Status and prospects of $B_s^0 \to K^- \mu^+ \nu_\mu$ analysis at LHCb

5^{th} Beyond the Flavour Anomalies Workshop

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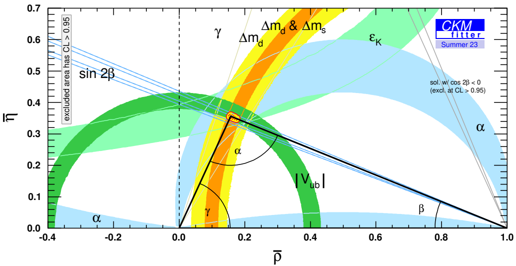
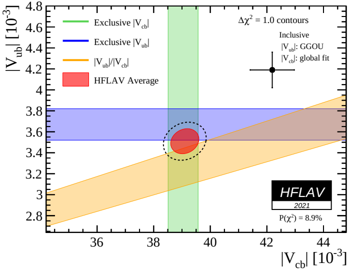
- $|V_{ub}|$, $|V_{cb}|$: coupling between b and $u(c)$ quarks, fundamental to constrain SM
- Complementary experimental approaches:
  - **inclusive decays**: clean, only B-factories, large backgrounds
  - **exclusive decays**: LHCb & B-factories, backgrounds under control
- HFLAV: combine all exclusive measurements from LHCb, BaBar and Belle:

$$|V_{ub}| = (3.51 \pm 0.12) \times 10^{-3} \qquad |V_{cb}| = (39.10 \pm 0.50) \times 10^{-3}$$

- Inclusive & exclusive measurements are in disagreement ($\sim 3\sigma$)





$B_s^0 \to K^- \mu^+ \nu_\mu$ analysis using Run1 data ($\sim 2\text{fb}^{-1}$)

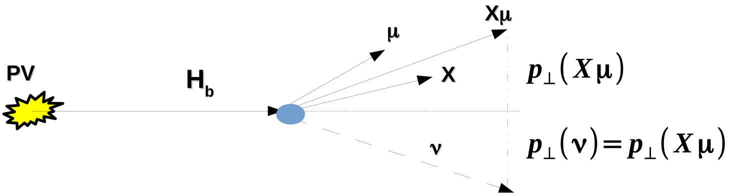
- Measure of BRs of $B_s^0 \to K^- \mu^+ \nu_\mu$ and $B_s^0 \to D_s^- \mu^+ \nu_\mu$:

$$R_{BF} = \underbrace{\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}}_{\textit{experiment}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \underbrace{\frac{d\Gamma(B_s^0 \to K^- \mu^+ \nu_\mu)/dq^2}{d\Gamma(B_s^0 \to D_s^- \mu^+ \nu_\mu)/dq^2}}_{\text{theory input}}$$

- The measurement of ratios allows to reduce some systematic uncertainties on the signal selection effiencies and provides the absolute normalization
- Convert to $|V_{ub}|/|V_{cb}|$: requires calculations of Form Factors
- Theory input: decay rates predicted as a function of q^2
- Meaurement of the $\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)$ for the first time
- Split in two q^2 regions for $B_s^0 \to K^- \mu^+ \nu_\mu$ ($q^2 \lessgtr 7\ Gev^2/c^4$)
  - $B_s^0 \to K^- \mu^+ \nu_\mu$: LCSR (low q^2) & LQCD (high q^2)
  - $B_s^0 \to D_s^- \mu^+ \nu_\mu$: LQCD (full q^2 spectrum)

Technique for SL in LHCb

- Momentum of missing neutrino recover by means of regression method



$$M_{corr} = \sqrt{M_{X\mu}^2 + p_{\perp}^2} + p_{\perp} \qquad q^2 = (p_{\mu} + p_{nu_{\mu}})^2$$

- $p_{||}(\nu_{\mu})$ determined from $p_{H_b}^2 = m(H_b)^2$
- Two fold ambiguity solved exploiting a regression method[1]
- M_{corr} used as variable in a binned template fit, perfomed in two q^2 bins ($\lessgtr 7\ Gev^2/c^4$) (boundary chosen to get about the same expected number of signal candidates)

[1] https://link.springer.com/article/10.1007/JHEP02(2017)021

Main background sources

Charged backgrounds

- $b \to c(\to KX)\mu\nu_\mu$ **[Dominant]**
- Inclusive $B \to c\bar{c}K(X)$: suppressed via charged isolation MVA output

Neutral backgrounds

- $B_s^0 \to K^{*-}_{(0,2)}(\to K^+\pi^0)\mu^+\nu_\mu$: three resonances partially suppressed via neutral isolation

Other backgrounds

- MisID background:
  - dominant contribution comes from the kaon mis-identification
  - rejected via particle identification requirements
- Combinatorial
  - reduced with geometrical and kinematic requirements
  - further suppression achieved with a MVA algorithm

- Residual contamination modelled with templates and included in the fit

Yields: $B_s^0 \to K^- \mu^+ \nu_\mu$ & $B_s^0 \to D_s^- \mu^+ \nu_\mu$ [10.1103/PhysRevLett.126.081804]

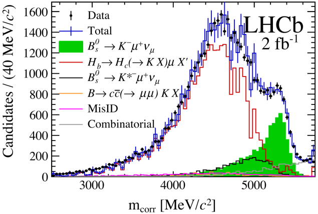
- Yields extracted via binned likelihood fit to B_s^0 corrected mass distribution

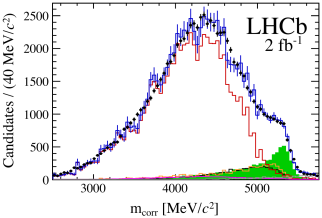
Signal yield

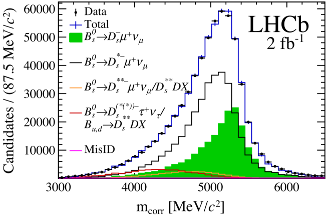
$$N_{sig}^{low\ q^2} = 6922 \pm 285$$
$$N_{sig}^{high\ q^2} = 6399 \pm 370$$

Normalization yield

$$N_{norm} = 201450 \pm 5200$$







- R_{BF} can be measured as:

$$R_{BF} = \frac{N_{sig}}{N_{norm}} \times \frac{\varepsilon_{norm}}{\varepsilon_{sig}} \times \mathcal{B}(D_s \to K^- K^+ \pi^+)$$

Run1 systematics breakdown [10.1103/PhysRevLett.126.081804]

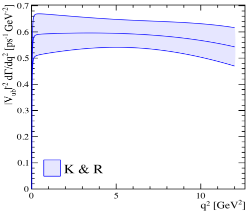
Uncertainty	$\frac{\mathcal{B}(B_s \to K\mu\nu)}{\mathcal{B}(B_s \to D_s\mu\nu)}$ [%]		
	No q^2 sel.	low q^2	high q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle ID	1.0	1.0	1.0
$m_{\rm corr}$ error	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration		2.0	2.0
ε gen& reco	1.2	1.6	1.6
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$	$^{+3.0}_{-3.4}$
Total	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$
$\mathcal{B}(\mathrm{D_s^-} \to \mathrm{K^-K^+}\pi^-)$	2.8	2.8	2.8

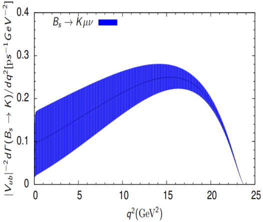
- Main systematics are:
  - tracking
  - q^2 migration
  - fit templates
  - $\mathcal{B}(D_s \to K^-K^+\pi^+)$
- Many systematic sources are reducible with larger dataset and simulation samples

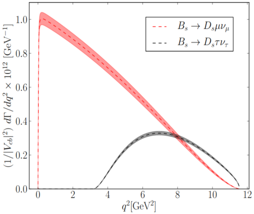
Results: $|V_{ub}|/|V_{cb}|$ ingredients [10.1103/PhysRevLett.126.081804]

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

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







JHEP08(2017)112 — Phys. Rev. D 100, 034501 (2019) — Phys. Rev. D 101, 074513 (2020)

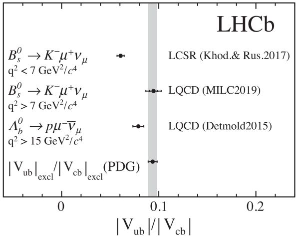
$\mathrm{FF_K} = 4.14 \pm 0.38\,\mathrm{ps}^{-1}$, $\mathrm{FF_K} = 3.23 \pm 0.46\,\mathrm{ps}^{-1}$, $\mathrm{FF_{D_s}} = 9.15 \pm 0.37\,\mathrm{ps}^{-1}$

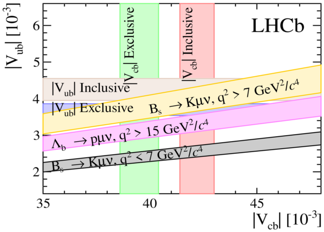
[low q^2] [high q^2] [full q^2]

Results: $\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)$ [10.1103/PhysRevLett.126.081804]

$$|V_{ub}|/|V_{cb}|(low\ q^2) = 0.0607 \pm 0.0015(stat) \pm 0.0013(syst) \pm 0.0008(D_s) \pm 0.0030(FF)$$

$$|V_{ub}|/|V_{cb}|(high\ q^2) = 0.0946 \pm 0.0030(stat)^{+0.0024}_{-0.0025}(syst) \pm 0.0013(D_s) \pm 0.0068(FF)$$





- Two different FFs were used: LCSR (low q^2) & LQCD (high q^2)

Run2 analysis prospects

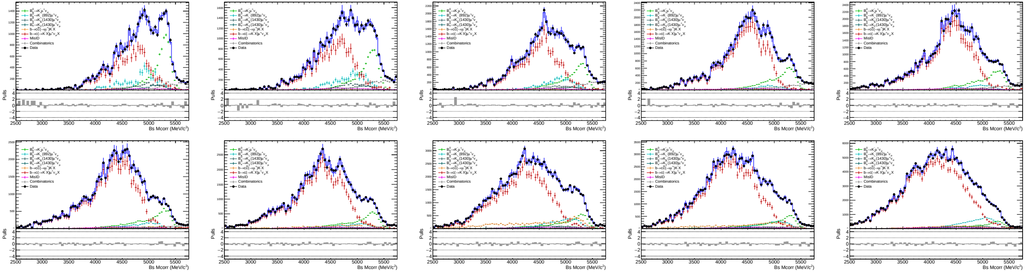
- The Run2 analysis update is already started
- **Goal**: determination of $\frac{d\Gamma}{dq^2}(B_s^0 \to K^- \mu^+ \nu_\mu)$ and $|V_{ub}|$ from a measurement of $B_s^0 \to K^- \mu^+ \nu_\mu$ decays
- **Dataset**: full Run2 data sample ~ 5.4 fb^{-1}
- Expected around a factor 6 increase in statistics wrt Run1 analysis (2012 only):
  - $\sim \times 3$ for the increased luminosity
  - $\sim \times 2$ for the increased *bb* cross section
- This opens to the possibility of increasing the number of q^2 bins up to $\sim 8 - 10$
  $\Longrightarrow$ provide a $\frac{d\Gamma}{dq^2}(B_s^0 \to K^- \mu^+ \nu_\mu)$ distribution
  $\Longrightarrow$ determination of the FFs + $|V_{ub}|$
- Based on Run1 strategy, working to optimize the various steps
- Analysis is still on-going, first results expected early next year

Normalization channel

- In Run1 analysis the $B_s^0 \to D_s^-(\to K^-K^+\pi^-)\mu^+\nu_\mu$ was used as normalization channel
- In Run2, make an absolute measurement of $|V_{ub}|$ using $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ as normalization mode
- Will be the first LHCb measurement of $|V_{ub}|$ independent on $|V_{cb}|$:
  - new contribution to the $|V_{ub}|$ VS $|V_{cb}|$ plane with respect to the previous analyses
- $B^+ \to J/\psi K^+$ selection is clean and the statistics is high
- A more signal-like final state: "μK" VS "$\mu\mu K$" instead of "$\mu KK\pi$"
  $\Longrightarrow$ systematic uncertainty on tracking efficiency will decrease

Simultaneous fit in multiple q^2 bins

- The idea is to perform a simultaneous fit in $\sim 10\ q^2$ bins on the M_{corr} variable
- Fit tested with **pseudo-experiments** based on Run1 templates:
  - scaling up the statistics ($\sim \times 6$)
  - FF parameters fixed to Run1 values (to be updated to the latest determinations)
- Simultaneous fit over 10 bins defined equalizing the expected signal yield
- Resulting yields compatible with the expected ones within two standard deviations



[Toy MC]

FF parameterization

- FF parameterization will play an important role
- **Baseline**: FF parameterized according to the BCL scheme, central values taken from the most recent HFLAV average
- The idea is to use **Hammer** to implement a FF variation in the signal templates

- In addition, we want also to investigate the effect of other FF parameterizations, e.g. the recent combination of LQCD and LCSR results [JHEP11(2023)082]
  - found a more compatible $|V_{ub}|/|V_{cb}|$ value than when using LQCD and LCSR separately and with the older LQCD determination

- Furthermore, having $\sim$ 10 bins give the opportunity to perform a LHCb determination of the FFs from the $d\Gamma/dq^2$ distribution

Main challenges

Background rejection

- Current main focus is on the development of the various MVAs algorithms
- Trying to develop a new MVA for a better neutral rejection

Modelling of the residual backgrounds

- Description of the residual backgrounds will be also very important
- Previous analyses proved that misID and combinatorial can be hard to model
- K^* backgrounds can mimic the signal and bias the FFs determinations
  $\Longrightarrow$ FFs for these decay modes never measured before and not very well known
  $\Longrightarrow$ additional theory inputs are important

q^2 migration

- It was already a large source of systematics in Run1 analysis
- Need careful unfolding when increasing the q^2 bins
- Optimization of the regression & q^2 binning scheme is crucial

LHCb Upgrade prospects

- LHCb Upgrade is now completed and Run3 data taking has started
- Expected integrated luminosity is 50 fb^{-1} ($\sim$ 10 Run2 statistics)
- This will allow to:
  - significant reduction of the statistical uncertainty
  - further increase of the number of q^2 bins
    (maybe at high q^2 where the theory predictions are more precise)
    $\Longrightarrow$ better constraint of the FFs shape

- **Very important not to be systematically limited!**

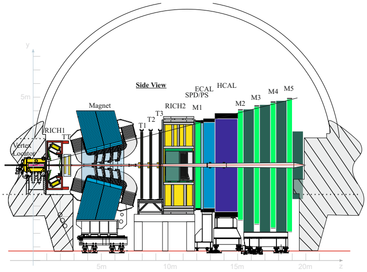
- Main experimental systematic sources are due to the **MC statistics**
  $\Longrightarrow$ they can be reduced requiring larger MC samples
- Fundamental to improve the **modelling of the K^* resonances**
  $\Longrightarrow$ this will require new inputs from both experiments and theory

Backup

The Large Hadron Collider beauty (LHCb) Experiment

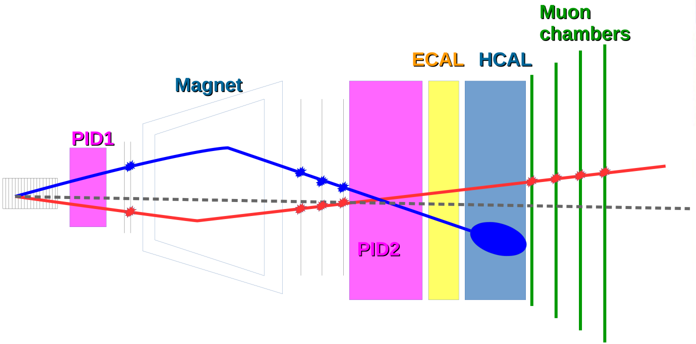
- LHCb detector is a single-arm forward spectrometer optimized for b/c hadron physics
  - pseudorapidity range: [2,5] $\Longrightarrow \sim 25\%$ $b\bar{b}$ pairs in LHCb acceptance
- **High precision measurements** in flavour physics (e.g. CKM, beyond SM)
- Collected data:
  - Run1 (2010-2012) $\Longrightarrow \approx 3\ \text{fb}^{-1}$
  - Run2 (2015-2018) $\Longrightarrow \approx 6\ \text{fb}^{-1}$

- Excellent performances [Int. J. Mod. Phys. A 30, 1520022 (2015)]:
  - **Momentum resolution**: $\frac{\sigma_p}{p} \approx 0.5 - 0.8\%$ ($p < 100$ GeV/c)
  - **Impact Parameter (IP) resolution**: $\sigma_{IP} \approx 20\ \mu m$ (at high p_T)
  - **Decay time resolution**: $\sigma_t \approx 50\ fs$
  - **Particle Identification (PID)**: $\varepsilon(K) \approx 95\%, \pi$ mis-ID $\approx 5\%$ ($p < 100$ GeV/c) $\varepsilon(\mu) \approx 97\%, \pi$ mis-ID $\approx$ 1-3%



$B_s^0 \to K^- \mu^+ \nu_\mu$ reconstruction

- Only two tracks (K & μ)in the final state + invisible neutrino
- Any physics decay with the same tracks + extra neutral/charged particle can be a source of background
  $\Longrightarrow$ require dedicated MVA algorithms



$B_s^0 \to K^- \mu^+ \nu_\mu$ branching ratio

- The $B_s^0 \to K^- \mu^+ \nu_\mu$ analysis performed with Run1 data provided the first observation of this decay mode

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

  where
  - $|V_{cb}|$ is exclusive value $(39.5 \pm 0.9) \times 10^{-3}$
  - FF_{D_s} is the FF integral based on a LQCD computation
  - $\tau_{B_s^0}$ is the B_s^0 lifetime

- The result found was:

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

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