$B \to \mu^+\mu^-$ and tests of Lepton Flavour Universality

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UK Flavour Physics Meeting, 5 September 2017

Outline

Talk will focus on recent rare decay results from LHCb and future prospects:

- $B_s^0 \to \mu^+\mu^-$ branching fraction and effective lifetime
- Tests of lepton flavour universality (LFU):
  - Motivation: $R(K)$, $R(D^*)$
  - New measurements: $R\left(K^{*0}\right)$
  - Future measurements: $R(\phi)$, $R(K)$, $R\left(K_{\mathrm{S}}^0\right)$...

See also Kostas's earlier talk on $b \to sll$ and Mika's talk on semileptonic B decays in the next session.

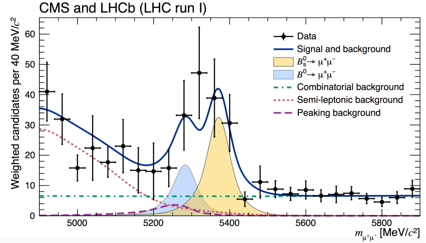
$B \to \mu^+\mu^-$

$B \to \mu^+\mu^-$ branching fractions

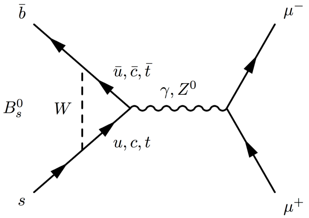
Great place to look for new physics:

- Low branching fraction due to loop mediation and helicity suppression
- Precise theoretical predictions:
  $\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right) = 3.65 \pm 0.23 \times 10^{-9}$
  $\mathcal{B}\left(B^0 \to \mu^+\mu^-\right) = 1.06 \pm 0.09 \times 10^{-10}$
  [C. Bobeth *et al.*, PRL 112 (2014) 101801]

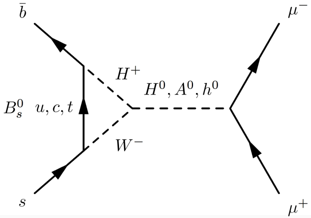
Previously observed by combined CMS + LHCb analysis.



[CMS and LHCb collaborations, Nature 522 (2015) 68]



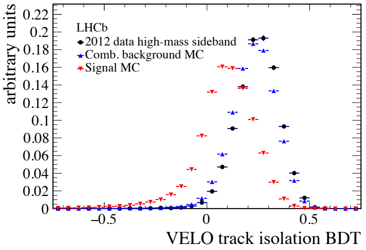
Sensitive to extended Higgs sector.

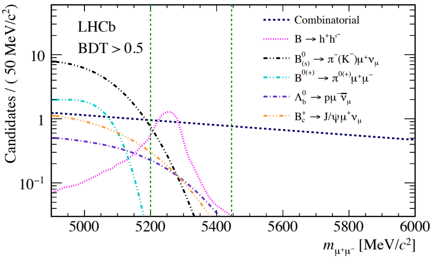


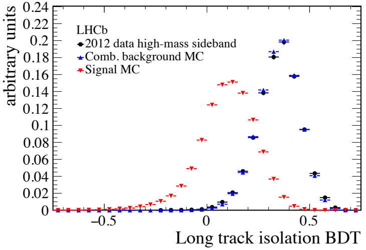
$B \to \mu^+\mu^-$ branching fractions

Recently published updated measurement with $3.0\,\mathrm{fb}^{-1}$ Run 1 data and $1.4\,\mathrm{fb}^{-1}$ Run 2 data. Improved version of previous LHCb analysis:

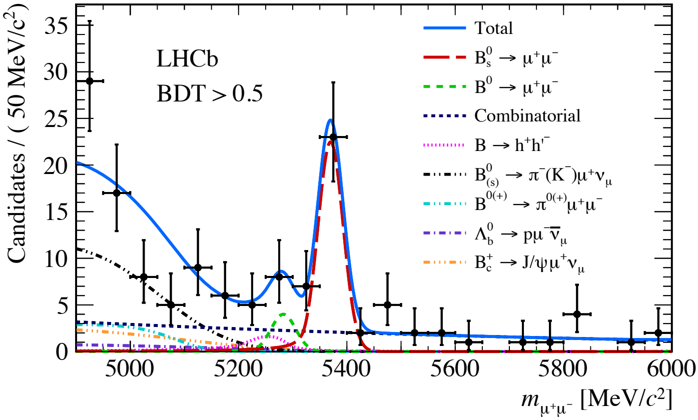
- Normalised w.r.t. $B^0 \to J/\psi K^+$ and $B^0 \to K^+\pi^-$
- New isolation variables
- Improved BDT
- Tightened muon PID requirements cut $B \to h^+h'^-$ background by 50% to improve sensitivity to $B^0 \to \mu^+\mu^-$







First single experiment observation of $B_s^0 \to \mu^+\mu^-$



$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right) = 3.0 \pm 0.6\,^{+0.3}_{-0.2} \times 10^{-9} \text{ at } 7.8\sigma$$
$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\right) = 1.5\,^{+1.2}_{-1.0}\,^{+0.2}_{-0.1} \times 10^{-10} \text{ at } 1.6\sigma$$

Consistent with SM.

[LHCb collaboration, Phys.Rev.Lett. 118 (2017) no.19, 191801]

$B_s^0 \to \mu^+\mu^-$ effective lifetime

NP effects can appear in via the parameter

$$A_{\Delta\Gamma} \equiv \frac{\Gamma\left(B_s^H \to \mu^+\mu^-\right) - \Gamma\left(B_s^L \to \mu^+\mu^-\right)}{\Gamma\left(B_s^H \to \mu^+\mu^-\right) + \Gamma\left(B_s^L \to \mu^+\mu^-\right)}$$

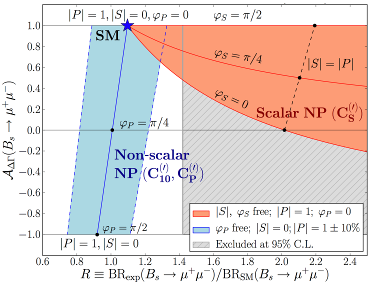
even if the branching fraction agrees with the SM.

In the SM $A_{\Delta\Gamma} = 1$ and meauring its sign can resolve a two-fold ambiguity in the sign of the real part of the Wilson Coefficient C_S.

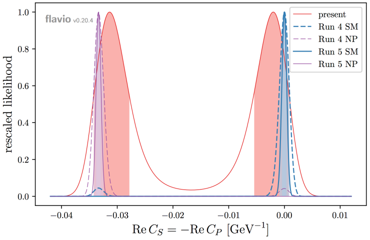
The effective lifetime defined as the mean decay time of an untagged sample of $B_s^0 \to \mu^+\mu^-$ decays

$$\tau_{\mu^+\mu^-} = \frac{\int_0^\infty t\Gamma\left(B_s^0 \to \mu^+\mu^-\right) dt}{\int_0^\infty \Gamma\left(B_s^0 \to \mu^+\mu^-\right) dt}$$

is easier to measure directly and depends on $A_{\Delta\Gamma}$.



[De Bruyn *et al.*, PRL 109 (2012) 041801]

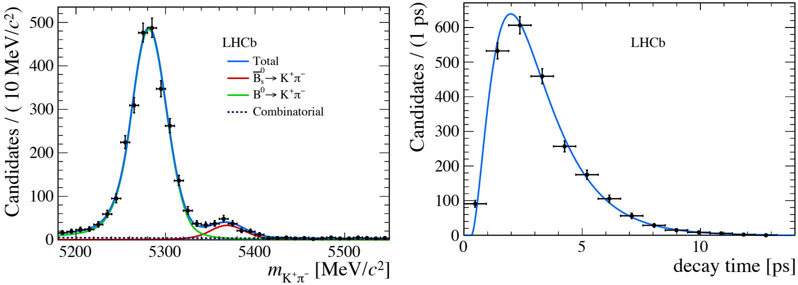


[Altmannshofer *et al.*, JHEP 1705 (2017) 076]

$B_s^0 \to \mu^+\mu^-$ effective lifetime

First measurement of $B_s^0 \to \mu^+\mu^-$ effective lifetime made by LHCb:

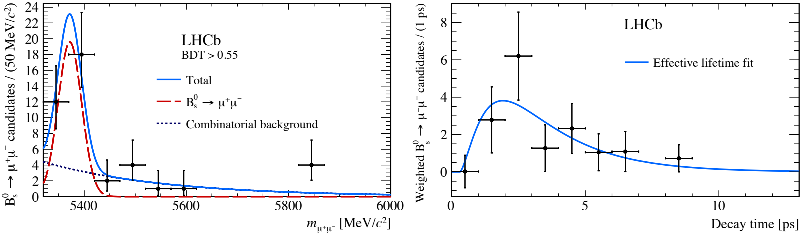
- Softer selection compared to branching fraction
- Decay time distribution extracted using sWeights
- Decay time acceptance calculated from reweighted simulation
- Method verified on $B^0 \to K^+\pi^-$



Effective $B^0 \to K^+\pi^-$ lifetime measured as: $\tau_{K\pi} = 1.52 \pm 0.03\,(\text{stat.})$ ps compared to PDG value of $1.520 \pm 0.004\,\text{ps}$.

$B_s^0 \to \mu^+\mu^-$ effective lifetime

Lower mass cut at 5320 MeV to reject part reco background, found to give smallest stat uncertainty using toys - contamination treated as a systematic.

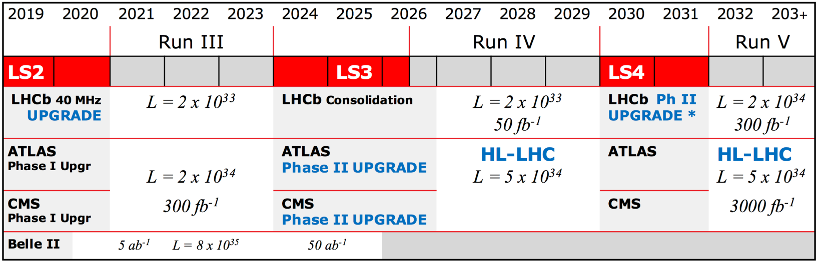


Effective lifetime measured as: $\tau_{\mu^+\mu^-} = 2.04 \pm 0.44\,(\text{stat.}) \pm 0.05\,(\text{syst.})$ ps

Systematics dominated by the $B^0 \to K^+\pi^-$ lifetime measurement used to validate the acceptance correction. Will decrease with increasing statistics in future.

Currently statistically limited but consistent with SM prediction of $1.610 \pm 0.010\,\text{ps}$ and favouring $A_{\Delta\Gamma} = +1$.

$B \to \mu^+\mu^-$ future prospects



[Plot from Niels Tuning]

Projected $B \to \mu^+\mu^-$ uncertainties:

	Current 4.4 fb^{-1}	LHCb Upgrade 50 fb^{-1}	Phase II LHCb Upgrade 300 fb^{-1}
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	0.6×10^{-9}	0.31×10^{-9}	0.27×10^{-9}
R_{B_d/B_s}	-	$[23, 27]\%$	$[11, 13]\%$
$\tau_{\mu\mu}$	$0.44\,\mathrm{ps}$	$0.08\,\mathrm{ps}$	$0.03\,\mathrm{ps}$

$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ uncertainty dominated by f_s/f_d. Theory uncertainty currently 0.23×10^{-9}.

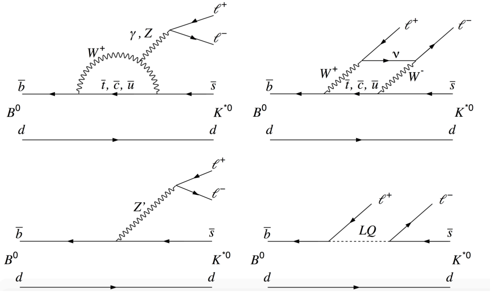
$0.038\,\mathrm{ps}$ required for the lifetime to distinguish $A_{\Delta\Gamma} = \pm 1$ at 5σ.

Testing Lepton Flavour Universality

In SM the electroweak couplings to each lepton generation (e,μ,τ) are identical - any differences in particle interactions due to effect of mass differences on phase space and highly suppressed Higgs diagrams.

Almost all experimental tests to date have confirmed LFU, though a 2.8σ tension exists in the branching fraction of $W \to \tau\nu_\tau$ compared to $W \to \mu\nu_\mu$ and $W \to e\nu_e$.

FCNC $b \to sl^+l^-$ decays are highly suppressed in SM due and may be sensitive to contributions from NP which violate LFU.



e.g. Z' bosons or leptoquarks, which could also account for $B \to K\mu^+\mu^-$ branching fraction anomalies.

Results from BaBar, Belle and LHCb have hinted at violation of LFU in semileptonic B decays:

$$R(D^{(*)}) \equiv \frac{\mathcal{B}\left(B \to D^{(*)}\tau\nu_\tau\right)}{\mathcal{B}\left(B \to D^{(*)}\mu\nu_\mu\right)}$$

Naive world-average of D^*, D^+ and D^0 ratios is 4.1σ from SM (see Mika's talk).

In 2014 LHCb measured deviation from SM in the ratio of $B^+ \to K^+ l^+ l^-$ decays, for $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$ using Run I data:

$$R\left(K\right) = \frac{\mathcal{B}\left(B^+ \to K^+\mu^+\mu^-\right)}{\mathcal{B}\left(B^+ \to K^+e^+e^-\right)} = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst}).$$

2.6σ deviation from SM prediction of 1.0 ± 0.0001 for $q^2 > 0.1\,\mathrm{GeV}^2/c^4$ (where lepton mass may be ignored).

[LHCb collaboration, Phys.Rev.Lett. 113 (2014) 151601], [Bobeth *et al.*, JHEP 12 (2007) 040]

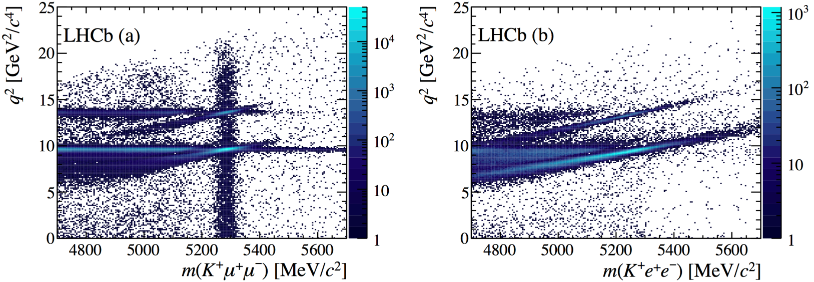
Tests of Lepton Flavour Universality

General approach to $R(H)$ measurements at LHCb - measure with respect to J/ψ control modes to cancel systematics

$$R(H) \equiv \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2} dq^2}$$

$$= \frac{N_{B\to H\mu^+\mu^-}}{N_{B\to He^+e^-}} \frac{N_{B\to HJ/\psi(e^+e^-)}}{N_{B\to HJ/\psi(\mu^+\mu^-)}} \frac{\epsilon_{B\to He^+e^-}}{\epsilon_{B\to H\mu^+\mu^-}} \frac{\epsilon_{B\to HJ/\psi(\mu^+\mu^-)}}{\epsilon_{B\to HJ/\psi(e^+e^-)}}$$

and assume no violation of lepton flavour universality in the J/ψ modes.

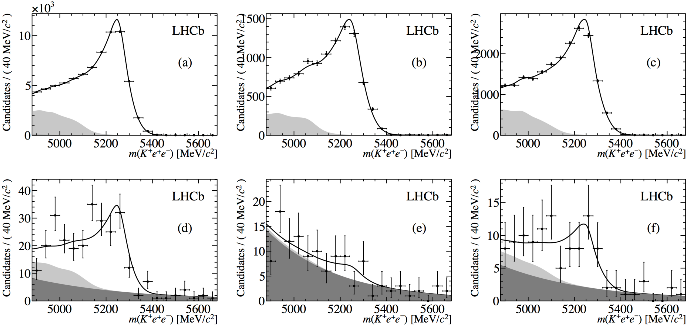


[LHCb collaboration, Phys.Rev.Lett. 113 (2014) 151601]

Tests of Lepton Flavour Universality

General approach to $R(H)$ measurements at LHCb:

- Electron data split into three independent Level-0 trigger categories, with different resolutions: triggered by one of the **electrons**, triggered by one of the **hadrons**, triggered **independently** of the candidate.



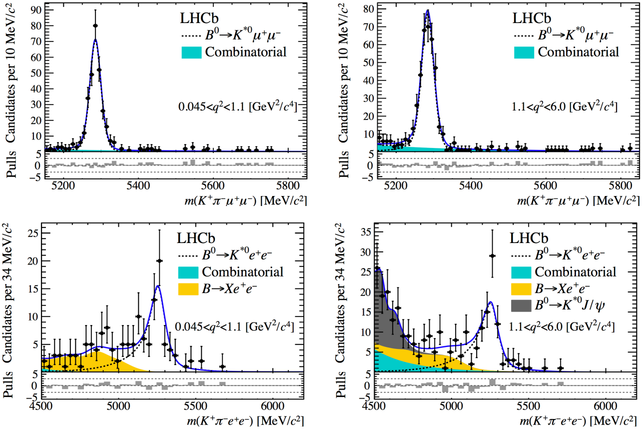
[LHCb collaboration, Phys.Rev.Lett. 113 (2014) 151601]

- MVA selection (BDT or Neural Network)
- Efficiencies determined from simulation

$R\left(K^{*0}\right)$

Analysis performed using $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$ decays in two q^2 bins:

- **Low** : $0.045 < q^2 < 1.1\,\mathrm{GeV}^4/c^2$
- **Central** : $1.1 < q^2 < 6.0\,\mathrm{GeV}^4/c^2$

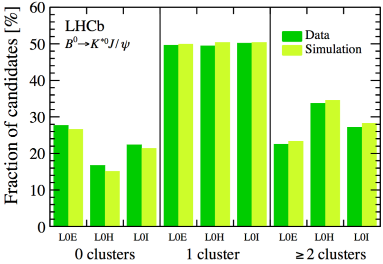


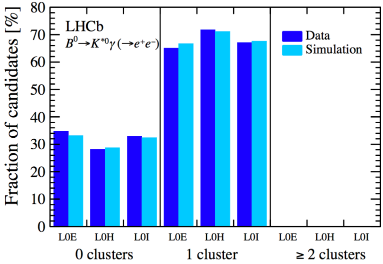
[LHCb collaboration, JHEP 1708 (2017) 055]

Electron momentum resolution improved by dedicated bremsstrahlung recovery process:

- Electron track extrapolated upstream of the magnet
- Search made for ECAL energy deposits with $E_T > 75\,\mathrm{MeV}$
- Brem clusters added to the electron momentum
- If a cluster can be assigned to both e^+ and e^- then it is assigned to one at random

Data are split into three categories with different mass resolutions: no photons added, 1 photon added, >1 photon added. Overall mass PDF is sum of three Crystal Ball functions - one for each category - fitted to simulation.





Data and simulation in good agreement on number of brem photos recovered.

$R\left(K^{*0}\right)$ cross-checks

Cross-check of the quantity

$$R\left(J/\psi\right) \equiv \frac{\mathcal{B}\left(B^0 \to K^{*0} J/\psi\left(\mu^+\mu^-\right)\right)}{\mathcal{B}\left(B^0 \to K^{*0} J/\psi\left(e^+e^-\right)\right)} = 1.043 \pm 0.006(\text{stat.}) \pm 0.045(\text{syst.})$$

Stringent rest as $R\left(J/\psi\right)$ doesn't benefit from systematic cancellations.

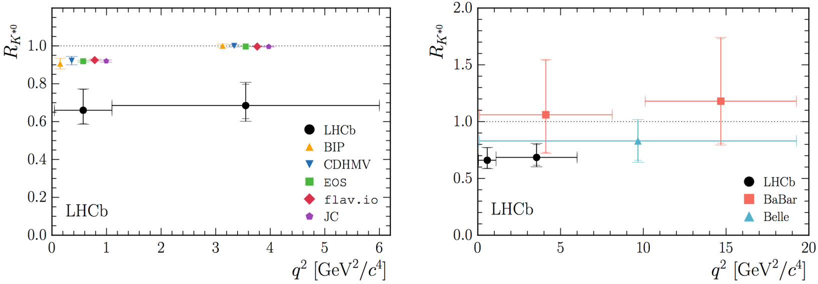
Double ratio $R(\psi(2S))$ also measured to 2% precision and agrees with unity within 1σ.

$\mathcal{B}\left(B^0 \to K^{*0}\mu^+\mu^-\right)$ and $\mathcal{B}\left(B^0 \to K^{*0}\gamma(\to e^+e^-)\right)$measured and found to agree with previous LHCb measurement [LHCb collaboration, JHEP 11 (2016) 047] and expectations, respectively.

Corrections to simulation turned off and found to only shift the result by 5%.

$R\left(K^{*0}\right)$ results

Final result shows similar tension to the SM as $B^+ \to K^+ l^+ l^-$:



$$R\left(K^{*0}\right) = \begin{cases} 0.66^{+0.11}_{-0.07}(\text{stat.}) \pm 0.03(\text{syst.}) & \text{for} \quad 0.045 < q^2 < 1.1\,\text{GeV}^2/c^4 \\ 0.69^{+0.11}_{-0.07}(\text{stat.}) \pm 0.05(\text{syst.}) & \text{for} \quad 1.1 \quad < q^2 < 6.0\,\text{GeV}^2/c^4 \end{cases}$$

deviating from SM by $[2.1 - 2.3\sigma]$ and $[2.4 - 2.5\sigma]$ in low and central q^2 bins.

[LHCb collaboration, JHEP 1708 (2017) 055]

Future prospects for LFU

$R\left(K\right)$ and $R\left(K^{*0}\right)$ have generated a lot if interest in LFU tests at LHCb. A number of new analyses are in the pipeline:

- $R(B_s^0 \to \phi l^+ l^-)$
- $R(\Lambda_b^0 \to p K^- l^+ l^-)$
- $R(K\pi\pi)$
- $R(B^0 \to K_{\rm S}^0 l^+ l^-)$
- $R(B^+ \to K^{*+} l^+ l^-)$
- Inclusive $R(KX)$ where X is not reconstructed
- Angular LFU analysis of $B^0 \to K^{*0} l^+ l^-$ and $B^+ \to K^+ l^+ l^-$

Plan to harmonise analysis techniques across LFU measurements and develop common tools.

Future prospects for LFU

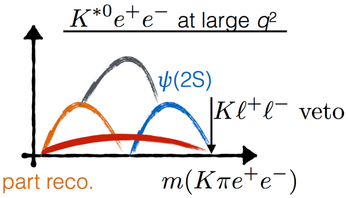
Measurement of $R(\phi)$ using $B_s^0 \to \phi l^+ l^-$ exploring making a measurement in additional high q^2 region $15 < q^2 < 19$ thanks to smaller and better separated partially (and over) reconstructed backgrounds and reduced peaking backgrounds due to narrow ϕ resonance.

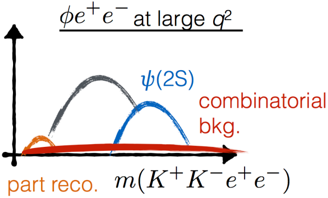
Also increased interest in Lepton Flavour Violating decays, which naturally accompany LFU violation, e.g. $B \to K\mu\tau$, $B \to e\mu$.

Limits already set for $1\,\text{fb}^{-1}$:

- $\mathcal{B}(B_s^0 \to e^{\pm}\mu^{\mp}) < 1.1(1.4) \times 10^{-8}$
- $\mathcal{B}(B^0 \to e^{\pm}\mu^{\mp}) < 2.8(3.7) \times 10^{-9}$

[LHCb collaboration, Phys.Rev.Lett. 111 (2013) 141801]





Plot from Tom Blake

Future prospects for LFU

$R(K)$ and $R(K^{*0})$ will remain the most statistcally powerful measurements and updates using the Run II data sample are in progress.

Observable	Run I 3 fb^{-1}	Run II 8 fb^{-1}	LHCb Upgrade 50 fb^{-1}	LHCb Phase II Upgrade 300 fb^{-1}
$N(B^+ \to K^+\mu^+\mu^-)$	4746	18,159	139,491	861,709
$N(B^+ \to K^+e^+e^-)$	254	972	7465	46,118
$R(K)$ uncertainty	0.090	0.046	0.017	0.007
$N(B^0 \to K^{*0}\mu^+\mu^-)$	2398	9175	70,480	435,393
$N(B^0 \to K^{*0}e^+e^-)$	111	425	3262	20,154
$R(K^{*0})$ uncertainty	0.11	0.056	0.020	0.008

If central values remain the same then lepton flavour universality violation should be observed at $> 5\sigma$ by the end of Run II.

Thanks