Status and future prospects of Lepton Universality tests at LHCb

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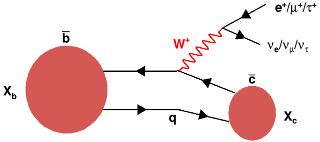
Lepton Flavour Universality

- SM is Lepton flavour universal
  - Electroweak couplings to all charged leptons are universal
  - Difference between e, μ and τ driven only by mass
- LFU tests with ratios of branching fractions of decays involving different $\ell = e, \mu, \tau$

- In $b \to c\ell\nu_\ell$ transitions:

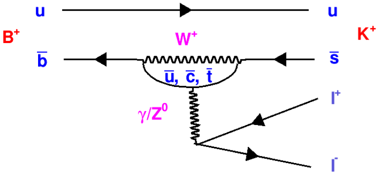
$$R(X_c) = \frac{\mathcal{B}(X_b \to X_c \tau^+ \nu_\tau)}{\mathcal{B}(X_b \to X_c \ell \nu_\ell)}$$



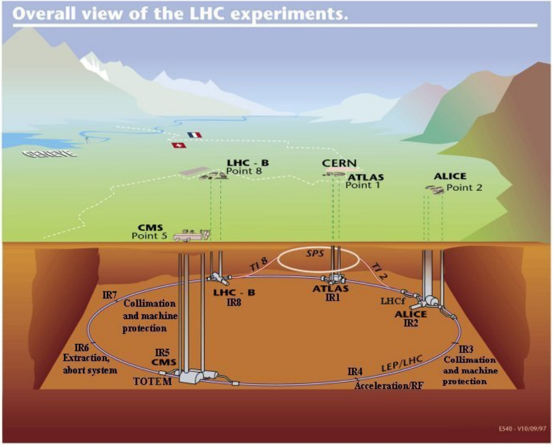
- In $b \to s\ell\ell$ transitions:

$$R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^{*0} e^+ e^-)}$$

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$

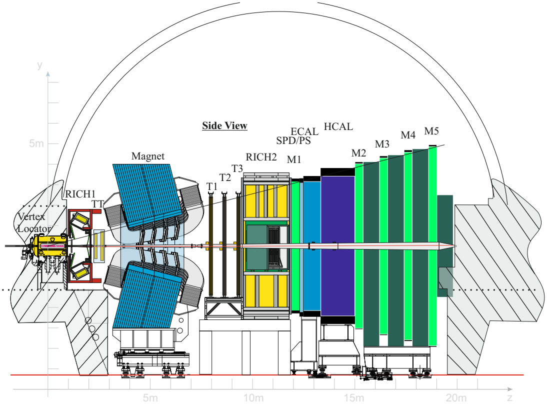


LHCb experiment



- LHCb is one of the experiments based at LHC, CERN, Geneva
- Forward spectrometer with a broad physics programme including beauty, charm and top quarks, heavy ions, electro-weak physics, Higgs physics,...

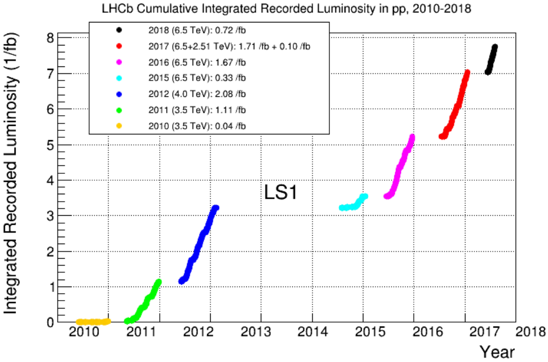
LHCb experiment



- Excellent vertex resolution (10 – 40 μm in xy-plane and 50 – 300 μm in z-axis)
- Particle identification efficiencies 80% – 95% for correct kaon and 3% – 10% misidentification of pion as kaon

JINST 3 (2008) S08005, Nucl. Phys. B 871 (2013) 1-20, JHEP 74 (2017)

LHCb experiment

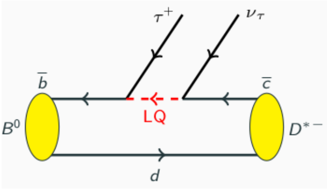


Period	Integrated luminosity	$\sqrt{s}$	Number of $b\bar{b}$
Run1 2011-2012	$3.2\,\text{fb}^{-1}$	7-8 TeV	2.5×10^{11}
Run2 2015-2016	$2.0\,\text{fb}^{-1}$	13 TeV	2.9×10^{11}
Run2 2017-2018	$3.9\,\text{fb}^{-1}$	13 TeV	5.7×10^{11}

$b \to c\ell\nu_\ell$ transitions

$R(X_c)$ measurements

- Tree-level semileptonic decays
- Uncertainties related to Form Factor normalizations *mostly* cancel in the ratio
- Ratios sensitive to possible enhanced coupling to the 3rd generation (*e.g.* Leptoquarks[1]) predicted by some NP models

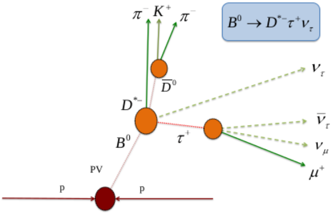


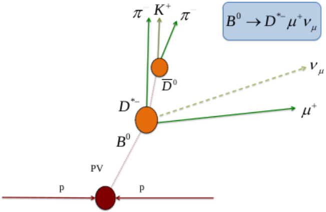
[1] PRL 116, 081801, PRD 94, 115201

$R(X_c)$ measurements at LHCb

- LHCb Run 1 data : 3 fb^{-1}, 2011-12
- Neutrinos not detected; approximation needed for B reconstruction
- Measurements with muonic τ decays
  - $\tau^- \to \mu^- \nu_\mu \nu_\tau$
  - $R(D^*)$ and $R(J/\psi)$ measurements
  - Same visible final state $X_c \mu^+$
- Measurements with hadronic τ decays
  - $\tau^- \to \pi^+ \pi^- \pi^- (\pi^0) \nu_\tau$ 3-prong decays
  - $R(D^*)$ measurement

$R(D^*)$ muonic at LHCb [PRL **115**, 111803 (2015)]





$$R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu)}{\mathcal{B}(B \to D^*\mu\nu)}.$$

- B reconstruction with the approximation

$$(p_B)_z = \frac{m_B}{m_{reco}}(p_{reco})_z$$

- Separate τ and μ via 3D binned template fit to kinematic variables
  - $q^2 = (p_B - p_{D^*})^2$
  - $m^2_{\text{miss}} = (p_B - p_{D^*} - p_\ell)^2$
  - $E^*_{\mu^+}$, muon energy

$R(D^*)$ muonic at LHCb [PRL **115**, 111803 (2015)]

- Backgrounds with additional charged tracks rejected using BDT
- Main remaining backgrounds:
  - $B \to D^{**}\mu\nu$, $B \to D^{**}\tau\nu$
  - $B_s \to D_s\mu\nu$
  - $B \to D^{*+}H_cX$, where H_c decays semileptonically
  - combinatorial - wrong-sign final state combinations
  - Hadrons (π, K, p) misidentified as muons
- Binned maximum likelihood fit with 3D templates of signal, normalization and background sources
- Signal and background shapes extracted from control samples and simulations validated against data

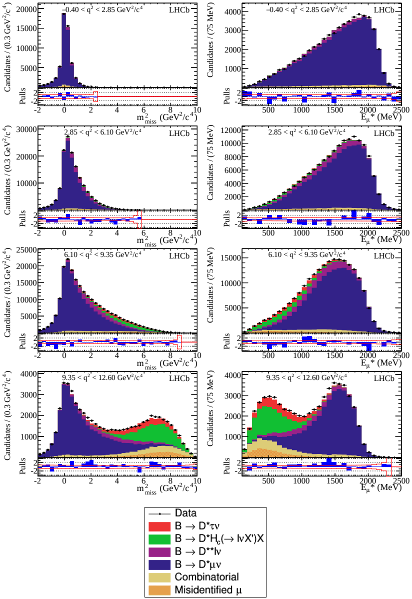
$R(D^*)$ muonic at LHCb [PRL **115**, 111803 (2015)]

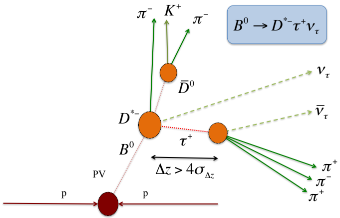
- The fit extracts the relative contributions of signal and normalization modes and their form factors
- Signal more visible in the high q^2 bin

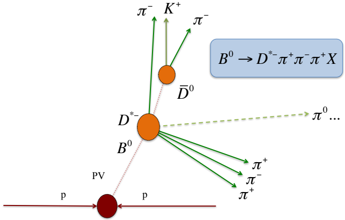
$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

2.1σ above SM

- Dominant systematic uncertainty - size of simulation sample



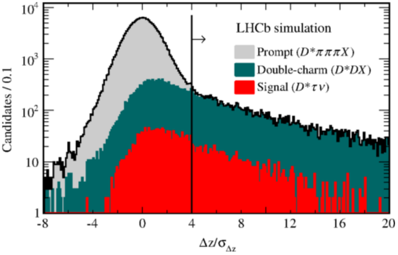


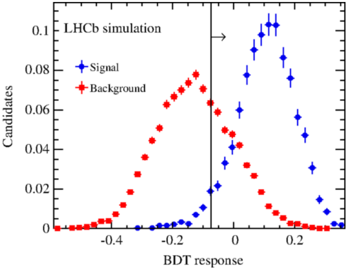


- Three-prong decays $\tau^+ \to 3\pi^\pm(\pi^0)\overline{\nu}_\tau$

$$R(D^*) = \mathcal{K}(D^*)\frac{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}{\mathcal{B}(B^0 \to D^{*-}\ell\nu_\ell)} \qquad \mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}$$

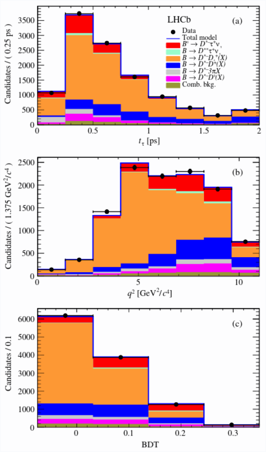
- Same visible final state for the normalization mode $B^0 \to D^{*-}3\pi^\pm$
- Main backgrounds
  - $B \to D^{*-}3\pi^\pm X$
  - Double charm $(B \to D^{*-}(D_s^+, D^+D^0)X)$





- $B \to D^{*-}3\pi^{\pm}X$ suppressed by requiring the τ vertex to be downstream w.r.t B vertex along the beam direction
- $\Delta z > 4\sigma_{\Delta z}$ improves S/B by 160
- A BDT based on kinematics and resonant structure to suppress $B \to D^{*-}D_s^{+}X$

- A 3D binned template fit to extract the signal yield
  - $q^2 \equiv |P_{B^0} - P_{D^*}|^2$,
  - τ^+ decay time,
  - Output of BDT trained to discriminate τ from D_s^+.
- Templates selected from simulation and data control samples
- $N(B^0 \to D^{*-}\tau^+\nu_\tau) = 1296 \pm 86$

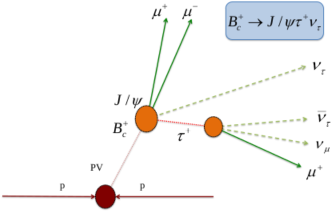


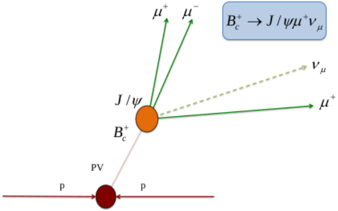
$$R(D^*) = 0.280 \pm 0.018(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{ext})^*$$

1σ above SM

*Latest value after rescaling the updated value of $\mathcal{B}(B^0 \to D^{*-}\ell\nu_\ell)$

$R(J/\psi)$ at LHCb [PRL **120**, 121801 (2018)]





$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$$

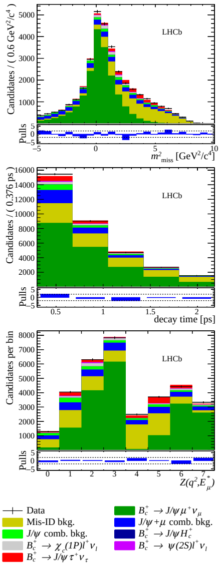
- Muonic τ final state
- Form factors directly from data
- Signal extraction using binned template fit to m^2_{miss}, B_c decay time and Z,
  - Z contains 8 bins in E_μ and q^2 (first 4 bins with $q^2 < 7.14$ GeV^2, the rest $q^2 > 7.14$ GeV^2)

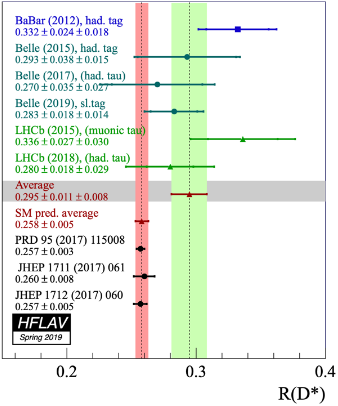
- Component shapes are derived from control samples or simulations validated against data
- Main backgrounds - $B_c \to H_c X$, hadron mis-ID for μ
- First evidence for the decay mode (3σ)

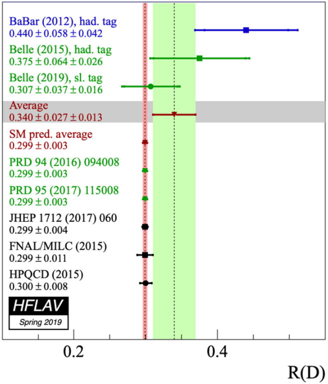
$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$$

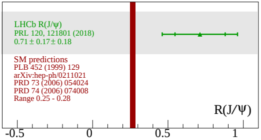
2σ above SM

- Main systematics - form factor and size of simulation sample



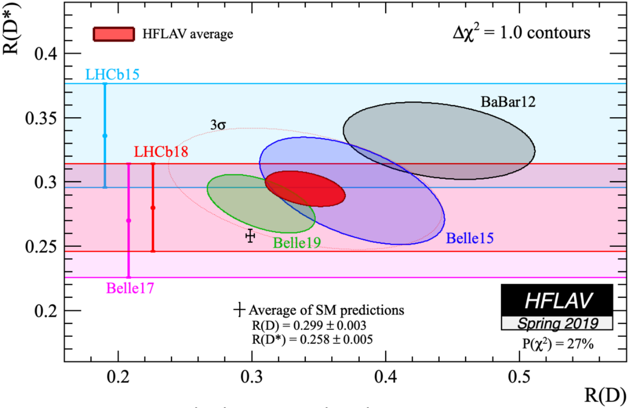






- **All** $R(X_c)$ measurements so far have central values above SM expectation

$R(D) - R(D^*)$



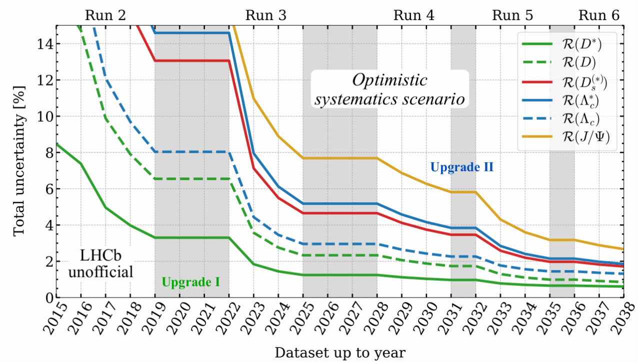
- Combination of $R(D)$ and $R(D^*)$ is 3.1σ from SM
  - **increase to 3.8σ** with latest SM prediction from LCSR + LQCD + UB + HQET[2]

$$R(D)_{SM} = 0.2989 \pm 0.0032;\ R(D^*)_{SM} = 0.2472 \pm 0.0050$$

[2] M. Bordone, N. Gubernari, M. Jung, D. van Dyk, EPJC **80**,347 (2020),1912.09335

Ongoing analyses

- $R(D^{+})$
- $R(D^{*})$ - $(e-\mu)$
- Combined $R(D^{*})-R(D^{0})$ measurement
- $R(D^{**})$
- $R(D_s^{*})$
- $R(J/\psi)$
- $R(\Lambda_c^{(*)})$



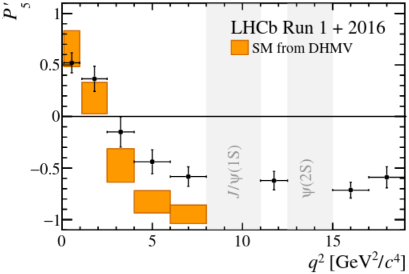
arXiv:2101.08326, arXiv:1808.08865

- Exploring new observables beyond the branching fraction ratios, *e.g.* angular observables to determine spin structure of potential NP
  - $B\to D^{*}\mu(\tau)\nu$ - muonic and hadronic

$b \to s\ell\ell$ transitions

Anomalies in $b \to s\ell\ell$ transitions

- Several deviations seen in branching fractions and angular observables
- Hadronic effects largest contributor to the theoretical uncertainties



PRL 125 011802 (2020)

- BF and angular observables potentially suffer from underestimated hadronic effects
- Ratios between decays to different leptons very well predicted

$$R_H = \frac{\mathcal{B}(H_B \to H\mu^+\mu^-)}{\mathcal{B}(H_B \to He^+e^-)} = 1.00 \pm 0.01^{[3]}$$

- Deviations would point towards NP!

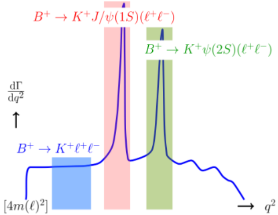
[3] JHEP 06 (2016) 092, EPJC 76 (2016) 440

$R_{K^{(*)}}$ measurements at LHCb

- At LHCb, we measure the double ratios

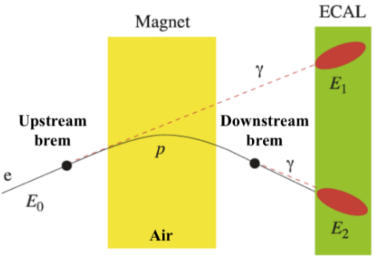
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \bigg/ \frac{\mathcal{B}(B \to J/\psi(\mu^+\mu^-)K^{(*)})}{\mathcal{B}(B \to J/\psi(e^+e^-)K^{(*)})}$$

- Better control of efficiency in double ratio with control mode
- Cancellation of most experimental systematics
- Detector efficiencies from simulation are calibrated with control channels in data
- Define three regions
    - Rare mode ($1.1 < q^2 < 6.0$ GeV^2)
    - Control mode, dominated by J/ψ resonance
    - $\psi(2S)$ mode



LFU electrons vs muons

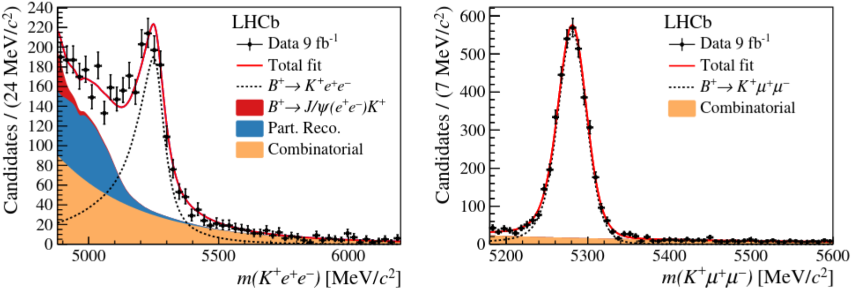
- Electrons are light, scatter more in detector ⇒ Bremsstrahlung emission



- Recover the energy loss by adding photon cluster energy compatible with electron direction, to the electron momentum

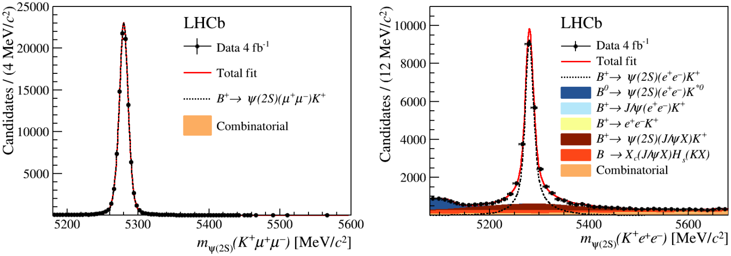
R_K measurement at LHCb [arXiv:2103.11769 [hep-ex]]

- In fits to the rare mode, R_K extracted as fit parameter



- Relative efficiencies gaussian constraints in fit
- Fit model dominant systematics ($\sim 1\%$)

- Fit crosschecks in J/ψ and $\psi(2S)$ regions to validate the procedure
- No expected LFU violation effects
- Tests control of electron vs muon efficiencies in J/ψ region
  - $r_{J/\psi} = 0.981 \pm 0.020$
  - $R_{\psi(2S)} = 0.997 \pm 0.011$



R_K measurement at LHCb [arXiv:2103.11769 [hep-ex]]

- Updated R_K at LHCb with 9 fb^{-1} is

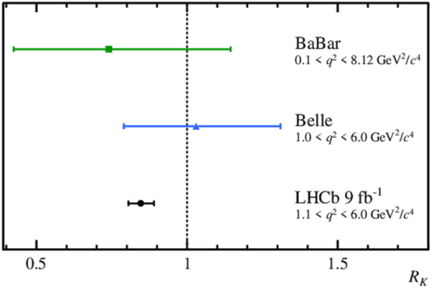
$$R_K(1.1 < q^2 < 6.0\text{GeV}^2) = 0.846^{+0.042}_{-0.039}(\text{stat.})^{+0.013}_{-0.012}(\text{syst.})$$

- Significance 3.1σ w.r.t SM

- **Evidence of LFU violation in $B^+ \to K^+\ell^+\ell^-$ decays!**

[BaBar - PRD 86 03 (2012)]

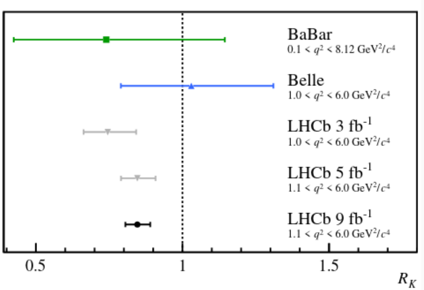
[Belle - JHEP 03 (2021) 105]



LFU measurements at LHCb

R_K in $B^+ \to K^+\ell^+\ell^-$

arXiv:2103.11769 [hep-ex]

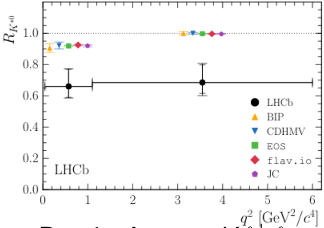


Evidence of LFU violation at 3.1σ

Updated measurements underway

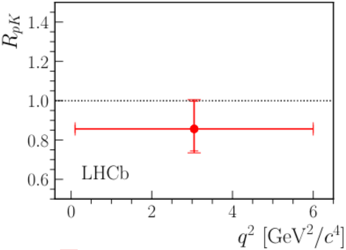
R_{K^*} in $B^0 \to K^{*0}\ell^+\ell^-$

JHEP 08 (2017) 055



R_{pK} in $\Lambda_b \to pK\ell^+\ell^-$

JHEP 05 (2020) 040



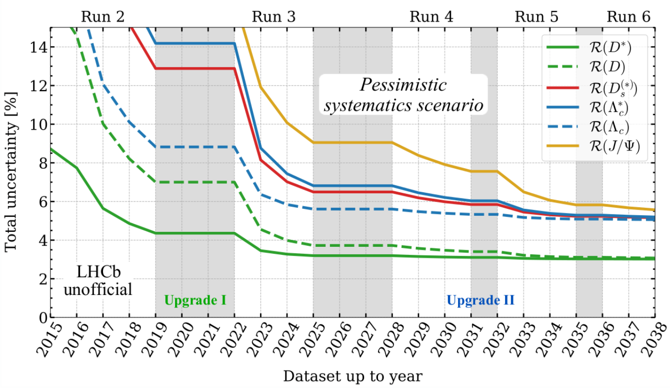
Tensions upto 2.5σ

Summary and prospects

- Discrepancies observed in behaviour of leptons in B decays
- Tensions seen in $b \to c\ell\nu_\ell$ decays
- Evidence of LFU violation at 3.1σ in $b \to s\ell\ell$ decays
- Many new measurements and updates underway at LHCb
- LHCb Run 3 will start very soon and expect to collect 25 fb^{-1}
- Interesting times ahead!

thank you!

Back up slides


Run 2
Run 3
Run 4
Run 5
Run 6
Total uncertainty [%]
Dataset up to year
Pessimistic
systematics scenario
LHCb
unofficial
Upgrade I
Upgrade II
$\mathcal{R}(D^*)$
$\mathcal{R}(D)$
$\mathcal{R}(D_s^{(*)})$
$\mathcal{R}(\Lambda_c^*)$
$\mathcal{R}(\Lambda_c)$
$\mathcal{R}(J/\Psi)$