Physics with semileptonic B decays at LHCb

Fabio Ferrari

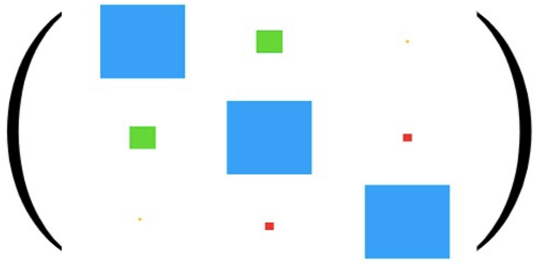
University of Bologna and INFN

106° Congresso Nazionale SIF

The CKM matrix

- In the Standard Model, the transitions between quarks of different flavours are mediated by a W boson
- The mixing between the six flavours is encoded in a 3x3 matrix: **CKM matrix** (3 angles and 1 phase)

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} =$$

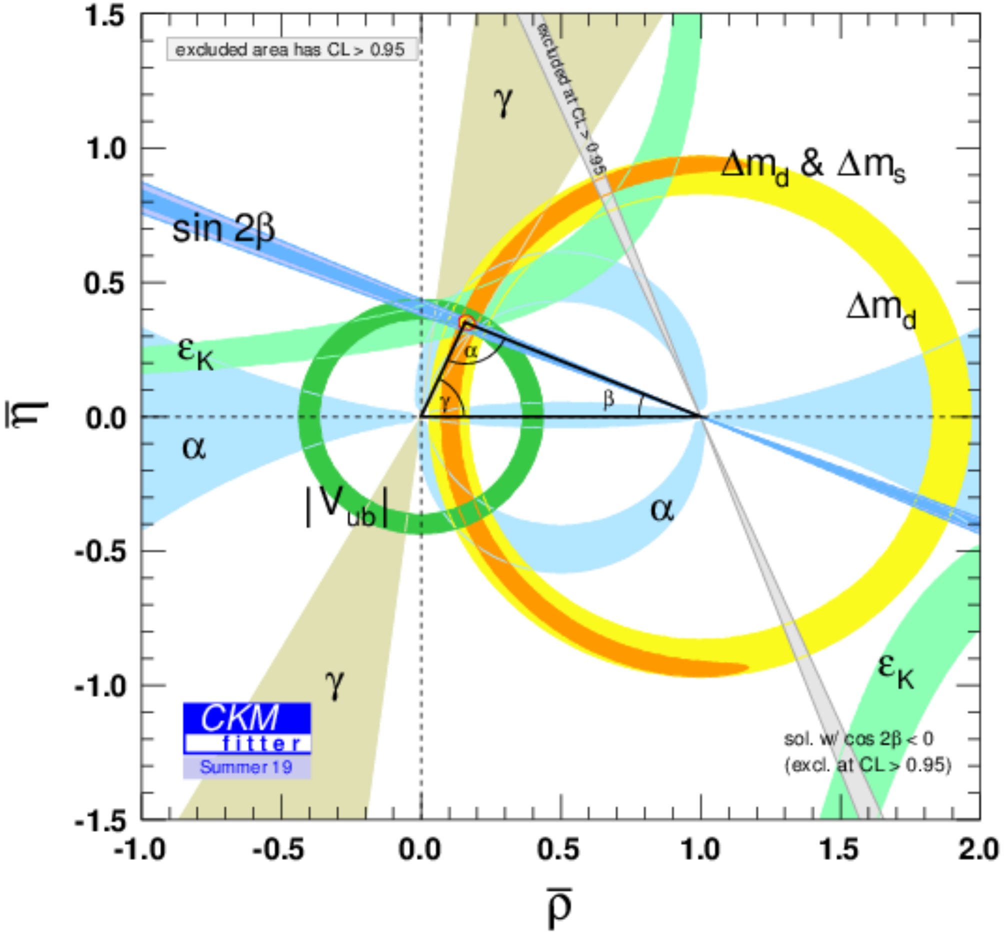


- Hierarchical structure and almost diagonal
- Mixing between different quark generations suppressed
- **Suppression** of **tree-level $b \rightarrow c$ transitions** ($V_{cb} \sim 0.04$)

Status so far

[CKM fitter]

- 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



New physics in the triangle

- The triangle is built **assuming unitarity**. No other flavour changing coupling apart from W exchange
- New Physics could **violate unitarity**
- Need to over-constraint all angles and sides with independent measurements to check if the SM holds
- The side opposite to β is proportional to $|V_{ud}|/|V_{cb}| \rightarrow$ **high priority** of heavy flavor physics program
- I will present a measurement of the CKM matrix element $|V_{cb}|$

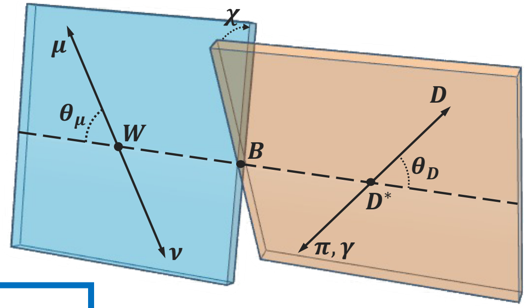
*Caprini, Lellouch, Neubert (CLN) [Nucl. Phys. B530 (1998) 153]
**Boyd, Grinstein, Lebed (BGL) [PRL 74 (1995) 4603, PLB 353 (1995) 306]

Measuring $|V_{cb}|$

- Semileptonic B mesons decays can be used to measure $|V_{cb}|$
- Two possible approaches: exclusive vs inclusive
- Exclusive
  - Decays involving one specific meson (D, D^*, D_s, ...) in the final state
  - Strong part of the decay is described in terms of scalar functions, the so-called **form factors (FF)** → different parameterizations available on the market (CLN*, BGL**, ...)
- Inclusive
  - Analyze all possible final states
  - Based on Operator Product Expansion (OPE). Accuracy depends on how many terms are included in the series expansion
- **Take home message**: exclusive and inclusive determination of $|V_{cb}|$ are **complementary** and have **different advantages and disadvantages**, both for theory and experiment

$w \equiv (m_B^2 + m_{D^{(*)}}^2 - q^2)/(2 m_B m_{D^{(*)}})$, where q^2 is the di-lepton momentum transfer

Form factor functions



$$\frac{d\Gamma(B^0 \to D^* \mu \nu)}{dw\, d\cos\theta_D\, d\cos\theta_\mu\, d\chi} = \frac{3 m_B^3 m_{D^*}^2 G_F^2}{16(4\pi)^4} \eta_{EW}^2 |V_{cb}|^2 |\mathcal{A}(w, \theta_\mu, \theta_D, \chi)|^2$$

3 FF functions

- In the massless lepton limit, $|A(w, \theta_\mu, \theta_D, \chi)|^2$ is decomposed in 3 form-factor functions: $h_{A1}(w), R_1(w)$ and $R_2(w)$
- These form-factor functions can be expressed in different parameterisations: CLN or BGL
  - Different parameterizations could lead to different $|V_{cb}|$ values

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

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: $\boldsymbol{\rho^2, R_1(1)}$ **and** $\boldsymbol{R_2(1)}$

$$h_{A_1}(w) = h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right],$$
$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2,$$
$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2.$$

- $h_{A_1}(1)$ needs to be calculated. It is an external input from lattice QCD (LQCD)

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

BGL parameterisation

- The BGL parametrization follows from 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

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

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

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

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

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

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

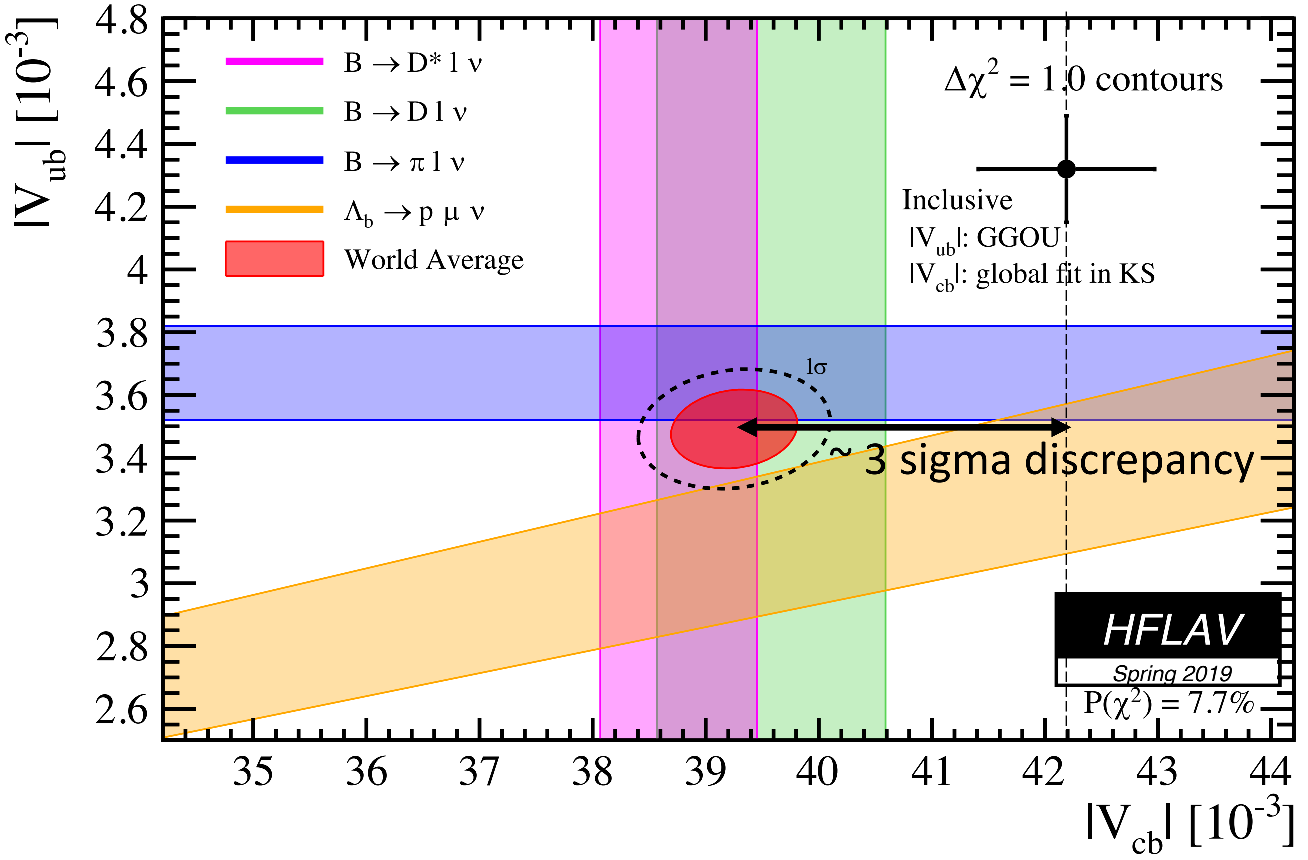
Blaschke factors and outer functions, see backup for definitions

- The series coefficients are parameters to be determined, either experimentally or from calculations. Coefficient a_0 and c_0 **fixed from** $\boldsymbol{h_{A1}}(1)$. The other parameters need to be determined.

Inclusive vs exclusive

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

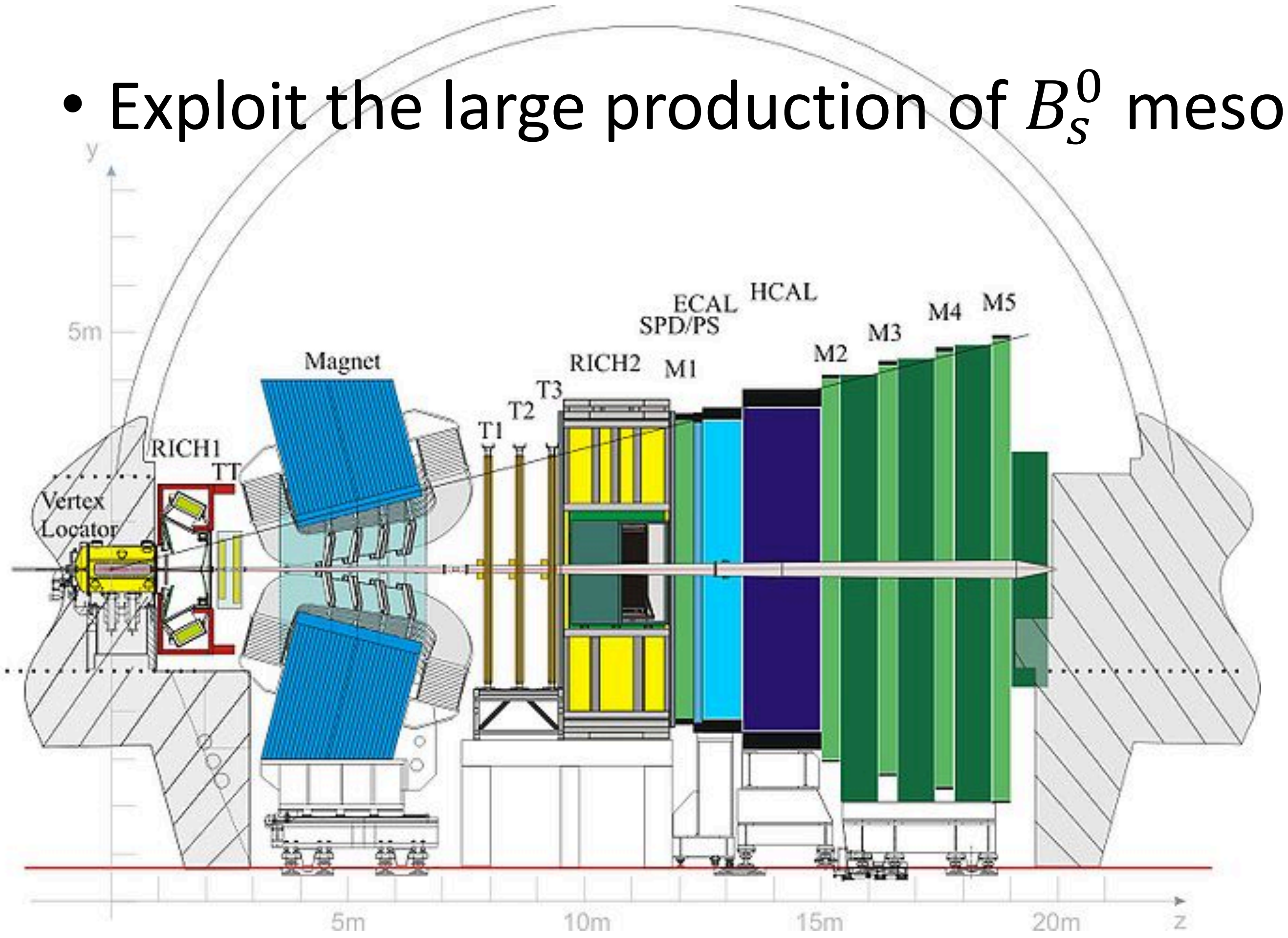
[HFLAV 2019]



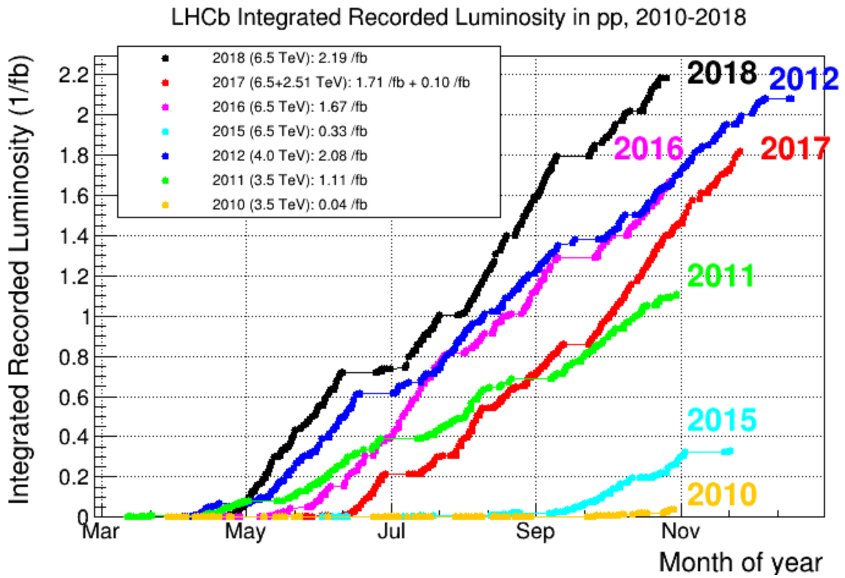
Long standing discrepancy calls for new measumrents of $|V_{cb}|$!

The LHCb detector

- Exploit the large production of B_s^0 mesons at the LHC



Approximately $\mathbf{1.8{\times}10^{10}}$ **and** $\mathbf{3.6{\times}10^{10}}$ $\boldsymbol{B_s^0}$ **mesons produced/fb**$^{-1}$ in the acceptance in Run I and Run II, respectively.
[PRL 118 (2017) 052002, PRL 119 (2017) 169901]

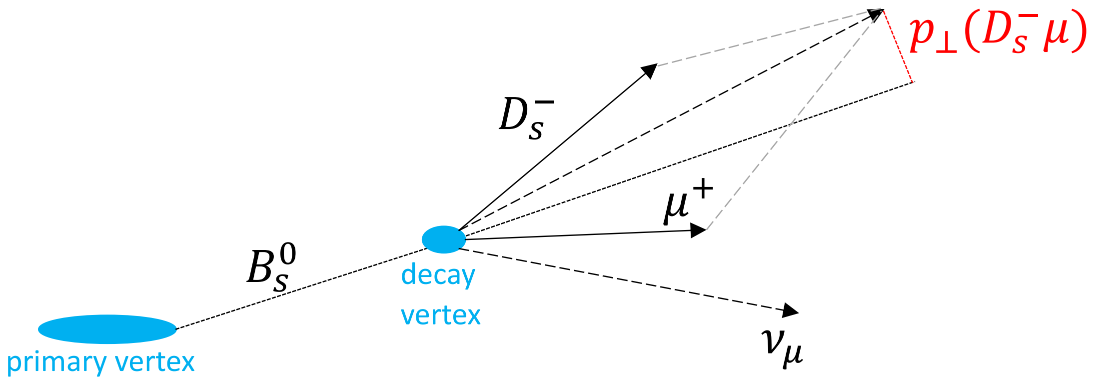


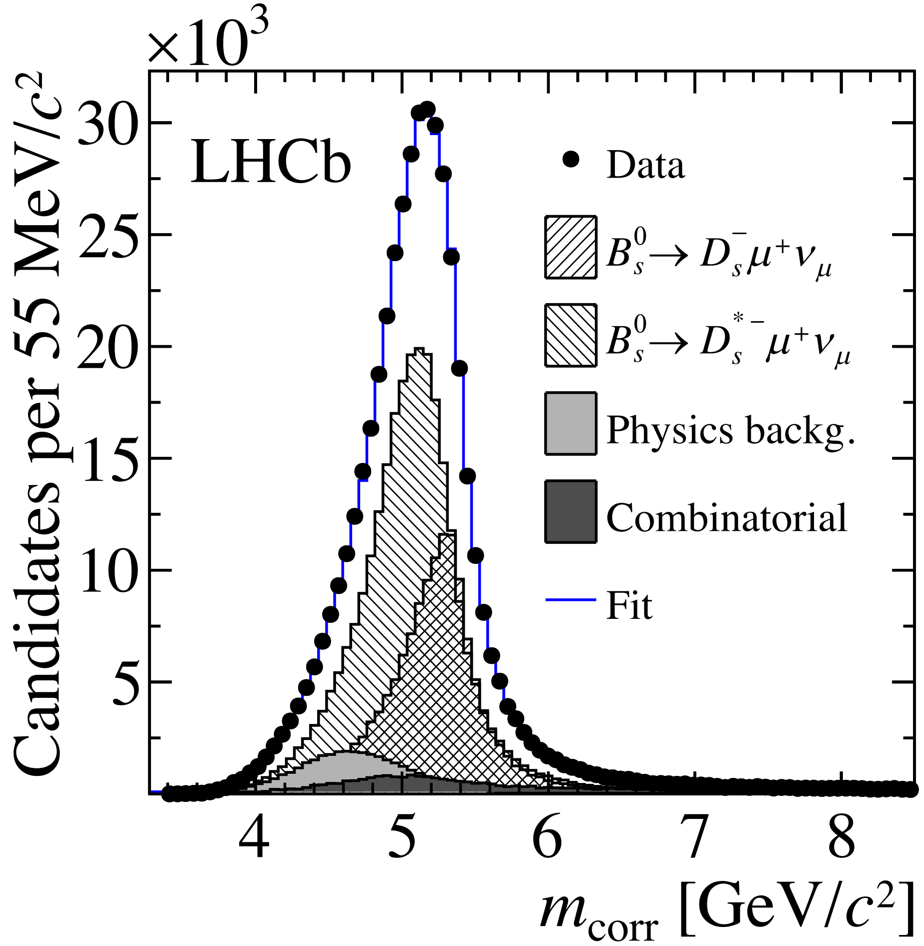
*[PRL 119 (2017) 101801]

The experimental challenge

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

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

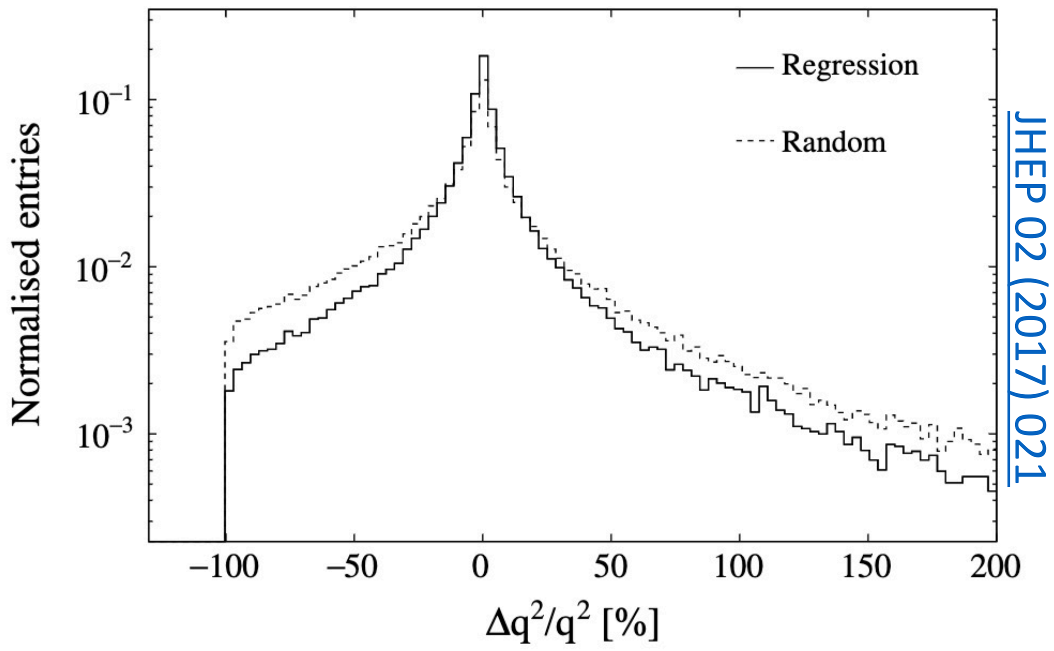




[PRL 119 (2017) 101801]

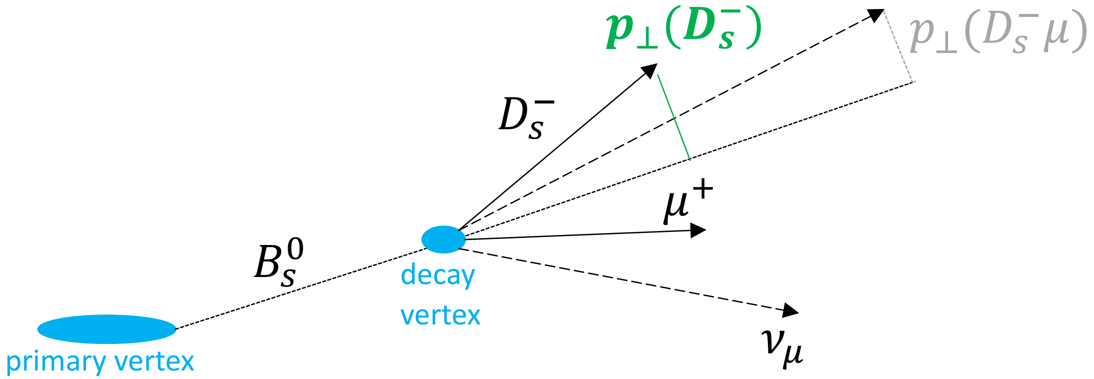
The experimental challenge

- Initial collision energy **not know with good precision** and LHCb is **not a 4π experiment** → **not possible** to close the kinematics of the decay and reconstruct the neutrino 4-momentum
- The di-lepton momentum transfer squared (q^2), commonly used by experimentalists, can be known up to a 2-fold ambiguity
  - MVA based techniques yield the correct solution ~ 70% of the cases



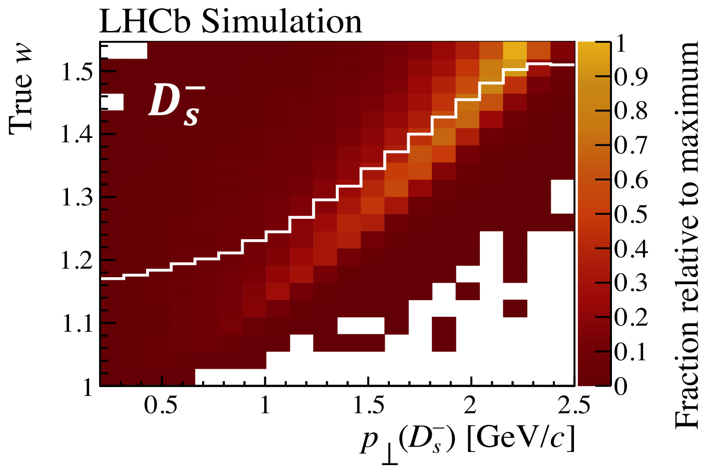
JHEP 02 (2017) 021

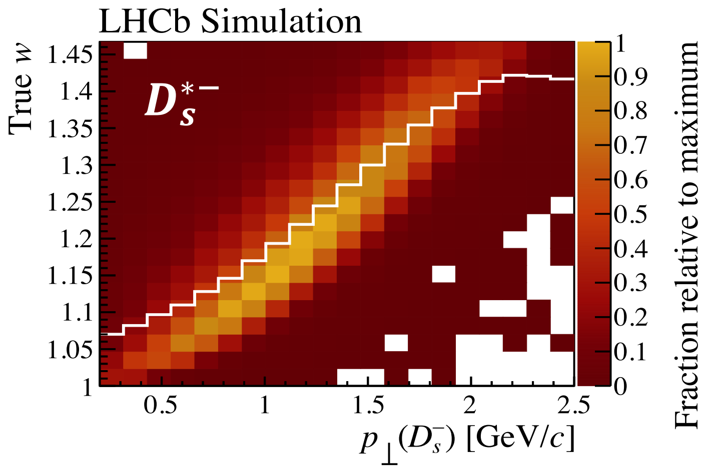
New tools



- New idea: exploit $\boldsymbol{p_\perp(D_s^-)}$
  - Fully reconstructed variable
  - Highly correlated with **recoil *w***
- Can **obtain $|V_{cb}|$** from a measurement of the decay rate as a function of w *(i.e. q^2)*

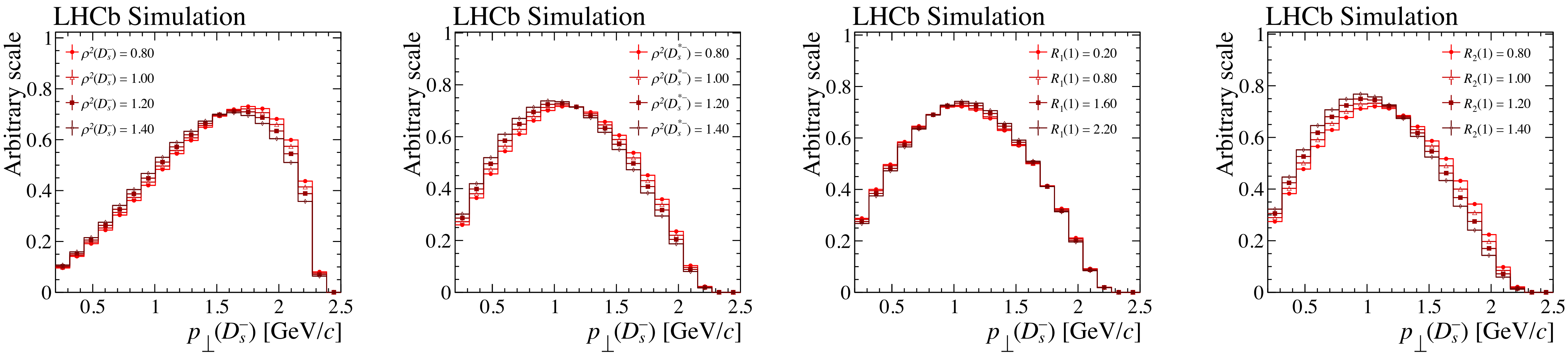
$$w = (m_B^2 + m_{D^{(*)}}^2 - q^2)/(2m_B m_{D^{(*)}})$$





Sensitivity to form factors

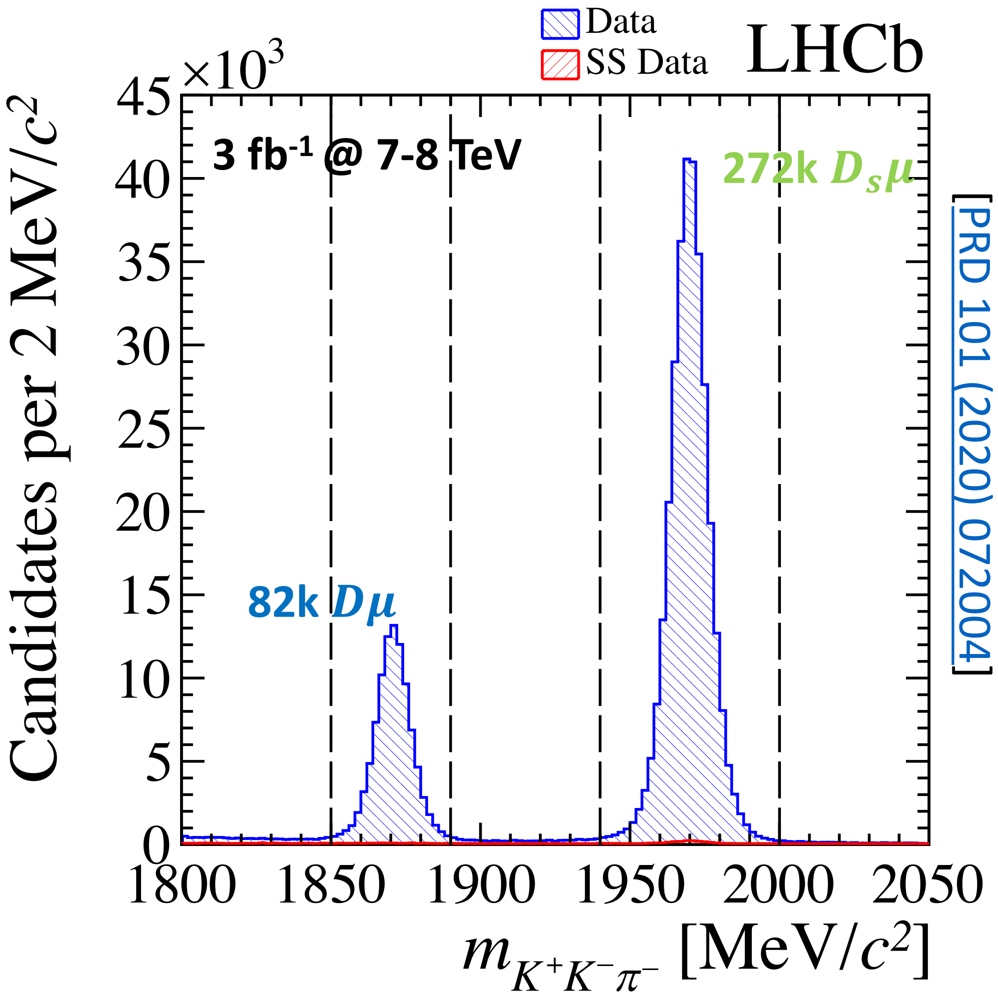
- Form factors are functions of w → possible to measure them using $p_\perp(D_s^-)$



*[PRL 118 (2017) 052002, PRL 118 (2017) 052002]
**[PRD 100 (2019) 031102]

Strategy & dataset

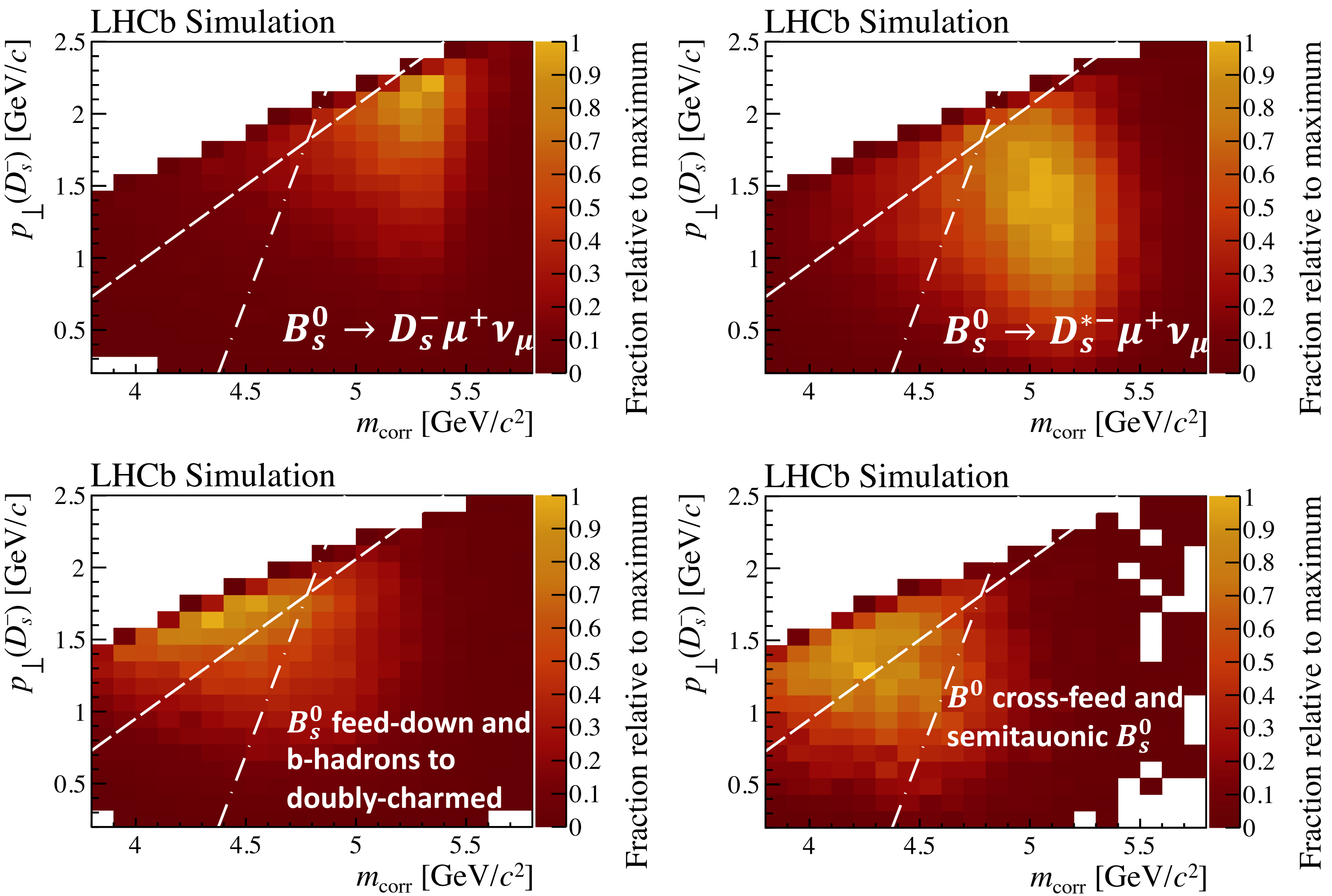
- Imprecise knowledge of the collected integrated luminosity and $pp \to bbX$ cross-section* would **limit precision** on $|V_{cb}|$ at O(5-8%)
- Systematic uncertainty from this could be **greatly reduced** by using a normalisation channel: $B^0 \to D^{(*)}\mu\nu$ reconstructed in the **same visible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



[PRD 101 (2020) 072004]

Signal and backgrounds

- The 2D plane ($m_{corr} - p_{\perp}(D_s^-)$) is also useful to separate the signal modes from the backgrounds
- Simple 2D cut rejects most of the backgrounds while preserving the signal
- Dot-dashed cut used to asses the systematic uncertainty related to this choice



*[McLean, Davies, Koponen, Lytle (HPQCD collaboration), PRD 101 (2020) 074513]
**[McLean, Davies, Koponen, Lytle (HPQCD collaboration), PRD 99 (2019) 114512]

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 $\varepsilon\left(m_{corr}, p_\perp(D_s^-)\right)$

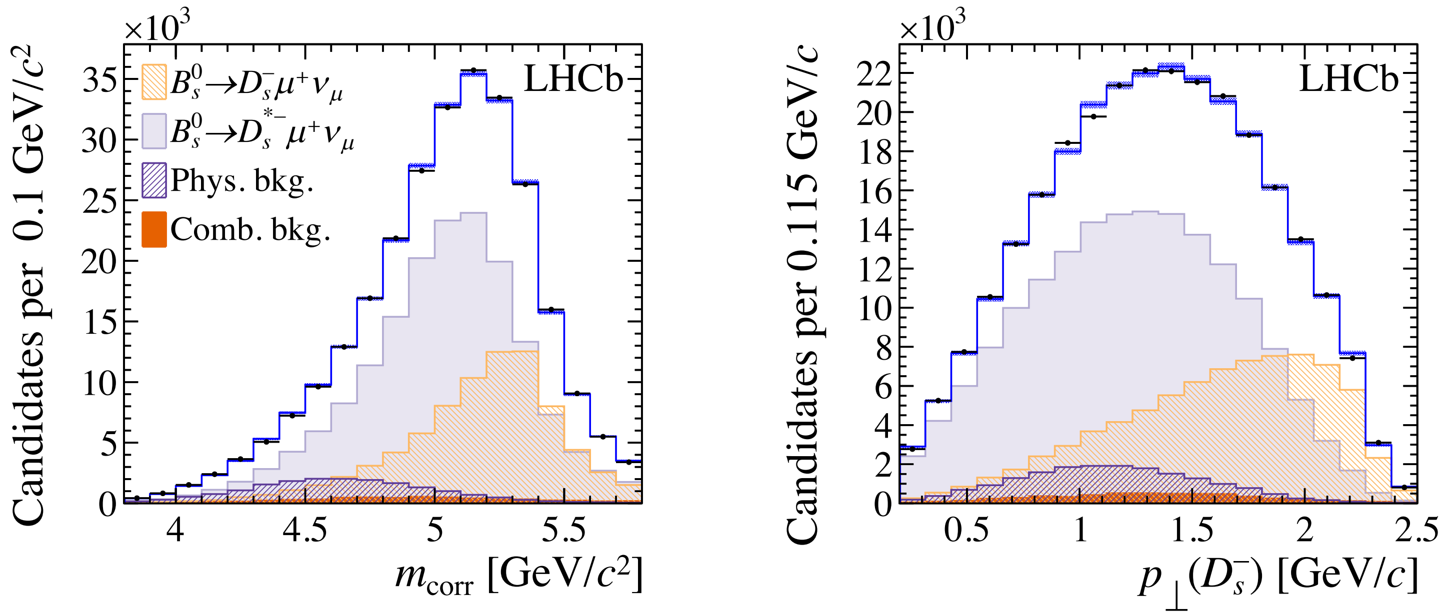
$$\frac{\mathrm{d}N_{obs}}{\mathrm{d}m_{corr}\mathrm{d}p_\perp(D_s^-)} = \kappa \frac{\mathrm{d}\Gamma(|V_{cb}|, h_{A_1}, \dots)}{\mathrm{d}m_{corr}\mathrm{d}p_\perp(D_s^-)} \varepsilon(m_{corr}, p_\perp(D_s^-))$$

- 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)

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



$\chi^2/ndf = 276/284$

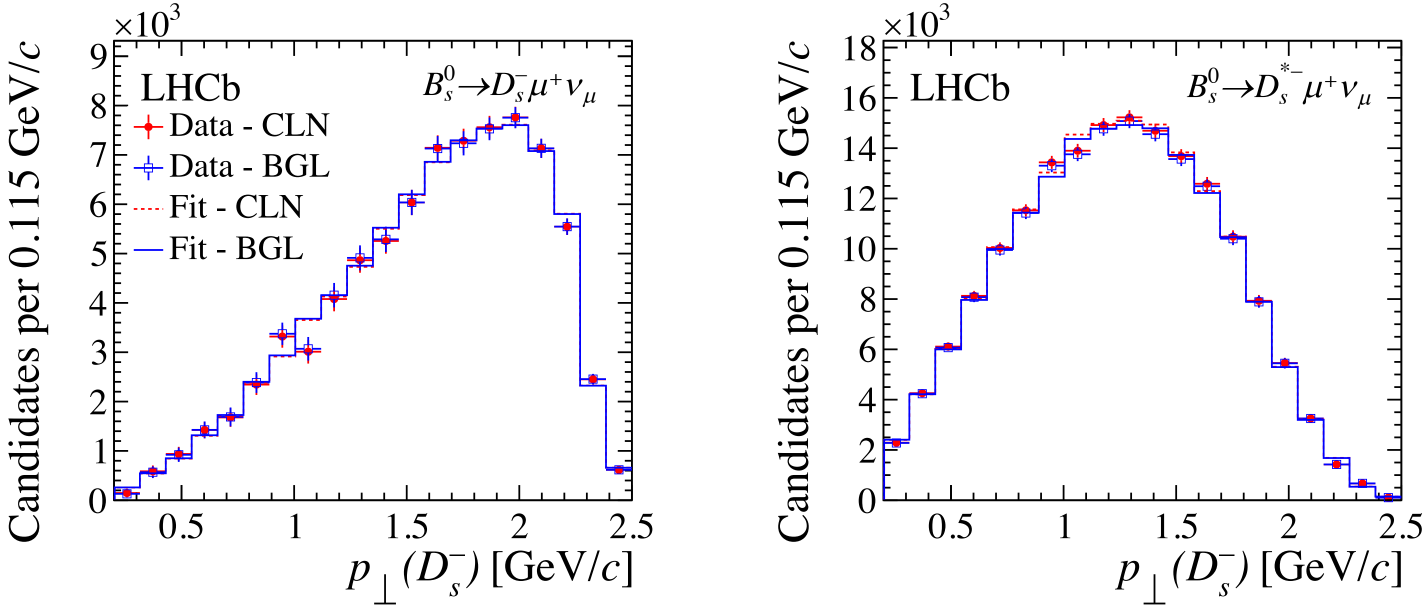
p-value = 63%

Comparing different parameterisations

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

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

Background subtracted data with fit projections overlaid



[PRD 101 (2020) 072004]

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 $D^-_{(s)} \to KK\pi$ Dalitz stucture, 2% relative on $|V_{cb}|$
- Additional result of the analysis, **first measurement of relative BR**

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

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

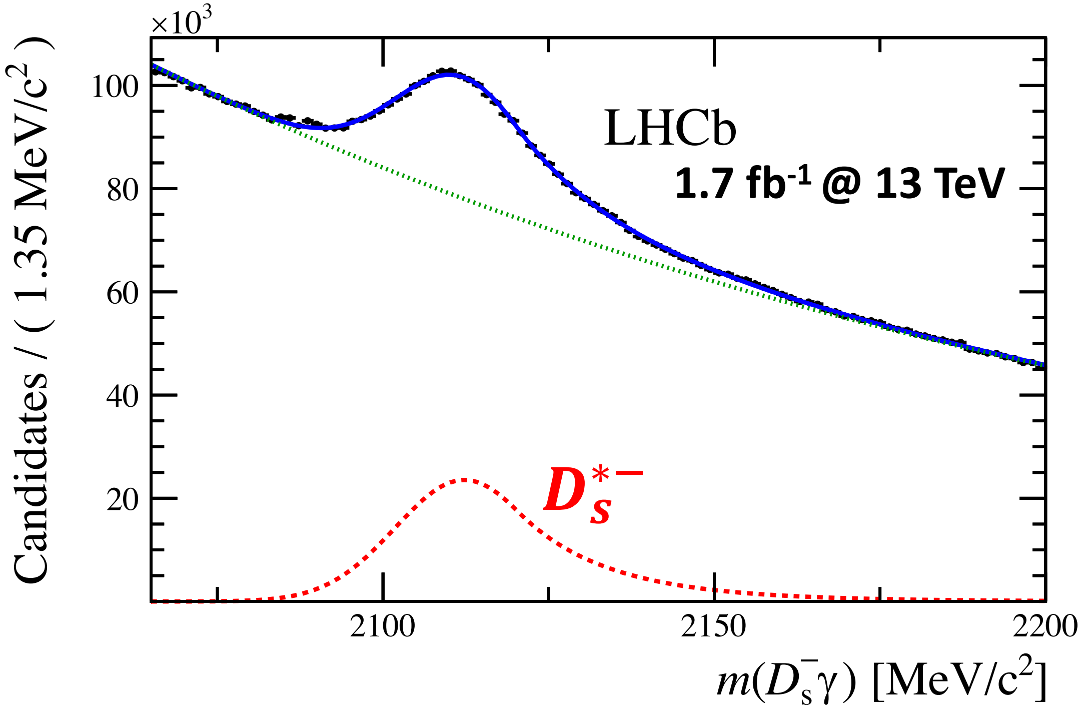
$$\frac{\mathcal{B}(B^0_s \to D^-_s \mu^+ \nu_\mu)}{\mathcal{B}(B^0_s \to D^{*-}_s \mu^+ \nu_\mu)} = 0.464 \pm 0.013\,(\text{stat}) \pm 0.043\,(\text{syst})$$

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

[arXiv:2003.08453]

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

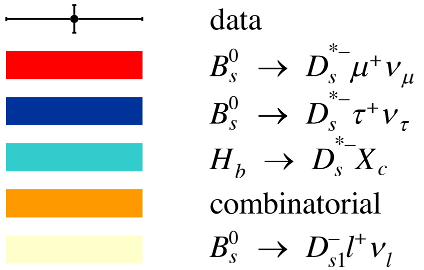
- Completely independent dataset
- Different approach: fully reconstruct the D_s^{*-}
  - Challenge: reconstruct the photon in $D_s^{*-} \to D_s^- \gamma$ in a cone around the D_s^- flight direction
- Fit $m(D_s^-\gamma)$ to subtract background from random photons

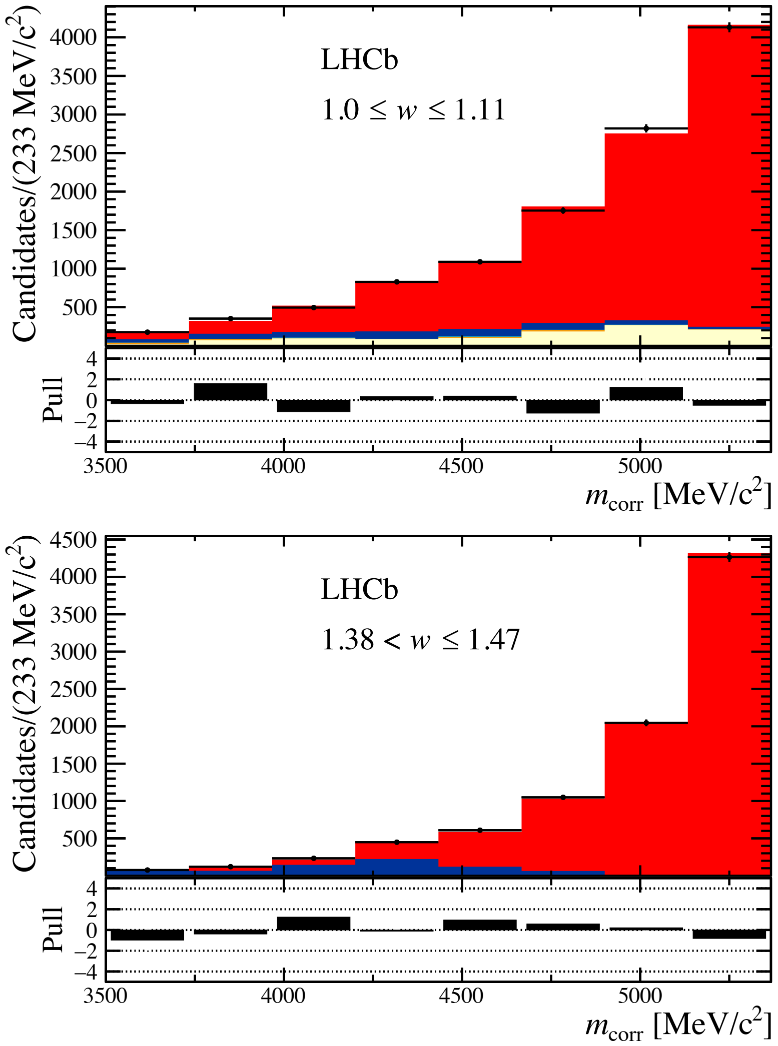


*[JHEP 02 (2017) 021] [arXiv:2003.08453]

Building the differential decay rate

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





Systematic uncertainties

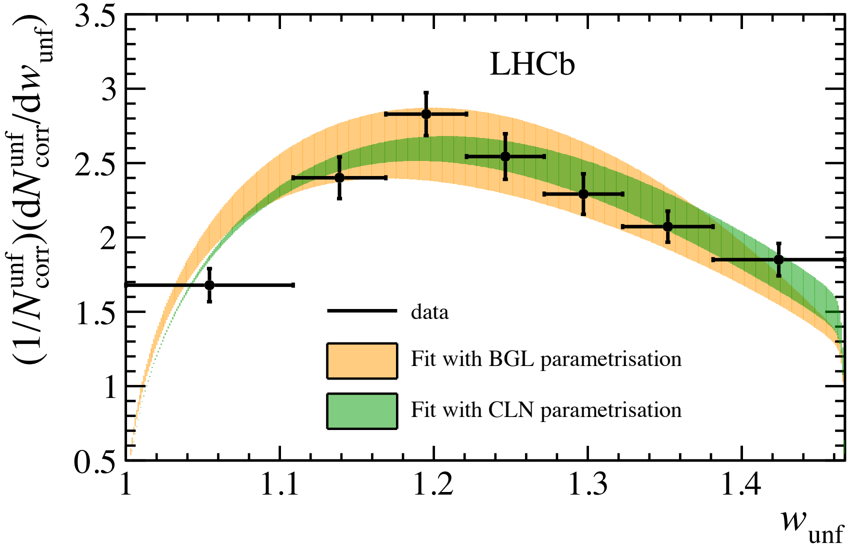
- Dominated from the simulation statistics for the templates
  - Accounts for more than 60% of the total systematic uncertainty

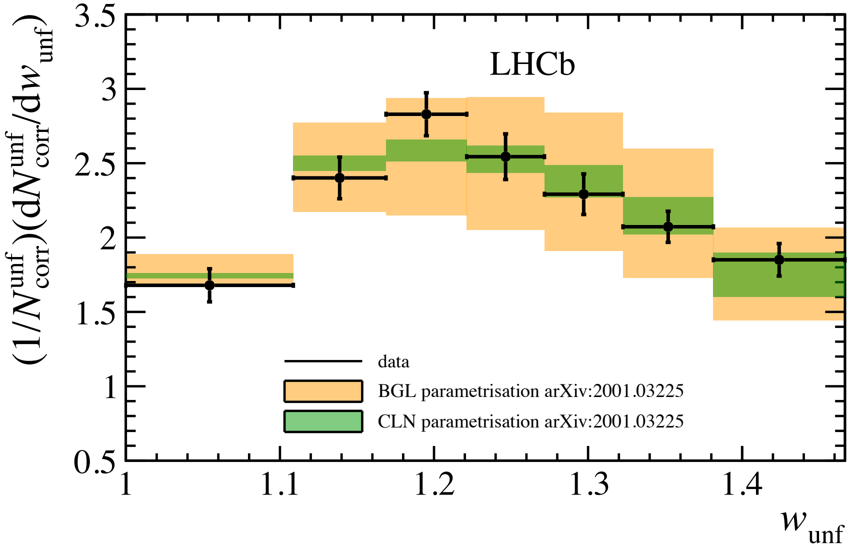
	w bin						
	1	2	3	4	5	6	7
Fraction of $N^{\text{unf}}_{\text{corr},i}$	0.183	0.144	0.148	0.128	0.117	0.122	0.158
Uncertainties (%)							
Simulation sample size	3.5	3.0	2.8	3.1	3.4	3.0	3.7
Sample sizes for effs and corrections	3.6	3.2	3.0	2.8	2.8	2.7	2.8
SVD unfolding regularisation	0.5	0.5	0.1	0.7	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

[arXiv:2003.08453]

Results

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





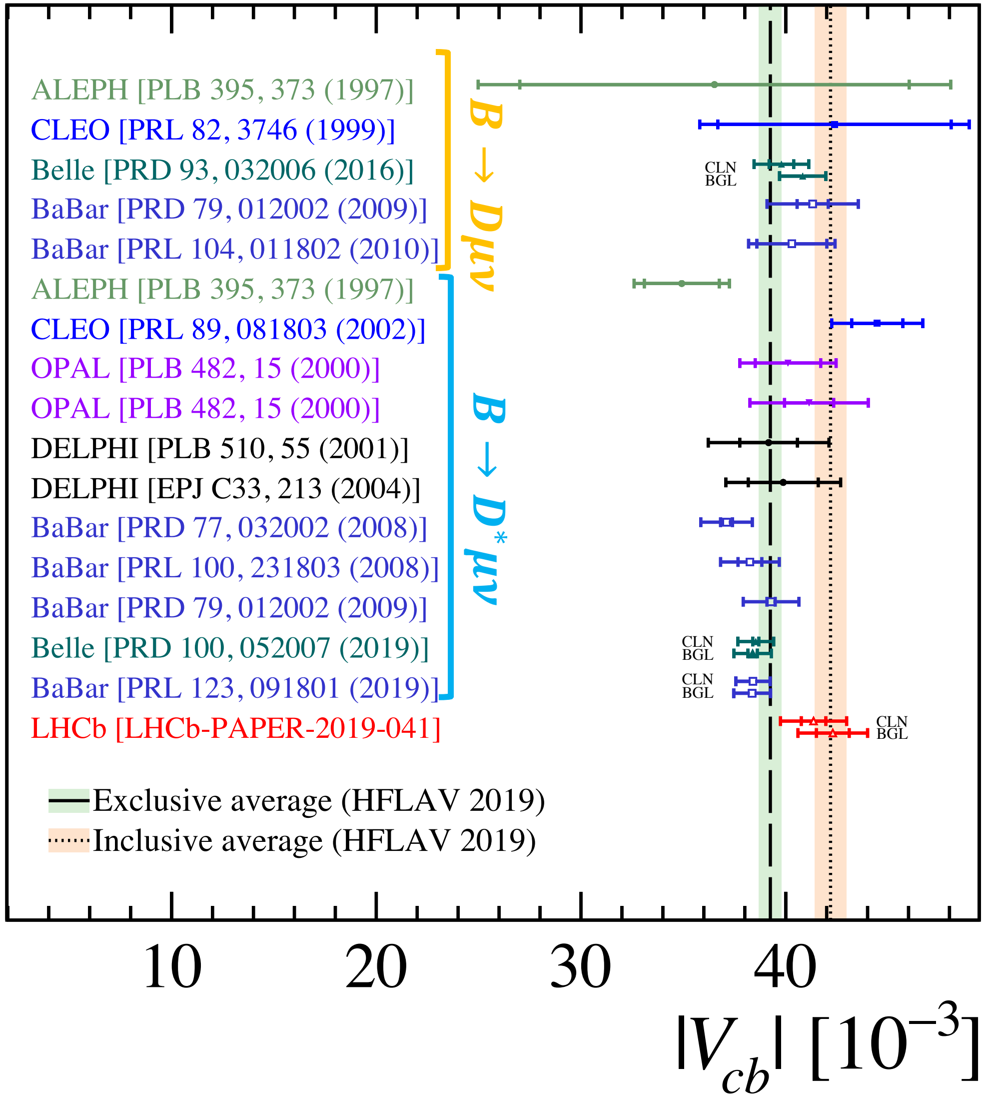
[PRD 101 (2020) 072004]

Conclusions

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

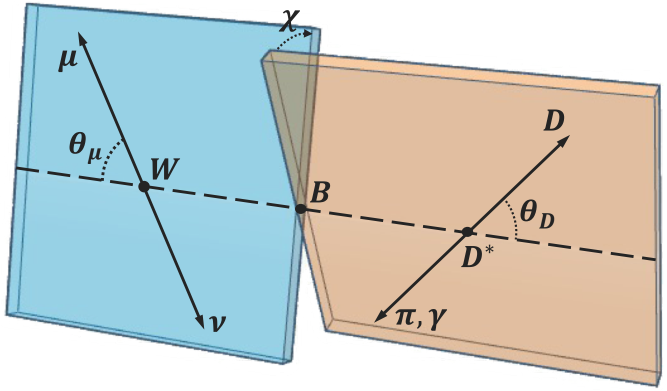
$$|V_{cb}|_{\rm CLN} = (41.4 \pm 0.6\,({\rm stat}) \pm 0.9\,({\rm syst}) \pm 1.2\,({\rm ext})) \times 10^{-3}$$
$$|V_{cb}|_{\rm BGL} = (42.3 \pm 0.8\,({\rm stat}) \pm 0.9\,({\rm syst}) \pm 1.2\,({\rm ext})) \times 10^{-3}$$

- Results are in **agreement** with **both exclusive and inclusive determinations**
  - Need for more measurements to solve the $|V_{cb}|$ puzzle



Backup

[PRD 101 (2020) 072004]



Decay rates

- 4-D decay rate for vector case

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

$\mathcal{A}$ can be decomposed in terms of 3 helicity amplitudes that in turn depend on 3 form factors

- 1-D decay rate for scalar case

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

$\mathcal{G}$ 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

Blaschke factors and outer functions

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

$$\phi_f(z) = \frac{4r}{m_B^2}\sqrt{\frac{n_I}{3\pi\chi_{1^+}^T(0)}}\frac{(1+z)(1-z)^{3/2}}{[(1+r)(1-z)+2\sqrt{r}(1+z)]^4},$$

$$\phi_{F_1}(z) = \frac{4r}{m_B^3}\sqrt{\frac{n_I}{6\pi\chi_{1^+}^T(0)}}\frac{(1+z)(1-z)^{5/2}}{[(1+r)(1-z)+2\sqrt{r}(1+z)]^5},$$

$$\phi_g(z) = \sqrt{\frac{n_I}{3\pi\tilde{\chi}_{1^-}^T(0)}}\frac{2^4r^2(1+z)^2(1-z)^{-1/2}}{[(1+r)(1-z)+2\sqrt{r}(1+z)]^4},$$

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

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

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

$C_{+(-)} = 2.02159\ (2.52733)$

$n_I = 2.6$

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

[PRD 101 (2020) 072004]

Relation between CLN FFs and BGL series

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

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

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