Semileptonic b decays at LHCb

Svende Braun
on behalf of the LHCb collaboration
University of Maryland

BEAUTY 2020
September 21-24, 2020

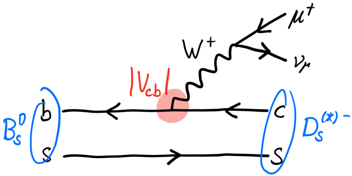
Semileptonic b decays

Advantages

- Large data samples:
  $\sim$ 10% of all B-decays
- Theoretically clean:
  hadronic and leptonic part factorizes
  $\rightarrow$ only 1 hadronic current parametrized by form factors

Challenges

- Partially reconstructed decays due to neutrino
- Large bkg contributions
- Huge simulation samples needed

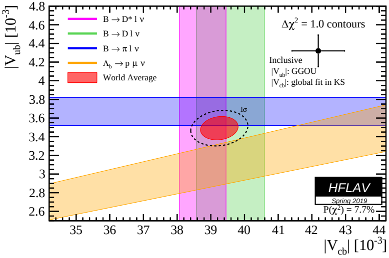


Most recent measurements covered today:

- Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ Phys. Rev. D101 072004
- Measurement of the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential distribution arXiv:2003.08453

Motivation

- Precisely measure CKM matrix elements
  $\rightarrow$ fundamental SM parameters
- Discrepancy between exclusive and inclusive $|V_{cb}|$ measurements: $\approx 3\sigma$ tension
  $\rightarrow$ new complementary measurements needed
- Exclusive determinations rely on form factors (FF)
    - Nonpertubative QCD calculations: Lattice QCD (LQCD) or QCD sum rules
    - Extracted in experimental measurements from data



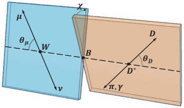
- B_s^0 decays are advantageous compared to $B^{0/+}$
    - Easier to calculate in LQCD due to heavier spectator quark $\rightarrow$ more precise predictions
    - Experimentally less backgrounds contamination (D_s^{**} feed down)

$B_s \to D_s^{(*)}\mu\nu$ form factors

- Functions of di-lepton momentum transfer squared q^2 or hadron recoil w: $w = \frac{m_B+m_D-q^2}{2m_Bm_D}$
- Differential decay rates:

$$\frac{d\Gamma(B_s\to D_s\mu\nu)}{dw} = \frac{G_F^2 m_{D_s}^3}{48\pi^3}(m_{B_s}+m_{D_s})^2\eta_{EW}^2|V_{cb}|^2(w^2-1)^{3/2}\underbrace{|\mathcal{G}(w)|^2}_{\hookrightarrow\text{one FF}}$$

$$\frac{d^4\Gamma(B_s\to D_s^*\mu^+\nu_\mu)}{dw\,d\cos\theta_\mu\,d\cos\theta_D\,d\chi} = \frac{3m_{B_s}^3 m_{D_s^*}^2 G_F^2}{16(4\pi)^4}\eta_{EW}^2|V_{cb}|^2 \quad \underbrace{|\mathcal{A}(w,\theta_\mu,\theta_D,\chi)|^2}_{\hookrightarrow 3\text{ FF: } h_{A1}(w), R_1(w), R_2(w)}$$



- At zero recoil point (q^2_{max}, $w=1$) FF can be computed precisely with LQCD, whereas experimental measurements done at different q^2 range

  → needs extrapolation, done through different FF parametrisations:
  - **CLN** (Caprini-Lellouch-Neubert) Nucl. Phys. B530 (1998) 153
  - **BGL** (Boyd-Grinstein-Lebed) Phys. Rev. Lett. 74 (1995) 4603

    → so far no significant differences observed

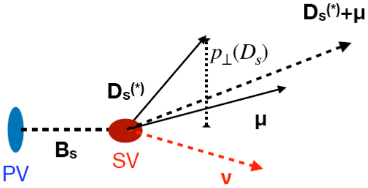
Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu$

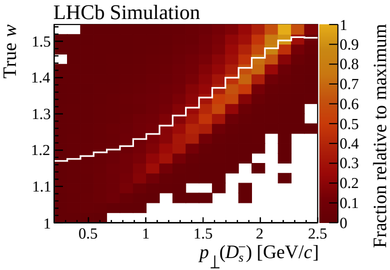
Phys. Rev. D101 072004

Measurement strategy

Phys. Rev. D101 072004

- Uses full Run 1 data (1 fb^{-1} @ 7 TeV + 2 fb^{-1} @ 8 TeV)
- Both decays $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ are reconstructed through $D_s(\to [KK]_\phi \pi)\mu$
- Normalized to $B^0 \to D^{(*)-}\mu^+\nu_\mu$ as kinematically similar decay
  $\to$ reduce systematic uncertainties, but needs as external input hadronization fraction f_s/f_d and measured branching fractions
- Measure $\mathcal{R}^{(*)} = \frac{\mathcal{B}(B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)}$ $\to$ extract $|V_{cb}|$ and branching fraction from that
- New idea: use variable $p_\perp(D_s^-)$ which is highly correlated with w and fully reconstructible

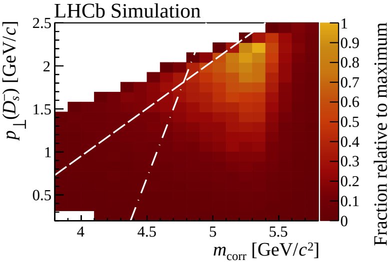




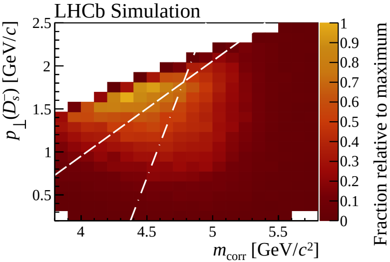
Signal and normalization fits

Phys. Rev. D101 072004

signal



double charm background

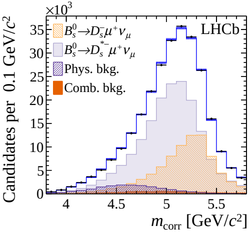


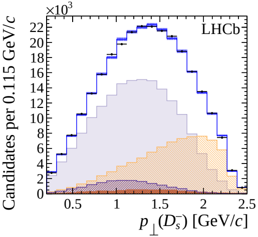
- Perform 2D template fit to $p_\perp(D_s)$ and corrected mass
  $m_{corr} = \sqrt{m^2(D_s\mu) + p_\perp^2(D_s\mu)} + p_\perp(D_s\mu)$
  $\rightarrow$ allows to discriminate between signal and different backgrounds
- Signal templates depend on form factors $\rightarrow$ recalculated at each fit iteration
  $\rightarrow$ fit also sensitive to FF parameters
  $\rightarrow$ use both parametrisations CLN and BGL
- simultaneous fit to signal and normalisation decays

Signal fit results

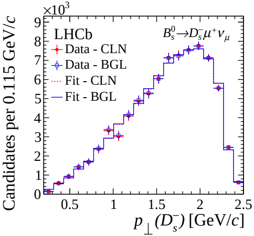
- Signal fit using CLN parametrisation:

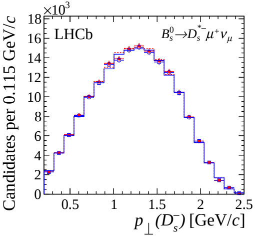
Phys. Rev. D101 072004





- Background-subtracted distributions of D_s and D_s^*



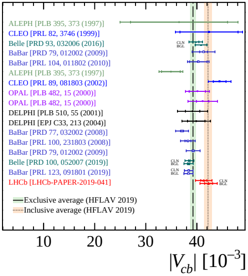


→ good agreement between CLN and BGL

Results

Phys. Rev. D101 072004

- $|V_{cb}|_{CLN} = (41.6 \pm 0.6(stat) \pm 0.9(syst) \pm 1.2(ext)) \times 10^{-3}$
- $|V_{cb}|_{BGL} = (42.3 \pm 0.8(stat) \pm 0.9(syst) \pm 1.2(ext)) \times 10^{-3}$
  $\rightarrow$ both are in agreement with each other
  $\rightarrow$ confirms trend that parametrisation not responsible for inclusive vs exclusive disagreements



$\rightarrow$ Both results are in agreement with previous exclusive and inclusive $|V_{cb}|$ determinations

$\rightarrow$ First exclusive $|V_{cb}|$ measurement at hadron collider and using B_s mesons

Exclusive branching fractions

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

$\rightarrow$ dominant uncertainty comes from external inputs f_s/f_d, then $D_s \rightarrow KK\pi$ Dalitz structure

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

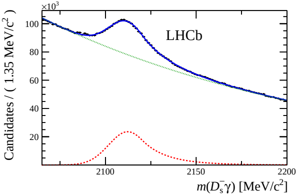
arXiv:2003.08453

Measurement strategy

arXiv:2003.08453

- Uses Run 2 data from 2016 (1.7 fb^{-1} @ 13 TeV)
- Aim to measure $B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$ FF more precisely using CLN and BGL parametrisations
- Reconstruct $B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$ through $D_s^{*-} \to D_s^- \gamma$
  - $D_s^- \to \phi(\to K^+ K^-)\pi-$
  - $D_s^- \to K^{*0}(\to K^+ \pi^-)K^-$

  $\to$ Reconstruct soft photon in cone around D_s^- flight direction
  $\to$ fit to D_s^{*-} mass removes background

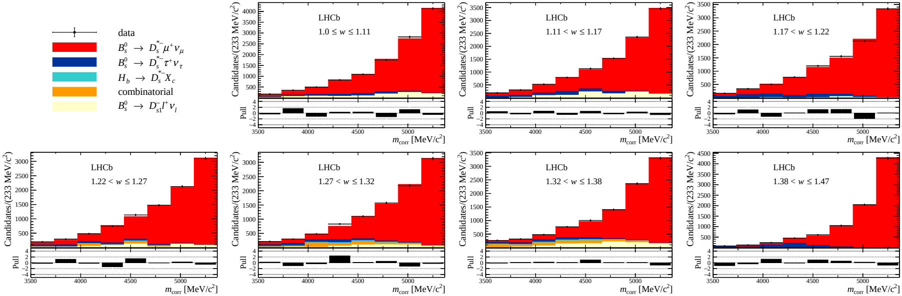


- Measure differential decay rate as function of w, integrate out angles due to small FF dependence
  $\to$ template fit to corrected mass in bins of w using simulation
- Correct raw yields for detector resolution (unfolding), selection and reconstruction efficiencies
  $\to$ fit resulting spectrum with CLN and BGL parametrisations

Signal fits

arXiv:2003.08453

- Extended binned maximum-likelihood fit in 7 bins of w to extract raw yields
  $\rightarrow$ w binning chosen to have same amount of signal yield
- w known up to quadratic ambiguity $\rightarrow$ use MVA regression method JHEP 02 (2017) 021 to select solution with 70% purity
- Backgrounds coming from semitaounic B_s decays, double charm decays, feed-down from higher excited D_s^{*-} and combinatorial background from SS data

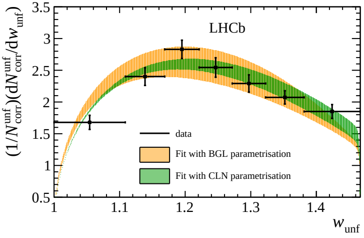


Form factor Fit

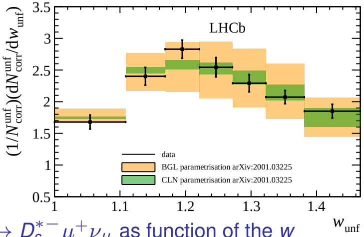
arXiv:2003.08453

- Measured w spectrum must be unfolded and corrected using bin-by-bin efficiencies for FF fit
  $\rightarrow$ CLN and BGL parametrisations consistent with each other and data
- Leading FF results:
  - CLN:
    $\rho^2 = 1.16 \pm 0.05(stat) \pm 0.07(syst)$
  - BGL:
    $a_1^f = -0.002 \pm 0.034(stat) \pm 0.046(syst)$,
    $a_2^f = 0.93^{+0.05}_{-0.20}(stat)^{+0.06}_{-0.38}(syst)$

  $\rightarrow$ systematically limited measurement, mainly from simulation statistics



$\rightarrow$ Values agree with HFLAV world average from $B^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu$
$\rightarrow$ Consistent results with previously discussed analysis Phys. Rev. D101 072004



$\rightarrow$ First unfolded normalised differential decay rate for $B_s^0 \rightarrow D_s^{*-}\mu^+\nu_\mu$ as function of the w

Conclusion

- Two most recent semileptonic measurements from LHCb on B_s meson decays

- First exclusive $|V_{cb}|$ measurement at hadron collider and using B_s mesons
  - Result in agreement with previous exclusive and inclusive measurements from B^0 and B^+ decays
  - measured branching fraction of $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ for the first time

  $\to$ Techniques exported to different decay channels can lead to more precise $|V_{cb}|$ values

- First measurement of the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate
  - Data consistent with both CLN and BGL FF parametrisations
  - Obtained FF values in agreement with world-average from HFLAV assuming SU(3) symmetry and with previous analysis

  $\to$ Paves the way towards future $R(D_s^{(*)})$ measurements

More semileptonic B_s results about to come
$\to$ B_c decays are also being investigated

Thanks for your attention!

You can also contact me via svende.braun@cern.ch

Backup Slides

CLN parametrisation

based on Heavy Quark Effective Theory $\rightarrow$ includes more constraints: dispersion relations and reinforced unitarity bounds $\rightarrow$ simplified FF expression

for **vector case**:

$$\begin{aligned} h_{A1}(w) &= h_{A1}(1)[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3] \\ R_1(w) &= R_1(1) - 0.12(w-1) + 0.05(w-1)^2 \\ R_2(w) &= R_2(1) - 0.11(w-1) - 0.06(w-1)^2 \end{aligned}$$

with $z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$
$\rightarrow$ form factors depend on 4 parameters: ρ^2, $R_1(1)$, $R_2(1)$ and $h_{A1}(1)$, $h_{A1}(1)$ taken from LQCD

for **scalar case**:

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

$\rightarrow$ form factors expressed in terms of ρ^2 and $\mathcal{G}(0)$, $\mathcal{G}(0)$ taken from LQCD

BGL parametrisation

follows from more general arguments based on dispersion relations, analyticity and crossing symmetry, form factors expressed as series expansion:

in **vector case** 3 series:

$$f(z) = \frac{1}{P_{1+}(z)\phi_f(z)} \sum_{i=0}^{N} b_i z^i,\ g(z) = \frac{1}{P_{1-}(z)\phi_g(z)} \sum_{i=0}^{N} a_i z^i,\ \mathcal{F}_1(z) = \frac{1}{P_{1+}(z)\phi_{\mathcal{F}_1}(z)} \sum_{i=0}^{N} c_i z^i$$

for 3 FF:

$$h_{A1}(w) = \frac{f(w)}{\sqrt{m_B m_{D*}}(1+w)},\ R_1(w) = (1+w) m_B m_{D*} \frac{g(w)}{f(w)},\ R_2(w) = \frac{w-r}{w-1} - \frac{\mathcal{F}_1(w)}{m_B(w-1)f(w)}$$

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

in **scalar case** 1 series for 1 FF:

$$f_+(z) = \frac{1}{P_{1-}(z)\phi(z)} \sum_{i=0}^{N} d_i z^i,\ |\mathcal{G}(z)|^2 = \frac{4r}{(1+r)^2} |f_+(z)|^2 \text{ with } r = m_D/m_B$$

$P_{1\pm}(z)$ Blaschke factors and $\phi_{f,g,\mathcal{F}_1}(z)$ so-called outer functions

$\rightarrow$ coefficients of series a_i, b_i, c_i, d_i to be determined, either from data or calculations, bound by unitarity constraints, with small ranges for z series converge fast

Selection for Phys. Rev. D101 072004

- Selection closely follows paper Phys. Rev. Lett. 119 101801
- Apply vetoes to suppress misID bkg:
  - $B_s \to \psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ where muon misid. as kaon
  - $\Lambda_b \to \Lambda_c(\to pK^-\pi^+)\mu\nu X$ where the proton is mis-identified as a kaon or a pion
  - $B^0_{(s)} \to D^-_{(s)}\pi^+$ with pion is mis-identified as muon
- Suppress partially reconstructed background via $p_\perp(D_s) < 1.5 + 1.1 \times (m_{corr} - 4.5))$

  $\to$ 2.72x10^5 signal and 0.82x10^5 normalization channel candidates remain
- remaining background from D_s^{**} feed-down such as $D^*_{s0}(2317)^-$,$D_{s1}(2460)^-$, semitauonic B_s decays, double charm decays

  $\to$ very similar shape therefore merged together as 'physics background' in signal fit

Complete fit results for Phys. Rev. D101 072004

CLN parametrization

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)

BGL parametrization

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)

external inputs:

experiment

Parameter	Value
$f_s/f_d \times \mathcal{B}(D_s^- \to K^-K^+\pi^-) \times \tau$ [ps]	0.0191 ± 0.0008
$\mathcal{B}(D^- \to K^-K^+\pi^-)$	0.00993 ± 0.00024
$\mathcal{B}(D^{*-} \to D^- X)$	0.323 ± 0.006
$\mathcal{B}(\ \mathrm{B}\ ^0 \to D^-\mu^+\nu_\mu)$	0.0231 ± 0.0010
$\mathcal{B}(\ \mathrm{B}\ ^0 \to D^{*-}\mu^+\nu_\mu)$	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

theory

Parameter	Value
η_{EW}	1.0066 ± 0.0050
$h_{A_1}(1)$	0.902 ± 0.013
CLN parametrization	
$\mathcal{G}(0)$	1.07 ± 0.04
$\rho^2(D_s^-)$	1.23 ± 0.05
BGL parametrization	
$\mathcal{G}(0)$	1.07 ± 0.04
d_1	-0.012 ± 0.008
d_2	-0.24 ± 0.05

Systematic uncertainties for Phys. Rev. D101 072004

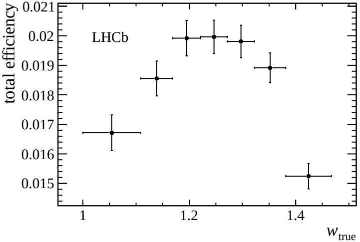
Source	Uncertainty															
	CLN parametrization						BGL parametrization									
	$\lvert V_{cb}\rvert$ $[10^{-3}]$	$\rho^2(D_s^-)$ $[10^{-1}]$	$\mathcal{G}(0)$ $[10^{-2}]$	$\rho^2(D_s^{*-})$ $[10^{-1}]$	$R_1(1)$ $[10^{-1}]$	$R_2(1)$ $[10^{-1}]$	$\lvert V_{cb}\rvert$ $[10^{-3}]$	d_1 $[10^{-2}]$	d_2 $[10^{-1}]$	$\mathcal{G}(0)$ $[10^{-2}]$	b_1 $[10^{-1}]$	c_1 $[10^{-3}]$	a_0 $[10^{-2}]$	a_1 $[10^{-1}]$	$\mathcal{R}$ $[10^{-1}]$	$\mathcal{R}^*$ $[10^{-1}]$
$f_s/f_d \times \mathcal{B}(D_s^- \to K^+K^-\pi^-)(\times\tau)$	0.8	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.4
$\mathcal{B}(D^- \to K^-K^+\pi^-)$	0.5	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.3
$\mathcal{B}(D^{*-} \to D^-X)$	0.2	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.0	0.2	0.0	0.3	–	0.2
$\mathcal{B}(B^0 \to D^-\mu^+\nu_\mu)$	0.4	0.0	0.3	0.1	0.2	0.1	0.5	0.1	0.0	0.1	0.1	0.4	0.1	0.7	–	–
$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$	0.3	0.0	0.2	0.1	0.1	0.1	0.2	0.0	0.0	0.1	0.1	0.3	0.1	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	0.0	0.0	0.0	0.1	–	–
η_{EW}	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	–	–
$h_{A_1}(1)$	0.3	0.0	0.2	0.1	0.1	0.1	0.3	0.0	0.0	0.1	0.1	0.3	0.1	0.5	–	–
External inputs (ext)	1.2	0.0	0.4	0.1	0.2	0.1	1.2	0.1	0.0	0.1	0.1	0.6	0.1	0.8	0.5	0.5
$D_{(s)}^- \to K^+K^-\pi^-$ 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	0.5	0.4
Background	0.4	0.3	2.2	0.5	0.9	0.7	0.1	0.5	0.2	2.3	0.7	2.0	0.5	2.0	0.4	0.6
Fit bias	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.4	0.2	0.4	0.0	0.0
Corrections to simulation	0.0	0.0	0.5	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0
Form-factor parametrization	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.1
Experimental (syst)	0.9	0.3	2.2	0.5	0.9	0.7	0.9	0.5	0.2	2.3	0.7	2.1	0.5	2.0	0.6	0.7
Statistical (stat)	0.6	0.5	3.4	1.7	2.5	1.6	0.8	0.7	0.5	3.4	0.7	2.2	0.9	2.6	0.5	0.5

Complete fit results for arXiv:2003.08453

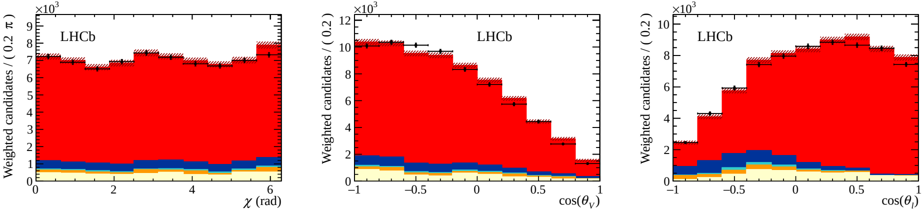
different fit results

CLN fit	
Unfolded fit	$\rho^2 = 1.16 \pm 0.05 \pm 0.07$
Unfolded fit with massless leptons	$\rho^2 = 1.17 \pm 0.05 \pm 0.07$
Folded fit	$\rho^2 = 1.14 \pm 0.04 \pm 0.07$
BGL fit	
Unfolded fit	$a_1^f = -0.002 \pm 0.034 \pm 0.046$ $a_2^f = 0.93^{+0.05}_{-0.20}{}^{+0.06}_{-0.38}$
Folded fit	$a_1^f = 0.042 \pm 0.029 \pm 0.046$ $a_2^f = 0.93^{+0.05}_{-0.20}{}^{+0.06}_{-0.38}$

total efficiency dependence



cross check: data-MC comparisons after fit using fitted fractions



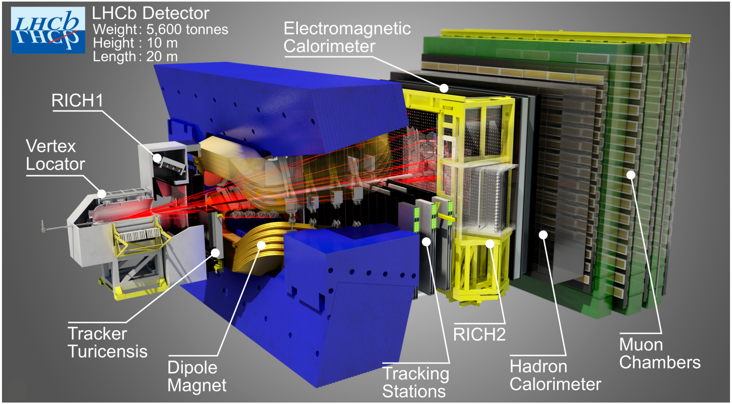
→ MC describes angular distributions well!

Systematic uncertainties for arXiv:2003.08453

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	$^{+0.05}_{-0.20}$

LHCb Detector

JINST 3 S08005 (2008), Int. J. Mod. Phys. A 30, 1530022 (2015)



- VELO: primary and secondary vertex
- Tracking: momentum of charged particle
- RICHs: particle identification $K^{\pm}$, $\pi^{\pm}$

- MUON: trigger on high p_{T} $\mu^{\pm}$ & PID
- Calorimeter: ECAL and HCAL for γ, $e^{\pm}$ and hadronic energy