CKM measurements and hadronic form factors

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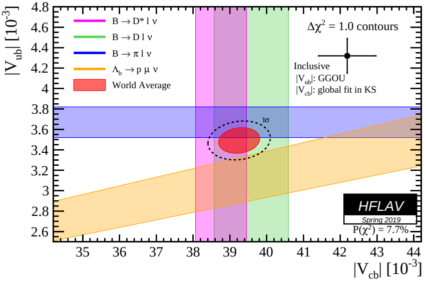
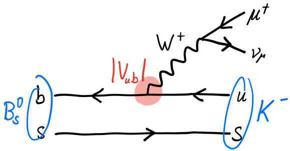
Motivation

- Precisely measure **CKM matrix elements**
  $\rightarrow$ fundamental SM parameters

- Discrepancy between **exclusive** and **inclusive** $|V_{ub}|$ and $|V_{cb}|$ measurements: **$\approx 3\sigma$ tension**
  $\rightarrow$ new complementary measurements needed

- Using **semileptonic decays**: theoretically clean but experimentally challenging





- **Exclusive** determinations rely on **form factors** (FF) to parametrize hadronic current as function of q^2 ($\mu\nu$ invariant mass)
  $\rightarrow$ Lattice QCD (LQCD) or QCD sum rules
  $\rightarrow$ 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^{**} mainly decays to $D^{(*)}K$)

First observation of the decay $B_s^0 \to K^- \mu^+ \nu_\mu$ and a measurement of $|V_{ub}|/|V_{cb}|$

Phys. Rev. Lett. 126 081804

(published 25 February 2021)

Measurement strategy

Phys. Rev. Lett. 126 081804

- Using 2012 data ($2\,\text{fb}^{-1}$ @ $8\,\text{TeV}$)
- **Signal** decay $B_s^0 \to K^- \mu^+ \nu_\mu$
- **Normalized** to $B_s^0 \to D_s^- \mu^+ \nu_\mu$ with $D_s^- \to K^+ K^- \pi^+$
- Measure

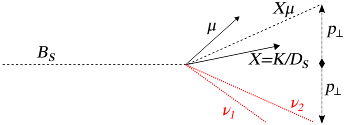
$$\underbrace{\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}}_{\textbf{Experiment}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \underbrace{\frac{\text{FF}_K}{\text{FF}_{D_s}}}_{\textbf{Theory input}}$$

- Split signal into **2 regions of q^2** to exploit different FF_K
  - Light-Cone sum rules (LCSR) @ low q^2 ($q^2 < 7\,\text{GeV}^2/c^4$)
  - LQCD @ high q^2 ($q^2 > 7\,\text{GeV}^2/c^4$)
- Normalization mode FF fully described by LQCD [Phys Rev D. 101 074513]

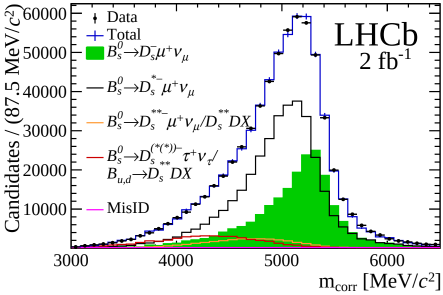
Signal and normalization fits

Phys. Rev. Lett. 126 081804

- Perform binned maximum likelihood fit to B_s corrected mass $m_{corr} = \sqrt{m^2(X\mu) + p_\perp^2} + p_\perp$, with $X = K, D_s$ $\rightarrow$ allows to discriminate between signal and different backgrounds



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



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

Signal and normalization fits

Phys. Rev. Lett. 126 081804

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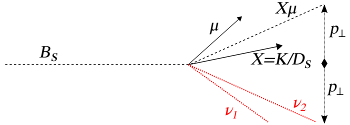
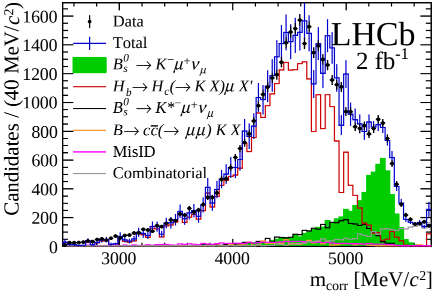
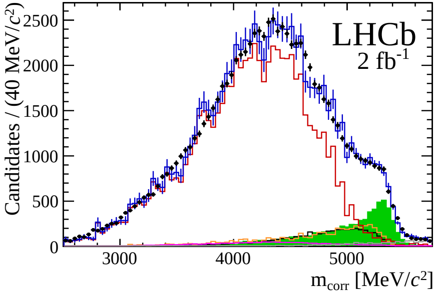


$B_s^0 \rightarrow K^- \mu^+ \nu_\mu$ low q^2



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



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

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

$\rightarrow$ First observation of the decay $B_s^0 \rightarrow K^- \mu^+ \nu_\mu$

Phys. Rev. Lett. 126 081804

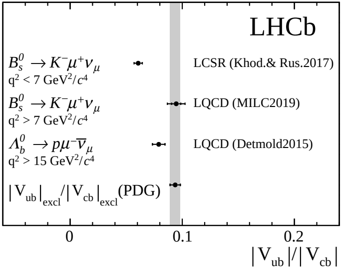
low q^2: $$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = 1.66 \pm 0.08(stat) \pm 0.07(syst) \pm 0.05(D_s) \times 10^{-3}$$

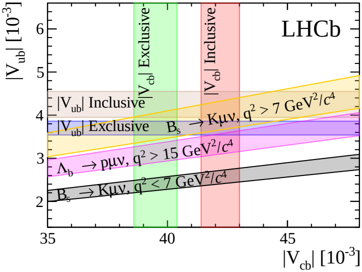
high q^2: $$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = 3.25 \pm 0.21(stat)^{+0.16}_{-0.17}(syst) \pm 0.09(D_s) \times 10^{-3}$$

together with FF predictions from LCSR [JHEP 08 (2017) 112] for low q^2 and LQCD [Phys Rev D.100 034501] for high q^2:

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

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





$\Rightarrow$ discrepancy related to difference in theoretical calculations of FF_K

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

Phys. Rev. D101 072004

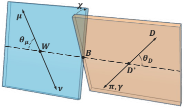
(published 20 April 2020)

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

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

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

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



- 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

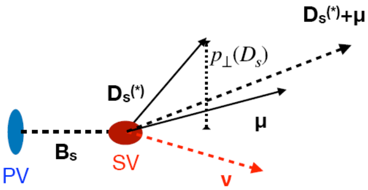
  $\to$ needs extrapolation, done through different FF parametrisations:
  - **CLN** (Caprini-Lellouch-Neubert) Nucl. Phys. B530 (1998) 153
  - **BGL** (Boyd-Grinstein-Lebed) Phys. Rev. Lett. 74 (1995) 4603

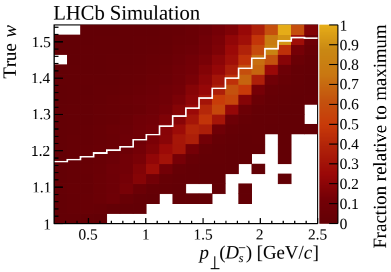
    $\to$ so far no significant differences observed

Measurement strategy

Phys. Rev. D101 072004

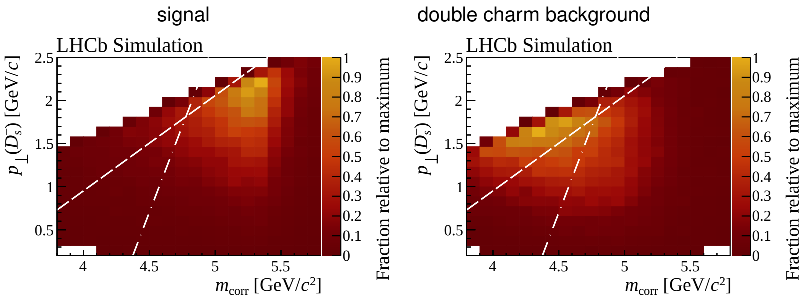
- Uses full Run 1 data (1 fb^{-1} @ 7 TeV + 2 fb^{-1} @ 8 TeV)
- **Signal** decays $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ are reconstructed through $D_s(\to [KK]_\phi \pi)$
- **Normalized** to $B^0 \to D^{(*)-}\mu^+\nu_\mu$ kinematically similar $\to$ reduce systematic uncertainties, needs as external input 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 $p_\perp(D_s^-)$ $\to$ highly correlated with w and fully reconstructible





Signal and normalization fits

Phys. Rev. D101 072004

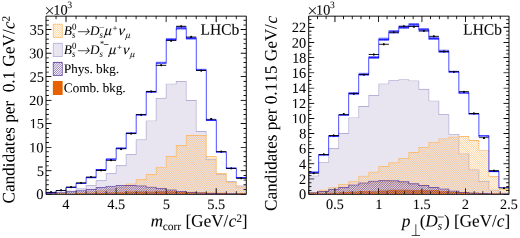


- Perform 2D template fit to $p_{\perp}(D_s)$ and corrected mass
  $m_{corr} = \sqrt{m^2(D_s\mu) + p_{\perp}^2(D_s\mu)} + p_{\perp}(D_s\mu)$
  $\rightarrow$ allows to discriminate between signal and different backgrounds
- Signal templates depend on form factors $\rightarrow$ recalculated at each fit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

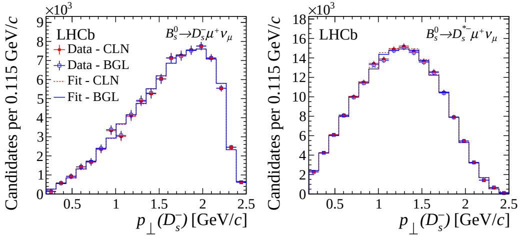
Signal fit results

- Signal fit using CLN parametrisation:

Phys. Rev. D101 072004



- Background-subtracted distributions of D_s and D_s^*



→ good agreement between CLN and BGL

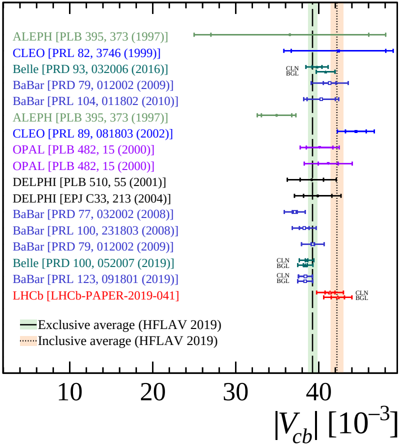
Results

Phys. Rev. D101 072004

- $|V_{cb}|_{CLN} = (41.6 \pm 0.6(stat) \pm 0.9(syst) \pm 1.2(ext)) \times 10^{-3}$
- $|V_{cb}|_{BGL} = (42.3 \pm 0.8(stat) \pm 0.9(syst) \pm 1.2(ext)) \times 10^{-3}$

- Both in agreement with each other
- Confirms trend that parametrisation not responsible for inclusive vs exclusive disagreements
- Dominant uncertainty comes from external inputs f_s/f_d, then $D_s \to KK\pi$ Dalitz structure
- Both results are in agreement with previous exclusive and inclusive $|V_{cb}|$ determinations

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



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

JHEP 12 (2020) 144

(published 22 December 2020)

Measurement strategy

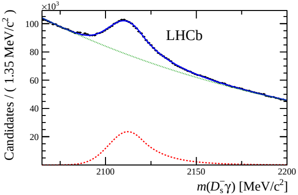
JHEP 12 (2020) 144

- Uses Run 2 data from 2016 (1.7 fb^{-1} @ 13 TeV)
- Goal: measure $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ FF precisely using CLN and BGL parametrisations

- Reconstruct $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ through $D_s^{*-} \to D_s^-\gamma$ with $D_s^- \to \phi(\to K^+K^-)\pi-$ and $D_s^- \to K^{*0}(\to K^+\pi^-)K^-$

  $\to$ 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

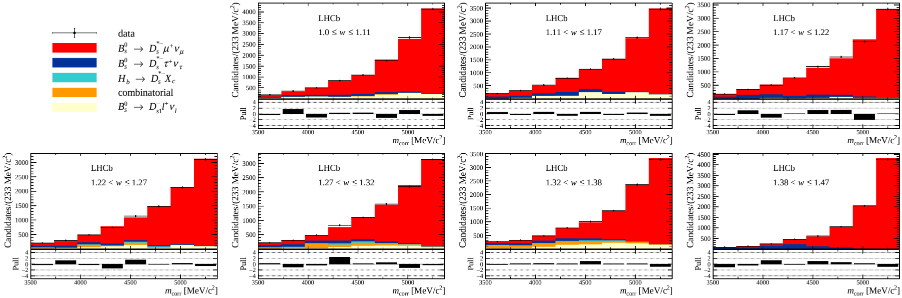
  $\to$ template fit to corrected mass in bins of w using simulation
- Correct raw yields for detector resolution (unfolding), selection and reconstruction efficiencies

  $\to$ fit resulting spectrum with CLN and BGL parametrisations

Signal fits

JHEP 12 (2020) 144

- 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
- Signal component and backgrounds from semitauonic B_s decays, double charm decays, feed-down from higher excited D_s^{*-} and combinatorial background from SS data



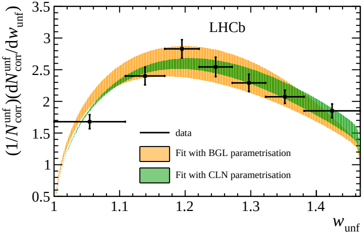
Form factor Fit

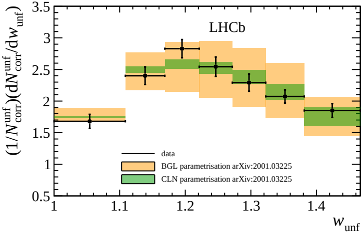
JHEP 12 (2020) 144

- Measured w spectrum unfolded and corrected using bin-by-bin efficiencies to extract FF
  $\rightarrow$ 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 differential decay rate for $B_s^0 \rightarrow D_s^{*-}\mu^+\nu_\mu$ as function of the w

Conclusion and Outlook

1. Measurement of $|V_{ub}|/|V_{cb}|$ from $B_s^0 \to K^- \mu^+ \nu_\mu$ in two q^2 regions
   - Discrepancy between low and high q^2 found
   - $|V_{ub}|/|V_{cb}|$ in high q^2 region compatible with previous measurements

   $\to$ Planned measurement of differential q^2 spectrum of $B_s^0 \to K^- \mu^+ \nu_\mu$ with full Run 1 + Run 2 data
2. Exclusive $|V_{cb}|$ measurement using $B_s \to D_s^{(*)-} \mu^+ \nu_\mu$
   - Result in agreement with previous exclusive and inclusive measurements from $B^{0/+}$ decays
3. Measurement of $B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$ FF
   - Data consistent with both CLN and BGL FF parametrisations & in agreement with HFLAV world-average

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

Outlook:

- Several other $|V_{ub}|/|V_{cb}|$ analysis in the pipeline using $B_c^+ \to D^{0(*)} \mu^+ \nu$ and $B^+ \to \rho^0 \mu^+ \nu$ decays $\to$ theoretical FF predictions needed
- $|V_{cb}|$ and FF measurement of $B^0 \to D^{*-} \mu^+ \nu$ and differential $d\Gamma/dq^2$ from $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}$

Thanks for your attention!

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

Backup Slides

Ongoing measurements

$|V_{ub}|/|V_{cb}|$ analyses:

- $B_c^+ \to D^{0(*)}(\to K^-\pi^+)\mu^+\nu$ as signal wrt. $B_c^+ \to \mathrm{J}/\psi(\to \mu^+\mu^-)\mu^+\nu$ as normalization channel
  - $B_c^+ \to D$ FF in progress by L. Cooper et al, HPQCD using heavy-HISQ approach, expect 10%(20%) uncertainty at $q^2_{max}(q^2 = 0)$ presented by Christine Davies at Implications Workshop 2020
- $B^+ \to \rho^0(\to \pi^+\pi^-)\mu^+\nu$ as signal wrt. $B^+ \to \bar{D}^0(\to \pi^+\pi^-)\mu^+\nu$

$\to$ precise theoretical FF predictions needed

$|V_{cb}|$ analyses:

- $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}$: normalise to inclusive Λ_b^0 semileptonic decays and employ equal semileptonic partial widths (JHEP 09(2011)012), by measuring
  $\Gamma(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}) = \frac{n_{corr}(\Lambda_b^0\to\Lambda_c^+\mu^-\bar{\nu})}{n_{corr}(\Lambda_b^0\to X_c\mu^-)\times\Gamma(\Lambda_b^0\to X_c\mu^-\bar{\nu})}$
  $\to$ perform differential measurement $d\Gamma/dq^2$ as function of q^2 to control FF uncertainties Phys Rev D 96 112005
- $B^0 \to D^{*-}\mu^+\nu$ measure also FF using similar method:
  $\frac{\mathcal{B}(B^0\to D^{*-}\mu^+\nu)}{\mathcal{B}(B\to\bar{X}_c\mu^+\nu X)} = \frac{2n_{corr}(B^0\to D^{*-}\mu^+\nu)}{n_{corr}(\bar{D}^0\mu^+X)+n_{corr}(D^-\mu^+X)}$

Prospects for the Upgrade II

- Potential gains in detector performance arXiv 1808.08865:
  - **RF foil**: removal or further thinning reduces multiple scattering and such improves corrected mass resolution, selection efficiency, purity and q^2 resolution
  - **TORCH detector**: improves low momentum PID performance $\rightarrow$ important for kaon reconstruction at large q^2

  $\rightarrow$ together with large dataset of 300 fb^{-1} expected experimental systematic uncertainty on $|V_{ub}|/|V_{cb}|$ of 0.5%
- External inputs from branching fractions for B_s, Λ_c need to be measured up to 1% uncertainty by BesIII & others
- Further Lattice QCD improvements needed $\rightarrow$ uncertainty of 1%

$\Rightarrow$ Official goal: total uncertainty of 1% expected with Upgrade II dataset, same precision as for Belle II experiment (50 ab^{-1} by 2031)

Also other decay modes accessible: 30k $B_c^+ \rightarrow D^0\mu^+\nu$ and $B^+ \rightarrow \mu^+\mu^-\mu^+\nu$ expected and large datasets for precise shape & $|V_{cb}|$ measurements available

Branching fraction result

Phys. Rev. Lett. 126 081804

Full ratio of branching fractions gives:

$$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = 4.89 \pm 0.21(stat)^{+0.20}_{-0.21}(syst) \pm 0.14(D_s) \times 10^{-3}$$

including external branching fraction $\mathcal{B}(D_s^- \to K^+ K^- \pi^-)$. This can be converted into total branching fraction using external inputs:

$$\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu) = \tau_{B_s} \times \frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} \times |V_{cb}|^2 \times FF_{D_s},$$

with $\tau_{B_s} = 1.515 \pm 0.004\,\mathrm{ps}$, $|V_{cb}|_{excl} = (39.5 \pm 0.9) \times 10^{-3}$ from PDG and $FF_{D_s} = 9.15 \pm 0.37\,\mathrm{ps}^{-1}$ [Phys Rev D. 101 074513] gives

$$\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu) = (1.06 \pm 0.05(stat) \pm 0.04(syst) \pm 0.06(ext) \pm 0.04(FF)) \times 10^{-4}$$

→ First observation of the decay $B_s^0 \to K^- \mu^+ \nu_\mu$ and measurement of its branching fraction

Systematic Uncertainties

Phys. Rev. Lett. 126 081804

$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}$ [%]	All q^2	low q^2	high q^2
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$	$^{+3.0}_{-3.4}$
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
q^2 migration	–	2.0	2.0
Efficiency	1.2	1.6	1.6
Neutral BDT	1.1	1.1	1.1
Particle identification	1.0	1.0	1.0
$\sigma(m_{\mathrm{corr}})$	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Total	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$
MC statistical uncert.	2.1	2.4	3.2

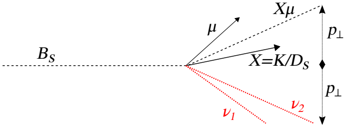
- Largest systematic from fit templates:
  - variations of FF models
  - relative K^* contributions
  - modelling of $B \to c\bar{c}(\to \mu\mu)KX$ component
- Tracking systematic due to remaining differences between 2-track signal and 4-track normalization channel $\to$ hadronic interaction with detector material
- q^2 migration & efficiency evaluated from MC simulation $\to$ reducible with larger simulation samples

$\to$ **Systematically limited measurement**

Neutrino and q^2- reconstruction

1) Infer Neutrino momentum p_ν from B_s^0-topology:

- transverse momentum of neutrino component $p_\perp$ easy to calculate



- longitudinal component $p_{||}$ determined up to 2-fold ambiguity with quadratic equation:

$$p_{||} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a},$$

where a, b and c are defined as $a = |2p_{||}m_{X\mu}|^2$, $b = 4p_{||}(2p_\perp p_{||} - m^2_{miss})$, $c = 4p_\perp(p^2_{||} + m^2_{B_s}) - |m^2_{miss}|^2$, $m^2_{miss} = m^2_{B_s} - m^2_{X\mu}$.

$\rightarrow$ known to 2-fold ambiguity

2) Use linear regression method [JHEP02(2017)021] to choose solution most consistent with B_s momentum

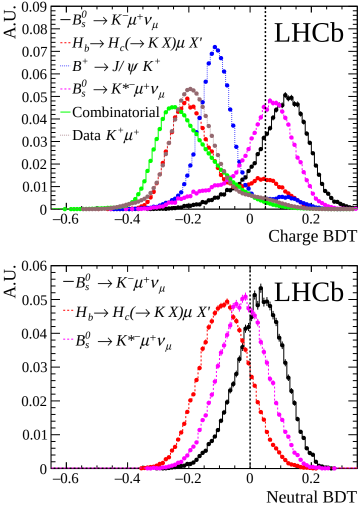
$B_s^0 \to K^- \mu^+ \nu_\mu$ Signal Selection

Phys. Rev. Lett. 126 081804

- Large background contributions from
  - $|V_{cb}|$-decays: $B \to D(\to KX)\mu X'$
  - $B \to c\bar{c}(\to \mu\mu)KX$ background, dominated by $B^+ \to \mathrm{J}/\psi(\to \mu\mu)K^+$, $B^+ \to \mathrm{J}/\psi(\to \mu\mu)K^{*+}$
  - higher excited kaon resonances: $B_s^0 \to K^{*+}\mu\nu_\mu$, $B_s^0 \to K_2^{*+}(1430)\mu\nu_\mu$, $B_s^0 \to K^{*,+}(1430)\mu\nu_\mu$ with $K^{*+} \to K^+\pi^0$
  - MisID & combinatorial background: estimated from data

$\to$ require signal tracks to be isolated

$\to$ train two BDT classifiers against additional charge and neutral particles

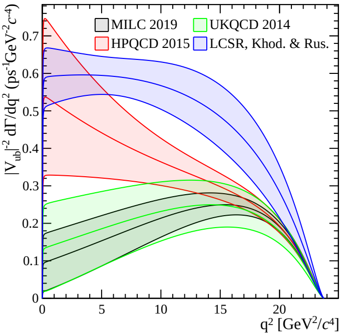


$B_s^0 \to K^- \mu^+ \nu_\mu$ FF predictions

Phys. Rev. Lett. 126 081804

Theoretical calculations:

- LCSR [JHEP 08 (2017) 112] at low q^2
- 3 different LQCD predictions at high q^2:
  - UKQCD [Phys. Rev. D 91, 074510 (2015)]
  - HPQCD [Phys. Rev. D 90, 054506 (2014)]
  - MILC [Phys Rev D.100 034501 (2019)]



Integrated decay width:

	full q^2	low q^2	high q^2
LCSR	11.07 ± 1.14	4.14 ± 0.38	6.94 ± 1.04
UKQCD	4.54 ± 1.29	1.18 ± 0.63	3.37 ± 0.74
HPQCD	7.75 ± 1.56	3.29 ± 1.00	4.47 ± 0.58
MILC	4.26 ± 0.92	0.94 ± 0.48	3.32 ± 0.46

Recent update from Flavour Lattice Averaging Group (FLAG) [arXiv 1902.08191]
→ dominated by MILC FFs

→ preliminary fit to lattice and LHCb data gives value of $|V_{ub}|/|V_{cb}|$ consistent with our high q^2 value

(Stefan Meinel @Snowmass Mini-workshop, January 2021)

Normalization Fit

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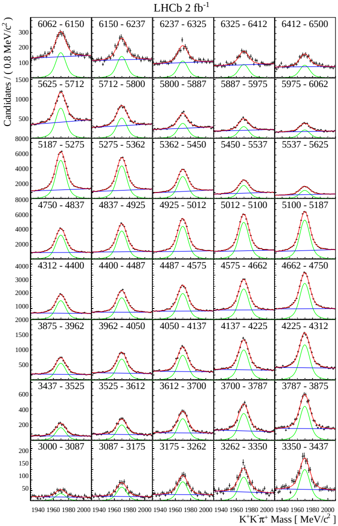
Fit is performed in two stages:

1. Fit to $D_s^- \to K^+K^-\pi^-$ invariant mass in 40 bins of B_s corrected mass (3000-6500 MeV/c^2) $\to$ gives *Ds* yield as function of *mcorr* & removes combinatorial background
2. binned maximum likelihood fit to B_s corrected mass

   Background contributions from:
   - higher excitations: $B_s^0 \to D_s^{*-}(\to D_s^-\gamma)\mu^+\nu_\mu$, $B_s^0 \to D_s^{**-}(\to D_s^- X)\mu^+\nu_\mu$ where $D_s^{**-} = D_{s0}^{*-}(2317), D_{s1}^-(2460), D_{s1}^-(2536)$
   - double charm decays: $B_{u,d,s} \to D_s^{(*)-} D^{(*)}(\to \mu\nu X')$
   - semitauonic decays: $B_s^0 \to D_s^-\tau^+\nu_\tau$
   - MisID muon background

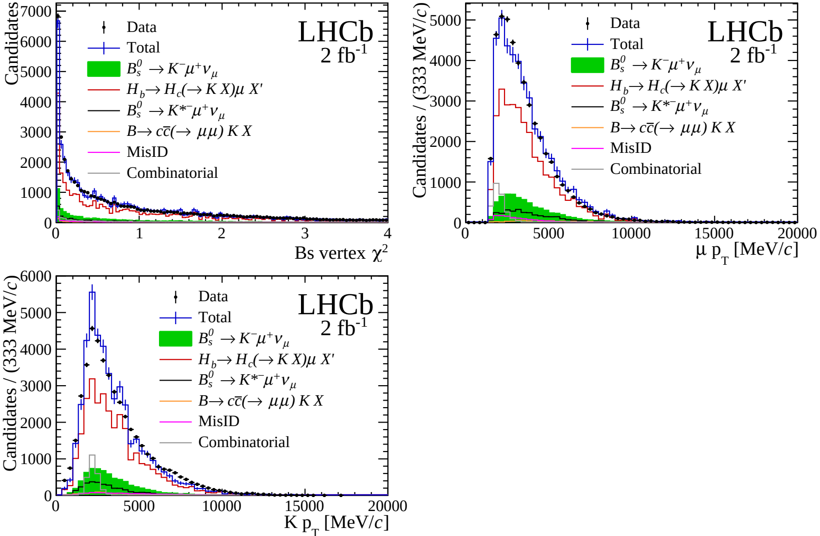
   $\to$ templates of similar shape are grouped together



$B_s^0 \to K^-\mu^+\nu_\mu$ Fit projections

Phys. Rev. Lett. 126 081804

projections on control variables for low q^2 bin:



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
$\mathcal{B}(\text{ B }^0 \to D^-\mu^+\nu_\mu)$	0.0231 ± 0.0010
$\mathcal{B}(\text{ B }^0 \to D^{*-}\mu^+\nu_\mu)$	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

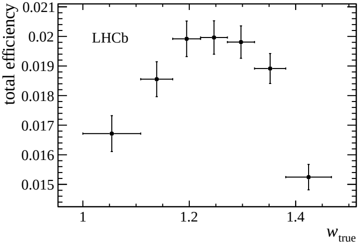
Source	Uncertainty															
	CLN parametrization						BGL parametrization									
	$\lvert V_{cb}\rvert$ $[10^{-3}]$	$\rho^2(D_s^-)$ $[10^{-1}]$	$\mathcal{G}(0)$ $[10^{-2}]$	$\rho^2(D_s^{*-})$ $[10^{-1}]$	$R_1(1)$ $[10^{-1}]$	$R_2(1)$ $[10^{-1}]$	$\lvert V_{cb}\rvert$ $[10^{-3}]$	d_1 $[10^{-2}]$	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	–	–
$\eta_{\rm EW}$	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 JHEP 12 (2020) 144

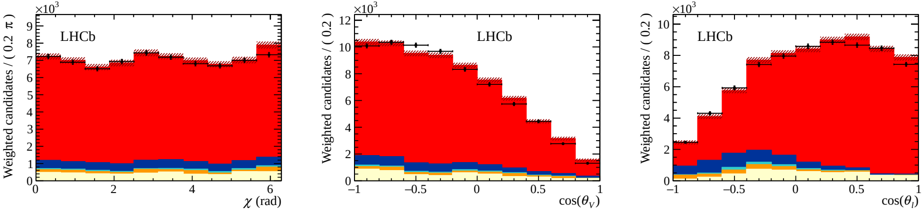
different fit results

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!

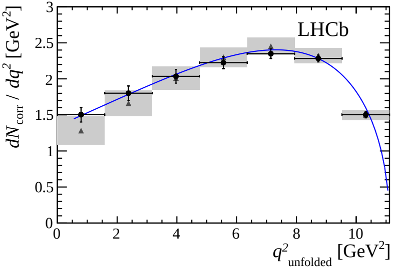
Systematic uncertainties for JHEP 12 (2020) 144

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

Previous measurements

$\Lambda_b \to \Lambda_c^+ \mu^- \nu$ differential decay rate [Phys Rev D. 96 112005 (2017)]

- Using Run 1 data (1 fb^{-1} @ 7 TeV + 2 fb^{-1} @ 8 TeV)
- Signal reconstructed through $\Lambda_c(\to pK^-\pi^+)\mu$
- Use decay $\Lambda_b \to \Lambda_c^+ \pi^+\pi^-\mu^-\nu$ to estimate bkg from $\Lambda_b \to \Lambda_c^{*+}\mu^-\nu$ with $\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-$ $\to$ contributions subtracted from data
- Measured as function of q^2, w $\to$ reconstructed up to 2-fold ambiguity (50-60% purity), lower momentum solution chosen
- Correct raw yields for detector resolution and efficiencies and fit spectrum with FF predictions from LQCD [PhysRevD 92 034503] and HQET [Phys Rev D 79 014023]



$\to$ spectrum is well described by both

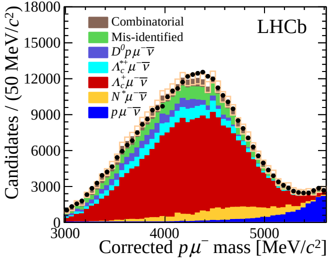
Previous measurements

$|V_{ub}|/|V_{cb}|$ using $\Lambda_b \to p\mu^-\nu$ [Nature Physics 11 (2015) 743]

- Using 2012 data (2 fb^{-1} @ 8 TeV)
- Signal: $\Lambda_b \to p\mu^-\nu$, normalisation: $\Lambda_b \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\nu$
- Measure

$$\underbrace{\frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu)_{q^2>15\,\text{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu)_{q^2>7\,\text{GeV}^2/c^4}}}_{\textbf{Experiment}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \underbrace{\frac{\text{FF}_p}{\text{FF}_{\Lambda_c}}}_{\textbf{Theory input}}$$

with FF from LQCD [PhysRevD 92 034503]

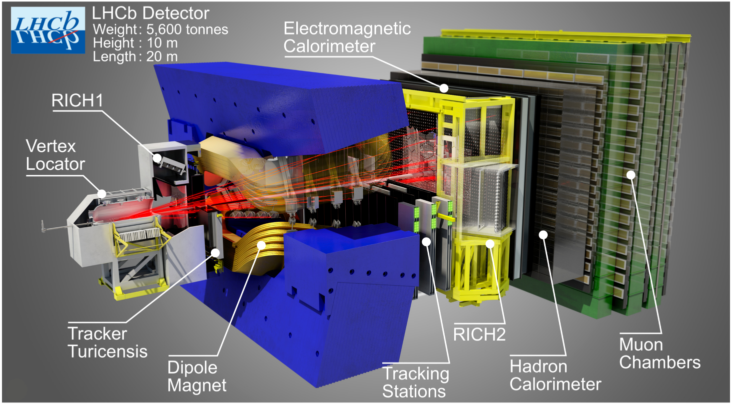


$\to |V_{ub}|/|V_{cb}| = 0.079 \pm 0.004(exp.) \pm 0.004(FF)$

gives 17687 ± 733

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