# First determination of $|V_{cb}|$ and $B_s \to D_s^*$ hadronic form factors using $B_s$ semileptonic decays at LHCb

Ricardo Vazquez Gomez (ICCUB)
on behalf of the LHCb collaboration

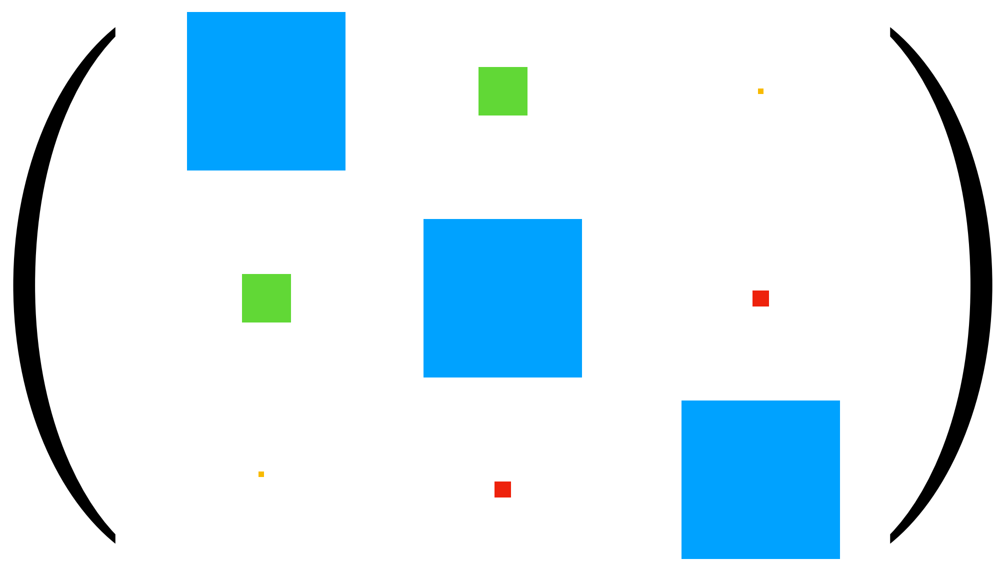
CERN seminar
11 February 2020

LHCb-PAPER-2019-041 (arXiv:2001.03225),
LHCb-PAPER-2019-046

# 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.**

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

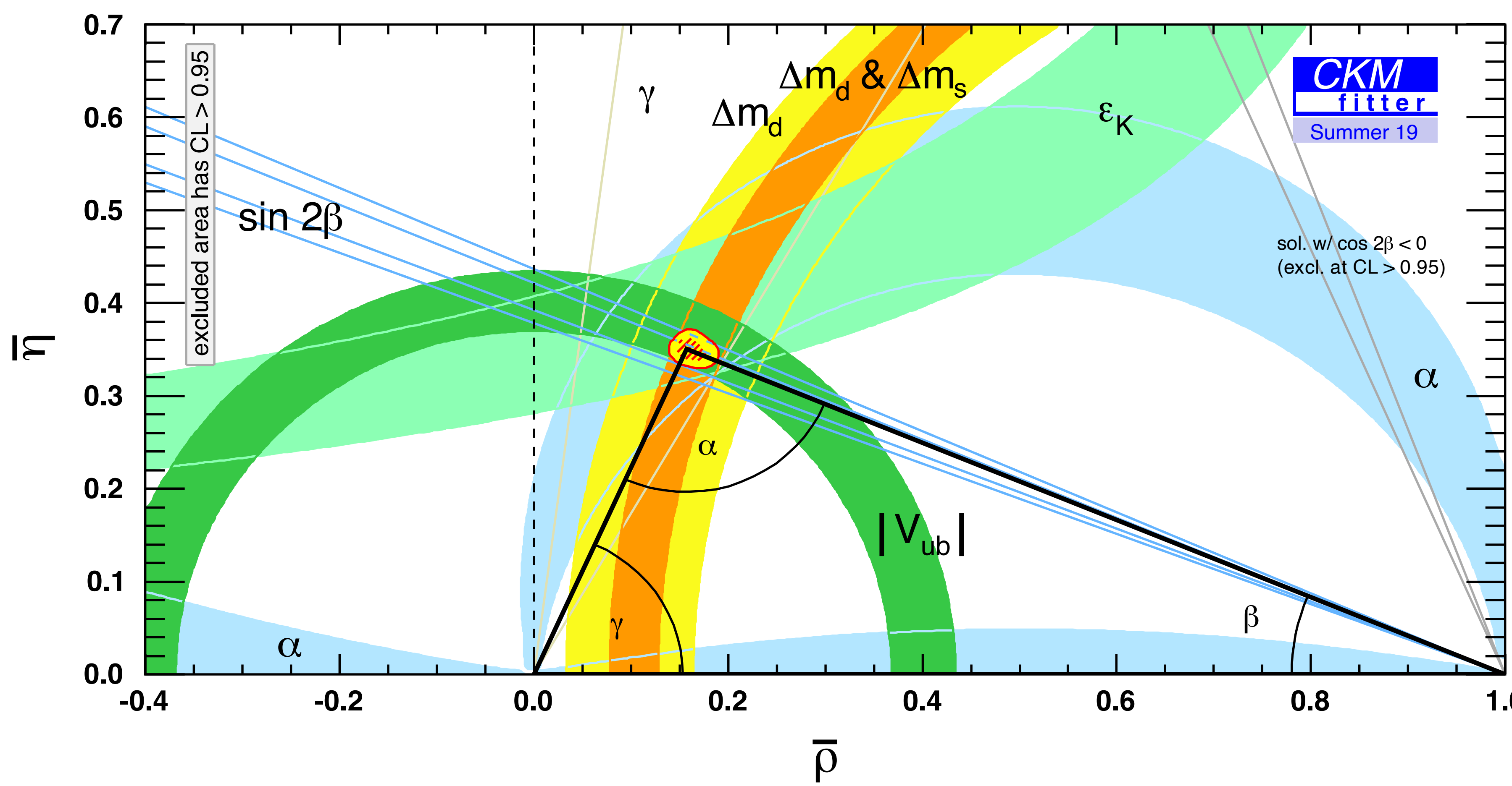


- Hierarchical and almost diagonal.
- Mixing between generations is suppressed.
- Leads to suppression of tree-level *b*-quark decay amplitudes ($V_{cb}$ ~0.04).
- Makes B physics sensitive to New Physics misaligned with CKM.

# CKM unitarity

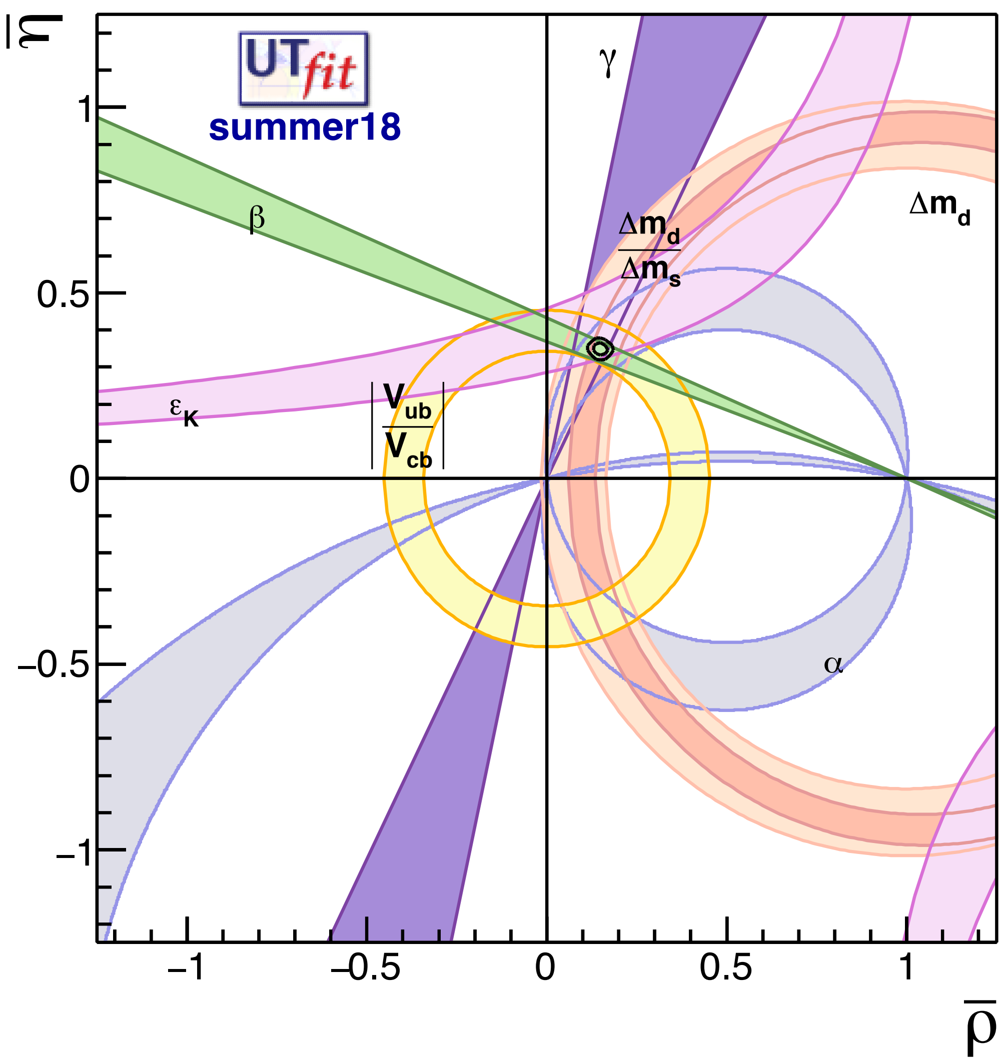
- The CKM matrix is unitary in the SM - 4 free parameters.
- Leads to different unitarity conditions, commonly represented as a triangle i.e.:

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



# New Physics in the triangle

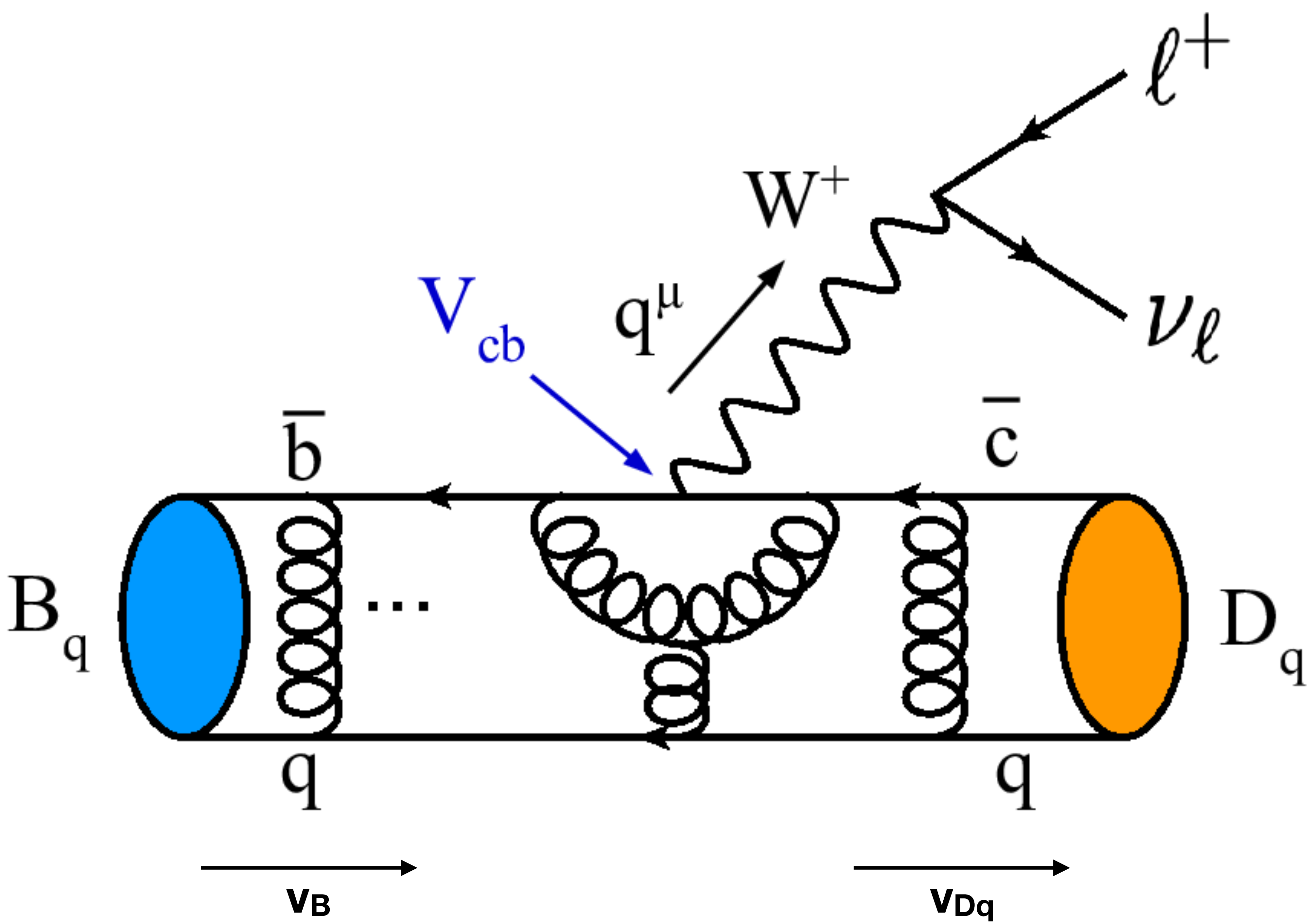
- The triangle is built assuming unitarity. No other flavour changing coupling apart from *W* exchange.
    - New Physics could violate unitarity.
- Need to over-constrain all sides and angles with independent measurements.
    - See if the various constrains agree.




- The side opposite to β is proportional to $|V_{ub}|/|V_{cb}|$.
    - sin(2β) is very well measured, need to improve the precision on the side.
    - Their precise determination is of high priority in the heavy flavour physics program.
- **I will describe the recent measurement of the matrix element relating the b→c transition: $V_{cb}$.**

# Semileptonic B decays

- Semileptonic B decays are used to extract the magnitude of $V_{cb}$.

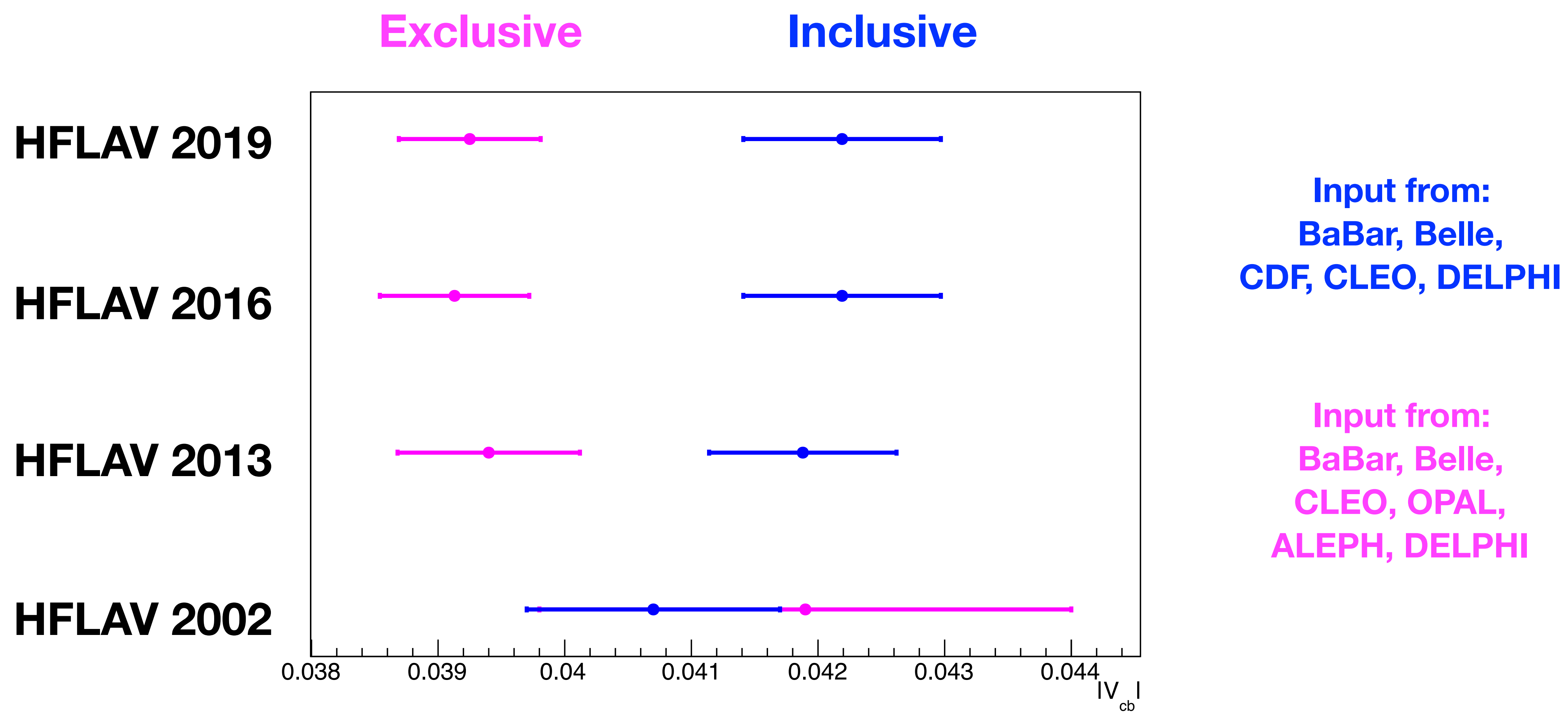


# Measuring $V_{cb}$

- Semileptonic B decays are used to extract the magnitude of $V_{cb}$.
  - Two approaches followed: exclusive and inclusive
- The experimental and theoretical techniques employed are independent and complementary.
  - Exclusive:
    - Decays involving a specific meson (D, D*, $D_s$,…).
    - Measurement precision around 2%. Comparable contributions from theory and experiment.
  - Inclusive:
    - Sum of all possible final states.
    - Measurement precision around 2%. Highly dominated by theory inputs.
- Expect both measurements to be compatible but…

# Exclusive vs Inclusive

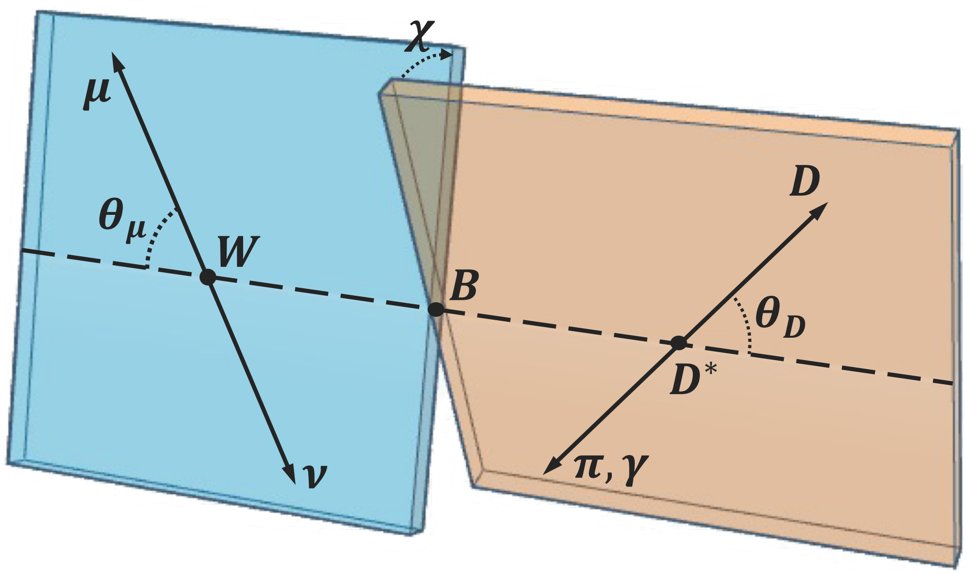
- Long lasting discrepancy between exclusive and inclusive approaches.

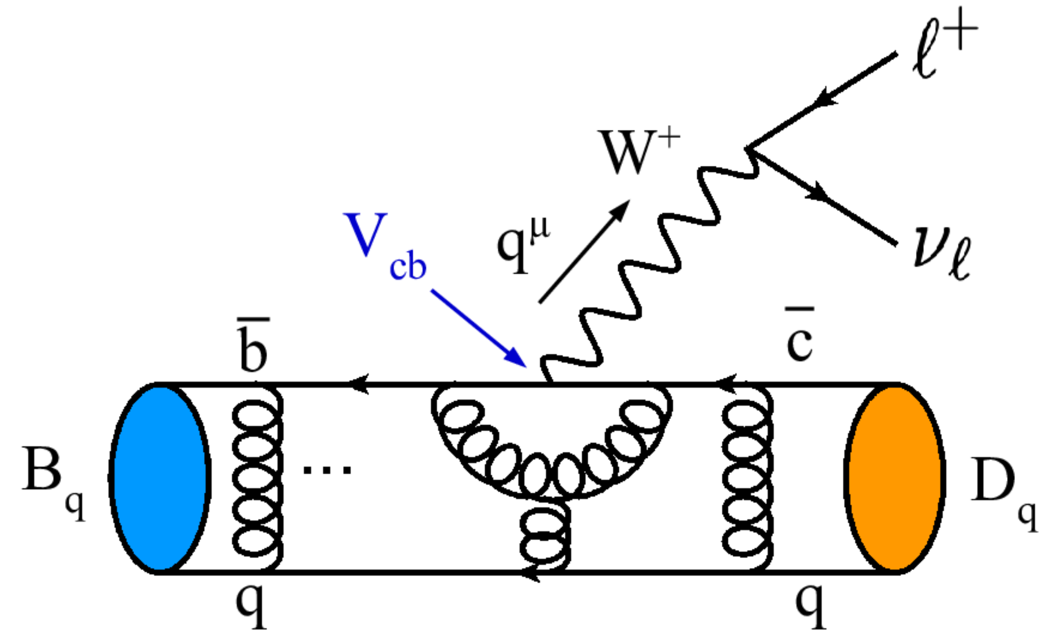



- Marginally consistent results between both approaches.
  - Could it be NP? Or badly described backgrounds?
- New measurements needed, exploit the $B_s$ sector.
- Similar incl. vs excl. differences seen on $V_{ub}$. [CERN seminar 24/05/2015]

# Exclusive measurements

- Measure the differential decay rate of $B_{(s)} \to D^{(*)}_{(s)} \mu\nu$ decays as a function of the di-lepton momentum transfer squared, $q^2$




- Factorise the electroweak and strong parts of the decay.
  - The strong part can be described in terms of scalar functions, ***form factors***, as a function of $q^2$. Form factors cannot be computed in perturbation theory.
  - Experimental measurement is $V_{cb}$ x $FF(q^2)$. The determination of $V_{cb}$ requires a determination of the form factors (either from data or from lattice QCD).

# Form factors

- The decays $B_s \rightarrow D_s^* \mu\nu$ are described by four form factors. In the literature leptons are usually considered massless.

EW + phase space contribution

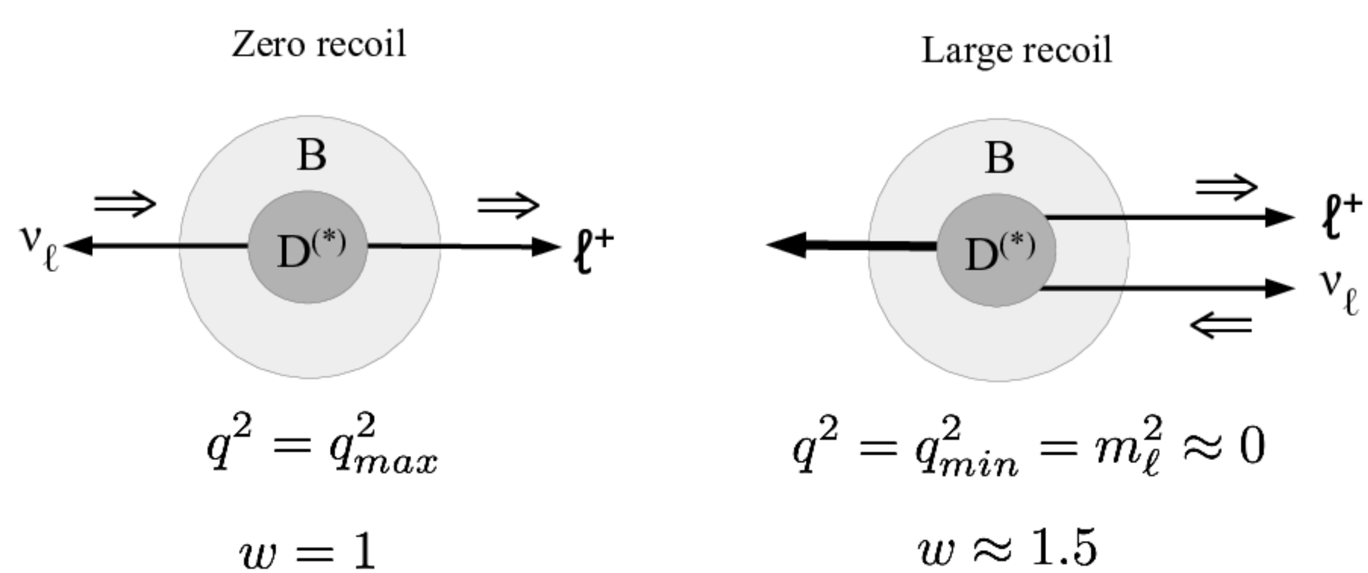
QCD contribution

$$\frac{d\Gamma(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu)}{dq^2} = \frac{G_F^2 \, |V_{cb}|^2 \, |\eta_{EW}|^2 \, |\vec{p}| q^2}{96 \, \pi^3 \, m_{B_s^0}^2} \left(1 - \frac{m_\mu^2}{q^2}\right)^2 \times \left[ \left(|H_+|^2 + |H_-|^2 + |H_0|^2\right) \left(1 + \frac{m_\mu^2}{2\, q^2}\right) + \frac{3}{2} \frac{m_\mu^2}{q^2} |H_t|^2 \right]$$

- The helicity amplitudes ($H_{+,-,0,t}$) can be described in terms of the four form factors $V(q^2)$, $A_0(q^2)$, $A_1(q^2)$, $A_2(q^2)$ which encode the properties of the current.
- At the *zero recoil point* ($q^2_{max}$), $FF(q^2_{max})$ can be computed with precision LQCD.
- Experimental measurements are done at $q^2 \neq q^2_{max}$ as phase-space vanished.
  - Need an extrapolation of the measured distribution of the decay rate spectrum to $q^2_{max}$.
  - **The extrapolation relies on the form factor parametrisation.**
- Two commonly used parametrisations:
  - Caprini-Lellouch-Neubert (CLN) [Nucl. Phys. B530 (1998) 153]
  - Boyd-Grinstein-Lebed (BGL) [PRL 74 (1995) 4603, PLB 353 (1995) 306]

# Intermezzo: $q^2$ vs *w*

- The quantity $q^2$ represents the di-lepton momentum transfer squared. Commonly used by the experimentalists.
  - Easier to obtain experimentally after accessing the B momentum.
- The quantity *w* represents the hadron recoil (Lorentz boost of the D meson in the B rest frame). Commonly used by the theorists.
  - Dimensionless and better defined properties in the $m_{b,c} >> \Lambda_{QCD}$ limit (w=1).
- Related by $w = \dfrac{m_B^2 + m_D^2 - q^2}{2m_B m_D}$. The ***zero recoil point*** means $q^2 = q^2_{max}$ or $w = 1$.
- Present the results in terms of *w.*



# CLN parametrisation

Nucl. Phys. B530 (1998) 153

- Define the functions $h_{A_1}(w), R_0(w), R_1(w), R_2(w)$ as a leading function and three ratios of form factors.

$$h_{A_1}(w) \propto \frac{A_1(w)}{w+1}, \quad R_0(w) \propto \frac{A_0(w)}{h_{A_1}(w)}, \quad R_1(w) \propto \frac{V(w)}{h_{A_1}(w)}, \quad R_2(w) \propto \frac{A_2(w)}{h_{A_1}(w)}$$

- Express the leading form factor $h_{A_1}(w)$ as an expansion around the variable $z = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$, with one single free parameter ($\rho^2$) representing the slope of the function.

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

- The three ratios are simply functions of *w* with parameters $R_0(1), R_1(1), R_2(1)$.

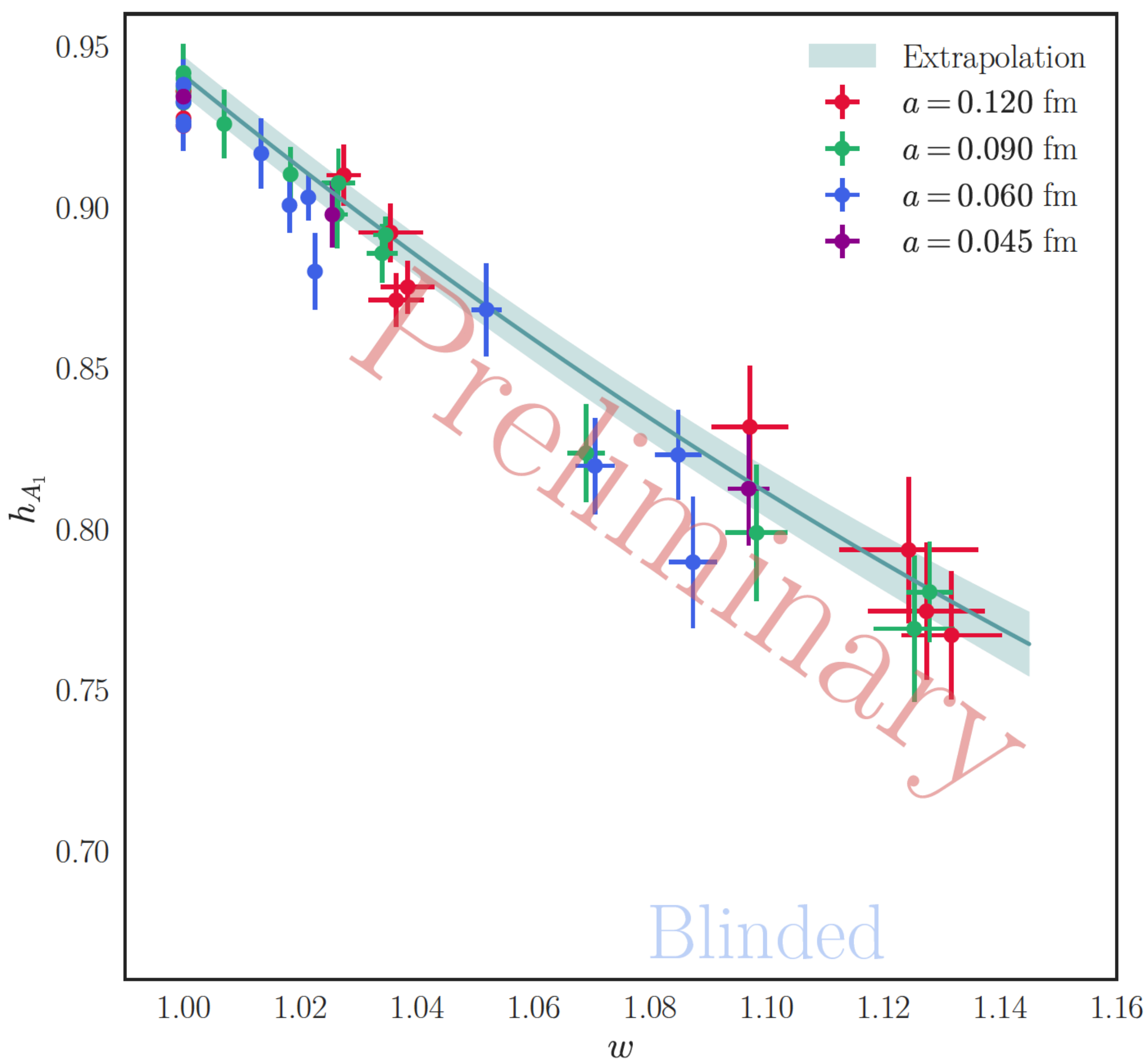
$$R_0(w) = R_0(1) - 0.11(w-1) + 0.01(w-1)^2$$

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

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

# Form factor shape from lattice

- Effort from the lattice community to compute the form factor at different w values.
  - So far effort for the $B \to D^*$. Computations are still blinded. [arXiv:1906.01019]
  - Expect $B_s \to D_s^*$ to follow.




**Each set of points correspond to different lattice configurations.**

# BGL parametrisation

PRL 74 (1995) 4603
PLB 353 (1995) 306

- Define the functions $f(w), g(w), \mathcal{F}_1(w), \mathcal{F}_2(w)$ as a convergent series of z.

$$f(z) = \frac{1}{P_{1^+}(z)\phi_f(z)} \sum_{n=0}^{\infty} a_n^f z^n \qquad \mathcal{F}_1(z) = \frac{1}{P_{1^+}(z)\phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{\infty} a_n^{\mathcal{F}_1} z^n$$

$$g(z) = \frac{1}{P_{1^-}(z)\phi_g(z)} \sum_{n=0}^{\infty} a_n^g z^n \qquad \mathcal{F}_2(z) = \frac{\sqrt{m_{D_s^*}/m_{B_s}}}{(1 + m_{D_s^*}/m_{B_s})P_0^-(z)\phi_{\mathcal{F}_2}(z)} \sum_{n=0}^{\infty} a_n^{\mathcal{F}_2} z^n$$

- The sum of the $a_i$ coefficients in each function is bounded to unity.
- These functions can be related to the CLN parametrisation as

$$f(w) \propto (w+1)h_{A_1}(w) \qquad g(w) \propto \frac{f(w)R_1(w)}{(w+1)}$$

$$\mathcal{F}_1(w) \propto f(w)R_2(w)(w-1) \qquad \mathcal{F}_2(w) \propto f(w)R_0(w)$$

- In the $B_s \to D_s^*$ case, 0 < z < 0.06, the functions converge fast and can be truncated, usually at n=2.

# Inclusive decays

- Disregard form factors, measure all $b \to cl\nu$ transitions.
    - Measure total semileptonic BR and moments of the lepton energy and hadronic invariant mass spectra as a function of different lepton energy.
- Inclusive measurements performed at LEP and B-factories.
- Theoretically based on the Operator Product Expansion.

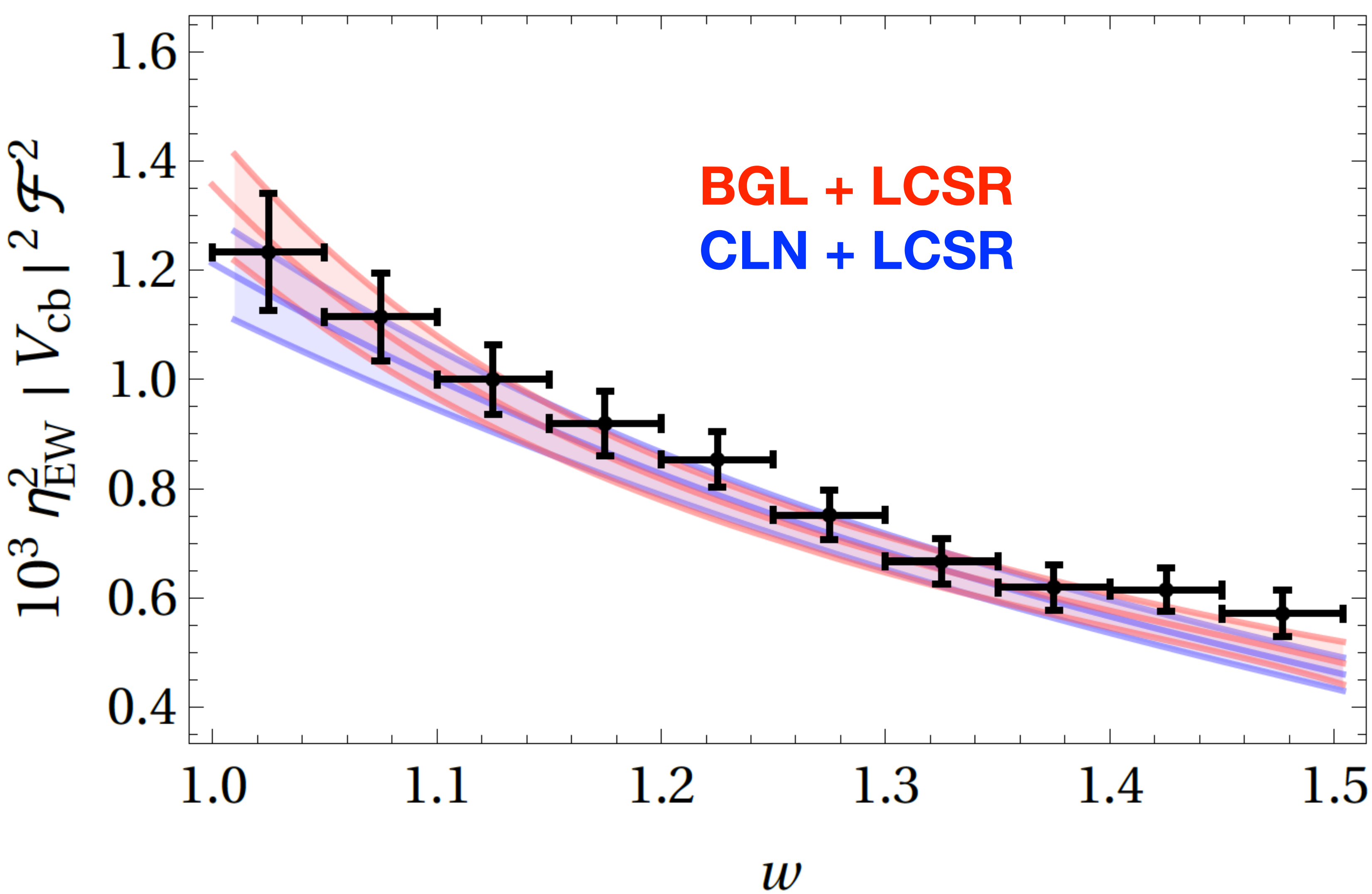
$$\Gamma \propto |V_{cb}|^2 \left[ O(\alpha_s) + O(\alpha_s^2) + .. + O(\Lambda_{QCD}^2/m_b^2) + O(\Lambda_{QCD}^3/m_b^3) + \ldots \right]$$

**perturbative expansion** **non-perturbative corrections**

- The total decay rate or the moments of distributions of lepton energy and hadronic energy depend on Γ, and are sensitive to $V_{cb}$.
    - Last experimental update from B-factories in 2010.

# The role of the parametrisation

- Tagged analysis by Belle [arXiv:1702.01521].
  - Allowed to fit for the first time different parametrisations.
  - Variation of 6% depending on the parametrisation!
    - Better agreement between inclusive and exclusive with BGL.



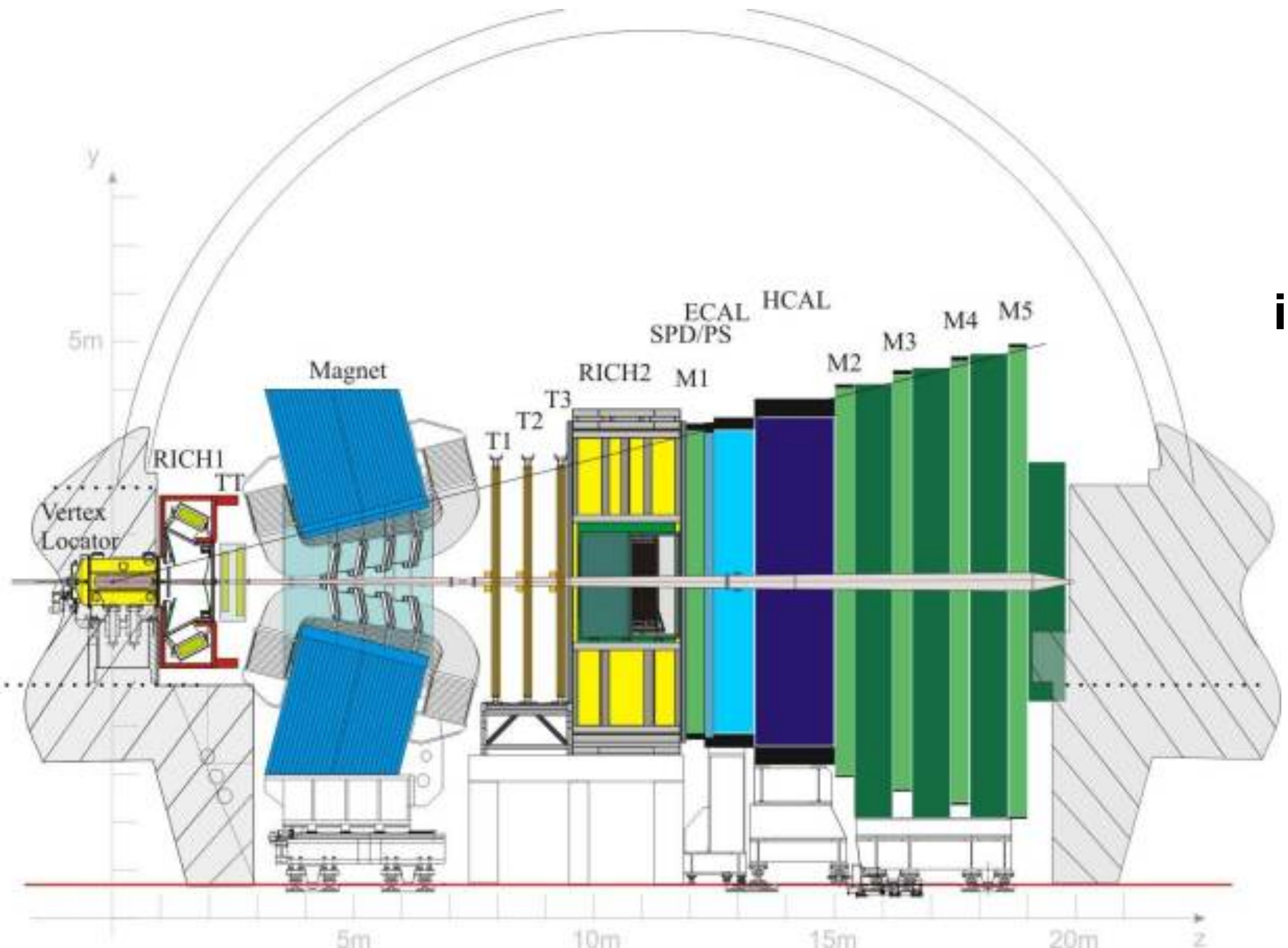

**Different results at w=1. Lead to different values of $V_{cb}$.**

# The role of the parametrisation

- Tagged analysis by Belle [arXiv:1702.01521].
  - Allowed to fit for the first time different parametrisations.
  - Variation of 6% depending on the parametrisation!
    - Better agreement between inclusive and exclusive with BGL.
- Tagged analysis by BaBar [PRL 123 (2019) 091801].
  - No difference observed in $V_{cb}$ between parametrisations. Aligned with exclusive measurements.
- Untagged analysis by Belle [PRD 100 (2019) 052007].
  - No difference observed in $V_{cb}$ between parametrisations. Aligned with exclusive measurements.
- As more datasets were published, this allowed the theorist to reinterpret the data with latest lattice results. **There is no significant difference between parametrisations.**

# The LHCb detector

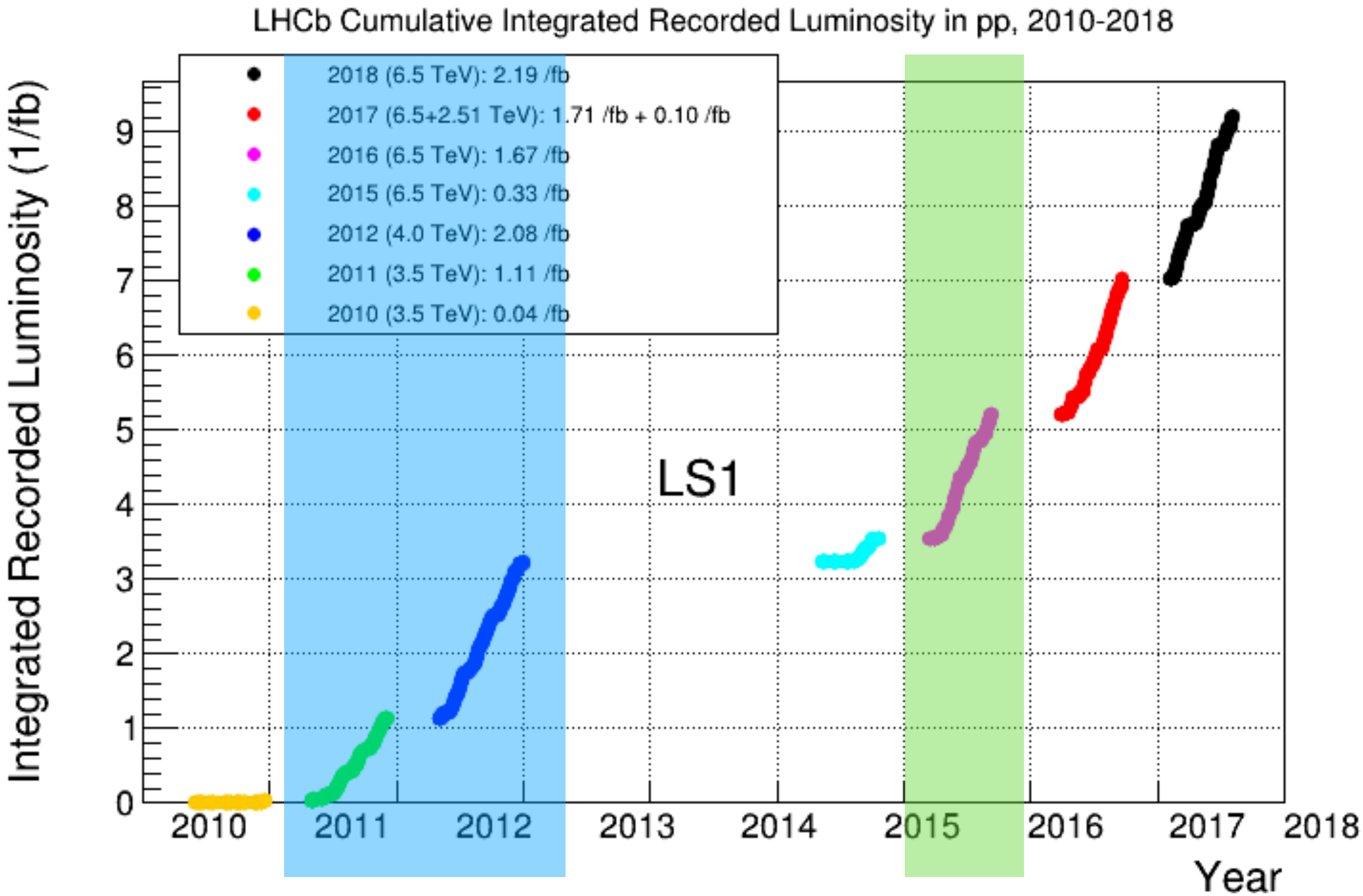
- Exploit the large production of $B_s$ mesons at the LHC.




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

**Belle's dataset is $O(10^7)$ $B_s$ mesons.**
**[PRD 92 (2015) 072013]**

# The LHCb dataset

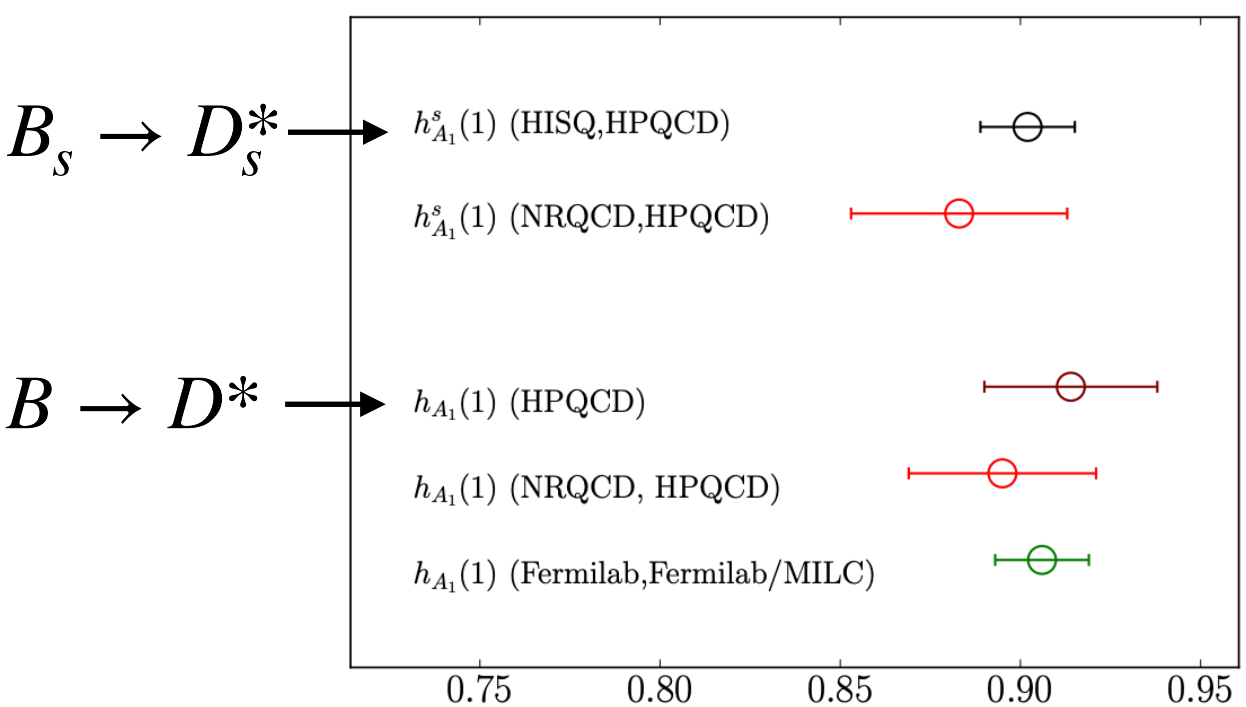


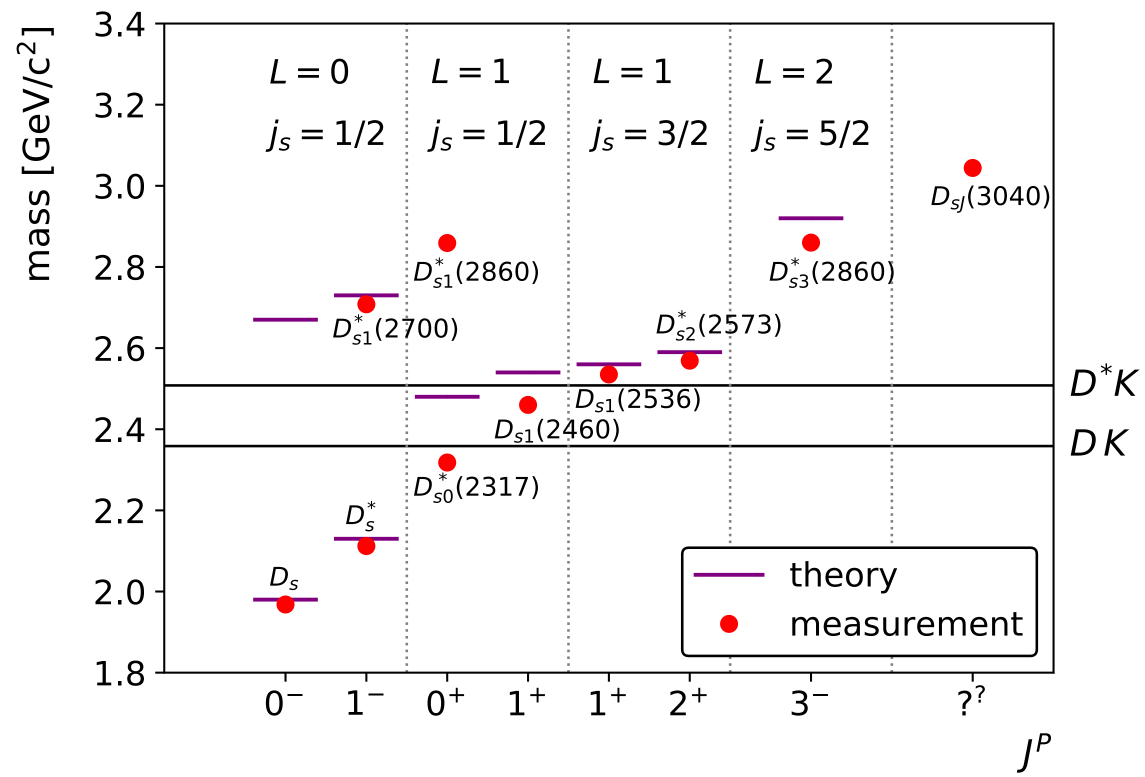

$V_{cb}$ measurement

FF measurement

# The advantage of $B_s$ decays

- Complementary measurements to those from $B^0$ and $B^+$.
- Lattice QCD calculations are easier due to the heavier spectator quark → more precise predictions [PRD 99 (2019) 114512].
- Different background composition from excited $D_s$ mesons than in $B \to D^{(*)}$ decays.
    - Above certain mass of the $D_s$ mesons, the decay is through $D^{(*)}K$.

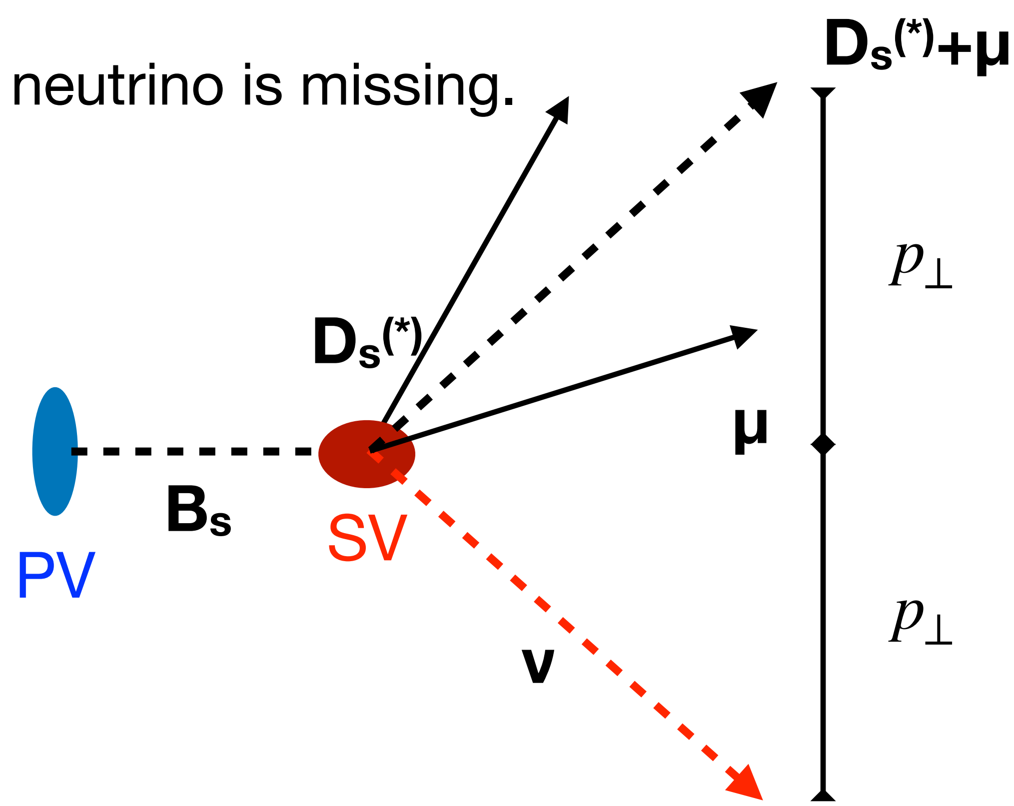


# Tools for semileptonic decays

- Difficult to compute $q^2$ without fully reconstructing the decay.
- $B_s$ flight direction is well-measured. Use $B_s$ mass to constrain the decay and solve $q^2$ with a two-fold ambiguity.
- Improve on finding the correct solution by using an MVA based on the $B_s$ flight direction [JHEP 02 (2017) 021]. Gives the correct solution in ~70% of the cases.
- Reconstruct the corrected mass using the imbalance of momentum transverse to $B_s$ flight direction.
    - $m_{corr}$ peaks at the $B_s$ mass if only one neutrino is missing.

$$m_{\mathrm{corr}} = \sqrt{m_{\mathrm{vis}}^2 + p_\perp^2} + p_\perp$$

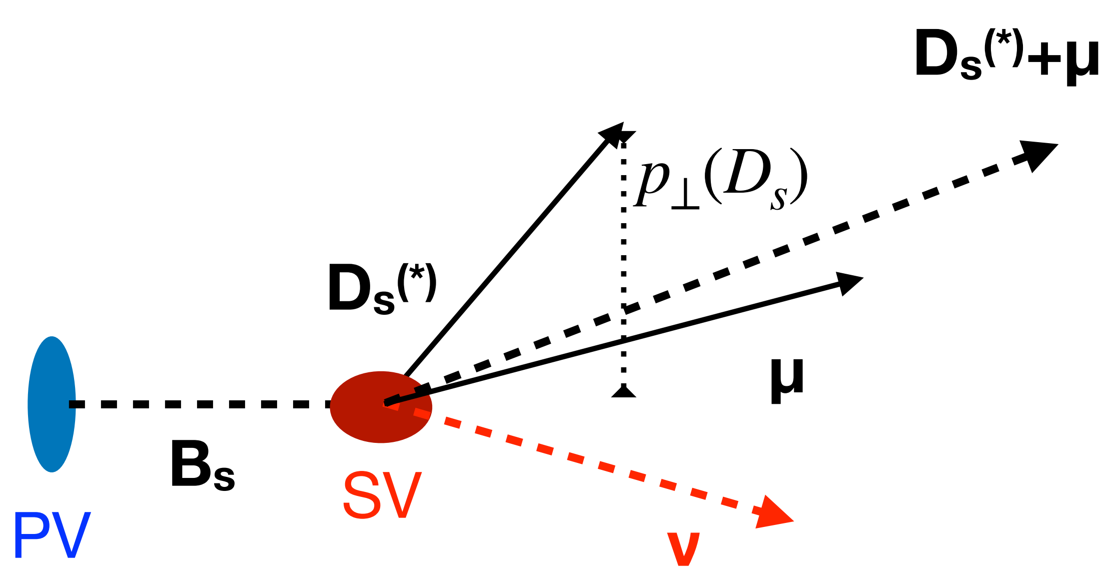


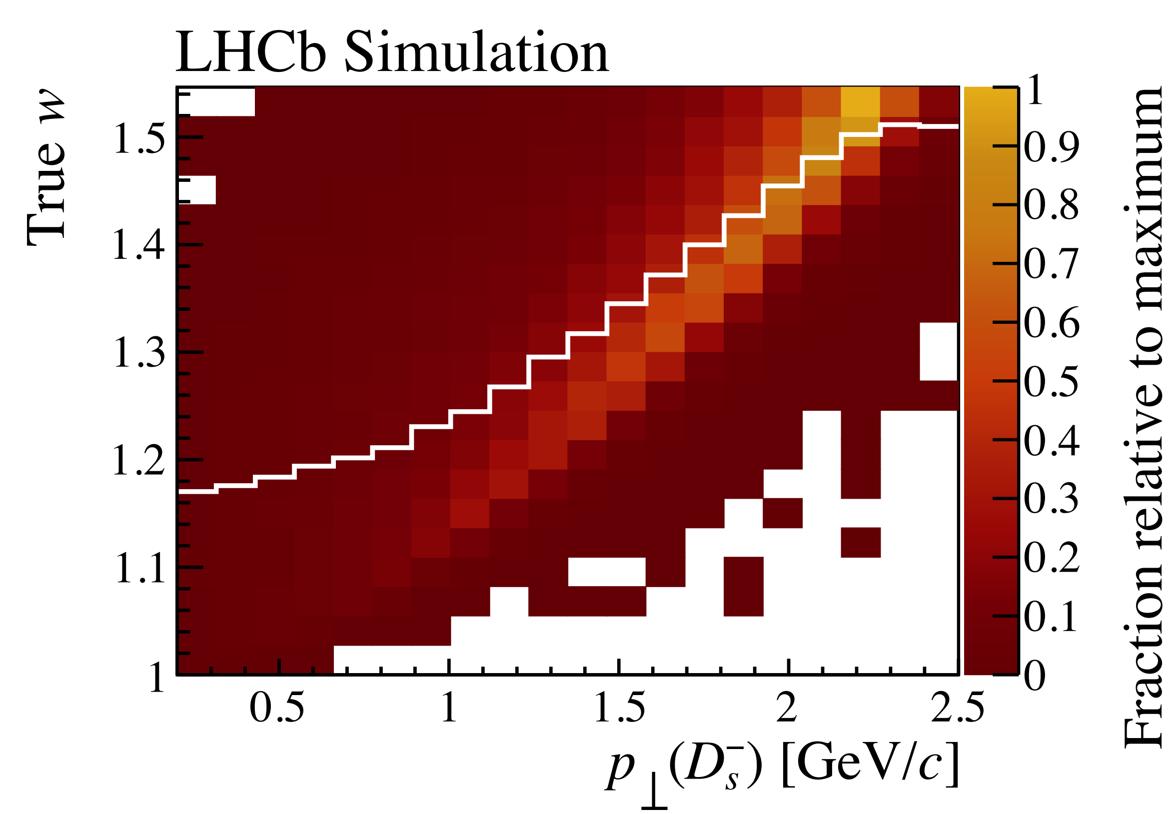
# Measurement of $V_{cb}$ from $B_s$ decays

LHCb-PAPER-2019-041
(arXiv:2001.03225 submitted to PRD)

# Extraction of $V_{cb}$

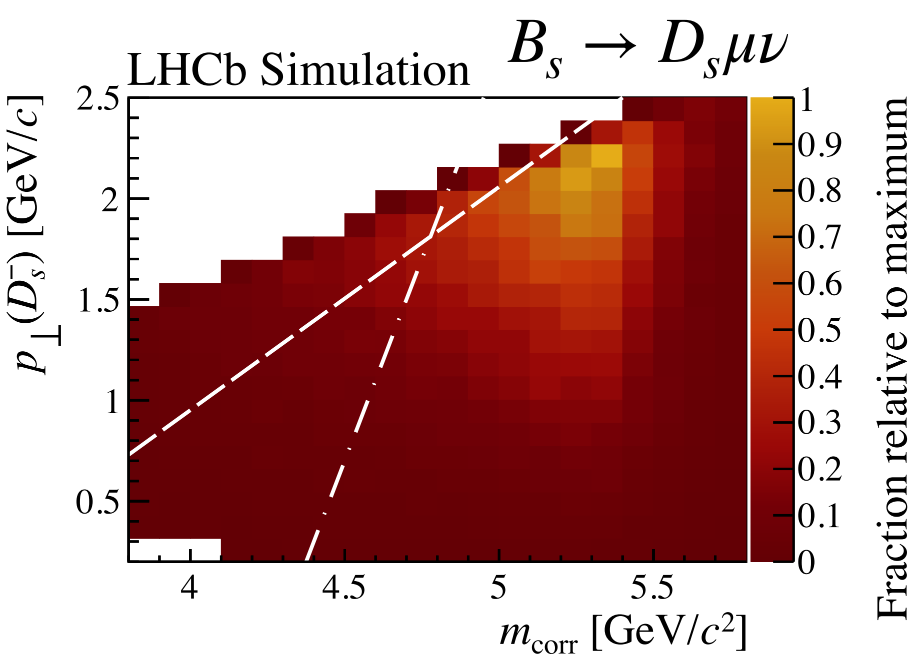
- Extract the value of $V_{cb}$ from $B_s \to D_s^- \mu^+ \nu$ and $B_s \to D_s^{*-} \mu^+ \nu$ decays reconstructing only the $D_s^-(\to K^- K^+ \pi^-)\mu^+$ final state using Run 1 data.
  - Use $B^0 \to D^{-(*)} \mu^+ \nu$ as normalisation. Decays are kinematically identical -> reduce systematic uncertainties.
  - The ratios of yields is proportional to $V_{cb}$.
- Do not use the value of *w* from any approximation. Instead use $p_\perp(D_s)$ which is correlated with *w*. **Advantage of being fully reconstructed.**

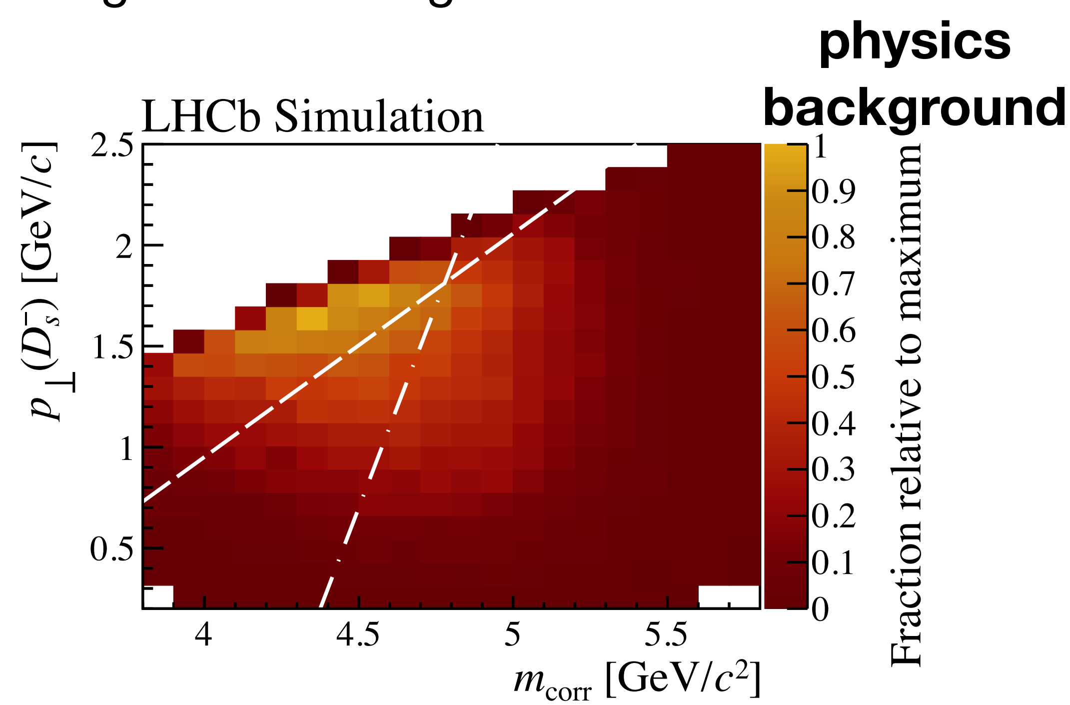


# Analysis strategy

- Template fit to $m_{\text{corr}}$ and $p_{\perp}$ identify the signal decays and provides a simultaneous measurement of $V_{cb}$ and the form factors or ratios $R^{(*)}$.
  - Use of large simulation samples to describe the signal and backgrounds.

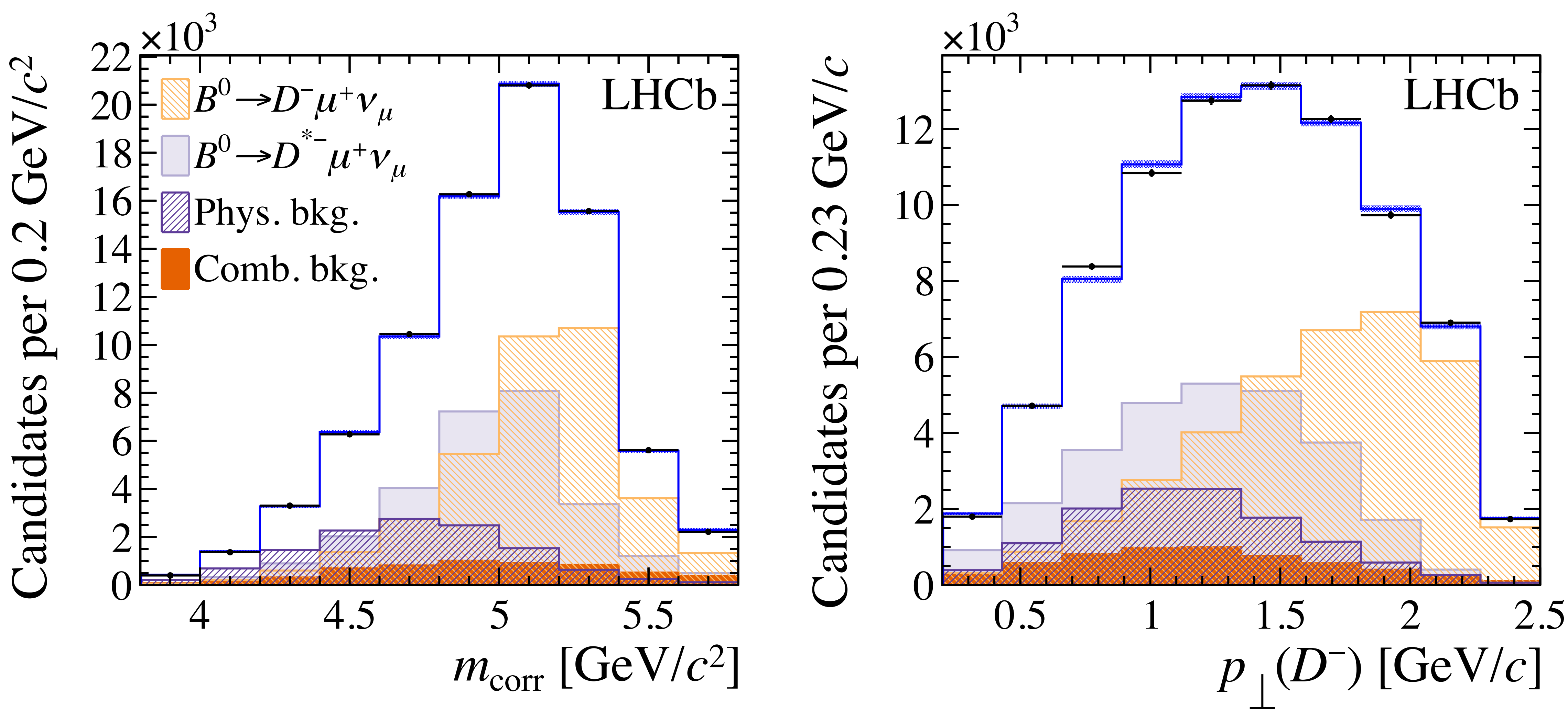



- Signal template depend on form factors which are recalculated at each iteration of the fit. Fit is also sensitive to the form factor parameters.
  - Use CLN and BGL parametrisations.
- Simultaneous fit to the signal and normalisation mode.
  - Fit for $V_{cb}$ or for the ratios $R^{(*)} = \dfrac{\mathscr{B}(B_s \to D_s^{-(*)}\mu^+\nu)}{\mathscr{B}(B^0 \to D^{-(*)}\mu^+\nu)}$.

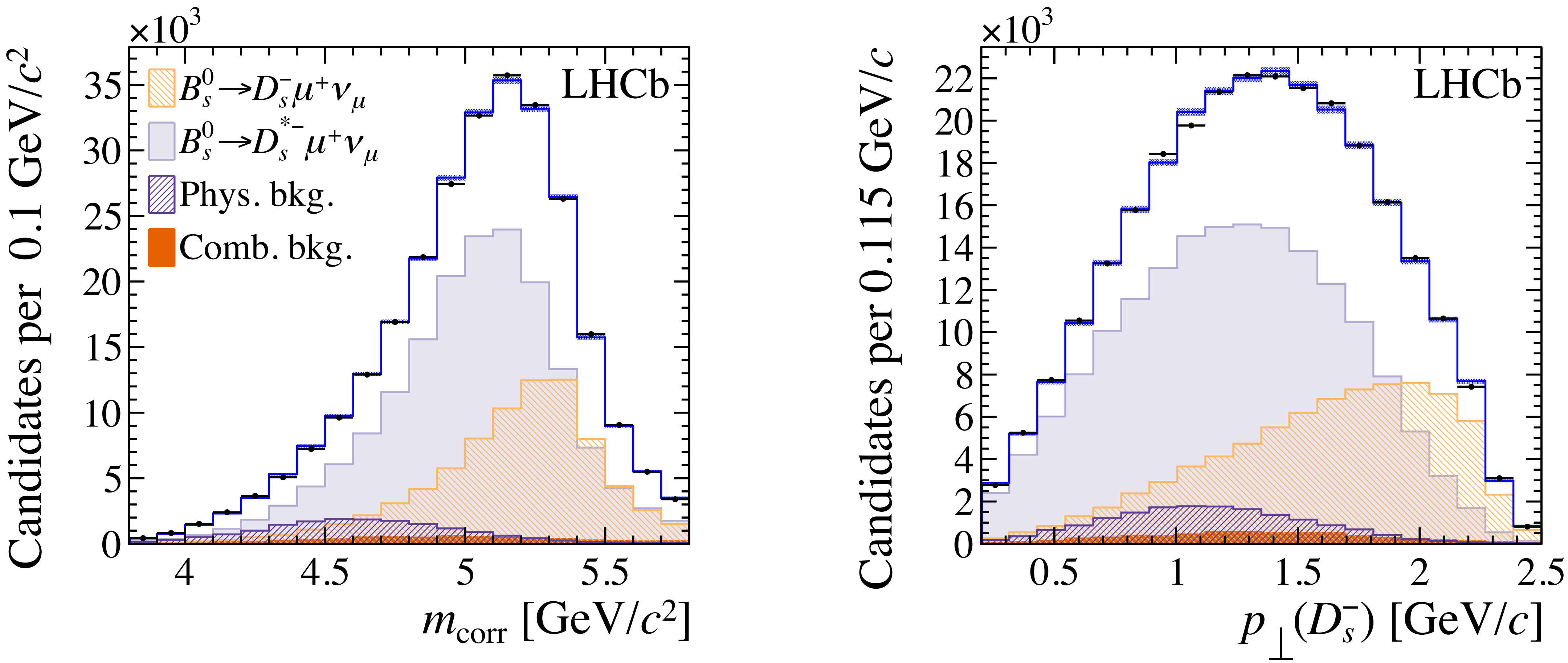
# Fits to normalisation mode

- Yields and $B^0 \to D^{-(*)}\mu^+\nu$ form factors are free parameters.
  - 36k and 28k candidates for $D^-$ and $D^{*-}$, respectively.
- Use only with CLN parametrisation as it contains less parameters.
  - Form factors parameters found to be consistent with the world average with larger uncertainties.



# Fits to signal mode

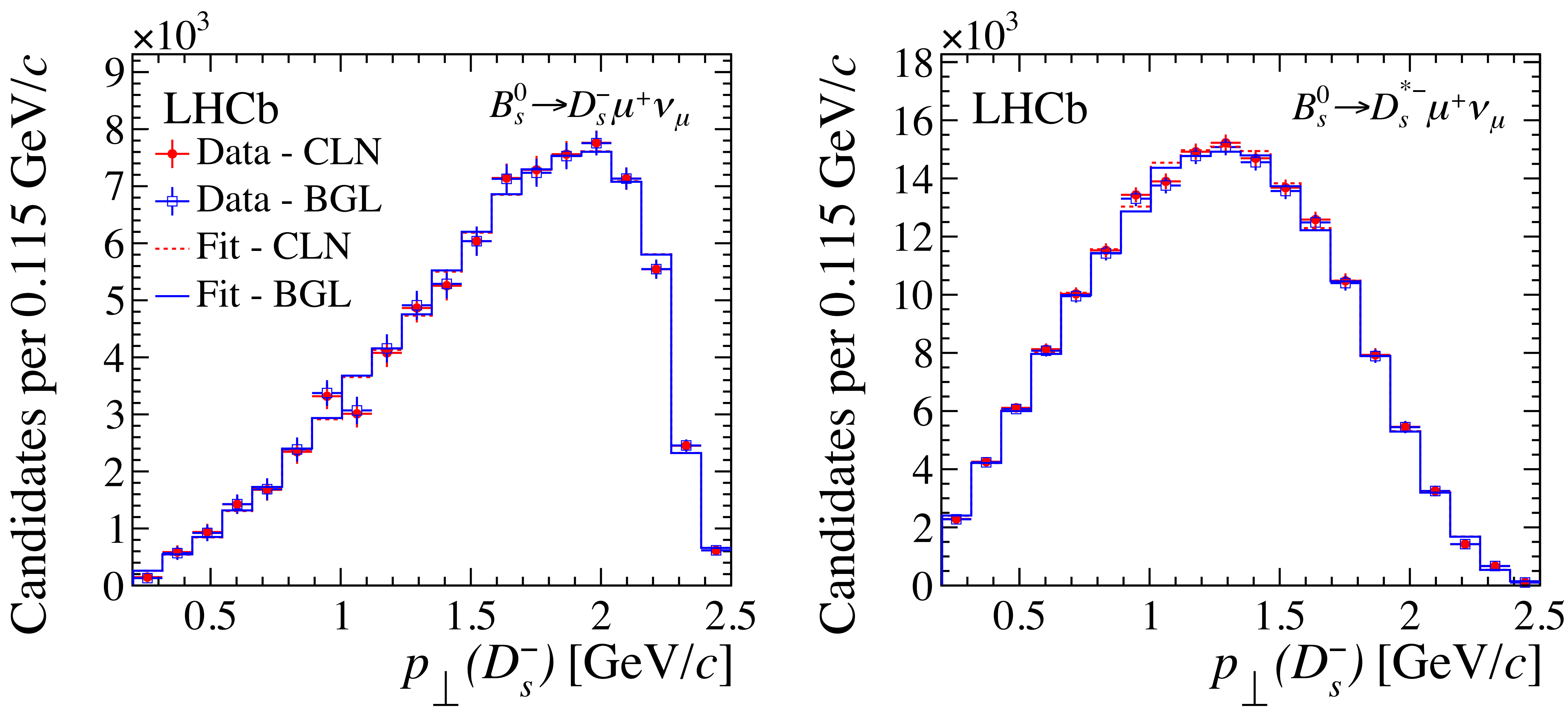
- Yields and $B_s \to D_s^{*-}\mu^+\nu$ form factors are free parameters.
- Use CLN and BGL parametrisations.




1D projections when using CLN parametrisation.
Extremely pure signal samples.

# $V_{cb}$ using CLN and BGL

- Compare the background subtracted distributions obtained with the CLN and BGL fits.
  - No significant differences found between both parametrisations.



# Systematic uncertainties on $V_{cb}$ (CLN)

- Dominated by the external inputs needed in the fit i.e.: $f_s/f_d$.

| | Source | CLN parametrization | | | | | |
|---|---|---|---|---|---|---|---|
| | | $\lvert V_{cb}\rvert$ $[10^{-3}]$ | $\rho^2(D_s^-)$ $[10^{-1}]$ | $\mathcal{G}(0)$ $[10^{-2}]$ | $\rho^2(D_s^{*-})$ $[10^{-1}]$ | $R_1(1)$ $[10^{-1}]$ | $R_2(1)$ $[10^{-1}]$ |
| **external** | $f_s/f_d \times \mathcal{B}(D_s^- \to K^+K^-\pi^-)(\times\tau)$ | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | $\mathcal{B}(D^- \to K^-K^+\pi^-)$ | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | $\mathcal{B}(D^{*-} \to D^-X)$ | 0.2 | 0.0 | 0.1 | 0.0 | 0.1 | 0.0 |
| | $\mathcal{B}(B^0 \to D^-\mu^+\nu_\mu)$ | 0.4 | 0.0 | 0.3 | 0.1 | 0.2 | 0.1 |
| | $\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$ | 0.3 | 0.0 | 0.2 | 0.1 | 0.1 | 0.1 |
| | $m(B_s^0)$, $m(D^{(*)-})$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | $\eta_{\rm EW}$ | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | $h_{A_1}(1)$ | 0.3 | 0.0 | 0.2 | 0.1 | 0.1 | 0.1 |
| | External inputs (ext) | 1.2 | 0.0 | 0.4 | 0.1 | 0.2 | 0.1 |
| **syst** | $D_{(s)}^- \to K^+K^-\pi^-$ model | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Background | 0.4 | 0.3 | 2.2 | 0.5 | 0.9 | 0.7 |
| | Fit bias | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Corrections to simulation | 0.0 | 0.0 | 0.5 | 0.0 | 0.1 | 0.0 |
| | Form-factor parametrization | – | – | – | – | – | – |
| | Experimental (syst) | 0.9 | 0.3 | 2.2 | 0.5 | 0.9 | 0.7 |
| **stat** | Statistical (stat) | 0.6 | 0.5 | 3.4 | 1.7 | 2.5 | 1.6 |

# Systematic uncertainties on $V_{cb}$ (BGL)

- Dominated by the external inputs needed in the fit i.e.: $f_s/f_d$.

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

# Systematic uncertainties on ratios

- Dominated by the background modelling and $D_s^- \to K^+K^-\pi^-$ decay model.
  - Related to the available size of the simulation.

$$R^{(*)} = \frac{\mathscr{B}(B_s \to D_s^{-(*)}\mu^+\nu)}{\mathscr{B}(B^0 \to D^{-(*)}\mu^+\nu)}$$

| | Source | $\mathcal{R}$ $[10^{-1}]$ | $\mathcal{R}^*$ $[10^{-1}]$ |
|---|---|---|---|
| external | $f_s/f_d \times \mathcal{B}(D_s^- \to K^+K^-\pi^-)(\times\tau)$ | 0.4 | 0.4 |
| | $\mathcal{B}(D^- \to K^-K^+\pi^-)$ | 0.3 | 0.3 |
| | $\mathcal{B}(D^{*-} \to D^-X)$ | – | 0.2 |
| | $\mathcal{B}(\mathrm{B}^0 \to D^-\mu^+\nu_\mu)$ | – | – |
| | $\mathcal{B}(\mathrm{B}^0 \to D^{*-}\mu^+\nu_\mu)$ | – | – |
| | $m(B_s^0)$, $m(D^{(*)-})$ | – | – |
| | $\eta_{\mathrm{EW}}$ | – | – |
| | $h_{A_1}(1)$ | – | – |
| | External inputs (ext) | 0.5 | 0.5 |
| syst | $D_{(s)}^- \to K^+K^-\pi^-$ model | 0.5 | 0.4 |
| | Background | 0.4 | 0.6 |
| | Fit bias | 0.0 | 0.0 |
| | Corrections to simulation | 0.0 | 0.0 |
| | Form-factor parametrization | 0.0 | 0.1 |
| | Experimental (syst) | 0.6 | 0.7 |
| stat | Statistical (stat) | 0.5 | 0.5 |

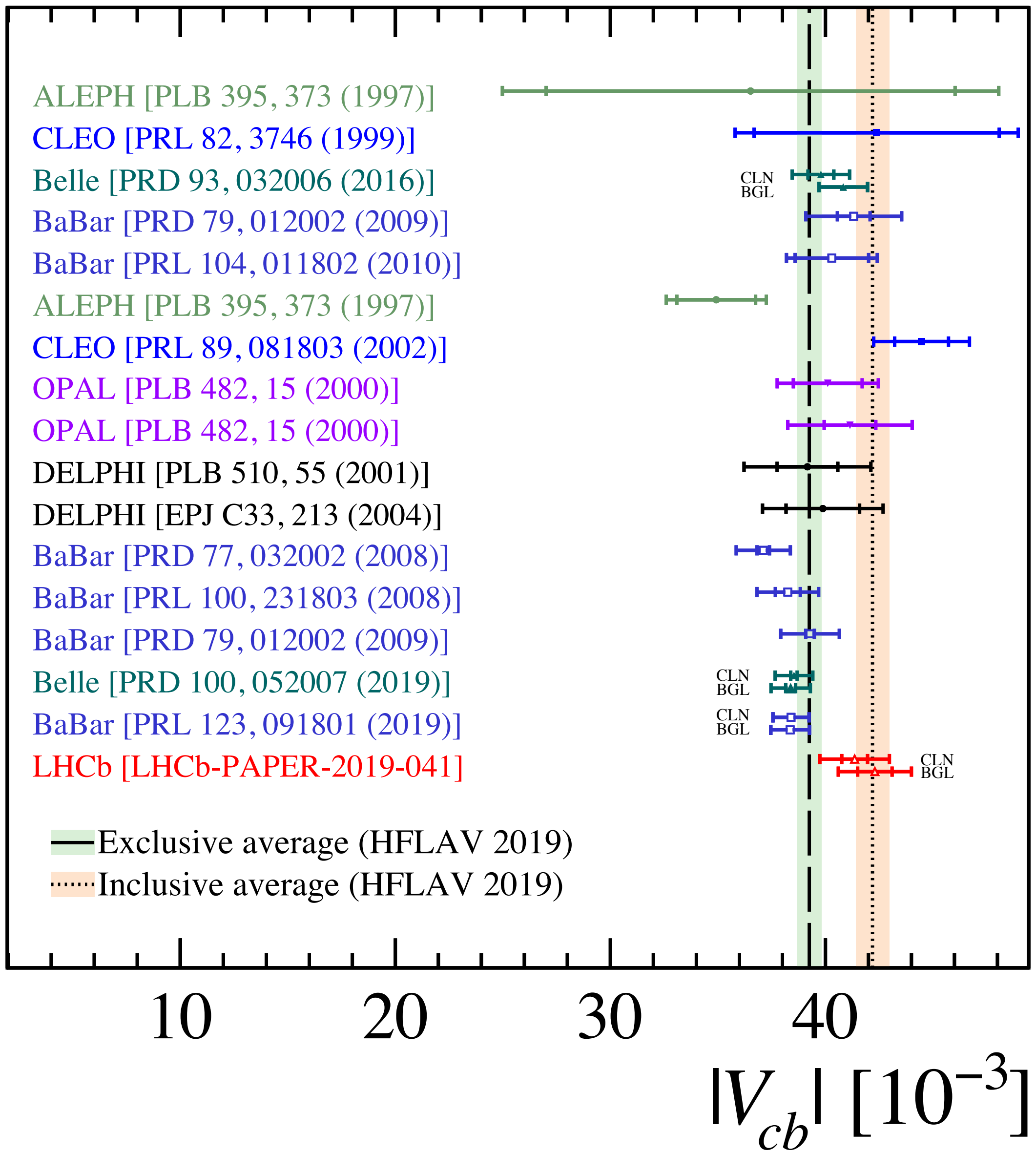
# Results on $V_{cb}$

- First measurement of $V_{cb}$ on a hadronic environment and first measurement using $B_s$ mesons.

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

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

- Confirm the trend that the **parametrisation is not responsible** for inclusive vs exclusive disagreements.
- **Both results are in agreement** with the exclusive and inclusive determinations.



# Results on $\mathscr{B}(B_s \to D_s^{-(*)}\mu^+\nu)$

- From the ratios of branching fractions and using the measured values of $\mathscr{B}(B^0 \to D^-\mu^+\nu)$ and $\mathscr{B}(B^0 \to D^{*-}\mu^+\nu)$, the exclusive branching fractions are determined for the first time.
  - Around 10% total uncertainty on both branching fractions.

$$\mathscr{B}(B_s \to D_s^-\mu^+\nu) = (2.49 \pm 0.12(\text{stat}) \pm 0.14(\text{syst}) \pm 0.16(\text{ext})) \times 10^{-2}$$

$$\mathscr{B}(B_s \to D_s^{*-}\mu^+\nu) = (5.38 \pm 0.25(\text{stat}) \pm 0.46(\text{syst}) \pm 0.30(\text{ext})) \times 10^{-2}$$

$$\frac{\mathscr{B}(B_s \to D_s^-\mu^+\nu)}{\mathscr{B}(B_s \to D_s^{*-}\mu^+\nu)} = 0.464 \pm 0.013(\text{stat}) \pm 0.043(\text{syst}))$$

# Measurement of $B_s \to D_s^*$ form factors

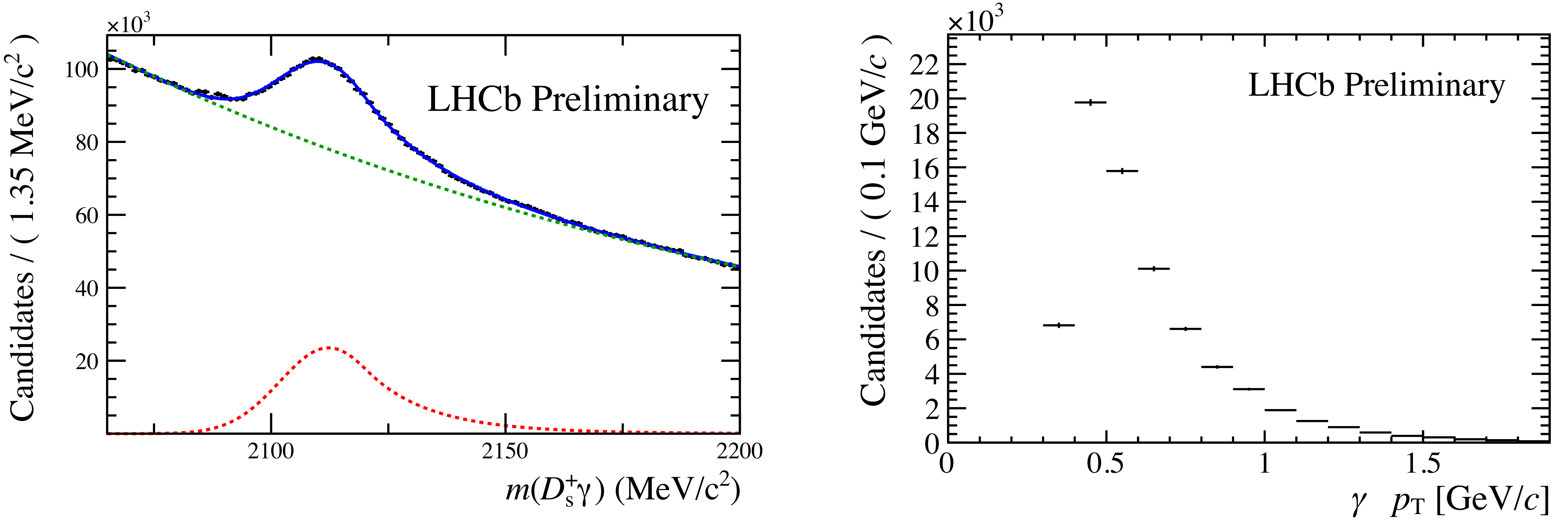
LHCb-PAPER-2019-046 in preparation

# Extraction of form factors

- Aim to measure more precisely the form factors in the CLN and BGL parametrisations.
- Extract the differential decay rate of $B_s \to D_s^{*-}\mu^+\nu$ decays as a function of *w* using 2016 data.
  - Integrate over the angles as they have small dependency on FF.
  - Fully reconstruct the $D_s^{*+} \to D_s^+\gamma$ decay.
  - Use templates from simulation to fit the corrected mass in bins of *w*.
- Correct the raw yields for detector resolution (unfolding) and selection and reconstruction efficiencies.
- Fit the unfolded and efficiency corrected spectrum with CLN and BGL parametrisations.
  - **CLN**: fit the leading form factor $h_{A_1}(w)$ and extract the slope $\rho^2$
  - **BGL**: fit the leading form factor $f(w)$ and extract two coefficients $a_1^f, a_2^f$
    - Take from external source the parameters for the other functions.

# Candidate selection

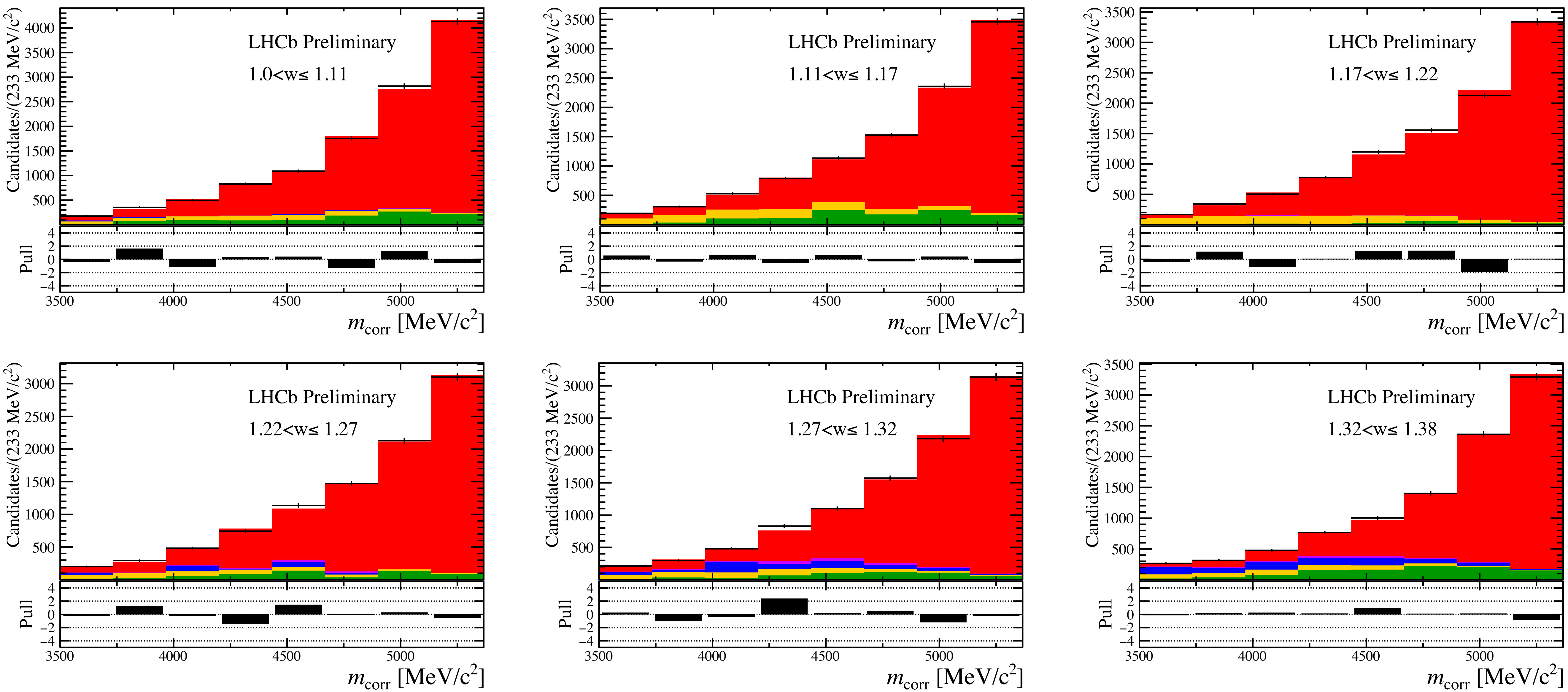
- Fully reconstruct the $D_s^{*+} \rightarrow D_s^+\gamma$ decay.
  - Soft photon is selected in a cone around the $D_s^+$ flight direction.

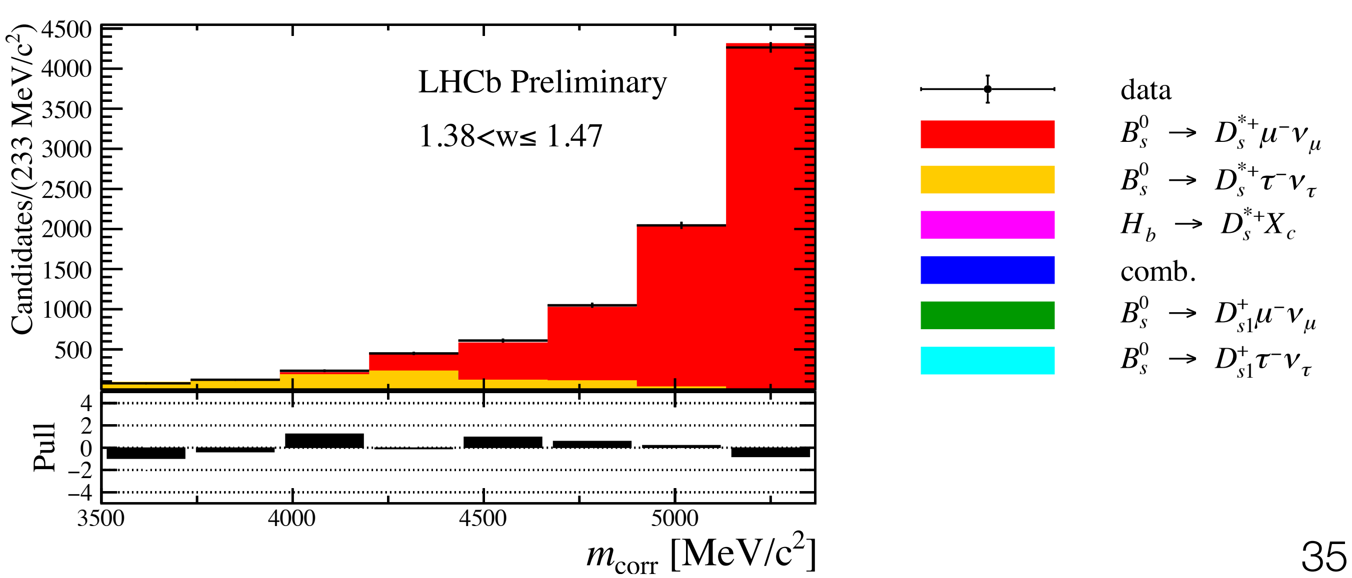



  - Use sPlots to subtract the combinatorial photon background.
    [Nucl. Instrum. Meth. A555 (2005) 356]

- Employ isolation on the muon candidate and $p_T$ cuts to avoid contamination from τ decays.

# Signal yields

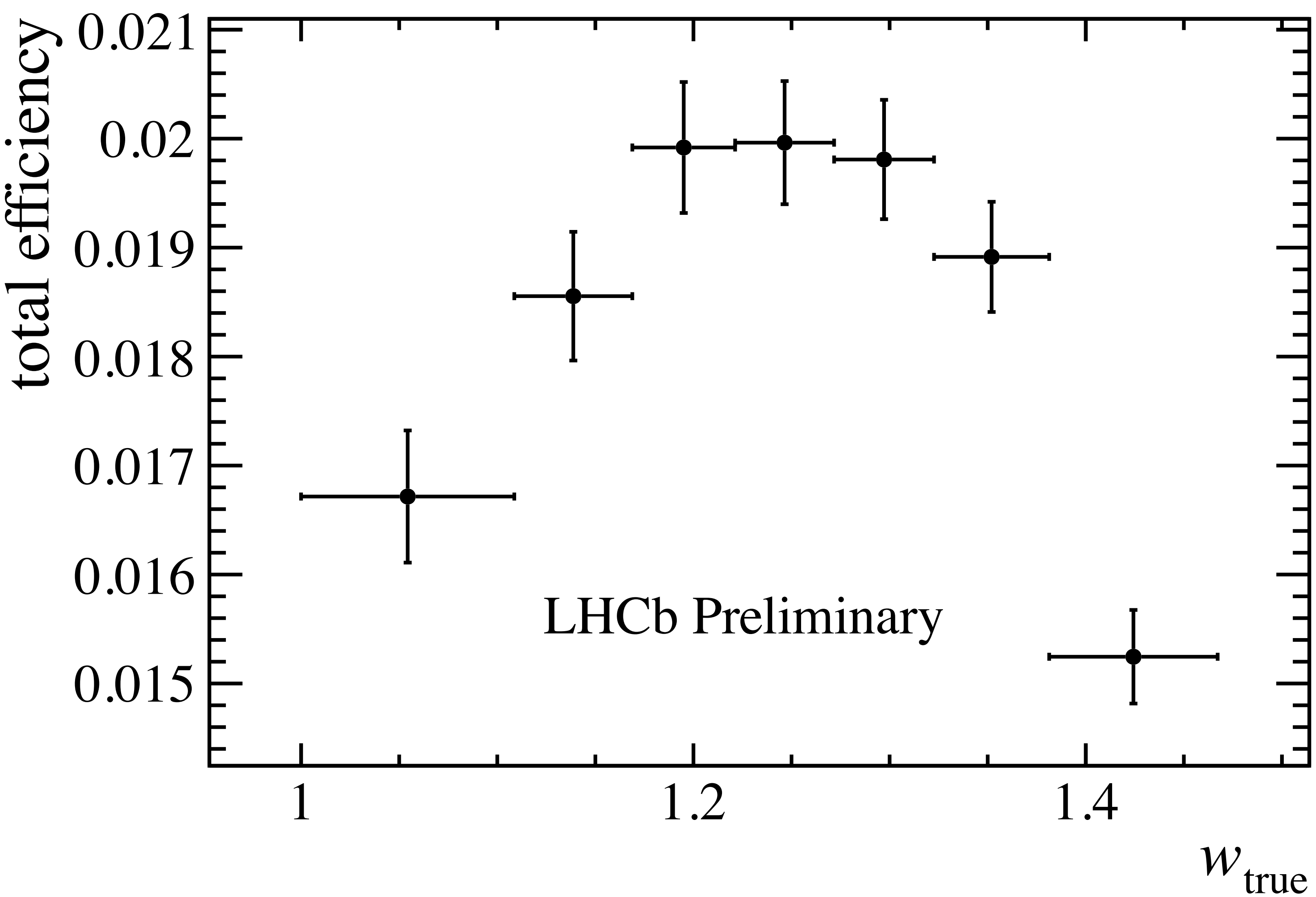



**Extremely pure signal samples**

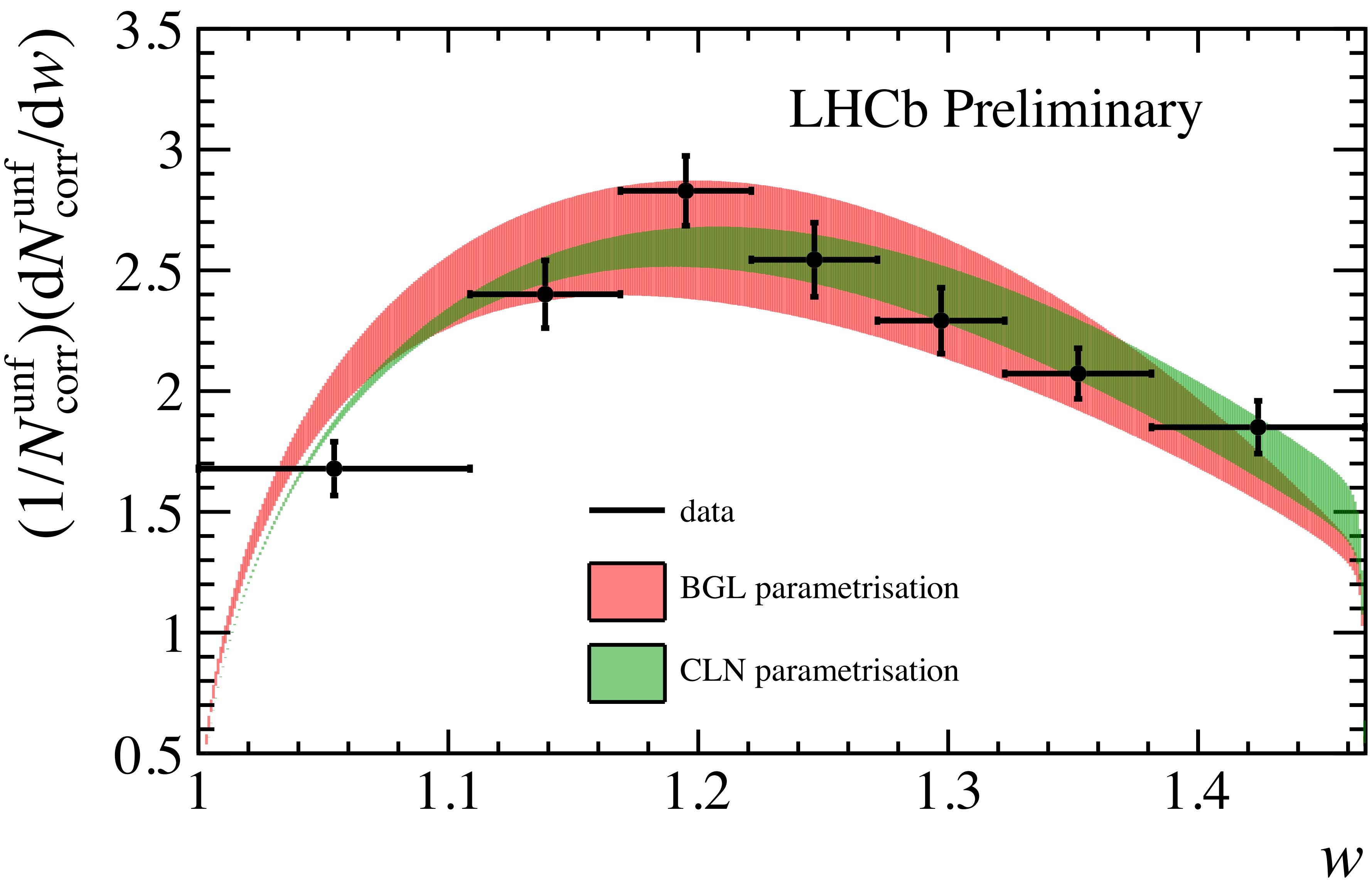
# Efficiency correction

- Use data calibration samples when possible to extract the efficiencies.
    - When using simulation, correct it using data from know inaccuracies i.e: trigger efficiencies.
- Is crucial to describe well the efficiency as a function of *w*. Less relevant to have a correct absolute normalisation.



# Fitting the form factors

- After unfolding and correcting the measured yield for the efficiencies, fit the differential decay rate with two parametrisation of the form factors.




No significant differences found between CLN and BGL

# Systematic uncertainties

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

| Source | $\sigma(\rho^2)$ | $\sigma(a_1^f)$ | $\sigma(a_2^f)$ |
|---|---|---|---|
| Simulation sample size | 0.053 | 0.036 | ${}^{+0.04}_{-0.35}$ |
| Control sample size | 0.020 | 0.016 | ${}^{+0.02}_{-0.16}$ |
| SVD unfolding regularisation | 0.008 | 0.004 | 0.00 |
| Radiative corrections | 0.004 | 0.000 | 0.00 |
| Simulation FF parametrisation | 0.007 | 0.005 | 0.00 |
| Kinematic weights | 0.024 | 0.013 | 0.00 |
| Hardware trigger efficiency | 0.001 | 0.008 | 0.00 |
| Software trigger efficiency | 0.004 | 0.002 | 0.00 |
| $D_s^-$ selection efficiency | 0.000 | 0.008 | 0.00 |
| $D_s^{*-}$ weights | 0.002 | 0.014 | 0.00 |
| External parameters in fit | 0.024 | 0.002 | 0.00 |
| Total systematic uncertainty | 0.068 | 0.046 | ${}^{+0.04}_{-0.38}$ |
| Statistical uncertainty | 0.052 | 0.034 | ${}^{+0.05}_{-0.20}$ |

# Results on $B_s \to D_s^*$ form factors

- For CLN parametrisation:

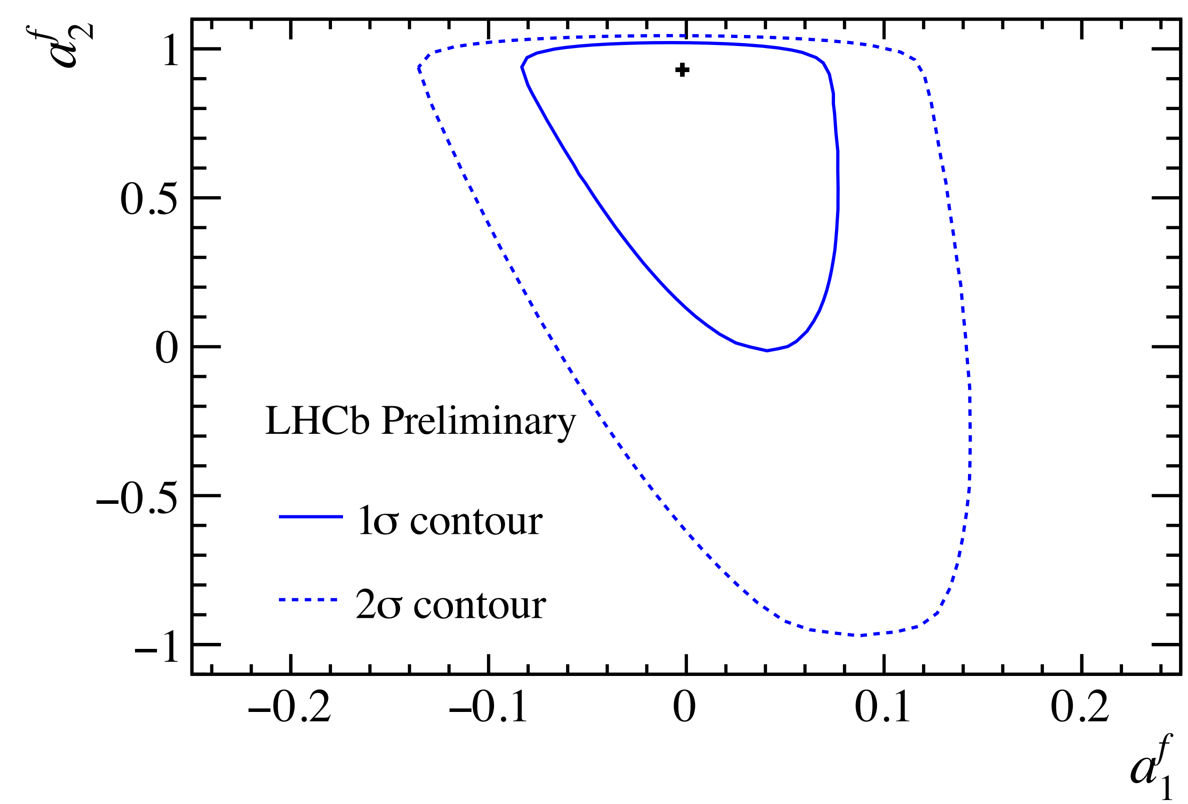
$$\rho^2 = 1.16 \pm 0.05(\text{stat}) \pm 0.07(\text{syst})$$ massive leptons

$$\rho^2 = 1.17 \pm 0.05(\text{stat}) \pm 0.07(\text{syst})$$ massless leptons

  - In agreement with the results from $B^0 \to D^{*-}\mu^+\nu$. No flavour SU(3) breaking.

- For BGL parametrisation:

$$a_1^f = -0.002 \pm 0.034(\text{stat}) \pm 0.046(\text{syst})$$
$$a_2^f = 0.93^{+0.05}_{-0.20}(\text{stat})\,^{+0.04}_{-0.38}(\text{syst})$$




- Will publish the unfolded spectrum so other parametrisation can be tested.

# Conclusions

- First measurements of $V_{cb}$, hadronic form factors and semileptonic branching fractions using $B_s$ decays.
    - First time that these quantities are extracted on a hadronic environment.
- Use the two most common parametrisation of form factors to get $V_{cb}$.
    - Confirms the trend observed that the parametrisation is not responsible for inclusive vs exclusive differences in $V_{cb}$.
    - Not conclusive about inclusive vs exclusive differences.
- Parameters of the leading form factor extracted for $B_s \to D_s^*$
    - Compatible with SU(3) flavour symmetry.
    - Data is not yet able to distinguish between parametrisations.

# Prospects

- Several new methods developed to tackle semileptonic decays at a hadronic machine.
  - Can be exported to other B decays. External uncertainties can be dramatically reduced.
  - Expected uncertainty on $V_{cb}$ from $B^0$ decays using only Run I is comparable to uncertainties from B-factories.
- These results and techniques are paving the road for ongoing measurements of LFU ratios in the $B_s$ sector i.e: $R(D_s^*)$.

# Back-up

# Datasets used

# BGL parametrisation

- Form factors:

$$f(z) = \frac{1}{P_{1^+}(z)\phi_f(z)} \sum_{n=0}^{\infty} a_n^f z^n \,, \qquad F_1(z) = \frac{1}{P_{1^+}(z)\phi_{F_1}(z)} \sum_{n=0}^{\infty} a_n^{F_1} z^n \,,$$

$$g(z) = \frac{1}{P_{1^-}(z)\phi_g(z)} \sum_{n=0}^{\infty} a_n^g z^n \,, \qquad F_2(z) = \frac{\sqrt{r}}{(1+r)P_{0^-}(z)\phi_{F_2}(z)} \sum_{n=0}^{\infty} a_n^{F_2} z^n$$

- Unitarity constrains:

$$\sum_{n=0}^{N} (a_n^g)^2 < 1 \,, \qquad \sum_{n=0}^{N} (a_n^f)^2 + \sum_{n=0}^{N} (a_n^{F_1})^2 < 1 \,, \qquad \sum_{n=0}^{N} (a_n^{F_2})^2 < 1 \,.$$

# CLN parametrisation

- Form factors:

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

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

$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2 \ ,$$

$$R_0(w) = R_0(1) - 0.11(w-1) + 0.01(w-1)^2 \ ,$$

# Unfolding

- Use Singular Value Decomposition (SVD) for the unfolding. Takes into account the migration across bins due to resolution effects.

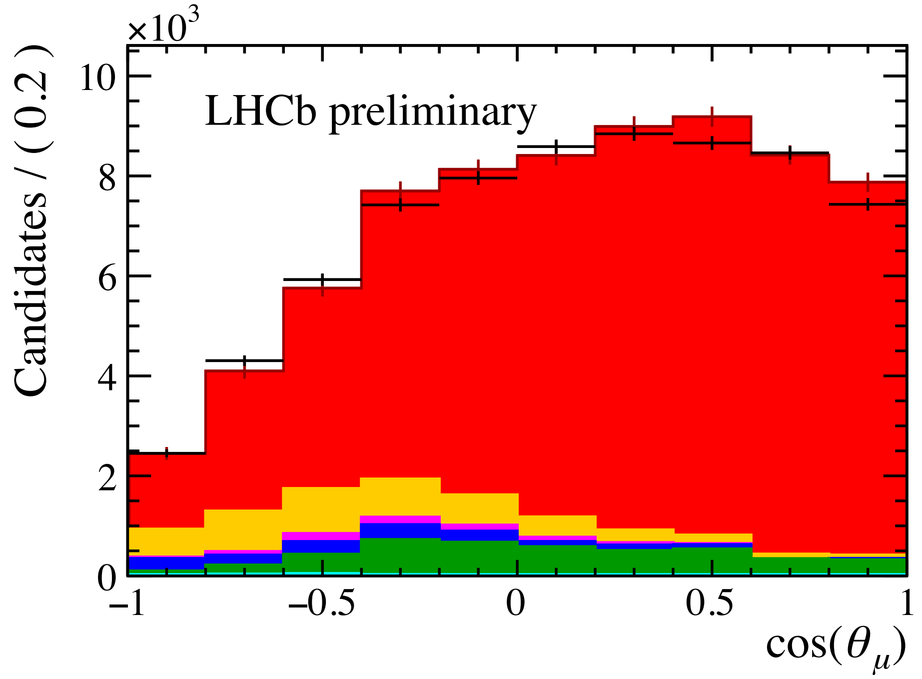
# External parameters

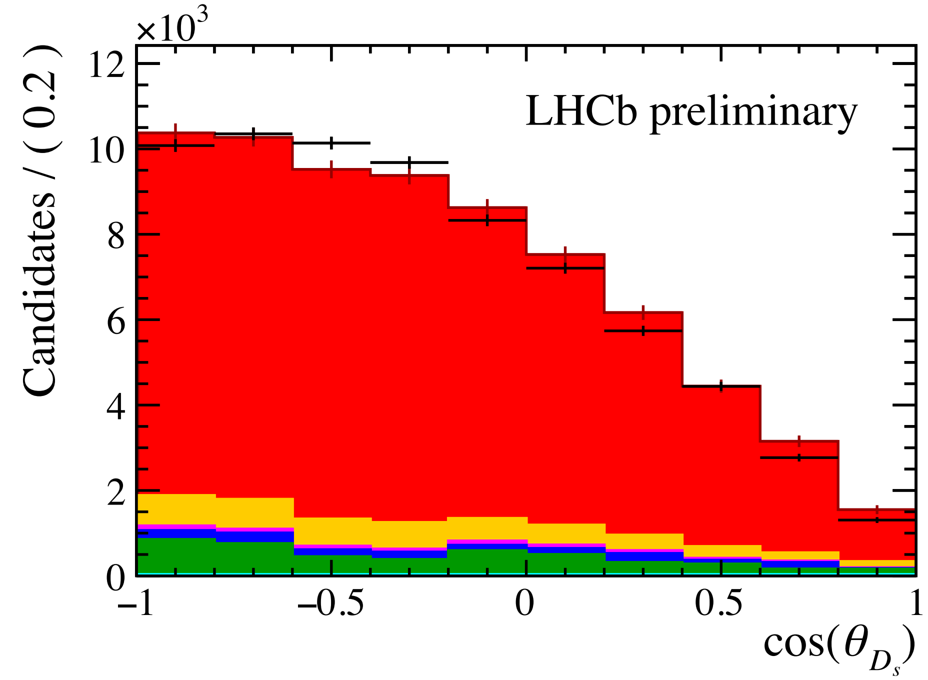
- For the BGL fit, need to fix the parameters of the other functions.
  - Use Belle data + Lattice QCD inputs [Phys. Lett B795 (2019) 386, JHEP 11 (2017) 061].
  - The series is truncated at N=2. The small value of *z* ensures the fast convergence.

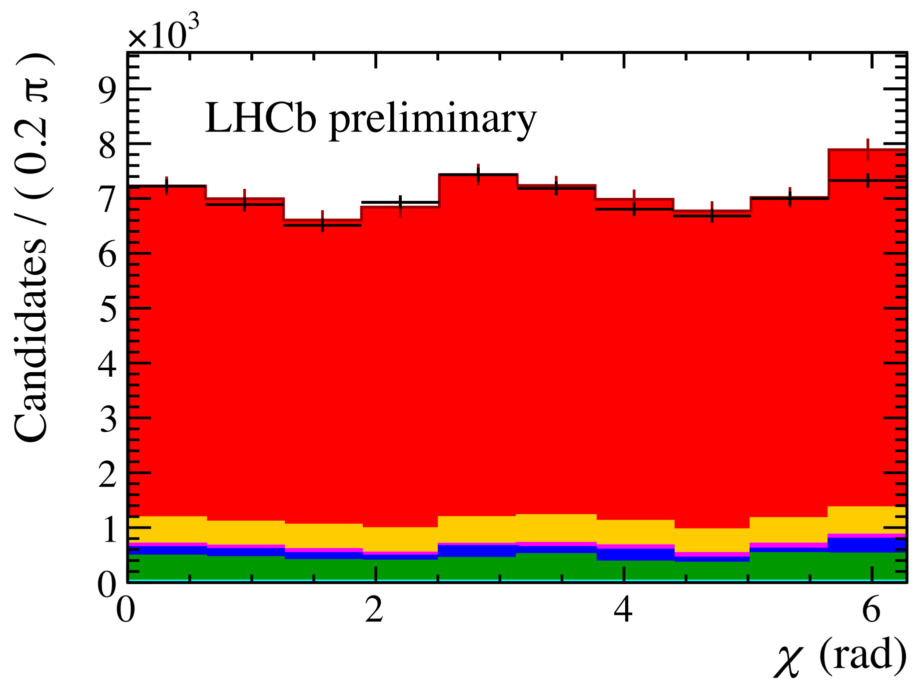
| BGL parameter | values from Ref. [18] and Ref. [19] |
|---|---|
| $a_0^f$ | $0.01221 \pm 0.00016$ |
| $a_1^{\mathcal{F}_1}$ | $0.0042 \pm 0.0022$ |
| $a_2^{\mathcal{F}_1}$ | $-0.069^{+0.041}_{-0.037}$ |
| $a_0^g$ | $0.024^{+0.021}_{-0.009}$ |
| $a_1^g$ | $0.05^{+0.39}_{-0.72}$ |
| $a_2^g$ | $1.0^{+0.0}_{-2.0}$ |
| $a_0^{\mathcal{F}_2}$ | $0.0595 \pm 0.0093$ |
| $a_1^{\mathcal{F}_2}$ | $-0.318 \pm 0.170$ |

# Checks on angular distributions

- After we perform the fit to the yields, we compare the distributions on the integrated angles on data and simulation.




**This is not a fit, just the different components overlaid compared to the data distribution.**

**Good agreement on the angular distributions.**