Measurement of the CKM matrix elements $|V_{ub}|/|V_{cb}|$ from semileptonic B_s decays at LHCb

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First Observation of the Decay $B_s^0 \to K^-\mu^+\nu_\mu$ and a Measurement of $|V_{ub}|/|V_{cb}|$

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(LHCb Collaboration)

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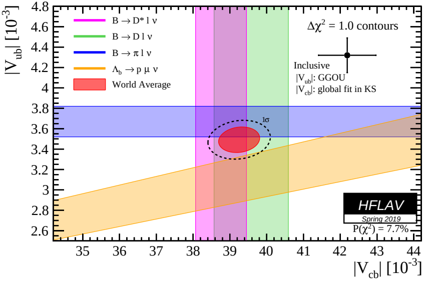
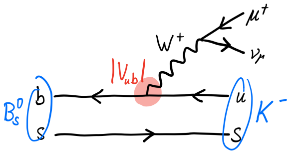
APS April Meeting 2021

- 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

First $|V_{ub}|/|V_{cb}|$ measurement from semileptonic B_s decays

Measurement strategy

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- Using 2012 data ($2\,\text{fb}^{-1}$ @ $8\,\mathrm{TeV}$)
- **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

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

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

Signal and normalization fits

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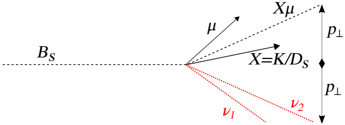
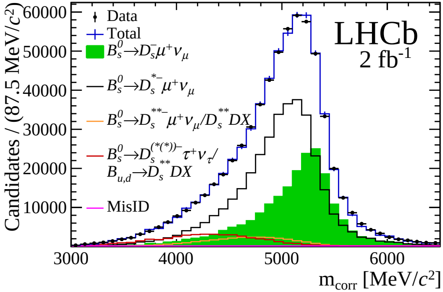


- Perform binned maximum likelihood fit to B_s corrected mass $m_{corr} = \sqrt{m^2(X\mu) + p_\perp^2} + p_\perp$, with $X = K, D_s$
  $\rightarrow$ allows to discriminate between signal and different backgrounds

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



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

Signal and normalization fits

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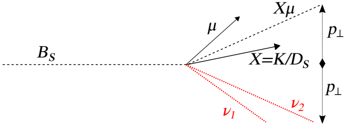
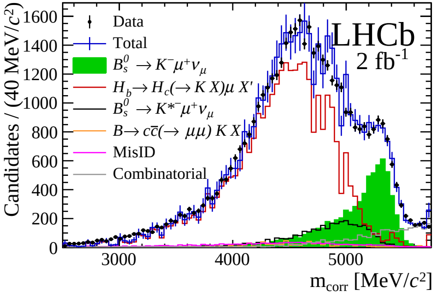
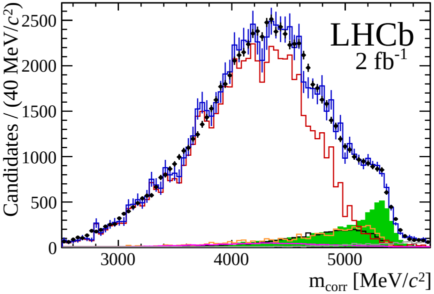


$B_s^0 \rightarrow K^-\mu^+\nu_\mu$ low q^2



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

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



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

Systematic Uncertainties

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$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}$ [%]	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**

Branching fraction result

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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

$|V_{ub}|/|V_{cb}|$ result

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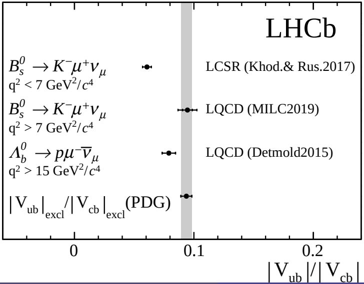
low q^2: $$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = 1.66 \pm 0.08(stat) \pm 0.07(syst) \pm 0.05(D_s) \times 10^{-3}$$

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

Conclusion and Outlook

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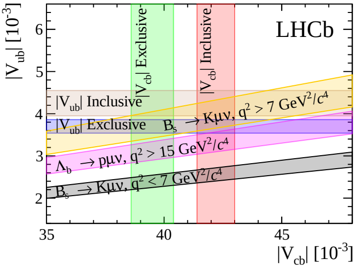
- First measurement of $B_s^0 \to K^- \mu^+ \nu_\mu$ branching fraction
- Measure $|V_{ub}|/|V_{cb}|$ using $B_s^0 \to K^- \mu^+ \nu_\mu$ and $B_s^0 \to D_s^- \mu^+ \nu_\mu$ in two q^2 regions
  - Discrepancy between low and high q^2 found
  - $|V_{ub}|/|V_{cb}|$ in high q^2 region compatible with previous measurements



Outlook:

- Interest in measuring the differential q^2 spectrum of $B_s^0 \to K^- \mu^+ \nu_\mu$ with full Run 1 + Run 2 data $\to$ up to 7 bins in q^2 possible
- 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
- Improvements in FF calculations expected from LQCD
  $\to$ promising preliminary results by UKQCD Collaboration shown at ICHEP 2020 [2012.04323]

Stay tuned!

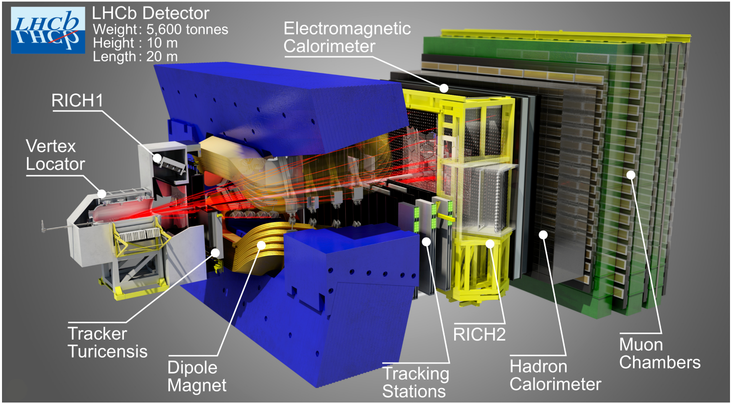
Thanks for your attention!

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

Backup Slides

LHCb Detector

JINST 3 S08005 (2008), Int. J. Mod. Phys. A 30, 1530022 (2015)

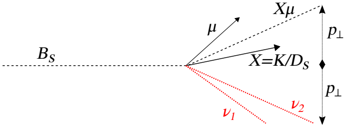


- VELO: primary and secondary vertex
- Tracking: momentum of charged particle
- RICHs: particle identification $K^{\pm}$, $\pi^{\pm}$
- MUON: trigger on high p_{T} $\mu^{\pm}$ & PID
- Calorimeter: ECAL and HCAL for γ, $e^{\pm}$ and hadronic energy

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

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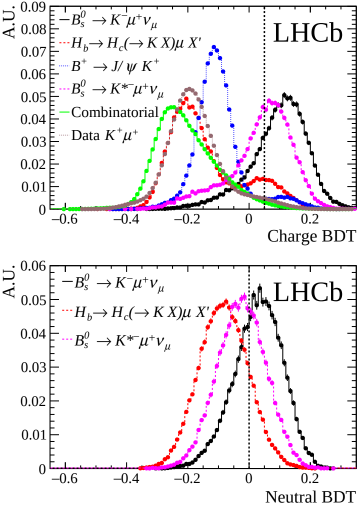
- Large background contributions from
  - $|V_{cb}|$-decays: $B \to D(\to KX)\mu X'$
  - $B \to c\bar{c}(\to \mu\mu)KX$ background, dominated by $B^+ \to \mathrm{J}/\psi(\to \mu\mu)K^+$, $B^+ \to \mathrm{J}/\psi(\to \mu\mu)K^{*+}$
  - higher excited kaon resonances: $B_s^0 \to K^{*+}\mu\nu_\mu$, $B_s^0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

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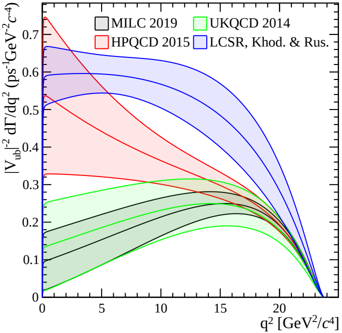
Theoretical calculations:

- 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]
$\to$ dominated by MILC FFs

$\to$ 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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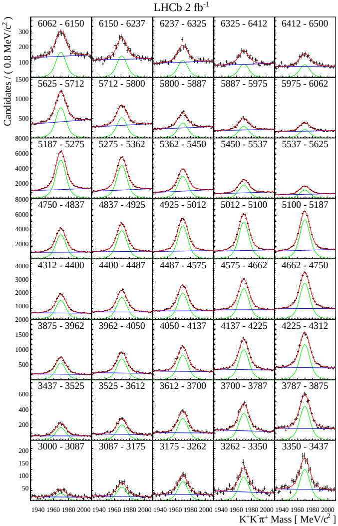
Fit is performed in two stages:

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

projections on control variables for low q^2 bin:

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