

Lepton Universality tests using semileptonic b -hadron decays

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(on behalf of the LHCb Collaboration)

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Lepton Flavour Universality

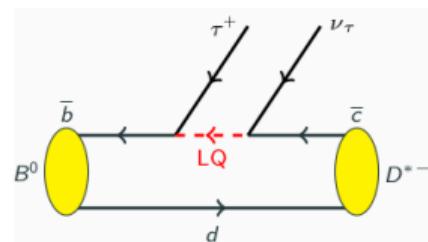
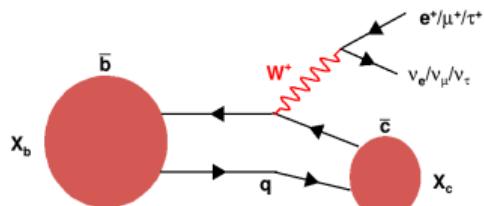
- In the Standard Model (SM), electroweak couplings to all charged leptons are universal; difference between e, μ and τ driven only by mass
- LFU tests with ratios of branching fractions of decays involving different $\ell = e, \mu, \tau$
- In $b \rightarrow c\ell^\pm\nu_\ell^{(-)}$ transitions (tree-level semileptonic decays):

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

$$X_b = B^0, B_s^+, B_s^0, \Lambda_b, \dots \quad X_c = D, D^*, D_s, \Lambda_c, \dots$$

- Ratios sensitive to possible enhanced coupling to the 3rd generation (e.g. Leptoquarks) predicted by some models involving physics beyond SM

[PRL 116, 081801, PRD 94, 115201]



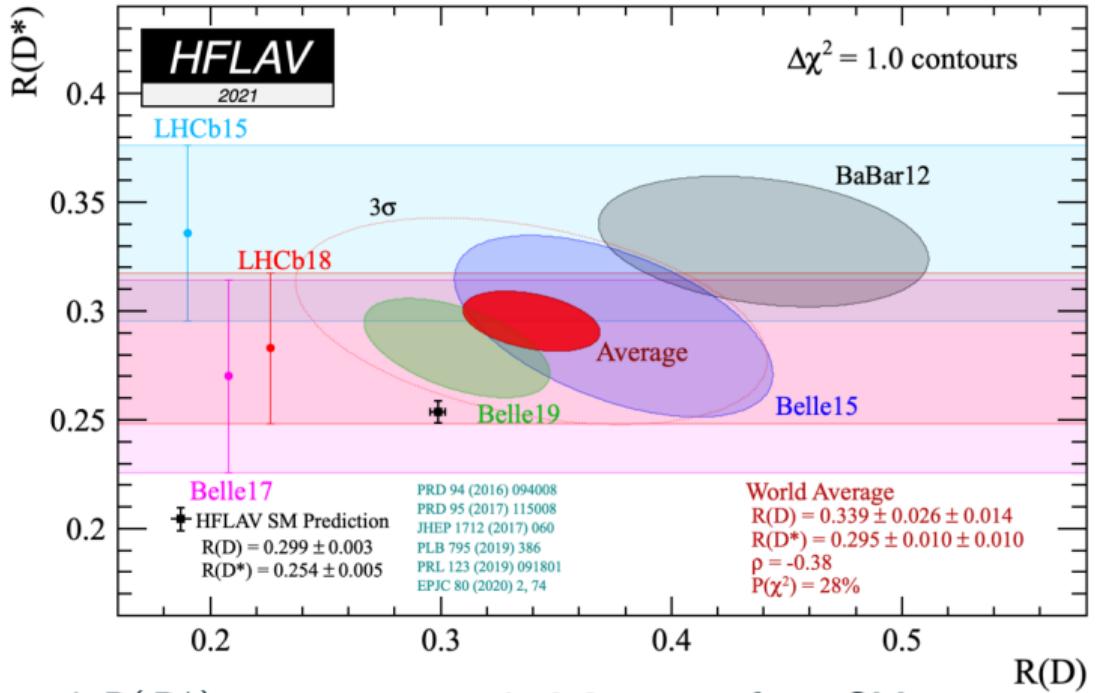
$$R(D) - R(D^*)$$

$$R(D) = \frac{\mathcal{B}(B^0 \rightarrow D\tau^+\nu_\tau)}{\mathcal{B}(B^0 \rightarrow D\ell\nu_\ell)}$$

$$R(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^*\tau^+\nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^*\ell\nu_\ell)}$$

$\ell = e, \mu$ for B-factories

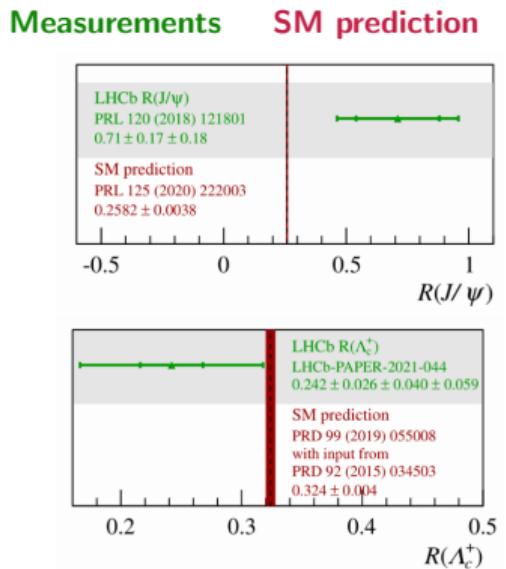
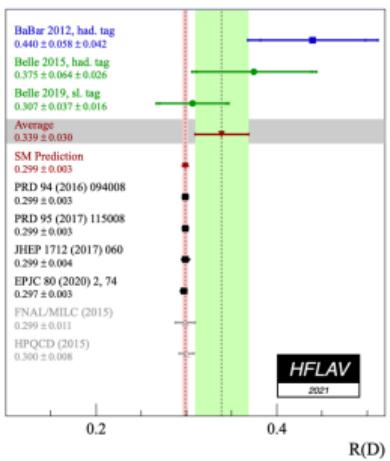
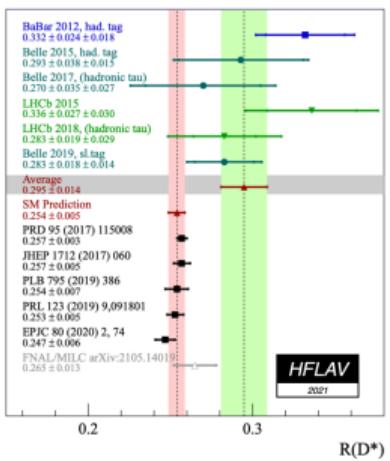
$\ell = \mu$ for LHCb



- Combination of $R(D)$ and $R(D^*)$ measurements is 3.3σ away from SM predictions!

$R(X_c)$ measurements

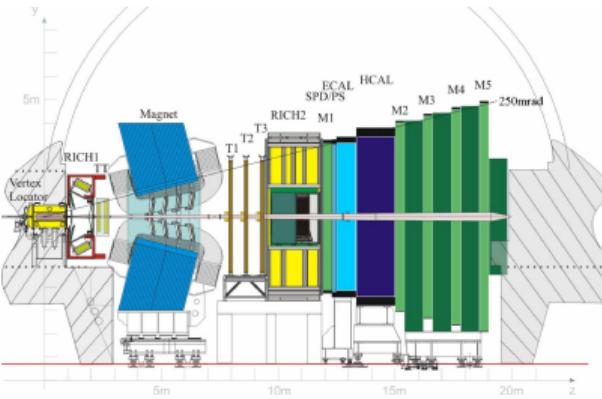
- More than 10 measurements from the B -factories and LHCb
- Different approaches and techniques



- Deviations seen between the measurements and SM predictions!
- Details of $R(X_c)$ measurements at LHCb \Rightarrow in this talk

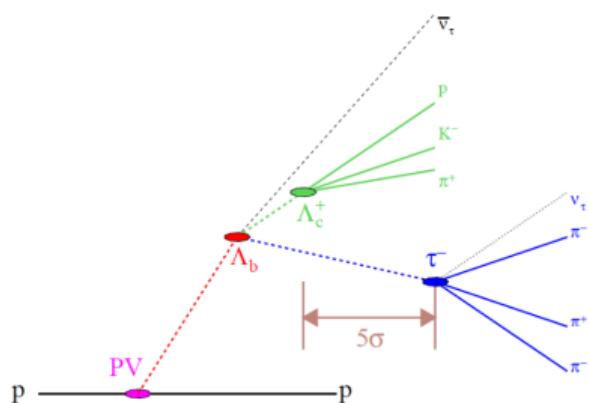
LFU ratios measured at LHCb

- $R(D^*)$ with $B^0 \rightarrow D^{*-} \ell^+ \nu_\ell$
- $R(J/\psi)$ with $B_c^+ \rightarrow J/\psi \ell^+ \nu_\ell$
- $R(\Lambda_c)$ with $\Lambda_b^0 \rightarrow \Lambda_c^+ \ell^- \bar{\nu}_\ell$
- LHCb Run 1 data: 3 fb^{-1} , collected during 2011-12
- Neutrinos not detected; approximations used for signal reconstruction
- Two τ decay modes reconstructed:
 - **Muonic** τ decays: $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$
 - **Hadronic** τ decays: $\tau^- \rightarrow \pi^+ \pi^- \pi^- (\pi^0) \nu_\tau$



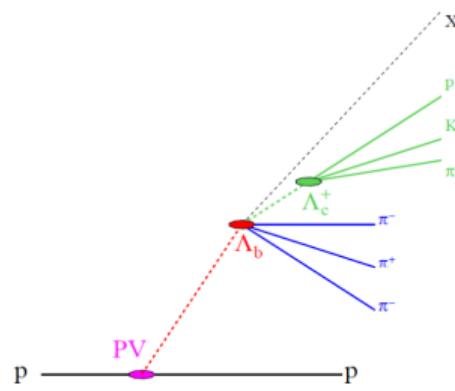
- First LFU test in a baryonic $b \rightarrow c\ell\nu$ decay Run 1: 3 fb^{-1}
- Initial state spin $\frac{1}{2}$ \Rightarrow could couple to different physics beyond SM
- Three-prong hadronic decays $\tau^- \rightarrow \pi^+ \pi^- \pi^- (\pi^0) \nu_\tau$

$$\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau$$



$$\mathcal{K}(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi)}$$

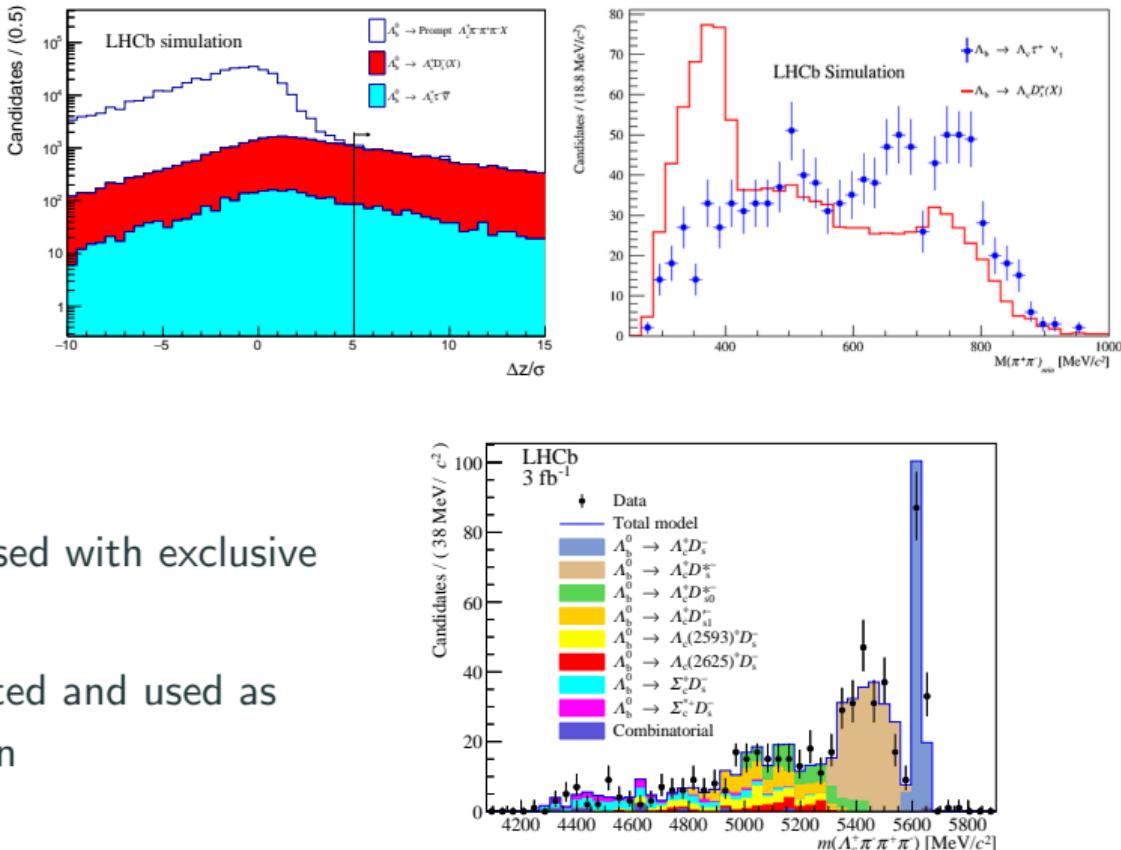
$$\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi$$



$$R(\Lambda_c^+) = \mathcal{K}(\Lambda_c^+) \left\{ \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu)} \right\} \text{ext. input}$$

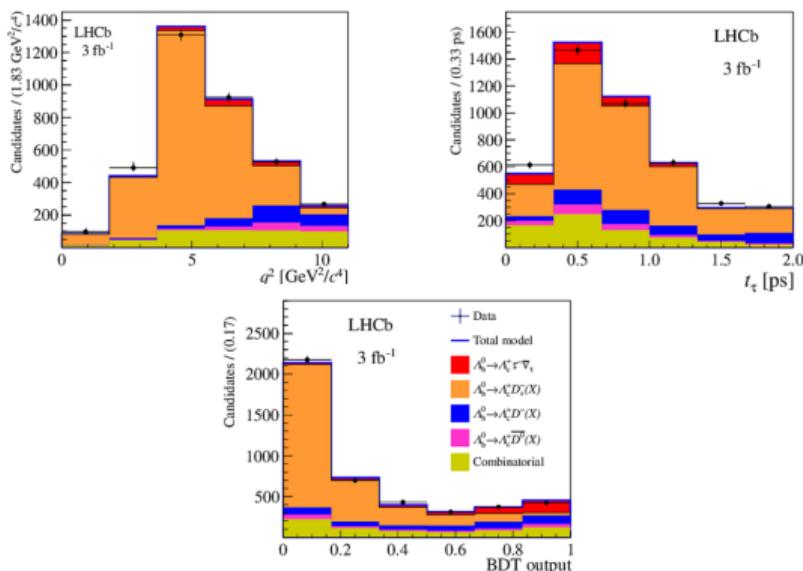
Main sources of backgrounds:

- $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi\pi\pi X$
 - suppressed using displaced τ vertex
- $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s (\rightarrow \pi\pi\pi X)$
 - suppressed using a BDT exploiting τ decay dynamics
- $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s (\rightarrow \pi\pi\pi X)$ analysed with exclusive control samples
- Different fractions are estimated and used as constraints in signal extraction

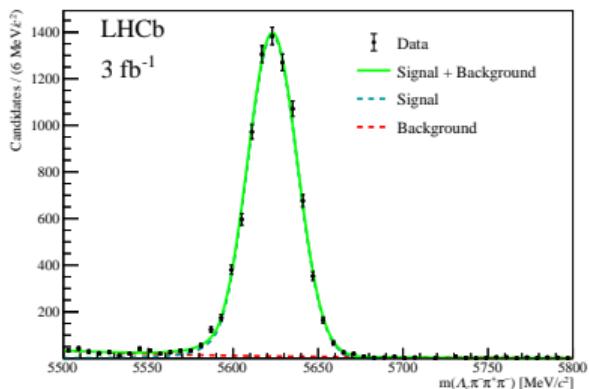


$R(\Lambda_c)$ at LHCb [PRL 128, 191803 (2022)]

- Signal yield extracted from fit to $q^2 \equiv (p_{\Lambda_b} - p_{\Lambda_c})^2$, τ^+ decay time and BDT output
- $$\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau$$



- $\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi$ yield extracted from fit to $\Lambda_c^+ 3\pi$ invariant mass
- $$\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi$$



- $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau$ yield = 346 ± 40
- $\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi$ yield = 8584 ± 102

First observation of the mode $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau$ with **6σ** significance

- $\mathcal{K}(\Lambda_c^+) = 2.46 \pm 0.27 \text{ (stat)} \pm 0.40 \text{ (syst)}$
- Dominant source of systematic uncertainty is double charm background template shapes
- $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau)$ is measured as $(1.50 \pm 0.16 \text{ (stat)} \pm 0.25 \text{ (syst)} \pm 0.23 \text{ (ext)})\%$

Systematic uncertainties

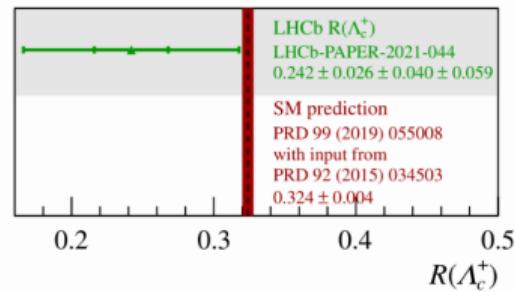
Source	$\delta \mathcal{K}(\Lambda_c^+)/\mathcal{K}(\Lambda_c^+)[\%]$
Simulated sample size	3.8
Fit bias	3.9
Signal modelling	2.0
$\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau$ feeddown	2.5
$D_s^- \rightarrow 3\pi Y$ decay model	2.5
$\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- X$, $\Lambda_b^0 \rightarrow \Lambda_c^+ D^- X$, $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 X$ background	4.7
Combinatorial background	0.5
Particle identification and trigger corrections	1.5
Isolation BDT classifier and vertex selection requirements	4.5
D_s^- , D^- , \bar{D}^0 template shapes	13.0
Efficiency ratio	2.8
normalization channel efficiency (modelling of $\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi$)	3.0
Total uncertainty	16.5

$$R(\Lambda_c^+) = 0.242 \pm 0.026 \text{ (stat)} \pm 0.040 \text{ (syst)} \pm 0.059 \text{ (ext)}$$

SM prediction $R(\Lambda_c^+) = 0.324 \pm 0.004$

[Bernlochner *et al.* PRD 99 055008 (2019)]

Agreement within 1σ



$R(\Lambda_c)$ at LHCb - new interpretation [arXiv:2206.11282]

- $R(\Lambda_c^+)$ obtained with $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c \mu \bar{\nu})$ as external input taken from a PDG fit incorporating a measurement from DELPHI
- The PDG fit might not incorporate potentially important corrections or correlations
- Robust and precise way is to calculate SM prediction for $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c \mu \bar{\nu})$ and in turn obtain $R(\Lambda_c^+)$ - [Bernlochner et al. arXiv:2206.11282]
- This reduces the significance of a hint for a suppression of $R(\Lambda_c^+)$
- The fraction of excited states in inclusive Λ_b decays greater than in B decays \Rightarrow more experimental and theoretical insights needed!

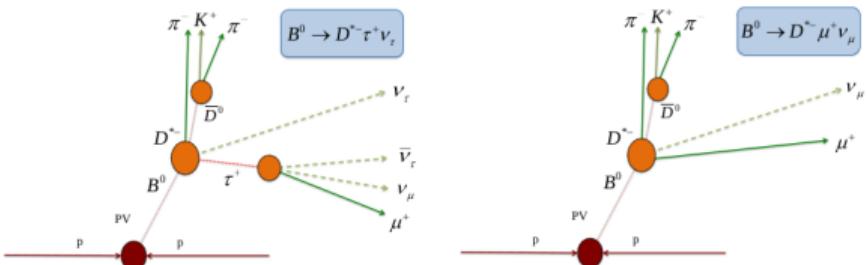


$R(D^*)$ muonic at LHCb [PRL 115, 111803 (2015)]

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

Muonic $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$

Run 1: 3 fb^{-1}



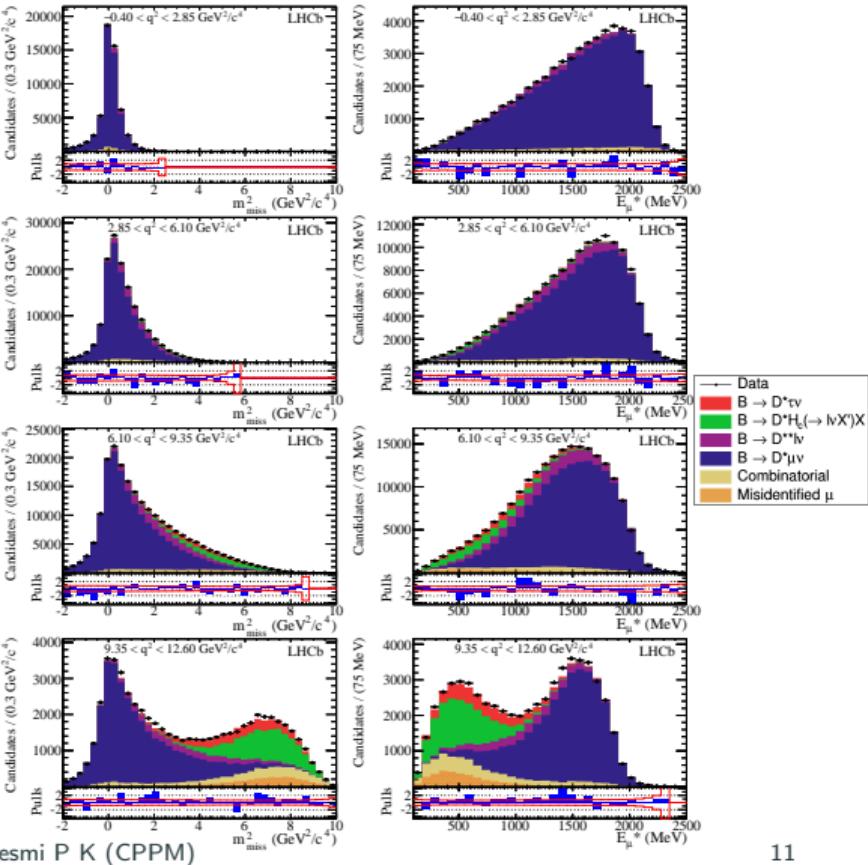
- Separate τ and μ via 3D binned template fit to kinematic variables
 - $q^2 \equiv (p_B - p_{D^*})^2$
 - $m_{\text{miss}}^2 = (p_B - p_{D^*} - p_\ell)^2$
 - $E_{\mu^+}^*$, muon energy
- Main sources of backgrounds:
 - $B \rightarrow D^{**} \ell \nu$
 - $B \rightarrow D^{*+} H_c X$, where H_c decays semileptonically
 - combinatorial - wrong-sign final state combinations
 - Hadrons (π, K, p) misidentified as muons

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

$$R(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$$

2.1σ above SM

- Dominant systematic uncertainty - size of simulation sample



$R(D^*)$ hadronic at LHCb [PRL 120, 171802 (2018)], [PRD 97, 072013 (2018)]

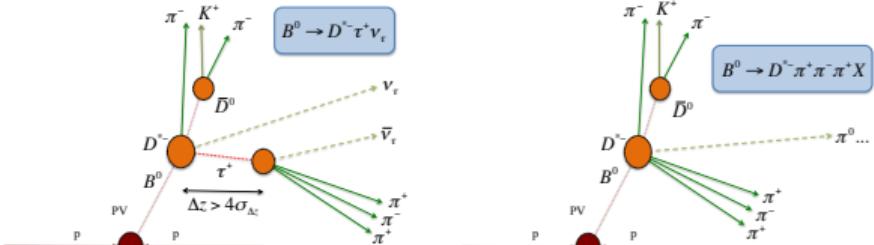
$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^\pm)}$$

$$R(D^*) = \mathcal{K}(D^*) \left\{ \frac{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^\pm)}{\mathcal{B}(B^0 \rightarrow D^{*-} \ell\nu_\ell)} \right\}$$

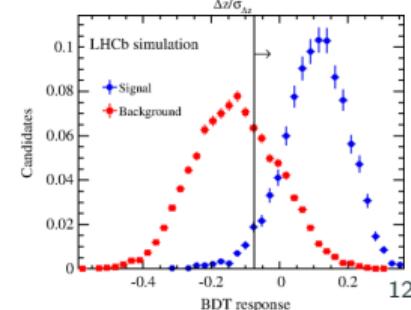
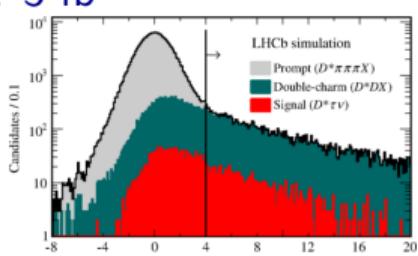
ext. input

Three-prong **hadronic** decays $\tau^+ \rightarrow \pi^+ \pi^- \pi^+(\pi^0) \bar{\nu}_\tau$

- Main sources of backgrounds
 - $B \rightarrow D^{*-} 3\pi^\pm X$
 - Double charm ($B \rightarrow D^{*-} (D_s^+, D^+, D^0) X$)
- $B \rightarrow D^{*-} 3\pi^\pm X$ suppressed by requiring the τ vertex to be downstream w.r.t B vertex along the beam direction
- A BDT based on kinematics and resonant structure to suppress $B \rightarrow D^{*-} D_s^+ X$



Run 1: 3 fb^{-1}



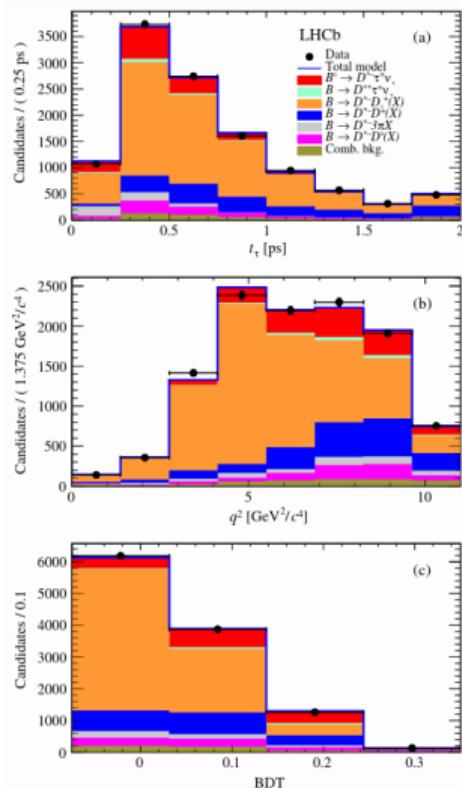
$R(D^*)$ hadronic at LHCb [PRL 120, 171802 (2018)], [PRD 97, 072013 (2018)]

- 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
- $N(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau) = 1296 \pm 86$

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

1 σ above SM

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



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

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

Muonic $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$

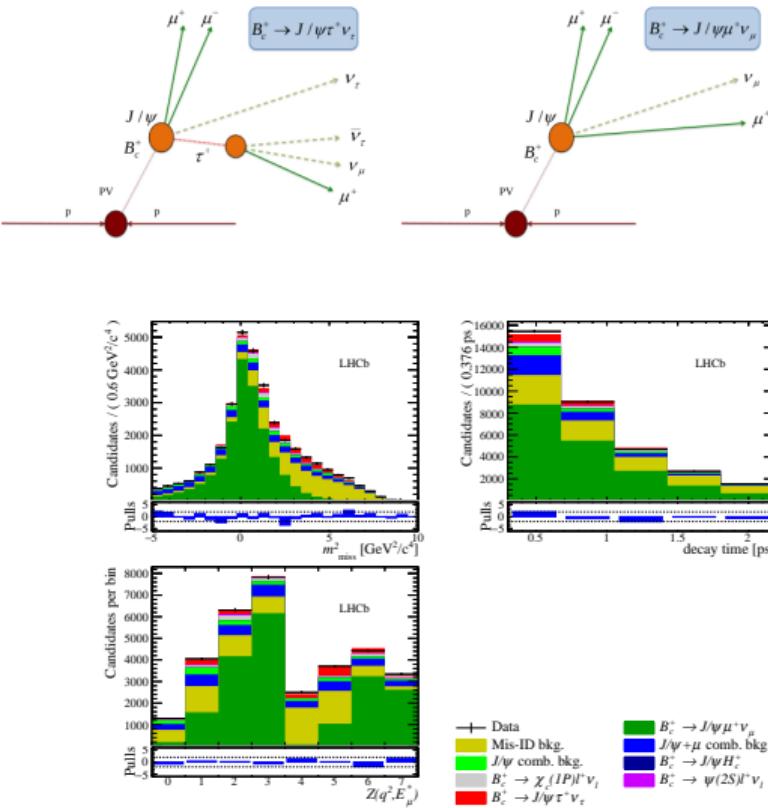
Run 1: 3 fb^{-1}

- Signal extraction using binned template fit to m_{miss}^2 , B_c decay time and Z (Z contains 8 bins in E_μ and q^2).
- Main backgrounds - $B_c \rightarrow H_c X$, hadron mis-ID for μ

$$R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$$

2 σ above SM

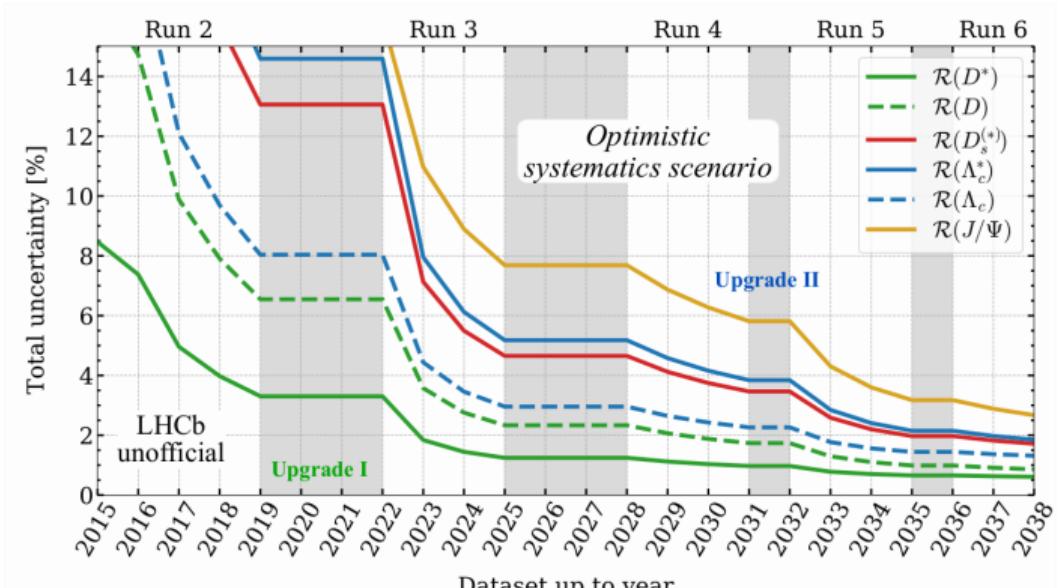
LFU tests at LHCb



Resmi P K (CPPM)

Prospects

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



[arXiv:2101.08326, arXiv:1808.08865]

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

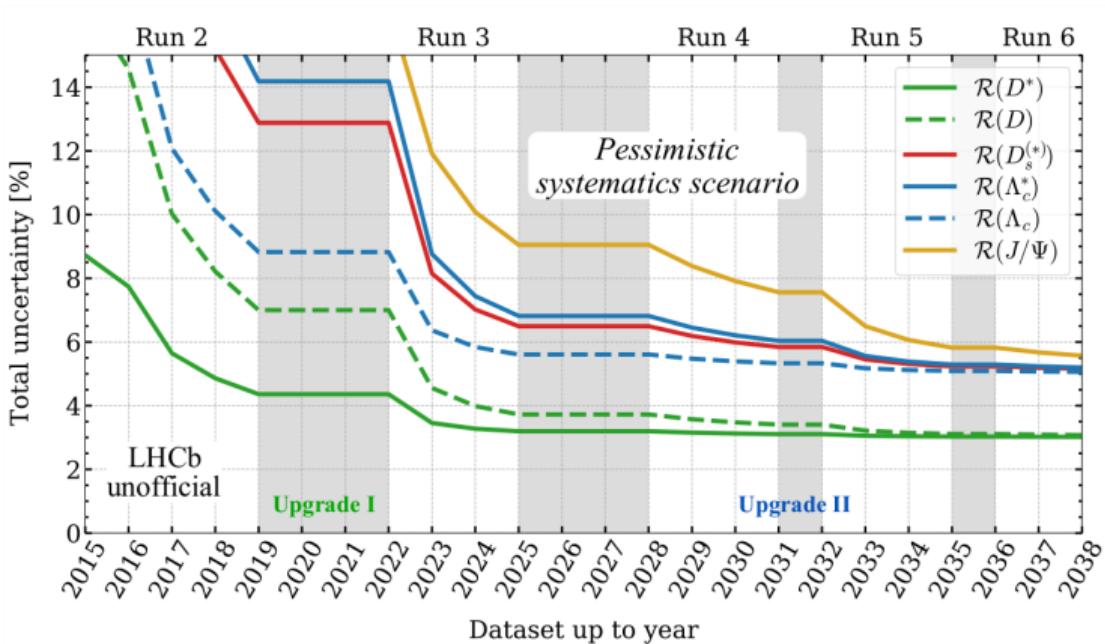
Summary

- LHCb has performed various LFU ratio measurements in $b \rightarrow c\ell^\pm\nu_\ell^{(-)}$ decays, and they show tensions with the SM predictions
- The decay $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau$ has been observed for the first time with a significance of 6σ
- $R(\Lambda_c^+)$ measurement \Rightarrow first involving a baryonic decay
- Measurements are being updated with the full LHCb dataset
- New LFU ratios and new observables are being explored
- Data from LHCb upgrade will further improve the measurements and give a clearer picture
- With the start of LHCb Run 3, interesting times ahead!

thank you!

Back-up slides

$R(X_c)$ prospects



[arXiv:2101.08326, arXiv:1808.08865]