CKM parameter measurement with semileptonic B_s decays at LHCb

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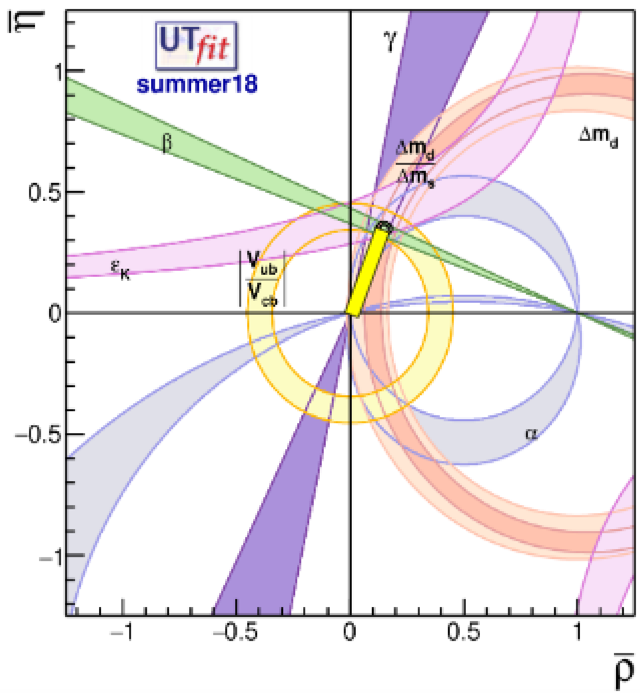
Measurement of $|V_{xb}|$

- The parameters of the CKM matrix must be constrained in order to
  - test the unitarity of the CKM matrix
  - precisely measure the amount of CP violation in the quark sector

  → measurement of observables sensitive to the magnitudes of CKM matrix elements



- Measurements of $|V_{xb}|$ provide a crucial input for indirect searches of New Physics

- Discrepancy between exclusive and inclusive measurements: ≈ 3σ tension

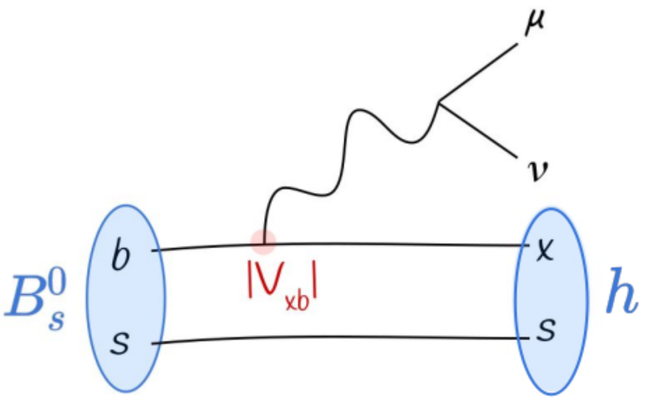
  → new complementary measurements needed

Measurement of $|V_{xb}|$

- $|V_{ub}|$ and $|V_{cb}|$ measurement have been made using the semileptonic *b* hadron decays
  - The contributions to decay rate can be factorized into the weak and strong parts
    → The theoretical calculation are simplified;

$$\frac{d\Gamma(B_s \rightarrow H\, l\, \nu)}{dq^2} \propto G_F^2 |V_{xb}|^2 |f(q^2)|^2$$

  - Experimentally challenging



- Two main ways to measure $|V_{ub}|$ and $|V_{cb}|$:
  - Inclusive decays:
    - $B^+ \rightarrow X_c l\nu, B^0 \rightarrow X_u l\nu$
    - Focus on all final states
    - Need to know QCD correction to parton level decay rate
    - Operator Product Expansion in α_s and $\Lambda_{QCD}/m_{b,c}$ predicts the total rate Γ_c
    - Challenges: background contamination and model of shape functions
  - Exclusive decays (next slide)

Measurement of $|V_{xb}|$

- Exclusive decays:
  - Focus on a single final state
  - Exclusive determinations rely on form factors (FF) to parameterize hadronic current as function of q^2 ($\mu\nu$ invariant mass)
    - Lattice QCD (LQCD) or QCD sum rules
    - Extracted in experimental measurement from data
  - Challenges: possibly small signal yields and knowledge of form factors.
  - Ground state hadrons in the final state are the golden modes for lattice QCD predictions and have the lowest theoretical uncertainties.
  - $B \to D^*/Dl\nu, B \to \pi l\nu$
  - B_s decays are advantageous compared to $B^{0/+}$
    - Easier to calculate in LQCD due to heavier spectator quark → more precise predictions
    - For the $B_s \to D_s^*$: the zero-width approximation of the D_s^* should work better than the B case (no $D\pi$ pollution)

$|V_{xb}|$ Exclusive measurements at LHCb

- First observation of the decay $B_s^0 \to K^-\mu^+\nu$ and a measurement of $|V_{ub}|/|V_{cb}|$
[Phys. Rev. Lett. 126 081804]

- (Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{*-}\mu^+\nu$ decays
[Phys. Rev. D 101 072004])

The strategy

[Phys. Rev. Lett. 126 081804]

- Dataset: pp collision events collected by LHCb experiment during 2012, 2 fb^{-1} @ 8TeV
- Signal: $B_s^0 \to K^- \mu^+ \nu$
- Normalization: $B_s^0 \to D_s^- \mu^+ \nu$ where $D_s \to K^+ K^- \pi^-$
- CKM extraction strategy:

$$\underbrace{\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}}_{\text{Experiment}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \underbrace{\frac{\mathrm{FF}_K}{\mathrm{FF}_{D_s}}}_{\text{Theory}}$$

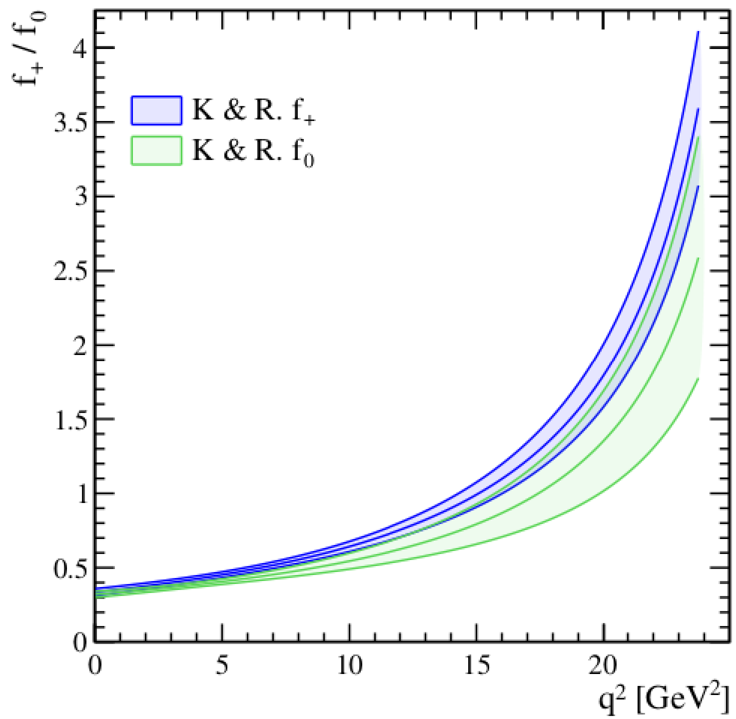
- The $|V_{ub}|/|V_{cb}|$ ratio is derived in two regions of q^2 ($\mu\nu$ invariant mass) to exploit different FF_K calculation method
  - Light cone sum rules (LCSR) @ low q^2 ($q^2 < 7$ GeV^2/c^4)
  - LQCD @ high q^2 ($q^2 > 7$ GeV^2/c^4)
- Normalization mode FF_{Ds} fully described by LQCD [Phys Rev D. 101 074513]

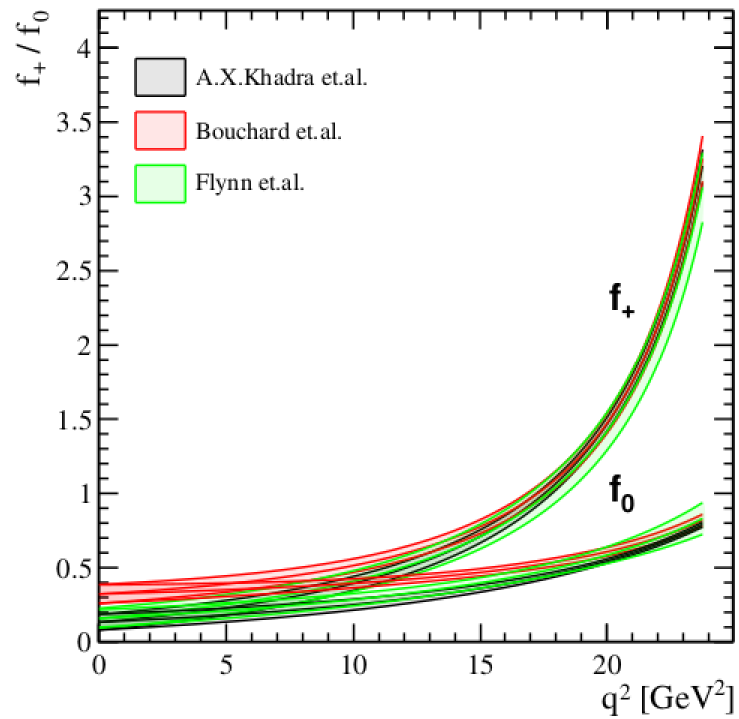
The FF_K

[Phys. Rev. Lett. 126 081804]

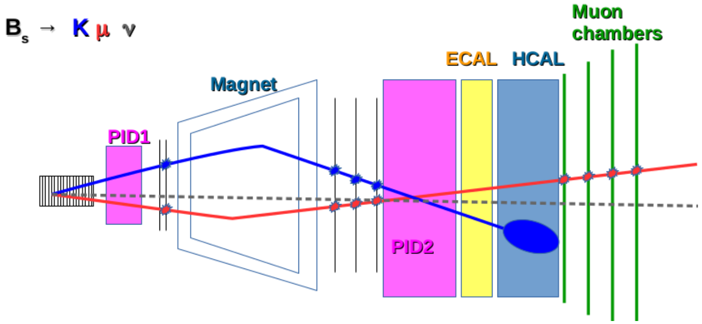
- Lattice QCD predictions provide a precise determination of the form factors at low recoil transfer (high q^2)
  [Phys. Rev. D 90, 054506] [Phys. Rev. D 91, 074510] [Phys. Rev. D 100, 034501]

- Calculations from QCD light-cone sum rules are most precise at large recoil (low q^2)
  [JHEP 08 (2017) 112]





- $B_s^0 \rightarrow K^- \mu^+ \nu$
  - main background originates from $H_b \rightarrow H_c(\rightarrow K^- X)\mu^+ X'$ (unreconstructed particles)
  - $B_s^0 \rightarrow K^{*-}(\rightarrow K^- \pi^0)\mu^+ \nu$
  - $B_s^0 \rightarrow [cc]^-(\rightarrow \mu^+ \mu^-)K^- X$



- $B_s^0 \rightarrow D_s^- \mu^+ \nu$
  - $B_s^0 \rightarrow D_s^{*-}(\rightarrow D_s \gamma)\mu^+ \nu$
  - $B_s^0 \rightarrow D_s^{**-} \mu^+ \nu$, $B_{u,s,d} \rightarrow D_s D X$ and $B_s^0 \rightarrow D_s^{*-} \tau^+ \nu$

- To suppress background
  - the candidates are required to be isolated from the other tracks in the event
  - BDT classifiers exploit the kinematics of the decays

- The B_s^0 momentum can be calculated with a two fold ambiguity → regression model that exploit the B_s flight information [JHEP 02 (2017) 021]
  - Ambiguity solved by selection the solution most consistent with the regression value
  - $\varepsilon \approx 70\%$

Signal and normalization fits [Phys. Rev. Lett. 126 081804]

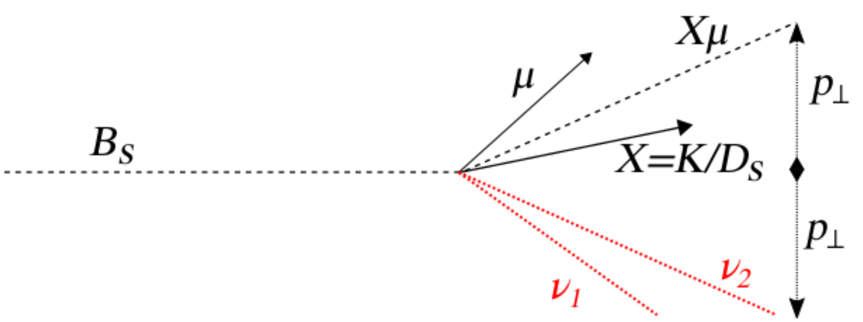
- The measured ratio is

$$R_{\mathrm{BF}} \equiv \frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = \overbrace{\frac{N_K}{N_{D_s}}}^{\text{Ratio of yields}} \underbrace{\frac{\epsilon_{D_s}}{\epsilon_K}}_{\text{Efficiency ratio}} \times \mathcal{B}(D_s^- \to K^+ K^- \pi^-)$$

[Prog. Theor. Exp. Phys. 2020, 083C01 (2020)]

- A binned maximum likelihood fit to the B_s corrected mass

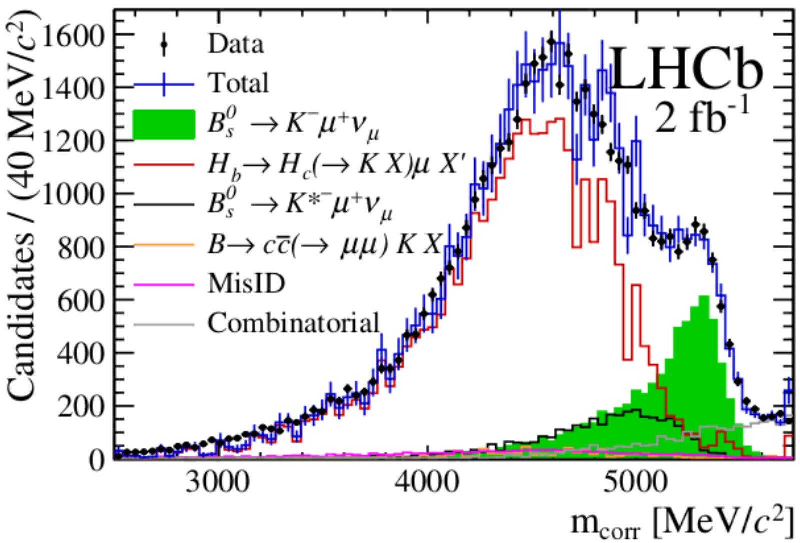
$$m_{\mathrm{corr}} = \sqrt{m^2(Y\mu) + p_\perp^2(Y\mu)} + p_\perp(Y\mu), \; Y = K^-, D_s^-$$



- If only missing particle is a neutrino the corrected mass distribution will peak at the B_s mass
- the resolution on the corrected mass is significantly improved if one rejects events with a large corrected mass uncertainty (>100 MeV/c^2)

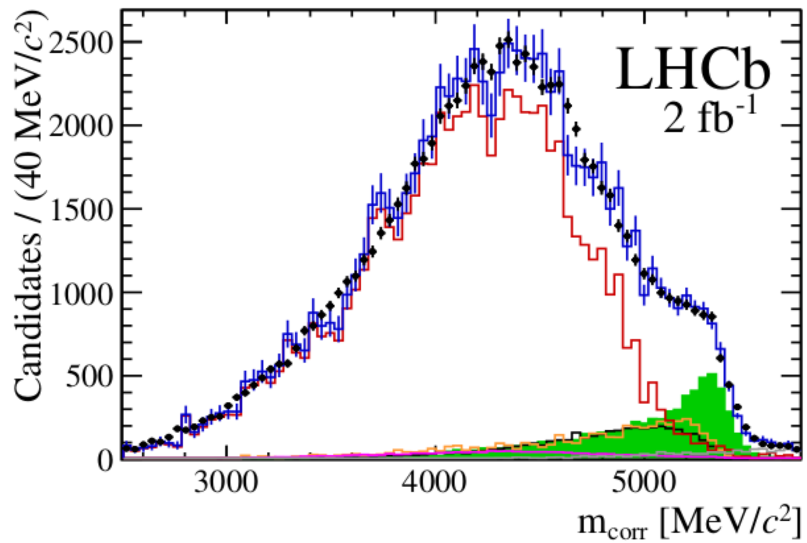
Signal and normalization fits [Phys. Rev. Lett. 126 081804]

$B_s^0 \to K^-\mu^+\nu_\mu$ low q^2



$N(B_s^0 \to K^-\mu^+\nu_\mu)_{low} = 6922 \pm 285$

$B_s^0 \to K^-\mu^+\nu_\mu$ high q^2

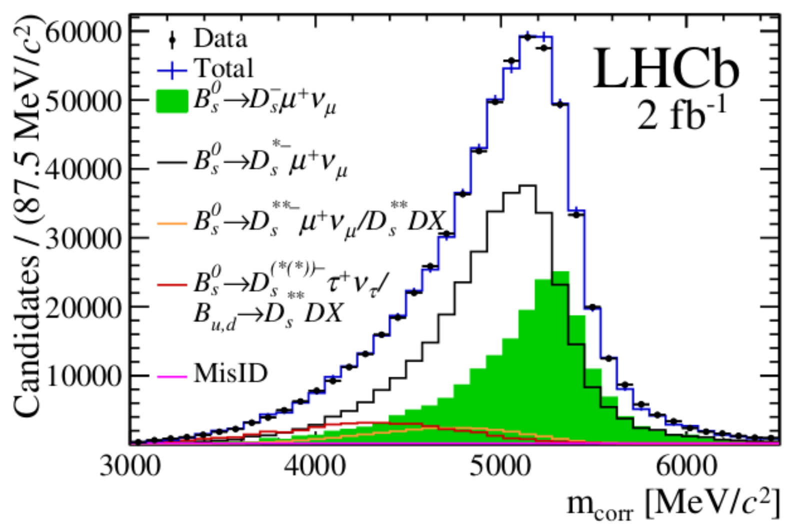


$N(B_s^0 \to K^-\mu^+\nu_\mu)_{high} = 6399 \pm 370$

- The largest systematical uncertainty is from the fit templates

- First observation of the decay $B_s^0 \to K^-\mu^+\nu$

$B_s^0 \to D_s^-\mu^+\nu_\mu$



$N(B_s^0 \to D_s^-\mu^+\nu_\mu) = 201450 \pm 5200$

$|V_{ub}|/|V_{cb}|$ results

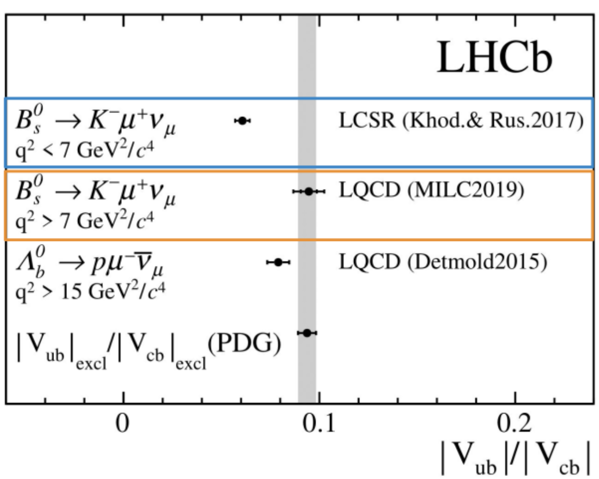
- The obtained values are

$$\underbrace{\frac{\mathcal{B}(B_s^0\to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0\to D_s^-\mu^+\nu_\mu)}}_{\text{Experiment}} = \frac{|V_{ub}|^2}{|V_{cb}|^2}\times\underbrace{\frac{\mathrm{FF}_K}{\mathrm{FF}_{D_s}}}_{\text{Theory}}$$

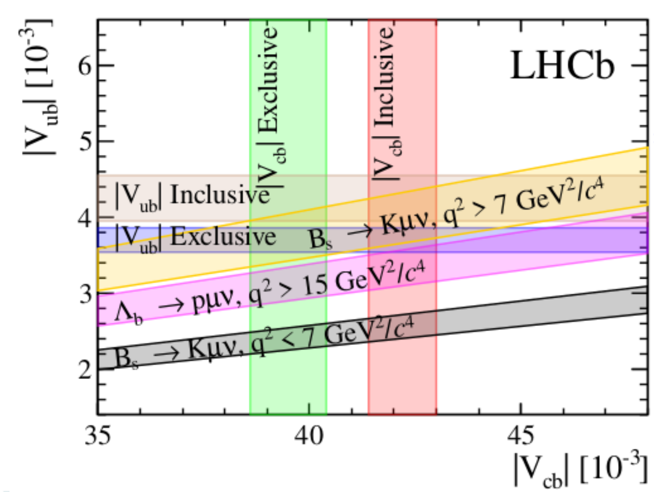
- $q^2>7\ \mathrm{GeV}^2/c^4$: $$\frac{\mathcal{B}(B_s^0\to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0\to D_s^-\mu^+\nu_\mu)} = 1.66\pm0.08(stat)\pm0.07(syst)\pm0.05(D_s)\times10^{-3}$$
- $q^2<7\ \mathrm{GeV}^2/c^4$ $$\frac{\mathcal{B}(B_s^0\to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0\to D_s^-\mu^+\nu_\mu)} = 3.25\pm0.21(stat)^{+0.16}_{-0.17}(syst)\pm0.09(D_s)\times10^{-3}$$

$$\boxed{|V_{ub}|/|V_{cb}|_{(\mathrm{low})} = 0.0607\pm0.0015(\mathrm{stat})\pm0.0013(\mathrm{syst})\pm0.0008(D_s)\pm0.0030(\mathrm{FF})}$$

$$\boxed{|V_{ub}|/|V_{cb}|_{(\mathrm{high})} = 0.0946\pm0.0030(\mathrm{stat})^{+0.0024}_{-0.0025}(\mathrm{syst})\pm0.0013(D_s)\pm0.0068(\mathrm{FF})}$$



Discrepancy related to the difference in the theoretical calculations of the form factors.



$|V_{xb}|$ Exclusive measurements at LHCb

- First observation of the decay $B_s^0 \to K^- \mu^+ \nu$ and a measurement of $|V_{ub}|/|V_{cb}|$ [Phys. Rev. Lett. 126 081804]

- (Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-} \mu^+ \nu$ decays [Phys. Rev. D 101 072004])

$|V_{cb}|$

[Phys. Rev. D 101 072004]

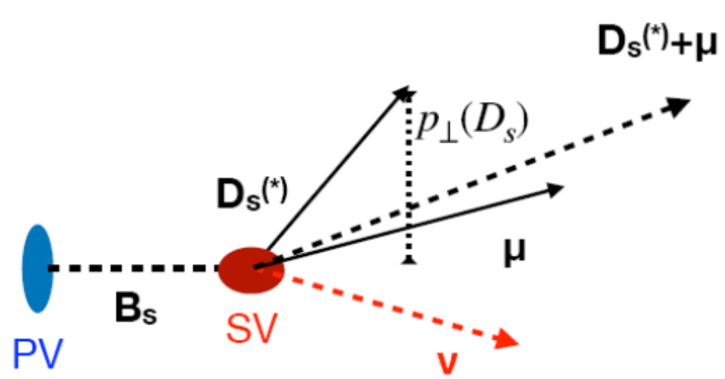
- Dataset: 1 fb^{-1} @ 7TeV - 2 fb^{-1} @ 8TeV

- Signal: $B_s^0 \to D_s^{(*)-}\mu^+\nu$ where $D_s \to K^+K^-\pi^-$
- Normalization: $B^0 \to D^{(*)-}\mu^+\nu$
- Extract $|V_{cb}|$ from $\mathcal{R}^{(*)} = \frac{\mathcal{B}(B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)}$

  external input: hadronization fractions f_s/f_d [PRD(2019)031102] and branching fraction[PDG]

- Use variable $p_\perp(D_s)$: high correlated with hadron recoil and fully recostructible

$$w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$

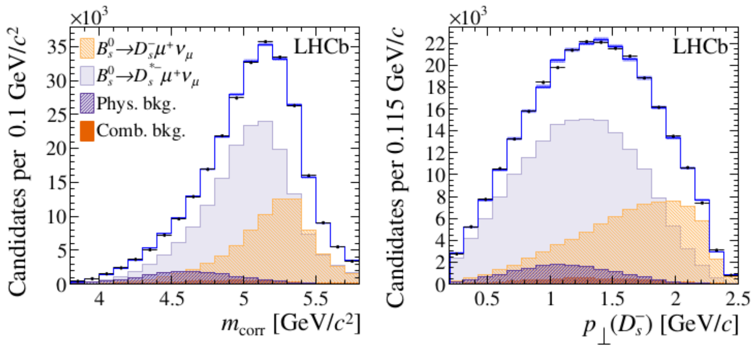


$|V_{cb}|$

[Phys. Rev. D 101 072004]

- 2-D template fit to M_{corr} and $p_\perp(D_s)$ identify the signal yields and provides a simultaneous measurement of the ratios R(*) and the form factors

- Parametrizations used: CLN and BGL



- The results are

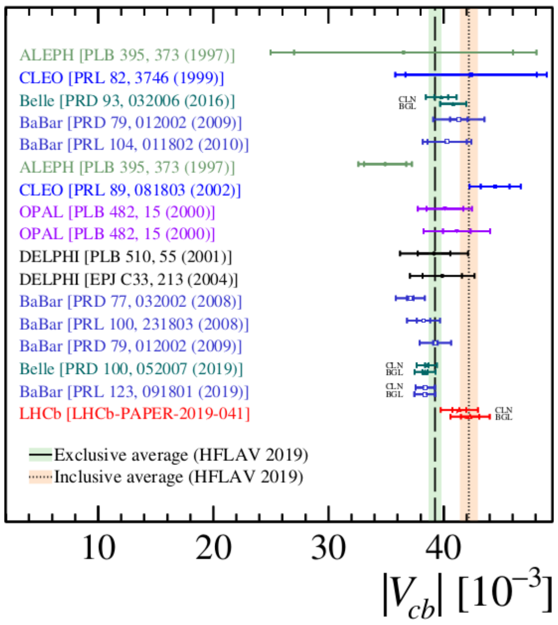
$$|V_{cb}|_{CLN} = (41.1 \pm 0.6(stat) \pm 0.9(syst) \pm 1.2(ext))\text{x}10^{-3}$$
$$|V_{cb}|_{BGL} = (42.3 \pm 0.8(stat) \pm 0.9(syst) \pm 1.2(ext))\text{x}10^{-3}$$

- First measurement of $|V_{cb}|$ using B_s
- First measurement of $|V_{cb}|$ at an hadronic environment

- Compatible with world average for both inclusive and exclusive determinations
- Confirms trend that parametrisation is not responsible for inclusive vs exclusive disagreements

- New f_s/f_d → new updated V_{cb} [arXiv:2103.06810]

$$|V_{cb}|_{CLN} = (40.8 \pm 0.6(stat) \pm 0.9(syst) \pm 1.1(ext))\text{x}10^{-3}$$
$$|V_{cb}|_{BGL} = (41.7 \pm 0.8(stat) \pm 0.9(syst) \pm 1.1(ext))\text{x}10^{-3}$$



Conclusion and outlook

- LHCb performed the first measurements of $|V_{ub}|$ and $|V_{cb}|$ using the B_s^0 decays.
- The ratio $|V_{ub}|/|V_{cb}|$ has been measured using the $B_s^0 \to K^- \mu^+ \nu$ in two q^2 bins:
  - Discrepancy found between low and high q^2 bins.
  - The ratio found in the high q^2 bin is compatible with previous measurement
- Planned measurement of differential q^2 spectrum of $B_s^0 \to K^- \mu^+ \nu$ with full Run 1 + Run 2 data
- The $|V_{cb}|$ parameter has been measured using $B_s^0 \to D_s^{(*)-} \mu^+ \nu$:
  - It results in agreement with previous exclusive and inclusive measurement from B decays
- Inclusive-Exclusive puzzle has to be understood
- Several other $|V_{ub}|$ and $|V_{cb}|$ analyses in the pipeline using $B_c \to D^{0(*)} \mu\nu$ and $B^+ \to \rho\mu\nu$ decays → theoretical FF predictions needed