Lepton flavour universality tests in rare $b \to s\ell\ell$ decays

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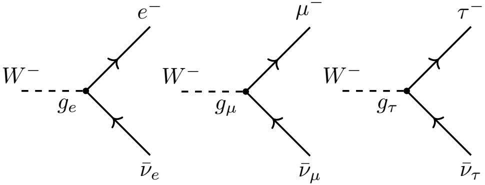
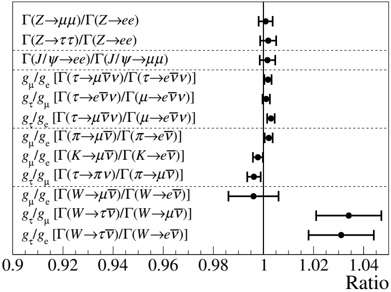
Lepton Flavour Universality in the SM

- Lepton Flavour Universality: In the Standard Model (SM), the couplings of the charged leptons to the gauge bosons are equal ($g_e = g_\mu = g_\tau$)
- Differences in branching fractions only due to lepton mass differences
- Well established in $Z \to \ell\ell$, $J/\psi \to \ell\ell$, $\tau \to \ell\bar{\nu}\nu$, $\pi \to \ell\bar{\nu}$, $K \to \ell\bar{\nu}$



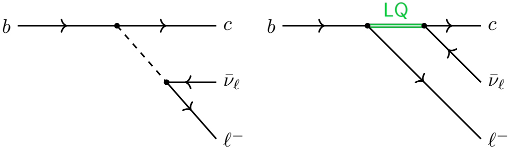
[A. Pich PPNP 75 (2014) 41-85] [PRD 98 (2018) 030001]



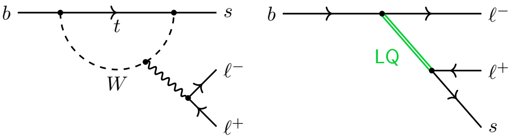
- Tension in $W \to \ell\nu$: $\frac{2\mathcal{B}(W\to\tau\bar{\nu}_\tau)}{\mathcal{B}(W\to e\bar{\nu}_e)+\mathcal{B}(W\to\mu\bar{\nu}_\mu)} = 1.066 \pm 0.025\ (2.6\sigma)$ (but uncertainties large, strong contraints from other measurements)
- Large number of BSM models with non-universal couplings to third generation quarks and leptons (Charged Higgs, Leptoquarks, ...).

Lepton Flavour Universality in heavy flavour decays

- Lepton universality tests in *tree-level* decays
  - Abundant $b \to c\ell\nu$ transition
  - Possible NP coupling mainly to 3rd family
  - $R_{D^*} = \frac{\mathcal{B}(B\to D^*\tau\nu)}{\mathcal{B}(B\to D^*\mu\nu)}$ from LHCb covered by [M. Tilley]



- Lepton universality tests in rare *loop-level* decays
  - $b \to s\ell\ell$ FCNC
  - Forbidden at tree-level in SM
  - Sensitive to NP contributions in loops



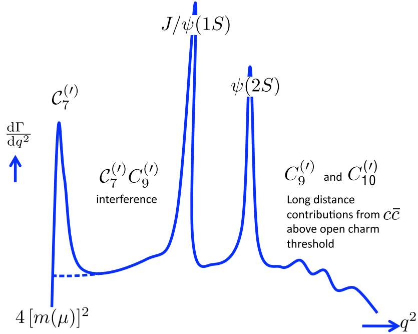
- Determine ratios $R_{K^{(*)}} = \frac{\int \frac{\mathrm{d}\Gamma(B\to K^{(*)}\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int \mathrm{d}\frac{\Gamma(B\to K^{(*)}e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2} \overset{\mathrm{SM}}{=} 1 \pm \mathcal{O}(10^{-3})$
  - Experimentally clean: cancellation of many systematic uncertainties
  - Theoretically clean: cancellation of hadronic uncertainties QED effects $\mathcal{O}(10^{-2})$ [Bordone et al., EPJC 76 (2018) 8:440]

Effective theory and $B \to K^{(*)}\ell\ell$ differential decay rate

Effective couplings in $b \to s\ell\ell$ transitions

	Wilson coefficient	Operator
γ-penguin[1]	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$
scalar	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$
pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$

[1] Not for $B^+ \to K^+\ell^+\ell^-$



- $b \to s\ell\ell$ transitions described model-ind. in eff. theory (Details: [A. Vicente])

Local operator

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \frac{e^2}{16\pi^2} \sum_i \boxed{\mathcal{C}_i} \boxed{\mathcal{O}_i}$$

Wilson coefficient ("effective coupling")

Flavour-violating coupling

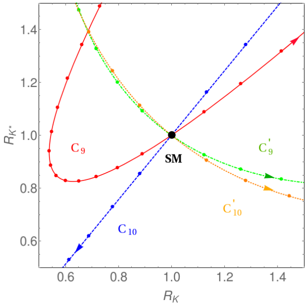
$$\Delta\mathcal{H}_{\text{NP}} = \frac{\boxed{\kappa}}{\boxed{\Lambda_{\text{NP}}^2}} \mathcal{O}_i$$

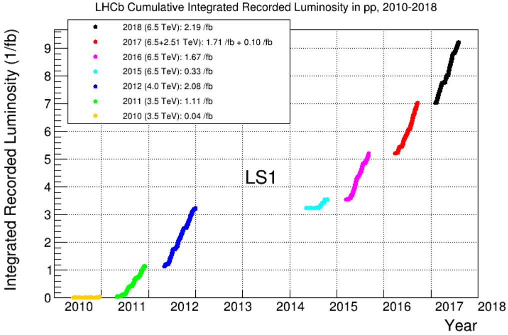
NP scale

- Different $q^2 = m^2(\ell\ell)$ regions probe different operator combinations

R_K and R_{K^*} at LHCb and data samples

[Geng et al., PRD 96 (2017) 093006]



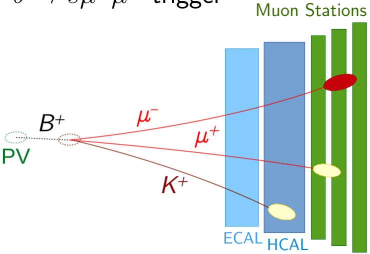


- Due to different spin R_K and R_{K^*} probe different combinations of Wilson coefficients
- Published LHCb measurements:

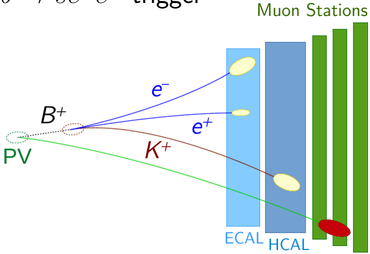
	q^2-region(s)	data
R_K [PRL 122 (2019) 191801]	$[1.1, 6.0]\,\mathrm{GeV}^2/c^4$	Run 1+2015+2016 ($5\,\mathrm{fb}^{-1}$)
R_{K^*} [JHEP 08 (2017) 055]	$[0.045, 1.1], [1.1, 6.0]\,\mathrm{GeV}^2/c^4$	Run 1 ($3\,\mathrm{fb}^{-1}$)

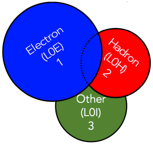
Trigger for muon and electron modes

$b \to s\mu^+\mu^-$ trigger



$b \to s e^+ e^-$ trigger





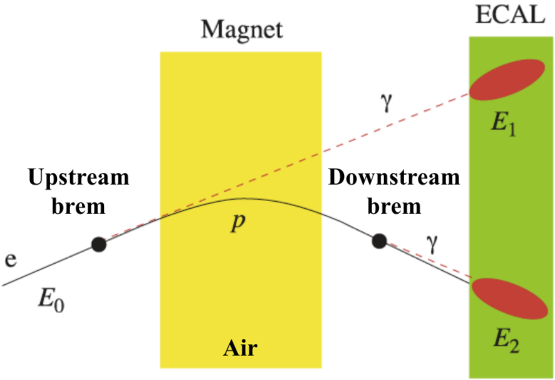
L0E: trigger fired on one of the electrons

L0H: trigger fired on the final state hadron(s)

L0I: trigger fired by other particles in the event

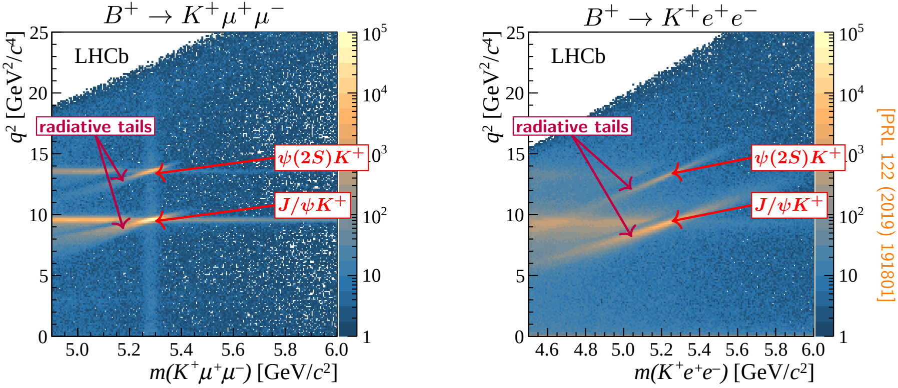
- Trigger signatures for muon and electron modes very different
- Lower p_{T} thresholds for muons $(1.5\text{–}1.8\,\mathrm{GeV}/c)$ compared to electrons $(2.5\text{–}3.0\,\mathrm{GeV})$ / hadrons $(3.5\,\mathrm{GeV}/c)$
  → lower trigger efficiency for e^+e^- modes
- Combine exclusive trigger categories to improve ϵ for electron modes

Bremsstrahlung



- Electrons heavily radiate Bremsstrahlung photons
- Correct electron momentum by adding matching photons ($E_{\mathrm{T}} > 75\,\mathrm{MeV}/c^2$) reconstructed in the ECAL
- Bremsstrahlung reconstruction impacts momentum resolution

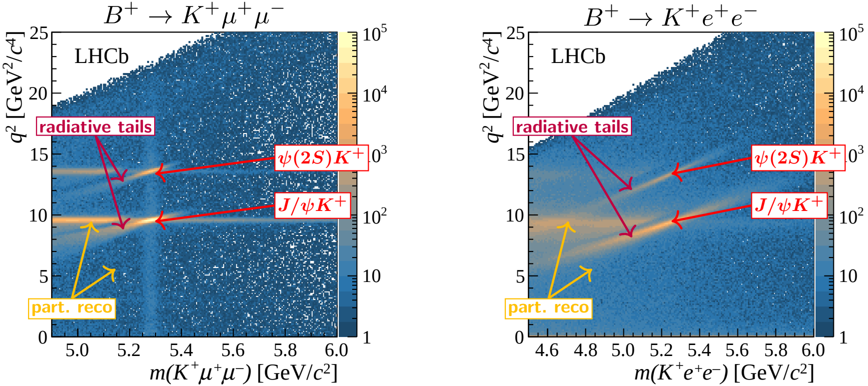
Electron reconstruction and mass resolution (R_K)



[PRL 122 (2019) 191801]

- Resolution degraded by energy loss from Bremsstrahlung
  - Recovery of Bremsstrahlung not 100% efficient
  - Recovery of Bremsstrahlung γ in ECAL has limited resolution $\frac{\sigma_E}{E} \sim 1\% \otimes \frac{10\%}{\sqrt{E(\text{ GeV})}}$
- Contribution from partially reconstructed backgrounds e.g. $B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$ where π^- is not reconstucted

Electron reconstruction and mass resolution (R_K)



[PRL 122 (2019) 191801]

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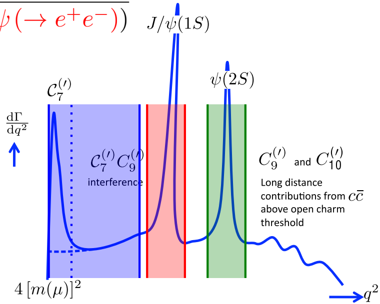
Analysis strategy: Double ratio

- Analysis strategy: Double ratio of rare $B \to K^{(*)}\ell^+\ell^-$ with resonant mode $B \to K^{(*)}J/\psi(\to \ell^+\ell^-)$:

$$R_{K^{(*)}} = \frac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to K^{(*)}J/\psi(\to\mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B\to K^{(*)}e^+e^-)}{\mathcal{B}(B\to K^{(*)}J/\psi(\to e^+e^-))}$$

$$= \frac{N_{B\to K^{(*)}\mu^+\mu^-}}{N_{B\to K^{(*)}J/\psi(\to\mu^+\mu^-)}} \times \frac{\epsilon_{B\to K^{(*)}J/\psi(\to\mu^+\mu^-)}}{\epsilon_{B\to K^{(*)}\mu^+\mu^-}}$$

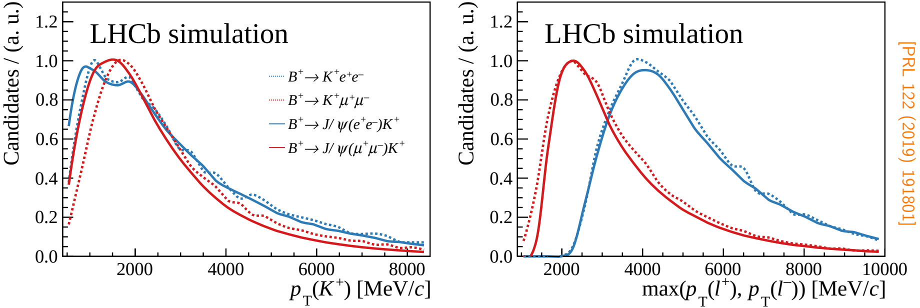
$$\times \frac{N_{B\to K^{(*)}J/\psi(\to e^+e^-)}}{N_{B\to K^{(*)}e^+e^-}} \times \frac{\epsilon_{B\to K^{(*)}e^+e^-}}{\epsilon_{B\to K^{(*)}J/\psi(\to e^+e^-)}}$$



- Double ratio cancels most experimental systematic effects
- Nevertheless crucial to control efficiencies

Efficiencies and double ratio

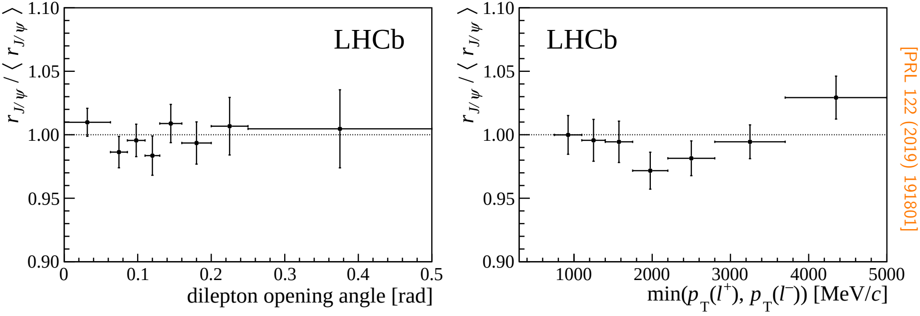
- Efficiencies corrected and controled using data-driven techniques
  - Trigger ϵ determined on data using control mode
  - Particle identification from high stat. samples (*e.g.* $D^{*0} \to \pi^+ D^-$)
  - B kinematics, mass resolution from control mode
- In lab frame rare and control mode similar due to large boost at LHCb



[PRL 122 (2019) 191801]

- Systematic effects largely cancel in efficiency ratio

Crosschecks $r_{J/\psi}$ and $R_{\psi(2S)}$



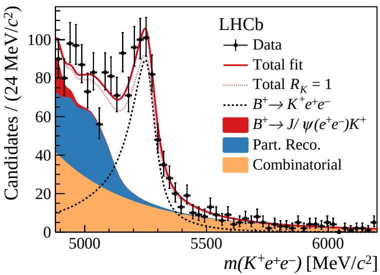
[PRL 122 (2019) 191801]

- Ratio $r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(\to e^+e^-))} = 1$ important cross-check for ϵs
- $r_{J/\psi}$ single ratio, differences in e/μ reconstruction do not cancel
- Integrated $r_{J/\psi} = 1.014 \pm 0.035$, flat and independent of kinematics
- Checked independently for Run 1 and Run 2
- Also checked double ratio

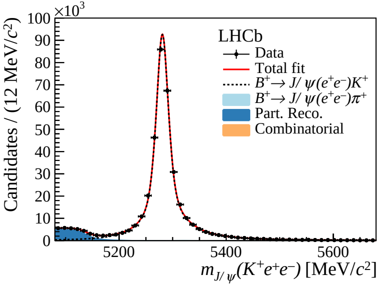
$$R_{\psi(2S)} = \frac{B^+ \to K^+ \psi(2S)(\to \mu^+\mu^-))}{B^+ \to K^+ J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{B^+ \to K^+ \psi(2S)(\to e^+e^-))}{B^+ \to K^+ J/\psi(\to e^+e^-))} = 0.986 \pm 0.013$$

Yields $B^+ \to K^+\ell\ell$

$N(B^+ \to K^+e^+e^-) = 766 \pm 48$

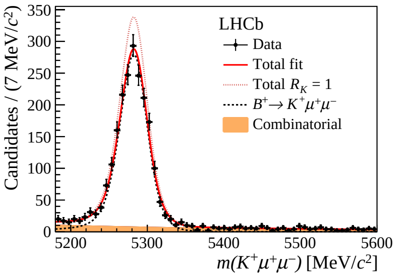


$N(B^+ \to K^+J/\psi(\to e^+e^-)) = 344\,100 \pm 610$

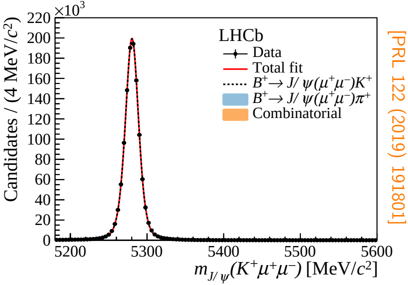


[PRL 122 (2019) 191801]

$N(B^+ \to K^+\mu^+\mu^-) = 1\,943 \pm 49$

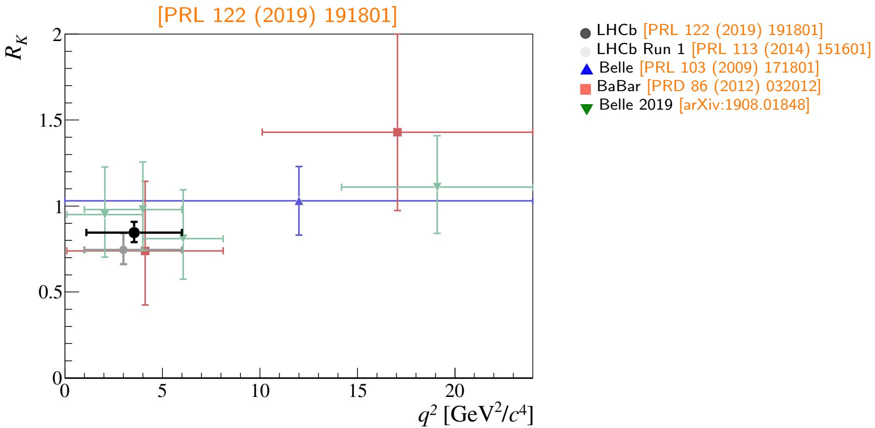


$N(B^+ \to K^+J/\psi(\to \mu^+\mu^-)) = 1\,161\,800 \pm 1\,100$



[PRL 122 (2019) 191801]

R_K results



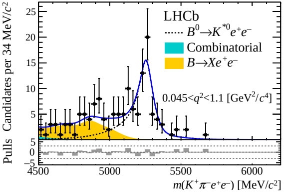
- $R_K(1 < q^2 < 6.0\,\mathrm{GeV}^2) = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}$ [PRL 122 (2019) 191801]

  $R_K(1 < q^2 < 6.0\,\mathrm{GeV}^2) = 0.745^{+0.090}_{-0.075} \pm 0.036$ [PRL 113 (2014) 151601]
- $2.5\,\sigma$ tension with SM prediction

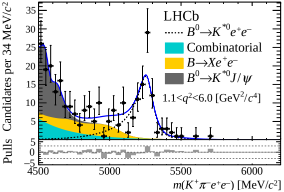
Yields $B^0 \to K^{*0}\ell\ell$

[JHEP 08 (2017) 055]

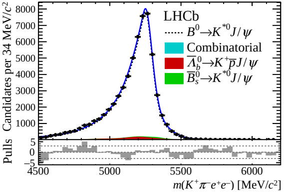
$B^0 \to K^{*0}e^+e^-$



Low q^2: 89 ± 11

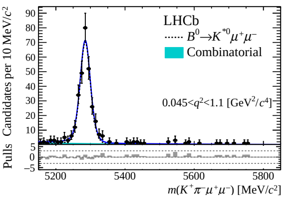


Central q^2: 111 ± 14

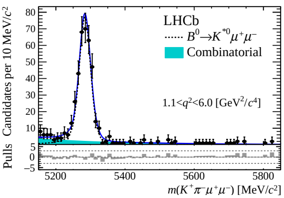


J/ψ: $58\,\mathrm{k}$

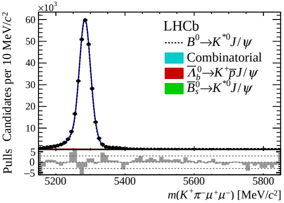
$B^0 \to K^{*0}\mu^+\mu^-$



Low q^2: 285 ± 18



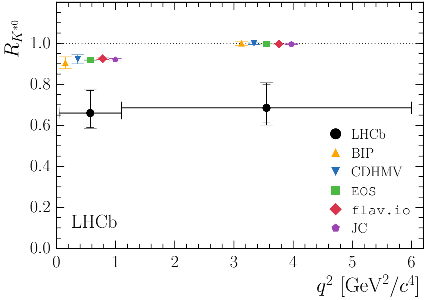
Central q^2: 353 ± 21

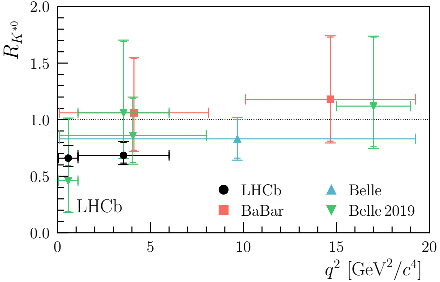


J/ψ: $274\,\mathrm{k}$

R_{K^*} Results

[JHEP 08 (2017) 055]





▲ BIP [EPJC 76 (2016) 440]
▼ CDHMV [JHEP 04 (2017) 016]
■ EOS [PRD 95 (2017) 035029]
◆ flav.io [EPJC 77 (2017) 377]
⬟ JC [PRD 93 (2016) 014028]

■ Babar [PRD 86 (2012) 032012]
▲ Belle [PRL 103 (2009) 171801]
▼ Belle 2019 [arXiv:1904.02440]

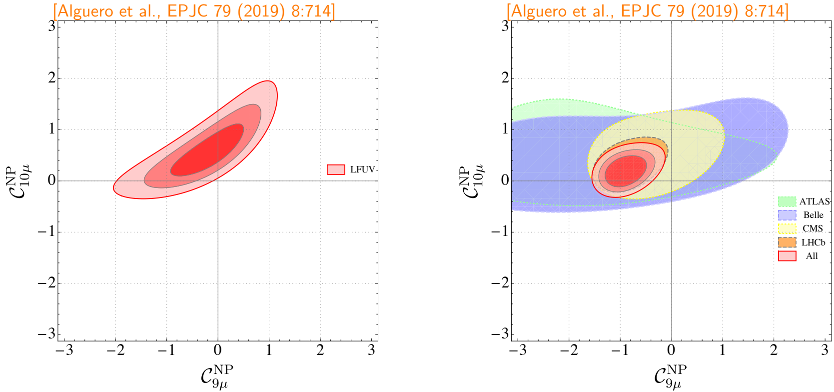
- Numerical result and compatibility with SM prediction(s):

$$R_{K^*}(0.045 < q^2 < 1.1\,\text{GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.03 \qquad 2.1\text{-}2.3\,\sigma \text{ at low } q^2$$

$$R_{K^*}(1.1 < q^2 < 6.0\,\text{GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05 \qquad 2.4\text{-}2.5\,\sigma \text{ at central } q^2$$

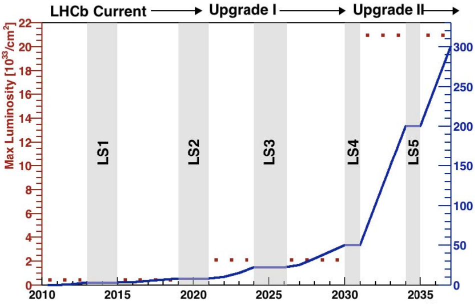
- Compatible with Babar and Belle with smaller uncertainties

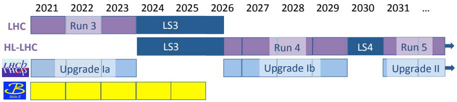
Combination of LFU observables

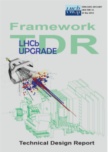


- Combine LFU observables in effective theory framework to determine Wilson coefficients (here: eff. Vector- and axialvector coupling $\mathcal{C}_9$ and $\mathcal{C}_{10}$)
- Combination of R_{K^*} and R_K shows tension with clean SM prediction at $3–4\,\sigma$ [Alguero et al., EPJC 79 (2019) 8:714]
- Inclusion of $b \to s\mu\mu$ $\mathcal{B}$ and angular obs. (details in talk by [F. Kress]) further increases significance $\gtrsim 5\,\sigma$

LFU prospects at LHCb

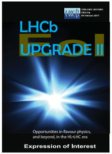





Framework TDR

LHCb UPGRADE

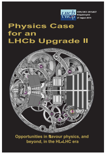
Technical Design Report


LHCb UPGRADE II

EoI

Opportunities in flavour physics, and beyond, in the HL-LHC era

Expression of Interest


Physics Case for an LHCb Upgrade II

Opportunities in flavour physics, and beyond, in the HL-LHC era

- Ongoing updates of R_K and R_{K^*} profit from full LHCb data sample
  - Full Run 2 R_K $\sim$ doubles available statistics wrt. [PRL 122 (2019) 191801]
  - Full Run 2 R_{K^*} $\sim$ quadruples available statistics wrt. [JHEP 08 (2017) 055]
- Additional measurements of R_{pK}, R_ϕ, $R_{K\pi\pi}$ soon
- $b \to s e^+ e^-$ angular analyses also ongoing
- LHCb Upgrade: $50\,\mathrm{fb}^{-1}$ of data after LS2 [Framework TDR]
- LHCb Upgrade II with $300\,\mathrm{fb}^{-1}$ planned [arXiv:1808.08865]

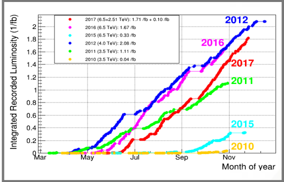
Conclusions

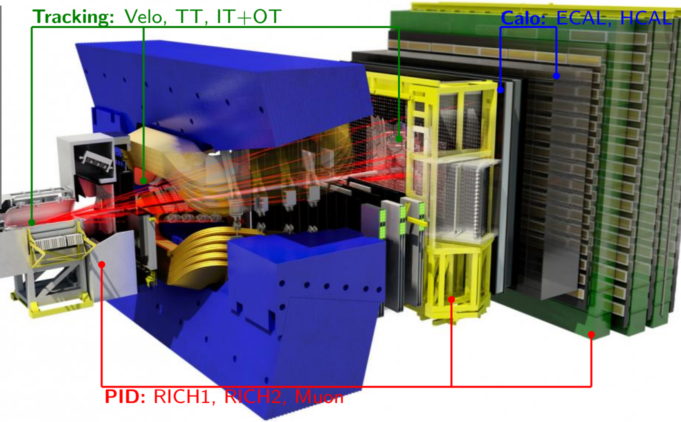
- Tests of LFU show interesting tensions with clean SM prediction
- Both R_K and R_{K^*} below SM prediction at $\sim 2\,\sigma$
- Combination yields tension of 3–$4\,\sigma$
- Similar anomalies in (less clean) $b \to s\mu^+\mu^-$ $\mathcal{B}$ and angular obs.
- Updates using full Run 2 data sample will clarify picture
- Additional modes (R_{pK}, R_{ϕ}, $R_{K\pi\pi}$,...) in preparation
- Please stay tuned!

Backup

The LHCb experiment: Optimized for heavy flavour

Run 1: $3\,\mathrm{fb}^{-1}$, 2015-2017: $3.8\,\mathrm{fb}^{-1}$

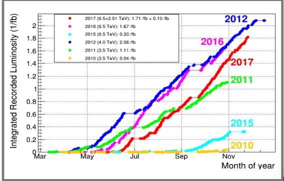




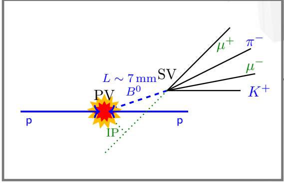
- Large $\sigma_{b\bar{b}}$: $(284 \pm 53)\,\mu\mathrm{b}$ at $7\,\mathrm{TeV}$ and $(495 \pm 52)\,\mu\mathrm{b}$ at $13\,\mathrm{TeV}$ [PLB 694 (2010) 209-216] [JHEP 10 (2015) 172]
- Excellent IP resolution $\sim 20\,\mu\mathrm{m}$ to identify B decay vertices, $\Delta p/p = 0.5 - 1\%$
- Particle identification: $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$ and $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1 - 3\%$
- Low trigger thresholds: $p_{\mathrm{T}}(\mu) > 1.8\,\mathrm{GeV}$, $E_{\mathrm{T}}(e) > 3.0\,\mathrm{GeV}$

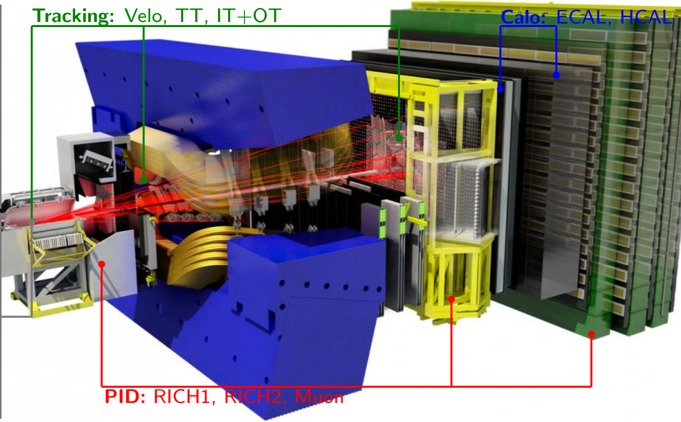
The LHCb experiment: Optimized for heavy flavour

Run 1: $3\,\mathrm{fb}^{-1}$, 2015-2017: $3.8\,\mathrm{fb}^{-1}$



Heavy flavour signature

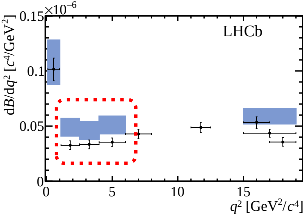




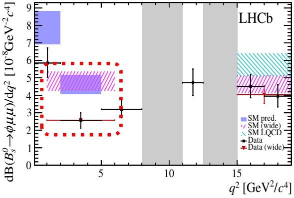
- Large $\sigma_{b\bar{b}}$: $(284 \pm 53)\,\mu\mathrm{b}$ at $7\,\mathrm{TeV}$ and $(495 \pm 52)\,\mu\mathrm{b}$ at $13\,\mathrm{TeV}$ [PLB 694 (2010) 209-216] [JHEP 10 (2015) 172]
- Excellent IP resolution $\sim 20\,\mu\mathrm{m}$ to identify B decay vertices, $\Delta p/p = 0.5 - 1\%$
- Particle identification: $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$ and $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1 - 3\%$
- Low trigger thresholds: $p_{\mathrm{T}}(\mu) > 1.8\,\mathrm{GeV}$, $E_{\mathrm{T}}(e) > 3.0\,\mathrm{GeV}$

Branching fractions of rare $b\to s\mu^+\mu^-$ decays

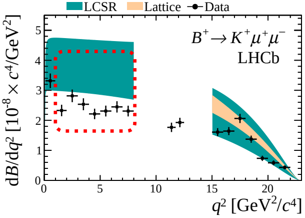
LHCb $B^0\to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



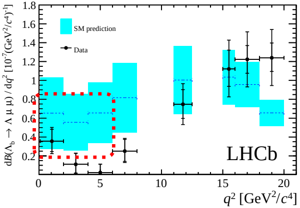
LHCb $B_s^0\to\phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



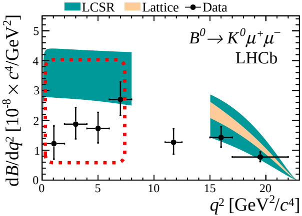
LHCb $B^+\to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



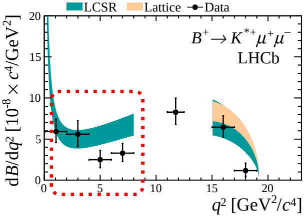
$\Lambda_b^0\to\Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



LHCb $B^0\to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]



$B^+\to K^{*+}\mu^+\mu^-$ [JHEP 06 (2014) 133]



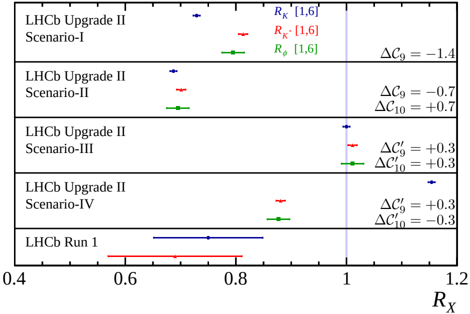
- Pattern: Data consistently below SM predictions
- But sizeable hadronic theory uncertainties
- Tensions at $1-3\,\sigma$ level

Prospects summary

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_\mathrm{S}^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_sl^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x\sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_\mathrm{S}^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Upgrade II expectations for R_X ratios

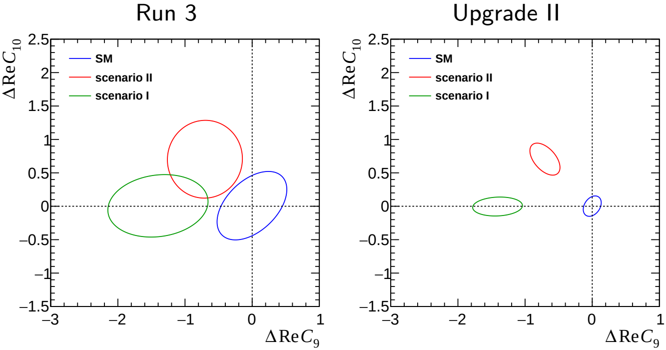


[Upgrade II Physics case] [Physics of the HL-LHC WG 4]

Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	300 fb^{-1}
$B^+ \to K^+e^+e^-$	254 ± 29	1120	3300	46000
$B^0 \to K^{*0}e^+e^-$	111 ± 14	490	1400	20000
$B_s^0 \to \phi e^+e^-$	–	80	230	3300
$\Lambda_b^0 \to pKe^+e^-$	–	120	360	5000
$B^+ \to \pi^+e^+e^-$	–	20	70	900
R_X precision	Run 1 result	9 fb^{-1}	23 fb^{-1}	300 fb^{-1}
R_K	$0.745 \pm 0.090 \pm 0.036$	0.043	0.025	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$	0.052	0.031	0.008
R_ϕ	–	0.130	0.076	0.020
R_{pK}	–	0.105	0.061	0.016
R_π	–	0.302	0.176	0.047

- Huge samples of rare electron modes available in Upgrade II $N_{K^+e^+e^-} \sim 46\,000$, $N_{K^{*0}e^+e^-} \sim 20\,000$
- Ultimate precision on R_{K,K^*} will be better than 1%
- Different R_X allow to probe different combinations of Wilson coefficients, separation of NP scenarios with high significance

Angular analyses with electrons



[Upgrade II Physics case]

Scenario	$\Delta\mathcal{C}_9^{\mu\mu}$	$\Delta\mathcal{C}_{10}^{\mu\mu}$
SM	0	0
I	-1.4	0
II	-0.7	$+0.7$

- Differences between angular observables in electrons and muons theoretically clean, simultaneous fit useful
- Sensitivity to additional combinations of Wilson coefficients compared to R_X measurements
- Excellent NP sensitivity unaffected by hadronic contributions