Imperial College London

Recent results & prospects on (charged current) semileptonic decays from LHCb

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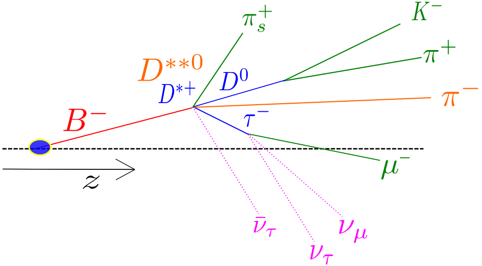
Semileptonic decays at LHCb

- Produce B^+, B^0, B_s^0, B_c, Λ_b^0 etc.
- Large H_b production x-section
- Efficient muon trigger

- Significant bkgs (combinatoric + part-reco)
- No beam-energy constraint
- Reliance on simulation

- Reduce backgrounds with isolation techniques
- Estimate H_b kinematics with approximations



Analyses for exclusive CKM measurements and NP lepton non-universality.

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

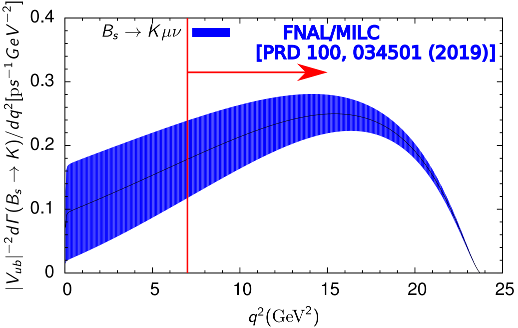
$$R_{\rm BF} = \frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = \frac{N(B_s^0 \to K^- \mu^+ \nu_\mu)}{N(B_s^0 \to D_s^- \mu^+ \nu_\mu)} \frac{\epsilon(D_s^-)}{\epsilon(K^-)} \times \mathcal{B}(D_s^- \to K^- K^+ \pi^-) = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \frac{FF_K}{FF_{D_s}}$$

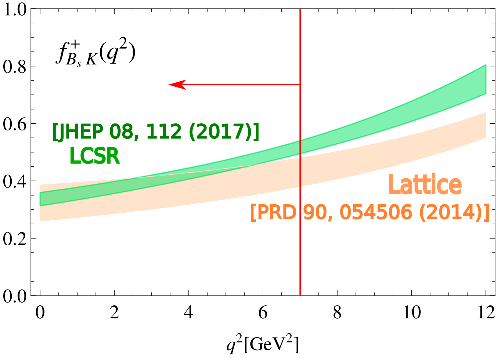
Data and simulation, PDG, theory

Split $B_s^0 \to K^- \mu^+ \nu_\mu$ into two q^2 regions

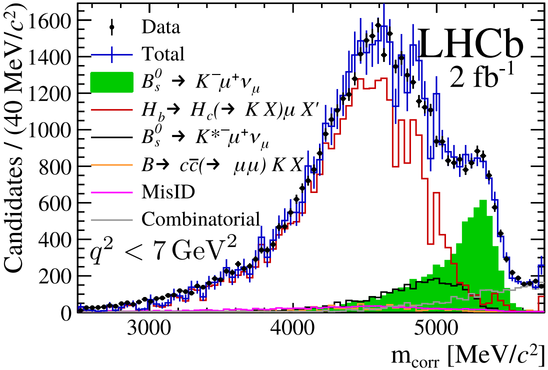
$q^2 < 7\,\mathrm{GeV}^2$ - LCSR [JHEP 08,112 (2017)]

$q^2 > 7\,\mathrm{GeV}^2$ - LQCD [PRD 100, 034501 (2019)]



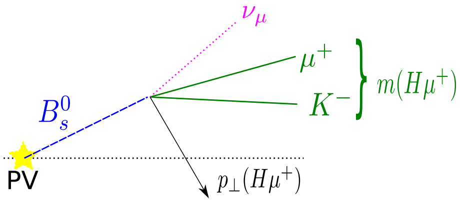


Fit $2\,\mathrm{fb}^{-1}$ of Run 1 data at $8\,\mathrm{TeV}$:



$$m_{\mathrm{corr}} = \sqrt{m(H\mu^+)^2 + p_\perp(H\mu^+)^2} + p_\perp(H\mu^+)$$

$$H = K^-, D_s^-$$



- Partially reconstructed backgrounds from MC
- Mis-ID and combinatorial from data control samples

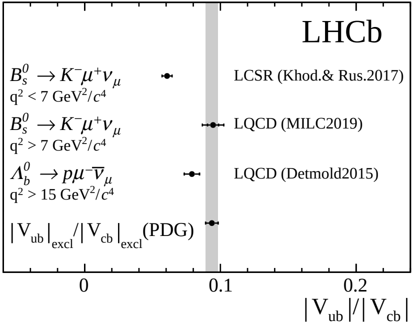
- Find q^2 with two-fold ambiguity
- Use multivariate regression to pick 70% correct solution [JHEP 02, 021 (2017)]

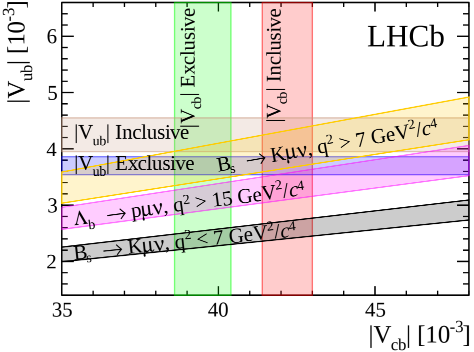
First observation of $B_s^0 \to K^- \mu^+ \nu_\mu$

$$R_{\rm BF}(\text{low}) = (1.66 \pm 0.08(\text{stat}) \pm 0.07(\text{syst}) \pm 0.05(D_s)) \times 10^{-3}$$

$$R_{\rm BF}(\text{high}) = (3.25 \pm 0.21(\text{stat})^{+0.16}_{-0.17}(\text{syst}) \pm 0.09(D_s)) \times 10^{-3}$$

Including systematic and FF uncertainties, experimental results:





Large differences between LQCD and LCSR predictions

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

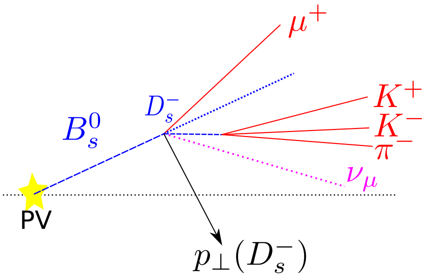
$$\frac{d\Gamma(B_s^0 \to D_s^-\mu^+\nu_\mu)}{dw} = \frac{G_F^2 m_{D_s}^3}{48\pi^3}(m_{B_s} + m_{D_s})^2\eta_{EW}^2(w^2-1)^{\frac{3}{2}}|V_{cb}|^2|\mathcal{G}(w)|^2$$

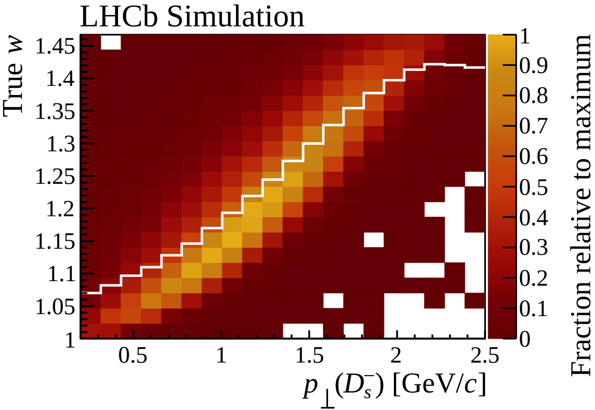
- Heavier s spectator helps with theory calculation cf. d or u
- Fewer feed-down backgrounds
- Large yield of B_s^0 at LHCb
- Use $B^0 \to D^{(*)-}\mu^+\nu_\mu$ for control mode

External inputs required:

- $\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)$, $\mathcal{B}(D^- \to K^-K^+\pi^-)$, $\mathcal{B}(D_s^- \to K^-K^+\pi^-)$ from [PDG]
- $\frac{f_s}{f_d}$ from LHCb measurement: [PRD 100, 031102 (2019)]
    - Update with a more recent result: [PRD 104, 032005 (2021)]
- Form factors of $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$
    - Constrain with data

Missing neutrino → reduces w or angle resolution → *use proxy variable $p_\perp(D_s^-)$*



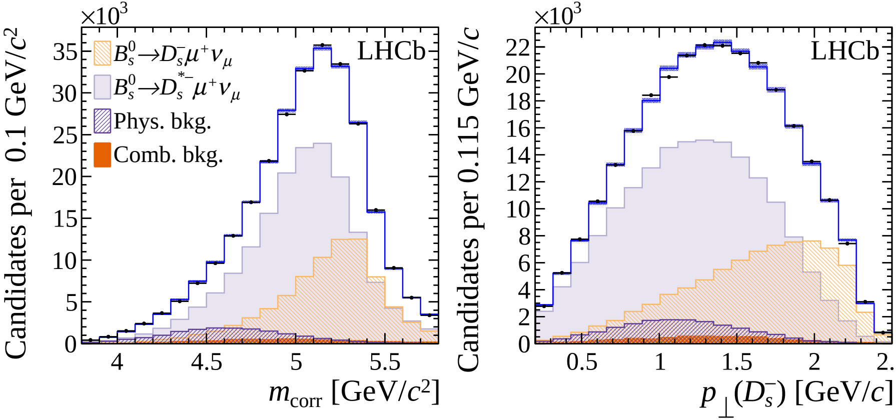


2D fit of $m_{\rm corr} - p_\perp(D_s^-)$ to extract yield and FF parameters

$$m_{\rm corr} = \sqrt{m(D_s^-\mu^+)^2 + p_\perp(D_s^-\mu^+)^2} + p_\perp(D_s^-\mu^+)$$

$3\,\text{fb}^{-1}$ at $7/8\,\text{TeV}$- Run 1 data set:

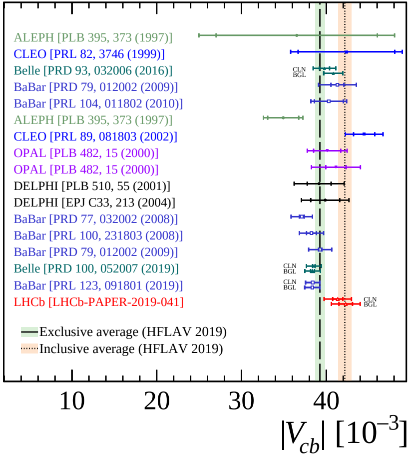
Fit with two FF parametrisations - CLN and BGL. Eg. CLN:



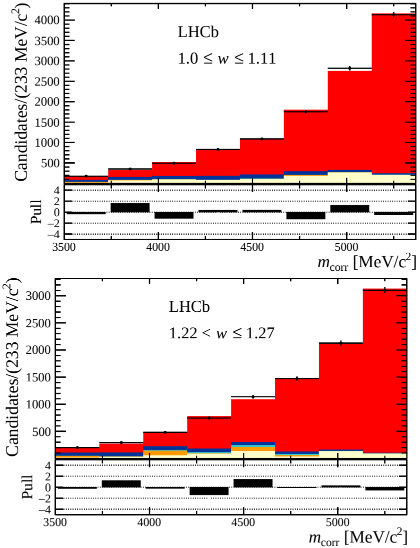
$$|V_{cb}|_{\rm CLN} = (41.4 \pm 0.6({\rm stat}) \pm 0.9({\rm syst}) \pm 1.2({\rm ext})) \times 10^{-3}$$
$$|V_{cb}|_{\rm BGL} = (42.3 \pm 0.8({\rm stat}) \pm 0.9({\rm syst}) \pm 1.2({\rm ext})) \times 10^{-3}$$

- First measurement of $|V_{cb}|$ with B_s^0 decays
- Agreement between FF parametrisations
- Agreement with exclusive and inclusive $|V_{cb}|$ averages
- Recent update to $\frac{f_s}{f_d}$ [PRD 104, 032005 (2021)]

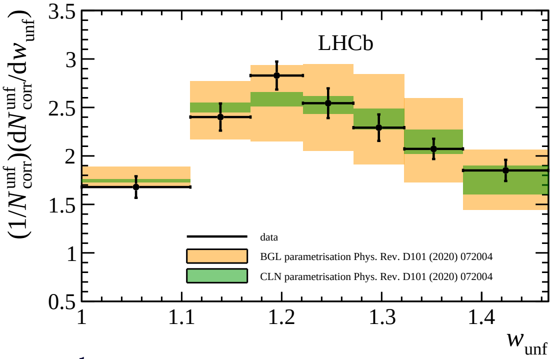
$$|V_{cb}|_{\rm CLN} = (40.8 \pm 0.6 \pm 0.9 \pm 1.1) \times 10^{-3}$$
$$|V_{cb}|_{\rm BGL} = (41.7 \pm 0.8 \pm 0.9 \pm 1.1) \times 10^{-3}$$



$B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ FF measurement [JHEP 12, 144 (2020)]



Analysis of $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential rate



$1.7\,\text{fb}^{-1}$ at 13 TeV- 2016 data set:

- Measure yields in bins of q^2_{reco} with m_{corr} fits
- Unfold to q^2_{true} and correct efficiency
- Differential rate for direct theory comparison

Lepton universality

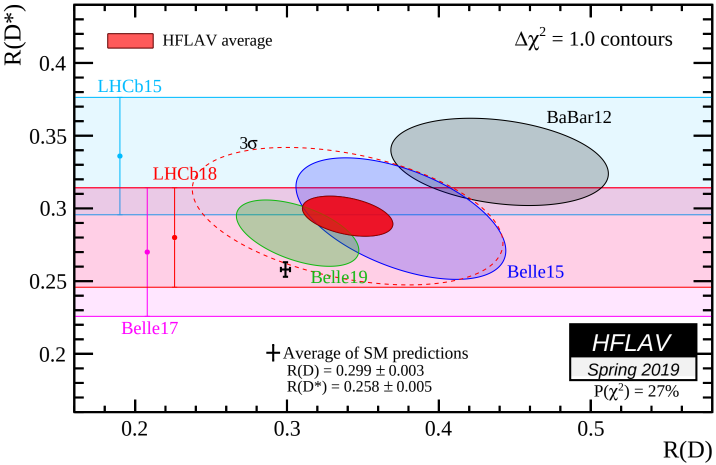
$$R(H) = \frac{\mathcal{B}(H_b \to H_c \tau^+ \nu_\tau)}{\mathcal{B}(H_b \to H_c \mu^+ \nu_\mu)}$$

LHCb15: $\tau^+ \to \mu^+ \nu_\mu \overline{\nu}_\tau$
[PRL 115, 111803 (2015)]

LHCb18:
$\tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0) \overline{\nu}_\tau$
[PRL 120, 171802 (2018)]
[PRD 97, 072013 (2018)]

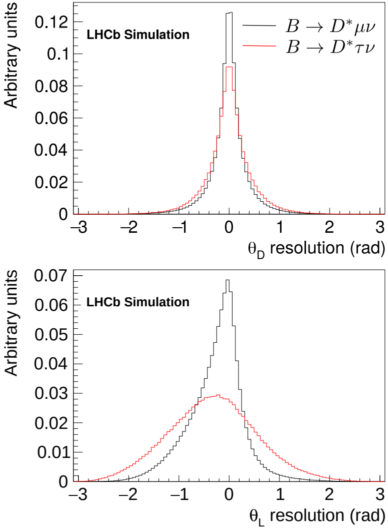
$R(J/\psi)$: $B_c^+ \to J/\psi \ell^+ \nu_\ell$
$\approx 2\,\sigma$ from SM
[PRL 120, 121801 (2018)]

All with 3 fb^{-1} from Run 1



Still to come

[arXiv:1808.08865]



Exploit the data in hand

- $6\,\text{fb}^{-1}$ at $13\,\text{TeV}$ in Run 2 $\to 4\times$ Run 1 data set
  - Take advantage of latest theory calculations
- More decay modes
  - Both hadronic and leptonic τ decays
  - Other b hadrons: $B_s \to D_s^{(*)}$, $\Lambda_b^0 \to \Lambda_c^{(*)+}$
  - Other c hadrons: D^0, D^+, D^{*0}, D^{**} etc
  - $b \to u$ modes: $B^+ \to \rho\ell^+\nu_\ell$, $B^+ \to p\bar{p}\tau^+\nu_\tau$
- Angular analyses?
  - A model independent method: [JHEP 11, 133 (2019)]
  - Use HAMMER to fit WCs and FFs [EPJC 80, 883 (2020)][arXiv:2007.12605]
  - Initially target μ modes

Looking forward at LHCb

7-8 TeV | 13 TeV | 14 TeV | —— HL-LHC ——>

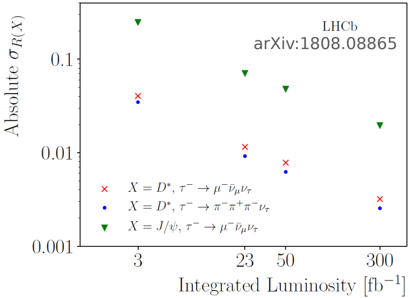
Run 1 2010 - 2012	Run 2 2015 - 2018	Run 3 2022 - 2024	Run 4 2027 - 2030	Run 5 2032 -
$3\,\mathrm{fb}^{-1}$	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$

Upgrade I (between Run 2 and Run 3)

Upgrade II (between Run 4 and Run 5)

Continued improvement reliant on:

- Simulation size
- Theory collaboration
- Experimental input



Conclusion

Disparate set of measurements made

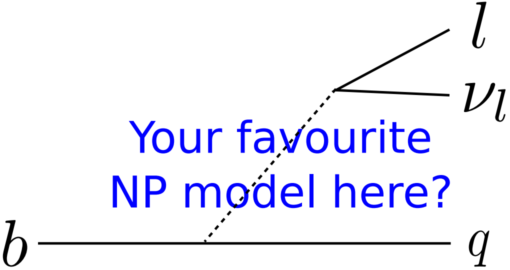
- Exclusive CKM elements
- Unfolded differential distributions and FFs
- Lepton universality

Many more results to come

- Fully exploit the data in hand
  - Update existing measurements
  - Many new analyses in progress
  - New methods to maximise physics reach
- Continued precision with Upgrade I and Upgrade II $\rightarrow$ complements Belle II

BACKUP

Reminder - Semileptonic decays



- Tree level $\rightarrow$ abundant
- Theoretically clean
  - Factorise hadron and lepton current
  - Hadron current described by form-factors
- Experimentally tricky - ≥ 1 missing ν_ℓ

SM measurements:

- CKM elements: V_{cb} and V_{ub}
  - Confirm unitarity of CKM matrix
  - Solve inclusive - exclusive discrepancy
- Form-factors
  - Confirm theory calculations
  - Input to q^2 extrapolation

New physics searches at tree level:

- Lepton non-universality
  - Ratio of decay rates for τ, μ, e final states
- Angular analyses
  - Evidence for NP operators in angular distributions of decay products