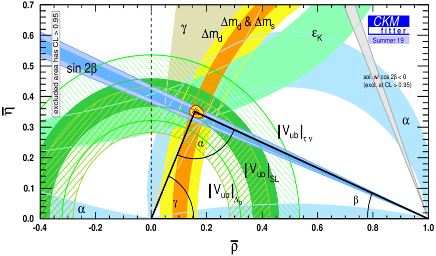
- **$\mathrm{b} \to \mathrm{u}$ decays @ LHCb**
  - $|V_{\mathrm{ub}}|/|V_{\mathrm{cb}}|$ with $\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu$ [Phys. Rev. Lett. 126 (2021) 081804]
- **$\mathrm{b} \to \mathrm{c}$ decays @ LHCb**
  - $|V_{\mathrm{cb}}|$ with $\mathrm{B_s^0} \to \mathrm{D_s^{(*)-}} \mu^+ \nu_\mu$ [Phys. Rev. D101 (2020) 072004])

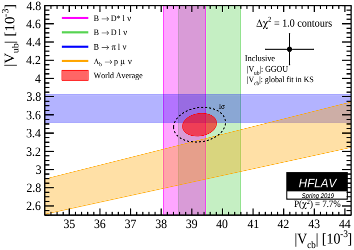
$|V_{\rm ub}|, |V_{\rm cb}|$: introduction

- $|V_{\rm ub}|, |V_{\rm cb}|$: coupling between $\rm b$ and $\rm u$ $(\rm c)$ quarks, fundamental to constrain SM
- Complementary experimental approaches:
    - Inclusive decays: clean, only B-factories, large backgrounds
    - Exclusive decays: theory input, LHCb & B-factories, backgrounds under control
- HFLAV(2019): Combine all exclusive measurements from LHCb, BaBar and Belle:

$$|V_{\rm ub}| = (3.49 \pm 0.13) \times 10^{-3} \quad , \quad |V_{\rm cb}| = (39.25 \pm 0.56) \times 10^{-3}$$

- Inclusive & exclusive measurements are in disagreement ($\sim 3\sigma$)





$|V_{ub}|/|V_{cb}|$ with $B_s^0 \to K^- \mu^+ \nu_\mu$

[Phys. Rev. Lett. 126 (2021) 081804]

$|V_{\mathrm{ub}}|/|V_{\mathrm{cb}}|$ in $\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu$ [Phys. Rev. Lett. 126 (2021) 081804]

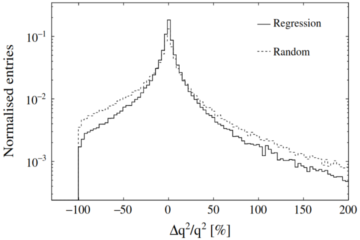
- Measure of BRs ratio of $\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu$ & $\mathrm{B_s^0} \to \mathrm{D_s^-} \mu^+ \nu_\mu$

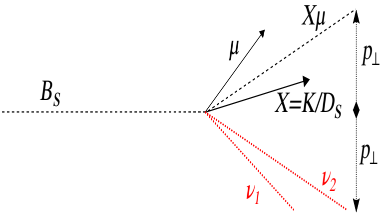
$$\underbrace{\frac{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu)}{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{D_s^-} \mu^+ \nu_\mu)}}_{\textbf{experiment}} = \frac{|V_{\mathrm{ub}}|^2}{|V_{\mathrm{cb}}|^2} \times \underbrace{\frac{\mathrm{d}\Gamma(\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu)/\mathrm{d}q^2}{\mathrm{d}\Gamma(\mathrm{B_s^0} \to \mathrm{D_s^-} \mu^+ \nu_\mu)/\mathrm{d}q^2}}_{\textbf{theory input}}$$

- Convert to $|V_{\mathrm{ub}}|/|V_{\mathrm{cb}}|$: requires calculations of Form Factors
- Theory input: Complementary approaches, decay rates predicted as a function of q^2 ($\mu\nu$ invariant mass)
- Split in two q^2 regions for $\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu$ ($q^2_{\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu} < (>) 7\,\mathrm{GeV}^2$)
  - $\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu$: LCSR(precise at low q^2) & LQCD(precise at high q^2)
  - $\mathrm{B_s^0} \to \mathrm{D_s^-} \mu^+ \nu_\mu$: LQCD(precise over full q^2 spectrum)

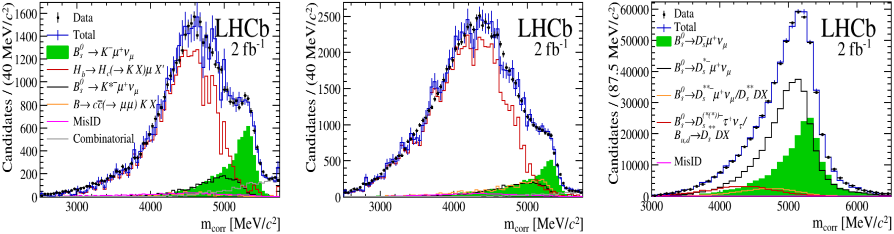
$|V_{ub}|/|V_{cb}|$ @ LHCb: Strategy [Phys. Rev. Lett. 126 (2021) 081804]

- Analysis requires q^2 reconstruction:
  1. Infer P_ν from B^0_s topology $\rightarrow$ two-fold ambiguity
  2. Use linear regression (JHEP 02 (2017) 021) to choose correct P_ν solution
- $B^0_s \rightarrow K^- \mu^+ \nu_\mu$ & $B^0_s \rightarrow D^-_s \mu^+ \nu_\mu$
  - Fit data using "corrected mass"
  - $M_{corr} = \sqrt{M^2_{X\mu} + p^2_\perp} + p_\perp$
- Similar vetoes to select/reconstruct $B^0_s \rightarrow K^- \mu^+ \nu_\mu$& $B^0_s \rightarrow D^-_s \mu^+ \nu_\mu$
  - Use inclusive $D^-_s \rightarrow K^+ K^- \pi^-$ decays





- Binned likelihood fit to $\mathrm{B_s^0}$ corrected mass
- $N_{\mathrm{B_s^0} \to \mathrm{D_s^-} \mu^+ \nu_\mu} = 201450 \pm 5200$
- $N_{\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu (\mathrm{low})} = 6922 \pm 285$
- $N_{\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu (\mathrm{high})} = 6399 \pm 370$



Low q^2 High q^2

Systematics breakdown [Phys. Rev. Lett. 126 (2021) 081804]

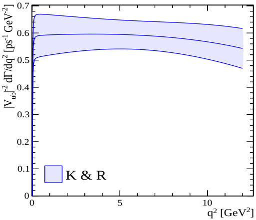
Uncertainty	$\frac{\mathcal{B}(B_s \to K\mu\nu)}{\mathcal{B}(B_s \to D_s\mu\nu)}$ [%]		
	No q^2 sel.	low q^2	high q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle ID	1.0	1.0	1.0
m_{corr} error	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration		2.0	2.0
ε gen& reco	1.2	1.6	1.6
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$	$^{+3.0}_{-3.4}$
Total	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$
$\mathcal{B}(\mathrm{D_s^-} \to \mathrm{K^-K^+\pi^-})$	2.8	2.8	2.8

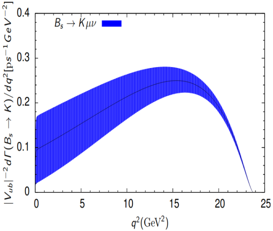
- Similar contribution to systematic budget from fit and ϵ
- Multiple Systematic sources for fit and ϵ are reducible with larger data sets and simulation samples

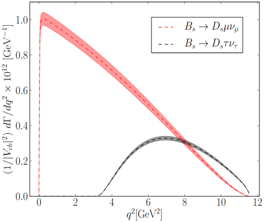
Results: $|V_{ub}|/|V_{cb}|$ ingredients [Phys. Rev. Lett. 126 (2021) 081804]

$$\frac{\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu)_{q^2<7}}{\mathcal{B}(B_s^0 \to D_s^-\mu^+\nu_\mu)_{\text{Full } q^2}} = (1.66 \pm 0.08(\text{stat}) \pm 0.07(\text{syst}) \pm 0.05(D_s)) \times 10^{-3}$$

$$\frac{\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu)_{q^2>7}}{\mathcal{B}(B_s^0 \to D_s^-\mu^+\nu_\mu)_{\text{Full } q^2}} = (3.25 \pm 0.21(\text{stat}) \, {}^{+0.16}_{-0.17}(\text{syst}) \pm 0.09(D_s)) \times 10^{-3}$$





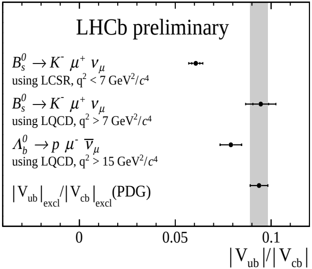


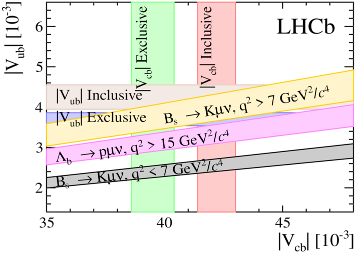
JHEP08(2017)112 Phys. Rev. D 100, 034501 (2019) Phys. Rev. D 101, 074513 (2020)

$$\text{FF}_K = 4.14 \pm 0.38\,\text{ps}^{-1}\,,\ \text{FF}_K = 3.23 \pm 0.46\,\text{ps}^{-1}\,,\ \text{FF}_{D_s} = 9.15 \pm 0.37\,\text{ps}^{-1}$$

Results: $\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)$ [Phys. Rev. Lett. 126 (2021) 081804]

$$\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu) = (1.06 \pm 0.05(\text{stat}) \pm 0.04(\text{syst}) \pm 0.06(\text{ext}) \pm 0.04(\text{FF})) \times 10^{-4}$$
$$|V_{ub}|/|V_{cb}|(\text{low}) = 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008(D_s) \pm 0.0030(\text{FF})$$
$$|V_{ub}|/|V_{cb}|(\text{high}) = 0.0946 \pm 0.0030(\text{stat})^{+0.0024}_{-0.0025}(\text{syst}) \pm 0.0013(D_s) \pm 0.0068(\text{FF})$$





- First observation of the golden channel: $B_s^0 \to K^- \mu^+ \nu_\mu$
- Discrepancy $|V_{ub}|/|V_{cb}|(\text{low})$: clash in theory predictions $\to$ solved when measuring full q^2 shape of $B_s^0 \to K^- \mu^+ \nu_\mu$

$\mathrm{b} \to \mathrm{c}$ transitions @ LHCb

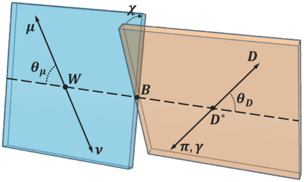
$|V_{\mathrm{cb}}|$ with $\mathrm{B}_{\mathrm{s}}^{0} \to \mathrm{D}_{\mathrm{s}}^{(*)-}\mu^{+}\nu_{\mu}$ [Phys. Rev. D101 (2020) 072004]

$|V_{\rm cb}|$ using $\mathrm{B_s^0} \to \mathrm{D_s^{(*)-}} \mu^+ \nu_\mu$ [Phys. Rev. D101 (2020) 072004]

- Phys. Rev. D101 (2020), $3\,\mathrm{fb}^{-1}$, Run 1 data
- Model the decays with CLN, BGL parametrization to investigate inclusive/exclusive discrepancy
- Using $\mathrm{B}^0 \to \mathrm{D}^{(*)-} \mu^+ \nu_\mu$ as input, exctract $|V_{\rm cb}|$ from:

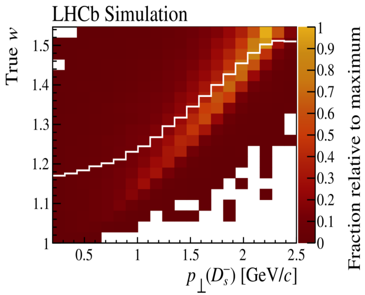
$$\frac{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{D_s^{(*)-}} \mu^+ \nu_\mu)}{\mathcal{B}(\mathrm{B^0} \to \mathrm{D^{(*)-}} \mu^+ \nu_\mu)} \propto \frac{f_s}{f_d} \frac{|V_{\rm cb}|^2 \times A(w, \theta_\mu, \theta_D, \chi)}{\mathcal{B}(\mathrm{B^0} \to \mathrm{D^{(*)-}} \mu^+ \nu_\mu)}$$

- w 4-velocity $(m_{\rm B}^2 + m_{\rm D}^2 - q^2)/(2 m_{\rm B} m_{\rm D})$



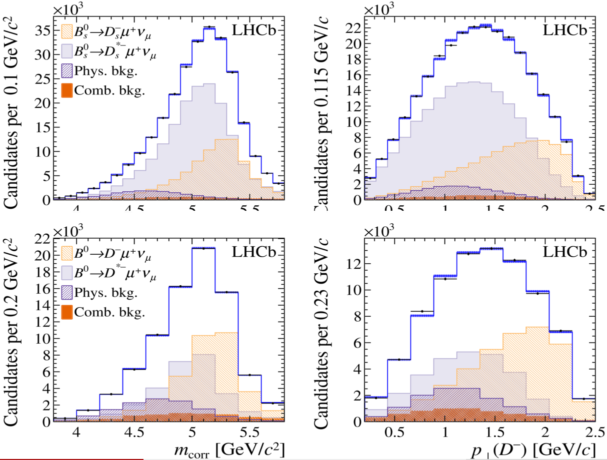
Strategy for $|V_{cb}|$ using $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ [Phys. Rev. D101 (2020) 072004]

- FF are studied using q^2 variable, however need to deal with missing neutrino(as shown before)
- $|V_{cb}|$ analyses at LHCb adopted an alternative strategy w.r.t to other analyses:
  - Use reconstructed variable correlated with q^2
  - D_s Momentum transverse to B_s^0 flight direction $\propto$ form factors
- Fit in corrected mass-$P_\perp(D_s)$: $|V_{cb}|$ is extracted from signal yields, form factors are accessed through $P_\perp(D_s)$



Fit $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ [Phys. Rev. D101 (2020) 072004]

- Perform two sets of χ^2 2D fits using templates from simulation for Signal, normalization and physics background
- CLN and BGL from latest Lattice calculations, left floating in the fit



$|V_{\rm cb}|$ using $B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu$ [Phys. Rev. D101 (2020) 072004]

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)

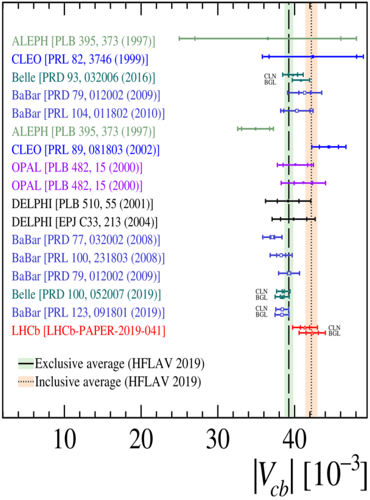
- Compatible extractions of $|V_{\rm cb}|$ using BGL and CLN parametrization
- Measurement of exclusive $\mathcal{B}$ using known $\mathcal{B}(B^0 \to D^{(*)-} \mu^+ \nu_\mu)$:

$$\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu) = (2.49 \pm 0.6(\text{stat}) \pm 0.12(\text{syst}) \pm 0.12(\text{ext})) \times 10^{-2}$$

$$\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu) = (5.38 \pm 0.8(\text{stat}) \pm 0.25(\text{syst}) \pm 0.46(\text{ext})) \times 10^{-2}$$

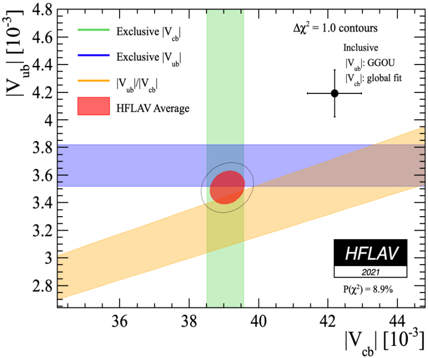
Systematics on $|V_{cb}|$ using $B_s^0 \to D_s^- \mu^+ \nu_\mu$ and $B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$ [Phys. Rev. D101 (2020) 072004]

- $|V_{cb}|$ is compatible with the world average
- External inputs (fs/fd) are the dominant systematics source on $|V_{cb}|$
- Modeling Dalitz plane $D_s^- \to K^+ K^- \pi^-$ is the second dominant source
- Limited knowledge on physical backgrounds



Conclusion

- Measure $|V_{\rm ub}|/|V_{\rm cb}|$ using $\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu$ and $\mathrm{B_s^0} \to \mathrm{D_s^-} \mu^+ \nu_\mu$ in two q^2 regions
  - First measurement of $\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu$ Branching fraction
  - Discrepancy between low and high q^2 regions
- First measurement of $|V_{\rm cb}|$ at hadron collider using $\mathrm{B_s^0}$ semileptonic decays
  - Compatible with exclusive world average of $|V_{\rm cb}|$
- HFLAV 2021: combination of all available exlusive $|V_{\rm ub}|$, $|V_{\rm cb}|$, $|V_{\rm ub}|/V_{\rm cb}|$ measurements
  - Discrepancy of exclusive versus inclusive measurements of $|V_{\rm ub}|$ & $|V_{\rm cb}|$ still hold



Backups

Systematics breakdown

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- Similar contribution to systematic budget from fit and ϵ
- Multiple Systematic sources for fit and ϵ are reducible with larger data sets and simulation samples

Neutrino reconstruction

- Transverse component of the neutrino momentum $p_\perp$ is trivial to calculate
- Longitudinal component $p_\parallel$ is determined up to a two-fold ambiguity with the quadratic equation

$$p_\parallel = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}, \tag{1}$$

$$\begin{aligned} a &= |2p_{\parallel,X\mu} m_{X\mu}|^2, \\ b &= 4p_{\parallel,X\mu}(2p_\perp p_{\parallel,,X\mu} - m^2_{miss}), \\ c &= 4p^2_\perp(p^2_{\parallel,X\mu} + m^2_{\mathrm{B}^0_\mathrm{s}}) - |m^2_{miss}|^2, \\ m^2_{miss} &= m^2_{\mathrm{B}^0_\mathrm{s}} - m^2_{X\mu}. \end{aligned} \tag{2}$$