LHCb Measurements on Semileptonic Decays of b-hadrons

Anna Lupato

on behalf of the LHCb Collaboration

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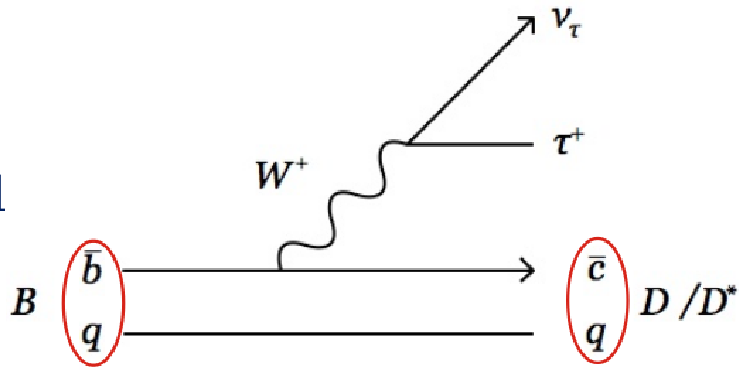
Charged current transitions

- Tree level quark transition with W emission



- **Advantages:**
  - The contributes to decay rate can be factorized in weak and strong part

$$\frac{d\Gamma(B\to Xl\nu)}{dq^2} \propto G_F^2 |V_{bq}|^2 f(q^2)^2$$

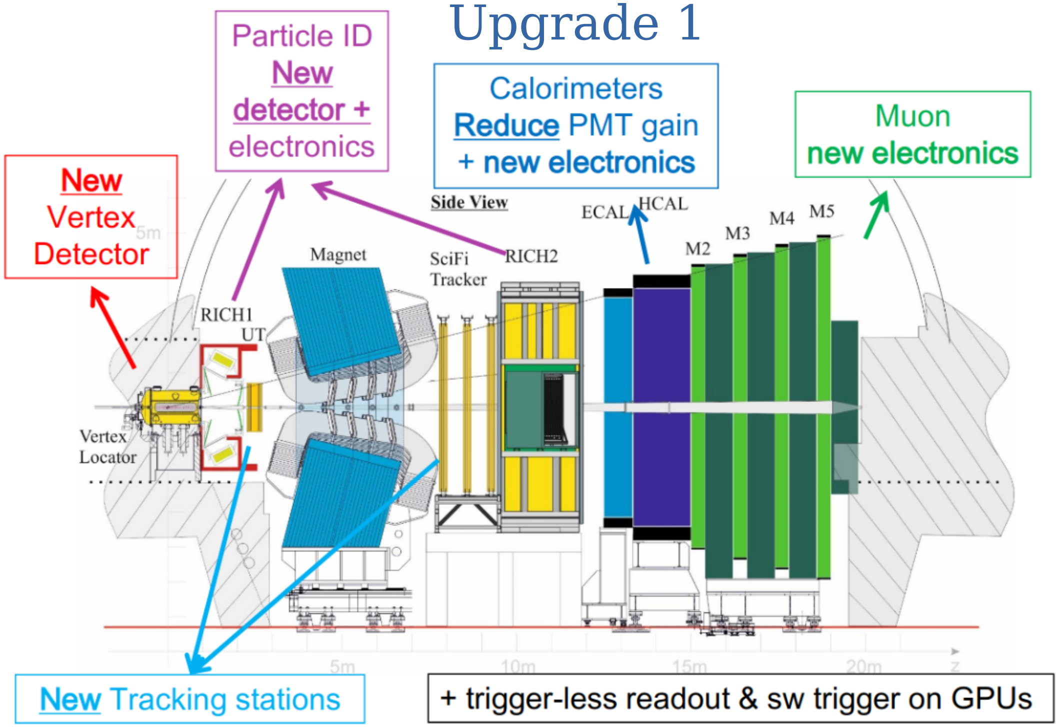
  - The theoretical calculation can be simplified
    - Factorize long (form factors) and short (Wilson Coefficients) distance effects

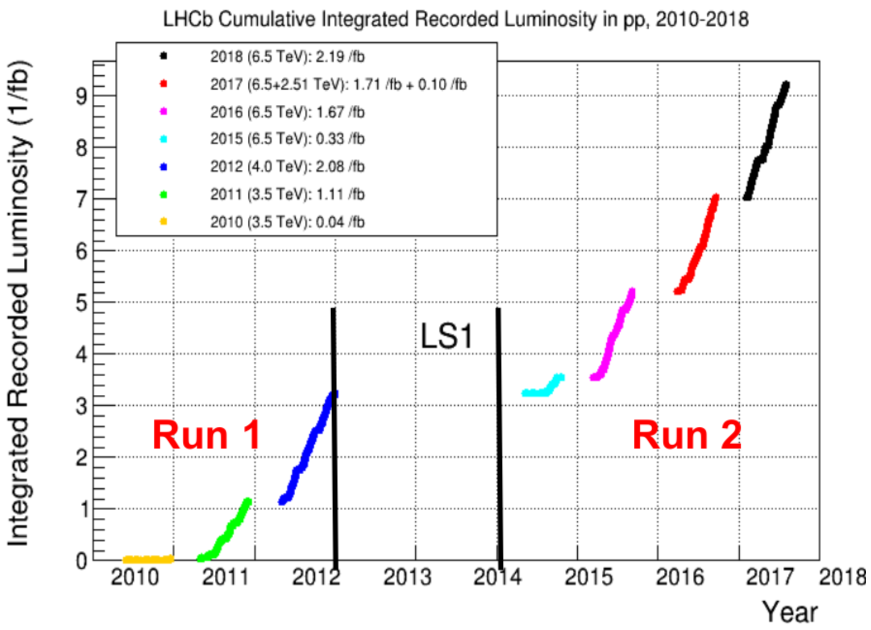
- **Challenges:**
  - Missing neutrinos → lower resolutions
  - Large partially reconstructed backgrounds
  - Large and perfectly calibrated simulation samples needed for modeling signal and backgrounds

LHCb

- LHCb was originally designed for CP violation and rare beauty & charm decays
- But now it is a general purpose detector: *exotic spectroscopy, EW precision physics, heavy ions, fixed target program…*

Upgrade 1





Run1: 3 fb^{-1} @ $\sqrt{s}$ =7-8 TeV
Run2: 6 fb^{-1} @ $\sqrt{s}$ =13 TeV

- LHCb is a spectrometer in the forward direction ($2<\eta<5$)
- Excellent vertexing, tracking and particle identification
- Low trigger threshold on hadrons, muons and photons
- Production of all types of *b* and *c* hadrons

Recent LHCb semileptonic results

- Measurement of the ratios of branching fractions $R(D^*)$ and $R(D^0)$
  [Phys.Rev.Lett. 131 (2023) 111802]

- Test of Lepton flavour universality using $B^0 \rightarrow D^{*-}\tau^+\nu$ decay with hadronic τ channels
  [Phys. Rev. D108 (2023) 012018]

- Observation of the decay $\Lambda^0_b \rightarrow \Lambda_c^+ \tau^- \overline{\nu}$
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- Measurement of D^* longitudinal polarization in $B^0 \rightarrow D^{*-}\tau^+\nu$ decays
  [arXiv:2311.05224 – Submitted to PRD]

- First observation of the decay $B_s^0 \rightarrow K^-\mu^+\nu$ and a measurement of $|V_{ub}|/|V_{cb}|$
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Longitudinal D^* polarization: beyond the LFU

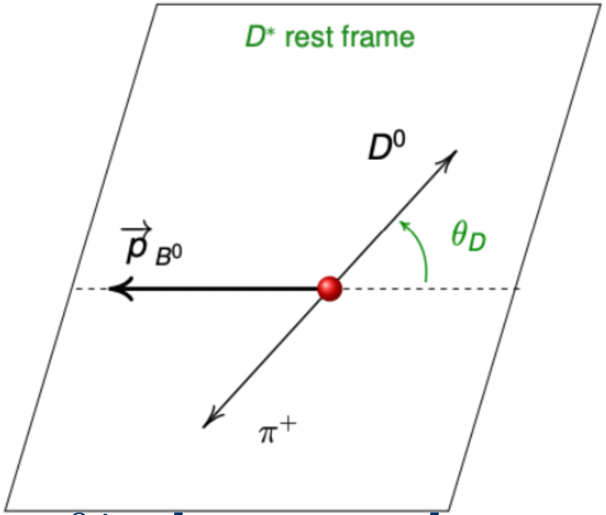
[arXiv:2311.05224]

- Lepton Flavour Universality tests using charged current decays of D and D^* show a tension from the Standard Model of 3.2σ
- New physics can strongly affect the D^* longitudinal polarization $F_L^{D^*}$ also if LFU ratios align with the SM prediction [arXiv:1907.02257]
- Measured by Belle: 0.60 ± 0.08 ±0.04 [arXiv:1903.03102]
- The differential decays rate of $D^* \to D^0 \pi$ can be expressed as

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$$

- $F_L^{D^*}$ can be calculated as

$$F_L^{D^*} = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$



q^2 is the squared invariant mass of τν

where
- a_θ and c_θ are linear combinations of the angular coefficients

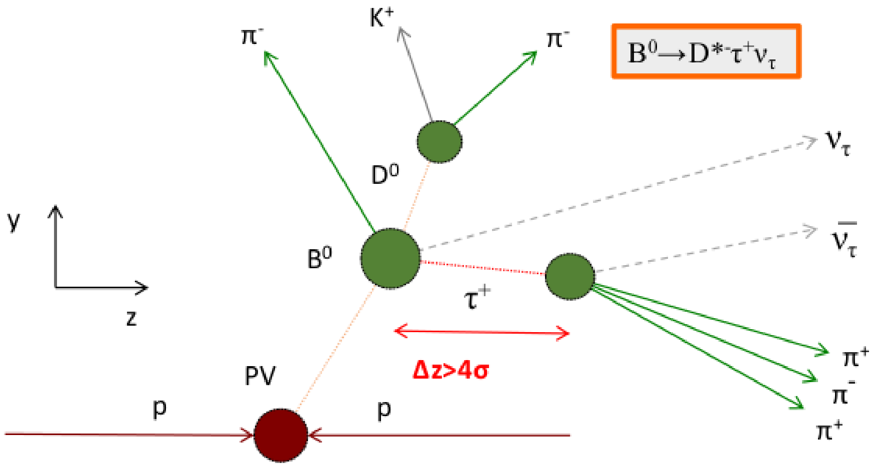
$$a_{\theta_D}(q^2) = N^{unpol} \cdot \mathcal{PDF}_{unpol}|_{\cos\theta_D=0}, \qquad c_{\theta_D}(q^2) = \frac{3}{2} N^{pol} \Delta_{bin}$$

Longitudinal D^* polarization: signal selection

- Dataset: Run1(3 fb^{-1}) and Run2 (2 fb^{-1})

[arXiv:2311.05224]

- $B^0 \to D^{*-}\tau^+\nu$, $\tau^+ \to 3\pi^\pm(\pi^0)\nu$
  - \+ good tau vertex reconstruction
  - \- large hadronic background

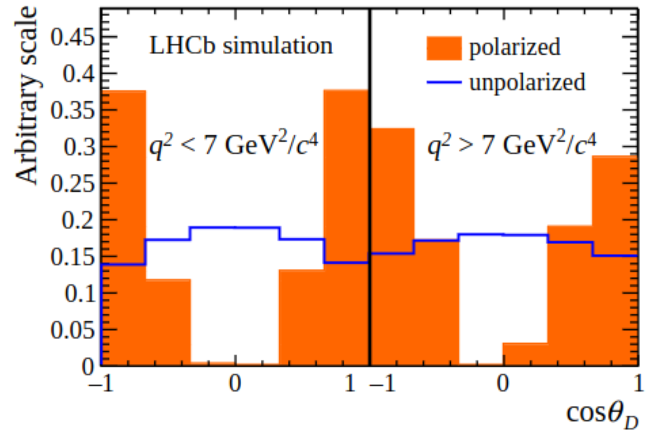


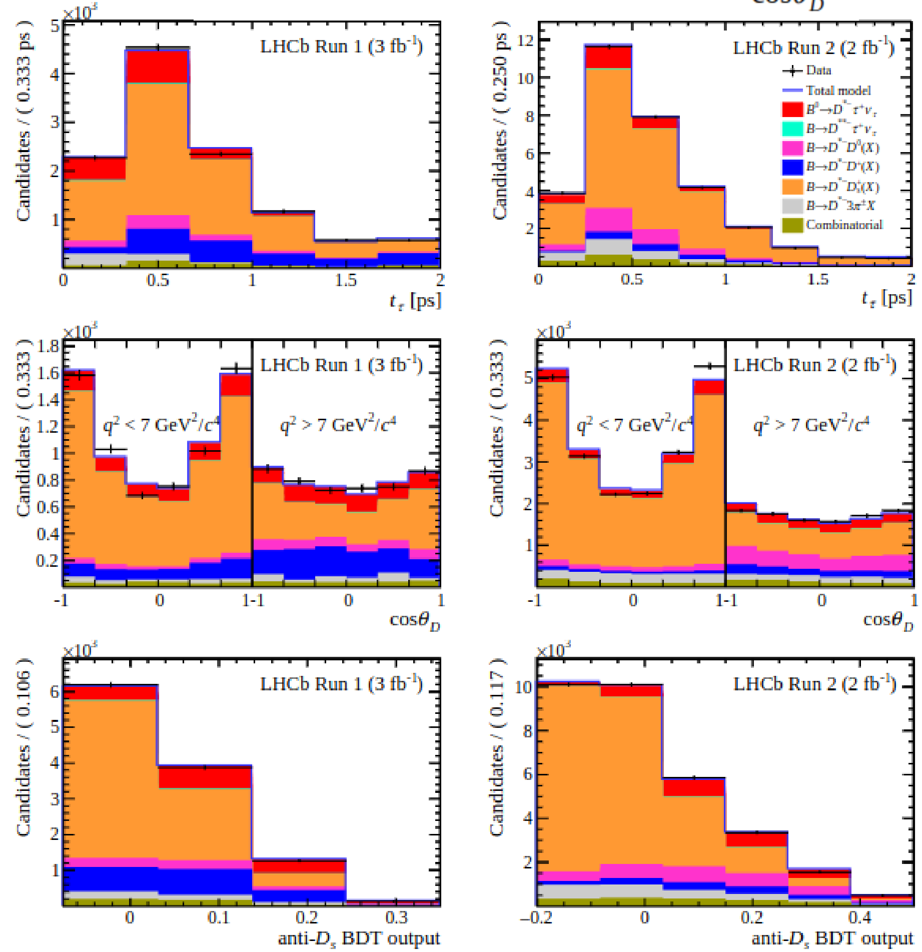
- **Most dominant: $B \to D^* 3\pi X$ (BF ~ 100x signal)**
  - Suppressed by requiring the τ vertex to be downstream wrt B vertex along beam direction with a 4σ significance
  - additional BDT in Run2 to reach Run1 (rejection >99.9%)

- **$B \to D^* D^{+,0}_{(s)} X$ (BF ~10x signal)**
  - Similar topology to that of signal but detached vertex due to non-negligible lifetime
  - Suppressed by rejecting candidates with extra charged tracks from B/τ vertex
    → rejected through isolation algorithm and BDT classifier, whose output used in template fit

Longitudinal D^* polarization: template fit

- $F_L^{D^*}$ determined in two q^2 regions: $q^2 > 7 GeV^2/c^4$, $q^2 < 7 GeV^2/c^4$
- $F_L^{D^*}$ is extracted from a_θ and c_θ determined by splitting the simulated signal sample in
  - $N_{unpolarized} \propto a_\theta$
  - $N_{polarized} \propto c_\theta$
- 4D template fit:
  - τ lifetime
  - q^2
  - $\cos\theta_D$
  - Anti-D_s BDT output
- Simulated $\cos\theta_D$ signal distribution corrected for reconstruction effect
- $\cos\theta_D$ distribution corrected through fully reconstructed control samples:
  - $D_s \rightarrow 3\pi^\pm$, $D^+ \rightarrow K^- 2\pi^+$, $D^0 \rightarrow K^- 3\pi^\pm$
- simultaneous fit to Run1 and Run2
- Dominant sources of systematic uncertainties:
  - limited size of simulations samples
  - form factors parametrization



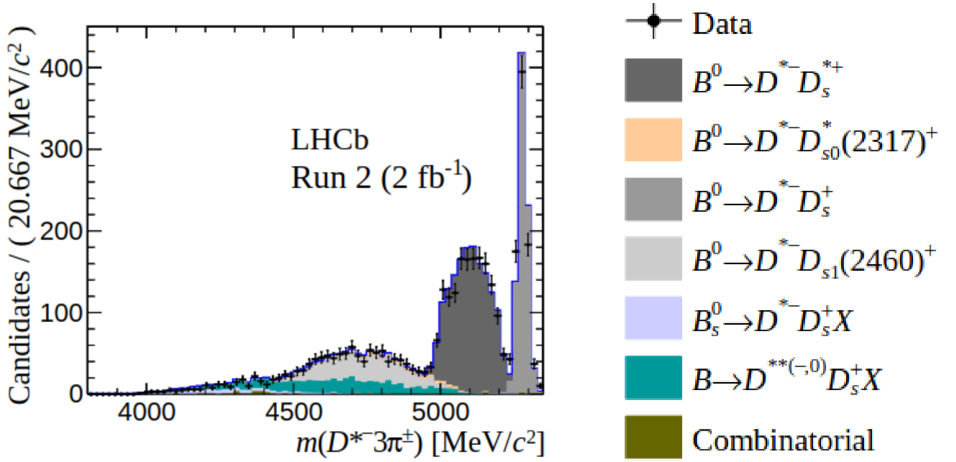


[arXiv:2311.05224]

Longitudinal D^* polarization: template fit

[arXiv:2311.05224]

- Two different control samples are used to validate the D^+_s backgrounds due to the poor knowledge of the BF and the relative fractions:
  - $D^+_s \to 3\pi X$ to correct the BF relevant to D^+_s meson production
  - $B \to D^{*-} D^+_s (X)$ decays to constrain the relative components in the final fit →



- Results integrated over run1 and run2

$$
\begin{aligned}
q^2 < 7\,\mathrm{GeV}^2/c^4 \;&: \quad 0.51 \pm 0.07\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}),\\
q^2 > 7\,\mathrm{GeV}^2/c^4 \;&: \quad 0.35 \pm 0.08\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst}),\\
q^2 \text{ whole range} \;&: \quad 0.43 \pm 0.06\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}).
\end{aligned}
$$

- All results are found compatible with the SM within 1σ
- Plan is to update the $F_L^{D^*}$ value in parallel with the $R(D^*)$ measurement in hadronic τ channel.

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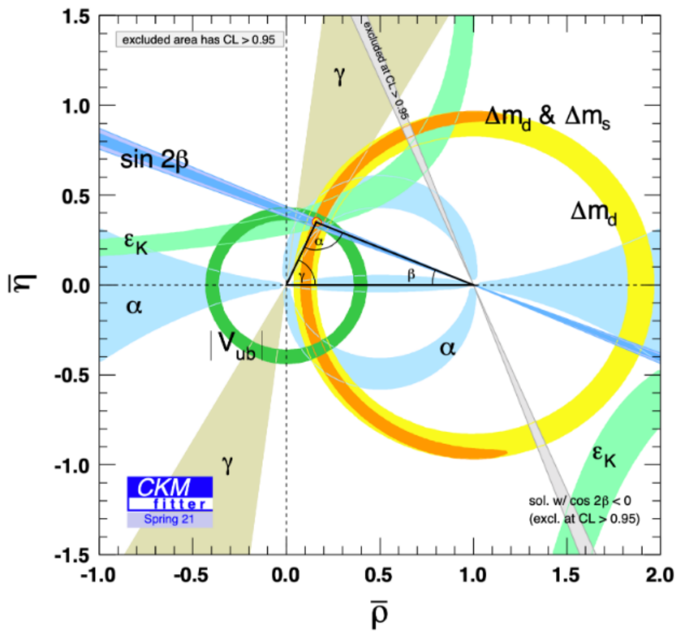
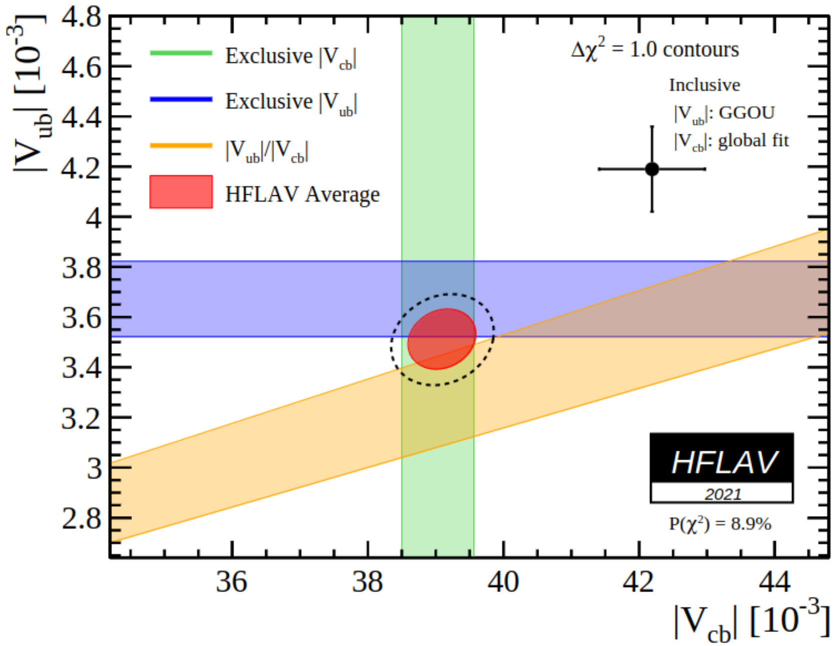
Measurement of $|V_{xb}|$

- The parameters of the CKM matrix must be constrained in order to
  - test the unitarity of the CKM matrix
  - precisely measure the amount of CP violation in the quark sector

  → measurement of observables sensitive to the magnitudes of CKM matrix elements



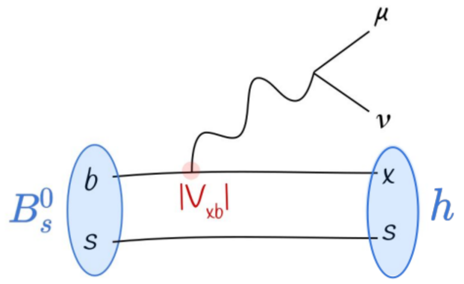


- Measurements of $|V_{xb}|$ provide a crucial input for indirect searches of New Physics

- Discrepancy between exclusive and inclusive measurements: ≈ 3σ tension

  → new complementary measurements

Measurement of $|V_{xb}|$



- Two main ways to measure $|V_{ub}|$ and $|V_{cb}|$:
  - **Inclusive decays**:
    - $B^+ \to X_c l\nu, B^0 \to X_u l\nu$
    - Focus on all final states
    - Need to know QCD correction to parton level decay rate
  - **Exclusive decays**:
    - Focus on a single final state
    - Exclusive determinations rely on form factors (FF) to parameterize hadronic current as function of q^2 ($\mu\nu$ invariant mass): LQCDor QCD sum rules
      - Extracted in experimental measurement from data
- **Ground state hadrons** in the final are the golden modes for lattice QCD predictions and have the lowest theoretical uncertainties.
- **B_s decays are advantageous compared to $B^{0/+}$**
  - Easier to calculate in LQCD due to heavier spectator quark → more precise predictions

Measurement of $|V_{ub}/V_{cb}|$

[Phys. Rev. Lett. 126 081804]

- The strategy:
  - Dataset: 2012, 2 fb^{-1} @ 8TeV
  - Signal: $B_s^0 \rightarrow K^- \mu^+ \nu$
  - Normalization: $B_s^0 \rightarrow D_s^- \mu^+ \nu$ where $D_s \rightarrow K^+ K^- \pi^-$
  - CKM extraction strategy:

$$\underbrace{\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}}_{\text{Experiment}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \underbrace{\frac{\mathrm{FF}_K}{\mathrm{FF}_{D_s}}}_{\text{Theory}}$$

  - The $|V_{ub}|/|V_{cb}|$ ratio is derived in two regions of q^2 ($\mu\nu$ invariant mass) to exploit different FF_K calculation method:
    - Light cone sum rules (LCSR) @ low q^2 ($q^2 < 7$ GeV^2/c^4)
    - LQCD @ high q^2 ($q^2 > 7$ GeV^2/c^4)

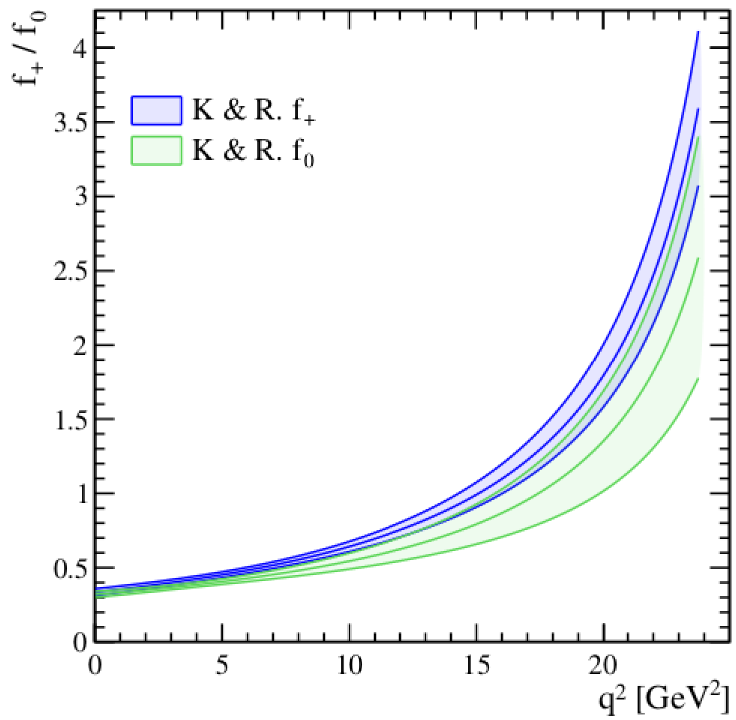
Normalization mode FF_{Ds} fully described by LQCD [Phys Rev D. 101 074513]

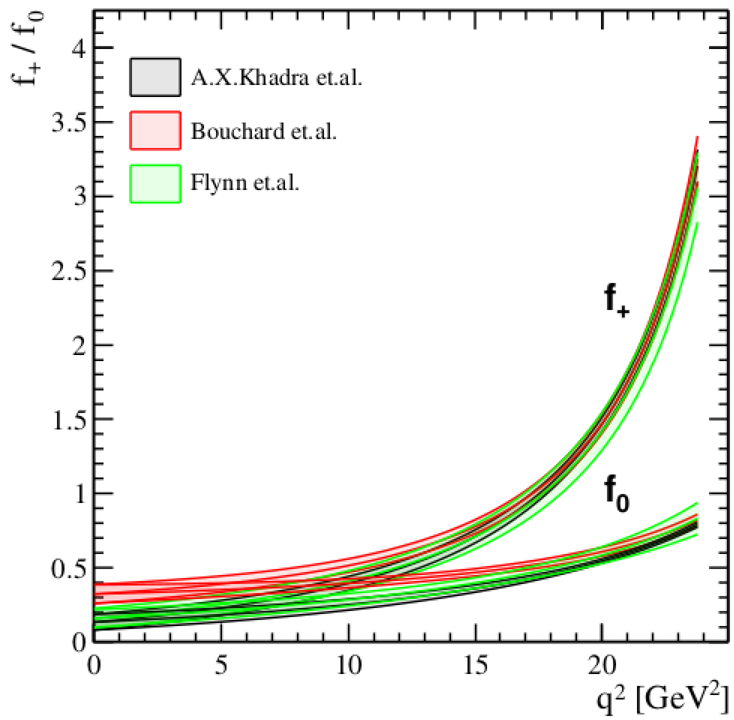
The FF_K

[Phys. Rev. Lett. 126 081804]

- Calculations from QCD light-cone sum rules are most precise at large recoil (low q^2)
  [JHEP 08 (2017) 112]

- Lattice QCD predictions provide a precise determination of the form factors at low recoil transfer (high q^2)
  [Phys. Rev. D 90, 054506] [Phys. Rev. D 91, 074510] [Phys. Rev. D 100, 034501]

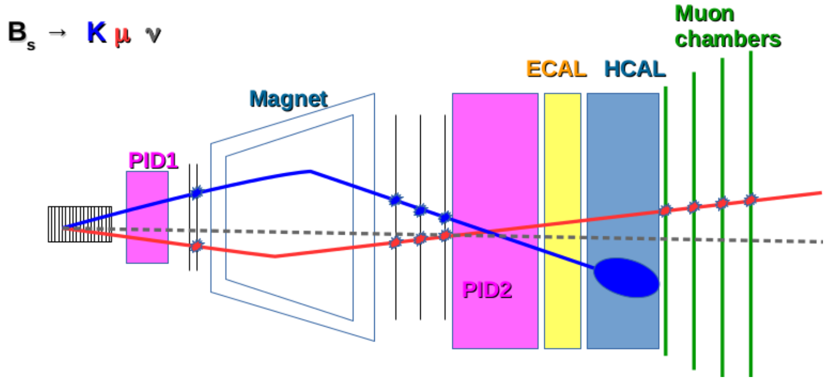




The backgrounds

[Phys. Rev. Lett. 126 081804]

- $B_s^0 \to K^- \mu^+ \nu$
  - main background originates from $H_b \to H_c(\to K^- X)\mu^+ X'$ (unreconstructed particles)
  - $B_s^0 \to K^{*-}(\to K^- \pi^0)\mu^+\nu$
  - $B_s^0 \to [cc]^-(\to \mu^+\mu^-)K^- X$



- $B_s^0 \to D_s^- \mu^+ \nu$
  - $B_s^0 \to D_s^{*-} (\to D_s \gamma)\mu^+\nu$
  - $B_s^0 \to D_s^{**-}\mu^+\nu$, $B_{u,s,d} \to D_s D X$ and $B_s^0 \to D_s^{*-} \tau^+\nu$

- To suppress background
  - the candidates are required to be isolated from the other tracks in the event
  - BDT classifiers exploit the kinematics of the decays

- The B_s^0 momentum can be calculated with a two fold ambiguity → regression model that exploit the B_s flight information [JHEP 02 (2017) 021]
  - Ambiguity solved by selection the solution most consistent with the regression value
  - $\varepsilon \approx 70\%$

Signal and normalization fits

[Phys. Rev. Lett. 126 081804]

- The measured ratio is

$$R_{\mathrm{BF}} \equiv \frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = \frac{N_K}{N_{D_s}} \frac{\epsilon_{D_s}}{\epsilon_K} \times \mathcal{B}(D_s^- \to K^+ K^- \pi^-)$$

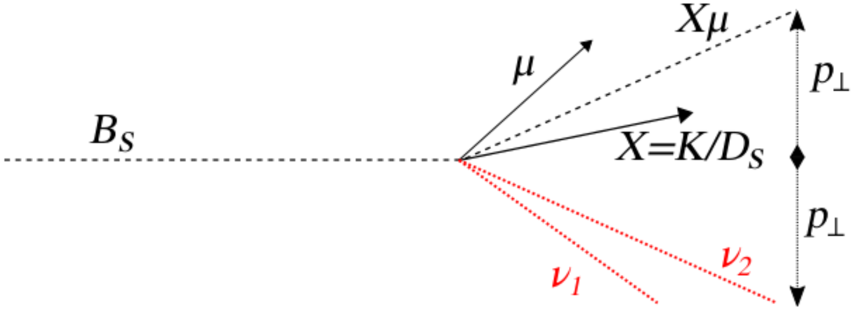
Ratio of yields

Efficiency ratio

[Prog. Theor. Exp. Phys. 2020, 083C01 (2020)]

- A binned maximum likelihood fit to the B_s corrected mass

$$m_{\mathrm{corr}} = \sqrt{m^2(Y\mu) + p_\perp^2(Y\mu)} + p_\perp(Y\mu), \; Y = K^-, D_s^-$$

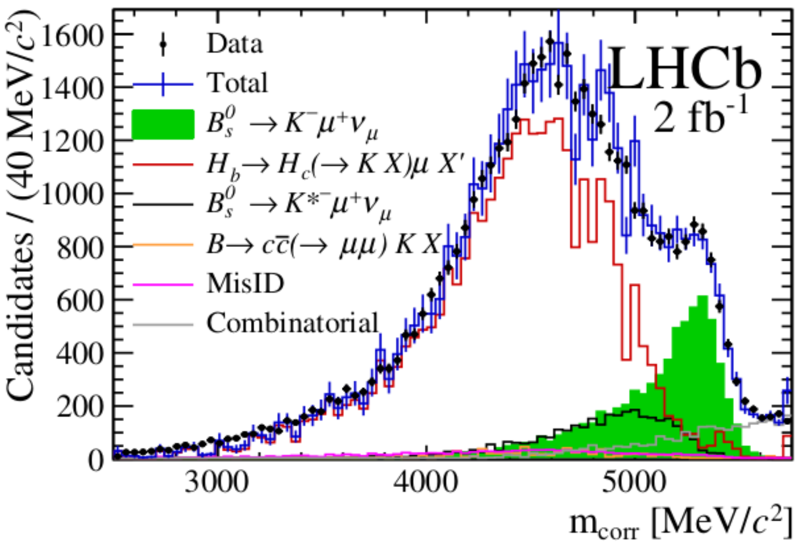


- If only missing particle is a neutrino the corrected mass distribution will peak at the B_s mass
- Resolution improved by rejecting events with a large corrected mass uncertainty (>100 MeV/c²)

Signal and normalization fits

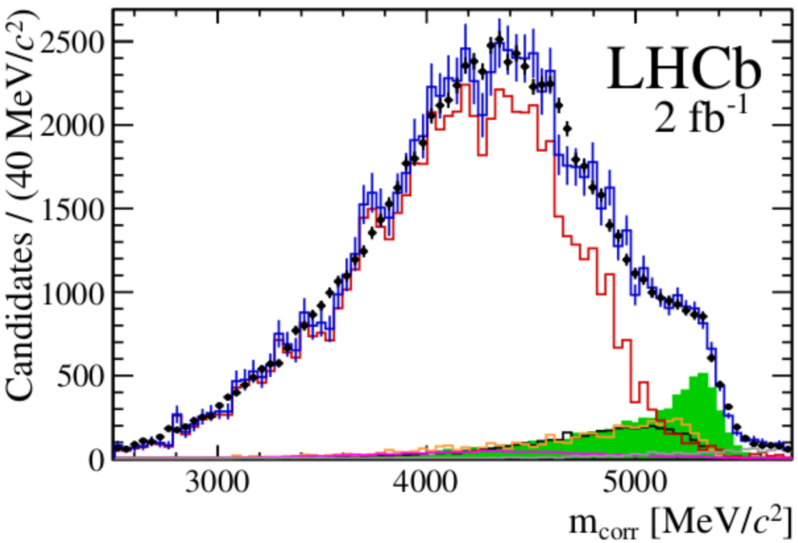
[Phys. Rev. Lett. 126 081804]

$B_s^0 \to K^- \mu^+ \nu_\mu$ low q^2



$N(B_s^0 \to K^- \mu^+ \nu_\mu)_{low} = 6922 \pm 285$

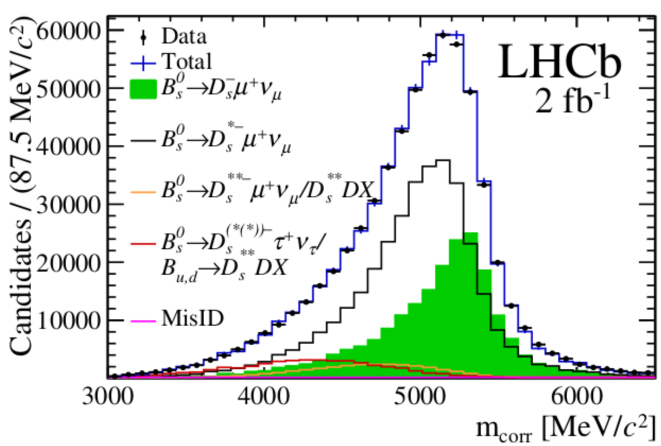
$B_s^0 \to K^- \mu^+ \nu_\mu$ high q^2



$N(B_s^0 \to K^- \mu^+ \nu_\mu)_{high} = 6399 \pm 370$

- The largest systematic uncertainty is from the fit templates
- First observation of the decay $B_s^0 \to K^- \mu^+ \nu$

$B_s^0 \to D_s^- \mu^+ \nu_\mu$



$N(B_s^0 \to D_s^- \mu^+ \nu_\mu) = 201450 \pm 5200$

Extraction of $|V_{ub}|/|V_{cb}|$

[Phys. Rev. Lett. 126 081804]

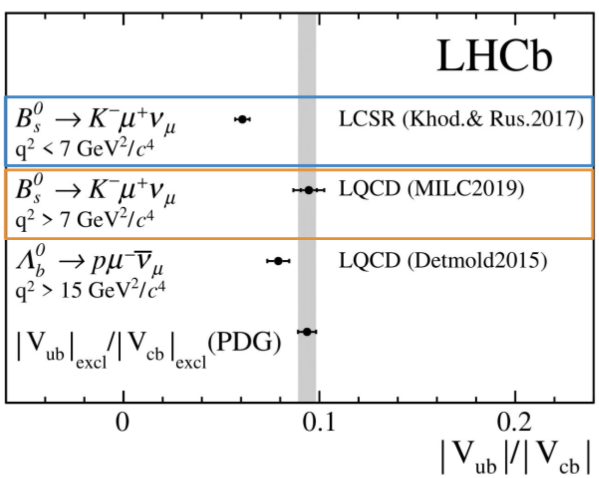
- The obtained values are

$$\underbrace{\frac{\mathcal{B}(B_s^0\to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0\to D_s^-\mu^+\nu_\mu)}}_{\text{Experiment}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \underbrace{\frac{\mathrm{FF}_K}{\mathrm{FF}_{D_s}}}_{\text{Theory}}$$

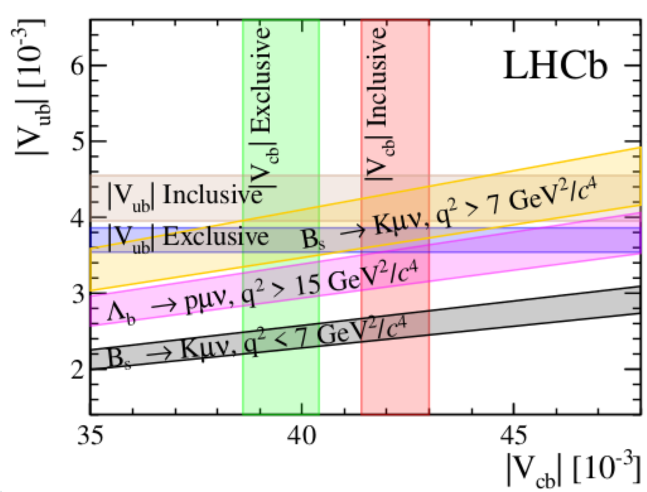
- $q^2 > 7$ GeV^2/c^4: $$\frac{\mathcal{B}(B_s^0\to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0\to D_s^-\mu^+\nu_\mu)} = 1.66 \pm 0.08(stat) \pm 0.07(syst) \pm 0.05(D_s) \times 10^{-3}$$
- $q^2 < 7$ GeV^2/c^4: $$\frac{\mathcal{B}(B_s^0\to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0\to D_s^-\mu^+\nu_\mu)} = 3.25 \pm 0.21(stat)^{+0.16}_{-0.17}(syst) \pm 0.09(D_s) \times 10^{-3}$$

$$|V_{ub}|/|V_{cb}|_{(\mathrm{low})} = 0.0607 \pm 0.0015(\mathrm{stat}) \pm 0.0013(\mathrm{syst}) \pm 0.0008(D_s) \pm 0.0030(\mathrm{FF})$$

$$|V_{ub}|/|V_{cb}|_{(\mathrm{high})} = 0.0946 \pm 0.0030(\mathrm{stat})^{+0.0024}_{-0.0025}(\mathrm{syst}) \pm 0.0013(D_s) \pm 0.0068(\mathrm{FF})$$



Discrepancy related to the difference in the theoretical calculations of the form factors.



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$|V_{cb}|$: with $B_s^0 \to D_s^{*-}\mu^+\nu$ decays

[Phys. Rev. D 101 072004]

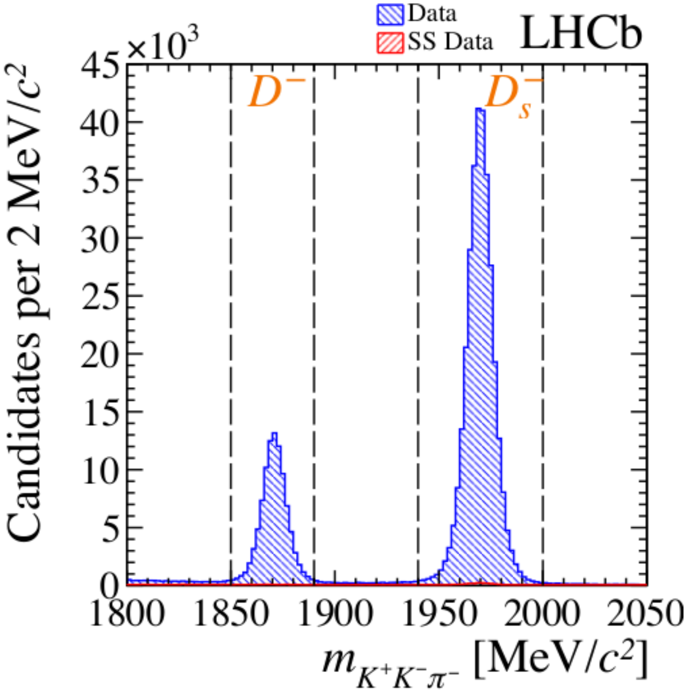
- Signal: $B_s^0 \to D_s^{(*)-}\mu^+\nu$ where $D_s \to \varphi(\to K^+K^-)\pi$, γ or π^0 not reconstructed

- Normalization: $B^0 \to D^{(*)-}\mu^+\nu$

- Both channels reconstructed in the same final states

- Extract $|V_{cb}|$ from

$$\mathcal{R}^* \equiv \frac{\mathcal{B}(B_s^0 \to D_s^{*-}\mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} \qquad \mathcal{R} \equiv \frac{\mathcal{B}(B_s^0 \to D_s^{-}\mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^{-}\mu^+\nu_\mu)}$$

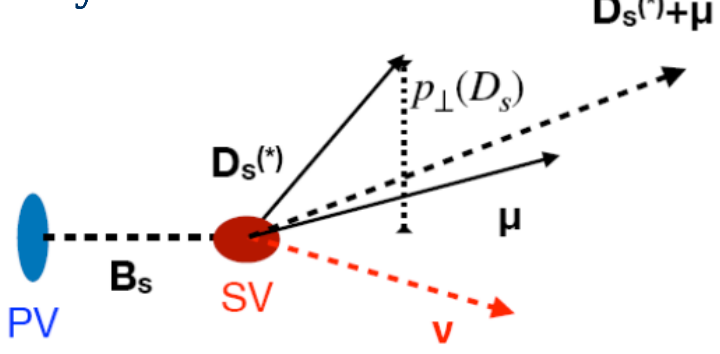


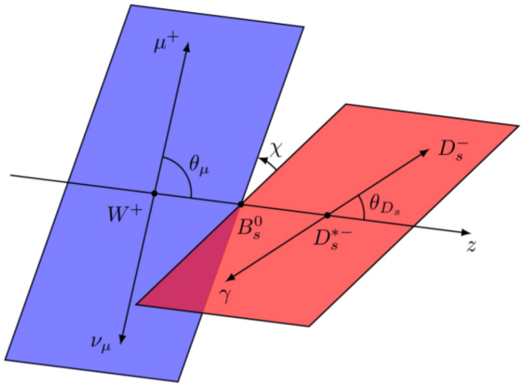
- external input:
  - hadronization fractions f_s/f_d [PRD(2019)031102]
  - branching fractions [PDG]

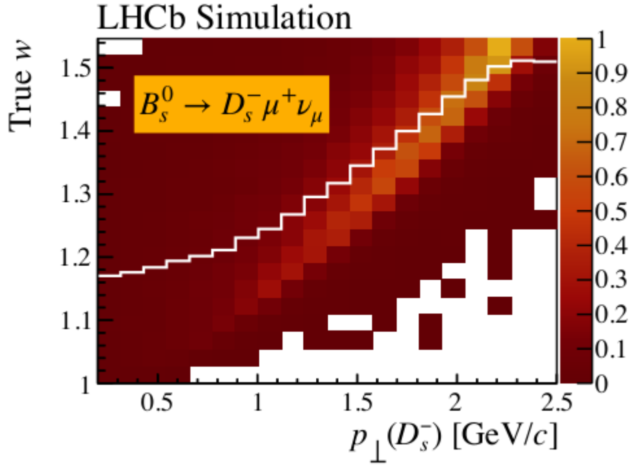
$|V_{cb}|$: with $B_s^0 \to D_s^{*-}\mu^+\nu$ decays

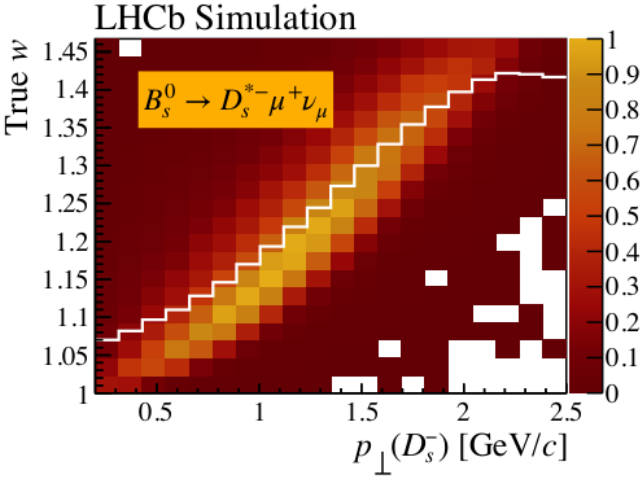
[Phys. Rev. D 101 072004]

- Due to the undetected neutrino we cannot determine precisely the q^2 → use variable $p_\perp(D_s)$ with respect to B flight distance:
  - high correlated with hadron recoil w
  - fully recostructible









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

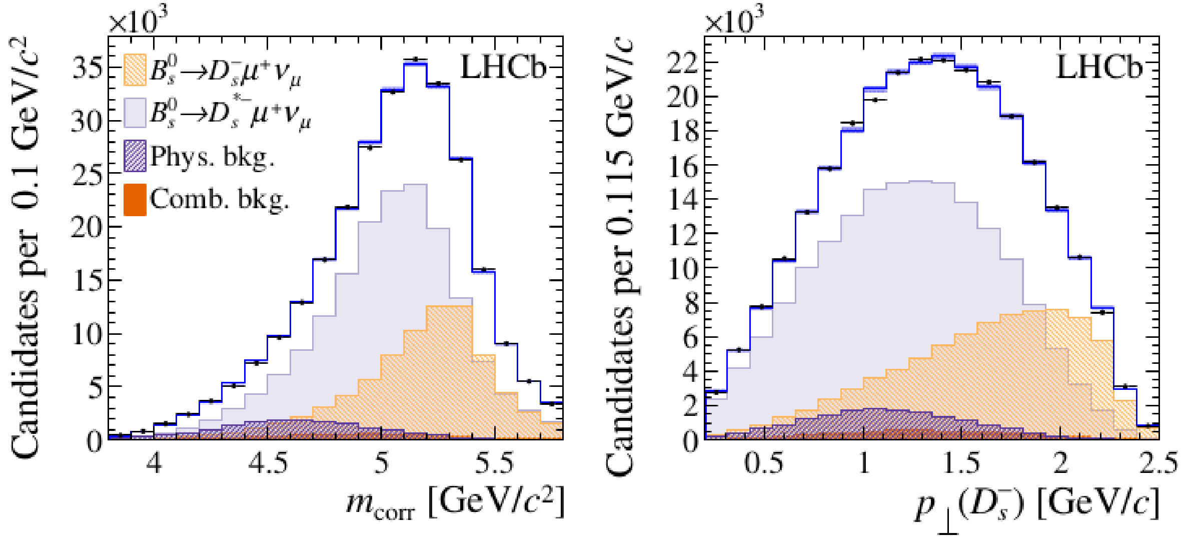
- $$w = v_B\cdot v_{D^*} = (m_B^2+m_{D^*}^2-q^2)/(2m_B m_{D^*})$$

- 2-D template fit to M_{corr} and $p_\perp(D_s)$ identify the signal yields and provides a simultaneous measurement of the ratios $R^{(*)}$ and the form factors

$|V_{cb}|$: with $B_s^0 \to D_s^{*-}\mu^+\nu$ decays

[Phys. Rev. D 101 072004]

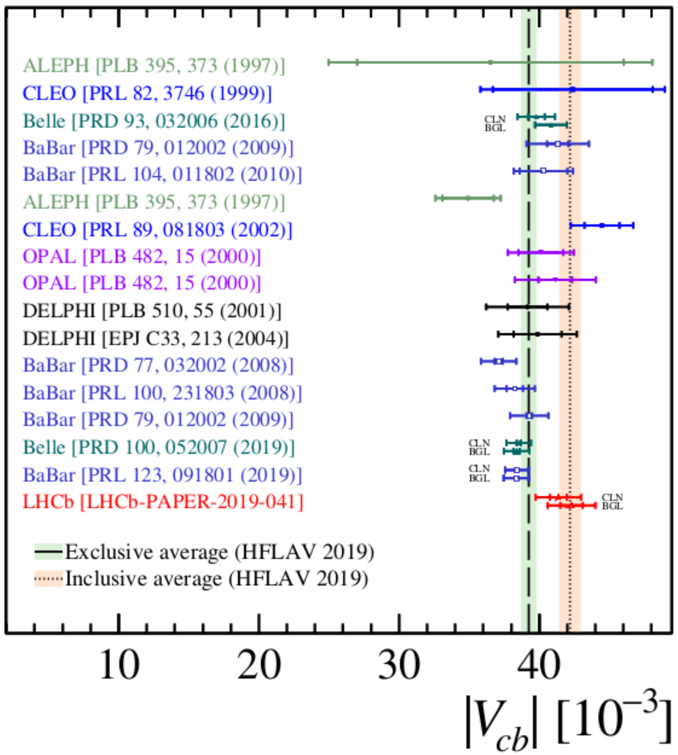
- FF Parametrizations used:
  - CLN and BGL



- The results are

$$|V_{cb}|_{CLN} = (41.1 \pm 0.6(stat) \pm 0.9(syst) \pm 1.2(ext))\text{x}10^{-3}$$
$$|V_{cb}|_{BGL} = (42.3 \pm 0.8(stat) \pm 0.9(syst) \pm 1.2(ext))\text{x}10^{-3}$$

- First measurement of $|V_{cb}|$ using B_s and in a hadronic environment
- Compatible with world average for both inclusive and exclusive determinations
- Confirms trend that parametrisation is not responsible for inclusive vs exclusive disagreements



- New $f_s/f_d \to V_{cb}$ [arXiv:2103.06810]

$$|V_{cb}|_{CLN} = (40.8 \pm 0.6(stat) \pm 0.9(syst) \pm 1.1(ext))\text{x}10^{-3}$$
$$|V_{cb}|_{BGL} = (41.7 \pm 0.8(stat) \pm 0.9(syst) \pm 1.1(ext))\text{x}10^{-3}$$

Conclusion

- Broad SL physics program at LHCb
- Successful Run1 and Run2: 3+6 fb^{-1}, still many analysis ongoing
- Upgrade Phase I:
  - 10 times more data (20 times more hadronic events)
  - Complementarity with Belle
  - Synergy between LHCb, ATLAS and CMS on some important channels
- Strong program beyond flavour exploiting unique acceptance

Original 2009-2018

Upgrade I 2022-2032

Upgrade II 2033-