Overview of Heavy Flavour results from the LHCb experiment

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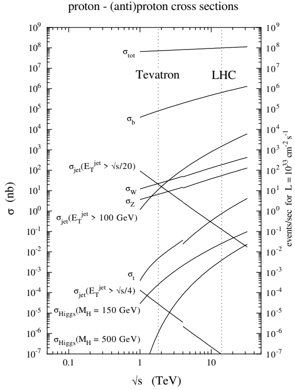
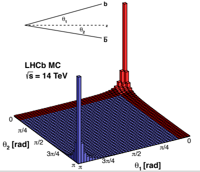
LHCb physics

- huge b and c production x-sections at LHC
  - relatively light: both b and $\overline{b}$ in tight cone around either beam
- LHCb has largest samples of b and c decays
  - can probe SM and NP using precision measurements
    - (over-)constrain SM parameters (CKM matrix!)
    - new sources of CP violation
    - rare decays
  - gain better understanding of (effective models of) QCD

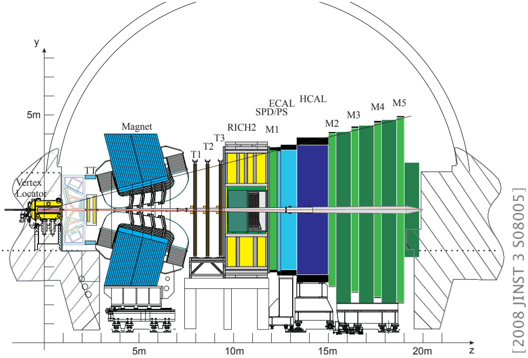


[CERN 2000-004]



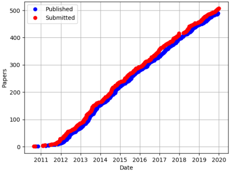
G. Elsässer, LHCb

LHCb experiment



- originally designed to study CPV and rare b and c decays, nowadays GPD in forward region
  - tracking efficiency $> 96\%$ (multibody final states!)
  - excellent vertexing: decay time resolution ~ 45 fs
  - very good momentum resolution: $dp/p \sim 0.5 - 1.0\%$
  - software trigger (HLT) input rate: 1 MHz

LHCb physics



- LHCb has largest samples of b and c decays
- steady stream of publications
  - Nov 15th, 2019: 500th publication
  - now: 507 papers (submitted)
- here are the publications since July 2019:

- First observation of excited Ω_b^- states, PAPER-2019-042, [arXiv:2001.00851], PRL, 03 Jan 2020
- Search for CP violation and observation of P violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays, PAPER-2019-028, [arXiv:1912.10741], PRL, 23 Dec 2019
- Test of lepton universality with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays, PAPER-2019-040, [arXiv:1912.08139], JHEP, 17 Dec 2019
- Measurement of CP violation in $B^0 \to D^{*\pm}D^{\mp}$ decays, PAPER-2019-036, [arXiv:1912.03723], JHEP, 08 Dec 2019
- Isospin amplitudes in $\Lambda_b^0 \to J/\psi\Lambda(\Sigma^0)$ and $\Xi_b^0 \to J/\psi\Xi^0(\Lambda)$ decays, PAPER-2019-039, [arXiv:1912.02110], PRL, 04 Dec 2019
- Precision measurement of the Ξ_{cc}^{++} mass, PAPER-2019-037, [arXiv:1911.08594], JHEP, 19 Nov 2019
- Observation of the semileptonic decay $B^+ \to p\overline{p}\mu^+\nu_\mu$, PAPER-2019-034, [arXiv:1911.08187], JHEP, 19 Nov 2019
- Determination of quantum numbers for several excited charmed mesons observed in $B^- \to D^{*+}\pi^-\pi^-$ decays, PAPER-2019-027, [arXiv:1911.05957], PRD, 14 Nov 2019
- Measurement of the $\eta_c(1S)$ production cross-section in pp collisions at $\sqrt{s}$=13 TeV, PAPER-2019-024, [arXiv:1911.03326], EPJC, 08 Nov 2019
- Updated measurement of decay-time-dependent CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays, PAPER-2019-032, [arXiv:1911.01114], PRD, 04 Nov 2019
- Measurement of the B_c^- meson production fraction and asymmetry in 7 and 13 TeV pp collisions, PAPER-2019-033, [arXiv:1910.13404], Phys. Rev. D100 (2019) 112006, 29 Oct 2019
- Measurement of Ξ_{cc}^{++} production in pp collisions at $\sqrt(s)$ =13 TeV, PAPER-2019-035, [arXiv:1910.11316], Chin. Phys. C, 24 Oct 2019
- Measurement of f_s/f_u variation with proton-proton collision energy and kinematics, PAPER-2019-020, [arXiv:1910.09934], PRL, 22 Oct 2019
- Search for $A' \to \mu^+\mu^-$ decays, PAPER-2019-031, [arXiv:1910.06926], PRL, 15 Oct 2019
- Search for the doubly charmed baryon Ξ_{cc}^+, PAPER-2019-029, [arXiv:1909.12273], Sci.China Phys.Mech.Astron. (2020) 63 221062, 26 Sep 2019
- Amplitude analysis of the $B^+ \to \pi^+\pi^+\pi^-$ decay, PAPER-2019-017, [arXiv:1909.05212], PRD, 11 Sep 2019
- Observation of several sources of CP violation in $B^+ \to \pi^+\pi^+\pi^-$ decays, PAPER-2019-018, [arXiv:1909.05211], PRL, 11 Sep 2019
- Search for the lepton-flavour violating decays $B^+ \to K^+\mu^\pm e^\pm$, PAPER-2019-022, [arXiv:1909.01010], Phys. Rev. Lett.123 (2019) 241802, 03 Sep 2019
- Measurement of $\psi(2S)$ production cross-sections in proton-proton collisions at $\sqrt{s}$ =7 and 13 TeV, PAPER-2018-049, [arXiv:1908.03099], EPJC, 08 Aug 2019
- Observation of new resonances in the $\Lambda_b^0\pi^+\pi^-$ system, PAPER-2019-025, [arXiv:1907.13598], Phys. Rev. Lett. 123 (2019) 152001, 31 Jul 2019
- Measurement of CP violation in the $B_s^0 \to \phi\phi$ decay and search for the $B^0 \to \phi\phi$ decay, PAPER-2019-019, [arXiv:1907.10003], JHEP, 23 Jul 2019
- Observation of the $\Lambda_b^0 \to \chi_{c1}(3872)pK^-$ decay, PAPER-2019-023, [arXiv:1907.00954], 01 Jul 2019

outline

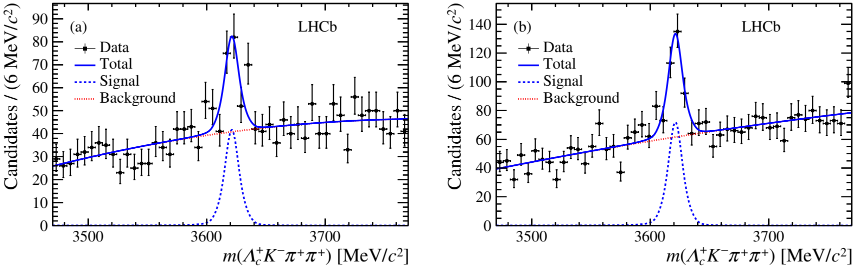
- list on last page is clearly far too much to cover
- will therefore pick or point to a few highlights:
  - first, there are excellent talks by other LHCb collaborators:
    - Wednesday: Carla Marin Benito: Test of Lepton Universality with $\Lambda_b \to pK\ell\ell$ decays LHCb-PAPER-2019-040, [arXiv:1912.08139]
    - Thursday: Cesar Luiz Da Silva: Physics opportunities with a future soft particle tracker in LHCb
    - Thursday: Jozef Tomasz Borsuk: $b \to s\ell\ell$ transitions at LHCb
    - Thursday: Milosz Zdybal: Particle Correlations at LHCb
    - Thursday: Mateusz Jacek Goncerz: Exotic searches at LHCb
    - Thursday: Simone Meloni: Test of lepton flavour universality in $b \to c\ell\nu$ decays at the LHCb experiment
- will cover some of the excellent work that was done in various areas
  - can only cover so much in half an hour — my apologies…

- Precision measurement of the Ξ_{cc}^{++} mass, PAPER-2019-037, [arXiv:1911.08594], JHEP, 19 Nov 2019
- Measurement of Ξ_{cc}^{++} production in pp collisions at $\sqrt{(s)}$ =13 TeV, PAPER-2019-035, [arXiv:1910.11316], Chin. Phys. C, 24 Oct 2019
- Measurement of the B_c^- meson production fraction and asymmetry in 7 and 13 TeV pp collisions, PAPER-2019-033, [arXiv:1910.13404], Phys. Rev. D100 (2019) 112006, 29 Oct 2019
- First observation of excited Ω_b^- states, PAPER-2019-042, [arXiv:2001.00851], PRL, 03 Jan 2020
- Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ decays, preliminary, to appear shortly

(some) highlights

(some) highlights

Ξ_{cc}^{++} production



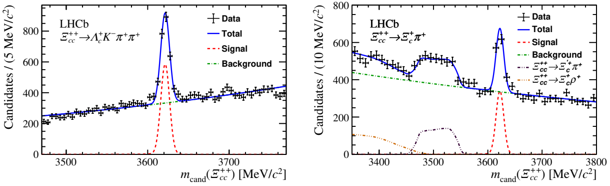
trigger on signal | excl. trigger independent of signal

[arXiv:1910.11316]

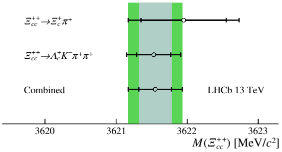
- 2016 data, 1.7 fb^{-1}
- $m_{\Xi_{cc}^{++}} = (3621.34 \pm 0.74)$ MeV/c^2 (stat. only — it's a production measurement)
- measure production cross-section of Ξ_{cc}^{++} in $\Lambda_c^+ K^- \pi^+ \pi^+$
  - in kinematic region $4 < p_T < 15$ GeV/c^2 and $2.0 < y < 4.5$
  - relative to the Λ_c^+ production cross-section:

$$\frac{\sigma(\Xi_{cc}^{++})}{\sigma(\Lambda_c^+)} = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$$

Ξ_{cc}^{++} mass



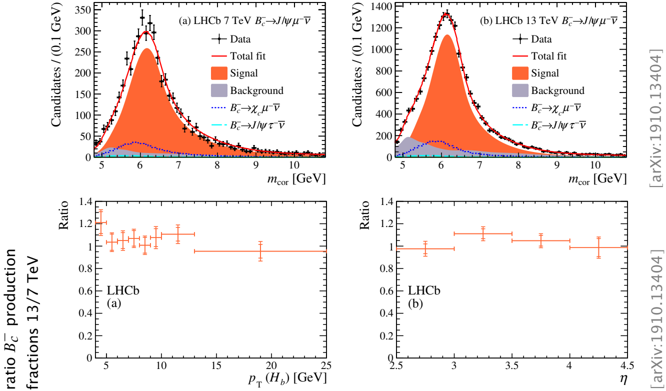
[arXiv:1911.08594]



[arXiv:1911.08594]

- 2016-2018 data, 5.6 fb^{-1}, published not one month apart
- precision measurement of mass of Ξ_{cc}^{++} in $\Lambda_c^+K^-\pi^+\pi^+$ and $\Xi_c^+\pi^+$: $m_{\Xi_{cc}^{++}} = (3621.55 \pm 0.23\ \text{(stat)} \pm 0.30\ \text{(syst)})\ \text{MeV}/c^2$
- world's most precise measurement of Ξ_{cc}^{++} mass

B_c^- production fraction



- data samples: 7 and 13 TeV data
- measurement of production fraction ratio $\frac{f_c}{f_u+f_d}$ in $B_c^- \to J/\psi\mu^-\overline{\nu}_\mu$

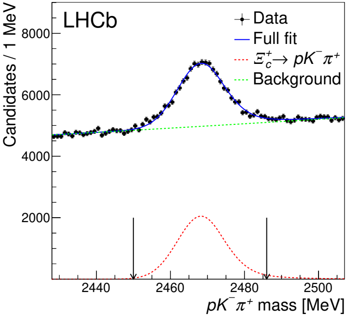
$$\frac{f_c}{f_u+f_d} = \begin{cases} (3.63 \pm 0.08 \pm 0.12 \pm 0.86)\cdot 10^{-3} & \text{for 7 TeV} \\ (3.78 \pm 0.04 \pm 0.15 \pm 0.89)\cdot 10^{-3} & \text{for 13 TeV} \end{cases}$$

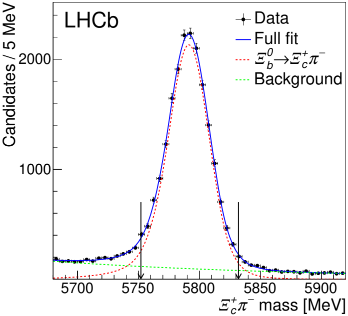
  - first uncertainty statistical, second from $\mathcal{B}(B_c^- \to J/\psi\mu^-\overline{\nu}_\mu)$, last from fractions of B_s^0 and Λ_b^0
- continue to test QCD (predictions) with measurements like this

First observation of excited Ω_b^0 states

First observation of excited Ω_b^0 states

selection



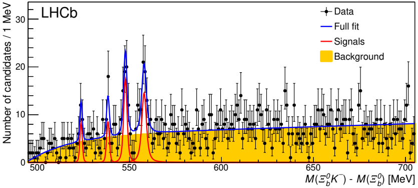


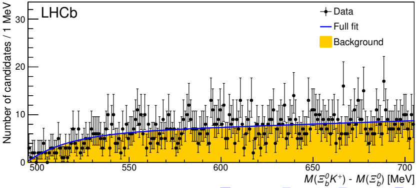
[arXiv:2001.00851]

- reconstruct $\Xi_c^+ \to pK^-\pi^+$ (arrows indicate cuts)
  - data samples: 1 fb^{-1} at $\sqrt{s} = 7$ TeV, 2 fb^{-1} at 8 TeV and 6 fb^{-1} at 13 TeV
  - from displaced tracks with clear PID assignment forming good vertex
  - veto main BG from mid-ID'ed $D^+_{(s)} \to K^+(K/\pi)^-\pi^+$, $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$, and $\phi \to K^+K^-$ + random track
- reconstruct $\Xi_b^0 \to \Xi_c^+\pi^-$ (arrows indicate cuts)
  - use BDT to further suppress combinatorial BGs by factor 2.5 (90% efficiency)
  - 19.2 ± 0.2 k very clean Ξ_b^0 candidates

selection and fit

- take Ξ_b^0 and add prompt charged K
  - $\Xi_b^0 K$ vertex kinematically constraint to primary vertex
  - study $\delta M = M(\Xi_b^0 K) - M(\Xi_b^0)$ distribution
  - right sign candidates ($\Xi_b^0 K^-$) and wrong sign ones ($\Xi_b^0 K^+$)
    - wrong sign candidates crucial to control background shape
  - optimize PID requirements on K^- using FOM $\epsilon_{MC}/(\sqrt{B} + 5/2)$ from WS for $520 < \delta M/\text{MeV} < 570$ (expected BG yield scaled to a 10 MeV window for narrow peaks)
  - double-gaussian resolution function σ_M; in relevant δM range, $\sigma_M = 0.7 - 0.8\,\text{MeV}$
  - fit peaks: Breit-Wigner with Blass-Weisskopf barrier factor, convolved with resolution function





[arXiv:2001.00851]

results, systematics

Peak of δM [MeV]	width [MeV]	signal yield	local significance	global significance
523.74 ± 0.31	$0.00^{+0.65}_{-0.00}$	$14.6^{+6.2}_{-5.1}$	3.6	2.1
538.40 ± 0.28	$0.00^{+0.42}_{-0.00}$	$17.5^{+6.4}_{-5.4}$	3.7	2.6
547.81 ± 0.26	$0.47^{+0.64}_{-0.47}$	$47.2^{+11.0}_{-9.9}$	7.2	6.7
557.98 ± 0.35	$1.4^{+1.0}_{-0.8}$	$56.8^{+13.9}_{-12.5}$	7.0	6.2

[arXiv:2001.00851]

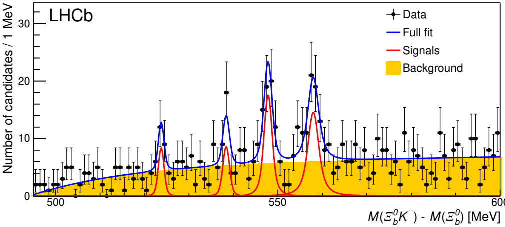
- local significance from $\mathscr{S}_{data} = \sqrt{2\log(\mathscr{L}_{max}/\mathscr{L}_0)}$ where $\mathscr{L}_0$ is LH with signal yield fixed to 0
- global significance (incl. “look-elsewhere” effect) from distribution of $\mathscr{S}_{pe}$ in pseudo-experiments (with yields fixed to 0)
- (non-negligible) sources of systematic uncertainty on δM:

source	peak 1 [MeV]	peak 2 [MeV]	peak 3 [MeV]	peak 4 [MeV]
momentum scale	0.01	0.02	0.02	0.03
energy loss	0.04	0.04	0.04	0.04
signal shape	0.02	0.02	0.02	0.02
background	0.05	0.05	0.01	0.01
total	0.07	0.07	0.05	0.05

[arXiv:2001.00851]

summary

	δM [MeV]	mass [MeV]	width [MeV]
$\Omega_b(6316)^-$	$523.74 \pm 0.31 \pm 0.07$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.05$	<2.8 (4.2)
$\Omega_b(6330)^-$	$538.40 \pm 0.28 \pm 0.07$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.05$	<3.1 (4.7)
$\Omega_b(6340)^-$	$547.81 \pm 0.26 \pm 0.05$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.05$	<1.5 (1.8)
$\Omega_b(6350)^-$	$557.98 \pm 0.35 \pm 0.05$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.05$	<2.8 (3.2)
			$1.4^{+1.0}_{-0.8} \pm 0.1$



[arXiv:2001.00851]

- mass uncertainties are: stat., syst., syst. from $m_{\Xi_b^0}$
- widths at 90(95) % CL, and central value for heaviest peak

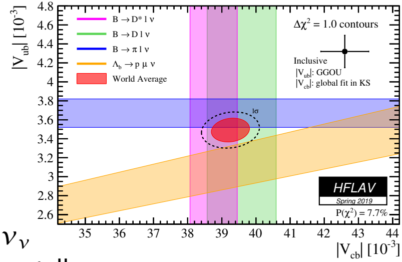
→ two new excited Ω_b^- states observed, and hints of two more

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

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

$|V_{cb}|$ introduction

- determine $|V_{cb}|$ from $b \to c$ transition
  - inclusively, i.e. b-hadron $\to$ c-hadron + charged lepton
    - + no hard-to-calculate bound QCD states
    - − difficult to ensure truely selection inclusive
    - inclusive average: $|V_{cb}| = (42.19 \pm 0.78) \times 10^{-3}$ (HFLAV 2018)



[arXiv:1909.12524v2]

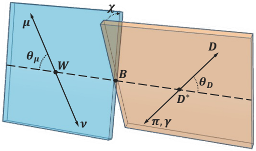
  - exclusively, e.g. $B^0 \to D^- \mu^+ \nu_\nu$
    - + much easier to do experimentally
    - − need **form-factors** (FF) to interpret result: quarks in strongly bound system
    - exclusive average: $|V_{cb}| = (39.25 \pm 0.56) \times 10^{-3}$
  - slight tension between averages!
    - CLN FF parametrisation used in excl. measurements cause of tension?
    - new measurements: try also e.g. BGL FF param. (more general, but truncation of series in BGL somewhat arbitrary), and compare
  - will show preliminary exclusive determination on next few pages...

$|V_{cb}|$ from semileptonic $b \to c$: (some) theory

- vector case:

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

  - with recoil variable $w = v_B \cdot v_{D^*} = (m_B^2 + m_{D^*}^2 - q^2)/(2m_B m_{D^*})$
  - express amplitude in terms of w and helicity angles: $|\mathcal{A}(w,\theta_\mu,\theta_D,\chi)|^2 = \sum_{i=1}^{6}\mathcal{H}_i(w)k_i(\theta_\mu,\theta_D,\chi)$
  - terms $\mathcal{H}_i(w)$ depend on w, B and D^* masses, and **form factors (FF)** $h_{A_1}(w)$, $R_1(w)$, $R_2(w)$



i	$\mathcal{H}_i(w)$	$k_i(\theta_\mu,\theta_D,\chi)$: $D^* \to D\gamma$	$k_i(\theta_\mu,\theta_D,\chi)$: $D^* \to D\pi^0$
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	$-\sin 2\theta_D\sin\theta_\mu(1+\cos\theta_\mu)\cos\chi$	$2\sin 2\theta_D\sin\theta_\mu(1+\cos\theta_\mu)\cos\chi$

- pseudoscalar case similar: (form factor here $\mathcal{G}(w)$)

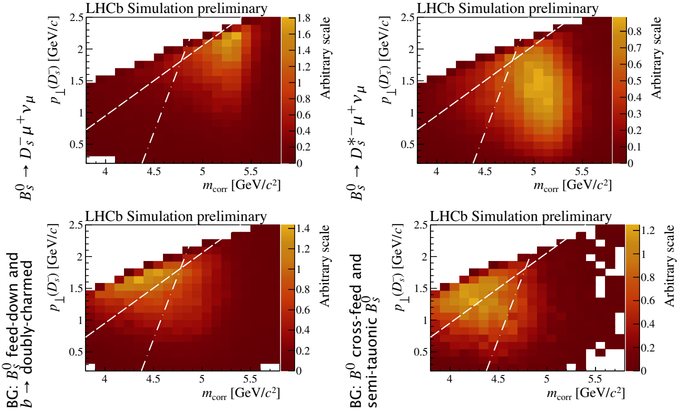
$$\frac{\mathrm{d}\Gamma(B \to D\mu\nu)}{\mathrm{d}w} = \frac{G_\mathrm{F}^2 m_D^3}{48\pi^3}(m_B + m_D)^2\eta_{EW}^2|V_{cb}|^2(w^2-1)^{3/2}|\mathcal{G}(w)|^2$$

data sample, selection

- analysis based on 7 and 8 TeV data (3 fb^{-1})
- use $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ decays
  - trigger on high p_T μ associated with 1-3 charged displaced tracks
  - offline, select μ^+ plus three tracks consistent with $D_{(s)}^- \to K^+K^-\pi^-$
    - $m_{K^+K^-} \in [1008, 1032]$ MeV$/c^2$ to suppress BG under $D_{(s)}^-$ peaks, and keep signal and reference channel kinematics similar
    - $m_{K^+K^-\pi^-}$ mass in D^- or D_s^- range
  - produce clean $D_{(s)}^-$ peaks by optimising selection using track/vertex quality, vertex displacement, p_T and PID criteria
  - measure yields relative to reference decays ($B^0 \to D^{(*)-}\mu^+\nu_\mu$)
- only partial reconstruction: $D_{(s)}^-(\to \phi(K^+K^-)\pi^-)\mu^+$
  - cross-contamination between $D^-\mu^+$ and $D_s^-\mu^+$ samples below 0.1% (based on simulation)
  - combinatorial BG from same-sign $D_{(s)}^-\mu^-$ candidates
  - veto misreconstructed/mis-IDed $B_s^0 \to \psi^{(')}(\to \mu^+\mu^-)\phi(\to K^+K^-)$, $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\overline{\nu}_\mu X$ and $B_{(s)}^0 \to D_{(s)}^-\pi^+$

partial reconstruction

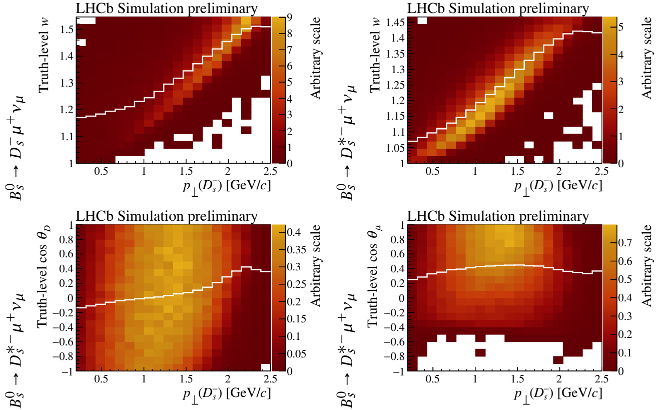
- final state not fully reconstructed (γ/π^0 from D_s^{*-} and also ν_μ)
- separate signal/remaining BGs in
  - $p_\perp(D_s^-\mu^+)$ (transverse to the B_s^0 flight direction)
  - $m_{corr} = \sqrt{m^2(D_s^-\mu^+) + p_\perp^2(D_s^-\mu^+)} + p_\perp(D_s^-\mu^+)$
- white dashed line: cut for analysis (dashed-dotted for systematics)



preliminary, [LHCb-PAPER-2019-041] in preparation

partial reconstruction

- cannot fully reconstruct recoil variable w (for form factors!)
  - but $p_\perp(D_s^-)$ is a good proxy (white line: average)
  - $p_\perp(D_s^-)$ also has some small correlation with helicity angles $\cos\theta_D$ and $\cos\theta_\mu$

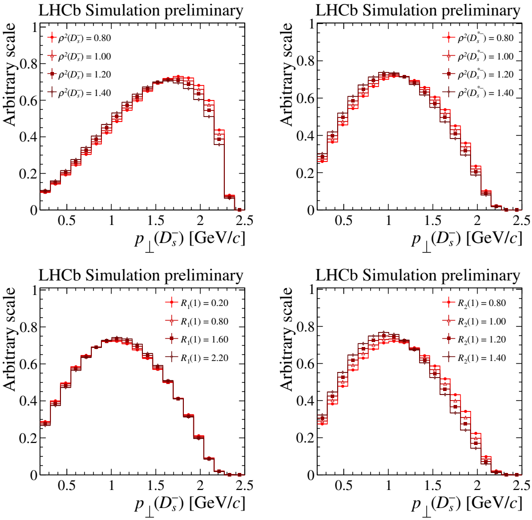


preliminary, [LHCb-PAPER-2019-041] in preparation

analysis strategy

- signal and reference yields from fit to 2D distribution of $p_\perp$, m_{corr}
  - use B_s^0 modes are signal
    - easier LQCD calculation due to heavier s quark
    - FF theory calculations available for whole q^2 spectrum
    - less contamination due to less contamination from partially reconstructed decays)
- 2D templates from simulation (signal, reference decays and physics bkg) and same-sign data (combinatorial bkg)
  - floating FF parameters used to rebuild the 2D templates for signal and reference decays at each fit iteration
- $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ yields expressed as a function of $|V_{cb}|$ by integrating over the respective differential decay rates (equations in 2 slides)
  - FF described by either the CLN or BGL parametrization, with some parameters constrained to their LQCD determinations
- all other yields left free to float in the fit

analysis strategy illustration

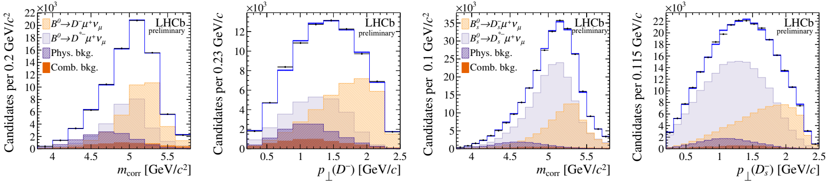


preliminary, [LHCb-PAPER-2019-041] in preparation

- recalculate 2D templates in $p_\perp$, m_{corr} for each FF parameter change

fit

- first, fit reference channel, keeping total signal yields floating $N_{ref}^{(*)}$



preliminary, [LHCb-PAPER-2019-041] in preparation

- for signal fit: express signal yields $N_{sig}^{(*)}$ in terms of $N_{ref}^{(*)}$:
  - $N_{sig}^{(*)} = N^{(*)}\tau \int \frac{d\Gamma(B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu)}{d\zeta} d\zeta$ where
    - $\zeta = \begin{cases} w & \text{for } B_s^0 \to D_s^- \mu^+ \nu_\mu \\ (w, \cos\theta_\mu, \cos\theta_D, \chi) & \text{for } B_s^0 \to D_s^{*-} \mu^+ \nu_\mu \end{cases}$
    - $N^{(*)} = \frac{N_{ref}^{(*)} \xi^{(*)} \mathcal{K}^{(*)}}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)}$, with $\xi^{(*)}$ efficiency ratio signal/reference mode
    - $K = \frac{f_s}{f_d} \frac{\mathcal{B}(D_s^- \to K^+K^-\pi^-)}{\mathcal{B}(D^- \to K^+K^-\pi^-)}$ and $K^* = \frac{f_s}{f_d} \frac{\mathcal{B}(D_s^- \to K^+K^-\pi^-)}{\mathcal{B}(D^{*-} \to D^- X)\mathcal{B}(D^- \to K^+K^-\pi^-)}$
    - take a f_s/f_d measurement from an independent data sample

results

external inputs (experimental/theory, preliminary):

Parameter	Value
$f_s/f_d \times b(D_s^- \to K^-K^+\pi^-) \times \tau$ [ps]	0.01913 ± 0.00076
$\mathcal{B}(D^- \to K^-K^+\pi^-)$	0.00993 ± 0.00024
$\mathcal{B}(D^{*-} \to D^-X)$	0.323 ± 0.006
$\mathcal{B}(B^0 \to D^-\mu^+\nu_\mu)$	0.0231 ± 0.0010
$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$	0.0505 ± 0.0014
B_s^0 mass [GeV/c^2]	5.36688 ± 0.00017
D_s^- mass [GeV/c^2]	1.96834 ± 0.00007
D_s^{*-} mass [GeV/c^2]	2.1122 ± 0.0004

Parameter	Value
η_{EW}	1.0066 ± 0.0050
$h_A(1)$	0.902 ± 0.013
CLN parametrisation	
$\mathcal{G}(0)$	1.073 ± 0.037
$\rho^2(D_s^-)$	1.299 ± 0.051
BGL parametrisation	
$\mathcal{G}(0)$	1.072 ± 0.037
d_1	-0.0117 ± 0.0081
d_2	-0.239 ± 0.048

preliminary, [LHCb-PAPER-2019-041] in preparation

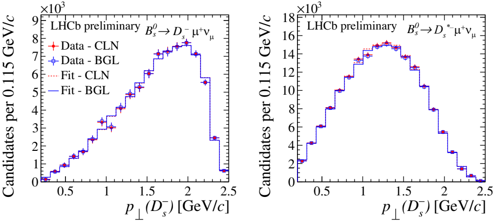
preliminary result:

CLN form factor fit

Parameter	Value
$|V_{cb}|$ [10^{-3}]	$41.4 \pm 0.6(stat) \pm 1.2(ext)$
$\mathcal{G}(0)$	$1.102 \pm 0.034(stat) \pm 0.004(ext)$
$\rho^2(D_s^-)$	$1.268 \pm 0.047(stat) \pm 0.001(ext)$
$\rho^2(D_s^{*-})$	$1.23 \pm 0.17(stat) \pm 0.01(ext)$
$R_1(1)$	$1.34 \pm 0.25(stat) \pm 0.02(ext)$
$R_2(1)$	$0.83 \pm 0.16(stat) \pm 0.01(ext)$

BGL form factor fit

Parameter	Value
$|V_{cb}|$ [10^{-3}]	42.3 ± 0.8 (stat) ± 1.2 (ext)
$\mathcal{G}(0)$	1.097 ± 0.034 (stat) ± 0.008 (ext)
d_1	-0.0172 ± 0.0074 (stat) ± 0.0007 (ext)
d_2	-0.256 ± 0.047 (stat) ± 0.002 (ext)
b_1	-0.060 ± 0.068 (stat) ± 0.013 (ext)
a_0	0.0374 ± 0.0086 (stat) ± 0.0008 (ext)
a_1	0.28 ± 0.26 (stat) ± 0.08 (ext)
c_1	0.0031 ± 0.0022 (stat) ± 0.0006 (ext)



preliminary, [LHCb-PAPER-2019-041] in preparation

systematics

Source	CLN: $\lvert V_{cb}\rvert$ $[10^{-3}]$	CLN: $\rho^2(D_s^-)$ $[10^{-2}]$	CLN: $\mathcal{G}(0)$ $[10^{-2}]$	CLN: $\rho^2(D_s^{*-})$ $[10^{-1}]$	CLN: $R_1(1)$ $[10^{-1}]$	CLN: $R_2(1)$ $[10^{-1}]$	BGL: $\lvert V_{cb}\rvert$ $[10^{-3}]$	BGL: d_1 $[10^{-3}]$	BGL: d_2 $[10^{-2}]$	BGL: $\mathcal{G}(0)$ $[10^{-2}]$	BGL: b_1 $[10^{-2}]$	BGL: c_1 $[10^{-3}]$	BGL: a_0 $[10^{-3}]$	BGL: a_1 $[10^{-1}]$
$f_s/f_d \times \mathcal{B}(D_s^- \to K^+K^-\pi^-)(\times\tau)$	0.8	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.3	0.0	0.2	0.1
$\mathcal{B}(D^- \to K^-K^+\pi^-)$	0.5	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.3	0.0	0.2	0.1
$\mathcal{B}(D^{*-} \to D^-X)$	0.2	0.0	0.1	0.0	0.1	0.0	0.1	0.2	0.0	0.1	0.5	0.2	0.5	0.3
$\mathcal{B}(B^0 \to D^-\mu^+\nu_\mu)$	0.4	0.1	0.3	0.1	0.2	0.1	0.5	0.6	0.1	0.1	1.3	0.4	1.1	0.7
$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$	0.3	0.1	0.2	0.1	0.1	0.1	0.2	0.4	0.1	0.1	0.8	0.3	0.7	0.4
$m(B_s^0)$, $m(D^{(*)-})$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.2	0.1
η_{EW}	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.0	0.2	0.1
$h_{A_1}(1)$	0.3	0.1	0.2	0.1	0.1	0.1	0.3	0.4	0.1	0.1	0.9	0.3	0.8	0.5
External inputs (ext)	1.2	0.1	0.4	0.1	0.2	0.1	1.2	0.7	0.2	0.8	1.3	0.6	0.8	0.8
$D^- \to K^+K^-\pi^-$ model	0.8	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Background	0.4	3.2	2.2	0.5	0.9	0.7	0.1	4.9	1.5	2.3	6.9	2.0	5.2	2.0
Fit bias	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	1.8	0.4	1.6	0.4
Corrections to simulation	0.0	0.1	0.5	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.2	0.1
Form-factor parametrization	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Experimental (syst)	0.9	3.2	2.2	0.5	0.9	0.7	0.9	4.9	1.5	2.3	7.2	2.1	5.4	2.0
Statistical (stat)	0.6	4.7	3.4	1.7	2.5	1.6	0.8	7.4	4.7	3.4	6.8	2.2	8.6	2.6

(All values are uncertainties; CLN = CLN parametrization, BGL = BGL parametrization.)

preliminary, [LHCb-PAPER-2019-041] in preparation

- largest systematic uncertainties on $|V_{cb}|$ from f_s/f_d and $D_{(s)}^- \to K^+K^-\pi^-$ model

summary

- novel approach for exclusive determination of $|V_{cb}|$:
  - exploit ratio $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu / B_d^0 \to D^{(*)-}\mu^+\nu_\mu$ to cancel systematics
  - template-based fit in $m_{corr} - p_\perp(D^-_{(s)})$ plane
    - helps to suppress BGs
    - express form-factor dependence in terms of observed quantities

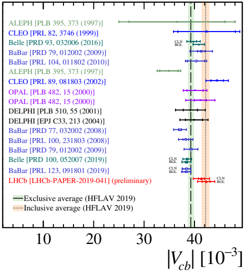
$|V_{cb}|$ (CLN) $= (41.4 \pm 0.6 \text{ (stat)} \pm 0.9 \text{ (syst)} \pm 1.2 \text{ (ext)}) \times 10^{-3}$

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

$$\frac{\mathcal{B}(B_s^0 \to D_s^- \mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^- \mu^+\nu_\mu)} = 1.093 \pm 0.054 \text{ (stat)} \pm 0.060 \text{ (syst)} \pm 0.051 \text{ (ext)}$$

$$\frac{\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+\nu_\mu)} = 1.059 \pm 0.047 \text{ (stat)} \pm 0.074 \text{ (syst)} \pm 0.053 \text{ (ext)}$$

preliminary, [LHCb-PAPER-2019-041] in preparation



preliminary, [LHCb-PAPER-2019-041] in preparation

- tension with inclusive average reduced
- consistent results from both FF parametrisations!
- stay tuned: paper will come out soon

conclusion

conclusion

conclusion

- LHCb continues to provide precision results in wide-ranging topics
  - precision CKM physics
  - spectroscopy
  - ...
- stay tuned:
  - run 2 data set is being more fully exploited by analyses
  - we're also busy building and commissioning the LHCb Upgrade
    - full detector read out at 40 MHz with higher pile-up
    - full software trigger running at full rate, important especially for hadronic channels
    - hope for an order of magnitude more in statistics