

Measurements of CKM matrix elements

Tasting a strange flavor in the $|V_{cb}|$ puzzle



Fabio Ferrari on behalf of the LHCb collaboration

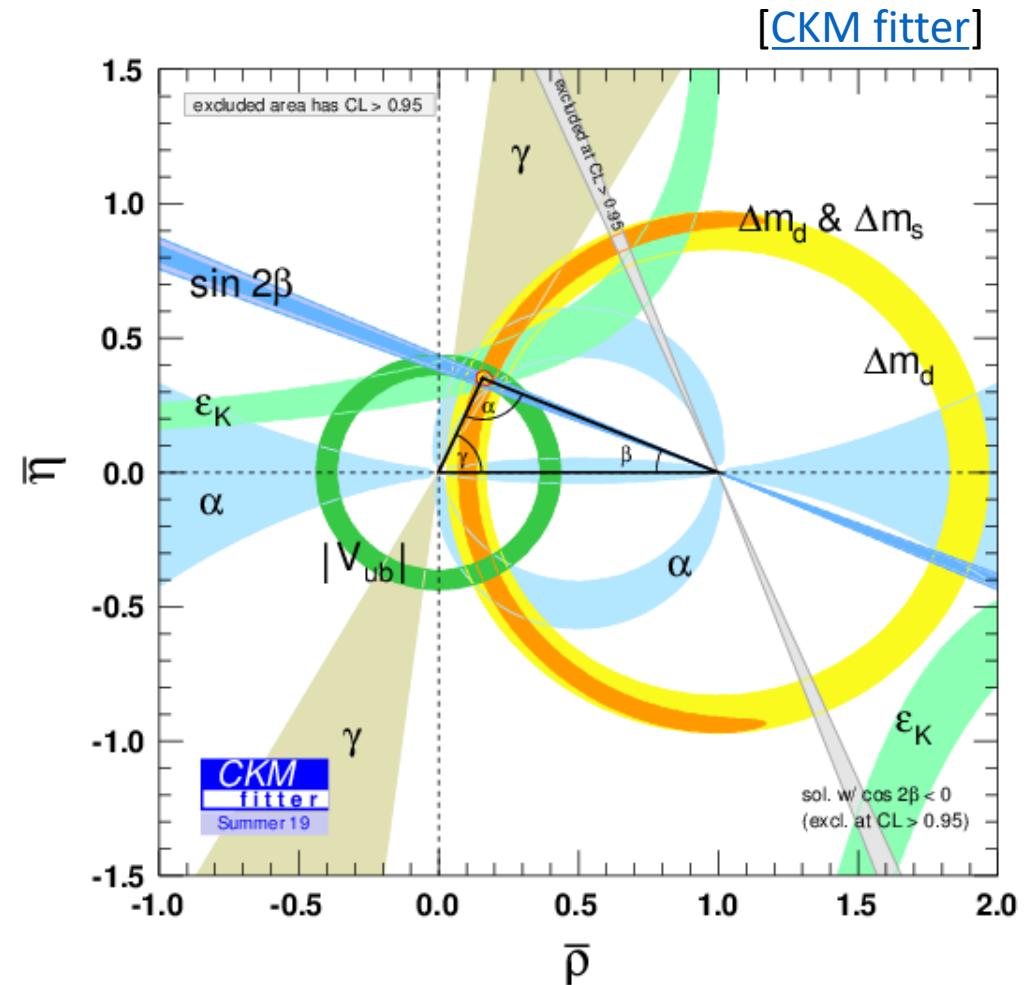
University of Bologna and INFN

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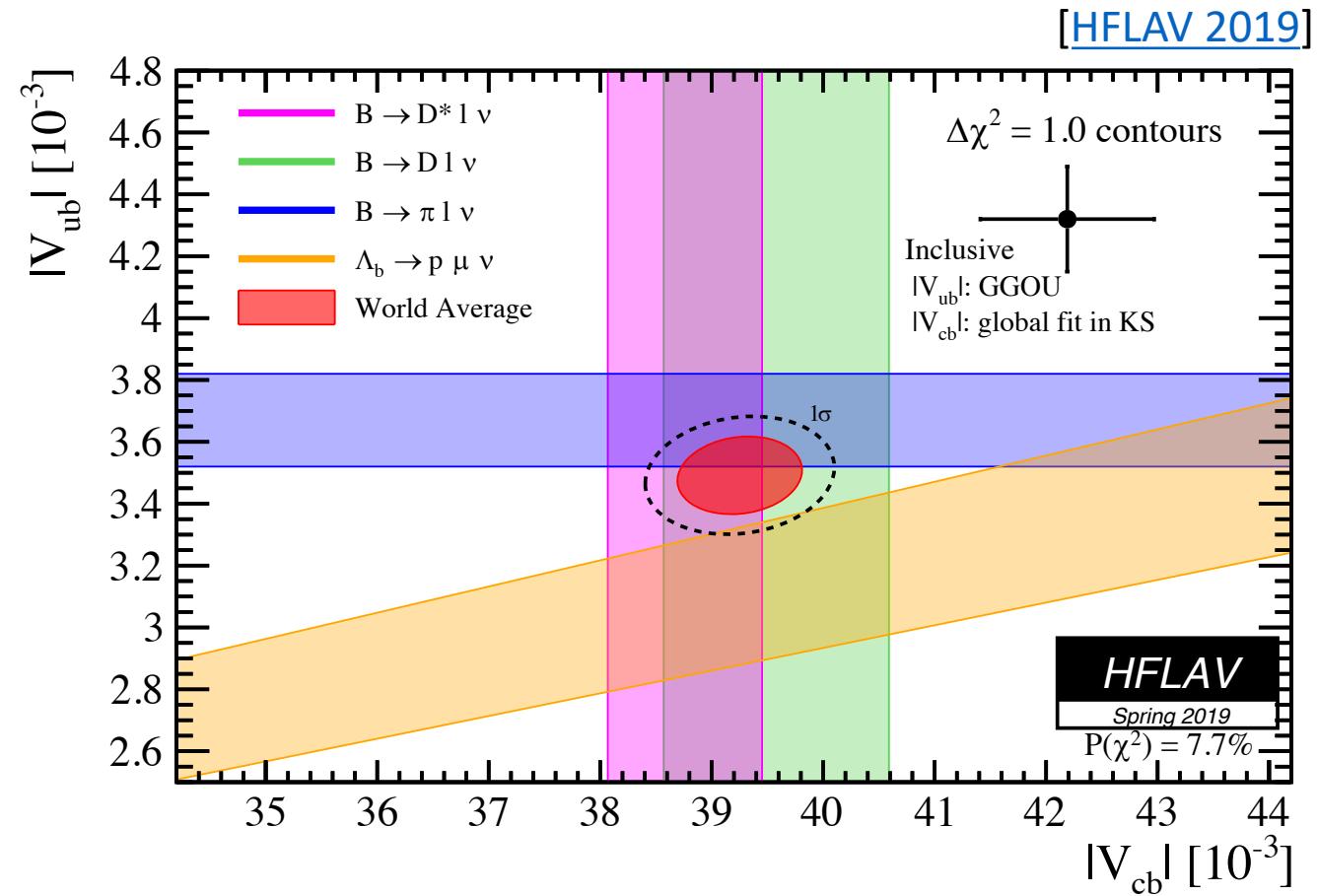
Status so far

- CKM paradigm tested to a **very high precision** by several independent measurements
- B decays are exploited in **many ways**
 - CKM angles from CPV measurements are getting more and more precise
 - $|V_{td}|$ and $|V_{ts}|$ are constrained by oscillation measurements (limited by theory uncertainties)
 - $|V_{cb}|$ and $|V_{ub}|$ from semileptonic decays (main players: b-factories), long standing puzzle



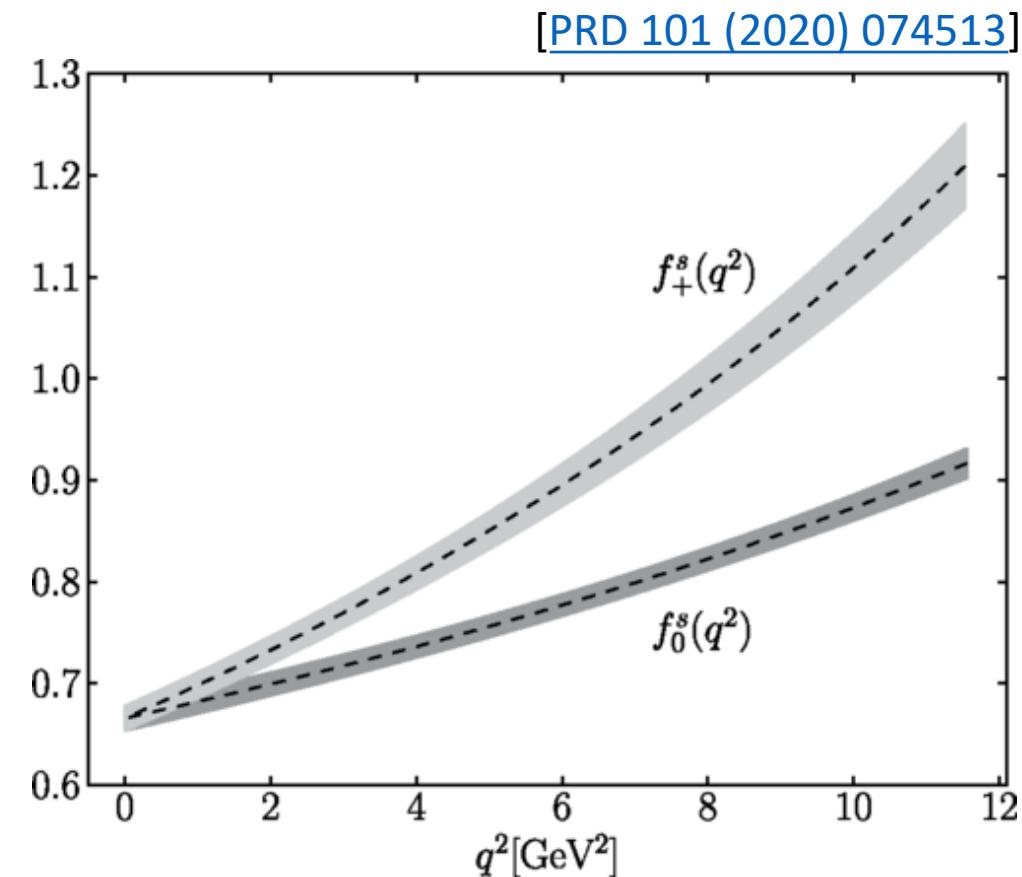
Inclusive vs exclusive

- b-factories performed several measurements with B^0/B^- decays
- First step into the field by LHCb: $|V_{ub}|/|V_{cb}|$ with Λ_b^0 decays*
 - Different systematic uncertainties
 - Independent information
- Also B_s^0 decays can be exploited for $|V_{ub}|(B_s^0 \rightarrow K^{(*)}\mu\nu)$ and $|V_{cb}|(B_s^0 \rightarrow D_s^{(*)}\mu\nu)$



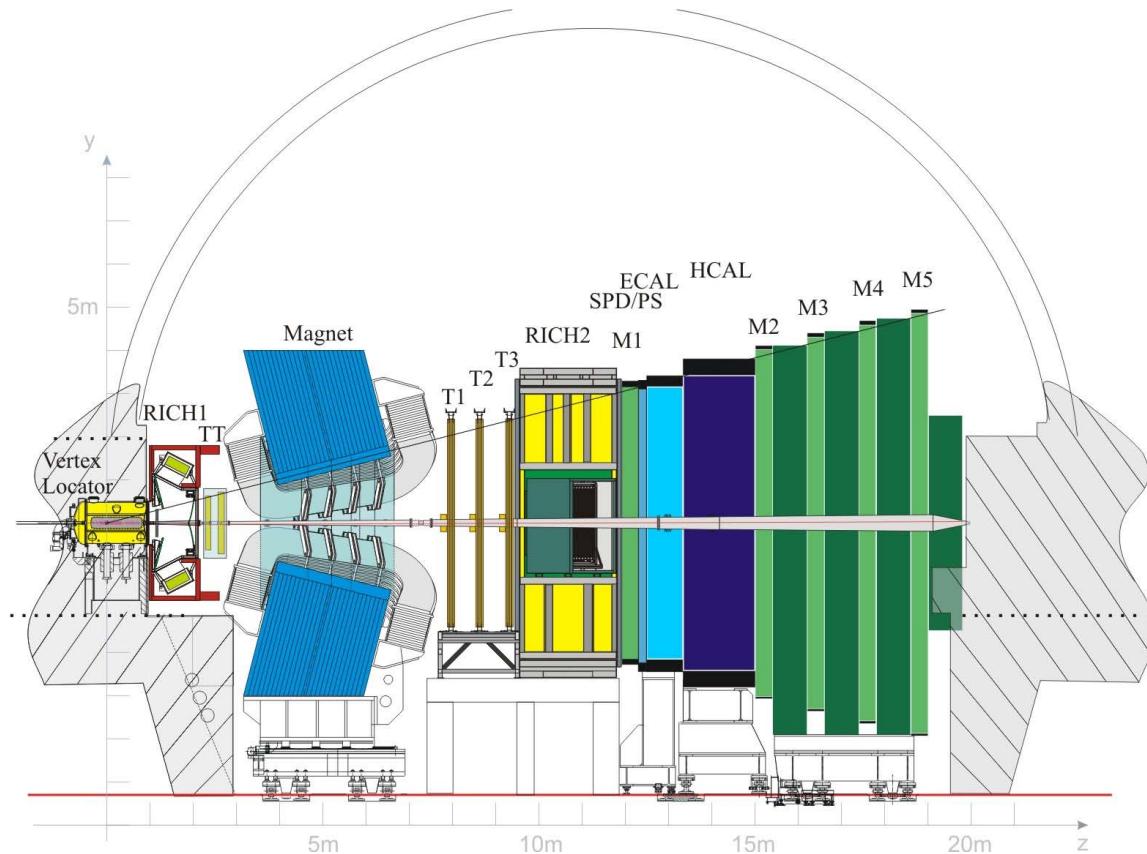
Interplay with theory

- Lattice QCD calculations are promising, will have very good precision on B_s^0 form-factors to extract $|V_{cb}|$ (see talk by Oliver Witzel)
- Form factors for $B_s^0 \rightarrow D_s^- \mu \nu$ available over full q^2 spectrum*
- Form factors for $B_s^0 \rightarrow D_s^{*-} \mu \nu$ measured with a good precision at zero-recoil**



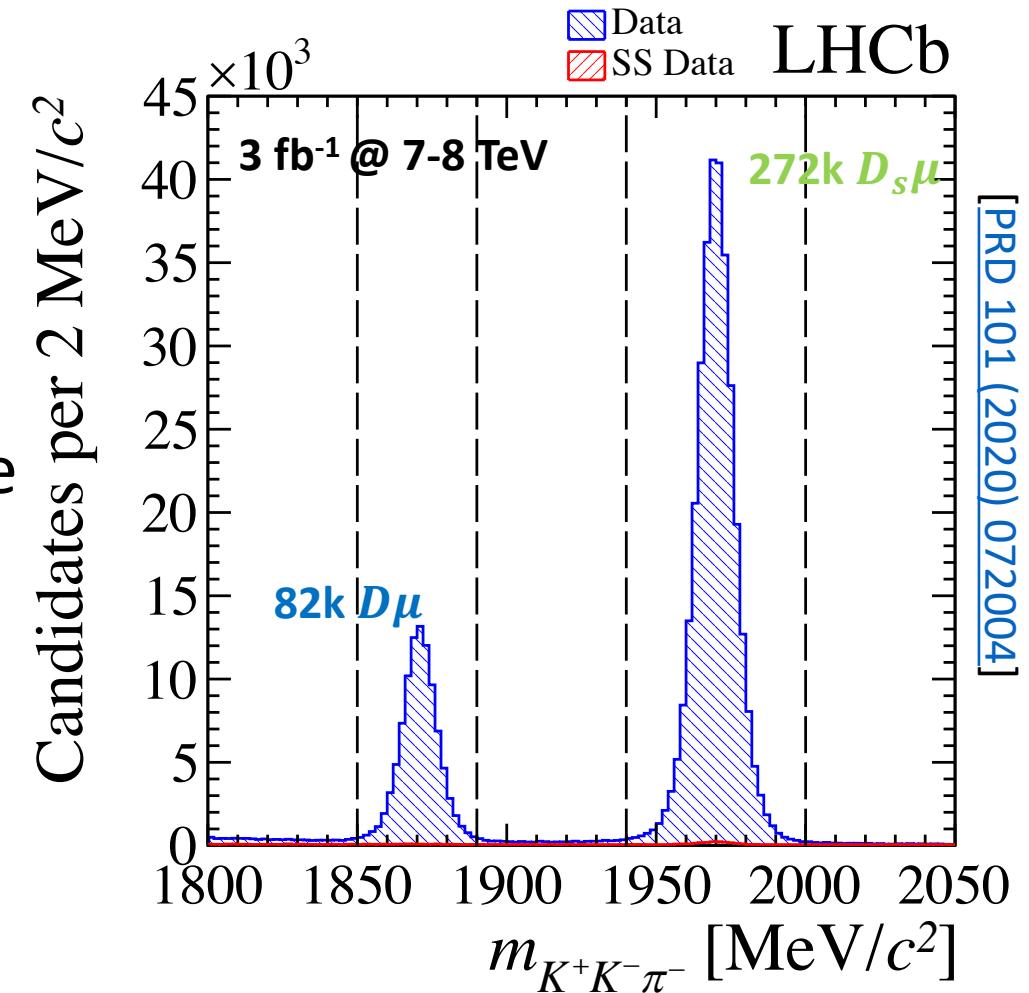
LHCb performance

- Collected 9 fb^{-1} @ 7, 8 and 13 TeV in 6 years of data-taking
 - About $10^{10} B_s^0$ per fb^{-1} produced
- 1 kHz of reconstructible B_s^0 are interesting for physics
 - Selected mainly thanks to the **muons**, requiring p_T and **displacement from primary vertex**
- Results: **hundreds of thousands of B_s^0 candidates** saved on disk and available for physics analyses
- All of this paves way towards a measurement of $|V_{cb}|$ with $B_s^0 \rightarrow D_s^{(*)} \mu\nu$ decays



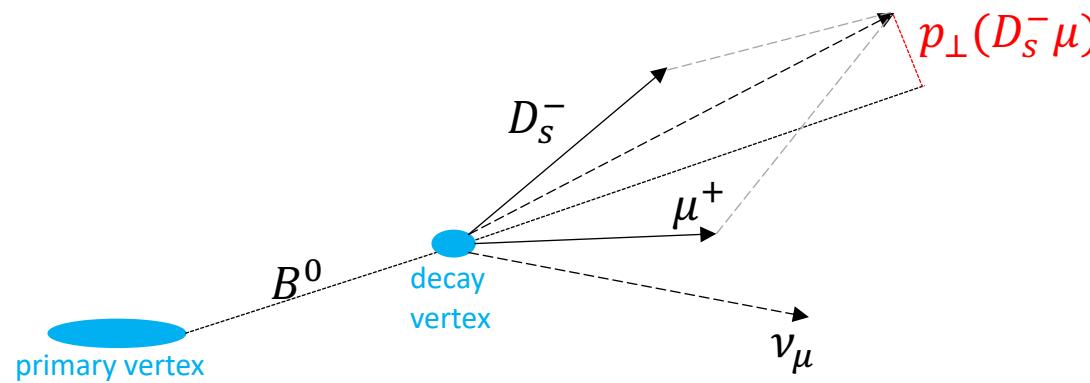
Strategy & dataset

- Imprecise knowledge of the collected integrated luminosity and $pp \rightarrow bbX$ cross-section* would **limit precision** on $|V_{cb}|$ at O(5-8%)
- Systematic uncertainty from this could be **greatly reduced** by using a normalisation channel: $B^0 \rightarrow D^{(*)}\mu\nu$ reconstructed in the **same visible final state** $[KK\pi]\mu$
- Need to plug in ratio of hadronization fractions (f_s/f_d)**
- Precision: 5% \rightarrow 2.5% uncertainty on $|V_{cb}|$

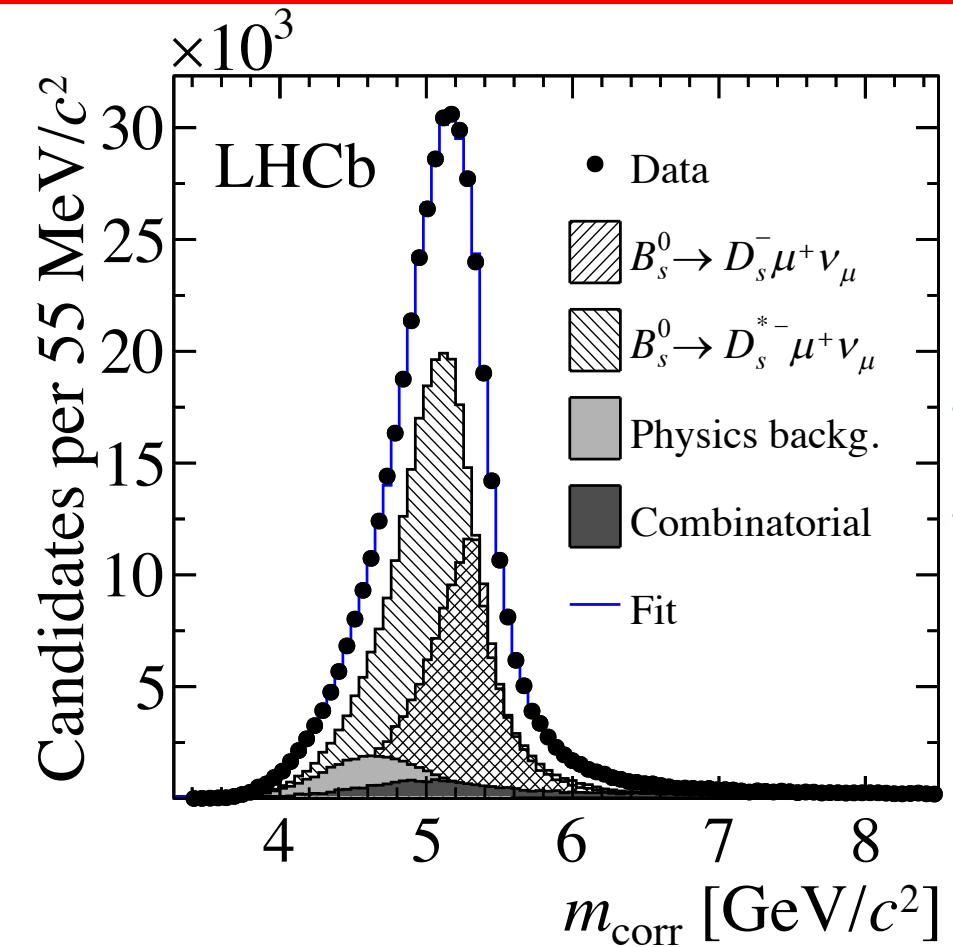


Separating signal from background

- Due to unreconstructed neutrino, cannot have clear B_s^0 peak (unlike b-factories)
 - Difficult to separate signal from background
- LHCb already overcame this challenge by employing the **corrected mass***



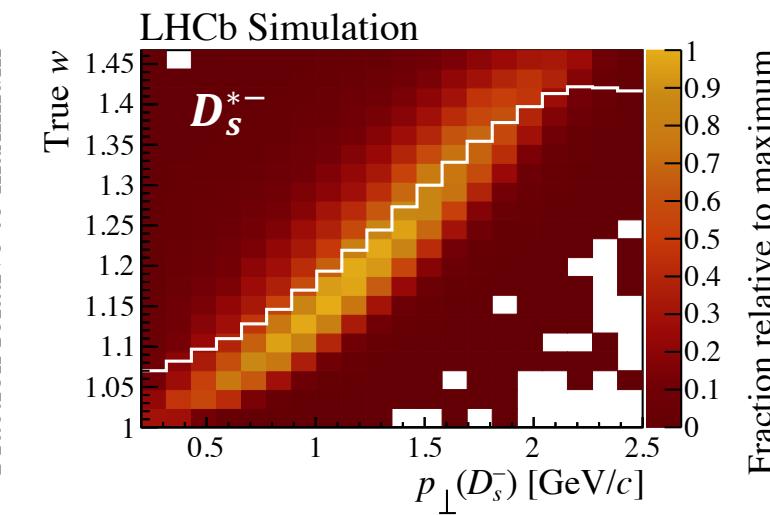
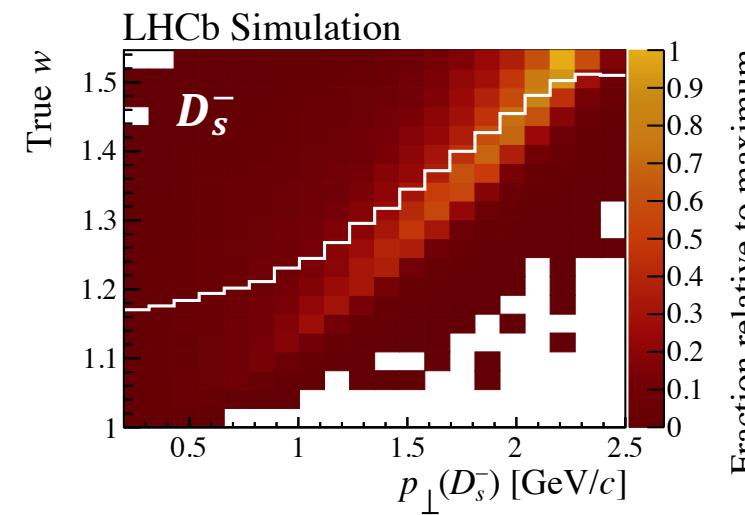
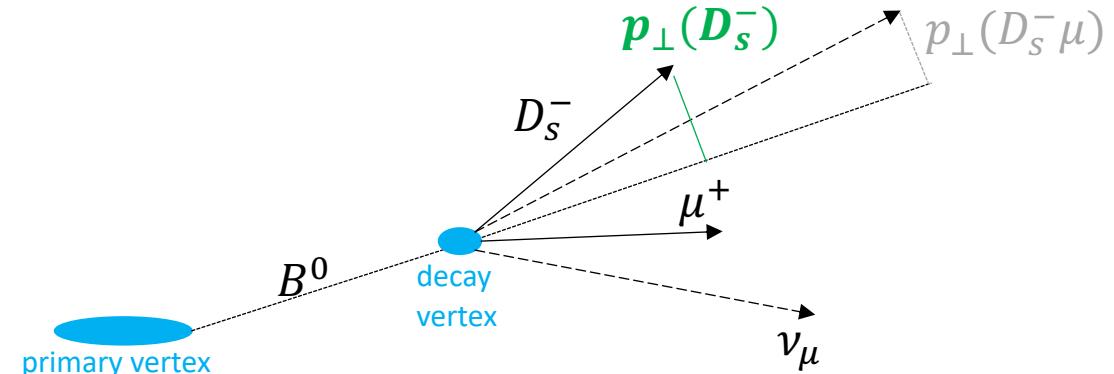
$$m_{\text{corr}} \equiv \sqrt{m^2(D_s^- \mu^+) + p_\perp^2(D_s^- \mu^+)} + p_\perp(D_s^- \mu^+)$$



A new approach

- $|V_{cb}|$ obtained from measurement of decay rate as a function of **recoil w**
 - Need to approximate it due to missing neutrino
- **New idea: exploit $p_\perp(D_s^-)$, which is fully reconstructed and highly correlated with w**
- Form factors are functions of $w \rightarrow$ possible to measure them

$$w = (m_B^2 + m_{D^{(*)}}^2 - q^2)/(2m_B m_{D^{(*)}})$$



Differential decay rate

- Analyse inclusive sample of $D_s^- \mu$ (D_s^{*-} partially reconstructed)
- 2D fit of m_{corr} and $p_\perp(D_s^-)$ to determine $|V_{cb}|$ and form factors
 - Use 2D templates built from simulation, accounting for efficiency $\varepsilon(m_{corr}, p_\perp(D_s^-))$

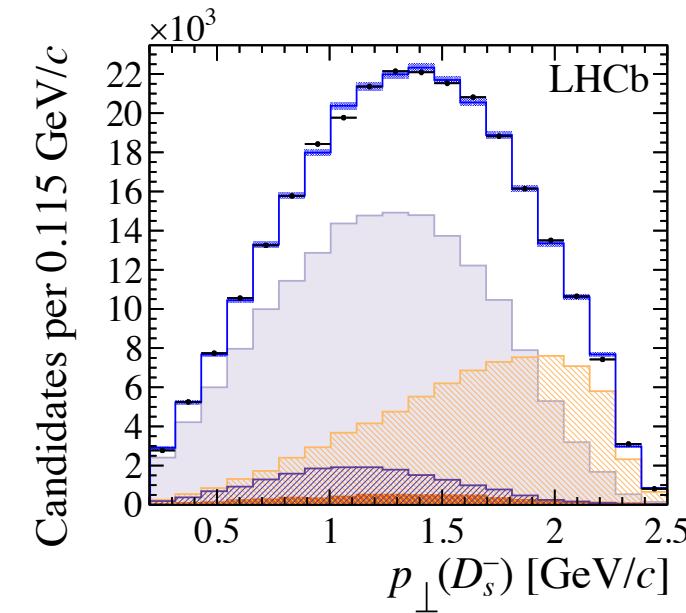
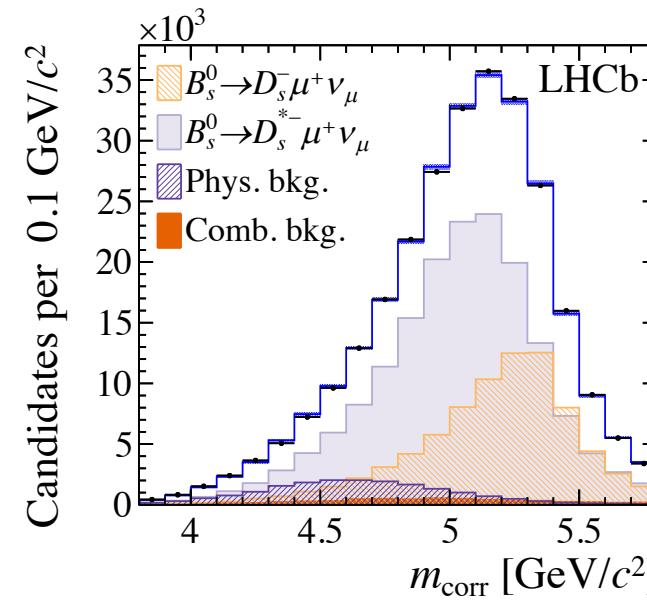
$$\frac{dN_{obs}}{dm_{corr} dp_\perp(D_s^-)} = \kappa \frac{d\Gamma(|V_{cb}|, h_{A_1}, \dots)}{dm_{corr} dp_\perp(D_s^-)} \varepsilon(m_{corr}, p_\perp(D_s^-))$$

- Constrain form factors from lattice QCD*,** to gain precision on $|V_{cb}|$
- Factor κ contains measured B^0 reference yields, input branching fractions, f_s/f_d and B_s^0 lifetime

Results

- Need to choose form factor parameterisation to determine $|V_{cb}|$
 - General model from Boyd, Grinstein and Lebed (BGL, [PRL 74 \(1995\) 4603](#))

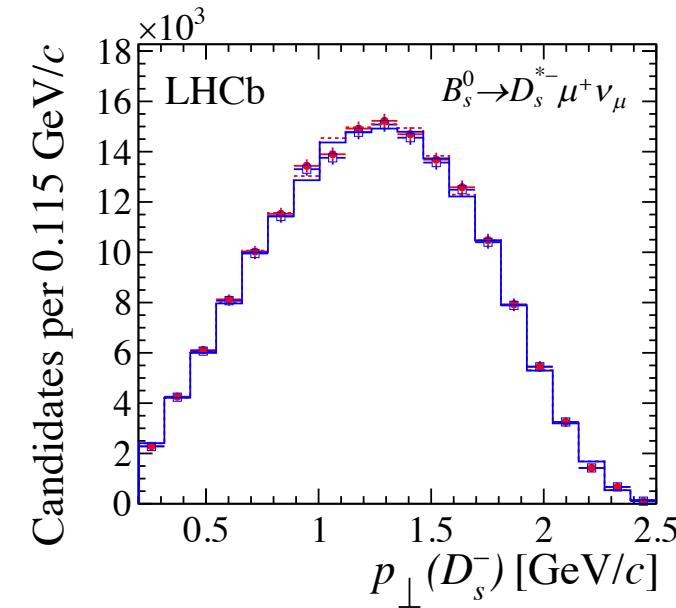
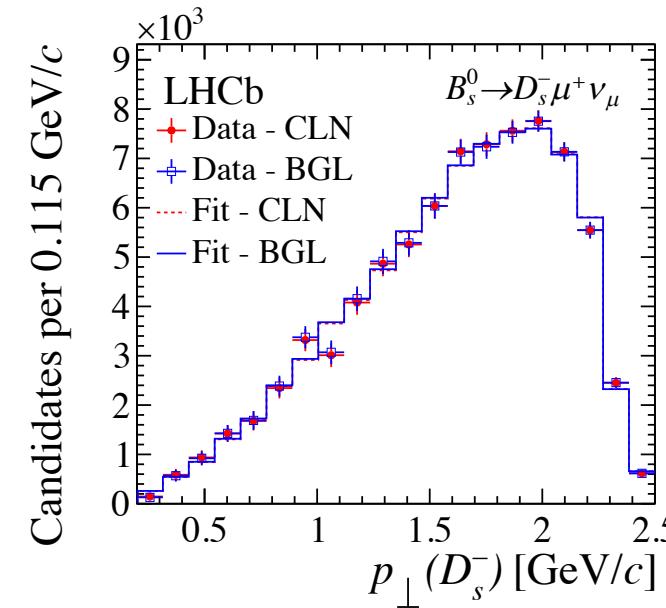
$$|V_{cb}| = (42.3 \pm 0.8 \text{ (stat)} \pm 0.9 \text{ (syst)} \pm 1.2 \text{ (ext)}) \times 10^{-3}$$



Comparing different parameterisations

- Perform fit also using Caprini, Lellouch and Neubert parameterisation (CLN, [NPB 530 \(1998\) 153](#)) → no significant difference found

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



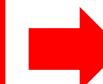
Systematic uncertainties and BR measurement

- **Dominant uncertainty:** external inputs, 3% relative on $|V_{cb}|$ (mostly due to f_s/f_d)
- 2nd dominant: knowledge of $D_{(s)}^- \rightarrow KK\pi$ Dalitz structure, 2% relative on $|V_{cb}|$
- Additional result of the analysis, **first measurement of relative BR**

$$\frac{\mathcal{B}(B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \rightarrow D^- \mu^+ \nu_\mu)} = 1.09 \pm 0.05 \text{ (stat)} \pm 0.06 \text{ (syst)} \pm 0.05 \text{ (ext)}$$

$$\frac{\mathcal{B}(B_s^0 \rightarrow D_s^{*-} \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)} = 1.06 \pm 0.05 \text{ (stat)} \pm 0.07 \text{ (syst)} \pm 0.05 \text{ (ext)}$$

$$\frac{\mathcal{B}(B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \rightarrow D_s^{*-} \mu^+ \nu_\mu)} = 0.464 \pm 0.013 \text{ (stat)} \pm 0.043 \text{ (syst)}$$

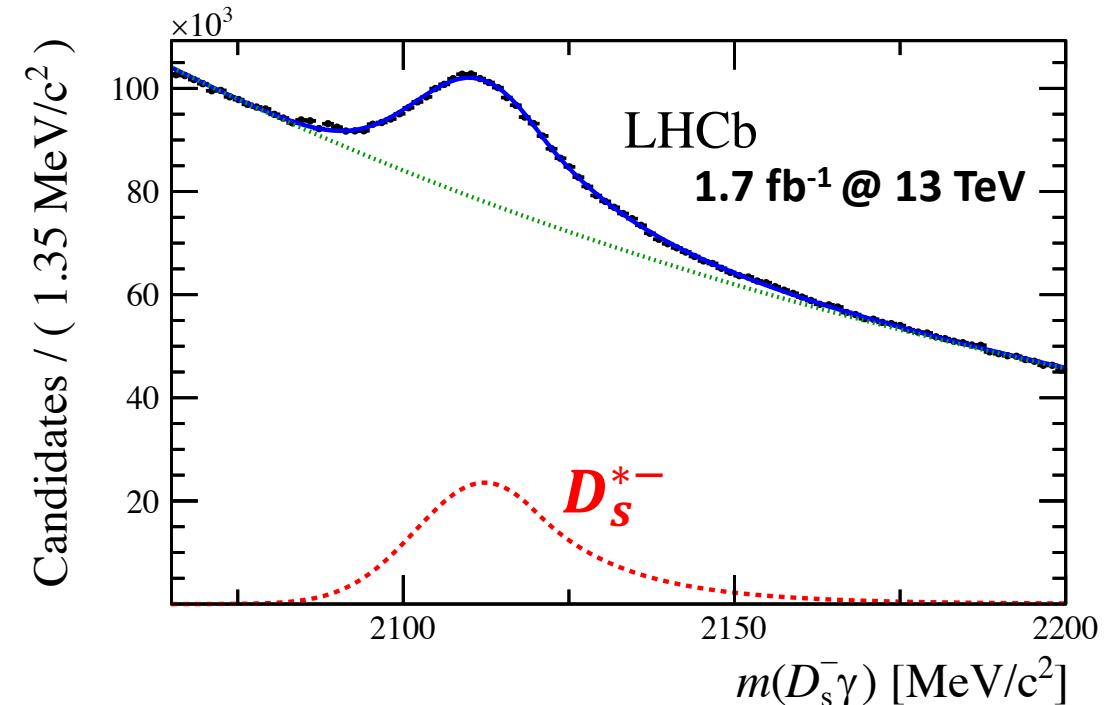


Compatible within **0.1σ**
and **0.7σ** with
predictions from
Bordone, Gubernari, van
Dyk and Jung
[EPJC 80 (2020) 347]



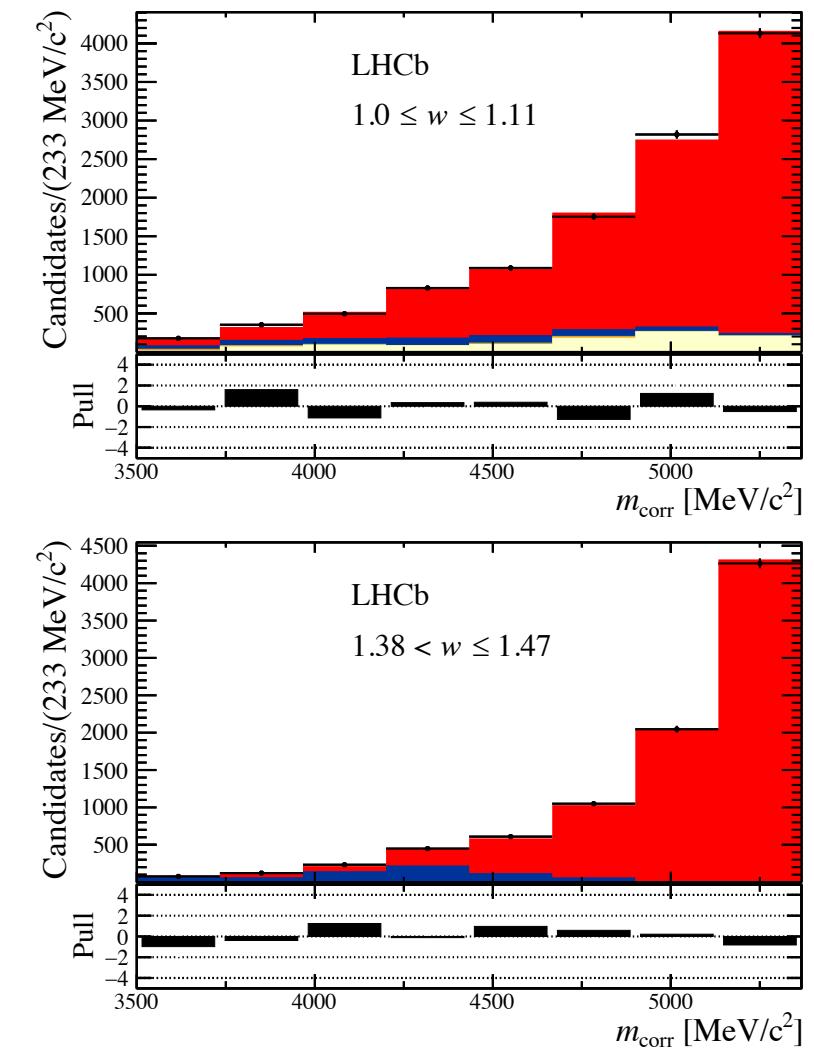
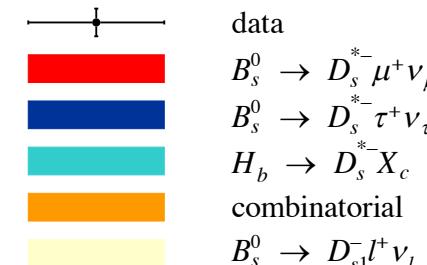
Complementary measurement: shape of the $B_s^0 \rightarrow D_s^{*-} \mu^+ \nu_\mu$ differential decay rate

- Completely independent dataset
- Main challenge: reconstruct the photon in $D_s^{*-} \rightarrow D_s^- \gamma$ in a cone around the D_s^- flight direction
- Fit $m(D_s^- \gamma)$ to subtract background from random photons



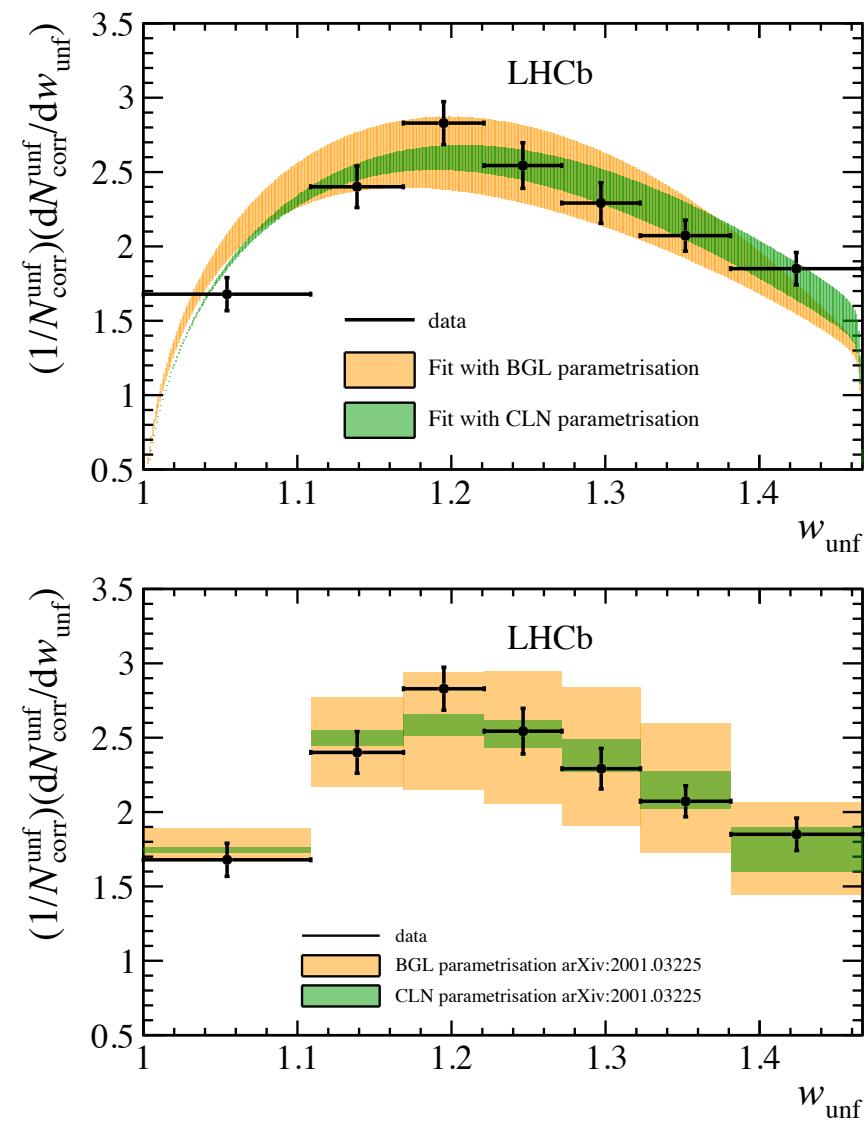
Building the differential decay rate

- Approximate w employing an MVA based algorithm*
- Fit corrected mass in bins of approximate w
- Main backgrounds: $B_s^0 \rightarrow D_s^{*-} \tau^+ \nu_\tau$ and $B_s^0 \rightarrow D_{s1}(2460)^- \mu^+ \nu_\mu$



Results

- Unfold efficiency and resolution using simulated events
- Fit differential decay rate with **both CLN and BGL** parameterisation
- **Good agreement** with form factors measured in $|V_{cb}|$ analysis (coloured shaded histograms)



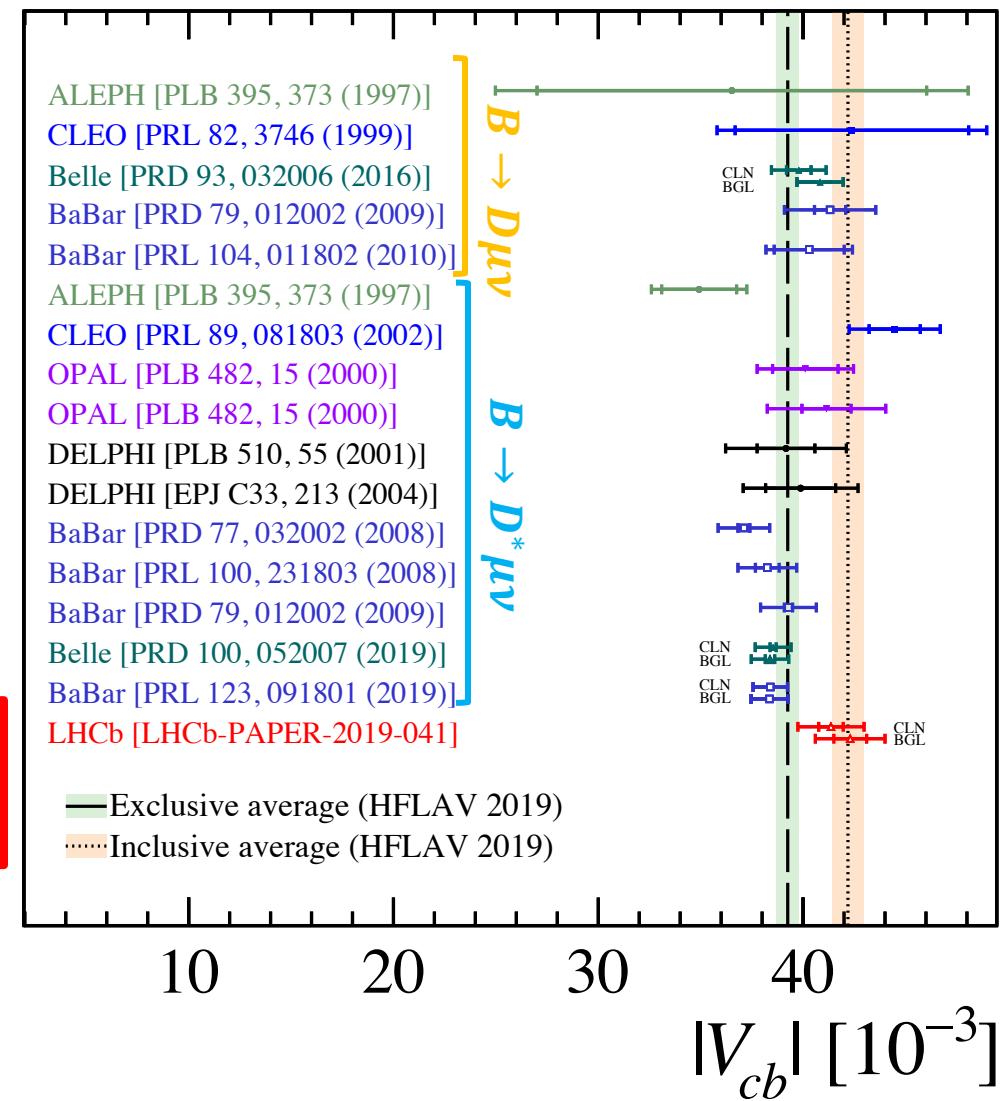
Conclusions

- LHCb proved that $B_s^0 \rightarrow D_s^{(*)} \mu \nu$ decays are a viable option to measure form factors and $|V_{cb}|$
- First measurement of the shape of the $B_s^0 \rightarrow D_s^{*-} \mu^+ \nu_\mu$ differential decay rate
- First measurement of $|V_{cb}|$ at a hadron collider, using $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ and $B_s^0 \rightarrow D_s^{*-} \mu^+ \nu_\mu$ decays

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

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

- Results are in **agreement with both exclusive and inclusive determinations**



Thanks for your attention!

Feel free to contact me for any comment or question

Backup

Decay rates

- 4-D decay rate for vector case

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

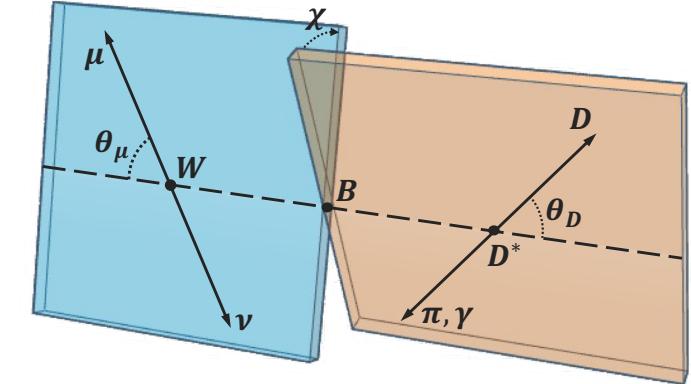
A can be decomposed in terms of 3 helicity amplitudes that in turn depend on 3 form factors

- 1-D decay rate for scalar case

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

G can be written as a function of 1 form factor

- w if the 4-velocity defined as: $(m_B^2 + m_{D^{(*)}}^2 - q^2)/(2m_B m_{D^{(*)}})$, where q^2 is the square of the $\mu\nu$ invariant mass



$$z \equiv \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

CLN parameterisation

- Uses dispersion relations and reinforced unitarity bounds based on Heavy Quark Effective Theory
- In the vector case, the form factors functions depend on three parameters: ρ^2 , $R_1(1)$ and $R_2(1)$

$$h_{A_1}(w) = h_{A_1}(1) [1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3] ,$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2 ,$$

$$R_2(w) = R_2(1) - 0.11(w-1) - 0.06(w-1)^2 .$$

- In the scalar case, the form factor function depends on one parameter: ρ^2

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

- $h_{A_1}(1)$ (often referred to as $F(1)$) and $G(0)$ need to be calculated. They are external inputs from lattice QCD (LQCD)

$$z \equiv \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

BGL parameterisation

- The BGL parametrization follows from more general arguments based on dispersion relations, analyticity, and crossing symmetry. Form factors are expressed as **series expansions** (details in backup).
- In the vector case, 3 series for 3 form factors, which are

$$f(z) = \frac{1}{P_{1+}(z)\phi_f(z)} \sum_{i=0}^N b_i z^i,$$

$$g(z) = \frac{1}{P_{1-}(z)\phi_g(z)} \sum_{i=0}^N a_i z^i,$$

$$\mathcal{F}_1(z) = \frac{1}{P_{1+}(z)\phi_{\mathcal{F}_1}(z)} \sum_{i=0}^N c_i z^i$$

- In the scalar case, 1 series for 1 form factor, which is

$$f_+(z) = \frac{1}{P_{1-}(z)\phi(z)} \sum_{n=0}^N d_n z^n$$

- The series coefficients are parameters to be determined, either experimentally or from calculations. Coefficient a_0 and c_0 **fixed from F(1)**, coefficient d_0 from G(0). The other parameters need to be determined

Blaschke factors and outer functions

For outer functions and Blaschke factors we follow Gambino's arXiv:1703:06124 with proper changes for B_S^0

$$\begin{aligned}\phi_f(z) &= \frac{4r}{m_B^2} \sqrt{\frac{n_I}{3\pi\chi_{1+}^T(0)}} \frac{(1+z)(1-z)^{3/2}}{[(1+r)(1-z) + 2\sqrt{r}(1+z)]^4}, \\ \phi_{F_1}(z) &= \frac{4r}{m_B^3} \sqrt{\frac{n_I}{6\pi\chi_{1+}^T(0)}} \frac{(1+z)(1-z)^{5/2}}{[(1+r)(1-z) + 2\sqrt{r}(1+z)]^5}, \\ \phi_g(z) &= \sqrt{\frac{n_I}{3\pi\tilde{\chi}_{1-}^T(0)}} \frac{2^4 r^2 (1+z)^2 (1-z)^{-1/2}}{[(1+r)(1-z) + 2\sqrt{r}(1+z)]^4},\end{aligned}$$

$$P_{1^\pm,0^-}(z) = \prod_{P=1}^n \frac{z - z_P}{1 - zz_P} \mathbf{C}_{+-}$$

$$z_P = \frac{\sqrt{t_+ - m_P^2} - \sqrt{t_+ - t_-}}{\sqrt{t_+ - m_P^2} + \sqrt{t_+ - t_-}},$$

$$t_\pm = (m_B \pm m_{D^*})^2$$

$$c_{+(-)} = 2.02159 \text{ (2.52733)}$$

$$n_I = 2.6$$

Res.	type	Mass (GeV)	χ funcs. in zero
1 ⁻		6.329(3)	$5.131 \cdot 10^{-4} \text{ GeV}^{-2}$
		6.920(18)	
		7.020	
		7.280	
1 ⁺		6.739(13)	$3.894 \cdot 10^{-4} \text{ GeV}^{-2}$
		6.750	
		7.145	
		7.150	

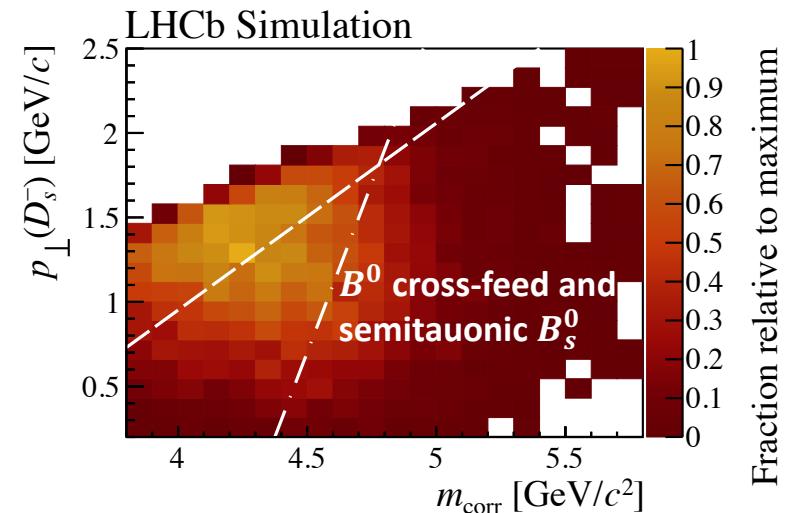
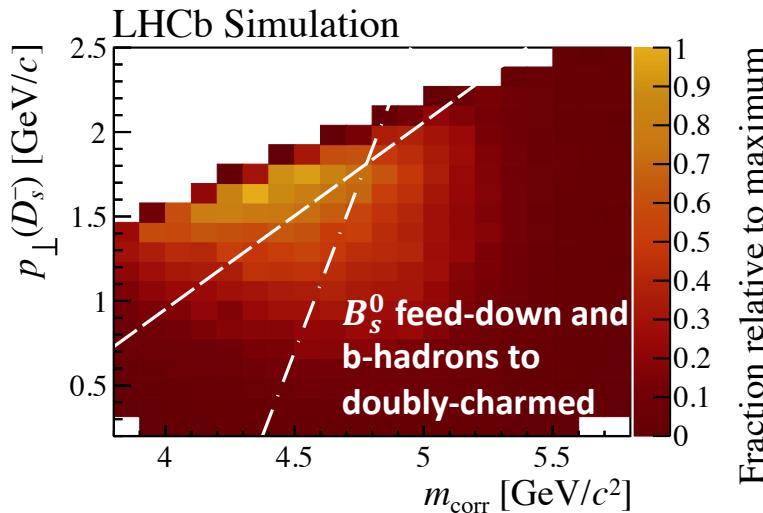
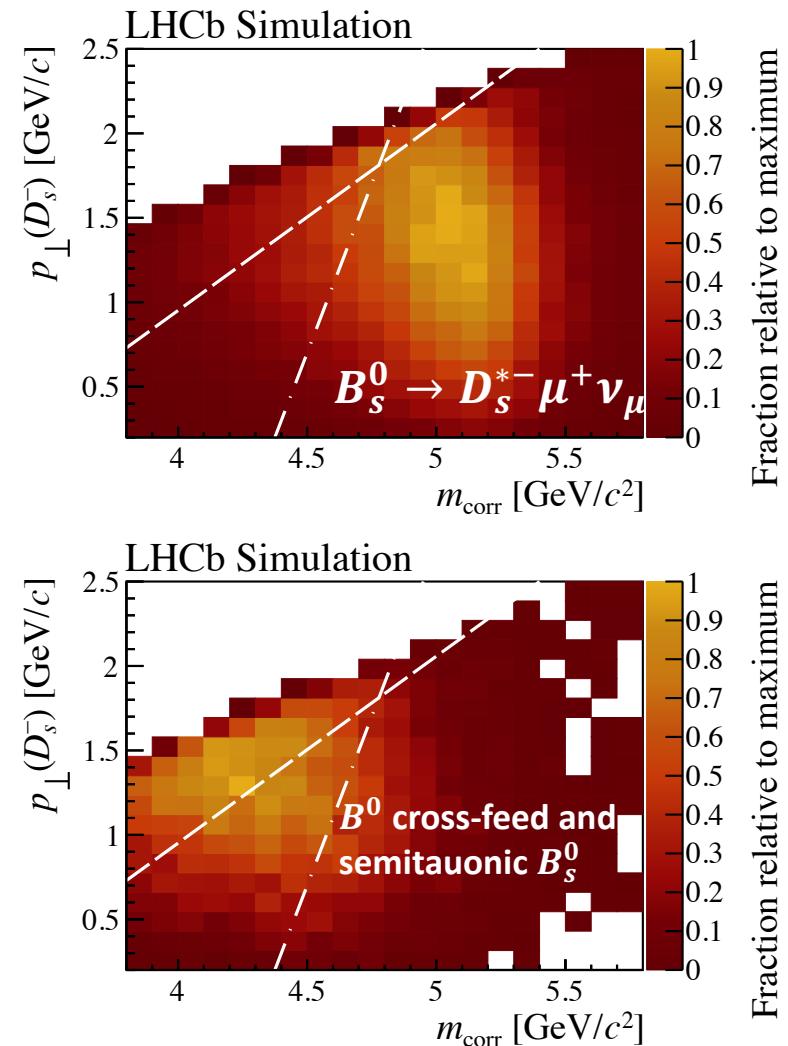
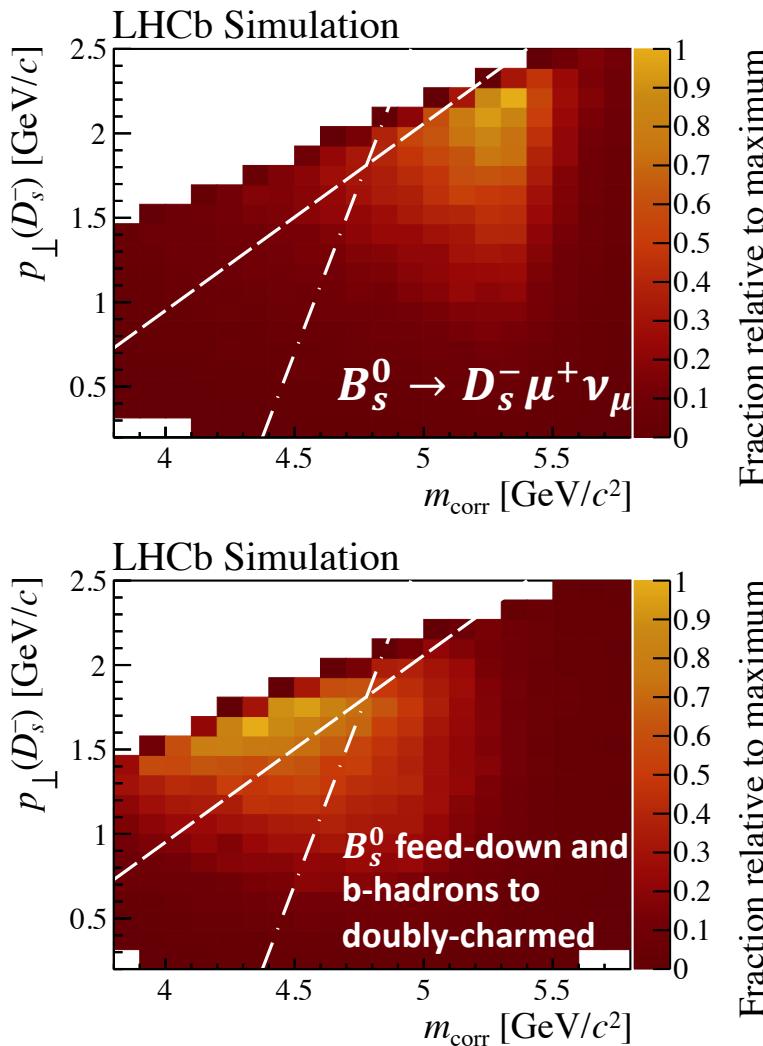
Relation between CLN FFs and BGL series

$$h_{A_1}(w) = \frac{f(w)}{\sqrt{m_B m_{D^*}}(1+w)},$$

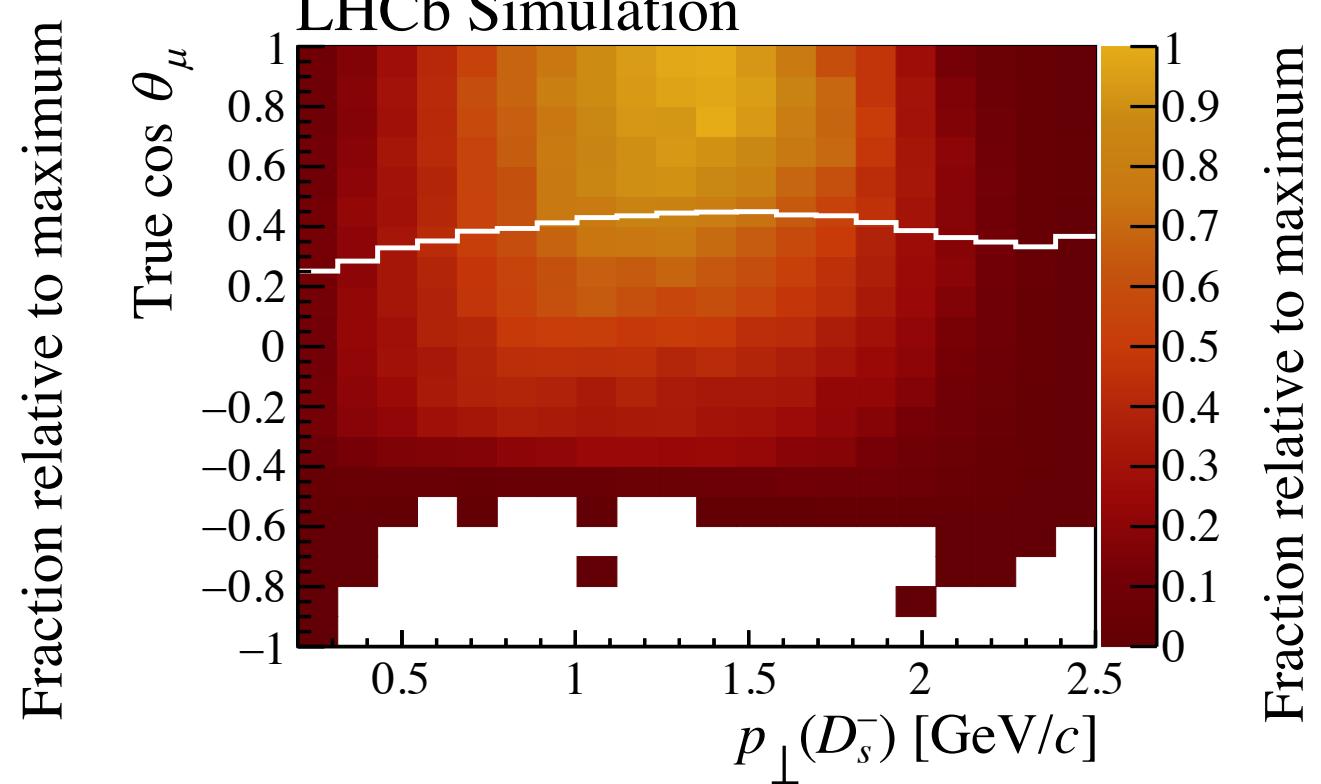
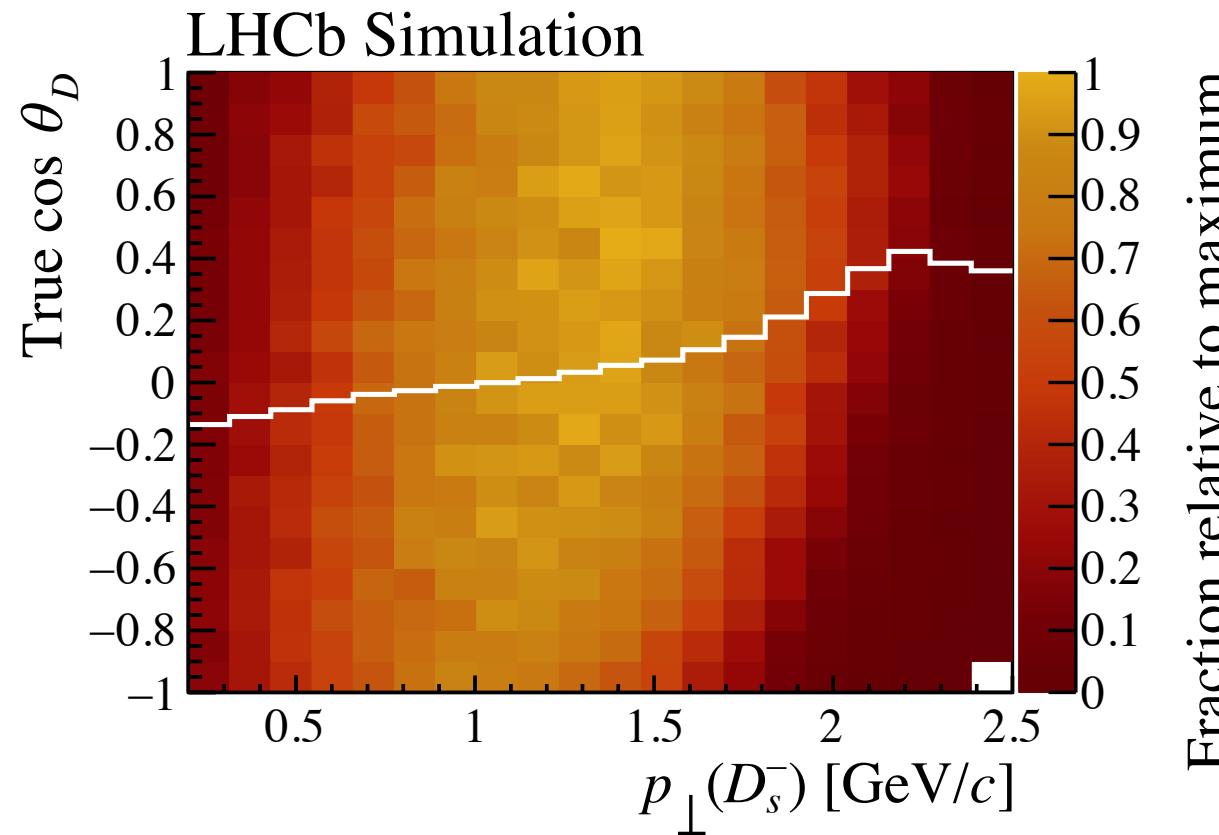
$$R_1(w) = (w+1)m_B m_{D^*} \frac{g(w)}{f(w)},$$

$$R_2(w) = \frac{w-r}{w-1} - \frac{\mathcal{F}_1(w)}{m_B(w-1)f(w)}.$$

Signals and backgrounds in 2D plane



Dependence of angles on $p_\perp(D_s^-)$



Complete fit results

CLN parameterisation	
Parameter	Value
$ V_{cb} [10^{-3}]$	$41.4 \pm 0.6 \text{ (stat)} \pm 1.2 \text{ (ext)}$
$\mathcal{G}(0)$	$1.102 \pm 0.034 \text{ (stat)} \pm 0.004 \text{ (ext)}$
$\rho^2(D_s^-)$	$1.27 \pm 0.05 \text{ (stat)} \pm 0.00 \text{ (ext)}$
$\rho^2(D_s^{*-})$	$1.23 \pm 0.17 \text{ (stat)} \pm 0.01 \text{ (ext)}$
$R_1(1)$	$1.34 \pm 0.25 \text{ (stat)} \pm 0.02 \text{ (ext)}$
$R_2(1)$	$0.83 \pm 0.16 \text{ (stat)} \pm 0.01 \text{ (ext)}$

BGL parameterisation	
Parameter	Value
$ V_{cb} [10^{-3}]$	$42.3 \pm 0.8 \text{ (stat)} \pm 1.2 \text{ (ext)}$
$\mathcal{G}(0)$	$1.097 \pm 0.034 \text{ (stat)} \pm 0.001 \text{ (ext)}$
d_1	$-0.017 \pm 0.007 \text{ (stat)} \pm 0.001 \text{ (ext)}$
d_2	$-0.26 \pm 0.05 \text{ (stat)} \pm 0.00 \text{ (ext)}$
b_1	$-0.06 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (ext)}$
a_0	$0.037 \pm 0.009 \text{ (stat)} \pm 0.001 \text{ (ext)}$
a_1	$0.28 \pm 0.26 \text{ (stat)} \pm 0.08 \text{ (ext)}$
c_1	$0.0031 \pm 0.0022 \text{ (stat)} \pm 0.0006 \text{ (ext)}$

Summary of uncertainties

Source	Uncertainty															
	CLN parametrization						BGL parametrization									
	$ V_{cb} $ [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]	$ V_{cb} $ [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]
$f_s/f_d \times \mathcal{B}(D_s^- \rightarrow K^+ K^- \pi^-)(\times \tau)$	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
$\mathcal{B}(D^- \rightarrow K^- K^+ \pi^-)$	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
$\mathcal{B}(D^{*-} \rightarrow D^- X)$	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
$\mathcal{B}(B^0 \rightarrow D^- \mu^+ \nu_\mu)$	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	–	–
$\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)$	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
$D_s^- \rightarrow K^+ K^- \pi^-$ 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

Breakdown of systematic uncertainties for the measurement of the shape of the $B_s^0 \rightarrow D_s^{*-} \mu^+ \nu_\mu$ differential decay rate

	w bin						
	1	2	3	4	5	6	7
Fraction of $N_{\text{corr},i}^{\text{unf}}$	0.183	0.144	0.148	0.128	0.117	0.122	0.158
Uncertainties (%)							
Simulation sample size	3.5	3.0	2.8	3.1	3.4	3.0	3.7
Sample sizes for effs and corrections	3.6	3.2	3.0	2.8	2.8	2.7	2.8
SVD unfolding regularisation	0.5	0.5	0.1	0.7	1.2	0.0	0.5
Radiative corrections	0.1	0.2	0.1	0.3	0.4	0.2	0.2
Simulation FF parametrisation	0.3	0.1	0.1	0.1	0.2	0.4	0.2
Kinematic weights	2.4	1.0	1.1	0.1	0.2	0.1	0.9
Hardware-trigger efficiency	0.3	0.3	0.0	0.2	0.2	0.3	0.1
Software-trigger efficiency	0.0	0.1	0.0	0.0	0.1	0.0	0.0
D_s^- selection efficiency	0.5	0.2	0.3	0.3	0.2	0.1	0.3
D_s^{*-} weights	0.0	2.3	0.8	2.9	2.0	0.9	0.4
Total systematic uncertainty	5.6	5.1	4.4	5.2	5.0	4.2	4.8
Statistical uncertainty	3.4	2.9	2.7	3.1	3.2	2.9	3.4